Exoplanet atmospheres at high spectral resolution

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The research group:
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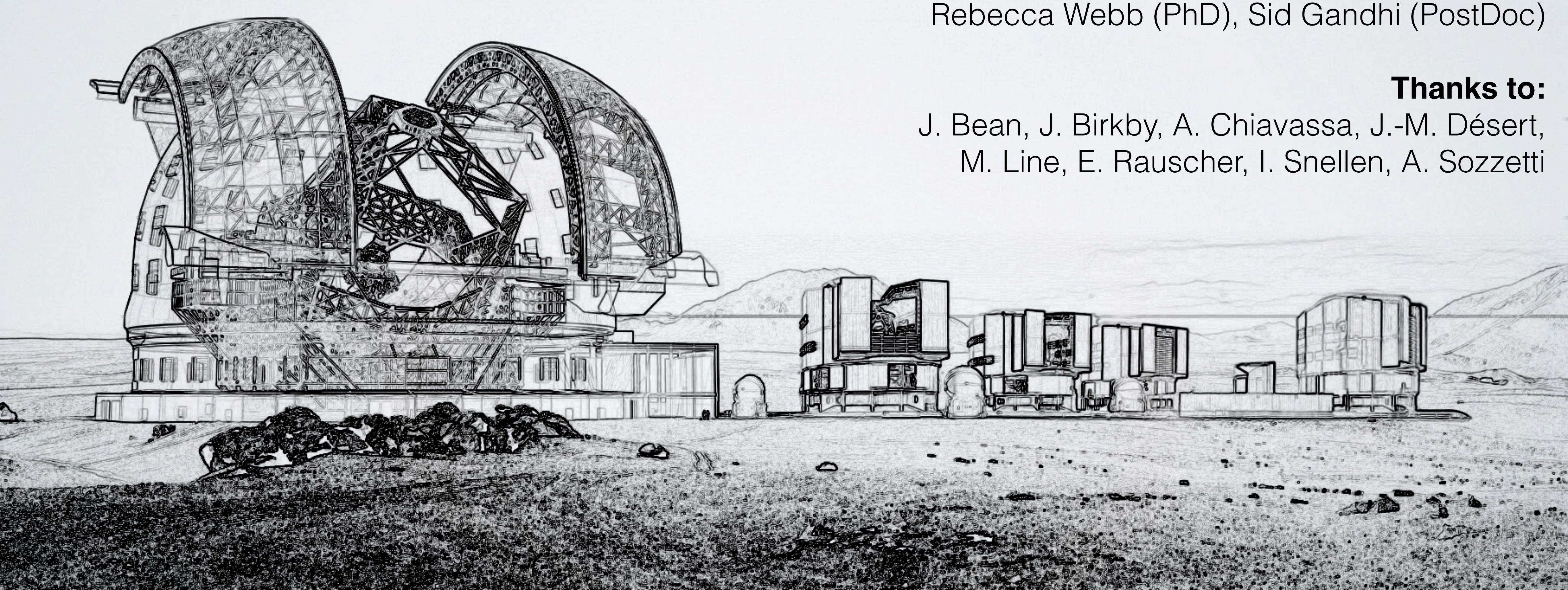
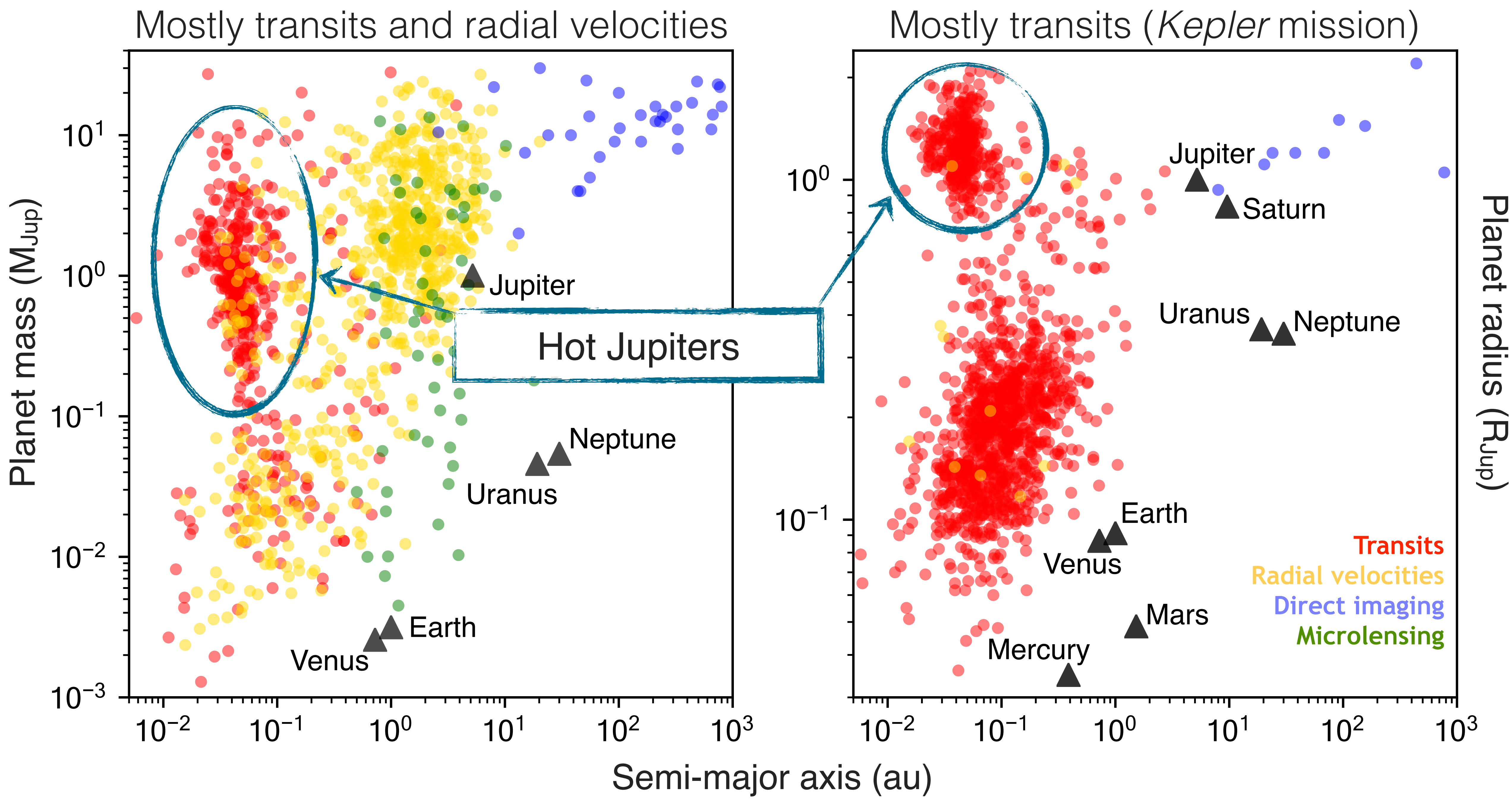
Thanks to:
J. Bean, J. Birkby, A. Chiavassa, J.-M. Désert, M. Line, E. Rauscher, I. Snellen, A. Sozzetti



The golden era of exoplanet discoveries

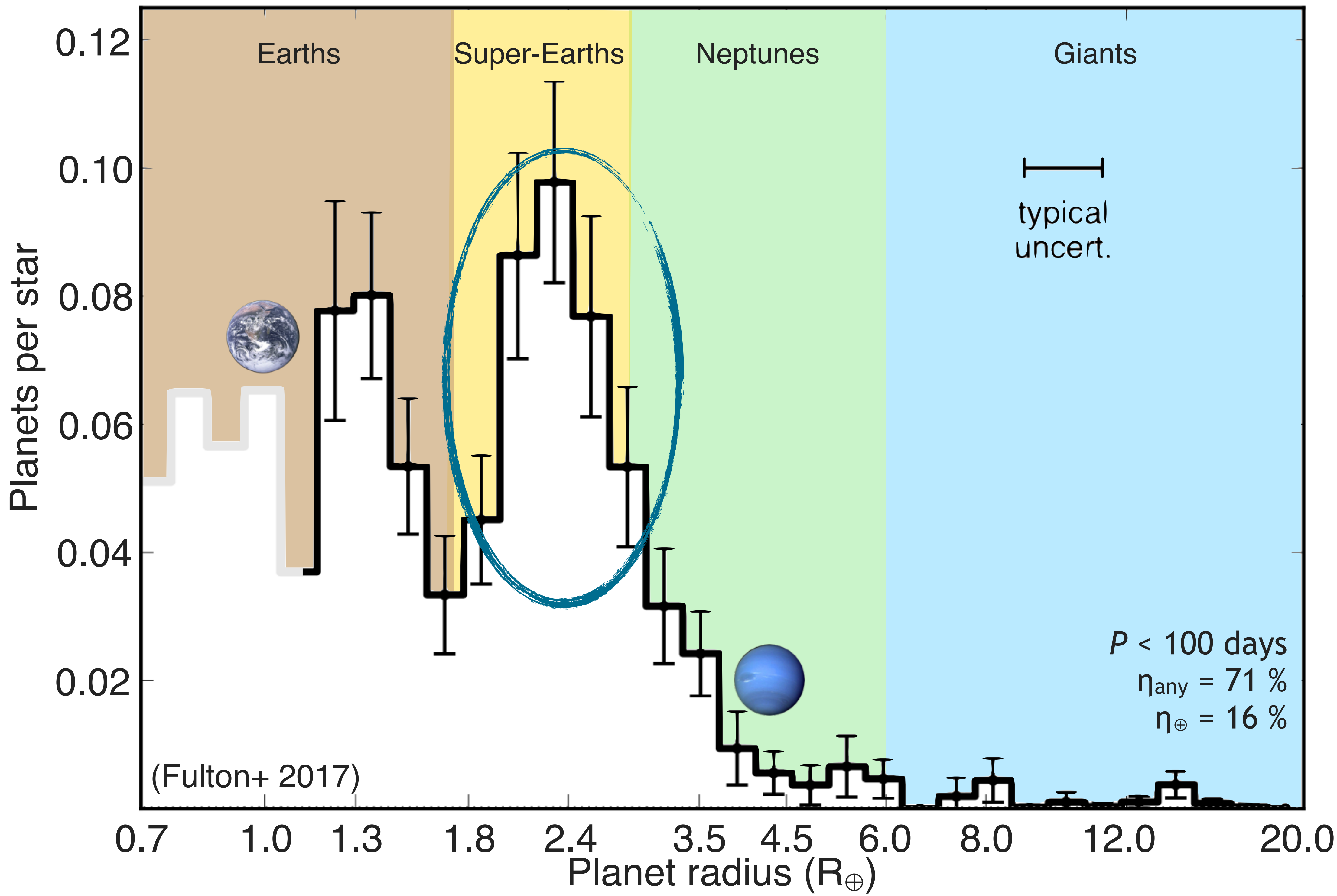
1995-2019 ⇒ 4,000+ confirmed exoplanets



Both plots are biased by ***detection limits!***
Smaller and further away planets are harder to detect

The most common exoplanets are not giants

Statistics from *Kepler* detections of transiting planets around FGK stars

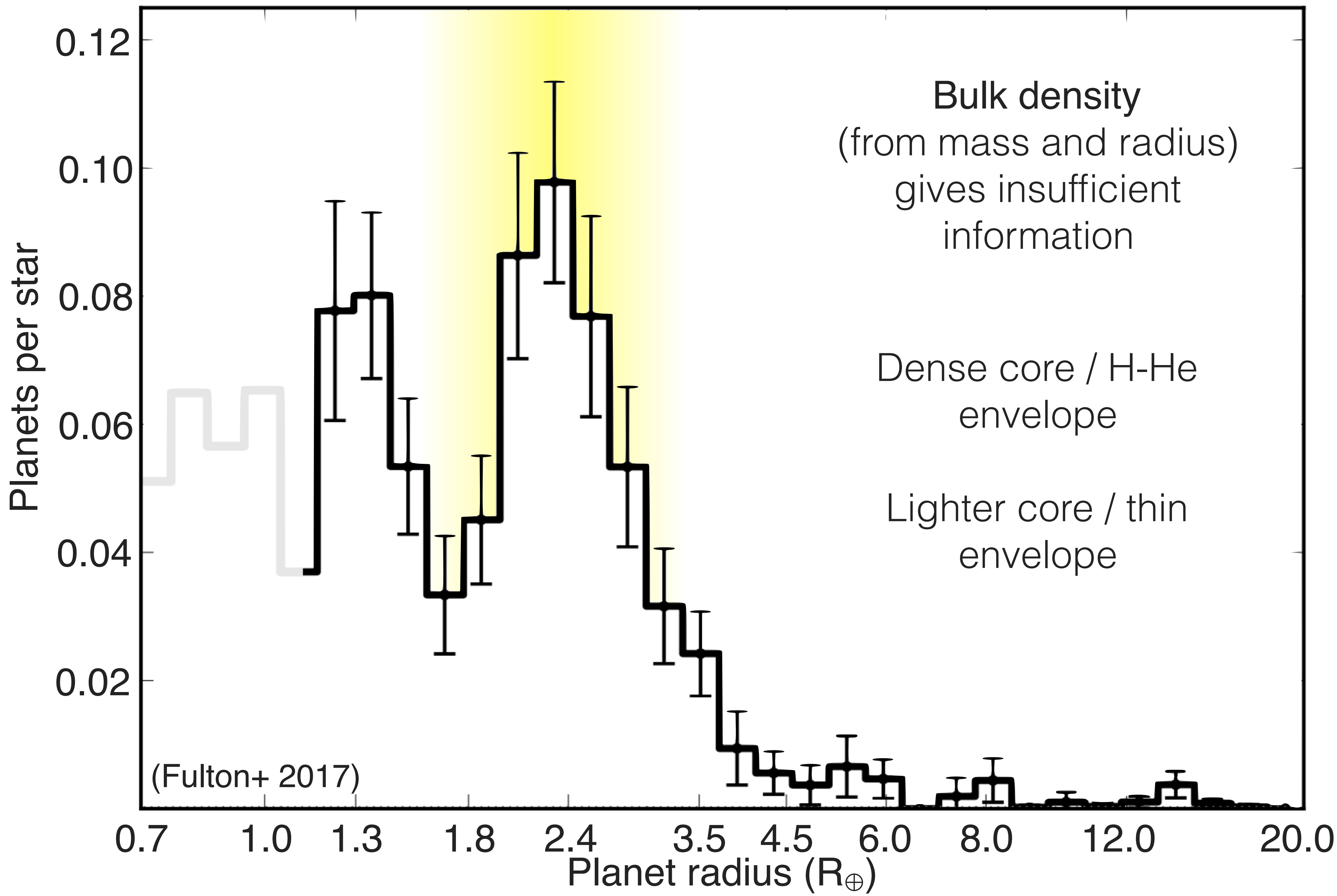


The most common planets have no analogues in the solar system

(their size is intermediate between Earth and Neptune)

What is the nature of the most common exoplanets?

The mini-Neptune / super-Earth dilemma

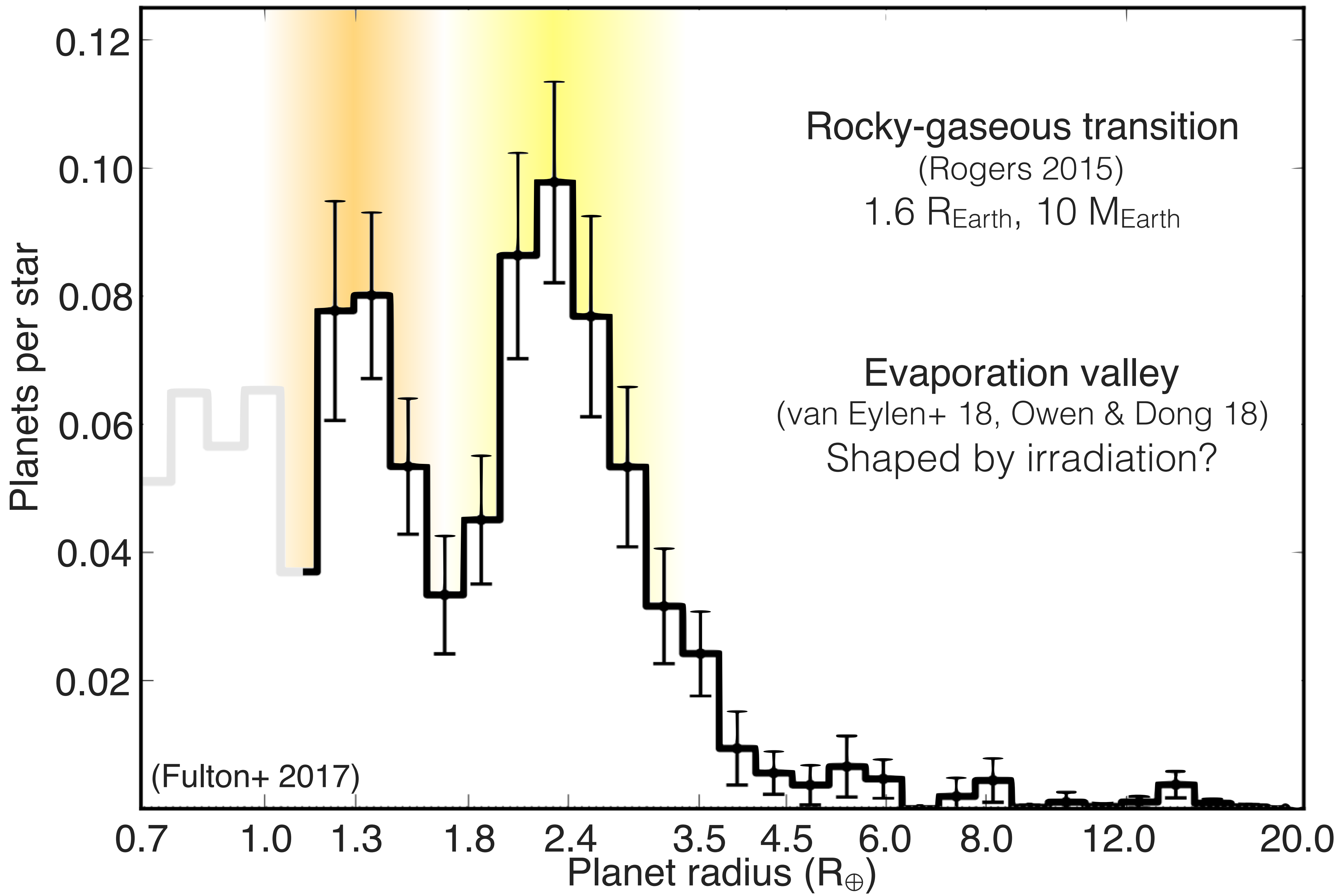


Studying the atmospheres can lift the envelope-interior degeneracy

(Adams+08, Miller-Ricci+09 Rogers & Seager 10, Dorn+15)

The gaseous/rocky transition and the evaporation valley

What shapes the transition between gas and rocky planets?



Studying the atmospheric composition (and mean molecular weight) can inform about physical processes shaping the valley

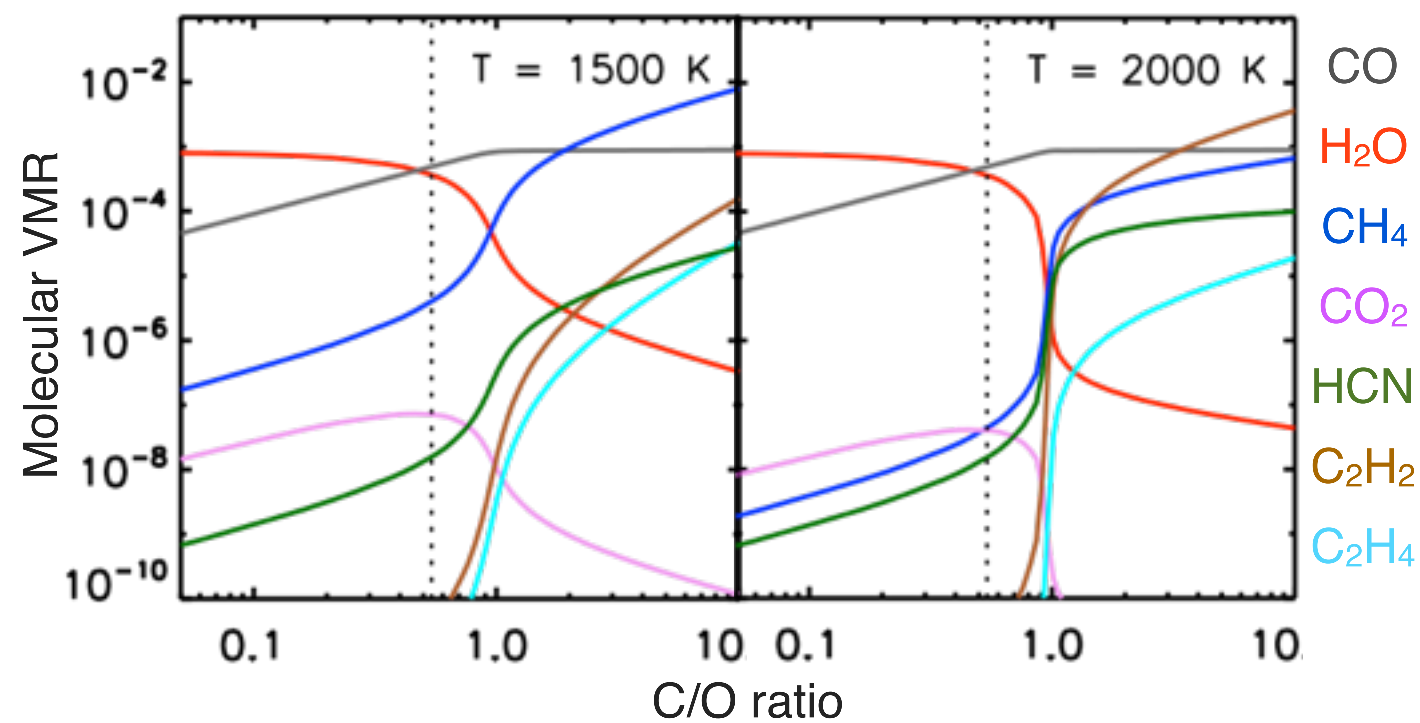
Why hot Jupiters?

A "simplified" chemistry

CO, H_2O and CH_4 are the main spectroscopically active species

Relative abundances (especially $[H_2O]/[CH_4]$) strong function of C/O ratio

(e.g. Madhusudhan 12)



No major "cold traps"

Unlike Solar System giants, HJ spectra are representative of composition

Homogenised species

Atmospheric circulation equalises day/night abundances

Negligible chemical evolution / mass loss

Evolved atmospheres relate to primordial atmospheres

Can we link hot-Jupiter composition to their formation scenarios?

C/O versus snow lines (Öberg+11; Piso+15; Eistrup+18)

Atmospheric characterisation of transiting planets

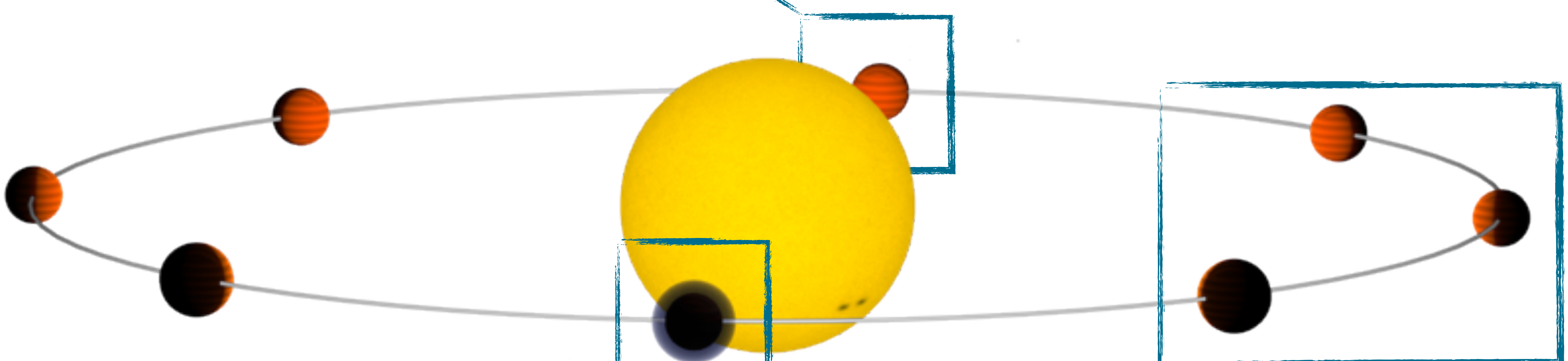
Star and planet are *not* spatially resolved

Time variations of total light from star+planet system (at various wavelengths)

Eclipse (Dayside spectrum)

Planet occulted by the stellar disk

Measuring the missing planet flux



Transit (Transmission spectrum)

Starlight filtering through the planet atmosphere

Measuring the planet radius

Phase curve

Relative contribution of planet day/night side

Spectra and phase curves constrain

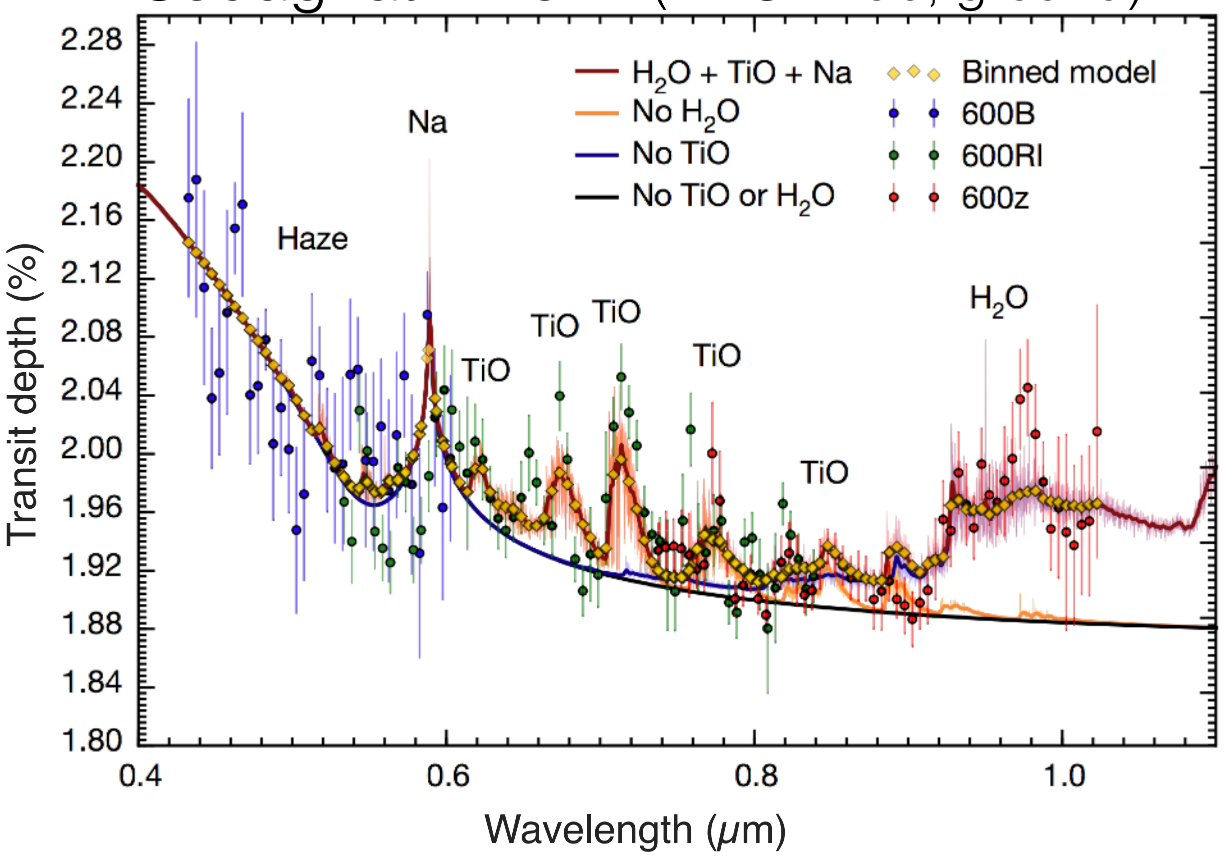
molecular species, abundances, atmospheric structure, energy balance

Credits: E. de Mooij

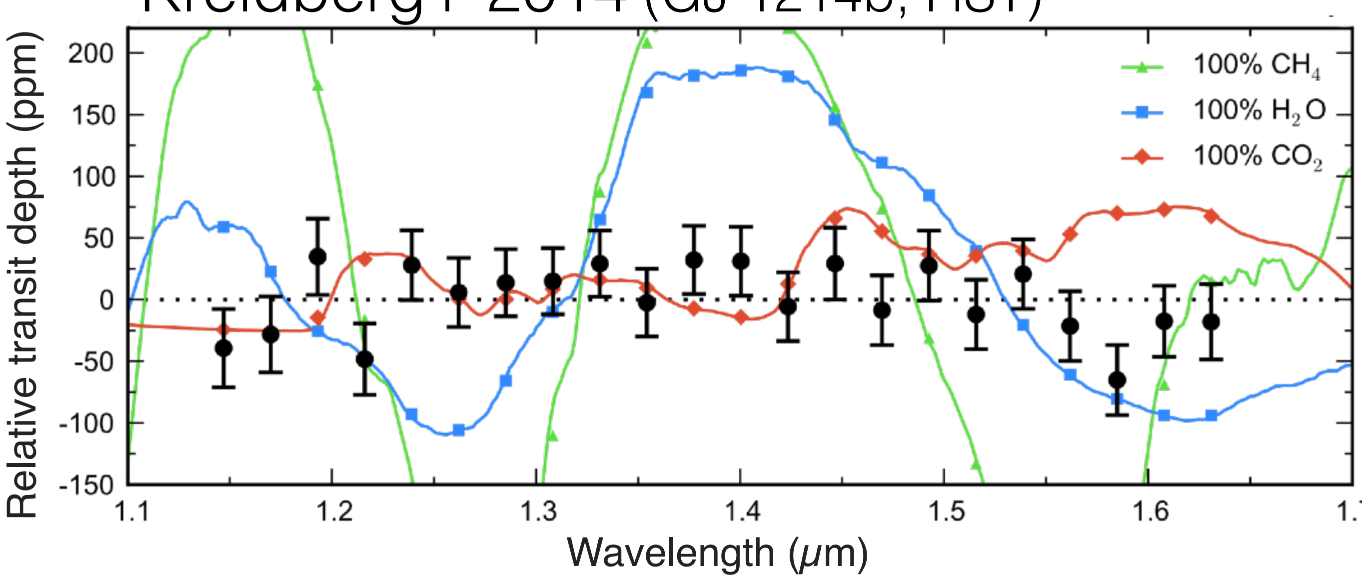
Low-resolution spectroscopy of exoplanets

H2O, Na, K, [TiO] Inferred from broad-band shape of the spectrum

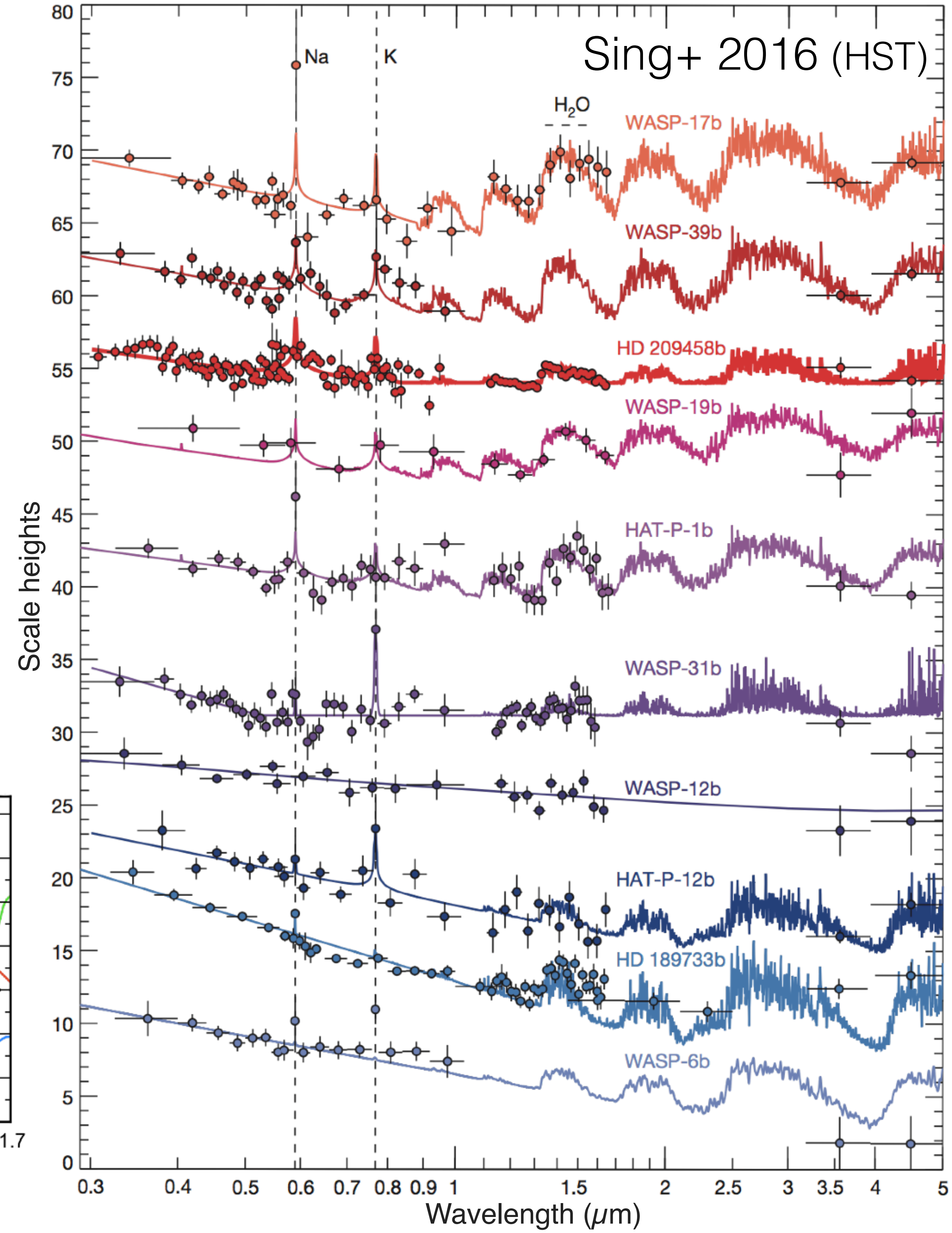
Sedaghati+ 2017 (WASP-19b, ground)



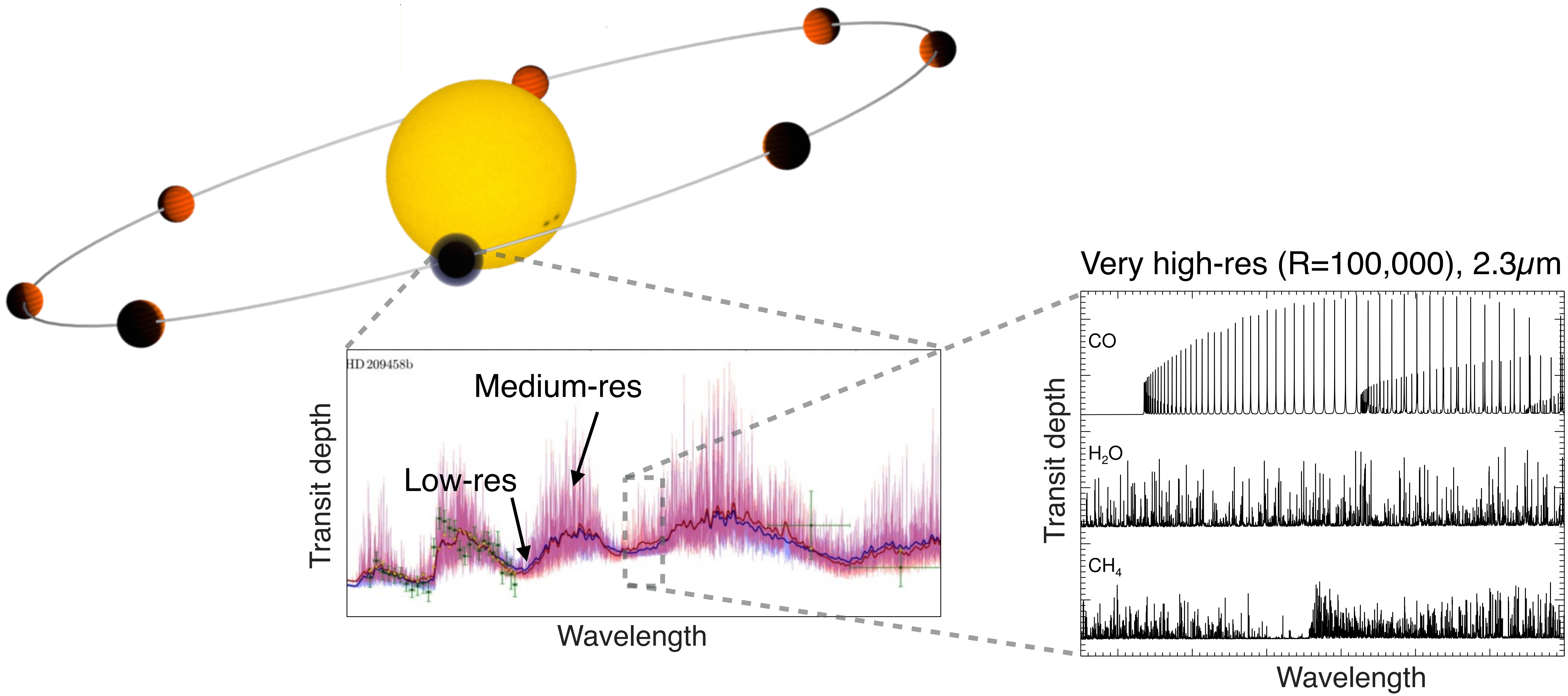
Kreidberg+ 2014 (GJ 1214b, HST)



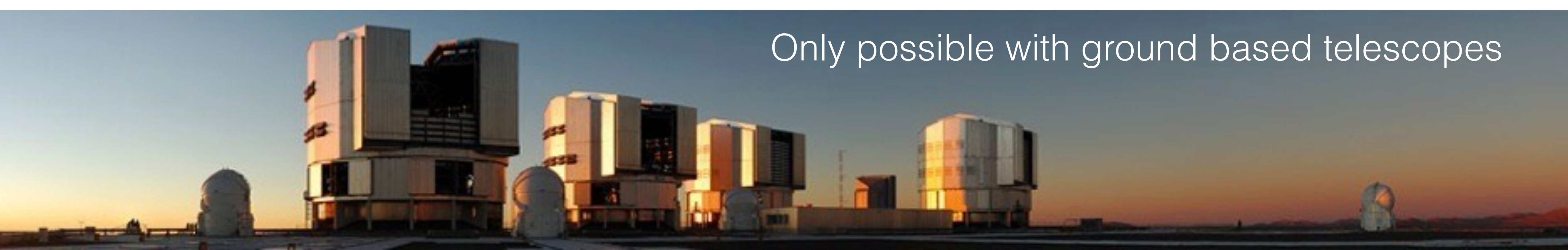
Sing+ 2016 (HST)



Exoplanets at high spectral resolution



Each species has a unique pattern of spectral lines
Species can be "matched" line by line to templates, e.g. via *cross correlation*

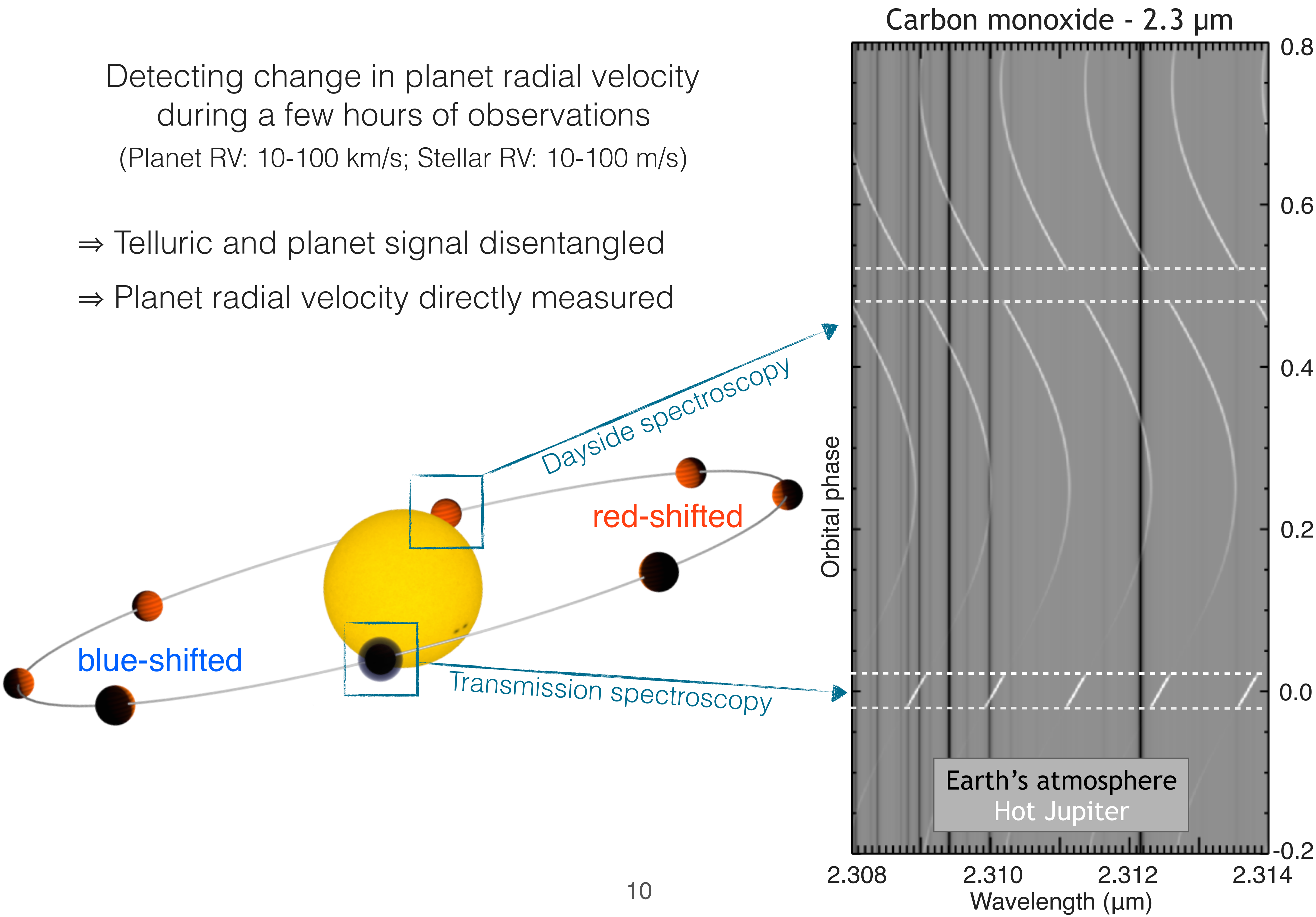


Detecting the orbital motion of close-in planets

Detecting change in planet radial velocity
during a few hours of observations
(Planet RV: 10-100 km/s; Stellar RV: 10-100 m/s)

⇒ Telluric and planet signal disentangled

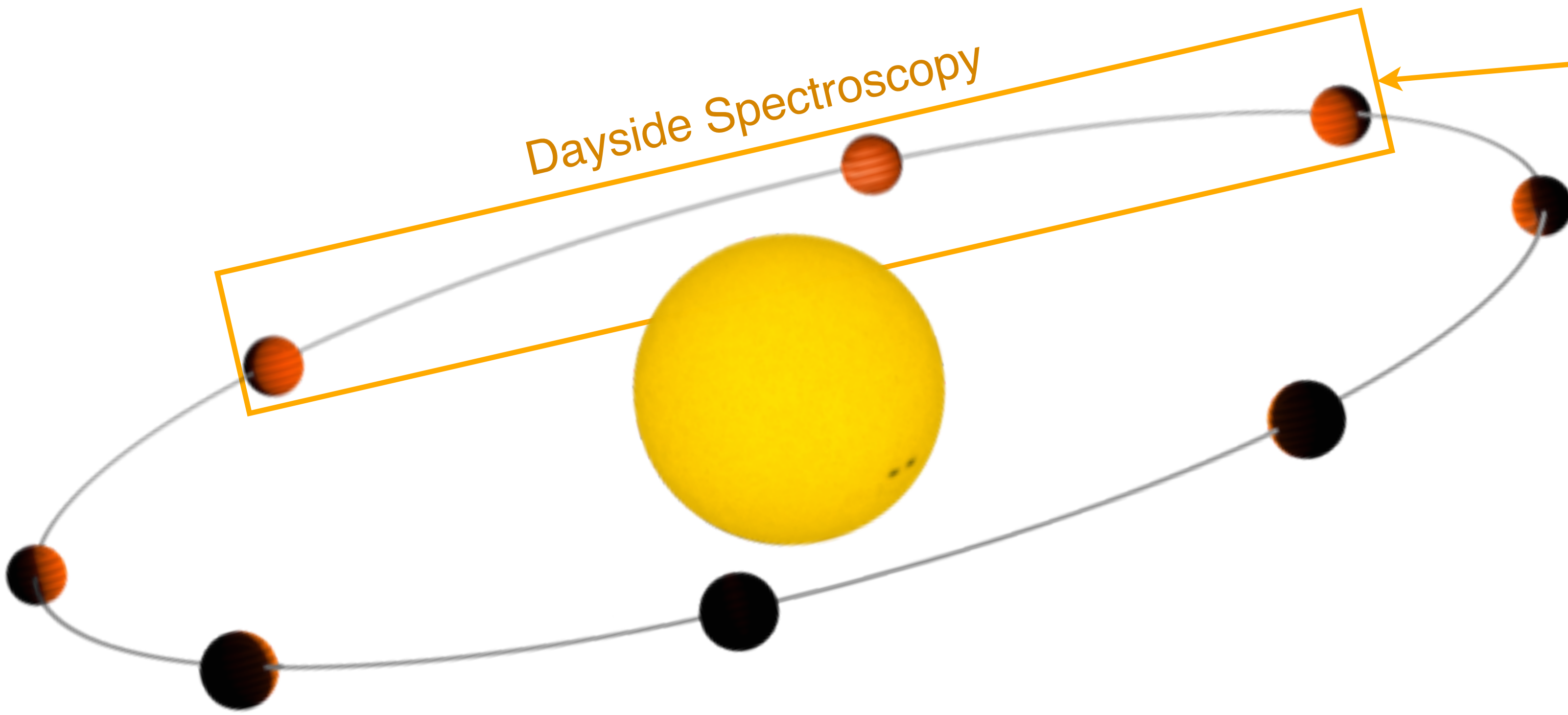
⇒ Planet radial velocity directly measured

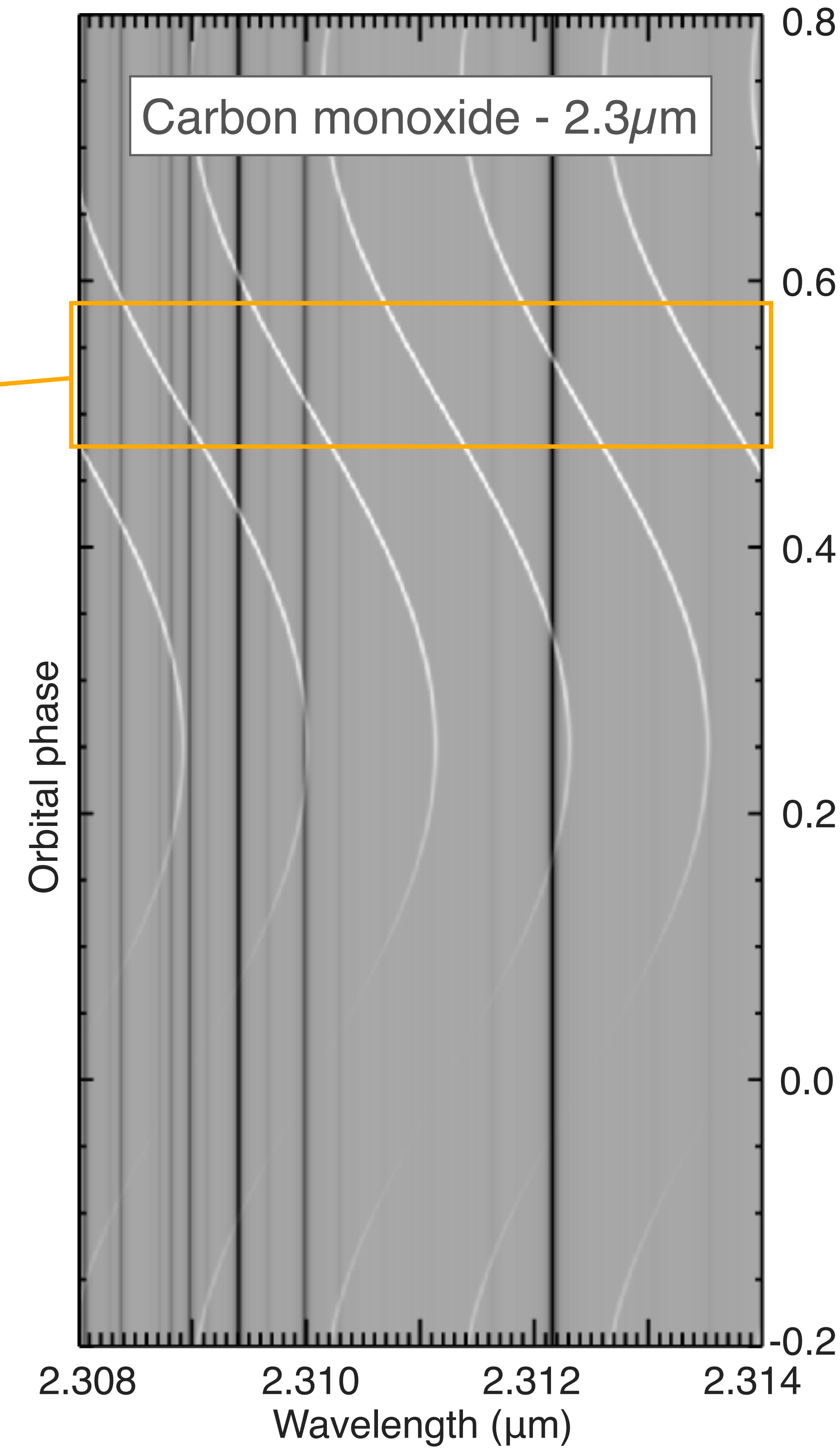


High spectral resolution of non-transiting planets

The thermal spectrum
of the planet is targeted directly

Dayside spectroscopy
applicable to non-transiting planets!



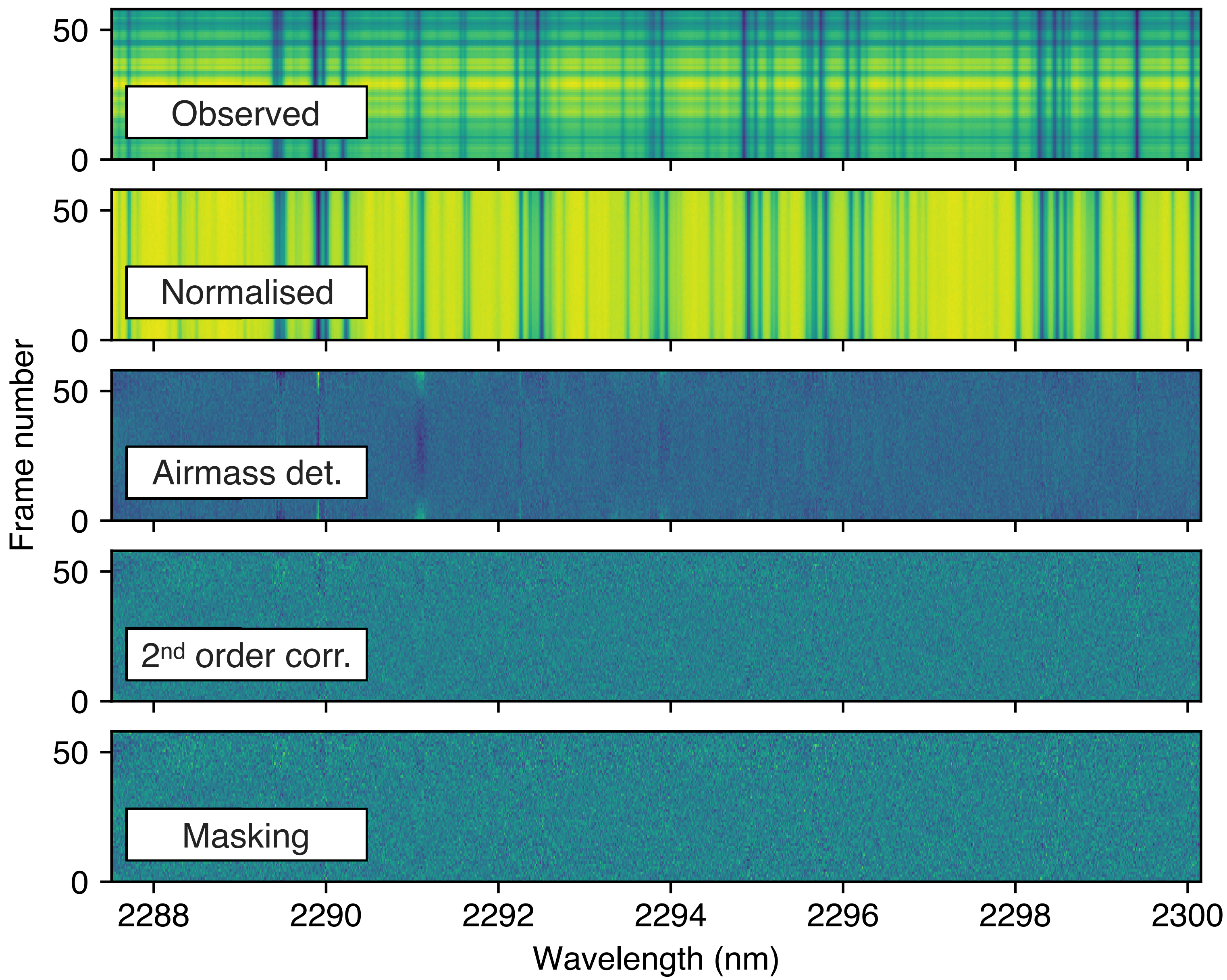


The first and only method to study
atmospheres of most non-transiting planets
(evolved, on close-in orbits)

Can solve for planet mass and orbital inclination

Reverse-engineering the exoplanet spectrum

Every spectral line stationary in wavelength (vertical in our figures) is removed



Starting sequence

Divide each spectrum (each row) by the median

Fitting of each spectral channel (each column) with exp(airmass)

Sampling strong residuals and dividing them out of each column

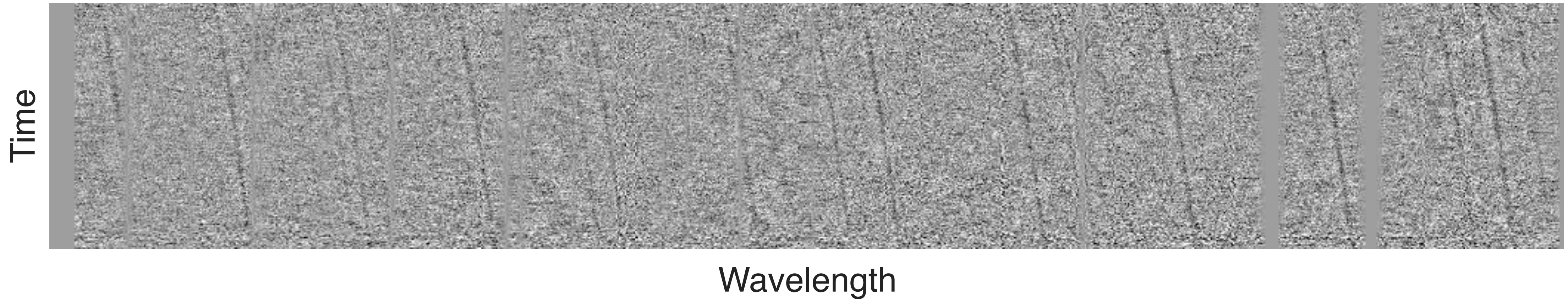
Final masking of very noisy columns

These steps can be"automated" by algorithms decomposing data into a linear combination of eigenvectors (e.g. PCA)

The process "auto-calibrates" the data: no reference star required!

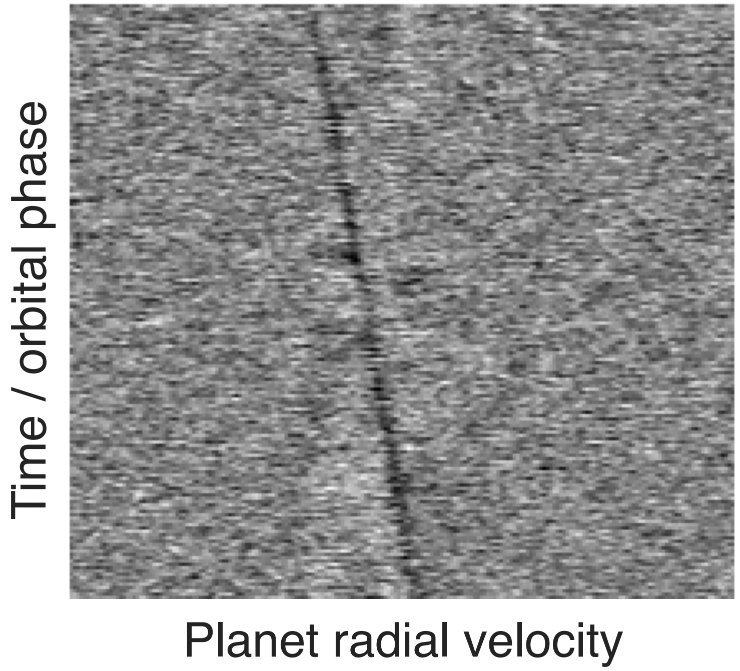
Extracting the (faint) planet signal: cross correlation

5 hours of real data + 20x planet signal (CO)



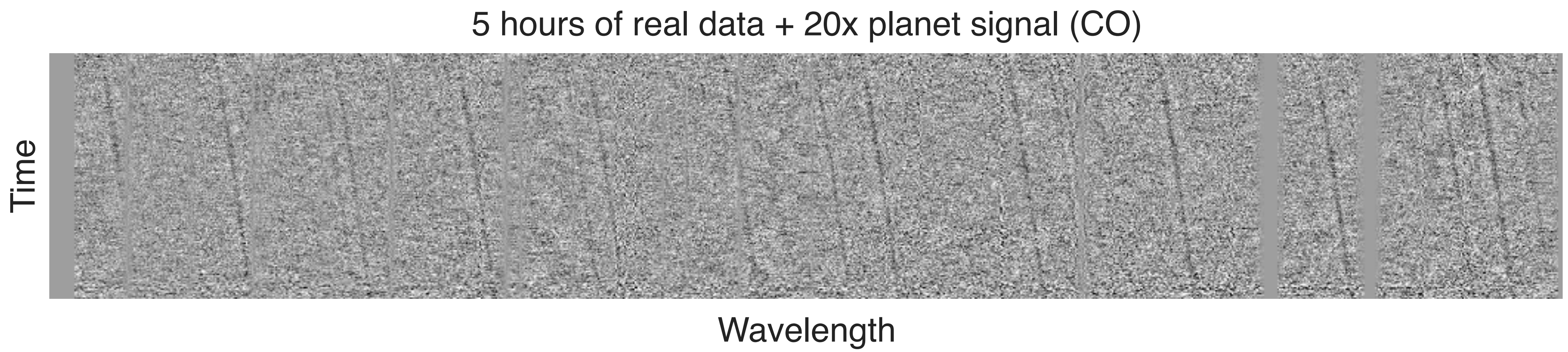
Cross-correlation with model spectra

Cross-correlation matrix
CC(RV, t)



The peak CC tracks the planet radial velocity in time

Extracting the (faint) planet signal: cross correlation



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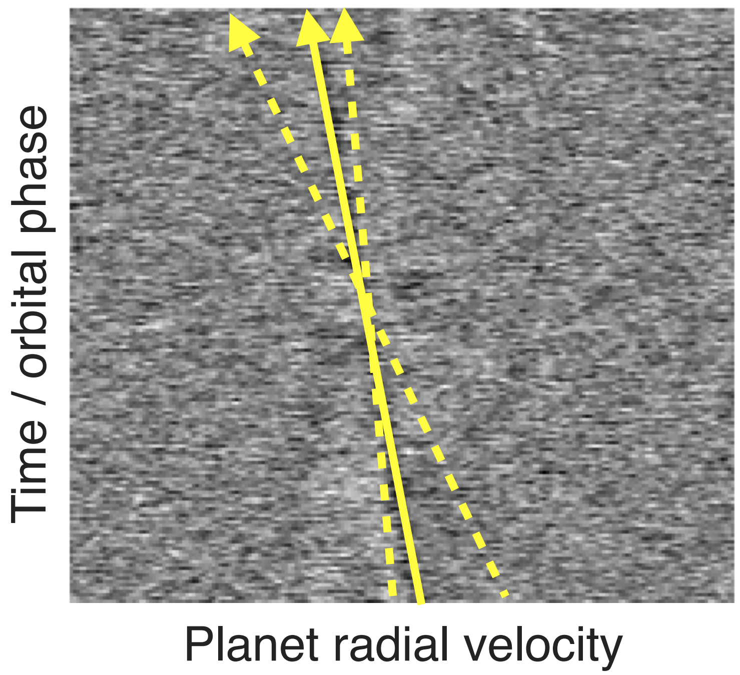
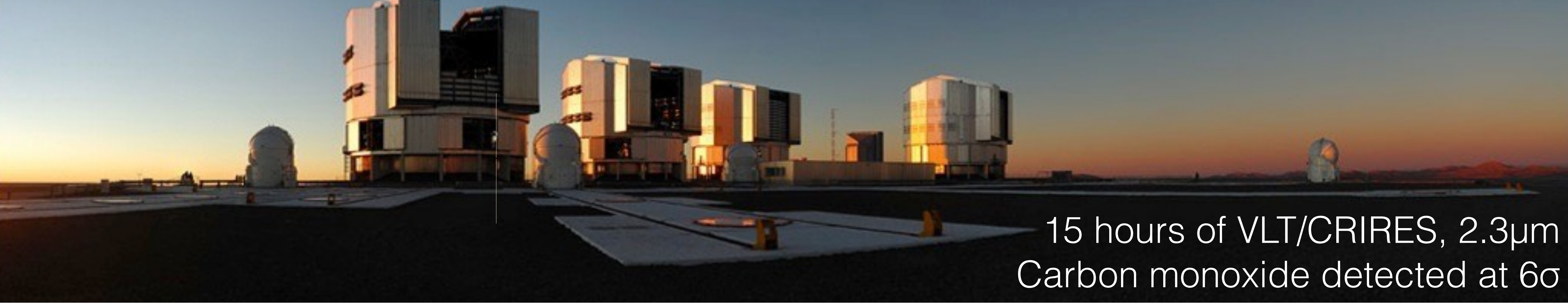


The peak CC tracks the planet radial velocity in time

Shifting and co-adding to planet rest-frame requires knowledge of planet orbital velocity (two parameters: ***slope*** and ***shift***)

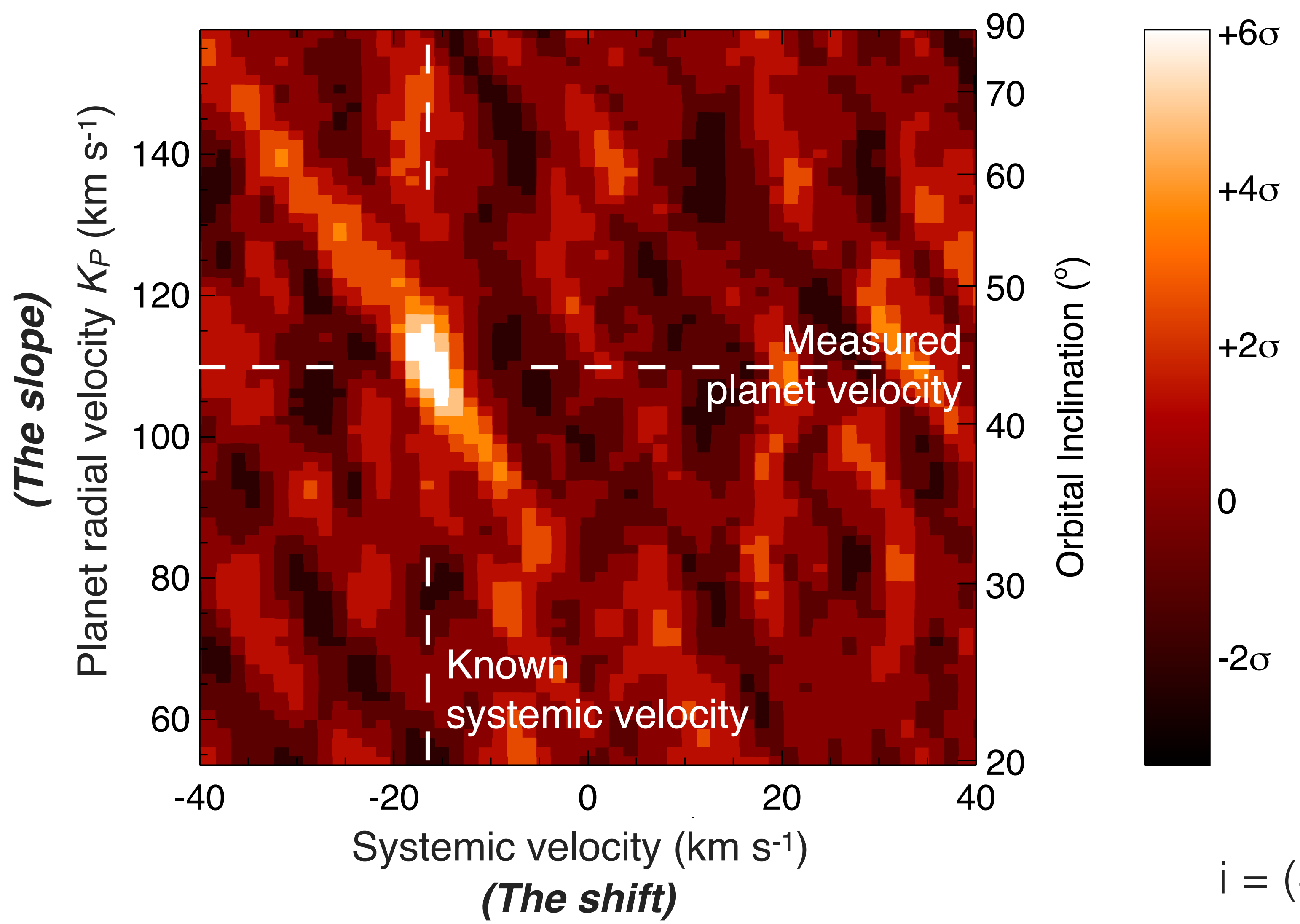
Star and planet as spectroscopic binaries

Pilot study: τ Boo b (Brogi+ 2012)



15 hours of VLT/CRIRES, 2.3μm

Carbon monoxide detected at 6σ



Measured:

RV semi-amplitude ratio: K_P/K_S

⇒ Mass ratio: M_P/M_S

Inferred:

Orbital inclination i

Planet mass $M_P = f(M_S)$

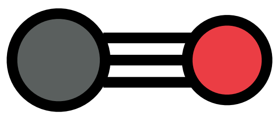
Uncertainties in planet mass dominated by uncertainties in stellar mass.

For τ Boo b:

i = (45.5 ± 1.5) deg, M_P = (5.95 ± 0.28) M_{Jup}

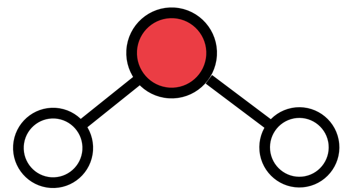
The story so far: hot Jupiters at high spectral resolution

5 molecules (cross-correlation) + H, He, Ca, Na, Ti, Fe (single line)



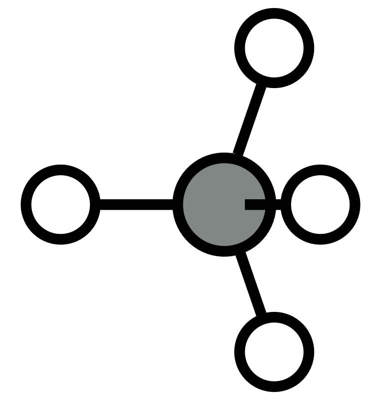
CO

Brogi+12,13,14
Cabot+19
de Kok+13
Hawker+18
Rodler+ 12,13
Schwarz+16
Snellen+10,14

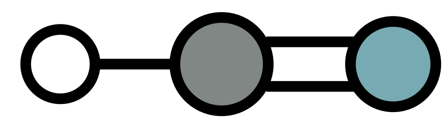


H_2O

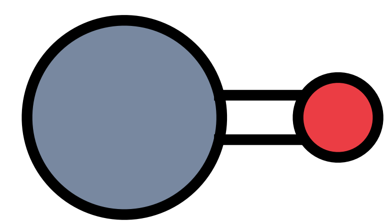
Alonso-Floriano+19
Birkby+13,17
Brogi+13,14,16,18
Cabot+19; Guilluy+19
Hawker+18
Lockwood+14
Piskorz+16,17,18
Schwarz+16



CH_4 Guilluy+19



HCN Cabot+19, Hawker+18



TiO Nugroho+17

<u>Observed sample</u>

15 planets searched (5 non-transiting, 8 transiting, 2 directly imaged)

<u>Potential sample (pre-TESS)</u>

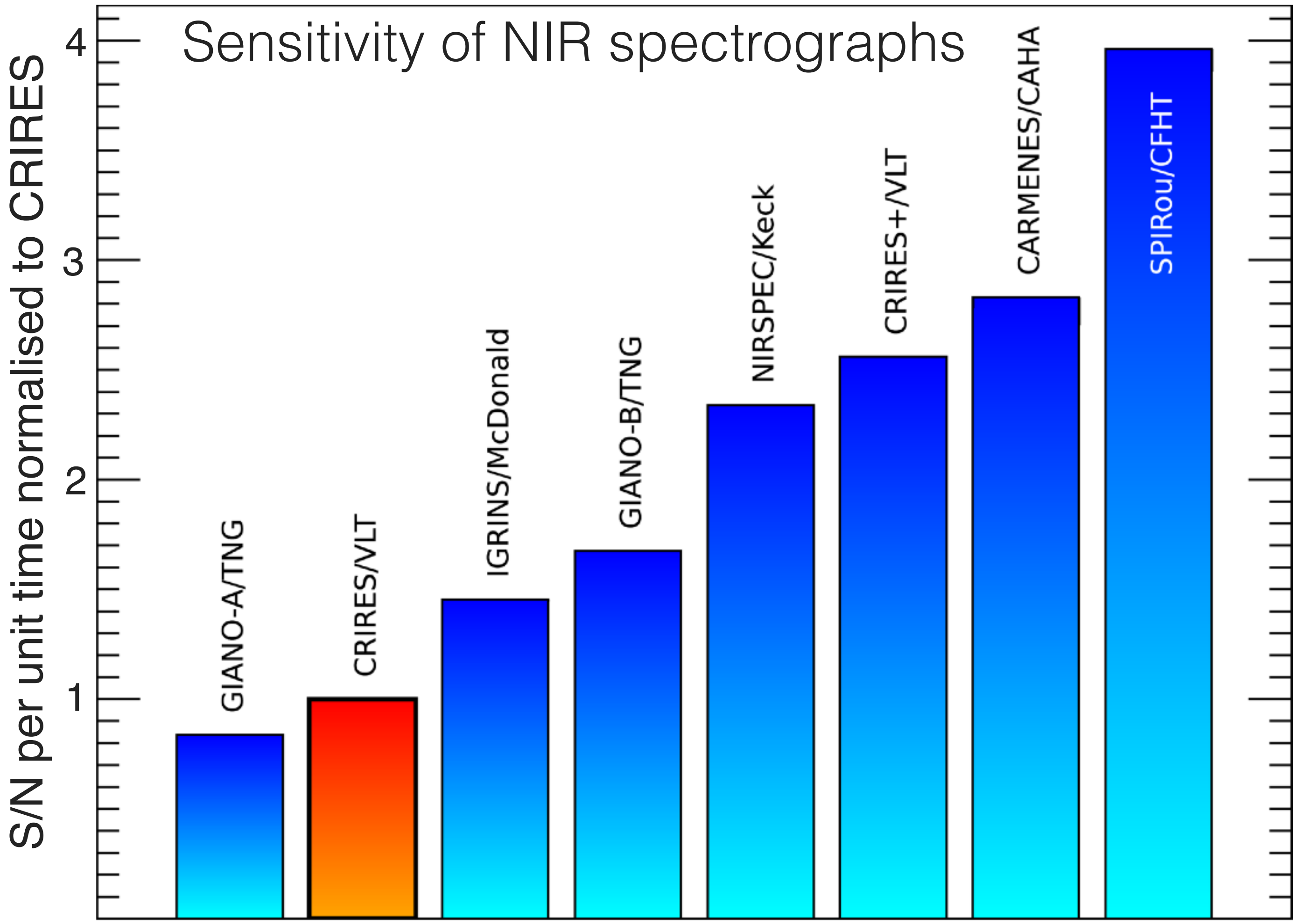
15 non-transiting (K < 6.5 mag) + 15 transiting (K < 8 mag)

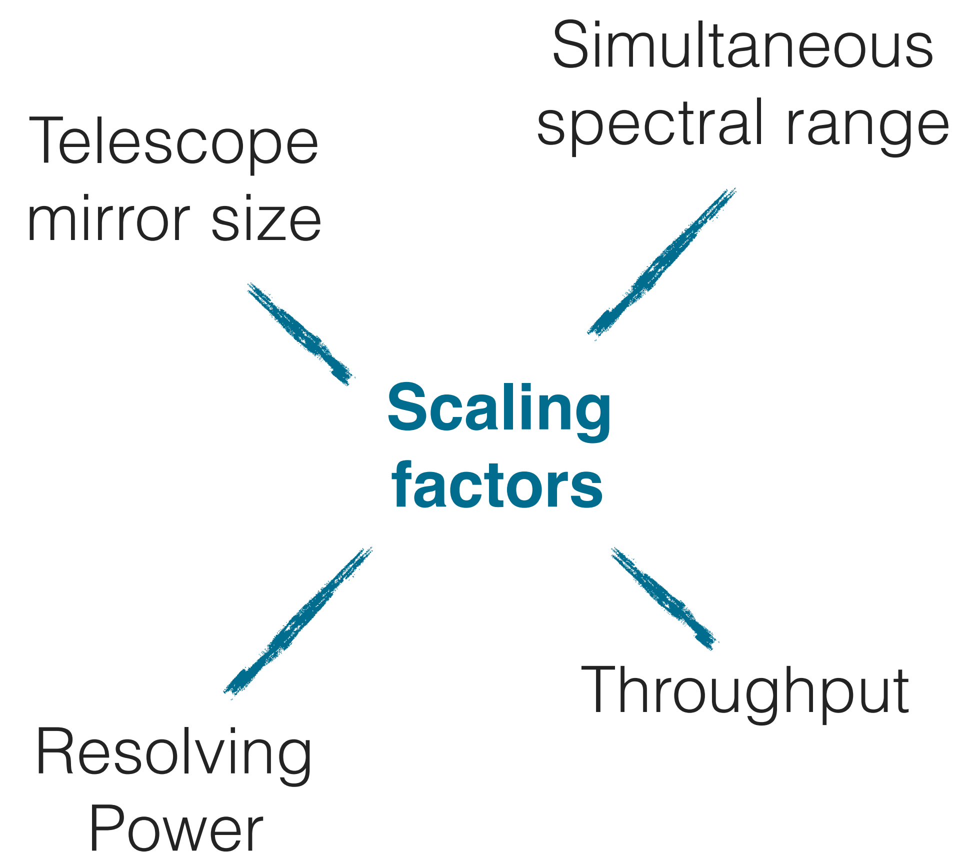
Constraints on C/O

3 planets, all consistent with solar (“oxygen-rich” C/O<1)

From demonstration to comparative exo-planetology

Modern spectrographs have wider spectral range and/or higher throughput





Past detections of H_2O scaled to the TESS yield of Sullivan+ 2015

A few dozen TESS planets can be followed up at high spectral resolution
Smaller and cooler than current hot giants - breaking the 10 ppm barrier

Timely and legacy aspect

Observations can be done 2 yrs in advance of JWST

Line lists are key to modelling high resolution spectra

We do not measure spectra, but level of correlation with model spectra
Uncertainties in line lists can bias or even prevent detection of molecular species

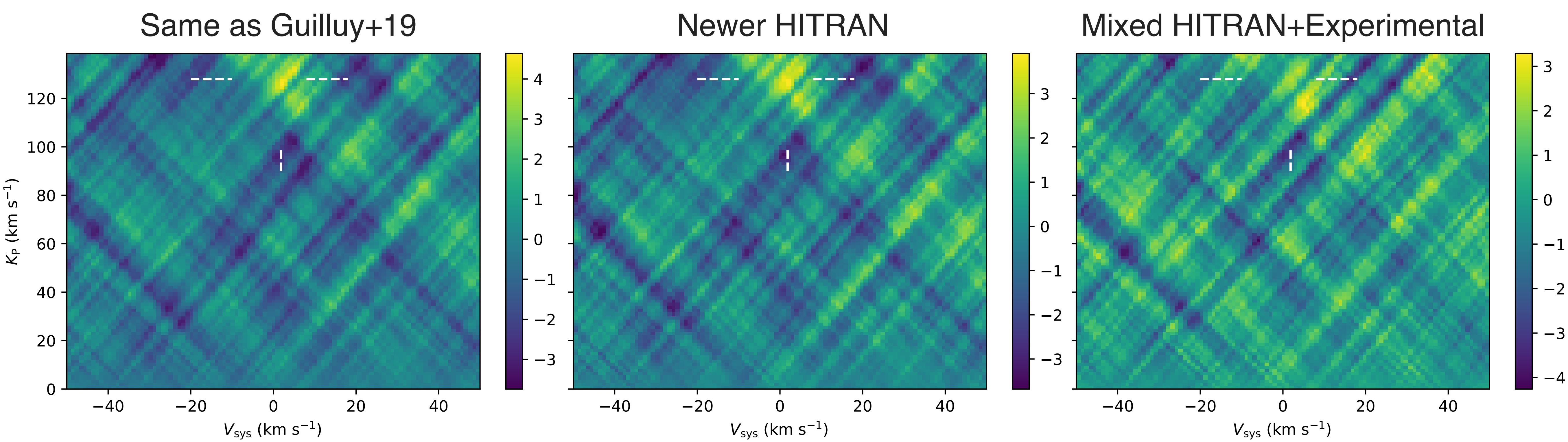
Completeness (low-res) versus accuracy (high-res)

Current state of the art line lists for CO, H_2O, CO_2, HCN, CH_4, NH_3
Led by Sid Gandhi, in collaboration with ExoMol

<u>Reliable:</u> **CO** (everywhere) and **H_2O** (particularly around 3.1-3.5 μm)

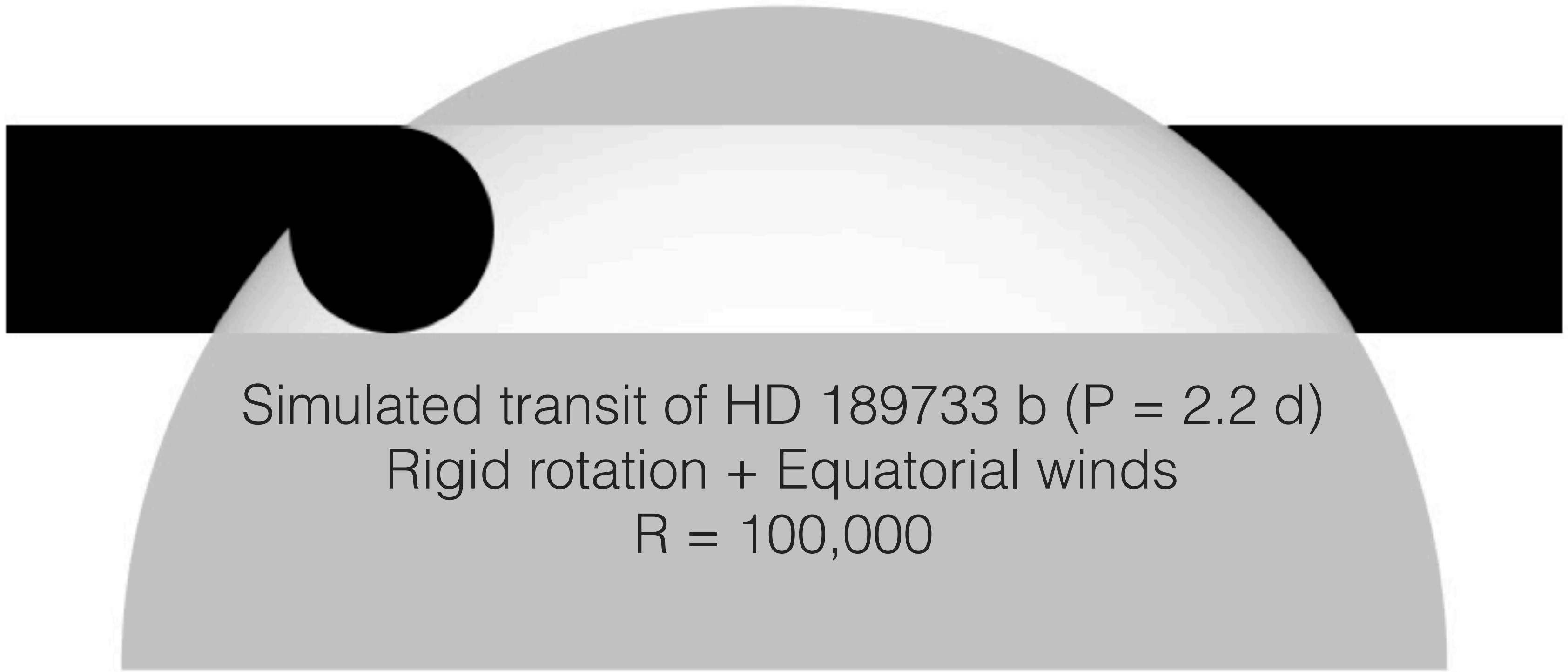
<u>Usable:</u> **HCN** and soon **CO_2**

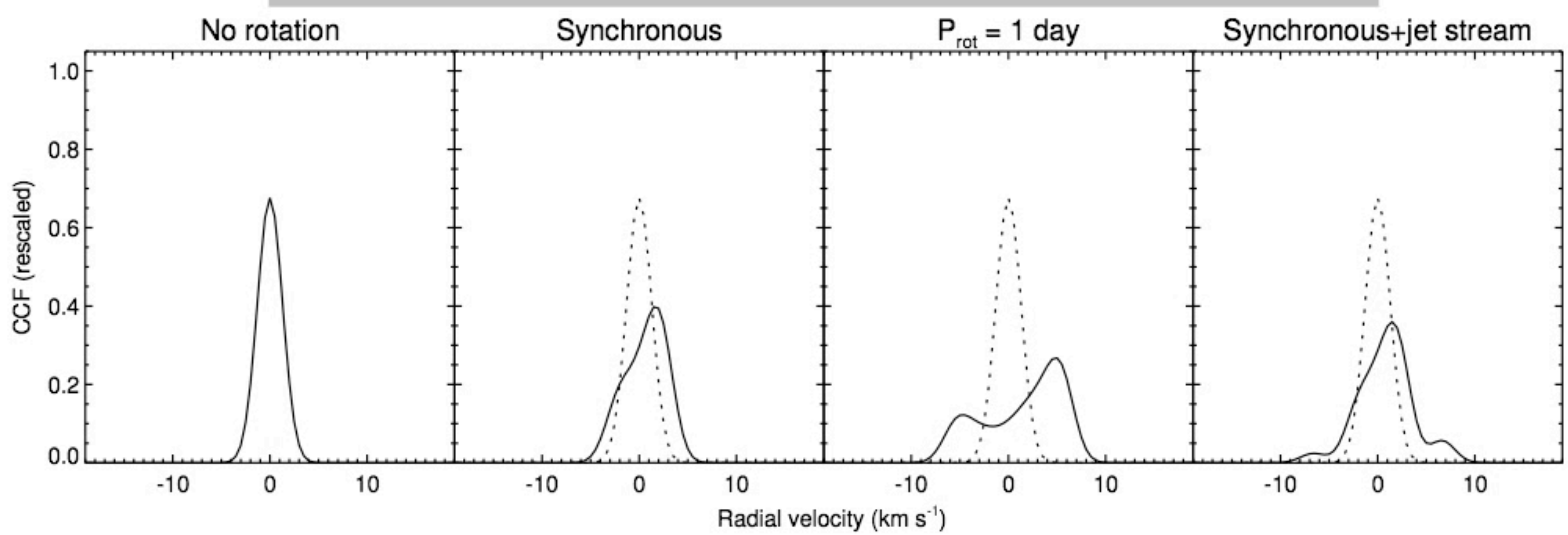
Example: **CH_4** - First detection at high-res by Guilluy et al. (2019)



Rotation and winds of hot Jupiters

Hot Jupiters should become tidally locked on short timescales
Rotational and orbital periods are the same (a few days)





Rotation and winds distort the planet line profile ⇒ imprint on CCF / Na line
(Snellen+10,14; Wyttenbach+15; Louden & Wheatley 15; Brogi+16; Schwarz+16; Flowers+18)

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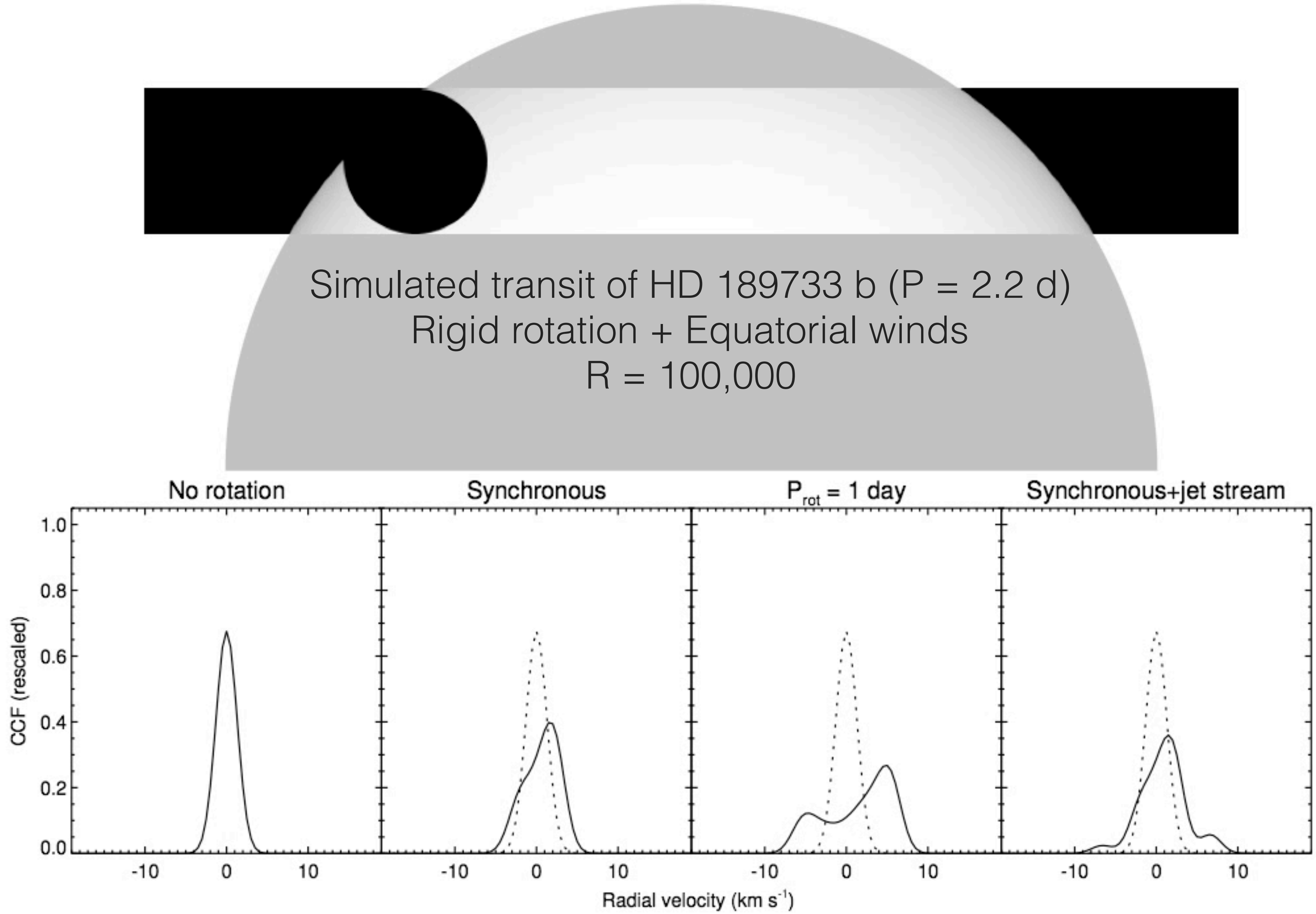
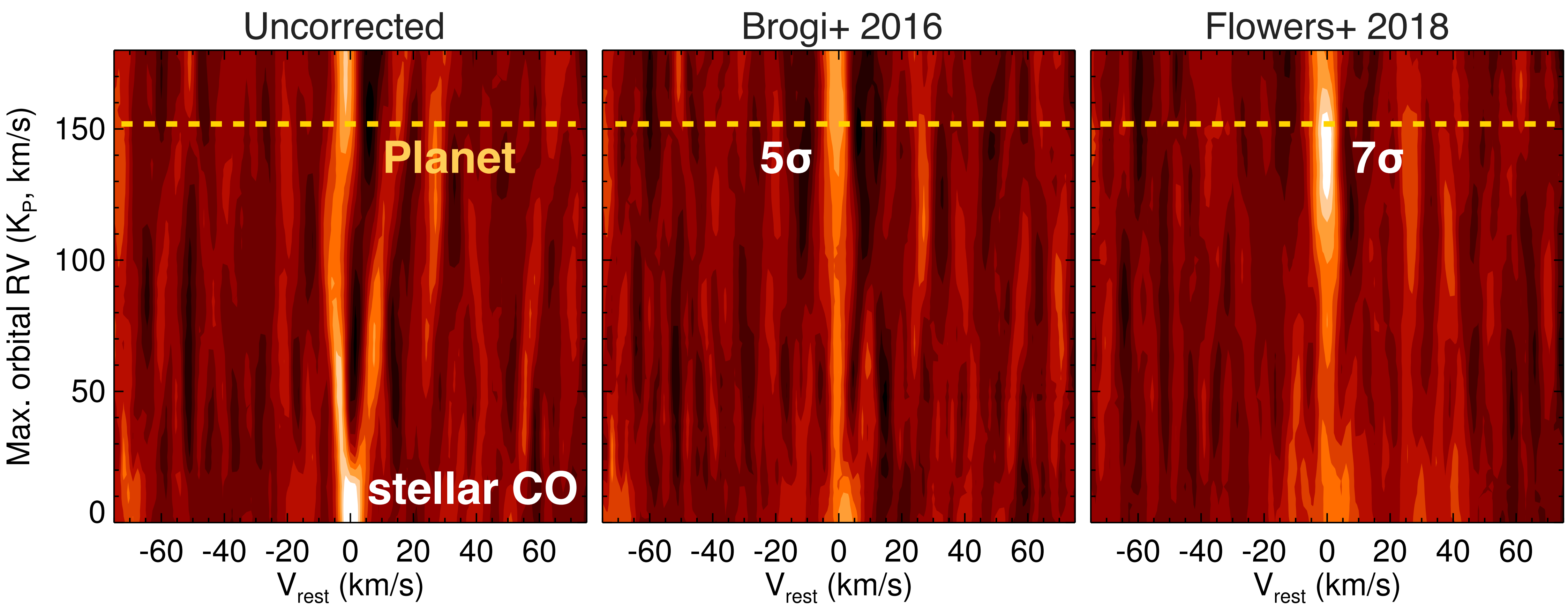


Rotation and winds distort the planet line profile ⇒ imprint on CCF / Na line
(Snellen+10,14; Wyttenbach+15; Louden & Wheatley 15; Brogi+16; Schwarz+16; Flowers+18)

Beware of the star! Additional Doppler signatures

Transiting planets block a changing fraction of the stellar disk
Projected stellar rotation + center-to-limb variations => Doppler signature

Impact on spectral features in common between planet & star (Na, CO)

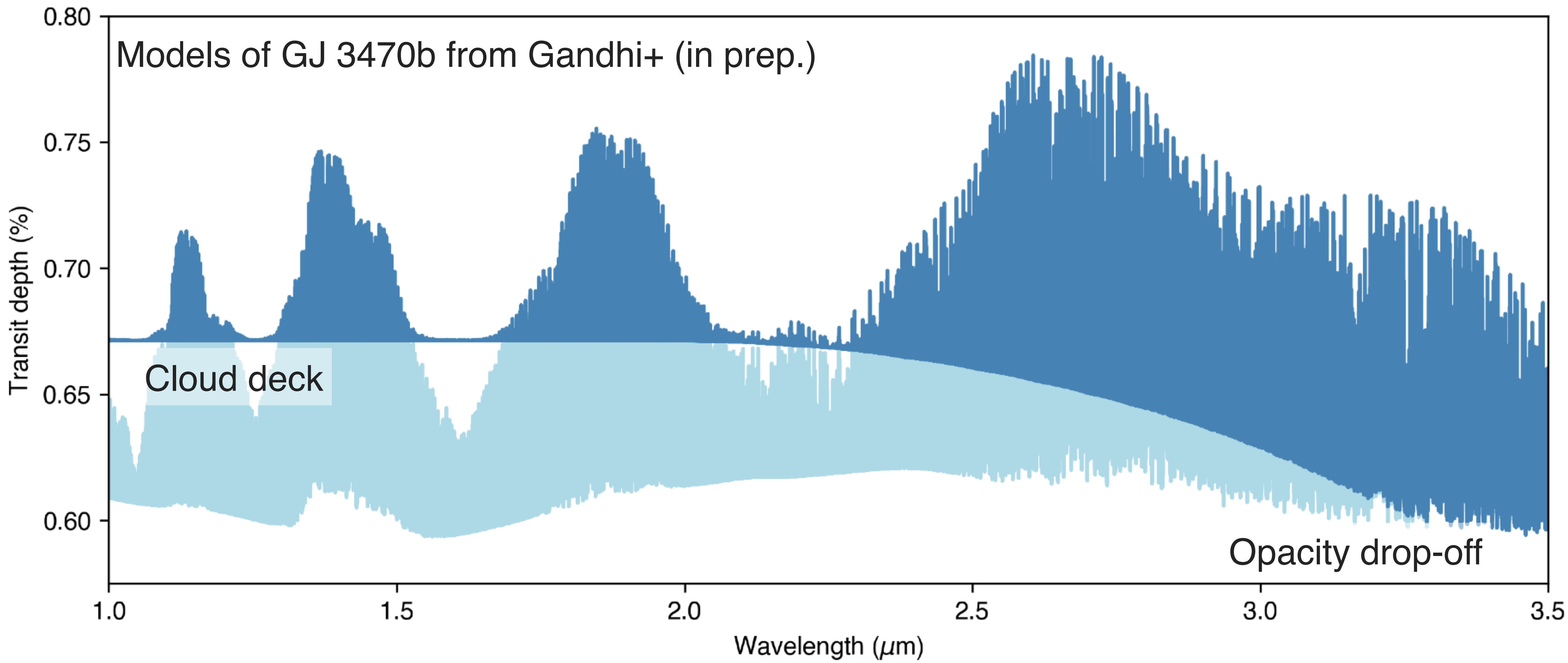


Currently modelled and effectively corrected for F,G,K stars in the optical
(e.g. Louden & Wheatley 15; Brogi+16; Casasayas-Barris+17; Yan+17; Wyttenbach+17)

Chiavassa & Brogi (2019): 3D stellar modelling in NIR - correction of CO lines

Seeing above the clouds at high spectral resolution

H_2O transmission spectrum of a hot Neptune across the NIR spectral range

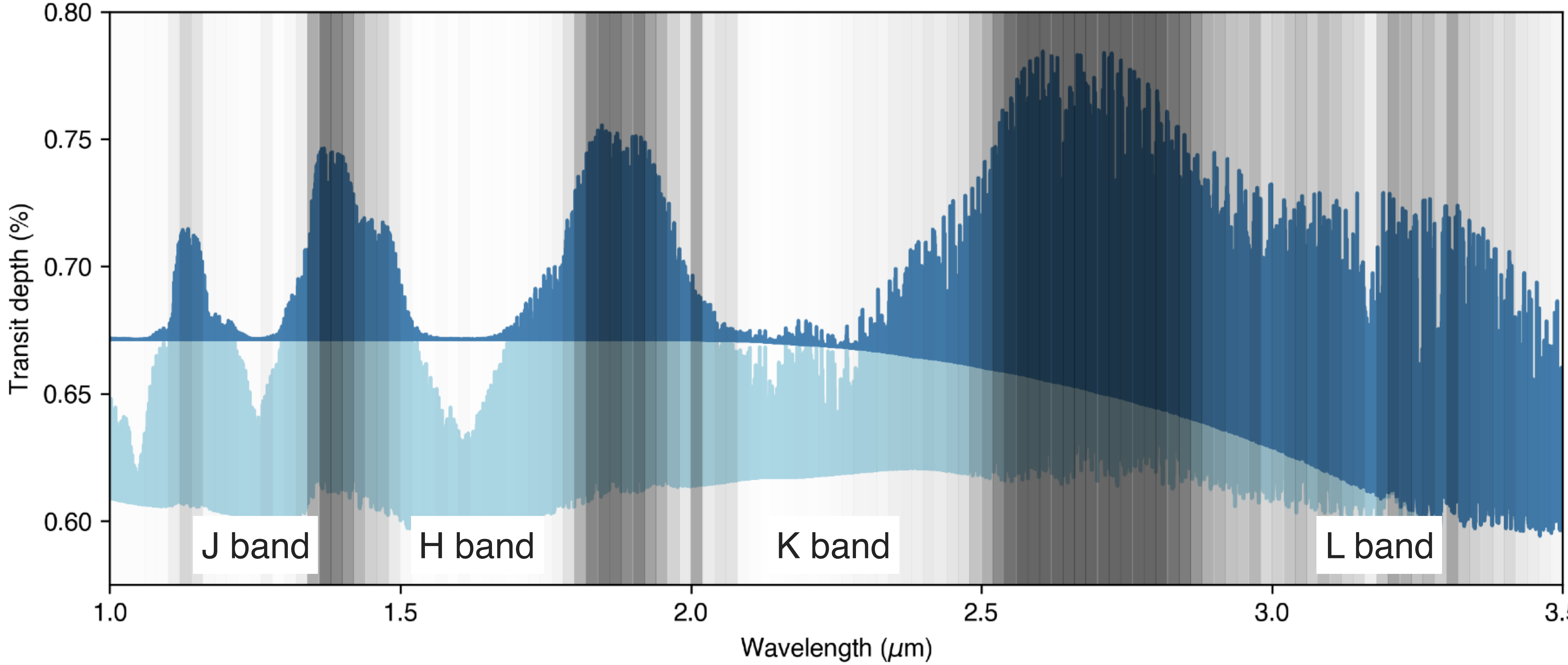


High-altitude cloud deck (0.1-1 mbar) completely mutes "weak" water lines
Peaks of H_2O band still form above the clouds

Degeneracy with **high metallicity** (high mean molecular weight)
at low spectral resolution

Seeing above the clouds at high spectral resolution

H_2O transmission spectrum of a hot Neptune across the NIR spectral range



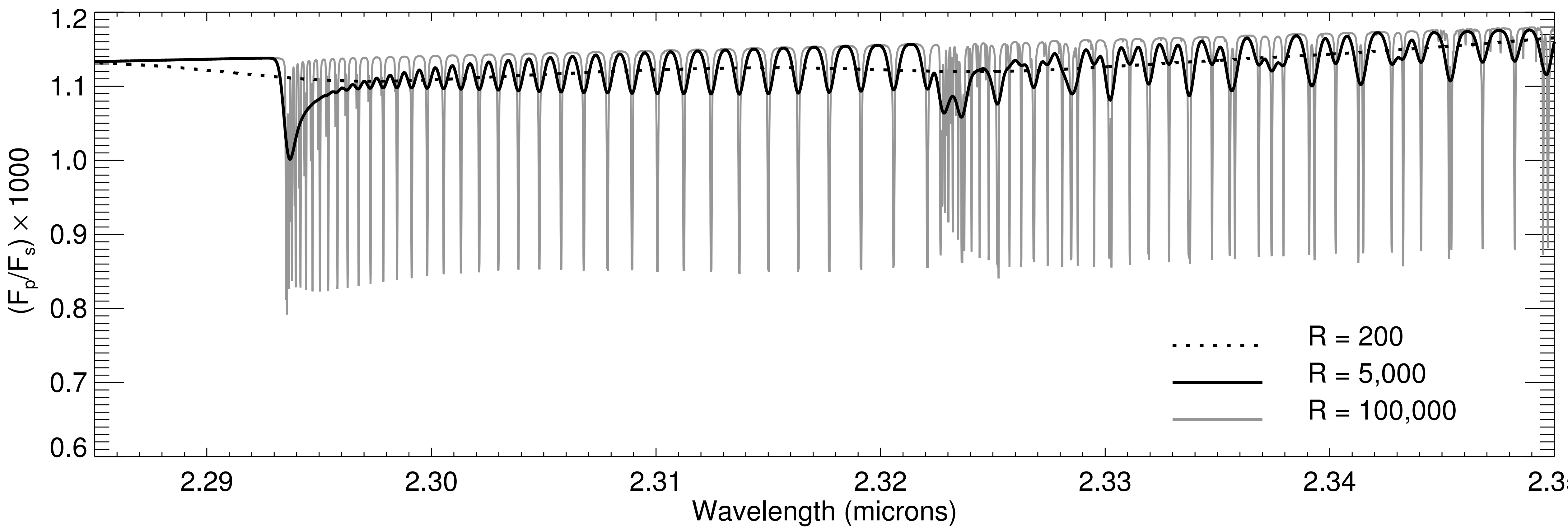
High-altitude cloud deck (0.1-1 mbar) completely mutes "weak" water lines
Peaks of H_2O band still form above the clouds, **except for telluric transmission**

Most of residual signal is away from "classic" NIR bands (J, H, K)
Need to push our data analysis techniques to the edge of the telluric bands

Cloudy / high-Z atmospheres are much less degenerate at high-resolution

A joint analysis of low- and high-resolution spectra

Enabling a true synergy between space and ground observations
In collaboration with M. Line, J. Bean, J.-M. Désert

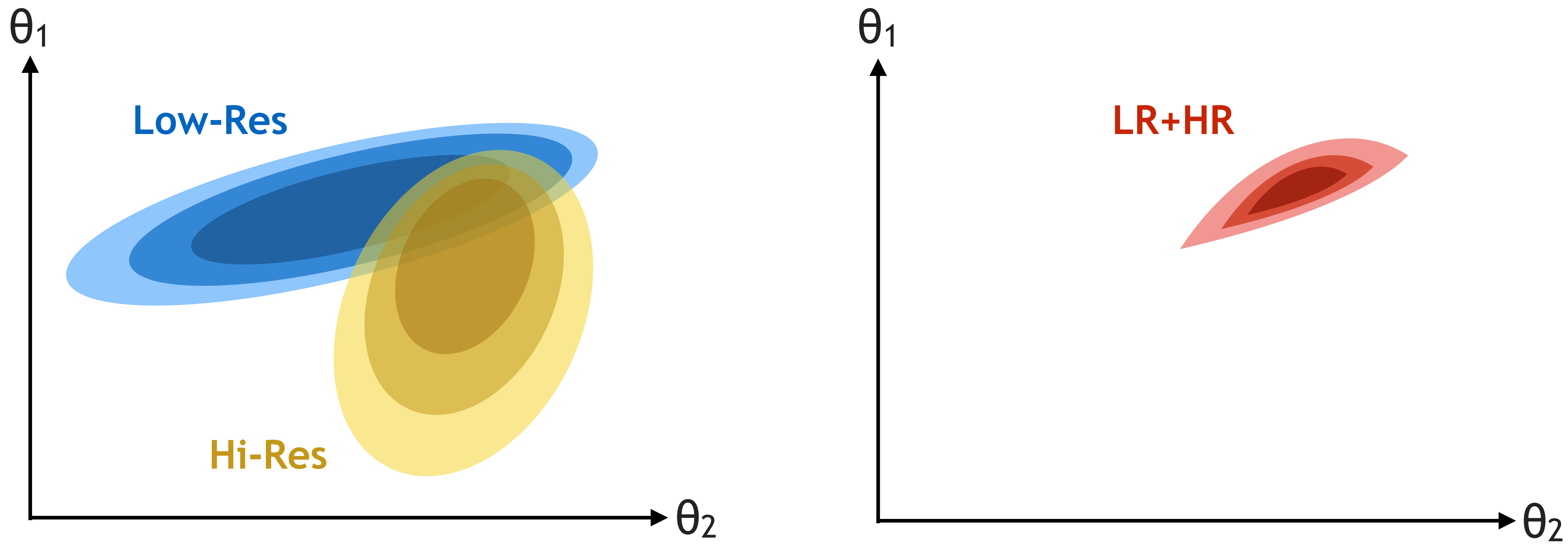


High-resolution spectroscopy
Core-to-continuum line contrast and line shape

Low-resolution spectroscopy
Absolute fluxes and broad-band variations

Two *independent* measurements encoding the same atmospheric parameters
(composition, temperature and pressure)

A joint analysis of low- and high-resolution spectra



Computing a *joint posterior distribution* hi-res + low-res
requires a full MonteCarlo (a random walk in parameters space) in high-res data

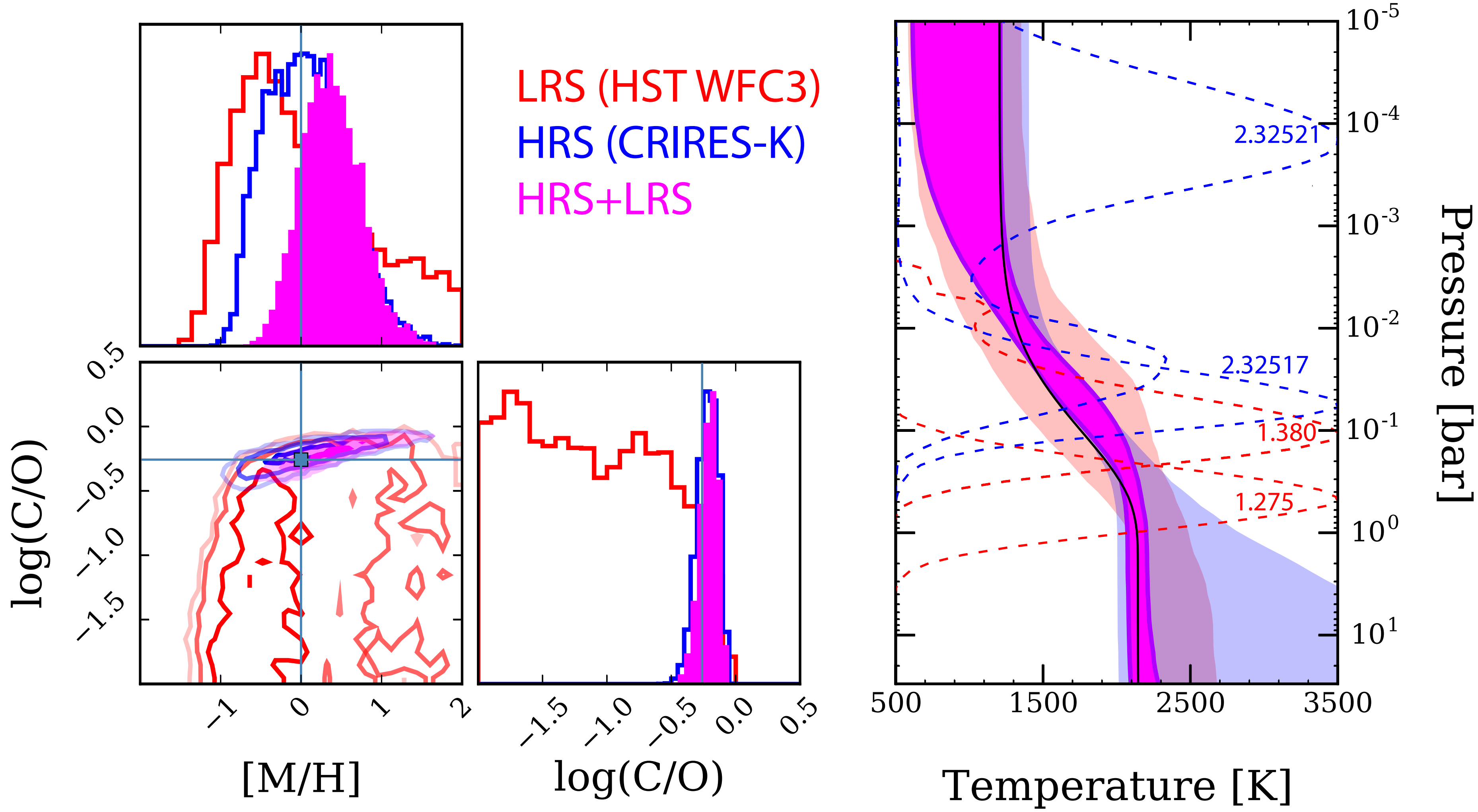
Cross correlation values → Likelihood values → Nested sampler (MCMC) → High-res posteriors

Orbital parameters become MCMC parameters

Conceptually simple, but implementation took ~ 2 years of work
(unbiased CC-to-L mapping, unbiased analysis, speeding up of code)

Measuring C/O and metallicity in a Bayesian framework

Brogi & Line (2019): simulated HST + VLT/CRIRES observations
Noise level of current observatories (1 eclipse / 5 hours)

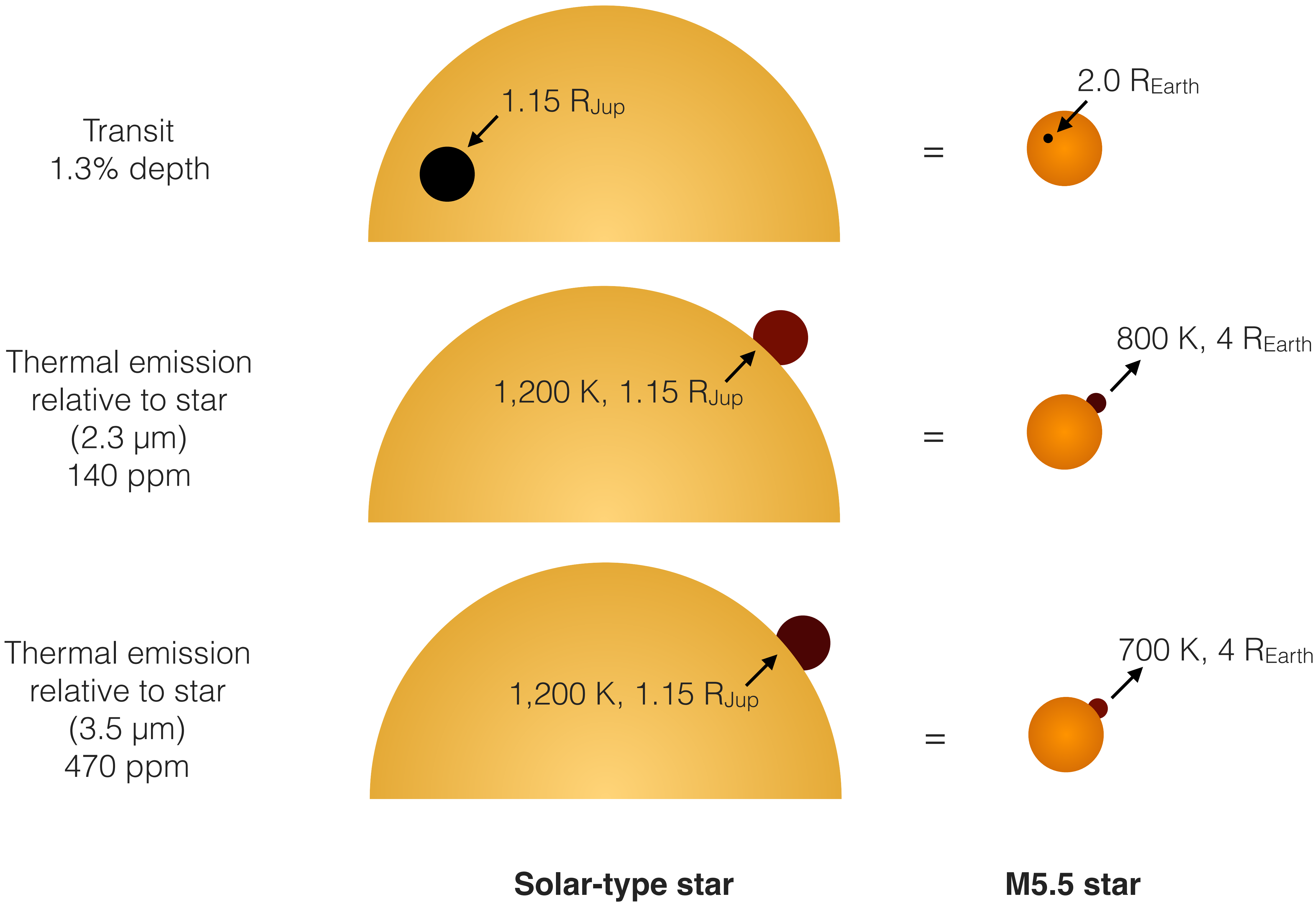


Space: good absolute abundances => metallicity
Ground: good relative abundances => C/O ratio

Combined precision: 1.0 dex in metallicity; 0.3 dex in C/O ratio
Consistency: same modelling/assumptions between LRS and HRS

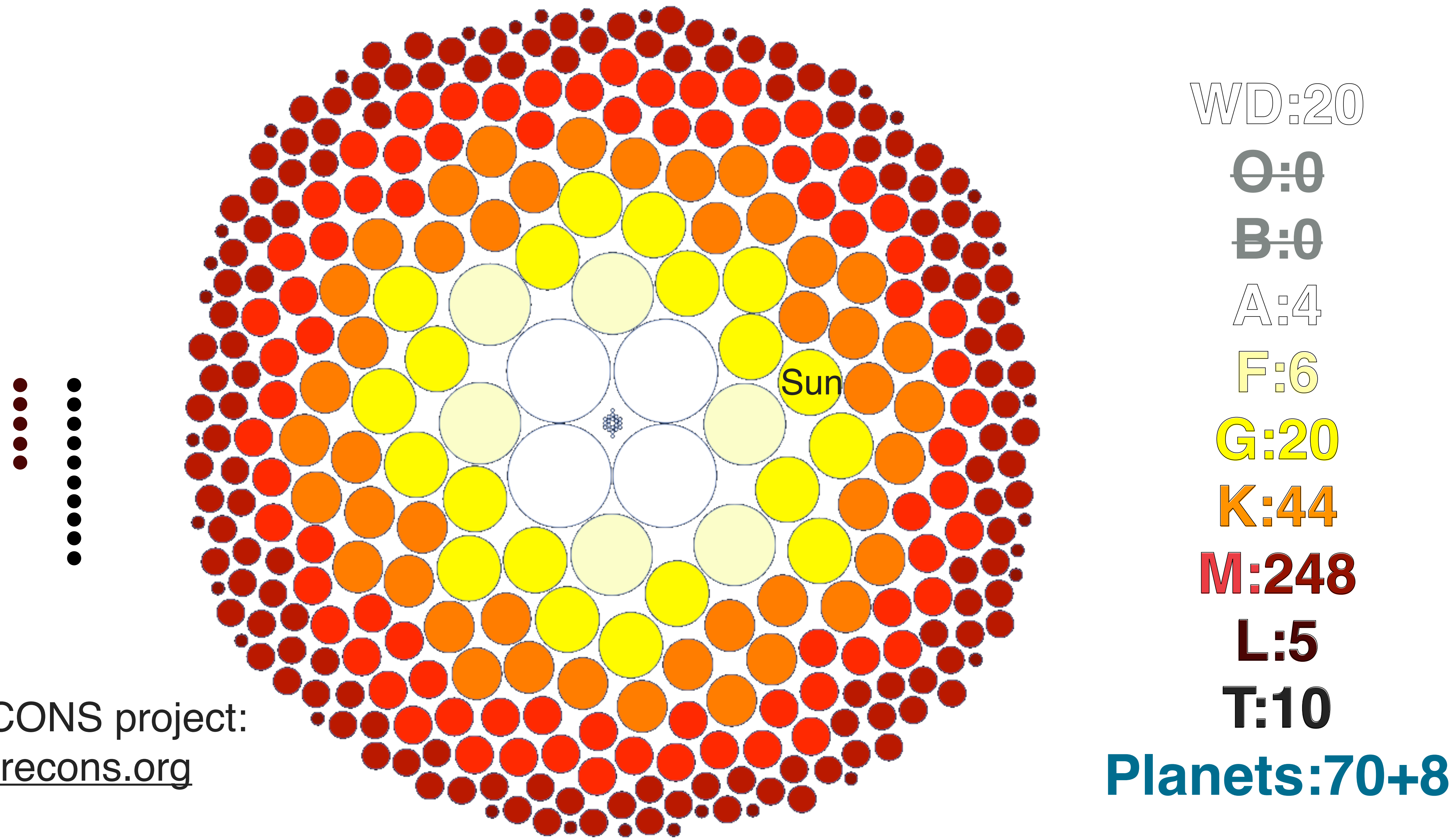
Moving towards M-dwarf planets

M-dwarfs are smaller and cooler than the Sun, but still bright in the infrared
Warm sub-Neptunes around (nearby) M-dwarfs are within reach of current techniques



Planets around M-dwarf stars are abundant

Dressing & Charbonneau (2015): 2.5 planets / star, 30% in the classic habitable zone
M-dwarf stars are abundant ⇒ Temperate M-dwarf planets are nearby

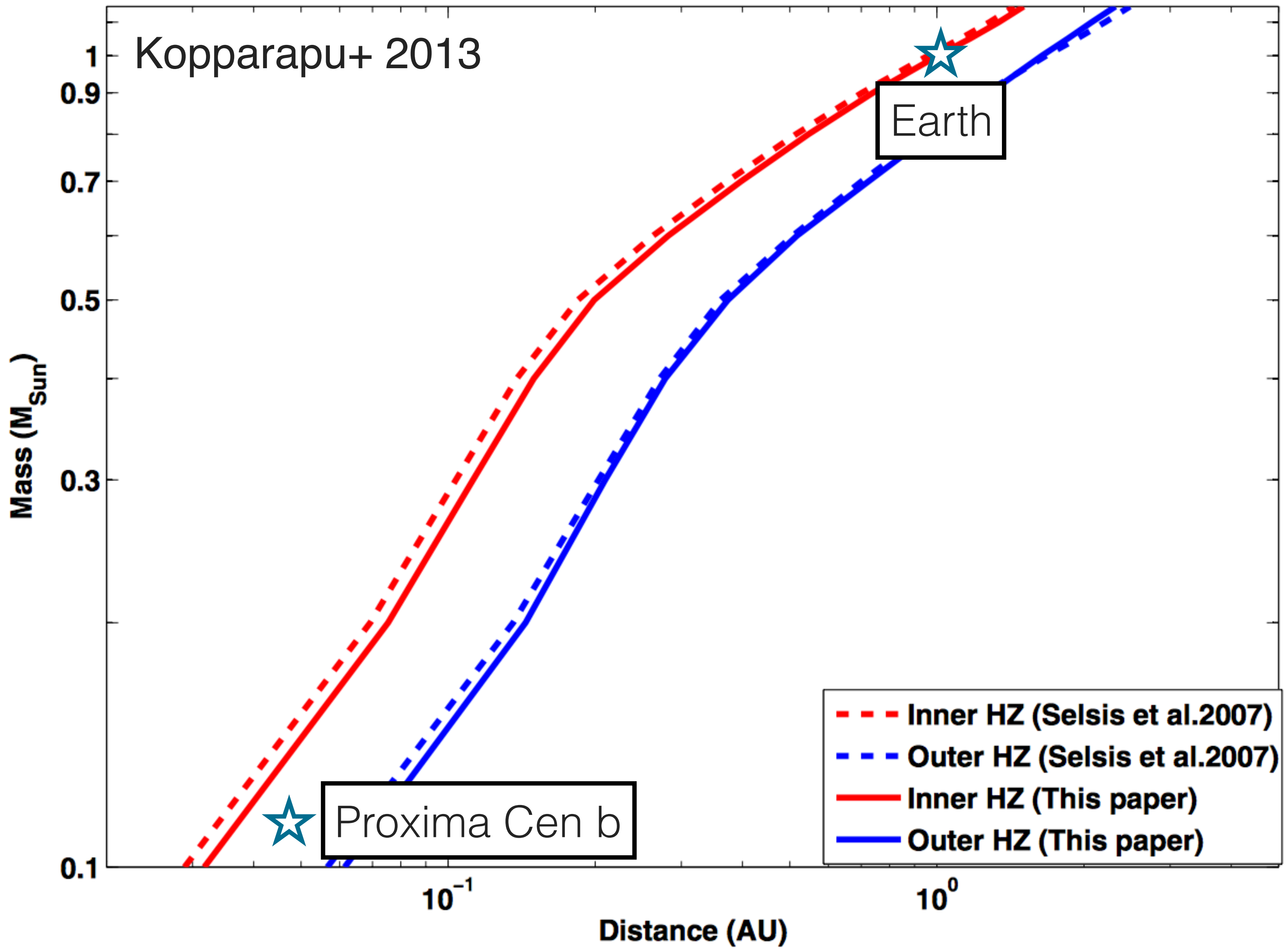


The RECONS project:
www.recons.org

Current (incomplete) census: 70 planets within 10 pc, 35 within 5 pc
Notable examples: Proxima Cen b,c (1.3 pc) & Trappist-1 a-g (12 pc)

Habitable zones around M-dwarfs

Habitable zone (Earth-based) moves inward with decreasing stellar mass
Potentially habitable planets orbit very close to M-dwarfs

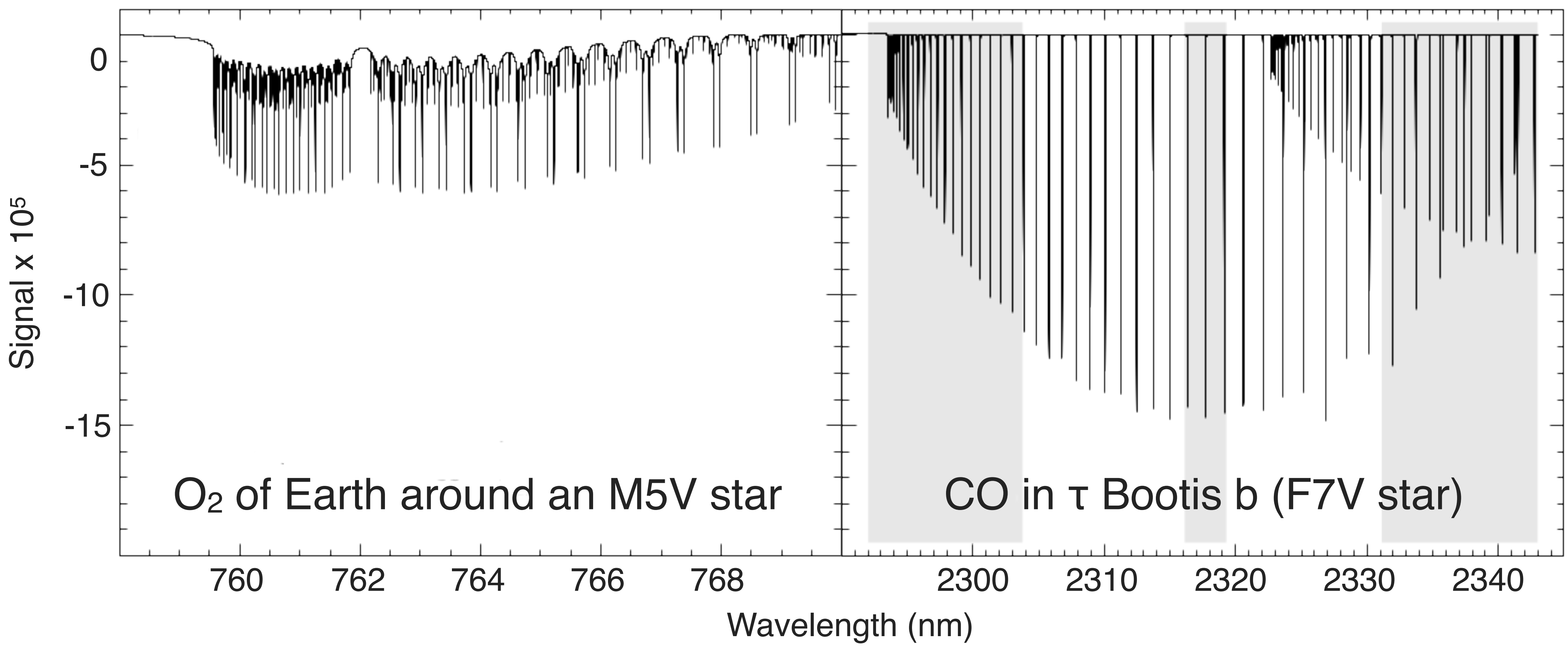


Key observational consequences

Temperate planets have an increased probability to transit M-dwarfs
Transits repeat every few days only and can be stacked quickly to increase S/N

Transiting terrestrial planets around M dwarfs

Oxygen in high-resolution transmission spectra
Average line depth is 1/3 of the CO dayside signal from τ Boo b



Challenge: even the closest M-dwarf is much fainter than τ Boo (at least 6 magnitudes)
Extremely Large Telescopes + Hi-res spectroscopy are needed to reach the S/N

39m E-ELT, 30 transits (3 years) ⇒ 3σ detection

High instrumental efficiency and RV separation from telluric oxygen is key
(Snellen+13, Rodler & Lopez-Morales14; Serindag & Snellen 19; Lopez-Morales+19)

Combining spectral and spatial resolution

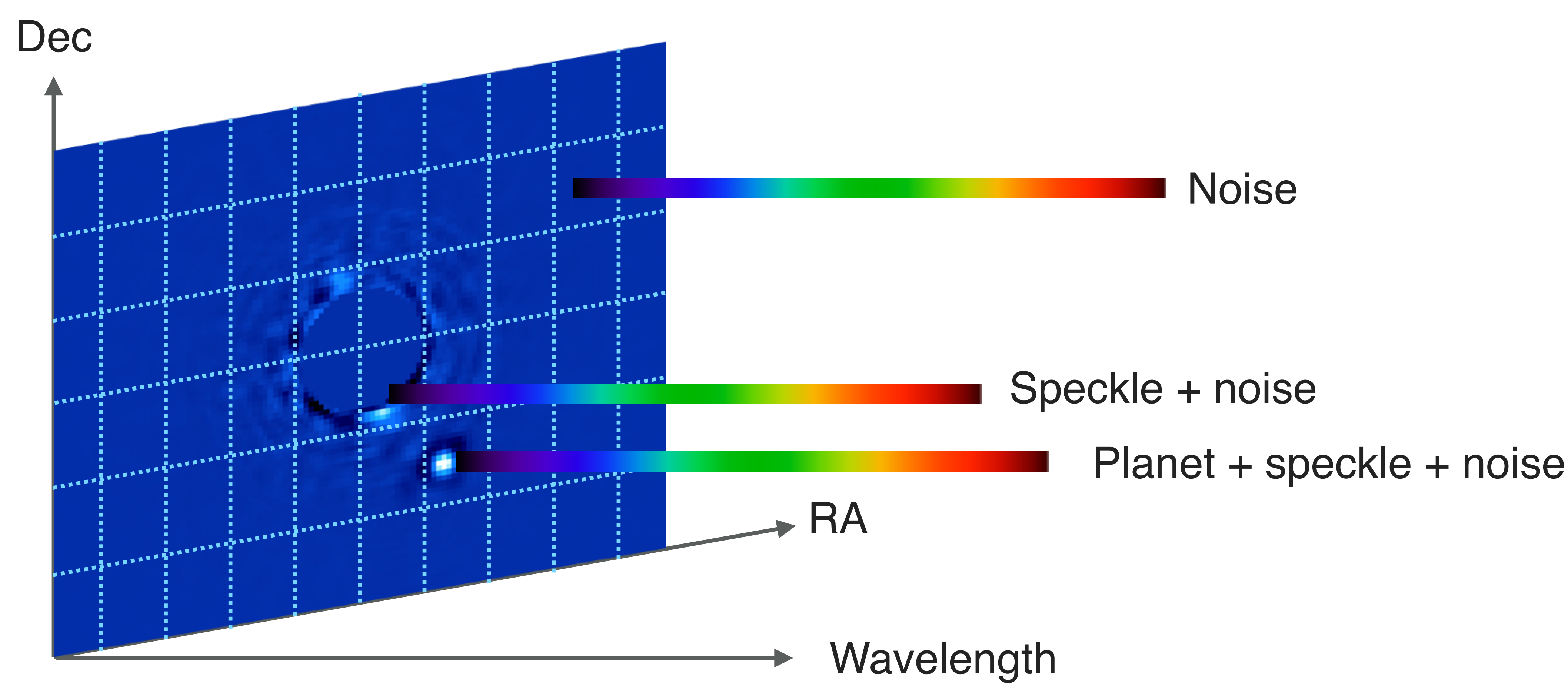
Snellen+ 2014, 2015; Lovis+ 2016; Mawet+ 2017; Wang+ 2017

$$S/N = \frac{S_{\rm planet}}{\sqrt{S_{\rm star}/K + \sigma^2_{\rm bg} + \sigma^2_{\rm RN} + \sigma_{\rm Dark}}}\sqrt{N_{\rm lines}},$$

Direct imaging suppression

Cross-correlation gain

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

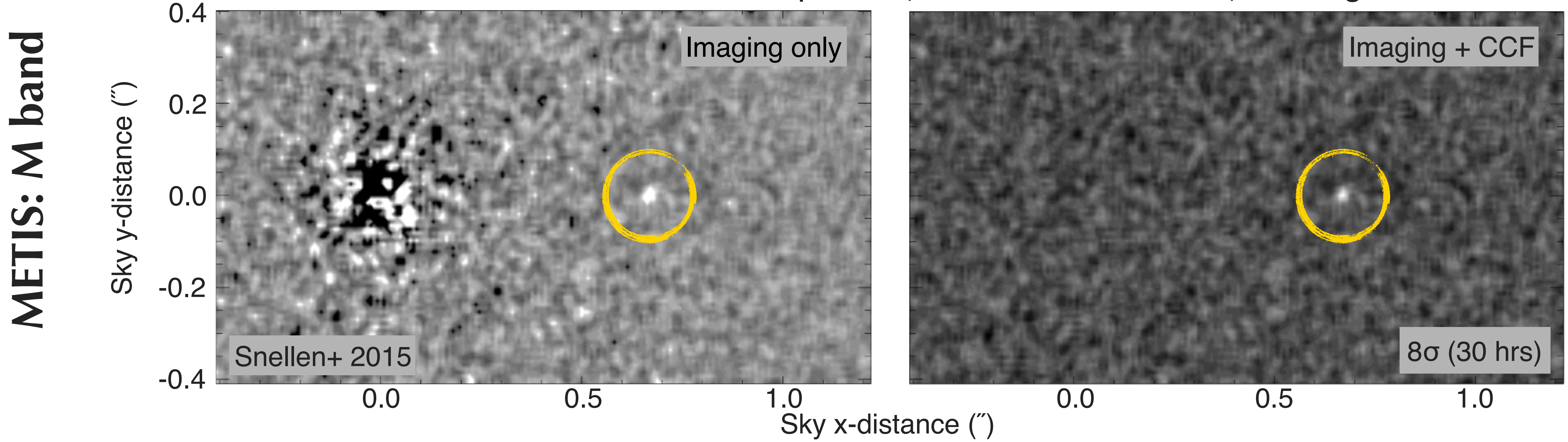


Stage 1: classic AO + DI algorithms to suppress starlight
Stage 2: cross-correlation of residual spectra at each pixel

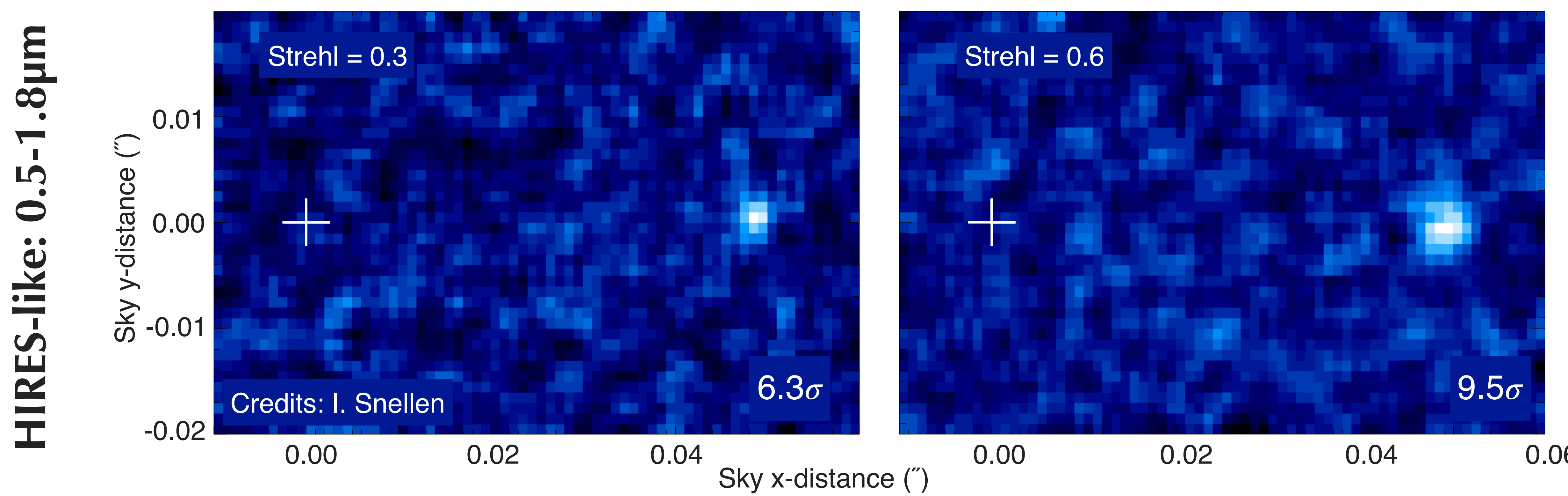
Spectral + spatial resolution with the ELT

Simulating ~30 hours of observations on our nearest neighbours (I. Snellen)

Thermal emission of **"Earth-like"** planet (1.5 $R_\oplus$, 300 K, 30 km/s) orbiting α Cen B



Reflected light from **Proxima Cen b** (1.1 $R_\oplus$, 0.048 AU, 40 km/s)



Exoplanets at high spectral resolution: wrapping-up

Ideal ground-based technique

Bigger aperture, higher resolving power, no need for reference stars

Probing physics and chemistry of atmospheres

Molecular and atomic species, thermal structure, winds and rotation

Compatible with space observations

Complementarity with JWST

Combination with direct imaging

Theoretically hitting the 10^{-9} contrast