# THE HERSCHEL BRIGHT SOURCES SAMPLE 

TOM J. L. C. BAKX

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The cover image is a grey-scale image of the GAMA- 15 fields from Figure 2.1, to which I owe my gratitude to Mattia Negrello. I refer to the various ground-based observations with an image of a telescope, and allude to multi-wavelength analysis on the right-hand side. In the centre is the ALMA-observation of SDP. 81 Negrello et al. (2010), which is currently the most famous of the sub-millimetre selected lensed sources, observed with unprecidented detail by the ALMA Science Verification (ALMA Partnership, 2015).
Tom J. L. C. Bakx: The Herschel Bright Sources Sample, The brightest high-redshift galaxies found in the H-ATLAS survey, © July 18, 2018

Mountains should be climbed with as little effort as possible, and without desire.

The reality of your own nature should determine the speed.

If you become restless, speed up. If you become winded, slow down.

You climb the mountain in an equilibrium between restlessness and exhaustion.

Then, when you're no longer thinking ahead, each footstep isn't just a means to an end, but a unique event in itself...

To live only for some future goal is shallow. It's the sides of the mountains which sustain life, not the top.

When I heard the learn'd astronomer,
When the proofs, the figures, were ranged in columns before me,

When I was shown the charts and diagrams, to add, divide, and measure them,

When I sitting heard the astronomer where he lectured with much applause in the lecture-room,

How soon unaccountable I became tired and sick, Till rising and gliding out I wander'd off by myself,
In the mystical moist night-air, and from time to time, Look'd up in perfect silence at the stars.

- Walt Whitman

Far-infrared observations have detected dusty star-forming galaxies, a subset of galaxies which is extremely dust-extincted from the ultraviolet down to near-infrared colours. Recent studies show that this population of sources contributes significantly to the history of starformation, especially out to very high redshift.

Recent surveys with the Herschel Space Observatory have uncovered around half a million of these sources, with the largest of these surveys, the H-ATLAS, covering 616 square degrees. One of the most exciting discoveries is the lensing nature of the brightest of these sources, where the gravitational potential of a foreground galaxy lenses and amplifies the signal. The applications of gravitational lensing range from studying individual sources down to unprecidented resolution at high redshift in sub-mm wavelengths with ALMA, to cosmological studies by analysing the distribution of groups of lenses.

In this thesis, I explore the effect of applying a more inclusive selection criterion for lensed sources, and study the properties of the sources that are selected. Whereas the first attempts at finding lensed sources use a strict $S_{500 \mu \mathrm{~m}}>100 \mathrm{mJy}$ flux density cut, the sample I study is selected with a flux cut at 80 mJy : The Herschel Bright Sources (HerBS) sample. A photometric redshift cut of $z_{p h o t}>2$ is also taken, as most lensing takes place out at higher redshift. This redshift is calculated by fitting a spectral template to the 250,350 and $500 \mu \mathrm{~m}$ observations from the Herschel SPIRE instrument.

I push down the selection flux in order to select more lensed sources from the sub-mm surveys, whilst potentially including several unlensed sources. These unlensed sources could be among the most intrinsically luminous and star-forming objects in the Universe. Only less than five of such objects are known to exist, while our HerBS sample could contain up to 35 of these sources, which could teach us about the upper-limits of star-formation and their contribution to forming the most massive galaxies in the Universe.

I use $850 \mu \mathrm{~m}$ SCUBA-2 observations on the James Clerk Maxwell Telescope (JCMT) to remove blazar interlopers, which results in 209 sources in the HerBS sample, after removing 14 blazar sources. At the time I wrote the paper upon which Chapter 2 is based, 24 sources had a spectroscopic redshift. I use this sub-sample to fit a two-temperature modified blackbody, and find a cold-body temperature of 21.3 K , a warm-body temperature of 45.8 K , a mass ratio of 26.7 and a dustemissivity index of 1.8 . These values do not challenge the current knowledge of sub-mm galaxies, but the quality of the fit suggests a

Section 1.3 gives an overview of the
power of
gravitational lensing

Figure 1.5 shows the selection criteria for lensed sources
Figure 2.8 shows the luminosity and redshift distribution of HerBS sources

Section 1.3.3 details
the importance of these unlensed sources

Figure 2.4 shows how the selection was implemented

Figure 2.7 shows the fitting of the two-temperature modified black-body

Figure 3.7 shows the spectra fitted to the photometric data with a fixed spectroscopic redshift
Figure 3.5 shows the spectra found with the IRAM 3om observations

Cutouts of all HerBS sources can be found in the Appendix . 2

Figures .33 and .35 show the spectroscopic observations for these two sources

Figure 5.6 shows we find many of the VIKING counterparts

Figure 4.6 shows the angular probability distributions
Figure 4.4 shows the lensing offset proability distribution
large diversity among the galaxies in the sub-sample, and that they are poorly fitted by a single template.
This diversity is also found by the spectroscopic observations with the IRAM 3om-telescope observations on eight of the highest-redshift ( $\mathrm{z}_{\text {phot }}>4$ ) sources of the HerBS sample. We found five spectroscopic redshifts, with one of the sources at the highest known HerBS redshift at $z_{\text {spec }}=4.8$. The spectrum fitted in Chapter 2 shows a poor agreement with the photometric data points.
The spatial resolution of the SPIRE instrument on Herschel is not fine enough to resolve the structure of these high-redshift sources. Worse still, the beam width is so large, ranging from 18 to 36 arcseconds, that it is unsure whether we observe a single galaxy, or perhaps observe multiple galaxies together. The beam width of the SCUBA-2 instrument at $850 \mu \mathrm{~m}$ is only 13 arcseconds. In the case the sample would be dominated by blended sources, one would expect to resolve several of the sources into their individual components. This is not seen in any of the continuum images, although the blended sources might be blended on scales smaller than 13 arcseconds.

The IRAM-observations of two sources have detected multiple, contradicting spectral lines, suggesting we might be observing multiple sources, instead of a single source, that are aligned along the line-ofsight. Unfortunately, only single spectral lines have been observed per source, and we are awaiting more observations verifying the blending nature of these sources, which are still expected to lie at high redshift.
The hypothesis that our sample consists for a significant portion out of blended sources is in contradiction with multi-wavelength observations. When I look at the positions of these sources at different wavelengths, I find that most sources have a counterpart in these multi-wavelength observations, also when chance-encounters are considered. Considering the high redshift nature of our sources, together with the possibility of lensing, these counterpart sources are most likely foreground, lensing galaxies.
I compare the positions of the HerBS sources to both the Sloan Digital Sky Survey (SDSS), which covers 121 out of the 209 sources, and the VISTA Kilo-Degree Infrared Galaxy (VIKING) survey, which covers 98 HerBS sources. For the SDSS counterparts, I use the H-ATLAS catalogue of counterpart sources, which was done by using a statistical estimator. This statistical estimator assumes a certain angular distribution between the sources in the Herschel position, and the optical or near-infrared observations. I expect the majority of my sources to be lensed, and therefore I adjust the original angular distribution by including the effect of gravitational lensing. The adjustment is based on 15 ALMA observations of lensed, bright H-ATLAS sources. The revised analysis finds 41 counterparts, instead of the 31 that were found by the initial analysis.

This catalogue is not available for VIKING counterparts, and therefore I had to do the entire analysis for the VIKING counterparts, starting from the VIKING fields. I use the sextractor package to extract the potential counterparts, and then derive the necessary estimators for the statistical method. I find a significantly different angular distribution, even than the one derived from the 15 ALMA observations of lensed H-ATLAS sources. The angular distribution extends to much larger angular scales, potentially suggesting a stronger contribution to galaxy-cluster lensing, which produces larger angular offsets due to the larger masses and different mass profiles associated with galaxy clusters.

In total, I find 60 counterparts with a reliability greater than $80 \%$ to the 98 HerBS sources covered by VIKING. Possibly, not all counterparts could be positively identified, as the analysis showed $88 \%$ of sources has a source within 10 arcseconds when taking chance encounters into account. This is mostly due to ambiguity between several nearby sources, which causes a low reliability of the counterpart identification, but it does allow us to state that an counterpart could be present.

A cosmological model suggest that $76 \%$ of our sources are gravitationally lensed. This model assumes a certain distribution of halo masses, and lensing magnification based on mass density profiles. The validity of these models has been shown with the 15 ALMA observations of lensed H-ATLAS sources, and also agree with the SMA observations from Bussmann et al. (2013).

The IRAM observations provide me with both line luminosities and line velocity widths. Larger galaxies are expected to be brighter, and have larger line velocity widths. The five sources with confirmed redshift (and therefore line luminosity) have a luminosity-to-velocity width ratio agreeing with a magnification of around 10 , when compared to unlensed, and known lensed sources.

I show that the SDSS is not deep enough to observe all the foreground galaxies, while the VIKING observations agree with the results from the simulation, with 60 sources actually cross-compared, and $88 \%$ of sources have a source nearby, when accounting for random chance.

Figure 5.2 shows the results of the
SEXTRACTOR routine

Figures 5.6 and 5.7 show the angular probability distributions derived from the VIKING routines

Figure 5.10 and Appendix .8 show the images from the VIKING fields and their counterpart identification

Figure 3.10 shows the line luminosity and velocity, which suggests the sources are lensed
Figure 5.13 shows how the fraction of lensed sources changes with flux density in the HerBS sample using the SDSS and VIKING counterparts

## SAMENVATTING

Waarnemingen in het ver-infrarood hebben een type sterrenstelsels ontdekt wiens hoeveelheid stof een extreem fel en rood sterrenstelsel veroorzaakt. In deze sterrenstelsels absorbeert het interstellaire stof het sterrenlicht dat wordt uitgestraald door pasgevormde sterren. Dit stof zendt zijn warmte-straling weer uit in submillimeter golflengten. Dit licht ontsnapt makkelijk uit deze stoffige contreien. Hedendaagse studies hebben aangetoond dat deze submillimeter sterrenstelsels verantwoordelijk zijn voor het vormen van significante portie van alle sterren in het Universum, en dat ze vooral actief zijn in het vroege Universum.

Het Herschel Ruimte Observatorium heeft met verscheidene waarnemingsprojecten grote delen van de hemel geobserveerd, en heeft in totaal rond een half miljoen objecten van zulke objecten gedetecteerd. De grootste van deze projecten is, met 616.4 vierkante graad, de zogenaamde Herschel-Astrophysical Terahertz Large Area Survey (HATLAS). Een van de spannendste recente ontdekkingen is de realisatie dat de felste van deze objecten wordt versterkt door het zwaartekra veld van sterrenstelsels op de voorgrond. Deze zogenaamde zwaartekrach lenzen kunnen ons veel vertellen over ons Universum: het lens-effect dient als een vergrootglas voor het bestuderen van individuele bronnen tot ongekende resolutie in submillimeter golflengten, maar ook kunnen grote verzamelingen van deze zwaartekrachtslenzen de eigenschappen van het Universum zelf bepalen.

In dit thesis onderzoek ik het effect van een ruimer selectiecriterium bij de zoektocht naar submillimeter zwaartekrachtslenzen, en bestudeer ik de eigenschappen van deze objecten. Eerdere zoektochten nemen een strikt criterum op de felheid aan ( $\mathrm{S}_{500 \mu \mathrm{~m}}>100 \mathrm{mJy}$ ), terwijl ik in dit onderzoek het criterium laat zakken naar $\mathrm{S}_{500 \mu \mathrm{~m}}$ $>80 \mathrm{mJy}$. Aangezien de meeste zwaartekrachtslenzen zich op grote afstand van ons bevinden, stel ik een afstands-eis in van $\mathrm{z}_{\text {phot }}>2$. Deze roodverschuiving is berekend met de 250, 350 and $500 \mu \mathrm{~m}$ intensiteiten van het Herschel-SPIRE instrument.

Omdat ik de selectie-criteria verzwak, selecteer ik niet louter meer zwaartekrachtslenzen. De bronnen die niet versterkt worden door objecten in de voorgrond zijn intrinsiek de felste en meest extreem sterrenvormende sterrenstelsels in het Universum. In totaal zijn er minder dan 5 van dit soort bronnen bekend, terwijl er mogelijk 35 van deze objecten zich in mijn collectie bevinden. Deze kunnen ons iets vertellen over de limieten van stervorming in sterrenstelsels, en hoe dit de evolutie van de zwaarste sterrenstelsels in het Universum beinvloed.
reis ver
drink wijn
denk na
lach hard
duik diep
kom terug
— Spinvis

Sectie 1.3 geeft een betsrzicht van het wetenschappelijke potentieel van zwaartekrachtslenzen

Grafiek 1.5 laat de effectiviteit van de lens-selectiecriteria zien

Sectie 1.3 .3 bespreekt het belang van deze
niet-versterkte bronnen

Grafiek 2.4 laat de selectie van blazar-bronnen zien
Grafiek 2.8 laat de helderheid en de roodverschuiving van de HerBS bronnen zien

Grafiek 2.7 laat de passing op deze bronnen zien

Grafiek 3.7 laat de gepaste spectra zien

Grafiek 3.5 laat alle spectra van de $30 m$ telescoop zien

## http:

//www.astro.ucla. edu/~wright/ CosmoCalc.html is een handige manier
roodverschuiving inzichtelijker te maken

Plaatjes in alle HerBS bronnen zijn te zien in de Appendix . 2

Grafieken. 33 en. 35 laten de spectra van deze twee bronnen zien

Ik gebruik de $850 \mu \mathrm{~m}$ SCUBA-2 waarnemingen met de James Clerk Maxwell Telescope (JCMT) om blazar-bronnen te verwijderen uit de oorspronkelijke collectie. Dit rest mij met 209 bronnen in de Herschel Bright Sources (HerBS) collectie, waarbij ik 14 blazar-objecten heb verwijderd. Ten tijde van het schrijven van Hoofdstuk 2 waren er 24 HerBS bronnen met een roodverschuiving die berekend is aan de hand van hun spectraallijnen. Deze afstandsmeting is betrouwbaarder dan de oorspronkelijke selectie, en met hun roodverschuiving kan ik een een spectraal model passen. Ik neem het model van een warm-en-koud grijslichaam aan, dat rekening houdt met de hoeveelheid stof. De passing vindt een temperatuur van het koude onderdeel van 21.3 K , een warm onderdeel op 45.8 K . De massaverhouding tussen koude en warme onderdelen is 26.7 , en de stof-emissie index is 1.8 . Deze waarden zijn allemaal binnen de verwachtingen van eerdere waarnemingen, maar het spectrum zelf past niet goed met de data. Dit sugereert dat er een grote diversiteit is tussen de verschillende sterrenstelsels, en dat ze niet goed te beschrijven zijn met één enkel spectrum.
Ik vind dezelfde variëteit ook bij de acht bronnen die met de IRAM 30m-telescoop spectroscopisch waargenomen zijn. Deze bronnen zijn geselecteerd om hun hoge roodverschuiving ( $\mathrm{z}_{\mathrm{phot}}>4$ ). Vijf van deze bronnen vertonen meerdere spectraallijnen die instemmen met één enkele roodverschuiving, waarvan een bron de hoogste bekende roodverschuiving heeft binnen HerBS collectie, met $\mathrm{z}_{\text {phot }}=4.8$, toen het Universum slechts $9 \%$ van zijn huidige leeftijd was.
De ruimtelijke resolutie van het SPIRE-instrument op Herschel is niet fijn genoeg om samenstelling van deze bronnen op hoge roodverschuiving te zien. Sterker nog, de resolutie is zo grof (tussen 18 en 36 boogseconden), dat het niet zeker is of we een enkel fel sterrenstelsel zien, of meerdere sterrenstelsels verwarren als een enkele bron. De 850 micron waarnemingen met het SCUBA-2 instrument hebben een fijnere resolutie, met 13 boogseconden. In het geval dat onze collectie veel van dit soort samengestelde bronnen bevat, zouden we verwachten dat verschillende van deze bronnen uiteen vallen in hun individuele componenten. Dit is niet waargenomen, alhoewel het mogelijk is dat deze componenten op een kleinere schaal samenklonteren dan 13 boogseconden.
De spectroscopische IRAM-observaties vinden twee bronnen met meerdere tegengestelde spectraallijnen, die niet verklaard worden door een enkele bron. Het is dus mogelijk dat meerdere bronnen in een lijn liggen. Jammergenoeg zijn er louter enkele lijnen gedetecteerd, en is het dus nog niet een robuust resultaat. We wachten nog op extra waarneemtijd om de samenstelling van meerdere hoge-roodverschuiving bronnen te bevestigen of te ontkrachten.
De hypothese dat onze collectie uit samengestelde bronnen bestaat is ook in tegenspraak met de waarnemingen in verschillende golflengten.

Als ik de posities rond deze bronnen bekijk, vind ik dat de meeste bronnen een tegenhanger hebben, ook als ik rekening houd met de kans van een nabij-liggende, ongerelateerde bron. Gezien het feit dat mijn bronnen zich op hoge roodverschuiving bevinden, en in de wetenschap dat er een grote hoeveelheid zwaartekrachtslenzen zijn, doet dit vermoeden dat ik louter de sterrenstelsels in de voorgrond zie, die als lens dienen.

Ik vergelijk de posities van de HerBS sterrenstelsels met de waarnemingen in de optische Sloan Digital Sky Survey (SDSS) en de infrarode VISTA Kilo-Degree Infrared Galaxy (VIKING) waarnemingen. 121 van de 209 HerBS bronnen liggen in de SDSS waarnemingen, en 98 bronnen bevinden zich in de VIKING waarnemingen. Voor de SDSS tegenhangers gebruik ik de H-ATLAS catalogus, die door middel van een statistische schatter een kans en betrouwbaarheid voor elke bron bepaalt. Omdat de SDSS waarnemingen niet de Herschelbron bekijkt, maar alleen de sterrenstelsels in de voorgrond ziet, verwacht ik dat alle HerBS bronnen zich niet op precies dezelfde plek bevinden. Hierom pas ik de statistische schatter aan, aan de hand van een model dat gebaseerd is op 15 hoge resolutie ALMA observeringen. De aangepaste analyse voorziet ons van 41 tegenhangers, in plaats van de 31 tegenhangers die oorspronkelijk gevonden waren.

Deze catalogus is niet beschikbaar voor de VIKING waarnemingen, en daarom moet ik zelf de hele statistische analyse voor de VIKING tegenhangers doen, startend vanaf de VIKING waarnemingen. Allereerst identificeer ik alle individuele bronnen met het sexTRACTOR programma, en daarna leid ik alle schatters van de statistische methode af. Hier vind ik een significant andere verdeling van de positie dan dat ik verwacht, zelfs dan met de ALMA-afgeleide nieuwe verdeling. Wellicht suggereert dit een grotere contributie van het lens-effect door sterrenstelsel-clusters, in plaats van individuele sterrenstelsels. Deze clusters zorgen voor grotere afstandsverschillen, door hun grotere massa en meer uniforme massa-verdelingen.

In totaal vind ik 60 tegenhangers in de VIKING waarnemingen, met een kans groter dan $80 \%$ dat het echt de tegenhanger is, van in totaal 98 HerBS bronnen. Het is mogelijk dat niet alle tegenhangers betrouwbaar geidentificeerd konden worden, aangezien de analyse laat zien dat $88 \%$ van de bronnen een object binnen 10 boogseconden zou moeten hebben, zelfs wanneer er rekening wordt gehouden met de kans op nabij-liggende, ongerelateerde bronnen. De voornaamste reden dat het niet lukt om een statistisch betrouwbare tegenhanger te vinden is door de ambiguïteit tussen meerdere objecten, waardoor het wel mogelijk is om te stellen dat er een tegenhanger is, maar welke het precies is, blijft onduidelijk.

Kosmologische modellen, dewelke de evolutie van sterrenstelsels nabootsen, laten zien dat $76 \%$ van de bronnen waarschijnlijk zwaartekrachtslenzen zijn. Het gebruikte model neemt een bepaalde massa-distributie

Grafiek 5.6 laat zien dat we de meeste tegenhangers in andere golflengten terugvinden

Grafiek 4.6 laat de aangepaste
positie-verdeling zien
Grafiek 4.4 laat deze ALMA
positie-verdeling zien

Diagram 5.2 laat de
sextractor
procedure zien
Grafieken 5.6 en 5.7
laten de positie
distributie zien die
uit de VIKING
analyse komt

Plaatjes van de VIKING analyse bevinden zich in Figuur 5 .10 en de Appendix 8

Grafiek 3.10 laat de felheid en snelheid van de viif bronnen zien, die ons doen vermoeden dat de bronnen zwaartekrachtslenzen
$z i j n$
Grafiek 5.13 laat zien hoe de fractie van zwaartekrachtslenzen veranderd met de HerBS flux-dichtheid in de SDSS en VIKING
tegenhangers
van de donkere materie halo aan doorheen het hele Universum, en daarnaast neemt het een bepaalde verdeling aan van de vergrotingsfactor als functie van de halo-massa van de lens. Deze modellen zijn in overeenstemming met de data van de 15 ALMA-geobservereerde H-ATLAS bronnen, en ook met eerder geobserveerde bronnen met het SMA observatorium (Bussmann et al., 2013), die de gelensde structuur kunnen observeren.
Mijn IRAM-waarnemingen leveren beide de felheid van de lijnen, maar ook de gemiddelde snelheid van de sterrenstelsels. De aanname is dat een fellere lijn behoort bij een groter sterrenstelsel, die dan weer een grotere rotatie-snelheid heeft. De vijf bronnen met een bevestigde roodverschuiving, waarvan we ook lijn-felheid weten, hebben een felheid en een rotatie-snelheid die overeenkomt met een vergrotingsfactor van 10 keer, wanneer ik ze vergelijk met normale sterrenstelsels en met bekende zwaartekrachtlenzen.
Ik laat zien dat de SDSS observeringen niet diep genoeg is om alle voorgrond lenzen te detecteren, maar de VIKING velden zijn wel diep genoeg om een fractie van voorgrond bronnen te vinden die overeenkomt met de modellen, met 60 bronnen die betrouwbaarder zijn dan $80 \%$, en $88 \%$ van HerBS bronnen heeft een object binnen 10 boogseconden heeft liggen, wanneer rekening wordt gehouden met de kans van een nabij-liggende, ongerelateerde bron.

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S. and Cooray, A. and Covone, G. and Danese, L. and Dannerbauer, H. and Fu, H. and Greenslade, J. and Gurwell, M. and Hopwood, R. and Koopmans, L. V. E. and Napolitano, N. and Nayyeri, H. and Omont, A. and Petrillo, C. E. and Riechers, D. A. and Serjeant, S. and Tortora, C. and Valiante, E. and Verdoes Kleijn, G. and Vernardos, G. and Wardlow, J. L. and Baes, M. and Baker, A. J. and Bourne, N. and Clements, D. and Crawford, S. M. and Dye, S. and Dunne, L. and Eales, S. and Ivison, R. J. and Marchetti, L.
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> Travel changes you.
> As you move through this life and this world, you change things slightly, you leave marks behind, however small. And in return, life - and travel - leaves marks on you.
> _- Anthony Bourdain (1956-2018)

I owe an enormous debt of gratitude towards a large group of people, without whom it would have been difficult (or downright boring) to work on this project for the past four years. Foremost, I have to thank my supervisor, Steve Eales, who had to put up with numerous readings of marginally-improving drafts of my papers and this thesis. He taught me a lot, and I feel we are kindred spirits with our regard of bureaucratic policies.

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Figure 2.10

Figure 3.1

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Figure $4.7 \quad$ This figure shows the measured position from the catalogues on the x-axis, with the maximum angle on the $y$-axis. At this maximum angle, the reliability is equal to o.8, which is the threshold for a reliable and unreliable detection. I see that $\mathrm{R}>0.8$ counterparts (orange plusses) lie on the left-hand side of the $\mathrm{y}=\mathrm{x}$ line, whilst $\mathrm{R}<0.8$ counterparts (black and white crosses) lie on the right-hand side. This is as expected, as on this line, the reliability of the counterparts would be o.8. I note many $\mathrm{R}<0.8$ sources close to the $\mathrm{y}=\mathrm{x}$ line (grey line).

Figure 4.8 The left image shows several SDSS counterparts (orange cross) around a single SPIRE-source (blue circle). The dotted circle indicates the angle at which the reliability is equal to o.8. When I recalculate the reliability, I divide the likelihood of the most likely counterpart, L, by the value of the angular probability distribution, $f(r) \sim \exp \left(-\theta^{2} / 2\right)$. This gives me the likelihood, in the case both SPIRE and SDSS source were on exactly the same position, as shown in the centre image, $\mathrm{L}_{0}$. In the right-hand image, I calculate the new likelihood. Here I use the angular probability distribution $f^{\prime}(r)$, which has been adjusted to include the offset from gravitational lensing, and follow the normalization of equation 4.5 . The black-dashed line indicates the new maximum angle, within which the most likely counterpart has a reliability greater than o.8, $\theta_{\text {max }}$.

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## Part I

## THEORY \& SAMPLE DEFINITION

Far-infrared observations have detected dusty star-forming galaxies, which are severely dust-extincted in the optical and near-infrared colours. Recent studies show this population of sources to be important for understanding the cosmic history of star-formation, and these sources might explain the existence of massive passive galaxies in the local Universe. Here, we provide a theoretical overview, and introduce a new sample of sources that might help uncover some of the mysteries surrounding these extreme sources and help study one of their most intriguing properties: gravitational lensing.

### 1.1 THE COMPLETE PICTURE



Figure 1.1: Telescopes and bathyscaphes and sonar probes of Scottish lakes, Tacoma Narrows bridge collapse explained with abstract phase-space maps, some x-ray slides, a music score, Minard's Napoleonic war: the most exciting new frontier is charting what's already here

This stranded man is not alone in his restricted consideration of the reality around him. Only with the advent of sub-mm technology, did astronomers find out how much of the total energy budget is radiated in far-infrared colours. In the nineties, the Far-InfraRed Absolute Spectrophotomer (FIRAS) aboard the space-based Cosmic Background Explorer (COBE) measured the absolute energy spectrum above $150 \mu \mathrm{~m}$, and showed that the total energy emitted in far-infrared and submillimetre wavelengths is similar to all energy emitted in optical and ultra-violet observations (Puget et al., 1996).

Up until that moment, as far as the eye could see* only provided a partial picture of the Universe, blind to half of the star-formation activity. The far-infrared and sub-mm components are thus crucial to get a complete picture of what is actually there.

# It's all really there. That's what really gets you. But you gotta stop and think about it, to really get the pleasure, about the complexity, the inconceivable nature of nature. 

K-correction was first used to describe magnitudes, and hence the fact that it is negative actually refers to brighter sources

- Richard P. Feynman

With the advent of sub-millimetre detector technology came the discovery of a new type of galaxies, which are extremely bright in the sub-mm, but have their optical and near-infrared components obscured by dust (for an initial review: Blain et al. (2002), with an excellent follow-up review: Casey, Nayarayan, and Cooray (2014)). Their high luminosity suggests a star-formation rate that significantly contributes to the stellar population, especially out at high redshifts.
These star-formation rates range from hundreds to several thousands of solar masses per year, and might be close to the theoretical limit (Chapman et al., 2015). The comoving density of ULIRGs cal limit (Chapman et al., 2015). The comoving density of ULIRGs
$\left(10^{13} \mathrm{~L}_{\odot}>\mathrm{L}_{\mathrm{FIR}}>10^{12} \mathrm{~L}_{\odot}\right)$ at $\mathrm{z}=2$ to 4 is about a thousand times greater than in the local universe, and these dusty star-forming galaxies are estimated to contribute about $10 \%$ of the total star formation in this redshift range (Hughes et al., 1998; Blain et al., 1999; Smail et al., 2002; Wardlow et al., 2011; Casey, Nayarayan, and Cooray, 2014). This means that sub-millimeter galaxies (SMGs) contribute significantly to the peak in cosmic star formation, which occurred around z ~ 2.3 (Chapman et al., 2005).
While the star-formation rate of the Universe has been measured up to redshift $\mathrm{z} \sim 8$ to 10 in rest-frame UV surveys, these studies only measure the unobscured star-formation rates (Madau and Dickinson, 2014; Casey et al., 2018), see Figure 1.2. The star formation processes in these dusty star-forming galaxies (DSFGs) tend to be obscured by the dust, and are missed by current optical and ultra-violet investigations of the cosmic star-formation rate. An added benefit of using sub-mm observations to measure the obscured star-formation rate is that sub-mm flux density falls only slowly with redshift, because of the negative K-correction: sub-mm observations observe the Rayleigh-Jeans part of the modified blackbody spectrum, which causes the flux density to increase as the galaxy's redshift increases. This increase is able to compensate for the cosmological dimming due to the increase of luminosity distance, e.g. a redshift 1 or 4 galaxy has a similar flux density in sub-mm wavelengths (Blain and Longair, 1993; Blain et al., 2002; Bethermin et al., 2015). Figure 1.3 graphically shows the K-correction for different wavelengths.
While the star-formation rate of the Universe has been measured


Figure 1.2: The period of maximum star-formation occurred around $z=2$. The rest-frame UV surveys are able to probe unobscured starformation out to a redshift $z \sim 8$ to 10 , while infrared and submm measurements are no longer complete from a redshift $z \sim 2$. While there exist measurements of sub-mm and infrared sources out to redshifts of 7 and 9 (Strandet et al., 2017; Marrone et al., 2018; Hashimoto et al., 2018), they do not provide a clear picture of the behaviour of a complete sample of galaxies out at these redshifts. Figure is adapted from Casey et al. (2018).

### 1.2.1 Sub-millimetre observations

The relatively late development of sub-mm astronomy was due to the high atmospheric absorption of sub-mm radiation and the late development of sub-mm technology. The atmospheric absorption required telescopes to be at high-and-dry locations such as Mauna Kea, the South Pole and the Atacama desert. The late development of instruments caused these initial observations to be slow, detecting a single source every couple of hours (Hughes et al., 1998).

This state changed with the launch of the Herschel Space Observatory, whose instruments PACS (Poglitsch et al., 2010) and SPIRE (Griffin et al., 2010) managed to detect sources significantly faster. Large area surveys increased the number of detected sub-mm sources from hundreds to half a million. The largest two of these surveys cover over a 1000 square degrees: the H-ATLAS survey (Herschel Astrophysical Terahertz Large Area Survey - Eales et al. (2010); Valiante et al. (2016))
or precariously dangling the telescopes from weatherbaloons


Figure 1.3: A fixed-luminosity galaxy is observed at different wavelengths (different colour lines) for a varying redshift on the x-axis. The cosmological dimming decreases the brightness, but this is compensated in the sub-mm by the shape of the spectrum. As the galaxy is pushed to higher redshift, the rest-frame observers see more of the brighter components of the Rayleigh-Jeans part of the blackbody spectrum. The startling conclusion: the same source appears brighter at a larger distance. Adapted from Blain et al. (2002)
and the Herschel Multi-tiered Extragalactic Survey (HerMES; Oliver et al. (2012)).
These large-area surveys allow us to select sources that are among the brightest sources in the Universe. Models and observations find a large percentage are gravitationally lensed ULIRGs (Ultra-Luminous Infrared Galaxies, $10^{12} \mathrm{~L}_{\odot}<\mathrm{L}_{\text {FIR }}<10^{13} \mathrm{~L}_{\odot}$ ) and unlensed HyLIRGs (Hyper-Luminous Infrared Galaxy, $\mathrm{L}_{\text {FIR }}>10^{13} \mathrm{~L}_{\odot}$ ) at high redshift (Negrello et al., 2010). A similar effort to finding high-redshift sources was undertaken by the South Pole Telescope (Vieira et al., 2013; Weiß et al., 2013). They select their sources at 1.4 mm , resulting in a higher fraction of sources at high redshift.

### 1.2.2 Distance estimates of high-redshift sub-mm sources

In order to study the intrinsic properties of these sub-mm sources accurately, we need to find their distance. With this distance, we can calculate the luminosity, dust mass and temperature of these sources. Furthermore, distance (or redshift) distributions also can be used to compare populations of galaxies against one another, which could be used to figure out the evolutionary phase of the populations, and their significance to the history of star-formation (Casey, Nayarayan, and Cooray, 2014; Strandet et al., 2016).

These large-area sub-mm surveys observe the emission of warmedup dust, typically radiated in the form of a modified black-body spectrum. Dust is heated up by stellar light from recently formed stars. Unfortunately, this typical spectrum has a degeneracy between temperature and redshift in sub-mm photometry. This means that in sub-mm colours, a high-redshift galaxy with hotter dust appears the same as a low-redshift galaxy with colder dust. Due to this, reliable distance estimates have to use the frequency shift of spectral lines to find the redshift of sub-mm galaxies accurately.

Initial attempts at finding the redshifts through optical and nearinfrared spectral lines ran into the problem of the large beam-size of sub-mm wavelengths. Since single-dish sub-mm surveys typically have beamsizes of the order of 10 to 30 arcseconds, up to tens of optical and near-infrared sources could be found within a single beam, which made it difficult to find the counterpart of the sub-mm source. This was only exacerbated by the dust-extinction, causing the bright sub-mm source to be difficult to detect in the optical or near-infrared follow-up. To this end, continuum images from high-resolution radio observatories were used as precursors to find the position. Unlike submm colours, the optical, near-infrared and radio colours of a sub-mm galaxy do not have a negative K-correction, and thus an increase in redshift causes a significant decrease in the source brightness. Samples selected by such redshift searches will struggle to include the highest redshift sources.

Due to these drawbacks of optical, near-infrared and radio redshift searches, there was a strong push towards the development of spectroscopic instruments in the sub-mm with a wide relative bandwidth, $\delta f / \mathrm{f}$, necessary for finding spectral lines. Early sub-mm spectroscopic instruments had relative bandwidths of less than $1 \%$, but the development of Z-Spec (Bret J. Naylor, 2003), the Redshift Search Receiver (Erickson, 2007), Zpectrometer (A. J. Baker and M. S. Yun, 2007) and EMIR (Carter, M. et al., 2012) pushed the relative bandwidths up to $10 \%$ and higher.

These receivers made it possible to look for molecular lines in submm colours, avoiding the difficulties associated with optical and nearinfrared spectroscopic redshifts. Initially, the focus was on finding the

CO lines. Weiss et al. (2009) reported the detection of two CO-lines with EMIR on the IRAM telescope, determining the spectroscopic redshift for $a z=2.93$ galaxy. Frayer et al. (2011) reported finding two spectroscopic redshifts using the Zpectrometer on the Greenbank Telescope. Lupu et al. (2012) reports finding four spectroscopic redshifts using Z-Spec on the Caltech Submillimetre Observatory. Zavala et al. (2015) reports finding three spectroscopic redshifts using the RSR on the Large Millimetre Telescope. Vieira et al. (2013) and Weiß et al. (2013) used the incredible observation speed of ALMA to detect a robust redshift for 12 high redshift sources, with 11 additional sources only having a single spectral line detected.

At the same time, instruments were developed that focus on slightly shorter wavelengths, smaller than 1 mm , which are more efficient in detecting the blind redshifts with atomic and ionic lines, such as the ZEUS spectrometer. Stacey et al. (2010) reports detecing the CII-line of 12 sources with known redshifts with the ZEUS instrument. The redshifts of these galaxies range from 1.1 to 2 . This spectral line is significantly brighter than the CO-line, with this first ZEUS survey finding a luminosity ratio, $\mathrm{L}_{\mathrm{C}[I I]} / \mathrm{L}_{\mathrm{CO}(1-0) \text {, of } 4100 \text {. While this value }}$ depends strongly on the internal properties of the galaxies, it does suggest that the [CII] line would be detected significantly faster than any CO line. This redshift identification is, however, not robust, and does require a further identification of a second spectral line to confirm the redshift.
The negative K-correction of course does not influence the spectral lines. So while the sources themselves are still bright in sub-mm colours, the brightness of the spectral line drops with the cosmic distance or redshift. This makes it difficult for spectroscopic observations to detect the highest-redshift sources, which will then require more time for spectroscopic redshift confirmation.

### 1.3 GRAVITATIONAL LENSING

### 1.3.1 Theory and experiments

Gravitational lensing occurs when an intervening mass bends the light from a background object, causing the observers to see an distorted image (Treu, 2010). Usually, the object appears brighter than its intrinsic brightness, and the observed image has arced features. Typically, a distinction is made between a lensing magnification greater than two and smaller than two. The case of a lensing magnification greater than 2 is called strong lensing, while a magnification less than 2 is called weak lensing.
The properties of the lensed sources depend on the properties of the intervening mass. Different mass profiles and distances result in different lensed images, and a larger number of foreground sources

Emergent gravity posits that gravity is the result from an entropic force, attempting to maximise entropy by spatially clustering particles (Verlinde, 2011; Verlinde, 2017)
will result in a larger number of lensed sources. Gravitational lensing thus becomes an important tool to probe cosmological parameters, and even to test new theories regarding the origins of gravity. For example, the optical KIDS-microlensing survey was used to test the viability of emergent gravity as an alternative to the general relativity paradigm set by Einstein (Brouwer et al., 2017). While this test did not result in conclusive evidence for one theory or the other, it does show that more extended samples might be able to provide a better description of reality.

The rest of this discussion will only follow strong-lensing studies, which can be separated into two distinct catagories. Firstly, the lensing system is selected on the foreground, lensing galaxy. The other possibility is to select the lensed sources by their background, lensed source.

The Sloan Lens ACS (SLACS, with ACS standing for Hubble's Advanced Camera for Surveys (Bolton et al., 2006)) survey uses the spectral information in the Sloan Digital Sky Survey (SDSS) to find lenses. The approach was to find objects with high-redshift spectral lines, while also having a lower-redshift continuum. These were then followed-up with the Hubble ACS, who found 63 clear lensing systems. The SLACS survey was extended by the BOSS Emission-Line Lens Survey (BELLS, with BOSS standing for the Baryon Oscillation Spectroscopic Survey (Brownstein et al., 2012)). This project resulted in the detection of 25 definite (and 11 probable) lensing systems.

One of the lasting legacies of Hubble is the deep observations of several foreground galaxy clusters, as can be seen in Figure 1.4 (Ishigaki et al., 2015). Named the Hubble Frontier Fields, these clusters were expected to provide significant lensing to background sources, and act as a magnifying glass to the outer edges of our Universe. McLeod, McLure, and Dunlop (2016) for example, reports on finding five $z=9$ Lyman-break galaxies within these fields.

Finding the lensed sources by focussing on foreground sources, however, results in complicated selection criteria. This reduces the viability for finding cosmological parameters, and testing models, as they do not homogeneously probe the cosmos, but depend on the properties of the foreground sources.

Finding lensed sources by just the properties of these background, lensed sources, gets around these selection criteria. It, however, does require a large sample of sources, which need to be readily visible even at redshifts greater than 1 and beyond. To this end, both the Cosmic Lens All-Sky Survey (CLASS, (Myers et al., 2003; Browne et al., 2003)) and Sloan Digital Sky Surveys Quasar Lens Search (SQLS, (Oguri et al., 2006)) look for lensed quasars. CLASS started with slightly less than 10000 flat-spectrum quasars, which were observed with high-resolution radio observations to result in a statistically welldefined sample of 13 lensed sources. Similarly, the SQLS produced a


Figure 1.4: Abell-2744 - One of the five main Hubble Frontier Fields. These fields observe foreground galaxy clusters, with the objective of finding lensed, high-redshift sources. This has proven successful, as several $z=9$ Lyman-break galaxies have been found (McLeod, McLure, and Dunlop, 2016). Courtesy to NASA, ESA, and J. Lotz, M. Mountain, A. Koekemoer, and the HFF Team (STScI).
well-defined sample of 26 lensed sources from an initial sample of 50000 SDSS quasars.

These parent samples are large compared to the resulting number of confirmed lensed galaxies. To this end, Serjeant (2014) suggested using the wide field imaging survey of the Euclid space telescope to find strong gravitational lenses. This survey covers around half the sky, and would be able to find a thousand lenses by combining Euclid and Square Kilometre Array observations. The lenses would be identified both by their lensing arcs, and interlopers such as tidal tails etc. would be removed by SKA-observations.

### 1.3.2 Observations of lensed sub-mm sources

The dramatic increase of known sub-mm sources from the large area surveys of Herschel Space Observatory led to the idea of finding gravitational lenses within these samples (Negrello et al., 2007; Negrello et al., 2010). Selecting lensed galaxies by their sub-mm brightness is not straightforward. The large beamwidth of single-dish sub-mm observatories is not large enough to resolve the lensing structure. However, sub-mm lens selection also has its advantages. Due to the negative K-correction, sub-mm sources can be found out to very high redshift, which leaves a large potential space for foreground lensing galaxies. Also, typically the foreground galaxies are sub-mm faint, and thus they do not influence the selection of lensed sources. This makes foreground sources easy to remove, when one just wants to study the lensed galaxy. Similarly, this means that sub-mm selected lensed systems are only included based on the properties of the background source, which is crucial for statistical analyses of samples of lensed sources.

The steep number counts at high flux densities result in an effective gravitational lens selection, see Figure 1.5. At a certain brightness, the chance of a naturally-occuring galaxy with that flux-density is lower than a fainter source being magnified by gravitational lensing. This high flux density cut-off ( $\mathrm{S}_{500 \mu \mathrm{~m}}>100 \mathrm{mJy}$ ) was already exploited in the 14.4 sqr. deg. Science Demonstration Phase (SDP) of H-ATLAS by Negrello et al. (2010), who used a simple flux cut-off to select lensed sources. They were able to remove all contaminants from their selection, local galaxies and blazars, and identified five lensed galaxies.

Wardlow et al. (2013) followed a similar approach on the 94 sqr. deg. HerMES (Herschel Multi-tiered Extragalactic Survey) maps, and selected 13 sources with $\mathrm{S}_{500 \mu \mathrm{~m}}>100 \mathrm{mJy}$. Nine of these sources had follow-up data, done with the Sub-Millimetre Array (SMA), the Hubble Space Telescope (HST), Jansky Very Large Array (JVLA), Keck, and Spitzer. Wardlow et al. (2013) combined these data for six sources and confirmed their lensing nature, while three other sources had

Elk nadeel heb
$z^{\prime} n$ voordeel
Every disadvantage
has its advantage
— Johan Cruijff


Figure 1.5: The number counts at high brightness are dominated by lensed sources (dashed red line). As such, Negrello et al. (2010) selects towards lensed sources by taking a high flux density selection. Late-type galaxies (blue line) and radio AGNs (green line) are also included in this selection, yet they are easily removed with optical and radio catalogues. This method was successful, and resulted in the correct identification of five lensed sources, among which SDP. 81 which was observed with ALMA (ALMA Partnership (2015)). At lower flux densities, more galaxies are expected to be un-lensed SMGs (solid red line). These sources are expected to have extremely large intrinsic luminosities, and therefore extreme star-formation rates, which are close to the theoretical limit on star-formation. Figure adapted from Negrello et al. (2010).
their lensing nature already confirmed by Borys et al. (2006), Conley et al. (2011), and Ikarashi et al. (2011).

Recently, Negrello et al. (2017) and Nayyeri et al. (2016) used the same $S_{500 \mu m}>$ 100mJy flux density cut-off on the full H-ATLAS (616.4 sqr. deg.) and HeLMS (HerMES Large Mode Survey; 372 sqr. deg.) maps, and created samples containing 77 and 80 sources, respectively. Spectroscopic and optical follow-up observations have been able, so far, to confirm that 20 sources are indeed lensed, one is a protocluster (Ivison et al., 2013), while the remaining sources in Negrello et al. (2017) await more observations to be carried out to confirm their nature.

These large samples of lensed sources are interesting, both because of the lensed source and the intervening lensing galaxy (Grillo, Lombardi, and Bertin, 2008; Treu, 2010). The lensed source has an amplified flux density and increased angular size. The amplification in flux density allows us to study sources that would otherwise be too faint to detect. The increase in angular size allows us to study the internal properties of high redshift sources with high resolution sub-mm/mm and radio observatories, such as ALMA (Atacama Large Millimeter Array) and the VLA (Very Large Array). As most intervening, lensing sources are passively evolving ellipticals, they are sub-mm dim and their contribution to the total measured flux density is minimal.

The Science Verification observations by ALMA (ALMA Partnership, 2015) observed the lensed galaxy SDP.81, see top-left of Figure 1.6, resolving the nearly-complete Einstein ring. This high-resolution image has allowed research groups to reconstruct the original image, observing the galaxy down to 30 parsec scales (Dye et al., 2015; Hatsukade et al., 2015; Rybak et al., 2015; Swinbank et al., 2015; Tamura et al., 2015), shown in the top-right panel of Figure 1.6. These groups exploit the increase in angular size in order to resolve the morphological and dynamical properties of a galaxy at a redshift of 3 .

The bottom panels of Figure 1.6 show one of the observations discussed in Dye et al. (2018). These observations are taken at a courser spatial resolution, which makes it difficult to directly compare the sources, as can be seen in the small inset figure in the lower righthand corner, which is set to the same spatial scale. However, tentatively, the emission appears more extended and smoother for HerBS13 than for SDP.81.

The foreground galaxy's total mass (dark and baryonic) distribution determines the lensed morphology of the sub-mm detected system (Vegetti et al., 2012; Hezaveh et al., 2016a; Hezaveh et al., 2016b). Therefore, high-resolution imaging of the lensed morphology allows the detection of low-mass substructures in lensing galaxies. These substructures can then be used to test the formation of structure in large-scale cosmological simulations, such as the Millennium (Springel et al., 2005) and the recent Eagle simulation (Schaye et al., 2015).


Figure 1.6: Observations of lensed H-ATLAS galaxies SDP.81 (top, ALMA Partnership (2015); Dye et al. (2015) - HerBS-19) and H-ATLAS J142413.9+022303 (bottom, Bussmann et al. (2013); Dye et al. (2018) - HerBS-13) are shown on the left. The upper observations are part of the Science Verification campaign of the Atacama Large Millimeter Array (ALMA) at 1.1 mm , and are taken at higher resolution than the bottom observations, which are also taken by ALMA at $870 \mu \mathrm{~m}$. The partial Einstein rings are clearly visible, confirming the lensed nature of both sources. The images are reconstructed back onto the image plane, resulting in a delensed picture of the galaxy, at a higher resolution on the right. The small inset in the bottom right image shows the scale of the reconstructed image of SDP. 81 at the same spatial scale as HerBS-13. The difference in resolution makes it difficult to compare the sources directly, however tentatively, the emission of SDP. 81 appears more clumpy and less extended than HerBS-13.

The statistics of galaxy-galaxy lensing systems furthermore allows for a measurement of global cosmological parameters. For example, the lensing statistics of 28 lensed quasars in the before-mentioned Sloan Digital Sky Survey (SDSS) Quasar Lens Search (SQLS) gave an estimate of $\Omega_{\Lambda}=0.74 \pm 0.17$, assuming a spatially flat universe (Oguri et al., 2012). Selecting lensed sources from bright sub-mm samples is simple and unbiased method because it is based on the source, as the lens is usually faint in the sub-mm. Eales (2015) showed that observations of a sample of 100 lensed Herschel sources would be enough to estimate $\Omega_{\Lambda}$ with a precision of 5 per cent and observations of 1000 lenses would be enough to estimate $w$, the equation-of-state parameter of dark energy, with a precision similar to that obtained from the Planck observations of the cosmic microwave background.

All current gravitational lensing selections have used a high flux density cut-off ( $\mathrm{S}_{500 \mu \mathrm{~m}}>100 \mathrm{mJy}$ ), as can be seen in Figure 1.5. This eliminates a large amount of possible lenses in order to achieve a low contamination rate from unlensed sources (González-Nuevo et al., 2012). An initial attempt at studying the effects of lowering the cut-off flux density to 80 mJy was done in Wardlow et al. (2013), although they only studied four such galaxies in total. Out of the four galaxies with lensing verification, only one was confirmed to be a lens. Lensing models by Negrello et al. (2007); Cai et al. (2013) suggest such a sample would contain a mixture of lensed ULIRGs and unlensed HyLIRGs.

While the only conclusive evidence of gravitational lensing is by resolving the Einstein ring, there are other methods for finding out the lensing nature of sub-mm galaxies. One such way of is by looking for the optical and near-infrared counterparts of these sources. The lensed object will have both too much optical and near-infrared dust extinction, and will be at a too high redshift to be detected itself. Similarly, fitting the optical and near-infrared spectrum will result in a failure to predict the sub-mm fluxes. This method was shown by Hopwood et al. (2011), and Figure 1.7 shows the two spectra for the SDP. 81 source, split into the foreground and background source. The foreground source fails to produce enough sub-mm radiation, whilst the background source is not bright enough in sub-mm colours to fit all of the data points.

### 1.3.3 The nature of non-lensed SMGs

The lensed nature of our sources is not always a blessing. Without high-resolution observations, this lensing effect creates an uncertainty in the precise magnification, and thus to the intrinsic brightness of the source. This is a big enough problem that new studies resort to select-


Figure 1.7: The foreground (blue) and background (red) sources can be separated by means of their multi-wavelength nature. The red and dusty nature of the background source does not agree with the bluer colours of the foreground source. This image was taken from Hopwood et al. (2011)
ing fainter sources just to avoid this uncertainty (Ivison et al., 2016), with only modest success (Fudamoto et al., 2017).
These bright high-redshift sources that are unlensed are of great interest, because they must have extremely high intrinsic luminosities, and thus extreme star-formation rates. In total, there are only less than 5 of these HyLIRGs known (Ivison et al., 2013; Chapman et al., 2015; Gómez et al., 2018). While all sub-mm sources have intrinsic brightnesses which indicate they are forming stars at $>100 \mathrm{M}_{\odot} / \mathrm{yr}$, these unlensed HyLIRGs appear to be close to the theoretical maximum star-formation, the Eddington limit (Chapman et al. 2015). Due to the restricted number of known HyLIRGs, it is unclear whether this limit significantly influences galaxy formation of the brightest galaxies, and what exactly their role is in the cosmic star-formation history of the Universe.

### 1.4 THESIS OUTLINE

Figure 1.5 shows that all sources are gravitationally lensed (dashed red line) at the highest flux densities, greater than 100 mJy at $500 \mu \mathrm{~m}$. When we lower the selection flux density to 80 mJy at $500 \mu \mathrm{~m}$, more unlensed sub-mm galaxies are included in the selection, as can be seen by the solid red line.
This thesis tests the effects of using a lower cut-off flux, by selecting a sub-sample of galaxies identified from the Herschel-ATLAS survey:
the Herschel Bright Sources (HerBS) sample. I detail the sample definition in Chapter 2. I further report on $850 \mu \mathrm{~m}$ SCUBA-2 observations, which were used to remove blazar interlopers. I use a sub-set of 24 HerBS sources that have a known and robust redshift, and use this to fit a spectrum in order to study the properties of the galaxies in the sample. I also compare the flux densities of the sources to a galaxy evolution model, in order to find an estimate for percentage of gravitational lensing in the sample.

The third chapter reports on observations of eight of the highestredshift sources with the IRAM 30 meter telescope. Here, I examine the ability of the EMIR instrument as a high-redshift hunter. Chapter 4 and 5 both detail attempts at cross-correlating multi-wavelength counterparts to the HerBS sources using a statistical estimator. I also adjust the existing method to include the effect of gravitational lensing, which I expect influences many of the HerBS sources. I conclude the results and findings in Chapter 6, where I finish with a subset of future work, needed to answer the fundamental questions around these sources.

Throughout this thesis, we assume a flat $\Lambda$ CDM model with the best-fit parameters derived from the results from the Planck Observatory (Planck Collaboration, 2015), which are $\Omega_{\mathrm{m}}=0.307$ and $\mathrm{h}=$ o.693. At $z=4$, one arcsecond corresponds to 7.0 kpc , and a $\delta z=0.01$ corresponds to a comoving distance of 7 Mpc .

Golflengte afstand van je hemellichaam. Ze is van spectrale klasse. Ooh, onaardse krachten, losgebarsten toen ze naar me lachte. Je kijkt terug in de tijd, als je naar d'r kijkt.

- De Jeugd van Tegenwoordig

In this chapter, I will reinvestigate the question of using a lower cutoff flux, by selecting galaxies from the 616.4 sqr. deg. H-ATLAS survey. In order to decrease the contamination rate, I impose a photometric cut-off redshift $\mathrm{z}_{\text {phot }}>2$ based on the Herschel-SPIRE fluxes. The probability of lensing below this redshift falls off sharply, because of the smaller volume available between us and the source (Strandet et al., 2016). I will calculate the expected amount of lensed galaxies in our sample, by comparing the fluxes of our sources to a cosmological evolution model that takes lensing into account.

### 2.1 HERSCHEL BRIGHT SOURCES (HERBS) SAMPLE

Our sample selection is based on Herschel fluxes, and a known problem of sources selected at $500 \mu \mathrm{~m}$ with Herschel is the large solid angle of the beam (Scudder et al., 2016). This could lead to several sources blending into a single source, and result in a flux that is too large. This is why I observed the majority of our sources at $850 \mu \mathrm{~m}$ with the SCUBA-2 instrument on the James Clerk Maxwell Telescope (JCMT), whose beam has a six times smaller solid angle on the sky. The extra data point should also improve the photometric redshift estimates of our sources.

In Section 2.2, I discuss the selection of the Herschel Bright Sources (HerBS) sample, as well as the observations with SCUBA-2. I describe the results of the JCMT observations in Section 2.5, where I also remove several blazar contaminants from the sample. I re-derive a spectral template for our sources with spectroscopically determined redshifts in Section 2.6. I discuss the effects of source confusion, the properties of the template, the redshift distribution of our sample, and estimates of the lensing fraction in Section 2.7.


Figure 2.1: Herschel/SPIRE color maps of the H-ATLAS fields. The orange circles mark the positions of the 209 HerBS sources. This figure is similar to Figure 2 in Negrello et al. (2017), and shows how the sources are distributed over the sky.

Table 2.1: The H-ATLAS fields

| Field | Centre |  | Approximate dimensions |  | Final surface area [sqr. deg.] | Sources | Surface density [1/sqr. deg] |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | RA [hms] | DEC [dms] | RA [deg] | DEC [deg] |  |  |  |
| NGP | 13:18:00 | 29:00:00 | 15 | 10 | 170.1 | 49 | 0.288 |
| GAMA Total | - | - | - | - | 161.6 | 72 | 0.446 |
| GAMA 9 | 09:00:00 | 00:00:00 | 12 | 3 | 53.43 | 23 | 0.430 |
| GAMA 12 | 12:00:00 | 00:00:00 | 12 | 3 | 53.56 | 26 | 0.485 |
| GAMA 15 | 14:30:00 | 00:00:00 | 12 | 3 | 54.56 | 23 | 0.422 |
| SGP | 23:24:46 | -33:00:00 | 42 | 6 | 284.8 | 88 | 0.309 |
| Total fields | - | - | - | - | 616.4 | 209 | 0.339 |

Notes: Reading from the left, the columns are: Column 1 - name of field; Column 2 and 3 - The location of the centre of the field; Column 4 and 5 - The approximate dimensions of the field; Column 6 - The surface area from the final maps (Valiante et al., 2016); Column 7 - The number of final HerBS sources in each field; Column 8 - The surface density of HerBS sources per field.

### 2.2 SAMPLE AND MEASUREMENTS

### 2.2.1 The selection of the HerBS sample

The sample was selected from the brightest, high-redshift sources in the H-ATLAS survey. The H-ATLAS survey used the PACS (Poglitsch et al., 2010) and SPIRE (Griffin et al., 2010) instruments on the Herschel Space Observatory to observe the North and South Galactic Pole Fields and three equatorial fields to a $1 \sigma$ sensitivity of 5.2 mJy at $250 \mu \mathrm{~m}$ to 6.8 mJy at $500 \mu \mathrm{~m}$, although the noise varies per source (Valiante et al., 2016). The three equatorial fields overlap with the Galaxy And Mass Assembly (GAMA) fields 9, 12 and 15 hours, and from here on I adopt this naming convention for the equatorial fields (Driver et al., 2011; Liske et al., 2015). The fields are defined in Table 2.1. In total the H-ATLAS survey detected approximately half a million sources.

I initially selected the HerBS sample from the H-ATLAS pointsource catalogues (Valiante et al., 2016), who extracted the flux densities at the $250 \mu \mathrm{~m}$ position, and used this position for flux extraction at 350 and $500 \mu \mathrm{~m}$. The flux densities in the catalogues are not deboosted, however the flux boosting is negligible compared to the flux uncertainty; around 1 per cent at 80 mJy , and diminishing for increasing flux density, as can be seen in Table 6 of Valiante et al. (2016). I estimated the redshift of each source by fitting a source template to the 250, 350 and $500 \mu \mathrm{~m}$ flux densities (Pearson et al., 2013). I selected the sources at an estimated redshift, $z_{\text {phot }}$, greater than 2 and a 500 $\mu \mathrm{m}$ flux density, $\mathrm{S}_{500 \mu \mathrm{~m}}$, greater than 80 mJy . The source template was a two-temperature modified blackbody from Pearson et al. (2013) (see eq. 2.3 and Table 2.5 in our Section 2.5). This modified blackbody was derived from the Herschel PACS and SPIRE flux densities of 40
sources with spectroscopically determined redshifts, with 25 sources at low redshifts $(\mathrm{z}<1)$, and only 12 sources at high redshifts ( $\mathrm{z}>2$ ). Our initial sample consisted of the 223 sources.

Where possible I removed sources that are coincident with a large nearby galaxy or a blazar (Negrello et al., 2010; López-Caniego et al., 2013). However, the preselection of blazars was not complete, and it only became clear after I had carried out the SCUBA-2 observations that I had actually observed several blazars (see Section 2.5). The final HerBS sample consists of 209 sub-millimetre galaxies after removing all nearby galaxies and blazars, and is listed in Table .1. I plot the positions of the final 209 HerBS sources in the various fields in Figure 2.1.

### 2.2.2 Famous HerBS sources

Several of the HerBS sources have been investigated individually. Fu et al. (2012) showed that HATLAS J114637.9-001132 (HerBS-2) is a strongly lensed sub-mm galaxy, with a magnification between 7 to 17. Cox et al. (2011) and Bussmann et al. (2012) found that HATLAS
 nification of 4 . At a redshift of 4.24 , the source has one of the highest redshifts in our sample. HATLAS Jo90311.6+003907 (HerBS-19) is also known as SDP.81, and has recently been observed by ALMA Partnership (2015). Negrello et al. (2010) showed SDP.81 is lensed using 880 $\mu \mathrm{m}$ Sub-Millimetre Array observations. Dye et al. (2015) and Tamura et al. (2015) reconstructed the galaxy from the ALMA observation, by modelling the distorting effect of the lens. They found a magnification of $\sim 11$. This reconstructed image features details on the scale of hundreds of parsecs, and the image shows resolved individual giant molecular clouds in a $z=3.04$ galaxy. SDP. 81 appears, through reconstructed HST and ALMA imaging, to be two interacting objects, where the dust disk is in a state of collapse.
However, not all our sources are lensed. Ivison et al. (2013) studied HATLAS Jo84933.4+021442 (HerBS-8), and found it was not a strongly lensed galaxy. Instead, it consists of multiple large galaxies in the process of merging, which has probably triggered starbursts in the individual galaxies, explaining the brightness in sub-mm wavelengths.
Our HerBS sample overlaps partially with the sample from Negrello et al. (2017), as 53 out of the 8o sources in their sample are also found in the HerBS sample. Their sample was designed specifically to find lensed systems, by imposing a flux-density cut-off at 100 mJy at $500 \mu \mathrm{~m}$ and did not have a lower redshift limit.

I observed 203 sources with the SCUBA-2 array on the JCMT. The instrument consists of 10,000 Transition Edge Sensor (TES) bolometers, distributed over 4 arrays that observe at $450 \mu \mathrm{~m}$ and 4 arrays that observe at $850 \mu \mathrm{~m}$ (Holland et al., 2013). Both wavelengths are observed simultaneously, with the use of a dichroic mirror. The voltage across each array is optimised to ensure as many functional bolometers as possible. The optimised voltage places the majority of the bolometers within their sensitive resistance transition, whereupon any temperature fluctuation causes a current change. The resulting magnetic field variations are read out with separate Superconducting Quantum Interference Devices (SQUIDs) located under each bolometer.

The instrument scans the sky in a DAISY pattern, circling around the source following a continuous petal-like track, providing a central 3 arc-minute region of uniform exposure time, and keeping one part of the array on-source at all times (Chapin et al., 2013).

The observations conditions were in the grade-3 weather band [0.08 $<\tau_{1.3} \mathrm{~mm}<0.12$ ], which is only suitable for $850 \mu \mathrm{~m}$ observations. The data were flux-calibrated against Uranus, Mars, CRL 618 and CRL 2688 (the Westbrook and Egg Nebulae). The calibrators were observed between 2 and 4 times per observing run, and the flux calibration factors (FCFs) were estimated linearly for observations in between calibrators, and the closest calibrator was used otherwise (Dempsey et al., 2013).

Our observations consisted of ten-minute exposures for each source. The bolometers are sampled at roughly 200 Hz , and the data is stored in 30 -second time slices for each of the arrays, where the first and last time slice of each exposure are flat-fields. Flat-fields probe the responsivity of individual bolometers, and are derived from the bolometer's response to the resistance heaters, which are located next to each bolometer.

### 2.4 DATA REDUCTION

The entire data reduction method is shown schematically in Figure 2.2, and is described below. The data reduction was done with the ORAC_DR pipeline, which uses the KAPPA and SMURF packages from STARLINK, and the PICARD procedures (Thomas et al., 2014).

The basic data consists of the time-dependent signals from each bolometer and information about the specific scanning pattern of the arrays on the sky. The first step of the data reduction method flatfields and downsamples the data, to correct for individual bolometer performance and to reduce the file size by matching the sampling speed to the spatial scale of the maps. The second step removes the noise components in the signal iteratively, starting with the largest
noise component (Chapin et al., 2013). Our final reduced map is achieved with additional data reduction steps: jackknife, fake pointsource injection and matched filtering. The final result is a 4 by 4 arcminute image with one arcsecond resolution.

The iterative data reduction step (makemap)

Sky emission is the dominant noise component, and it is shared by all bolometers. This common-mode signal (COM) is calculated by averaging the signals of all bolometers into one signal per subarray. The common-mode signal is then subtracted from the signal for each bolometer, taking care to adjust for individual bolometer amplification differences (GAI). Bolometers that have a signal that is inconsistent with the common-mode signal are rejected at this stage.

The signal is then corrected for the atmospheric extinction (EXT), a function of precipitable water vapour and telescope pitch, after which a high-pass Fourier filter (FLT) removes low-frequency, i/f noise. The frequency cut-off is 0.8 Hz , which corresponds to a spatial scale of 200 arc-seconds.
The next step removes the astronomical signal (AST) from the total signal, in order to estimate convergence of our iterative data reduction step. The signals of all bolometers are projected onto the sky, creating an astronomical map of our observation. Many data points contribute to the estimate of the astronomical signal in each spatial pixel, which greatly reduces the noise compared to the time-series data. The map still contains noise, but the assumption made in this step of the iterative data-reduction procedure is that everything in this map is real. The astronomical, space-domain map is then used to create a time-domain signal for each bolometer, by simulating an observation of our astronomical map. This is then removed from the signal for each bolometer.

The time-domain signal for each bolometer should now consist only of noise. This noise is calculated and compared to the convergence criterion (NOI), which is a minimum number of loops (four in this case) and a threshold noise level. If convergence is not reached in the NOI step, all the data-processing steps (FLT, EXT, GAI, COM) are undone, except for the removal of the astronomical signal. This adds back the common-mode noise and the noise removed in the Fourier-filtering step. All the steps (see upper half of Figure 2.2) are then repeated until the convergence criterion is met. After each cycle the new estimate of the astronomical signal is added to the previous estimate. The final image is obtained when the convergence criterion is met.


Figure 2.2: This flowchart shows the data reduction steps schematically, starting from the raw data files at the top, working to the reduced cutouts at the bottom. The intricacies are detailed in the data reduction section. For each observation, two sets of timeslices are cleaned and processed through the iterative mapmaker, and these resulting maps are subtracted to provide a jackknife estimate of the noise. A fake source is injected to estimate peak attenuation due to the filtering process, and allows us to create a PSF for the final matched filter step.

## Extra data reduction steps

Apart from this standard data-reduction procedure, shown in the top half of Figure 2.2, I added the following additional steps.
For each source, I split the time-slices into two sets. Each set consists of the flat-fields (first and last time slice) and either the odd or even half of the time slices. I ran the iterative mapmaker over each set, separately, which allows us to execute a jackknife step (ORAC_DR procedure: SCUBA2_JACKKNIFE).
I used the iterative data reduction step to create a separate map for each half of the data. I subtracted one map from the other to create a noise-map, from which I calculate the angular power spectrum of the noise. I used this angular power spectrum to construct a map-specific Fourier filter. A combined signal map is calculated by adding the two signal maps, and I then applied this Fourier-filter to the signal map.
The high-pass filtering step attenuates the signal, and to account for this, I reran the entire data reduction algorithm with an injected fake source. This fake 10 Jy point-source (FWHM of 13 arc seconds - the main beam size of $850 \mu \mathrm{~m}$ observations with JCMT (Dempsey et al., 2013)) was injected into both the odd and even timeslices, offset at 30 arc seconds from the centre. This extremely bright, fake source allowed us to calculate an effective point spread function (PSF) and also provided an estimate of the signal attenuation due to the highpass filtering, which usually was around 15 to $20 \%$.
Finally, I applied a matched filter to the signal map, in which I convolved our signal map with the PSF found by injecting a fake source. This provided the final, reduced observation map. I cropped the observation to a 4 by 4 arcminute image, and measured the fluxes by measuring the highest flux density pixel in the central 50 by 50 arcsecond region around the SPIRE-estimated position. I determine a SCUBA-2 detection by a combination of proximity to the HerschelSPIRE $250 \mu \mathrm{~m}$ position and the signal to noise, as shown in Section 2.5.

### 2.5 SCUBA-2 RESULTS

I observed 203 of our preselected H-ATLAS sources with the SCUBA2 instrument. In the following analysis, I find that fourteen detected sources turn out to be blazars, which leaves our entire HerBS galaxy sample containing 209 sources. 152 of these sources are detected, 27 sources are not detected due to a signal-to-noise cut, and ten sources do have a $3^{-\sigma}$ detection, but not within the 10 arcsecond circle around the SPIRE position. These results are summarised in Table 2.2.
Figure 2.3 shows the distribution of the maximum signal to noise in a 50 by 50 arcsecond box centered on the SPIRE position, as a function of the position offset.

I decide to define a detected source by a signal-to-noise greater than 3 and a positional offset smaller than 10 arcseconds. Initially, I find 159 sources that satisfy this criterion, 27 sources that are not detected by the signal-to-noise cut, and 17 sources whose positional offset was too large.

For each of the seventeen sources that do not have their maximum flux within the 10 arcsecond circle around the SPIRE position, that do have a signal-to-noise greater than 3, I decreased the size of the searching box to find the peak in flux. Of these seventeen sources, seven sources have fluxes within 10 arc seconds from the SPIRE position with a signal-to-noise greater than 3, as show in boldface in Table 2.3. These seven sources are added to the detected sources.

Of the sources with signal to noise ratios between three and five, fifteen are originally situated outside of the 10 arcsecond circle. These sources are distributed over 89 per cent of the map (the area outside the 10 arcsecond circle). An even distribution of such false detections would result in two ( $\sim 1.7$ ) false detections inside the HerBS catalogue. The overlay graph inside Figure 2.3 shows a strong correlation for most points around the centre, however all other non-detections appear uniformly scattered, making an even distribution likely.

I know from Negrello et al. (2007) that there is a risk that several of these sources are blazar contaminations. In order to find these contaminants, I plot their flux ratios in Figure 2.4.

The top panel shows the flux ratios based on just Herschel fluxes. I plot $S_{500 \mu \mathrm{~m}} / \mathrm{S}_{250 \mu \mathrm{~m}}$ versus $\mathrm{S}_{350 \mu \mathrm{~m}} / \mathrm{S}_{250 \mu \mathrm{~m}}$. The sources that lie very close to a known blazar (within 10 arc seconds) in the NASA Extragalactic Database (NED) (black circles) lie in the same region as the high-redshift HerBS sources (gray triangles, blue squares and red circles). I also plot the track for the template I derive in Section 2.6 through the diagram as the redshift changes (black line and circles). Similarly, I show the expected blazar track (assuming synchrotron radiation), for various possible alpha-values (black dash-dot line and triangles). Note that both these tracks do not differ significantly from each other. The bottom panel shows the flux ratios of the 203 sources with SCUBA-2 observations. I plot $\mathrm{S}_{850 \mu \mathrm{~m}} / \mathrm{S}_{250 \mu \mathrm{~m}}$ against $\mathrm{S}_{350 \mu \mathrm{~m}} / \mathrm{S}_{250 \mu \mathrm{~m}}$. Most of the galaxies close to a known blazar occupy a different region of the graph, and can be easily identified and removed from the sample.

One of the sources, HerBS-16, does not have the typical flux ratios of a blazar, and has therefore not been removed. The spectrum also looks dust-like, and has consistent photometric redshift estimates, as can be seen in Figure 2.5. The source, in this case, could be close to the blazar by accident. Only one source close to a known blazar has not been observed, and I have therefore kept it in our HerBS sample (HerBS-112).

The difference between the graphs indicates the need for multiwavelength observations, in order to reliably remove blazar contam-


Figure 2.3: The majority of high signal-to-noise SCUBA-2 fluxes lie in a 10 arcsecond circle around the SPIRE position. I choose a cut-off signal-to-noise ratio of $3-\sigma$, and a maximum radius of 10 arcseconds. The fifteen sources with a signal-to-noise ratio between 3 and 5 suggest that the HerBS sources might have two false detections. The overlay graph shows the position of the SCUBA-2 observation, where each point was centered on the SPIRE position. Orange points refer to sources with a S/N greater than 5 , blue points refer to sources between 3 and 5, and grey points refer to sources with a S/N smaller than 3 .


Figure 2.4: The top panel shows the flux ratios based on just Herschel fluxes. I plot $S_{500 \mu \mathrm{~m}} / \mathrm{S}_{250 \mu \mathrm{~m}}$ versus $\mathrm{S}_{350 \mu \mathrm{~m}} / \mathrm{S}_{250 \mu \mathrm{~m}}$. Sources close to a known blazar in NED (black circles) lie in the same region as the high-redshift HerBS sources (gray triangles, blue squares and red circles). The bottom panel shows the flux ratios when I include the SCUBA-2 observations. I plot $\mathrm{S}_{850 \mu \mathrm{~m}} / \mathrm{S}_{250 \mu \mathrm{~m}}$ against $\mathrm{S}_{350 \mu \mathrm{~m}} / \mathrm{S}_{250 \mu \mathrm{~m}}$. Most sources close to a known blazar occupy a different region of the graph, and can be easily identified and removed (black circles). The difference between the graphs indicates the necessity of the $850 \mu \mathrm{~m}$ observations for removing blazar contaminants from the sample. I also plot the track for the template I derive in Section 2.6 through the diagram as the redshift changes (black line and circles). Similarly, I show the expected blazar track, for alpha-values ranging from o to 1.5 (black dash-dot line and triangles).
inants from the sample. I list the Herschel SPIRE and SCUBA-2 positions and fluxes of the removed blazars in Table .2.

After removing fourteen blazars from our sample, I am left with 189 HerBS galaxies with SCUBA-2 observations. While some sources close to NED blazars did not have irregular flux ratios, all of the sources with irregular flux ratios are close to known blazars. This suggests our method for finding contaminants in our sample is robust, and thus that the 19 unobserved sources that do not lie close to a NED blazar are not likely to have emission dominated by synchrotron radiation.

For completeness, I plot the blazar spectrum, assuming solely synchrotron radiation, in Figure 2.4, following equation

$$
\begin{equation*}
S_{v}=A \times v^{-\alpha} \tag{2.1}
\end{equation*}
$$

Here $S_{v}$ is the flux density at a specific frequency $(v), A$ is a constant factor, and $\alpha$ determines the steepness of the slope in the far-infrared wavelength regime. Most of the blazars lie close to this line. I also calculate the value for $\alpha$ for each galaxy, by minimizing $\chi^{2}$ :

$$
\begin{equation*}
\chi^{2}=\sum^{i>j}\left[\frac{\left(S_{i} / S_{j}\right)_{\text {model }}-\left(S_{i} / S_{j}\right)_{\text {meas }}}{\sigma_{i, j, \text { meas }}}\right]^{2} \tag{2.2}
\end{equation*}
$$

The index $i$ and $j$ iterate over all four wavelengths (250, 350, 500 and $850 \mu \mathrm{~m}$ ), where $i$ 's wavelength is always larger than $j . \sigma_{i, j, \text { me as }}$ is the combined error of $\left(S_{i} / S_{j}\right)_{\text {meas }}$. $\alpha$-values range from 0.24 to 1.66. The individual values can be found in Table .2, and agree well with the positions of the blazar sources in Figure 2.4.

I provide poststamp cutouts of the observations with SPIRE, SCUBA2 and fits of our templates (Section 2.6.1) to the 250, 350, 500 and 850 $\mu \mathrm{m}$ flux densities of each source in Appendix .2. Typical cutouts of a source detected by SCUBA-2, a source undetected by SCUBA-2, and a blazar are shown in Figure 2.5. The bottom row of cutouts shows HerBS-16, which is close to a NED blazar, but has an SED typical of a sub-mm galaxy.

### 2.6 GALAXY TEMPLATES

I derived a galaxy template for our total sample, by using the subset of HerBS sources that have spectroscopic redshifts. I fitted a twotemperature, modified blackbody spectral energy distribution to the Herschel and the SCUBA-2 flux densities of each source. I list the sources with spectroscopic redshifts in Table 2.4. These spectroscopic redshifts were found by observing sub-mm spectral lines, in order to ensure I am looking at the same source.
This template is necessary to estimate photometric redshifts and luminosities for our entire sample. Similar to the analysis of Pearson


Figure 2.5: This figure shows the four different types of sources I found in the SCUBA-2 $850 \mu \mathrm{~m}$ observations of our sample: a galaxy detected with SCUBA-2, a galaxy undetected with SCUBA-2, a blazar, and HerBS-16, which is close to a known blazar, but has an SED typical of thermal emission from dust. The first three columns of cutouts of each source are the Herschel observations shown in 4 by 4 arc minute poststamps. The fourth column shows the $850 \mu \mathrm{~m}$ SCUBA-2 observation in a 4 by 4 arc minute poststamp. All poststamps are centred at the $250 \mu \mathrm{~m}$ extraction position of the Herschel catalogue. The final frame is a fitted SED, with the best-fit template in orange, fixed $\beta$ template in blue and Pearson's template in grey (Pearson et al., 2013). Similar figures for the entire HerBS sample can be found in Appendix .2.

Table 2.2: SCUBA-2 observations of the HerBS sample

|  | Sources | Percentage |
| :--- | ---: | ---: |
| HerBS galaxies | $\mathbf{2 0 9}$ | $\mathbf{1 0 0} \%$ |
| SCUBA-2 observed | $\mathbf{1 8 9}$ | $\mathbf{9 0 . 4} \%$ |
| Detected $\quad\left(>3 \sigma, \theta<10^{\prime \prime}\right)$ | 152 | $69.4 \%$ |
| Not detected $\quad(<3 \sigma)$ | 27 | $12.9 \%$ |
| Not detected $\quad(>3 \sigma, \theta>10 ")$ | 10 | $8.1 \%$ |
| Not observed | $\mathbf{2 0}$ | $\mathbf{9 . 6} \%$ |
| Blazar contaminants | 14 |  |

Table 2.3: Re-examined SCUBA-2 observations of HerBS sources with $\theta>$ 10 arc second.

| HerBS <br> [-] | $\begin{array}{r} \theta \\ {["]} \end{array}$ | $\begin{array}{r} \mathrm{S} / \mathrm{N} \\ {[-]} \end{array}$ | $\begin{array}{r} \mathrm{S}_{850 \mu \mathrm{~m}} \\ {[\mathrm{mJy}]} \end{array}$ |
| :---: | :---: | :---: | :---: |
| 63 | 9.45 | 3.19 | 33.8 |
| 75 | 7.59 | 4.24 | 44.9 |
| 96 | 7.84 | 2.10 | 19.5 |
| 97 | 6.57 | 2.49 | 28.1 |
| 101 | 1.93 | 3.42 | 32.5 |
| 118 | 2.28 | 2.12 | 23.3 |
| 122 | 6.97 | 2.43 | 21.9 |
| 131 | 5.54 | 2.95 | 30.3 |
| 140 | 7.14 | 3.59 | 30.3 |
| 145 | 9.59 | 3.17 | 33.0 |
| 146 | 7.85 | 2.92 | 32.1 |
| 148 | 5.40 | 3.02 | 29.0 |
| 151 | 6.33 | 2.34 | 23.9 |
| 163 | 6.66 | 1.85 | 19.1 |
| 172 | 5.92 | 1.40 | 13.7 |
| 181 | 4.06 | 3.81 | 32.9 |
| 195 | 3.94 | 2.61 | 29.5 |

et al. (2013), I fitted the template to the SPIRE ( 250,350 , and $500 \mu \mathrm{~m}$ ) fluxes, and included our JCMT/SCUBA- $2850 \mu \mathrm{~m}$ flux densities. I choose to exclude the PACS photometry of our sources in our analysis, as even the brightest sources are poorly detected, due to the high-redshift limit of our sample. Our spectroscopic sample includes 8 sources used in Pearson's analysis, and 16 new sources, all of which are at high redshifts ( $\mathrm{z}_{\text {spec }}>1.5$ ). I only used HerBS sources for our template to ensure there is $850 \mu \mathrm{~m}$ photometry of our sources, and only used the galaxies with spectroscopic redshifts estimated from more than one line.

### 2.6.1 Template fitting

I fitted the template to the sources' flux densities and rest wavelengths, calculated from their spectroscopic redshifts. I assumed a two-temperature modified blackbody template for the SED,

$$
\begin{equation*}
S_{v}=A_{\text {off }}\left[B_{v}\left(T_{h}\right) v^{\beta}+\alpha B_{v}\left(T_{c}\right) v^{\beta}\right] \tag{2.3}
\end{equation*}
$$

where $S_{v}$ is the flux at the rest-frame frequency $v, A_{\text {off }}$ is the normalisation factor, $B_{v}$ is the Planck blackbody function, $\beta$ is the dust emissivity index, $T_{h}$ and $T_{c}$ are the temperatures of the hot and cold dust components, and $\alpha$ is the ratio of the mass of the cold to hot dust.

I aimed to minimize the following $\chi^{2}$ for the fluxes that were detected,

$$
\begin{equation*}
\chi^{2}=\sum_{i=1}^{n} \chi_{i}^{2}=\sum_{i=1}^{n} \sum^{\lambda}\left[\frac{A_{i} S_{\text {model }, i}-S_{\text {meas }, i}}{\sigma_{\text {meas }, i}}\right]^{2}, \tag{2.4}
\end{equation*}
$$

where $S_{\text {model, } i}$ is the predicted flux of the $i^{\text {th }}$ source (out of $n$ ) according to equation 2.3, with the amplitude $A_{\text {off }}$ set to one. $S_{\text {meas }, i}$ and $\sigma_{\text {meas }, i}$ are the measured signal and noise values. In the case all fluxes of the source were detected, I fitted the amplitude of our template, $A_{i}$, to the rest-wavelength data points analytically in order to decrease computation time,

$$
\begin{equation*}
A_{i}=\left(\sum \frac{S_{\text {model }, j} S_{\text {meas }, j}}{\sigma_{\text {meas }, j}^{2}}\right) /\left(\sum \frac{S_{\text {model }, \mathrm{j}}^{2}}{\sigma_{\text {meas }, \mathrm{j}}^{2}}\right) . \tag{2.5}
\end{equation*}
$$

Equation 2.5 is derived by solving $\mathrm{d} \chi_{i}^{2} / \mathrm{dA}_{i}=0$.
One source with a spectroscopic redshift did not have a detected SCUBA-2 flux, HerBS-71. In this upper-limit case, I calculated the $\chi^{2}$ contribution using the method detailed in Sawicki (2012) and Thomson et al. (2017),

$$
\begin{equation*}
\chi^{2}=-2 \sum_{j} \ln \int_{-\infty}^{3 \sigma} \exp \left[-\frac{1}{2}\left(\frac{f-A_{j} S_{\text {model }, j}}{\sigma_{\text {meas }, j}}\right)^{2}\right] d f, \tag{2.6}
\end{equation*}
$$

Table 2.4: The sources from the HerBS sample with measured spectroscopic redshifts.

| Robust, multi-line detections |  |  |  |  |  |
| :--- | :--- | :--- | :--- | :--- | :--- |
| H-ATLAS name: | HerBS | $z_{\text {spec }}$ | $z_{\text {phot }}$ | $\Delta z /(1+z)$ | Ref. |
| J134429.5+303034 | 1 | 2.30 | 2.20 | 0.03 | H12 |
| J114637.9-001132 | 2 | 3.26 | 2.80 | 0.11 | H12 |
| J132630.1+334408 | 3 | 2.95 | 3.75 | -0.20 | H-p |
| Jo83051.0+013225 | 4 | 3.63 | 3.09 | 0.12 | R-p |
| J125632.5+233627 | 5 | 3.57 | 3.72 | -0.03 | R-p |
| J132427.0+284450 | 6 | 1.68 | 2.11 | -0.16 | G13 |
| J132859.2+292327 | 7 | 2.78 | 2.89 | -0.03 | K-p |
| Jo84933.4+021442 | 8 | 2.41 | 2.64 | -0.07 | L-p |
| J125135.3+261458 | 9 | 3.68 | 3.87 | -0.04 | K-p |
| J113526.2-014606 | 10 | 3.13 | 2.32 | 0.20 | H12 |
| J133008.6+245900 | 12 | 3.11 | 2.29 | 0.20 | R-p |
| J142413.9+022303 | 13 | 4.28 | 4.53 | -0.05 | C11 |
| J141351.9-000026 | 15 | 2.48 | 2.62 | -0.04 | H12 |
| Jo90311.6+003907 | 19 | 3.04 | 3.76 | -0.18 | F11 |
| J132504.4+311534 | 20 | 1.84 | 1.88 | -0.02 | R-p |
| J133846.5+255055 | 29 | 2.34 | 2.69 | -0.11 | R-p |
| J132301.7+341649 | 30 | 2.19 | 3.28 | -0.34 | R-p |
| Jo91840.8+023048 | 32 | 2.58 | 3.03 | -0.13 | H12 |
| J133543.0+300402 | 35 | 2.68 | 2.73 | -0.01 | H-p |
| Jo91304.9-005344 | 59 | 2.63 | 2.87 | -0.07 | N10 |
| J115820.1-013752 | 66 | 2.19 | 2.49 | -0.09 | H-p |
| J113243.0-005108 | 71 | 2.58 | 3.73 | -0.32 | R-p |
| Tentative, single line detections (not used) |  |  |  |  |  |
| J125652.5+275900 | 31 | 2.79 | 3.25 | -0.12 | - |
| Jo83344.9+o00109 | 88 | 3.10 | 3.25 | -0.04 | - |
| J113803.6-011737 | 96 | 3.15 | 2.88 | -0.07 | H12 |
| J113833.3+004909 | 100 | 2.22 | 2.66 | -0.14 | - |

Notes: Reading from the left, the columns are: Column 1 - the official H-ATLAS name; Column 2 - HerBS number; Column 3 spectroscopic redshift; Column 4 - photometric redshift using the best-fit model; Column $5-\left(z_{\text {spec }}-z_{\text {phot }}\right) /\left(1+z_{\text {spec }}\right)$; Column 6 Reference for the spectroscopic redshift: Nio = Negrello et al. (2010), $\mathrm{F}_{11}=$ Frayer et al. (2011), H12 = Harris et al. (2012), G13 = George et al. (2013), L13 = Lupu et al. (2012), B13 = Bussmann et al. (2013), $\mathrm{H}-\mathrm{p}=$ Harris et al. (in prep.) $\mathrm{R}-\mathrm{p}=$ Riechers et al. (in prep.) $\mathrm{K}-\mathrm{p}=$ Krips et al. (in prep.) L-p = Lupu et al. ('in prep.')
where I sum over all non-detections $\mathfrak{j}$, which in our case is only the SCUBA-2 flux of HerBS-71, and integrate the gaussian distribution up to the detection criterion of three times the measured noise (3б). The modified $\chi^{2}$ statistic quantifies the probability of an event where the noise affected the signal to drop below the detection criterion. In the case the model predicts a flux under the detection limit, there is no discrepancy with the model, and I set the $\chi^{2}$-value to zero.

I did this template fitting for two templates: best-fit, where I varied all the parameters ( $T_{c}, T_{h}, \alpha$, and $\beta$ ), and fixed $\beta$ where $I$ varied all parameters except $\beta$, which I fixed to 2 . I also tried keeping $T_{c}, T_{h}, \alpha$ and $\beta$ fixed to the values found by Pearson et al. (2013). In this case I found the set of $A_{i}$ that gave the minimum $\chi^{2}$ fit. The point of this was to determine whether our new templates gave any improvement in the quality of fit over that found by Pearson et al. (2013). I estimated the uncertainty on each parameter by incrementally changing this parameter until the minimised $\chi^{2}$ changes by of one (one interesting parameter, Avni (1976)). The $\chi^{2}$ was minimised by allowing the other (two or three) parameters to vary. The best-fit templates are given in Table 2.4 .

### 2.6.2 Template results

I find a cold- and hot-dust temperature of $21.29_{-1.66}^{+1.35} \mathrm{~K}$ and $45.80_{-3.48}^{+2.88}$ K , a cold-to-hot dust mass ratio of $26.62_{-6.74}^{+5.61}$ and a $\beta$ of $1.83_{-0.28}^{+0.14}$ for the best-fit template. The results for the other templates, including the fitting of the templates to redshift and luminosity subsets, can be found in Table 2.5 .

I investigated the usefulness of each template for estimating photometric redshifts, by using each template to estimate the photometric redshift of each source, and then calculating $\left(z_{\text {spec }}-z_{\text {phot }}\right) /\left(1+z_{\text {spec }}\right)$ for each source. The root mean squared value of $\left(z_{\text {spec }}-z_{\text {phot }}\right) /(1+$ $\left.z_{\text {spec }}\right)$ for the best-fit template is $13 \%$, which is similar to the fixed- $\beta$ and Pearson templates. The value of the relative error derived from the best-fit template for each source is given in Table 2.4, and the mean and standard deviations of this quantity for each template are given in Table 2.5 .

Figure 2.6 shows $\left(z_{\text {spec }}-z_{\text {phot }}\right) /\left(1+z_{\text {spec }}\right)$ plotted against spectroscopic redshift for the three templates. The three distributions are very similar. I compare the redshift estimates against the method used in Ivison et al. (2016). They fit three different templates (ALESS (Swinbank et al., 2014), Cosmic Eyelash (Ivison, R. J. et al., 2010; ), and the template from Pope et al. (2008)) to the flux measurements, and use the redshift estimate from the spectrum with lowest $\chi^{2}$-value. When I apply this method to our sample of sources with spectroscopic redshifts, I achieve a slightly better redshift accuracy of $\sim 12 \%$.


Figure 2.6: The top three panels show $\left(z_{\text {spec }}-z_{\text {phot }}\right) /\left(1+z_{\text {spec }}\right)$ plotted against the spectroscopic redshift for the three templates. The blue dots in each panel show the points for the specified template, while the smaller grey dots show the points for the other two templates. The bottom panel shows $\left(z_{\text {spec }}-z_{\text {phot }}\right) /\left(1+z_{\text {spec }}\right)$ for the three templates used for the redshift estimation in Ivison et al. ( (2016)), where the blue dots correspond to the template fit with the lowest $\chi^{2}$ for each source individually, and the smaller grey dots are the values of the two remaining templates.

Table 2.5: The results of the fitting of the total sample, with a variable and fixed beta, and applying the template from Pearson et al. (2013) to our sources.

|  | Total | Fixed-Beta | Pearson |
| :--- | :---: | :---: | :---: |
| $\mathrm{T}_{\mathrm{c}}[\mathrm{K}]$ | $21.29_{-1.66}^{+1.35}$ | $20.47_{-0.26}^{+0.26}$ | 23.9 |
| $\mathrm{~T}_{\mathrm{h}}[\mathrm{K}]$ | $45.80_{-3.48}^{+2.88}$ | $44.05_{-0.55}^{+0.52}$ | 46.9 |
| $\alpha$ | $26.69_{-6.74}^{+5.61}$ | $30.46_{-1.42}^{+1.32}$ | 30.1 |
| $\beta$ | $1.83_{-0.28}^{+0.14}$ | 2 (fixed) | 2 (fixed) |
| $\chi^{2}$ | 812.58 | 812.96 | 1101.03 |
| $\Delta \mathrm{z} /\left(\mathrm{z}_{\text {spec }}+1\right)$ | $-0.03 \pm 0.14$ | $-0.03 \pm 0.14$ | $-0.01 \pm 0.12$ |

I note that the uncertainty in photometric redshift estimation using our new template, obtained from SCUBA-2 and Herschel measurements, is not actually any smaller than that using the template that Pearson et al. (2013) obtained from Herschel measurements alone. I discuss the significance of this in the Section 2.7.

Figure 2.7 shows the normalised flux densities of the spectroscopic sources against their rest-frame wavelength, with the three templates overlaid. The flux-densities are normalised to give each galaxy the same bolometric luminosity as HerBS-1.

I used the photometric redshifts estimates of our best-fit template to derive observed bolometric luminosities of the HerBS sources. As the redshift estimates are determined from a different spectrum, some of the photometric redshift estimates, $\mathrm{z}_{\text {phot }}$, fall below two. They are, however, kept in the HerBS sample, as not to increase the complexity of the selection functions.

I calculate the observed bolometric luminosities by deriving the photometric redshift from our best-fit template, and integrating the template from $\lambda_{\text {rest }}=8$ to $1000 \mu \mathrm{~m}$. The estimated redshifts and bolometric luminosities are listed in Table .I, as well as the photometric redshift estimates using the method from Ivison et al. (2016). Figure 2.8 shows the distribution of sources as a function of redshift and luminosity. This figure shows that the majority of our sources with a spectroscopic redshift are in the higher luminosity range, as typically spectroscopic campaigns aim for the brightest sources first.

### 2.7 DISCUSSION

### 2.7.1 Source confusion

I have selected our HerBS sample using a $500 \mu \mathrm{~m}$ flux limit. The large beam-width at this wavelength could cause us to confuse multiple


Figure 2.7: The flux densities of the spectroscopic sources plotted against rest-frame wavelength. The curves show the three templates (best-fit is the thick orange line, fixed- $\beta$ is the thin blue line, and Pearson's model is the dashed grey line), and all the flux densities of each source are scaled to produce the same bolometric luminosity as the brightest source (HerBS: 1). The sample is split up in three redshift intervals, to associate each galaxy's four data points more easily.


Figure 2.8: Observed bolometric far-infrared luminosity ( $\lambda_{\text {rest }}=8-1000 \mu \mathrm{~m}$ ) plotted against photometric redshift, calculated with the best-fit template. Sources with spectroscopic redshifts are plotted in orange plusses, although the redshifts used in the diagram are their photometric redshifts. The smoothed distributions of redshift and luminosity are shown on the sides of the scatter plots. The grey line shows bolometric luminosity for the best-fit template, assuming $\mathrm{S}_{500 \mu \mathrm{~m}}=80 \mathrm{mJy}$, as a function of redshift. I use the python-package Seaborn to create this graph.
line-of-sight sources into a single observed source, and hence yield a $500 \mu \mathrm{~m}$ flux density that is too large.

Observationally, high resolution studies of sub-millimetre galaxies show this to be the case, although the severity of this effect varies from study to study (Hodge et al., 2013; Koprowski et al., 2014). An SMA study by Chen et al. (2013) of sources selected at $450 \mu \mathrm{~m}$ only found $10 \%$ of the sources to be significantly amplified by line-ofsight sources. An ALMA survey of $870 \mu \mathrm{~m}$ selected ALESS sources finds that up to $50 \%$ of the sources are significantly affected (Hodge et al., 2013; Karim et al., 2013). Longer wavelengths and higher selection flux densities correlate with more source confusion, although all observational multiplicity studies so far focus on SMGs with a low probability of lensing.

A recent study by Scudder et al. (2016) used Bayesian inference methods to estimate the effects of source confusion in Herschel observations at $250 \mu \mathrm{~m}$. They concluded that individual $250 \mu \mathrm{~m}$ sources are often the combination of emission from more than one galaxy.

The solid angle of the beam of the JCMT at $850 \mu \mathrm{~m}$ is six times smaller than the beam of the $500 \mu \mathrm{~m}$ SPIRE observations. I do not see any of our HerBS sources resolve into multiple $>3 \sigma$-detected components. This suggests that our long-wavelength observations are not confused, unless the sources are clustered on a scale smaller than the JCMT's beam size. The small clustering size could be the case, as Karim et al. (2013) finds the multiple emissions are separated less than $6^{\prime \prime}$ in the majority of cases of source confusion. Similarly, Chen et al. (2016) measured the clustering of SMGs on scales down to $1.5^{\prime \prime}$ using SCUBA-2 combined with deep near-infrared and optical data, and they also report a steep increase in angular correlation below 6 ". However, Hayward et al. (2013) simulated light cones to estimate the blending ratio of associated and unassociated SMGs for a 15 arcsecond beam, and found that at least 50 per cent of all blended SMGs show an unassociated SMG. The HerBS sources are selected by their $500 \mu \mathrm{~m}$ flux, which has a 36 arcsecond beam, and should therefore be more influenced by unassociated SMGs. As these unassociated SMGs are spatially unrelated to the source, they should have shown up in our JCMT analysis. A reason for the lack of source confusion could be due to our selection of lensed sources, as the probability for gravitational lensing is small, and two unrelated sources in the same Herschel beam are unlikely to be both lensed by the same galaxy.

Strong gravitational lensing could also be caused by a cluster of galaxies, which acts on a longer angular scale. These events are less common (Negrello et al., 2017), however Zavala et al. (2015) did report on the redshifts of cluster-lensed sources, one of which turned out to be three sources that was blended and lensed. I did not exclude these possibilities, however considering their infrequency, I can state that this lensing type would not influence the entire sample.

### 2.7.2 The diversity of galaxies

In Section 2.6, I fitted a two-temperature modified blackbody template to 22 HerBS sources with spectroscopic redshifts, the results of which can be seen in Table 2.5 .

Both the fixed- $\beta$ and best-fit templates result in similar templates, as the $\beta$-value of the best-fit template is similar within the error bars. The errors on the best-fit template are slightly larger, as more parameters are being fitted. The temperatures on both fitted templates are slightly cooler than the template from Pearson et al. (2013), however I do not find an indication of a cool gas component with a temperature $\mathrm{T}<$ 20 K , as found in Planck Collaboration et al. (2011) and Clements, Dunne, and Eales (2010). The values I find for the temperatures agree broadly with the initial fitting attempts by Dunne and Eales (2001), and the overall findings of Clements, Dunne, and Eales (2010).

The large $\chi^{2}$ values in Table 2.5 imply that a single template is not actually a good representation of the data. I fit our template to 22 galaxies, each with 4 data points, except one source where I only fitted the three SPIRE fluxes, as its SCUBA-2 flux remained undetected. The free parameters in our model are the template parameters (3 or $4)$ and the amplitudes for each galaxy (22, eq. 2.5). The expected $\chi^{2}$ values for the two models, on the assumption that they are a good representation of the data, are therefore

$$
\begin{aligned}
\chi_{\text {Best-fit }}^{2} & \approx N_{\text {data }}-N_{\text {param }}-1 \\
& \approx 4 \times 22-22-4-1 \\
& \approx 61, \\
\chi_{\text {Fixed- }}^{2} & \approx N_{\text {data }}-N_{\text {param }}-1 \\
& \approx 4 \times 22-22-3-1 \\
& \approx 62 .
\end{aligned}
$$

However, I observe $\chi^{2}$-values of $\sim 812$, indicating that our sources are poorly modelled by a single galaxy template.

I tested the photometric redshift estimates of the templates using the same sources I used to derive the best-fit template. However, I found no improvement in accuracy (Table 2.5) compared to the older template of Pearson et al. (2013). Similarly, Figure 2.6 shows a similar pattern of redshift errors for all three templates. The redshift estimation by Ivison et al. (2016) might provide a slightly better estimation of the redshift, which are therefore added to the catalogue Table .1. The explanation for this lack of improvement is almost certainly the diversity of the population; the limit on the accuracy of photometric redshift estimates is not set by the accuracy of the average template but by the fact that galaxies have different spectral energy distributions.

### 2.7.3 Redshift distribution of the HerBS sample

Figure 2.9 shows the redshift distribution of the HerBS sample, compared against various other galaxy samples, that are summarised in Table 2.6. The top panel compares the distribution to samples selected with a simple flux cut-off at $500 \mu \mathrm{~m}$. The sample from Negrello et al. (2017) used a $\mathrm{S}_{500} \mu \mathrm{~m}>100 \mathrm{mJy}$ flux cut on 600 sqr . deg. of the H-ATLAS field (they used a conservative mask on the SGP field). The sample from Nayyeri et al. (2016) used the same flux cut on the 372 sqr. deg. HeLMS and HeRS fields. I plot the total sample from Wardlow et al. (2013). They used the 95 sqr. deg. HerMES survey, and their $500 \mu \mathrm{~m}$ flux cut-off went down to 80 mJy .
The bottom panel compares the HerBS redshift distribution against samples selected at various wavelengths. The sample from Ivison et al. (2016) is also from the H-ATLAS fields, and contains sources with a color-cut at $S_{500 \mu \mathrm{~m}} / \mathrm{S}_{250 \mu \mathrm{~m}}>1.5$ and $\mathrm{S}_{500 \mu \mathrm{~m}} / \mathrm{S}_{350 \mu \mathrm{~m}}>0.85$, in order to select sources at high redshift. The sources were also selected to have relatively low $500 \mu \mathrm{~m}$ flux density of around 50 mJy , in order to select unlensed sources. Their unlensed nature reduces the uncertainty in the intrinsic luminosity of the source. The South Pole Telescope (SPT) lensed sample was selected from 2500 sqr. deg. SPT survey by a flux cut at $\mathrm{S}_{1.4 \mathrm{~mm}}>20 \mathrm{mJy}$, and demanding the source has a dust-like spectrum. Low-redshift sources were removed with radio and far-infrared flux limits (Weiß et al., 2013; Strandet et al., 2016). The ALESS sample is initially selected from the LESS sample at $\mathrm{S}_{870 \mu \mathrm{~m}}>4.4 \mathrm{mJy}$ from the 0.25 sqr . deg. Extended Chandra Deep Field South (ECDFS) field (Weiss et al., 2009). ALMA observations of the LESS sample removed all contaminants, resulting in a final ALMA-LESS (ALESS) sample of 96 SMGs (Simpson et al., 2014).
All samples selected at $500 \mu \mathrm{~m}$ with a simple flux cut have a similar redshift profile, and do not differ significantly from the HerBS sample when I take the photometric redshift cut-off into account. Also, without the photometric redshift cut-off, the standard deviation of the HerBS sample would have been larger.
Typically, higher average redshifts are expected for longer selection wavelengths (Bethermin et al., 2015). I see this for the SPT sample, which has higher average redshifts. The ALESS sample, selected at $870 \mu \mathrm{~m}$, has a higher average redshift than the $500 \mu \mathrm{~m}$ without redshift constraints, but a lower average redshift than the HerBS sample due to HerBS photometric redshift constraint. The SPT and ALESS samples have a larger standard deviation in their redshifts, because the K-correction is negative for wavelengths between $850 \mu \mathrm{~m}$ and $\sim 3$ mm . Comparison with the Ivison sample is difficult because of the more complicated selection criteria they employ.
A way of quantifying the similarity between the samples is using the Kolmogorov-Smirnov test. I compare each sample's sources with
a redshift (spectroscopically or photometrically determined) greater than 2 to the photometric redshifts of the HerBS sources with $z_{\text {phot }}>$ 2. For each sample, I run this method 100.000 times while randomly varying the redshift of each source acccording to a gaussian distribution with a width of $\Delta z=0.15(1+z)$. For the comparison to Ivison's sample, I only compare it to HerBS sources with a similar colour cut as they employed ( $\mathrm{S}_{500 \mu \mathrm{~m}} / \mathrm{S}_{250 \mu \mathrm{~m}}>1.5$ and $\mathrm{S}_{500 \mu \mathrm{~m}} / \mathrm{S}_{350 \mu \mathrm{~m}}>0.85$ ), which only 26 HerBS sources follow. For the SPT sample, I used our best-fit template to estimate the flux at 1.4 mm , and only compared the sources that follow the SPT flux cut ( $\mathrm{S}_{1.4 \mathrm{~mm}}>20 \mathrm{mJy}$ ), a property only 60 HerBS sources have. The ALESS flux criterion $\left(S_{870} \mu \mathrm{~m}>4.4\right.$ mJy ) was also estimated using the best-fit template, and was met by all our 209 sources.

I detail the KS probability values in terms of disagreement between two samples in standard deviations ( $\sigma$ ) in Table 2.6. A comparison between the redistributed redshifts and the original, unvaried redshift estimates of the HerBS sources gives a $1.27 \pm 0.45$ times the standard deviation, which indicates I should expect rather large uncertainties in the probability measurements. The spectroscopic redshifts of the HerBS sources disagree with $2.01 \pm 0.31$ times the standard deviation with the redistributed redshifts. When I compare the photometric redshift estimates of these spectroscopic sources to the HerBS sample, this value drops to $0.79 \pm 0.56$. Our HerBS sample thus appears probed evenly by the current set of HerBS sources with spectroscopic redshifts.

The sample from Negrello features more galaxies at low selected redshifts ( $2<z<3$ ), causing the disagreement seen by the relatively high KS value. This is contrary to both Nayyeri and Wardlow's samples, who agree strongly with the HerBS sample, suggesting that these sources are drawn from the same population. Only one out of four sources with low $500 \mu \mathrm{~m}$ flux densities ( $\sim 80 \mathrm{mJy}$ ) in Wardlow's sample was found to be lensed. This seems contradictory to the high likeness with the HerBS sample, which has a high lensing fraction of 76 per cent, found in Section 2.7.4. Only four of Wardlow's sources were checked for their lensing nature, which could indicate that their low lensing fraction is caused by small-number statistics. I can also think of two physical reasons for the low lensing fractions, namely the absence of a redshift selection and the actual decrease in the lensed fraction at lower flux densities. Redshift selection lifts the probability of lensing, by ensuring the sources are drawn from the redshift space most lensed sources are in (Strandet et al., 2016). Similarly, at lower flux densities, the fraction of lensed sources decreases, as can be seen in Figure 2.10.

The SPT also seem to probe similar populations to the HerBS sources, further increasing our suspicion of a high lensing fraction in our sample. A slightly less strong agreement with the ALESS sample was

Table 2.6: Redshift distributions of several sub-mm samples.

| Sample | $\langle\mathrm{z}\rangle \pm \sigma$ | Sources | Surface | KS $\sigma$-value | Selection criterion |
| :--- | :---: | :---: | :---: | :---: | :--- |
| HerBS | $3.09 \pm 0.71$ | 209 | 616.4 | $1.27 \pm 0.45$ | $\mathrm{~S}_{500 \mu \mathrm{~m}}>80 \mathrm{mJy} ; \mathrm{z}_{\text {phot }}>2.0$ |
| HerBS with $\mathrm{z}_{\text {spec }}$ | $3.07 \pm 0.72$ | 22 | 616.4 | $2.01 \pm 0.31$ | $\mathrm{~S}_{500 \mu \mathrm{~m}}>80 \mathrm{mJy} ; \mathrm{z}_{\text {phot }}>2.0$ |
| Negrello | $2.64 \pm 0.75$ | 80 | 616.4 | $1.82 \pm 0.77$ | $\mathrm{~S}_{500 \mu \mathrm{~m}}>100 \mathrm{mJy}$ |
| Nayyeri | $2.77 \pm 1.02$ | 77 | 372 | $0.66 \pm 0.50$ | $\mathrm{~S}_{500 \mu \mathrm{~m}}>100 \mathrm{mJy}$ |
| Wardlow | $2.65 \pm 0.90$ | 42 | 95 | $0.93 \pm 0.66$ | $\mathrm{~S}_{500 \mu \mathrm{~m}}>80 \mathrm{mJy}$ |
| Ivison | $3.80 \pm 0.67$ | 112 | 616.4 | $2.31 \pm 0.84$ | $\mathrm{~S}_{500 \mu \mathrm{~m}} \sim 50 \mathrm{mJy} ;$ |
|  |  |  |  |  | $\mathrm{S}_{500 \mu \mathrm{~m} / \mathrm{S}_{250 \mu \mathrm{~m}}>1.5 ;}$ |
|  |  |  |  |  | $\mathrm{S}_{500 \mu \mathrm{~m}} / \mathrm{S}_{350 \mu \mathrm{~m}}>0.85$ |
| SPT sample | $3.81 \pm 1.07$ | 39 | 2500 | $0.88 \pm 0.55$ | $\mathrm{~S}_{1.4 \mathrm{~mm}}>20 \mathrm{mJy}$ |
| ALESS | $2.90 \pm 1.22$ | 96 | 0.25 | $1.26 \pm 0.54$ | $\mathrm{~S}_{870 \mu \mathrm{~m}}>4.4 \mathrm{mJy}$ |

found, which probes deeper on a smaller part of the sky. Interestingly, Strandet et al. (2016) reports a disagreement of around 2.4 standard deviations between the SPT and ALESS sample. The HerBS sample likeness to the SPT sample is larger, suggesting this sample is more similar than to the deeper ALESS sample, especially as Strandet et al. (2016) found those two samples to be different. This is further proven by the small lensing fraction in the ALESS sample, compared to the sizeable lensing fraction in the SPT sample, and the lensing fraction I find in Section 2.7.4. However, Hodge et al. (2013) and Karim et al. (2013)'s studies of the ALESS sample did suggest a source confusion fraction on the order of 50 per cent of their sample. Even though our samples are not completely similar, this high blending percentage might indicate that our method of estimating the effects of source confusion with the JCMT's beam is incomplete. The low agreement to Ivison's sample suggests that their selection of unlensed SMGs was effective, and it indicates they might select different galaxies than our sample.

### 2.7.4 Lensing fraction

The SCUBA-2 observations do not resolve lensing directly, as the beam size ( 13 ") is much larger than the typical Einstein rings caused by galaxy-galaxy lensing ( $\sim 1$ ") (Bussmann et al., 2013; ALMA Partnership, 2015). However, I can estimate the lensing fraction of our sample when I compare the distribution of flux densities of our sources to the predictions of galaxy evolution models that include gravitational lensing.


Figure 2.9: The top panel compares the redshift distribution of the HerBS sample (black) to that of three samples selected with Herschel/SPIRE at $500 \mu \mathrm{~m}$. The bottom panel compares the redshift distribution of the HerBS sample (black) to that of three samples with different selection wavelengths and colour cuts.

Here I use the hybrid model by Cai et al. (2013) with a cut-off lensing magnification factor of $\mu=30$. The hybrid model is based on a parametric backward model for redshifts lower than 1.5 , whilst it calculates galaxy evolution for redshifts greater than 1.0 using physical models for the evolution of proto-spheroidal galaxies and their associated AGN. The model matches these two approaches to each other in the region between redshift 1.0 and 1.5. I assume all unlensed sources are high-redshift, proto-spheroidal galaxies. I did not observe all of the sample at $850 \mu \mathrm{~m}$, so I expect that our observed number counts are a lower limit.
Figure 2.10 shows a comparison of our number counts at $850 \mu \mathrm{~m}$ with the predictions of the model of Cai et al. (2013). I have plotted the number counts for each of our fields, by summing the number of sources brighter than a given flux, and dividing by the corresponding area of the field, see Table 2.1. I estimate the error on the counts as the square root of the number of sources in each bin. A comparison of our counts with the predicted counts of the unlensed sources (grey dashed line) immediately suggests most of our sources are lensed. I can quantify this as follows.
At the low fluxes, the data deviate from the model, because of the incompleteness of the HerBS sample at fluxes lower than $\sim 50 \mathrm{mJy}$. There are more sources than the model predicts at high fluxes, the significance of which is difficult to pin down due to the small number of sources. It is possible our sources have over-estimated $850 \mu \mathrm{~m}$ fluxes, possibly due to source confusion. However, it is important to realise that the model of Cai et al. (2013) is based on fitted luminosity functions. The high flux end of the luminosity function require large area surveys to be accurately fitted. As our sample is extracted from the largest area Herschel survey, the model is thus comparably uncertain as our data.
I calculate the total number of lensed sources,

$$
\begin{equation*}
N_{\text {lens }}\left(>S_{v}\right)=\sum_{i}^{N_{\text {gal }}\left(>S_{v}\right)} p_{\text {lens }}\left(S_{v, i}\right) . \tag{2.7}
\end{equation*}
$$

I sum the lensing probability, $p_{\text {lens }}\left(S_{v, i}\right)$, over all galaxies brighter than the flux cutoff, $\mathrm{N}_{\mathrm{gal}}\left(>\mathrm{S}_{\mathrm{\gamma}}\right)$. I calculate the probability, $\mathrm{p}_{\text {lens }}\left(\mathrm{S}_{\gamma, i}\right)$, from the relative proportions of the differential number counts predicted for lensed and unlensed galaxies,

$$
\begin{equation*}
p_{\text {lens }}\left(S_{v, i}\right)=\left[\frac{d N_{\text {lens }}}{d S_{v}} /\left(\frac{d N_{\text {proto }}}{d S_{v}}+\frac{d N_{\text {lens }}}{d S_{v}}\right)\right]_{S_{v, i}} \tag{2.8}
\end{equation*}
$$

The $N_{\text {lens }}$ term refers to the lensed sources, and the $N_{\text {proto }}$ term refers to the unlensed proto-spheroidal galaxies. I evaluate the probability at the flux density of the source, $\mathrm{S}_{v, i}$. Using the bottom panel of Figure 2.10, $p_{\text {lens }}$ can be thought of as the fraction lenses (thin blue line) over the total sources (thick orange line).


Figure 2.10: The top panel shows the cumulative number counts and the bottom panel shows the differential number counts of our HerBS sample, compared to the predictions of the model of Cai et al. ( (2013)) for unlensed (dashed grey line) and lensed (solid blue line) galaxies.

Table 2.7: Predicted lenses in the HerBS sample

| $\mathrm{S}_{850 \mu \mathrm{~m}}[\mathrm{mJy}]$ | $\mathrm{N}\left(>\mathrm{S}_{850 \mu \mathrm{~m}}\right)$ | Lenses | Percentage |
| :--- | ---: | ---: | ---: |
| all | $152.0 \pm 0.0$ | $128.4 \pm 2.1$ | $84.5 \pm 1.4 \%$ |
| 30 | $133.8 \pm 3.4$ | $123.3 \pm 2.9$ | $92.2 \pm 0.9 \%$ |
| 40 | $107.6 \pm 3.9$ | $105.2 \pm 3.7$ | $97.8 \pm 0.3 \%$ |
| 50 | $80.8 \pm 3.6$ | $80.5 \pm 3.6$ | $99.6 \pm 0.1 \%$ |
| 60 | $60.0 \pm 3.2$ | $59.9 \pm 3.2$ | $99.9 \pm 0.0 \%$ |
| 70 | $44.2 \pm 2.9$ | $44.2 \pm 2.9$ | $100.0 \pm 0.0 \%$ |
| 80 | $32.4 \pm 2.4$ | $32.4 \pm 2.4$ | $100.0 \pm 0.0 \%$ |
| 90 | $23.7 \pm 2.0$ | $23.7 \pm 2.0$ | $100.0 \pm 0.0 \%$ |
| 100 | $17.4 \pm 1.7$ | $17.4 \pm 1.7$ | $100.0 \pm 0.0 \%$ |
| 120 | $9.5 \pm 1.3$ | $9.5 \pm 1.3$ | $100.0 \pm 0.0 \%$ |

I iterate this procedure a 1000 times, varying the $850 \mu \mathrm{~m}$ flux with a gaussian distribution with a width of the measurement uncertainty. Table 2.7 shows the predicted number of lensed sources (eq. 2.7) and the observed number of sources for all SCUBA-2 detected HerBS sources. All of the errors are the standard deviations. Even for sources at $S_{850} \mu \mathrm{~m}>30 \mathrm{mJy}$, the predicted lensing fraction is $\sim 92 \%$, increasing to nearly all sources with $\mathrm{S}_{850} \mu \mathrm{~m}>40 \mathrm{mJy}$.
I rerun the same procedure on the $500 \mu \mathrm{~m}$ SPIRE fluxes, which shows that out of all 209 HerBS sources, I expect $158.1 \pm 1.7$ lensed sources, giving a total lensing fraction of $75.6 \pm$ o.8 per cent. This suggests that I am missing $29.7 \pm 1.6$ lensed sources with our SCUBA2 observations.

Finally I note that our counts in the GAMA fields are systematically higher than those in the other H-ATLAS fields, a point also noticed by Negrello et al. (2017). Using a similar method for the KS-test as described in Subsection 2.7.3, I calculate the probability for the GAMA and non-GAMA sources, and find a disagreement of $0.61 \pm 0.47$ standard deviations. This suggests the sources themselves do not differ significantly between the GAMA and the NGP+SGP fields.

### 2.8 CONCLUSIONS

The HerBS catalogue consists of the brightest, high-redshift sources in the H-ATLAS survey, selected with $\mathrm{S}_{500 \mu \mathrm{~m}}>80 \mathrm{mJy}$ and $\mathrm{z}_{\text {phot }}>$ 2. Initially, I selected 223 sources. SCUBA-2 observations of 203 of these sources allowed us to remove 14 blazars from the HerBS sample, leaving 20 HerBS sources unobserved. 152 out of the 189 confirmed high-redshift galaxies were detected at more than 3- $\sigma$, within 10 arc seconds of the SPIRE position. Currently, our HerBS sample consists of 209 galaxies.

While recent studies like Scudder et al. (2016) suggest a significant effect of source confusion in Herschel observations, none of our sources feature spatially-extended emission with $>3 \sigma$. While some sources could be confused on a scale not probed by the SCUBA-2 observations, the lack of any signs at the detectable scales gives us little evidence of source confusion significantly affecting the purity of our sample. A reason for this could be due to our high lensing fraction, especially those caused by galaxy-galaxy lensing systems, whose influence is on a smaller angular scale than the less common galaxy-cluster lensing event.

I fitted a two-temperature blackbody as a template to the subset of 22 HerBS sources with spectroscopically determined redshifts, as well as to sub-samples where I divided our sources in redshift or luminosity. I find a cold- and hot-dust temperature of $21.29_{-1.66}^{+1.35} \mathrm{~K}$ and $45.80_{-3.48}^{+2.88} \mathrm{~K}$, a cold-to-hot dust mass ratio of $26.62_{-6.74}^{+5.61}$ and a $\beta$ of $1.83_{-0.28}^{+0.14}$. Overall, the fitted parameters are similar to previous work from Pearson et al. (2013), and they agree broadly with the previous work from Dunne and Eales (2001); Clements, Dunne, and Eales (2010). I do not find evidence of any cold gas with temperatures below 20 K, as was found in Planck Collaboration et al. (2011).

I find a high $\chi^{2}$ for the template, implying that the spectral energy distributions of the high-redshift population are diverse and cannot be represented by a single template. I showed that our improved template, which incorporates the SCUBA-2 flux densities, does not give a more accurate redshift estimates, which can also be explained by the diversity of the population.

Our sample has a similar redshift distribution as other samples selected at $500 \mu \mathrm{~m}$, when I take the photometric redshift cut-off into account. Kolmogorov-Smirnov tests indicate that I probe a similar sample of galaxies as the SPT sample.

I calculated the number counts of the $850 \mu \mathrm{~m}$ observations of our sources, and compared them to a galaxy population model by Cai et al. (2013). From this comparison I predict that $128.4 \pm 2.1$ out of the 152 SCUBA-2 detected, high-redshift galaxies are strongly lensed. A model based around the $500 \mu \mathrm{~m}$ flux suggests a total of $158.1 \pm 1.7$ of the 209 HerBS sources to be strongly lensed. I report finding more lensed galaxies in the GAMA equatorial fields, when compared to the galaxy population model of Cai et al. (2013), and the other fields (SGP + NGP).

## Part II

## FOLLOW-UP AND MULTI-WAVELENGTH ANALYSIS

This part details the follow-up observations and analysis we applied on the HerBS sample. I report on the spectroscopic observations of 8 HerBS sources with $\mathrm{z}_{\text {phot }}>$ 4 with the IRAM 3om-telescope. I also look at the multiwavelength counterparts of the HerBS sources in both the optical SDSS and the near-infrared VIKING surveys. Here, I employ existing statistical methods, and test an adapted method, which should adjust for the effects of gravitational lensing.

# We are all in the gutter, but some of us are looking at the stars 

—— Oscar Wilde

This chapter reports our attempts at finding the spectroscopic redshifts of eight Herschel-detected galaxies using their CO lines with the IRAM (Institute Radioastronomie Millimétrique) 3om telescope. We search for the spectral lines in the 3 mm window, and follow up potential lines in the 2 mm window. We characterize the gas and dust properties of the five sources with successfully spectroscopic redshift identification, and look for signs of gravitational lensing. We conclude with a discussion of the ability of IRAM to hunt for high spectroscopic redshifts, and the prospects of future telescopes and instruments that promise a faster blind redshift searches of high-redshift SMGs.

### 3.1 SOURCE SELECTION

Our sources are selected from the Herschel Bright Sources sample (HerBS; Bakx et al. (2018)), which contains the brightest, high-redshift sources in the 616.4 sqr. deg. H-ATLAS survey. The H-ATLAS survey used the PACS (Poglitsch et al., 2010) and SPIRE (Griffin et al., 2010) instruments on the Herschel Space Observatory to observe the North and South Galactic Pole Fields and three equatorial fields to a $1 \sigma$ sensitivity of 5.2 mJy at $250 \mu \mathrm{~m}$ to 6.8 mJy at $500 \mu \mathrm{~m}$ (Valiante et al., 2016). We estimated the redshift of each source by fitting the two-temperature modified blackbody (MBB) template from Pearson et al. (2013) to the 250,350 and $500 \mu \mathrm{~m}$ flux densities. We selected the sources with an estimated redshift, $z_{\text {phot }}$, greater than 2 and a $500 \mu \mathrm{~m}$ flux density, $\mathrm{S}_{500 \mu \mathrm{~m}}$, greater than 80 mJy . Blazar contaminants were removed with $850 \mu \mathrm{~m}$ SCUBA-2 observations (Bakx et al., 2018). In this way, models suggest we select a collection of lensed ULIRGs and unlensed HyLIRGs. These unlensed sources are among the brightest galaxies in the Universe.

Significant work with the Zpectrometer (Harris et al., 2012) identified five HerBS redshifts (HerBS-1, $-2,-10,-15,-32$ ), Cox et al. (2011) found that HATLAS J142413.9+022303 (HerBS-13) is a lensed sub-mm galaxy at a redshift of 4.24, and Frayer et al. (2011) found that HATLAS Jo90311.6+003907 (HerBS-19, SDP.81) is located at $z=3.04$. Recently, Yang et al. (2017) studied the properties of HerBS-4, -19, -10, $-2,-15,-66,-72$, and 8 non-HerBS sources with the IRAM-30m. As the
spectroscopic redshift of these sources was already known, they were able to target 47 CO lines and seven $\mathrm{CI}(2-1)$ lines, and deduce the star-formation behaviour in great detail.
From the 209 HerBS sources, we selected eight sources for followup with IRAM 30 m telescope, with photometric redshifts greater than 4. This redshift selection is on the tail-end of the HerBS photometric redshift distribution, where the Universe was only $\sim 10 \%$ of its current age. We selected sources from the NGP and GAMA fields, as the SGP field is only poorly visible from the IRAM 30 m location. We detail the properties of these eight selected sources in Table 3.1, and Figure 3.1 shows the position of the sources in a colour-colour diagram for SPIRE, and SPIRE+SCUBA-2 colours. Figure 3.2 shows the SPIRE and SCUBA-2 observations of the selected sources.

Table 3.1: Sample location, photometry and photometric redshifts

| Source | H-ATLAS name | $\begin{gathered} \mathrm{RA} \\ {[\mathrm{hms}]} \end{gathered}$ | $\begin{gathered} \text { DEC } \\ {[\mathrm{dms}]} \end{gathered}$ | $\begin{gathered} \mathrm{S}_{250 \mathrm{~m} \mathrm{~m}} \\ {[\mathrm{mJy}]} \\ \hline \end{gathered}$ | $\begin{gathered} \mathrm{S}_{350 \mu \mathrm{~m}} \\ {[\mathrm{mJy}]} \end{gathered}$ | $\mathrm{S}_{500 \mu \mathrm{~m}}$ <br> [mJy] | $\mathrm{S}_{850 \mu \mathrm{~m}}$ [mJy] | $\mathrm{z}_{\text {phot }}$ | $\begin{gathered} \log \mu \mathrm{L}_{\mathrm{FIR}} \\ {\left[\log \mathrm{~L}_{\odot}\right]} \end{gathered}$ | $\begin{gathered} \mu \mathrm{SFR} \\ {\left[\mathrm{M}_{\odot} / \mathrm{yr}\right]} \end{gathered}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| HerBS-38 | J144608.6+021927 | 14:46:08 | 02:19:27 | $73.4 \pm 7.1$ | $111.7 \pm 8.1$ | $122.1 \pm 8.7$ | $33.3 \pm 12.4$ | $4.1 \pm 0.4$ | $13.75 \pm 0.02$ | $9696 \pm 433$ |
| HerBS-52 | J125125.8+254930 | 12:51:25. | 25:49:30 | $57.4 \pm$ | $96.8 \pm 5$. | $109.4 \pm 7.2$ | $80.1 \pm 12.0$ | $4.8 \pm 0.5$ | $13.83 \pm 0.02$ | $11656 \pm 459$ |
| HerBS-61 | J120127.6-014043 | 12:01:27.6 | -01:40:43 | $67.4 \pm 6.5$ | $112.1 \pm 7.4$ | $103.9 \pm 7.7$ | $9.6 \pm 9.4$ | $4.4 \pm 0.5$ | $13.79 \pm 0.02$ | $10631 \pm 437$ |
| HerBS-64 | J130118.0+253708 | 13:01:18.0 | 25:37:08 | $60.2 \pm 4.8$ | $101.1 \pm 5.3$ | $101.5 \pm 6.4$ | $96.5 \pm 10.6$ | $4.7 \pm 0.5$ | $13.83 \pm 0.01$ | $11656 \pm 398$ |
| HerBS-83 | J121812.8+011841 | 12:18:12.8 | 01:18:41 | $49.5 \pm 7.2$ | $79.7 \pm 8.1$ | $94.1 \pm 8.8$ | $71.2 \pm 10.0$ | $4.8 \pm 0.5$ | $13.77 \pm 0.02$ | $10152 \pm 577$ |
| HerBS-89 | J131611.5+281219 | 13:16:11.5 | 28:12:19 | $71.8 \pm 5.7$ | $103.4 \pm 5.7$ | $95.7 \pm 7.0$ | $81.8 \pm 7 \cdot 3$ | $4.2 \pm 0.5$ | $13.75 \pm 0.02$ | $9696 \pm 343$ |
| HerBS-150 | J122459.1-005647 | 12:24:59.1 | -00:56:47 | $53.6 \pm 7.2$ | $81.3 \pm 8.3$ | $92.0 \pm 8.9$ | $64.0 \pm 10.5$ | $4.6 \pm 0.5$ | $13.71 \pm 0.02$ | $8842 \pm 514$ |
| HerBS-177 | J115433.6+005042 | 11:54:33.6 | 00:50:42 | $53.9 \pm 7.4$ | $85.8 \pm 8.1$ | $83.9 \pm 8.6$ | $94.4 \pm 10.9$ | $4.7 \pm 0.5$ | $13.76 \pm 0.02$ | $9921 \pm 542$ |

Notes: Reading from the left, the columns are: Column 1 - HerBS-ID; column 2 - official H-ATLAS name (Valiante et al., 2016; Bourne et al., 2016); column 3 and 4 - SPIRE $250 \mu$ m positions; column 5, 6 and $7-$ SPIRE fluxes; column 8 -SCUBA-2 fluxes; column 9 and 10 - photometric redshift and luminosity derived from best-fit template of Bakx et al. (2018); column 11 - Star-formation rate derived from Robert C. Kennicutt (1998).

Table 3.2: Summary of the IRAM observations

| Source | Dates | Time per setup [h] | $\mathrm{tau}_{\text {eff }}$ |
| :---: | :---: | :---: | :---: |
| HerBS-38 | 18/10/16 26+30/07/16 20/11/16 | 11.8 (Eo: 11.4; Eo+E1: 0.4) | 0.02-0.6 |
|  | 09/04/17 17+19+21+22+23/05/17 |  |  |
| HerBS-52 | 28+29/07/15 03/08/15 | 13.4 (Eo: 9.7; E1: 3.7) | 0.03-0.6 |
| HerBS-61 | 06+27/07/16 20+21/10/16 10/04/17 | 9.2 (Eo: 4.0; E1: 5.2) | 0.05-0.8 |
| HerBS-64 | 20+21/05/17 29:31/07/15 01/08/15 | 12.8 (Eo: 10; E1: 2.8) | 0.02-0.6 |
| HerBS-83 | 26/07/16 20/10/16 27/11/16 | 15.45 (Eo: 14.85; E1: 0.6) | 0.02-0.4 |
|  | $06+09+13 / 04 / 17$ 16:22+23/05/17 |  |  |
| HerBS-89 | 20/05/17 | 1.6 (Eo: 1.6) | 0.05-0.15 |
| HerBS-150 | 06/07/16 20+21/10/16 12+13/04/17 21/05/17 | 5.0 (Eo: 5.0) | 0.05-0.58 |
| HerBS-177 | 06+11/07/16 20+21/10/16 28/11/16 06+12/04/17 | 9.8 (Eo: 7.3; E1: 2.5) | 0.03-0.6 |

Notes: Reading from the left, the columns are: Column 1 - HerBS-ID; column 2 - dates of observation, where a colon indicates observations also occurred on all days in between; column 3 - the number of hours spent on each source, and using each band; column 4 - tau corrected for the elevation.

### 3.2 OBSERVATIONS

### 3.2.1 IRAM observations and data reduction

We performed our blind redshift search at IRAM by an initial sweep of the 3 mm window (Eo: $73-117 \mathrm{GHz}$ ) using the multi-band heterodyne receiver EMIR. This window is guaranteed to contain at least one CO line. After a first line detection, we retune either to the 3 mm , to the 2 mm (E1: $125-184 \mathrm{GHz}$ ) or to a combined state of 3 and 2 mm ( $E o+E 1$ ) to look for a second spectral line. As backends, we used the WIde-band Line Multiple Auto-correlator (WILMA) and fast Fourier Transform Spectrometer (FTS200), which have a 2 MHz and 200 kHz resolution respectively. A major advantage of observing with the 30 m telescope is the possibility of pool observations. Here, the observer is present and can make real-time line confirmations or adjustments to the observing schedule. Typically, we expect to require between 2 and 4 hours for a spectral line detection.
Our IRAM observations were carried out in three separate programs, from 2015 until 2017, 080-15 (PI: Helmut Dannerbauer), 079-16 and 195-16 (PI: Tom Bakx). These observations took place with good to acceptable weather conditions, the details of which are in Table 3.2.
We reduced the IRAM data using the GILDAS package CLASS and Python. Initially, we used CLASS to remove the baseline of individual scans, and to remove bad data from our selection. After that, we combined the data and redid the baseline removal while masking out the positions of the spectral lines in order to get accurate flux estimates.
Each six minute scan consists of eight 4 GHz sidebands, split according to horizontal or vertical polarization, and covering the lowerinner (LI), lower-outer (LO), upper-inner (UI) and upper-outer (UO). In total, each scan covered 16 GHz in both horizontal and vertical po-


Figure 3.1: This colour-colour plot shows the high-redshift nature of our selected sources, and compares them against the underlying HerBS sample: grey points have $\mathrm{z}_{\text {phot }}<2.5$, blue points $\mathrm{z}_{\text {phot }}<3.5$, and orange points indicate $\mathrm{z}_{\mathrm{phot}}>3.5$. The solid black line indicates the redshift evolution of the average HerBS spectrum (Bakx et al., 2018), and the dash-dotted line in the top panel indicates the selection criterion for ultra-red sources (Ivison et al., 2016).


Figure 3.2: This figure shows the continuum images of our IRAM-observed sample. The first three columns of cutouts of each source are the Herschel/SPIRE observations (250, 350, 500 $\mu \mathrm{m})$ shown in 4 by 4 arc minute poststamps. The fourth column shows the $850 \mu \mathrm{~m}$ SCUBA-2 observation in a 4 by 4 arc minute poststamp. All poststamps are centred at the $250 \mu \mathrm{~m}$ extraction position of the Herschel catalogue. The final frame is a fitted SED, with the best-fit template in orange, fixed $\beta$ template in blue and Pearson's template in grey (Pearson et al., 2013).
larization. Further, FTS200 processes the data from each subband in three separate chunks, which are later stitched together. We remove the baseline by fitting a first-order polynomial to each of these three chunks separately.

After the baseline-subtraction, we removed bad data by visual inspection of each subband (up to $10 \%$ of data was bad). Typical examples of when a subscan was considered bad data include a strong sinusoidial interference, a strong peak, or a baseline that did not appear linear. All good data was then combined into a spectrum with a lower frequency resolution, weighted by both the amount of data points which mapped onto the lower frequency binning and by the noise level of the subscan:

$$
\begin{equation*}
S_{j}=\frac{\sum^{k} \frac{\sum_{\operatorname{VAR}\left(N_{k}\right)}^{i \in j} N_{i, k}}{\sum^{k} n_{i \in j} / \operatorname{VAR}\left(N_{k}\right)} .}{} \tag{3.1}
\end{equation*}
$$

Here, $S_{j}$ is the lower-resolution spectrum for a source, where $j$ is the frequency index. The subband data, $N_{i, k}$, has $i$ data points, for all $k$ subbands available for each source. $\operatorname{VAR}\left(\mathrm{N}_{\mathrm{k}}\right)$ is the variance of the subband data (equal to the square of the noise), and $n_{i \in j}$ is the number of data points $i$ that map onto each lower-resolution frequency bin $j$.

These binned spectra facilitate the identification of spectral lines. Once we found the location of a spectral line in a spectrum, we return to the raw data in order remove the baseline while masking out the position of the spectral line. In the case we do not detect any spectral line, we attempt to mask out the highest features in the spectrum, in order to tease out any potential spectral lines.

We convert the fluxes from Temperature to Flux using the different point source conversion factors (in the range of $5.4-9.7 \mathrm{Jy} / \mathrm{K}$ depending on the optics and the frequency). A typical absolute flux calibration uncertainty of $10 \%$ is also taken into account.

### 3.2.2 GBT observations and data reduction

Observations of the lower-J CO transitions of HerBS-52 and HerBS64 out were carried out using the Robert C. Byrd Green Bank Telescope (GBT). Five observing sessions were competed in 2016 October through December (GBT program: 16B210), and two observing sessions were carried out in 2018 March (GBT program: 18A459). For HerBS-52, we observed $\mathrm{CO}(1-0)$ in K-band and $\mathrm{CO}(3-2)$ in W -band (Table 3), while for HerBS-64 CO(1-0), $\mathrm{CO}(2-1)$, and $\mathrm{CO}(3-2)$ were observed in K, Q, and W-band respectively. All observations used the Versatile GBT Astronomical Spectrometer (VEGAS) with a bandwidth of 1500 MHz and a raw spectral resolution of 1.465 MHz , which

This part was written by David
Frayer
provided sufficient velocity coverage and velocity resolution for all bands.

For K-band and W-band, the NOD observing mode was adopted. This mode alternates observations between two beams by moving the telescope. At Q-band, we used the SubBeamNod observing mode which moves the sub-reflector to alternate observations between two beams. SubBeamNod observations allow for faster position switched observations and yield better baselines for receivers whose beam separations are small (e.g., the Ka-band, Q-band, and Argus instruments on the GBT). For K-band and W-band, NOD observations yield better baselines.

A nearby bright continuum source was used to correct the pointing and focus of the telescope every 30 to 60 minutes, depending on the observing frequency and conditions. For observations with $Q$ and W-band the surface thermal corrections for the telescope were made using the AutoOOF observations of 3C273. This method adjusts the surface actuators of the telescope for the current conditions to improve the aperture efficiency at high frequency.

The pointing of the telescope as well as the methods for correcting the surface work best in nighttime under stable thermal conditions. The $\mathrm{CO}(3-2)$ observations for HerBS-52 were taken in the afternoon under very clear, sunny skies which greatly degraded the quality of these data. During the afternoon with clear skies, the changing of the surface and the structure yield large effective telescope losses at W-band.

The GBT spectral-line data were reduced using GBTIDL. Each individual NOD and SubBeamNod scan was visually inspected for the two polarizations and two beams. Low-order polynomial baselines were removed and scans showing large residual baseline features were removed before data co-addition. The data were corrected for atmospheric losses. This correction was particularly large for the $\mathrm{CO}(3-2)$ data of HerBS-64 since the observed frequency of 68.6 GHz is within the wing of the strong atmospheric $\mathrm{O}_{2}$ band. The data were corrected for drifts in pointing by using the measured the pointing offsets and assuming a Gaussian beam.
The absolute flux density scales for the K-band and Q-band observations were derived from observations of 3 C 286 based on the VLA calibration results of Perley \& Butler (2013). For W-band, we used observations of 3 C 273 and the known flux density as a function of time provided by the ALMA Calibrator Source Catalog online database. Factoring in estimates of all errors, including the uncertainty on the calibration scales, measurement errors, uncertainty for the atmosphere correction, and the uncertainty associated with the pointing and focus drifts, we estimated flux uncertainties errors of $15 \%$ at K-band, $20 \%$ at Q-band, $40 \%$ at W-band for HerBS-64, and $60 \%$ at W -band for HerBS-52. The calibration at W -band was particu-
larly challenging for HerBS-52 due to the sunny afternoon conditions which significantly impacted the ability to derive accurate telescope corrections.

### 3.2.3 Line parameterization and redshift determination

I extract the line properties from a spectrum binned at a velocity resolution of $70 \mathrm{~km} / \mathrm{s}$. I calculate the noise by taking the off-line standard deviation. Then I proceed by generating a 1000 realisations of the spectrum, to which I add artificial noise, based on the calculated noise. To each of these realisations, I fit a gaussian, and I thus extract one thousand estimates for each line parameter: frequency, integrated flux and velocity width. I fit the distribution of these thousand data points for each line parameter by a gaussian function, where the central position of the gaussian is our best estimate for the parameter, and the standard-deviation of this gaussian function is an accurate measure for the uncertainty.

This method does not work on lines below a certain signal-to-noise ratio, typically around $3 \sigma$. In the case a line was not detected, we assume the flux to be less than three times the off-line standard deviation, assuming $500 \mathrm{~km} / \mathrm{s}$ line width.

### 3.3 Results

We display the results of the observations in Table 3.3. In total, we observe 24 spectral lines for our eight sources, 4 with the GBT observations, and 20 with the EMIR instrument on the IRAM $30 m$ telescope. The fitting estimates for each spectral line are detailed in the Appendix .4. Five sources have spectral lines that agree with a single spectroscopic redshift. Our IRAM observations find velocity-integrated fluxes ranging from 1.5 to $13 \mathrm{Jy} \mathrm{km} / \mathrm{s}$, while our lower-J transitions, observed with the GBT range between 0.1 and $0.8 \mathrm{Jy} \mathrm{km} / \mathrm{s}$. The velocity-width of our sources ranges between 250 and $750 \mathrm{~km} / \mathrm{s}$. For each galaxy with a confirmed redshift, we detect the $\mathrm{CO}(4-3)$ transition.

We are able to identify 14 CO -lines, two $\mathrm{CI}(1-0)$, and one water line. We provide upper limits on four CO-lines, one $\mathrm{CI}(1-0)$, and two CI (21) lines. We did not detect any HCN lines in our spectra, as they are significantly fainter than the CO and CI lines. We have also detected six spectral lines of a unidentified nature, for the sources that lack a robust spectroscopic redshift. We discuss the significance of these lines in Section 3.4.

Figure 3.3 shows the integrated flux of each CO transition of the sources with identified J-transitions. The CO-ladders of HerBS-38, 52, and -64 appear to peak around $\mathrm{J}=5$ or 6 , whilst both HerBS-61 and -177 appear to have already sloped downward before $\mathrm{J}=4$.

Table 3.3: Observed spectral lines

| Source | Redshift | Transition | Frequency [GHz] | $\mathrm{I}_{\mathrm{CO}}[\mathrm{Jy} \mathrm{km} / \mathrm{s}]$ | FWHM [km/s] |
| :---: | :---: | :---: | :---: | :---: | :---: |
| Robust redshifts |  |  |  |  |  |
| HerBS-38 | $4.7930 \pm 0.0028$ | $\mathrm{CO}(4-3)$ | $79.593 \pm 0.038$ | $2.214 \pm 0.745$ | $765 \pm 215$ |
|  | $4.7983 \pm 0.0006$ | $\mathrm{CO}(5-4)$ | $99.401 \pm 0.011$ | $3.151 \pm 0.658$ | $314 \pm 68$ |
|  | $4.7980 \pm 0.0006$ | $\mathrm{CO}(7-6)$ | 139.287 | $<3.620$ | 500 |
|  | $4.7980 \pm 0.0006$ | $\mathrm{CI}(2-1)$ | 139.652 | $<3.620$ | 500 |
| HerBS-52 | $3.4419 \pm 0.0006$ | $\mathrm{CO}(1-0)$ | $25.951 \pm 0.004$ | $0.388 \pm 0.064$ | $519 \pm 85$ |
|  | $3.4419 \pm 0.0002$ | $\mathrm{CO}(3-2)$ | 77.854 | $<3.524$ | 500 |
|  | $3.4428 \pm 0.0005$ | $\mathrm{CO}(4-3)$ | $103.783 \pm 0.012$ | $6.067 \pm 0.793$ | $507 \pm 52$ |
|  | $3.4423 \pm 0.0006$ | $\mathrm{CO}(5-4)$ | $129.744 \pm 0.017$ | $6.517 \pm 0.949$ | $515 \pm 72$ |
|  | $3.4409 \pm 0.0005$ | $\mathrm{CO}(6-5)$ | $155.742 \pm 0.016$ | $6.223 \pm 1.518$ | $229 \pm 33$ |
| HerBS-61 | $3.7275 \pm 0.0005$ | $\mathrm{CO}(4-3)$ | $97.532 \pm 0.011$ | $5.658 \pm 0.873$ | $456 \pm 88$ |
|  | $3.7281 \pm 0.0030$ | $\mathrm{CI}(1-0)$ | $104.086 \pm 0.066$ | $<3.630$ | 500 |
|  | $3.7271 \pm 0.0006$ | $\mathrm{CO}(6-5)$ | $146.312 \pm 0.018$ | $2.247 \pm 0.624$ | $247 \pm 41$ |
| HerBS-64 | $4.0484 \pm 0.0009$ | $\mathrm{CO}(1-0)$ | $22.833 \pm 0.004$ | $0.177 \pm 0.046$ | $310 \pm 81$ |
|  | $4.0462 \pm 0.0006$ | $\mathrm{CO}(2-1)$ | $45.686 \pm 0.005$ | $0.508 \pm 0.117$ | $455 \pm 79$ |
|  | $4.0462 \pm 0.0003$ | $\mathrm{CO}(3-2)$ | $68.630 \pm 0.017$ | 5.493 | 500 |
|  | $4.0473 \pm 0.0007$ | $\mathrm{CO}(4-3)$ | $91.352 \pm 0.013$ | $2.057 \pm 0.532$ | $364 \pm 99$ |
|  | $4.0471 \pm 0.0005$ | $\mathrm{CO}(6-5)$ | $137.035 \pm 0.0149$ | $2.399 \pm 0.580$ | $331 \pm 123$ |
|  | $4.0431 \pm 0.0009$ | $\mathrm{H}_{2} \mathrm{O} 2_{11}-2_{02}$ | $149.122 \pm 0.027$ | $1.597 \pm 0.536$ | $345 \pm 73$ |
|  | $4.0462 \pm 0.0003$ | $\mathrm{CO}(7-6)$ | 159.902 | < 1.692 | 500 |
|  | $4.0462 \pm 0.0003$ | $\mathrm{CI}(2-1)$ | 160.457 | < 1.692 | 500 |
| HerBS-177 | $3.9633 \pm 0.0006$ | $\mathrm{CO}(4-3)$ | $92.898 \pm 0.011$ | $4.351 \pm 1.026$ | $490 \pm 204$ |
|  | $3.9616 \pm 0.0009$ | $\mathrm{CI}(1-0)$ | $99.187 \pm 0.018$ | $2.000 \pm 0.599$ | $308 \pm 102$ |
|  | $3.9673 \pm 0.0007$ | $\mathrm{CO}(6-5)$ | $139.236 \pm 0.019$ | $7.047 \pm 0.698$ | $677 \pm 62$ |


| Single line detections |  |  |  |  |  |
| :--- | :--- | :---: | :---: | :---: | :---: |
| HerBS-83 | - | Unknown | $89.594 \pm 0.018$ | $2.976 \pm 0.486$ | $636 \pm 82$ |
|  | - | Unknown | $93.235 \pm 0.070$ | $1.844 \pm 0.692$ | $255 \pm 96$ |
|  | - | Unknown | $101.759 \pm 0.022$ | $2.567 \pm 0.541$ | $539 \pm 93$ |
| HerBS-89 | - | Unknown | $76.153 \pm 0.033$ | $4.309 \pm 1.401$ | $629 \pm 191$ |
| HerBS-150 | - | Unknown | $83.466 \pm 0.024$ | $13.14 \pm 3.633$ | $635 \pm 117$ |
|  | - | Unknown | $94.089 \pm 0.288$ | $2.059 \pm 0.779$ | $580 \pm 111$ |

Notes: Italics indicate undetected lines. Reading from the left, the columns are: Column 1 - HerBS-ID; column 2 - redshift derived from specific spectral line, or if the line is undetected, the redshift follows from the best-fit estimate; column 3 - spectral line; column 4 - (expected) frequency; column 5 - integrated flux of spectral line, unobserved lines assume $500 \mathrm{~km} / \mathrm{s}$ and $3 \sigma$ upper limit; column 6 - line width expressed in Full-Width at Half-Maximum (FWHM), set to $500 \mathrm{~km} / \mathrm{s}$ for undetected lines (Bothwell et al., 2013).


Figure 3.3: Integrated flux for each CO transition, Jup, show the diverse behaviour of the CO spectral line energy distributions. Arrows indicate upper-estimates, where the integrated flux is taken to be less than three times the off-line standard deviation, assuming $500 \mathrm{~km} / \mathrm{s}$ line width.

We overplot each of the line profiles per source in Figure 3.4, centered on the line's frequency. The different scales of the fluxes make it difficult to identify a combined profile. Dotted lines are unidentified lines.
We discuss the observations of each source seperately, and plot their spectra in Figure 3.5.
HerBS-38: The most significant CO line detection allowed for several possible spectroscopic redshifts. A second CO line was observed at the frequency corresponding to $\mathrm{z}=4.7980 \pm 0.0006$, making it the highest known redshift in the HerBS sample. We observed the Eo+E1 ( $\sim 150 \mathrm{GHz}$ ) waveband combination to increase the observation time on the $\mathrm{CO}(4-3)$ line, as well as look for the higher CO transition and the CI emission, but we detected neither due to short observing time (o.4 hours).

HerBS-52: This source is observed both by the GBT and IRAM/EMIR. We initially detected a spectral line in the Eo wavelband. This was followed up with two tunings in the E1 range, leading to two observed spectral lines, $\mathrm{CO}(5-4)$ and $\mathrm{CO}(6-5)$. Initially, we did not detect any CO emission in the GBT observations, leading us to repropose the $\mathrm{CO}(1-\mathrm{o})$ observations and detect it. The GBT observations of the $\mathrm{CO}\left(3^{-}\right.$ 2) lines of HerBS-52 had poor baselines, and hence failed to result in a detection. We will leave out this $\mathrm{CO}(3-2)$ spectral line in further analysis.
HerBS-61: We detected the first CO line, $\mathrm{CO}(4-3)$, and the $\mathrm{CI}(1-0)$ line in our first tuning in Eo. This was followed by observations of the E1, which was chosen to cover all possible spectroscopic redshifts. In this tuning, we detected the $\mathrm{CO}(6-5)$ line, which confirmed the redshift.
HerBS-64: This source is both observed by the GBT and IRAM/EMIR. The IRAM observations cover two tunings in the Eo band, which detected the $\mathrm{CO}(4-3)$ line. This was followed by two tunings in E1, which detected the $\mathrm{CO}(6-5)$ and provide an upper limit for the $\mathrm{CO}(7-6)$ and CI line. The $C O(1-0)$ and $C O(2-1)$ are observed clearly with the GBT, however the GBT observations of the CO(3-2) line of HerBS-64 were impacted by high $\mathrm{T}_{\text {sys }}$ and opacity, since the line is on the wing of the atmospheric $\mathrm{O}_{2}$ line. We still detected the $\mathrm{CO}(3-2)$ line of HerBS-64, however, as we will see in Section 3.4, the flux we find is too low.
HerBS-83: We observed both tunings in Eo for this source for a significant time ( 14.7 h in total), reveiling several spectral lines. These lines do not agree with each other regarding the potential redshifts. No spectral lines were detected in the first scan of E1. The reason for the non-identification of a unique redshift will be discussed in Section 3.4.

HerBS-89: This source was only observed for 1.6 hours in a single Eo tuning. Within this short time, we detected a potential spectral line, however did not have the time to follow-up in E1.


Figure 3.4: All detected spectral lines are centered on their rest velocity, and show the difficulty in obtaining blind redshifts for for the highz sources due to the low signal-to-noise. Dashed lines indicate unidentified lines. Orange, blue and grey cycle through the CO ladder, meaning orange both refers to $\mathrm{CO}(1-0)$ and $\mathrm{CO}(4-3)$, blue to $\mathrm{CO}(2-1)$ and $\mathrm{CO}(5-4)$ and grey to $\mathrm{CO}(3-2)$ and $\mathrm{CO}(6-5))$. Red refers to any other spectral line, which in this case refers to $\mathrm{CI}(1-$ o) and $\mathrm{H}_{2} \mathrm{O}$.


Figure 3.5: The rest-frame spectrum of the IRAM observations of all sources visualizes where we expect and detect spectral lines. The order of the spectral lines is, unlike throughout the rest of the chapter, from highest to lowest redshift. Blue spectra indicate spectra that result in robust spectroscopic redshifts. Grey lines are from galaxies with non-robust redshifts, with either conflicting or singly-detected spectral lines. Here I assume the spectroscopic redshift of the highest signal-to-noise line which is closest to the photometric redshift estimate. This graph was inspired by Figure 2 from Vieira et al. (2013).

HerBS-150: The first Eo tuning was observed significantly longer than the other tuning ( 4 h vs. 1 h ). The deeper tuning reveiled a potential spectral line, and the shallow observation also detected a spectral line. The frequencies of these spectral lines, however, do not agree with a single source.
HerBS-177: The Eo observations cover two tunings, and show a single detected CO-line, which was later confirmed to be $\mathrm{CO}(4-3)$ line. We also detect the $\mathrm{CI}(1-0)$ line. Observations in the $\mathrm{EI}_{1}$ band detect the $\mathrm{CO}(6-5)$ line.

### 3.4 DISCUSSION

### 3.4.1 Spectroscopic redshifts

For each source, we calculate the total redshift estimate of our sources by a weighted average of the redshift estimate from each individual spectral lines,

$$
\begin{equation*}
\bar{z}=\sqrt{\frac{\sum^{i}\left(z_{i} / d z_{i}\right)^{2}}{\sum^{i}\left(1 / d z_{i}\right)^{2}}} . \tag{3.2}
\end{equation*}
$$

The uncertainty in redshift, $d z$, is calculated from the uncertainty in the frequency from Table 3.3.

We list these in Table 3.4. For the sources with inconsistent or singly-detected lines, we assume the line to be closest to the photometric redshift estimated in Bakx et al. (2018), shown in Table 3.3, a similar approach as Vieira et al. (2013). Four of the photometric redshift estimates overestimated the actual redshift by 13 to $30 \%$, significantly more than the average HerBS source with a spectroscopic redshift in Bakx et al. (2018). This suggests the assumed spectrum does not discribe the sources accurately.

Figure 3.6 shows the difference of each spectral line from the combined spectroscopic redshift, expressed in $\mathrm{km} / \mathrm{s}$. The uncertainty is given by the uncertainty in the frequency, in Table 3.6.

HerBS-52 and -61 appear to have very consistent spectral lines, all agreeing with each other, within the uncertainty. HerBS-38 has an accurate, and an inaccurate spectral line, which disagree slightly. This could be an indication of two interacting sources (Hayward et al., 2013). HerBS-64 has a large spread among the spectral lines. Especially the $\mathrm{CO}(3-2)$ spectral line provides a poor estimate of the spectroscopic redshift, which is probably due to the poor baselines in the GBT observation. HerBS-177 has a similarly large spread.

This plot does not indicate any systemic offsets for the different spectral lines, which could be due to calibration errors, observation errors or systemic behaviour among spectral lines.

We fit the photometric datapoints from Table 3.1 with three spectra, fixed to the spectroscopic redshifts, and plot them in Figure 3.7. These

I calculate the uncertainty by subtracting the redshift for a frequency $\mathrm{f}_{\text {obs }}+\mathrm{df}$ and from the redshift for the frequency $\mathrm{f}_{o b s}$


Figure 3.6: Most average spectroscopic redshifts (black) agree with the individual line detections. Orange, blue and grey cycle through the CO ladder, meaning orange both refers to $\mathrm{CO}(1-0)$ and $\mathrm{CO}(4-3)$, blue to $\mathrm{CO}(2-1)$ and $\mathrm{CO}(5-4)$ and grey to $\mathrm{CO}(3-2)$ and $\mathrm{CO}(6-5))$. Red refers to any other spectral line, which in this case refers to $\mathrm{CI}(1-\mathrm{o})$ and $\mathrm{H}_{2} \mathrm{O}$.
spectra are the best-fit template for Bakx et al. (2018), the spectra from the method from Ivison et al. (2016), and a single-temperature modified blackbody (MBB) with a $\beta$ set to 2.0 . The best-fit template in Bakx et al. (2018) was derived from the Herschel/SPIRE and SCUBA2 photometry of 24 HerBS sources with spectroscopic redshifts. The spectral fit in Ivison et al. (2016) fits three different templates (ALESS (Swinbank et al., 2014), Cosmic Eyelash (Ivison, R. J. et al., 2010; ), and the template from Pope et al. (2008)) to the flux measurements, and choses the spectrum with lowest $\chi^{2}$-value. For the single-temperature MBB we allow the temperature to vary, and note the results in Table 3.4. In the case the galaxy was not detected in the photometric band, we use the upper-limit fit discussed in Sawicki (2012), Thomson et al. (2017) and Bakx et al. (2018). For the sources with inconclusive spectroscopic redshifts, we take the redshifts from Table 3.4.

None of the templates appear to fit the photometric data points well, except for HerBS-83 and -150. This fact is also reflected by the small value of $\Delta z /(1+z)$ for HerBS-83 and -150 in Table 3.4. The template fits underestimate the $850 \mu \mathrm{~m}$ flux for HerBS-52, $-61,-64,-89$ and -177 . This suggests that we should not put too much weight on the temperature findings of the single-temperature MBB fit. The single-temperature MBB fit overlaps completely for the sources with multiple possible spectroscopic redshifts, i.e. the grey lines overlap for HerBS-83, -89 and -150 . This is due to the degeneracy between the temperature and the redshift in the single-temperature MBB fit, where the shape of the fitted spectrum of a higher spectroscopic redshift will be negated by a higher temperature.
We estimate the dust mass according to equation 1 in Magdis et al. (2011),

$$
\begin{equation*}
M_{d}=\frac{S_{v} D_{\mathrm{L}}^{2}}{(1+z) \kappa_{\text {rest }} \mathrm{B}_{v}\left(\lambda_{\text {rest }}, T_{\mathrm{d}}\right)} . \tag{3.3}
\end{equation*}
$$

$S_{v}$ is the observed flux density, $D_{L}$ is the luminosity distance, $z$ is the spectroscopic redshift, $\kappa_{\text {rest }}$ is derived by interpolating the values from Draine (2003), and $B_{v}\left(\lambda_{\text {rest }}, T_{d}\right)$ is the black-body radiation expected for a $T_{d}[K]$ source at $\lambda_{\text {rest }}$. We use the $850 \mu \mathrm{~m}$ fluxes, as they probe the cold dust component of the spectrum, which provides a better dust-mass estimate.

We find similar bolometric luminosities for our sources as detailed in Table 3.1, which were calculated using the photometric redshifts and by integrating the template from Bakx et al. (2018) from 8 to 1000 $\mu \mathrm{m}$. We determine the temperature of the sources by fitting a singletemperature modified blackbody, with a $\beta$ of 2.0, to the galaxy. With 42.0 K, HerBS-38 is significantly warmer than the other galaxies. Since the photometric redshift estimate assumes a two fixed temperatures across all HerBS galaxies, its high high temperature could explain why the photometric redshift under-estimated the spectroscopic red-


Figure 3.7: Most spectra have difficulty fitting the continuum data points. The photometric datapoints of each source are fitted with three spectra at the spectroscopic redshifts; the best-fit template for Bakx et al. (2018) (orange), the spectra from the method from Ivison et al. ( (2016)) (blue), and a single-temperature MBB with a $\beta$ set to 2.0 (grey). We also detail the temperature we find from fitting the single-temperature MBB. In the case we did not detect a conclusive spectroscopic redshift, we use the single-line spectroscopic redshifts from Table 3.4, the order of the temperature is the same as the order in the table, the first-mentioned line is dash-dot, the second is dotted, and in the case of HerBS-83, the final line is solid.

Table 3.4: Spectroscopic redshifts of our detected and undetected sources.

| HerBS | $\mathrm{z}_{\text {spec }}$ | $\Delta \mathrm{z} /(\mathrm{I}+\mathrm{z})$ | $\begin{gathered} \mu \mathrm{L}_{\mathrm{FIR}} \\ \log \left[\mathrm{~L}_{\odot}\right] \end{gathered}$ | $\begin{gathered} \hline \mathrm{T} \\ {[\mathrm{~K}]} \\ \hline \end{gathered}$ | $\begin{gathered} \mu \mathrm{M}_{\text {dust }} \\ {\left[10^{9} \mathrm{M}_{\odot}\right]} \end{gathered}$ |
| :---: | :---: | :---: | :---: | :---: | :---: |
| Robust redshifts |  |  |  |  |  |
| 38 | $4.7980 \pm 0.0006$ | 0.124 | 13.87 | 42.0 | $<3.6$ |
| 52 | $3.4419 \pm 0.0002$ | -0.297 | 13.56 | 29.7 | 24.4 |
| 61 | $3.7273 \pm 0.0004$ | -0.138 | 13.66 | 33.1 | 17.0 |
| 64 | $4.0462 \pm 0.0003$ | -0.132 | 13.70 | 34.7 | 17.4 |
| 177 | $3.9644 \pm 0.0004$ | -0.150 | 13.63 | 32.5 | 20.3 |
| Single line detections |  |  |  |  |  |
| 83 | $4.1464{ }^{(b)} \pm 0.0011$ | -0.125 | 13.65 | 32.9 | 14.6 |
|  | $3.9417^{(\mathrm{b})} \pm 0.0037$ | -0.172 | 13.61 | 31.7 | 16.4 |
|  | $4.6639^{(\text {c) }} \pm 0.0012$ | -0.022 | 13.74 | 36.2 | 11.2 |
| 89 | $3.5410^{(a)} \pm 0.0009$ | -0.147 | 13.61 | 31.9 | 20.2 |
| 150 | $4.5242^{(\mathrm{b})} \pm 0.0016$ | -0.008 | 13.72 | 37.1 | 9.43 |
|  | $3.9005^{(\mathrm{b})} \pm 0.0149$ | -0.137 | 13.60 | 32.9 | 13.5 |

Notes: Reading from the left, the columns are: Column 1 - HerBS-ID; column 2 - redshift calculated from all spectral lines using equation 3.2; column 3 - the error in photometric redshift estimate, given by $\left(Z_{\text {spec }}-Z_{\text {phot }}\right) /\left(1+Z_{\text {spec }}\right)$; column 4 - the logarithm of the far-infrared bolometric luminosity, integrated from 8 to $1000 \mu \mathrm{~m}$; column 5 - the average temperature, assuming a single temperature grey-body with $\beta=2$. In the case we do not find a consistent second line, we calculate the redshift assuming: ${ }^{(a)}$ the line is $\mathrm{CO}(3-2)$, ${ }^{\text {b })}$ the line is $\mathrm{CO}(4-3)$ or ${ }^{(c)}$ the line is $\mathrm{CO}(5-4)$. The redshifts are sorted by frequency.
shift. Similarly, the colder temperatures of HerBS-52, -61, -64 and -177 have caused overestimated photometric redshifts.

### 3.4.2 Undetected sources

For three of our sources, we did not have enough detected spectral lines to find a conclusive redshift identification. For HerBS-89, this is due solely to a lack of observation time spent on this source. However, for sources HerBS-83 and -150 , we find several spectral lines, with inconclusive redshifts associated with them. This points to several sources in a line-of-sight (LOS) alignment, blended into a single sub-mm source in the Herschel selection image. Hayward et al. (2013) found the possibility for LOS blending to be larger than the possibility of spatially associated blending ( $\Delta \mathrm{z}<0.02$ ). Similarly, Zavala et al. (2015) found one of their sources to actually be three LOS blended sources, which could be a similar situation to HerBS-83.

Table 3.5 details the possible spectral line identifications for the individual spectral lines, and I calculate the spectroscopic redshift for the two CO-lines that will give a redshift closest to the photometric redshift estimate. I also list the frequencies of the CO-lines for each potential spectroscopic redshift. I am able to rule out several of the spectral line possibilities.

Table 3.5: Possible spectroscopic redshifts of unidentified lines

| Source | Spectral line | $\mathrm{S} / \mathrm{N}[\sigma]$ | Redshift | Other CO lines [GHz] |
| :--- | :--- | :--- | :--- | :--- |
| 83 | 89.594 | 6.1 | 4.146 | $112 \& 134.4 \& 156$ |
|  |  |  | 5.433 | $143.35 \& 161$ |
|  | 93.235 | 2.7 | 3.945 | 140 \& 161 |
|  |  |  | 5.182 | $74.6 \& 130 \& 149$ |
|  | 101.759 | 4.7 | 3.531 | $76 \& 127.2 \& 152$ |
|  |  |  | 4.664 | $81.46 \& 142.56$ |
| 89 | 76.153 | 3.1 | 3.541 | $101.5 \& 126.9 \& 152$ |
|  |  |  | 5.055 | $95.15 \& 133.2 \& 152.3$ |
| 150 | 83.466 | 3.6 | 4.524 | $104.3 \& 146.07$ |
|  |  |  | 5.905 | $100.2 \& 133.6 \& 150.4$ |
|  | 94.089 | 2.6 | 3.901 | $141 \& 164$ |
|  |  |  | 5.126 | $75.3 \& 131 \& 150.6$ |

Notes: This table lists the spectroscopic redshift based on the two CO-identifications that would be closest to $z_{\text {phot }}$. I then list the other spectral lines, some of which are in frequencies that have already been observed, and cursive CO lines are unlikely given the current data.

### 3.4.3 Spectral line properties

From previous work (Bothwell et al., 2013), we know there exists a significant spread in the conversion of $\mathrm{CO}(4-3)$ flux to $\mathrm{CO}(1-0)$, and we therefore examine the properties of our sources using the $\mathrm{CO}\left(4^{-}\right.$ 3) line, and comparing their properties against sources with detected $\mathrm{CO}(4-3)$ fluxes. We detail the CO line properties in Table 3.6. We calculate the line luminosity of the line with the equation from Solomon et al. (1997):

$$
\begin{equation*}
\mathrm{L}^{\prime}=3.25 \times 10^{7} \mathrm{~S}_{\mathrm{CO}} \Delta v \mathrm{f}_{\mathrm{obs}}^{-2} \mathrm{D}_{\mathrm{L}}^{2}(1+z)^{-3} . \tag{3.4}
\end{equation*}
$$

with the integrated flux, $\mathrm{S}_{\mathrm{CO}} \Delta v$, in $\mathrm{Jy} \mathrm{km} \mathrm{s}^{-1}$, the observed frequency, $\mathrm{f}_{\mathrm{obs}}$, in GHz , and the luminosity distance, $\mathrm{D}_{\mathrm{L}}$, in Mpc. We use the line luminosity ratios from Bothwell et al. (2013) to calculate the $\mathrm{CO}(1-\mathrm{o})$ line luminosity. The molecular hydrogen mass in the galaxy is calculated using

$$
\begin{equation*}
M_{\mathrm{H}_{2}}=\alpha \mathrm{L}_{\mathrm{CO}(1-0)}^{\prime} . \tag{3.5}
\end{equation*}
$$

We adopt the typical value for star-forming galaxies of $\alpha=0.8 \mathrm{M}_{\odot} /(\mathrm{K}$ $\mathrm{km} / \mathrm{s} \mathrm{pc}^{2}$ ) (Magdis et al., 2011). The depletion time is defined as the molecular gas mass divided by the star-formation rate found in Table 3.4 , and the gas to dust ratio, $\delta$, is the molecular gas mass divided by the dust mass.

### 3.4.4 The CO ladder $\mathcal{E}$ line ratios

Figure 3.8 shows the integrated flux of each detected CO line of the sources with a spectroscopic redshift. We normalize the ladder to the $\mathrm{CO}(4-3)$, as this transition was observed for each source. We compare the CO Spectral Line Energy Densities (SLEDs) against several types of SLED profiles. The Constant brightness profile plots the theoretical maximum emission, in the case all excitations are equally populated. The ULIRG profile is from Papadopoulos et al. (2012), who studied the CO emission of local ULIRGs. The Cosmic Eyelash is a well-studied lensed ULIRG at a redshift of 2.3 (Danielson et al., 2011). Our Milky Way has a lot less star-formation than these high-redshift SMGs, and we expect it to be a lower limit on the type of SLEDs we will see of our sample (Fixsen, Bennett, and Mather, 1999). Bothwell et al. (2013) studied the CO properties of the sample of galaxies from the optical-spectroscopic sample of Chapman et al. (2005), and range in redshifts from 1 to 4 . These galaxies have been selected because they have spectroscopic redshifts from optical observations. The $\mathrm{S}_{850 \mu \mathrm{~m}}$ flux densities of their sources are about 6 to 20 times lower than the sources in our sample, and hence represent slightly less luminous galaxies. We plot the individual SLEDs of sources from Yang et al. (2017) with $\mathrm{CO}(4-3)$ detected emission. Some of their sources are also in the HerBS sample, and are therefore expected to behave similarly to our sources.

We derive the line luminosity ratios for each of our sources, using equation

$$
\begin{equation*}
r_{\mathrm{J}_{\mathrm{a}}, \mathrm{~J}_{\mathrm{b}}}=\frac{\mathrm{r}_{\mathrm{Ja}, 1}}{\mathrm{r}_{\mathrm{J}_{\mathrm{b}}, 1}}=\frac{\mathrm{L}_{\mathrm{a}}^{\prime}}{\mathrm{L}_{\mathrm{b}}^{\prime}}=\frac{\mathrm{I}_{\mathrm{a}}}{\mathrm{I}_{\mathrm{b}}} \frac{\mathrm{~J}_{\mathrm{a}}^{2}}{\mathrm{~J}_{\mathrm{a}}^{2}} . \tag{3.6}
\end{equation*}
$$

For each of our sources, we plot the ratios in Figure 3.9. We compare the sample to the ratio from Bothwell et al. (2013), and the constant brightness SLED profile. The constant brightness profile assumes all excitation states of the CO molecule are equally occupied, and effectively is an upper limit for transitions where $\mathrm{J}_{\mathrm{a}}$ is greater than $\mathrm{J}_{\mathrm{b}}$, and an under limit when $\mathrm{J}_{\mathrm{a}}$ is smaller than $\mathrm{J}_{\mathrm{b}}$.

We calculate the uncertainty using the typical error propagation formula

$$
\begin{equation*}
\Delta \mathrm{r}_{\mathrm{Ja}, \mathrm{~J}}=\sqrt{\left(\frac{\Delta \mathrm{L}_{\mathrm{a}}^{\prime}}{\mathrm{L}_{\mathrm{a}}^{\prime}}\right)^{2}+\left(\frac{\Delta \mathrm{L}_{\mathrm{b}}^{\prime}}{\mathrm{L}_{\mathrm{b}}^{\prime}}\right)^{2}} \tag{3.7}
\end{equation*}
$$

Table 3.6: Spectral line properties

| Source | Transition | $\begin{gathered} \mu \mathrm{L}_{\text {specline }}^{\prime} \\ {\left[10^{10} \mathrm{~K} \mathrm{~km} / \mathrm{s} \mathrm{pc}^{2}\right]} \end{gathered}$ | $\begin{gathered} \mu \mathrm{L}_{\mathrm{CO}(1-\mathrm{o})}^{\prime} \\ {\left[10^{10} \mathrm{~K} \mathrm{~km} / \mathrm{s} \mathrm{pc}^{2}\right]} \end{gathered}$ | $\begin{gathered} \mu \mathrm{M}_{\mathrm{mol}} \\ {\left[10^{10} \mathrm{M}_{\odot}\right]} \end{gathered}$ | $\begin{gathered} \mathrm{t}_{\mathrm{dep}} \\ {[\mathrm{Myr}]} \end{gathered}$ | $\delta$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Robust redshifts |  |  |  |  |  |  |
| HerBS-38 | $\mathrm{CO}(4-3)$ | $12.1 \pm 3.7$ | $29.4 \pm 9.0$ | $23.5 \pm 7.2$ | $24.3 \pm 7 \cdot 4$ | $67 \pm 21$ |
|  | $\mathrm{CO}(5-4)$ | $11.0 \pm 2.1$ | $34.4 \pm 6.5$ | $27.5 \pm 5.2$ | $28.4 \pm 5.4$ | $79 \pm 15$ |
|  | $\mathrm{CO}(7-6)$ | $<5.82$ | $<32.3$ | $35.5 \pm 11.8$ | $36.6 \pm 12.2$ | $101 \pm 34$ |
|  | $\mathrm{CI}(2-1)$ | $<5.82$ |  |  |  |  |
| HerBS-52 | $\mathrm{CO}(1-0)$ | $20.1 \pm 3.1$ | $20.1 \pm 3.1$ | $16.1 \pm 2.4$ | $13.8 \pm 1.9$ | $6.6 \pm 1.0$ |
|  | $\mathrm{CO}(4-3)$ | $19.7 \pm 2.3$ | $48.0 \pm 5.7$ | $38.4 \pm 4.6$ | $32.9 \pm 3.9$ | $15 \pm 1.9$ |
|  | $\mathrm{CO}(5-4)$ | $13.5 \pm 1.8$ | $42.3 \pm 5.6$ | $33.8 \pm 4.5$ | $29.0 \pm 3.8$ | $14 \pm 1.8$ |
|  | $\mathrm{CO}(6-5)$ | $8.96 \pm 1.99$ | $42.7 \pm 9.5$ | $34.1 \pm 7.6$ | $29.3 \pm 6.5$ | $14 \pm 3.1$ |
| HerBS-61 | $\mathrm{CO}(4-3)$ | $20.8 \pm 2.9$ | $50.8 \pm 7.1$ | $40.7 \pm 5.7$ | $38.2 \pm 5.4$ | $24 \pm 3.4$ |
|  | $\mathrm{CI}(1-0)$ | < 10.7 |  |  |  |  |
|  | $\mathrm{CO}(6-5)$ | $3.68 \pm 0.93$ | $17.5 \pm 4.4$ | $14.0 \pm 3.5$ | $13.2 \pm 3.3$ | $8.2 \pm 2.1$ |
| HerBS-64 | $\mathrm{CO}(1-0)$ | $11.9 \pm 2.3$ | $11.9 \pm 2.3$ | $9.51 \pm 1.83$ | $8.16 \pm 1.57$ | $5.5 \pm 1.0$ |
|  | $\mathrm{CO}(2-1)$ | $8.13 \pm 1.17$ | $9.68 \pm 1.4$ | $7.75 \pm 1.12$ | $6.65 \pm 0.96$ | $4.5 \pm 0.6$ |
|  | $\mathrm{CO}(3-2)$ | $6.29 \pm 2.24$ | $12.1 \pm 4.3$ | $9.68 \pm 3.45$ | $8.31 \pm 2.96$ | $5.6 \pm 2.0$ |
|  | $\mathrm{CO}(4-3)$ | $8.63 \pm 2.03$ | $21.0 \pm 5.0$ | $16.8 \pm 4.0$ | $14.4 \pm 3.4$ | $9.7 \pm 3.1$ |
|  | $\mathrm{CO}(6-5)$ | $4.47 \pm 0.98$ | $21.3 \pm 4.6$ | $17.0 \pm 3.7$ | $14.6 \pm 3.2$ | $9.8 \pm 2.3$ |
|  | $\mathrm{H}_{2} \mathrm{O} 2_{11}-2_{02}$ | $2.51 \pm 0.77$ |  |  |  |  |
|  | $\mathrm{CO}(7-6)$ | $<2.11$ | $<11.7$ | $<9.36$ | $<8.03$ | $<5.4$ |
|  | $\mathrm{CI}(2-1)$ | $<2.09$ |  |  |  |  |
| HerBS-177 | $\mathrm{CO}(4-3)$ | $17.7 \pm 3.8$ | $43.1 \pm 9.2$ | $34 \cdot 5 \pm 7 \cdot 4$ | $34.7 \pm 7 \cdot 4$ | $17 \pm 3.6$ |
|  | $\mathrm{CI}(1-0)$ | $7.12 \pm 1.94$ |  |  |  |  |
|  | $\mathrm{CO}(6-5)$ | $12.7 \pm 1.2$ | $60.6 \pm 5.5$ | $48.5 \pm 4.4$ | $48.9 \pm 4.4$ | $24 \pm 2.2$ |
| Single line detections |  |  |  |  |  |  |
| HerBS-83 | $\mathrm{CO}(4-3)$ | $13.0 \pm 1.9$ | $31.6 \pm 4.7$ | $25.3 \pm 3.8$ | $24.9 \pm 3.7$ | $17 \pm 2.6$ |
|  | $\mathrm{CO}(4-3)$ | $7.43 \pm 2.54$ | $18.1 \pm 6.2$ | $14.5 \pm 4.9$ | $14.3 \pm 4.9$ | $8.8 \pm 3.0$ |
|  | $\mathrm{CO}(5-4)$ | $8.58 \pm 1.64$ | $27.7 \pm 5.3$ | $22.1 \pm 4.2$ | $21.8 \pm 4.2$ | $20 \pm 3.8$ |
| HerBS-89 | $\mathrm{CO}(3-2)$ | $26.0 \pm 7.7$ | $50.0 \pm 14.8$ | $40.0 \pm 11.9$ | $41.2 \pm 12.2$ | $20 \pm 5.9$ |
| HerBS-150 | $\mathrm{CO}(4-3)$ | $65.5 \pm 16.5$ | $160 \pm 40$ | $128 \pm 32.1$ | $145 \pm 36$ | $136 \pm 34$ |
|  | $\mathrm{CO}(4-3)$ | $8.15 \pm 2.80$ | $19.9 \pm 6.8$ | $15.9 \pm 5.5$ | $18.0 \pm 6.2$ | $12 \pm 4.1$ |

Notes: Reading from the left, the columns are: Column 1 - HerBS-ID; column 2 - The assumed transition; column 3-The line luminosity with no magnification correction; column 4 - The predicted $\mathrm{CO}(1-0)$ line luminosity according to the average CO-ladder from Bothwell et al. (2013); column 5 - The molecular hydrogen mass in the galaxy, derived from $\alpha=0.8$; column 6 - The depletion time is defined as the molecular gas mass divided by the star-formation rate found in Table 3.4; column 7 - The gas to dust ratio, $\delta$, is the molecular gas mass divided by the dust mass.


Figure 3.8: Comparison of the individual CO line luminosity ratios, normalised against $\mathrm{CO}(4-3)$, for different $\mathrm{J}_{\mathrm{up}}$. For comparison, we plot against several SLEDS; constant brightess, ULIRG from Papadopoulos et al. (2012), the Cosmic Eyelash (Danielson et al., 2011), our Milky Way Fixsen, Bennett, and Mather (1999), and the average SLED of (Bothwell et al., 2013).


Figure 3.9: We compare the luminosities of the CO-lines to calculate the flux ratios between the lines. Each sub-figure refers to a different $J_{a}$, while the x -axis lists the $\mathrm{J}_{\mathrm{b}}$. We compare the ratios to the expected ratios of the measurements of Bothwell et al. ( (2013)), and the constant brightness profile.

Typically, the fluxes are reasonably-well predicted by the Bothwell et al. (2013) ratios. The only major outlier is the CO(6-5) flux of HerBS61, which is significantly brighter than predicted. Notably, the lowerJ fluxes of HerBS-52 suggest these transitions are fully thermalised, while the higher transitions are not. The figure also shows the unpredictability of the CO-lines. Whilst most CO-lines behave according to the literature, there still is a significant spread, and predicting the fluxes of other transitions carries a large uncertainty.

### 3.4.5 Lensing nature of our sources

We plot the line width against the line luminosity, in an effort to demonstrate the lensing nature of our sources. The basic assumption here is that heavier galaxies have faster rotation velocities, and because they are heavier, they have more gas that emits radiation. Brighter lines should therefore correspond to wider velocity widths, unless the lines are brightened by gravitational lensing. This method was demonstrated successfully in Harris et al. (2012). Figure 3.10 shows the $\mathrm{CO}(4-3)$ line luminosity of each source plotted for the Full-Width at Half-Maximum (FWHM) of the line width. We compare against the $\mathrm{CO}(4-3)$ luminosity of other samples:

Bothwell+2013: Sources from Bothwell et al. (2013)
Planck: Sources from Harrington et al. (2016) and Cañameras, R. et al. (2015)

Herschel: Sources from Yang et al. (2017), Zavala et al. (2015) and George et al. (2013)

Ivison+2013: The weakly lensed source of Ivison et al. (2013)
Fudamoto+2017: Sources from Fudamoto et al. (2017), drawn from the sample of Ivison et al. (2016) which was explicitly selected to contain only a few amount lensed sources

The solid line in Figure 3.10 is derived from the line luminosity versus FWHM found in Bothwell et al. (2013). This equation is given for the line luminosity of the $\mathrm{CO}(1-0)$, which I change to the $\mathrm{CO}(4-3)$ line luminosity by multiplying by the median brightness temperature ratio of 0.41 (Bothwell et al., 2013). The magnified relation is found by simply multiplying by the magnification $(\times 10)$.

We note a distinct split between the lensed and unlensed sources, depending on the lensing nature of the sample we select from. All our sources lie close to the lensed distribution, with perhaps HerBS38 showing a lower magnification than the others.


Figure 3.10: The $\mathrm{CO}(4-3)$ line luminosity versus the line width indicates our sources are gravitationally lensed. Unlensed sources the follow solid line from Bothwell et al. (2013), such as the mostly unlensed sources from Bothwell et al. (2013),Ivison et al. (2013) and Fudamoto et al. (2017). Lensed sources, such as the ones selected from the Planck (Harrington et al., 2016; Cañameras, R. et al., 2015) and Herschel surveys (Yang et al., 2017; Zavala et al., 2015; Cox et al., 2011) have higher line luminosities due to the amplification. Our sources are found in the same region, suggesting these sources are lensed.

### 3.4.6 The nature of the individual sources

We now use the previous work to discuss all sources individually.
HerBS-38: This source has the highest known spectroscopic redshift in the HerBS sample. This is the only source with $\mathrm{dz} /(1+\mathrm{z})$ that is positive, at 0.12 . dz refers to the difference between the spectroscopic redshift and the photometric redshift, and hence a galaxy with a positive value has a spectroscopic redshift greater than the photometric redshift estimate. Since the photometric redshift is calculated from fitting a two-temperature modified blackbody, and due to the temperatureredshift degeneracy, the underestimation of the photometric redshift is probably due to a higher internal temperature.

Integrated fluxes show a highly star-forming galaxy, as the shape of the SLED follows the SLED of a source with a constant CO brightness, which is the brightness ratio one would expect if all CO-excitations are equally populated, and therefore the gas is fully thermalized. Due to the non-detection at $850 u m$, we find a low dust-mass estimate, resulting in a large gas-to-dust ratio. The $t_{\text {dep }}$ appears an average value for a HerBS galaxy. The galaxy lies quite close to the unlensed population in Figure 3.10.
HerBS-52: The photometric redshift estimate of this source disagrees most with the discovered spectroscopic redshift, with $\mathrm{dz} /(1+z)$ at o.30. Unlike HerBS-38, whose hotter gas produced an underestimated photometric redshift, this galaxy has an overestimated photometric redshift due to a colder dust temperature. All the redshifts deduced from the individual spectral lines agree with each other.

The shape of the CO SLED suggests the source follows the constant brightness profile until $\mathrm{CO}(4-3)$, demonstrating a highly starforming source. The galaxy appears very dusty, with a relatively secure gas-to-dust ratio of $\sim 10$, derived from the $\mathrm{CO}(1-0)$. The higher CO-transitions fail to accurately predict $\mathrm{CO}(1-0)$ flux. This is because the SLED of this galaxy disagrees with the SLED from Bothwell et al. (2013), which is usually used to calculate the other line brightnesses. Instead the SLED of this source has a more strongly thermalized inter-stellar medium. Figure 3.10 suggests this source is gravitationally lensed.
HerBS-61: Even though the CI line has a high uncertainty in its frequency, all the redshifts deduced from the individual spectral lines agree with each other. The photometric redshift estimate slightly overestimates the spectroscopic redshift. The steep drop-off of the integrated flux SLED suggests a less strongly thermalized environment than the other sources discussed in this chapter. The gas-to-dust ratio of this source is calculated for both the $\mathrm{CO}(4-3)$ and $\mathrm{CO}(6-5)$ spectral lines, which differ by about a factor of 3 . The molecular mass in the galaxy is calculated from the $\mathrm{CO}(1-0)$ line flux, however the shape of the SLED suggests that the brightness temperature ratios of Bothwell
et al. (2013) underestimate the $C O(1-0)$ line flux. Hence I expect there to be more molecular gas, and hence that the ratio is around $\sim 30$ or higher. The depletion time, similarly, is of the order of 50 Myr. Figure 3 .10 suggests this source is gravitationally lensed.
HerBS-64: The redshift estimates of most of the individual lines agree with the average spectroscopic redshift, although the redshift estimate from the water line appears to be $100 \mathrm{~km} / \mathrm{s}$ offset from the central spectroscopic redshift. The photometric redshift estimate slightly over-estimated the spectroscopic redshift. Similar to HerBS-52, the CO SLED appears thermalised up to $\mathrm{CO}(4-3)$, after which it behaves similar to the average SLED that found by Bothwell et al. (2013). Also similar to HerBS-52, this source has a low gas-to-dust ratio of around 10. The higher CO-transitions fail to adequately predict $\mathrm{CO}(1-0)$ and the associated parameters by about 50 per cent due to the stronglythermalized nature of the inter-stellar medium. Figure 3.10 suggests this source is gravitationally lensed.
HerBS-83: The redshifts of spectral lines of this source do not agree with a single source. This could be explained by a line-of-sight blend of sources. The continuum images, Figure 3.2, show potentially an extended profile at $850 \mu \mathrm{~m}$. High-resolution images of this source are needed to resolve the spatial distribution of these sub-mm sources. This could be used to test sub-mm galaxy distribution models, as has been suggested in Hayward et al. (2013); Bethermin et al. (2015). Zavala et al. (2015) found a source similar to this, lensed by a galaxy cluster.
HerBS-89: The lack of observing time on this source only resulted in a single spectral line detection. In the case this spectral line is a CO-line, this source would lie either at a redshift of 3.5 or at a redshift of 5.1. Both these values disagree with the expected photometric redshift of 4.2 .

HerBS-150: The redshift estimates from the two detected spectral lines do agree with a single source, which could point to a line-ofsight source blending.
HerBS-177: The redshift estimations of the two individual spectrallines of this source disagree by up to two standard deviations with the average spectroscopic redshift. The photometric redshift estimate slightly over-estimated the spectroscopic redshift. Similar to HerBS61, the SLED of this source has steep drop-off, which suggests that the inter-stellar medium is less thermalized than in the HerBS-52 and -64. The estimates predict a typical gas-to-dust ratio, and a typical depletion time. Given the shape of the SLED, I expect the gas-to-dust ratio and depletion time of $\mathrm{CO}(4-3)$ to serve as an effective upper limit. Figure 3.10 suggests this source is gravitationally lensed.

### 3.4.7 Current and future high-redshift searches

Our observations with the IRAM 30 m telescope resulted in the addition of five extra spectroscopic redshifts. The large collecting area, with a 30 m telescope, meant we were able to find the CO-lines relatively quickly. Combined with the real-time data analysis, this telescope is able to quickly probe the properties of the sub-mm sources. However, when the expansion of the collecting area of the LMT is complete, increasing the telescope size from 32 to 50m, this telescope will become the new standard for finding spectroscopic redshifts, especially since the Redshift Search Receiver has a large bandwidth. A single tuning ranges from 73 to 110.5 GHz , and thus only requires a single tuning for the detection of the first CO line. While the LMT will be faster, the tunability of the wavebands at the 30 m telescope and at NOEMA mean more CO-lines, and other spectral lines can be followed up in a single pointing.

The brightness of higher-J CO-lines is unpredictable, and depends strongly on the internal properties of the galaxies. Large follow-up programs could suffer from biases due to this. Finding spectroscopic redshifts with atomic spectral lines could prevent this, as they are typically more luminous than the CO-lines. These atomic spectral lines are typically at slightly higher frequencies, $\lambda<1 \mathrm{~mm}$, although a recent band-7 ( 0.8 to 1.1 mm ) observation with ALMA detected a redshift 9.1 galaxy (Hashimoto et al., 2018).

New instruments are under development which will probe this regime with a wide enough bandwidth to increase the speed of redshift hunts. This promises a time where entire sub-mm samples can be followed-up with sub-mm spectroscopy, offering an unbiased view on samples of extremely star-forming galaxies. The upgrade to ZEUS, ZEUS-2, has already demonstrated a significant increase in the bandwidth (Ferkinhoff et al., 2014; Vishwas et al., 2018). The relatively new technology, so-called Microwave Kinetic Inductance Detectors (M-KIDs - Yates et al. (2011)), promise a similar increase in bandwidth, with the added versatility, and a significant decrease in instrument size and complexity. Instruments as DESHIMA (Endo et al., 2012) and MOSAIC (Baselmans, J. J. A. et al., 2017) will allow 1om-class telescopes to compete with ALMA in blind redshift searches. This evolution in detector technology comes in a time when new telescopes are being drawn up, such as the 50m-class telescope AtLAST (Ryohei Kawabe, 2016), CCAT and the SPICA space mission.

> 'The world is curved, the sky is blue, the sea is wet, and water too, and space is big, and so are stars, and so's the sun, and Earth, and Mars.
> A fact's a fact, and true is true, and can't be changed by me and you.'
> 'But then, of course,' his friend began: '... that's just like your opinion, man.'
—_/u/poem_for_your_sprog

### 4.1 INTRODUCTION

Recent developments in far-infrared technology have allowed us to detect a population of sub-mm bright, optically faint galaxies at high redshift. These sources are forming stars at several hundreds or thousand times the typical rates of galaxies in the local Universe, and we expect them to be the progenitors of the most massive galaxies. As these sources are optically hard to detect, sub-mm observations are a necessary element to understanding the high star-forming environments in the Universe.

The first sub-mm observation of the Hubble Deep Field North shows the importance of far-infrared observations in order to get a complete picture of the processes in the Universe. A bolometer instrument (SCUBA) on the James Clerk Maxwell Telescope detected 5 separate sources over 8 square arcminutes, however with very poor angular resolution, see Figure 4.1 (Hughes et al., 1998; Walter et al., 2012). When these observations are cross-compared to the optical observations, the difficulty of cross-correlating sub-mm sources becomes clear. Actually, the brightest source, HDF850.1, has not been optically identified to this day (Casey, Nayarayan, and Cooray, 2014; Serjeant and Marchetti, 2014).

For small samples of sources, it is possible to identify counterparts by observing them at higher spatial resolutions, using near-infrared or radio observatories. This, however, is impossible for the hundreds of thousands of sources following from recent large surveys. The typical spectrum of a sub-mm galaxy further complicates the counterpart searching method using mid-infrared and radio wavelengths. Radio emission drops off more quickly with redshift than the sub-mm


Figure 4.1: The Hubble Deep Field North look completely different when observed at sub-mm and optical wavelengths. Left: The sub-mm observation shows five distinguishable sources. The brightest of these sources has a SFR of $850 \mathrm{M}_{\odot} / \mathrm{yr}$ at a redshift of 5.2 , and has not been optically identified to this date (Walter et al., 2012; Serjeant and Marchetti, 2014). Right: The optical image shows a hundred times more sources than the sub-mm observations. The positions of the bright sub-mm sources are marked, however there are no obvious counterpart to most sources. This indicates that sub-mm bright sources are not necessarily optically bright, and vice versa. The surplus of optical sources causes further difficulties in cross-identifying sources. Adapted from Hughes et al. (1998)
emission, causing only 60 per cent of sub-mm sources to have detectable radio emission. Redshifted mid-infrared observations probe emission and absorption features from Polycyclic Aromatic Hydrocarbons (PAHs), whose narrow features cause irregular redshift selections. The varying sensitivity to redshifts makes both near-infrared and radio frequencies prone to complex selection functions.

From 2009 until 2013, the Herschel Space Observatory observed several large fields, all together covering more than 1000 square degrees, and detecting around a million new sub-mm selected sources. One of these large surveys is the H-ATLAS (Herschel Astrophysical Terahertz Large Area Survey - Eales et al. (2010); Valiante et al. (2016)), which covers 660 square degrees.

In an effort to understand the multi-wavelength nature of these sub-mm selected sources, Bourne et al. (2016) looked for potential counterparts to the H-ATLAS sources covered by the Sloan Digital Sky Survey (SDSS - Blanton et al. (2017)) in the equatorial fields. Similarly Furlanetto et al. (2018) looked for the SDSS counterparts in the North Galactic Pole (NGP). They used a statistical estimator in order to cross-correlate the SDSS sources to the Herschel-sources. The estimator uses the magnitude-distribution of SDSS sources to calculate the likelihood of an SDSS source of a given magnitude close to the Herschel position. The estimator also takes the angular separation between the SDSS and Herschel position into account. The full description of the method is given in Section 4.2.2. In this chapter, I will use their results to look at the counterparts to sources in a special sample of galaxies, which were selected to be among the brightest sources in the high-redshift Universe: the Herschel Bright Sources (HerBS Bakx et al. (2018)) sample.

### 4.2 OPTICAL HERBS COUNTERPARTS

### 4.2.1 HerBS sample

I have created the HerBS sample of the brightest sources from the 660 sqr. deg. Herschel-ATLAS survey. HerBS galaxies are selected with SPIRE $\mathrm{S}_{500 \mu \mathrm{~m}}>80 \mathrm{mJy}$ and photometric redshifts $\mathrm{z}_{\text {phot }}>2$. These photometric redshifts were calculated using the best-fit template from Pearson et al. (2013). Local galaxies and blazars have been removed with the use of $850 \mu \mathrm{~m}$ SCUBA-2 observations (Bakx et al., 2018).

This sample is created from a large area, nearly one sixtieth of the sky, which allows me to study rare events such as gravitational lensing. A gravitationally lensed source has its light bent by a large foreground mass, either a galaxy or a cluster of galaxies.

Actually, I expect the HerBS sample to consist mostly of lensed Ultra Luminous InfraRed Galaxies (ULIRGs; $10^{12}-10^{13} \mathrm{~L}_{\odot}$ ), with the other sources being unlensed Hyper-Luminous InfraRed Galax-

Both these catalogues can be found in the official data release at www.h-atlas.org
ies (HyLIRGS; > $10^{13} \mathrm{~L}_{\odot}$ ). Estimates from galaxy evolution models of Cai et al. (2013) indicate that over our entire sample, $76 \%$ of the galaxies are gravitationally lensed ULIRGs.
I do not expect to detect any of the actual sub-mm sources in the SDSS cross-correlated catalogues, as the optical emission from farinfrared selected sources is notoriously faint due to the dust absorbing and reradiating most of the optical light. However, I do expect to see several of the foreground lensing galaxies, for the HerBS sources that are gravitationally lensed.
Lensing galaxies are typically red and dead ellipticals, with dominant emission in the rest-frame near-IR. These lensing galaxies span redshifts from 0.15 to 1 and above (Negrello et al., 2010; Fu et al., 2012; Wardlow et al., 2013). All five sources of Negrello et al. (2010) have optical counterparts in the SDSS. Therefore, I assume the majority of our lensed sources have visible lensing galaxies in the SDSS survey.
In total, the HerBS sample contains 209 sub-mm sources from the H-ATLAS survey. This survey covers 660 square degrees, and is distributed over 5 fields, namely the North and South Galactic Poles (NGP and SGP, respectively), and three equatorial fields corresponding with the GAMA09, GAMA12 and GAMA15. The analysis of Bourne et al. (2016) and Furlanetto et al. (2018) both resulted in two catalogues. These catalogues contain 72 HerBS sources in GAMA, and 49 HerBS sources in the NGP. Unfortunately, there is no SDSS coverage of the SGP pole, and hence this study will only cover the 121 sources in GAMA and NGP.
The likelihood analysis calculates a probability for all SDSS sources close to a Herschel-source. These individual probabilities are then combined into a value called the reliability. The reliability is the probability that the counterpart actually is genuine, and typically one takes a reliability greater than 0.8 to indicate a counterpart is actually genuine. When I cross-correlate our sources with the catalogues from Bourne et al. (2016) and Furlanetto et al. (2018), I find the following:

Table 4.1: The SDSS reliabilities of Herschel sources.

| R | $<0.8$ | $>0.8$ | All |
| :--- | :---: | :---: | :---: |
| GAMA | 52 | 20 | 72 |
| NGP | 38 | 11 | 49 |
| Total | 90 | 31 | 121 |

Notes: Reading from the left, the columns are: Column 1 - field; column 2 - sources with reliabilities smaller than o.8; column 3 - sources with reliabilities greater than 0.8 ; column 4 - all sources in the sample.

Out of 121 sources, only 31 sources have a reliability greater than o.8. This is unlike the $92(\sim 121 \times 76 \%)$ lensed counterparts I expected from the galaxy evolution models of Cai et al. (2013). This model
predicts the number of lensed sources as a function of flux density, based on theoretical predictions of the distribution of dark-matter haloes, and their expected lensing behaviour. This means that only $34 \%$ of expected lensed sources is detected in the SDSS, which is unlike what was found by Negrello et al. (2010), who detected all five sources to have an SDSS counterpart. This low detection fraction could indicate we are not detecting all foreground galaxies using the SDSS likelihood analysis, in the case we trust the galaxy models.

Another possible cause of this could be that the lens is too far away from the Herschel source for the statistical method to produce a value of $R>0.8$. The foreground, SDSS-observed source is not in exactly the same position as the background, Herschel-observed source. Typically, these offsets are of the order of one arcsecond for galactic lenses, and up to several tens of arcseconds for galaxy cluster lenses.

In the rest of this chapter, I will investigate how many sources are missed because of this positional offset. I will do so by adjusting the angular probability distribution of Bourne et al. (2016), in order to also include the added positional offset expected from gravitational lensing. I will first briefly explain how the likelihood estimator works, and how it is dependent on angular separation of the counterparts. Following this, I detail how I adjust the angular separation dependency of the likelihood method to include the effect of gravitational lensing. I use two separate methods for predicting the number of missed SDSS counterparts. I discuss the effects of gravitational lensing on our sample, on the SDSS counterparts, and on future surveys. I will conclude with a discussion on the new method I used.

### 4.2.2 The likelihood estimator

I start off by giving a brief explanation of the mathematical backbone to the cross-correlations done by Bourne et al. (2016). The likelihood, L , of a counterpart is calculated from the following equation:

$$
\begin{equation*}
L=\frac{q(m, c) f(r)}{n(m, c)} \tag{4.1}
\end{equation*}
$$

Here $q(m, c)$ represents the magnitude distribution of genuine counterparts in class $c$ (i.e. stars or galaxies), $\mathfrak{n}(m, c)$ represents the background magnitude distribution per square degree of unrelated objects in class $c$ and $f(r)$ represents the positional offset distribution due to positional errors between both catalogues.
$\mathrm{q}(\mathrm{m}, \mathrm{c})$ and $\mathfrak{n}(m, c)$ are calculated from the SDSS catalogues. For the positional offset distribution $f(r)$, Bourne et al. (2016) assumes a gaussian probability distribution:

$$
\begin{equation*}
f(r)=\frac{1}{2 \pi \sigma_{\text {pos }}^{2}} \exp \left(-\frac{r^{2}}{2 \sigma_{\text {pos }}^{2}}\right), \tag{4.2}
\end{equation*}
$$

The denominator, $\mathrm{n}(\mathrm{m}, \mathrm{c})$, is a surface and magnitude probability distribution. The nominator combines a separate magnitude distribution $\mathrm{q}(\mathrm{m}, \mathrm{c})$ and a separate surface distribution, $\mathrm{f}(\mathrm{r})$, into the same measure.


Figure 4.2: Graphical representation of a (blue) Herschel/SPIRE source, close to four (orange) SDSS sources. The dotted ring shows the maximum radius at which the closest orange source is considered a counterpart.
where

$$
\begin{equation*}
\sigma_{\text {pos }}=2.1 \times\left[\mathrm{SNR}_{250 \mu \mathrm{~m} / 5]^{-0.88}},\right. \tag{4.3}
\end{equation*}
$$

or $\sigma_{\text {pos }}$ is set to 1 arcsecond, in case this value drops below 1 arcsecond, in order to account for systematic uncertainties. Here $S N R_{250} \mu \mathrm{~m}$ refers to the signal to noise ratio at $250 \mu \mathrm{~m}$.
Bourne et al. (2016) calculates the probability of a galaxy being genuinely associated with the Herschel source - a value referred to as the reliability. A reliability is calculated for each potential counterpart, j, by comparing it to the sum of the likelihood of all nearby sources, i,

$$
\begin{equation*}
R_{j}=\frac{L_{j}}{\sum_{i} L_{i}+\left(1-Q_{0}\right)} . \tag{4.4}
\end{equation*}
$$

I graphically represent this with Figure 4.2, where I show the blue Herschel source, close enough to an orange SDSS source, to be crossidentified.
The reliability $R_{j}$ of each potential match, $j$, was computed as the ratio of its likelihood $\left(\mathrm{L}_{\mathrm{j}}\right)$ to the sum of likelihoods of all potential matches within 10 arcseconds. An extra term in the denominator, ( $1-$ $\left.Q_{0}\right)$, accounts for the possibility that the source is not visible in the SDSS. $\mathrm{Q}_{0}$ is the probability that a SPIRE-detected source is detected in the SDSS, and is taken to be 0.583 from Smith et al. (2011). They calculated this value from a likelihood analysis of SDSS counterparts to a sample of $250 \mu \mathrm{~m}$ selected sources from the H-ATLAS science demonstration phase.
I will consider sources with a reliability greater than 0.8 as likely to be associated with our source, which is the same threshold as Bourne et al. (2016) adopted. This threshold value is rather arbitrary, but will allow me to discretely discuss the number of likely counterparts.
However, these equations assume that the SDSS and Herschel catalogues look at the same source. In the case of gravitational lensing, there is an extra contribution to the positional offset distribution.


Figure 4.3: One of the 15 sources from the sample of Amvrosiadis et al. (2018). Typically, high-resolution observations of lensed sources show a partial Einstein ring, as can be seen in this image. I assume throughout our work, that the additional angular offset due to lensing is equal to the radius of this ring.

### 4.2.3 Systematic angular offset due to lensing

Typically, the offset between the lensing and lensed source is of the order of one Einstein radius. The Einstein radius is the radius of the ringed image of a lensed source, as seen in Figure 4.3.

In this section, I will use a probability distribution of Einstein radii from Amvrosiadis et al. (2018). They carried out an ALMA pilot study of 15 potentially lensed sources. Their sources were selected for lenses by their high $500 \mu \mathrm{~m}$ brightness and a redshift greater than $1 . \mathrm{Ne}-$ grello et al. (2010) showed this to be a robust method for selecting gravitational lenses. These sources are solely selected on the properties of the lensed source, which removes uncertainties associated with the selection functions. Cosmological studies using lensed galaxies require simple selection functions, which is why sub-mm lens selection is well-suited for these studies.

Their ALMA observations provide high-resolution images, that allowed Amvrosiadis et al. (2018) to measure the image separations (i.e. two times the Einstein radius). From these individual image sep-


Figure 4.4: The distribution of image separations for the 15 ALMA sources, observed and discussed in Amvrosiadis et al. (2018). The SIS and SISSA models (green and red dashed and solid lines) require two fitting parameters, shown in the figure inset. The solid and dashed lines assume different virialization times for the foreground, lensing galaxies. The EAGLE model (black solid) agrees with the data within the errorbars, and does not require any fitting parameters.
arations, they calculate an image separation distribution, which they attempt to reproduce using theoretical models. The results of this can be seen in Figure 4.4.
They model the redshift and mass distribution of the lenses with the use of analytical halo mass functions, as described in Bocquet et al. (2016). These functions describe the comoving number density of dark matter haloes as a function of redshift and comoving mass interval. As such, these functions tell me how many dark matter haloes I can expect where, and how heavy they are.
They model the lensing properties of these halo masses with several halo density profiles. Two density profiles (SIS and SISSA) have a sharp increase in mass at small radii. This corresponds to a more clustered centre, which characterises baryonic matter in the centre of heavy, virialized galaxies. The other density profile (NFW) is flatter, which corresponds to the density profiles seen in both smaller galaxies and large galaxy clusters.


Figure 4.5: A foreground galaxy is observed in the SDSS at the position of the left grey star. The lensed, background galaxy is positioned at the right grey star. Due to measurement uncertainty, the lensed source is actually observed with SPIRE in the empty star, annotated by the word Measured.

### 4.3 CALCULATING A NEW ANGULAR PROBABILITY DISTRIBUTION

In this section, I will calculate a positional offset distribution that includes the effects of gaussian scatter and gravitational lensing. This will allow me to replace the $f(r)$ in equation 4.1, in order to understand the effects gravitational lensing has on cross-identifying submm samples to the SDSS sample.

I use a Monte Carlo simulation to generate a distribution of $f(r)$ that includes the effects of gaussian scatter from Bourne et al. (2016) and image separation due to gravitational lensing from Amvrosiadis et al. (2018). I simulate the gaussian scatter in the $x$ and $y$ direction, where I assume a positional uncertainty in both $x$ and $y$ to be equal to $\sigma_{\text {pos }}$. I use axial symmetry, and include the lensing offset only in the $x$ direction, as schematically shown in Figure 4.5 . With these positions, I can calculate the total effective angular offset, $\theta_{\text {tot }}$.

The formalism for $f(r)$ of Bourne et al. (2016) for the probability distribution has two specific properties. Firstly, it is normalised to be integrated to 1 over all area, as it is a surface probability distribution:

$$
1=\int f\left(r^{\prime}\right) d A=\int_{0}^{\infty} f\left(r^{\prime}\right) 2 \pi r^{\prime} d r^{\prime}
$$

Secondly, $f(r)$ is the probability distribution per square degree. However, the direct information I have of my sources is the angular separation between the H-ATLAS and SDSS position. Therefore, if I want to compare the $f(r)$ against the distribution of angular distances between SPIRE and SDSS sources, I need to change the units of the probability distribution to be per degree, instead of per square degree.


Figure 4.6: The old (grey) and new (orange) radial distribution functions vary slightly, however the new angular distribution extends further due to gravitational lensing. The histogram of sources with $\mathrm{R}>$ o. 8 agrees poorly with the old and new angular distributions at low angular distances, however seems to agree with the tail end of our new distribution.

The original $f(r)$ is a surface density, and hence I move towards a probability distribution per radius, $\mathrm{f}^{\dagger}(\mathrm{r})$. This radial density is the original $f(r)$, multiplied by the change in area, $A$, per change in radius, $r$ :

$$
\begin{equation*}
f^{\dagger}(r) \equiv(d A / d r) f(r)=2 \pi r f(r) . \tag{4.6}
\end{equation*}
$$

I show the $\mathrm{f}^{\dagger}(\mathrm{r})$ resulting from my MC method in Figure 4.6. I compare this result to the histogram of the angular separation of the sources, in order to compare our model with our measured data. I split the sample into two groups; R values greater and R values smaller than o.8.
In our Monte Carlo simulation, I use a gaussian distribution based on a bright source with a positional uncertainty of 1 arcsecond. Some of our sources, however, have positional uncertainties larger than 1 arcsecond. To compensate for this, I divide their angular distance by their positional uncertainty. This is not entirely correct, as their lensing image separation is not dependent on positional uncertainty. However, from the graph I can see that the gaussian scatter appears to be the most dominant contribution to the positional offset, and therefore believe this approach to be sufficient.
Figure 4.6 shows the old radial distribution function, and compares it to the result of our Monte-Carlo simulation. A comparison with our
$R>0.8$ sources show poor agreement at low angular distances between both radial distributions, but general agreement at the higher values of angular distance. I discuss the significance of this in the discussion.

### 4.4 FINDING THE MISSING COUNTERPARTS

In this section, I use two methods for calculating the total number of missed counterparts. I define the missed counterparts as the sources with SDSS sources too far from the SPIRE-position to have a reliability greater than o.8.
In the first method, I use the new $f(r)$ to calculate the number of missed counterparts statistically. In the second method, I recalculate the reliability using our new radial distribution function, which also accounts for a systematic offset due to gravitational lensing. The results are summarised in Table 4.2.

### 4.4.1 First method: Statistical approach

This statistical approach uses all the counterparts that are reliabily detected, with an $\mathrm{R}>\mathrm{o} .8$. From the likelihood value of this counterpart, I can calculate the maximum radius until which this source would have an $R$ equal to 0.8 with the original radial probability distribution, as shown in Figure 4.2. I can then use the radial distribution that includes gravitational lensing to calculate the probability that this source would have been located outside of this region, and would thus have an $\mathrm{R}<0.8$.

I use an example to illustrate why approach works: if an actual counterpart source, with $\mathrm{R}>0.8$, has only a $20 \%$ chance to lie within the detectable area, this indicates that for each counterpart I identify, I will statistically have missed four.

Mathematically, I calculate the total number of missed sources by summing the inverse of the probability it was detected:

$$
\begin{equation*}
\mathrm{N}_{\text {missed }}=\sum^{i}\left[\frac{1}{\int_{0}^{\theta_{\max , i}} p_{\text {tot }}(\theta) \mathrm{d} \theta}-1\right] \tag{4.7}
\end{equation*}
$$

Here i refers to every source with $R>0.8, \theta_{\max , i}$ refers to the maximum angle at which $R=0.8$, and $p_{\text {tot }}$ is the total probability, which includes the effects of scatter and gravitational lensing.

The total probability, $p_{\text {tot }}(\theta)$, is simply the new angular separation distribution from the Monte-Carlo method, shown in Figure 4.6, normalized to unity. I calculate maximum angle, $\theta_{\max }$, analytically. To this end, I will rewrite equations 4.1, 4.2 and 4.4. Furthermore, I impose that at $\theta_{\text {max }}, \mathrm{R}$ is equal to o.8:
$S$ is the sum of all
likelihood
components, apart
from the main component.
$\mathrm{L}_{\mathrm{lim}}$ is the
likelihood at which the reliability is o.8.
$\mathrm{L}_{\text {meas }}$ and $\mathrm{r}_{\text {meas }}$ are the measured likelihood and angular separation from the catalogues.
$\mathrm{r}_{\mathrm{lim}}$ is the angular separation at which the reliability is o.8.

$$
\begin{aligned}
R_{j} & =\frac{L_{j}}{\sum^{i} L_{i}+\left(1-Q_{0}\right)} \\
\sum_{i}^{i} L_{i} & =S+L_{j} \\
R_{j} & =\frac{L_{j}}{S+L_{j}+\left(1-Q_{0}\right)} \\
R_{l i m} & =0.8 \\
0.8 & =\frac{L_{l i m}}{S+L_{l i m}+1-Q_{0}} \\
L_{l i m} & =4\left(S+1-Q_{0}\right) \\
L_{l i m} & =L_{r=0} e^{-r_{l i m}^{2} / 2 \sigma_{\text {pos }}^{2}} \\
L_{m e a s} & =L_{r=0} e^{-r_{\text {meas }}^{2} / 2 \sigma_{\text {pos }}^{2}} \\
L_{l i m} & =L_{m e a s} e^{\left(r_{\text {meas }}^{2}-r_{\text {lim }}^{2}\right) / 2 \sigma_{\text {pos }}^{2}} \\
e^{\left(r_{\text {meas }}^{2}-r_{l i m}^{2}\right) / 2 \sigma_{\text {pos }}^{2}} & =4 \frac{\left(S+1-Q_{0}\right)}{L_{\text {meas }}} \\
r_{l i m} & =\sqrt{-2 \sigma_{\text {pos }}^{2} \ln \left(4 \frac{\left(S+1-Q_{0}\right)}{L_{\text {meas }}}\right)+r_{\text {meas }}^{2}}
\end{aligned}
$$

The maximum angle, $\mathrm{r}_{\mathrm{lim}}$, is the angular separation between the SPIRE and SDSS position where the reliability, R , is equal to o.8. The measured angle, $r_{\text {meas }}$, is the angular separation from the catalogue. I plot these two values against each other in Figure 4.7.
The figure also shows the $y=x$ line, where the measured angular separation and the maximum angular separation are equal. A source on this line would thus have a relability of o.8. As can be expected, the $\mathrm{R}>0.8$ counterparts lie on the left-hand-side of the $\mathrm{y}=\mathrm{x}$ line, while $\mathrm{R}<0.8$ counterparts lie on the right-hand-side of this line. I note a surplus of $\mathrm{R}<0.8$ counterparts close to the line. These will not be used in the calculations.
Equation 4.7 shows a total of 1.5 sources that are expected to be missed by the likelihood method due to gravitational lensing.

### 4.4.2 Second method: Recalculating the reliability

In our other method, I calculate the number of missed sources by recalculating the reliability for all sources with reliabilities greater than o.0001. Several sources have reliability values of the order $10^{-12}$, which I did not trust, and therefore not included in the analysis. Here I change the $f(r)$ in equation 4.1. I assume that the magnitude distribution of the lensing galaxies (i.e. $q(m, c)$ ) is equal to that of typical SDSS counterparts.
I will use Figure 4.8 to demonstrate how I recalculate the reliability. I use the original $f(r)$, which is given by equation 4.2 , to calculate the likelihood with an angular separation between SDSS and SPIRE


Figure 4.7: This figure shows the measured position from the catalogues on the $x$-axis, with the maximum angle on the $y$-axis. At this maximum angle, the reliability is equal to o.8, which is the threshold for a reliable and unreliable detection. I see that $R>0.8$ counterparts (orange plusses) lie on the left-hand side of the $\mathrm{y}=\mathrm{x}$ line, whilst $\mathrm{R}<0.8$ counterparts (black and white crosses) lie on the right-hand side. This is as expected, as on this line, the reliability of the counterparts would be o.8. I note many $\mathrm{R}<0.8$ sources close to the $\mathrm{y}=\mathrm{x}$ line (grey line).


Figure 4.8: The left image shows several SDSS counterparts (orange cross) around a single SPIREsource (blue circle). The dotted circle indicates the angle at which the reliability is equal to o.8. When I recalculate the reliability, I divide the likelihood of the most likely counterpart, $L$, by the value of the angular probability distribution, $f(r) \sim \exp \left(-\theta^{2} / 2\right)$. This gives me the likelihood, in the case both SPIRE and SDSS source were on exactly the same position, as shown in the centre image, $\mathrm{L}_{0}$. In the right-hand image, I calculate the new likelihood. Here I use the angular probability distribution $f^{\prime}(r)$, which has been adjusted to include the offset from gravitational lensing, and follow the normalization of equation 4.5 . The black-dashed line indicates the new maximum angle, within which the most likely counterpart has a reliability greater than $0.8, \theta_{\max }$.
positions of zero. This is seen as the middle image in Figure 4.8. I do this by simply dividing by the value of $f(r)$ for the measured angular separation. This gives me the likelihood value in case there were no angular separation, $\mathrm{L}_{0}$. After this, I calculate the likelihood with the angular separation distribution that also includes the source separation due to a gravitational lensing event, ( $L^{\prime}$ ), by multiplying with the value from $f^{\prime}(r)$. Then I calculate the reliability using equation 4.4.
Our re-analysis shows that I now find 41 sources with $R>0.8$. Figure 4.9 shows the new reliabilities plotted against the old reliabilities. It shows that almost all reliabilities increase, and that even very low reliabilities can be increased to above $R_{\text {new }}>0.8$. I will discuss this result in the discussion.
I recreate Figure 4.7, where I originally plot the maximum angular separation versus the measured angular separation. At the maximum angular separation, the reliability is equal to 0.8 , whilst the measured angular separation follows straight from the catalogues. The result can be seen in Figure 4.10. I note a significant increase in the maximum position offset, allowing me to cross-identify sources beyond 6 arcseconds, whereas the maximum position offset in the original method was only up to 4 arcseconds.


Figure 4.9: The new reliabilities are plotted against the old reliabilities. Even low original reliabilities can result in reliabilities greater than o. 8 with our new analysis. The blue line is the $y=x$ line, which shows that (almost) all reliabilities increase.

### 4.4.3 Combined results

I show the results of the two methods in Table 4.2. I detail all relevant properties of the studied HerBS sources in Table .3, where I show the HerBS number, reliability, new reliability, measured $r$, maximum $r$ (or $\theta_{\max }$ ), the new maximum $r$, the measured likelihood, the contributions of nearby sources ( $S$ ), the uncertainty $\sigma$, the individual results of the inverse probability method.

Table 4.2: Reliability estimates excluding and including lensing

| Model | $1 / \mathrm{p}$ method | R-new |
| :--- | :---: | :---: |
| No lens | 31 | 31 |
| Total model | 32.5 | 41 |

Notes: Reading from the left, the columns are: Column 1 - whether lensing was included or not; column 2 - sources with reliabilities greater than 0.8 , assuming the $1 / \mathrm{p}$ method; column 3 - sources with reliabilities greater than 0.8 , when recalculating the reliability with the new angular distribution function


Figure 4.10: This figure shows the measured position from the catalogues on the $x$-axis, with the maximum angle on the $y$-axis, using the reliability calculated from the angular separation distribution which includes gravitational lensing. At this maximum angle, the reliability is equal to 0.8 , which is the threshold for a reliable and unreliable detection. I see that $\mathrm{R}>0.8$ counterparts (orange plusses) lie on the left-hand side of the $\mathrm{y}=\mathrm{x}$ line, whilst $\mathrm{R}<$ o. 8 counterparts (black and white crosses) lie on the right-hand side. This is as expected, as on this line, the reliability of the counterparts would be o. 8 (grey line). I note that several crosscorrelations are at large distances, beyond even 6 arcseconds.

### 4.5 DISCUSSION

I find 31 SDSS counterparts with a reliability greater than 0.8 to the Herschel-selected HerBS sample. In total, I looked for 121 HerBS sources. The galaxy evolution models (Cai et al., 2013) predict that 92 of these HerBS sources should be lensed. I only expect to see the foreground, lensing galaxies in the SDSS, however, I only find 34 per cent of HerBS sources to have a reliable SDSS counterpart, and are thus likely to be lensed. This low percentage could be due to the redshifts of the foreground galaxies, which can go up to and beyond 1 (Cox et al., 2011), and thus I do not expect to detect all of them.

It is also possible our galaxy models overestimate the number of lensed sources. However, as shown in Negrello et al. (2010), and several studies since (Wardlow et al., 2013; Negrello et al., 2017; Nayyeri et al., 2016), most galaxies above a flux density of 100 mJy at $500 \mu \mathrm{~m}$ are found to be gravitionally lensed, which is in agreement with the galaxy evolution models. A different possibility, is that the missing counterparts could be due to a different distance-distribution than assumed in the likelihood method from Bourne et al. (2016).

I tested two methods for finding the number of missed $R>0.8$ sources. In the first method, I calculate the number of sources I expected to miss, due to a different angular separation distribution produced by lensing. This method suggests I miss 1.5 sources. In the other method, I recalculate the reliability for all sources with reliabilities greater than o.0001 using a new angular separation distribution which takes account of the lensing. This method suggests I have missed 10 sources. This elevates the ratio of reliable counterparts, with $\mathrm{R}>0.8$, up to 45 per cent, which is closer to what I was expecting, but still nowhere near to the 76 per cent expected from galaxy evolution models.

The results show a strong variation between the two complementary models. This might suggest that there is a discrepancy in the model, as they should result in similar source estimates. The significant increase in missed sources could be due to many sources residing close to the $\mathrm{y}=\mathrm{x}$ line in Figure 4.7. A small change in $\theta_{\max }$ will push many sources within the $\mathrm{R}>0.8$ regime.

The first method only uses the sources with $R>0.8$ to calculate the number of missed counterparts with $R>0.8$, and as such, it does not use all the information. Therefore, it seems that the second method results in a more secure estimate for the number of total SDSS counterparts.

One problem with both methods, however, is that Figure 4.6 shows poor agreement with the actual distribution of angular distance. A potential explanation for this can be a different shape of the distribution of the Einstein radii of the sources. I will explore this possibility in the next subsection.

### 4.5.1 Testing different lensing functions

I find poor agreement between our distribution of angular separations to the work of Amvrosiadis et al. (2018), especially at shorter angular distances, as seen in Figure 4.6. Their work is only based on 15 lensed sources, so in reality there might be more cluster-scale lenses with large Einstein radii or less galaxy-galaxy lenses than expected.
In this subsection, I will test the effects of varying the distribution of angular separations due to lensing. As Amvrosiadis et al. (2018) is based on theoretical models, I would like to keep the shape of the distribution the same, and instead scale the $x$-axis. I will redo the MC method with varying forms of the models. I will stretch the lensing function in the $x$-axis, by multiplying the $x$-axis with $0,0.5,1$ (the original), $1.5,2,3,4$ and 5 times. This will then be used to recalculate the new angular separation distribution, which I will then compare to our current distribution of sources.
Figure 4.11 shows the new angular separation distribution for various adaptations of the image separation function from Amvrosiadis et al. (2018). Here, I multiplied $\mathrm{r}_{\text {lens }}$ by 0 ( r -model, black line), o.5 (grey dashed), 1 (original, orange dashed), and multiplied by 1.5, 2, 3, 4 and 5 times (grey dashed). After that, I reran the Monte-Carlo simulation which generates a new angular separation distribution.
At the small angular distances, none of the profiles are able to recreate our source distribution. On the longer angular distances, I note that our current profile appears to match the data well. The poor agreement at small angles could thus be due to statistical noise. However, if this feature persists for larger samples, this dearth of sources at low distances would be unexplained with current fits of dark matter halo distributions and halo profiles. Further study of these types of sources could thus provide evidence of the dark matter distribution throughout the Universe.

### 4.5.2 What does this mean for future observations?

Increasingly, astronomy is turning to multi-wavelength observations in order to fully understand the processes going on at high redshifts. The different wavelengths causes a change in the coverage of the redshift space for lensing sources. Surveys that probe larger redshifts will thus be affected more by this effect. Similarly, it could also mean I detect the lensed Herschel-sources themselves. These direct counterparts should behave according to the expected gaussian distribution.
More sensitive surveys would also increase the redshift coverage, as more distant, fainter objects will also appear. This would thus increase the effects of misalignment due to lensing. A more unpredictable effect would be the increase of sources with significant non-


Figure 4.11: I ran the MC-script for various versions of the angular separation distributions due to gravitational lensing from Amvrosiadis et al. ( (2018)). Each of the curves is generated using a different realisation of this function, where I stretched the $x$-axis. The black line shows the case where I multiplied the angular scale of the gravitational lensing contribution by 0 , essentially removing the effects of gravitational lensing and this line is thus equal to gaussian scatter. The orange line has the $x-$ axis multiplied by unity, and thus gives the same result I used throughout this paper, the grey dashed lines are multiplied by 0.5, 1.5,2,3,4 and 5. I note a general disagreement at low angular distance, but the original model $(\times 1$, orange line) seems to fit the distribution reasonably well.

Although there is no mention of these sources with a counterpart contribution in the extended catalogues
counterpart contributions (S), as the survey becomes more densely populated. Only three sources had a significant counterpart contribution (S), and all three were detected significantly. Their S-values were similar to the lower Likelihood (L) values of the reliably detected sources, which could mean that a more dense map would have difficulty cross-comparing fainter sources. This might also interfere with our re-calculation method for finding lensed sources, as I do not adjust our S-values while re-calculating the reliability. Hence in dense maps, re-calculating the reliability for gravitationally lensed sources needs to be done from the initial catalogues.
The variation in the angular resolutions of the more accurate map (usually at smaller wavelength, such as SDSS), do not affect the results. However, an increase in the positional accuracy of the less accurate map (SPIRE in our case) would pronounce the effect more, as the lensing model becomes a more dominant part of the scattering process. A separate issue of poor angular resolution in the maps would be source confusion, where multiple sources would blend into each other and appear as a single, brighter source. The effects of this are hard to predict. In the case the blend is due to a line-of-sight alignment, the lower-redshift components might be detected. There is no reason to assume that these low-redshift contributors would obey the gaussian scatter, as the Herschel-position is a combination of the position of all the blends. In the case the blended sources are physically associated, they will all be at high redshift. This is because the Her-schel-observed spectrum is a combination of dusty spectra around the same redshift, which peak around the same wavelength. As the photometric redshift is calculated by the peak of the flux distribution, we can expect their redshifts to be at the same place.

### 4.5.3 Concluding remarks

The majority of sources detected in sub-mm surveys are not expected to be lensed, so I do not recommend adjusting the mathematical methods used for finding counterparts. However, I recommend a level of caution whenever a sample is expected to contain lensed sources. I further recommend using our method of re-running of the reliability estimates, and not simply relying on a statistical argument as done by the $1 / \mathrm{p}$-method. For dense fields, I might even suggest running the likelihood-method twice, once with a gaussian angular distance distribution, and once with our assumed angular distribution. This might tease out lensed sources, which could be interesting for followup.

All good art is the intelligent use of space
—— Dave Dimmick

In the previous chapter, we only found $34 \%$ of sources had an optical counterpart. The sources responsible for the gravitational lensing are expected to be red-and-dead elliptical galaxies, out to redshifts of 1 and beyond. These massive elliptical galaxies contain a significant old, red stellar component, and would therefore be significantly brighter in the near-infrared. It could thus be that the optical SDSS survey fails to pick up these sources. In this chapter, we look for counterparts in the near-infrared VIKING survey, which is potentially able to detect more of the foreground lensing galaxies.

In this chapter, I aim to discuss our attempts at finding near-infrared counterparts to the HerBS sources in the VIKING fields. Firstly, I extract the sources using the sextractor package. I then use the likelihood method, explained in Chapter 4, to find the VIKING source associated with the HerBS source. I conclude with a discussion on the implications of the VIKING (non-)detections, and compare them to the SDSS observations.

### 5.1 VIKING SOURCE EXTRACTION

The VISTA telescope observed 1500 square degrees for the VISTA Kilo-degree Infrared Galaxy (VIKING) survey in zYJHK s to sub-arcsecond resolution, to an AB-magnitude $5 \sigma$ point source depth of 23.1, 22.3, 22.1, 21.5 and 21.2, respectively. The near-complete overlap with the equatorial GAMA fields and the partial overlap with the South Galactic Pole (SGP) fields qualify this survey to find near-infrared counterparts to our Herschel-ATLAS selected sources. Only two HerBS sources are missing from the GAMAog field, while the other GAMA fields are completely covered. However, of the 88 HerBS sources in the SGP, only 28 are covered by the VIKING survey. In total, the VIKING survey covers 98 HerBS sources. The VIKING data used in this chapter comes in the form of SWarped images (Bertin, 2010), with both a weight-file and an image file. The exact data reduction procedure of these files are described in Driver et al. (2016).

I am interested in the properties of the sources close to the HerBS sources, in an effort to find the foreground lensing galaxies. I therefore need the properties of individual sources from the VIKING fields.

To this end, I use the sextractor package to extract individual sources. This package looks for pixels above a specified threshold value. If several adjacent pixels exceed the threshold, the package calls this a source.
A significant problem with extracting sources from a survey is the question: what constitutes a source? The Source-Extractor package has many extraction-parameters that can be tuned in order to extract exactly what I require for our analysis. I opt to select the parameters in order to create a robust catalogue of VIKING sources with the most accurate flux estimates of the point sources. This means I am not looking to 'push' our source extraction to low fluxes, with the inherent risk of including noise as sources, as this affects the statistical estimator. Similarly, I do not aim to extract the most accurate combined fluxes of the extended sources.
Our interest lies in finding the counterparts to HerBS sources. These VIKING sources are likely to be the lensing sources, which show up as point-like sources at redshifts between $\mathrm{z}=0.1$ and 1 and beyond (Fu et al., 2012). In order to probe the highest redshifts, I select at the longest wavelength of the VIKING fields, $\mathrm{K}_{\mathrm{S}}$ at $\sim 2.1 \mu \mathrm{~m}$.

### 5.1.1 SExtractor set-up

In order to fine-tune the Sextractor set-up, I cut out five 1000 by 1000 arcsecond maps of the VIKING fields to test the source extraction procedure. The package is not able to generate output-images for the entire VIKING images, as each file is several tens of gigabyte in size. These smaller files are only several megabyte, and sextracTOR can create output-images that show the source-subtracted image. Furthermore, it can produce output-images that show just the objects, with the background set to zero.

I use the dual-mode extraction, where sources are detected on the $\mathrm{K}_{\mathrm{S}}$ image, and the photometry is done on the other images, using the source parameters provided from the $K_{S}$ image. This method is shown graphically in Figure 5.1, and the entire data analysis script is in the Appendix .6. Now, I discuss the steps of the data reduction protocol step by step, and detail the important decisions I made.
The analysed image map will provide the photometry reported in the catalogue. The analysed weighting file is essentially the amount of observing time spent on each pixel in the map, and influences the background subtraction and the error calculation for the photometry. In the case there is a variation in the background flux over the survey, the source extraction might be misled, extracting the entire background as a source. Therefore, sextractor calculates and removes the background. It does so by smoothing the foreground significantly and then subtracting it. I set our background smoothing parameter to 130 pixels. The algorithm then calculates the noise from a square area


Figure 5.1: A schematic representation of the Sextractor execution I use. The backgrounds of the analysed and precursor maps are subtracted, followed by a filtering step. The deblended sources from the precursor map are used to find the sources in the analysed map. A neural network looks for the typical behaviour of the stars and galaxies, and sorts them as such. In the case I am still testing, I export the output test maps. Finally, I export the output catalogue.

> A great introductory explanation of Neural Networks is done by the YouTube channel 3Blue1Brown: https:
> //www. youtube. com/watch?v= aircAruvnKk
of 130 by 130 pixels. On top of this, I choose a background medianfilter size of 7 . The algorithm then calculates the noise 7 times for the same size square, however it changes where the squares are put. The noise is then calculated from the median value of these 7 noisecalculations. This process gets rid of deviations caused by bright or extended objects. After this, a Gaussian filter with a width of 2 pixels is passed over the background-subtracted map. This maximizes the signal-to-noise of point-sources (North, 1943).

I choose the $K_{S}$ flux selection criterion by varying the thresholds, and adjusting the thresholds such that no spurious sources appeared to be extracted in the five test-files. I define the spurious detections by means of a visual inspection of the five cutout fields. I demand at least four adjacent pixels have fluxes ranging from 1 to $5 \sigma$. From this, I find that $2.5 \sigma$ guarantees no spurious inclusions. While I could lower the threshold, my main aim is to only include definitive sources. As such, I choose $2.5 \sigma$ as a threshold.

SEXTRACTOR has a deblending algorithm which it uses to determine the nature of individual sources. I am interested in the accurate fluxes of point sources, and therefore I set the deblending parameter to a strict, low value of $0.01 \%$. A low value is more prone to splitting up sources into several sub-sources, and thus it fails to extract nearby galaxies as single sources, but it does guarantee I extract point sources that lie close to each other.

The positions are extracted from the $\mathrm{K}_{\mathrm{S}}$ image. These $\mathrm{K}_{S}$ positions are now used for the photometry of the $\mathrm{z}, \mathrm{Y}, \mathrm{J}, \mathrm{H}$, and $\mathrm{K}_{S}$ maps. I use the standard AUTO flux extraction. Sextractor extracts the flux by fitting an elliptical profile to a source.

SEXTRACTOR calculates a probability of a source being a galaxy or a star. Stars (and QSO's) typcally are more sharply-defined, whereas galaxies look more extended or fuzzy. While Bertin and Arnouts (1996) lists a series of different algebraic methods for making this selection, SEXTRACTOR actually employs a neural network. Contrary to the algebraic methods, a neural network does not provide a clean formulation of what exactly selects stars or galaxies. It simply is the optimisation of a combination of all given parameters, that most robustly provides a correct star or galaxy identification.

The neural network is produced from analysing a training-set of simulated observations. Both simulated and actual observations, with individually identified stars, show that the neural network is accurate at identifying stars and galaxies for bright sources. The accuracy falls significantly at higher magnitudes.

### 5.1.2 SExtractor on the test-files

The extraction results of the first test-field in Figure 5.2, and the other four can be found in the Appendix .7. The left column shows the
cutout in the five different VIKING colours, where the reddest colour, $K_{S}$ is at the top. The $K_{S}$-band observation is the detection image. The weight file shows that the middle of our images have multiple overlapping observations, and hence have less noise in this part of the field. The background is shown in the middle column. The fourth column shows the cutout's objects, where the rest of the map is set to zero. The final column is the difference between the model image and the actual image. This residual shows how successful the point source extraction was. The removal of sources at the K-band is uniform, while some faint sources are visible, they could also be due to noise. When I move to shorter wavelengths, most notably at the zband, I see difficulty in an accurate flux removal of extended sources. Our source extraction, however, is focussed more on an accurate flux estimate of point sources. I therefore choose not to fix this issue in our analysis.

### 5.2 LIKELIHOOD METHOD

I first remove stellar interlopers to increase the statistics of our analysis. At the risk of repeating several parts of the likelihood method discussed in Chapter 4, I provide a detailed overview of the exact mathematics I used to calculate the counterpart probability, and I discuss the calculation of the various components that go in to this statistical analysis.

### 5.2.1 Star/Galaxy separation

A significant number of sources in the VIKING fields are stars. These interlopers result in poor statistics when calculating the likelihood of a VIKING counterpart to the Herschel sources. Fleuren et al. (2012) removed these stellar interlopers by means of a colour cut on both SDSS and VIKING fluxes, as can be seen in Figure 5.4. They studied the GAMAog field as a part of a precursor study, which also had coverage from the SDSS. Not all our fields have coverage from the SDSS, so I choose to pick a single VIKING colour cut, in order to study the entire sample similarly. The sextractor method provides neural network-derived value for the probability of a star or galaxy, which will be useful to test the validity of each of our assumptions.

Firstly, I look at all potential VIKING colours and test their ability to separate galaxies from stars using just the VIKING colours in Figure 5.3. Here I plot all possible colours against each other, in two different groups. One group has only sources with a star/galaxy criterion greater than o.8, meaning these are likely to be stars (green). The other group plotted has a criterion smaller than o.2 (blue), which thus are most likely galaxies. The figure indicates that no single or


Figure 5.2: This is one of the five fields that was used to test the extraction quality of the sexTRACTOR set-up. I adjusted the extraction parameters to extract point-sources accurately. From top to bottom in order of decreasing wavelength: $K_{S}, H, Y, J$, and z. The $\mathrm{K}_{\mathrm{S}}$ observations are the extraction image, and hence I see the lowest residuals in the $\mathrm{K}_{\mathrm{S}}$ observations, which gradually get worse for shorter wavelengths. From left to right, the first image is the unedited, 1000 by 1000 arcsecond cutout, the second image shows the weighting map, essentially how much observing time was spent per map, the third image is the background, which is removed prior to source extraction, the fourth image is are the objects that are selected from the background-subtracted, weighted map. The final image shows the residuals after the sources are removed from the backgroundsubtracted map.
combination of colours provide a robust method to cleanly separate the stars from galaxies.

I continue the search for a clean-cut method by means of the fluxcut, based on the results of Fleuren et al. (2012), as shown in Figure 5.4. They employed a colour-cut ranging from J- $\mathrm{K}_{\mathrm{S}}>-0.34$ to 0.21 as a function of increasing $g$ - i colour. High g-i values correspond to blue-er galaxies, while redder galaxies have low values, with a more inclusive colour cut. As most of our lensing galaxies are expected to be passive, red galaxies, I need to consider that a too strict flux-cut might remove the exact sources we are looking for.

In Figure 5.5, I look for the average star/galaxy criterion value for the sources within each magnitude bin, for different potential colour cuts. I choose three colour-cuts: J - $\mathrm{K}_{\mathrm{S}}>-0.1,0$ and 0.21 . This way, I hope to preserve the redder galaxies in our sample.

The figure shows a similar separation ability for both the 0 and 0.21 colour cuts, however the -0.1 colour cut includes a significant portion of stars. From Bertin and Arnouts (1996), I know that the neural network is more accurate for brighter sources, and it becomes less accurate at higher magnitudes. This seems to explain why all the flux cuts converge to the same value at high magnitudes.

I choose to use the $\mathrm{J}-\mathrm{K}_{\mathrm{S}}>0$ colour cut, as it includes as many galaxies as possible, without an excessive inclusion of stars, however I still keep in mind that I might be excluding potential galaxies throughout my analysis, and thus the observations require a 'by-eye' discussion. While this flux cut also converges at high magnitudes, it is good to realise that due to the high-redshift nature, some of the lensing galaxies in the VIKING fields will not be resolved. Thus these sources might have star-like properties, especially for the fainter fluxes.

### 5.2.2 Statistical method

Unlike our work in Chapter 4, I need to apply the entire statistical method to the two catalogues: the VIKING catalogue from sextractor, and the HerBS catalogue. This statistical method calculates the probability that a source found in the VIKING field, is associated with the far-infrared Herschel source, as described by Sutherland and Saunders (1992). To this end, I need to figure out the probability that a VIKING source of a certain magnitude is randomly located close to my source, and compare that to the specific location and magnitude of the sources close to my HerBS sources. Mathematically, this is expressed in a value referred to as the likelihood, which can be quantified as

$$
\begin{equation*}
L=\frac{q(m) f(r)}{n(m)} \tag{5.1}
\end{equation*}
$$



Figure 5.3: I fail to find a potential colour-identifier for stars and galaxy in the VIKING sample. I plot all possible colours against each other, for sources with a star/galaxy criterion greater than 0.8 (green - stars) and smaller than 0.2 (blue - galaxies). In total I plot 100 randomly selected sources in each group.


Figure 5.4: The galaxy-star separation from Fleuren et al. (2012) assumes a flux-cut of g-i versus J - $\mathrm{K}_{\mathrm{S}}$ flux. Because our sample does not have g - i colours for all sources, I attempt uniform J-Ks flux cuts of >-0.1, o and 0.21.


Figure 5.5: In each flux bin, I average the star/galaxy estimator from Sextractor for three different J - K colour cuts from Fleuren et al. ( (2012)): J $-\mathrm{K}_{\mathrm{S}}>-0.1,>0$ and $>0.21$. Low values of the star/galaxy estimator suggest it is more likely to be a galaxy, while values close to one suggest it is more likely to be a star. All orange lines refer to the greater-than colour cut ( $>$ ), while all blue lines correspond to the less than $(<)$ colour cut. The black line looks at all sources. The thin lines correspond to the analysis on the individual fields (GAMA-9, $-12,-15$ and SGP). I do not have the SDSS fluxes, and therefore I test the effect of a range of selection cuts on the average amount of stars per magnitude bin. While the J-K $>0.21$ shows the most reliable cut for a galaxy selection cut, I know that I will be throwing away a subset of red galaxies. Therefore, I choose the $\mathrm{J}-\mathrm{K}_{\mathrm{S}}>$ o selection. All colour cuts converge to a similar value at high magnitudes, potentially because the star/galaxy classifier fails for faint sources.

Here $q(m)$ represents the magnitude probability density distribution of genuine counterparts, $n(m)$ represents the background magnitude surface density distribution of unrelated objects and $f(r)$ represents the positional offset surface density distribution due to positional errors between both catalogues. Essentially, I am comparing two probabilities, where the nominator gives the chance that a source is associated with a HerBS source given a specific magnitude and angular separation, and the denominator gives the chance that a source is a coincidence.

Since our sample consists of a large fraction of lensed sources, I will derive the positional offset distribution separately, since I cannot assume a simple gaussian distribution. All components are probability density distributions, which causes some constraints on these statistics. $q(m)$ should, integrated over all magnitudes, equal the probability that the SPIRE-detected source is detected in VIKING, which we will call $\mathrm{Q}_{0}$. Hence,

$$
\begin{equation*}
\mathrm{Q}_{0}=\int_{-\infty}^{\infty} \mathrm{q}(\mathrm{~m}) \mathrm{dm} . \tag{5.2}
\end{equation*}
$$

Similarly, the integral of the positional offset surface density distribution, $f(r)$, over all available area should equal 1 , and in the case the distribution is axi-symmetric around $\phi$ :

$$
\begin{equation*}
1=\int_{\mathcal{A}} f(r) d A=\int_{0}^{2 \pi} \int_{0}^{\infty} f(r) r d r d \phi=\int_{0}^{\infty} 2 \pi r f(r) d r \tag{5.3}
\end{equation*}
$$

The background magnitude surface density distribution, $\mathfrak{n}(\mathfrak{m})$, is the number of sources found in the background, away from the sources I am interested in (in this case HerBS sources), found per magnitude bin, normalized for the observed area,

$$
\begin{equation*}
n(m)=\frac{n_{\text {back }}(m)}{\text { Area }}=\frac{n_{\text {back }}(m)}{\pi r^{2} N_{\text {random }}} . \tag{5.4}
\end{equation*}
$$

Here, $n_{\text {back }}(\mathfrak{m})$ refers to the magnitude distribution of sources in a 10 arcsecond radius of a random position, and Area refers to the total area ( $\pi r^{2}$ with $r=10$ arcseconds) of all these random positions combined ( $\mathrm{N}_{\text {random }}$ ).

I gather the actual probability of each source association by the weighted combination of all likelihoods of all sources near to the Herschel source. I refer to this probability as the reliability of a VIKING source to be associated to the Herschel source. The reliability is calculated for each potential counterpart, $\mathfrak{j}$, by comparing it to the sum of the likelihood of all nearby sources, $i$,

$$
\begin{equation*}
R_{j}=\frac{L_{j}}{\sum_{i} L_{i}+\left(1-Q_{0}\right)} . \tag{5.5}
\end{equation*}
$$

The reliability $R_{j}$ of each potential match, $j$, is computed as the ratio of its likelihood $\left(\mathrm{L}_{\mathrm{j}}\right)$ to the sum of likelihoods of all potential matches

I also make sure the
source is not located close to the edge of the map
within 10 arcseconds. An extra term in the denominator, $\left(1-Q_{0}\right)$, accounts for the possibility that the source is not visible in the VIKING survey. Unlike in the SDSS analysis, I need to derive the $\mathrm{Q}_{0}$ value for ourselves. For a comparison, Fleuren et al. (2012) did a pilot analysis of cross-correlating the VIKING survey with H-ATLAS sources, and found a $Q_{0}=0.7342 \pm 0.0257$.

Unlike the SDSS analysis, where I simply used the existing catalogues of counterparts, I need to derive the density distribution of both sources close to HerBS positions and the background magnitude distribution of sources for the VIKING fields. Furthermore, the lensing nature of our sources means I cannot simply use a gaussian distribution of $f(r)$ to our sources. To this end, I analyse the properties of the sources close to our HerBS sources, as well as the properties of a selection of sources close to a random position not near to the HerBS position.

### 5.2.3 Estimation of parameters and distributions

In total, 98 HerBS sources are located within the VIKING maps. Similarly, I distribute 1000 random positions over each VIKING map, resulting in 4000 random positions in total. For each of these HerBS and random sources, I collect the VIKING catalogue information of the sources within 15 arcsecond, and use this to calculate the $Q_{0}$ value, where $Q_{0}$ is equal to the probability that a SPIRE-source is detected in the VIKING fields.
I find the value of $Q_{0}$ by comparing the number of VIKING sources I find near the positions of the HerBS sample to the randomly selected positions. If I were to calculate the value of $Q_{0}$ directly from these parameters, I could be overestimating our value for $Q_{0}$ by overcounting due to the clustering of galaxies or potential multiple counterparts to the sub-mm source due to source blending. A less biased method of finding $Q_{0}$ is by calculating the number of blanks, $B(r)$, the percentage of sources without any VIKING source within a radius $r$. This method is not influenced by the clustering nor by multiple counterparts. In the case there are no background sources, the fraction of sources with counterparts in VIKING would simply be equal to 1 $B(r)$ for large values of $r$.
Figure 5.6 shows the blanks for the random positions (blue plusses) and for the positions close to HerBS sources (red squares). As the search radius ( $r$ ) increases, the number of blank random positions decreases steadily, while the positions close to HerBS sources decreases rapidly for small search radii. This is because of counterparts close to the HerBS sources.
The red squares do not just trace the HerBS sources, but are also affected by the background distribution. Fleuren et al. (2012) showed mathematically that one can correct for this by dividing the blanks
$Q_{0}$ is equal to 0.8851


Figure 5.6: The blanks are plotted versus the search radius, where blanks refer to the fraction of sources without a VIKING source within a search radius r . The blue plusses indicate the blanks on random, non-HerBS positions, while the red squares show the blanks on HerBS positions. The background-corrected blanks that just probe the HerBS counterparts are calculated by dividing the blanks of HerBS positions by the blanks of random positions, as seen in black circles (Fleuren et al., 2012). I fit equation 5.10 to the blanks (black line), and compare it against the fit found by Fleuren et al. (2012) (black dash-dotted line). I also show the expected blanks given the positional uncertainty of 1 arcsecond FWHM (grey line, Bourne et al. (2016)) and from our calculations that adapt this relationship using the image separation of lensed sources, as described in Chapter 4 (orange line). I plot a continuous interpolation between the true HerBS sources (black points) by a so-called cubic fit (cyan line), which I use to calculate an angular probability distribution. I find more sources are expected to have a source counterpart than Fleuren et al. (2012). Whereas Fleuren et al. (2012) found $\mathrm{Q}_{0}$ to be $0.7342 \pm 0.0257$, I find the background-corrected HerBS blanks at $\theta=10$ arcsecond to be 0.8851 . Unlike Fleuren et al. (2012), I take the value of $1-B(r)$ at 10 arcseconds to be $Q_{0}$, as the assumed gaussian profile does not fit the data well. This difference in angular distributions could indicate a significant portion of gravitational lenses within the HerBS sample, as they are expected to have a non-gaussian distribution. Both the positional uncertainty expected from Bourne et al. (2016) as well as the lensing-adjusted version underestimate the positional uncertainty for the HerBS sources, which could suggest there is a different lensing behaviour among the HerBS sources than with the 15 ALMA sources that the lensing-adjusted version is based on Amvrosiadis et al. (2018).
of the HerBS positions by the background position. There is however also an intuitive way of thinking about this. As the search radius increases, the blanks of HerBS that are able to probe the true HerBS sources decreases equally with the random positions. For example, if the blanks of random positions is 0.8 at $r=0.8$, this means that only 80 per cent of the HerBS blanks probe the actual HerBS sources. Therefore, if we divide the HerBS blanks by the blanks of random positions, we find the true HerBS blanks.

Similar to both Fleuren et al. (2012) and Bourne et al. (2016), I assume a 10 arcsecond radius, within which I expect all true SPIRE counterparts to fall. Their method extracted the true $Q_{0}$ by a fit of an assumed radial distribution. However, the lensed nature of our sources means I cannot assume a radial distribution, and I will simply take the value of $Q_{0}=1-B(r)$ at 10 arcseconds, giving $Q_{0}=$ o.8851.

I will fit a gaussian positional separation distribution function to our sources, in order to compare the results to other samples and analyses. The fraction of sources with a counterpart within radius $r, F(r)$, is given by the surface integral over the angular probability distribution function, which in this case is assumed to be a simple gaussian:

$$
\begin{align*}
\mathrm{F}(\mathrm{r}) & =\int_{0}^{r} f\left(\mathrm{r}^{\prime}\right) \mathrm{dA}  \tag{5.6}\\
& =\int_{0}^{r} 2 \pi r f\left(r^{\prime}\right) d r^{\prime}  \tag{5.7}\\
& =1-\exp \left(-\frac{r^{2}}{2 \sigma^{2}}\right) \tag{5.8}
\end{align*}
$$

where $f(r)$ is assumed to be

$$
\begin{equation*}
f(r)=\frac{1}{2 \pi \sigma_{\mathrm{pos}}^{2}} \exp \left(-\frac{r^{2}}{2 \sigma_{\mathrm{pos}^{2}}}\right) \tag{5.9}
\end{equation*}
$$

The probability that a counterpart is detected within the search radius, is thus equal to the probability that the source is visible in the VIKING field, $Q_{0}$,times $F(r)$. One minus this fraction is thus the blanks within the search radius:

$$
\begin{equation*}
\text { blanks } \equiv=B(r)=1-Q_{0} F(r) \tag{5.10}
\end{equation*}
$$

I find a value for $Q_{0}$ from the true HerBS blanks (black points in Figure 5.6) at $\theta=10$ of o.8841, significantly higher than Fleuren et al. (2012). Within the first 6 arcseconds our fitting agrees remarkably with Fleuren et al. (2012), however unlike their fitting, I find a poor quality of fit to the true HerBS blanks (black points), as the shape of the data does not resemble a Gaussian distribution.

The positional uncertainty on the SPIRE-positions from both Fleuren et al. (2012) and Bourne et al. (2016) assume a dependence on the 250
$\mu \mathrm{m}$ signal-to-noise. My sources have typical brightnesses which indicate that the positional uncertainty should be around 1 arcsecond. This is shown as the grey line in Figure 5.6.

In Chapter 4, I considered the contribution from gravitational lensing, where I assumed the Einstein-radius distribution from ALMA observations from Amvrosiadis et al. (2018). I also plot this line with the orange line in Figure 5.6, and note that this function also significantly underestimates the positional scatter on the source position. This indicates that the gravitational lensing offset is more profound than expected, which could be due to different origins of gravitational lensing, such as a higher fraction of galaxy cluster lenses.
Figure 5.6 shows that all analytical methods I tried fail to describe the positional offset distribution. As such, I derive the positional offset, $f(r)$, from the blanks themselves. I know that the blanks found relate to $F(r)$ by

$$
\begin{equation*}
B(r)=1-Q_{0} F(r), \tag{5.11}
\end{equation*}
$$

which in turn relates to $f(r)$ as follows

$$
\begin{equation*}
\mathrm{F}(\mathrm{r})=\int_{0}^{r} 2 \pi r f\left(\mathrm{r}^{\prime}\right) \mathrm{dr}^{\prime} \tag{5.12}
\end{equation*}
$$

By taking the derivative to $r$ on both sides, I find

$$
\begin{equation*}
\frac{d F(r)}{d r}=\frac{d}{d r} \int_{0}^{r} 2 \pi r^{\prime} f\left(r^{\prime}\right) d r^{\prime}=\left[2 \pi r^{\prime} f\left(r^{\prime}\right)\right]_{0}^{r} \tag{5.13}
\end{equation*}
$$

Re-arranging leads to

$$
\begin{equation*}
f(r)=-\frac{1}{2 \pi Q_{0} r} \frac{d(\text { blanks }(r))}{d r} \tag{5.14}
\end{equation*}
$$

where it is important to note the unpredictability at $\mathrm{r}=\mathrm{o}$. In this case, $Q_{0}$ is actually the value $\bar{S} / \bar{R}$ at $\theta=10$ arcsec, and I artificially cut off the density profile at 10 arcseconds. I find the derivative of the blanks by a cubic interpolation routine in python, which attempts to fit the values between the points continuously. I show the fit in Figure 5.7 in the orange line. The shape of this distribution function is different to any of the gaussian functions.

### 5.2.4 Fitting the magnitude distributions

Next up, is the calculation of the magnitude distribution of the geniune counterparts, $q(m)$. I calculate this distribution by comparing the magnitude distribution within 10 arcseconds of the HerBS positions $\left(n_{\text {total }}\right)$ to the VIKING properties of sources at within 10 arcseconds around random positions ( $n_{\text {back }}$ ). I take a 10 arcsecond search radius,


Figure 5.7: Using equation 5.14, I derived the angular distribution for the HerBS sources (orange), and it appears different to the gaussian shape we have seen for non-lensed sources, where I plot both a gaussian distribution with $\sigma=1$ arcsecond (black line), and a gaussian distribution $\sigma=2.4$ from Fleuren et al. (2012) (blue line).
similar to both Fleuren et al. (2012) and Bourne et al. (2016). First, I define the magnitude distribution of the real counterparts,

$$
\begin{equation*}
n_{\text {real }}(m)=\frac{n_{\text {total }}}{\text { Area }_{\text {total }}}-\frac{n_{\text {back }}}{\text { Area }_{\text {back }}} . \tag{5.15}
\end{equation*}
$$

Then, I apply a normalization to ensure that the integral of $q(m)$ is equal to the probability that a source is visible in the VIKING fields, Q0,

$$
\begin{equation*}
q(m)=Q_{0} \frac{n_{\text {real }}(m)}{\int_{-\infty}^{\infty} n_{\text {real }}(m) d m} . \tag{5.16}
\end{equation*}
$$

The background surface distribution, $n(m)$, is given by equation 5.4 , repeated here:

$$
\begin{equation*}
\mathfrak{n}(\mathfrak{m})=\frac{\mathfrak{n}_{\text {back }}(\mathfrak{m})}{\text { Area }} \tag{5.17}
\end{equation*}
$$

Here Area refers to the total area probed by all the random positions, thus equal to the number of random positions times $\pi \times 10 \times 10$ square arcseconds.

Whereas Fleuren et al. (2012) and Bourne et al. (2016) have thousands of Herschel sources to estimate their probability distributions, I have less than a hundred. This can be seen in Figure 5.8, which shows the magnitude distribution of both the HerBS and random positions. The orange histogram shows the magnitude distribution close to HerBS sources, and the solid blue histogram shows the background magnitude distribution.

If I were to simply use these distributions, it will result in a noisy estimation of the true HerBS magnitude distribution ( $n_{\text {real }}(m)$ ) due to low-number statistics. This true HerBS magnitude distribution is necessary for the calculation of $\mathrm{q}(\mathrm{m})$. Similarly, the small number of data points creates a non-continuous magnitude distribution, which is an inconvenience for a successful implementation of the statistical method. I attempt to circumvent this with two methods. Firstly, I will fit a skewed gaussian distribution to the random and the HerBS magnitude distribution, from which a simple subtraction gives me $n_{\text {real }}(m)$, shown by the solid orange line and solid black line for the HerBS and background magnitude distributions, respectively. Secondly, I apply a simple gaussian smoothing to the two histograms, which should decrease bin-to-bin variation, exposing the global trend of $n_{\text {real }}(m)$, shown by the grey histogram and green histogram for the HerBS and background magnitude distributions, respectively.

By eye, I determined the shape of the magnitude distribution, shown in Figure 5.8, is remenicent of a skewed Gaussian. As such, I chose to fit a skewed normal function, given by

$$
\begin{equation*}
f(x)=\frac{2}{\omega} \phi\left(\frac{x-\xi}{\omega}\right) \Phi\left(\alpha \frac{x-\xi}{\omega}\right) . \tag{5.18}
\end{equation*}
$$



Figure 5.8: The orange histogram shows the magnitude distribution within 10 arcseconds of HerBS sources, and the solid blue histogram shows the background magnitude distribution within 10 arcseconds of random non-HerBS positions. The small number of sources contributing to the HerBS magnitude distribution would give a noisy estimation of the true HerBS magnitude distribution, $n_{\text {real }}(m)$. I therefore use two methods to compensate for this. Firstly, I fit a skewed gaussian to both distributions, which can be seen fitted by the solid orange line and solid black line for the HerBS and background magnitude distributions, respectively. The dashed black line shows the true HerBS magnitude distribution, $n_{\text {real }}(m)$, from the skewed gaussian fit. This is calculated simply by subtracting the background from the HerBS magnitude distribution. In the second method, I smooth the histograms using a gaussian spread with a width of 0.5 magnitudes, which gives the grey histogram and green histogram for the HerBS and background magnitude distributions, respectively. The histogram smoothing is better at predicting the brightest sources than the skewed gaussian fit, but underestimates the sources near the peak of the distributions.

Table 5.1: Skewed normal fitting parameters to the magnitude distributions of HerBS and random positions

| Parameters | HerBS | Random |
| :--- | :--- | :--- |
| Offset [mag] $\xi$ | 21.04 | 21.40 |
| Standard deviation [mag] $\omega$ | 1.67 | 1.61 |
| Skewedness $\alpha$ | -2.25 | -4.21 |

Here, $\phi(\mathrm{x})$ is a standard Gaussian probability density function,

$$
\begin{equation*}
\phi=\frac{1}{\sqrt{2 \pi}} \exp \left(-\frac{x^{2}}{2}\right) \tag{5.19}
\end{equation*}
$$

The factor $\Phi(x)$ is the cumulative distribution function,

$$
\begin{equation*}
\Phi(x)=\int_{-\infty}^{x} \phi(t) d t=\frac{1}{2}\left[1+\operatorname{erf}\left(\frac{x}{\sqrt{2}}\right)\right] . \tag{5.20}
\end{equation*}
$$

Here the $\operatorname{erf}(x)$ refers to the error function, which is essentially the area under a normalized gaussian between $-x$ and $+x$. The factor $a$ is the skewedness, and if this value is positive the distribution extends further on the right, if this value is negative, the distribution extends further on the left. $\omega$ is similar to the standard deviation, and $\xi$ is simply the offset in $x$. I detail the results of the fitting in Table 5.1.

The other method I use to counteract the uncertainty from small number statistics, is a smoothing of the histograms with a gaussian profile. Contrary to the previous method, this is method is unphysical, and the smoothing effect is arbitrary and is guaranteed to misrepresent the data. In order to minimize the unphysical nature, I choose to smooth with a gaussian with a standard deviation of only half a magnitude.

Figure 5.8 shows the magnitude distribution of both the HerBS and random positions, and the results of creating a smooth magnitude distribution. Both the HerBS and background histograms appear to be well-fitted by the skewed gaussian distribution, however the function fails to properly fit the low magnitude values of the HerBS distribution. The contrast of the $n_{\text {real }}(m)$ fit from the background distribution promises an adequate cross-correlation of VIKING sources. The histogram-smoothing method seems to better represent the brightest sources, however it does diminish the value near the peak of both distributions.

I compare the two methods with each other in Figure 5.9, where I divide the genuine counterparts probability distribution, $q(m)$, to the background probability surface density of VIKING sources from both methods, $n(m)$. I calculate $q(m)$ from equation 5.16. I plot the skewed gaussian fit in the orange line, and the smoothed histogram as the blue histogram. I also include the unsmoothed values of the HerBS and


Figure 5.9: The expected number of genuine counterparts, $q(m)$, divided by the background VIKING interloper, $n(m)$, are estimated using two methods. The likelihood value calculated for each counterpart is essentially the multiplication the value in Figure 5.7 at the radial offset by value inside this graph at the magnitude of the source. The orange line is determined by fitting two skewed gaussian functions to the HerBS and random points, while the blue histogram is calculated by smoothing the magnitude distributions by a gaussian with 0.5 magnitude. The noise in the original source distribution (black line) shows the need for smoothing. Both smoothing methods appear to give similar values as the original histogram. The low values of the histogram smoothing for bright sources appears unphysical, which I circumvent by fixing the value, and use the grey histogram smoothing to derive the likelihood.
background magnitude distribution in the dash-dotted black histogram. Both functions agree from 16 to 21 magnitude. However, at the lower magnitudes there the smoothed histogram seems to suggest less likelihood on counterparts, as well as at the higher magnitudes. The fitted method might overestimate the $\mathrm{q}(\mathrm{m}) / \mathrm{n}(\mathrm{m})$, especially at high magnitude, and the increasing nature at low magnitude is uncertain too. I adjust the fitted histogram to give a constant value for magnitude between 14 and 16 , shown in grey, this is similar to a fixed value, set in low data regions by Fleuren et al. (2012) and Bourne et al. (2016).
Fleuren et al. (2012) found typical values of $\mathrm{q}(\mathrm{m}) / \mathrm{n}(\mathrm{m})$ ranging from 10000 at $K_{S}=15 \mathrm{mag}$ to $\sim 200$ at $K_{S}=21 \mathrm{mag}$. Both our methods give values within these ranges, and with a similar trend, however less steep than the values Fleuren et al. (2012) finds. This could

Table 5.2: VIKING reliabilities

| R | $<0.8$ | $>0.8$ | All |
| :--- | :---: | :---: | :---: |
| SGP | 6 | 22 | 28 |
| GAMA09 | 13 | 8 | 21 |
| GAMA12 | 9 | 17 | 26 |
| GAMA15 | 10 | 13 | 23 |
| Total | 38 | 60 | 98 |

Notes: Reading from the left, the columns are: Column 1 - the field; column 2 - sources with reliabilities less than o.8; column 3 - sources with reliabilities greater than o.8; column $4^{-}$the total number of sources in each field.
potentially also be due to the nature of our sources, as we are only looking at sources that are relatively hard to detect.

## $5 \cdot 3$ RESULTS

I summarize the results of the reliability estimates in Table 5.2, where I list the reliabilities of the different regions. I find, over the entire VIKING fields, 60 counterparts to the HerBS sources, equal to about $61 \%$ of sources.

I show the VIKING observations of each covered HerBS source, where I show the first collation in Figure 5.10 and detail the rest in the Appendix .8. The background image shows $K_{S}$-band observations in a 30 by 30 arcsecond cutout, centered on the $250 \mu \mathrm{~m}$ Herschel position, which is indicated by a plus. I show the extracted sources with $\mathrm{J}-\mathrm{K}_{\mathrm{S}}>\mathrm{o}$ in the collations (crosses), where I highlight the most likely source, if present, with a circle. All sources that were extracted, but with $\mathrm{J}-\mathrm{K}_{\mathrm{S}}<$ o have been marked with a small circle. The white lines indicate the $250 \mu \mathrm{~m}$ contour lines, which I choose, as this is the flux at which the position is determined by Valiante et al. (2016).

In the discussion, I sort the sources into various catagories, which I note in the bottom-right part of each cutout as well. In the case the source has $R>0.8$ I place a checkmark $(\checkmark)$; in the case the source is not detected because of a large angular separation I place an anglesign ( $\measuredangle$ ); in the case the source was not picked up by sextractor I place a circle with a cross within it $(\otimes)$; in the case the source is excluded because of the colour cut I place a less-or-equal than sign $(\leqslant)$; in the case several sources are conflicting about being a counterpart I place two parallel lines $(\|)$. Finally, in the case there is no nearby source, I place a circle with a line through it $(\varnothing)$.


Figure 5.10: This figure is the first of twelve cutouts of HerBS sources in the VIKING fields. The 30 by 30 arcsecond VIKING image is centred on the Herschel $250 \mu \mathrm{~m}$ position, which is indicated by a plus. All VIKING-extracted sources with J- $\mathrm{K}_{S}>\mathrm{o}$ are indicated with a cross, and the most likely counterpart has a circle placed around it. We mention the reliability in terms of a percentage. I mention the type of detection as follows: $\checkmark-$ detected, $\measuredangle$ - angle too large, $\otimes$ - missed by sextractor, $\|$ - conflicting sources, $\leqslant-$ colour cut, $\varnothing$ - nothing nearby.

### 5.4 DISCUSSION

I firstly discuss the results the global results of the reliability estimator and its components. Secondly, a by-eye analysis of each of the counterparts, in order to analyse the performance of the SExtractor results and counterpart search. Finally, the GAMA sources are both analysed in the SDSS as well as in the VIKING fields. We use this to compare the results from Bourne et al. (2016), our analysis in Chapter 4 and our current results.

Unlike the SDSS observations, we expect that $88 \%$ of HerBS sources have a VIKING source associated with them, as I find a $\mathrm{Q}_{0}$-value of $\sim 0.88$, which suggests we detect most of the foreground sources. Furthermore, for a search radii larger than 10 arcseconds, the blanks appear to drop to o, suggesting all HerBS sources have an associated VIKING source, although this could be due to the small number of galaxies in our sample.

In total, we only have a counterpart with a reliability greater than $0.8(\mathrm{R}>0.8)$ for $61 \%$ of the VIKING-covered HerBS sources. This can be attributed to the statistical difficulty of accurately ascribing a VIKING identification to every SPIRE source. Cosmological models predict around $78 \%$ of sources to be gravitationally lensed Cai et al. (2013); Bakx et al. (2018), which is between the $61 \%$ of $R>0.8$ sources, and the $88 \%$ of sources we expect to have a counterpart in the VIKING fields, statistically.

### 5.4.1 Visual inspection of counterparts

The quality of the entire likelihood analysis of the VIKING fields depends mostly on how well it fairs on the HerBS sources. In order to find out why so many HerBS sources have a nearby source, but only $61 \%$ have a VIKING counterpart with $\mathrm{R}>\mathrm{o} .8$, I will visually inspect the results of the VIKING read-out shown in Figure 5.10 and in the Appendix .8.

When I inspect the sources, several different explanations for an $R<0.8$ become apparent. Several of these will contribute to a high $Q_{0}$ value, whilst others will make $Q_{0}$ smaller. Sources adding to a higher $\mathrm{Q}_{0}$ can be divided into (i) counterparts whose image separation is too large for $\mathrm{R}>0.8$, or (ii) multiple counterparts, which are comparable in distance and brightness, which lowers their overall reliability. The sources that will make for a smaller $Q_{0}$ can be divided into (iii) objects which appear as sources in the VIKING image, but that were not picked up by the sextractor method, (iv) counterparts excluded due to $\mathrm{J}-\mathrm{K}_{\mathrm{S}}<\mathrm{o}$ cut, or (v) where there are no visible nearby sources in the VIKING field.

In total, 23 sources are seen to still contribute to increasing the $\mathrm{Q}_{0}$ value, which adds around 23 per cent to the 61 per cent of sources

Table 5.3: VIKING visual inspection results

| Counterpart with $\mathrm{R}<0.8$ because $\ldots$ | Number | HerBS- |
| :--- | :--- | :--- |
| . . i. large angular separation | $\measuredangle: 9$ | $51,80,83,84,105,119,147,188,190$ |
| $\ldots$. ii. nearby, competing sources | $\\|: 14$ | $2,8,91,97,99,100,110,124,137$, |
|  |  | $157,171,183,195,202$ |
| $\ldots$. iii. close source not picked up | $\otimes: 6$ | $67,78,121,126,165,187$ |
| $\ldots$. iv. close source with J - K $\mathrm{S}<\mathrm{o}$ | $\leqslant: 2$ | 38,206 |
| $\ldots$ v. nothing nearby is detected | $\varnothing: 7$ | $142,161,169,172,175,197,208$ |

with an identified counterpart. This adds up to 84 per cent, close to the 88 per cent we expect from the $Q_{0}$ value. The main contributor to the sources with $\mathrm{R}<0.8$ appears to be the sources that have nearby sources with similar likelihoods. As was already mentioned in Sutherland and Saunders (1992), this is because of the counter-intuitive notion that deeper surveys might struggle with correctly identifying counterparts.
Only 2 VIKING sources were excluded due to the J - $\mathrm{K}_{\mathrm{S}}<$ o colour cut, which was implemented to remove stellar interlopers. Furthermore, only 6 potential VIKING sources were missed due to the strict sextractor set-up that was chosen.
Finally, only 7 HerBS sources had no nearby detections or even galaxies that show up in the VIKING survey. These sources are likely to be unlensed, as there is no foreground lensing source visible, although it could also be that the foreground sources are not bright enough in the $K_{S}$ band to show up in the VIKING survey. In the case these sources are actually unlensed, their bolometric luminosities (8$1000 \mu \mathrm{~m}$ ) range from $\log \mathrm{L}_{\odot} \sim 13.4$ to 13.6, indicating star-formation rates greater than $4000 \mathrm{M}_{\odot} / \mathrm{yr}$ and up to $7000 \mathrm{M}_{\odot} / \mathrm{yr}$ assuming the equation from Robert C. Kennicutt (1998) and the bolometric luminosities derived in Chapter 2,

$$
\begin{equation*}
\frac{\mathrm{SFR}}{1 \mathrm{M}_{\odot} \mathrm{yr}^{-1}}=\frac{\mathrm{L}_{\mathrm{FIR}}}{5.8 \times 10^{9} \mathrm{~L}_{\odot}} . \tag{5.21}
\end{equation*}
$$

While most of the $\mathrm{R}<0.8$ sources have a potential explanation on their low reliability value, it is important to note that this is no indication that these sources are definitely related to the Herschel sources.

### 5.4.2 Comparison to the SDSS

All three GAMA fields overlap in SDSS and VIKING, which allows for a comparison in the counterpart search between them. In total, 27
sources have any reliability value in the SDSS analysis, and are in both the VIKING and SDSS analysis. In total, 14 out of 27 HerBS sources have a counterpart with $\mathrm{R}>0.8$ in both VIKING and SDSS. 8 sources have an $\mathrm{R}>0.8$ in SDSS, but an $\mathrm{R}<0.8$ in VIKING, and 1 source has the reverse, an $R<0.8$ in SDSS and $R>0.8$ in VIKING. 4 sources have $\mathrm{R}<0.8$ in both SDSS and VIKING. Throughout this comparison, I use my lensing-adjusted angular probability distribution, discussed in Chapter 4.

First, however, I need to make sure that both the VIKING and the SDSS observations look at the same object. As a proxy for the same object, I plot the angular separation between the counterpart and the HerBS object in Figure 5.11. If we are looking at the same object, I would expect the sources to have the same angular distance, whilst if there is a discrepancy, I would expect to see an uncorrelated scatter in this line.

Most of the sources with $\mathrm{R}>\mathrm{o} .8$ in both the VIKING and SDSS analysis lie on $\mathrm{y}=\mathrm{x}$ line, which provides confidence in the crossidentification analysis for those sources, and suggests that the VIKING and SDSS analysis look at the same source. A single source, HerBS116 , has $\mathrm{R}>\mathrm{o} .8$, but does not lie on the $\mathrm{y}=\mathrm{x}$ line. Visual inspection of this source does not give any clues to why this is. The visual inspection of the sources with a $\mathrm{R}>0.8$ in the SDSS analysis, but R $<0.8$ in the VIKING analysis show that their low R in VIKING is due to multiple counterparts with conflicting likelihoods. This could explain difference in angular separation, as we could be looking different sources.

The reliability of the sources in VIKING and SDSS not only depends on the source with the highest likelihood, but also on other nearby sources. A better measure for the comparison between SDSS and VIKING is found by comparing the likelihood values themselves, which is essentially the individual probability for each counterpart. This value does not depend on nearby sources, which most likely differ because of the two different survey's depths and wavelengths. I compare the likelihoods from both VIKING and the SDSS in Figure 5.12. The SDSS likelihoods are calculated using the lensing-adjusted radial distribution function. The likelihoods of the $\mathrm{R}>0.8$ counterparts in both VIKING and SDSS agree with each other, and the $\mathrm{y}=\mathrm{x}$ line appears to fit the points reasonably well. The sources without any $\mathrm{R}>0.8$ counterpart in the VIKING fields are usually due to multiple nearby sources with competing likelihoods. These are also relatively close to the $y=x$ line.

### 5.4.3 Optical and near-IR counterparts

Sutherland and Saunders (1992) already warned about the possibility that a deeper survey could actually lead to a less reliable counterpart


Figure 5.11: The angular separation between the HerBS source and the most likely SDSS object on the $y$-axis, plotted against the angular separation of the HerBS source and the most likely VIKING object. HerBS sources with $\mathrm{R}_{\text {lens }}>0.8$ detections in both VIKING and SDSS (orange points). HerBS sources with $\mathrm{R}>0.8$ in the SDSS analysis, but $\mathrm{R}<0.8$ in the VIKING analysis are shown in black. The blue source has an $\mathrm{R}>0.8$ VIKING counterpart, but an $\mathrm{R}<0.8$ SDSS counterpart, and the grey sources refer to the sources with $\mathrm{R}<0.8$ in both analyses. Most of the orange points lie on $\mathrm{y}=\mathrm{x}$ line, which provides confidence in the cross-identification analysis for those sources, and suggests that the VIKING and SDSS analysis look at the same source. A single source, HerBS-116, has $R>0.8$, but does not lie on the $y=x$ line. Visual inspection of this source does not give any clues to why this is. The visual inspection of the sources indicated by the black points shows that their low R in VIKING is due to multiple counterparts with conflicting likelihoods. This could explain difference in angular separation, as we could be looking different sources.


Figure 5.12: I plot their SDSS likelihood against the VIKING likelihood for each HerBS source. The likelihoods of the VIKING counterparts agree well with the SDSS likelihoods for the sources with an $\mathrm{R}>0.8$ in both analyses (orange points). Similar to Figure 5.11, I indicate sources with $\mathrm{R}>0.8$ in VIKING, but $\mathrm{R}<0.8$ in the SDSS analysis with blue points, and black points indicate sources with $\mathrm{R}<0.8$ in VKING but $\mathrm{R}>0.8$ in SDSS. Grey points indicate sources with $\mathrm{R}<0.8$ in both analyses. The isolated orange point with the lowest likelihood is again source 116. Most of the black points scatter around the $\mathrm{y}=\mathrm{x}$ line. These points do not have $\mathrm{R}>0.8$ in VIKING due to nearby b which could be explained by the similar likelihoods of the and the single blue point has a high VIKING likelihood, but a very poor SDSS likelihood.
identification, due to more likelihoods contributing to the overall reliability. The visual inspection of 38 potential VIKING counterparts with a reliability less than 0.8 showed that 14 sources have multiple nearby counterparts with competing likelihoods. Of the 121 SDSS potential counterparts, only 3 sources had a likelihood contribution of nearby sources, and these 3 sources still have reliabilities greater than o.8, as can be seen in the Appendix Table .3.

In Chapter 4, I showed in Figure 4.11 that the angular separation distributions predict more sources at small separations than were actually seen in the SDSS catalogues. This is true both for the original gaussian distribution, as well as for the model that was adjusted to include the effects of gravitational lensing. In Figure 5.6, I further note the angular separation distribution of VIKING counterparts, which extends to higher angular separations than even the lensing-adjusted distribution from the SDSS analysis. Both these observations seem to disagree with the predicted behaviour of gravitational lensing of sub-mm galaxies, as seen in Amvrosiadis et al. (2018).
I use the counterpart analysis in both VIKING and SDSS to provide an estimate of the lensing fraction as a function of flux density at $500 \mu \mathrm{~m}$. Here, I assume that only lensing galaxies show up in the optical and near-infrared surveys. Figure 5.13 shows this lensing fraction, and compares it to the model of Cai et al. (2013). I calculate the lensing fraction by simply adding the number of counterparts with $\mathrm{R}>0.8$ in each flux bin, and dividing this by the number of sources within each flux bin. The error bars are calculated by dividing one by the square root of the number of sources in each bin, as is typical for a binomial distribution.
The blue points show the VIKING counterparts with $\mathrm{R}>0.8$ for all the sources over every field. The grey points show the fraction of SDSS sources with $\mathrm{R}>0.8$, using the results from Bourne et al. (2016), and the orange points show the fraction of SDSS sources with $\mathrm{R}>0.8$ corrected with the model of Amvrosiadis et al. (2018). The upper limits $(r e d)$ are found by taking the sources without any counterpart from Table 5.3. The lack of any counterpart removes the possiblity that our sources were not reliable, due to the statistical limits of our estimator, and they are thus more likely to not have a foreground, lensing galaxy. These are not the only sources without a counterpart, but they provide a more robust upper estimate. I plot three realizations of the lensing fraction from the galaxy evolution model by Cai et al. (2013), where the thick black line has a maximum magnification, $\mu_{\max },=30$. The other three, thinner lines correspond to the realizations with 20 , 15 and 10 as their maximum magnification.
The scatter on the calculated values is large, but an increase in the lensing fraction is seen for VIKING sources with increasing $500 \mu \mathrm{~m}$ fluxes. The galaxy evolution model suggests a significant fraction of lenses at lower fluxes, which show up in the VIKING analysis, but


Figure 5.13: The VIKING and SDSS counterparts give a measure of the lensing fraction as a function of flux density, which disagrees with the lensing fraction estimates from Cai et al. (2013), where the thick line refers to a maximum magnification of 30 . The other three, thinner lines correspond to the realizations with 20,15 and 10 as their maximum magnification. Blue and orange circles refer to the original and lensing-adjusted VIKING counterparts, grey and black circles refer to the original and lensing-adjusted SDSS counterparts. The red upper limits calculated from the sources without any visible nearby counterparts.
are not seen in the SDSS analysis, except for brightest sources. The upper limits also agree with the model, with only sources in the first bin, putting an upper limit of the lensing model. The uncertainty on the analysis, together with the closeness of all four models, make it difficult to say anything robustly, although the lowest maximum magnification does not seem to agree with the lensing fraction in the lowest flux density bin.

The number of rational hypotheses that can explain
any given phenomenon is infinite.

$$
- \text { Robert M. Pirsig }
$$

Finally, I discuss and summarize the findings of this thesis on a topic by topic basis. I use the diversity among chapters to say something about our improved understanding of source confusion, the number of lensed galaxies, and the internal properties of these galaxies. I finish with a recommendation for future work.

### 6.1 SOURCE CONFUSION

High resolution follow-up observations of many bright sub-mm selected sources resolve the sources into multiple components (Karim et al., 2013; Hodge et al., 2013; Chen et al., 2013). This could indicate that many of the HerBS sources are actually composites, since they were selected with the single-dish Herschel telescope. Multiple sources can then appear as a single source, due to the large beamwidth of these single-dish telescopes, which is typically around 10 30 arcseconds in diameter, and is actually 36 arcseconds for the 500 $\mu \mathrm{m}$ flux selection of HerBS sources. Most of the high-resolution observations that show source blending observe sources that are selected from less-luminous samples (such as the Revised Bright Galaxy Sample; Chapman et al. (2005)), which are less affected by gravitational lensing.

The smaller beam-width of SCUBA-2 on the JCMT allow for higher resolution observations of the HerBS sources. These observations of the HerBS sources do not show any sign source multiplicity, however this could also be due to the only-marginal increase in resolution (36 arcsecond at $500 \mu \mathrm{~m}$ SPIRE observations, to $\sim 13$ arcseconds at $850 \mu \mathrm{~m}$ with JCMT). Also, Hodge et al. (2013) found that the source multiplicity mostly occurs on scales of up to 7 arcseconds, and hence we could miss these cases of source confusion.

The IRAM observations of 8 of highest redshift sources resulted in the spectroscopic redshifts of 5 sources with an origin at the same redshift and similar velocities. While the nature of one of the three unidentified sources remains uncertain due to the short observation time, two of the sources have multiple spectral lines $(\mathrm{S} / \mathrm{N}>3)$ that do not agree with a single redshift. It could thus be that these sources


The combined results of SDSS and VIKING are discussed in Section 5.4.3
ull discussion in Section 2.7.4

Discussion in Section 3.4.5

SDSS discussion in Section 4.5

VIKING discussion in Section 5.4.1

Full discussion in Section 5.4.3
are actually line-of-sight blended sources, where a chance-allignment amplifies the signal of these sources. Confirmation of this suspicion will have to wait on follow-up observations, looking for the second spectral lines associated with each of the composite galaxies.

In the case our sample would be influenced significantly by blending, I would expect to detect significantly less optical and near-infrared counterparts, because the bright sub-mm emission would be due to a combination of multiple high-redshift sources, instead of a foreground lensing source. While the optical SDSS counterparts are only 31 or 41 , out of 121 SDSS sources, the VIKING near-IR observations are able to statistically determine the counterparts to 60 sources, out of 98 sources. Furthermore, 88 percent of HerBS sources have VIKING counterparts within 10 arcseconds, when corrected for chance-encounters. This severely limits the hypothesis that many HerBS-sources are blended sources.

### 6.2 GRAVITATIONALLY LENSED HERBS GALAXIES

Cosmological models predict $76 \%$ of the HerBS sources are gravitationally lensed. These models are based on analytical models, and perhaps do not represent reality. Previous lensing samples (Nayyeri et al., 2016; Negrello et al., 2017) have already determined a high lensing fraction for the brightest HerBS sources with $S_{500 \mu m}>100 \mathrm{mJy}$.

The line velocity and $\mathrm{CO}(4-3)$ line brightness of the five sources that have their redshift spectroscopically determined by IRAM all agree with magnifications around $\mu \sim 10$, and thus suggest that our sources are gravitationally lensed.

Even with the revised likelihood function, I only find 41 out of 121 SDSS sources with a reliability greater than o.8, while the galaxy evolution models predict around $76 \%$ of the sources to have foreground counterparts. Although not all lensing, foreground galaxies are expected to be observed in this shallow optical survey, this result could point to a smaller fraction of lensed sources than was initially expected. This view was significantly changed with the VIKING analysis. I find counterparts to 60 of the 98 sources in the VIKING survey. More than that, I find that 88 percent of sources have a source within 10 arcseconds, when corrected for chance-encounters. These values agree with the lensing fraction of 76 percent, derived from a cosmological model.

One of the major consequences of the VIKING analysis follows from the angular distribution of HerBS sources with VIKING counterparts. I find a different distribution than expected from the current best estimates of the Einstein radius distribution (Amvrosiadis et al., 2018), with Herschel-sources out to significantly higher angular separation than expected. The Einstein radius distribution takes galaxy-cluster lensing into account, but perhaps the percentage of
this type of lensing is higher than expected from the 15 ALMA observations.

## 6.3 source diversity

The spectrum of a dusty source depends mostly on the temperature of the dust inside the galaxy. This dust is heated up by stars, whose optical and near-infrared light cannot escape from the large dustclouds inside these galaxies. This explains the lack of optical and near-infrared radiation from these extremely bright, star-forming sources. In Chapter 2, I fit a two-temperature modified black-body (MBB) to the restframe intensity of a subset of 24 galaxies with spectroscopic redshifts. The expected quality of fit, $\chi^{2}$, in the case our MBB was a good representation of our sources would be around 60 . The $\chi^{2}$ is around 812, indicating that the assumption that two-temperature modified blackbody I fitted in Chapter 2 are do able to describe all the galaxies.

The photometric fits to the 8 highest-redshift sources further this assumption. All sources with confirmed redshifts are poorly predicted by the two-temperature MBB, even at high redshift, $z>4$. This is a consequence of the spectral diversity among all HerBS galaxies, as I calculate the photometric redshift by fitting a single spectrum to all the HerBS galaxies.

The internal properties of the galaxies also seem to differ significantly, when I analyse the five different Spectral Line Energy Densities (SLED). Some sources have a downward-sloping SLED, indicating a less thermalized, and therefore less intensely star-forming environment, while others appear to be fully thermalized until the $\mathrm{CO}(5-4)$ line and perhaps beyond.

### 6.4 FUTURE WORK

A significant part of my work during this thesis was spent writing observation proposals. As such, I discuss the future work in terms of potential proposals and projects that can be undertaken with the HerBS sample and related far-infrared samples.

### 6.4.1 Spectroscopic surveys

- What is the nature of the $z>4$ IRAM sources? Four of the eight high-redshift sources observed by the IRAM campaign require additional observation time with the telescope. One source, HerBS38, has a second spectral line detected, only with a signal to noise of 3 . Follow-up observations can make use of the combinatory power of EMIR, and tune into the $\mathrm{CO}(4-3)$ and $\mathrm{CO}(7-6)$ spectral lines. Three other sources need second spectral line(s),

Full discussion in Section 2.7.2

This discussion follows from Figure 3.7

Full discussion in Section 3.4-4
in order to make the spectroscopic redshifts robust, and perhaps confirm source multiplicity.

- Is there any regularity to the galaxy diversity? The lack of a complete set of spectroscopic redshifts limits our understanding. Sources with a spectroscopic redshift have varying internal properties, and thus photometric redshifts cannot be trusted completely. Broad-band spectroscopic surveys of the HerBS sample could find spectroscopic redshifts for the entire sample. I could use this to find out whether this variation breaks down into a clear separation between galactic properties, or that this diversity is less discretely distributed. This could help us understand whether we are seeing galaxies in a single state of their galaxy evolution, such as mergers, or whether other causes lie at the root of their bright sub-mm colours?
- How does the amount of molecular and atomic gas evolve with redshift? Aside from the redshift distributions, which allow the comparison of galaxy samples to one-another, the spectral lines also probe the processes inside these extreme galaxies. Furthermore, a complete overview of the spectral lines throughout this sample, either with CO-lines, HCN-lines or atomic lines will give a good insight into the formation of dust and molecular gas through cosmic time. Especially with the advent of ultrawideband spectrometers, such as DESHIMA and MOSAIC, the time is ripe for full characterization of the properties of highredshift bright SMGs.


### 6.4.2 Optical and near-infrared counterparts

- Are all these VIKING and SDSS sources foreground galaxies? The analysis in Chapters 4 and 5 determined the counterparts to a significant portion of the HerBS sources. Packages such as MAGPHYS and CIGALE are able to estimate the likelihood that these counterparts belong to either a foreground galaxy, or to a background lensed source, as was demonstrated in Hopwood et al. (2011), see Figure 1.7.
- Can we use these counterparts to find more lenses? In Chapter 5, I have demonstrated the effectiveness of looking for counterparts in the VIKING fields with the adjusted angular distribution model. As was suggested by González-Nuevo et al. (2012), by decreasing the selection criteria in both redshift and 500 $\mu \mathrm{m}$ flux density, I might be able to vastly expand the number of known lensed sources, and exploit the full potential of these large-area Herschel surveys. Or, vice versa, I could use this method to find unlensed HyLIRGs by selecting the sources with-
out foreground VIKING sources, in order to study the upper limits of star-formation.


### 6.4.3 High resolution follow-up

- Where does lensing stop? While previous lensing samples (Nayyeri et al., 2016; Negrello et al., 2017) use high $500 \mu \mathrm{~m}$ flux cutoffs ( $>100 \mathrm{mJy}$ ), my sample probes down to 80 mJy . Cosmological models, such as Cai et al. (2013), predict the fraction of unlensed sources increases towards lower fluxes. However, these models are based on single-dish, low-resolution surveys and have never been tested against actual measurements of the lensing fraction. The predicted fraction of lensed sources is very sensitive to the slope of the luminosity function, which is poorly known at high redshift (Gruppioni et al., 2013; Bourne et al., 2017). High-resolution observations will provide an accurate measurement on the flux-dependency of the lensing fraction, and will thus will be the first direct test of the models.
- Do all massive galaxies form the same way? High-resolution observations by Dye et al. (2015); Dye et al. (2018), see Figure 1.6, show a difference between the structure of unlensed emission of high-redshift SMGs. A large enough sample of highresolution observations of lensed HerBS sources might be able to study this diversity, and might be able to answer how many of these sources are interacting, how many contain massive clumps like SDP.81, and how many consist of isolated disks. Furthermore, these observations will also provide magnifications of our lensed sources, allowing me to study the intrinsic properties of the lensed sources.
- Can foreground galaxies explore the nature and evolution of dark-matter haloes? Sub-mm lensing surveys offer a clean and direct way of finding dark-matter haloes. High resolution imaging data at sub-mm/mm wavelengths can probe the contents of the foreground sources in great detail (Vegetti et al., 2012), because foreground galaxies are sub-mm faint, and unlike in optical lensing surveys, they are easily subtracted. The HerBS galaxies are among the brightest sub-mm galaxies in the Universe, and thus the lensed galaxies in it will be able to study the contents of foreground and background sources in great detail and with a high signal-to-noise.
- Will sub-mm lenses be the next big cosmological tool? The distribution of the image separations for the lensed sources depends on the dark-matter and dark-energy content of the Universe. In both Chapter 4 and 5, I have found that the image
separations do not agree with the theoretical predictions. Highresolution observations are the only way to determine whether the theoretical predictions are based on imprecise assumptions, or whether the problem is of a different nature.
- How luminous do galaxies get? The unlensed HerBS galaxies could be limited by the theoretical Eddington limit (Chapman et al., 2015). Whether this significantly influences the galaxy formation is still unclear, as in total, less than 5 high-redshift unlensed HyLIRGs are known (Ivison et al., 2013; Chapman et al., 2015). High resolution observations will be able to confirm the unlensed nature of the HyLIRGs, and investigate the statistical properties of this HyLIRG population, since galaxy evolution models suggest that we might tenfold increase the number of unlensed HyLIRGs with the HerBS sample. The immediate goals are answering simple questions, such as: how many HyLIRGs are the result of multiple sources within the Herschel beam? How many are isolated sources? How many are the result of interactions between galaxies? What are the star-formation rates in these systems?


## Part III

## APPENDIX

I list the HerBS sample properties and provide cutouts of the photometric observations with Herschel/SPIRE and SCUBA-2. I provide the results of the Monte-Carlo line fits, and the complete spectra of the IRAM observations. I list the properties of the SDSS analysis. Finally, I provide the SExtractor code for the VIKING extraction, the four other VIKING test-files, and the collation of the VIKING observations of HerBS sources.

Table .1: The HerBS sample - SPIRE and SCUBA-2 data. The HerBS number hyperlinks to the NED database at the position of the source. The RA and DEC are the SPIRE-positions, $\triangle$ RA and $\triangle \mathrm{DEC}$ are the SPIRE positions minus the SCUBA-2 positions. Cursive SCUBA-2 observations are classed as non-detections, as discussed in Section 2.2. The spectroscopic redshifts are discussed in Section 2.5, $\mathrm{Z}_{\text {phot,temp }}$ refers to the template derived in Section 2.5, and $\mathrm{z}_{\mathrm{phot}, \text { temp }}$ refers to the photometric redshift estimates in Ivison et al. ( (2016)). The bolometric luminosity is calculated using the fitted photometric template. The fluxes in italics are below a signal-to-noise of 3 .

| ${ }^{1} 1$ | J134429.5+303034 | 206.1228 | 30.5095 | -1.4 | 2.04 | $461.9 \pm 5.8$ | $465.7 \pm 6.5$ | $343.3 \pm 7.1$ | $142.0 \pm 8.1$ | 2.30 | 2.21 | 2.33 | 13.94 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 2 | J114637.9-001132 | 176.6582 | -0.1923 | $-3.61$ | 5.15 | $316.0 \pm 6.6$ | $357.9 \pm 7.4$ | $291.8 \pm 7.7$ | $148.1 \pm 10.0$ | 3.26 | 2.81 | 2.54 | 13.98 |
| ${ }^{1} 3$ | J132630.1+334408 | 201.6255 | 33.7355 | -2.11 | 4.02 | $190.5 \pm 5.6$ | $281.3 \pm 5.9$ | $278.6 \pm 7 \cdot 5$ | $121.7 \pm 8.7$ | 2.95 | 3.77 | 3.21 | 14.08 |
| ${ }^{1} 4$ | Jo83051.0+013225 | 127.7127 | 1.5403 | -0.34 | 4.02 | $248.5 \pm 7.5$ | $305.3 \pm 8.1$ | $269.1 \pm 8.7$ | $120.9 \pm 8.5$ | 3.63 | 3.10 | 2.81 | 13.98 |
| ${ }^{1} 5$ | J125632.5+233627 | 194.1352 | 23.6076 | -1.71 | 1.98 | $209.3 \pm 5.6$ | $288.5 \pm 6.0$ | $264.0 \pm 7.0$ | $160.0 \pm 9.7$ | 3.56 | 3.73 | 3.11 | 14.09 |
| ${ }^{1} 6$ | J132427.0+284450 | 201.1126 | 28.7472 | -3.17 | 2.97 | $342.3 \pm 5.6$ | $371.0 \pm 5.9$ | $250.9 \pm 6.9$ | $71.3 \pm 10.5$ | 1.68 | 2.11 | 2.27 | 13.79 |
| ${ }^{1} 7$ | J132859.2+292327 | 202.2468 | 29.3907 | -2.95 | 5.97 | $268.4 \pm 4.4$ | $296.3 \pm 4.8$ | $248.9 \pm 5.9$ | $149.1 \pm 10.9$ | 2.78 | 2.90 | 2.53 | 13.93 |
| 8 | Jo84933.4+021442 | 132.3893 | 2.2453 | -3.39 | -0.95 | $216.7 \pm 7.5$ | $248.5 \pm 8.2$ | $208.6 \pm 8.6$ | $61.7 \pm 9.7$ | 2.41 | 2.65 | 2.57 | 13.78 |
| ${ }^{1} 9$ | J125135.3+261458 | 192.8972 | 26.2494 | 0.44 | 0.01 | $157.9 \pm 5.9$ | $202.2 \pm 6.0$ | $206.8 \pm 6.9$ | $138.3 \pm 10.4$ | 3.68 | 3.88 | 3.17 | 13.99 |
| 10 | J113526.2-014606 | 173.8596 | -1.7685 | -0.01 | -0.05 | $278.8 \pm 7.4$ | $282.9 \pm 8.2$ | $204.0 \pm 8.6$ | $116.3 \pm 9.0$ | 3.13 | 2.33 | 2.35 | 13.76 |
| ${ }^{1} 11$ | Jo12407.4-281434 | 21.0308 | -28.2428 | -4.57 | 0.97 | $257.5 \pm 6.4$ | $271.1 \pm 6.3$ | $204.0 \pm 7.2$ | $94.0 \pm 10.3$ | - | 2.37 | 2.40 | 13.75 |
| ${ }^{1} 12$ | J133008.6+245900 | 202.5358 | 24.9833 | 2.06 | 0.03 | $271.2 \pm 5.4$ | $278.2 \pm 5.9$ | $203.5 \pm 6.9$ | $108.0 \pm 10.8$ | 3.11 | 2.30 | 2.34 | 13.74 |
| ${ }^{1} 13$ | J142413.9+022303 | 216.0582 | 2.3842 | -3.49 | 1.97 | $112.2 \pm 7.3$ | $182.2 \pm 8.2$ | $193.3 \pm 8.5$ | $141.3 \pm 9.2$ | 4.24 | 4.54 | 3.85 | 14.06 |
| ${ }^{1} 14$ | Jo13840.5-281856 | 24.6687 | -28.3154 | -4.55 | -2.01 | $116.3 \pm 6.1$ | $177.0 \pm 6.3$ | $179.3 \pm 7.5$ | $103.8 \pm 10.8$ | - | 4.14 | 3.35 | 13.96 |
| ${ }^{1} 15$ | J141351.9-000026 | 213.4666 | -0.0075 | -2.14 | 2.97 | $188.6 \pm 7.4$ | $217.0 \pm 8.1$ | $176.4 \pm 8.7$ | $61.8 \pm 8.7$ | 2.48 | 2.63 | 2.55 | 13.71 |


| No. | H-ATLAS ID | $\begin{gathered} \text { RA } \\ {[\mathrm{deg}]} \end{gathered}$ | DEC <br> [deg] | $\Delta \mathrm{RA}$ <br> ["] | $\triangle \mathrm{DEC}$ <br> ["] | $\begin{gathered} \mathrm{S}_{250} \\ {[\mathrm{mJy}]} \\ \hline \end{gathered}$ | $\begin{gathered} \mathrm{S}_{350} \\ {[\mathrm{mJy}]} \end{gathered}$ | $\begin{gathered} S_{500} \\ {[\mathrm{mJy}]} \\ \hline \end{gathered}$ | $\begin{gathered} \mathrm{S}_{850} \\ {[\mathrm{mJy}]} \\ \hline \end{gathered}$ | $\mathrm{Z}_{\text {spec }}$ | $\mathrm{Z}_{\text {phot,temp }}$ | $\mathrm{Z}_{\text {phot,Ivi }}$ | Lum. $\log (\mathrm{L} \odot)$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 16 | J141004.7+020306 | 212.5196 | 2.0519 | $-2.81$ | -1.95 | $119.4 \pm 7.3$ | $151.0 \pm 8.4$ | $176.0 \pm 8.7$ | $123.6 \pm 8.9$ | - | 4.18 | 3.36 | 13.95 |
| ${ }^{1} 17$ | J232531.4-302236 | 351.3806 | $-30.3765$ | -5.33 | 1.98 | $175.6 \pm 4.7$ | $227.0 \pm 5.0$ | $175.7 \pm 6.1$ | $100.3 \pm 8.7$ | - | 3.16 | 2.77 | 13.84 |
| ${ }^{1} 18$ | J232419.8-323927 | 351.0825 | -32.6574 | -4.59 | 0.05 | $212.9 \pm 4.7$ | $244.2 \pm 5.0$ | $169.4 \pm 6.2$ | $72.6 \pm 9.7$ | - | 2.40 | 2.65 | 13.69 |
| ${ }^{1} 19$ | Jo90311.6+003907 | 135.7987 | 0.6521 | -0.24 | -0.97 | $133.2 \pm 7.4$ | $186.1 \pm 8.2$ | $165.2 \pm 8.8$ | $108.4 \pm 10.4$ | 3.04 | 3.77 | 3.11 | 13.90 |
| ${ }^{1} 20$ | J132504.4+311534 | 201.2682 | 31.2595 | -0.44 | 4.04 | $240.6 \pm 5.4$ | $226.6 \pm 6.0$ | $164.9 \pm 7.3$ | $38.8 \pm 8.2$ | 1.84 | 1.89 | 2.07 | 13.53 |
| ${ }^{121}$ | J234418.1-303936 | 356.0755 | -30.6601 | -3.05 | 3.05 | $125.8 \pm 5.5$ | $185.5 \pm 5.8$ | $155.1 \pm 7.4$ | $80.4 \pm 9.1$ | - | 3.59 | 3.01 | 13.84 |
| ${ }^{1} 22$ | Joo2624.8-341738 | 6.6035 | -34.2938 | -3.21 | 1.99 | $137.7 \pm 5.6$ | $185.9 \pm 6.1$ | $148.8 \pm 7.2$ | $91.9 \pm 12.8$ | - | 3.42 | 2.84 | 13.82 |
| ${ }^{1} 23$ | Jo12046.5-282403 | 20.1936 | -28.401 | -5.14 | -0.98 | $103.3 \pm 6.1$ | $149.8 \pm 6.0$ | $145.7 \pm 7.8$ | $100.2 \pm 9.3$ | - | 4.07 | 3.32 | 13.88 |
| 24 | Jo04736.0-272951 | 11.9 | -27.4974 | $-3.42$ | -1.98 | $170.9 \pm 5.7$ | $197.1 \pm 6.3$ | $145.6 \pm 7.4$ | $65.9 \pm 9.7$ | - | 2.57 | 2.53 | 13.65 |
| ${ }^{1} 25$ | J235827.7-323244 | 359.6153 | -32.5456 | $-3.82$ | -0.01 | $112.5 \pm 5.0$ | $148.0 \pm 5.4$ | $143.4 \pm 6.5$ | $72.9 \pm 9.6$ | - | 3.64 | 3.07 | 13.79 |
| ${ }^{1} 26$ | J225844.8-295125 | 344.6867 | -29.8569 | -0.03 | 2.04 | $175.4 \pm 5.6$ | $186.9 \pm 6.2$ | $142.6 \pm 7.8$ | $70.0 \pm 12.2$ | - | 2.48 | 2.42 | 13.62 |
| 27 | Jo11424.0-333614 | 18.6002 | -33.6038 | -6.66 | -1.98 | $72.2 \pm 5.3$ | $129.8 \pm 5.6$ | $138.6 \pm 7.0$ | $132.5 \pm 9.6$ | - | 4.96 | 4.04 | 14.00 |
| ${ }^{1} 28$ | J230815.6-343801 | 347.065 | -34.6337 | 1.09 | 3.98 | $79.4 \pm 5.8$ | $135.4 \pm 6.0$ | $140.0 \pm 7.4$ | $104.4 \pm 10.9$ | - | 4.60 | 3.81 | 13.93 |
| ${ }^{1} 29$ | J133846.5+255055 | 204.6939 | 25.8485 | -1.72 | 2.97 | $159.0 \pm 5.8$ | $183.1 \pm 6.0$ | $137.6 \pm 7.5$ | $73.5 \pm 10.9$ | 2.34 | 2.70 | 2.54 | 13.65 |
| 30 | J132301.7+341649 | 200.757 | 34.2804 | $-3.89$ | 2.98 | $124.1 \pm 5.6$ | $144.5 \pm 6.0$ | $137.0 \pm 7.2$ | $73.6 \pm 8.8$ | 2.19 | 3.29 | 2.87 | 13.72 |
| ${ }^{1} 31$ | J125652.5+275900 | 194.2186 | 27.9834 | 1.61 | 1.0 | $133.9 \pm 5.8$ | $164.1 \pm 6.0$ | $131.8 \pm 7.4$ | $88.6 \pm 8.8$ | 2.79 | 3.25 | 2.79 | 13.74 |
| ${ }^{1} 32$ | Jo91840.8+023048 | 139.6702 | 2.5135 | -0.45 | 2.04 | $125.7 \pm 7.2$ | $150.7 \pm 8.2$ | $128.4 \pm 8.7$ | $61.5 \pm 9.2$ | 2.58 | 3.04 | 2.73 | 13.66 |

[^0]| No. | H-ATLAS ID | $\begin{gathered} \text { RA } \\ {[\mathrm{deg}]} \\ \hline \end{gathered}$ | DEC <br> [deg] | $\Delta \mathrm{RA}$ <br> ["] | $\triangle \mathrm{DEC}$ ["] | $\begin{gathered} \mathrm{S}_{250} \\ {[\mathrm{mJy}]} \end{gathered}$ | $\begin{gathered} \mathrm{S}_{350} \\ {[\mathrm{mJy}]} \\ \hline \end{gathered}$ | $\begin{gathered} S_{500} \\ {[\mathrm{mJy}]} \\ \hline \end{gathered}$ | $\begin{gathered} \mathrm{S}_{850} \\ {[\mathrm{mJy}]} \\ \hline \end{gathered}$ | $\mathrm{Z}_{\text {spec }}$ | $\mathrm{Z}_{\text {phot,temp }}$ | $\mathrm{Z}_{\text {phot,Ivi }}$ | Lum. $\log \left(\mathrm{L}_{\odot}\right)$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| ${ }^{1} 33$ | J224805.4-335820 | 342.0223 | -33.9723 | $-1.84$ | 1.05 | $122.3 \pm 6.1$ | $135.6 \pm 6.6$ | $126.9 \pm 7.5$ | $68.4 \pm 9.2$ | - | 3.14 | 2.74 | 13.66 |
| ${ }^{1} 34$ | J133413.8+260458 | 203.5577 | 26.0828 | -7.14 | 1.05 | $136.1 \pm 5.4$ | $161.0 \pm 5.5$ | $126.5 \pm 6.8$ | $61.4 \pm 12.6$ | - | 2.84 | 2.60 | 13.63 |
| ${ }^{1} 35$ | J133543.0+300402 | 203.929 | 30.0671 | -2.74 | 3.04 | $136.6 \pm 5.4$ | $145.7 \pm 5.8$ | $125.0 \pm 6.9$ | $58.7 \pm 8.7$ | 2.68 | 2.74 | 2.53 | 13.59 |
| 36 | J235623.1-354119 | 359.0961 | -35.6886 | -1.68 | 4.02 | $121.5 \pm 6.1$ | $161.0 \pm 6.7$ | $125.5 \pm 7.7$ | $100.1 \pm 13.1$ | - | 3.47 | 2.83 | 13.76 |
| ${ }^{1} 37$ | J232623.0-342642 | 351.596 | -34.4451 | -0.49 | -1.96 | $153.7 \pm 4.8$ | $178.4 \pm 5.2$ | $123.5 \pm 6.6$ | $57.0 \pm 11.3$ | - | 2.46 | 2.67 | 13.57 |
| ${ }^{1} 38$ | J144608.6+021927 | 221.5359 | 2.3242 | 19.42 | -12.99 | $73.4 \pm 7.1$ | $111.7 \pm 8.1$ | $122.1 \pm 8.7$ | $33.3 \pm 12.4$ | - | 4.08 | $3 \cdot 35$ | 13.75 |
| ${ }^{1} 39$ | J232900.6-321744 | 352.2526 | -32.2956 | -0.7 | 6.99 | $118.3 \pm 5.1$ | $141.2 \pm 5.5$ | $119.7 \pm 6.8$ | $52.1 \pm 10.6$ | - | 3.00 | 2.68 | 13.62 |
| ${ }^{1} 40$ | Jo13240.0-330907 | 23.1666 | -33.1518 | 4.41 | 2.08 | $112.0 \pm 5.9$ | $148.8 \pm 6.5$ | $117.7 \pm 7.3$ | $40.7 \pm 11.0$ | - | 2.99 | 2.99 | 13.61 |
| 41 | Jooo124.9-354212 | 0.3537 | -35.7033 | 2.42 | -2.05 | $63.3 \pm 6.2$ | $91.1 \pm 6.1$ | $121.7 \pm 7.4$ | $56.7 \pm 9.3$ | - | 4.39 | 3.91 | 13.75 |
| ${ }^{1} 42$ | Jooo007.5-334060 | 0.0312 | -33.6833 | -2.62 | -0.03 | $130.3 \pm 5.8$ | $160.0 \pm 6.1$ | $116.2 \pm 6.8$ | $84.6 \pm 9.0$ | - | 3.05 | 2.66 | 13.67 |
| ${ }^{1} 43$ | J132419.0+320752 | 201.0792 | 32.1311 | $-3.38$ | 2.0 | $84.4 \pm 4.9$ | $116.0 \pm 5.2$ | $115.4 \pm 6.3$ | $81.2 \pm 11.4$ | - | 4.02 | 3.19 | 13.77 |
| ${ }^{1} 44$ | J133255.8+342208 | 203.2325 | 34.3689 | -1.36 | 1.99 | $164.3 \pm 5.8$ | $186.8 \pm 5.8$ | $114.9 \pm 7.2$ | $51.1 \pm 10.2$ | - | 2.14 | 2.54 | 13.49 |
| ${ }^{1} 45$ | J005132.8-301848 | 12.8867 | -30.3134 | 0.12 | -5.96 | $164.6 \pm 5.8$ | $160.2 \pm 6.1$ | $113.1 \pm 7.6$ | $27.3 \pm 10.4$ | - | 1.93 | 2.11 | 13.39 |
| ${ }^{1} 46$ | J144556.1-004853 | 221.4838 | -0.8148 | 3.08 | 4.99 | $126.7 \pm 7.3$ | $132.6 \pm 8.4$ | $111.8 \pm 8.7$ | $39.8 \pm 10.2$ | - | 2.53 | 2.52 | 13.49 |
| ${ }^{1} 47$ | J225250.7-313658 | 343.2114 | -31.6161 | -0.7 | 4.01 | $127.4 \pm 4.6$ | $138.7 \pm 5.1$ | $111.4 \pm 6.3$ | $35.5 \pm 11.2$ | - | 2.54 | 2.51 | 13.50 |
| 48 | J121301.5-004922 | 183.2566 | -0.8229 | -3.14 | -0.37 | $136.6 \pm 6.6$ | $142.6 \pm 7.4$ | $110.9 \pm 7.7$ | $40.7 \pm 9.5$ | - | 2.39 | 2.39 | 13.47 |
| ${ }^{1} 49$ | J230546.3-331039 | 346.4427 | -33.1774 | $-1.87$ | 4.95 | $76.8 \pm 6.0$ | $110.9 \pm 6.2$ | $110.4 \pm 7.3$ | $40.9 \pm 11.6$ | - | 3.78 | 3.18 | 13.68 |
| 50 | J120319.1-011253 | 180.8296 | -1.215 | $-1.83$ | 3.0 | $114.3 \pm 7.3$ | $142.8 \pm 8.2$ | $110.2 \pm 8.6$ | $88.8 \pm 8.4$ | - | 3.40 | 2.82 | 13.71 |


| No. | H-ATLAS ID | $\begin{gathered} \text { RA } \\ {[\mathrm{deg}]} \end{gathered}$ | DEC <br> [deg] | $\Delta \mathrm{RA}$ <br> ["] | $\Delta \mathrm{DEC}$ <br> ["] | $\begin{gathered} \mathrm{S}_{250} \\ {[\mathrm{mJy}]} \end{gathered}$ | $\begin{gathered} \mathrm{S}_{350} \\ {[\mathrm{mJy}]} \end{gathered}$ | $\begin{gathered} \mathrm{S}_{500} \\ {[\mathrm{mJy}]} \\ \hline \end{gathered}$ | $\begin{gathered} \mathrm{S}_{850} \\ {[\mathrm{mJy}]} \\ \hline \end{gathered}$ | $\mathrm{Z}_{\text {spec }}$ | $\mathrm{Z}_{\text {phot,temp }}$ | $\mathrm{Z}_{\text {phot,Ivi }}$ | Lum. $\log \left(\mathrm{L}_{\odot}\right)$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 51 | J120709.2-014702 | 181.7886 | -1.7841 | $-6.67$ | -0.04 | $143.2 \pm 7.4$ | $149.2 \pm 8.1$ | $110.3 \pm 8.7$ | $42.5 \pm 9.0$ | - | 2.25 | 2.35 | 13.45 |
| ${ }^{1} 52$ | J125125.8+254930 | 192.8577 | 25.8249 | -2.67 | 3.0 | $57.4 \pm 5.8$ | $96.8 \pm 5.9$ | $109.4 \pm 7.2$ | $80.1 \pm 12.0$ | 3.44 | 4.76 | 3.89 | 13.83 |
| 53 | J115112.2-012637 | 177.801 | -1.4437 | -3.76 | 0.16 | $141.2 \pm 7.4$ | $137.7 \pm 8.2$ | $108.4 \pm 8.8$ | $27.2 \pm 8.9$ | - | 2.11 | 2.33 | 13.39 |
| ${ }^{1} 54$ | J131540.6+262322 | 198.9192 | 26.3895 | -8.92 | 1.01 | $94.0 \pm 5.7$ | $116.1 \pm 6.1$ | $108.6 \pm 7.1$ | $96.5 \pm 11.1$ | - | 3.81 | 3.10 | 13.73 |
| ${ }^{1} 55$ | Jo13951.9-321446 | 24.9664 | -32.2462 | 2.99 | 5.02 | $109.0 \pm 5.3$ | $116.5 \pm 5.5$ | $107.1 \pm 6.6$ | $38.2 \pm 10.3$ | - | 2.80 | 2.53 | 13.51 |
| ${ }^{1} 56$ | Jo03207.7-303724 | 8.0321 | -30.6234 | -5.82 | 2.0 | $80.3 \pm 5.4$ | $106.1 \pm 5.5$ | $105.8 \pm 6.7$ | $47.0 \pm 10.3$ | - | 3.64 | 3.09 | 13.65 |
| ${ }^{1} 57$ | Jo04853.3-303110 | 12.2219 | -30.5193 | 1.75 | -2.06 | $118.1 \pm 4.9$ | $147.3 \pm 5.2$ | $105.4 \pm 6.4$ | $85.9 \pm 10.4$ | - | 3.09 | 2.65 | 13.64 |
| ${ }^{1} 58$ | J130333.1+244643 | 195.8881 | 24.7786 | -2.63 | 2.0 | $99.0 \pm 5.5$ | $111.5 \pm 5.9$ | $104.5 \pm 7.1$ | $59.5 \pm 13.0$ | - | 3.22 | 2.72 | 13.59 |
| ${ }^{1} 59$ | Jo91304.9-005344 | 138.2708 | -0.8956 | -2.25 | 3.02 | $118.2 \pm 6.4$ | $136.8 \pm 7.4$ | $104.3 \pm 7.7$ | $67.1 \pm 9.0$ | 2.63 | 2.88 | 2.57 | 13.57 |
| 60 | Jo05724.2-273122 | 14.351 | -27.5229 | -7.39 | 0.03 | $73.3 \pm 5.8$ | $101.2 \pm 6.1$ | $103.6 \pm 7.5$ | $56.7 \pm 9.8$ | - | 3.88 | 3.21 | 13.68 |
| ${ }^{1} 61$ | J120127.6-014043 | 180.3652 | -1.6789 | -1.65 | -5.96 | $67.4 \pm 6.5$ | $112.1 \pm 7.4$ | $103.9 \pm 7.7$ | $79.6 \pm 9.4$ | - | 4.38 | 3.36 | 13.79 |
| 62 | J121542.7-005220 | 183.9281 | -0.8723 | -1.16 | -0.53 | $119.7 \pm 7.4$ | $135.5 \pm 8.2$ | $103.4 \pm 8.6$ | $36.1 \pm 9.6$ | - | 2.44 | 2.50 | 13.46 |
| ${ }^{1} 63$ | J005132.0-302012 | 12.8833 | -30.3366 | -8.09 | -4.97 | $119.3 \pm 5.4$ | $121.0 \pm 6.0$ | $102.0 \pm 7.0$ | $33.8 \pm 10.6^{2}$ | - | 2.44 | 2.41 | 13.43 |
| ${ }^{1} 64$ | J130118.0+253708 | 195.3252 | 25.619 | -1.62 | -2.05 | $60.2 \pm 4.8$ | $101.1 \pm 5.3$ | $101.5 \pm 6.4$ | $96.5 \pm 10.6$ | 4.04 | 4.71 | 3.88 | 13.83 |
| ${ }^{1} 65$ | J134422.6+231952 | 206.0943 | 23.3311 | -0.49 | 1.95 | $109.6 \pm 6.4$ | $98.3 \pm 7.2$ | $101.6 \pm 7.7$ | $46.3 \pm 7.3$ | - | 2.75 | 2.53 | 13.47 |
| 66 | J115820.1-013752 | 179.584 | -1.6313 | -1.67 | -1.88 | $119.8 \pm 6.8$ | $123.7 \pm 7.7$ | $101.5 \pm 7.9$ | $40.2 \pm 9.2$ | 2.19 | 2.50 | 2.48 | 13.45 |
| ${ }^{1} 67$ | J224207.2-324159 | 340.5301 | -32.6999 | -2.19 | 1.01 | $73.0 \pm 5.9$ | $88.1 \pm 6.5$ | $100.8 \pm 8.0$ | $61.3 \pm 9.8$ | - | 3.88 | 3.20 | 13.65 |

[^1]| No. | H-ATLAS ID | $\begin{gathered} \text { RA } \\ {[\mathrm{deg}]} \end{gathered}$ | $\begin{gathered} \text { DEC } \\ {[\mathrm{deg}]} \end{gathered}$ | $\begin{gathered} \Delta \mathrm{RA} \\ {["]} \\ \hline \end{gathered}$ | $\begin{gathered} \Delta \mathrm{DEC} \\ {["]} \end{gathered}$ | $\begin{gathered} \mathrm{S}_{250} \\ {[\mathrm{mJy}]} \\ \hline \end{gathered}$ | $\begin{gathered} \mathrm{S}_{350} \\ {[\mathrm{mJy}]} \\ \hline \end{gathered}$ | $\begin{aligned} & \mathrm{S}_{500} \\ & {[\mathrm{mJy}]} \end{aligned}$ | $\begin{gathered} \mathrm{S}_{850} \\ {[\mathrm{mJy}]} \end{gathered}$ | $\mathrm{z}_{\text {spec }}$ | $\mathrm{z}_{\text {phot,temp }}$ | $\mathrm{z}_{\text {phot,Ivi }}$ | $\begin{gathered} \text { Lum. } \\ \log \left(\mathrm{L}_{\odot}\right) \end{gathered}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| ${ }^{1} 68$ | J223753.8-305828 | 339.4743 | -30.9745 | -4.33 | 4.02 | $139.1 \pm 5.3$ | $144.8 \pm 5.4$ | $100.5 \pm 6.6$ | $48.5 \pm 9.1$ | - | 2.20 | 2.33 | 13.42 |
| ${ }^{1} 69$ | Jo12416.0-310500 | 21.0666 | -31.0834 | -5.03 | 2.04 | $140.4 \pm 5.8$ | $154.5 \pm 6.0$ | $100.3 \pm 7.3$ | $41.8 \pm 11.2$ | - | 2.16 | 2.53 | 13.42 |
| 70 | J130140.2+292918 | 195.4176 | 29.4882 | -14.49 | 20.02 | $119.6 \pm 5.8$ | $136.8 \pm 5.8$ | $100.0 \pm 7.1$ | $20.2 \pm 9.7$ | - | 2.32 | 2.48 | 13.42 |
| 71 | J113243.0-005108 | 173.1795 | -0.8525 | -21.18 | 3.19 | $67.8 \pm 7.3$ | $105.8 \pm 8.2$ | $99.8 \pm 8.8$ | $25.4 \pm 10.0$ | 2.58 | 3.72 | 3.25 | 13.62 |
| 72 | J144512.1-001510 | 221.3006 | -0.253 | -1.38 | 0.97 | $78.8 \pm 6.5$ | $100.7 \pm 7.4$ | $99.6 \pm 7.7$ | $68.5 \pm 10.0$ | - | 3.81 | 3.10 | 13.67 |
| 73 | Jo12853.0-332719 | 22.2208 | -33.4554 | 0.04 | 6.0 | $117.1 \pm 6.0$ | $129.0 \pm 6.2$ | $99.6 \pm 7.4$ | $73.3 \pm 10.1$ | - | 2.90 | 2.53 | 13.56 |
| 74 | J120600.7+003459 | 181.5029 | 0.5832 | -0.91 | 16.21 | $88.7 \pm 7.4$ | $104.1 \pm 8.1$ | $98.8 \pm 8.7$ | $29.8 \pm 9.9$ | - | 2.99 | 3.03 | 13.50 |
| 75 | Jo11823.8-274404 | 19.5991 | -27.7344 | -6.97 | 2.98 | $124.4 \pm 5.8$ | $134.7 \pm 5.9$ | $98.7 \pm 7.8$ | $44.9 \pm 10.7^{2}$ | - | 2.41 | 2.42 | 13.45 |
| 76 | J133534.1+341835 | 203.892 | $34 \cdot 3097$ | 5.77 | -0.0 | $108.5 \pm 5.9$ | $124.3 \pm 6.0$ | $98.5 \pm 7.0$ | $31.5 \pm 8.9$ | - | 2.53 | 2.53 | 13.44 |
| 77 | Joo5629.6-311206 | 14.1234 | -31.2017 | 17.72 | -14.01 | $93.2 \pm 5.8$ | $135.2 \pm 5.9$ | $98.3 \pm 7.7$ | $28.6 \pm 10.4$ | - | 2.94 | 2.72 | 13.54 |
| 78 | J143352.4+020417 | 218.4685 | 2.0715 | -4.33 | 1.03 | $87.7 \pm 7.3$ | $102.4 \pm 8.1$ | $98.2 \pm 8.8$ | $60.8 \pm 8.9$ | - | 3.45 | 2.90 | 13.60 |
| 79 | J131434.1+335219 | 198.642 | 33.8719 | 4.69 | -5.03 | $103.4 \pm 5.6$ | $115.3 \pm 6.0$ | $97.9 \pm 7.3$ | $48.8 \pm 9.1$ | - | 2.87 | 2.62 | 13.51 |
| 80 | J230002.6-315005 | 345.0109 | $-31.8348$ | 3.68 | 6.97 | $122.7 \pm 5.7$ | $122.1 \pm 6.3$ | $97.7 \pm 7.6$ | $22.0 \pm 9.5$ | - | 2.18 | 2.34 | 13.36 |
| 81 | Joo2054.6-312752 | 5.2274 | $-31.4646$ | -7.33 | -1.02 | $82.8 \pm 5.6$ | $114.8 \pm 5.9$ | $97.5 \pm 7.2$ | $42.7 \pm 9.6$ | - | 3.36 | 2.93 | 13.59 |
| 82 | J121144.8+010638 | 182.9369 | 1.1106 | -5.57 | -5.04 | $114.5 \pm 6.7$ | $123.2 \pm 7.6$ | $96.8 \pm 8.0$ | $35.3 \pm 9.4$ | - | 2.57 | 2.53 | 13.45 |
| 83 | J121812.8+011841 | 184.5534 | 1.3116 | -2.73 | 4.87 | $49.5 \pm 7.2$ | $79.7 \pm 8.1$ | $94.1 \pm 8.8$ | $71.2 \pm 10.0$ | - | 4.79 | 4.03 | 13.77 |
| 84 | J224400.8-340031 | 341.0035 | -34.0086 | -7.78 | 4.01 | $105.1 \pm 5.9$ | $123.0 \pm 6.4$ | $97.0 \pm 7.6$ | $36.8 \pm 9.6$ | - | 2.66 | 2.57 | 13.47 |
| 85 | J114752.7-005831 | 176.9699 | -0.9754 | -9.42 | 3.97 | $92.1 \pm 6.6$ | $104.2 \pm 7.4$ | $96.0 \pm 7.7$ | $27.2 \pm 10.4$ | - | 2.86 | 2.63 | 13.47 |


| No. | H-ATLAS ID | $\begin{gathered} \text { RA } \\ {[\mathrm{deg}]} \end{gathered}$ | $\begin{gathered} \text { DEC } \\ {[\mathrm{deg}]} \\ \hline \end{gathered}$ | $\Delta \mathrm{RA}$ <br> ["] | $\triangle$ DEC ["] | $\begin{gathered} \mathrm{S}_{250} \\ {[\mathrm{mJy}]} \end{gathered}$ | $\begin{gathered} \mathrm{S}_{350} \\ {[\mathrm{mJy}]} \end{gathered}$ | $\begin{aligned} & \mathrm{S}_{500} \\ & {[\mathrm{mJy}]} \end{aligned}$ | $\begin{gathered} \mathrm{S}_{850} \\ {[\mathrm{mJy}]} \end{gathered}$ | $\mathrm{Z}_{\text {spec }}$ | $\mathrm{Z}_{\text {phot,temp }}$ | $\mathrm{Z}_{\text {phot,Ivi }}$ | Lum. $\log \left(\mathrm{L}_{\odot}\right)$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 86 | J235324.7-331111 | 358.3528 | -33.1864 | -5.37 | -0.96 | $77 \cdot 4 \pm 5.6$ | $90.7 \pm 5.8$ | $96.0 \pm 7.4$ | $53.0 \pm 8.1$ | - | 3.56 | 3.00 | 13.58 |
| 87 | Joo2533.6-333826 | 6.3899 | -33.6406 | -7.5 | 3.02 | $114.7 \pm 5.2$ | $127.8 \pm 6.1$ | $96.0 \pm 7.3$ | $30.3 \pm 8.0$ | - | 2.36 | 2.46 | 13.40 |
| 88 | Jo83344.9+000109 | 128.4374 | 0.0193 | -1.37 | -12.98 | $71.0 \pm 7.6$ | $96.0 \pm 8.1$ | $95.9 \pm 8.8$ | $19.4 \pm 8.9$ | 3.10 | 3.25 | 3.10 | 13.50 |
| 89 | J131611.5+281219 | 199.0479 | 28.2053 | -2.16 | -1.03 | $71.8 \pm 5.7$ | $103.4 \pm 5.7$ | $95.7 \pm 7.0$ | $81.8 \pm 7.3$ | - | 4.21 | 3.37 | 13.75 |
| 90 | Joo5659.4-295039 | 14.2473 | -29.8441 | -1.76 | -1.02 | $59.5 \pm 5.9$ | $96.9 \pm 6.2$ | $95.6 \pm 7.4$ | $48.4 \pm 9.2$ | - | 4.08 | $3 \cdot 36$ | 13.67 |
| 91 | Jo92135.6+000131 | 140.3987 | 0.0255 | -0.08 | 1.01 | $139.2 \pm 7.3$ | $128.8 \pm 8.1$ | $95.1 \pm 8.6$ | $34.0 \pm 9.5$ | - | 1.97 | 2.07 | 13.32 |
| 92 | J133808.9+255153 | 204.5371 | 25.8647 | - | - | $42.2 \pm 5.7$ | $75.3 \pm 6.0$ | $94.9 \pm 7.2$ | - | - | 5.23 | 4.02 | 13.82 |
| 93 | J234750.5-352931 | 356.9606 | -35.492 | -0.62 | 0.03 | $77 \cdot 3 \pm 5.4$ | $87.3 \pm 5.7$ | $94.8 \pm 7.0$ | $30.2 \pm 8.3$ | - | 3.15 | 2.87 | 13.48 |
| 94 | Jooo950.5-353829 | 2.4605 | -35.6414 | 4.08 | -2.02 | $100.0 \pm 5.4$ | $114.4 \pm 6.0$ | $94.7 \pm 6.9$ | $33.3 \pm 9.4$ | - | 2.70 | 2.57 | 13.45 |
| 95 | J134342.5+263919 | 205.9272 | 26.6552 | - | - | $61.9 \pm 5.7$ | $101.3 \pm 5.7$ | $94.7 \pm 7.6$ | - | - | 4.39 | 3.48 | 13.76 |
| 96 | J113803.6-011737 | 174.5151 | -1.2937 | -6.99 | -4.28 | $85.1 \pm 7.3$ | $98.4 \pm 8.2$ | $94.8 \pm 8.8$ | $19.5 \pm 9.3^{2}$ | 3.15 | 2.89 | 2.72 | 13.44 |
| 97 | J224027.8-343135 | 340.1158 | -34.5263 | -2.68 | 6.0 | $96.1 \pm 6.0$ | $98.5 \pm 6.3$ | $94.4 \pm 7.7$ | $28.1 \pm 11.3^{2}$ | - | 2.70 | 2.78 | 13.42 |
| 98 | Jo01030.1-330622 | 2.6255 | -33.106 | -11.67 | -3.01 | $56.3 \pm 4.9$ | $51.7 \pm 5.0$ | $94.4 \pm 6.5$ | $23.4 \pm 9.7$ | - | 3.79 | 4.40 | 13.49 |
| 99 | Jo91809.5+001929 | 139.5397 | 0.3248 | 8.41 | -4.04 | $93.2 \pm 7.4$ | $116.6 \pm 8.2$ | $94.3 \pm 8.7$ | $28.7 \pm 8.9$ | - | 2.75 | 2.67 | 13.46 |
| 100 | J113833.3+004909 | 174.639 | 0.8194 | -0.54 | -13.92 | $96.8 \pm 7 \cdot 3$ | $106.4 \pm 8.1$ | $93.4 \pm 8.7$ | $21.6 \pm 10.4$ | 2.22 | 2.67 | 2.53 | 13.43 |
| 101 | J011246.5-330611 | 18.1935 | -33.103 | -1.94 | 0.03 | $118.1 \pm 5.8$ | $120.0 \pm 6.2$ | $93.9 \pm 7.5$ | $32.5 \pm 9.5^{2}$ | - | 2.28 | 2.35 | 13.38 |
| 102 | J233024.1-325032 | 352.6006 | -32.8422 | -2.92 | 6.03 | $74.5 \pm 5.7$ | $100.2 \pm 6.0$ | $93.7 \pm 7.5$ | $52.2 \pm 10.2$ | - | 3.67 | 3.09 | 13.62 |

[^2]| No. | H-ATLAS ID | $\begin{gathered} \text { RA } \\ {[\mathrm{deg}]} \end{gathered}$ | DEC <br> [deg] | $\Delta \mathrm{RA}$ <br> ["] | $\triangle$ DEC <br> ["] | $\begin{gathered} \mathrm{S}_{250} \\ {[\mathrm{mJy}]} \end{gathered}$ | $\begin{gathered} \mathrm{S}_{350} \\ {[\mathrm{mJy}]} \end{gathered}$ | $\begin{gathered} \mathrm{S}_{500} \\ {[\mathrm{mJy}]} \end{gathered}$ | $\begin{gathered} \mathrm{S}_{850} \\ {[\mathrm{mJy}]} \end{gathered}$ | $\mathrm{z}_{\text {spec }}$ | $\mathrm{Z}_{\text {phot,temp }}$ | $\mathrm{Z}_{\text {phot,Ivi }}$ | Lum. $\log \left(\mathrm{L}_{\odot}\right)$ | $\stackrel{+}{\infty}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 103 | J225324.2-323504 | 343.351 | -32.5845 | 6.64 | 4.01 | $126.1 \pm 5.3$ | $131.2 \pm 5.7$ | $93.5 \pm 7.0$ | $59.1 \pm 10.9$ | - | 2.36 | 2.35 | 13.43 | ${ }_{6}$ |
| 104 | Joo1838.7-354133 | 4.6613 | -35.6925 | 0.07 | 5.96 | $134.0 \pm 5.6$ | $128.5 \pm 6.1$ | $93.4 \pm 6.9$ | $28.2 \pm 8.7$ | - | 1.98 | 2.21 | 13.32 | ç |
| 105 | Jo83932.2-011758 | 129.8843 | -1.2995 | -4.69 | -5.0 | $73.8 \pm 7 \cdot 4$ | $88.5 \pm 8.1$ | $93.2 \pm 8.7$ | $37.6 \pm 7 \cdot 5$ | - | 3.31 | 2.96 | 13.51 | 0 |
| 106 | Joo1802.2-313505 | 4.509 | -31.5847 | -1.75 | 0.94 | $126.7 \pm 5.8$ | $125.6 \pm 5.9$ | $93.1 \pm 7.4$ | $33.1 \pm 9.9$ | - | 2.13 | 2.33 | 13.35 | \% |
| 107 | J014520.0-313835 | 26.3335 | -31.643 | 4.22 | 3.94 | $97.3 \pm 6.1$ | $99.1 \pm 6.4$ | $93.1 \pm 7.8$ | $28.1 \pm 7.7$ | - | 2.54 | 2.53 | 13.38 | 号 |
| 108 | Jo83817.4-004134 | 129.5726 | -0.6929 | -5.77 | 1.04 | $84.5 \pm 7.4$ | $106.1 \pm 8.2$ | $93.0 \pm 8.8$ | $48.4 \pm 8.5$ | - | 3.27 | 2.87 | 13.56 | $\theta$ |
| 109 | J132900.4+281914 | 202.2519 | 28.3206 | - | - | $121.7 \pm 5.4$ | $140.1 \pm 5.9$ | $92.8 \pm 7.6$ | - | - | 2.35 | 2.34 | 13.43 | 0 8 |
| 110 | J141832.9+010212 | 214.6375 | 1.0368 | -7.04 | 0.05 | $66.0 \pm 6.6$ | $106.5 \pm 7.5$ | $92.8 \pm 7.8$ | $51.8 \pm 8.3$ | - | 3.96 | 3.22 | 13.67 | $\bigcirc$ |
| 111 | J223942.4-333304 | 339.9268 | -33.5512 | 23.34 | 1.04 | $105.9 \pm 6.5$ | $115.6 \pm 6.2$ | $92.7 \pm 7.4$ | $24.7 \pm 10.6$ | - | 2.42 | 2.70 | 13.39 | ¢ |
| 112 | J133108.4+303034 | 202.7852 | 30.5095 | - | - | $71.8 \pm 5.8$ | $87.0 \pm 5.8$ | $92.2 \pm 7.0$ | - | - | 3.77 | 3.05 | 13.61 | O |
| 113 | J131211.5+323837 | 198.0479 | 32.6436 | $3 \cdot 39$ | -1.95 | $80.7 \pm 5.9$ | $103.4 \pm 6.0$ | $92.0 \pm 7.0$ | $44.6 \pm 8.7$ | - | 3.28 | 2.89 | 13.55 | © |
| 114 | Jo12209.5-273824 | 20.5394 | -27.6401 | -1.74 | -3.99 | $81.7 \pm 5.9$ | $93.8 \pm 6.0$ | $91.8 \pm 7.7$ | $30.2 \pm 10.4$ | - | 2.99 | 2.73 | 13.46 |  |
| 115 | J133538.3+265742 | 203.9095 | 26.9617 | - | - | $116.2 \pm 5.6$ | $133.5 \pm 6.0$ | $91.8 \pm 6.9$ | - | - | 2.38 | 2.63 | 13.42 |  |
| 116 | J121348.0+010812 | 183.4504 | 1.1368 | -2.55 | 0.49 | $65.1 \pm 7.4$ | $96.6 \pm 8.2$ | $93.6 \pm 8.5$ | $80.8 \pm 9.3$ | - | 4.33 | 3.38 | 13.74 |  |
| 117 | Jooo806.8-351205 | 2.0283 | -35.2014 | -2.4 | 3.04 | $81.0 \pm 5.6$ | $112.7 \pm 5.9$ | $91.6 \pm 6.9$ | $62.7 \pm 10.7$ | - | 3.59 | 2.94 | 13.63 |  |
| 118 | J232200.1-355622 | 350.5003 | -35.9395 | 0.98 | -1.97 | $60.0 \pm 6.3$ | $84.3 \pm 6.6$ | $90.9 \pm 7.7$ | $23.3 \pm 11.1^{2}$ | - | 3.80 | 3.28 | 13.57 |  |
| 119 | J113833.8-014655 | 174.6412 | -1.7822 | -10.21 | -12.84 | $68.5 \pm 7.2$ | $85.6 \pm 8.1$ | $91.2 \pm 8.6$ | $17.4 \pm 11.3$ | - | 3.46 | 2.96 | 13.52 |  |
| 120 | Jo12222.3-274456 | 20.593 | -27.749 | -1.89 | 3.04 | $61.8 \pm 5.9$ | $101.3 \pm 6.4$ | $90.7 \pm 7.6$ | $29.5 \pm 9.3$ | - | 3.63 | 3.05 | 13.57 |  |


| No. | H-ATLAS ID | $\begin{gathered} \text { RA } \\ {[\mathrm{deg}]} \end{gathered}$ | DEC <br> [deg] | $\Delta \mathrm{RA}$ <br> ["] | $\triangle \mathrm{DEC}$ ["] | $\begin{gathered} \mathrm{S}_{250} \\ {[\mathrm{mJy}]} \end{gathered}$ | $\begin{gathered} \mathrm{S}_{350} \\ {[\mathrm{mJy}]} \end{gathered}$ | $\begin{gathered} \mathrm{S}_{500} \\ {[\mathrm{mJy}]} \\ \hline \end{gathered}$ | $\begin{aligned} & \mathrm{S}_{850} \\ & {[\mathrm{mJy}]} \end{aligned}$ | $\mathrm{Z}_{\text {spec }}$ | $\mathrm{Z}_{\text {phot,temp }}$ | $\mathrm{Z}_{\text {phot,Ivi }}$ | $\begin{gathered} \text { Lum. } \\ \log \left(\mathrm{L}_{\odot}\right) \\ \hline \end{gathered}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 121 | J223615.2-343301 | 339.0635 | -34.5503 | -2.9 | 0.01 | $85.4 \pm 6.0$ | $99.1 \pm 6.3$ | $90.6 \pm 7.2$ | $54.1 \pm 11.4$ | - | 3.28 | 2.93 | 13.55 |
| 122 | Jo03717.0-323307 | 9.3208 | -32.5519 | 1.16 | 5.0 | $73.7 \pm 5.7$ | $95.8 \pm 6.0$ | $90.3 \pm 7.6$ | $21.9 \pm 9.1^{2}$ | - | 3.09 | 3.16 | 13.46 |
| 123 | J233037.3-331218 | 352.6554 | -33.2049 | -22.8 | -0.01 | $106.2 \pm 5.9$ | $107.9 \pm 6.0$ | $90.0 \pm 7.5$ | $29.1 \pm 11.4$ | - | 2.38 | 2.39 | 13.36 |
| 124 | J122158.5+003326 | 185.494 | 0.5573 | -3.13 | $-3.85$ | $135.7 \pm 7.3$ | $116.1 \pm 8.2$ | $89.8 \pm 8.6$ | $42.5 \pm 9.3$ | - | 2.03 | 2.06 | 13.31 |
| 125 | J130432.2+295338 | 196.1341 | 29.894 | -0.15 | -2.0 | $75.7 \pm 5.8$ | $103.4 \pm 5.7$ | $89.8 \pm 7.1$ | $38.9 \pm 7.2$ | - | 3.22 | 2.96 | 13.52 |
| 126 | J145135.2-011418 | 222.8969 | -1.2383 | 1.49 | 2.05 | $81.9 \pm 7.2$ | $95.9 \pm 8.2$ | $89.8 \pm 8.8$ | $48.2 \pm 10.2$ | - | 3.29 | 2.95 | 13.53 |
| 127 | J132128.6+282020 | 200.369 | 28.3389 | - | - | $110.0 \pm 5.5$ | $122.7 \pm 6.1$ | $89.5 \pm 6.9$ | - | - | 2.44 | 2.43 | 13.41 |
| 128 | J130414.6+303538 | 196.0607 | 30.5938 | 0.74 | 0.02 | $106.4 \pm 5.7$ | $111.2 \pm 5.9$ | $89.2 \pm 7.1$ | $37.6 \pm 8.0$ | - | 2.47 | 2.49 | 13.40 |
| 129 | J130053.8+260303 | 195.2242 | 26.0509 | -0.91 | -0.02 | $59.4 \pm 5.9$ | $85.4 \pm 5.9$ | $89.0 \pm 7.0$ | $56.4 \pm 8.9$ | - | 4.12 | 3.35 | 13.65 |
| 130 | J142706.4+002258 | 216.777 | 0.3829 | -6.15 | -4.95 | $119.4 \pm 7.3$ | $118.7 \pm 8.1$ | $88.8 \pm 8.6$ | $24.8 \pm 8.4$ | - | 2.03 | 2.29 | 13.29 |
| 131 | J225339.1-325550 | 343.413 | -32.9305 | -5.52 | -0.01 | $85.5 \pm 5.2$ | $99.7 \pm 5.5$ | $88.0 \pm 6.9$ | $30.3 \pm 10.5^{2}$ | - | 2.88 | 2.66 | 13.44 |
| 132 | J231205.2-295027 | 348.0216 | -29.8407 | -2.59 | 3.08 | $86.7 \pm 5.8$ | $102.6 \pm 6.0$ | $90.6 \pm 7.8$ | $31.0 \pm 10.2$ | - | 2.94 | 2.71 | 13.46 |
| 133 | J134441.5+240345 | 206.1728 | 24.0626 | - | - | $85.4 \pm 5.5$ | $98.5 \pm 6.1$ | $88.1 \pm 7.3$ | - | - | 3.16 | 2.66 | 13.51 |
| 134 | J133440.4+353141 | 203.6684 | 35.5281 | 2.85 | -1.0 | $69.9 \pm 5.9$ | $97.3 \pm 6.2$ | $87.9 \pm 7.3$ | $61.9 \pm 10.6$ | - | 3.86 | 3.16 | 13.64 |
| 135 | J225611.7-325653 | 344.0486 | -32.948 | - | - | $85.4 \pm 5.5$ | $96.7 \pm 6.2$ | $87.8 \pm 7.5$ | - | - | 3.14 | 2.65 | 13.50 |
| 136 | Jo85308.5-005728 | 133.2857 | -0.9578 | -5.61 | 0.97 | $68.3 \pm 7 \cdot 5$ | $97.5 \pm 8.2$ | $87.7 \pm 8.6$ | $50.7 \pm 12.2$ | - | 3.78 | 3.10 | 13.62 |
| 137 | J145337.2+000407 | 223.4052 | 0.0689 | -8.27 | -0.96 | $86.0 \pm 7.2$ | $103.6 \pm 8.0$ | $87.7 \pm 8.6$ | $38.3 \pm 8.9$ | - | 2.97 | 2.72 | 13.48 |

[^3]| No. | H-ATLAS ID | $\begin{gathered} \text { RA } \\ {[\mathrm{deg}]} \end{gathered}$ | $\begin{gathered} \mathrm{DEC} \\ {[\mathrm{deg}]} \\ \hline \end{gathered}$ | $\begin{gathered} \Delta \mathrm{RA} \\ {["]} \\ \hline \end{gathered}$ | $\triangle \mathrm{DEC}$ ["] | $\begin{gathered} \mathrm{S}_{250} \\ {[\mathrm{mJy}]} \\ \hline \end{gathered}$ | $\begin{gathered} \mathrm{S}_{350} \\ {[\mathrm{mJy}]} \\ \hline \end{gathered}$ | $\begin{gathered} \mathrm{S}_{500} \\ {[\mathrm{mJy}]} \end{gathered}$ | $\begin{gathered} \mathrm{S}_{850} \\ {[\mathrm{mJy}]} \end{gathered}$ | $\mathrm{z}_{\text {spec }}$ | $\mathrm{z}_{\text {phot,temp }}$ | $\mathrm{z}_{\text {phot,Ivi }}$ | $\begin{gathered} \text { Lum. } \\ \log \left(\mathrm{L}_{\odot}\right) \\ \hline \end{gathered}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 138 | Jo11730.3-320719 | 19.3764 | -32.122 | -5.53 | 1.03 | $120.4 \pm 5.8$ | $111.2 \pm 6.4$ | $87.4 \pm 7.8$ | $32.1 \pm 9.6$ | - | 2.09 | 2.24 | 13.30 |
| 139 | J134855.6+240745 | 207.2317 | 24.1292 | - | - | $76.9 \pm 5.9$ | $82.9 \pm 5.9$ | $87.4 \pm 6.8$ | - | - | 3.38 | 2.77 | 13.52 |
| 140 | J142140.3+000447 | 215.4183 | 0.08 | -5.15 | 4.96 | $96.8 \pm 7.2$ | $98.5 \pm 8.2$ | $87.4 \pm 8.7$ | $30.3 \pm 8.5^{2}$ | - | 2.53 | 2.53 | 13.37 |
| 141 | J224759.7-310135 | 341.9986 | -31.0264 | -11.19 | -19.03 | $122.1 \pm 6.1$ | $124.4 \pm 6.5$ | $87.3 \pm 7.5$ | $28.4 \pm 10.5$ | - | 2.03 | 2.24 | 13.30 |
| 142 | Jo91454.0-010358 | 138.7253 | -1.0663 | -2.55 | 5.05 | $69.0 \pm 7.3$ | $72.2 \pm 8.1$ | $87.2 \pm 8.5$ | $29.0 \pm 9.7$ | - | 3.22 | 2.96 | 13.44 |
| 143 | J141810.0-003747 | 214.542 | -0.6298 | -1.26 | -0.96 | $77.7 \pm 6.5$ | $97.3 \pm 7.4$ | $87.1 \pm 7.9$ | $27.6 \pm 7.4$ | - | 3.03 | 2.78 | 13.46 |
| 144 | J222629.4-321112 | 336.6226 | -32.1866 | 3.76 | -6.0 | $98.9 \pm 8.4$ | $116.5 \pm 8.2$ | $87.0 \pm 11.5$ | $32.4 \pm 9.5$ | - | 2.48 | 2.55 | 13.39 |
| 145 | Jo12335.1-314619 | 20.8963 | $-31.7718$ | -3.3 | 8.95 | $54.7 \pm 6.0$ | $67.4 \pm 6.2$ | $86.8 \pm 7.7$ | $33.0 \pm 10.4^{2}$ | - | 3.87 | 3.35 | 13.54 |
| 146 | J232210.9-333749 | 350.5454 | -33.6304 | -7.27 | -2.99 | $122.4 \pm 5.2$ | $134.6 \pm 5.4$ | $86.6 \pm 6.8$ | $32.1 \pm 11.1^{2}$ | - | 2.09 | 2.25 | 13.34 |
| 147 | J143403.5+000234 | 218.5149 | 0.0429 | -2.33 | 4.04 | $103.3 \pm 7.4$ | $103.3 \pm 8.1$ | $86.6 \pm 8.5$ | $42.5 \pm 9.1$ | - | 2.55 | 2.42 | 13.40 |
| 148 | J224026.5-315155 | 340.1106 | $-31.8652$ | -5.29 | -0.97 | $120.6 \pm 5.0$ | $121.2 \pm 5.5$ | $86.3 \pm 6.8$ | $29.0 \pm 9.6^{2}$ | - | 2.08 | 2.24 | 13.31 |
| 149 | J133827.6+313956 | 204.6149 | 31.6654 | $-3.83$ | 1.0 | $101.5 \pm 5.5$ | $103.3 \pm 6.0$ | $86.0 \pm 7.0$ | $26.0 \pm 8.9$ | - | 2.31 | 2.40 | 13.32 |
| 150 | J122459.1-005647 | 186.2466 | -0.9465 | -2.84 | -6.19 | $53.6 \pm 7.2$ | $81.3 \pm 8.3$ | $92.0 \pm 8.9$ | $64.0 \pm 10.5$ | - | 4.57 | 3.54 | 13.71 |
| 151 | Jo12530.5-302509 | 21.3772 | -30.4192 | 6.26 | -1.0 | $64.2 \pm 5.8$ | $92.9 \pm 5.8$ | $85.8 \pm 6.9$ | $23.9 \pm 10.2^{2}$ | - | 3.49 | 3.08 | 13.53 |
| 152 | J133057.5+311734 | 202.7394 | 31.2928 | -2.85 | 9.98 | $47.7 \pm 5.6$ | $53.4 \pm 6.0$ | $85.8 \pm 6.9$ | $23.3 \pm 9.0$ | - | 3.91 | 4.05 | 13.49 |
| 153 | J144243.4+015504 | 220.6809 | 1.9179 | 1.22 | 0.04 | $123.2 \pm 7.2$ | $133.4 \pm 8.1$ | $85.7 \pm 8.8$ | $44.5 \pm 10.3$ | - | 2.18 | 2.51 | 13.37 |
| 154 | J132258.2+325050 | 200.7423 | 32.8473 | -0.68 | 0.0 | $79.1 \pm 5.6$ | $87.9 \pm 5.9$ | $85.6 \pm 7.2$ | $52.1 \pm 8.4$ | - | 3.35 | 3.04 | 13.53 |
| 155 | Jooo330.7-321136 | 0. 8778 | -32.1934 | 3.1 | -2.97 | $59.9 \pm 5.8$ | $94.2 \pm 5.8$ | $85.6 \pm 7.2$ | $46.0 \pm 10.6$ | - | 3.95 | 3.22 | 13.63 |


| No. | H-ATLAS ID | $\begin{gathered} \text { RA } \\ {[\mathrm{deg}]} \end{gathered}$ | $\begin{gathered} \text { DEC } \\ {[\mathrm{deg}]} \end{gathered}$ | $\Delta \mathrm{RA}$ <br> ["] | $\triangle \mathrm{DEC}$ ["] | $\begin{aligned} & \mathrm{S}_{250} \\ & {[\mathrm{mJy}]} \end{aligned}$ | $\begin{aligned} & \mathrm{S}_{350} \\ & {[\mathrm{mJy}]} \end{aligned}$ | $\begin{aligned} & S_{500} \\ & {[\mathrm{mJy}]} \end{aligned}$ | $\begin{aligned} & \mathrm{S}_{850} \\ & {[\mathrm{mJy}]} \end{aligned}$ | $\mathrm{Z}_{\text {spec }}$ | $\mathrm{Z}_{\text {phot,temp }}$ | $\mathrm{Z}_{\text {phot,Ivi }}$ | Lum. $\log \left(\mathrm{L}_{\odot}\right)$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 156 | Joo2144.8-295218 | 5.4368 | -29.8716 | 0.35 | 3.97 | $103.7 \pm 5.7$ | $91.3 \pm 6.1$ | $85.4 \pm 6.9$ | $35.0 \pm 10.4$ | - | 2.40 | 2.34 | 13.34 |
| 157 | Jo84957.7+010713 | 132.4905 | 1.1204 | -4.84 | -1.03 | $81.2 \pm 7.3$ | $98.9 \pm 8.2$ | $85.2 \pm 8.7$ | $49.3 \pm 8.2$ | - | 3.25 | 2.83 | 13.53 |
| 158 | J132329.9+311528 | 200.8745 | 31.2579 | -0.17 | -2.03 | $64.7 \pm 5.4$ | $75.7 \pm 6.2$ | $85.1 \pm 7.2$ | $39.5 \pm 7.7$ | - | 3.52 | 3.11 | 13.50 |
| 159 | J235122.0-332902 | 357.8416 | -33.4839 | -0.12 | 5.99 | $92.1 \pm 5.9$ | $98.3 \pm 5.9$ | $85.0 \pm 7.1$ | $40.5 \pm 10.6$ | - | 2.77 | 2.53 | 13.43 |
| 160 | Jo11014.5-314814 | 17.5604 | -31.8038 | -0.06 | -5.01 | $48.6 \pm 5.6$ | $84.2 \pm 6.0$ | $84.8 \pm 7.1$ | $57.6 \pm 10.1$ | - | 4.50 | $3 \cdot 53$ | 13.70 |
| 161 | J122407.4-003247 | 186.031 | -0.5465 | 1.1 | -1.12 | $56.5 \pm 7 \cdot 3$ | $75.7 \pm 8.1$ | $82.4 \pm 8.8$ | $32.7 \pm 9.7$ | - | 3.82 | 3.24 | 13.55 |
| 162 | J144334.3-003034 | 220.893 | -0.5095 | -1.81 | 6.0 | $76.1 \pm 6.5$ | $92.5 \pm 7.3$ | $84.6 \pm 7.7$ | $42.7 \pm 11.0$ | - | 3.34 | 2.81 | 13.52 |
| 163 | Joo0745.8-342014 | 1.941 | -34.3373 | 2.99 | -5.96 | $92.7 \pm 5.9$ | $92.6 \pm 5.9$ | $84.5 \pm 7.6$ | $19.1 \pm 10.3^{2}$ | - | 2.50 | 2.43 | 13.34 |
| 164 | J121416.3-013704 | 183.5682 | -1.6179 | -4.33 | 0.7 | $88.0 \pm 6.4$ | $99.3 \pm 7.4$ | $84.3 \pm 7 \cdot 7$ | $39.6 \pm 10.0$ | - | 2.98 | 2.64 | 13.46 |
| 165 | J090613.8-010042 | 136.5576 | -1.0118 | -14.64 | 9.98 | $73.4 \pm 7.4$ | $80.2 \pm 8.0$ | $84.3 \pm 8.7$ | $26.7 \pm 9.7$ | - | 3.01 | 2.73 | 13.41 |
| 166 | J222503.8-304848 | 336.2657 | -30.8133 | -1.5 | 5.97 | $32.4 \pm 7.2$ | $50.1 \pm 8.5$ | $84.3 \pm 10.3$ | $26.7 \pm 10.4$ | - | 4.52 | 4.91 | 13.54 |
| 167 | J130341.5+313754 | 195.9229 | 31.6315 | 4.51 | 16.01 | $52.1 \pm 5.6$ | $82.2 \pm 6.0$ | $84.3 \pm 7.2$ | $21.5 \pm 9.1$ | - | 3.77 | 3.34 | 13.53 |
| 168 | J225045.5-304719 | 342.6896 | -30.7887 | 1.13 | 3.04 | $65.5 \pm 6.1$ | $88.1 \pm 6.1$ | $84.0 \pm 7.5$ | $68.9 \pm 10.6$ | - | 4.02 | 3.19 | 13.65 |
| 169 | Jo83859.3+021325 | 129.7472 | 2.2239 | 3.33 | 4.97 | $95.2 \pm 7.5$ | $105.2 \pm 8.2$ | $84.0 \pm 8.7$ | $42.3 \pm 7.9$ | - | 2.71 | 2.53 | 13.43 |
| 170 | Jooo455-4-330812 | 1.2307 | -33.1366 | 0.81 | -1.0 | $61.9 \pm 5.4$ | $78.8 \pm 6.0$ | $83.8 \pm 7.0$ | $76.4 \pm 9.7$ | - | 4.24 | 3.35 | 13.67 |
| 171 | Jo83945.0+021021 | 129.9378 | 2.1728 | - | - | $71.3 \pm 7.3$ | $97.4 \pm 8.1$ | $83.4 \pm 8.6$ | - | - | 3.66 | 2.88 | 13.60 |
| 172 | J145040.5+003333 | 222.6688 | 0.5594 | 5.1 | $-3.0$ | $76.1 \pm 7.4$ | $85.1 \pm 8.1$ | $83.3 \pm 8.9$ | $13.7 \pm 9.6^{2}$ | - | 2.90 | 2.72 | 13.39 |

[^4]| No. | H-ATLAS ID | $\begin{gathered} \text { RA } \\ {[\mathrm{deg}]} \end{gathered}$ | $\begin{gathered} \text { DEC } \\ {[\mathrm{deg}]} \end{gathered}$ | $\Delta \mathrm{RA}$ <br> ["] | $\triangle \mathrm{DEC}$ ["] | $\begin{gathered} \mathrm{S}_{250} \\ {[\mathrm{mJy}]} \end{gathered}$ | $\begin{gathered} \mathrm{S}_{350} \\ {[\mathrm{mJy}]} \end{gathered}$ | $\begin{gathered} \mathrm{S}_{500} \\ {[\mathrm{mJy}]} \end{gathered}$ | $\begin{gathered} \mathrm{S}_{850} \\ {[\mathrm{mJy}]} \end{gathered}$ | $\mathrm{z}_{\text {spec }}$ | $\mathrm{Z}_{\text {phot,temp }}$ | $\mathrm{Z}_{\text {phot,Ivi }}$ | Lum. $\log \left(\mathrm{L}_{\odot}\right)$ | N |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 173 | J131804.7+325016 | 199.5195 | 32.8379 | -5.11 | -4.99 | $73.3 \pm 5.6$ | $92.7 \pm 6.0$ | $83.3 \pm 7.2$ | $31.7 \pm 9.0$ | - | 3.14 | 2.83 | 13.46 | \% |
| 174 | Joo3728.7-284125 | 9.3696 | -28.6903 | -15.94 | 8.96 | $95.6 \pm 5.7$ | $84.8 \pm 5.9$ | $83.2 \pm 7.4$ | $19.6 \pm 9.3$ | - | 2.33 | 2.51 | 13.28 | ${ }^{\text {c }}$ |
| 175 | J121900.8+003326 | 184.7537 | 0.5575 | -0.63 | -0.93 | $56.7 \pm 7.4$ | $81.5 \pm 8.0$ | $81.9 \pm 8.8$ | $54.8 \pm 10.5$ | - | 4.24 | 3.36 | 13.65 | 0 |
| 176 | J131222.2+270219 | 198.0926 | 27.0386 | - | - | $76.7 \pm 5.5$ | $90.1 \pm 5.8$ | $82.9 \pm 6.9$ | - | - | 3.30 | 2.72 | 13.51 | \% |
| 177 | J115433.6+005042 | 178.6402 | 0.8451 | 1.79 | 2.0 | $53.9 \pm 7.4$ | $85.8 \pm 8.1$ | $83.9 \pm 8.6$ | $94.4 \pm 10.9$ | - | 4.71 | 3.89 | 13.76 | z |
| 178 | Jo11850.1-283642 | 19.7087 | -28.6118 | -3.51 | 1.06 | $93.3 \pm 5.9$ | $113.2 \pm 6.1$ | $82.7 \pm 7.4$ | $34.9 \pm 8.6$ | - | 2.61 | 2.58 | 13.41 | $\theta$ |
| 179 | J115521.0-021329 | 178.8376 | -2.2249 | -1.16 | 1.33 | $62.9 \pm 7.3$ | $79.9 \pm 8.2$ | $82.2 \pm 8.5$ | $70.2 \pm 11.3$ | - | 4.07 | 3.19 | 13.63 | O |
| 180 | J131539.2+292219 | 198.9134 | 29.372 | -2.16 | 5.97 | $88.2 \pm 5.4$ | $102.6 \pm 5.8$ | $82.6 \pm 7.1$ | $31.7 \pm 7.2$ | - | 2.65 | 2.58 | 13.39 | $\bigcirc$ |
| 181 | Jo05850.0-290122 | 14.7082 | -29.0229 | -0.61 | -4.02 | $92.5 \pm 5.7$ | $116.6 \pm 6.0$ | $82.6 \pm 7.2$ | $32.9 \pm 8.8^{2}$ | - | 2.61 | 2.81 | 13.41 | c 0 0 |
| 182 | J230538.5-312204 | 346.4106 | -31.3678 | - | - | $89.0 \pm 5.7$ | $109.1 \pm 6.2$ | $82.3 \pm 7.9$ | - | - | 2.93 | 2.59 | 13.48 | \% |
| 183 | Jo90453.2+022017 | 136.222 | 2.3383 | -1.34 | -3.03 | $87.0 \pm 7.2$ | $98.2 \pm 8.0$ | $82.3 \pm 8.8$ | $44.5 \pm 8.8$ | - | 2.94 | 2.64 | 13.46 | $\omega$ |
| 184 | J234955.7-330833 | 357.4821 | -33.1425 | - | - | $91.9 \pm 5.9$ | $107.6 \pm 6.0$ | $82.3 \pm 7.1$ | - | - | 2.73 | 2.54 | 13.43 |  |
| 185 | J092408.8-005017 | 141.0368 | -0.8382 | -2.64 | 1.03 | $71.8 \pm 7.4$ | $87.7 \pm 8.2$ | $82.2 \pm 8.5$ | $61.6 \pm 9.4$ | - | 3.68 | 3.08 | 13.58 |  |
| 186 | Jo13217.0-320953 | 23.0708 | -32.1647 | -8.36 | 3.0 | $57.5 \pm 5.4$ | $79.2 \pm 5.9$ | $82.2 \pm 7.0$ | $51.3 \pm 10.4$ | - | 4.03 | 3.25 | 13.60 |  |
| 187 | Jo83705.2+020033 | 129.2719 | 2.0092 | 2.4 | 0.02 | $108.0 \pm 7.2$ | $97.0 \pm 8.1$ | $82.0 \pm 8.6$ | $31.3 \pm 7 \cdot 4$ | - | 2.19 | 2.24 | 13.29 |  |
| 188 | Jo84259.9+024959 | 130.7498 | 2.8331 | - | - | $84.2 \pm 7.4$ | $101.5 \pm 8.1$ | $81.8 \pm 8.6$ | - | - | 3.02 | 2.63 | 13.48 |  |
| 189 | J225600.7-313232 | 344.0029 | -31.5421 | -1.36 | 0.99 | $119.5 \pm 5.9$ | $132.1 \pm 6.2$ | $81.7 \pm 7.6$ | $74.2 \pm 10.2$ | - | 2.50 | 2.58 | 13.45 |  |
| 190 | J090405.3-003332 | 136.0222 | -0.5591 | -0.5 | 0.99 | $82.7 \pm 7 \cdot 3$ | $90.8 \pm 8.2$ | $81.6 \pm 8.7$ | $42.3 \pm 8.2$ | - | 3.00 | 2.69 | 13.45 |  |


| No. | H-ATLAS ID | $\begin{gathered} \text { RA } \\ {[\mathrm{deg}]} \\ \hline \end{gathered}$ | DEC <br> [deg] | $\Delta \mathrm{RA}$ <br> ["] | $\triangle \mathrm{DEC}$ ["] | $\begin{aligned} & \mathrm{S}_{250} \\ & {[\mathrm{mJy}]} \end{aligned}$ | $\begin{aligned} & \mathrm{S}_{350} \\ & {[\mathrm{mJy}]} \end{aligned}$ | $\begin{aligned} & \mathrm{S}_{500} \\ & {[\mathrm{mJy}]} \end{aligned}$ | $\begin{aligned} & \mathrm{S}_{850} \\ & {[\mathrm{mJy}]} \end{aligned}$ | $\mathrm{z}_{\text {spec }}$ | $\mathrm{Z}_{\text {phot,temp }}$ | $\mathrm{Z}_{\text {phot,Ivi }}$ | Lum. $\log \left(\mathrm{L}_{\odot}\right)$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 191 | J124753.3+322448 | 191.9722 | 32.4134 | -3.12 | 0.97 | $57.7 \pm 5.9$ | $81.5 \pm 5.8$ | $81.5 \pm 7.5$ | $37.8 \pm 9.2$ | - | 3.74 | 3.19 | 13.54 |
| 192 | J222628.8-304421 | 336.6202 | -30.739 | - | - | $101.3 \pm 7.7$ | $97.0 \pm 8.3$ | $81.5 \pm 9.9$ | - | - | 2.34 | 2.33 | 13.32 |
| 193 | Jo85352.0-000804 | 133.4669 | -0.1346 | -3.58 | -0.99 | $96.0 \pm 7.3$ | $95.0 \pm 8.1$ | $81.4 \pm 8.9$ | $52.9 \pm 9.5$ | - | 2.77 | 2.53 | 13.43 |
| 194 | Jo85521.1-003603 | 133.8382 | -0.6011 | 4.66 | -0.99 | $95.6 \pm 7.5$ | $98.8 \pm 8.1$ | $81.3 \pm 8.5$ | $45.8 \pm 8.1$ | - | 2.71 | 2.53 | 13.41 |
| 195 | J145754.2+000018 | 224.476 | 0.0051 | 3.61 | 4.02 | $70.3 \pm 7.3$ | $92.7 \pm 8.1$ | $81.0 \pm 8.8$ | $29.5 \pm 10.0^{2}$ | - | 3.14 | 2.85 | 13.45 |
| 196 | J134403.1+242628 | 206.0131 | 24.4411 | - | - | $86.9 \pm 5.7$ | $92.3 \pm 6.3$ | $81.0 \pm 7.1$ | - | - | 2.79 | 2.53 | 13.41 |
| 197 | J122034.2-003805 | 185.1429 | -0.635 | 11.49 | 13.92 | $81.9 \pm 7.5$ | $93.8 \pm 8.2$ | $84.8 \pm 8.7$ | $37.7 \pm 11.6$ | - | 2.96 | 2.65 | 13.44 |
| 198 | J222235.8-324528 | 335.6493 | -32.7577 | - | - | $71.3 \pm 8.3$ | $82.1 \pm 8.0$ | $80.7 \pm 10.7$ | - | - | 3.39 | 2.73 | 13.50 |
| 199 | J133352.2+334913 | 203.4674 | 33.8203 | 19.0 | -18.05 | $112.4 \pm 5.4$ | $108.8 \pm 5.9$ | $80.6 \pm 7.0$ | $18.4 \pm 9.7$ | - | 2.01 | 2.22 | 13.25 |
| 200 | Jo14313.2-332633 | 25.8052 | -33.4425 | -9.04 | 20.05 | $107.1 \pm 6.1$ | $109.7 \pm 6.0$ | $80.5 \pm 7.5$ | $21.5 \pm 11.0$ | - | 2.19 | 2.33 | 13.30 |
| 201 | J141117.8-010655 | 212.8246 | -1.1155 | 1.97 | 3.02 | $52.2 \pm 7.2$ | $78.6 \pm 8.2$ | $80.5 \pm 8.7$ | $39.4 \pm 9.4$ | - | 4.00 | $3 \cdot 31$ | 13.58 |
| 202 | J143328.4+020811 | 218.3684 | 2.1365 | -5.9 | 4.03 | $117.5 \pm 7.3$ | $100.7 \pm 8.3$ | $80.4 \pm 8.5$ | $35.7 \pm 8.4$ | - | 2.02 | 2.05 | 13.26 |
| 203 | J141827.4-001703 | 214.6145 | -0.2843 | 5.53 | -19.01 | $117.2 \pm 6.5$ | $116.4 \pm 7.4$ | $80.2 \pm 7.6$ | $22.0 \pm 10.6$ | - | 2.01 | 2.13 | 13.27 |
| 204 | J132909.5+300957 | 202.2896 | 30.1658 | - | - | $57.9 \pm 5.5$ | $95.3 \pm 6.1$ | $80.1 \pm 7.1$ | - | - | 4.18 | 3.01 | 13.67 |
| 205 | J145132.7+024101 | 222.8866 | 2.6837 | -6.1 | 1.98 | $84.5 \pm 7.2$ | $104.4 \pm 8.3$ | $80.2 \pm 8.9$ | $45.5 \pm 10.5$ | - | 3.01 | 2.67 | 13.48 |
| 206 | J140421.7-001217 | 211.0907 | -0.2048 | 0.43 | 1.96 | $79.3 \pm 7.4$ | $102.6 \pm 8.4$ | $80.2 \pm 8.8$ | $32.2 \pm 10.1$ | - | 2.94 | 2.72 | 13.44 |
| 207 | J005506.5-300027 | 13.777 | -30.0076 | -6.0 | -0.01 | $96.9 \pm 5.9$ | $121.7 \pm 6.1$ | $80.2 \pm 7.5$ | $41.8 \pm 9.7$ | - | 2.60 | 2.77 | 13.42 |

[^5]| No. | H-ATLAS ID | $\begin{gathered} \text { RA } \\ {[\mathrm{deg}]} \end{gathered}$ | $\begin{gathered} \text { DEC } \\ \text { [deg] } \end{gathered}$ | $\begin{gathered} \Delta \mathrm{RA} \\ {["]} \\ \hline \end{gathered}$ | $\begin{gathered} \Delta \mathrm{DEC} \\ {["]} \\ \hline \end{gathered}$ | $\begin{gathered} \mathrm{S}_{250} \\ {[\mathrm{mJy}]} \\ \hline \end{gathered}$ | $\begin{gathered} \mathrm{S}_{350} \\ {[\mathrm{mJy}]} \\ \hline \end{gathered}$ | $\begin{gathered} S_{500} \\ {[\mathrm{mJy}]} \\ \hline \end{gathered}$ | $\begin{gathered} \mathrm{S}_{850} \\ {[\mathrm{mJy}]} \\ \hline \end{gathered}$ | $\mathrm{z}_{\text {spec }}$ | $\mathrm{z}_{\text {phot,temp }}$ | $\mathrm{z}_{\text {phot,Ivi }}$ | $\begin{gathered} \text { Lum. } \\ \log \left(\mathrm{L}_{\odot}\right) \\ \hline \end{gathered}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 208 | J225744.6-324231 | 344.4358 | -32.7086 | - | - | $69.4 \pm 5.1$ | $91.9 \pm 5.5$ | $80.1 \pm 6.6$ | - | - | 3.60 | 2.85 | 13.56 |
| 209 | J224920.6-332940 | 342.3358 | -33.4944 | - | - | $85.6 \pm 6.0$ | $102.6 \pm 6.3$ | $80.1 \pm 7.5$ | - | - | 2.90 | 2.59 | 13.45 |

Table .2: Blazars - SPIRE and SCUBA-2 data. The blazar index hyperlinks to the NED database at the position of the source. These sources have been removed from the HerBS sample in Section 2.2. The RA and DEC are the SPIRE-positions, $\triangle$ RA and $\triangle$ DEC are the SPIRE positions minus the SCUBA-2 positions. The spectroscopic redshifts are discussed in Section 2.5 . The $\alpha$ value defines the steepness of the slope of the synchrotron radiation, and is calculated in Section 2.2.

| 1 | J131028.7+322044 | 197.6197 | 32.3455 | -2.06 | 2.05 | $259.1 \pm 4.4$ | $363.1 \pm 5.1$ | $452.2 \pm 6.1$ | $820.0 \pm 6.0$ | 1.0 | $0.93 \pm 0.01$ |
| ---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 2 | Jo90910.2+012135 | 137.2924 | 1.3597 | -0.52 | -0.03 | $256.5 \pm 3.8$ | $327.0 \pm 4.5$ | $375.3 \pm 6.0$ | $390.7 \pm 7.7$ | 1.02 | $0.32 \pm 0.01$ |
| 3 | J014503.4-273333 | 26.264 | -27.5591 | -0.67 | 0.98 | $131.5 \pm 5.7$ | $179.1 \pm 6.3$ | $233.5 \pm 7.2$ | $365.8 \pm 6.7$ | 1.16 | $0.83 \pm 0.02$ |
| 4 | J125757.3+322930 | 194.4888 | 32.4918 | -2.12 | 3.03 | $143.7 \pm 5.1$ | $188.4 \pm 5.7$ | $214.9 \pm 6.7$ | $290.0 \pm 7.6$ | 0.81 | $0.54 \pm 0.02$ |
| 5 | J224838.6-323551 | 342.1608 | -32.5974 | -1.18 | 2.99 | $119.2 \pm 5.5$ | $152.8 \pm 5.8$ | $194.8 \pm 6.7$ | $173.5 \pm 7.2$ | 2.27 | $0.24 \pm 0.03$ |
| 6 | J121758.7-002946 | 184.4947 | -0.4961 | -2.62 | 1.01 | $115.7 \pm 5.3$ | $151.5 \pm 5.7$ | $179.2 \pm 6.6$ | $206.7 \pm 7.2$ | 0.42 | $0.44 \pm 0.03$ |
| 7 | J014310.0-320056 | 25.7917 | -32.0157 | -2.38 | 4.0 | $96.0 \pm 5.3$ | $119.5 \pm 5.9$ | $122.4 \pm 7.2$ | $405.6 \pm 8.5$ | 0.38 | $1.02 \pm 0.04$ |
| 8 | J133307.4+272518 | 203.2808 | 27.4217 | -5.76 | 1.01 | $89.3 \pm 5.3$ | $104.6 \pm 5.5$ | $117.1 \pm 6.4$ | $128.5 \pm 10.4$ | 2.13 | $0.3 \pm 0.05$ |
| 9 | J131736.4+342518 | 199.4017 | 34.4217 | 0.21 | 6.06 | $77.1 \pm 5.1$ | $99.5 \pm 5.5$ | $112.0 \pm 6.8$ | $129.0 \pm 7.8$ | 1.06 | $0.39 \pm 0.05$ |
| 10 | J235347.4-303746 | 358.4476 | -30.6294 | -2.06 | 3.99 | $77.1 \pm 5.1$ | $96.6 \pm 5.8$ | $103.1 \pm 7.0$ | $143.9 \pm 8.1$ | 1.06 | $0.48 \pm 0.05$ |
| 11 | J132952.9+315410 | 202.4703 | 31.9027 | -2.92 | -1.0 | $50.5 \pm 5.2$ | $71.0 \pm 5.5$ | $86.4 \pm 7.3$ | $253.4 \pm 7.8$ | 0.34 | $1.27 \pm 0.06$ |
| 12 | J235935.3-313343 | 359.8972 | -31.5621 | -4.16 | 5.04 | $61.4 \pm 5.5$ | $67.7 \pm 5.8$ | $83.7 \pm 7.4$ | $117.3 \pm 8.6$ | 0.99 | $0.54 \pm 0.06$ |


| No. | H-ATLAS ID | $\begin{gathered} \text { RA } \\ {[\mathrm{deg}]} \end{gathered}$ | $\begin{gathered} \mathrm{DEC} \\ {[\mathrm{deg}]} \end{gathered}$ | $\begin{gathered} \Delta \mathrm{RA} \\ {["]} \end{gathered}$ | $\triangle \mathrm{DEC}$ <br> ["] | $\begin{gathered} \mathrm{S}_{250} \\ {[\mathrm{mJy}]} \end{gathered}$ | $\begin{aligned} & \mathrm{S}_{350} \\ & {[\mathrm{mJy}]} \end{aligned}$ | $\begin{aligned} & \mathrm{S}_{500} \\ & {[\mathrm{mJy}]} \end{aligned}$ | $\begin{gathered} \mathrm{S}_{850} \\ {[\mathrm{mJy}]} \end{gathered}$ | $\mathrm{z}_{\text {spec }}$ | $\alpha$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 13 | J115043.6-002355 | 177.6818 | -0.3985 | -1.4 | 5.98 | $34.5 \pm 5.3$ | $56.1 \pm 5.5$ | $83.2 \pm 6.7$ | $187.9 \pm 9.3$ | 1.98 | $1.37 \pm 0.07$ |
| 14 | J131059.2+323331 | 197.7467 | 32.5587 | $7 \cdot 4$ | 2.03 | $37.6 \pm 5 \cdot 3$ | $63.2 \pm 5.7$ | $81.7 \pm 6.5$ | $313.7 \pm 7.8$ | 1.64 | $1.67 \pm 0.07$ |



Figure .1: 4 by 4 arcsecond cutouts of the Herschel and SCUBA-2 observations of the HerBS sources. The left three cutouts show the SPIRE 250, 350 and $500 \mu \mathrm{~m}$ observations, and where available, I show the $850 \mu \mathrm{~m}$ SCUBA-2 observations in the fourth column. The fifth column shows the best-fit (orange) and fixed-beta (blue) templates discussed in Chapter 2, and the grey line is the best fit from Pearson et al. (2013).


Figure .2: 4 by 4 arcsecond cutouts of the Herschel and SCUBA-2 observations of the HerBS sources. The left three cutouts show the SPIRE 250, 350 and $500 \mu \mathrm{~m}$ observations, and where available, I show the $850 \mu \mathrm{~m}$ SCUBA- 2 observations in the fourth column. The fifth column shows the best-fit (orange) and fixed-beta (blue) templates discussed in Chapter 2, and the grey line is the best fit from Pearson et al. (2013).


Figure .3: 4 by 4 arcsecond cutouts of the Herschel and SCUBA-2 observations of the HerBS sources. The left three cutouts show the SPIRE 250, 350 and $500 \mu \mathrm{~m}$ observations, and where available, I show the $850 \mu \mathrm{~m}$ SCUBA- 2 observations in the fourth column. The fifth column shows the best-fit (orange) and fixed-beta (blue) templates discussed in Chapter 2, and the grey line is the best fit from Pearson et al. (2013).


Figure .4: 4 by 4 arcsecond cutouts of the Herschel and SCUBA-2 observations of the HerBS sources. The left three cutouts show the SPIRE 250, 350 and $500 \mu \mathrm{~m}$ observations, and where available, I show the $850 \mu \mathrm{~m}$ SCUBA- 2 observations in the fourth column. The fifth column shows the best-fit (orange) and fixed-beta (blue) templates discussed in Chapter 2, and the grey line is the best fit from Pearson et al. (2013).


Figure .5: 4 by 4 arcsecond cutouts of the Herschel and SCUBA-2 observations of the HerBS sources. The left three cutouts show the SPIRE 250, 350 and $500 \mu \mathrm{~m}$ observations, and where available, I show the $850 \mu \mathrm{~m}$ SCUBA- 2 observations in the fourth column. The fifth column shows the best-fit (orange) and fixed-beta (blue) templates discussed in Chapter 2, and the grey line is the best fit from Pearson et al. (2013).


Figure .6: 4 by 4 arcsecond cutouts of the Herschel and SCUBA-2 observations of the HerBS sources. The left three cutouts show the SPIRE 250, 350 and $500 \mu \mathrm{~m}$ observations, and where available, I show the $850 \mu \mathrm{~m}$ SCUBA- 2 observations in the fourth column. The fifth column shows the best-fit (orange) and fixed-beta (blue) templates discussed in Chapter 2, and the grey line is the best fit from Pearson et al. (2013).


Figure .7: 4 by 4 arcsecond cutouts of the Herschel and SCUBA-2 observations of the HerBS sources. The left three cutouts show the SPIRE 250, 350 and $500 \mu \mathrm{~m}$ observations, and where available, I show the $850 \mu \mathrm{~m}$ SCUBA- 2 observations in the fourth column. The fifth column shows the best-fit (orange) and fixed-beta (blue) templates discussed in Chapter 2, and the grey line is the best fit from Pearson et al. (2013).


Figure .8: 4 by 4 arcsecond cutouts of the Herschel and SCUBA-2 observations of the HerBS sources. The left three cutouts show the SPIRE 250, 350 and $500 \mu \mathrm{~m}$ observations, and where available, I show the $850 \mu \mathrm{~m}$ SCUBA- 2 observations in the fourth column. The fifth column shows the best-fit (orange) and fixed-beta (blue) templates discussed in Chapter 2, and the grey line is the best fit from Pearson et al. (2013).


Figure .9: 4 by 4 arcsecond cutouts of the Herschel and SCUBA-2 observations of the HerBS sources. The left three cutouts show the SPIRE 250, 350 and $500 \mu \mathrm{~m}$ observations, and where available, I show the $850 \mu \mathrm{~m}$ SCUBA- 2 observations in the fourth column. The fifth column shows the best-fit (orange) and fixed-beta (blue) templates discussed in Chapter 2, and the grey line is the best fit from Pearson et al. (2013).


Figure .10: 4 by 4 arcsecond cutouts of the Herschel and SCUBA-2 observations of the HerBS sources. The left three cutouts show the SPIRE 250,350 and $500 \mu \mathrm{~m}$ observations, and where available, I show the $850 \mu \mathrm{~m}$ SCUBA-2 observations in the fourth column. The fifth column shows the best-fit (orange) and fixed-beta (blue) templates discussed in Chapter 2, and the grey line is the best fit from Pearson et al. (2013).


Figure .11: 4 by 4 arcsecond cutouts of the Herschel and SCUBA-2 observations of the HerBS sources. The left three cutouts show the SPIRE 250, 350 and $500 \mu \mathrm{~m}$ observations, and where available, I show the $850 \mu \mathrm{~m}$ SCUBA-2 observations in the fourth column. The fifth column shows the best-fit (orange) and fixed-beta (blue) templates discussed in Chapter 2, and the grey line is the best fit from Pearson et al. (2013).


Figure .12: 4 by 4 arcsecond cutouts of the Herschel and SCUBA-2 observations of the HerBS sources. The left three cutouts show the SPIRE 250, 350 and $500 \mu \mathrm{~m}$ observations, and where available, I show the $850 \mu \mathrm{~m}$ SCUBA-2 observations in the fourth column. The fifth column shows the best-fit (orange) and fixed-beta (blue) templates discussed in Chapter 2, and the grey line is the best fit from Pearson et al. (2013).


Figure .13: 4 by 4 arcsecond cutouts of the Herschel and SCUBA-2 observations of the HerBS sources. The left three cutouts show the SPIRE 250, 350 and $500 \mu \mathrm{~m}$ observations, and where available, I show the $850 \mu \mathrm{~m}$ SCUBA-2 observations in the fourth column. The fifth column shows the best-fit (orange) and fixed-beta (blue) templates discussed in Chapter 2, and the grey line is the best fit from Pearson et al. (2013).


Figure .14: 4 by 4 arcsecond cutouts of the Herschel and SCUBA-2 observations of the HerBS sources. The left three cutouts show the SPIRE 250, 350 and $500 \mu \mathrm{~m}$ observations, and where available, I show the $850 \mu \mathrm{~m}$ SCUBA- 2 observations in the fourth column. The fifth column shows the best-fit (orange) and fixed-beta (blue) templates discussed in Chapter 2, and the grey line is the best fit from Pearson et al. (2013).


Figure .15: 4 by 4 arcsecond cutouts of the Herschel and SCUBA-2 observations of the HerBS sources. The left three cutouts show the SPIRE 250, 350 and $500 \mu \mathrm{~m}$ observations, and where available, I show the $850 \mu \mathrm{~m}$ SCUBA-2 observations in the fourth column. The fifth column shows the best-fit (orange) and fixed-beta (blue) templates discussed in Chapter 2, and the grey line is the best fit from Pearson et al. (2013).


Figure .16: 4 by 4 arcsecond cutouts of the Herschel and SCUBA-2 observations of the HerBS sources. The left three cutouts show the SPIRE 250,350 and $500 \mu \mathrm{~m}$ observations, and where available, I show the $850 \mu \mathrm{~m}$ SCUBA-2 observations in the fourth column. The fifth column shows the best-fit (orange) and fixed-beta (blue) templates discussed in Chapter 2, and the grey line is the best fit from Pearson et al. (2013).


Figure .17: 4 by 4 arcsecond cutouts of the Herschel and SCUBA-2 observations of the HerBS sources. The left three cutouts show the SPIRE 250, 350 and $500 \mu \mathrm{~m}$ observations, and where available, I show the $850 \mu \mathrm{~m}$ SCUBA-2 observations in the fourth column. The fifth column shows the best-fit (orange) and fixed-beta (blue) templates discussed in Chapter 2, and the grey line is the best fit from Pearson et al. (2013).


Figure .18: 4 by 4 arcsecond cutouts of the Herschel and SCUBA-2 observations of the HerBS sources. The left three cutouts show the SPIRE 250, 350 and $500 \mu \mathrm{~m}$ observations, and where available, I show the $850 \mu \mathrm{~m}$ SCUBA-2 observations in the fourth column. The fifth column shows the best-fit (orange) and fixed-beta (blue) templates discussed in Chapter 2, and the grey line is the best fit from Pearson et al. (2013).


Figure .19: 4 by 4 arcsecond cutouts of the Herschel and SCUBA-2 observations of the HerBS sources. The left three cutouts show the SPIRE 250, 350 and $500 \mu \mathrm{~m}$ observations, and where available, I show the $850 \mu \mathrm{~m}$ SCUBA-2 observations in the fourth column. The fifth column shows the best-fit (orange) and fixed-beta (blue) templates discussed in Chapter 2, and the grey line is the best fit from Pearson et al. (2013).


Figure .20: 4 by 4 arcsecond cutouts of the Herschel and SCUBA-2 observations of the HerBS sources. The left three cutouts show the SPIRE 250, 350 and $500 \mu \mathrm{~m}$ observations, and where available, I show the $850 \mu \mathrm{~m}$ SCUBA-2 observations in the fourth column. The fifth column shows the best-fit (orange) and fixed-beta (blue) templates discussed in Chapter 2, and the grey line is the best fit from Pearson et al. (2013).


Figure .21: 4 by 4 arcsecond cutouts of the Herschel and SCUBA-2 observations of the HerBS sources. The left three cutouts show the SPIRE 250, 350 and $500 \mu \mathrm{~m}$ observations, and where available, I show the $850 \mu \mathrm{~m}$ SCUBA-2 observations in the fourth column. The fifth column shows the best-fit (orange) and fixed-beta (blue) templates discussed in Chapter 2, and the grey line is the best fit from Pearson et al. (2013).


Figure .22: 4 by 4 arcsecond cutouts of the Herschel and SCUBA-2 observations of the HerBS sources. The left three cutouts show the SPIRE 250, 350 and $500 \mu \mathrm{~m}$ observations, and where available, I show the $850 \mu \mathrm{~m}$ SCUBA-2 observations in the fourth column. The fifth column shows the best-fit (orange) and fixed-beta (blue) templates discussed in Chapter 2, and the grey line is the best fit from Pearson et al. (2013).


Figure .23: 4 by 4 arcsecond cutouts of the Herschel and SCUBA-2 observations of the HerBS sources. The left three cutouts show the SPIRE 250, 350 and $500 \mu \mathrm{~m}$ observations, and where available, I show the $850 \mu \mathrm{~m}$ SCUBA-2 observations in the fourth column. The fifth column shows the best-fit (orange) and fixed-beta (blue) templates discussed in Chapter 2, and the grey line is the best fit from Pearson et al. (2013).


Figure .24: 4 by 4 arcsecond cutouts of the Herschel and SCUBA-2 observations of the HerBS sources. The left three cutouts show the SPIRE 250, 350 and $500 \mu \mathrm{~m}$ observations, and where available, I show the $850 \mu \mathrm{~m}$ SCUBA-2 observations in the fourth column. The fifth column shows the best-fit (orange) and fixed-beta (blue) templates discussed in Chapter 2, and the grey line is the best fit from Pearson et al. (2013).


Figure .25: 4 by 4 arcsecond cutouts of the Herschel and SCUBA-2 observations of the HerBS sources. The left three cutouts show the SPIRE 250, 350 and $500 \mu \mathrm{~m}$ observations, and where available, I show the $850 \mu \mathrm{~m}$ SCUBA-2 observations in the fourth column. The fifth column shows the best-fit (orange) and fixed-beta (blue) templates discussed in Chapter 2, and the grey line is the best fit from Pearson et al. (2013).


Figure .26: 4 by 4 arcsecond cutouts of the Herschel and SCUBA-2 observations of the HerBS sources. The left three cutouts show the SPIRE 250,350 and $500 \mu \mathrm{~m}$ observations, and where available, I show the $850 \mu \mathrm{~m}$ SCUBA-2 observations in the fourth column. The fifth column shows the best-fit (orange) and fixed-beta (blue) templates discussed in Chapter 2, and the grey line is the best fit from Pearson et al. (2013).


Figure .27: 4 by 4 arcsecond cutouts of the Herschel and SCUBA-2 observations of the HerBS sources. The left three cutouts show the SPIRE 250, 350 and $500 \mu \mathrm{~m}$ observations, and where available, I show the $850 \mu \mathrm{~m}$ SCUBA-2 observations in the fourth column. The fifth column shows the best-fit (orange) and fixed-beta (blue) templates discussed in Chapter 2, and the grey line is the best fit from Pearson et al. (2013).


Figure .28: 4 by 4 arcsecond cutouts of the Herschel and SCUBA-2 observations of the HerBS sources. The left three cutouts show the SPIRE 250, 350 and $500 \mu \mathrm{~m}$ observations, and where available, I show the $850 \mu \mathrm{~m}$ SCUBA- 2 observations in the fourth column. The fifth column shows the best-fit (orange) and fixed-beta (blue) templates discussed in Chapter 2, and the grey line is the best fit from Pearson et al. (2013).

## . 3 INDIVIDUAL IRAM 3OM SPECTRA

I show the collated spectra of all eight observed HerBS sources. The resolved spectral lines are indicated, and the ones with a known origin are named. The grey lines indicate the separate horizontal and vertical polarizations, while the blue line is the combined line profile. HerBS-52 and HerBS-64 both have their GBT observations included.

Frequency [GHz]

Figure .29: The complete spectra taken of source HerBS-38.


Figure .30: The complete spectra taken of source HerBS-52.


Figure .31: The complete spectra taken of source HerBS-61.


Figure .32: The complete spectra taken of source HerBS-64.


Figure .33: The complete spectra taken of source HerBS-83.


Figure .34: The complete spectra taken of source HerBS-89.


Figure .35: The complete spectra taken of source HerBS-150.


Figure .36: The complete spectra taken of source HerBS-177.

I show the statistics from the monte-carlo fit of all the spectral lines I observed with both the GBT and IRAM. I plot f , which indicates the frequency in GHz , peak, which indicates the peak frequency in $m J y$, FWHM, which is the velocity width of the spectral line in $\mathrm{km} / \mathrm{s}$, and $\mathrm{I}_{\mathrm{CO}}$ is the velocity-integrated flux, in Jy km/s. I divide the figures per source, starting at the line with the lowest frequency. The second figure I show for each line, is the fit to the spectral line, where I show all the realizations of the Monte-Carlo plot as thin black lines beneath the original spectrum (blue histogram). The orange line shows the bestfit result to the original data.


Figure .37: The statistics of the $\mathrm{CO}(4-3)$ line of HerBS- 38 .


Figure .38: The spectrum around the $\mathrm{CO}(4-3)$ line of HerBS-38. I also show the best-fit, plus the thousand fits from the montecarlo method.


Figure .39: The statistics of the $\mathrm{CO}(5-4)$ line of HerBS-38.


Figure .40: The spectrum around the $\mathrm{CO}(5-4)$ line of HerBS-38. I also show the best-fit, plus the thousand fits from the montecarlo method.


Figure .41: The statistics of the $\mathrm{CO}(1-0)$ line of HerBS-52.


Figure .42: The spectrum around the $\mathrm{CO}(1-0)$ line of HerBS-52. I also show the best-fit, plus the thousand fits from the montecarlo method.


Figure .43: The statistics of the $\mathrm{CO}(3-2)$ line of HerBS- 52 .


Figure .44: The spectrum around the $\mathrm{CO}(3-2)$ line of HerBS-52. I also show the best-fit, plus the thousand fits from the montecarlo method.


Figure .45: The statistics of the $\mathrm{CO}(4-3)$ line of HerBS- 52 .


Figure .46: The spectrum around the $\mathrm{CO}(4-3)$ line of HerBS-52. I also show the best-fit, plus the thousand fits from the montecarlo method.


Figure .47: The statistics of the $\mathrm{CO}(5-4)$ line of HerBS-52.


Figure .48: The spectrum around the $\mathrm{CO}(5-4)$ line of HerBS-52. I also show the best-fit, plus the thousand fits from the montecarlo method.


Figure .49: The statistics of the $\mathrm{CO}(6-5)$ line of HerBS- 52 .


Figure .50: The spectrum around the $\mathrm{CO}(6-5)$ line of HerBS-52. I also show the best-fit, plus the thousand fits from the montecarlo method.


Figure .51: The statistics of the $\mathrm{CO}(4-3)$ line of HerBS-61.


Figure .52: The spectrum around the $\mathrm{CO}(4-3)$ line of HerBS-61. I also show the best-fit, plus the thousand fits from the montecarlo method.


Figure .53: The statistics of the CI line of HerBS-61.


Figure .54: The spectrum around the CI line of HerBS-61. I also show the best-fit, plus the thousand fits from the monte-carlo method.


Figure .55: The statistics of the $\mathrm{CO}(6-5)$ line of HerBS-61.


Figure .56: The spectrum around the $\mathrm{CO}(6-5)$ line of HerBS-61. I also show the best-fit, plus the thousand fits from the montecarlo method.


Figure .57: The statistics of the $\mathrm{CO}(1-0)$ line of HerBS-64.


Figure .58: The spectrum around the $\mathrm{CO}(1-0)$ line of HerBS-64. I also show the best-fit, plus the thousand fits from the montecarlo method.


Figure .59: The statistics of the $\mathrm{CO}(2-1)$ line of HerBS-64.


Figure .60: The spectrum around the $\mathrm{CO}(2-1)$ line of HerBS-64. I also show the best-fit, plus the thousand fits from the montecarlo method.


Figure .61: The statistics of the $\mathrm{CO}(3-2)$ line of HerBS-64.


Figure .62: The spectrum around the $\mathrm{CO}(3-2)$ line of HerBS-64. I also show the best-fit, plus the thousand fits from the montecarlo method.


Figure .63: The statistics of the $\mathrm{CO}(4-3)$ line of HerBS-64.


Figure .64: The spectrum around the $\mathrm{CO}(4-3)$ line of HerBS-64. I also show the best-fit, plus the thousand fits from the montecarlo method.


Figure .65: The statistics of the $\mathrm{CO}(6-5)$ line of HerBS-64.


Figure .66: The spectrum around the $\mathrm{CO}(6-5)$ line of HerBS-64. I also show the best-fit, plus the thousand fits from the montecarlo method.


Figure .67: The statistics of the $\mathrm{H}_{2} \mathrm{O}$ line of HerBS-64.


Figure .68: The spectrum around the $\mathrm{H}_{2} \mathrm{O}$ line of HerBS-64. I also show the best-fit, plus the thousand fits from the montecarlo method.


Figure .69: The statistics of the $\mathrm{CO}(7-6)$ line of HerBS-64.


Figure .70: The spectrum around the $\mathrm{CO}(7-6)$ line of HerBS-64. I also show the best-fit, plus the thousand fits from the montecarlo method.


Figure .71: The statistics of the CI line of HerBS-64.


Figure .72: The spectrum around the CI line of HerBS-64. I also show the best-fit, plus the thousand fits from the monte-carlo method.


Figure .73: The statistics of the first line of HerBS-83.


Figure .74: The spectrum around the first line of HerBS-83. I also show the best-fit, plus the thousand fits from the montecarlo method.


Figure .75: The statistics of the second line of HerBS-83.


Figure .76: The spectrum around the second line of HerBS-83. I also show the best-fit, plus the thousand fits from the montecarlo method.


Figure .77: The statistics of the third line of HerBS-83.


Figure .78: The spectrum around the third line of HerBS-83. I also show the best-fit, plus the thousand fits from the montecarlo method.


Figure .79: The statistics of the first line of HerBS-89.


Figure .80: The spectrum around the first line of HerBS-89. I also show the best-fit, plus the thousand fits from the montecarlo method.


Figure .81: The statistics of the first line of HerBS-150.


Figure .82: The spectrum around the first line of HerBS-150. I also show the best-fit, plus the thousand fits from the montecarlo method.


Figure .83: The statistics of the second line of HerBS-150.


Figure .84: The spectrum around the second line of HerBS-150. I also show the best-fit, plus the thousand fits from the montecarlo method.


Figure .85 : The statistics of the $\mathrm{CO}(4-3)$ line of HerBS-177.


Figure .86: The spectrum around the $\mathrm{CO}(4-3)$ line of HerBS-177. I also show the best-fit, plus the thousand fits from the monte-carlo method.


Figure .87: The statistics of the CI line of HerBS-177.


Figure .88: The spectrum around the CI line of HerBS-177. I also show the best-fit, plus the thousand fits from the montecarlo method.


Figure .89: The statistics of the $\mathrm{CO}(6-5)$ line of HerBS-177.


Figure .90: The spectrum around the $\mathrm{CO}(6-5)$ line of HerBS-177. I also show the best-fit, plus the thousand fits from the monte-carlo method.

Table .3: SDSS counterpart parameters of the HerBS sources

| HerBS- | R | $\mathrm{R}_{\text {new }}$ | $\mathrm{r}_{\text {meas }}$ | $\mathrm{r}_{\text {lim }}$ | $\mathrm{r}_{\text {lim,new }}$ | $\mathrm{L}_{\text {meas }}$ | S | $\sigma$ | $1 / \mathrm{p}$ |
| ---: | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| 1 | 0.986 | 0.985 | 0.432 | 2.449 | 2.783 | 33.66 | 0.044 | 1.0 | 1.05 |
| 2 | 0.99 | 0.989 | 0.416 | 2.563 | 2.948 | 43.464 | 0.026 | 1.0 | 1.042 |
| 3 | 0.922 | 0.946 | 2.164 | 2.619 | 3.037 | 5.484 | 0.045 | 1.0 | 1.038 |
| 4 | 0.957 | 0.965 | 1.813 | 2.597 | 2.997 | 9.94 | 0.024 | 1.0 | 1.039 |
| 5 | 0.997 | 0.997 | 1.183 | 3.17 | 4.339 | 138.855 | 0.043 | 1.0 | 1.019 |
| 8 | 0.777 | 0.81 | 1.648 | 1.563 | 1.66 | 1.54 | 0.024 | 1.0 | 1.219 |
| 12 | 0.986 | 0.987 | 1.376 | 2.77 | 3.288 | 33.139 | 0.043 | 1.0 | 1.032 |
| 13 | 0.986 | 0.985 | 0.737 | 2.512 | 2.87 | 31.455 | 0.023 | 1.0 | 1.046 |
| 15 | 0.98 | 0.98 | 1.119 | 2.511 | 2.869 | 22.057 | 0.024 | 1.0 | 1.046 |
| 16 | 0.999 | 0.999 | 0.862 | 3.463 | 5.947 | 517.512 | 0.049 | 1.0 | 1.014 |
| 19 | 0.996 | 0.996 | 1.859 | 3.395 | 5.477 | 99.657 | 0.023 | 1.0 | 1.015 |
| 20 | 0.749 | 0.839 | 2.421 | 2.297 | 2.577 | 1.381 | 0.045 | 1.0 | 1.062 |
| 29 | 0.965 | 0.973 | 1.952 | 2.768 | 3.286 | 12.71 | 0.045 | 1.0 | 1.032 |
| 30 | 0.464 | 0.5 | 1.648 | 0.586 | 0.295 | 0.4 | 0.045 | 1.0 | 2.522 |
| 31 | 0.925 | 0.925 | 1.197 | 1.92 | 2.093 | 5.708 | 0.045 | 1.0 | 1.117 |
| 35 | 0.477 | 0.771 | 3.132 | 2.619 | 3.037 | 0.422 | 0.045 | 1.0 | 1.038 |
| 48 | 0.972 | 0.974 | 1.513 | 2.565 | 2.952 | 15.096 | 0.024 | 1.0 | 1.042 |
| 52 | 0.97 | 0.973 | 1.621 | 2.743 | 3.24 | 15.001 | 0.045 | 1.081 | 1.032 |
| 53 | 0.996 | 0.996 | 0.448 | 2.945 | 3.637 | 122.482 | 0.026 | 1.0 | 1.025 |
| 59 | 0.987 | 0.991 | 2.164 | 3.254 | 4.686 | 33.635 | 0.023 | 1.0 | 1.018 |


| HerBS- | R | $\mathrm{R}_{\text {new }}$ | $\mathrm{r}_{\text {meas }}$ | $\mathrm{r}_{\lim }$ | $\mathrm{r}_{\text {lim,new }}$ | $\mathrm{L}_{\text {meas }}$ | S | $\sigma$ | $1 / \mathrm{p}$ |
| ---: | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| 70 | 0.098 | 0.579 | 3.751 | 2.619 | 3.036 | 0.05 | 0.045 | 1.0 | 1.038 |
| 82 | 0.915 | 0.904 | 0.163 | 1.42 | 1.484 | 10.596 | 0.563 | 1.0 | 1.28 |
| 88 | 0.987 | 0.989 | 1.8 | 3.026 | 3.851 | 33.967 | 0.023 | 1.0 | 1.023 |
| 89 | 0.02 | 0.139 | 3.551 | 1.428 | 1.495 | 0.009 | 0.046 | 1.0 | 1.28 |
| 91 | 0.004 | 0.53 | 4.701 | 2.842 | 3.417 | 0.002 | 0.026 | 1.0 | 1.028 |
| 96 | 0.959 | 0.958 | 1.041 | 2.151 | 2.386 | 27.464 | 0.751 | 1.0 | 1.081 |
| 105 | 0.254 | 0.873 | 3.916 | 3.226 | 4.619 | 0.15 | 0.024 | 1.0 | 1.018 |
| 108 | 0.148 | 0.618 | 3.617 | 2.609 | 3.027 | 0.077 | 0.024 | 1.0 | 1.039 |
| 110 | 0.892 | 0.962 | 3.006 | 3.236 | 4.631 | 3.624 | 0.024 | 1.0 | 1.018 |
| 112 | 0.997 | 0.998 | 2.196 | 3.687 | 7.006 | 150.902 | 0.052 | 1.0 | 1.012 |
| 116 | 0.107 | 0.971 | 4.676 | 3.853 | 7.633 | 0.053 | 0.024 | 1.0 | 1.01 |
| 128 | 0.996 | 0.997 | 1.519 | 3.292 | 4.877 | 132.014 | 0.047 | 1.0 | 1.017 |
| 129 | 0.182 | 0.812 | 4.174 | 3.287 | 4.816 | 0.103 | 0.045 | 1.07 | 1.017 |
| 133 | 0.227 | 0.808 | 3.8 | 3.036 | 3.88 | 0.136 | 0.045 | 1.0 | 1.023 |
| 137 | 0.927 | 0.965 | 2.687 | 3.087 | 4.014 | 5.601 | 0.024 | 1.0 | 1.021 |
| 149 | 0.678 | 0.803 | 2.562 | 2.297 | 2.577 | 0.97 | 0.045 | 1.0 | 1.062 |
| 152 | 0.83 | 0.92 | 3.413 | 3.5 | 6.114 | 2.251 | 0.045 | 1.232 | 1.014 |
| 153 | 0.935 | 0.945 | 1.73 | 2.354 | 2.65 | 15.924 | 0.697 | 1.0 | 1.059 |
| 165 | 0.867 | 0.864 | 1.078 | 1.462 | 1.537 | 2.875 | 0.024 | 1.0 | 1.261 |
| 167 | 0.094 | 0.714 | 4.534 | 3.329 | 5.112 | 0.048 | 0.045 | 1.139 | 1.016 |
| 171 | 0.049 | 0.418 | 3.79 | 2.381 | 2.692 | 0.023 | 0.024 | 1.0 | 1.055 |
| 173 | 0.59 | 0.86 | 3.227 | 2.893 | 3.53 | 0.663 | 0.045 | 1.0 | 1.027 |


| HerBS- | R | $\mathrm{R}_{\text {new }}$ | $\mathrm{r}_{\text {meas }}$ | $\mathrm{r}_{\text {lim }}$ | $\mathrm{r}_{\text {lim,new }}$ | $\mathrm{L}_{\text {meas }}$ | S | $\sigma$ | $1 / \mathrm{p}$ |
| ---: | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| 176 | 0.988 | 0.988 | 1.232 | 2.757 | 3.268 | 38.668 | 0.045 | 1.0 | 1.032 |
| 177 | 0.978 | 0.975 | 0.582 | 2.522 | 2.883 | 19.441 | 0.024 | 1.12 | 1.044 |
| 183 | 0.903 | 0.94 | 2.378 | 2.71 | 3.17 | 4.109 | 0.024 | 1.0 | 1.034 |
| 185 | 0.982 | 0.987 | 2.03 | 3.065 | 3.967 | 24.615 | 0.024 | 1.0 | 1.022 |
| 188 | 0.003 | 0.125 | 4.234 | 1.803 | 1.956 | 0.001 | 0.005 | 1.0 | 1.144 |
| 195 | 0.002 | 0.924 | 5.336 | 3.681 | 7.008 | 0.001 | 0.017 | 1.0 | 1.012 |
| 202 | 0.507 | 0.652 | 2.484 | 1.858 | 2.018 | 0.453 | 0.024 | 1.0 | 1.13 |
| 203 | 0.997 | 0.998 | 1.834 | 3.503 | 6.123 | 150.198 | 0.02 | 1.0 | 1.014 |
| 204 | 0.769 | 0.886 | 2.837 | 2.768 | 3.286 | 1.539 | 0.045 | 1.026 | 1.032 |

Write your code as if the person who will maintain it is a psychopath who knows where you live.
.6.1 The SExtractor configuration file
This is the code that was executed using SExtractor 2.19.5


CATALOG_TYPE ASCII_HEAD

PARAMETERS_NAME K_params.txt \# name of the file containing catalog contents CATALOG_NAME H_dual_extracted.txt

| DETECT_TYPE CCD | \# CCD (linear) or PHOTO (with gamma correction) |
| :---: | :---: |
| DETECT_MINAREA 4 | \# minimum number of pixels above threshold |

THRESH_TYPE RELATIVE
FILTER Y \# apply filter for detection (Y or $N$ )?
FILTER_NAME gauss_2.0_5x5.conv \# name of the file containing the filter
DEBLEND_NTHRESH 32 \# Number of deblending sub-thresholds
DEBLEND_MINCONT 0.0001 \# Minimum contrast parameter for deblending

CLEAN Y \# Clean spurious detections? (Y or N)?
CLEAN_PARAM 1.0 \# Cleaning efficiency
MASK_TYPE CORRECT \# type of detection MASKing: can be one of
\# NONE, BLANK or CORRECT

\#PHOT FLUXFRAC 0 25 $0.5,0.85,0,95,99$ \# flux fraction[s] used for FLUX RADIUS PHOT_AUTOPARAMS 2.0,4.0 \# MAG_AUT0 parameters: <Kron_fact>,<min_radius>
PHOT_PETROPARAMS 2.0,3.5 \# MAG_PETRO parameters: <Petrosian_fact>, \# <min_radius>
SATUR_LEVEL 200000
\#MAG_GAMMA 4.0
GAIN 0.3905
\# detector gain in e-/ADU
\# size of pixel in arcsec (0=use FITS WCS info)
\# stellar FWHM in arcsec
\# Neural-Network_Weight table filename
\# Background mesh: <size> or <width>,<height>
\# Background filter: <size> or <width>, <height>
\# Either GLOBAL or LOCAL
\# Thickness of the background LOCAL annulus

```
#-------------------------------Check Image
```

$\qquad$

```
\# Commented out for the non-testing execution:
\#CHECKIMAGE_TYPE BACKGROUND,BACKGROUND_RMS,-BACKGROUND,FILTERED,OBJECTS,-OBJECTS,APERTURES,SEGMENTATION \#CHECKIMAGE_NAME background.fits,background_rms.fits,minbackground.fits,filtered.fits,objects.fits, \#minusobjects.fits,apertures.fits,segmentation.fits
```



```
\begin{tabular}{ll} 
MEMORY_OBJSTACK 30000 & \# number of objects in stack \\
MEMORY_PIXSTACK 3000000 & \# number of pixels in stack \\
MEMORY_BUFSIZE 4096 & \# number of lines in buffer
\end{tabular}
```

$\qquad$

```
\begin{tabular}{ll} 
VERBOSE_TYPE NORMAL & \# can be QUIET, NORMAL or FULL \\
WRITE_XML N & \# Write XML file \((Y / N) ?\)
\end{tabular}
XML_NAME sex.xml \# Filename for XML output
```

$\qquad$

```\#INTERP_MAXXLAG 60000
#INTERP_MAXYLAG 60000
INTERP_TYPE ALL
```

$\qquad$

WEIGHT_GAIN
\#WEIGHT_GAIN
WEIGHT_IMAGE

WEIGHT_TYPE
\#WEIGHT_TYPE

## N, N

N
/home/vikdata/spxev/VIKING/swarped_mosaics/swpcw_viking_K_g09.fits, /home/vikdata/spxev/VIKING/swarped_mosaics/swpcw_viking_H_ge9.fits MAP_WEIGHT, MAP_WEIGHT
MAP_WEIGHT

ASSOCIATION $\qquad$
\#ASSOC_NAME \#ASSOC_RADIUS
\#ASSOC_TYPE
\#ASSOC_PARAMS \#ASSOCSELEC_TYPE
execution1_tinyfits.txt
2.0

NEAREST

ALL

The SExtractor catalogue file
The following code is the parameter file that is supplied to the sextractor program, and it tells sextractor what the output catalogue file should contain.

| NUMBER | Running object number |  |
| :--- | :--- | :--- |
| FLAGS | Extraction flags |  |
| XWIN_IMAGE | Windowed position estimate along x | [pixel] |
| YWIN_IMAGE | Windowed position estimate along y | [pixel] |
| ALPHAWIN_J2000 | Windowed right ascension (J2000) | [deg] |
| DELTAWIN_J2000 | windowed declination (J2000) | [deg] |
| MAG_AUTO | Kron-like elliptical aperture magnitude | [mag] |
| MAGERR_AUTO | RMS error for AUTO magnitude | $[\mathrm{mag}]$ |
| MAG_APER | Fixed aperture magnitude vector | [mag] |
| MAGERR_APER | RMS error vector for fixed aperture mag. | [mag] |
| ISOAREAF_IMAGE | Isophotal area (filtered) above Detection threshold [pixel**2] |  |
| VECTOR_ASSOC | ASSOCiated parameter vector |  |
| NUMBER_ASSOC | Number of ASSOCiated IDs |  |

## . 7 VIKING CUTOUTS

The four other test-files that were extracted from the VIKING fields, examined using the SExtractor code.


Figure .91: Second VIKING testfile of 1000 by 1000 arcseconds.


Figure .92: Third VIKING testfile of 1000 by 1000 arcseconds.


Figure .93: Fourth VIKING testfile of 1000 by 1000 arcseconds.


Figure .94: Fifth VIKING testfile of 1000 by 1000 arcseconds.

## . 8 VIKING POSTSTAMPS

The eight other combined images that were extracted from the VIKING fields.


Figure .95: Composite image of VIKING observations, in white contours the $250 \mu \mathrm{~m}$ overlay of the HerBS source.


Figure .96: Composite image of VIKING observations, in white contours the $250 \mu \mathrm{~m}$ overlay of the HerBS source.


Figure .97: Composite image of VIKING observations, in white contours the $250 \mu \mathrm{~m}$ overlay of the HerBS source.


Figure .98: Composite image of VIKING observations, in white contours the $250 \mu \mathrm{~m}$ overlay of the HerBS source.


Figure .99: Composite image of VIKING observations, in white contours the $250 \mu \mathrm{~m}$ overlay of the HerBS source.


Figure .100: Composite image of VIKING observations, in white contours the $250 \mu \mathrm{~m}$ overlay of the HerBS source.


Figure .101: Composite image of VIKING observations, in white contours the $250 \mu \mathrm{~m}$ overlay of the HerBS source.


Figure .102: Composite image of VIKING observations, in white contours the $250 \mu \mathrm{~m}$ overlay of the HerBS source.
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