High-resolution spectroscopy

A brief review and prospects for the future

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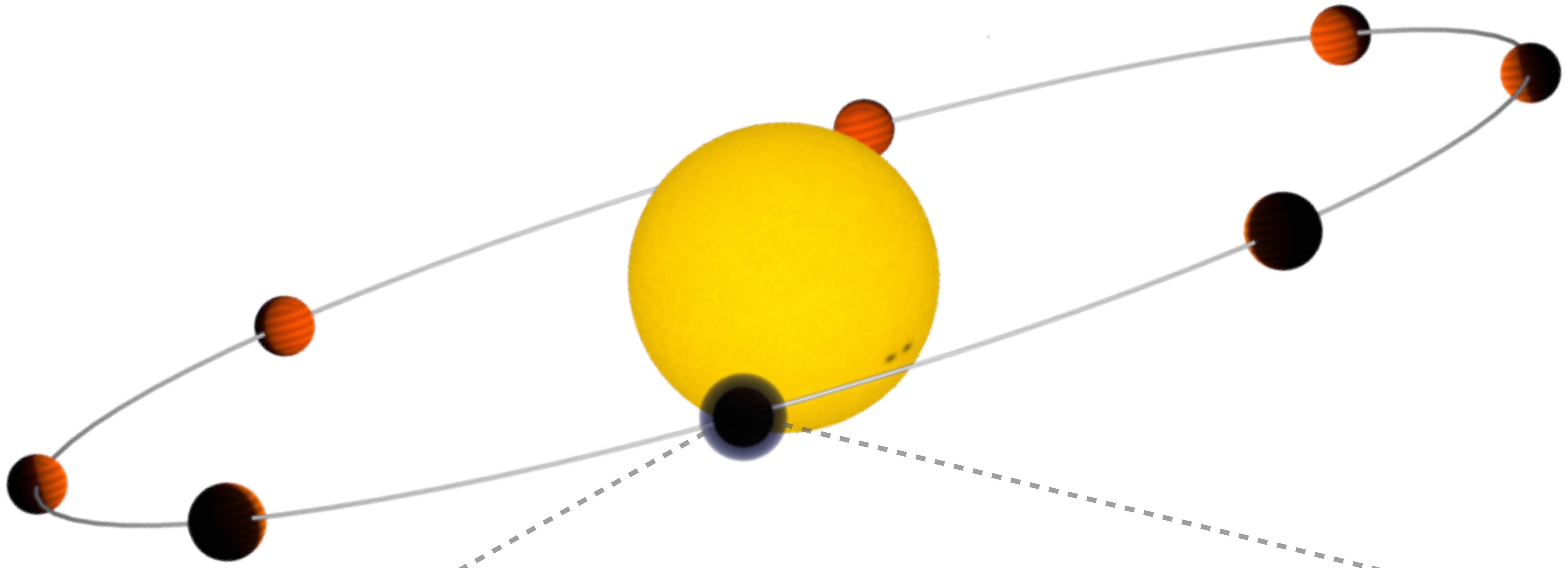
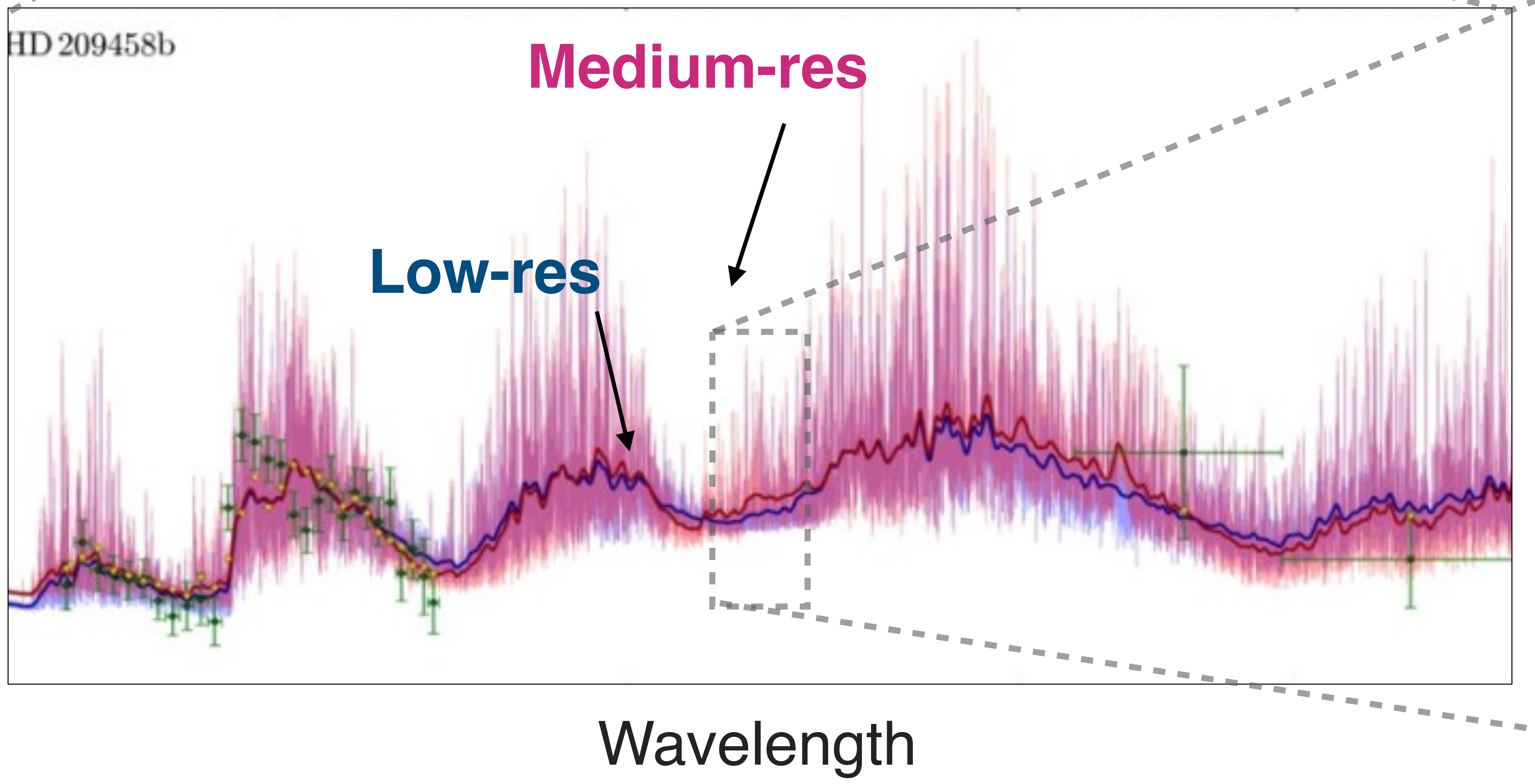
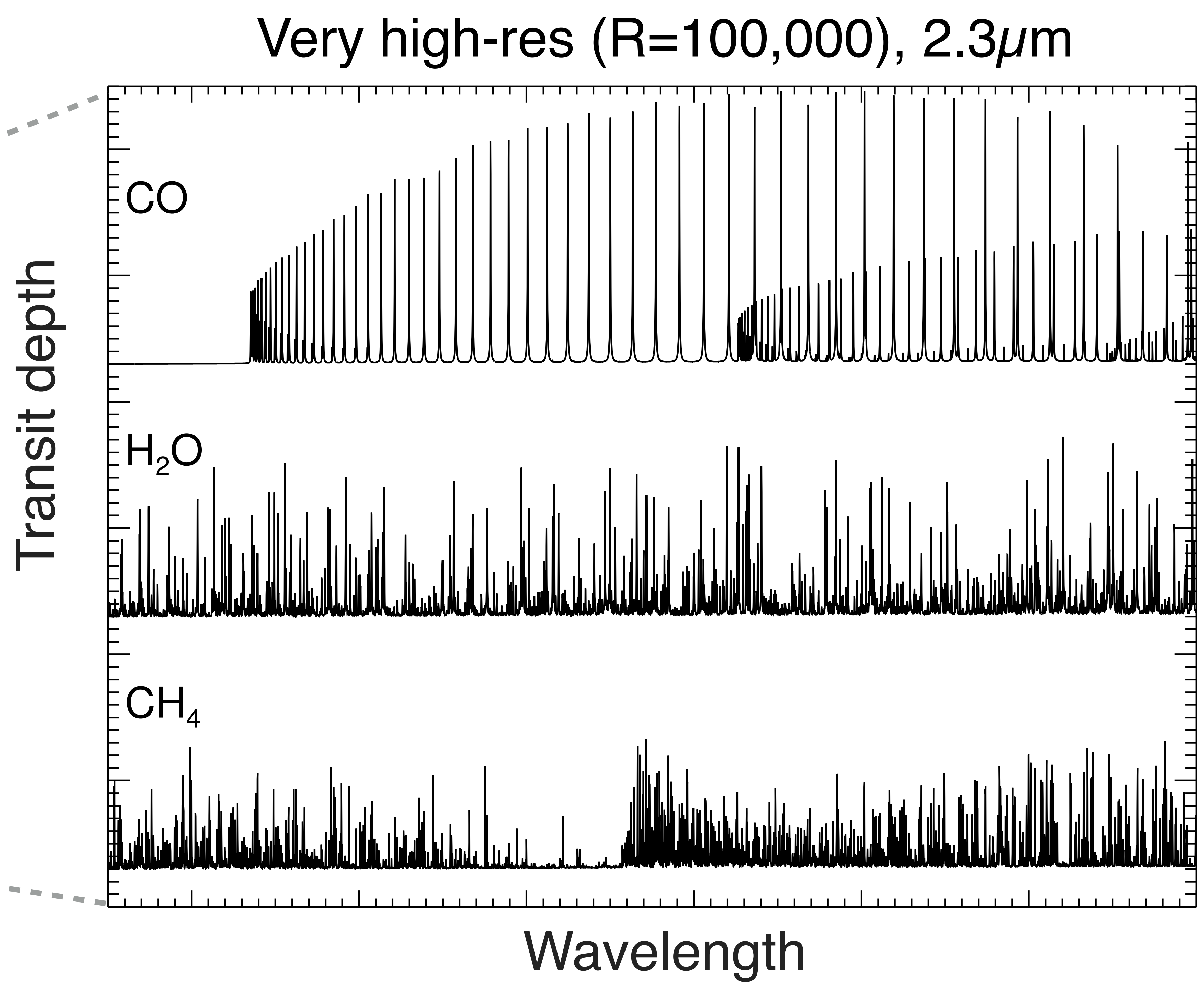
Sagan Summer Workshop - Pasadena, 25 July 2023

Exoplanets at high spectral resolution: matching species line by line



R=30-100k only achievable with **ground telescopes**





Each species has a **unique** pattern of spectral lines

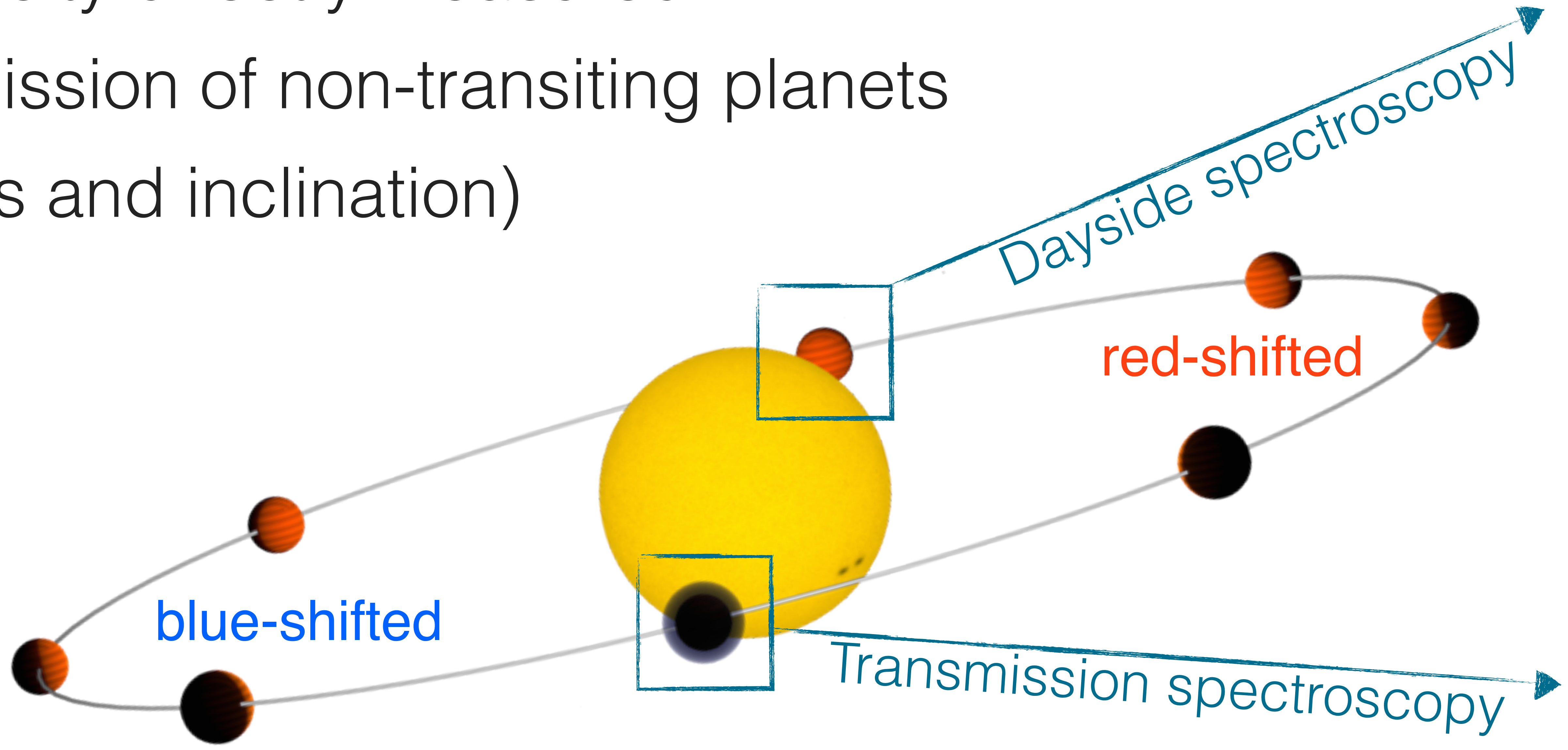
Species are “matched” line by line to templates via ***cross correlation***

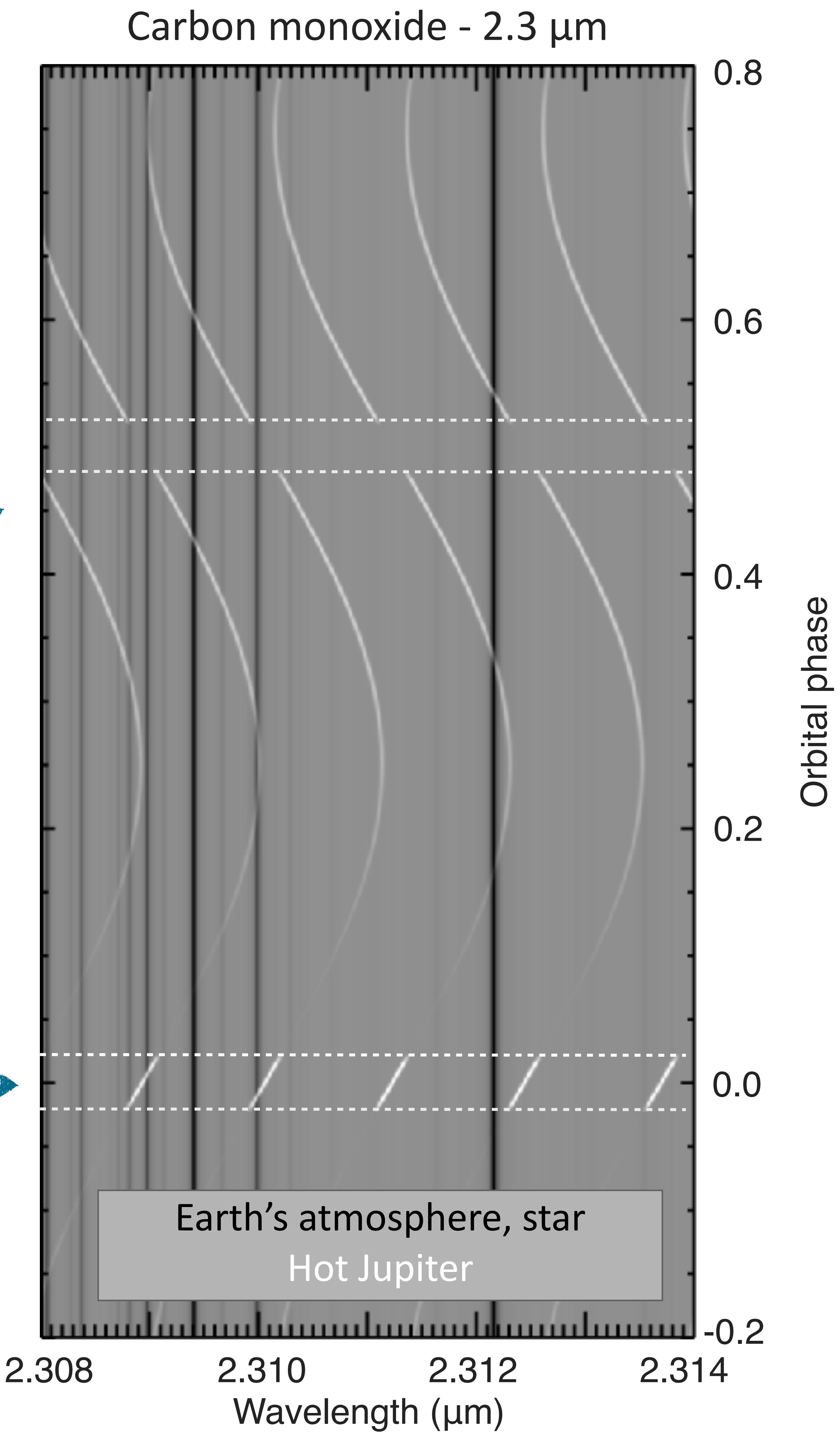
Exploiting the planet's orbital motion to isolate its signature

Change in planet radial velocity well resolved
over a few hours of observations

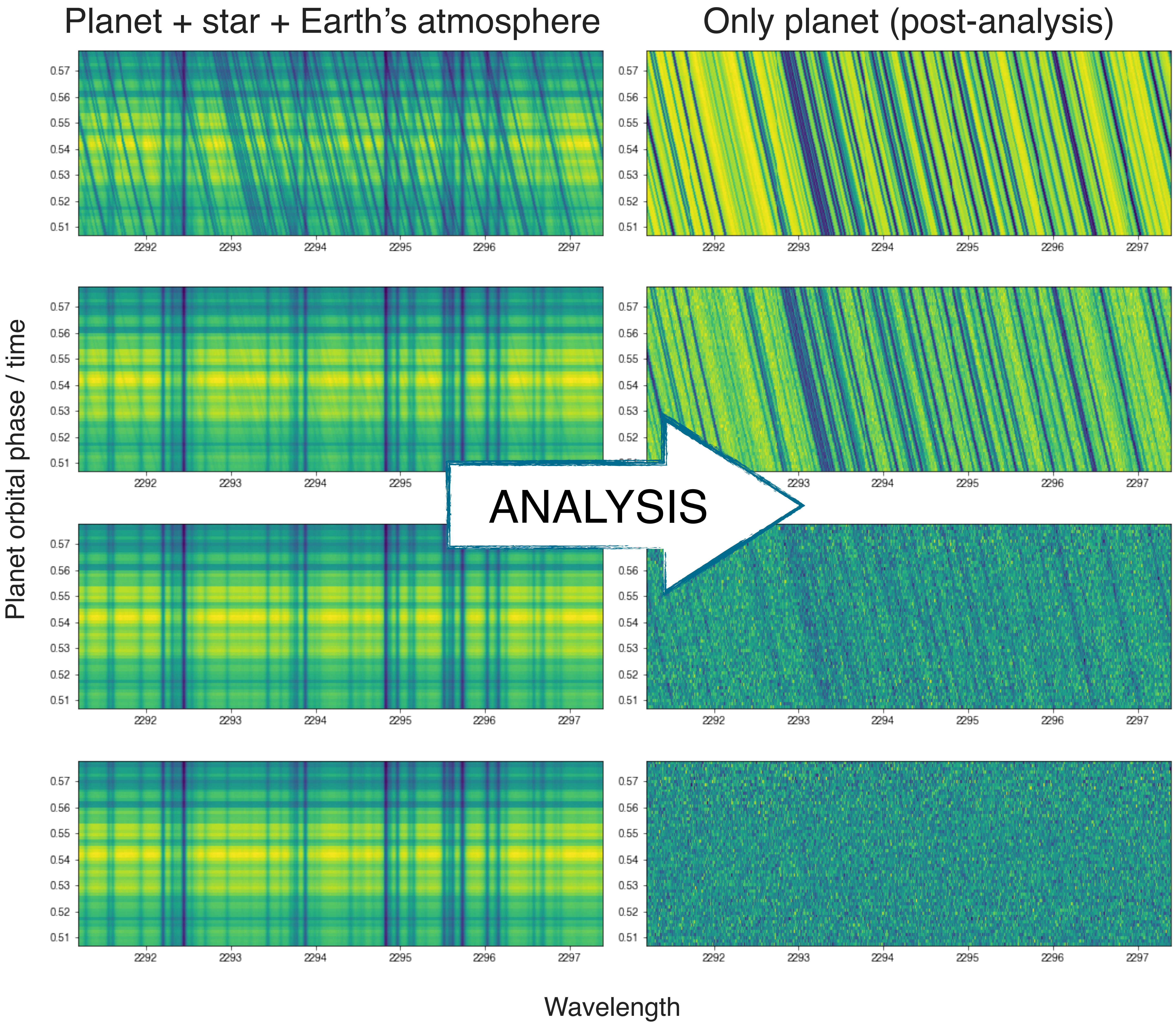
(Planet ΔRV: 10-100 km/s; Stellar ΔRV: 10-100 m/s)

- Planet signal disentangled from **telluric** / **stellar** lines
- Planet radial velocity directly measured
- Can measure emission of non-transiting planets (hence their mass and inclination)





HRS analysis is focussed on the removal of spectral contaminants



Planet/star contrast

1:1

1:10

1:100

1:1000

Step 1
Model stationary components,
i.e. stellar and telluric lines
(rows or columns)

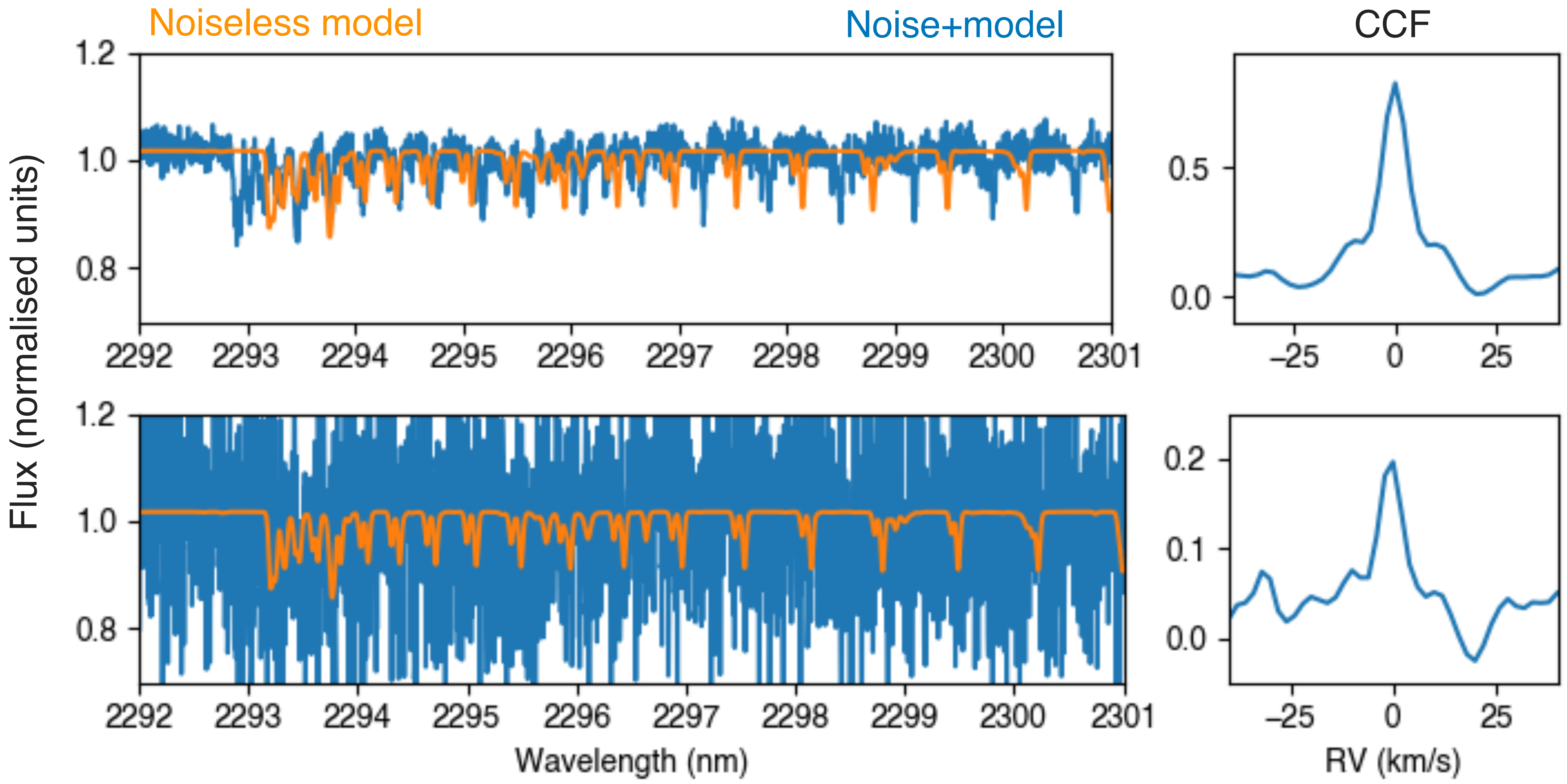
Step 2
Divide through the modelled
telluric and stellar spectra

Step 3
Do something to enhance
the planet signal

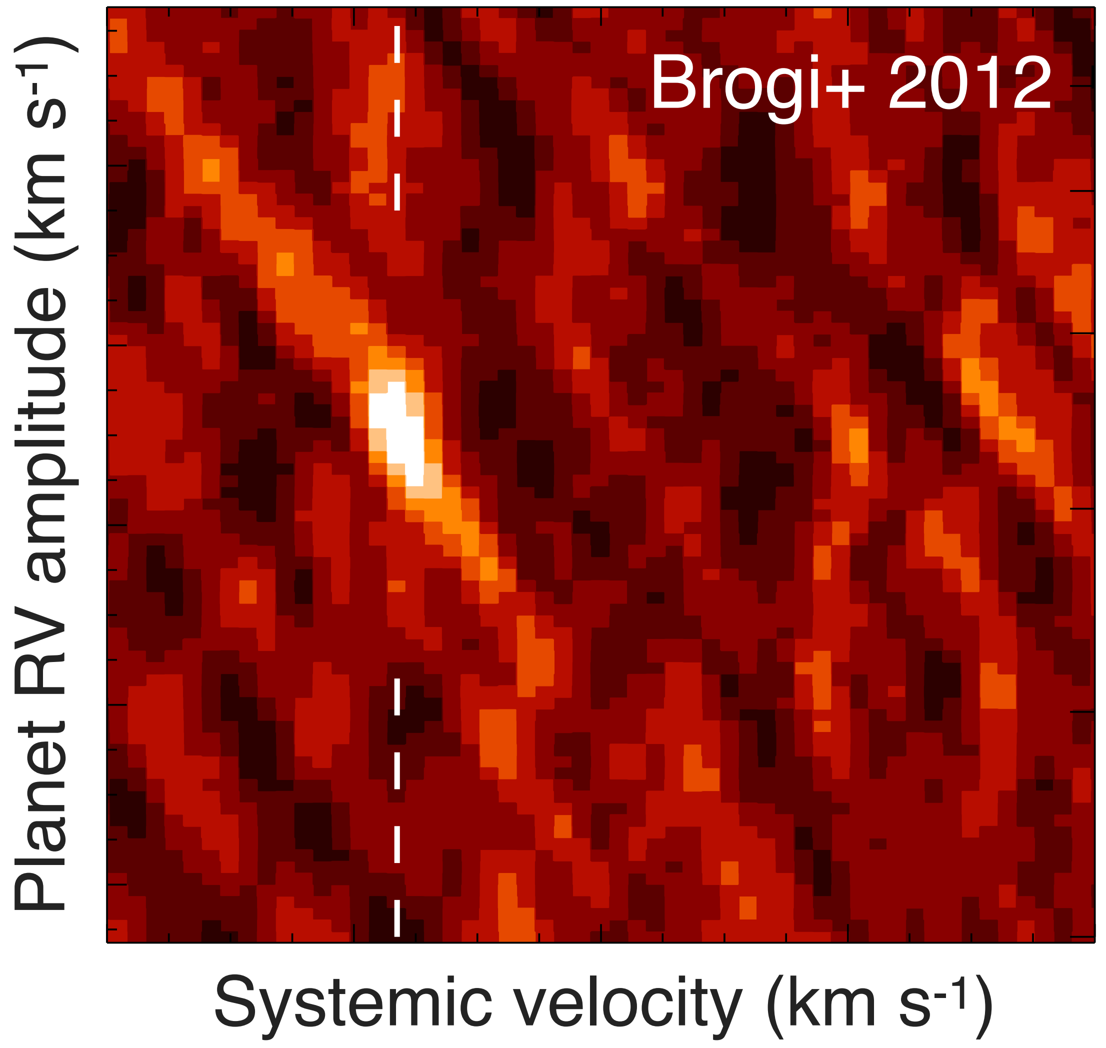
Planet signals are enhanced via cross correlation with model spectra

ELT-like
S/N/line ~5.0

VLT-like
S/N/line ~0.8



With *N* lines available, the S/N increases as ~ sqrt(*N*) via cross correlation



Detections are presented by exploring two velocities:

- The systemic velocity (the whole exo-system w.r.t. solar system)
- The planet RV semi-amplitude K_P (projected orbital velocity)

A detection is claimed when the CCF peak deviates significantly from the noise level

Nearly a decade of inconclusive attempts at ground-based, high-resolution spectroscopy

Molecules

Detected via cross-correlation in the infrared

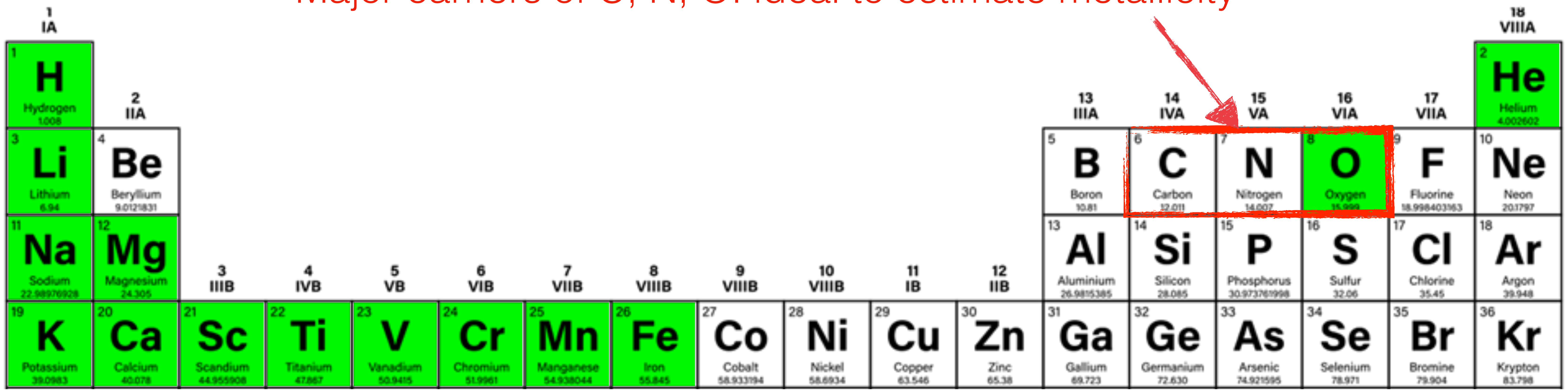
Major carriers of C, N, O: ideal to estimate metallicity

Atoms

Detected via cross-correlation (e.g. Fe) or as single lines (H, He, Na)

Probing exospheres, dissociation, atmospheric escape

(mostly optical)



1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIIIB	9 VIIIB	10 VIIIB	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
🟩 1 H Hydrogen 1.008																	🟩 2 He Helium 4.002602
🟩 3 Li Lithium 6.94	4 Be Beryllium 9.0121831											5 B Boron 10.81	6 C Carbon 12.011	7 N Nitrogen 14.007	🟩 8 O Oxygen 15.999	9 F Fluorine 18.998403163	10 Ne Neon 20.1797
🟩 11 Na Sodium 22.98976928	🟩 12 Mg Magnesium 24.305											13 Al Aluminium 26.9815385	14 Si Silicon 28.085	15 P Phosphorus 30.973761998	16 S Sulfur 32.06	17 Cl Chlorine 35.45	18 Ar Argon 39.948
🟩 19 K Potassium 39.0983	🟩 20 Ca Calcium 40.078	🟩 21 Sc Scandium 44.955908	🟩 22 Ti Titanium 47.867	🟩 23 V Vanadium 50.9415	🟩 24 Cr Chromium 51.9961	🟩 25 Mn Manganese 54.938044	🟩 26 Fe Iron 55.845	27 Co Cobalt 58.933194	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.630	33 As Arsenic 74.921595	34 Se Selenium 78.971	35 Br Bromine 79.904	36 Kr Krypton 83.798

Collier-Cameron et al. 1999; Charbonneau et al. 2000, 2002; Deming et al. 2005; Knutson et al. 2007; Redfield et al. 2008; Snellen et al. 2008, 2010; Brogi et al. 2012, 2014; Birkby et al. 2013; Wakeford et al. 2013; Lockwood et al. 2014; Kreidberg et al. 2014; Stevenson et al. 2014; Wyttenbach et al. 2015; Louden & Wheatlley 2015; Brogi et al. 2016; Nugroho et al. 2017; Allart et al. 2018; Nortmann et al. 2018; Hawker et al. 2018; Brogi & Line 2019; Guilluy et al. 2019; Giacobbe et al. 2021; Line et al. 2021

*High-resolution spectroscopy mostly focussed on **detecting***
*Space observations (mostly HST/WFC3) moved onto **comparing** exoplanets*

For ultra-hot Jupiters, HRS detected dozen of atomic species

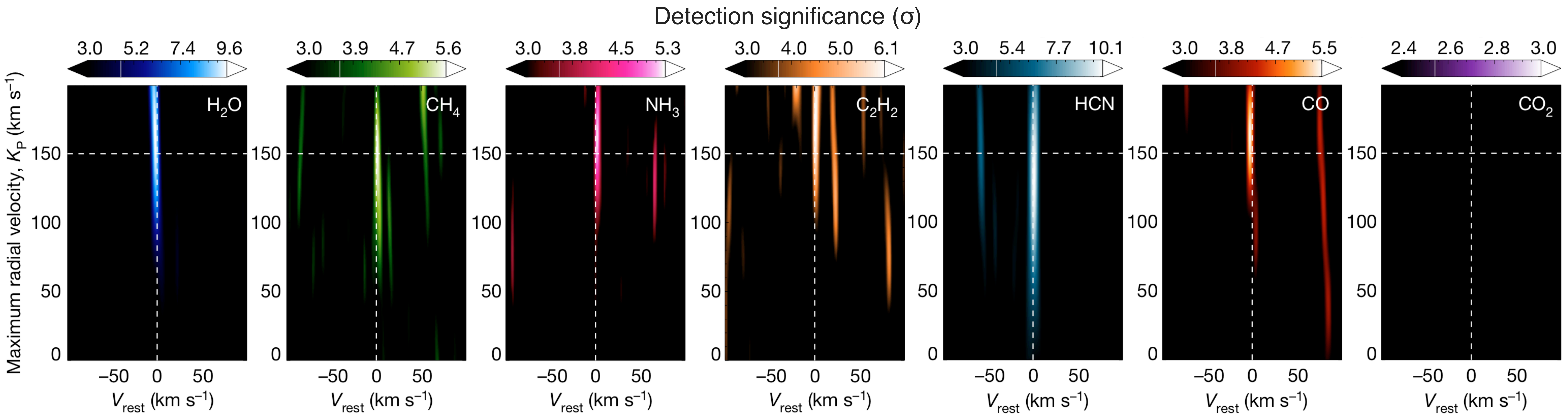
8 simultaneous detections in KELT-9b (Hoeijmakers et al. 2019, see update in Borsato et al. 2023)

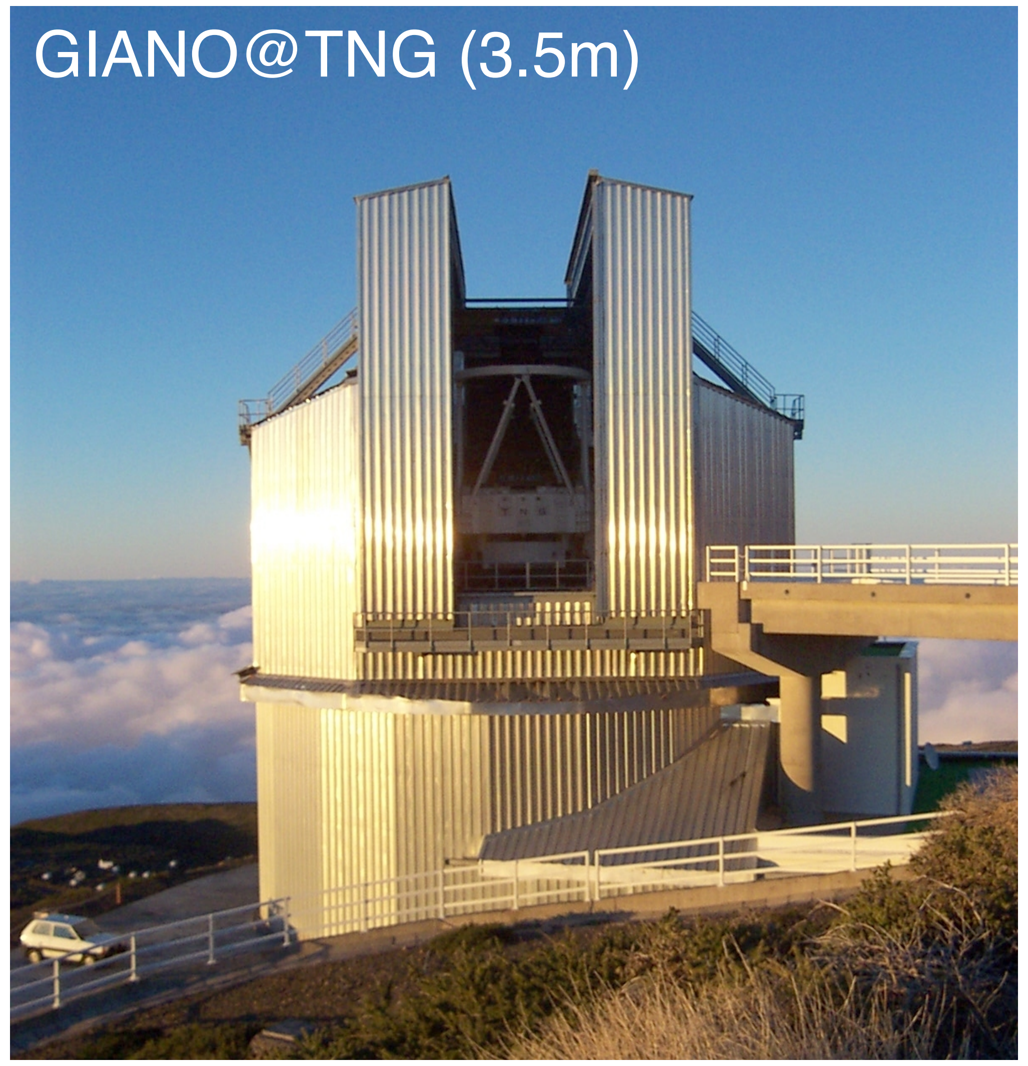
*Done via **optical** high-resolution spectroscopy (HARPS, ESPRESSO, MAROON-X)*

Atomic species (neutral and ionized) broadly expected in ultra-hot Jupiters (2500-4500K)
Ti, V are notably hard to detect (same for the molecular counterparts TiO, VO)

For an archetype exoplanets, HRCCS detected 6 species simultaneously

4 transits of hot Jupiter HD 209458b, 0.95-2.45 μm simultaneously at R=50,000 (Giacobbe et al. 2021)





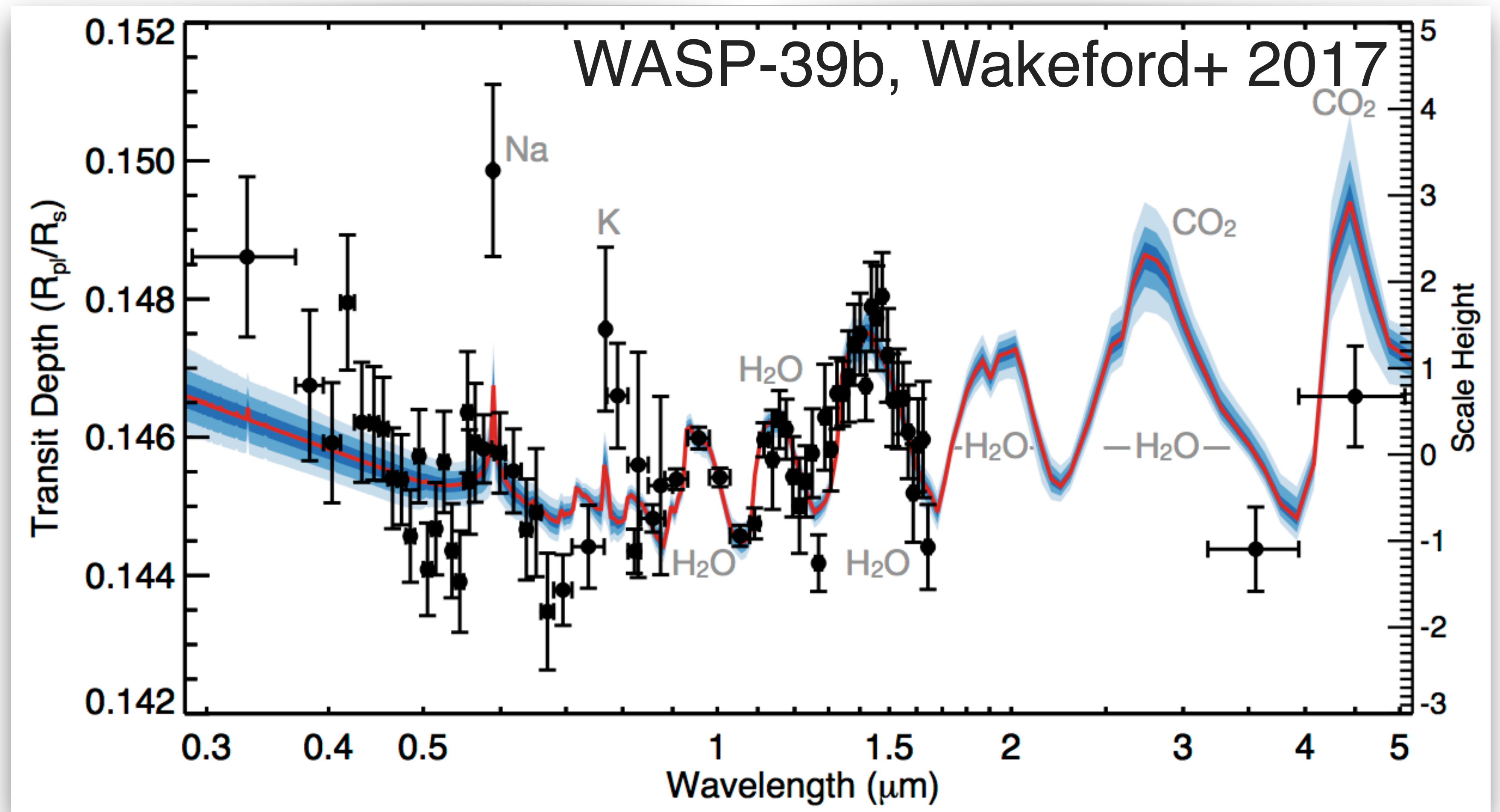
What does a detection mean for the atmosphere?

Templates optimised to "maximise" the level of correlation
(= obtain the strongest detection in velocity space)

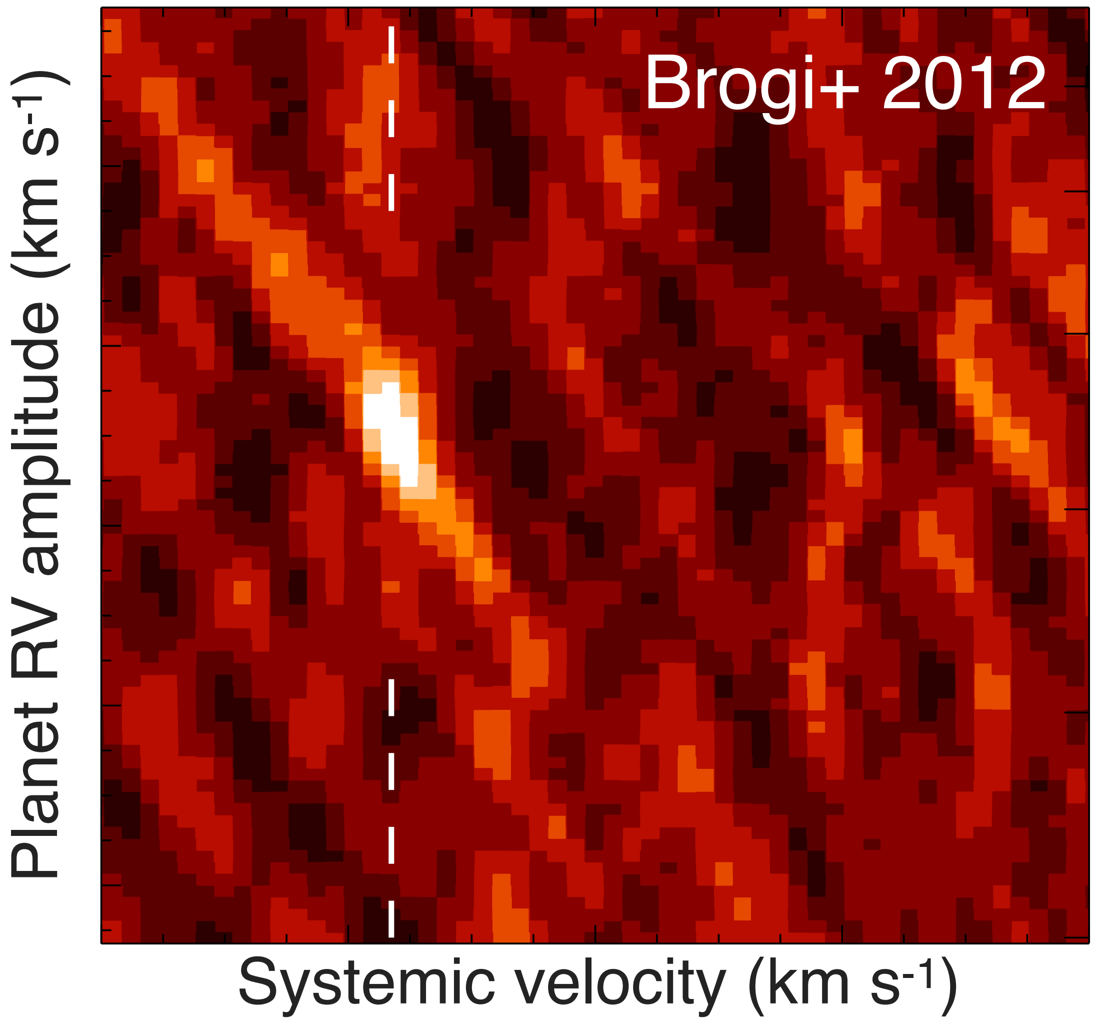
Need to move *beyond detecting* and towards *measuring*
also to compare ground and space (JWST) results

From detecting species to measuring abundances and temperatures

Low-res spectroscopy



High-res spectroscopy



Low-res spectroscopy recovers an actual spectrum

Data can be directly compared to model spectra (both forward modelling and retrievals possible)

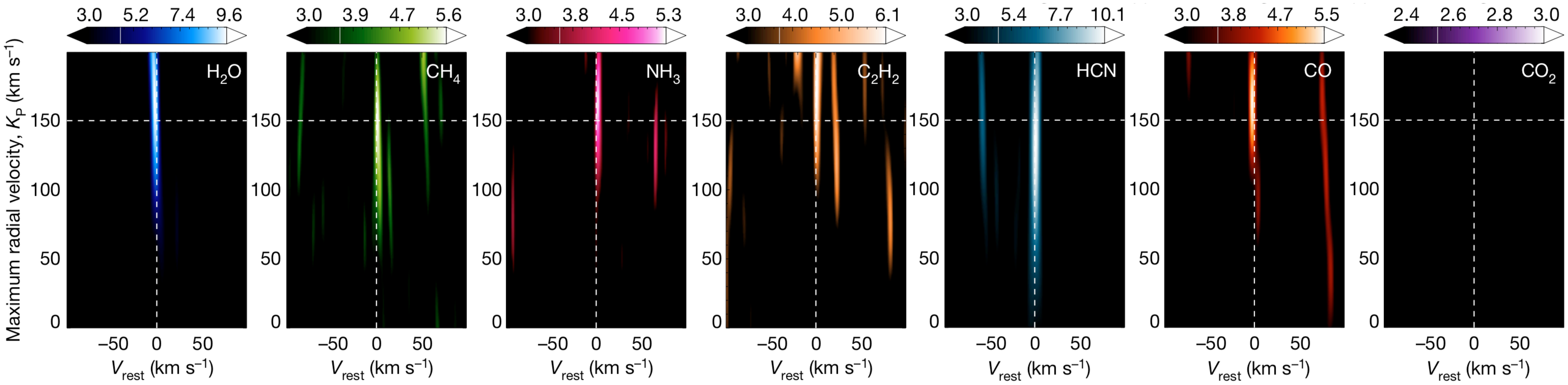
High-resolution spectroscopy measures a level of correlation

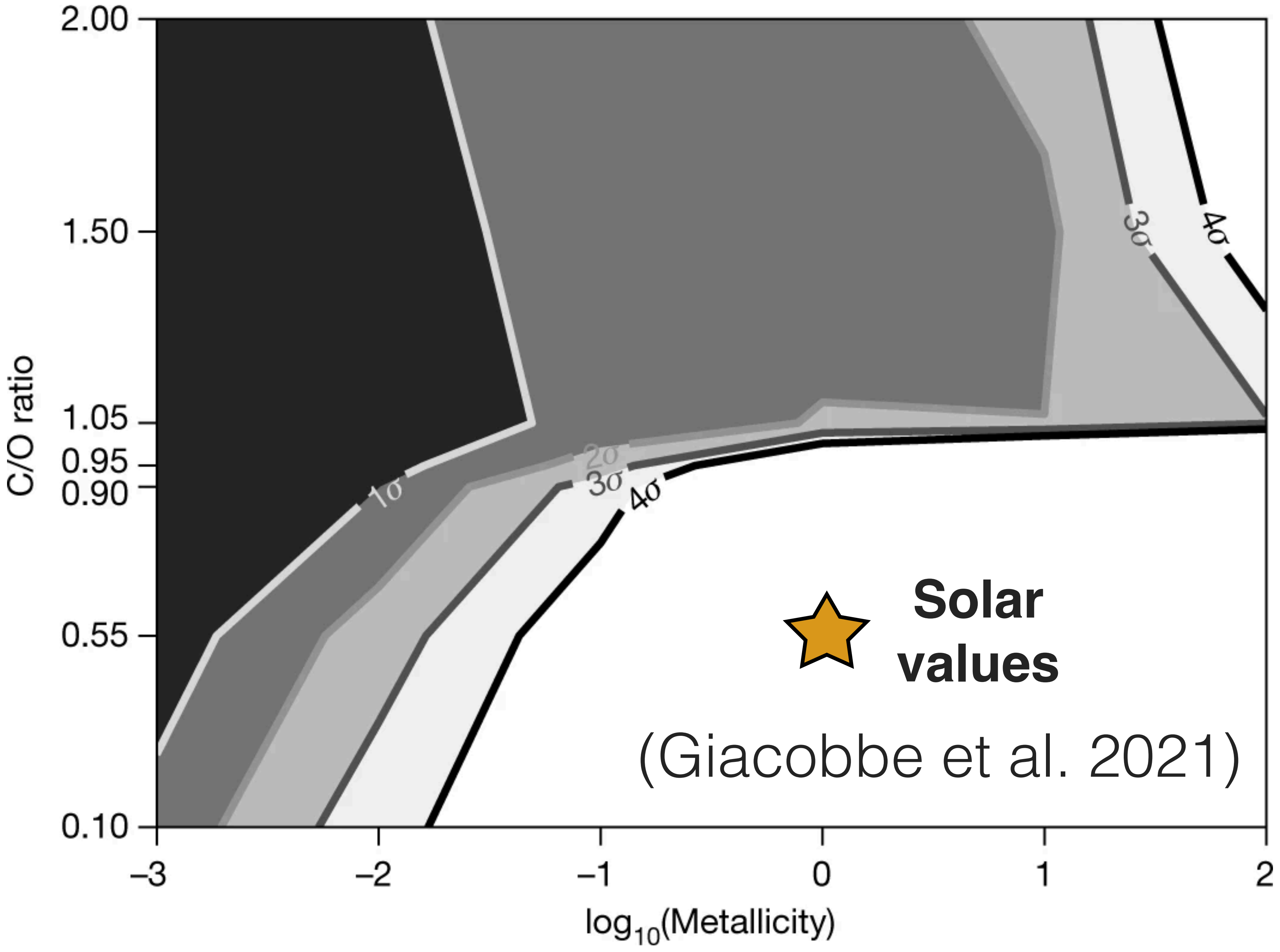
Requires accurate knowledge of molecular spectra + implementation of the correct physics

Significance “easier” to quantify, "goodness of fit" is not

Modern HRS has moved into measuring abundances and temperatures via purpose-built likelihood functions (e.g. Brogi & Line 2019; Gibson et al. 2020)

Translating detections into constraints on atmospheric composition





(Giacobbe et al. 2021)

Exploring a **grid of models in thermochemical equilibrium:**
constraints on C/O and metallicity,
no further inference about individual species

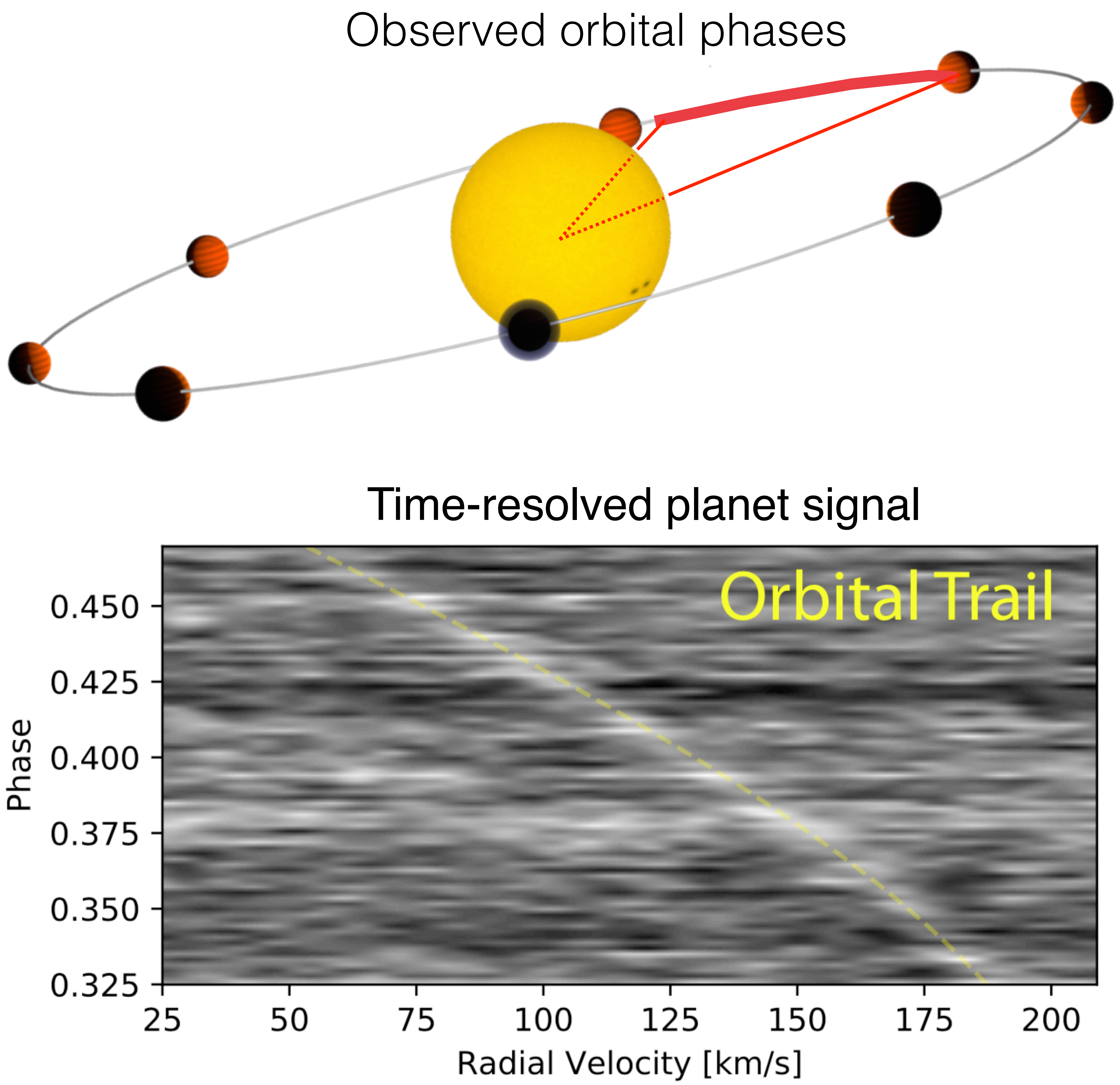
Interpretation can change by accounting for the *muting* effect of clouds and/or *disequilibrium* (photochemistry, quenching, etc.)

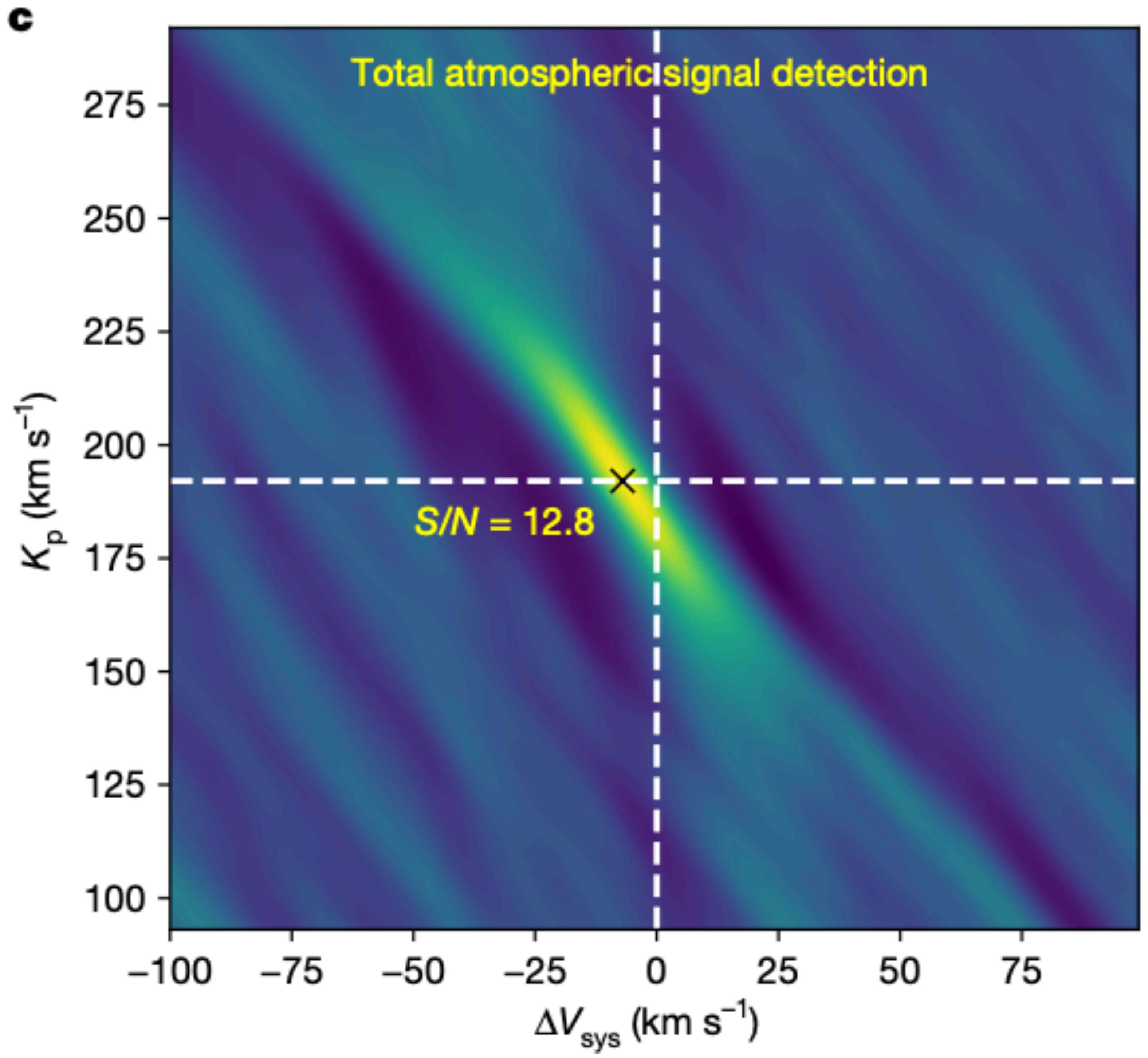
Simultaneous exploration of all parameters needed to understand their effect / inter-dependency
⇒ Bayesian retrievals (see M. Line's talk)

Running a Bayesian retrieval on high-resolution emission spectroscopy

Line et al. (2021): 4.7 hrs of IGRINS at Gemini-S (R=45,000, 1.55-2.45 μm)

Dayside spectrum of WASP-77 A b (1,500K, solar-type host)





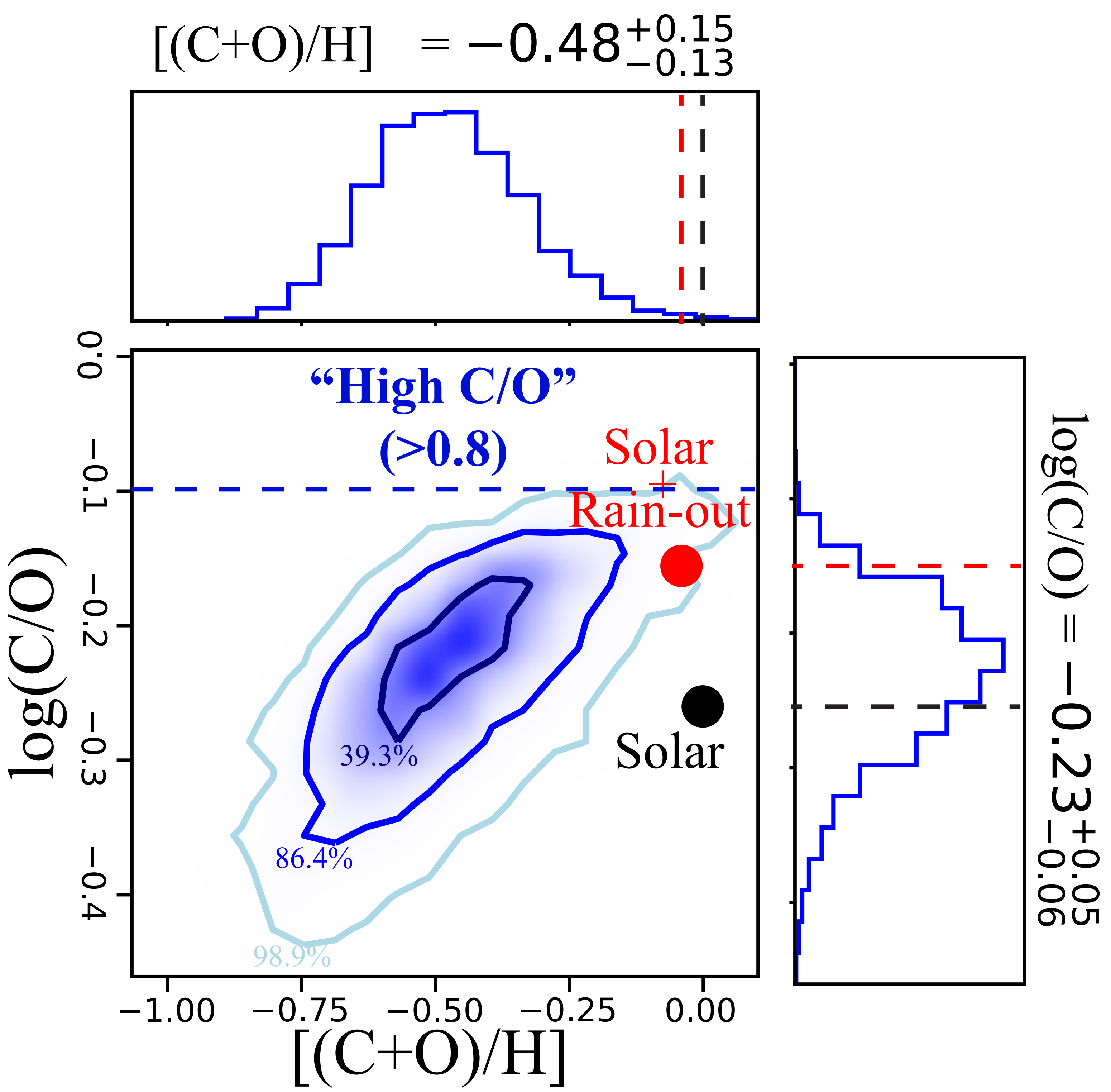
"Simple" chemistry with only CO & H_2O detected (plus ^{13}CO)

16-parameters model: 7 species, 6 T-p parameters, 2 velocities, 1 global scaling

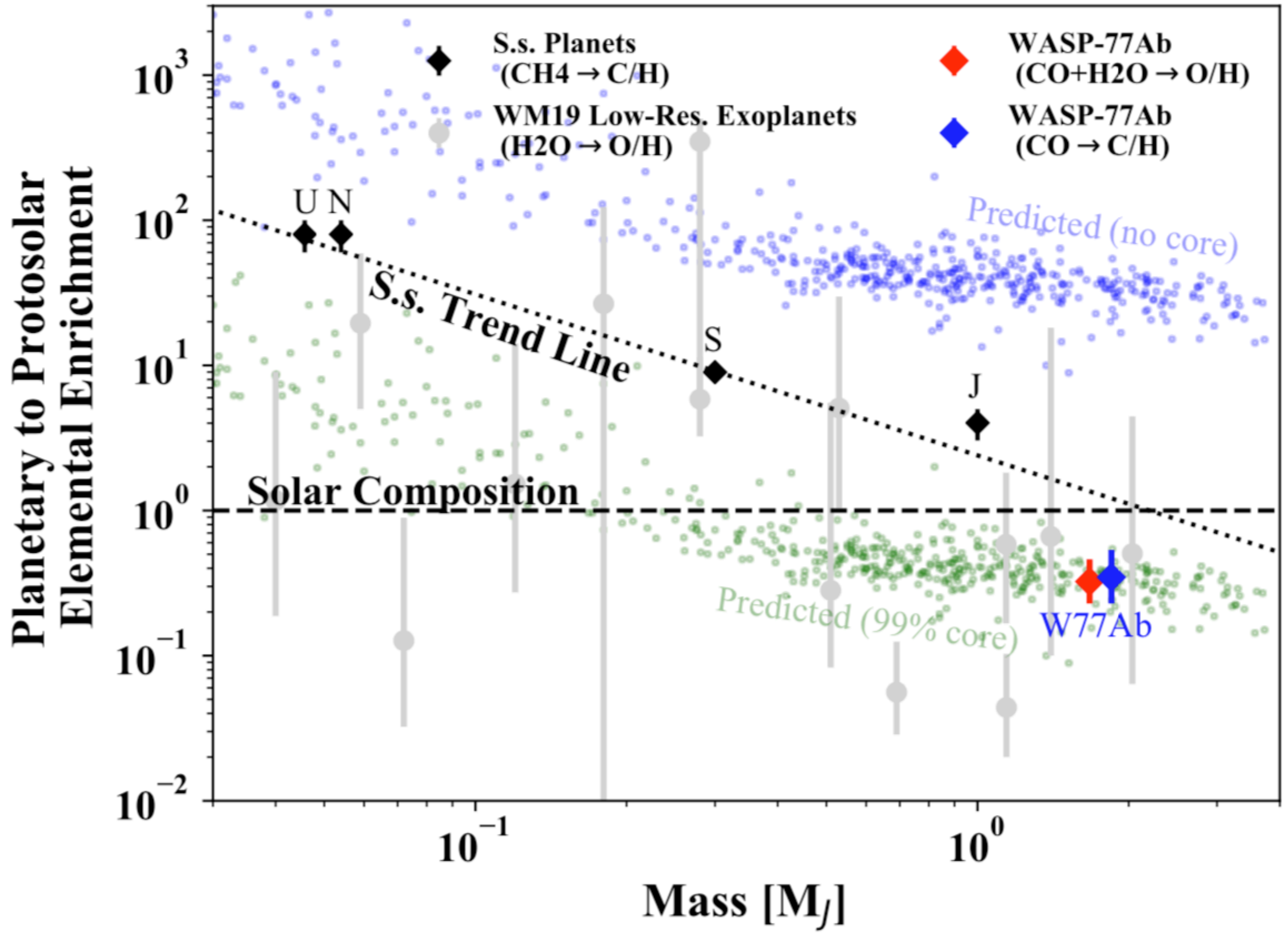
Deriving the chemistry with 0.1 dex precision in abundance

This is the precision expected from JWST ERS data on hot Jupiters

CO+H2O ⇒ Metallicity, C/O



Mass-metallicity relation



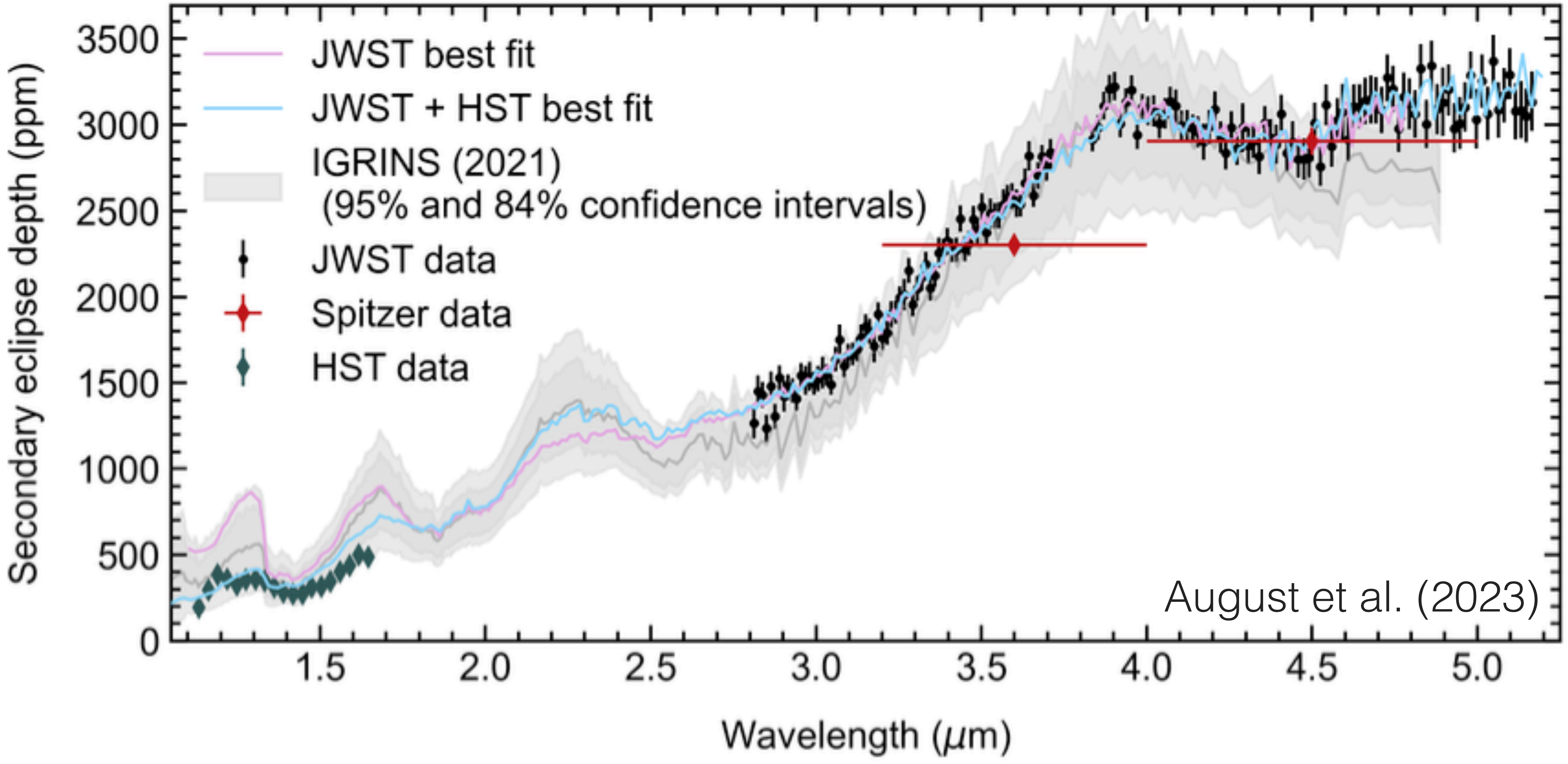
WASP-77 A b is below the mass-metallicity trend for the solar system

Reggiani+21 refined metallicity of parent star: higher planet C/O, lower [X/H]

(no envelope-core mixing, formation outside the snowline, no planetesimal bombardment)

High-resolution emission spectroscopy has good predictive power for JWST

JWST NIRSpec of WASP-77 Ab



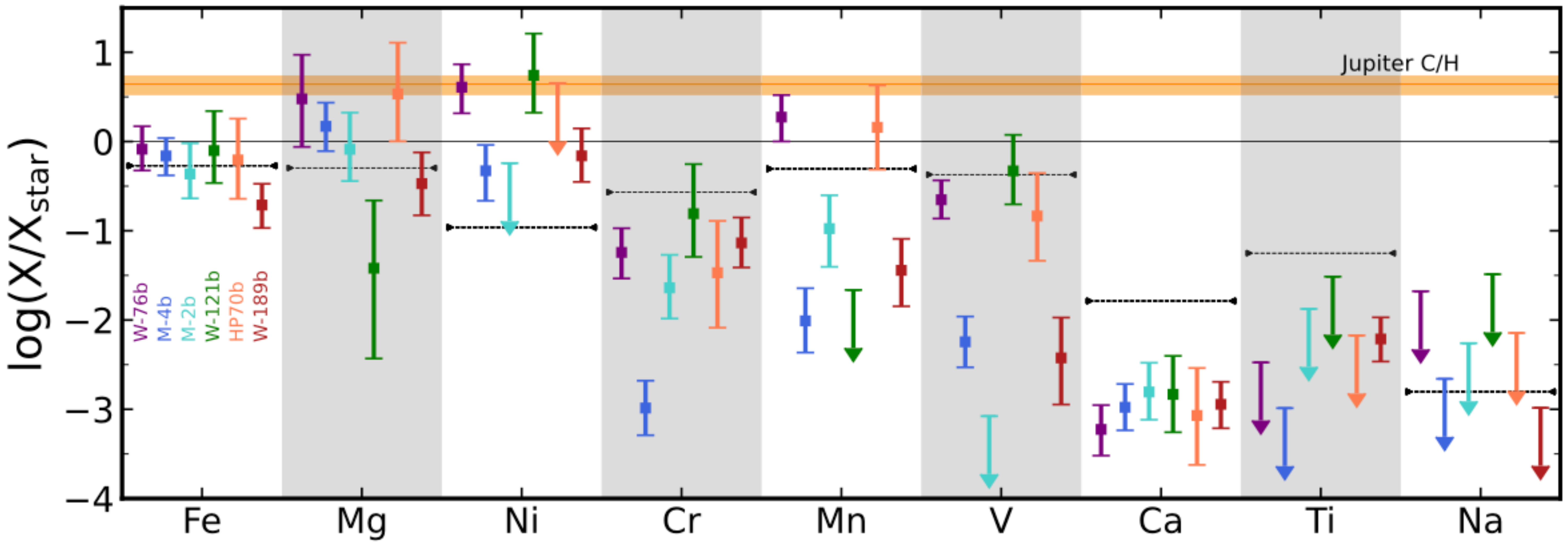
August et al. (2023)

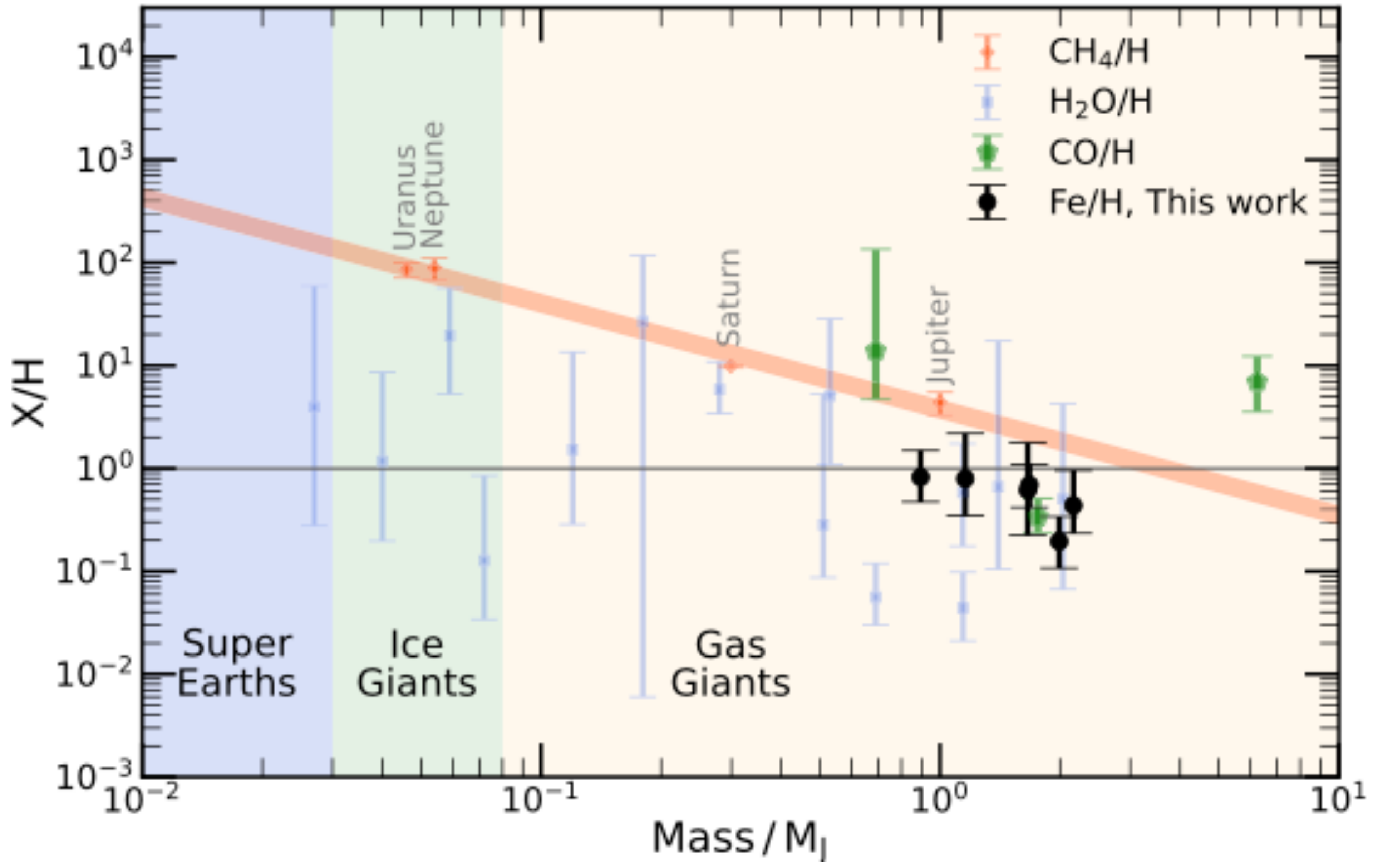
2020s: good potential to jointly analyze space and ground spectroscopy

Only possible for K ≤ 10 mag (50 "easy" targets) on 4-8m class telescopes
S/N ≥ 50 per spectral channel needed to model and normalize telluric and stellar lines

Atomic abundances of six ultra-hot Jupiters from optical HRS

Gandhi et al. (2023), but also see Gibson et al. (2022), Kasper et al. (2023)





Different atoms ⇒ different metallicity

Ca and Fe: uniform abundance within the sample

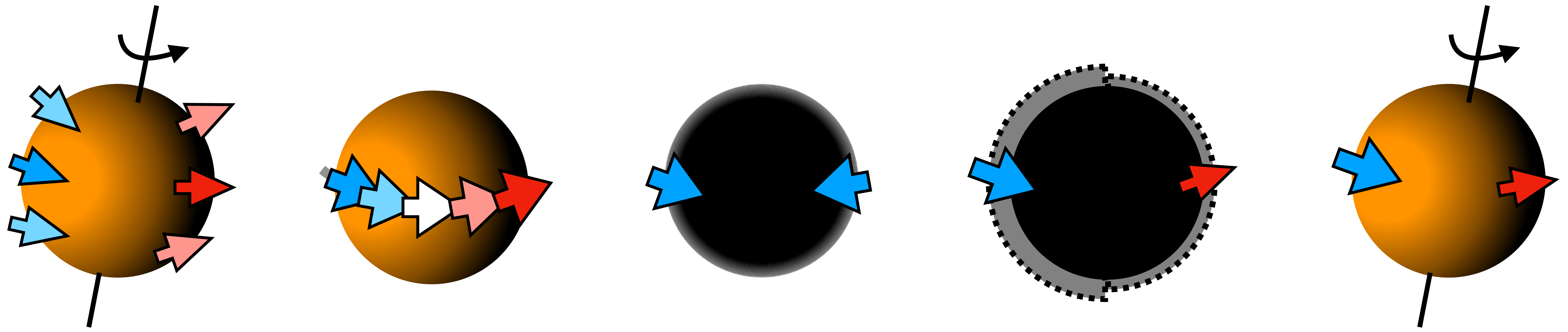
Fe: good probe of metallicity,
close to predicted equilibrium abundance
(horizontal lines)

The mass-metallicity diagram starts to populate with precise data points slightly below the solar-system trend

Synergy work with JWST in populating the diagram

Planets are 3-dimensional objects: direct probe of atmospheric dynamics

Changes in line **position** or **shape** due to **rotation, circulation,** and **chemical/thermal gradients**



Planet's bulk
rotation
(synchronous?)

Deep (0.1 bar)
equatorial jets
(super-rotation)

High-altitude
day-to-night
winds

Hotter (approaching)
vs cooler (receding)
half-terminator

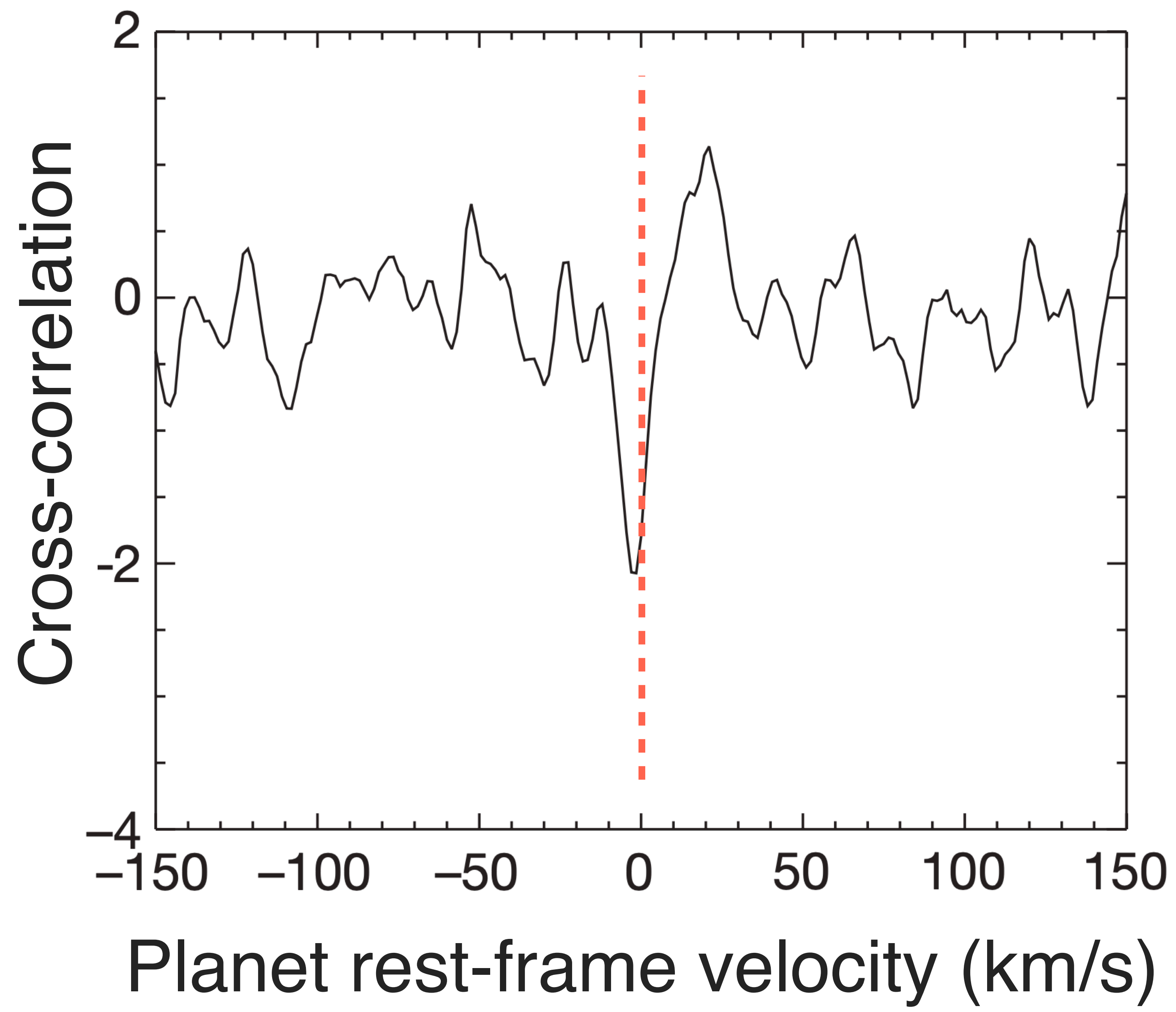
Hotter (approaching)
dayside vs cooler
(receding) night-side

Theory and Global Circulation Models (GCMs) supports the sensitivity of HRS to km/s effects

(Showman+13; Rauscher & Kempton 14; Zhang+17; Flowers+19; Beltz+21; Harada+21; Wardenier+21...)

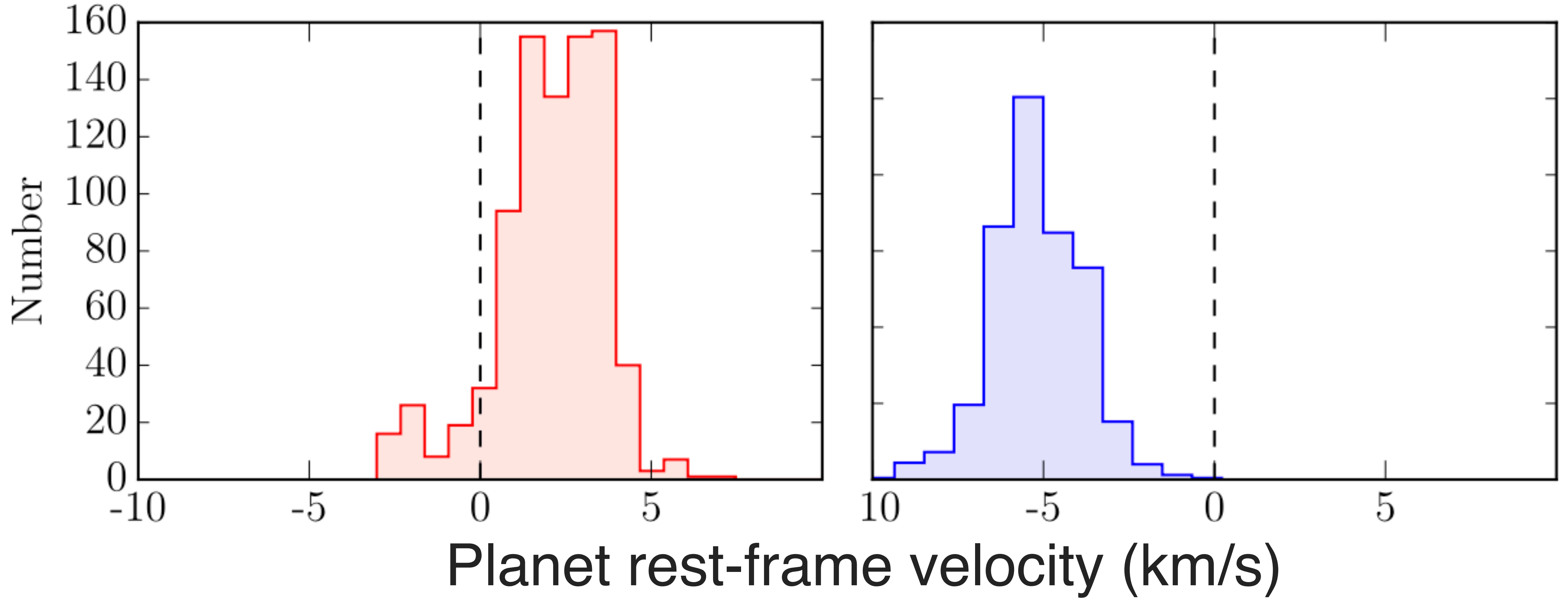
Observational evidence is mostly from transmission spectroscopy
by focussing on Na, Fe (optical), and CO+H2O (infrared)

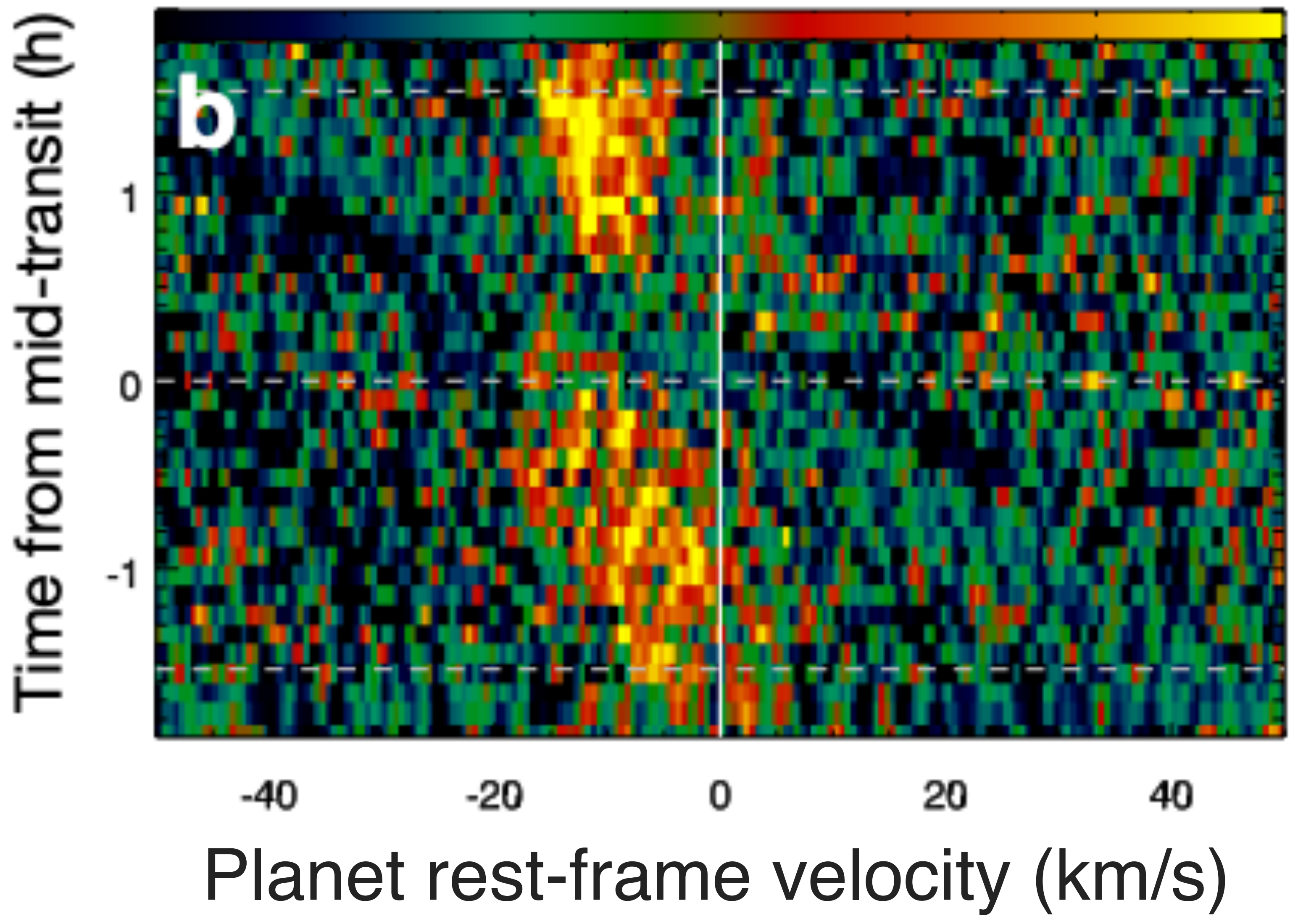
Measured winds and rotation from transmission high-resolution spectroscopy



Snellen+2010:
CO in HD 209458 b
blue-shifted
by 2±1 km/s

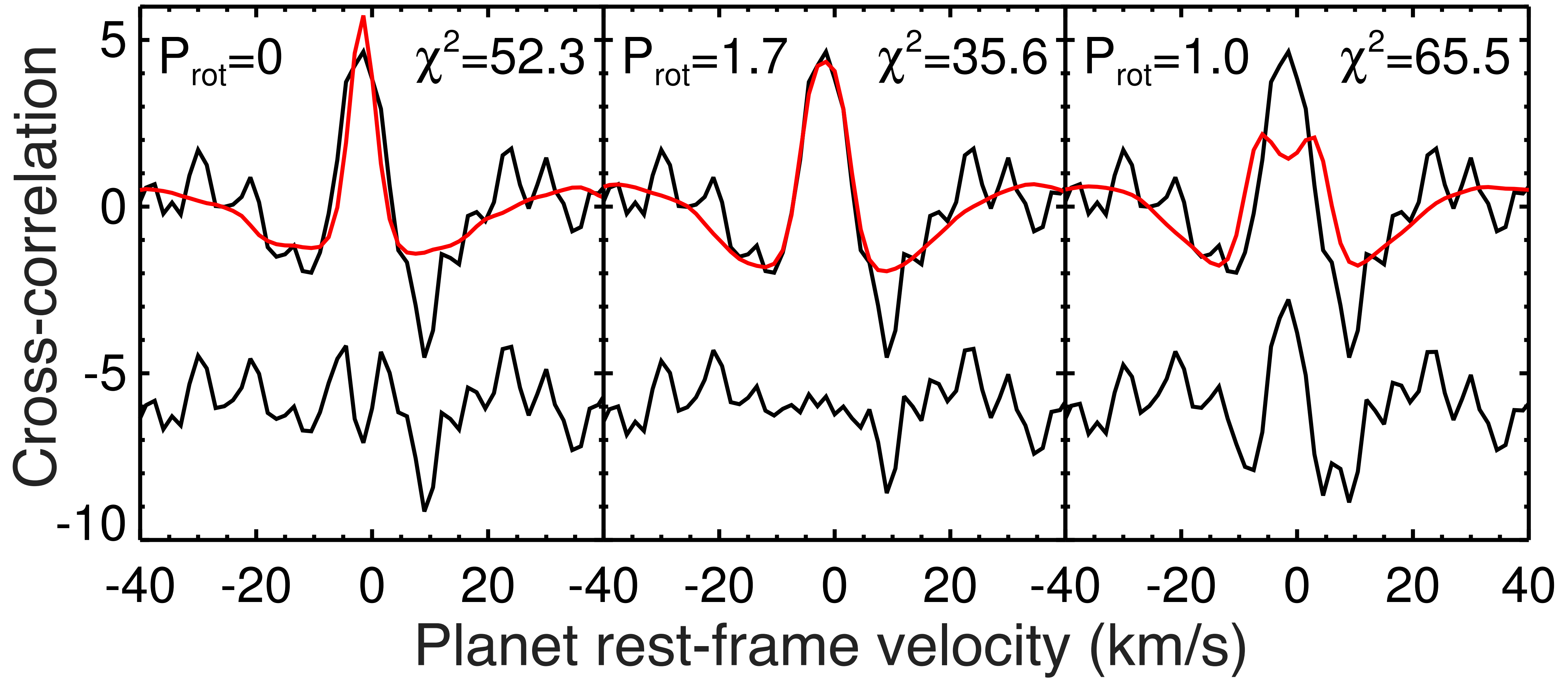
Louden & Wheatley 15: asymmetric RV
of Na from trailing / leading terminator, HD 189733 b





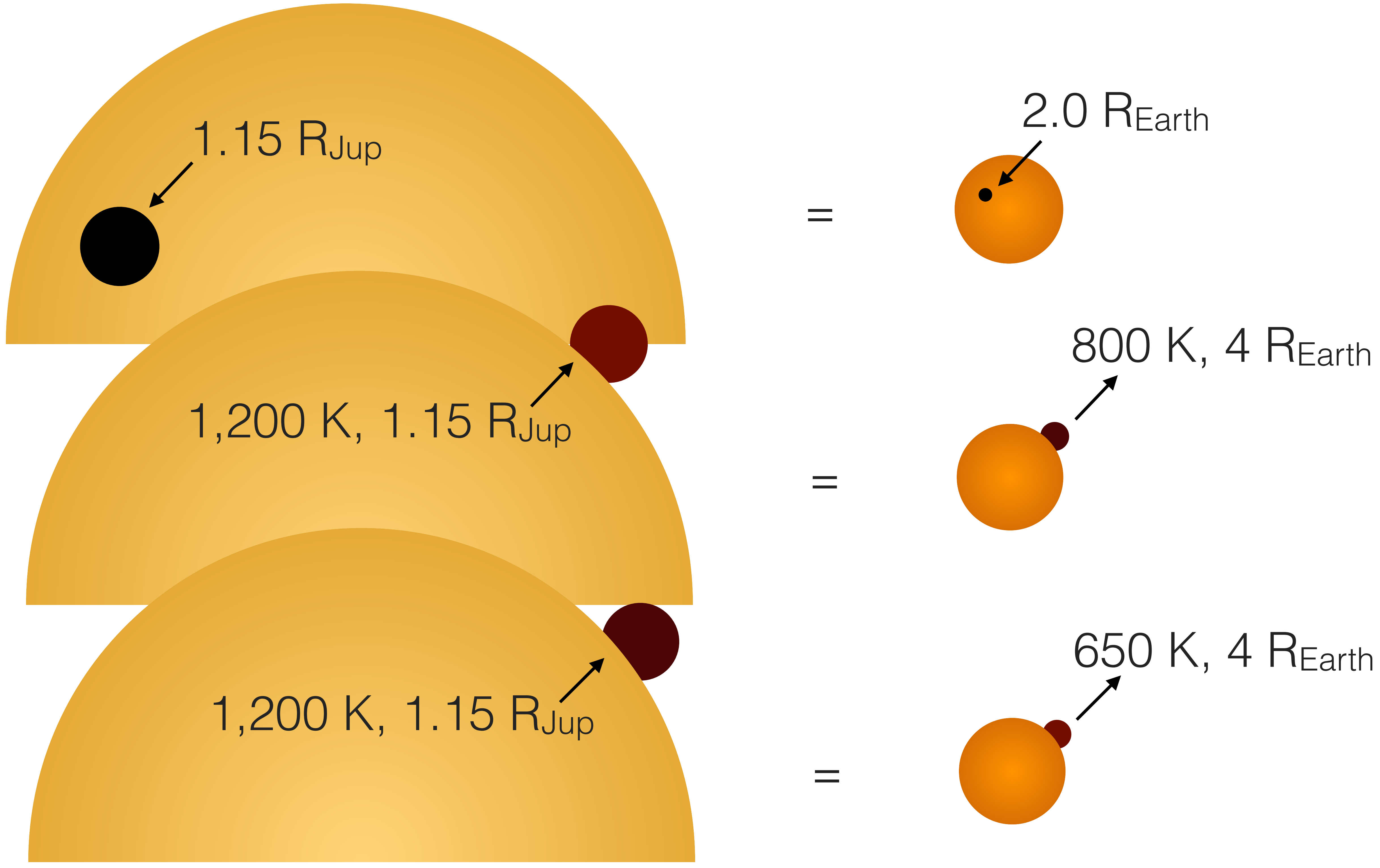
Ehrenreich+20
Asymmetric
RV
Fe signal
in KELT-9 b

Brogi+16: CO+H2O in HD 189733 b
broadened consistently with synchronous rotation



Studying exoplanets around M-dwarf planets in the near future

M-dwarfs: smaller and cooler than the Sun, bright in the infrared, form 75% of solar neighbourhood



Transit
1.3% depth

Thermal emission
relative to star
(2.3 μm, K band)
140 ppm

Thermal emission
relative to star
(3.5 μm, L band)
470 ppm

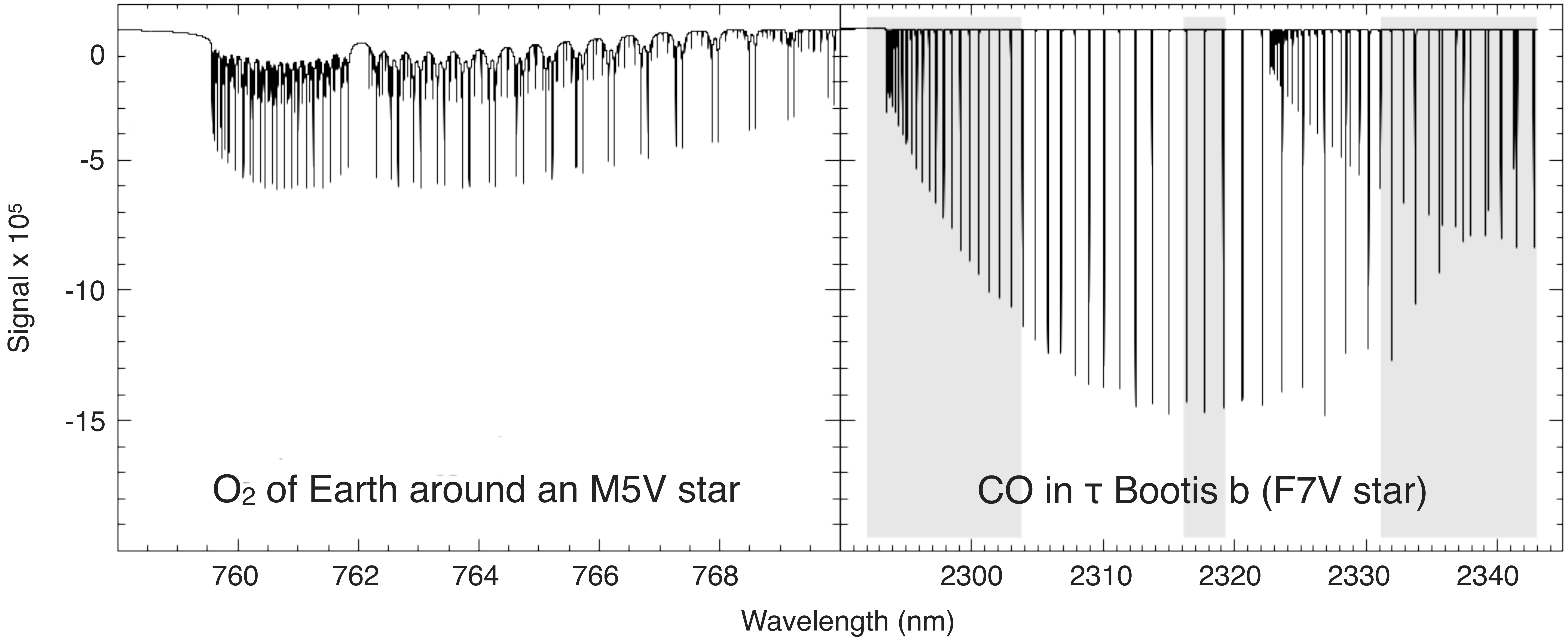
Solar-type star **M5.5 star (Proxima)**

Warm sub-giants around (nearby) M-dwarfs are within reach of current techniques

*M-dwarf systems **already found** and **matching predictions** (e.g. Dressing & Charbonneau 2015), including closest transiting (Trappist-1 a-g, 12 pc) and non-transiting (Proxima b-c, 1.3 pc)*

Oxygen in an Earth-like atmosphere: M-dwarf planets

High resolution (R=100,000) optical transmission spectrum:
average line depth ~1/3 of the *detected* CO dayside signal of Brogi+12



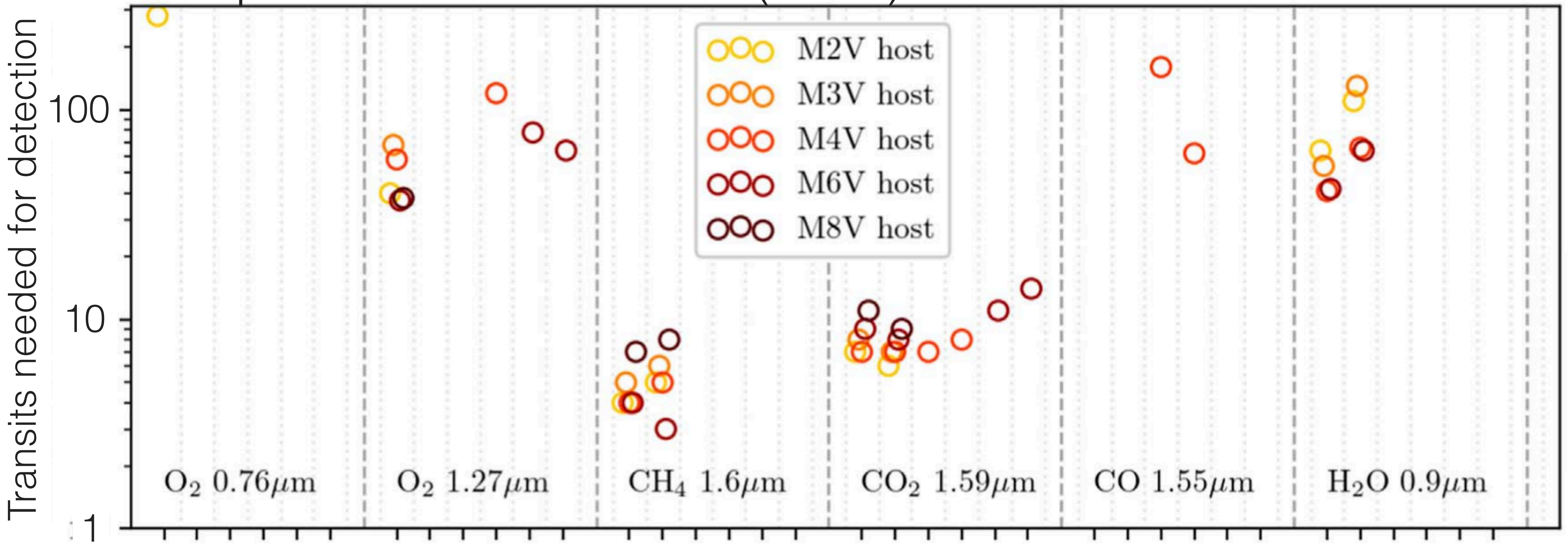
Challenge: closest M-dwarfs at least 6 mag fainter than τ Boo
39m ELT, 30 transits (3 years) for a detection

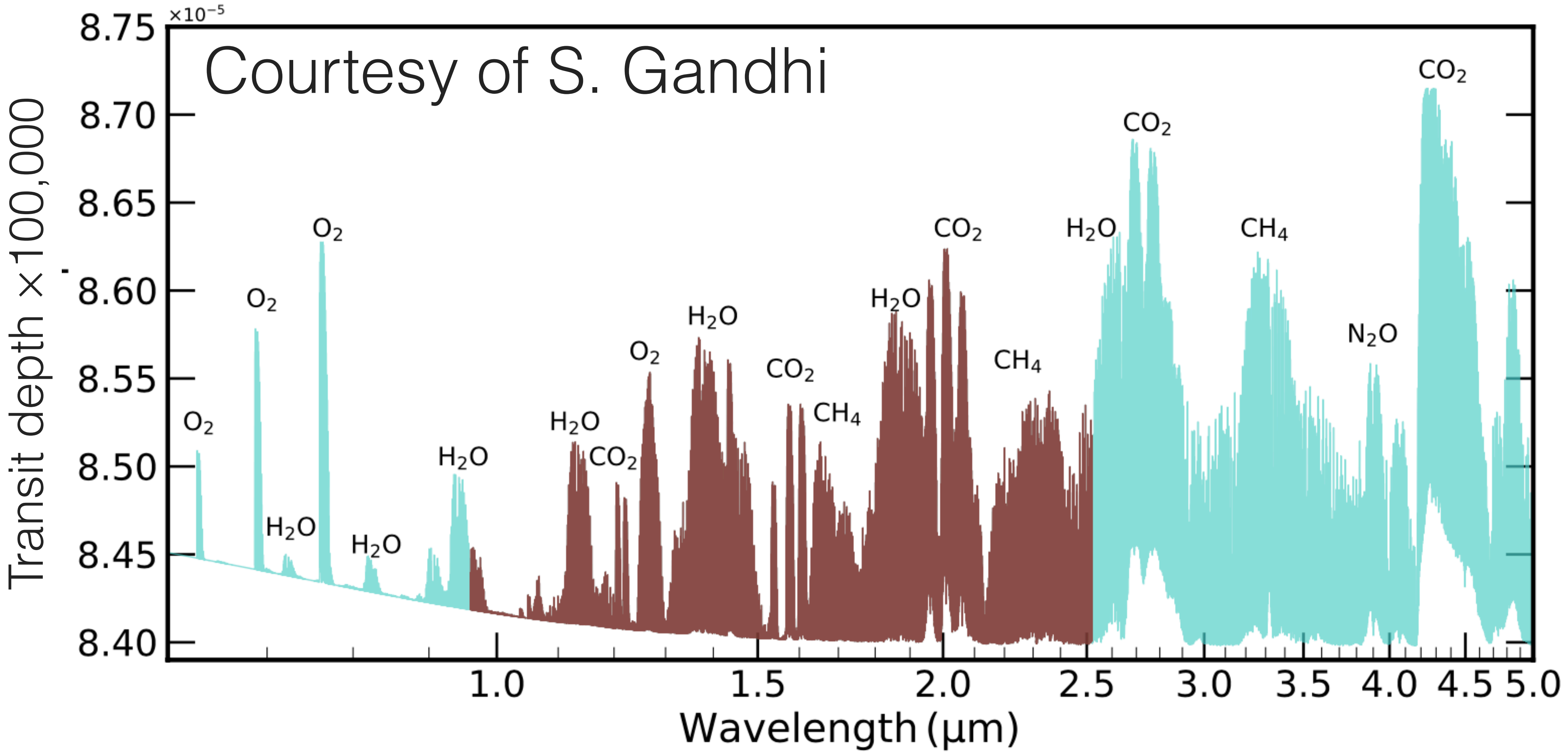
Assumes RV separation telluric-planet and ideal removal of telluric lines
(Snellen+13, Rodler & Lopez-Morales14; Serindag & Snellen 19; Lopez-Morales+19)

Looking at other "biomarkers" individually and collectively

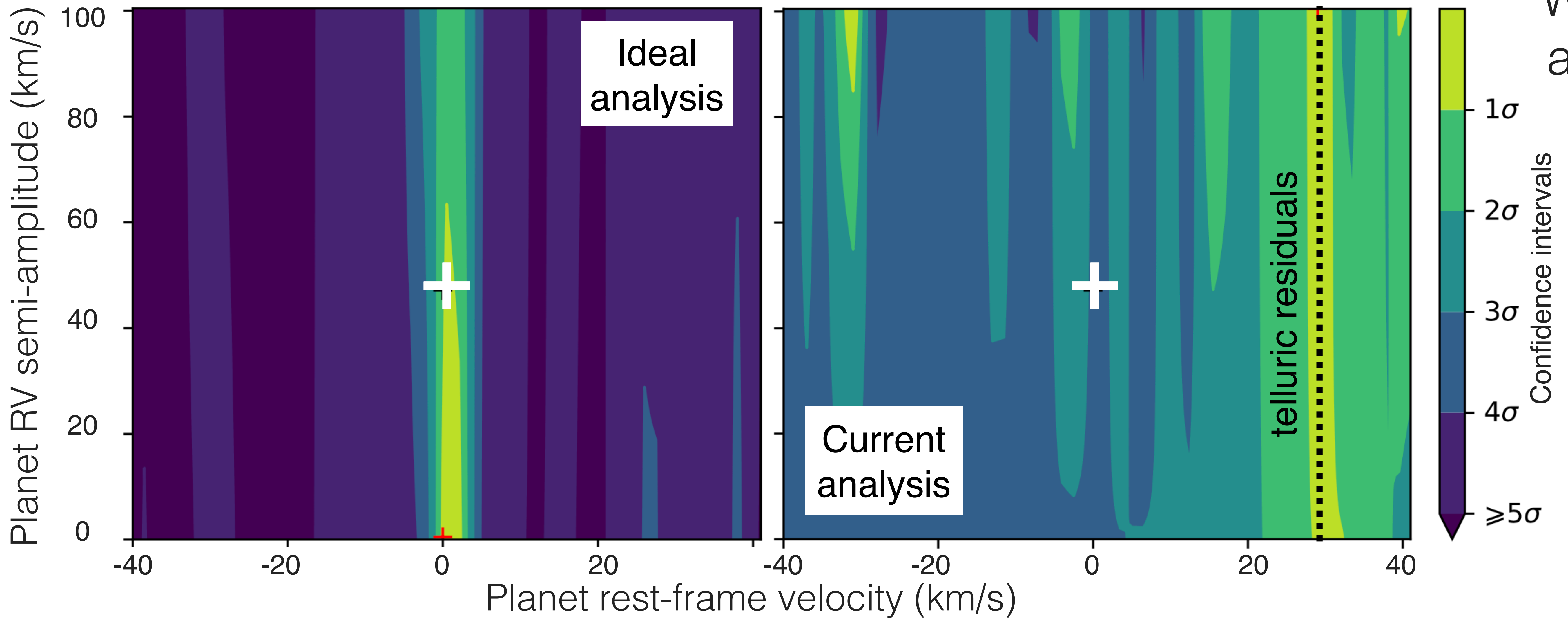
1-5 μm Earth-like spectrum: weaker features than O2, but 1,000s of lines to cross-correlate

Adapted from Currie et al. (2023)




Courtesy of S. Gandhi

15 transits, M5.5 host at 10 pc, ELT with SPIRou-like instrument



Work in prep. by V. Emeka-Okafor and former PhD student R. Webb

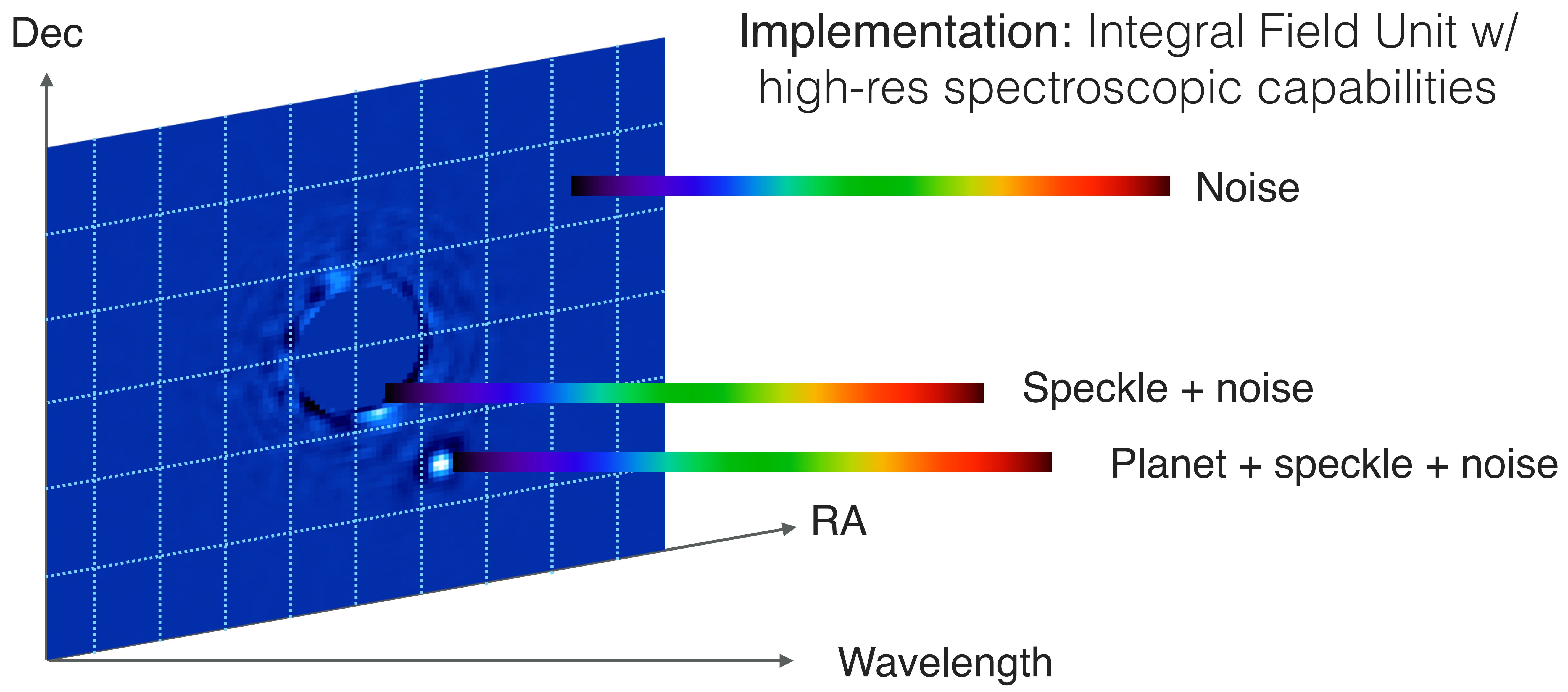
The ELT can detect Earth-like exoplanets around an M star, but likely not with current analysis techniques

Beyond high spectral resolution alone: combination with direct imaging

Combining gain in suppressing the photon noise of the star and enhancing the planet's signal

(Snellen+15; Lovis+16; Mawet+17; Wang+17; Haffert+20; Otten+21; Delorme+21, Houllé+21; Landman+23)

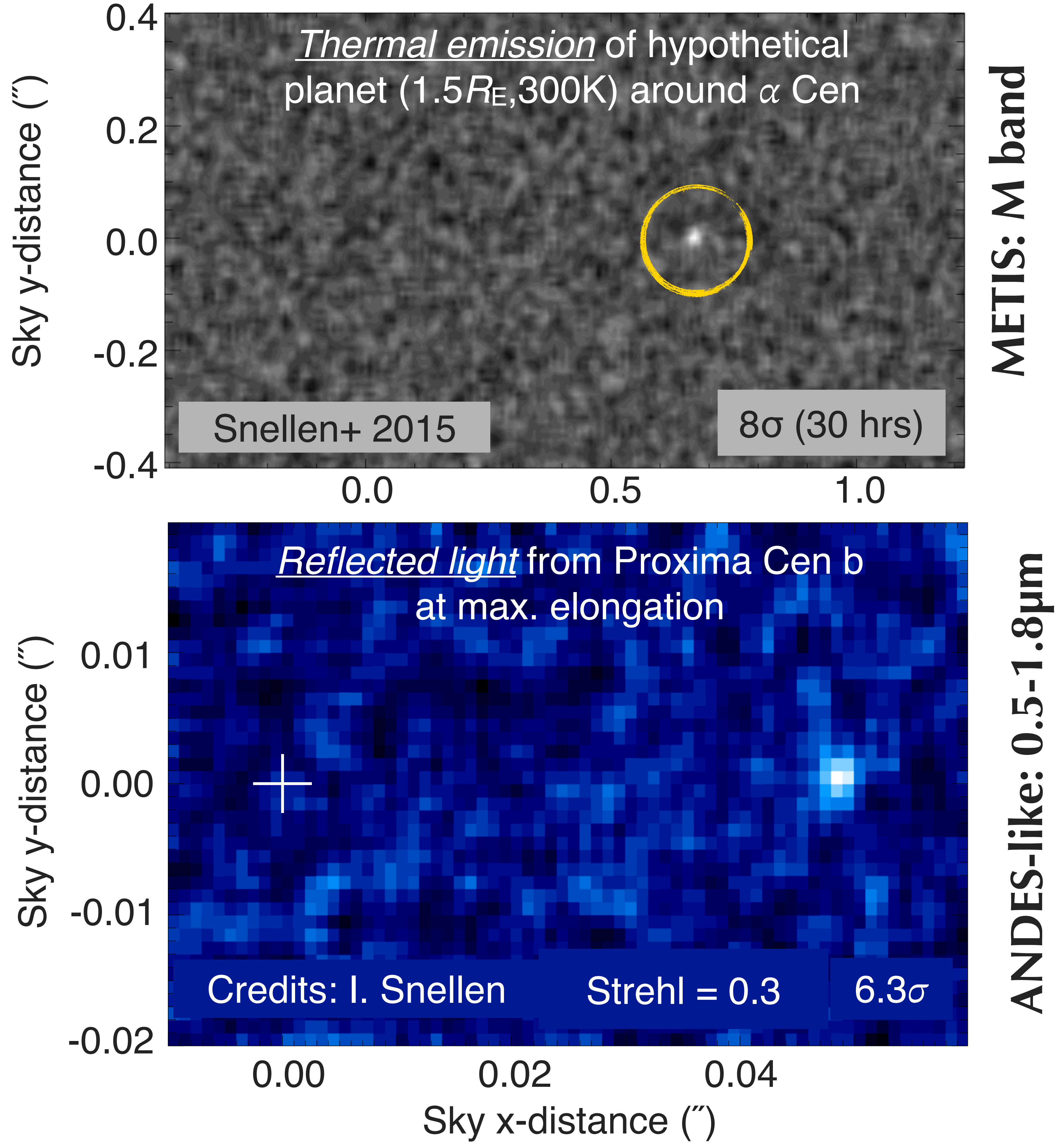
Implementation: Integral Field Unit w/ high-res spectroscopic capabilities



Already possible at medium-R or with long-slit

(Snellen+14; Schwarz+16; Hoeijmakers+18; Bryan+18; de la Roche+18; Keppler+18; Ruffio+19; Cugno+21)

~30 hours of ELT observations



Wrapping up: the role of HRS in the era of JWST (and beyond)

A personal view, open to discussion!

✗ Censing the chemistry of giant exoplanets

✓ Measuring composition of HJs / UHJs in synergy with JWST to understand population trends in mass-metallicity-(?)

✓ Measuring dynamics in a way complementary to JWST

⚠ **Preparing for ELT observations by identifying:**

- Strategies to best explore rocky exoplanets
- Revised analysis to target temperate (slowly-moving) planets
- End-to-end simulations including all sources of systematics

eso.org: ELT construction, 2023-07-11