A High Resolution View of Exoplanet Atmospheres in the TMT Era

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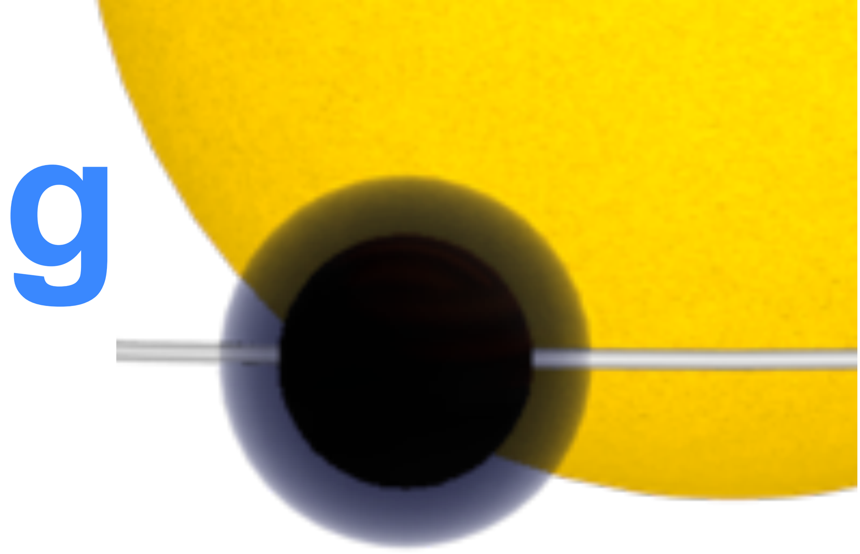
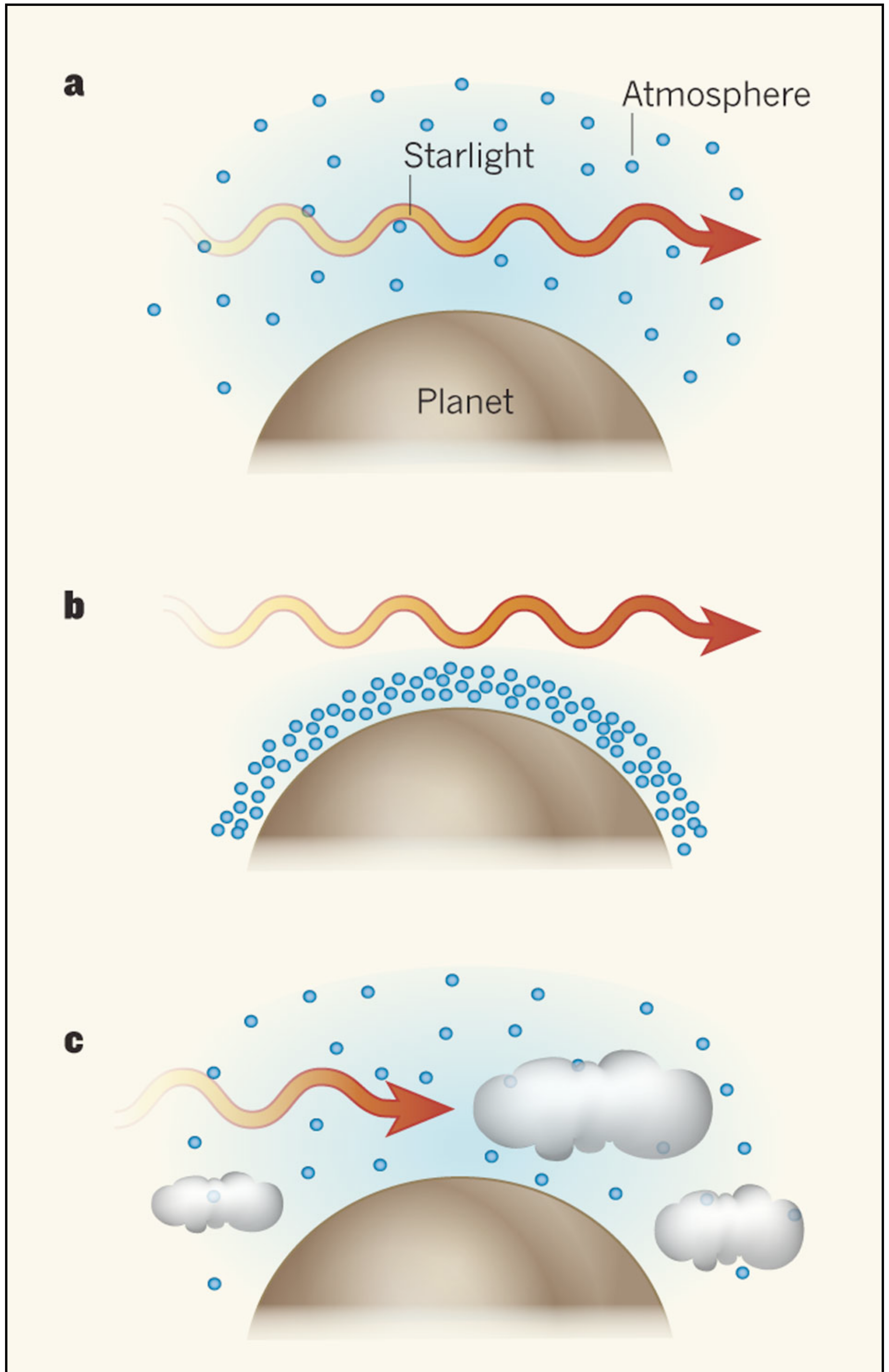
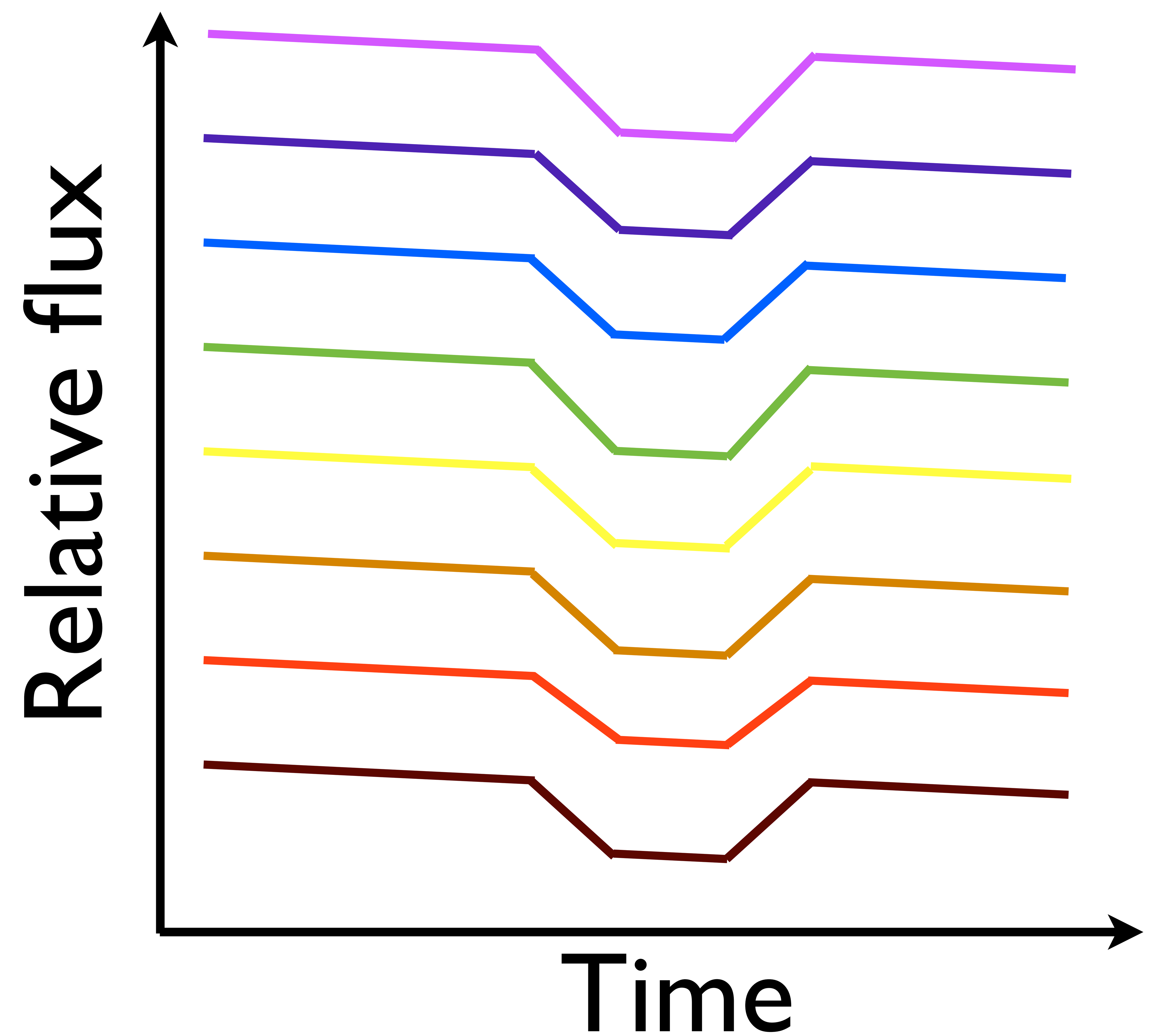
Detecting molecules with transmission spectroscopy

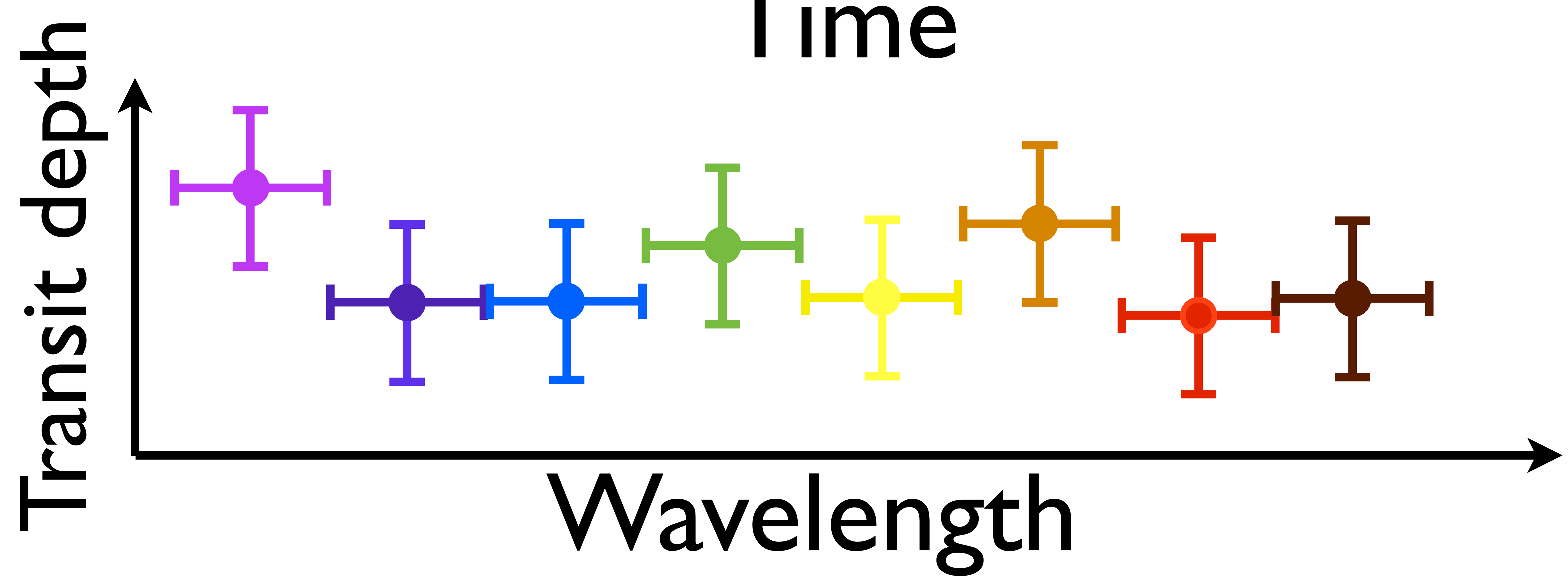
Starlight filtering through an atmosphere during transit is imprinted with the planet's spectrum





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





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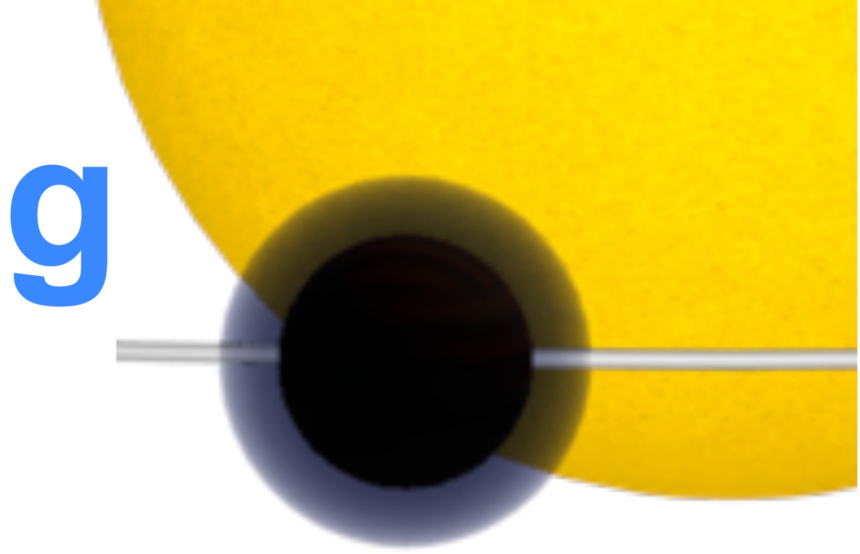

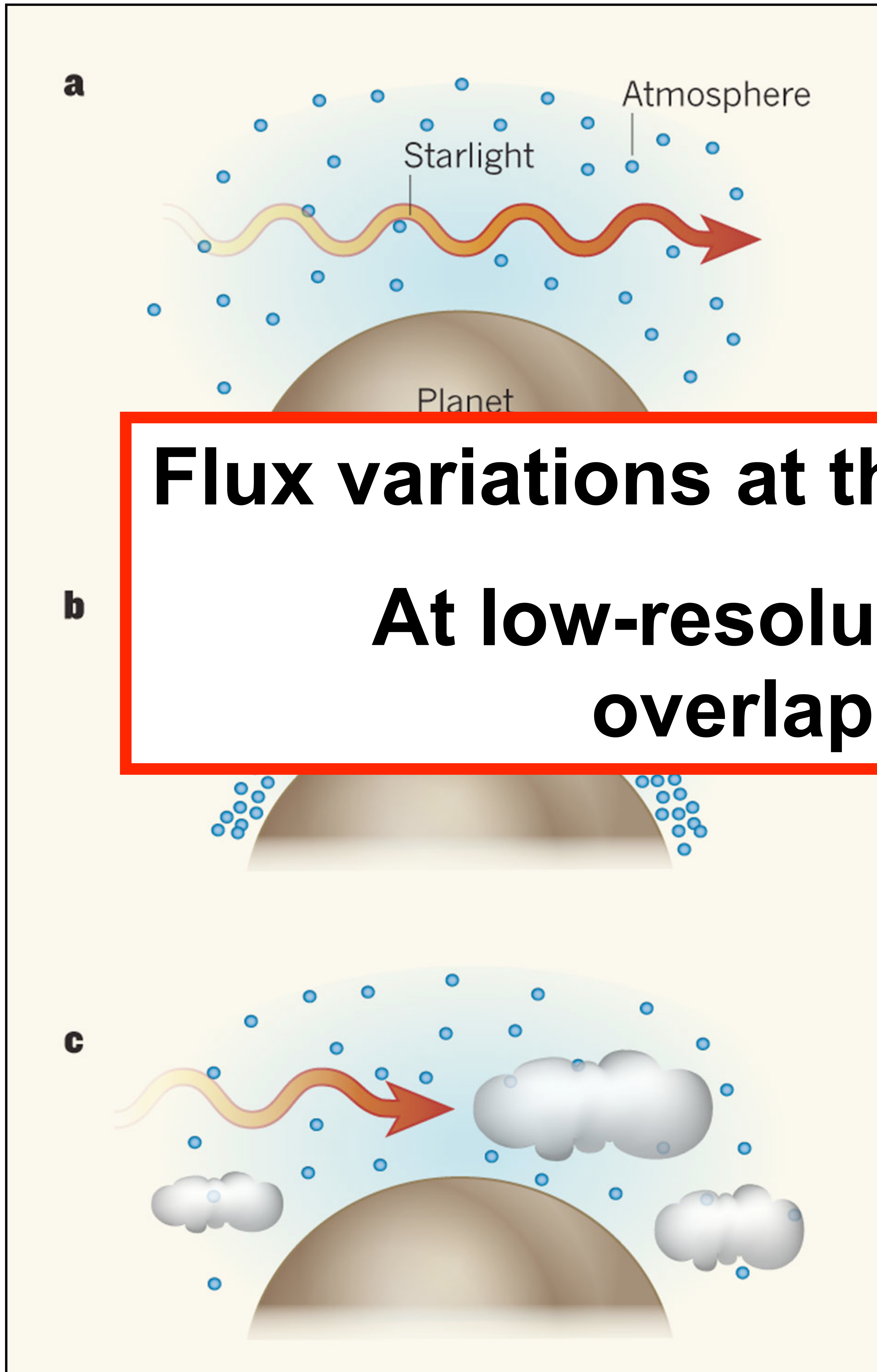

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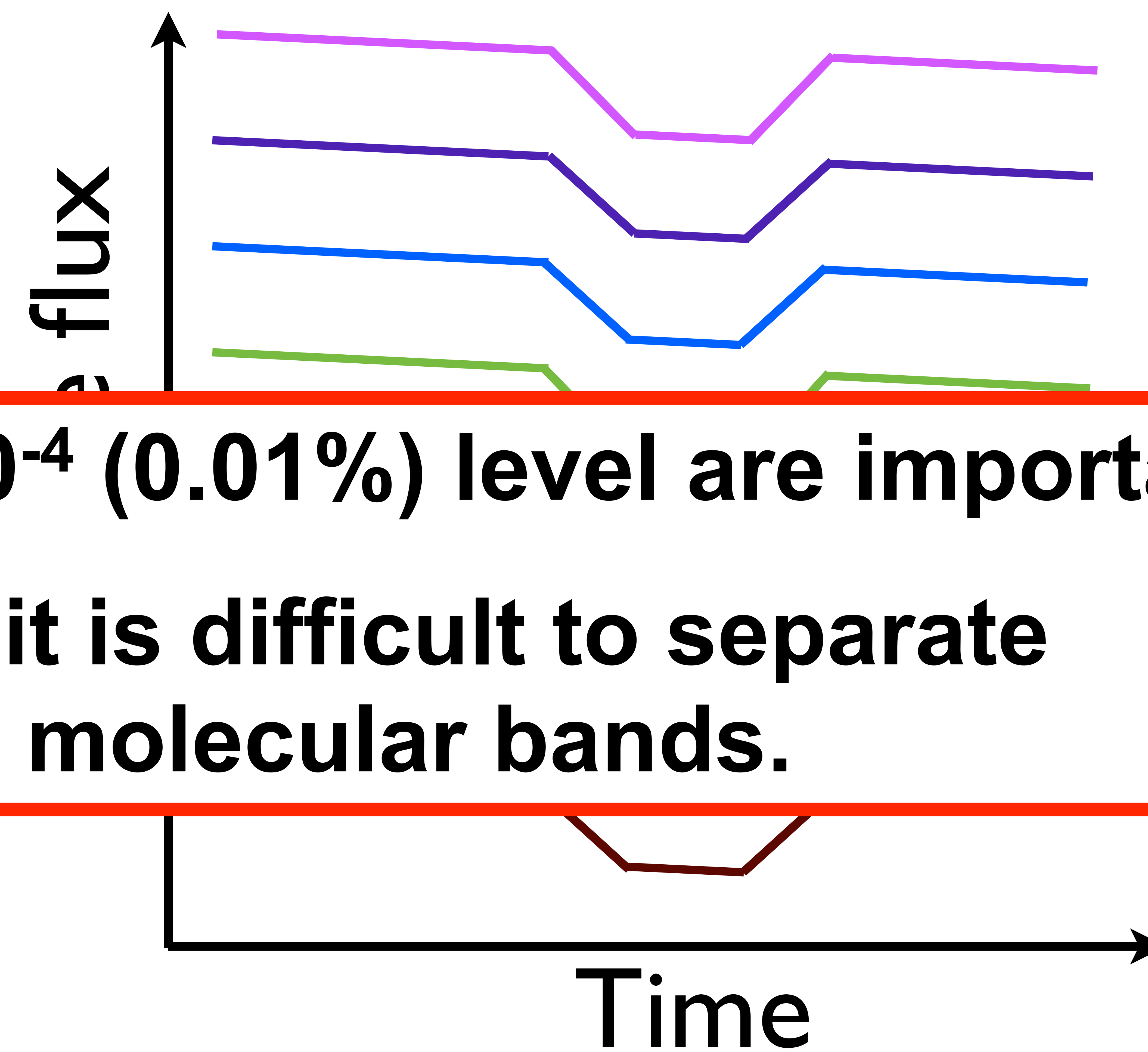
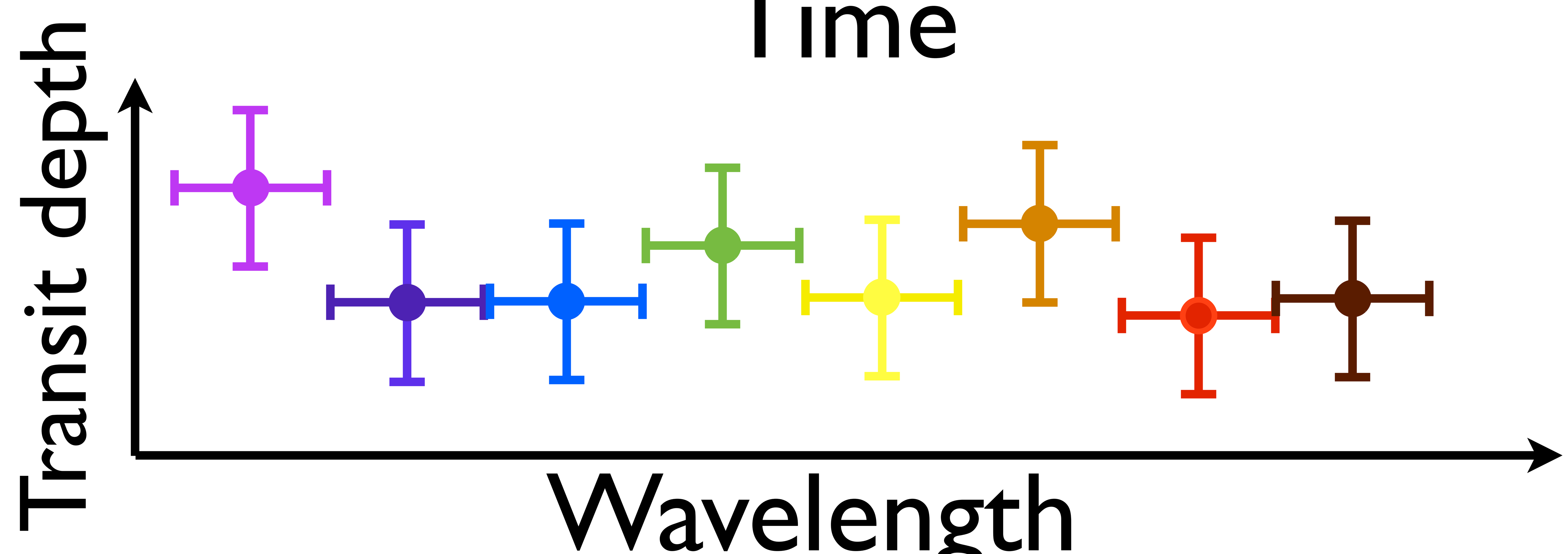


Flux variations at the 10^{-4} (0.01%) level are important.

At low-resolution it is difficult to separate overlapping molecular bands.



“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)

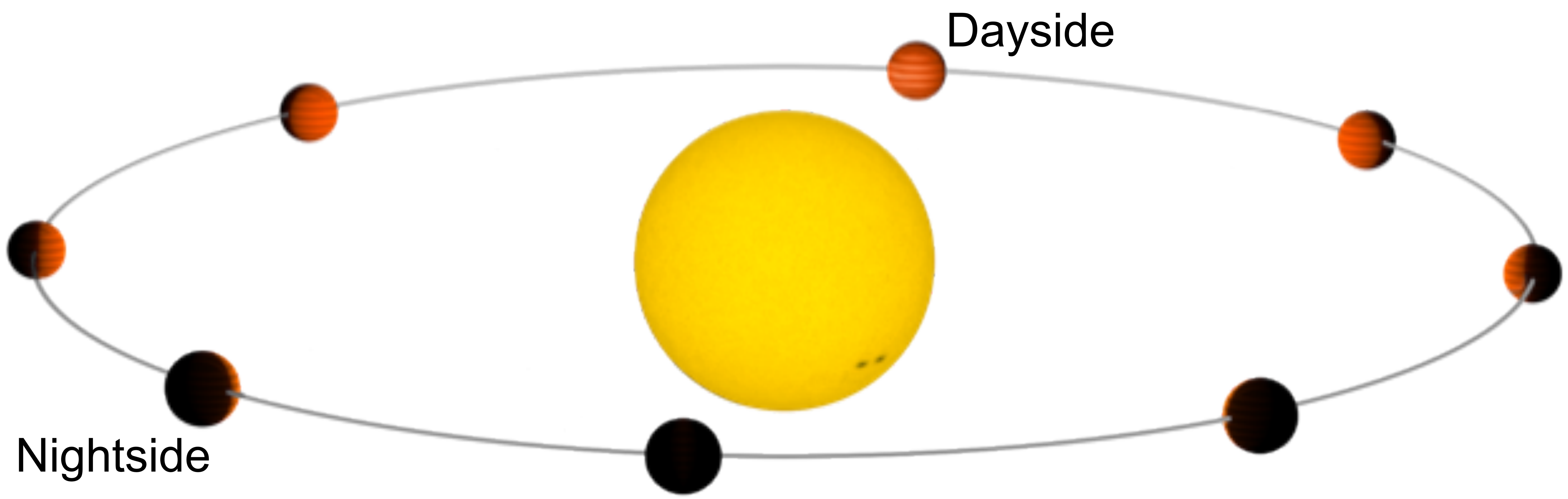
Detecting molecules with High Dispersion Spectroscopy (HDS)

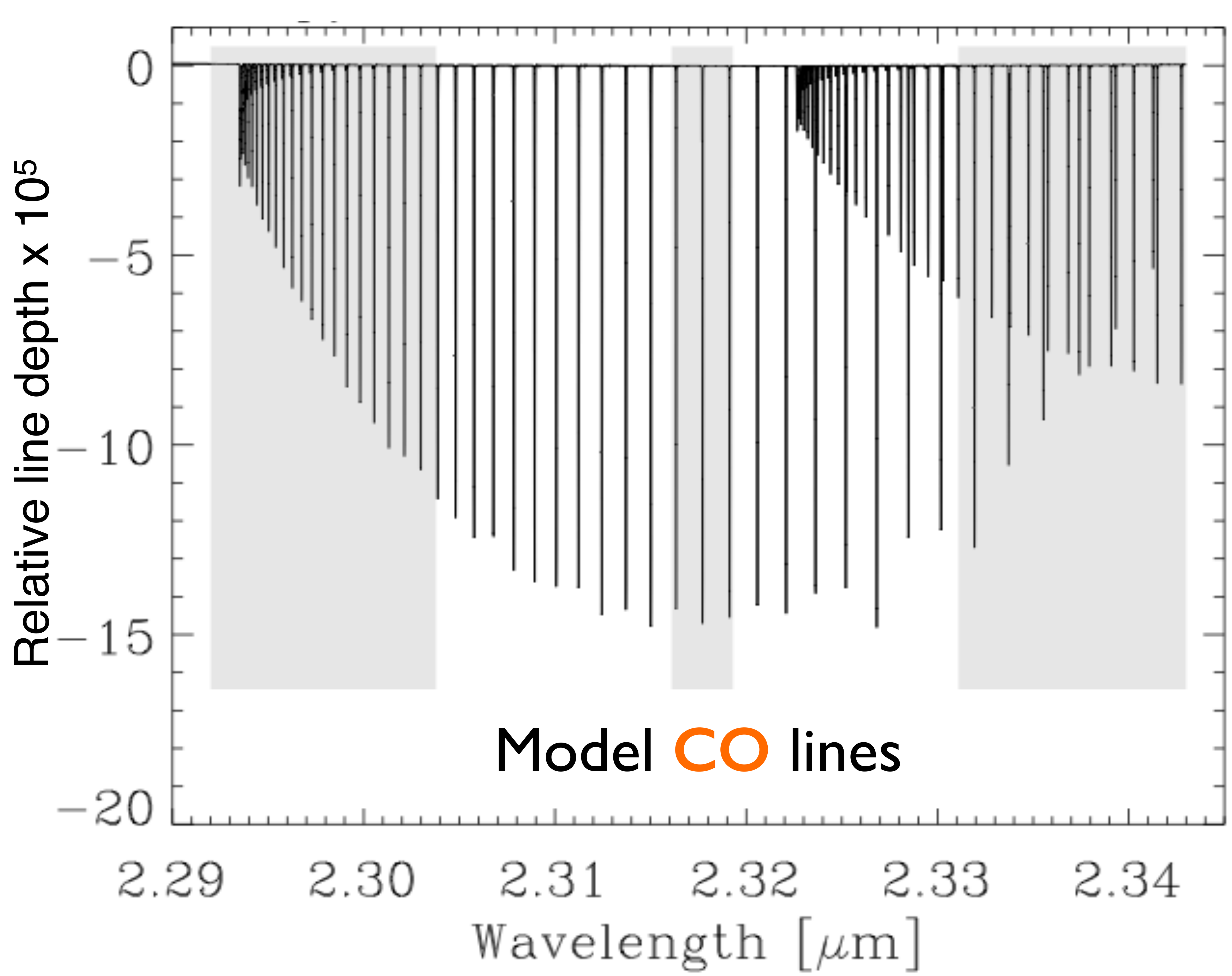
A CRIRES/VLT survey of hot Jupiter atmospheres

- 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





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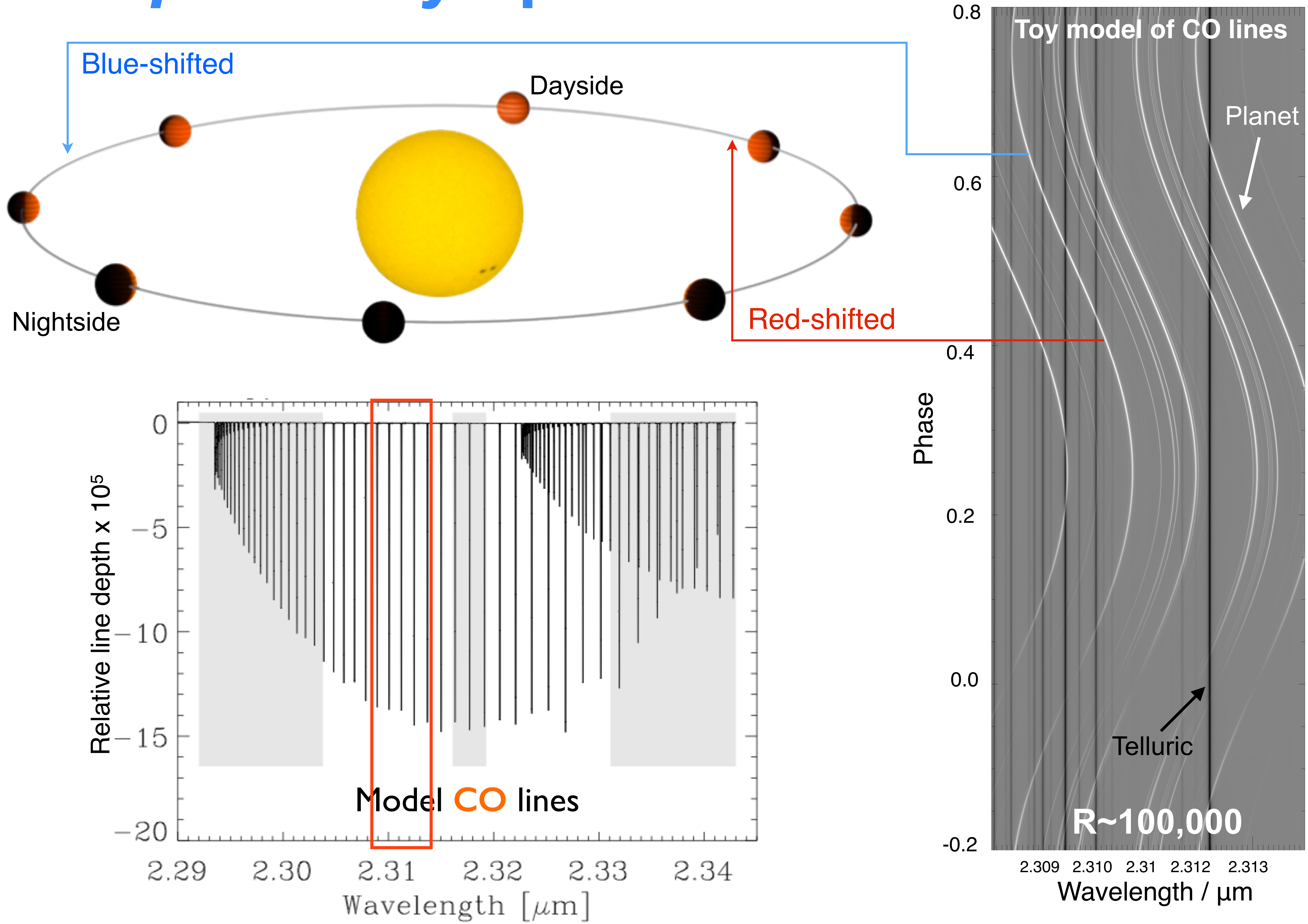
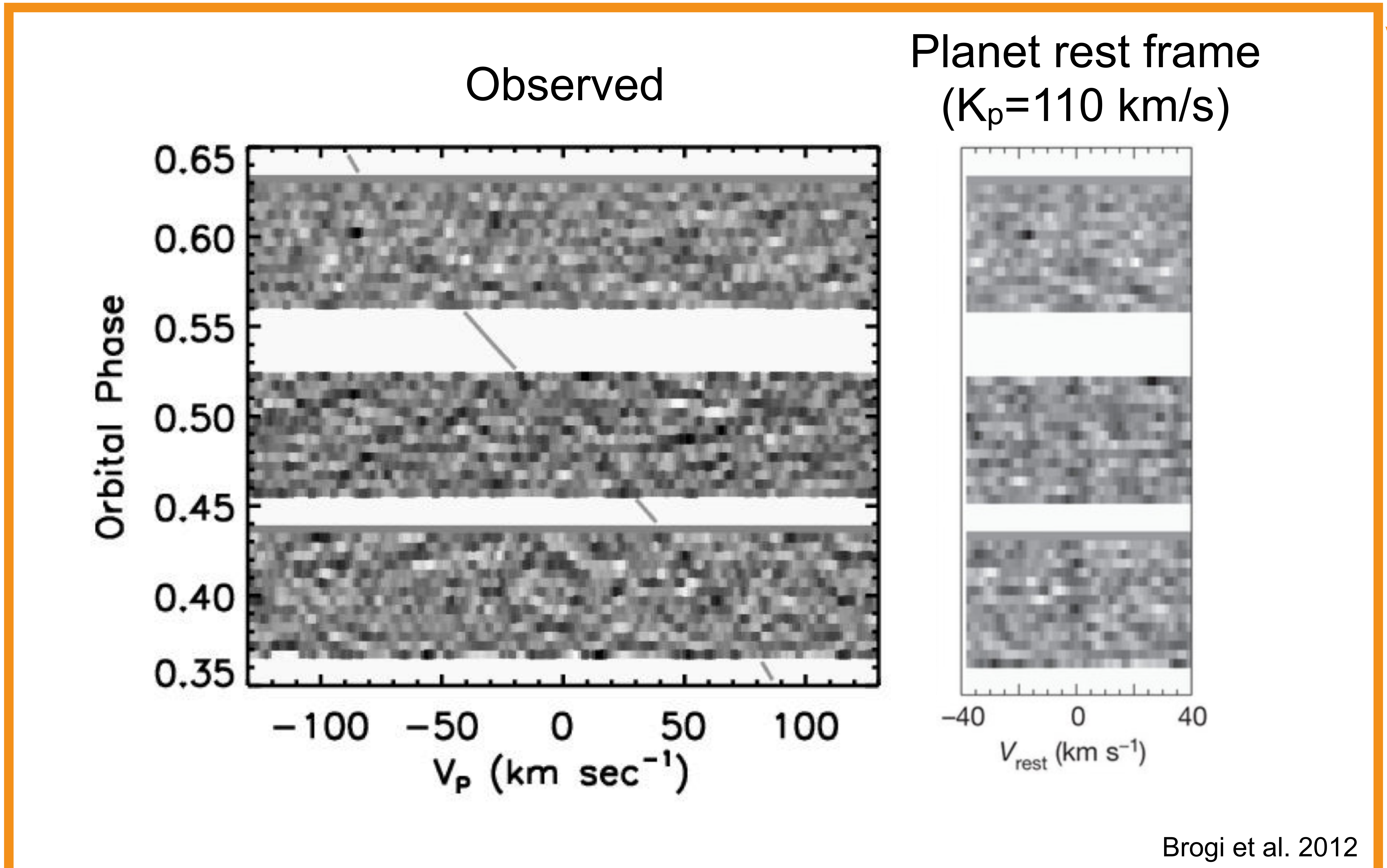
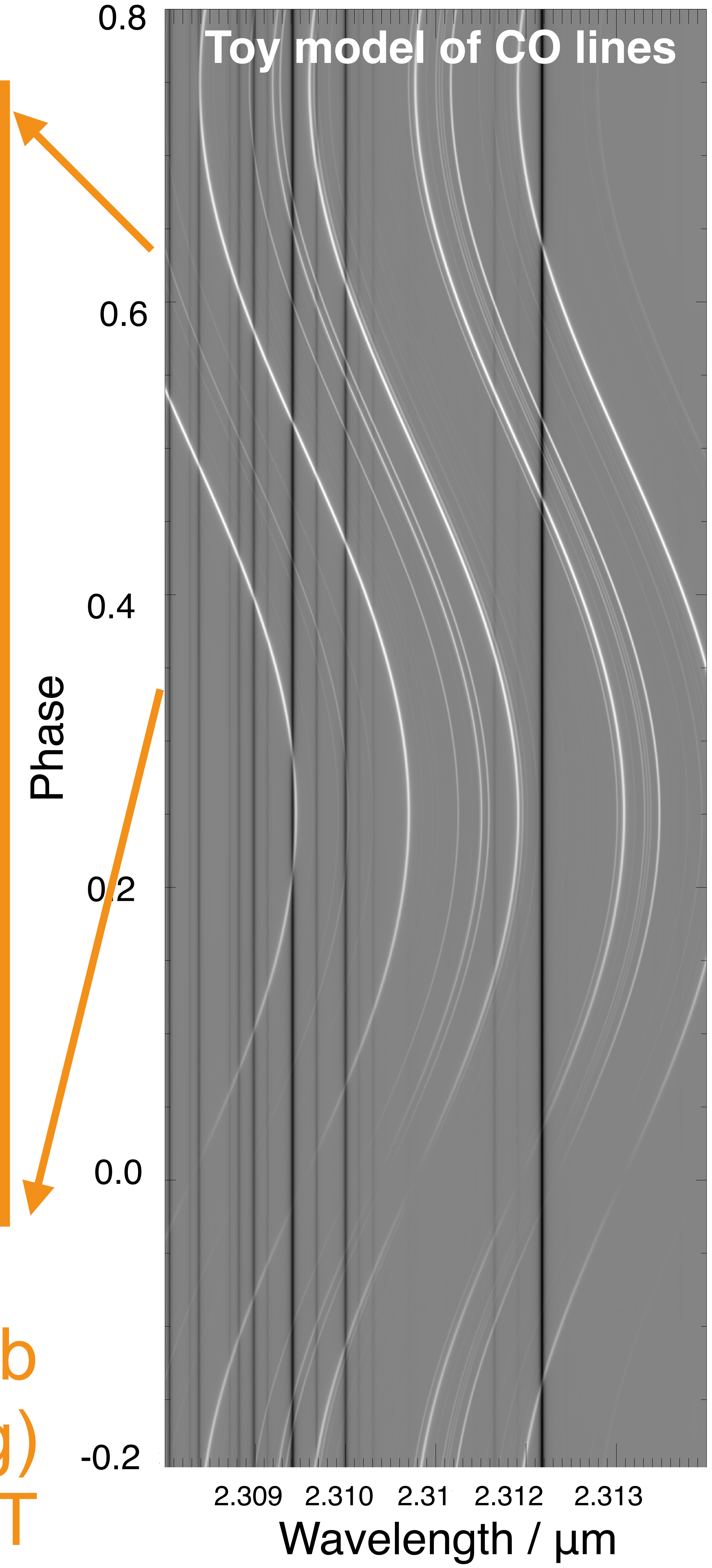
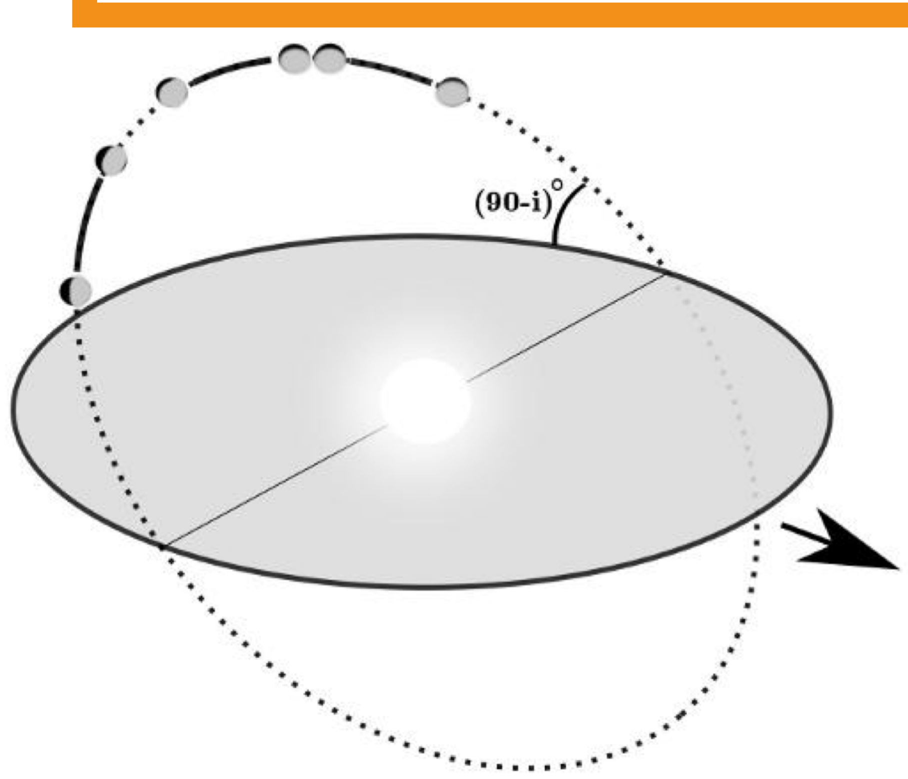


HDS detects carbon monoxide RV trail in a *non-transiting* hot Jupiter atmosphere





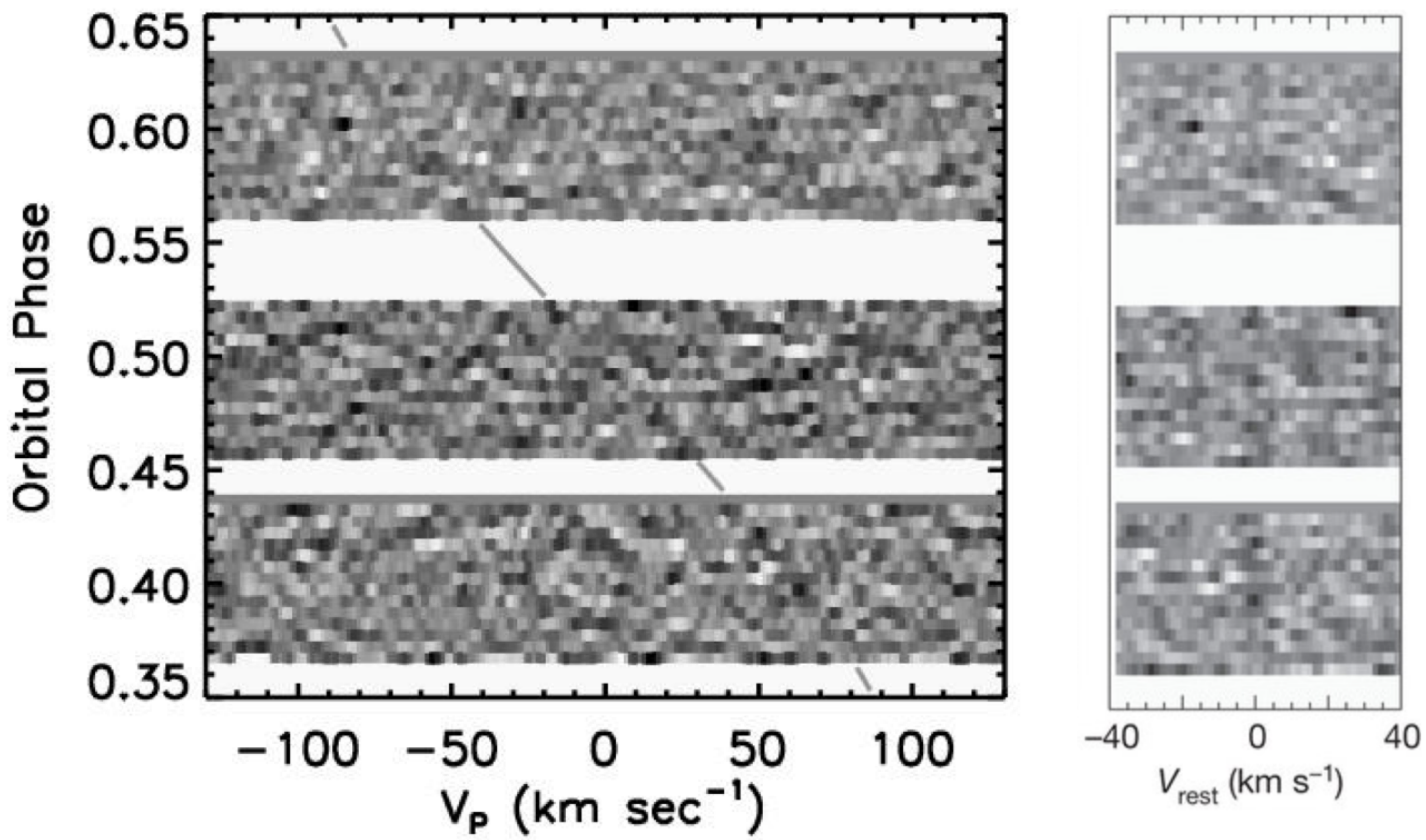


CO detected at **6σ** at **2.3 µm** in τ Boo b on the dayside hemisphere (non-transiting) with CRIRES/VLT

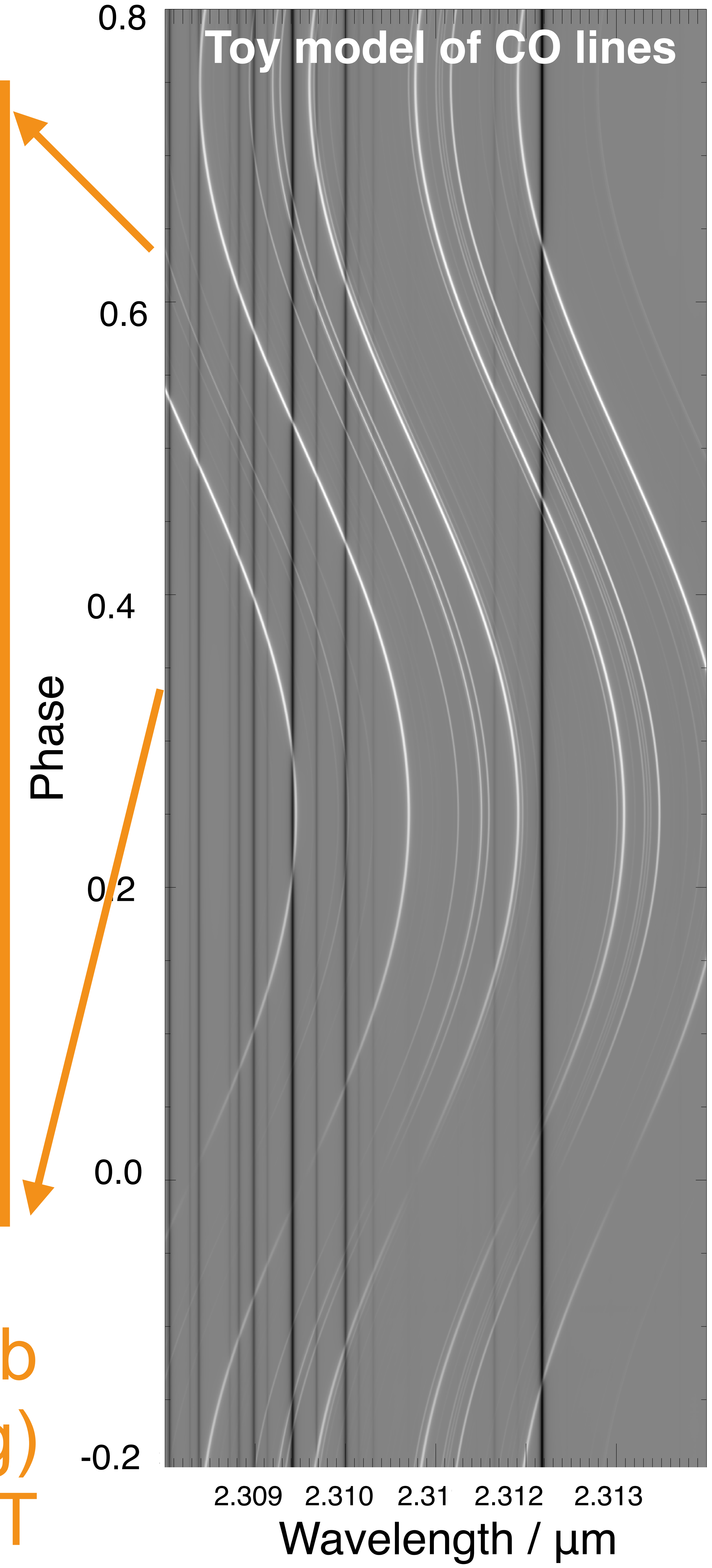
HDS detects carbon monoxide RV trail in a *non-transiting* hot Jupiter atmosphere

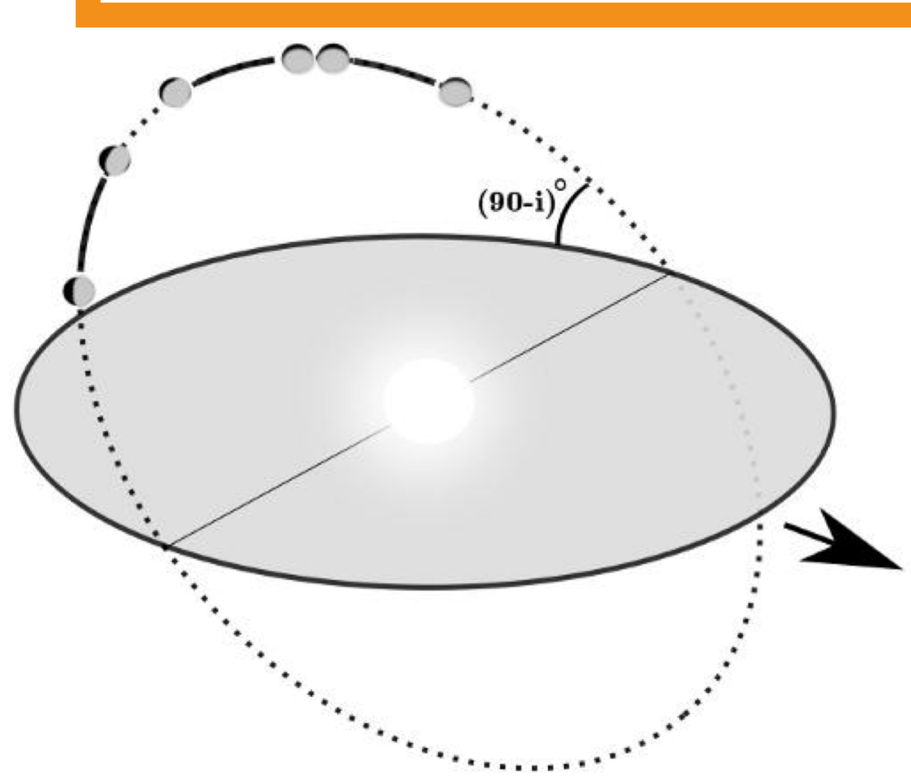
Slope = planet velocity
➔ spectroscopic binary

Planet rest frame
(K_p=110 km/s)



Brogi et al. 2012





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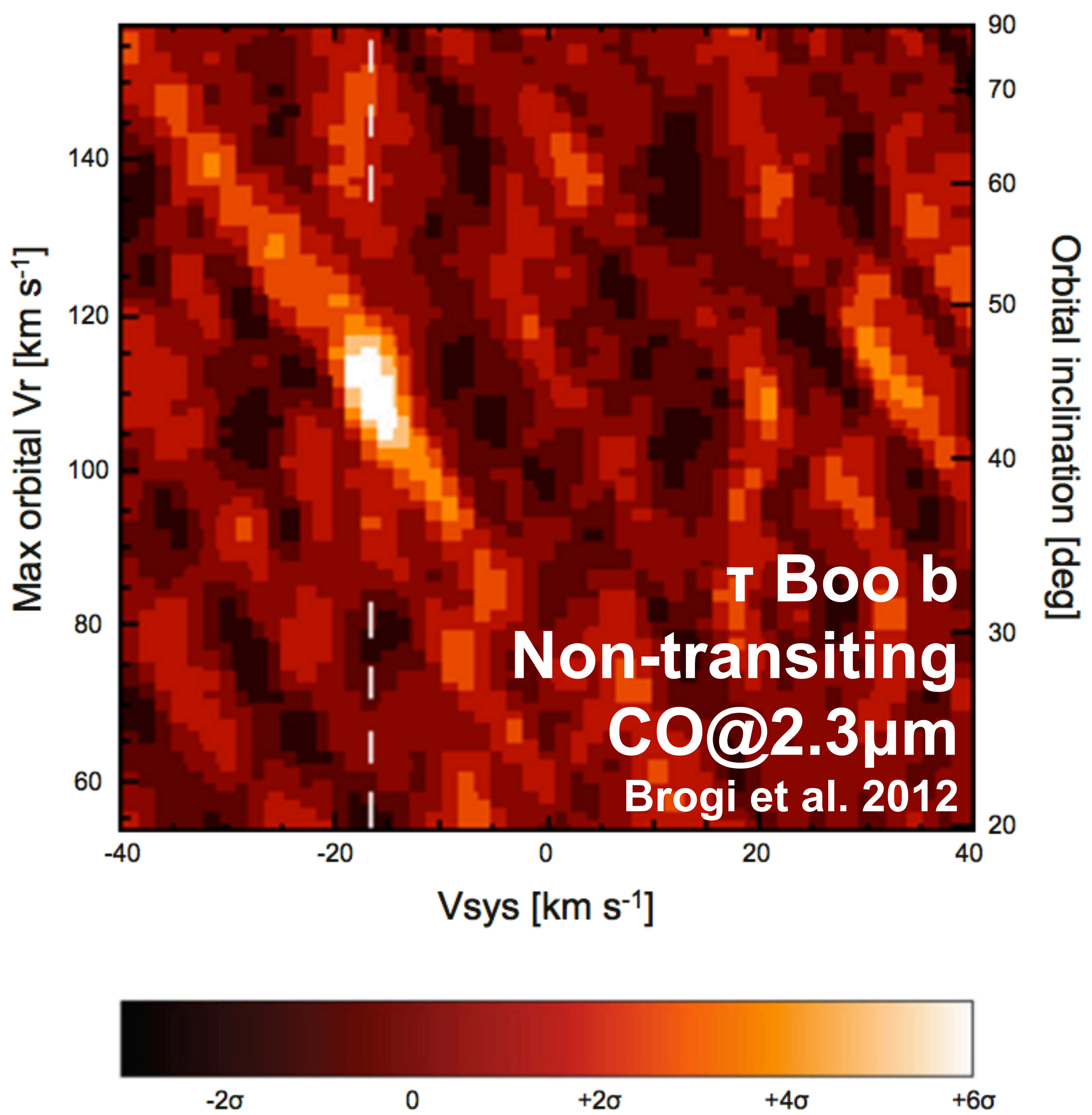
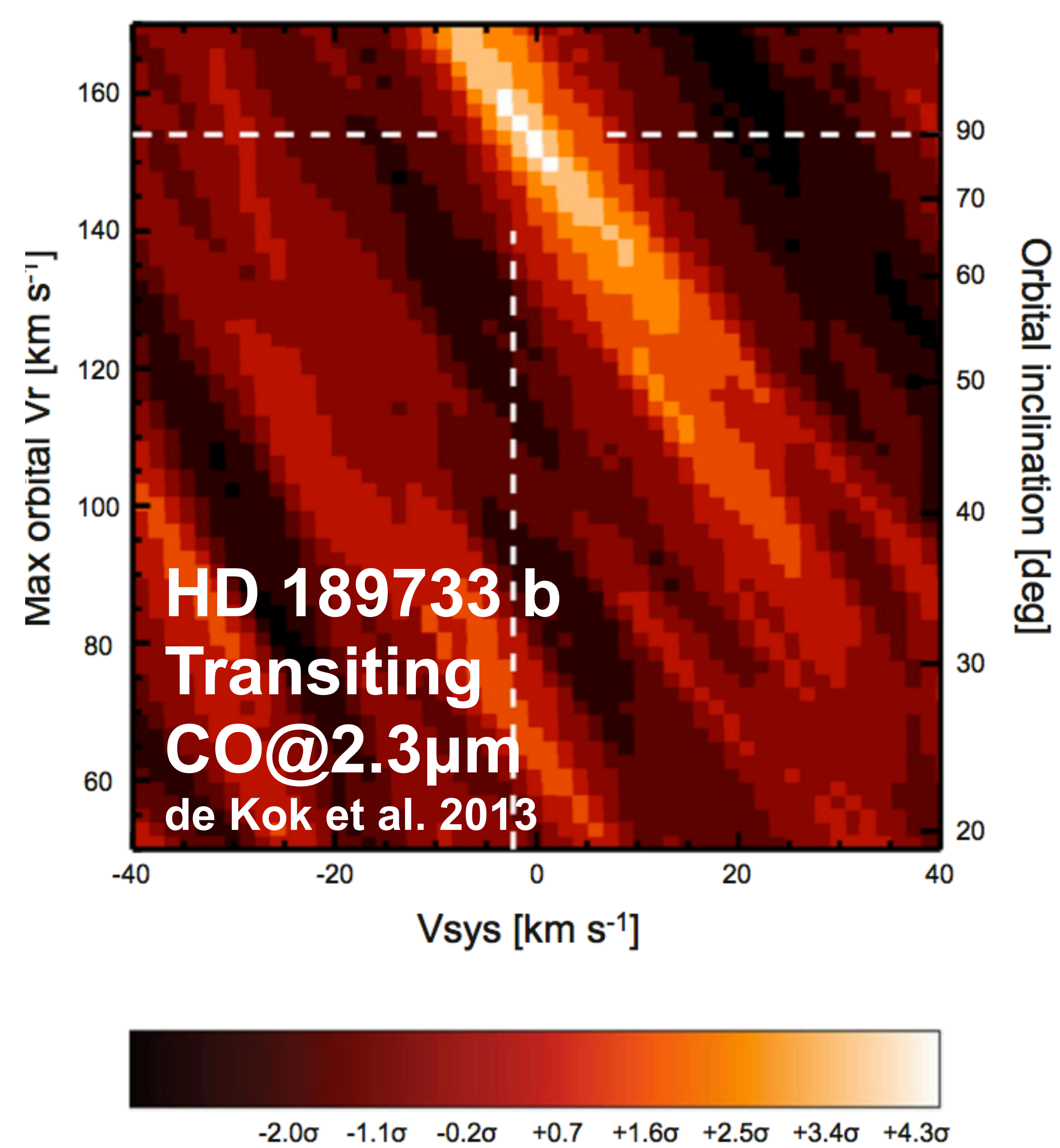
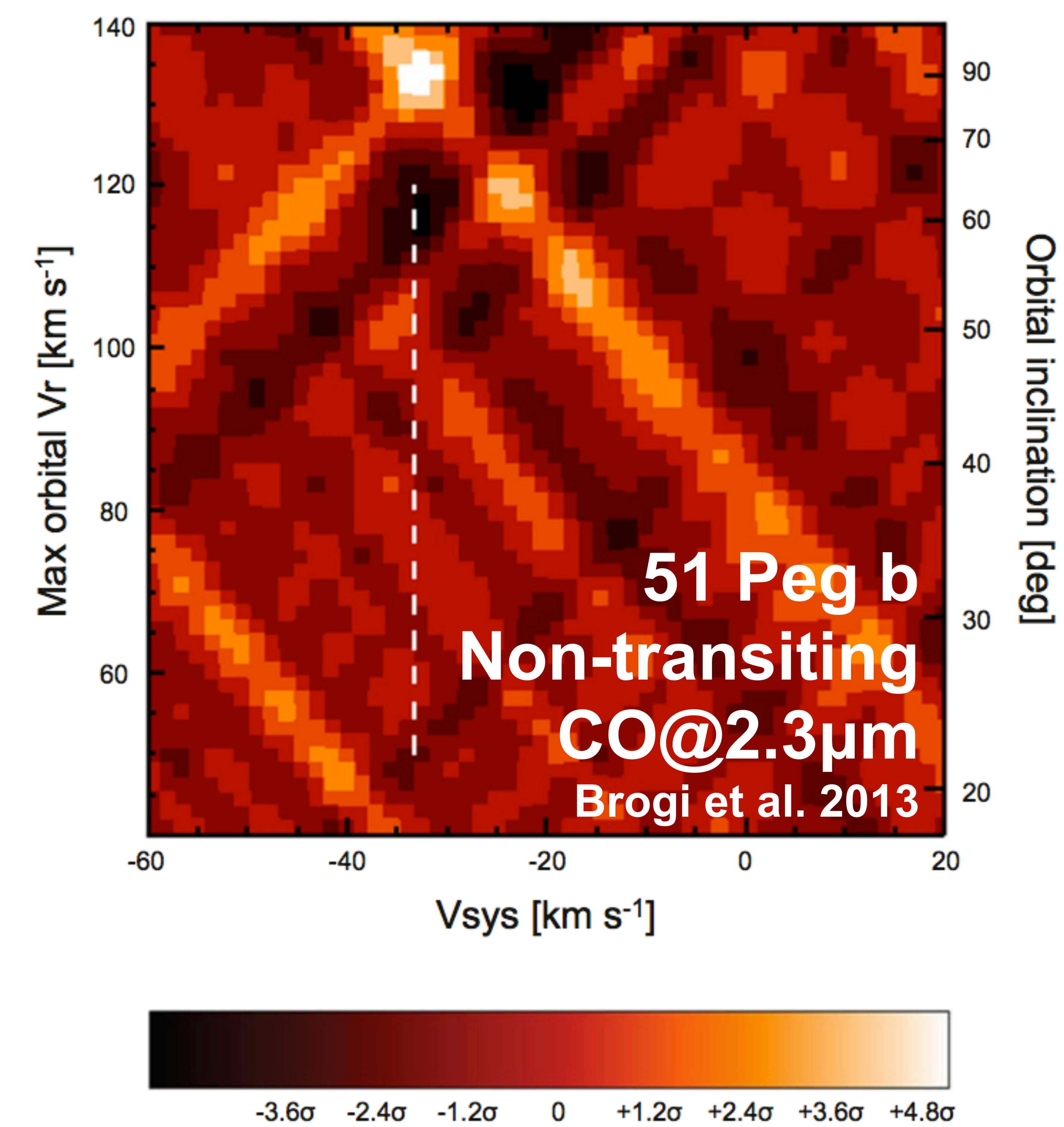
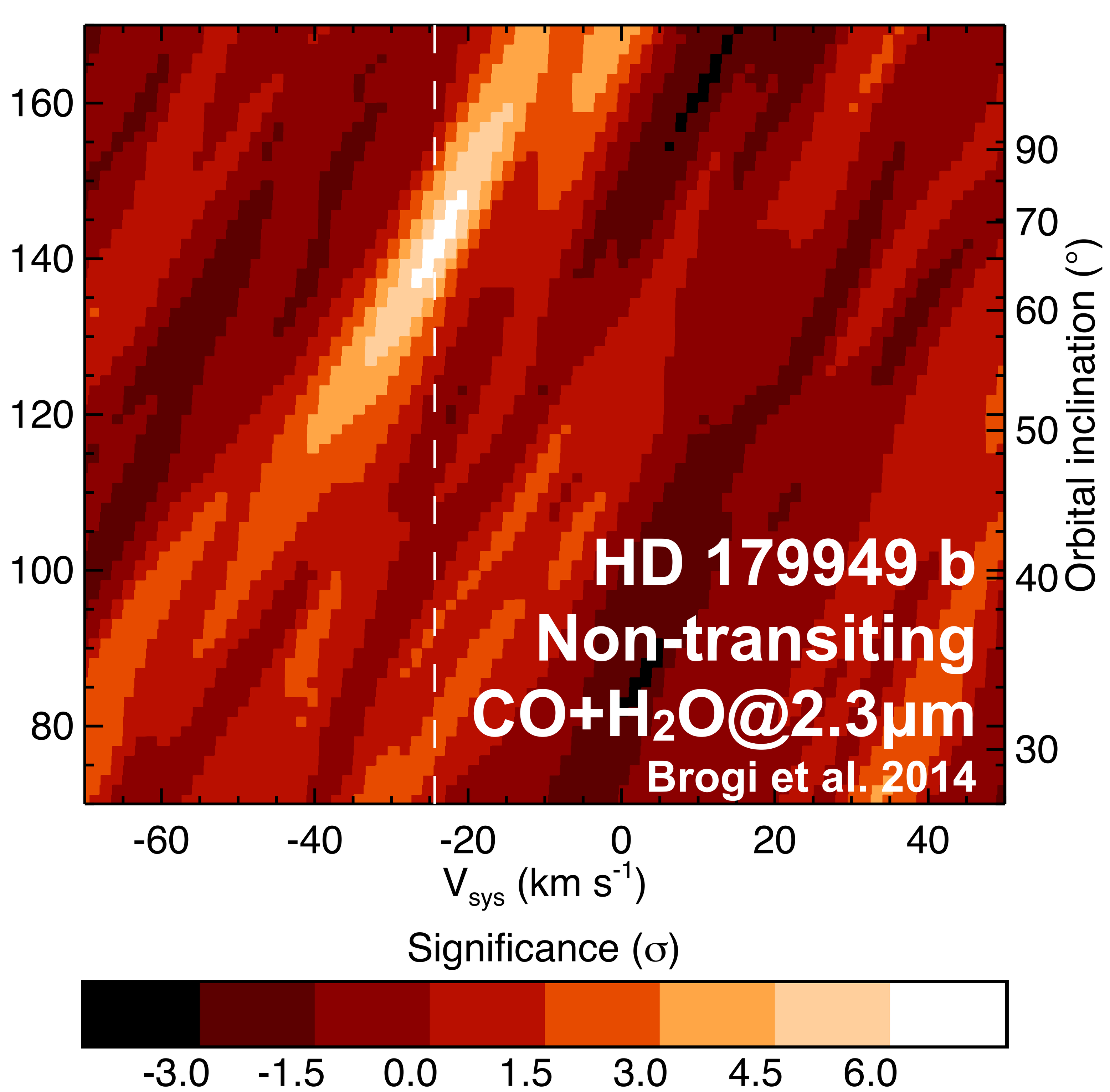
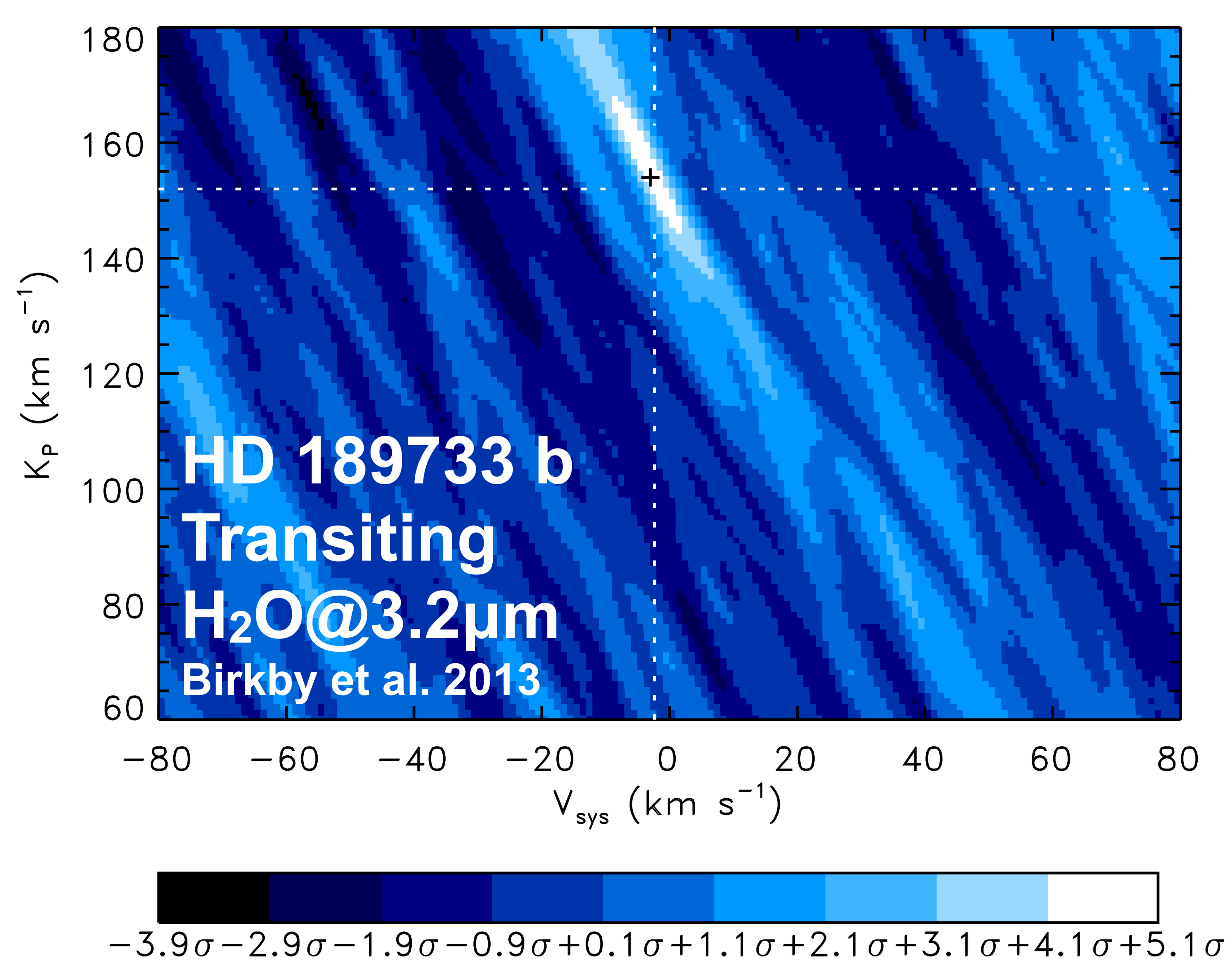
HDS provides unambiguous detections of complex molecules in hot Jupiter atmospheres





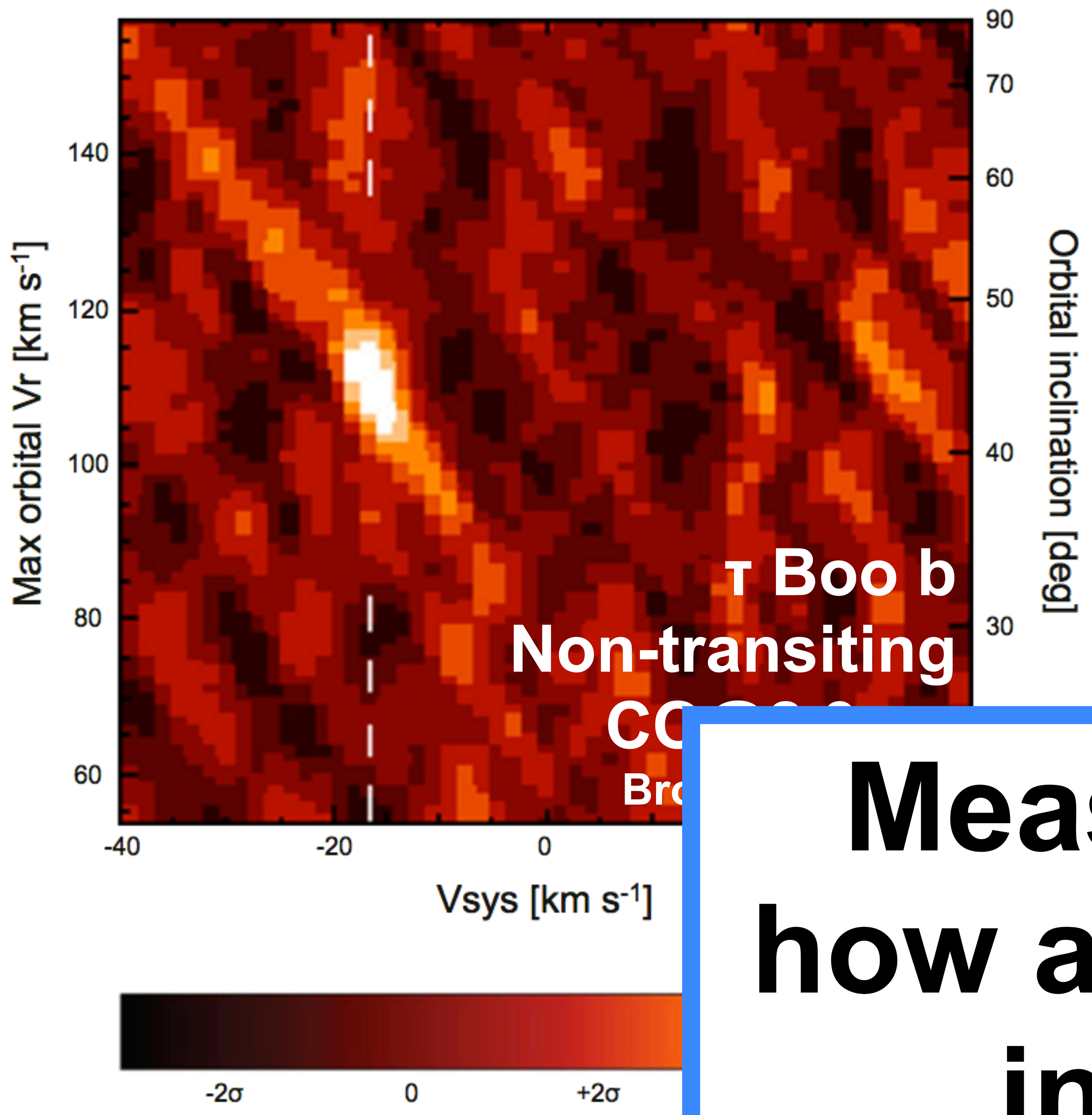


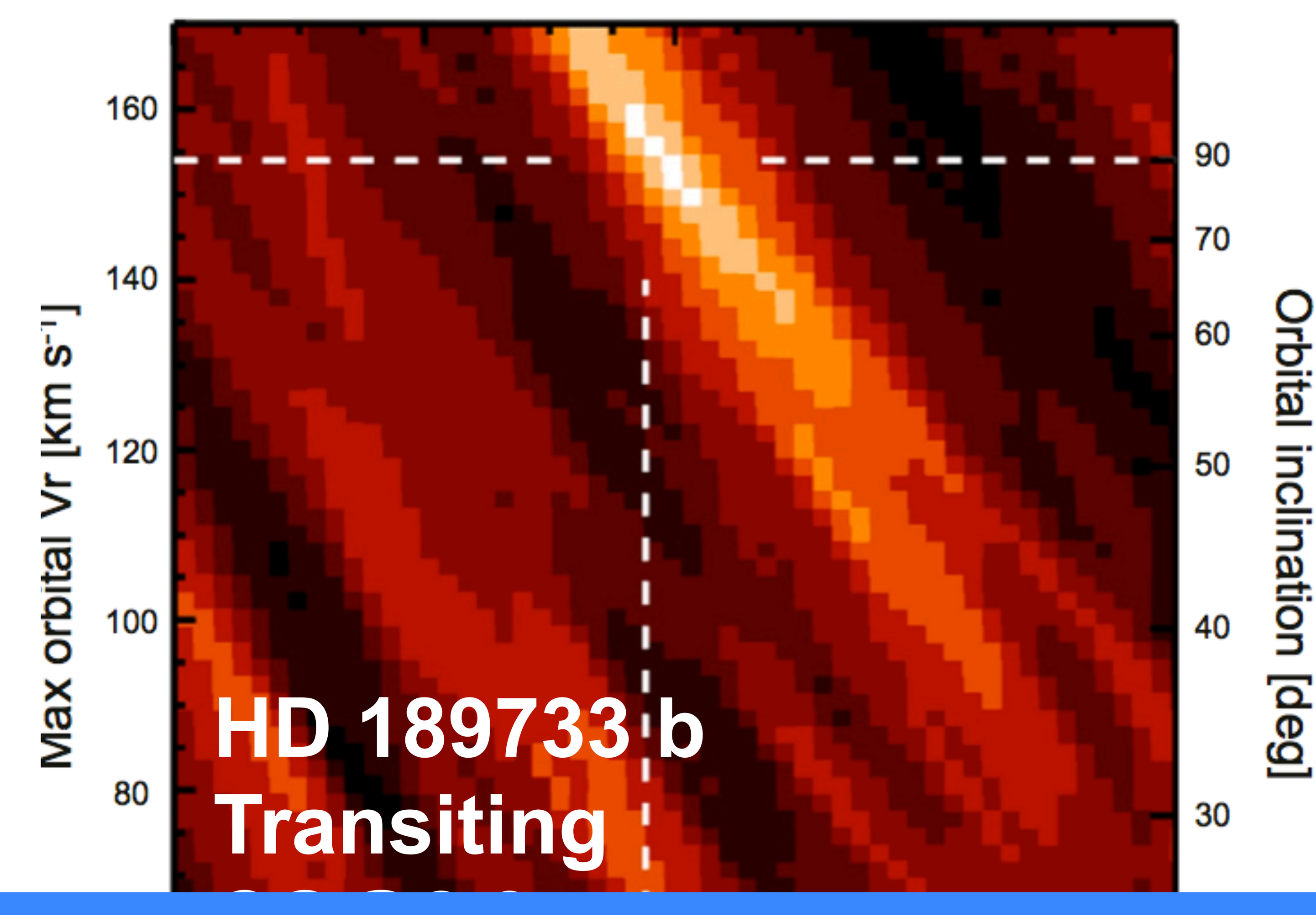


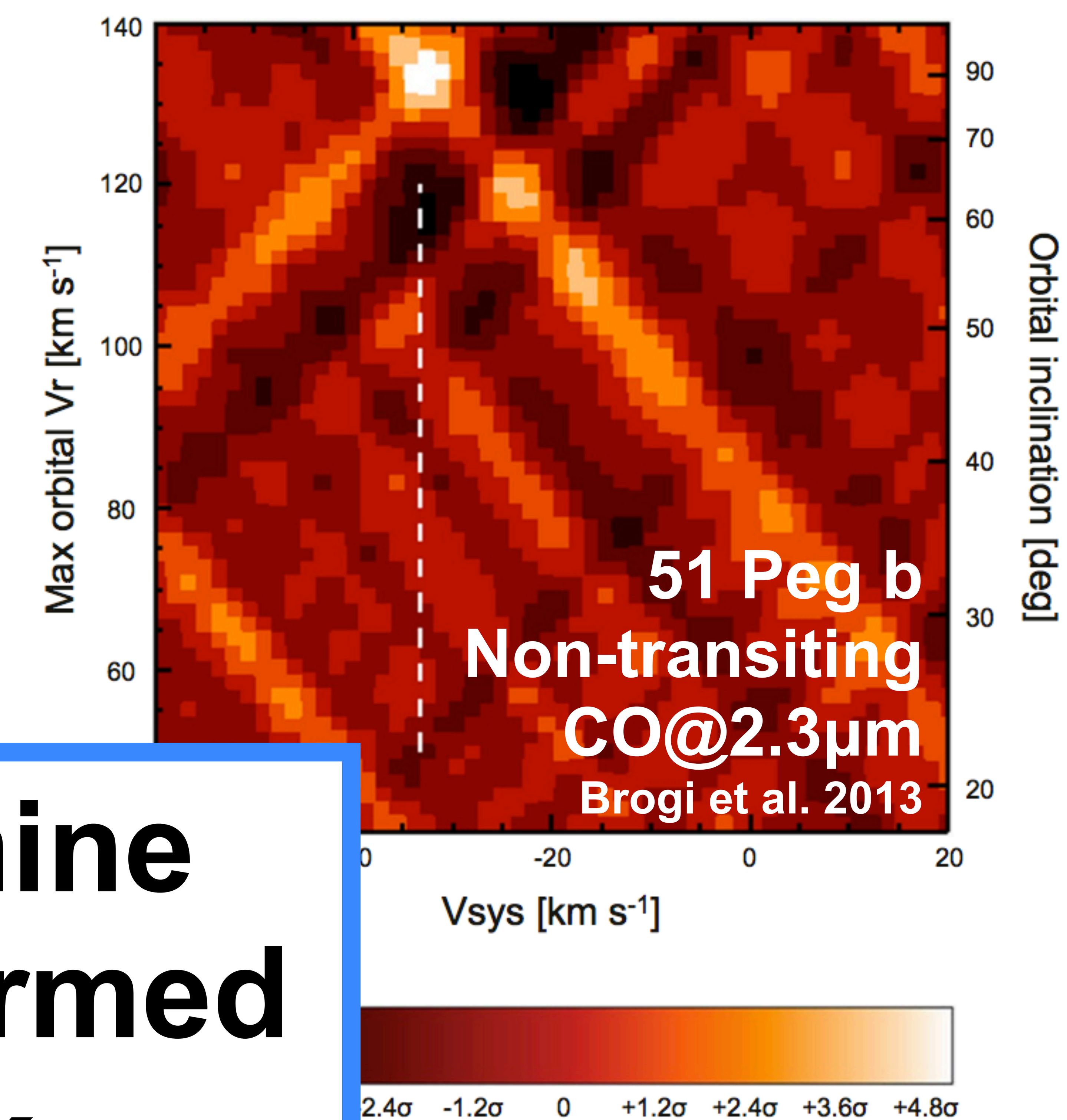


See also Rodler et al. 2012; 2013 (CO in τ Boo b & HD 189733 b); Lockwood et al. 2014 (H_2O in τ Boo b)

HDS provides unambiguous detections of complex molecules in hot Jupiter atmospheres

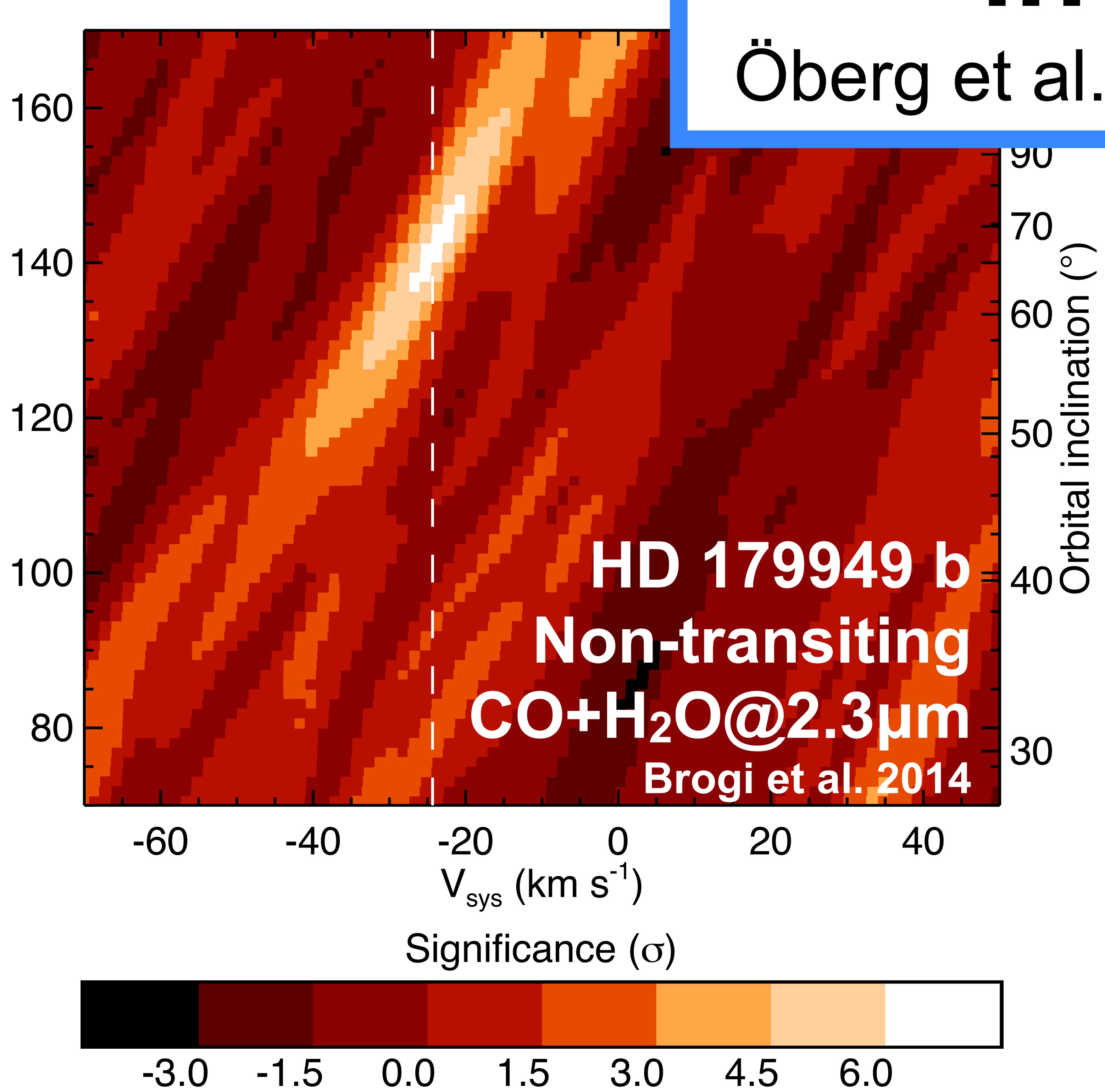


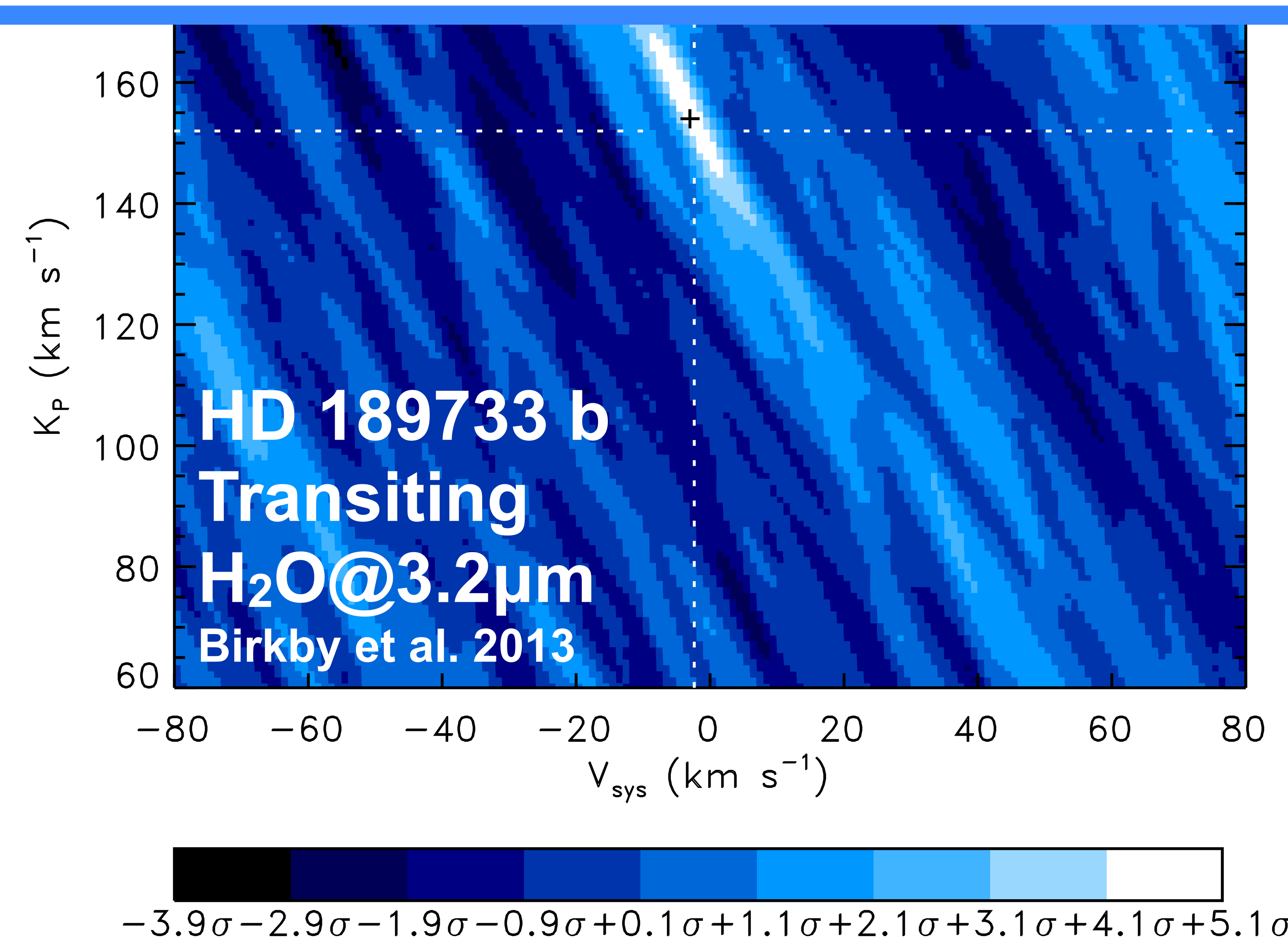




Measuring C/O may determine how and where the planet formed in its protoplanetary disk

Öberg et al. 2011, Konopacky et al. 2013, Barman et al. 2015





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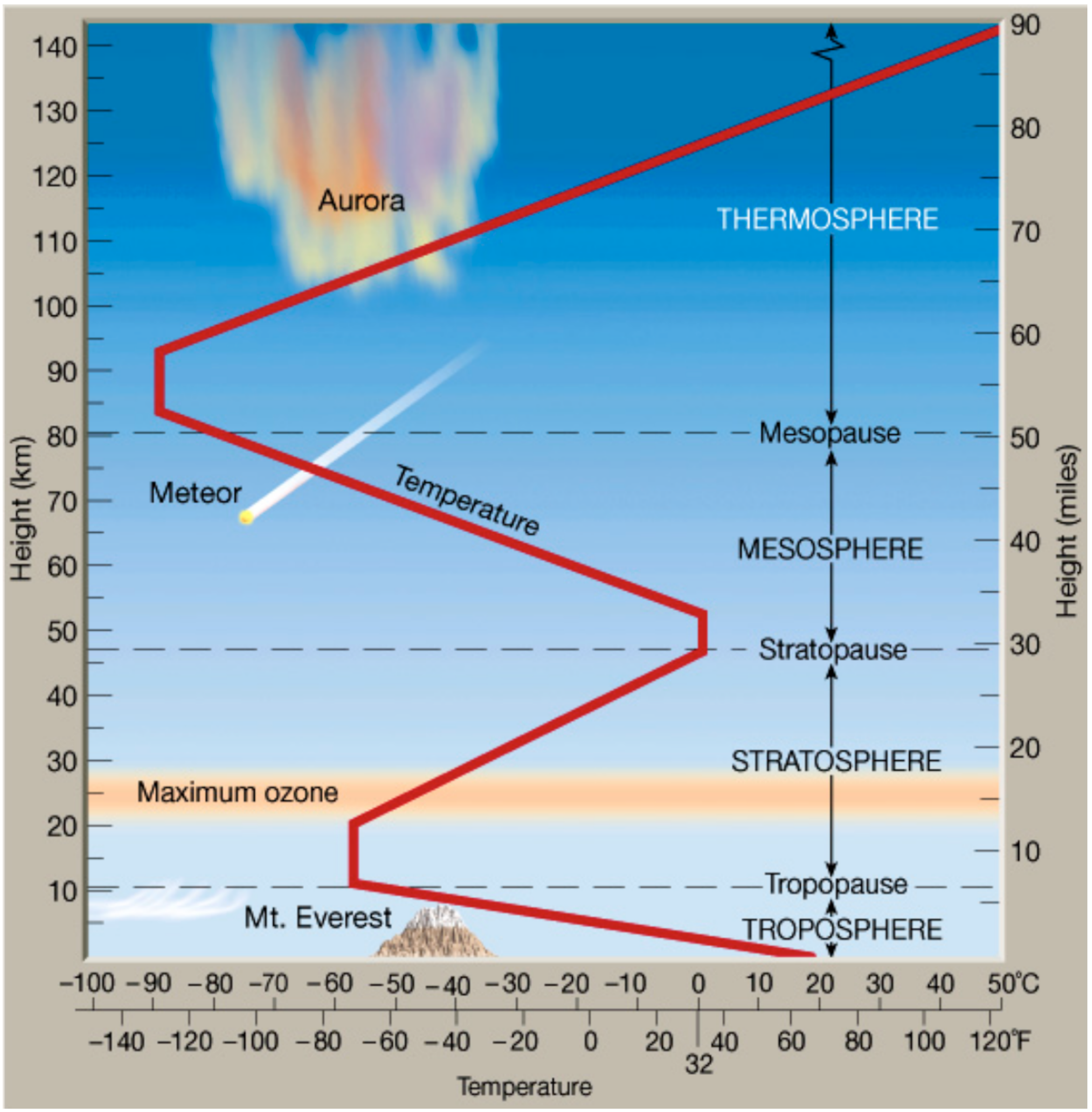
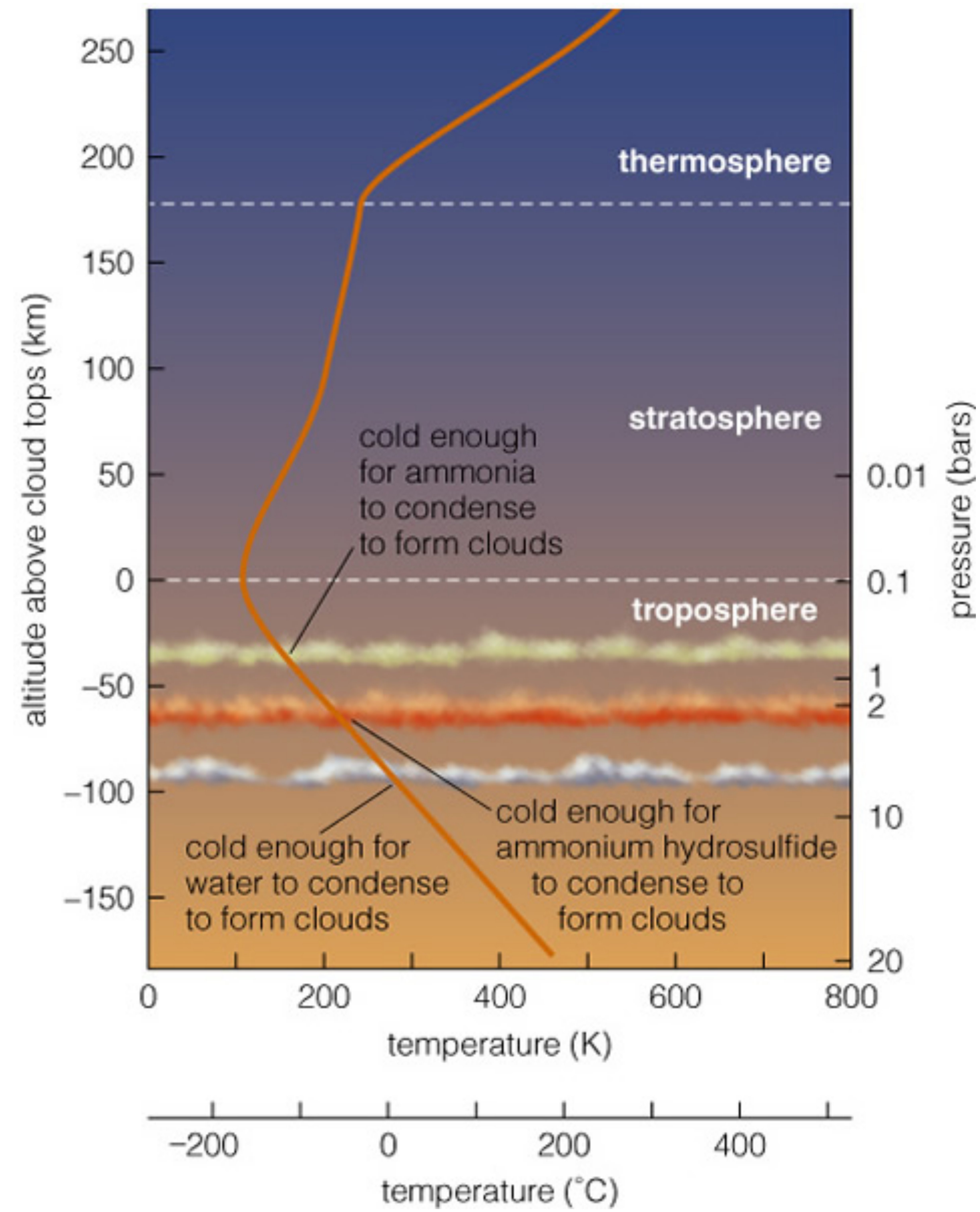
Atmospheric structure is tied to composition

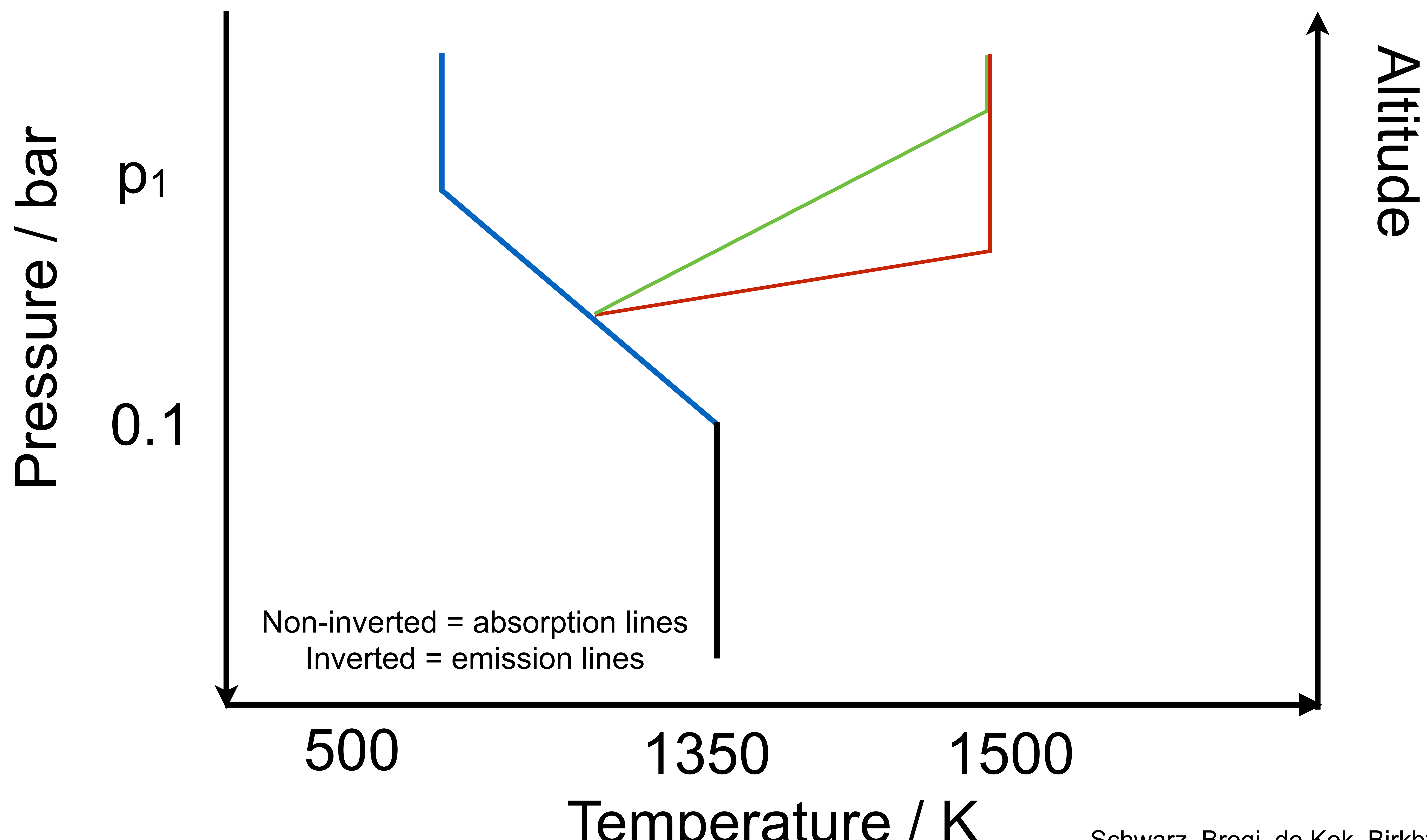
Earth



Jupiter



Dayside measurements probe atmospheric layers revealing a temperature-pressure profile



Schwarz, Brogi, de Kok, Birkby, Snellen (2015)

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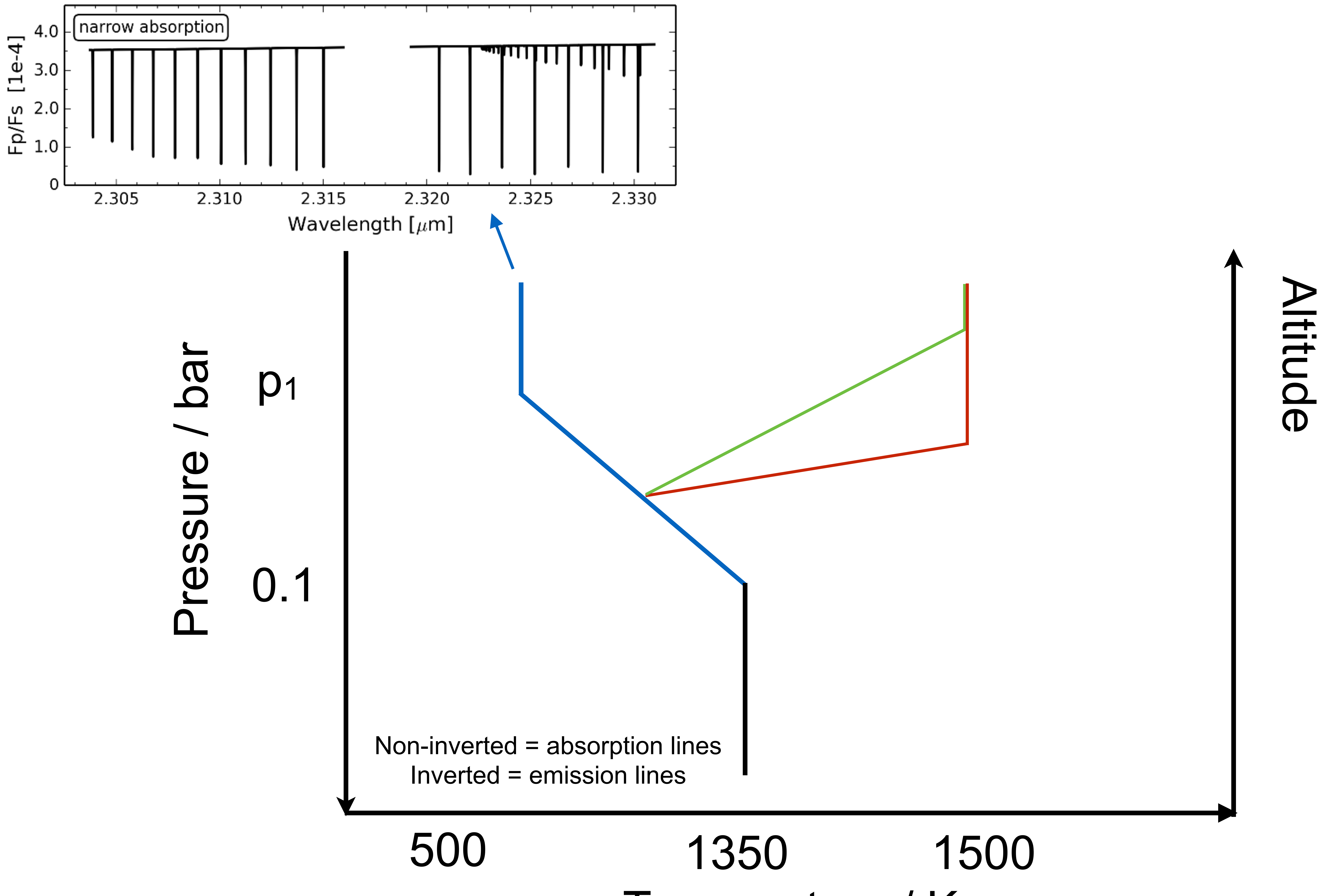

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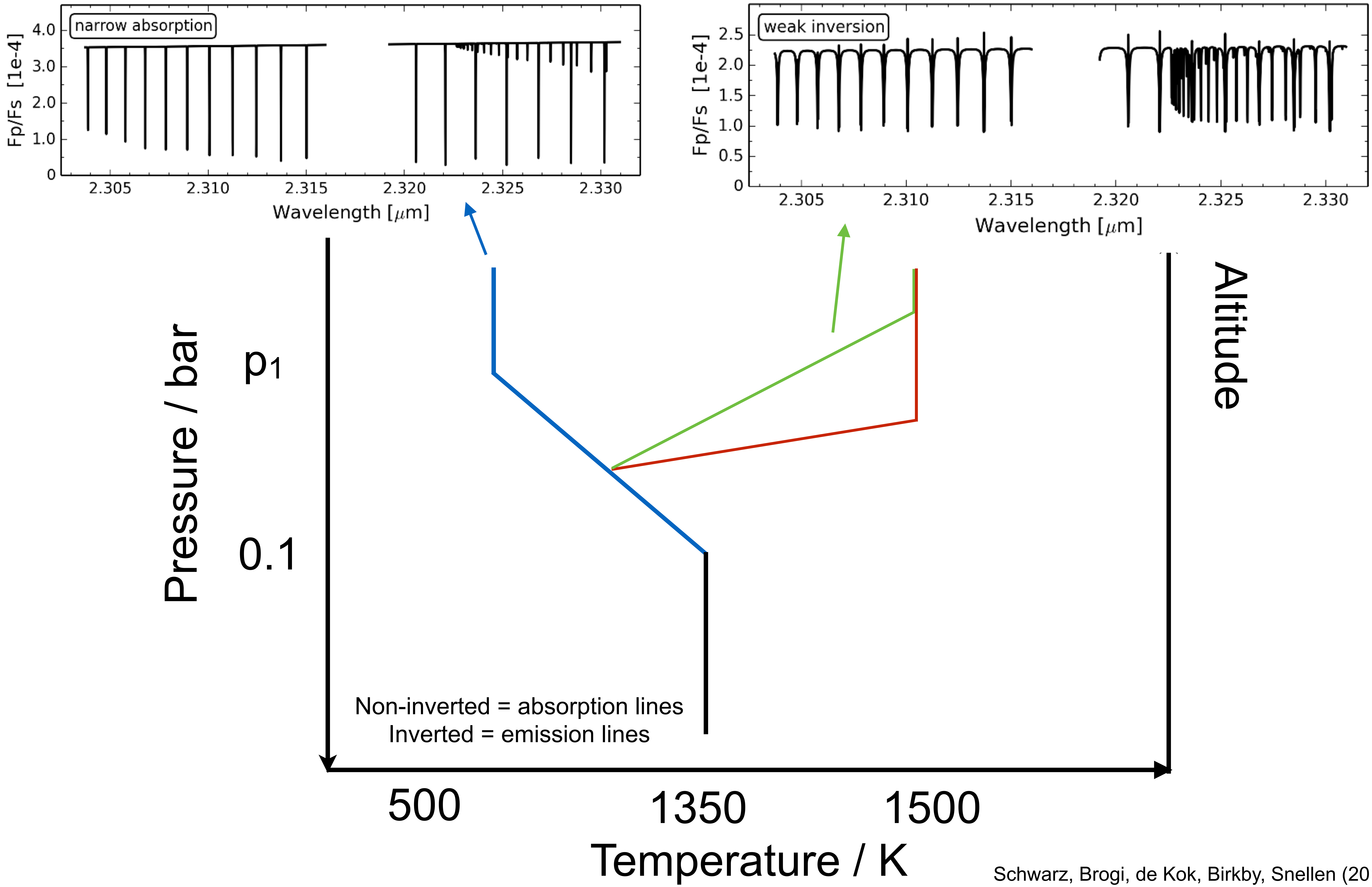


Schwarz, Brogi, de Kok, Birkby, Snellen (2015)

Dayside measurements probe atmospheric layers revealing a temperature-pressure profile

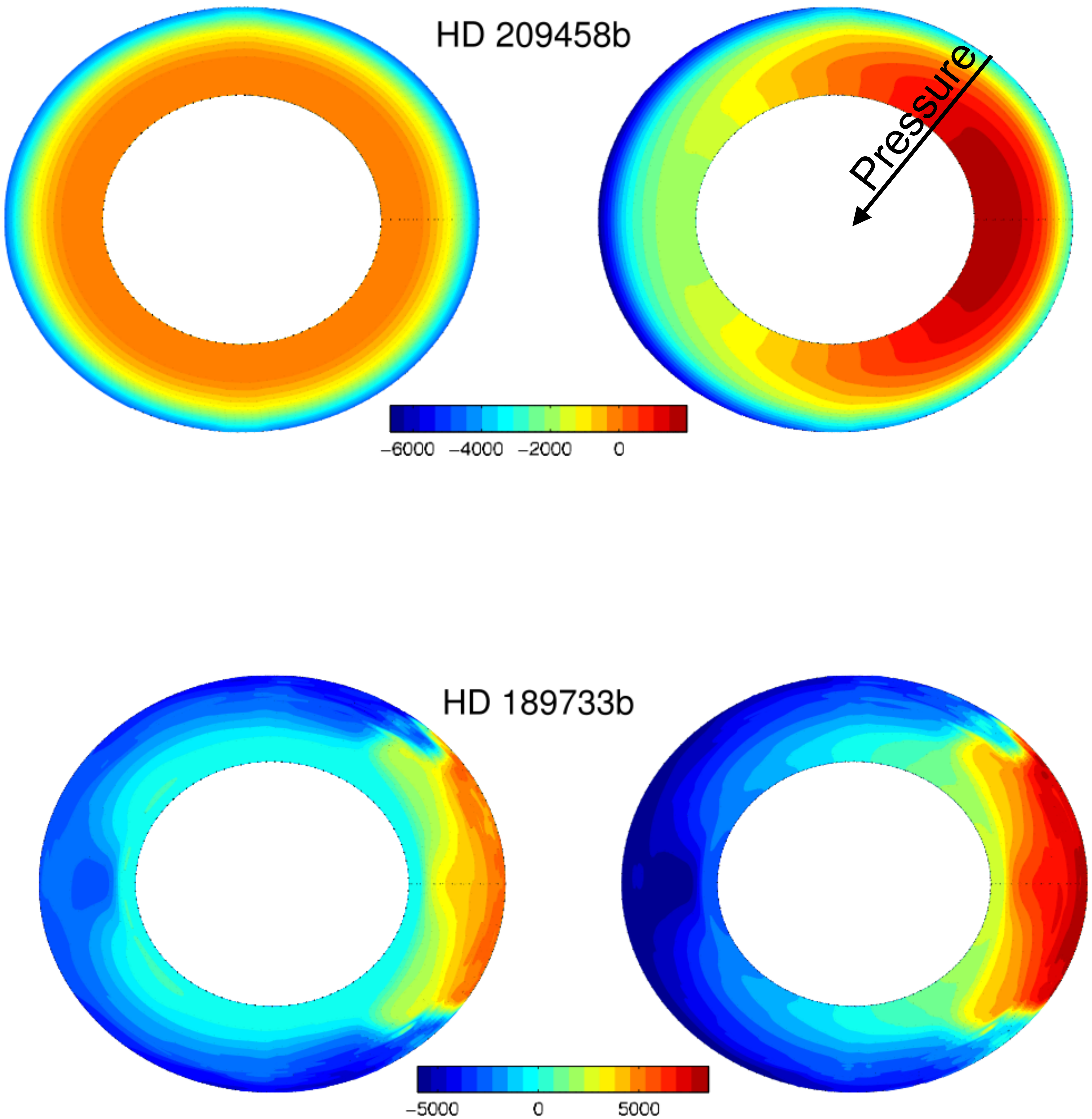
All detections in absorption (non-inversion) to date

Schwarz, Brogi, de Kok, Birkby, Snellen (2015)

Monitoring atmospheric dynamics with HDS

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

Winds only **Winds+rotation**



Kempton et al. 2012; Showman et al. 2013

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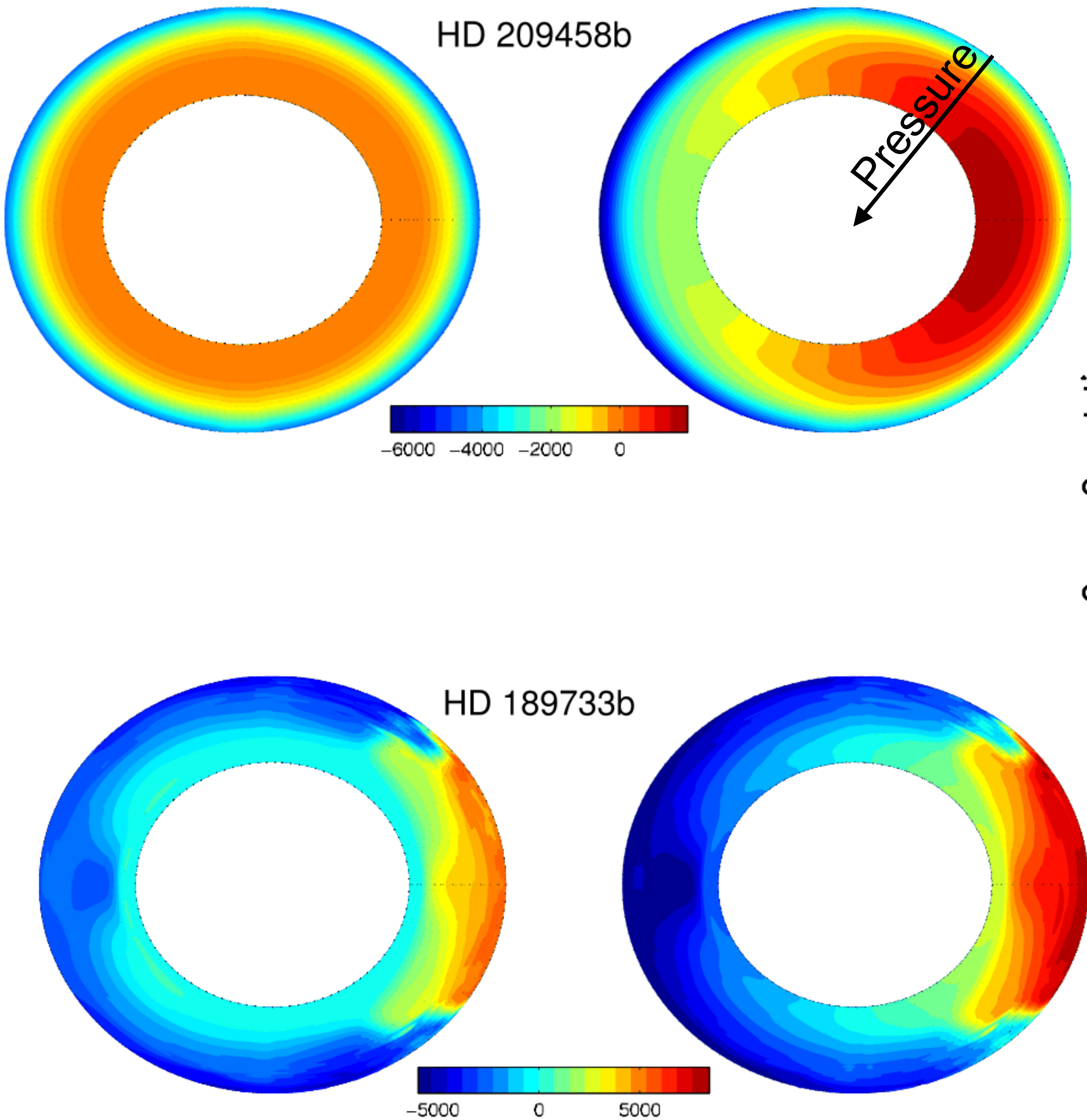

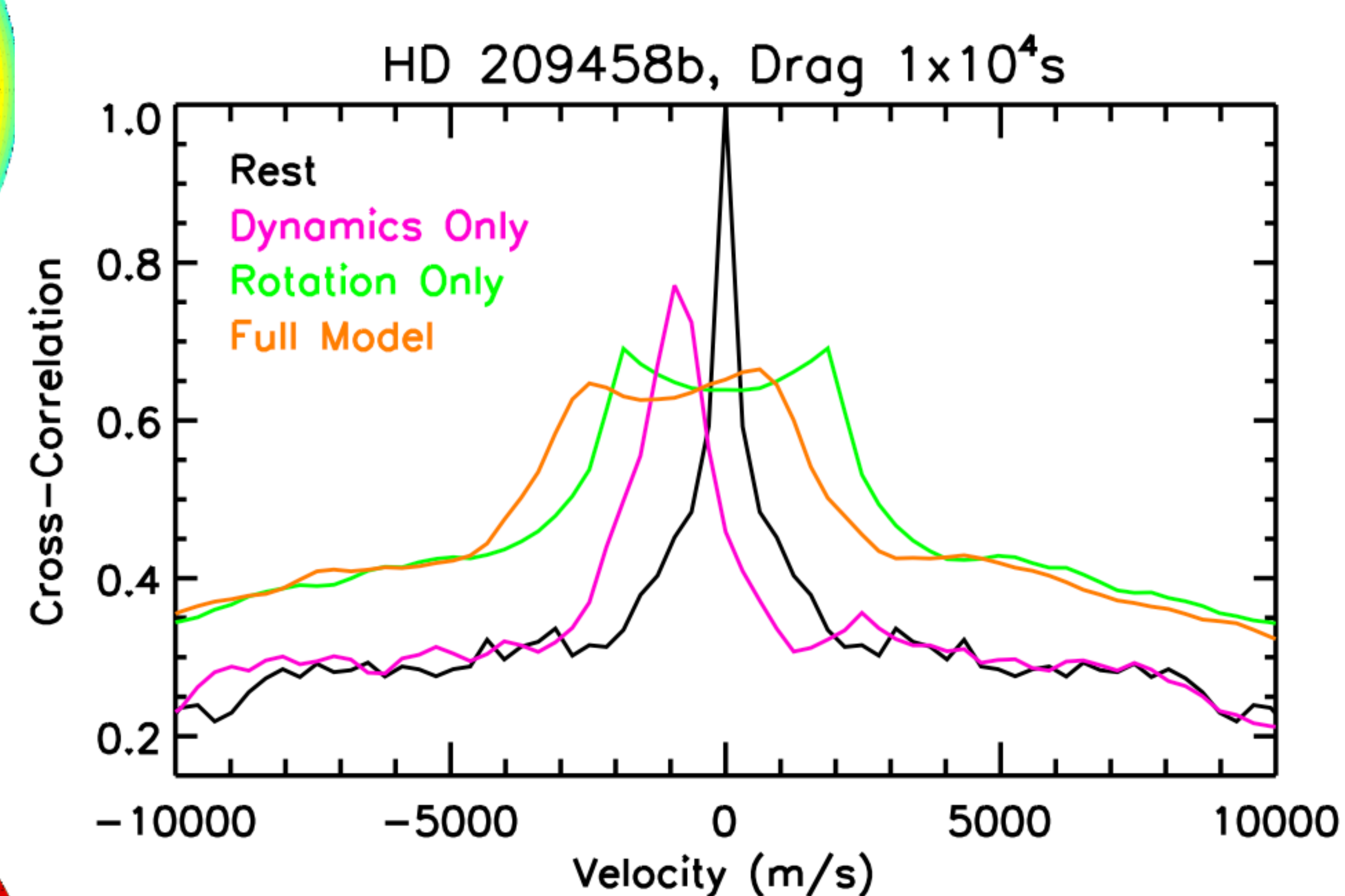

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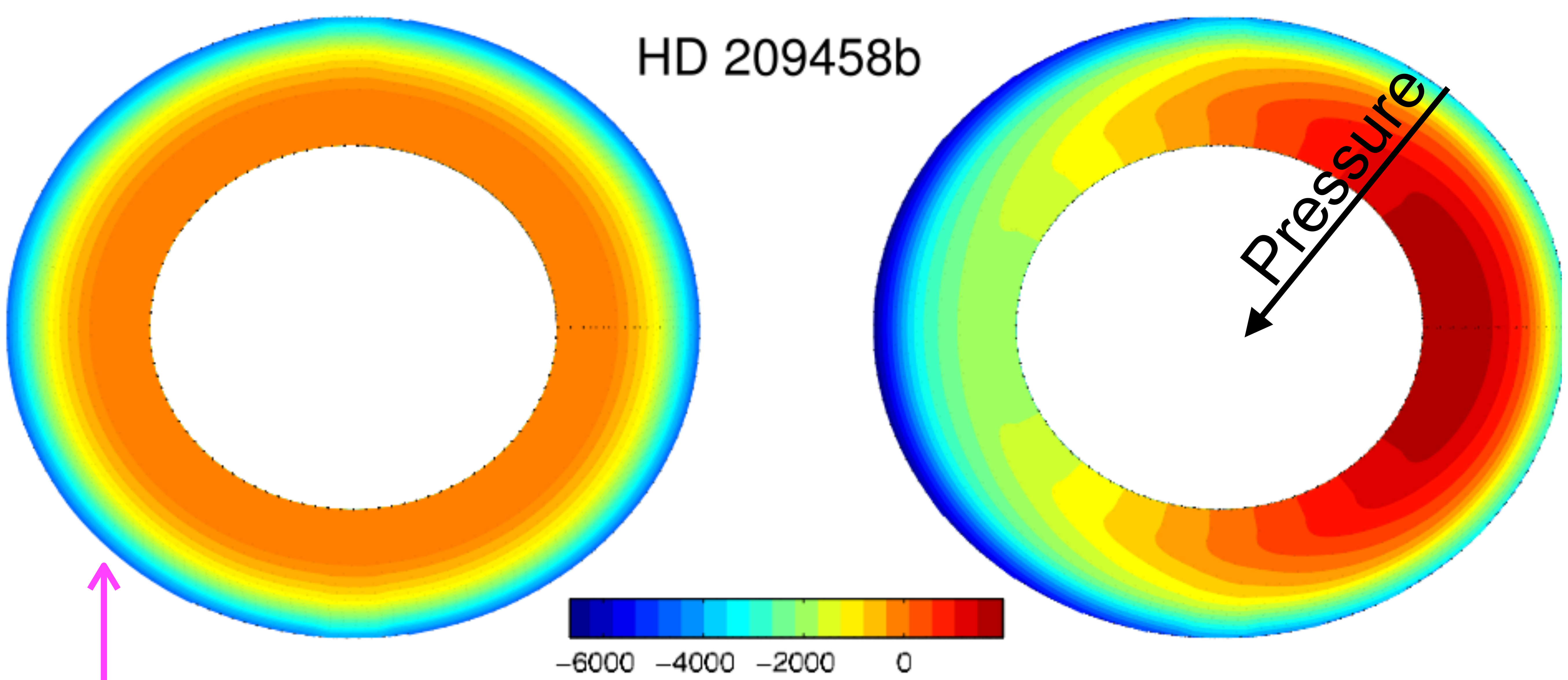
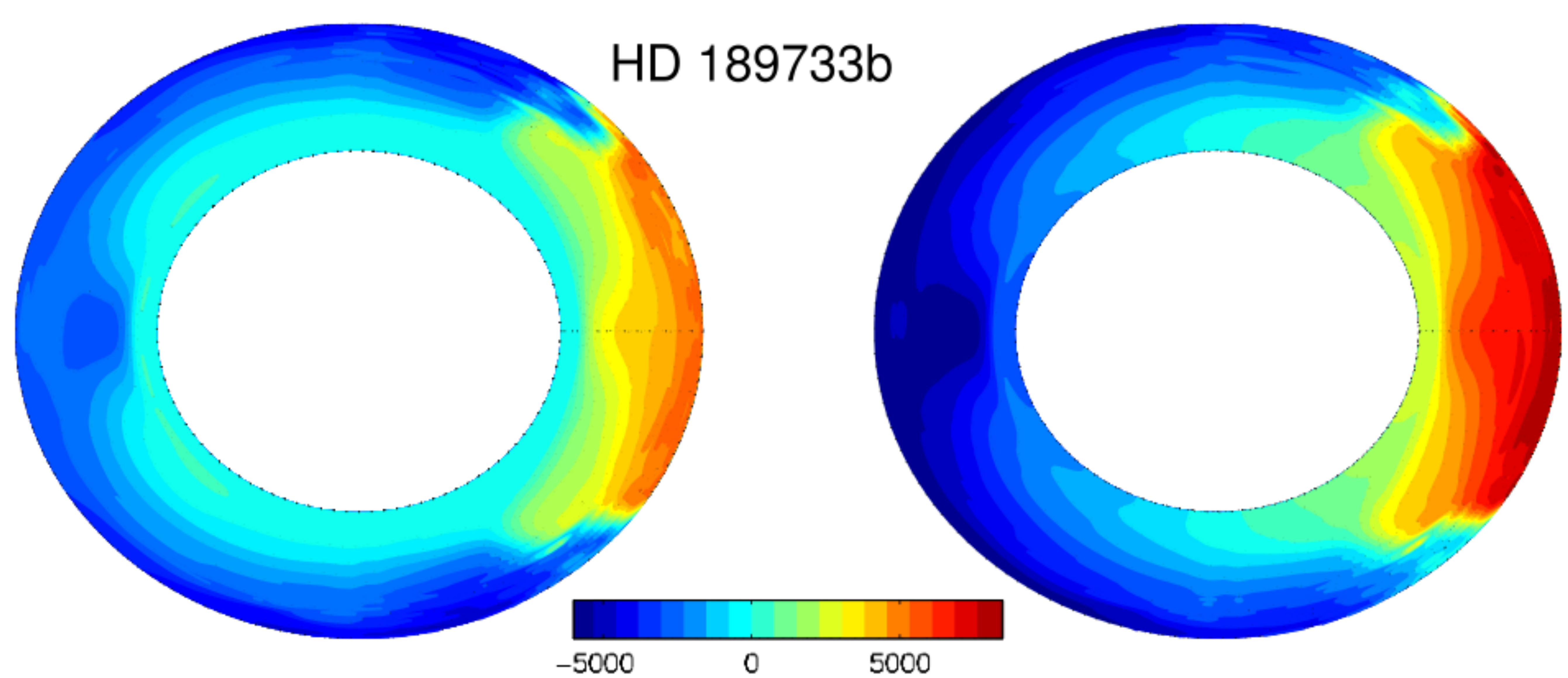
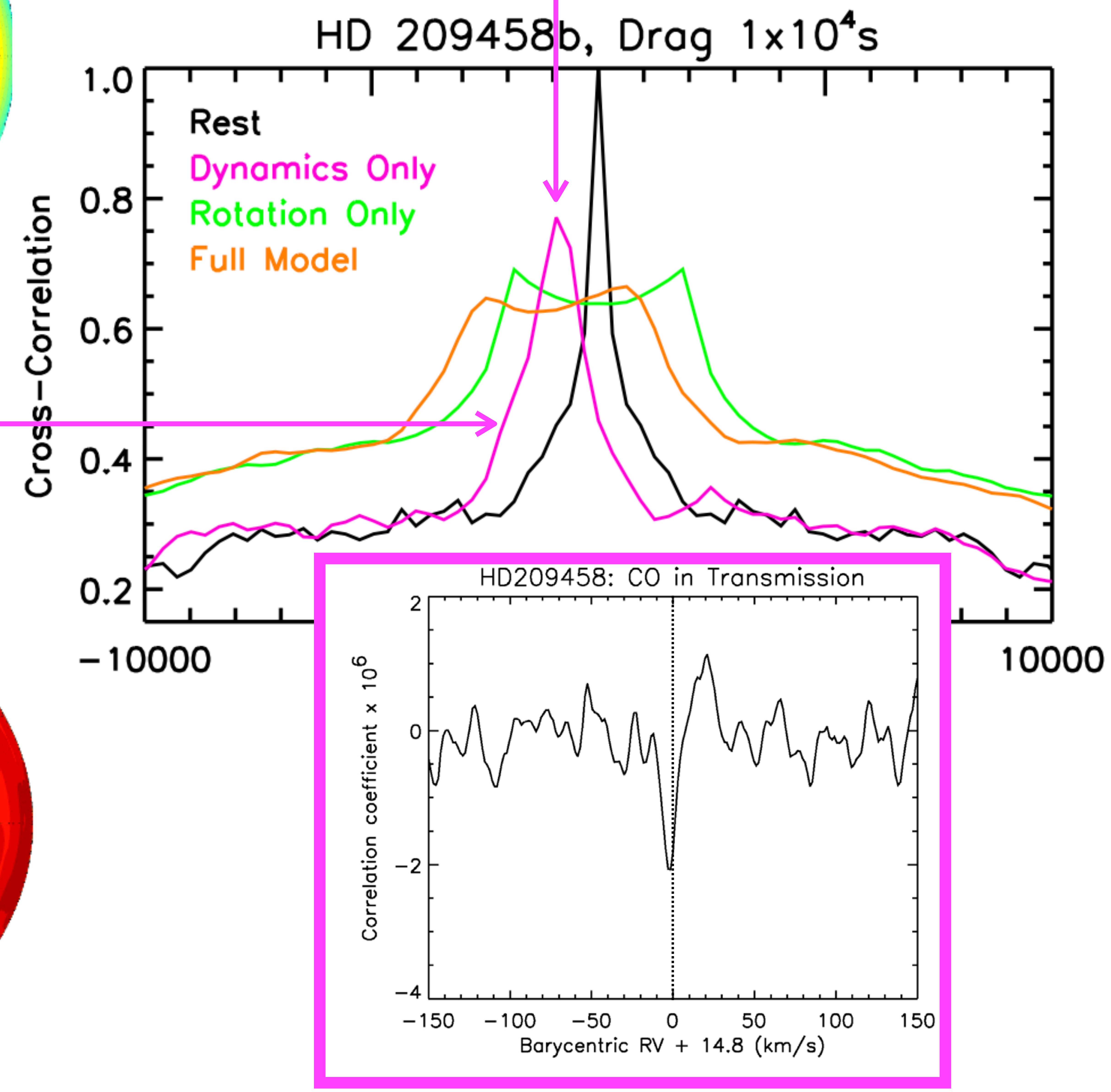


Winds blue-shift entire upper atmosphere



Wind shift observed in HD 209458 b at -2±1 km/s (Snellen et al. 2010)



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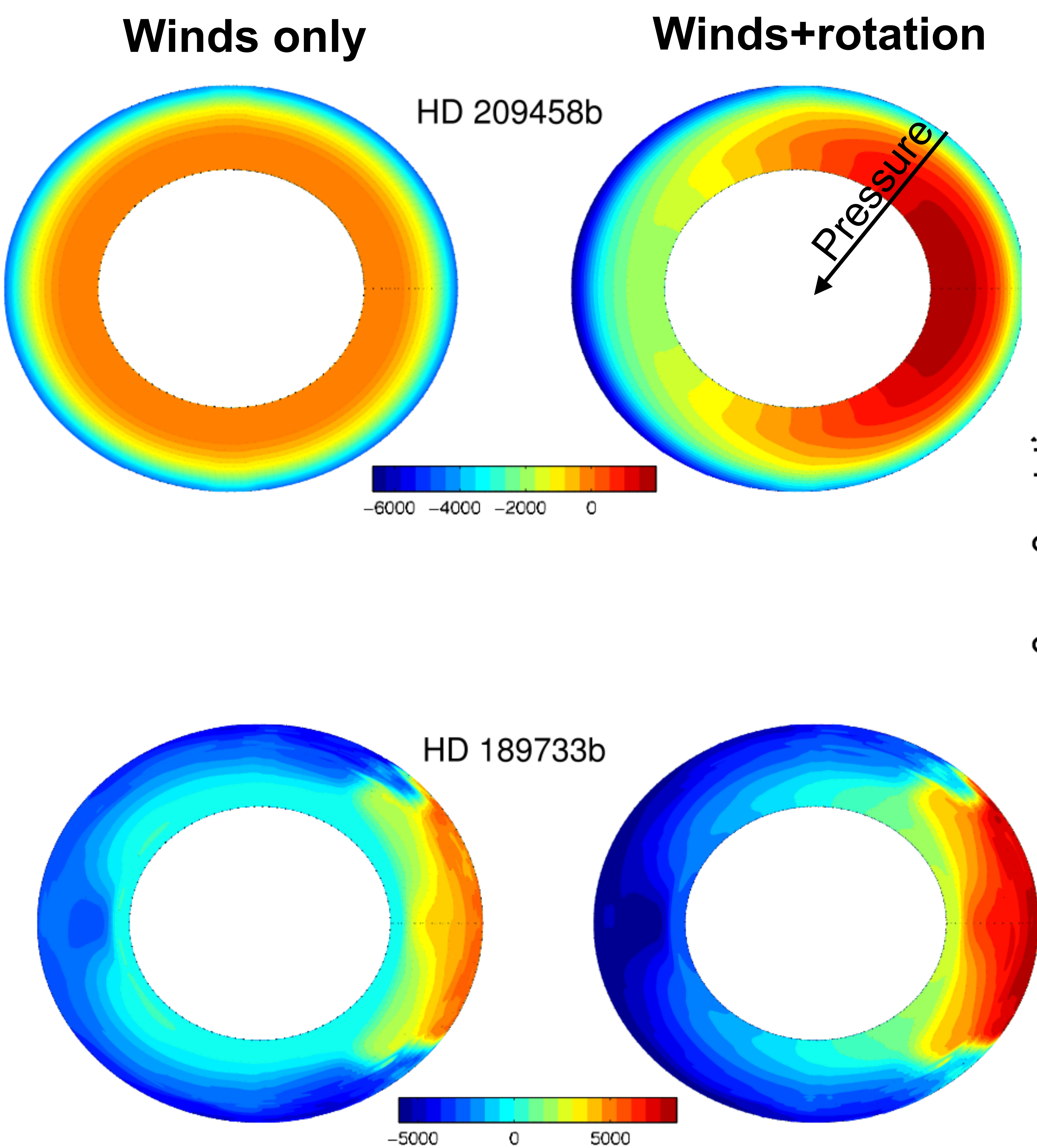

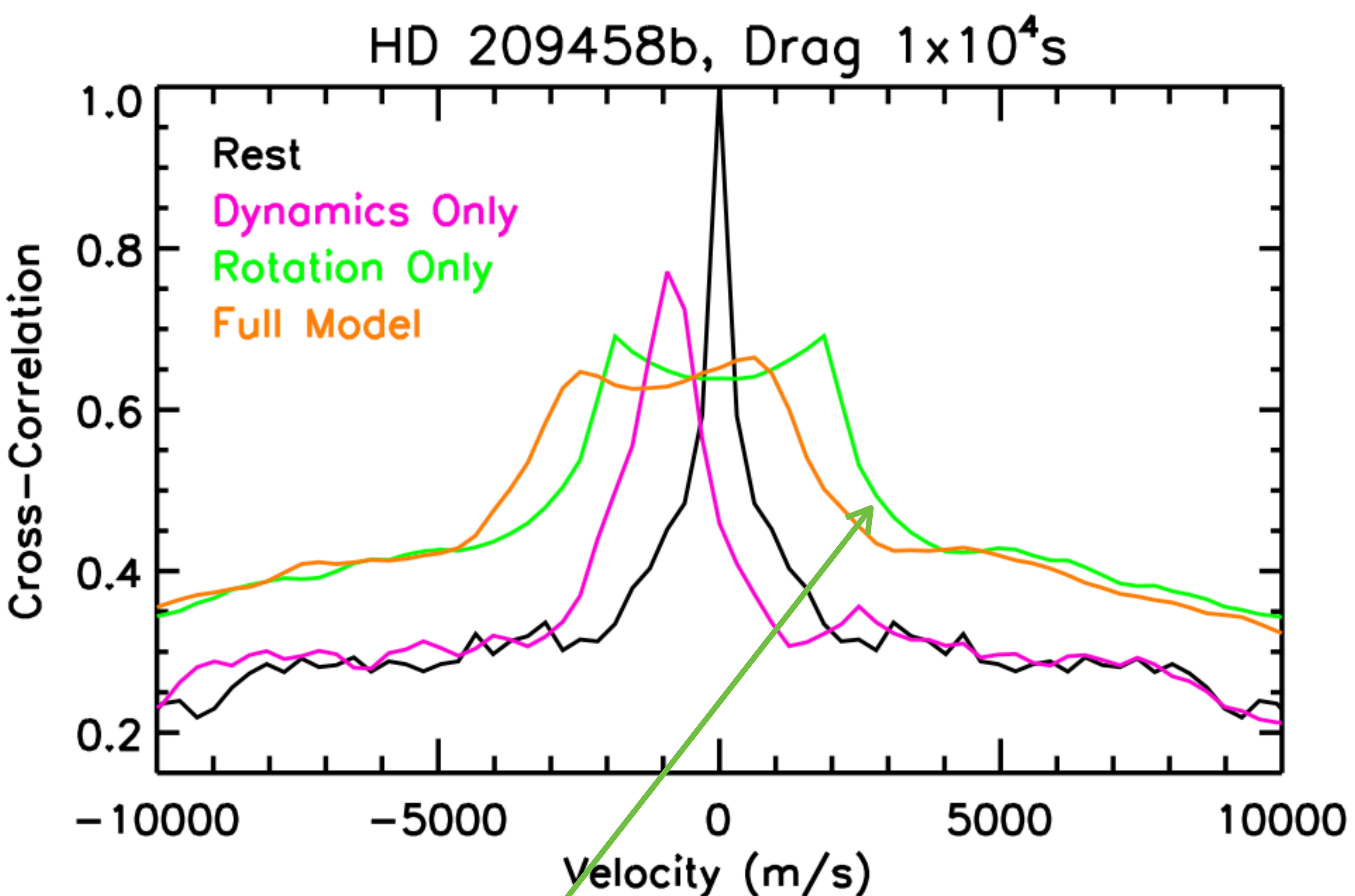

Rotation creates double-peaked line profile

Kempton et al. 2012; Showman et al. 2013

Measuring planet angular momentum with HDS + High Contrast Imaging (HCI)

Combining high contrast imaging (HCI) and HDS allows characterization of *directly imaged* planets

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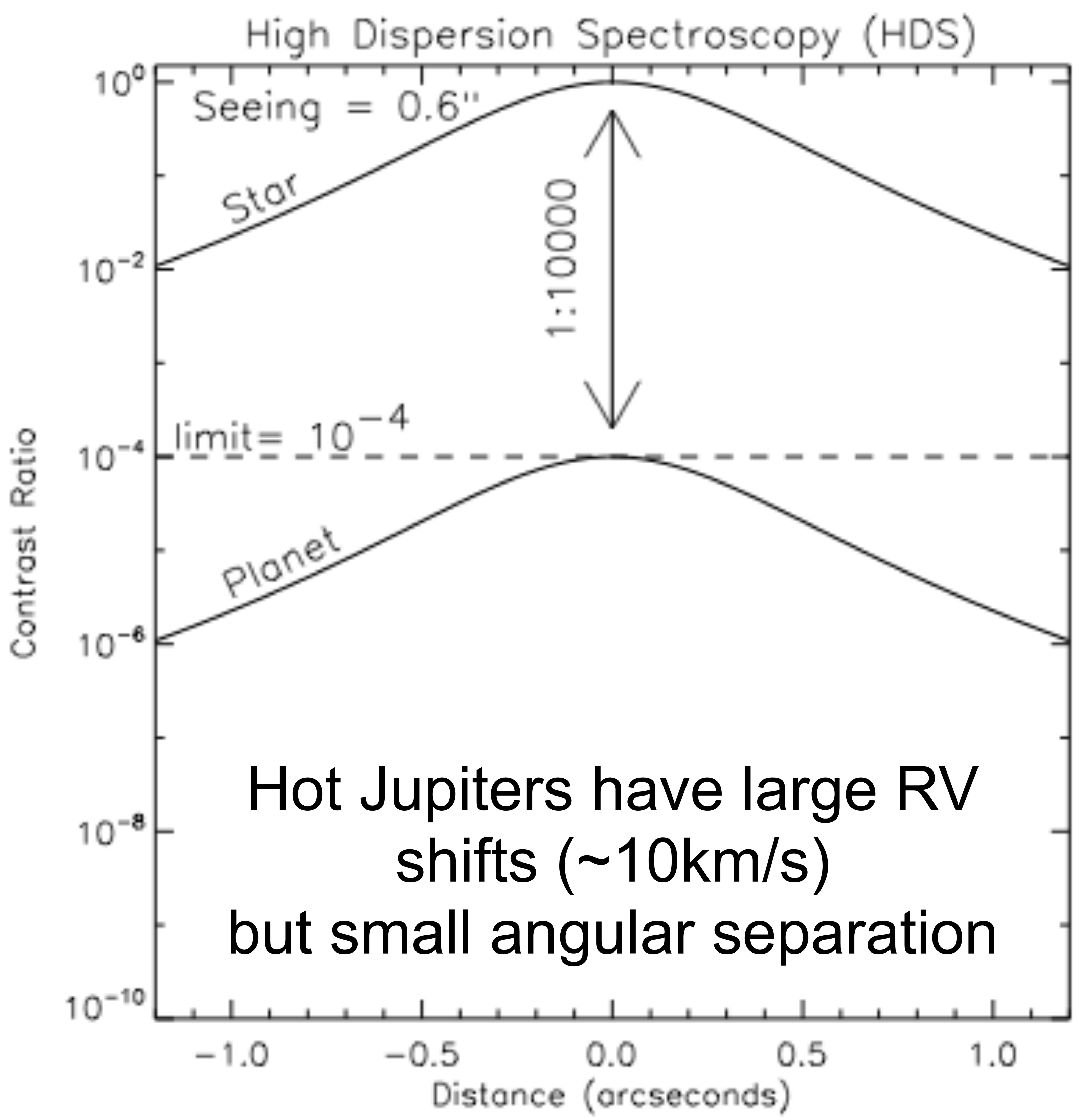

HDS currently reaches contrast ratios of 10^{-4}

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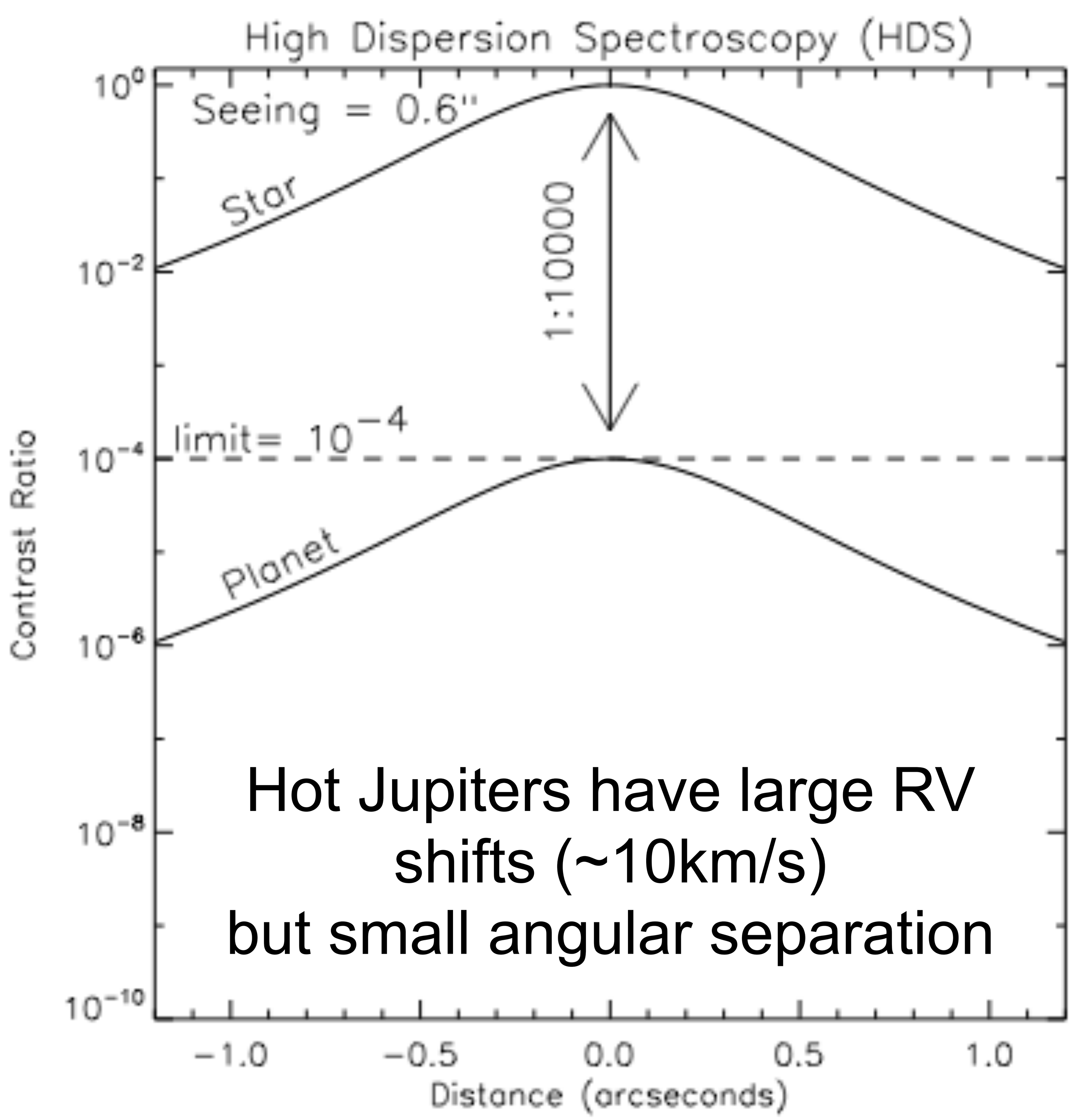

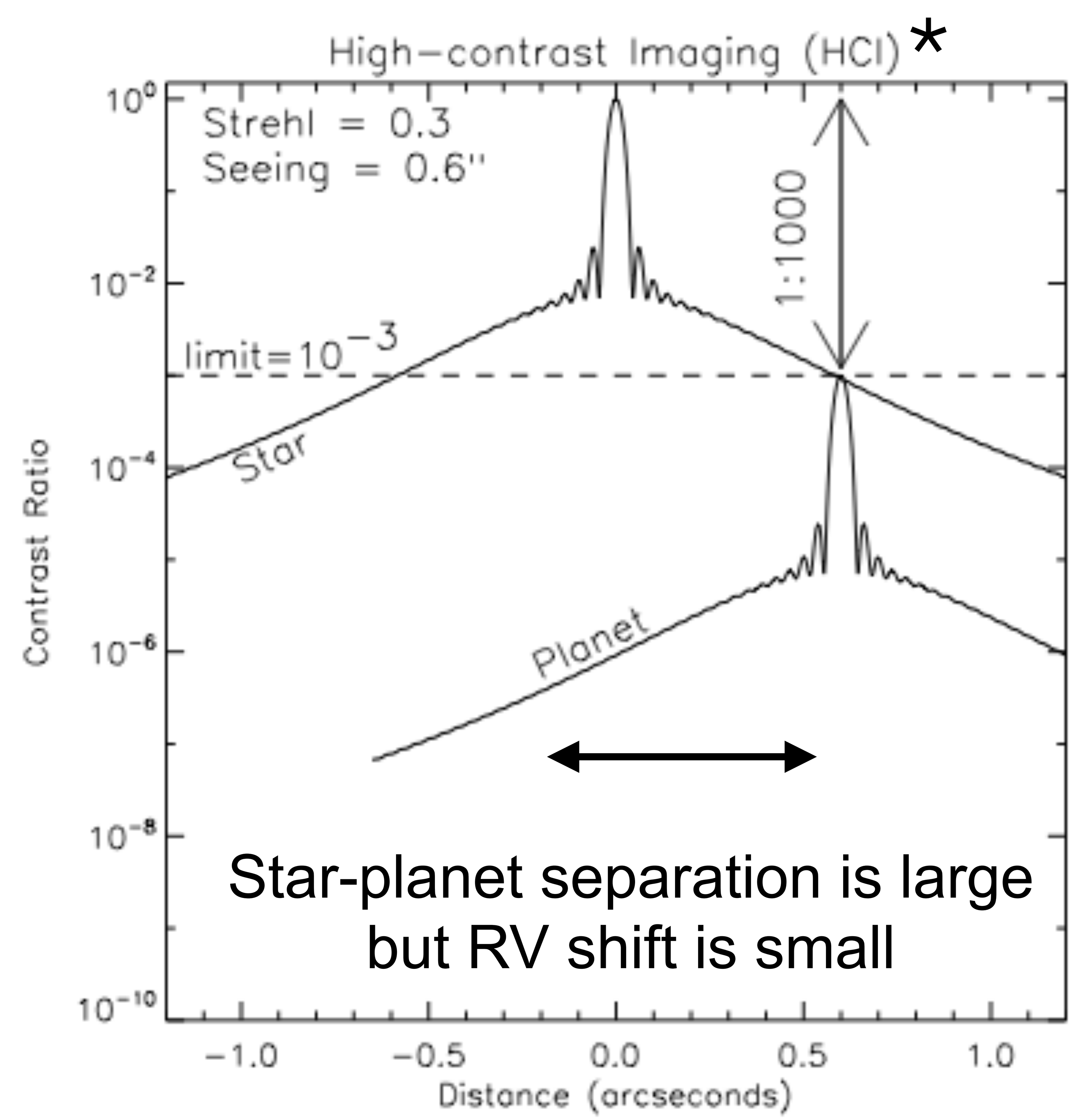

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High contrast imaging (HCI) on 8m telescope can reach a *raw* contrast ratio of 10^{-3}

*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)

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

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

Snellen, de Kok, Birkby et al. 2015

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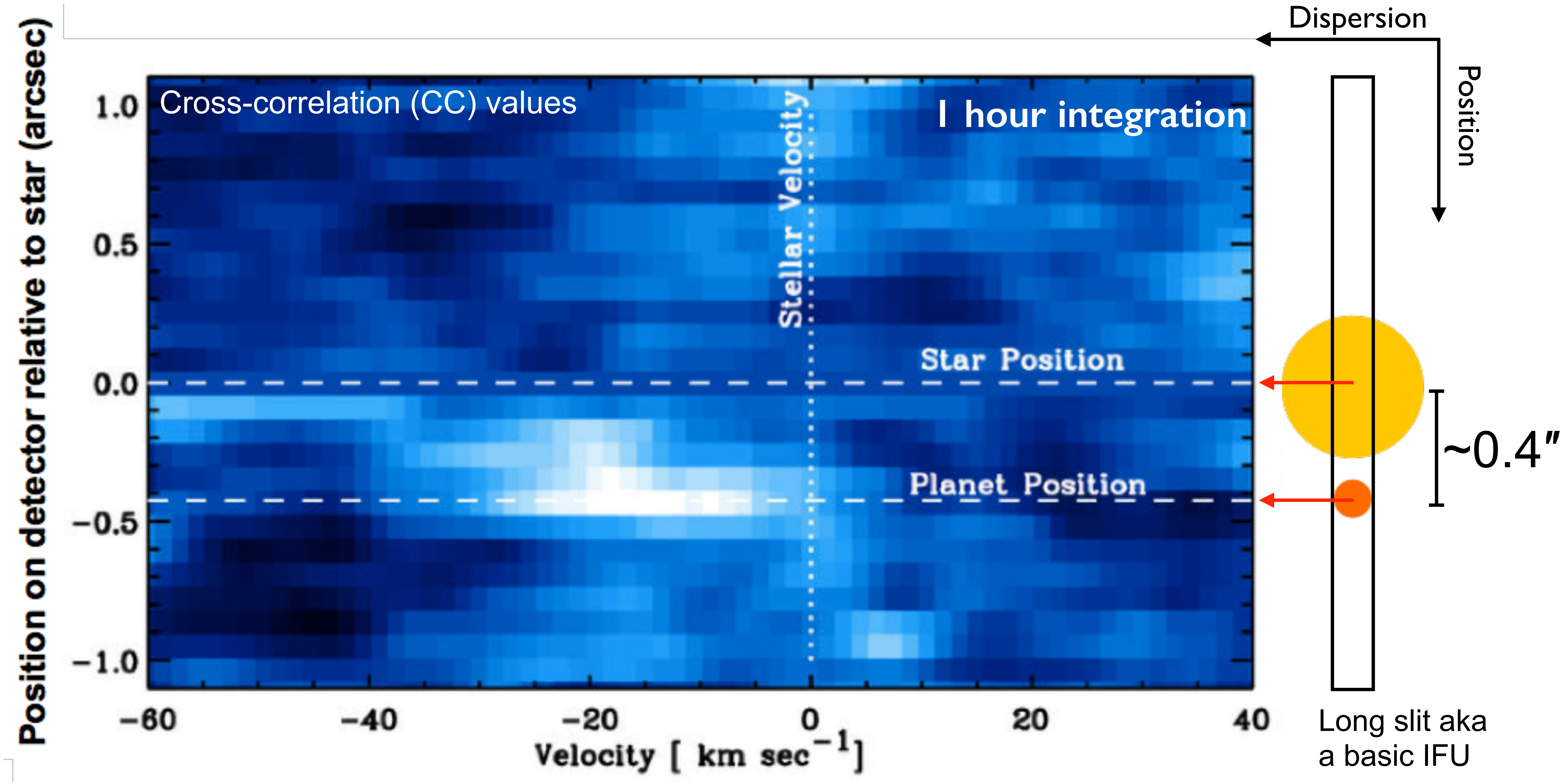
HDS+HCI offers improvement over HCI-only until the thermal background noise dominates

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

- Star and tellurics are dominant and identical over the whole field, speckles contain spectrum of the star, effectively filtered out, planet signal is *uniquely different* and *strongly localised.*

- Thermal background noise (σ_{bg}) dominates beyond ~5µm
  - classic HCI observations have the advantage.

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



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

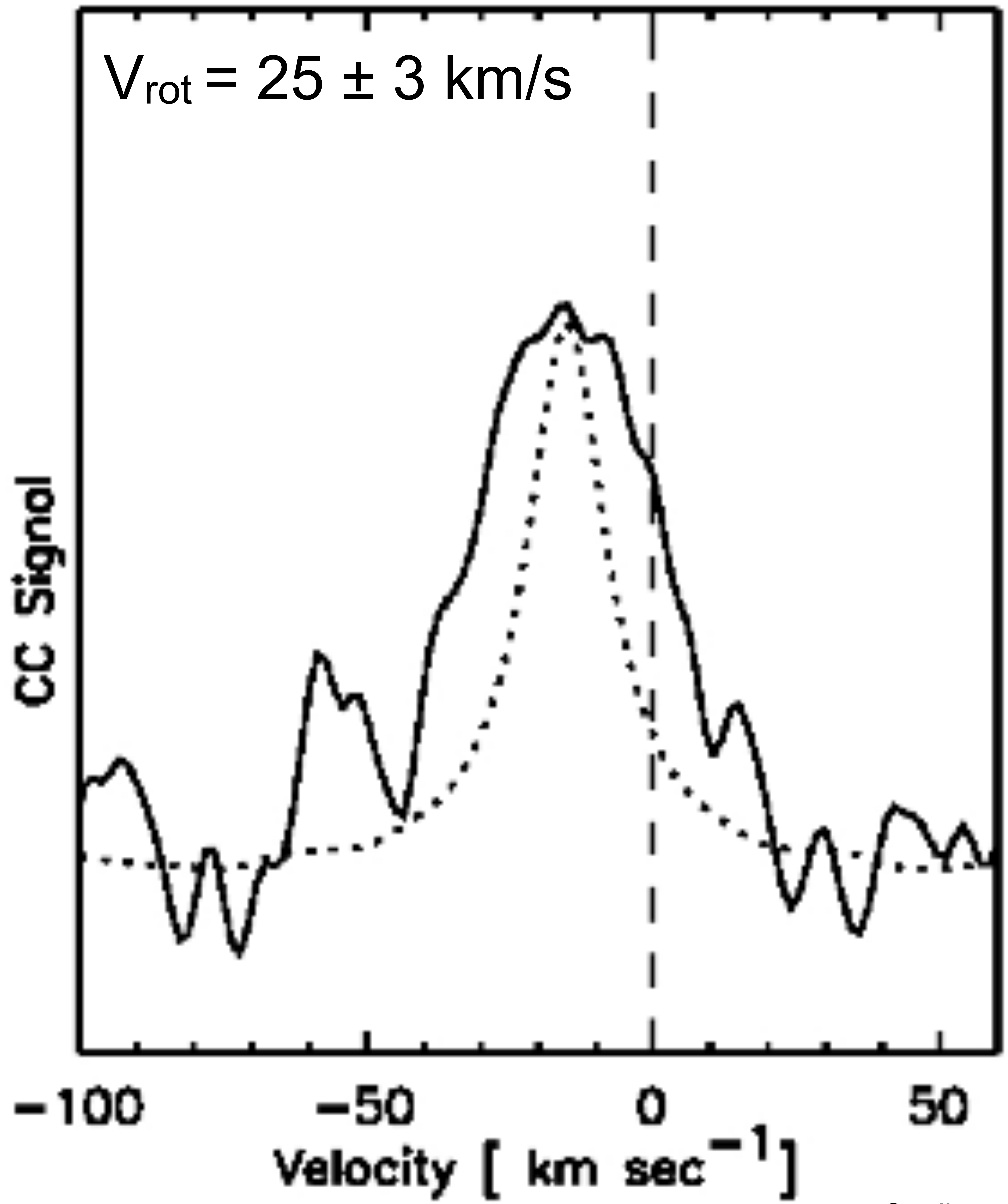
· · · · = instrument profile

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)

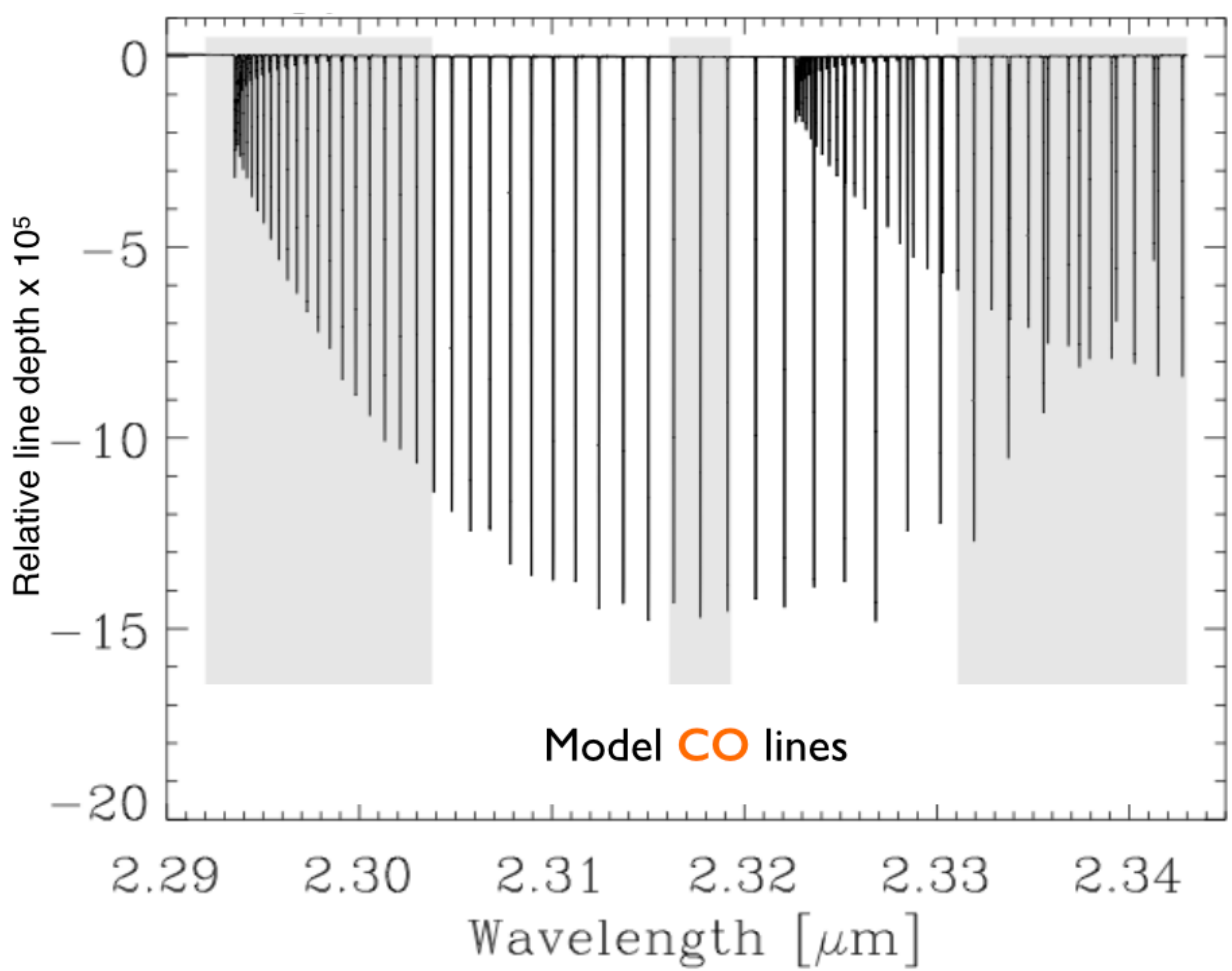
The length of one day on β Pic b is $P_{rot} \sim 8.1 \pm 1.0$ hours



Snellen et al., 2014

Near-term future of HDS (+HCI)

Cross-correlation strength scales with the square root of the number of lines ($S \propto \sqrt{N_{Line}}$)



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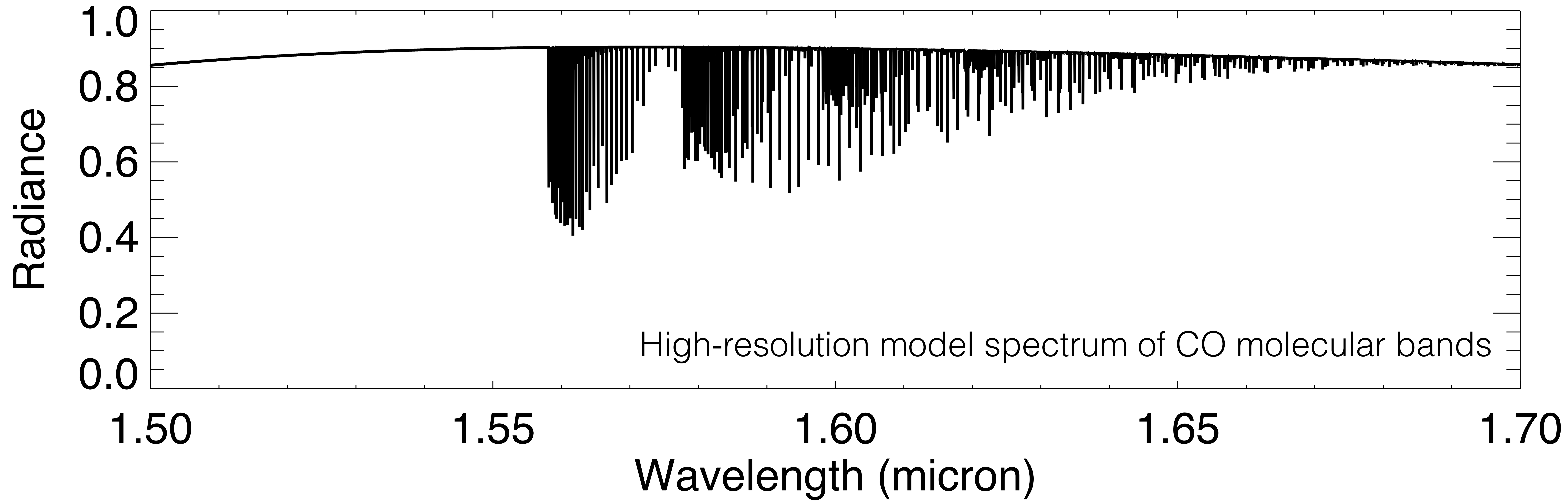
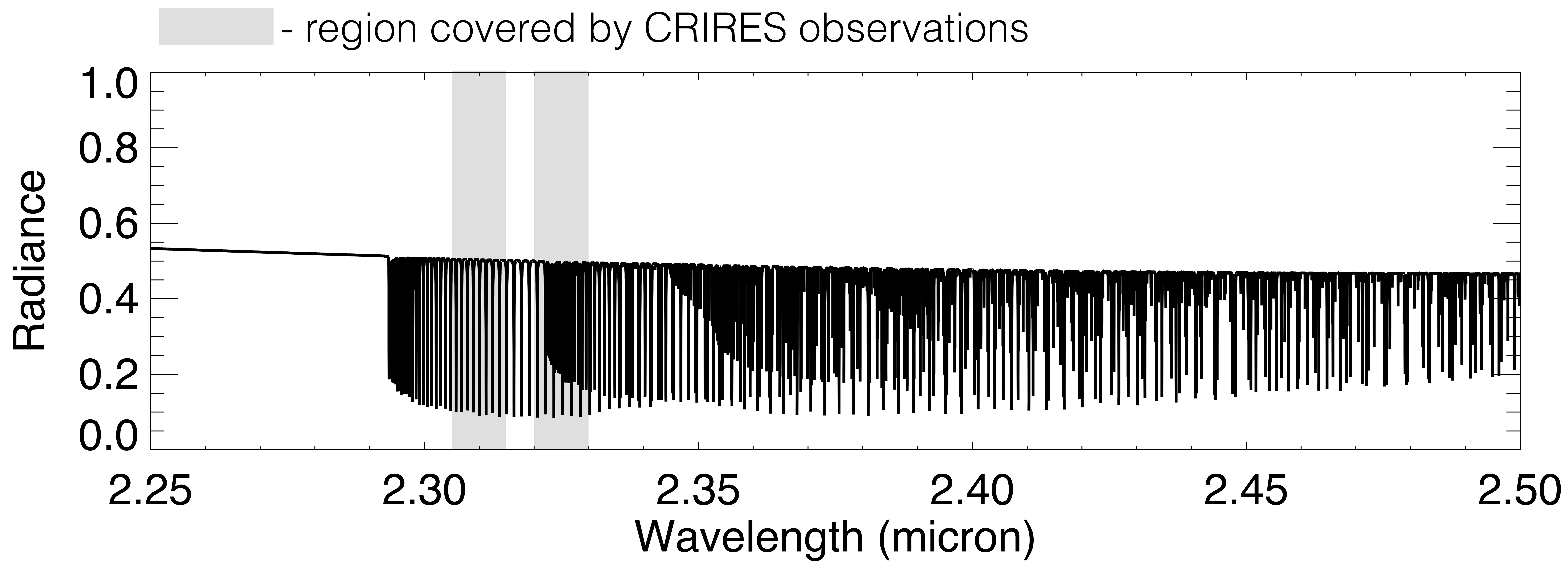




Multiple IR high-resolution spectrographs are planned for the near future

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

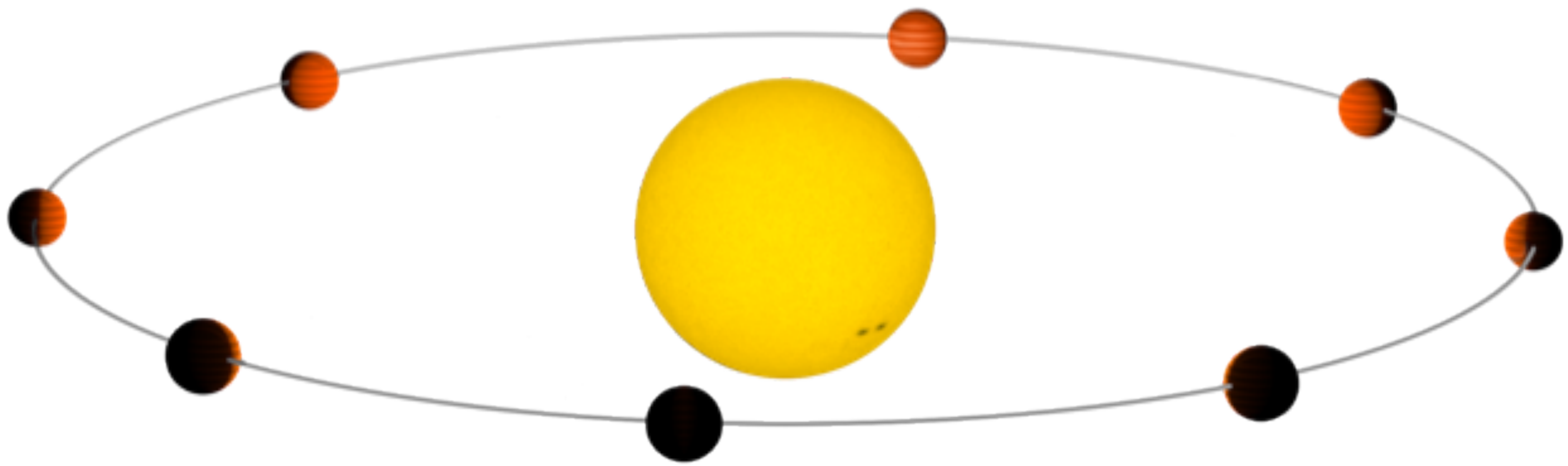
Instrument	Resolution	Wavelength Coverage	Telescope	Status	References
CSHELL	40,000	1–5 μm, $\sim 0.0025\lambda$ coverage	IRTF (3m)	Operating	Greene et al. (1993)
Phoenix	70,000	1–5 μm, $\sim 0.005\lambda$ coverage	KPNO (4m)	Operating	Hinkle et al. (1998)
ARIES	50,000	1–2.5 μm simultaneous	MMT (6.5m)	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.

Crossfield 2014

HDS(+HCl) in TMT era

The TMT will enable time/disk-resolved observations of exoplanet atmospheres



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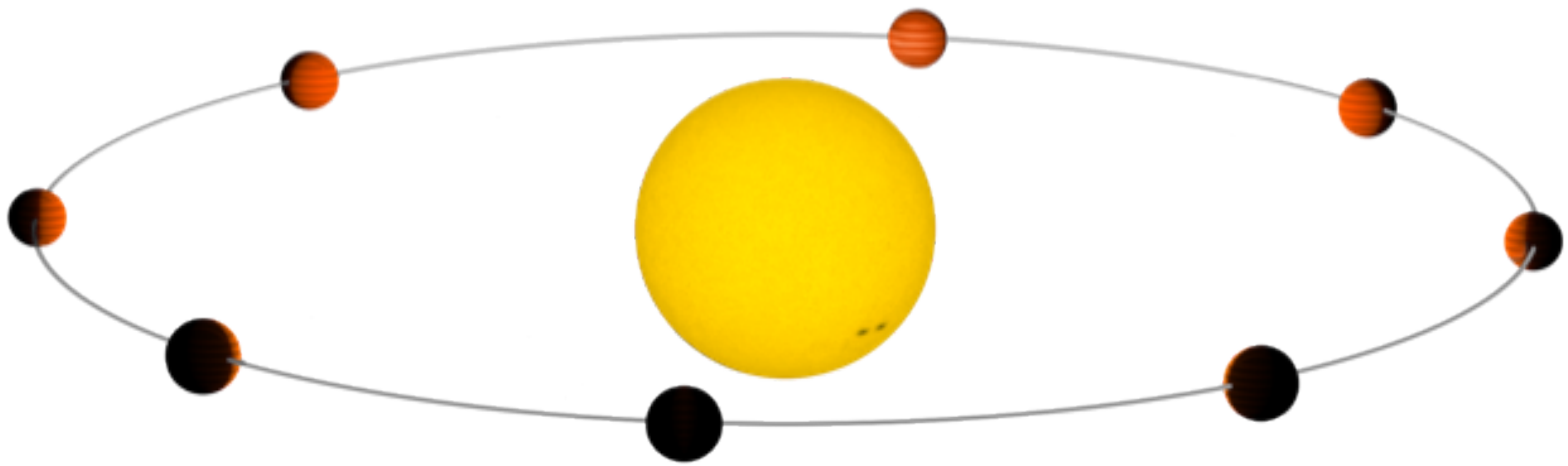


- Molecular abundance ratio variations and atmospheric structure probed as a function of orbital phase (morning, midday, evening, night side) ➔ photochemistry

- Individual molecular lines detected ➔ form at different altitudes

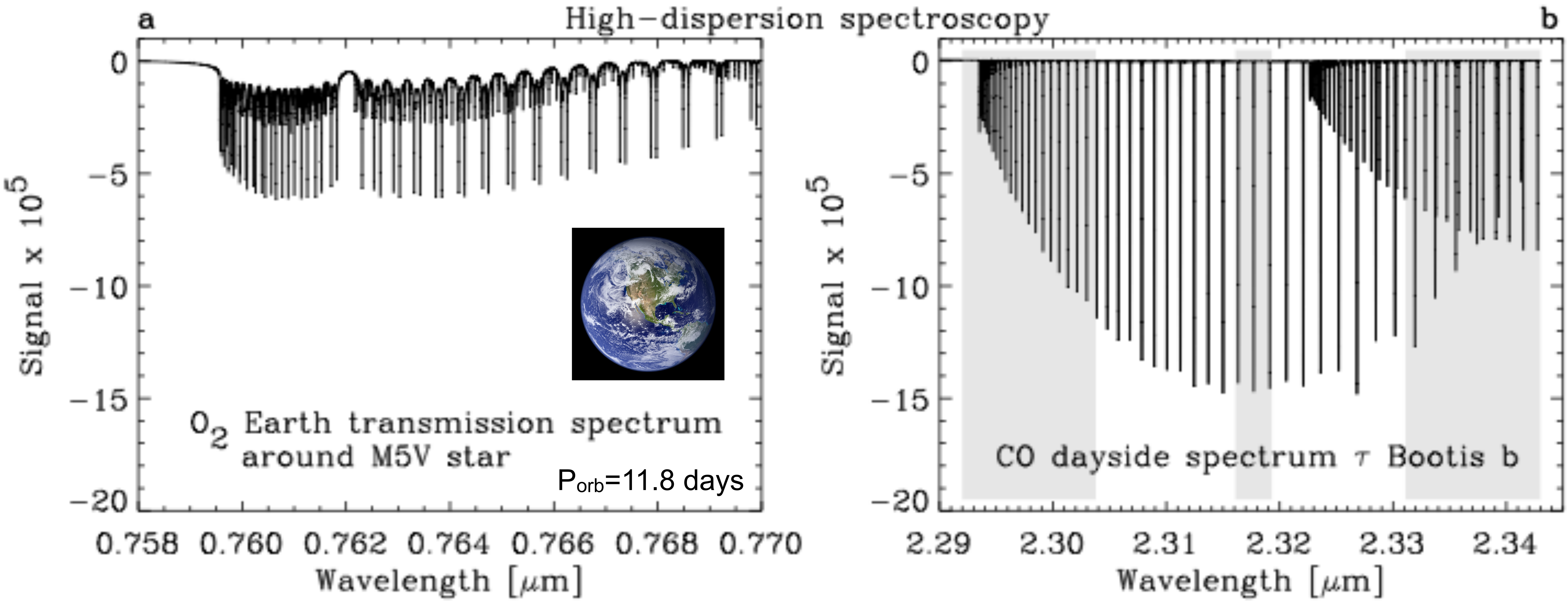
- Sensitive to isotopologue ratios ➔ insight into evolutionary history

- Rossiter-McLaughlin effect at secondary eclipse ➔ spin-orbit alignment of planet

Nikolov & Sainsbury-Martinez (2015)

Biomarkers

HDS with TMT/HROS-like instrument could detect oxygen in Earth-like planets in the habitable zone of M-dwarfs



M5V+Earth twin in habitable zone:

- observe 12-30 transits
- detect O_2 at 5σ
- takes *4-20 years* for the nearest systems ($I \sim 10.5$ mag, $\eta_\oplus=1$)

Snellen, de Kok, le Poole, Brogi, Birkby 2013; Rodler & Lopez-Morales 2014; Webb & Wormleaton 2001

Finding our nearest rocky neighbours

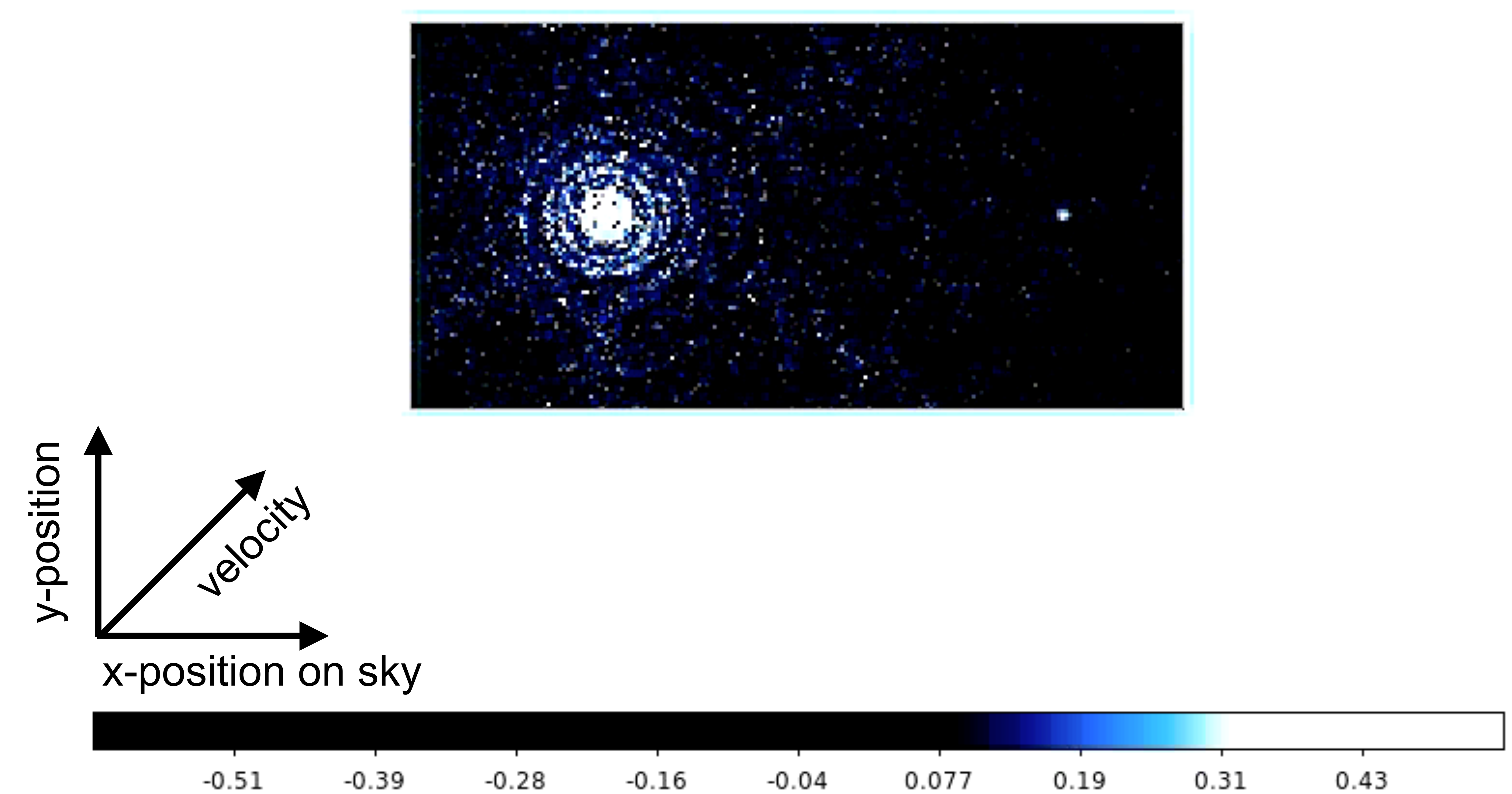
HDS+HCI with TMT could detect Earth-size planets in habitable zones of the nearest stars

Simulations for **infrared IFU**
(e.g. TMT/NIRES-R)

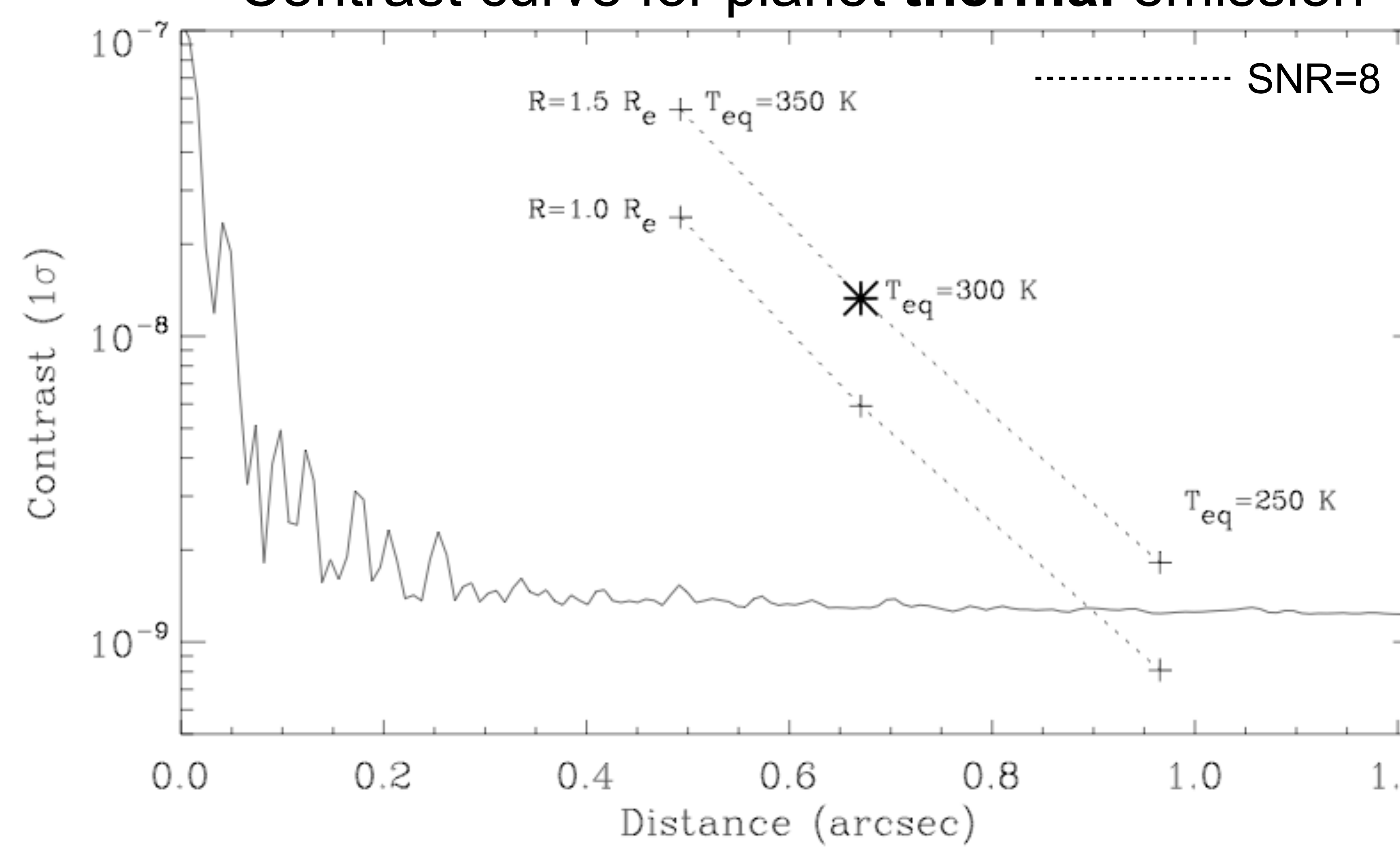
Telescope + Instrument	
* Telescope collecting area	976.3 m^2
Telescope temperature	280 K
Telescope emissivity	0.15
Telescope+instrument throughput	15%
AO Strehl (4.85 μm)	0.9
Spectral resolution	R = 100 000
* Exposure time	30 h
Spectral range	4.82–4.89 μm
Target: α Cen A	
Apparent K magnitude	−1.47
$T_{\rm eff}$ (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

*TMT area 655m^2, rescale time by ~1.5

Liske et al. 2012



Contrast curve for planet **thermal** emission



Snellen, de Kok, Birkby et al., 2015

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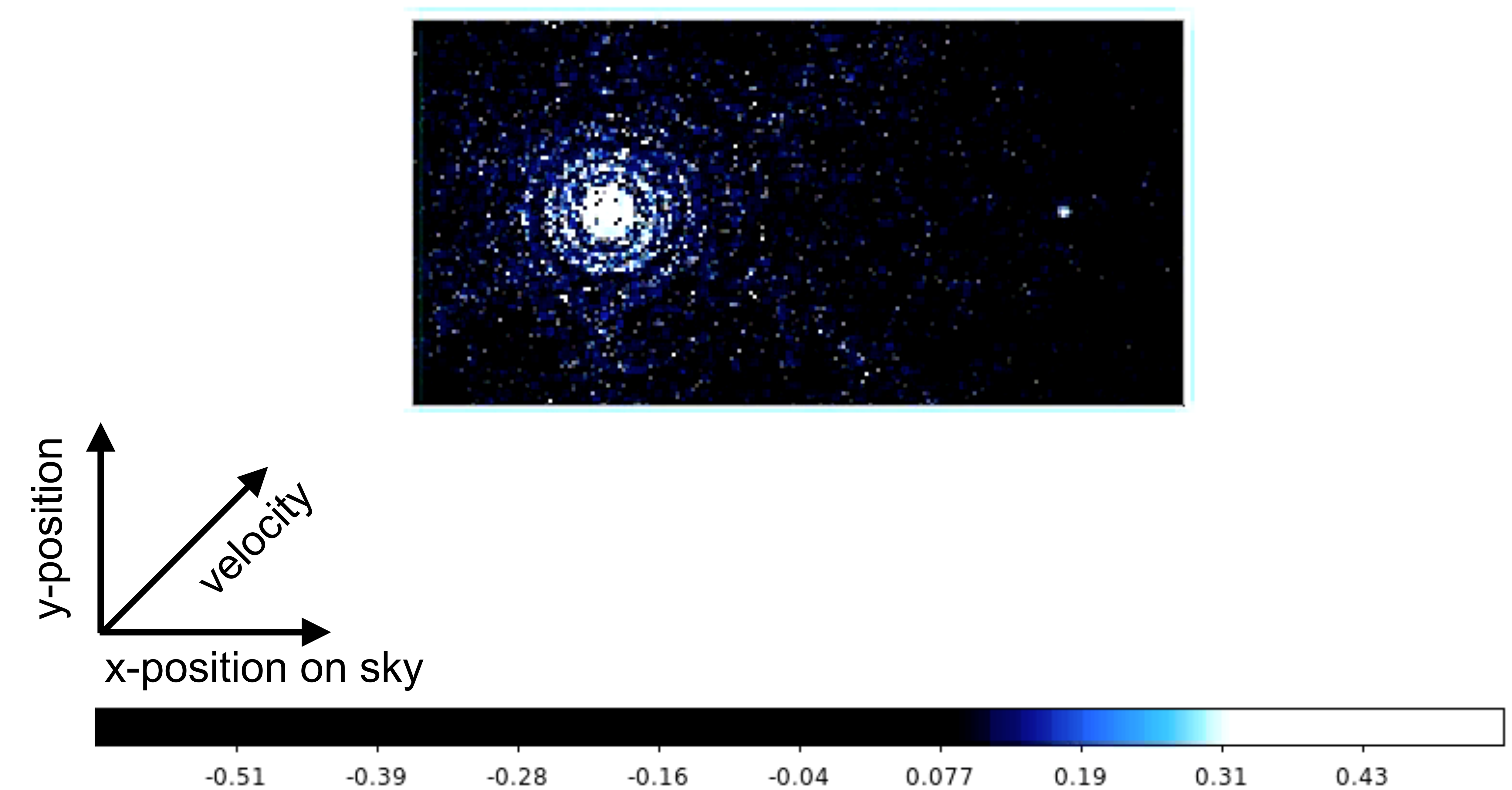
Liske et al. 2012



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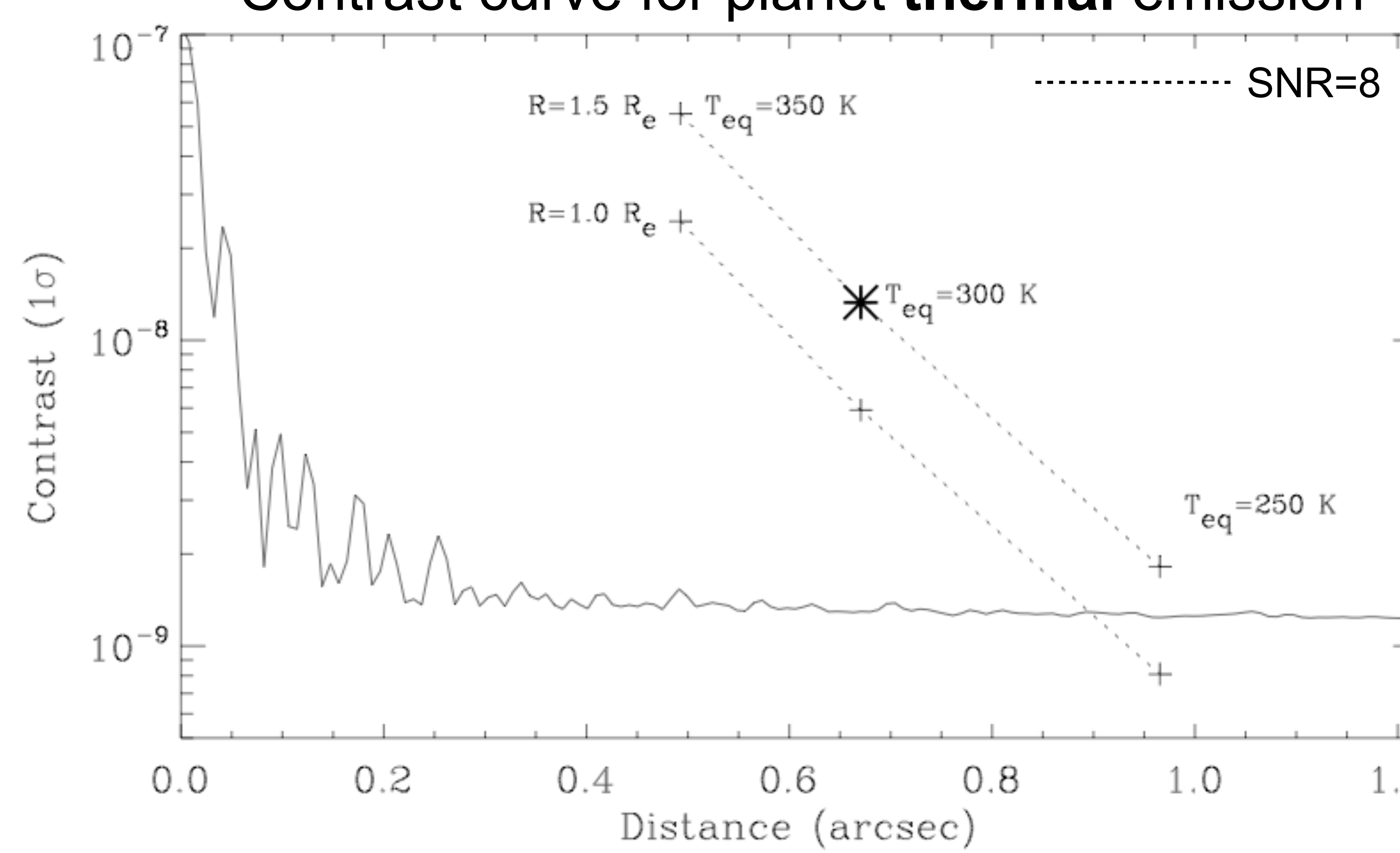


Snellen, de Kok, Birkby et al., 2015

HDS+HCI with TMT could detect Earth-size planets in habitable zones of the nearest stars

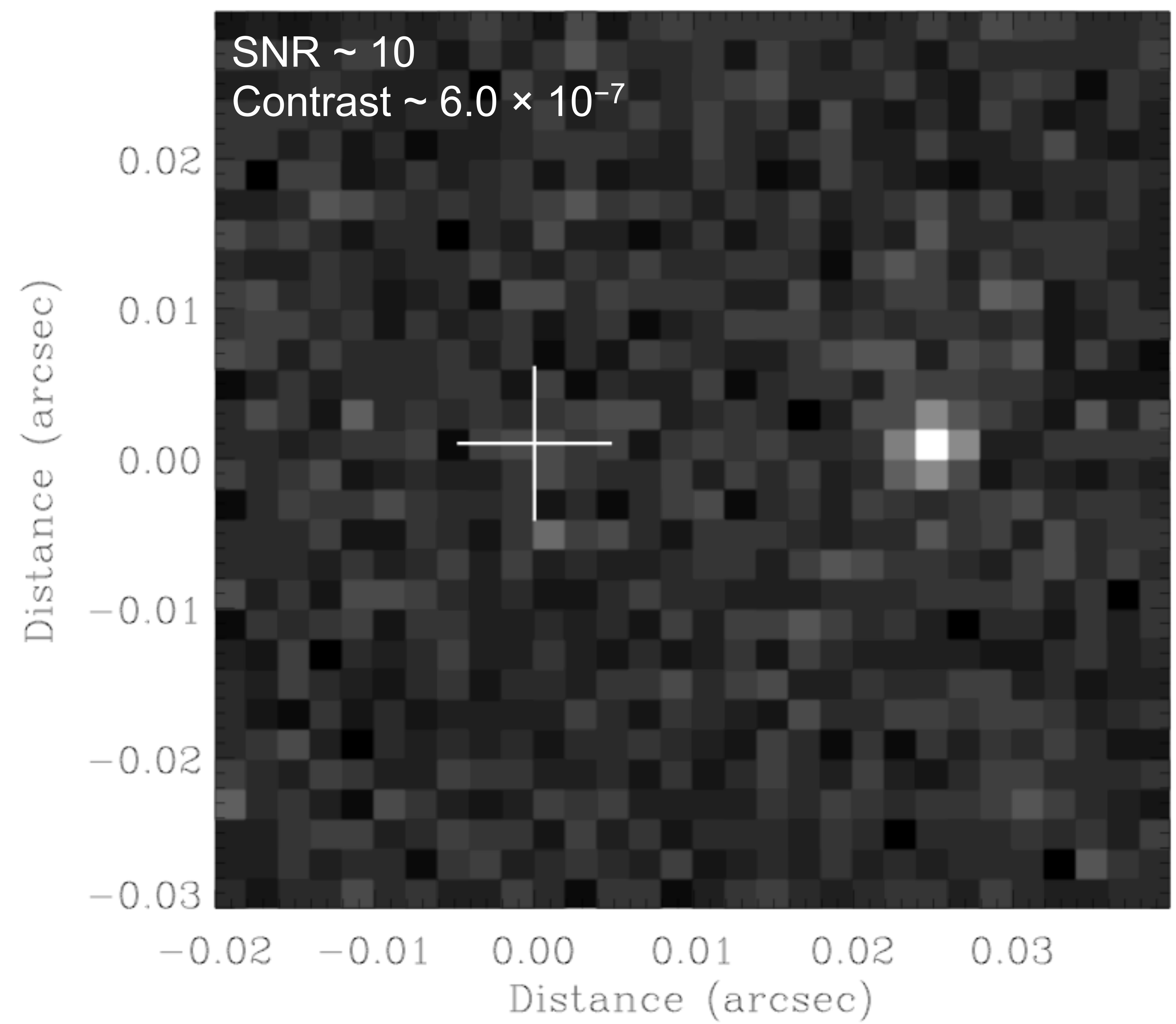
Simulations for **optical IFU** (e.g. HROS/TMT)

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

*TMT area 655m^2, rescale time by ~1.5

Liske et al. 2012

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

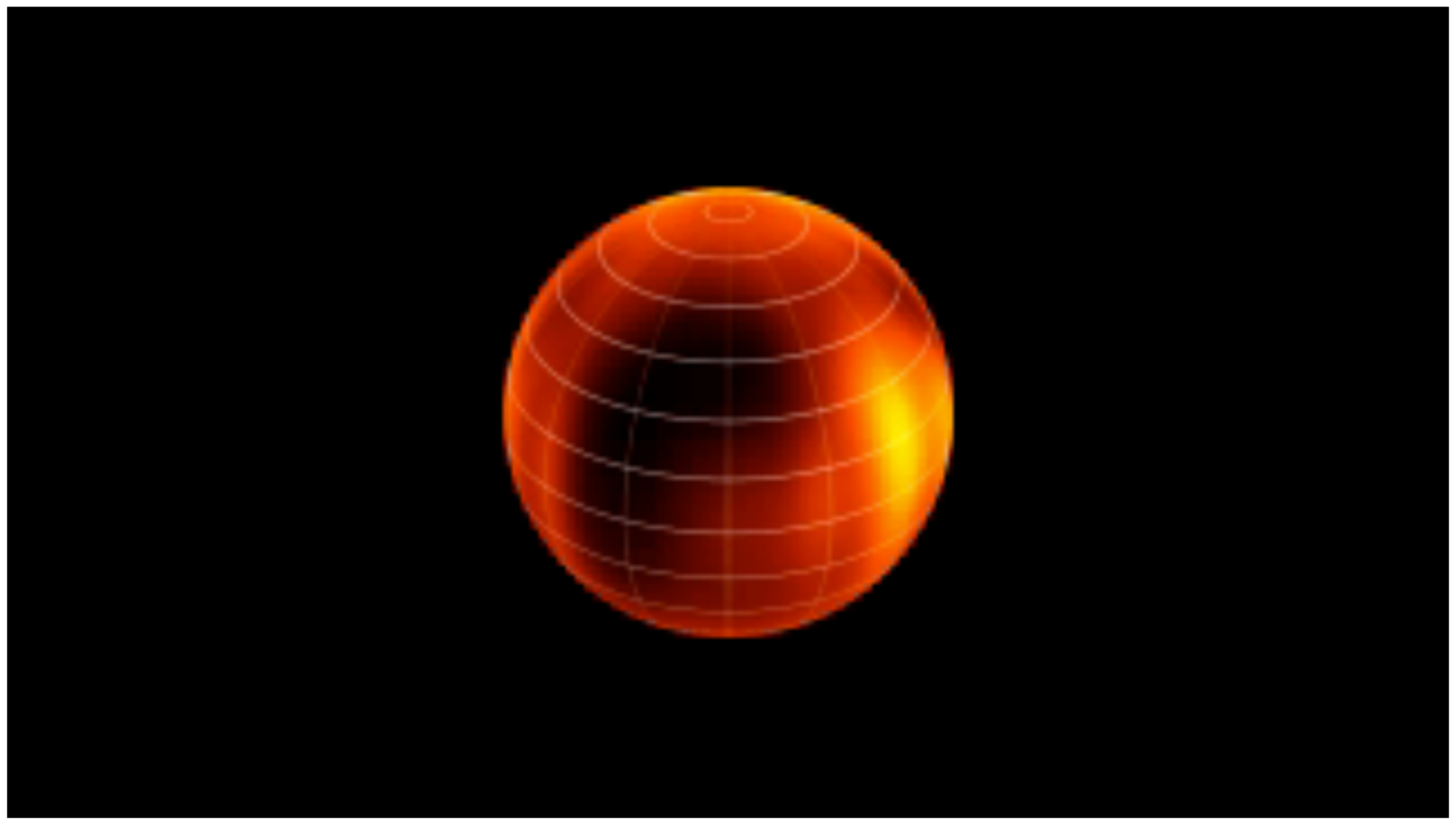


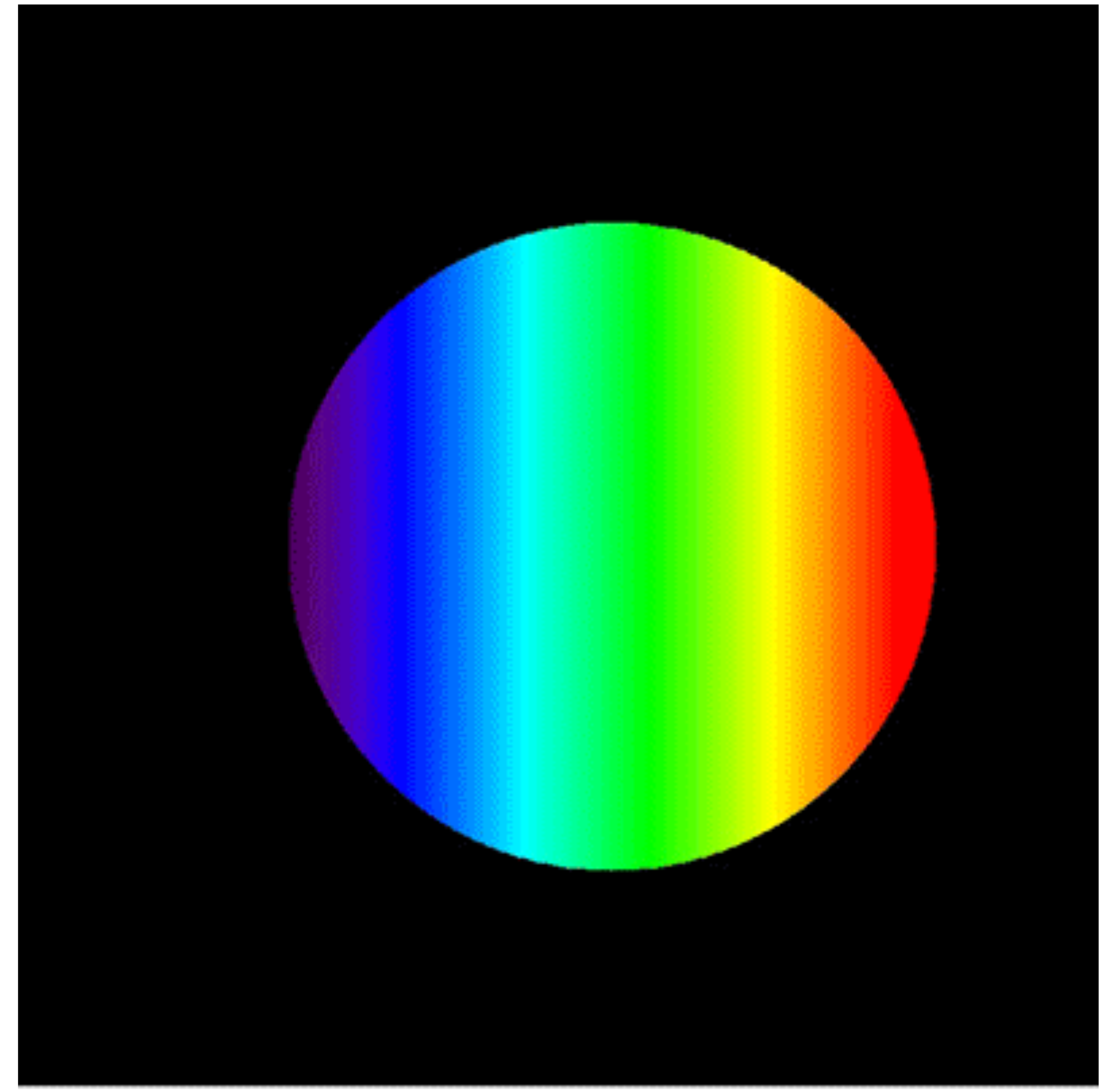
Snellen, de Kok, Birkby et al., 2015

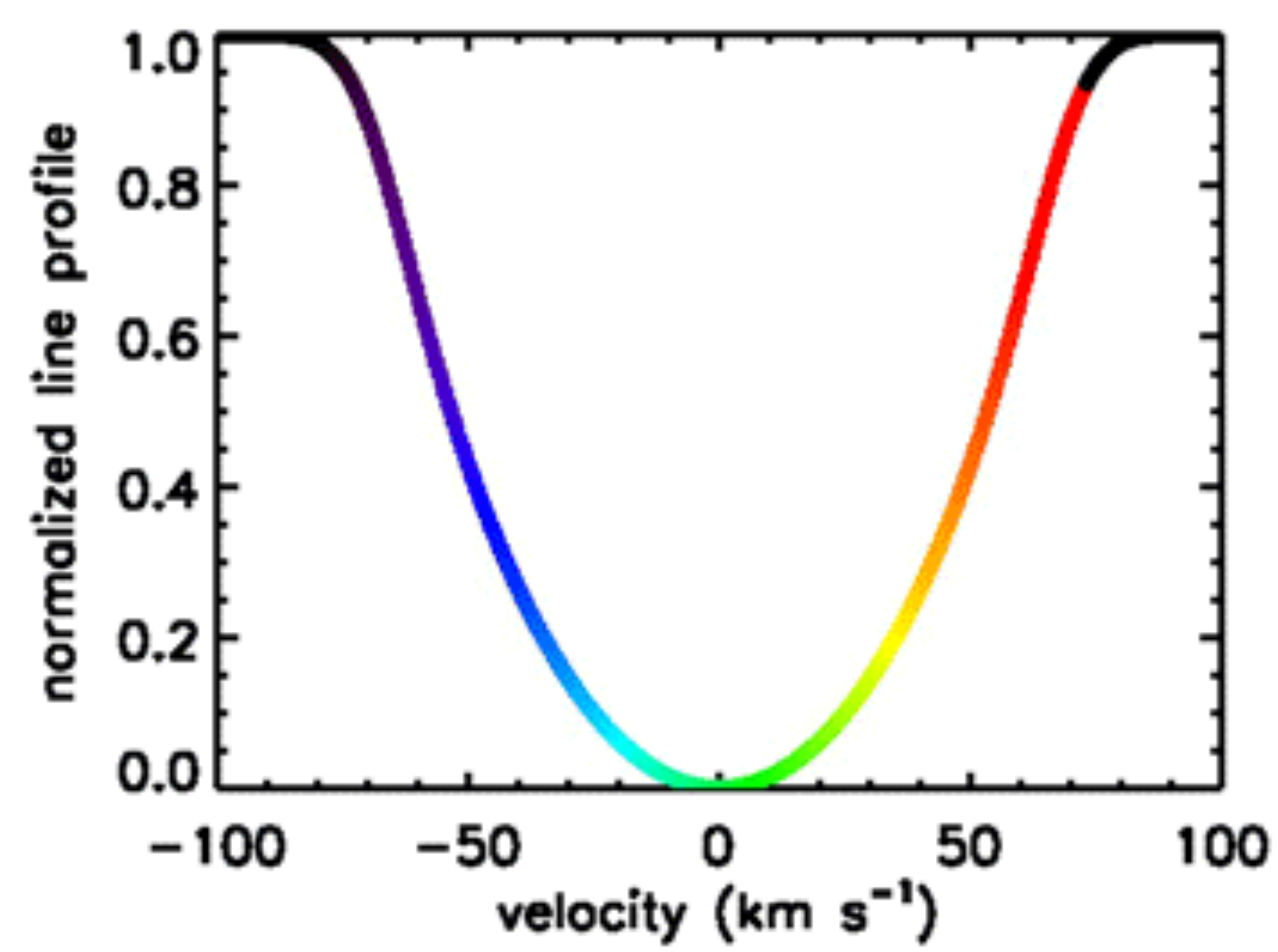
Sky-background is negligible in the optical

Mapping atmospheric surface features

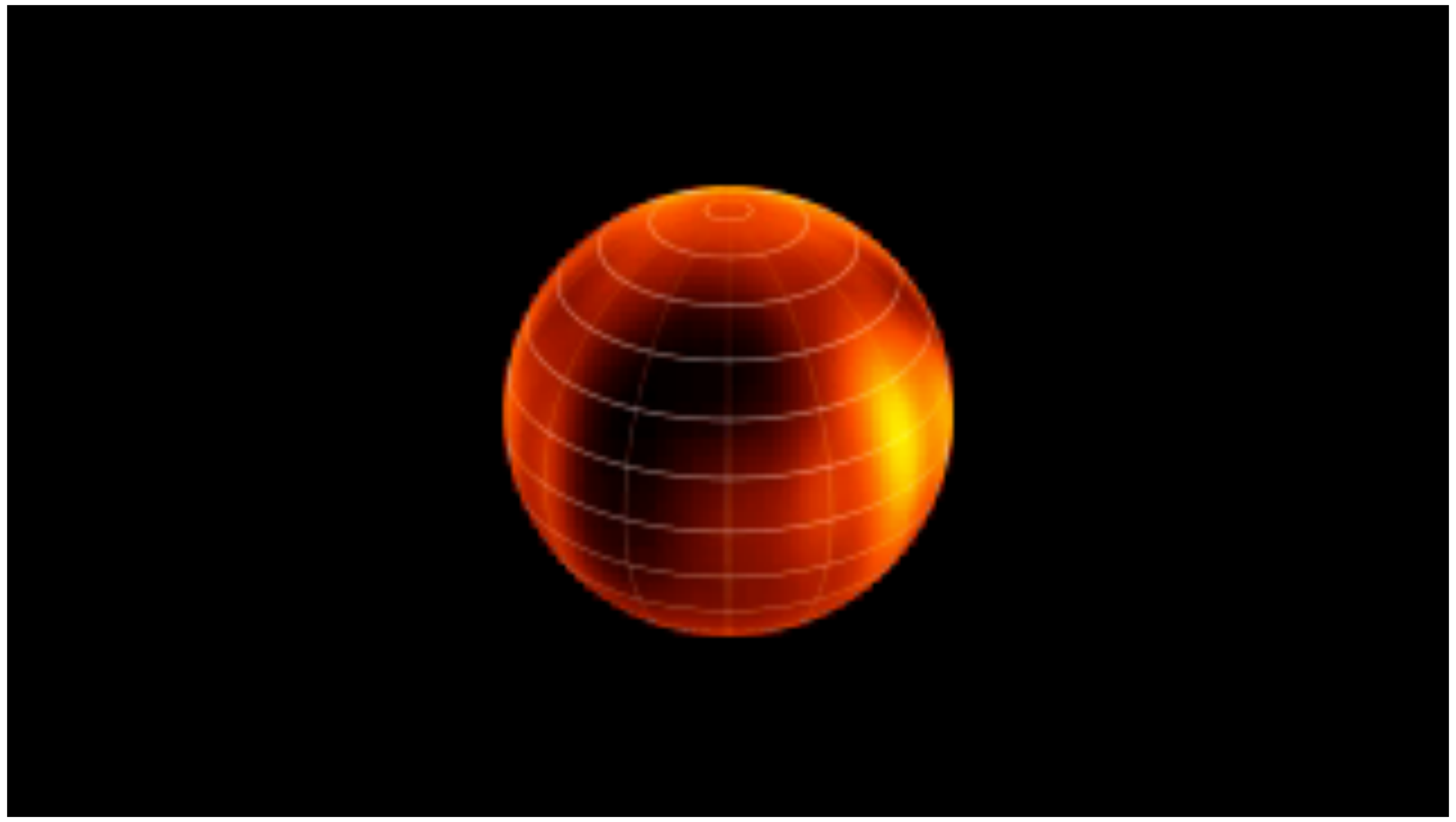
HDS+HCI with TMT permits Doppler imaging of exoplanets

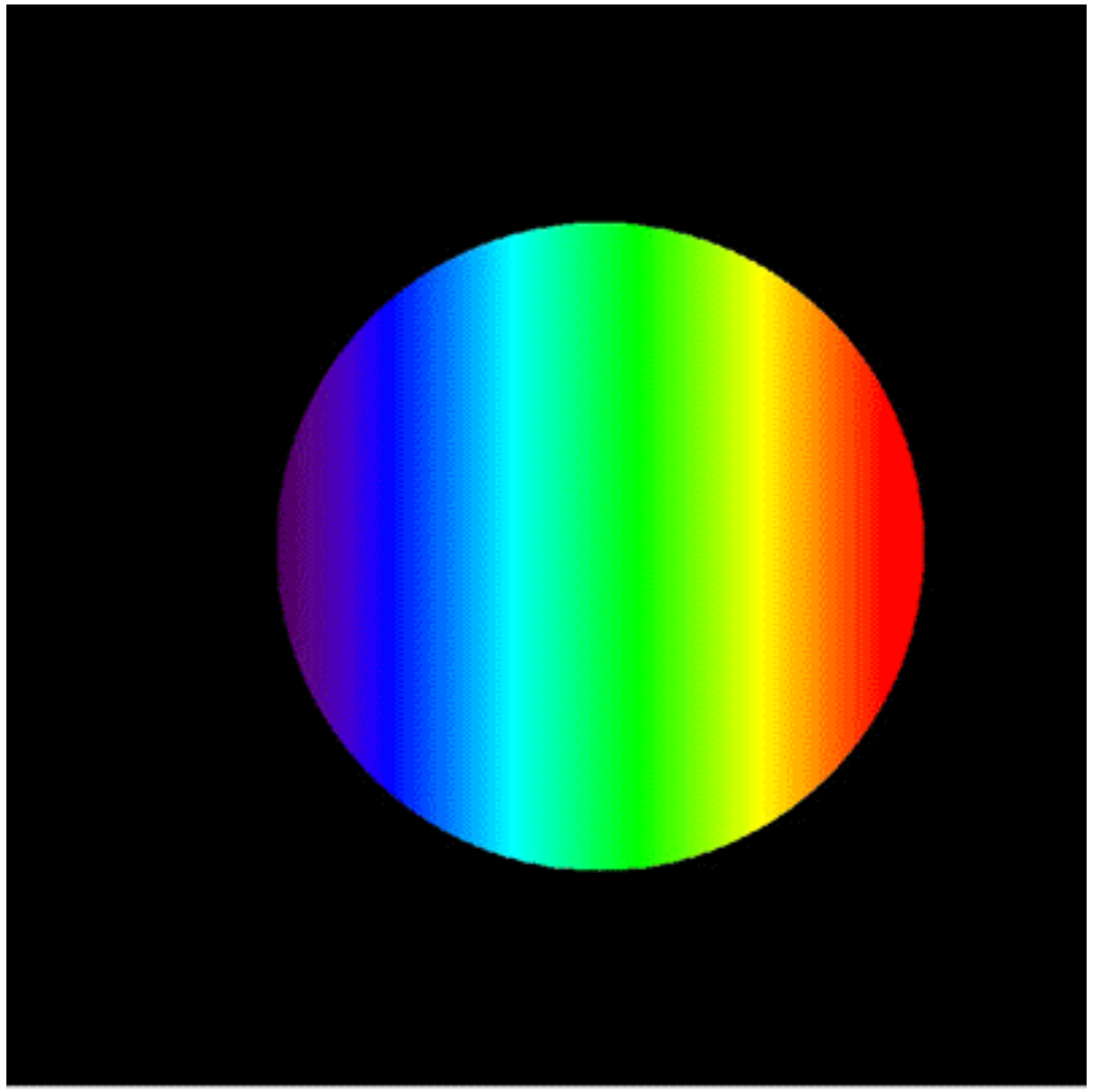


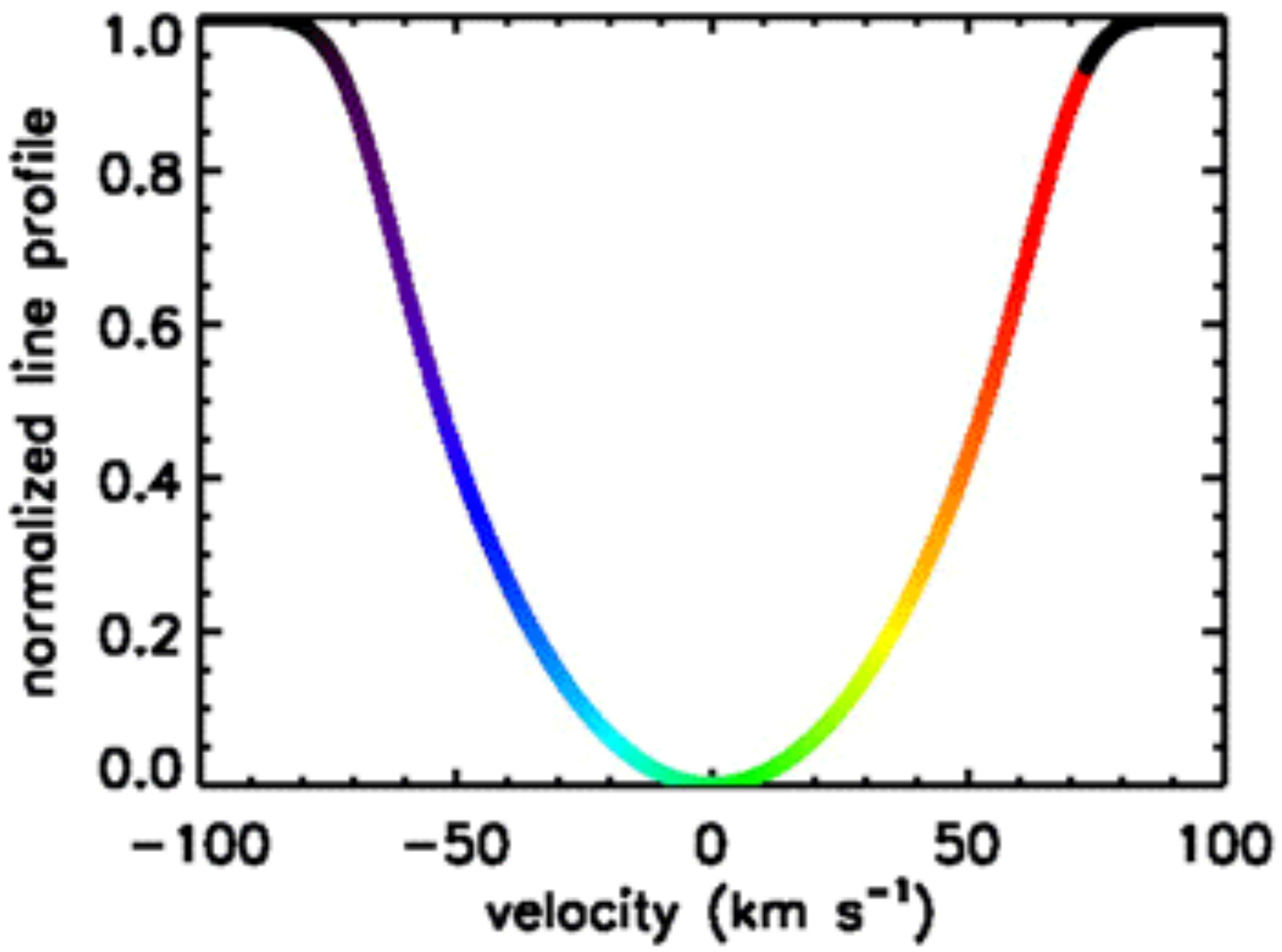




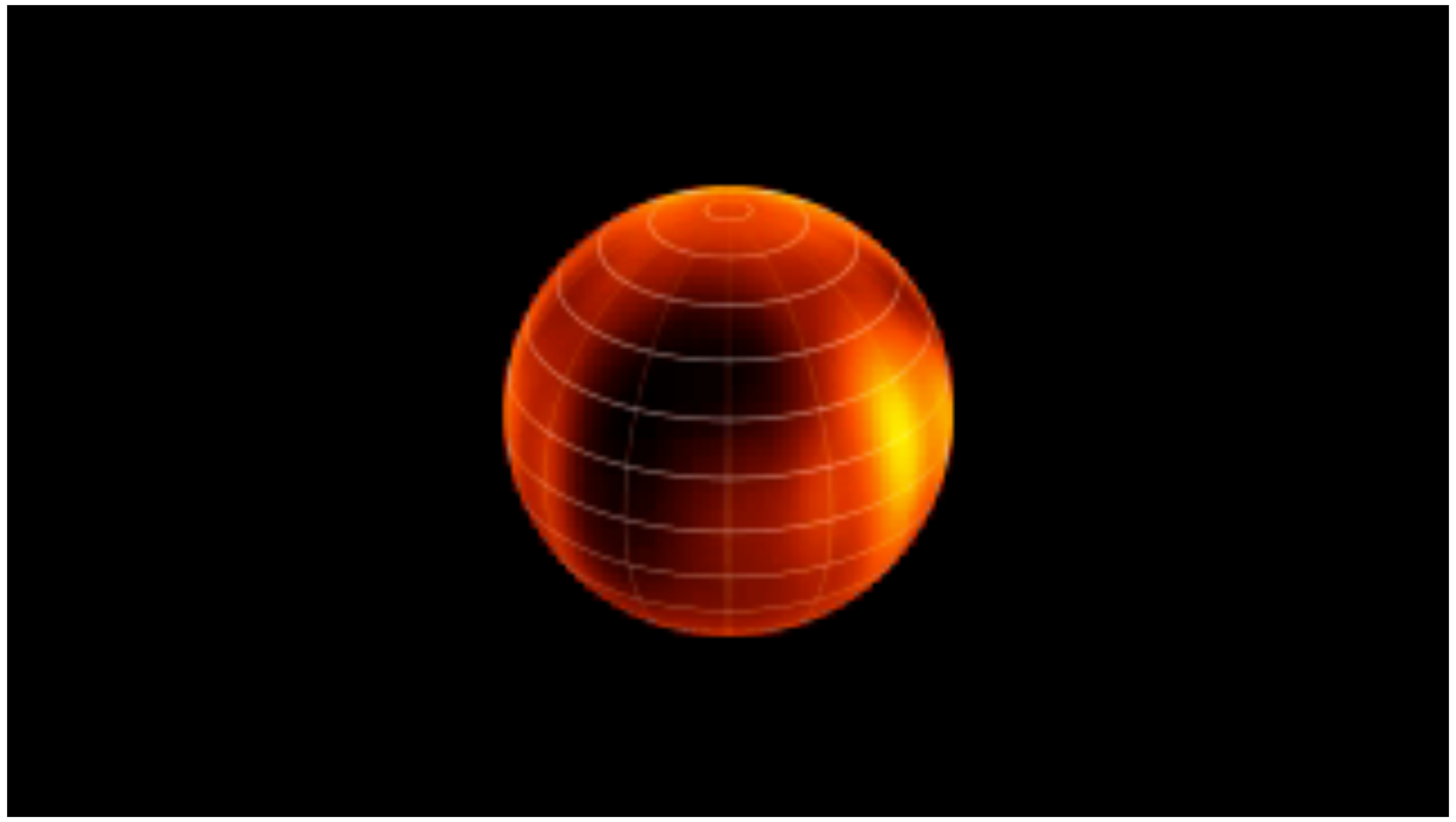
HDS+HCI with TMT permits Doppler imaging of exoplanets



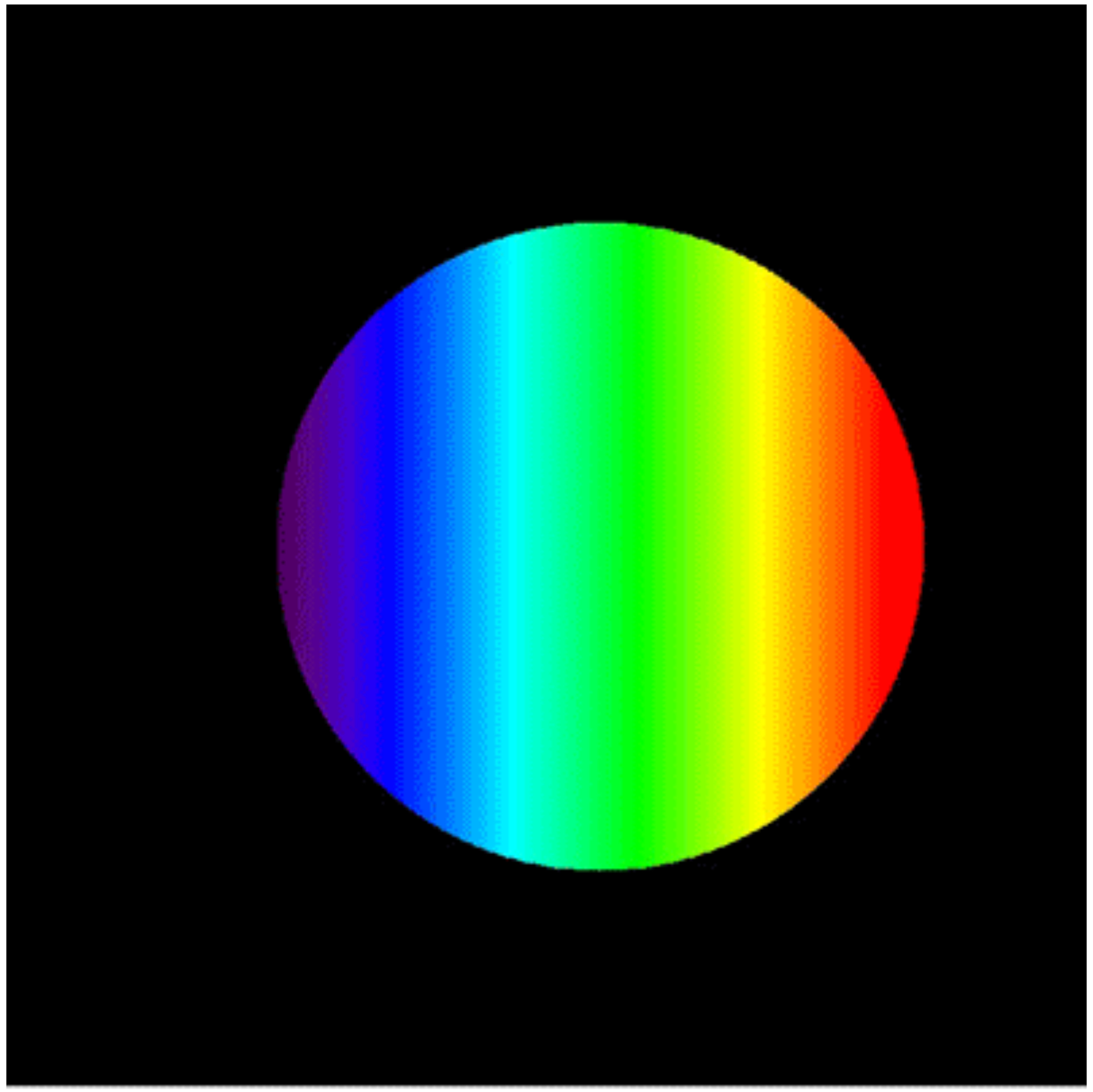


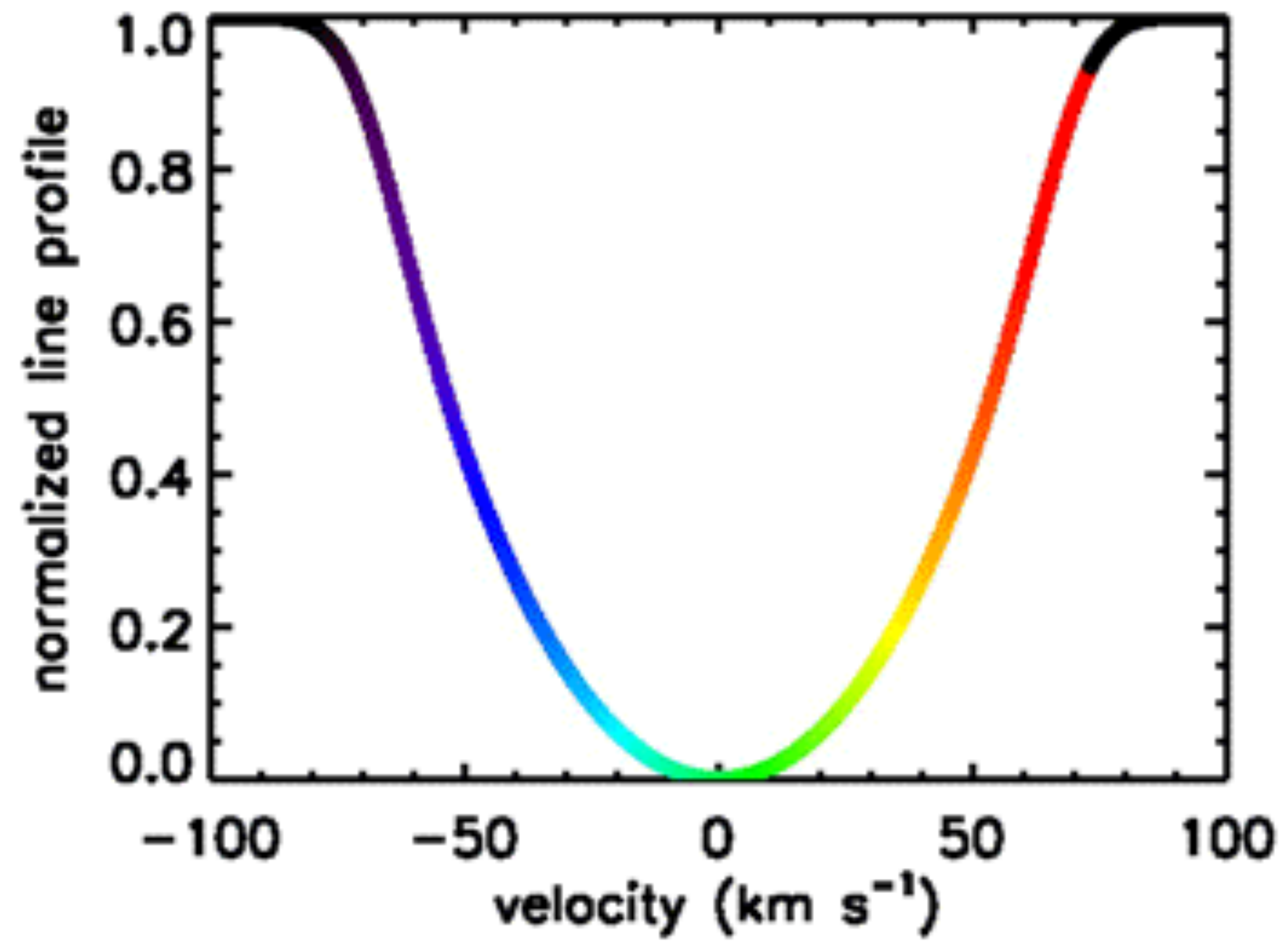


HDS+HCI with TMT permits Doppler imaging of exoplanets

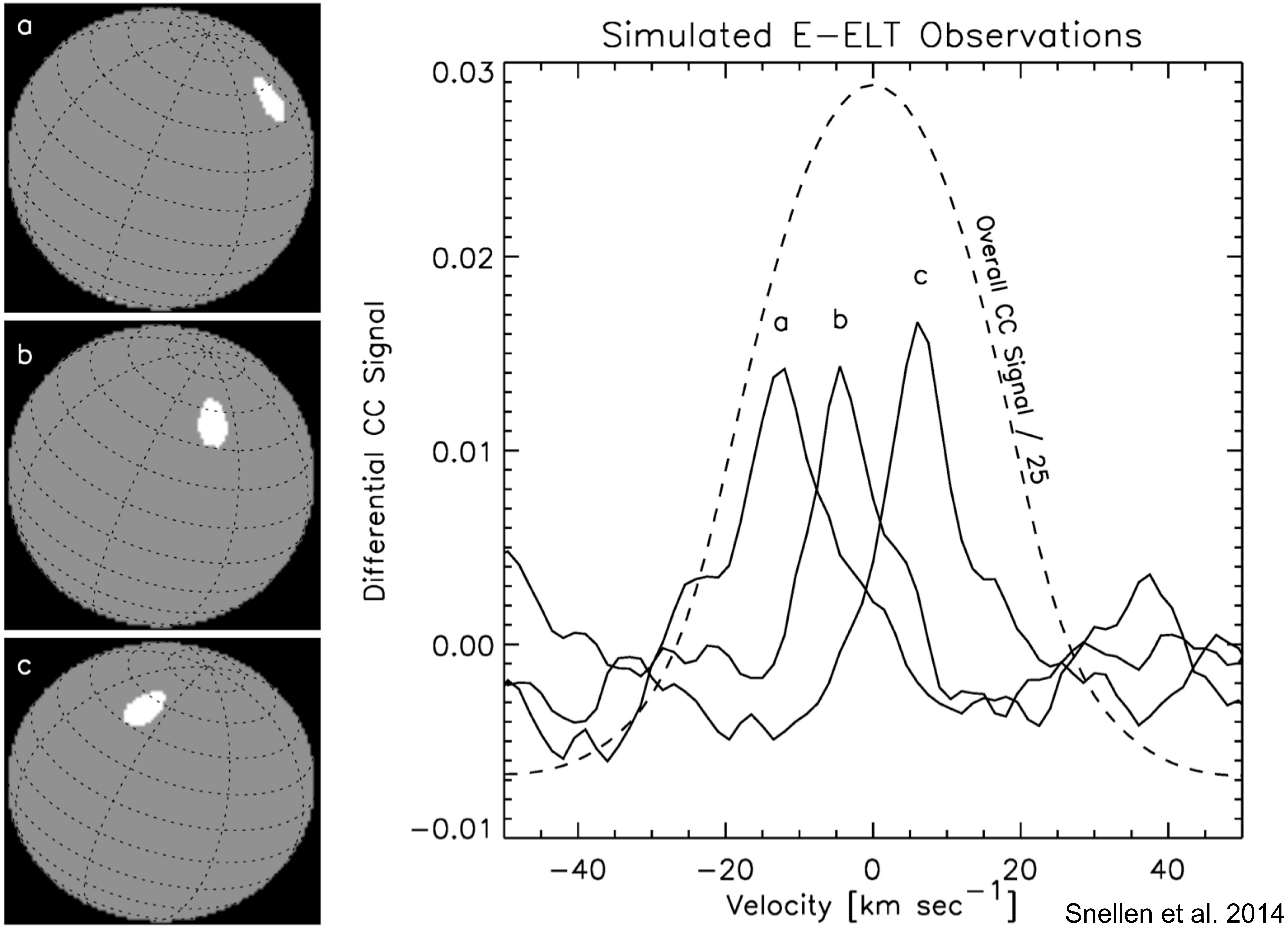


Global cloud map of brown dwarf Luhman 16B from Doppler imaging with CRIRES/VLT (Crossfield et al. 2014)





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



Snellen et al. 2014

Mapping of β Pic b would be twice as efficient as VLT mapping of a brown dwarf

(Crossfield et al. 2014)

Take home messages:

- **HDS** unambiguously identifies **molecular features** in exoplanet atmospheres and probes their **thermal structure**.
- 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(+HCI) in the era of the TMT will be time/disk-resolved and can identify **biomarkers, locate** our nearest habitable rocky neighbours, and create **maps** of atmospheric surface features.

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