Exoplanet atmospheres
at high spectral resolution

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Observatoire de la Côte d'Azur, Nice, France

Outline

From finding to characterizing exoplanets

by studying their atmospheres

Detecting molecular species at high spectral resolution

and measuring masses and inclinations in the meanwhile

Constraining the atmospheric properties

thermal inversion layers, rotation, winds

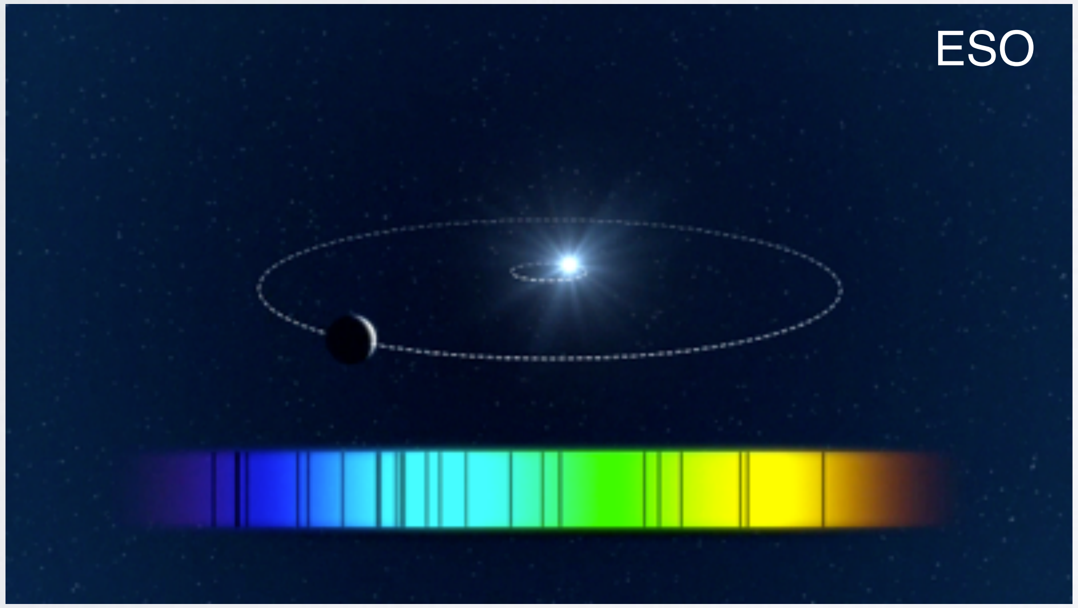
Future applications

Characterizing TESS targets, combining high-resolution spectroscopy and direct imaging

How do we find exoplanets?

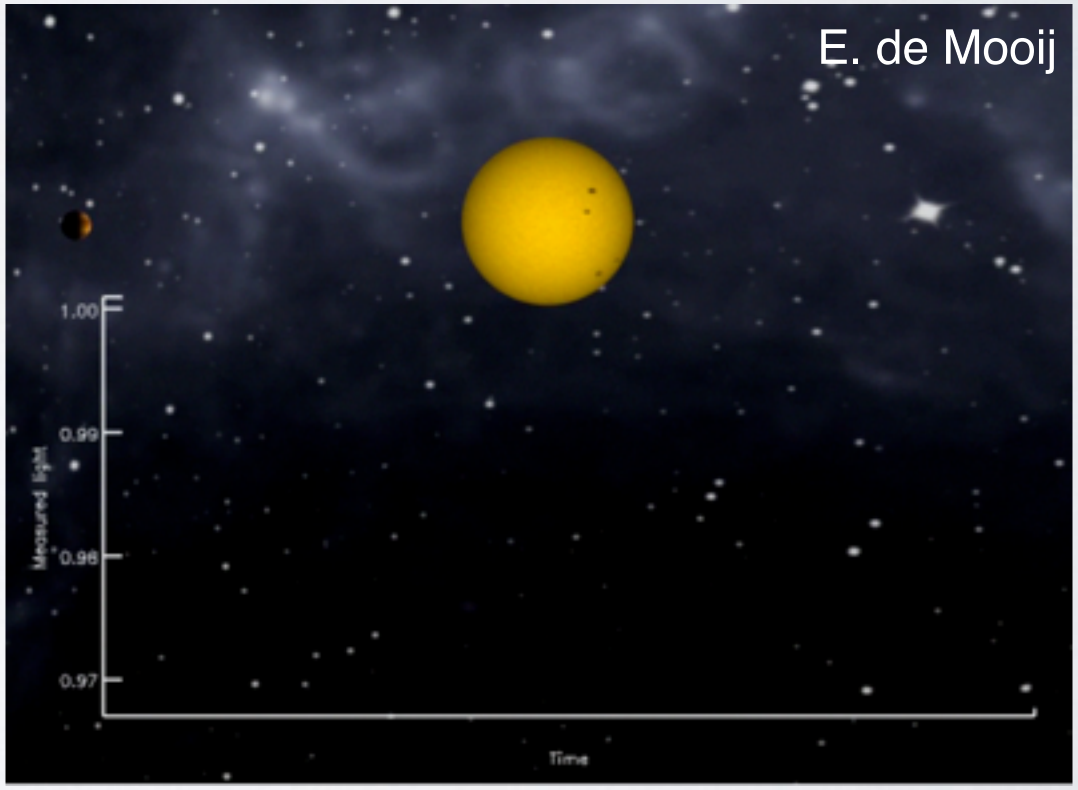
RADIAL VELOCITIES

- Periodic shift in stellar lines
- Fit to determine *P*, *a*, *e*
- Lower limit on M_P (i unknown)



TRANSITS

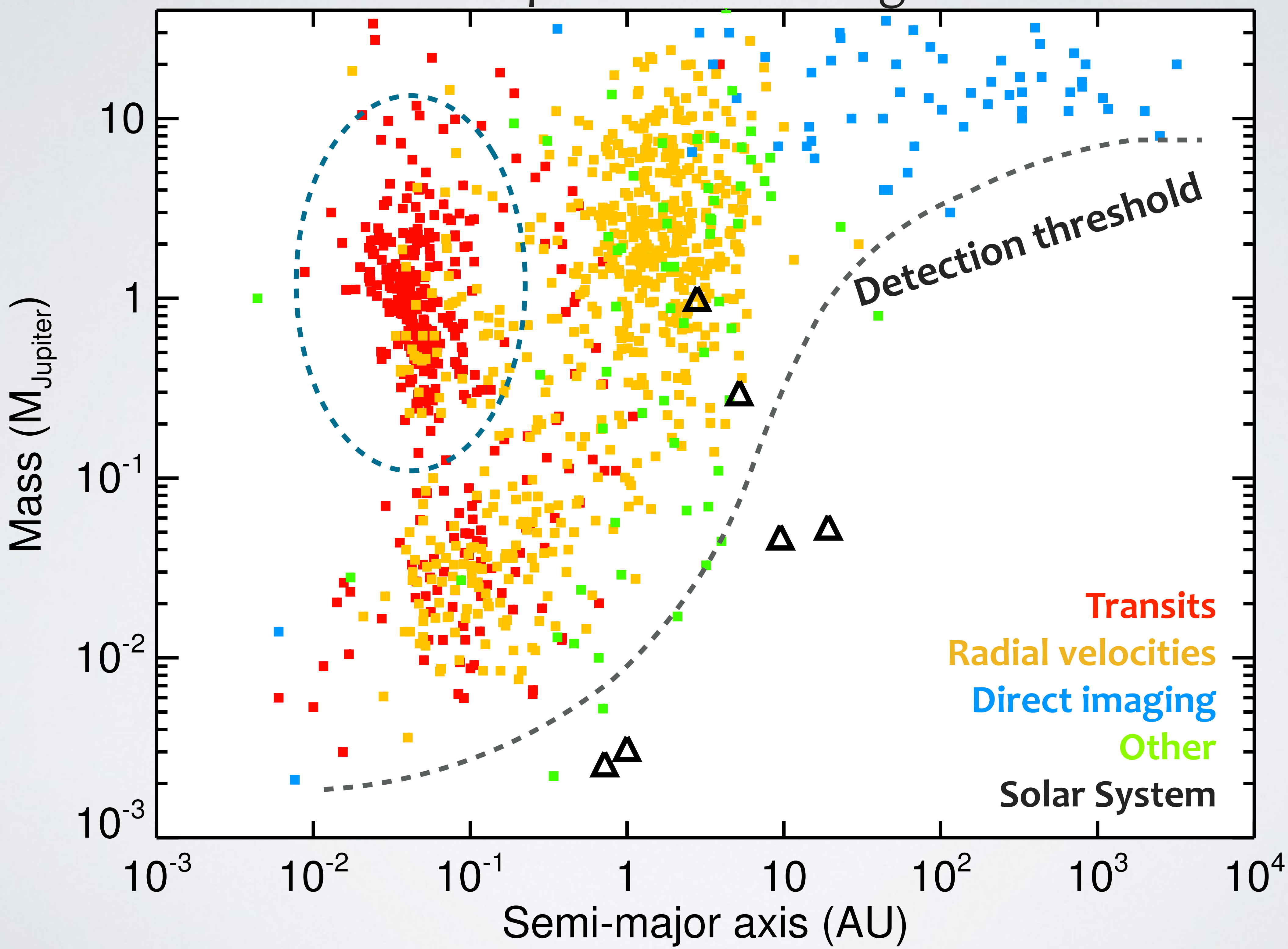
- Planet orbit seen "edge-on"
- Periodic dip in the light curve
- Depth ~ star/planet area



The golden era of exoplanet discoveries

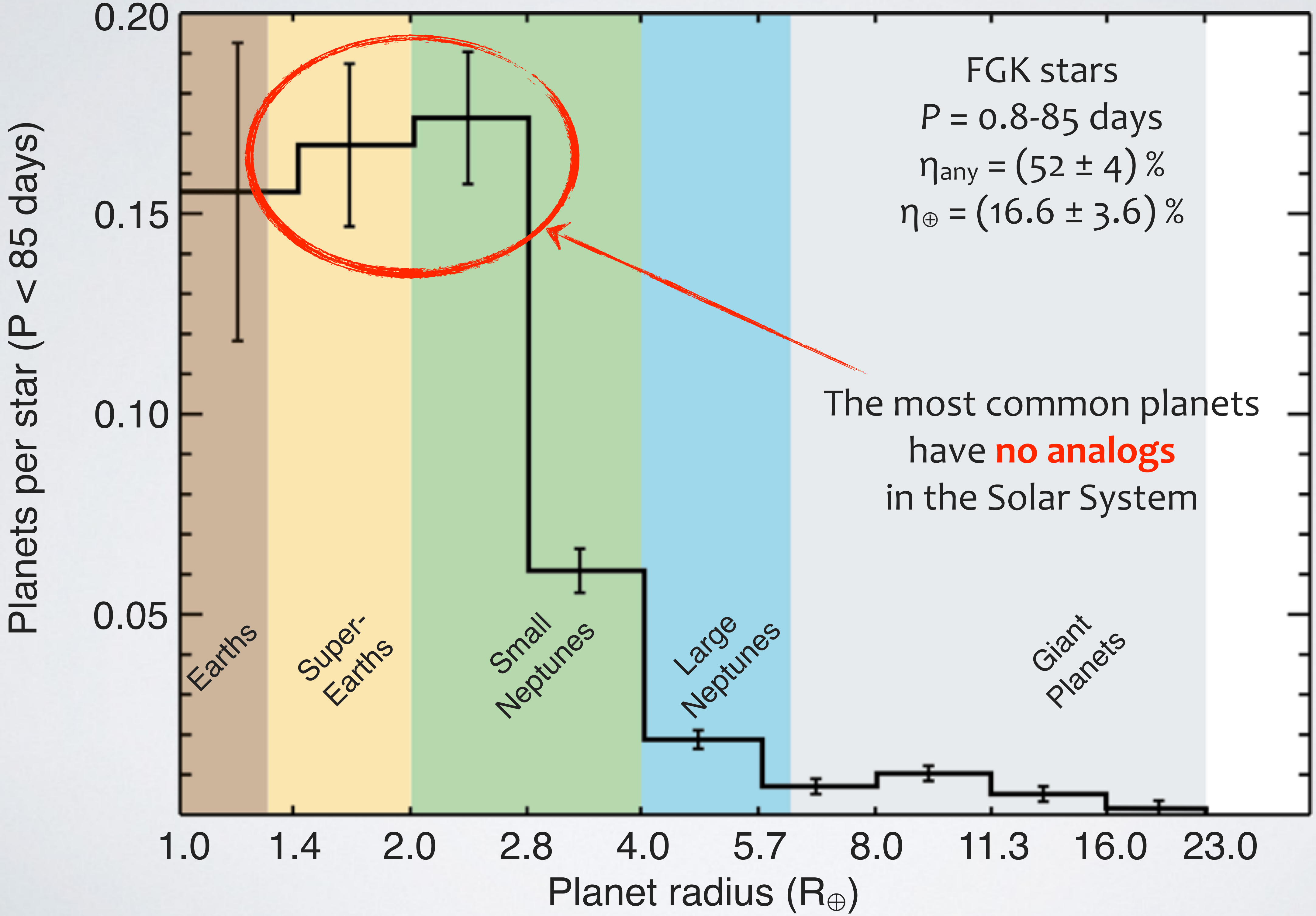
1995-2016 ⇒ 2,000+ confirmed exoplanets

This plot is misleading!



Statistics of exoplanet population

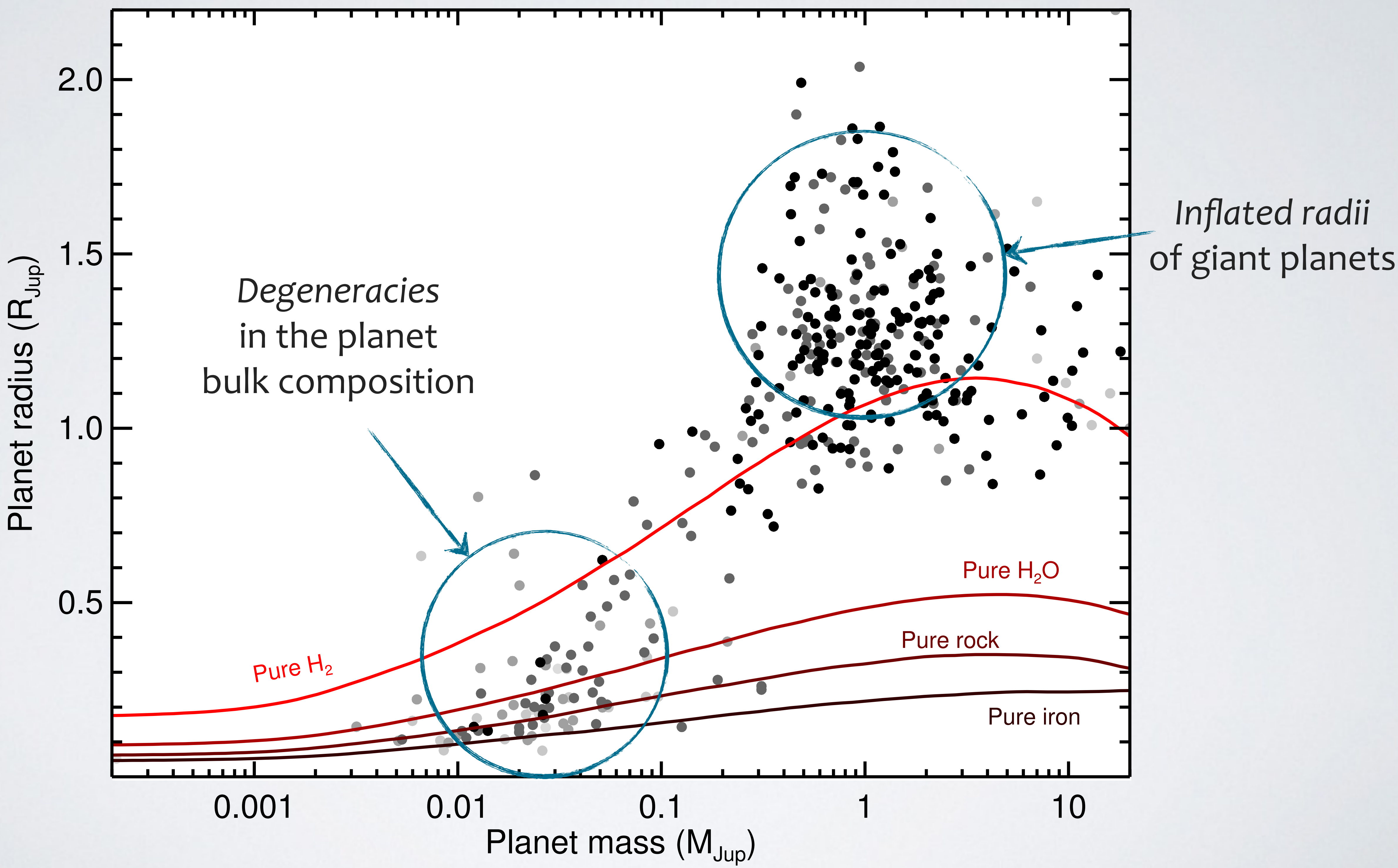
Mostly from *Kepler* on transiting planets (Fressin et al. 2013)



Measuring the planet bulk density

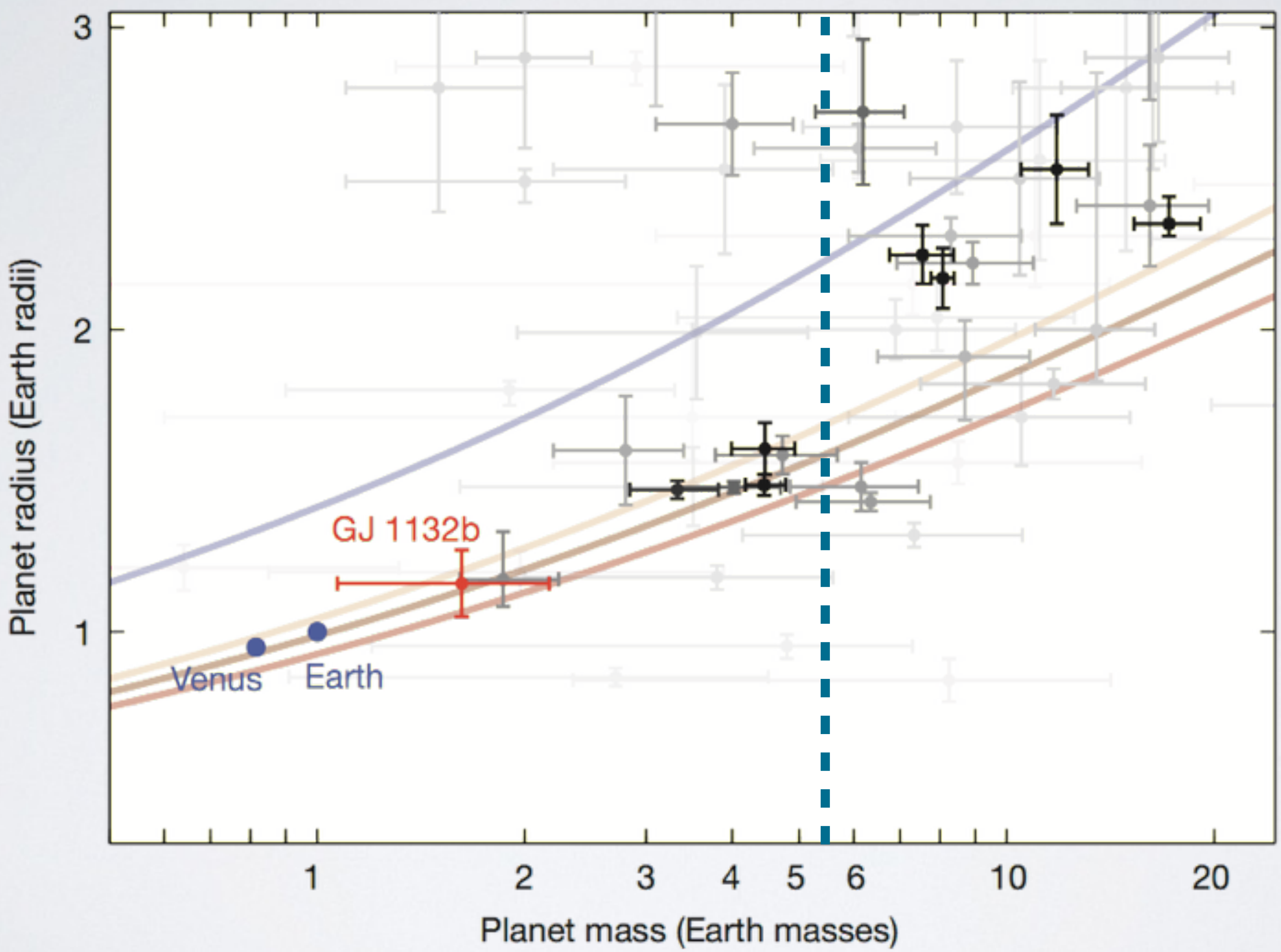
Planets with measurements of both radii and masses

Lighter gray = bigger error bars



The structure and composition of small planets

Plot from Berta et al. (2015)
Lighter gray = bigger error bars



The smallest planets seem to be compatible with Earth-Venus composition

Observing exoplanet atmospheres

From *statistical* to *individual* properties of exoplanets

Molecular/atomic species, inversion layers, clouds/hazes…

Solving *degeneracies* between planet interior-envelope

Super-Earths or mini-giants (or something unexpected?)

Linking composition to origin & evolution

Reliable estimates of C,N,O elemental abundances vs. stellar values

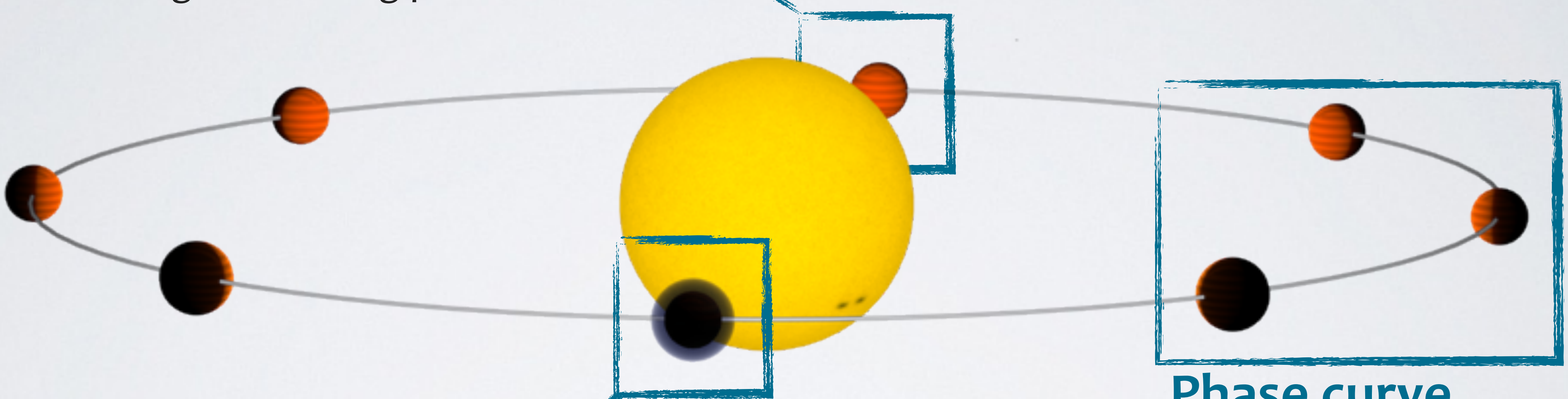
Determining surface conditions and hence *habitability*

Atmospheric circulation, T/p profile, composition, biomarkers…

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

Constraints on molecular species & abundances, T/p profile, longitudinal energy balance

Atmospheric composition and transmission signals

Transit depth

$D = (R_P/R_S)^2$

Jupiter-Sun ~ 1%

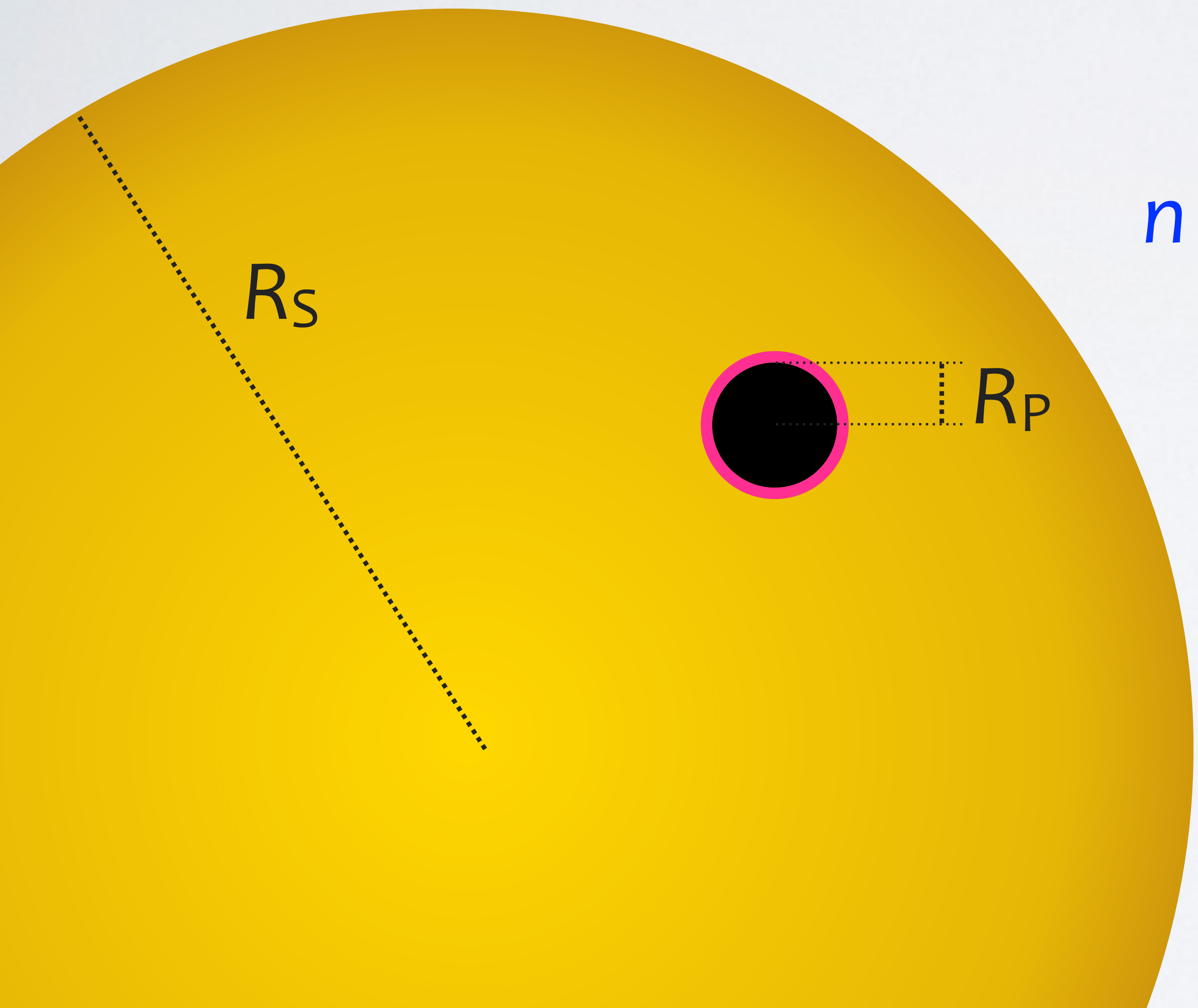
Earth-Sun ~ 0.008%

Change in transit depth
due to atmospheric opacity

$\Delta D = nHR_P/(R_S)^2$

$H = kT/g\mu$

$n \approx \log(\Delta\kappa)$



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$\Delta D = nHR_P/(R_S)^2$

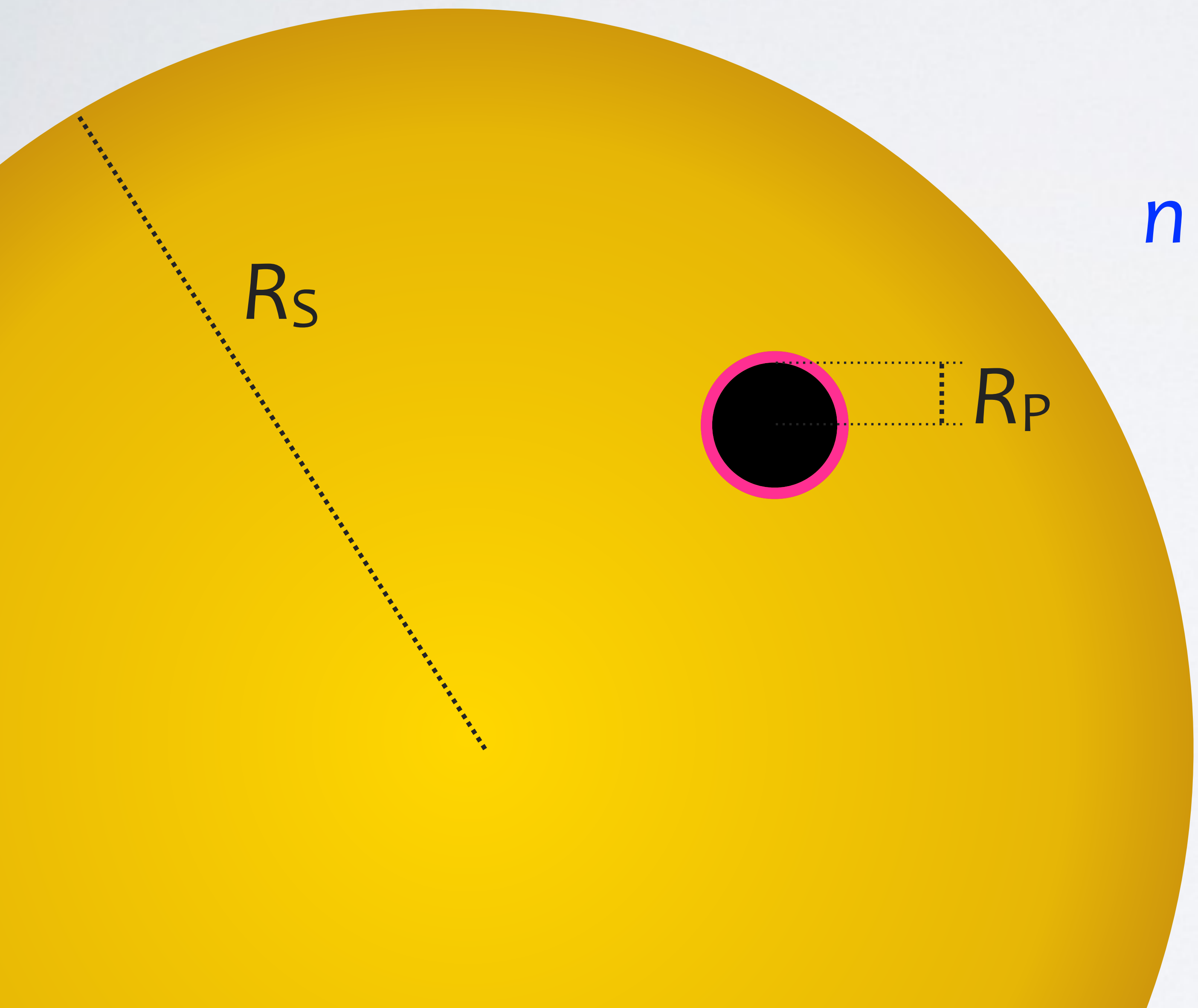
Find and target planets orbiting
small stars (late-K and M-dwarfs)

$H = kT/g\mu$

Target warmer planets
with lower density

$n \approx \log(\Delta\kappa)$

Maximize the change in opacity
between spectral channels

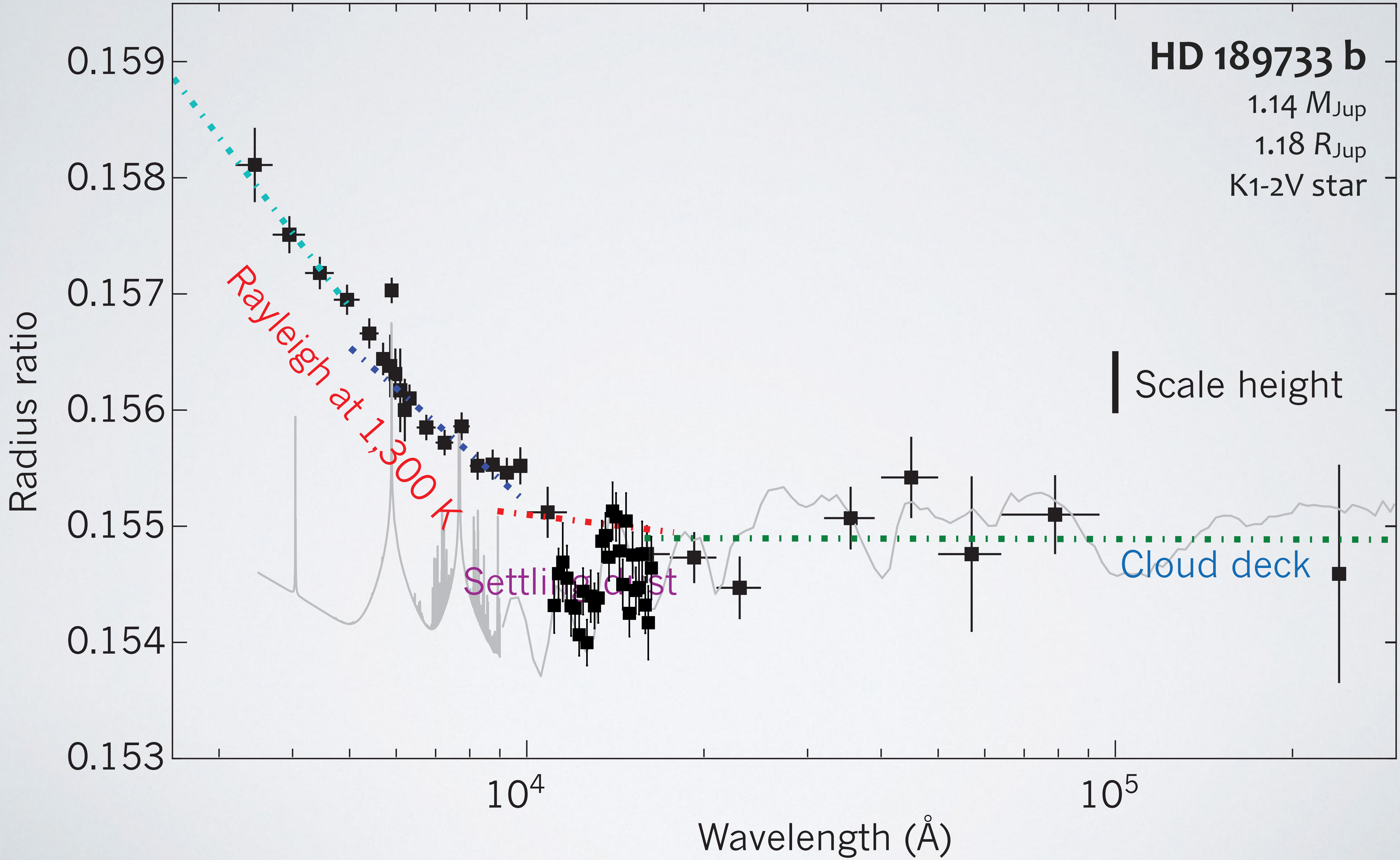


How do we maximize
the signal?

From low- to high-resolution spectra

Pont+ 2013; Burrows 2014

HST (low-res spectroscopy) + Spitzer (photometry)



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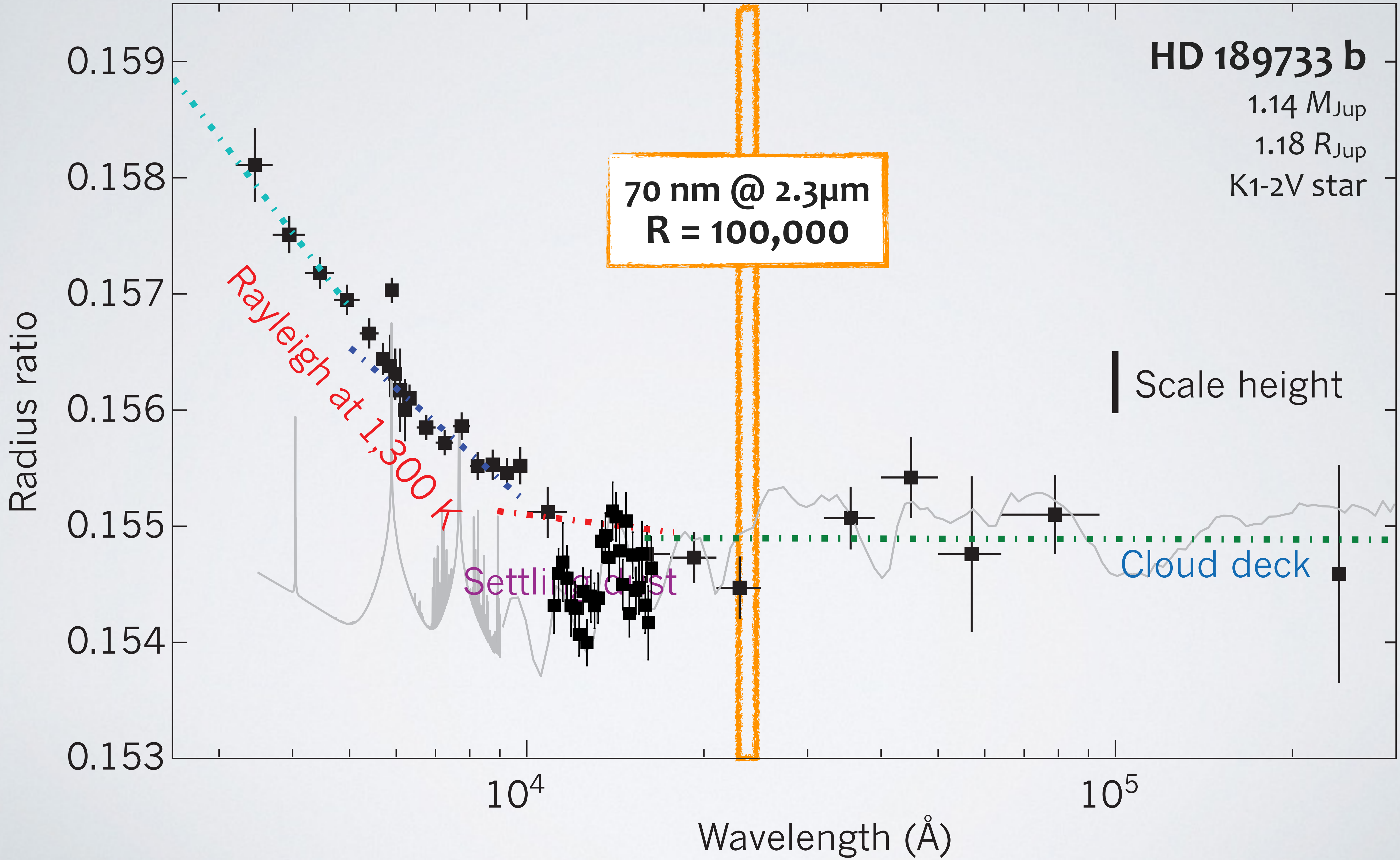
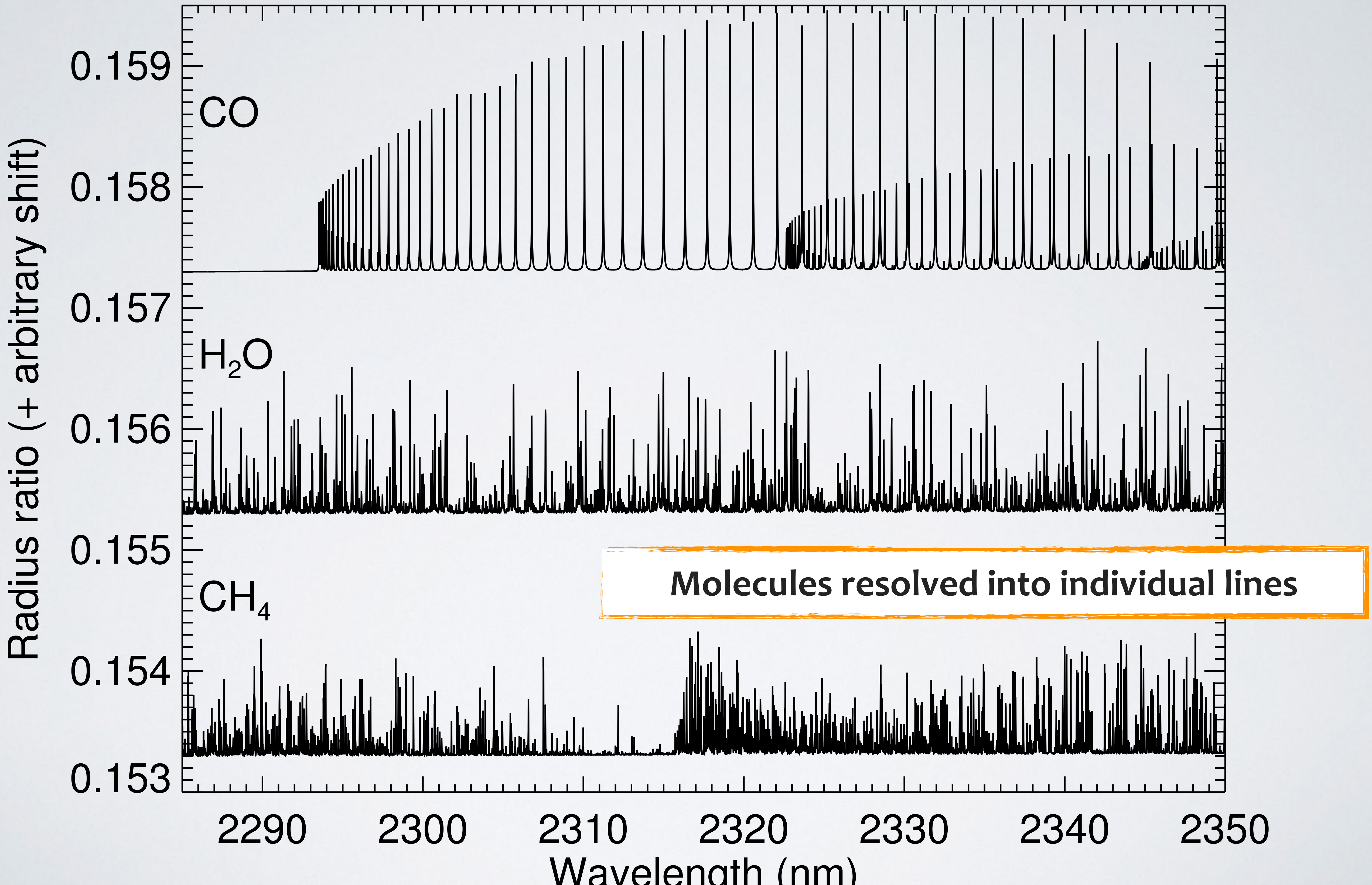


Molecular fingerprints at high spectral resolution

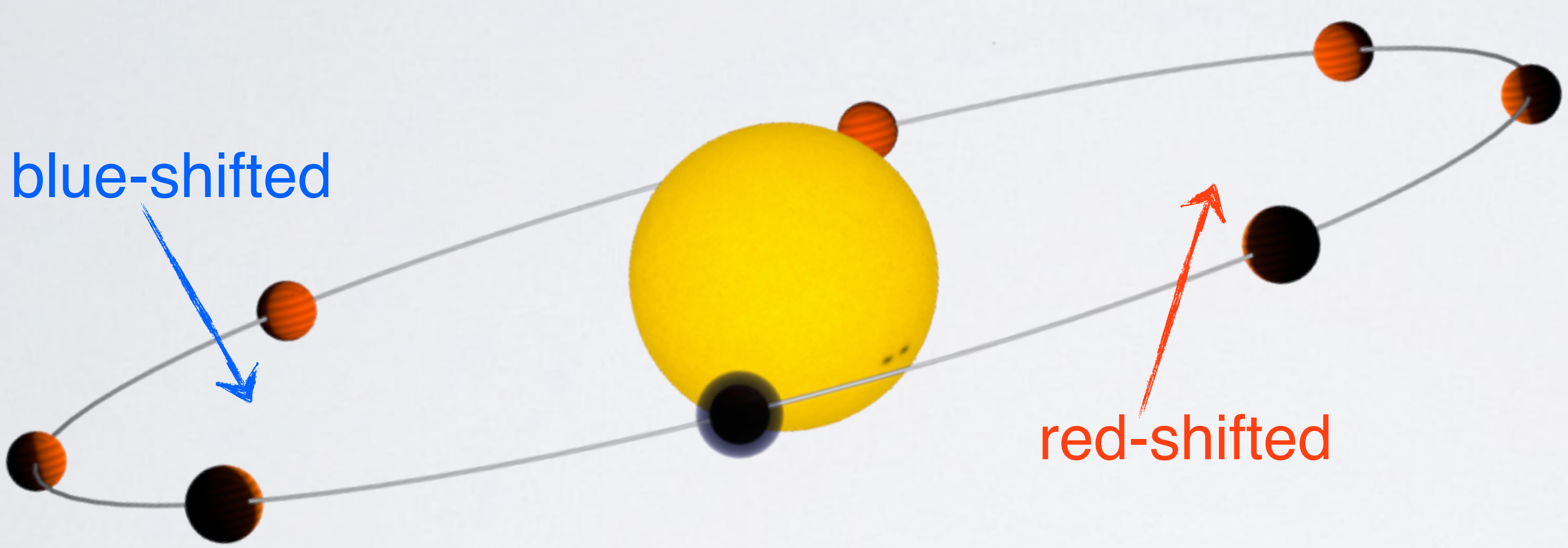
Models by Remco de Kok

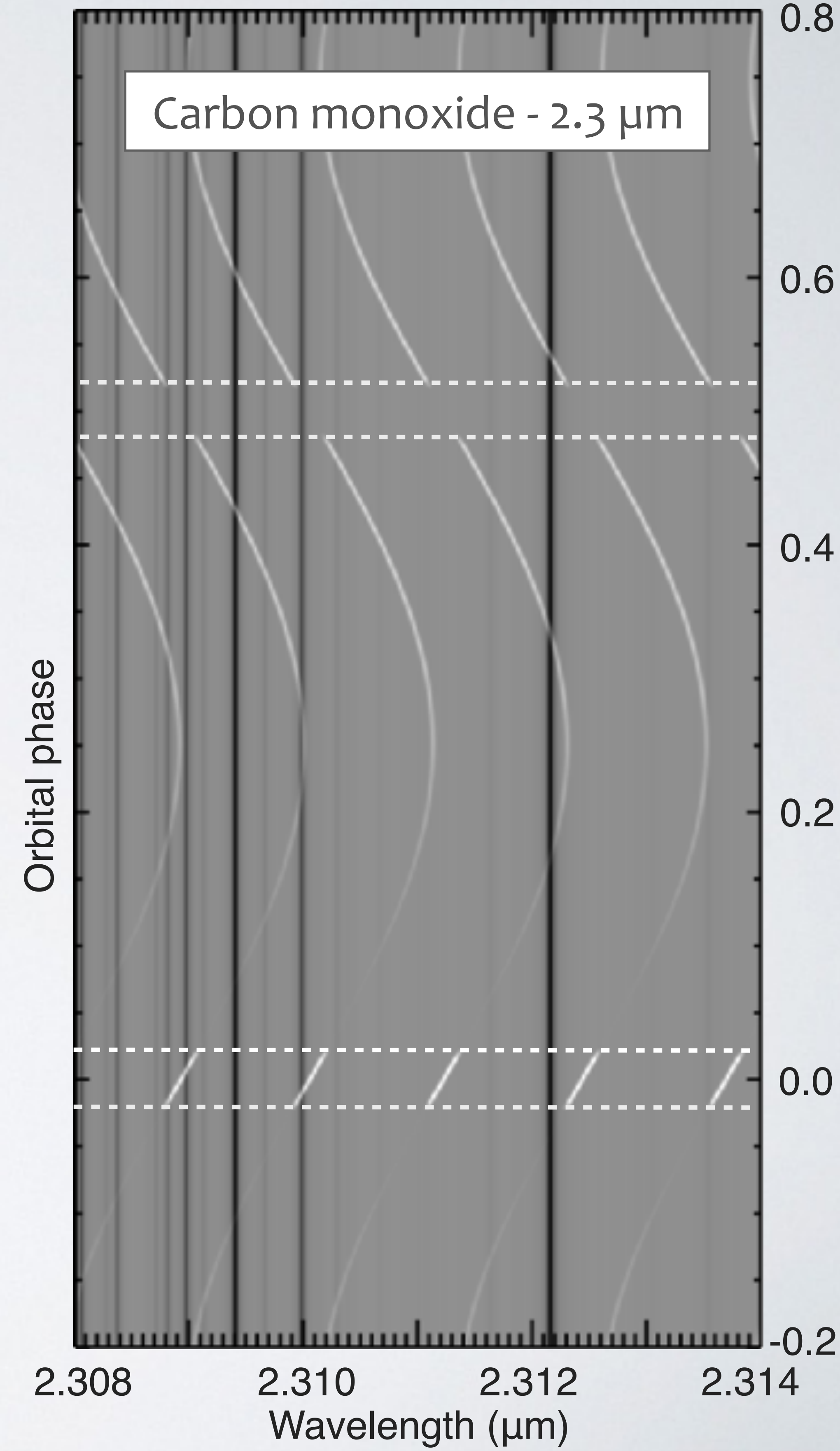


Hot Jupiters at high spectral resolution

HJs sensibly move along the orbit during few hours of observations

Planet motion resolved





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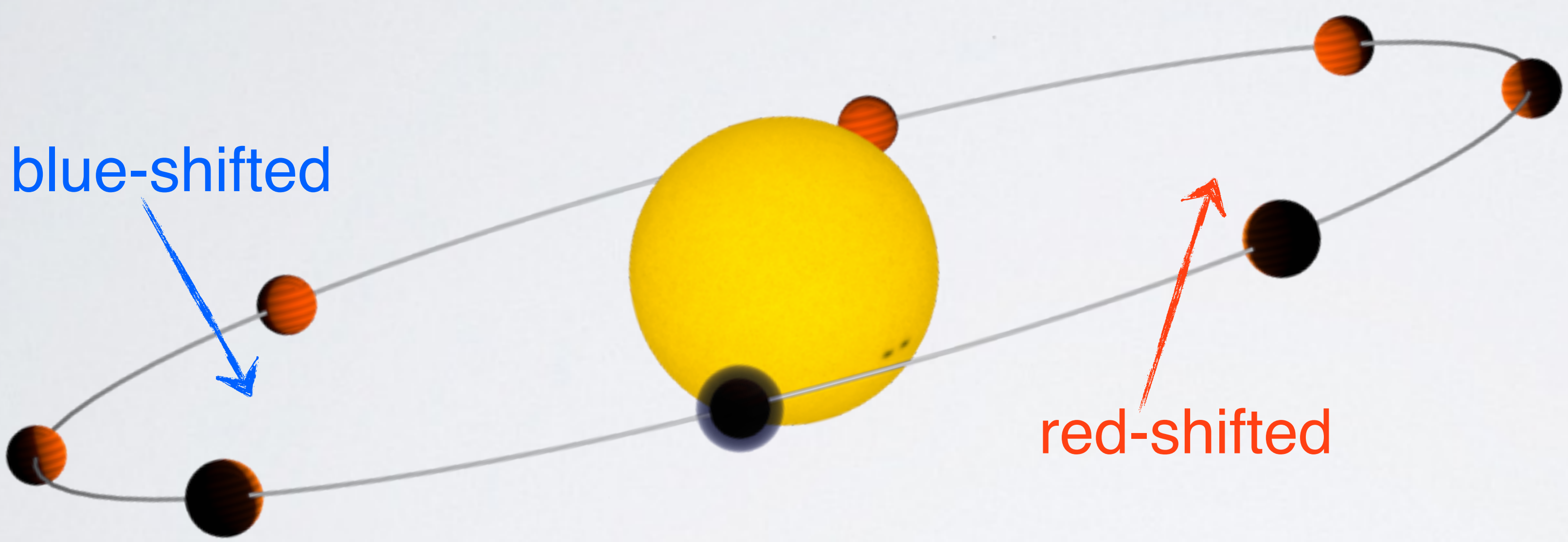
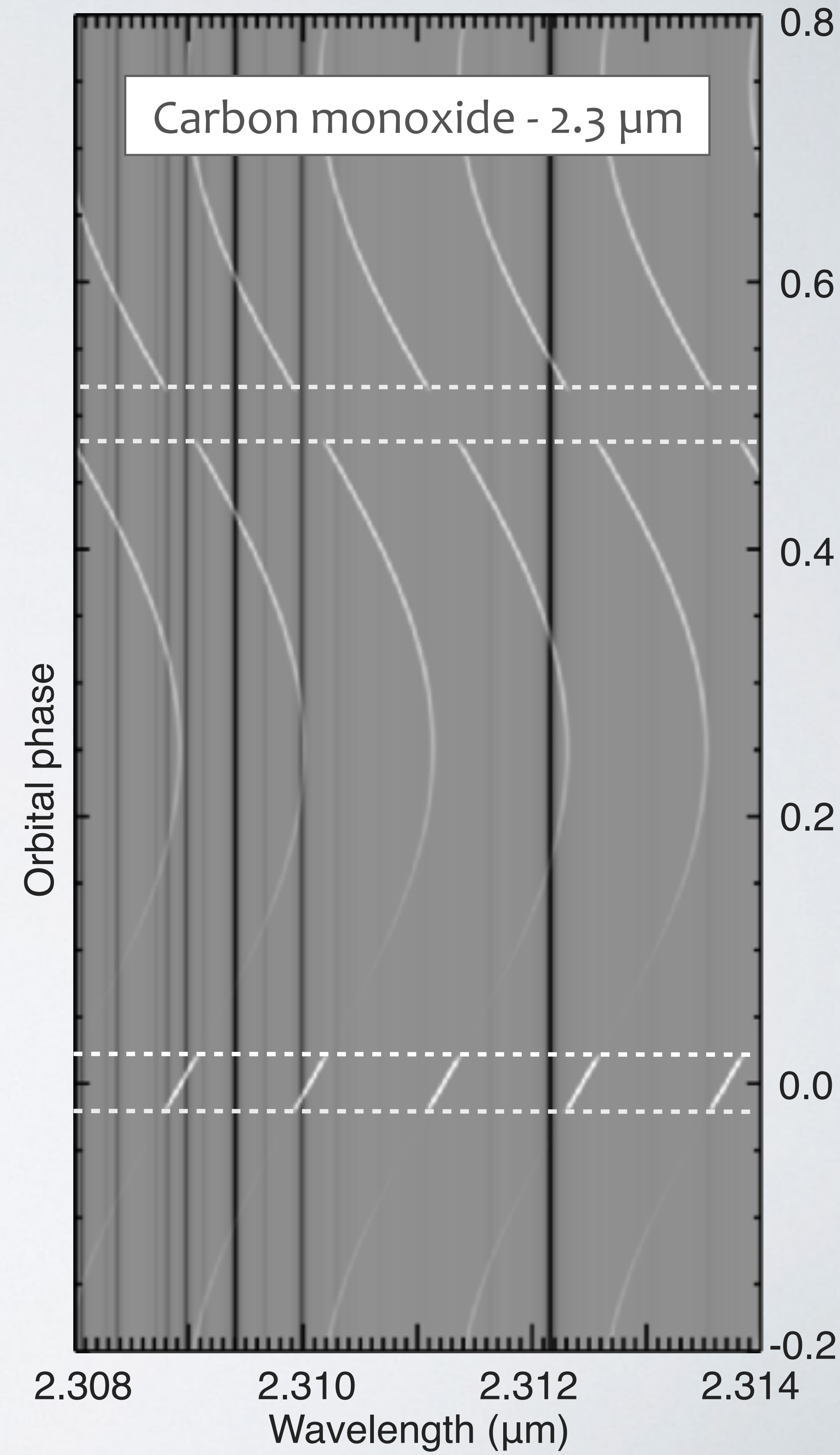


⇒ Telluric and planet signal disentangled

⇒ Planet radial velocity can be measured

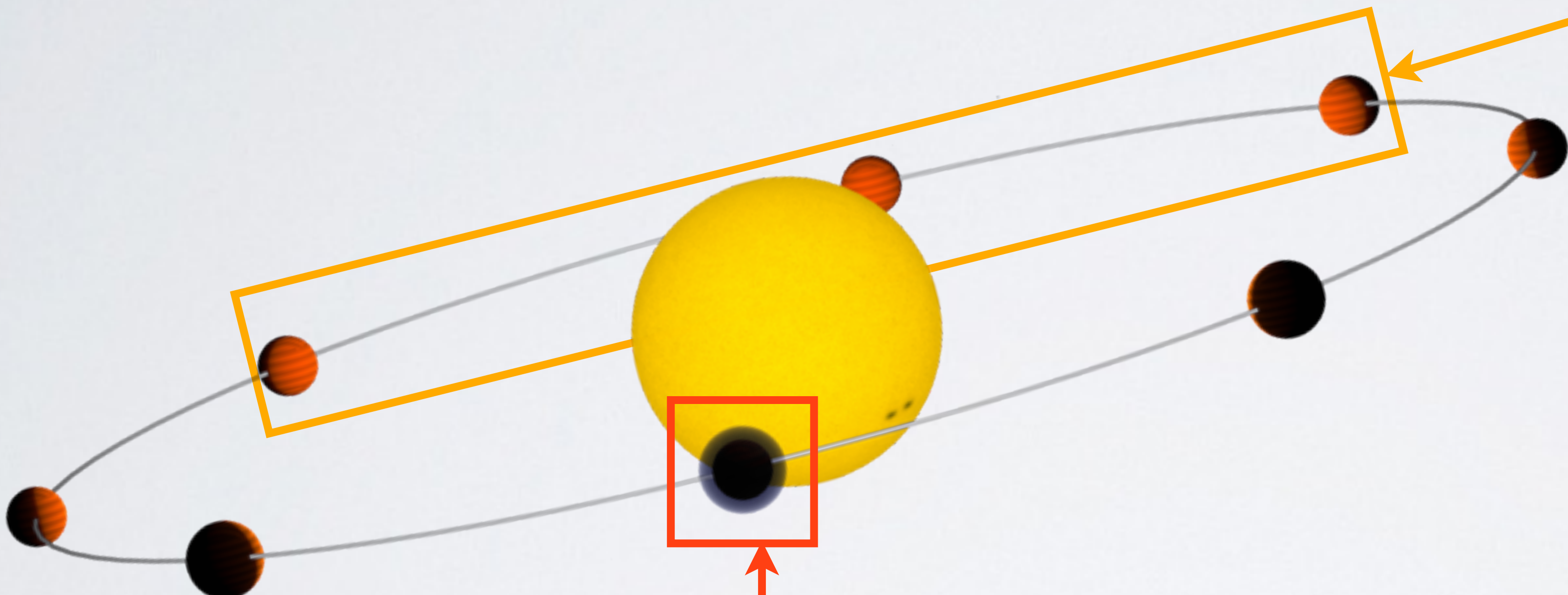
Planet: 10/100 km/s
Star: 10/100 m/s

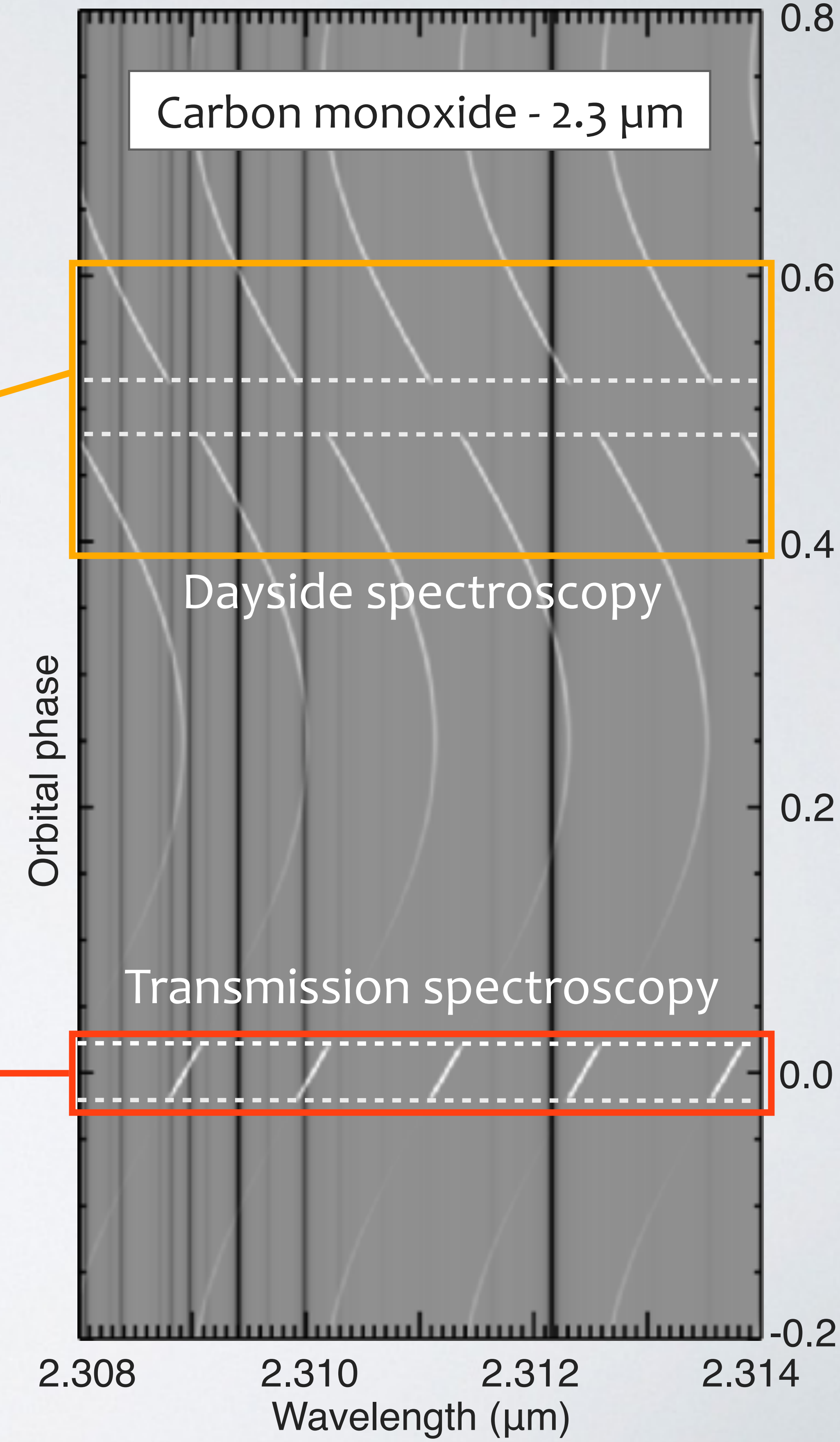


Exoplanets at high-spectral resolution

Transiting planets are observable:

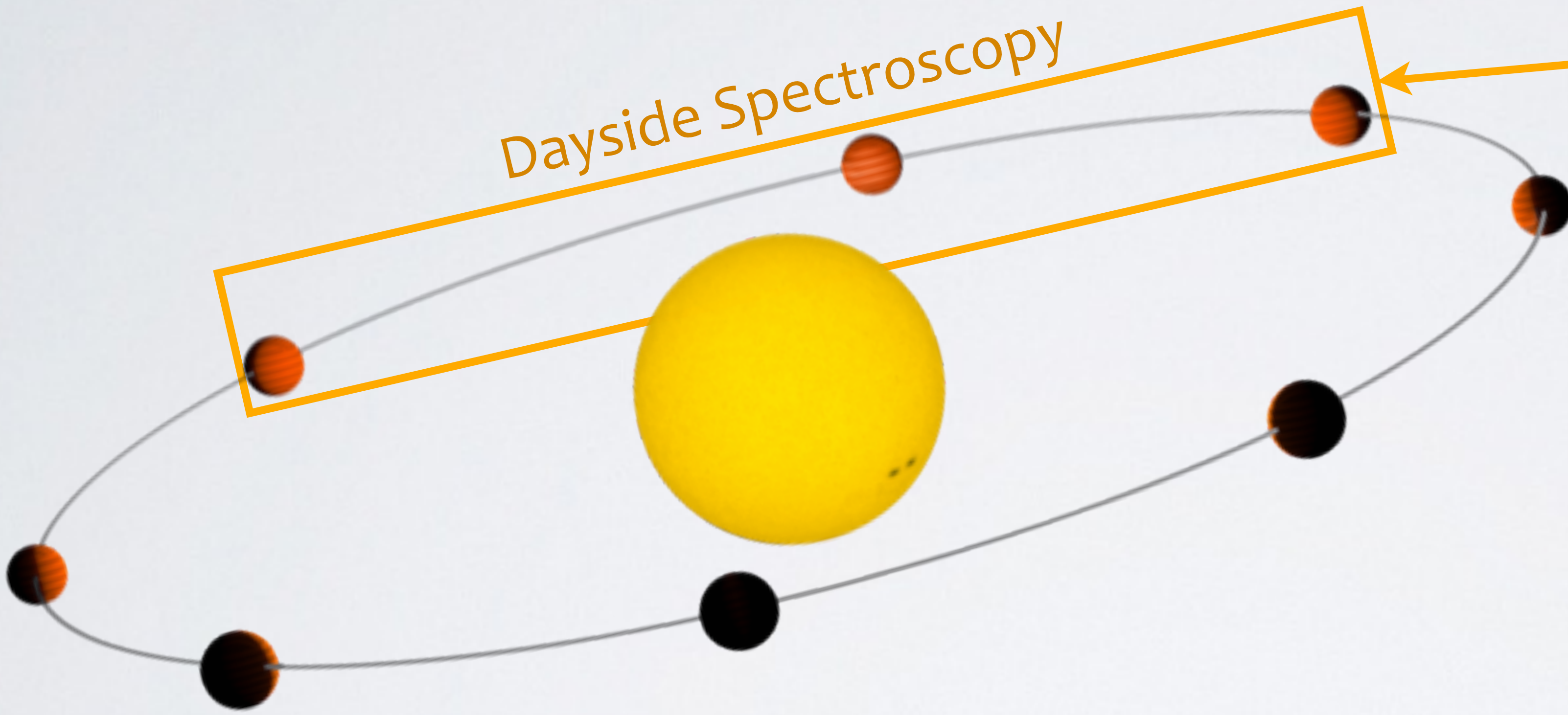
- During transit
- Before/after secondary eclipse

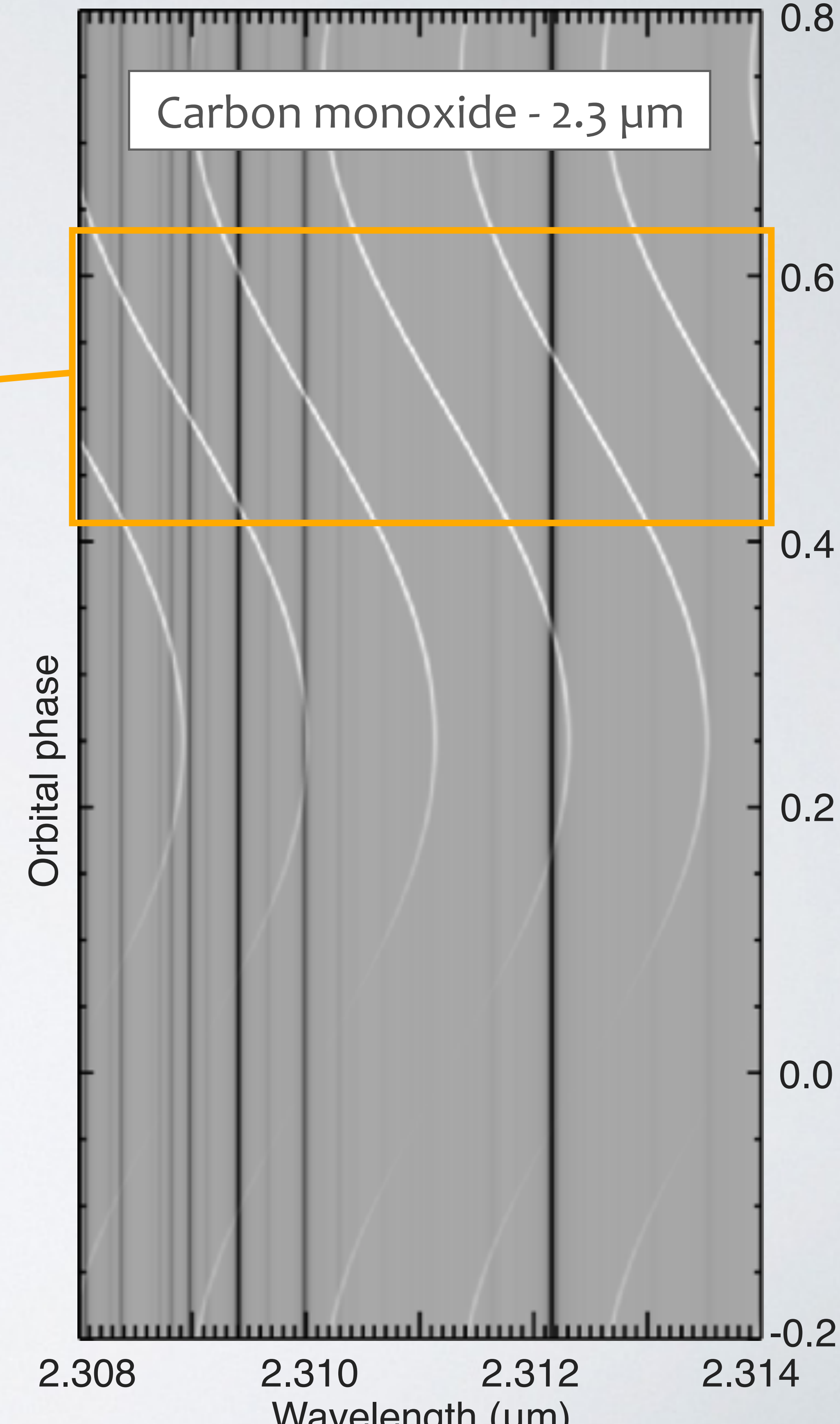




Exoplanets at high-spectral resolution

The thermal spectrum
of the planet is targeted directly





Dayside spectroscopy
applicable to non-transiting planets!

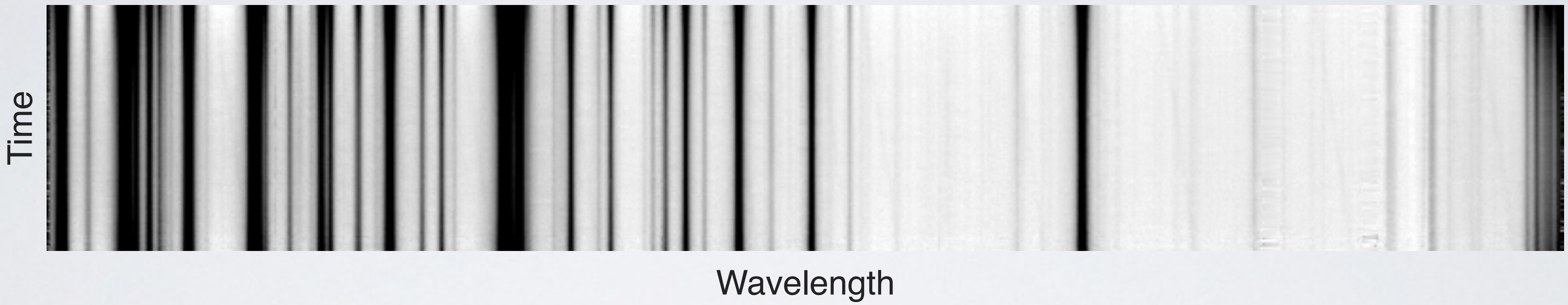
The data analysis: a two-step process

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)



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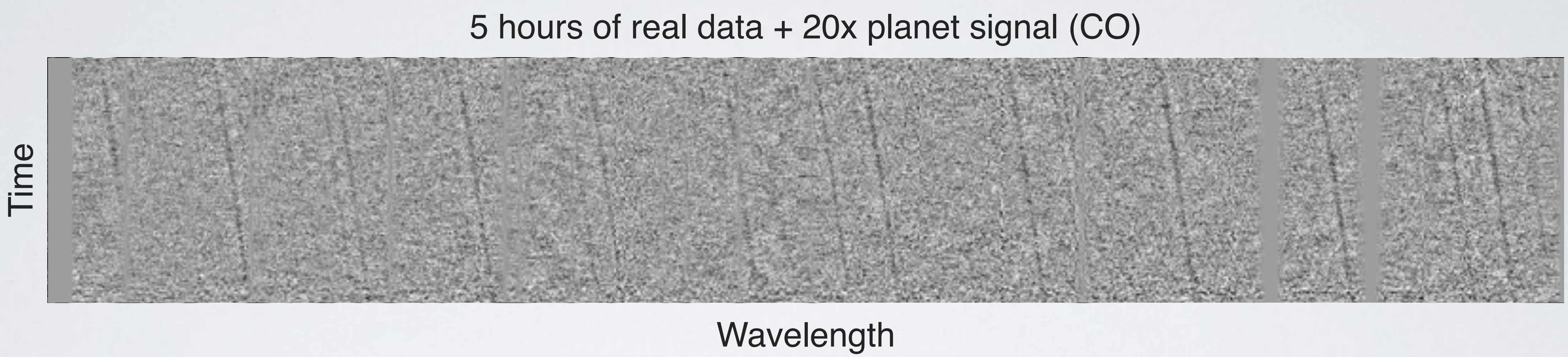

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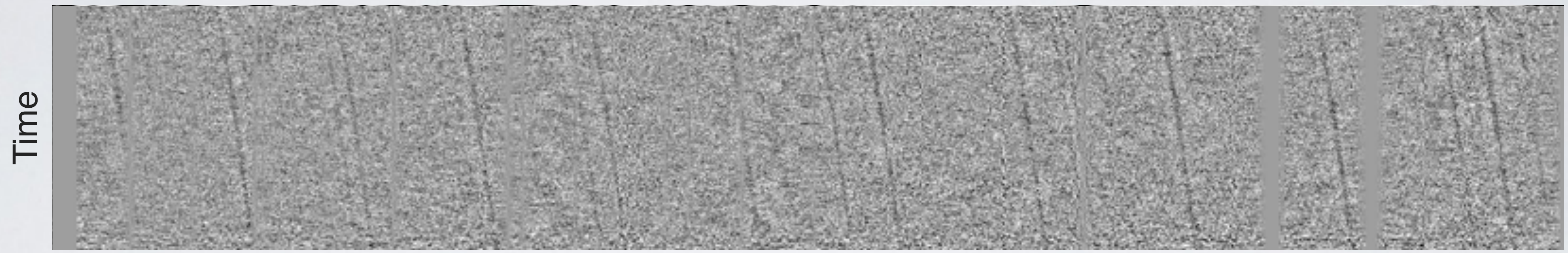
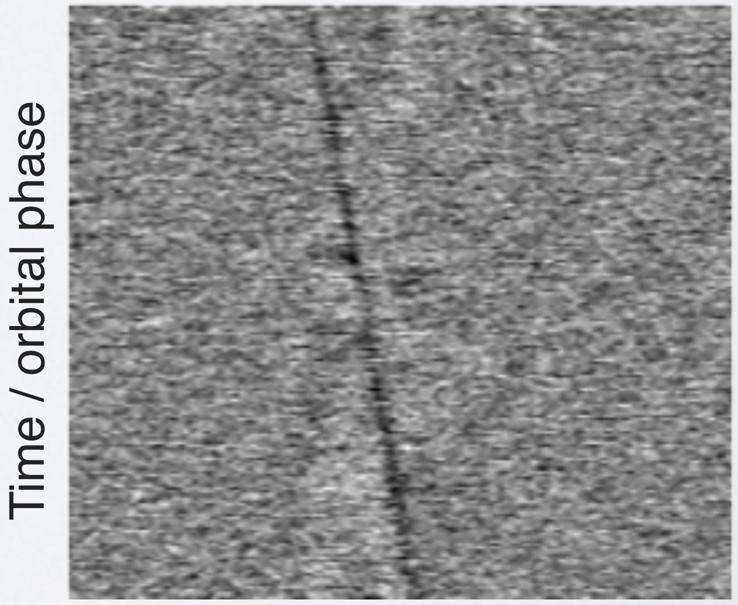


2 Cross-correlating with model spectra

(Models by Remco de Kok)

Cross-correlation matrix: CCF(RV, t)



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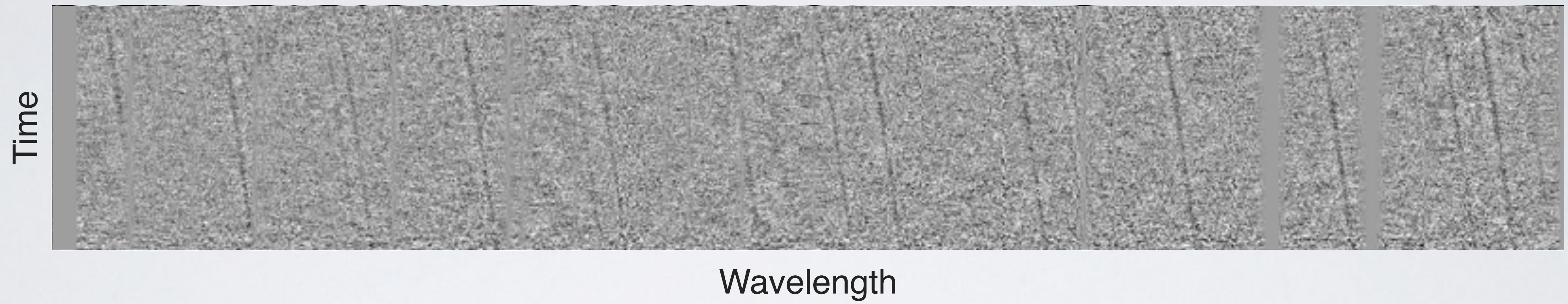

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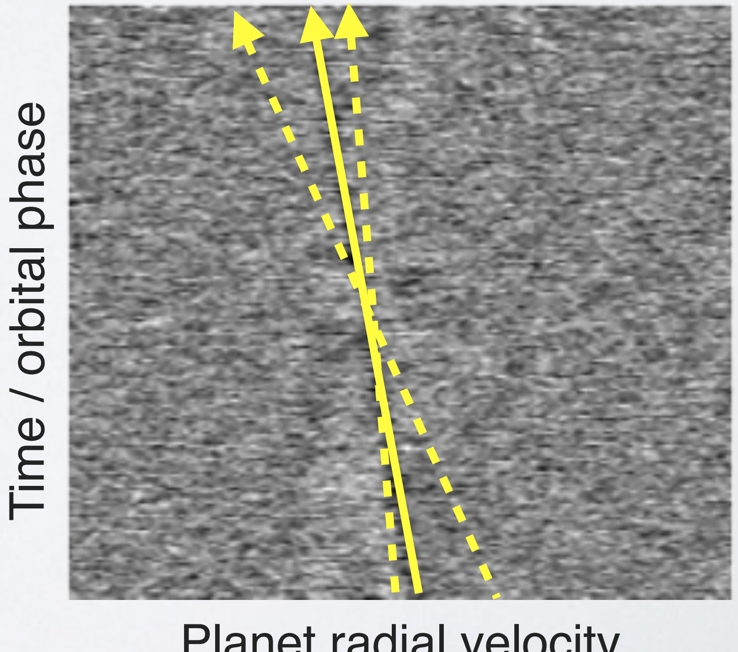
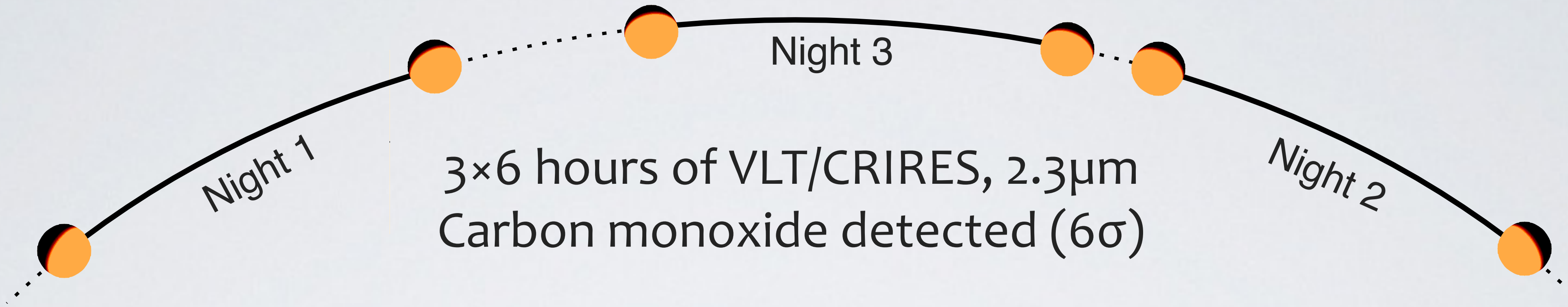
Cross-correlation matrix: CCF(RV, t)

Shifting and co-adding to planet rest-frame
(Requires knowledge of planet V_{orb})

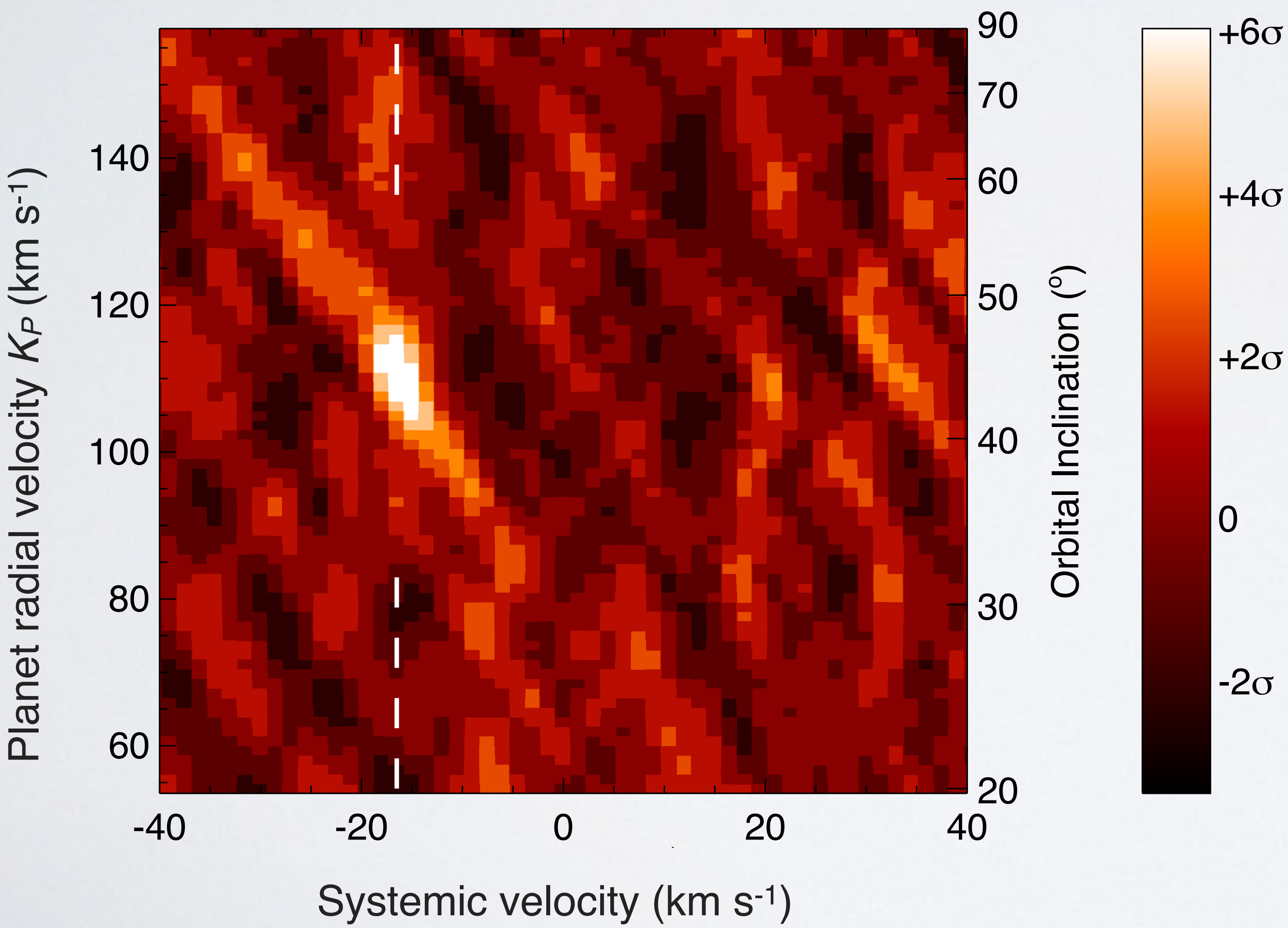


The orbital motion of τ Boo b

Brogi+ 2012



3×6 hours of VLT/CRIRES, 2.3μm
Carbon monoxide detected (6σ)



Measured:

RV ratio: K_P/K_S

⇒ Mass ratio: M_P/M_S

Inferred:

Orbital inclination i

Planet mass $M_P = f(M_S)$

Uncertainties in M_P dominated by uncertainties in M_S

For τ Boo b: $i = (45.5 \pm 1.5)°$, $M_P = (5.95 \pm 0.28)\ M_{Jup}$

Molecular detections to date

Snellen+ 2010, 2014; Brogi+ 2012, 2013, 2014, 2016; Brikby+ 2013, de Kok+ 2013; Schwarz+ 2014

Rodler+ 2012, 2013; Lockwood+ 2014

6 planets (2 transiting, 3 non transiting, 1 directly-imaged)

CO (6), H_2O (4) detected

Detections on 9/10 datasets

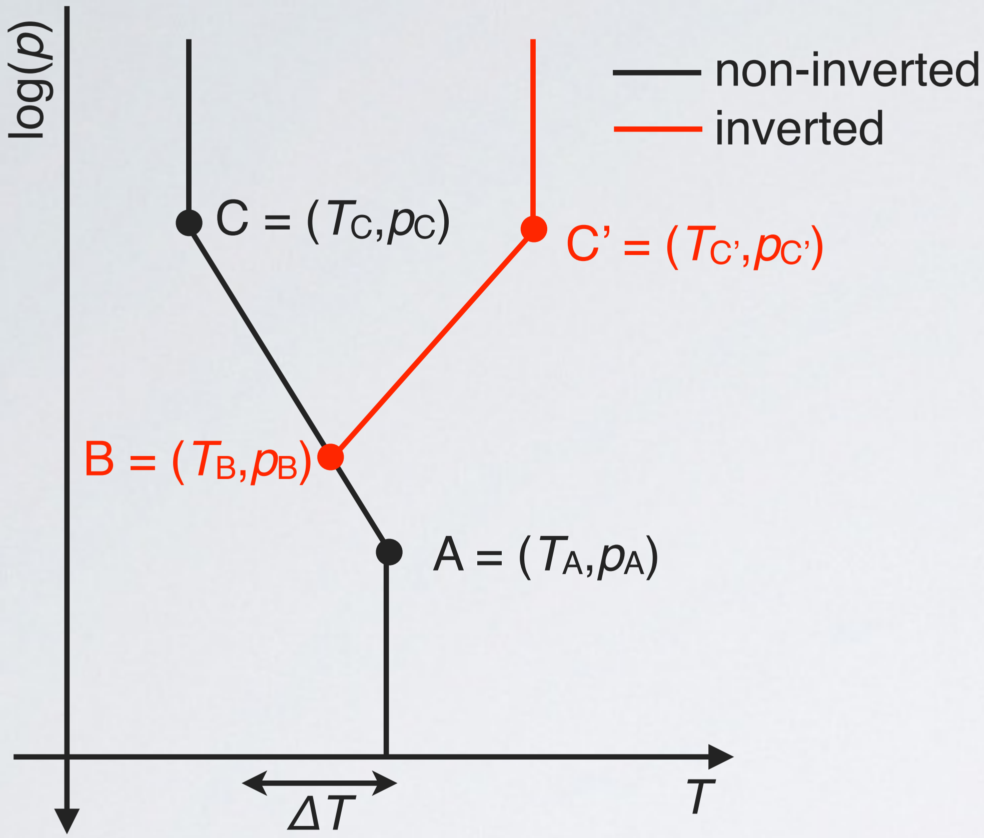
Masses and *inclinations* for non-transiting planets

CH_4 and CO_2 not (yet) detected

Low abundances expected for CO_2? (e.g. Heng & Lyons 2015)

Uncertainty: Incorrect / incomplete line lists

Modeling the planet atmosphere



- Parametrized *T*/*p* profile
- H_2-dominated (hot-Jupiters)
- Trace gases: CO, H_2O, CH_4, CO_2
- VMR: 10^{-7}-10^{-4} for CH_4, CO_2
- VMR: 10^{-5}-10^{-2} for H_2O, CO
- Clear atmosphere (inclusion of an optically-thick cloud deck is possible)

What do we measure?

1. Degree of match between data and models (strength of CCF)
2. Average line/continuum depth

Transit spectra

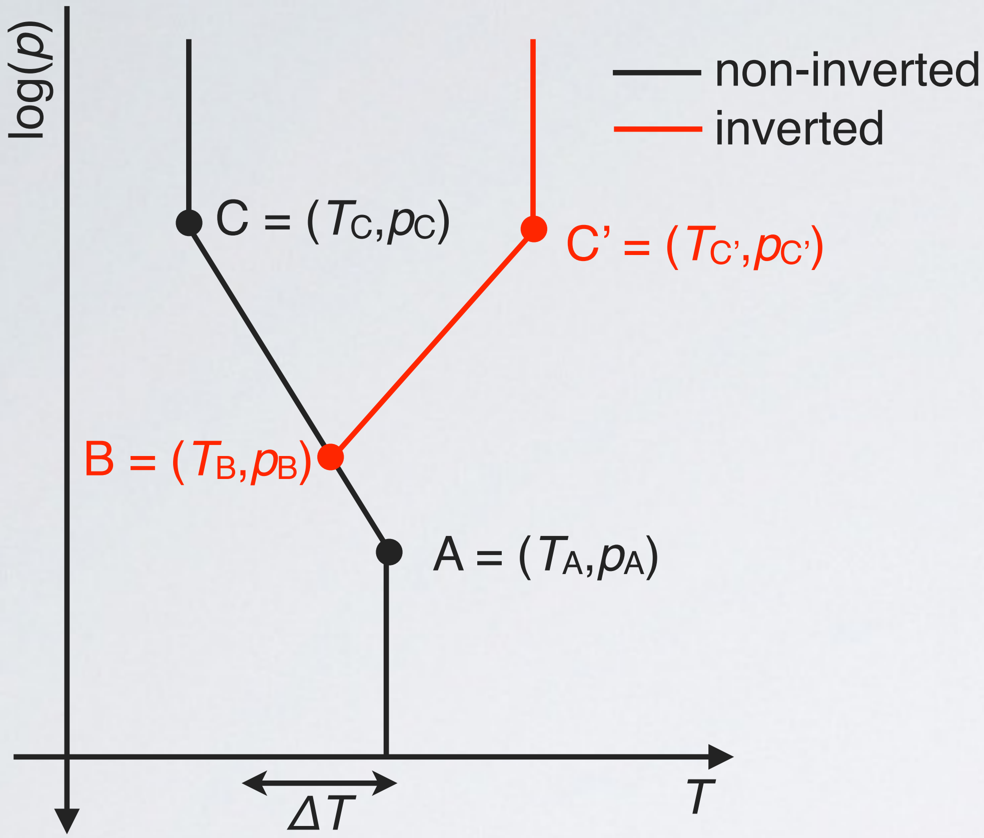
Weak dependence on *T* or lapse rate

Possible influence of hazes/clouds

Emission spectra

Line depth ≈ $\Delta T \Rightarrow$ degeneracy between T_A, lapse rate, abundances

Modeling the planet atmosphere



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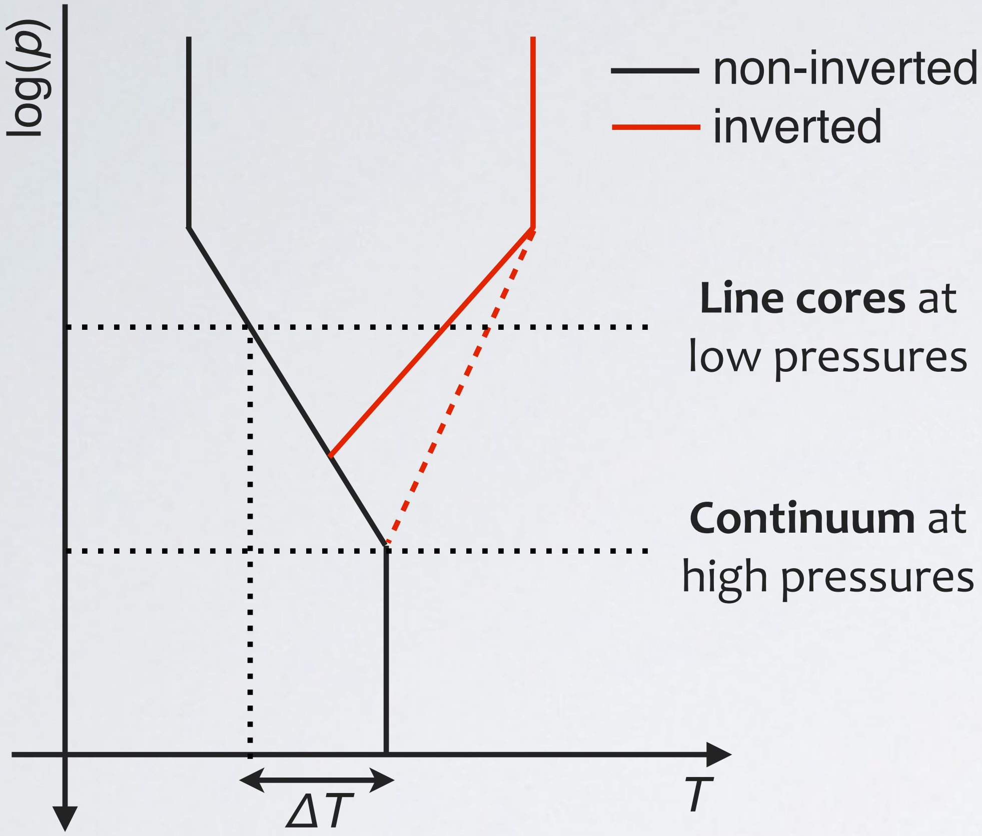
Removing degeneracies

Larger spectral range (ideally the whole NIR)
Absolute fluxes from broad-band / low-res measurement

Dayside spectra and thermal inversions



Line depth traces T difference
(continuum vs. core)

- $dT/d\log(p) > 0 \Rightarrow$ Absorption lines
- $dT/d\log(p) < 0 \Rightarrow$ Emission lines

The cross-correlation naturally detect inversion layers

(Models with the wrong *T-p* profile produce anti-correlation)

All high-resolution observations have detected *absorption* lines

(But stay tuned for Brogi+ in prep.)

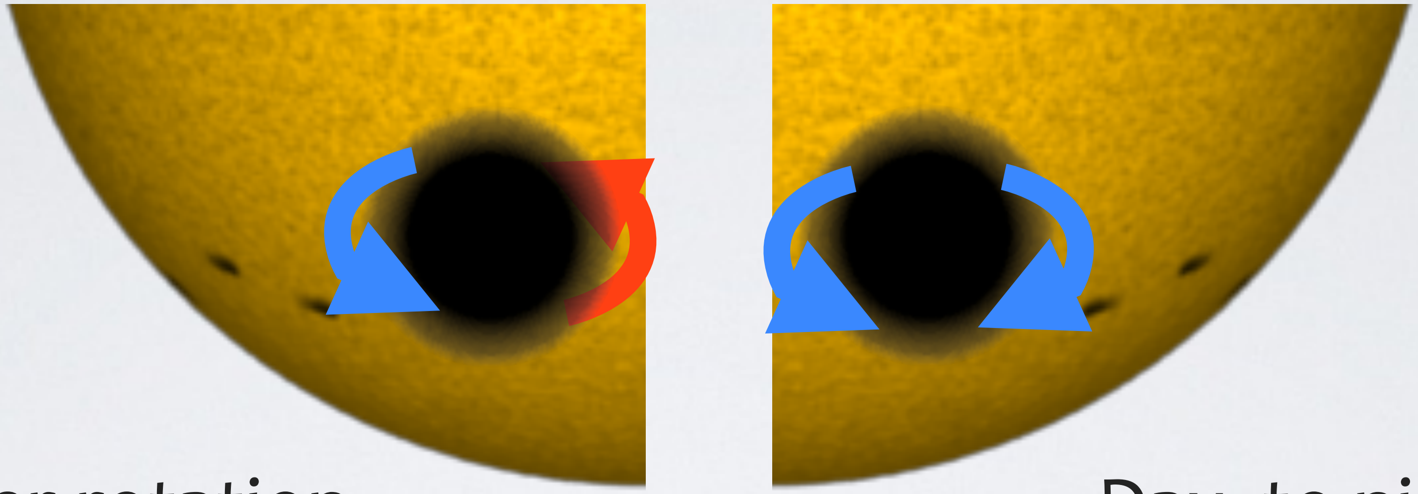
No evidence of inversion layers to date in the literature

(Knutson+ 2008, 2010; Diamond-Love+ 2014; Schwarz+ 2014)

Testing the synchronous rotation of hot Jupiters

HJs become **tidally locked** on short timescales: $P_{orb} = P_{rot}$

HJs have 2 main regimes of **atmospheric circulation**



Equatorial super-rotation

Day- to night-side winds

Rotation and winds **broaden** and **distort** the planet line profiles

(Showman+ 2012; Miller-Ricci Kempton+ 2012, 2014; Rauscher & Kempton 2014)

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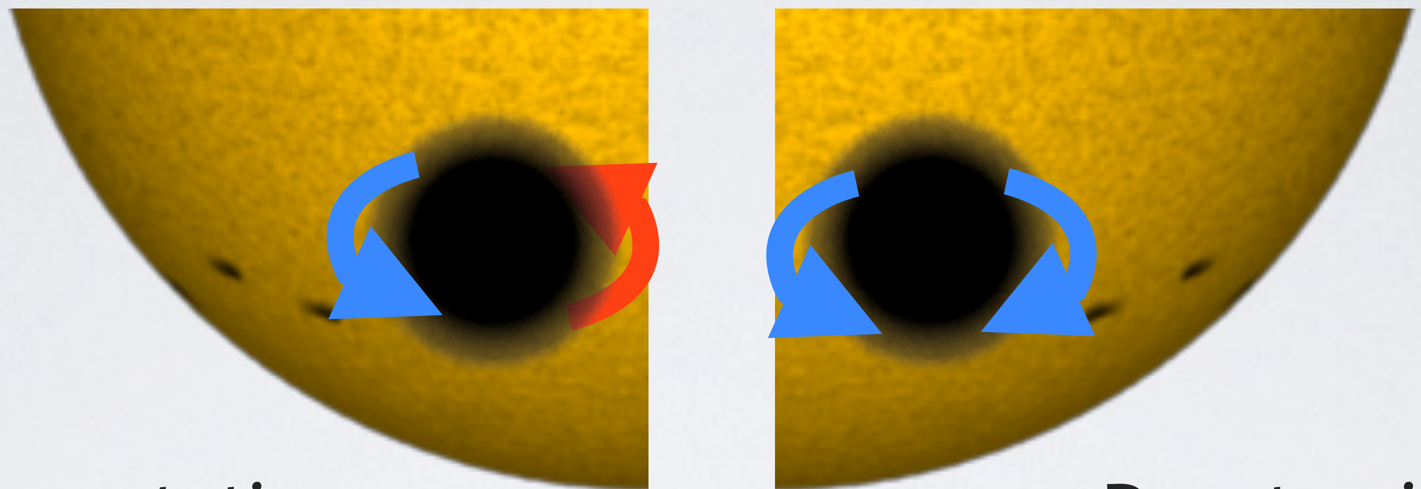

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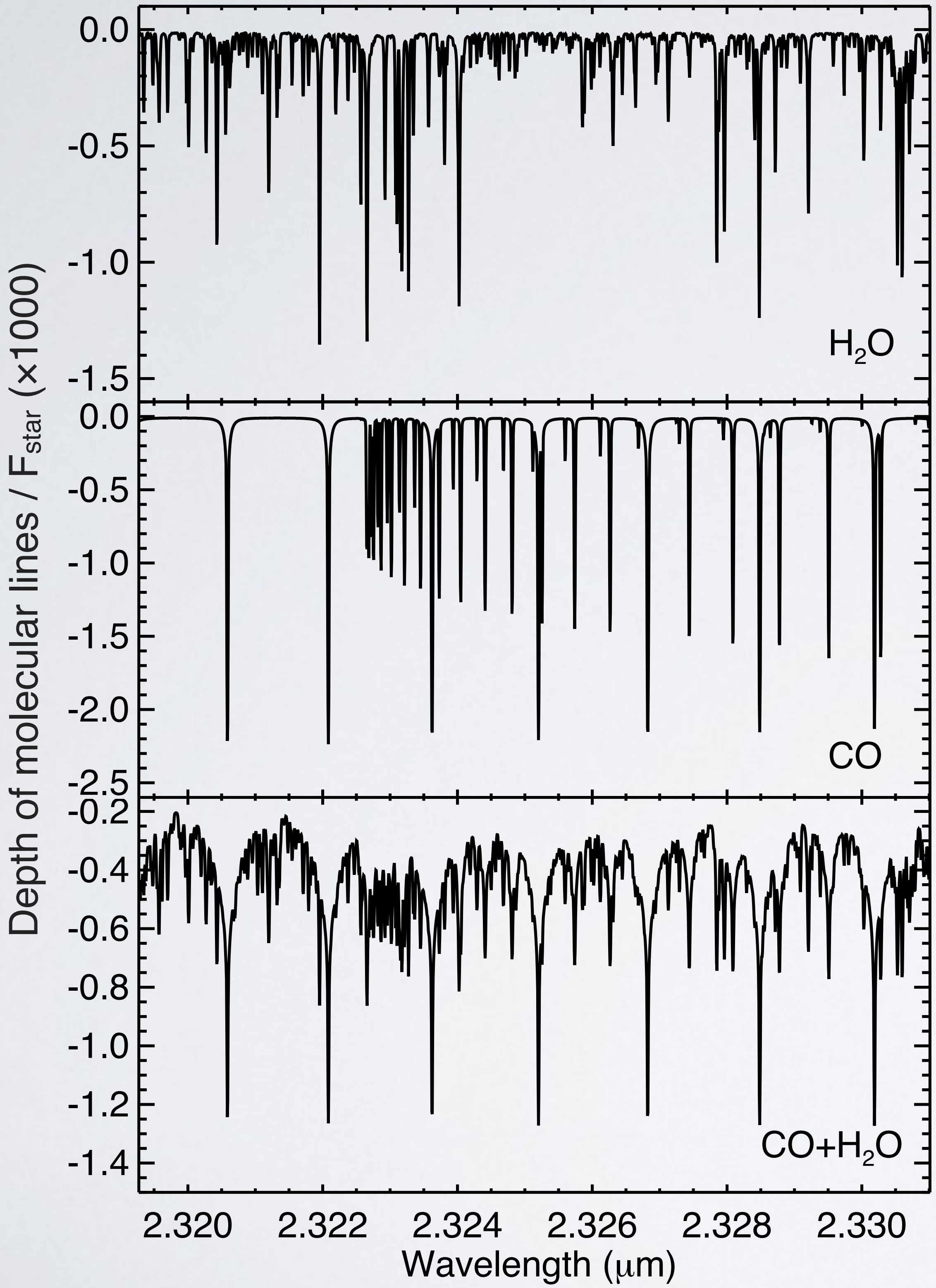
Testing predictions on **HD 189733 b**

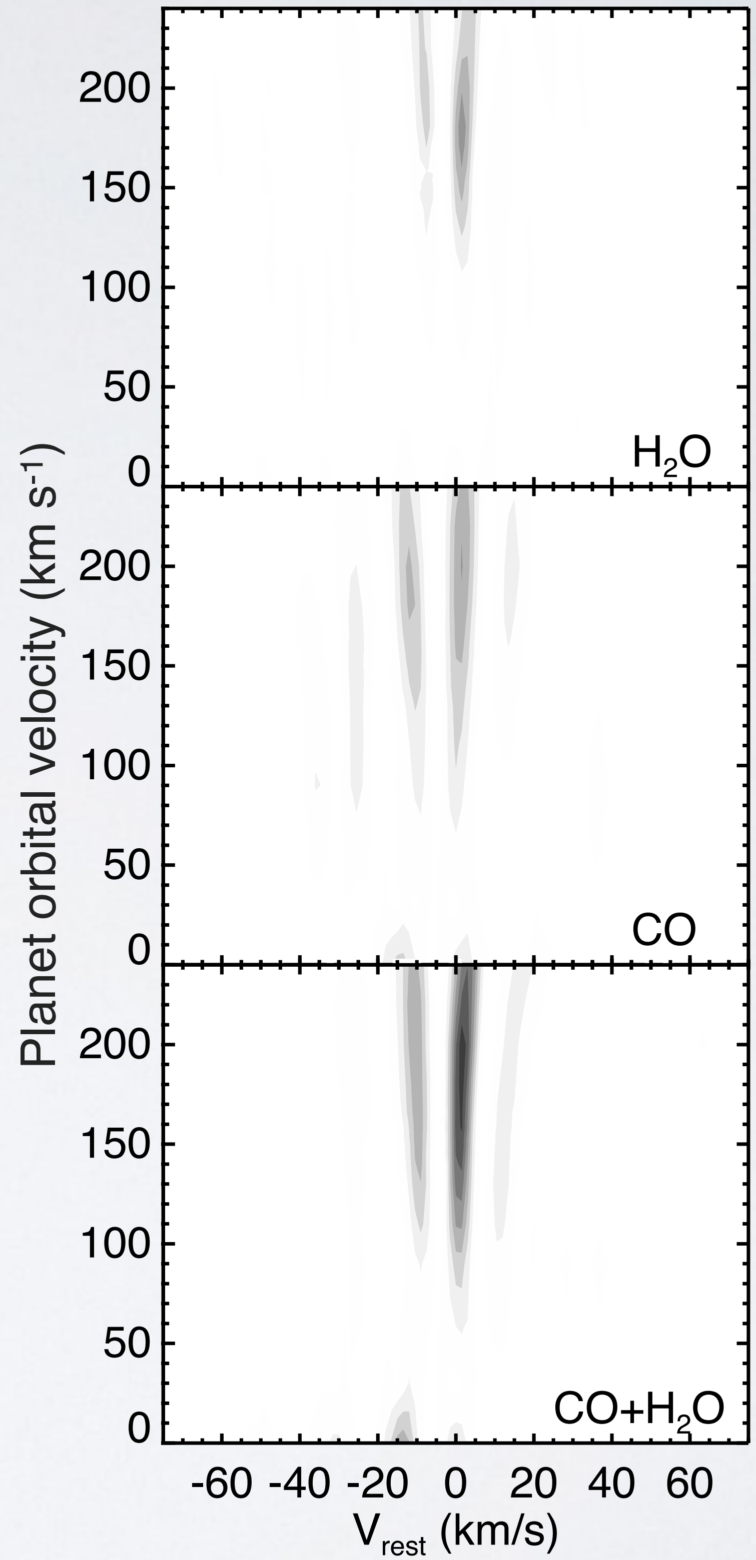
1.1 M_{Jupiter}, 1.2 R_{Jupiter}, K1-2V star

2 hrs of VLT/CRIRES = 1 transit @ 2.3μm

The transmission spectrum of HD 189733b

Brogi+ 2016





5.5σ
Water vapor

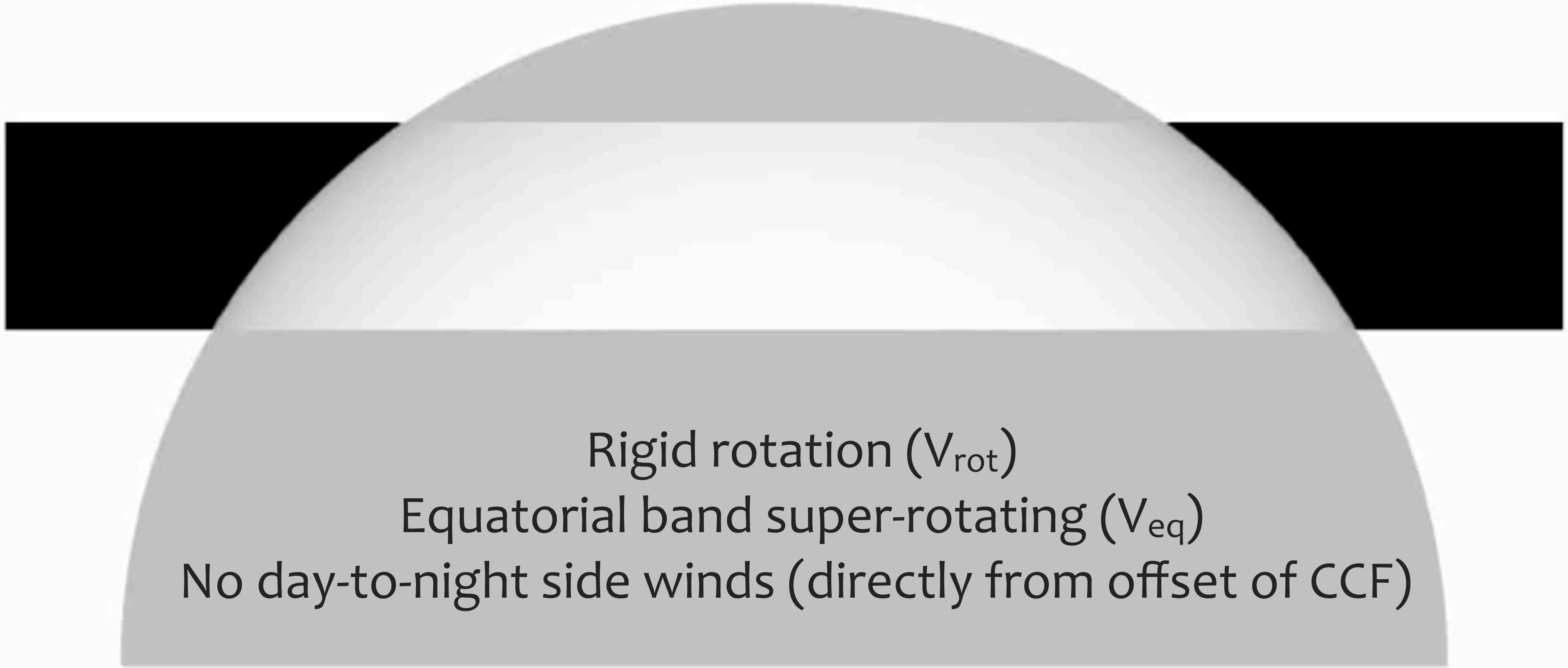
5.1σ
Carbon monoxide

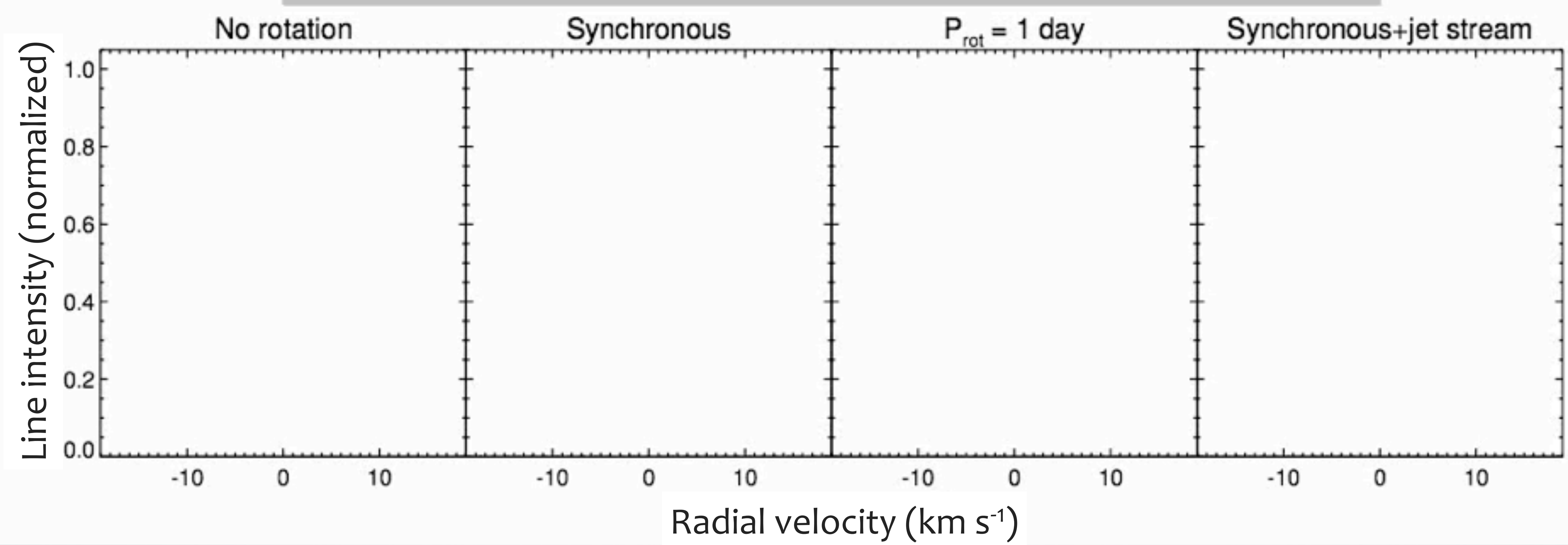
7.6σ
Combined signal

VMR(CO) = VMR(H_2O) = 10^{-3}

No detection of CH_4 or CO_2

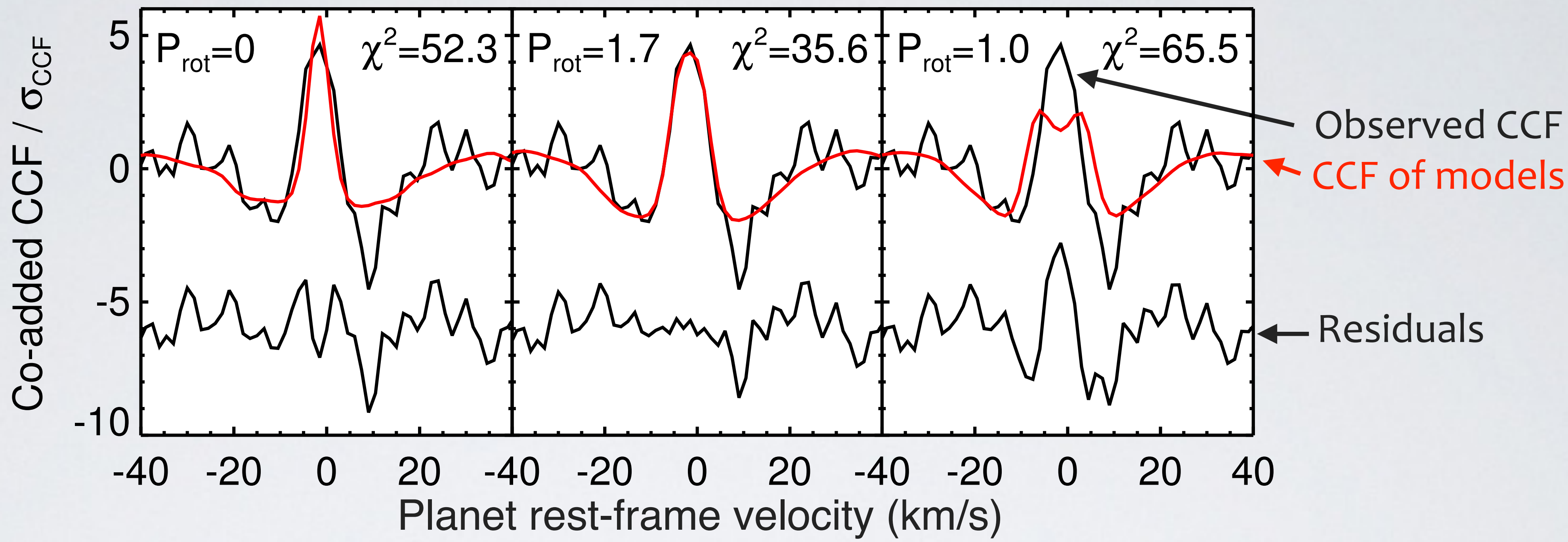
Modeling the broadened planet line profile





Measuring line broadening from the CCF

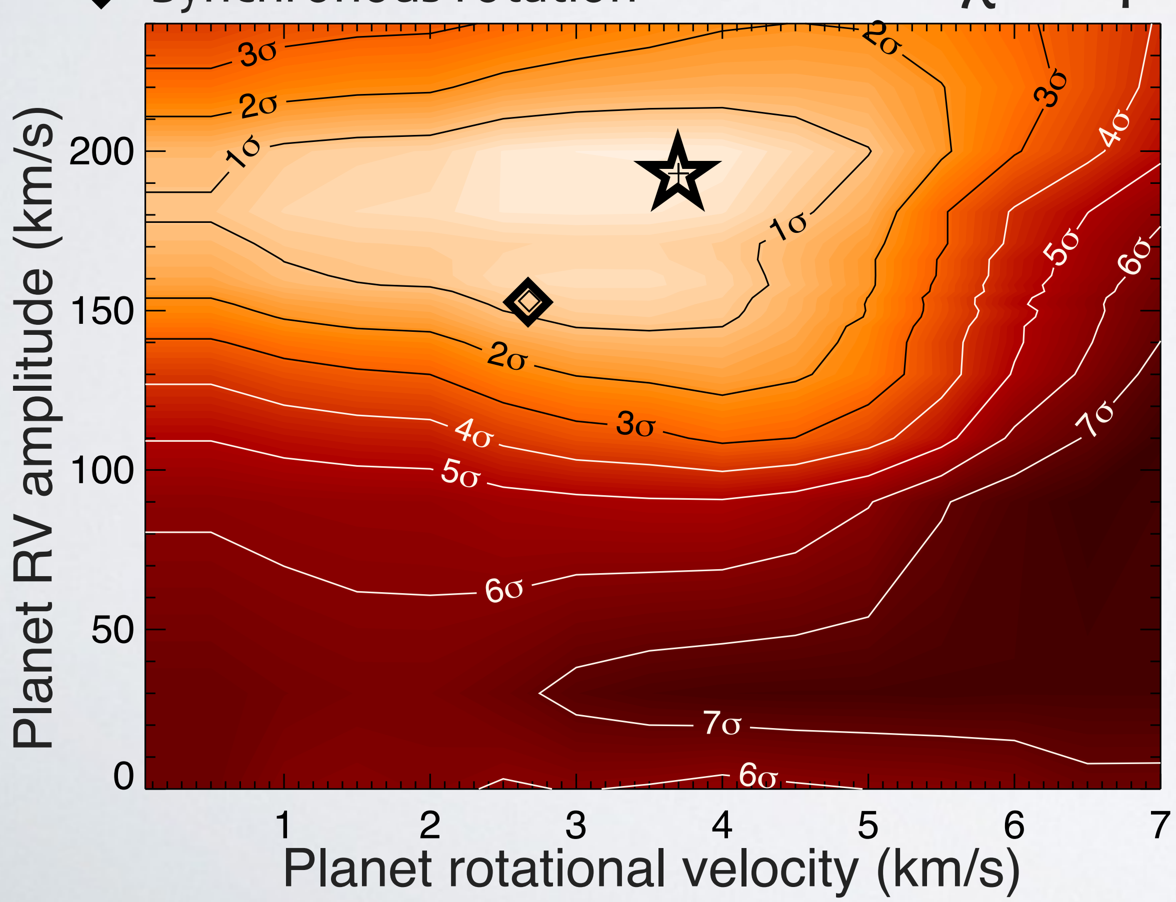
Challenge: CCF is **not** the true planet profile

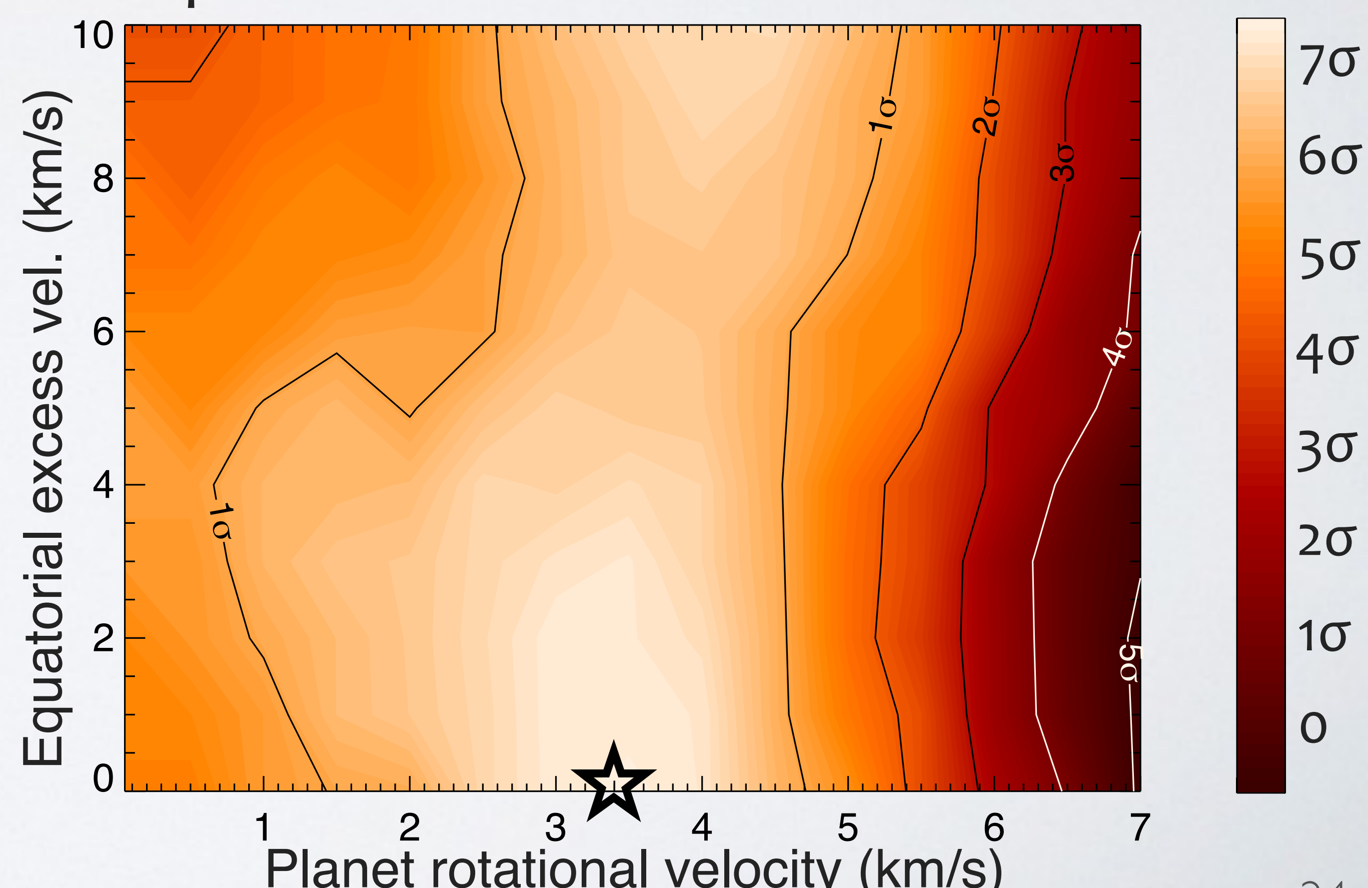


Best-fit value

Synchronous rotation

Full χ^2 maps of fitted parameters





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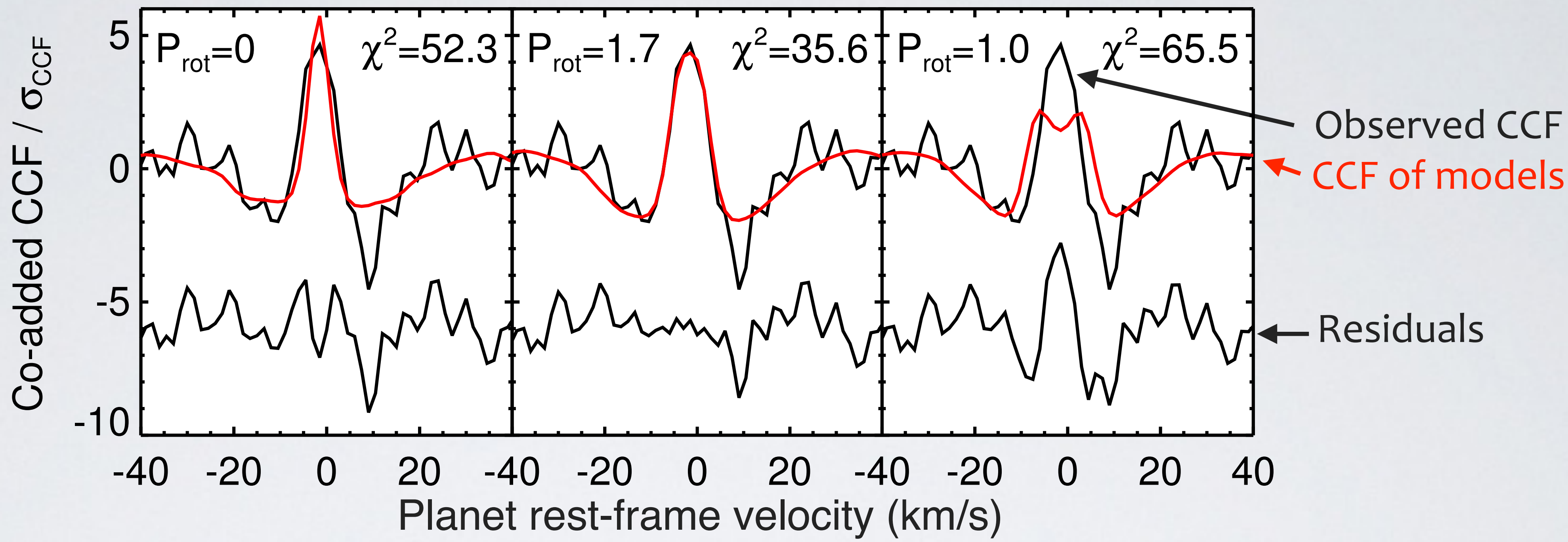

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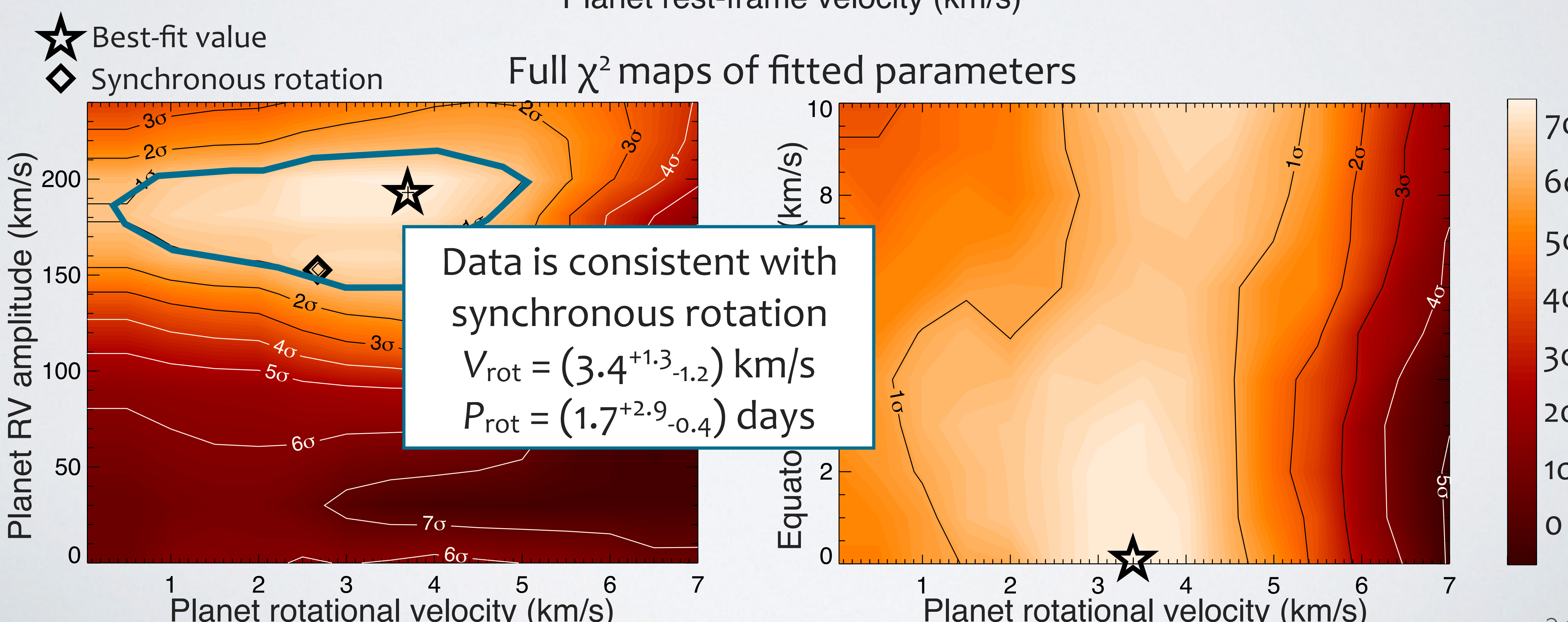

Data is consistent with synchronous rotation

$V_{rot} = (3.4^{+1.3}_{-1.2})$ km/s

$P_{rot} = (1.7^{+2.9}_{-0.4})$ days

Measuring line broadening from the CCF

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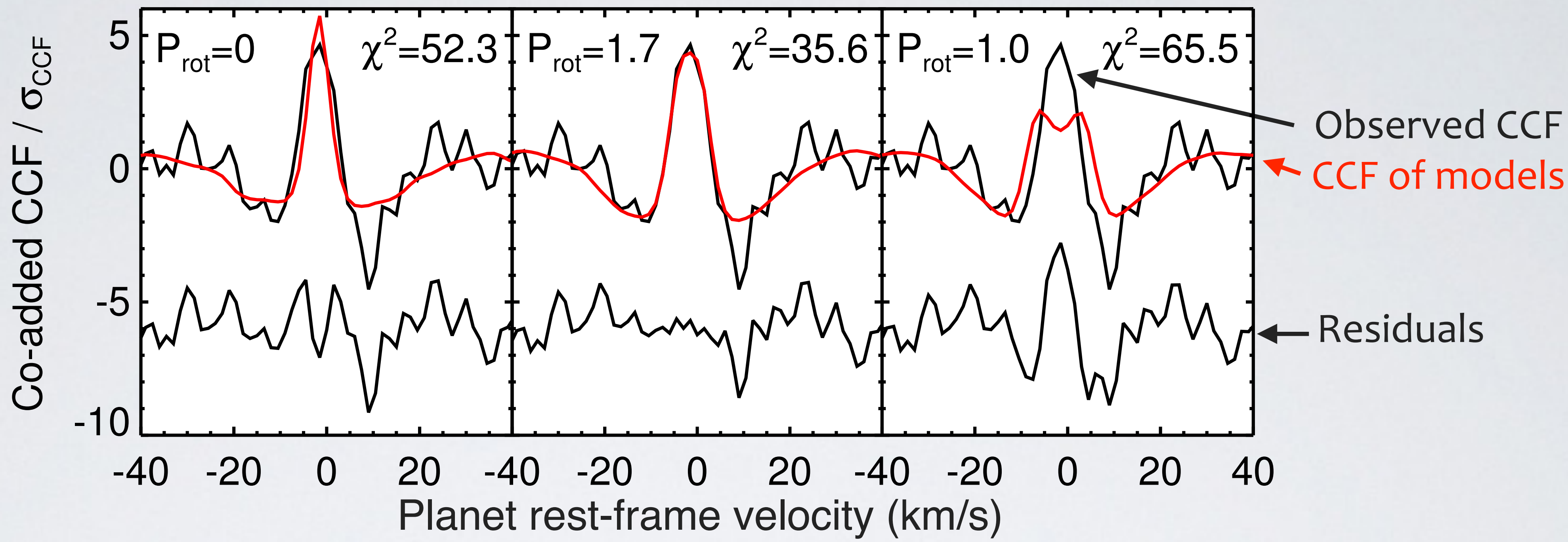

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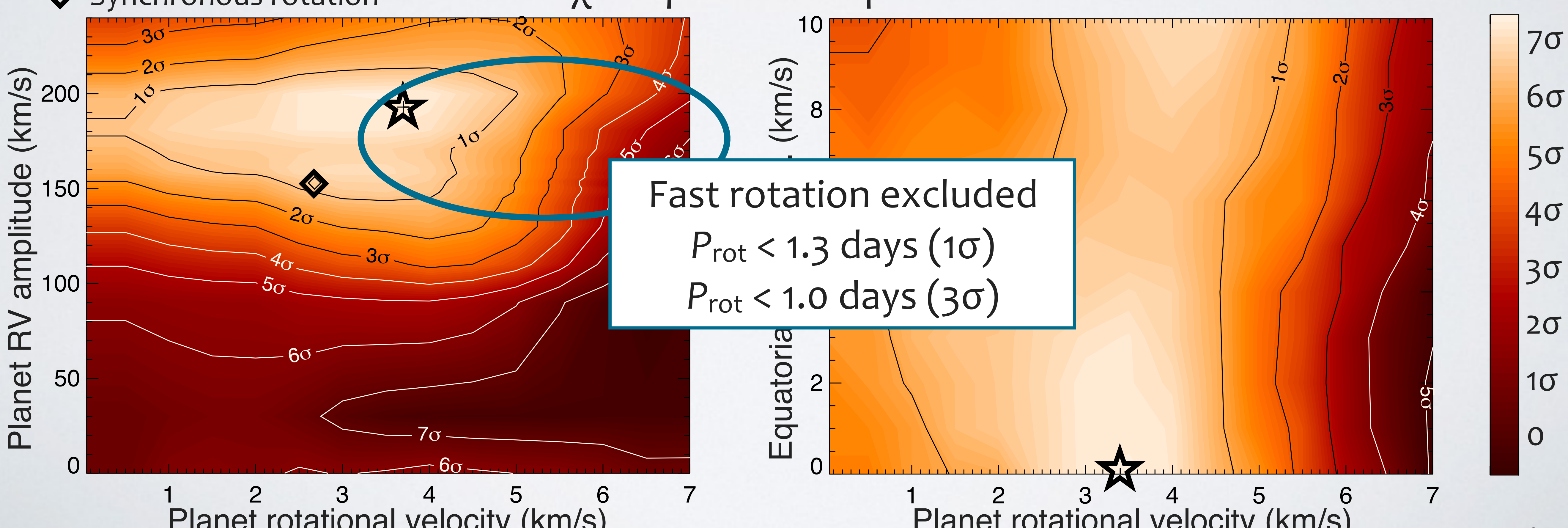


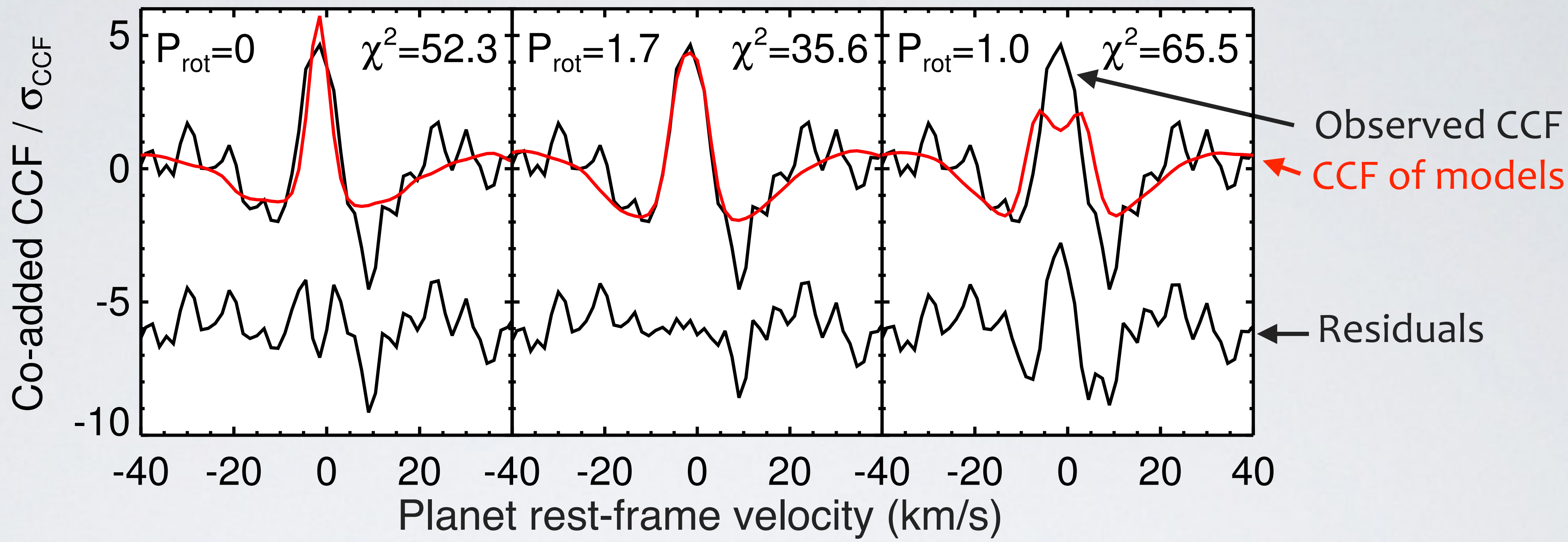
Fast rotation excluded

P_{rot} < 1.3 days (1σ)

P_{rot} < 1.0 days (3σ)

Measuring line broadening from the CCF

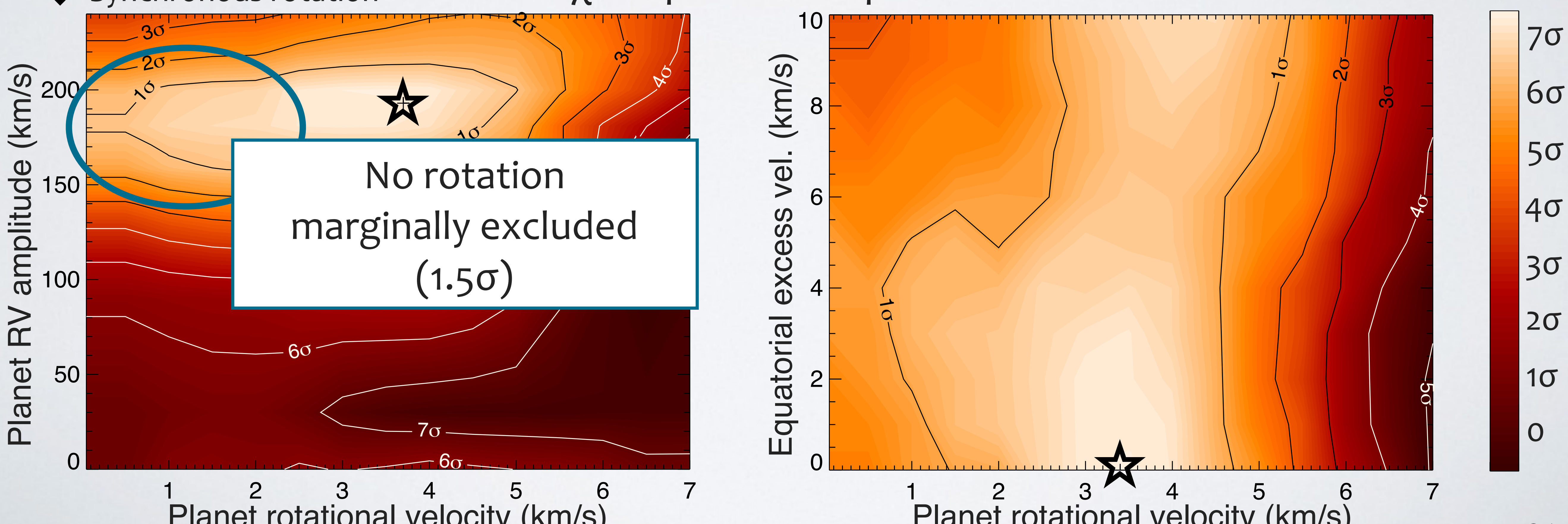
Challenge: CCF is **not** the true planet profile



★ Best-fit value

◇ Synchronous rotation

Full χ^2 maps of fitted parameters



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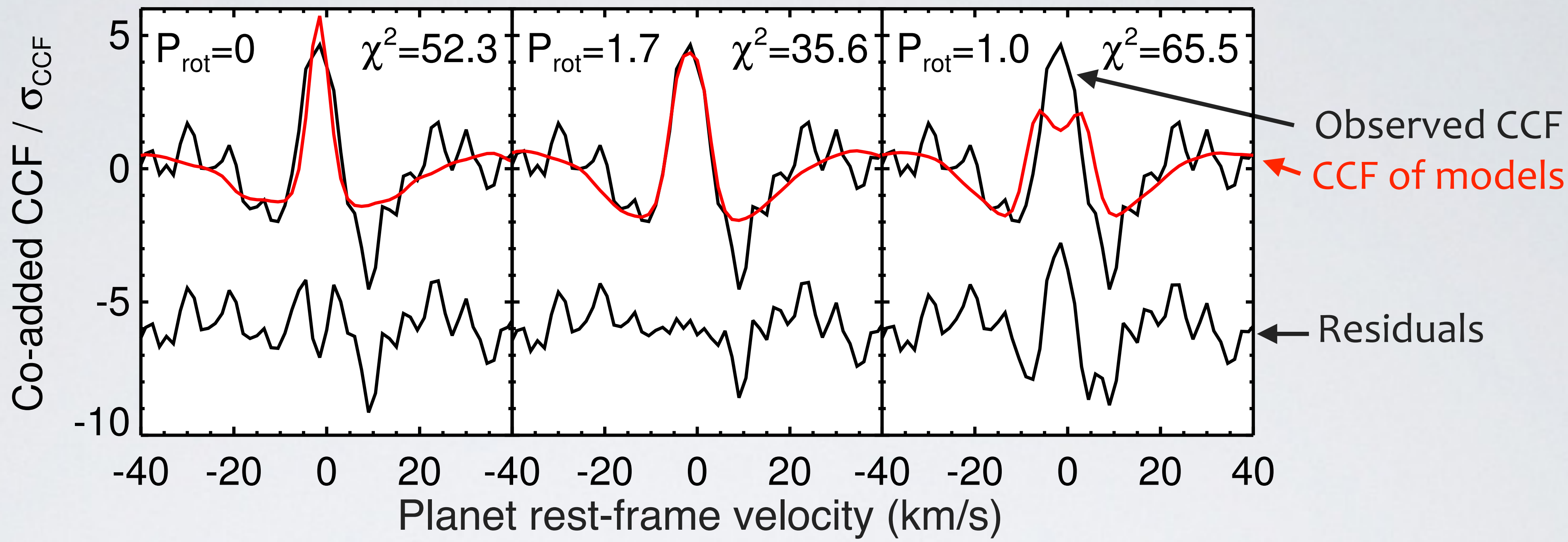

Best-fit value
Synchronous rotation

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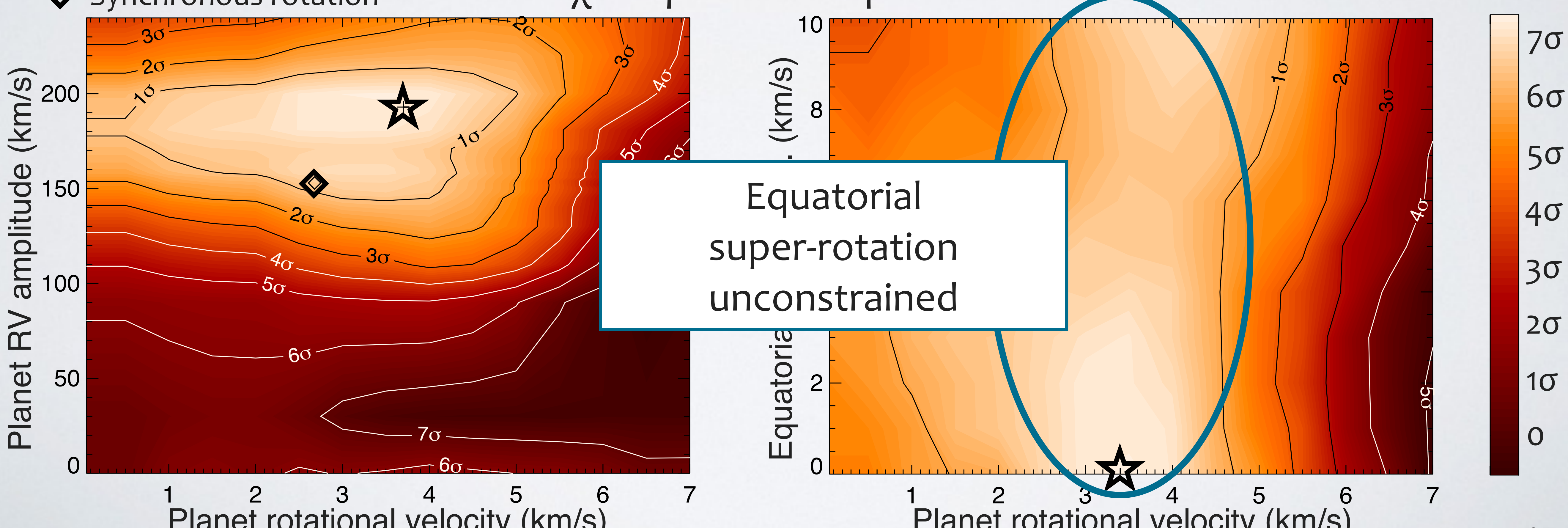
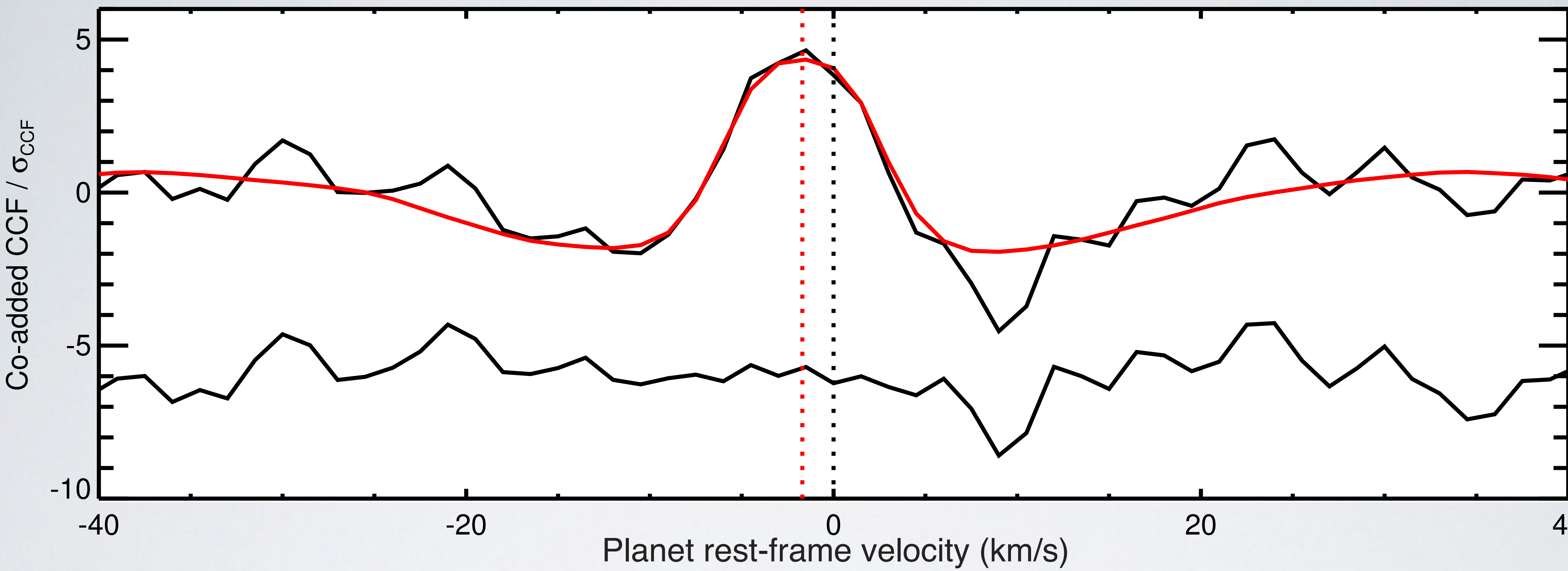


Day-to-night side winds



$$V_{\rm rest} = (-1.7^{+1.1}_{-1.2})\ \mathrm{km/s}$$

Compare with optical high-resolution transmission spectra (Na doublet)

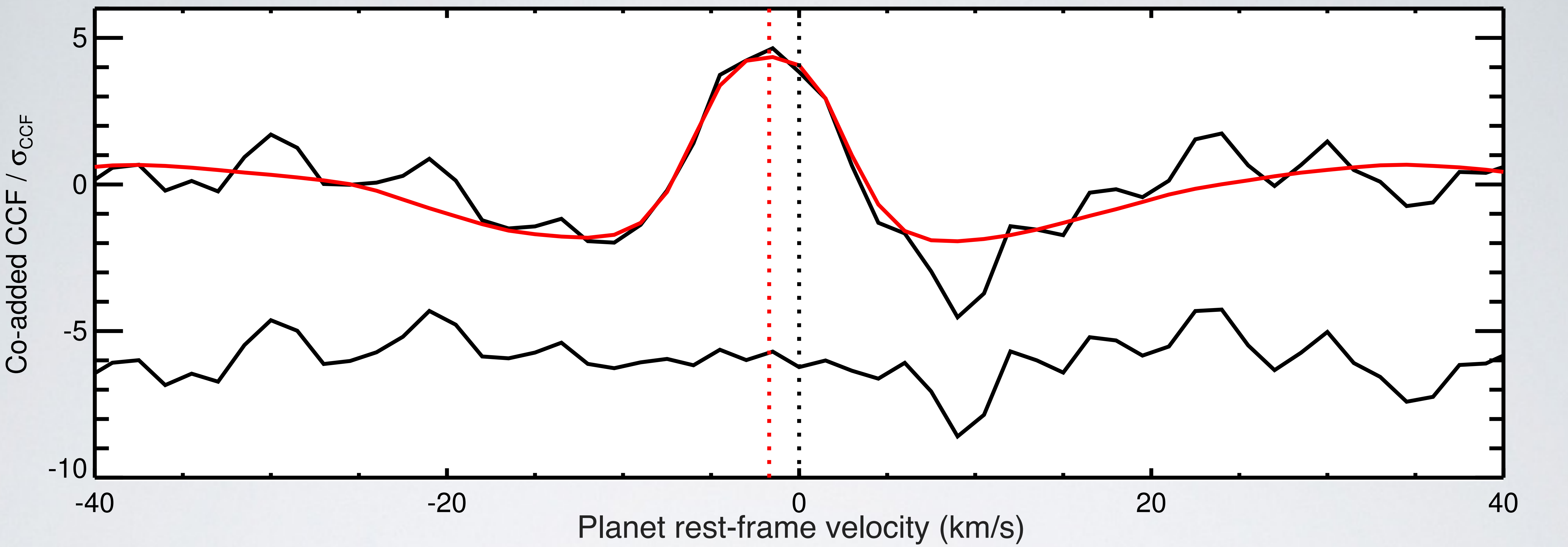
Wyttenbach+ (2015)

$V_{\rm rest} = (-8\pm2)\ \mathrm{km\ s^{-1}}$

Louden+ (2015)

$V_{\rm rest} = (-1.9^{+0.7}_{-0.6})\ \mathrm{km\ s^{-1}}$

Day-to-night side winds



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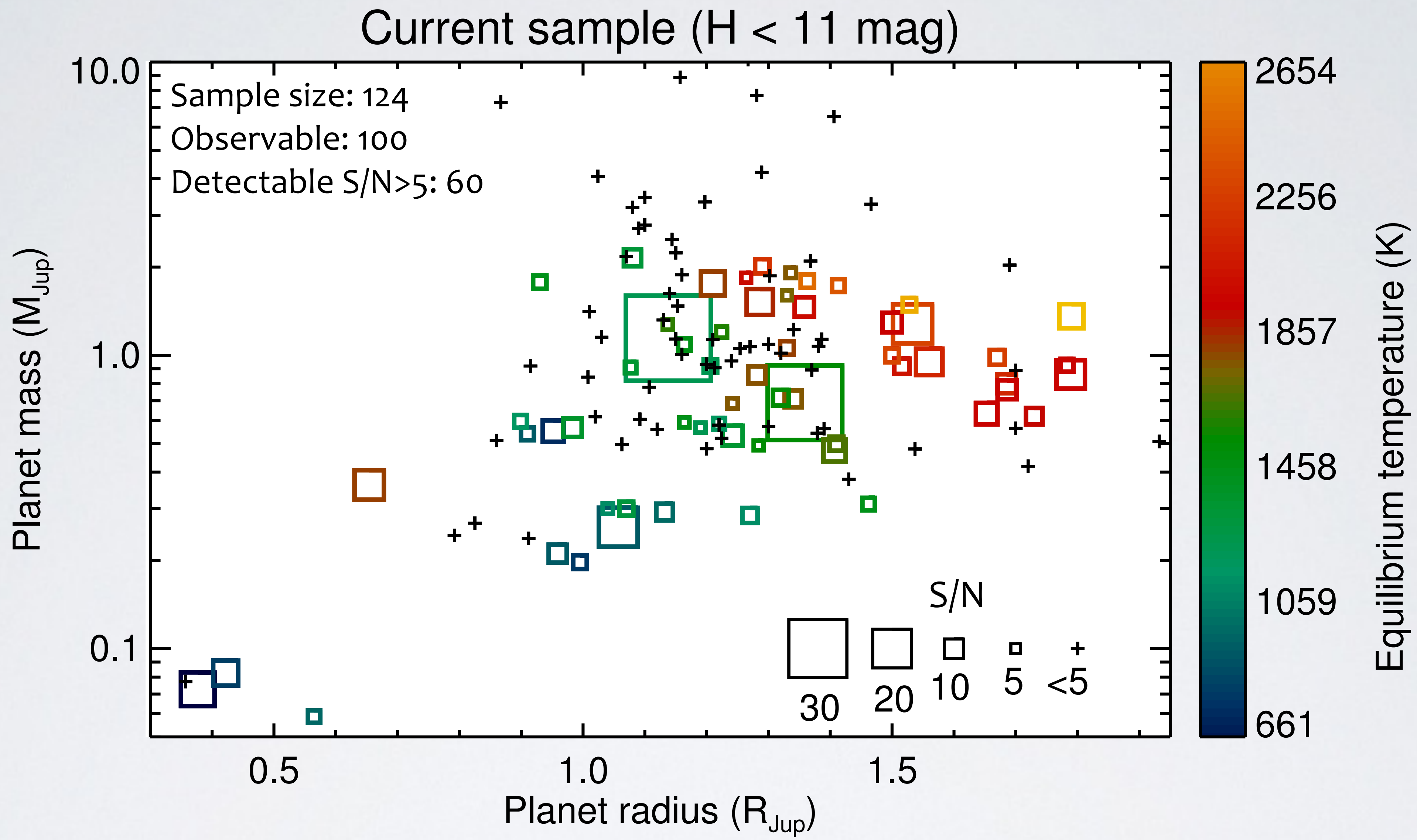
$V_{rest} = (-8 \pm 2)$ km s^{-1}

Louden+ (2015)
$V_{rest} = (-1.9^{+0.7}_{-0.6})$ km s^{-1}

NB: Our data constrains *independently* orbital, rotational, and wind velocity!

Targeting smaller and fainter planets

Brogi+ in prep.



Sample: H < 11 mag, M_P > 0.05 M_{Jup}, R_P > 0.35 R_{Jup}

Simulations: APO 2.5m + Apogee (R=22,500, full H band)

Spectrum: 1.5-1.7µm, H2O spectrum for HD 189733 b, scaled by: scale height, planet/star radius, host-star H-band magnitude

Trading mirror size for better spectrographs

Apogee@APO: ~70% S/N of VLT/CRIRES for equal observing time

	VLT	Apogee	SNR (Apogee/VLT)
Mirror size	8.2m	2.5m	0.305
Spectral resolution	100,000	22,500	0.47
Spectral range	50 nm	190 nm	1.9
Throughput	2.0-2.5%	~15%	2.6
Total			**0.71**

Detection estimated by observing a target every time there is a transit

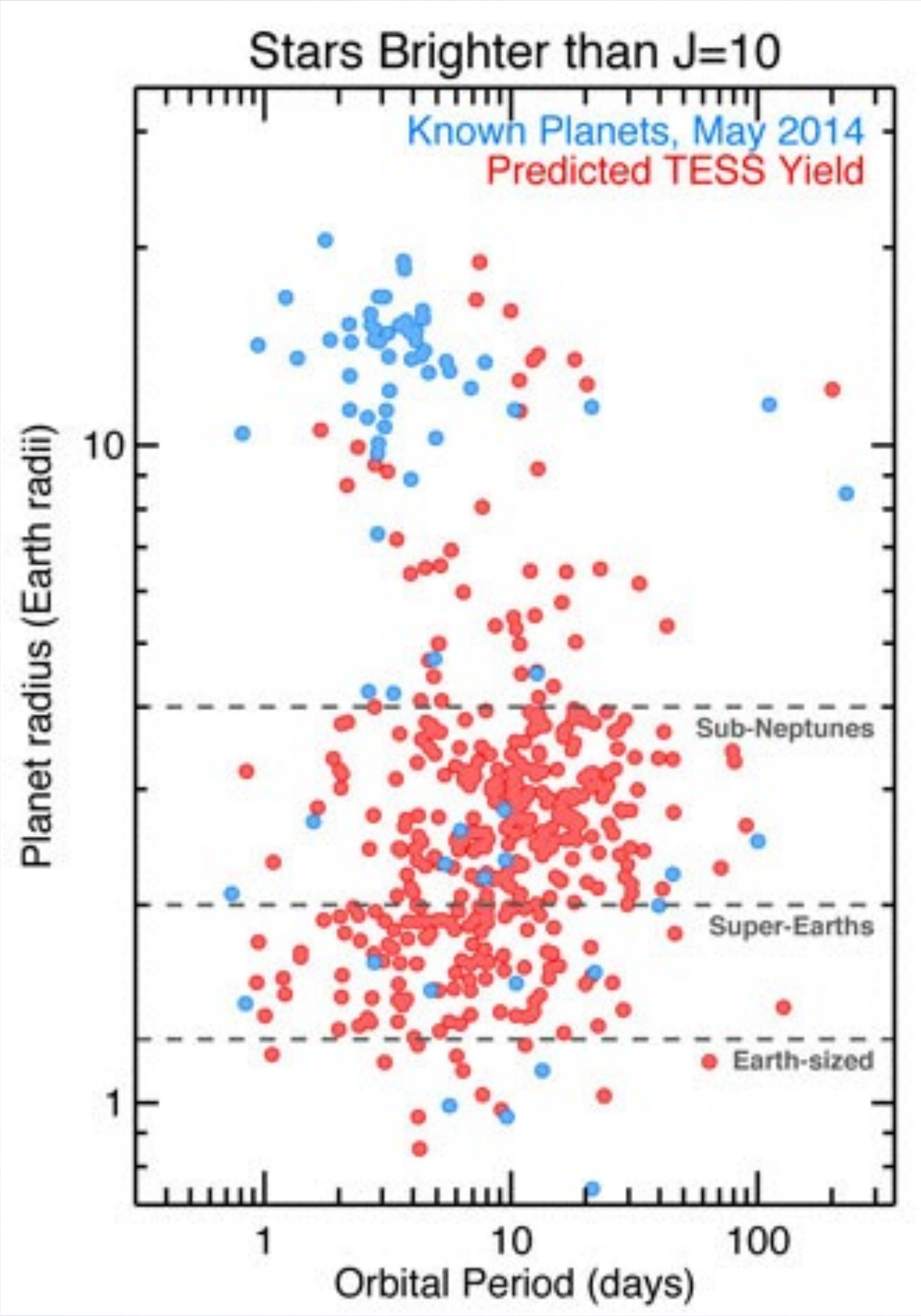
Work in progress

CH_4 and CH_4+H_2O models: relative VMRs

Apply the calculations to the expected yield of **TESS** (Sullivan+ 2015)

Work in progress: HDS in the TESS era

TESS yield from Sullivan+ 2015

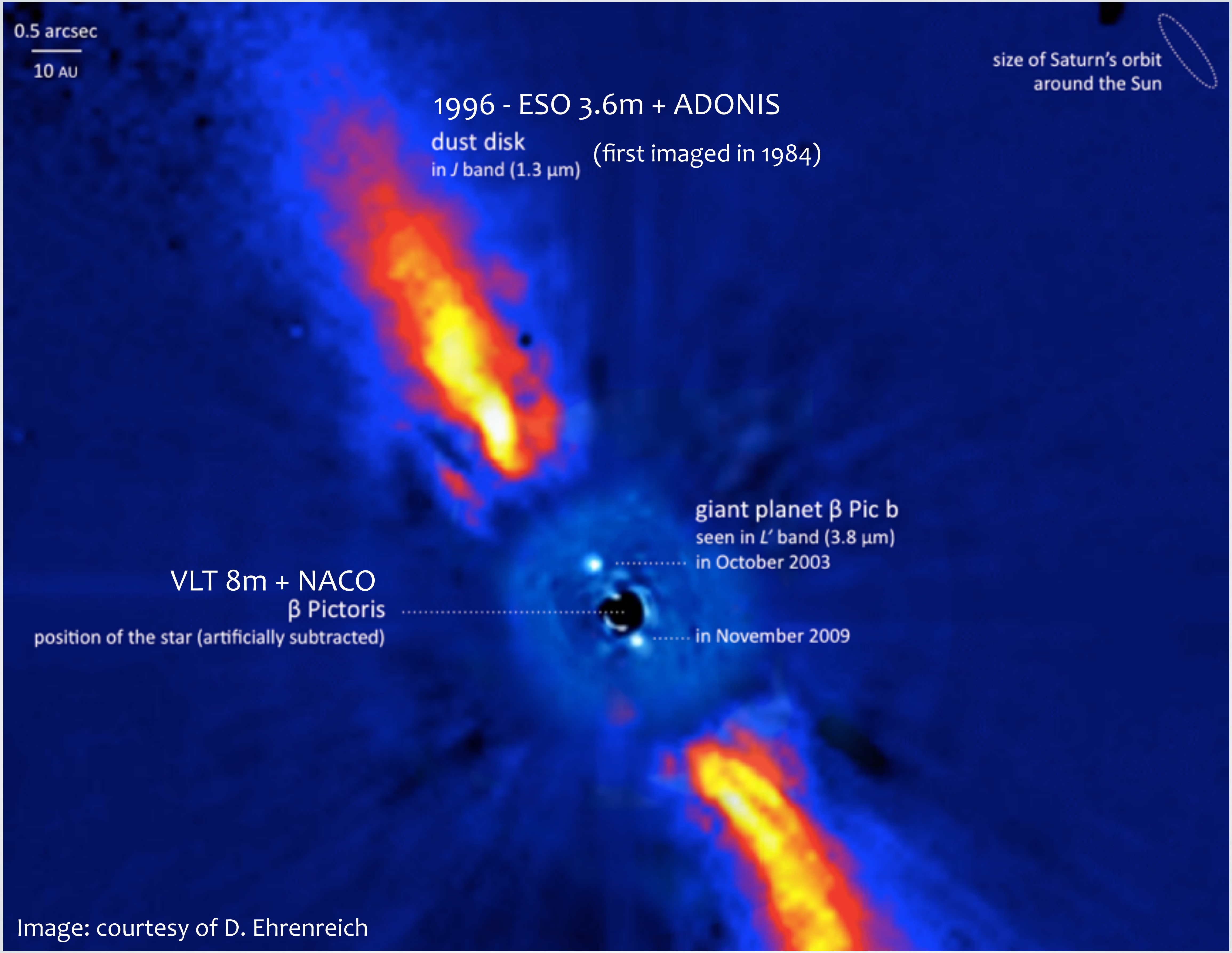


- 250,000 target stars
- 1,700 detections
- 67 $R_P > 4\ R_\oplus$
- 1,100 with $2\ R_\oplus < R_P < 4\ R_\oplus$
- 556 with $R_P < 2\ R_\oplus$:
  419 around M-dwarfs
  137 around FGK stars
  130 brighter than $K = 9$ mag

Adapting the APO simulations to range of spectra for super-Earths

Exploring a range of current and next-generation NIR spectrographs

Spectral and spatial resolution combined: β Pic b



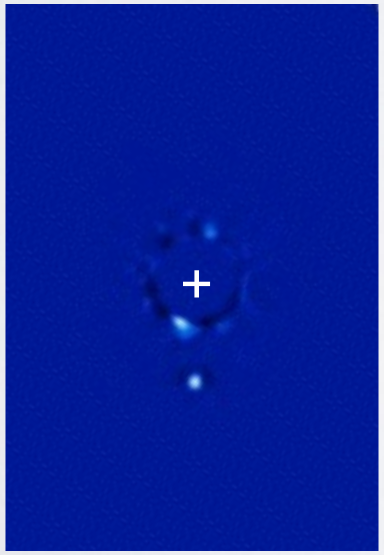
Spectral and spatial resolution combined: β Pic b

Snellen+, *Nature*, 2014

Young exoplanet (12-21 Myr)
0.44" separation (8.8 AU)
2.6×10^{-4} contrast

No change in planet RV during the night
(Combining high-dispersion spectroscopy and high-contrast imaging, Snellen+ 2015)

GPI first light - β Pic b
Macintosh et al. (2014)



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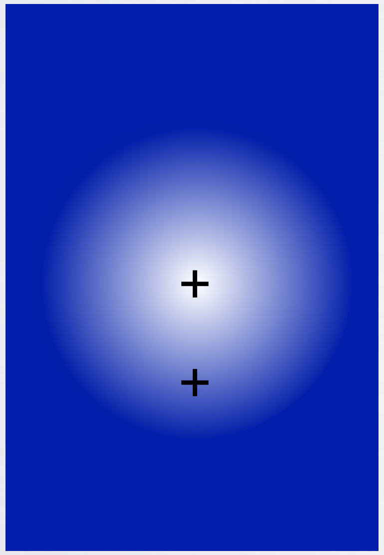
MACAO@VLT
(Simulated)



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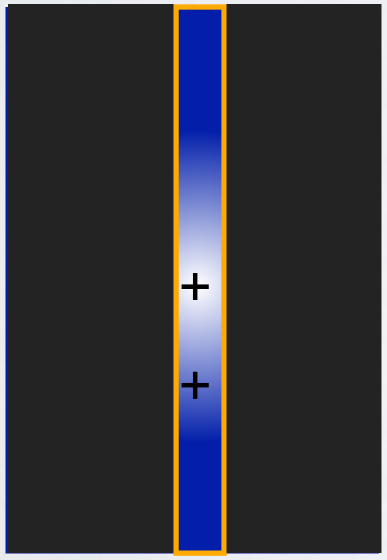

0".2 slit

Spectral and spatial resolution combined: β Pic b

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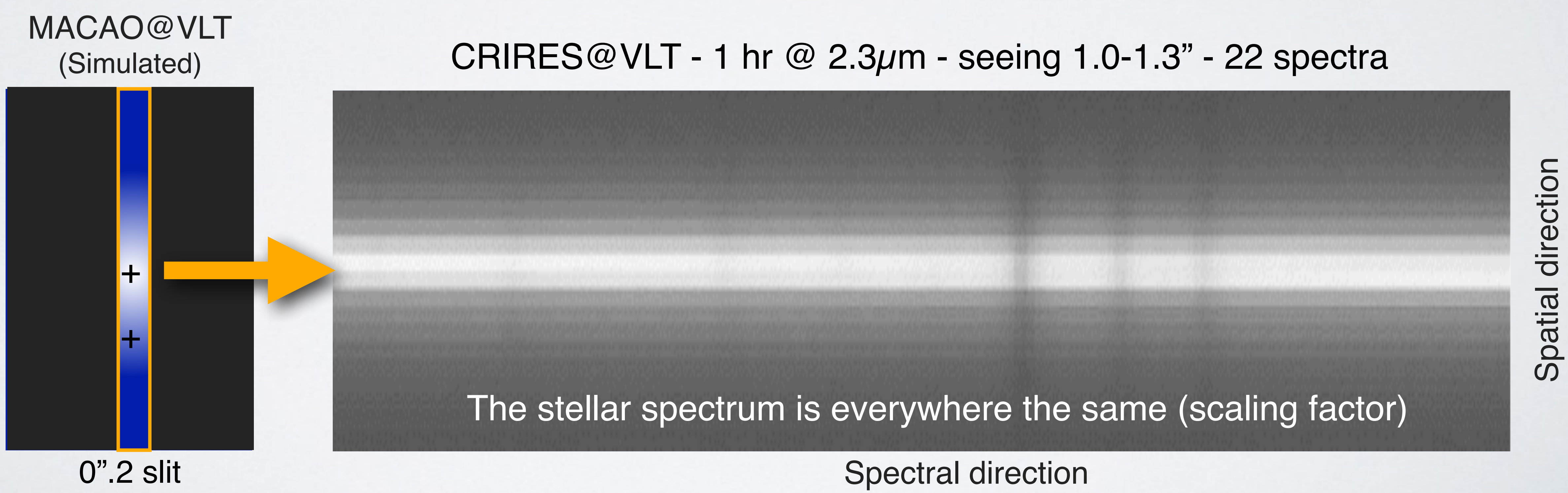

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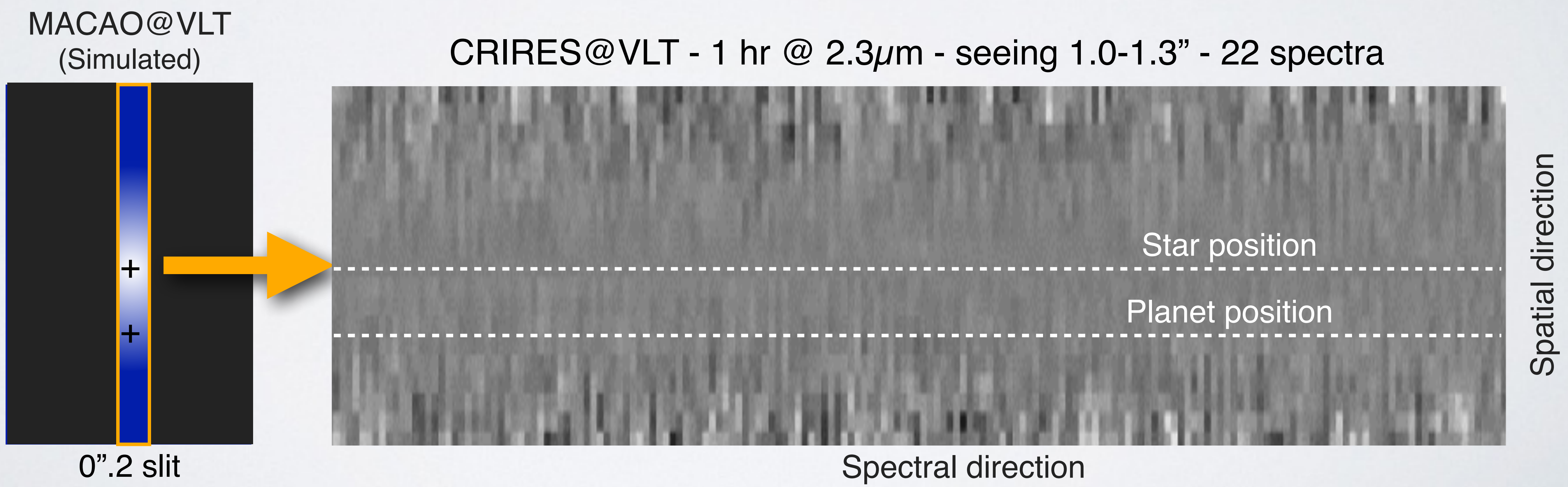
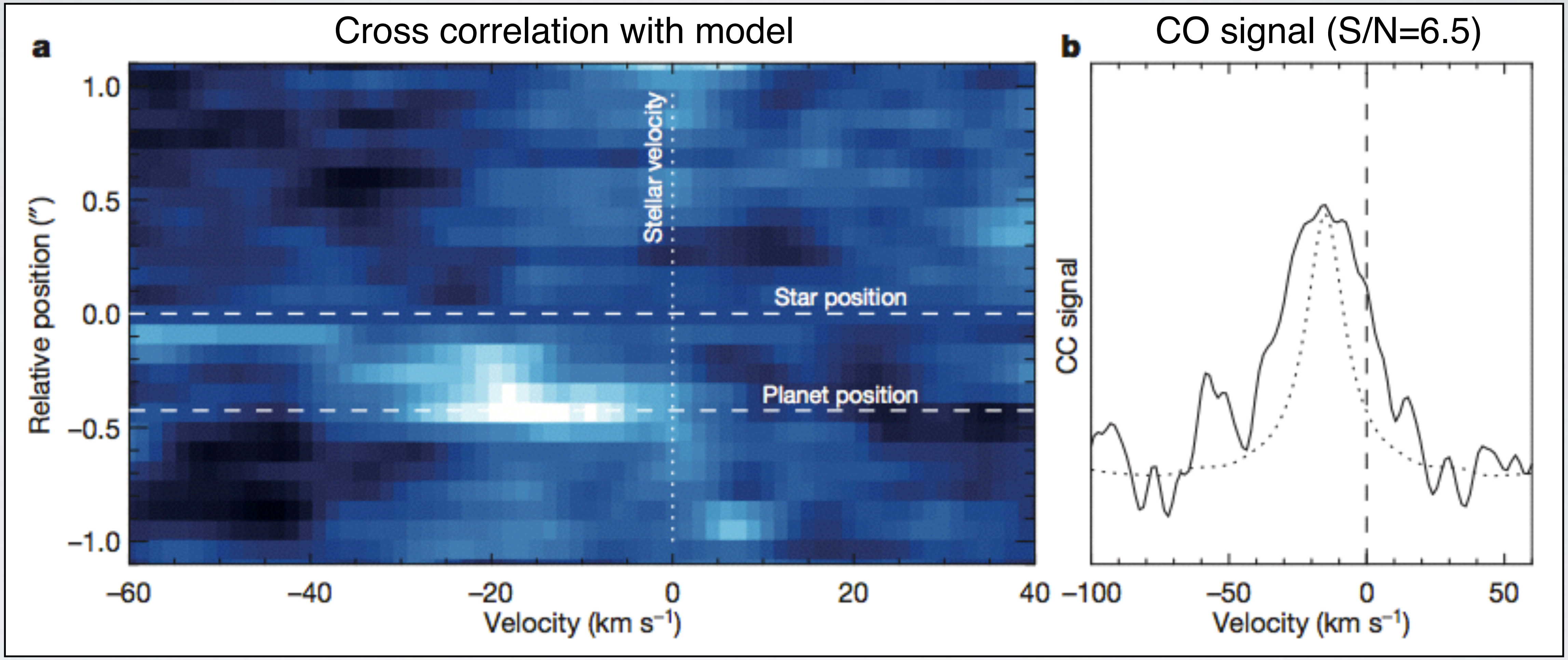


β Pic b rotates in only 8 hours!

Cross-correlation function broadened by 27 km/s



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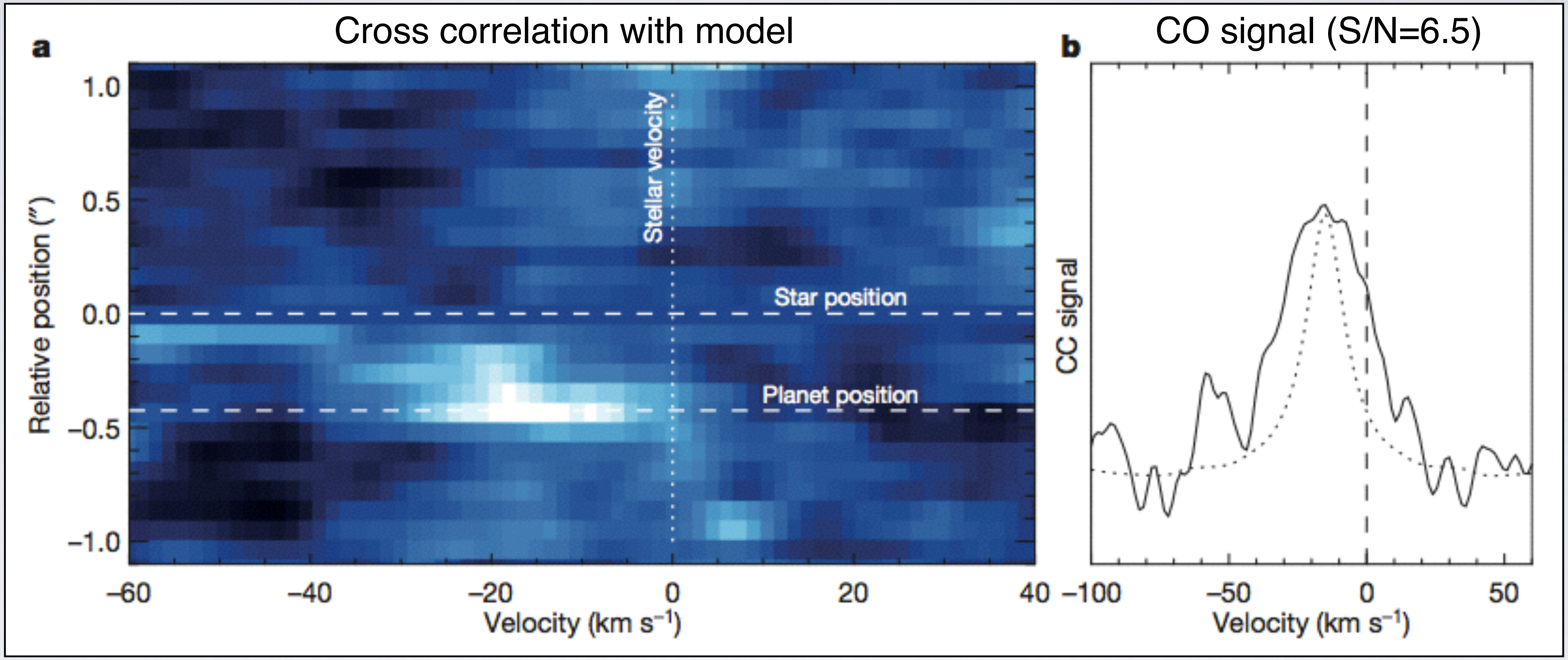


A test for the next decade!

High Contrast Imaging: 10^{-4} planet/star contrast

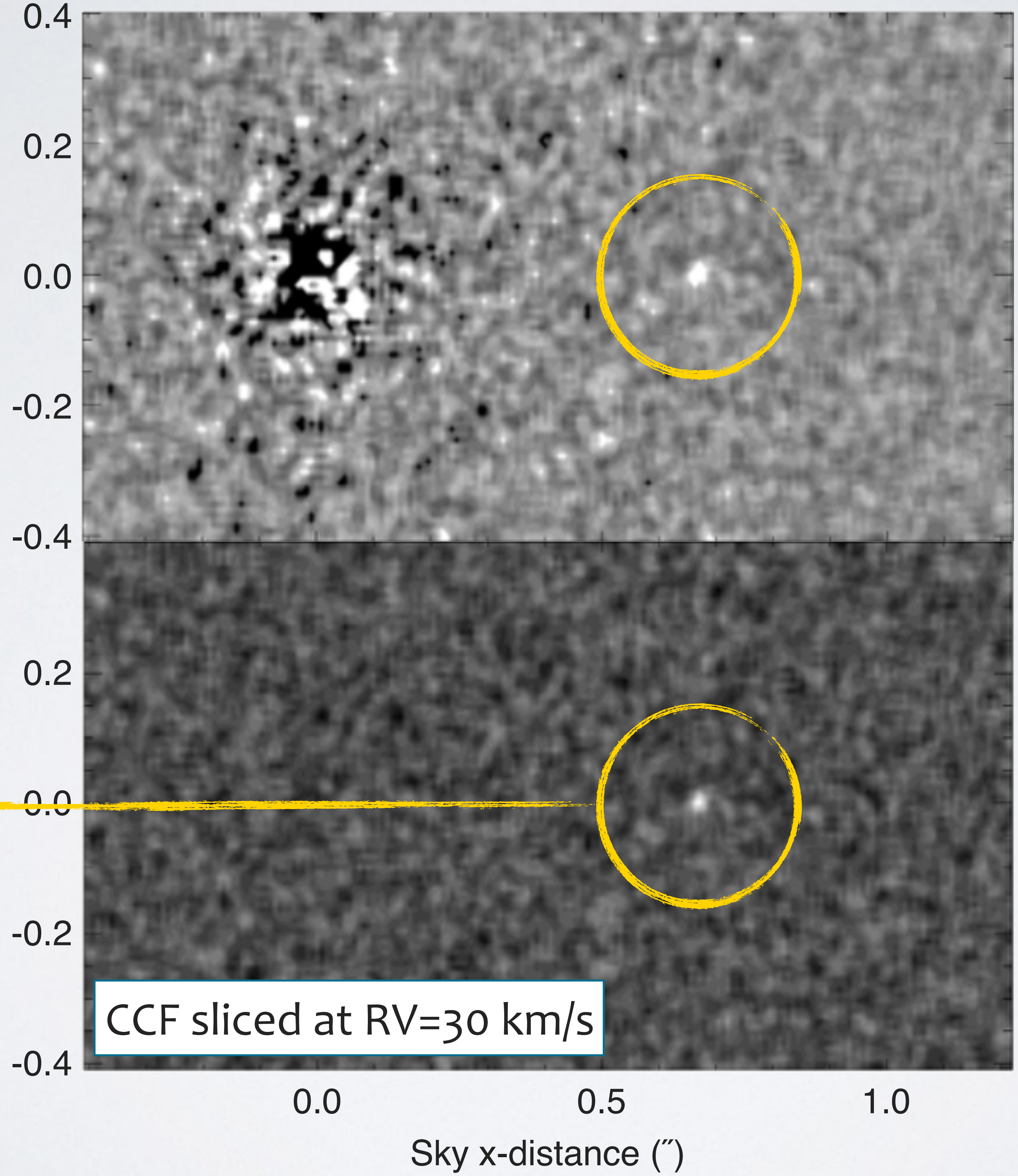
High-Dispersion Spectroscopy: 10^{-5} core/continuum contrast (photon limited)

$\Rightarrow 10^{-9}$ planet/star contrast achievable

Simulating HDS+HCI: Metis @ E-ELT

Earth-like planet ($R=1.5\ R_{\oplus}$, T=300K) orbiting α Cen B (Snellen+ 2015)

39m E-ELT
30 hours
4.85 μm
R=100,000
(IFU)



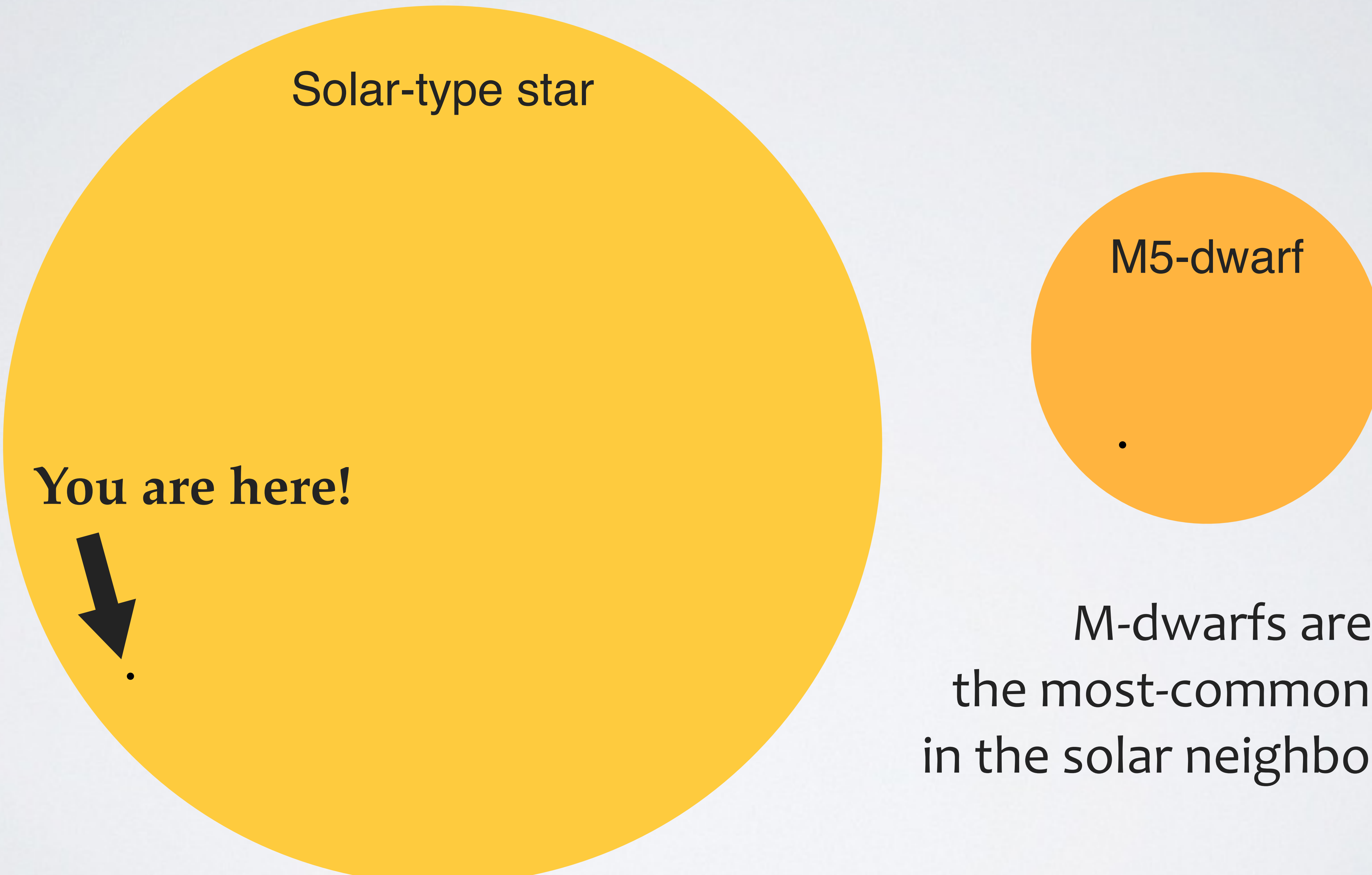
Traditional imaging

8σ (30 hrs)
5σ (10 hrs)

Traditional imaging
+
Integral field,
hi-res spectroscopy

Terrestrial planets around dwarf stars

The planet/star contrast increases for smaller stars



M-dwarfs are
the most-common stars
in the solar neighborhood!

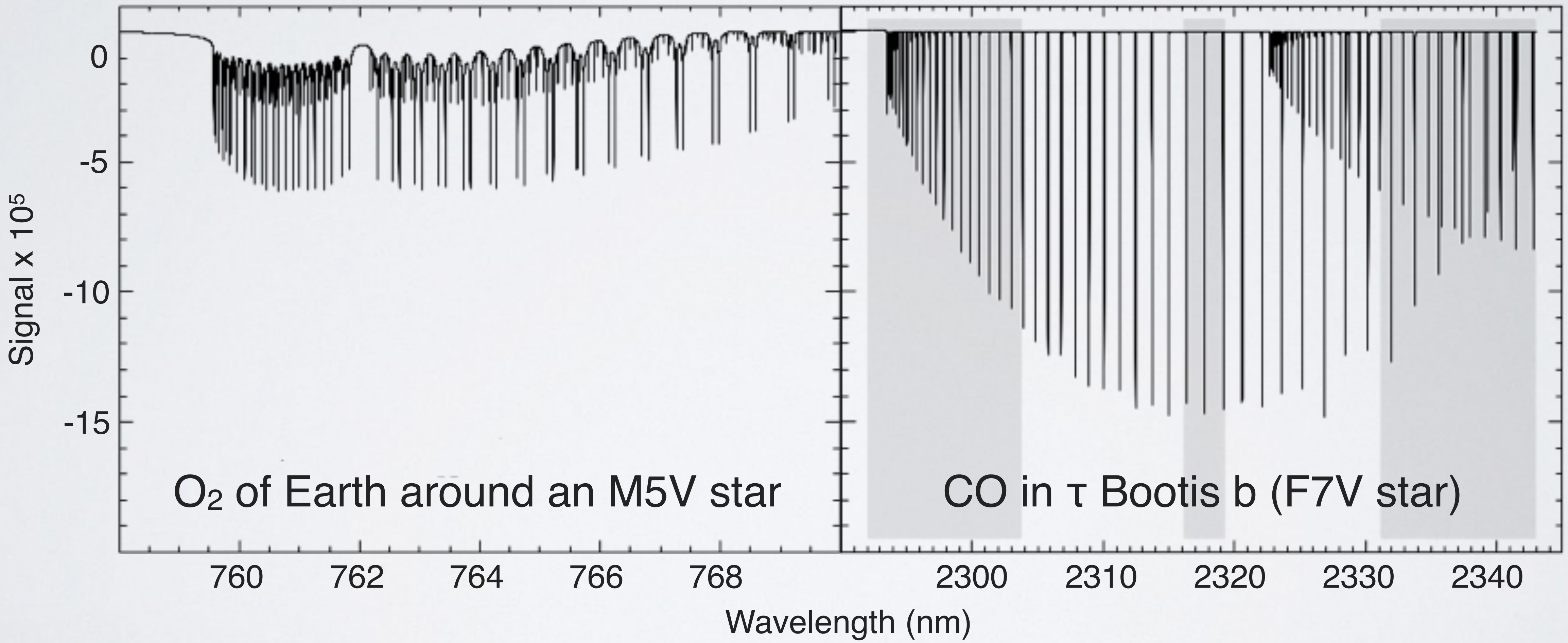
Transiting terrestrial planets around M-dwarfs

O_2 in transmission

Earth-size planets orbiting **M-dwarfs**

1/3 of the dayside signal from τ Boo b

Challenge: I = 10-11 mag (M-dwarf) vs. *K* = 3.4 mag (τ Boo)



Extremely Large Telescopes + Hi-res spectroscopy

39m E-ELT, 30 transits (3 years) ⇒ 5σ detection!

Conclusions

High-resolution transmission spectroscopy
can characterize exoplanets

- Robust **molecular detections**
- **Masses, inclinations** of non-transiting planets

- **Winds** and planet **rotation**
- Inversion layers
- Relative molecular **abundances** and **C/O ratio**

- Can be combined with direct imaging
- Ideal to complement JWST in following-up TESS targets
- Potentially suitable for targeting rocky planets in HZ of M-dwarfs!