Exoplanet Atmospheres at High Spectral Resolution

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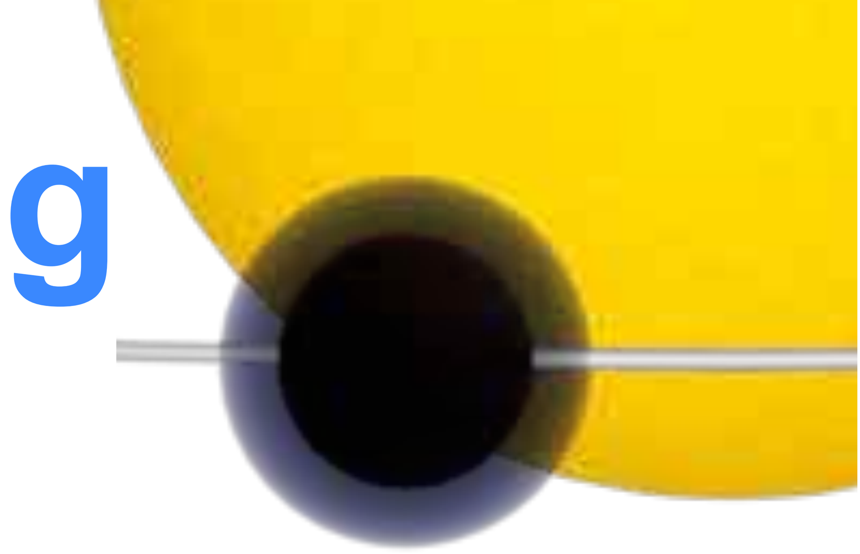
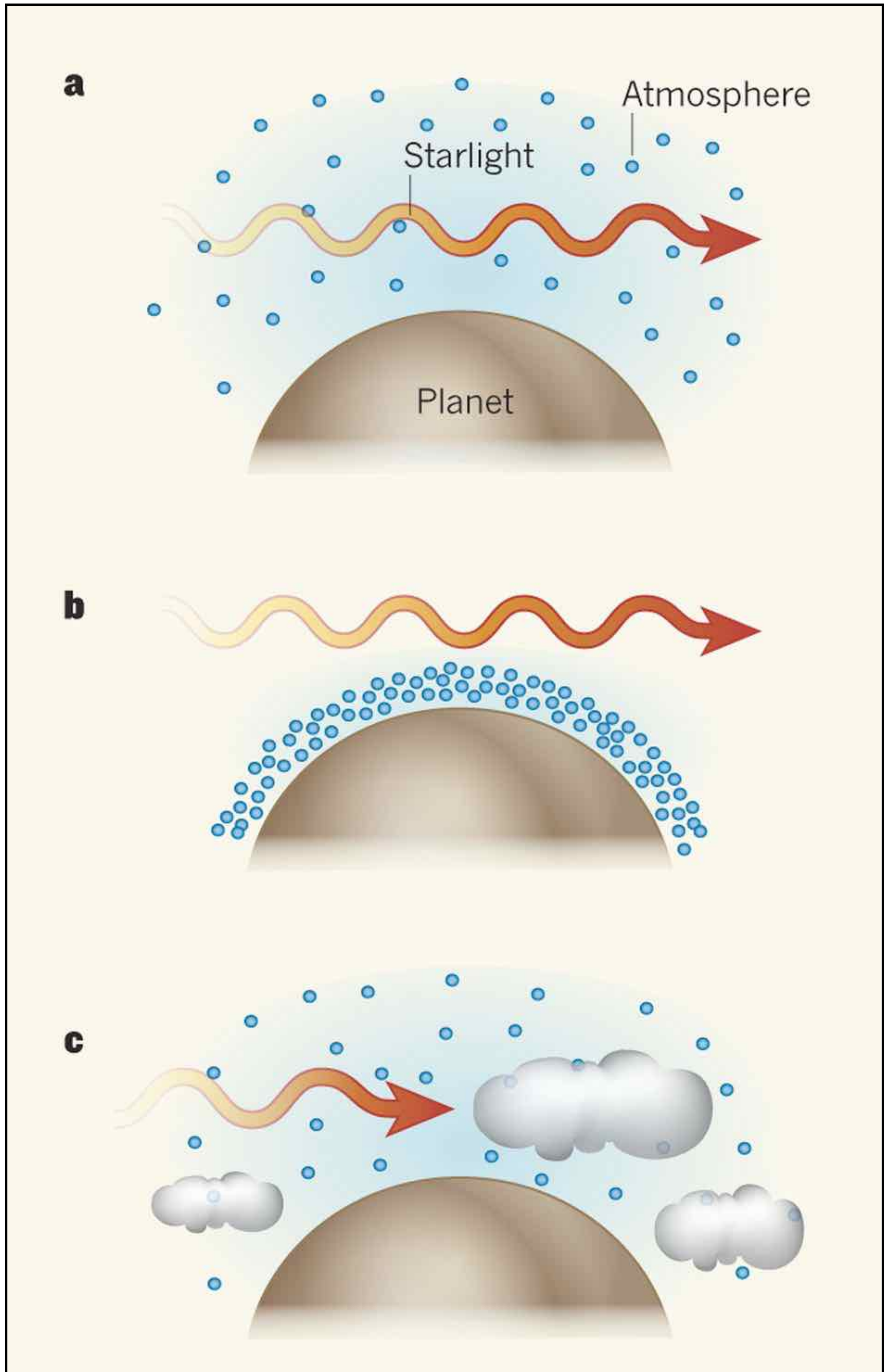
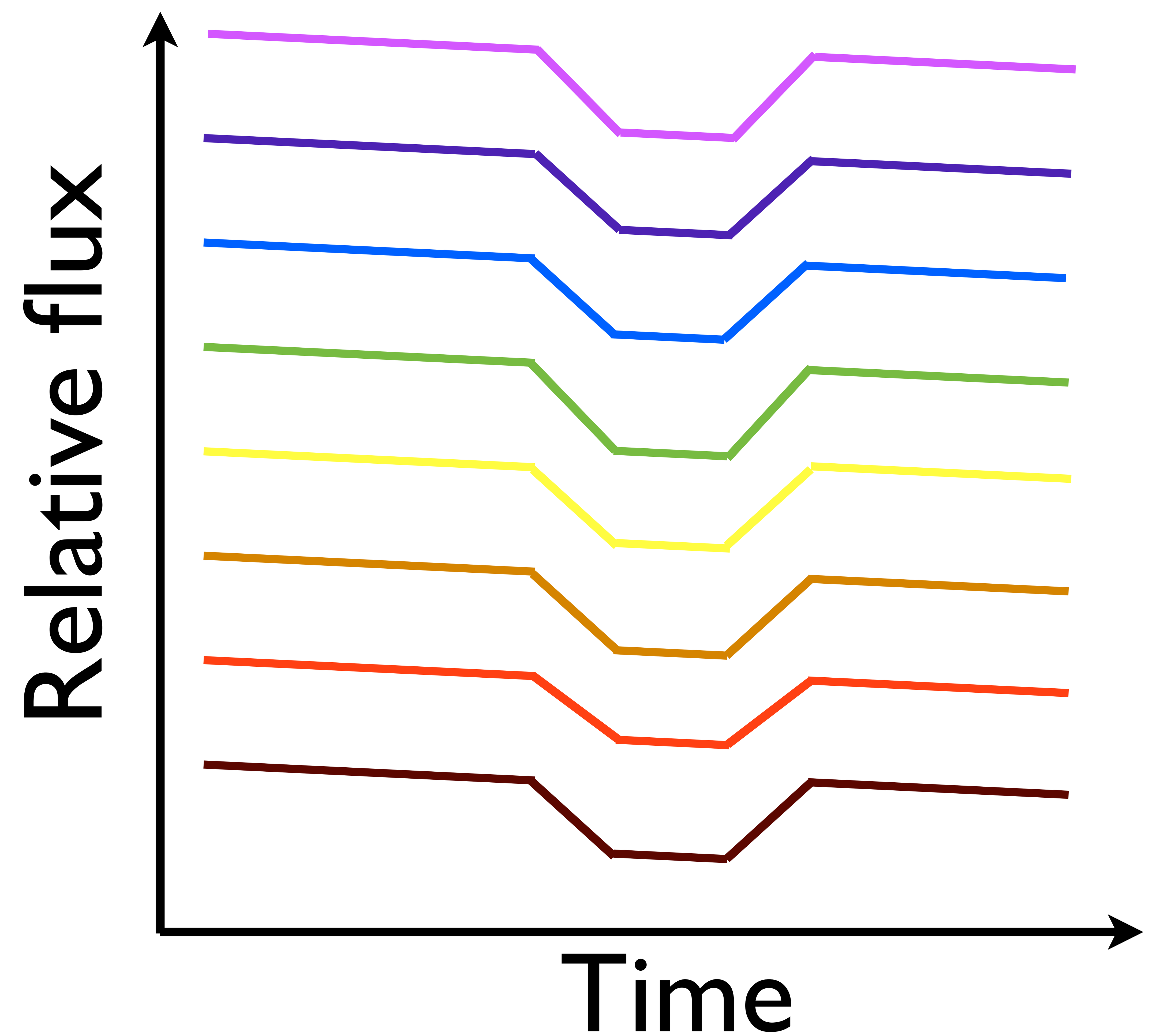
Detecting molecules with transmission spectroscopy

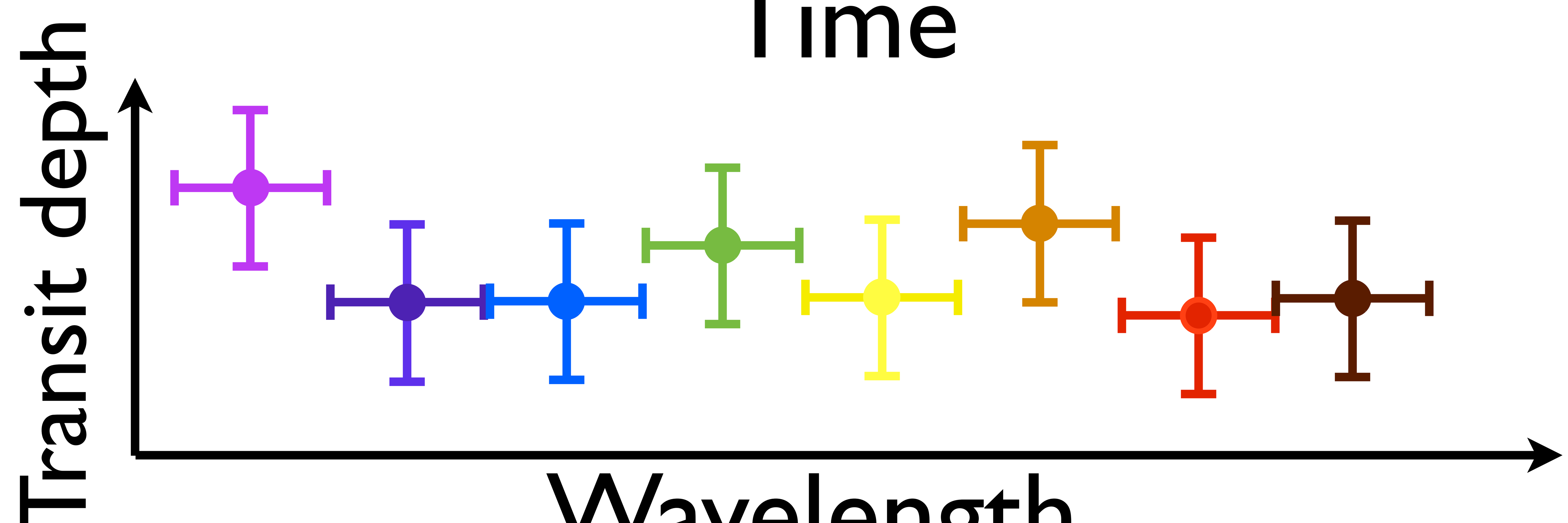
Starlight filtering through an atmosphere during transit is imprinted with the planet's spectrum



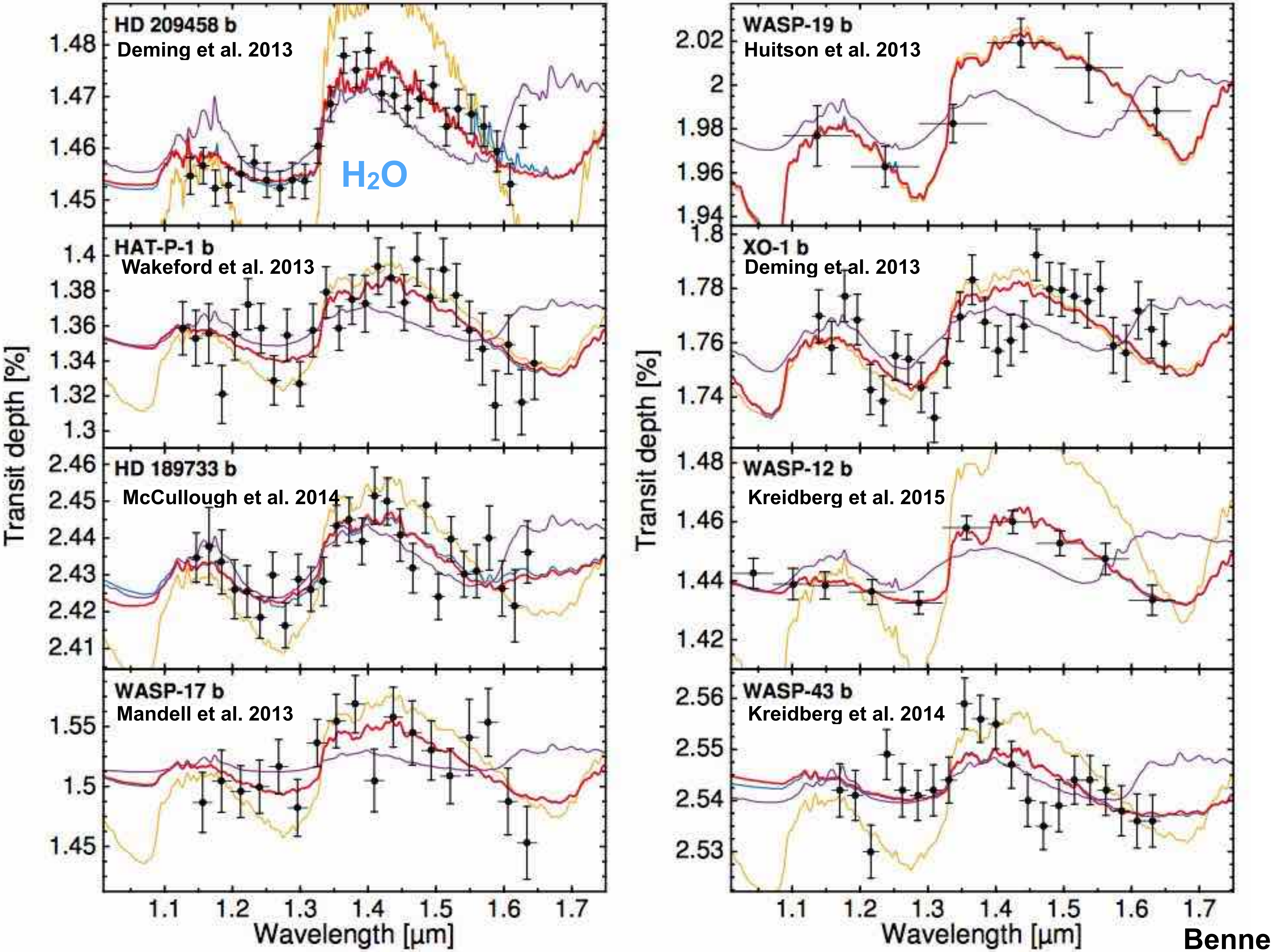


Transit depth ~ $(R_p/R_s)^2$



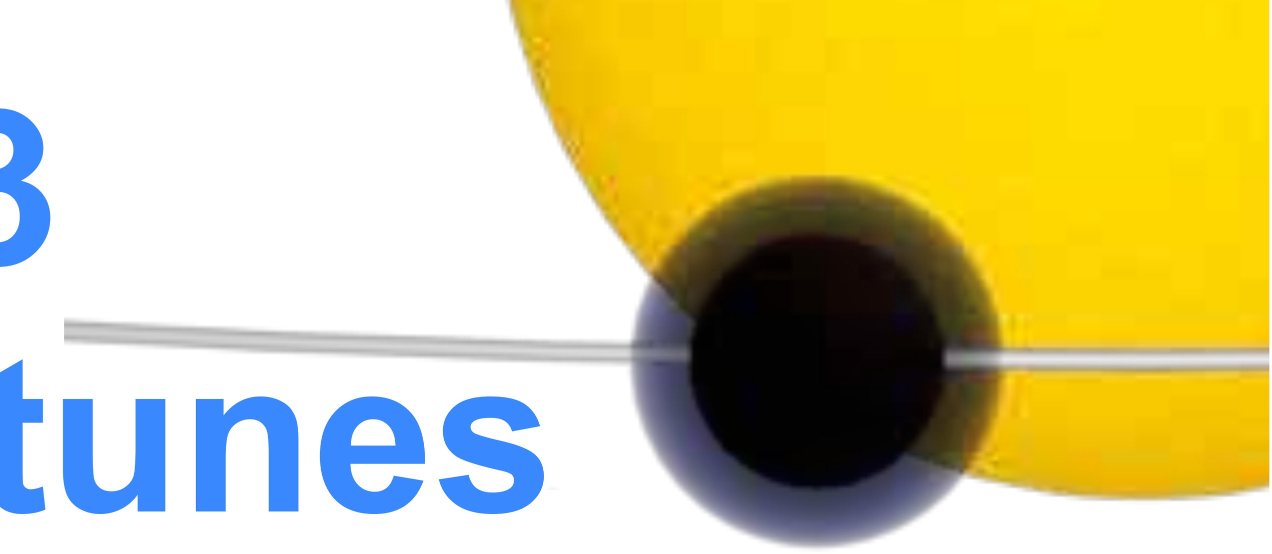


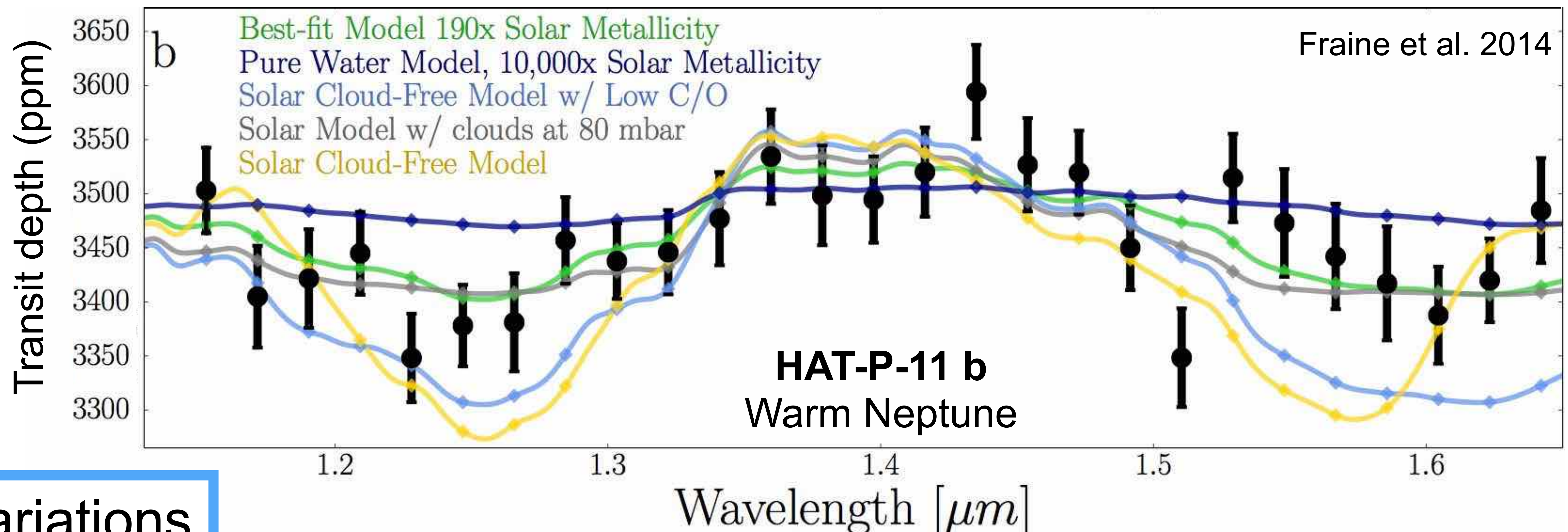
Transmission spectra with HST/WFC3 reveal water in hot Jupiters



Benneke 2015

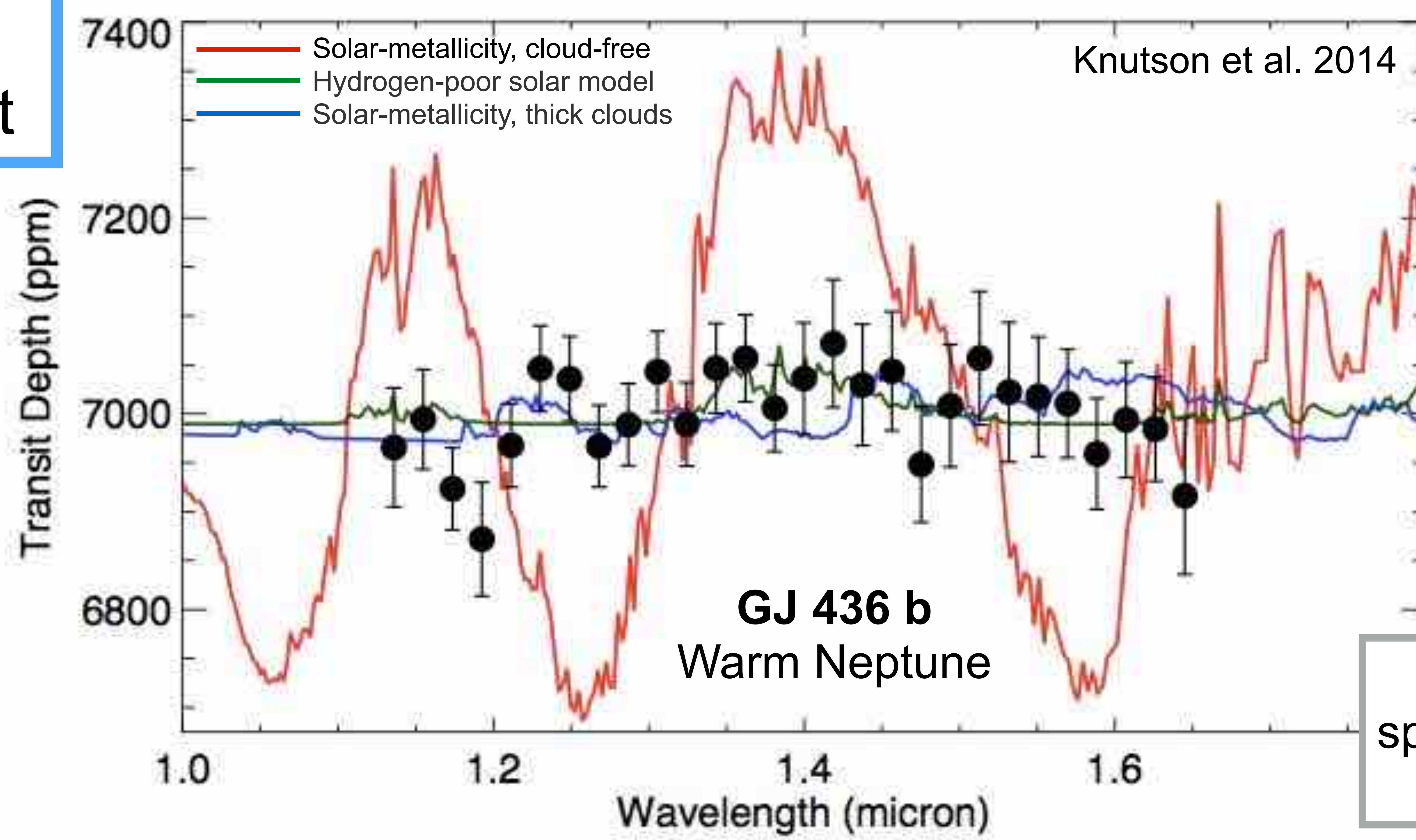
Transmission spectra with HST/WFC3 reveal water and clouds in warm Neptunes

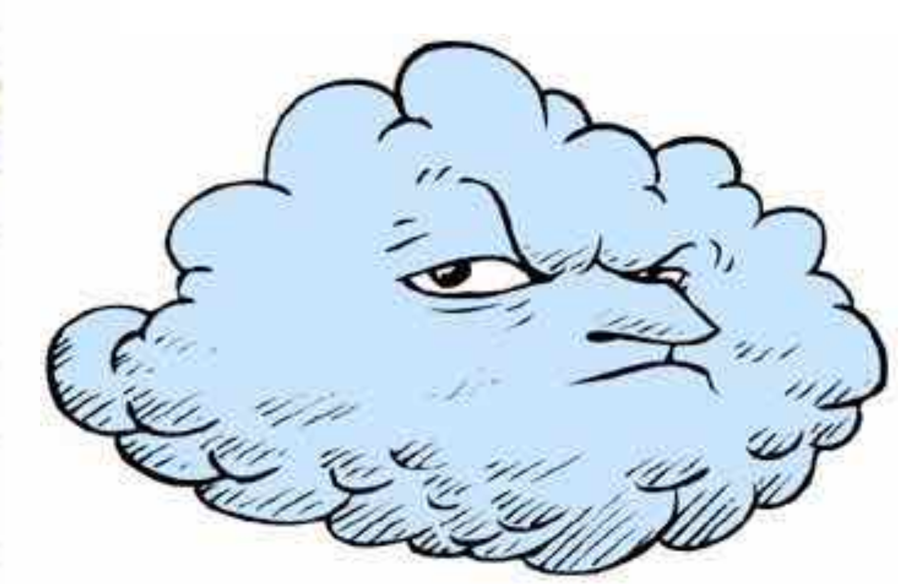




Water detected (5σ) in dust-free atmosphere

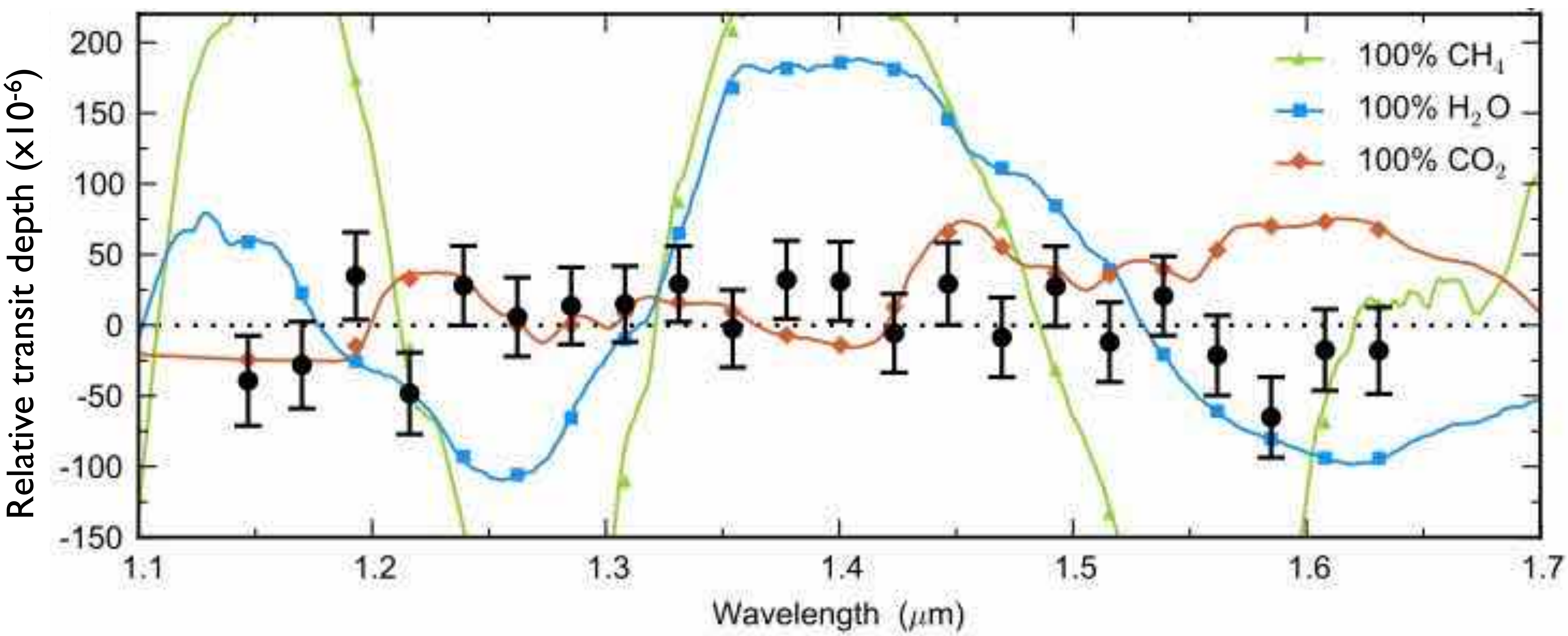
Flux variations at **10^{-4}** level are important





Flat featureless spectrum in cloudy/hazy atmosphere

60 orbits with HST/WFC3 revealed a featureless (cloudy) spectrum for super-Earth GJ 1214 b



Kreidberg et al. 2014

Even space telescopes suffer systematics >> planet signal

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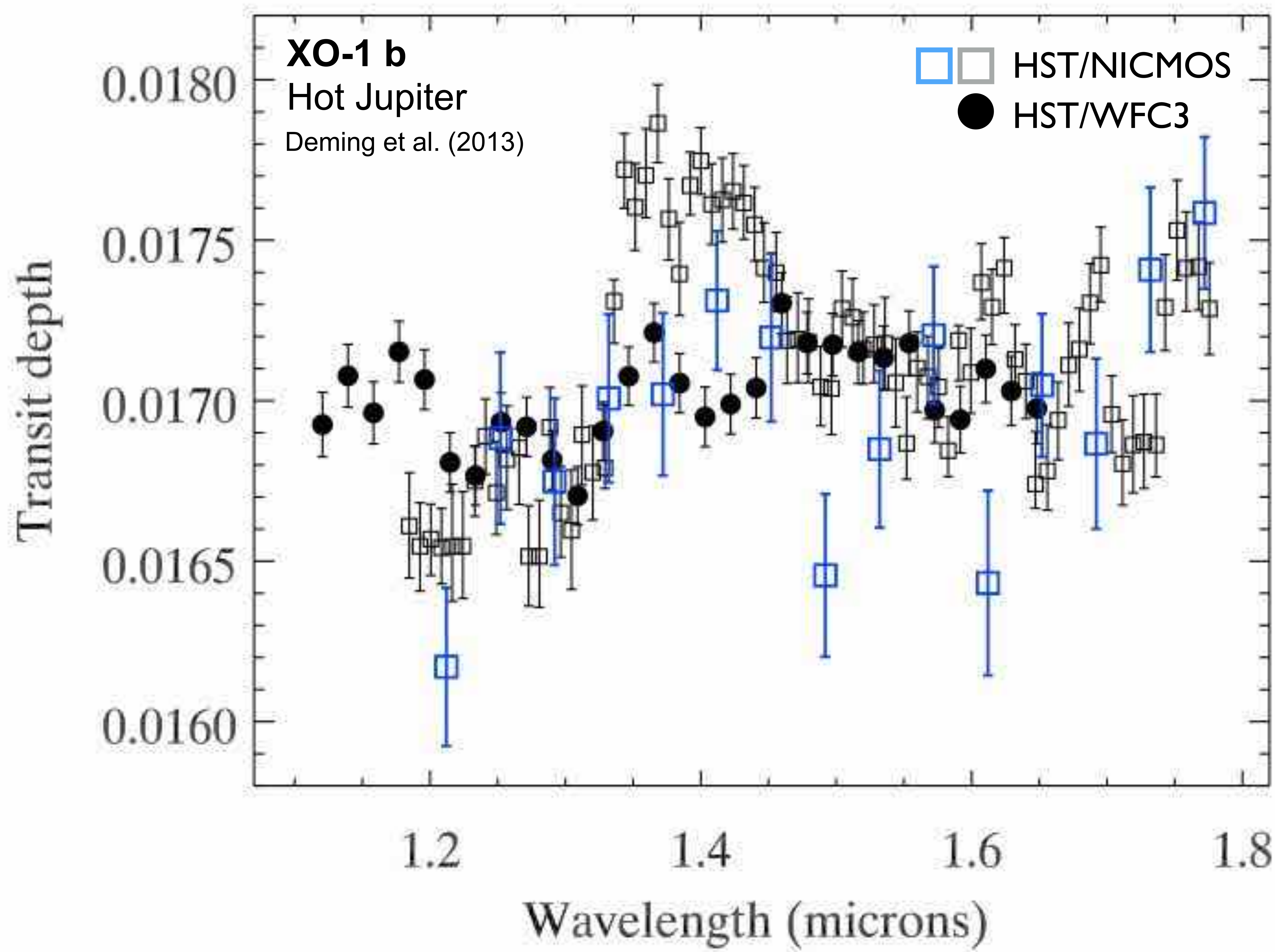
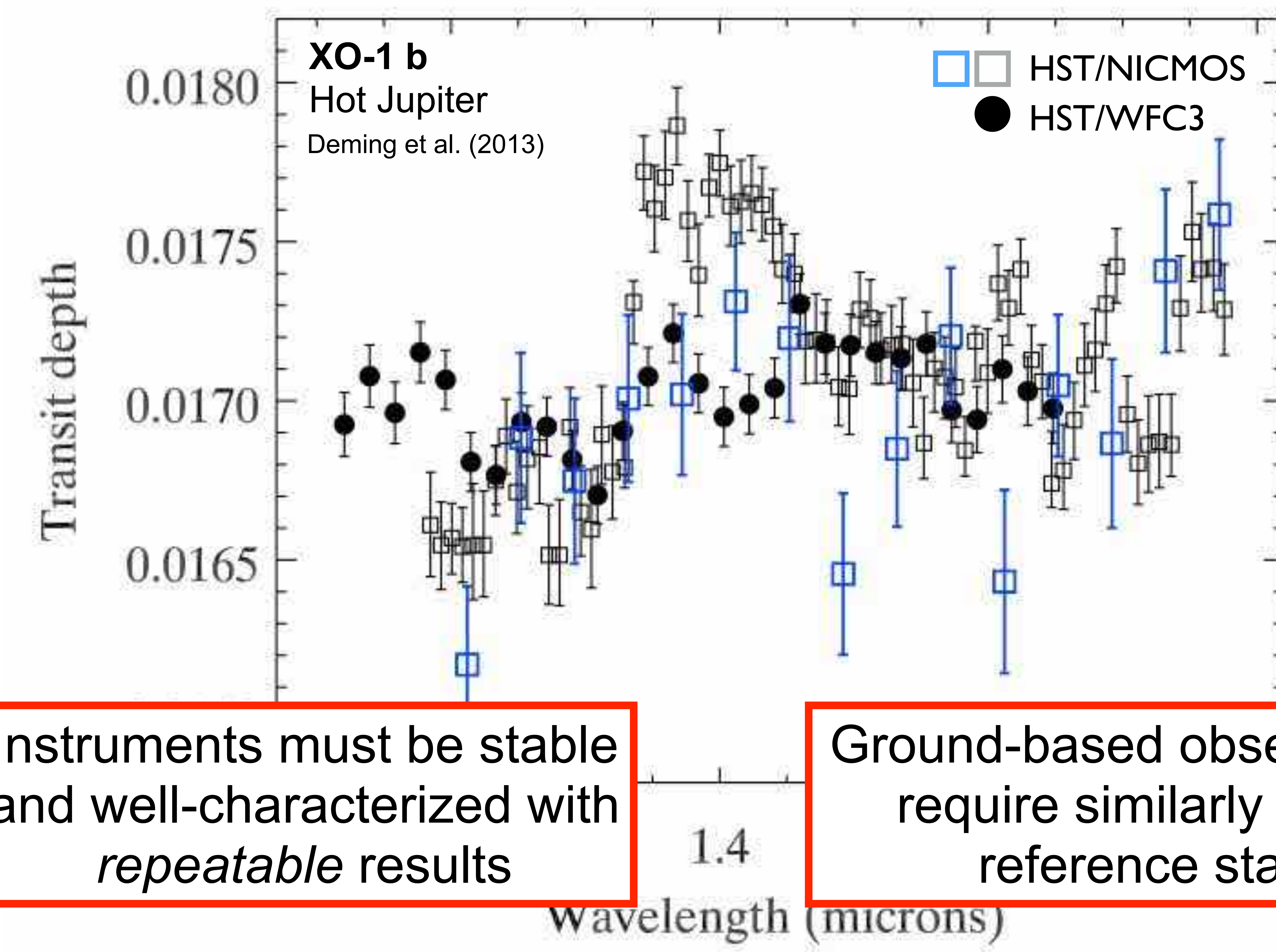


Even space telescopes suffer systematics >> planet signal



Instruments must be stable and well-characterized with *repeatable* results

Ground-based observations require similarly bright reference stars

“The nearest transiting potentially habitable planet is ~11 pc away.”

“The nearest [non-transiting] potentially habitable planet is ~2.5 pc away.”

(Dressing & Charbonneau 2015)

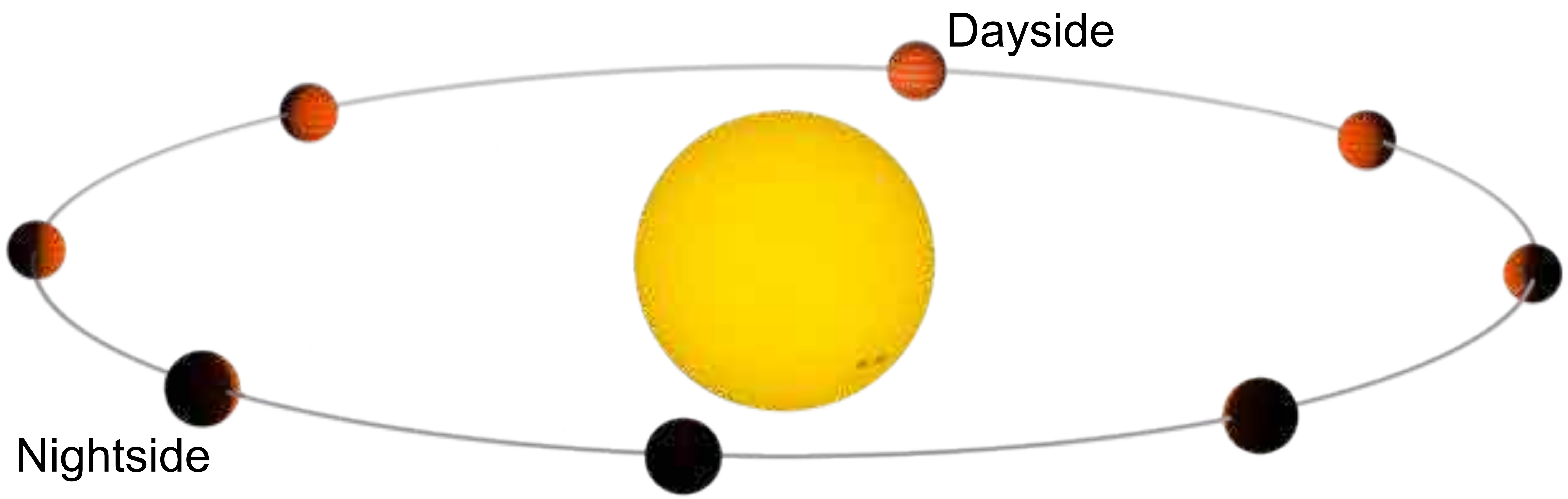
Detecting molecules with High Dispersion Spectroscopy (HDS)

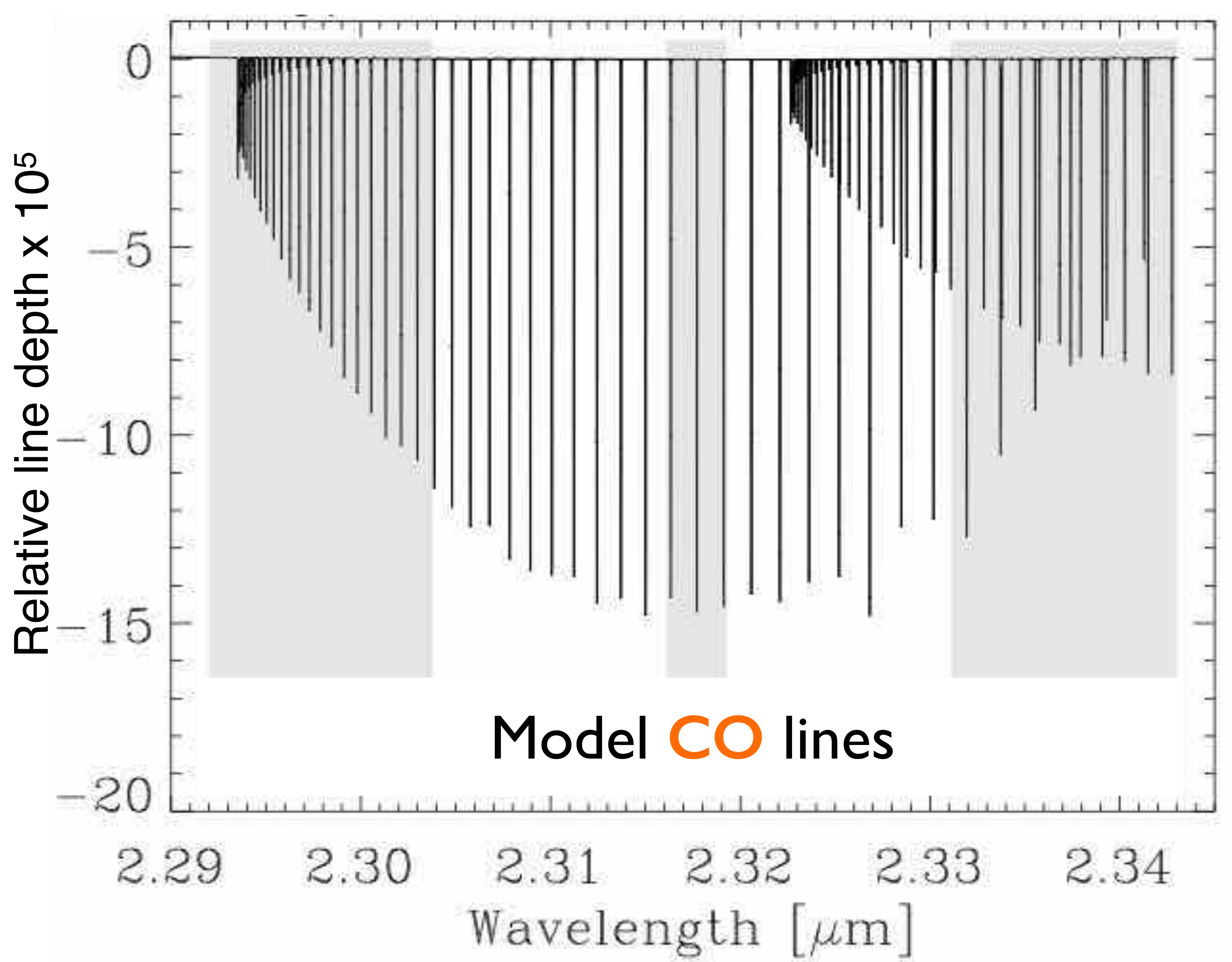
A CRIRES/VLT survey of hot Jupiter atmospheres

- CRIRES: CRyogenic high-resolution **InfraRed** Echelle Spectrograph
- **R=100,000 spectrograph, 8.2 m mirror**
- 155hrs
- 5 brightest host stars visible from Paranal, Chile (**K ~ 4 – 6 mag**):

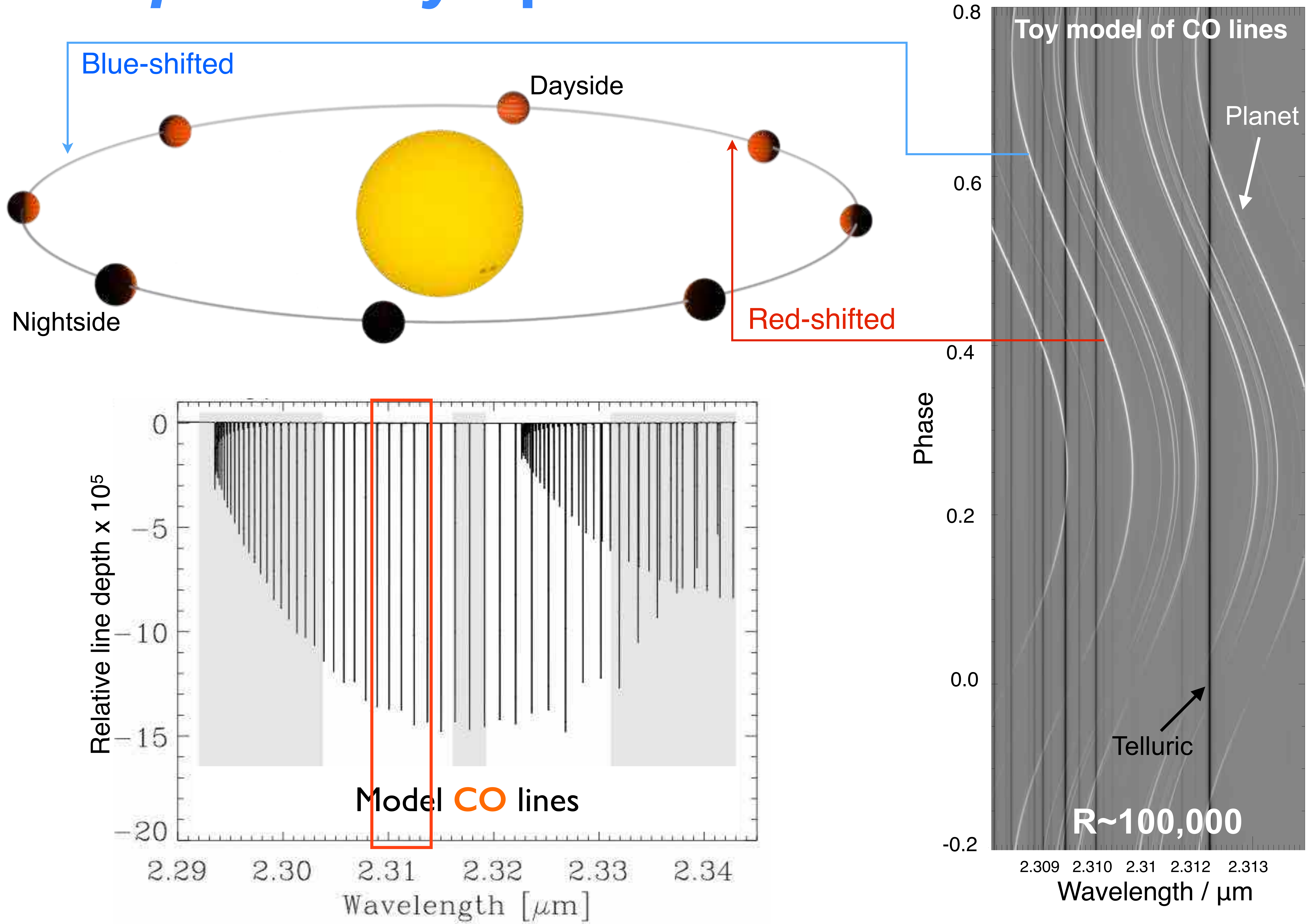
HD 209458 b, HD 189733 b, ***51 Peg b, τ Boo b, HD 179499 b***

HDS detects the radial velocity shift of the *planetary* spectrum





HDS detects the radial velocity shift of the *planetary* spectrum



Telluric features eliminated by removing common modes in time

Wavelength

CRIRES pipeline output after alignment

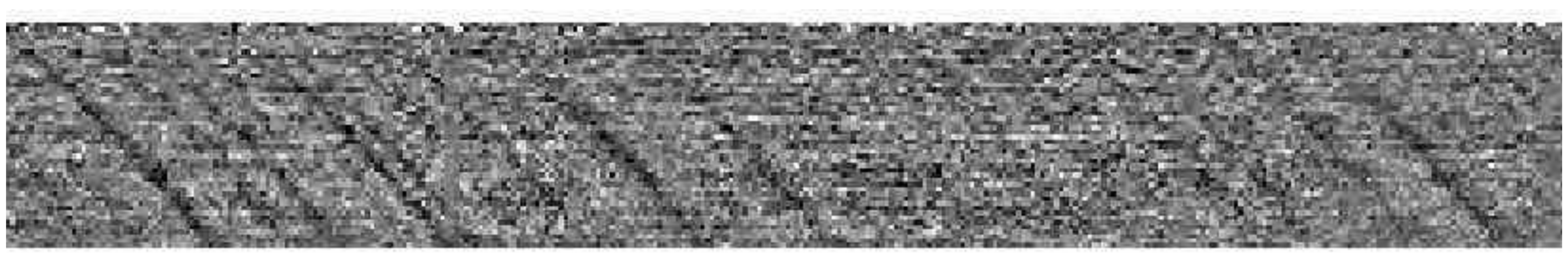
SNR~200 per resolution element

Mean-subtracted spectra as input to Sysrem

After first Sysrem iteration, airmass-like trend removed

After optimal Sysrem iterations

Standard deviation ~ 5×10^{-4}



10x nominal model injected

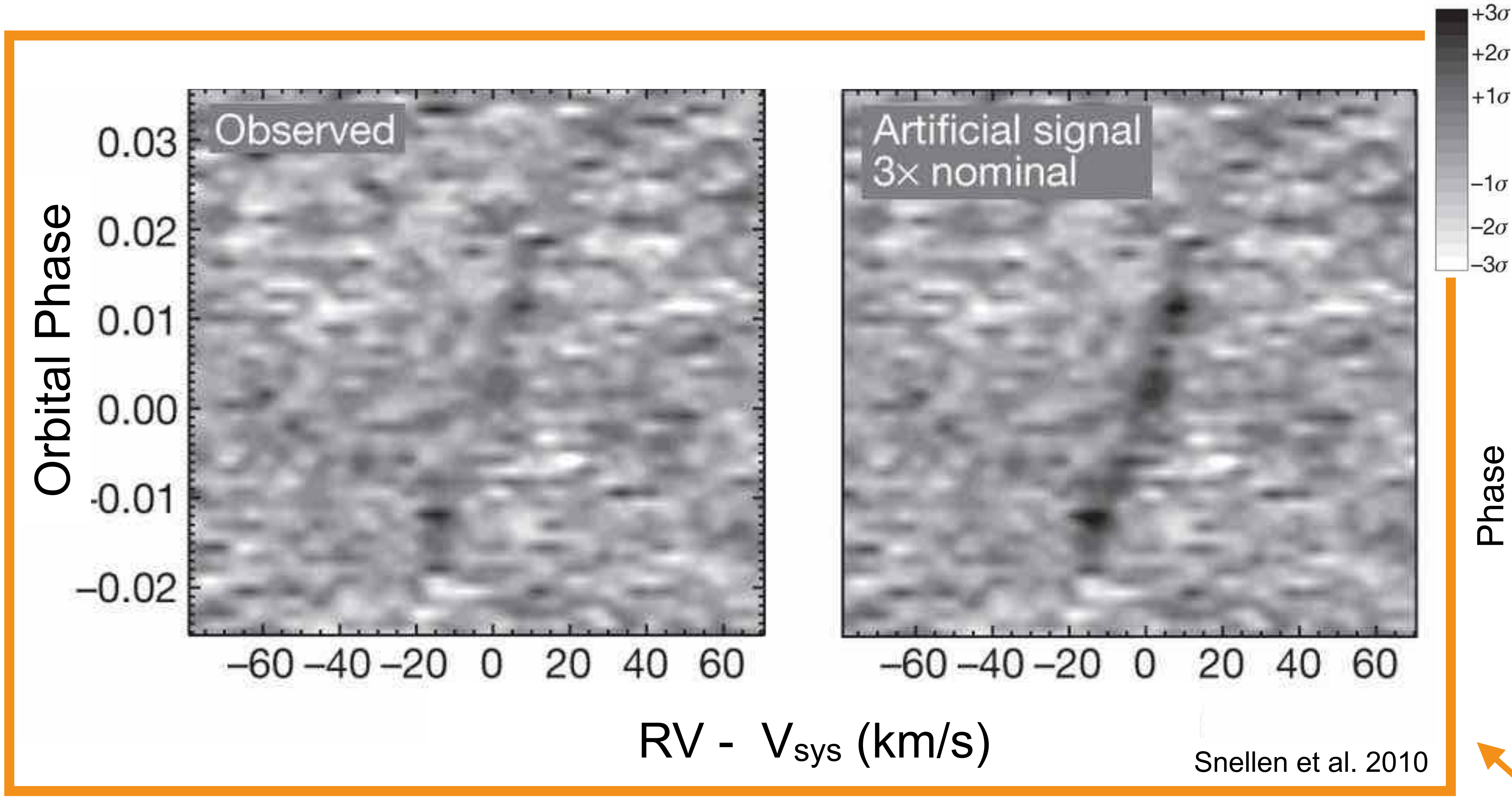
Birkby et al. 2013

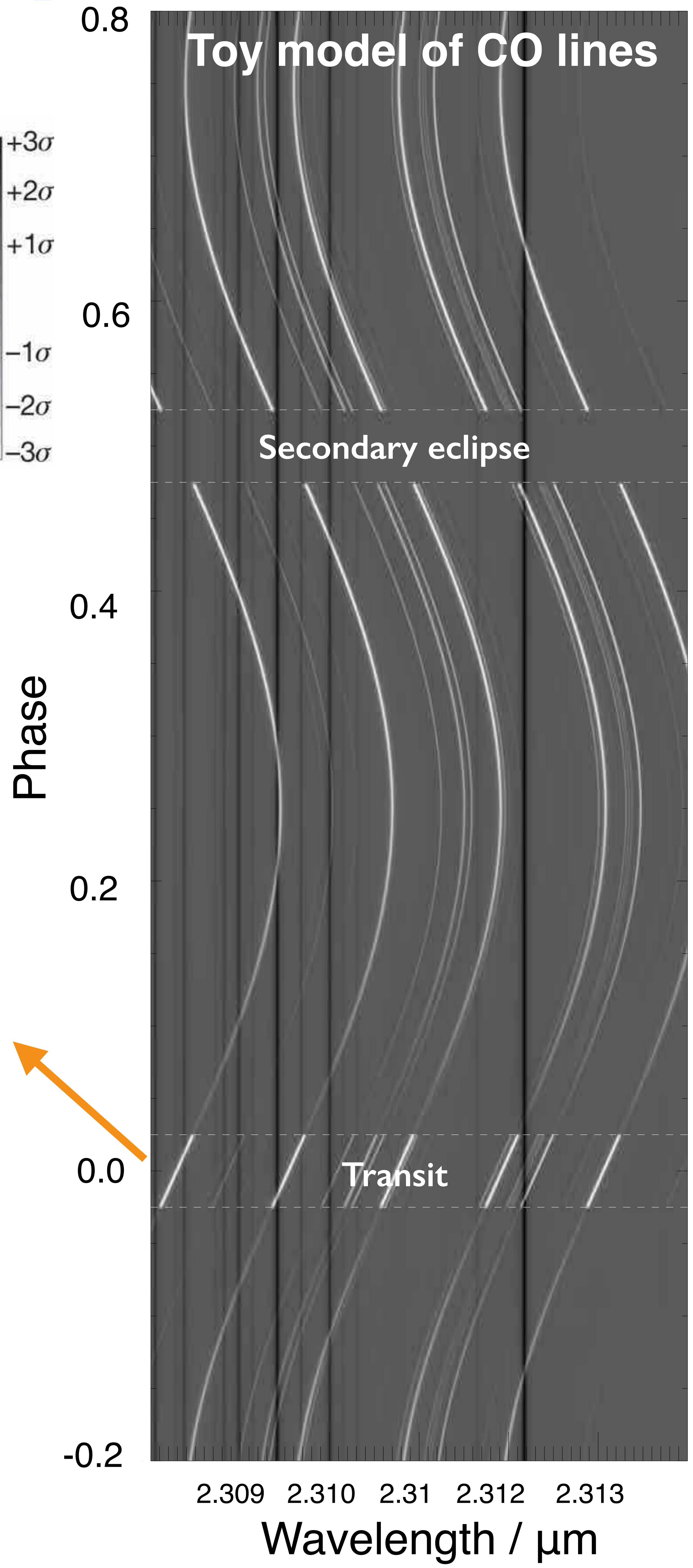
SYSREM

- Treats pixel channels as light curves (1024 light curves per detector)
- PCA-like algorithm identifies trends as a function of time
- Data are ***self-calibrating***

Combine signal from individual lines via cross-correlation

HDS detects carbon monoxide RV trail in a transiting hot Jupiter atmosphere





CO detected at **5.6σ** at **2.3 µm** in HD 209458 b during transit with **5 hrs** on CRIRES/VLT

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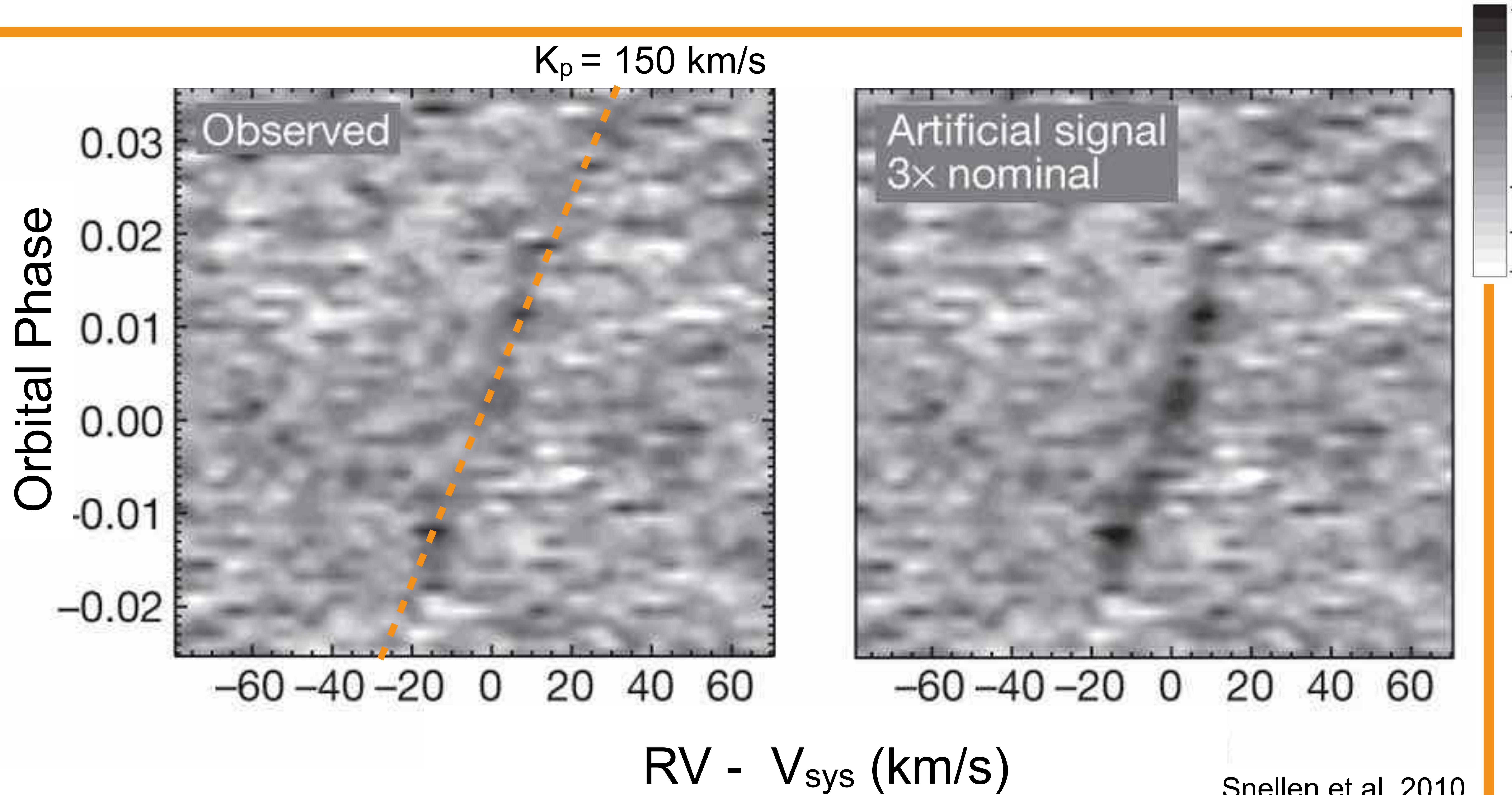
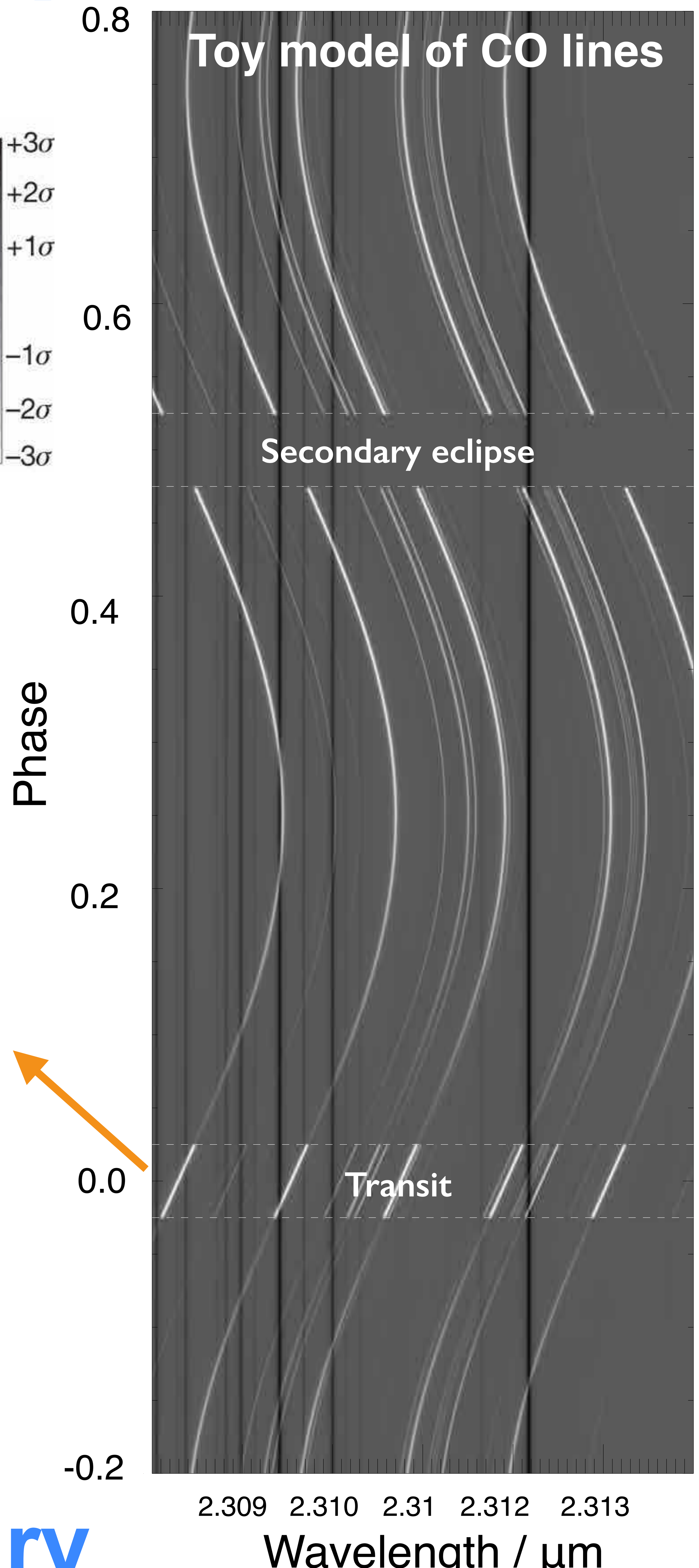


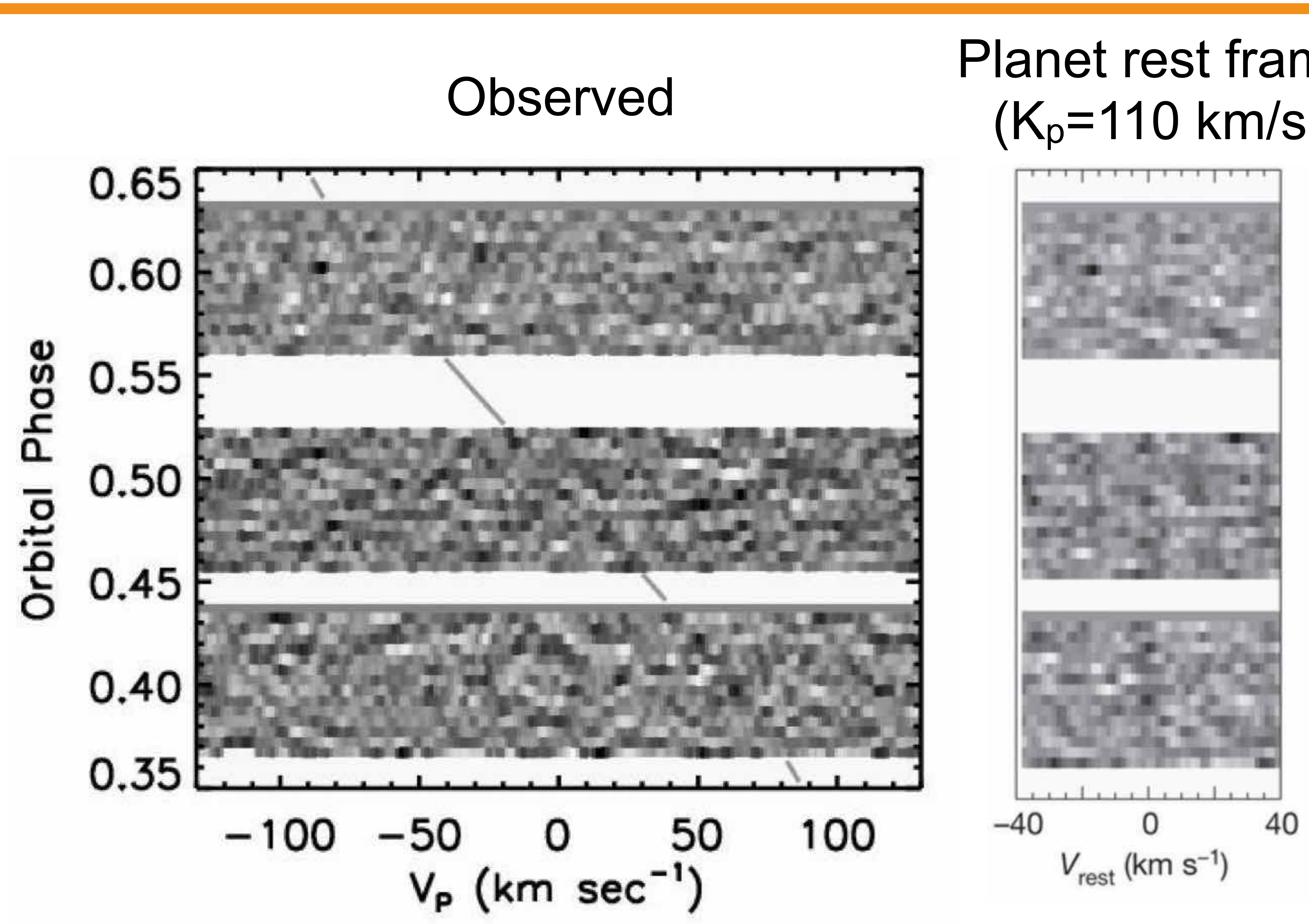
Snellen et al. 2010



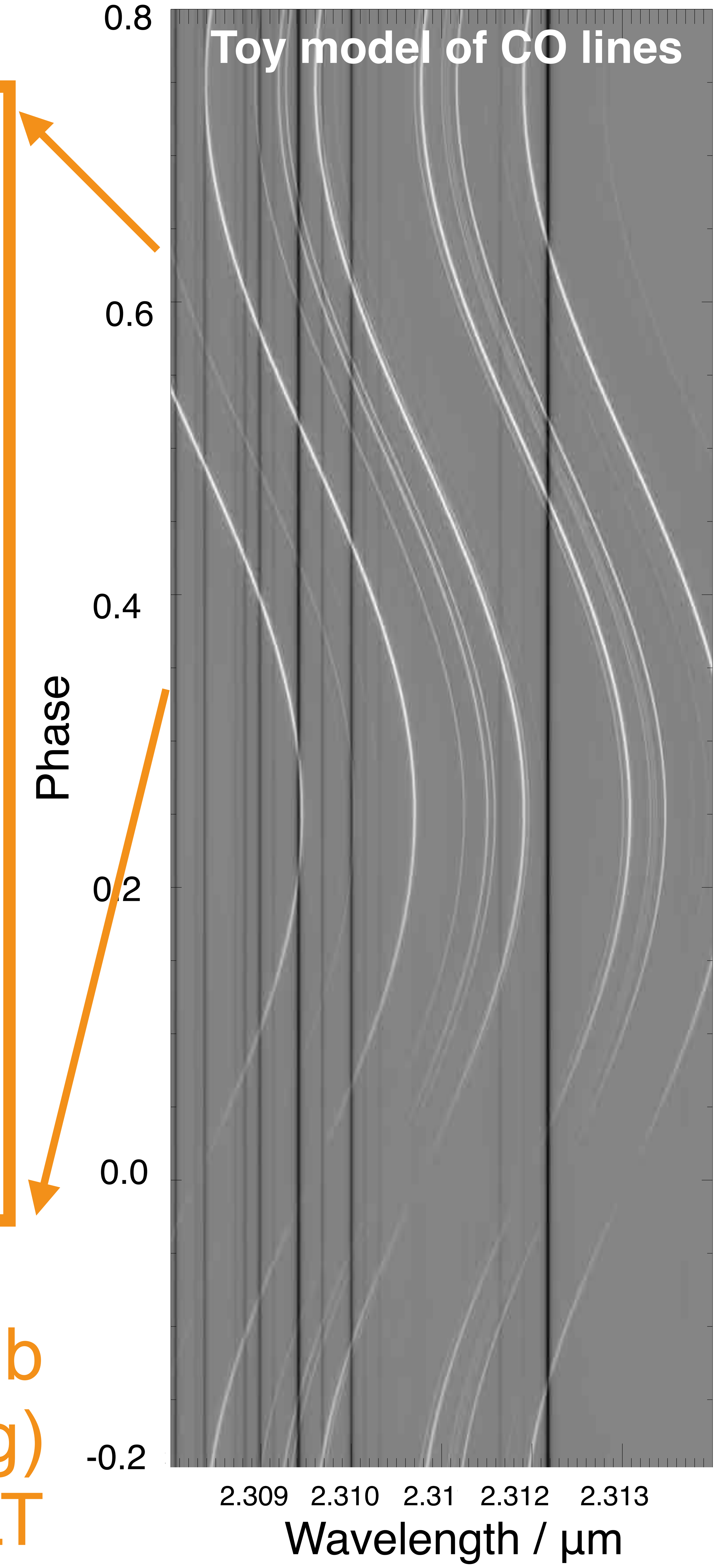
CO detected at **5.6σ** at **2.3 µm** in HD 209458 b during transit with **5 hrs** on CRIRES/VLT

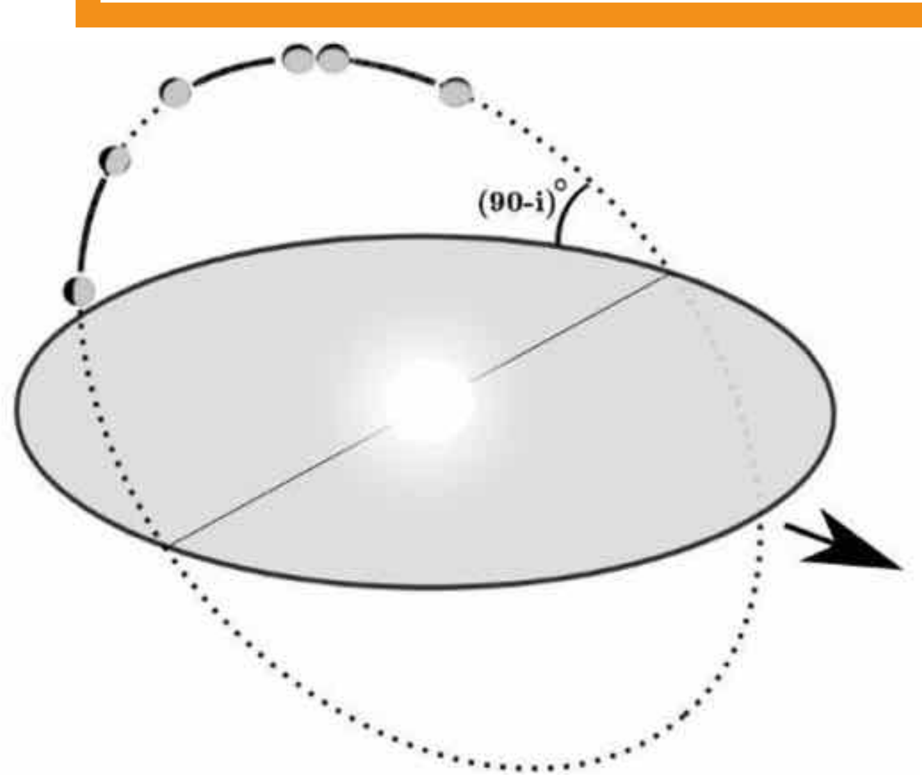
Non-transiting planet = spectroscopic binary

HDS detects carbon monoxide RV trail in a *non-transiting* hot Jupiter atmosphere



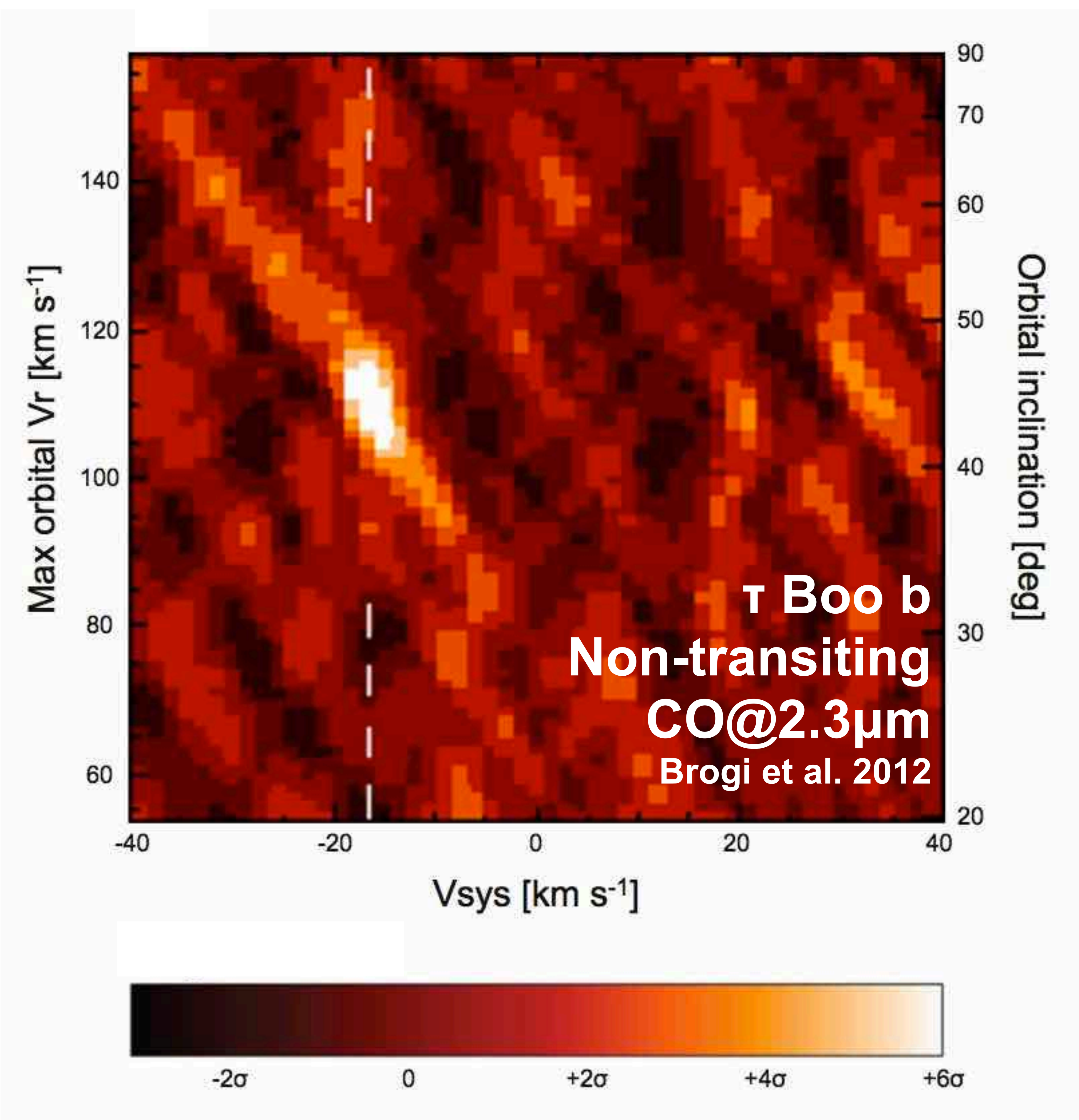
Brogi et al. 2012

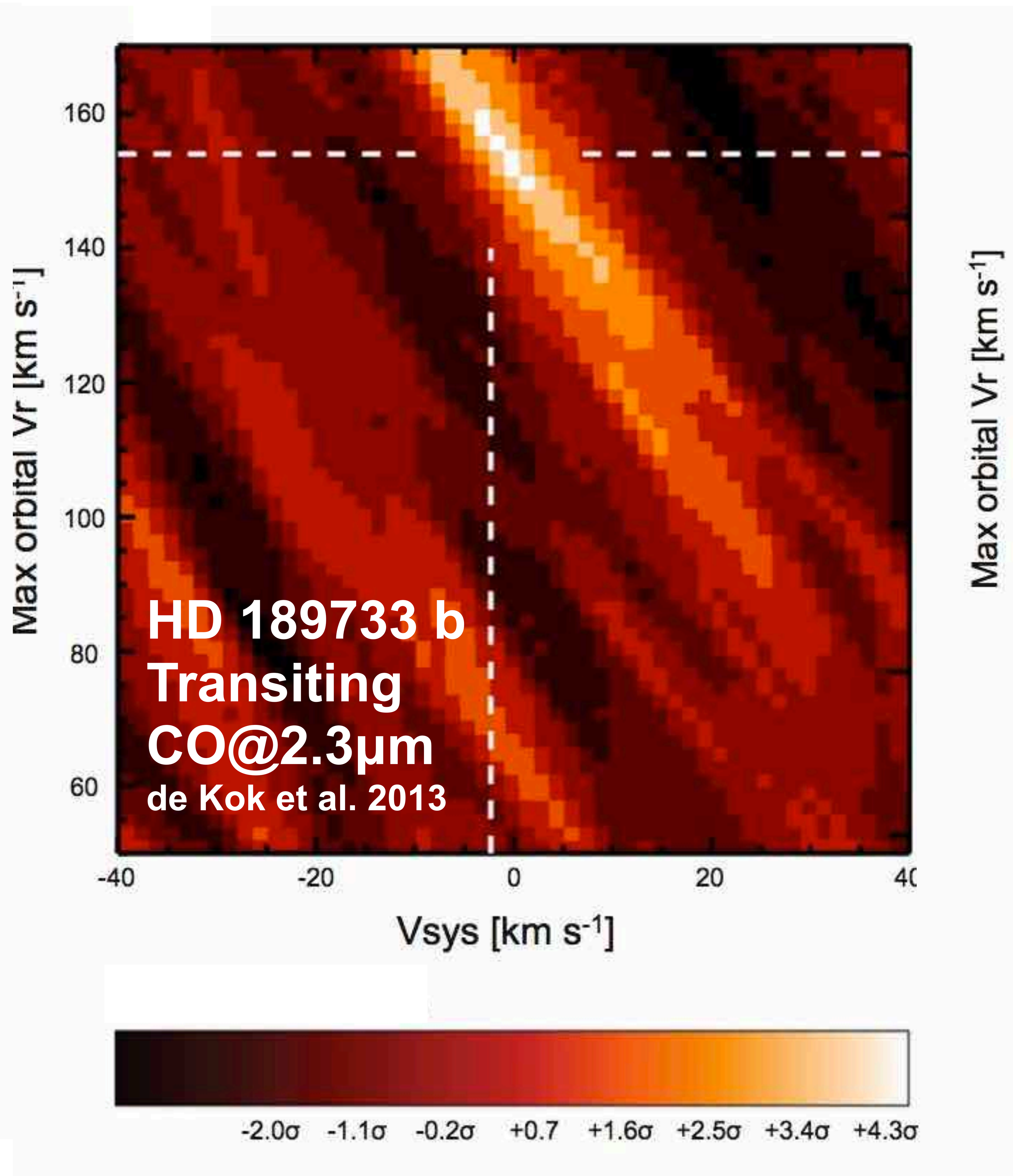


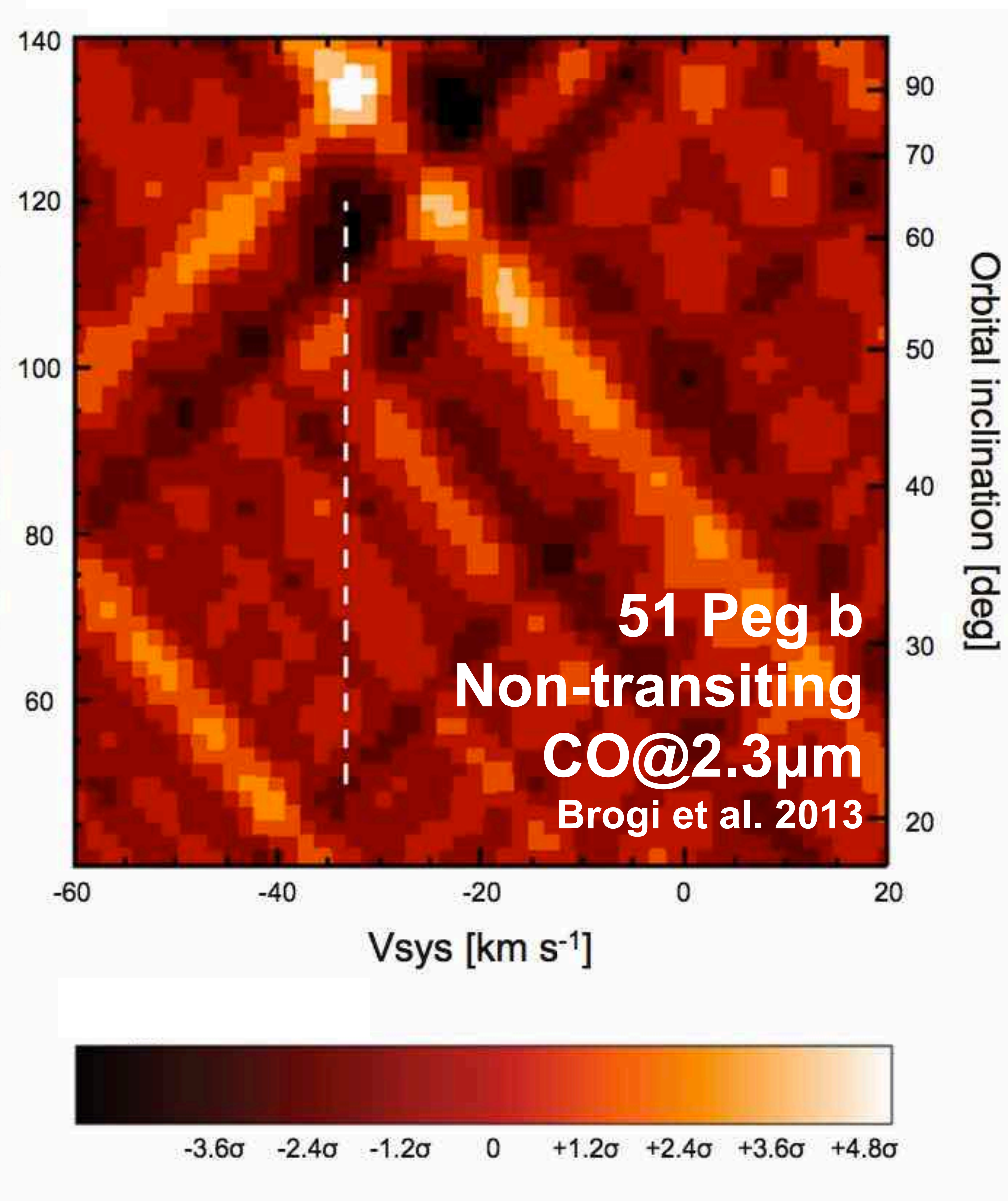


CO detected at **6σ** at **2.3 µm** in τ Boo b on the dayside hemisphere (non-transiting) with CRIRES/VLT

HDS provides unambiguous detections of CO in hot Jupiter atmospheres

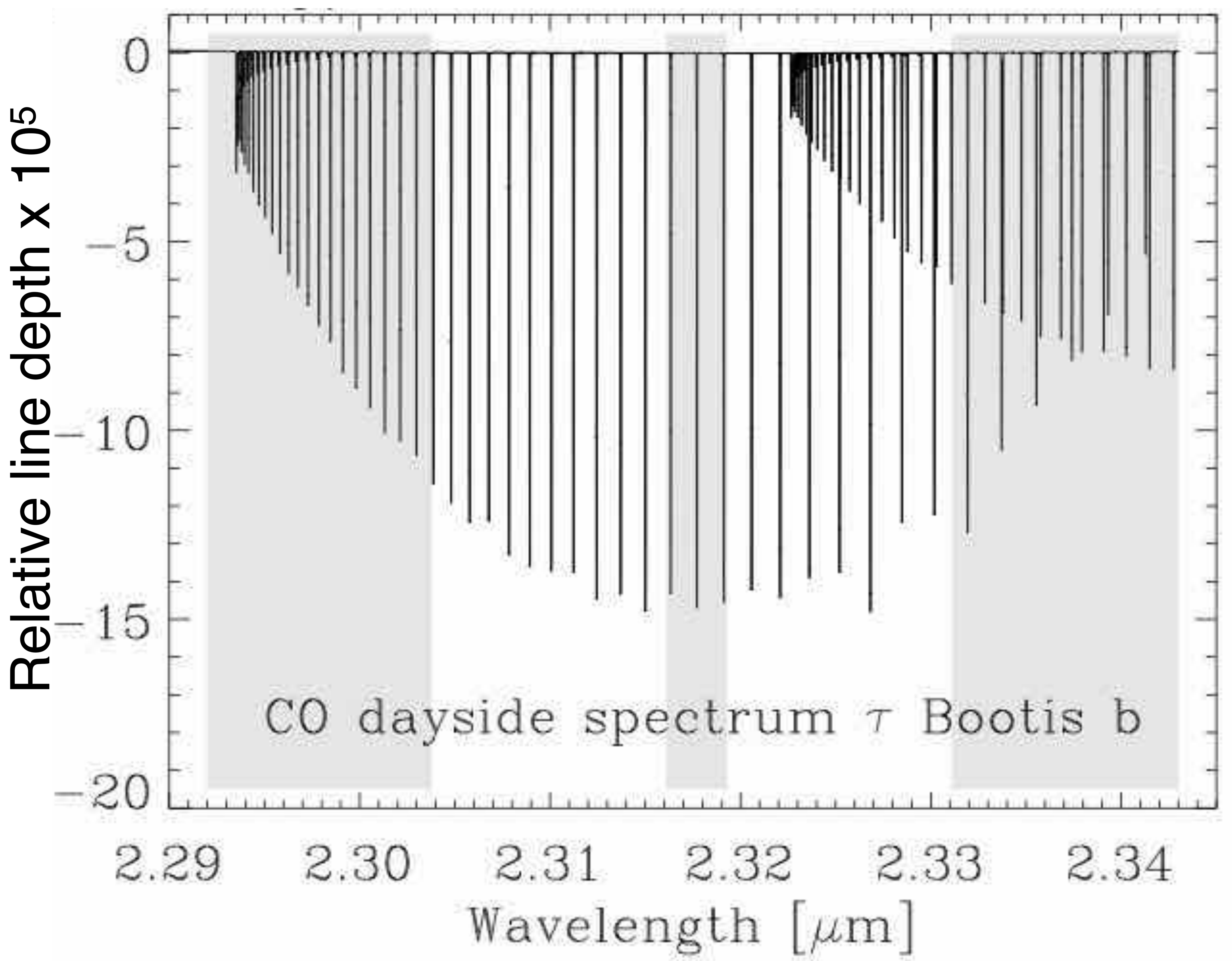




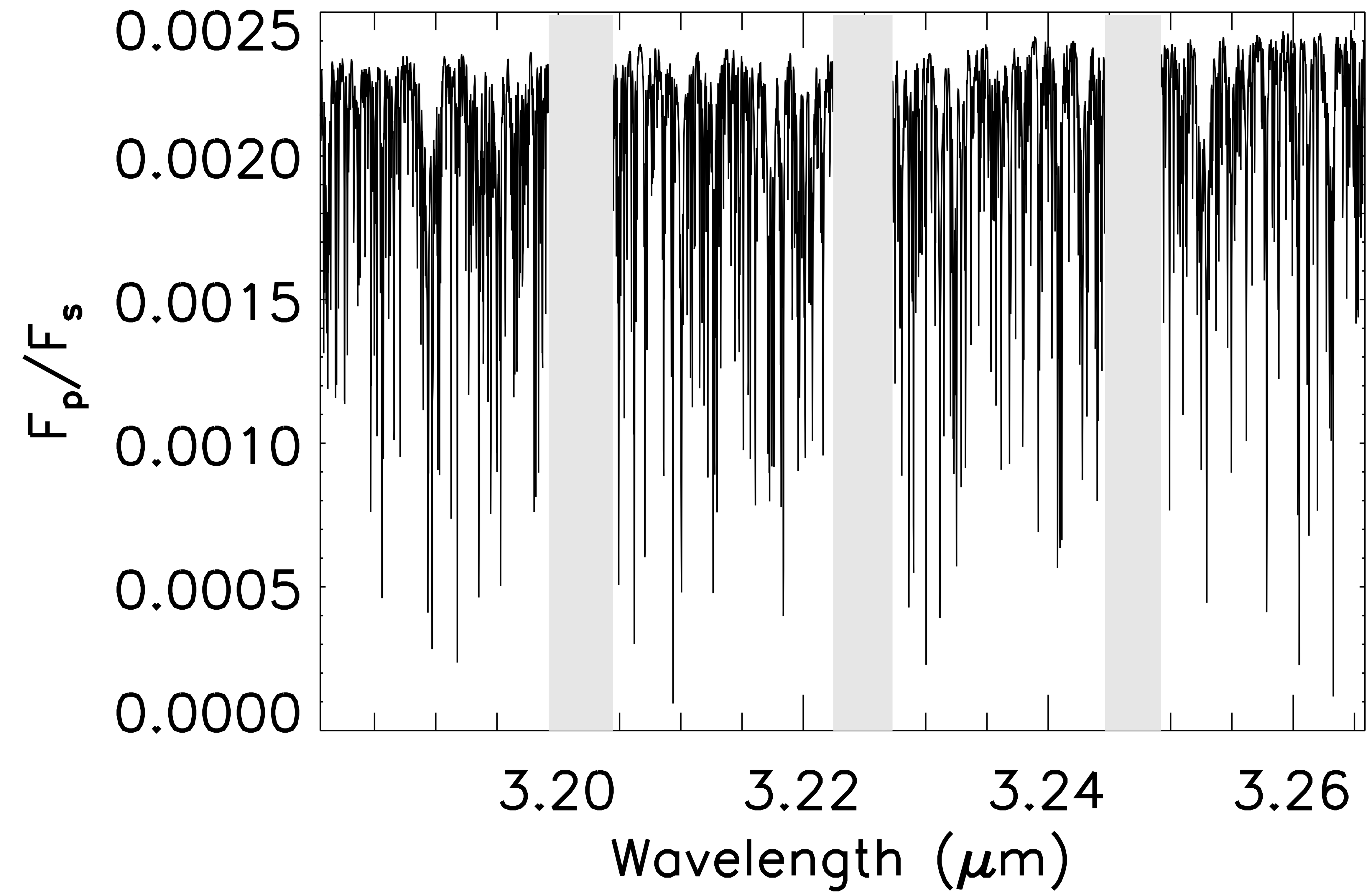


Other molecules are more complex and appear at different wavelengths

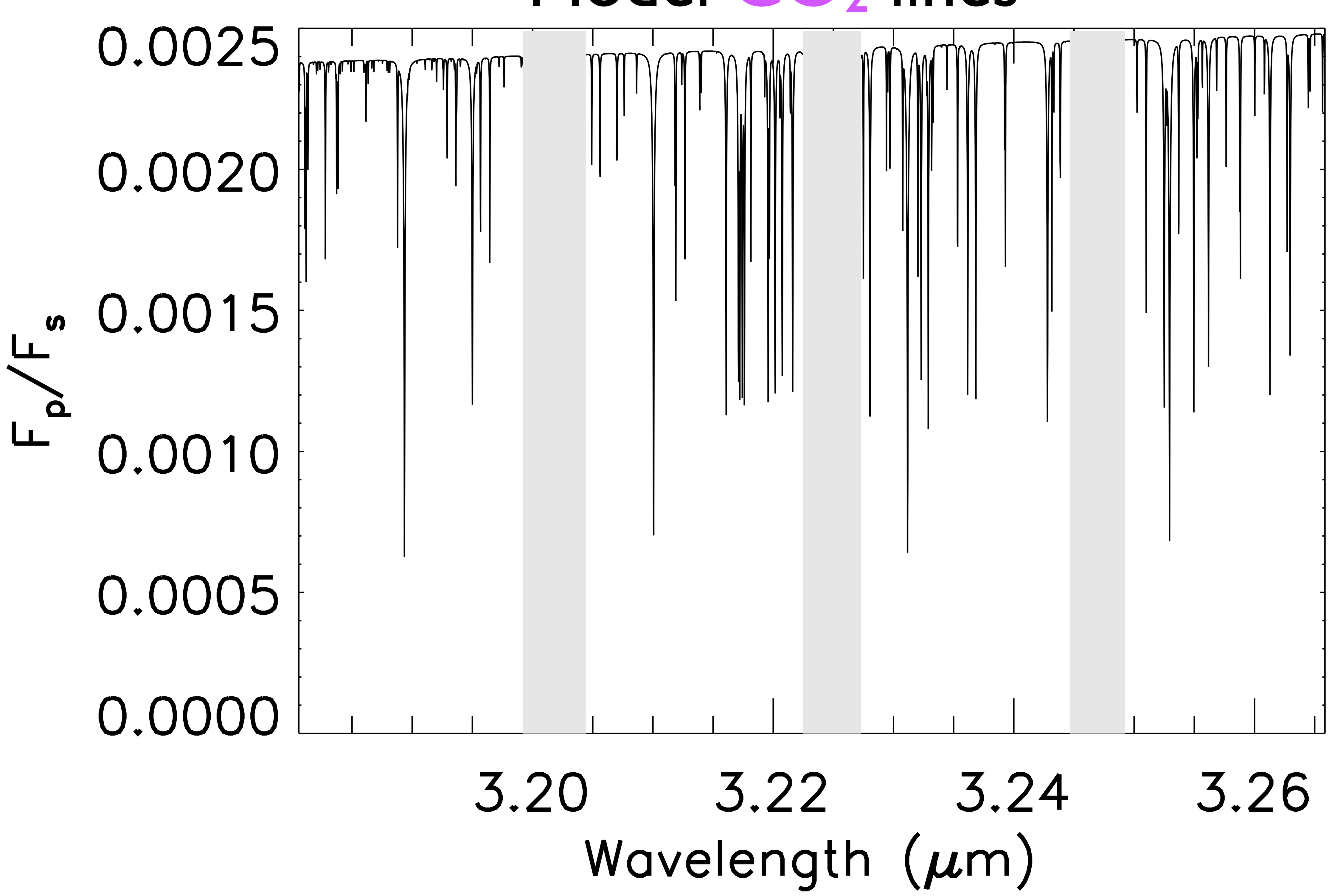
Model CO lines



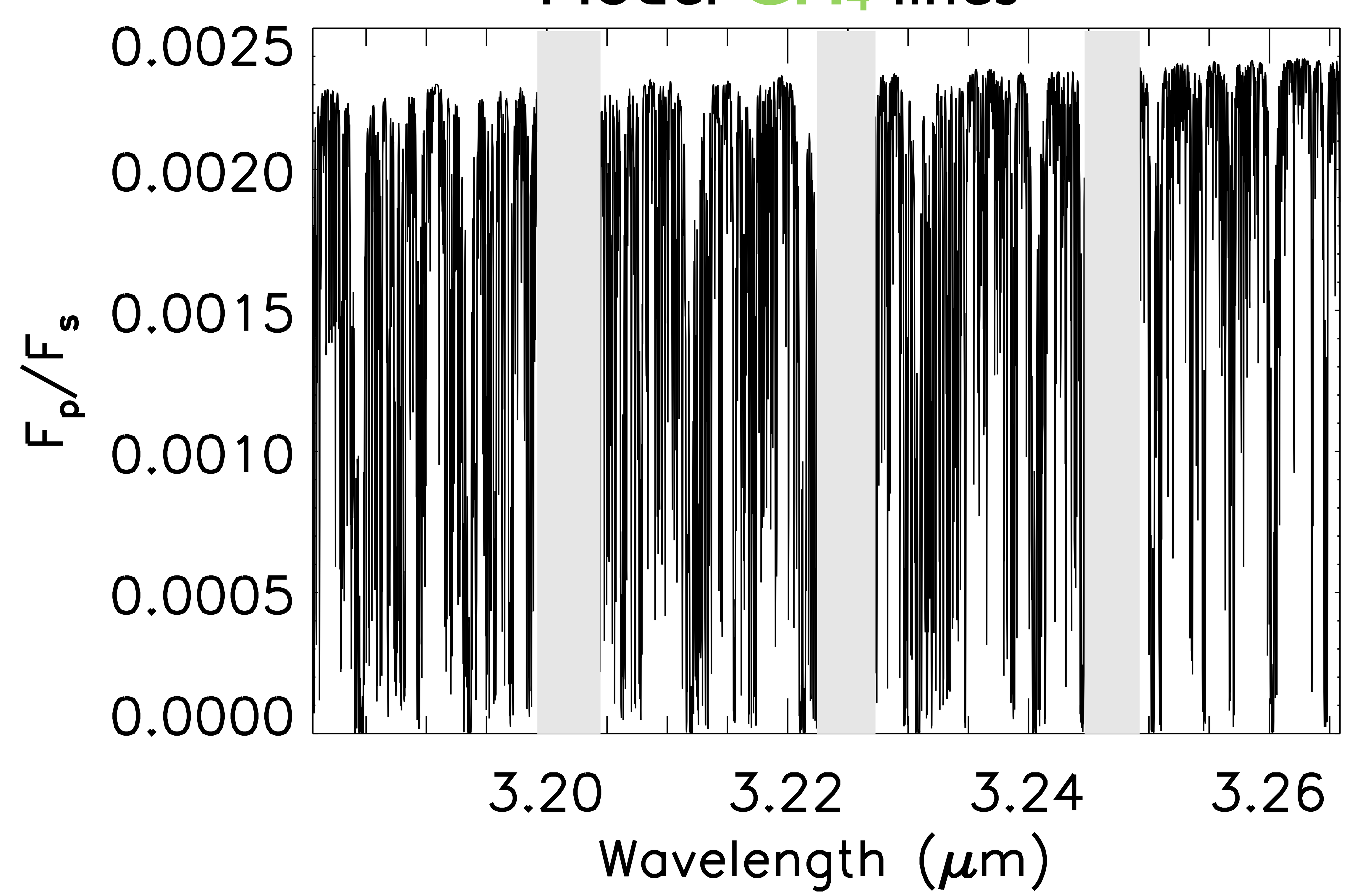
Model H_2O lines



Model CO_2 lines

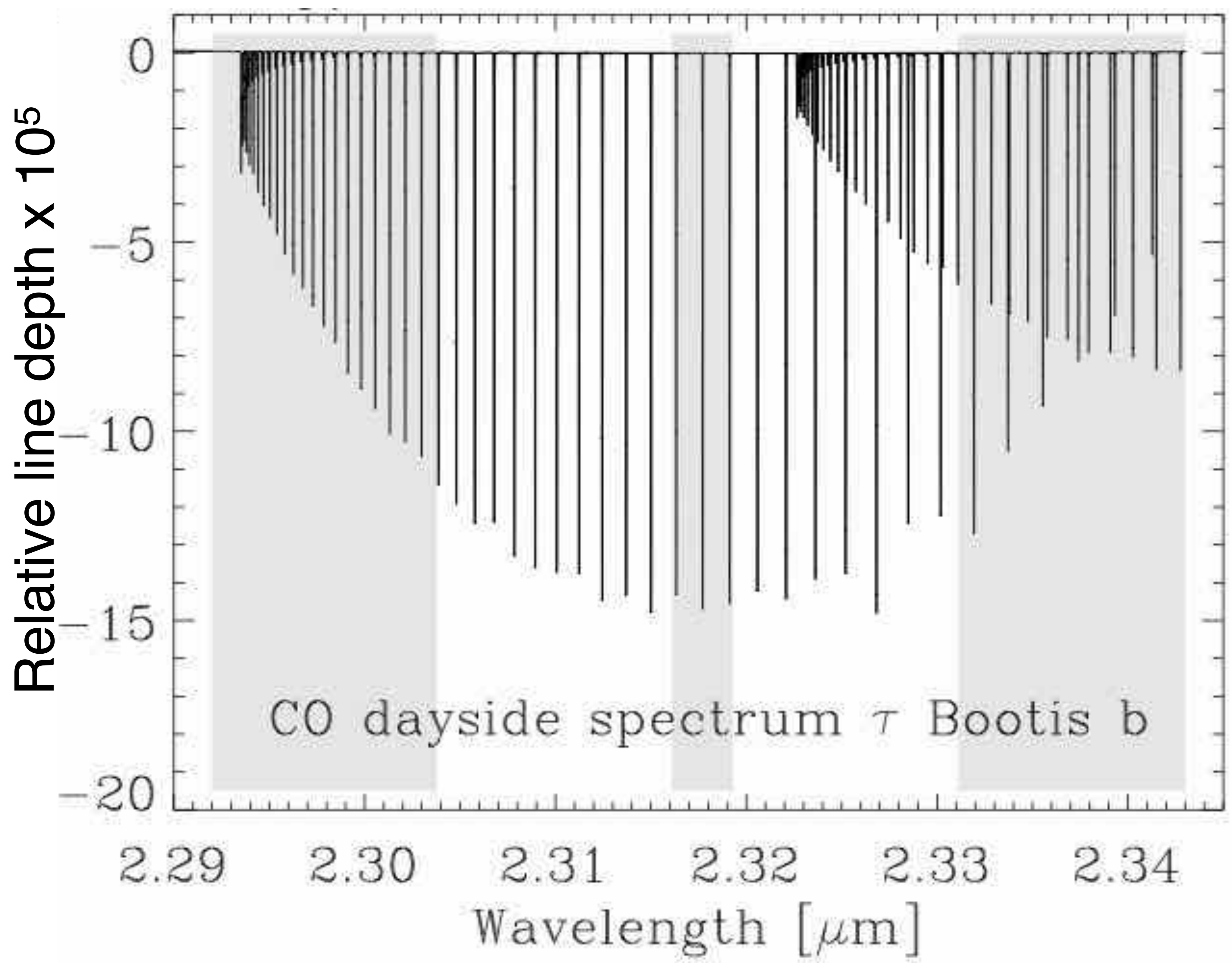


Model CH_4 lines



Other molecules are more complex and appear at different wavelengths

Model CO lines



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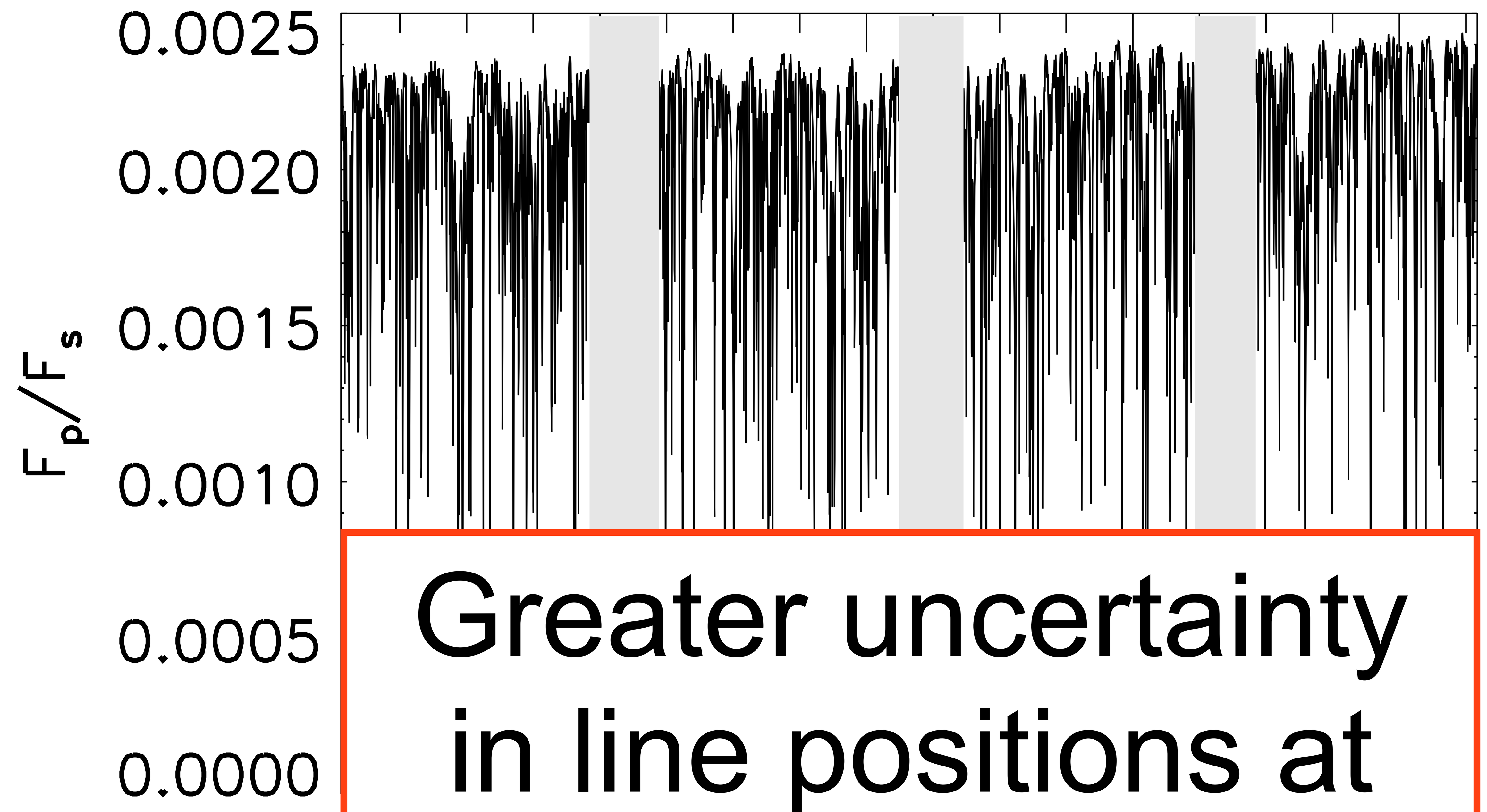
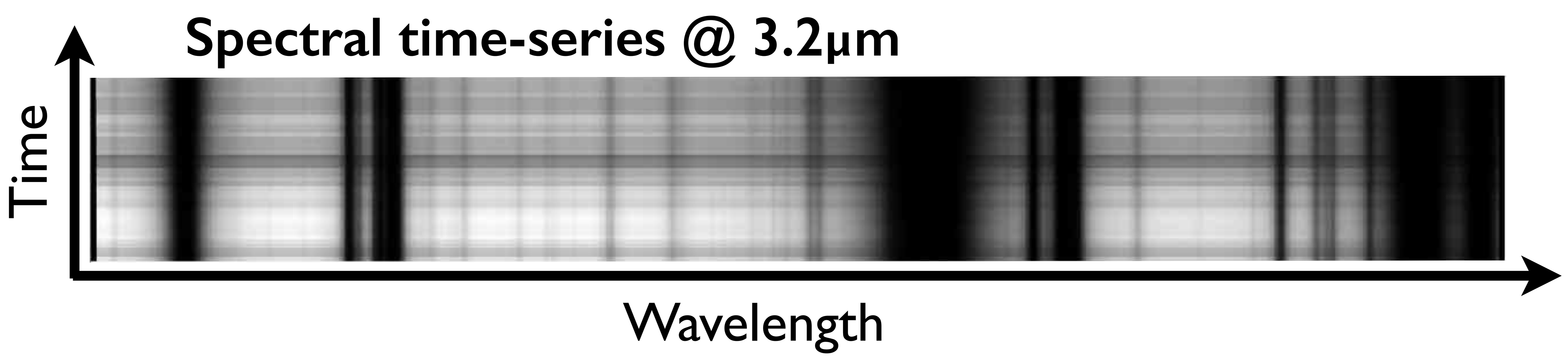


Greater uncertainty in line positions at *high temperatures*

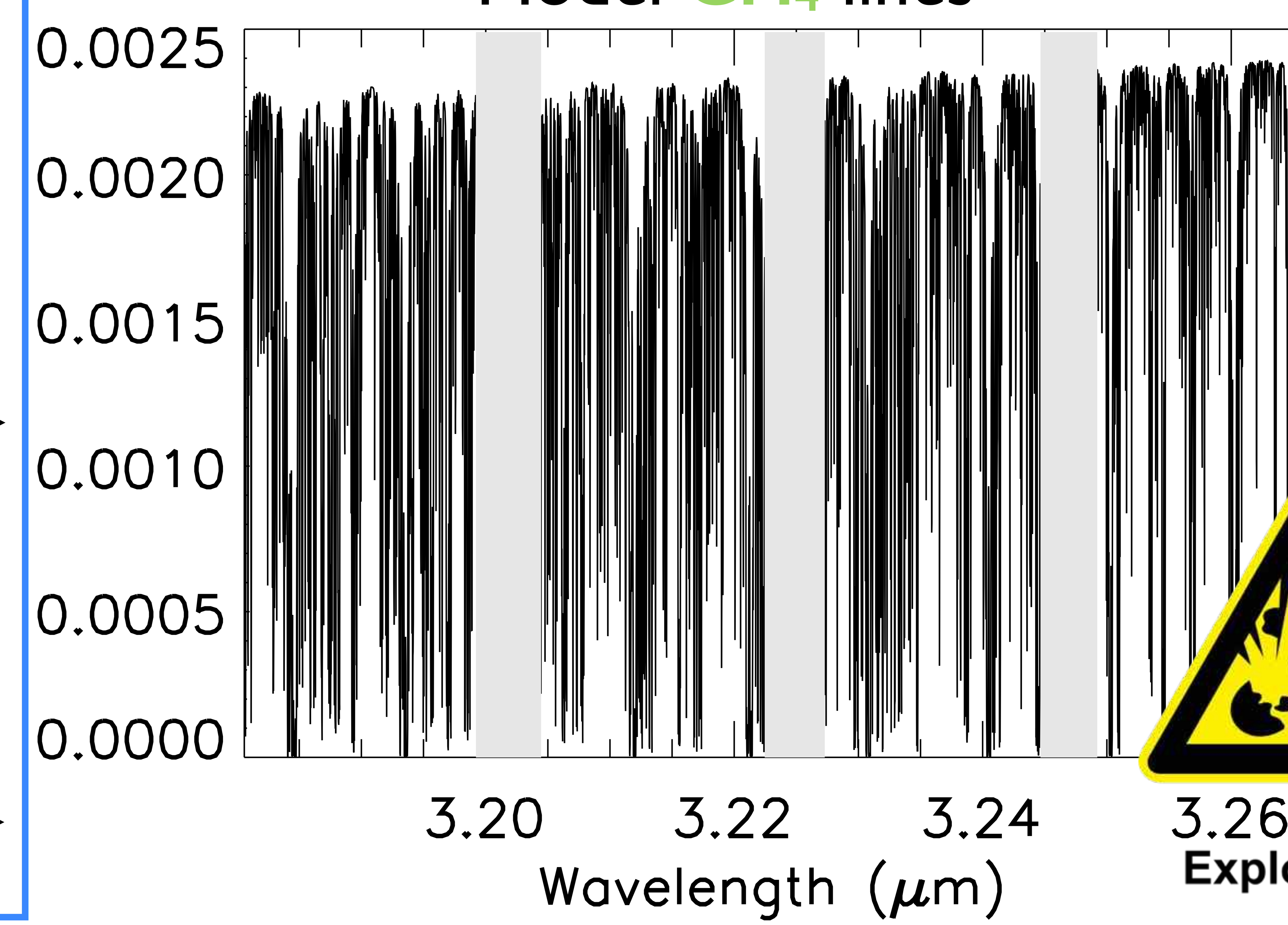
More telluric contamination

Spectral time-series @ 2.3μm

Spectral time-series @ 3.2μm

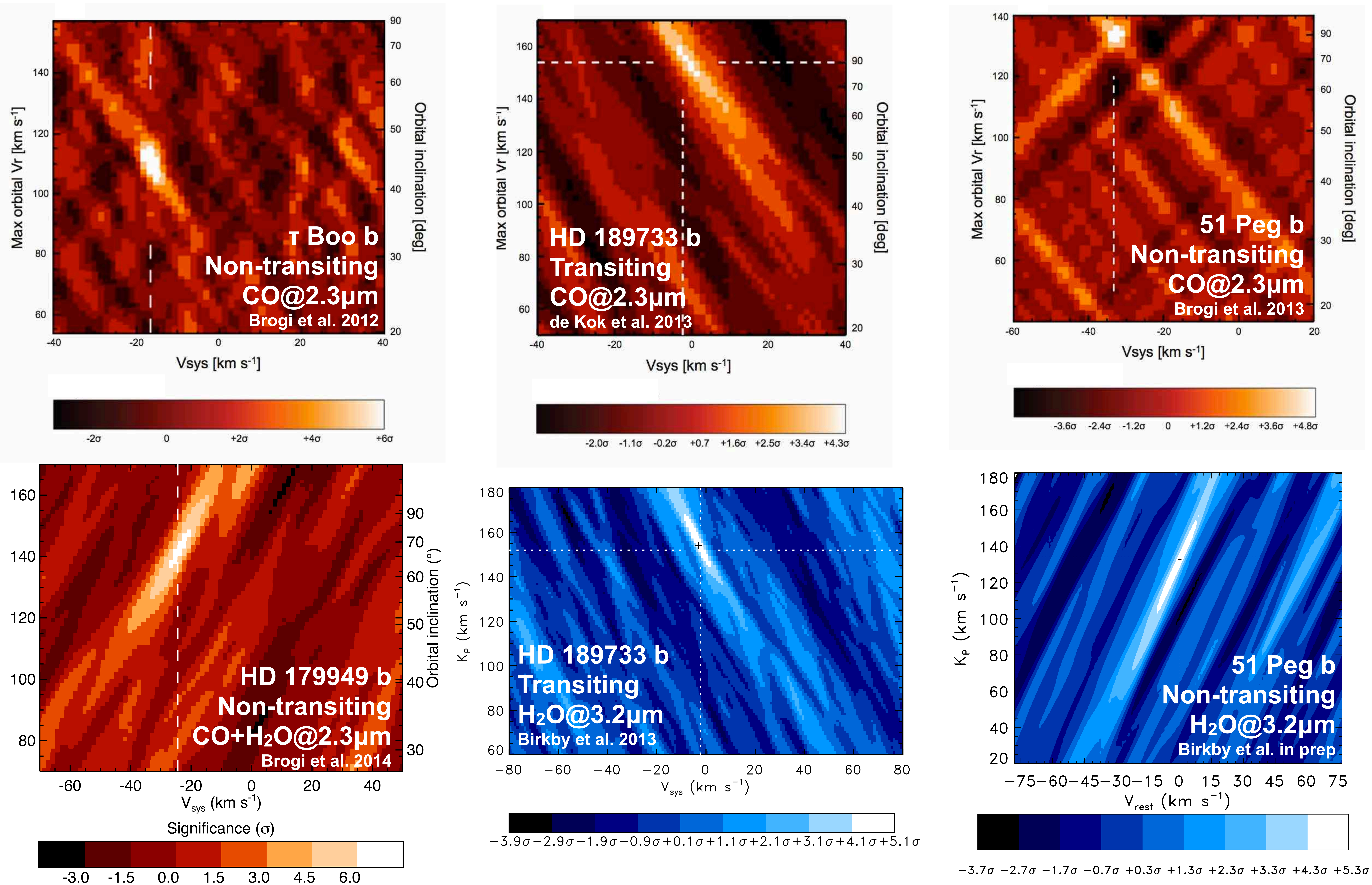


Model CH_4 lines



2000K
Explosion risk

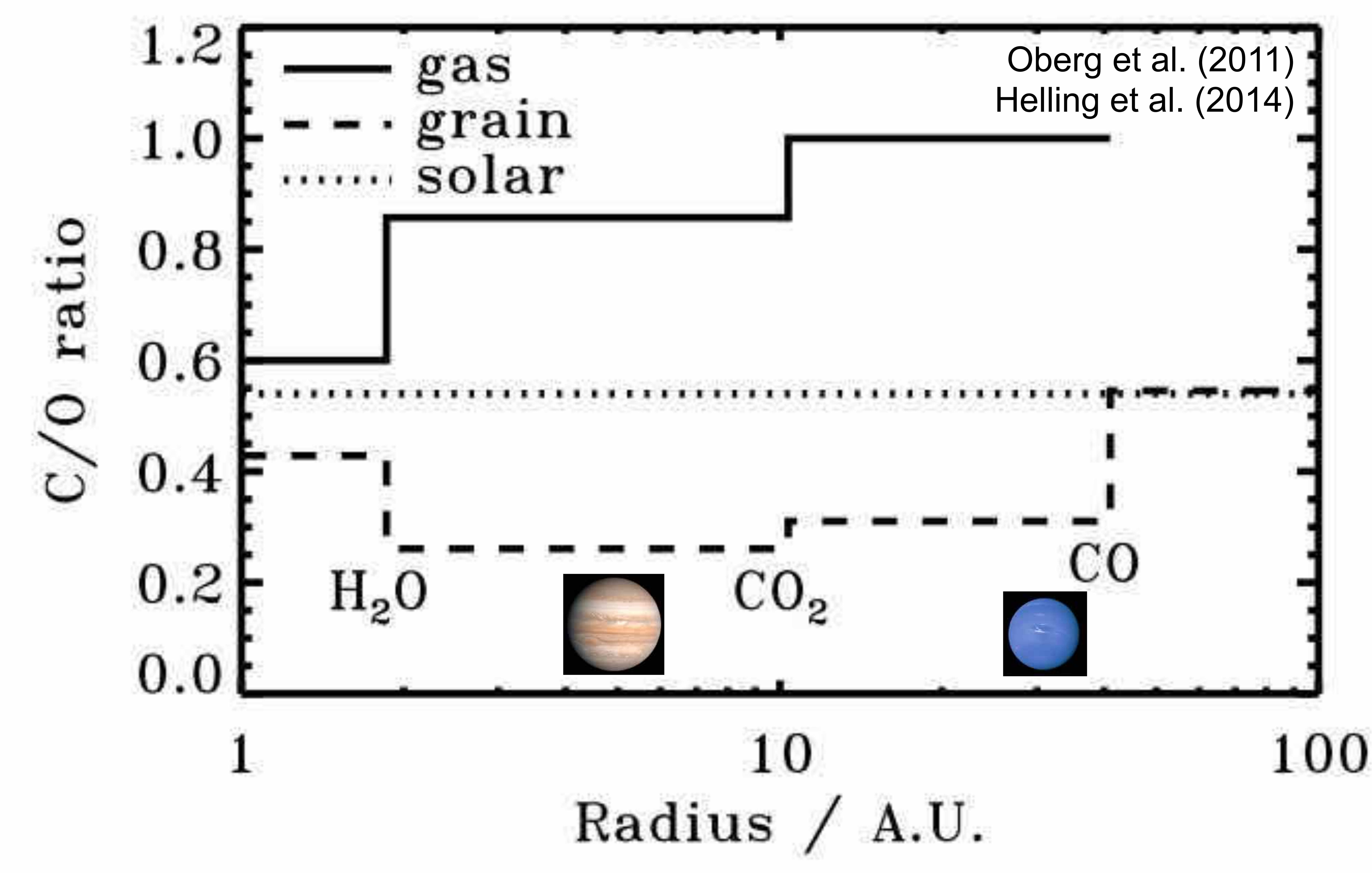
HDS provides unambiguous detections of complex molecules in hot Jupiter atmospheres



See also Rodler et al. 2012; 2013 (CO in τ Boo b & HD 189733 b); Lockwood et al. 2014 (H_2O in τ Boo b)

Exoplanet atmospheres as fossil records?

C/O ratio could reveal where and how a planet formed in its protoplanetary disk



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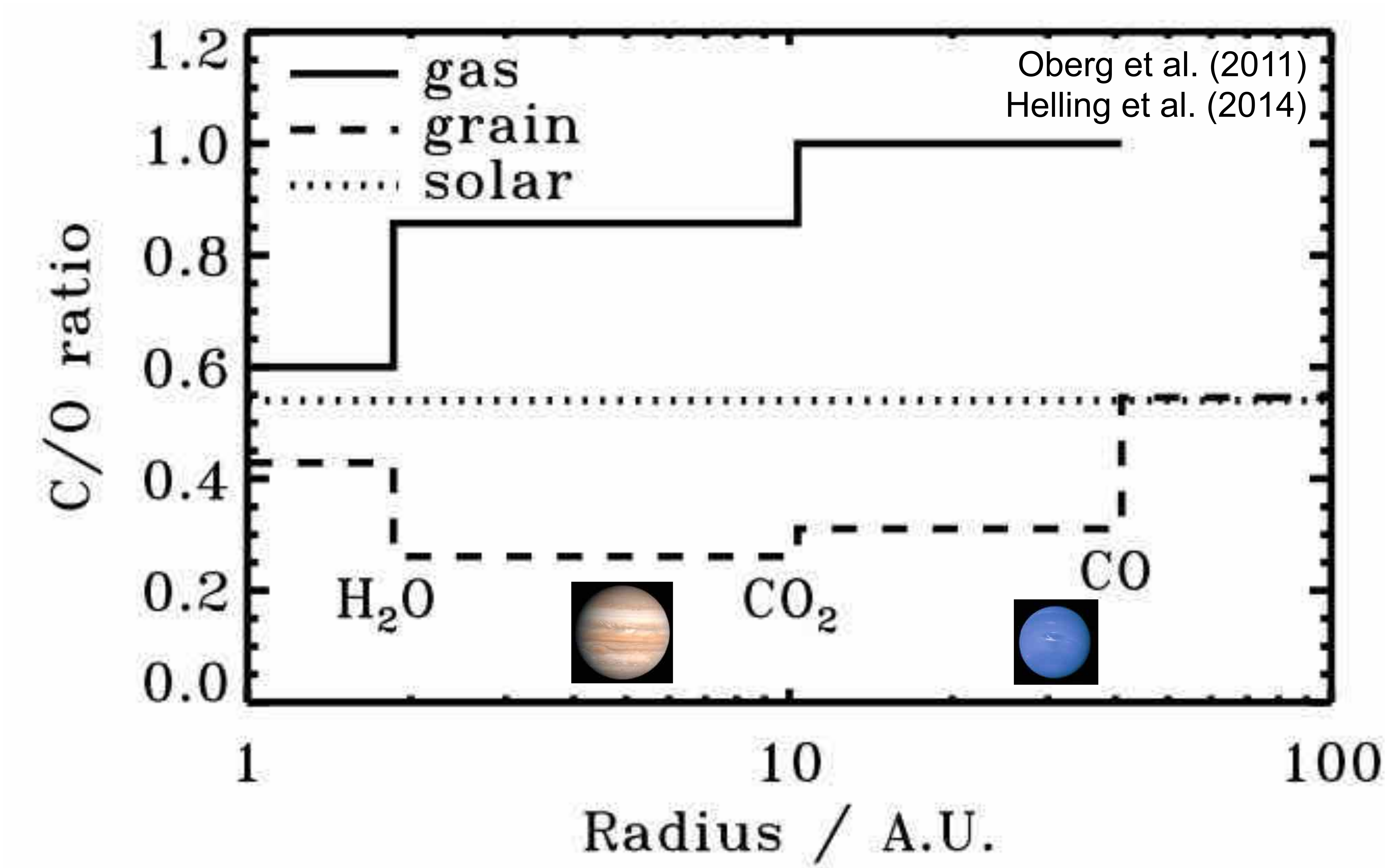
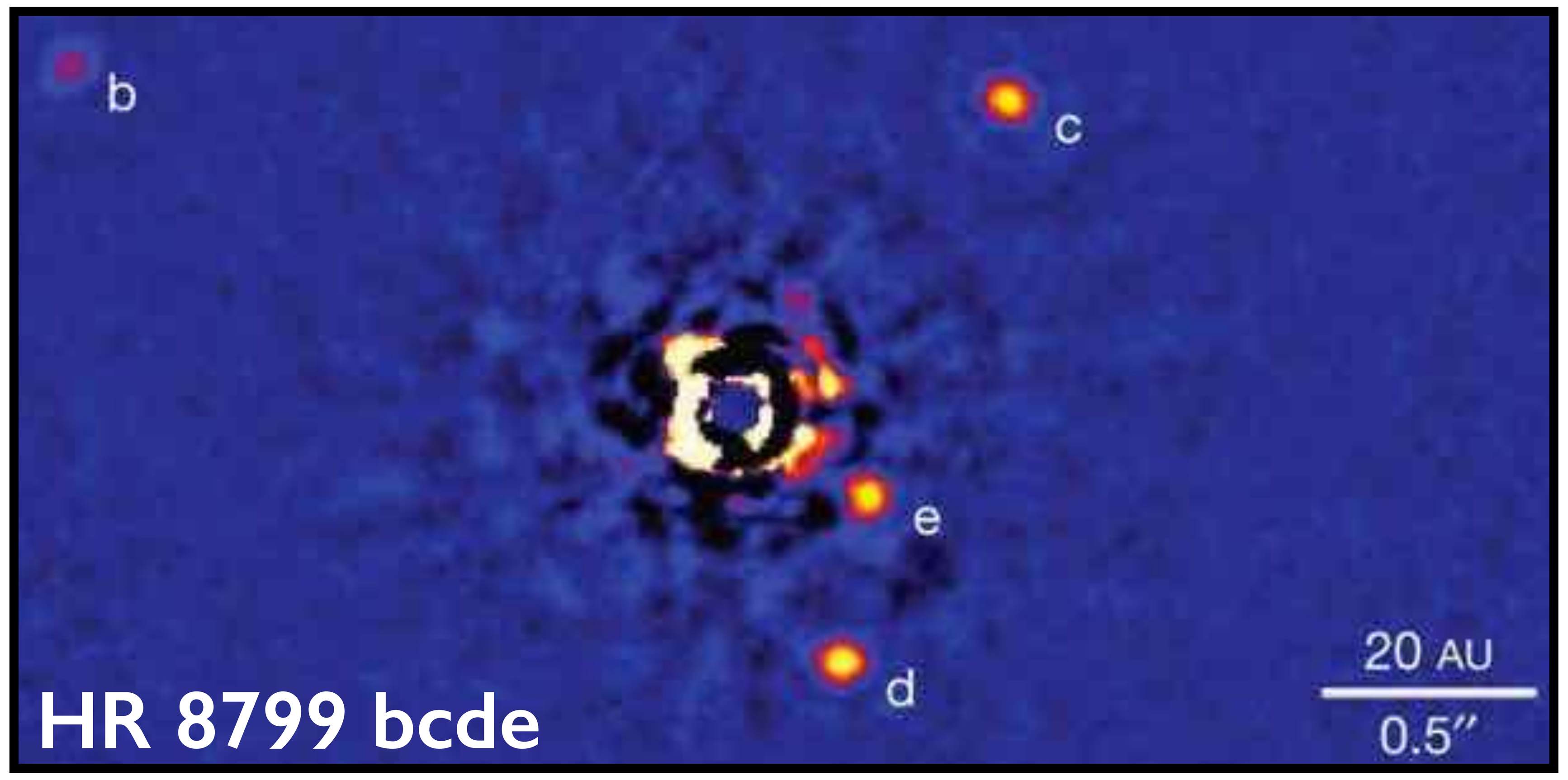


Marois et al. (2010)



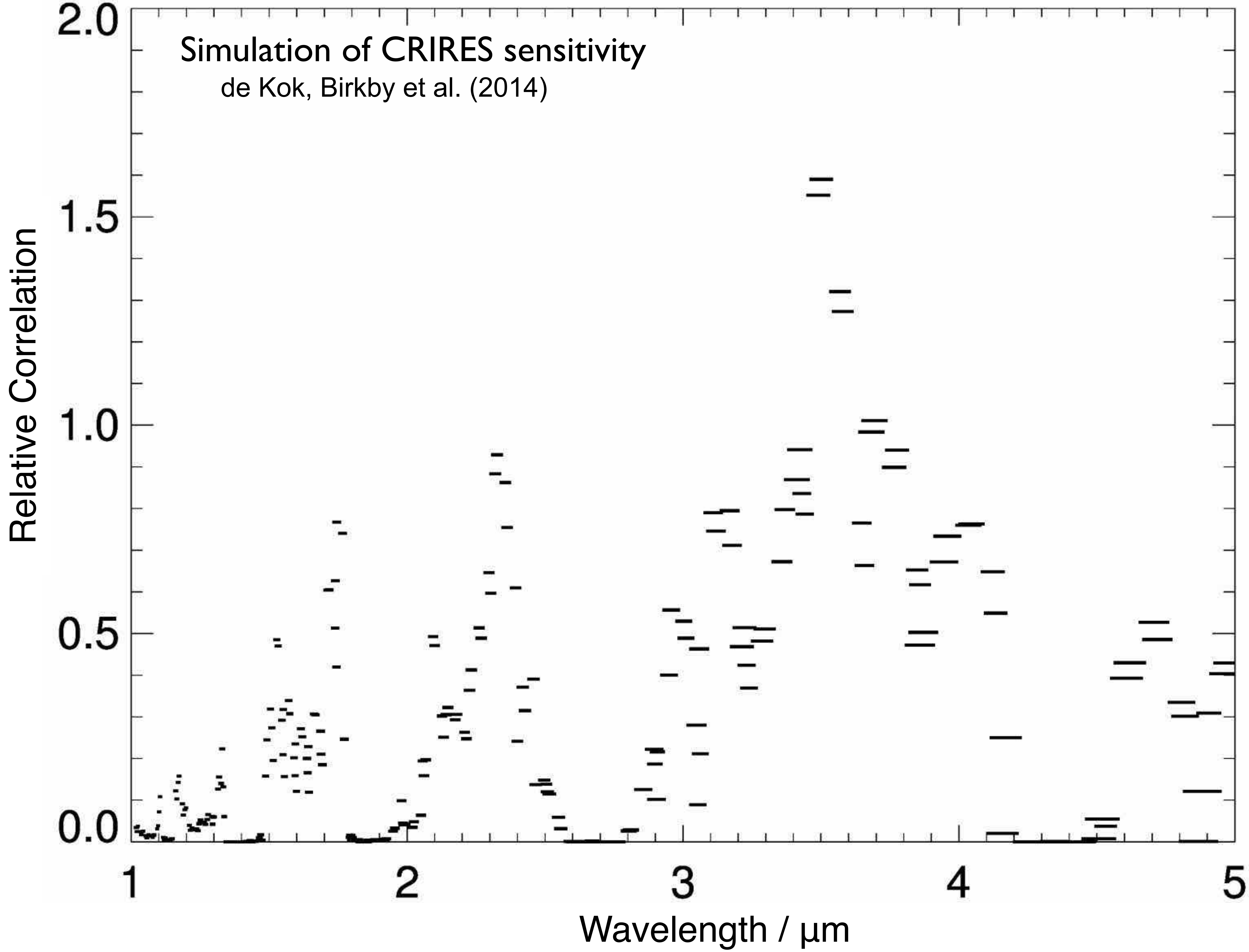
For HR 8799 planets:

i) Super-stellar C/O: core accretion at location

ii) Stellar C/O: gas collapse at location

Barman et al. 2015, Teske et al. 2014

Simulations identify 3.5μm as spectral *'sweet spot'* for measuring C/O ratio



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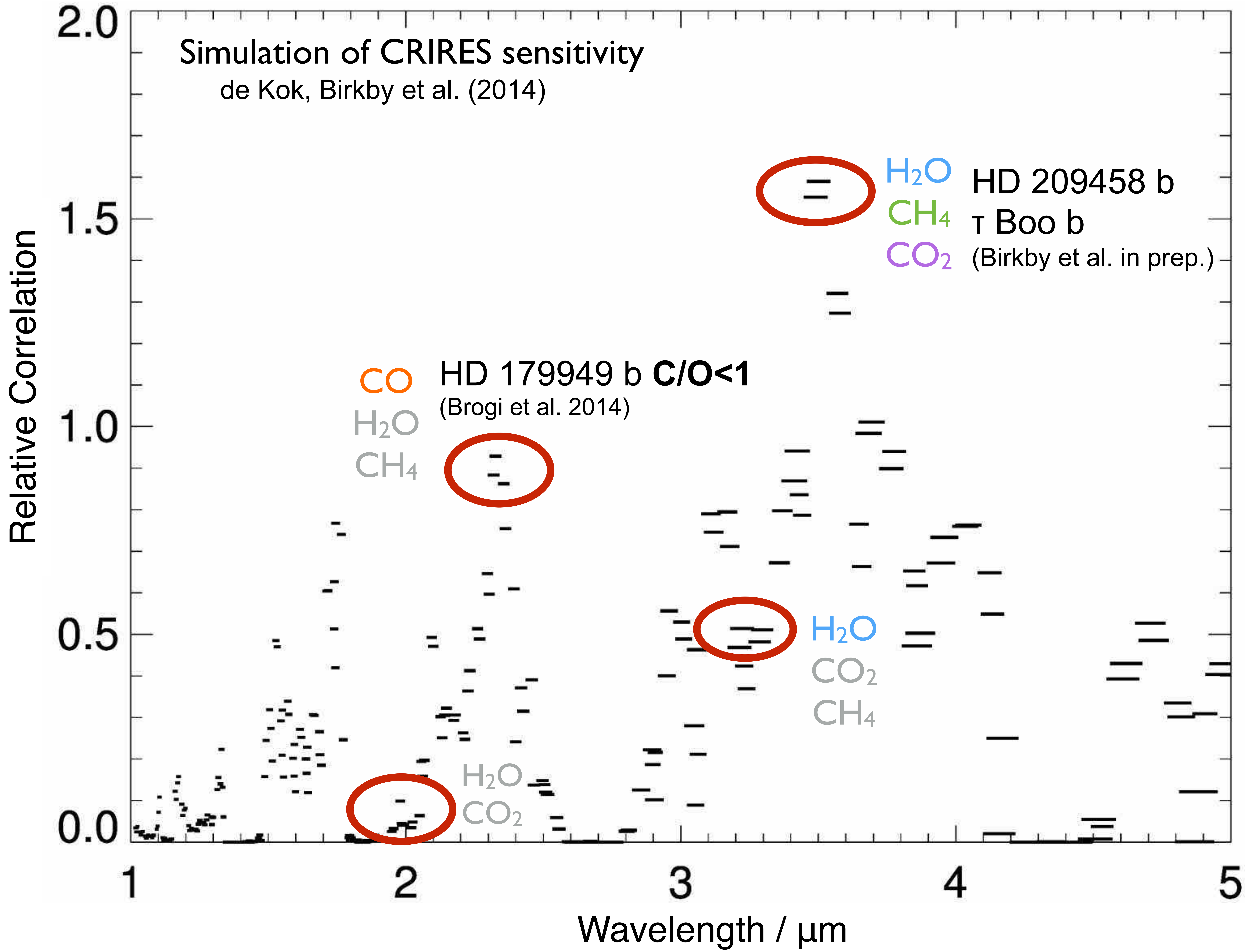
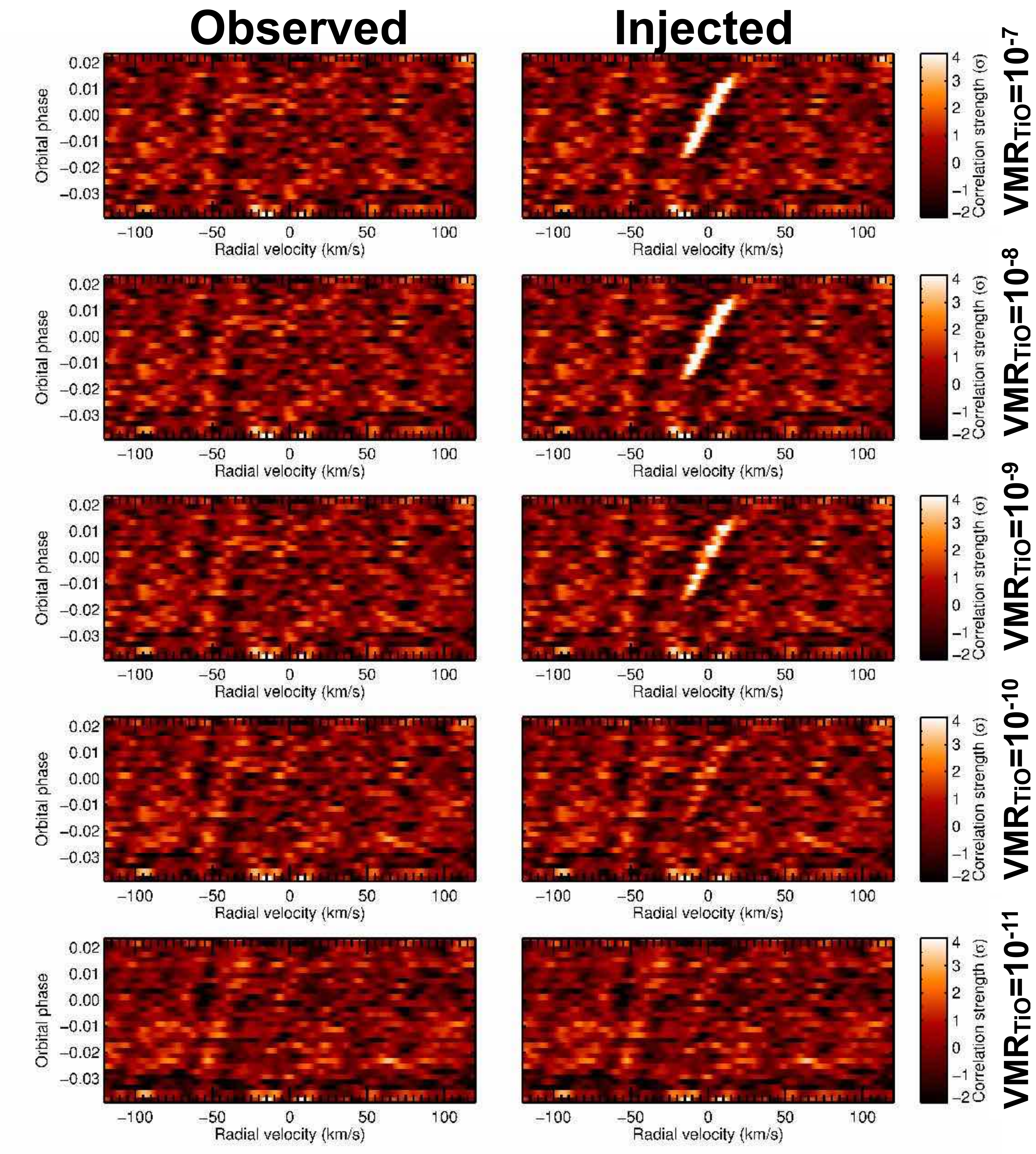


Accurate line lists are essential for HDS

HD 209458 b shows no evidence of TiO that could potentially cause an inversion layer



Hoeijmakers, de Kok, Snellen, Brogi, Birkby, Schwarz, 2014

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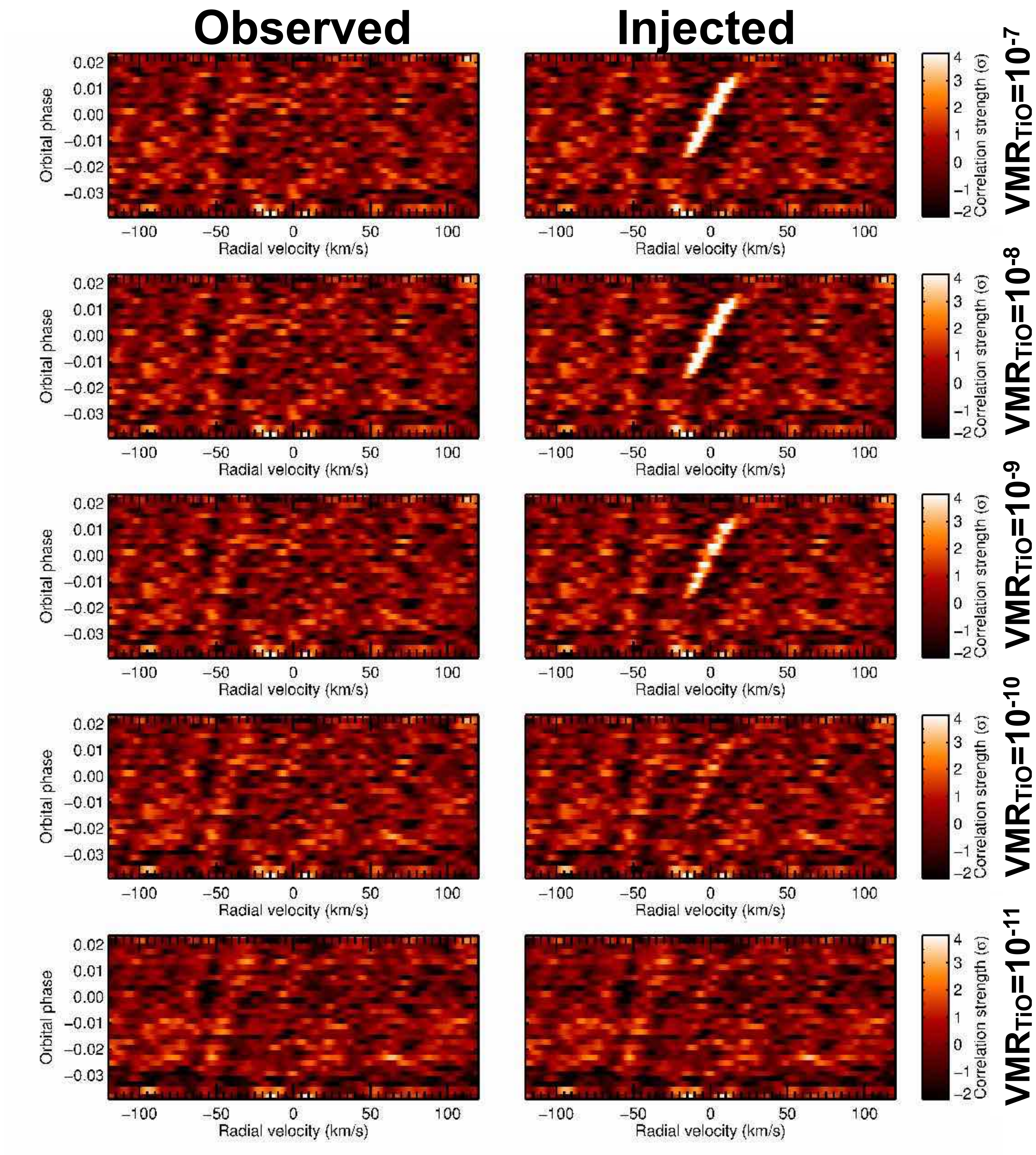

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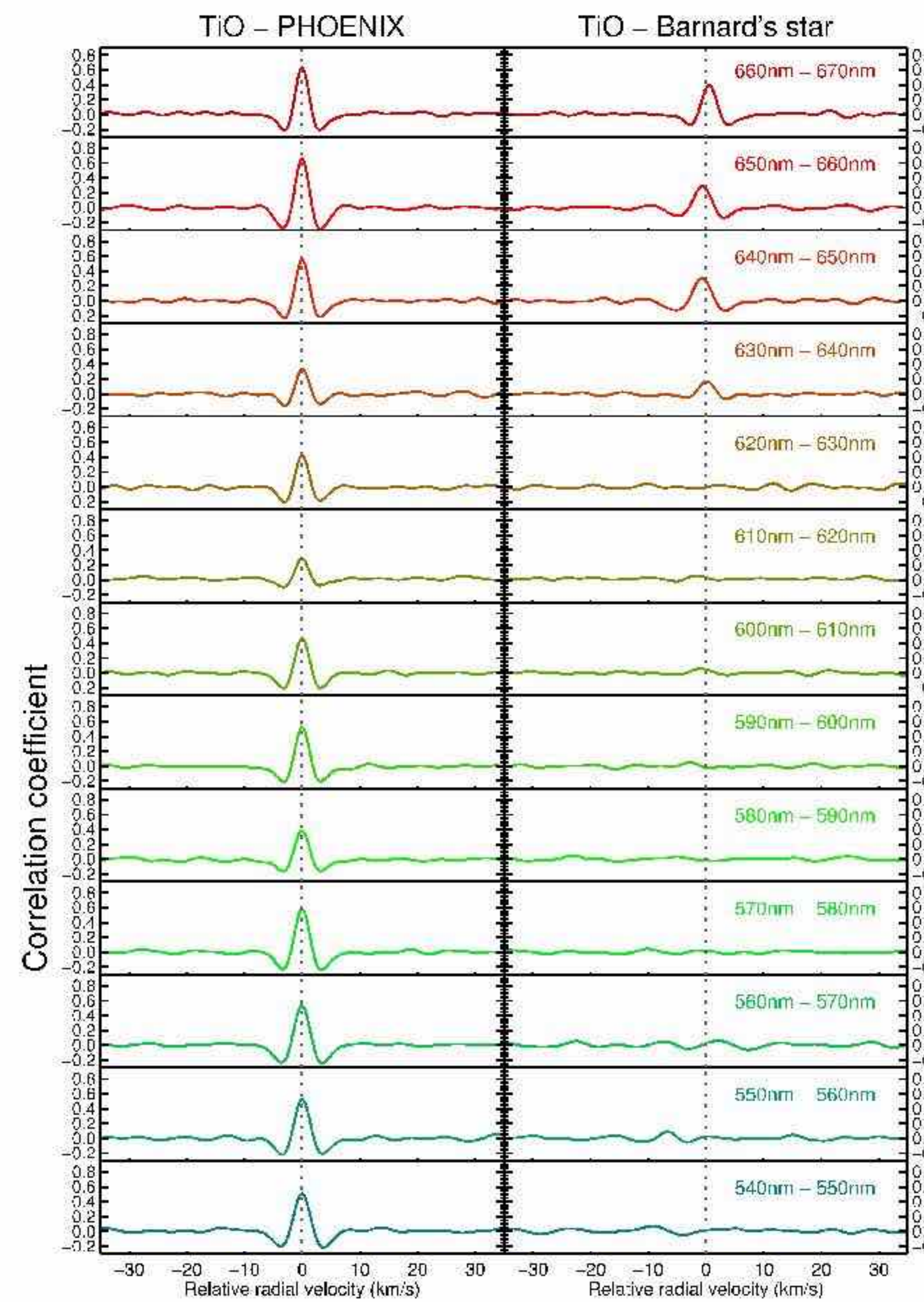

Stellar model atmospheres

M-dwarf observations

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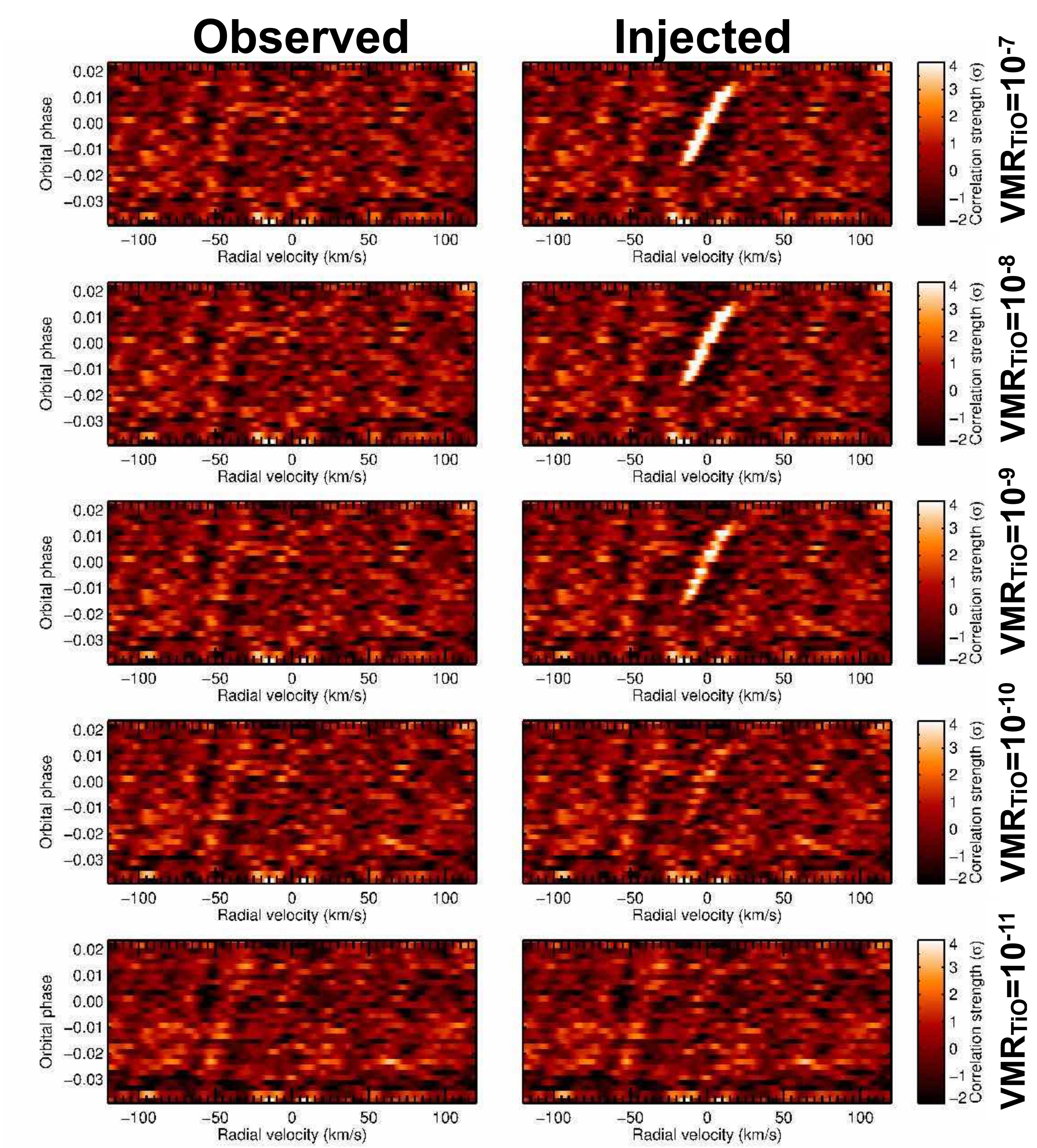
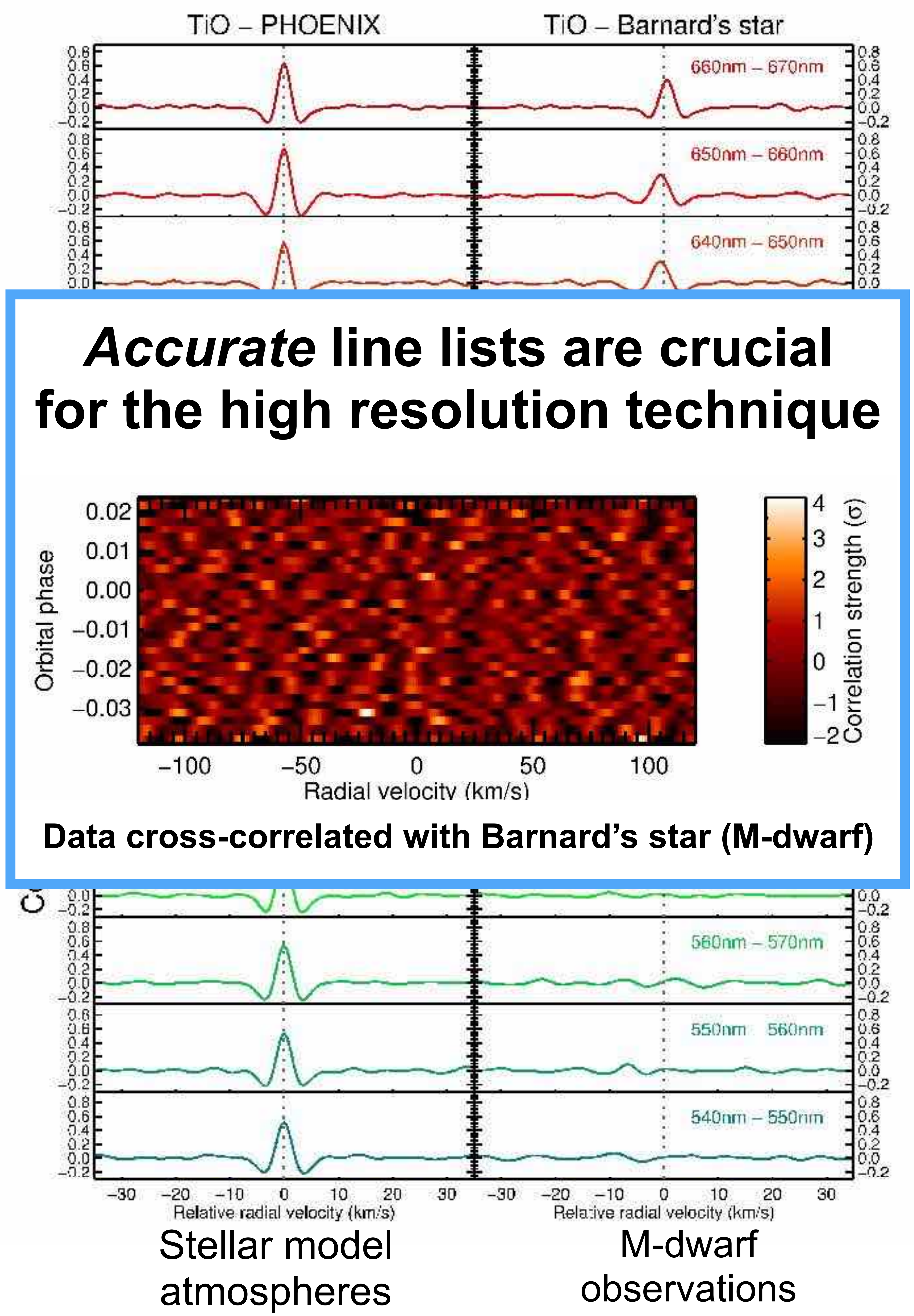
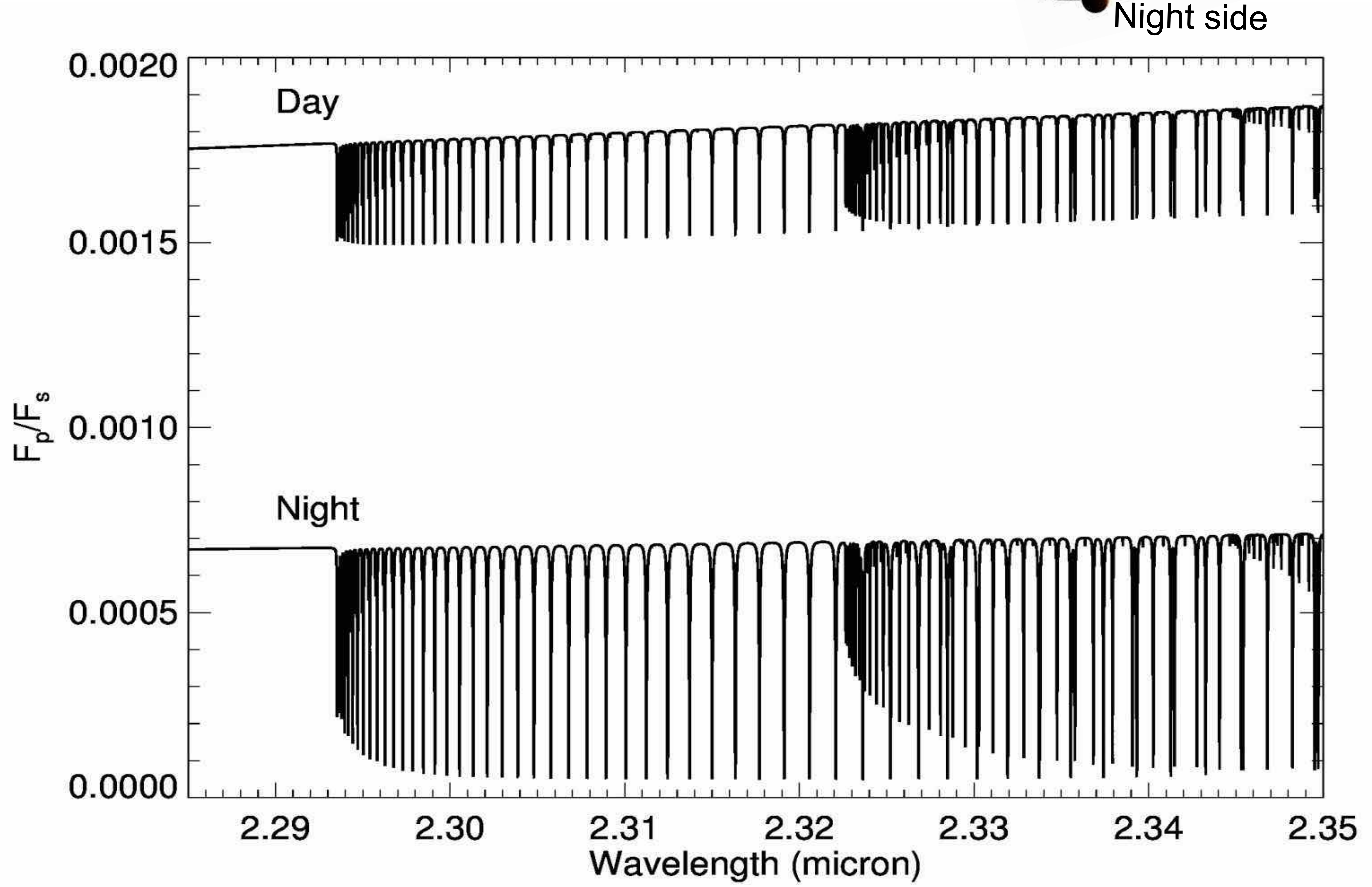




Hoeijmakers, de Kok, Snellen, Brogi, Birkby, Schwarz, 2014

Monitoring atmospheric dynamics with HDS

Nightside features are deeper and potentially easier to detect

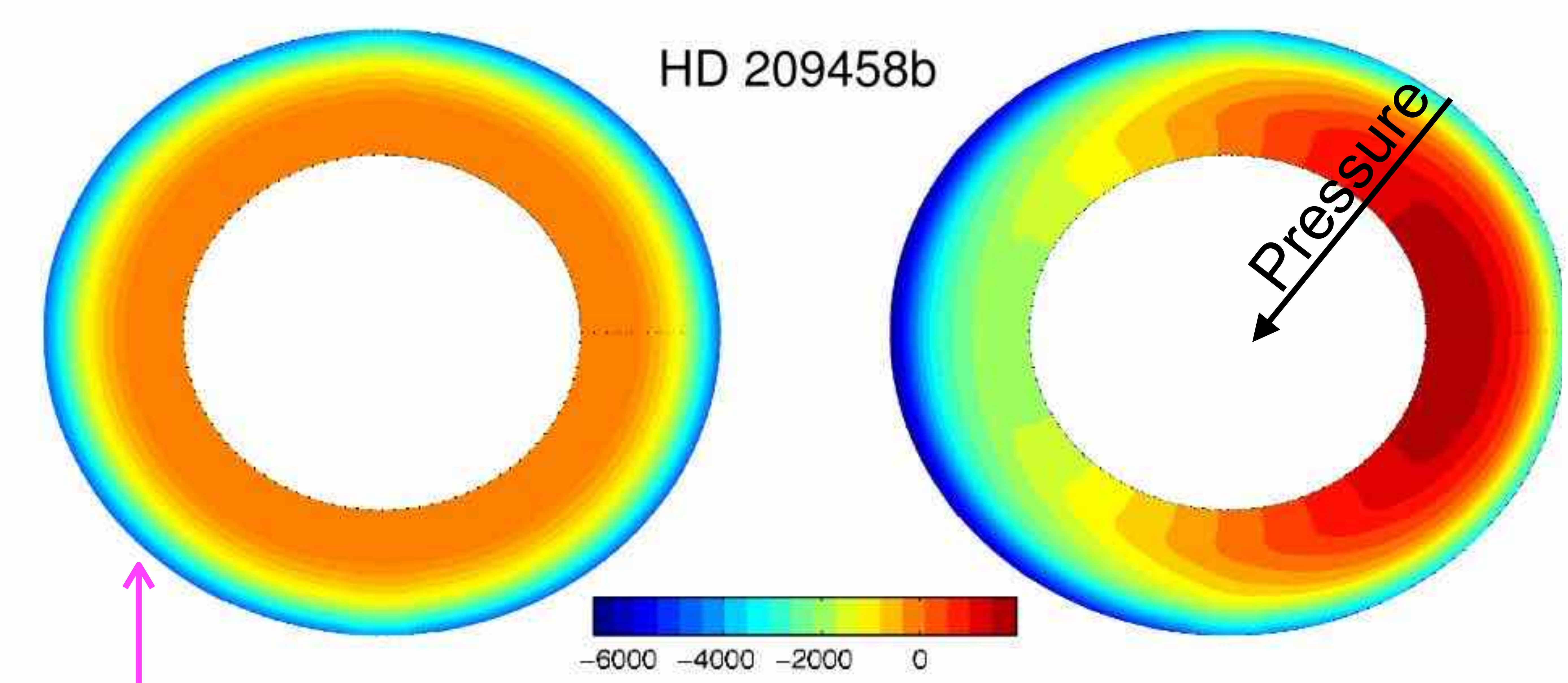


Reveals heat circulation

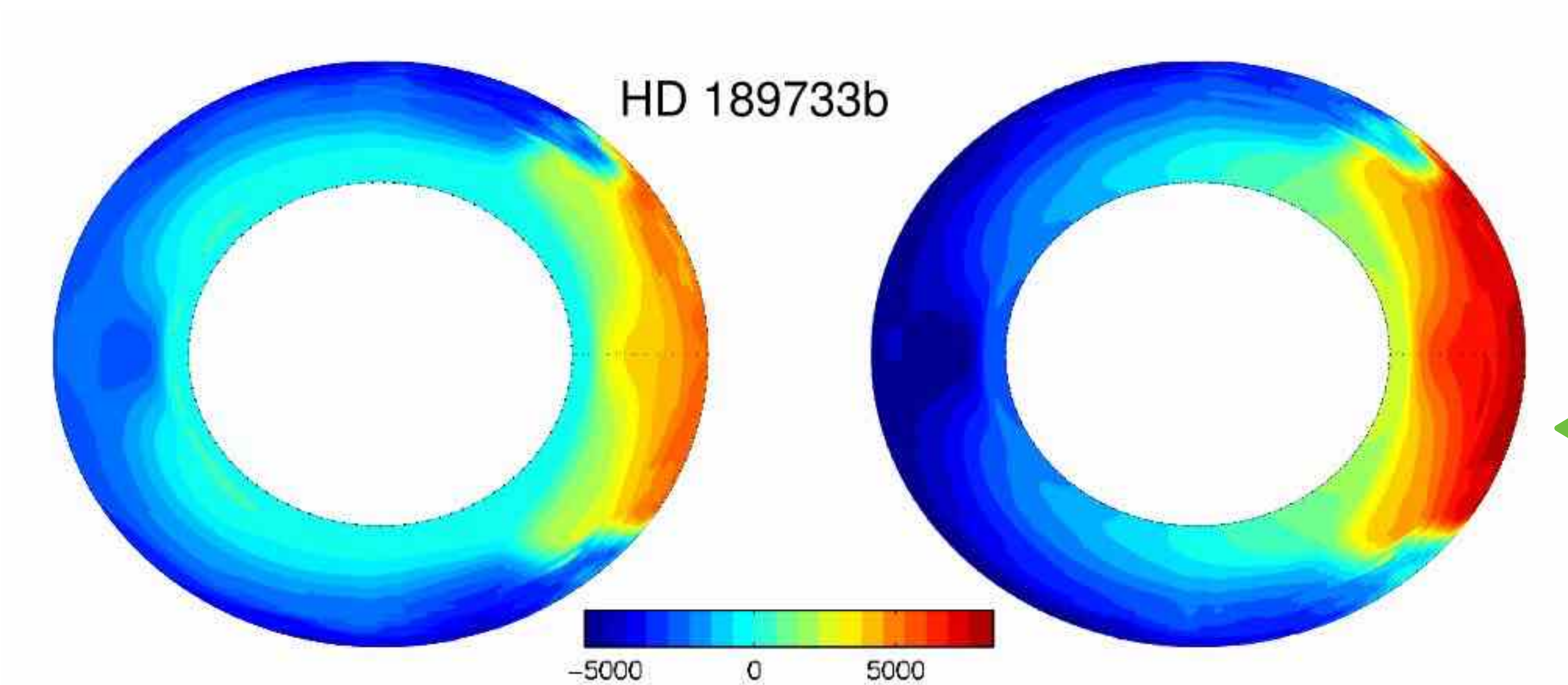
de Kok, Birkby et al. (2014)

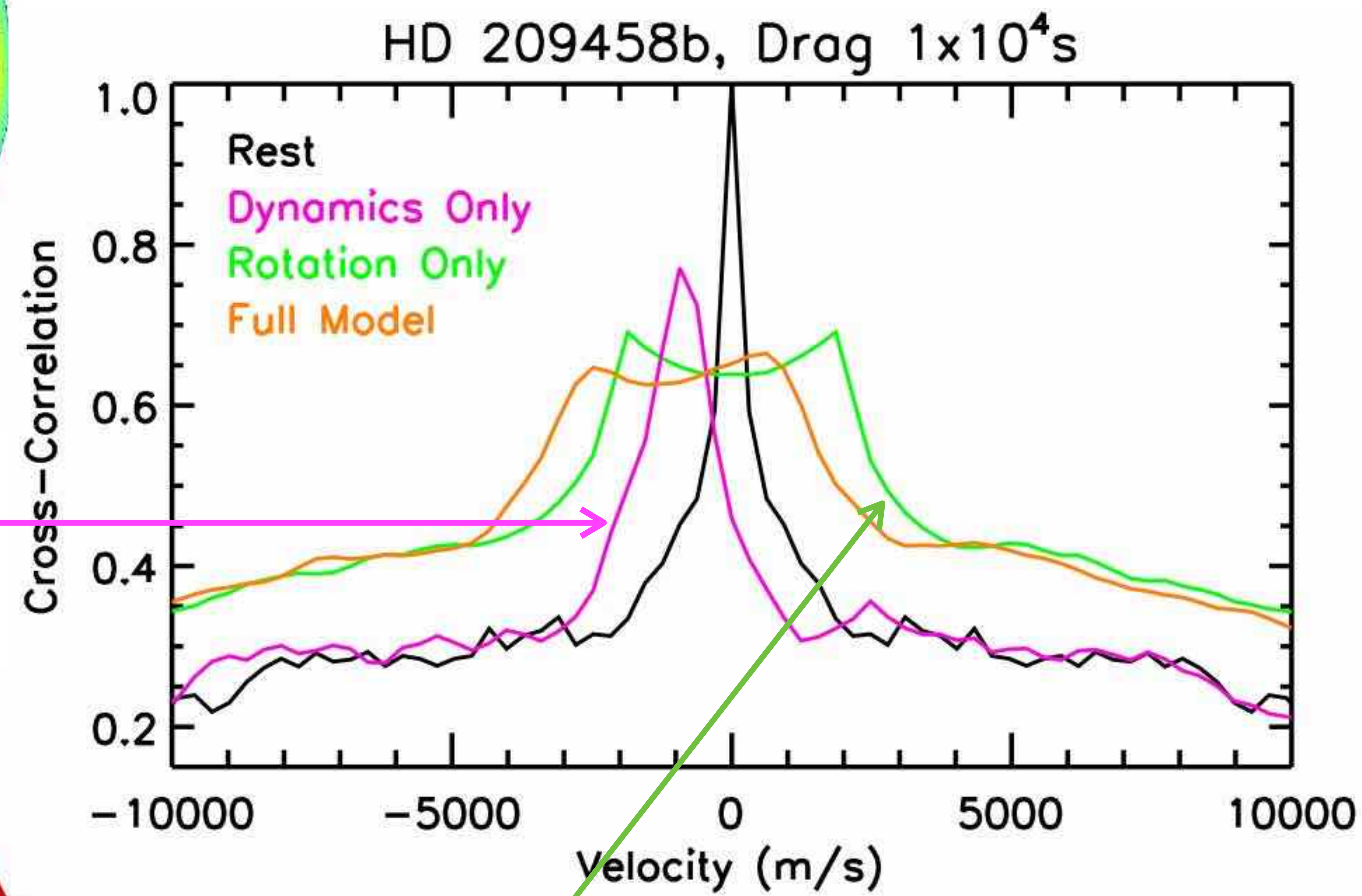
HDS is sensitive to line shape/shift from winds and rotation

Winds only **Winds+rotation**



Winds blue-shift entire upper atmosphere



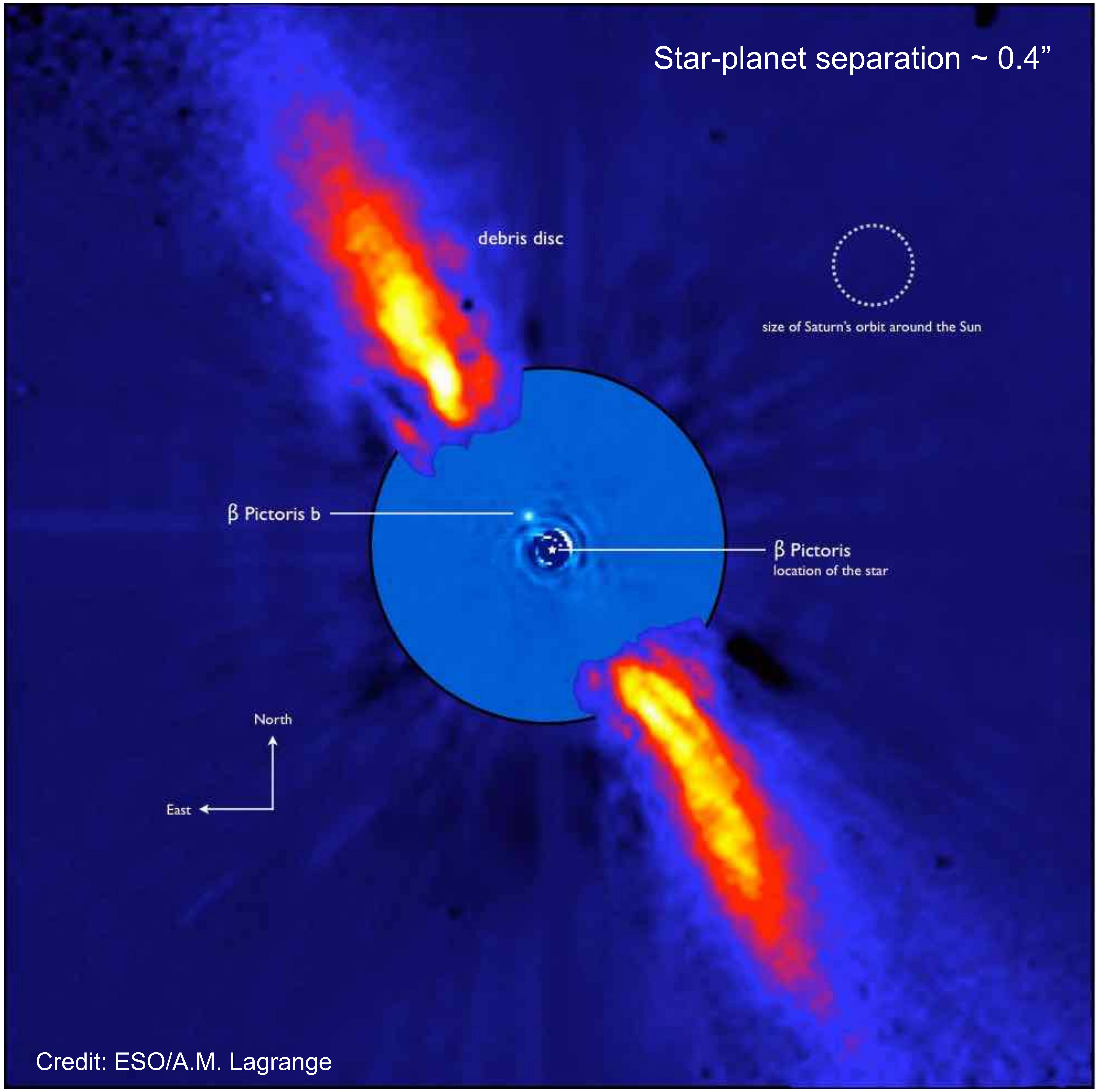


Rotation creates double-peaked line profile

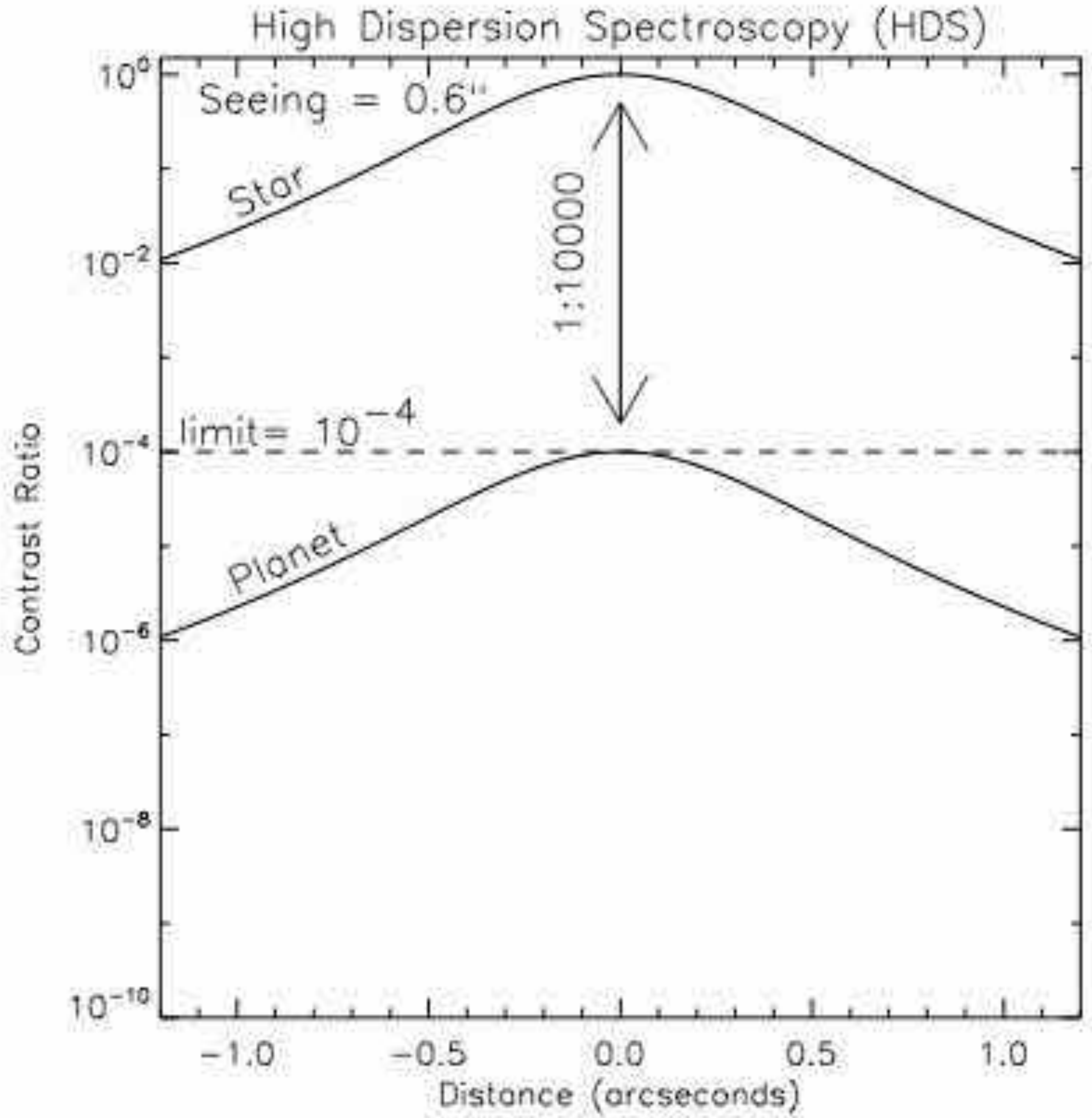
Showman et al. 2013

Measuring the length of an "exoday"

Combining high contrast imaging (HCI) and HDS reveals planet angular momentum

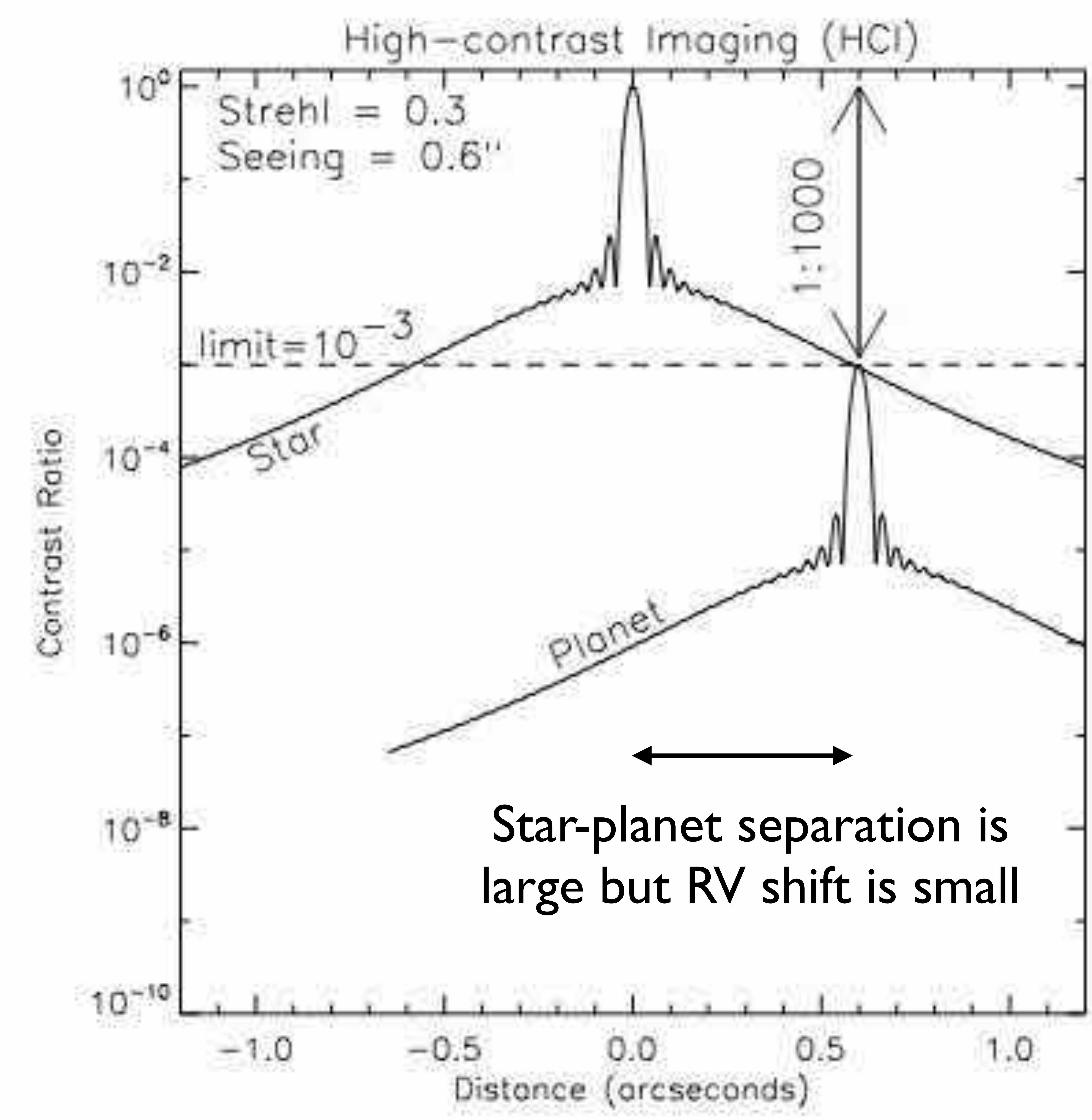


HDS currently reaches contrast ratios of 10^{-4}



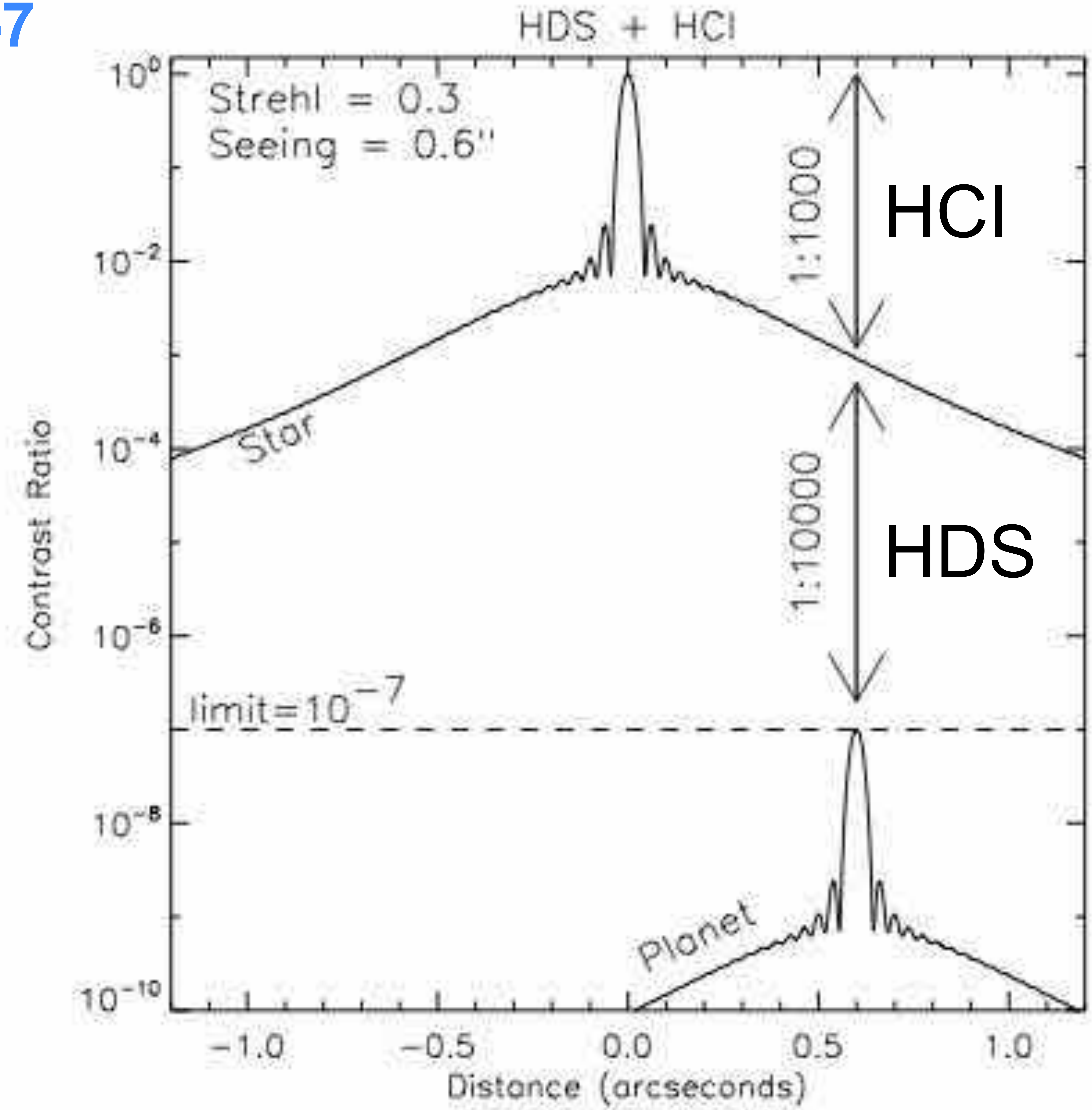
Hot Jupiters have large RV shifts (~10km/s) but small angular separation on the sky

High contrast imaging (HCI) on 8m telescope can reach a raw contrast ratio of 10^{-3}



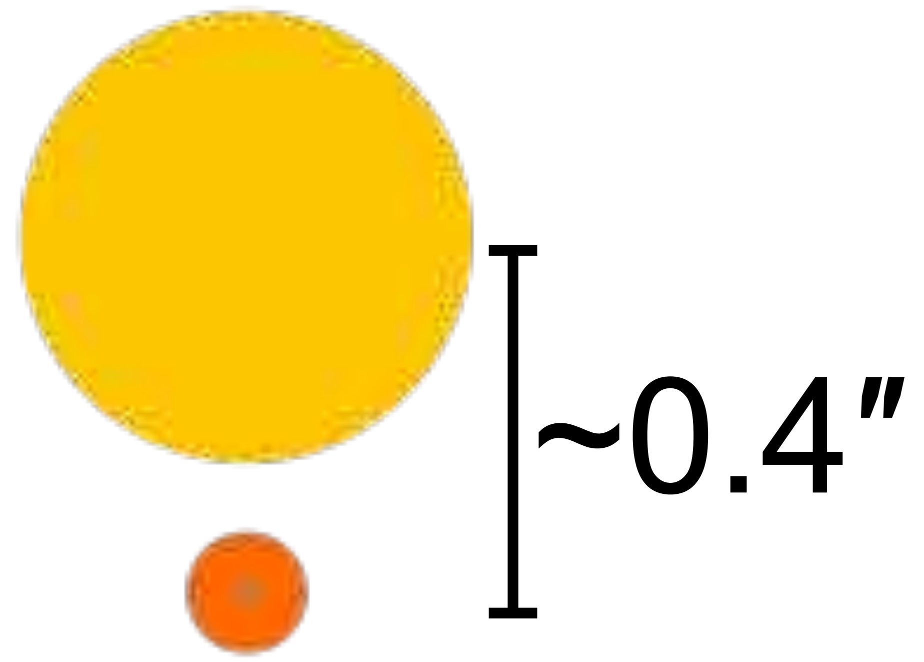
PSF of **AO-assisted** HCI observations with an 8m telescope at 0.5μm, with a Strehl ratio of 0.3 under 0.6 arcsecond seeing conditions (no SDI, ADI, etc)

∴HDS+HCI can achieve contrast ratios of 10^{-7}



Snellen, de Kok, Birkby et al. (2015)

Spectra extracted at every position along the slit and stellar/telluric profile removed



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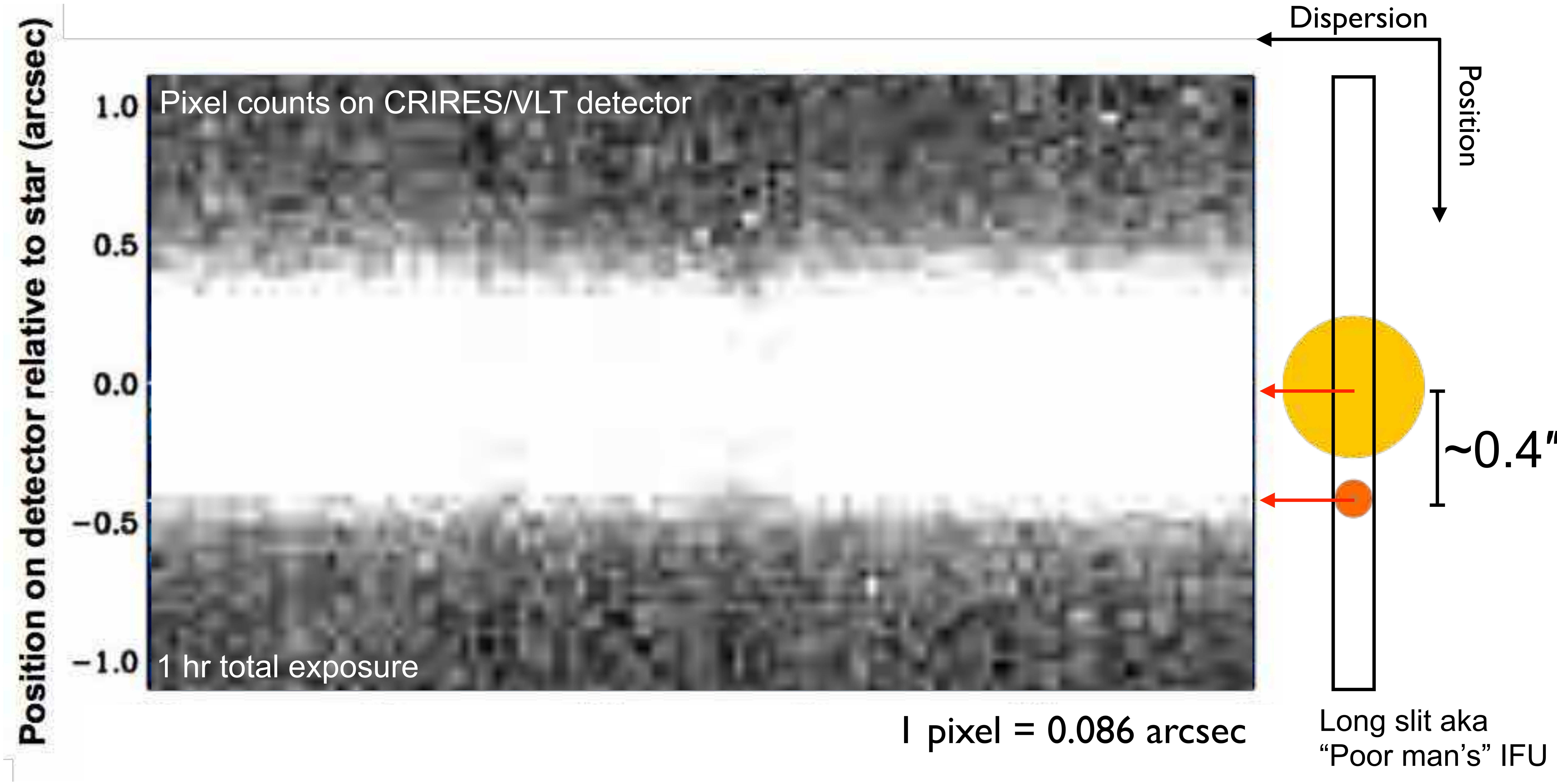
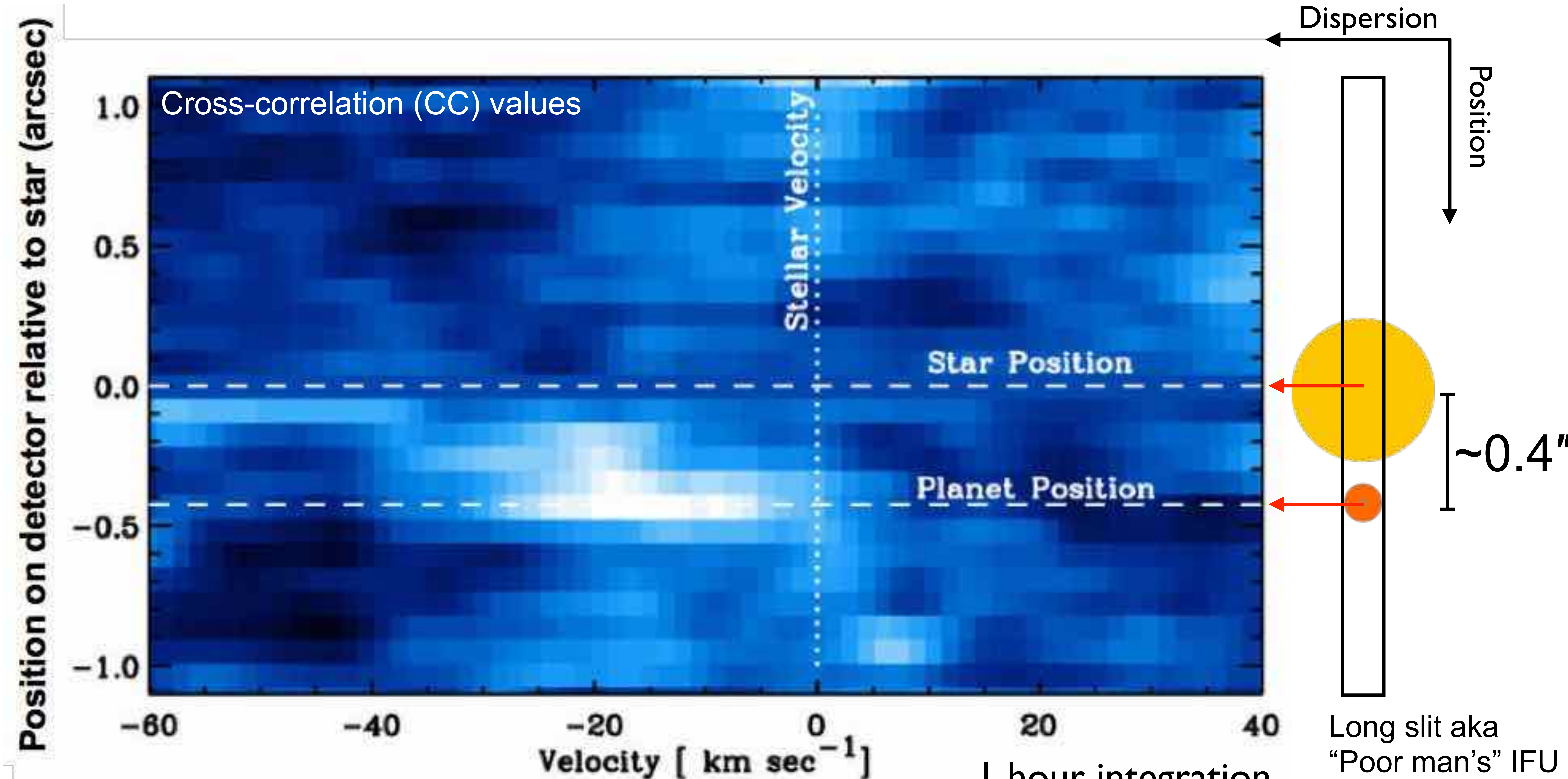


Residual spectra were cross-correlated with model atmospheres containing CO (and H_2O) at different abundances for a range of temperature-pressure profiles.

Spectra extracted at every position along the slit and stellar/telluric profile removed



1 hour integration

Long slit aka "Poor man's" IFU

CO detected in β Pic b. Strongest CC at RV = -15.4±1.7 km/s at ~0.4″

Consistent with position from direct imaging and with a circular orbit. H_2O only seen at SNR~2. No methane.

Snellen, Brandl, de Kok, Brogi, Birkby, Schwarz, 2014

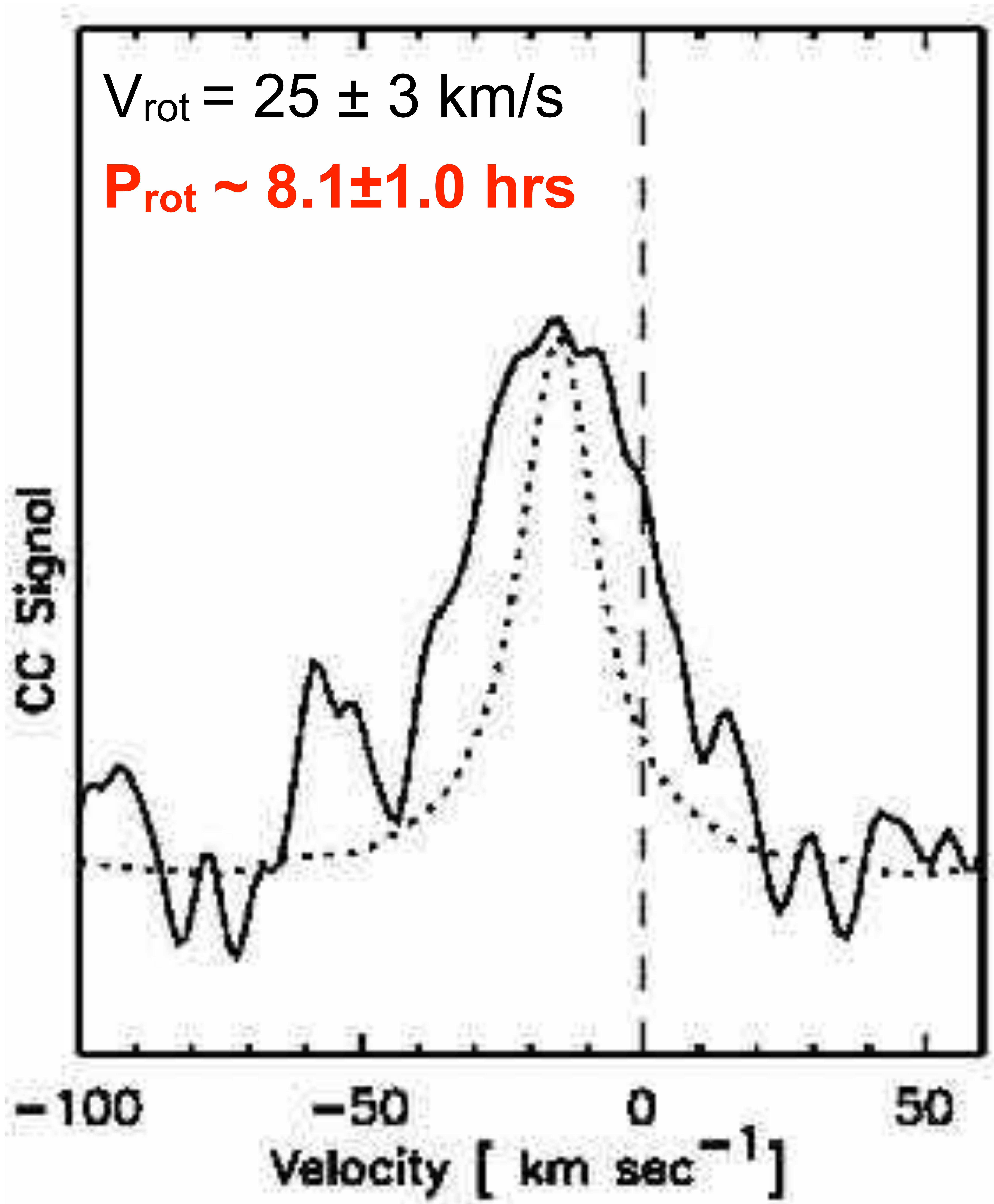
CC at planet position is rotationally broadened

· · · · = instrument profile

Assumed:

- $M_P = 11 \pm 5 M_J$
- $R_P = 1.65 \pm 0.06 R_J$
- Small obliquity

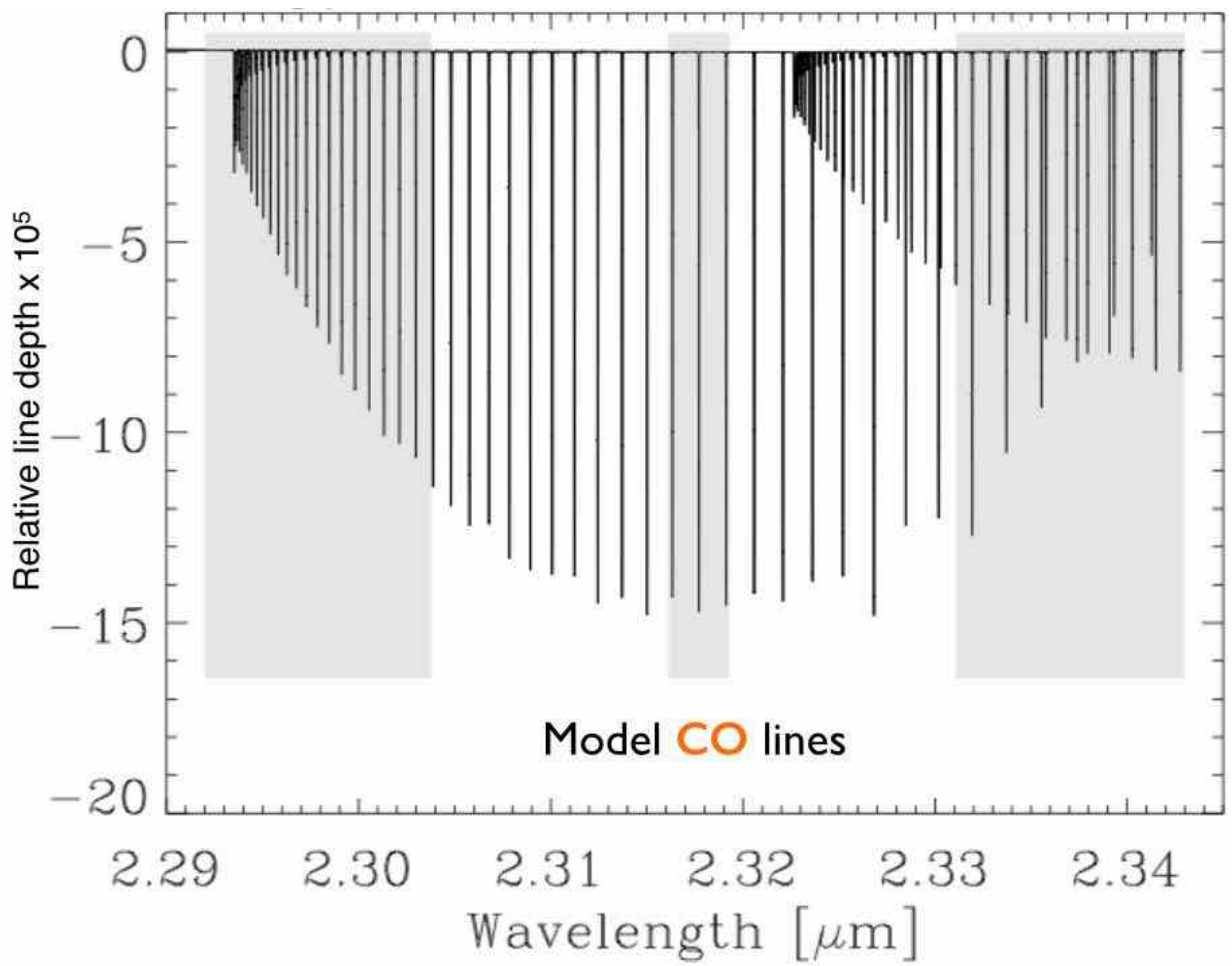
(Radius from Currie et al. 2013)



Snellen et al., 2014

HDS(+HCl) in the future

Cross-correlation strength scales ~with the square root of the number of lines



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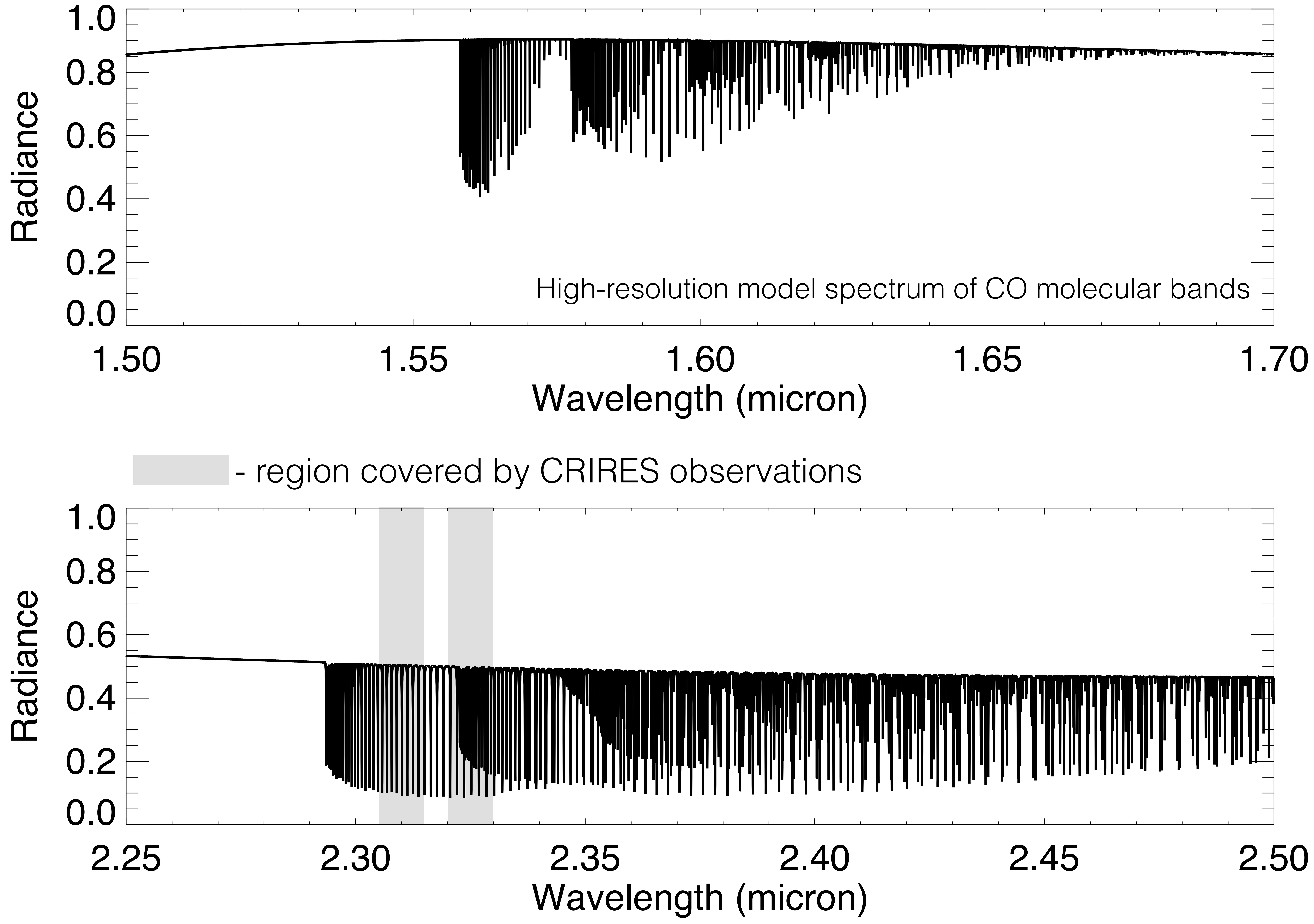

Multiple IR high-resolution spectrographs are planned for the near future

Table 1. Active, Planned, and Notional High-Resolution IR Spectrographs

Instrument	Resolution	Wavelength Coverage	Telescope	Status	References
CSHELL	40,000	1–5 μm, $\sim 0.0025\lambda$ coverage	IRTF (3m)	Operating	Greene et al. (1993)
Phoenix	70,000	1–5 μm, $\sim 0.005\lambda$ coverage	KPNO (4m)	Operating	Hinkle et al. (1998)
ARIES	50,000	1–2.5 μm simultaneous	MMT (6.5m)	Operating	McCarthy et al. (1998)
CRIRES	90,000	1–5 μm, $\sim 0.02\lambda$ coverage[a]	VLT (8m)	Operating[a]	Kaeufl et al. (2004)
IRCS	20,000	1–5 μm, $\sim 0.2\mu m$ coverage	Subaru (8m)	Operating	Tokunaga et al. (1998)
NIRSPEC	20,000	1–5 μm, $\sim 0.1\lambda$ coverage	Keck (10m)	Operating	McLean et al. (1998)
IGRINS	40,000	1.5–2.5 μm simultaneous	McDonald (2.7m)	Commissioning	Yuk et al. (2010)
GIANO	50,000	1–2.5 μm simultaneous	TNG (3.6m)	Commissioning	Oliva et al. (2012)
ISHELL	72,000	1–5 μm, $\sim 0.1\lambda$ coverage	IRTF (3m)	Under construction	Rayner et al. (2012)
CARMENES	82,000	0.6-1.7μm simultaneous	Calar Alto (3.5m)	Under construction	Quirrenbach et al. (2012)
SPIRou	75,000	1-2.4μm simultaneous	CFHT (3.6m)	Under construction	Thibault et al. (2012)
IRD	70,000	1–1.75 μm simultaneous	Subaru (8m)	Under construction	Tamura et al. (2012)
HPF	50,000	0.95–1.35 μm simultaneous	HET (9m)	Under construction	Mahadevan et al. (2012)
HiJak	60,000	0.8–2.5 μm simultaneous	DCT (4.3m)	Notional	Muirhead et al. (in prep.)
iLocater	100,000	0.95–1.1 μm simultaneous	LBT (8m)	Planned	Crepp et al. (2014)

[a]CRIRES is scheduled to be upgraded during 2014–2017 to provide $\sim 0.2\lambda$ coverage.

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Multiple IR high-resolution spectrographs are planned for the near future

Table 1. Active, Planned, and Notional High-Resolution IR Spectrographs

Instrument	Resolution	Wavelength Coverage	Telescope	Status	References
CSHELL	40,000	1–5 μm, $\sim 0.0025\lambda$ coverage	IRTF (3m)	Operating	Greene et al. (1993)
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ARIES	50,000	1–2.5 μm simultaneous	MMT (6.5m)	Operating	McCarthy et al. (1998)
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IGRINS	40,000	1.5–2.5 μm simultaneous	McDonald (2.7m)	Commissioning	Yuk et al. (2010)
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ISHELL	72,000	1–5 μm, $\sim 0.1\lambda$ coverage	IRTF (3m)	Under construction	Rayner et al. (2012)
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iLocater	100,000	0.95–1.1 μm simultaneous	LBT (8m)	Planned	Crepp et al. (2014)
METIS	100,000	2.9–5.5 μm simultaneous	E-ELT (39m)	Planned	Brandl et al. (2010, 2012)
HIRES	100,000	0.4–2.5 μm simultaneous	E-ELT (39m)	Notional	Maiolino et al. (2013)
NIRES-B	20,000	1–2.5 μm simultaneous	TMT (30m)	Notional	TMT Project (2013)
NIRES-R	100,000	3–5 μm simultaneous	TMT (30m)	Notional	TMT Project (2013)
GMTNIRS	$\gtrsim$60,000	1–5 μm simultaneous	GMT (25m)	Notional	Jaffe et al. (2006); Lee et al. (2010)

[a]CRIRES is scheduled to be upgraded during 2014–2017 to provide $\sim 0.2\lambda$ coverage.

Crossfield 2014

Molecular spectra (CO, H_2O, CO_2, CH_4) as function of orbital phase

➔ photochemistry, atmospheric structure versus longitude

Multiple IR high-resolution spectrographs are planned for the near future

R~25,000 with NIRSPEC/Keck is the lowest resolution so far proven to work for HDS

Instrument	Resolution				
CSHELL	40,000	1–5 μm, ~ 0.0025λ coverage	IRTF (3m)	Operating	Greene et al. (1993)
Phoenix	70,000	1–5 μm, ~ 0.005λ coverage	KPNO (4m)	Operating	Hinkle et al. (1998)
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NIRES-R	100,000	3–5 μm simultaneous	TMT (30m)	Notional	TMT Project (2013)
GMTNIRS	≳60,000	1–5 μm simultaneous	GMT (25m)	Notional	Jaffe et al. (2006); Lee et al. (2010)

[a]CRIRES is scheduled to be upgraded during 2014–2017 to provide ~ 0.2λ coverage.

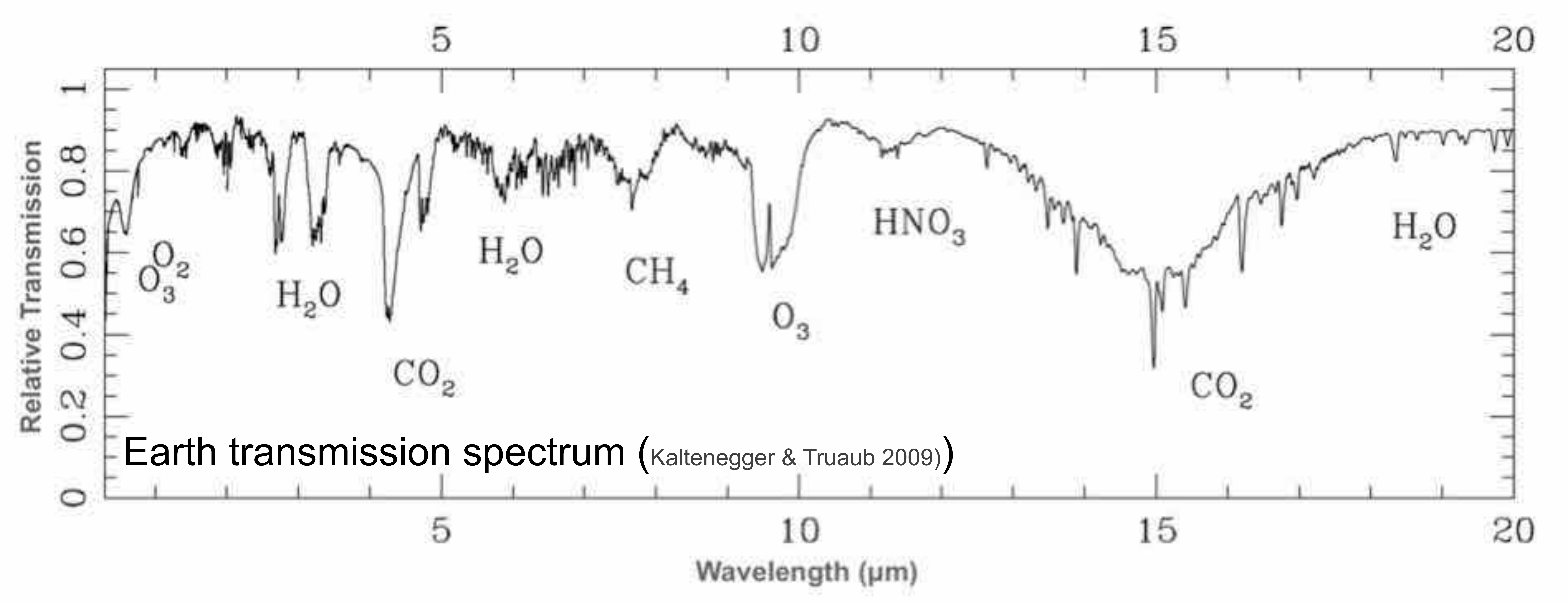
Crossfield 2014

Molecular spectra (CO, H_2O, CO_2, CH_4) as function of orbital phase

➔ photochemistry, atmospheric structure versus longitude

Biomarkers and maps

Biomarkers are spectral signatures that indicate past or present life



Water (H_2O)
needed for life

Oxygen (O_2)
produced by plants

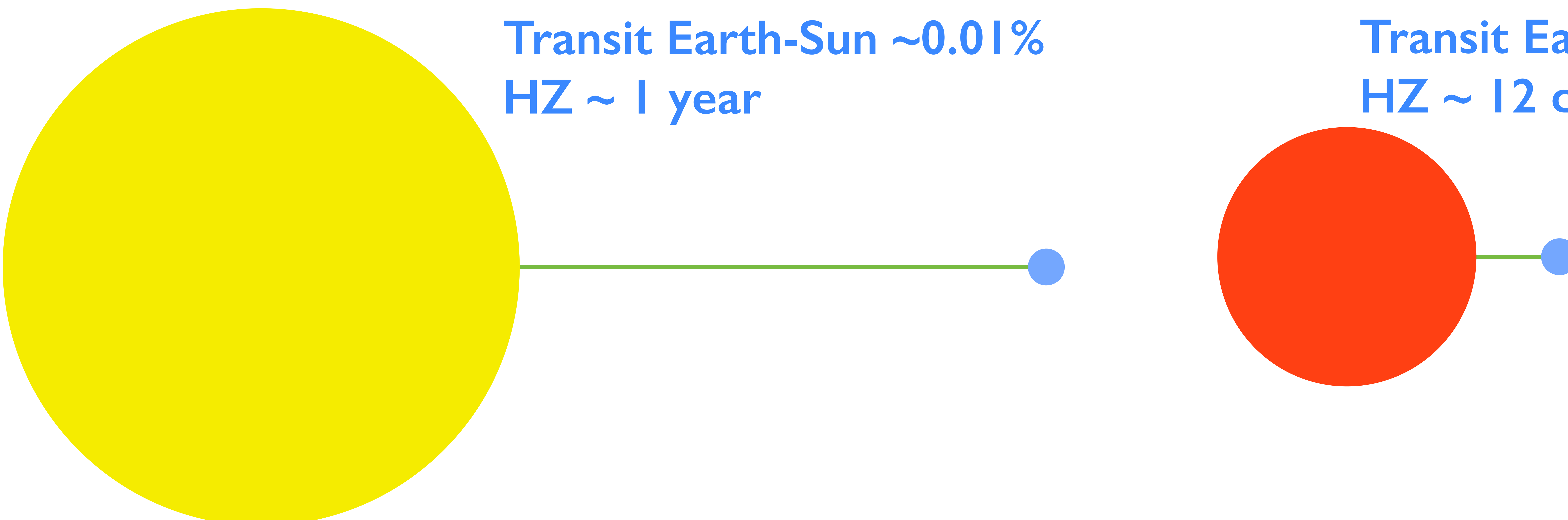
Ozone (O_3)
tracer of O_2

Methane (CH_4)
produced by bacteria

M-dwarfs are ideal for hunting Earth-like planets

RV Earth-Sun ~0.1 m/s
Transit Earth-Sun ~0.01%
HZ ~ 1 year

RV Earth-M5V ~1 m/s
Transit Earth-M5V ~0.1%
HZ ~ 12 days



HZ (habitable zone): where water is a liquid

M-dwarfs are ideal for hunting Earth-like planets

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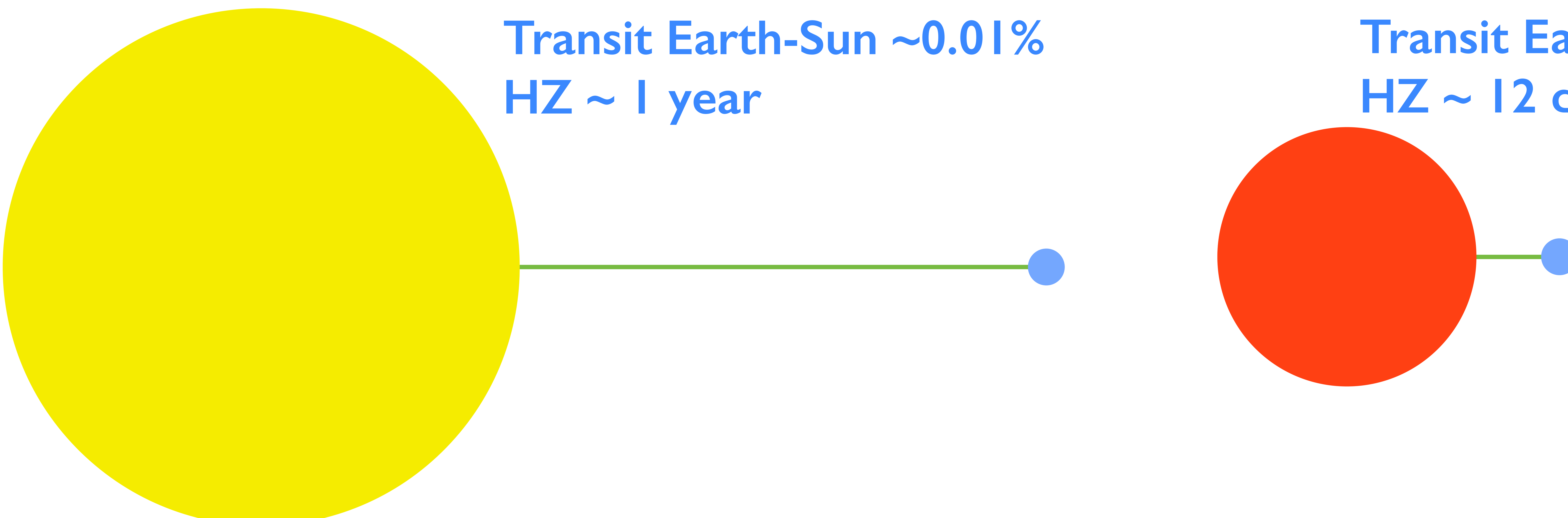
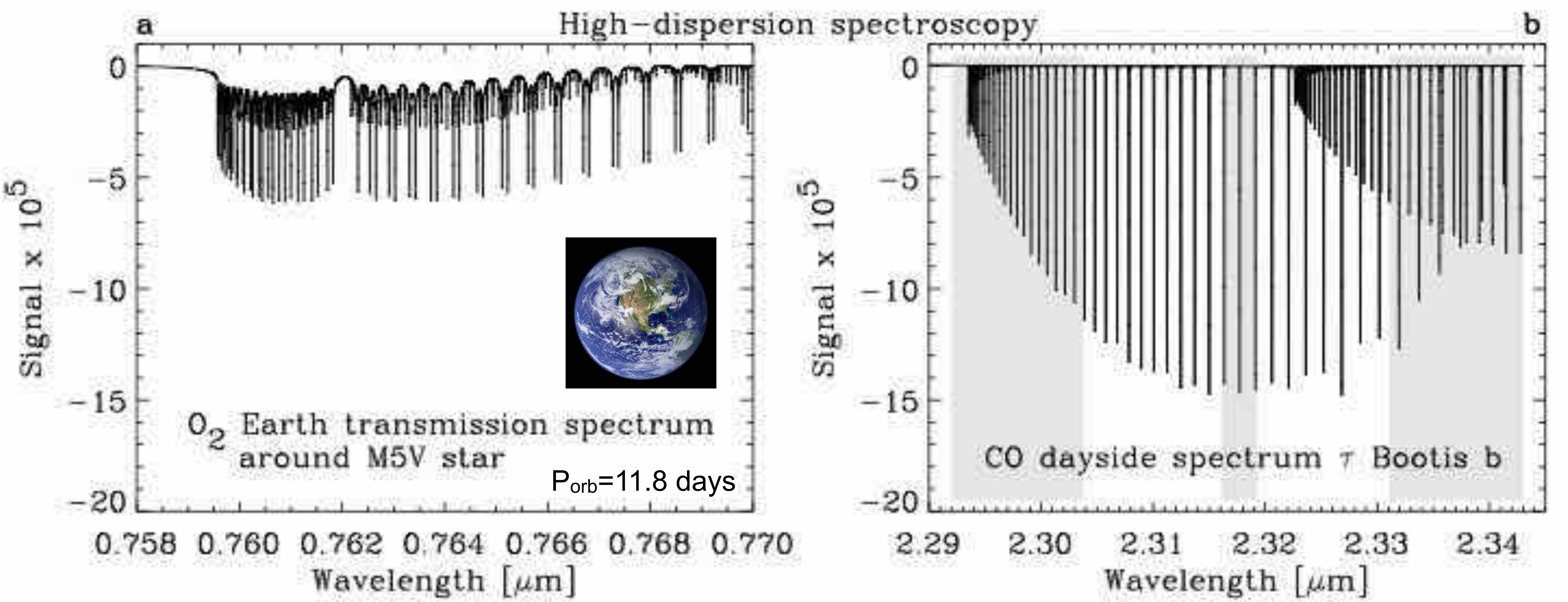
Transit Earth-M5V ~0.1%
HZ ~ 12 days



HZ (habitable zone): where water is a liquid

Hazard warning:
Oxygen and ozone produced abiotically by water photolysis
(Wordsworth & Pierrehumbert 2014)

HDS on an ELT could detect oxygen in Earth-like planets in the HZ of M-dwarfs



M5V+Earth twin in habitable zone:

- observe 12-30 transits (12 day orbit, 3 visible per year)
- detect O_2 at 5σ
- takes *4-20 years* for the nearest systems (I~10.5 mag, $\eta_\oplus$=1)

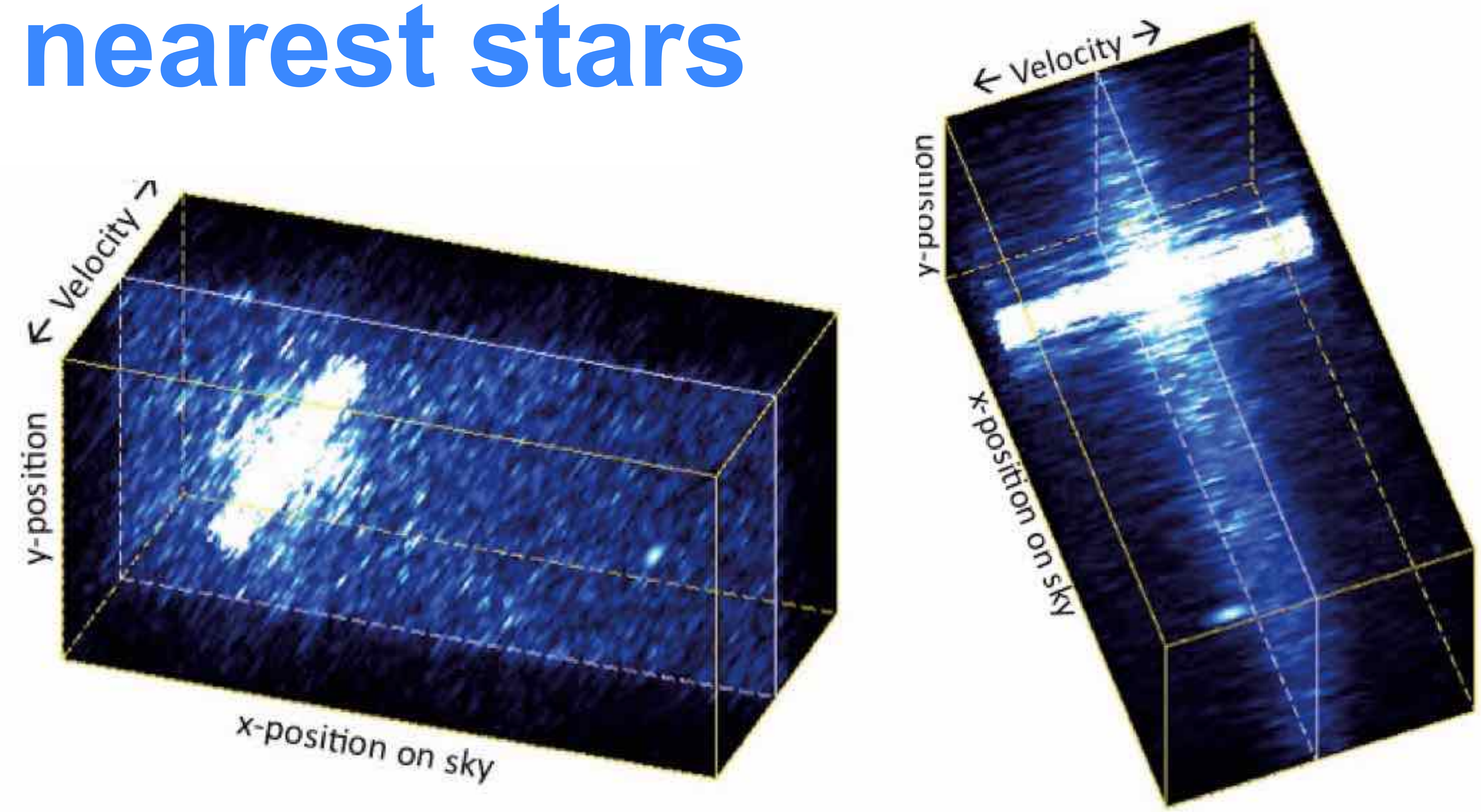
Uses velocity separation

Snellen, de Kok, le Poole, Brogi, Birkby 2013; Rodler & Lopez-Morales 2014

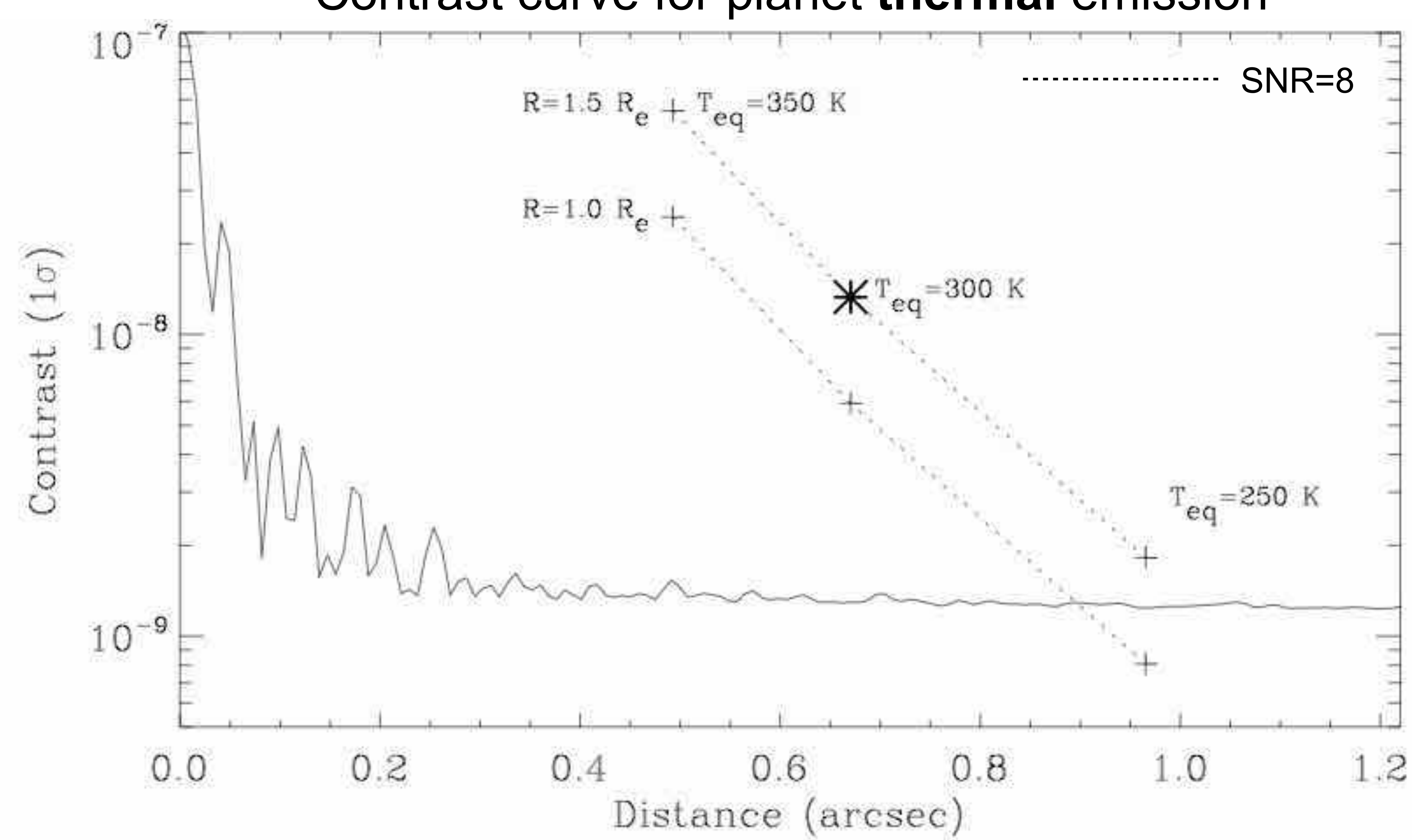
HDS+HCI with an ELT could detect Earth-size planets orbiting the nearest stars

E-ELT/METIS simulations (**infrared IFU**)

Telescope + Instrument	
Telescope collecting area	976.3 m^2
Telescope temperature	280 K
Telescope emissivity	0.15
Telescope+instrument throughput	15%
AO Strehl (4.85 μm)	0.9
Spectral resolution	R = 100 000
Exposure time	→ 30 h
Spectral range	4.82–4.89 μm
Target: α Cen A	
Apparent K magnitude	−1.47
$T_{\rm eff}$ (star)	5800 K
Stellar radius	1.22 $R_{\rm sun}$
Distance	1.34 pc
Planet radius	1.5 $R_{\rm Earth}$
Planet radial velocity	30 km s^{-1}
$T_{\rm eff}$ (planet)	300 K
Bond albedo	0.3
Planet spectrum	Earth-like



Contrast curve for planet **thermal** emission



Uses spatial separation

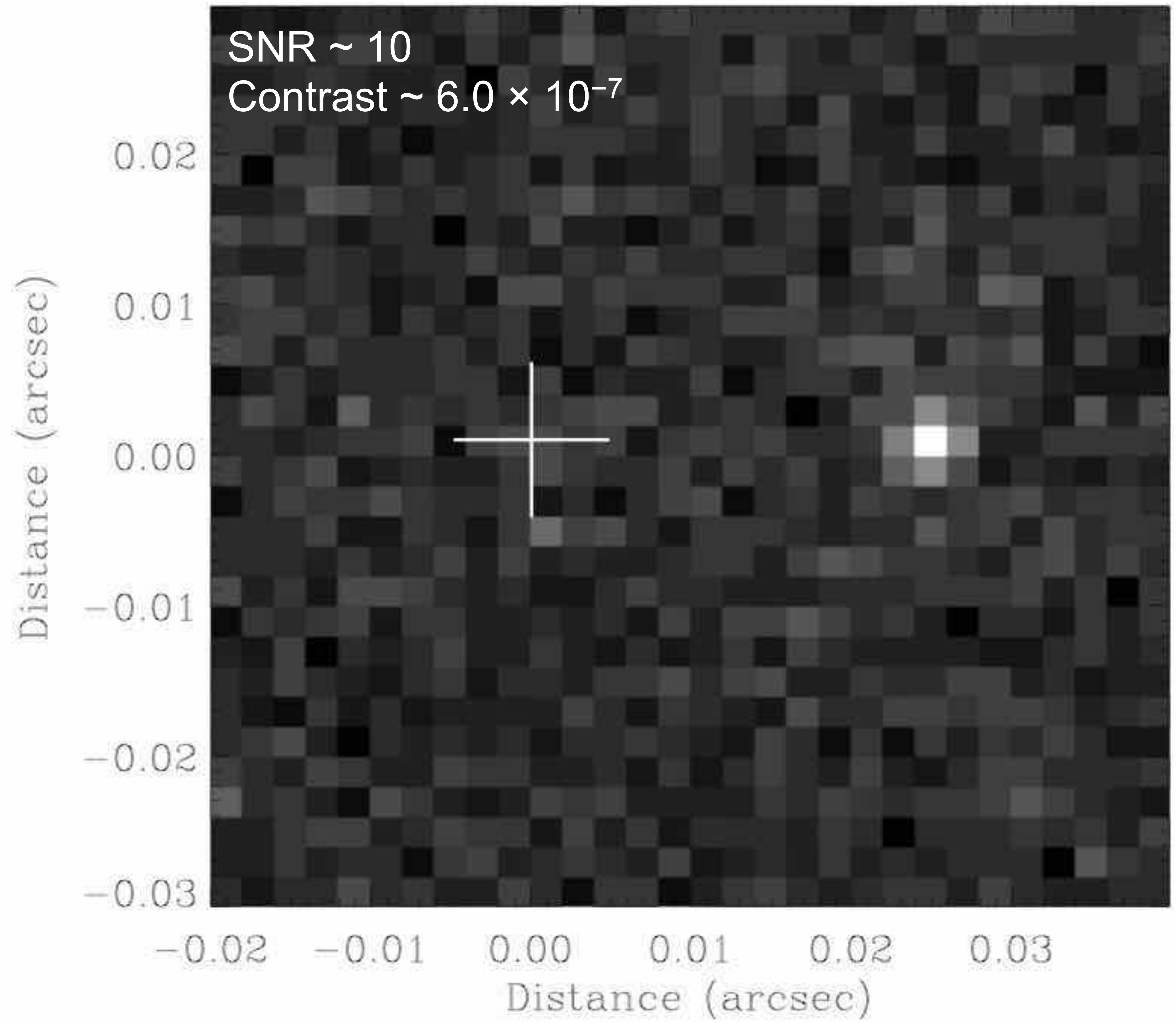
Snellen, de Kok, Birkby et al., 2015

HDS+HCI with an ELT could detect Earth-size planets orbiting the nearest stars

E-ELT/optical IFU simulations

Telescope + Instrument	
Telescope collecting area	976.3 m^2
Telescope+instrument throughput	15%
AO Strehl (0.75 μm)	0.3
Spectral resolution	$R = 100\,000$
Exposure time	10 h
Spectral range	0.6–0.9 μm
IFU pixels	30 × 30 2 mas
Target: Proxima Cen	
Apparent V magnitude	11.05
$T_{\rm eff}$ (star)	3040 K
Stellar radius	0.141 $R_{\rm sun}$
Distance	1.30 pc
Planet radius	1.5 $R_{\rm Earth}$
Planet radial velocity	30 km s^{-1}
$T_{\rm eff}$ (planet)	280 K
Grey geometric albedo	0.3
Orbital radius	0.032 AU
Angular distance from star	25 mas

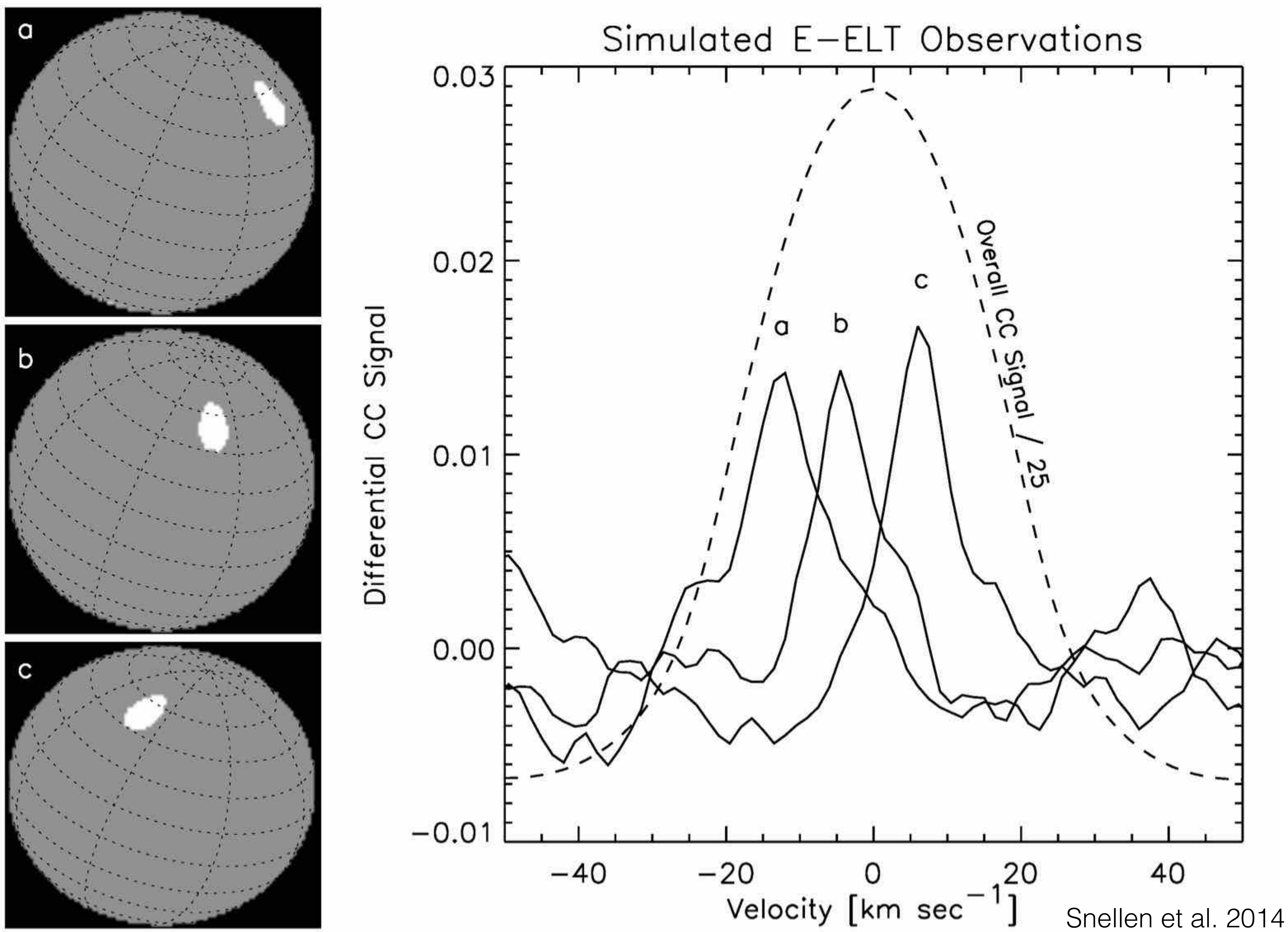
Cross-correlation map for **reflected** light around Proxima within the habitable zone



Uses spatial separation

Snellen, de Kok, Birkby et al., 2015

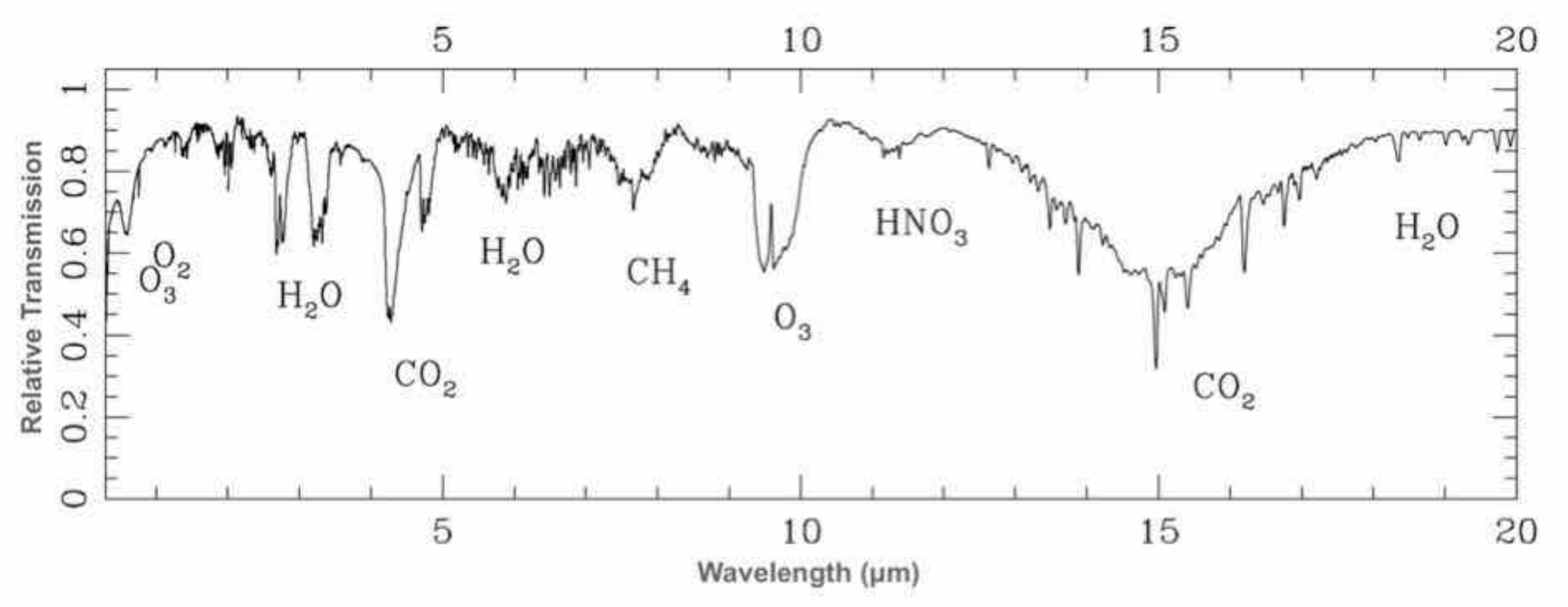
Simulations of HDS+HCI show ELTs can map exoplanet atmospheric surfaces



Snellen et al. 2014

Assuming CRIRES-like+AO instrument on an ELT (39m), mapping of β Pic b would be twice as efficient as VLT mapping of a brown dwarf (Crossfield et al. 2014)

Thoughts for ATLAST:



- HDS is robust against (most) tellurics/variations in the Earth's atmosphere
- Ground-based HDS becomes background limited beyond ~4-5 μm
- Ground-based HDS requires bright stars on an 8-m class telescope
- HDS should work in optical and UV with enough photons
- The future is bright - TESS will provide bright star targets
- Passively cooled ATLAST would open up the >5μm regime to HDS

Take home messages:

- **HDS** unambiguously identifies **molecular features** in exoplanet atmospheres and probes their **thermal structure**, but *accurate line lists* are crucial.
- C/O ratios measured with HDS may reveal **planet formation** mechanism and birth location in protoplanetary disk.
- HDS+HCI reveals the **rotational velocity** of giant planets at wide separations.
- HDS in the era of giant segmented mirror telescopes can identify **biomarkers** and create **maps** of atmospheric surface features.