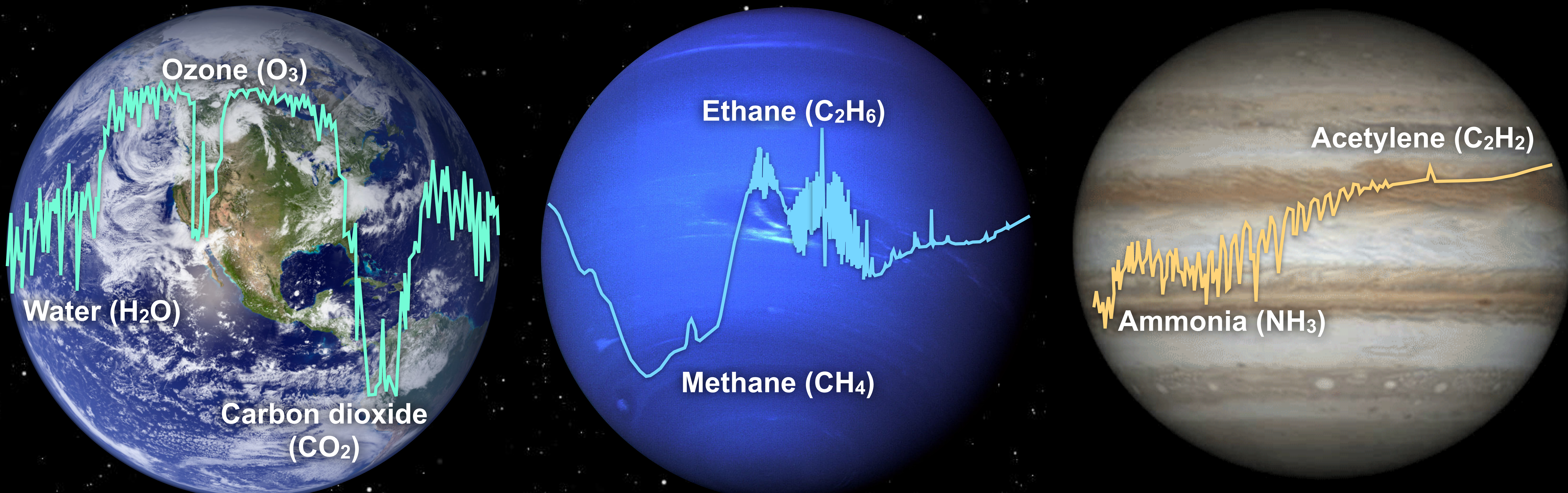
# High-resolution Spectroscopy of Exoplanet Atmospheres




**Jayne Birkby**
**University of Oxford**

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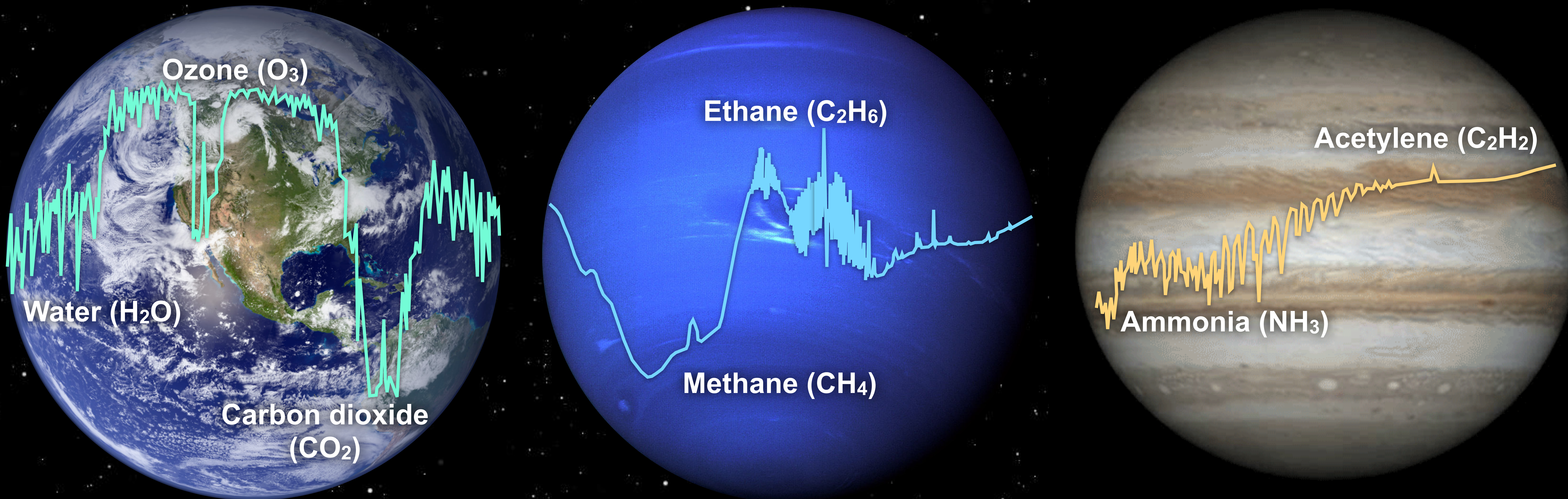


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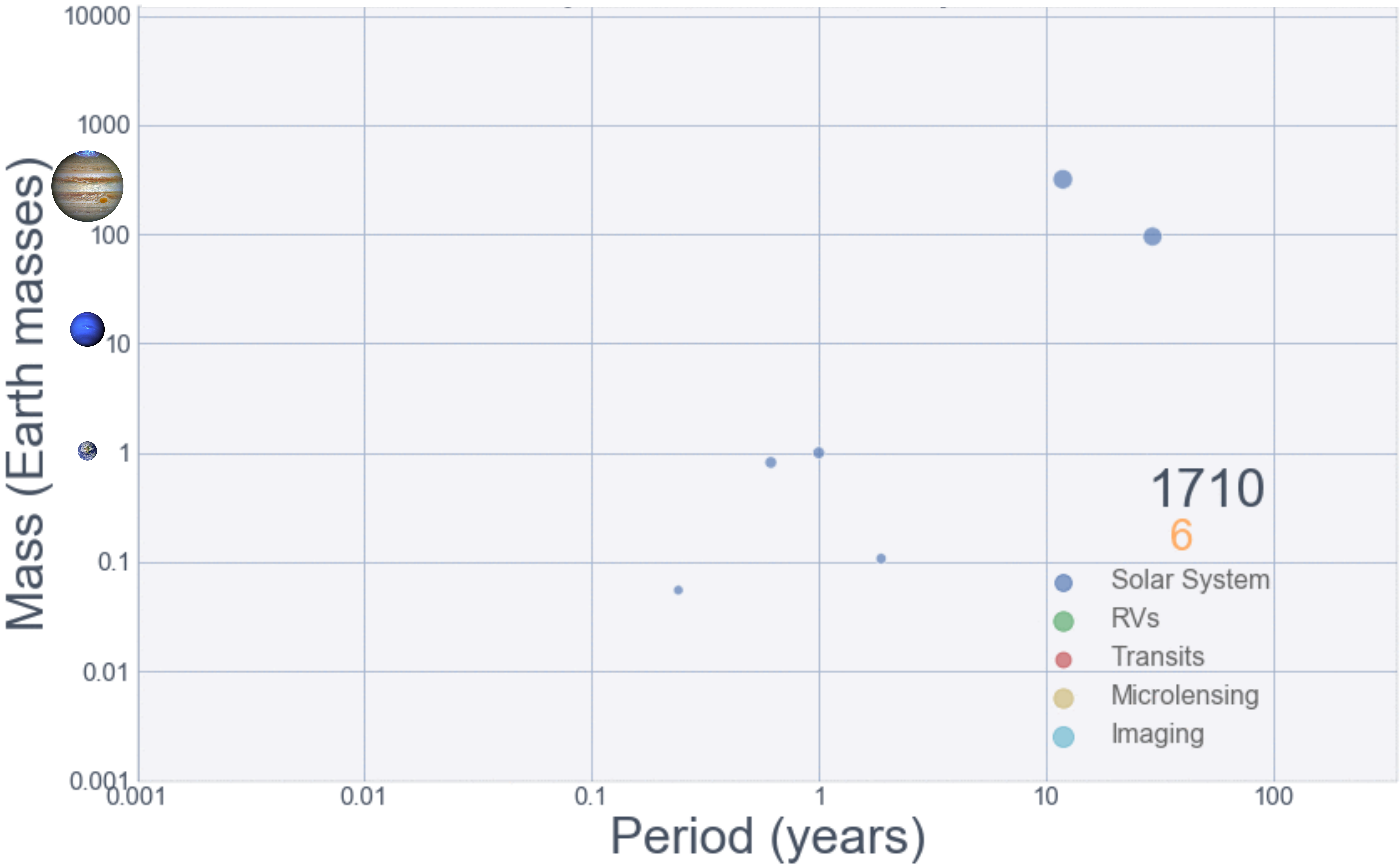
# The exoplanet zoo is incredibly diverse




Animation by Hugh Osborn

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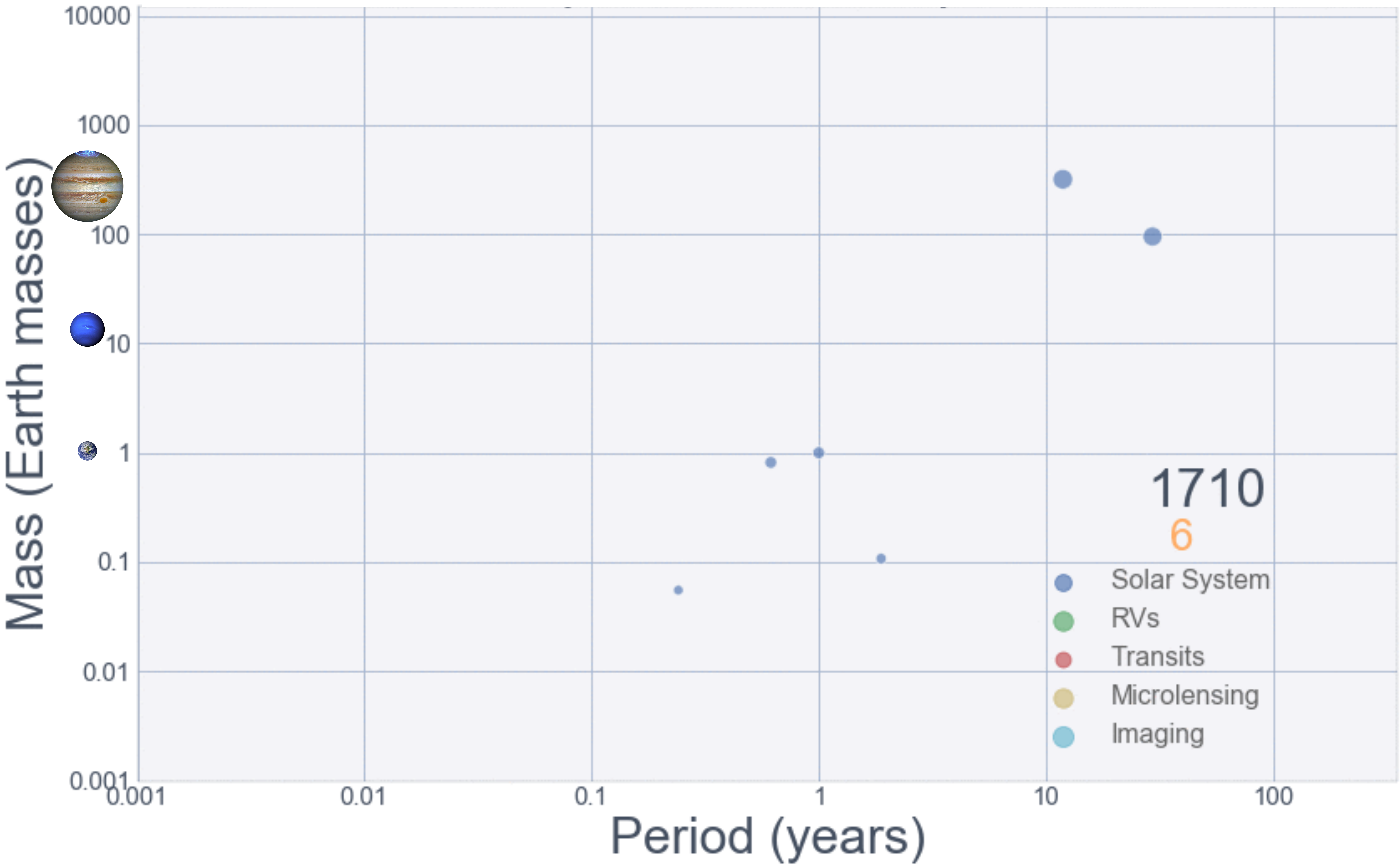


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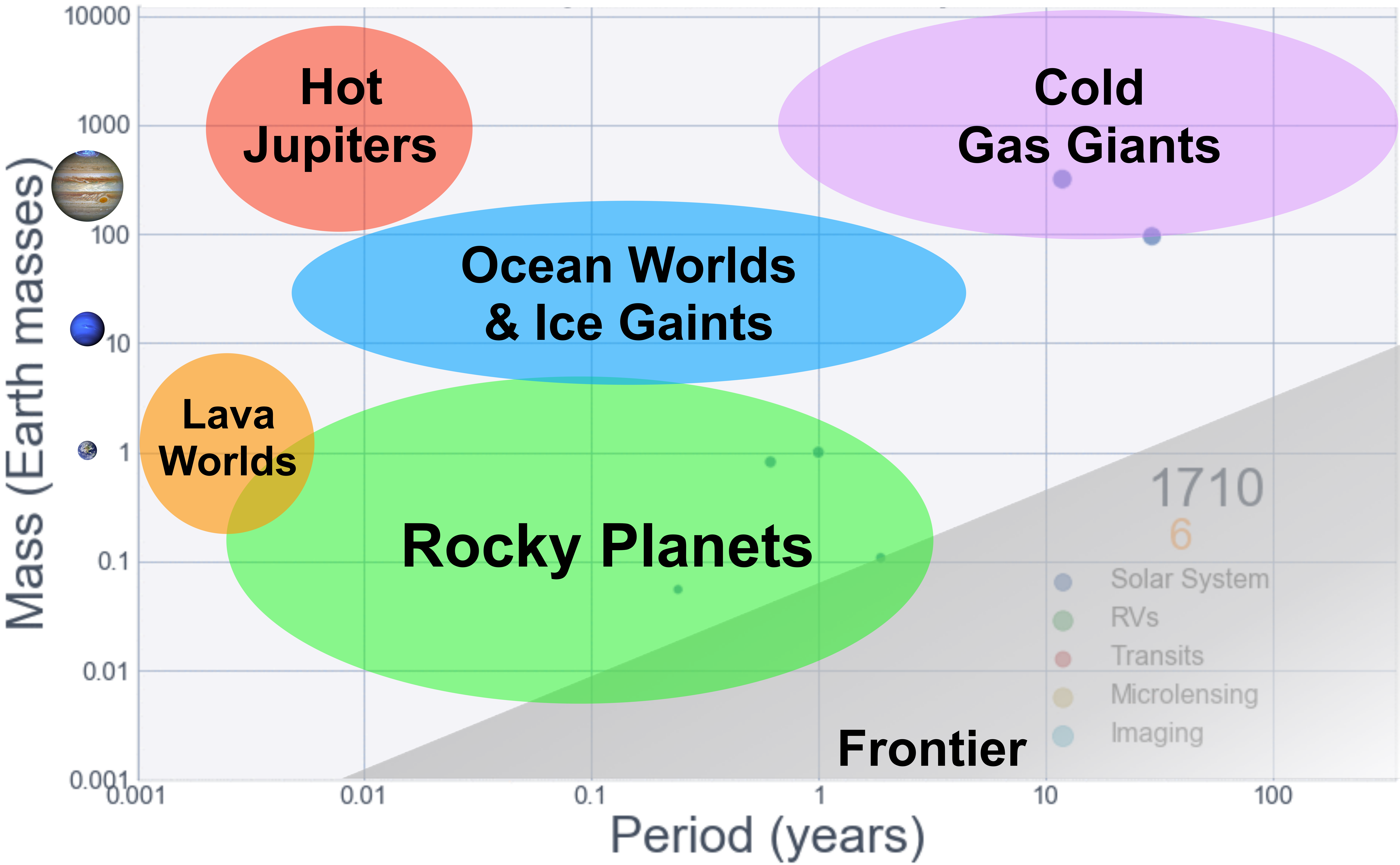


Animation by Hugh Osborn

# The EPRV Exoplanet Atmosphere Connection

**To study exoplanet atmospheres at high spectral resolution we need:**

- **High spectral resolution**

- **Stability**

**What we can get away with (a bit):**

- **wavelength calibration from telluric lines**

- **stellar activity but flares and pulsations (δ Scuti) still an issue**

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CRIRES VLT 8-m

NIRSPEC Keck 10-m

ARIES/MMT 6.5-m

GIANO-B TNG 3.5-m

IGRINS DCT/McDonald 4/2.7-m

iSHELL IRTF 3.5-m

SPIRou CFHT 4-m

CARMENES CAHA 3.5-m

HDS Subaru 8-m

UVES VLT 8-m

EXPRES DCT 4-m

HARPS/HARPS-N ESO/TNG 3.5-m

# https://arxiv.org/abs/1806.04617



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*[Submitted on 12 Jun 2018]*

## Exoplanet Atmospheres at High Spectral Resolution

J. L. Birkby

The spectrum of an exoplanet reveals the physical, chemical, and biological processes that have shaped its history and govern its future. However, observations of exoplanet spectra are complicated by the overwhelming glare of their host stars. This review chapter focuses on high resolution spectroscopy (HRS; R=25,000-100,000), which helps to disentangle and isolate the exoplanet's spectrum. At high spectral resolution, molecular features are resolved into a dense forest of individual lines in a pattern that is unique for a given molecule. For close-in planets, the spectral lines undergo large Doppler shifts during the planet's orbit, while the host star and Earth's spectral features remain essentially stationary, enabling a velocity separation of the planet. For slower-moving, wide-orbit planets, HRS aided by high contrast imaging instead isolates their spectra using their spatial separation. The lines in the exoplanet spectrum are detected by comparing them with high resolution spectra from atmospheric modelling codes; essentially a form of fingerprinting for exoplanet atmospheres. This measures the planet's orbital velocity, and helps define its true mass and orbital inclination. Consequently, HRS can detect both transiting and non-transiting planets. It also simultaneously characterizes the planet's atmosphere due to its sensitivity to the depth, shape, and position of the planet's spectral lines. These are altered by the planet's atmospheric composition, structure, clouds, and dynamics, including day-to-night winds and its rotation period. This chapter describes the HRS technique in detail, highlighting its successes in exoplanet detection and characterization, and concludes with the future prospects of using HRS to identify biomarkers on nearby rocky worlds, and map features in the atmospheres of giant exoplanets.

Comments: 24 pages, 5 figures, author's expanded version of invited review chapter accepted for publication in the Handbook of Exoplanets under title "Spectroscopic direct detection of exoplanets"
Subjects: **Earth and Planetary Astrophysics (astro-ph.EP)**; Instrumentation and Methods for Astrophysics (astro-ph.IM)
Cite as: arXiv:1806.04617 **[astro-ph.EP]**
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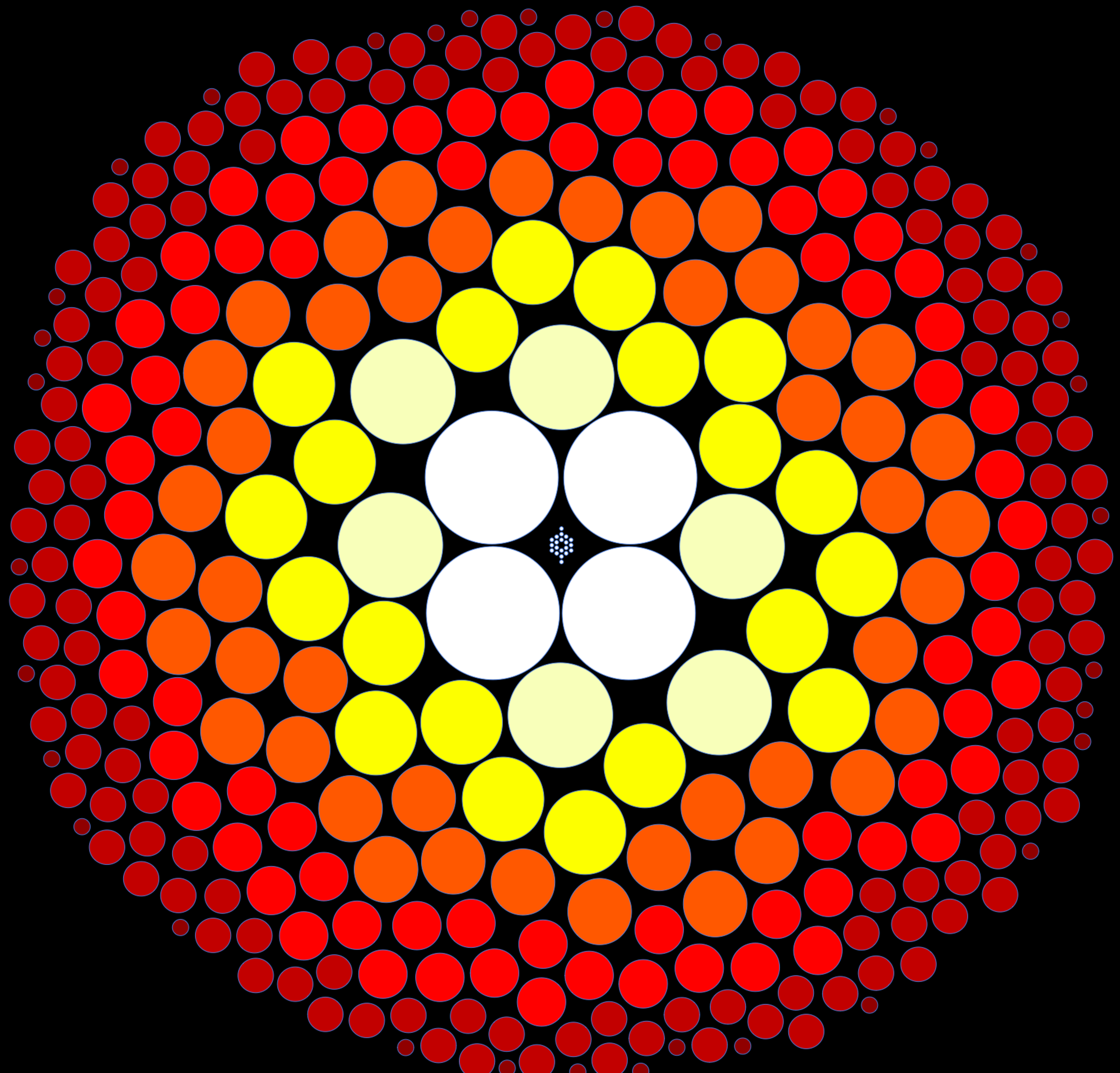
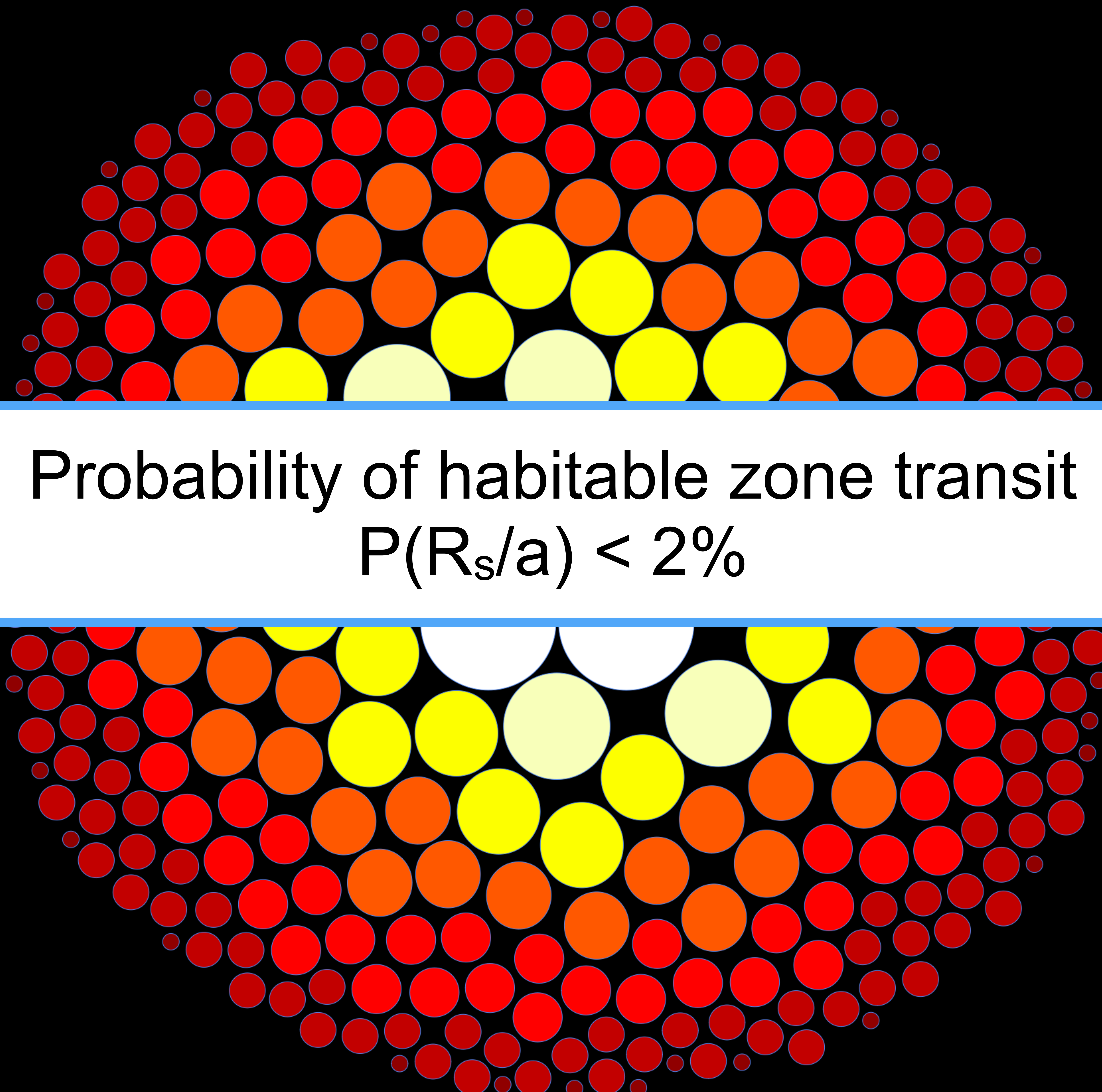
Graduate-level introduction to observing exoplanet atmospheres with high resolution spectroscopy

# There are ~300 stars within 10 pc



10 pc (33 lyr) sample from RECONS (T. Henry)

# There are ~300 stars within 10 pc



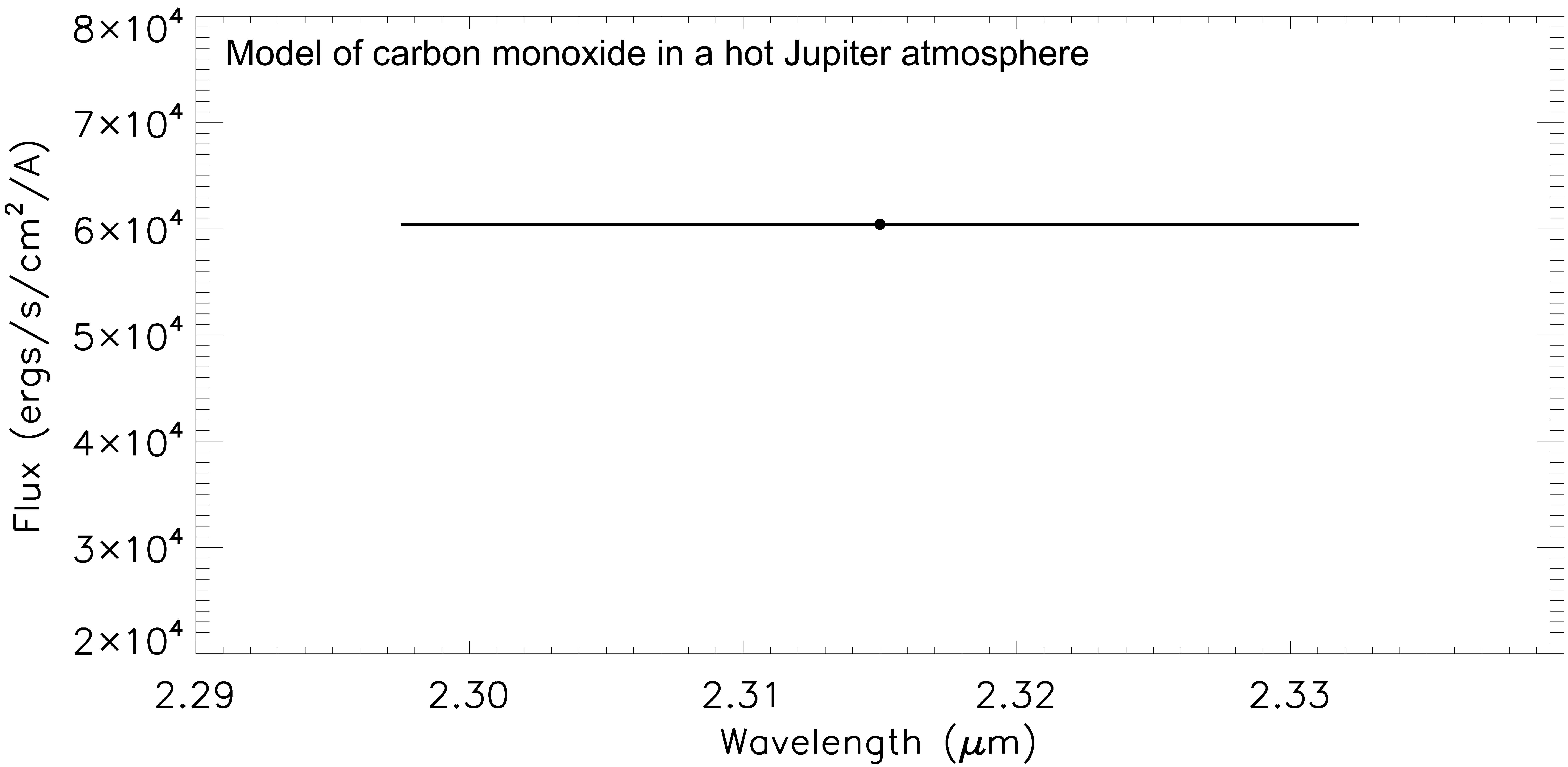
Probability of habitable zone transit
$P(R_s/a) < 2\%$

10 pc (33 lyr) sample from RECONS (T. Henry)

# Nearby habitable worlds, mostly M-dwarf hosts, unlikely to be transiting planets


Image credit: Nadieh Bremer, Jessie Christiansen, Eric Mamajek

# Molecules have unique patterns of many spectral lines that are difficult to mimic with systematics




CRIRES(+), METIS R=100,000

ARIES, NIRSPEC R=30,000

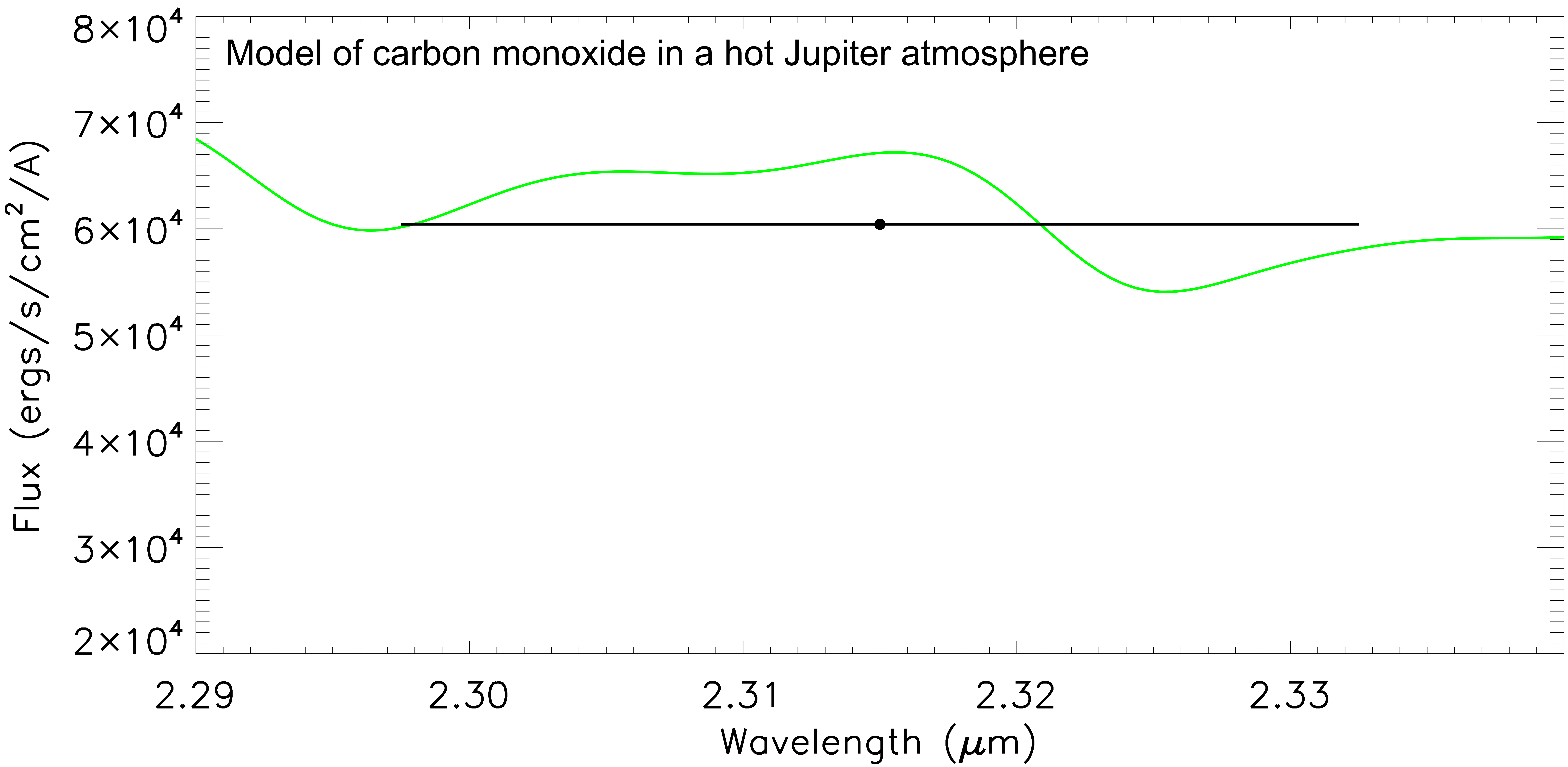
SINFONI, OSIRIS R=5,000

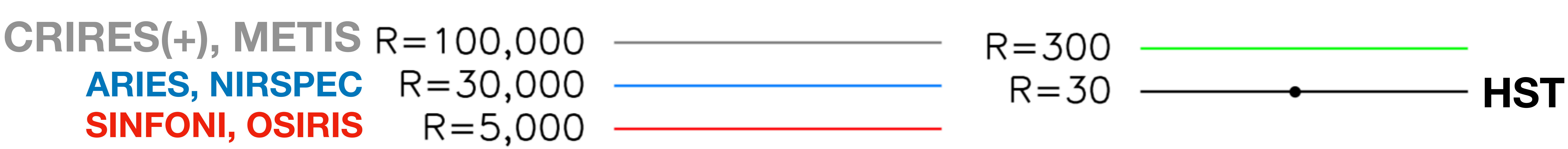
R=300

R=30 **HST**

Birkby 2018

# Molecules have unique patterns of many spectral lines that are difficult to mimic with systematics




Birkby 2018

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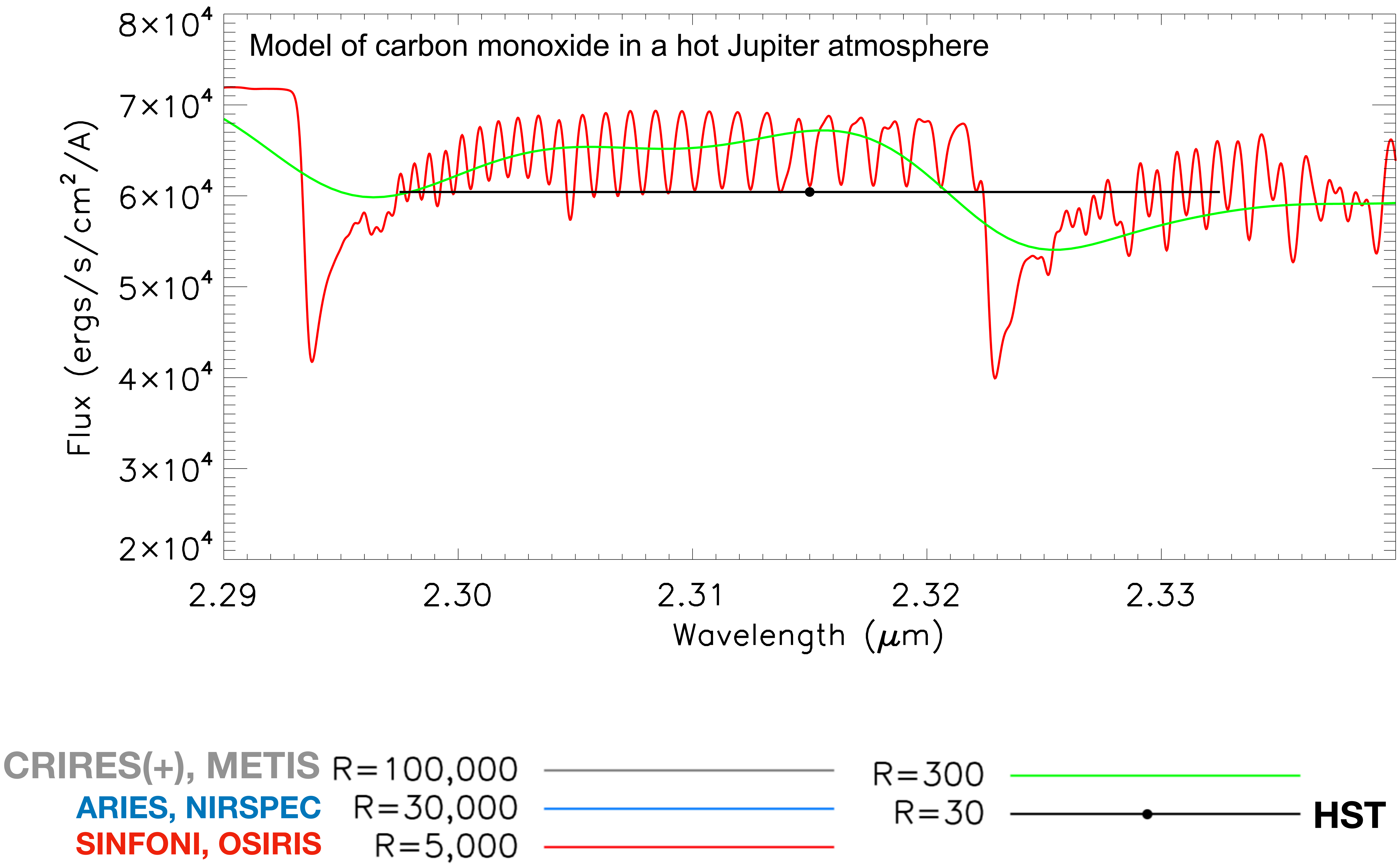


Birkby 2018

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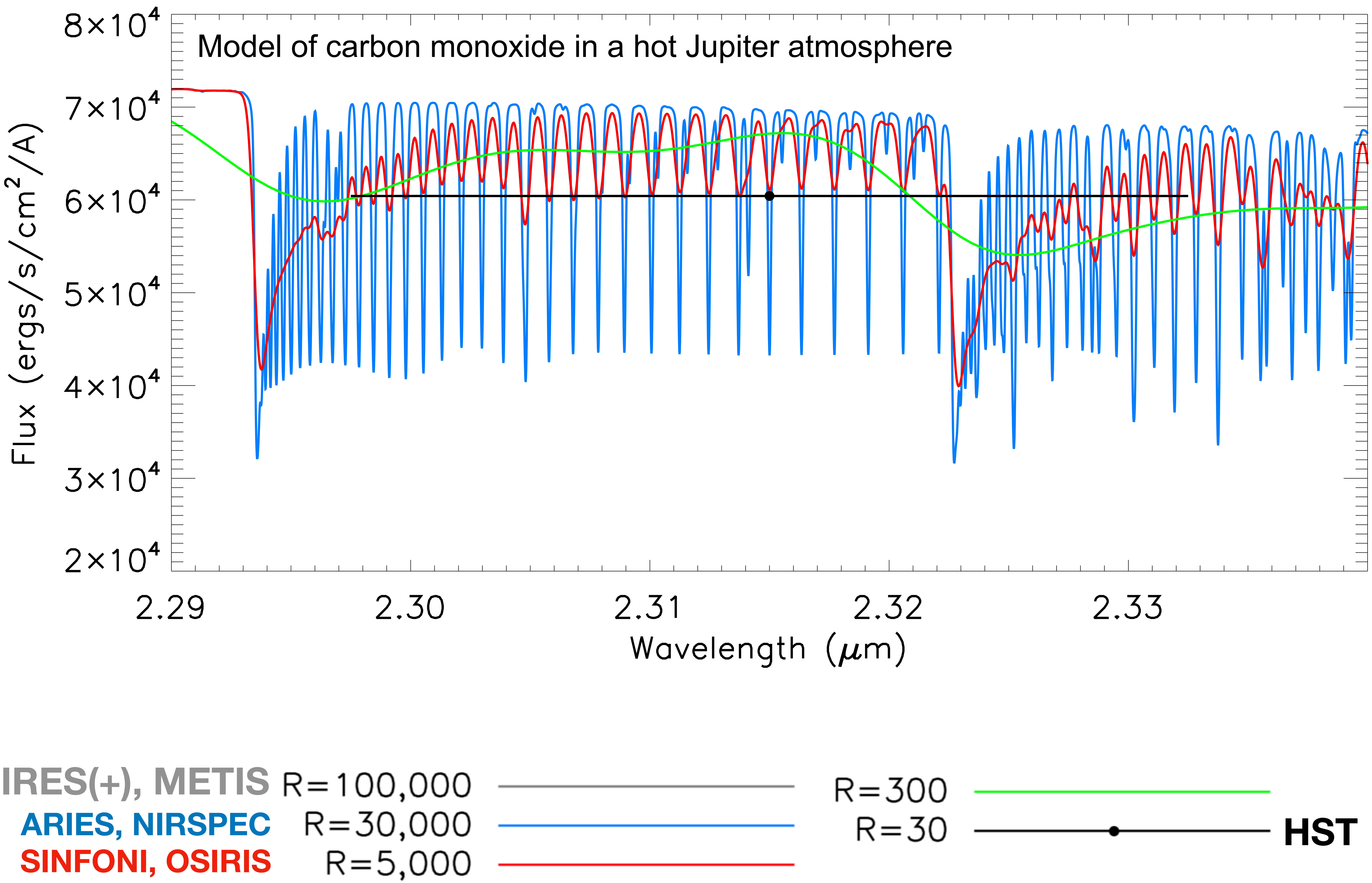


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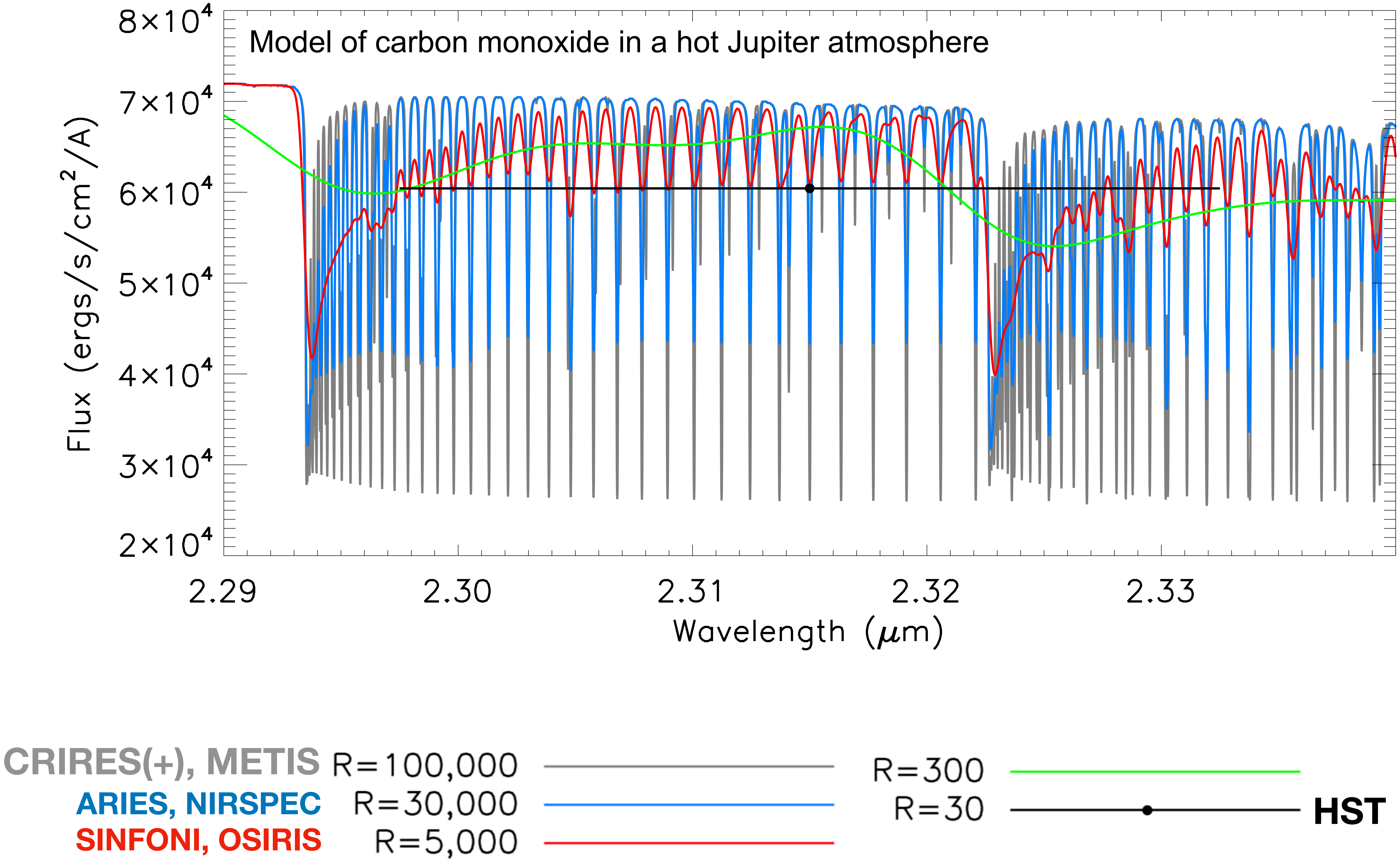


Birkby 2018

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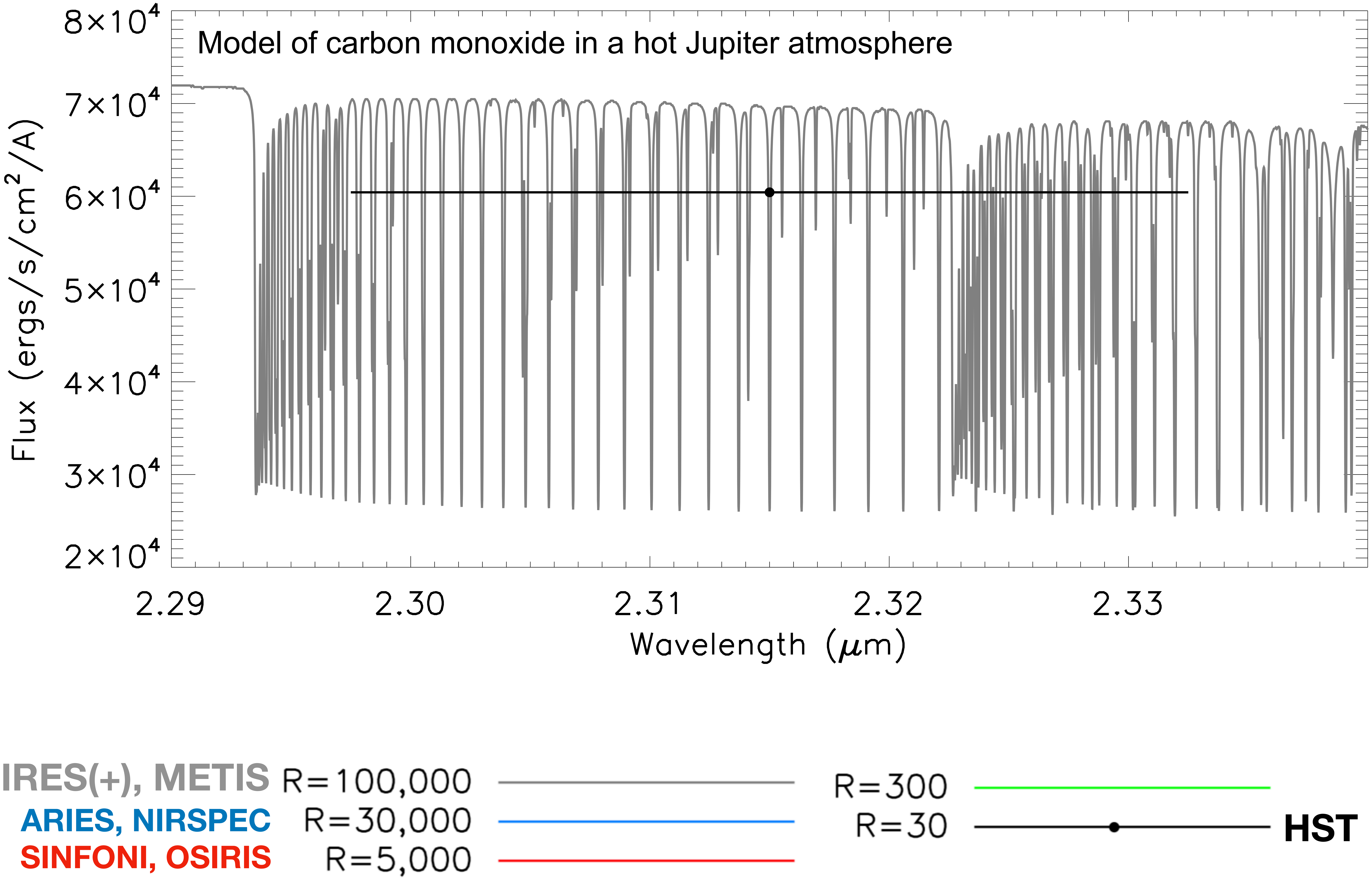
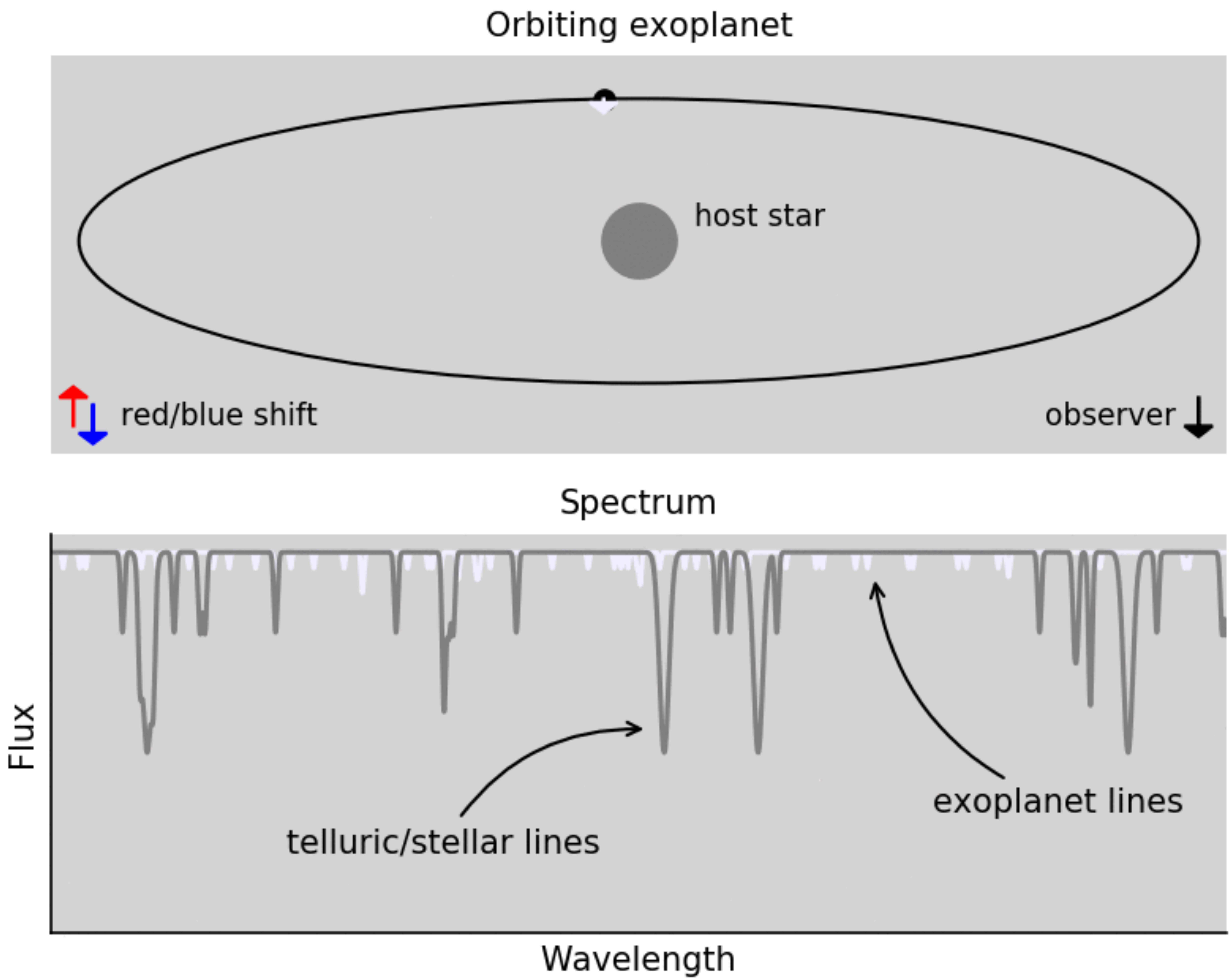



Birkby 2018

# Use the large Doppler-shift of the planet to disentangle its spectrum from the ~static host star and Earth's atmosphere




Video credit: Lennart van Sluijs

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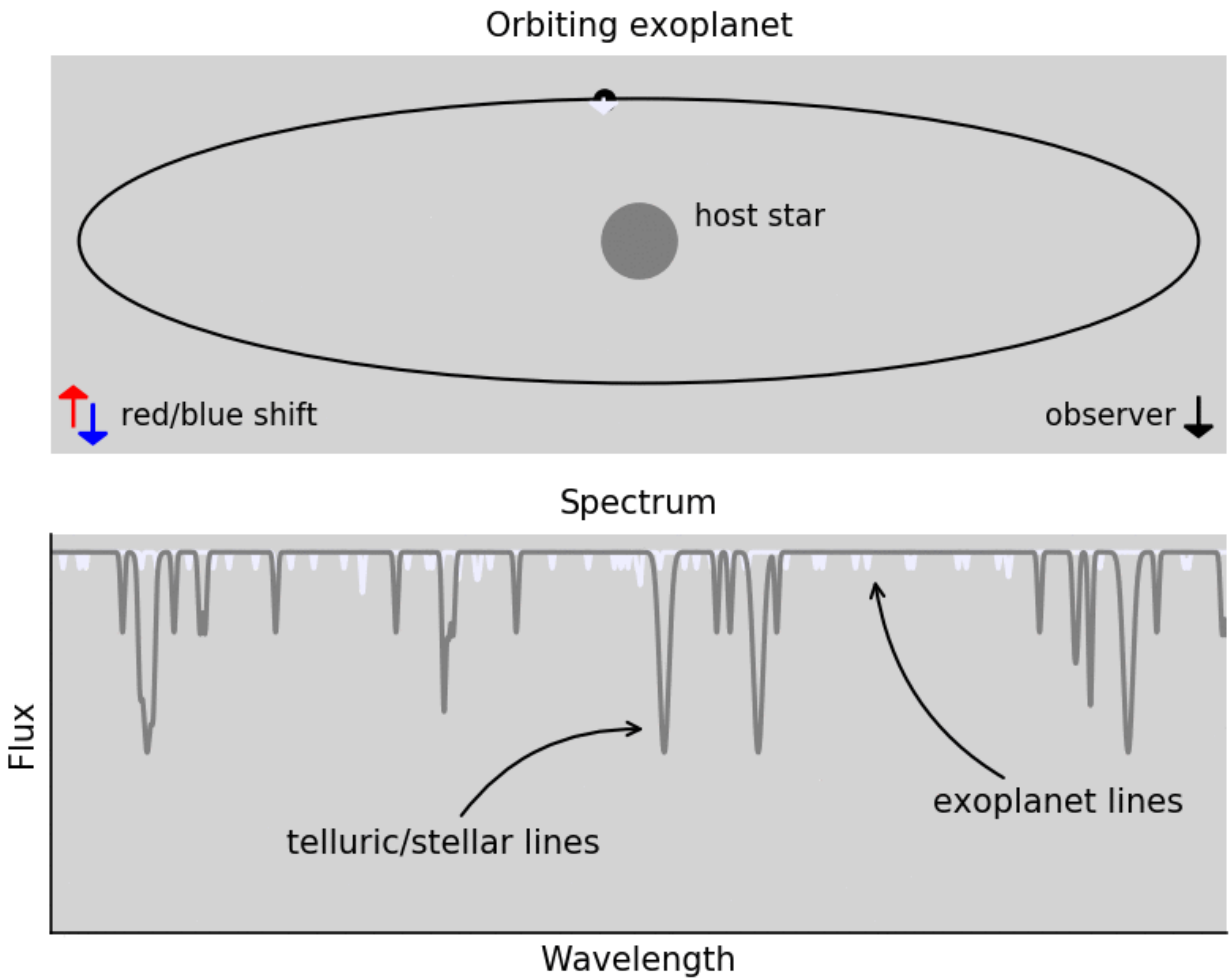


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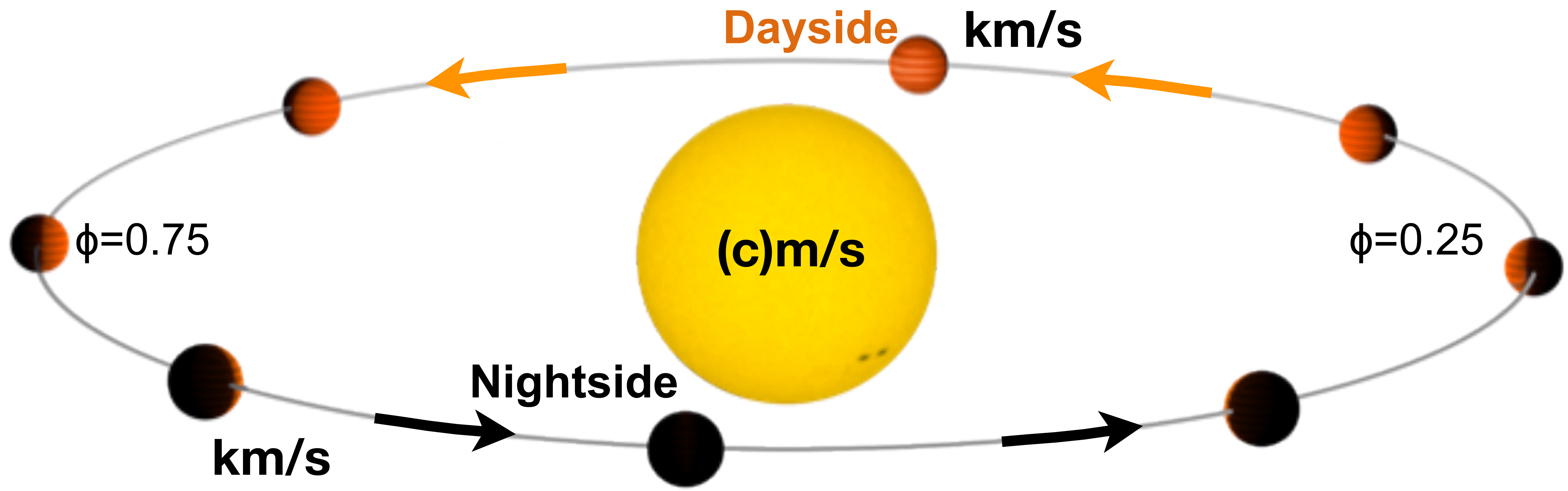


Birkby 2018

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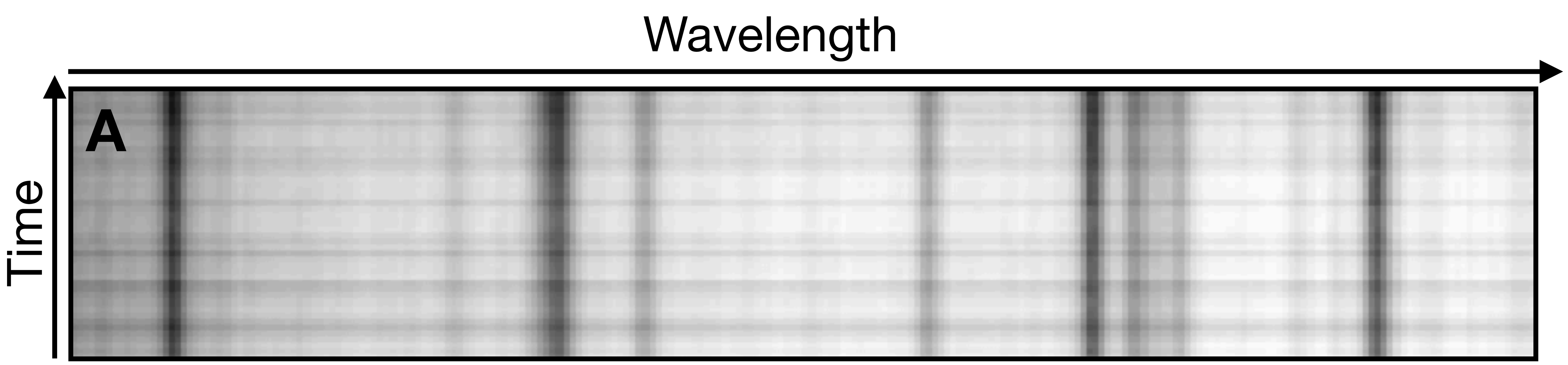
Birkby 2018

# Use the large Doppler-shift of the planet to disentangle its spectrum from the ~static host star and Earth's atmosphere


Model planet carbon monoxide lines at $\lambda/\Delta\lambda$ = 100,000

Birkby 2018

# Remove features that are stationary over time




**Goal**: remove star and telluric spectra such that only **photon noise** remains (plus planet spectrum buried in noise)

Extracted ARIES spectra

Birkby, Lothringer, Crossfield et al. in prep.

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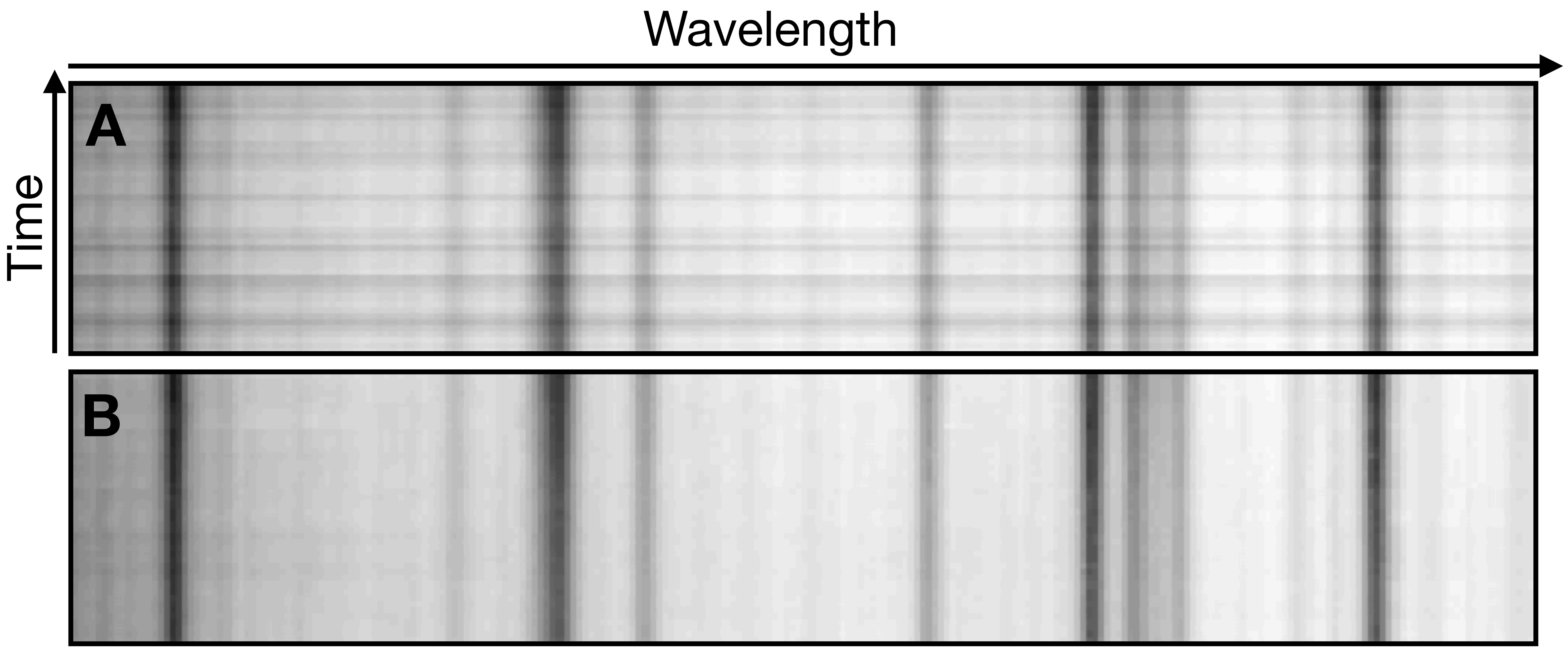


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Normalised (continuum information lost)

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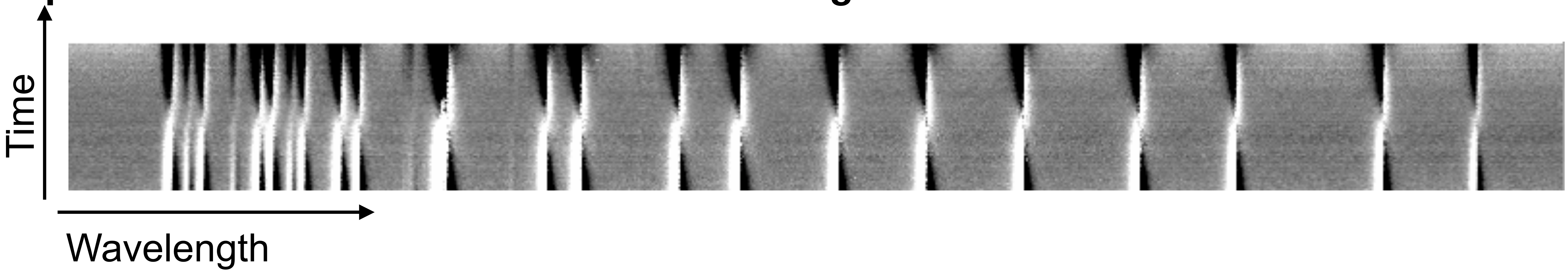
# Aligning the spectral is crucial for removing the tellurics/stellar lines

**Spectra where lines drift over time due to e.g. instrument or Earth motion**



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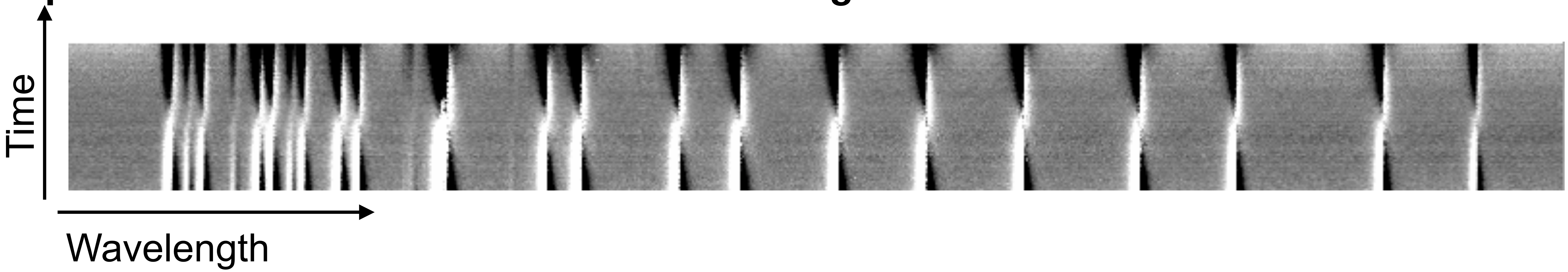
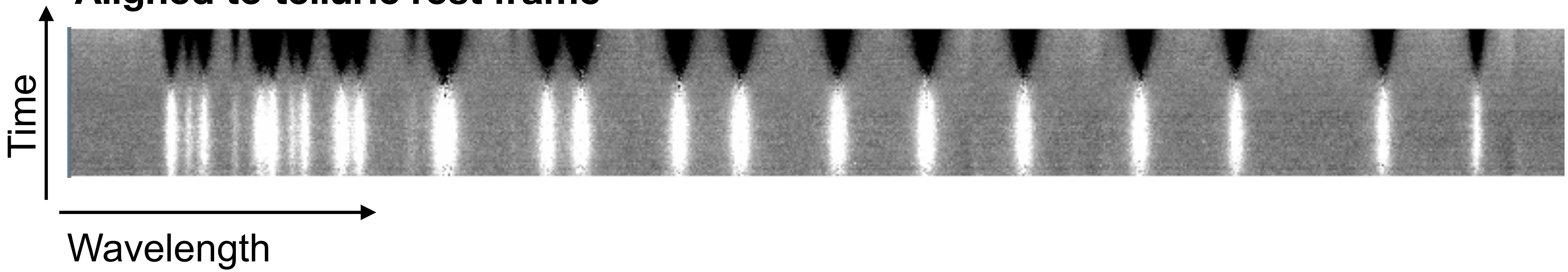



**Aligned to telluric rest frame**



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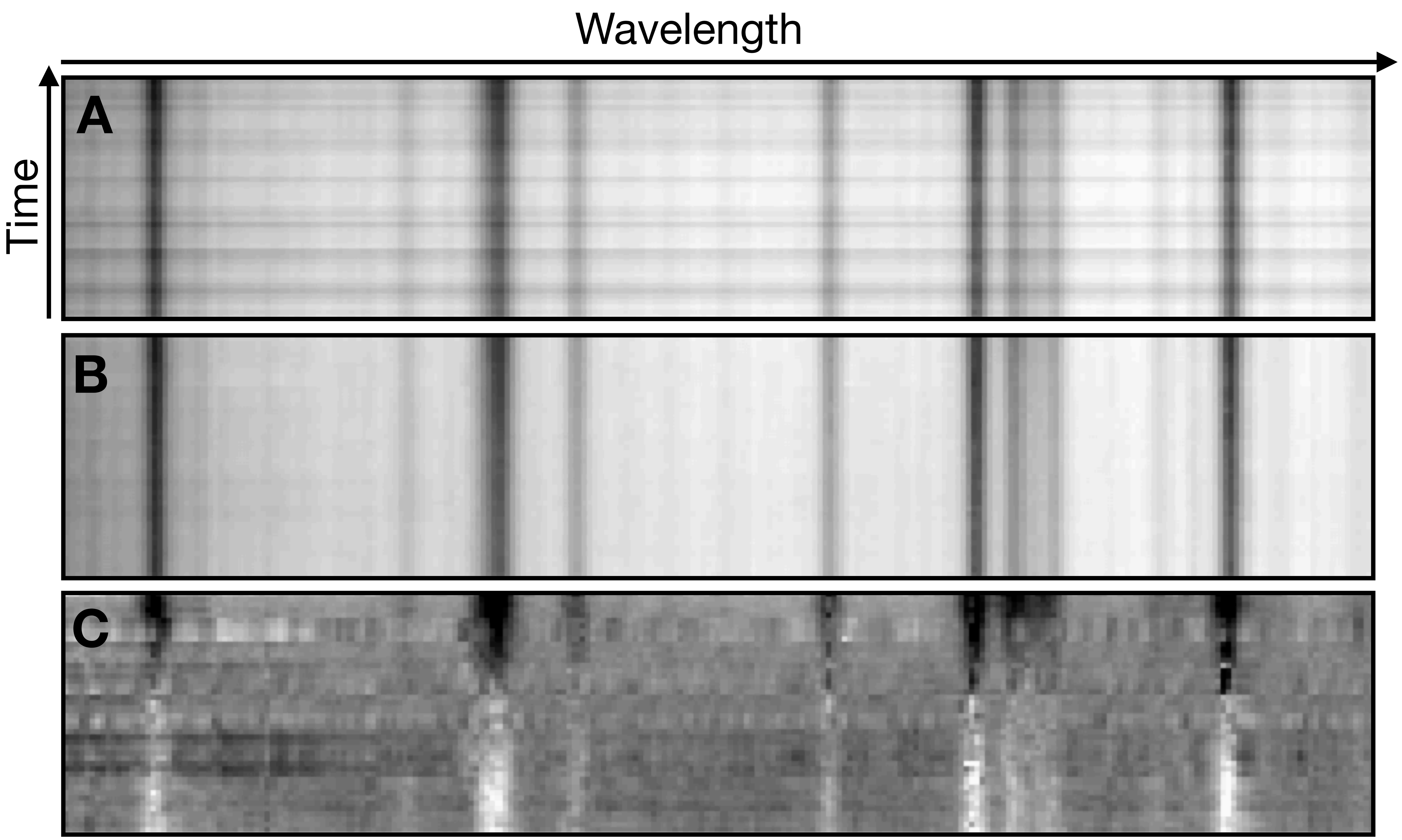


Extracted ARIES spectra

Normalised (continuum information lost)

After first common mode removed

Birkby, Lothringer, Crossfield et al. in prep.

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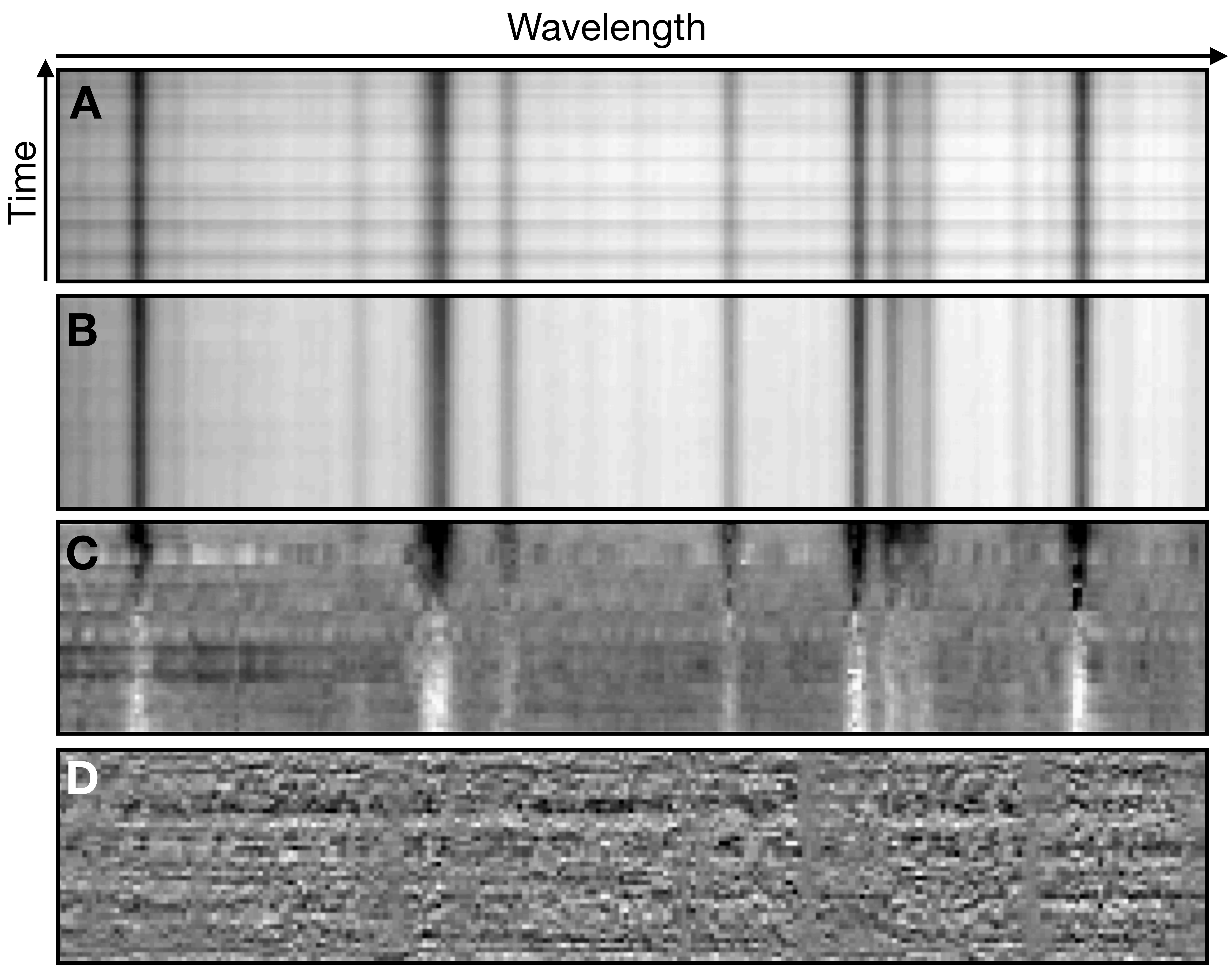


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After first common mode removed

After optimal common modes removed (Did we ‘hit the photon noise’?)

Birkby, Lothringer, Crossfield et al. in prep.

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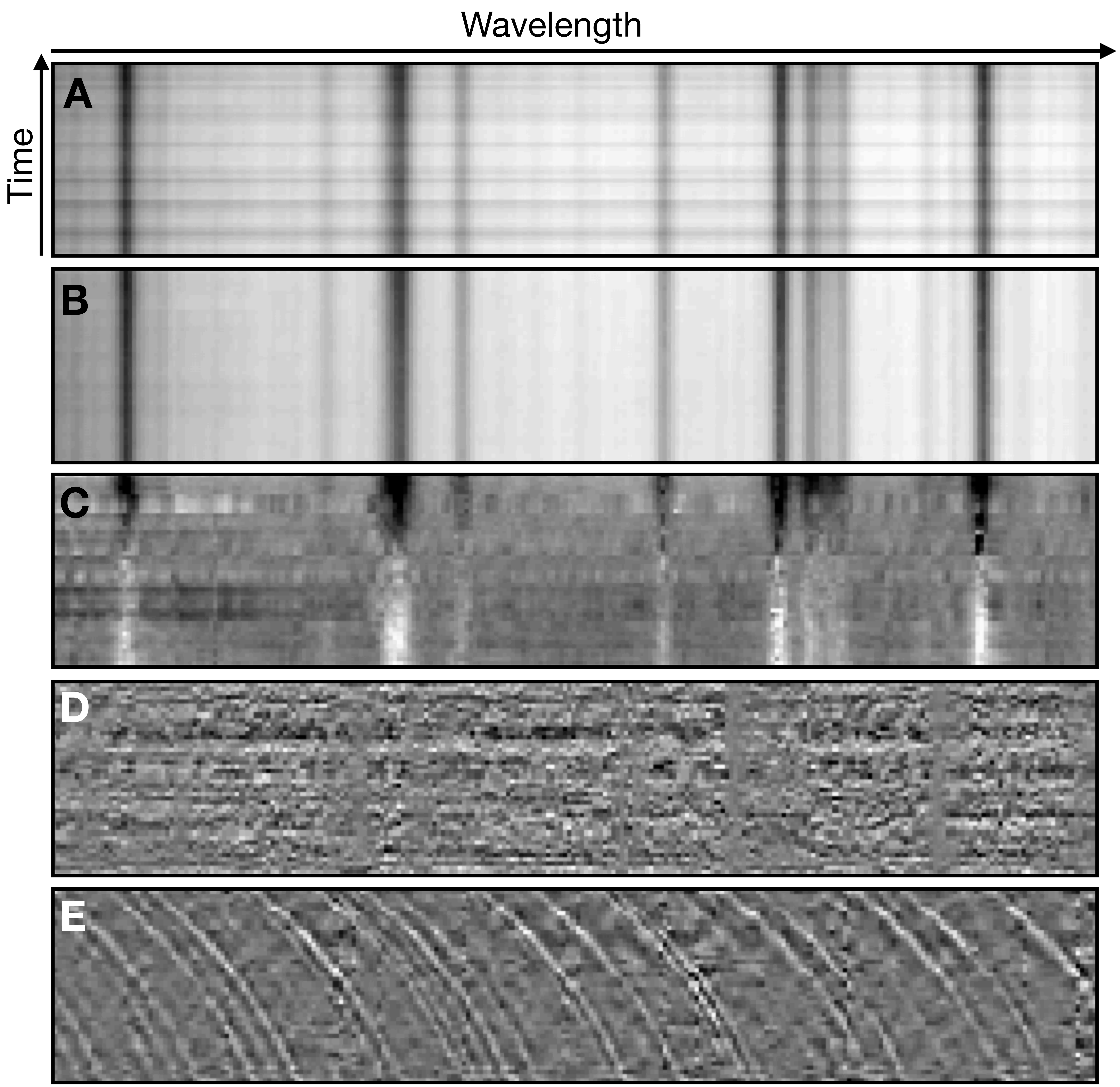


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Normalised (continuum information lost)

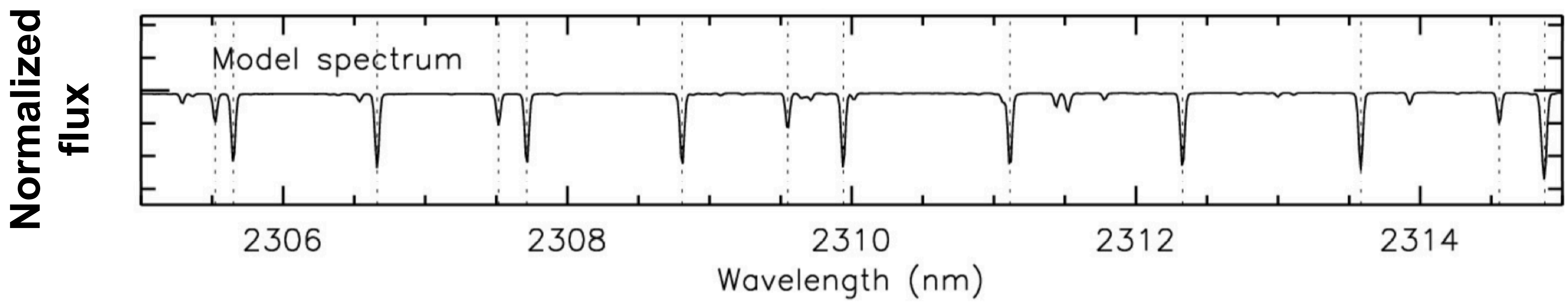
After first common mode removed

After optimal common modes removed
(Did we ‘hit the photon noise’?)

Model injected x100

Birkby, Lothringer, Crossfield et al. in prep.

# Final extracted spectrum of planet is very noisy




Brogi et al. 2012

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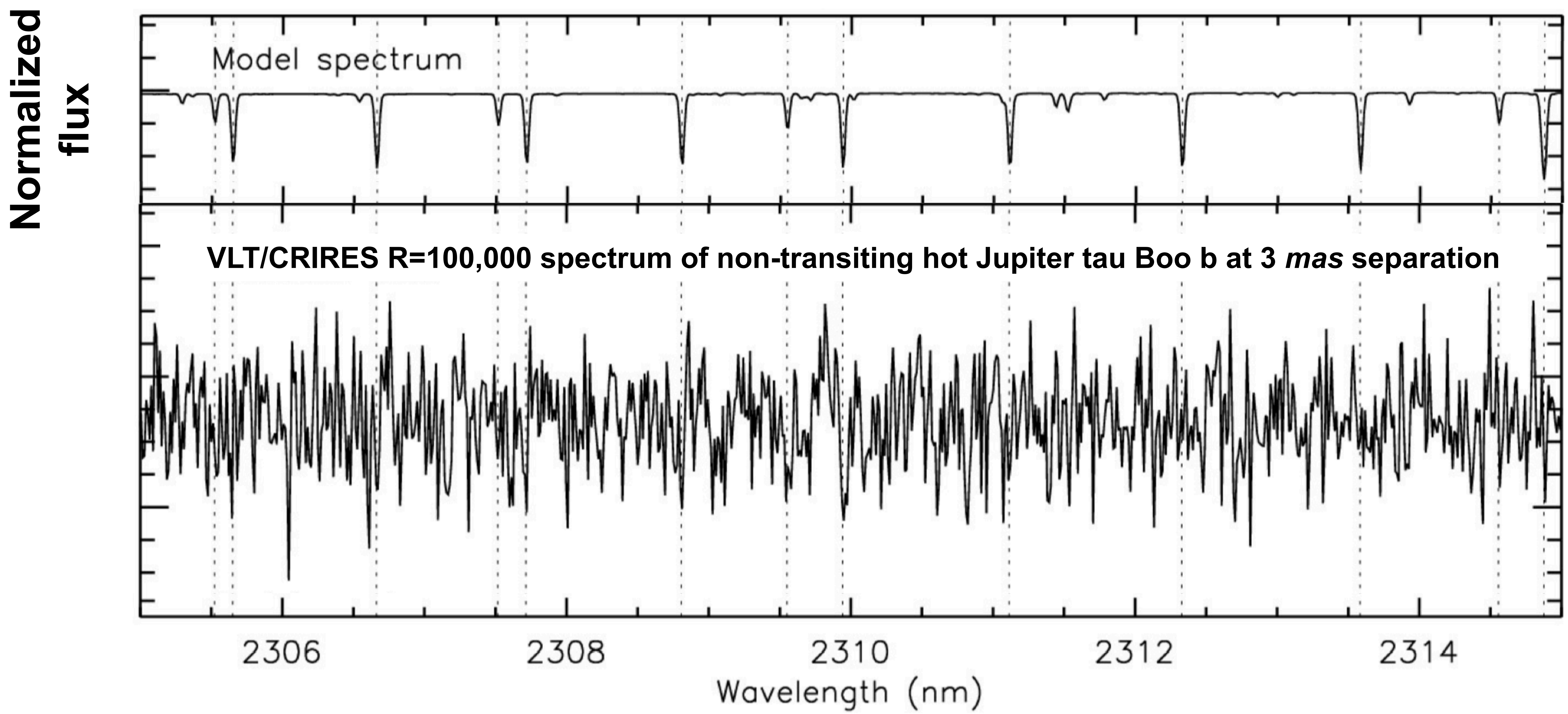


Brogi et al. 2012

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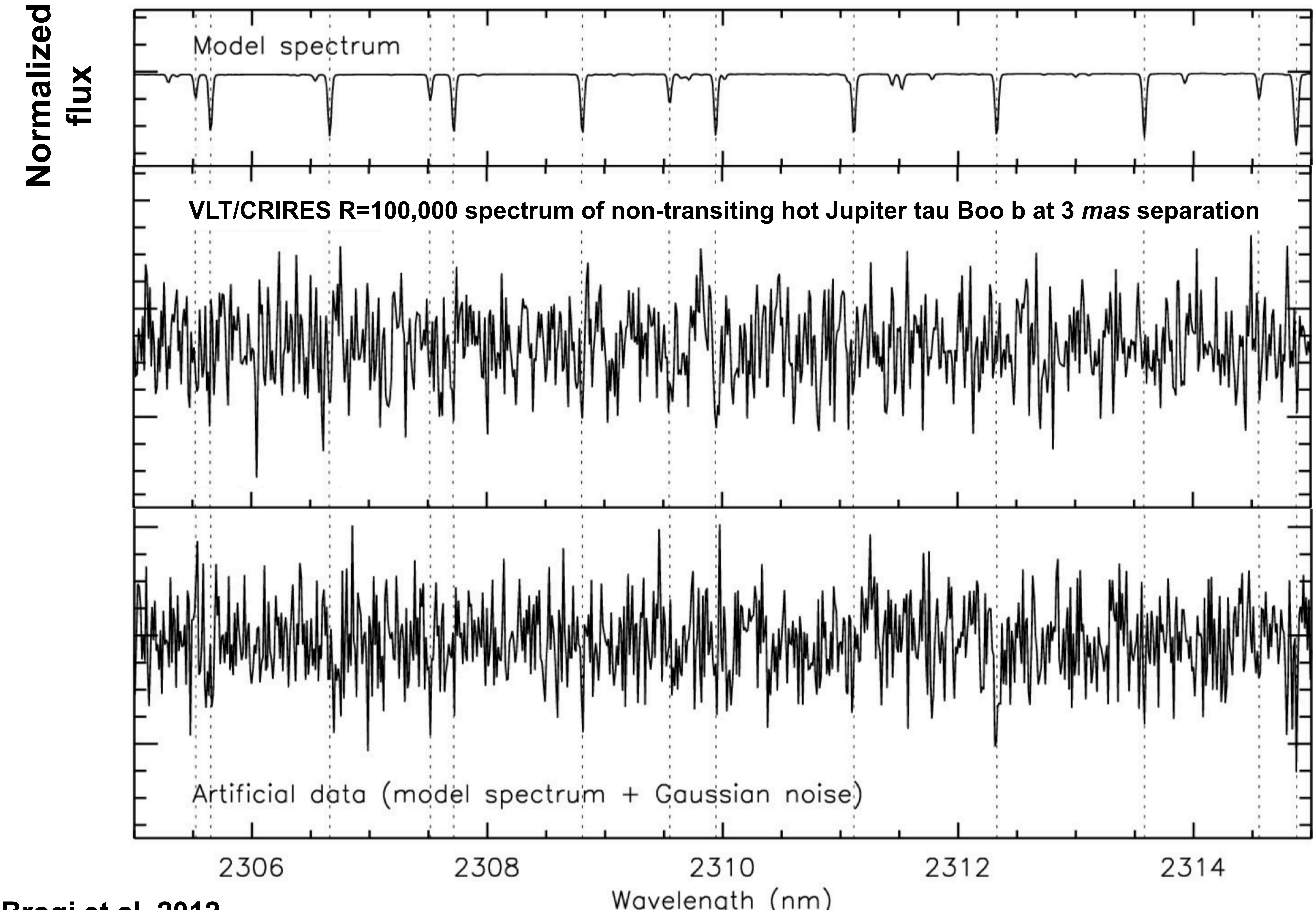


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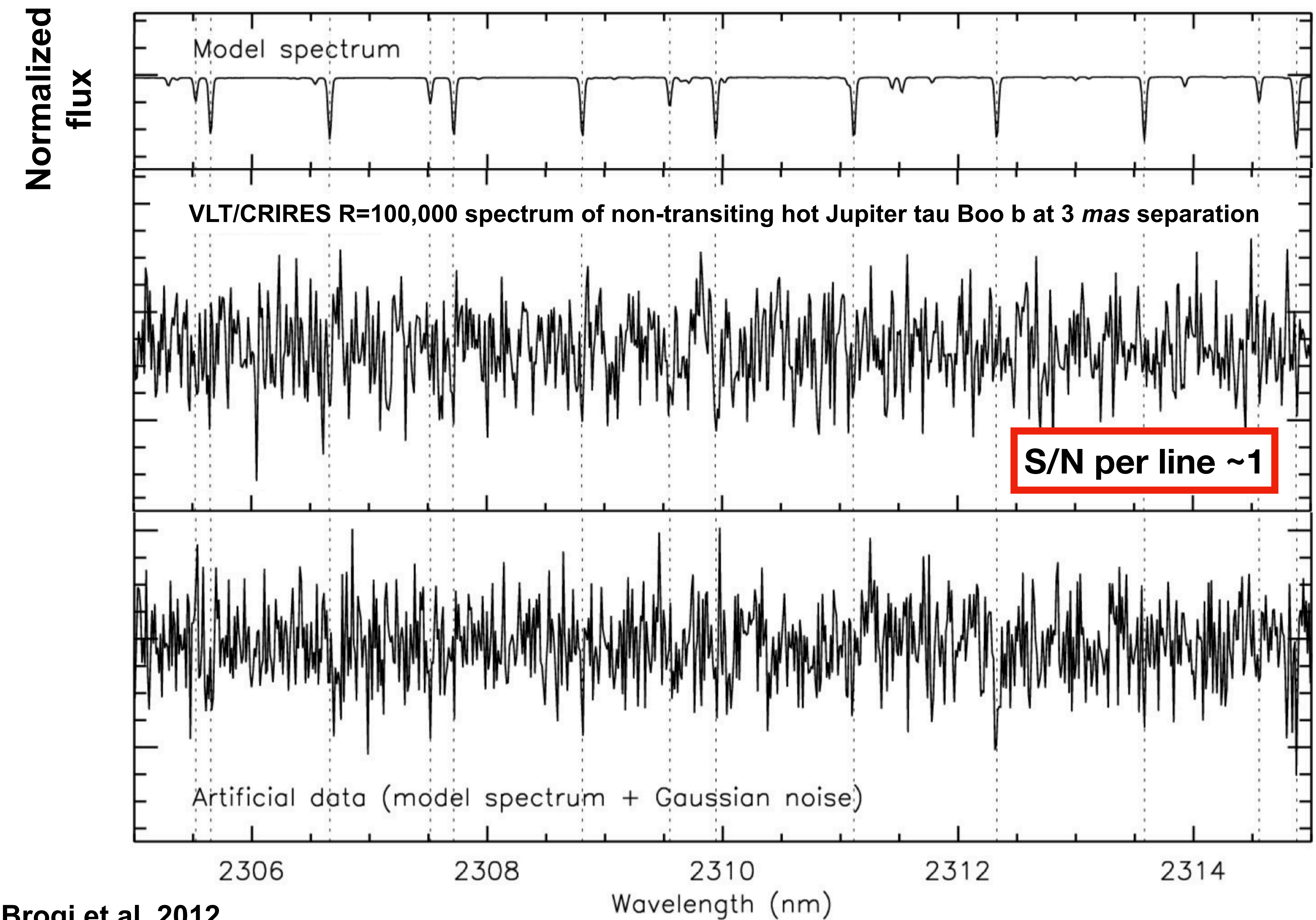


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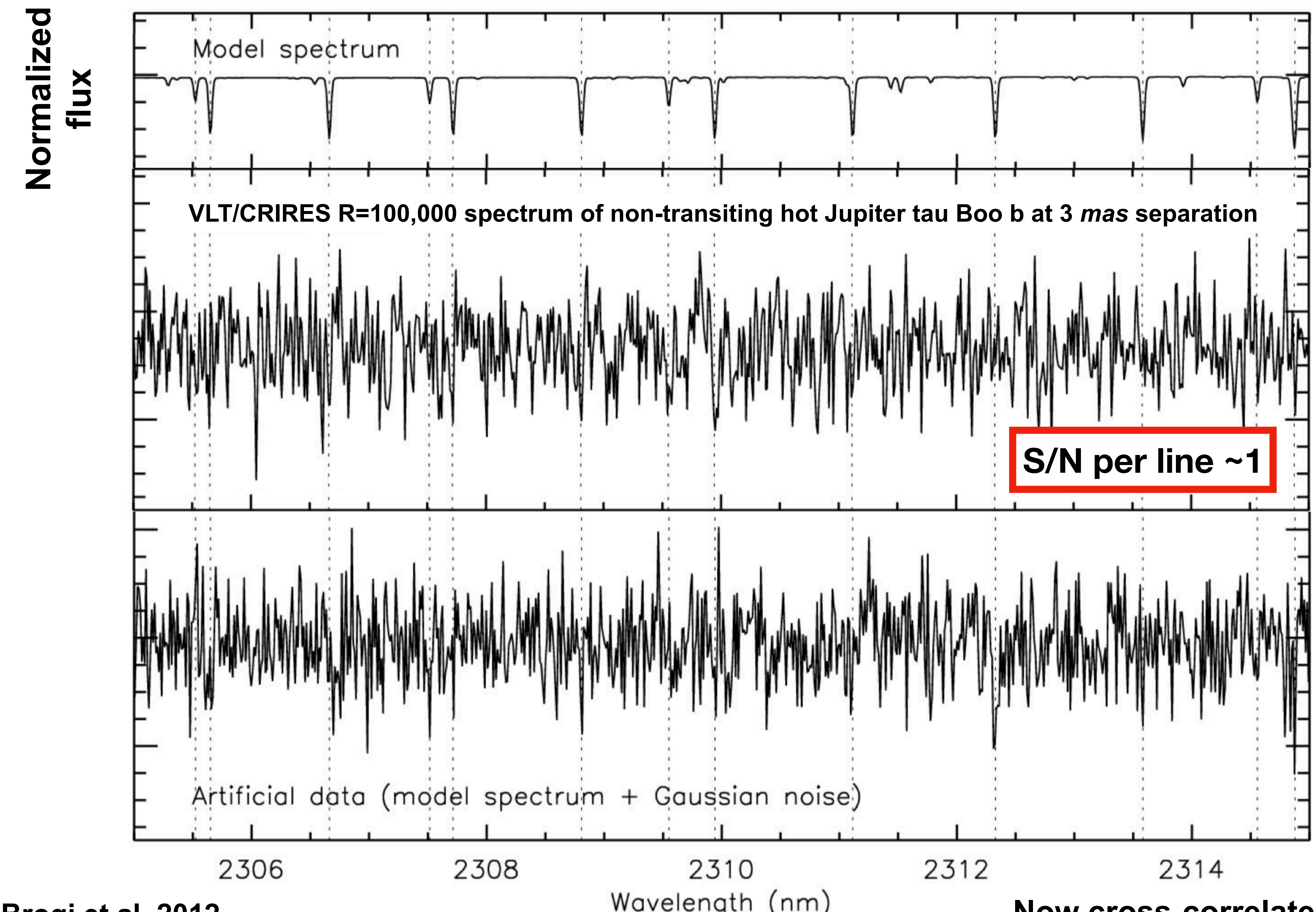
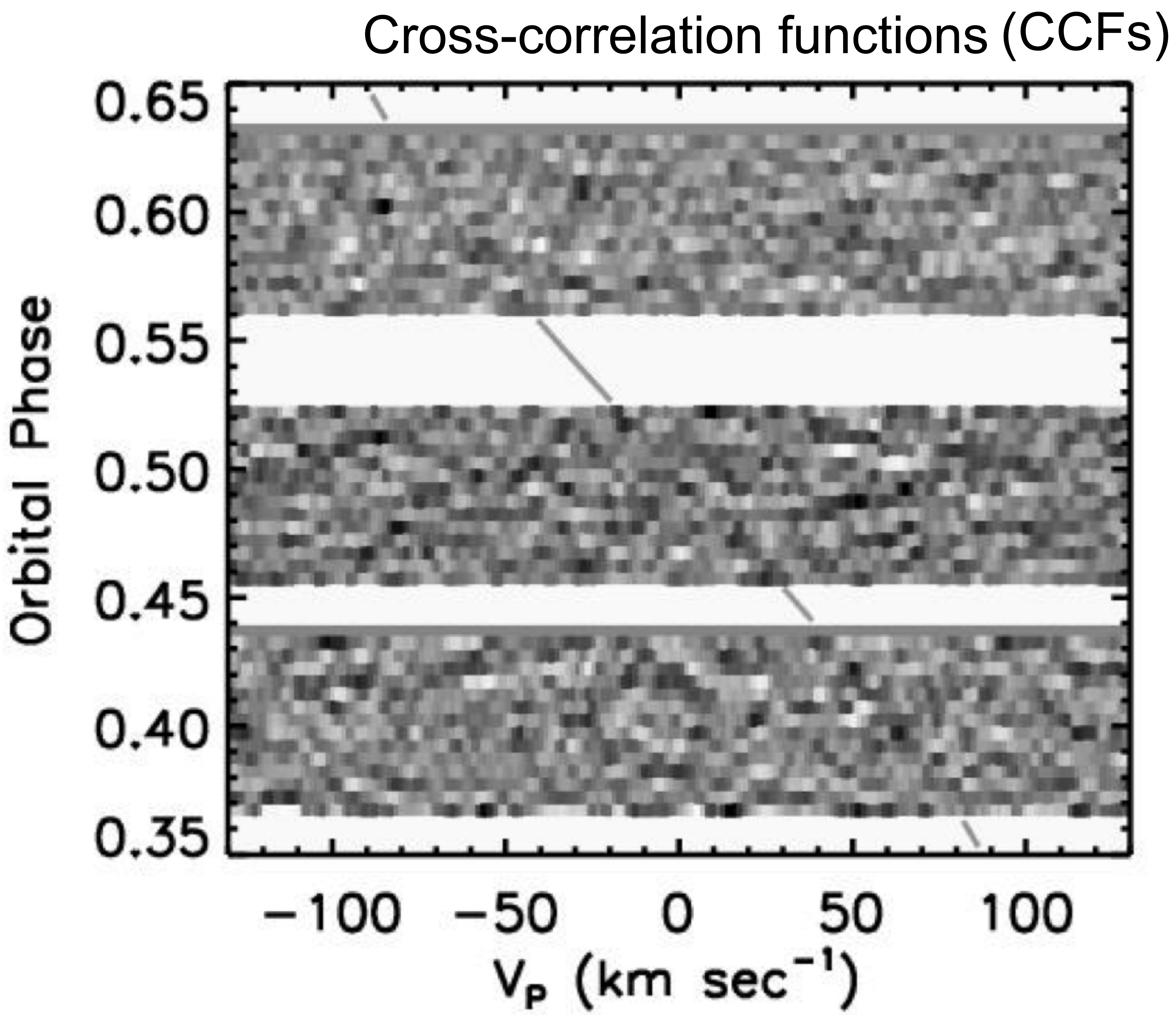



Brogi et al. 2012

**Now cross-correlate…**

# Each cleaned spectrum is cross-correlated with a model of the planet atmosphere



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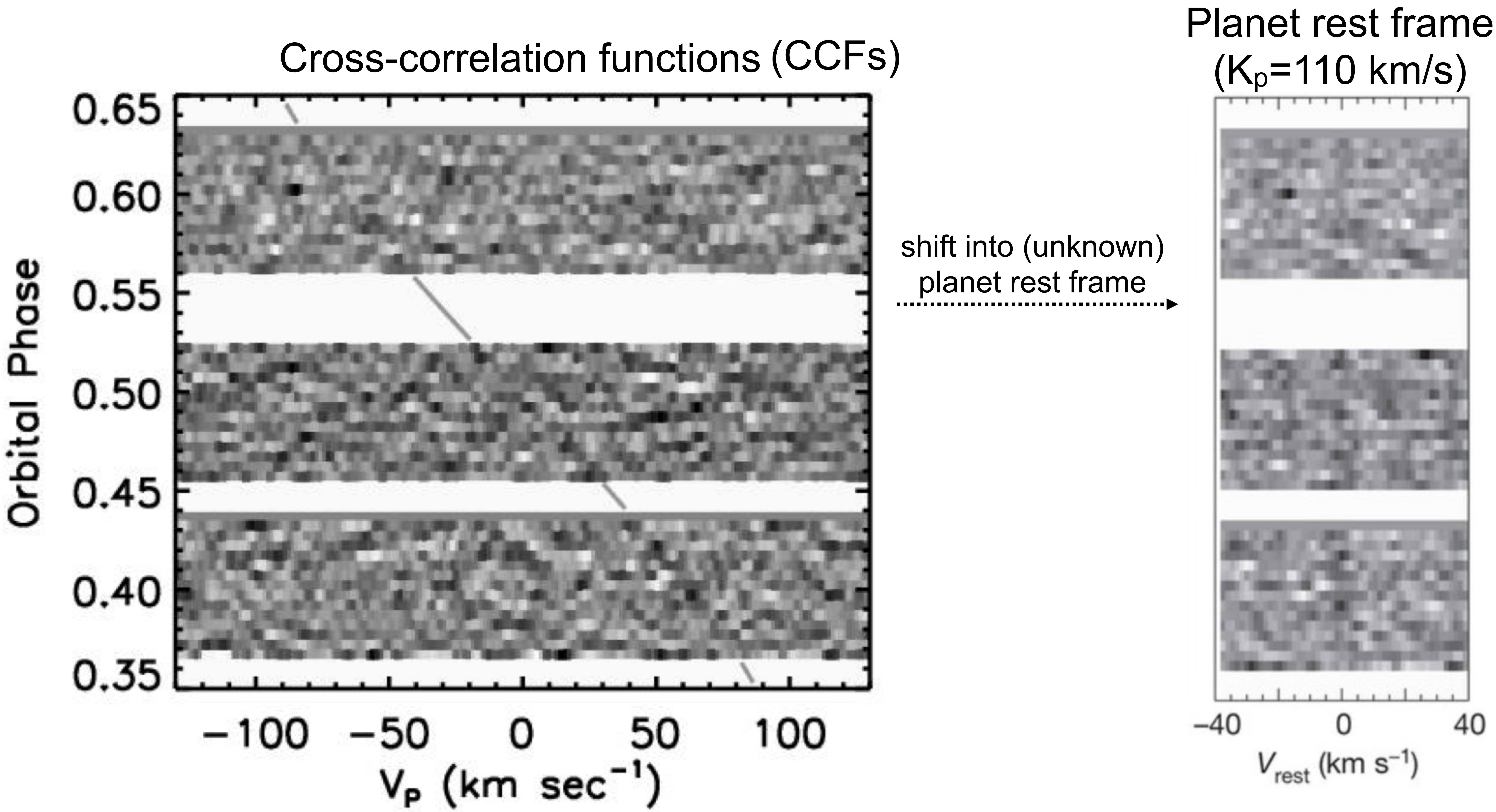

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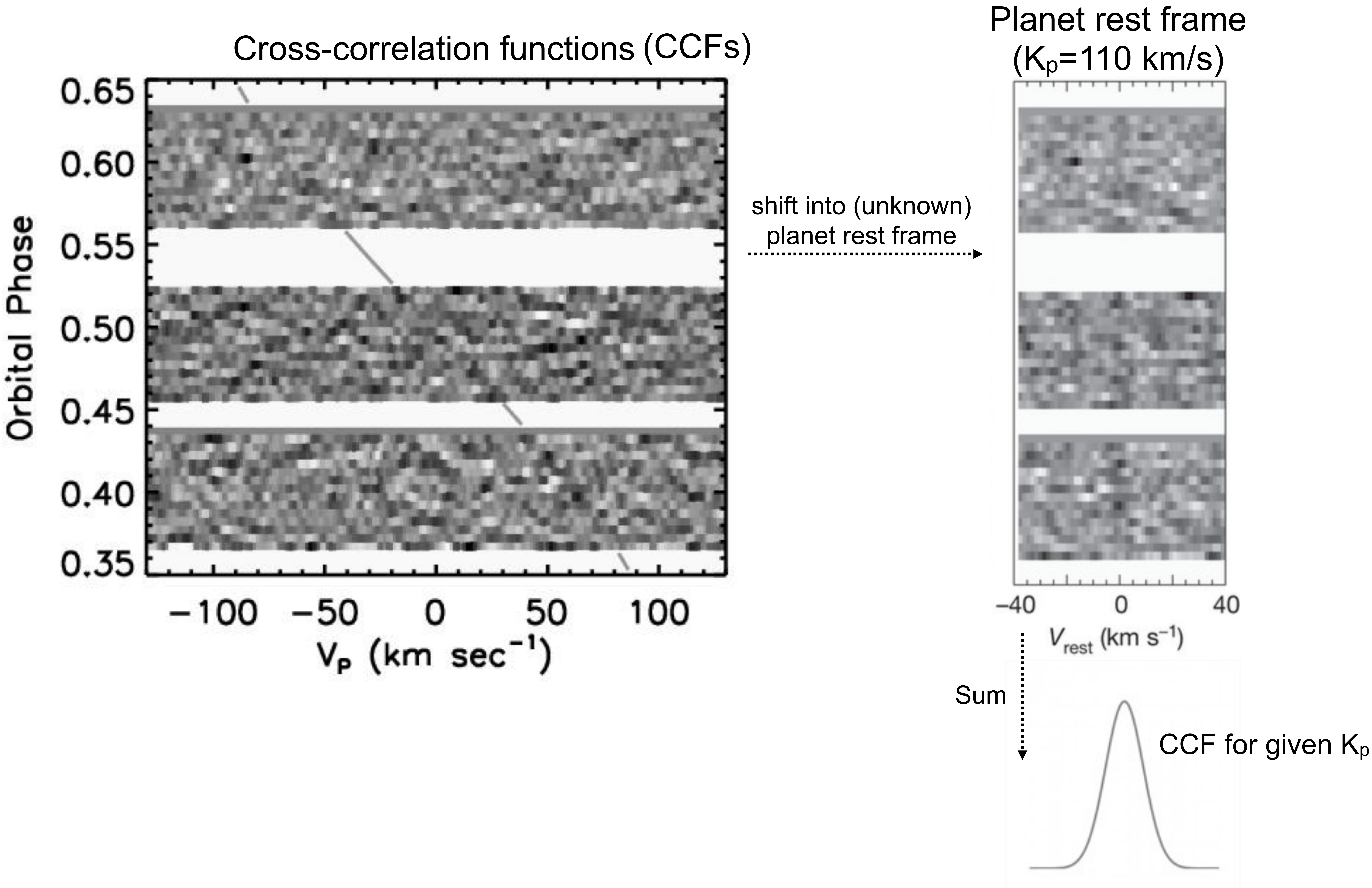
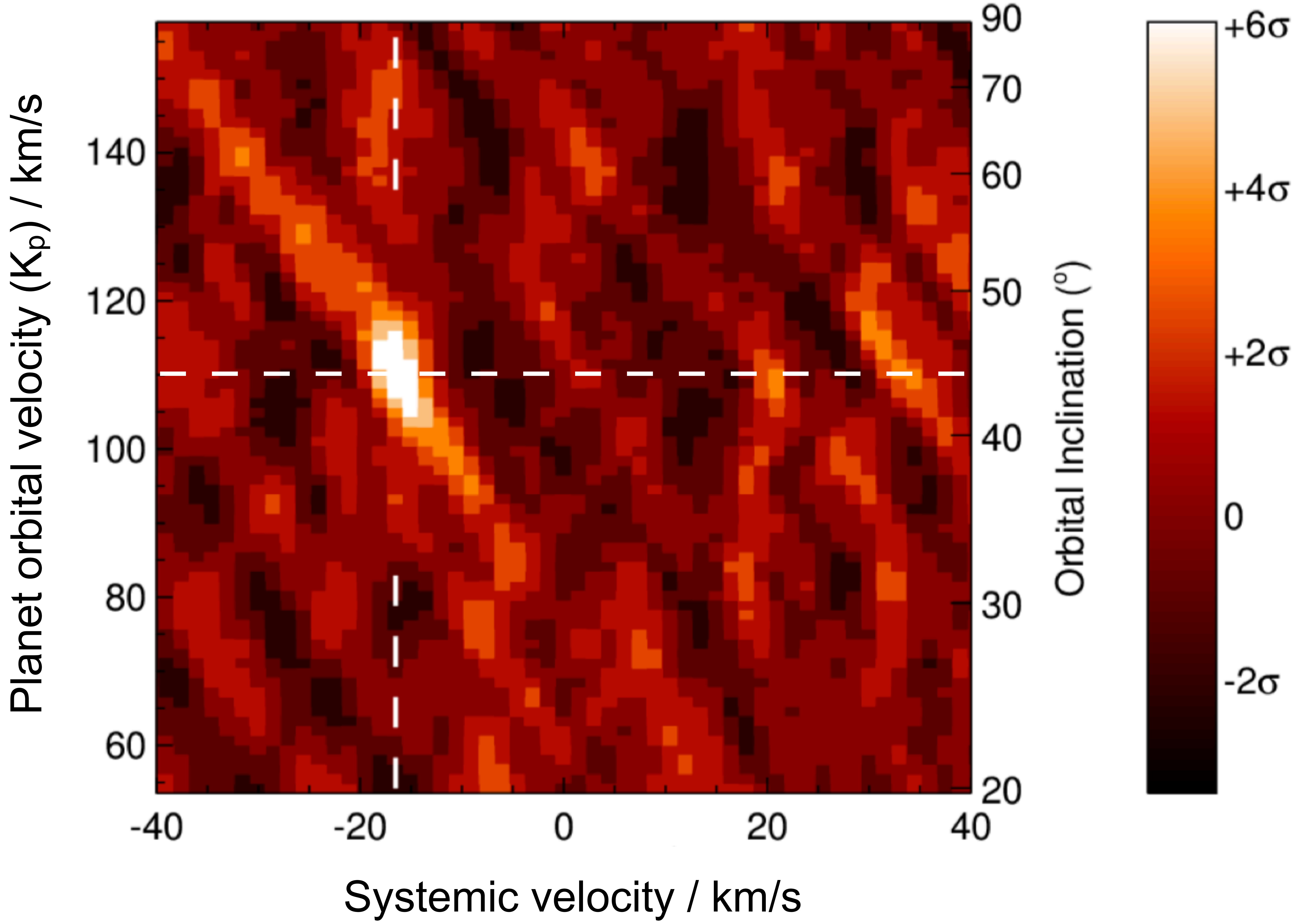


# Planet CCF strength peaks at known systemic velocity of the star-planet system and reveals its orbital velocity and inclination




**CO detected in τ Boo b - a non-transiting planet**

CRIRES/VLT, R=100,000, 18 hours

Brogi, Snellen, de Kok, Albrecht, Birkby et al., *Nature*, 2012

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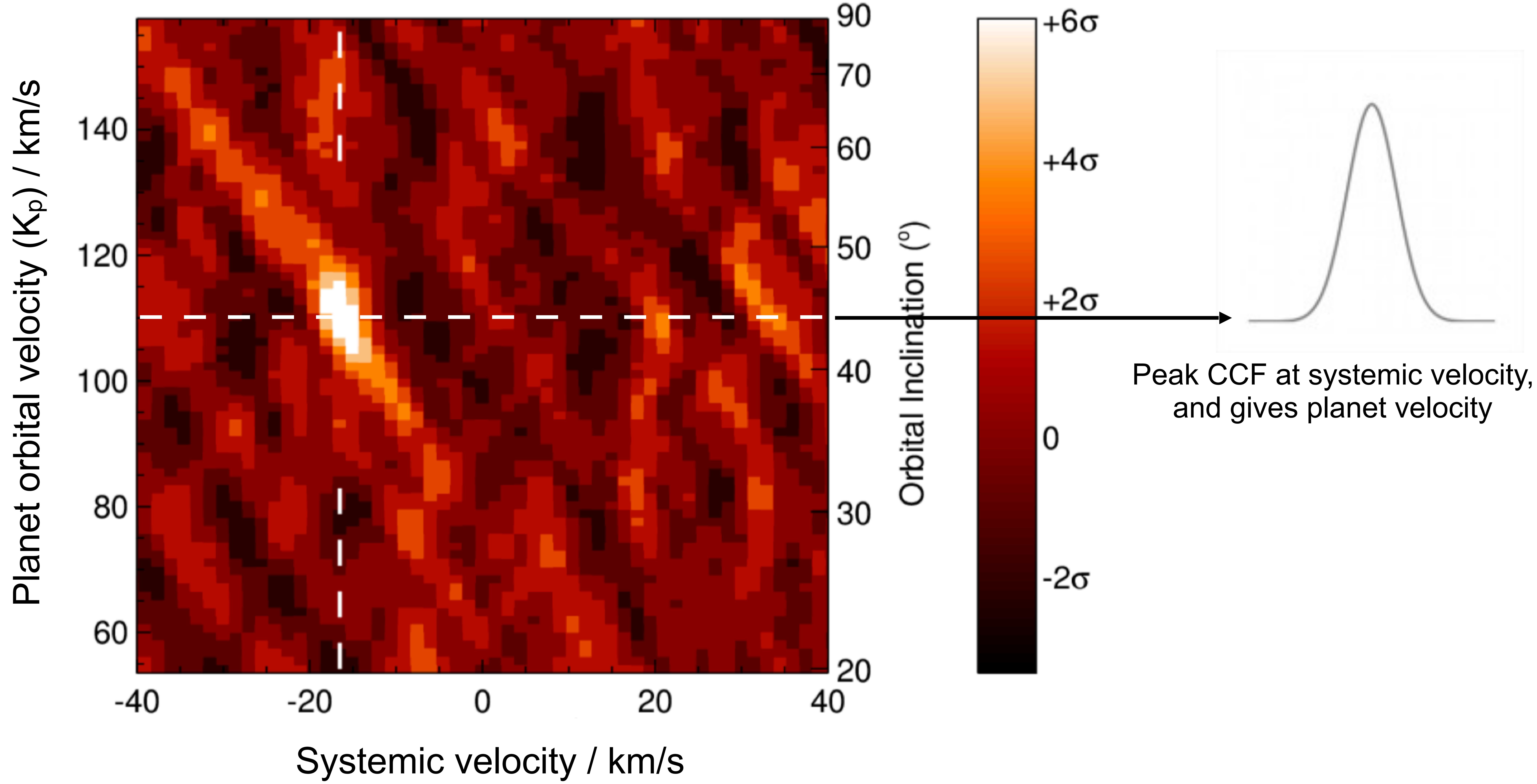


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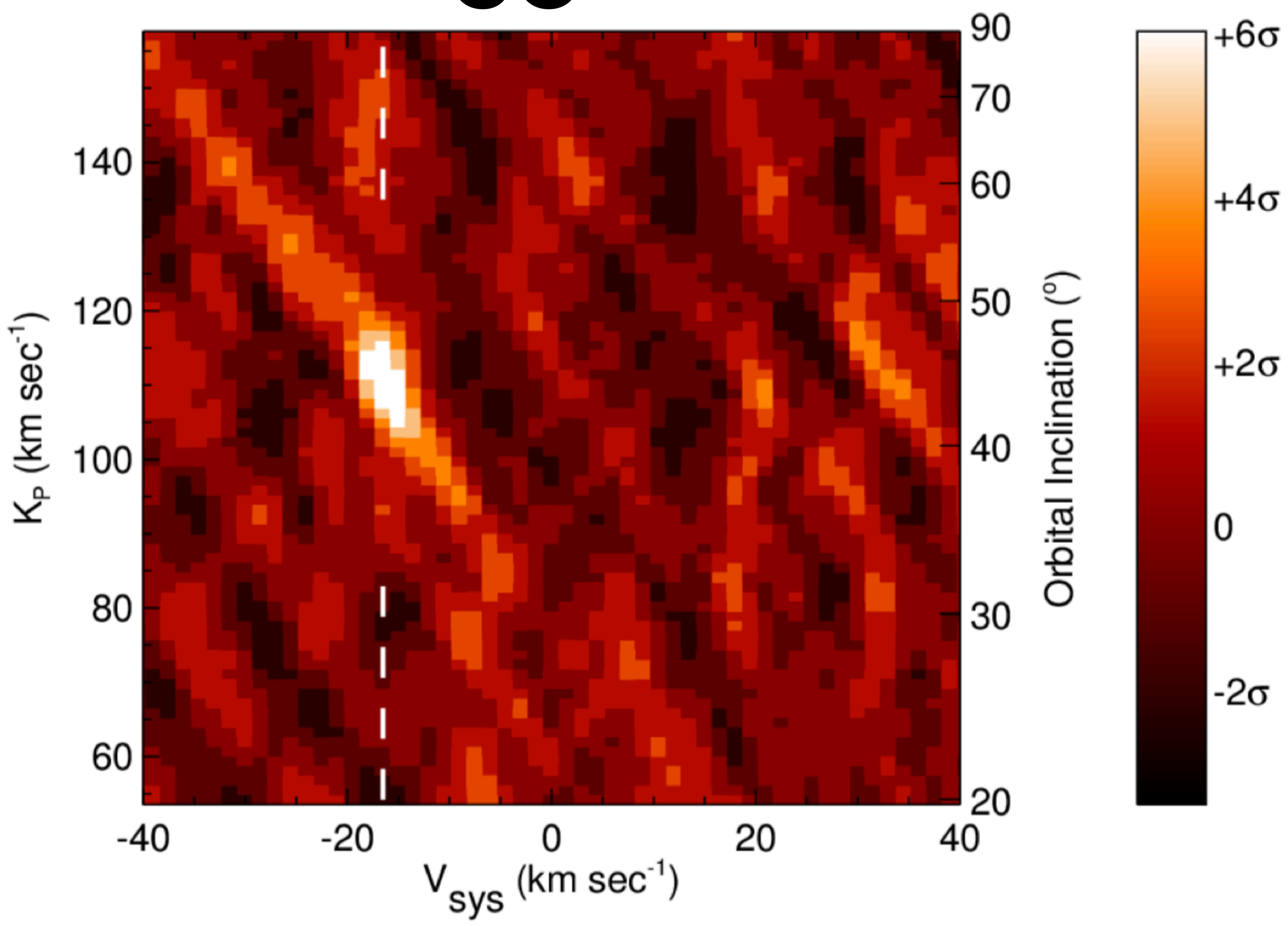
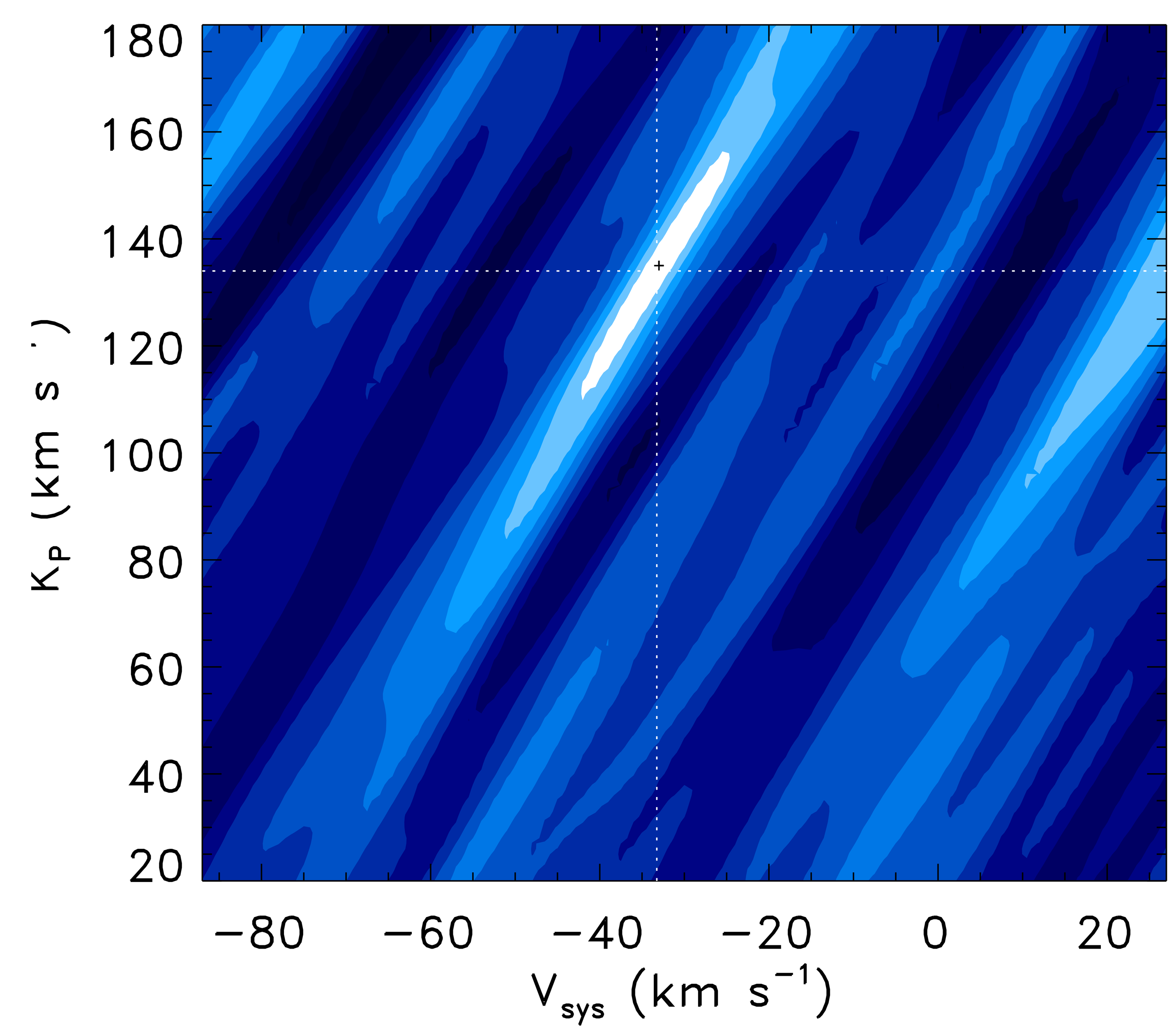
# Multiple species detected at high spectral resolution in hot Jupiters in transmission and emission for transiting and non-transiting planets

## CO



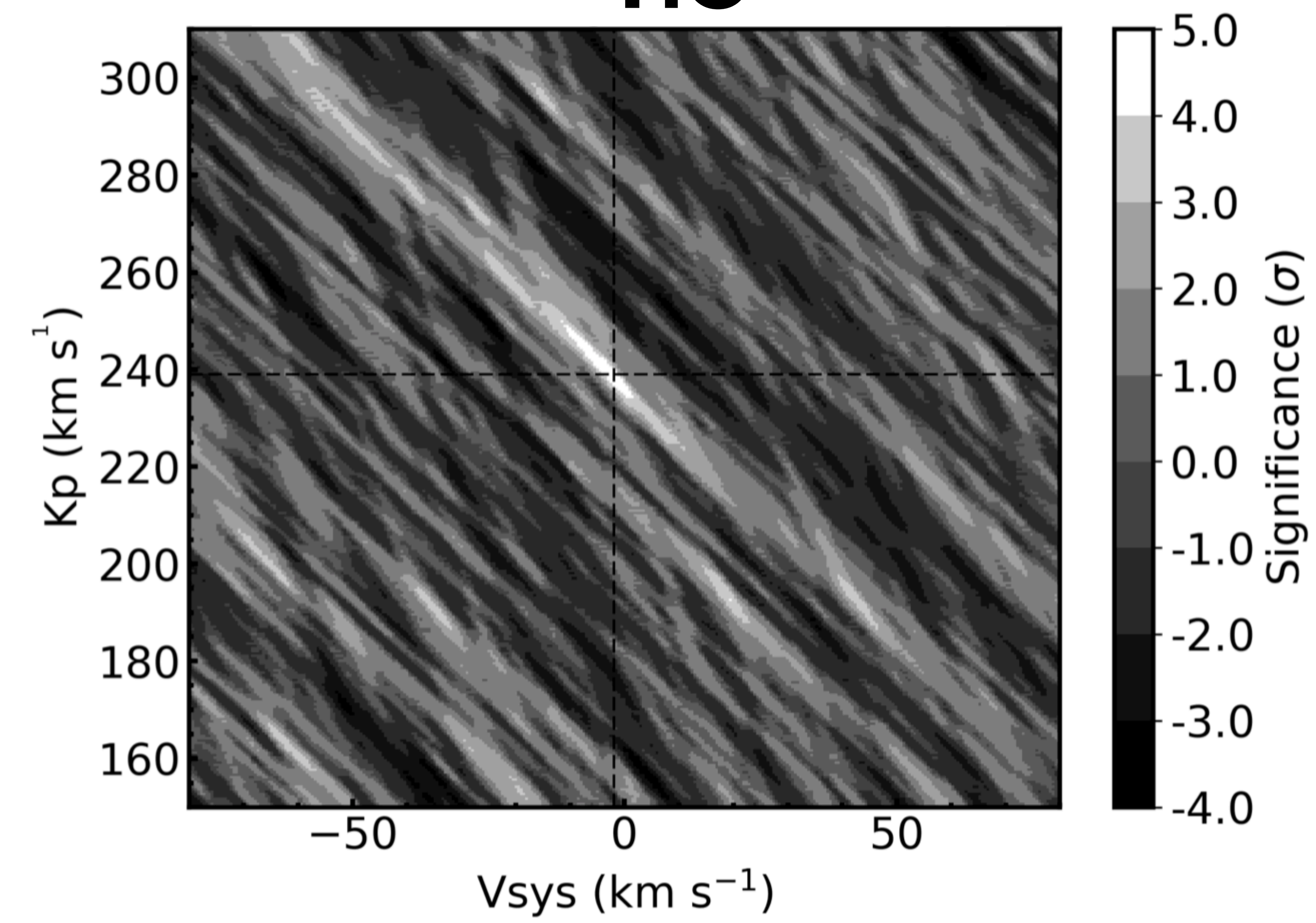

**τ Boo b**: Brogi et al. 2012

## H2O



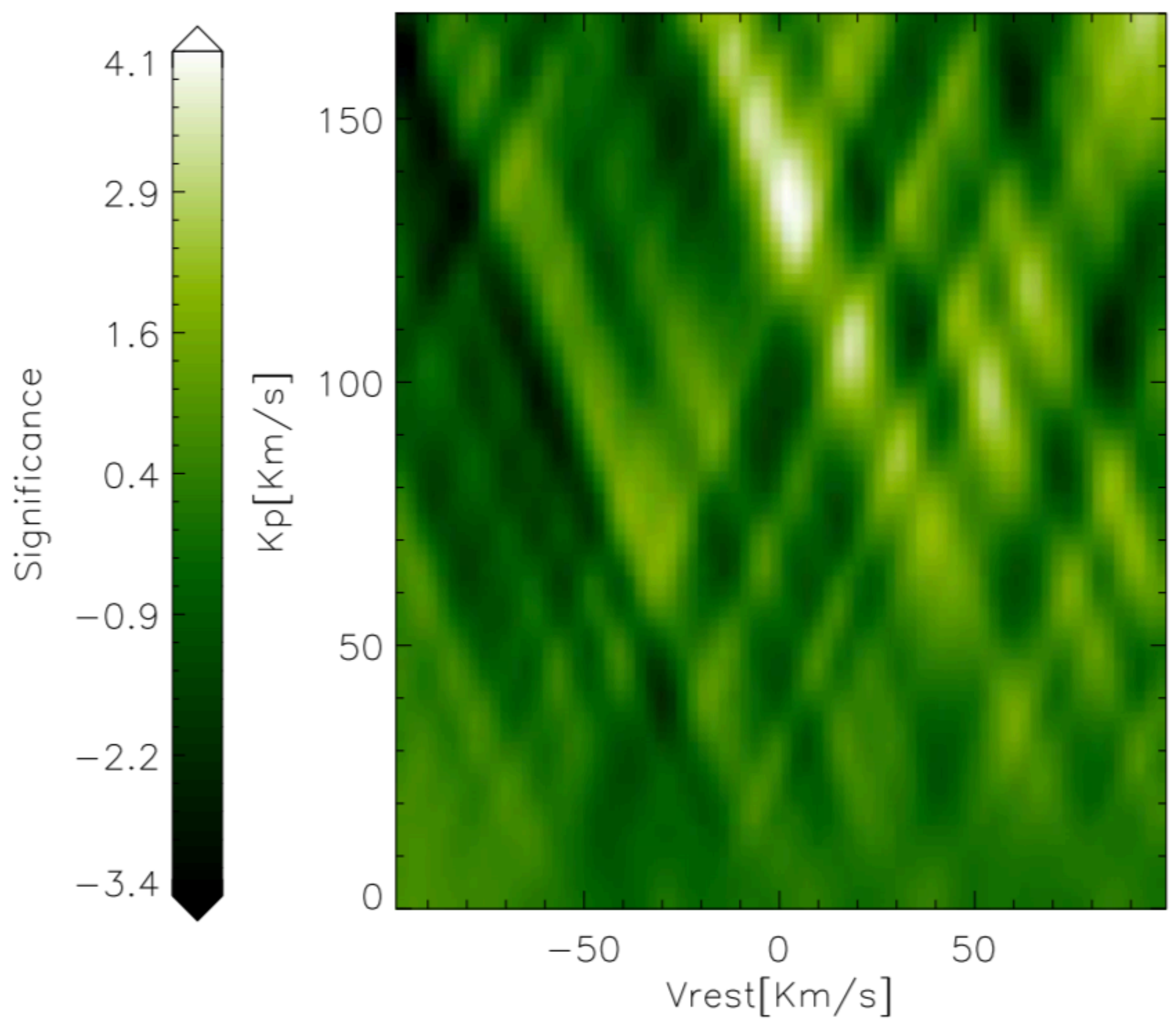

**51 Peg b**: Birkby et al. 2017

## TiO



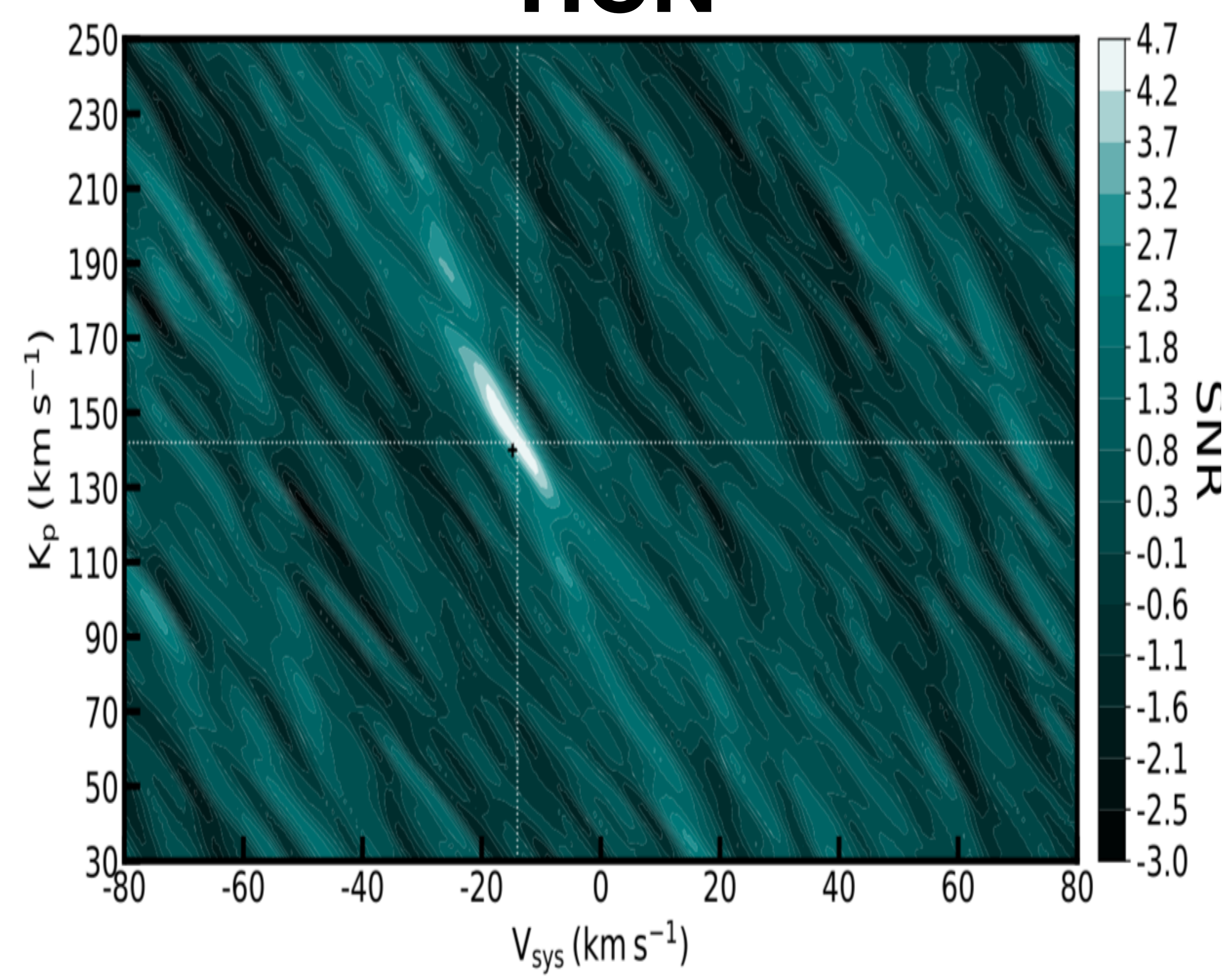

**WASP-33 b:** Nugroho et al. 2017

## CH4



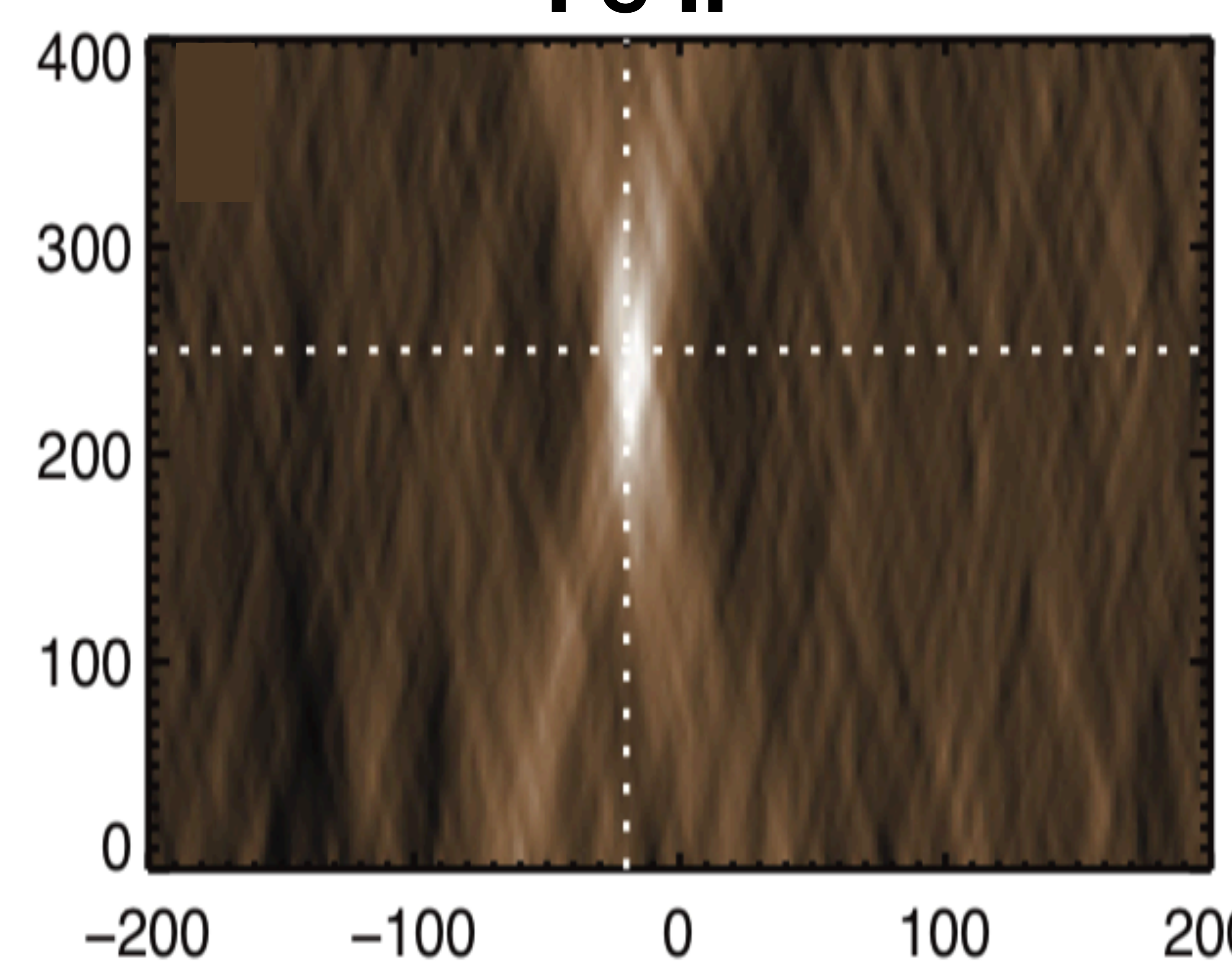

**HD 102195 b**: Guilluy et al. 2019

## HCN



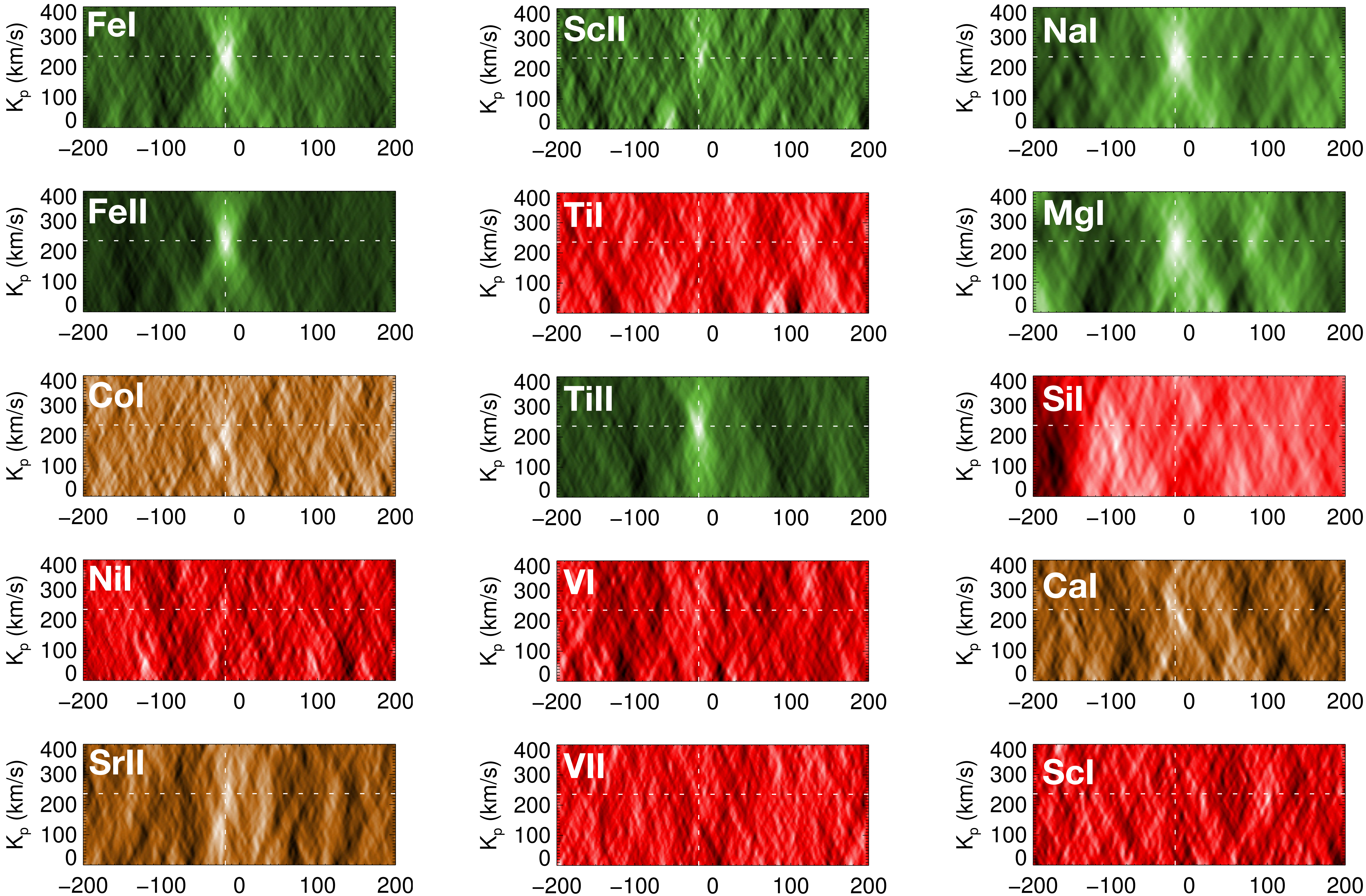

**HD 209458 b**: Hawker et al. 2018

## Fe II



**KELT-9 b**: Hoeijmakers et al. 2018

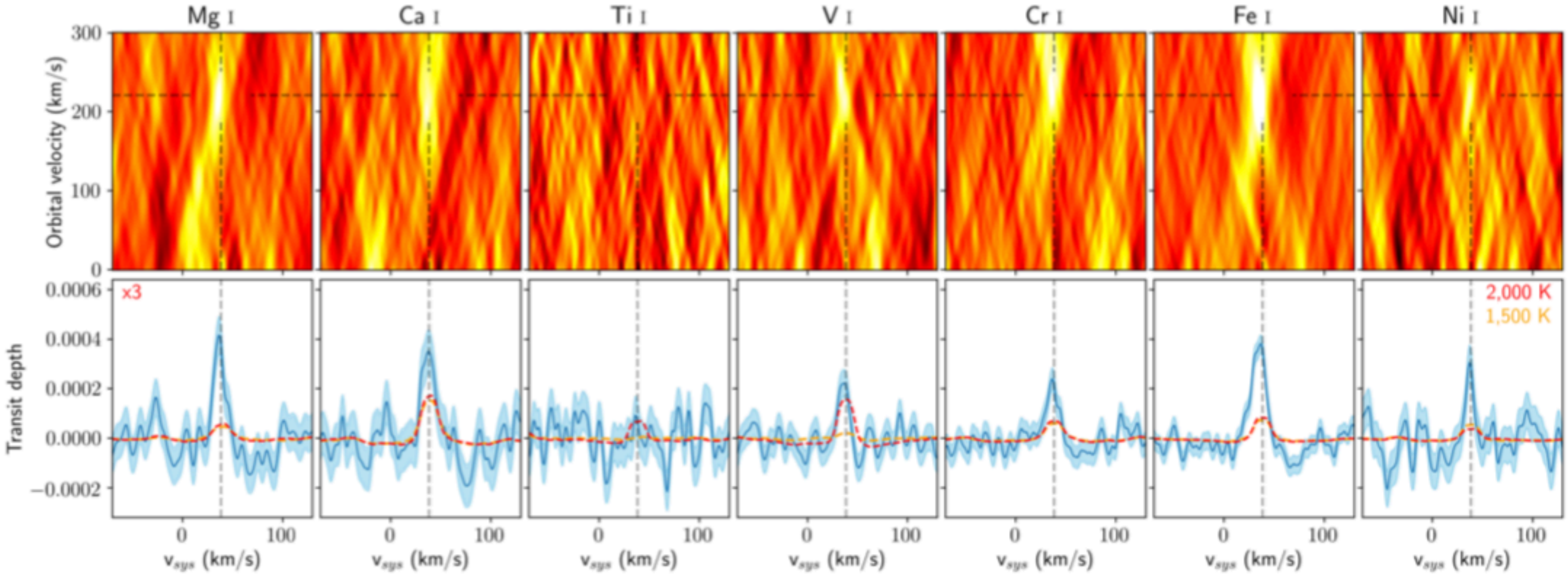
# Create a spectral atlas of a hot Jupiter by searching through periodic table




KELT-9 b (Hoeijmakers et al. 2019)

# WASP-121 b observed with HARPS

See Hoeijmakers, Seidel, Pino et al. 2020 and Gibson et al. 2020



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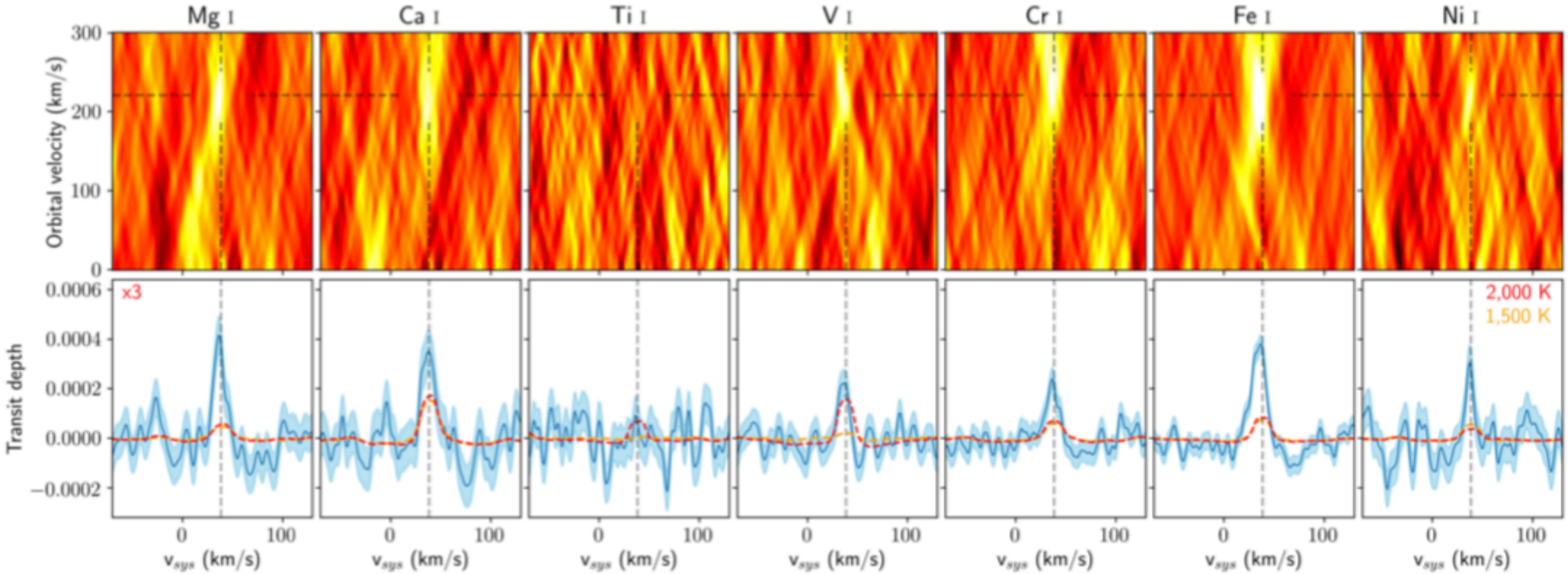
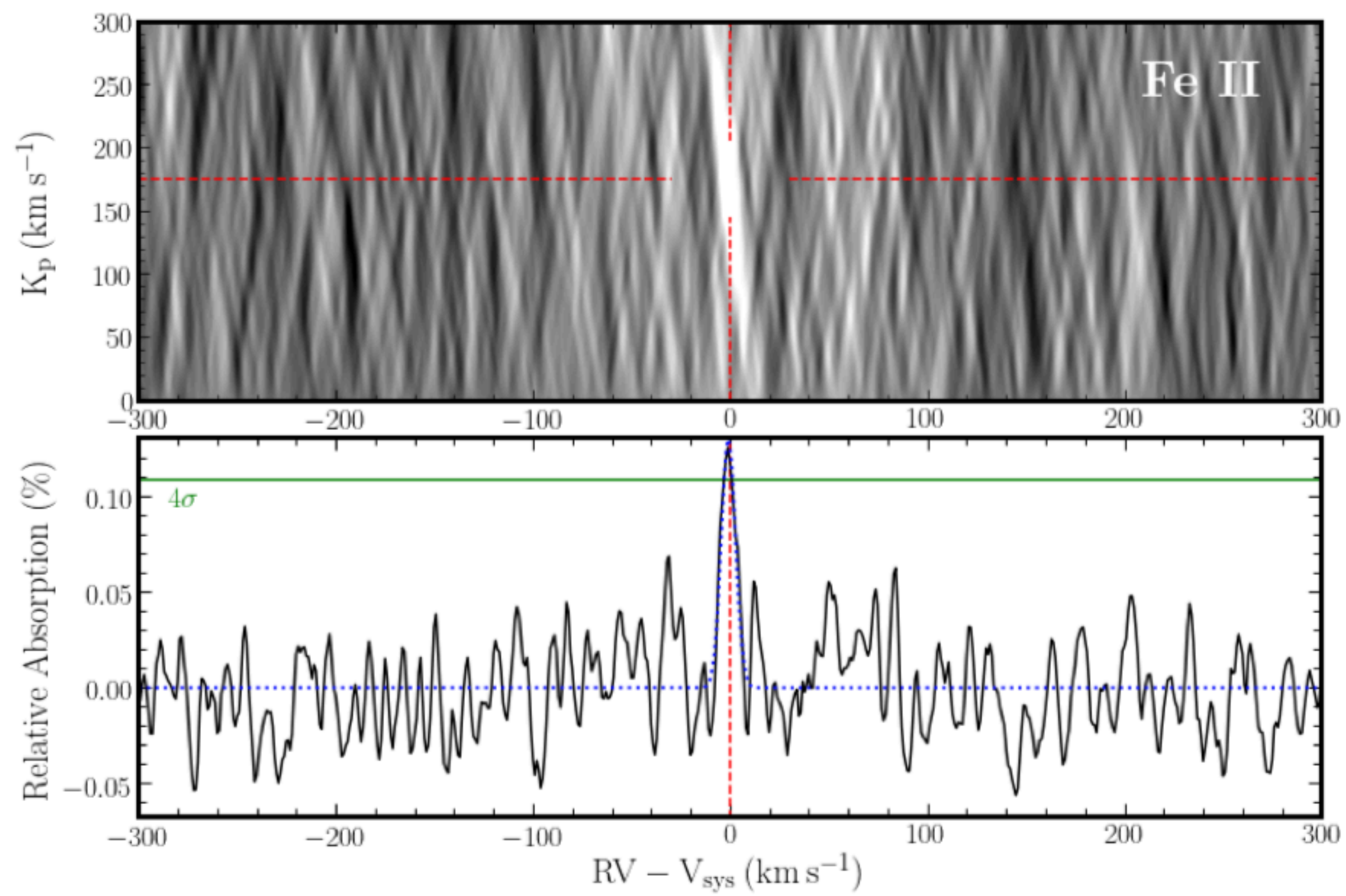


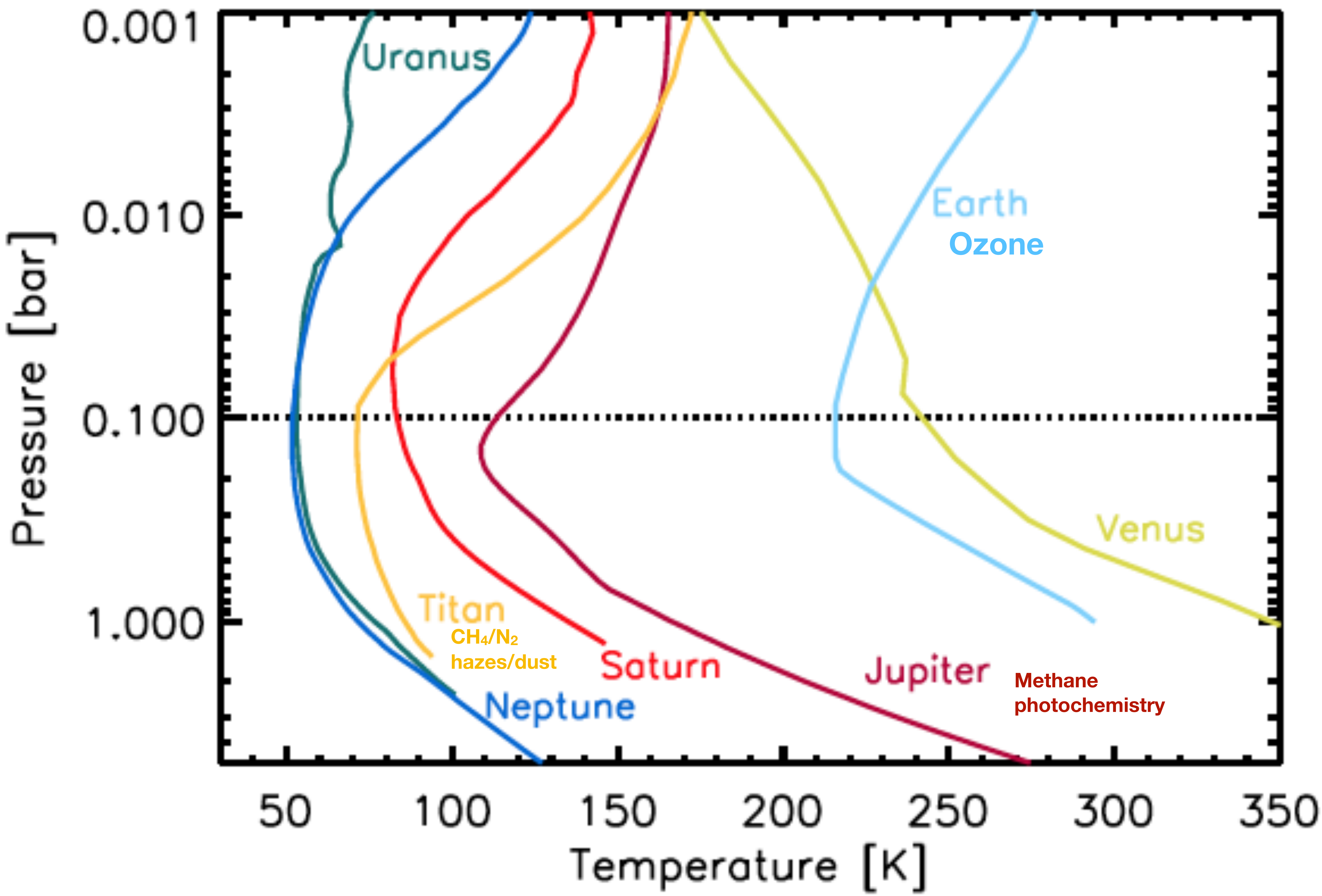

Transmission spectrum of MASCARA-2 b observed with **EXPRES**

- reveals Cr II and Mg I
- confirms Fe I, Fe II and Na I

Hoeijmakers, Cabot, Zhao et al. 2020

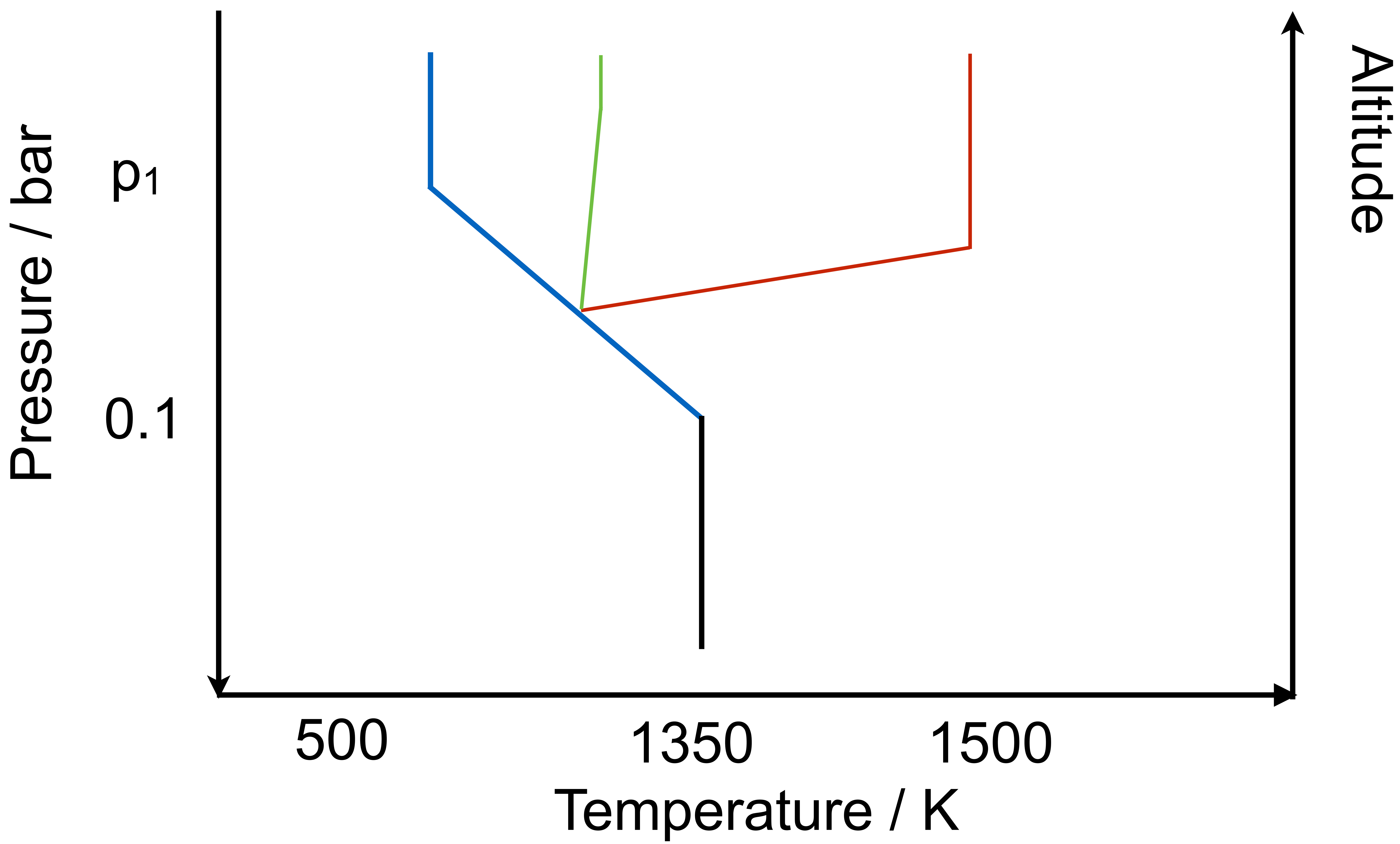


# Stratospheres or inversion layers are common in the Solar system

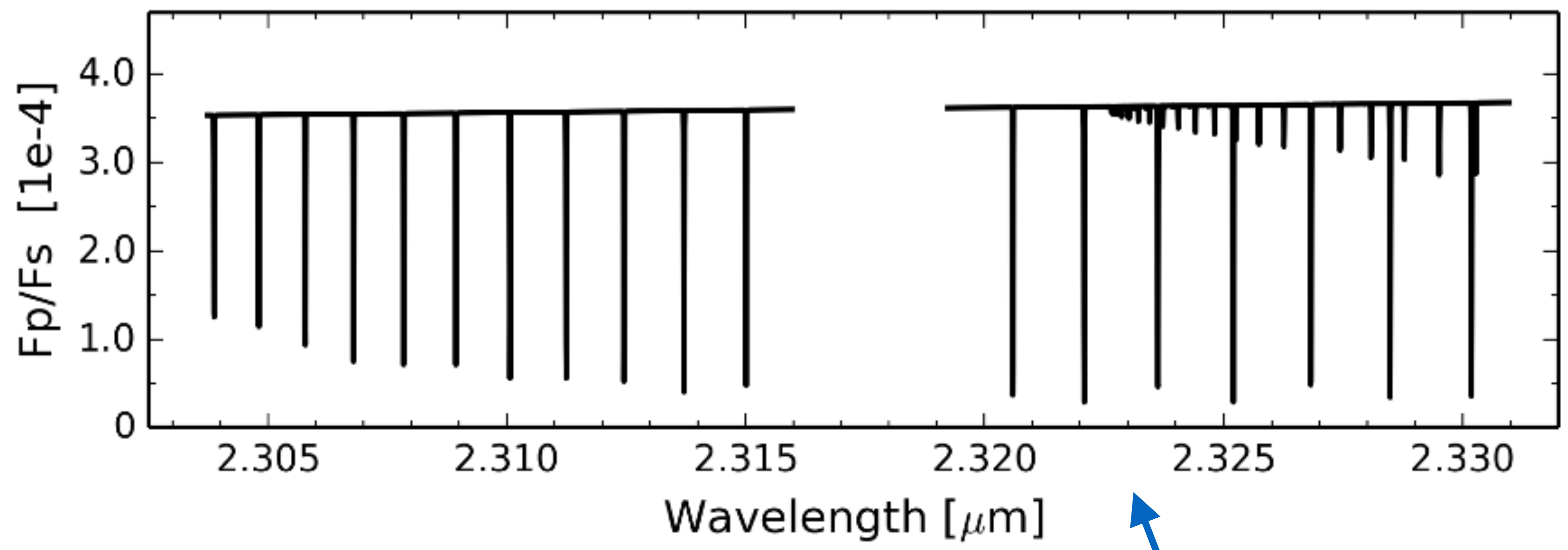


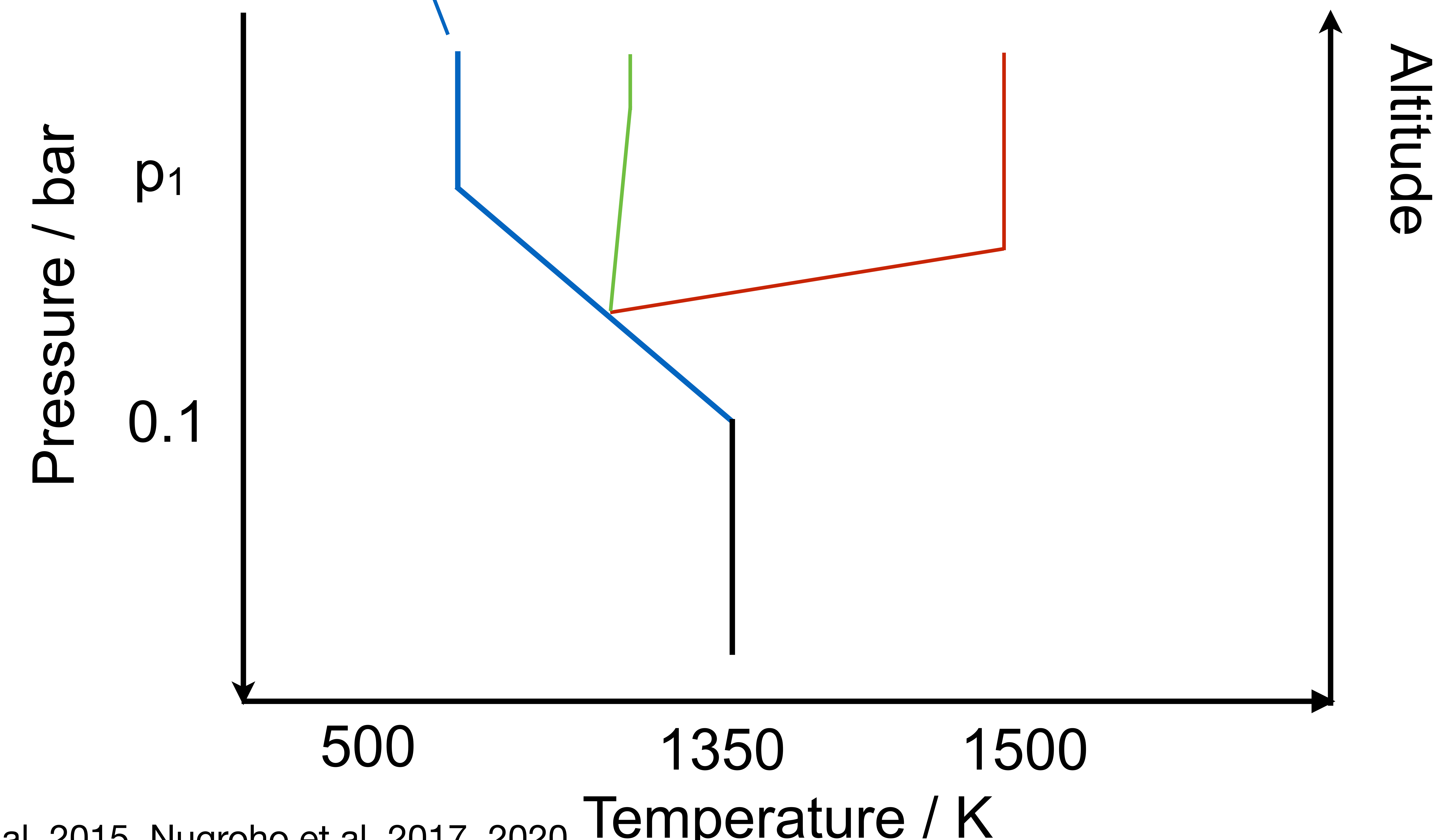

Robinson & Catling 2013

# Inversion layers are revealed by many emission lines at high spectral resolution



# Inversion layers are revealed by many emission lines at high spectral resolution




Schwarz et al. 2015, Nugroho et al. 2017, 2020

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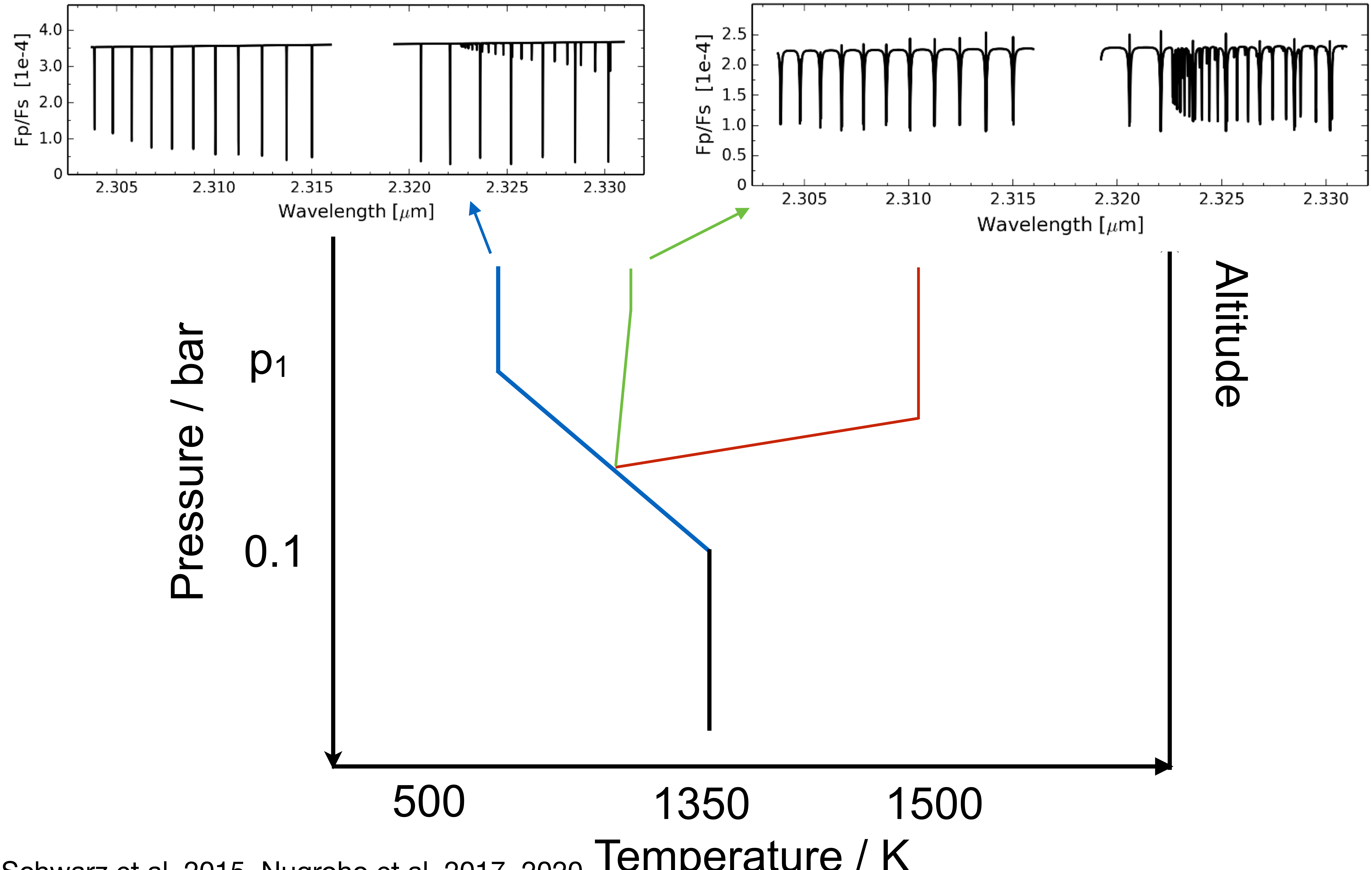
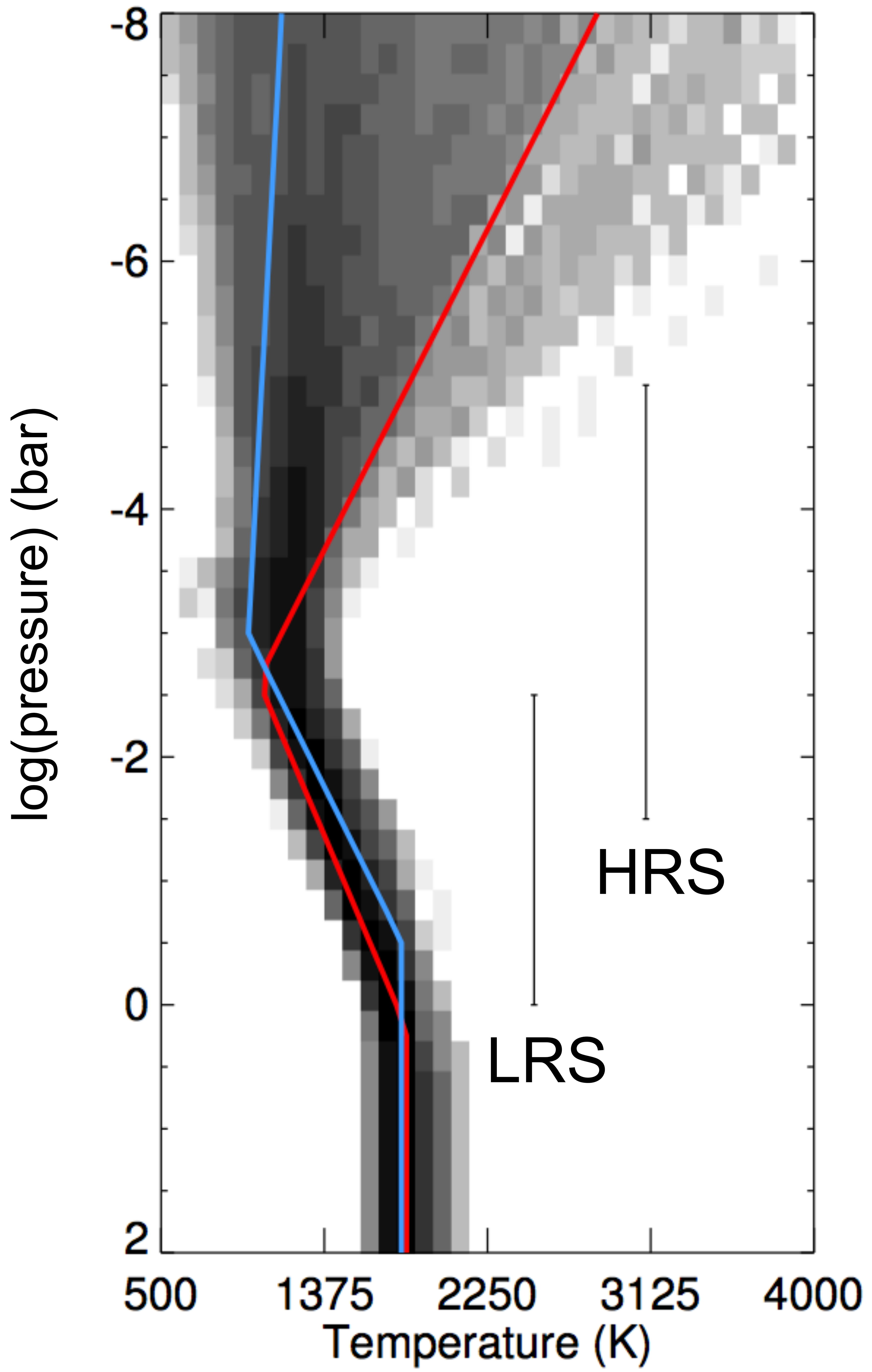



Schwarz et al. 2015, Nugroho et al. 2017, 2020

# Inversion layers are revealed by many emission lines at high spectral resolution


Schwarz et al. 2015, Nugroho et al. 2017, 2020

# Multi-resolution spectroscopy helps break degeneracy in composition and structure of the atmosphere




**Brogi & Line 2018**, see also Piskorz et al. 2018

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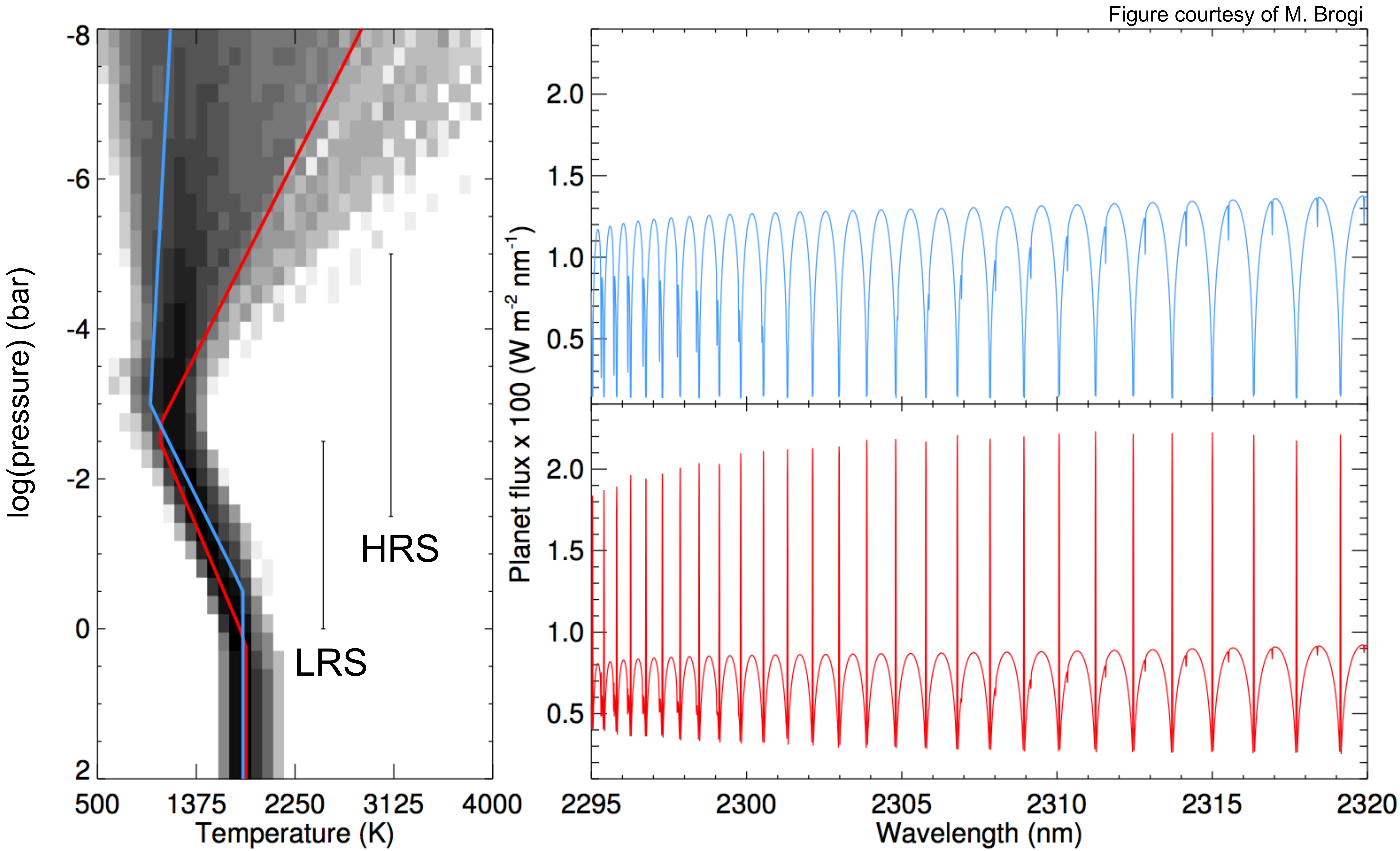
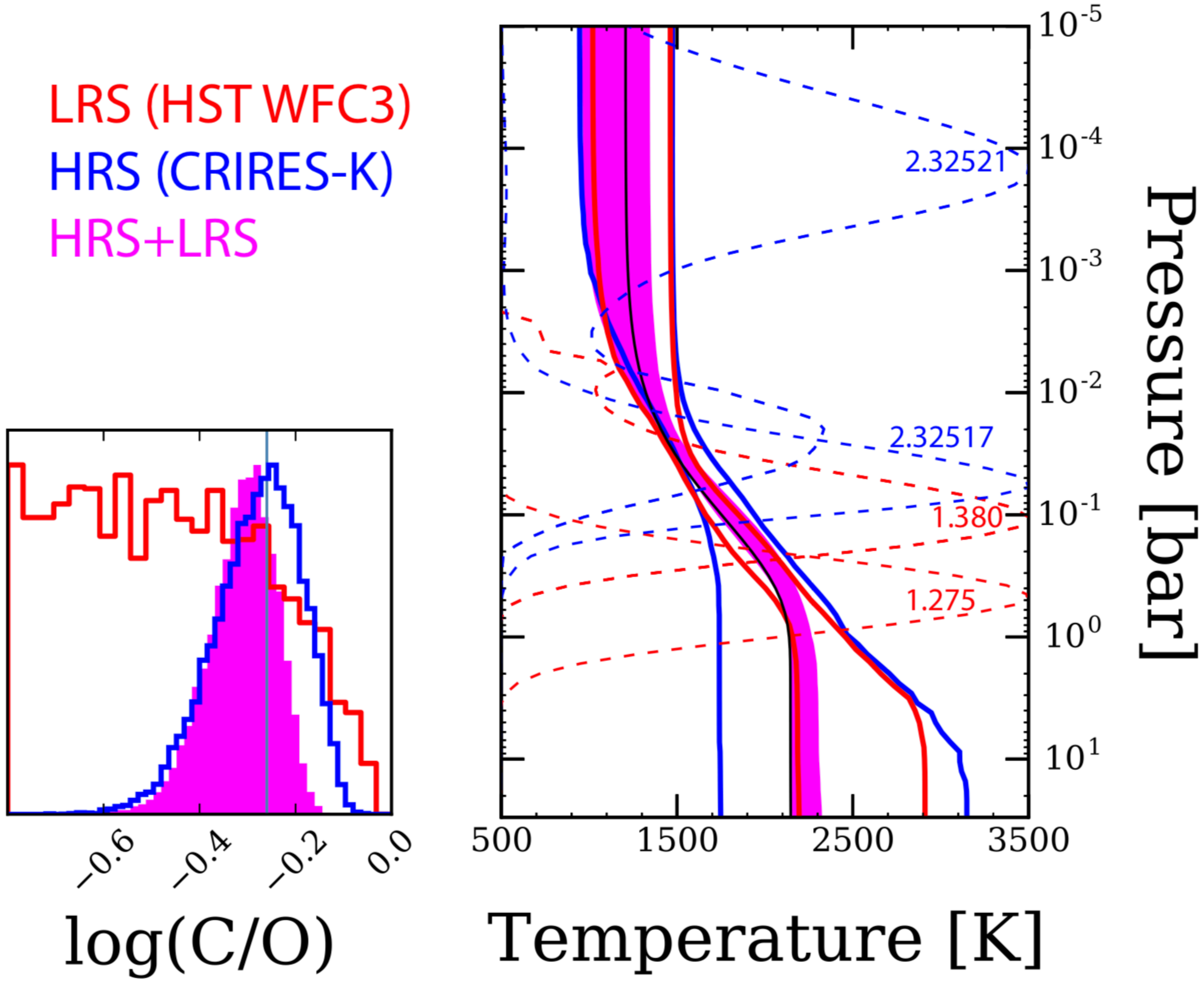



**Brogi & Line 2018**, see also Piskorz et al. 2018

# Combine multi-resolution observations using likelihood functions to reach most stringent constraints




Brogi & Line 2018

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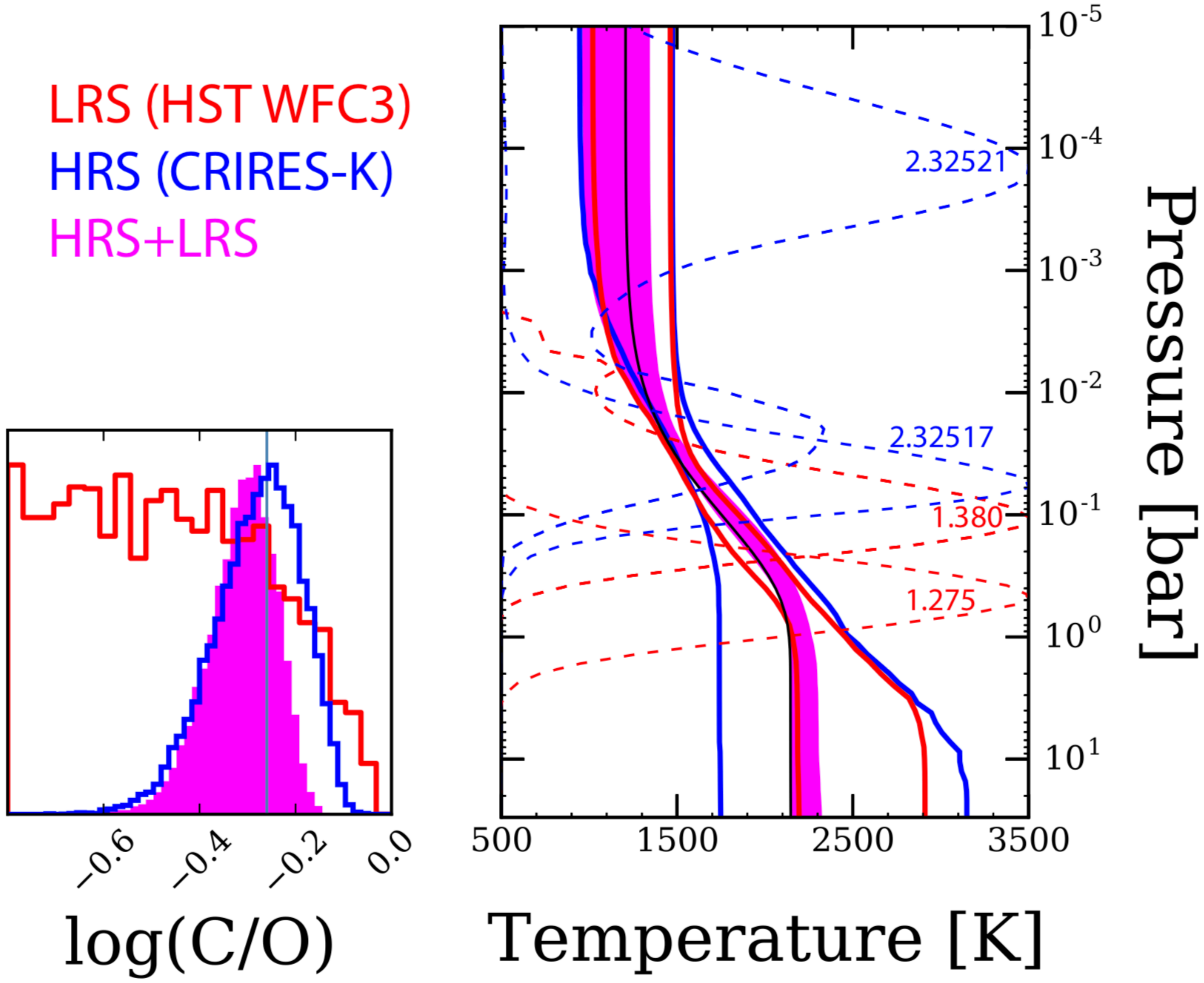


Brogi & Line 2018

CCF

$$\chi^2 = \frac{1}{\beta^2}\left[\sum \frac{f_i^2}{\sigma_i^2} + \alpha^2 \sum \frac{m_i^2}{\sigma_i^2} - 2\alpha \boxed{\sum \frac{f_i m_i}{\sigma_i^2}}\right]$$

f=data, m=model, σ=uncertainties

Gibson et al. 2020

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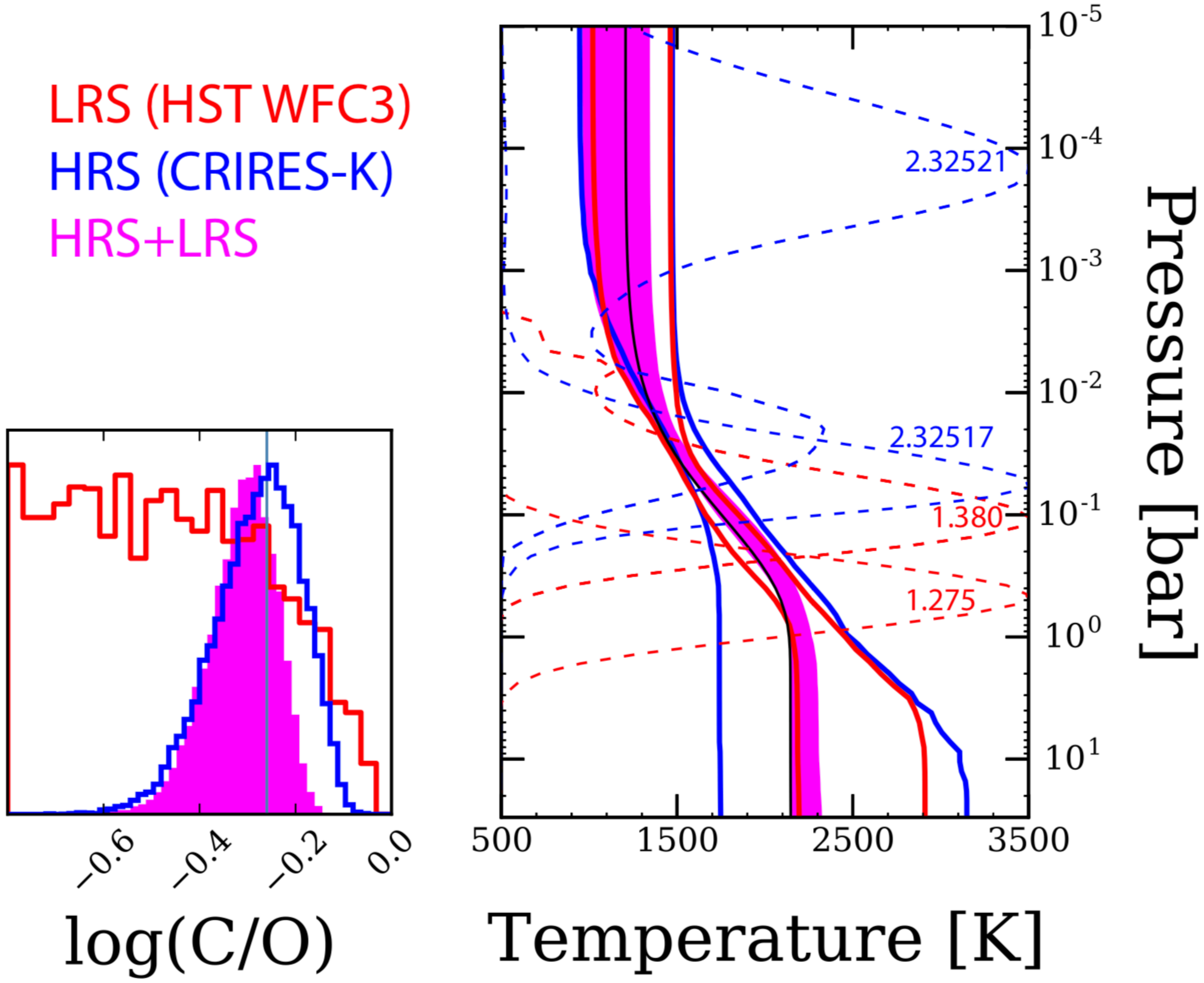
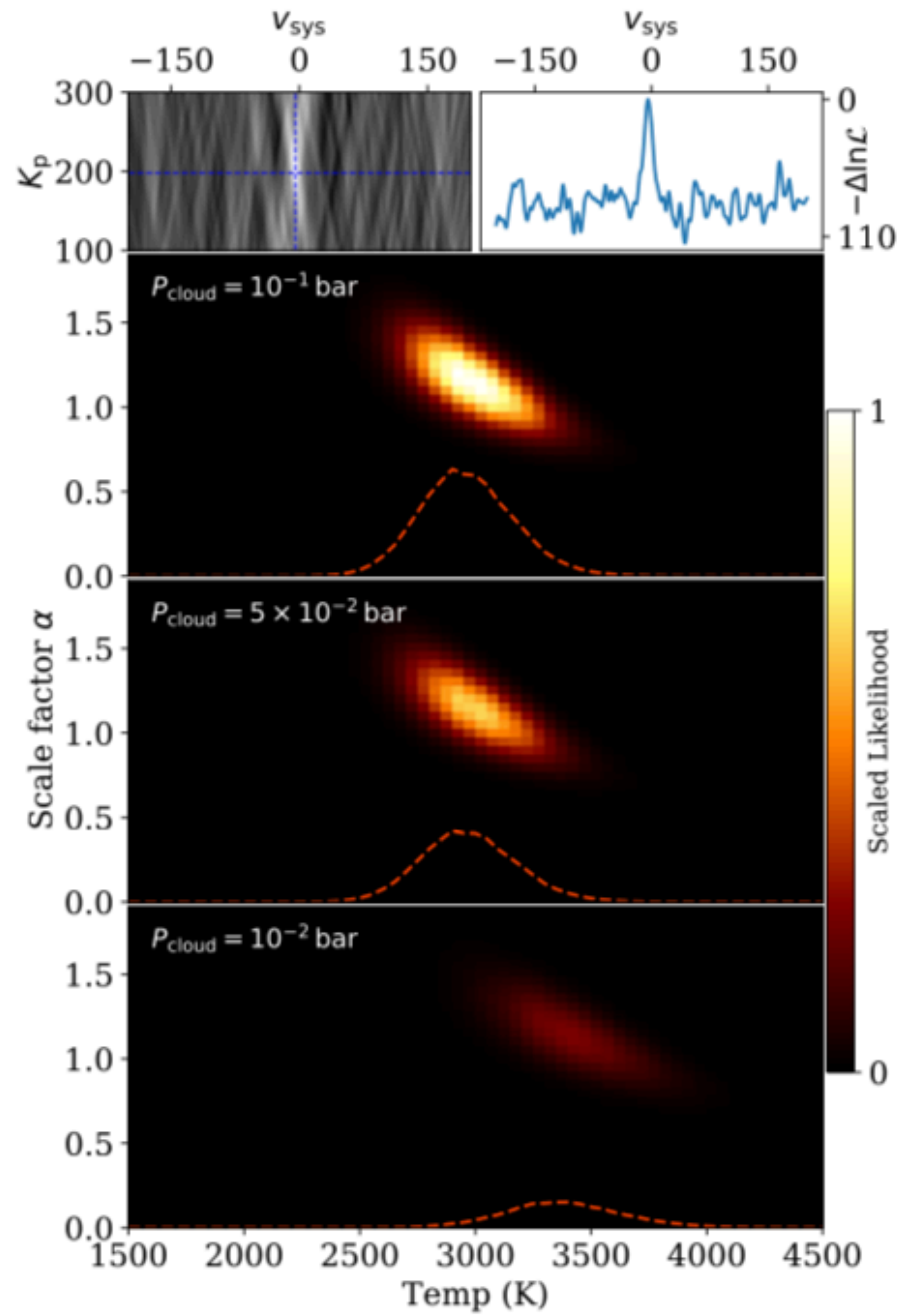



Brogi & Line 2018

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f=data, m=model, σ=uncertainties

Gibson et al. 2020

# High resolution spectroscopy can access spectral lines even in the presence of clouds

Simulated water spectrum for super-Earth GJ 1214 b with progressively higher cloud decks

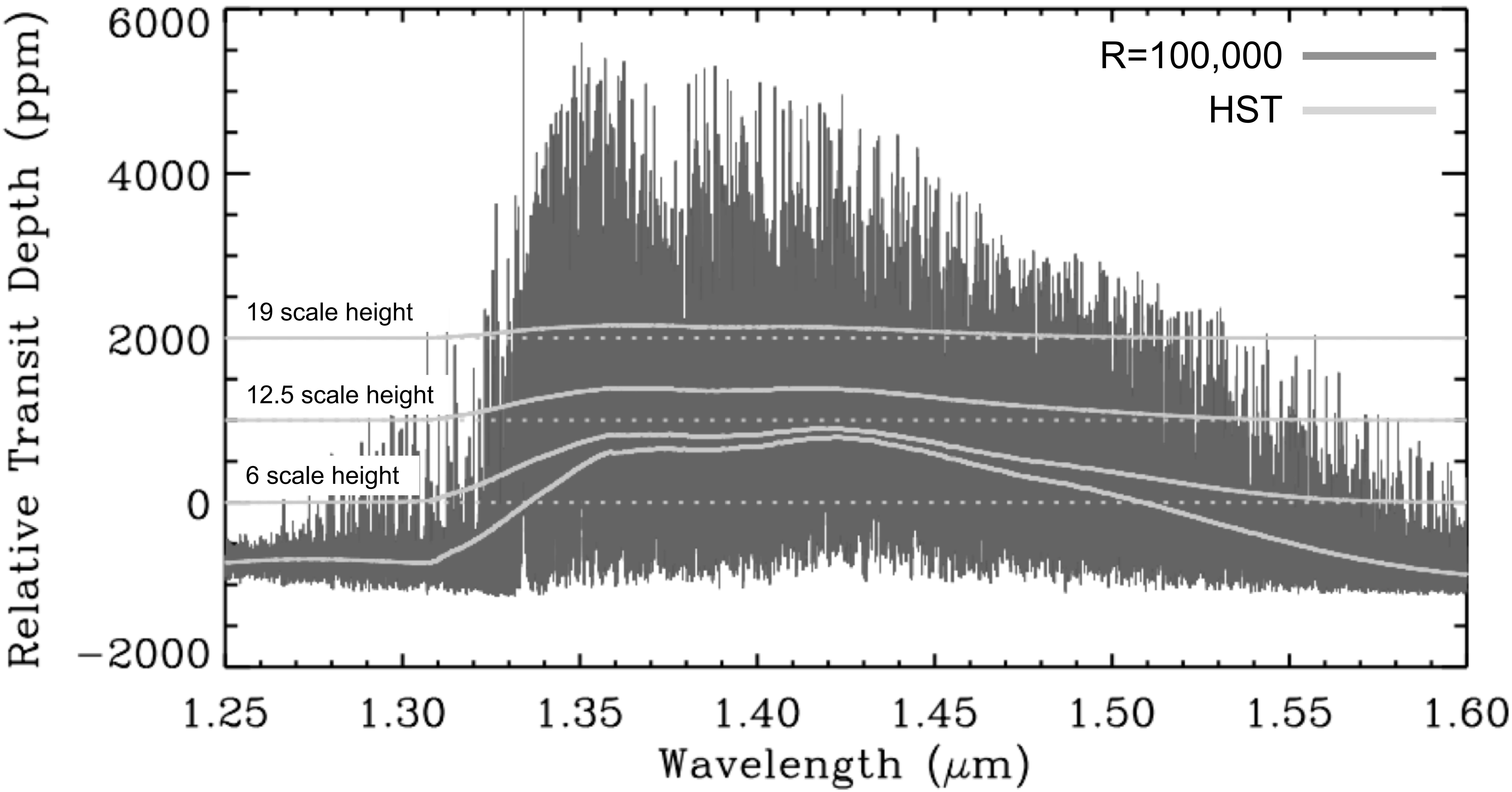
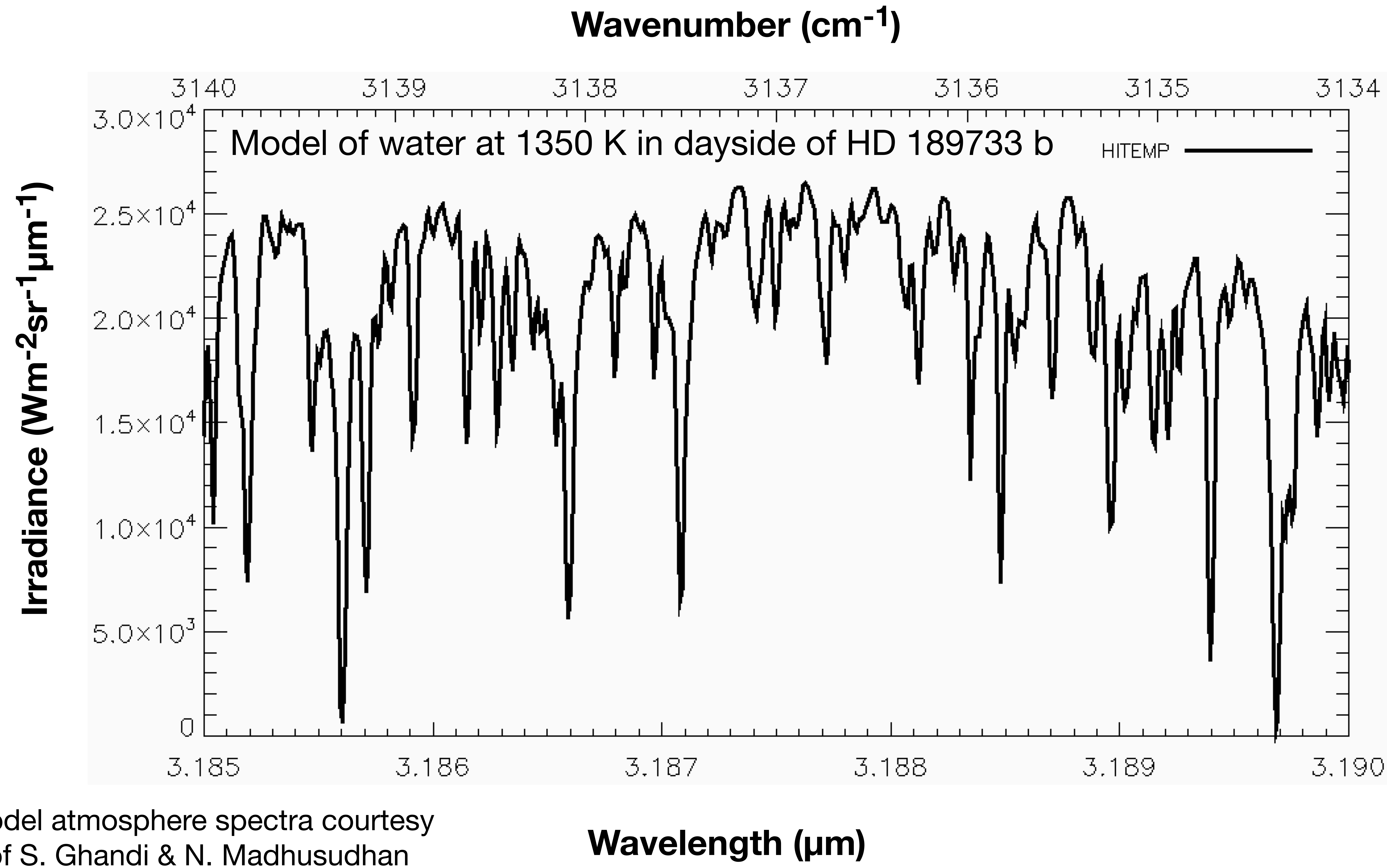



Figure courtesy I. A. G. Snellen, see de Kok et al. 2014 and Pino et al. 2018 for more detail

# Different line lists give conflicting model exoplanet atmosphere spectra at high spectral resolution




Model atmosphere spectra courtesy of S. Ghandi & N. Madhusudhan

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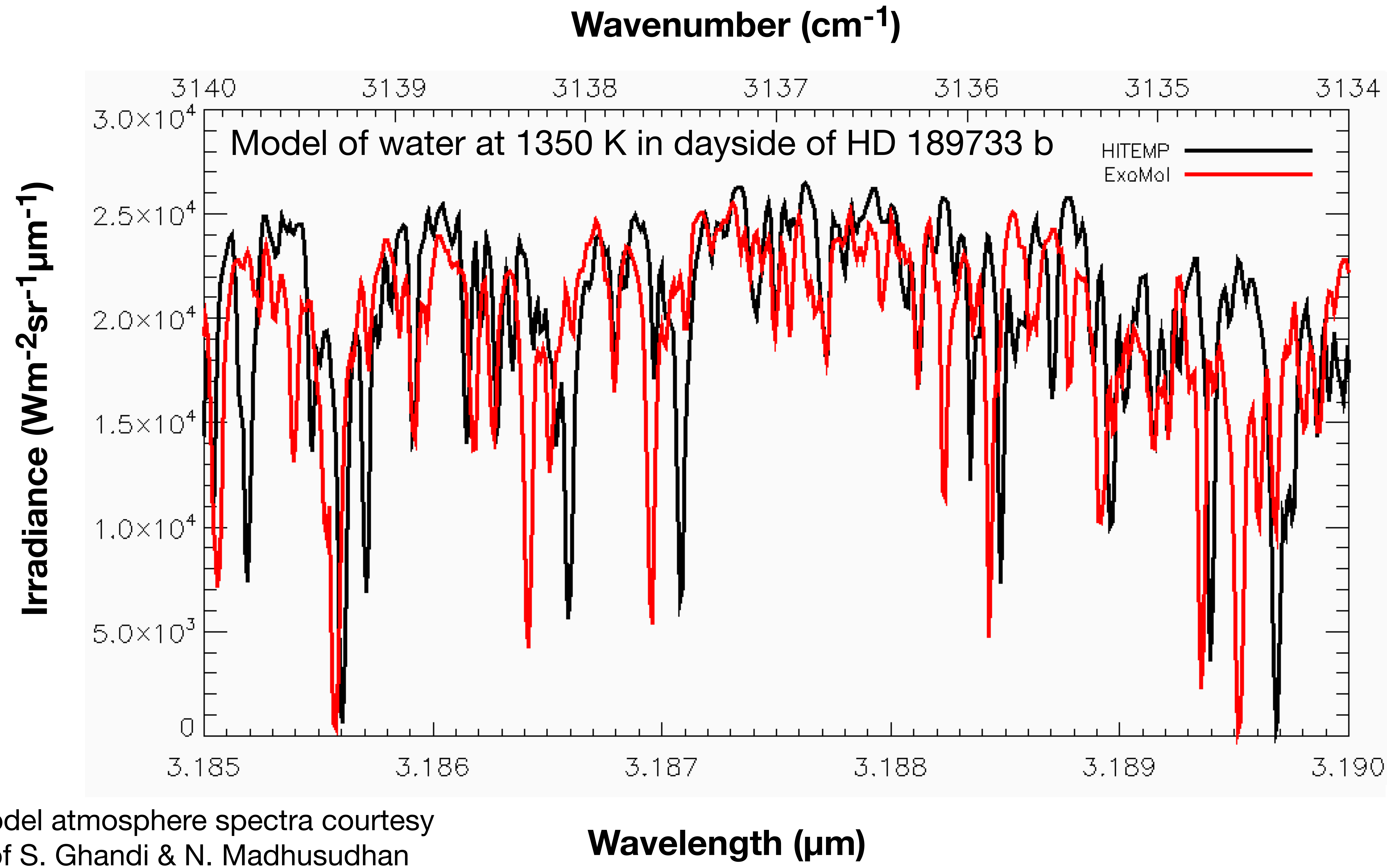
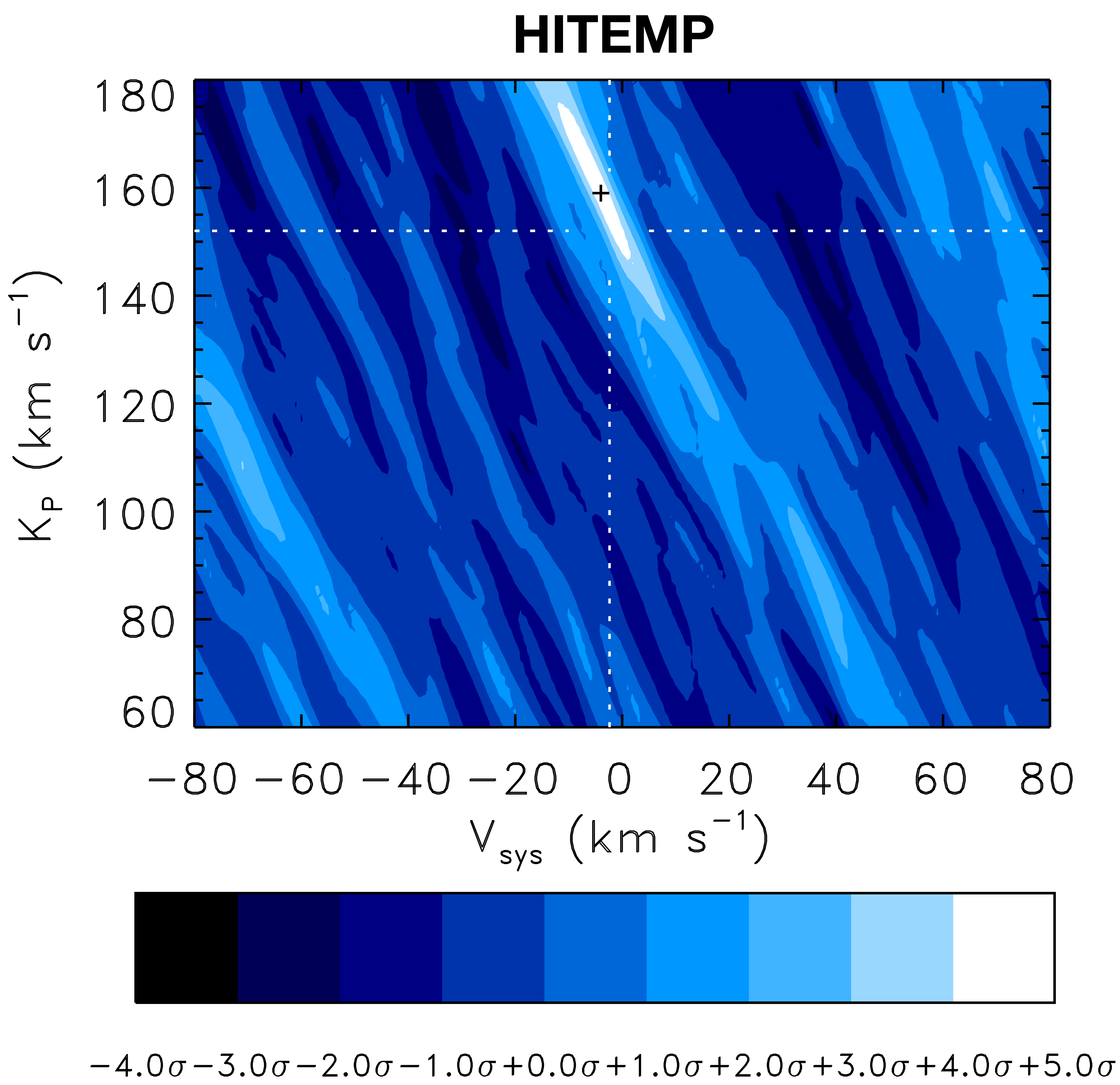



Model atmosphere spectra courtesy of S. Ghandi & N. Madhusudhan

# Line position accuracy is very important when studying high resolution spectroscopy of exoplanet atmospheres




Water in dayside of HD 189733 b
Birkby et al. 2013

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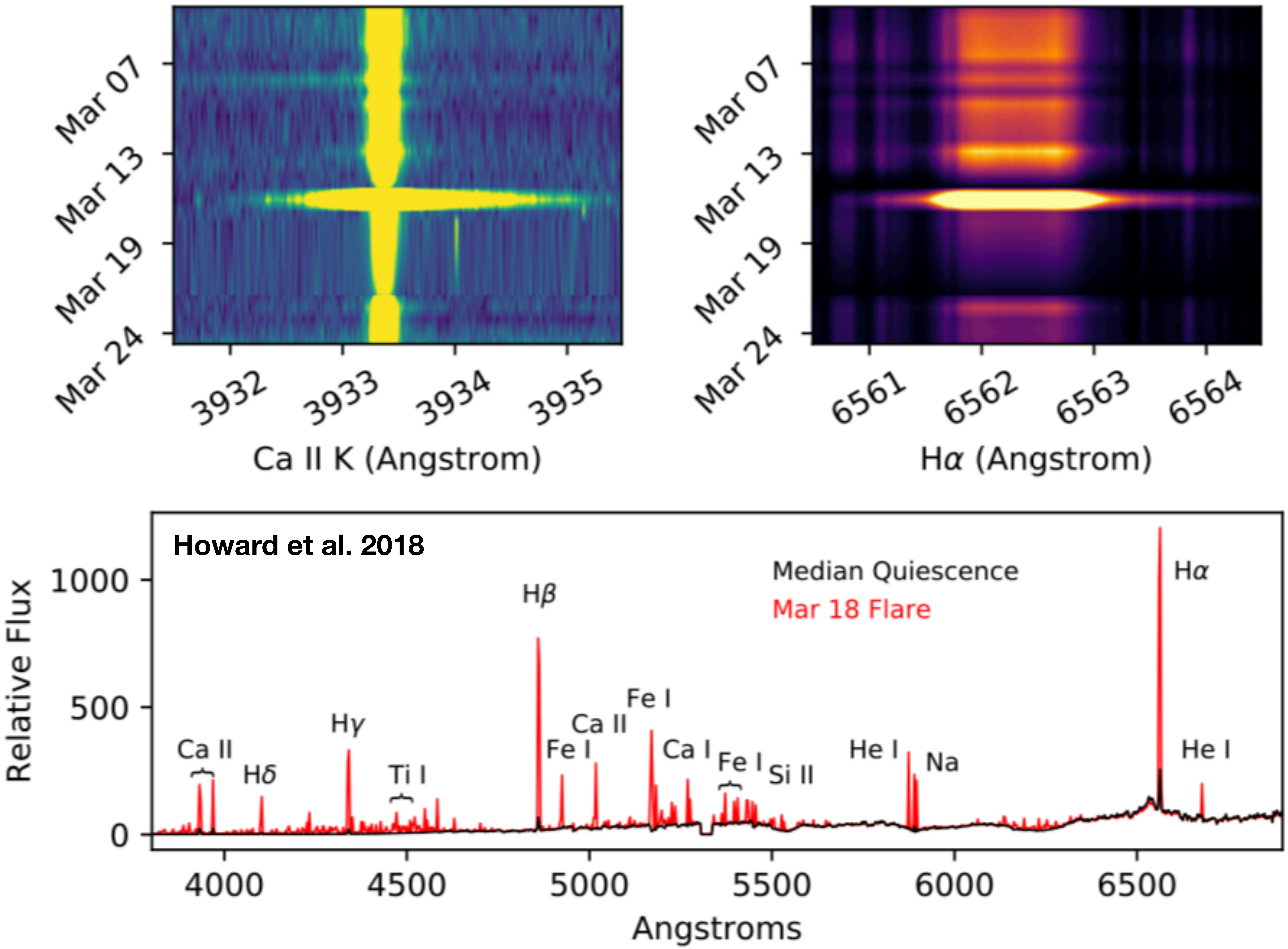
Water in dayside of HD 189733 b
Birkby et al. 2013

# M-dwarf super flares will be a complication for high resolution studies

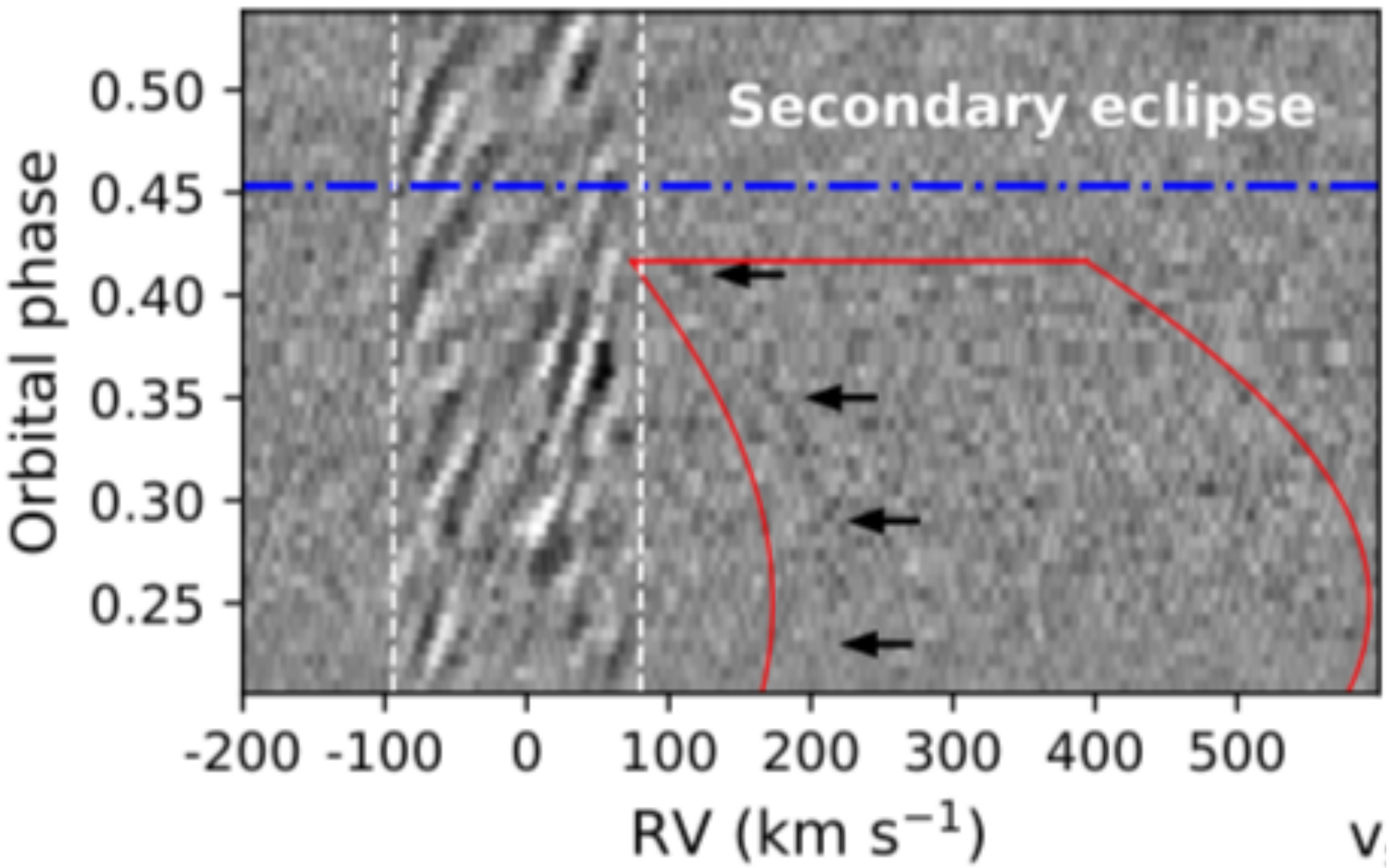



Lucas Stapper (BSc thesis) super flare resulted in 50 times more noise than in the quiescence state!

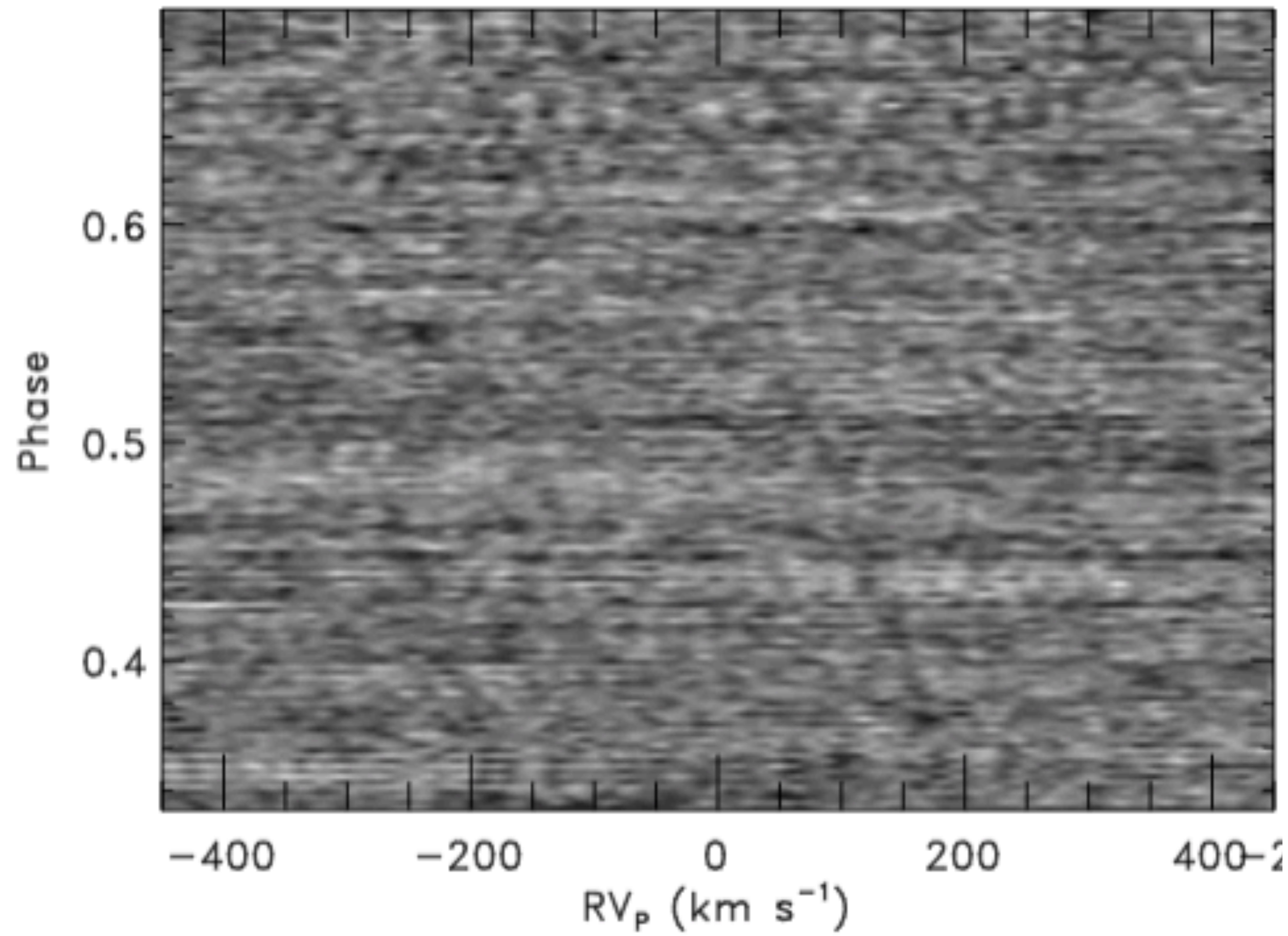
# Stellar pulsations can cause contamination if the planet spectrum contains the same species as the star

**Infrared observations with CO template**

**Optical observations with Fe I template**



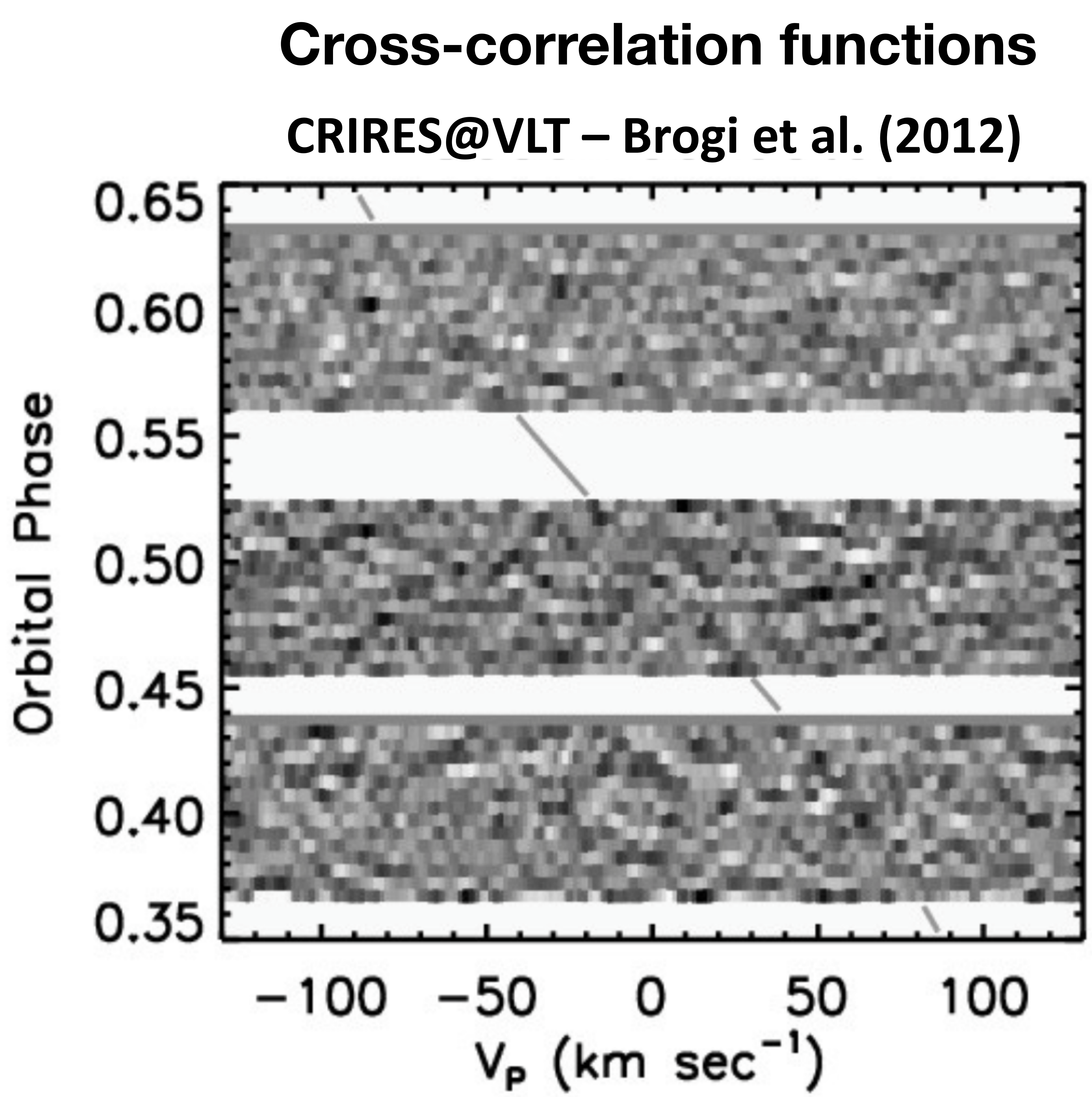

Nugroho et al. 2020

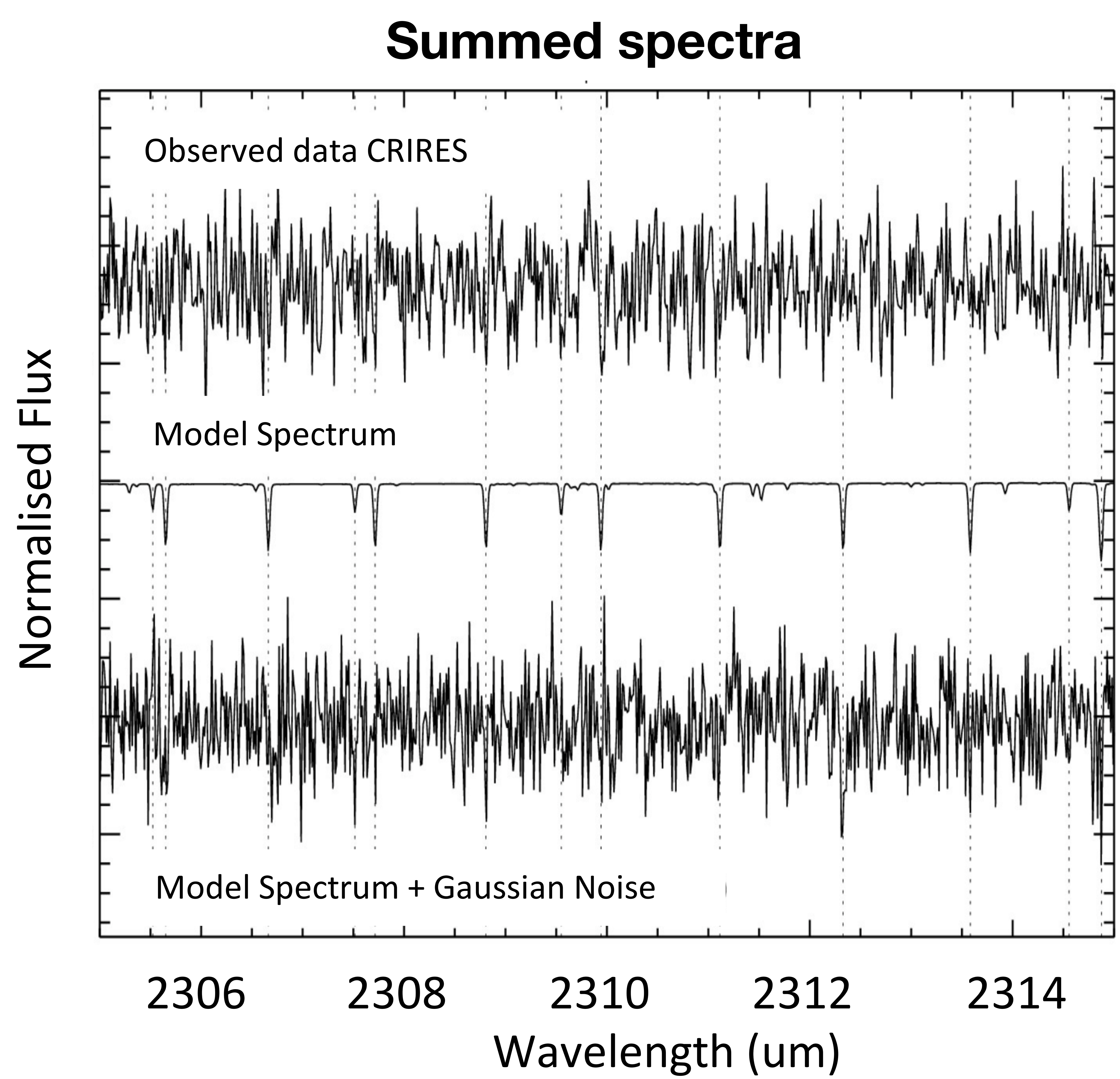



Birkby et al. in prep

**Host star A-type δ Scuti**

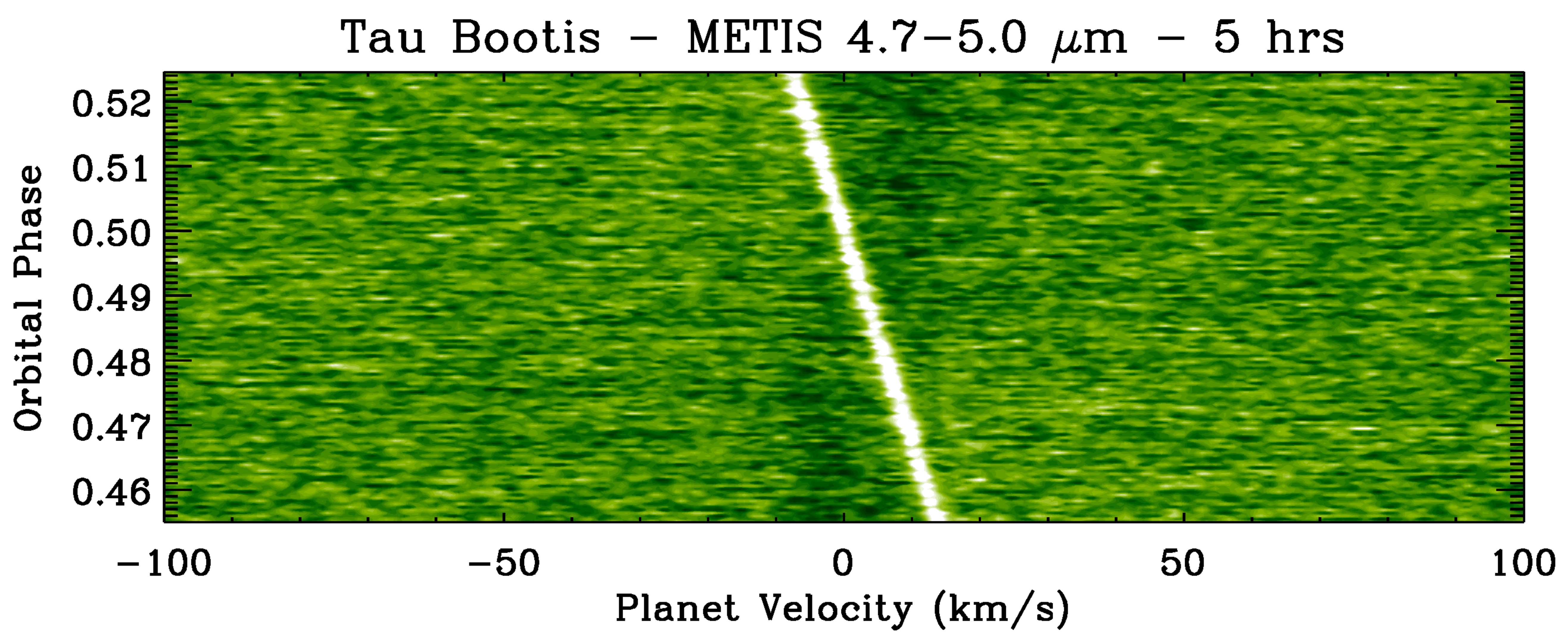
# High-resolution exoplanet spectra from existing facilities are very noisy




Brogi et al. 2012

# ELTs will provide sufficiently high S/N high resolution spectra to model the exoplanet atmosphere directly




I.A.G. Snellen, METIS Science Document

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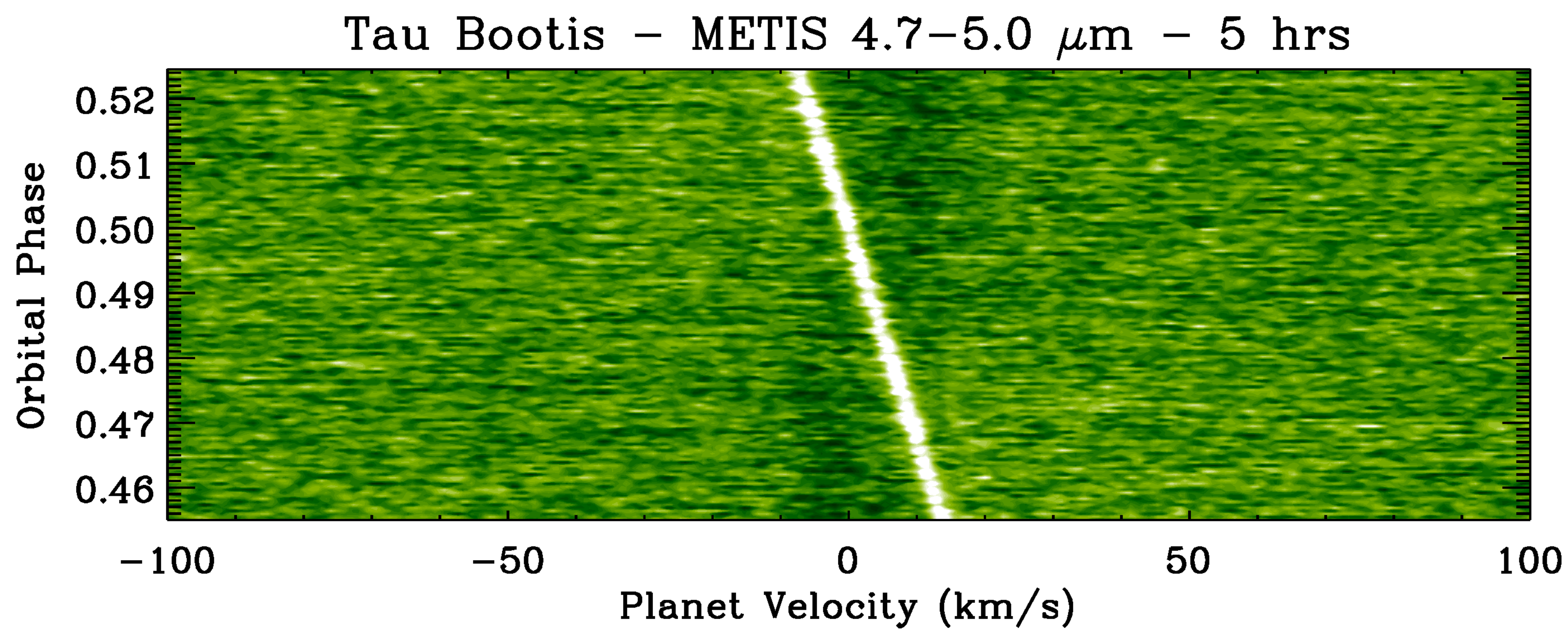
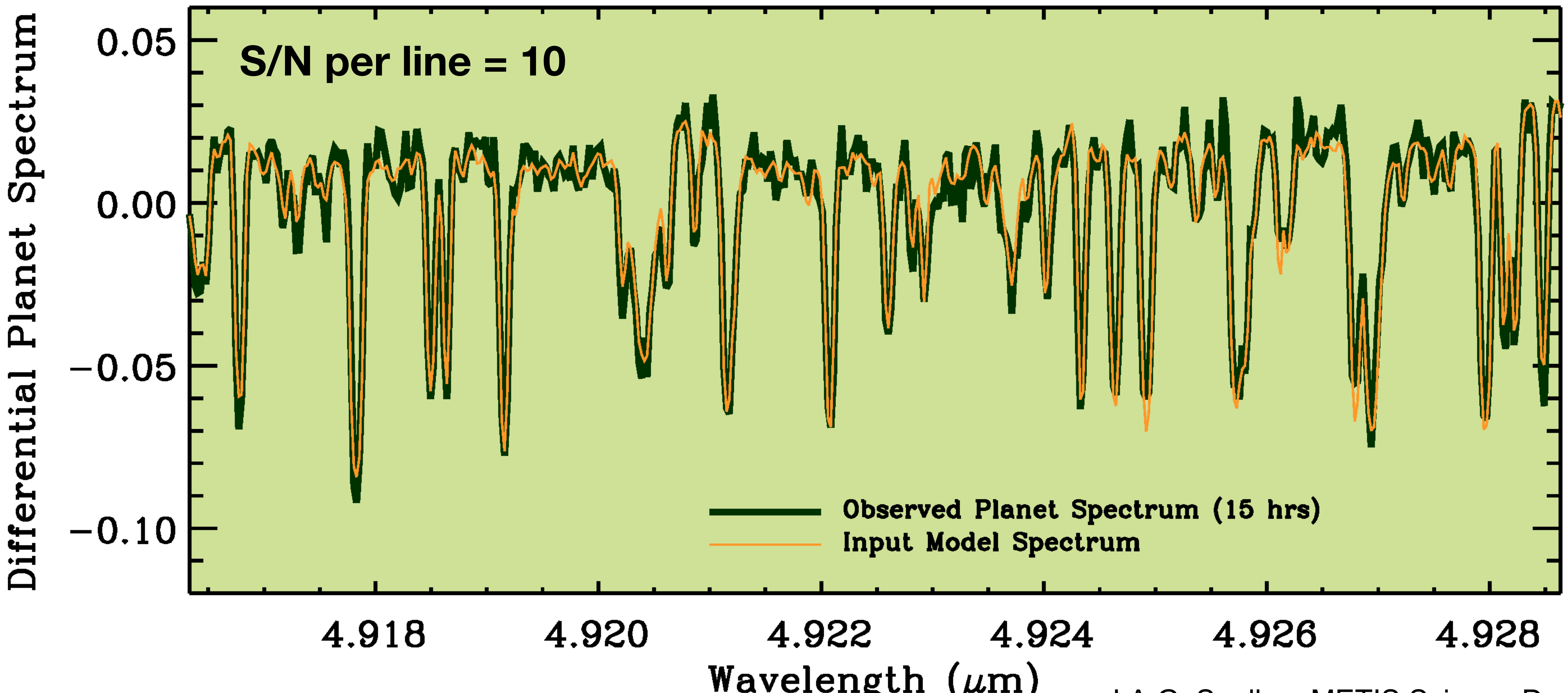


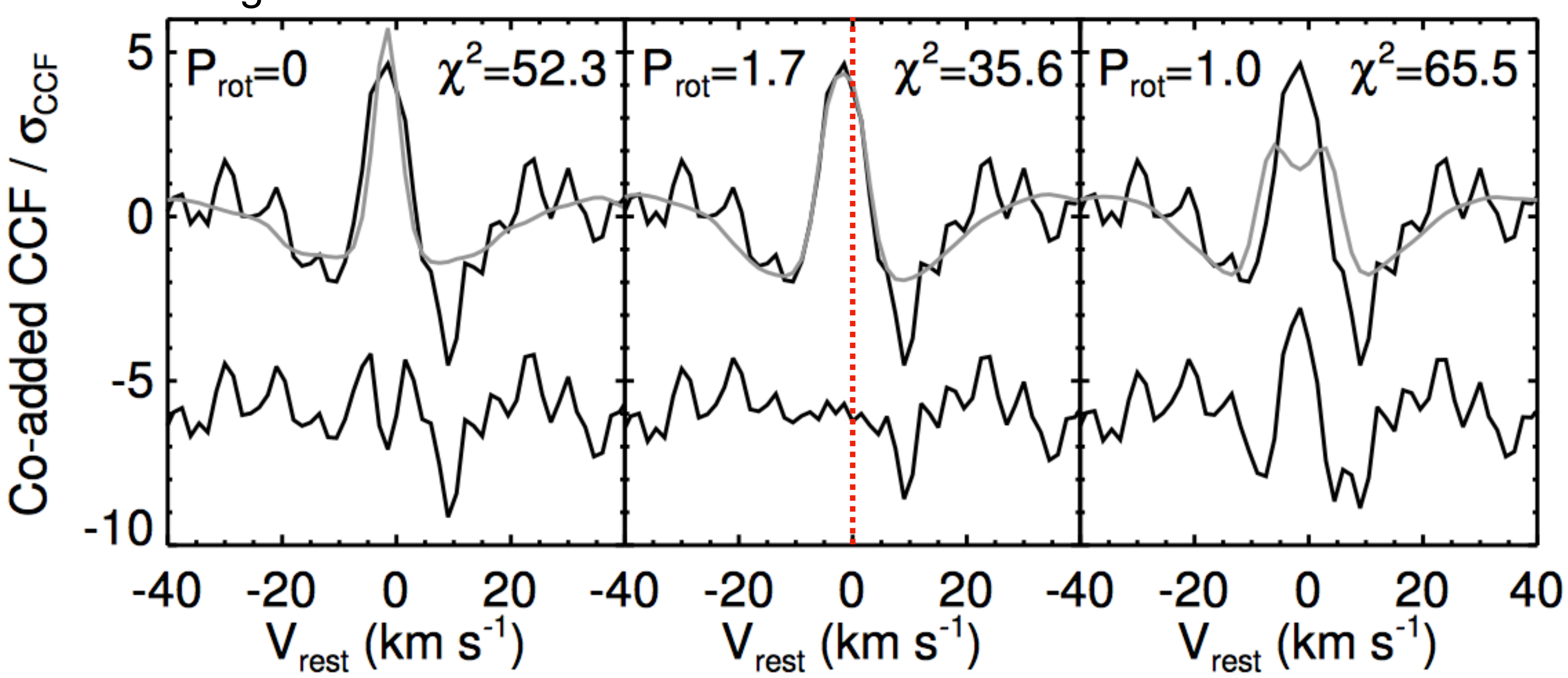




I.A.G. Snellen, METIS Science Document

© D Peach

# HD 189733 b consistent with synchronous rotation (tidally-locked) and full GCM models match well

Brogi et al. 2016




$P_{orb}$ = 2.21857567 +/- 1.5x$10^{-7}$ days

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

$V_{rot}$ = 3.4$^{+1.3}_{-2.1}$ km/s

$V_{shift}$ = -1.7$^{+1.1}_{-1.2}$ km/s

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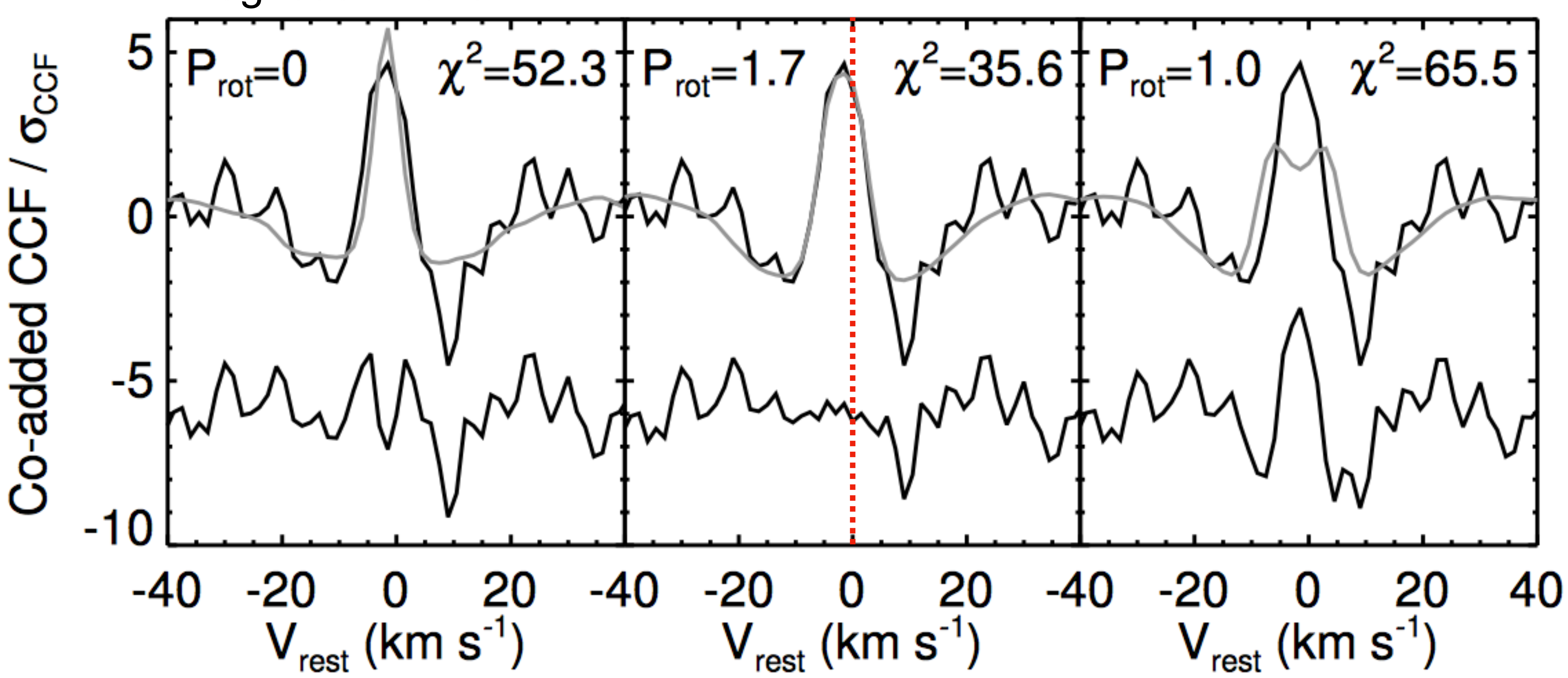


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Louden & Wheatley (2015) find spatially-resolved eastward rotating jet

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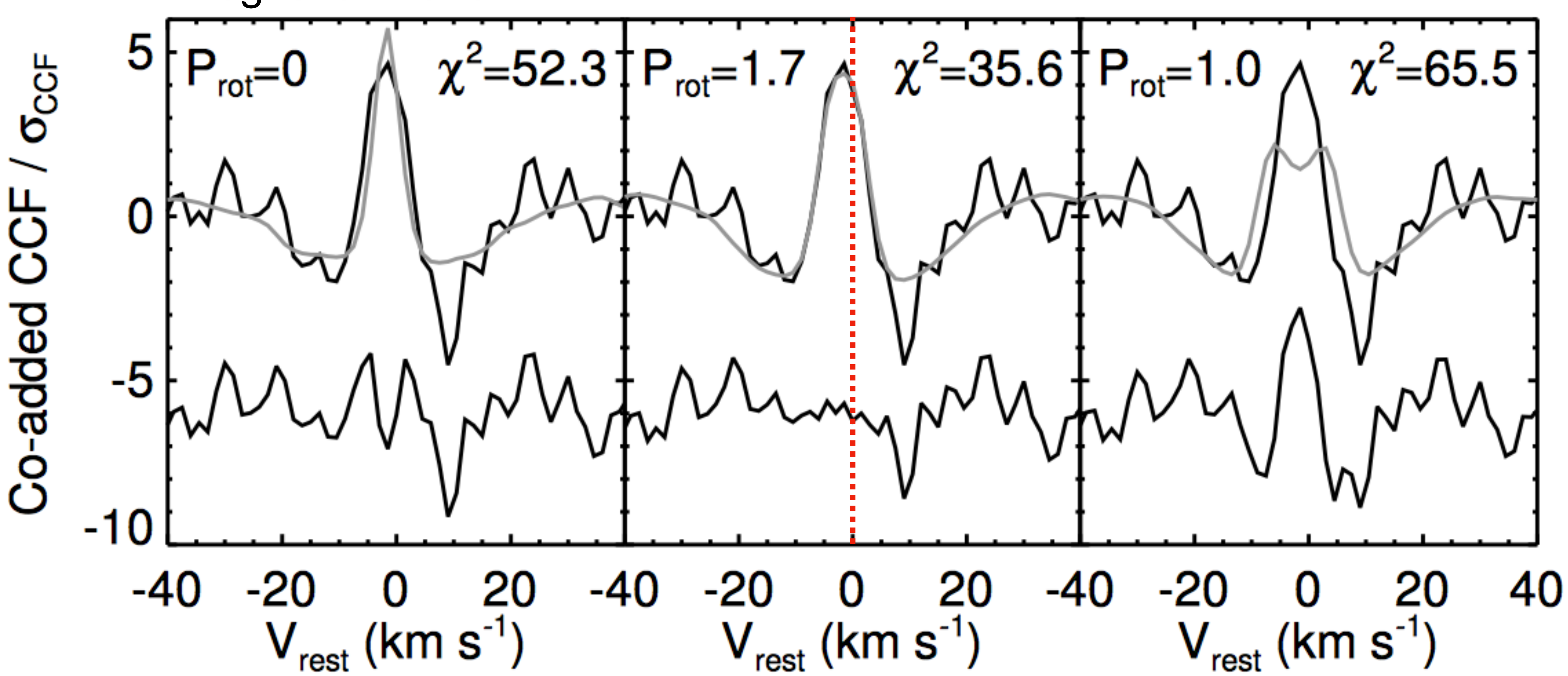


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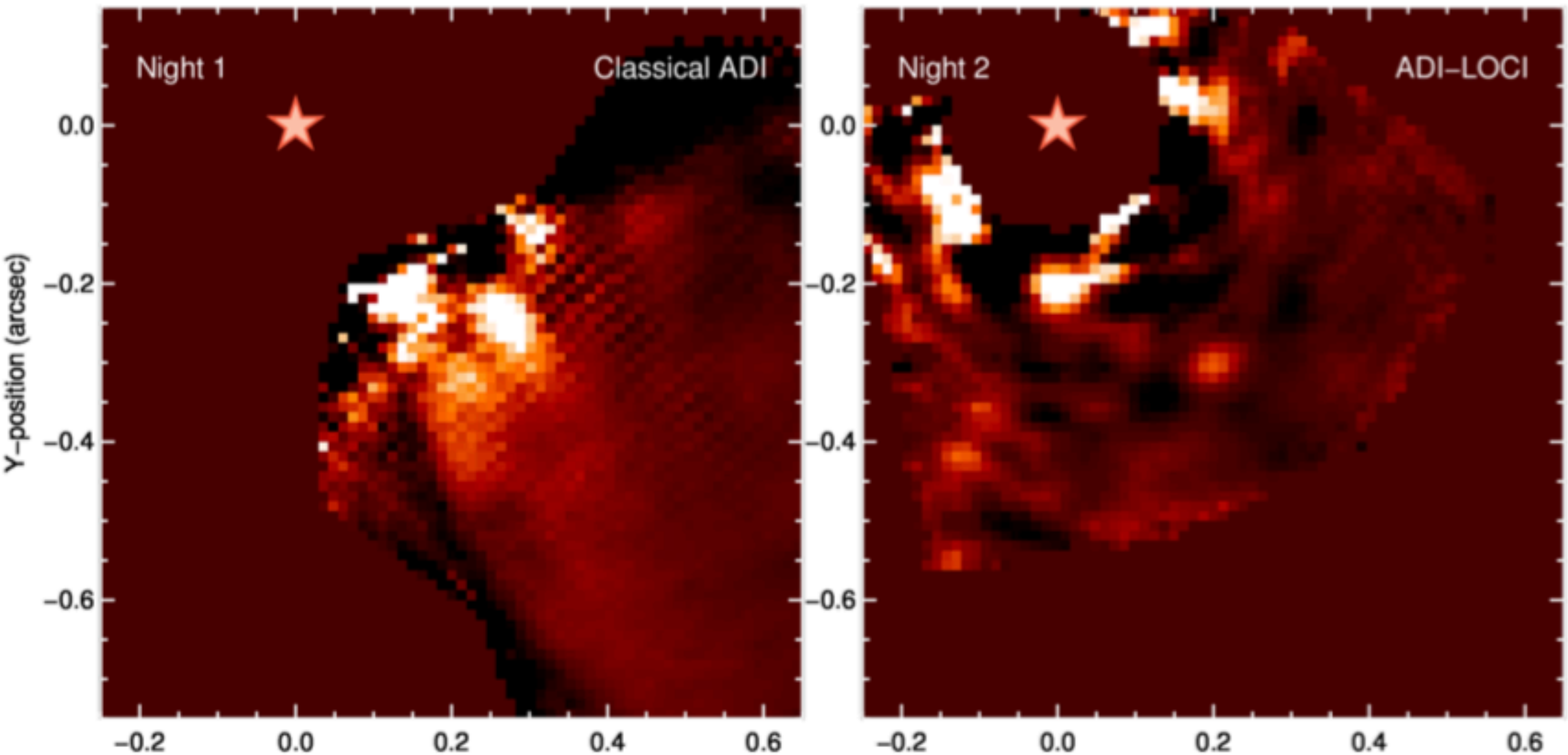
Louden & Wheatley (2015) find spatially-resolved eastward rotating jet

Full GCM models including rotation and winds match observations well
Flowers et al. 2018

# Molecule maps with high resolution spectroscopy offer a new approach for direct imaging surveys

White light images of β Pic b from SINFONI/VLT integral field spectrograph using standard direct imaging post-reduction techniques




Hoeijmakers et al. 2018, see also Petit dit de la Roche et al. 2018, Wang et al. 2018

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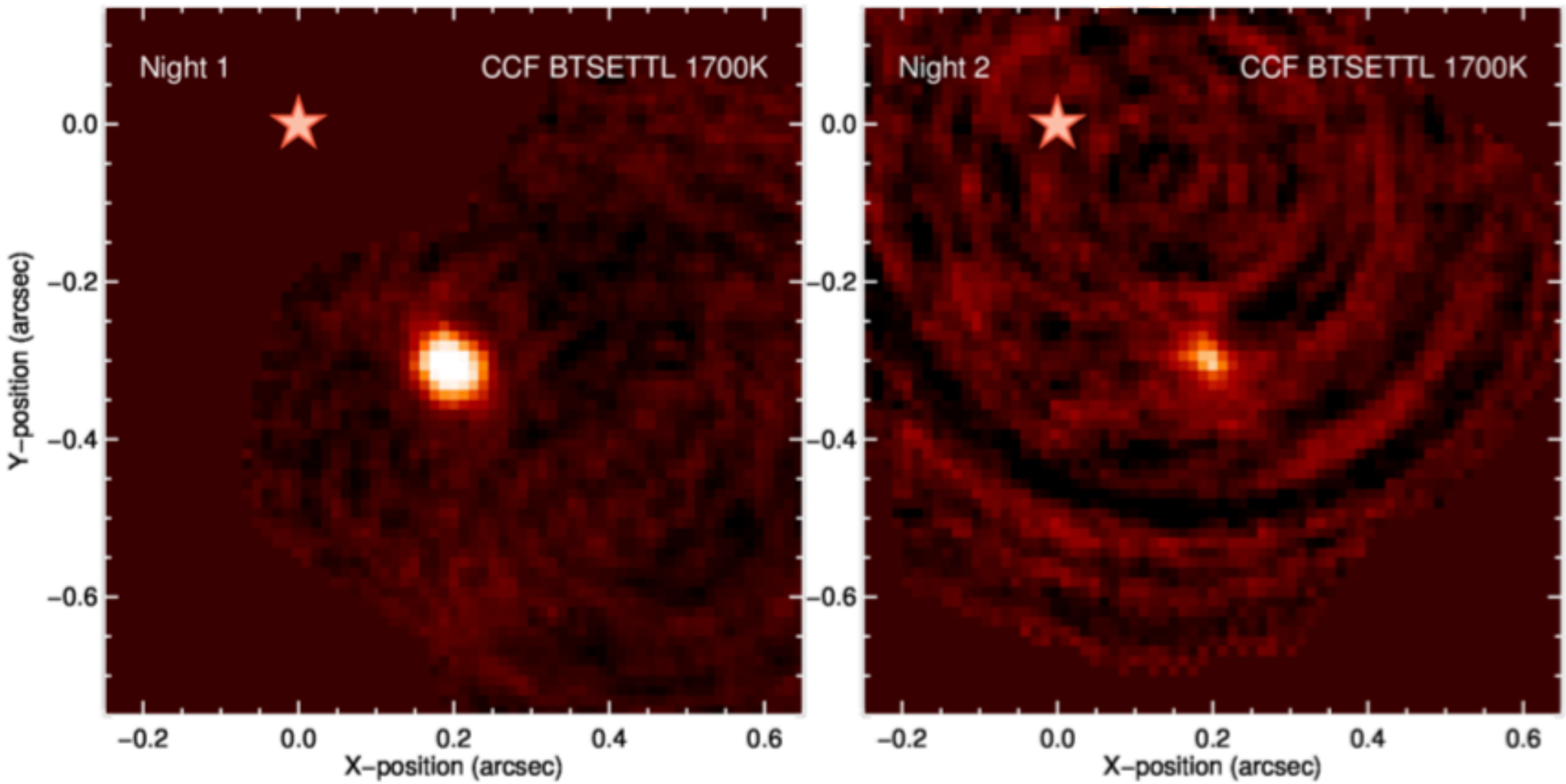


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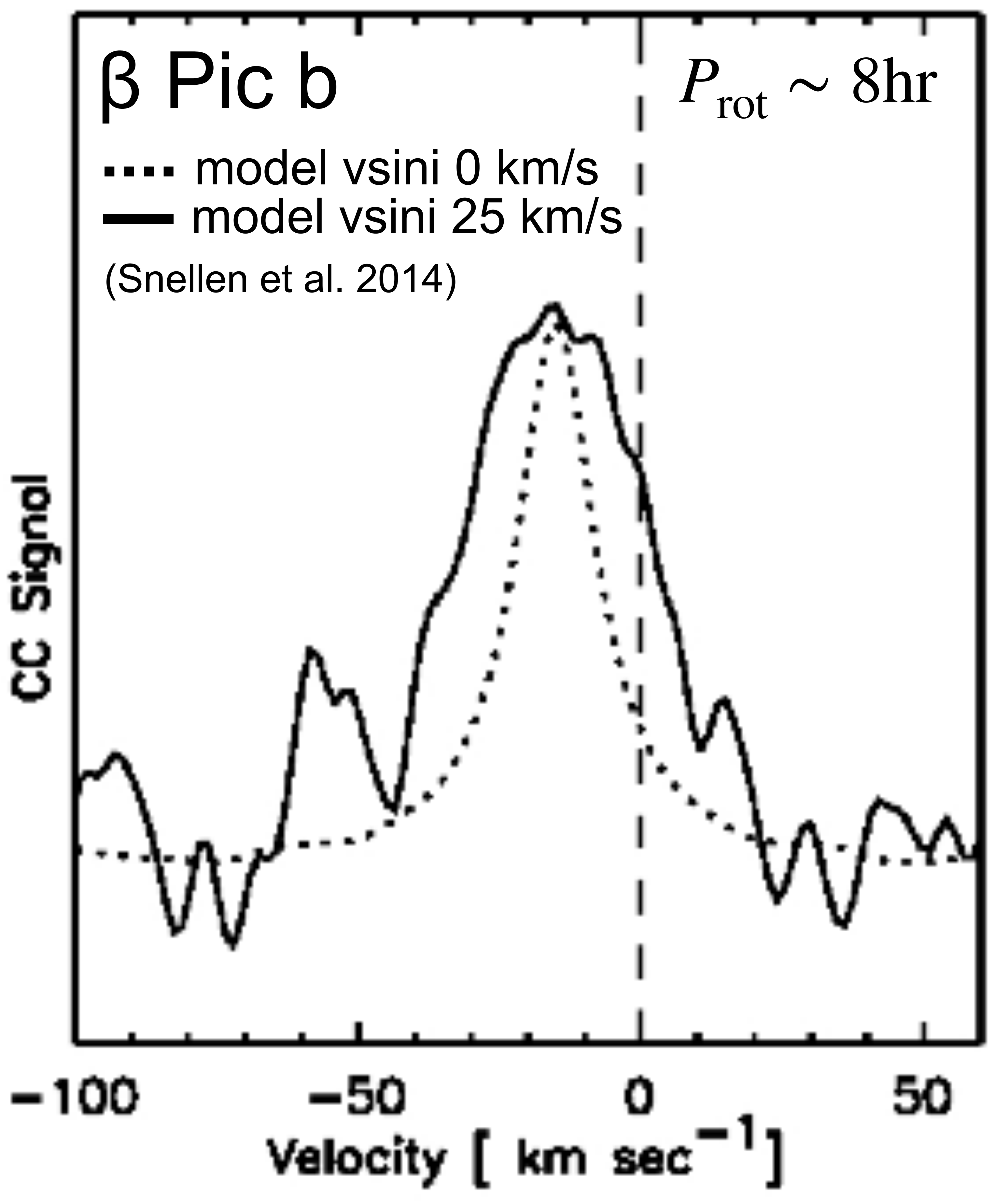
# How do planets gain their angular momentum?



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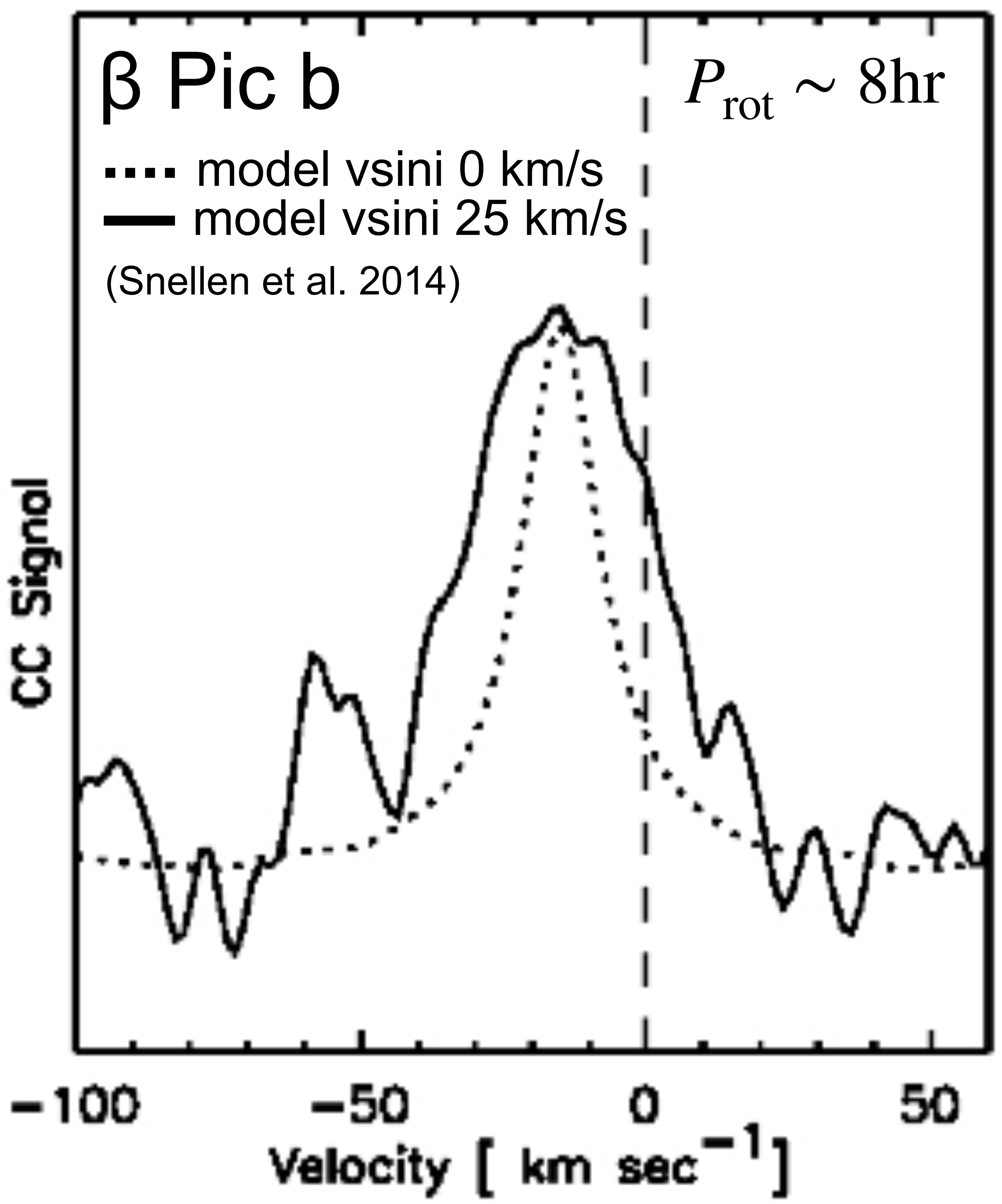


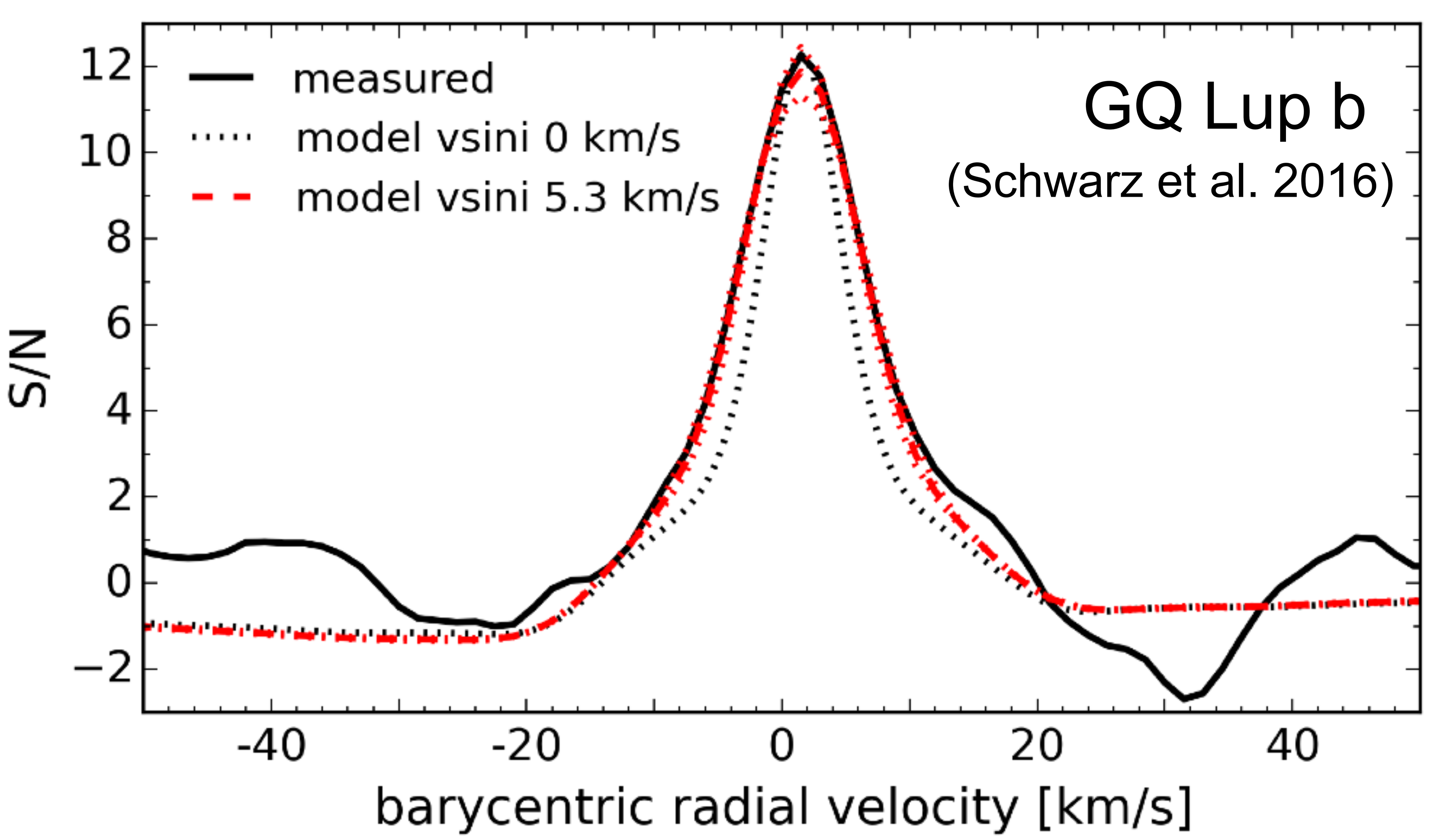

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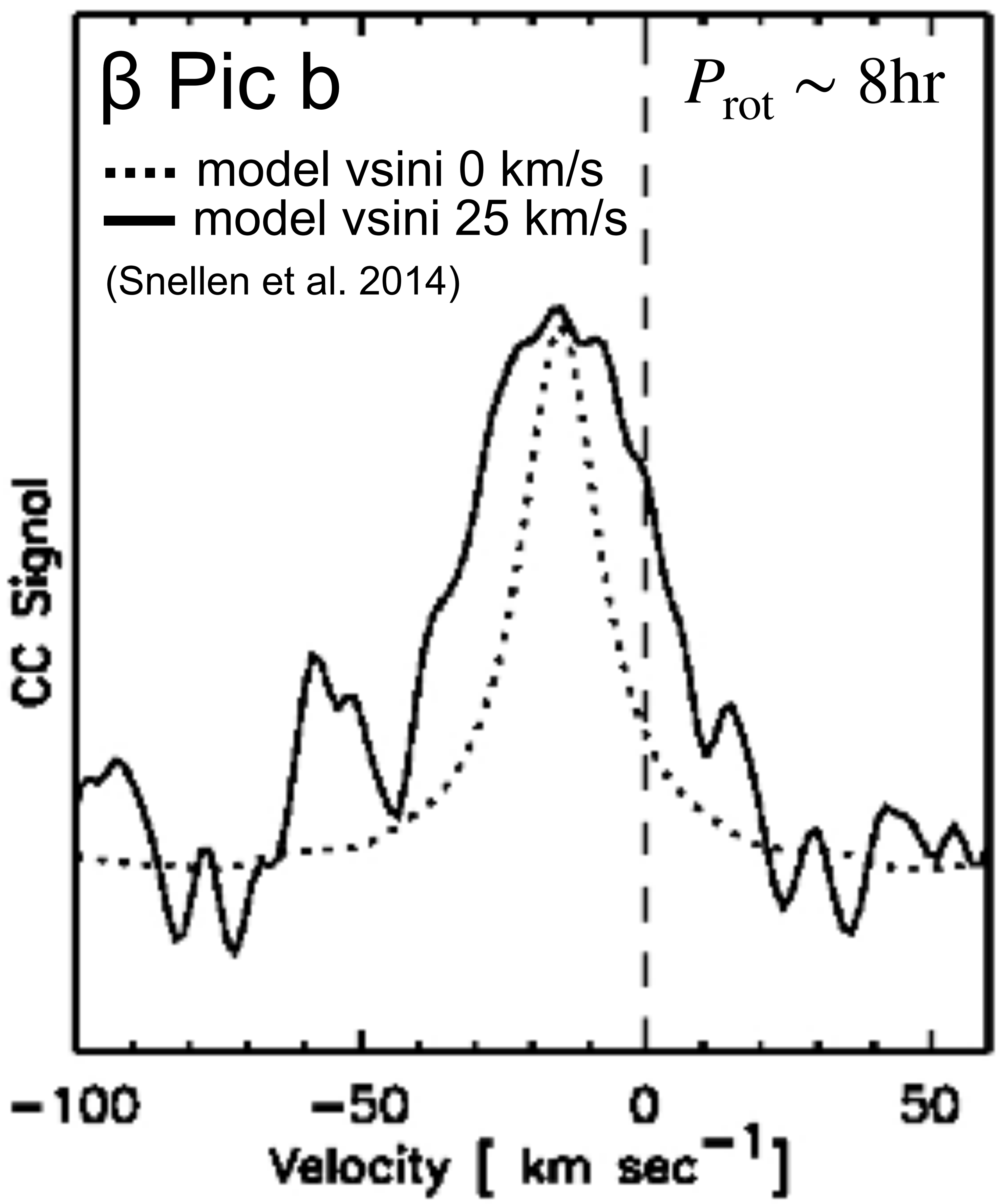


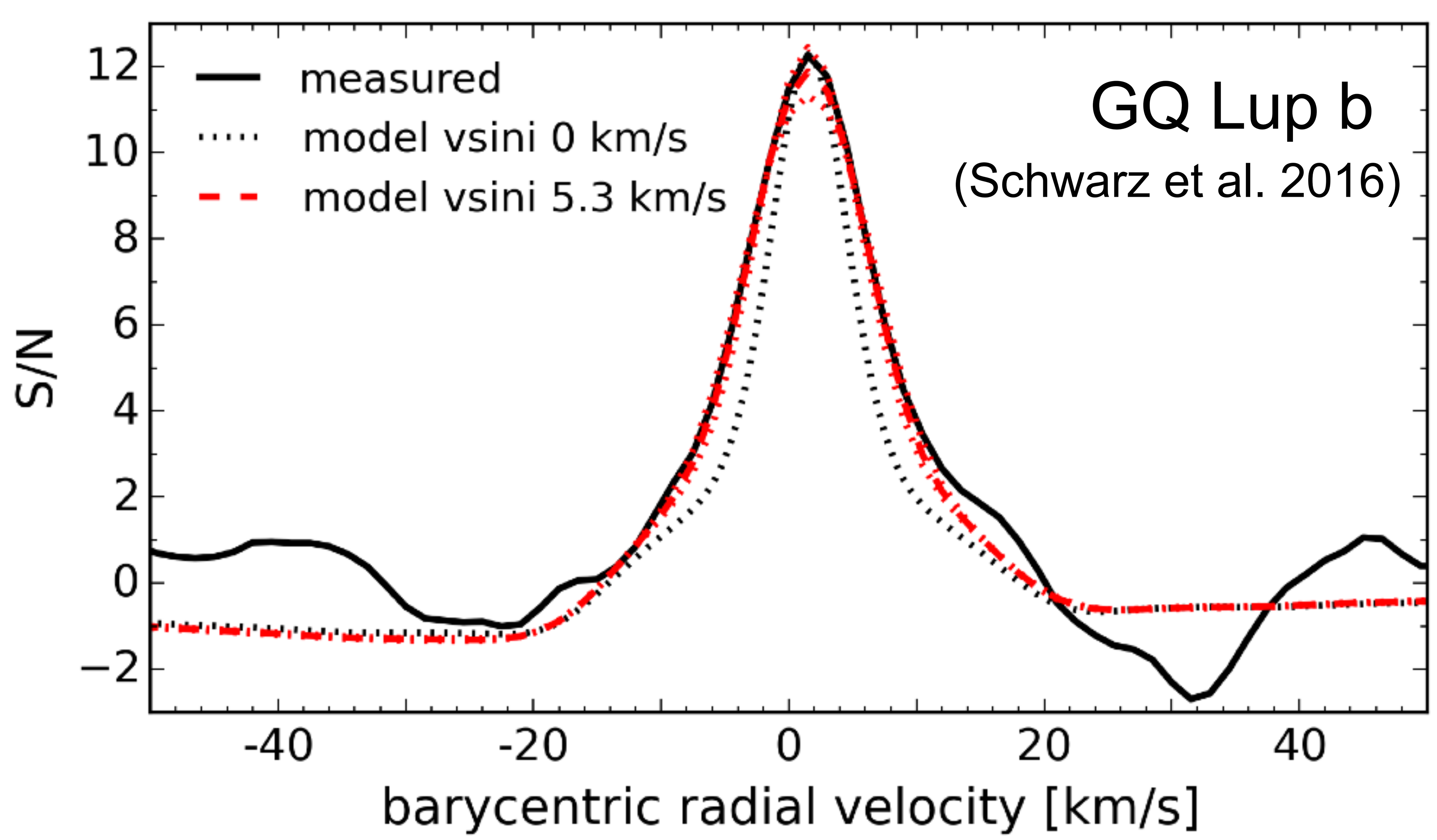


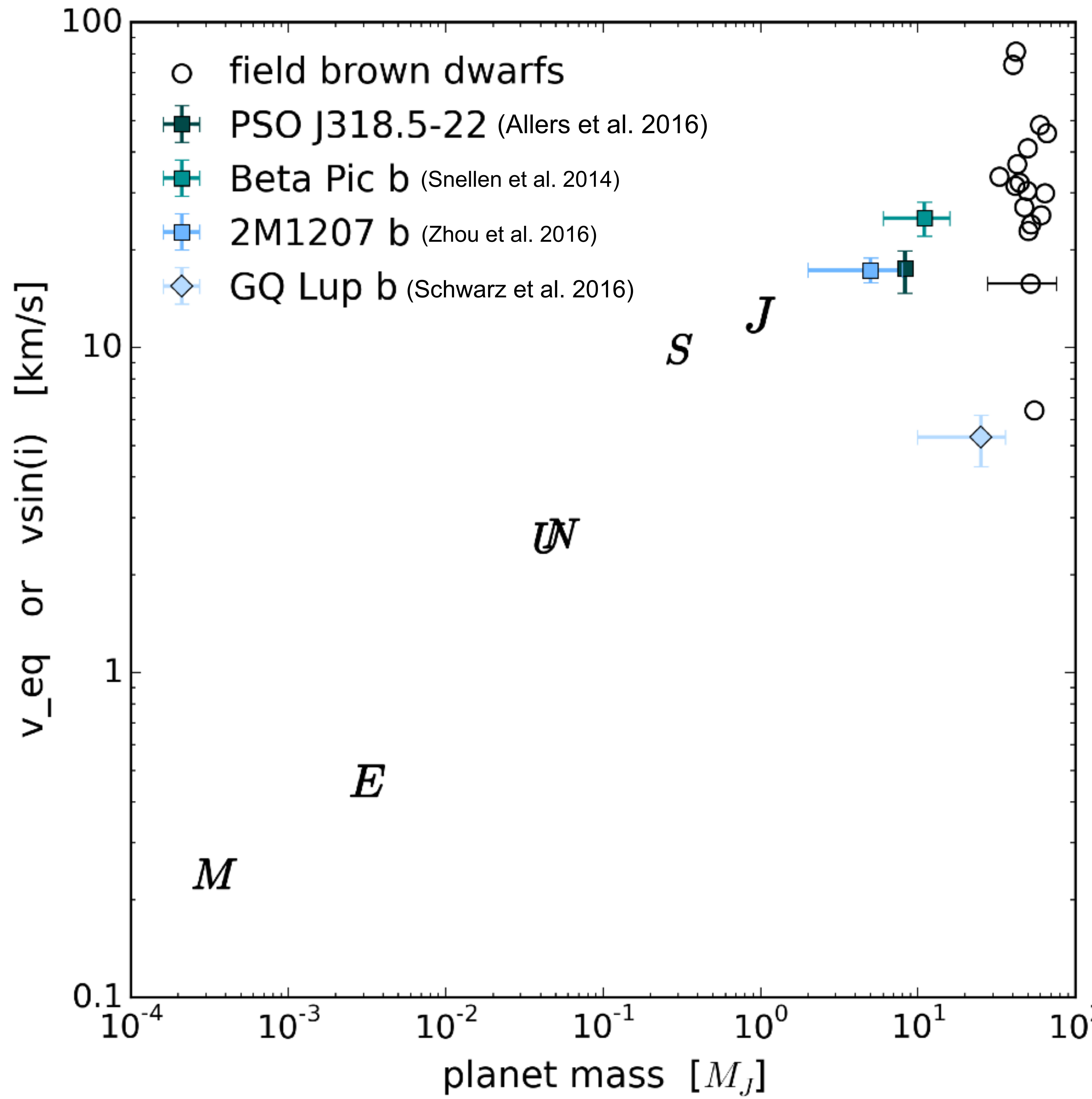

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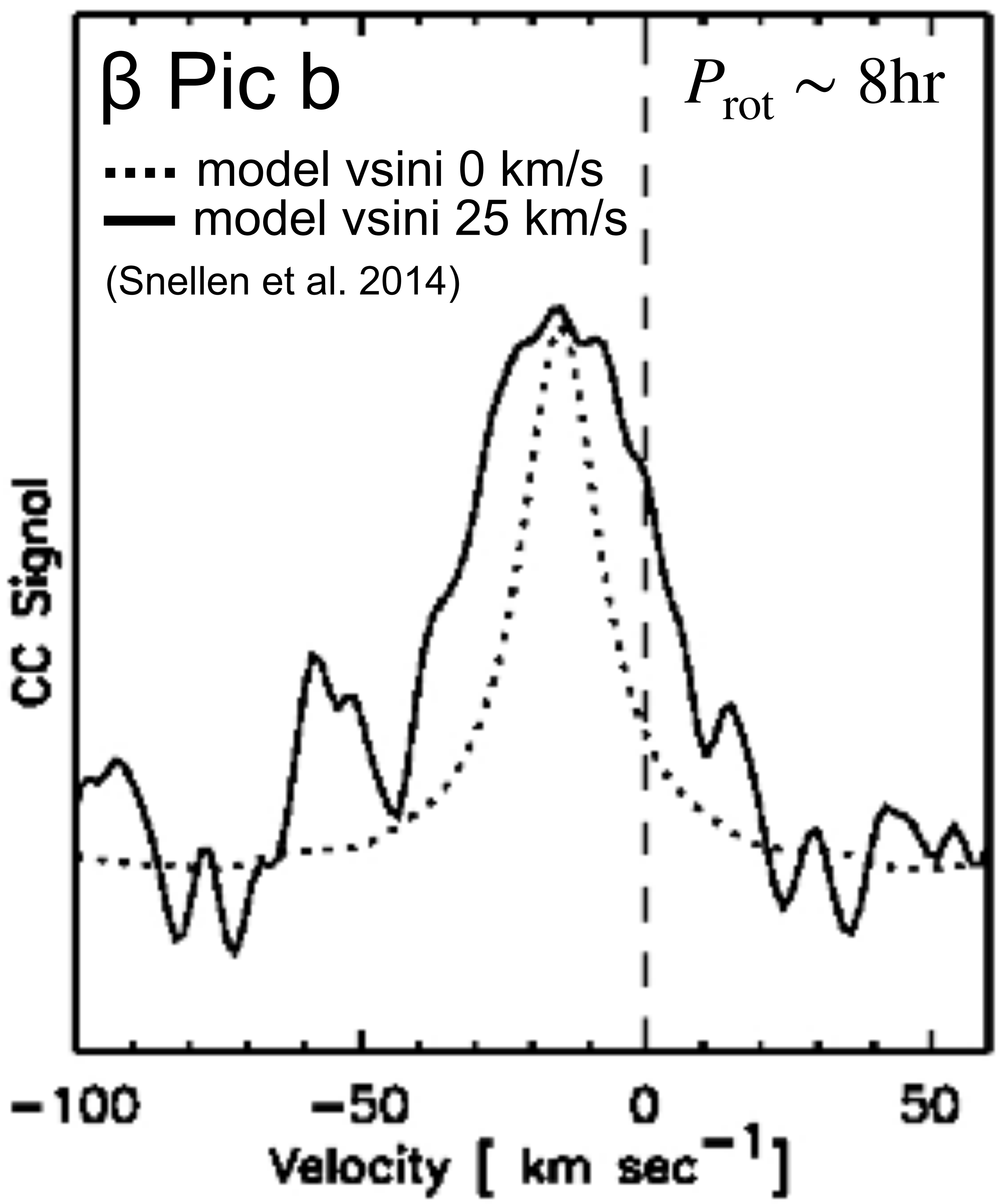
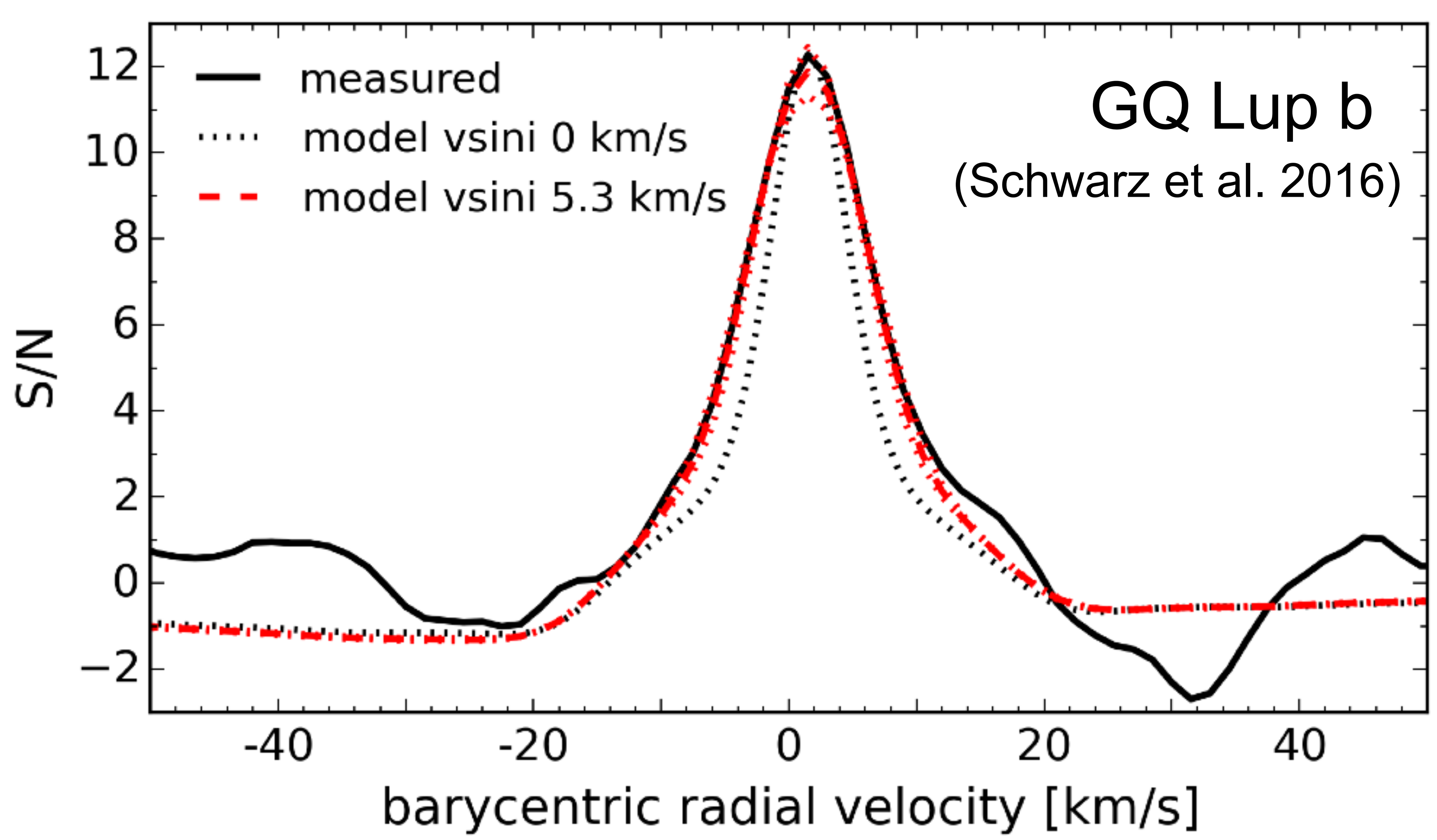
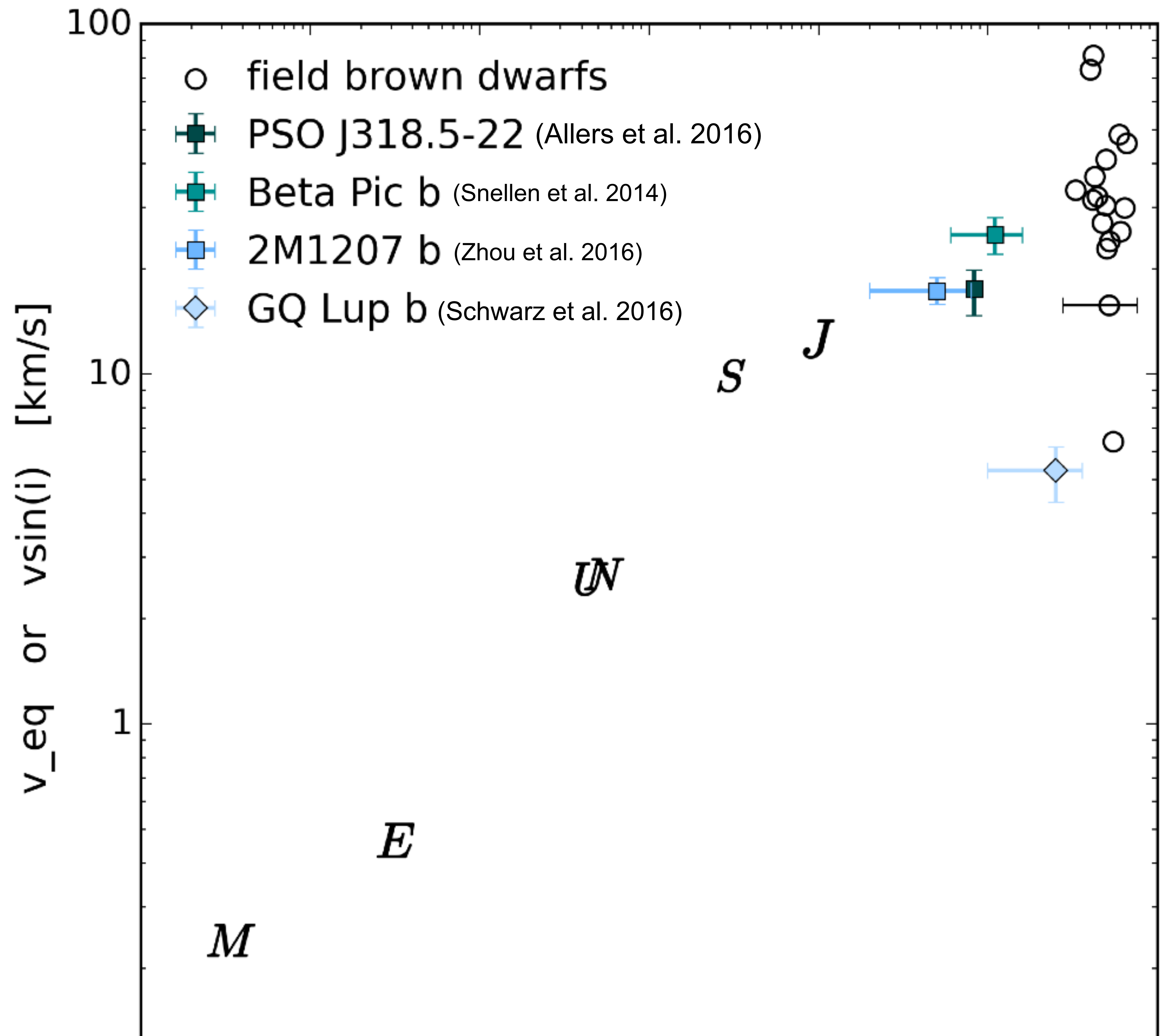


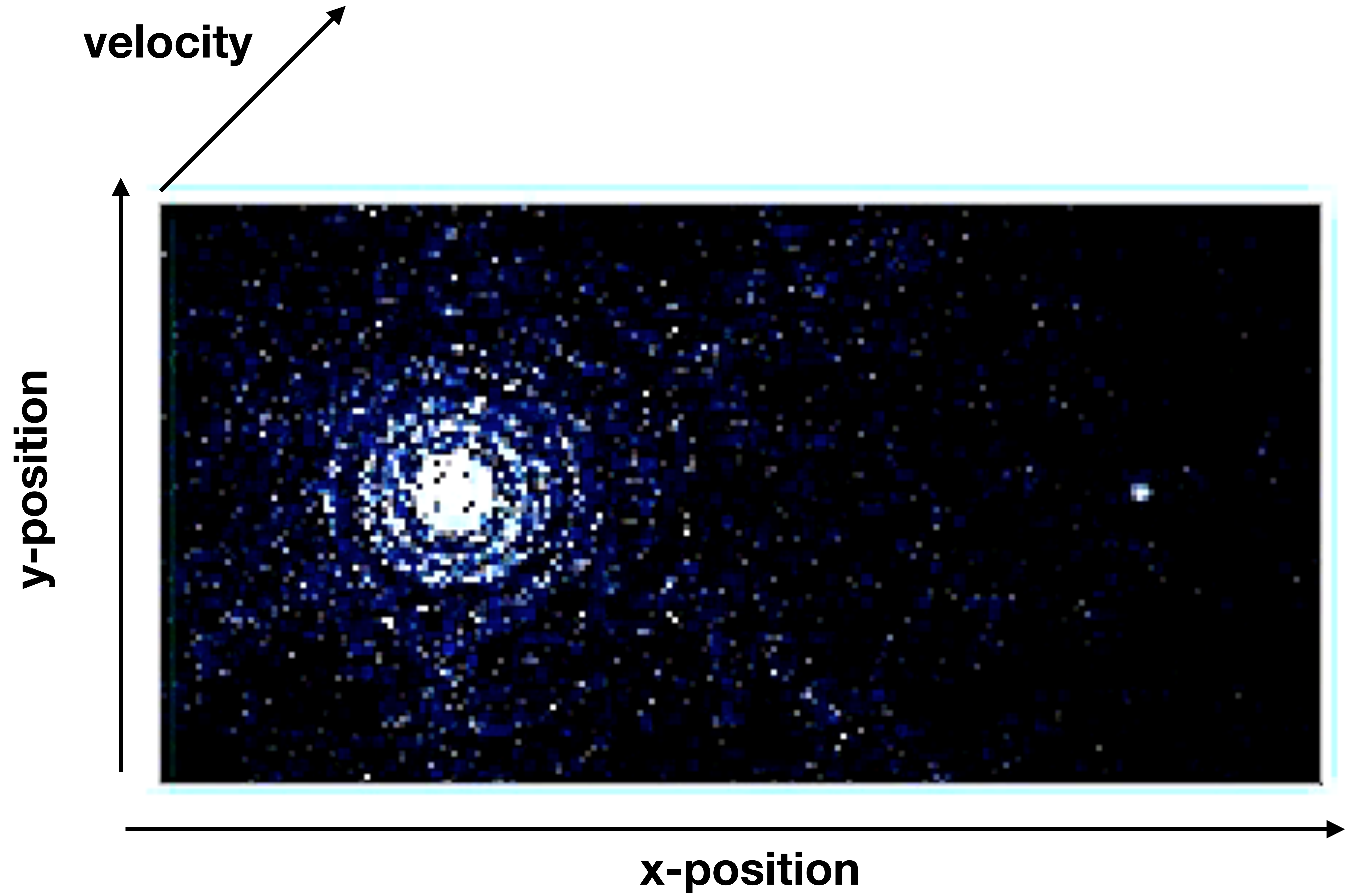




Statistical comparisons suggest rotation rate is independent of mass and set during late stages of accretion. (Bryan et al. 2017)

# ELT molecule map for Proxima b

**(simulated for METIS)**




Snellen, de Kok, Birkby et al. 2015

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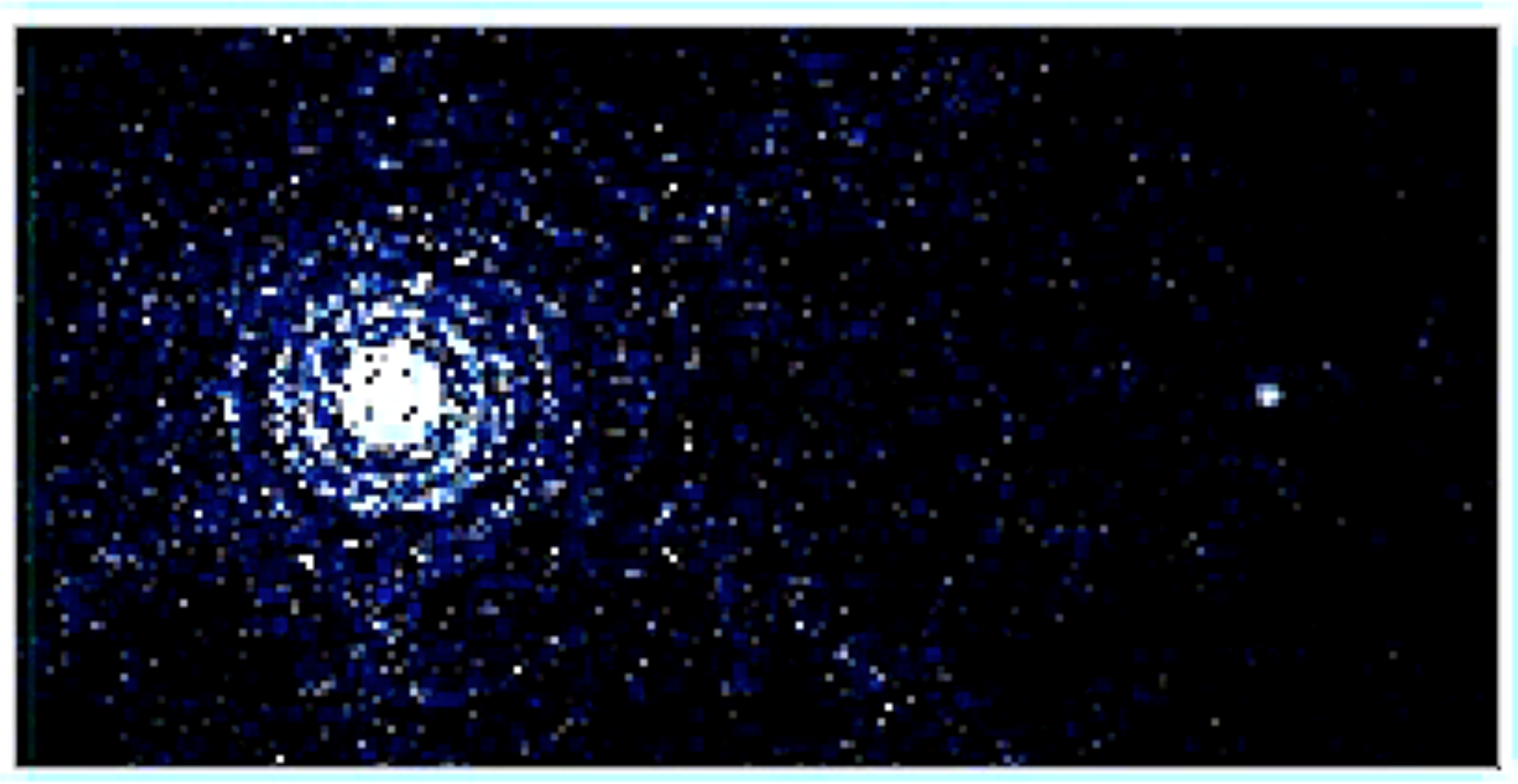
(simulated for METIS)



Snellen, de Kok, Birkby et al. 2015

# Key O2 biomarker in the optical where planets reflect light

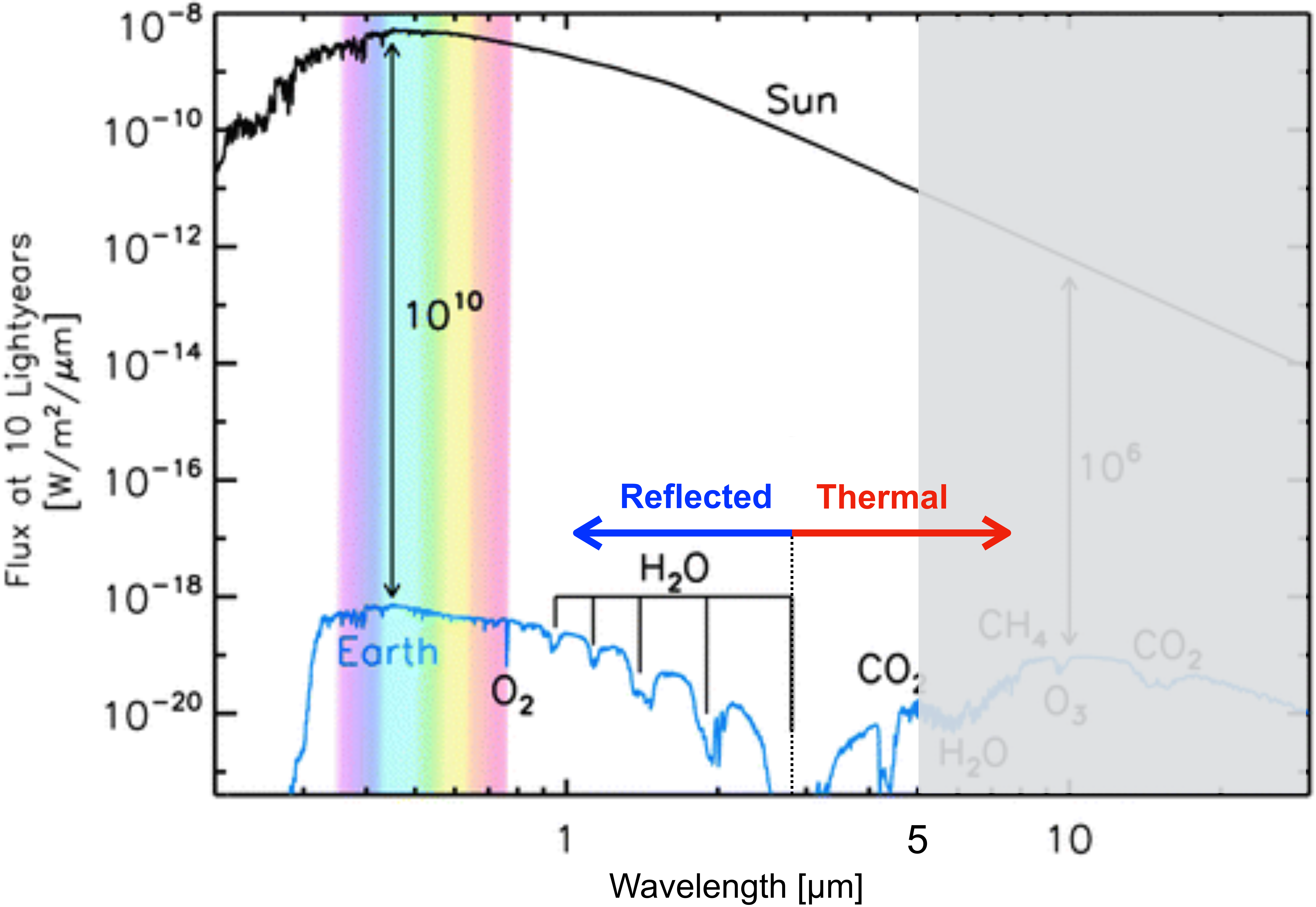



Figure credit: Sarah Rugheimer & Tyler Robinson in Domagal-Goldman et al. 2016

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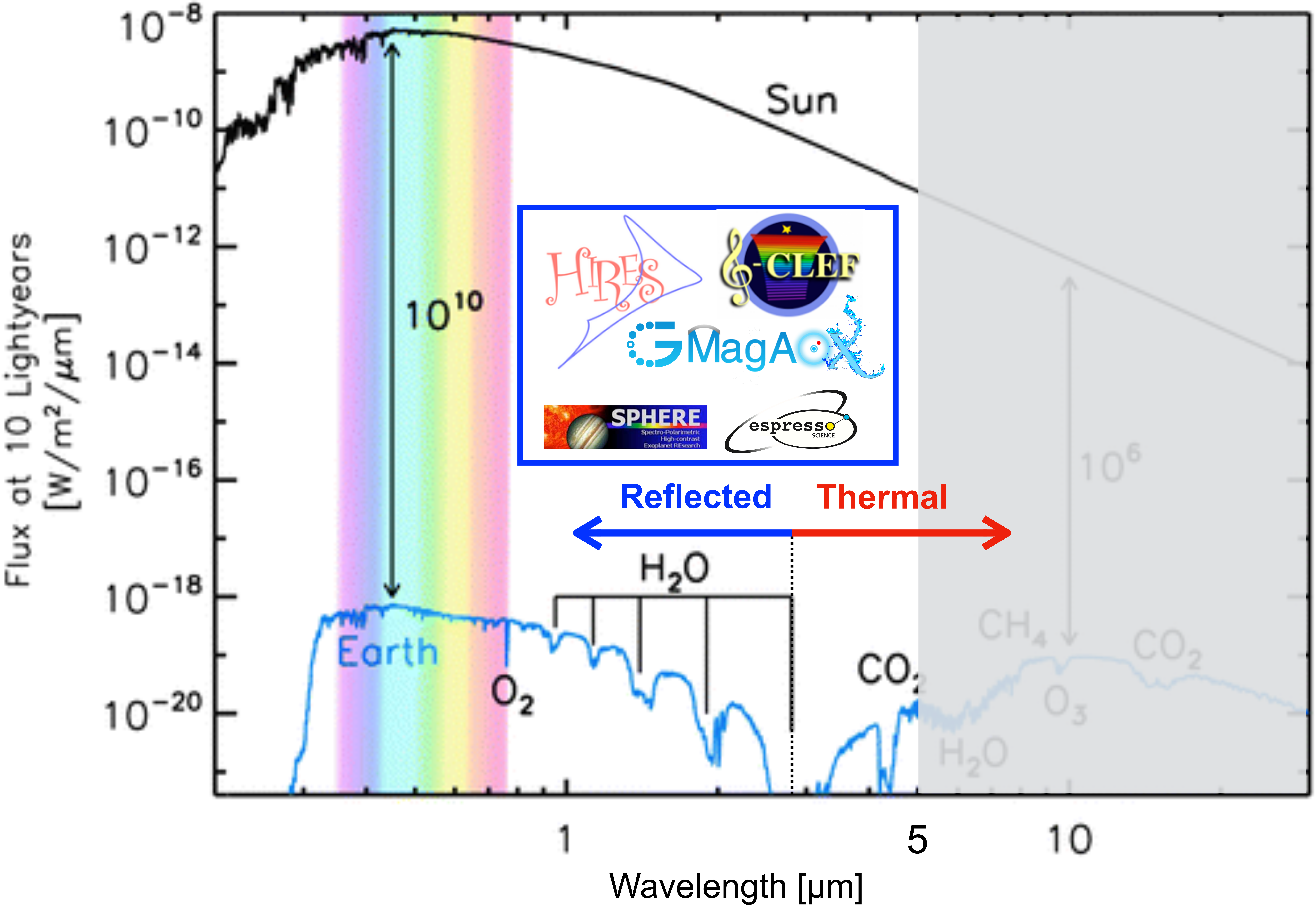
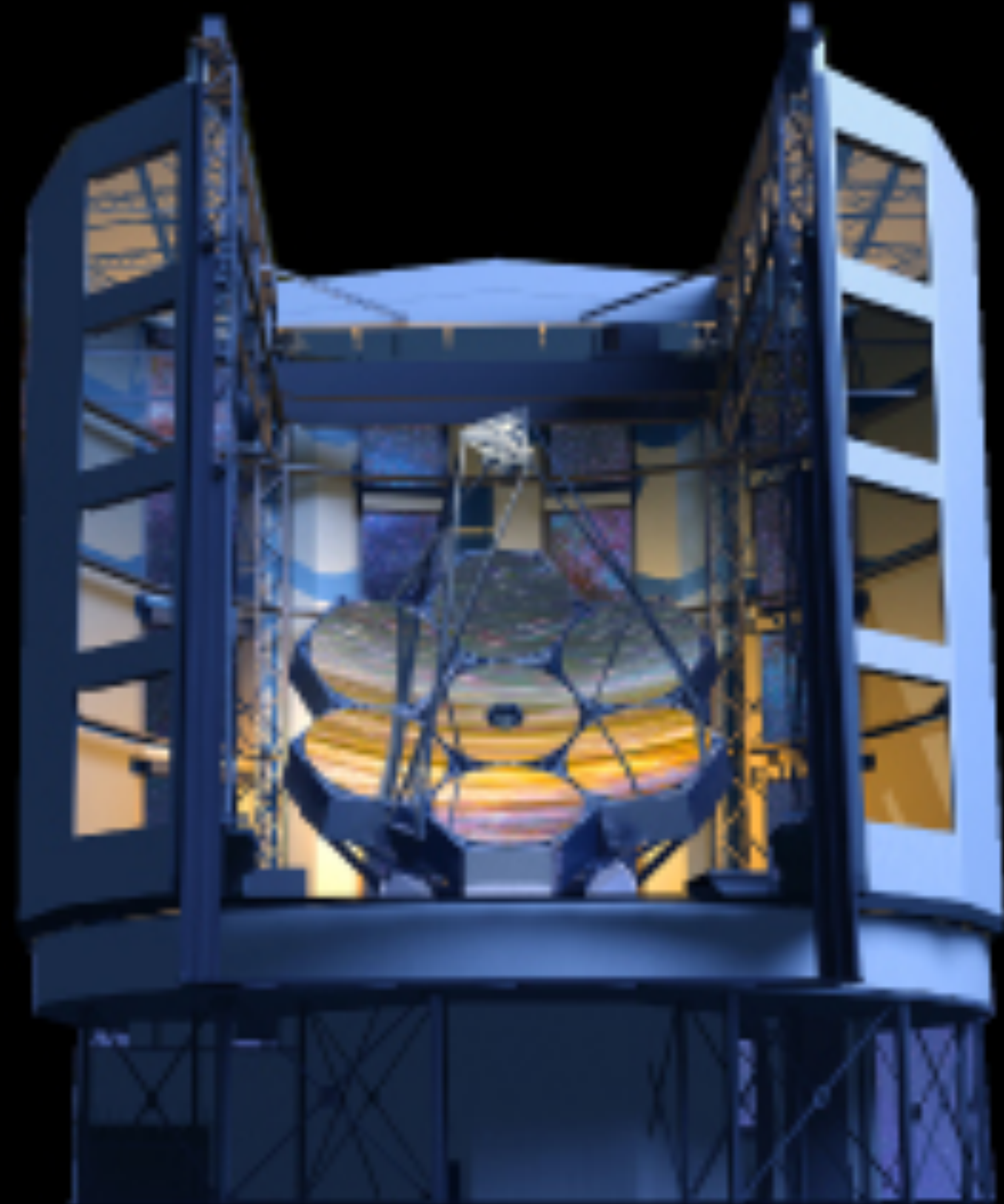
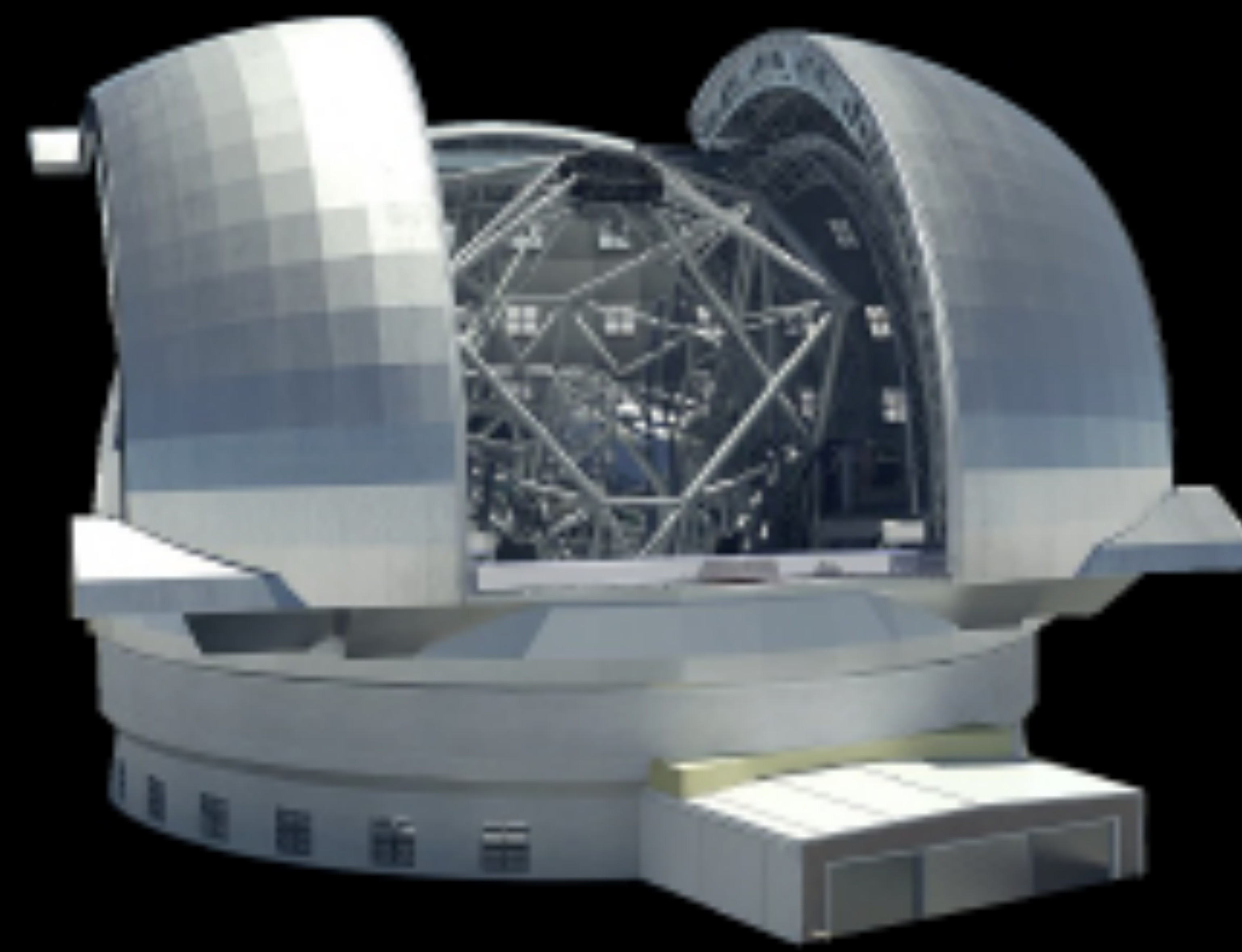



Figure credit: Sarah Rugheimer & Tyler Robinson in Domagal-Goldman et al. 2016

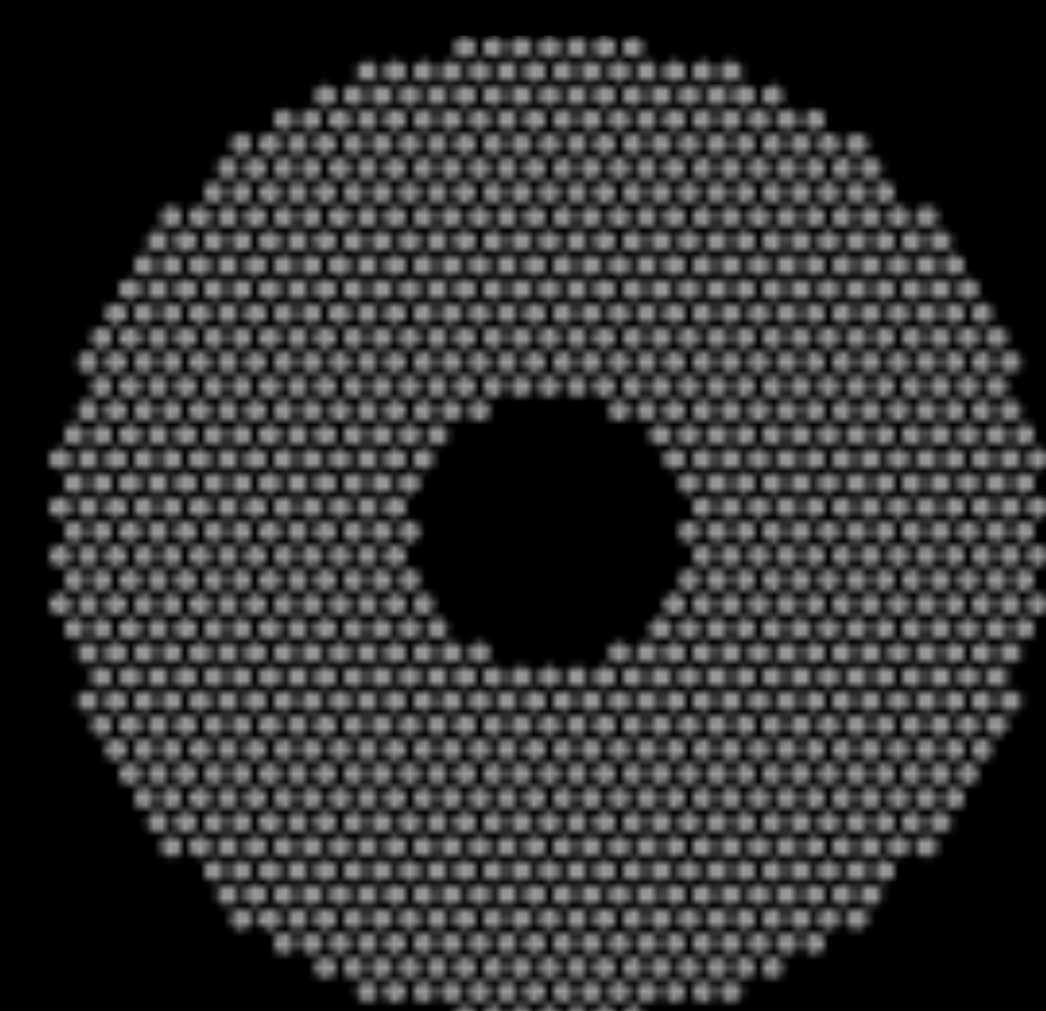


GIANT MAGELLAN TELESCOPE

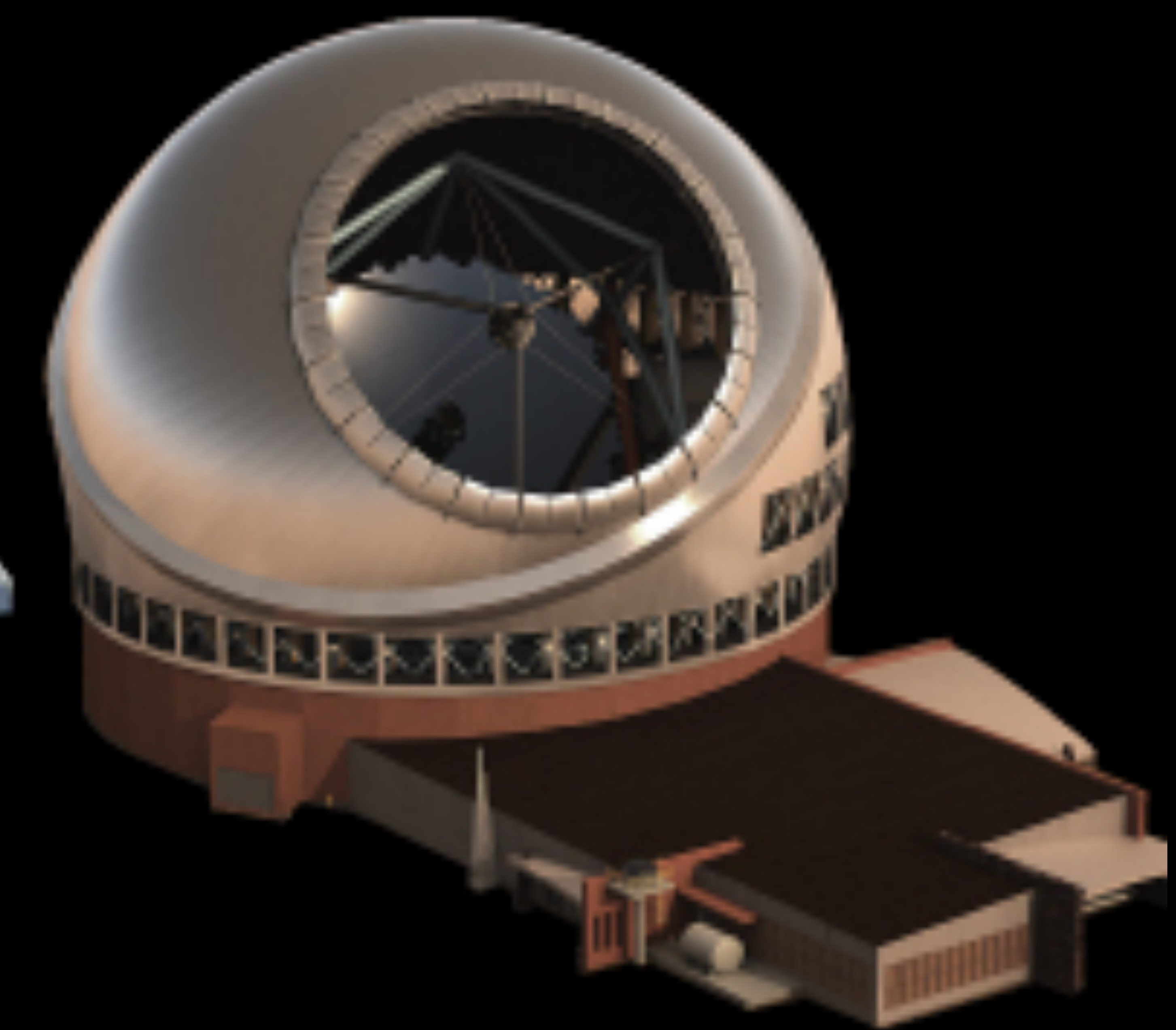
24.5 m, early-2020s



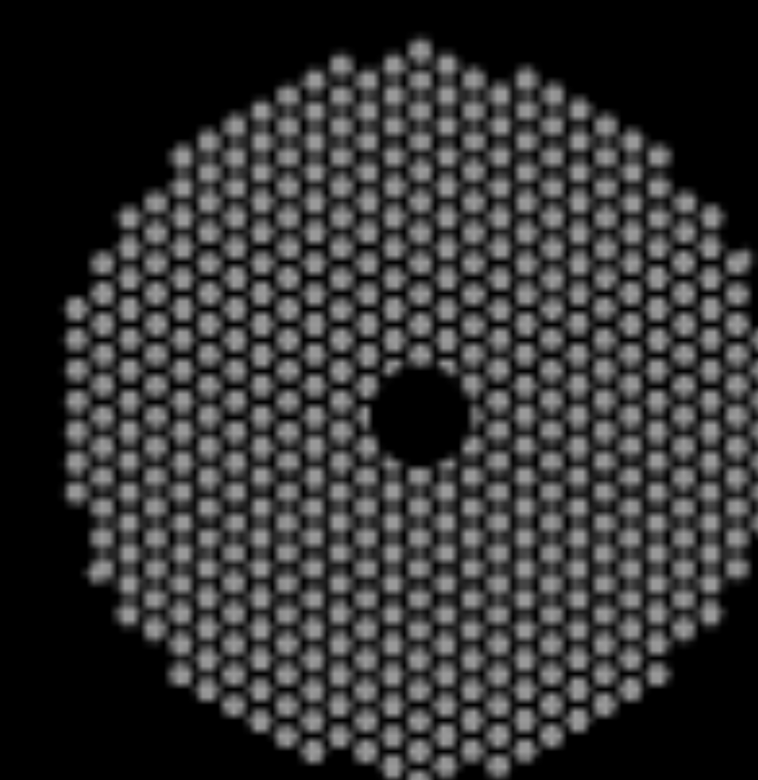
EUROPEAN EXTREMELY LARGE TELESCOPE



39 m, mid-2020s (2024)



THIRTY METER TELESCOPE

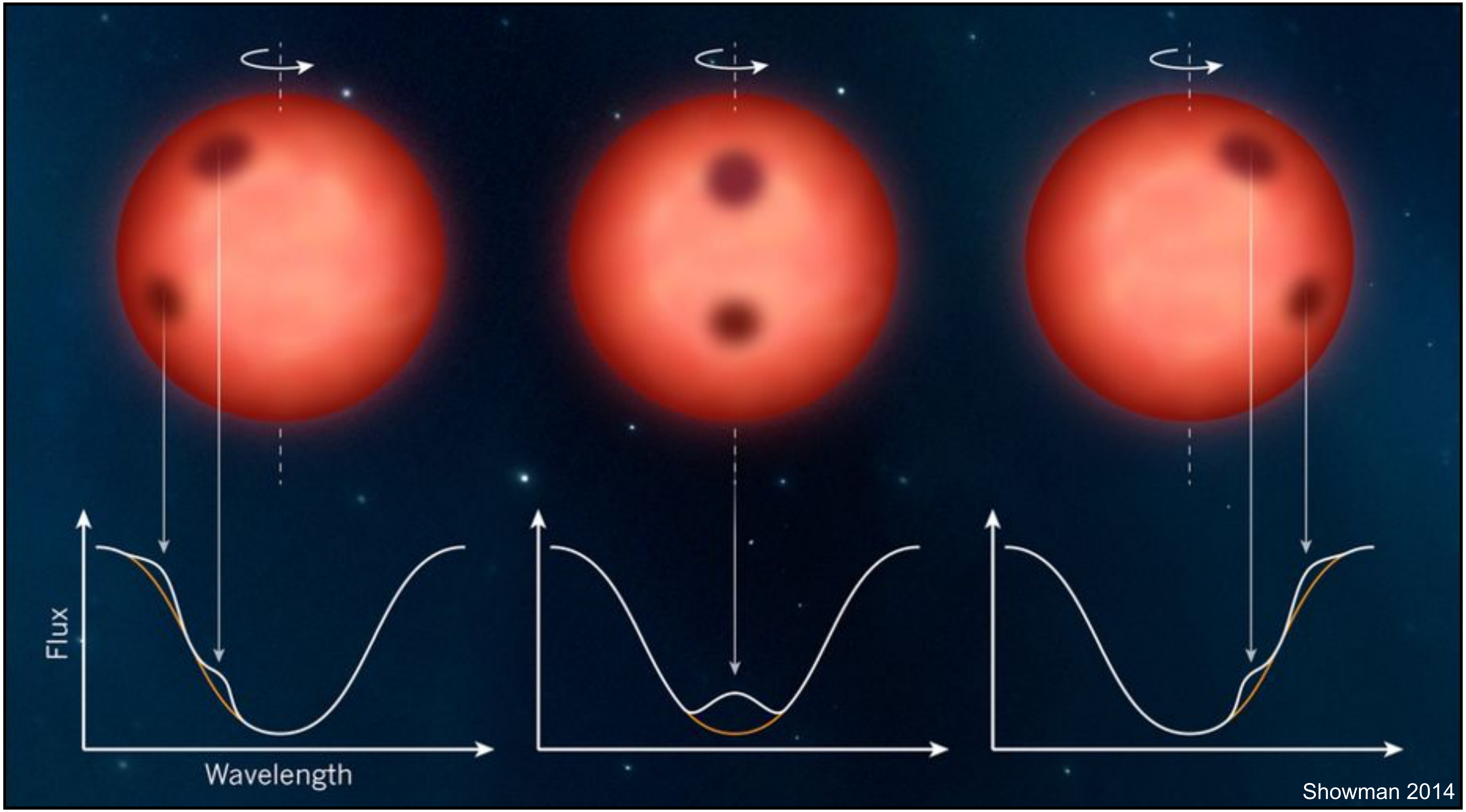


30 m, late-2020s

**Estimated time needed with optical IFU:**

**~100 hours (10 nights)** **~40 hours (4 nights)** **~60 hours (6 nights)**

# Potential to map exoplanet features with Doppler imaging



# Exocartography possible with ELTs

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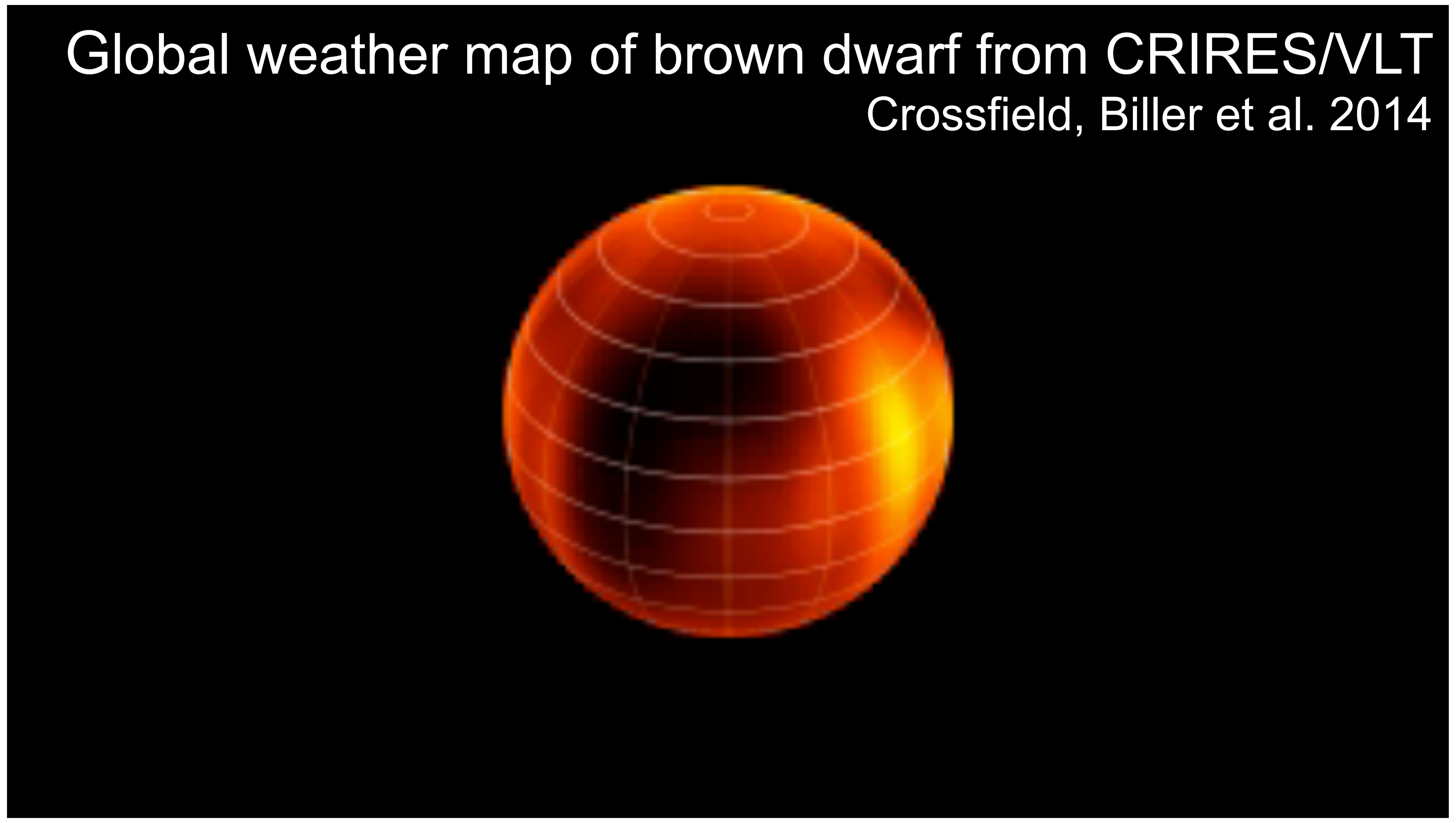

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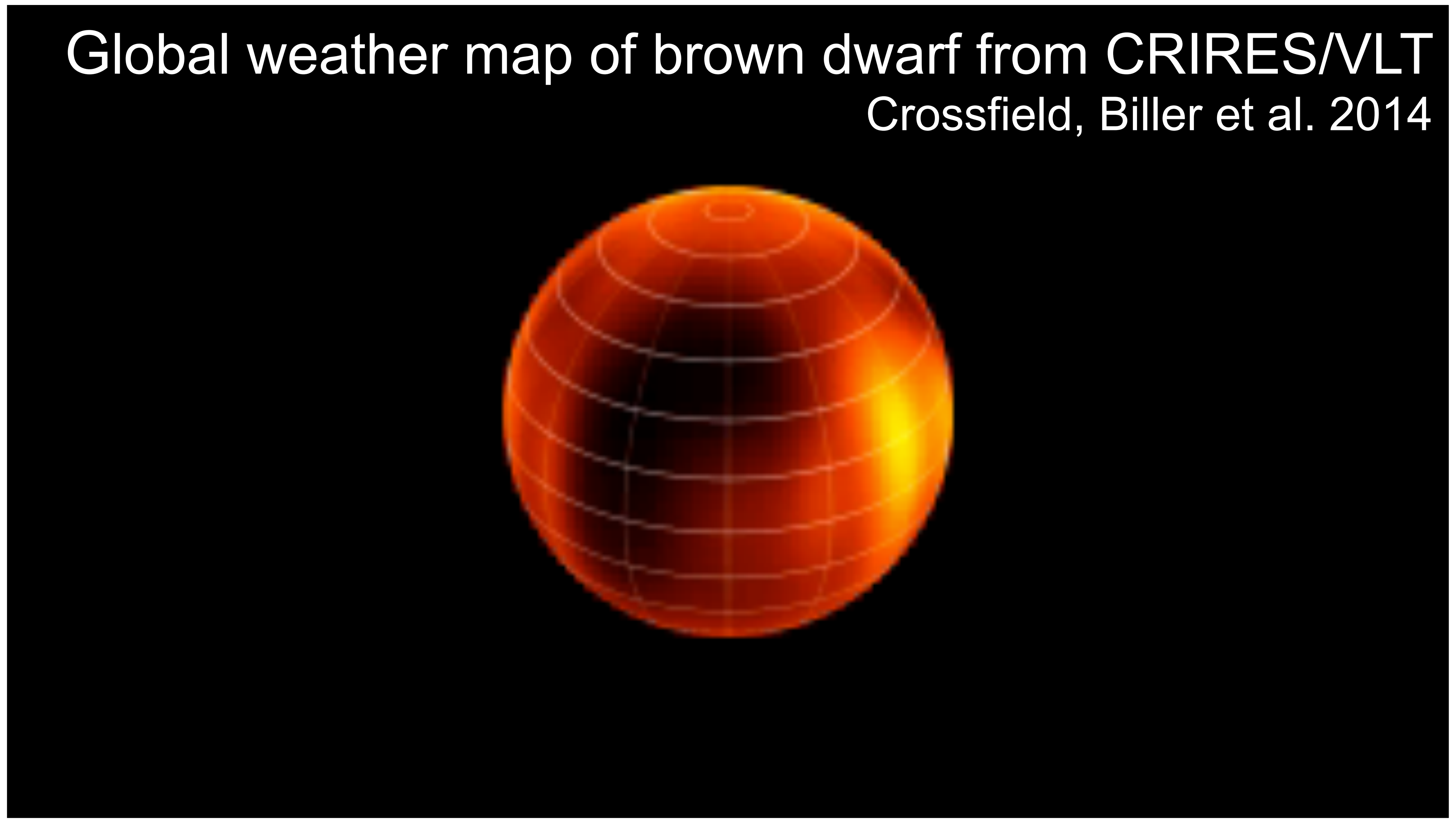


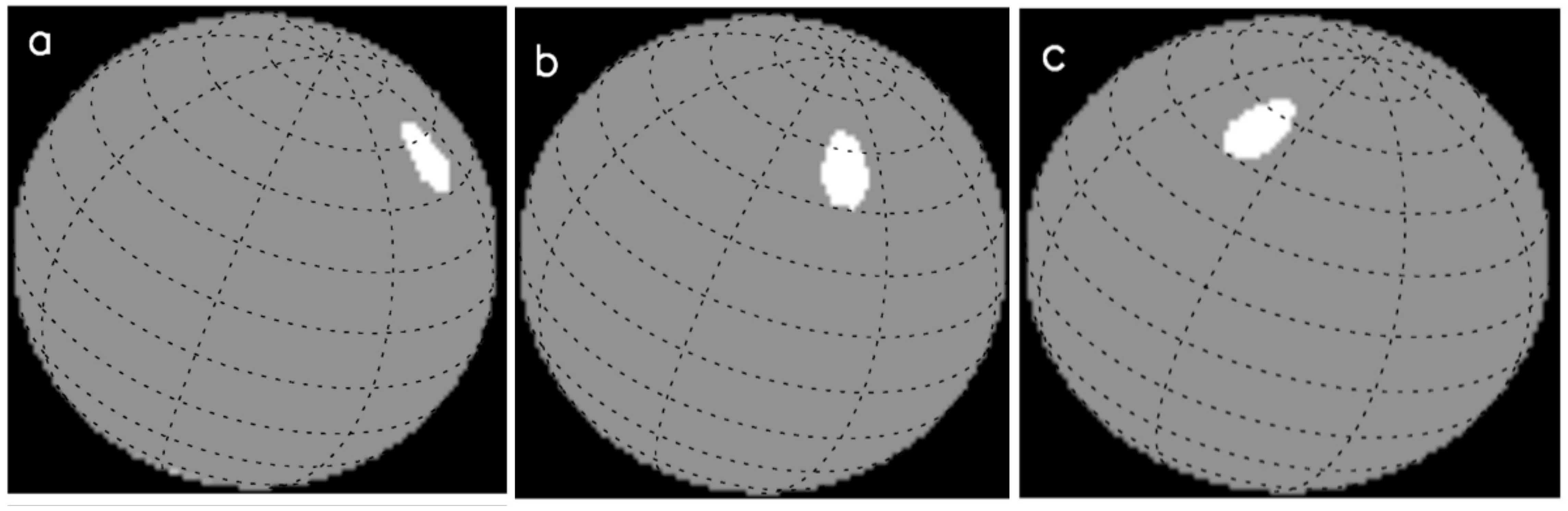


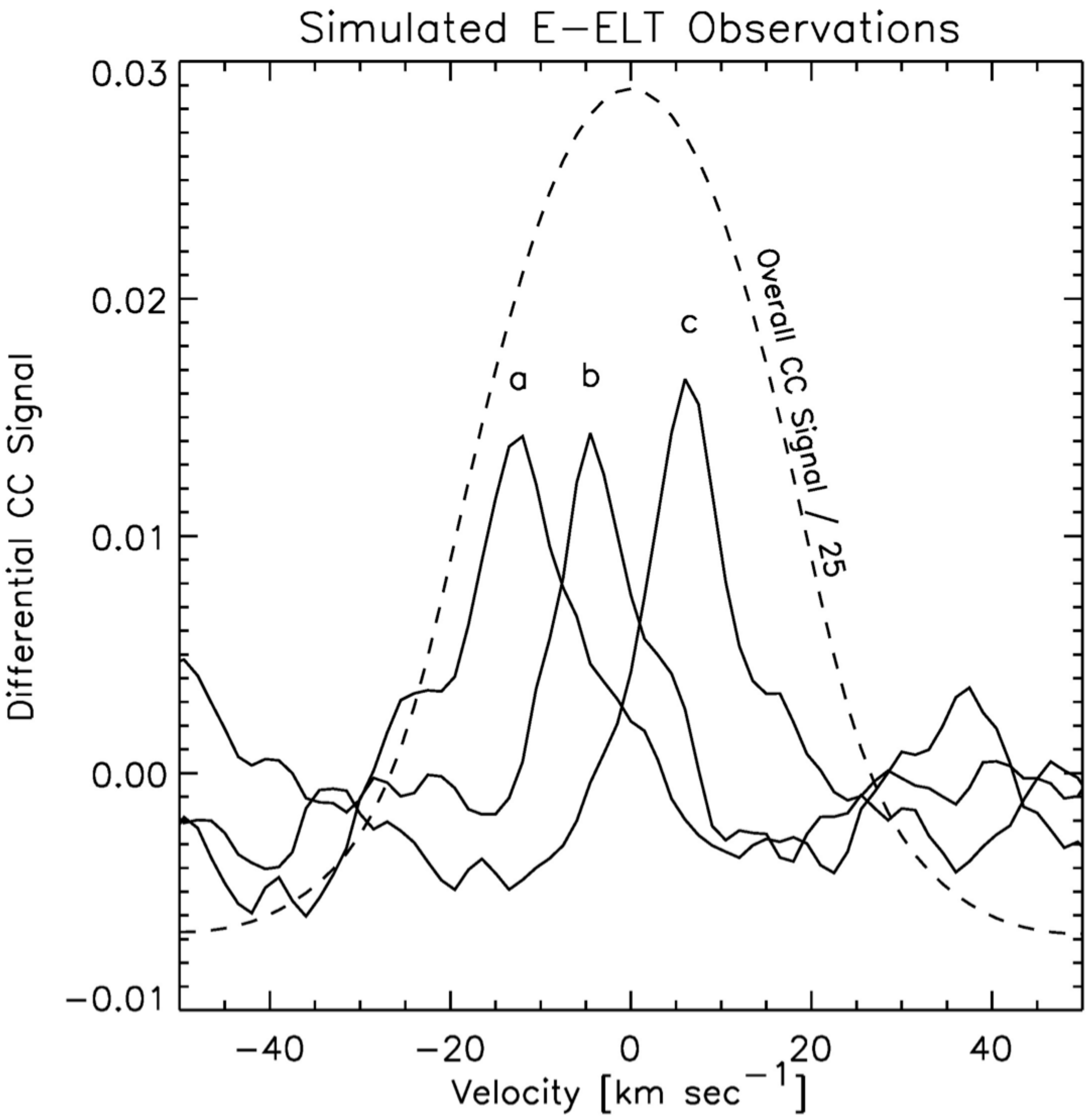


Mapping surface of β Pic b with E-ELT
(twice as efficient as VLT BDs)
Snellen et al. 2014

# Take home messages

exoZoo

European Research Council

- High resolution spectroscopy is a powerful and robust method to study exoplanet atmopsheres that uses the **stability** and **resolution** of EPRV instruments.

- It can measure atmospheric **composition**, **structure**, **winds** and **rotation,** for **mature** and **young** systems, across a **range** of orbital **separation**.

- **ELTs** with **HRS+HCI** may be our **only avenue forward** in the coming decades to characterize the **nearest temperate worlds** and **map** giant exoplanets.