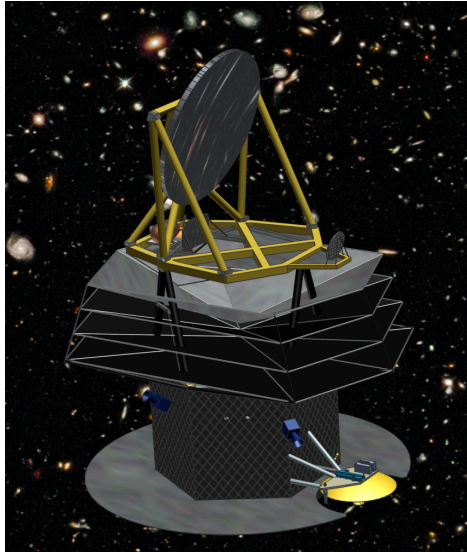


# The Galaxy Evolution Probe



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Thematic Activity:  
Medium-Scale, Space-Based Activity

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## 1 EXECUTIVE SUMMARY

The Galaxy Evolution Probe (GEP) is a NASA Astrophysics Probe concept designed to answer key questions about star formation and supermassive black hole growth in galaxies over cosmic time. GEP’s design includes a 2.0 m, 4 Kelvin primary mirror with sensitivity limited only by zodiacal and Galactic dust emission. It will have two instrument modules (Table 1). GEP-I is a large field-of-view imager with eighteen simultaneous  $R = 8$  spectral bands (10 – 95  $\mu\text{m}$ ) and five  $R = 3.5$  bands (95 – 400  $\mu\text{m}$ ), with an angular resolution of 3.4 arcsec at the shortest wavelengths. GEP-S is a four-grating,  $R = 200$ , long-slit spectrometer (24 – 193  $\mu\text{m}$ ).

Large, sensitive mid- and far-infrared (IR) surveys are necessary to measure the statistical star formation and super-massive black hole (SMBH) accretion properties of galaxies from the early universe to the present epoch. GEP will be dedicated to large surveys, ranging from an ultra-deep 3 square degrees to an all-sky survey with GEP-I, and 1.5 and 100 square degree spectral maps and pointed observations of galaxies with GEP-S. By using polycyclic aromatic hydrocarbon (PAH) emission features, GEP-I’s 23 bands enable photometric redshifts to a precision of  $\sigma_z \sim 0.03 - 0.1$  and its mid/far-IR spectral energy distributions (SEDs) enable separately deriving star formation rates (SFRs) and SMBH accretion rates. GEP-S’s  $R = 200$  spectral resolution provides accurate flux and redshift measurements of faint emission lines, and enables sensitive surveys of star formation, black hole growth, and the metal content in the hearts of galaxies over a wide range in cosmic time.

GEP will fill a critical parameter space by obtaining mid- and far-IR spectra of millions of galaxies from  $z = 0$  to high redshifts, reaching  $L^*$  at  $z = 2$ . GEP’s surveys will supersede *Spitzer* and *Herschel* by measuring galaxies’ redshifts and will be complementary to deep, high-resolution observations by JWST

**Table 1.** Basic GEP parameters.

GEP Mission Parameters	
Launch Date	January 2029
Orbit	Sun-Earth L2
Observing Mode	Dedicated Surveys
Duration	4 Years
GEP Payload	
Telescope	2.0 m, 4 K, unobscured, SiC
Detectors	Kinetic Inductance Detectors
GEP Imager (GEP-I)	
Wavebands	23 bands covering 10-400 $\mu\text{m}$
$R (N \Delta\lambda)$	8 (10-95 $\mu\text{m}$ ), 3.5 (95-400 $\mu\text{m}$ )
Surveys and Target Depths	All sky, $\sim 1$ mJy
	300 square degrees, $\sim 50$ $\mu\text{Jy}$
	30 square degrees, $\sim 20$ $\mu\text{Jy}$
	3 square degrees, $\sim 5$ $\mu\text{Jy}$
GEP Spectrometer (GEP-S)	
Bands	24-42, 40-70, 66-116, 110-193 $\mu\text{m}$
$R (N\Delta\lambda)$	200
Surveys	Selected galaxies, 1.5 and 100 square degrees

in the near- and mid-IR. GEP’s surveys will similarly complement ALMA and eROSITA, expand upon WFIRST and Euclid’s near-IR datasets, and complement SPHEREx’s near-IR all-sky survey.

GEP’s concept design study closed in the range \$910M - \$951M, and a detailed technology maturation plan for detectors and readout has been developed. Assuming a start in late 2023, GEP would launch in early 2029 on a Falcon 9 rocket. Hence, GEP is poised to make a significant impact to galaxy formation and evolution science should a Probe line be recommended.

## 2 SCIENCE BACKGROUND

Astronomers are within reach of creating a self-consistent model for galaxy evolution that starts from cosmology and incorporates star-formation, SMBH growth, and stellar dynamics and evolution. But critical questions remain: What was the role of feedback from black holes and stars themselves in regulating star-formation? How do a galaxy’s external environment and internal contents influence its evolutionary trajectory? Where and when were metals forged in galaxies?

Answering these questions requires measurements in the mid- and far-IR because star formation occurs deeply embedded in molecular clouds. Large-scale mid- and far-IR surveys that identify star-forming galaxies and correlate their SFRs with other physical properties are needed. Sensitivity is required that will be sufficient to detect  $L^*$  galaxies at  $z = 2$  ( $\sim 10^{12} L_{\odot}$ ), prior to when most cosmic stellar mass had been assembled. Determining the relative importance of star-formation and AGN in large samples of galaxies in a range of cosmological environments will be required to understand how stellar and SMBH growth were linked over cosmic time. Crucially, the galaxies must have measured redshifts for accurate luminosities and so that counterparts can be identified for panchromatic studies. Additionally, spectral mapping is required for unbiased ‘blind’ spatial-spectral surveys and line mapping of nearby galaxies to measure gas column densities, ionization parameters, and metallicities with tracers unaffected by dust obscuration. These IR observations must be made from space because the Earth’s atmosphere is opaque to mid- and far-IR radiation.

### 3 KEY SCIENCE GOALS AND OBJECTIVES

**Goal #1:** Map the history of galaxy growth by star formation and accretion by supermassive black holes and characterize the relation between those processes.

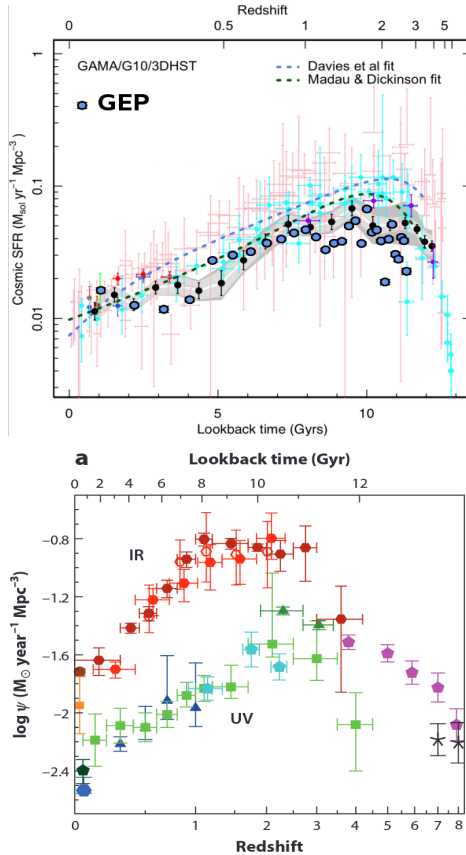
**Objective 1a:** Measure the coevolution of and discriminate between star formation and SMBH growth in galaxies. Star formation began in the first billion years of the Universe, rose to a peak rate in the range  $1 < z < 3$ , then declined (Fig. 1). Substantial uncertainties in the cosmic SFR history persist: SFRs derived from IR galaxy surveys of limited size did not probe low luminosities and are limited by sample variance, redshifts are unknown for large samples of far-IR continuum-detected galaxies, and extinction is uncertain in rest-frame UV observations. To meet the objective,

GEP-I dust continuum SEDs measurements will yield star formation and SMBH accretion rates (sections 4.2, 4.3) and IR luminosity functions within millions of galaxies. GEP-I photometry of the mid-IR PAH features will yield redshifts for the galaxies. PAHs have been detected spectroscopically with *Spitzer* at high redshifts,  $z = 1.09$  and  $2.96^1$  and  $z = 4.055^2$  in galaxies with and without prominent AGN, showing that these features are ubiquitous and strong, even at high redshifts.

GEP will identify obscured AGN in galaxies and relate their accretion luminosities to their SFRs on a source-by-source basis, essential for measuring co-evolution. GEP will quantify luminosities of dust-obscured AGN via mid-IR spectral signatures, including SEDs with GEP-I and high-ionization fine-structure atomic transitions with GEP-S. While X-ray observations also directly measure AGN power, IR estimates are critical for measuring SFRs and Compton-thick AGN luminosities, which can be missed in all but the deepest hard X-ray surveys.

GEP will access the earliest epochs of galaxy growth with gravitational lensing. Our current knowledge<sup>3</sup> of dust-obscured star formation from  $z \approx 2$  to 8 leaves considerable uncertainty about how much SFR density may be missed in the UV census (Fig. 1). Based on the number of galaxies detected by the SPT,<sup>4</sup> GEP is expected to detect  $10^4$  gravitationally lensed galaxies with mean redshift of  $z = 2$  and tail extending to  $z = 7$ . These galaxies will be prime targets for detailed follow-up with 30 m class telescopes and with ALMA.

**Objective 1b:** Determine whether feedback from buried accreting black holes could have caused the decline of luminosity density from star-formation in the last half of the Universe’s history. The masses of SMBHs in the centers of modern-day galaxies are correlated with galaxies’ bulge masses.<sup>6,7</sup> Theoretical models<sup>8-13</sup> invoke AGN feedback as a primary mechanism to explain the observed distribution of galaxy stellar masses today. Yet, the



**Figure 1.** GEP will provide a significant leap in our understanding of the evolution of the cosmic history of star formation by measuring the SFR density precisely across a wide range of redshifts. *Top:* A recent compilation by Driver et al.<sup>5</sup> shows the substantial uncertainties that persist with existing datasets. The principal source of uncertainty is the limitation of the far-IR data, which GEP will address. Blue circles – with (small, barely visible) error bars – from simulations (for  $0 < z < 3$ ) show expectations for GEP-I surveys, showing that GEP will measure the star formation history with unprecedented precision. *Bottom:* The SFR density of the Universe<sup>3</sup> showing that to at least a lookback time of 11 Gyr, most of the emission from stars in galaxies emerges in the far-IR (extinction corrections have not been applied to the UV observations).

efficiency of AGN feedback for regulating star formation remains controversial.<sup>14,15</sup> GEP will test a key hypothesis of evolutionary models by identifying galactic outflows from high-velocity spectral line wings with GEP-S, such

as in Peeters et al.,<sup>16</sup> to assess energy injection into the ISM.

**Objective 1c:** Obtain a spatially resolved view of feedback and the galactic baryon cycle with a detailed spectroscopic study of galactic outflows and fountains in local galaxies. This will be done for nearby galaxies with long-slit spectral mapping of atomic fine-structure emission lines, including: [C II], [N II], and [O III].

**Objective 1d:** Determine whether interstellar gas conditions at star-formation sites in galaxies changed as star formation declined. Measurement of atomic fine-structure lines will be used to infer the masses of interstellar gas components, UV radiation field hardnesses and their implications for stellar IMFs, and the densities in H II regions from which gas pressures can be inferred. Aggregate spectra created by stacking on near-IR positional priors will yield high signal-to-noise ratio (SNR) studies of star-formation sites in hundreds of thousands of galaxies. Star-formation environments will be probed with a suite of atomic fine structure lines from species with various ionization parameters, including, e.g., [C II], [N II], [O I], [O III], and [N II].

**Goal #2:** Measure the growth of metals over cosmic time.

**Objective 2:** Measure metal content and observe the buildup of metals in galaxies over the peak epoch of star-formation. Metallicity represents the integrated effects of star-formation, and inflow and outflow of matter from galaxies. Metallicities of galaxies have not been measured beyond the local universe with unbiased, extinction-free probes. GEP will measure the absolute metallicities in galaxies in the last  $\frac{2}{3}$  of Universe's history, reaching down to typical ( $L_* = 10^{12} L_\odot$ ) galaxies at  $z = 2$ , using the N/O ratio. Relative metallicities will be measured using the N/S ratio.

## 4 METHODS AND OUTCOMES

### 4.1 GEP-I and GEP-S Surveys

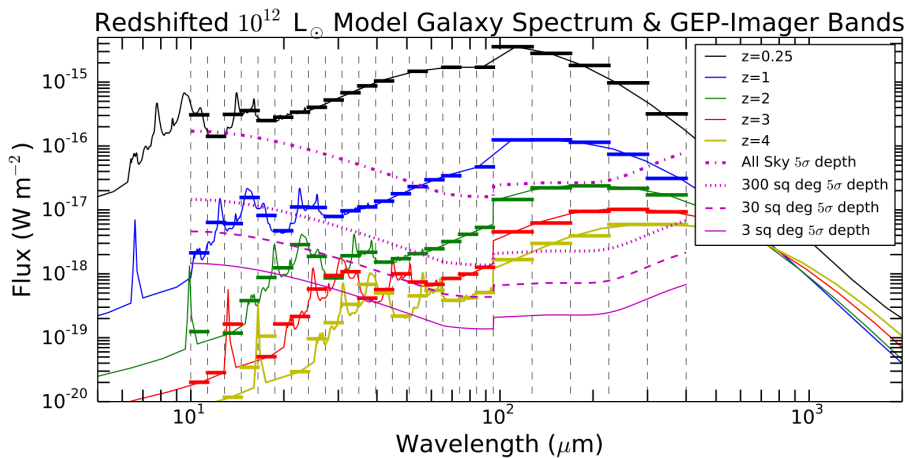
The combination of four GEP-I depths and areas in a two-year survey will sample low redshift and bright, rare galaxies, and faint, high-redshift galaxies. Sufficient numbers of galaxies will be detected to limit Poisson errors and sufficient volumes will be surveyed so that cosmic sample variance does not dominate, as with previous deep IR surveys. All of the surveys except the all-sky survey will be centered on and divided between the north and south ecliptic poles to minimize the photon backgrounds from primarily zodiacal dust and secondarily Galactic dust.<sup>17</sup> This will overlap with Euclid surveys, which will provide near-IR counterparts and stellar masses of galaxies for combined studies, and ground-based observatories in both hemispheres.

There will be three types of spectroscopic surveys with GEP-S, also requiring two years: 1) Observations of galaxies identified in the GEP-I surveys to provide precise redshifts to validate the photometric techniques, and to obtain high SNR measurements of the full suite of mid/far-IR spectral features. 2) ‘Blind’

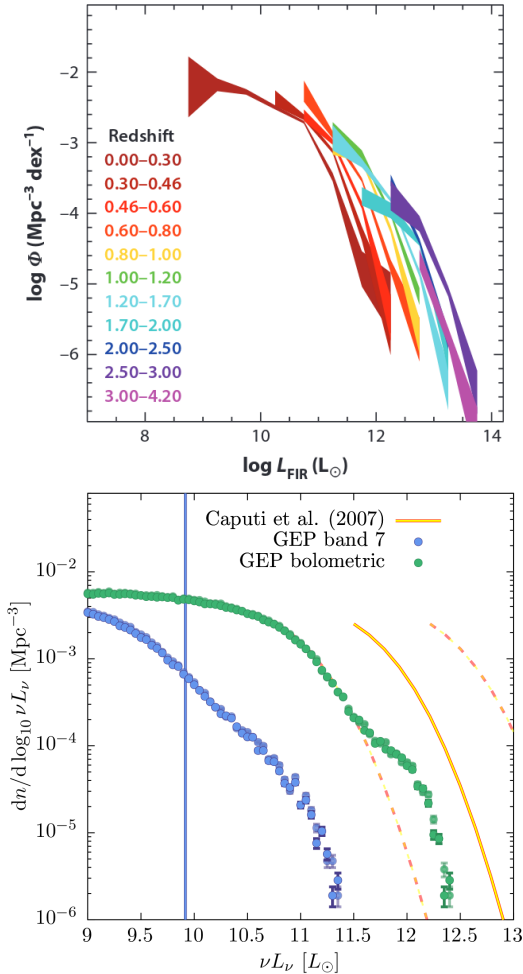
field-filling spectroscopic surveys obtained by rastering GEP on the sky: 1.5 and 100 sq deg detecting  $10^4$ - $10^5$  galaxies, with stacking on grism spectrometer datasets from Euclid and WFIRST. 3) Spectral maps of nearby galaxies. With its long-slit spectrometers with 40–70 spatial beams, GEP-S is much more efficient in performing blind spectral surveys than SPICA, which is limited to a few beams in the slit.

### 4.2 Measuring Redshifts, SFRs, and LFs

Using the GEP-I  $R = 8$  imaging spectroscopy targeting the powerful and ubiquitous mid-IR PAH features, GEP will simultaneously measure redshifts and SFRs of millions of galaxies (Fig. 2). PAH features carry several percent of the bolometric luminosities of star-forming galaxies. In the rest frame, PAH emission occurs at 3.3, 6.2, 7.7, 8.6, 12 and 13.5  $\mu\text{m}$ . GEP-I’s  $R = 8$  imaging bands are matched to the PAH line widths to enable redshift measurements to  $z > 5$ . A mock survey was constructed using the Millennium simulation,<sup>18</sup> the Galacticus model,<sup>19</sup> and IR spectra with a range of fractional AGN luminosities.<sup>20</sup> It indicates that GEP-I will detect  $10^8$  galaxies with more than  $10^6$



**Figure 2.** GEP-I’s wavebands (with bandpasses denoted by dashed vertical lines) and IR galaxy spectra. GEP will detect  $10^{12} L_{\odot}$  galaxies (corresponding to  $L^*$ ) at  $z = 2$  and higher luminosities at higher redshifts, and will measure photometric redshifts to  $z > 5$  (for bright or lensed galaxies). The spectra from models by Dale et al.<sup>20</sup> display PAH emission lines, silicate absorption at 10  $\mu\text{m}$  (rest frame), a rising mid-IR continuum from warm dust, and an SED peak just longward of 100  $\mu\text{m}$  from cold dust. The spectra are binned into GEP-I’s wavebands, shown by the bold, dashed horizontal lines. The bandwidths change at 95  $\mu\text{m}$  from  $R = 8$  to  $R = 3.5$ . Atomic fine-structure emission lines are not shown.



**Figure 3. GEP will measure the redshift dependence of the bright and faint end slopes of IR galaxy luminosity functions to characterize evolution.** *Top:* Current bolometric IR luminosity function measurements.<sup>3</sup> *Bottom:* GEP luminosity function for  $1.0 < z < 1.2$  derived from mock catalogs. Blue points: luminosity function in the GEP-I Band 7 (21.2 – 24.0  $\mu\text{m}$ ). The green points are the predicted bolometric IR luminosity function: comparison to the green  $z = 1.0 - 1.2$  curve in top panel shows that GEP will extend the faint end of the luminosity function more than an order of magnitude below the state of the art.

photometric redshifts. Photo-zs are obtainable for, e.g., the 3 sq deg survey for  $10^{11} L_{\odot}$  galaxies to  $z = 1$ , for  $10^{12} L_{\odot}$  galaxies to  $z = 2$ , and for  $10^{13} L_{\odot}$  galaxies to  $z = 4$ , with a precision of  $\sigma_z \sim 0.03 - 0.1$ , sufficient resolution to bin finely in redshift and for counterpart identification at other wavelengths.

GEP’s Science Objective 1a requires galaxy luminosity functions over a range of redshifts. With GEP-I surveys, faint-end slopes below  $\log_{10} (L_{\text{IR}}/L_{\odot}) = 12$  at  $z = 2$ , will be measured, an enormous step beyond the state of the art (Fig. 3).

### 4.3 Charting the History of Super-Massive Black Hole Accretion

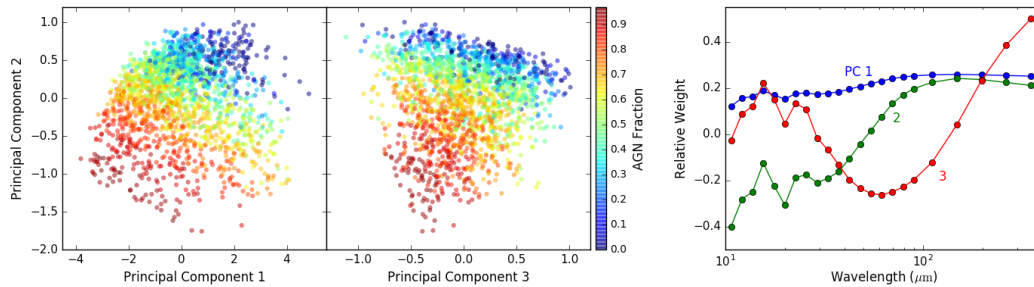
GEP will use two techniques to identify buried AGN and to measure their contribution to total luminosities: decomposition of the multi-band GEP-I data and GEP-S spectroscopic surveys targeting the high-ionization mid-IR fine-structure lines. The GEP team developed an approach that uses the PAH features and dust continuum in a principal component analysis that decomposes luminosity fractions from AGN and star formation (Fig. 4). The AGN luminosities correlate directly with SMBH accretion rates.<sup>21</sup> Precision will improve using JWST’s database of mid-IR spectra that will be in hand by GEP’s launch.

The rest-frame mid-IR has spectral-line tracers of highly ionized gas, such as [S IV] 10.5  $\mu\text{m}$ , [Ne V] 14.3  $\mu\text{m}$  and 24.3  $\mu\text{m}$ , and [O IV] 25.9  $\mu\text{m}$ , with ionization potentials of 35–97 eV. By ratioing these bright lines with much lower ionization potential (e.g., [Ne II] 12.7  $\mu\text{m}$ ),<sup>22-29</sup> GEP will discriminate the relative amount of heating from young stars and AGN.

### 4.4 Quantifying Feedback Mechanisms Spectroscopically

Stacked GEP-S spectra will reveal high velocity ( $\pm 500$  km/s) wings of AGN lines, such as [Ne V] and [O IV], that measure the AGN-powered mass outflow rate.<sup>30</sup> With total line flux SNRs in excess of 50 in stacked spectra, fractional fluxes in the wings (a proxy for mass fraction that is outflowing) can be measured with an RMS of 5% after deconvolution with the spectrometer  $R = 200$  (1500 km/s) response function.

GEP-S also will be used to study feedback by examining the impact of stellar energy



**Figure 4. GEP-I’s multiband observations will enable the relative contributions of galaxy IR luminosities from AGN and star formation to be discriminated.** *Left:* Outcome for analysis of the 3 sq deg survey at redshift  $z = 1.0 \pm 0.1$ . *Right:* Three principle components that measure the redshift, AGN fraction, and radiation field hardness.

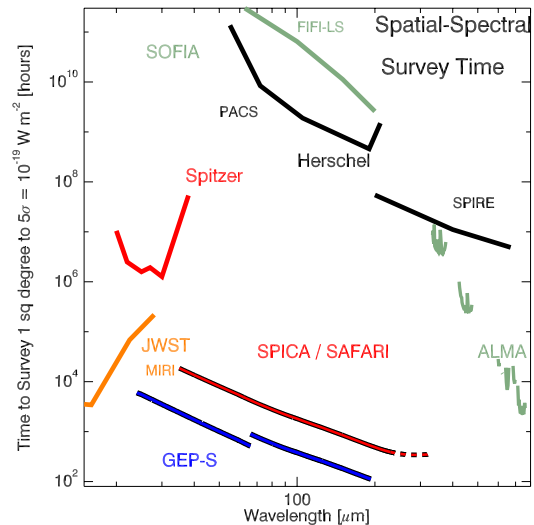
sources on the gas conditions in nearby galaxies. GEP will provide a resolved beamsize  $\theta = 150 \text{ pc} \left( \frac{D}{10 \text{ Mpc}} \right) \frac{\lambda}{24 \text{ } \mu\text{m}}$ , where  $\sim 10^3$  galaxies have  $D < 10 \text{ Mpc}$ . With its sensitive, long-slit spectrometers, GEP-S offers orders of magnitude improvement in mapping speed over the state of the art and exquisite surface brightness sensitivity (Fig. 5). GEP-S will use [C II] as a tracer of low column density material, reaching an order of magnitude below what can be done with a Jansky VLA deep HI 21 cm survey. This depth enables a census of material below the star formation threshold of  $1\text{-}10 \text{ M}_\odot/\text{pc}^2$ .<sup>31,32</sup>

#### 4.5 Metal Production in the Hearts of Galaxies

A complete history of the Universe’s metal production cannot rely solely on measurements of the intergalactic and least-obscured gas typically probed with UV absorption spectroscopy,<sup>33</sup> but must also chart the metallicity within galaxies where metals are forged. The metallicity *within* galaxies is not reliably measured with the presently used optical/UV techniques because they probe low-extinction regions. This may result in substantial underestimates: Santini et al.<sup>34</sup> infer a metallicity using far-IR dust measurements that is more than 10 times higher than that inferred from optical nebular lines.

The far-IR atomic fine-structure lines accessible to GEP offer metallicity

measurements that overcome these limitations because they are unaffected by extinction. For  $z \leq 1.2$ , GEP will use the O to N ratio as a measure of stellar processing. Groves et al.<sup>35</sup> and Nagao et al.<sup>36</sup> have shown the O/N ratio is measured cleanly in H II region gas with two [O III] transitions (52 and 88 μm) and one [N III] transition (57 μm). These transitions will be detectable in  $3 \times 10^{11} L_\odot$  galaxies for  $z \leq 1.2$ . For higher redshifts ( $1.2 < z < 4$ ) and lower metallicities, GEP will chart the relative metallicity evolution using the N/S ratio.<sup>37</sup>



**Figure 5. Spectral survey time to a given depth in the mid- and far-IR. GEP-S offers gains of 5-6 orders of magnitude relative to the current state of the art (*Herschel* and *SOFIA*) and an order of magnitude below the proposed *SPICA* by virtue of its low telescope temperature and long slits.**

#### 4.6 Star-Formation Conditions in the Milky Way and Nearby Galaxies

With the all-sky GEP-I survey, GEP will probe the ISM conditions over a large range of interstellar environments, from the Galactic Center, to the Milky Way’s 4 kpc molecular ring and less molecular gas-rich outer Galaxy, to the disks and nuclei of nearby galaxies.

#### 4.7 Extragalactic Confusion Noise

Extragalactic source confusion arises when point spread functions of galaxies overlap. Confusion ‘noise’ is the signal that arises from overlapping point spread functions. The expected GEP-I extragalactic confusion noise was estimated by considering previous observations.<sup>38-42</sup> GEP-I observations likely will reach the confusion noise level at approximately 70  $\mu\text{m}$  and longward in the deepest two surveys (3 and 30 sq deg). An empirical scaling relationship for confusion noise as a function of telescope aperture diameter,  $\sigma_{\text{conf}} \sim D^{-2}$  scaling was found, indicating that an aperture smaller than 2.0 m would be confusion limited at crucial far-IR wavelengths where the bulk of the cosmic far-IR background resides.

Using cross-identification with counterparts at shorter wavelengths, galaxy properties can be measured even when there is source confusion.<sup>43</sup> The Next Generation (X)Cross Identification (XID+) algorithm was developed to estimate flux densities accurately from confusion-limited *Herschel* using unconfused (shorter-wavelength) positional priors.<sup>44</sup> The performance of XID+ for far-IR wavelengths was quantified for GEP-I with  $\lambda < 70 \mu\text{m}$  GEP-I positional priors. Down to galaxy separations of the beam size, galaxy flux densities can be deblended with small fractional errors and little or no bias.

### 5 TECHNICAL OVERVIEW

#### 5.1 Optical Design, GEP-I and GEP-S

The GEP payload includes the optical telescope assembly, the GEP instrument comprised of one imager module (GEP-I) and

four spectrometer modules (GEP-S), both utilizing kinetic inductance detectors (KIDs), and a payload thermal subsystem.<sup>45,46</sup> The optical design utilizes an unobscured three-mirror astigmat with stray light suppression by pupil and field stops. The entire  $0.8^\circ \times 0.9^\circ$  field is diffraction limited at 10  $\mu\text{m}$ . The baseline for the GEP primary, secondary, and tertiary mirrors is silicon carbide (SiC), as was flown on *Herschel* and *GAI*A. U.S. vendors are currently able to manufacture a sintered 2 m SiC primary mirror.

The GEP-I concept is designed to obtain repeated measurements on-sky in each of the 23 wavebands by continuous scanning. The shortest wavebands are in the center of the focal plan, where the optical performance is the best. Metal-mesh filters define bandpasses for each KID subarray. GEP-I will have 25,735 KIDs. While GEP’s optical design is diffraction limited at 10  $\mu\text{m}$ , the primary mirror is only required to be diffraction limited at 24  $\mu\text{m}$ , corresponding to  $\sim 3''$  beam size (FWHM). The primary reason for this is that the smallest KID pixel size we expect to be able to fabricate without exceeding the readout bandwidth is 300  $\mu\text{m}$ , which corresponds to 3.43". Thus, bands 1–13 will not be Nyquist sampled while bands 14–23 will be. In the very likely event that greater bandwidth becomes feasible through improvements in data acquisition and computing speed (see section 7.2), the pixel sizes can be reduced, recovering Nyquist sampling at shorter wavelengths.

GEP-S was designed to meet the science requirements calling for observing mid- and far-IR atomic fine-structure lines for galaxies over a range of redshifts. Specifically, the 24  $\mu\text{m}$  [Ne V] and 26  $\mu\text{m}$  [O IV] lines starting at  $z = 0$  (for AGN identification) and the 63.2  $\mu\text{m}$  [O I] line to  $z = 2$ . The entire bandwidth should be available to identify spectral lines for galaxies of unknown redshift.  $R = 200$  spectral resolution is required to achieve sufficient sensitivity (through dispersion of the astrophysical background photons). GEP-S is



comprised of 24,640 KID detectors and is implemented with four gratings (Table 2).

**Table 2.** GEP-S spectral bands ( $R = 200$ ).

	Bandpass ( $\mu\text{m}$ )	KID Pixels	Slit length ( $^\circ$ )
Band 1	24–42	7840	3.8
Band 2	40–70	7840	6.4
Band 3	66–116	4480	6.0
Band 4	110–193	4480	10.0

## 5.2 Detectors and Readout

Over the past two decades, the superconducting KID has emerged as a powerful detector array technology applicable to a very broad wavelength range that includes the 10–400  $\mu\text{m}$  band needed for GEP.<sup>47–50</sup> Back-illuminated, lumped-element, microlens-coupled aluminum KIDs (Fig. 6) operating at 100 mK will meet the requirements of GEP-I and GEP-S. KIDs with sensitivity sufficient for GEP-I have been demonstrated<sup>55</sup> while improvement is needed for GEP-S. GEP baselines KIDs for GEP-I and GEP-S because, at present, this technology offers the most straightforward path to meeting the science requirements. Si:As IBCs as used in JWST’s MIRI and superconducting transition-edge sensors could be viable fallback detector technologies.

For all GEP focal planes, the KIDs are organized into groups of  $\sim 1,500$  detectors spread across a 0.6–1.6 GHz readout band. Each of 24 readout electronics modules generates an analog waveform using RF-DACs that is transmitted to the cold focal plane. The

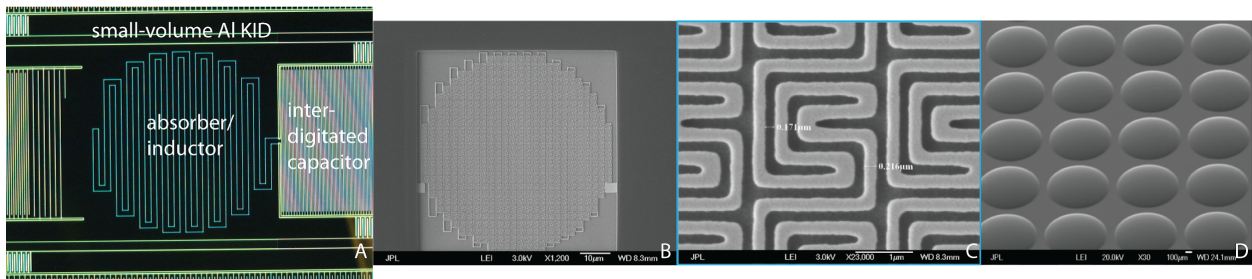
1 GHz bandwidth return signal from all 1,500 KIDs is digitized with RF-ADCs and digitally channelized. This processing scheme, initially demonstrated in 2006,<sup>56</sup> has been implemented in various forms for ground-based and balloon-borne instruments.<sup>51,57–65</sup> The total estimated power consumption for the readout electronics is 484 W. The GEP study adopted a conservative power consumption of 24.4 W per 1 GHz readout channel, within reach of current commercial technology.

## 5.3 Payload Thermal Design

The thermal system design for GEP employs multiple passive and active stages.<sup>66</sup> A continuous multi-stage adiabatic demagnetization refrigerator (ADR) provides 100 mK cooling for the detectors, with a 1 K thermal intercept to reduce thermal noise and parasitic loads. GSFC has a well-established program for ADR development,<sup>67,68</sup> with most individual components at TRL 9. A hybrid Joule-Thomson/Stirling cryo-cooler intercepts heat at 4 K from the ADR, cryogenic amplifiers, and parasitic loads. Multiple vendors, including NASA GSFC and Ball Aerospace, offer high TRL cryocoolers capable of meeting GEP heat-lift requirements with 100% margin. The sunshield assembly consists of three reflective shields with a total area of 33  $\text{m}^2$ , and an active 9.77  $\text{m}^2$  shield.

## 6 DESIGN REFERENCE MISSION

Table 3 summarizes high-level GEP mission parameters. The flight system is designed as a



**Figure 6.** KID designs suitable for the GEP-I and GEP-S wavebands. (A) This  $\lambda > 100 \mu\text{m}$  design uses a meandered inductor that acts as an efficient single-polarization absorber.<sup>51,52,53</sup> A microlens focuses the far-IR radiation onto the absorber. (B) This modified absorber/inductor provides high absorption efficiency at  $\lambda = 10 \mu\text{m}$ , and is shown in close-up in (C). (D) Illustrates prototype silicon microlenses produced at JPL/MDL.<sup>54</sup> Over 5,000 such microlenses have been produced on a 100 mm silicon wafer.

**Table 3.** GEP mission parameters.

Parameter	GEP's Design
Launch Date	January 1, 2029
Destination / Launch Vehicle	Sun-Earth L2 / Falcon 9
Mission Duration	4 years (w/ 46% margin)
Bus Design Life	5 years
Mission Class	B, dual string (hot/cold redundancy)
Bus	Ball BCP2000 (e.g., Kepler)
Dry Mass (CBE + Contingency)	1320 kg (26% ave contin.)
Max Power (CBE + Contingency)	1990 W (43% contingency)
Stabilization	Three axis (0.5 as/3 min), non-spinning
Primary Mirror Temperature	4 K design, 6 K allowable
Focal Plane Temperature	100 mK
Field of Regard	±20.6°
Total Mission Science Data	350 TB

Class B mission with substantial science and engineering margins. It utilizes a combination of high-heritage designs and new components, resulting in a low-risk mission below the Probe class cost cap. The flight system is based on the Ball Aerospace BCP2000 reference bus, of *Kepler* heritage.

### 6.1 Survey Operations

Following in-orbit checkout and science verification, the two-year GEP-I science phase will begin. GEP will continuously observe while rastering, approximately about the Sun-Probe axis. Then, the two-year GEP-S survey phase will follow, including spectral mapping surveys and pointed observations. There are no cryogenic consumables and the expected lifetime of the spacecraft exceeds 5 years; thus, an extended open-time phase will be possible after the surveys are complete.

### 6.2 Cost Assessment

The GEP Team and JPL Team X have each estimated GEP's lifecycle cost, yielding \$910M and \$951M FY18, respectively (Table 4). Both estimates assume 30% development reserve on Phases A–D and 15% on operational reserves in Phase E. The Team X evaluation (utilizing NICM v8) costed all aspects of the mission. The GEP Team cost was compiled based on estimates from Team X

and Ball Aerospace. WBS elements were costed using the JPL Institutional Cost Model assuming a Class B mission with spacecraft built by a subcontractor.

## 7 TECHNOLOGY MATURATION PLAN

With a launch in 2029, all technologies required for the GEP mission must be at or above TRL 6 in 2025. The KID focal planes and readout comprise the major technology maturation needs. The state of the art and technology maturation plans are described in the GEP Technology Development Plan.<sup>69</sup>

**Table 4.** GEP team and JPL Team X estimated GEP cost.

Work Breakdown Structure (WBS) Elements	GEP Estimate	Team X Estimate
<b>Development Cost (Phase A-D)</b>	<b>\$661M</b>	<b>\$702M</b>
1.0, 2.0, & 3.0 Management, Systems Engineering, and Mission Assurance	\$54M	\$54M
4.0 Science	\$16M	\$16M
5.0 Payload System	\$195M	\$168M
5.01, 5.02 Payload Mgmt, SE	\$6M	\$6M
5.1 GEP-I	\$91M	\$64M
5.2 GEP-S		
5.3 Active Cooling	\$71M	\$71M
5.4 OTA	\$27M	\$27M
6.0 Flight System	\$200M	\$232M
7.0 Mission Op Preparation	\$17M	\$17M
9.0 Ground Data Systems	\$22M	\$22M
10.0 ATLO	<i>*Included in WBS 6</i>	\$26M
12.0 Mission and Navigation Design	\$5M	\$5M
Development Reserves (30%)	\$152M	\$162M
<b>Operations Cost (Phase E)</b>	<b>\$99M</b>	<b>\$99M</b>
1.0 Management	\$4M	\$4M
4.0 Science	\$44M	\$44M
7.0 Mission Operations	\$30M	\$30M
9.0 Ground Data Systems	\$9M	\$9M
Operations Reserves (15%)	\$12M	\$12M
<b>Launch Vehicle (LV)</b>	<b>\$150M</b>	<b>\$150M</b>
<b>Total Cost (including LV)</b>	<b>\$910M</b>	<b>\$951M</b>

### 7.1 Kinetic Inductance Detectors

GEP will leverage existing KID technology development and planned future work to mature KIDs technology. The European SPACEKIDS results<sup>55</sup> are the closest to meeting the GEP requirements: they already

meet the GEP-I sensitivity requirement and are within a factor of several of the GEP-S requirement. By comparing the capability gap between GEP KID focal plane requirements and SPACEKIDS performance, specific advances required to achieve TRL 6 by 2025 were identified. The wavelength range, sensitivity (to be improved by reducing active-area volume<sup>70</sup>), multiplexing factor,<sup>71,72</sup> and detector pitch can all be made to meet the requirements with a three-year, \$8M, 6 FTE/year focused technology development leading to demonstration of GEP prototype arrays at the TRL 5 level by mid-23. A subsequent technology maturation program that includes space qualification would reach TRL 6 by 2025. Multiple long-duration balloons are flying KIDs.<sup>73-75</sup>

### 7.2 Detector Readout Electronics

GEP will have an option to use either FPGA or ASIC technology for its detector readout electronics. To date, all KID instrument readout systems use FPGAs.<sup>51,57-60,63,76</sup> Driven by commercial and defense industry needs, it is very likely FPGA technology will meet GEP’s bandwidth, power consumption, and radiation hardness requirements prior to 2022.<sup>77-90</sup> Concurrent with the GEP KID maturation effort, a parallel 3-year, \$3M effort to define and develop a readout electronics solution for GEP will start in 2020. ASICS could provide greater integration and lower power consumption,<sup>91</sup> but with a larger up-front engineering cost. A downselect between FPGAs and ASICS will be performed in 2022.

## 8 MANAGEMENT PLAN

Figure 7 outlines the high-level project schedule for GEP, with critical milestones and phase durations similar to other Class B NASA missions. Technology development work is expected to meet TRL 6 by 2025. This will include the development of focal planes, payload electronics, and cryogenics. JPL will be responsible for development of focal-plane and payload electronics while subcontracting telescope and cryocooler development. JPL or a spacecraft vendor will be responsible for integrating the bus and payload.

## 9 CONCLUSIONS

The GEP concept has shown the powerful science that can be accomplished on a Probe budget ( $\leq$  \$1B). Indeed, GEP surveys will directly or indirectly address science in many of the white papers submitted to ASTRO2020.<sup>92-161</sup> The GEP concept takes advantage of high-heritage technologies for the majority of its subsystems and GEP’s technology development will bring the detector and readout technology to TRL 6 in advance of Phase B. Probes would enable NASA Astrophysics to have multiple major missions per decade for a broad science portfolio that will engage a large part of the astronomical community.

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CY	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	
Fiscal Quarter	2 3 4 1	2 3 4 1	2 3 4 1	2 3 4 1	2 3 4 1	2 3 4 1	2 3 4 1	2 3 4 1	2 3 4 1	2 3 4 1	2 3 4 1	2 3 4 1	
Project Phase		A	B	C/D				E				F	
Key Milestones			PDR	CDR	ARR	KDP E				KDP F			

**Figure 7.** The GEP project schedule is in-class with other Class B NASA missions. With a five-year design life, GEP will have the option for an extended guest-observer science mission following the baselined four years of survey operations (which already have 46% time contingency included).

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