



A Homogeneous Survey of JWST-MIRI Transmission Spectra of 10 Exoplanets

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Abstract

The launch of JWST has enabled unprecedented atmospheric characterization of exoplanets. In particular, the JWST-MIRI instrument in the mid-infrared enables probing of molecular species that are harder to detect in the near-infrared. This has come to the fore with the first MIRI-LRS observation of a candidate hycean world, K2-18 b, with potential signs of dimethyl sulfide in its atmosphere. The statistical significance of this result has been debated in subsequent works, arguing instead for the possibility of random noise, instrumental systematics, or a different molecule. The same applies to similar spectra reported for several other exoplanets using MIRI-LRS and interpreted with similar retrieval architectures. In this work, we distinguish between these possibilities with a homogeneous survey of MIRI-LRS transmission spectra of 10 diverse exoplanets, from temperate sub-Neptunes to hot rocky planets and gas giants. We first perform a comparative assessment of the spectra, considering fits with featureless models and pairwise correlations, followed by extensive atmospheric retrievals. With the retrievals, we search for over 150 trace species in the atmosphere of each planet. We find hints of complex molecules in the temperate sub-Neptunes and candidate hycean worlds K2-18 b, TOI-732 c, and TOI-270 d, similar to previous works, but not in the other seven planets. Our results indicate that the observed spectral features are likely due to molecular absorption rather than instrument systematics or noise and underscore these temperate sub-Neptunes as a unique class of planets. More observations are required to robustly identify the specific molecules and constrain the underlying chemical processes, biotic or abiotic.

Unified Astronomy Thesaurus concepts: [Exoplanet atmospheres \(487\)](#); [Exoplanet atmospheric composition \(2021\)](#); [Exoplanets \(498\)](#); [James Webb Space Telescope \(2291\)](#); [Infrared spectroscopy \(2285\)](#); [Transmission spectroscopy \(2133\)](#)

1. Introduction

The launch of the James Webb Space Telescope (JWST; J. P. Gardner et al. 2023) has enabled atmospheric characterization of exoplanets with greater precision than ever before. With transit spectroscopy, some of the key discoveries have been robust detections of molecular species in near-infrared (NIR) observations of a wide range of planets, from hot gas giants to temperate sub-Neptunes. For gas giants, these include H₂O, CO₂, CO, and SO₂ in WASP-39 b (E.-M. Ahrer et al. 2023; L. Alderson et al. 2023; A. D. Feinstein et al. 2023); H₂S in HD 189733 b (G. Fu et al. 2024); CH₄ in WASP-80 b (T. J. Bell et al. 2023); and potentially OCS in the young planet V1298 Tau b (S. Barat et al. 2025). Several sub-Neptunes ($1.8 R_{\oplus} \lesssim R_p \lesssim 4 R_{\oplus}$) have also shown molecular features in H₂/He-dominated atmospheres, including CH₄ and CO₂ in K2-18 b (N. Madhusudhan et al. 2023) and TOI-270 d (B. Benneke et al. 2024; M. Holmberg & N. Madhusudhan 2024), as well as H₂O in TOI-421 b (B. Davenport et al. 2025). Even hints of secondary atmospheres have been inferred in some planets, including LHS 1140 b (M. Damiano et al. 2024), GJ 1214 b (E. M.-R. Kempton et al. 2023), GJ 9827 d (C. Piaulet-Ghorayeb et al. 2024) and L 98-59 d (A. Banerjee et al. 2024; A. Gressier et al. 2024), the latter being subsequently supported by ground-based observations (C. J. Cheverall et al. 2026). More detailed reviews of JWST

advances in exoplanet atmosphere characterization can be found in N. Espinoza & M. Perrin (2026) and N. Madhusudhan et al. (2025b), the latter being focused on sub-Neptunes.

Although NIR transit observations benefit from a higher signal-to-noise ratio (SNR) due to stronger stellar flux, those with the JWST Mid Infrared Instrument (MIRI) can give precious complementary information. In particular, the MIRI Low Resolution Spectrograph (MIRI-LRS, S. Kendrew et al. 2015) instrument provides a broad wavelength range (5–12 μ m), which encompasses spectral features of various molecules and condensate species (H. R. Wakeford & D. K. Sing 2015; A. Pinhas & N. Madhusudhan 2017; N. Madhusudhan 2026). This was demonstrated for several giant exoplanets starting with the JWST Transit Early Release Science (ERS) program for WASP-39 b. In this case, a transmission spectrum obtained with MIRI-LRS led to an inference of SO₂ in WASP-39 b, complementing previous findings with the NIR spectra (D. Powell et al. 2024). Similar inferences were also made for other hot Jupiters, including H₂O and SO₂ in WASP-107 b and silicate clouds in WASP-17 b (D. Grant et al. 2023b).

Most recently, the importance of MIRI-LRS has been demonstrated for transmission spectroscopy of temperate exoplanets, with the first mid-infrared spectrum of a habitable-zone sub-Neptune, K2-18 b (N. Madhusudhan et al. 2025a), followed by other temperate sub-Neptunes (F. E. Rigby et al. 2025; M. Holmberg et al. 2026). The MIRI-LRS spectrum of K2-18 b was used to infer tentative evidence for dimethyl sulfide (DMS) and/or dimethyl disulfide (DMDS), both potential biomarkers, at $\sim 3\sigma$ ($\ln B \sim 3$). The



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reported evidence is stronger than the previous hint of DMS reported using NIR observations with JWST NIRISS and NIRSpec G395H, which was affected by the degeneracy with CH_4 and CO_2 and a strong dependence on detector offsets (N. Madhusudhan et al. 2023). The broader wavelength coverage and single detector, combined with the multiple strong features of DMS in the mid-infrared, rendered it more observable with MIRI-LRS.

However, as alluded to in N. Madhusudhan et al. (2025a), the low SNR of this single MIRI-LRS observation allowed for other interpretations in the form of unknown systematics (K. B. Stevenson et al. 2025) or other chemical species besides DMS and DMDS (A. Y. Jaziri & T. Drant 2025; R. Luque et al. 2025; L. Pica-Ciamarra et al. 2026; L. Welbanks et al. 2026). If the observed feature is indeed from the planet, then a comprehensive exploration of over 650 molecules suggests that DMS is the most likely explanation of the data (L. Pica-Ciamarra et al. 2026). Similar interpretations of complex molecules are possible for other temperate sub-Neptunes such as TOI-732 c (F. E. Rigby et al. 2025) and TOI-270 d (M. Holmberg et al. 2026). However, it is important to consider the possibility of unknown systematics, which, in turn, could affect other observations (K. B. Stevenson et al. 2025).

The consideration of unknown systematics is particularly important given the diverse range of exoplanets being observed with JWST-MIRI. Indeed, the attributes of low SNR and detection significance observed for K2-18 b extend beyond temperate sub-Neptunes to similar observations of larger and hotter exoplanets. For example, as noted above, one of the earliest exoplanet observations with MIRI-LRS was of a transmission spectrum of the hot Jupiter WASP-17 b with an inference of silicate clouds in the atmosphere (D. Grant et al. 2023b). The reported model preference for silicate clouds over a generic gray-cloud setup was 2.6σ ($\ln B \sim 2$), which is comparable to the inference of DMS/DMDS in K2-18 b (N. Madhusudhan et al. 2025a), with comparable retrieval architectures considering three to four relevant gas-phase molecules to compute the model preferences. It is to be noted, however, that the inference for WASP-17 b was obtained with one of the two data reductions considered, so the robustness to different pipeline choices remains open. Similarly, another relevant example is the case of WASP-39 b observed in the JWST ERS program for which a MIRI-LRS spectrum was used to infer the presence of SO_2 at $\gtrsim 3\sigma$ ($\ln B \gtrsim 3$) and with a retrieval architecture including only two species, H_2O and SO_2 (D. Powell et al. 2024). Therefore, any competing hypotheses invoked to explain the spectrum of K2-18 b, such as unknown systematics or unexpected molecules, would also apply to these observations of hot Jupiters.

It is, therefore, imperative to address these various interpretations with a homogeneous survey of JWST-MIRI transmission spectra for a diverse range of targets. Such a survey is required to effectively disentangle the instrumental systematics and random noise from potential astrophysical signals. For example, if there are strong instrumental systematics, we expect to find similar signals across the datasets independent of the targets. Similarly, if random noise dominates the spectra, we do not expect to see significant correlations between different observations. On the other hand, if neither instrumental nor random noise dominates the spectra, the diverse datasets open an exciting avenue for comparative

characterization of the diverse atmospheres in the mid-infrared.

To achieve this goal, in this work, we conduct a comprehensive and homogeneous survey of 10 diverse exoplanets observed with JWST-MIRI using transmission spectroscopy, encompassing all the datasets published to date, and spanning gas giants, sub-Neptunes, and rocky exoplanets. In what follows, we discuss the target sample and observations along with a correlation analysis in Section 2. We then present our atmospheric retrieval setup in Section 3 and the results in Section 4. We summarize and discuss our findings in Section 5.

2. Target Sample and Observations

We start by listing the wide range of planets that constitute our target sample, providing information on their bulk characteristics, and atmospheric properties reported previously using transit spectroscopy. We then perform a homogeneous comparison of all the spectra by fitting them with a flat model, followed by pairwise comparisons using the Pearson correlation coefficient.

2.1. Planet Sample

In this work, we focus on transmission spectra observed with JWST-MIRI-LRS. There are 11 planets that have such publicly available spectra published in the literature, listed in Table 1 and Figure 1: K2-18 b, TOI-732 c, TOI-270 d, GJ 1214 b, WASP-107 b, L 168-9 b, WASP-39 b, GJ 367 b, WASP-43 b, WASP-17 b, and K2-22 b. From these, we discard the disintegrating rocky planet K2-22 b (R. Sanchis-Ojeda et al. 2015), which has a highly variable transit depth in its MIRI spectrum (N. Tusay et al. 2025). This leaves us with 10 planets, 7 of which are too large and/or hot ($T_{\text{eq}} \geq 500$ K) to be habitable. These will be compared with the temperate ($T_{\text{eq}} \leq 400$ K) sub-Neptunes K2-18 b, TOI-270 d, and TOI-732 c, which are potentially habitable as candidate hycean worlds (N. Madhusudhan et al. 2021). We first briefly summarize the previously published results from transit observations of these planets.

2.1.1. Uninhabitable Planets

We start by introducing the uninhabitable planets in the sample. First, we have the hot super-Earth L 168-9 b (N. Astudillo-Defru et al. 2020). Its MIRI transmission spectrum was first reduced in J. Bouwman et al. (2023). Then, M. K. Alam et al. (2025) independently reduced the MIRI observation and also observed a transit in the NIR with JWST NIRSpec G395H (2.9–5.1 μm). This ruled out any clear low-metallicity atmosphere, but the presence of a cloudy or metal-dominated atmosphere remains a possibility.

There is another rocky planet in this list, GJ 367 b, discovered in 2021 (K. Lam et al. 2021). Its only atmospheric observation was the MIRI phase curve presented in M. Zhang et al. (2024). As expected from its small size and high equilibrium temperature (0.68 $R_{\oplus}$, 1360 K), these data were consistent with the planet having a zero albedo and no heat redistribution, hence being a bare rock. This includes the transit spectrum being consistent with a flat line (see Section 2.2.2), but we still include it in our study for completeness.

Table 1
Planets with Published MIRI Transmission Spectra

Planet	R_p ($R_\oplus$)	M_p ($M_\oplus$)	T_{eq} (K)	R_* ($R_\odot$)	Previous Findings	M_p References
K2-18 b	2.56	8.63 ± 1.35	280	0.44	DMS , ^a CH ₄ , CO ₂	(1)
TOI-732 c	2.41	8.04 ± 0.50	360	0.38	Isobutene , ^a 1-pentene , ^a CH ₄	(2)
TOI-270 d	2.19	4.78 ± 0.43	390	0.38	CH ₄ , CO ₂ , H ₂ O, ^a CS ₂ ^a	(3)
GJ 1214 b ^{PC/+NIR}	2.73	8.41 ± 0.36	570	0.22	H₂O , ^a CO ₂ , ^a CH ₄ , ^a He ^a (clouds and/or high Z)	(4)
WASP-107 b ^{+HST}	9.70	30.5 ± 1.59	750	0.66	H₂O , SO₂ , Si clouds , H₂S , NH₃ , CO , CO ₂ , He, CH ₄	(5)
L 168-9 b ^{+NIR}	1.39	4.07 ± 0.45	960	0.60	None (likely bare rock or high Z)	(6)
WASP-39 b	14.3	89.3 ± 9.54	1150	0.93	H₂O , SO₂ , CO ₂ , CO, K, Na, H ₂ S, ^a SiO ^a	(7)
GJ 367 b ^{PC}	0.68	0.63 ± 0.05	1360	0.46	None (likely bare rock)	(8)
WASP-43 b ^{PC}	11.3	652 ± 16.5	1400	0.66	H₂O , NH₃ , CO ^a	(9)
WASP-17 b ^{+HST}	20.8	154 ± 10.2	1750	1.58	H₂O , Si clouds , ^a CO ₂ , H ⁺ , K, Na	(10)
K2-22 b ^{PC}	≤ 0.71	≤ 445	2100	0.57	Disintegrating planet (discarded)	(11)

Notes. The equilibrium temperatures T_{eq} are given for a Bond albedo of 0 and full heat redistribution. We list the species previously inferred in each atmosphere, starting with those found in the MIRI data in bold. Superscript PC indicates that the transit was studied as part of a phase curve observation. Superscript +NIR indicates that the transit was studied jointly with JWST NIR data; +HST indicates Hubble data.

^a Inferences below the threshold for strong evidence (see Appendix E). Wherever multiple degenerate molecules are reported, we only include those inferred in both MIRI and NIR data. References for previous findings are in Section 2.1.

References for M_p values. (1) R. Cloutier et al. (2019); (2) A. Bonfanti et al. (2024); (3) V. Van Eylen et al. (2021); (4) A. S. Mahajan et al. (2024); (5) Y. Wu et al. (2026); (6) M. J. Hobson et al. (2024); (7) F. Faedi et al. (2011); (8) E. Goffo et al. (2023); (9) A. S. Bonomo et al. (2017); (10) D. R. Anderson et al. (2011); (11) R. Sanchis-Ojeda et al. (2015).

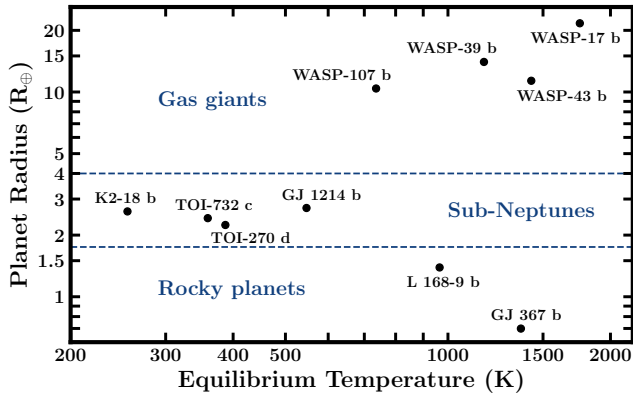


Figure 1. Sizes and temperatures of the ten planets studied in this work. The sample includes a wide variety, with four gas giants, four sub-Neptunes, and two rocky planets, spanning temperate to hot conditions.

Then, GJ 1214 b (D. Charbonneau et al. 2009) is a warm sub-Neptune that was first observed with JWST in E. M.-R. Kempton et al. (2023). This observation was a MIRI phase curve that found the planet to likely have a high-metallicity atmosphere with clouds or hazes, potentially water-dominated. This was also found in P. Gao et al. (2023) by combining the transit from this MIRI phase curve with Spitzer and Hubble Space Telescope (HST) transits from J. D. Fraine et al. (2013) and L. Kreidberg et al. (2014a), respectively. Later, it was also observed with NIRSpec, and new studies still found a high-metallicity atmosphere that also showed potential CO₂ and CH₄ features (E. Schlawin et al. 2024; K. Ohno et al. 2025). CO₂ was then also inferred in a CRISP⁺ high-resolution spectrum (L. Nortmann et al. 2026). As a side note, J. Orell-Miquel et al. (2022) also found tentative evidence for helium escape with the ground-based spectrograph CARMENES.

Next, the hot Saturn WASP-107 b (D. R. Anderson et al. 2017) was first observed in transit with Hubble’s WFC3 instrument (0.9–1.6 μm) and found to have a hydrogen-dominated atmosphere (as expected for a giant planet, and this is also true for the following planets) with water features

(L. Kreidberg et al. 2018) and escaping helium (J. J. Spake et al. 2018). Then, A. Dyrek et al. (2024) presented a MIRI observation and performed joint retrievals with the Hubble data. They confirmed H₂O and inferred both SO₂ and silicate clouds, all at $\geq 5\sigma$, as well as 2σ – 5σ evidence for H₂S, NH₃, and CO. Finally, H₂O, SO₂, NH₃, and CO were further confirmed by NIRCarn (L. Welbanks et al. 2024) and NIRSpec G395H (D. K. Sing et al. 2024), which also found CO₂ at $\geq 20\sigma$ and CH₄ at $\approx 5\sigma$, although these works did not infer silicate clouds or H₂S. Finally, V. Krishnamurthy et al. (2025) presented a NIRISS observation that confirmed the escaping helium detection.

Next in our list, the hot Jupiter WASP-17 b (D. R. Anderson et al. 2010) was found to have water features with Hubble WFC3 (A. M. Mandell et al. 2013) and the Space Telescope Imaging Spectrograph (STIS; 0.3–1.0 μm) (D. K. Sing et al. 2016), the latter also finding K and Na features. Then, L. Alderson et al. (2022) reanalyzed these datasets and also inferred $\approx 3\sigma$ – 4σ evidence for CO₂. Finally, the water absorption was confirmed with JWST-MIRI combined with HST (D. Grant et al. 2023b) and NIRISS (D. R. Louie et al. 2025), along with tentative evidence for silicate clouds in the former and H⁺ in the latter. WASP-17 b also has an eclipse MIRI observation (D. Valentine et al. 2024), which marginally further confirmed the water features.

As for WASP-39 b (F. Faedi et al. 2011), it is one of the planets most studied by JWST in transit, with multiple NIR instruments: NIRISS (A. D. Feinstein et al. 2023), NIRSpec G395H (L. Alderson et al. 2023; E. Esparza-Borges et al. 2023; D. Grant et al. 2023c; P. Niraula et al. 2023), NIRSpec PRISM (S. Constantinou et al. 2023; JWST Transiting Exoplanet Community Early Release Science Team et al. 2023; Z. Rustamkulov et al. 2023), NIRCarn (E.-M. Ahrer et al. 2023), or even combining multiple spectra (A. L. Carter et al. 2024; A. Lueber et al. 2024; S. Sarkar et al. 2024; S. Ma et al. 2026). Together, these studies found spectral contributions from H₂O, SO₂, CO, CO₂, K, and Na, as well as tentative evidence for H₂S and SiO. H₂O and SO₂ were also inferred with the MIRI observation of D. Powell et al. (2024).

Finally, WASP-43 b (C. Hellier et al. 2011) was first found to have water vapor features with HST WFC3 (L. Kreidberg et al. 2014b). This was then confirmed with a MIRI phase curve observation in T. J. Bell et al. (2024), which was then reanalyzed in J. Yang et al. (2024) to also infer NH_3 and CO at $\approx 3\sigma$ – 4σ .

We note that of these seven planets, WASP-39 b is the only one for which the MIRI transit data have been previously studied alone. This means that our retrieval results in Section 4.1 are directly comparable with D. Powell et al. (2024).

2.1.2. Habitable-zone Sub-Neptunes

Now, we present the three temperate sub-Neptunes of the sample, which were predicted to be potential hycean worlds. First, K2-18 b (B. T. Montet et al. 2015) was initially observed with Hubble WFC3 (B. Benneke et al. 2019; A. Tsiaras et al. 2019). The spectrum was first inferred to show a hydrogen-dominated atmosphere and water vapor absorption. The observation was reanalyzed in N. Madhusudhan et al. (2020), which arrived at the same conclusion. Other studies noted degeneracies with CH_4 (D. Blain et al. 2021; B. Bézard et al. 2022) and starspots (T. Barclay et al. 2021). However, the planet was later observed with JWST NIRISS and NIRSpec G395H (N. Madhusudhan et al. 2023), and the apparent water features turned out in fact to be CH_4 , inferred at $\approx 5\sigma$. CO_2 was also found at $\approx 3\sigma$, which was contested in S. P. Schmidt et al. (2025) but later supported at $\approx 4\sigma$ by additional data by R. Hu et al. (2025). This presence of both CH_4 and CO_2 but apparent depletion of CO , NH_3 , and H_2O pointed toward the possibility of K2-18 b being hycean: an ocean world with a thin (≤ 100 bars) atmosphere on top (N. Madhusudhan et al. 2021). Potential traces of DMS were also inferred, from this NIR observation but also from the later MIRI transit (N. Madhusudhan et al. 2025a), although there it was found to be degenerate with DMDS. As discussed in Section 1 and L. Pica-Ciamarra et al. (2026), some other works suggested alternate explanations (R. Luque et al. 2025; K. B. Stevenson et al. 2025; J. Taylor 2025; L. Welbanks et al. 2026), but the possibility of DMS was still supported considering all available data (R. Hu et al. 2025; L. Pica-Ciamarra et al. 2026).

Next, TOI-270 d (M. N. Günther et al. 2019) was again first observed with HST WFC3 (T. Mikal-Evans et al. 2023), also finding a hydrogen-dominated atmosphere with water vapor. Then, with JWST NIRSpec G395H and NIRISS data (B. Benneke et al. 2024; M. Holmberg & N. Madhusudhan 2024; L. Felix et al. 2025; S. Constantinou et al. 2026), the main species found were again CH_4 and CO_2 , although this time H_2O was still favored at $\approx 2\sigma$, along with CS_2 and potentially other species that are very degenerate (including C_2H_6 , NH_3 , CH_3F , CH_3Cl , H_2CS , CS , and DMS). These results have been interpreted as TOI-270 d being either a hycean planet (M. Holmberg & N. Madhusudhan 2024; F. E. Rigby & N. Madhusudhan 2025; S. Constantinou et al. 2026), a mixed-envelope planet (B. Benneke et al. 2024), or a magma ocean planet (M. C. Nixon et al. 2025). Then, M. Holmberg et al. (2026) analyzed the MIRI-LRS transmission spectrum of this planet and found evidence for excess absorption in the mid-infrared that could be explained by multiple species with degenerate spectral features, albeit different from those inferred in the NIR.

Finally, TOI-732 c (R. Cloutier et al. 2020) was, on the contrary, never observed with HST. Its first atmospheric

characterization was with ground-based spectroscopy, specifically with the IGRINS instrument of Gemini-South (S. H. C. Cabot et al. 2024). This study found marginal evidence ($\approx 2\sigma$) for CH_4 . Then, F. E. Rigby et al. (2025) presented three JWST transits, one from each of NIRISS, NIRSpec G395H, and MIRI. This work confirmed the presence of CH_4 in a hydrogen-dominated atmosphere but did not find substantial evidence for other major molecules. However, it found potential evidence for more complex molecules, including isobutene and 1-pentene, which were independently favored in both the NIR and MIRI data.

2.2. Datasets and Metrics

For each planet, there has been only one MIRI transit observation. However, apart from GJ 1214 b and GJ 367 b, each observation has been reduced with at least two different pipelines, among them Eureka! (T. J. Bell et al. 2022), Tiberius (J. Kirk et al. 2017; Z. Rustamkulov et al. 2023), CASCADE (L. Carone et al. 2021; J. Bouwman et al. 2023), ExoTiC-MIRI (D. Grant et al. 2023a), TEATRO (A. Dyrek et al. 2024; N. Crouzet et al. 2025), JExoRES (M. Holmberg & N. Madhusudhan 2023), JexoPipe (S. Sarkar et al. 2024), exoTEDRF (M. Radica 2024), and SPARTA (E. M.-R. Kempton et al. 2023). To ensure that our work is robust to the pipeline choices, we use spectra from at least two different pipelines per planet when available and list them in Table 2 and in Table 11 in Appendix B. Because WASP-107 b has two spectra obtained with the Eureka! pipeline, we will refer to the one from L. Welbanks et al. (2024) as the W24 spectrum throughout this work.

2.2.1. Wavelength Ranges

We consider the wavelength ranges of the spectra based on previous works as follows. First, for the JExoRES and JexoPipe spectra of K2-18 b, TOI-270 d, and TOI-732 c, we use the same wavelength ranges as the retrievals of L. Pica-Ciamarra et al. (2026), F. E. Rigby et al. (2025), and M. Holmberg et al. (2026), respectively. Then, the three K2-18 b spectra from R. Luque et al. (2025), obtained with the reduction pipelines SPARTA, exoTEDRF, and Eureka!, were plotted in their Figure 1. In that figure, we see that the bluest data point at $5.125 \mu\text{m}$ is somewhat inconsistent between the three spectra: 2858^{+40}_{-40} , 3006^{+46}_{-46} , and 3242^{+97}_{-97} ppm, respectively. This corresponds to a discrepancy of 3.7σ between SPARTA and Eureka!. All other data points are within $\lesssim 2\sigma$ between the three reductions. Thus, we decide to remove the $5.125 \mu\text{m}$ data point. For the other spectra, we remove any data outside of the 5 – $12 \mu\text{m}$ range, in order to be consistent with the temperate sub-Neptunes: the first data point of the L 168-9 b spectrum and the last 12 data points of the WASP-107 b spectrum. Finally, we note that all the spectral resolutions are kept as provided by each reference. We summarize the wavelength ranges in Table 2.

2.2.2. Flat Line Fit

We first fit each spectrum with a flat line model, to test the null hypothesis of a featureless spectrum. This is measured by the best-fit χ^2 (obtained for the mean transit depth weighted by the inverse uncertainties), which we write χ^2_{flat} . We then convert each χ^2_{flat} into a p -value, defined as the probability that

Table 2
List of Spectra Used in the Retrieval Exploration of Sections 3 and 4

Planet	Pipeline	N_p	λ Range	χ^2_{flat}	$\chi^2_{r,\text{flat}}$	p_{flat}	χ^2_{base}	n_c	$\chi^2_{r,\text{base}}$	p_{base}	$\ln Z_{\text{base}}$	References
GJ 1214 b	SPARTA	14	5.28–11.75	25.5	1.96	0.02	23.8	3	2.16	0.01	103.59	(1)
GJ 367 b	SPARTA	11	5.36–11.45	17.3	1.73	0.07	16.8	2	1.87	0.05	94.88	(2)
L 168-9 b	Eureka!	47 ^a	5.01–11.86	75.3	1.64	4·10 ⁻³	74.1	2	1.65	4·10 ⁻³	366.43	(3)
	CASCADE ^{×0.8}	47 ^a	5.01–11.86	62.5	1.36	0.05	52.8	2	1.17	0.20	384.18	(3)
	ExoTiC	47 ^a	5.01–11.86	52.8	1.15	0.23	49.3	3	1.12	0.27	379.79	(4)
WASP-107 b	Eureka!	46 ^b	5.06–11.83	613	13.6	≤10 ⁻⁶	74.8	9	2.02	2·10 ⁻⁴	310.69	(5)
WASP-17 b	Eureka!	28	5.13–11.88	55.2	2.04	1·10 ⁻³	29.3	3	1.17	0.25	186.41	(6)
	ExoTiC	28	5.13–11.88	39.1	1.45	0.06	23.2	3	0.93	0.57	189.21	(6)
WASP-39 b	Eureka!	28	5.13–11.88	75.7	2.80	2·10 ⁻⁶	45.5	3	1.82	3·10 ⁻³	172.60	(7)
	Tiberius	26	5.13–11.38	62.4	2.49	5·10 ⁻⁵	40.6	3	1.77	0.01	159.72	(7)
	SPARTA	26	5.13–11.38	56.9	2.11	7·10 ⁻⁴	35.2	3	1.53	0.05	180.25	(7)
WASP-43 b	Eureka! ^{×0.7}	14	5.25–11.75	22.9	1.76	0.04	22.6	2	1.88	0.03	99.14	(8)
	SPARTA	14	5.25–11.75	24.4	1.87	0.03	21.5	2	1.79	0.04	99.75	(8)
K2-18 b	JExoRES	29	5.78–11.79	29.7	1.06	0.38	29.1	2	1.08	0.36	213.08	(9)
	JexoPipe	29	5.78–11.79	32.4	1.16	0.26	29.2	3	1.12	0.30	207.97	(9)
	Eureka!	27 ^a	5.38–11.88	54.2	2.08	1·10 ⁻³	48.5	2	1.94	3·10 ⁻³	193.48	(10)
	exoTEDRF	27 ^a	5.38–11.88	53.2	2.05	1·10 ⁻³	44.3	2	1.77	0.01	195.94	(10)
	SPARTA	27 ^a	5.38–11.88	71.3	2.74	4·10 ⁻⁶	51.7	2	2.07	1·10 ⁻³	194.45	(10)
TOI-270 d	JExoRES	26	5.49–10.96	40.3	1.61	0.03	34.2	3	1.49	0.06	199.31	(11)
	JexoPipe	26	5.49–10.96	55.7	2.39	1·10 ⁻⁴	50.0	3	2.43	1·10 ⁻¹	193.12	(11)
TOI-732 c	JExoRES	29	5.78–11.79	44.3	1.58	0.03	37.9	3	1.46	0.06	208.61	(12)
	JexoPipe	29	5.78–11.79	54.4	1.94	2·10 ⁻³	47.6	3	1.83	6·10 ⁻³	199.97	(12)

Note. ^{×f}Uncertainties multiplied by a factor f (see Section 2.2.2). ^a First data point removed. ^b Last 12 data points removed (see Section 2.2.1). We give the number of data points N_p and the wavelength range after these removals. We then give the χ^2 and p -values of the flat line fit and the baseline retrievals (see Section 3), as well as the $\ln Z$ value for the latter. n_c is the number of constrained parameters, so $\chi^2_{r,\text{base}} = \frac{\chi^2_{\text{base}}}{N_p - n_c}$ (for the flat line fit, $n_c = 1$).

References. (1) E. M.-R. Kempton et al. (2023); (2) M. Zhang et al. (2024); (3) J. Bouwman et al. (2023); (4) M. K. Alam et al. (2025); (5) L. Welbanks et al. (2024); (6) D. Grant et al. (2023b); (7) D. Powell et al. (2024); (8) T. J. Bell et al. (2024); (9) N. Madhusudhan et al. (2025a); (10) R. Luque et al. (2025); (11) M. Holmberg et al. (2026); (12) F. E. Rigby et al. (2025).

a flat spectrum with random noise would produce a χ^2_{flat} higher than the one observed. If $p \leq 0.05$, then we can reject the null hypothesis of a flat spectrum at 95% confidence. However, the converse is not true; i.e., a spectrum with a higher p (hence a lower χ^2_{flat}) could still have correlated residuals and would not necessarily imply a flat spectrum.

Apart from GJ 367 b, each planet has at least one spectrum that can reject a flat line, and we demonstrate in Section 2.2.3 that the spectra of the same planet are consistent with each other. This justifies searching for atmospheric features fitting these spectra. This is specifically interesting for K2-18 b, where we see that the three spectra from R. Luque et al. (2025) have high χ^2_r values (1.77–2.07), yielding low p -values ($\leq 10^{-3}$). This means that one could expect to find a higher model preference for extra absorbers than in the spectra from N. Madhusudhan et al. (2025a) that only have $\chi^2_r = 1.08$ and 1.12, as noticed in J. Taylor (2025). This is discussed in Section 4.2.2. Finally, we multiply the uncertainties of the CASCADE spectrum of L 168-9 b and the Eureka! (v1) spectrum of WASP-43 b by 0.8 and 0.7, respectively, to have $\chi^2_{r,\text{base}} > 1$ for both, so that the retrievals are more likely to find molecules that improve the fit. As our conclusion is a nondetection of complex molecules on these spectra (see Section 4.1), this is a conservative choice. All this information is summarized in Table 2.

2.2.3. Pipeline Consistency

We now attempt to compare multiple spectra of the same planet. We include all planets except GJ 1214 b and GJ 367 b, which only have one spectrum each. We first remove the mean transit depth (weighted with uncertainties) of each spectrum, then divide the residuals by the uncertainties. Then, we compare two resulting arrays, X and Y, on their overlapping wavelength range with the Pearson correlation coefficient $r_{X,Y} := \frac{\overline{E(XY)} - E(\bar{X})E(\bar{Y})}{\sigma_X \sigma_Y}$. Here, $E(X)$ and σ_X are the error-weighted mean (which is zero here by definition) and standard deviations of X, respectively. $r_{X,Y}$ is always between -1 and 1, with positive and negative values indicating correlation and anticorrelation, respectively. Finally, we create samples of random arrays and compute their Pearson coefficients in order to get a cumulative distribution function and convert our correlation coefficient into p -values in the same way as for the χ^2_{flat} metric. In this case, p is thus the probability that two random arrays would have a higher correlation coefficient than the one observed.

We show the results in Figure 2. The JExoRES and JexoPipe spectra of K2-18 b cannot be compared with the other three with this metric, because the wavelength binning is different. We see that all the reduction pipelines give quite consistent spectra for each planet, with all p -values being less

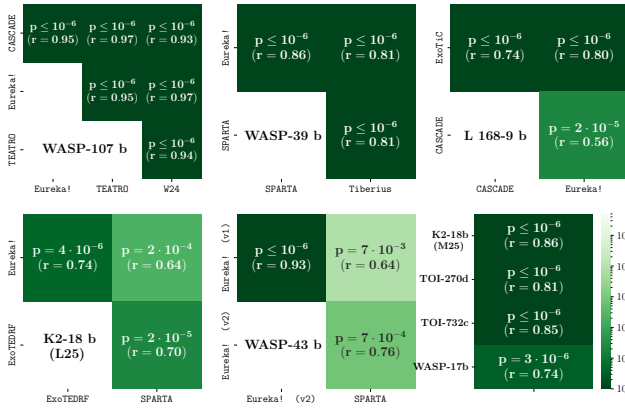


Figure 2. Correlations between different data reductions of the same transmission spectrum observed for each planet (see Section 2.2.3). We use all the spectra from Table 2 and Appendix B. For each pair of spectra compared, we show the p -value, which defines the log-linear color map, and the Pearson coefficient r below. Each of the first five heat maps corresponds to a single planet, and the last one shows the correlations between the only two available reductions of the four planets listed. For K2-18 b, the spectra from N. Madhusudhan et al. (2025a), shown as M25, cannot be compared with those of R. Luque et al. (2025), shown as L25, because of the different wavelength binning.

than 10^{-2} , and even $5 \cdot 10^{-4}$, except for WASP-43 b. The latter is due to the smaller number of data points.

2.2.4. Correlations between Planets

Now we compare the spectra of different planets. This is motivated by the similarities between the three sub-Neptunes in our sample, in terms of size, equilibrium temperature, and previously detected species (see Table 1). We now quantify this using the Pearson correlation coefficient defined in Section 2.2.3. We compare datasets that have the same wavelength binning, again on their overlaps. In addition, we bin down the L 168-9 b and WASP-107 b spectra that have higher resolution, to match the other spectral grids using SpectRes (A. C. Carnall 2017). Then, when comparing two planets with n and m different spectra each, there are in total $n \times m$ combinations, so instead of reporting all the values, we take the median correlation coefficients and p -values. We show the results in Figure 3. We see that, as expected, K2-18 b and TOI-270 d are highly correlated with a median p -value of 0.02. TOI-732 c also shows correlation with K2-18 b ($p = 0.03$) and tentative correlation with TOI-270 d ($p = 0.10$). These three sub-Neptunes do not seem correlated with any other planet ($p > 0.2$); however, WASP-107 b, WASP-17 b, and WASP-39 b all seem quite correlated ($p < 0.05$). This is also consistent with the fact that all three are hot gas giants with strong H_2O detections (see Section 2.1.1). This simple analysis already indicates that the features seen with MIRI seem unlikely to be merely random noise (otherwise there would not be such similarities between three planets) or systematics (otherwise these spectra would be quite similar regardless of their type).

3. Retrieval Setup

After this initial analysis of the transmission spectra in our sample, we conduct a more in-depth analysis using atmospheric retrievals (N. Madhusudhan & S. Seager 2009; B. Benneke & S. Seager 2013; N. Madhusudhan 2018) with the open-source retrieval code petitRADTRANS (pRT;

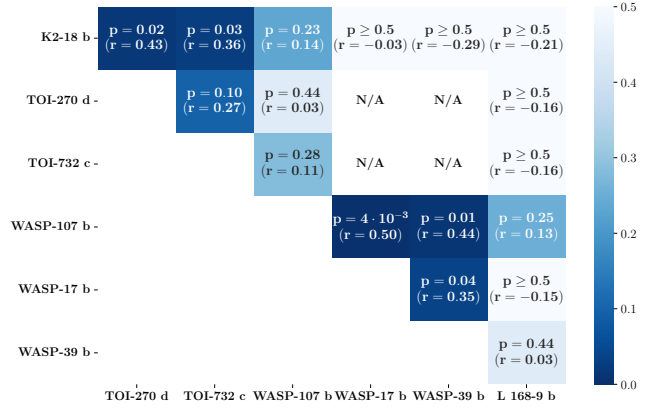


Figure 3. Correlations between transmission spectra of different planets (see Section 2.2.4). Note that here the color map is linear between $p = 0$ and 0.5, because the p -values are higher than in Figure 2 (as expected for different planets). TOI-270 d and TOI-732 c cannot be compared with WASP-17 b and WASP-39 b because of the different wavelength binning.

P. Mollière et al. 2019; E. Nasedkin et al. 2024). In each of these spectra, we look for multiple potential trace species, following the approach of N. Madhusudhan et al. (2025a), F. E. Rigby et al. (2025), M. Holmberg et al. (2026), L. Pica-Ciamarra et al. (2026), and L. Welbanks et al. (2026). Our main goal is to determine whether or not the additional absorbers found in these works are also found in other planets. To do this, we run retrievals with a selection of N baseline species, depending on the planet, and one additional molecule X at a time (we refer to these as “ $N+X$ ” retrievals). We compare the Bayesian evidence of each retrieval with one containing only the baseline species (which we refer to as the baseline retrieval) to get a model preference $\ln B$ for each molecule X for the given spectrum. We call $\ln B_{\max}$ and $\ln B_{\min}$ the highest and lowest preference obtained for a molecule across all the spectra of a given planet.

In what follows, we describe the general framework of the retrieval model in Section 3.1. We then motivate our choices of baseline species in Section 3.2 and discuss the opacity sources explored in Section 3.3. Then, we describe the temperature and cloud parameterization in Section 3.4 and the bulk parameter fitting in Section 3.5. Finally, we specify the different treatment of GJ 1214 b, L 168-9 b, and GJ 367 b in Section 3.6 and of WASP-107 b in Section 3.7. All the parameter priors are summarized in Appendix A.

3.1. General Framework

The retrieval framework considers the terminator atmosphere in one dimension, assuming hydrostatic equilibrium and uniform molecular abundances with pressure. The model has 100 pressure layers between 10^{-6} and 10 bars, spaced log-uniformly. We include collision-induced absorption for $\text{H}_2\text{--H}_2$, $\text{H}_2\text{--He}$, and He--He (J. Borysow et al. 1988; G. S. Orton et al. 2007; M. Abel et al. 2011; C. Richard et al. 2012). We sample from the posterior probability distribution using MultiNest (F. Feroz et al. 2009). We use 500 live points for most retrievals, but we increase this to 700 for WASP-107 b because of the higher SNR and to 1000 for each baseline retrieval. The latter improves the precision of all Bayesian comparisons, with minimal increase in computing time.

3.2. Choice of Baseline Species

In all our retrievals, we assume H_2 and He ($\text{He}/\text{H} = 0.17$ by number) as the background gas and fit for the abundances of additional species. This is because most of the planets were found to be H_2/He -dominated (see Section 2.1). The exceptions to this are GJ 1214 b, L 168-9 b, and GJ 367 b; we explain their different treatments in Section 3.6. Apart from H_2 and He, in the baseline retrievals, we add the species listed in Appendix A. For the three sub-Neptunes, these are chosen to be consistent with previous studies: CH_4+CO_2 for K2-18 b (N. Madhusudhan et al. 2025a; L. Pica-Ciamarra et al. 2026; 2+X setup), $\text{CH}_4+\text{CO}_2+\text{H}_2\text{O}$ for TOI-270 d (M. Holmberg et al. 2026; 3+X), and $\text{CH}_4+\text{CO}_2+\text{H}_2\text{O}+\text{CO}$ for TOI-732 c (F. E. Rigby et al. 2025; 4+X). For WASP-39 b, WASP-17 b, and WASP-43 b, we only add H_2O (1+X setup), which was found with the highest significance in previous MIRI works (see Section 2.1). In general, the effect of a simpler baseline retrieval is to increase the evidence for additional species. This was shown in previous works, including N. Madhusudhan et al. (2025a), and in this work in Appendix D.2. As mentioned in Section 2.2.2 and shown in Section 4.1, our conclusion in this work is a nondetection of complex molecules in these spectra, so this choice is conservative. Finally, we add $\text{SO}_2+\text{H}_2\text{O}+\text{H}_2\text{S}+\text{PH}_3+\text{SO}$ for WASP-107 b (5+X) and discuss this choice in Section 3.7.

One difference of pRT from most retrieval codes is that the abundance priors for species other than H_2/He are defined in mass fractions rather than volume mixing ratios (VMRs). In order to approximately match the standard bounds in the field for $\log(\text{VMR})$ of 10^{-12} – $10^{-0.3}$, we choose mass fraction bounds of 10^{-11} –1, except for WASP-107 b (see Section 3.7).

3.3. Species Explored

As mentioned earlier, we search for one molecule X at a time, in addition to the baseline ones in Appendix A. In total, we search for 160 such molecules, listed in Appendix I. Since pRT implements correlated- k opacities natively, we use molecular opacities in the correlated- k mode (A. A. Lacis & V. Oinas 1991) natively available in pRT or obtained from the ExoMol opacity database (K. L. Chubb et al. 2021; J. Tennyson et al. 2024) when available (CH_3Cl , CH_3F , CH_4 , CO , CO_2 , CS , CS_2 , C_2H_2 , C_2H_4 , HCN , H_2CS , H_2O , H_2S , NH_3 , OCS , PH_3 , SiH_4 , SiO , SO , SO_2 , and SO_3).

For the remaining species where only HITRAN cross sections are available (I. Gordon et al. 2026), we use the data at $T \approx 300$ K and $P \approx 1$ bar, or the closest available temperature and pressure, and we convert them to the correlated- k format. The exception is ethane (C_2H_6), for which we take the HITRAN line list and convert it into a pRT correlated- k table using Cthulhu (A. Agrawal & R. J. MacDonald 2024) and Exo_k (J. Leconte 2021). We use the pRT default model resolution $R = 1000$ and number of Gaussian points $N_g = 16$.

3.4. Temperature Profile and Clouds

In our retrievals, we apply an isothermal P – T profile with uniform priors depending on the planets’ equilibrium temperatures (see Appendix A). In Appendix G, we show that the results are mostly insensitive to setting narrower temperature priors. This reduces computation time. We also verified that for most planets, a more complex P – T profile prior yielded a

temperature posterior consistent with an isotherm. For aerosols, we use a patchy cloud deck with only two parameters: the opaque cloud-top pressure P_c and the cloud coverage fraction ϕ . This corresponds to two of the four parameters in the cloud+haze setup of R. J. MacDonald & N. Madhusudhan (2017) and A. Pinhas et al. (2019), because the haze in that prescription only provides significant extinction in the visible/NIR.

3.5. Bulk Parameters

For each planet, we fix its radius, mass, and host star radius according to the values in Table 1 and fit the reference pressure between 10^{-6} and 10 bars. In reality, the masses found from radial velocity observations have uncertainties. In Appendix G, we show that our results are mostly insensitive to adding Gaussian priors on the planetary mass or replacing the reference pressure prior by a radius prior.

3.6. Exception 1: Featureless Spectra

As mentioned in Sections 2.1 and 3.2, GJ 1214 b, L 168-9 b, and GJ 367 b have shown mostly featureless JWST-MIRI-LRS spectra (J. Bouwman et al. 2023; E. M.-R. Kempton et al. 2023; M. Zhang et al. 2024), indicative of either high clouds or non- H_2/He -dominated atmospheres. This means that in order to constrain their atmospheric composition, one could use different abundance priors from the ones described in Section 3.2, for instance, central-log-ratio (CLR) priors (B. Benneke & S. Seager 2012). However, because our goal is to conduct a comparative analysis of the ten exoplanet spectra, we only make small changes to the setup described in Section 3.2. First, we choose CO_2 as a baseline species, because it is a very weak absorber in the 5–12 μm range (see, for instance, Figure 2 of L. Pica-Ciamarra et al. 2026), so its main purpose is to allow the mean molecular weight (MMW) to increase. We also restrict its mass fraction prior between 10^{-3} and 1, because any value below $\approx 10^{-2}$ will have a negligible effect on the MMW. Finally, we restrict the mass fraction of the extra molecule added between 10^{-11} and 10^{-1} , so that it does not replace H_2/He or CO_2 as the main gas. We note that for these three planets, we tested replacing CO_2 with H_2O or combining both as baseline species, which did not have a considerable impact on the results presented in Section 4.1.

3.7. Exception 2: WASP-107 b

As mentioned earlier, the WASP-107 b spectra have by far the highest SNR. This is evident from the high $\chi^2_{r,\text{flat}}$ metric (see Section 2.2.2 and Appendix B). First, this means that we need to add multiple molecules in the baseline retrieval for it to achieve a reasonable fit. We first try with H_2O , SO_2 , and H_2S , the three gas-phase species found with highest significance in A. Dyrek et al. (2024). With each spectrum, these three species are well constrained, but the χ^2_r are still too high, ranging from 3 to 6, whereas all the other planets are below 2.5. The lowest value of 3 is obtained with the W24 spectrum, so we choose to focus on this one in what follows. Also, we notice that the retrievals are pushing toward high mass fractions of H_2S in order to increase the MMW. However, WASP-107 b being a gas giant, its atmosphere must be H_2/He -dominated. So as in Section 3.6, but here for all the molecules except H_2/He , we restrict the mass fraction priors between 10^{-11} and 10^{-1} .

The next step to find a well-suited baseline set of molecules is that we run a large retrieval with all the same gas-phase species as in A. Dyrek et al. (2024): H_2O , SO_2 , H_2S , NH_3 , CO , PH_3 , HCN , C_2H_2 , SiO , CH_4 , CO_2 , and SO . We keep basic patchy clouds rather than silicate clouds, and we note (as mentioned in Section 2.1.1) that A. Dyrek et al. (2024) used the MIRI data together with HST data, so we do not expect the exact same results. We find strong constraints on H_2O , SO_2 , H_2S , PH_3 , and SO , a weak constraint on SiO , and upper bounds on the other species. We then run a new retrieval with just the first five and get $\chi_r^2 = 2.02$, which is a comparable value to other baseline retrievals, so we choose this as the WASP-107 b baseline.

Finally, the high SNR and the five well-constrained molecules in the baseline cause the retrievals to be computationally expensive, so we decide to only use the W24 spectrum. In addition, we only explore a limited selection of 44 molecules, given in Appendix I.

4. Results

In this section, we present the results of our species exploration, described in Section 3. As in F. E. Rigby et al. (2025), M. Holmberg et al. (2026), and L. Pica-Ciamarra et al. (2026), we consider that a molecule is a good candidate to explain the planet's extra absorption if it reaches $\ln B \geq 2$ across all data reductions used; in other words, $\ln B_{\min}$ must be ≥ 2 . For completeness, we will also report some molecules that are below this threshold, although we do not consider them to be good candidates. We decide to not convert the $\ln B$ values into “ $N\sigma$ ” detection significances, following the recommendation of D. P. Thorngren et al. (2026), although we show a conversion table in Appendix E. This previous work also recommended using the BPICS metric in addition to the Bayes factor, so we do this and show the results in Appendix F.

In Figure 4, we plot one spectrum for each planet, along with its best-fit model for the molecule that achieved the highest $\ln B_{\min}$. Each spectrum has been converted from transit depth $\left(\frac{R_p}{R_*}\right)^2$ into radius ratio $\frac{R_p}{R_*}$, so that the scatter and uncertainties are of comparable size. These converted spectra are also the ones used in the χ^2 comparison presented in Appendix C. We then show more precise comparisons of multiple retrievals for each planet in Appendix H.

4.1. Uninhabitable Planets

We start with presenting the retrieval results for six of the seven uninhabitable planets of our sample, excluding WASP-107 b, which we show in Section 4.3. We first report the constraints obtained from the baseline retrievals, including H_2O abundance and temperature for WASP-39 b and WASP-17 b. Then, we list the additional absorbers that are potentially inferred in these planets.

4.1.1. Baseline Fits

These six planets are GJ 1214 b, L 168-9 b, WASP-17 b, WASP-39 b, and WASP-43 b. As explained in Section 3.2, their baseline retrievals only include H_2/He and H_2O or CO_2 . We find H_2O contributions in WASP-17 b and WASP-39 b, consistent with D. Grant et al. (2023b) and D. Powell et al. (2024), respectively. In contrast, we do not find any H_2O contribution for WASP-43 b, unlike in its

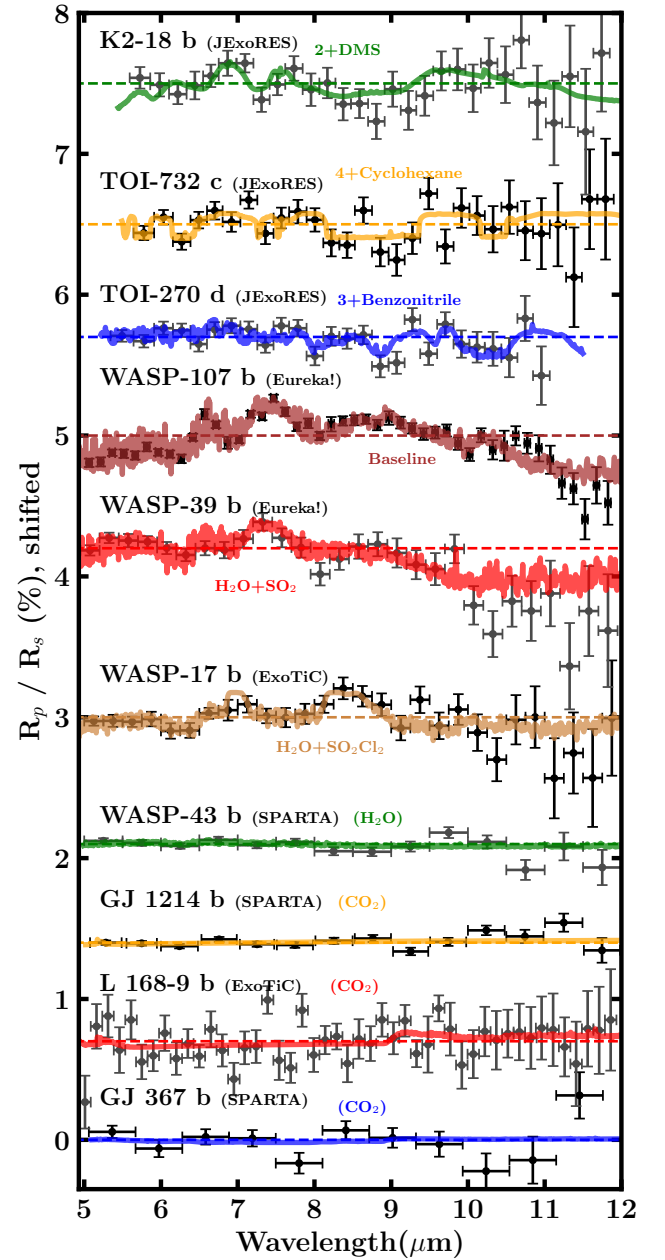


Figure 4. JWST MIRI-LRS transmission spectra of all ten planets considered in this work. In black and gray are the data from the indicated reduction pipeline. In colored dashed lines are the mean transit depths, and in colored solid lines are the best-fit model spectra from the retrieval, including the molecule reaching the highest $\ln B_{\min}$ for this planet, if $\ln B_{\min} \geq 2$ (see Section 4). When no molecule reaches this threshold, we display the baseline retrieval spectra, which are discussed in Section 3.2 and summarized in Appendix A. We write (H_2O) or (CO_2) when the molecule is weakly constrained. Each spectrum has been converted from transit depth $\left(\frac{R_p}{R_*}\right)^2$ into radius ratio $\frac{R_p}{R_*}$, as in Appendix C.

previous phase curve study (T. J. Bell et al. 2024). However, this is not necessarily contradictory, as the transit alone offers less information content. Finally, we also do not find any CO_2 contribution in GJ 1214 b, L 168-9 b, or GJ 367 b, as expected from the spectra being flat and CO_2 absorbing very weakly in this range. So, for these four planets, the atmospheric model is just marginally a better fit than a flat line, as shown in Table 2. Thus, the atmospheric temperature is

Table 3Model Preferences for the Two Species that Reach $\ln B_{\min} \geq 2$ in Uninhabitable Planets and the 12 Additional Species that Are Highlighted in Section 4.1.2

Molecule	WASP-39 b	WASP-17 b	WASP-43 b	GJ 1214 b	L 168-9 b	GJ 367 b	K2-18 b	TOI-270 d	TOI-732 c
SO ₂	3.1 – 6.3^{max}	...	...	...	<0.9	...	...	...	...
SO ₂ Cl ₂	...	2.8 – 3.0^{max}	...	...	...	...	<0.5	...	...
CH ₄	0.8–5.3	<0.1	...	...	...	...	<1.0	<0.3	<0.1
SO ₃	1.3–3.4	...	<0.3	...	...	...	<0.6	...	<1.2
SOF ₂	1.5–2.9	...	...	...	<1.0	...	...	...	...
C ₂ H ₂	0.2–2.2	...	...	...	...	...	<1.3	<0.1	<0.5
CH ₃ Cl	0.2–2.1	...	<0.1	...	...	...	0.4–3.0	<0.1	<1.5
HCN	0.1–2.0	...	...	...	...	...	<1.3	<0.3	<1.9
Benzene	...	...	0.1–2.7 ^{max}	...	...	0.3	<1.0	...	1.4–4.4
Cyclohexane	<0.1	...	<1.2	...	...	...	–1.1–2.1	...	4.3 – 6.2^{max}
C ₂ H ₄	...	...	...	1.6 ^{max}	...	0.2	<1.3	...	<1.7
Cyclopentane	...	...	...	1.5	...	...	–1.0–2.7	<0.1	0.9–3.1
CCl ₂ S	<0.7	...	...	...	<1.3 ^{max}	...	...	...	...
Toluene	<0.4	...	<1.3	...	...	0.7 ^{max}	<0.5	<0.9	<0.8

Note. If $\ln B_{\max} \geq 2$, we write “ $\ln B_{\min} - \ln B_{\max}$ ”; if $0 < \ln B_{\max} < 2$, we write “ $< \ln B_{\max}$ ”; finally, if $\ln B_{\max} \leq 0$, we write an ellipsis. Bold indicates $\ln B_{\min} \geq 2$. Italics indicate a spectrum plotted in Appendix H. Superscript “max” indicates the species with the highest $\ln B_{\max}$ for this planet.

only well constrained for WASP-17 b and WASP-39 b at $T \approx 1550$ – 1900 and 1050 – 1200 K, respectively (depending on the data reduction), which is consistent with their respective T_{eq} values of ~ 1750 and 1150 K. On the other hand, the patchy cloud deck stays unconstrained. Having not included SO₂ for WASP-39 b, the baseline fits are underfitting ($\chi^2_{\text{base}} \geq 1.5$), unlike in WASP-17 b, where $\chi^2_{\text{base}} \leq 1.2$, so we expect more potential extra absorbers to be inferred in the former (see the following Section 4.1.2).

4.1.2. Additional Absorbers

We now present the exploration results for these uninhabitable planets, summarized in Table 3. As discussed in Section 3.2, for these planets, we consider the 1+X exploration with H₂O or CO₂ being the only baseline species. Out of the ≥ 150 species explored, we find that only two species have $\ln B_{\min} \geq 2$ for at least one planet: SO₂ in WASP-39 b and SO₂Cl₂ in WASP-17 b. The former was expected, because it was also found in D. Powell et al. (2024). We show in Appendix D.1 that our results are consistent with this previous work. On the other hand, WASP-17 b’s extra absorption at $\lambda \approx 8.5$ – $9 \mu\text{m}$ is more likely to be caused by silicate clouds (D. Grant et al. 2023b) than by SO₂Cl₂, a chemical that has never been found naturally on Earth or detected in space.

We find a few other species with weaker evidence of $\ln B_{\max} \geq 2$. In this case, we infer six other molecules (CH₄, SO₃, SOF₂, C₂H₂, CH₃Cl, and HCN) in WASP-39 b and benzene (C₆H₆) in WASP-43 b. For WASP-39 b, we show in Appendix D.2 that this model preference vanishes (i.e., falls below $\ln B_{\max} = 1$) for all of them when including SO₂ in the baseline retrieval. As for benzene, it could potentially be present in WASP-43 b’s atmosphere if there were also lower-order hydrocarbons like CH₄ and C₂H₆; however, we would not expect it at the retrieved abundances of 10 ppm to 1% (J. I. Moses et al. 2005; C. A. Nixon 2024).

Next, five additional species are worth highlighting, even though they have $\ln B_{\max} < 2$. First, C₂H₄, CCl₂S, and toluene (C₇H₈) are the molecules with the highest $\ln B_{\max}$ values in GJ 1214 b (1.6), L 168-9 b (1.3), and GJ 367 b (0.7), respectively. We also mention cyclopentane (C₅H₁₀), which

obtains $\ln B = 1.5$ in the GJ 1214 b spectrum, because it is the only molecule apart from SO₂ and SO₂Cl₂ that crosses our threshold with the BPICS metric for one of these six planets (see Appendix F). Finally, we note that cyclohexane (C₆H₁₂) reaches $\ln B_{\max} = 1.2$ in WASP-43 b and is inferred in two of the temperate sub-Neptunes, namely, K2-18 b (only in the JExoPipe spectrum, at $\ln B = 2.1$) and TOI-732 c. In the latter, it is the molecule with the highest model preference for both the JExoRES ($\ln B = 4.3$) and JExoPipe ($\ln B = 6.2$) spectra (more information on this in Section 4.2).

4.2. Temperate Sub-Neptunes

Now, we present the results for the three temperate sub-Neptunes. We expect to see similarities between their retrieval results because of the spectral similarities presented in Section 2.2.4.

4.2.1. Reanalysis of Previous Spectra

We start by presenting the exploration results for the JExoRES and JExoPipe spectra of K2-18 b and TOI-732 c. These were previously run with the retrieval code POSEIDON (R. J. MacDonald & N. Madhusudhan 2017, 2024) in L. Pica-Ciamarra et al. (2026) and F. E. Rigby et al. (2025), respectively. For K2-18 b, we run CH₄+CO₂+X (i.e., 2+X) retrievals and find 14 species with $\ln B \geq 2$ for the JExoRES spectrum and 17 for the JExoPipe spectrum. We find that 10 of these species are above the threshold for both spectra, which is consistent with the finding of L. Pica-Ciamarra et al. (2026), and we show them in Table 4. The only difference is that we do not find cyclohexane (C₆H₁₂) but instead find diethyl sulfide (C₄H₁₀S). We also confirm that the species with the highest preference is chloroethane (C₂H₅Cl; $\ln B = 3.2$ and 4.4 in JExoRES and JExoPipe, respectively).

For TOI-732 c, we run CH₄+CO₂+H₂O+CO+X (i.e., 4+X) retrievals and also find 10 species with $\ln B \geq 2$ across both spectra, which we list in Table 5. Only two are common with K2-18 b: chloroethane and methacrylonitrile (C₄H₅N). These were not highlighted in F. E. Rigby et al. (2025), because chloroethane was not considered, and the method only looked in the MIRI data for species that had $\ln B \geq 2$ in the

Table 4
K2-18 b M25 2+X Results (See Section 4.2.1)

Molecule	$\ln B_{\text{JRES}}$	$\ln B_{\text{JPipe}}$
Chloroethane ($\text{C}_2\text{H}_5\text{Cl}$)	3.2	4.4
Methacrylonitrile ($\text{C}_4\text{H}_5\text{N}$)	2.6	2.9
Butane (C_4H_{10})	2.6	2.6
Propyne (C_3H_4)	2.5	2.8
DMS ($\text{C}_2\text{H}_6\text{S}$)	2.2	2.8
Diethyl sulfide ($\text{C}_4\text{H}_{10}\text{S}$)	2.1	2.7
Allyl chloride ($\text{C}_3\text{H}_5\text{Cl}$)	2.1	2.3
Bromoethane ($\text{C}_2\text{H}_5\text{Br}$)	2.5	2.0
Dichloromethane (CH_2Cl_2)	2.0	2.6
Cyclopentane (C_5H_{10})	2.0	2.1

Note. $\ln B_{\text{JRES}}$ and $\ln B_{\text{JPipe}}$ are the evidence obtained with the JExoRES and JExoPipe spectra, respectively. We show the 10 species with $\ln B_{\text{min},\text{M25}} \geq 2$. These values are consistent with Table 1 of L. Pica-Ciamarra et al. (2026).

Table 5
TOI-732 c 4+X Results (See Section 4.2.1)

Molecule	$\ln B_{\text{JRES}}$	$\ln B_{\text{JPipe}}$
Cyclohexane (C_6H_{12})	4.3	6.2
3-methylpentane (C_6H_{14})	3.7	4.3
2-butene (C_4H_8)	3.3	5.0
3-methylhexane (C_7H_{16})	2.8	4.0
1-pentene (C_5H_{10})	2.4	2.5
Methacrylonitrile ($\text{C}_4\text{H}_5\text{N}$)	2.4	4.3
Chloroethane ($\text{C}_2\text{H}_5\text{Cl}$)	2.4	2.4
Isobutene (C_4H_8)	2.3	4.8
cis-2-pentene (C_5H_{10})	2.1	2.7
Hexane (C_6H_{14})	2.0	5.8

Note. We show the 10 species with $\ln B_{\text{min}} \geq 2$. Out of these, only 1-pentene and isobutene were also looked for in the MIRI data in F. E. Rigby et al. (2025) (Table 2), and these results are consistent.

NIR data, which was not the case for methacrylonitrile. As mentioned in Section 4.1.2, the highest model preference is reached for cyclohexane, at $\ln B = 4.3$ and 6.2 in JExoRES and JExoPipe, respectively. We also highlight benzene, which was found in one of the WASP-43 b spectra and is favored at $\ln B = 4.4$ in the JExoPipe spectrum of TOI-732 c (although only 1.4 in the JExoRES spectrum). Lastly, we also look at ethane because it would be expected to be present in the atmosphere if there are also higher-order hydrocarbons (J. I. Moses et al. 2005; C. A. Nixon 2024). We find $\ln B = 4.3$ in the JExoPipe spectrum but only $\ln B = 1.0$ in the JExoRES one.

Finally, for TOI-270 d, the exploration was conducted with the exact same pRT setup as in M. Holmberg et al. (2026), so we only need to run a few species that were not considered previously. We note that this previous work had more than 200 species, so the selection was reduced for the current work; however, we made sure to include all the species that reached $\ln B \geq 2$ in at least one spectrum. We show the results in Table 6. In this planet, only three molecules have $\ln B_{\text{min}} \geq 2$: benzonitrile ($\text{C}_7\text{H}_5\text{N}$), methacrylonitrile, and isobutene (C_4H_8). These were already found in M. Holmberg et al. (2026), and isobutene was highlighted for both, being favored in TOI-270 d and being one of only two species favored across all NIR and

Table 6
TOI-270 d 3+X Results from M. Holmberg et al. (2026)

Molecule	$\ln B_{\text{JRES}}$	$\ln B_{\text{JPipe}}$
Benzonitrile ($\text{C}_7\text{H}_5\text{N}$)	3.4	5.3
Methacrylonitrile ($\text{C}_4\text{H}_5\text{N}$)	2.5	3.2
Isobutene (C_4H_8)	2.3	4.3

Note. Only three species have $\ln B_{\text{min}} \geq 2$.

Table 7
The 19 Species with $\ln B_{\text{min},\text{L25}} \geq 2$ for K2-18 b and the Corresponding $\ln B_{\text{min},\text{M25}}$

Molecule	$\ln B_{\text{min},\text{L25}}$	$\ln B_{\text{min},\text{M25}}$
Ethyl mercaptan ($\text{C}_2\text{H}_6\text{S}$)	6.1	1.6
Cyclooctane (C_8H_{16})	4.2	0.0
2-butene (C_4H_8)	4.0	1.1
β -pinene-1S- ($\text{C}_{10}\text{H}_{16}$)	3.9	0.3
DL-limonene ($\text{C}_{10}\text{H}_{16}$)	3.8	0.3
Octane (C_8H_{18})	3.7	0.8
n-decane ($\text{C}_{10}\text{H}_{22}$)	3.6	0.7
n-tridecane ($\text{C}_{13}\text{H}_{28}$)	3.6	0.6
n-undecane ($\text{C}_{11}\text{H}_{24}$)	3.5	0.7
Diethyl sulfide ($\text{C}_4\text{H}_{10}\text{S}$)	3.4	2.1
n-nonane (C_9H_{20})	3.3	0.8
DMS ($\text{C}_2\text{H}_6\text{S}$)	2.9	2.2
Diethyl sulfate ($\text{C}_4\text{H}_{10}\text{O}_4\text{S}$)	2.7	0.8
Dimethyl sulfoxide ($\text{C}_2\text{H}_6\text{OS}$)	2.4	0.4
Dimethyl sulfate ($\text{C}_2\text{H}_6\text{O}_4\text{S}$)	2.4	0.5
DMDS ($\text{C}_2\text{H}_6\text{S}_2$)	2.4	1.8
Hexane (C_6H_{14})	2.3	1.0
Chloroethane ($\text{C}_2\text{H}_5\text{Cl}$)	2.1	3.2
n-tetradecane ($\text{C}_{14}\text{H}_{30}$)	2.0	0.8

Note. Bold indicates the only three species that reach $\ln B \geq 2$ across the five spectra from the two works (M25 and L25).

mid-infrared datasets of TOI-732 c (F. E. Rigby et al. 2025). We further highlight methacrylonitrile for being favored in all six spectra of temperate sub-Neptunes considered so far.

4.2.2. Analysis of New K2-18 b Spectra

In addition to these six spectra, we also perform our retrieval exploration on the three K2-18 b spectra obtained with different data reductions in R. Luque et al. (2025), without the first data point (see Section 2.2.1). We show the results in Table 7. As predicted in Section 2.2.2, the higher χ^2_{flat} values of these spectra allow for some species to reach much higher model preferences than with the JExoRES and JExoPipe spectra of K2-18 b. Namely, the exoTEDRF and SPARTA spectra are best fitted by ethyl mercaptan ($\text{C}_2\text{H}_6\text{S}$, an isomer of DMS) at $\ln B = 6.3$ and 6.1, respectively, and the Eureka! spectrum by 2-butene at a surprisingly high $\ln B = 9.7$. We also find that a lot more molecules reach the $\ln B \geq 2$ threshold: 57, 34, and 28 for the Eureka!, exoTEDRF, and SPARTA data, respectively. Nineteen of these species are common between the three spectra, with ethyl mercaptan the only one at $\ln B \geq 5$ in all three. Finally, out of these 19 species, only 3 are in common with the JExoRES and JExoPipe list: DMS ($\ln B = 2.2 - 5.6$), diethyl sulfide ($\text{C}_4\text{H}_{10}\text{S}$; $\ln B = 2.1 - 9.1$), and chloroethane ($\ln B = 2.1 - 8.0$). Out of these three, only chloroethane is found in both spectra of another temperate sub-

Table 8
WASP-107 b 5+X Results for the W24 Spectrum

Molecule	$\ln B$
SO ₂	28.4
H ₂ O	18.6
H ₂ S	17.3
SO	9.0
PH ₃	7.7
p-xylene	1.9
Methacrylonitrile	1.8
CO	0.6
SiO	0.6
SOF ₂	0.4
H ₂ CS	0.2

Note. We first show the evidence for the five baseline species, with bold indicating $\ln B \geq 2$; then the six that reach $\ln B \geq 0$. As mentioned in Section 4.3, we only look for 44 molecules outside the baseline (see Appendix I), and none reach $\ln B \geq 2$.

Neptune, TOI-732 c. We also highlight that we find $\ln B = 3.0$ for CH₃Cl with the Eureka! spectrum, which was also found at $\ln B = 2.1$ in the Tiberius spectrum of WASP-39 b (see Section 4.1.2). In both cases, it is not robust to the different data reductions. Finally, we mention ethane, which was argued to be degenerate with DMS in R. Luque et al. (2025). We do not find ethane at $\ln B \geq 2$ in any of the five K2-18 b spectra, but it does reach a value of $\ln B = 1.8$ with the Eureka! reduction.

We note that just like for most of the uninhabitable planet data in our sample, these MIRI spectra were never studied alone but only together with the NIR data. So, our results are not directly comparable with those of R. Luque et al. (2025).

4.3. WASP-107 b Results

Finally, we look at WASP-107 b. As mentioned in Section 3.7, it has been singled out for its high SNR. The baseline retrieval includes H₂O, SO₂, H₂S, SO, and PH₃, and we focus on the W24 spectrum. We start by computing the evidence for each of these five species by removing them one at a time from the baselines. We show the results in Table 8. We see that they are preferred with high $\ln B$ values ranging from 7 to 26, so removing just one of them significantly worsens the fit, as shown in Figure 17 in Appendix H. We note that SO and PH₃ had not been inferred in A. Dyrek et al. (2024), but this work used silicate clouds instead of our simple patchy cloud deck model. Thus, we checked that we were also able to constrain silicate clouds and improve the fit (from $\chi^2 = 76$ to 70) with this pRT setup, which would likely give us lower evidence values for SO and PH₃. Then, as mentioned in Section 3.7, we only look for 44 potential extra absorbers, and we find that only six reach $\ln B \geq 0$ and none reach $\ln B \geq 2$. Even if we had looked at all four spectra, we thus know that they would not reach $\ln B_{\min} \geq 2$. There could still be other species reaching $\ln B \geq 2$, but at least none in common with any other planet. We note that p-xylene (C₈H₁₀) and methacrylonitrile come close, at 1.9 and 1.8, respectively. The former was included in the list because we have noticed in previous tests that it can fit the data well, reaching, for instance, $\ln B = 8.5$ with the same setup applied to the CASCADE spectrum. This is not true for methacrylonitrile, which is not preferred, at $\ln B = -0.5$. In Table 9, we

summarise all molecules that are favored at $\ln B_{\min} \geq 2$ in at least one planet.

5. Summary and Discussion

In this work, we carry out a homogeneous survey of 10 JWST-MIRI-LRS transmission spectra, each of a different planet. Three of these planets are temperate sub-Neptune, K2-18 b, TOI-732 c, and TOI-270 d, and were predicted to be potential hycean worlds (N. Madhusudhan et al. 2021). The other seven are all hot and/or giant planets, so they cannot be habitable. We compared these observations with the Pearson correlation coefficient and showed that the temperate sub-Neptune spectra are very similar to each other but different from the other spectra. This indicates that the features in their nonflat spectra are unlikely to be due to systematics or random noise. Then, we performed atmospheric retrievals and searched for more than 150 potential trace species in each transit observation. When available, we used spectra obtained with different data reductions, in order to improve the robustness of our search, for a total of 21 such reduced spectra explored. Similarly to previous works (N. Madhusudhan et al. 2025a; F. E. Rigby et al. 2025; M. Holmberg et al. 2026; L. Pica-Ciamarra et al. 2026; L. Welbanks et al. 2026), we find that the MIRI spectra of K2-18 b, TOI-732 c, and TOI-270 d can each be explained by any one of 2–10 complex molecules (the list of candidates depends on the planet) beyond CH₄, CO₂, and H₂O. In contrast, we find no similar evidence for complex molecules in any of the other planets, known to be uninhabitable. Their spectra can be well explained with absorption due to only simple molecules, if any.

In this survey, we have chosen to focus only on MIRI-LRS spectra. There are two main reasons for this choice. First, it enables us to directly test the exploration approach of previous works (N. Madhusudhan et al. 2025a; F. E. Rigby et al. 2025; M. Holmberg et al. 2026; L. Pica-Ciamarra et al. 2026; L. Welbanks et al. 2026), which were also carried out on MIRI data separately, by applying it to the MIRI spectra of the other seven planets in our sample. Second, a survey of NIR and mid-infrared spectra together would not be homogeneous, because not all the planets in the sample have NIR data, and those that do have different numbers of transits with different instruments, as presented in Section 2.1. Thus, while combining NIR and mid-infrared data is an avenue that should be explored in the future, in order to leverage all the information content available, it is beyond the scope of the present work. One benefit of this choice is that in this wavelength range (5–12 μm), the stellar activity is minimal compared to the NIR, which facilitates the identification of planetary spectral features. Then, another important limitation of our study is that most of our molecular opacities come from HITRAN cross-section data, which are only available at specific temperature–pressure points (usually $T = 300$ K and $P = 1$ bar) and air-broadened. More experimental work to extend these at higher temperatures, lower pressures, and H₂/He broadening would also improve the robustness of our retrievals. Finally, as noted in previous works (F. E. Rigby et al. 2025; M. Holmberg et al. 2026; L. Pica-Ciamarra et al. 2026), we have only considered adding single molecules to the baseline species for each planet, so future work could examine different combinations.

As a consequence of using only MIRI data, which have lower SNR than the NIR data, the current evidence for

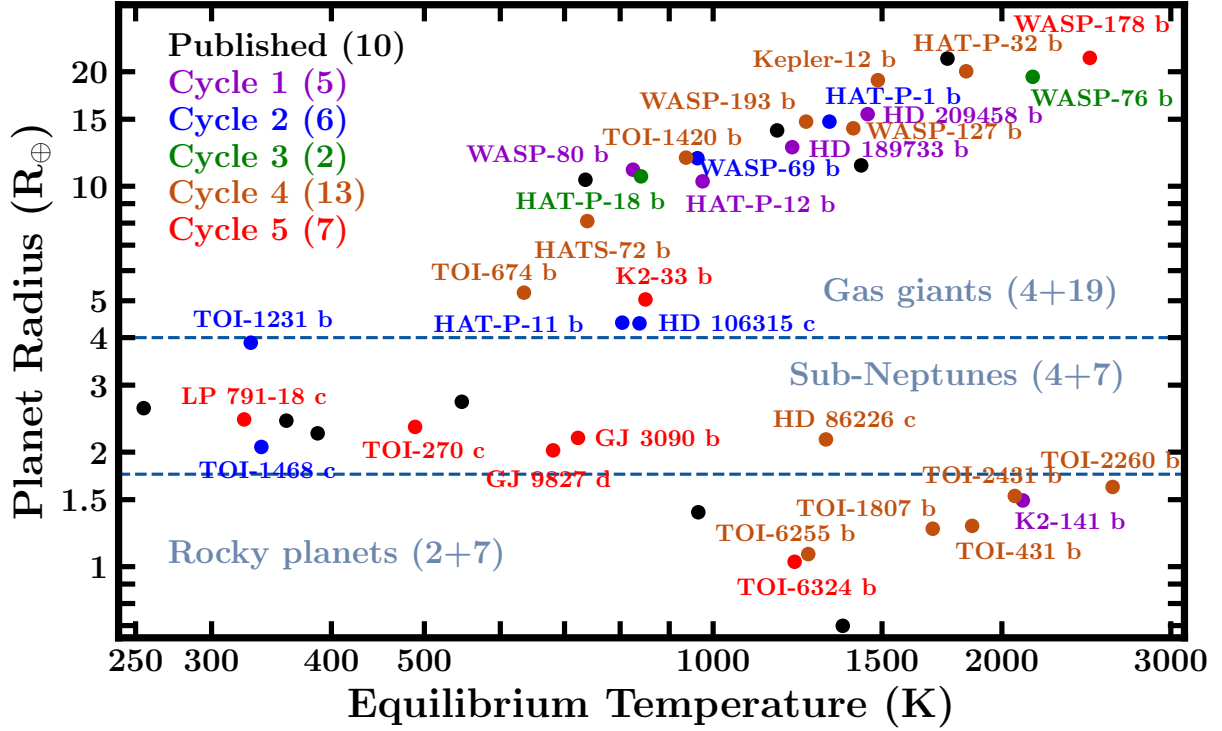


Figure 5. Planets that will be observed with MIRI in transit in JWST Cycles 1–5. As mentioned in Section 5, we see a wide variety of planet sizes and equilibrium temperatures. The currently published planets are shown in black dots and listed in Table 1 and Figure 1. We have omitted the white dwarf planet WD 1856 b ($T_{\text{eq}} = 160$ K, $R_p = 10.2 R_{\oplus}$, Cycle 4), as well as the disintegrating planets K2-22 b (see Section 2.1) and BD +05 4868 A b ($T_{\text{eq}} = 1820$ K, unknown R_p , Cycle 4).

Table 9
Summary of the 19 Molecules that Reach $\ln B_{\text{min}} \geq 2$ in at Least One Planet

Molecule	K2-18 b	TOI-270 d	TOI-732 c	WASP-39 b	WASP-17 b	WASP-43 b	GJ 1214 b	L 168-9 b	GJ 367 b	WASP-107 b
Chloroethane	2.1–8.0	<0.2	2.4–2.4	...	...	<0.2	...	...	...	...
DMS	2.2–5.6	<0.4	0.8–2.3	<0.3	...	<0.6	...	...	...	...
Diethyl sulfide	2.1–9.1	<0.1	1.8–2.6	<0.3	...	<0.1	...	...	...	...
Methacrylonitrile	–0.8–2.9	2.5–3.2	2.4–4.3	<0.2	...	<0.1	...	...	...	1.2
Isobutene	–0.9–2.4	2.3–4.3	2.3–4.8	...	...	...	...	...	...	...
Benzonitrile	<0.4	3.4–5.3	<0.5	<0.5	...	<0.9	...	...	0.1	...
Cyclohexane	–1.1–2.1	...	4.3–6.2	<0.1	...	<1.2	...	...	...	...
3-methylpentane	–0.9–2.2	...	3.7–4.3	...	...	...	...	...	...	...
2-butene	1.1–9.7	<1.1	3.3–5.0	<0.1	...	...	...	...	...	...
3-methylhexane	1.0–5.6	<0.5	2.8–4.0	<0.2	...	...	...	...	...	...
1-pentene	<1.5	<1.0	2.4–2.5	<0.2	...	...	0.4	...	...	...
cis-2-pentene	0.5–4.8	<1.3	2.1–2.7	...	...	...	...	...	...	...
Hexane	1.0–6.3	<0.1	2.0–5.8	<0.3	...	...	...	...	...	...
H ₂ O	<0.6	<1.9 ^a	<0.7 ^a	4.1–8.1^a	1.8–8.0 ^a	<0.3 ^a	0.3	...	0.5	18.6^a
SO ₂	...	...	...	3.1–6.3	...	...	...	<0.9	...	28.4^a
SO ₂ Cl ₂	<0.5	...	...	...	2.8–3.0	...	...	...	...	...
H ₂ S	<0.5	...	<0.2	<1.2	...	...	...	...	...	17.3^a
SO	...	...	...	<1.4	<1.9	...	...	...	...	9.0^a
PH ₃	<1.3	...	...	<0.1	<0.6	...	...	<0.3	...	7.7^a

Notes. The $\ln B$ values are presented in the same way as in Table 3, except for WASP-107 b, for which we only use one spectrum, so there is only one $\ln B$ value. We also keep bold font whenever $\ln B_{\text{min}} \geq 2$.

^a Indicates that a molecule is included in the baseline for the given planet, so the model comparison is done by removing it from that baseline. We note that the evidence for H₂O decreases to $\ln B = 4.0 - 5.2$ when including SO₂ in the model comparison (see Appendix D.1). We see a clear difference between the three temperate sub-Neptunes, where only complex molecules are favored, and the other planets that only show features of simple molecules, if any.

complex molecules in the atmosphere of temperate sub-Neptunes is low, with values of $\ln B_{\min} \approx 2 - 4$. However, we note that these values are comparable to inferences made on reference targets with similar retrieval architectures and data quality. This includes WASP-39 b, where D. Powell et al. (2024) inferred molecular absorption from H_2O at $\ln B_{\min} \approx 2 - 4$, and SO_2 at $\ln B_{\min} \approx 3 - 4$, and we have reproduced consistent values in Appendix D.1. This is also similar to the inference of silicate clouds in WASP-17 b (D. Grant et al. 2023b). However, while the silicate clouds were preferred at $\ln B \approx 2$ (2.6σ) compared to simple parametric clouds when using the `ExoTiC` reduction, they were not preferred with the $\ln B$ metric when using the `Eureka!` spectrum (D. Grant et al. 2023b). This means that in our framework, they would obtain a value of $\ln B_{\min} < 2$.

The present results motivate the need for more observations in order to increase the evidence for both complex molecules in temperate sub-Neptunes and simple gas species and/or clouds in other planets. From our current sample, only TOI-270 d has a new MIRI transit observation planned, with the JWST Cycle 5 GO Program 12157 (PI: B. Benneke). Nevertheless, 35 new planets are being observed in transit with MIRI-LRS in Cycles 1–5, as shown in Figure 5. Three of these are temperate sub-Neptunes (TOI-1231 b, TOI-1468 c, and LP 791-18 c), so it will be interesting to see whether they also show hints of extra absorption from complex molecules. The rest of these new planets are very diverse, with 7 rocky planets, 4 warm/hot sub-Neptunes (in addition to the 3 temperate ones), and 19 gas giants. However, we see that there is no temperate gas giant in this sample, which could be interesting to compare with temperate sub-Neptunes. One example of a possible target is TOI-1899 b (C. I. Cañas et al. 2020), which has upcoming NIRSpec transit observations (Cycle 2 GO Program 4227; PI: A. Claringbold). There is also no temperate or warm rocky planet; however, this is expected as their transmission spectroscopy metrics (E. M.-R. Kempton et al. 2018) are low. Altogether, these upcoming MIRI observations

will allow us to extend the comparative characterization of exoplanets as pursued in the present study and establish the robustness of our findings.

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Author Contributions

N.M. conceived and led the project. M.B. and N.M. planned the project. M.B. conducted the spectral comparisons and atmospheric retrievals and led the writing of the manuscript with input from N.M. N.M., M.H., and S.S. provided early access to the reduced data of TOI-270 d from JWST GO Program 3557. All authors provided comments on the manuscript.

Data Availability

The JWST MIRI-LRS spectra used in this Letter were obtained from previous works, and these sources are listed in Table 2. The raw observational data are published in the Mikulski Archive for Space Telescopes (MAST). Additional information including best-fit model spectra and some retrieval outputs are available at <https://osf.io/a892w/>.

Appendix A Retrieval Priors

In Table 10, we summarize our retrieval priors and baseline species per planet, described in Section 3.

Table 10
Priors and Baseline Species for Our Retrievals

Planet	N_{free}	$\log(P_{\text{ref}})$	T_0	$\log(P_c)$	ϕ	$\log(w_{\text{base}})$	$\log(w_X)$	Baseline Species
WASP-39 b	5	$\mathcal{U}(-6, 1)$	$\mathcal{U}(500, 3000)$	$\mathcal{U}(-6, 1)$	$\mathcal{U}(0, 1)$	$\mathcal{U}(-11, 0)$	$\mathcal{U}(-11, 0)$	H_2O
WASP-17 b	5	$\mathcal{U}(-6, 1)$	$\mathcal{U}(500, 3000)$	$\mathcal{U}(-6, 1)$	$\mathcal{U}(0, 1)$	$\mathcal{U}(-11, 0)$	$\mathcal{U}(-11, 0)$	H_2O
WASP-43 b	5	$\mathcal{U}(-6, 1)$	$\mathcal{U}(500, 3000)$	$\mathcal{U}(-6, 1)$	$\mathcal{U}(0, 1)$	$\mathcal{U}(-11, 0)$	$\mathcal{U}(-11, 0)$	H_2O
GJ 1214 b	5	$\mathcal{U}(-6, 1)$	$\mathcal{U}(200, 1500)$	$\mathcal{U}(-6, 1)$	$\mathcal{U}(0, 1)$	$\mathcal{U}(-3, 0)$	$\mathcal{U}(-11, -1)$	CO_2
GJ 367 b	5	$\mathcal{U}(-6, 1)$	$\mathcal{U}(500, 3000)$	$\mathcal{U}(-6, 1)$	$\mathcal{U}(0, 1)$	$\mathcal{U}(-3, 0)$	$\mathcal{U}(-11, -1)$	CO_2
L 168-9 b	5	$\mathcal{U}(-6, 1)$	$\mathcal{U}(200, 1500)$	$\mathcal{U}(-6, 1)$	$\mathcal{U}(0, 1)$	$\mathcal{U}(-3, 0)$	$\mathcal{U}(-11, -1)$	CO_2
WASP-107 b	9	$\mathcal{U}(-8, 1)$	$\mathcal{U}(200, 1500)$	$\mathcal{U}(-8, 1)$	$\mathcal{U}(0, 1)$	$\mathcal{U}(-11, -1)$	$\mathcal{U}(-11, -1)$	$\text{SO}_2, \text{H}_2\text{O}, \text{H}_2\text{S}, \text{PH}_3, \text{SO}$
K2-18 b	6	$\mathcal{U}(-6, 1)$	$\mathcal{U}(0, 600)$	$\mathcal{U}(-6, 1)$	$\mathcal{U}(0, 1)$	$\mathcal{U}(-11, 0)$	$\mathcal{U}(-11, 0)$	CH_4, CO_2
TOI-270 d	7	$\mathcal{U}(-6, 1)$	$\mathcal{U}(0, 600)$	$\mathcal{U}(-6, 1)$	$\mathcal{U}(0, 1)$	$\mathcal{U}(-11, 0)$	$\mathcal{U}(-11, 0)$	$\text{CH}_4, \text{CO}_2, \text{H}_2\text{O}$
TOI-732 c	8	$\mathcal{U}(-6, 1)$	$\mathcal{U}(0, 600)$	$\mathcal{U}(-6, 1)$	$\mathcal{U}(0, 1)$	$\mathcal{U}(-11, 0)$	$\mathcal{U}(-11, 0)$	$\text{CH}_4, \text{CO}_2, \text{H}_2\text{O}, \text{CO}$

Note. N_{free} is the number of free parameters in each baseline retrieval, so all other exploration retrievals have one more. The R_p (to which the radii are fixed) and M_p values are the ones in Table 1. See Appendix G for tested variations to this reference setup.

Appendix B Additional Spectra

In Table 11, we list the four spectra that were used in the comparisons of Section 2 but not in the retrievals (Sections 3 and 4). We note that eight more reductions of the K2-18 b observation were presented in K. B. Stevenson et al. (2025),

with different wavelength binning schemes. This means that they cannot be compared as in Section 2, and it would take too long to run the retrieval exploration in each of them. Because K2-18 b is already our planet with the most spectra (five), we choose to not study them.

Table 11
List of Spectra Used in the Comparisons of Section 2 but Not in the Retrievals (Sections 3 and 4)

Planet	Pipeline	N_p	λ Range	χ^2_{flat}	$\chi^2_{r,\text{flat}}$	p_{flat}	References
WASP-107 b	CASCADE	46 ^a	5.06–11.83	677	15.1	$\leq 10^{-6}$	(1)
	Eureka!	46 ^a	5.06–11.83	717	15.9	$\leq 10^{-6}$	(1)
	TEATRO	46 ^a	5.06–11.83	906	20.1	$\leq 10^{-6}$	(1)
WASP-43 b	Eureka! (v2)	14	5.25–11.75	8.88	0.68	0.78	(2)

Note.

^a Three first data points removed (see Section 2.2.1).

References. (1) A. Dyrek et al. (2024); (2) T. J. Bell et al. (2024).

Appendix C

Alternative Metric to Compare Spectra

In Sections 2.2.3 and 2.2.4, we have used the Pearson correlation coefficient to compare spectra. Here, we reproduce this study with a different method. We use the spectra converted from transit depths to $\frac{R_p}{R_*} - \left(\frac{R_p}{R_*}\right)_{\text{mean}}$, as plotted in Figure 4. For each pair of spectra (X, Y) with errors (σ_X, σ_Y), we compute their chi-squared difference $\chi_{X,Y}^2 = \frac{(X-Y)^2}{\sigma_X^2 + \sigma_Y^2}$ on their overlapping wavelength grid of N_p bins. From this, we get both $\chi_r^2 = \frac{\chi_{X,Y}^2}{N_p - 1}$ and a p -value (this time we do not need to compute it ourselves, we just use the known χ^2 cumulative distribution functions). With this new metric, we define the p -value as an increasing function of χ^2 , so that it is again a

decreasing function of the spectra’s consistency. This time, two spectra are consistent if $p \lesssim 0.95$. We show the pipeline comparison results in Figure 6. We see that this metric seems consistent with the Pearson coefficient, as for a given planet, the lower χ_r^2 correspond to higher correlations in Figure 2. We also see that every planet has all its p -values below the $p = 0.95$ threshold (although some pairs of WASP-107 b spectra come close), confirming again that the different reduction pipelines yield consistent data. Finally, in Figure 7, we see that K2-18 b is only “strongly consistent” ($p \leq 0.5$) with the other two temperate sub-Neptunes and somewhat consistent with L 168-9 b ($p = 0.92$), as is TOI-270 d with TOI-732 c ($p = 0.93$). Although it is not as clear as in Section 2.2.4, this metric again distinguishes the temperate sub-Neptune spectra from the others.

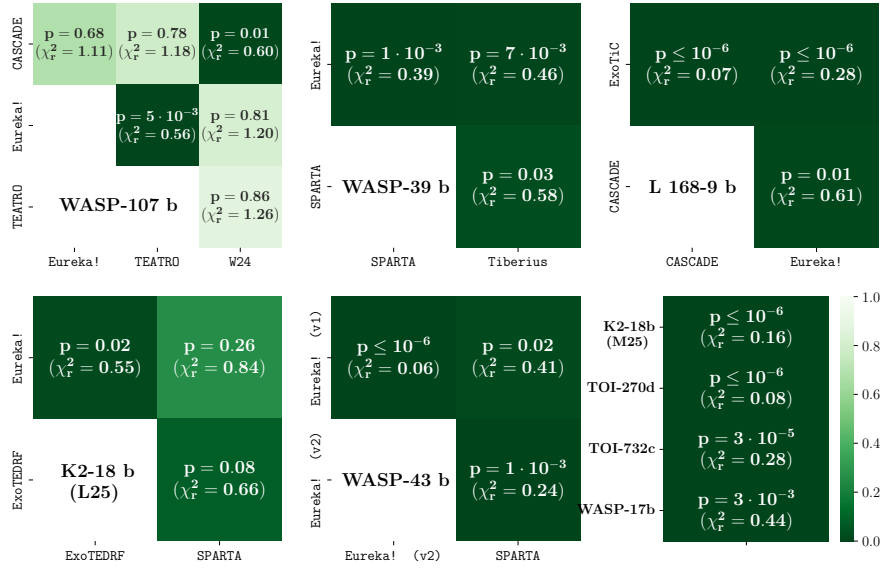


Figure 6. χ^2 and associated p -values between different reductions of the same planet’s transit observation.

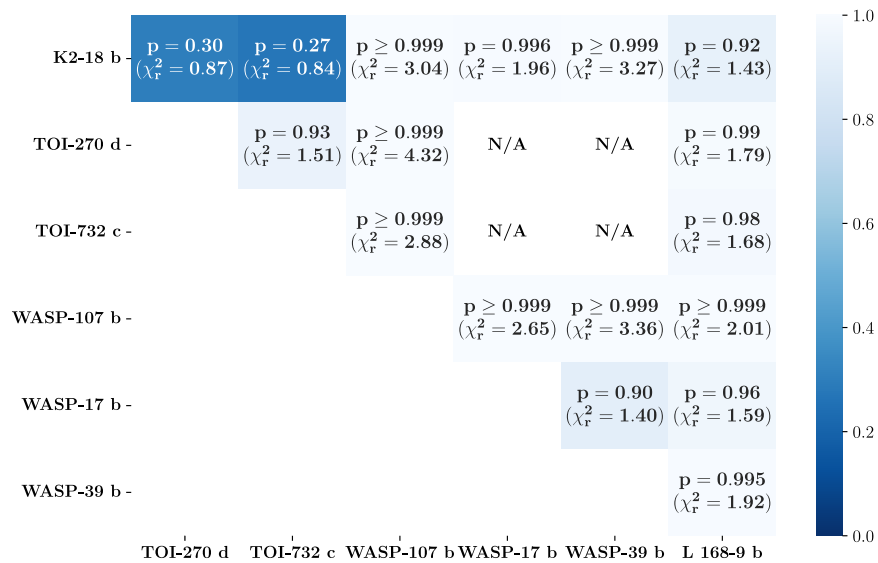


Figure 7. χ^2 and associated p -values between different planets’ transit spectra.

Appendix D

A Closer Look at WASP-39 b

In this section, we first check the consistency of our WASP-39 b retrievals with those of D. Powell et al. (2024), then quantify the degeneracy of SO₂ with the other molecules potentially favored in the planet's atmosphere (see Section 4.1.2).

D.1. Consistency with P24

As we said in Section 2.1.1, WASP-39 b is the only planet outside of the temperate sub-Neptunes for which retrievals were previously run on MIRI transit data alone, namely, in D. Powell et al. (2024). In this previous work, the final retrievals fitted for the planet radius (equivalent to our reference pressure), the isothermal temperature, the log mixing ratios of H₂O and SO₂, and clouds. The clouds depended on the seven different retrieval codes used, but three of them used the same patchy gray clouds parameterization as our work: ARCI_S (C. W. Ormel & M. Min 2019; M. Min et al. 2020), NEMESIS (P. Irwin et al. 2008; J.-M. Lee et al. 2012), and PyratBay (P. E. Cubillos & J. Blečić 2021). So, we can compare the results from these three codes with our own H₂O + SO₂ retrievals in terms of both posterior molecular abundances and detection significances. We show this comparison in Table 12. We see that all of our median retrieved abundances and most of our $\ln B$ values are within the range found in D. Powell et al. (2024). Only the $\ln B$ value for SO₂ is lower by 0.6 and 0.2 than their lower bound for the Eureka! and SPARTA spectra, respectively. These differences are lower than the range of their values, so we consider them consistent. This shows that our work is robust to the choice of pRT for the retrievals.

Table 12

WASP-39 b Comparison between Our Work and the ARCI_S, NEMESIS, and PyratBay Retrievals of D. Powell et al. (2024)

	$\log(X_{\text{H}_2\text{O}})$	$\ln B$ (H ₂ O)	$\log(X_{\text{SO}_2})$	$\ln B$ (SO ₂)
Eureka!				
This work	$-1.6^{+0.3}_{-0.5}$	5.2	$-5.7^{+0.5}_{-0.5}$	3.4
P24	-1.5 to -1.6	2.0–9.8	-5.4 to -5.8	4.0–4.8
Tiberius				
This work	$-2.0^{+0.4}_{-0.7}$	4.0	$-5.6^{+0.5}_{-0.6}$	6.3
P24	-1.9 to -2.1	2.2–9.3	-5.6 to -5.7	5.5–7
SPARTA				
This work	$-1.5^{+0.3}_{-0.7}$	4.3	$-5.5^{+0.5}_{-0.6}$	3.1
P24	-1.3 to -1.7	2.1–4.6	-5.3 to -5.6	3.3–4.0

Note. In the previous work, the model preferences were given as σ values, so we convert them to $\ln B$ values using the convention from T. Sellke & M. J. Bayarri (2001) (see Appendix E).

D.2. WASP-39 b: Degeneracy with SO₂

As mentioned previously, SO₂ was robustly identified in WASP-39 b (D. Powell et al. 2024) with all three data reductions. In this work, we find that its Tiberius spectrum can also be fitted at $\ln B \geq 2$ in the H₂O+X setup by six other molecules X. These include CH₄ at $\ln B = 5.3$, which is close to the $\ln B = 6.3$ reached by SO₂. However, we see in Figure 8 that the preference for CH₄ is mostly due to the data points at 7.5–8 μm , and this is also true for the other species. So, they could be degenerate with SO₂. To evaluate this, we use a new retrieval setup with both SO₂, one of these species (still named X), and we keep H₂O. We refer to this setup as 2+X, in contrast to the previous 1+X (or H₂O+X) setup. We run this setup on all three spectra for the six molecules that reached $\ln B_{\text{max}} \geq 2$ in the 1+X setup, as well as the five others with $\ln B_{\text{max}} \geq 1$. We show the results in Table 13.

We see that none of these 11 species is preferred at $\ln B \geq 1$ for any spectrum when SO₂ is included in the baseline. The highest preference with this 2+X setup is $\ln B = 0.9$, reached for tiophene (C₄H₄S) with the Tiberius spectrum. Even for this retrieval, the VMR constraints on H₂O and SO₂ are changed by less than 0.2 dex compared to the H₂O+SO₂ retrieval (as well as the other posteriors), whereas tiophene is highly unconstrained at $-6.3^{+1.0}_{-3.9}$. This analysis shows that although other species could potentially fit the WASP-39 b MIRI data, their evidence disappears when adding SO₂. As mentioned in Section 2.1.1, SO₂ was further confirmed by the NIR data (see Section 2.1.1), and none of these other species was found (apart from potentially H₂S), including CH₄, which has strong features in the NIR. In summary, SO₂ is by far the best explanation for the 7.5–8 μm feature seen in the MIRI transit of WASP-39 b, and no extra molecule is needed.

Table 13

Maximum Evidence $\ln B_{\text{max}}$ Values Obtained for the WASP-39 b 2+X Retrieval Results, as Described in Appendix D.2, Compared to the 1+X Results of Section 4.1.2

Molecule	1+X	2+X
SO ₂	6.3	N/A
CH ₄	5.3	0.5
SO ₃	3.4	0.3
SO ₂ F ₂	2.9	-0.1
C ₂ H ₂	2.2	0.4
CH ₃ Cl	2.1	0.5
HCN	2.0	0.3
Tiophene	2.0 ^a	0.9
Cumene	1.8	0.1
SO	1.4	0.5
H ₂ S	1.2	0.2
CS	1.1	0.3

Note.

^a Tiophene (C₄H₄S) was not listed in Table 3 because it has $\ln B_{\text{max}} = 1.97 \leq 2$.

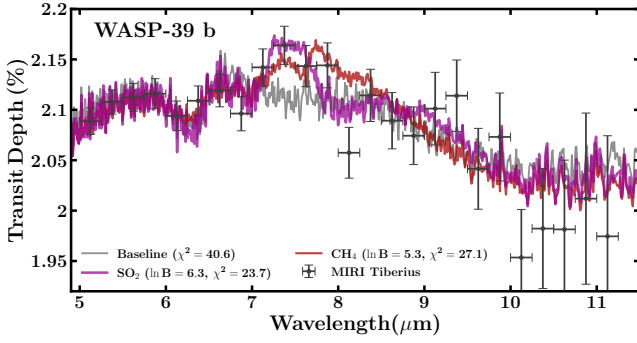


Figure 8. Retrieved spectra with the WASP-39 b Tiberius data. The solid curves show the best-fit retrieved spectra obtained from the pRT baseline retrieval (including H₂O) and the ones with added SO₂ and CH₄, as described in Section 4.1.2. We see that SO₂ and CH₄ both improve the fit in a similar wavelength range ($\approx 7.5\text{--}8\ \mu\text{m}$), hence their partial degeneracy described in Appendix D.2. We note that the last data point at $11.375\ \mu\text{m}$ is below the figure, with a transit depth of $1.75^{+0.117}_{-0.117}\%$.

Appendix E Conversion from B to σ Values

As mentioned in Section 4, we chose to not convert our $\ln B$ evidences into σ detection significances, following the recommendation of D. P. Thorngren et al. (2026). For completeness, we show a reminder of this conversion in Table 14.

Table 14
Conversion between $\ln B$ and σ Values from T. Sellke & M. J. Bayarri (2001) and Strength of Evidence from R. Trotta (2008)

$\ln B$	$N\sigma$	Strength of Evidence
0	1.0	None
1	2.0	Weak
2	2.5	Weak to moderate
3	3.0	Moderate
5	3.6	Strong
10	4.9	Definitive

Appendix F BPICS Metric for Model Preference

In this section, we compute the model preference for our retrievals using an alternative metric to the Bayes factor. We use the BPICS, introduced in T. Ando (2011) and recommended in D. P. Thorngren et al. (2026):

$$\text{BPICS} = -2E_\theta[\ln(p(y|\theta))] + 2k.$$

Here, $\ln(p(y|\theta))$ is the likelihood of the data y with the parameter values θ , E_θ is the mean across posterior samples, and k is the number of free parameters. When comparing two retrieval models, M_1 and M_2 , one computes $\Delta\text{BPICS} = \text{BPICS}_{M_2} - \text{BPICS}_{M_1}$, and M_2 is preferred if $\Delta\text{BPICS} \leq 0$. For an easier comparison with the $\ln B$ metric, in what follows, we will actually provide values of $-\frac{1}{2}\text{BPICS} = E_\theta[\ln(p(y|\theta))] - k$, which we will refer to as $\overline{\text{BPICS}}$.

Thus, the model preference for a given molecule X is defined the same way as $\ln B$: if there are N baseline molecules, it is $\Delta\overline{\text{BPICS}} = \overline{\text{BPICS}}_{N+X} - \overline{\text{BPICS}}_N$. We start with a side-to-side comparison of $\ln B$ and $\Delta\overline{\text{BPICS}}$ values for five spectra of K2-18 b in Table 15 for the 12 molecules that have $\ln B_{\min} \geq 1$. First, we see that both metrics scale approximately the same way, which confirms our choice of multiplying the BPICS values by $-\frac{1}{2}$. However, for an equal threshold, the BPICS is slightly more conservative: only five molecules have $\Delta\overline{\text{BPICS}}_{\min} \geq 1$, and DMS has $\Delta\overline{\text{BPICS}}_{\min} \geq 2$, with diethyl sulfide and chloroethane now falling below the threshold.

Then, we compute this metric on all the other planets' retrievals and again find mostly consistent values between $\ln B$ and $\overline{\text{BPICS}}$, summarized in Table 16. However, just like in K2-18 b, chloroethane has $\Delta\overline{\text{BPICS}}_{\min} \leq 2$ in TOI-732 c, and only benzonitrile remains above the threshold in TOI-270 d. On the other hand, H₂O and 2,4,4-trimethyl-1-pentene are now above the threshold in WASP-17 b and TOI-732 c, respectively. Finally, methacrylonitrile and p-xylene now have $\Delta\overline{\text{BPICS}} \geq 2$ in the W24 spectrum of WASP-107 b. But just like we found in Section 4.3, only p-xylene is also favored in the CASCADE spectrum.

Table 15
K2-18 b Model Preference per Molecule and Spectrum: $\ln B / \Delta \overline{\text{BPICS}}$

Molecule	Minimum	JExoRES	JexoPipe	Eureka!	ExoTEDRF	SPARTA
$\ln Z_{\text{base}}$	N/A	213.08	207.97	193.48	195.94	194.45
$\overline{\text{BPICS}}_{\text{base}}$	N/A	208.46	203.45	189.49	192.15	192.40
DMS	2.2/2.1	2.2/2.1	2.8/3.4	5.6/6.8	2.9/3.1	4.6/4.4
Diethyl sulfide	2.1/1.9	2.1/1.9	2.7/3.2	9.1/11.0	5.5/6.1	3.4/2.9
Chloroethane	2.1/1.3	3.2/3.5	4.4/5.4	8.0/9.2	4.7/5.2	2.1/1.3
Butane	1.9/1.4	2.6/2.6	2.6/2.9	9.2/10.2	4.5/5.0	1.9/1.4
DMS	1.8/1.5	1.8/1.5	2.1/2.1	5.5/6.3	2.4/2.2	5.5/5.1
1-chloropentane	1.6/0.8	1.6/0.9	2.4/2.7	4.2/4.6	1.7/1.4	1.8/0.8
Ethyl mercaptan	1.6/1.0	1.6/1.0	2.7/3.2	7.9/9.2	6.3/7.3	6.1/6.4
Dichloromethylphosphine	1.2/0.2	1.4/0.7	2.1/2.0	1.7/1.8	1.2/0.6	1.6/0.2
Heptane	1.1/0.2	1.1/0.2	1.2/0.6	5.7/7.0	2.3/2.4	1.2/1.2
Bromoethane	1.1/0.1	2.5/2.5	2.0/2.1	8.8/10.3	6.2/7.0	1.1/0.1
2-butene	1.1/0.6	2.2/2.3	1.1/0.6	9.7/11.9	4.4/5.1	4.0/3.8
Hexane	1.0/0.1	1.0/0.1	1.3/0.8	6.3/7.4	2.3/2.2	2.5/2.8

Note. Bold indicates the three molecules with $\ln B_{\text{min}} \geq 2$. Italics indicate DMS, the only molecule with $\Delta \overline{\text{BPICS}}_{\text{min}} \geq 2$.

Table 16
Summary of the 20 Molecules Reaching $\Delta \overline{\text{BPICS}}_{\text{min}} \geq 2$ in at Least One Planet

Molecule	K2-18 b	TOI-270 d	TOI-732 c	WASP-39 b	WASP-17 b	WASP-43 b	GJ 1214 b	L 168-9 b	GJ 367 b	WASP-107 b
DMS	2.1–6.8	...	0.1–2.0	...	...	...	...	...	...	...
Benzonitrile	...	2.8–3.4	...	—	...	<0.2	...	...	...	—
Cyclohexane	<1.8	...	5.7–7.3	...	...	<0.7	...	...	...	...
3-methylpentane	–1.2–2.4	...	4.9–5.0	...	...	...	...	...	...	...
2-butene	0.6–11.9	<0.6	4.7–6.0	...	...	...	...	...	...	...
3-methylhexane	0.1–6.5	...	3.4–4.8	...	...	...	...	...	...	...
cis-2-pentene	–0.2–6.0	<0.2	2.6–3.0	...	...	...	...	...	...	...
1-pentene	<1.4	<0.6	2.6–2.8	...	...	...	...	...	...	...
Isobutene	–0.9–3.1	1.2–3.9	2.5–5.5	...	—	...	...	...	...	...
Methacrylonitrile	–1.0–3.6	1.3–2.7	2.4–5.0	—	...	...	...	...	...	2.8
C ₈ H ₁₆	<0.4	<1.0	2.3–4.6	...	...	...	...	...	...	...
Hexane	0.1–7.4	...	2.2–7.2	...	...	...	...	...	...	...
H ₂ O	...	<0.8 ^a	<0.1 ^a	4.4–8.6^a	2.9–9.4^a	... ^a	...	...	...	22.9^a
SO ₂	...	...	...	3.9–7.6	...	...	...	...	...	29.5^a
SO ₂ Cl ₂	...	...	...	...	2.7–3.0	...	...	...	...	...
Cyclopentane	–1.3–3.0	...	0.2–3.3	...	...	...	2.2	...	...	...
H ₂ S	...	...	...	<1.0	...	...	...	...	...	13.1^a
SO	...	...	...	...	<1.8	...	...	...	...	9.3^a
PH ₃	<0.8	...	...	...	...	...	...	—	...	8.5^a
p-xylene	...	...	...	...	...	...	...	...	...	2.3

Note. We present the $\Delta \overline{\text{BPICS}}$ values in the same way as the $\ln B$ values in Tables 3 and 9. As in Table 9, superscript ^a indicates that a molecule is included in the baseline for the given planet. This is mostly the same list as in Table 9, except that C₈H₁₆ (2,4,4-trimethyl-1-pentene), p-xylene, and cyclopentane have been added, whereas chloroethane and diethyl sulfide have been removed.

Appendix G

Sensitivity to Bulk Parameter Priors

In this section, we test the sensitivity of our retrieval results to the selected priors, as described in Sections 3.4 and 3.5. The three changes we test are adding a Gaussian prior on the planet mass, with the uncertainties reported in Table 1; replacing the reference pressure prior by a uniform prior on the planet radius, between 0.8 and 1.2 R_p ; and narrowing the temperature priors. For this, we pick four different combinations of planet and extra absorber that are of particular interest: DMS on K2-18 b, isobutene on TOI-270 d, and SO₂ on WASP-39 b and WASP-107 b. The interest for the latter is because it is the highest model preference found in

our work ($\ln B = 28.4$). For K2-18 b and TOI-270 d, we pick the JExoRES reduction, as it is the one that causes the lowest $\ln B$ values for DMS and isobutene, respectively. We present our results in Table 17. We see that the changes in the baseline $\ln Z$ and $\overline{\text{BPICS}}$ values are small ($\lesssim 2$), and more importantly, that the changes in $\ln B$ and $\Delta \overline{\text{BPICS}}$ for each molecule are even smaller ($\lesssim 0.5$, except for WASP-107 b, in which case they are $\lesssim 1$). In particular, DMS and isobutene both remain at $\ln B \geq 2$ regardless of the retrieval prior choices, and DMS is also at $\Delta \overline{\text{BPICS}} \geq 2$ (as observed in Appendix F, isobutene does not reach that threshold). We conclude that most of the inferences made in this work are unlikely to be affected by these different prior choices.

Table 17
Sensitivity of Retrieval Results to Different Prior Choices

Data	Case	Reference		+ Gaussian M_p		$P_{\text{ref}} \rightarrow R_p$		Narrow T_0	
		ln Z	BPICS	ln Z	BPICS	ln Z	BPICS	ln Z	BPICS
K2-18 b JExoRES	Baseline	213.08	208.46	213.12	207.48	211.07	208.42	212.97	208.45
	+DMS	+2.2	+2.1	+2.1	+2.1	+2.6	+2.7	+2.2	+2.1
TOI-270 d JExoRES	Baseline	199.31	195.84	199.32	194.78	197.93	195.61	199.25	195.93
	+Isobutene	+2.3	+1.2	+2.3	+1.2	+2.2	+1.4	+2.1	+1.2
WASP-39 b Tiberius	Baseline	159.72	160.90	160.25	160.10	158.86	160.64	160.01	160.92
	+SO ₂	+6.3	+7.6	+5.5	+7.4	+5.1	+7.5	+6.3	+7.3
WASP-107 b W24	Baseline	310.46	321.18	310.26	320.44	309.64	321.34	310.79	321.40
	−SO ₂	−28.4	−29.5	−28.2	−30.1	−27.6	−29.7	−29.0	−30.4

Note. The reference retrieval setup is the one used throughout this work, described in Section 3 and Appendix A. The alternative setups and tested cases are discussed in Appendix G. For each setup and tested case, we provide the baseline ln Z and BPICS values, as well as the ln B and ΔBPICS values for adding the listed molecules (or removing SO₂ for WASP-107 b).

Appendix H Spectral Fits

In Figures 8–17, we show for each planet one of its data reductions, together with the best-fit model spectra obtained

for the baseline retrieval and some selected additional molecules. For clarity, these spectra are smoothed using the `scipy Gaussian_filter1d` function (P. Virtanen et al. 2020).

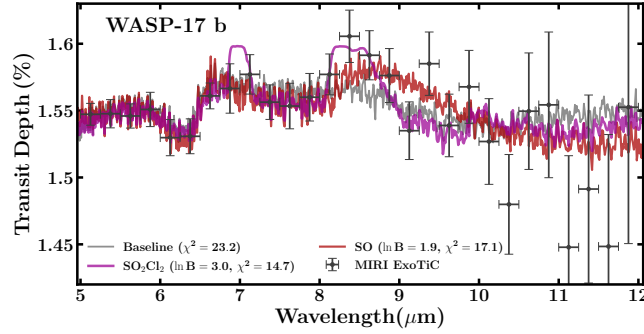


Figure 9. Retrieved spectra with the WASP-17 b ExoTiC data. The solid curves show the best-fit retrieved spectra obtained from the pRT baseline retrieval (including H₂O) and the ones with added SO₂Cl₂ and SO, as described in Section 4.1.2.

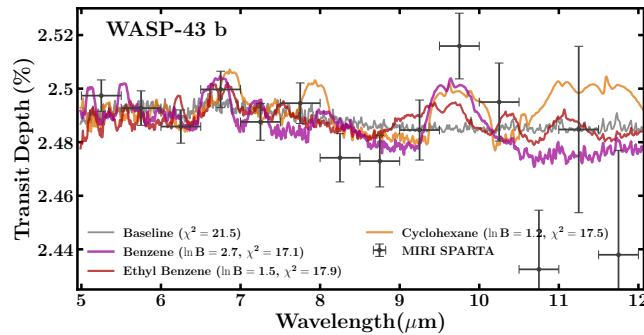


Figure 10. Retrieved spectra with the WASP-43 b SPARTA data. The solid curves show the best-fit retrieved spectra obtained from the pRT baseline retrieval (including H₂O) and the ones with added benzene, ethyl benzene, and cyclohexane, as described in Section 4.1.2.

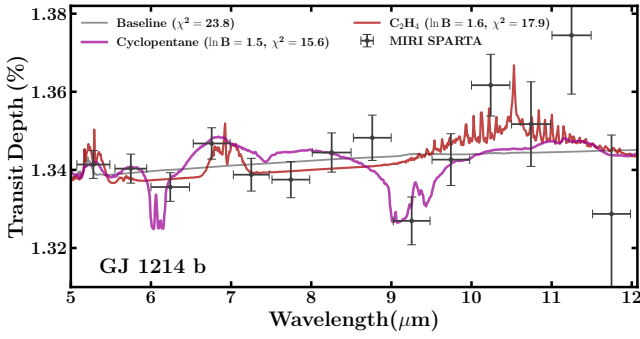


Figure 11. Retrieved spectra with the GJ 1214 b SPARTA data. The solid curves show the best-fit retrieved spectra obtained from the pRT baseline retrieval (including CO₂) and the ones with added cyclopentane and C₂H₄, as described in Section 4.1.2. We note that previous studies excluded the last four data points because of potential correlated noise, but we chose to keep them.

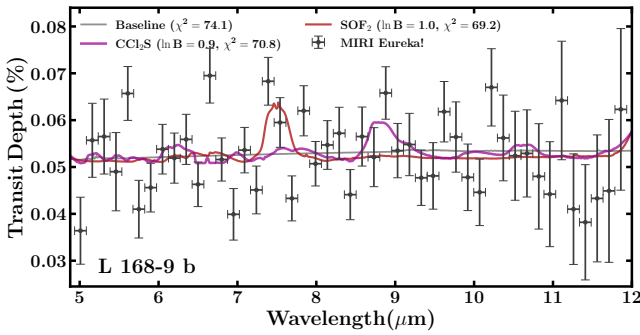


Figure 12. Retrieved spectra with the L 168-9 b Eureka! data. The solid curves show the best-fit retrieved spectra obtained from the pRT baseline retrieval (including CO₂) and the ones with added CCl₂S and SOF₂, as described in Section 4.1.2.

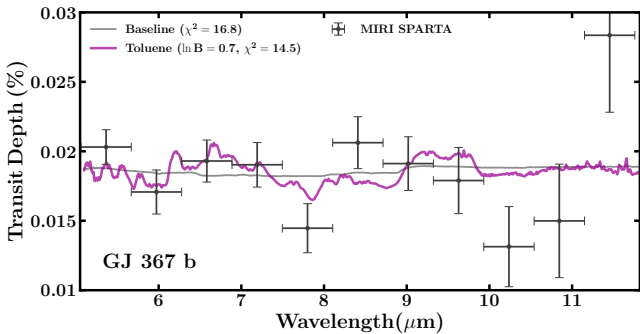


Figure 13. Retrieved spectra with the GJ 367 b SPARTA data. The solid curves show the best-fit retrieved spectra obtained from the pRT baseline retrieval (including CO₂) and the one with added toluene, as described in Section 4.1.2.

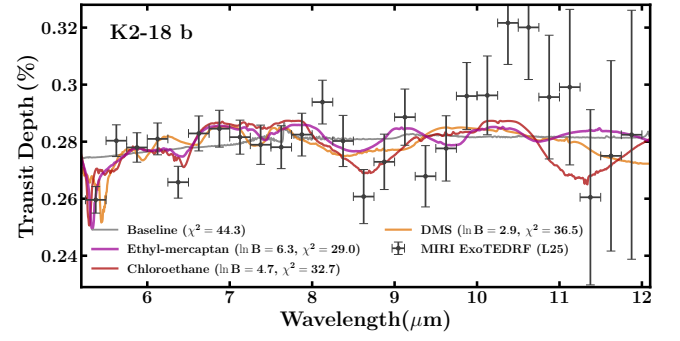


Figure 14. Retrieved spectra with the K2-18 b ExoTEDRF data. The solid curves show the best-fit retrieved spectra obtained from the pRT baseline retrieval (including CH₄ and CO₂) and the ones with added ethyl mercaptan, chloroethane, and DMS, as described in Section 4.2.1.

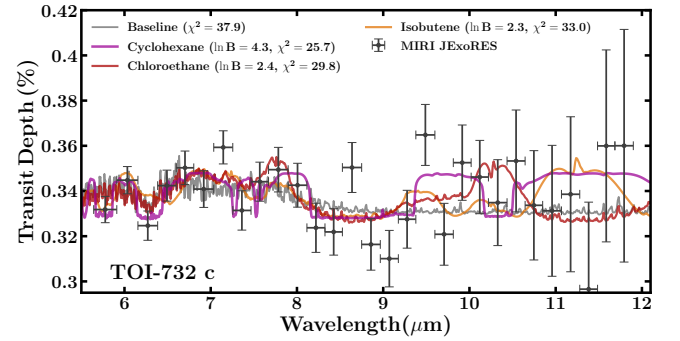


Figure 15. Retrieved spectra with the TOI-732 c JExoRES data. The solid curves show the best-fit retrieved spectra obtained from the pRT baseline retrieval (including CH₄, CO₂, H₂O, and CO) and the ones with added cyclohexane, chloroethane, and isobutene, as described in Section 4.2.1.

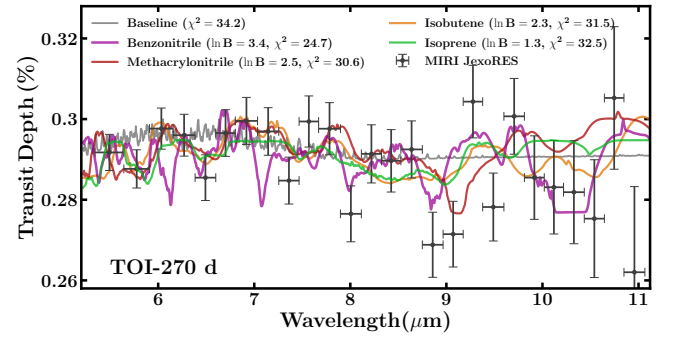


Figure 16. Retrieved spectra with the TOI-270 d JExoRES data (same as Figure 4 of M. Holmberg et al. 2026). The solid curves show the best-fit retrieved spectra obtained from the pRT baseline retrieval (including CH₄, CO₂, and H₂O) and the ones with added benzonitrile, methacrylonitrile, isobutene, and isoprene, as described in Section 4.2.1.

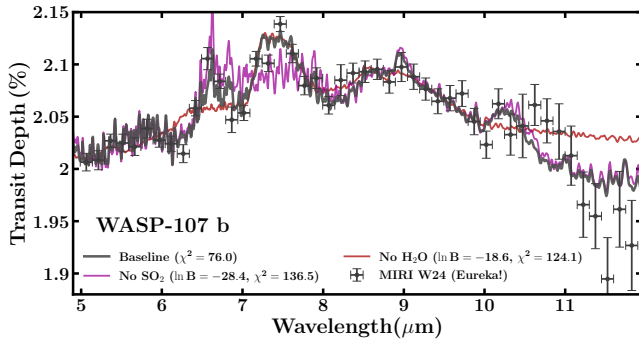


Figure 17. Retrieved spectra with the WASP-107 b W24 data. The solid curves show the best-fit retrieved spectra obtained from the pRT baseline retrieval (including SO₂, H₂O, H₂S, PH₃, and SO) and the ones with removed SO₂ and H₂O, as described in Section 4.3.

Appendix I

List of Species Explored

Here we provide the full list of the 160 molecular species used in our study, sorted by opacity source (see Section 3.3). Italics indicate species that were looked for in WASP-107 b (see Sections 3.7 and 4.3). Superscript ^b indicates species that are included in the baseline retrieval for at least one planet (see Section 3.2 and Appendix A).

ExoMol opacities (21): *chloromethane* (CH₃Cl), *fluoromethane* (CH₃F), *methane*^b (CH₄), *carbon monoxide*^b (CO), *carbon dioxide*^b (CO₂), *carbon monosulfide* (CS), *carbon disulfide* (CS₂), *ethyne* (C₂H₂), *ethylene* (C₂H₄), *hydrogen cyanide* (HCN), *thioformaldehyde* (H₂CS), *water*^b (H₂O), *hydrogen sulfide*^b (H₂S), *ammonia* (NH₃), *carbonyl sulfide* (OCS), *phosphine*^b (PH₃), *silane* (SiH₄), *silicon monoxide* (SiO), *sulfur monoxide*^b (SO), *sulfur dioxide*^b (SO₂), *sulfur trioxide* (SO₃).

HITRAN line lists: *ethane* (C₂H₆).

HITRAN cross sections, halogen-bearing (7): *dichloromethane* (CH₂Cl₂), *dichloromethylphosphine* (CH₃Cl₂P), *bromoethane* (C₂H₅Br), *chloroethane* (C₂H₅Cl), *allyl chloride* (C₃H₅Cl), *methacryloyl chloride* (C₄H₅OC(=O)Cl), *1-chloropentane* (C₅H₁₁Cl).

HITRAN cross sections, nitrogen-bearing (13): *methylamine* (CH₅N), *ethylamine* (C₂H₇N), *1,1-dimethylhydrazine* (C₂H₈N₂), *ethyl cyanide* (C₃H₅N), *trimethylamine* (C₃H₉N), *methacrylonitrile* (C₄H₅N), *amyl nitrate* (C₅H₁₁NO₃), *tert-amylamine* (C₅H₁₃N), *pyridine* (C₅H₅N), *4-picoline* (C₆H₇N), *benzonitrile* (C₇H₅N), *o-toluidine* (C₇H₉N), *2,6-diethylaniline* (C₁₀H₁₅N).

HITRAN cross sections, sulfur-bearing (28): *thiophosgene* (CCl₂S), *perchloromethyl mercaptan* (CCl₄S), *methanesulfonyl chloride* (CH₃SO₂Cl), *methanethiol* (CH₄S), *methyl isothiocyanate* (C₂H₃NS), *ethylene sulfide* (C₂H₄S), *dimethyl sulfate* (C₂H₆O₄S), *dimethyl sulfoxide* (C₂H₆OS), *thioglycol* (C₂H₆OS), *DMS* (C₂H₆S), *ethyl mercaptan* (C₂H₆S), *DMDS* (C₂H₆S₂), *propylene sulfide* (C₃H₆S), *1-propanethiol* (C₃H₈S), *2-propanethiol* (C₃H₈S), *diethyl sulfate* (C₄H₁₀O₄S), *2-methyl-1-propanethiol* (C₄H₁₀S), *diethyl sulfide* (C₄H₁₀S), *tert-butyl-mercaptan* (C₄H₁₀S), *thiophene* (C₄H₄S), *tetrahydrothiophene* (C₄H₈S), *cyclohexanethiol* (C₆H₁₂S), *benzenethiol* (C₆H₆S), *sulfur hexafluoride* (SF₆), *thionyl fluoride* (SOF₂), *sulfuryl chloride* (SO₂Cl₂), *sulfuryl fluoride* (SO₂F₂), *thiophosphoryl chloride* (SPCl₃).

HITRAN cross sections, hydrocarbons (87): *allene* (C₃H₄), *propyne* (C₃H₄), *cyclopropane* (C₃H₆), *propene* (C₃H₆), *propane* (C₃H₈), *butane* (C₄H₁₀), *isobutane* (C₄H₁₀), *1-butyne* (C₄H₆), *1,3-butadiene* (C₄H₆), *1-butene* (C₄H₈), *2-butene* (C₄H₈), *isobutene* (C₄H₈), *1-pentene* (C₅H₁₀), *2-methyl-1-butene* (C₅H₁₀), *2-methyl-2-butene* (C₅H₁₀), *cis-2-pentene* (C₅H₁₀), *trans-2-pentene* (C₅H₁₀), *3-methyl-1-butene* (C₅H₁₀), *cyclopentane* (C₅H₁₀), *isopentane* (C₅H₁₂), *pentane* (C₅H₁₂), *cyclopentene* (C₅H₈), *isoprene* (C₅H₈), *cyclohexene* (C₆H₁₀), *1-hexene* (C₆H₁₂), *2-methyl-1-pentene* (C₆H₁₂), *2-methyl-2-pentene* (C₆H₁₂), *4-methyl-1-pentene* (C₆H₁₂), *cis-4-methyl-2-pentene* (C₆H₁₂), *cyclohexane* (C₆H₁₂), *2,2-dimethylbutane* (C₆H₁₄), *2,3-dimethylbutane* (C₆H₁₄), *3-methylpentane* (C₆H₁₄), *hexane* (C₆H₁₄), *isohexane* (C₆H₁₄), *benzene* (C₆H₆), *cycloheptene* (C₇H₁₂), *1-heptene* (C₇H₁₄), *cycloheptane* (C₇H₁₄), *2,4-dimethylpentane* (C₇H₁₆), *3-methylhexane* (C₇H₁₆), *heptane* (C₇H₁₆), *toluene* (C₇H₈), *ethyl benzene* (C₈H₁₀), *m-xylene* (C₈H₁₀), *o-xylene* (C₈H₁₀), *p-xylene* (C₈H₁₀), *4-vinyl-1-cyclohexene* (C₈H₁₂), *1-octene* (C₈H₁₆), *2,4,4-trimethyl-1-pentene* (C₈H₁₆), *2,4,4-trimethyl-2-pentene* (C₈H₁₆), *cyclooctane* (C₈H₁₆), *isooctane* (C₈H₁₈), *octane* (C₈H₁₈), *styrene* (C₈H₈), *vinyl toluene* (C₉H₁₀), *1,2,3-trimethylbenzene* (C₉H₁₂), *2-ethyltoluene* (C₉H₁₂), *3-ethyltoluene* (C₉H₁₂), *4-ethyltoluene* (C₉H₁₂), *cumene* (C₉H₁₂), *isocumene* (C₉H₁₂), *mesitylene* (C₉H₁₂), *1-nonene* (C₉H₁₈), *n-nonane* (C₉H₂₀), *tetralin* (C₁₀H₁₂), *1,2,3,4-tetramethylbenzene* (C₁₀H₁₄), *1,2,3,5-tetramethylbenzene* (C₁₀H₁₄), *2-carene* (C₁₀H₁₄), *3-carene* (C₁₀H₁₄), *sec-butylbenzene* (C₁₀H₁₄), *tert-butylbenzene* (C₁₀H₁₄), *alpha-pinene-1S-* (C₁₀H₁₆), *beta-pinene-1S-* (C₁₀H₁₆), *D-limonene* (C₁₀H₁₆), *DL-limonene* (C₁₀H₁₆), *myrcene* (C₁₀H₁₆), *1-decene* (C₁₀H₂₀), *cyclodecane* (C₁₀H₂₀), *n-decane* (C₁₀H₂₂), *naphthalene* (C₁₀H₈), *1-undecene* (C₁₁H₂₂), *n-undecane* (C₁₁H₂₄), *n-tridecane* (C₁₃H₂₈), *n-tetradecane* (C₁₄H₃₀), *pentadecane* (C₁₅H₃₂), *hexadecane* (C₁₆H₃₄).

HITRAN cross sections, others (3): *dimethyl carbonate* (C₃H₆O₃), *isobutanol* (C₄H₁₀O), *tetramethylsilane* (C₄H₁₂Si).

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