

# New Frontiers of High-Resolution Spectroscopy

Probing the atmospheres of brown dwarfs and reflected light from exoplanets

**Jayne Birkby, NASA Sagan Fellow**  
**Harvard-Smithsonian Center for Astrophysics**

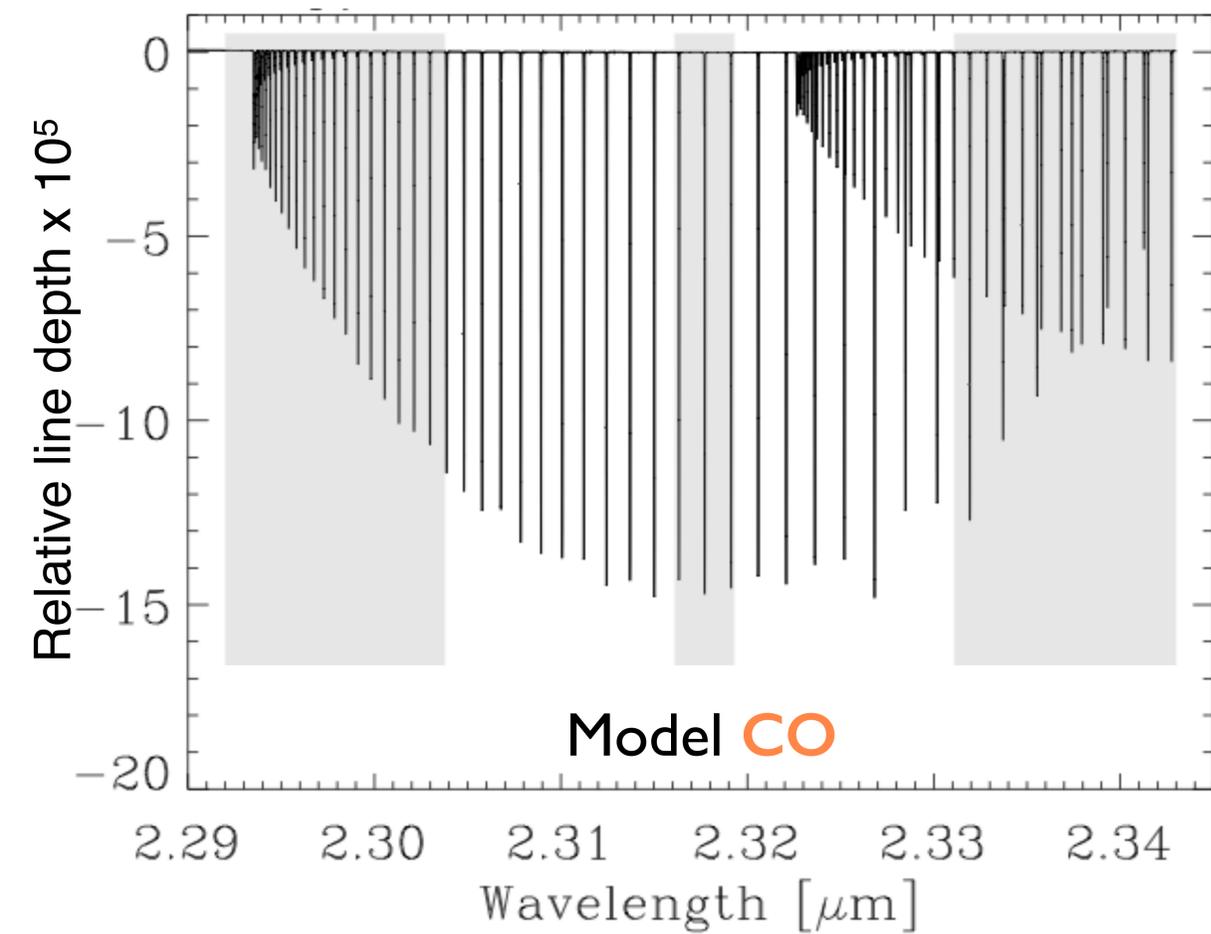
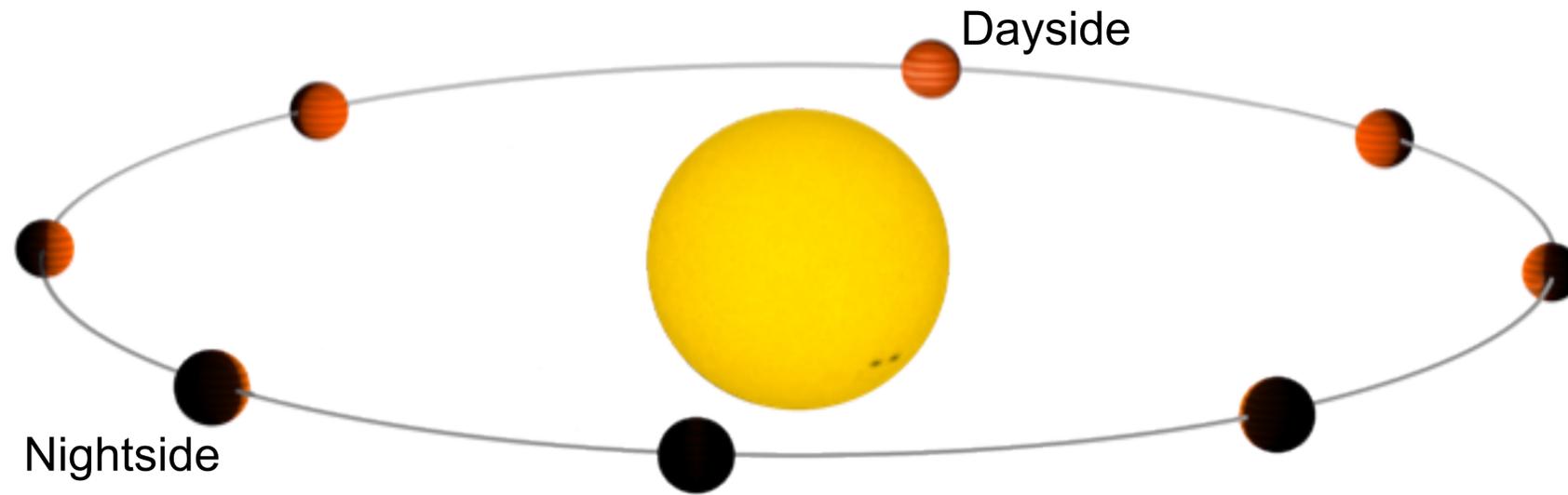
**In collaboration with:** Roi Alonso<sup>1</sup>, Matteo Brogi<sup>2</sup>, David Charbonneau<sup>3</sup>, Jonathan Fortney<sup>4</sup>, Sergio Hoyer<sup>1</sup>, John Johnson<sup>3</sup>, Remco de Kok<sup>5</sup>, Mercedes Lopez-Morales<sup>3</sup>, Ben Montet<sup>3</sup>, Ignas Snellen<sup>5</sup>

*<sup>1</sup>IAC, <sup>2</sup>UC Boulder, <sup>3</sup>CfA, <sup>4</sup>UC Santa Cruz, <sup>5</sup>Leiden Observatory*

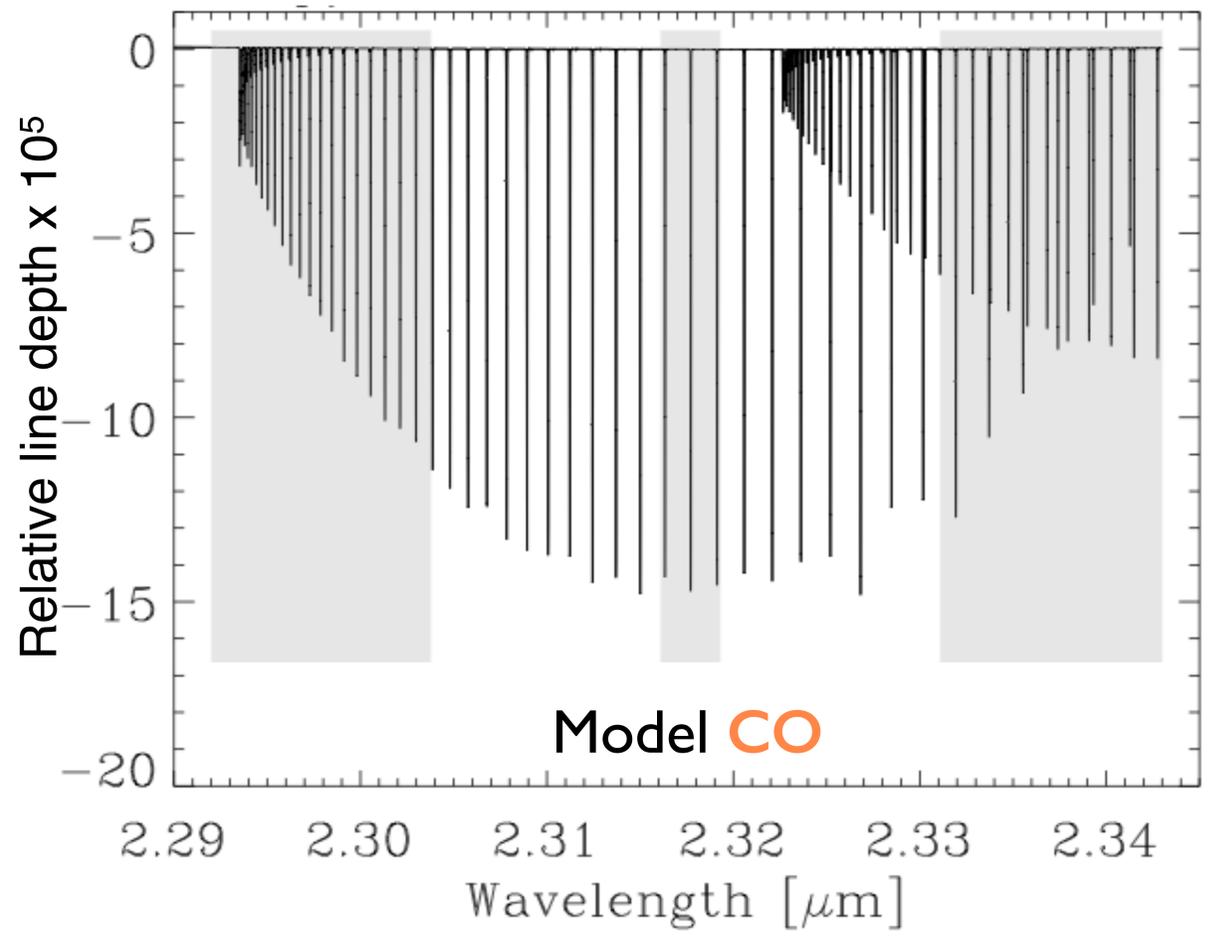
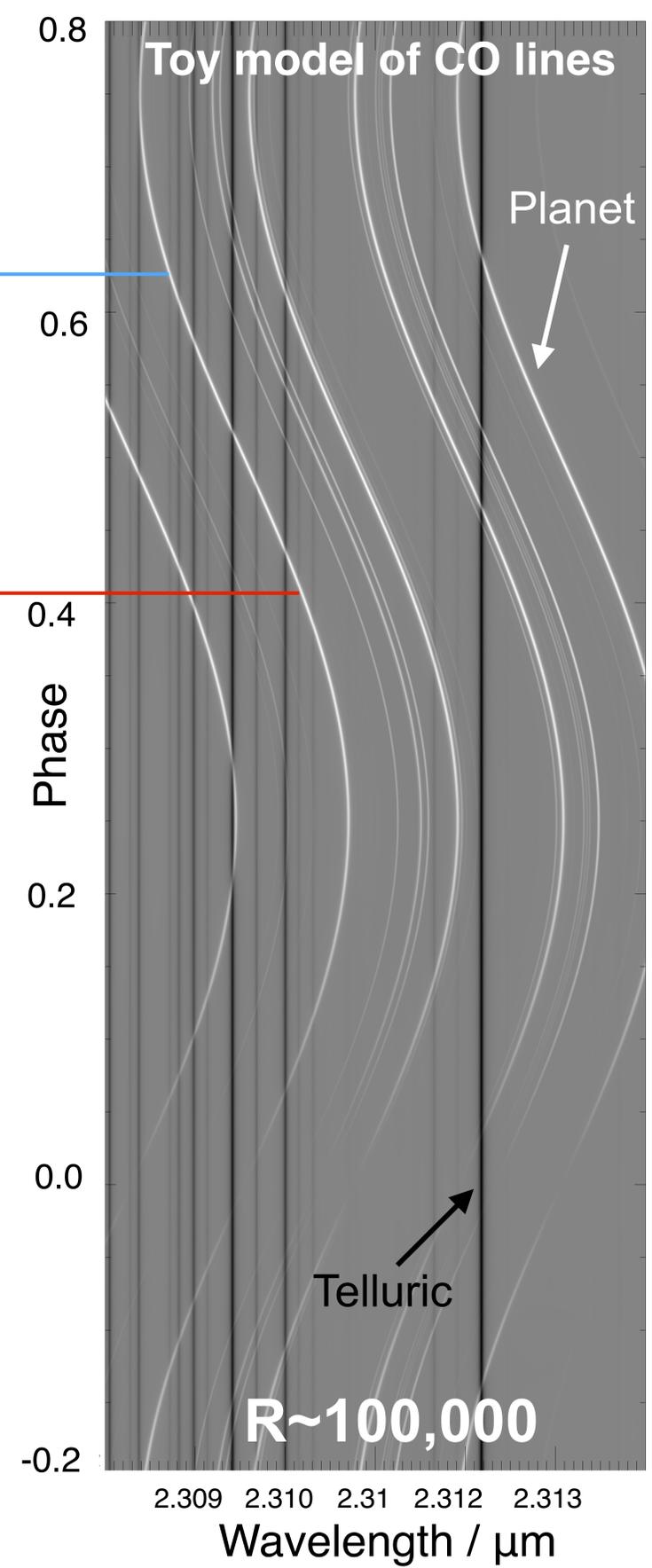
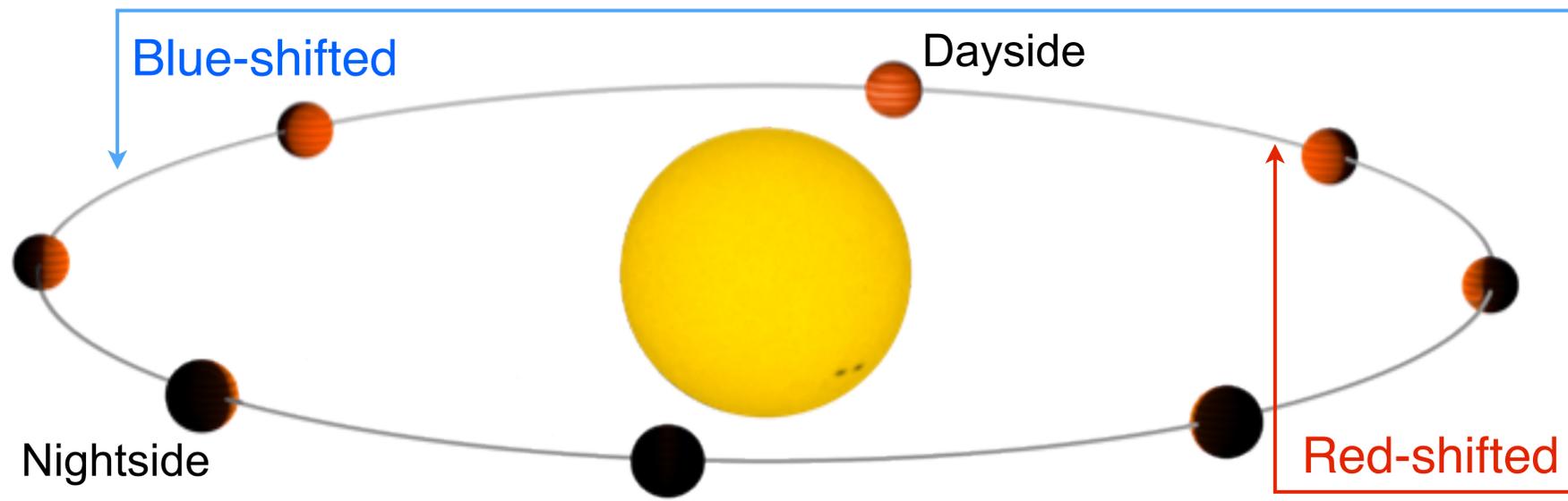


**Direct exoplanet spectra with  
high dispersion spectroscopy  
(HDS)**

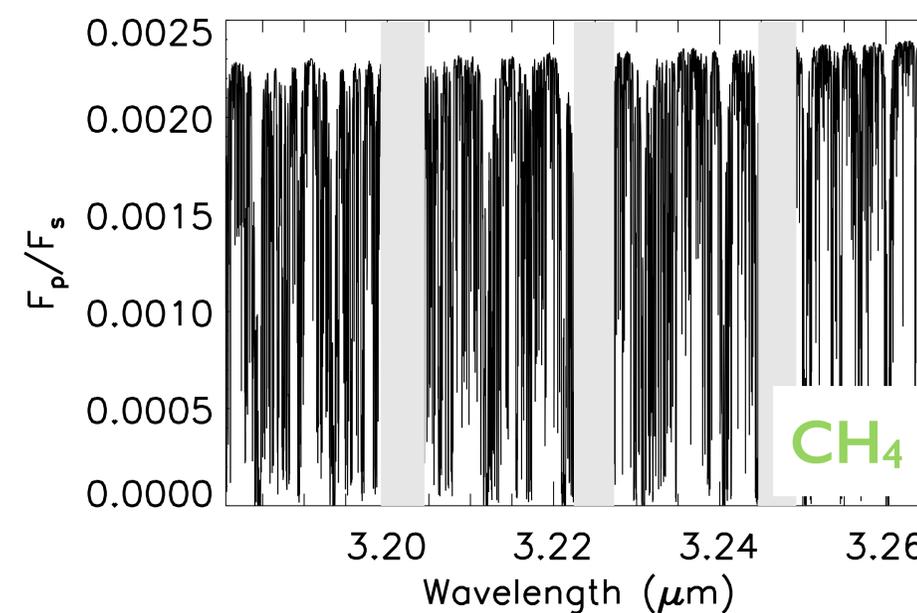
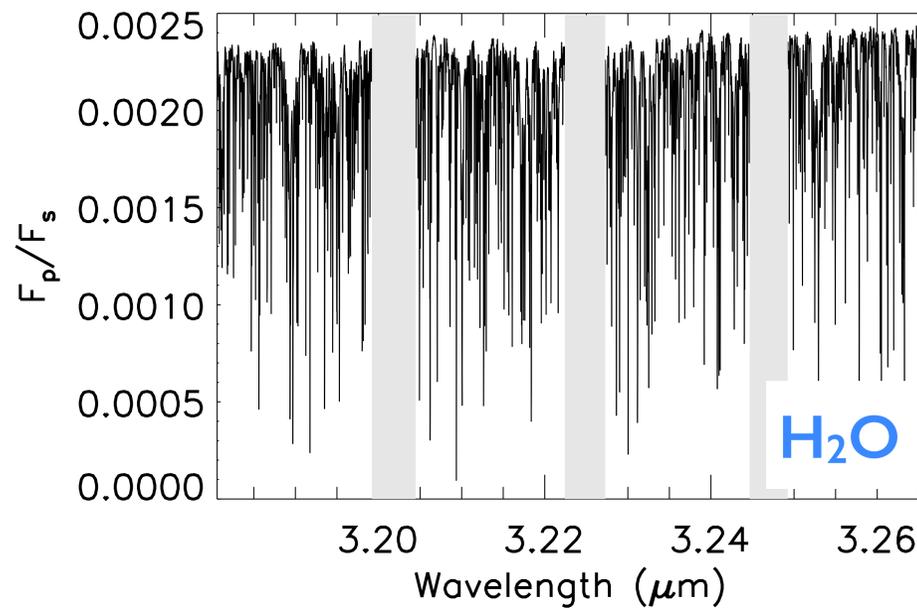
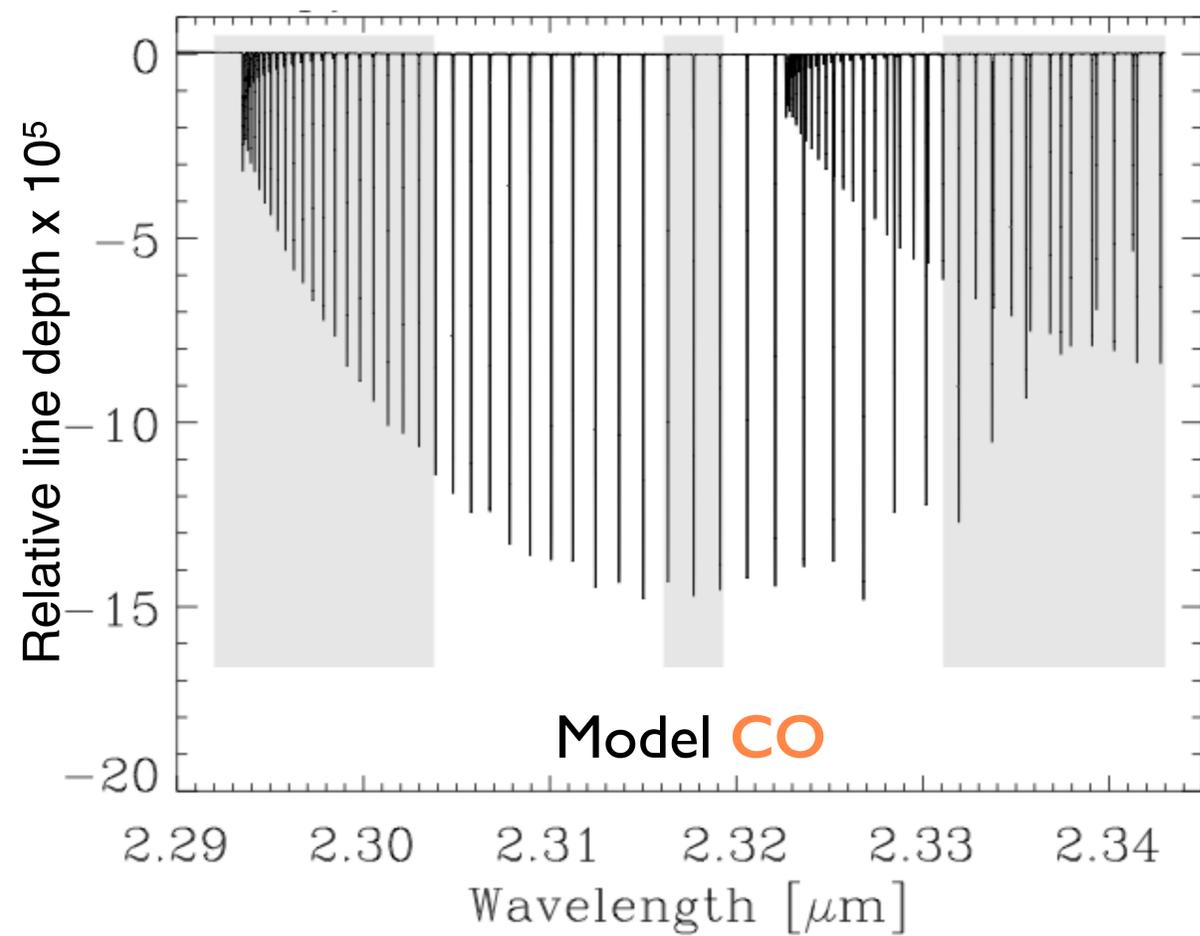
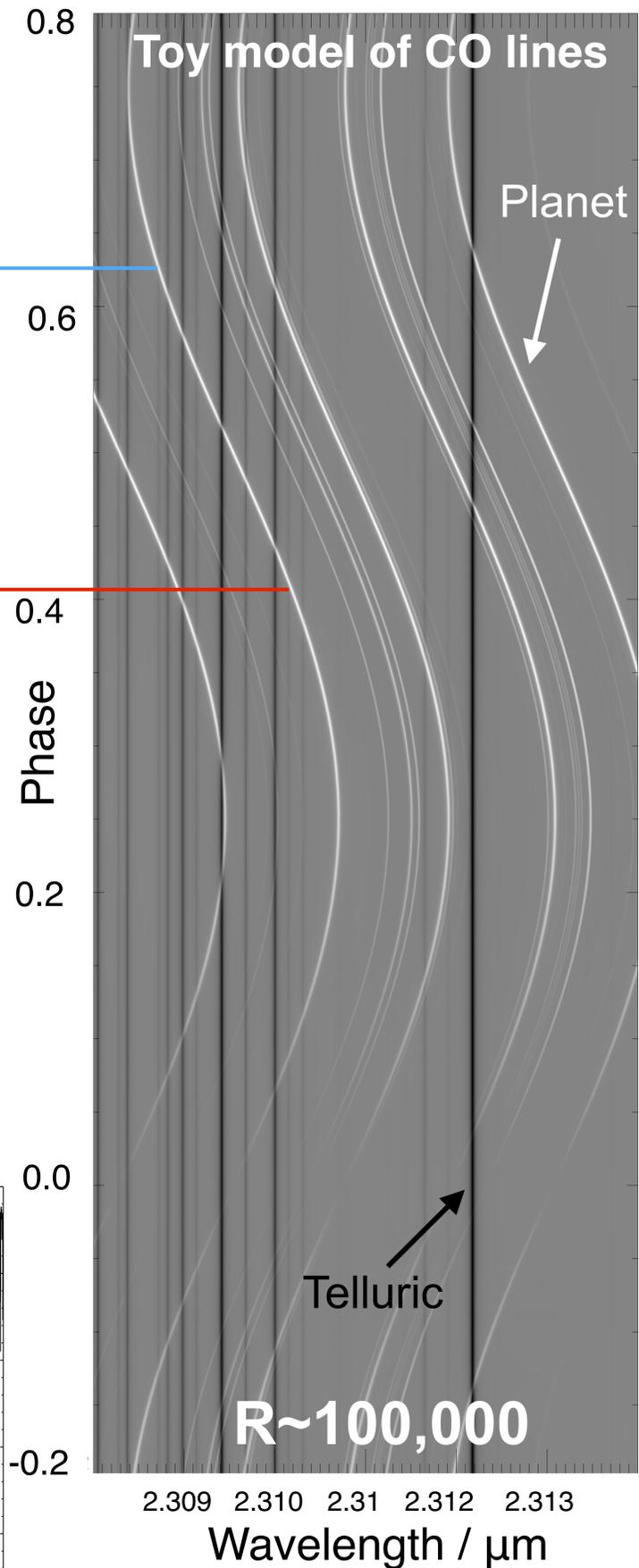
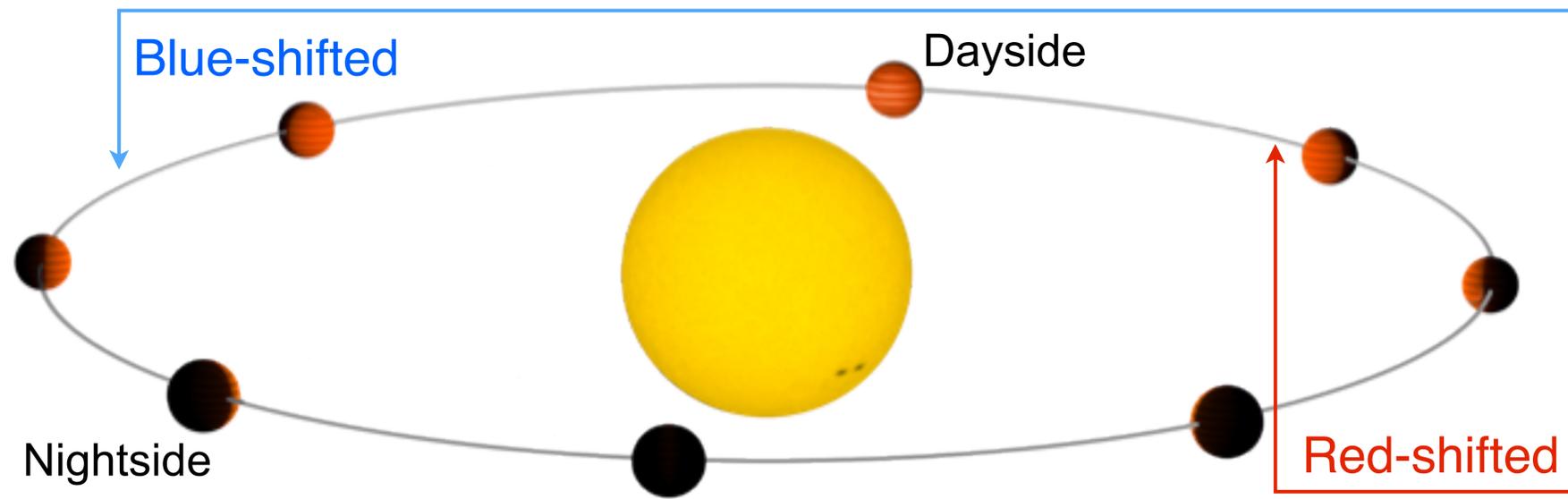
# High dispersion spectroscopy $R > 25,000$ detects the *RV* shift of the *planetary* spectrum



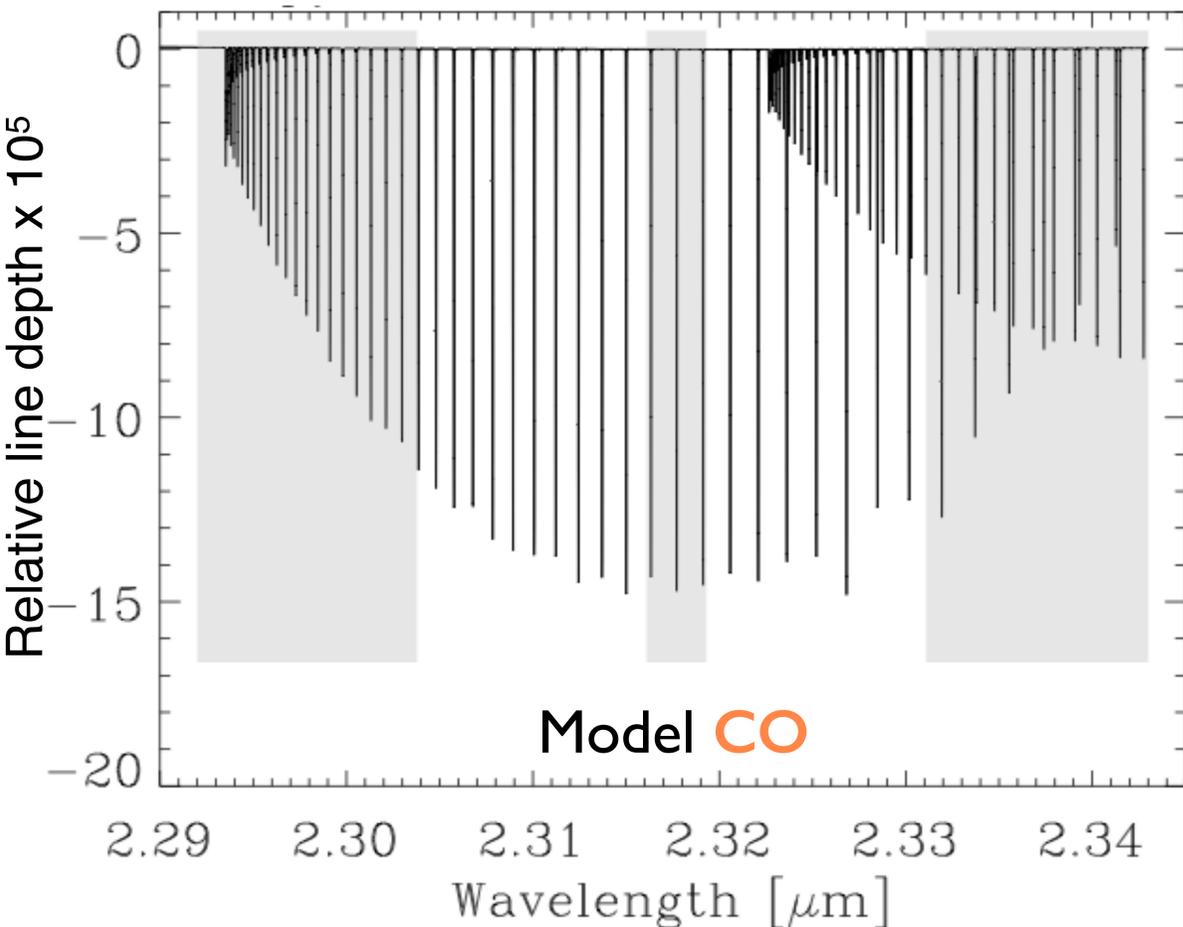
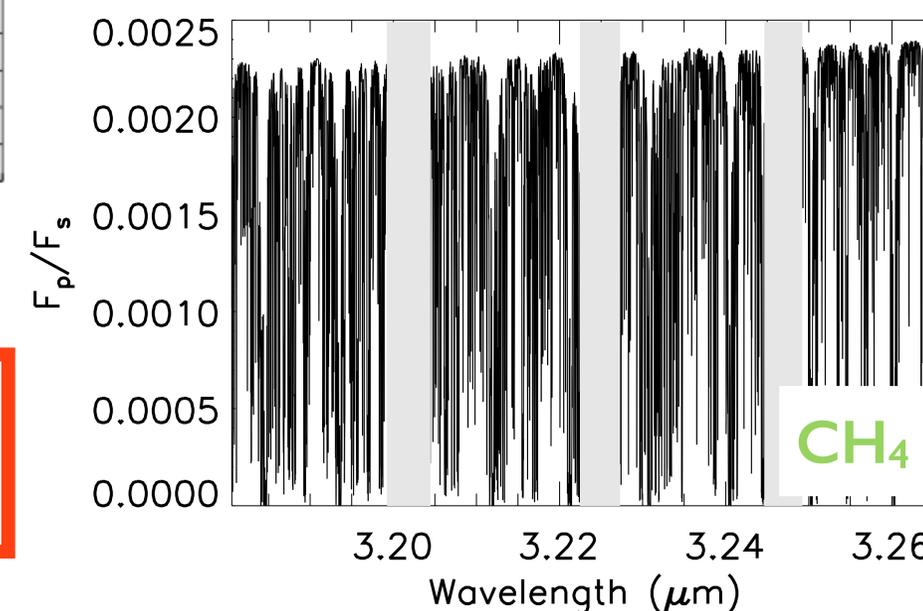
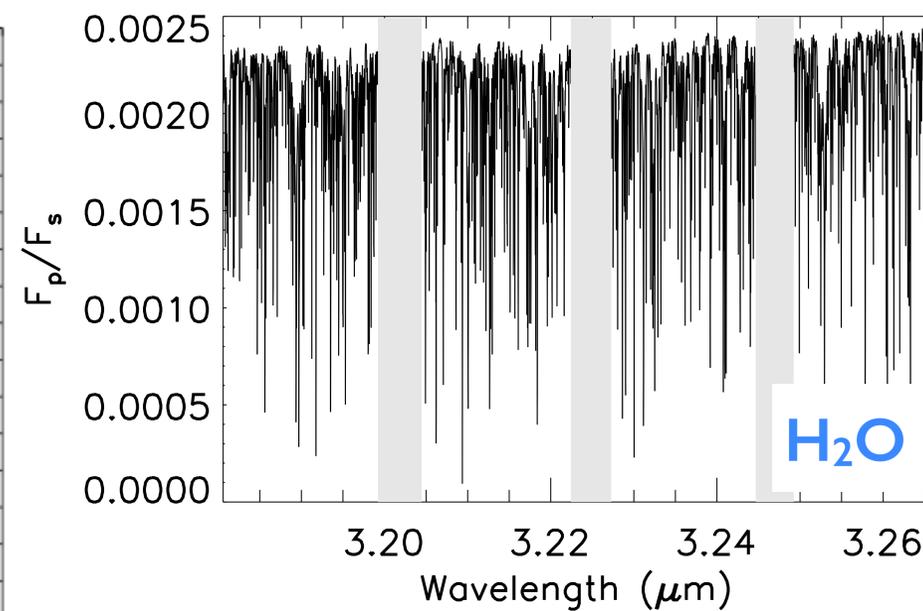
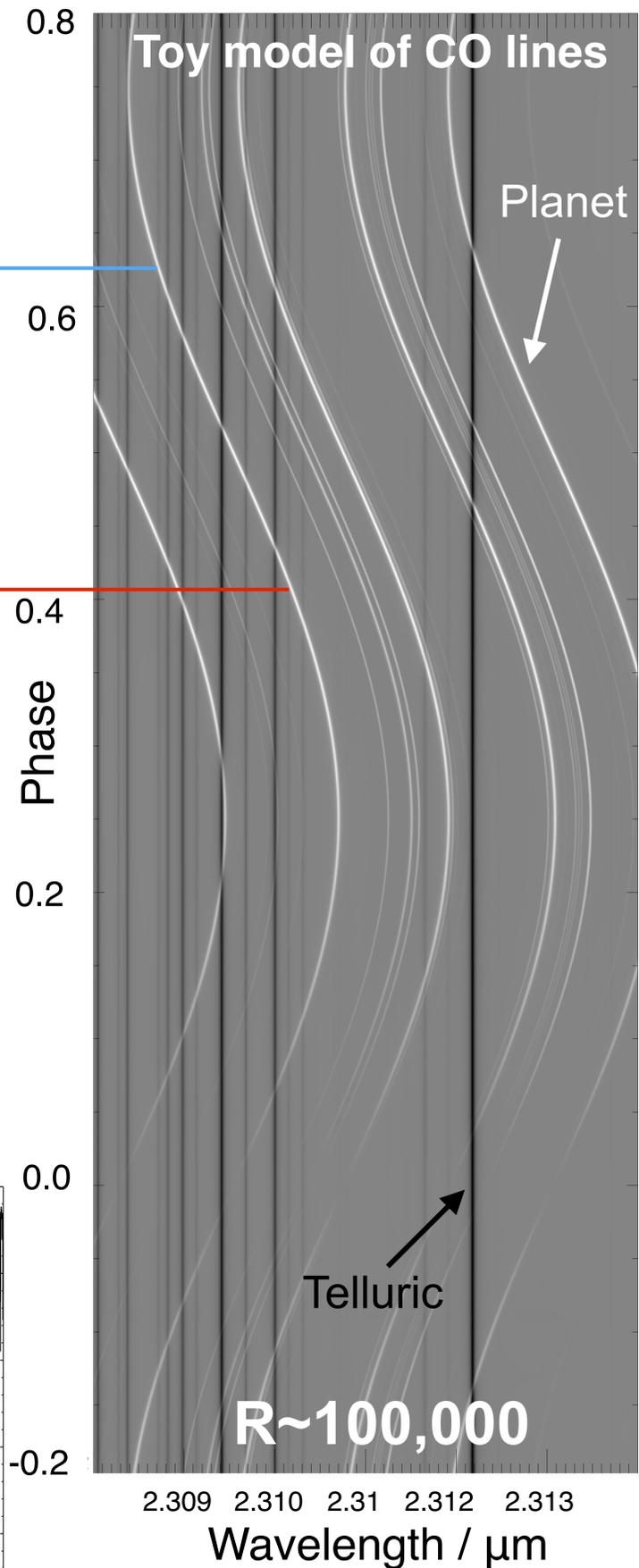
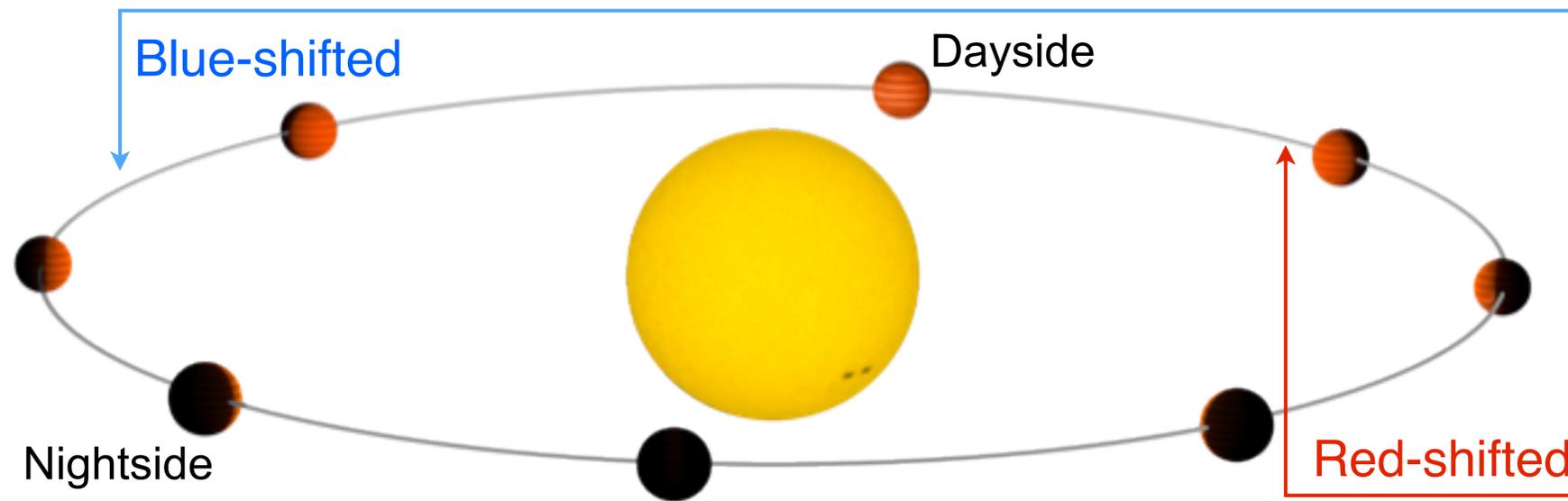
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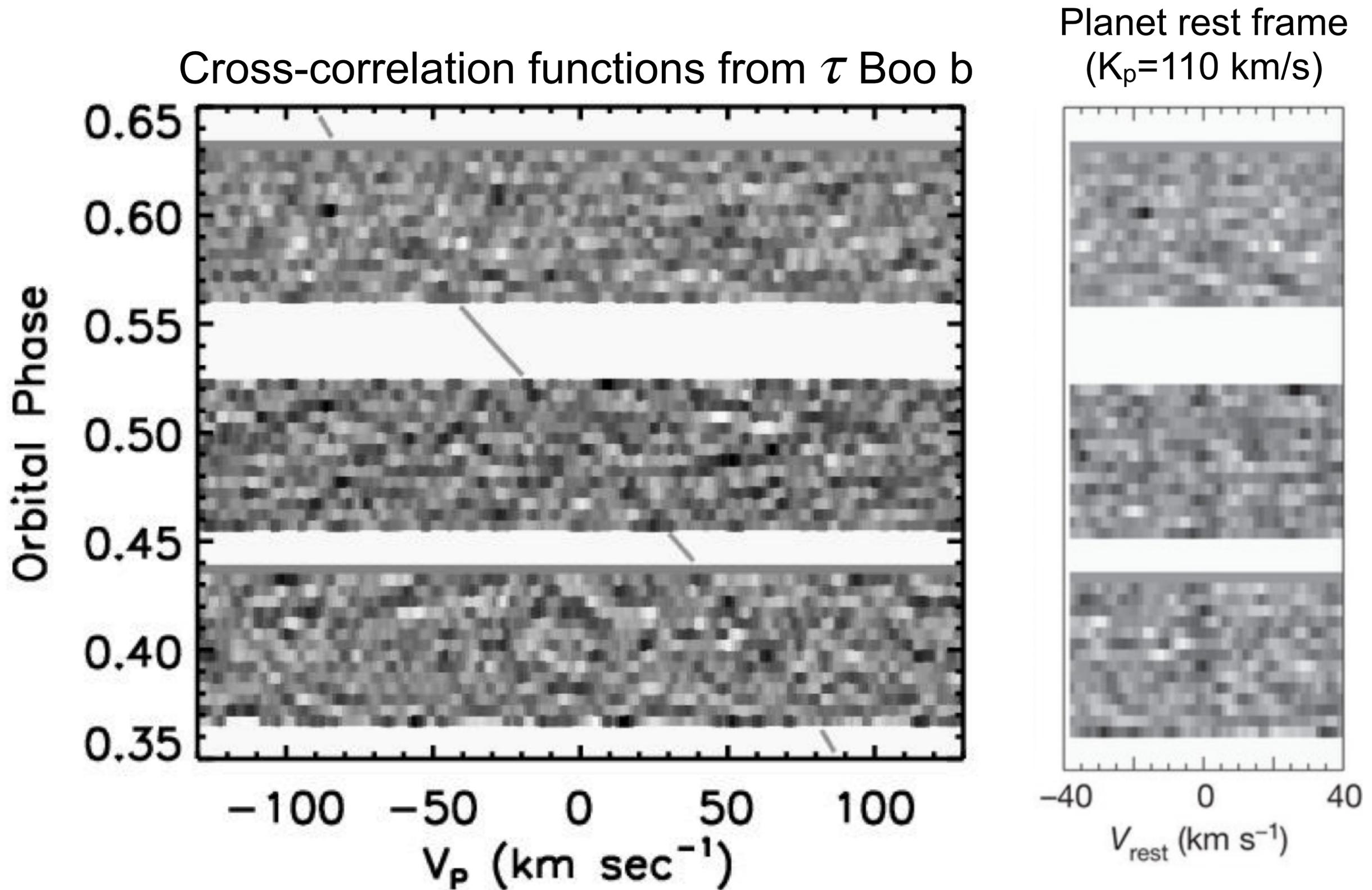


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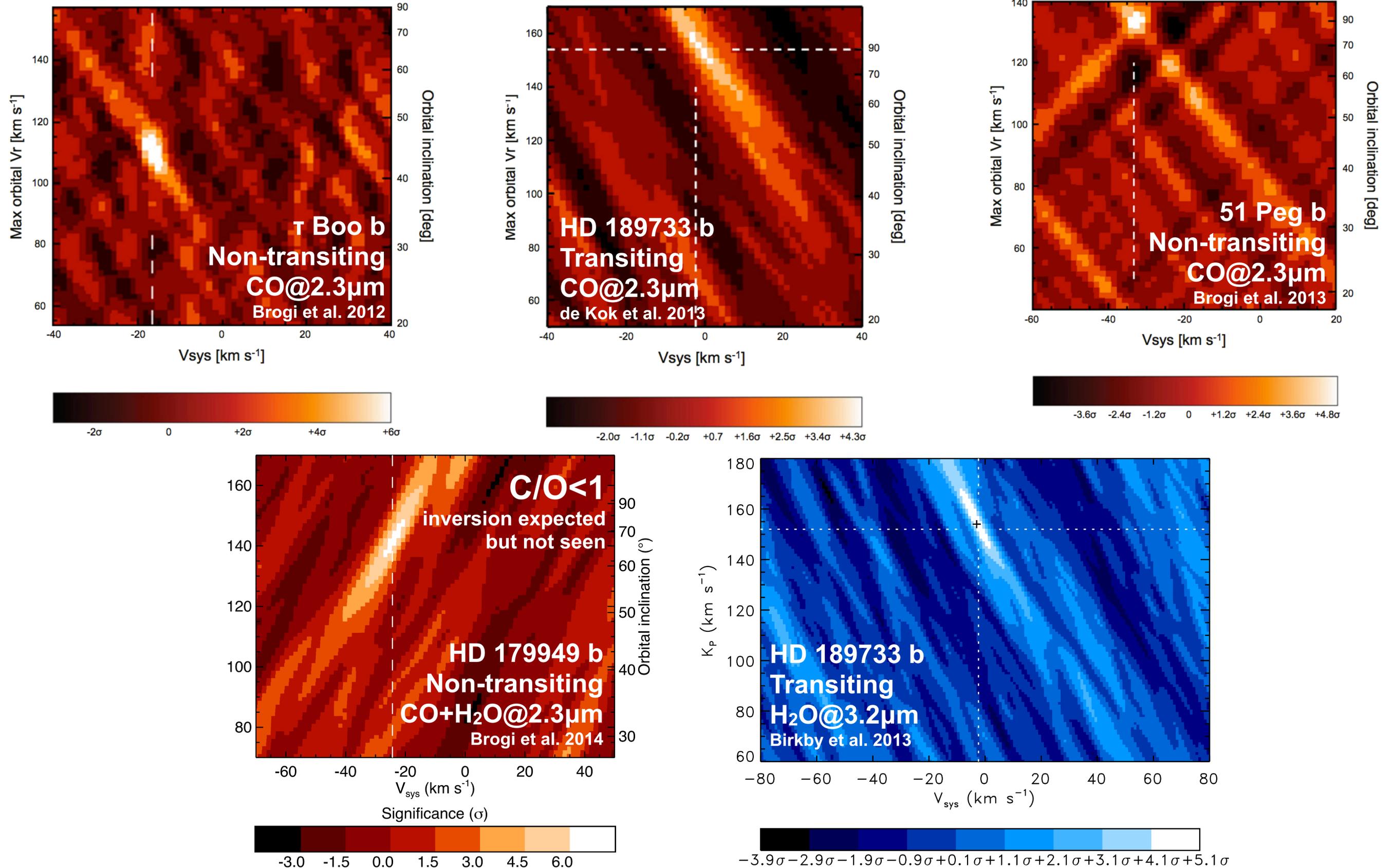


Greater uncertainty in line positions at high temperatures

# Cross-correlation functions trace out the radial velocity curve of the planet

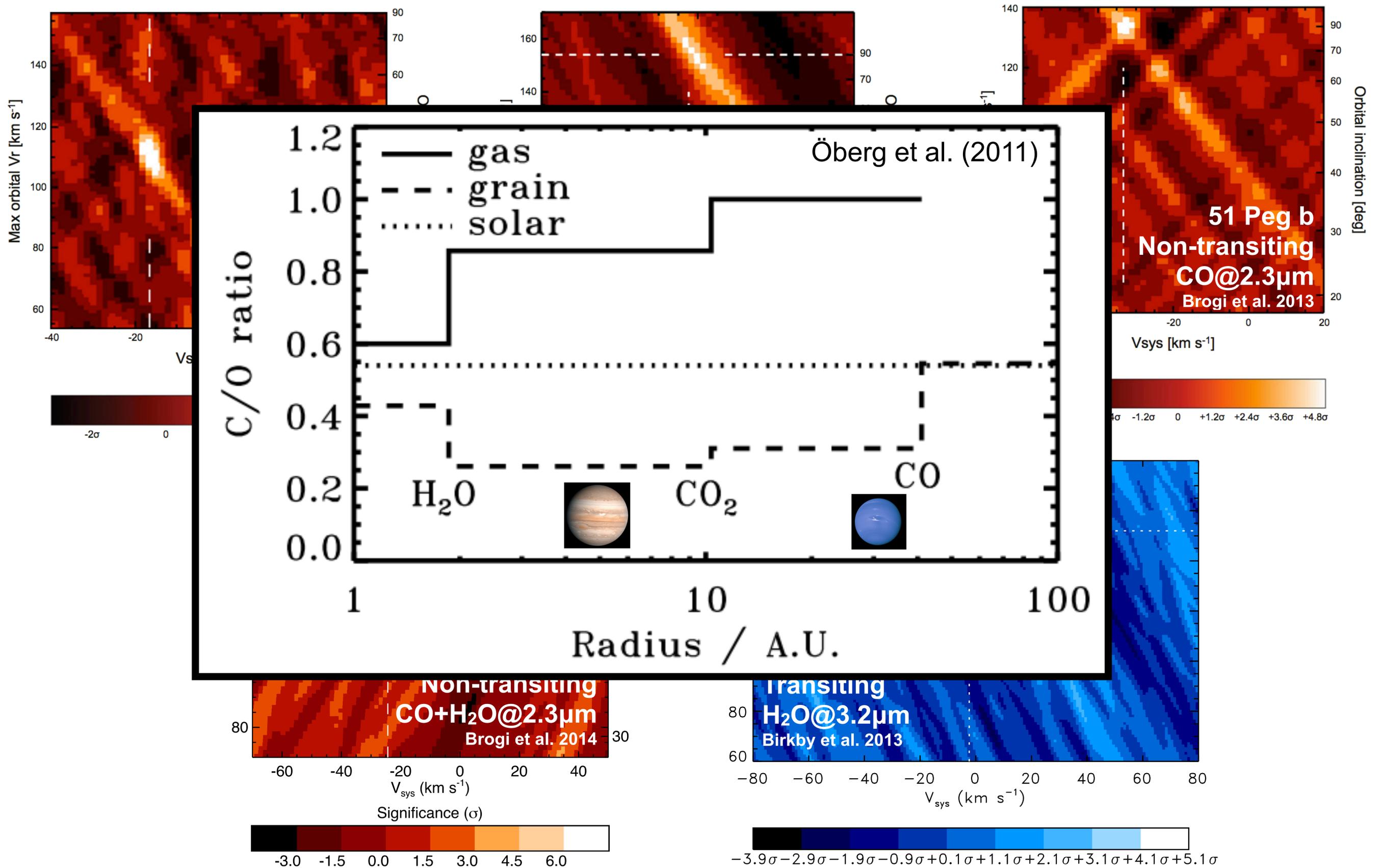


# Unambiguous detections of CO and H<sub>2</sub>O in hot Jupiter atmospheres and no stratospheres



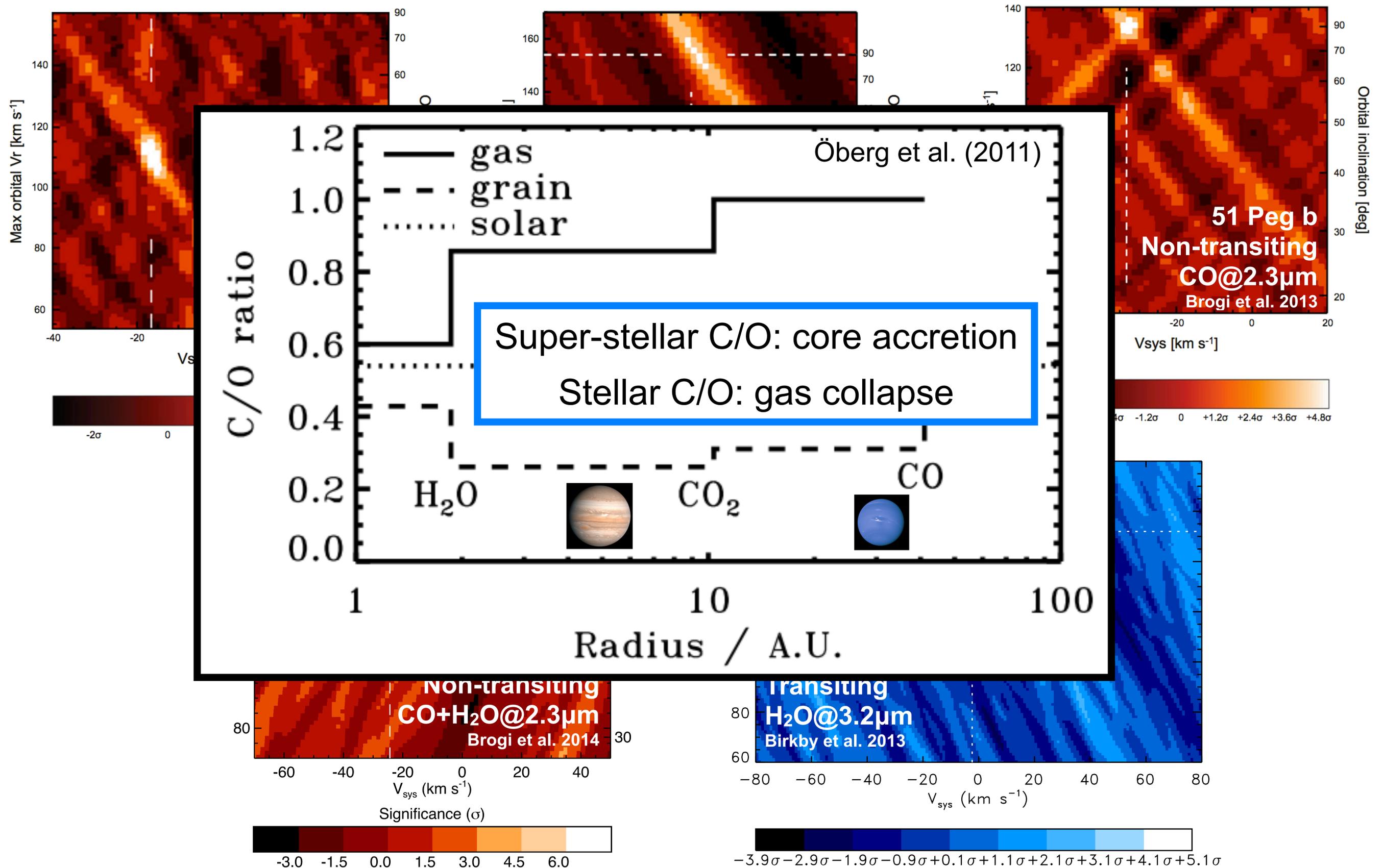
See also: **Rodler** et al. 2012; 2013 (CO in  $\tau$  Boo b & HD 189733 b); **Snellen** et al. 2010, 2013 (CO in HD 209458 b, beta Pic b), **Lockwood** et al. 2014 (H<sub>2</sub>O in  $\tau$  Boo b), **Schwarz** et al. 2015 (no dayside CO in HD 209458 b), **Hoeijmakers** et al. 2015 (probably no TiO in HD 209458 b), see also Ernst **de Mooij** poster here (Super-Earth 55 Cnc e)

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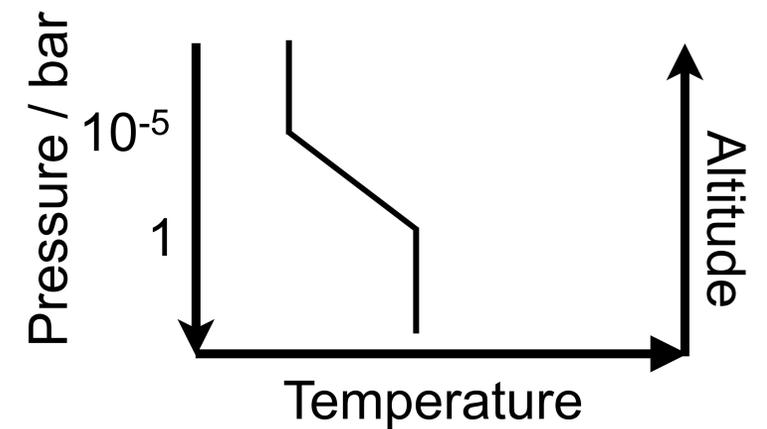


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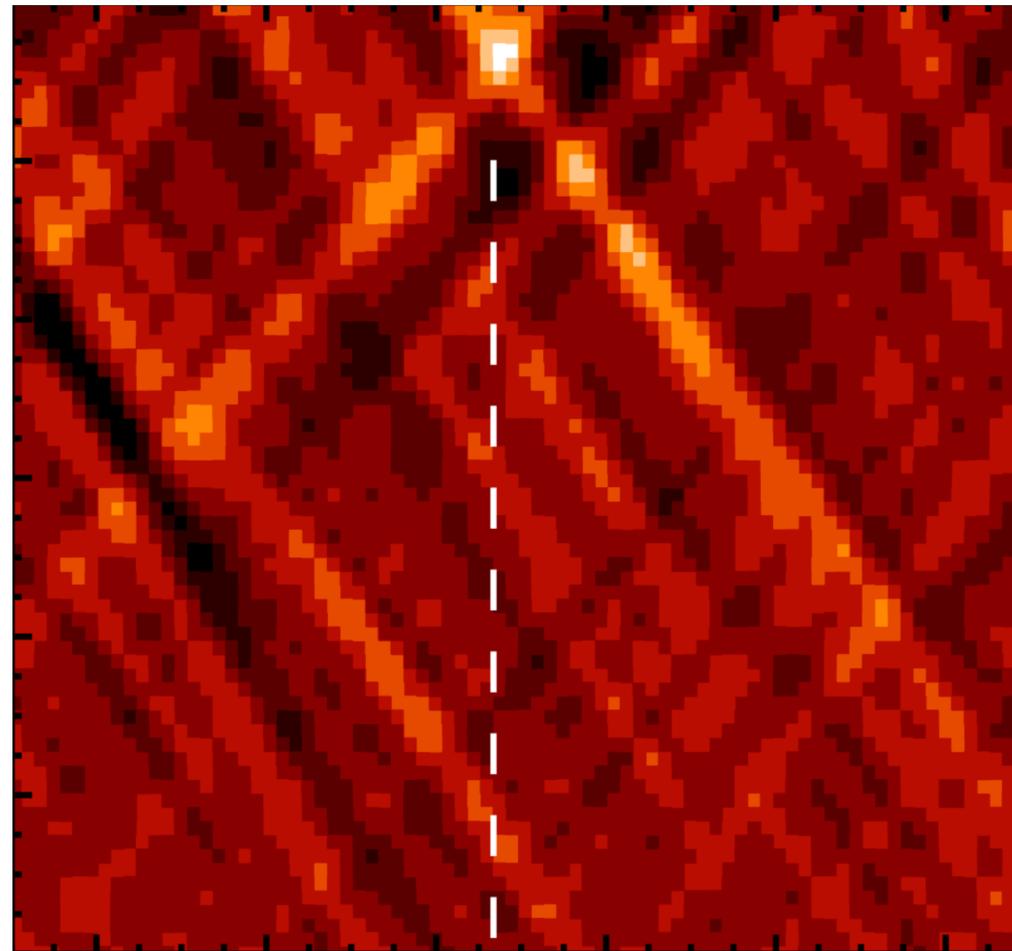
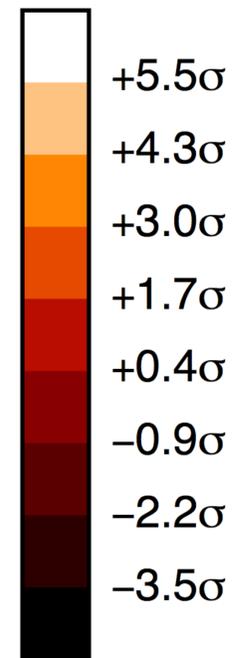
# Water absorption in 51 Peg b at 3.2 $\mu\text{m}$

# Confirmation of CO+H<sub>2</sub>O absorption at 2.3 μm

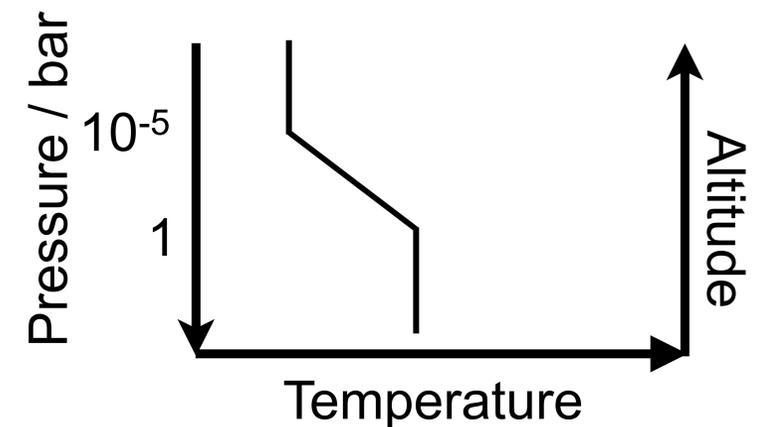
- Max. signal at  **$V_{\text{rest}}=0$  km/s**
- $K_P/K_S = M_S/M_P$
- $R K_P / 2\pi a = \sin(i)$



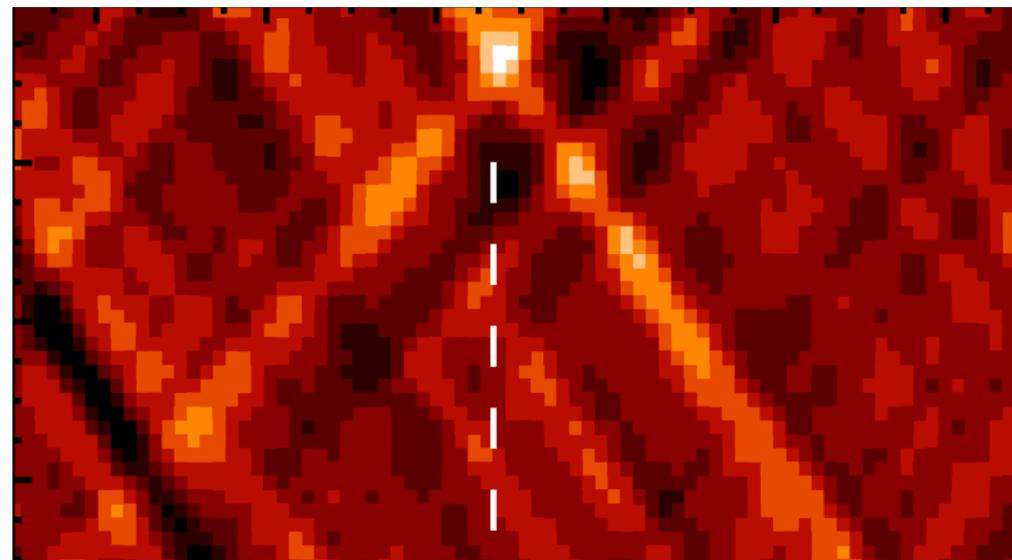
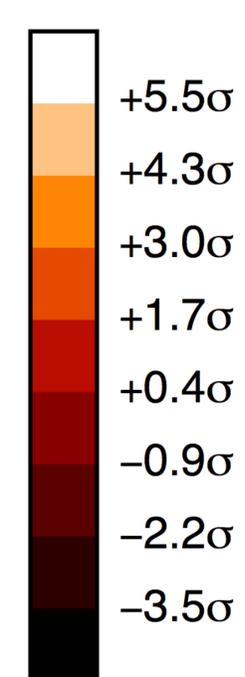
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- Max. signal at  $V_{\text{rest}}=0$  km/s
- $K_P/K_S = M_S/M_P$   
 $K_P=134\pm 1.8$  km/s  
 $M_P=0.46\pm 0.02$  M<sub>J</sub>
- $PK_P/2\pi a = \sin(i)$   
 $79.6^\circ < i < 82.2^\circ$

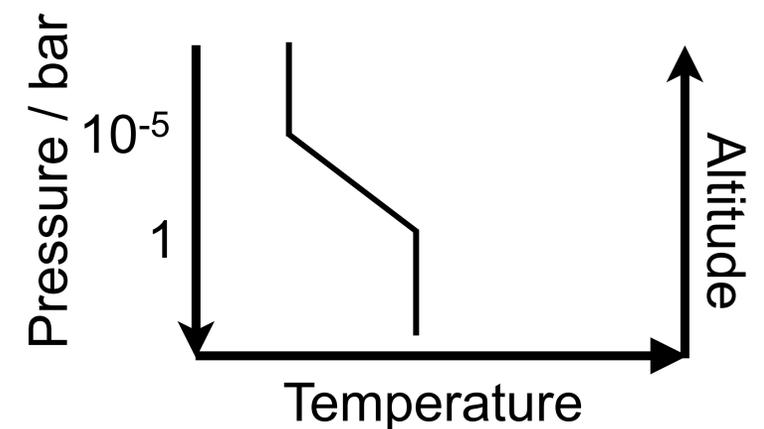


# Confirmation of CO+H<sub>2</sub>O absorption at 2.3 μm



Measure mass of planet  
to < 5% error

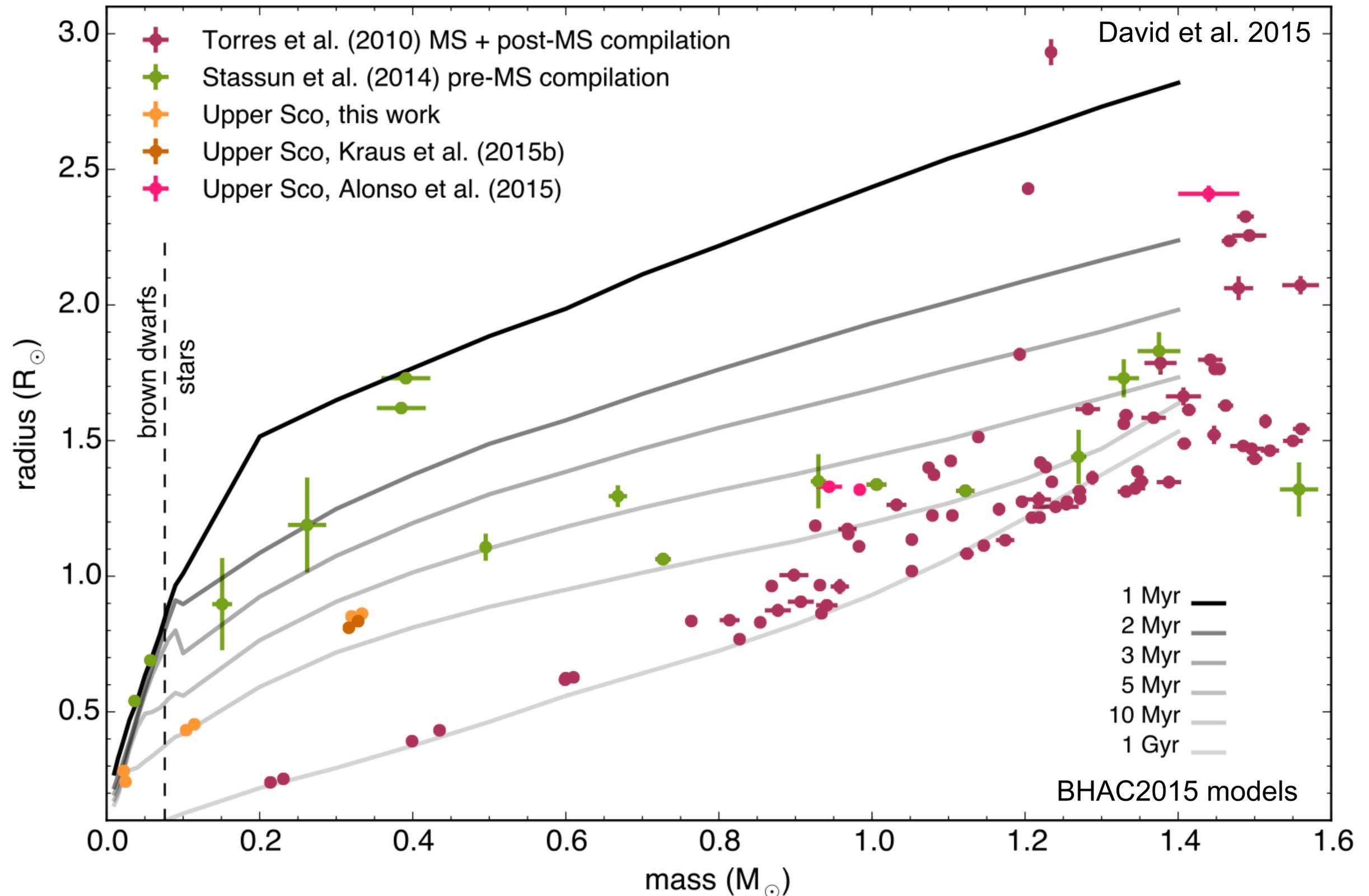
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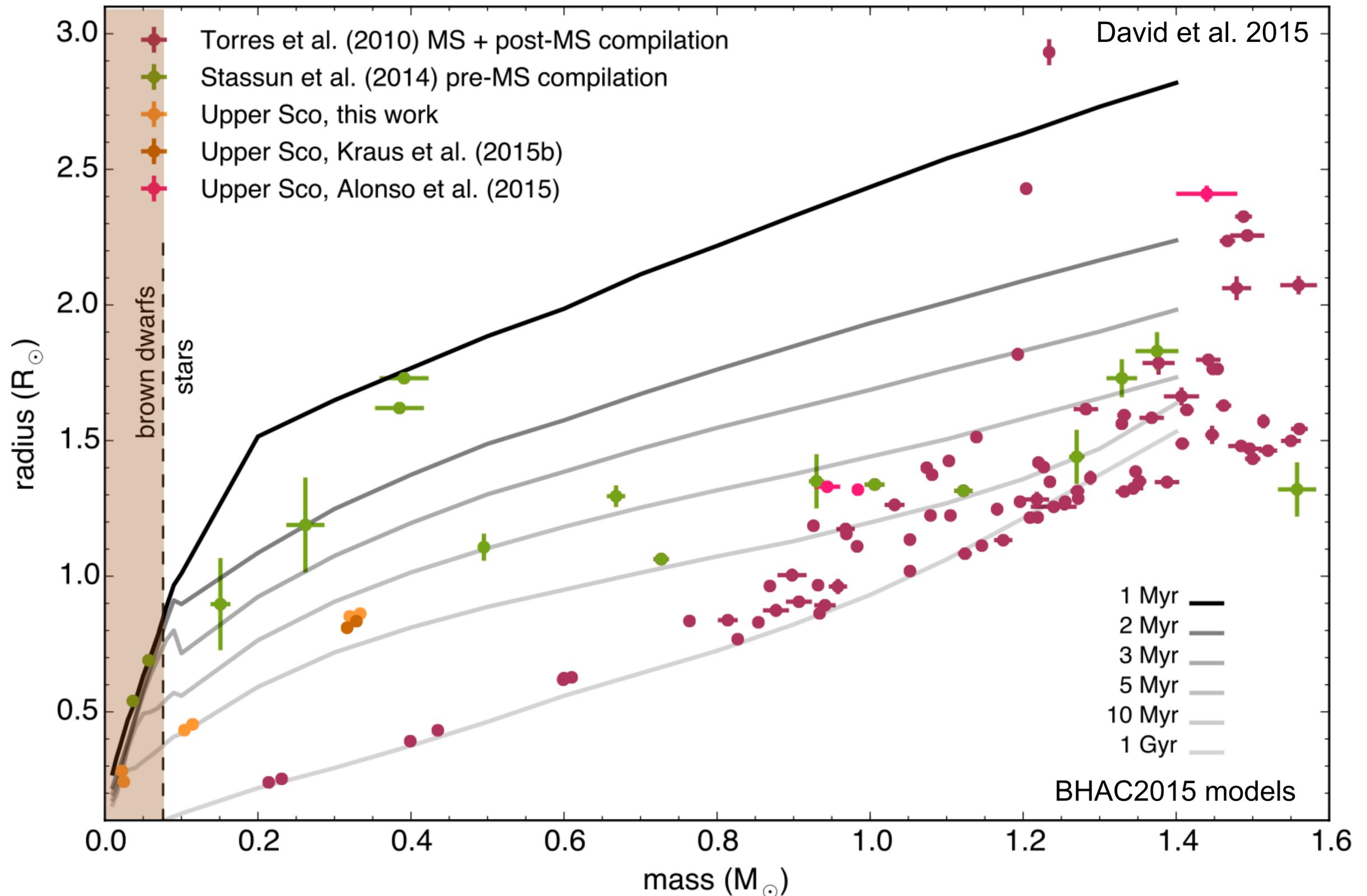
# **Model-independent masses and radii of brown dwarfs**

# There are only 2 (+2?) model-independent BD mass and radius measurements anchoring evolution models



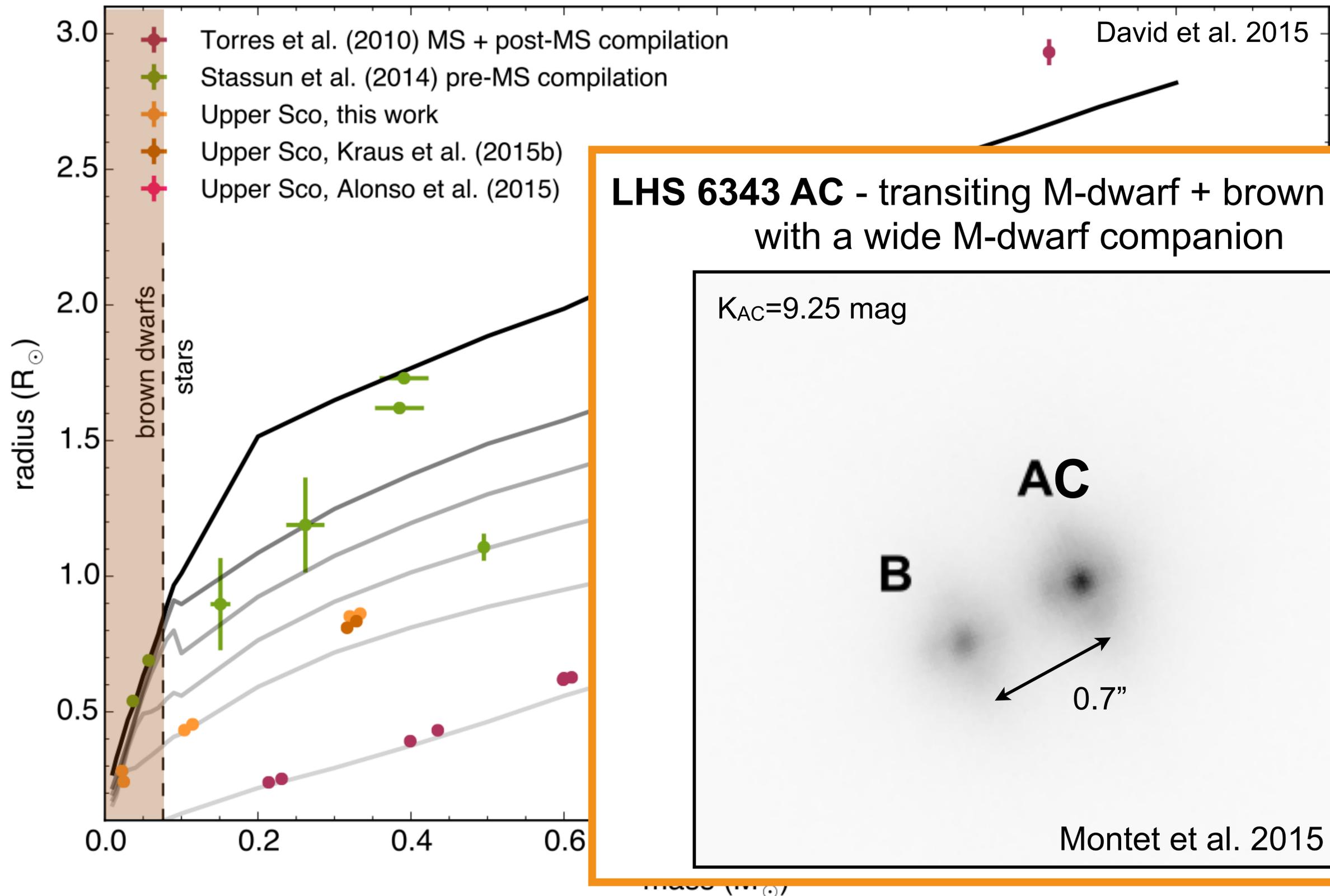
**Light curve:**  $P, i, e \cos \omega, R_1/a, R_2/a$ ; **RV curve:**  $K_1, K_2, e \sin \omega$   
 $K_1, K_2, i, e \Rightarrow M_1, M_2, a$ ;  $R_1/a, R_2/a, a \Rightarrow R_1, R_2$ ;  $T_{\text{eff}1}, T_{\text{eff}2}, R_1, R_2 \Rightarrow L_1, L_2, D$

# There are only 2 (+2?) model-independent BD mass and radius measurements anchoring evolution models



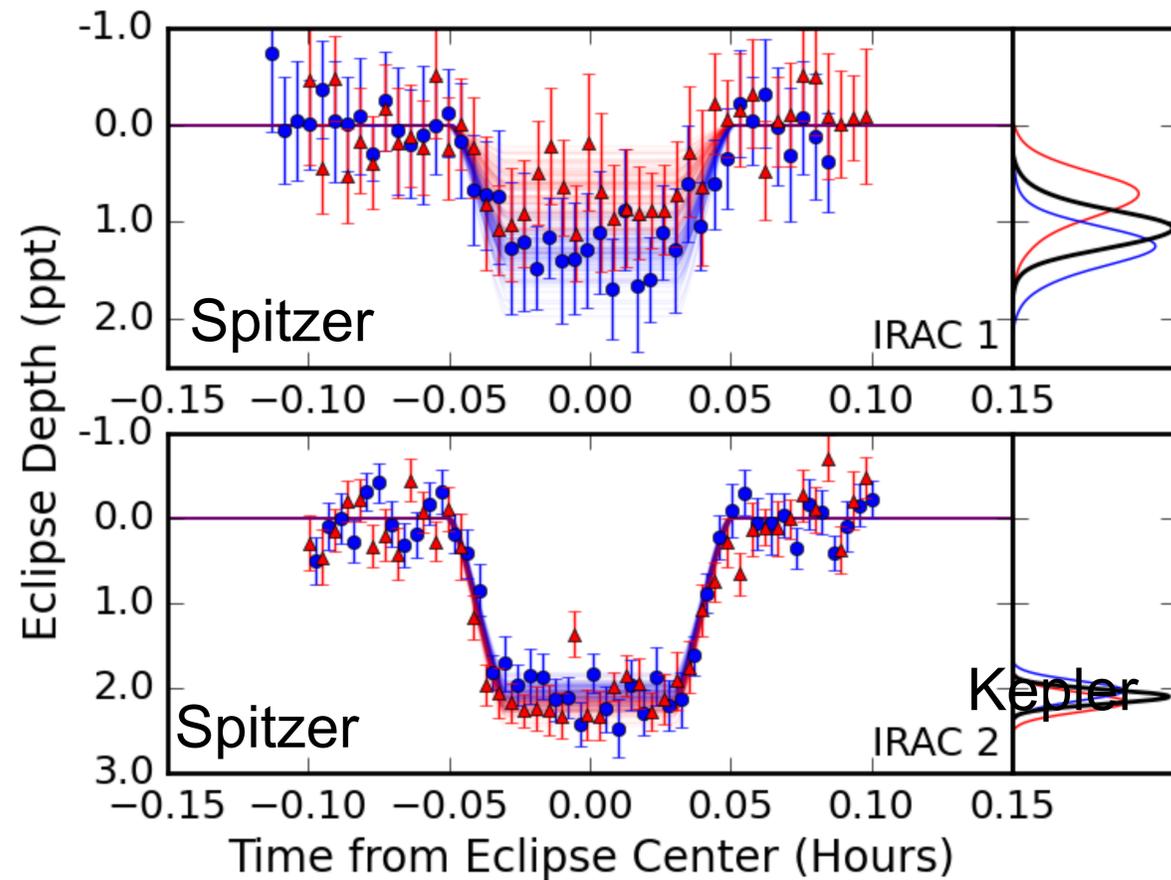
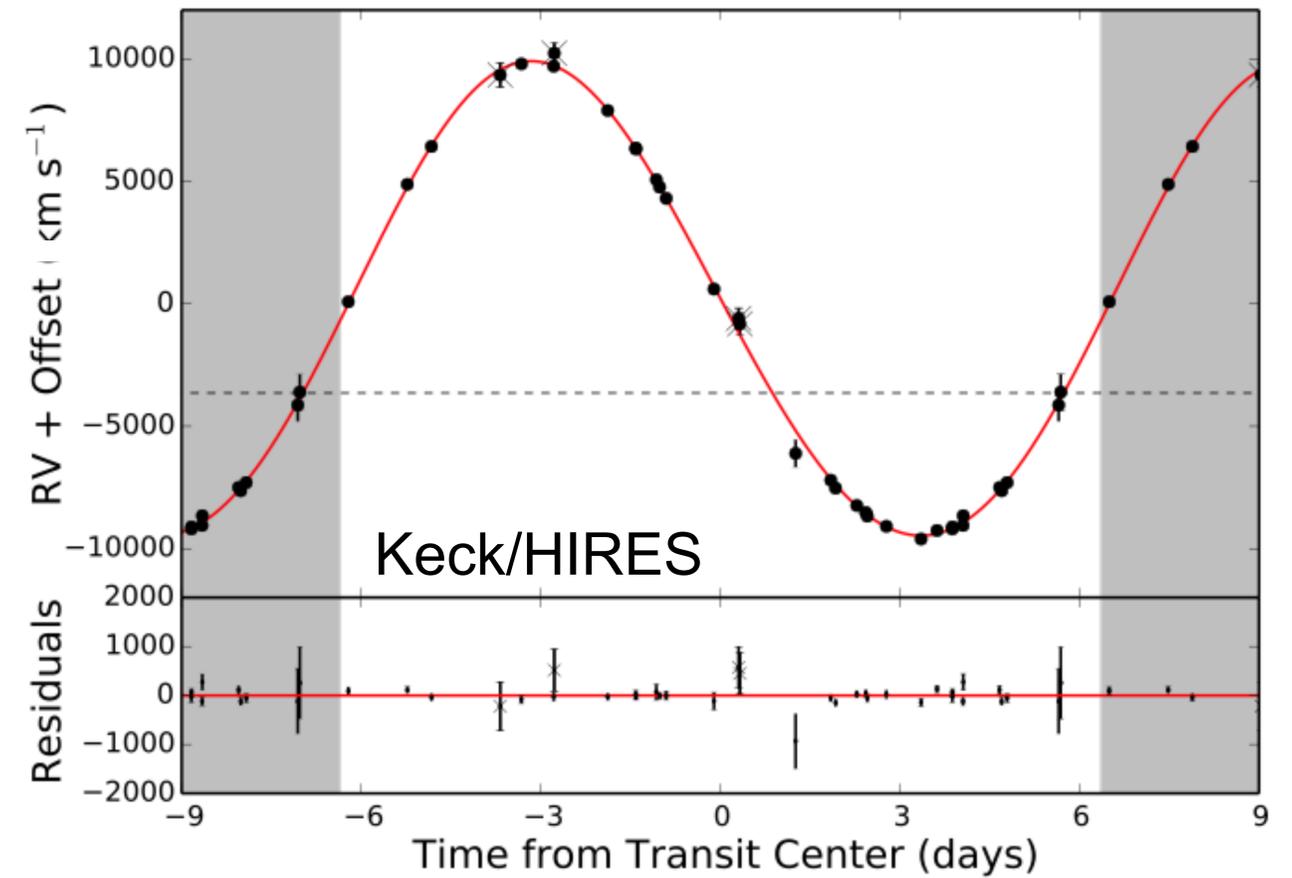
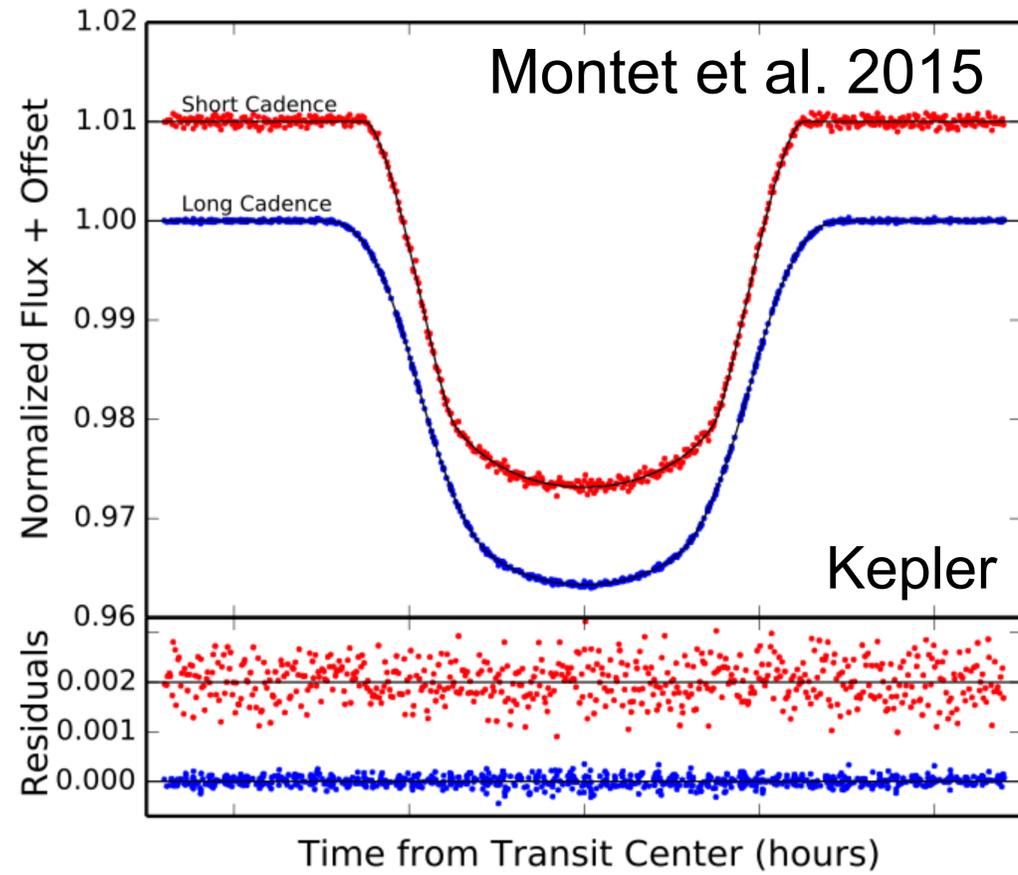
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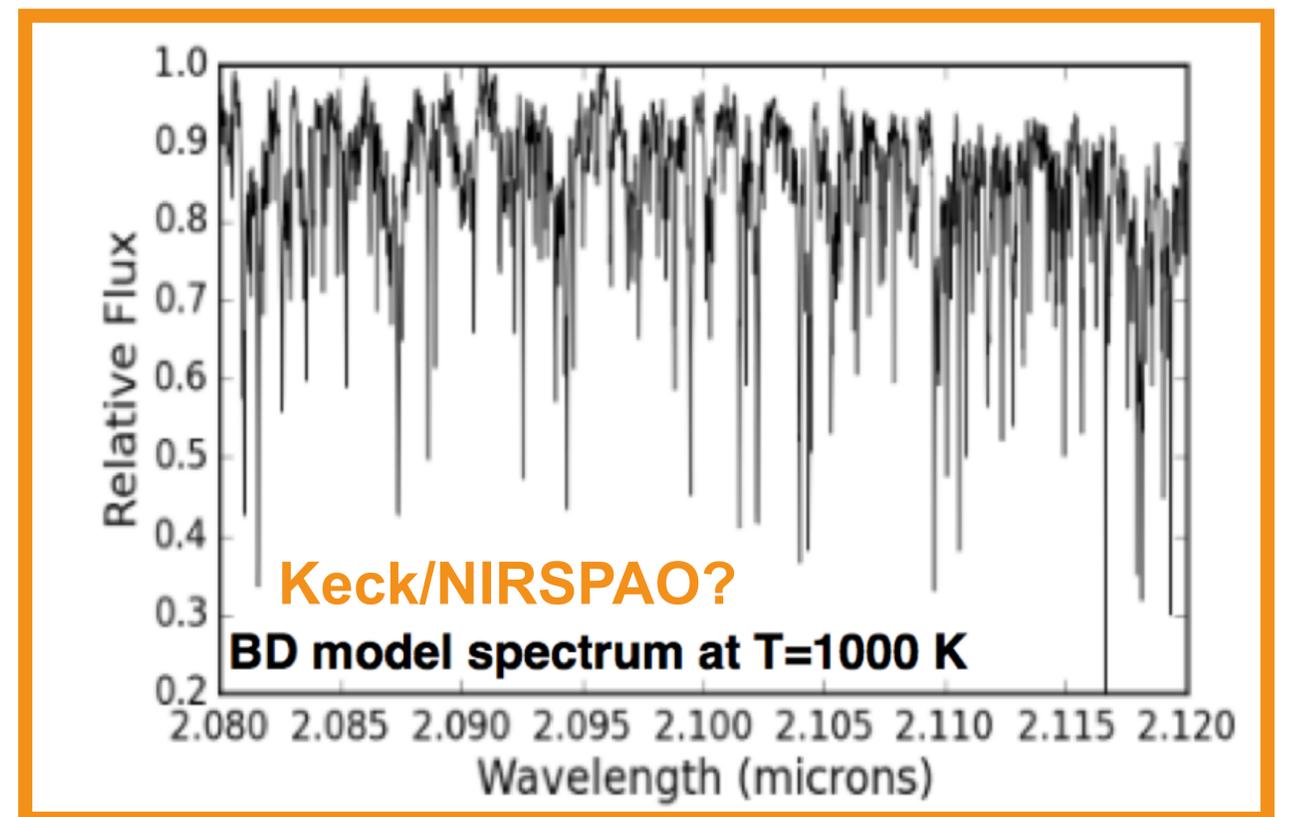
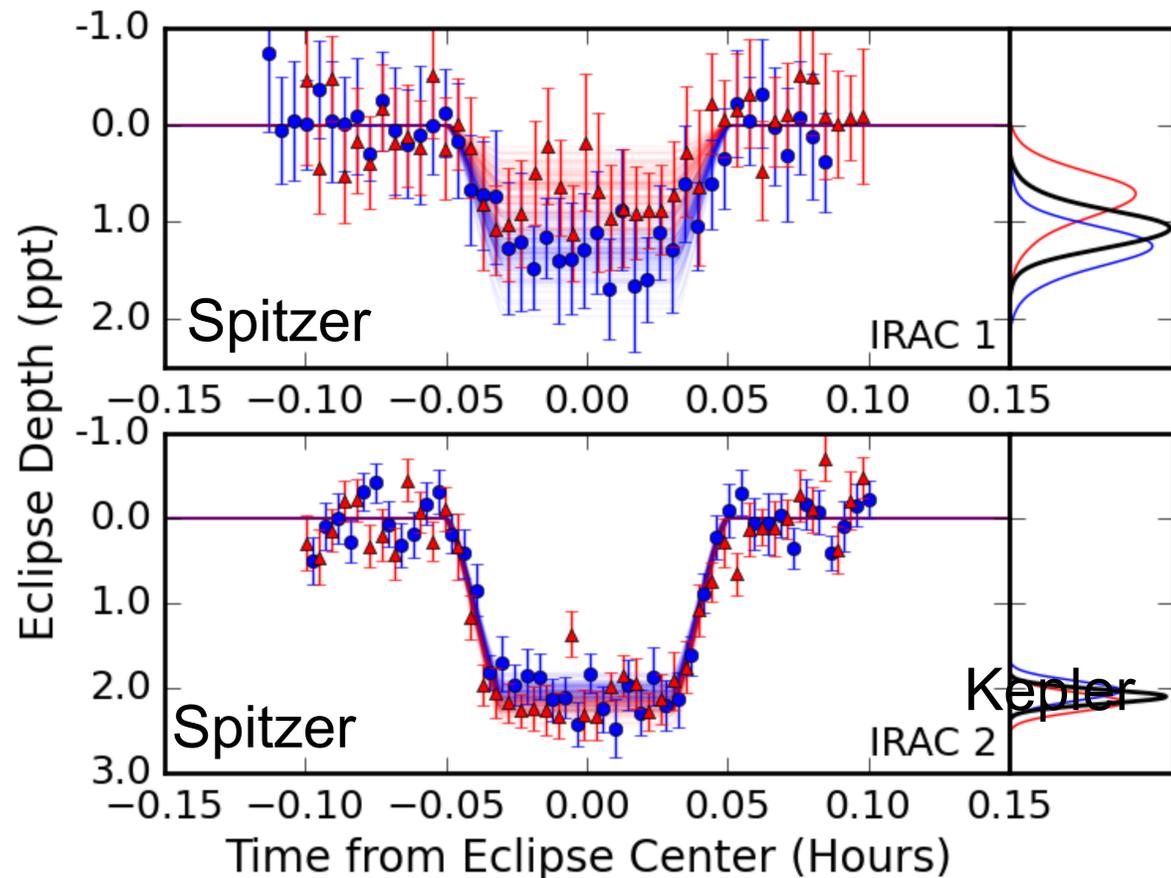
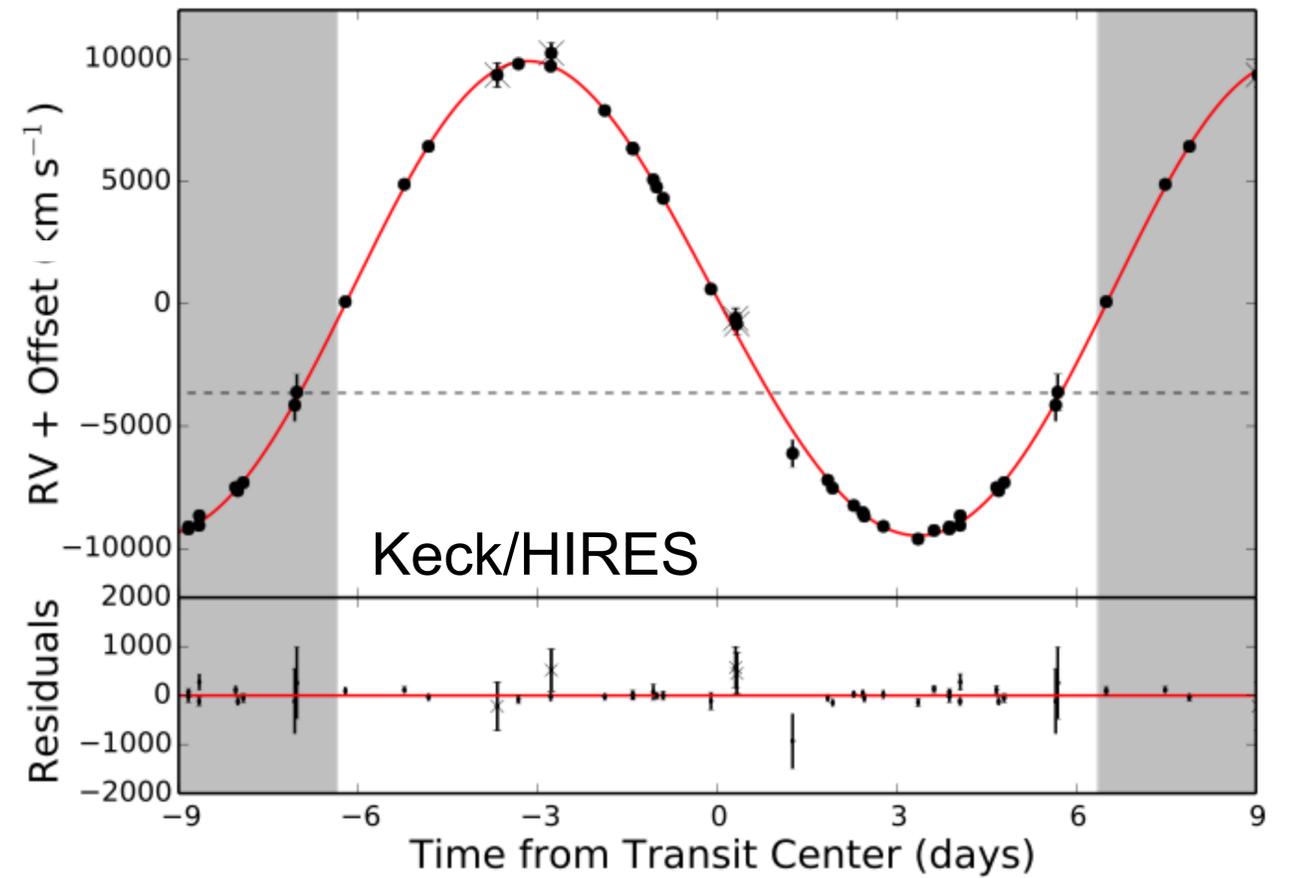
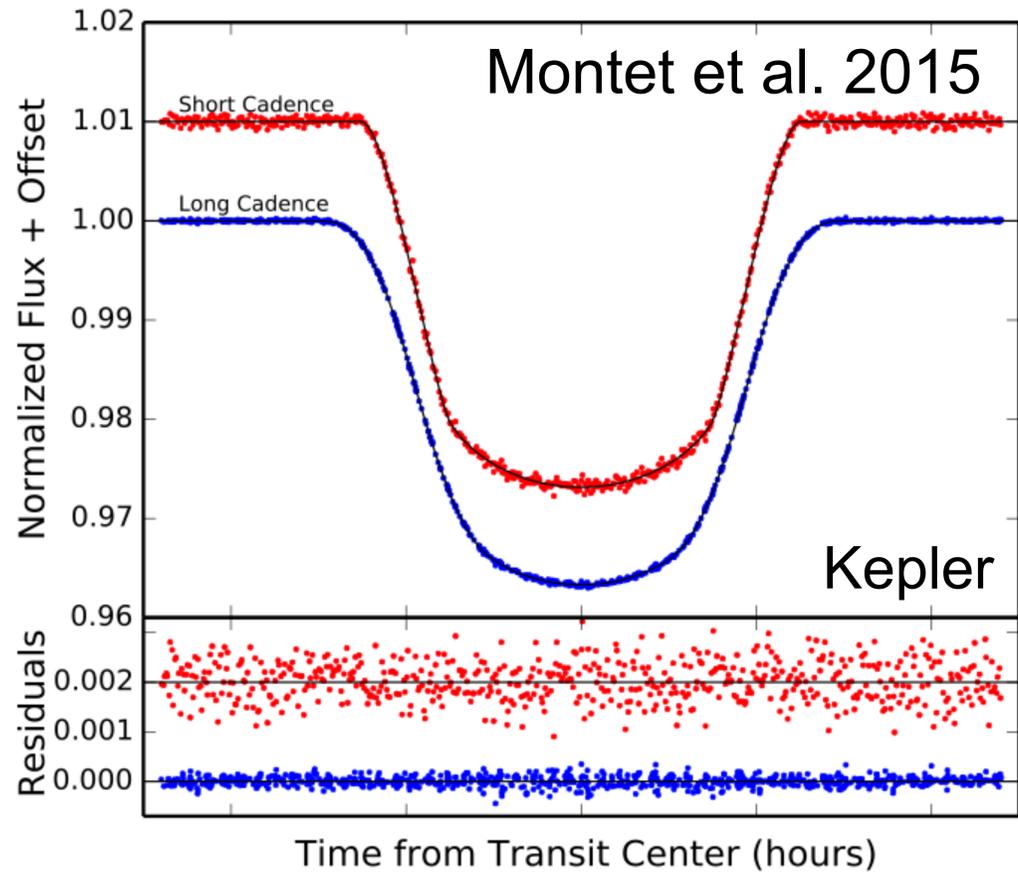


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# Transiting brown dwarfs converted into eclipsing double-lined spectroscopic binaries with HDS



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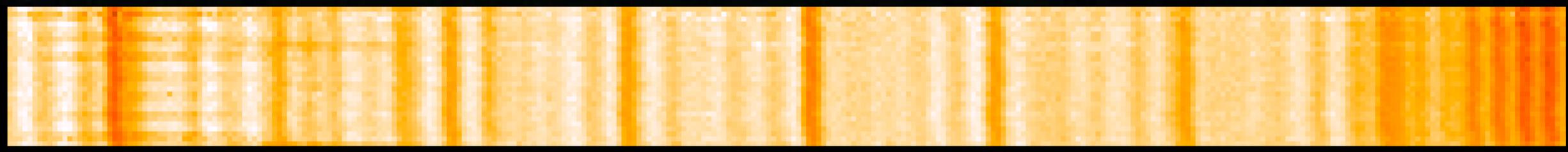


*Oh El Niño...*



Wavelength

Time



**NIRSPA0/Keck II spectra, 2-3  $\mu\text{m}$**

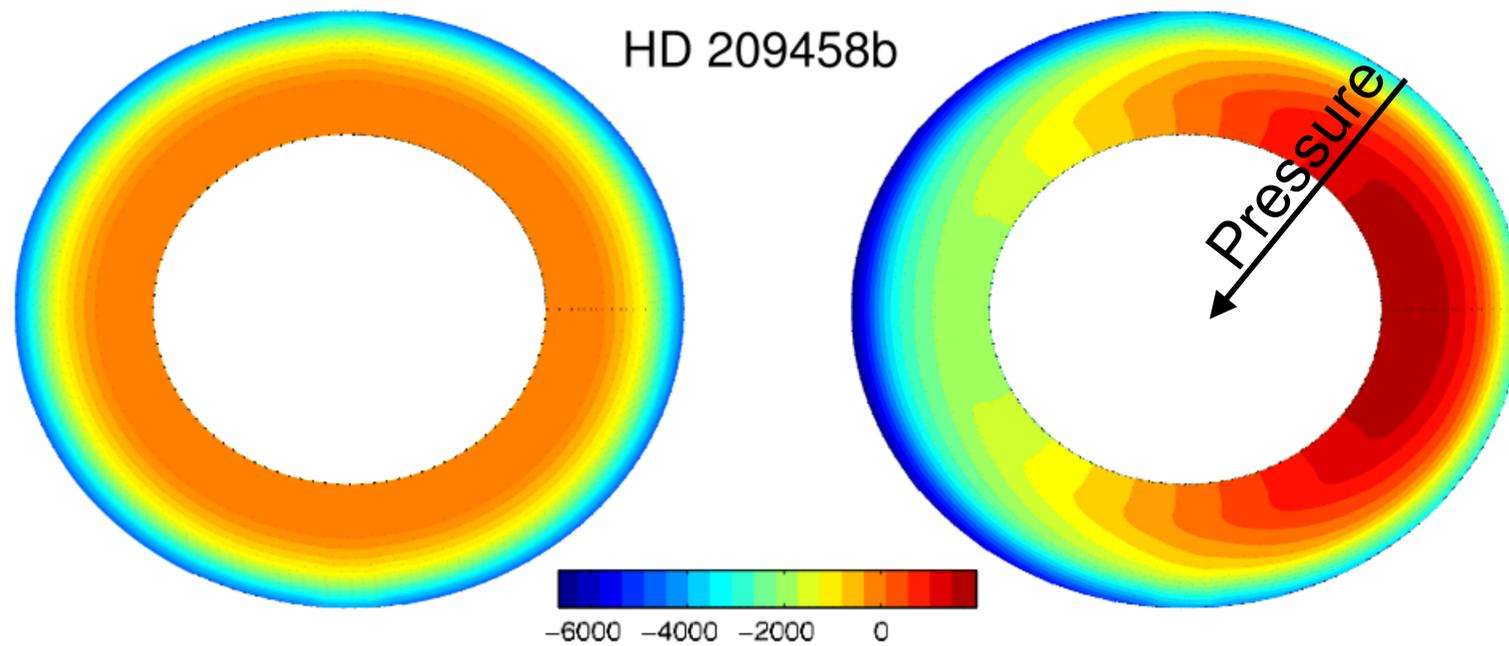
# **Rotation and winds in exoplanet atmospheres**

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

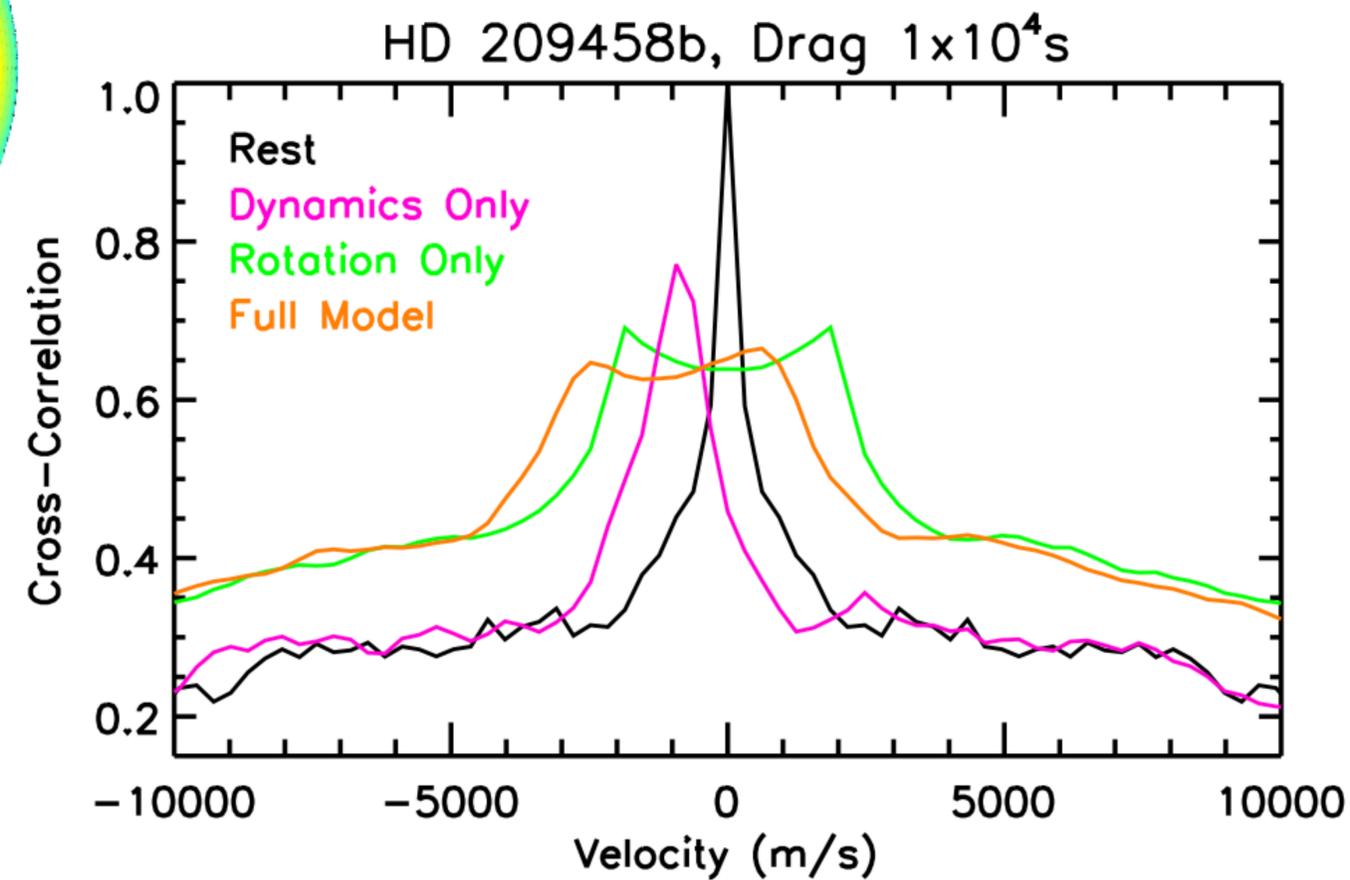
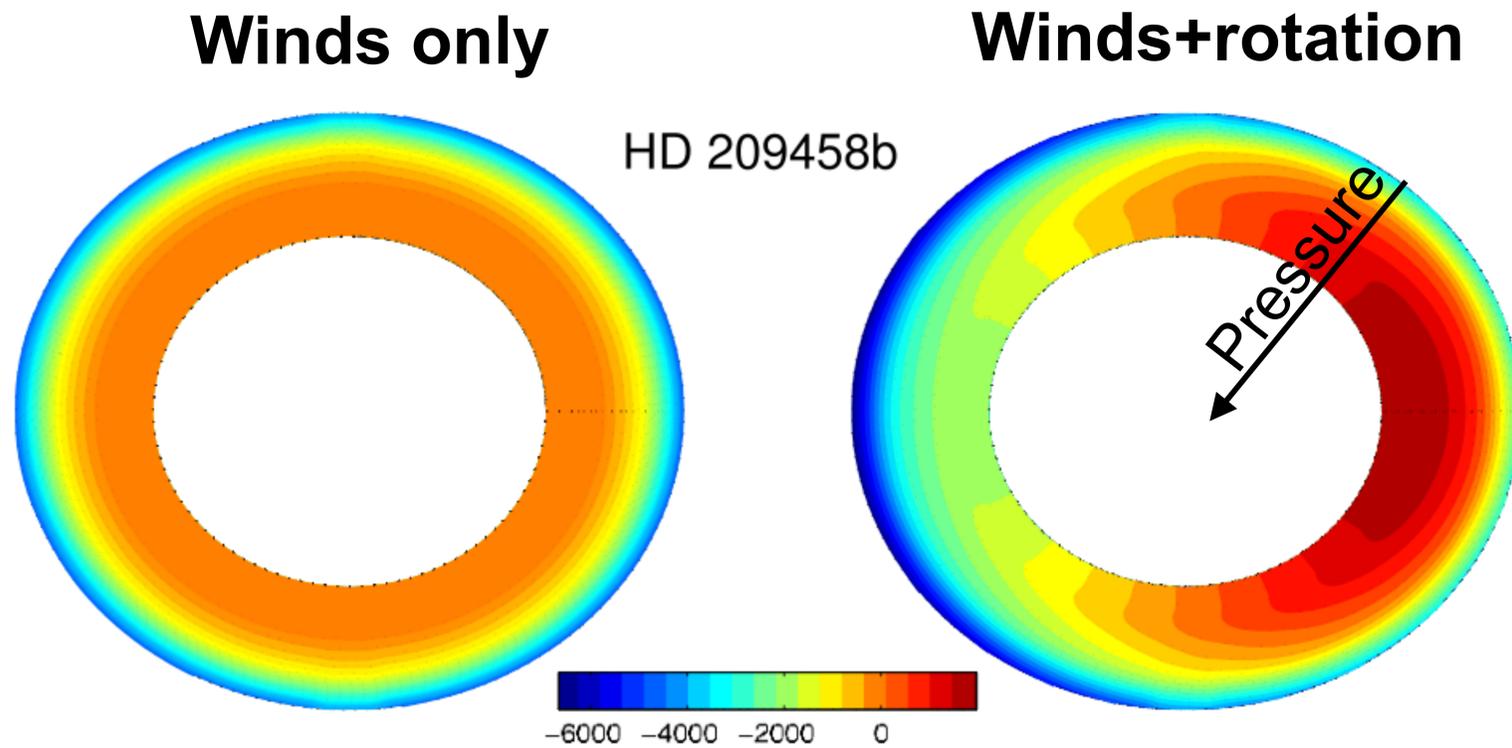
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**Winds only**

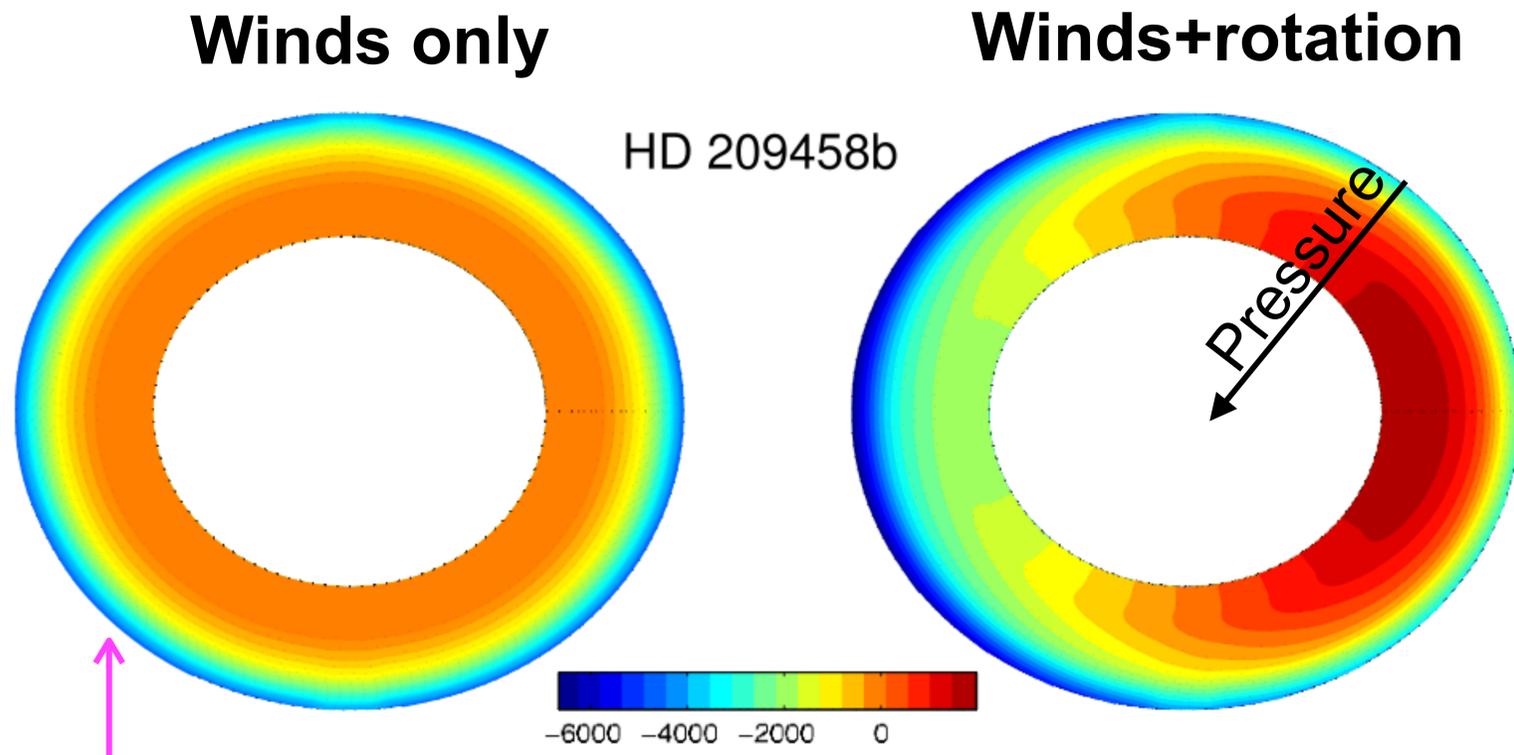
**Winds+rotation**



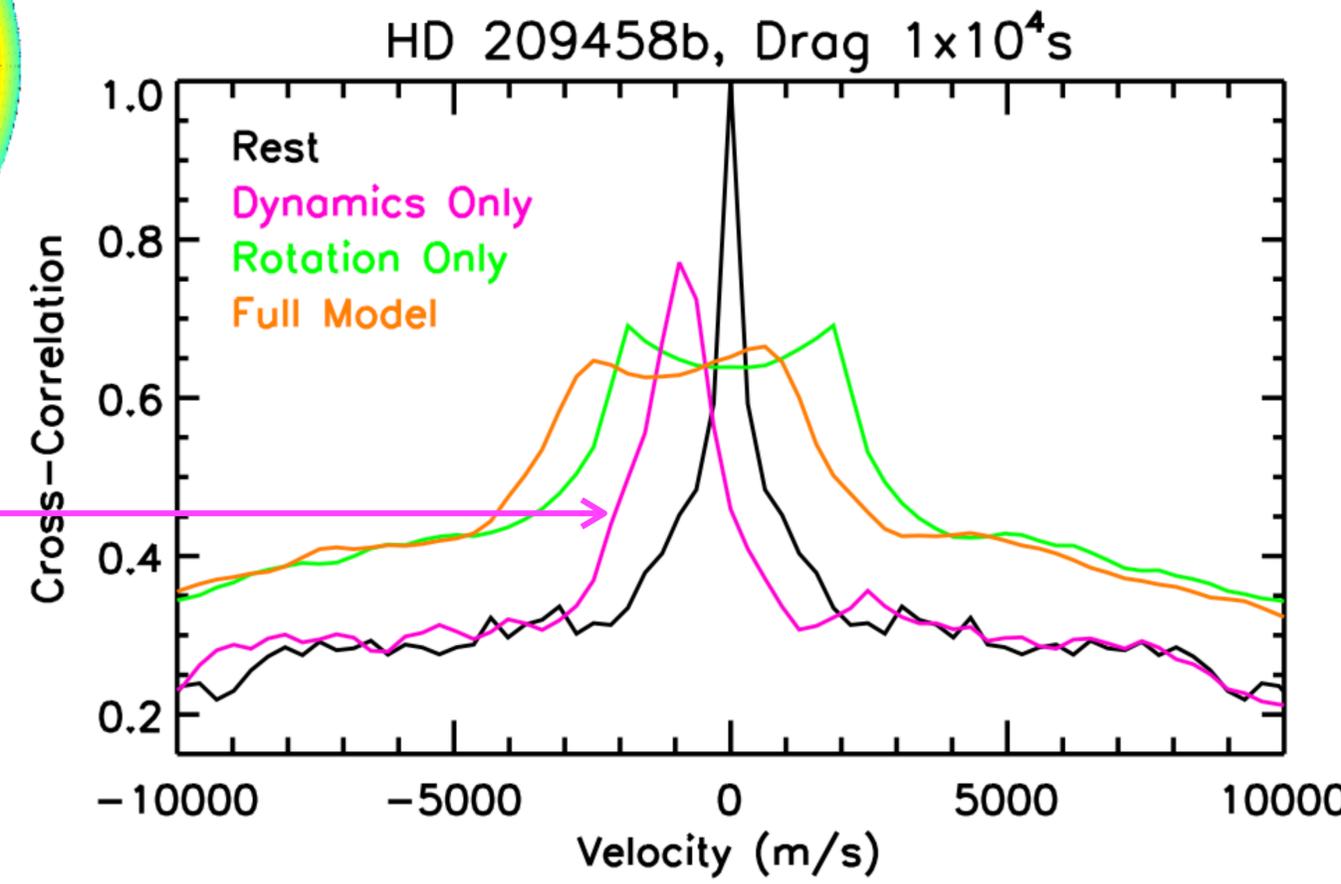
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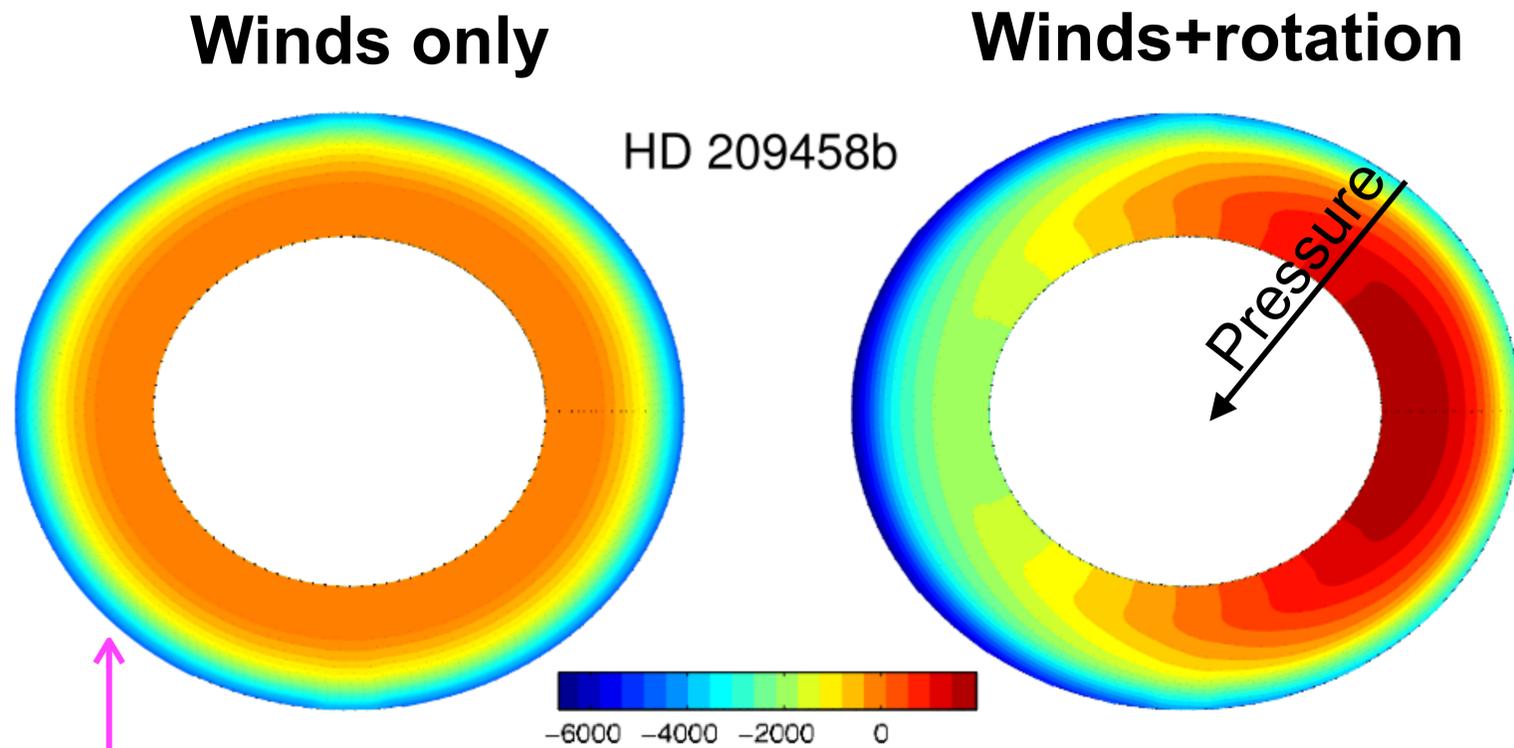
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Winds blue-shift entire upper atmosphere

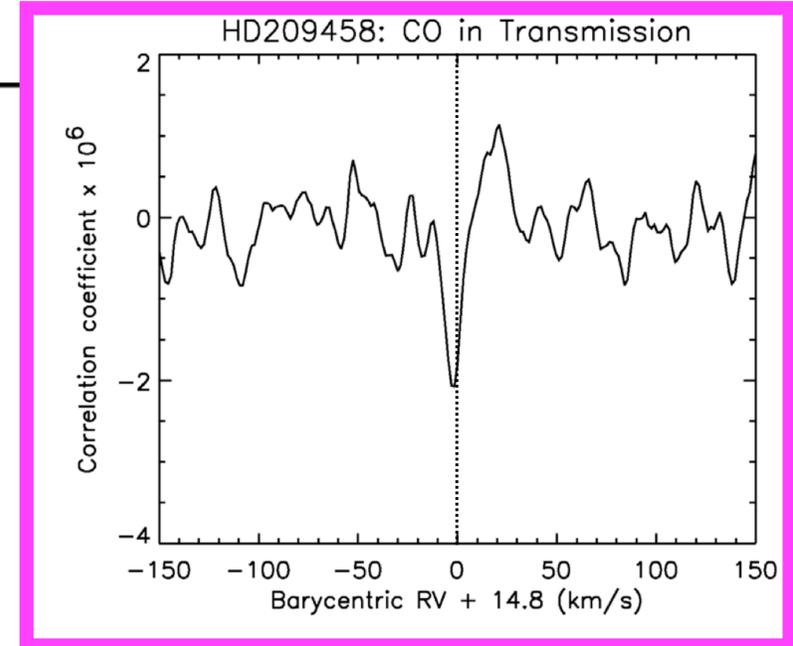
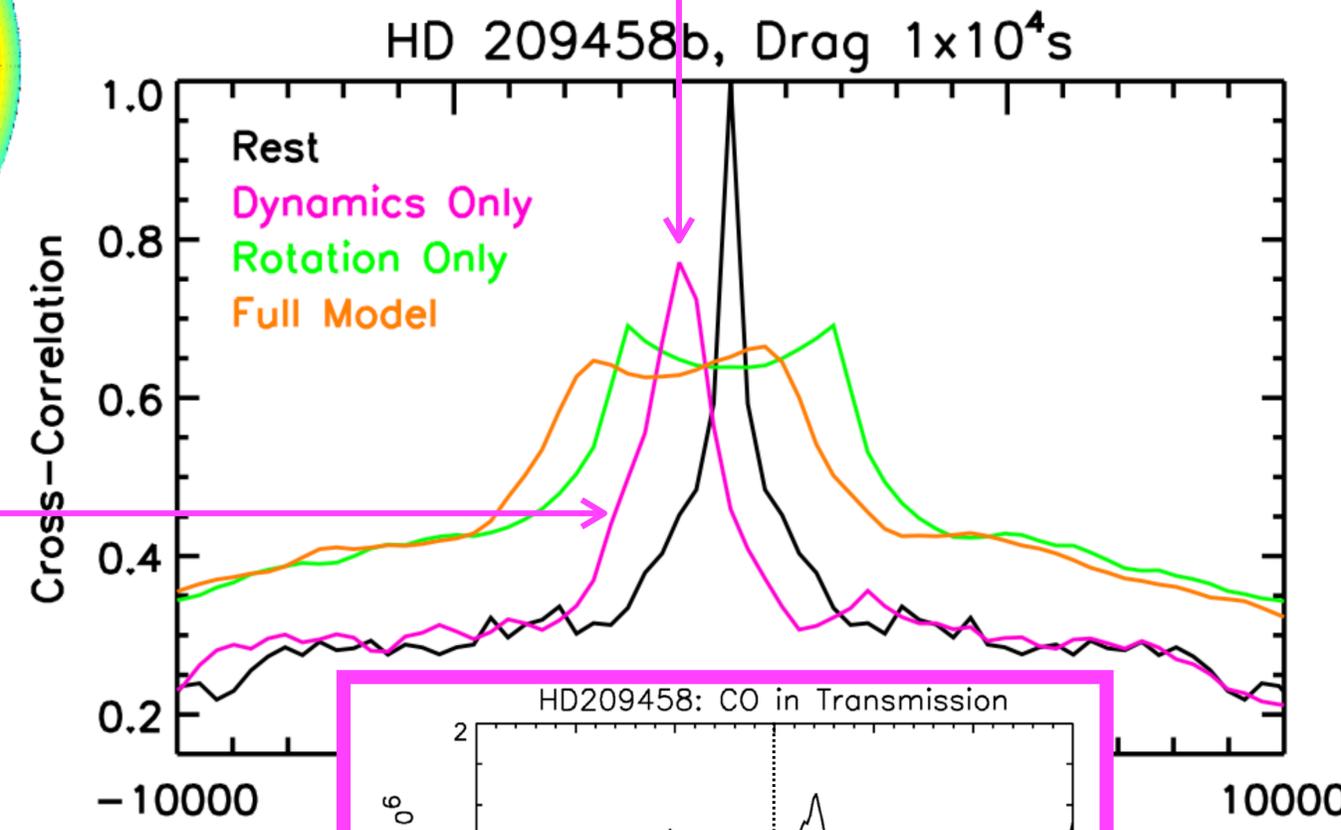


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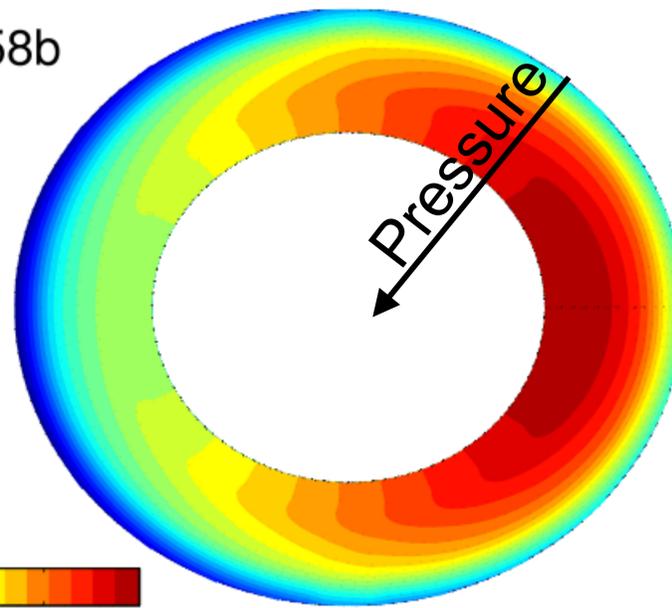
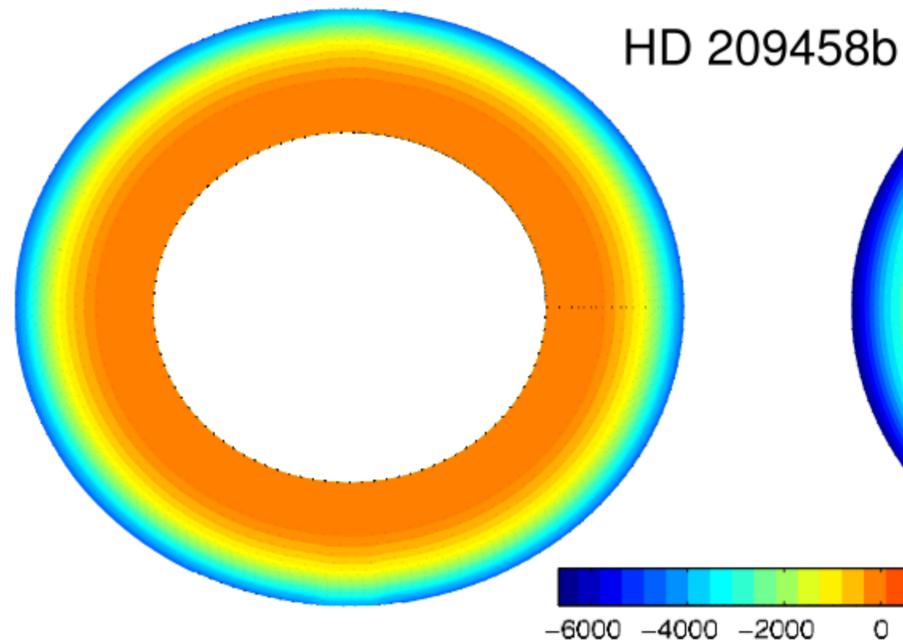
Wind shift observed in HD 209458 b at  $-2 \pm 1$  km/s (Snellen et al. 2010)



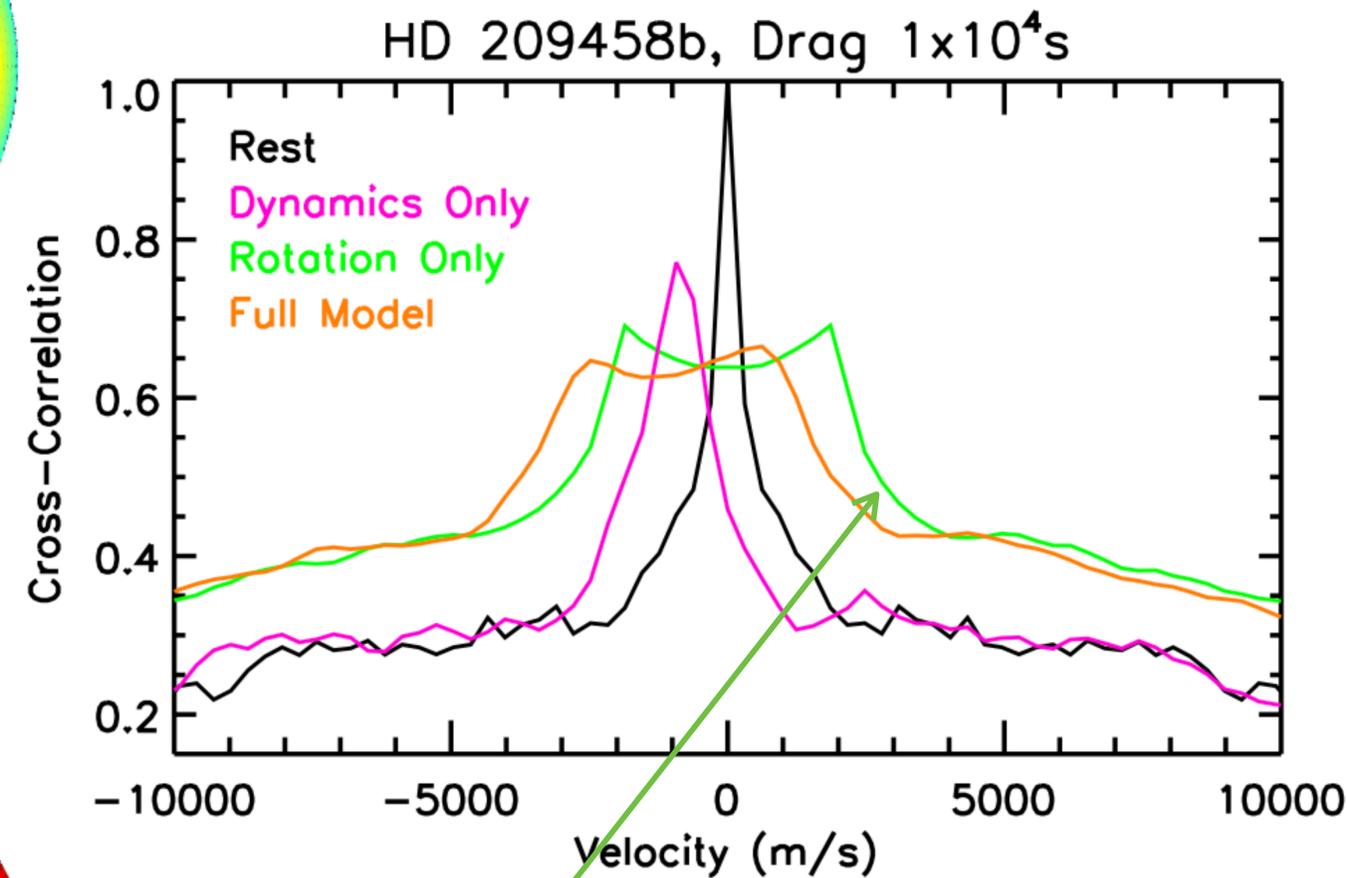
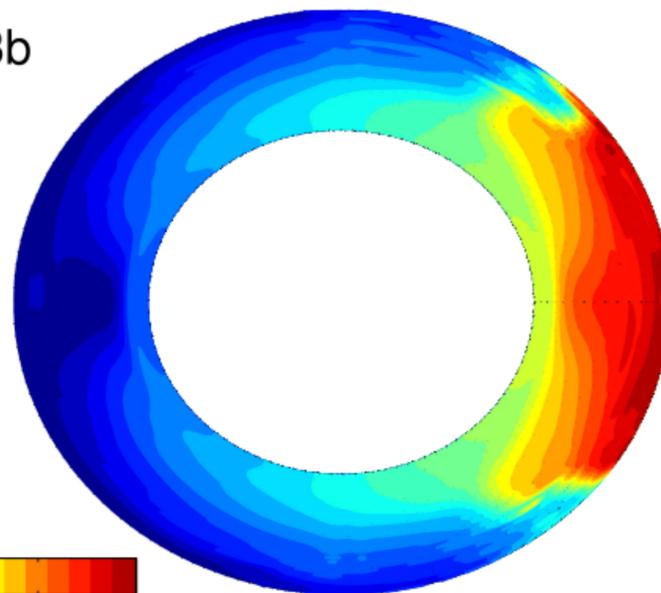
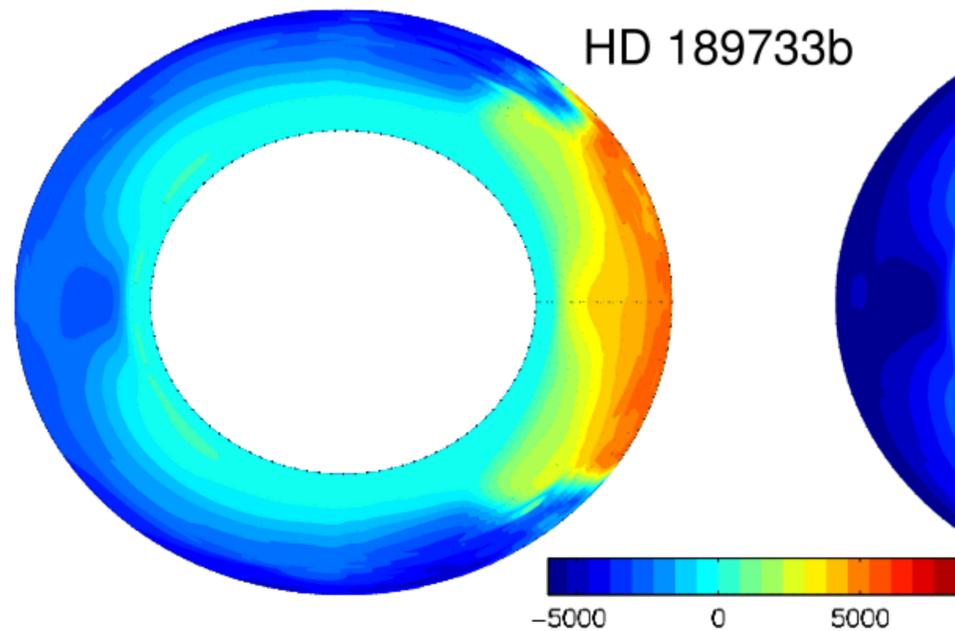
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**Winds only**

**Winds+rotation**



HD 189733b

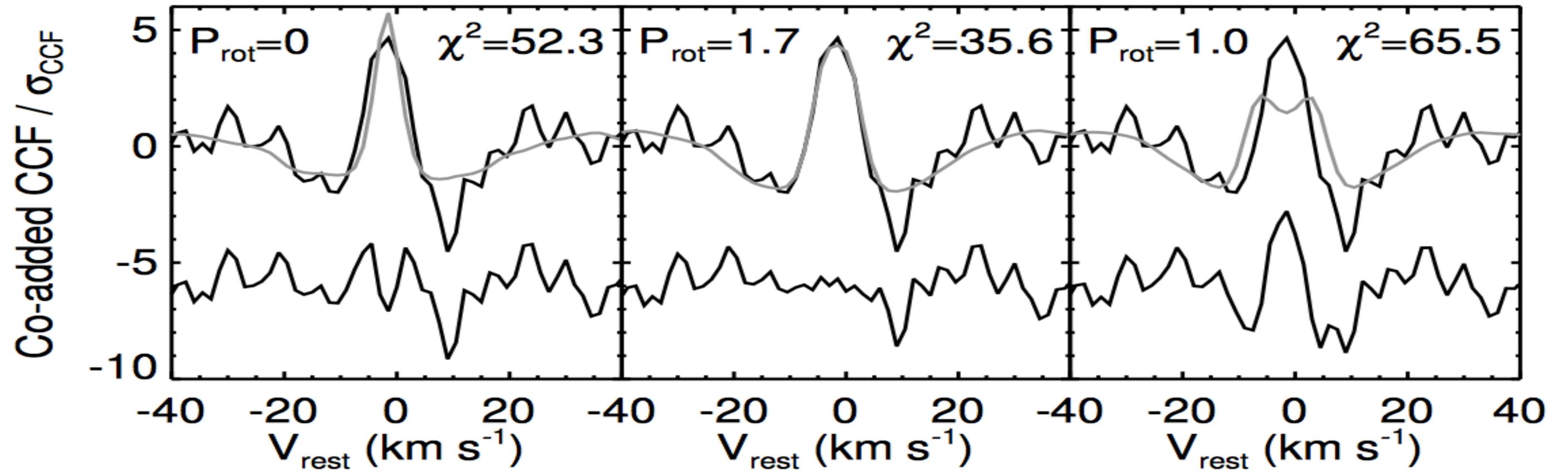


Rotation creates double-peaked line profile

Are hot Jupiters tidally locked?  
Brogi et al. 2016

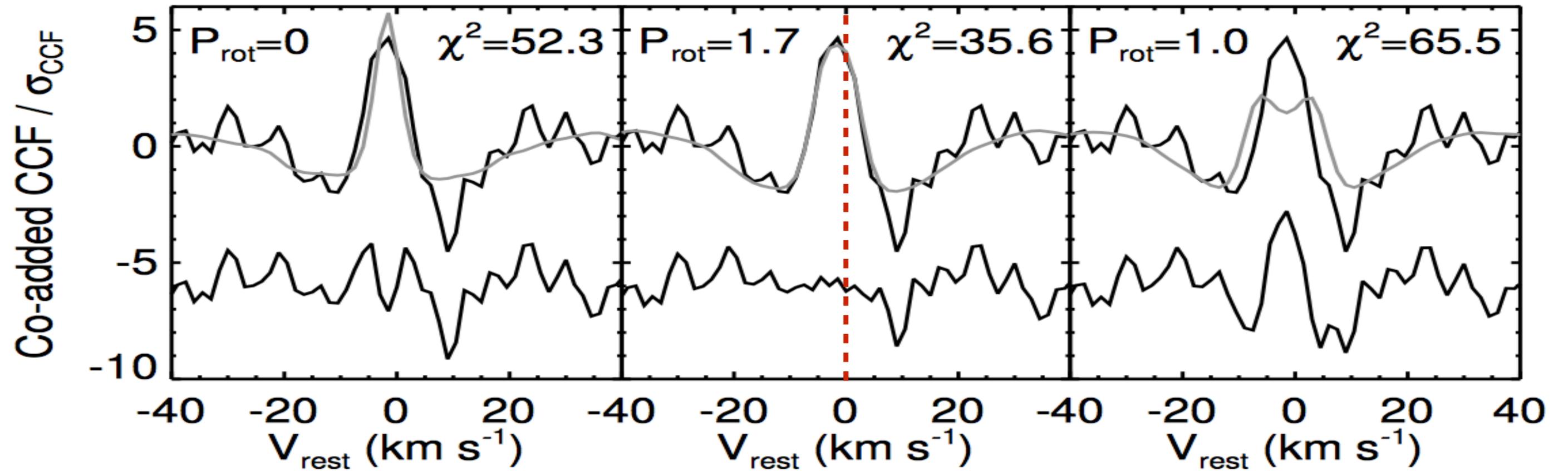
# Rotation period of HD 189733 b consistent with a tidally-locked planet

CRIRES infrared transit spectra (Brogi, de Kok, Albrecht, Snellen, Birkby, Schwarz 2016)



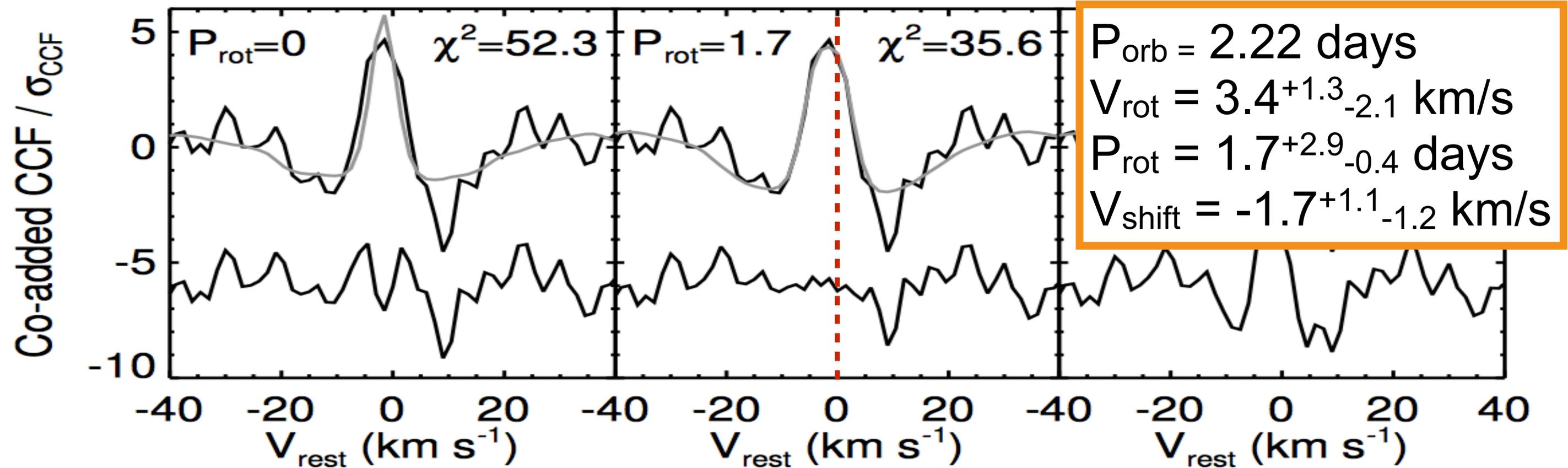
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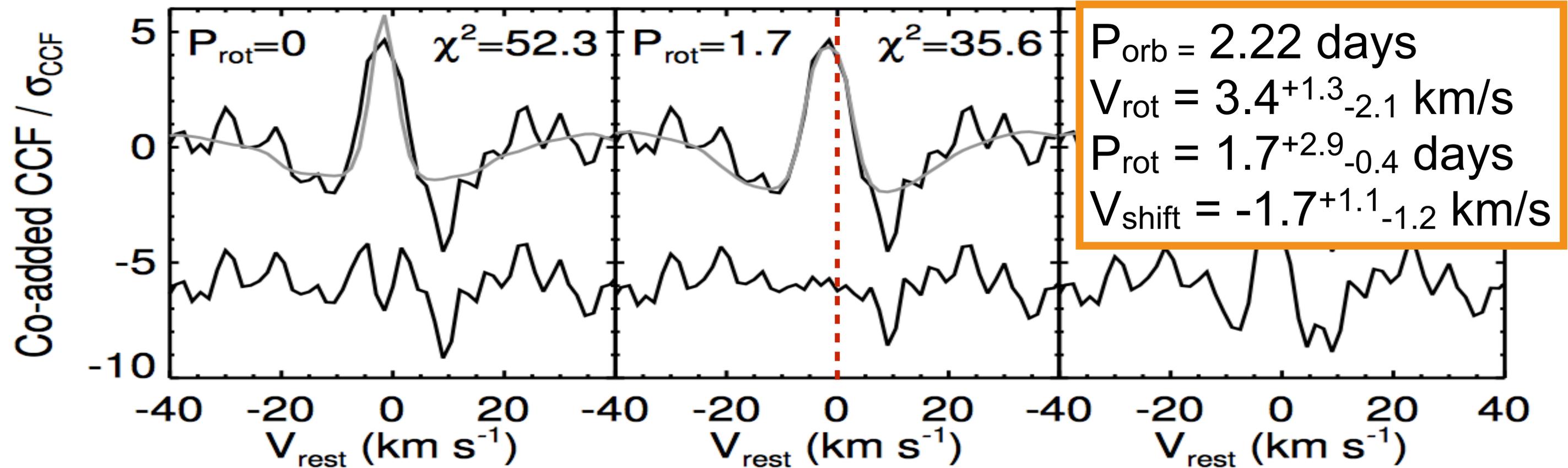
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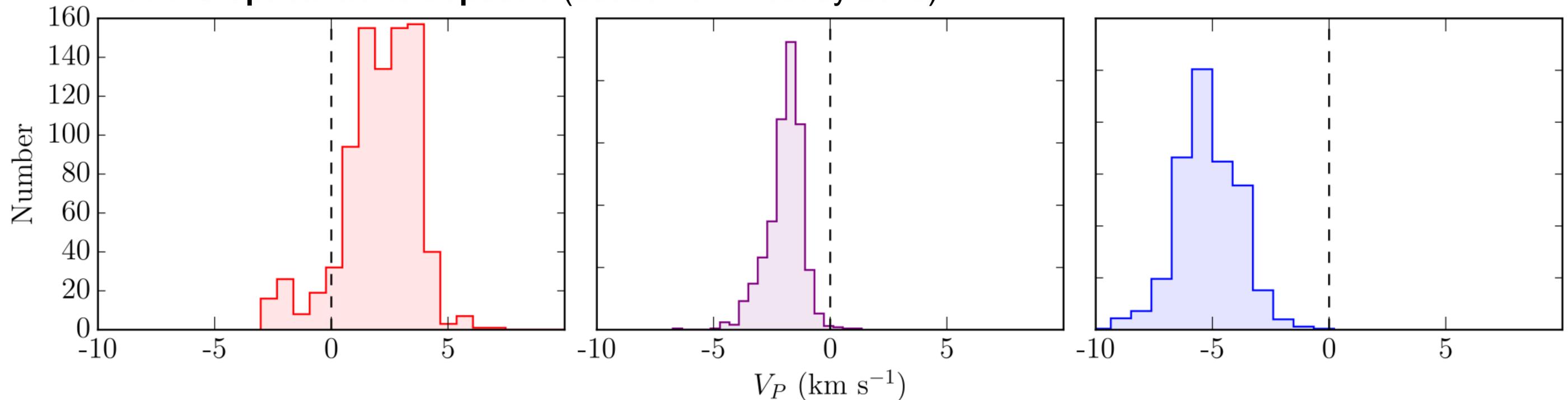


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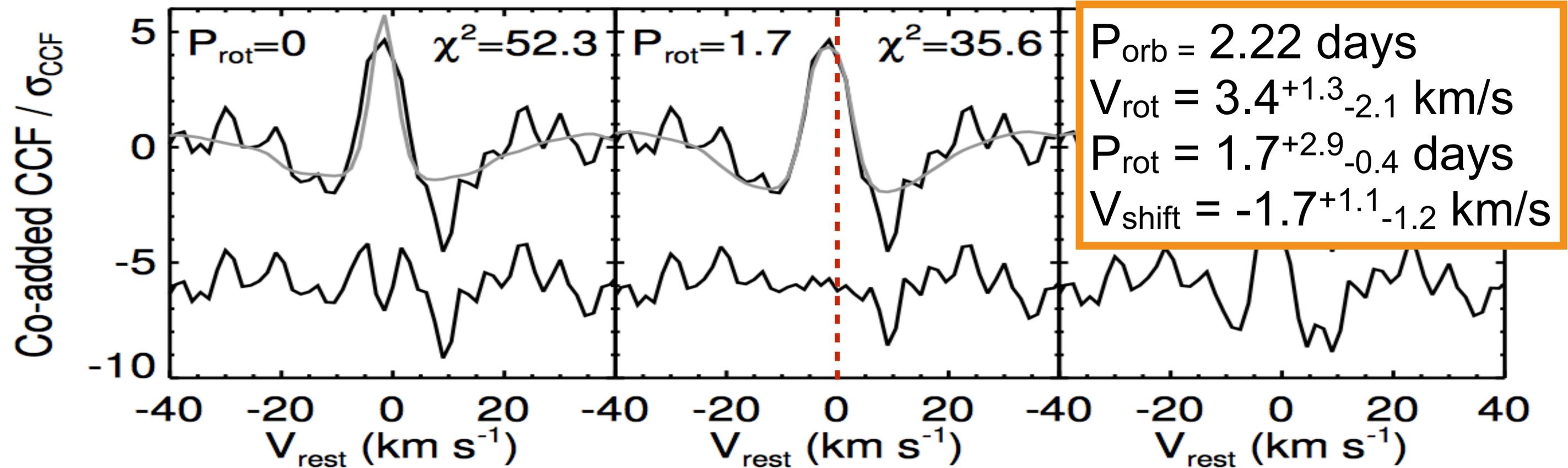


HARPS optical transit spectra (Louden & Wheatley 2015)

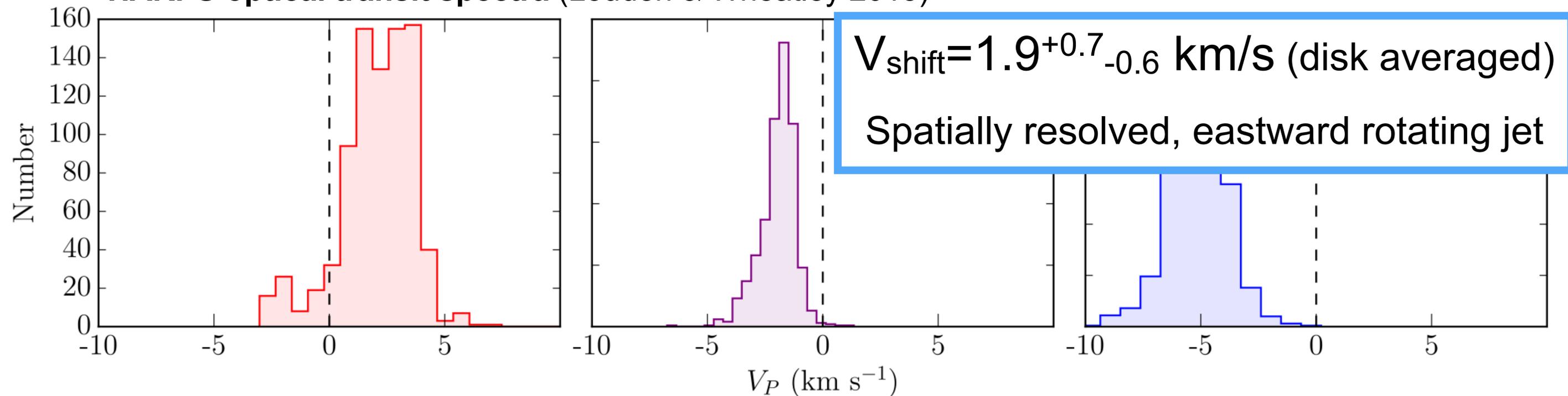


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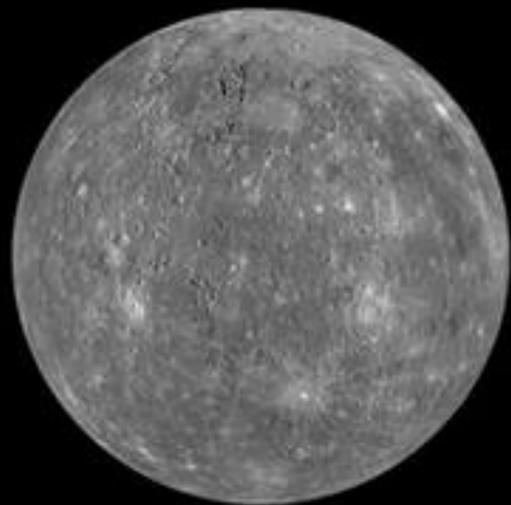


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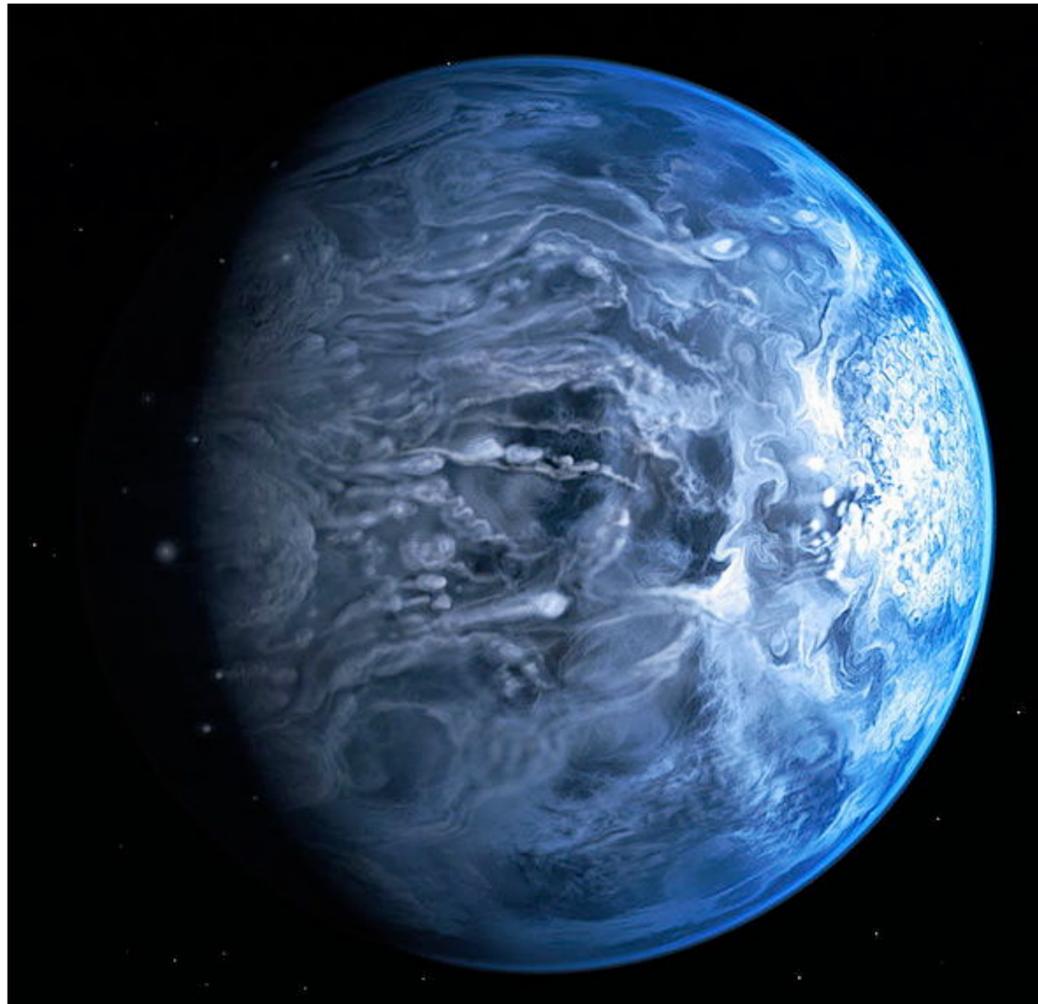




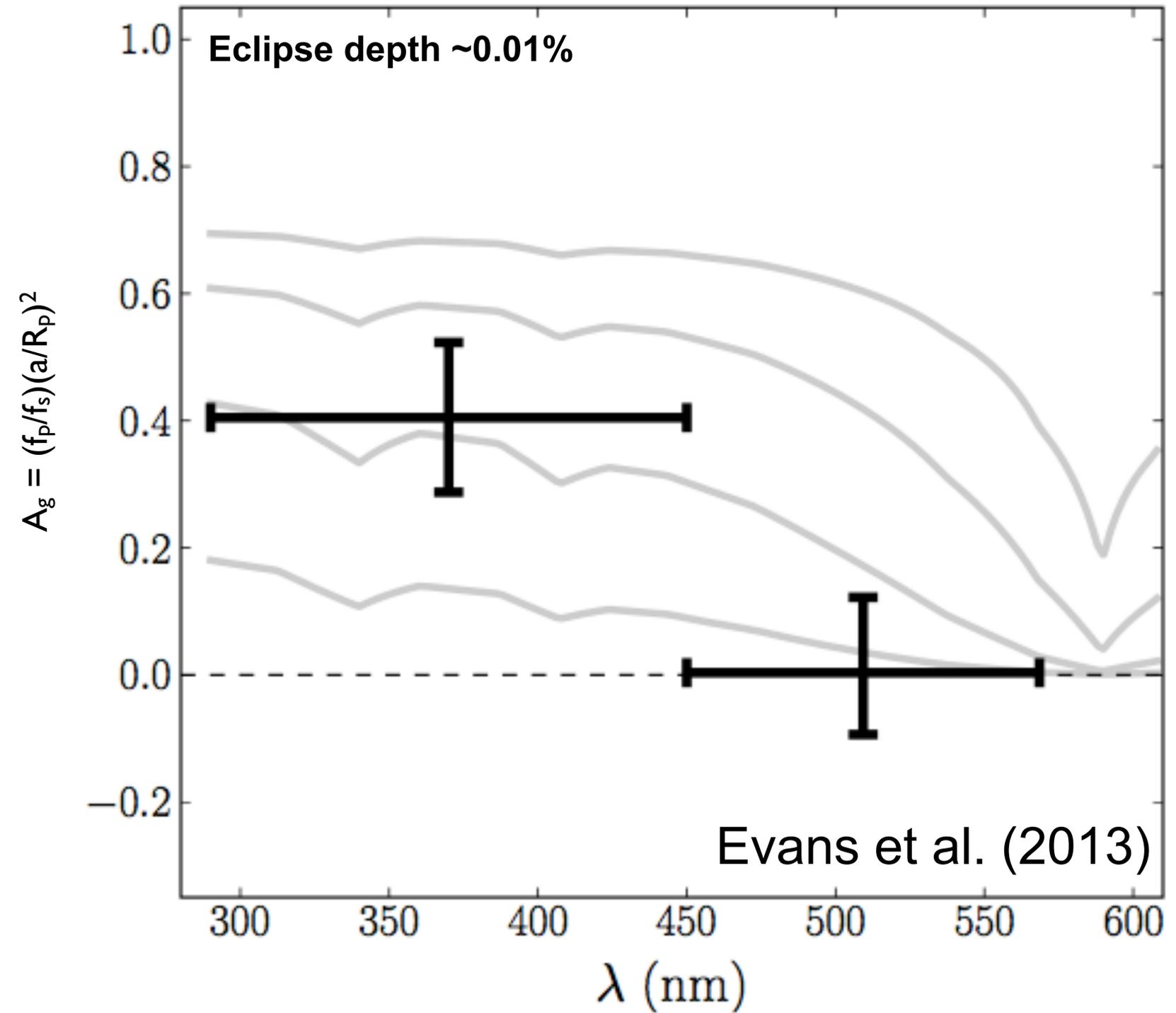
# **Exoplanets in Colour**



# Wavelength-dependency of reflected light varies with composition, structure, clouds, and dynamics



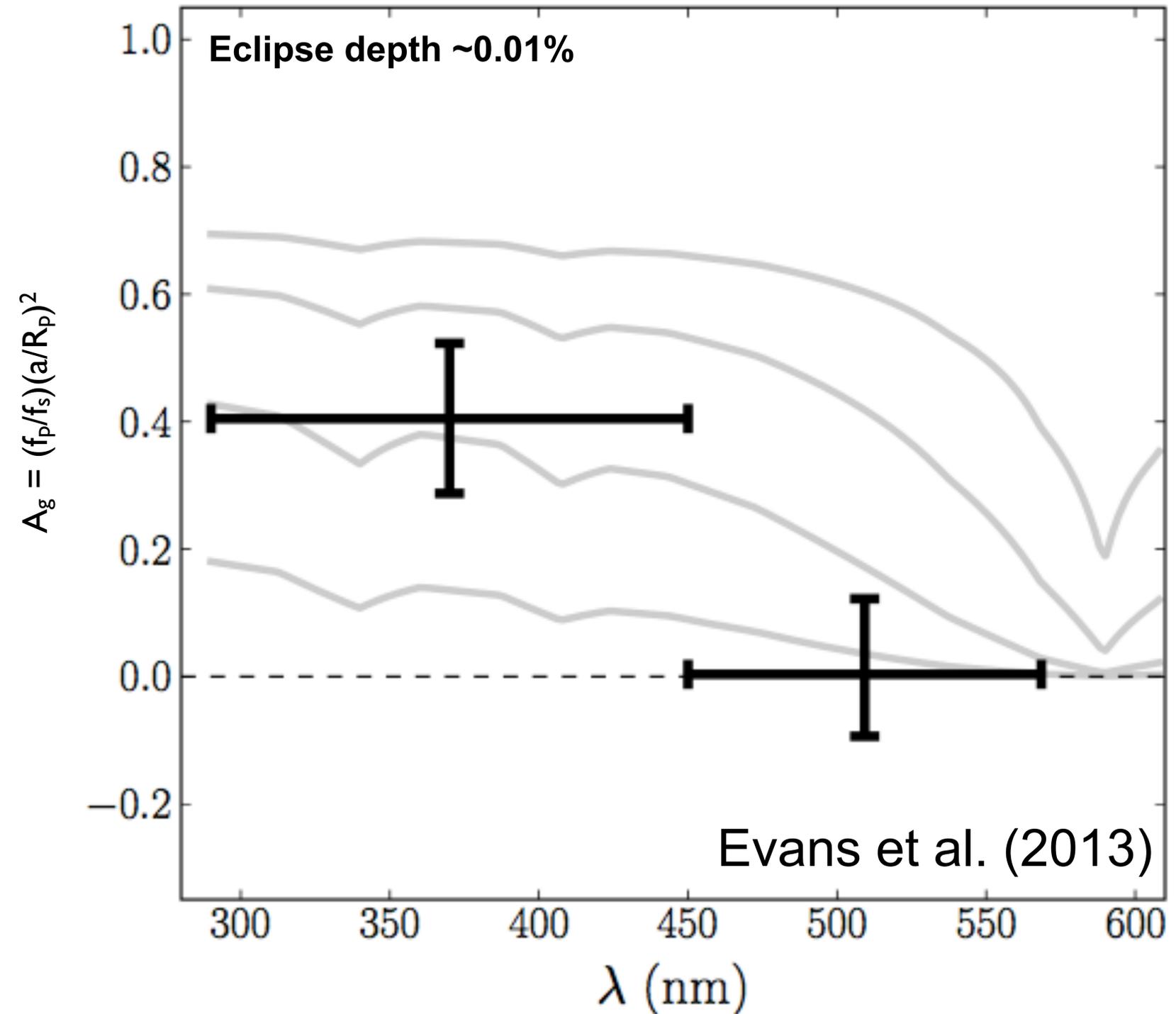
**HD 189733 b**



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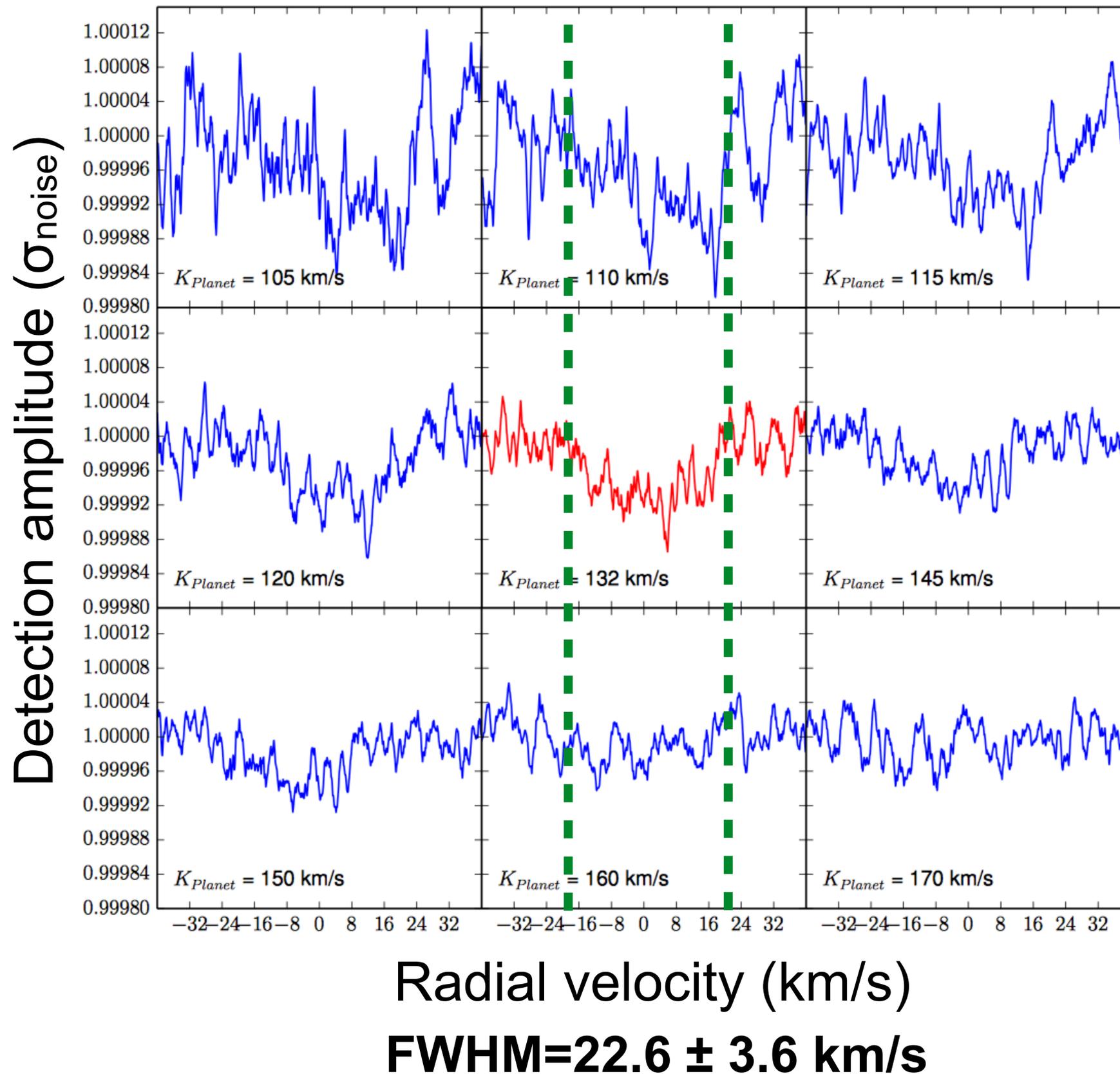
HD 189733 b



Use high-resolution spectroscopy to create 50nm binned albedo spectra with HARPS-N

# Tentative reflected light from 51 Peg b with HARPS suggesting highly inflated planet

3- $\sigma$  detection,  $A_g > 1$  for  $R_p = 1.2R_J$ ,  $A_g = 0.5$  assuming  $R_p = 1.9R_J$



# **New HARPS-N observations to measure moderate resolution albedo spectrum**

# New HARPS-N observations to measure moderate resolution albedo spectrum

**Preliminary reduction**

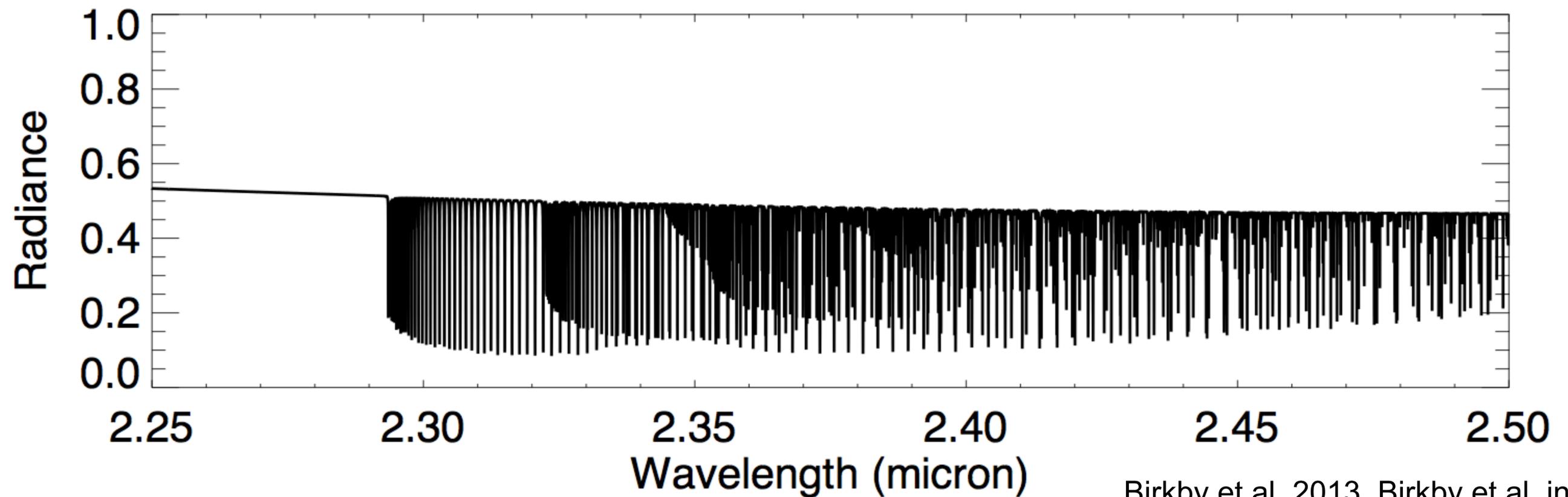
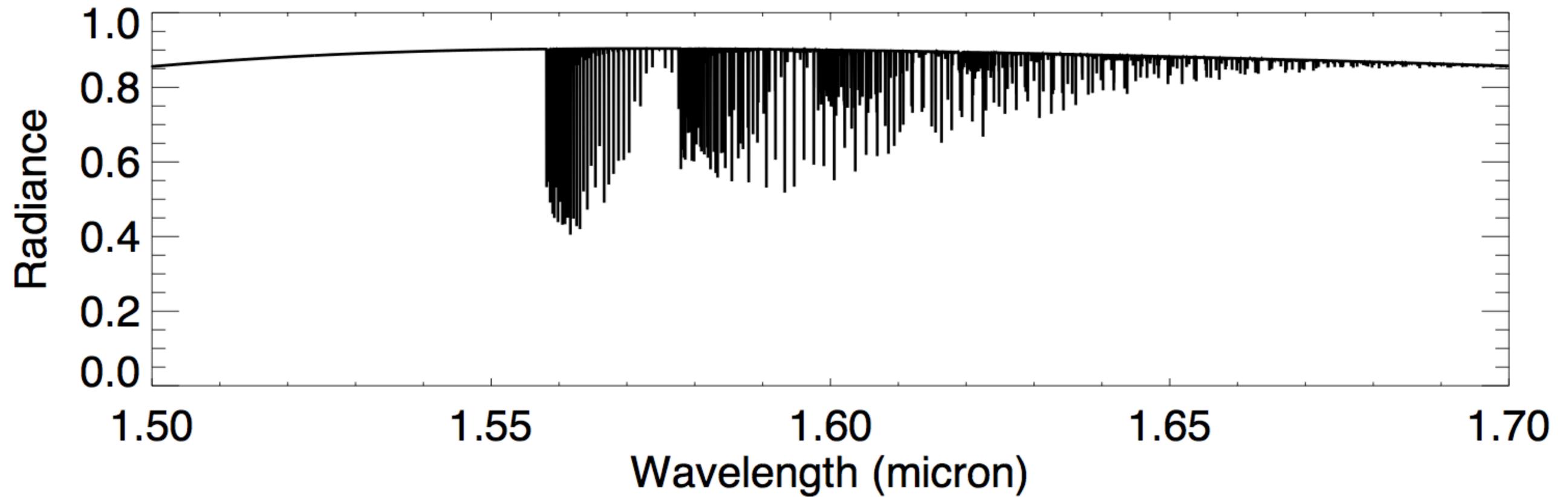


Model:  $R=300,000$  theoretical solar spectrum (courtesy of Paula Coelho)

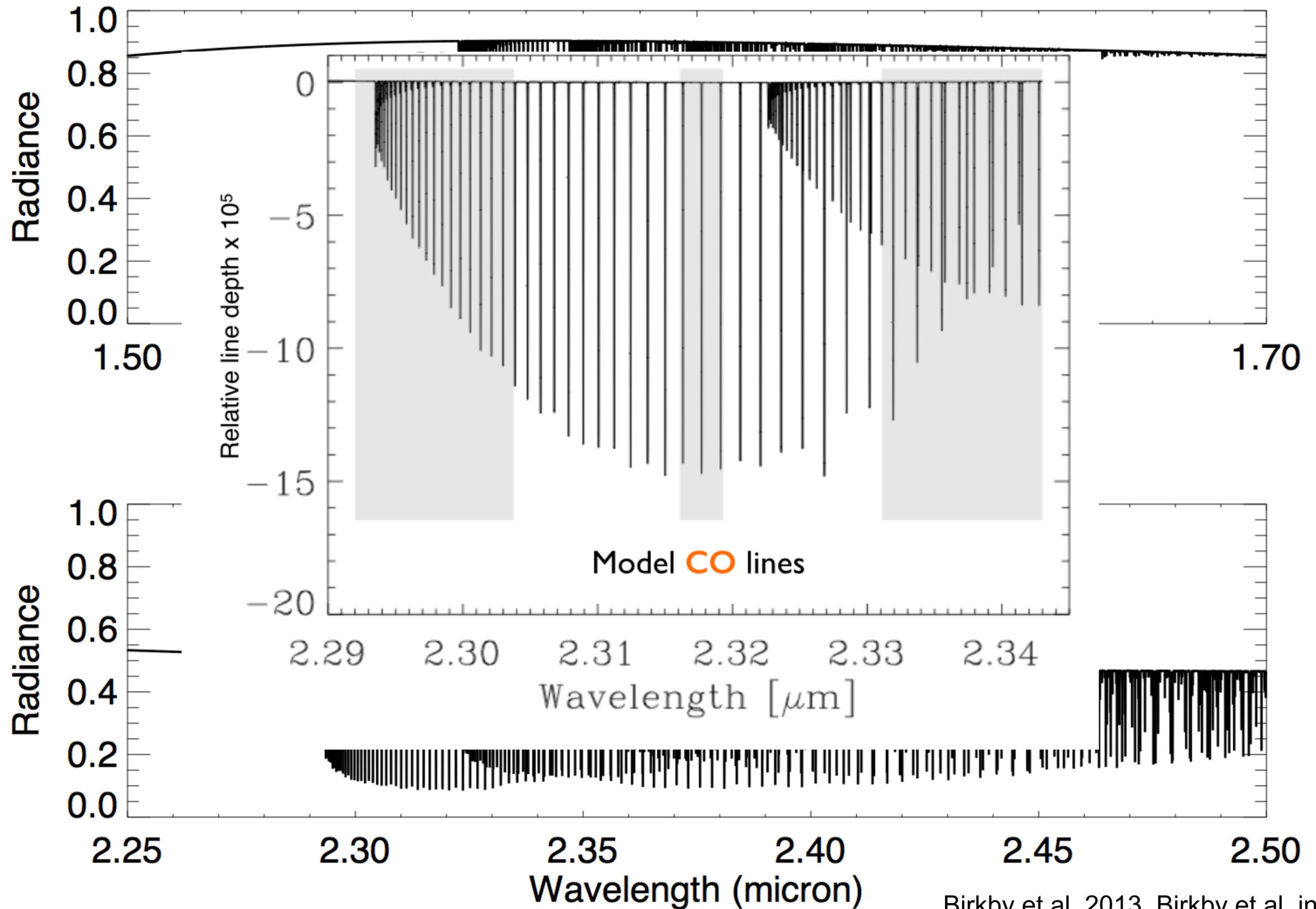


**Seeing through the clouds**

# Clouds alter the apparent T-P profile with $\lambda$

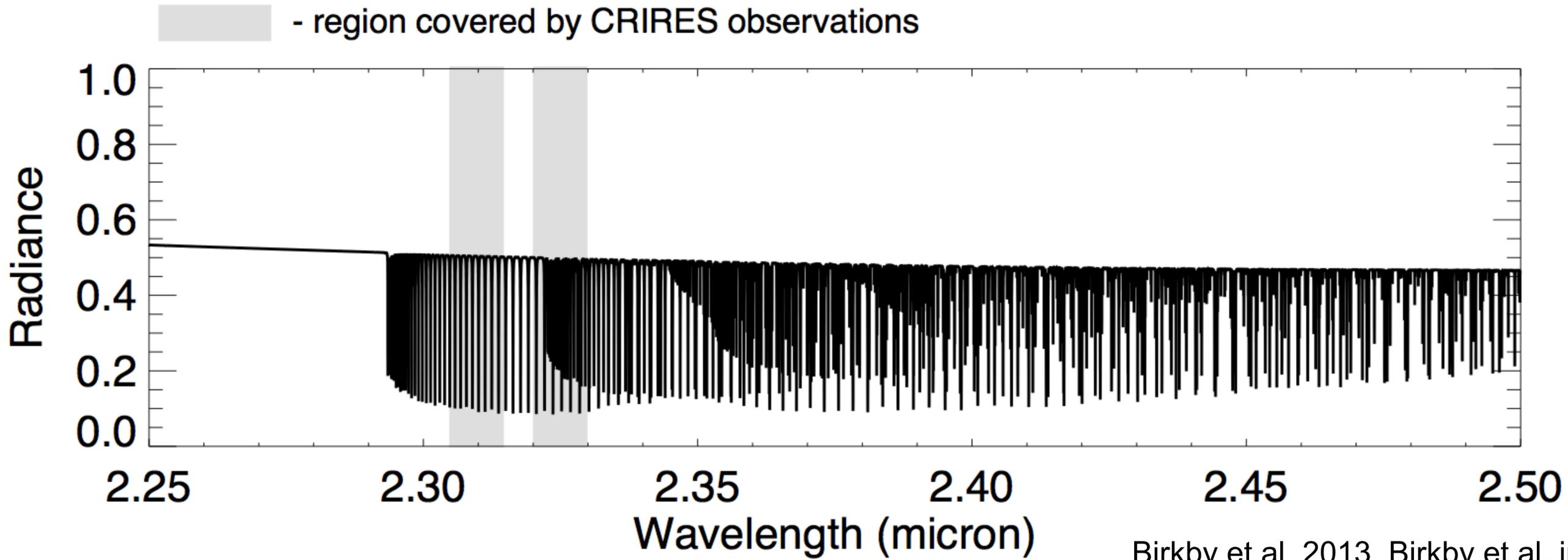
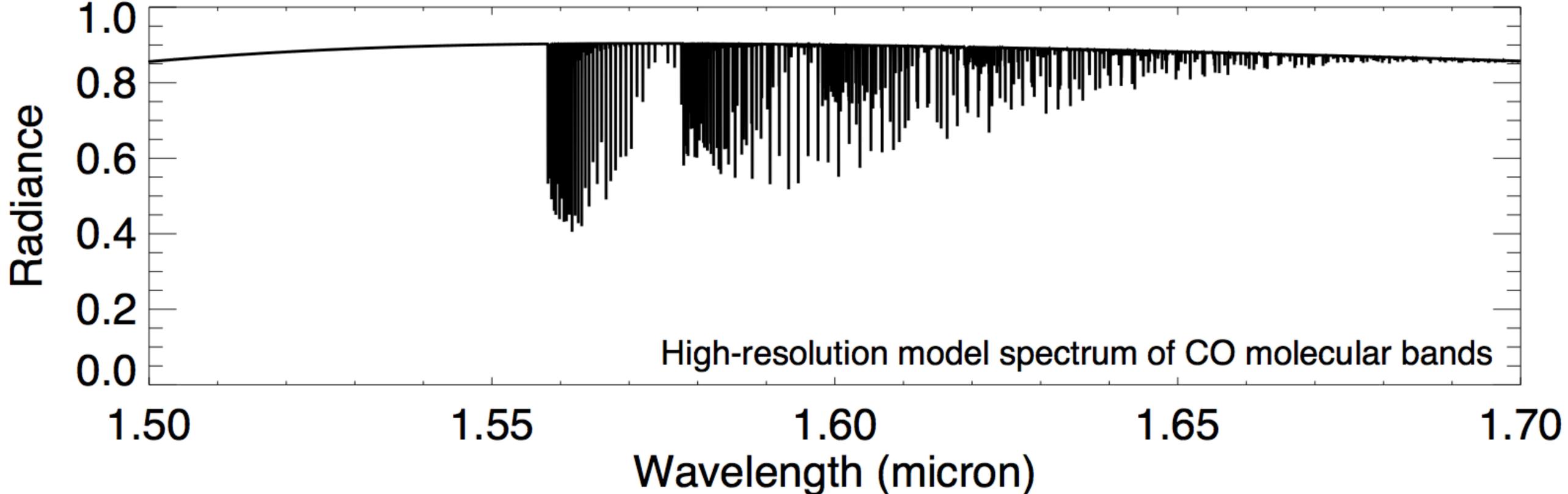


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ARIES/MMT simultaneous wavelength coverage (1.5-2.5 microns)

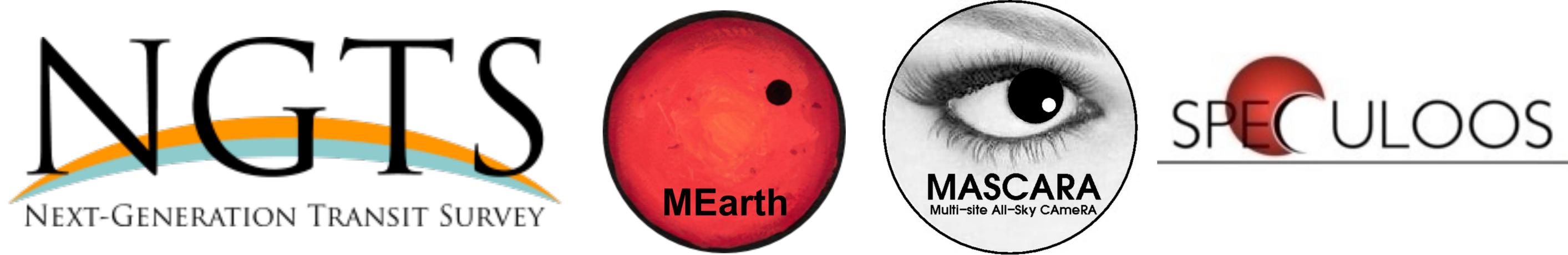




# **Future prospects for high spectral resolution exoplanet studies**

# The future is bright...

Ground-based transit hunters:



Ground-based direct-imagers:

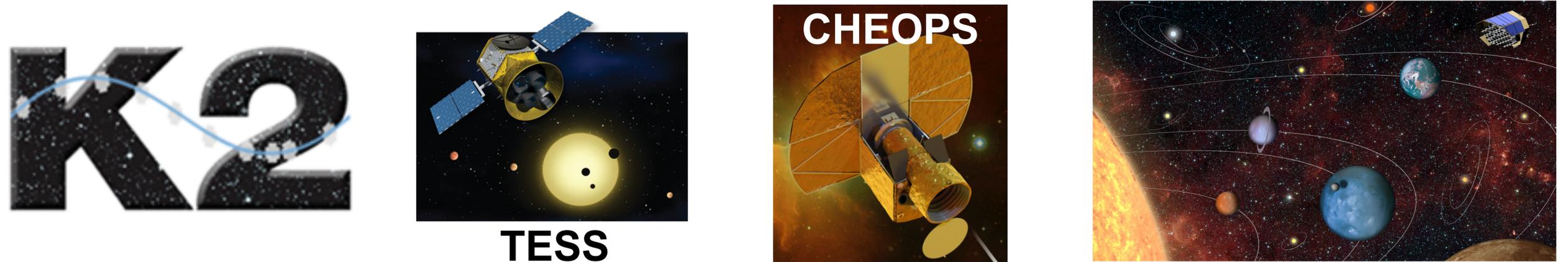


Ground-based precision RV planet hunters:

**HARPS, HARPS-N, SOPHIE, APF, MINERVA**

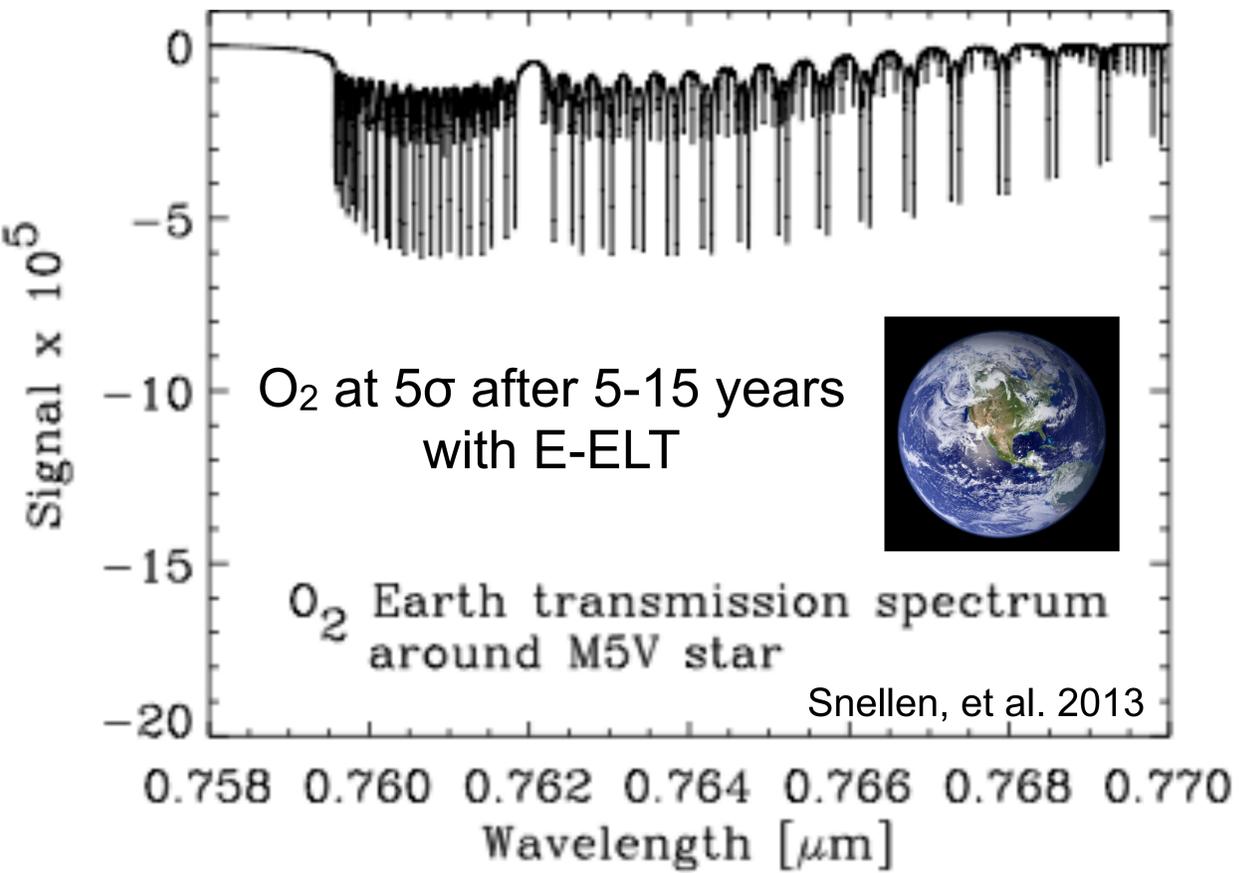


Space-based transit hunters:

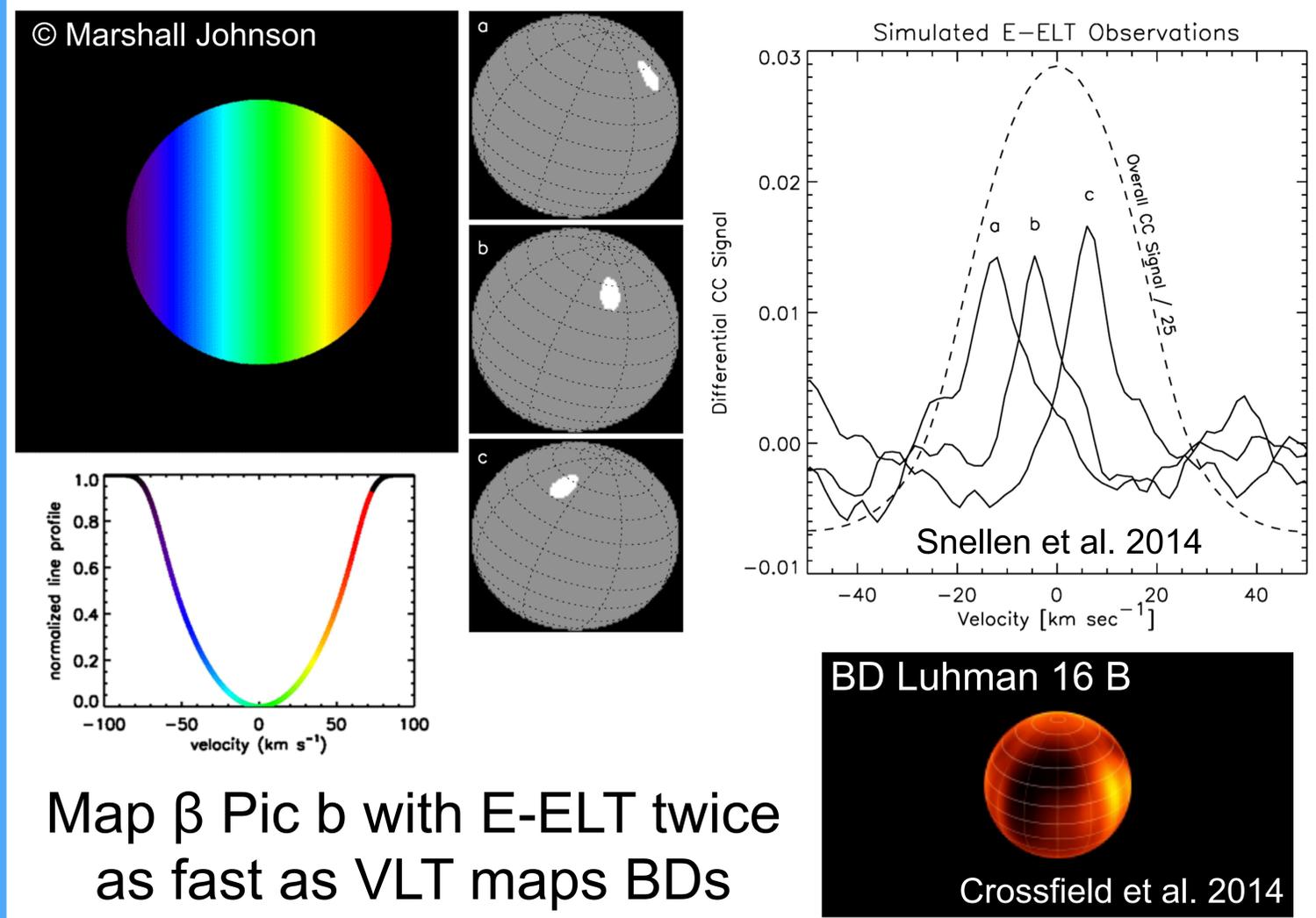


# ELTs enable time-resolved and exo-Earth studies

## Biomarkers in Earth-like planets

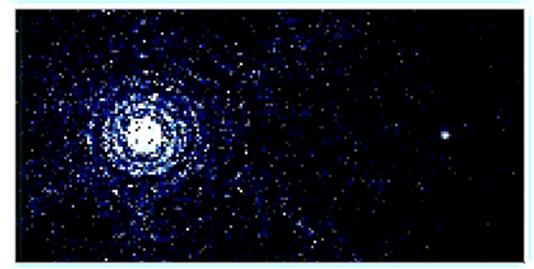


## Doppler imaging of surface features



## Our nearest rocky neighbour

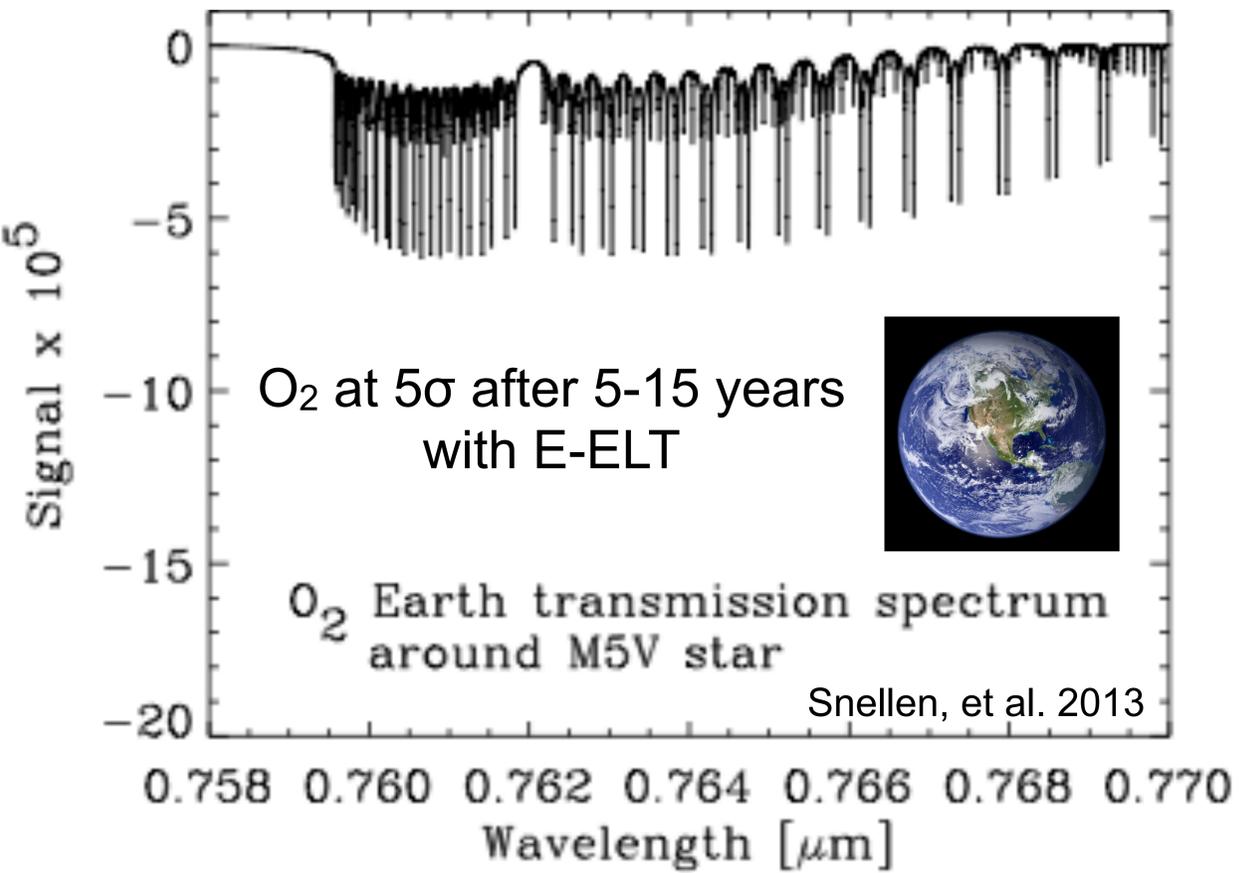
10hrs E-ELT/METIS detects  $1.5R_E$  Earth 'twin' orbiting  $\alpha$  Cen A at  $5\sigma$



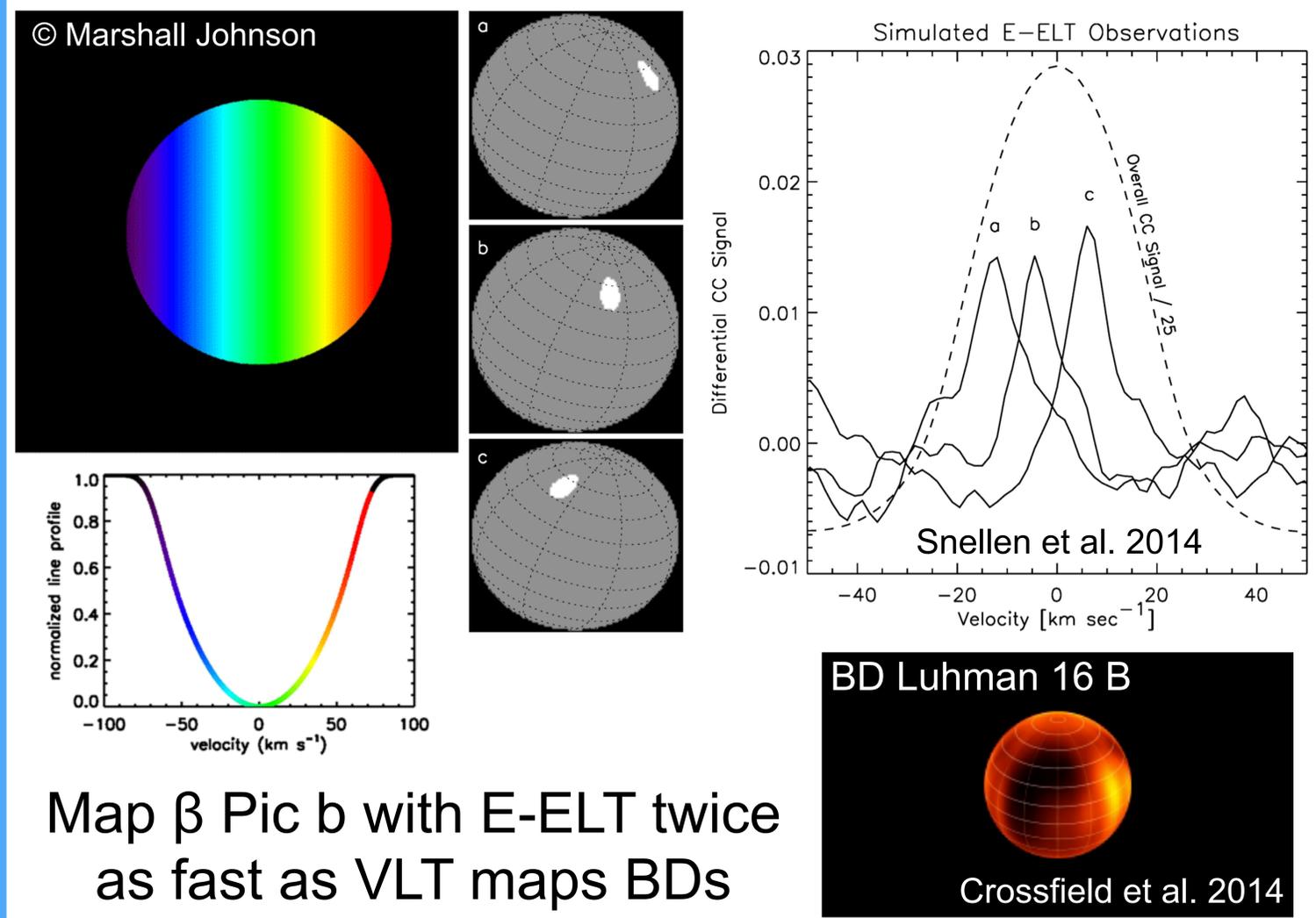
- Abundance and structure mapping as a function of longitude
- Isotopologue ratios (e.g. HDO) to study evolutionary history

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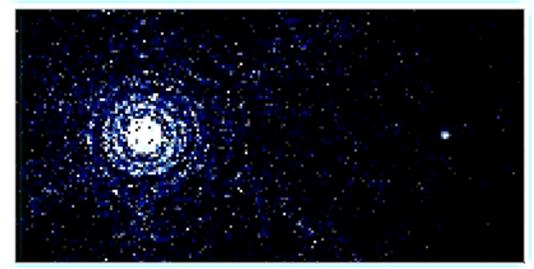


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Map  $\beta$  Pic b with E-ELT twice as fast as VLT maps BDs

- Abundance and structure mapping as a function of longitude
- Isotopologue ratios (e.g. HDO) to study evolutionary history

# Take home messages:

- High dispersion spectroscopy (**HDS**) provides *unambiguous* detections of **molecular features** and measures **C/O ratios**.
- HDS creates **double-lined (eclipsing) spectroscopic binaries** thus **model-independent masses and radii of BDs and exoplanets**.
- HDS measures the rotational broadening and shift of exoplanet spectral lines thus their **rotation periods** and **global wind patterns**.
- The **albedo, colour, and cloud** properties of exoplanets are accessible with HDS.
- **High-resolution optical-infrared spectrographs ( $R > 25,000$ )** are a **key resource** for exoplanet atmosphere characterization.