High-resolution spectroscopy for exoplanet characterisation

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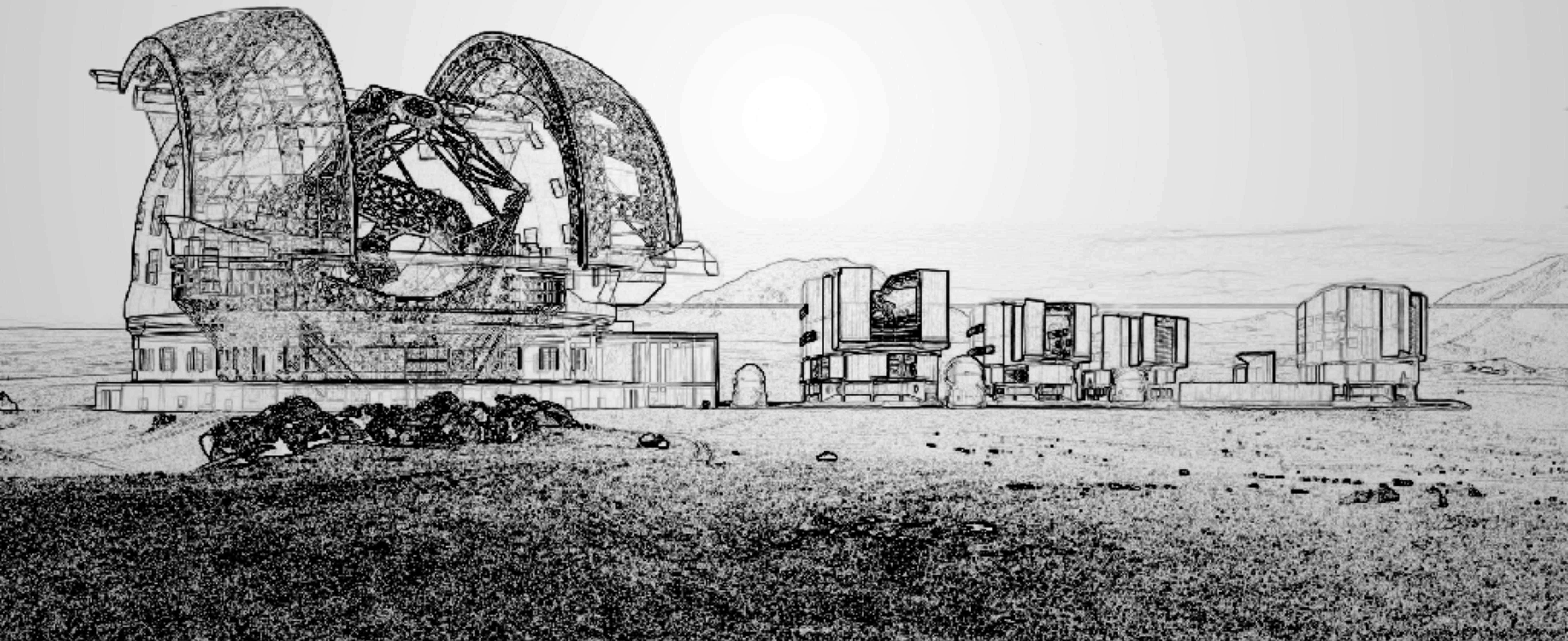


Basic concepts

Spectral resolution and spectrographs

Exoplanets and their orbits

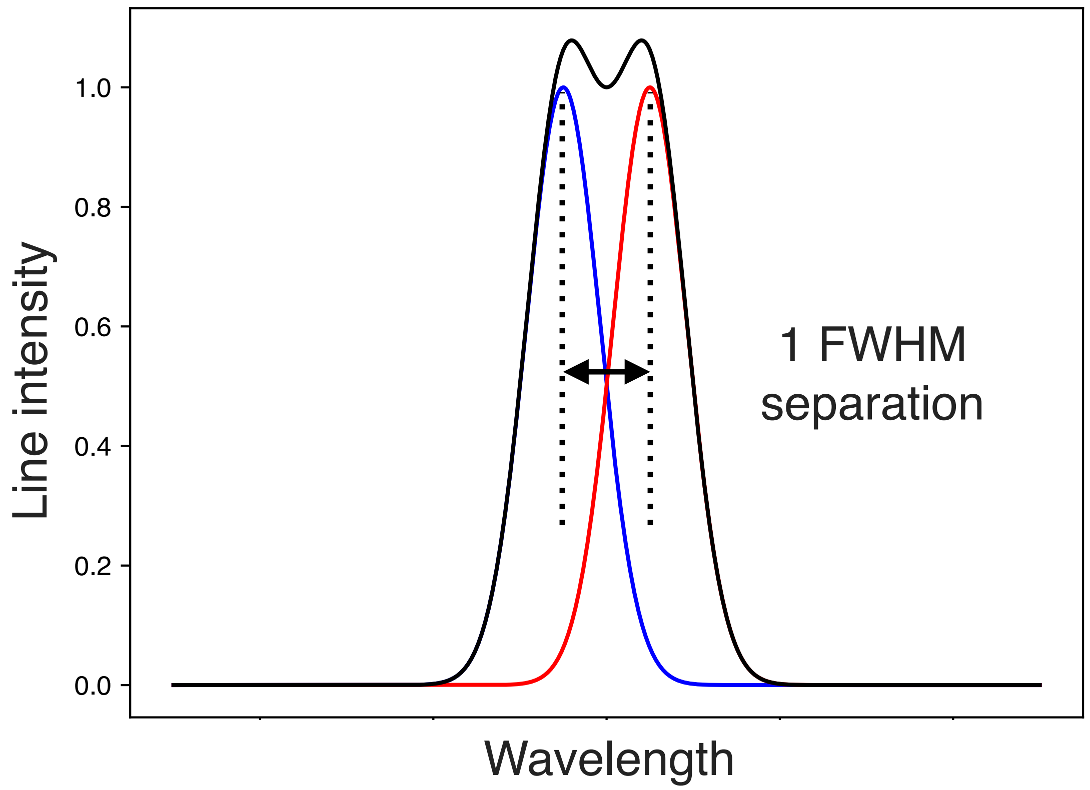
Low-resolution spectroscopy of transiting exoplanets

Basic concepts in spectroscopy: resolution

The ability to distinguish light of similar frequency

How close can two spectral lines be to be considered “spectrally resolved”?

Throughout these lectures we’ll adopt the Houston criterion



We’ll assume that spectrographs turn a delta function into a Gaussian with FWHM=λ/R

Spectrographs are characterised by a ~constant resolving power $R=\lambda/\Delta\lambda$

This translates into a variable spectral resolution $\Delta\lambda$ according to wavelength λ

Linking resolution to velocity

Objects in motion absorb/emit at shifted wavelengths λ' due to Doppler effect
We will use the non-relativistic Doppler formula

$$\lambda' = \lambda\left(1 + \frac{v}{c}\right) \qquad \Delta\lambda \equiv (\lambda' - \lambda) = \lambda\frac{v}{c}$$

$$R = \frac{\lambda}{\Delta\lambda} = \frac{c}{v}$$

The minimum velocity shift v that can be fully resolved is related to R via

$$v = \frac{c}{R}$$

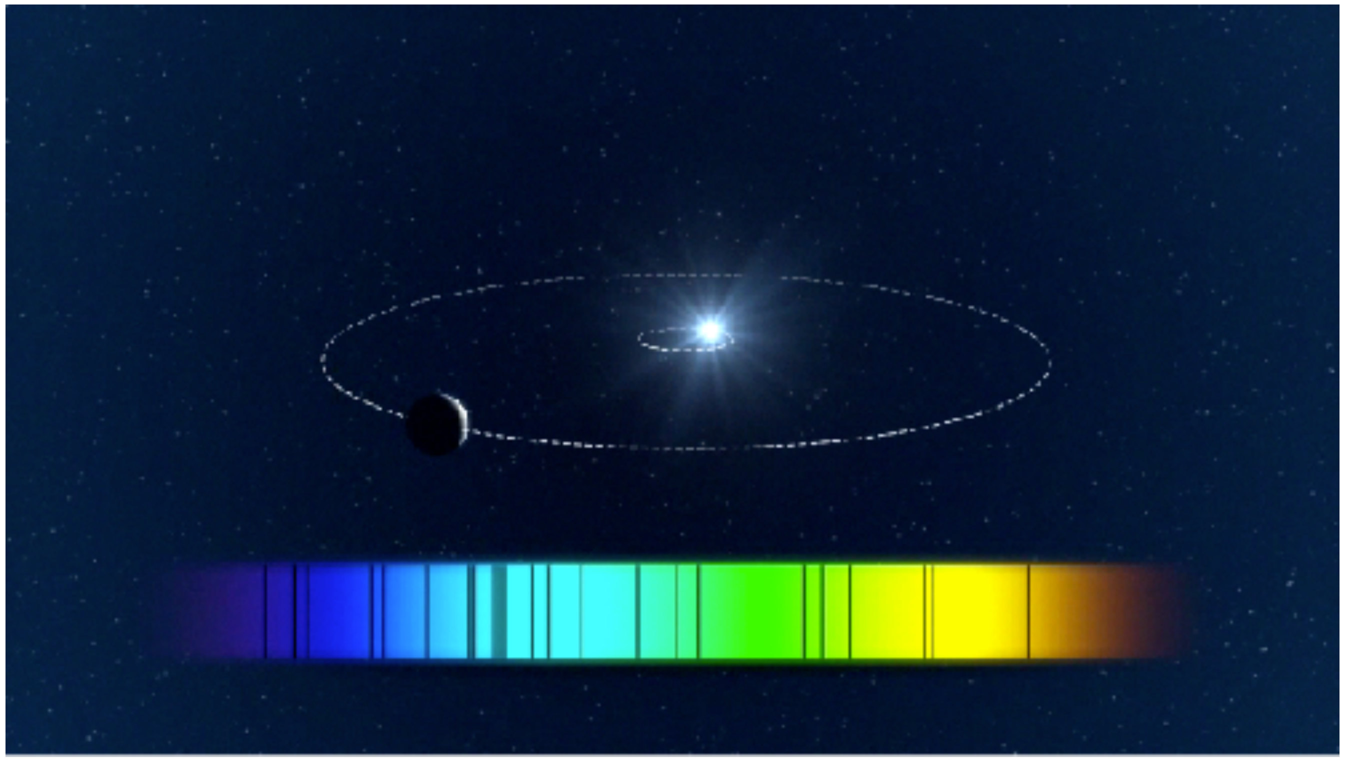
R = 500 (low-res) ⇒ Δv = 600 km s^{-1}
Generally insufficient for most astrophysical sources

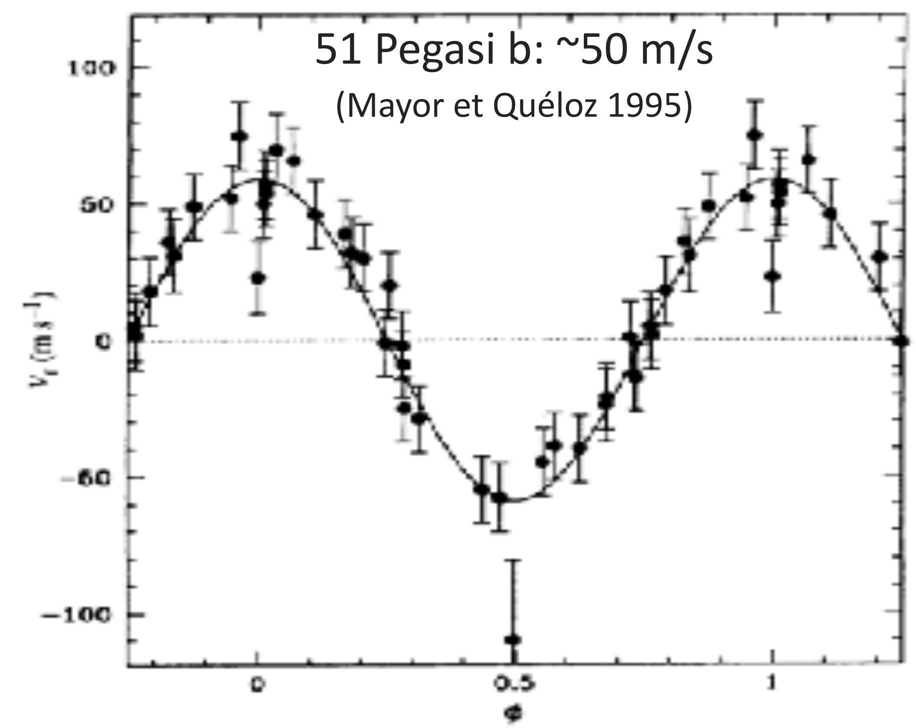
R = 5,000 (intermediate-res) ⇒ Δv = 60 km s^{-1}
OK for the broadest spectral lines

R = 50,000 (high-res) ⇒ Δv = 6 km s^{-1}
OK for most of spectral lines, and exoplanet orbital motion too!

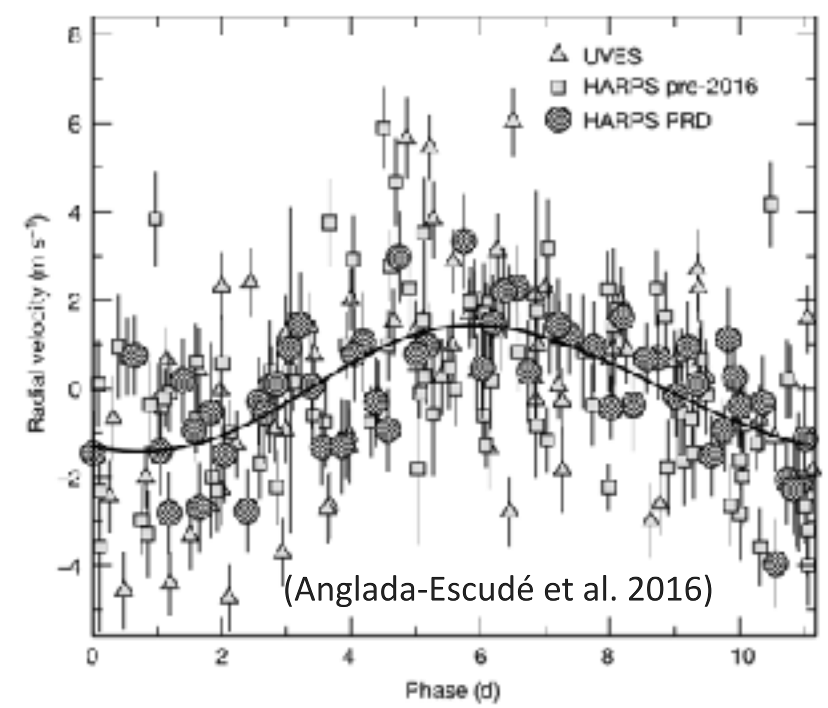
Using spectroscopy to *find* exoplanets

Periodic shift of spectral lines due to reflex motion around the centre of mass





Proxima Cen b: ~1.4 m/s

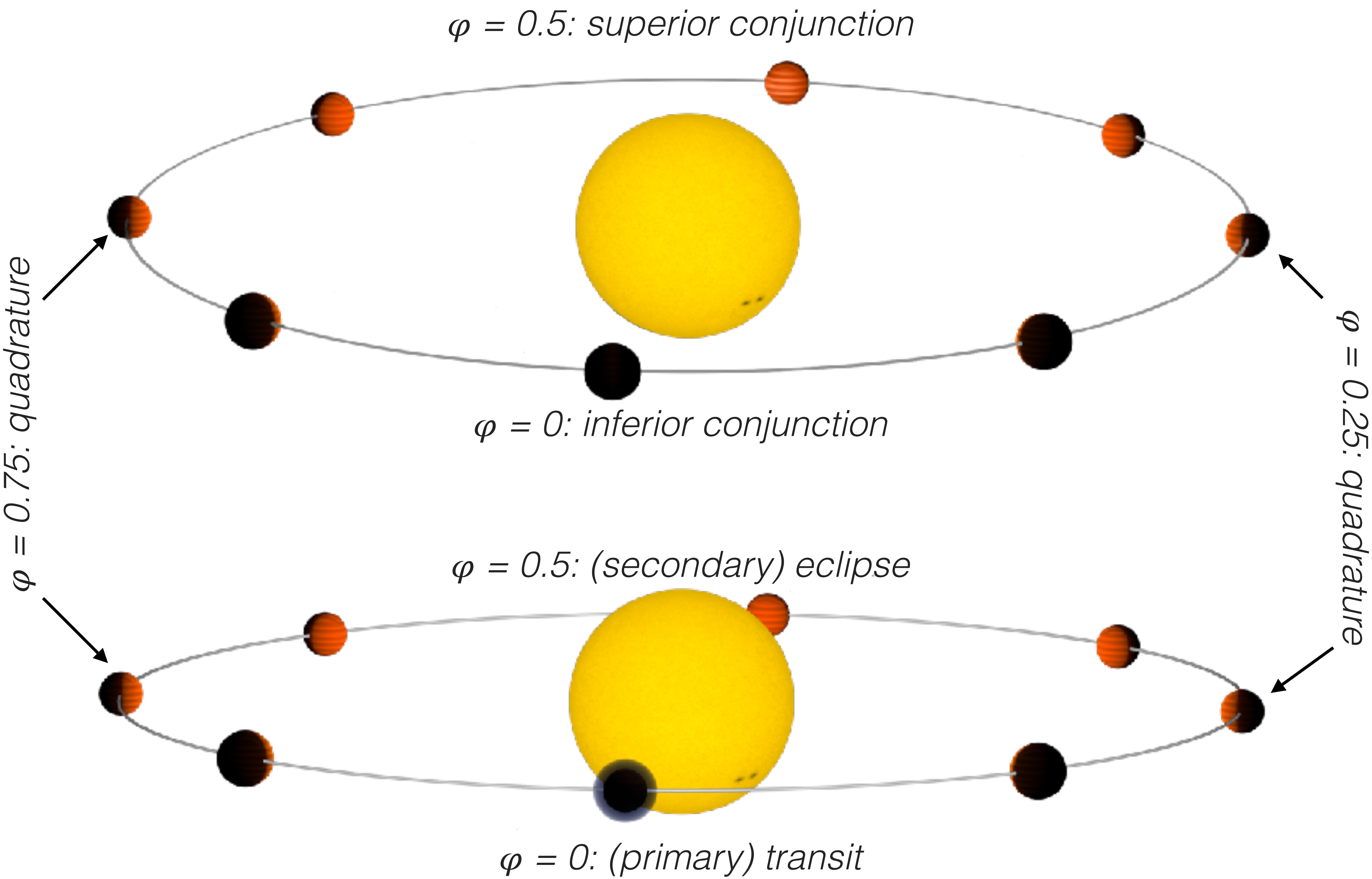


Period of the orbit
Eccentricity of the orbit

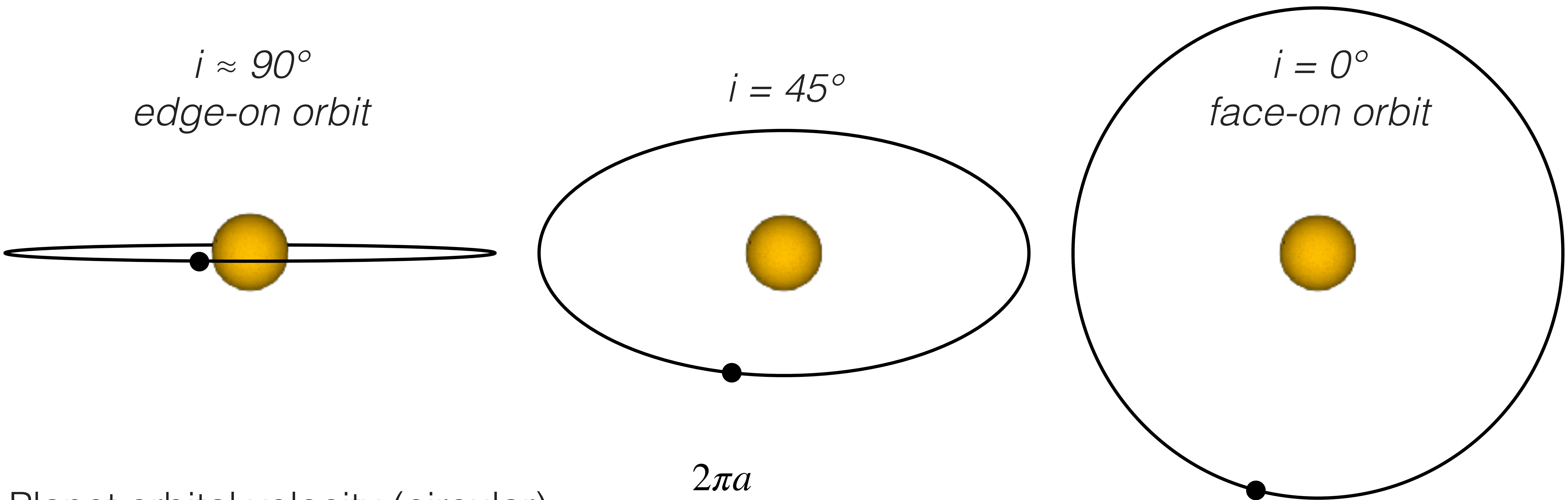
Only lower limit on planet mass
(orbital inclination unknown)

10 cm/s required to do Earth-Sun systems
current limits are 30 cm/s (instrumental)
and ~1 m/s (stellar)

Nomenclature for orbital phases φ of exoplanets



Orbital radial velocity of an exoplanet



Planet orbital velocity (circular): $v_{\rm orb} = \frac{2\pi a}{P}$

Maximum planet radial velocity: $K_{\rm P} = v_{\rm orb} \sin(i)$

Planet radial velocity at each orbital phase

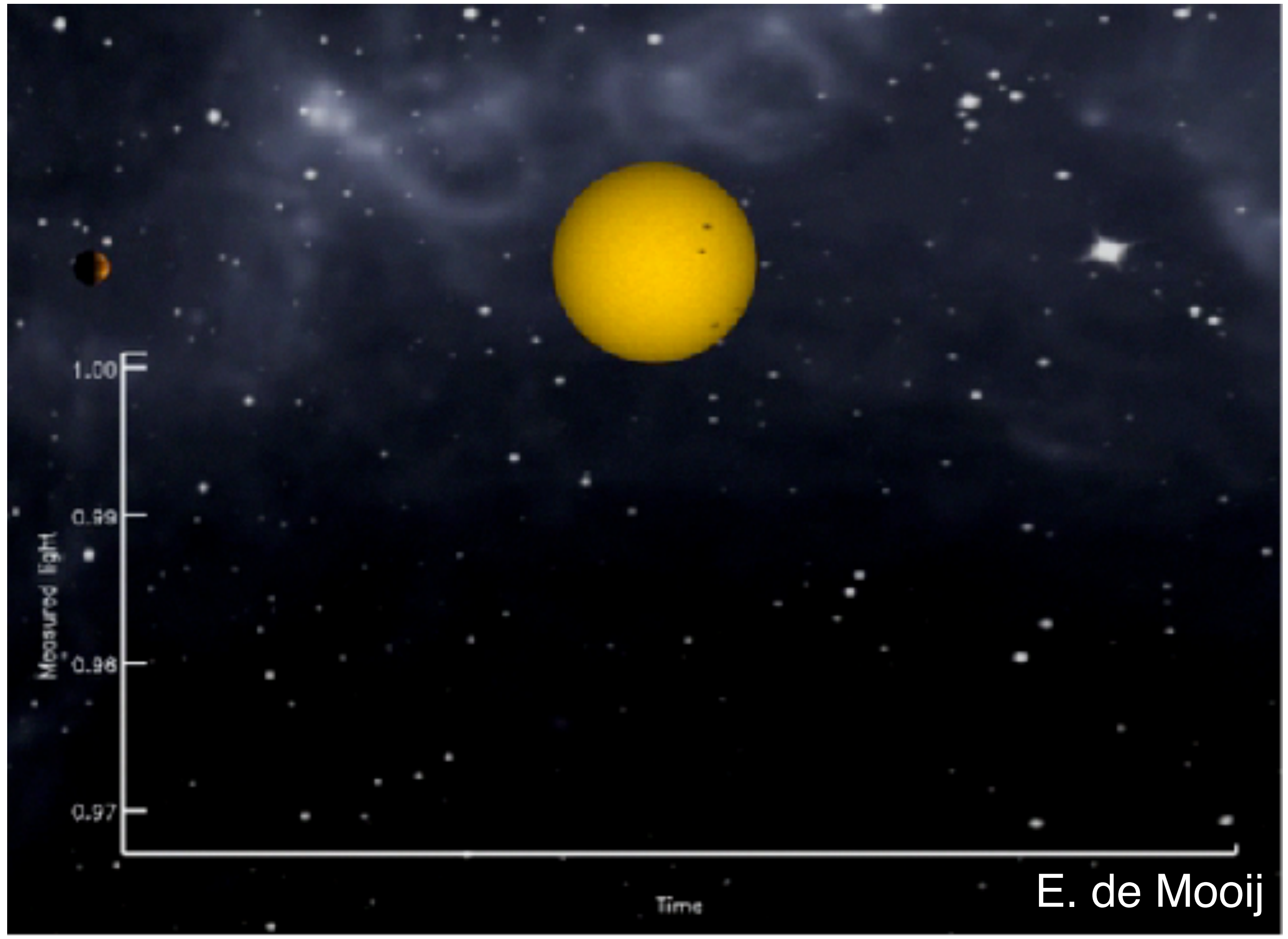
$$\mathrm{RV_P} = v_{\rm orb} \sin(i)\ \sin(2\pi\varphi) \equiv K_{\rm P} \sin(2\pi\varphi)$$

In the reference frame of the exoplanet system

Additional velocity terms are needed to compute the RV as measured by the observer (day 2)

Light curves of transiting exoplanets

Dimming of starlight due to transit or eclipse of planetary body

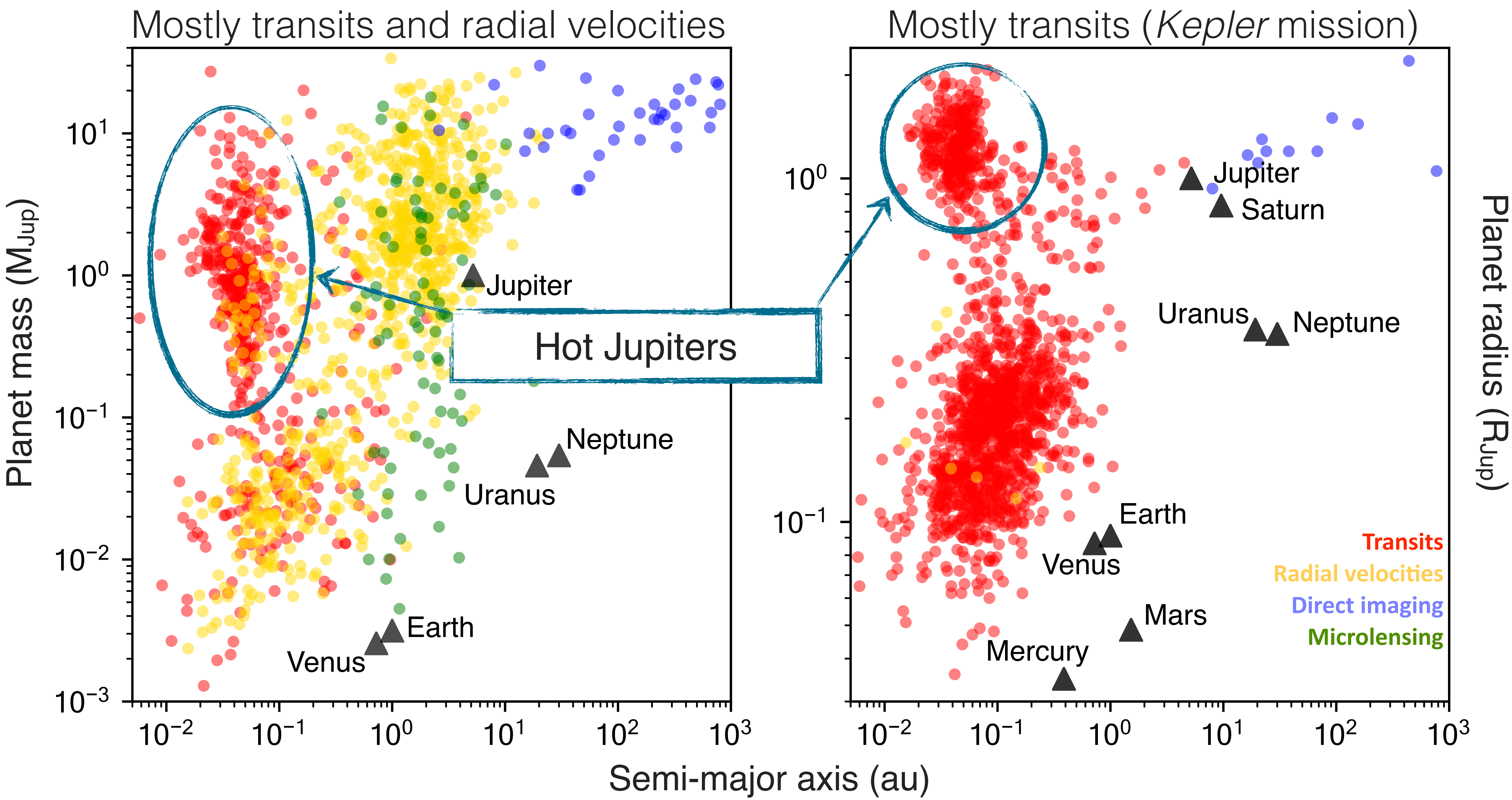


Period of the orbit
Radius of the planet relative to the star
Orbital inclination

Measuring the stellar light accurately is a challenging task from the ground due to instability of the instrument (flexure, pointing, etc.) and of the Earth's atmosphere (transparency, water vapour, etc.)

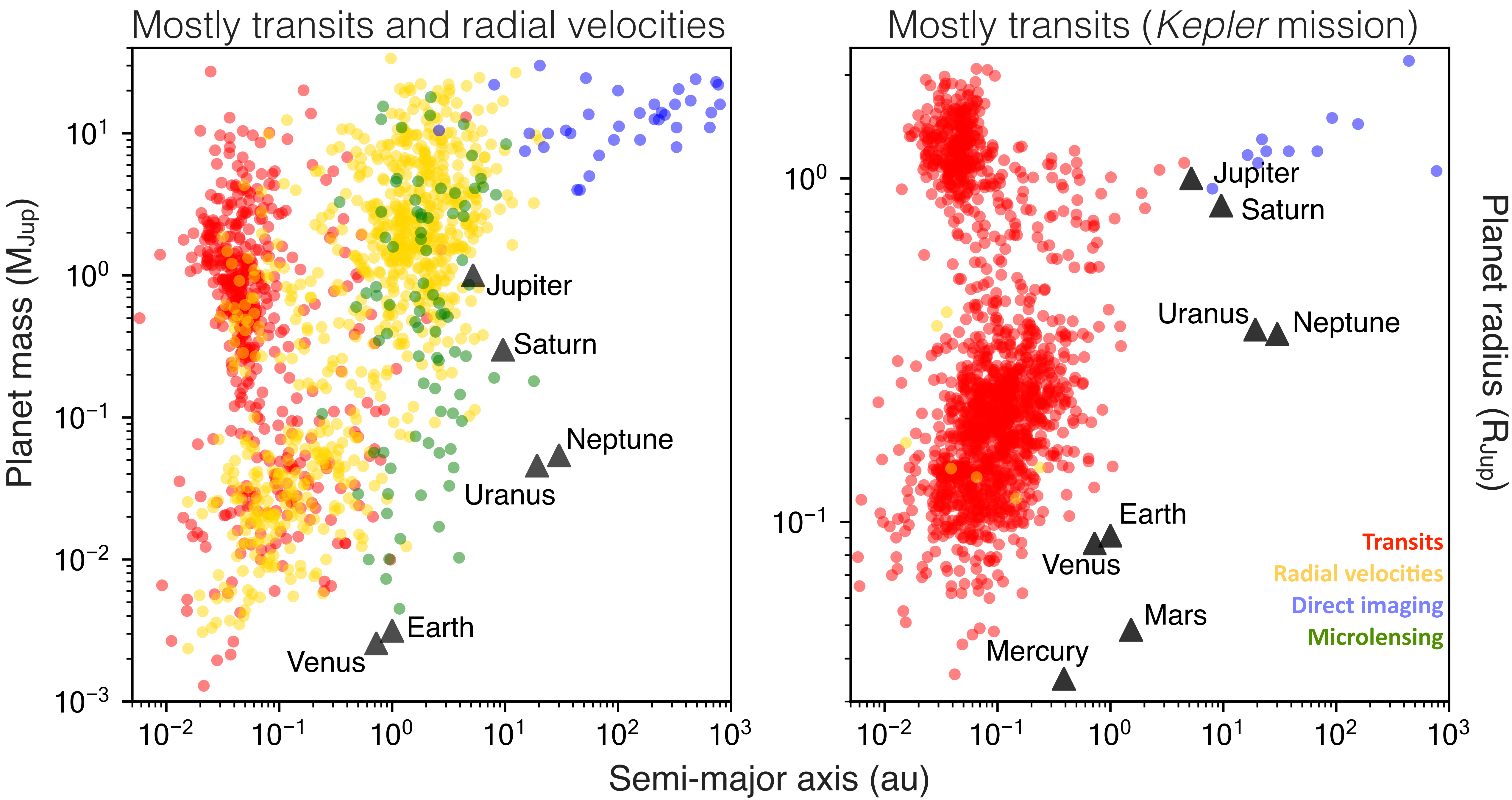
We live in the golden era of exoplanet discoveries

1995-2021 ⇒ 4,400 confirmed exoplanets



Is our solar system rare?

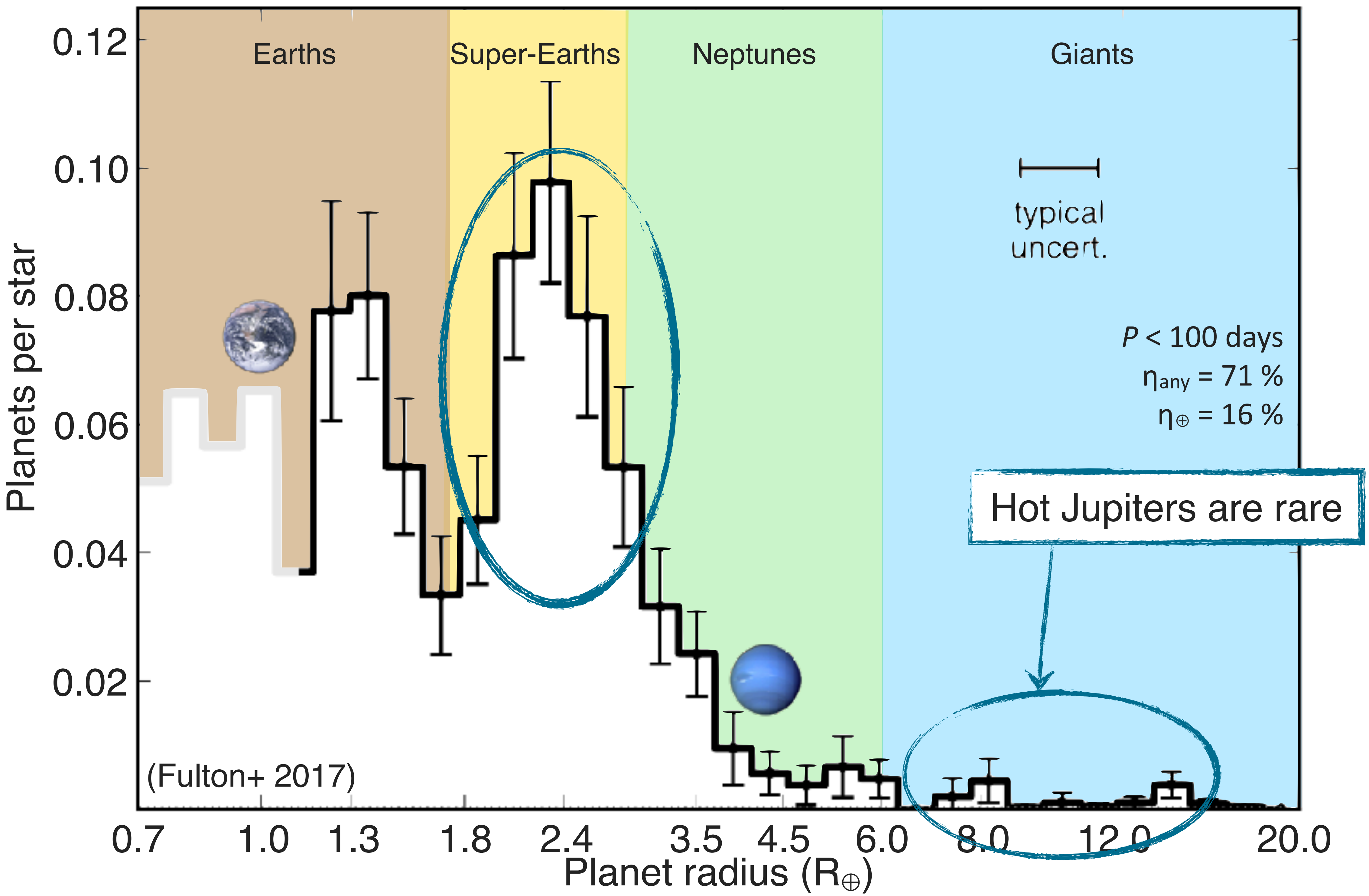
The discovery space corresponding to solar system planets is empty



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

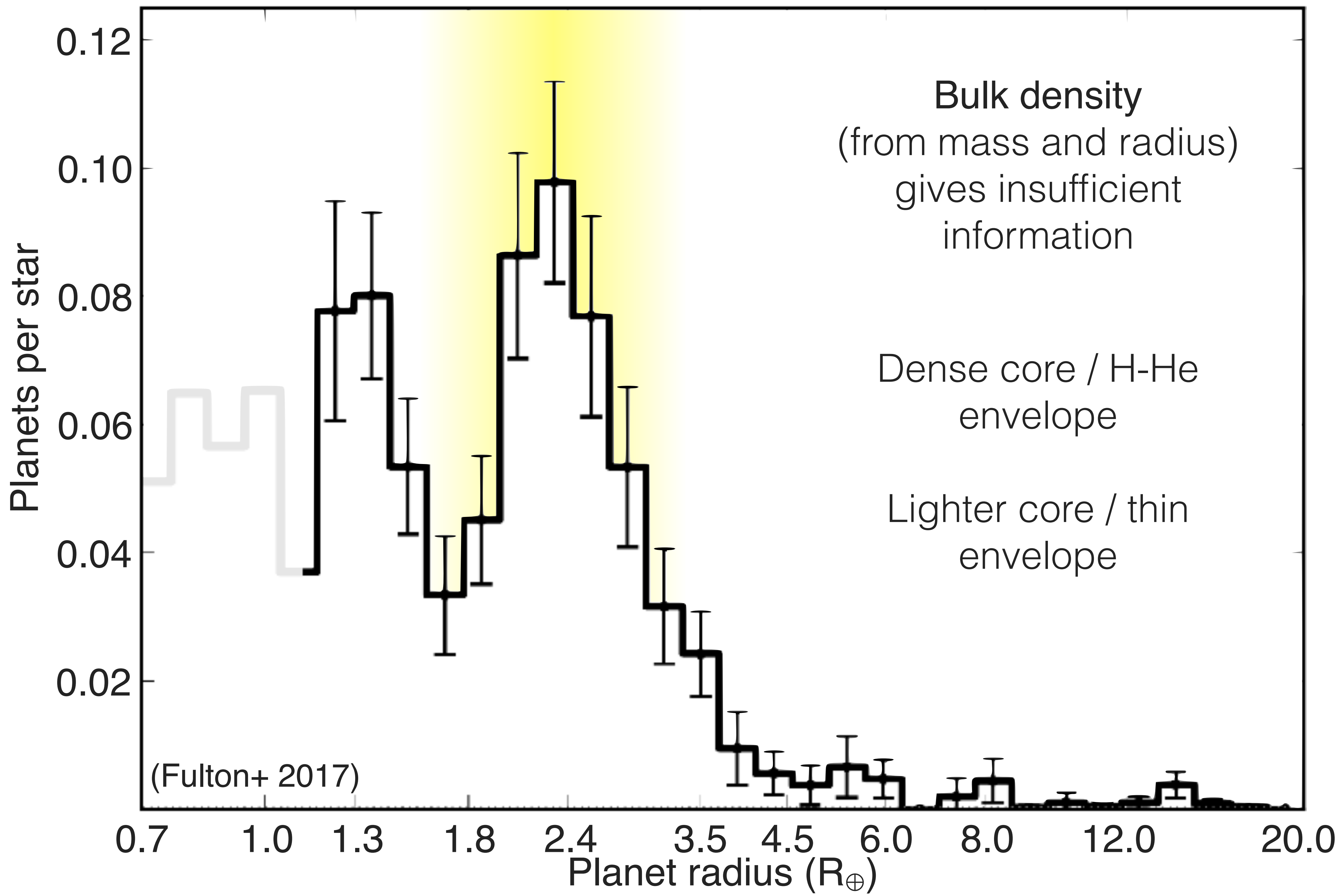


The most common planets have no analogues in the solar system

(their size is intermediate between Earth and Neptune)

What is the nature of the most common exoplanets?

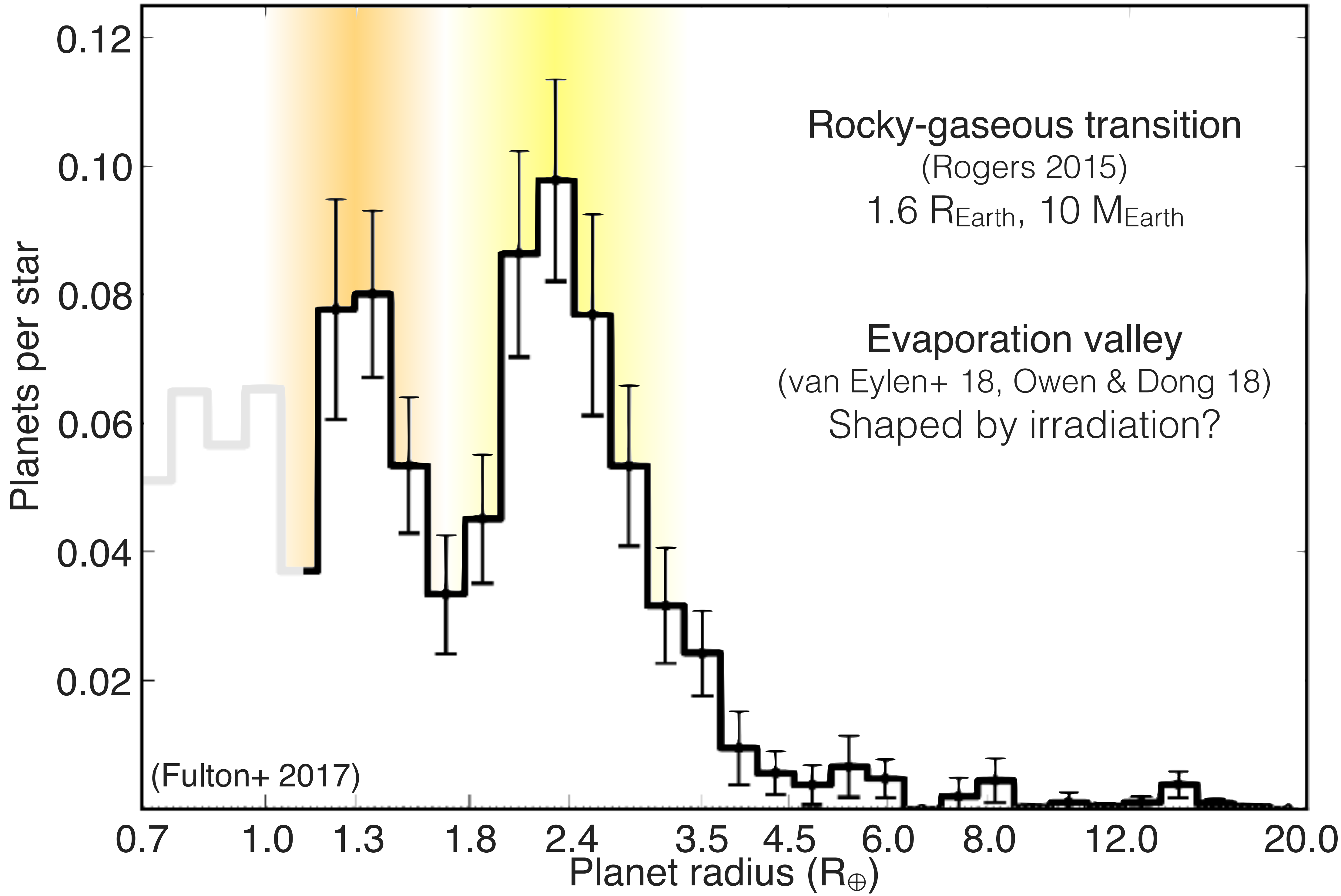
The mini-Neptune / super-Earth dilemma



Studying the atmospheres can lift the envelope-interior degeneracy
(Adams+08, Miller-Ricci+09 Rogers & Seager 10, Dorn+15)

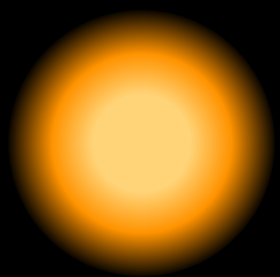
The gaseous/rocky transition and the evaporation valley

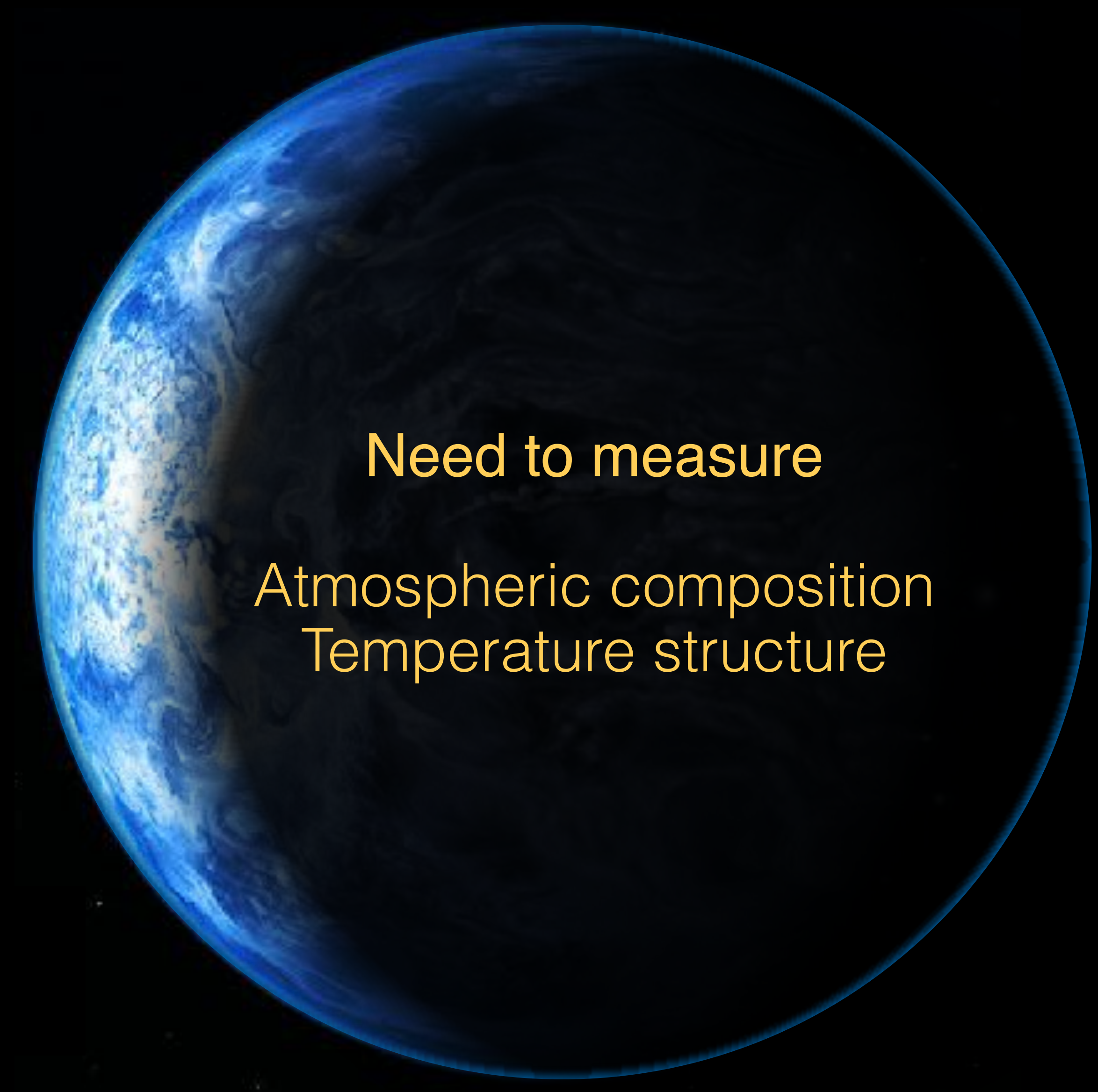
What shapes the transition between gas and rocky planets?



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

Key questions about exo-atmospheres





Need to measure

Atmospheric composition
Temperature structure

How do atmospheres form and evolve?

Does composition reflect formation conditions?

What is the range of planetary climates?

What are the driving chemical processes?

What is the prevalence of bio-signatures?

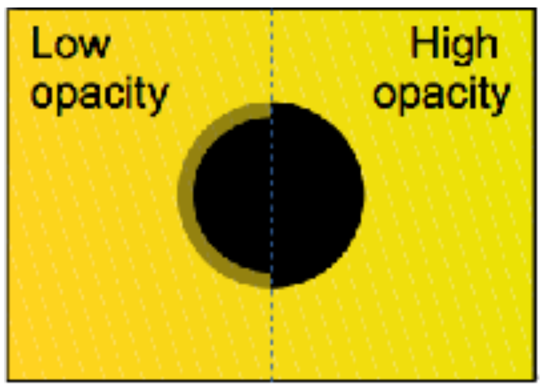
Must balance low measurement precision with sample size
(comparative / statistical studies)

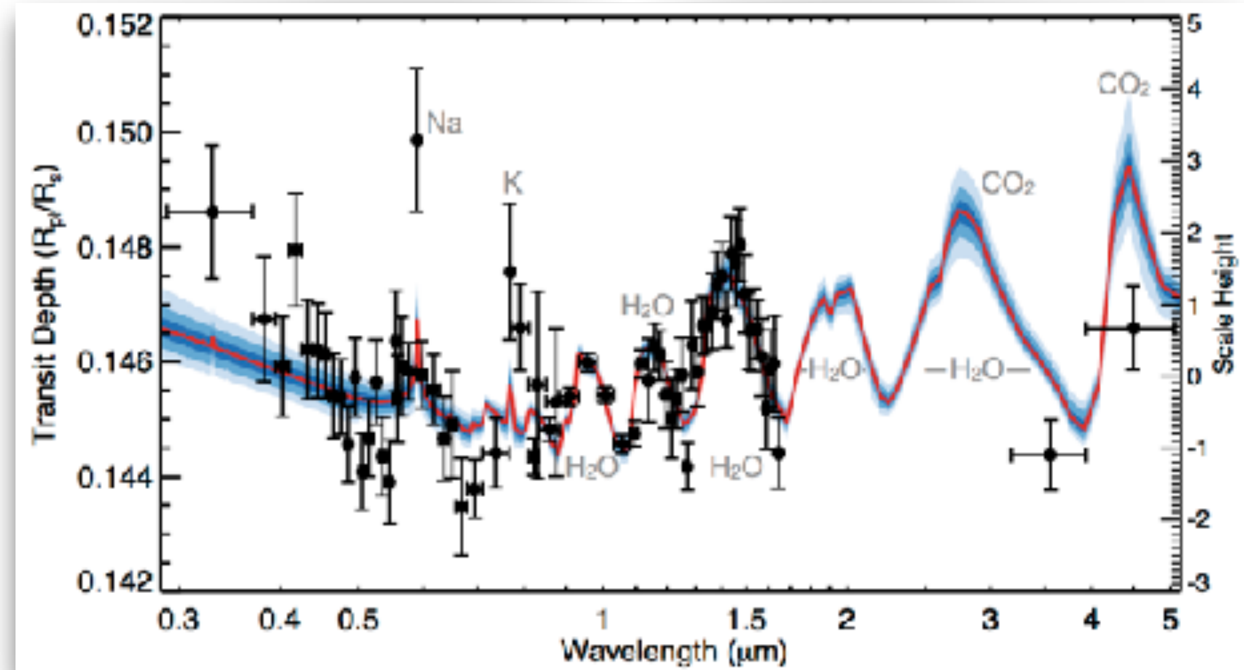
Transmission spectroscopy of exoplanets

$R_P = R_P(\lambda)$

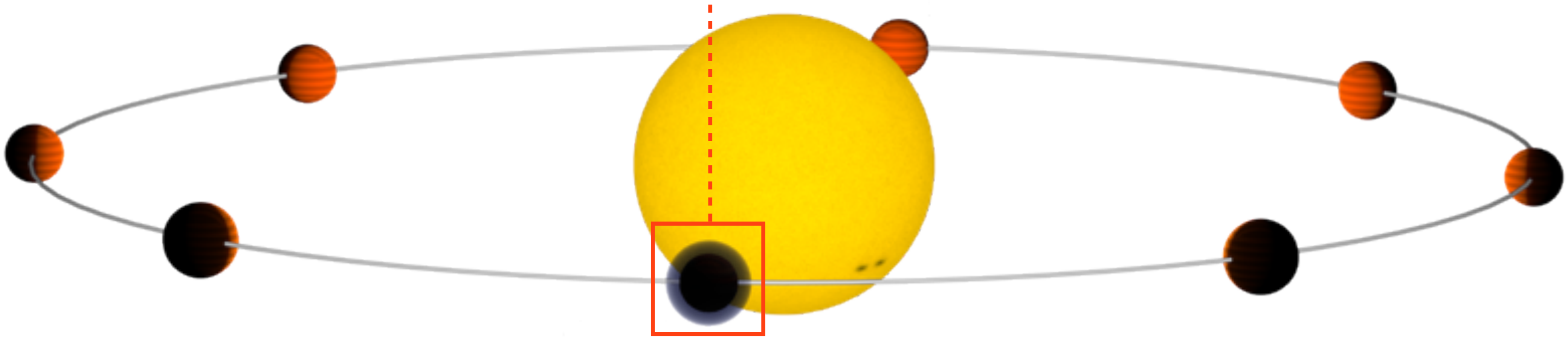
If the opacity increases
the planet appears bigger

Transmission spectroscopy





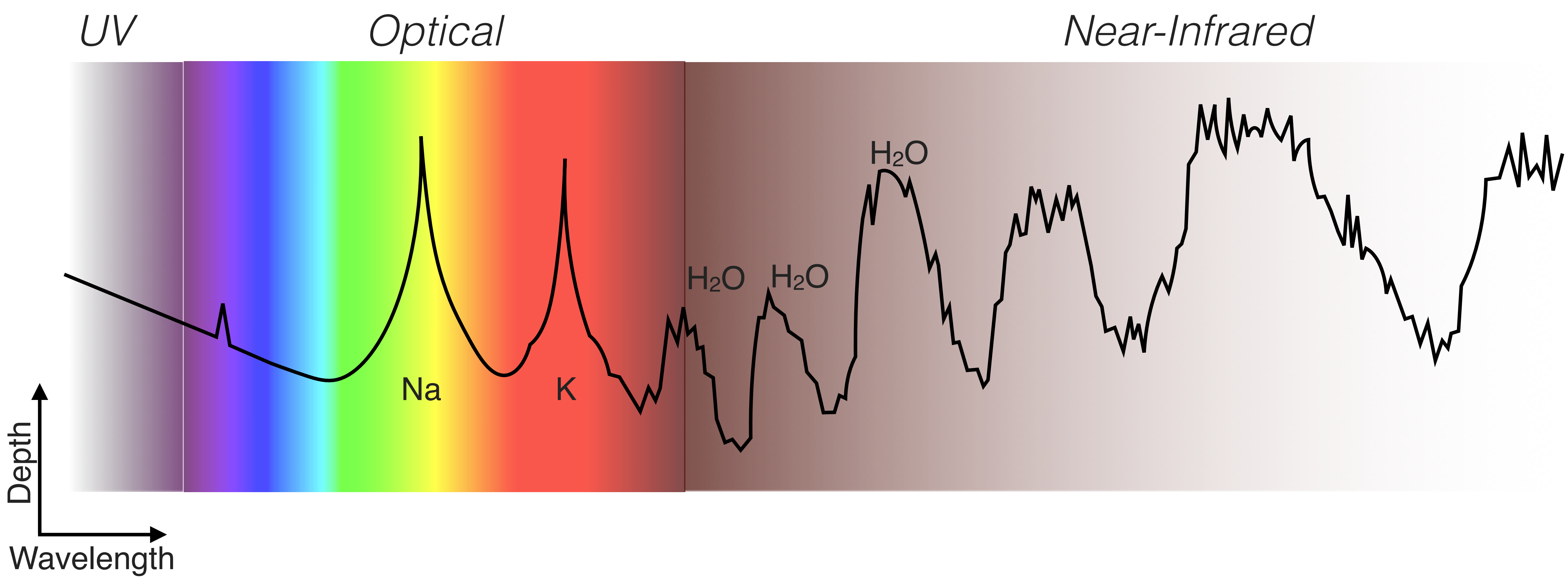
WASP-39b, Wakeford+ 2017



Transit

Missing stellar light
due to opaque planet disk

The information in exoplanet transmission spectra



Optical wavelengths

Dominated by lines of alkali metals (Na / K doublets), Rayleigh scattering from H_2, some (weak) H_2O
For very hot giants there can be TiO / VO in gas phase

Infrared wavelengths

Dominated by molecular absorption, mostly H_2O and possibly CH_4, CO, CO_2, HCN, NH_3, C_2H_2.

A first-order estimate of transmission signals

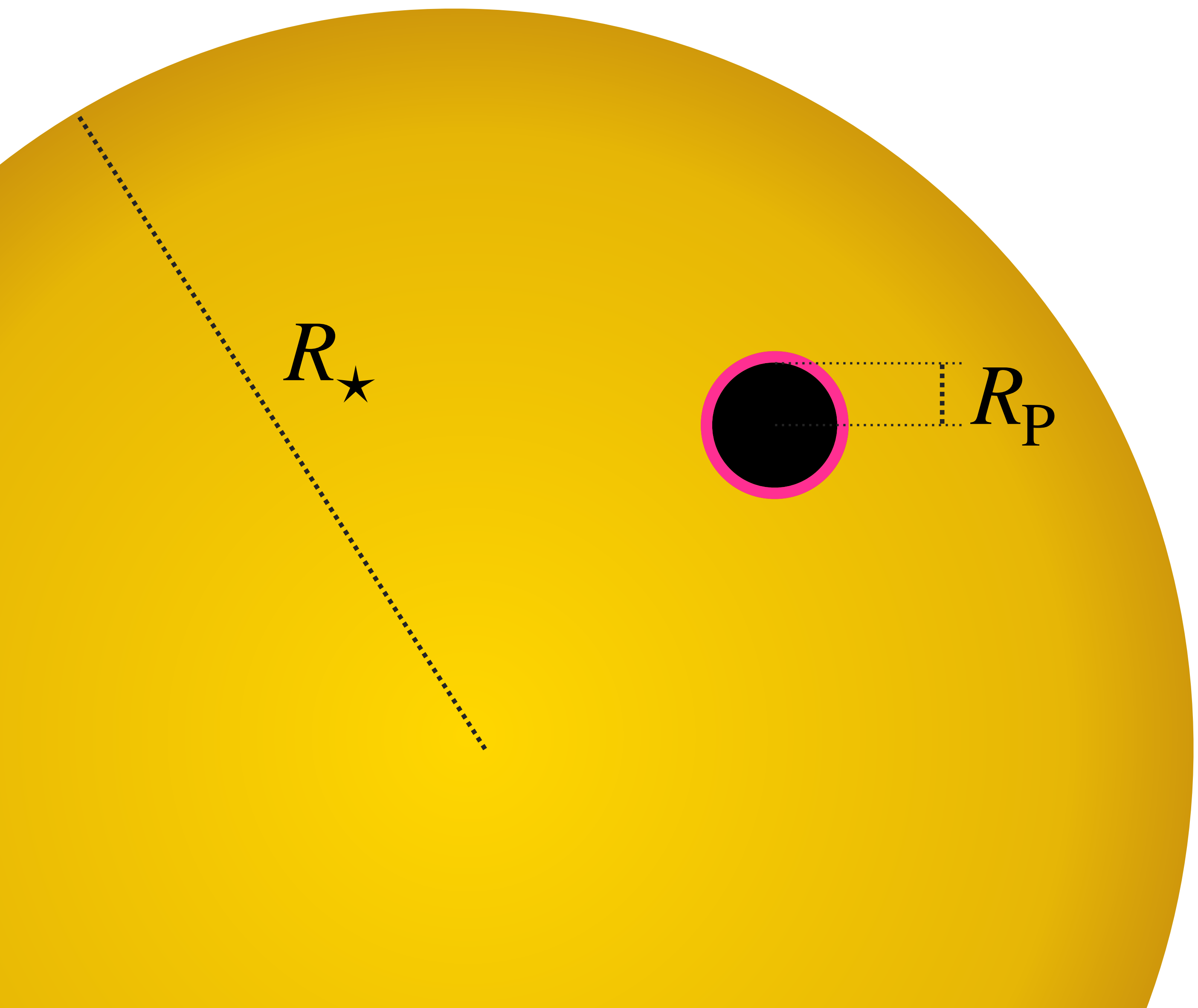
Transit depth

$$D = (R_P/R_\star)^2$$

Jupiter-Sun ~ 1%
Earth-Sun ~ 0.008%

Change in transit depth ΔD
due to atmospheric opacity
$\Delta D \approx A_{ring} / A_{star}$

A_{ring} = area outer radius - area inner radius
Outer radius = $R_P + \delta$
Inner radius = R_P



$$\begin{aligned} A_{ring} &= \pi(R_P + \delta)^2 - \pi R_P^2 \\ &= \pi(R_P^2 + 2\delta R_P + \delta^2 - R_P^2) \\ &= \pi\delta(2R_P + \delta) \approx \pi\delta R_P \end{aligned}$$

$$\Delta D = \frac{A_{ring}}{A_\star} = \frac{\delta R_P}{R_\star^2}$$

What is δ ?

A first-order estimate of transmission signals

Transit depth

$$D = (R_P/R_\star)^2$$

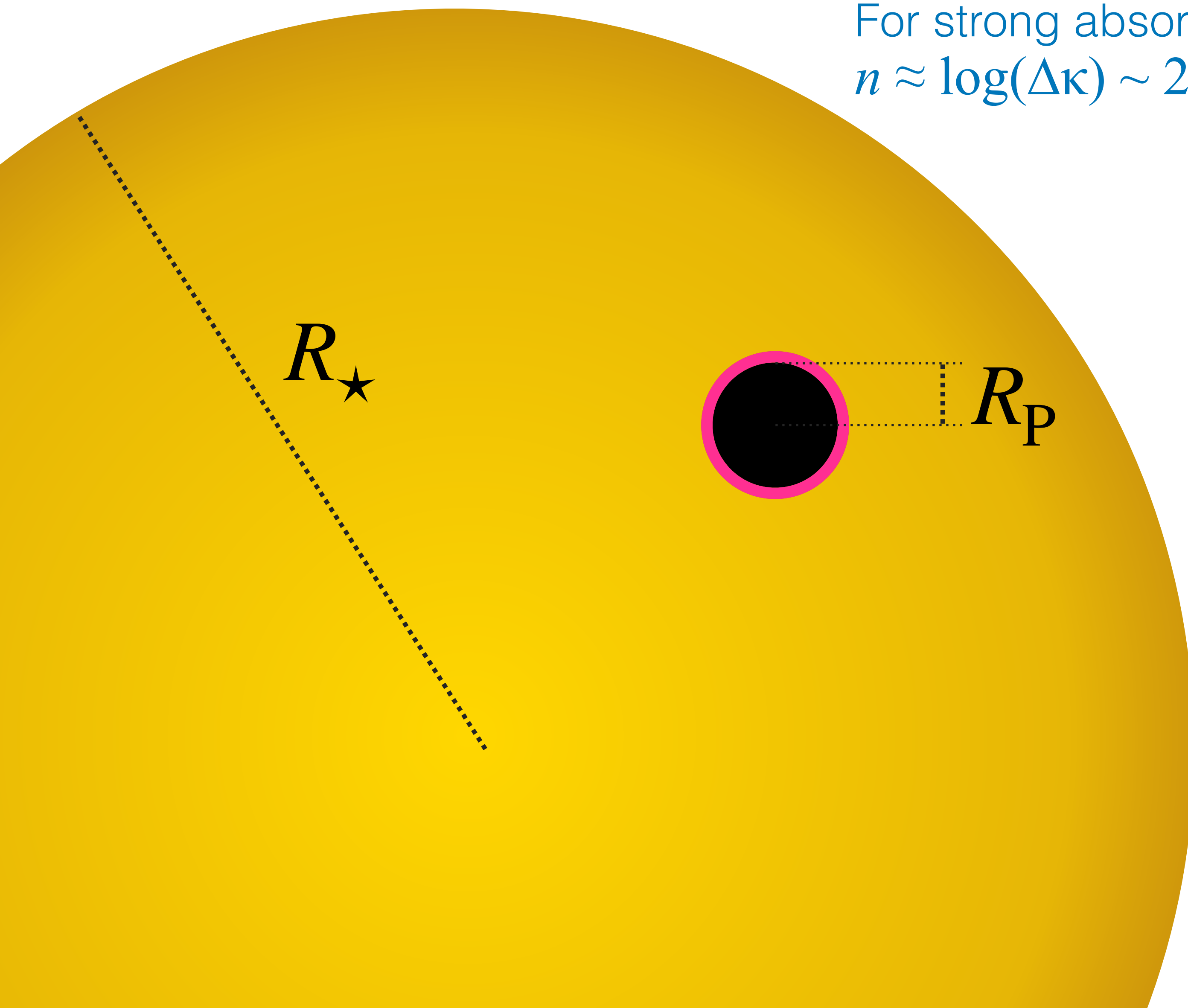
Jupiter-Sun ~ 1%
Earth-Sun ~ 0.008%

Change in transit depth ΔD
due to atmospheric opacity

$$\Delta D(\lambda) \approx n(\lambda) H R_P \,/\, (R_\star)^2$$

Change in planet opacity κ(λ)
Also dependent on abundance
For strong absorbers:
$n \approx \log(\Delta\kappa) \sim 2\text{-}5$

Planet scale height H
Dependent on temperature (Teq),
gravity (g) and mean molecular weight (μ)
$H = k_B T_{eq} \,/\, (g\mu)$



An atmosphere dominated by H-He (μ=2.2) will have atmospheric features 8× stronger than a water-dominated atmosphere (μ=18)

A first-order estimate of transmission signals

Transit depth

$$D = (R_P/R_\star)^2$$

Jupiter-Sun ~ 1%
Earth-Sun ~ 0.008%

Change in transit depth ΔD due to atmospheric opacity

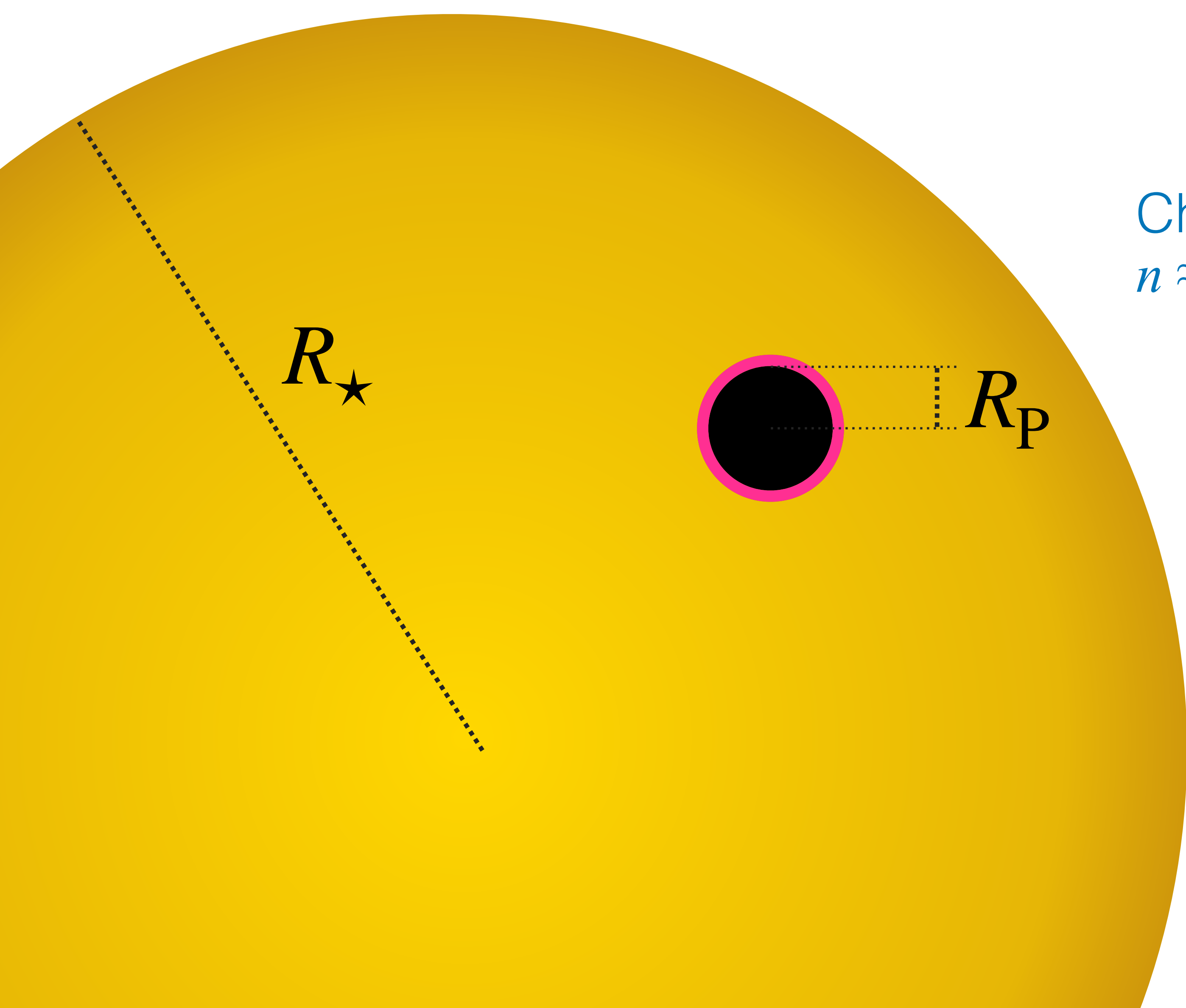
$$\Delta D(\lambda) \approx n(\lambda) H R_P \,/\, (R_\star)^2$$

Planet scale height H

$$H = k_B T_{eq} \,/\, (g\mu)$$

Change in planet opacity κ

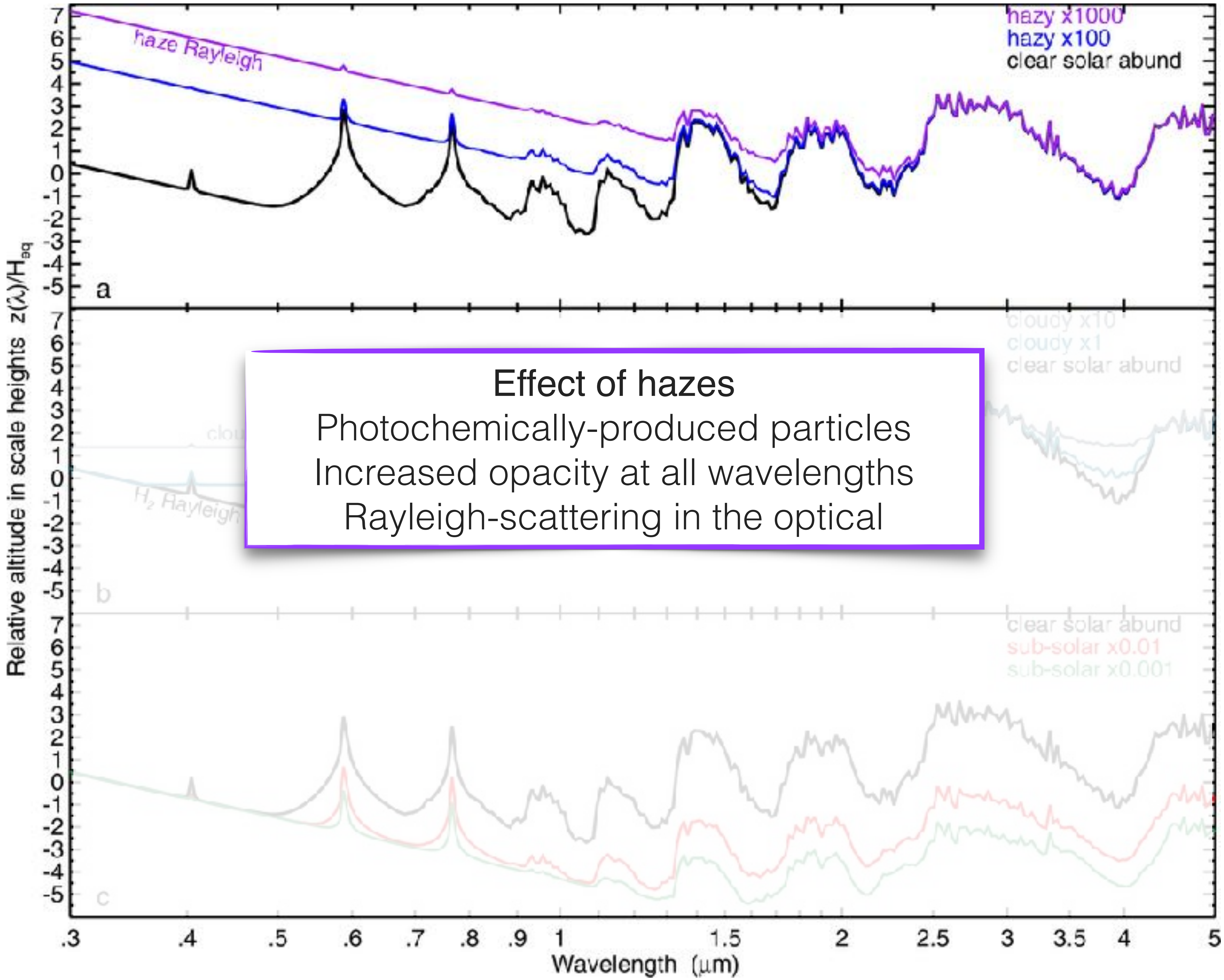
$$n \approx \log(\Delta\kappa) \sim 2\text{-}5$$



hot-giant planet (1,500K, μ=2.2)
ΔD ~ 0.01% = 100 ppm

water-world (2.5 R_E, 10M_E, 800K, μ=18)
ΔD ~ 4 ppm

The information in exoplanet transmission spectra



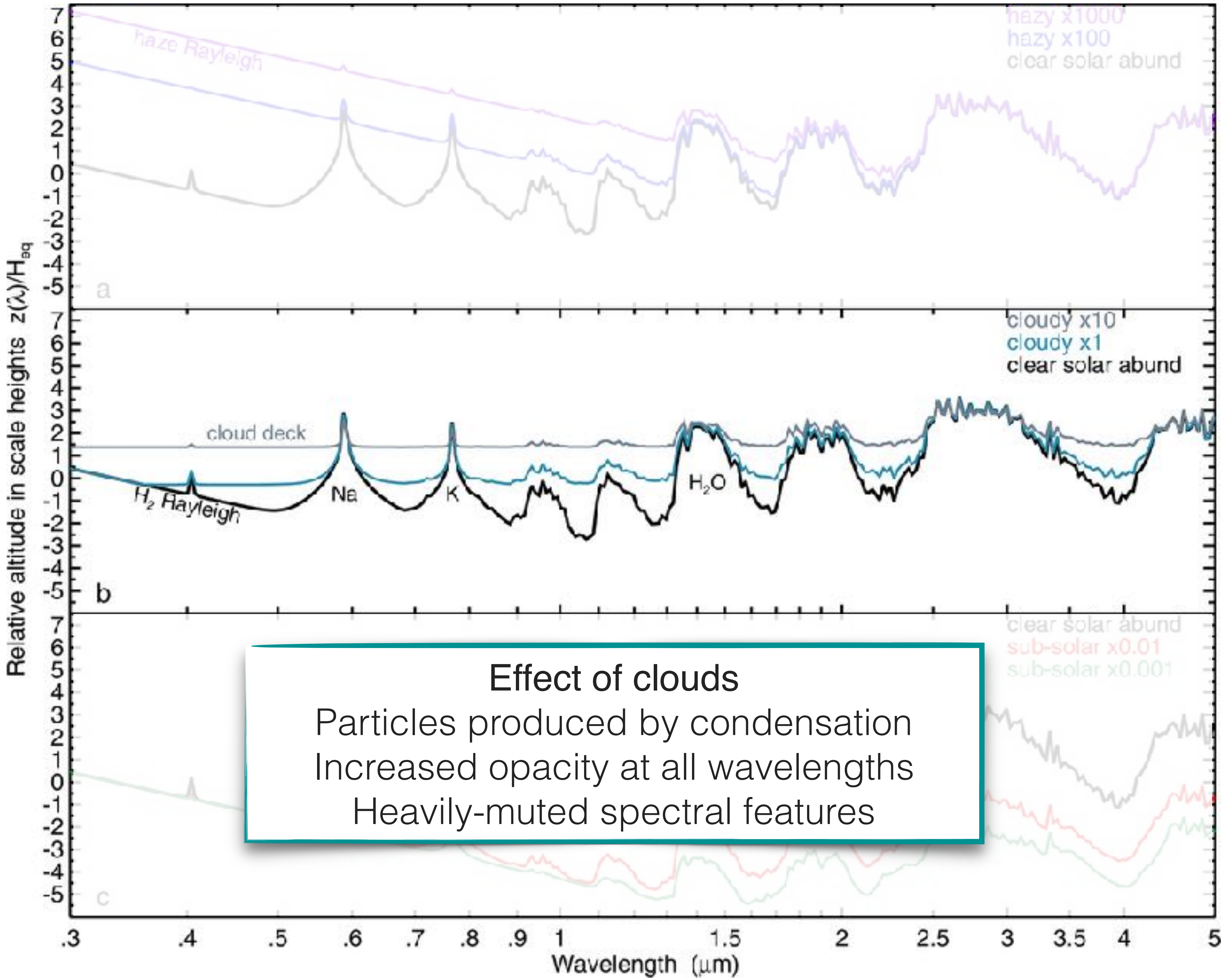
Effect of hazes

Photochemically-produced particles

Increased opacity at all wavelengths

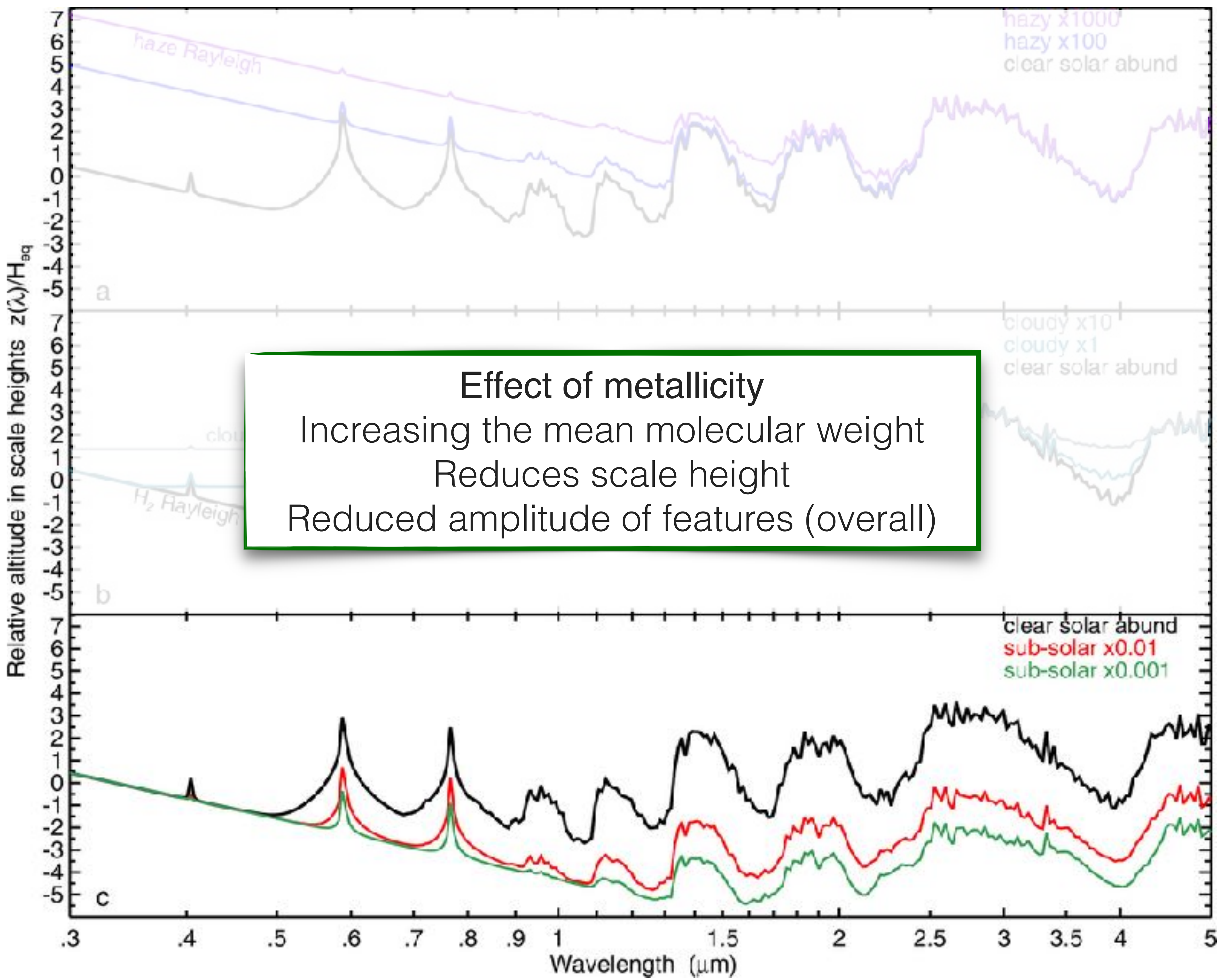
Rayleigh-scattering in the optical

The information in exoplanet transmission spectra



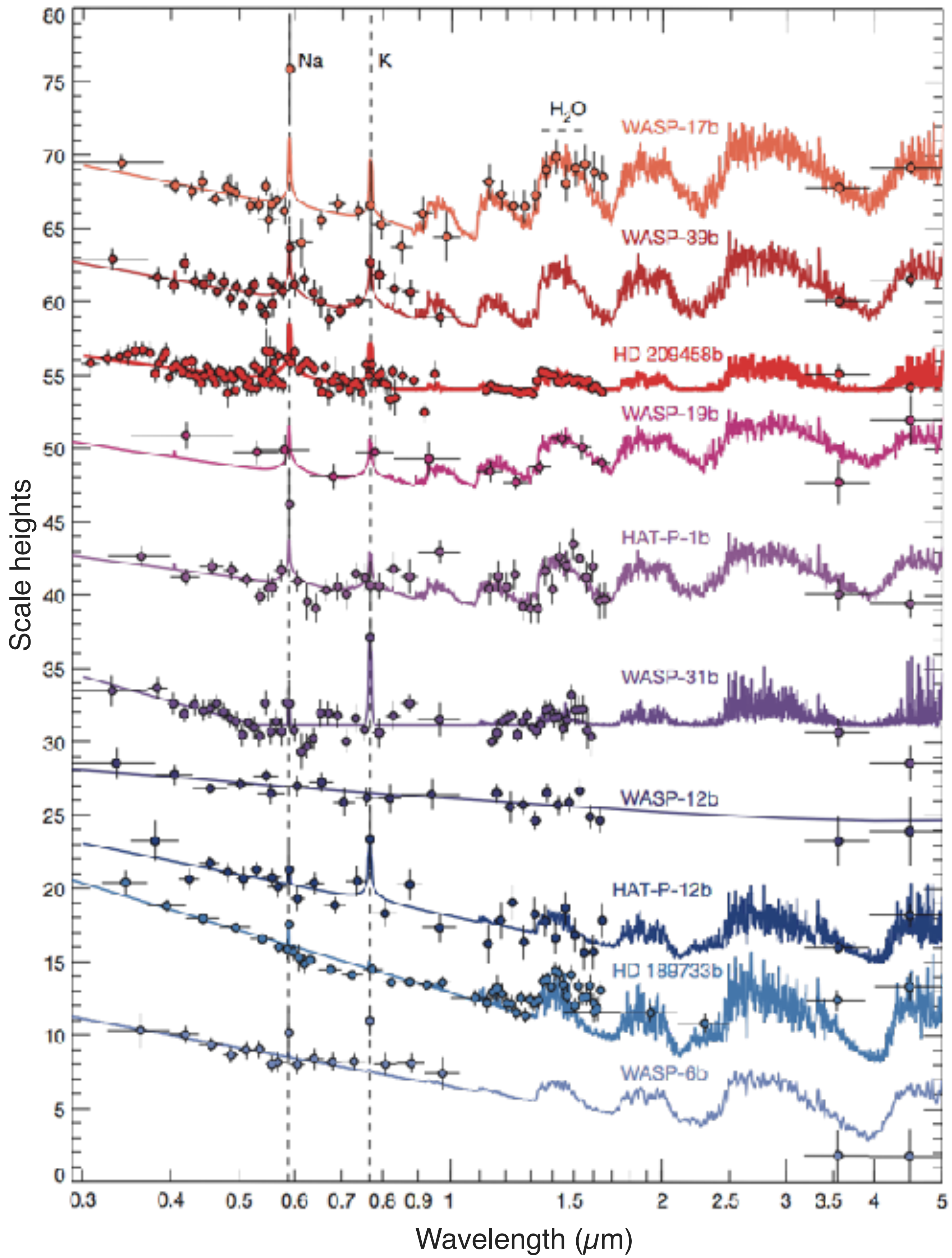
Effect of clouds
Particles produced by condensation
Increased opacity at all wavelengths
Heavily-muted spectral features

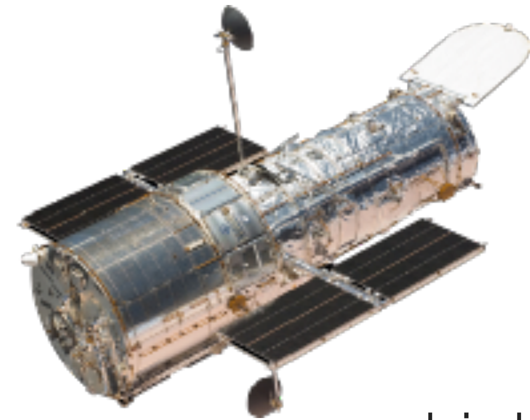
The information in exoplanet transmission spectra



Effect of metallicity
Increasing the mean molecular weight
Reduces scale height
Reduced amplitude of features (overall)

Example: the "cloudiness" levels of hot Jupiters





Key comparative study by Sing et al., *Nature* (2016)

10 exoplanets
high-quality optical-NIR data
(HST STIS & WFC3)

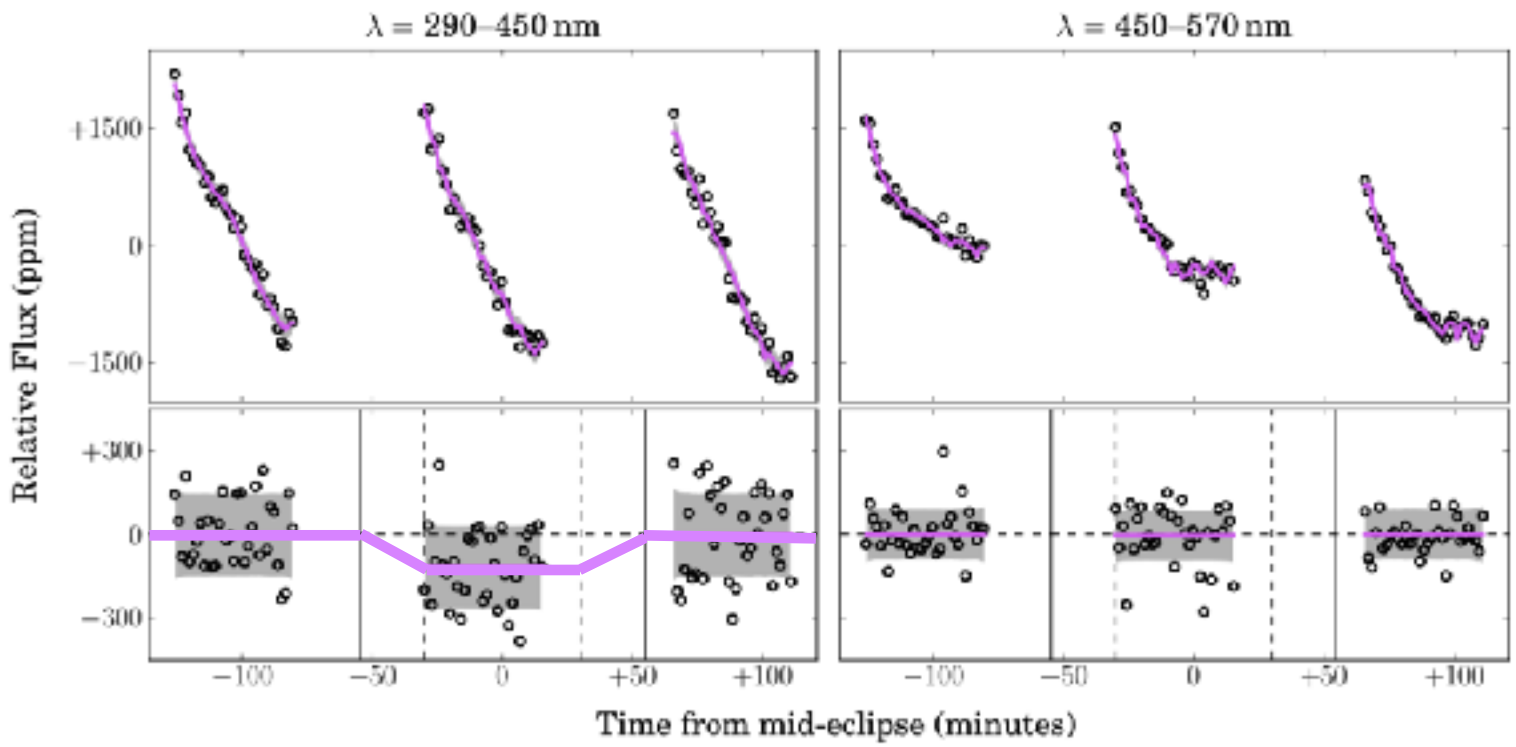
Weak IR water features are either due to low water abundance, or to muting effects of clouds

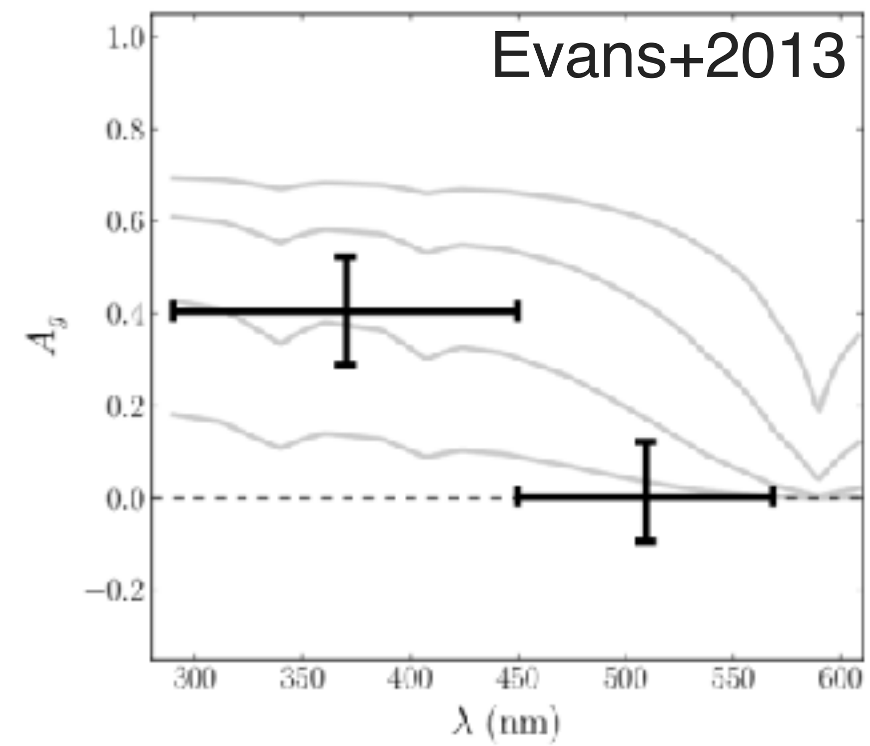
Answer is still not definitive

Ongoing research
Large HST proposals (100s hours) to increase the sample and complete the 0.8-1.3 μm region

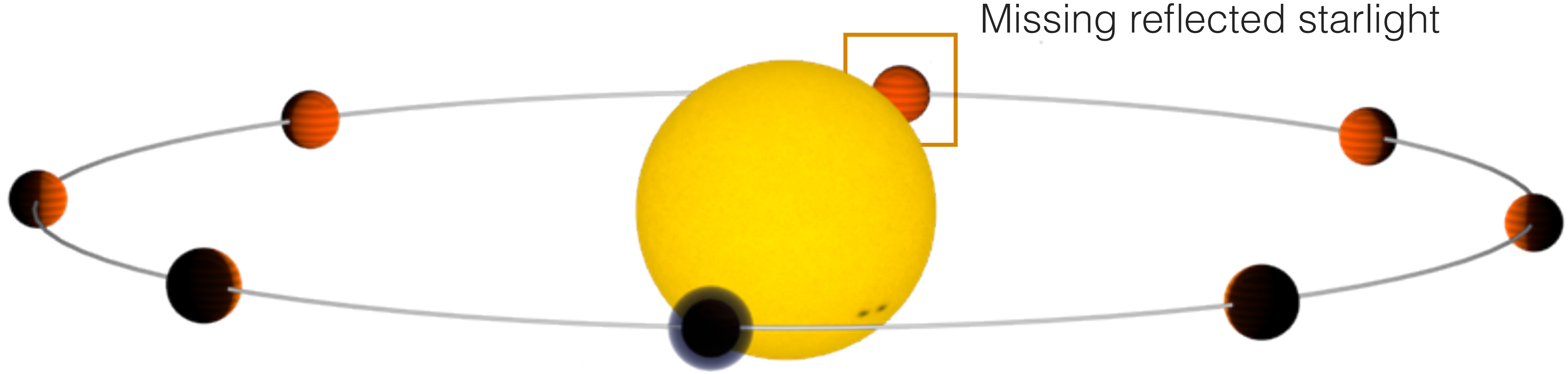
Reflected starlight from exoplanets

At visible wavelength, secondary eclipse depth = missing reflected starlight
Very challenging measurements, especially spectrally-resolved





Hot Jupiters are not reflective at visible wavelengths (Na and K lines absorb radiation)



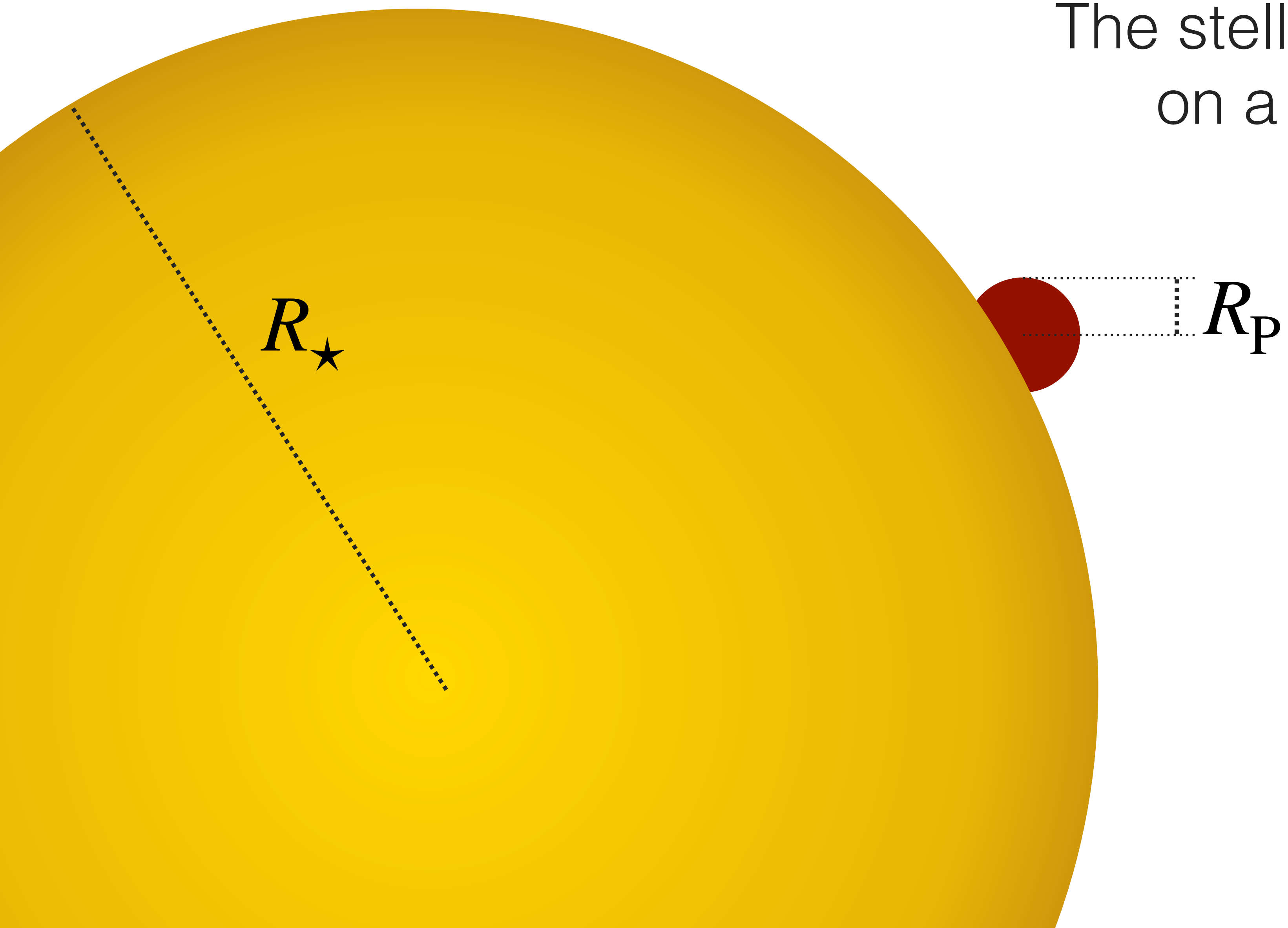
A first-order estimate of reflected-light signals

Stellar flux at planet: $F_{\star,\mathrm{pl}} = L_\star/(4\pi a^2)$ $L_\star = 4\pi\sigma R_\star^2 T_{\mathrm{eff}}^4$

Luminosity: energy / s ⇒ [W s^{-1}]

Flux: energy / s / unit area ⇒ [W s^{-1} m^{-2}]

The stellar luminosity is distributed on a sphere of surface $4\pi a^2$



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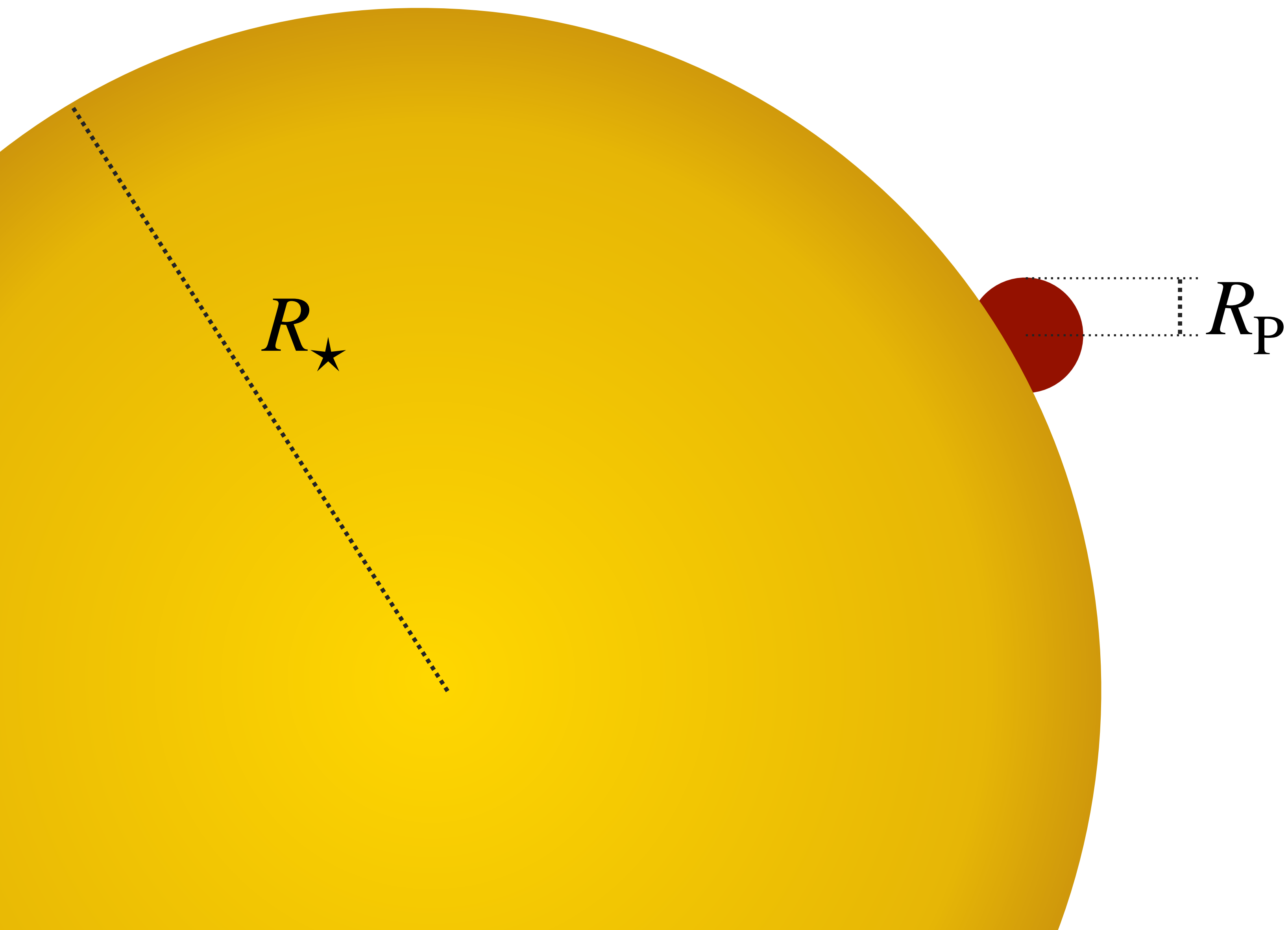
Energy reflected / s: $E_{\mathrm{refl}} = A\pi R_{\mathrm{P}}^2 F_{\star,\mathrm{pl}}$

The planet is a disk of area $\pi(R_{\mathrm{P}})^2$

An average reflectivity (albedo) A is assumed



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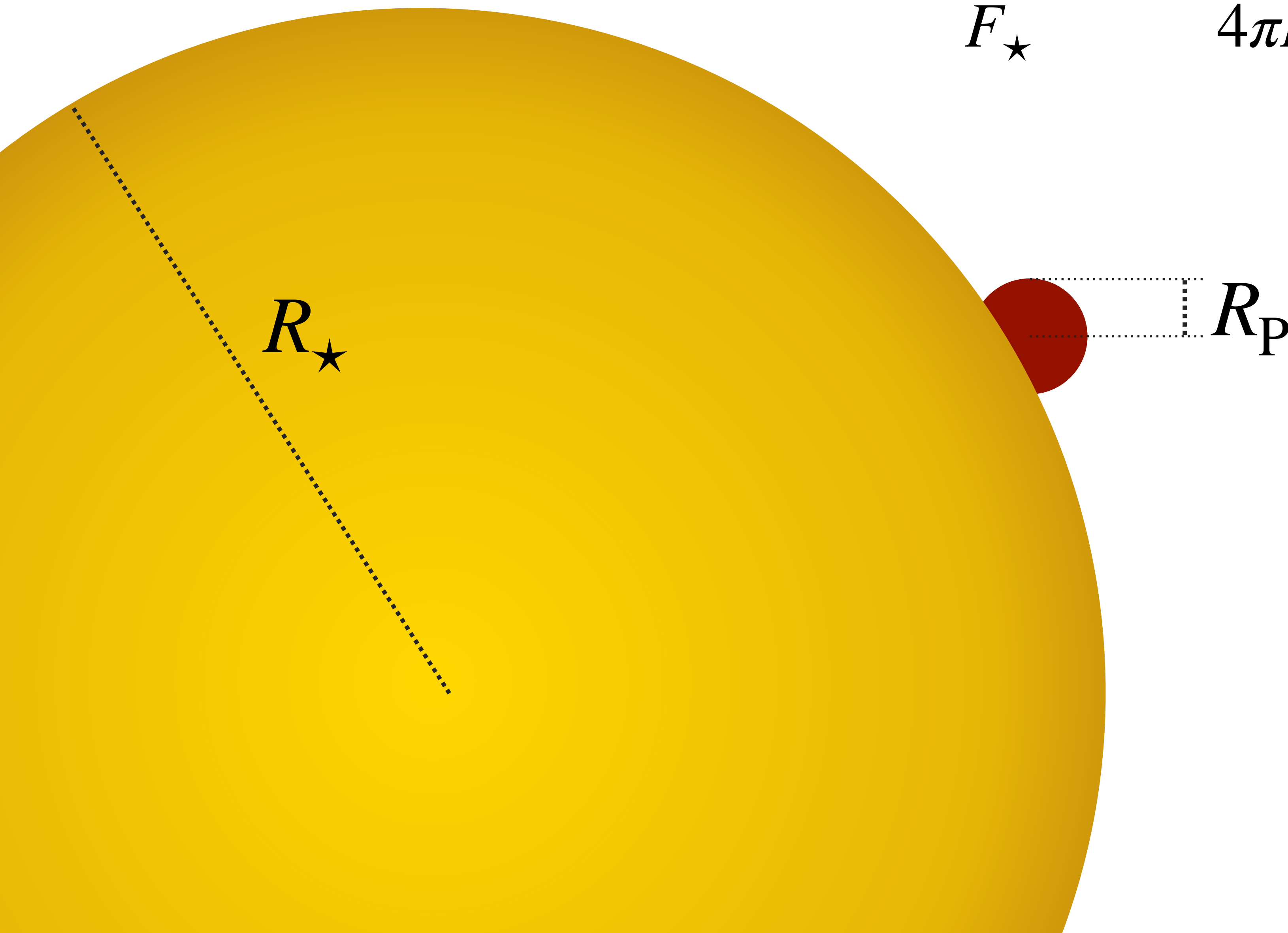
Energy reflected / s: $E_{\mathrm{refl}} = A\pi R_{\mathrm{P}}^2 F_{\star,\mathrm{pl}}$

Flux ratio at the observer (distance D)

$$\frac{F_{\mathrm{P,refl}}}{F_\star} = \frac{A\pi R_{\mathrm{P}}^2 F_{\star,\mathrm{pl}}}{4\pi D^2}\frac{4\pi D^2}{L_\star} = A\left(\frac{R_{\mathrm{P}}}{2a}\right)^2$$



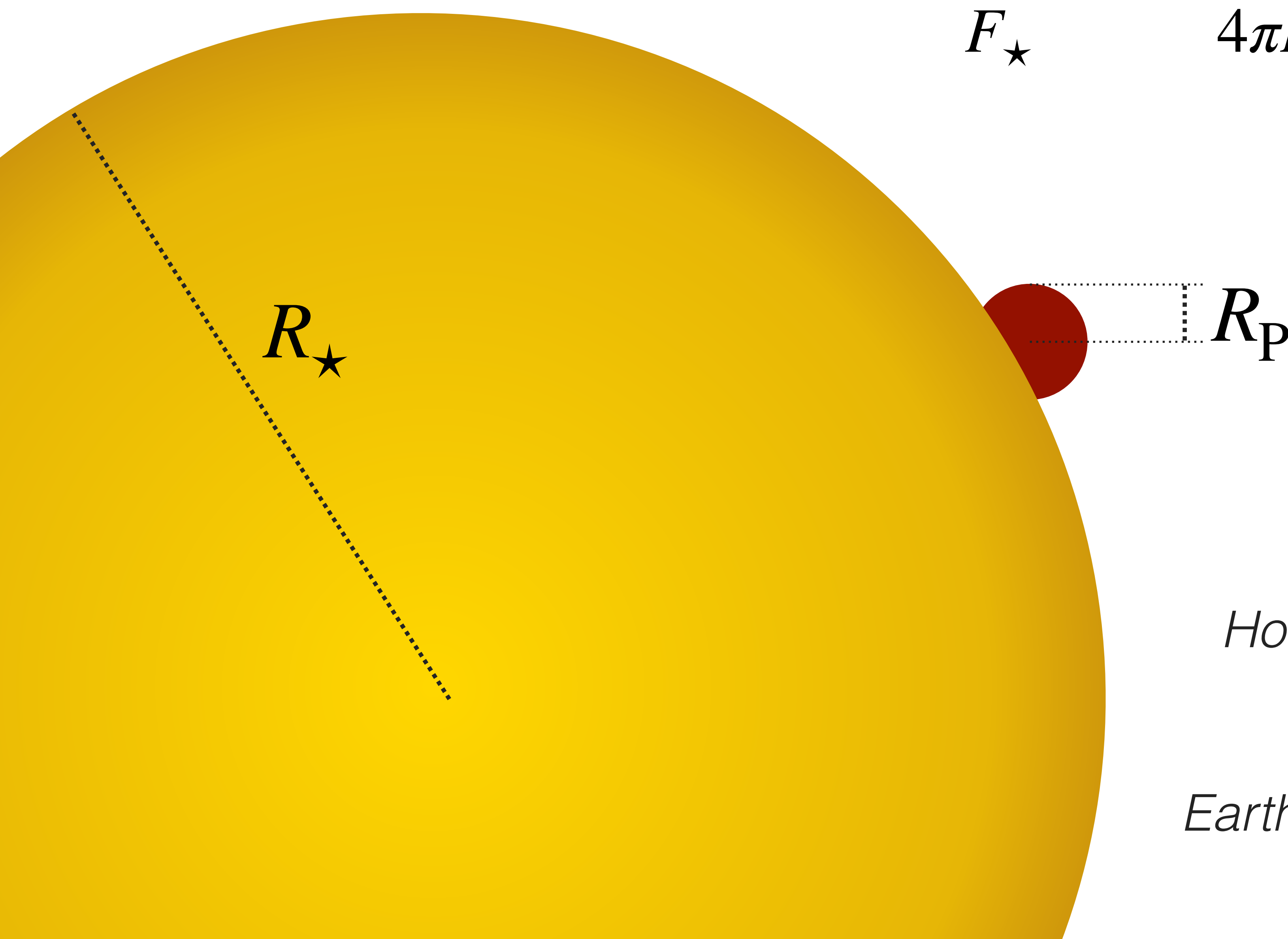
A first-order estimate of reflected-light signals

Stellar flux at planet: $F_{\star,\mathrm{pl}} = L_\star / (4\pi a^2)$ $\quad L_\star = 4\pi\sigma R_\star^2 T_{\mathrm{eff}}^4$

Energy reflected / s: $E_{\mathrm{refl}} = A\pi R_{\mathrm{P}}^2 F_{\star,\mathrm{pl}}$

Flux ratio at the observer (distance D)

$$\frac{F_{\mathrm{P,refl}}}{F_\star} = \frac{A\pi R_{\mathrm{P}}^2 F_{\star,\mathrm{pl}}}{4\pi D^2} \frac{4\pi D^2}{L_\star} = A\left(\frac{R_{\mathrm{P}}}{2a}\right)^2$$



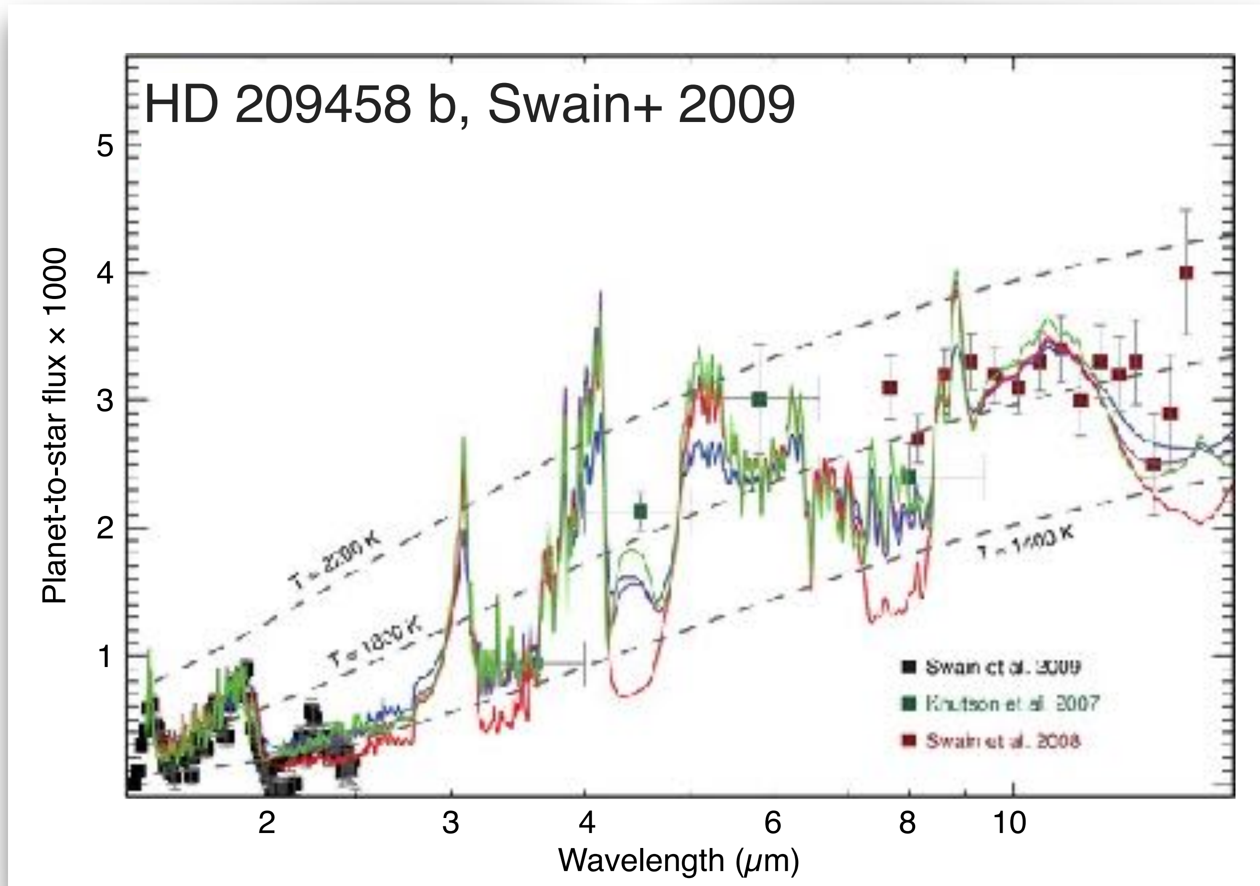
WASP-33b (0.025au, A=0.1, 1.6R_{Jup})
2×10^{-5} = 20 ppm

Hot-giant planet (0.04au, A=0.1, 1.15R_{Jup})
5×10^{-6} = 5 ppm

Earth around the Sun (1au, A=0.35, 0.09R_{Jup})
1.6×10^{-10} = 0.16 ppb

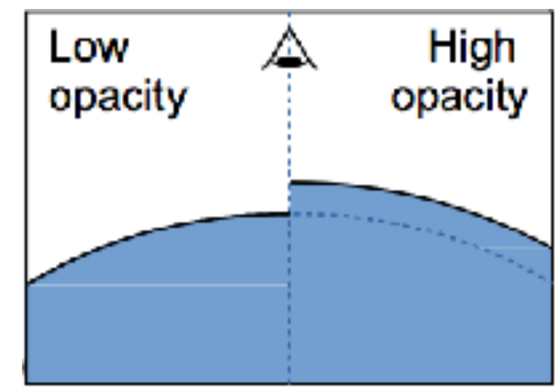
Emission spectroscopy of exoplanets

At infrared wavelength, secondary eclipse depth = missing planet thermal emission



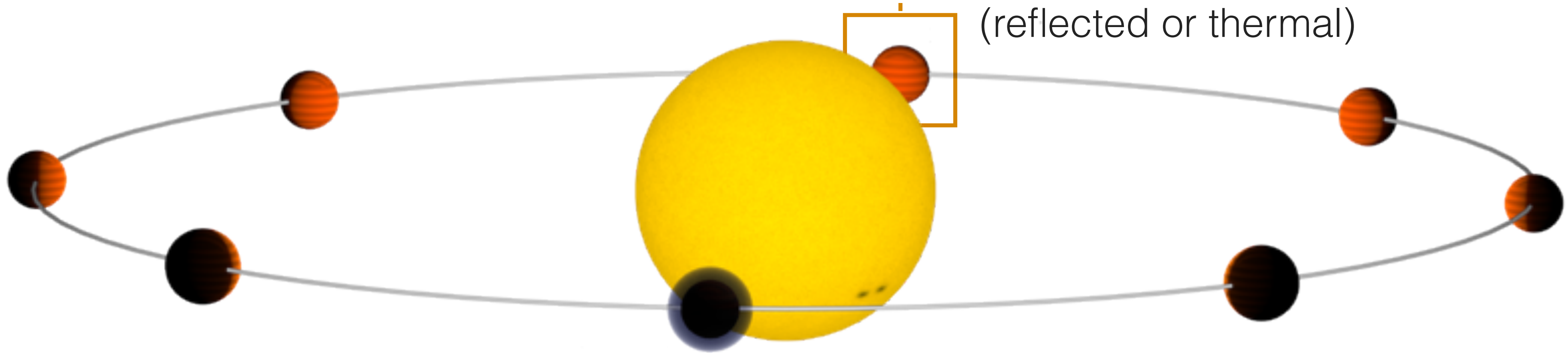
$F_P = F_P(\lambda)$

If the opacity *increases*
we probe *higher altitudes*
Dayside spectroscopy



Eclipse

Missing planet flux
(reflected or thermal)



A first-order estimate of emission signals

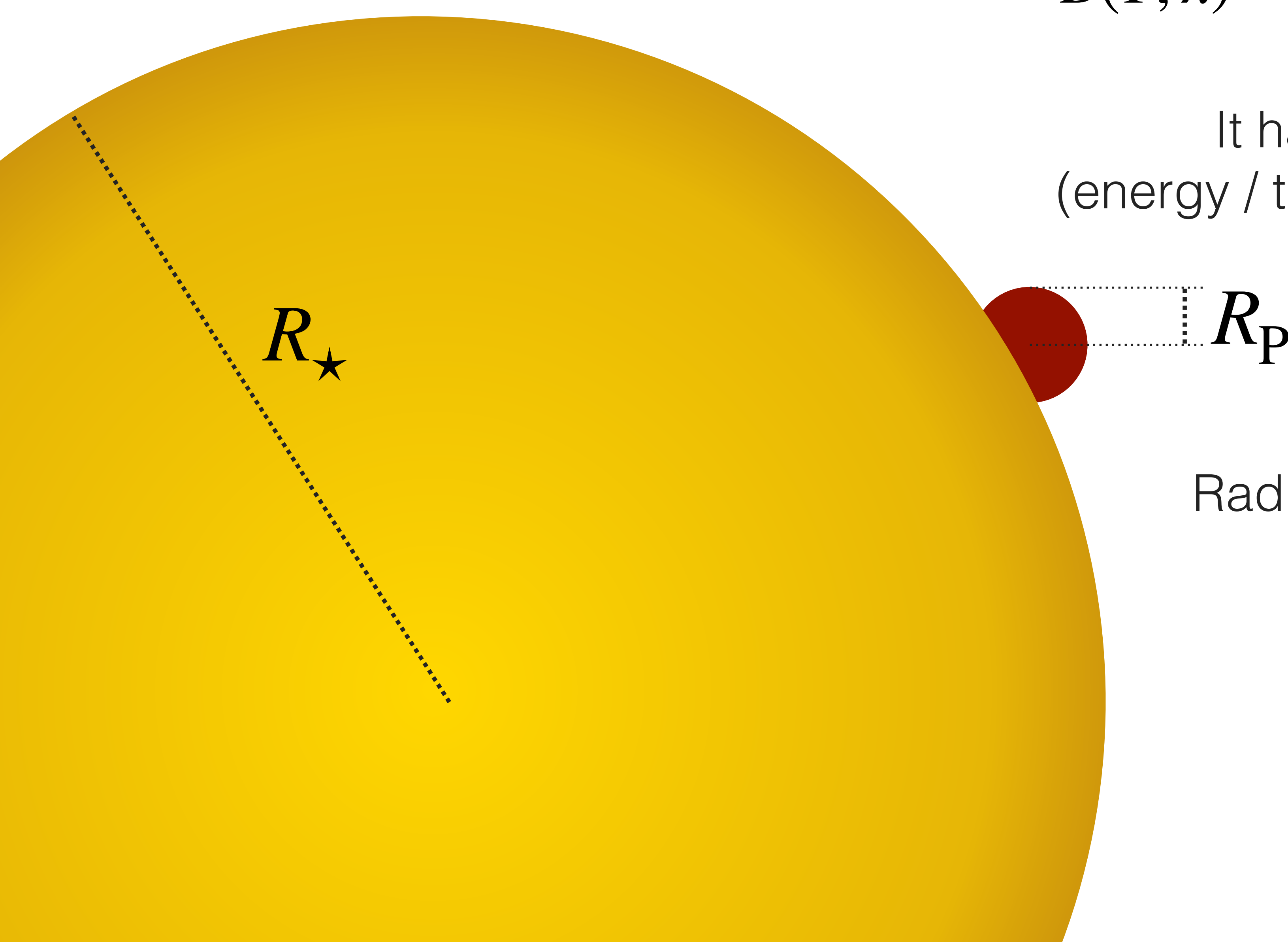
Approximating the star and the planet as black bodies

Stellar flux at planet: $F_\star = L_\star/(4\pi a^2)$ $L_\star = 4\pi\sigma R_\star^2 T_{\rm eff}^4$

Let's make it wavelength dependent
$B(T_{\rm eff}, \lambda)$ is the Planck function for black-body radiation

$$B(T,\lambda) = \frac{2hc^2}{\lambda^5}\frac{1}{\exp[hc/(\lambda k T)] - 1}$$

It has units of [W s^{-1} m^{-2} m^{-1} sr^{-1}]
(energy / time / area / wavelength / solid angle)



Radiation is isotropic so for the flux

$$F(T,\lambda) = \pi B(T,\lambda)$$

$$L_\star(\lambda) = 4\pi^2 R_\star^2 B(T_{\rm eff},\lambda)$$

A first-order estimate of emission signals

Approximating the star and the planet as black bodies

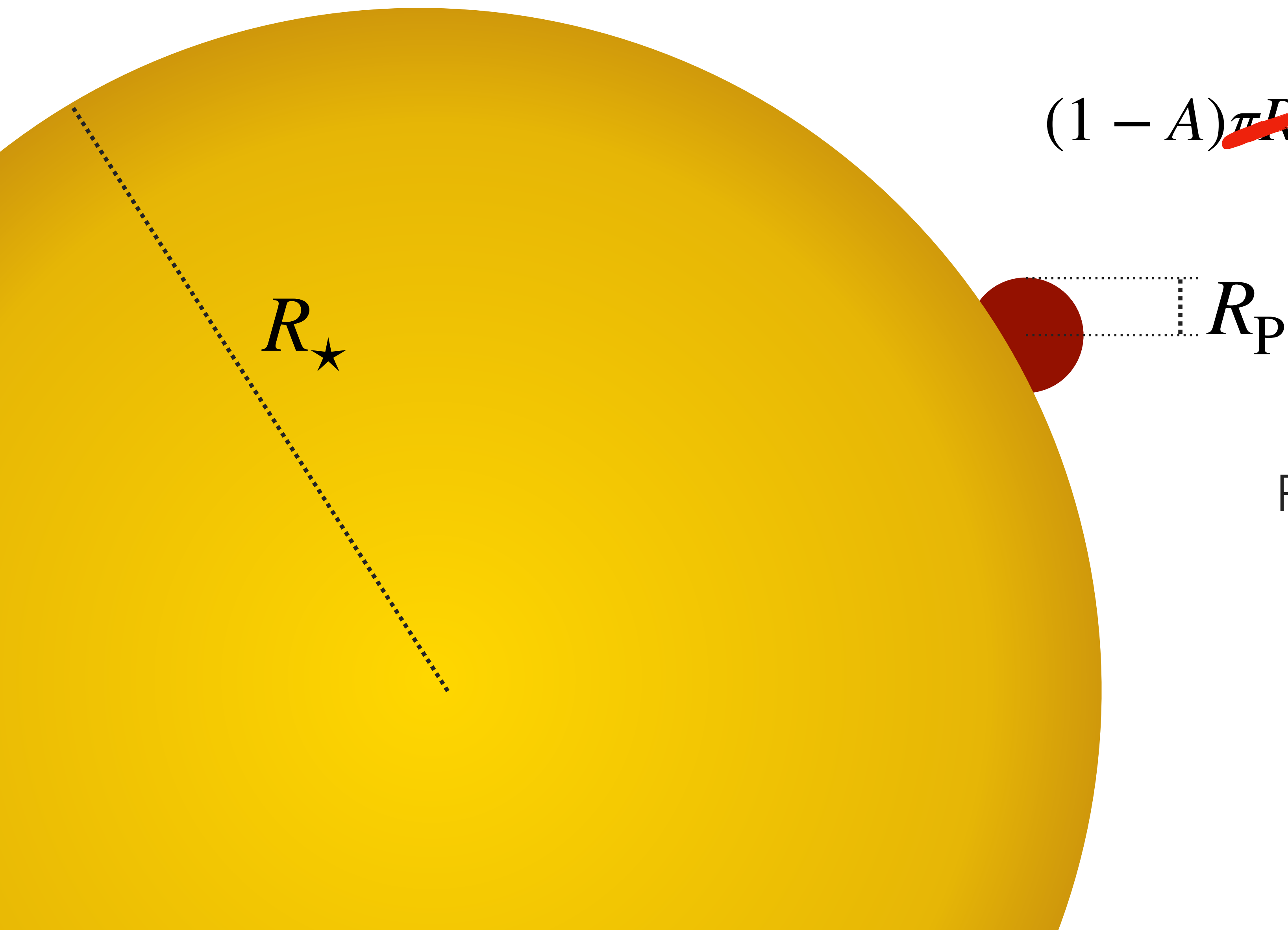
Stellar flux at planet: $F_\star(\lambda) = L_\star(\lambda)/(4\pi a^2)$ $\quad L_\star(\lambda) = 4\pi R_\star^2 B(T_{\rm eff}, \lambda)$

Energy absorbed / time: $E_{\rm abs}(\lambda) = (1-A)\pi R_{\rm P}^2 F_\star(\lambda)$

Energy absorbed = Energy re-emitted (over all wavelengths)

$$E_{\rm abs} = E_{\rm out}$$

$$(1-A)\cancel{\pi R_{\rm P}^2}\frac{\cancel{4\pi\sigma}R_\star^2 T_{\rm eff}^4}{4\cancel{\pi}a^2} = \cancel{4\pi\sigma R_{\rm P}^2}T_{\rm eq}^4$$



$$T_{\rm eq} \simeq T_{\rm eff}\sqrt{\frac{R_\star}{a}}$$

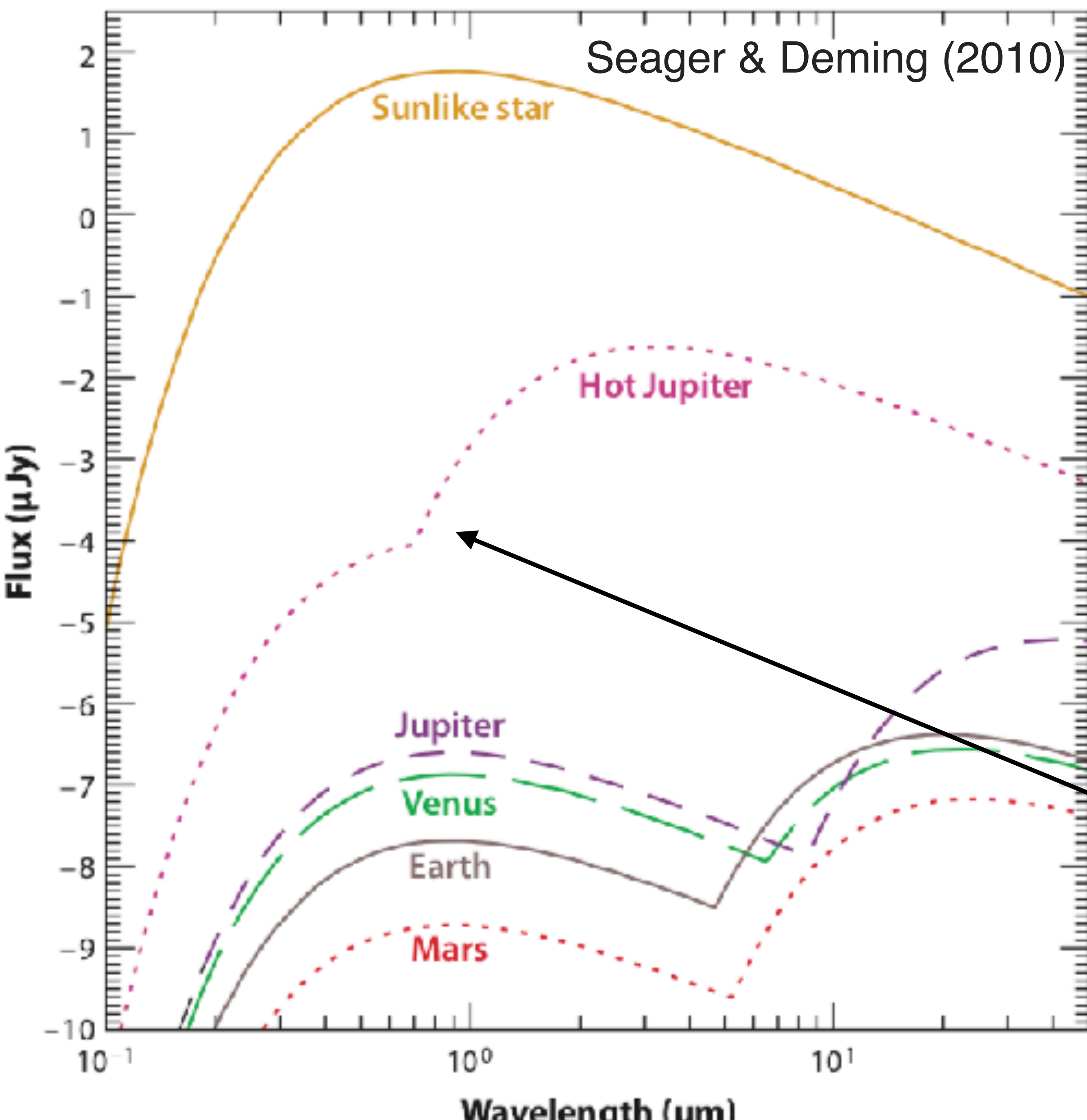
Planet equilibrium temperature

$$L_{\rm P}(\lambda) = 4\pi R_{\rm P}^2 B(T_{\rm eq}, \lambda)$$

A first-order estimate of emission signals

Approximating the star and the planet as black bodies
Estimating the planet / star flux as measured by an observer at distance D

$$\frac{F_{\mathrm{P,em}}(\lambda)}{F_\star(\lambda)} = \frac{L_\star(\lambda)}{4\pi D^2}\frac{4\pi D^2}{L_{\mathrm{P}}(\lambda)} = \frac{B(T_{\mathrm{eq}},\lambda)}{B(T_{\mathrm{eff}},\lambda)}\left(\frac{R_{\mathrm{P}}}{R_\star}\right)^2$$

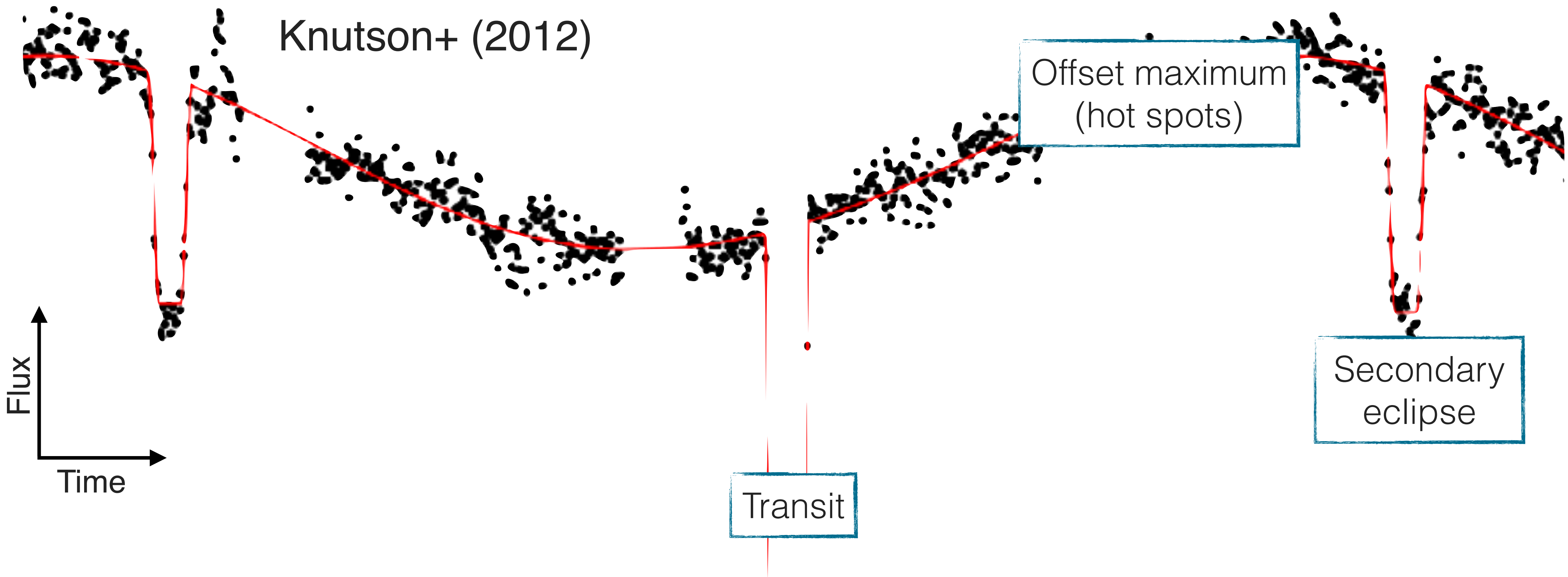


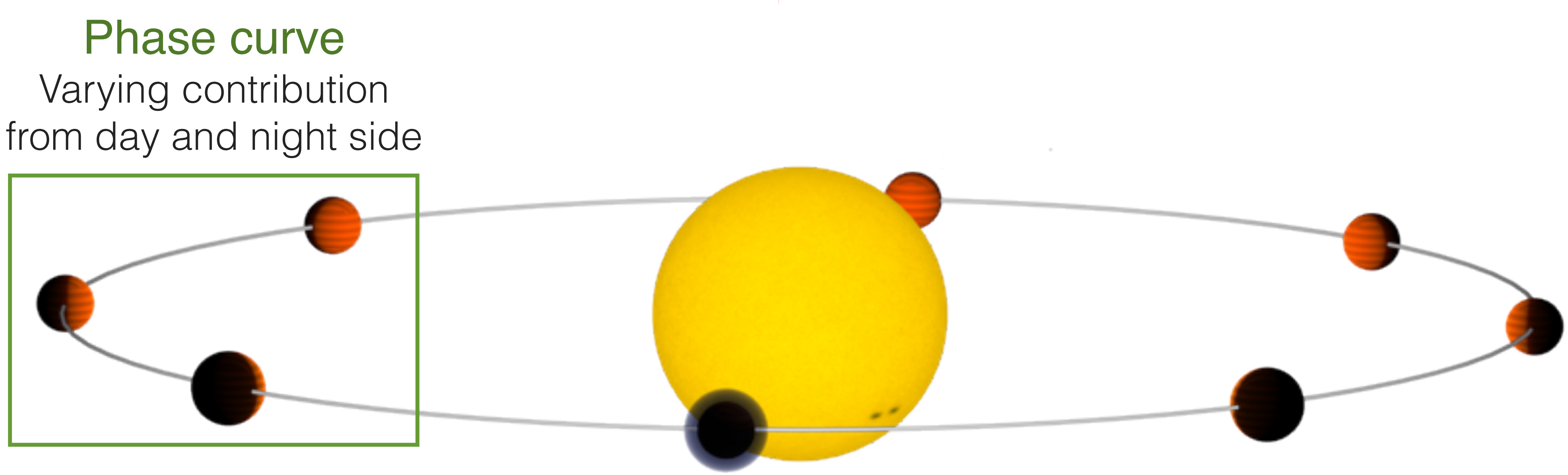
hot-giant planet (1,500K)
ΔD ~ 30 ppm (1.2 μm)
ΔD ~ 110 ppm (1.6 μm)
ΔD ~ 290 ppm (2.3 μm)

warm Neptune (800K)
ΔD ~ 3 ppb (1.2 μm)
ΔD ~ 70 ppb (1.6 μm)
ΔD ~ 640 ppb (2.3 μm)

In visible light the tail of the thermal emission can get confused with reflected light

Phase curves: light modulation along the orbit

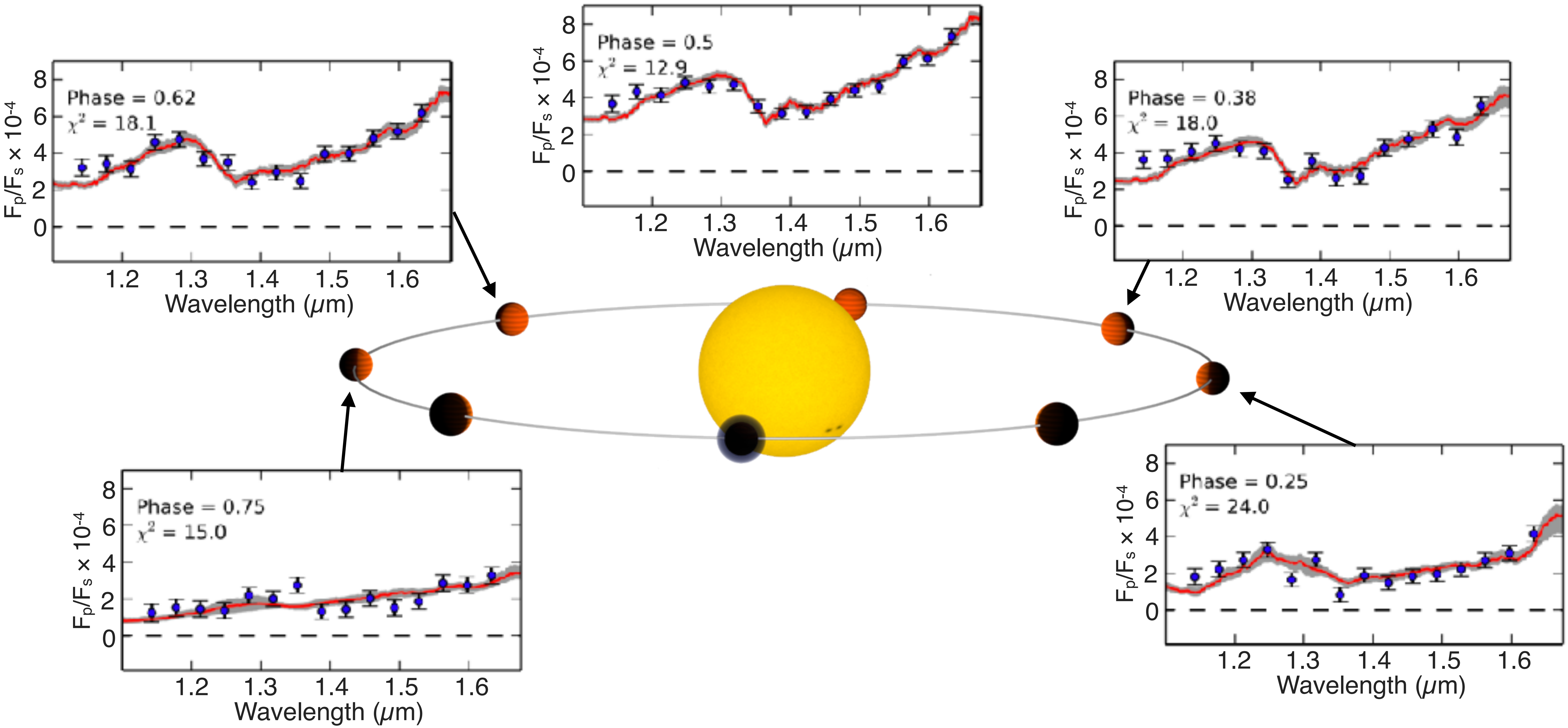




All together these measurements inform the chemical make-up and the energy balance in exoplanet atmospheres

Thermal vertical structure from dayside spectroscopy

Best-case scenario: the phase curve of WASP-43b (Stevenson+14)

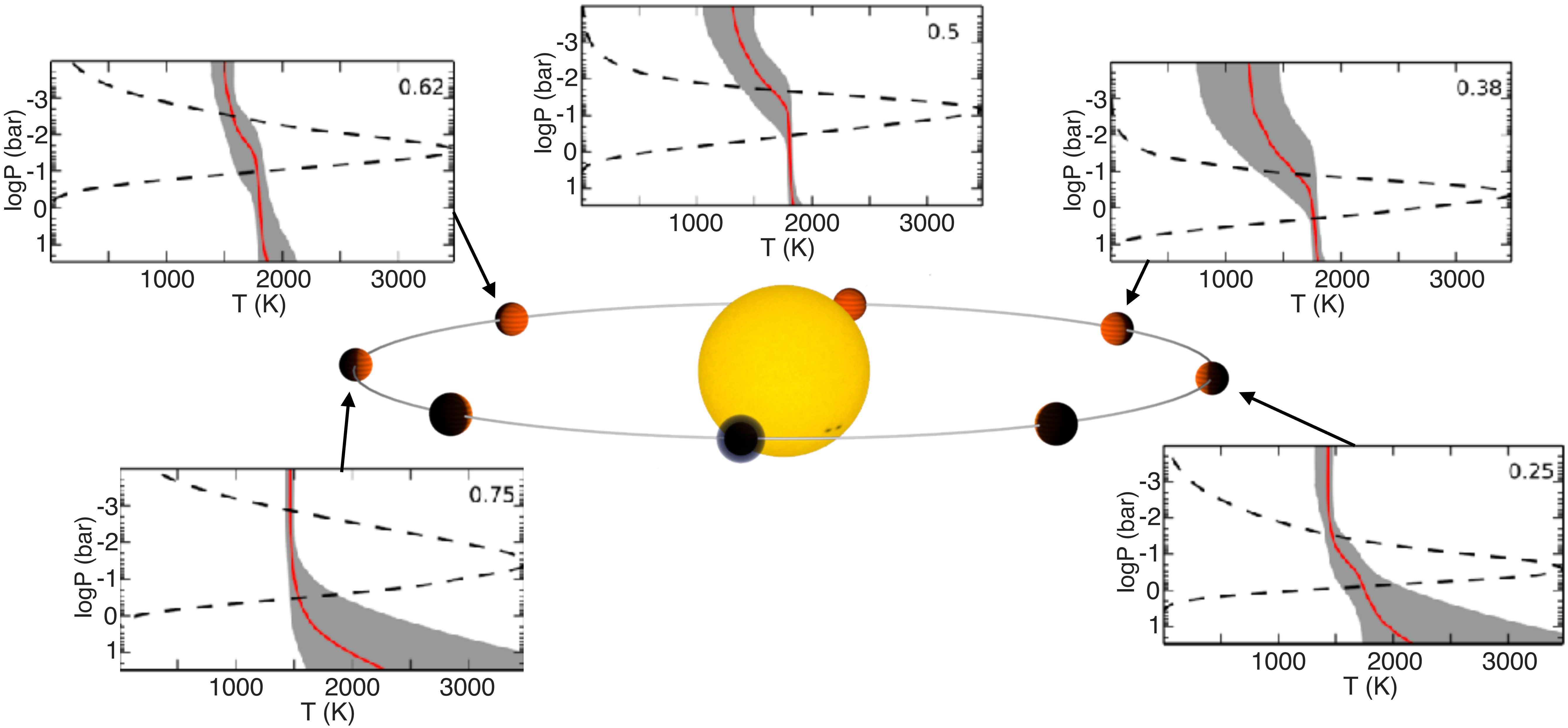


Large day-night temperature contrast, 18% albedo

Temperature monotonically decreasing with altitude

Thermal vertical structure from dayside spectroscopy

Best-case scenario: the phase curve of WASP-43b (Stevenson+14)



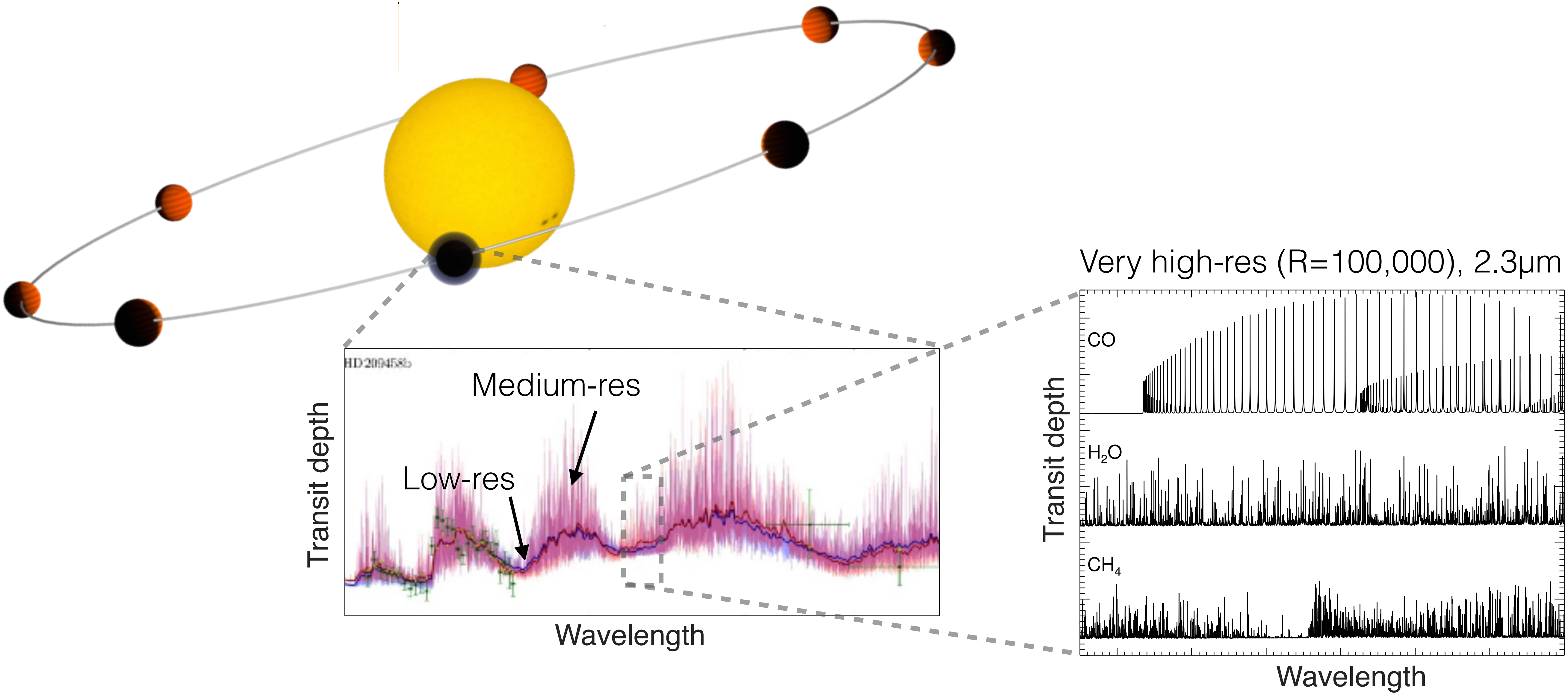
Large day-night temperature contrast, 18% albedo
Temperature monotonically decreasing with altitude

Only possible for a handful of objects so far

High-resolution spectroscopy of exoplanets

Key characteristics
The signal-to-noise formula
Cross correlation and data analysis

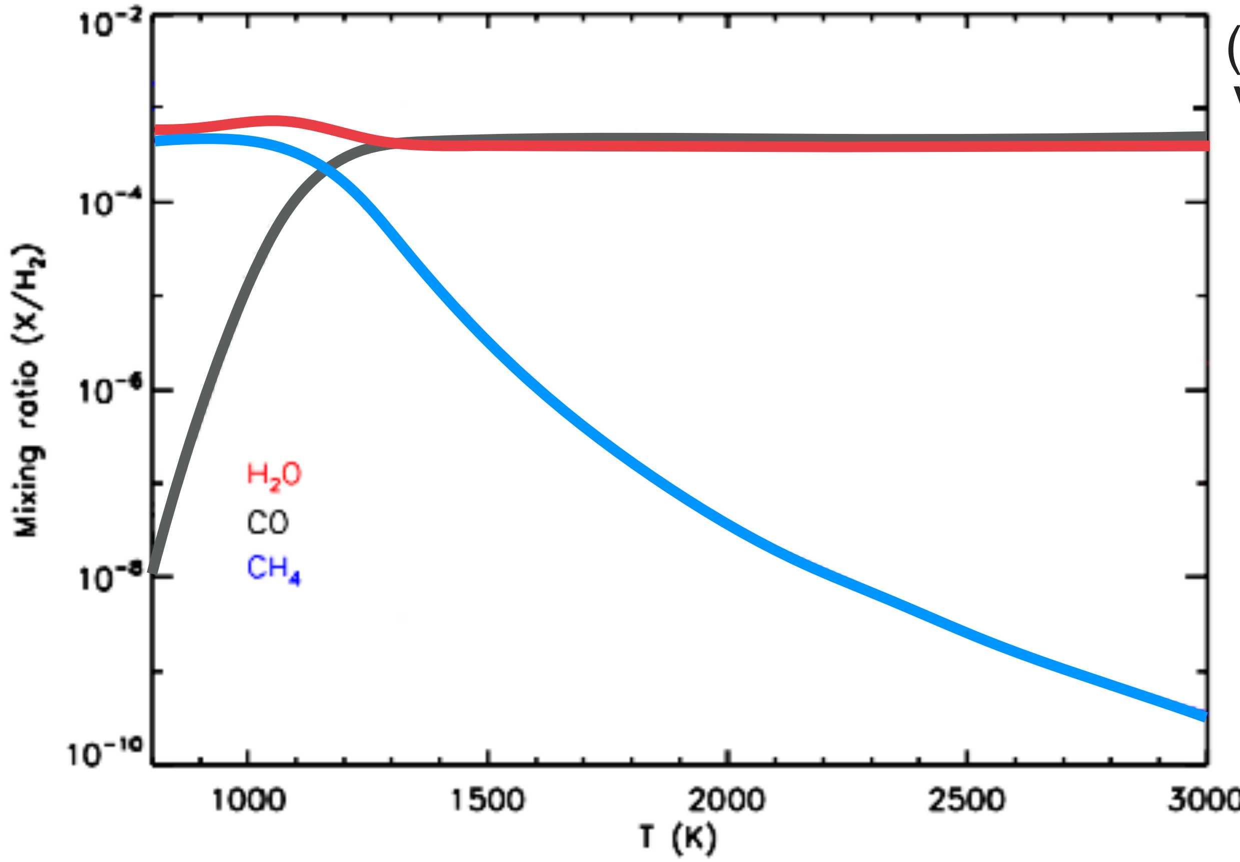
Exoplanets at high spectral resolution



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

Water is key to study exoplanet atmospheres

H_2O abundant for a wide range of temperatures relevant to hot Jupiters

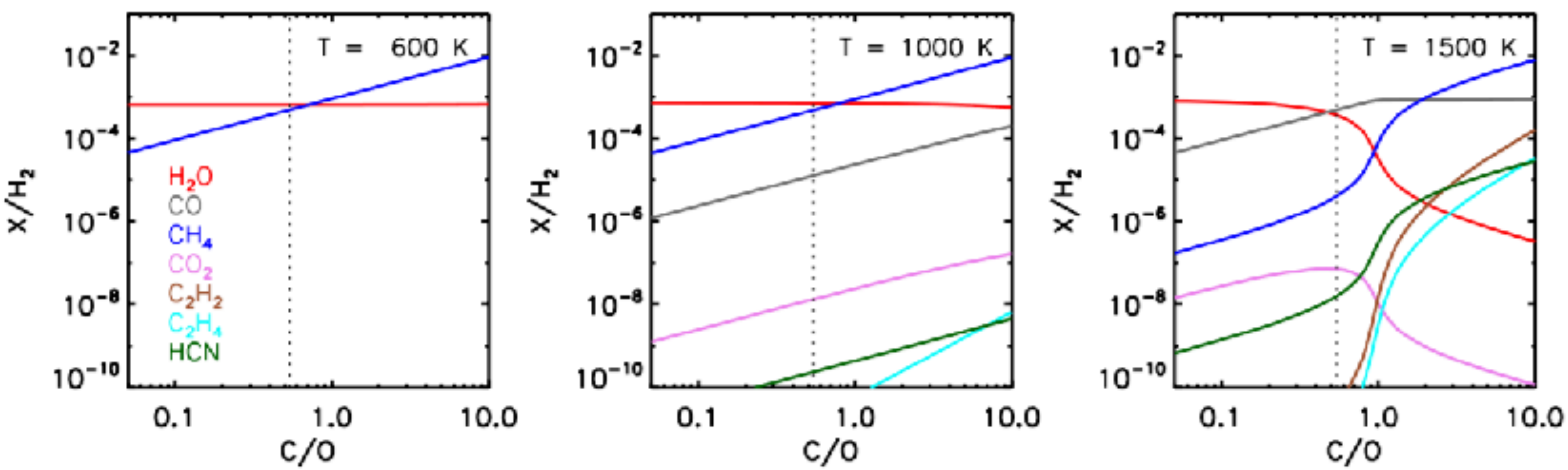


(Adapted from Madhusudhan 2012)
Valid for **solar** elemental abundances

H_2O abundant for a
wide range of temperatures

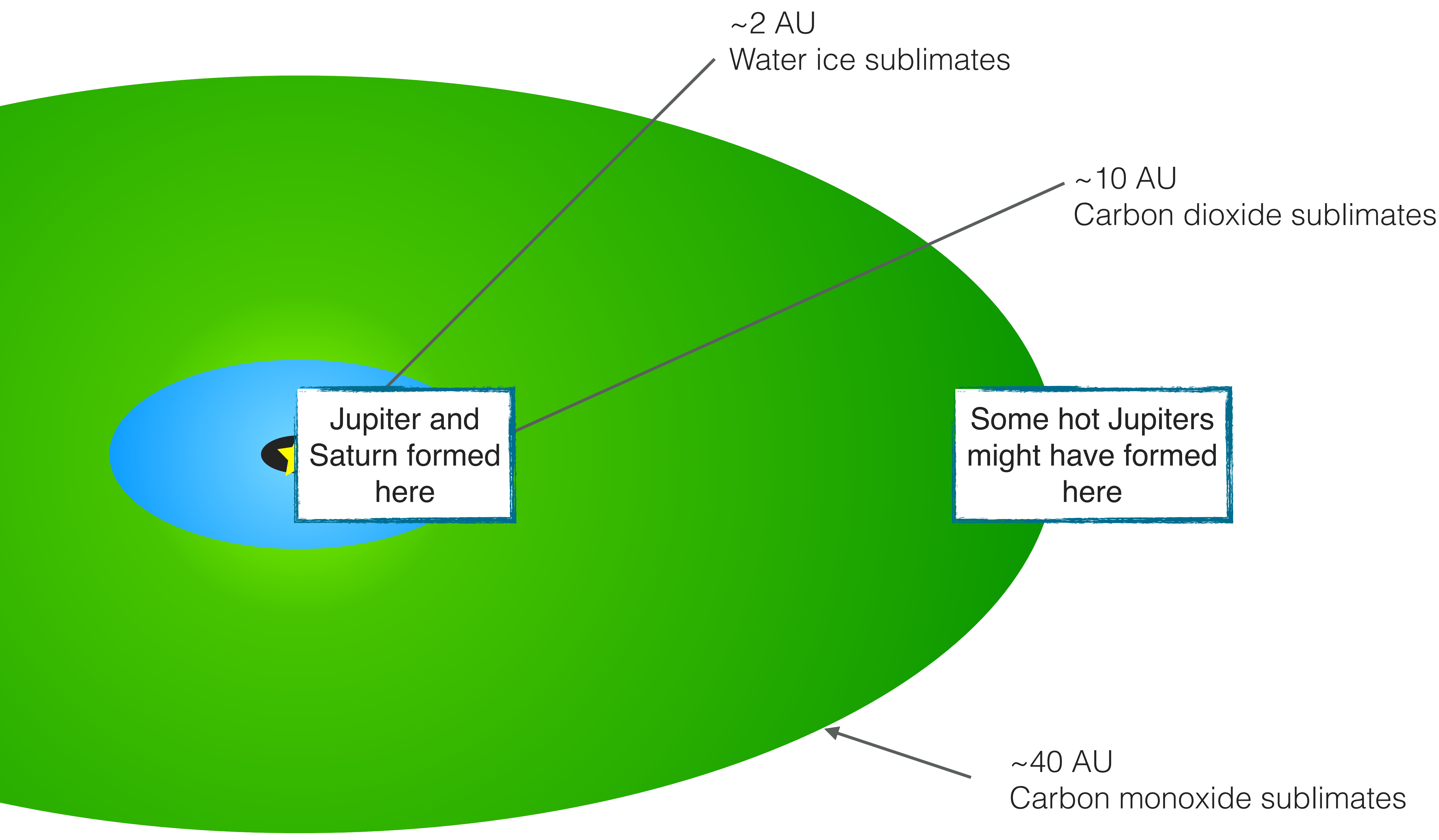
CO / CH_4 switch abundances
at around 1000 K

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



Connecting C/O to the origin of giant exoplanets

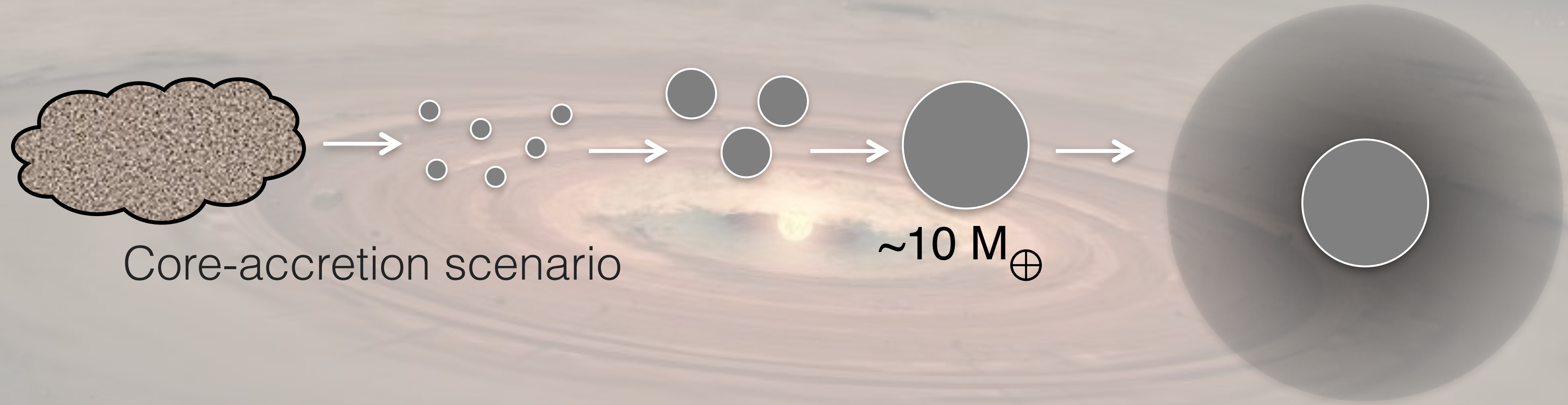
Hot Jupiters might form far away from the star and then migrate inward
Atmospheres will have different composition according to the formation location



(see Öberg+11; Piso+15; Eistrup+18)

Atmospheres to investigate formation and evolution

For the hottest exoplanets mostly in equilibrium (inverting observations into composition)



Planets can form at various distances from the star
⇒ different C and O content in solids/gas due to snowlines

Planets migrate through a disk and/or re-accrete planetesimals
⇒ C/O can change from the formation value

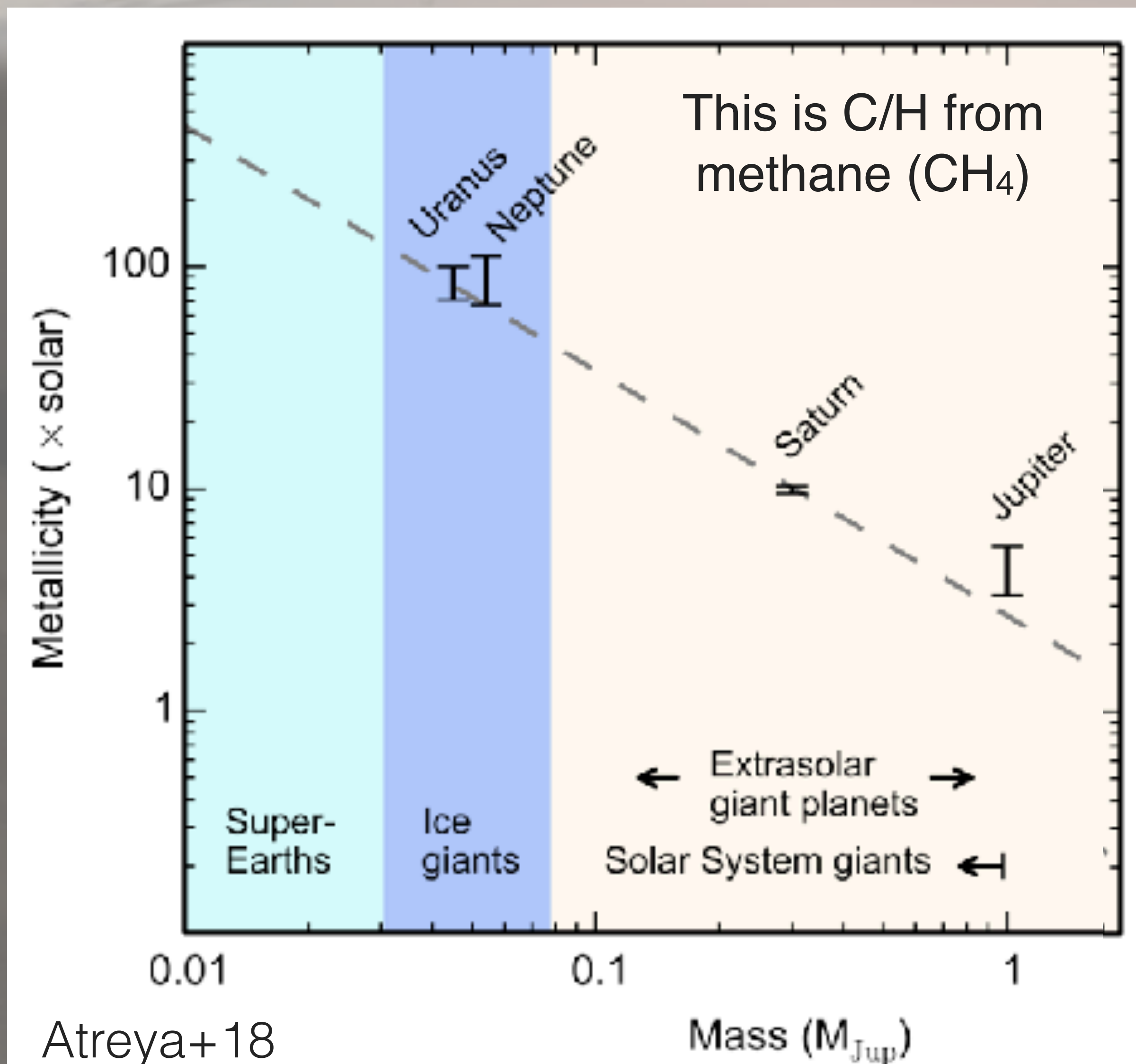
Cores can be partially eroded to “enrich” the metal content of the envelope
⇒ metallicity can change

Uncertainties on timescales / dominance of processes makes predictions hard
⇒ need for statistical studies of exoplanet atmospheres in metallicity-C/O

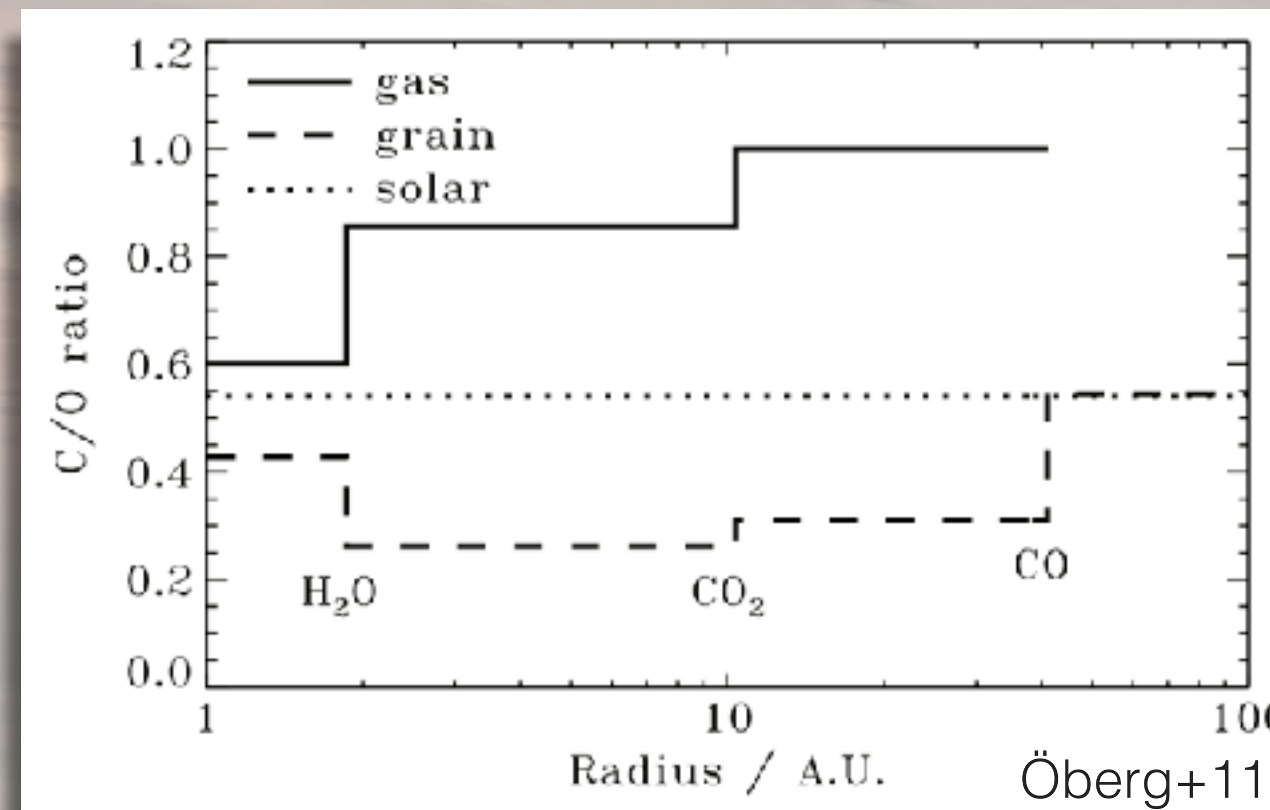
Possible formation/evolution predictions to test

Need to measure "metallicity" and C/O ratio

The mass-metallicity correlation



The C/O ratio



There should be a mass-metallicity relation as in the solar system but core erosion can alter it
(e.g. Madhusudhan+17)

Planets formed beyond the water snowline should have high C/O
(e.g. Öberg+11, Piso+16)

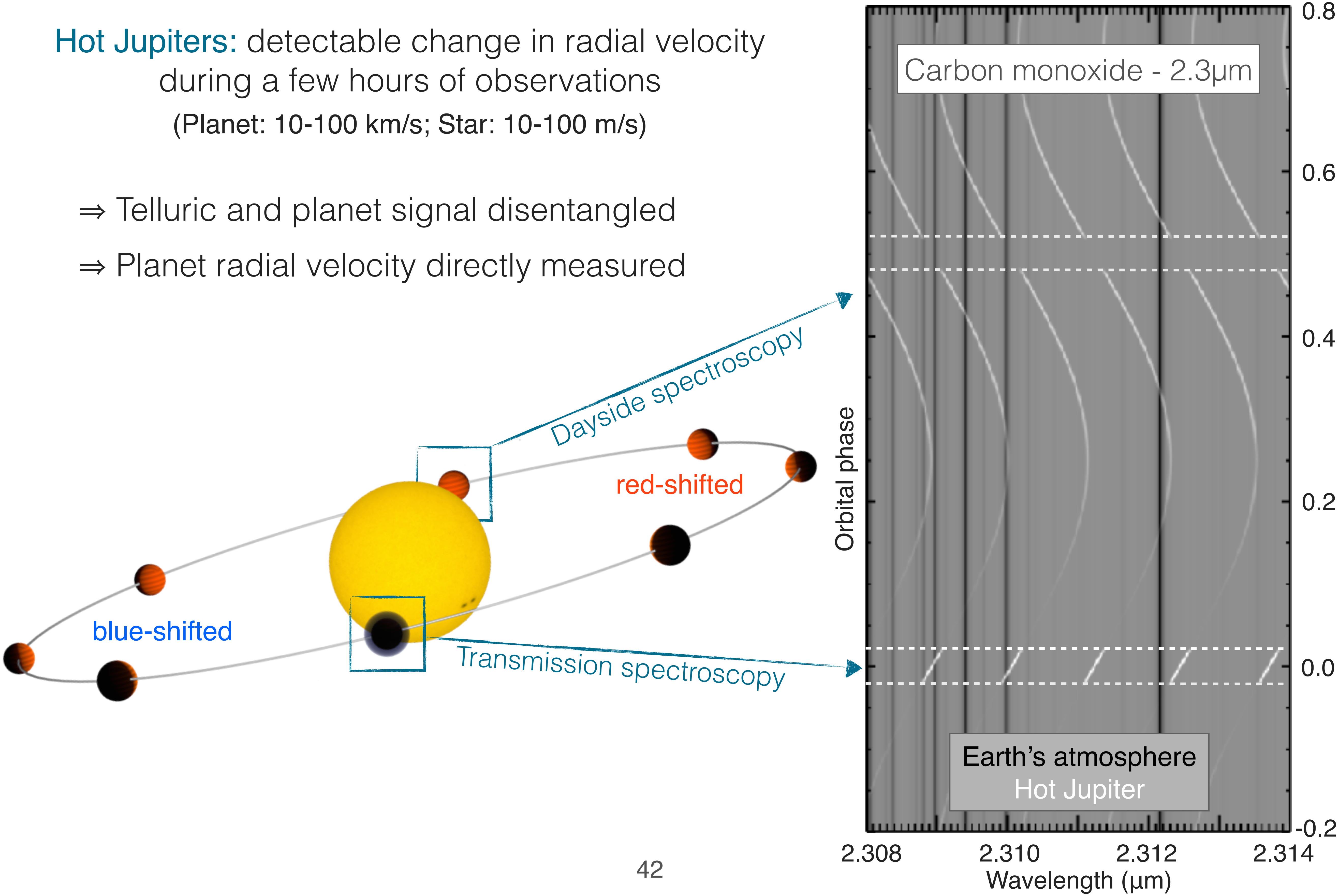
unless they re-accrete planetesimals, which lead to C/O<0.5
(e.g. Mordasini+16)

Detecting the orbital motion of close-in planets

Hot Jupiters: detectable change in radial velocity during a few hours of observations
(Planet: 10-100 km/s; Star: 10-100 m/s)

⇒ Telluric and planet signal disentangled

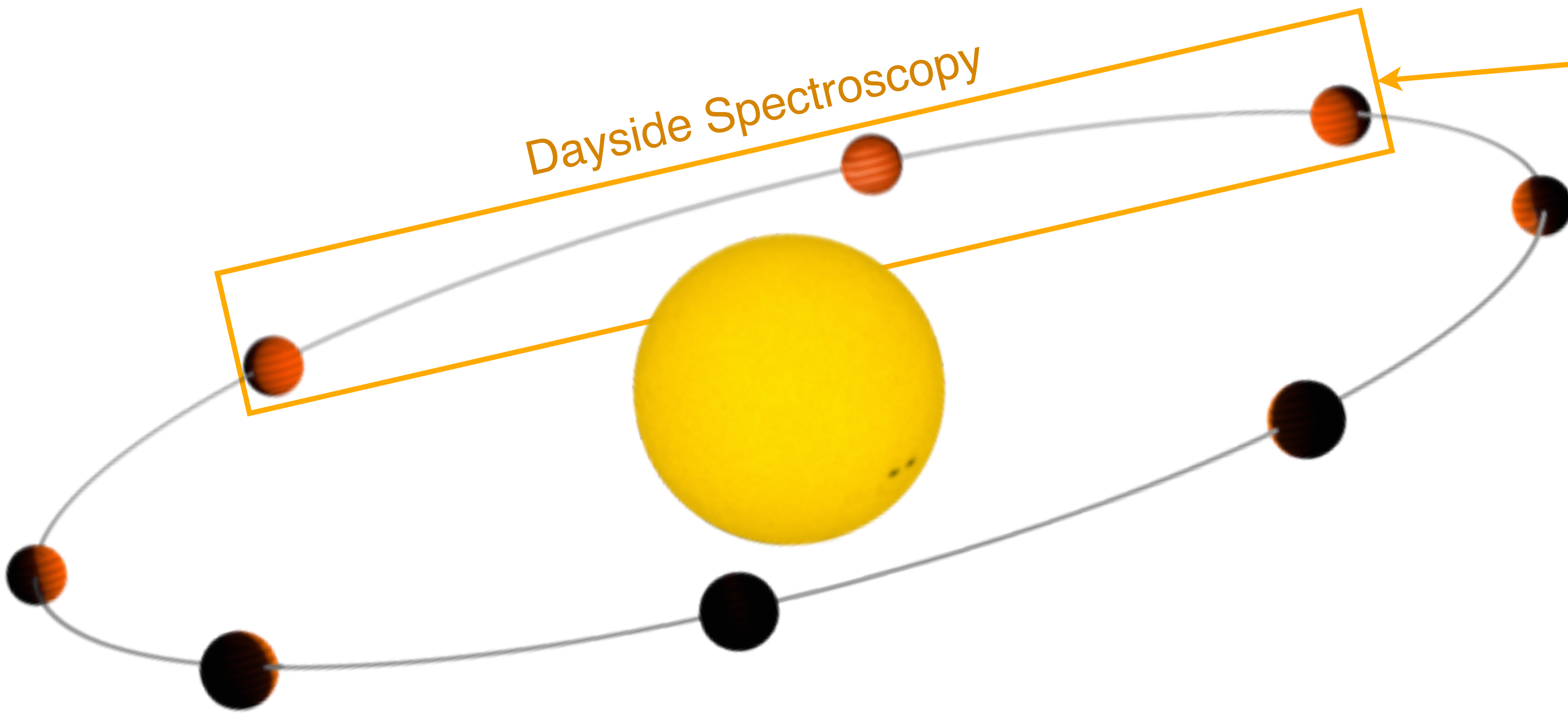
⇒ Planet radial velocity directly measured

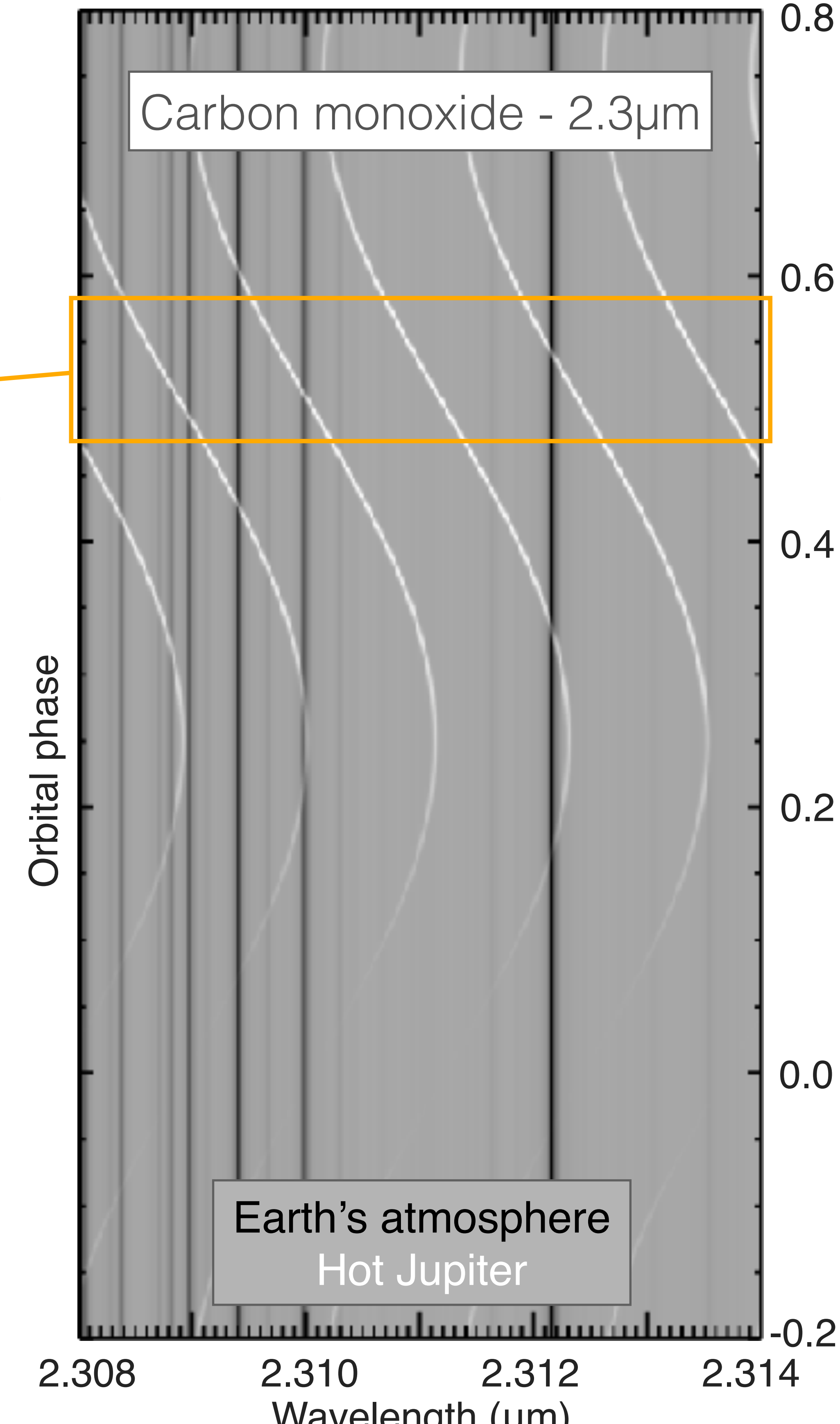


High spectral resolution of non-transiting planets

The thermal spectrum
of the planet is targeted directly

Dayside spectroscopy
applicable to non-transiting planets!





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

Understanding the data: the noise balance

Star and planet are not spatially separated
We measure photons coming from both, but stars are o.o.m. brighter!

Photons obey Poisson statistics: $\sigma = N^{1/2}$

The signal: number of photons emitted / absorbed / reflected by the planet

$$\frac{S}{N} = \frac{N_{\gamma,P}}{\sqrt{\underbrace{N_{\gamma,\mathrm{tot}} + N_{\gamma,\mathrm{sky}} + N_{\mathrm{dark}} + \sigma_{RO}^2}}}$$

The noise budget

Total number of photons $N_{\gamma,\mathrm{tot}} = N_{\gamma,\mathrm{P}} + N_{\gamma,\mathrm{star}}$
Photons from the sky (Earth) $N_{\gamma,\mathrm{sky}}$
Photons from the thermal current of the detector N_{dark}
Read-out noise from the detector electronics (σ_{RO})

Understanding the data: the noise balance

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$$\frac{S}{N} = \frac{N_{\gamma,P}}{\sqrt{\underbrace{N_{\gamma,\mathrm{tot}} + N_{\gamma,\mathrm{sky}} + N_{\mathrm{dark}} + \sigma_{RO}^2}_{\text{All independent sources of noise - summed in quadrature}}}}$$

Sources that come from photon counting have noise $\approx \sqrt{N_\gamma}$
Detector readout is just an extra noise budget ⇒ noise = σ_{RO}

Understanding the data: the noise balance

Star and planet are not spatially separated
We measure photons coming from both, but stars are o.o.m. brighter!

Photons obey Poisson statistics: $\sigma = N^{1/2}$

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$$\frac{S}{N} = \frac{N_{\gamma,P}}{\sqrt{\underbrace{N_{\gamma,\mathrm{tot}} + \cancel{N_{\gamma,\mathrm{sky}}} + \cancel{N_{\mathrm{dark}}} + \cancel{\sigma^2_{RO}}}_{\text{All independent sources of noise - summed in quadrature}}}} \approx \frac{N_{\gamma,P}}{\sqrt{N_{\gamma,\star}}} \leq 10^{-3}\sqrt{N_{\gamma,\star}}$$

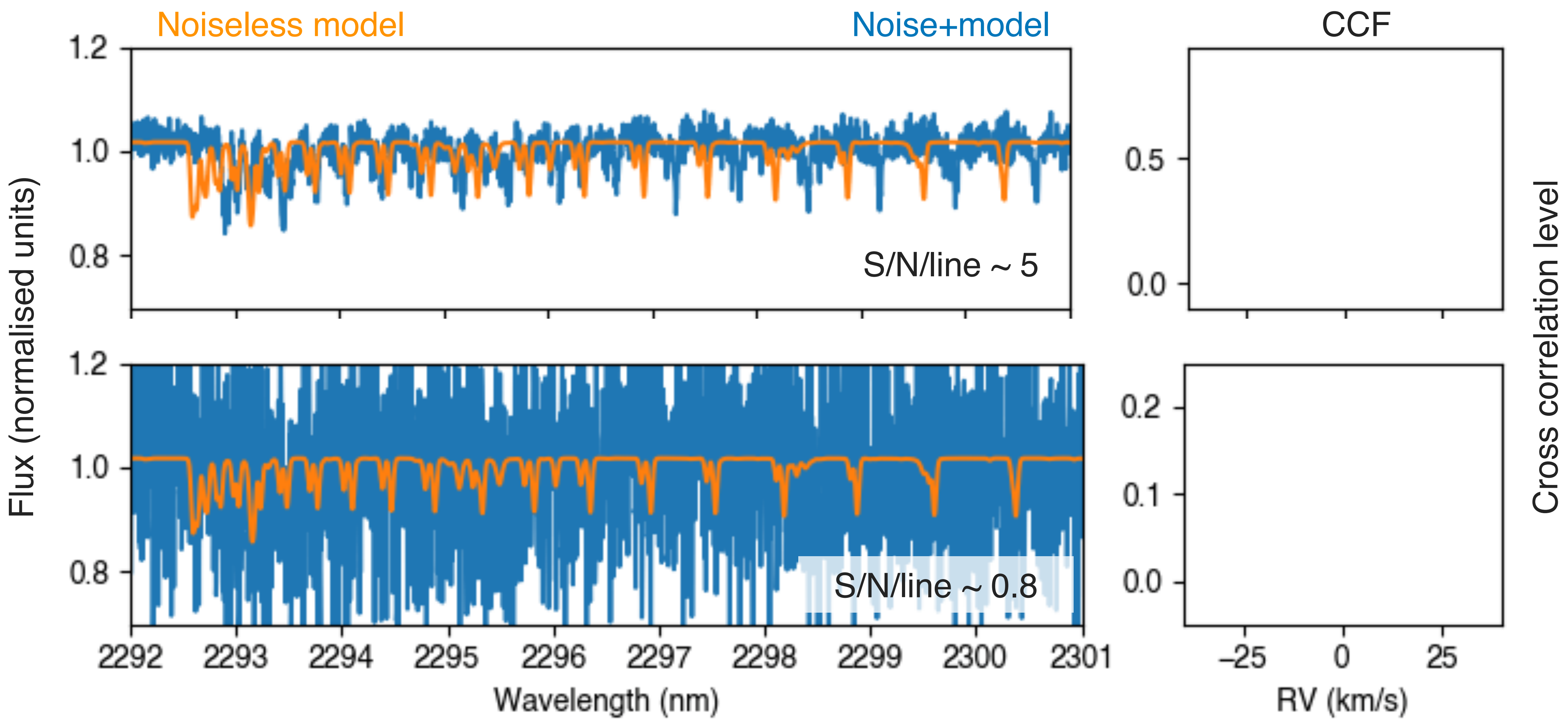
Sources that come from photon counting have noise $\approx \sqrt{N_\gamma}$
Detector readout is just an extra noise budget ⇒ noise = σ_{RO}

Even for the brightest stars $N_\gamma \leq 10^6$ / pixel

⇒ We expect each spectral line to be detected at most at S/N = 1
Some technique to “amplify” the signal is needed ⇒ cross correlation

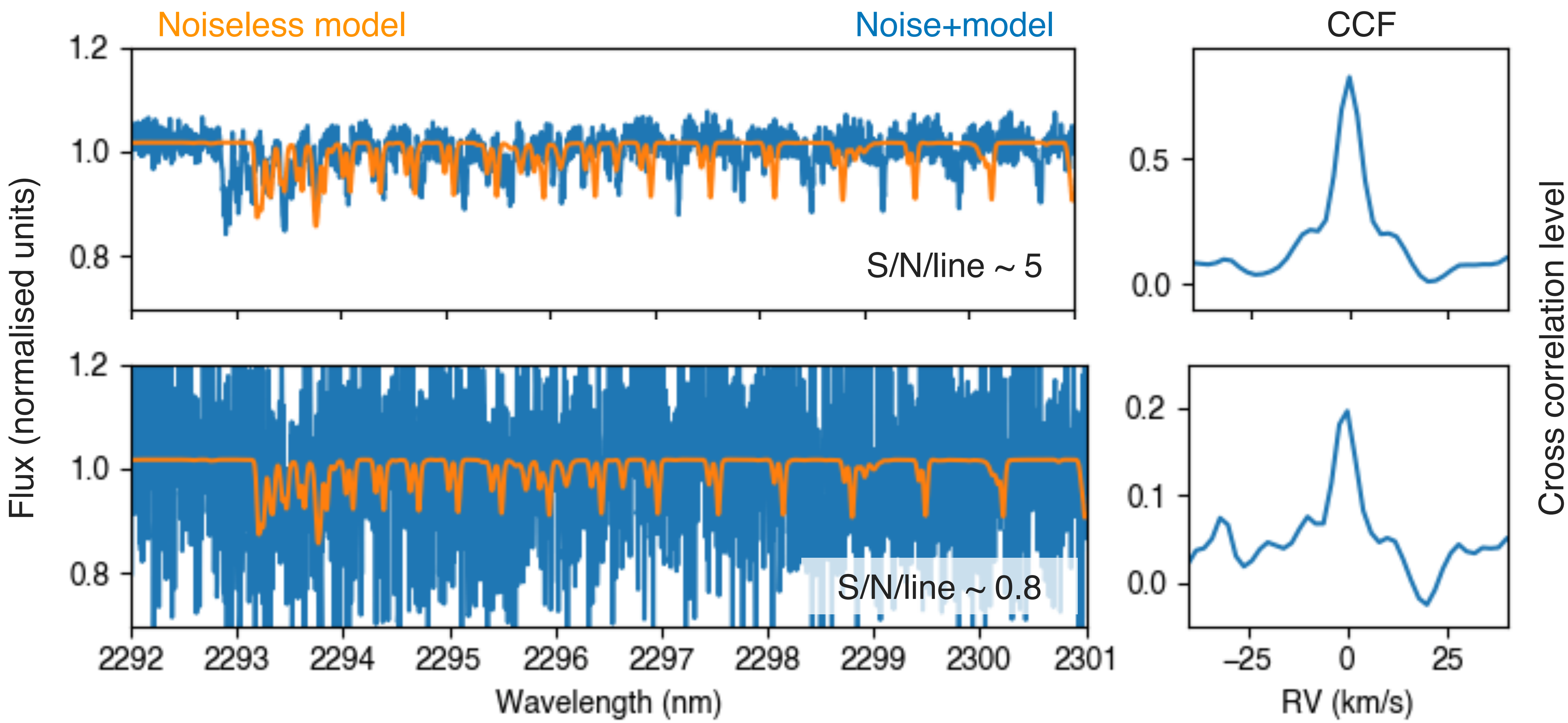
The cross correlation function

Measuring correlation between (noisy) data and a moving template



The cross correlation function

Measuring correlation between (noisy) data and a moving template



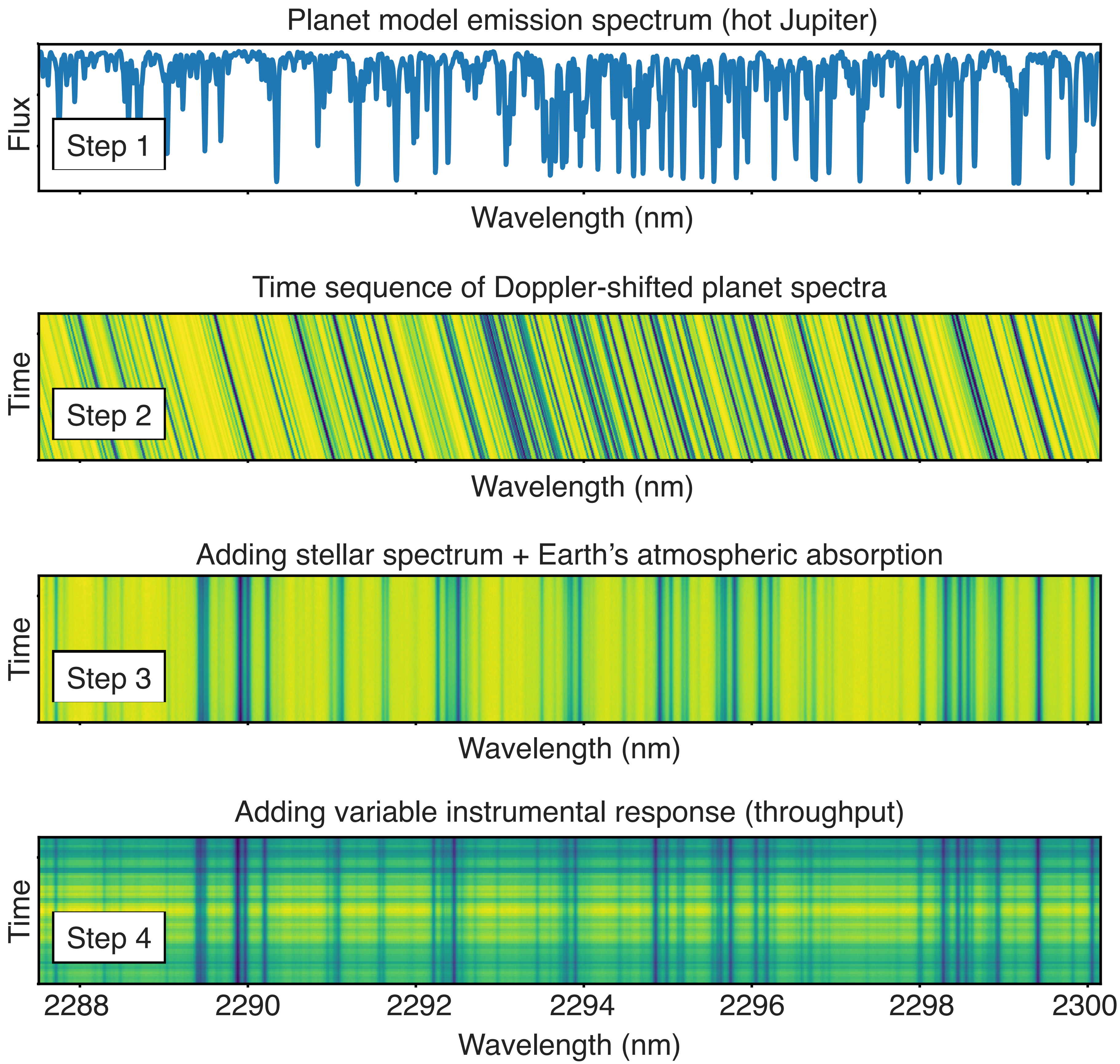
$$\left.\frac{S}{N}\right|_{\mathrm{CCF}} \approx \frac{n_{\mathrm{pix}} N_{\gamma,P}}{\sqrt{n_{\mathrm{pix}} N_{\gamma,\star}}} \propto \frac{S}{N} \sqrt{n_{\mathrm{lines}}}$$

Just one line

Typical hot-Jupiter has S/N~0.8/line and *n*=50

⇒ We expect a S/N~5-6 from cross correlation with strong lines (e.g. CO)

Understanding the data: a time sequence of spectra



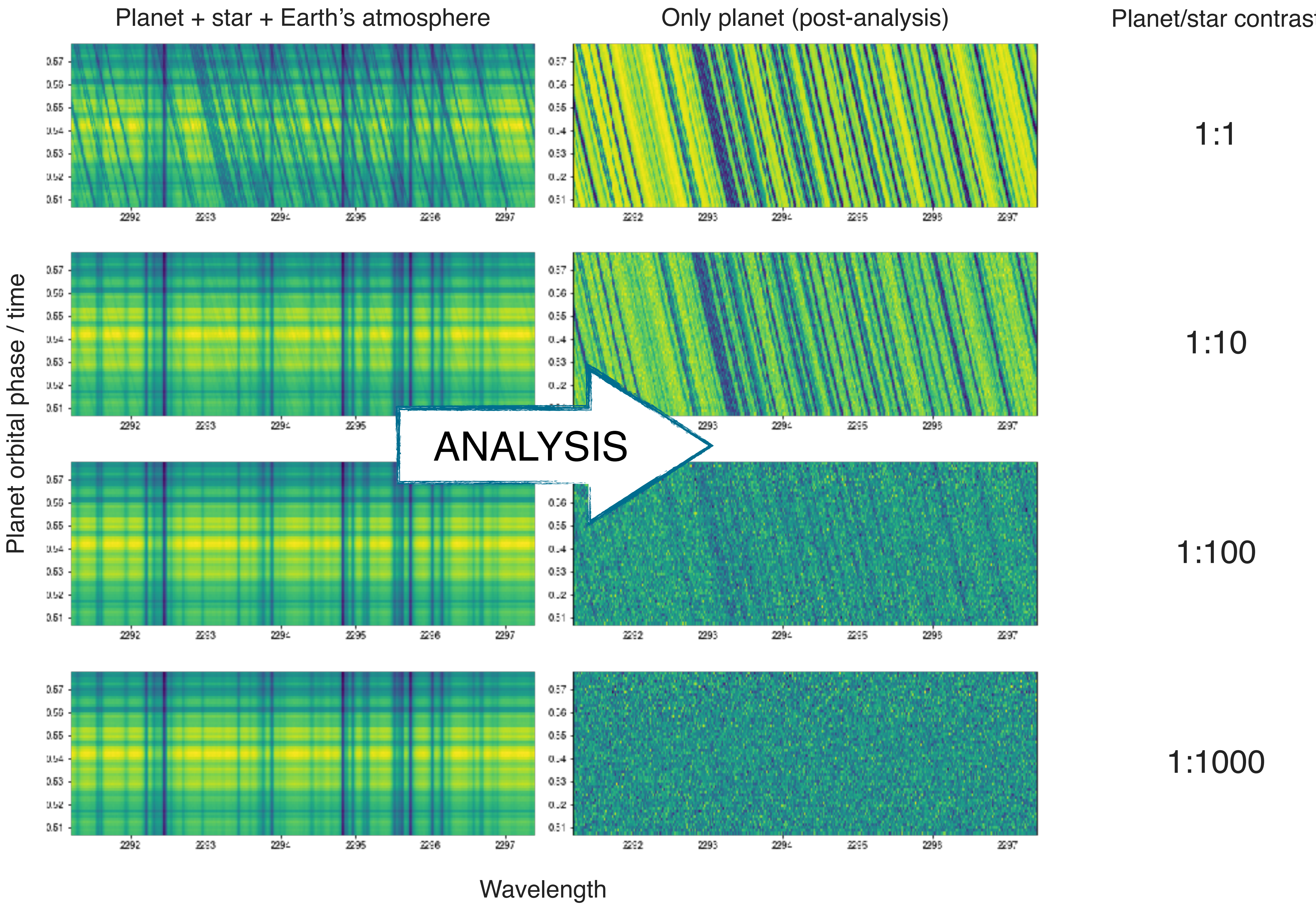
Planet spectral lines
~10^{-4} of stellar continuum

Radial component of planet orbital motion changes by ~10 km / s per hour of observation

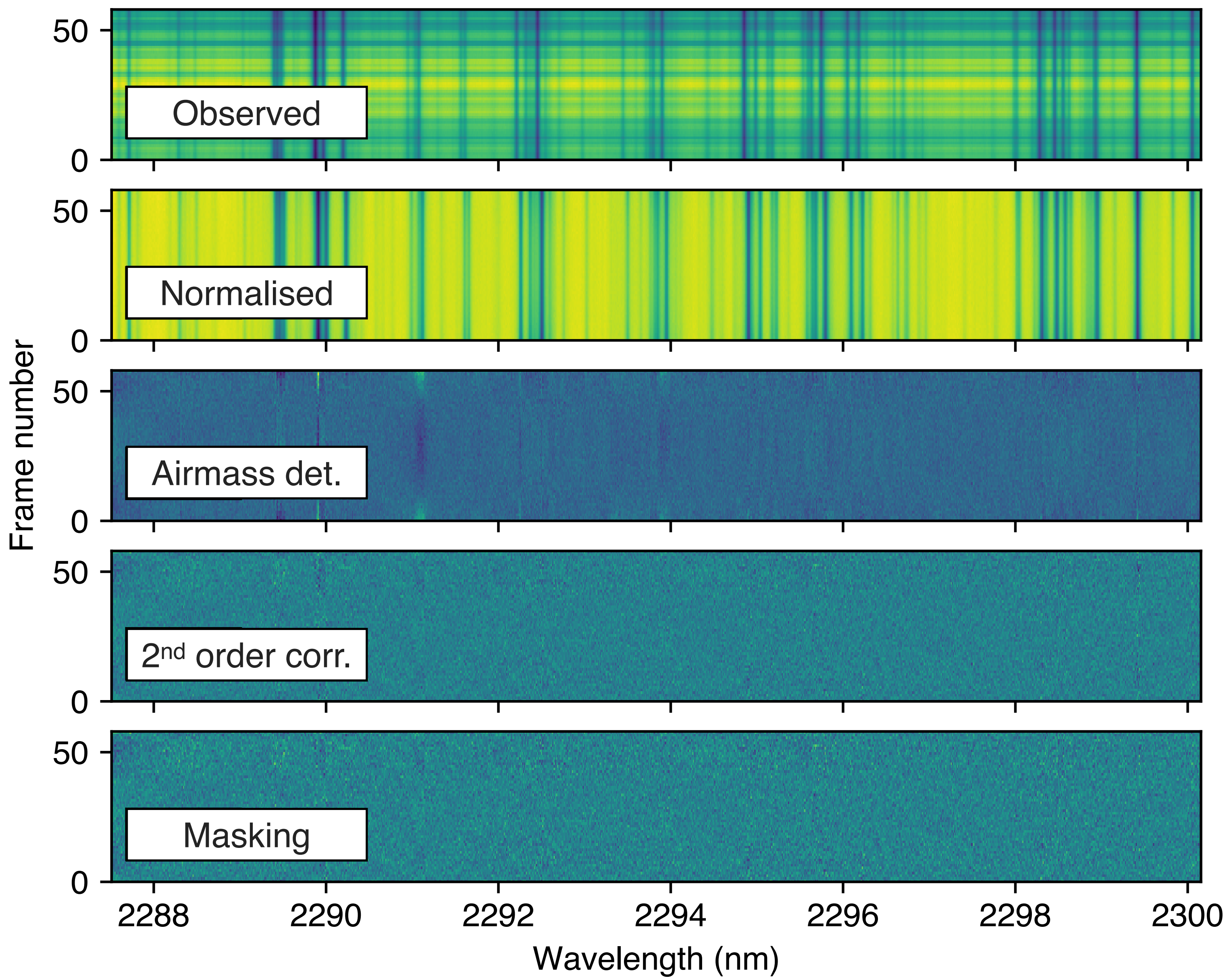
Dominant by orders of magnitude over the planet signal (up to 50-60% depth)

20-30% variation in overall measured flux (telescope pointing, atmospheric transparency, etc.)

Reverse-engineering the exoplanet spectrum



Reverse-engineering the exoplanet spectrum



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

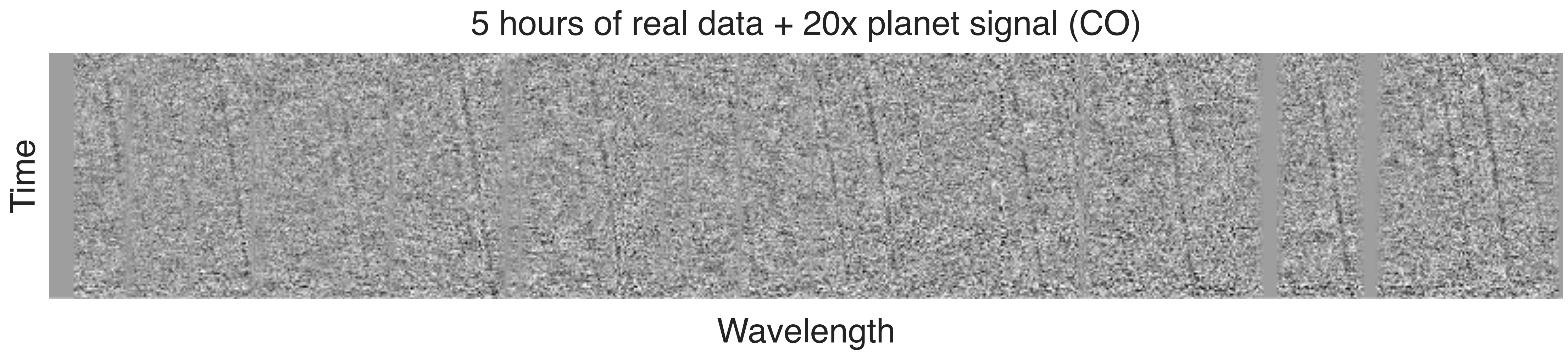
Final masking of very noisy columns

All the steps after normalisation can be done "automatically" by algorithms that decompose the data into a linear combination of eigenvectors (e.g. PCA)

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

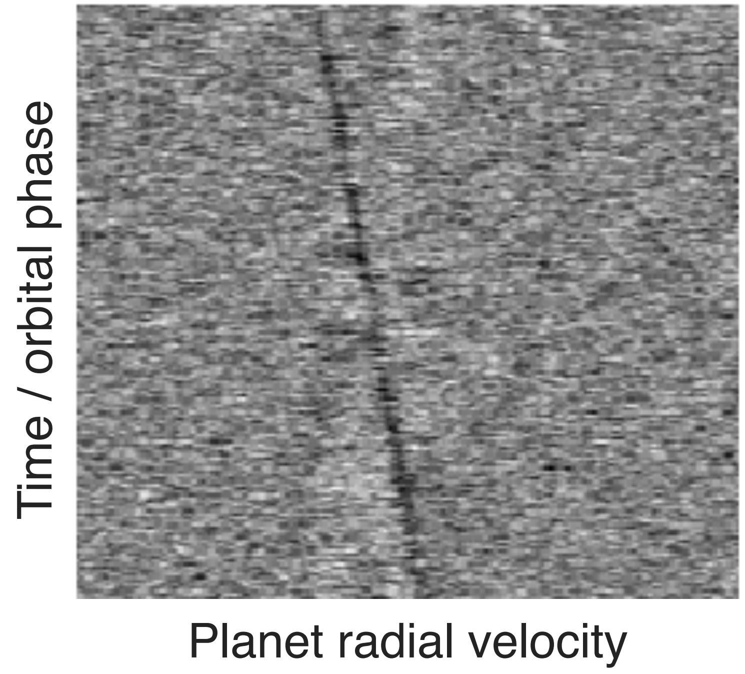
The process "auto-calibrates" the data: no reference star required!

Extracting the (faint) planet signal: cross correlation



Cross-correlation with model spectra

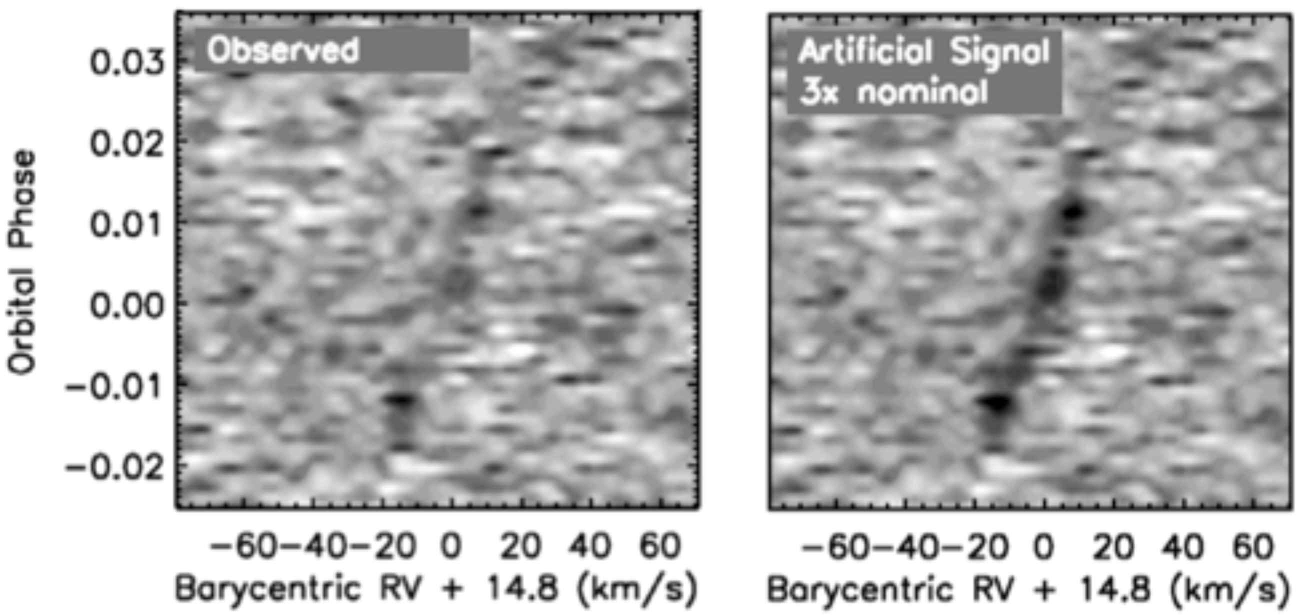
Cross-correlation matrix
CC(RV, t)



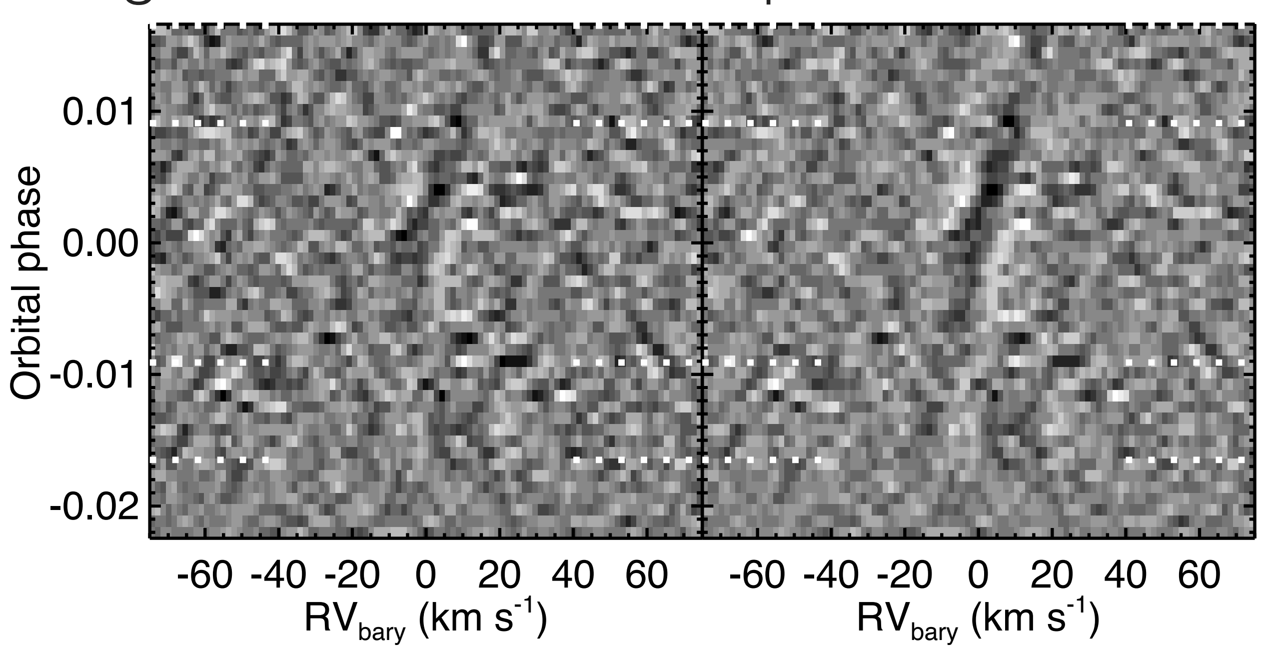
The peak CC tracks the planet radial velocity in time

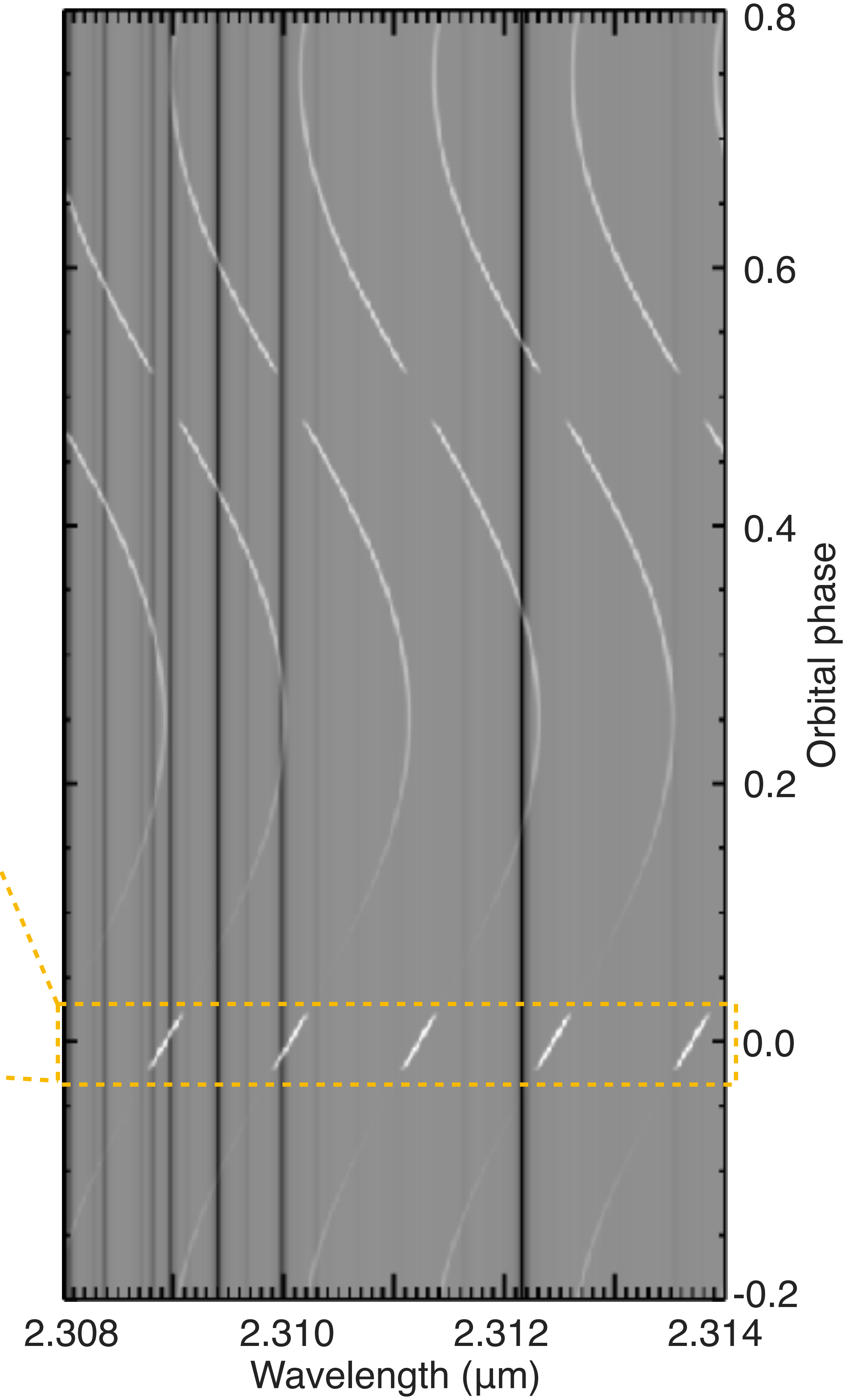
Phase-resolved cross-correlation: transmission

Snellen+2010: CO absorption in HD 209458 b



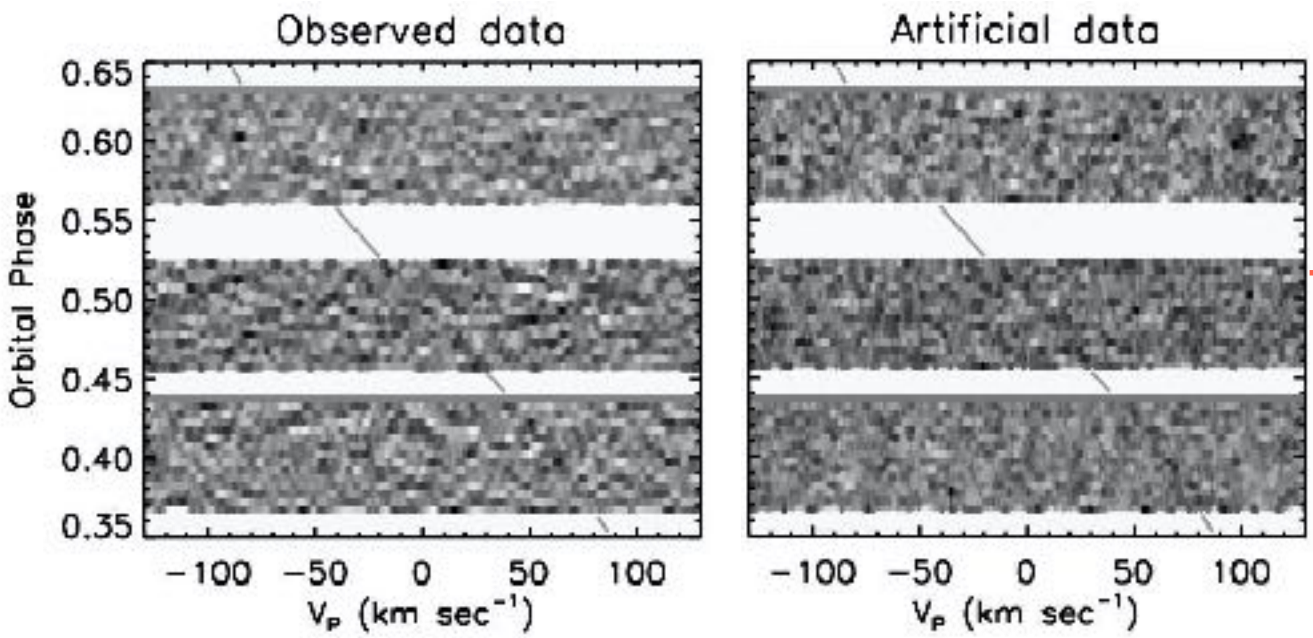
Brogi+16: CO+H_2O absorption in HD 189733 b



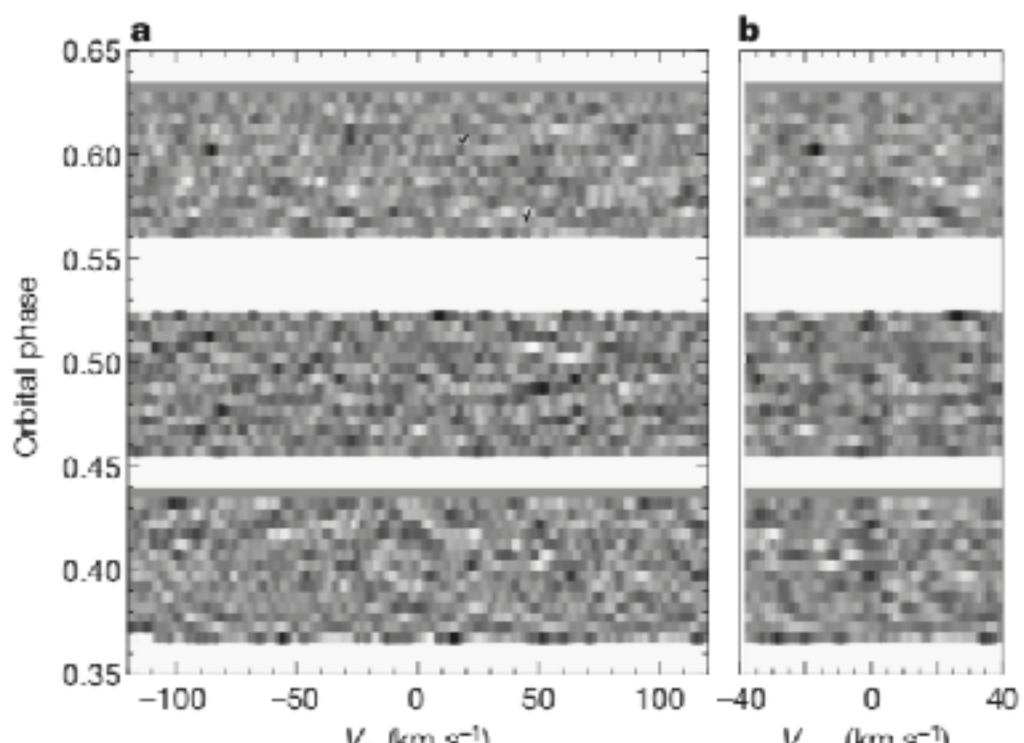


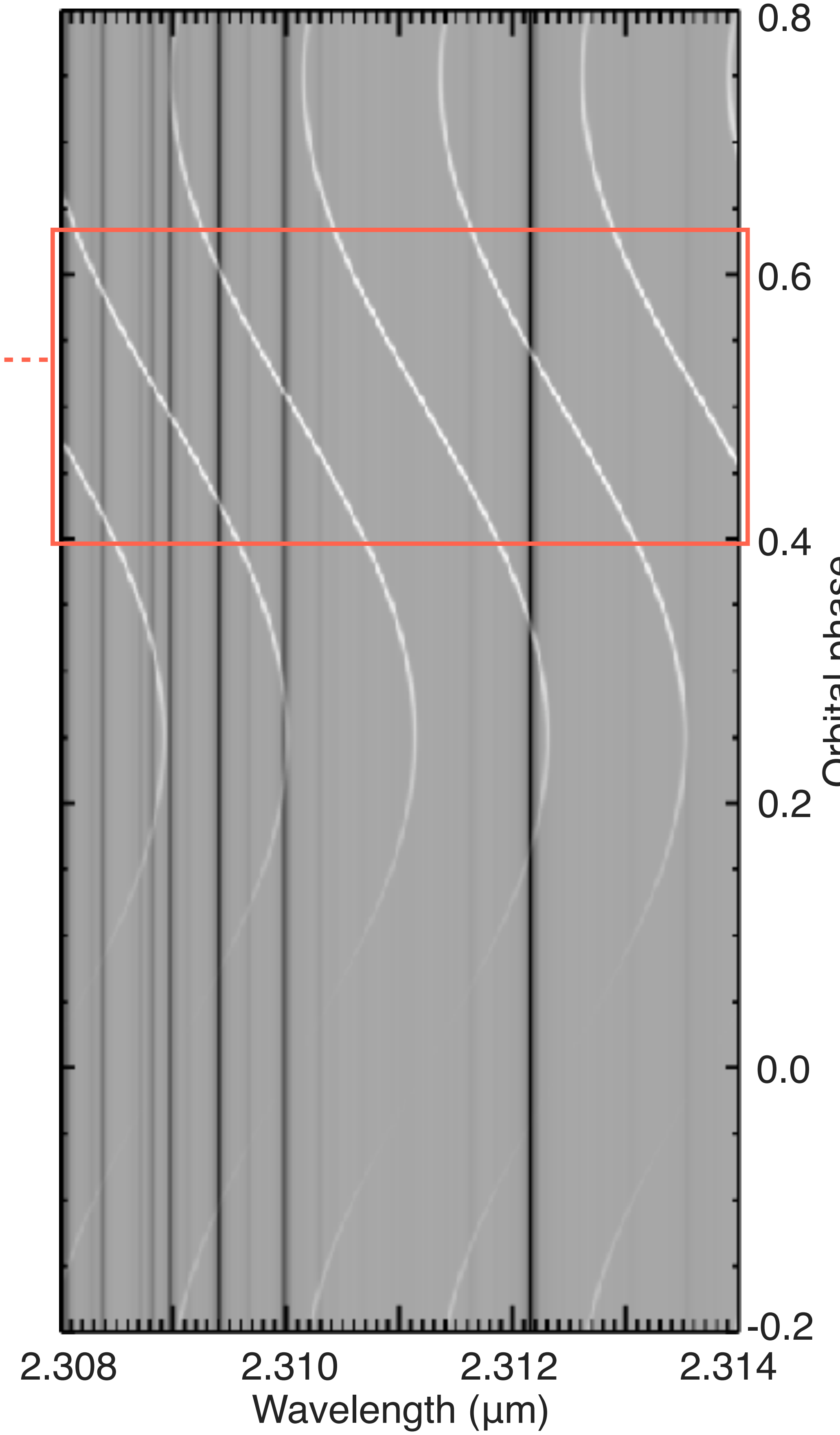
Phase-resolved cross-correlation: emission

Brogi+2012: CO absorption in tau Bootis b

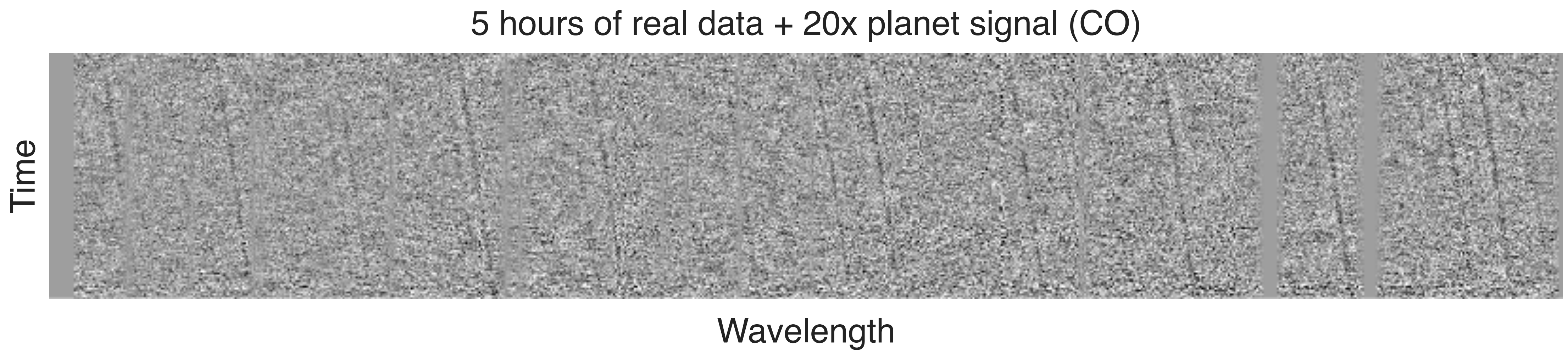


Signal is present at most at S/N=1 per spectrum
Needs co-adding in phase to enhance signal



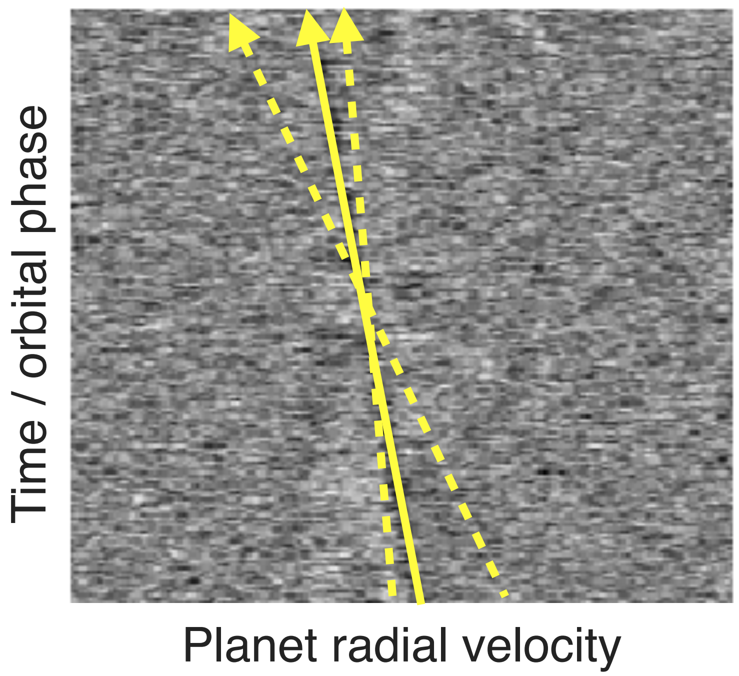


Extracting the (faint) planet signal: cross correlation



Cross-correlation with model spectra

Cross-correlation matrix
CC(RV, t)



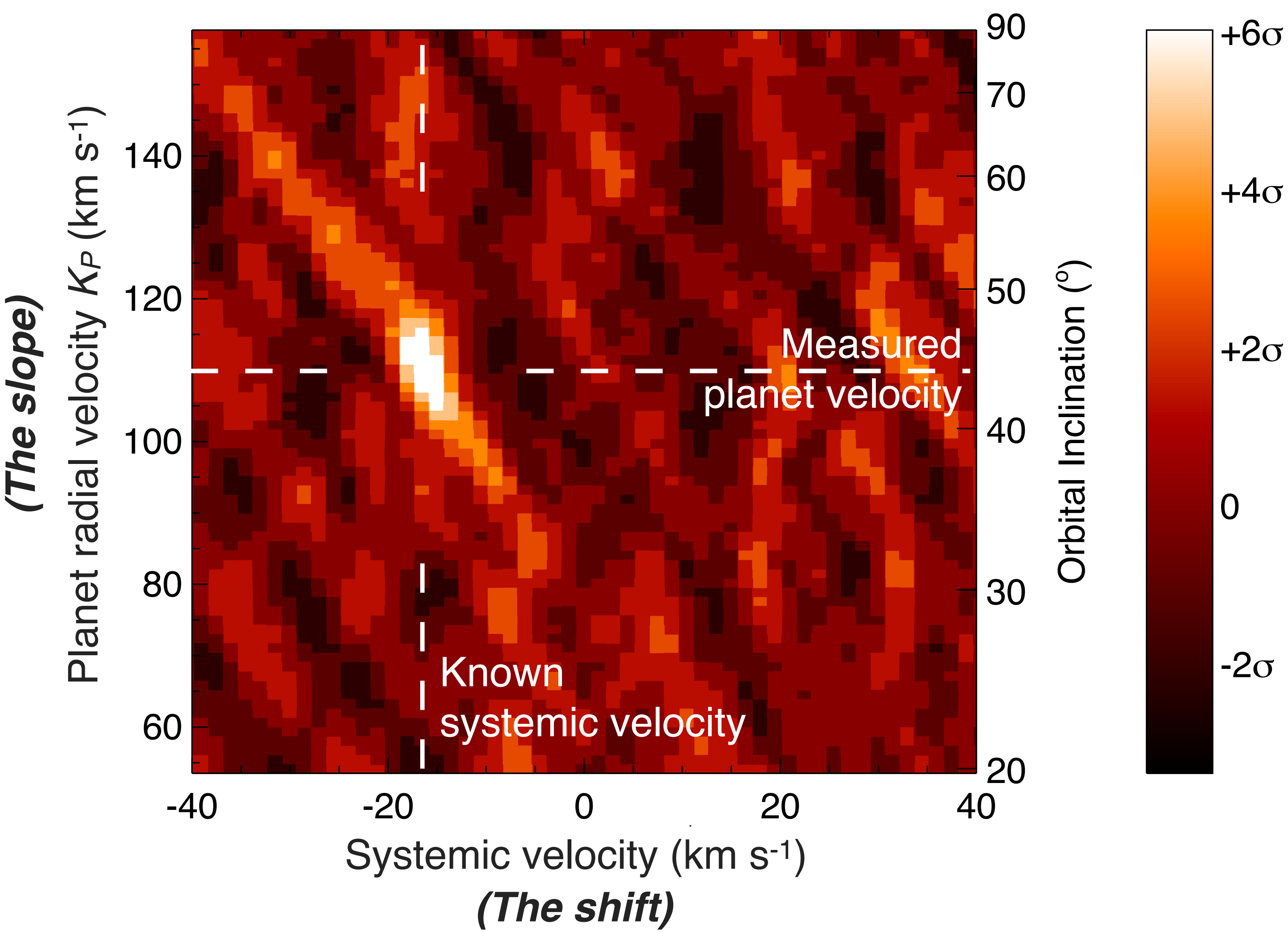
The peak CC tracks the planet radial velocity in time

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.

Star and planet as spectroscopic binaries

Deriving the true planet mass

$$\frac{K_P}{K_\star} = \frac{M_\star}{M_P}$$

Known stellar mass (within a few %)

$$M_P = M_\star \frac{K_\star}{K_P}$$

Stellar RV semi-amplitude (known from stellar RVs)

Planet RV semi-amplitude (measured through HRS of planet atmosphere)

Deriving the orbital inclination

$$\sin(i) = \frac{M_P \sin(i)}{M_P}$$

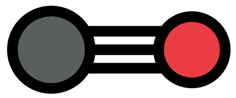
Known from fit of stellar RVs

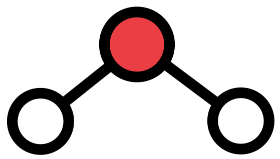
$$\sin(i) = \frac{K_P}{v_{orb}}$$

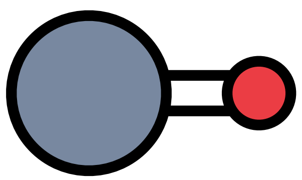
Known from fit of stellar RVs (see previous slides)

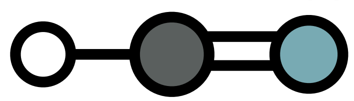
	Inclination (degrees)	Mass (M_{Jup})	Reference
τ Boötis b	45.5±1.5	5.95±0.28	Brogi+12
51 Pegasi b	>79.8	0.46±0.02	Brogi+13
HD 179949 b	67.7±4.3	0.98±0.04	Brogi+14
HD 88133 b	15^{+6}_{-5}	$1.02^{+0.61}_{-0.28}$	Piskorz+16
υ And b	24±4	$1.70^{+0.33}_{-0.24}$	Piskorz+17
HD 102195 b	>72.5	0.46±0.03	Guilluy+19

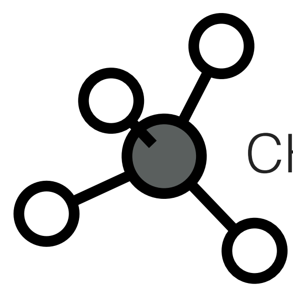
The chemical inventory at high spectral resolution

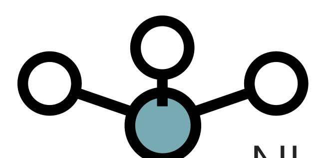
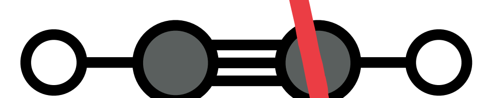
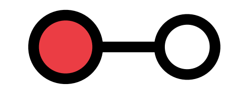
2010  CO

2013  H_2O

2017  TiO

2018  HCN

2019  CH_4

2021  NH_3  C_2H_2  OH

Observed sample: 30 planets

10 non-transiting, 18 transiting, 2 directly imaged

Potential sample: > 50 (currently)

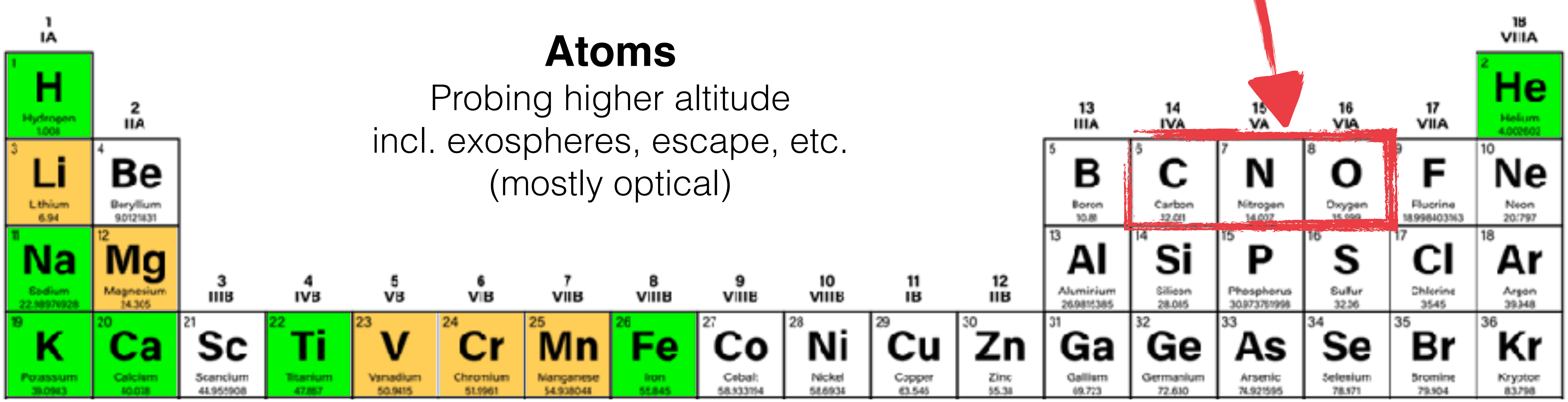
15 non-transiting (K < 6.5 mag) + 40 transiting (K < 10 mag)

Molecules

Constraints on T, abundances (mostly nIR)

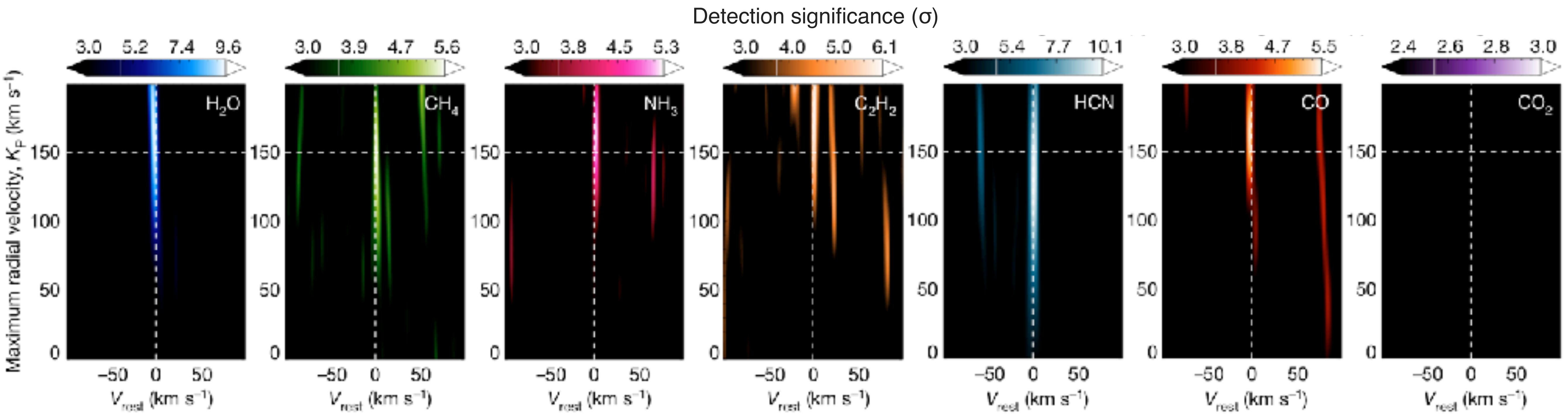
Atoms

Probing higher altitude incl. exospheres, escape, etc. (mostly optical)



Five carbon- and nitrogen-bearing species in a hot giant planet's atmosphere

P. Giacobbe, M. Brogi, S. Gandhi et al., *Nature* **592**, 205-208 (2021)



4 transits of hot Jupiter HD 209458b (1,500K) ⇒ H_2O + 5 species simultaneously detected

What does it mean for the atmosphere of HD 209548 b?

Need to move *beyond detecting* and towards *measuring*
(We will see this in the next lecture!)