Characterizing exoplanets through a collaboration between space-based and ground-based telescopes

(but not limited to synergy observations)

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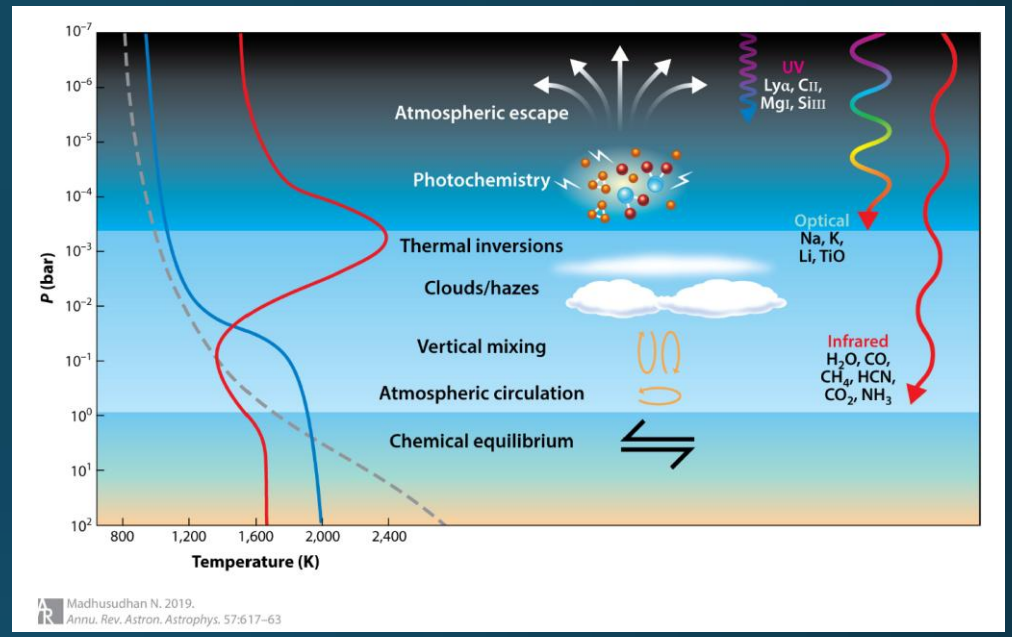
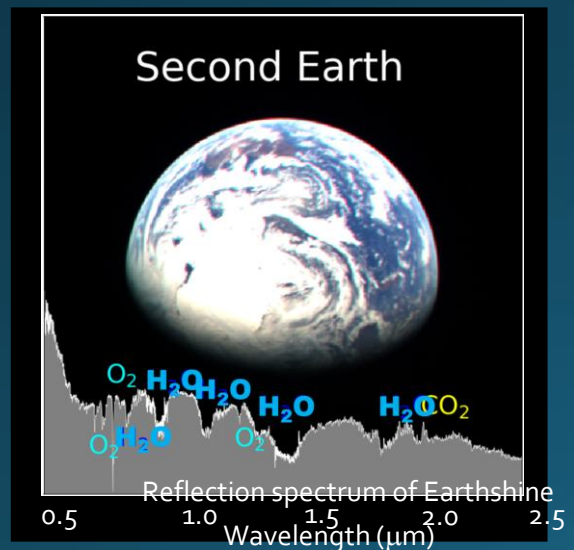
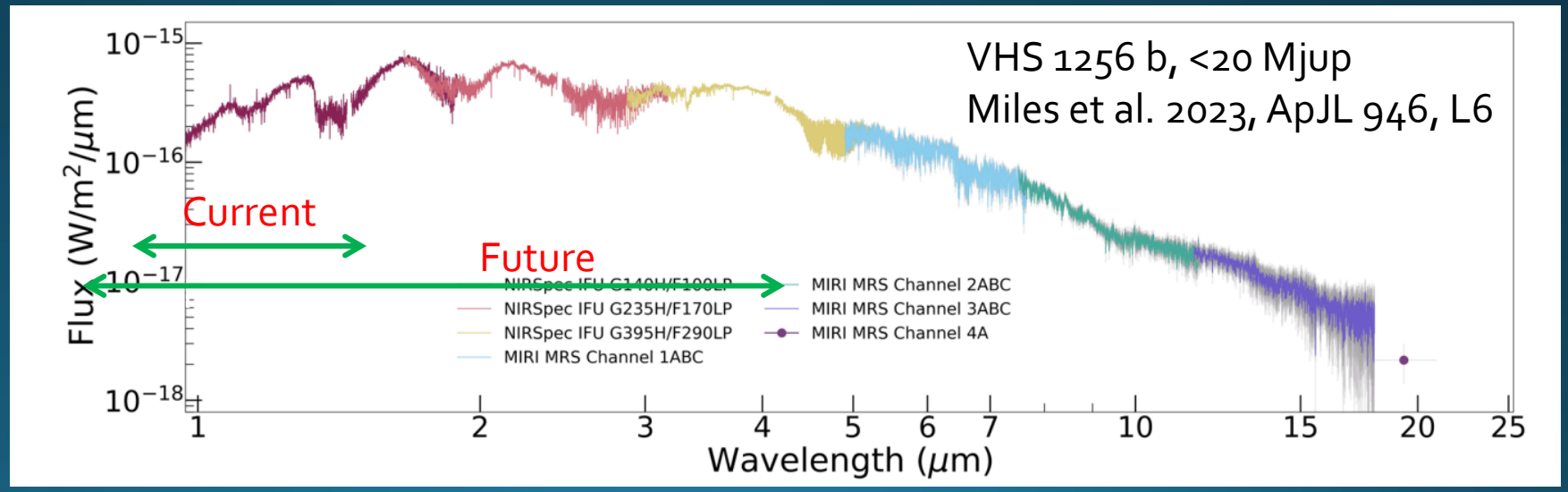
Detailed characterization of planet atmosphere by infrared high-resolution spectroscopy

- Characterization of planet atmosphere by resolving atomic and molecular absorption lines
  - Molecular abundance
  - Atmospheric structure
  - Planet rotation, atmospheric winds
  - Cloud
  - Mass estimation
- SIMULTANIOUS, KL(M)-band high-resolution (R~70,000) spectrometer + upgraded IRD/REACH (zYJH)
- Test-bed for TMT instruments for biomarker detection

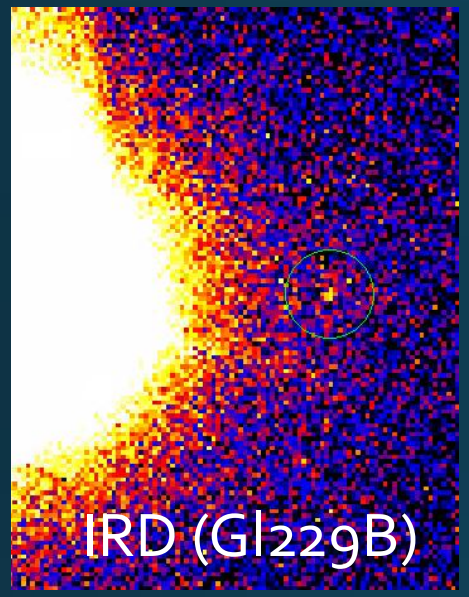


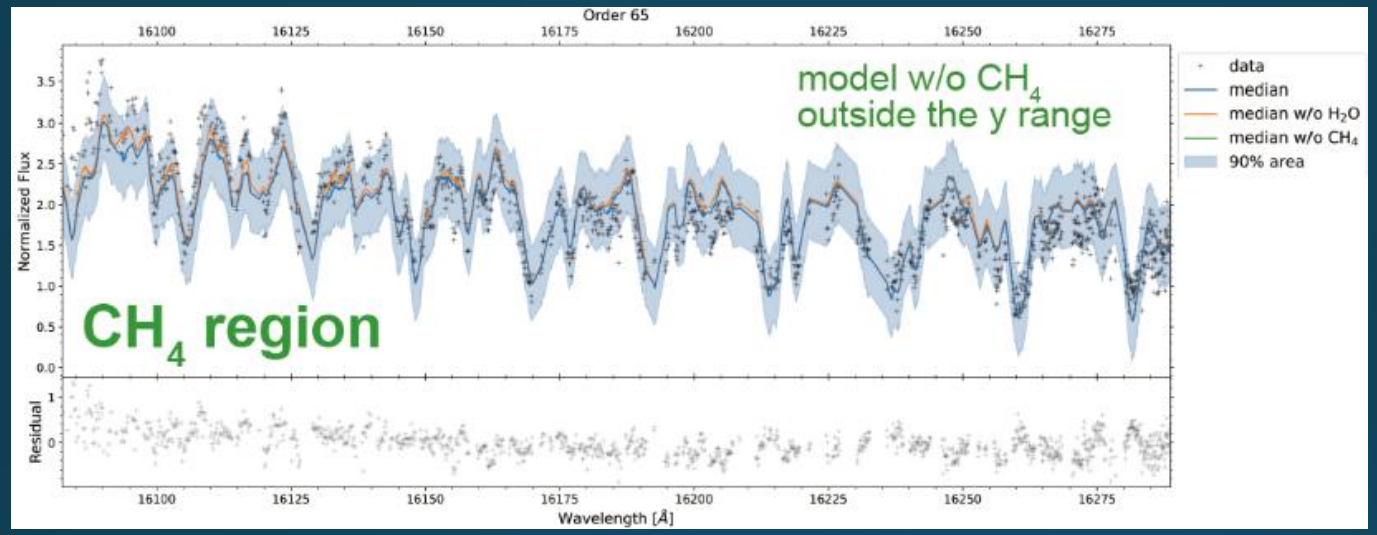


データ提供：ISAS/JAXA
Courtesy of E. Palle, H. Kawahara

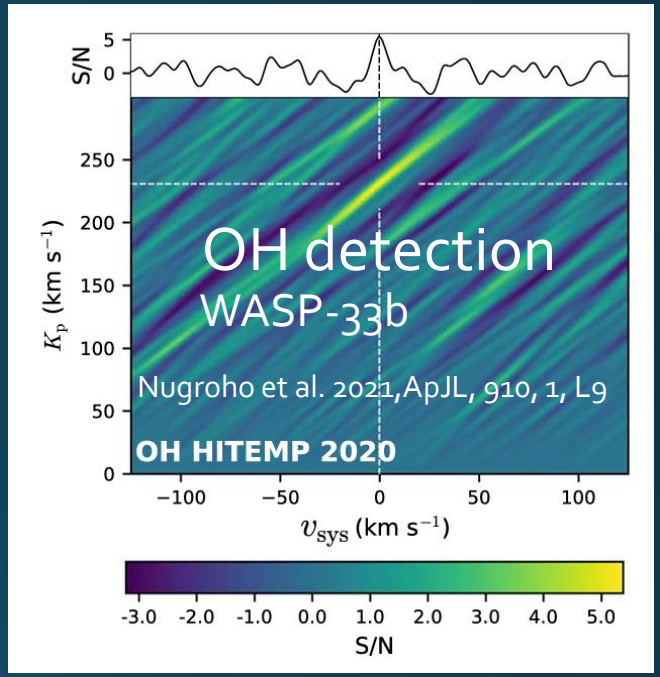


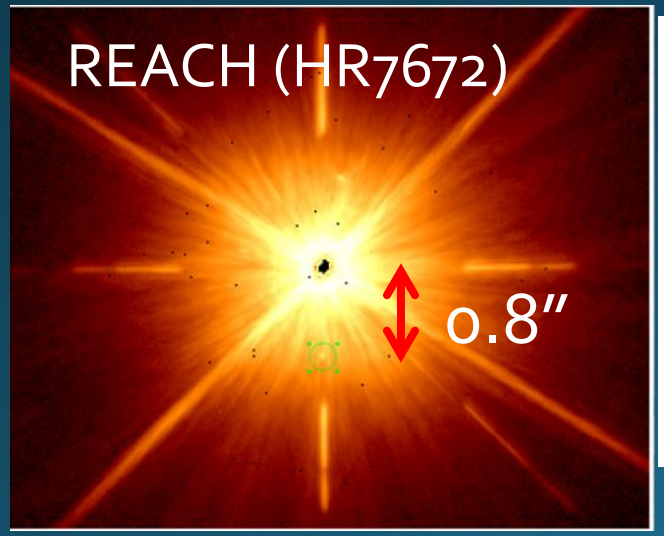
NIR high-dispersion spectroscopy of exoplanets with IRD/REACH

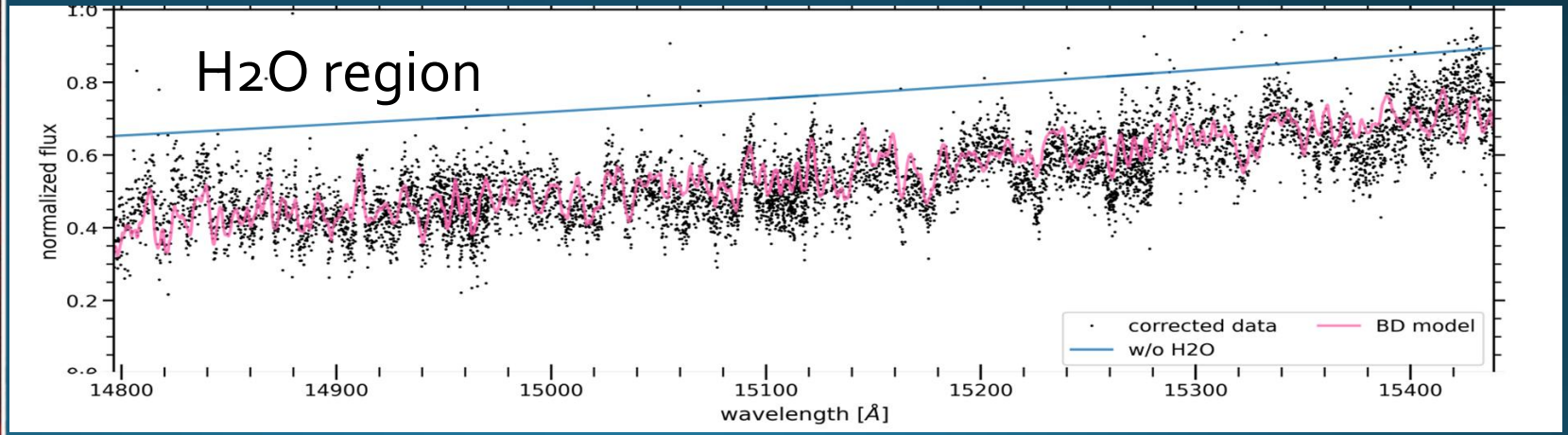




Kawashima+. Submitted arXiv:2410.11561





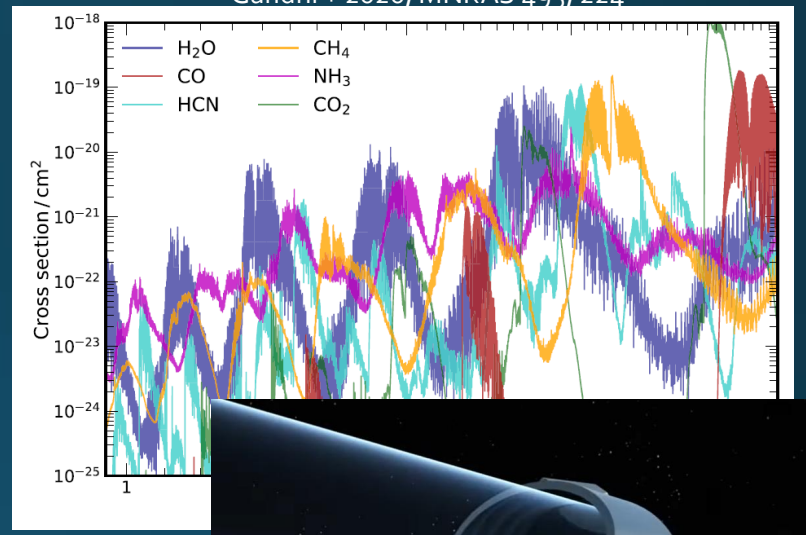


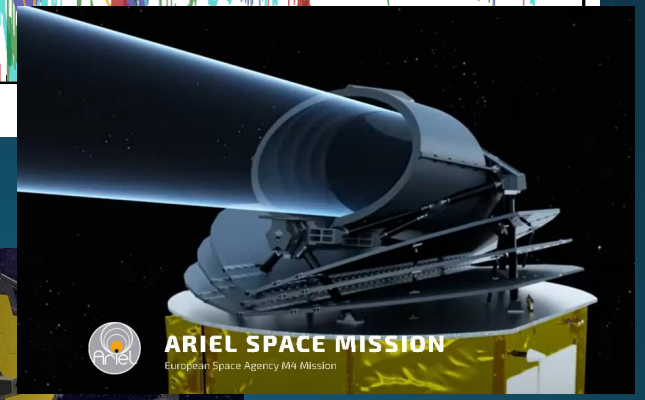
Kasagi+. in prep

Exoplanet atmosphere characterization by NIR-thermal infrared high-resolution spectroscopy

- A powerful tool to characterize low-temperature (<1000K) exoplanet atmospheres
- Relatively not well studied in this wavelength range because
  - Technically more difficult than NIR because of the large thermal background and telluric absorption
  - There are few high-resolution (R>50,000) spectrometer available for the 8-meter class telescope
- Complementary to low-mid resolution spectroscopy with JWST, ARIEL

Gandhi + 2020, MNRAS 495, 224





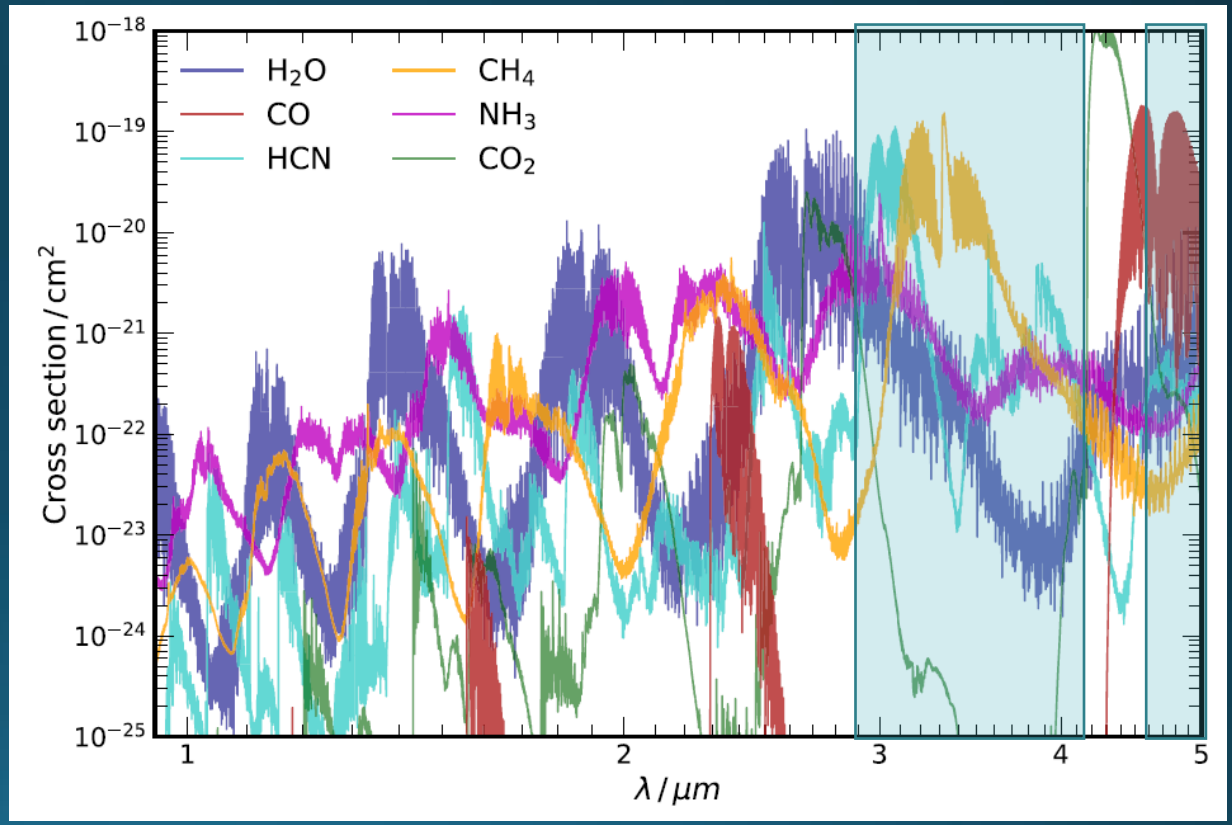
Credit: ESA

Credit: NASA

Why thermal infrared high-res spectroscopy?

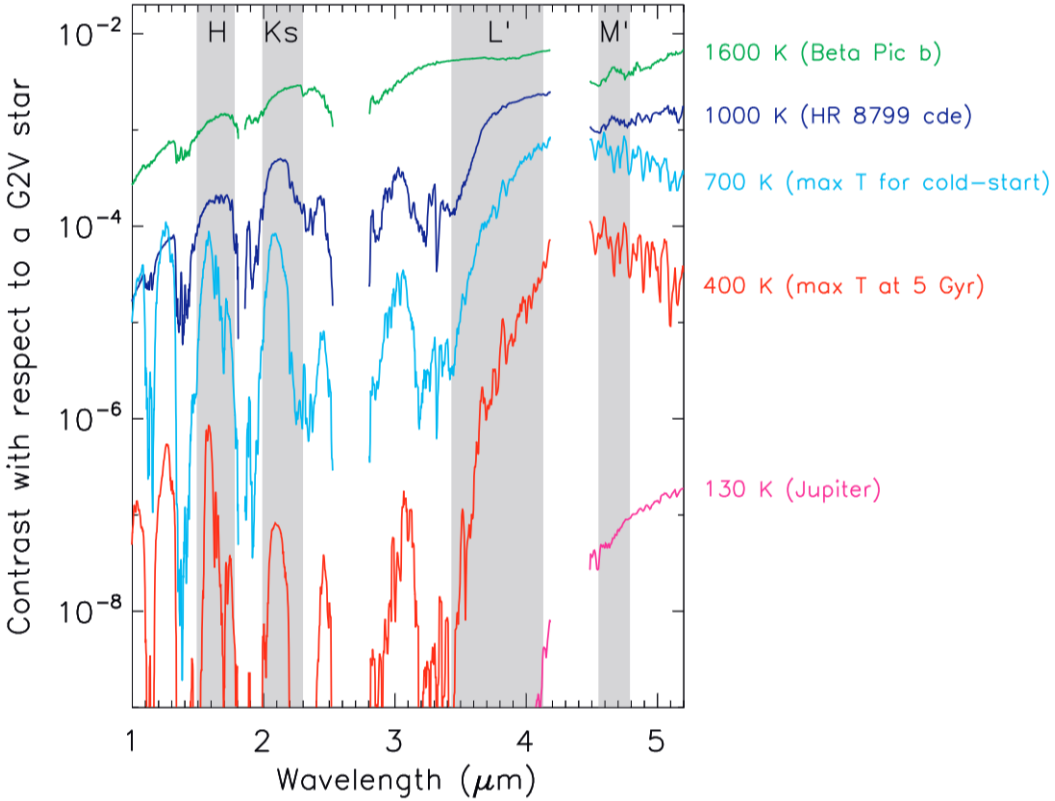
- A powerful tool to characterize low-temperature exoplanet atmosphere
- CH_4
  - There is a large peak of CH_4 absorption at 3.3 μm, where H_2O absorption is much less in the L band
  - At low temperatures < 1000K, carbon becomes not CO, but also CH_4 (in thermochemical equilibrium)
  - Measurement of the C/O ratio
- C_2H_2 and HCN are also important to probe the C/O ratio and photochemical reaction, and UV intensity dependence
- PH_3, H_3O^+, CH_3D, etc.

Molecular cross-sections



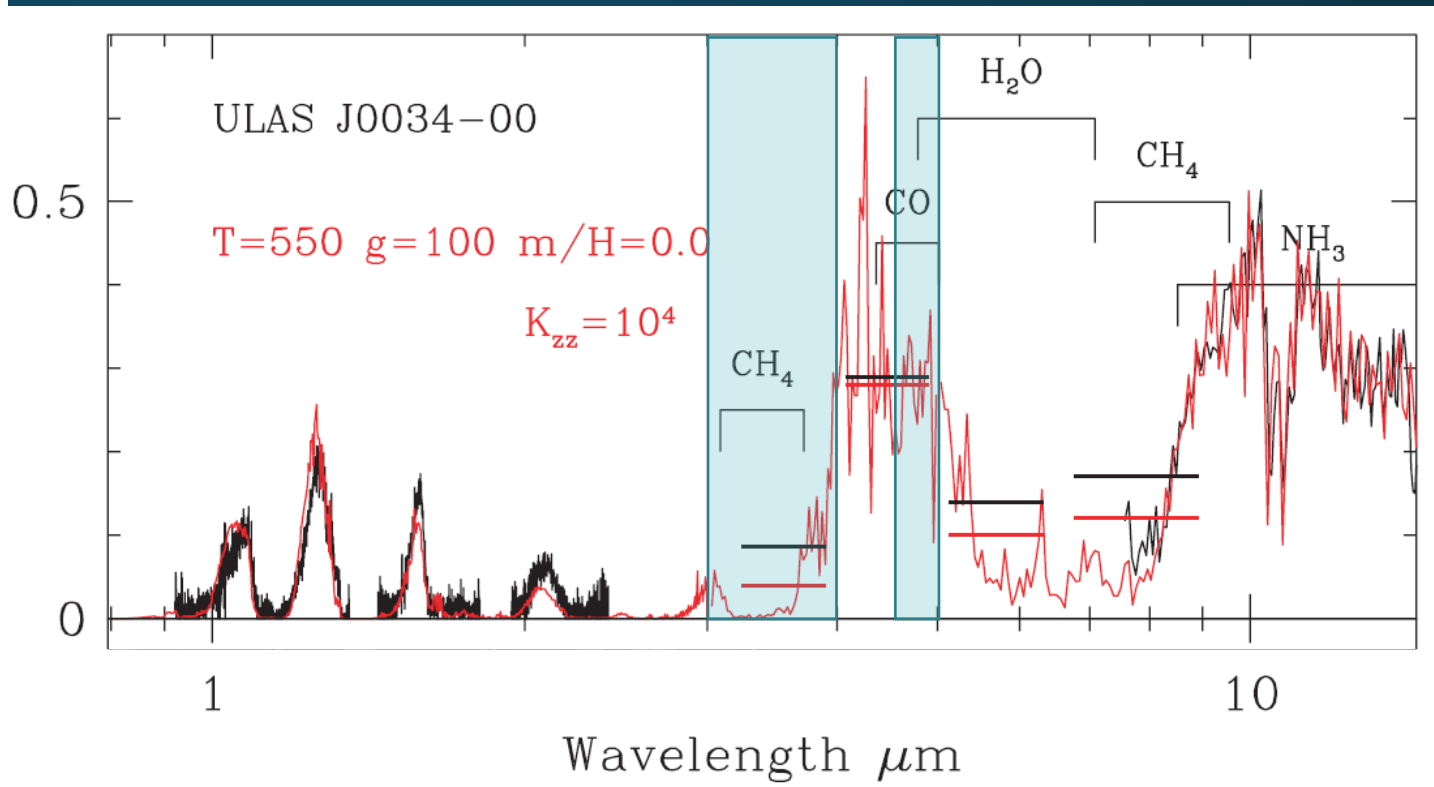
1000K, 0.1 bar, Gandhi + 2020, MNRAS 495, 224

Why thermal infrared high-res spectroscopy?



Currie et al. 2023, Protostars and Planets VII, Vol. 534, 799

Suitable for low temperature objects



Leggett et al. 2009,ApJ, 695,1517

Collaboration between space telescopes and the Subaru telescope

- The Ariel mission: Ariel will study what exoplanets are made of, how they formed and how they evolve, by surveying a diverse sample of about 1000 extrasolar planets, simultaneously in visible and infrared wavelengths
- Launch: 2029
- Spectral coverage: 0.5 – 7.8μm
- Spectral resolution 20 ~ 100
- Complementary to ground-based high-resolution spectroscopy
- Combination of ARIEL and HRS will provide better constraints on the temperature structure and molecular/atomic abundances (Guilluy+ 2022)

Credit: ESA

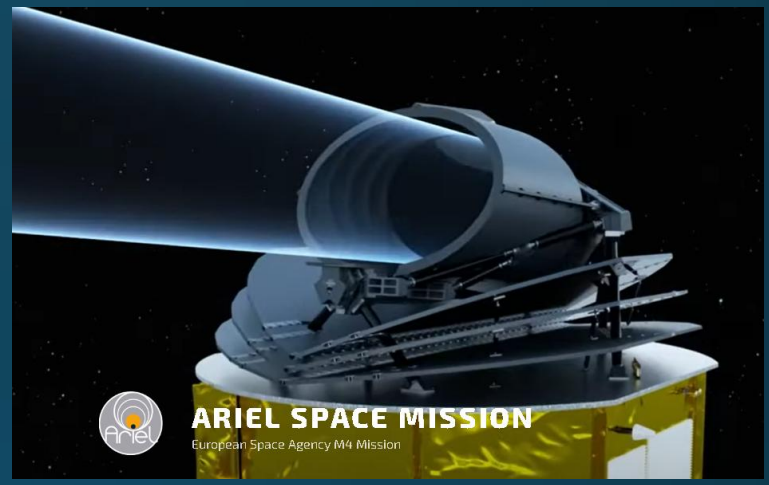
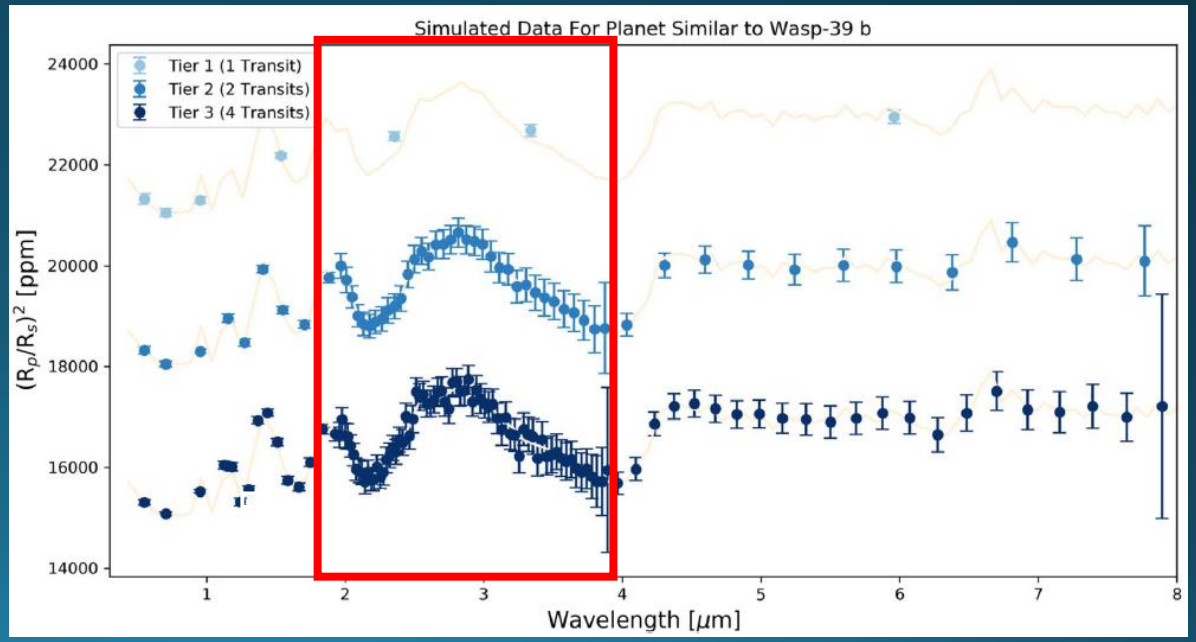


Table 1
Wavelength Ranges and Spectral Resolutions of Ariel's Instrumentation

Instrument Name	Wavelength Range (μm)	Resolution
VISPhot	0.5–0.6	
FGS 1	0.6–0.81	Photometric bands
FGS 2	0.81–1.1	
NIRSpec	1.1–1.95	20
AIRS Ch0	1.95–3.9	100
AIRS Ch1	3.9–7.8	30



Edwards et al. 2019 AJ, 157, 242

Why thermal infrared high-res spectroscopy?

JWST transit spectroscopy

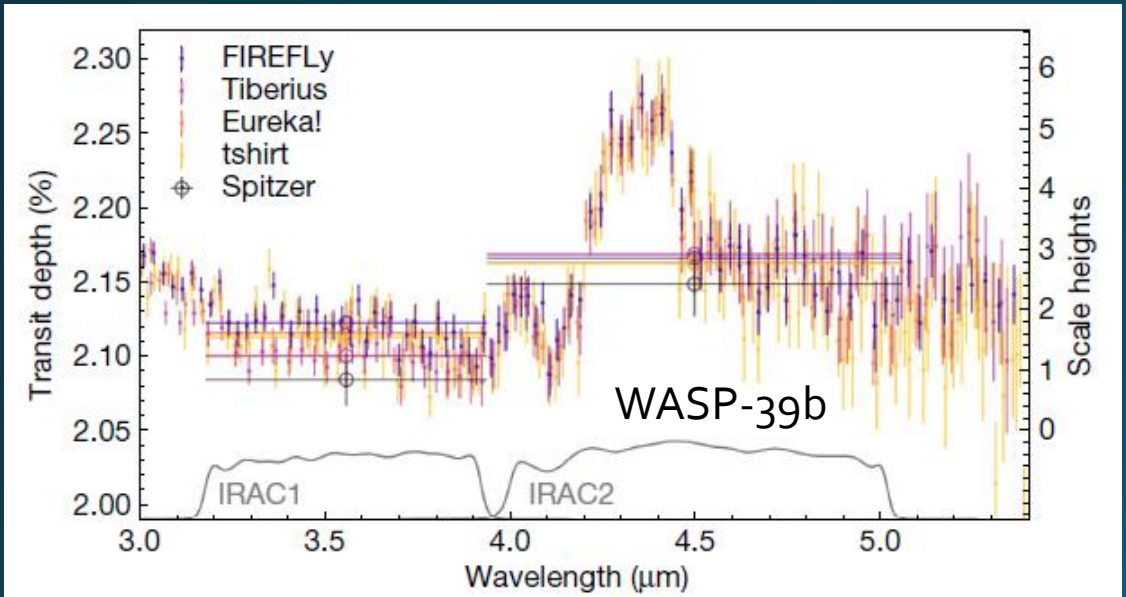


Fig. 2 | Independent reductions of the WASP-39b transmission spectrum.

JWST Transiting Exoplanet Community Early Release Science Team, 2022, Nature, 614, 649

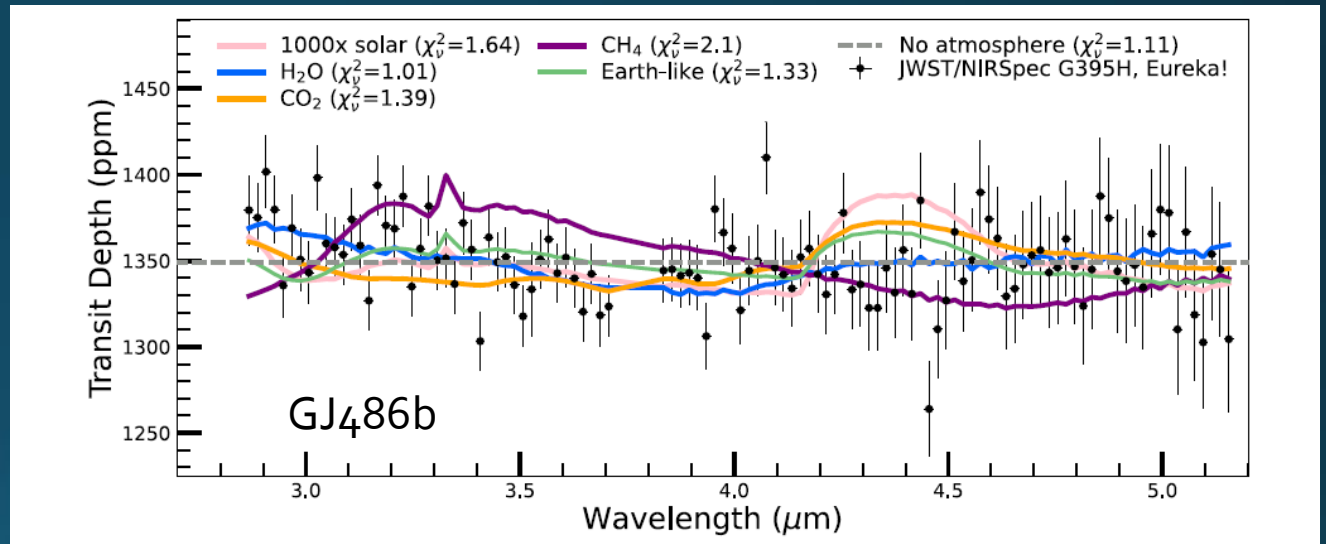


Figure 3. Our final `Eureka!` spectra of GJ 486b binned to $R \sim 200$ (black points) compared to a set of `PICASO` forward models (colored lines: 1000 × solar, pink; H_2O, blue; CO_2, orange; CH_4, purple; Earth composition, green). A 1 bar, pure water atmosphere on GJ 486b fits the data with the lowest reduced-χ^2 (1.01), and a flat line model (dashed gray line) is nearly as well fit by the data (reduced-χ^2 = 1.11) though is weakly rejected by Gaussian vs. flat line tests. Alternatively, stellar contamination with water in the atmosphere of the star, rather than the planet, can explain the observed transit depths (see Figure 4). The complete figure set (three images, one for each reduction) is available. The reduced data shown in this figure set is available.

Moran et al. 2023 ApJ, 948:L11

Thermal infrared Spectrometer for HIResolution characterization for the Subaru Telescope (TSHIRT)

- AO assisted, diffraction limited spectrometer
  - Compactness and low thermal background
  - Direct imaging-spectroscopy of exoplanets
  - Fiber or slit
- Hight throughput (total >10%) and low thermal background is a top primary
- Cassegrain for ultimate sensitivity (Secondary DM + own WFS)
- NasIR if prioritize more flexible observing schedule and high-contrast capability (AO3000+SCExAO)
- Slit view as a simple Kl-band high-resolution imager for disk science and embedded planet detection

Item	Specifications
Spectral resolution	70,000
Spectral coverage	KL-band (M-band optional)
AO	Secondary mirror DM (924 element) + own WFS or AO3000 + SCExAO
Detector	5um-cut H2RG
Imager	Slit viewer as a simple high-resolution KL-band imager + low-res spectrograph
Spatial filtering	Cryogenic single-mode fiber fed for further reducing thermal background

Originality and international competitiveness

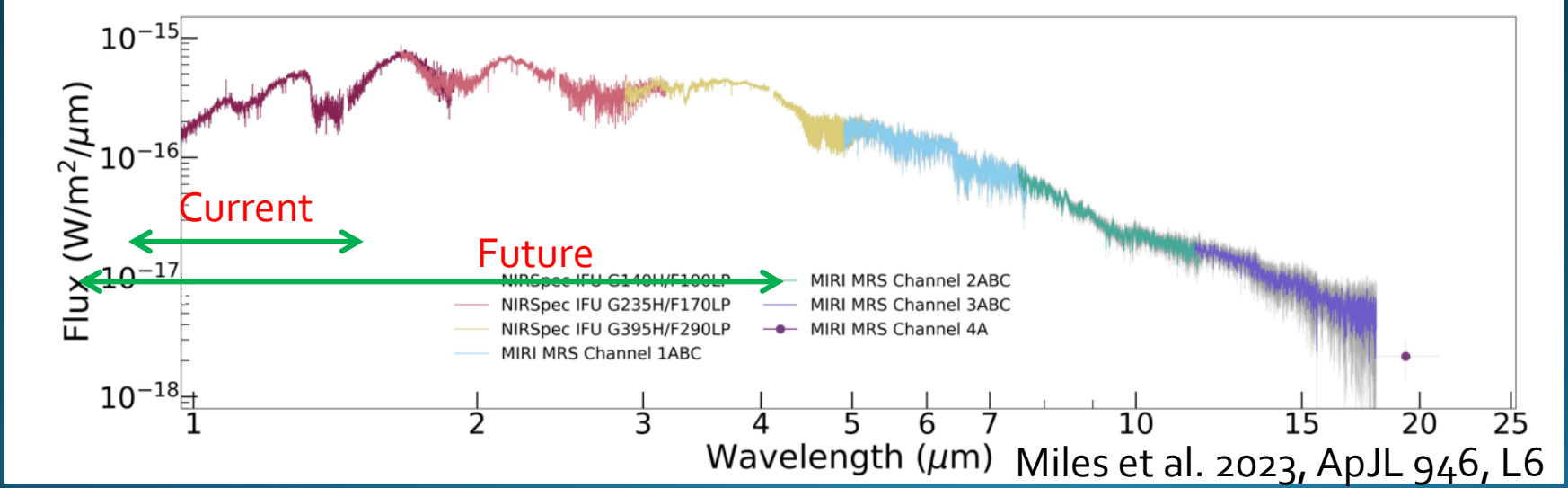
- Only few very high-res (R>50,000) spectrometer for the 8 meter-class telescopes covering KL-band
  - CRIRES+/VLT (Y,J,H,K,L,M, not simultaneous, requires 7 exposures to cover the full KL-band)
- No planned thermal infrared high-res spectrometer for the 8-meter class telescope
  - HISPEC/Keck (YJHK simultaneous, from 2026)
  - METIS/E-ELT, R=100,000 IFU spectroscopy at L/M-band
  - PSI/TMT (2nd generation instrument), R=100,000 spectroscopy (YJHKLM)
- Complementary to the IRD and REACH spectroscopy (YJH)

Current status, cost, budget, and schedule

- Current status
  - Conceptual design phase, science investigation, team organization
- Cost estimate
  - ~ 300M yen for the instrument development
- Budget plan
  - Mostly based on external funding (JSPS Kakenhi, etc.)
- Schedule
  - 2024-2025: Conceptual design phase
  - 2026-2027: Detailed design
  - 2028-2029: Manufacturing
  - 2030: Installation and engineering observation
  - 2031-2036: Operation

Why NAOJ? Why Subaru?

- Mauna Kea is one of the best sites for NIR-thermal infrared observation
  - Low thermal background, good seeing, high atmospheric transparency
- A lot of heritages of the AO development and high-resolution spectroscopy important for diffraction-limited spectroscopy
- Complementary to the NIR - optical high-resolution spectroscopy provided by IRD, ultra-doppler, HDS
- The TSHIRT project does not request direct funding from NAOJ but close collaboration with Subaru/NAOJ



Miles et al. 2023, ApJL 946, L6

Summary

- NIR-thermal infrared, high-resolution spectroscopy to better understand exoplanet atmosphere
  - Temperature-pressure structure
  - Cloud
  - Planet rotational, wind speed
  - Molecular abundances
  - Planet mass
- We propose a new high-dispersion spectrometer for the KL(M)-band for the Subaru Telescope (TSHIRT), with operations targeted to begin around 2030
- Coordinated observations with ARIEL, set to launch in 2029, will enable more precise constraints on exoplanet atmospheric compositions and structures