Prospects for ground-based characterization of Proxima Centauri b

Matteo Brogi
Hubble Fellow, CU-Boulder

Ignas Snellen, Remco de Kok, Henriette Schwarz (Leiden, NL)
Jayne Birkby (CfA, USA), Simon Albrecht (Aarhus, DK)

Searching for life across space and time, Irvine, CA
Dec 5, 2016

Image credits: ESO/M.Kornmesser

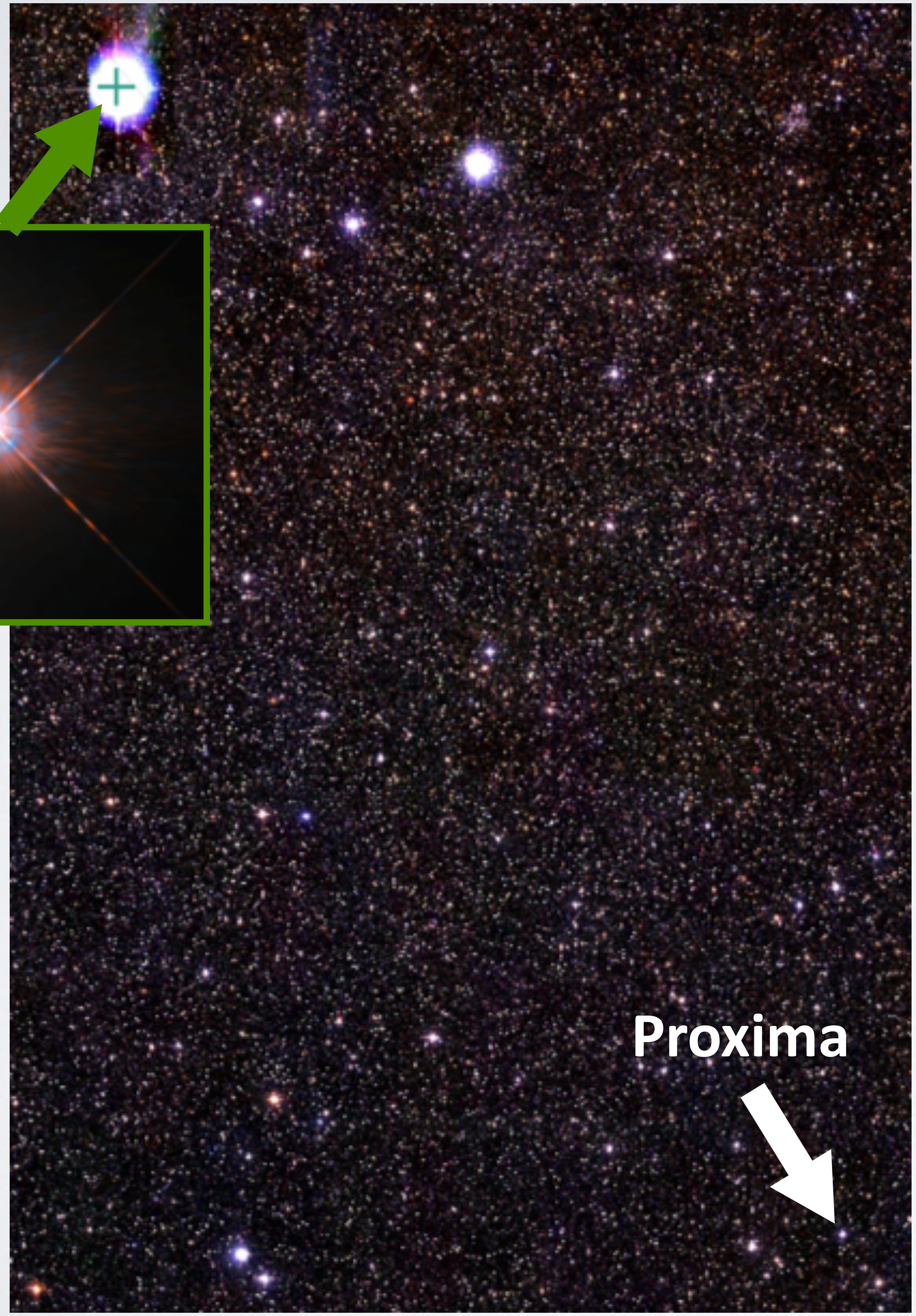
The planet around Proxima Centauri

The closest star to the Sun (1.3 pc)

The planet around Proxima Centauri

The closest star to the Sun (1.3 pc)

α Cen AB
Hubble/WFC2

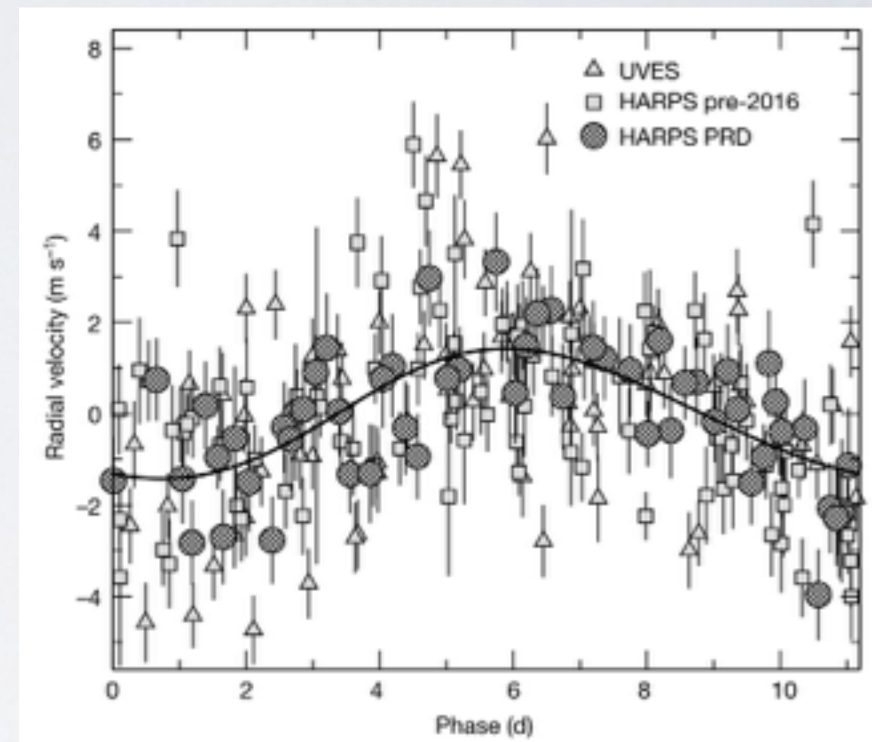


The star

M5.5V, 3050±100 K

0.120±0.015 M_{Sun}

0.141±0.021 R_{Sun}



The planet

$m \sin(i) = 1.27\ M_E$

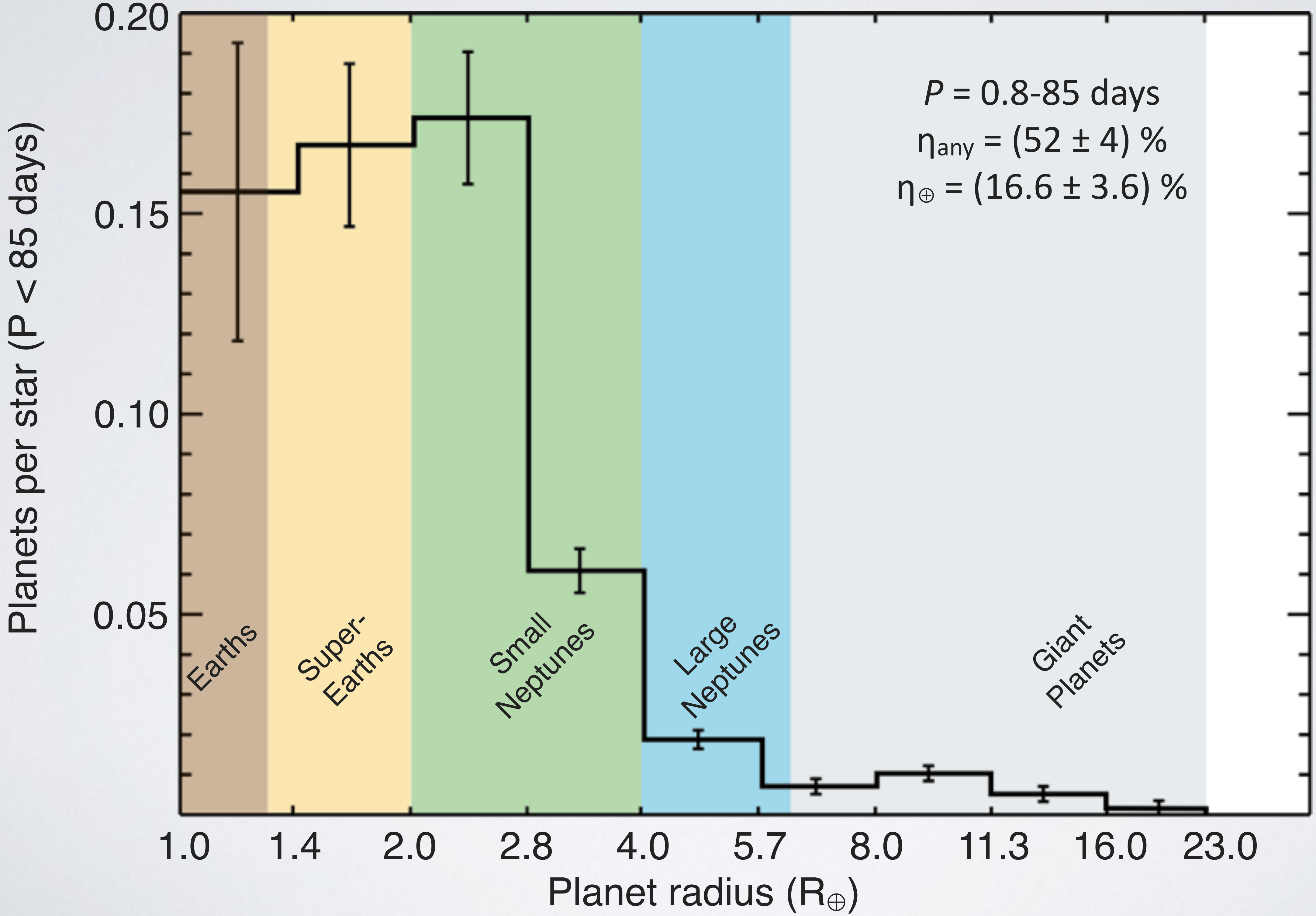
$K_S = 1.38 \pm 0.21$ m/s

$a = 0.0485$ AU

$P = 11.186$ d

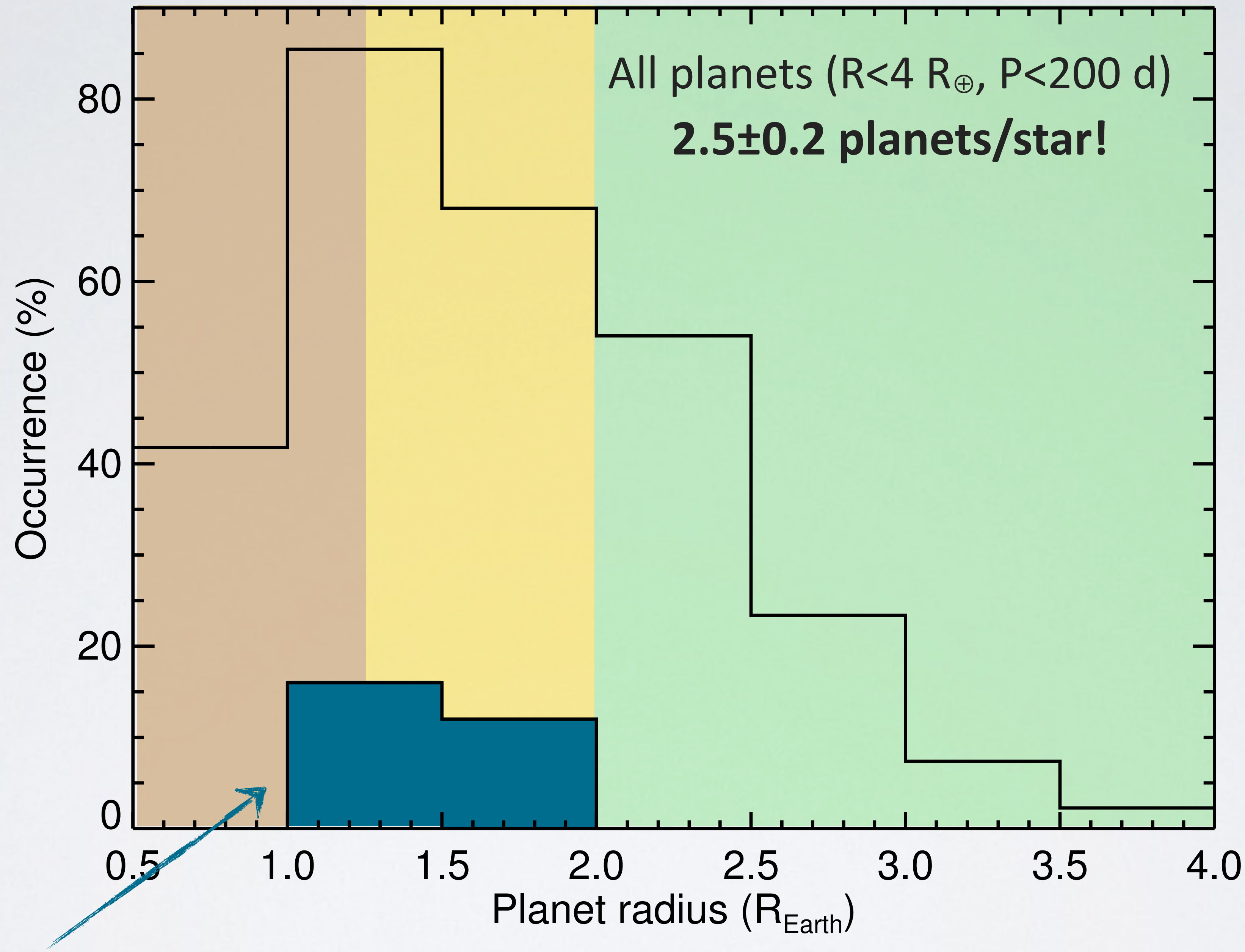
Small exoplanets are common

Extrapolations from *Kepler* detections of transiting planets around FGK stars (Fressin+ 2013)



Small planets around small stars are very abundant!

Based on *Kepler* detections around M dwarfs (Dressing & Charbonneau 2015)



Habitable planets

$0.16^{+0.17}_{-0.07}$ planets/star (1.0-1.5 R⊕)

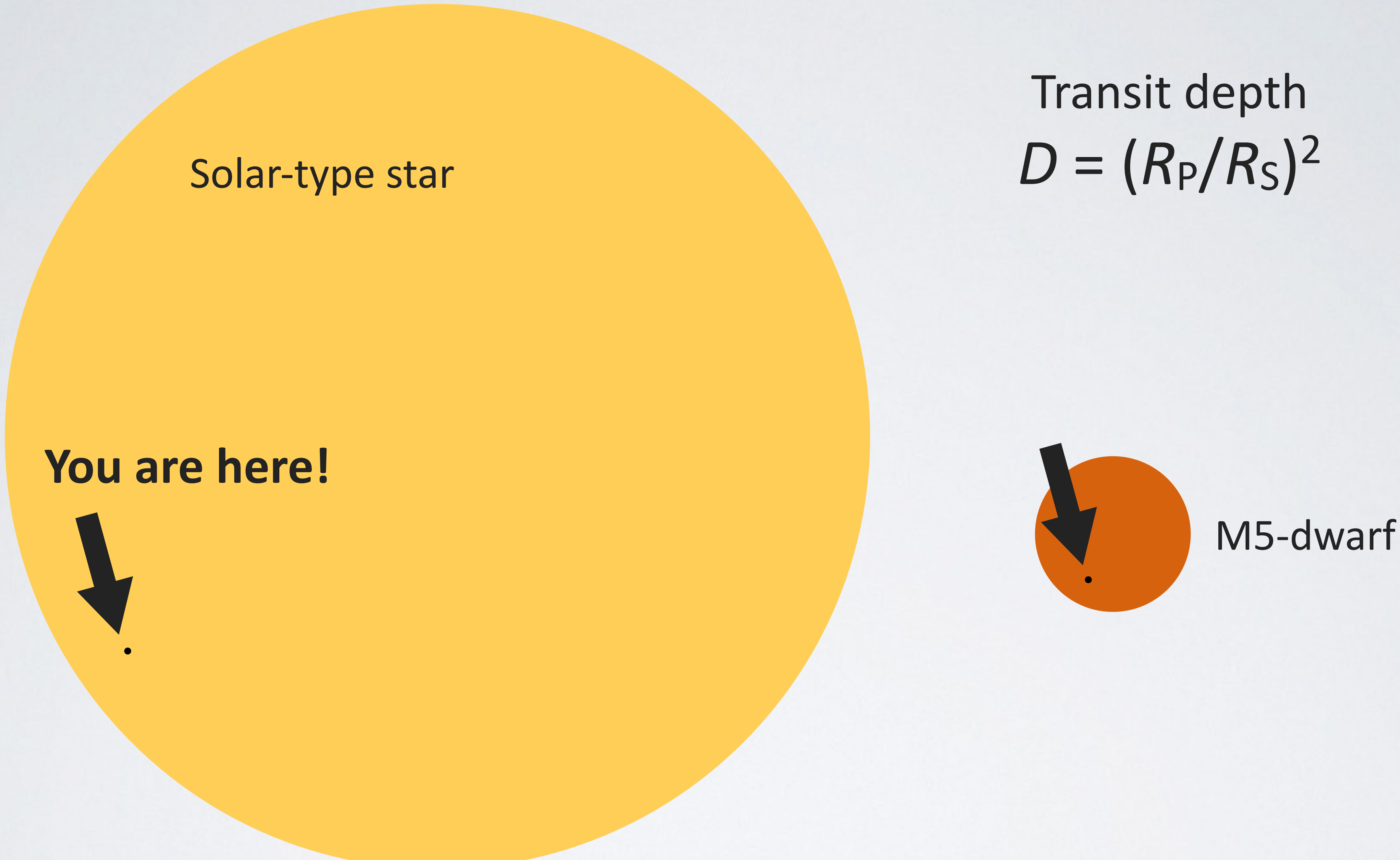
$0.12^{+0.10}_{-0.05}$ planets/star (1.5-2.0 R⊕)

Conservative HZ (runaway / max. greenhouse)

Smaller & fainter stars ⇒ higher planet/star contrast

Transit depth

$$D = (R_P/R_S)^2$$



Earth-Sun: $D \approx 0.008\%$

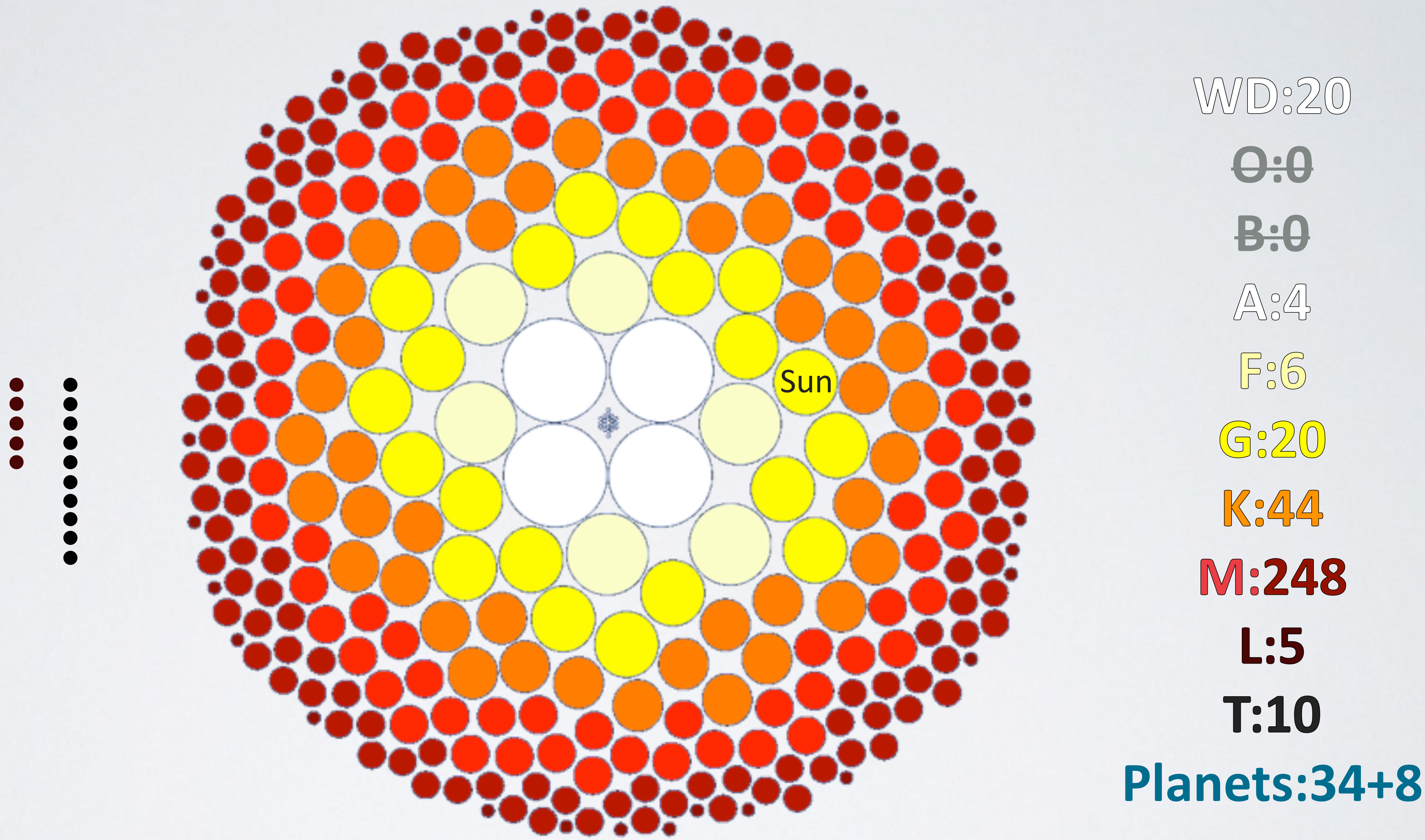
Earth-M5: $D \approx 0.25\%$

Similar gain for **reflected-light** and **thermal-emission** contrasts

Small planets around small stars are nearby!

Data from the RECONS project: www.recons.org

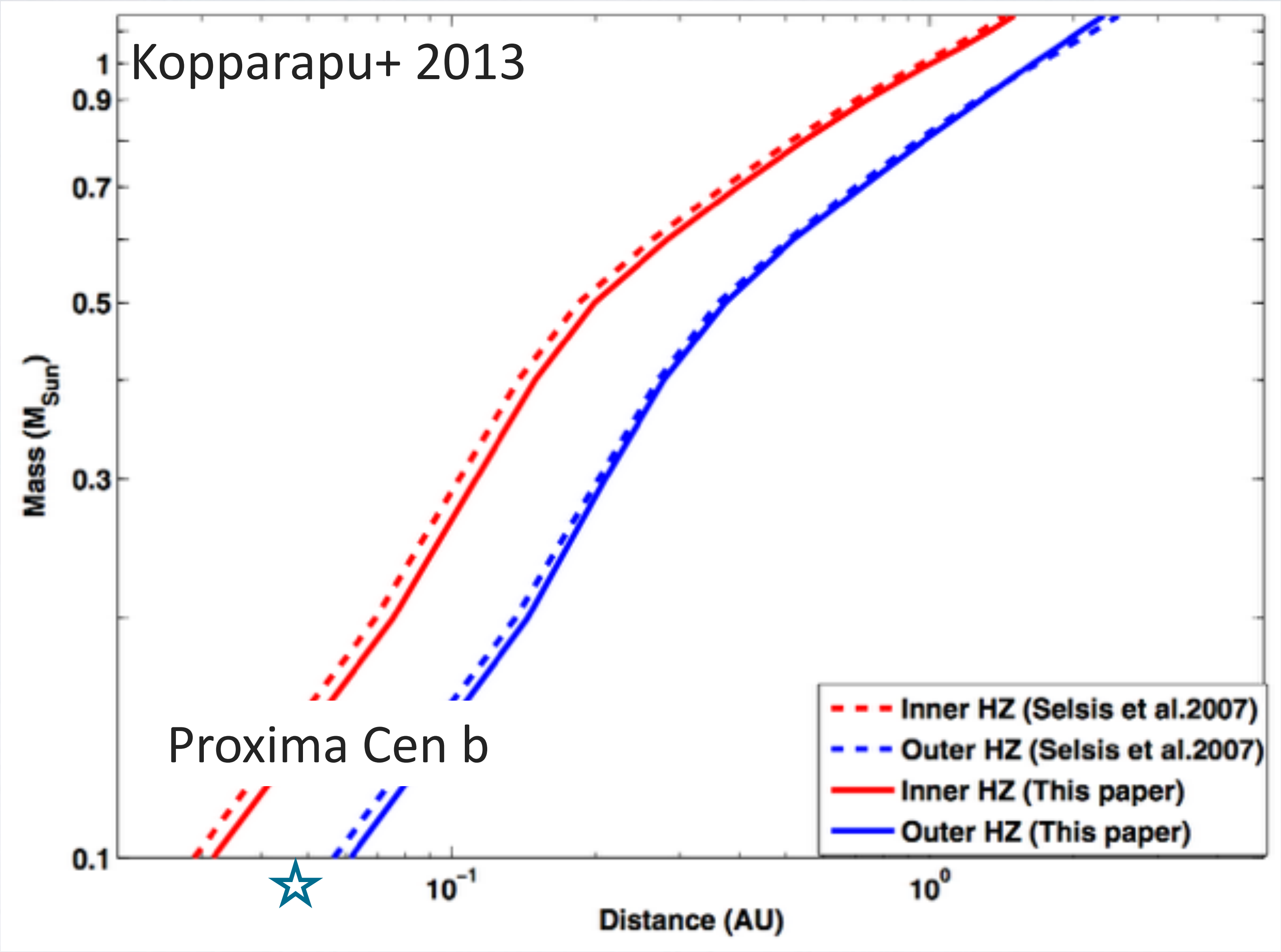
Solar neighborhood within 10 pc



Dressing & Charbonneau: the nearest transiting exoplanet in the HZ is at 10.6±1.7 pc, but the nearest non-transiting is only 2.6±0.4 pc away ⇒ **we found Proxima Cen b!**

Habitable zones around M dwarfs

"Classical" habitable zone (moist / max greenhouse)



Potentially-habitable planets orbit very close to M-dwarfs

⇒ Reflected-light signal enhanced (dependence on semi-major axis)

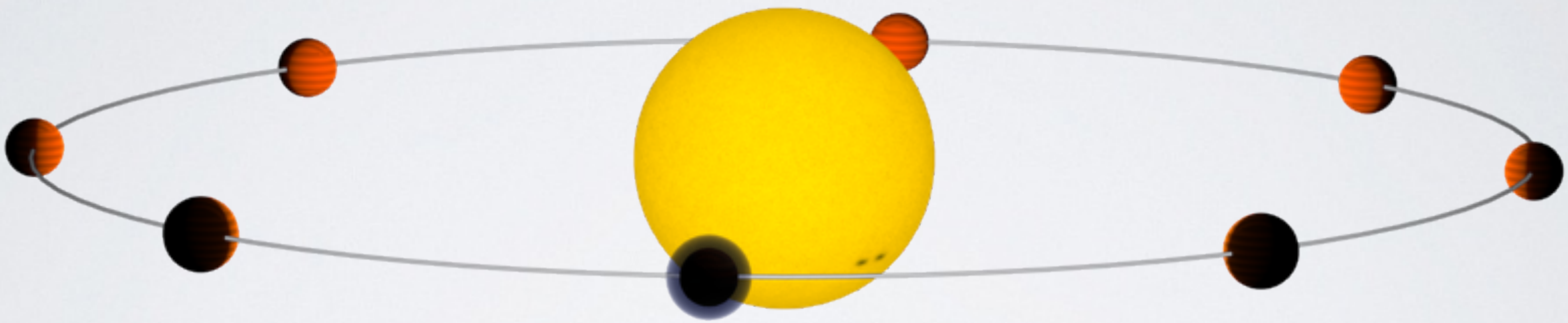
⇒ Increased geometric probability of a transit

⇒ Transits are frequent and S/N can be stacked

Atmospheric characterization: transiting planets

Star and planet are **not** spatially resolved

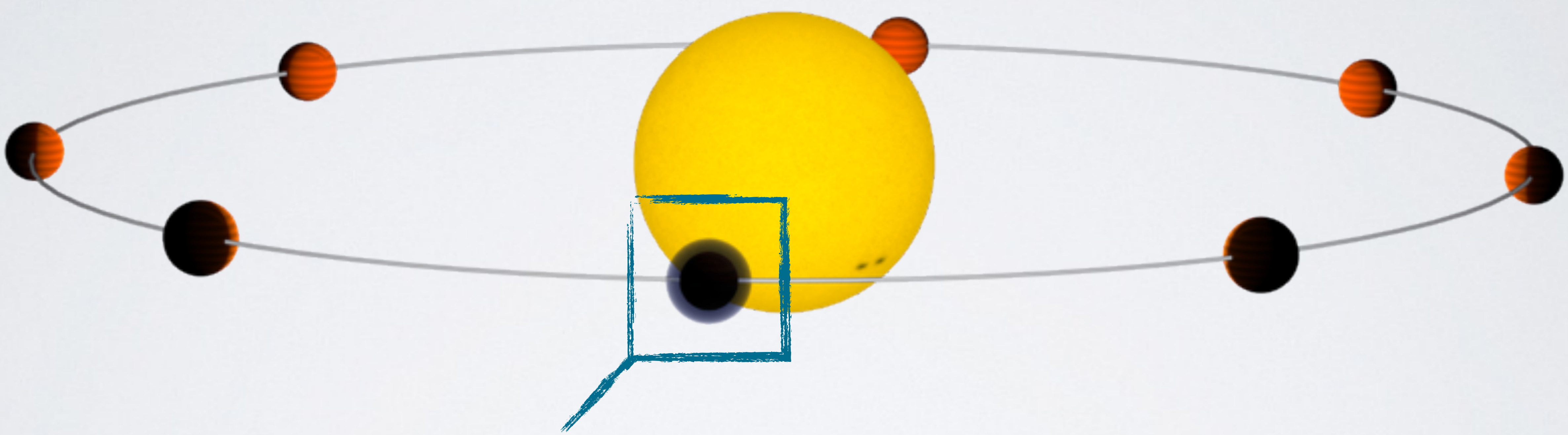
Monitoring of the total light from the star+planet system, at various wavelengths



Atmospheric characterization: transiting planets

Star and planet are **not** spatially resolved

Monitoring of the total light from the star+planet system, at various wavelengths



Transit (Transmission spectra)

Starlight filtering through the planet atmosphere

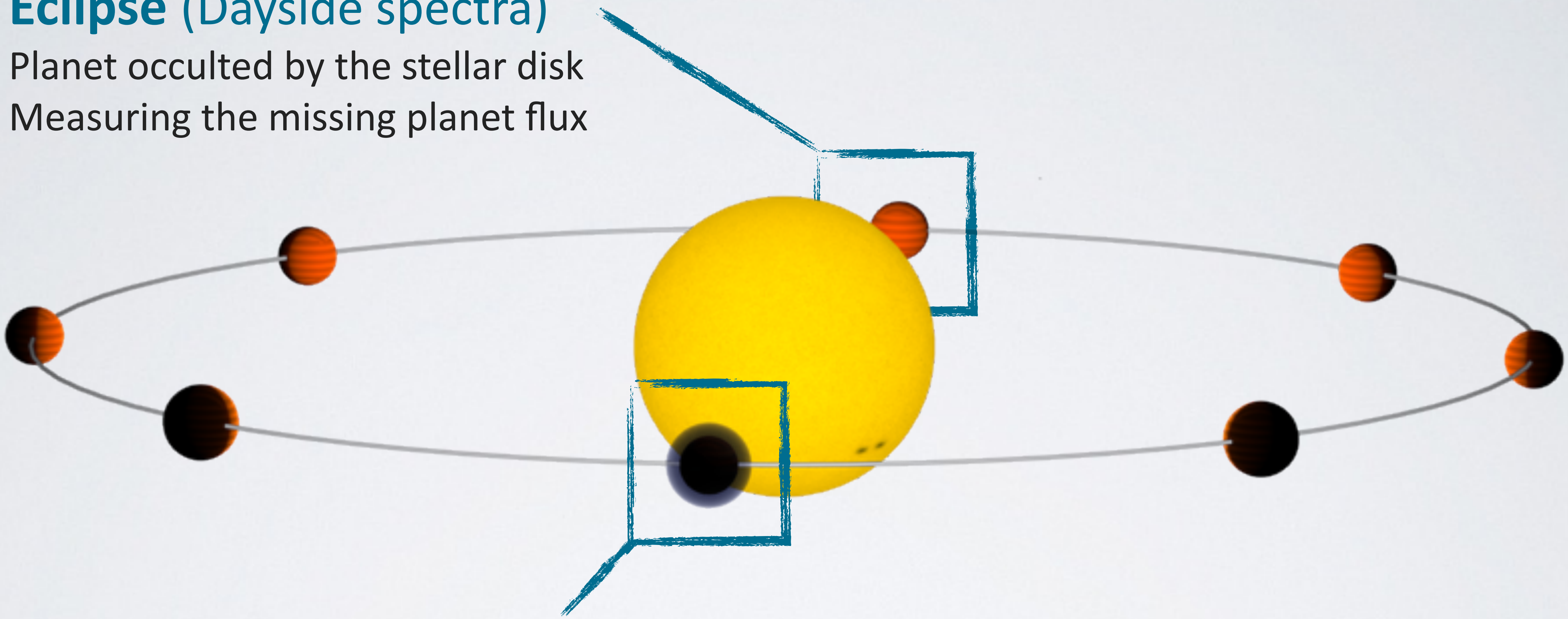
Measuring the planet radius

Atmospheric characterization: transiting planets

Star and planet are **not** spatially resolved
Monitoring of the total light from the star+planet system, at various wavelengths

Eclipse (Dayside spectra)

Planet occulted by the stellar disk
Measuring the missing planet flux



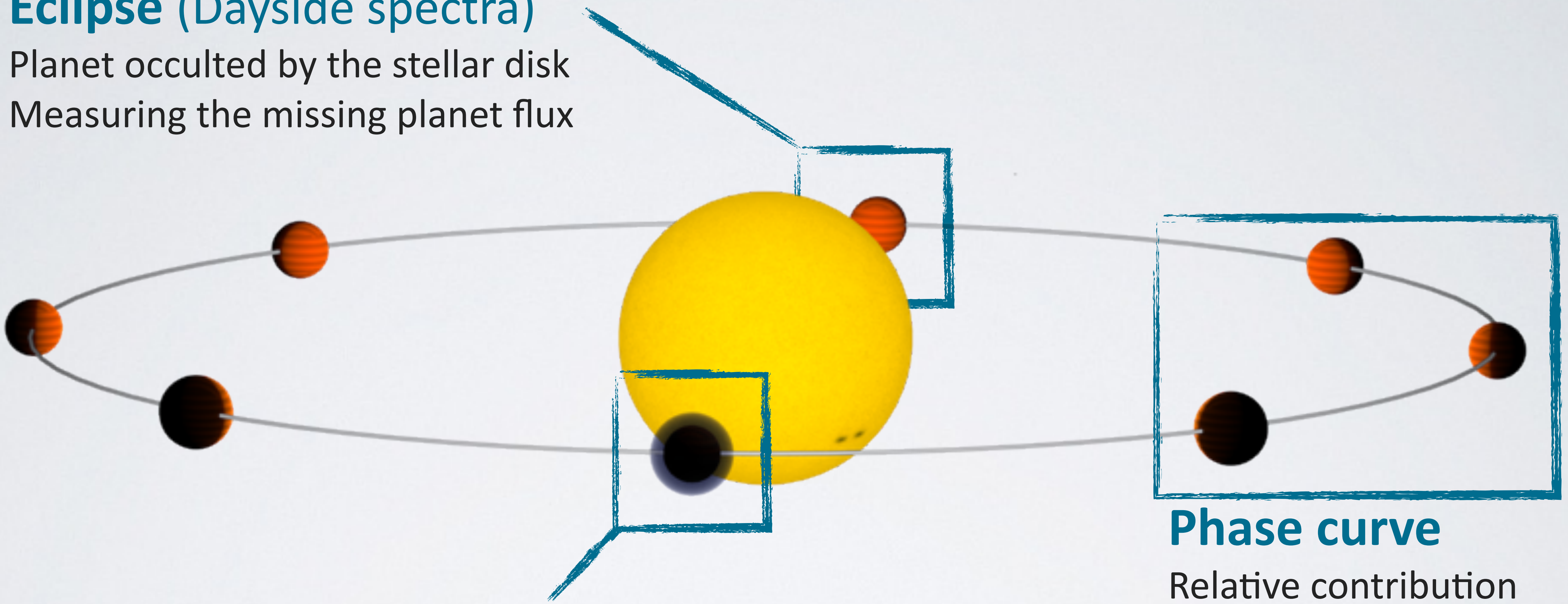
Transit (Transmission spectra)

Starlight filtering through the planet atmosphere
Measuring the planet radius

Atmospheric characterization: transiting planets

Star and planet are **not** spatially resolved
Monitoring of the total light from the star+planet system, at various wavelengths

Eclipse (Dayside spectra)
Planet occulted by the stellar disk
Measuring the missing planet flux



Phase curve
Relative contribution
of planet day/night side

Transit (Transmission spectra)
Starlight filtering through the planet atmosphere
Measuring the planet radius

Atmospheric characterization: transiting planets

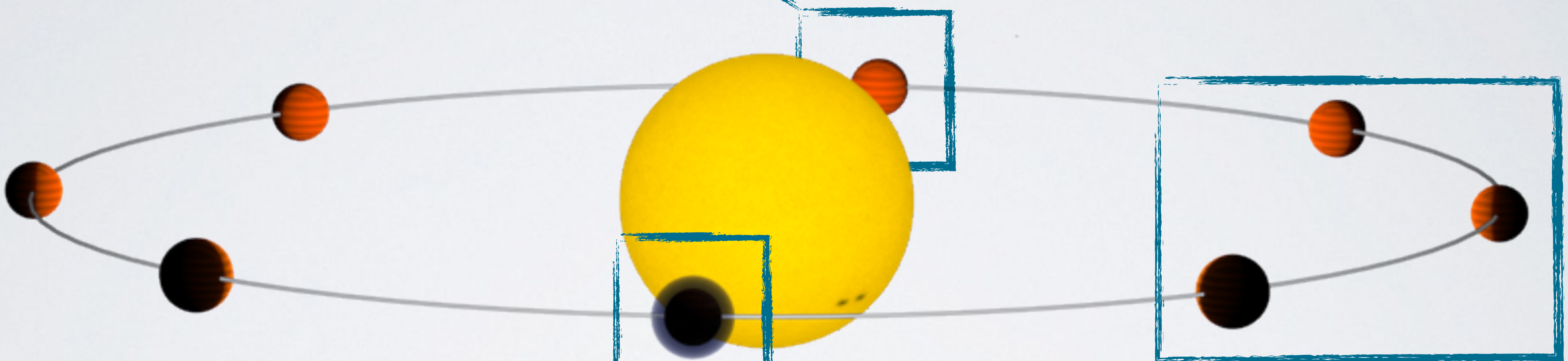
Star and planet are **not** spatially resolved

Monitoring of the total light from the star+planet system, at various wavelengths

Eclipse (Dayside spectra)

Planet occulted by the stellar disk

Measuring the missing planet flux



Phase curve

Relative contribution of planet day/night side

Transit (Transmission spectra)

Starlight filtering through the planet atmosphere

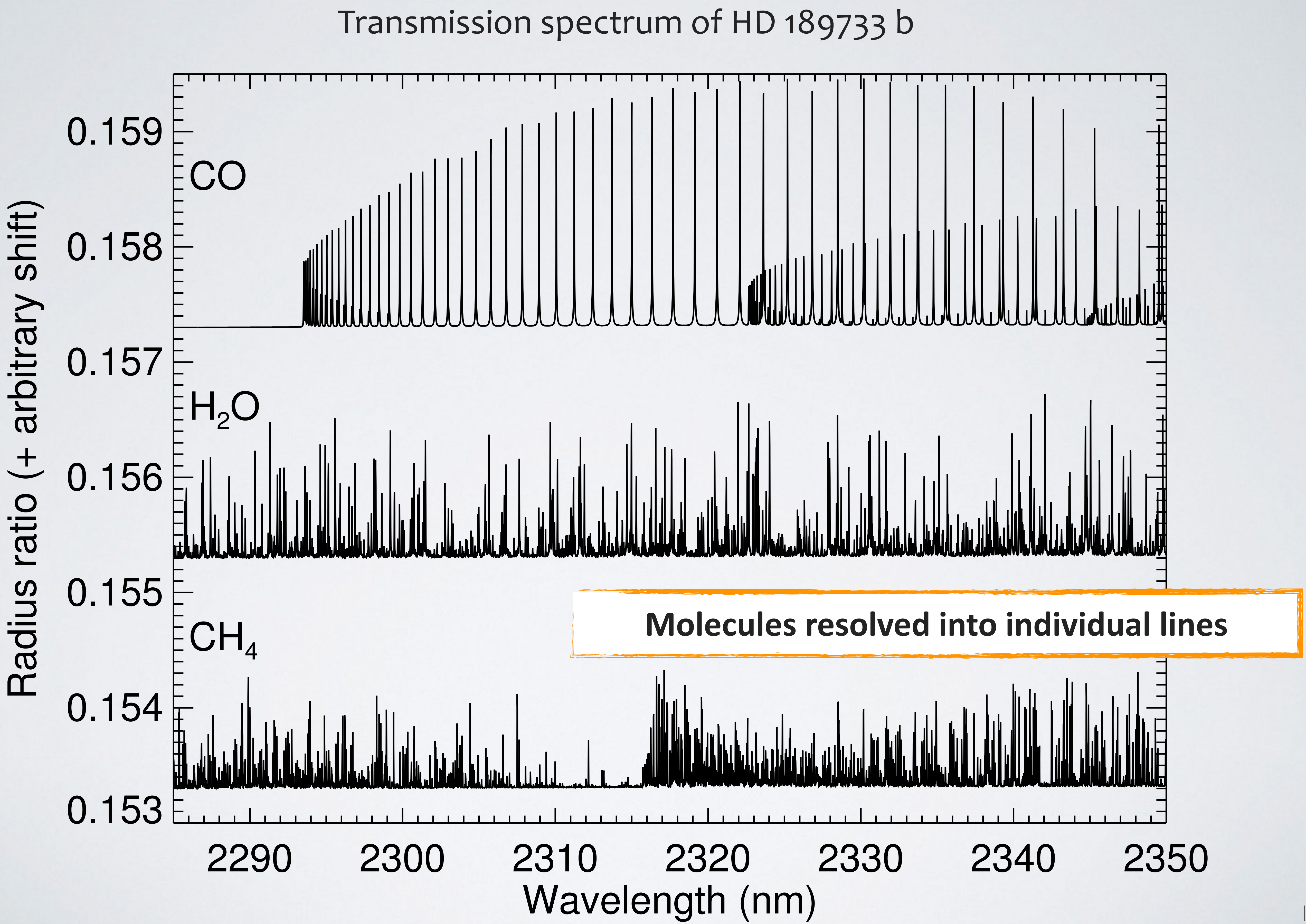
Measuring the planet radius

What about Proxima Cen b (non-transiting)?

High-dispersion spectroscopy to observe exoplanet atmospheres

Separating the planet from the star
in the *spectral* domain

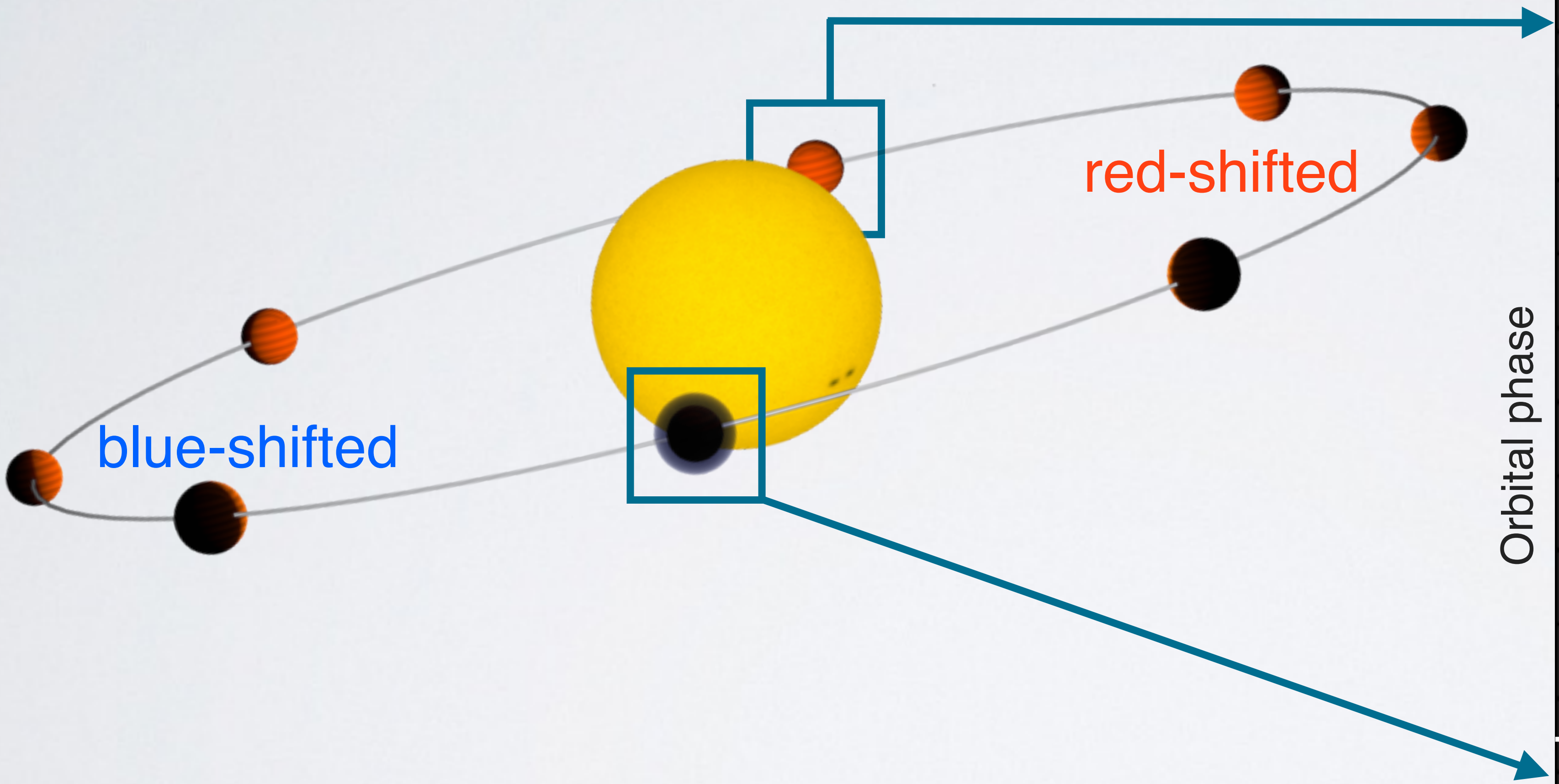
HDS detects the "fingerprint" of each molecule

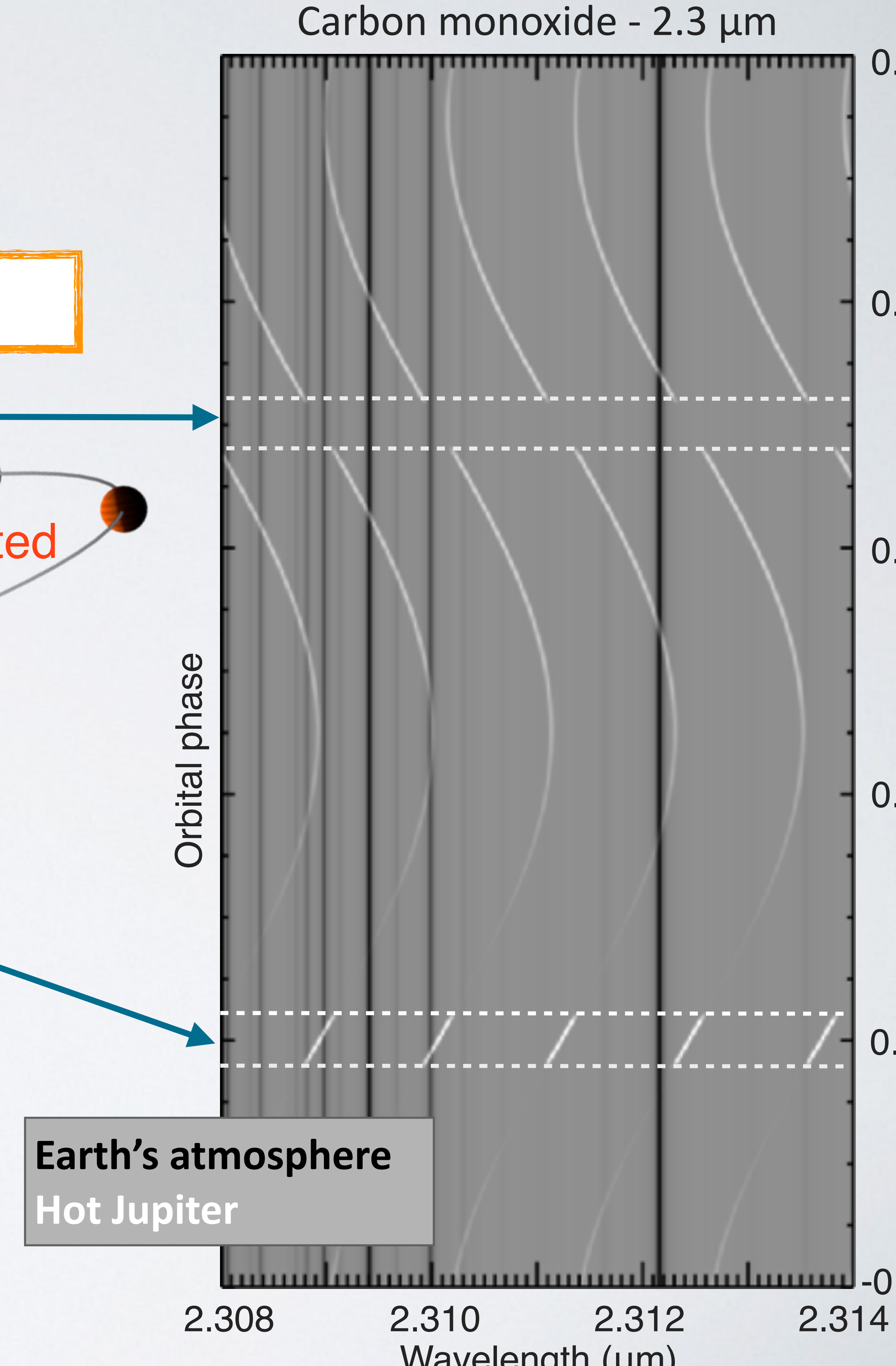


HDS detects the orbital motion of exoplanets

HJs sensibly move along the orbit
during few hours of observations

Planet motion resolved

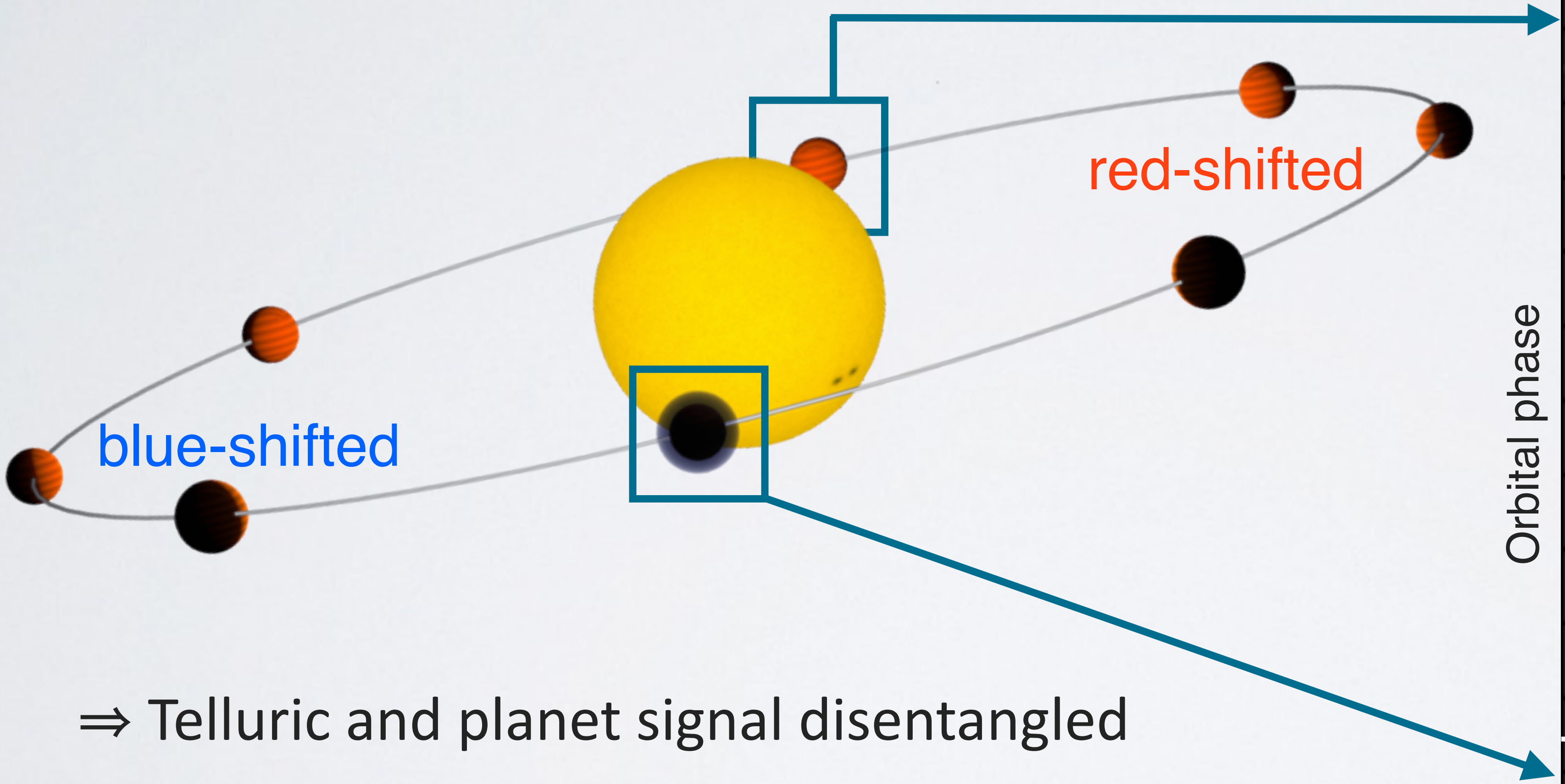


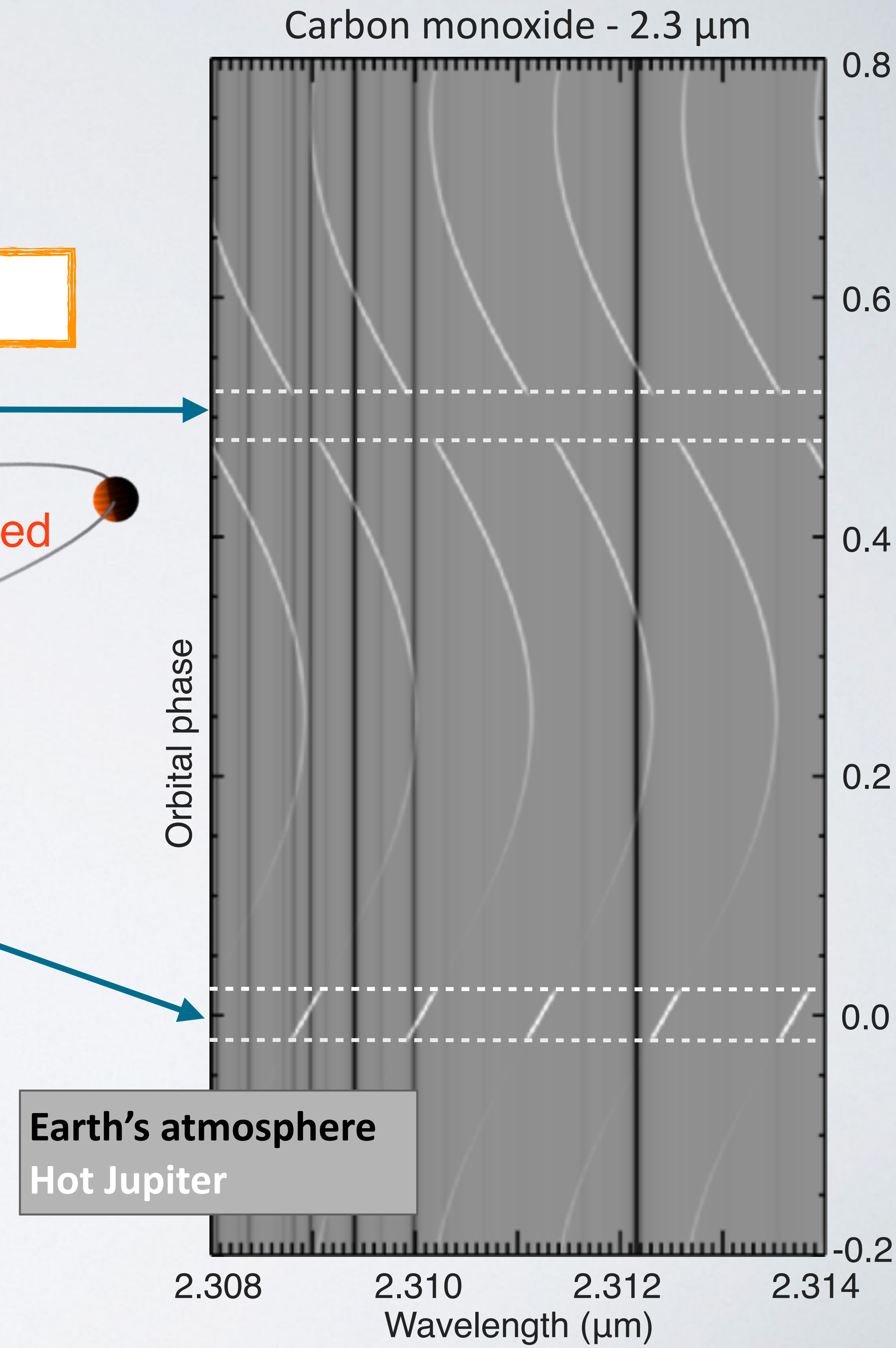


HDS detects the orbital motion of exoplanets

HJs sensibly move along the orbit
during few hours of observations

Planet motion resolved





⇒ Telluric and planet signal disentangled

⇒ Planet radial velocity can be measured

Star & planet can be treated as
spectroscopic binaries

The data analysis: a two-step process

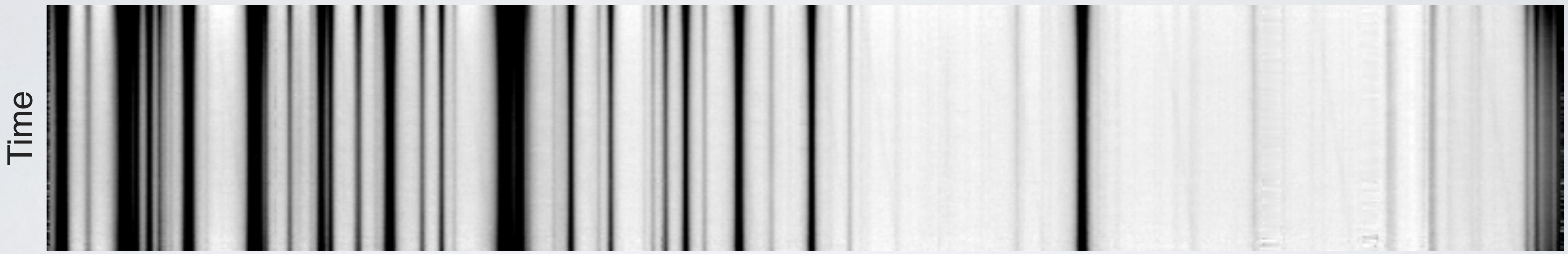
1

Removing telluric lines

The Earth's atmospheric absorption is stationary in wavelength

The planet moves along the orbit and it is Doppler-shifted

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



The data analysis: a two-step process

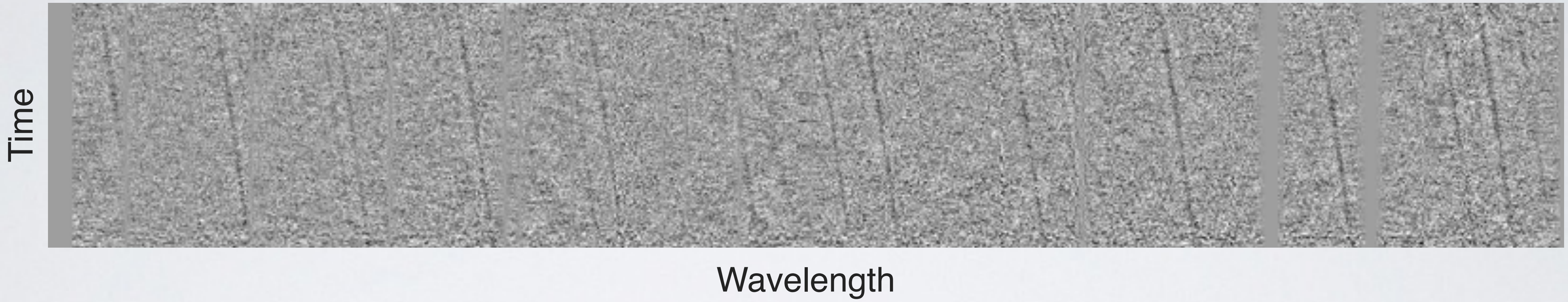
1

Removing telluric lines

The Earth's atmospheric absorption is stationary in wavelength

The planet moves along the orbit and it is Doppler-shifted

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



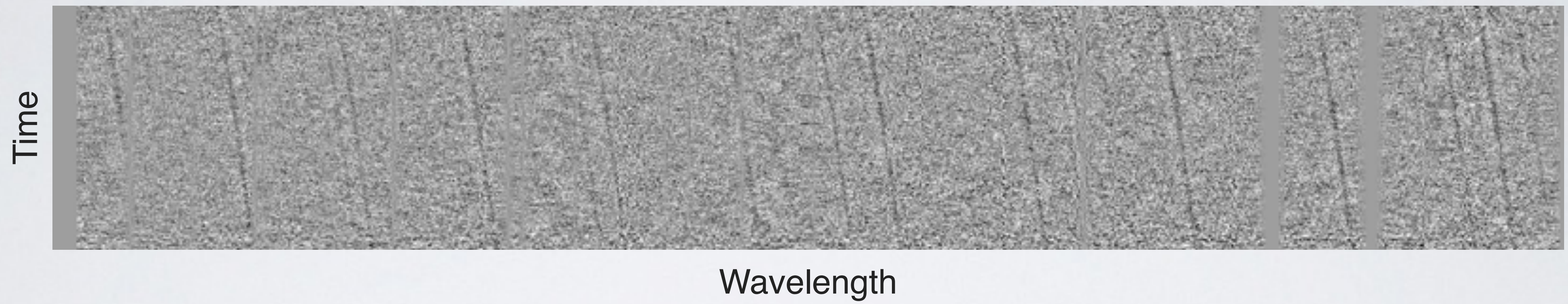
The data analysis: a two-step process

1 Removing telluric lines

The Earth's atmospheric absorption is stationary in wavelength

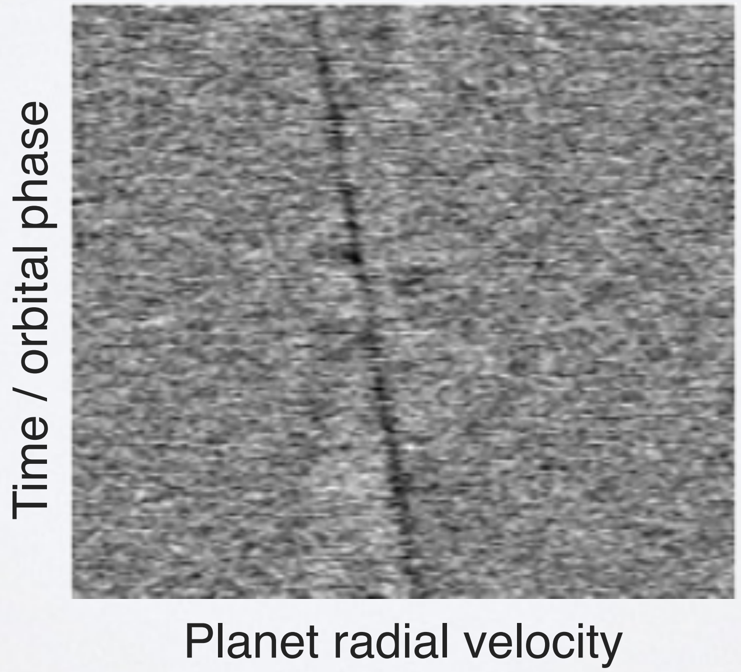
The planet moves along the orbit and it is Doppler-shifted

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



2 Cross-correlating with model spectra

(Models by Remco de Kok)



High-resolution studies of hot Jupiters

Masses and orbital inclinations of non-transiting planets

τ Boo b, HD 179949 b, 51 Peg b

CO and H2O confidently detected

CH4 not yet detected

Consistent with expectations for hot planets and solar abundances

No thermal inversions detected

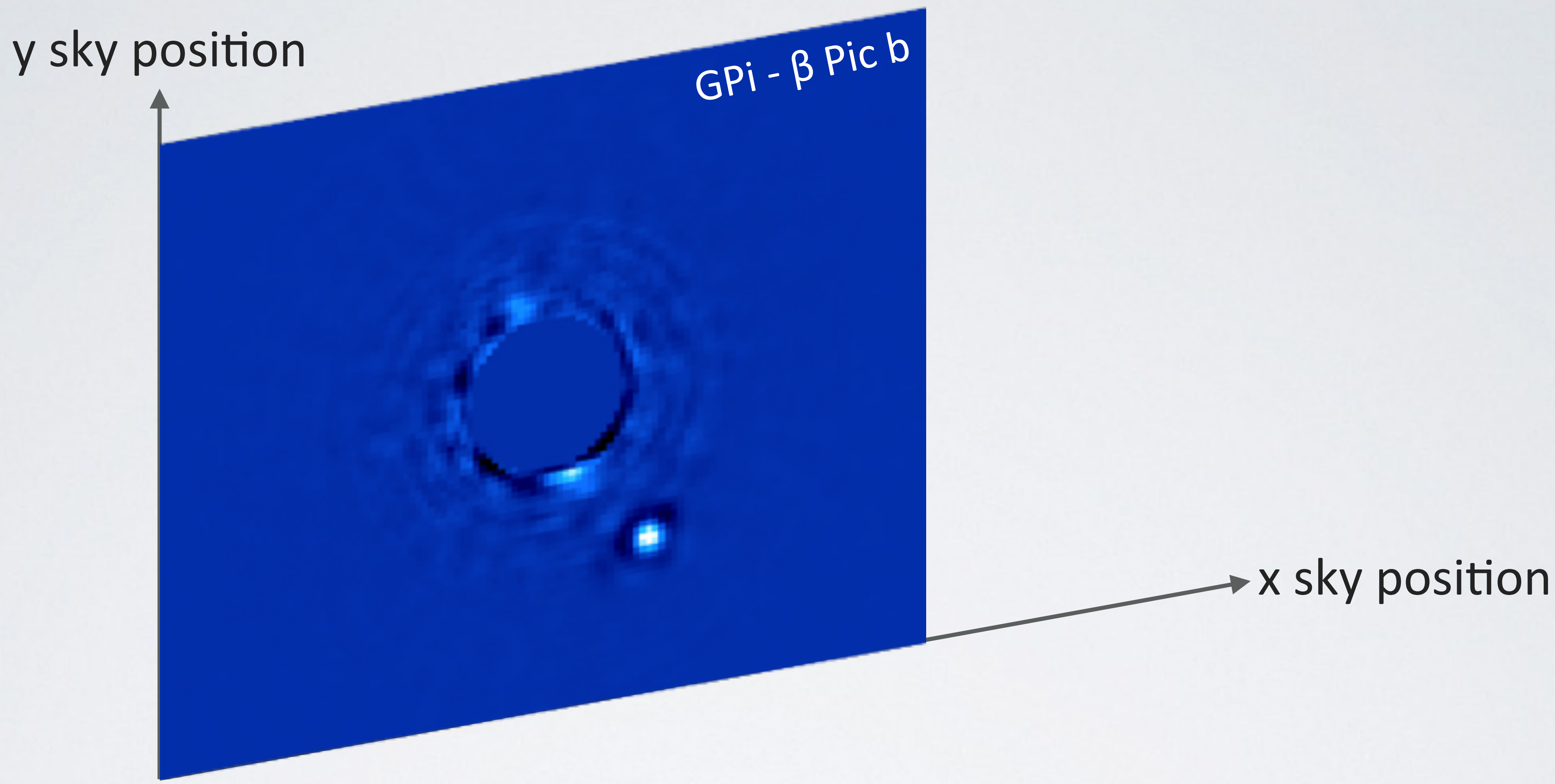
All emission spectra are well fit by models containing *absorption* lines

Rotation and winds of exoplanets measured

The planet line profile, and hence the cross-correlation functions, are broadened

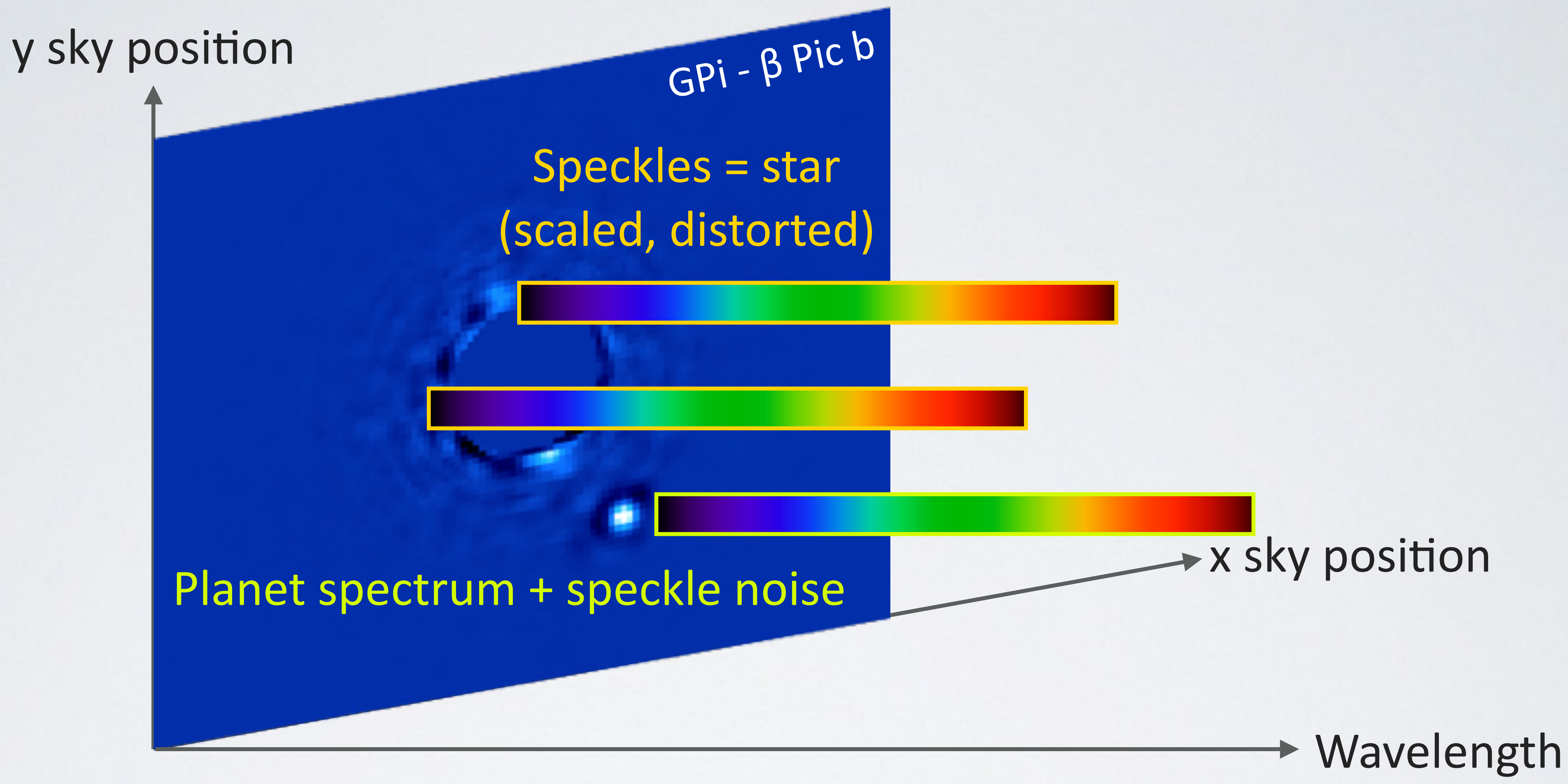
Spectral and spatial resolution combined

The contrast from high-resolution spectroscopy alone (10^{-6}-10^{-5}) is not enough!



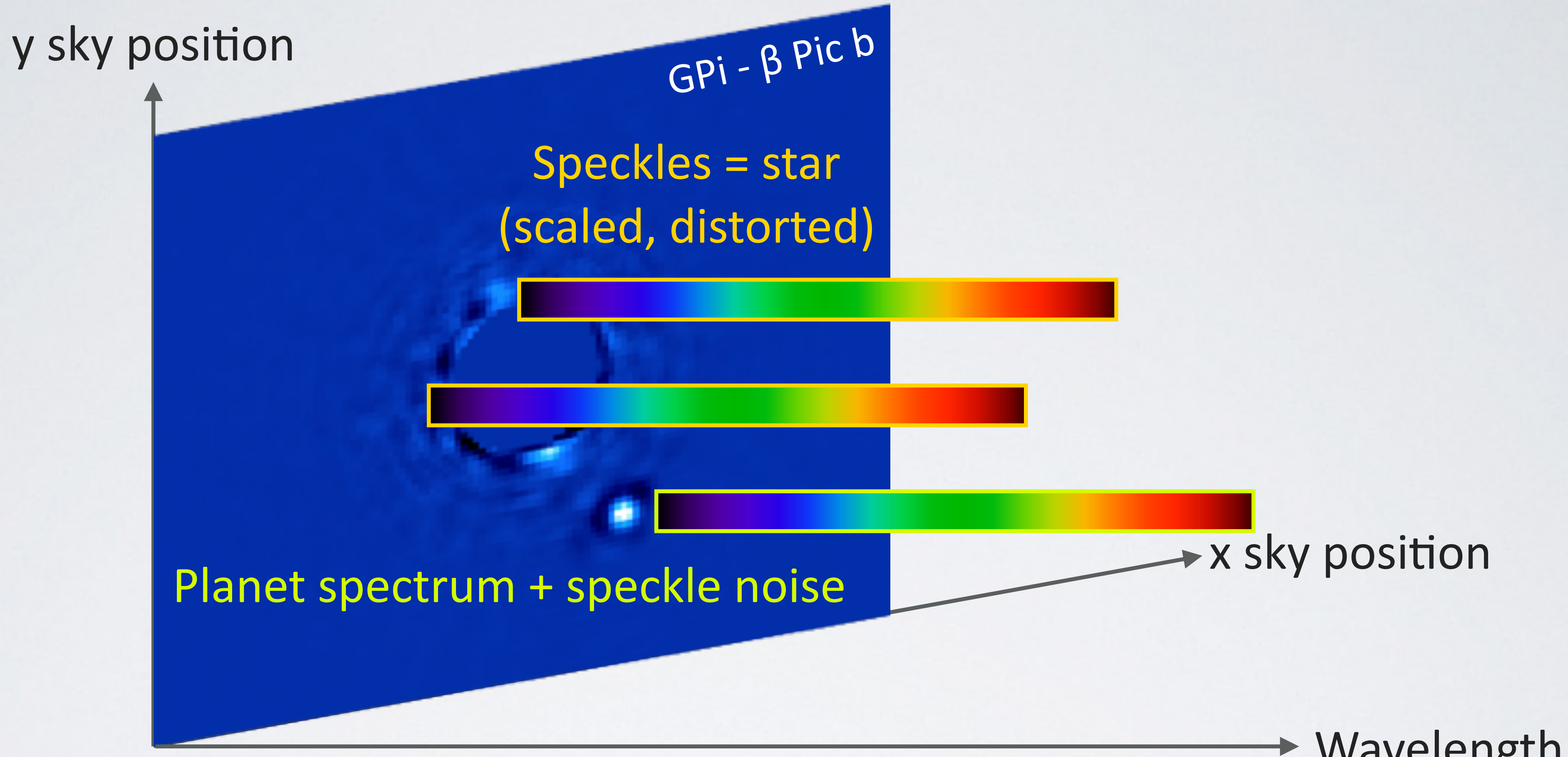
Spectral and spatial resolution combined

The contrast from high-resolution spectroscopy alone (10^{-6}-10^{-5}) is not enough!



Spectral and spatial resolution combined

The contrast from high-resolution spectroscopy alone (10^{-6}-10^{-5}) is not enough!



Current implementation with VLT-CRIRES:
Aligning the slit with the planet-star direction

Detections for a few directly-imaged planets
β Pic b (Snellen+ 2014, Nature); GQ Lup b (Schwarz+ 2016)

Spectral and spatial resolution combined

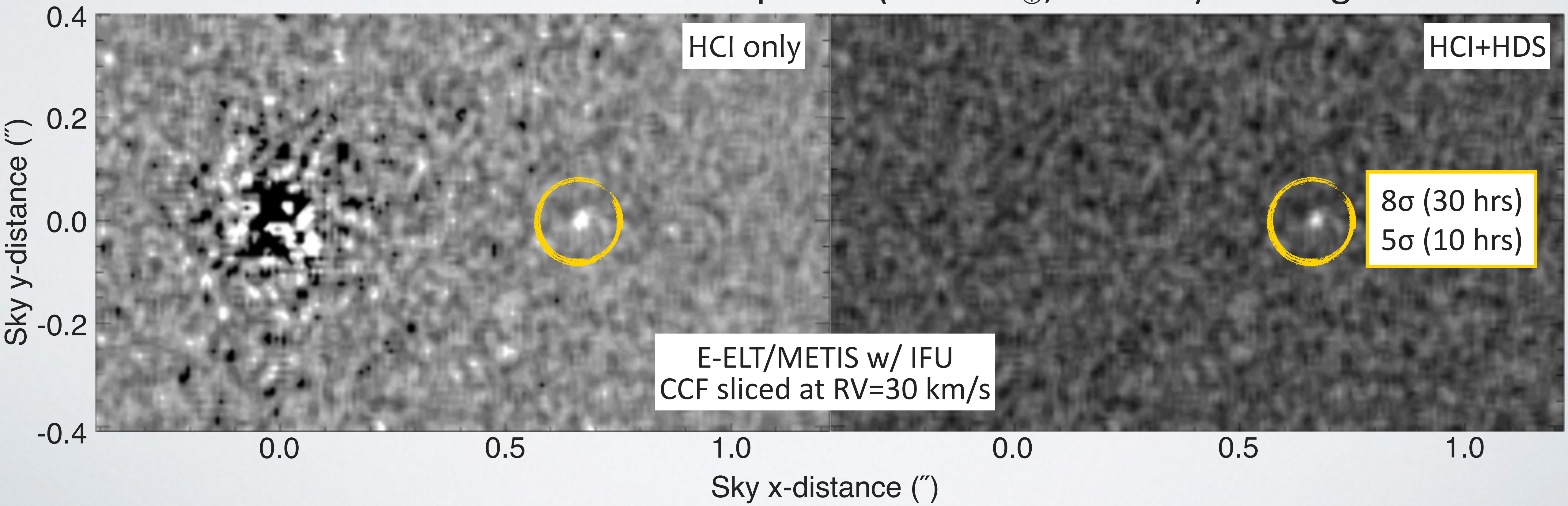
Simulations for **METIS@E-ELT**: Snellen+ 2015

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

Starlight suppression factor at planet position

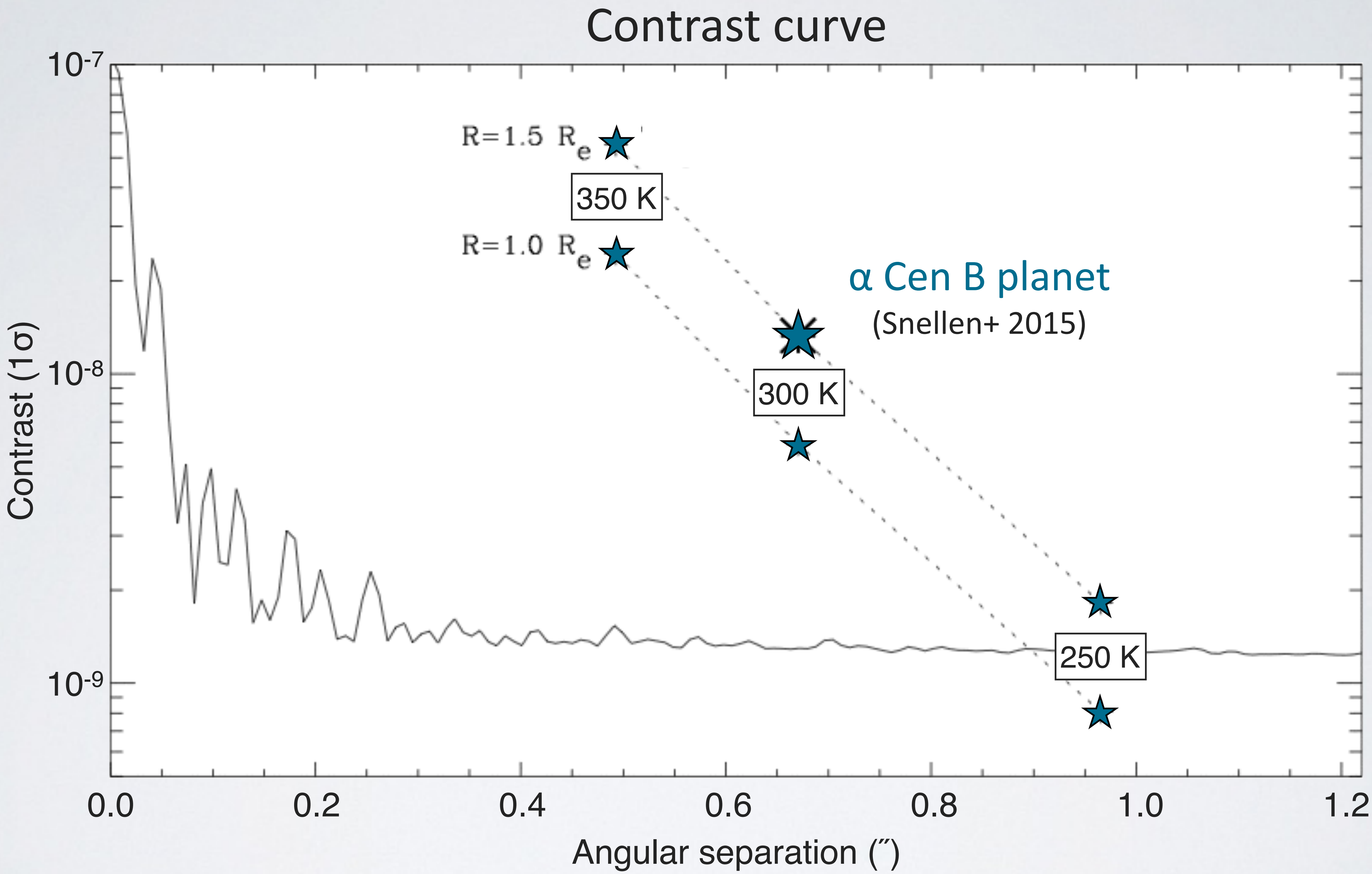
Number of lines to cross-correlate with

Thermal emission of "**Earth-like**" planet (R=1.5 $R_{\oplus}$, T=300K) orbiting α Cen B



Proxima Centauri b: thermal emission

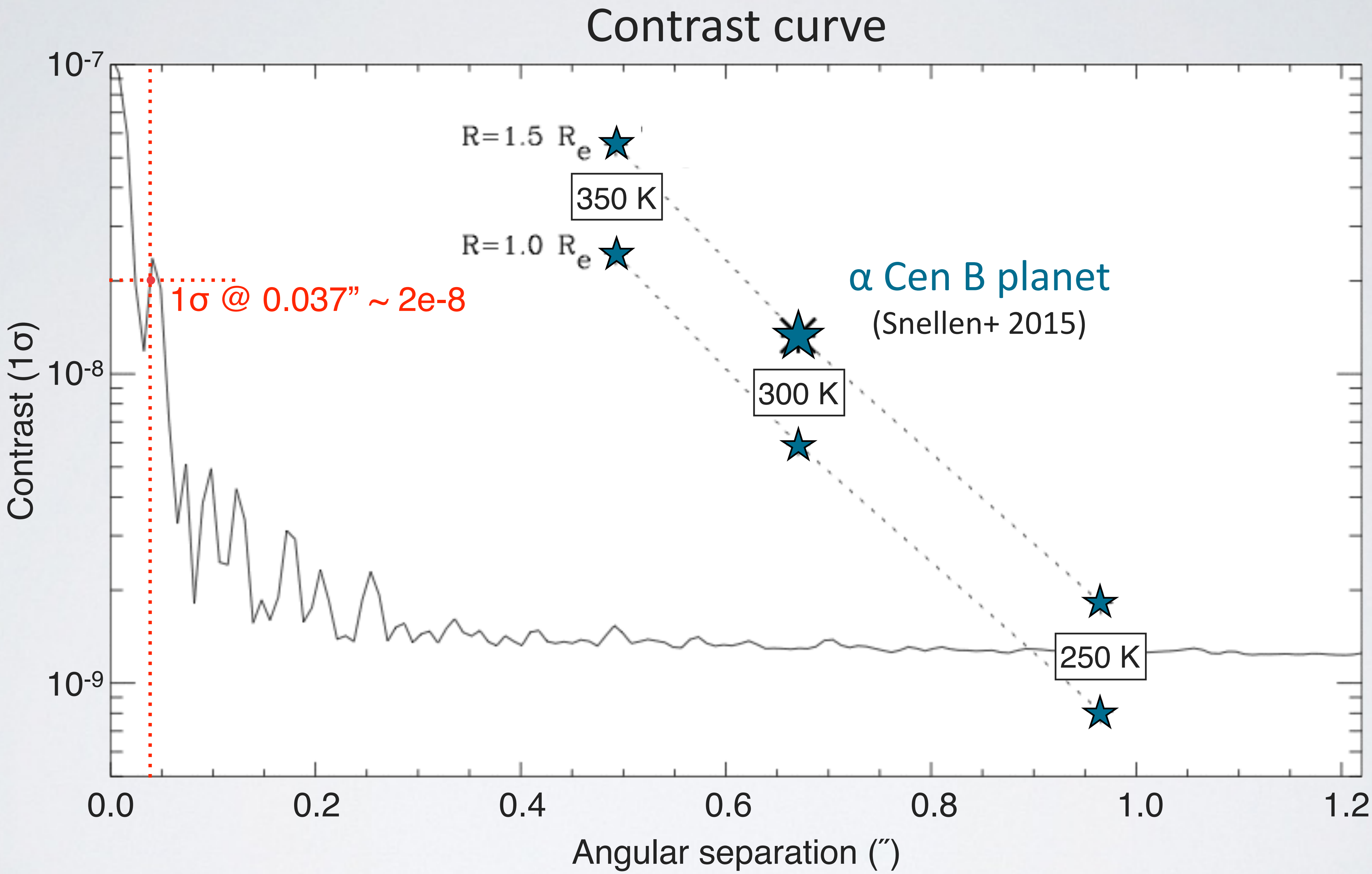
R = 1.1 $R_\oplus$, T = 250-265K, a = 0.0485 AU ⇒ 0.0373” separation



METIS observations centered at 4.85 μm, 30 hrs

Proxima Centauri b: thermal emission

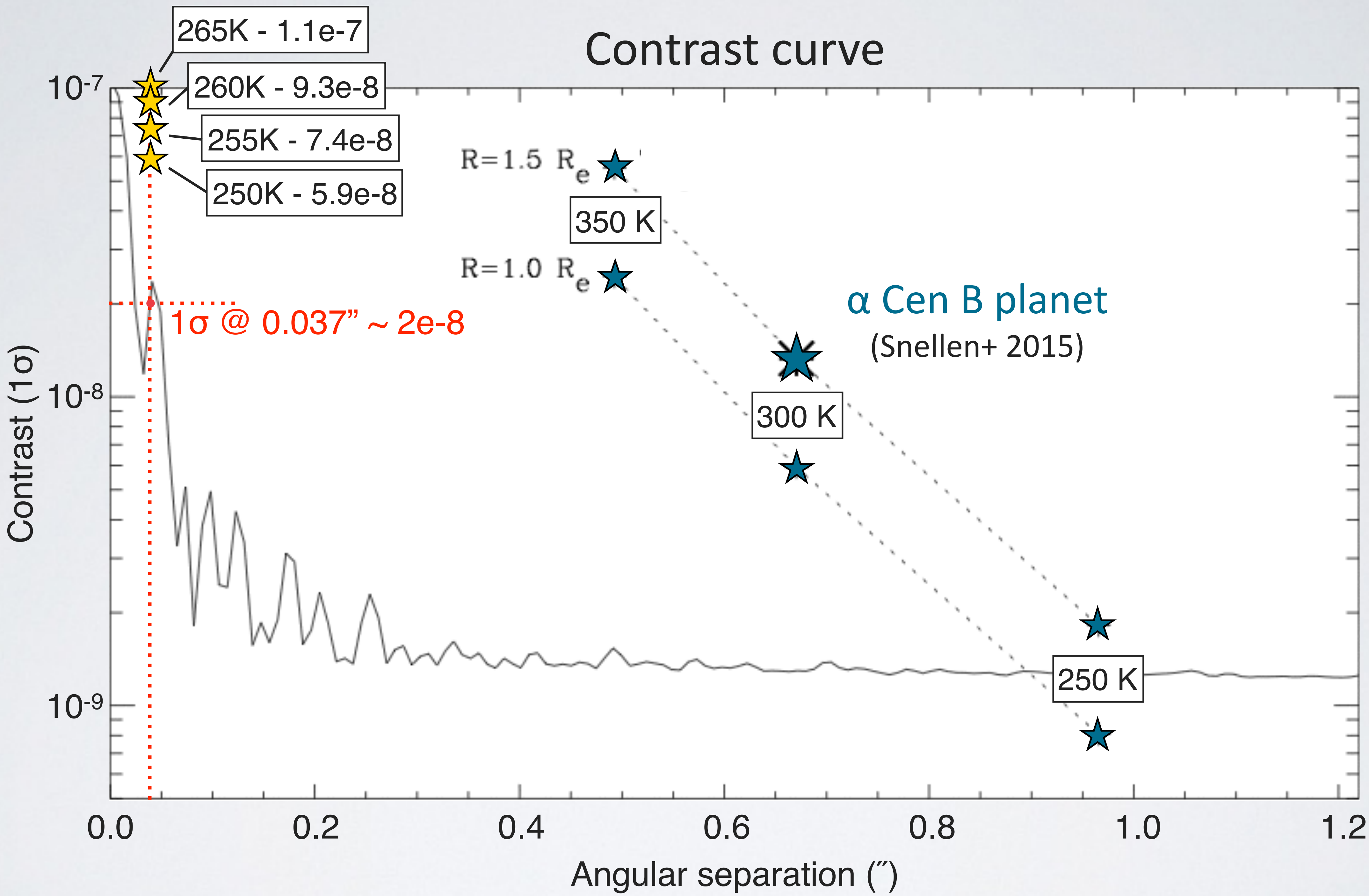
R = 1.1 $R_{\oplus}$, T = 250-265K, a = 0.0485 AU ⇒ 0.0373" separation



METIS observations centered at 4.85 µm, 30 hrs

Proxima Centauri b: thermal emission

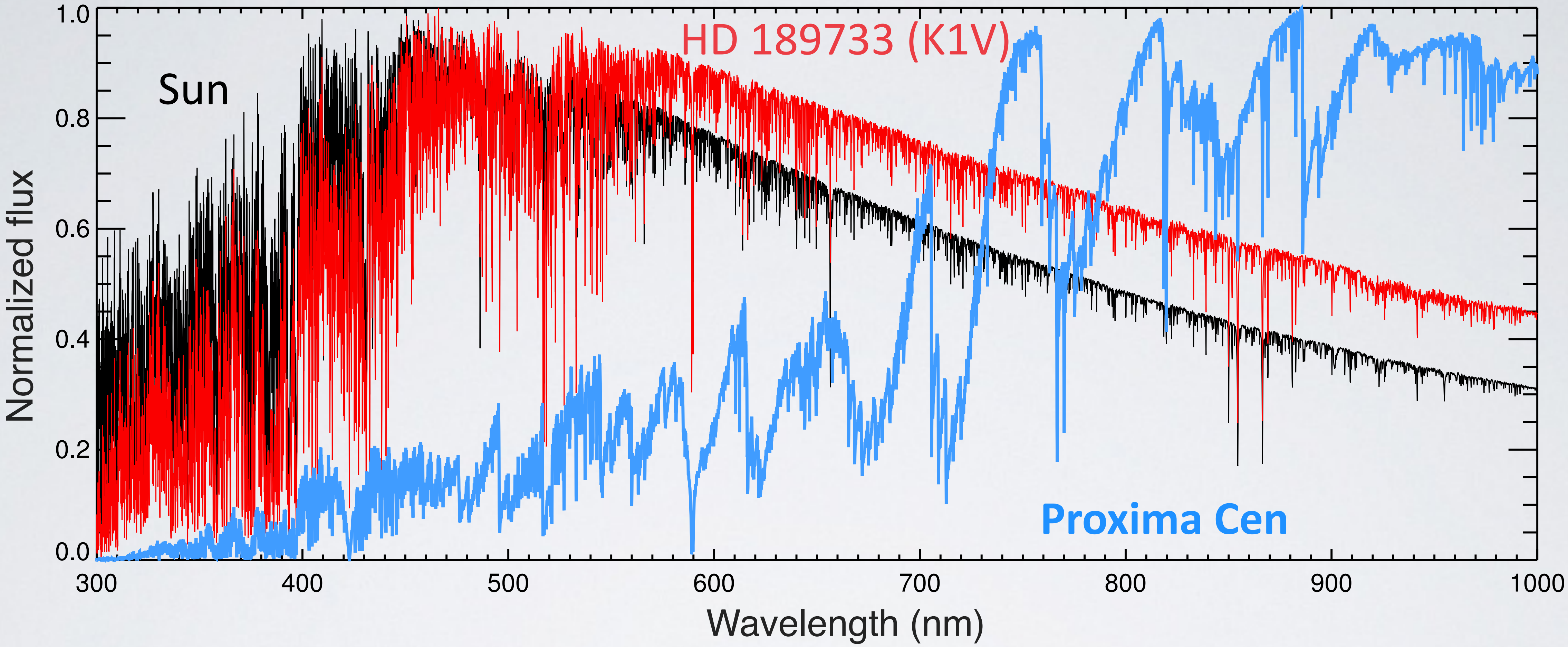
R = 1.1 $R_\oplus$, T = 250-265K, a = 0.0485 AU ⇒ 0.0373" separation



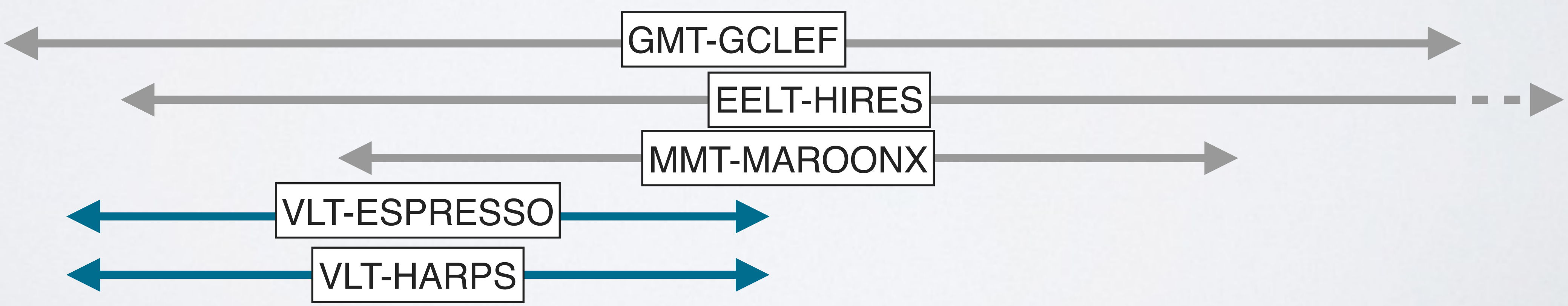
METIS observations centered at 4.85 µm, 30 hrs

Proxima Centauri b: reflected light

The star is faint in the optical (B=12.95, V=11.13, R=9.45) ⇒ low S/N



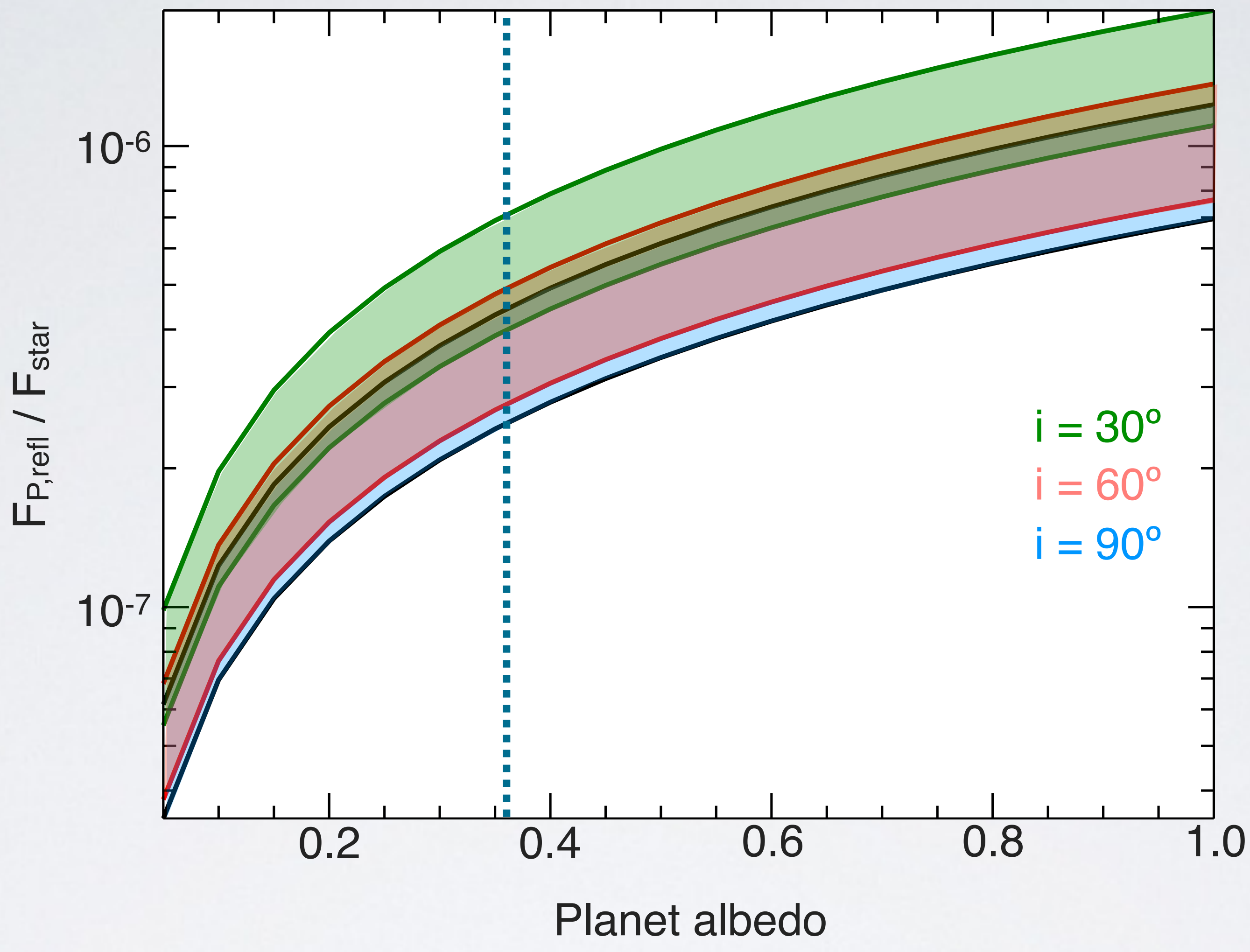
Current spectrographs are not optimized for M stars, **future** spectrographs will be



Gain in S/N from cross-correlating with thousands of lines: 65-80×

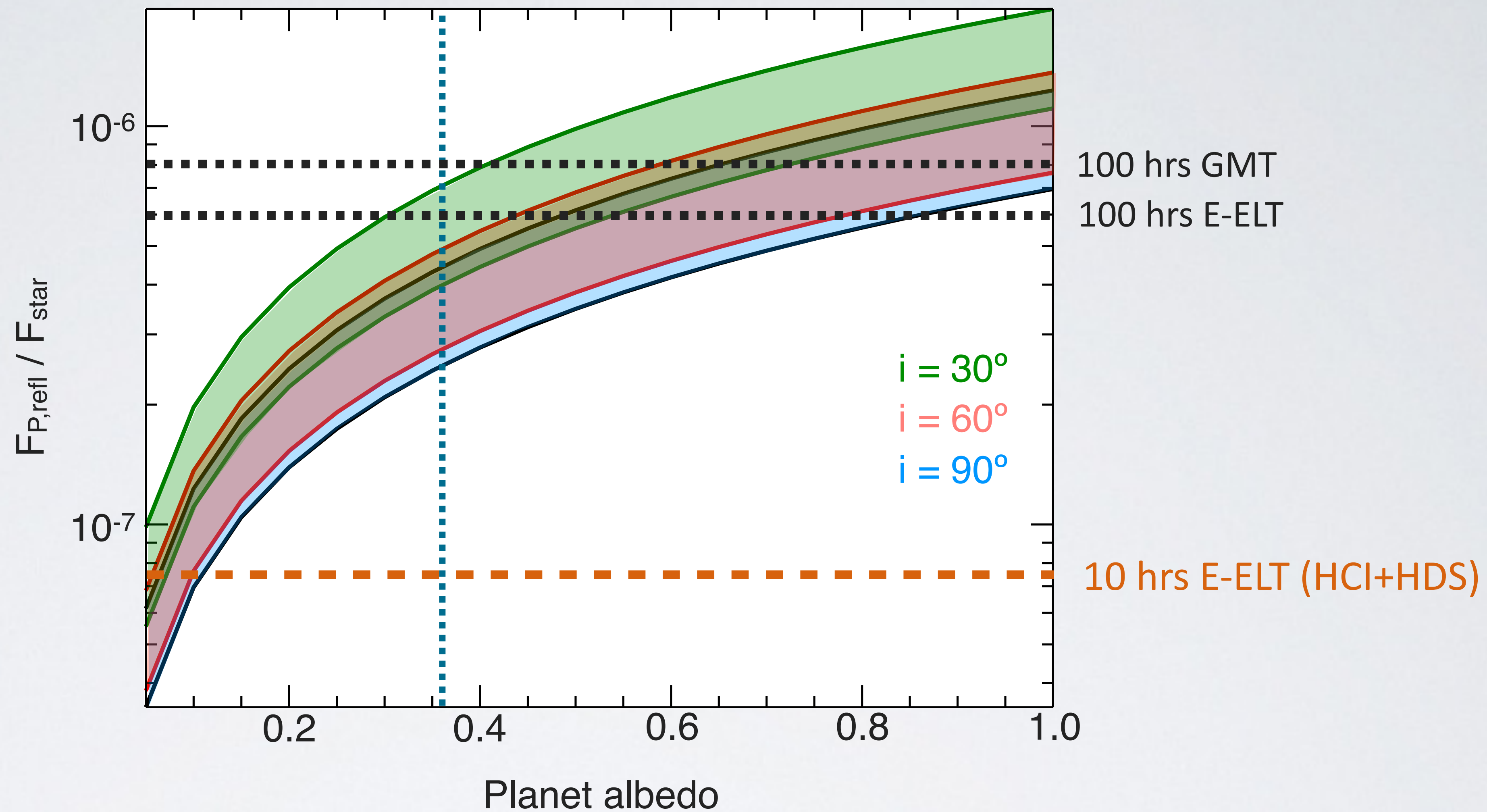
Proxima Centauri b: reflected light

The planet/star contrast is in the range (7e-7, 2e-6) × Albedo



Proxima Centauri b: reflected light

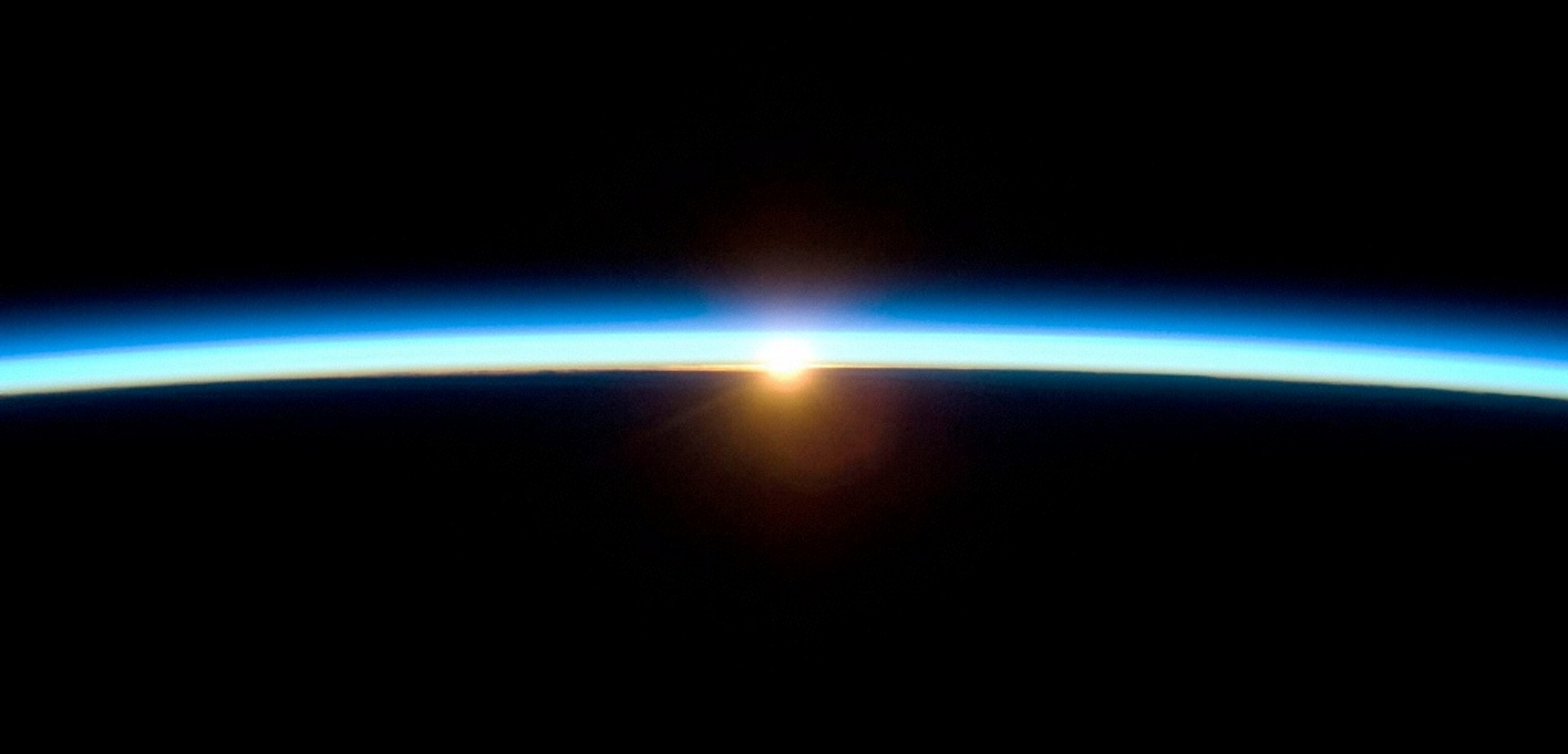
The planet/star contrast is in the range (7e-7, 2e-6) × Albedo



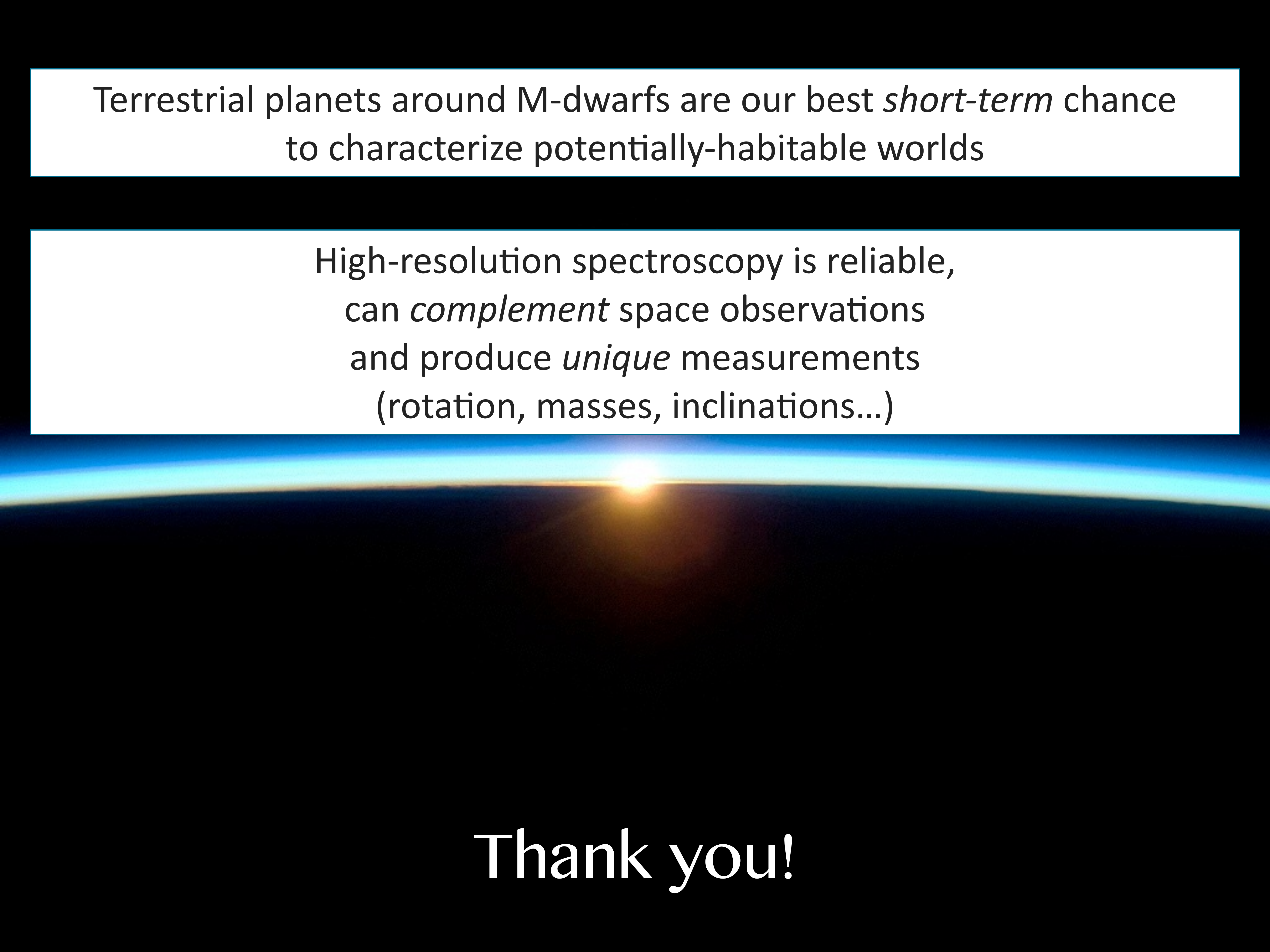
High-resolution spectroscopy only (350-1000nm, 10% throughput): challenging even with 100 hours of Extremely Giant Telescopes

Spectral and spatial resolution combined would easily succeed! (Revised Snellen+ 2015 estimates, strehl ratio 0.3, 10% throughput)

Terrestrial planets around M-dwarfs are our best *short-term* chance to characterize potentially-habitable worlds

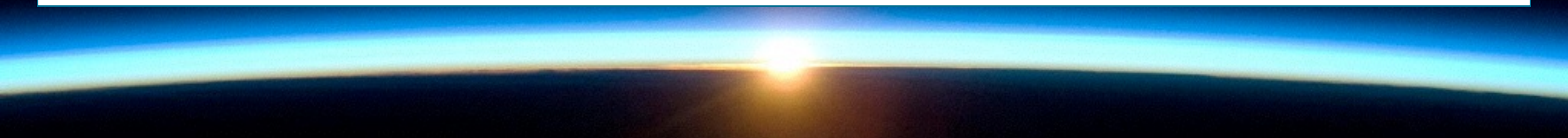


Thank you!


Terrestrial planets around M-dwarfs are our best *short-term* chance to characterize potentially-habitable worlds
High-resolution spectroscopy is reliable, can *complement* space observations and produce *unique* measurements (rotation, masses, inclinations…)
Thank you!

Terrestrial planets around M-dwarfs are our best *short-term* chance to characterize potentially-habitable worlds

High-resolution spectroscopy is reliable,
can *complement* space observations
and produce *unique* measurements
(rotation, masses, inclinations…)



Combined spectral and spatial resolution: suitable for characterizing
potentially habitable planets
from the ground, even if they non transit!

Thank you!