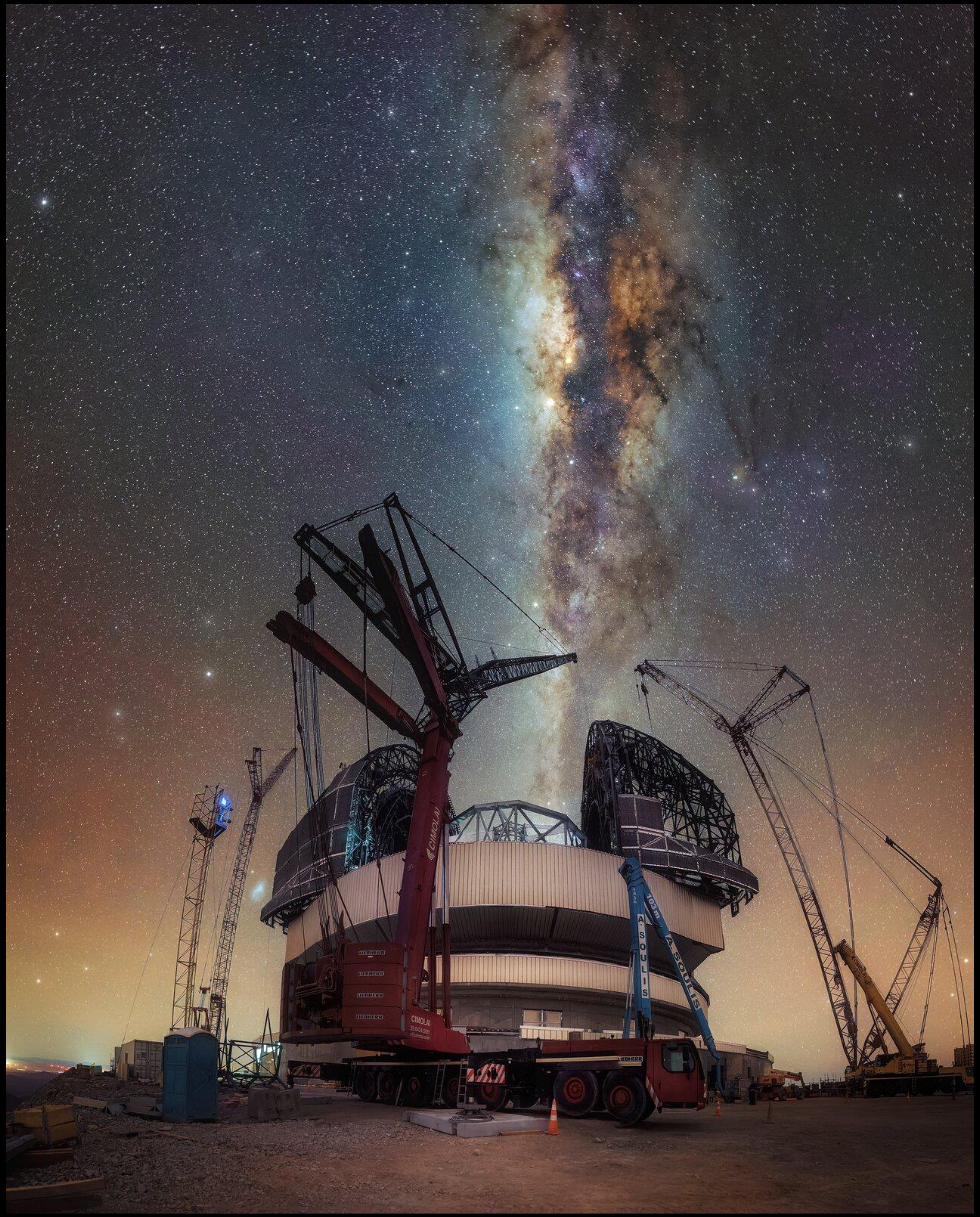
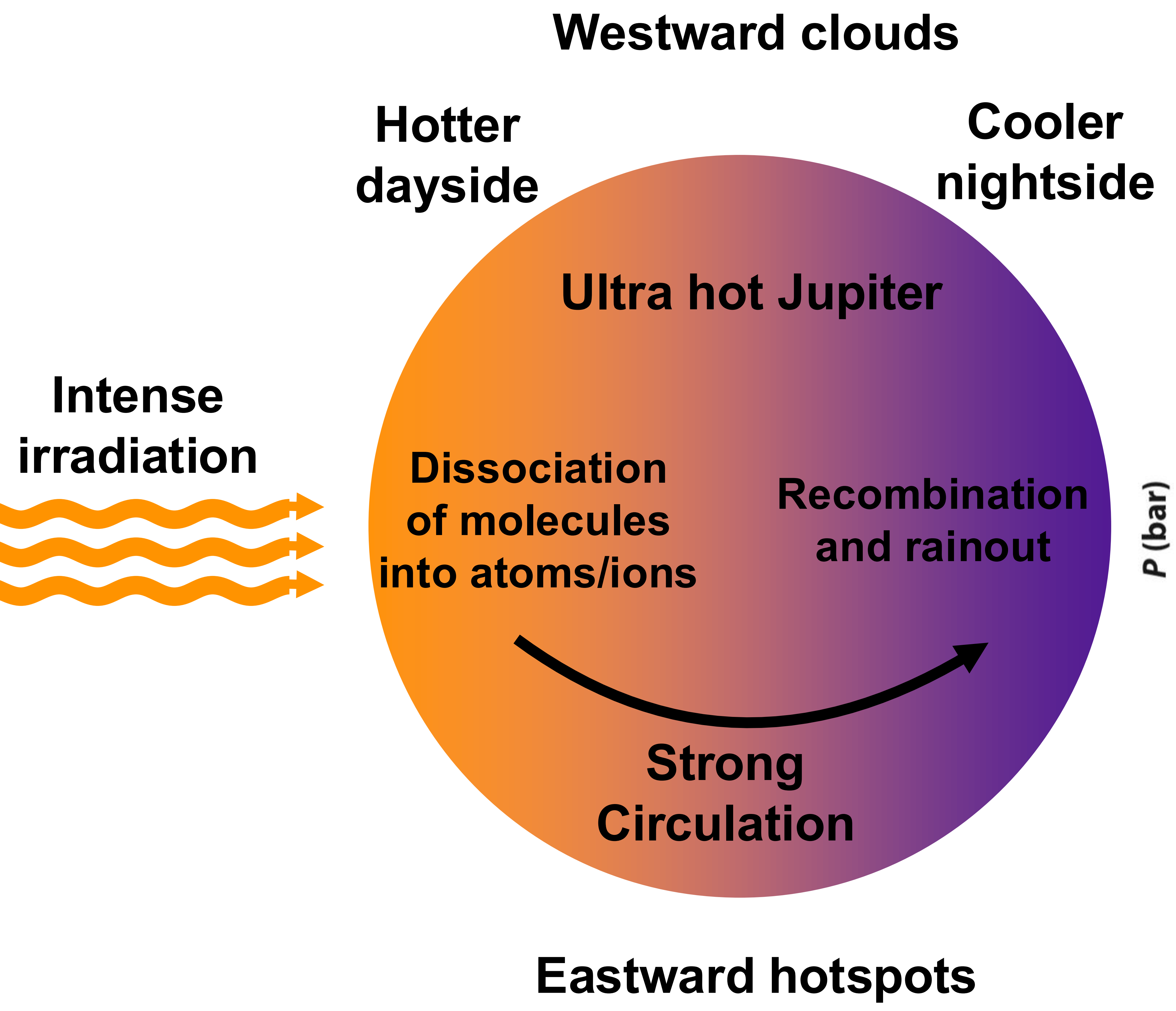
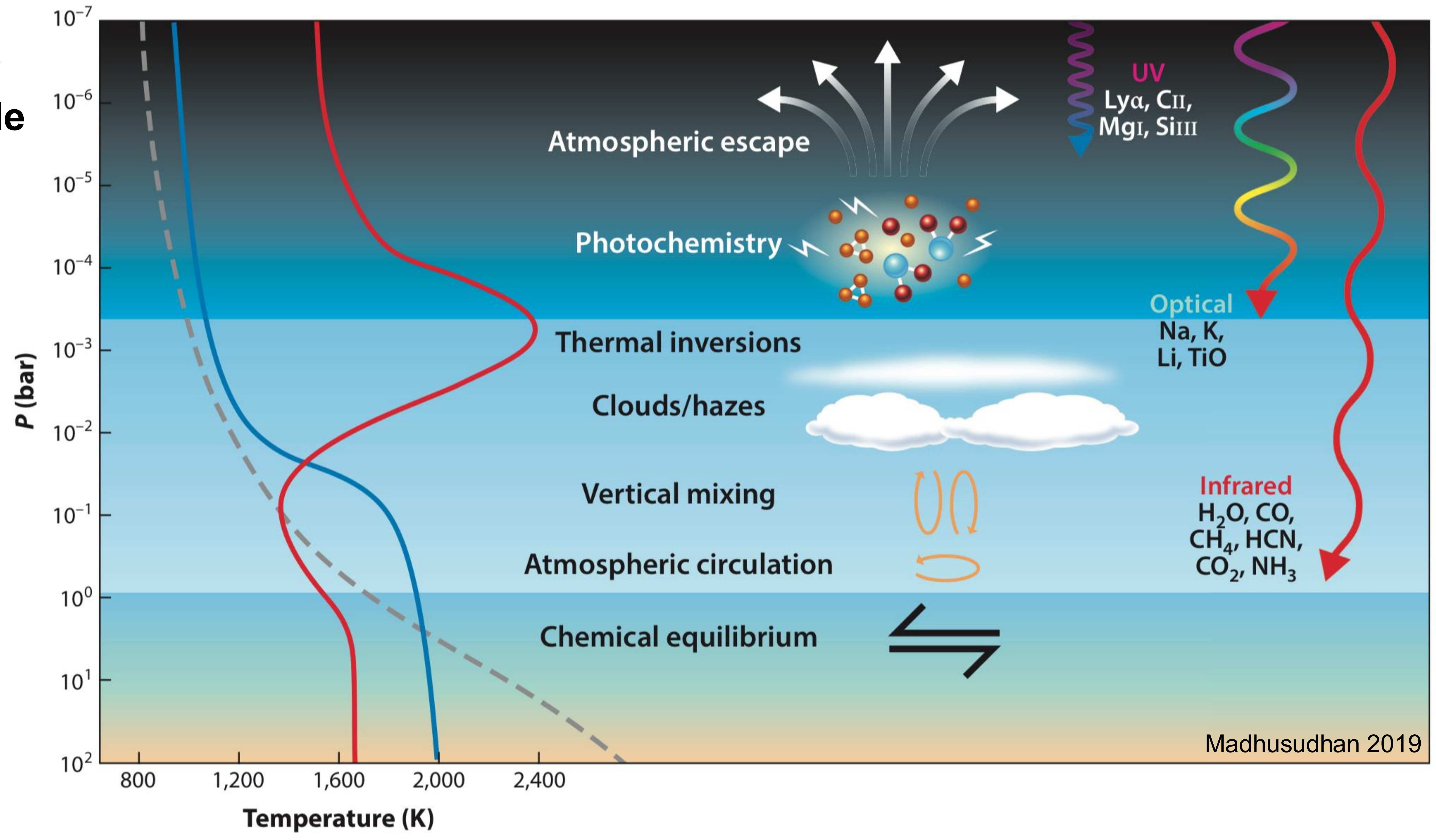
A High Spectral Resolution View of Exoplanet Atmospheres

Jayne Birkby (University of Oxford)

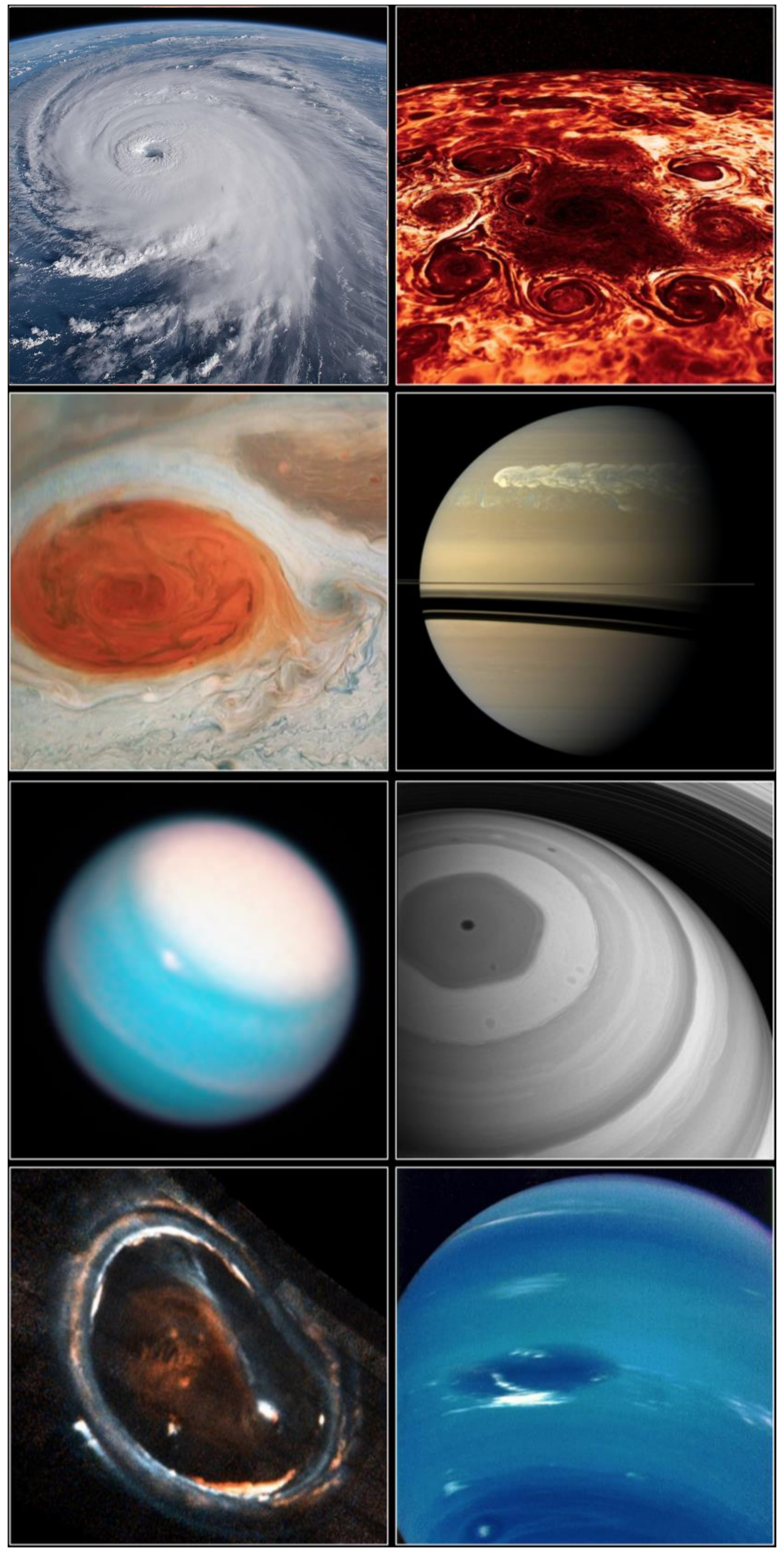


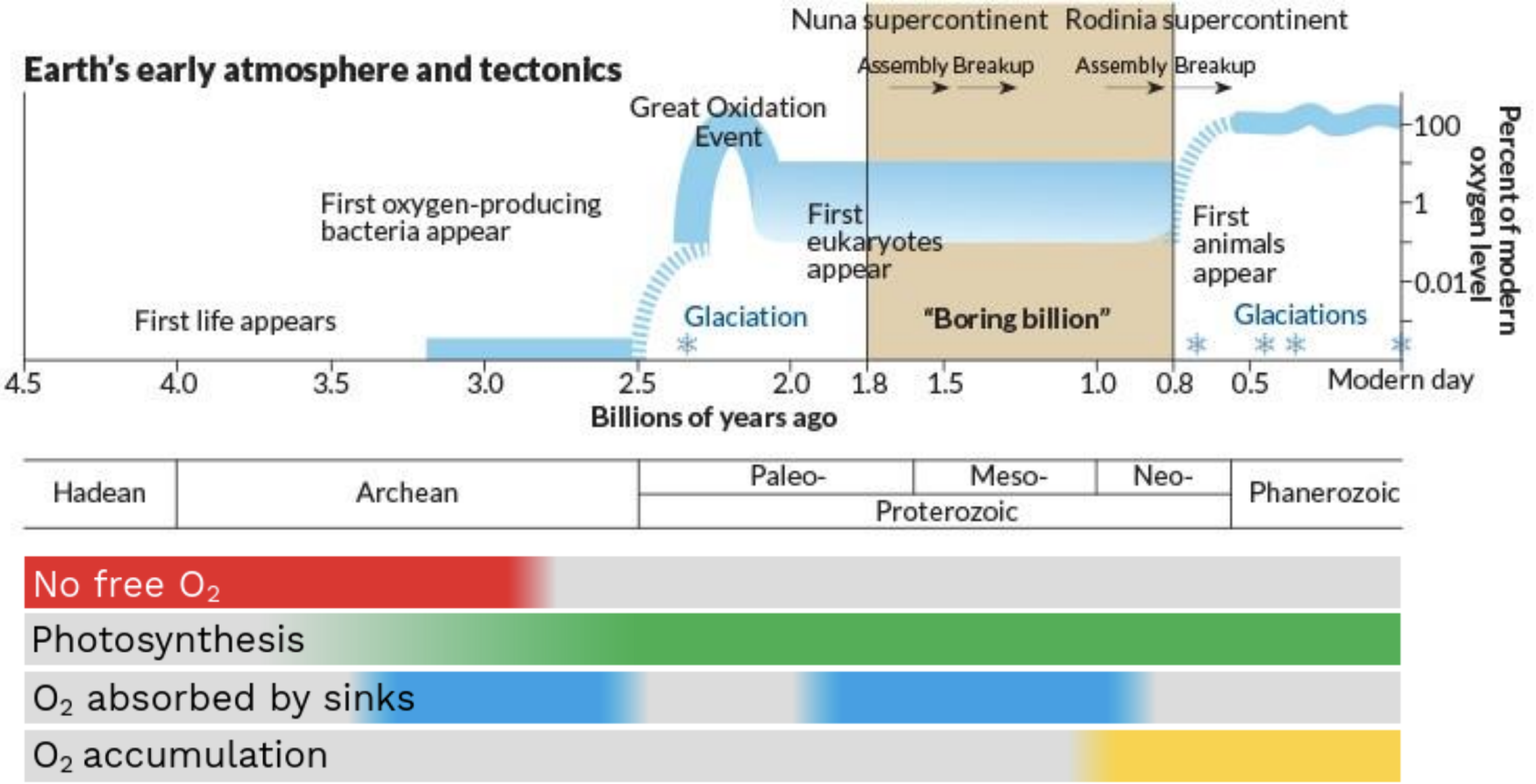
Exoplanets are complex objects requiring 4D treatment of their chemistry and dynamics



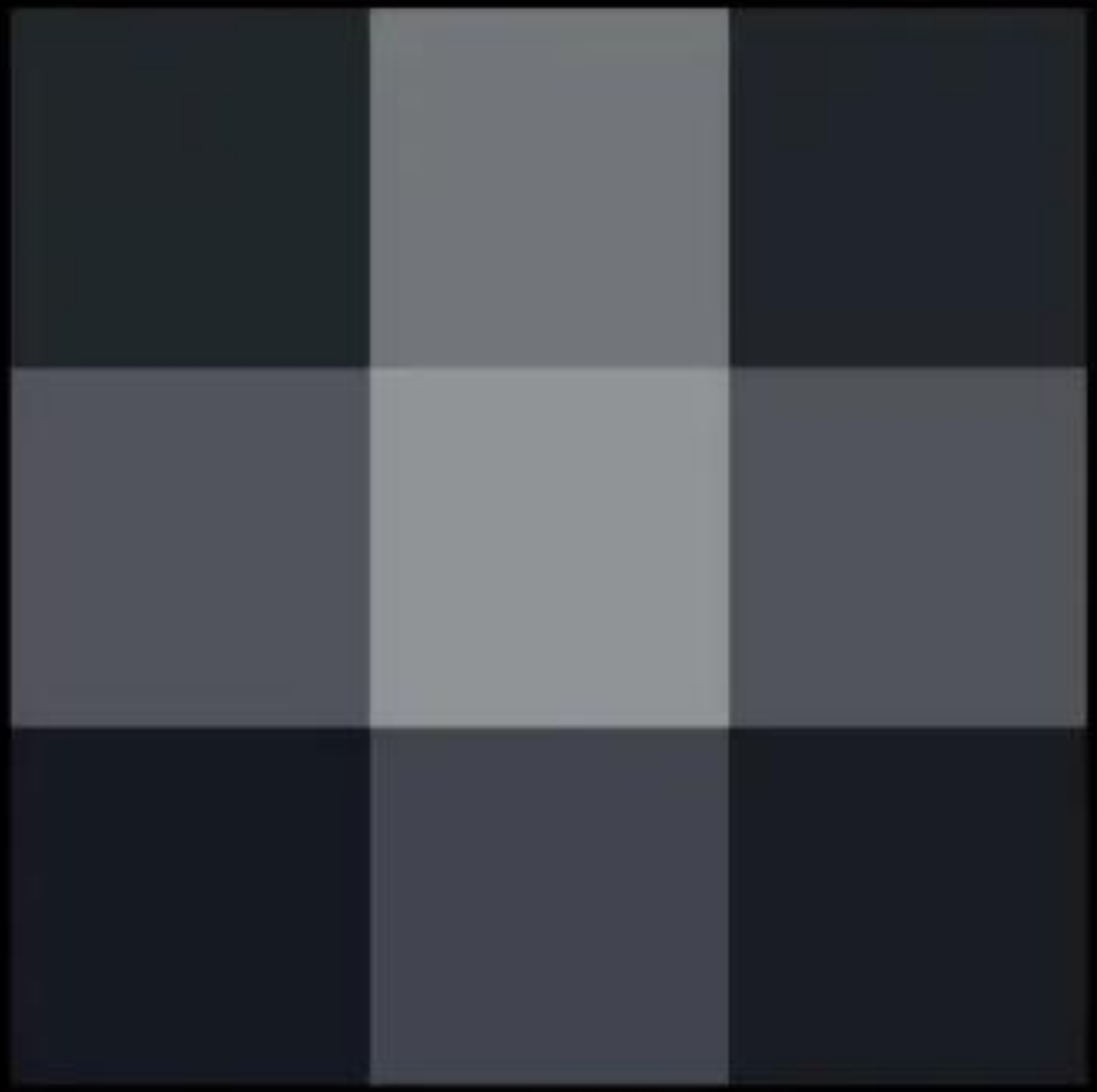


Exoplanet atmospheres evolve over many different timescales from short lived daily weather to billion-year long climate trends





All the information is contained within a single pixel

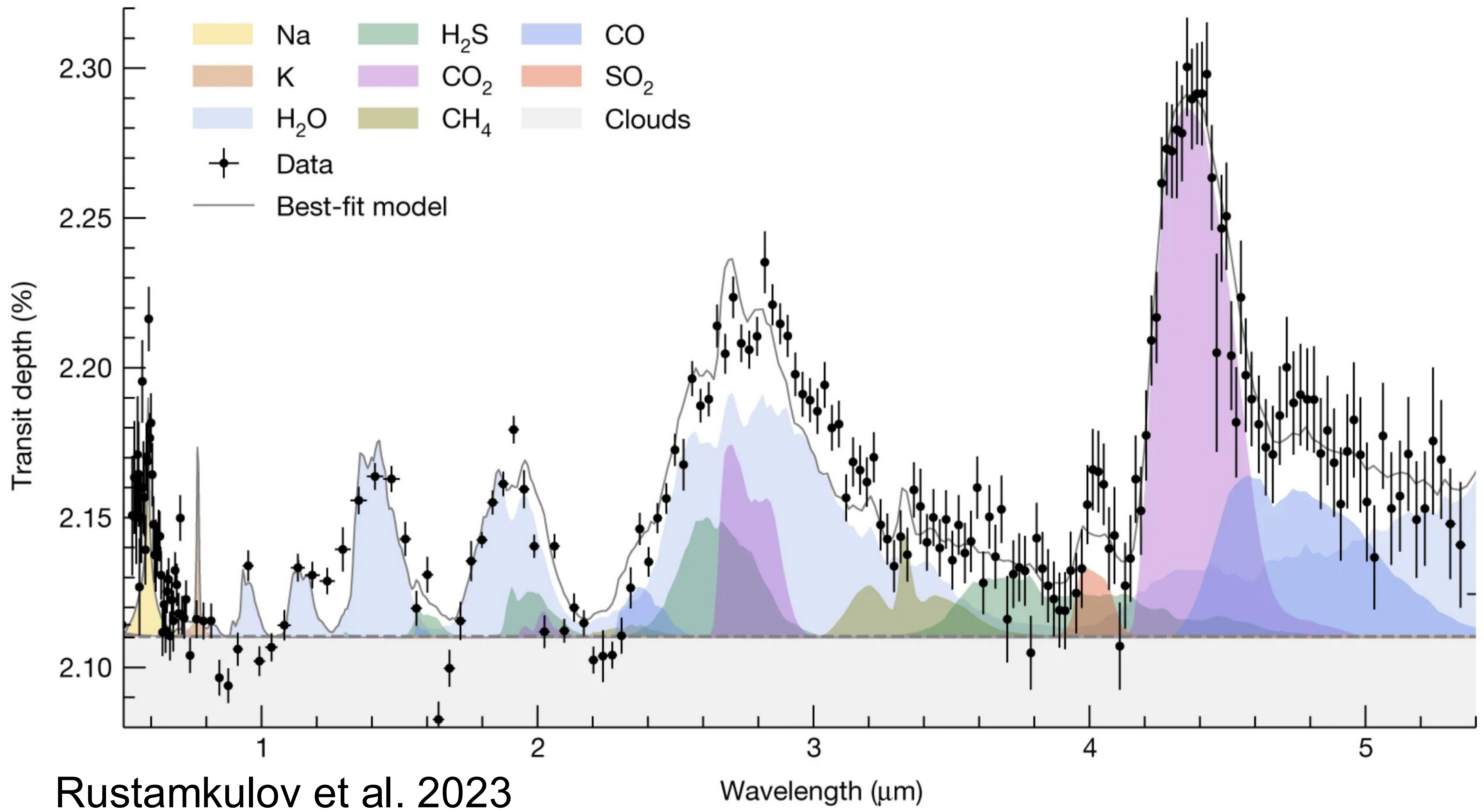


Simulation of an Earth at 1AU orbiting alpha Centauri A at 60 μ-arcsecond spatial resolution
(~200m telescope at 500nm, Kane et al. 2017)

Credit: NOAA/NASA/Kane et al., 2017

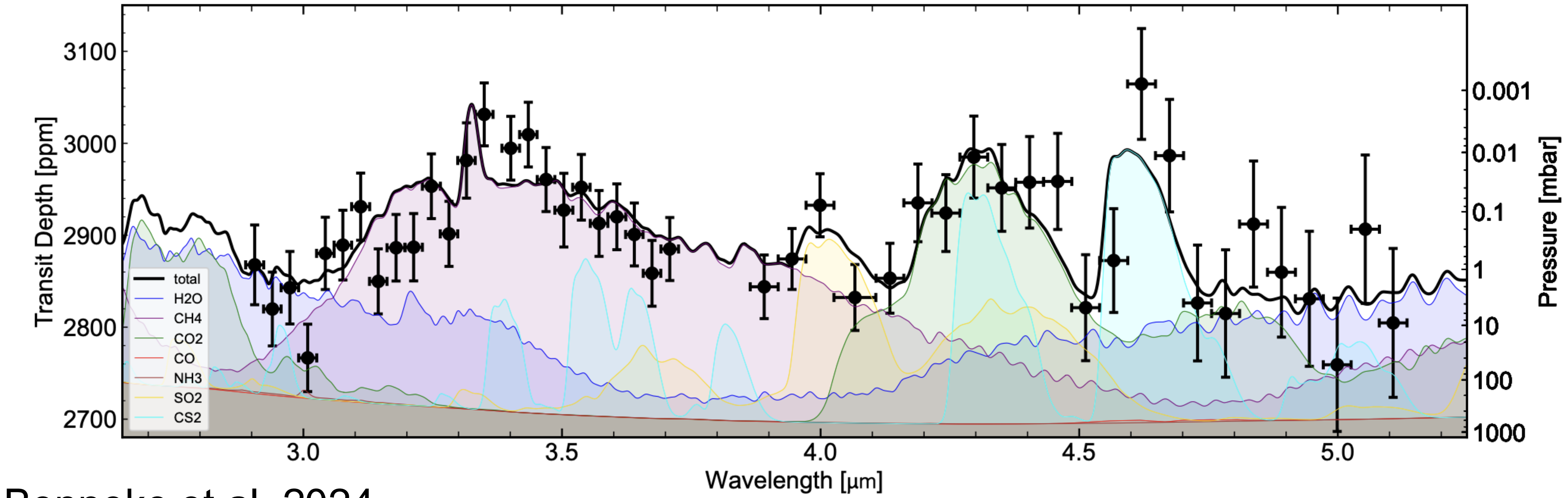
JWST low resolution spectroscopy (R<3,000) reveals overlapping broadband molecular features across the exoplanet population

Hot Saturn (WASP-39 b) ~2000ppm



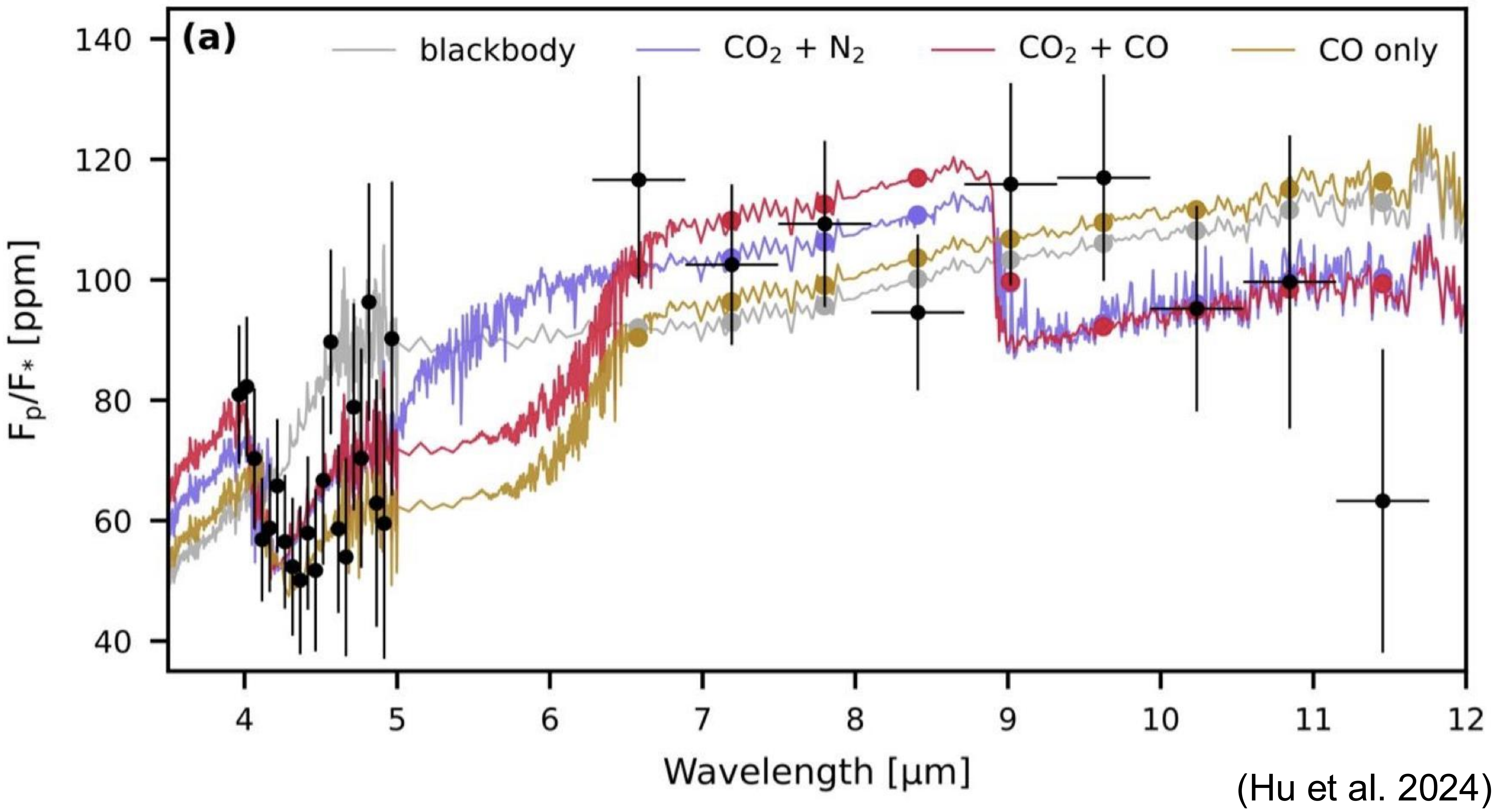
Rustamkulov et al. 2023

sub-Neptune (TOI-270 d) ~200ppm



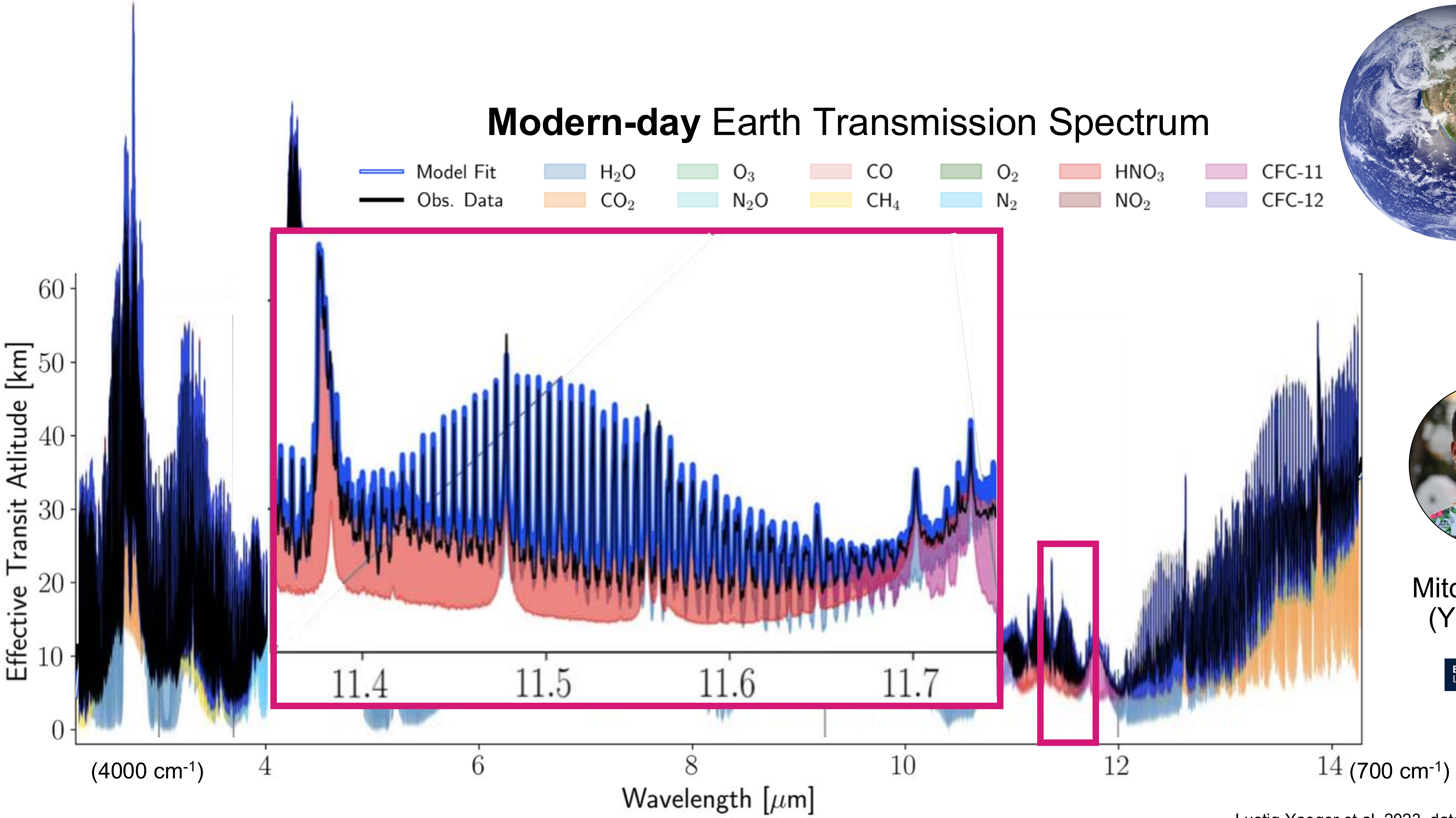
Benneke et al. 2024

Super Earth (55 Cnc e) ~20ppm



(Hu et al. 2024)

At high spectral resolution molecular bands have unique patterns that are difficult to mimic with random noise



Mitchell Yzer
(Y1 DPhil)

Lustig-Yaeger et al. 2023, data from SCISAT ACE

The ELTs will have a suite of instruments for *High Resolution Spectroscopy* of exoplanet atmospheres

METIS

ELT: 3-**5** µm (LM) coronagraphic IFU @ R=100,000

ANDES

ELT: YJH+K coronagraphic IFU @ R=100,000
and (**0.38**) 0.5–1.8 (2.4) µm seeing-limited fibre-fed spectrograph @ R=100,000

HARMONI

ELT: 1.45–2.45 µm (HK) coronagraphic IFU @ R=18,000

G-CLEF

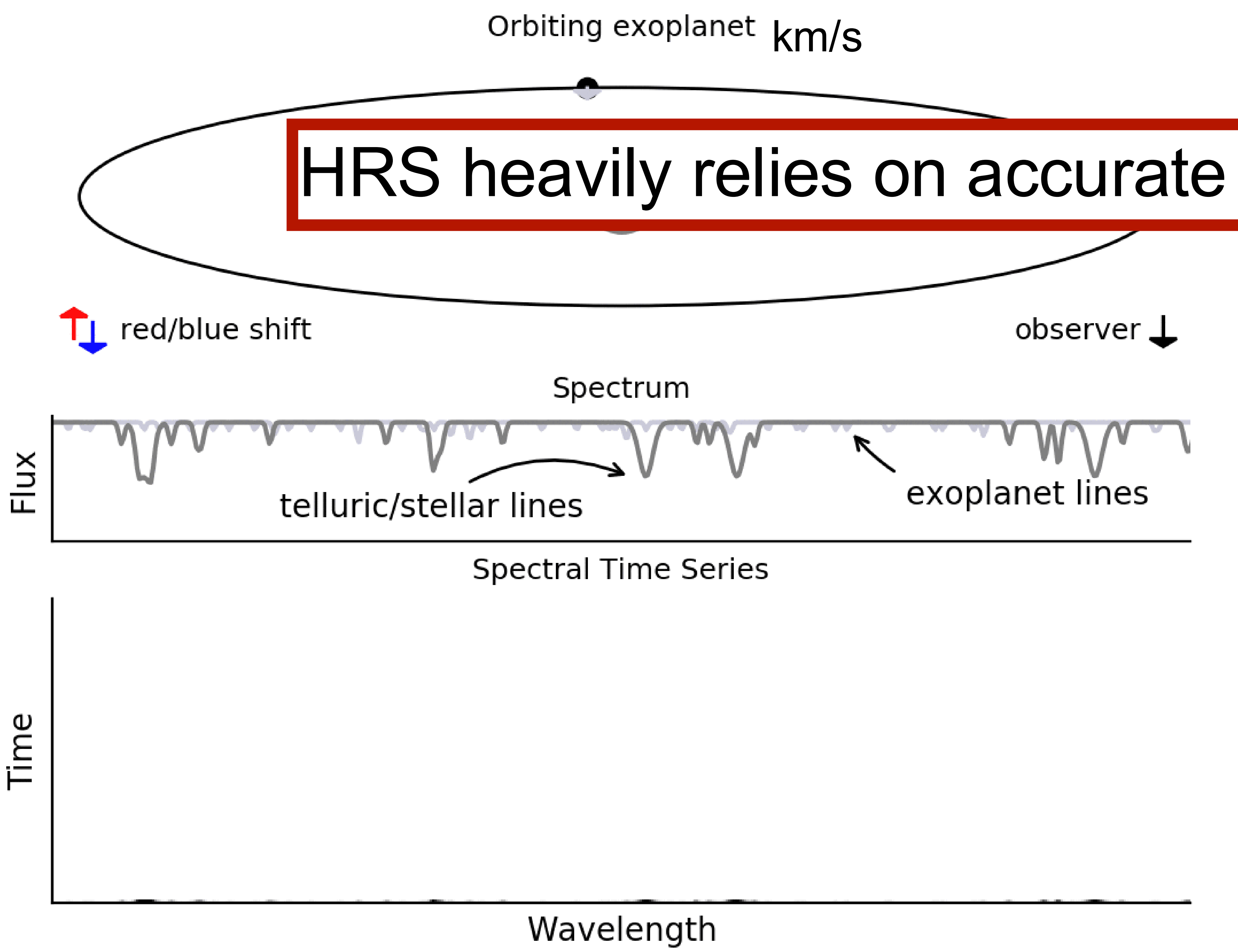
GMT: **0.35**–0.9 µm seeing limited fibre-fed spectrograph @ R=100,000

MODHIS

TMT: 0.95-2.4 µm AO-assisted single-mode fibre spectrograph @ R=100,000

Combine High Resolution Spectroscopy (HRS) with a large change in planet Doppler shift and cross-correlate

Planet spectrum is Doppler shifting much faster than the host star



Animation by Lennart van Sluijs

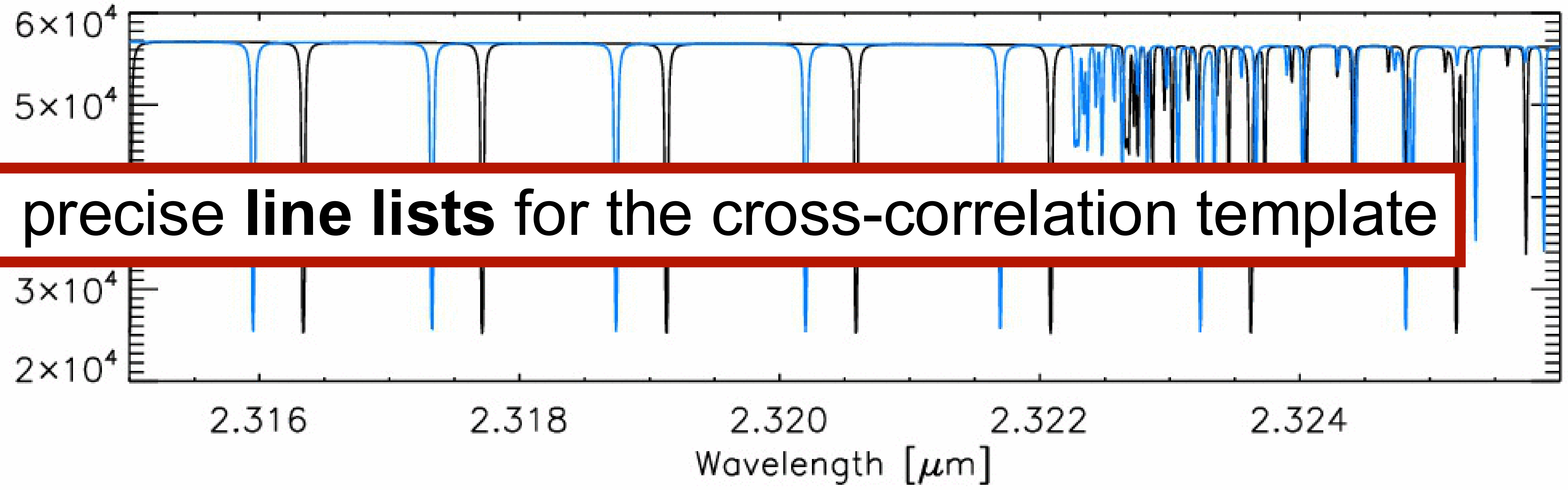
Toy model with planet injected at >1000x brighter

For real planet, each line has signal-to-noise << 1

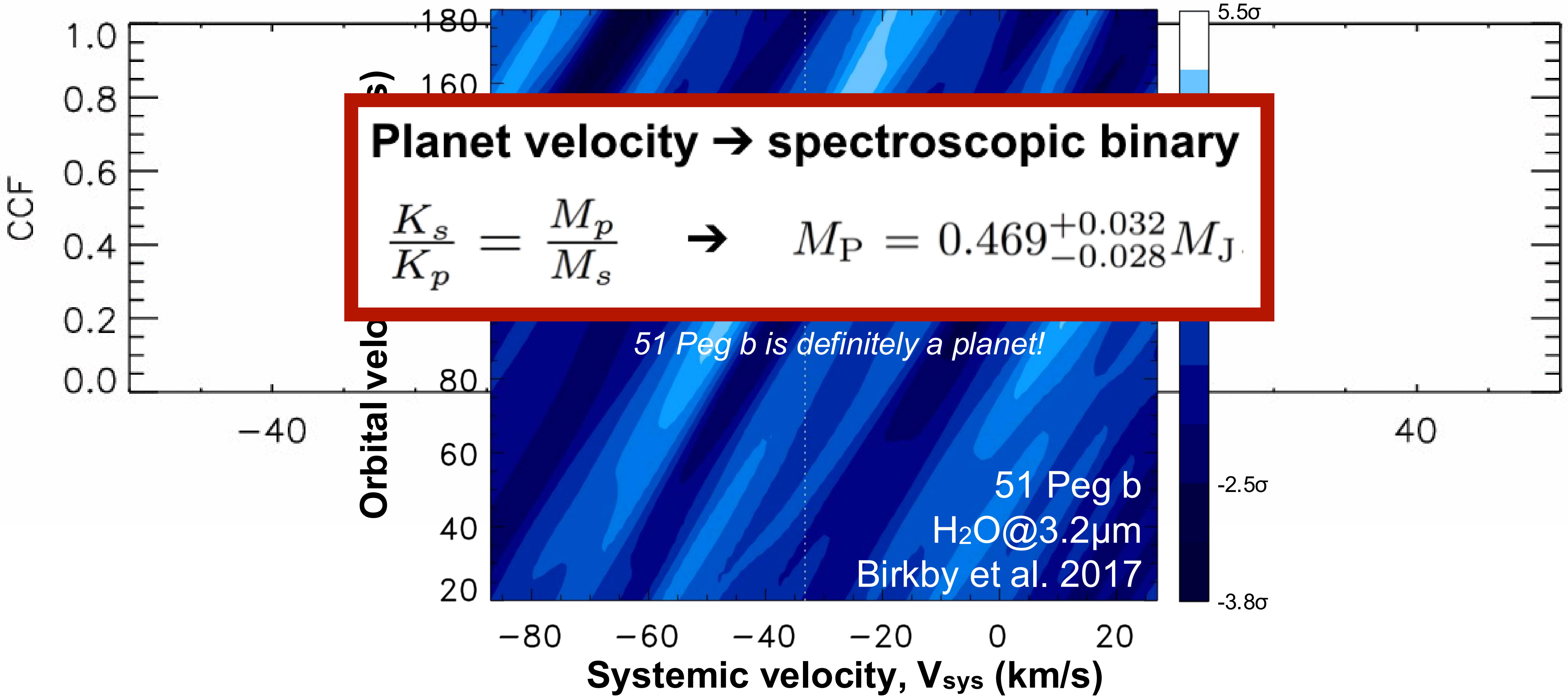
Also gives true mass, not lower limit, for non-transiting planets

Cross-correlations

Hot Jupiter HD 209458 b CO in transmission   Snellen et al. 2010



HRS heavily relies on accurate and precise **line lists** for the cross-correlation template

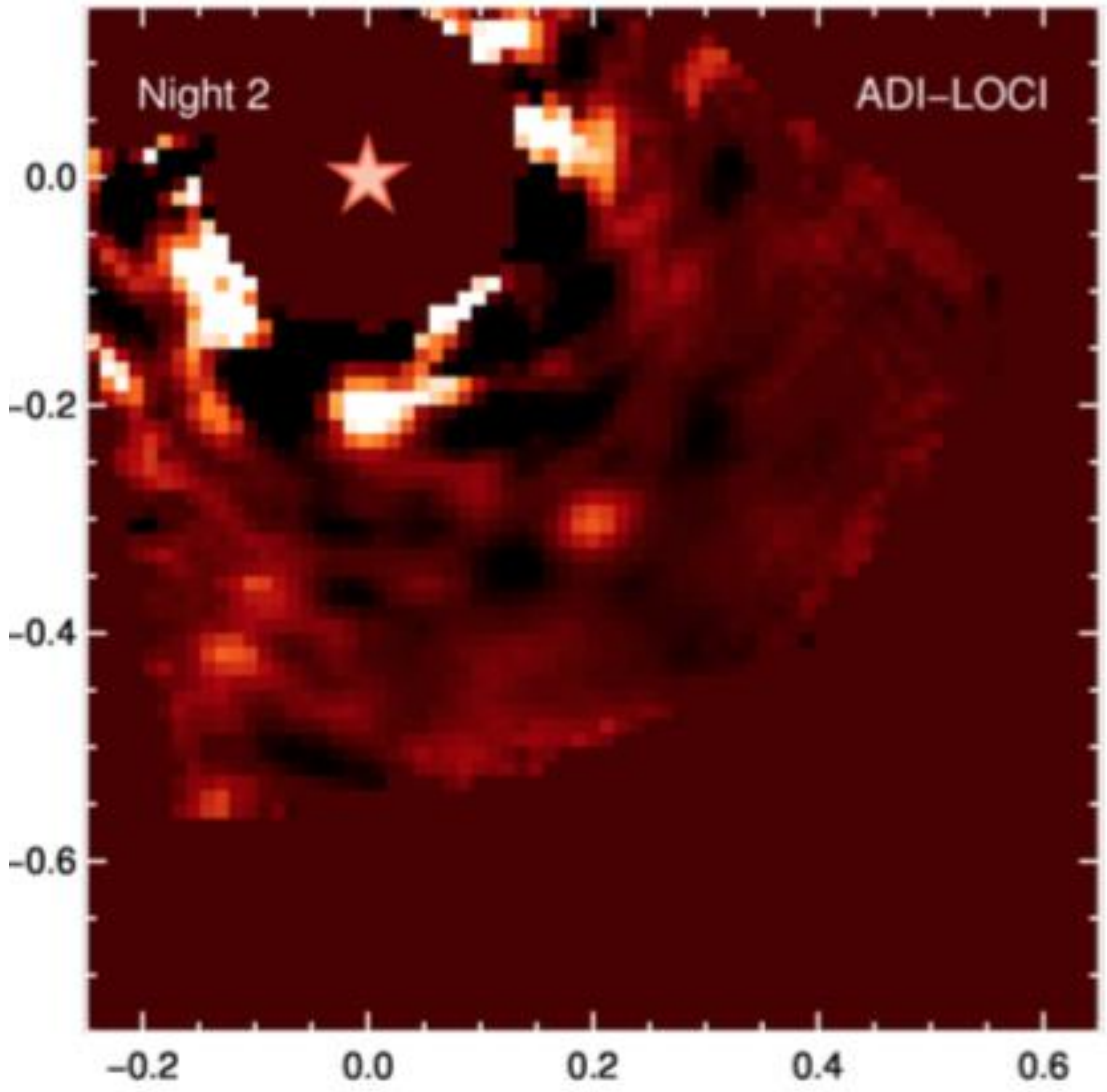


Planet velocity → spectroscopic binary

$$\frac{K_s}{K_p} = \frac{M_p}{M_s} \quad \rightarrow \quad M_{\rm P} = 0.469^{+0.032}_{-0.028} M_{\rm J}$$

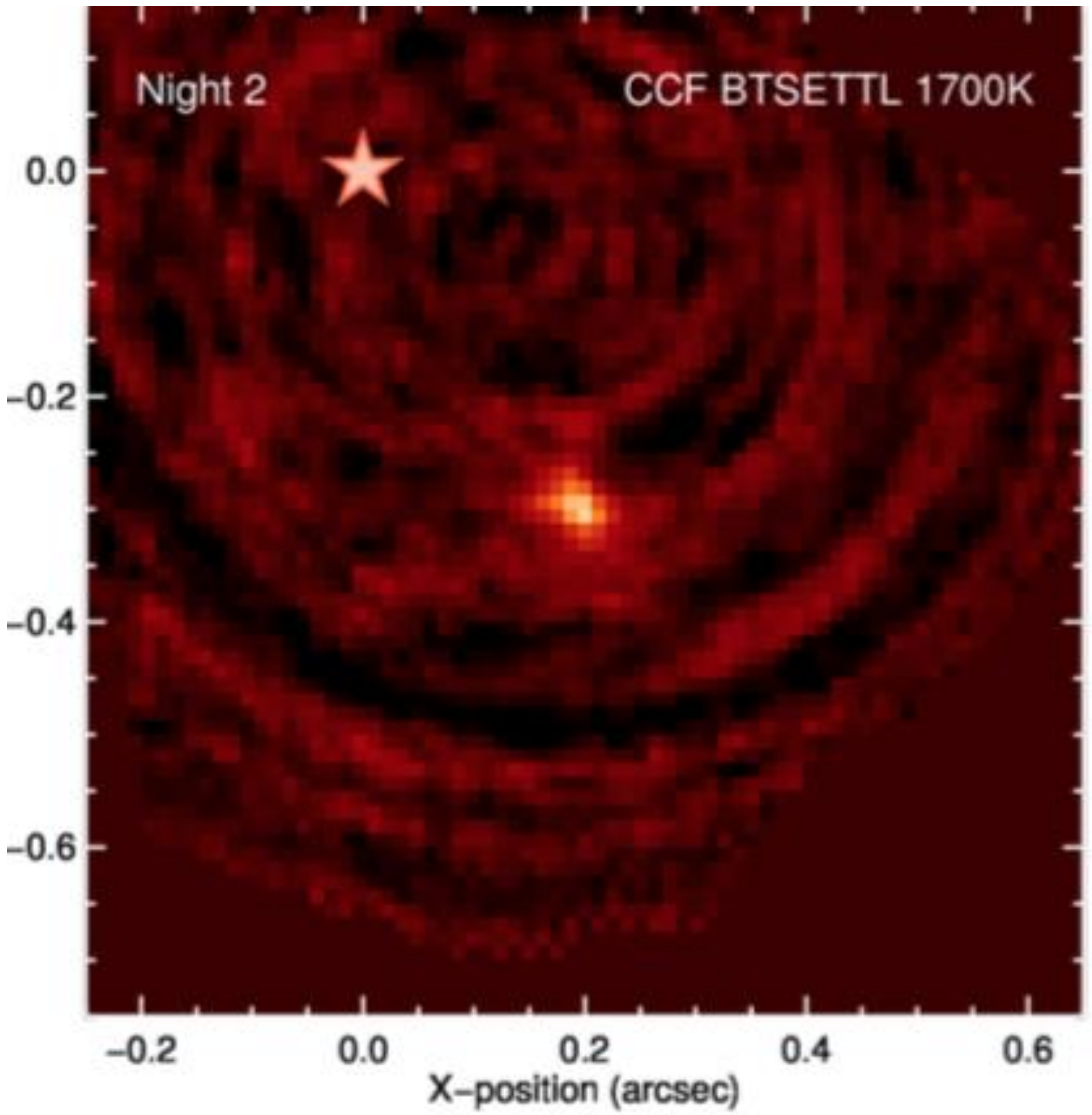
Combine HRS with spatial separation from high contrast imaging (HCI) then cross-correlate

Planet spectrum is spatial separated
and uniquely different to the host star



White light images of β Pic b from **SINFONI/VLT IFU R~4,000**
using standard direct imaging post-reduction techniques

Cross-Correlation with model spectrum
at each spectral pixel reveals planet location

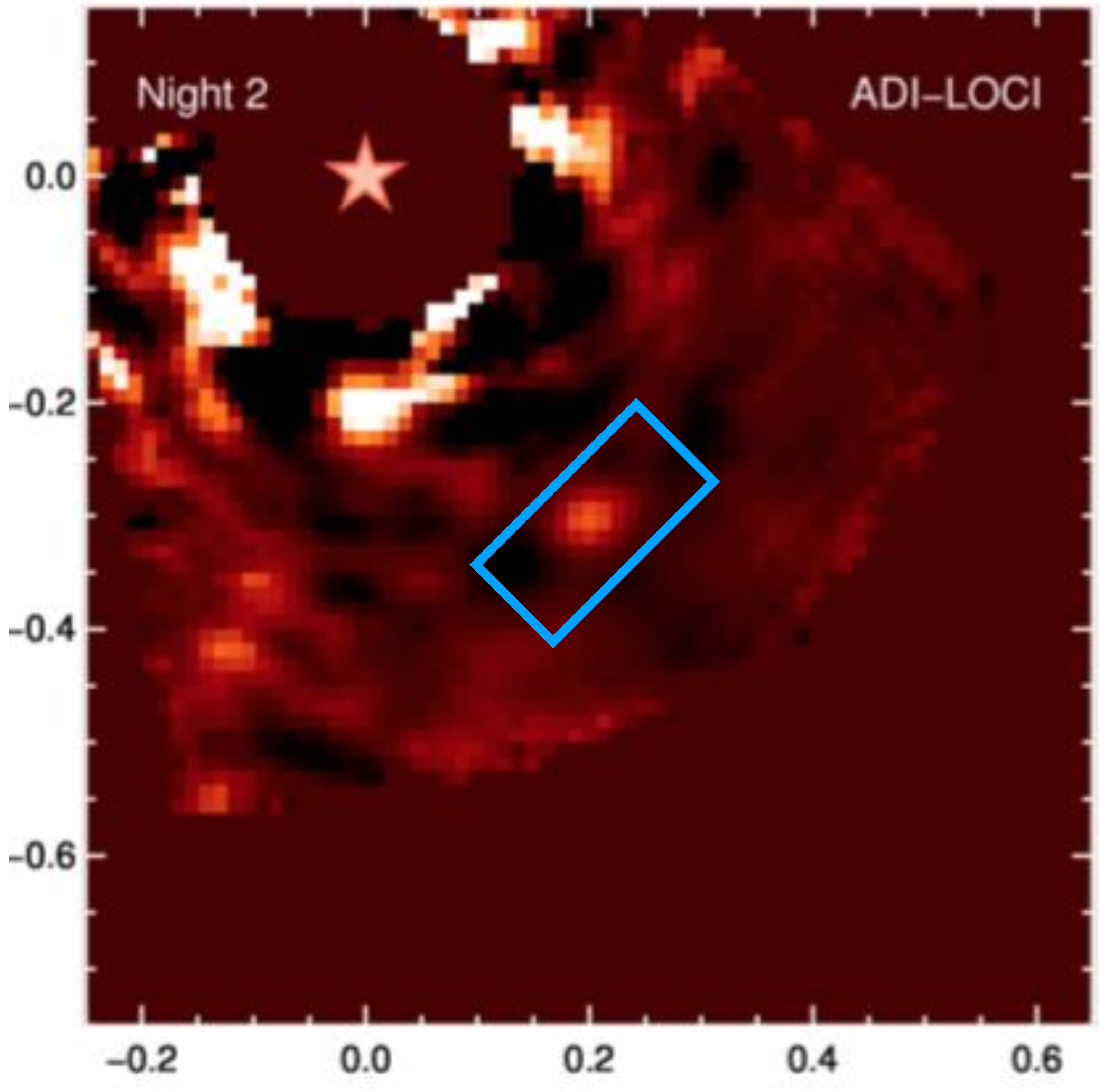


Radial velocity measured at R~4000! (-11.3 ± 1.1 km/s)
(Kiefer et al. 2024)

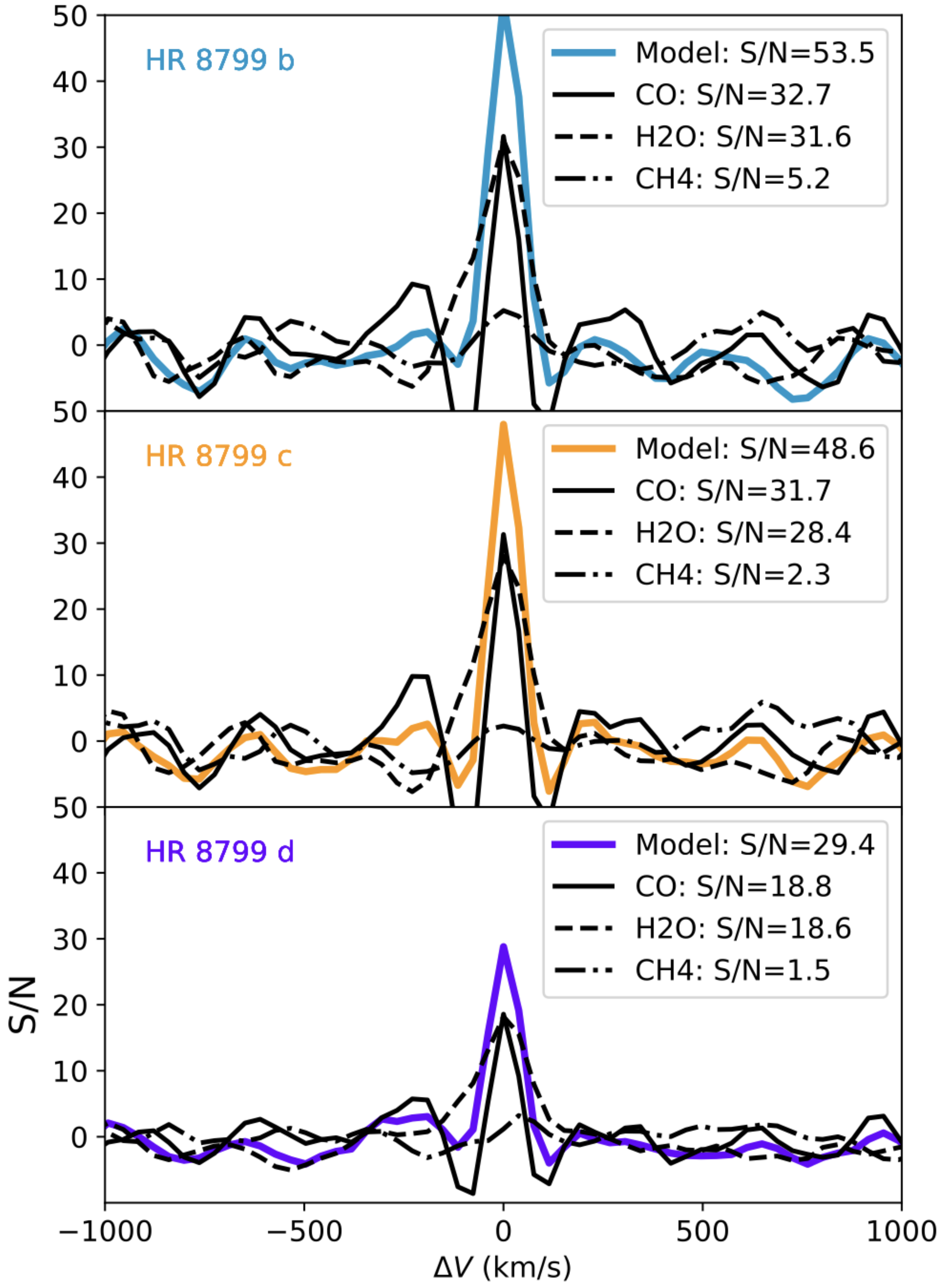
Hoeijmakers et al. 2018

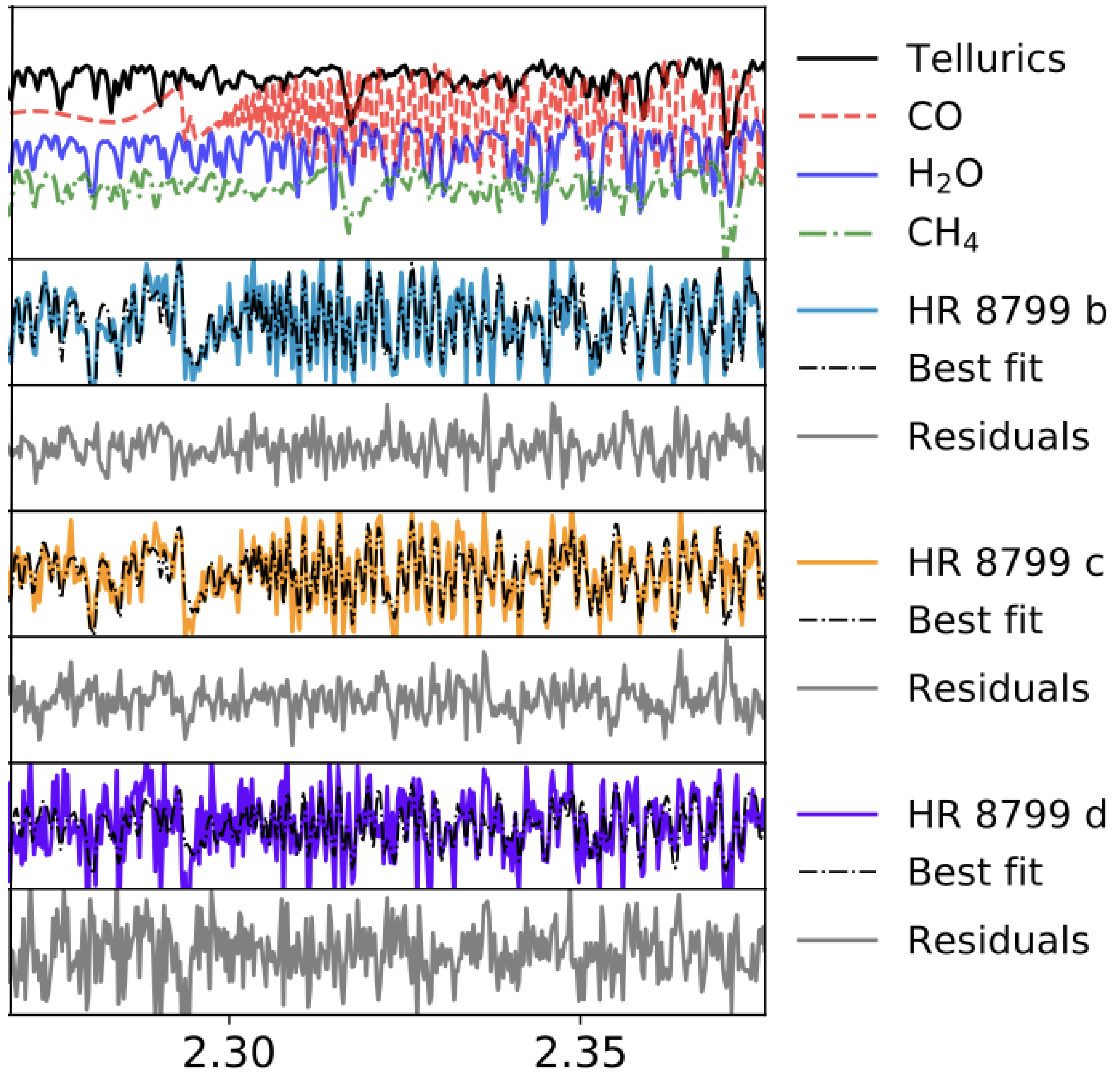
Combine HRS with spatial separation from high contrast imaging (HCI) then cross-correlate

Planet spectrum is spatial separated and uniquely different to the host star



ORISIS, R~4,000

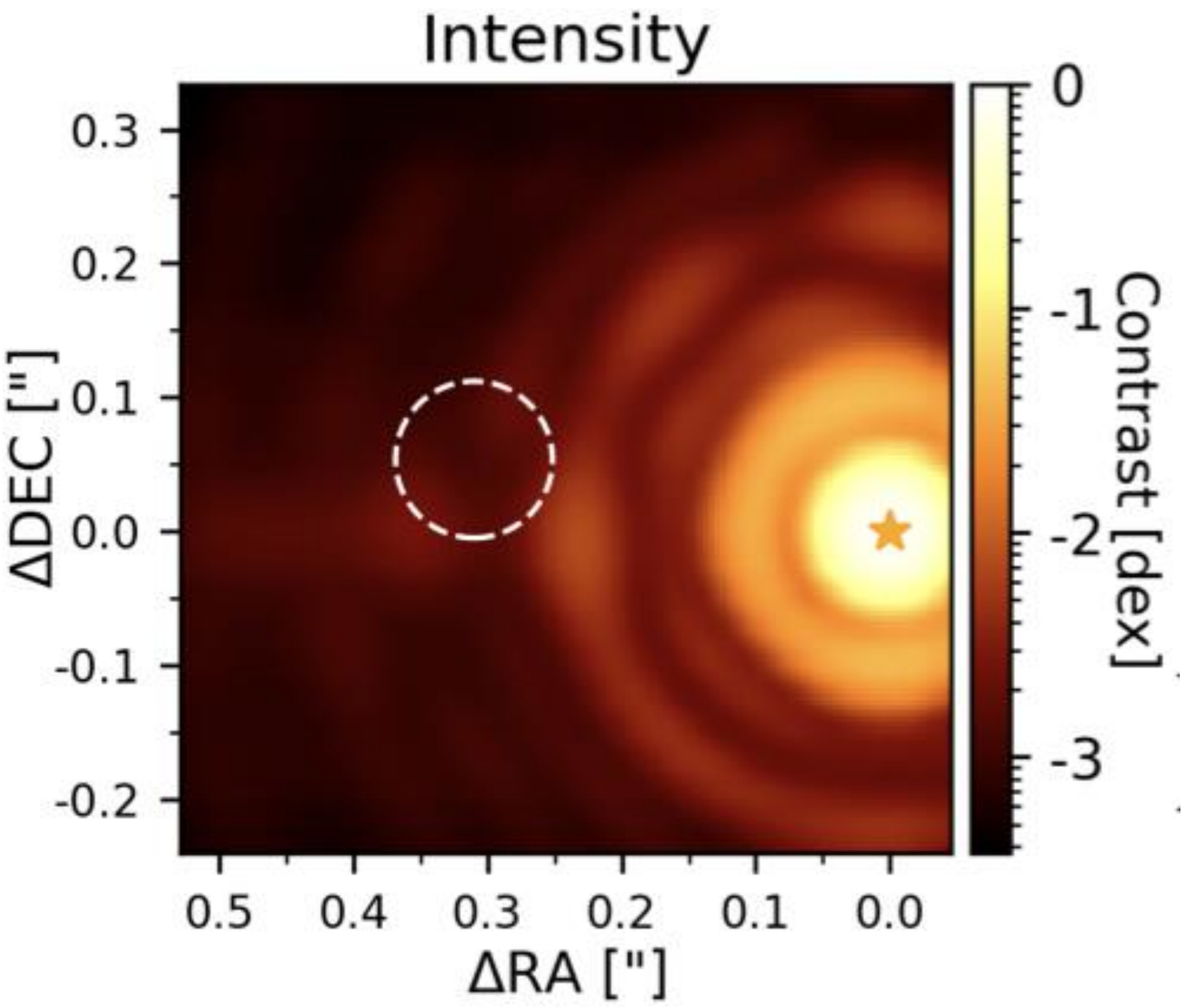




Konopacky et al. 2013, Barman et al. 2015, Ruffio et al. 2021

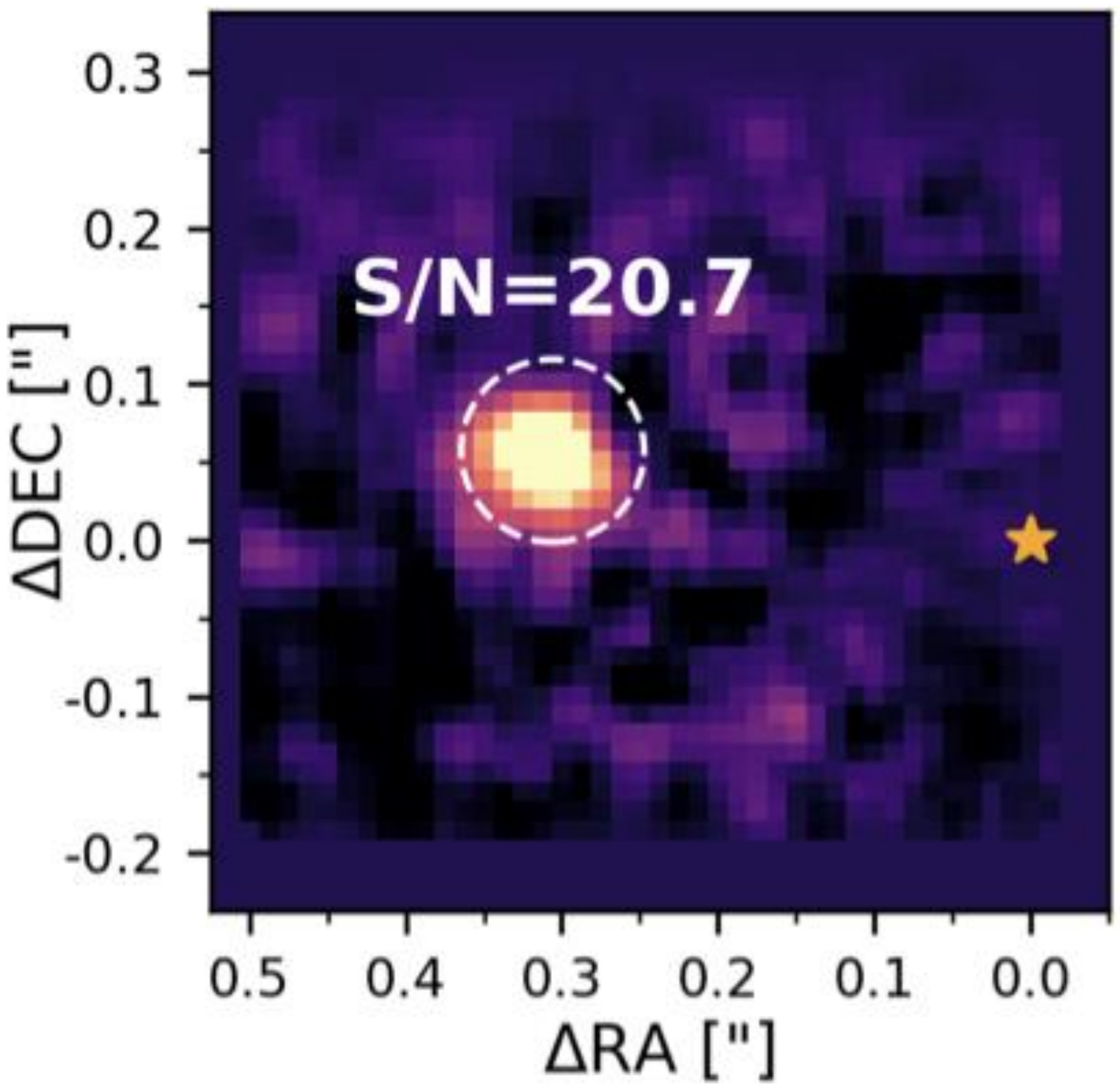
Combine HRS with spatial separation from high contrast imaging (HCI) then cross-correlate

ERIS-SPIFFIER/VLT, R~11,000



White light image of AF Lep from ERIS/VLT

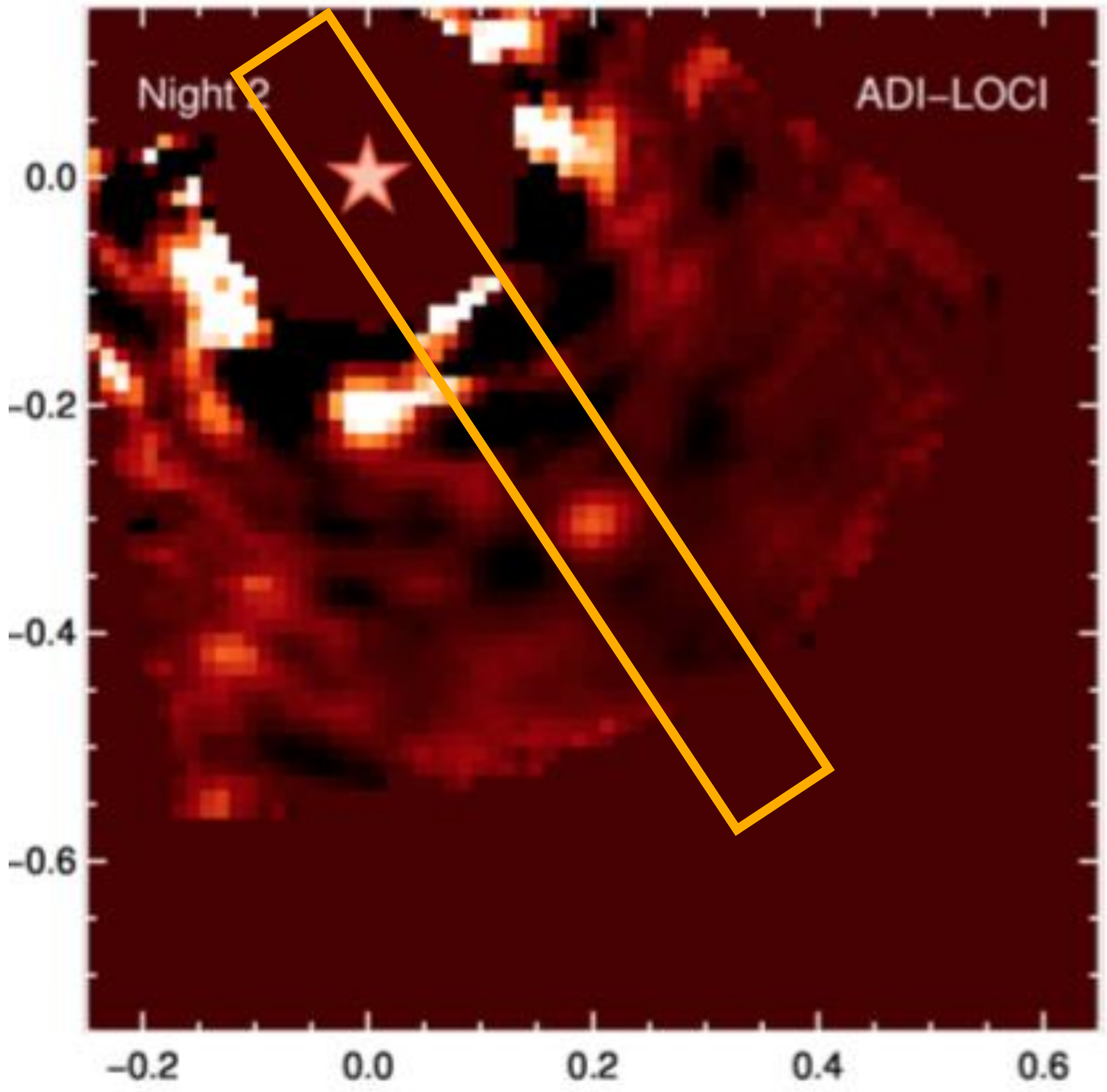
AF Lep b: CO+H2O, no CH4

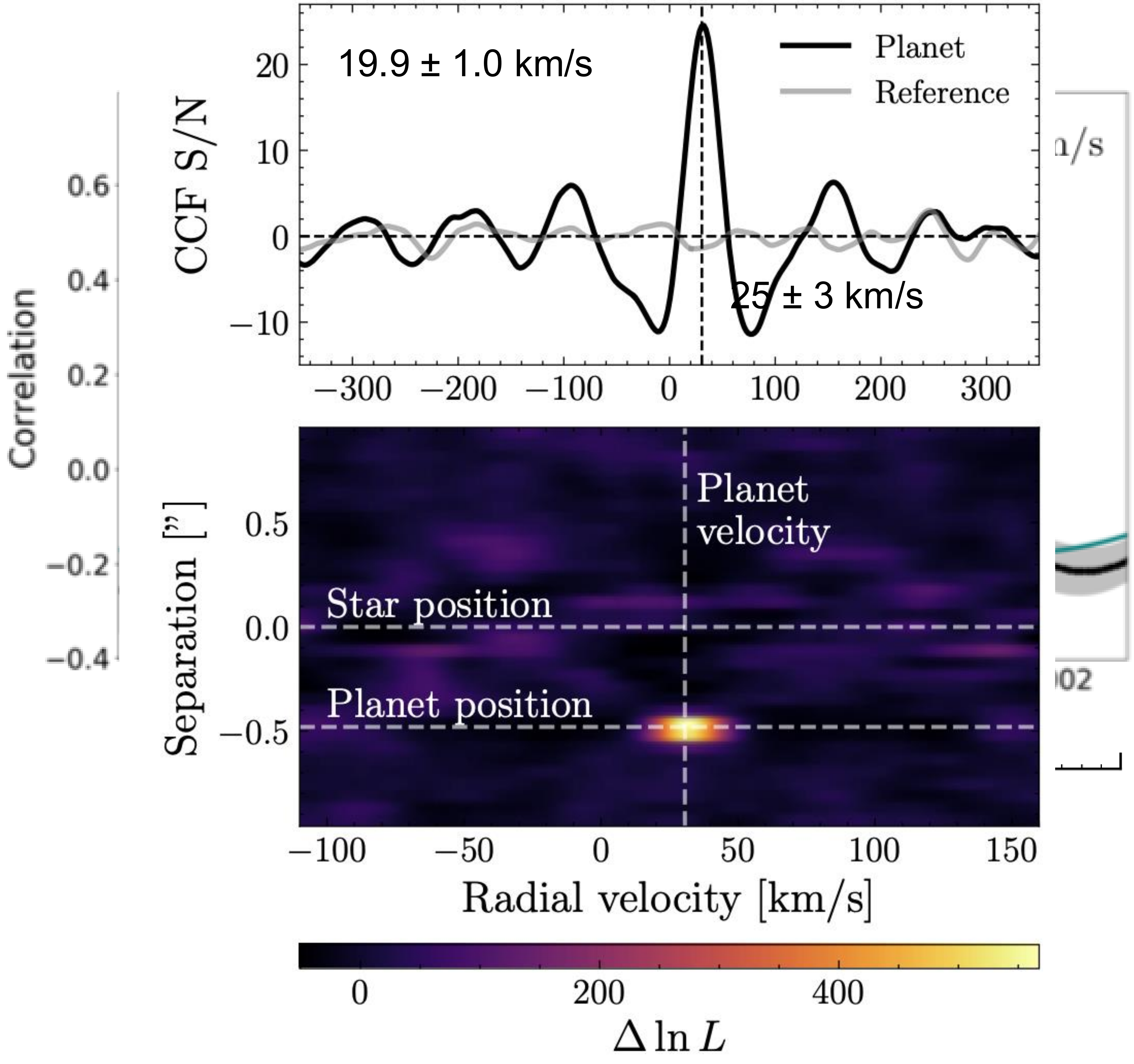


Hayoz et al. 2025

High resolution spectroscopy opened up a new fundamental parameter: exoplanet rotation rate

Planet spectrum is spatial separated
and uniquely different to the host star

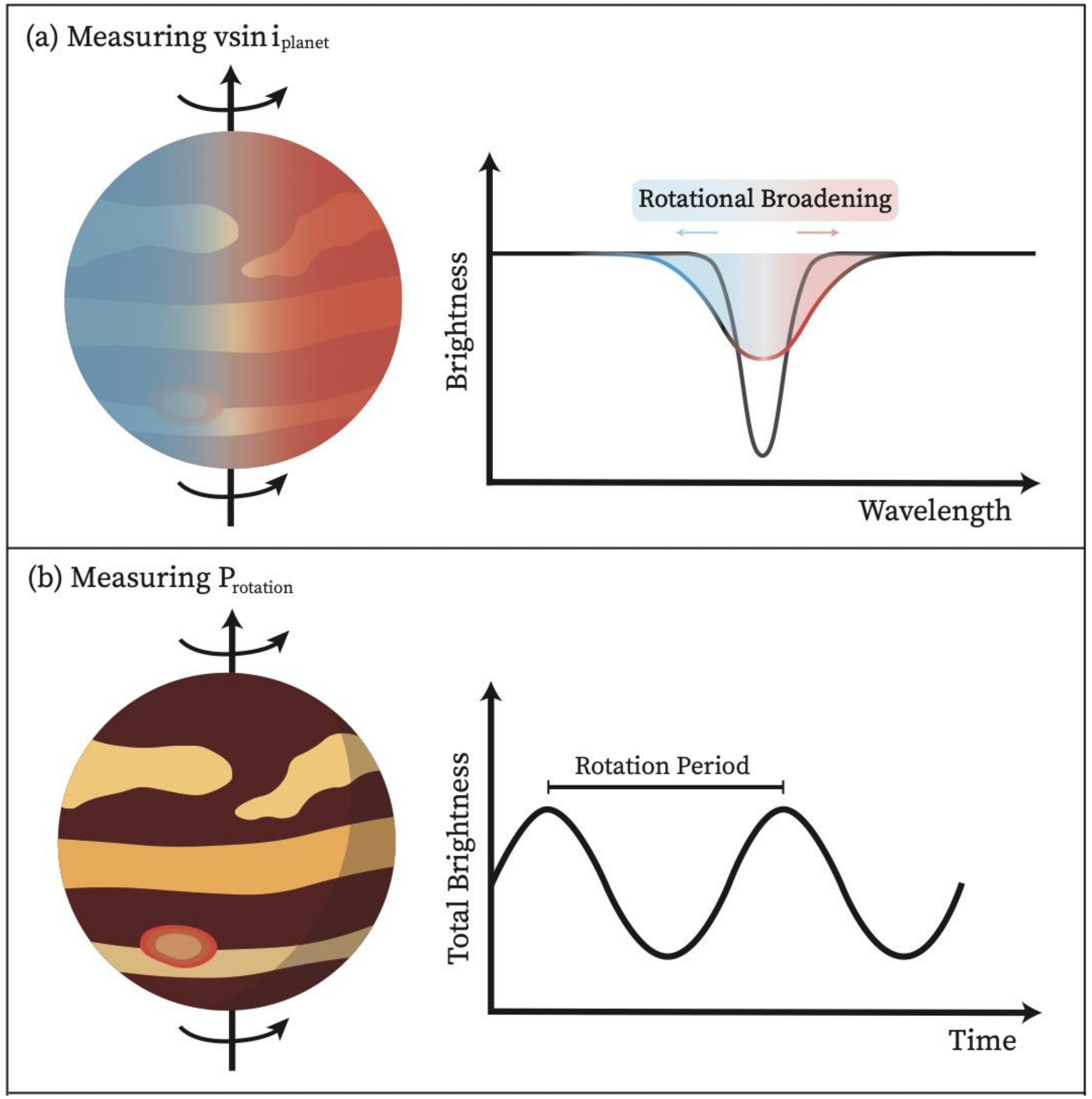




Landman et al. 2024

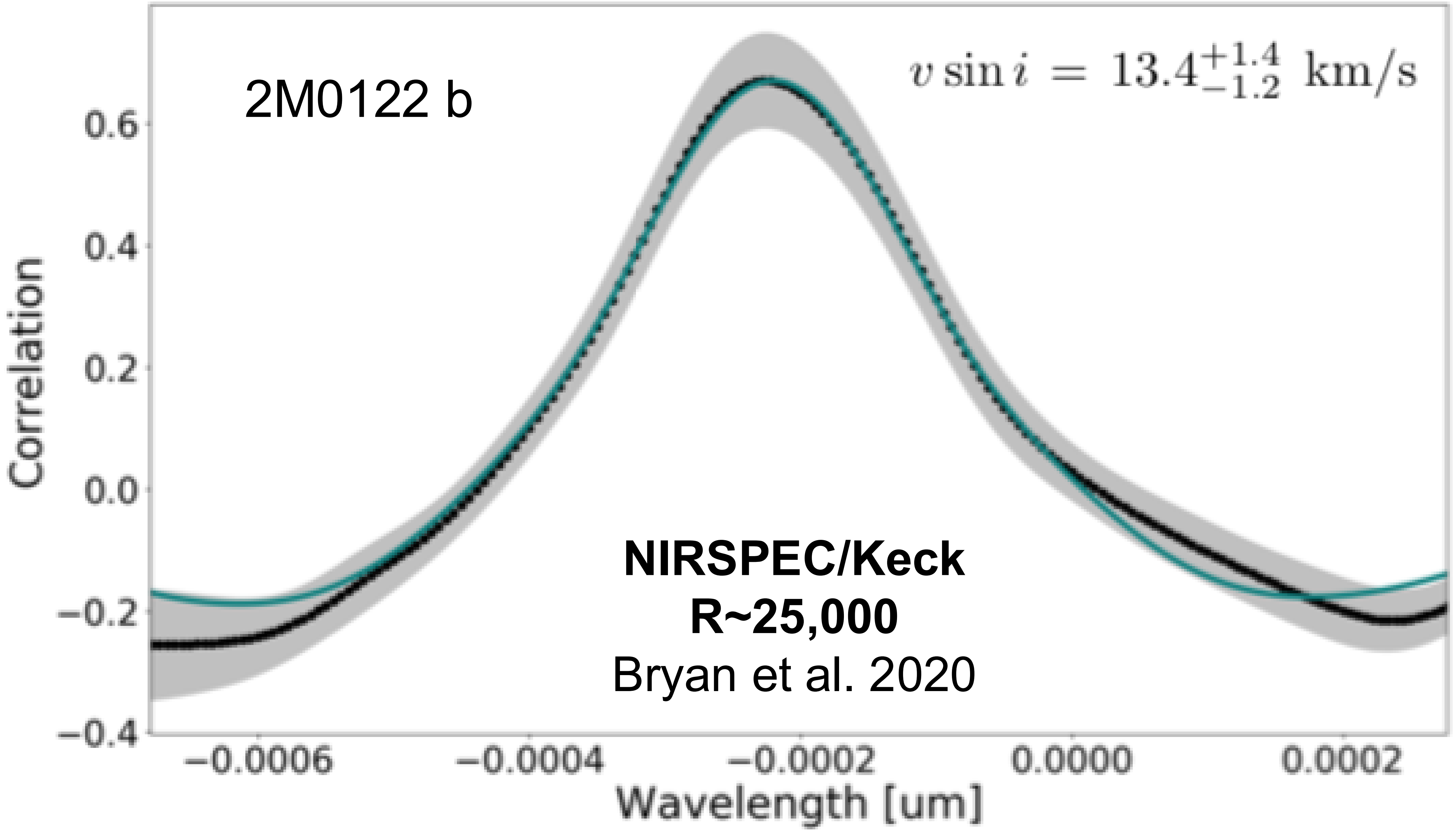
Snellen et al. 2014

Combining vsin*i* from HRS with photometric rotation period gives planet obliquity (planet spin-orbit alignment) which controls seasons

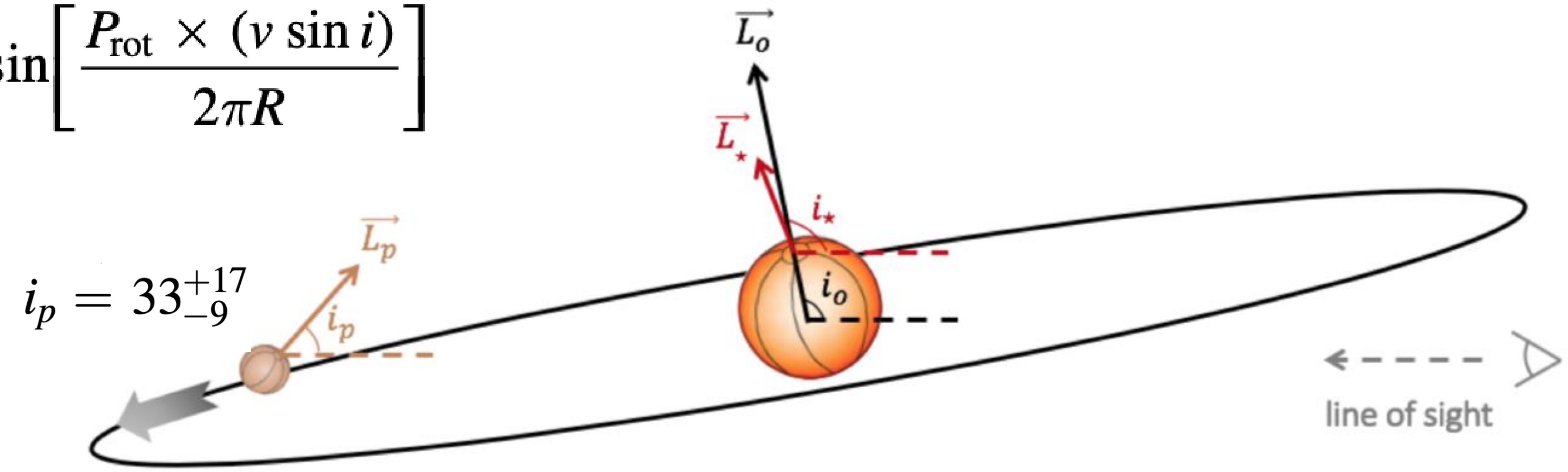


Poon et al. 2024

See Michael Poon's talk



$$i = \arcsin\left[\frac{P_{\rm rot} \times (v \sin i)}{2\pi R}\right]$$

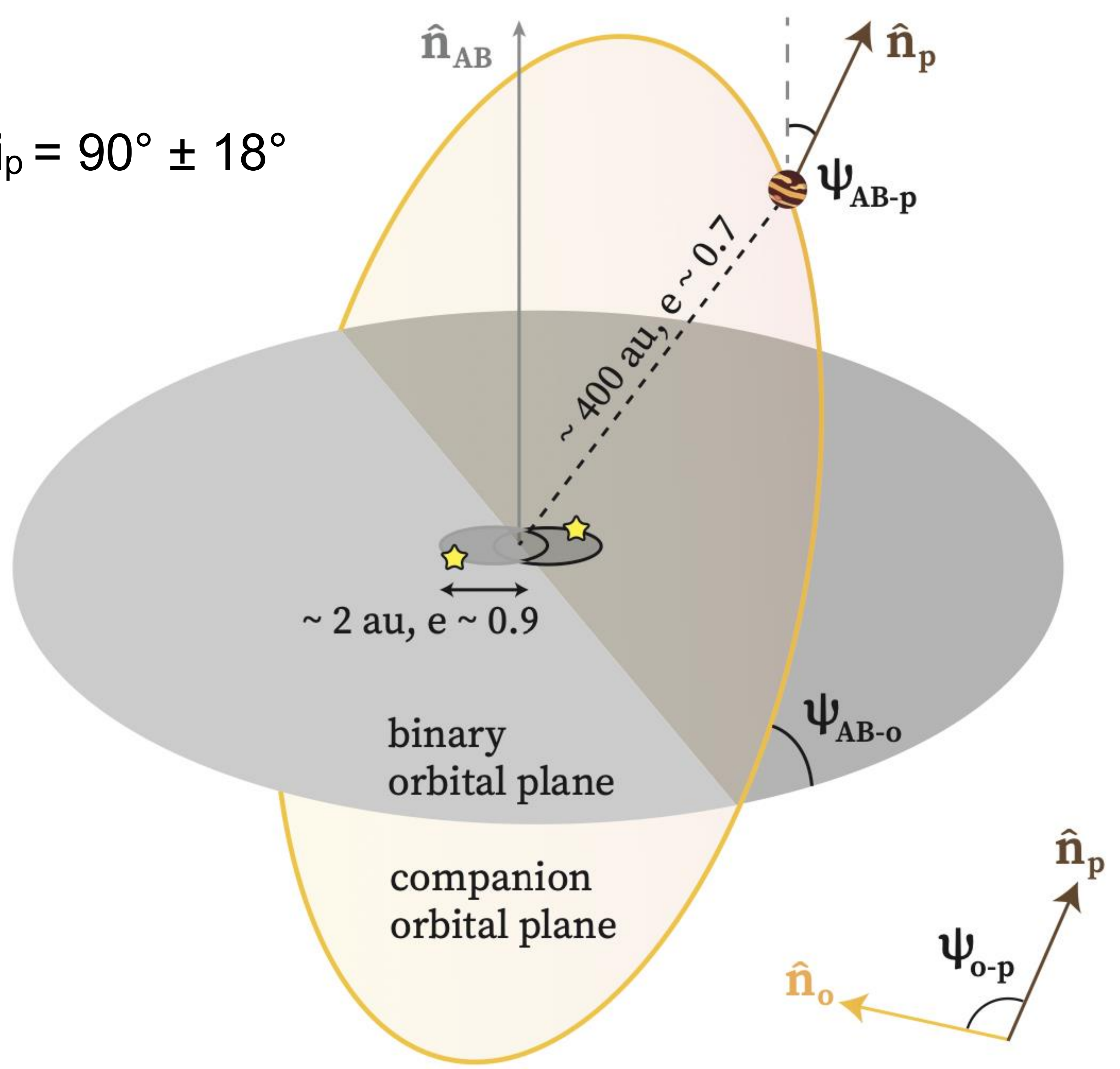


Bryan et al. 2020

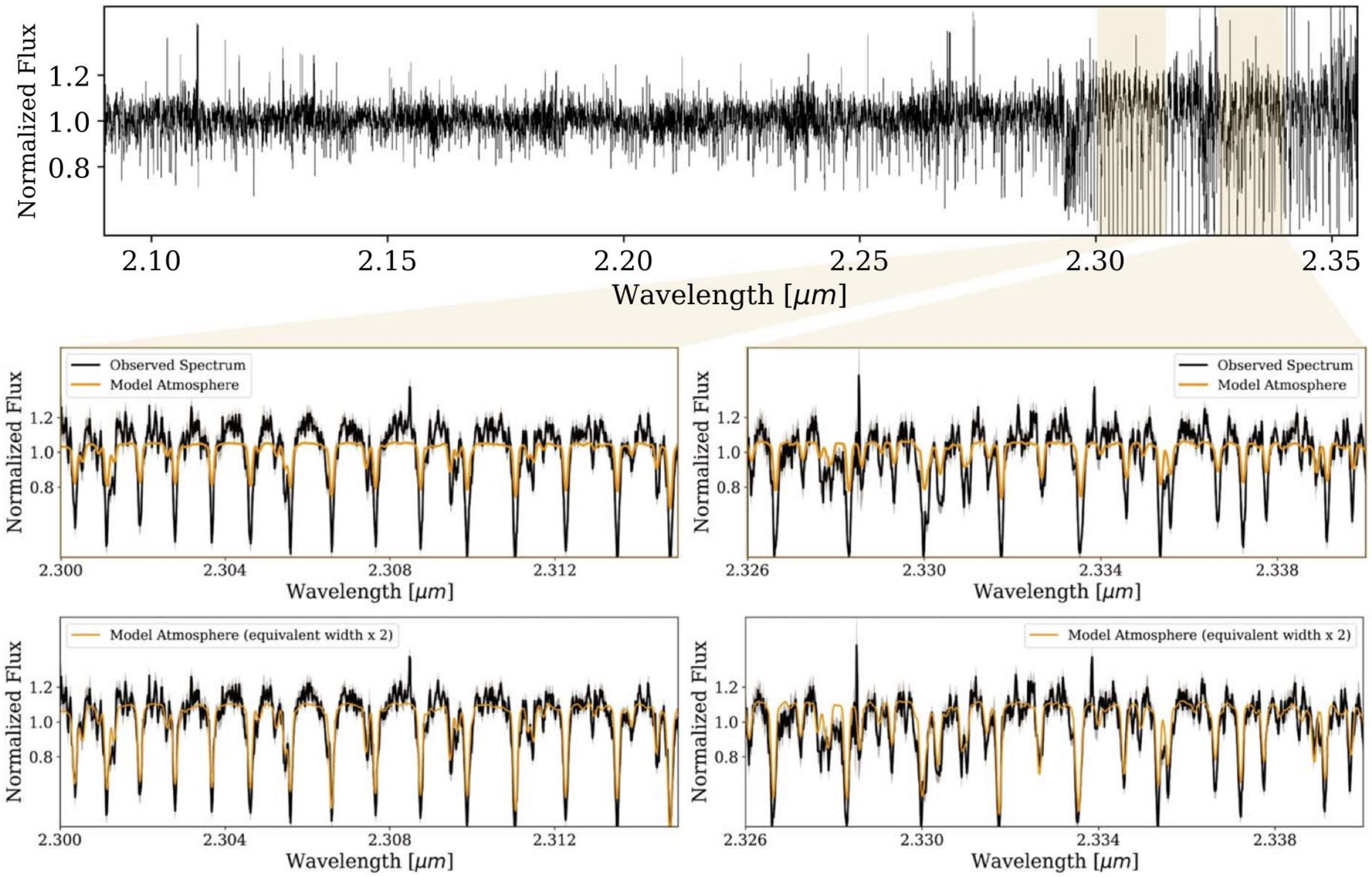
Planet obliquity, orbital architecture from HRS RVs, and composition allow deeper insight into system formation and migration history

$i_p = 90° \pm 18°$

VHS 1256 b



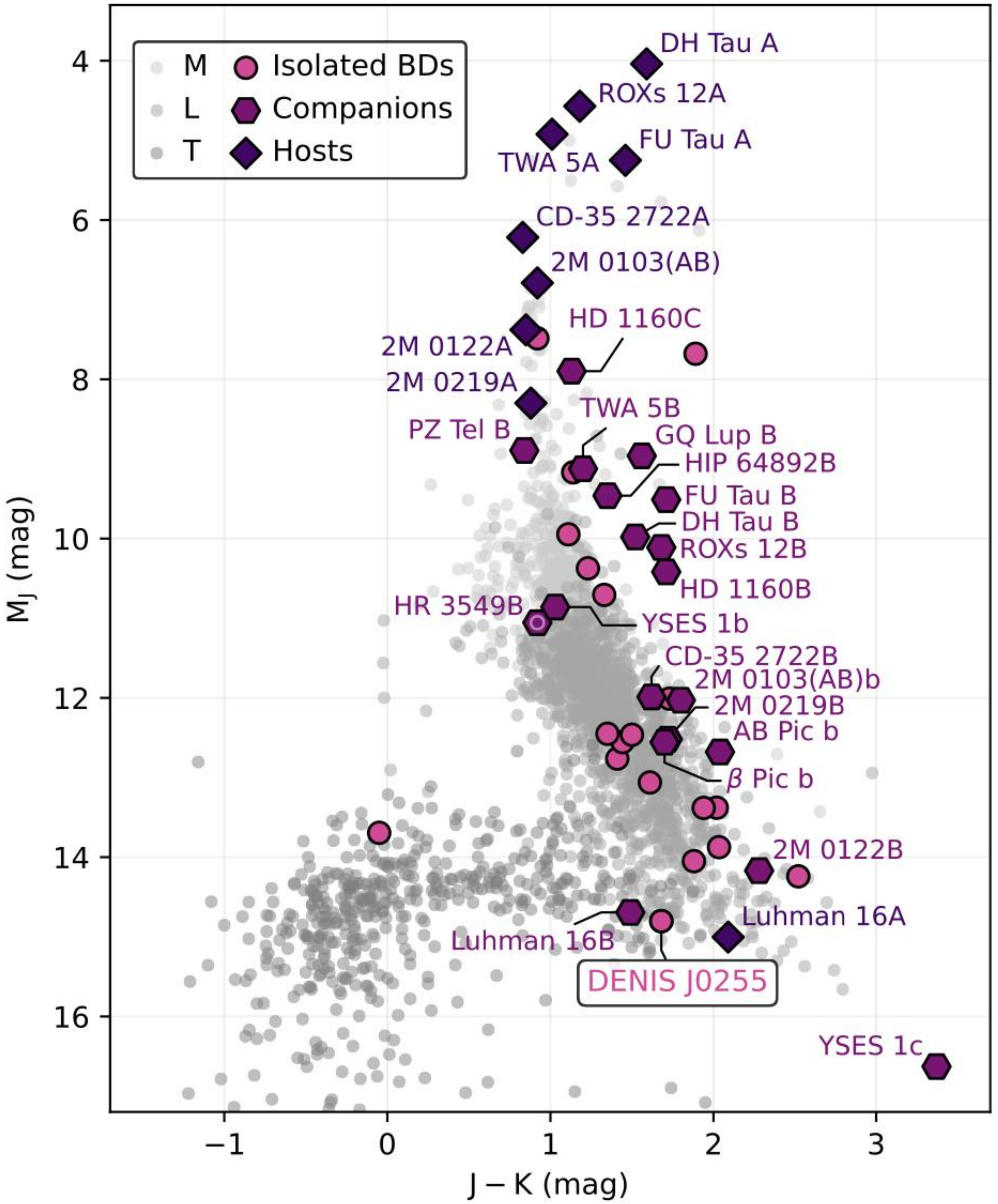
IGRINS/Gemini, R~45,000



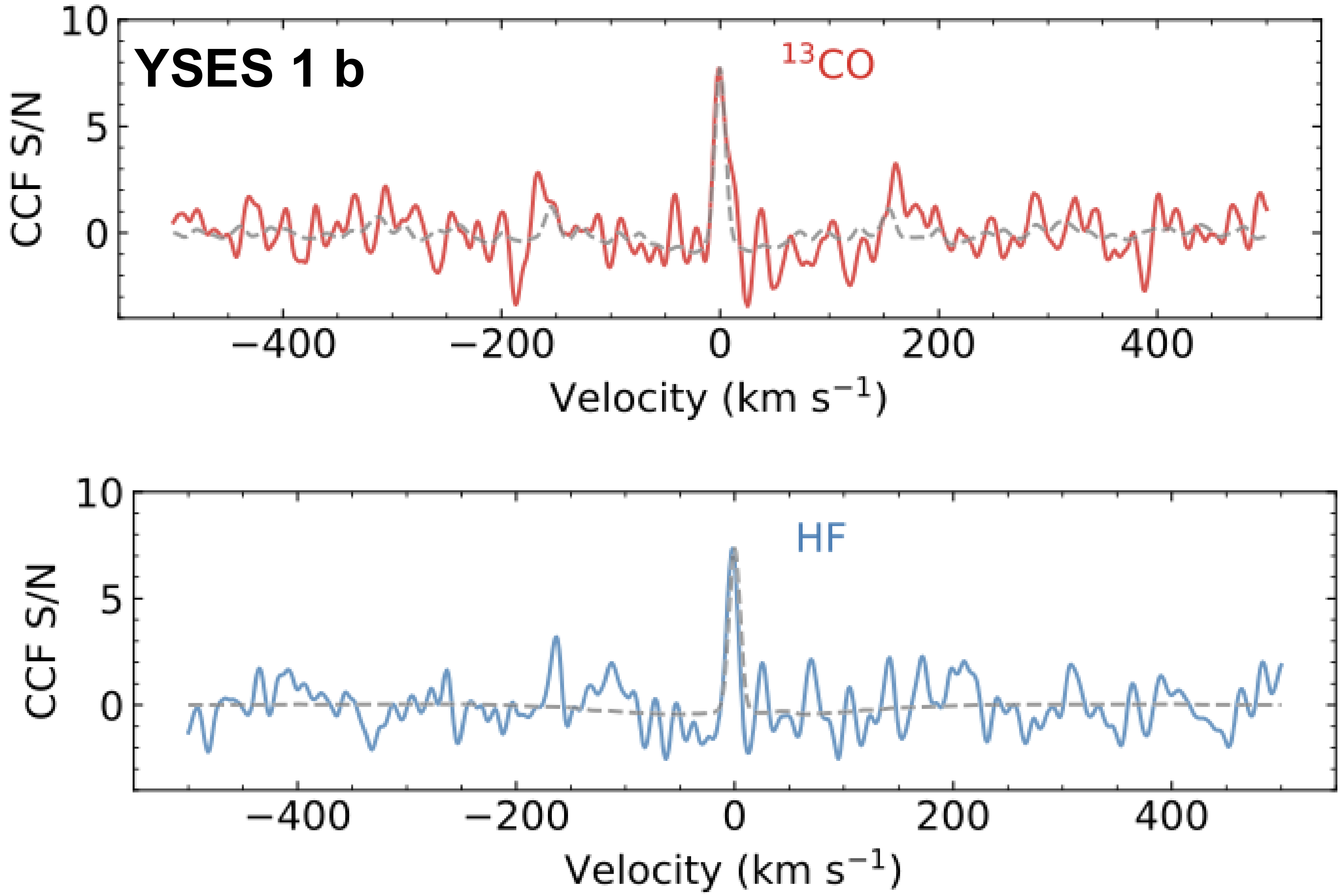
VHS 1256 b most likely top-down formation, through core/filament fragmentation, followed by gas-driven migration or ejection

Poon et al. 2024

Surveys with HRS give population statistics to address planet formation

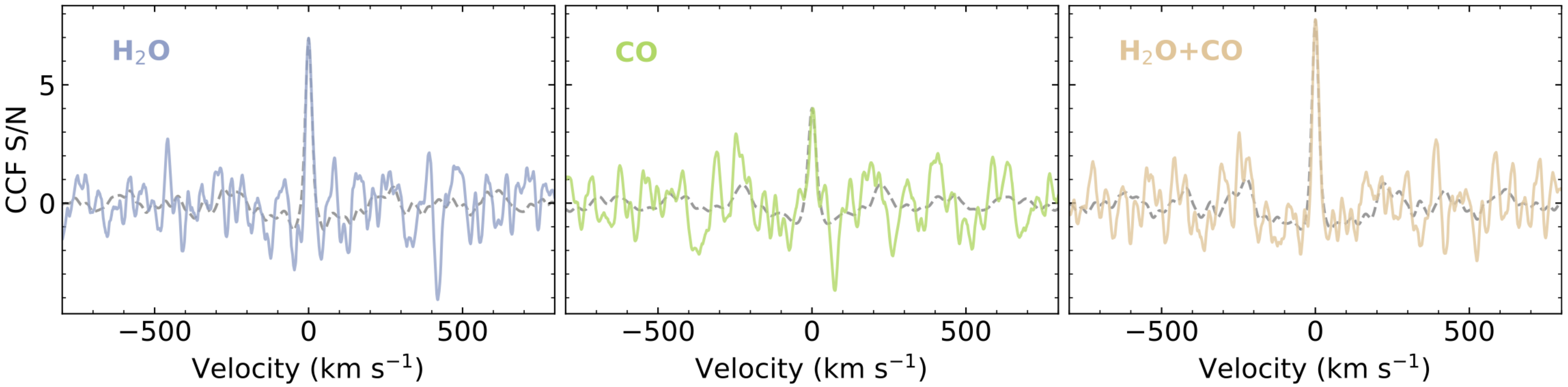


CRIRES/VLT, R~100,000



YSES 1 c

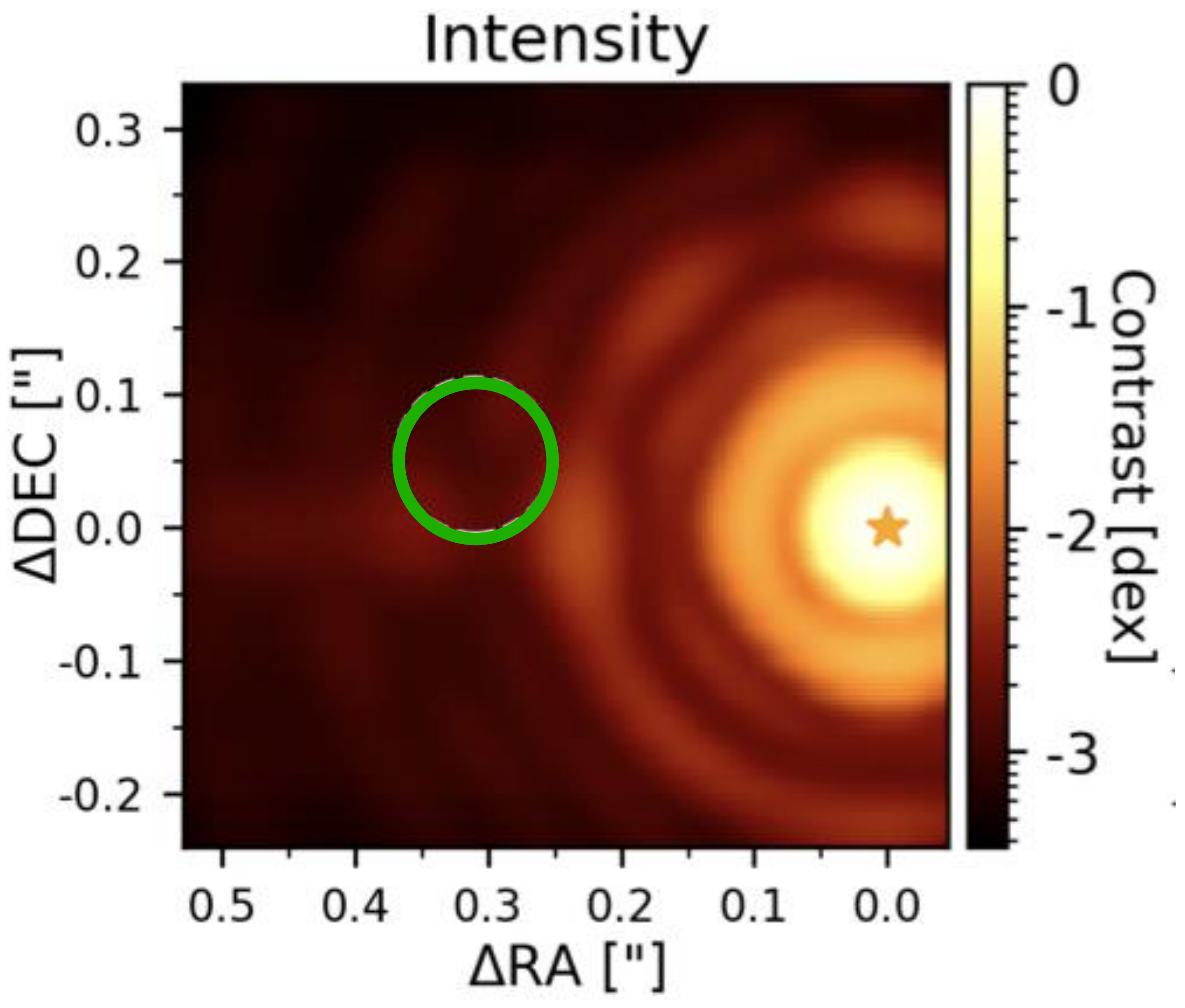
Zhang et al. 2024



ESO SupJup Survey (PI: Snellen):

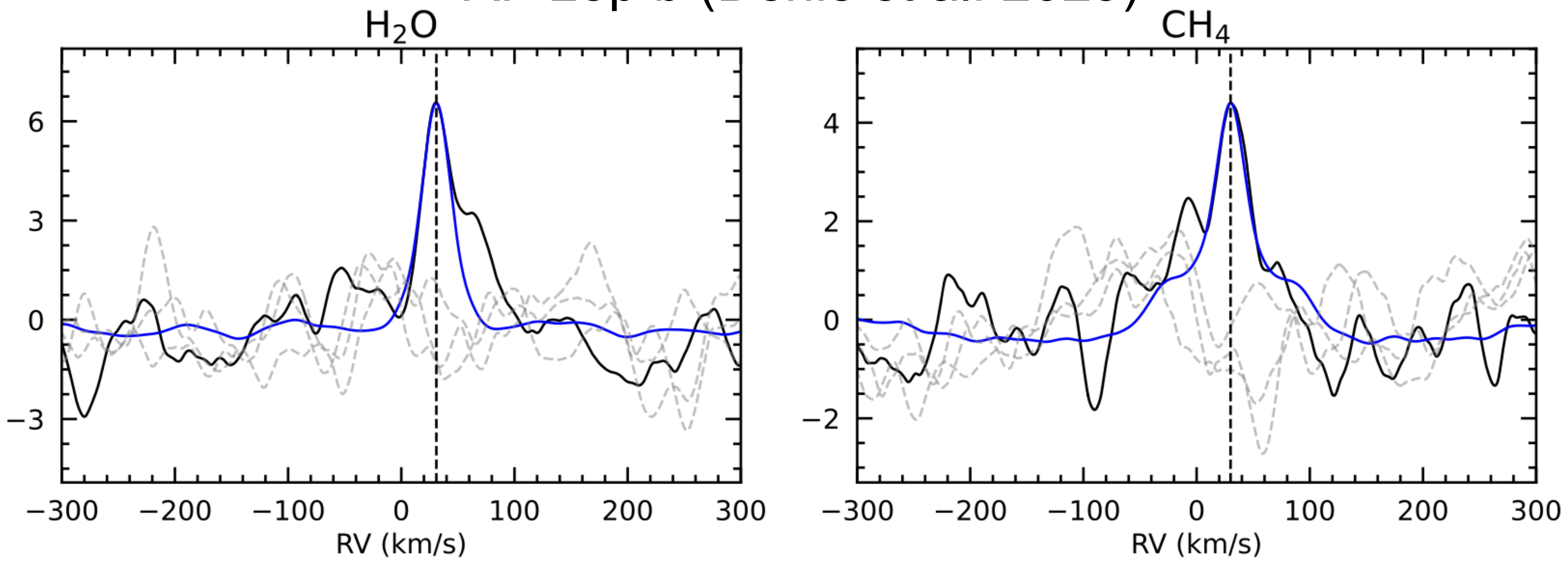
de Regt et al. 2024, 2025; González Picos et al. 2024, 2025; Zhang et al. 2024, Mulder et al. 2025; Gandhi et al. 2025; Grasser et al. 2025

Surveys with HRS give population statistics to address planet formation

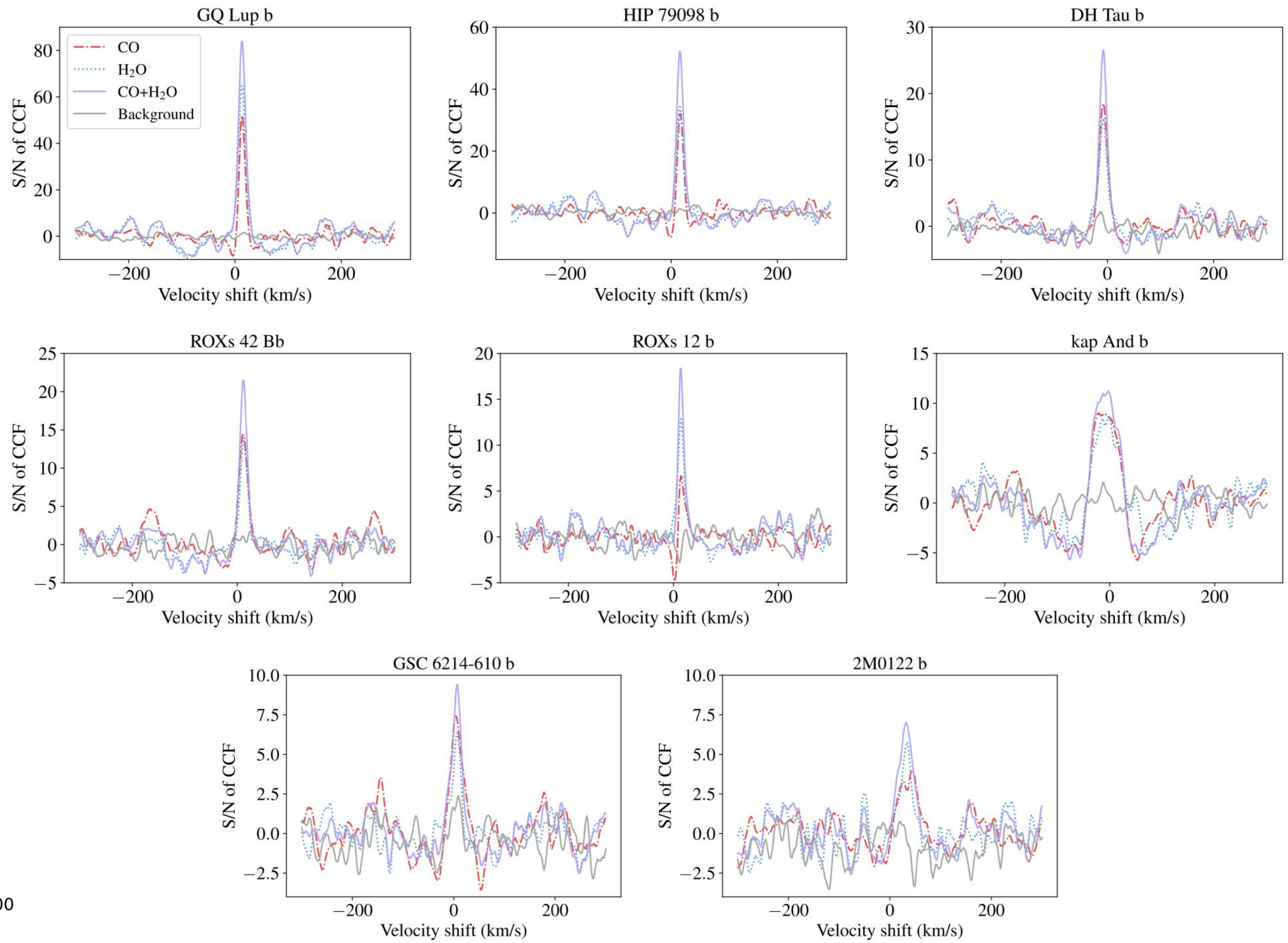


White light image of AF Lep from ERIS/VLT IFU

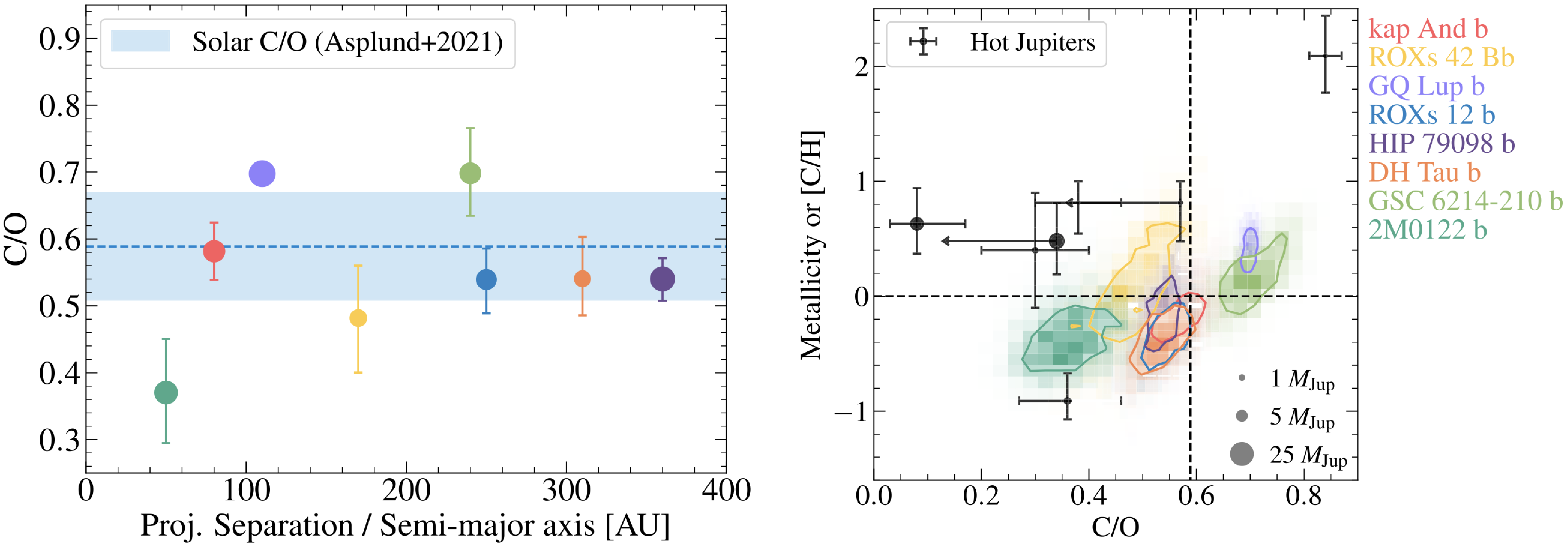
HiRISE (SPHERE+CRIRES)/VLT (R=100,000)
AF Lep b (Denis et al. 2025)



KPIC(+NIRSPEC)/Keck (R=35,000)
(Xuan et al. 2024)

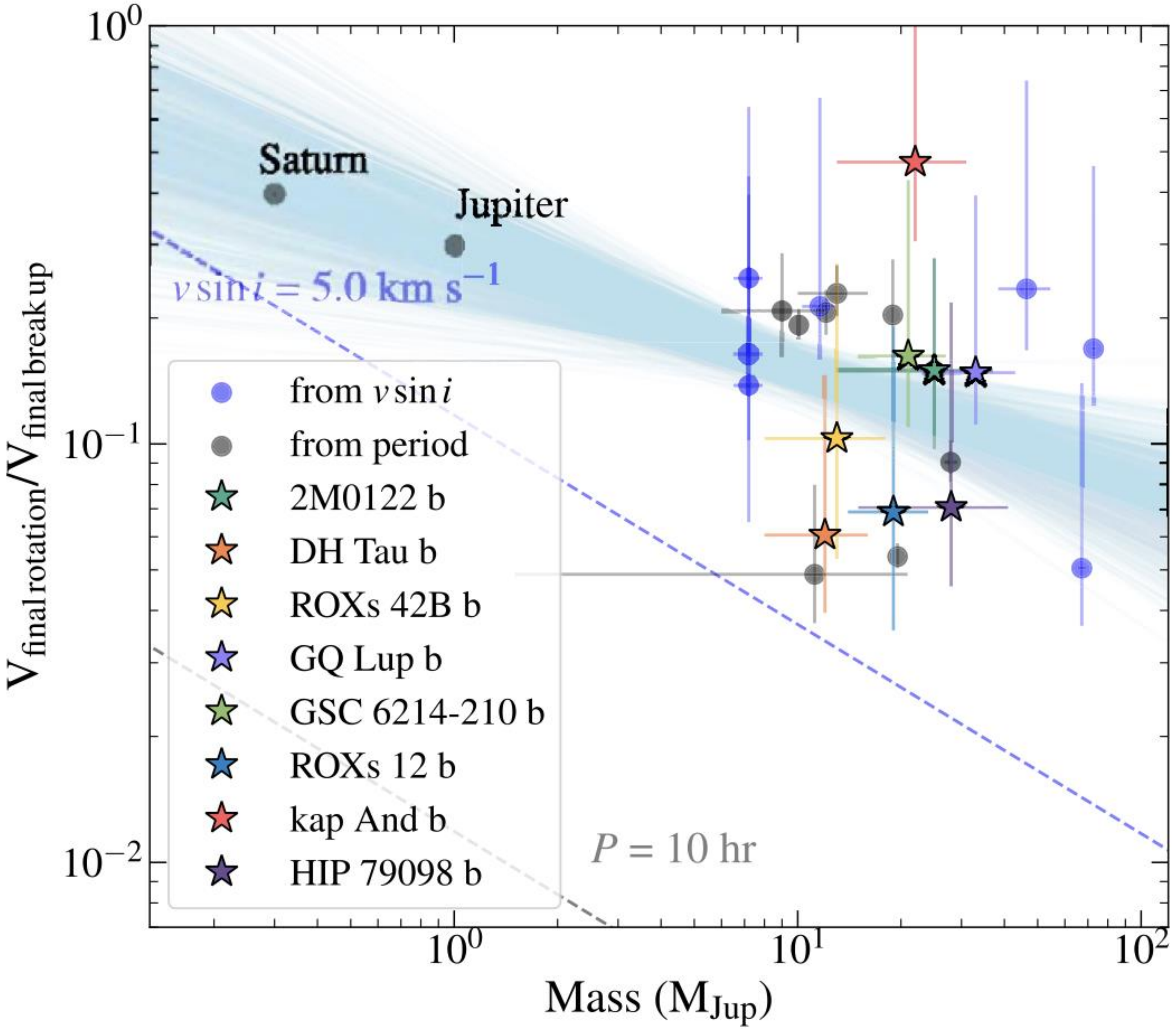


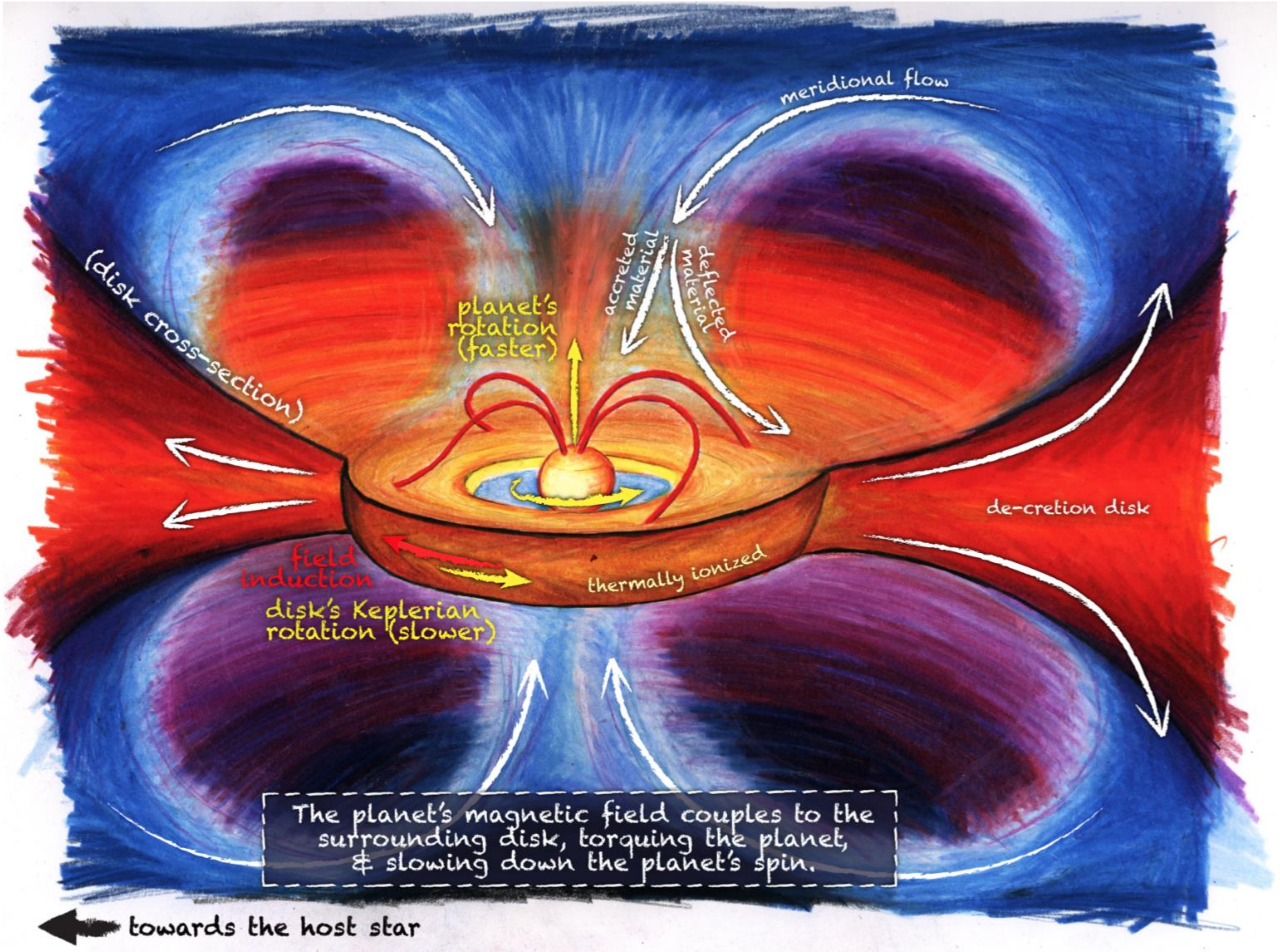
Indications of two distinct populations in composition when comparing hot Jupiters and wide companions



Xuan et al. 2024

Massive companions can ionise their circumplanetary disks (CPDs) and spin down through interactions between the magnetic field and the CPD

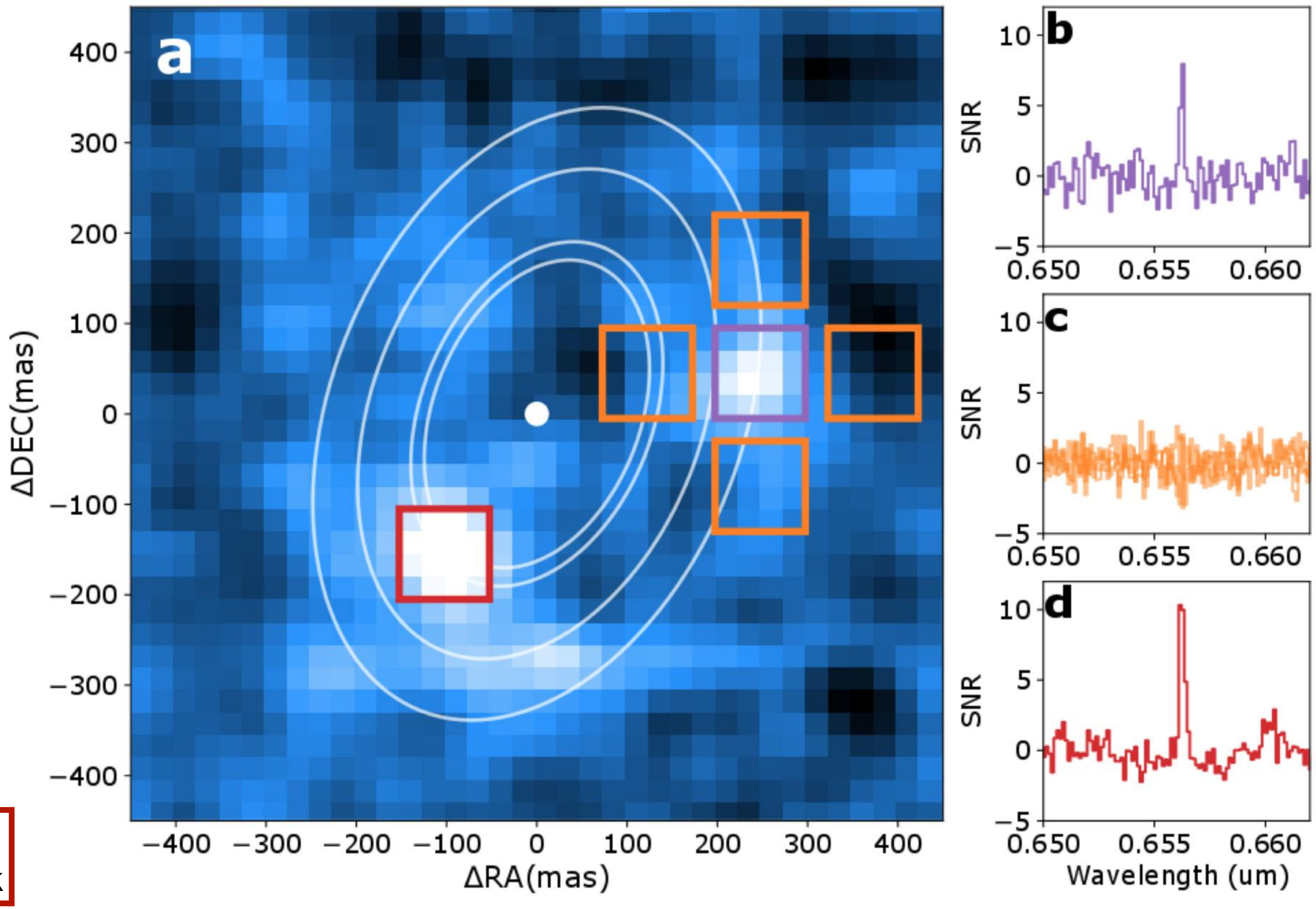




Batygin 2018

e.g. Bryan et al. 2020; Wang et al. 2021, Xuan et al. 2024, Zhang et al. 2024, Hsu et al. 2024

High Resolution Spectral Differential Imaging revealed Hα emission from young accreting exoplanets PDS 70 b and c



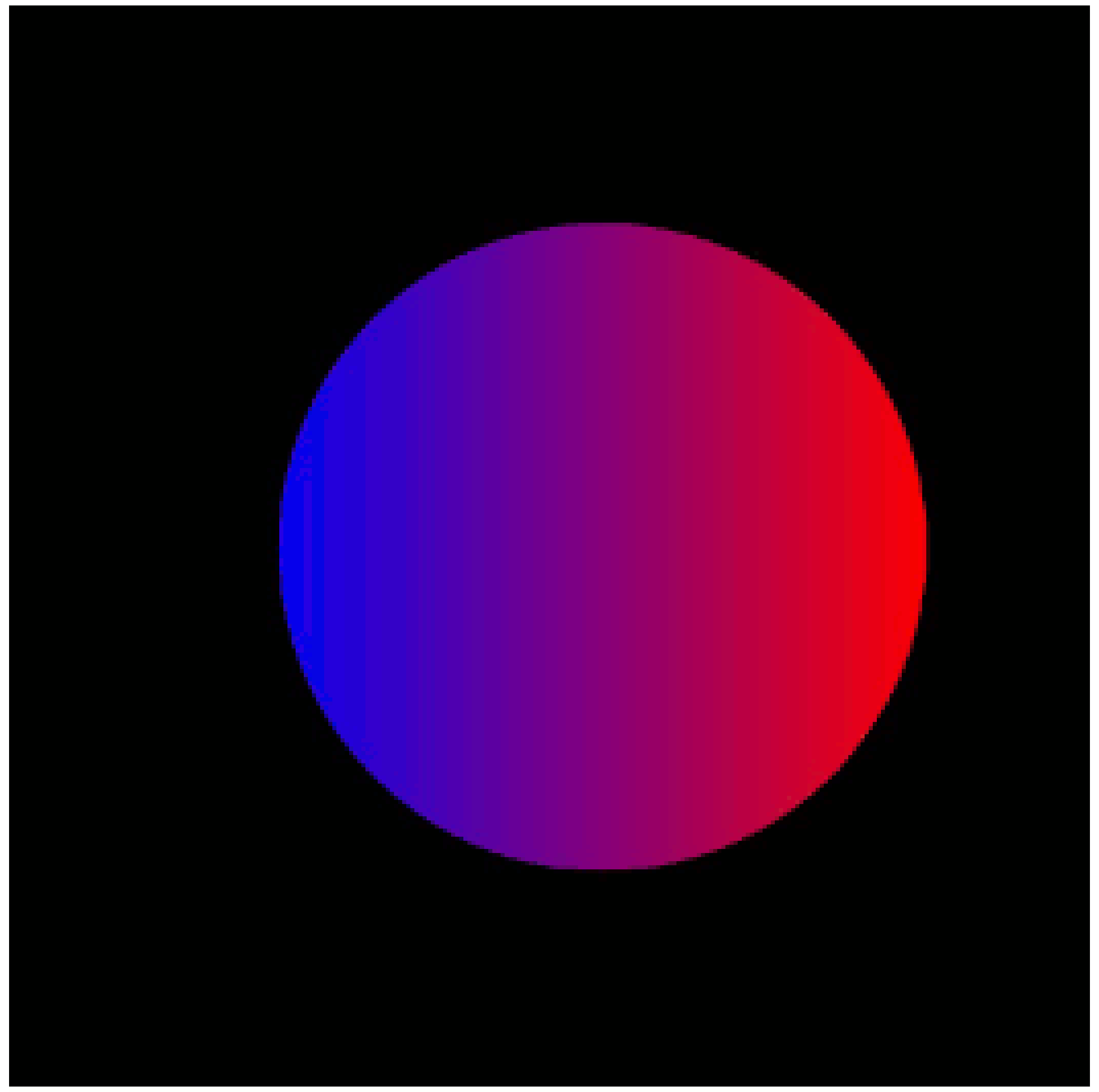
See also
Gabriel Marleau's talk

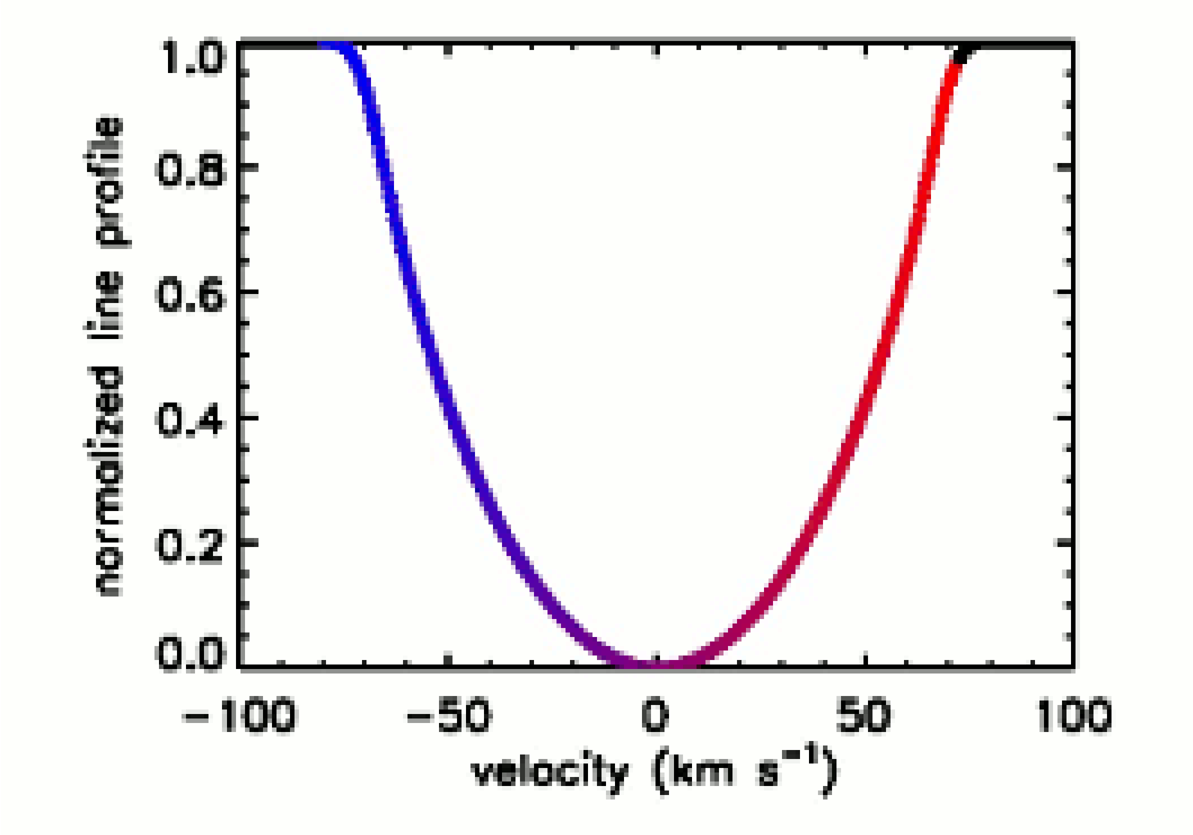
MUSE/VLT

Haffert et al. 2019

Variations in line profiles observed with ELT will enable mapping, searches for exomoons, and axial tilt measurements

Variations of line profile enables Doppler imaging with IFUs at R~100,000





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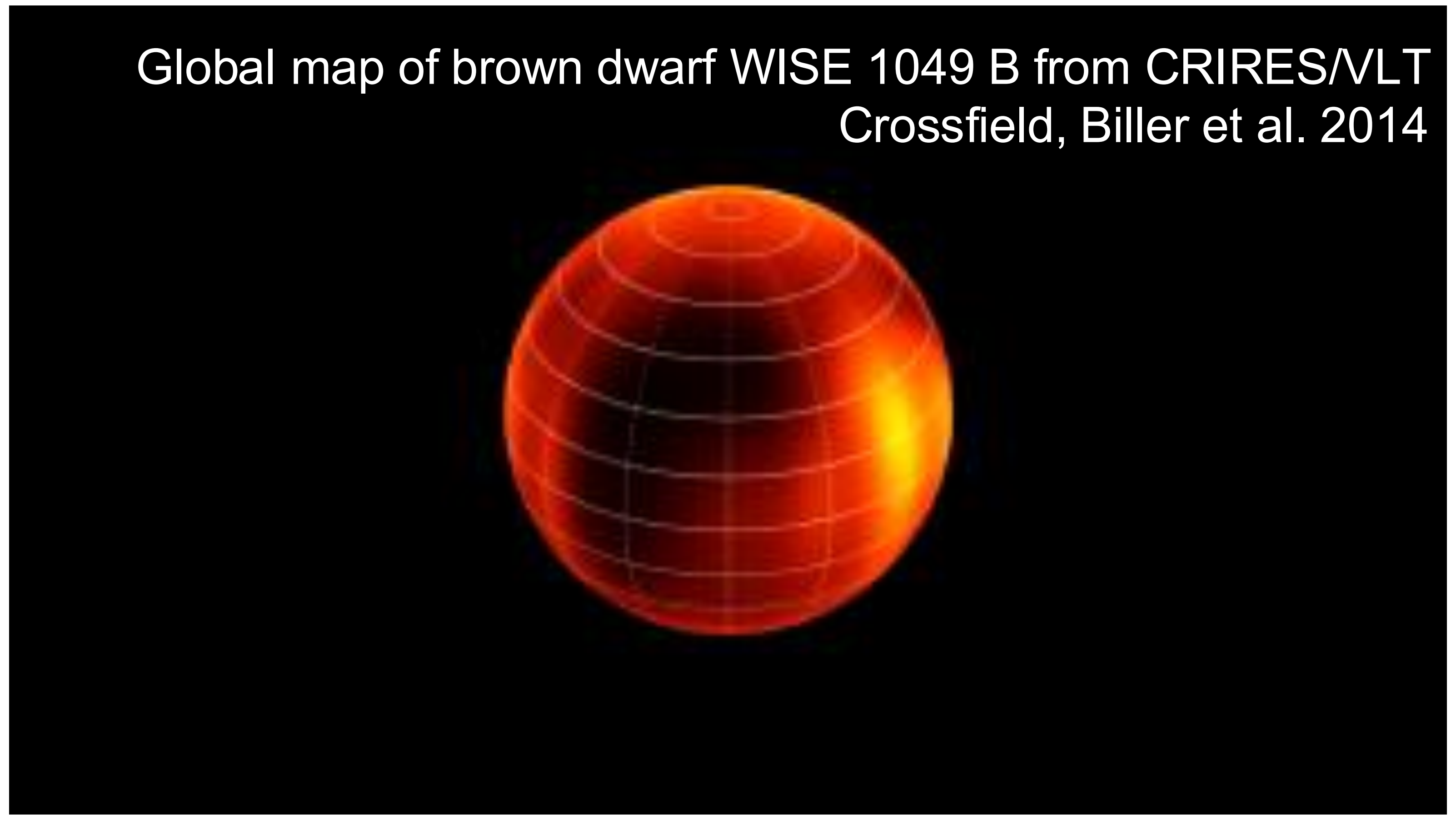
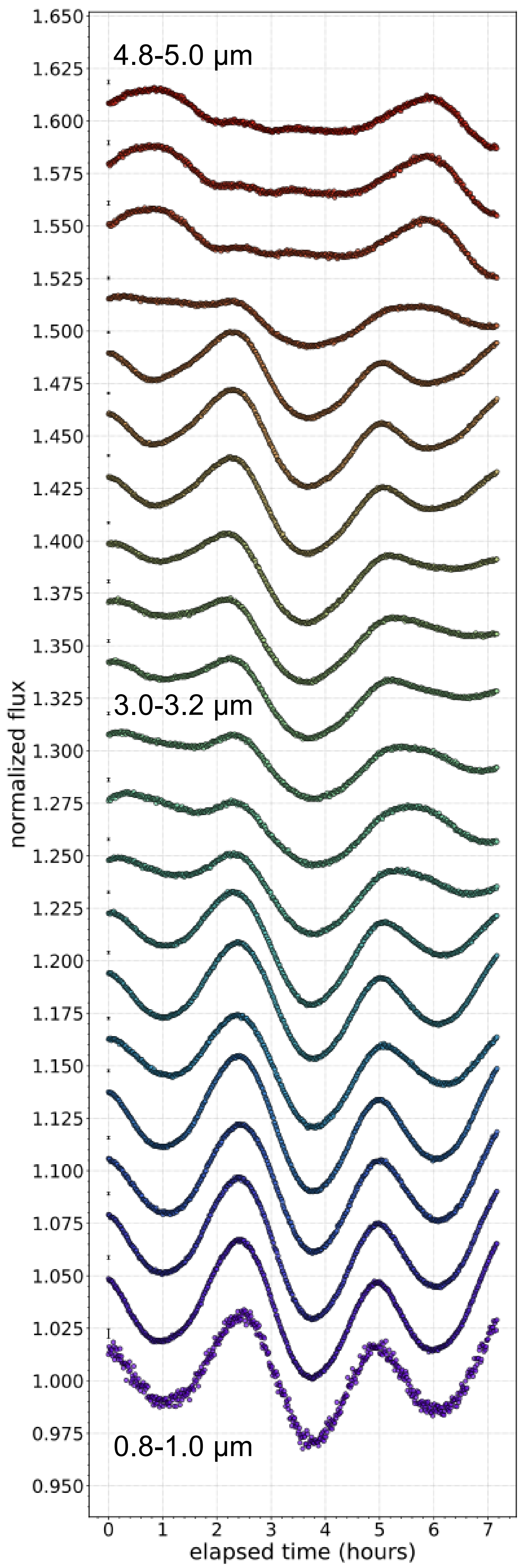


Global map of brown dwarf WISE 1049 B from CRIRES/VLT
Crossfield, Biller et al. 2014

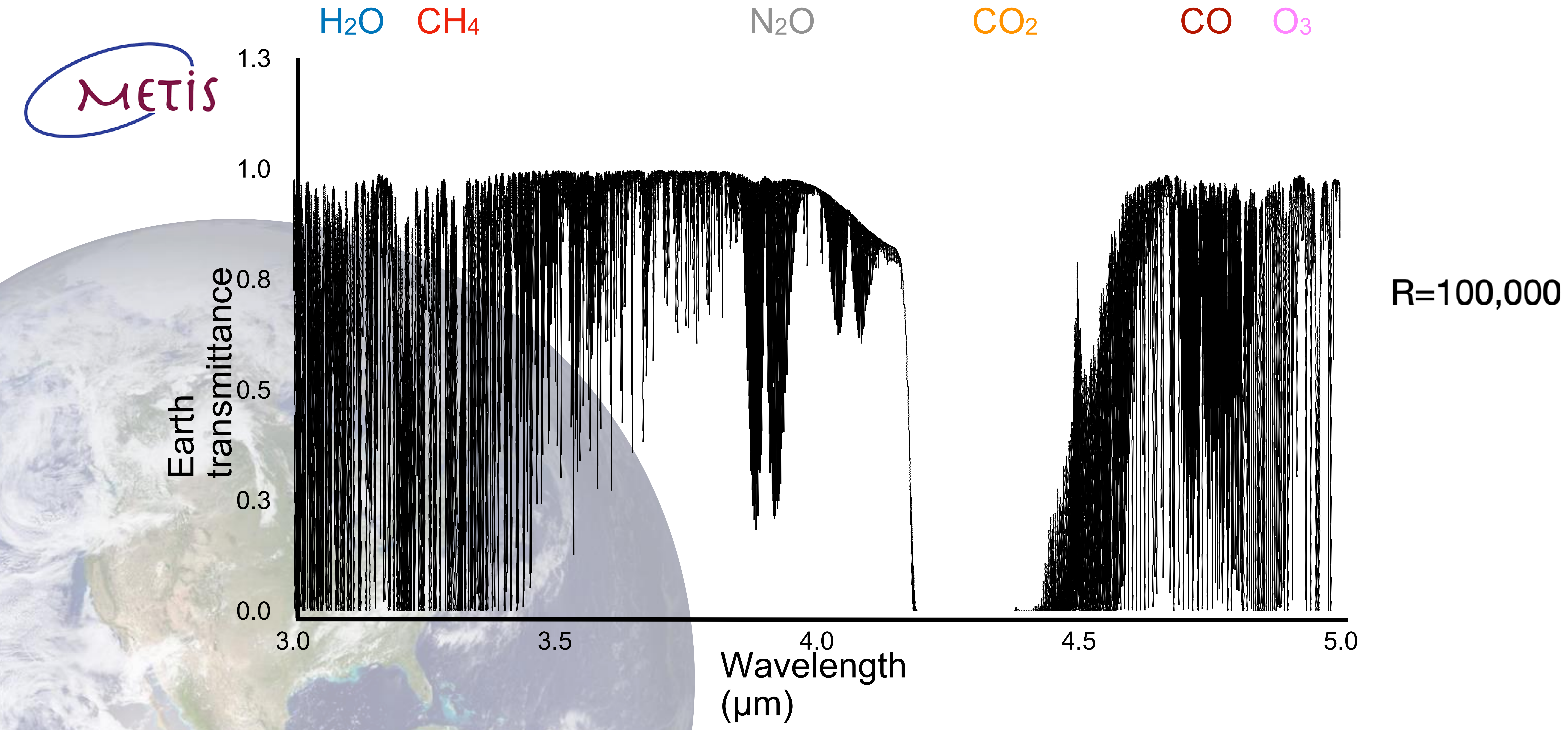
JWST light curves of WISE 1049 B



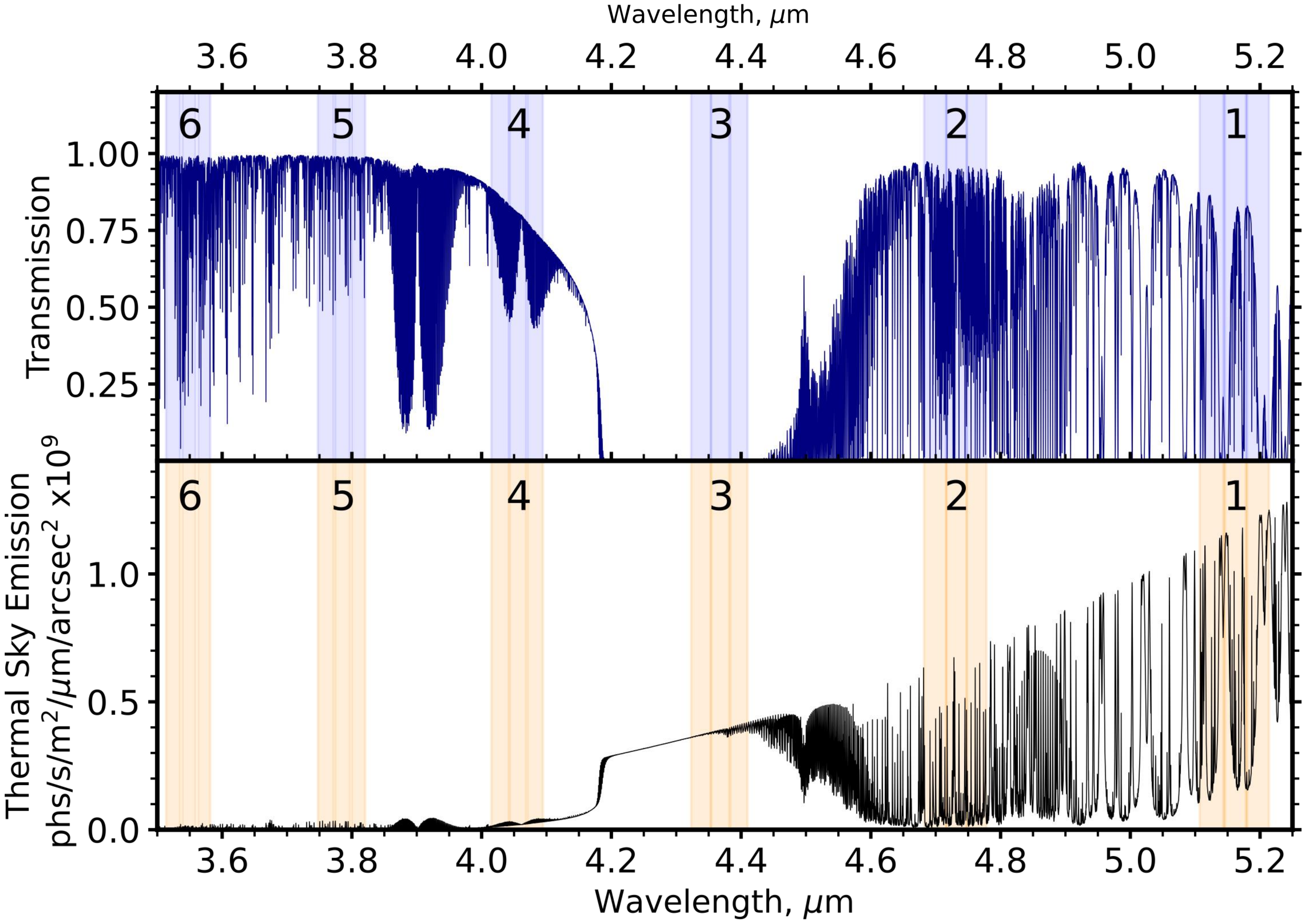
Biller et al. 2024

Into the red…

Opening the M-band for ELT first light: METIS/ELT 3-5 µm range contains biosignature gas features



High resolution spectroscopy beyond 3.8 μm is challenging



Telluric Contamination

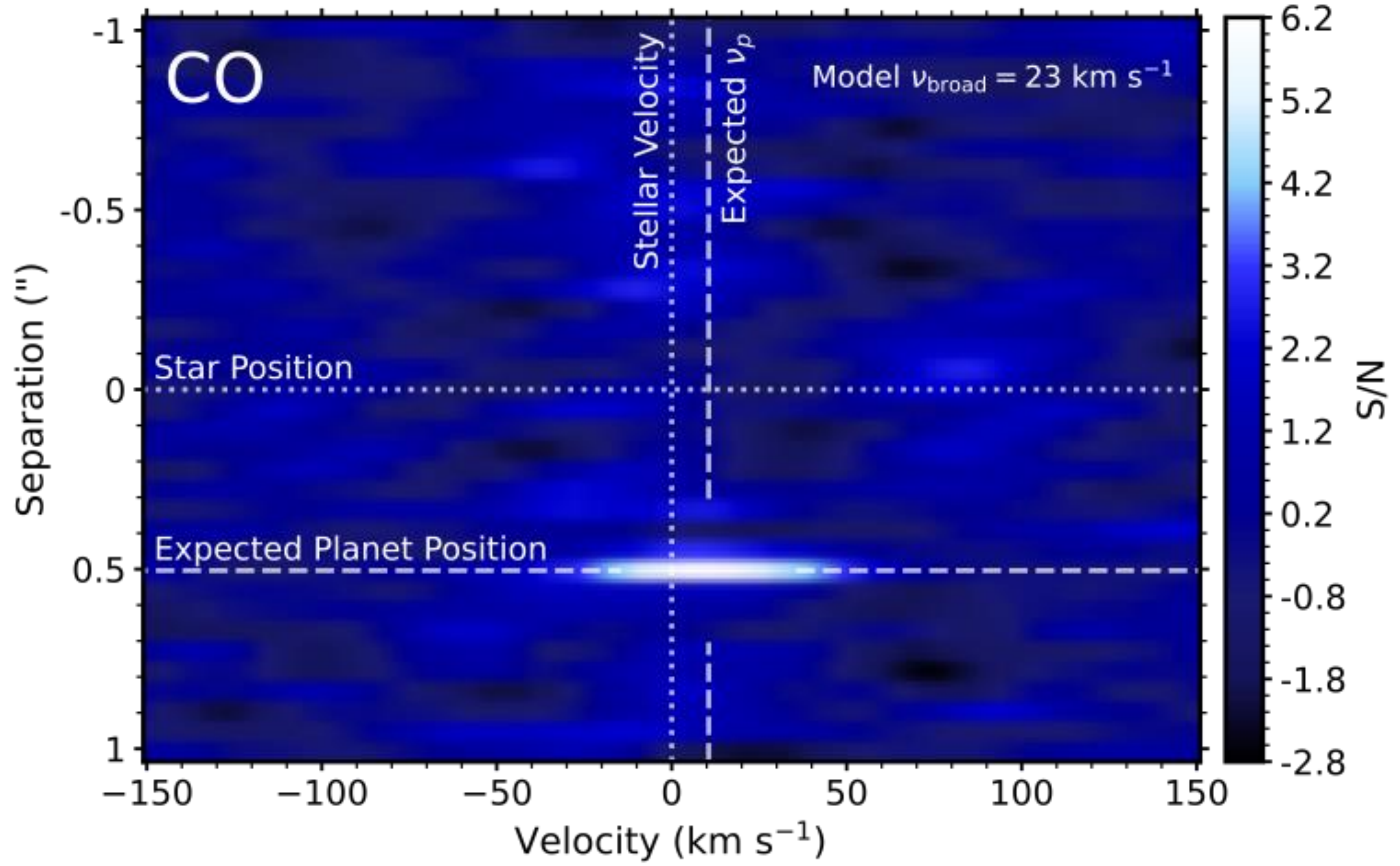
Thermal Sky Background

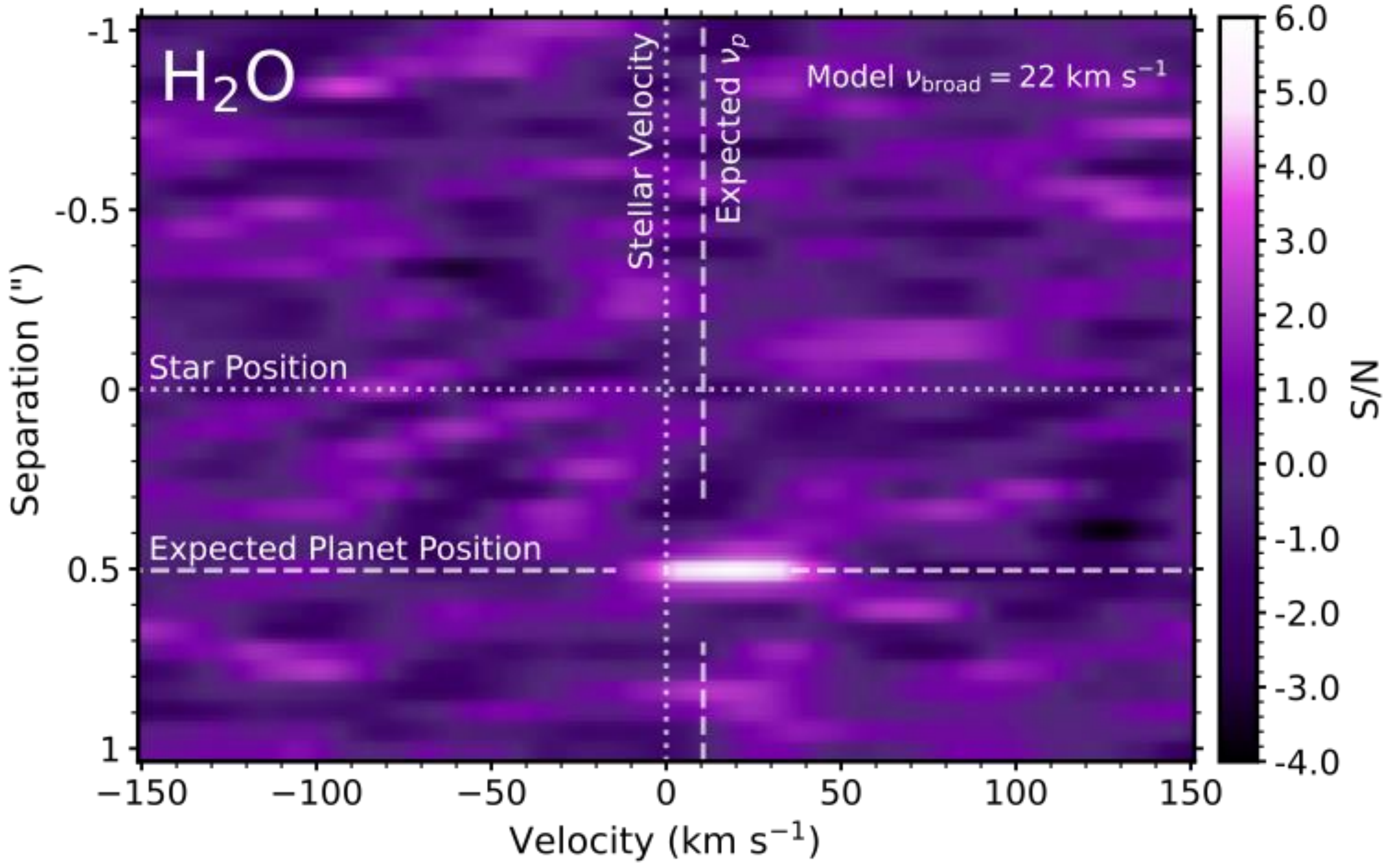
Only a few H2O and HCN detections from 3.2-3.8 μm, driven by CRIRES/VLT and NIRSPEC/Keck

(e.g. Birkby et al. 2013, 2017; Lockwood et al. 2014, Hawker et al. 2018, Wang et al. 2018, Cabot et al. 2019, Webb et al. 2020)

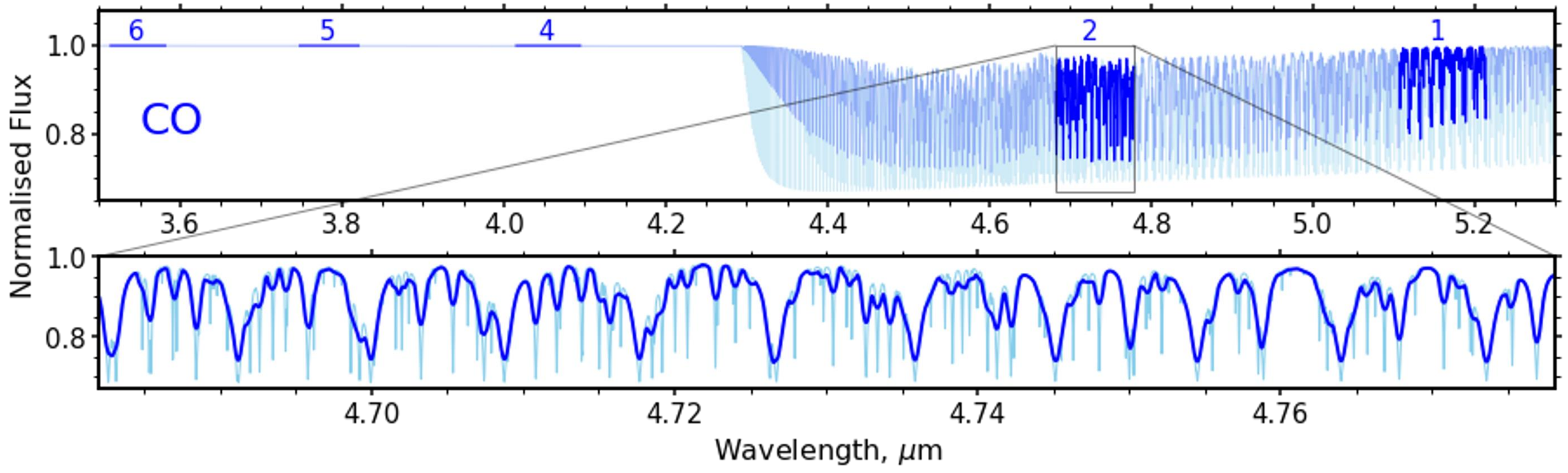
CO and H2O detected in β Pic b from 3.5 - 5.2 μm using CRIRES+

Luke Parker
(Final year DPhil, Oxford)



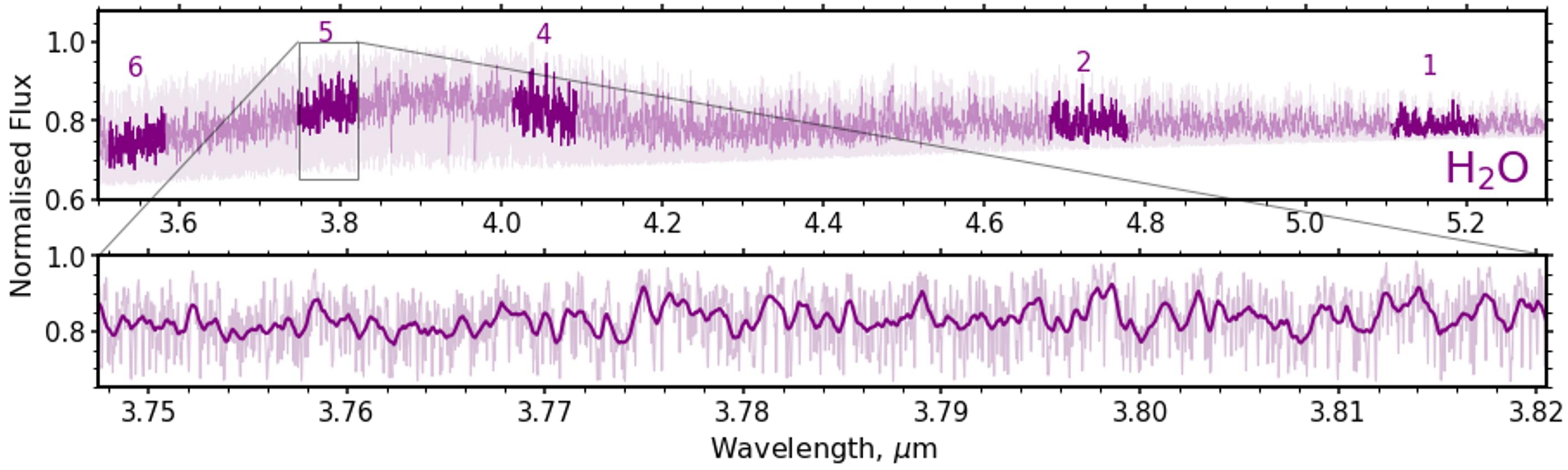


Model template used in cross-correlation



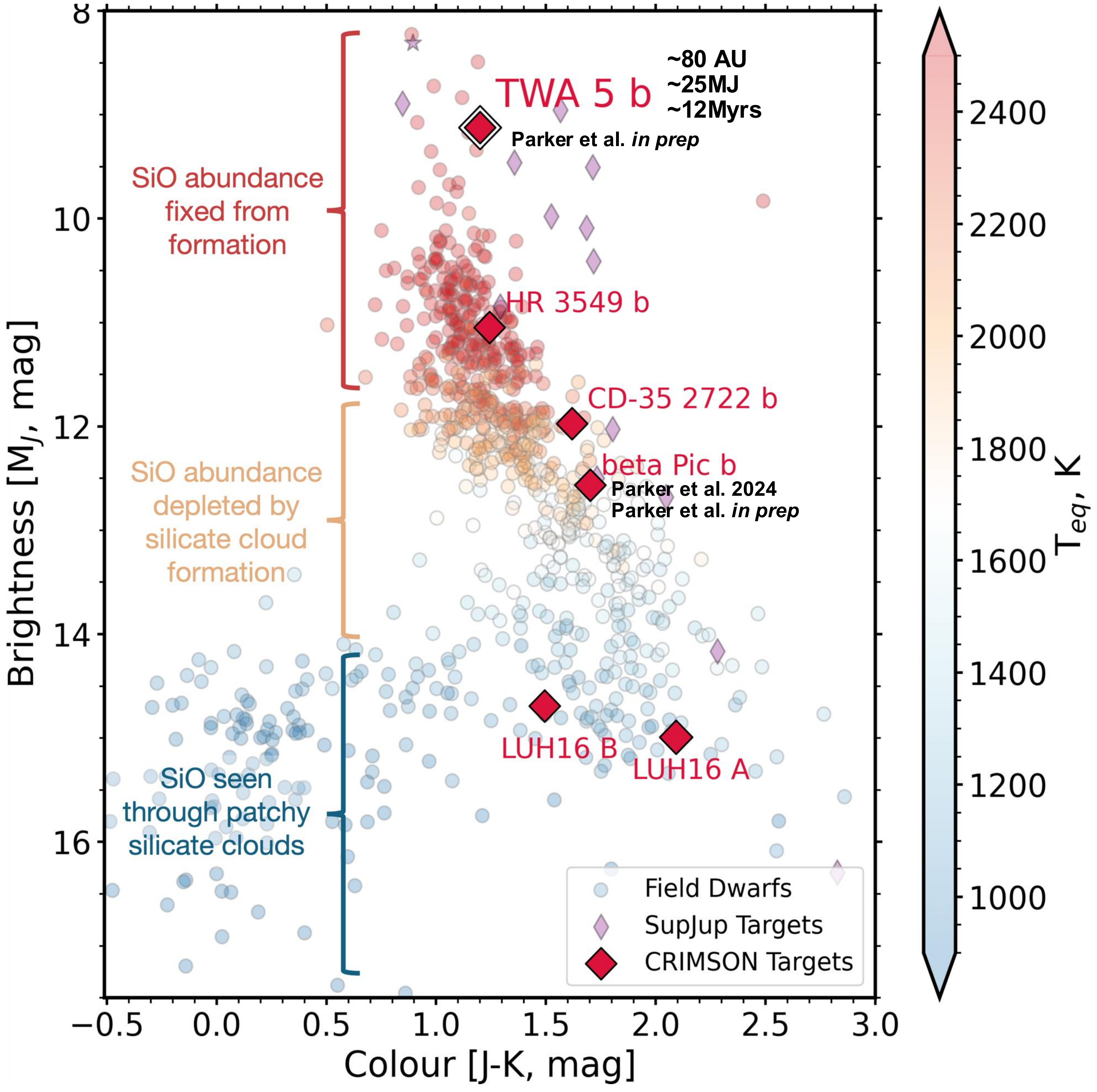
M band now open for business

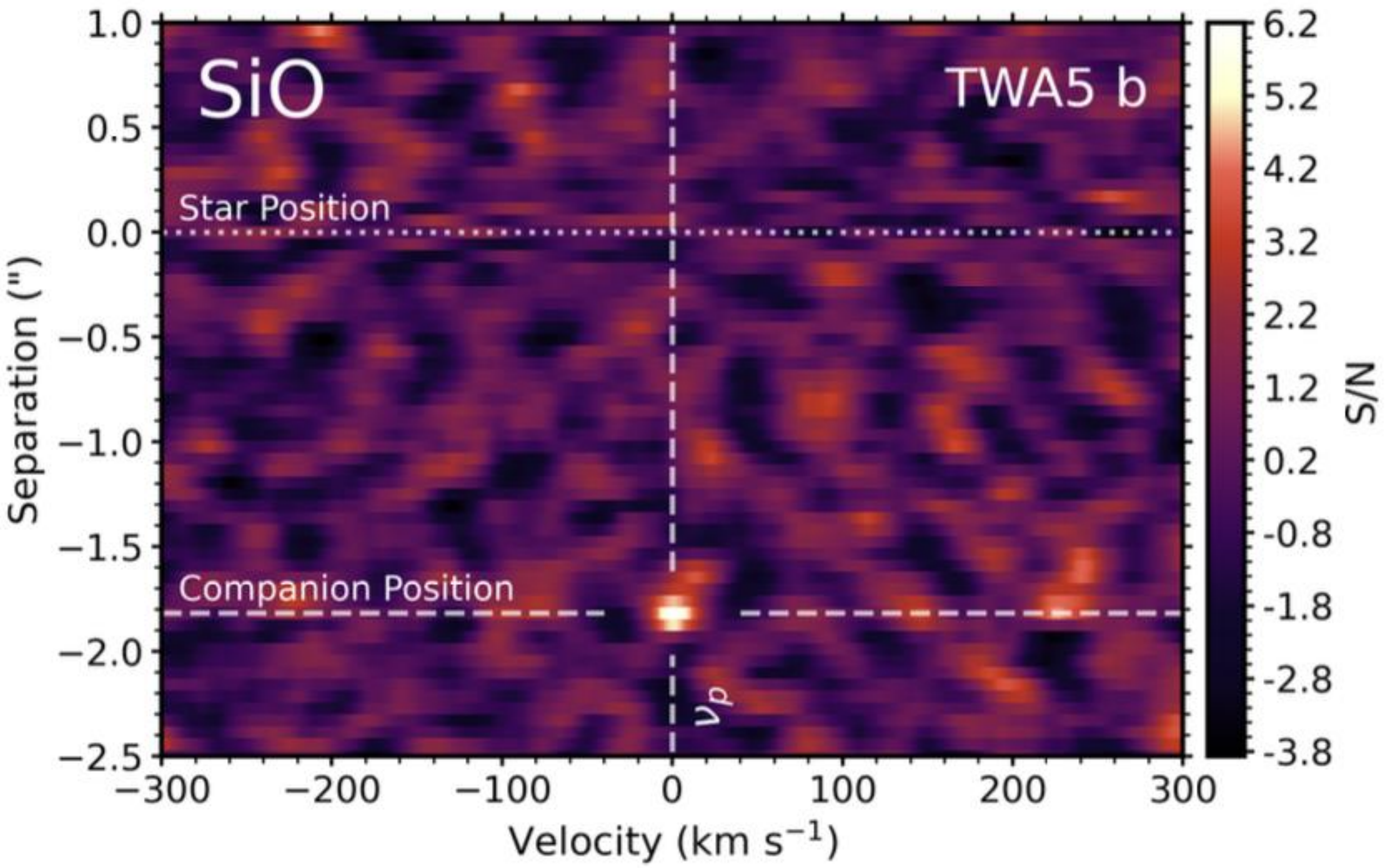
8x S/N in <2% of the exposure time for β Pic b (<30 sec needed)

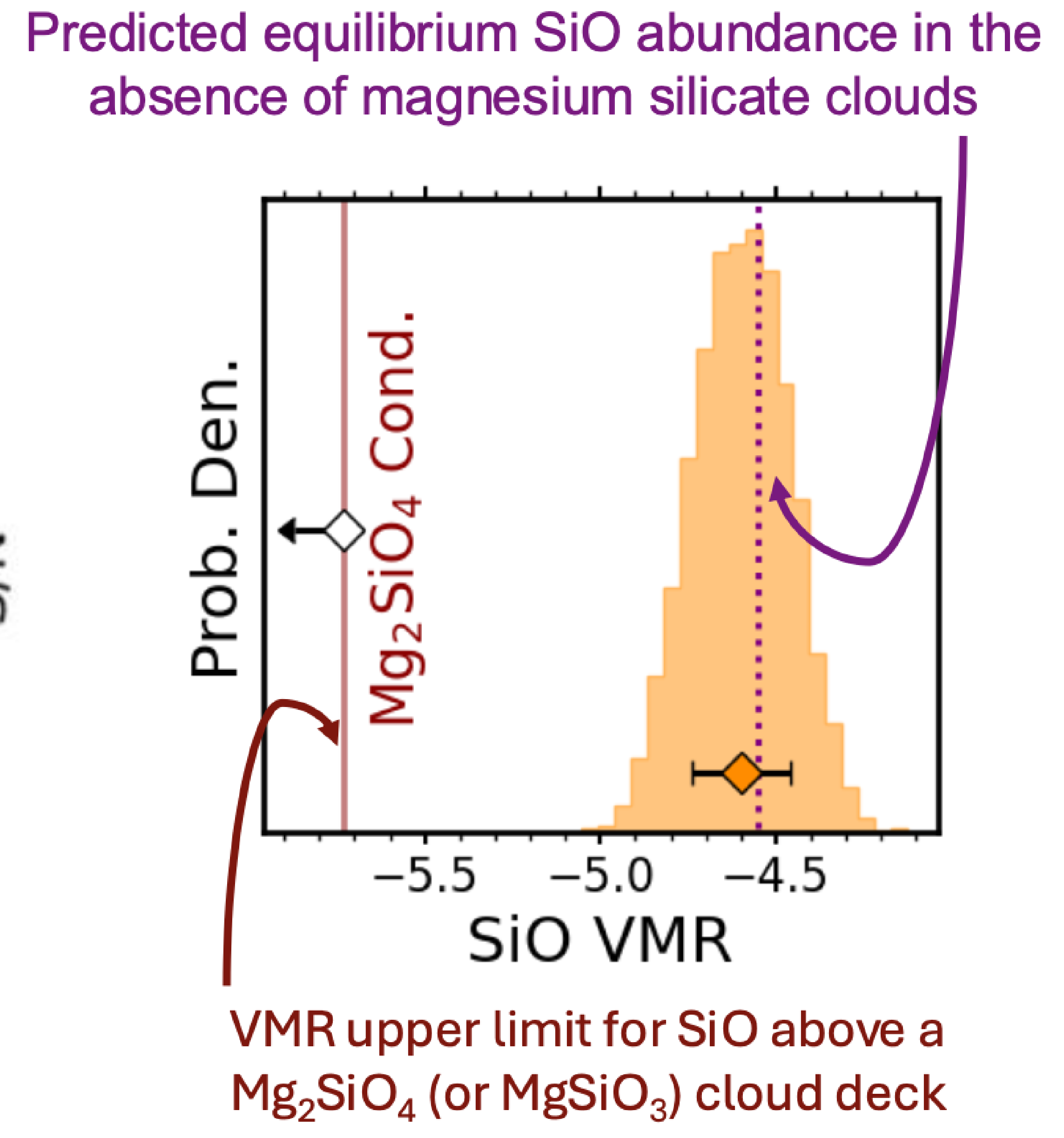


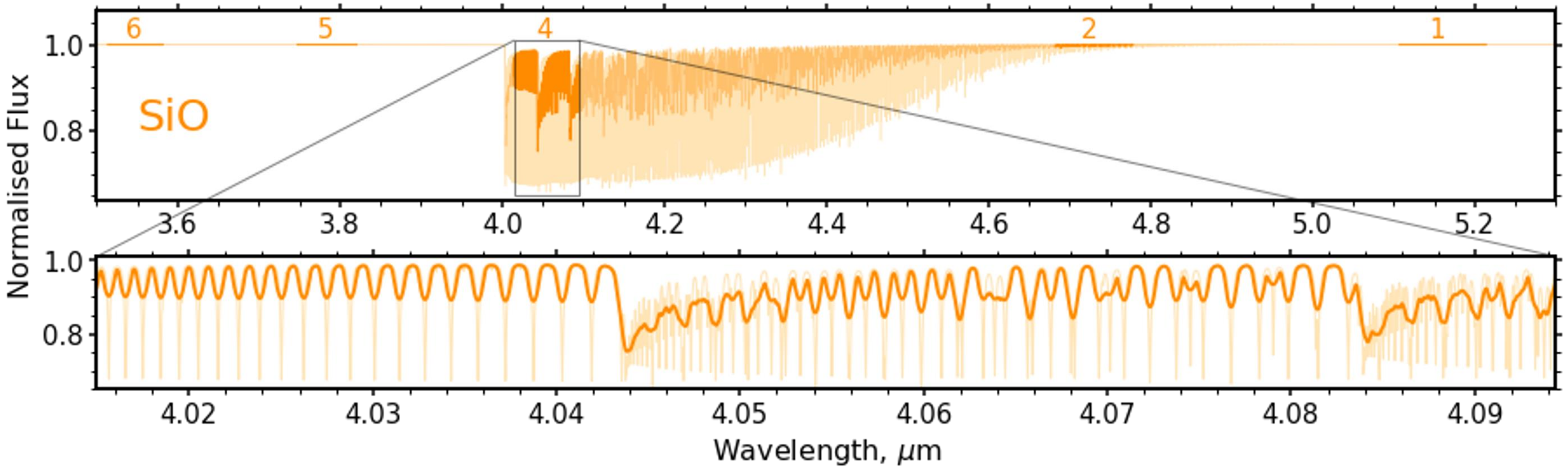
Parker et al. 2024

Cloud-free young super Jupiter TWA 5 b revealed in M-band









Luke Parker
(Final year DPhil, Oxford)

All silicon in hot giant planets locked up in SiO (Chachan et al. 2023)

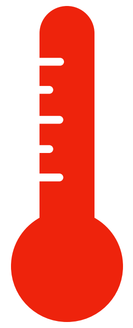
- alternative to Fe, Ni ratios measured for ultra hot Jupiters

Parker et al. *in prep*

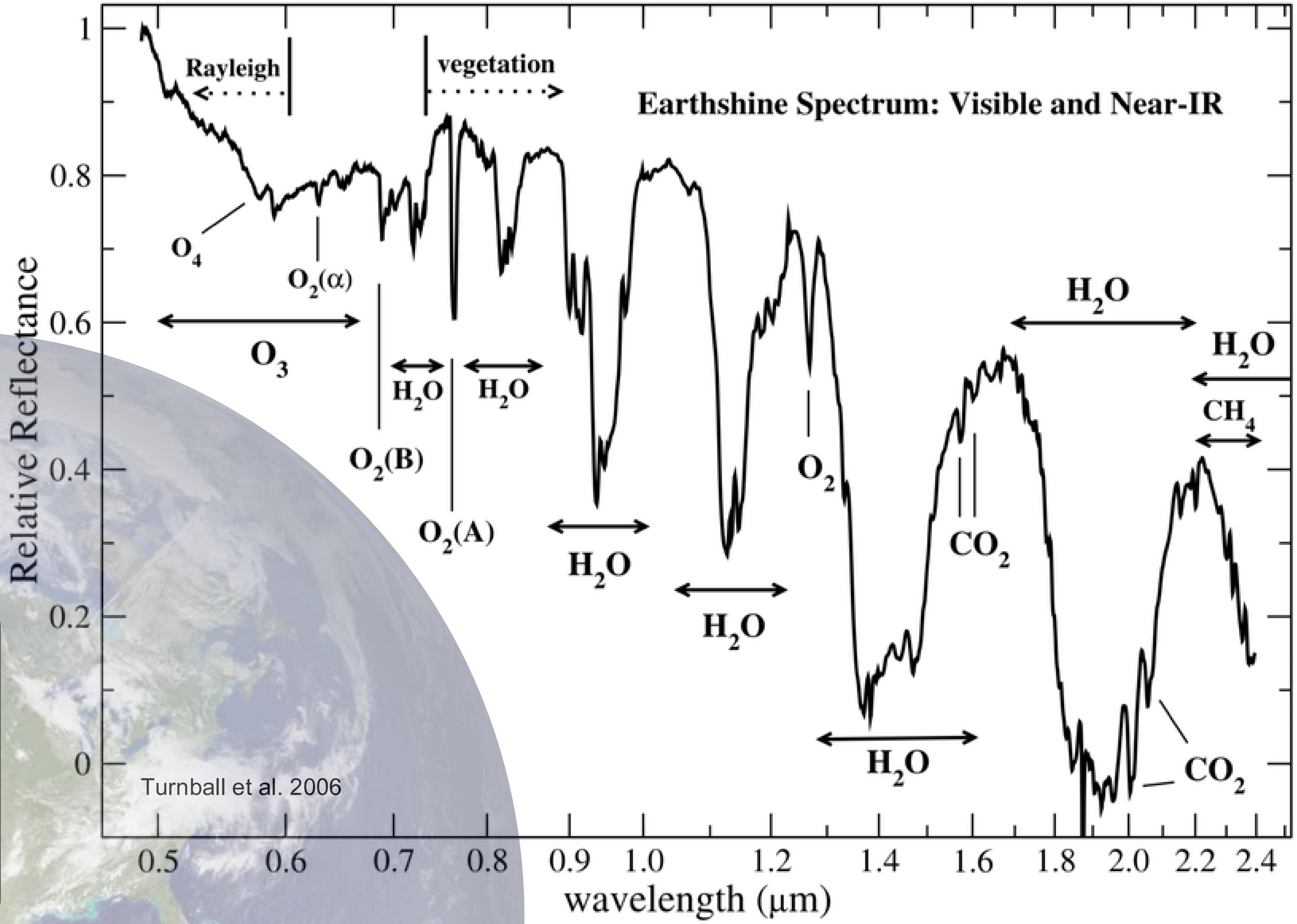
A future in reflected light

Optical-near infrared Earth reflectance shows multiple biosignatures

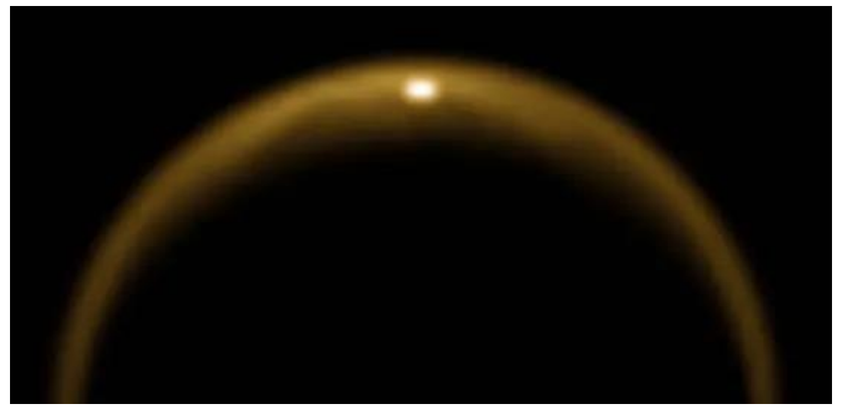
Temperature and Energy Balance



Cloud properties e.g. scattering phase function

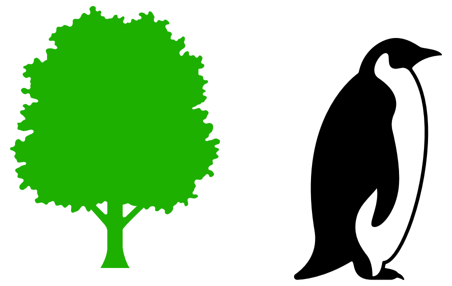


Surface structure e.g. ocean glint

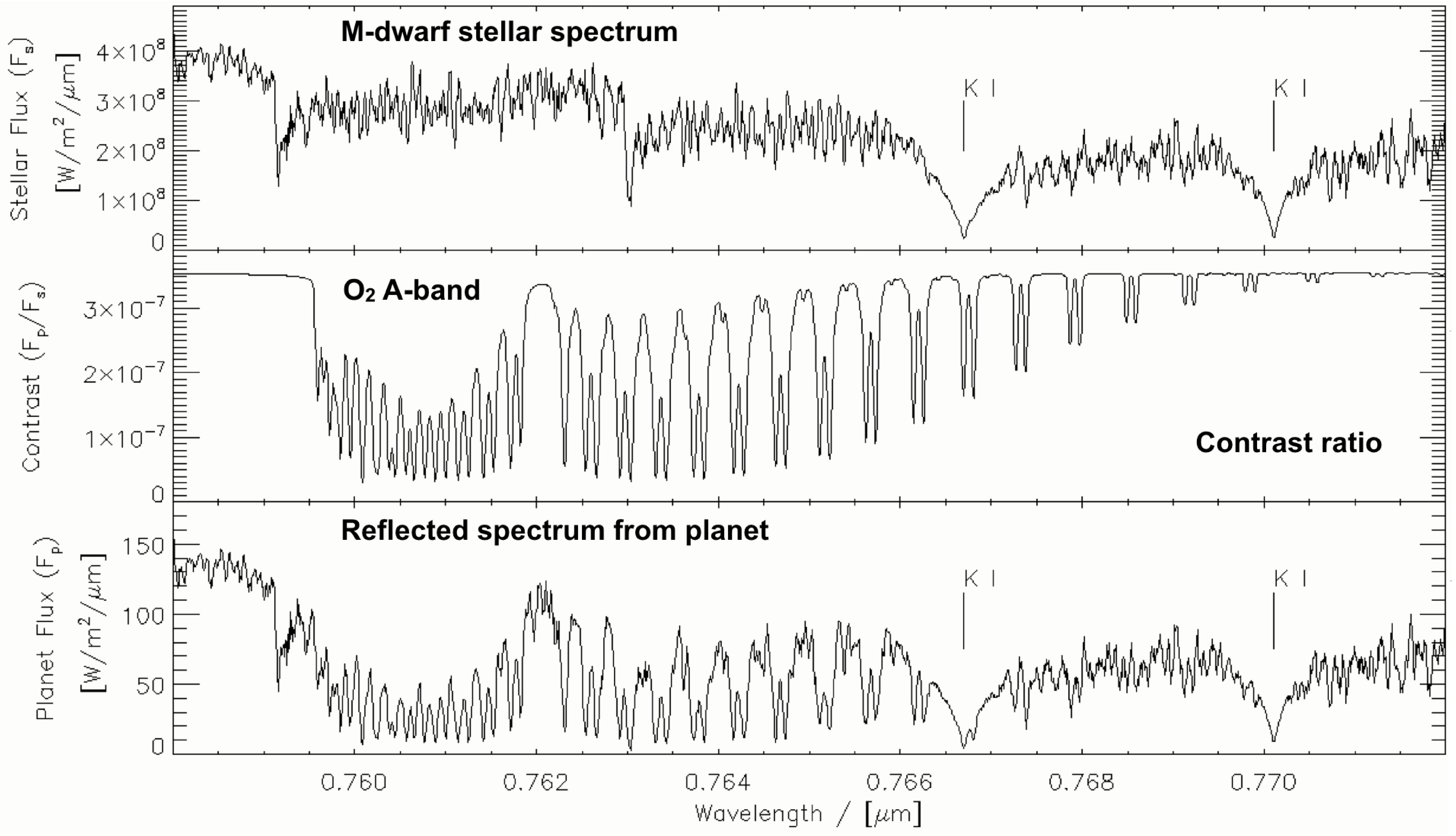


Ocean glint on Titan

Atmosphere composition and biosignatures



Planet reflection spectrum contains both planet absorption lines and the reflected spectrum of the host star

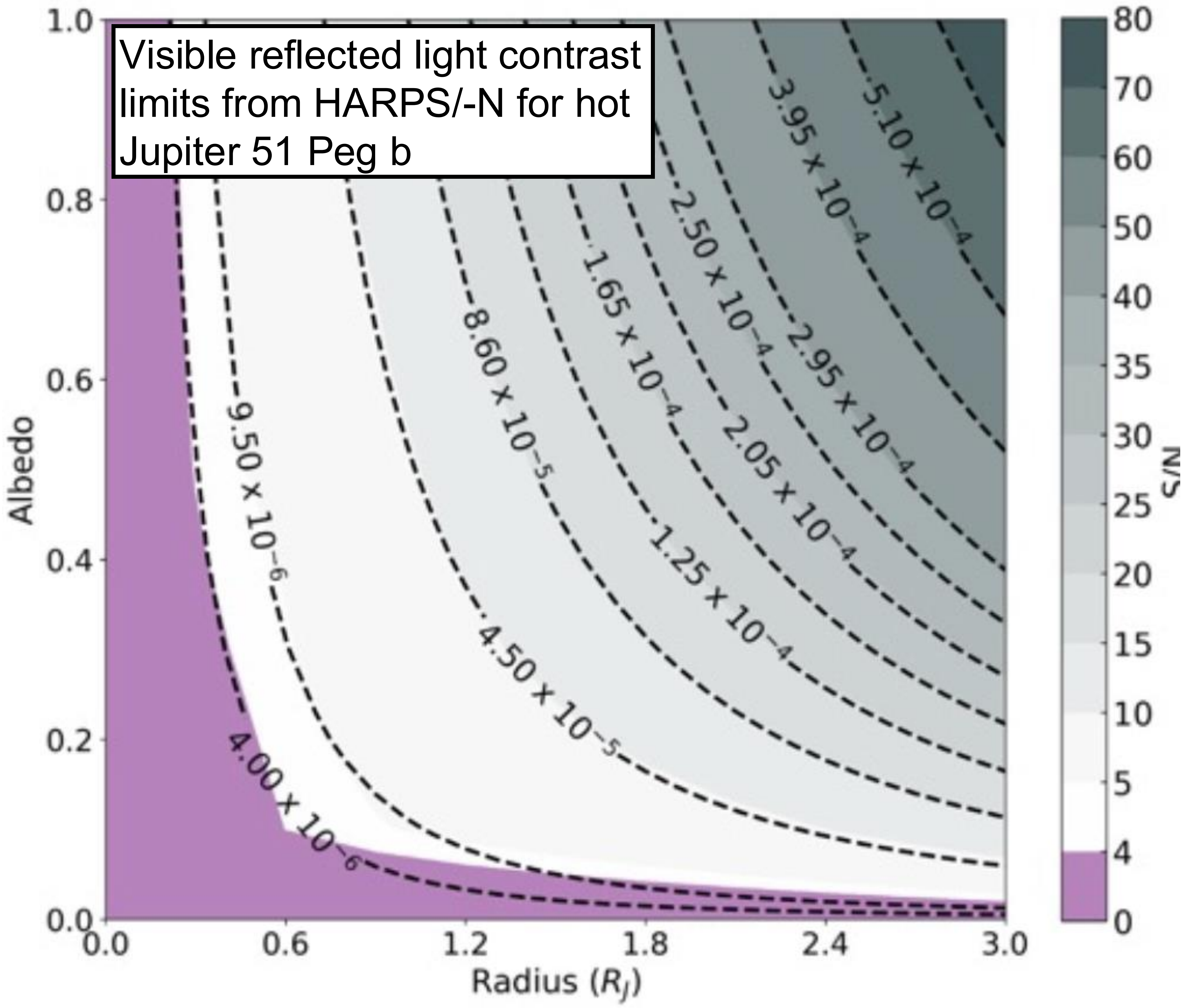


There are currently no robust detections of reflected light with HRS but it delivers visible wavelength contrast limits down to $4x10^{-6}$

51 Peg is a bright host star, original atmosphere target!

But planet is not reflective.

Hot Jupiter albedos typically low Ag<0.1

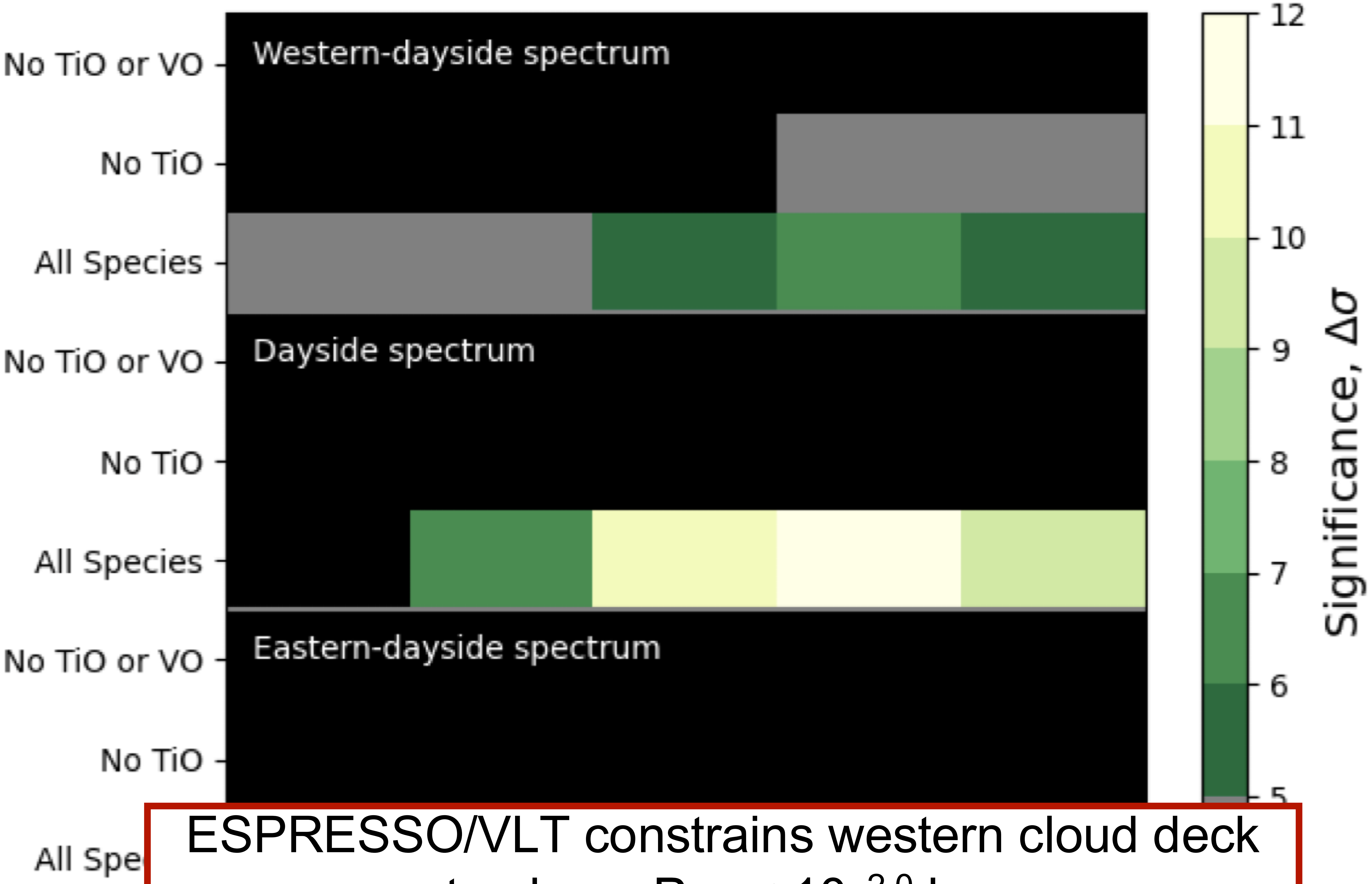


Eleanor Spring

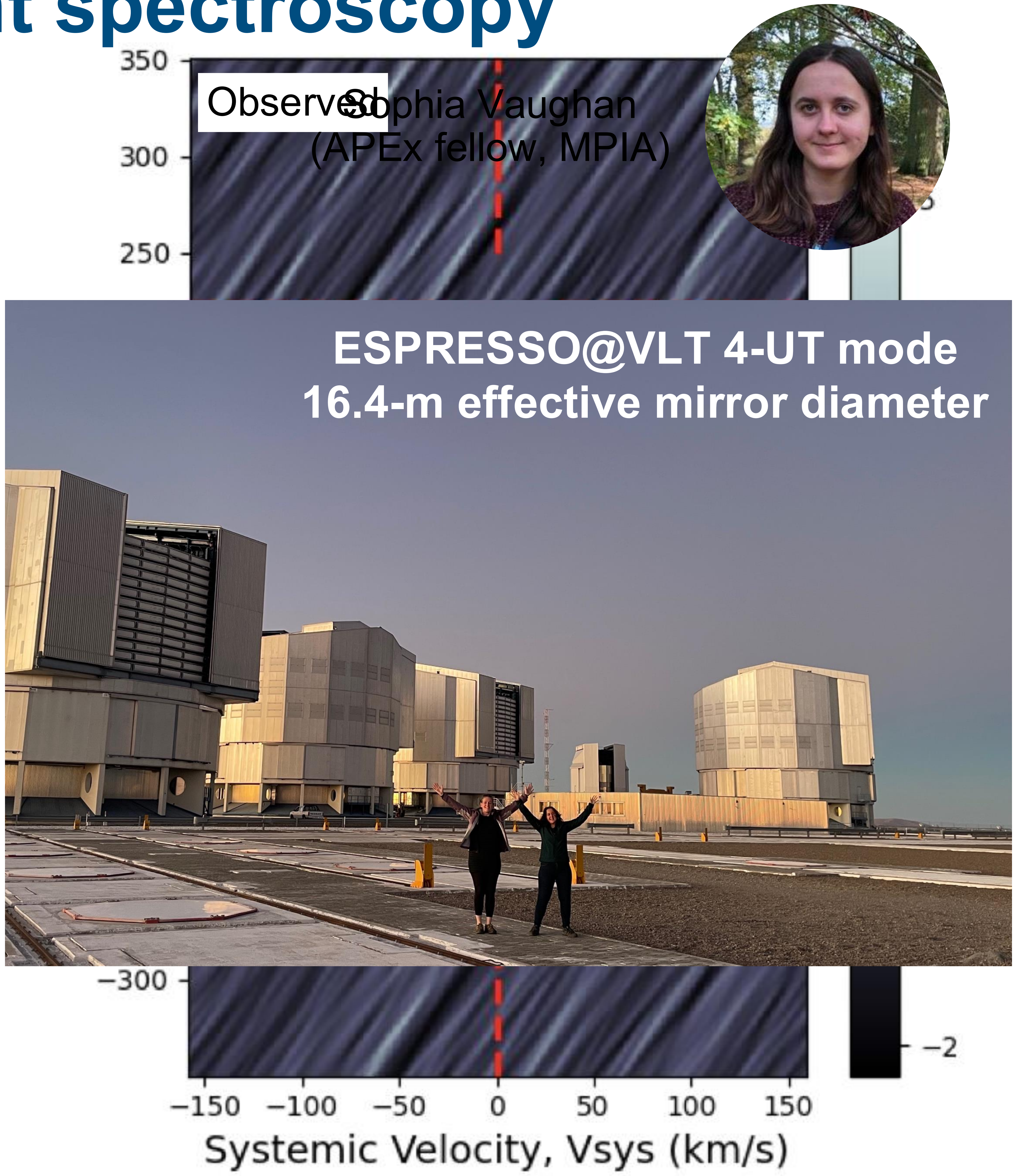
Spring & Birkby (in review); see also Hoeijmakers et al. 2018a; Scandariato et al. 2021; Spring et al. 2022

TiO depletion in the western hemisphere of LTT 9779 b revealed in high resolution reflected light spectroscopy

Reflected light detection with HRS requires a reflective target *and* sufficient spectral lines



ESPRESSO/VLT constrains western cloud deck to above $P_{top} < 10^{-2.0}$ bar
and eastern cloud deck $P_{top} < 10^{-0.5}$ bar, consistent with predicted MgSiO3 and Mg2SiO4 clouds from JWST.

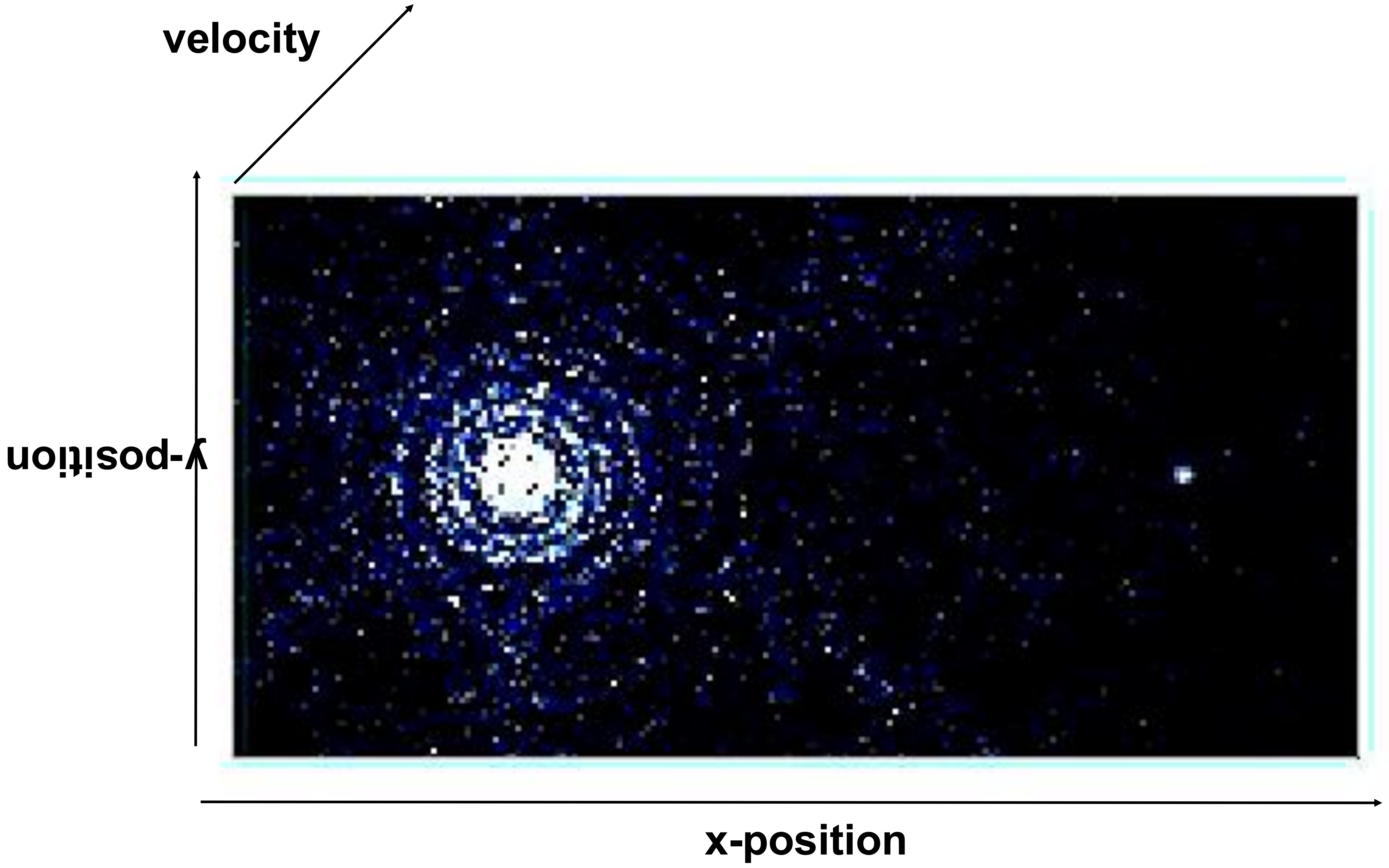


Sophia Vaughan
(APEx fellow, MPIA)

Vaughan, Birkby et al. in review

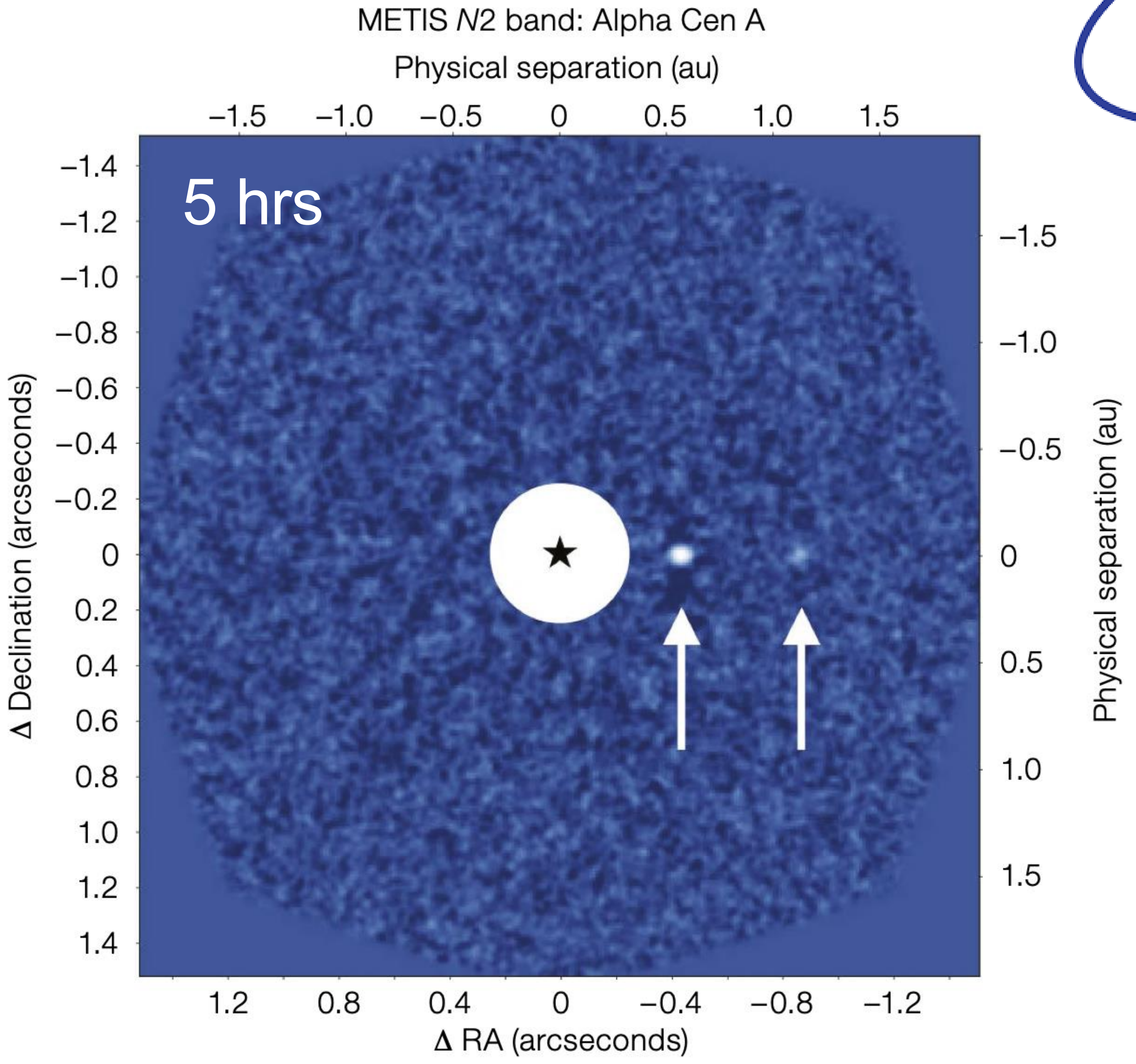
ELT molecule map for Proxima b

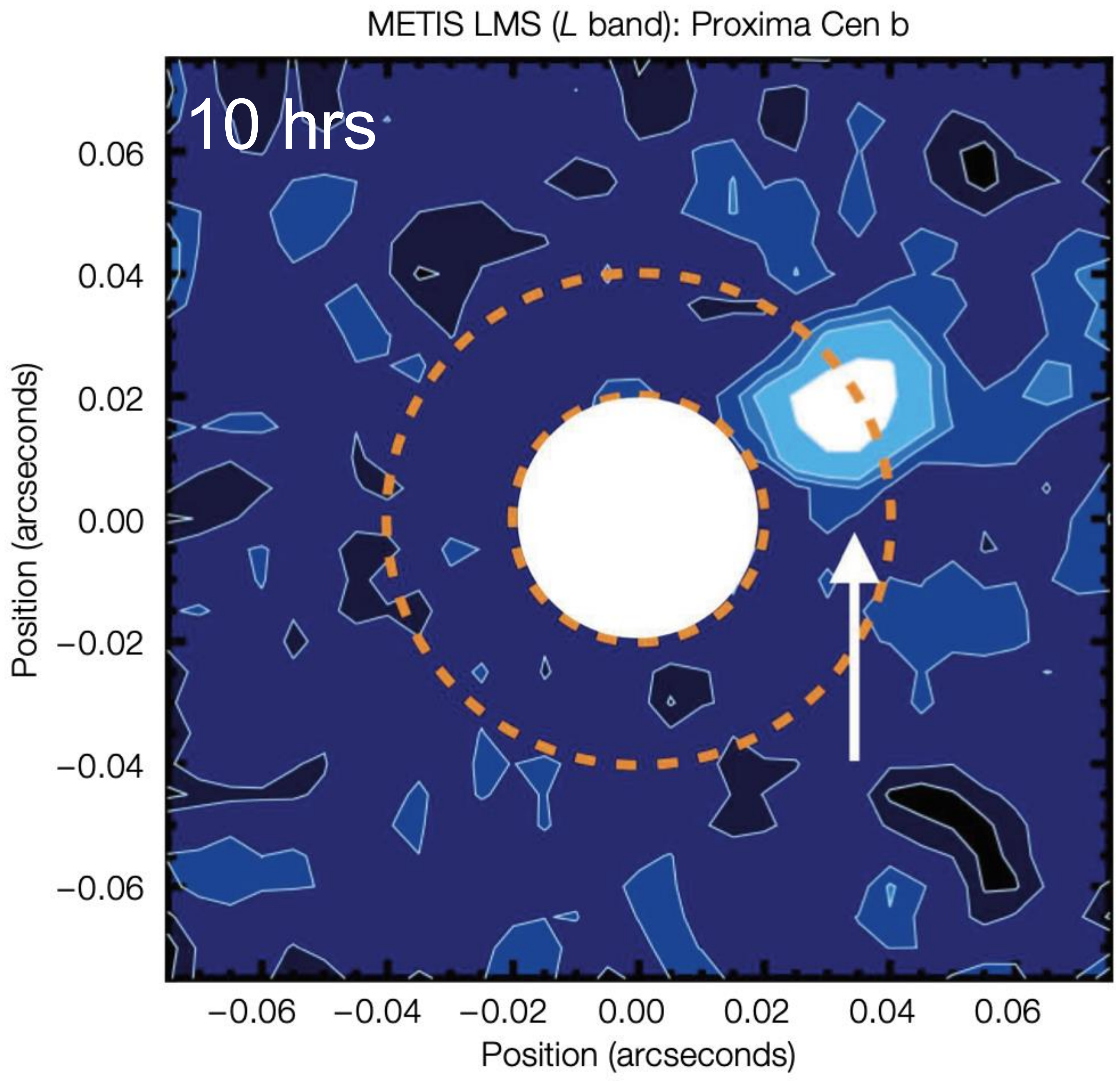
(simulated for METIS)



Snellen et al. 2015

METIS/ELT simulations predict atmosphere detection possible in 5-10 hours for the nearest habitable zone rocky exoplanets



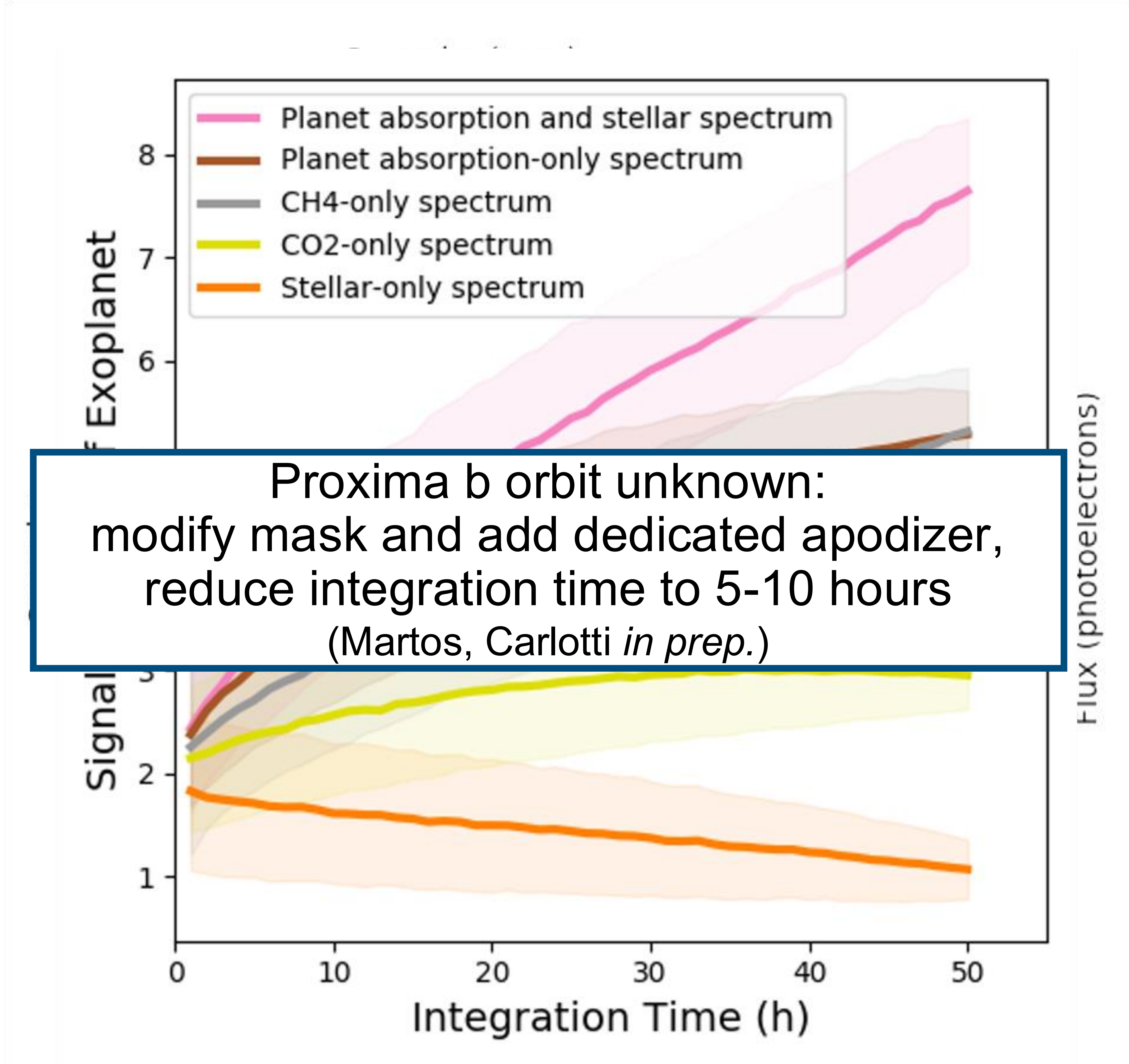


Proxima Cen: Simulation of an Earth @ 2 λ/D with 1:500 AO ➞ 10 hours for S/N=5 (Brandl et al. 2021)

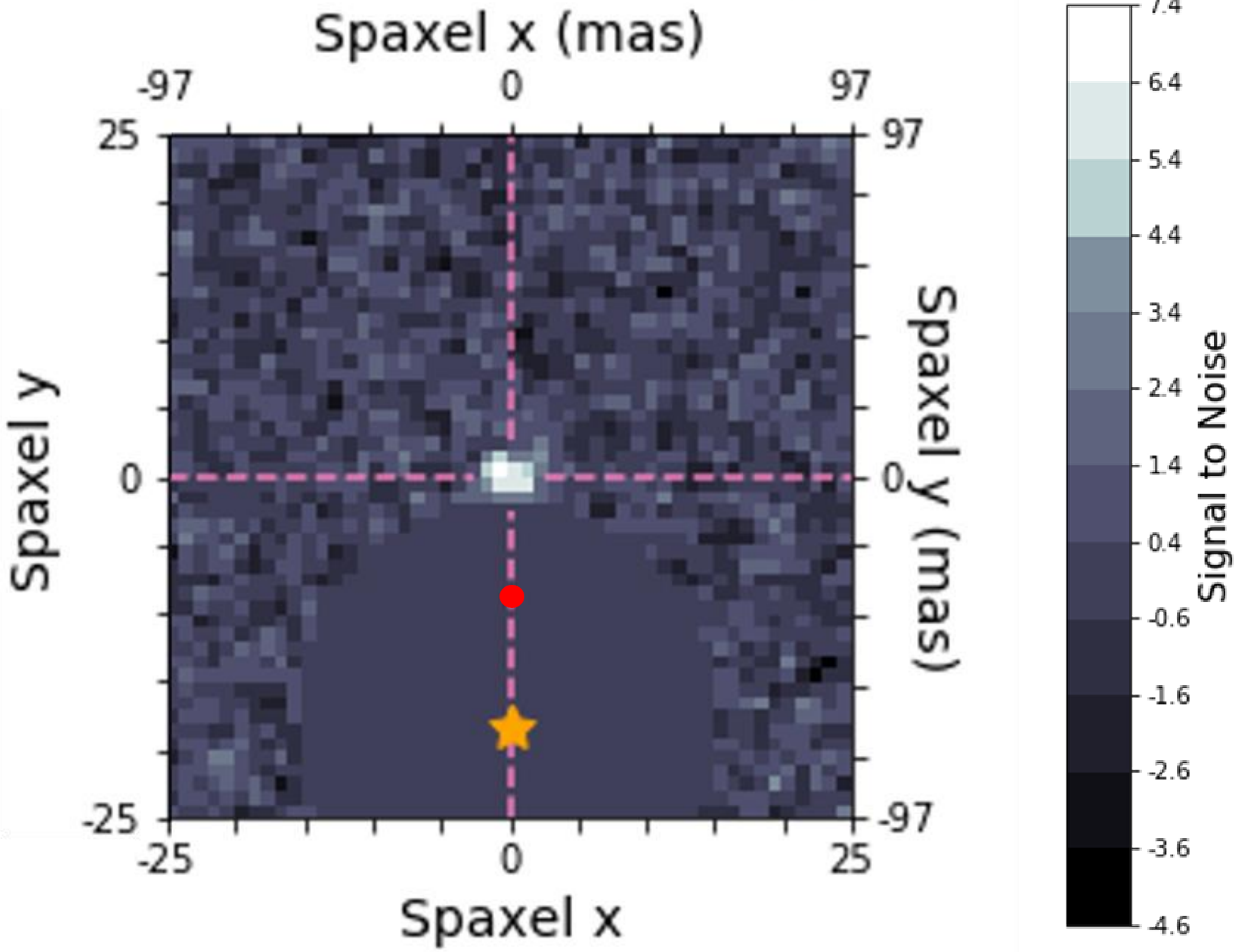
➞ Now updating for vAPP and vortex coronagraph PSFs with Proxima b atmosphere model

HARMONI simulation of a 10^{-7} contrast planet at 75 mas around Proxima Centauri processed with HCS techniques (molecule mapping)

Sophia Vaughan (MPIA)



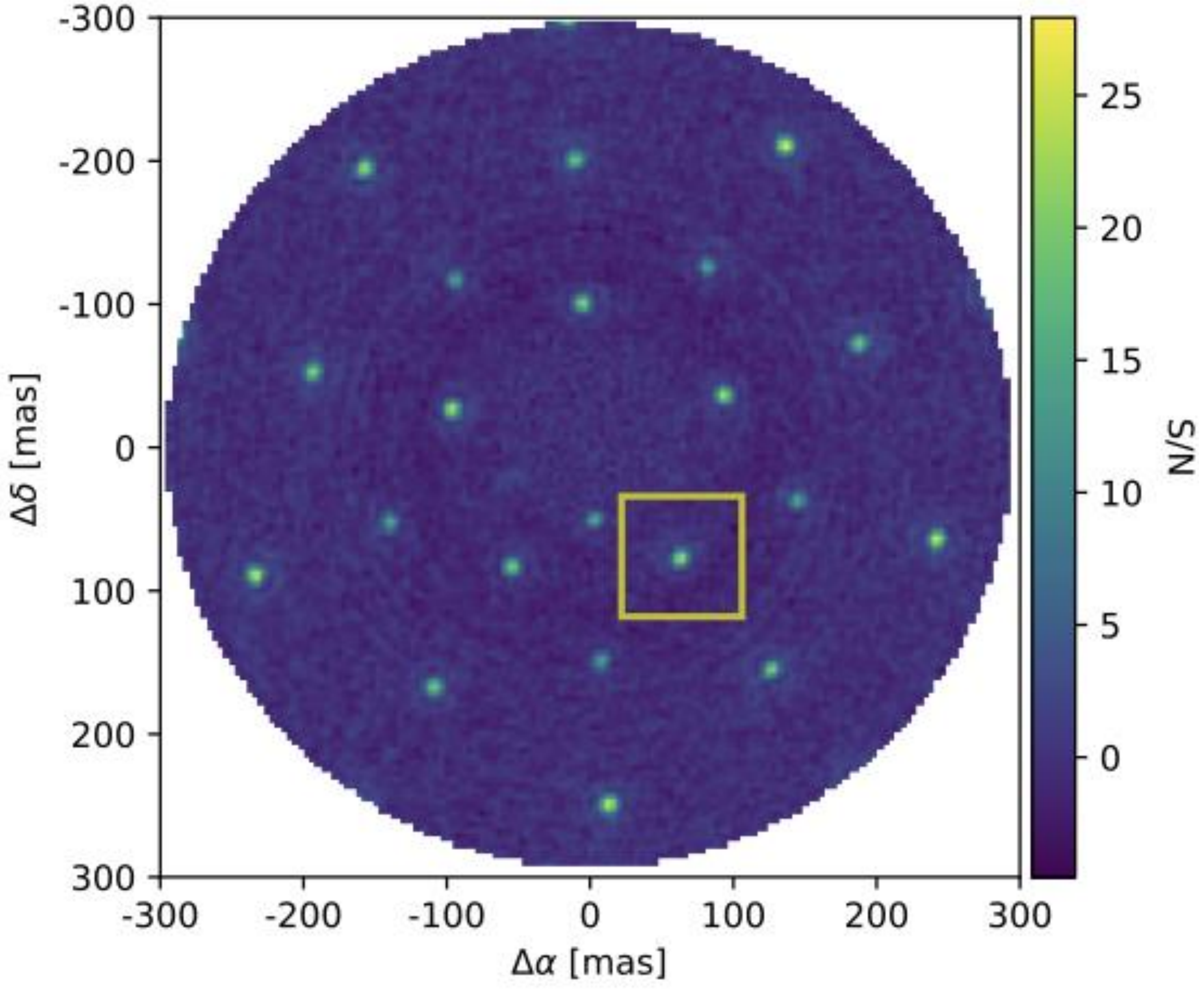
Proxima b orbit unknown:
modify mask and add dedicated apodizer,
reduce integration time to 5-10 hours
(Martos, Carlotti *in prep.*)

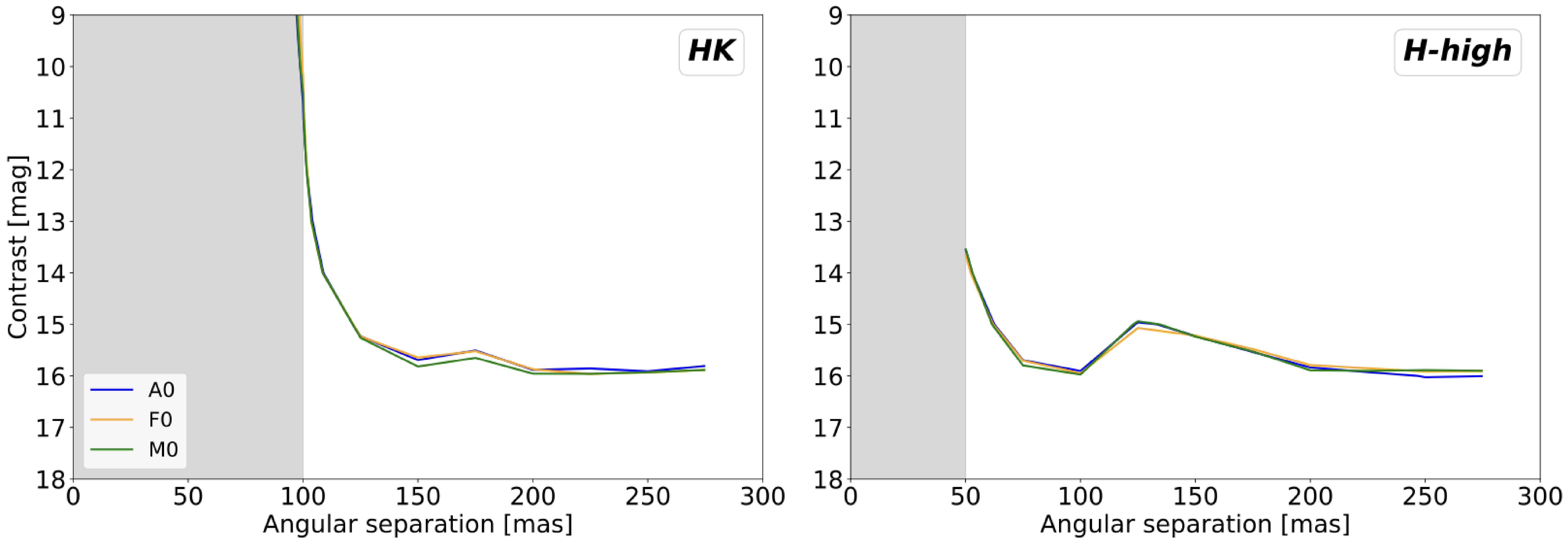


R=17,385, H-high band, includes visibility, orbital motion, tellurics, host star, and additional noise sources, processed as real data. High

Vaughan, Birkby, et al. 2024; Lin & Kaltenegger 2019

HARMONI simulation for widely separated companions give 5σ detections for contrasts up to 16 mag for separations down to 75 mas

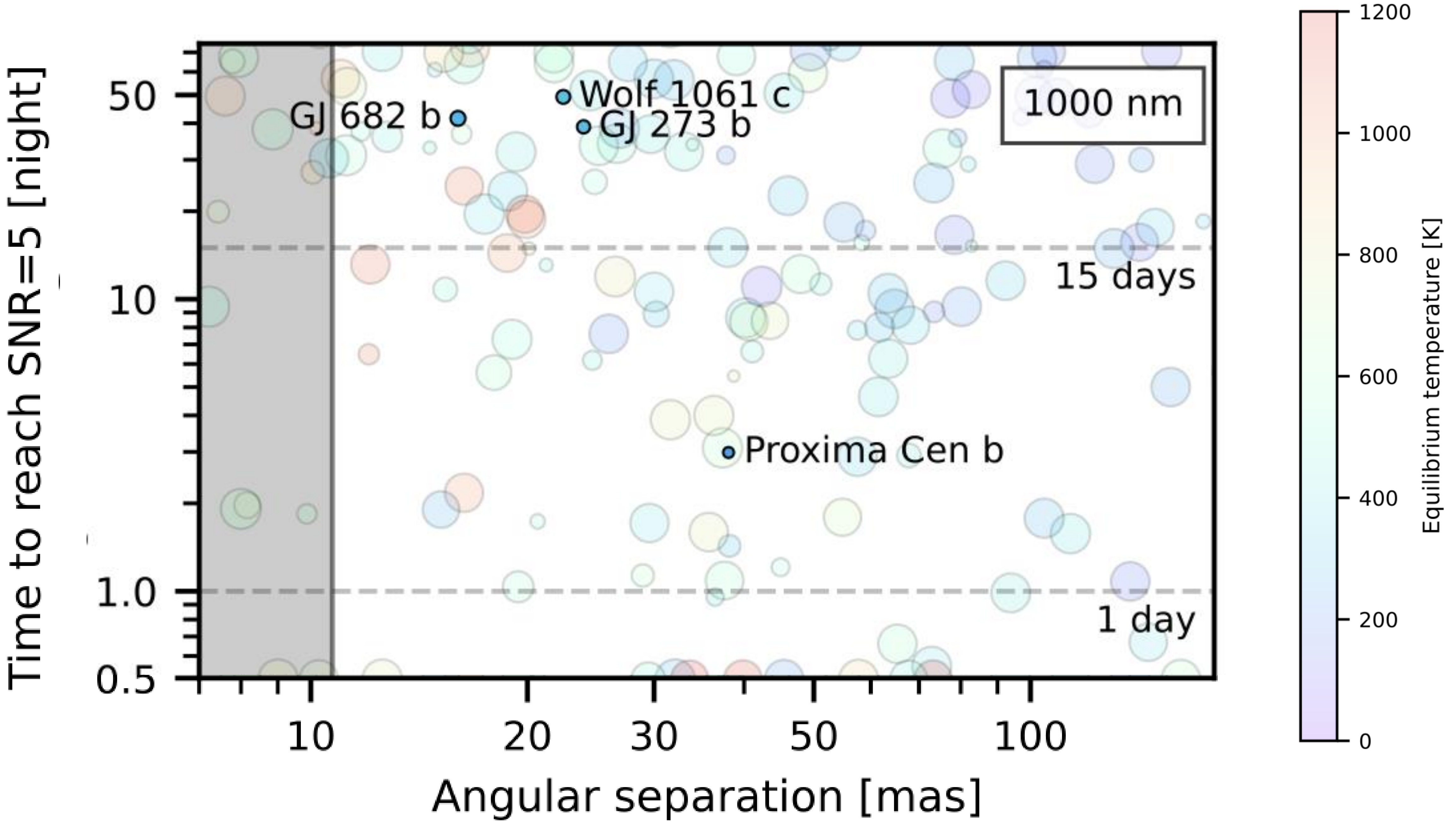


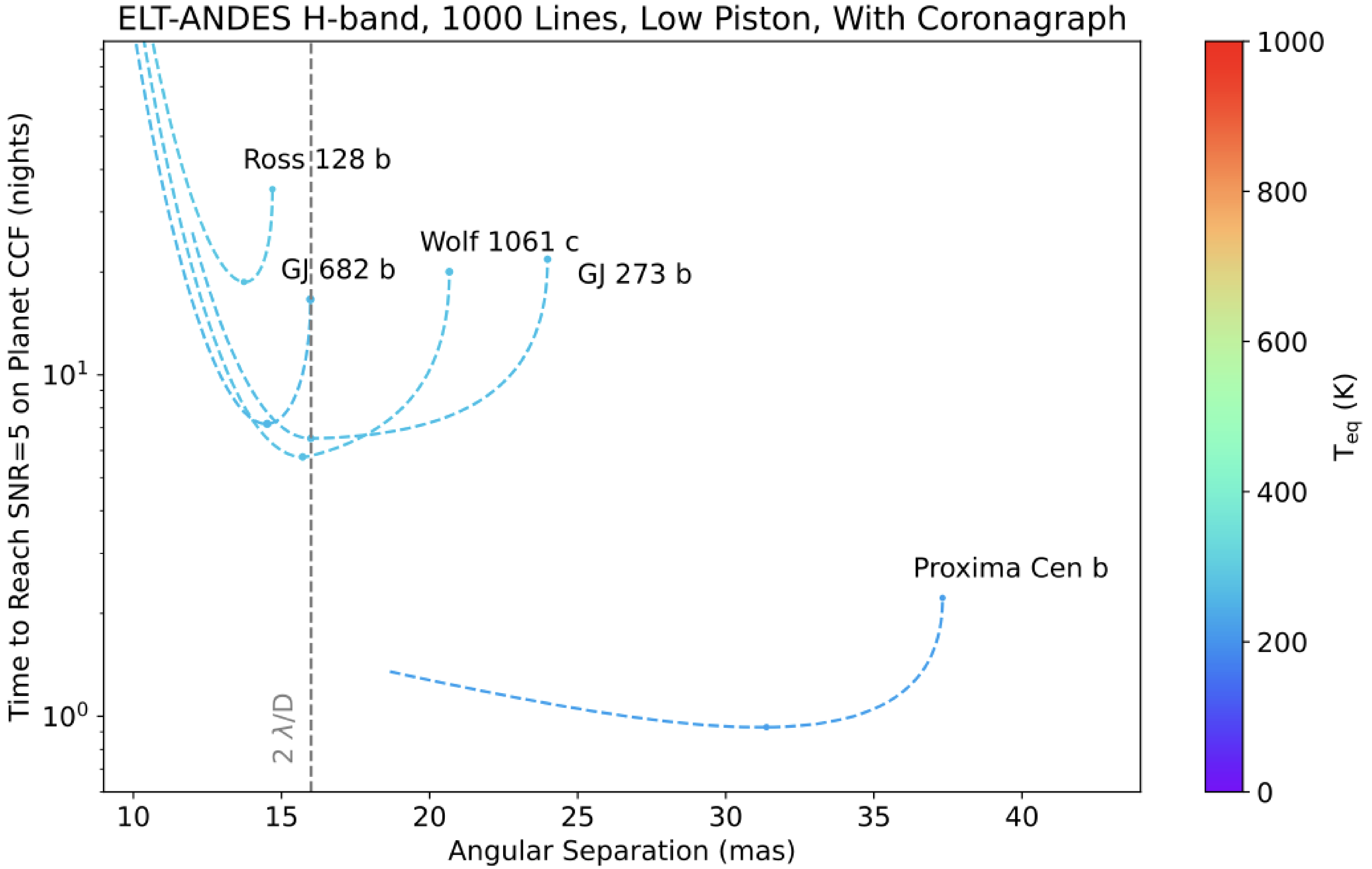


Achieve 2.5 mag fainter than current state-of-the-art with ADI

Houllé et al. 2021

The ANDES golden sample will deliver survey of nearby temperate rocky worlds in reflected light





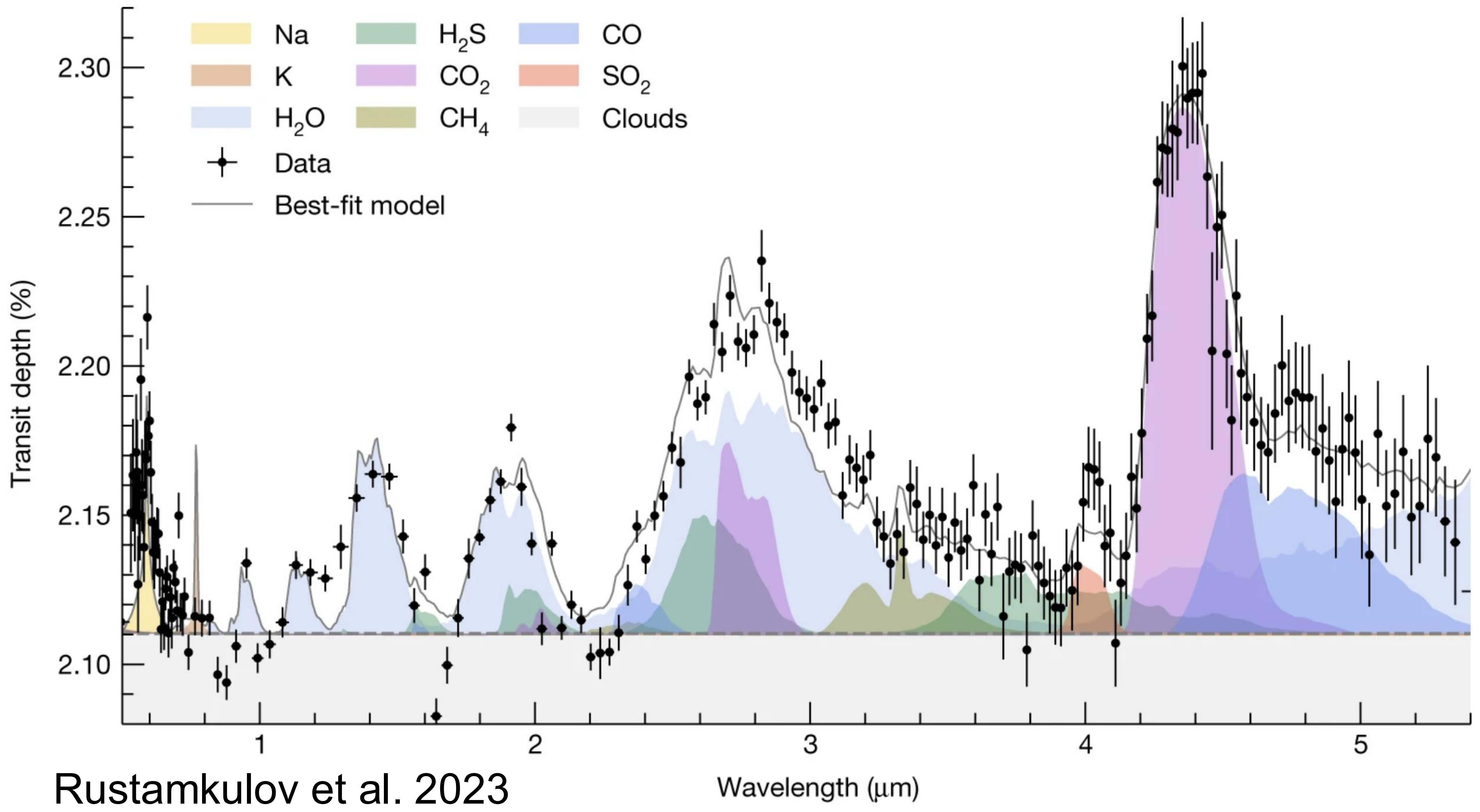
Palle et al. 2023

See also Hardegree-Ullman et al. 2025, Miles et al. 2025 for similar predictions for TMT and GMT

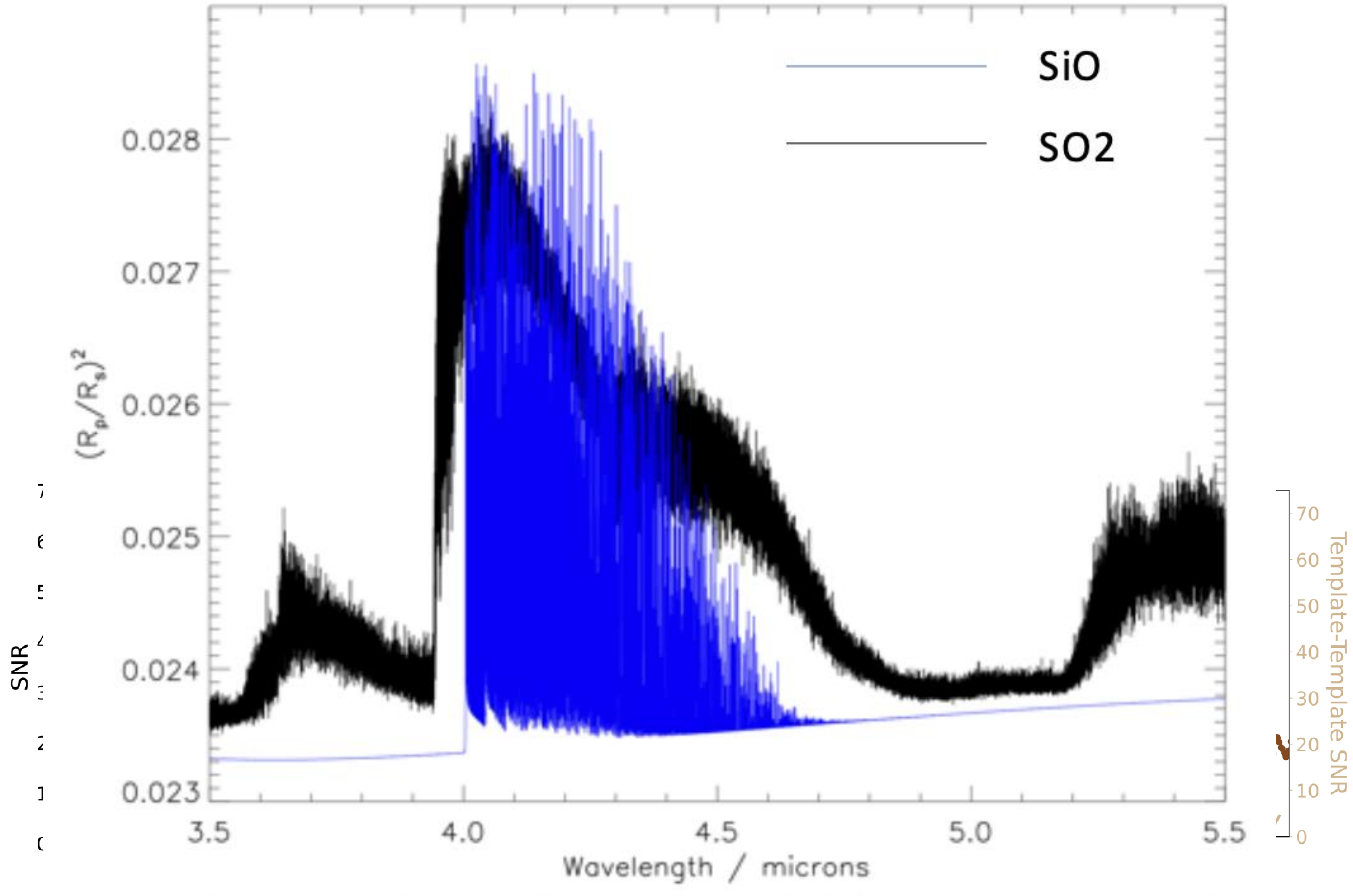
Big missions, big goals

Even at R~3000 cross-correlation can reveal major molecules although struggles to identify shallower lines from less abundant species

Hot Saturn (WASP-39 b) ~2000ppm



Rustamkulov et al. 2023

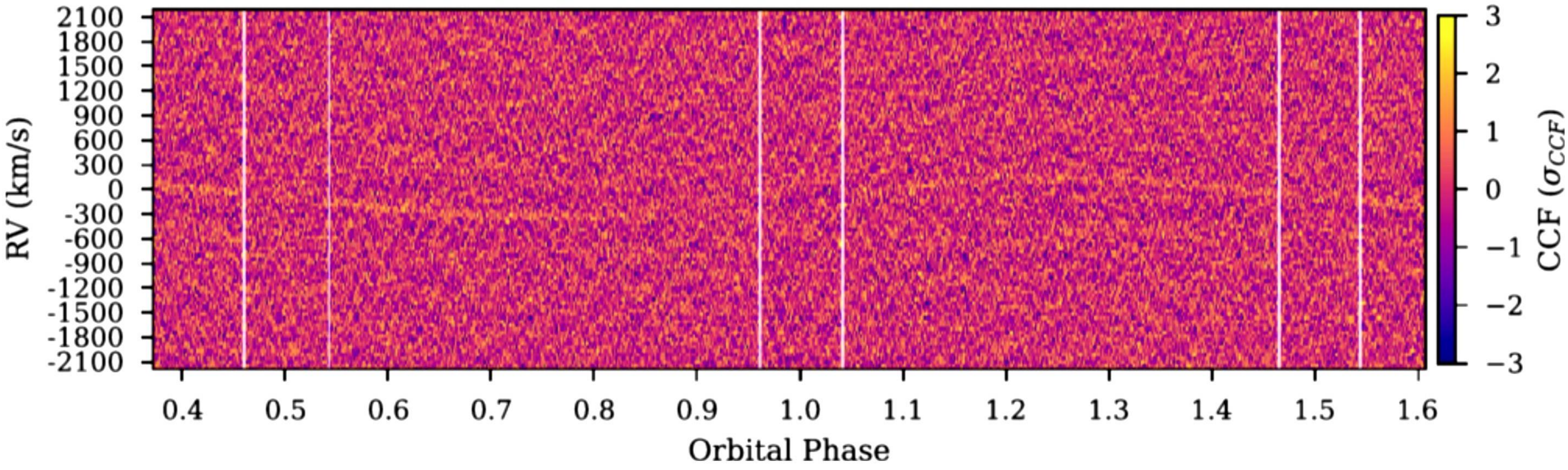


Stay tuned for Mathilde Mâlin's talk!

Esparza-Borges et al. 2025

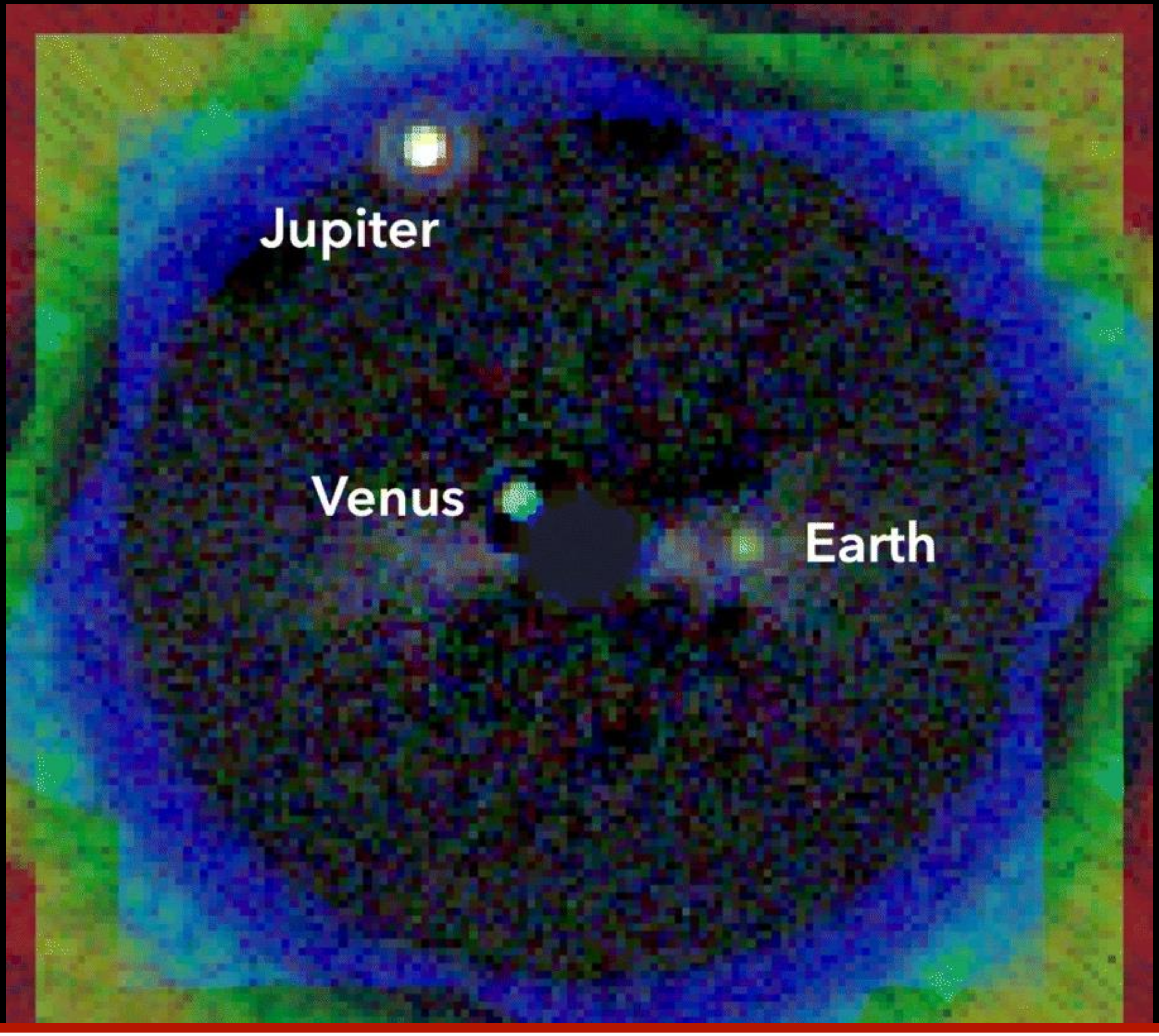
Cross-correlation spectroscopy in space: a possible avenue for the Habitable Worlds Observatory or LIFE?

Hot Jupiter WASP-121 b full phase cross-correlation trail from R~3,000 JWST spectroscopy



Sing et al. 2024; see also Esparza-Borges et al. 2023

Simulation of the inner Solar System viewed at visible wavelengths fro



A high resolution spectrograph in space?

Credit: R. Juanola Parramon, N. Zimmerman, A. Roberge (NASA GSFC)

Take home messages

- **High resolution spectroscopy** (HRS) enables the **robust detection** and **retrieval** of any **multi-lined spectral features**.

- HRS of widely separated companions reveals the **dynamics, architectures and compositions** that can inform **planet formation** scenarios.

- HRS in **reflected light** is close to detection providing route for **biosignature** searches with the ELTs of nearby, widely separated (on-sky) temperate worlds.

- Accuracy, precision, and completeness of **line list database crucial** for success.

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