Exoplanet atmospheres
at high spectral resolution

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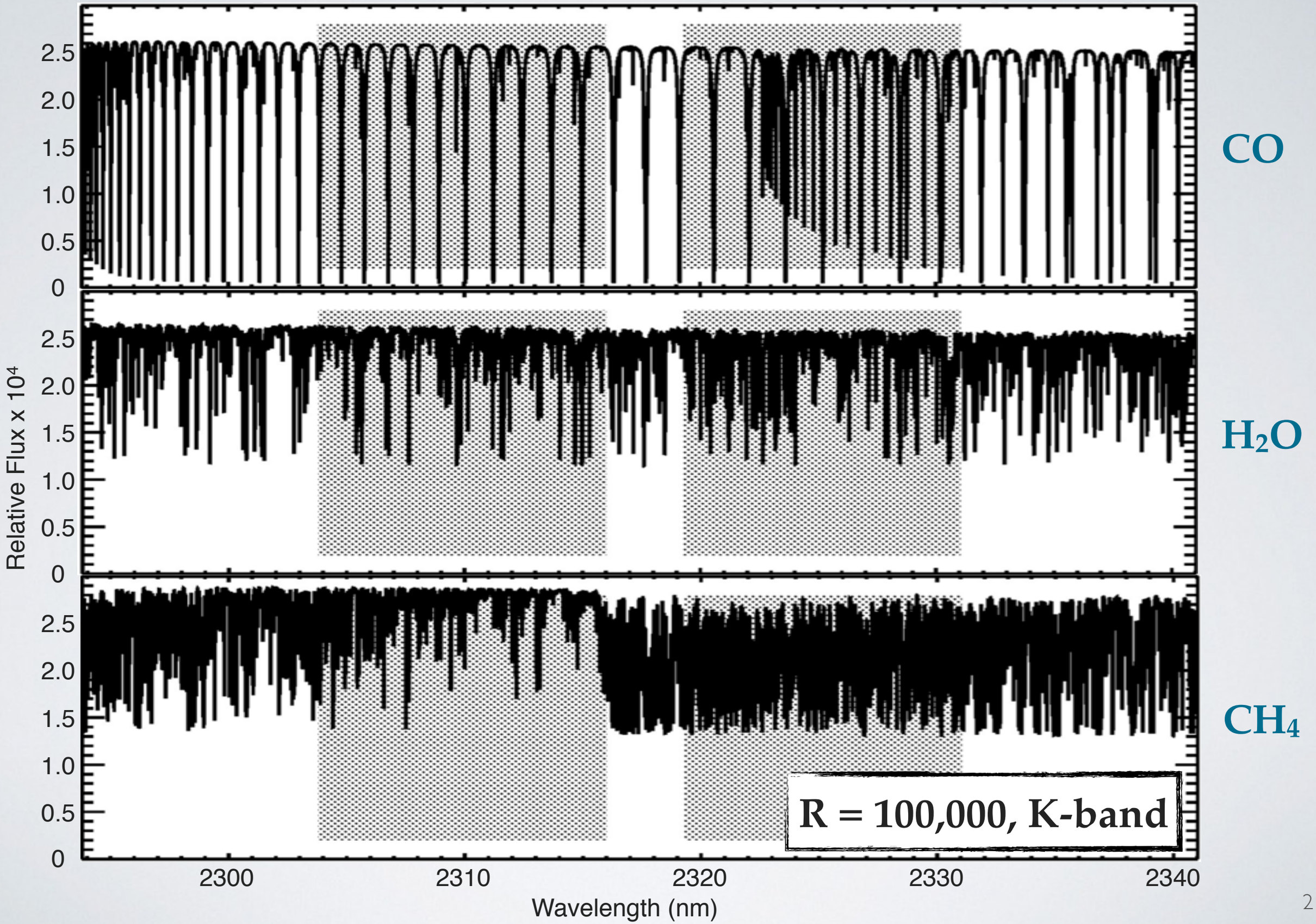
S. Albrecht (Aarhus)
J.-M. Désert (CU-Boulder)

July 3, 2015
From Super-Earths to Brown Dwarfs: Who is Who?
IAP, Paris

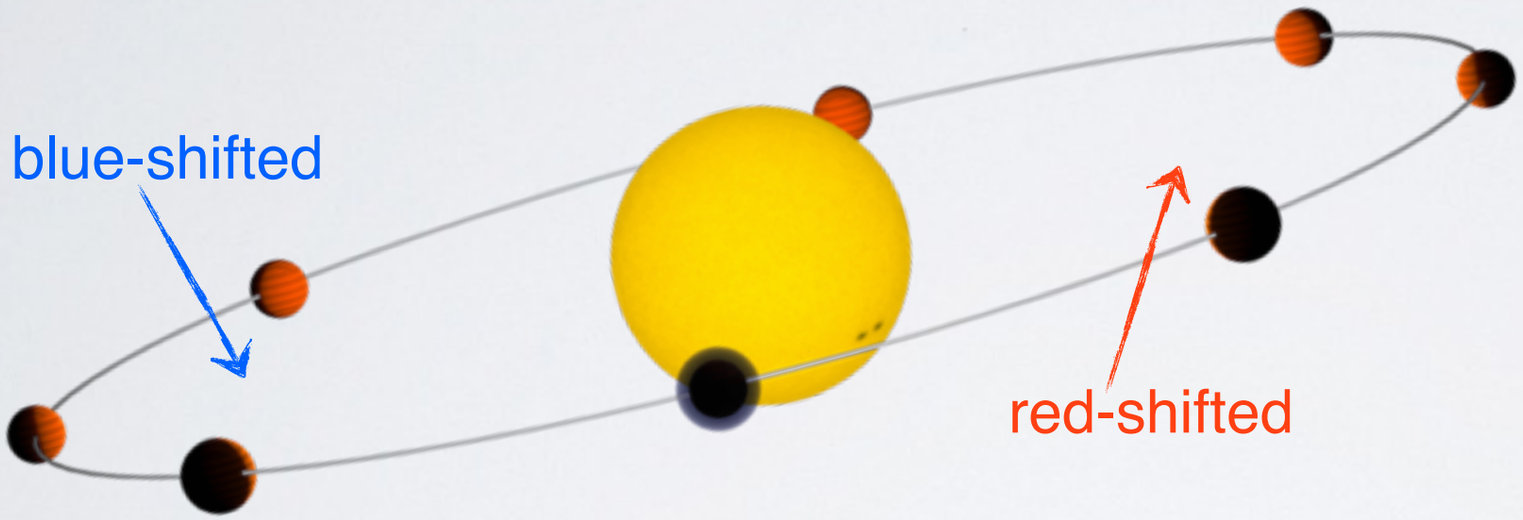
Molecular fingerprints at high-res

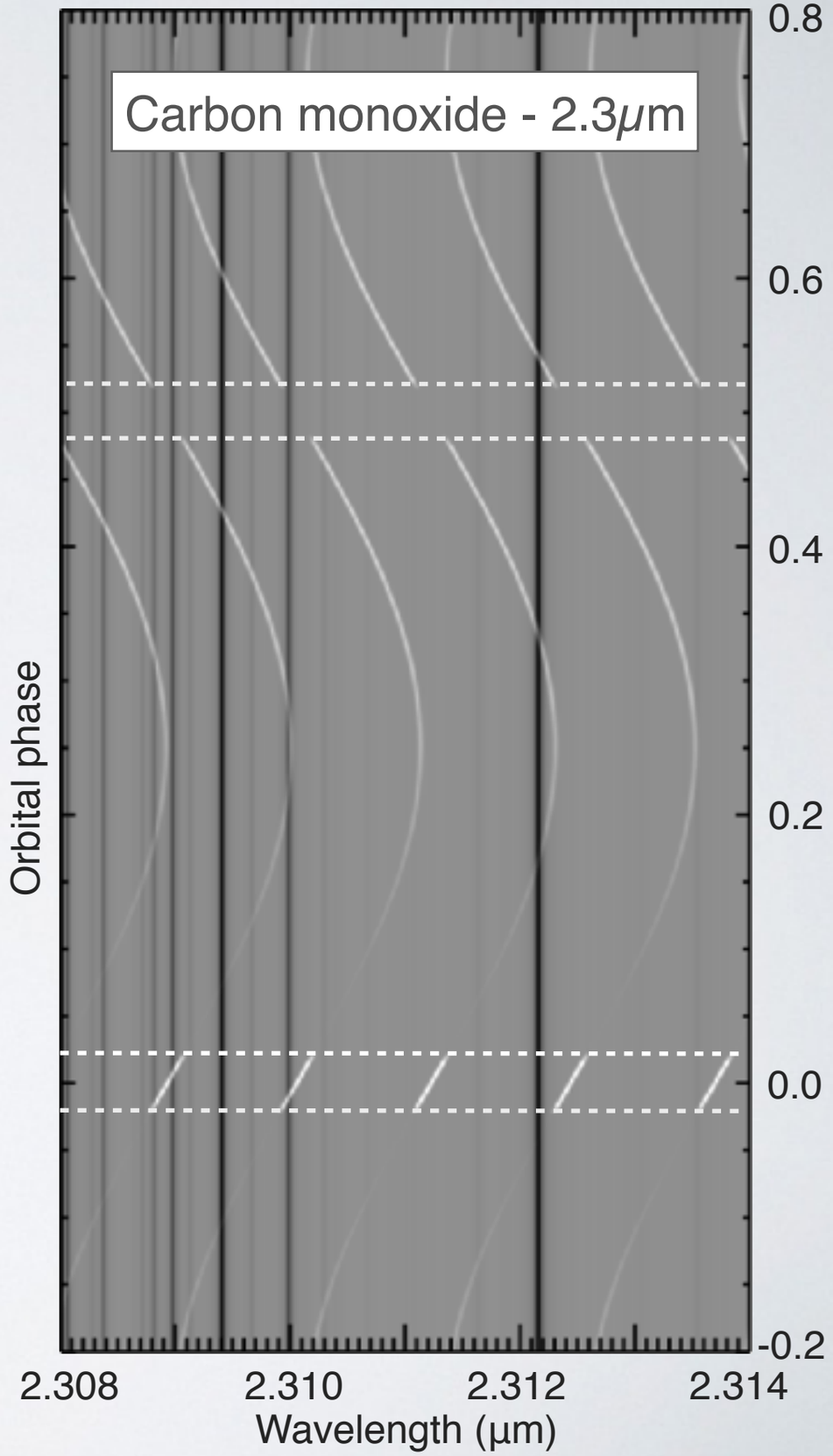


Exoplanets at high-spectral resolution

R = 100,000
Near InfraRed (J- to L-band)

Molecules resolved into **individual lines**
⇒ Robust identification via line matching





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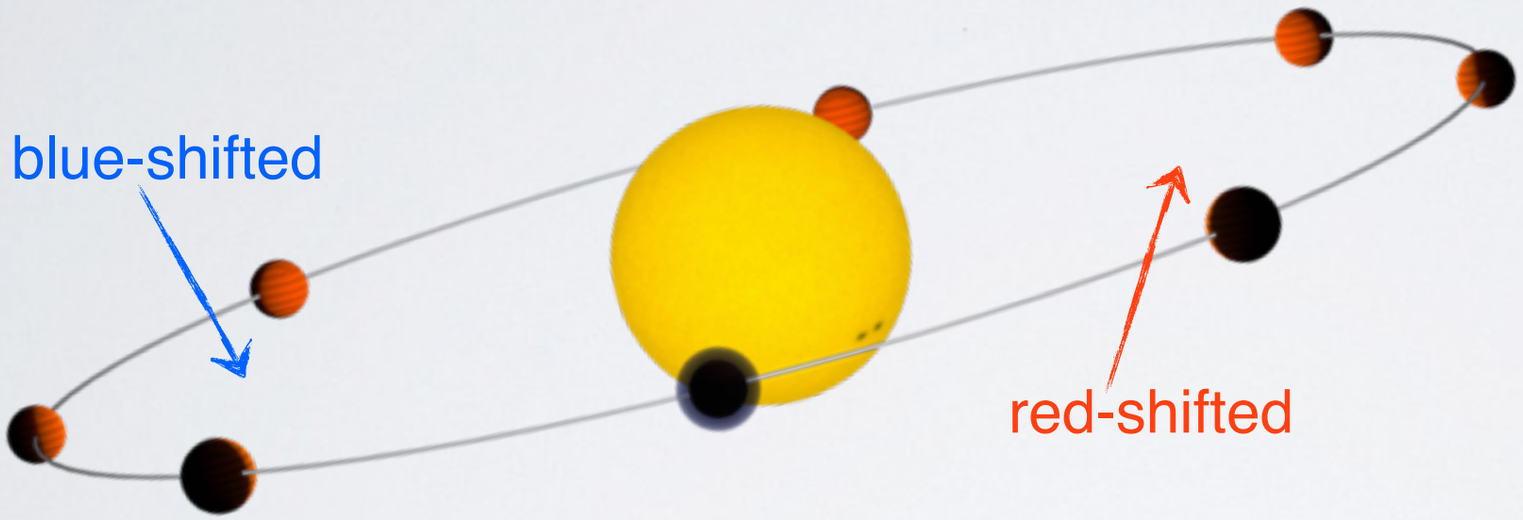
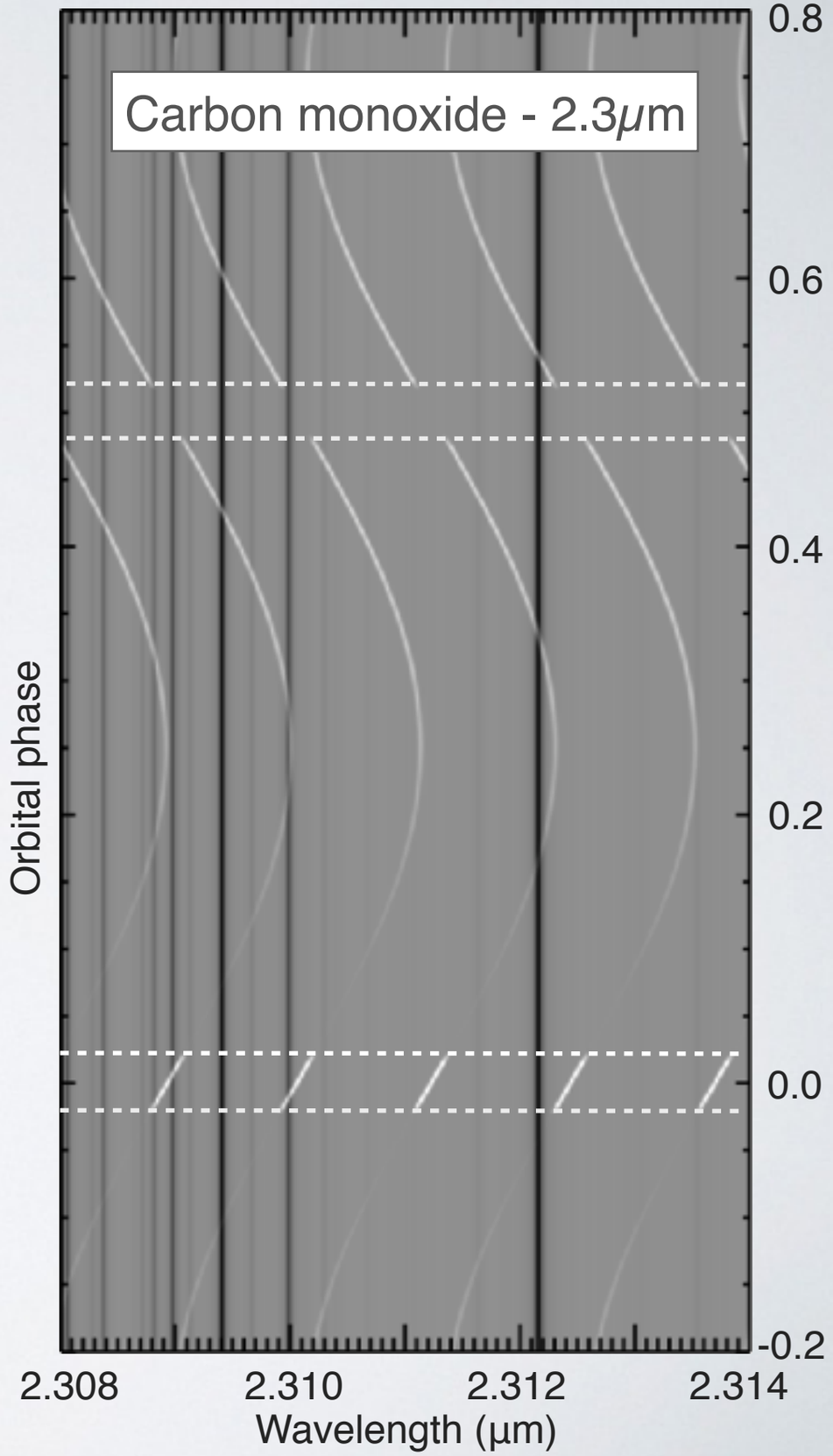


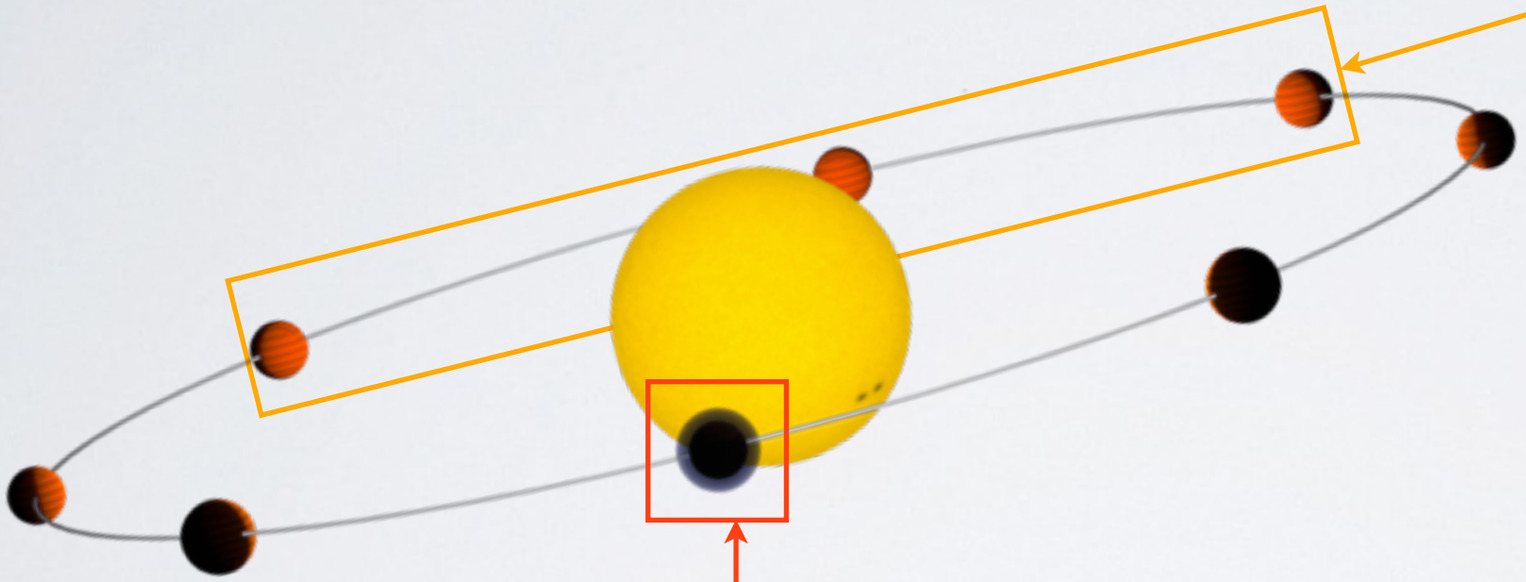
Planet motion resolved
⇒ Telluric and planet signal disentangled
⇒ Planet radial velocity can be measured

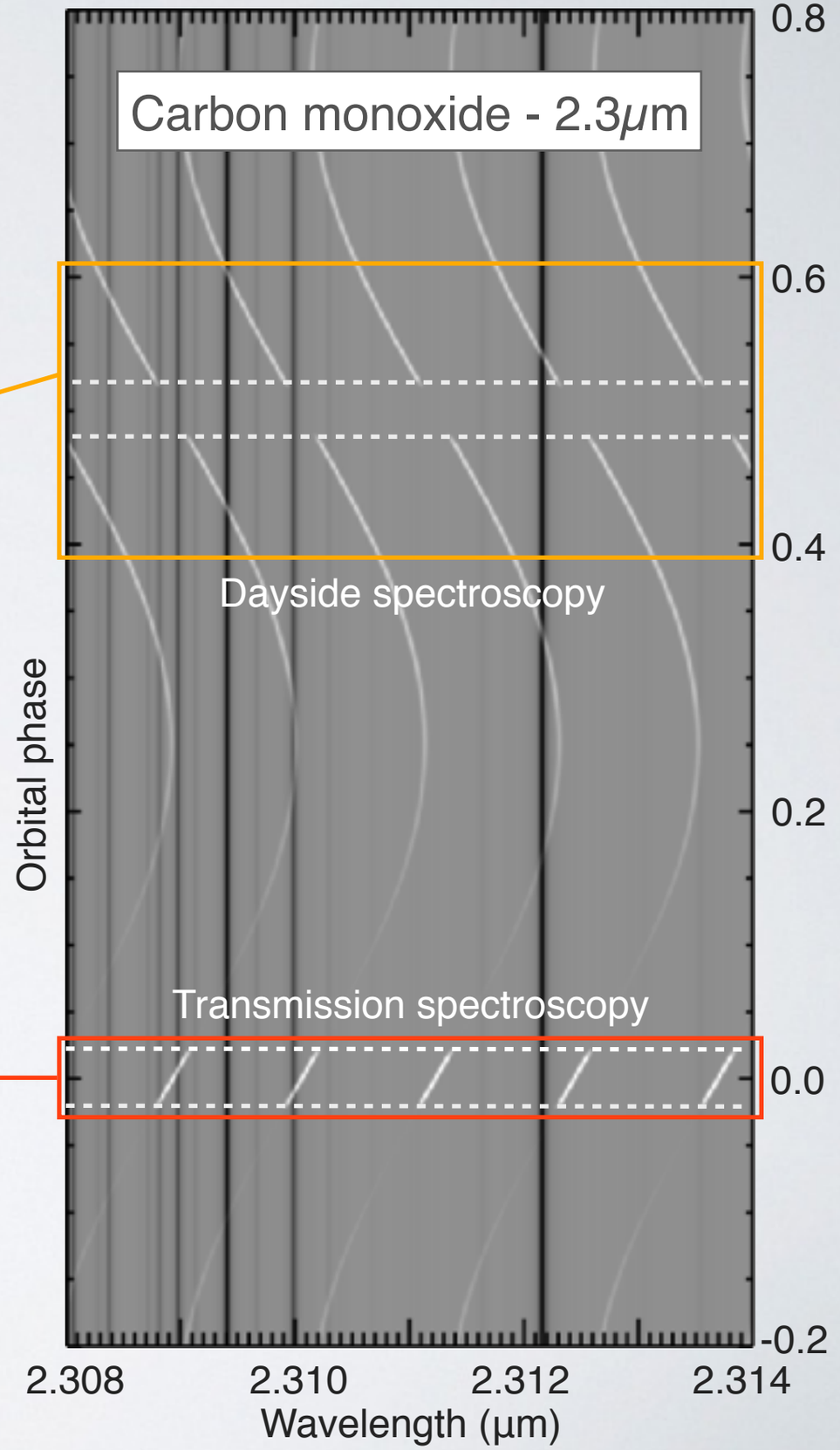


Exoplanets at high-spectral resolution

Transiting planets are observable:

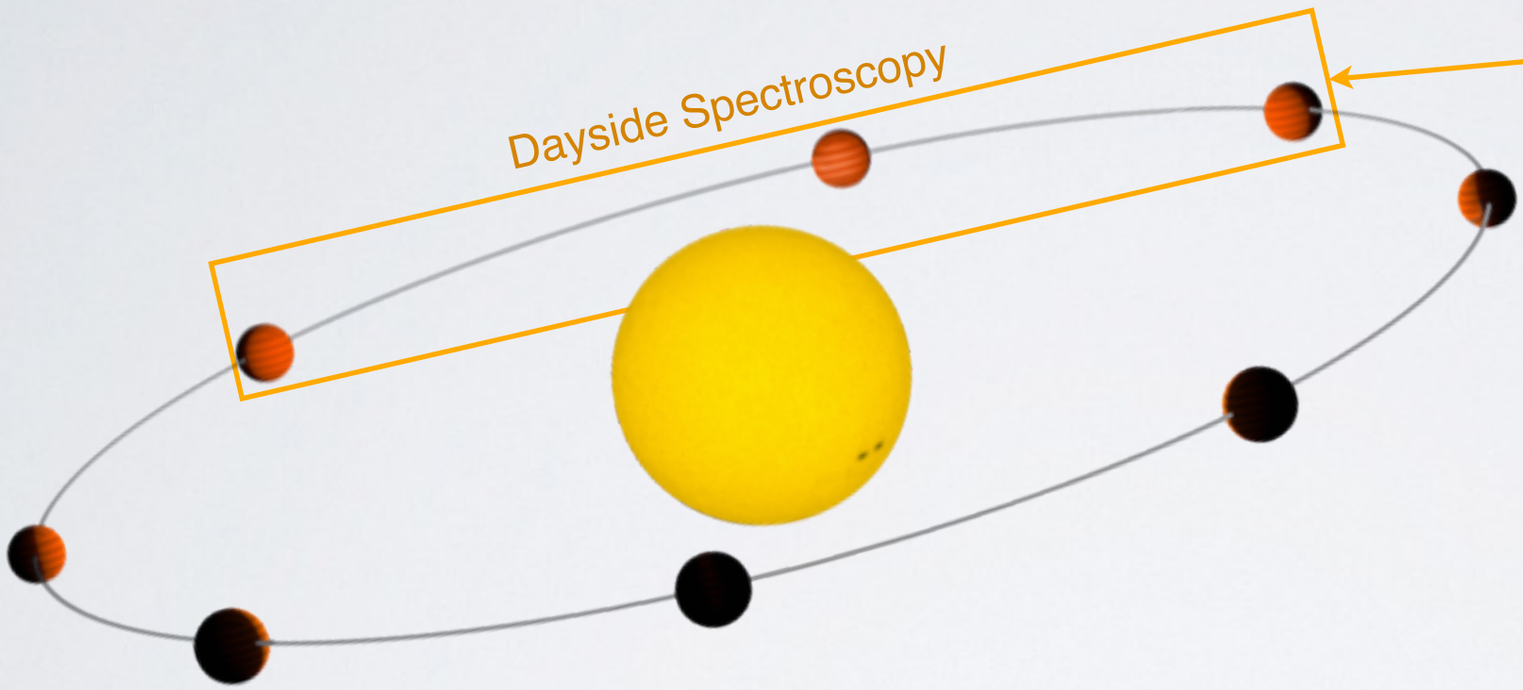
- During **transit**
- Before / after **secondary eclipse**

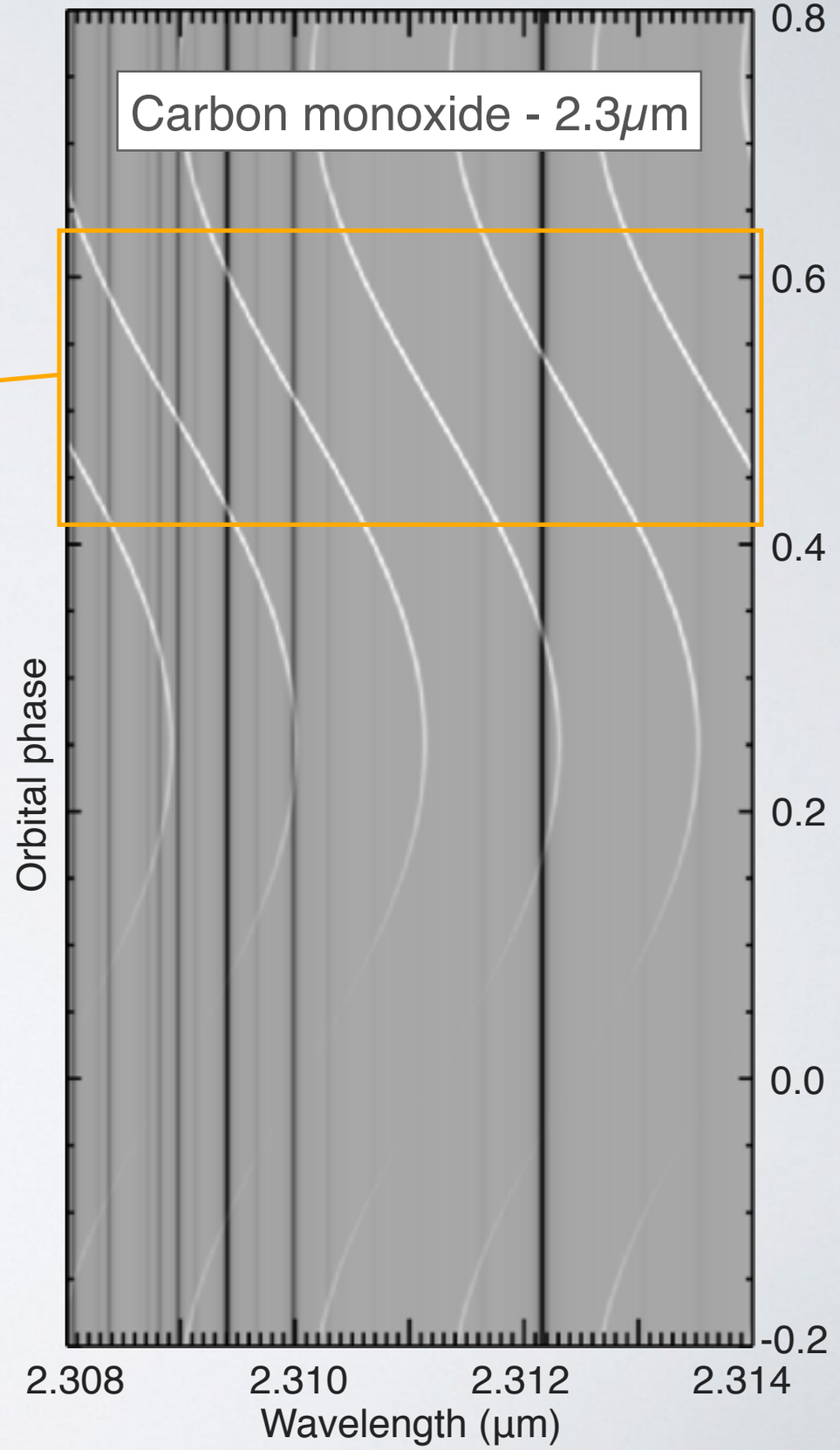




Exoplanets at high-spectral resolution

The thermal spectrum
of the planet is targeted directly





Dayside spectroscopy
applicable to non-transiting planets!

The analysis: a two-step process

The Earth's **atmospheric absorption** is **stationary** in wavelength

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

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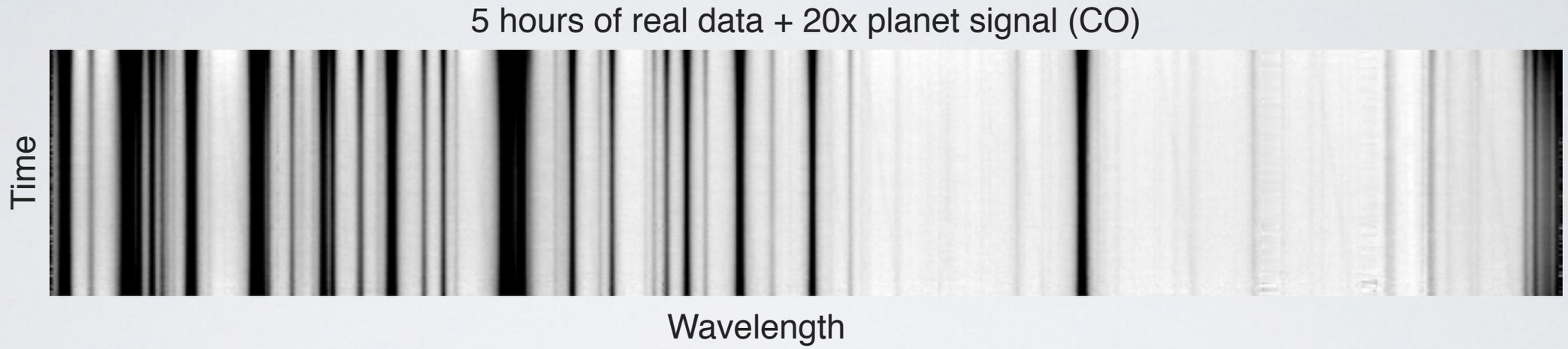

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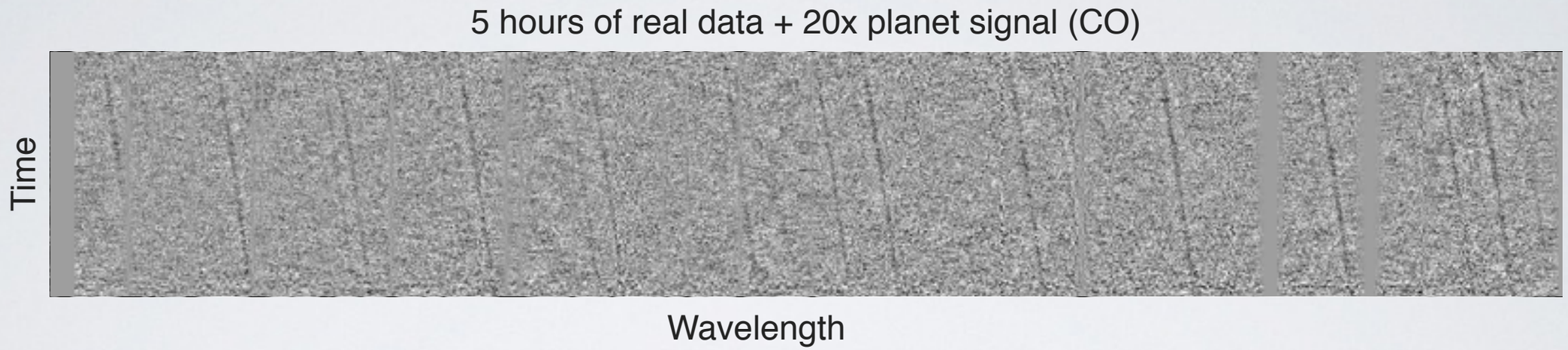

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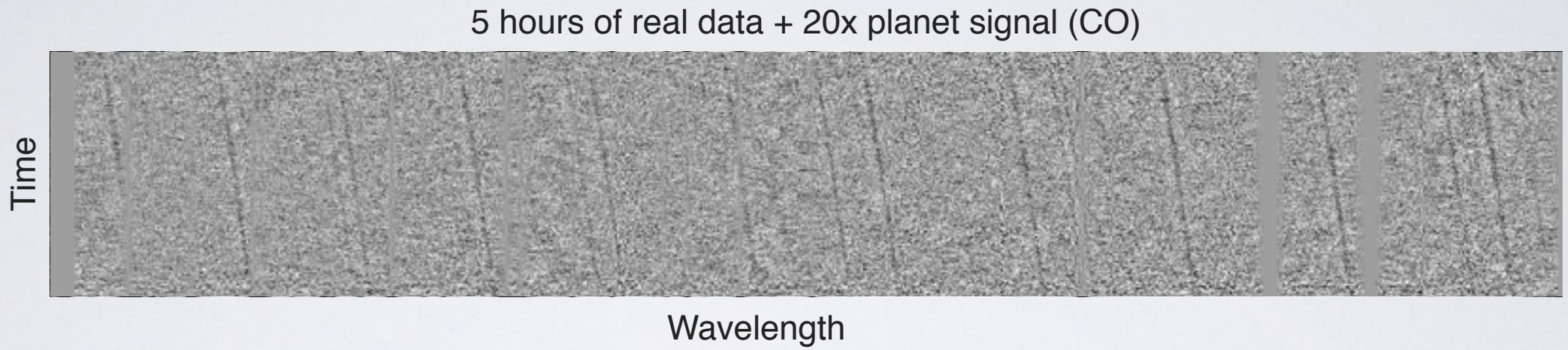

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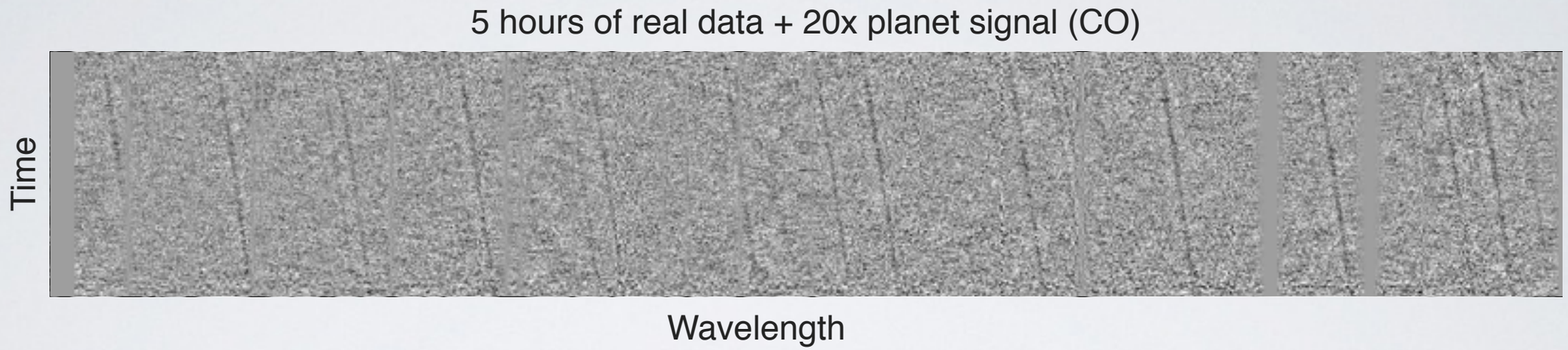

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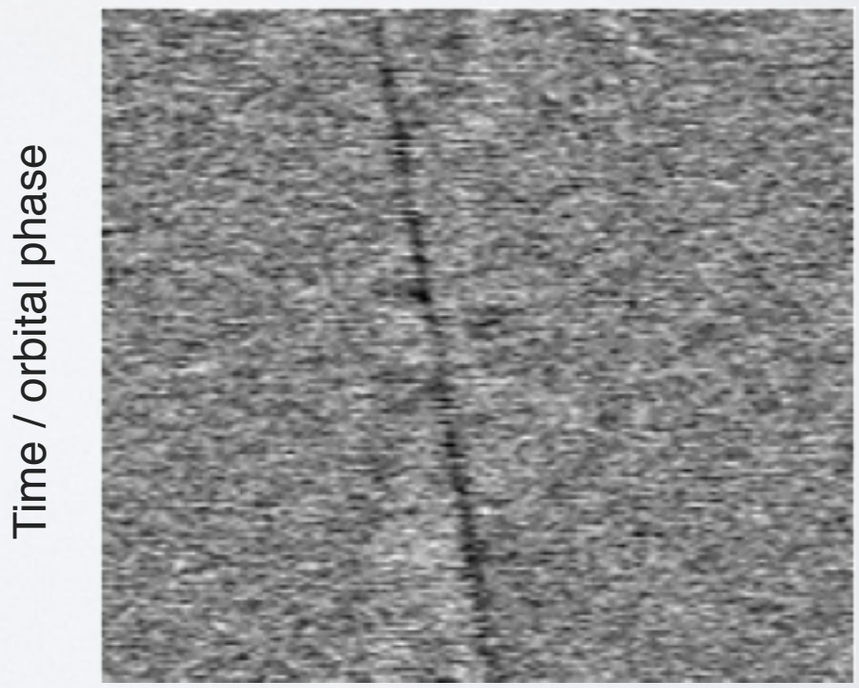
Cross-correlation matrix
CCF(RV, *t*)
Portion of **planet RV curve**



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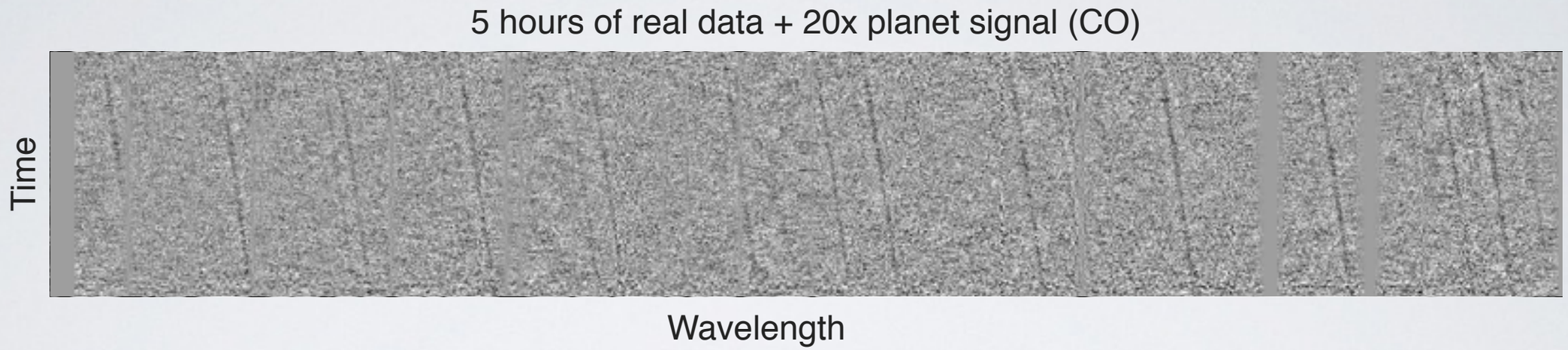

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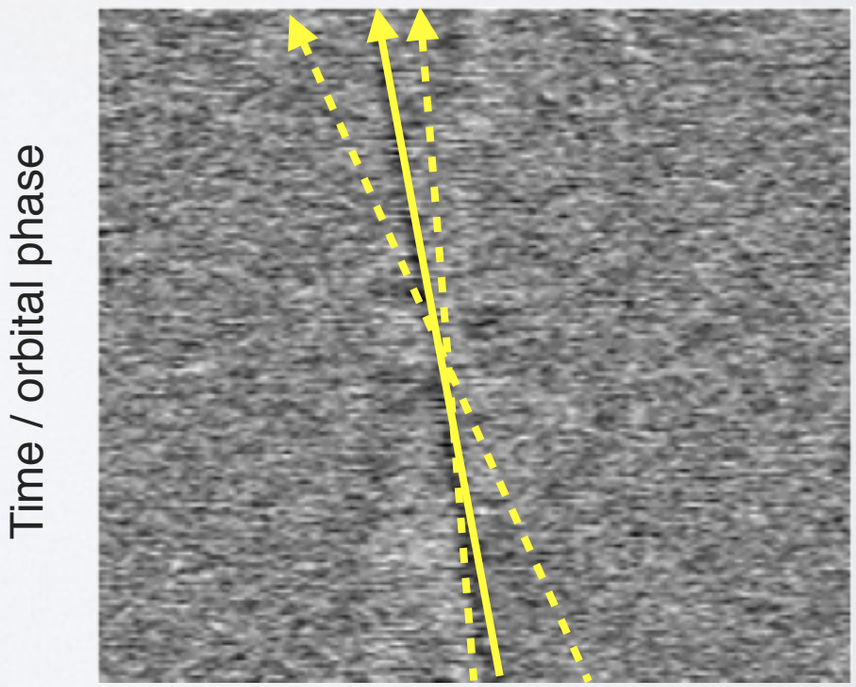
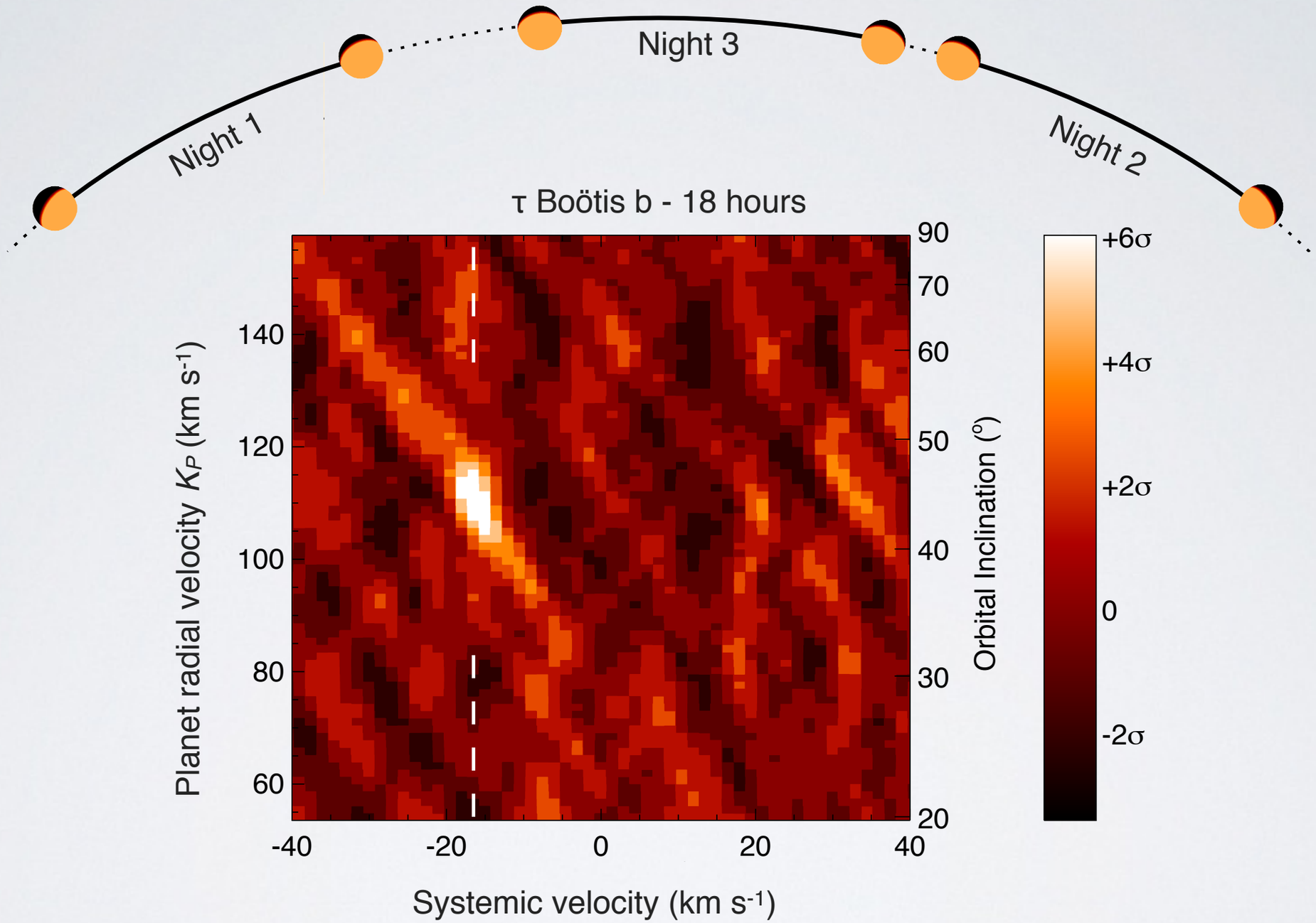


The orbital motion of τ Boo b

Brogi et al. 2012



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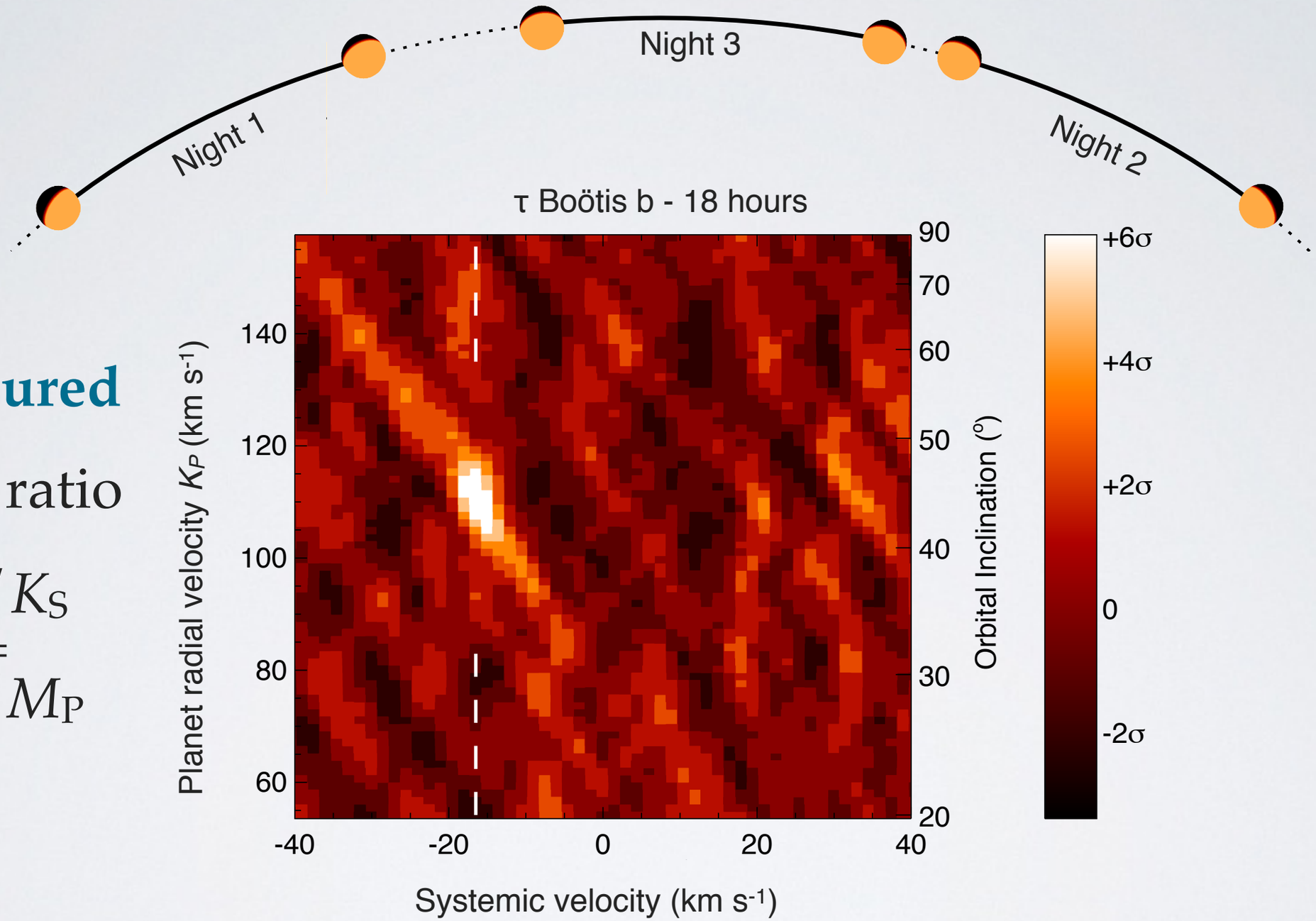

Measured

Mass ratio

$$K_P / K_S = M_S / M_P$$

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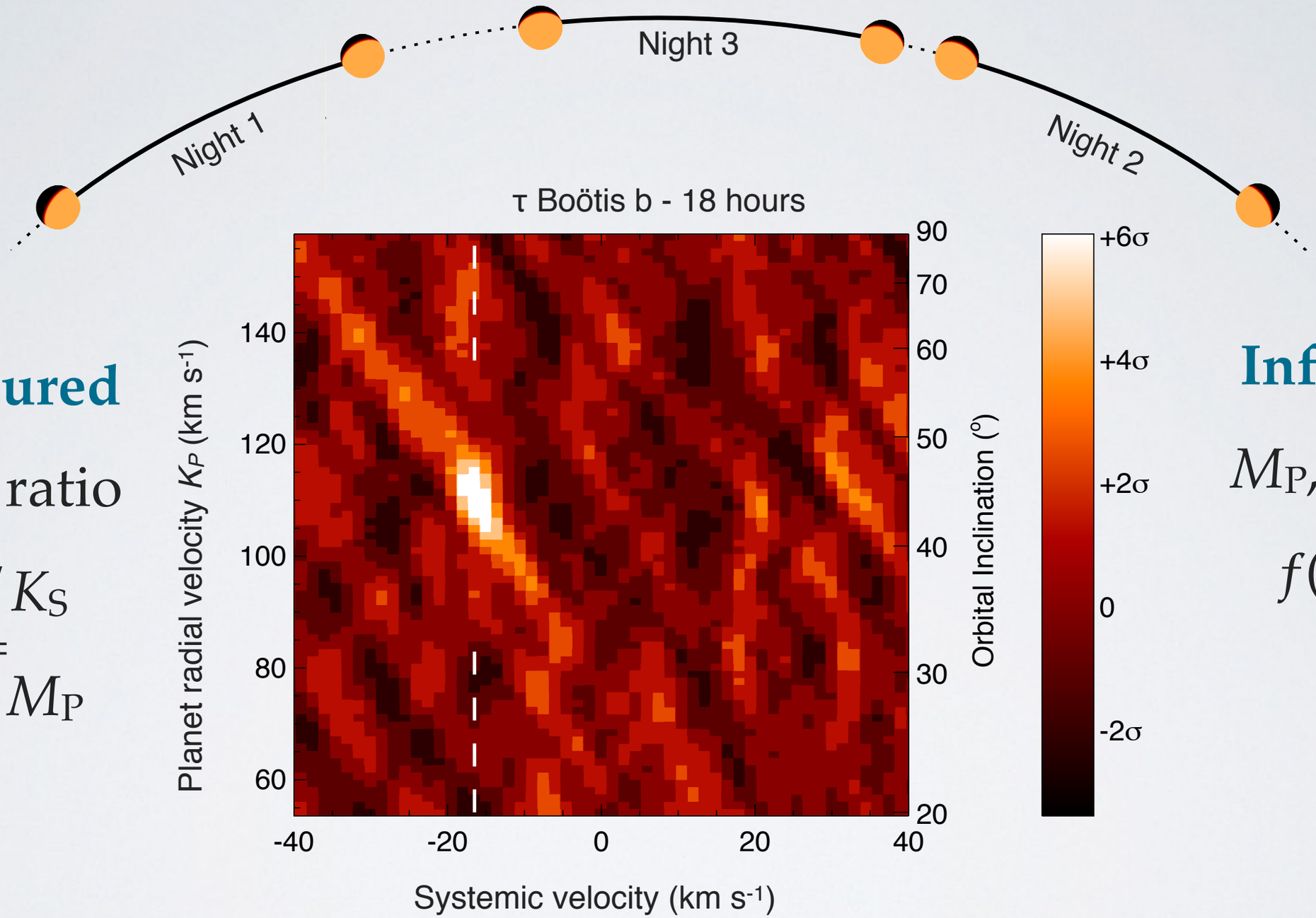

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Inferred

$$M_P, \sin(i) = f(M_S)$$

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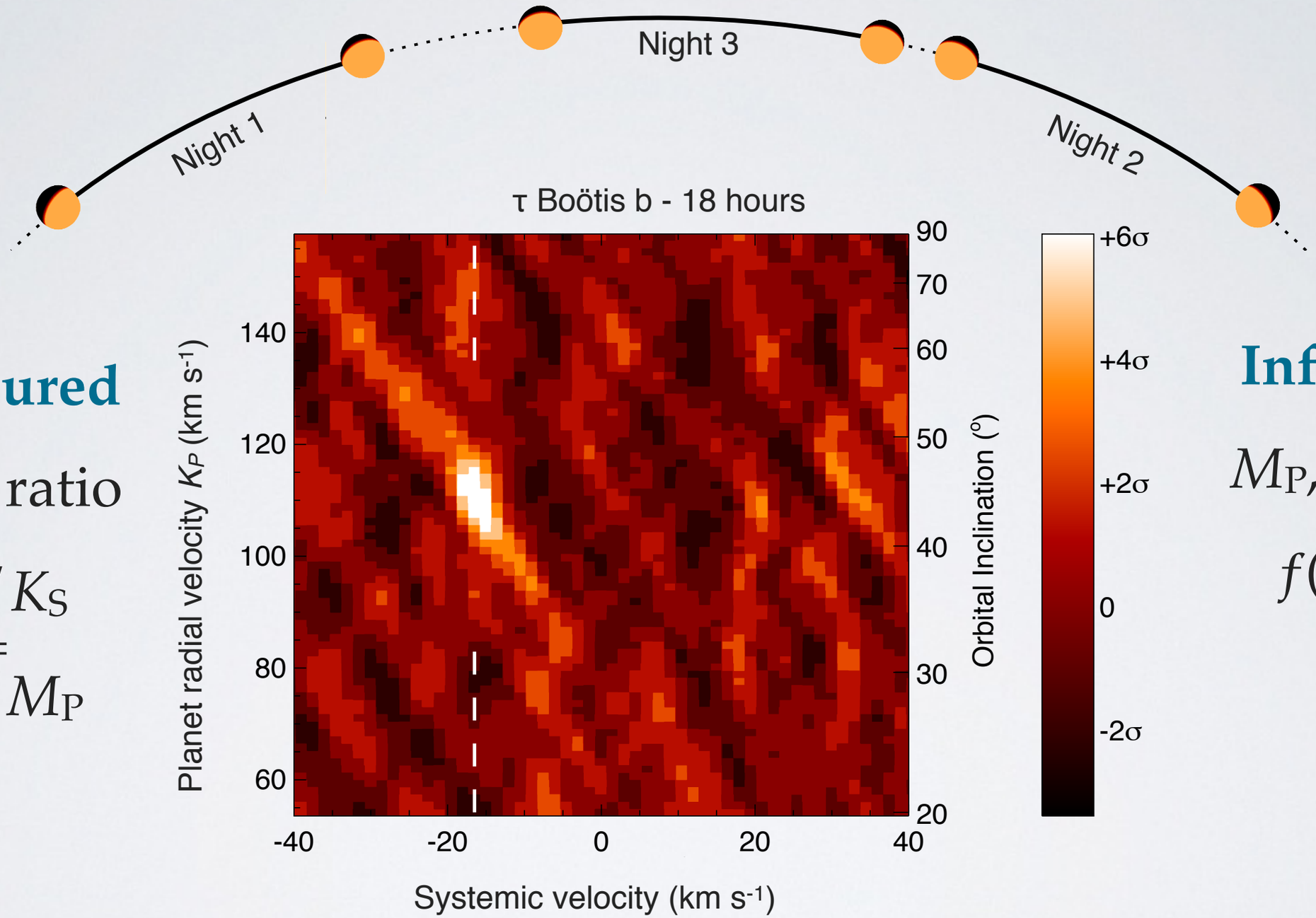

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Stellar mass ⇒ Planet mass, orbital inclination

Molecular detections to date

Planet	λ (μm)	T (hours)	S/N	Molecules	Phase	*i* (deg)	*M* (M
τ Boo b Brogi+ 2012	2.3	18	6.2	CO	Dayside	44.5±1.5	5.95±0.28
51 Peg b Brogi+ 2013 Birkby+ in prep.	2.3	10	5.9	CO, H	Dayside	>79.6	0.46±0.02
	3.2	5	4.0		Dayside		
HD 179949b Brogi+ 2014	2.3	14	6.5	CO, H	Dayside	68±4	0.98±0.04
HD 189733b de Kok+ 2013 Birkby+ 2013 Brogi+ in prep.	2.3 + 2.0	5+5	5.0	CO, H (CO	Dayside	Known 85.51±0.05	Known 1.14±0.08
	3.2	5	4.8		Dayside		
	2.3	2.5	7-8		Transit		
HD 209458b Snellen+ 2010 Schwarz+ 2015	2.3	5	5.6	CO	Transit	Known 86.59±0.05	Known 0.714±0.022
	2.3	15	-	[CO]	Dayside		

Additional science

- Molecular detections
- Global thermal vertical structure (inversion layers)
- Atmospheric C/O ratio (relative molecular abundances)
- Atmospheric dynamics / planet rotation

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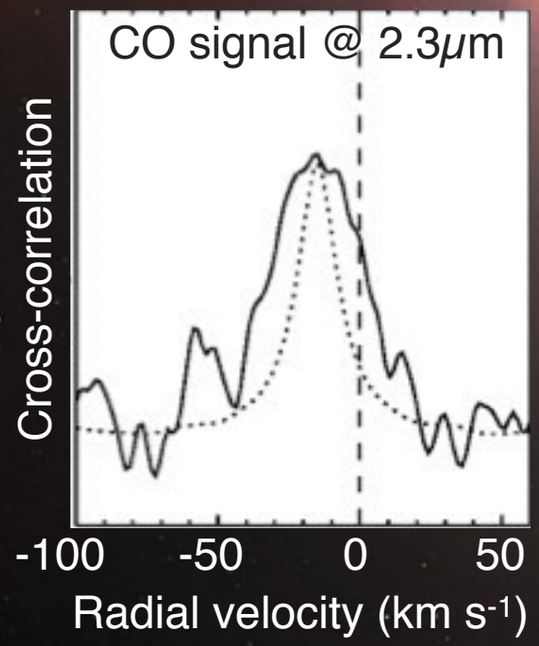
The fast rotation of exoplanet β Pic b

Snellen+ 2014



β Pic b rotates in only 8 hours!

Transmission spectroscopy of hot Jupiters

Tidally locked on short timescales + global atmospheric patterns

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

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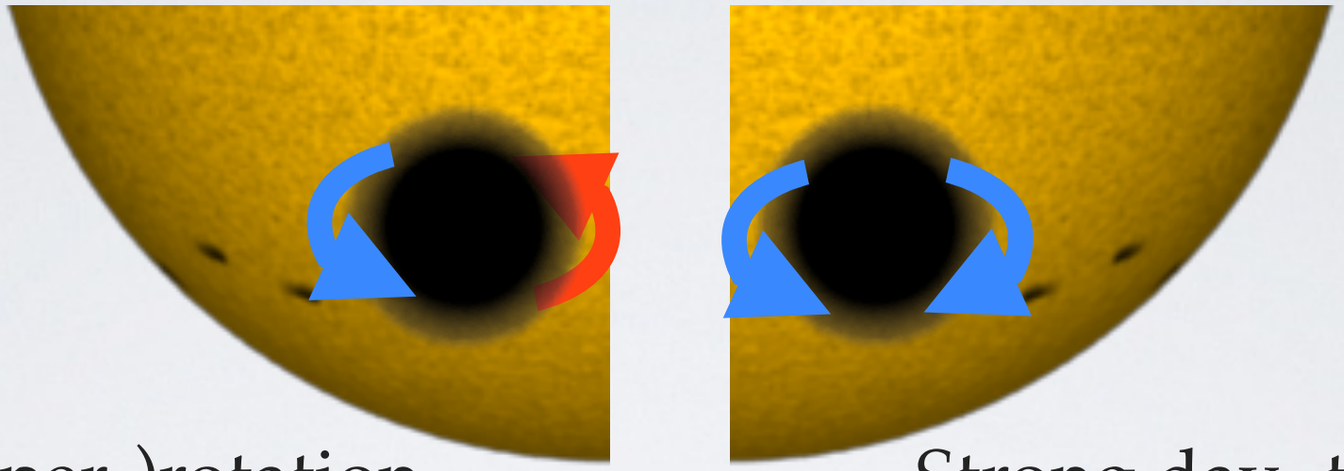

Atmospheric (super-)rotation

⇒ **Broadened** CCF

Strong day- to night-side flow

⇒ **Blue-shifted** CCF

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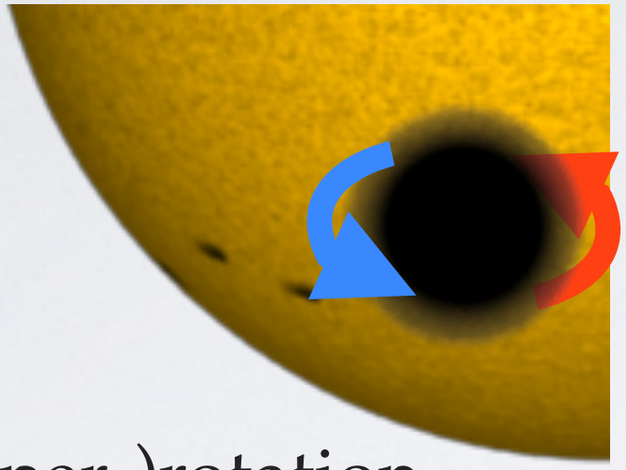

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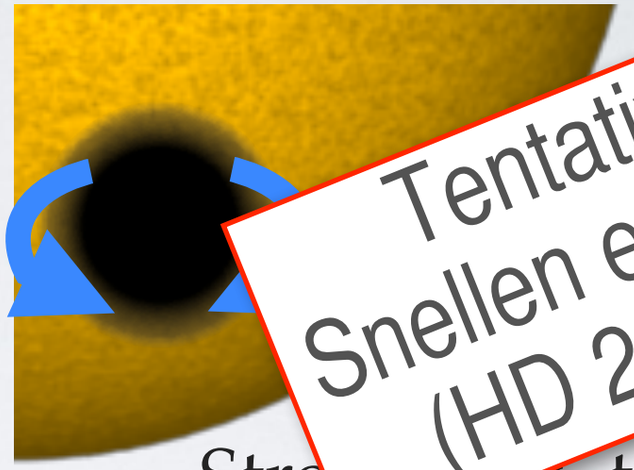

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Tentative in Snellen et al. 2010 (HD 209458b)

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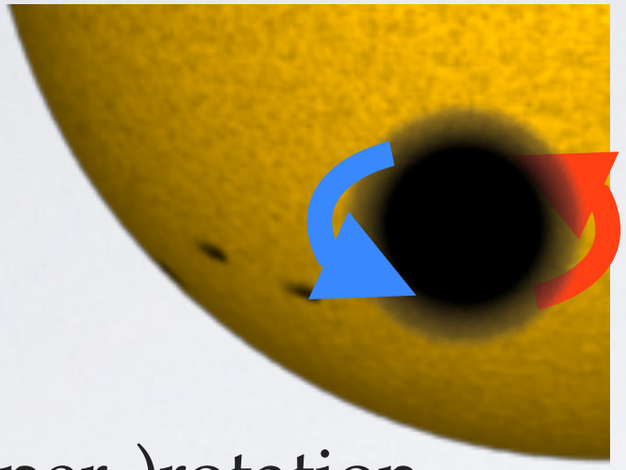

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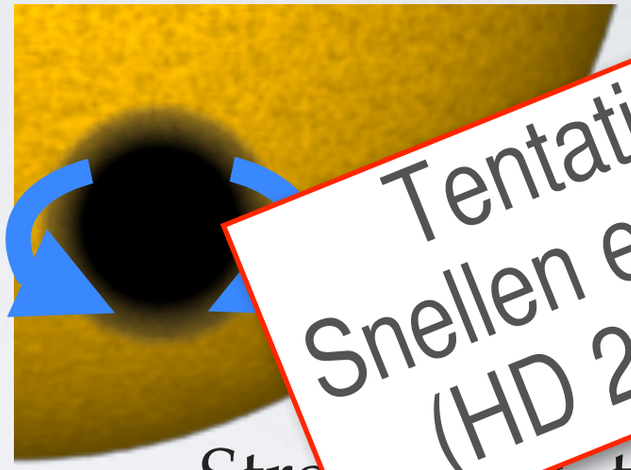

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Measuring atmospheric circulation of HD 189733b

VLT/CRIRES, 2.3μm, R=100,000

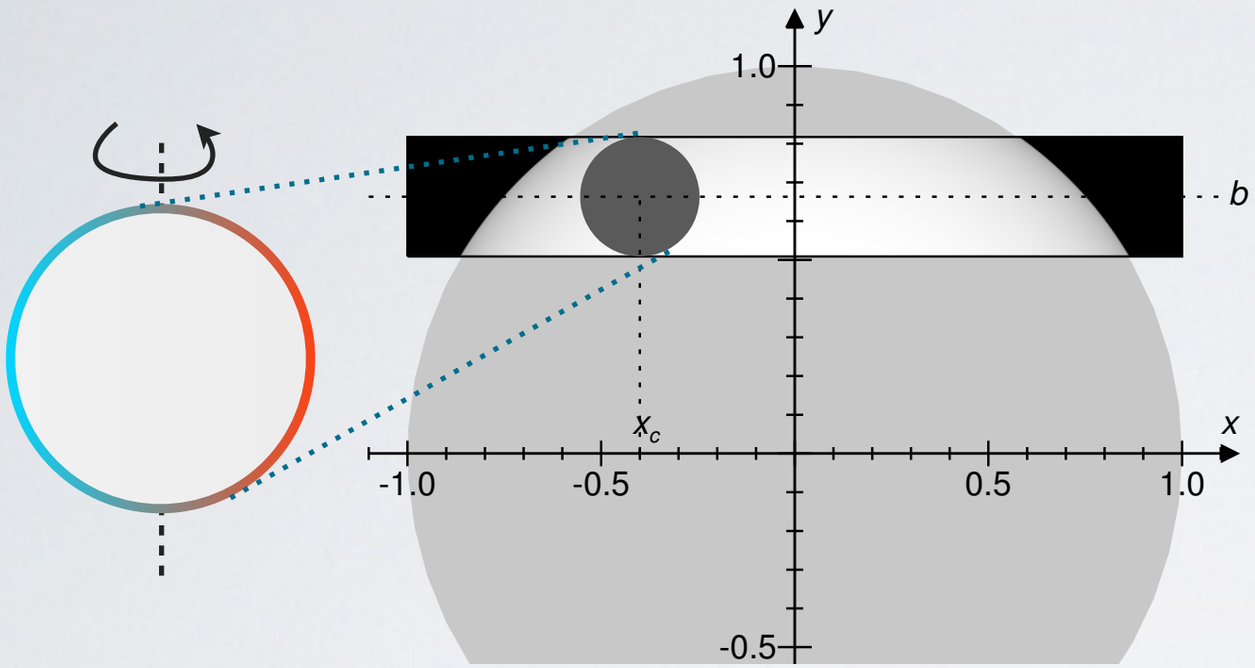
1 transit, stopped just after egress

1 night lost for bad weather

Testing predictions on HD 189733 b

Modeling the broadening function for the planet line profiles

(Brogi+ in prep.)



- Rigid rotation
- Equatorial band super-rotating
- No asymmetries
- No modeling of blue shift

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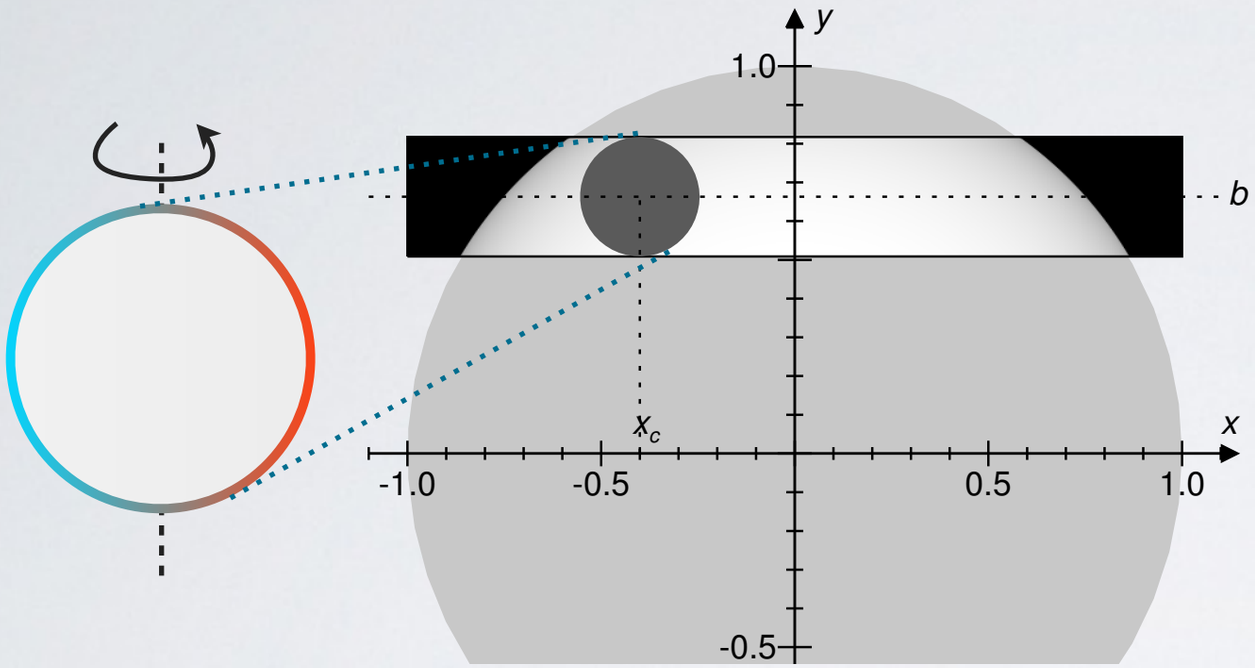

- Rigid rotation
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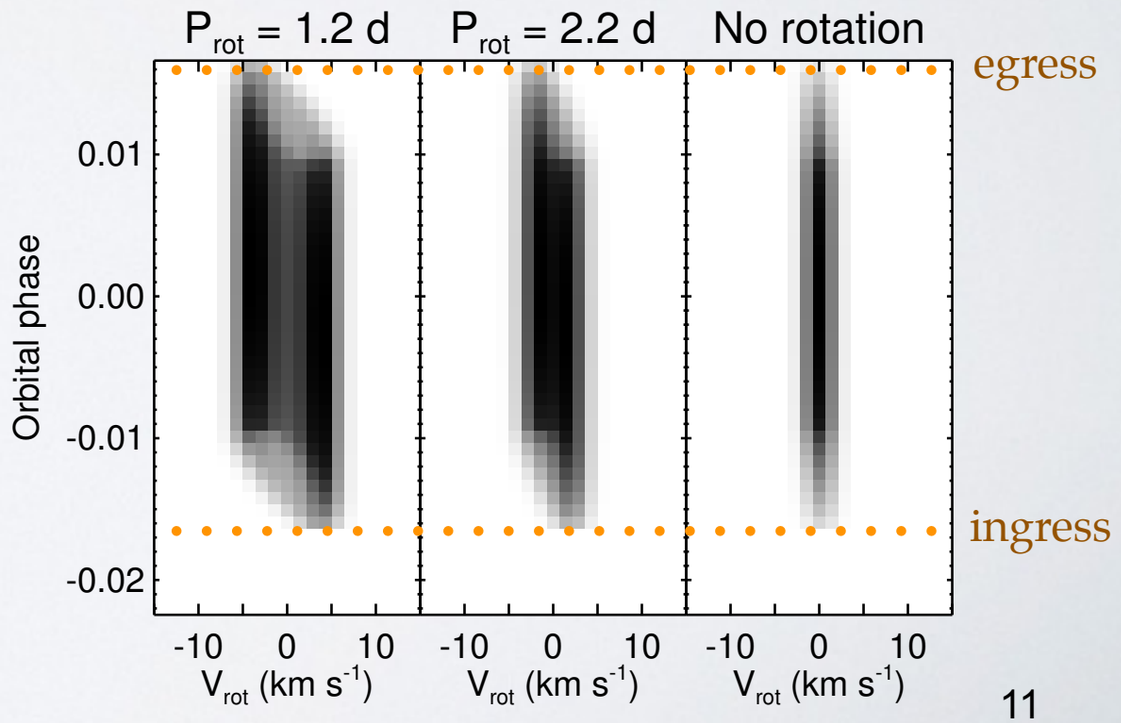
- No asymmetries
- No modeling of blue shift

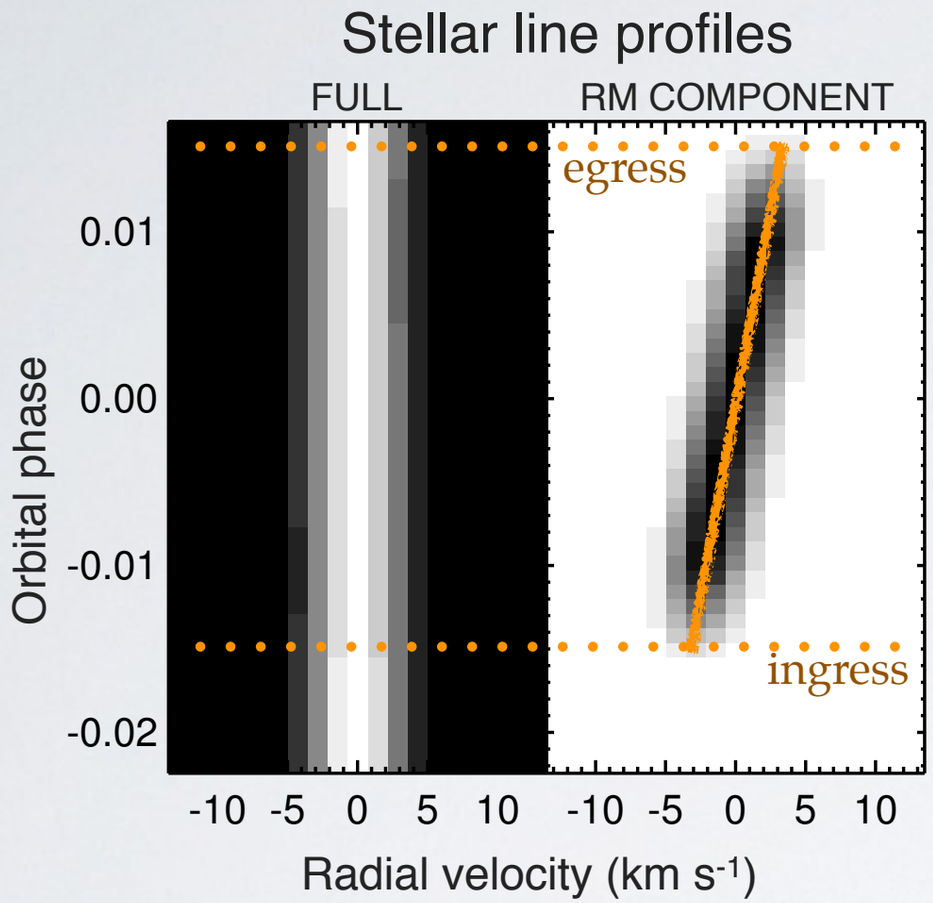
- Tidal locking detectable at R=10^5
- Ingress/egress asymmetric
- Planet profile splits for fast rotations



Caution! Spurious stellar signals

Rossiter-McLaughlin effect on HD 189733

(RM models by Simon Albrecht)



RM of aligned systems
mimics the signature of a planet

$v \sin i = 3.3$ km s^{-1}

$\Rightarrow K_P = 32$ km s^{-1}

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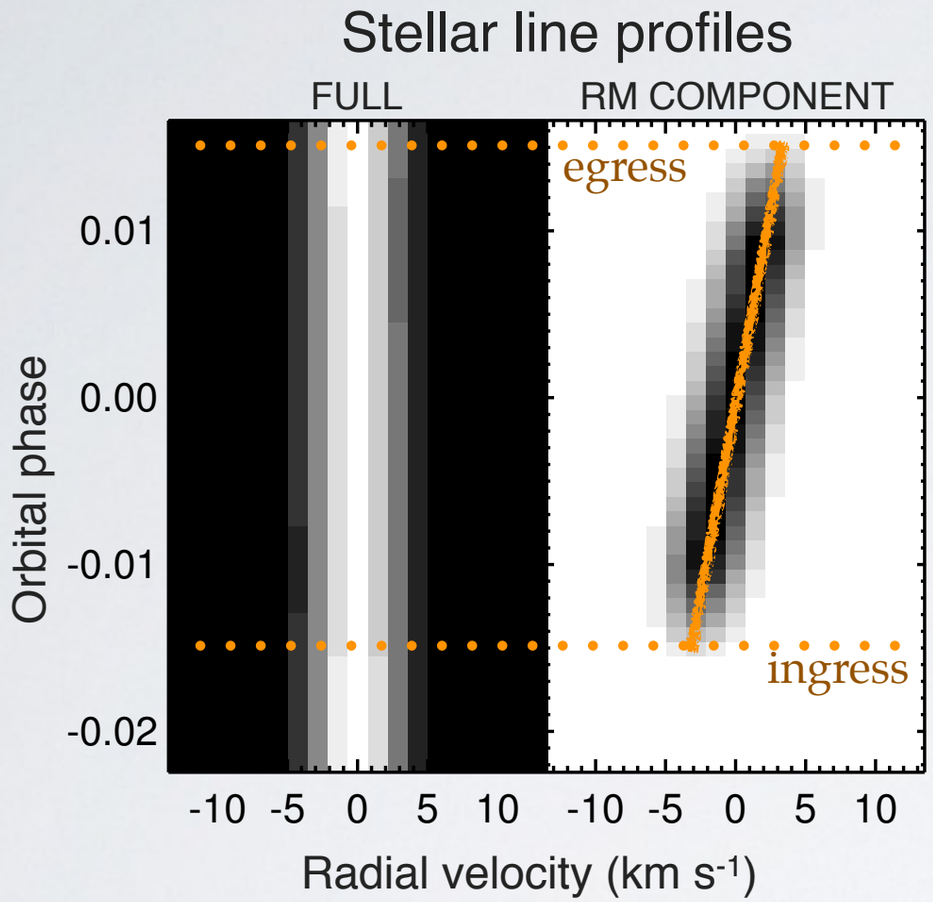

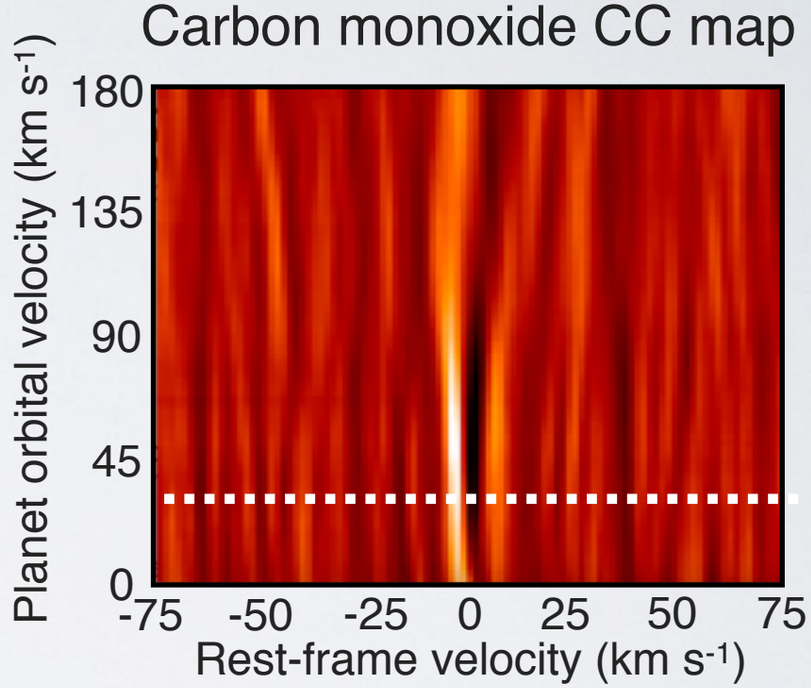

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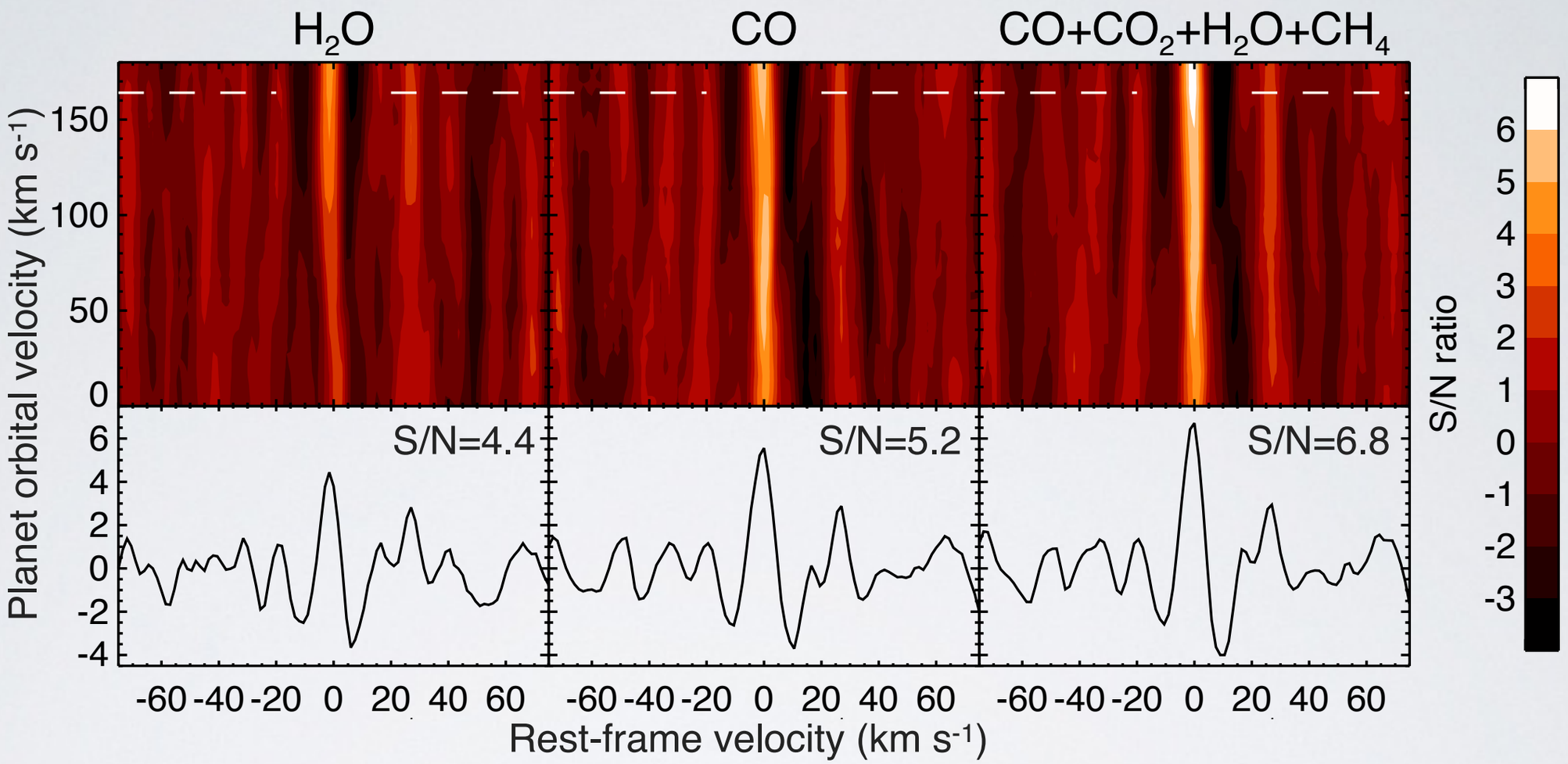
If uncorrected, RM produces
the dominant CC signature
when looking for CO

We modeled, fitted and removed stellar CO lines

($v$sin$i$, LD, line shape, IPs…)

The transmission spectrum of HD189733 b

Brogi+ in prep.



Best model: $\log_{10}(\mathrm{VMR}) = [-5,-4,-7,-5]$ for H_2O, CO, CH_4, CO_2

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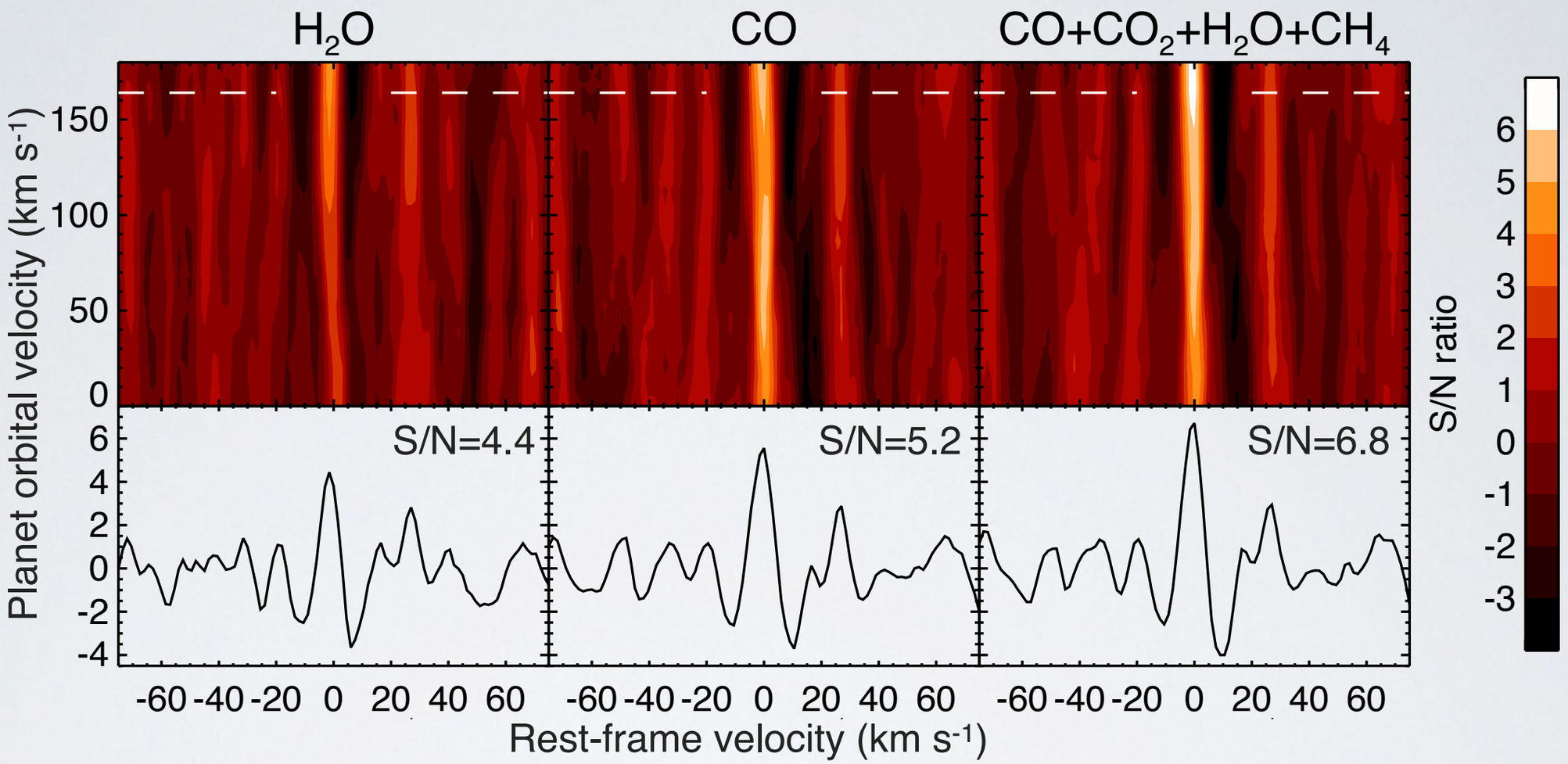

The signal does not show any blue shift

$v_{\rm rest} = (0.5^{+1.4}_{-1.7})$ km s^{-1}

⇒ No evidence for day-to-night winds

cfr. Wyttenbach et al. (2015): Na detection @ –8±2 km s^{-1}

Best model: $\log_{10}$(VMR) = [–5,–4,–7,–5] for H_2O, CO, CH_4, CO_2

The synchronous rotation of HD189733 b

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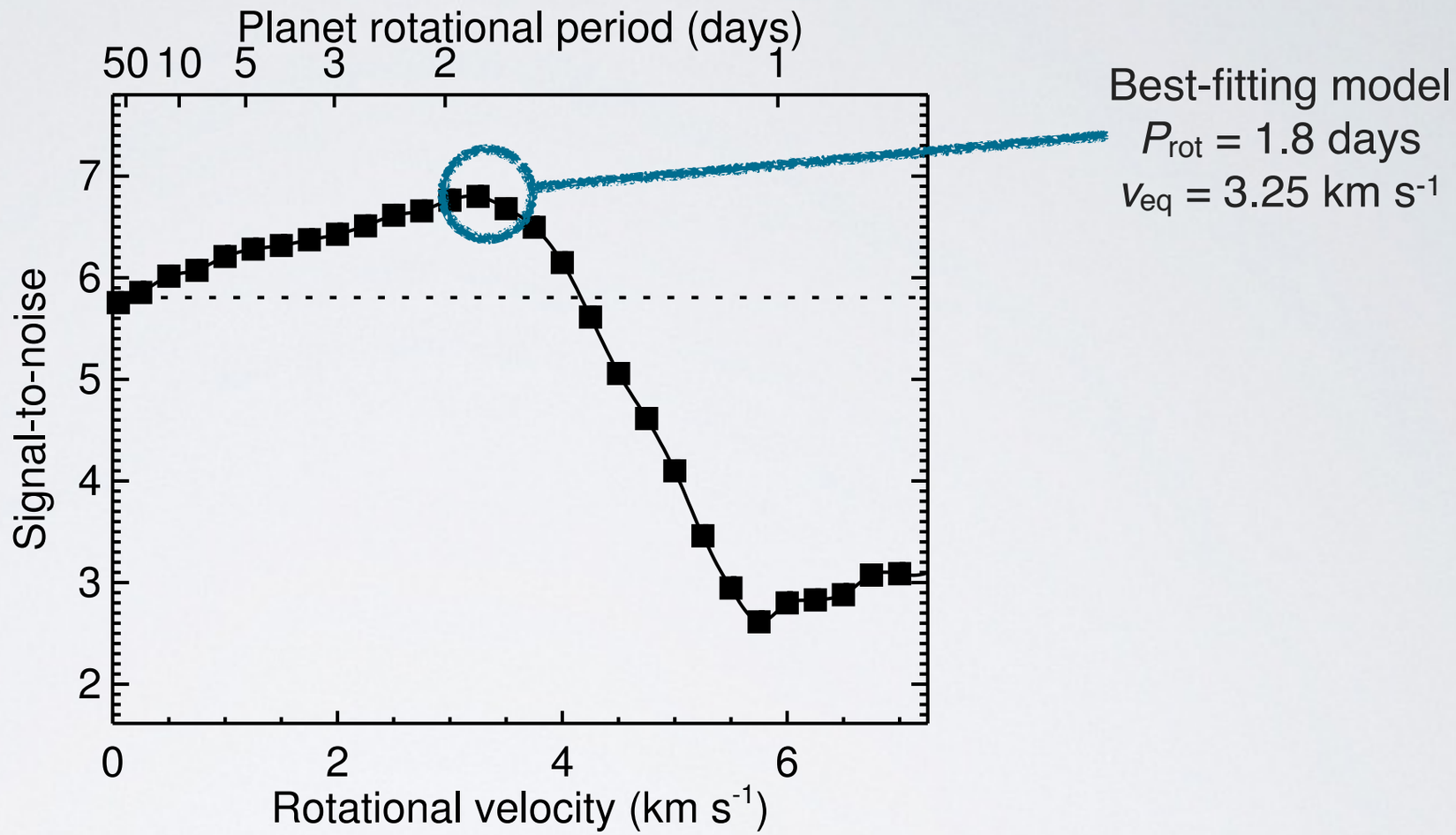

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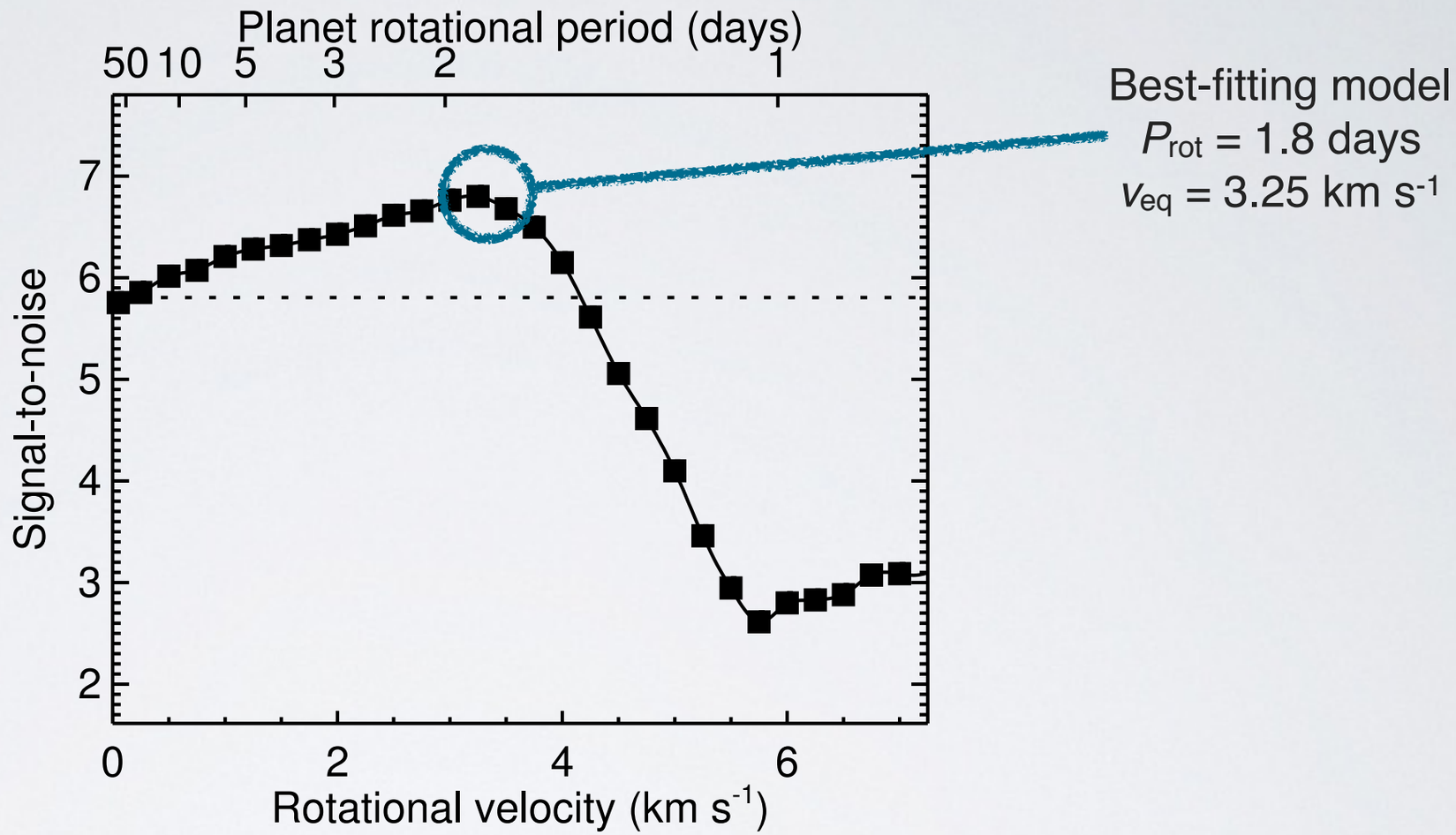


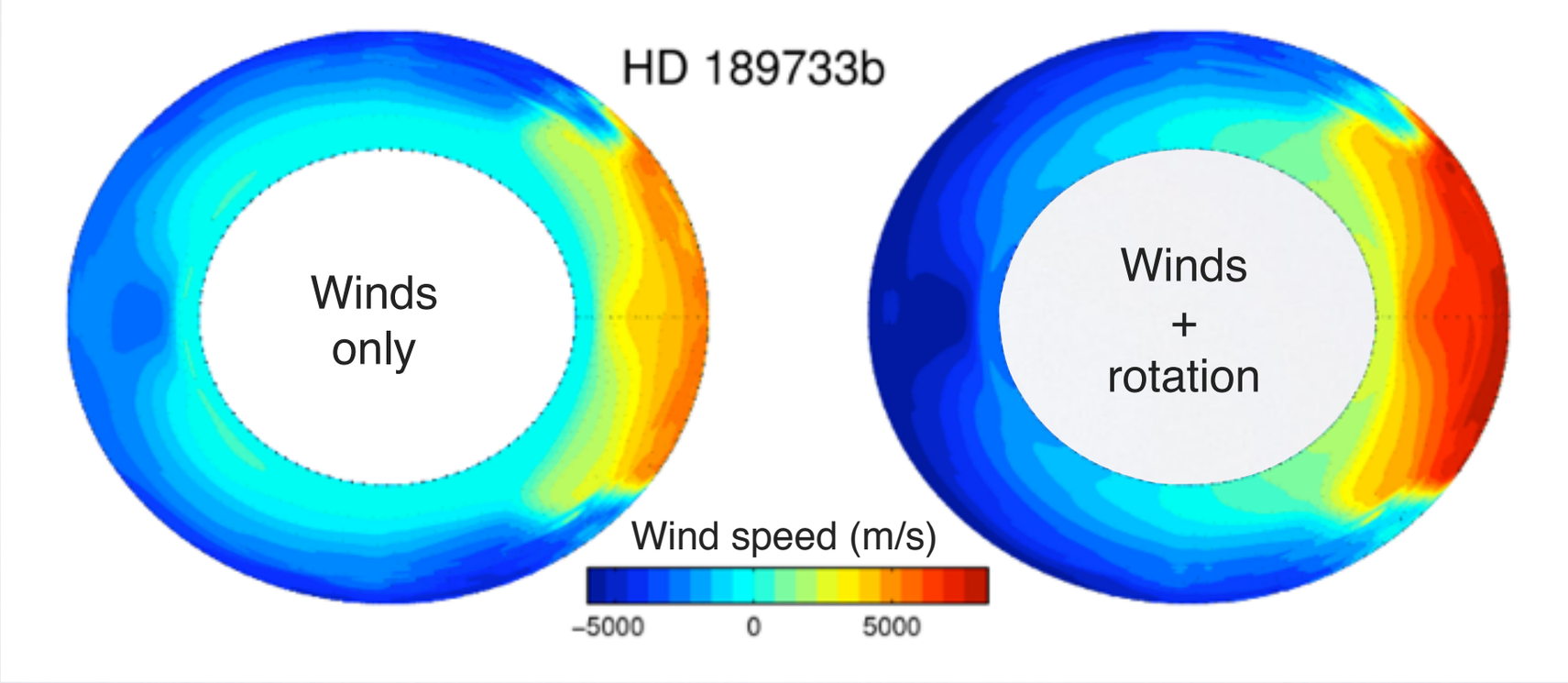
Fast rotation ($P_{rot} < 1d$) *strongly disfavored* by data

Weak evidence for synchronous rotation

(No variations in the signal if equatorial super-rotation is added)

Future prospects

- Try on hotter stars ⇒ no stellar noise
- Repeat observations ⇒ more S/N
- More baseline ⇒ better fit to stellar spectrum
- Apply modeled velocity fields:



Showman+ 2012

Thank you!