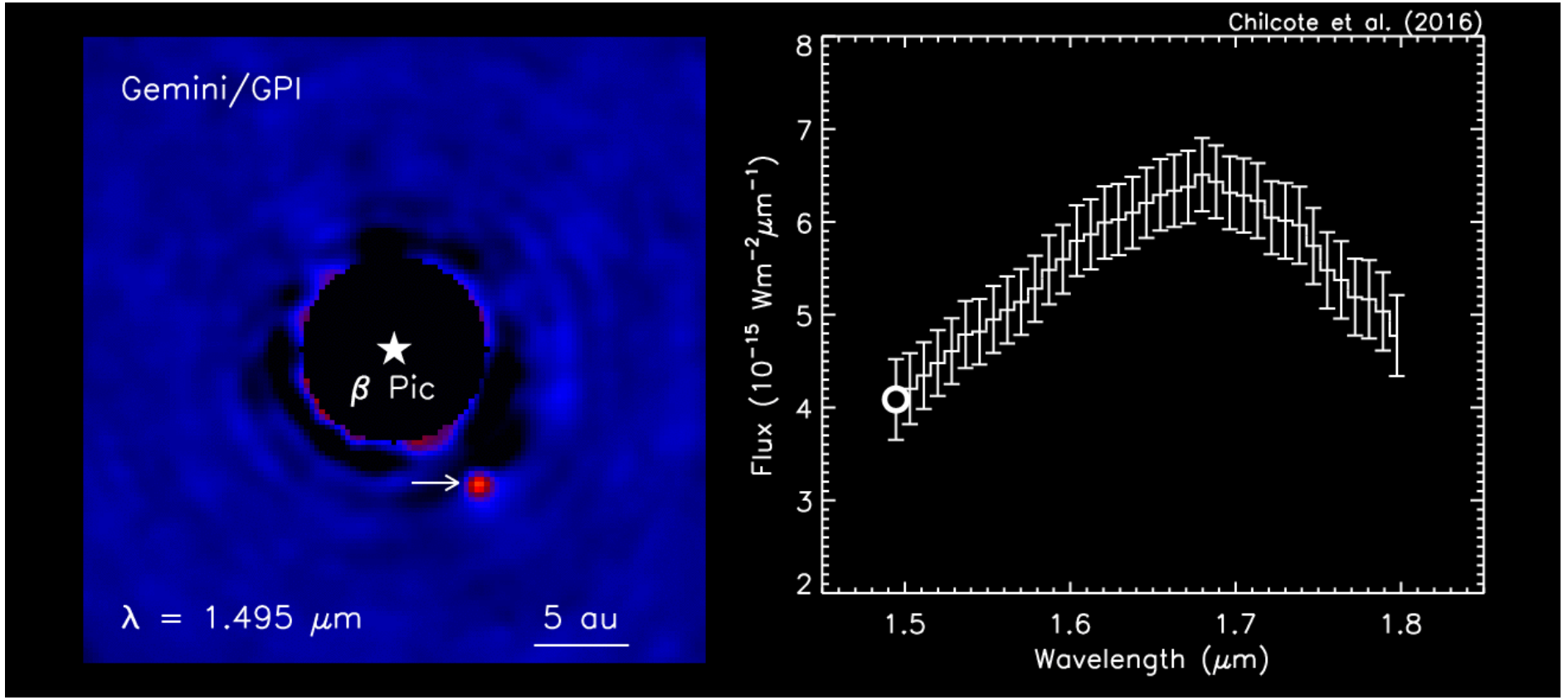
Atmospheric Characterization with Direct Imaging and Spectroscopy

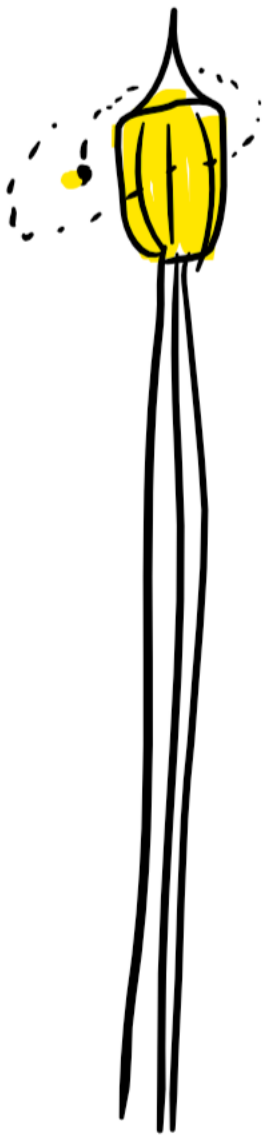


Jason Wang (Northwestern)

Direct Imaging is Hard

Direct Imaging is like watching a firefly circle a streetlight...

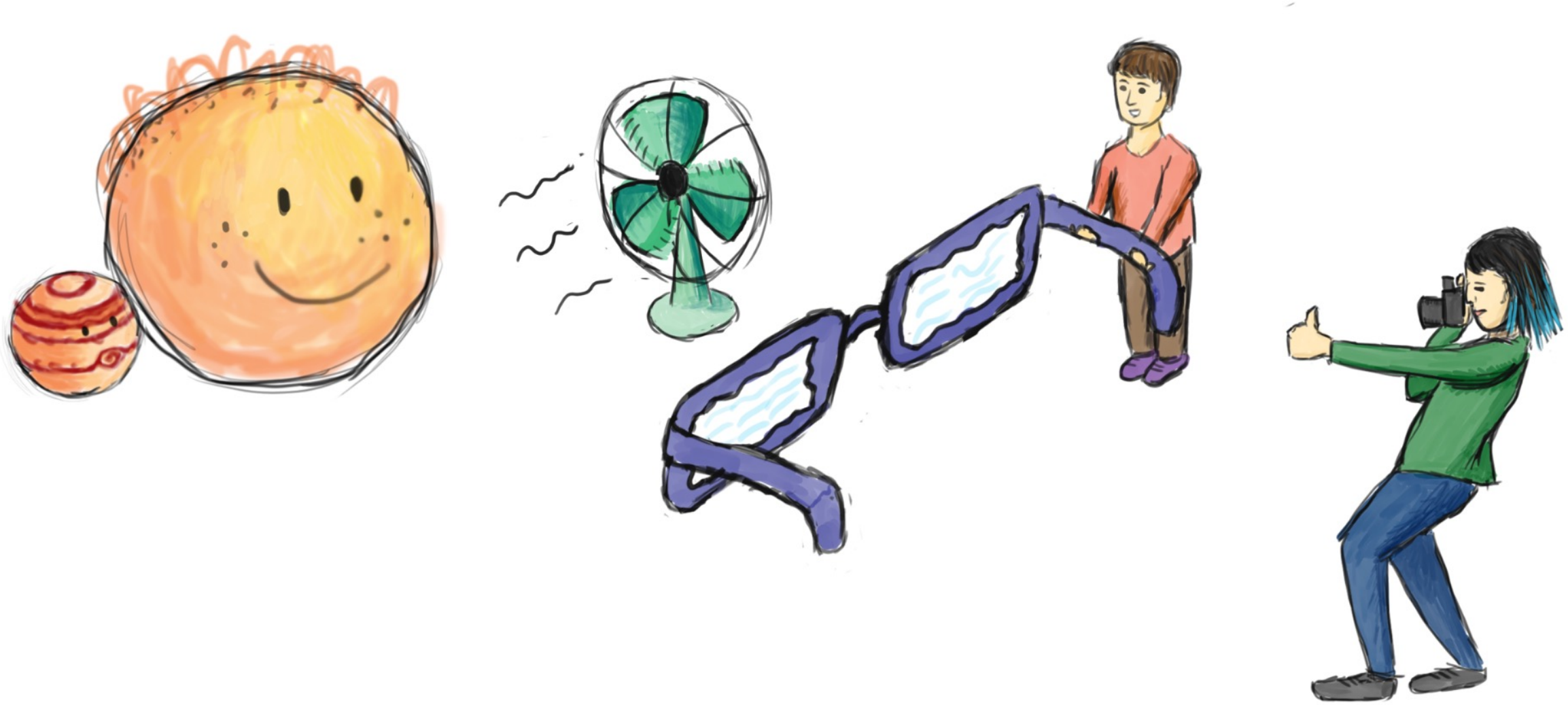
(Fainter by $x10^5$)



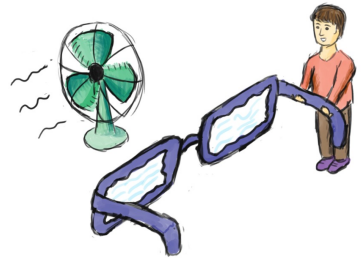
...from several miles away

(0.1-1 arcsec)

How to Image an Exoplanet

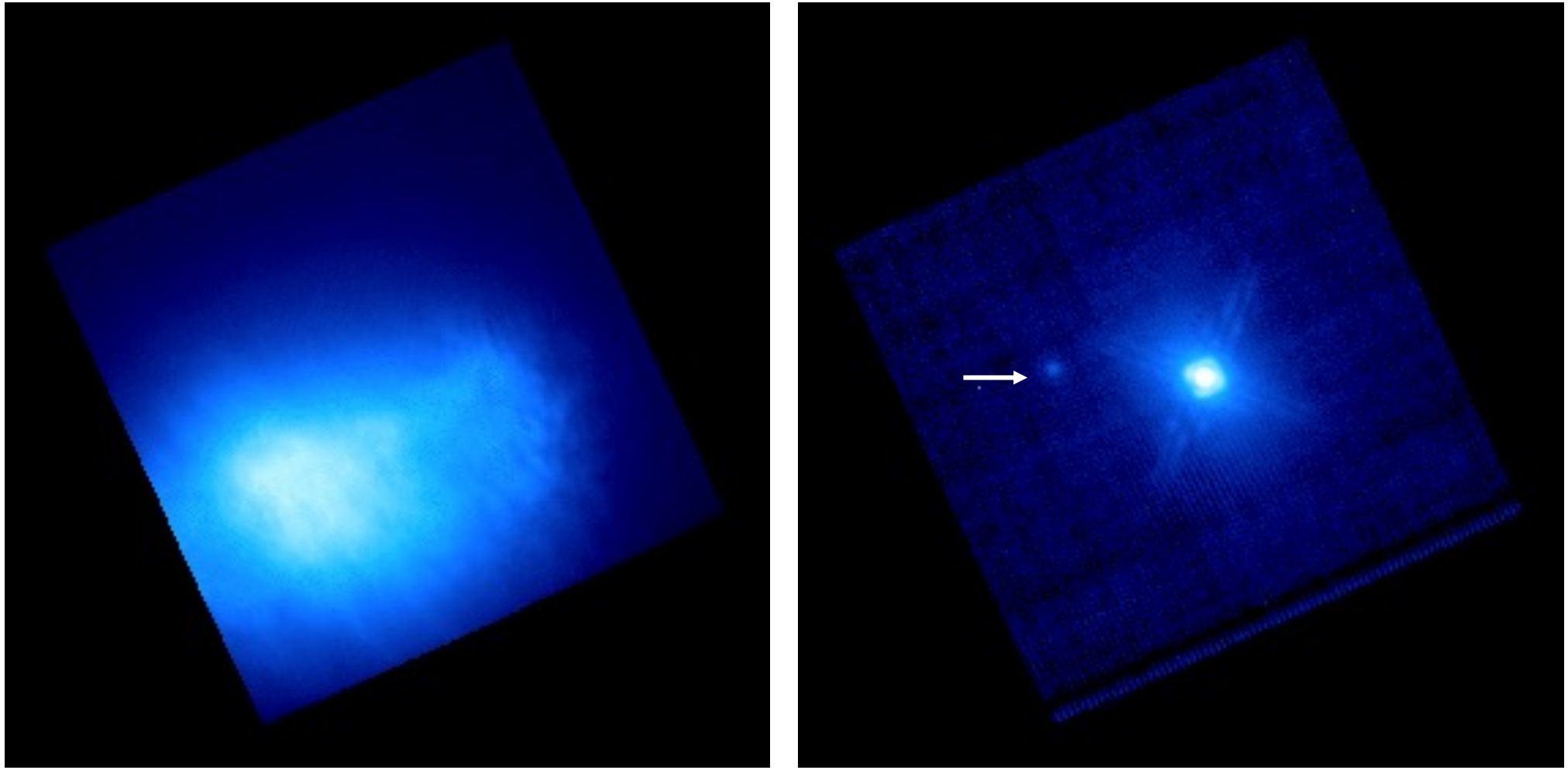


Atmospheric Turbulence



Without Adaptive Optics

With Adaptive Optics

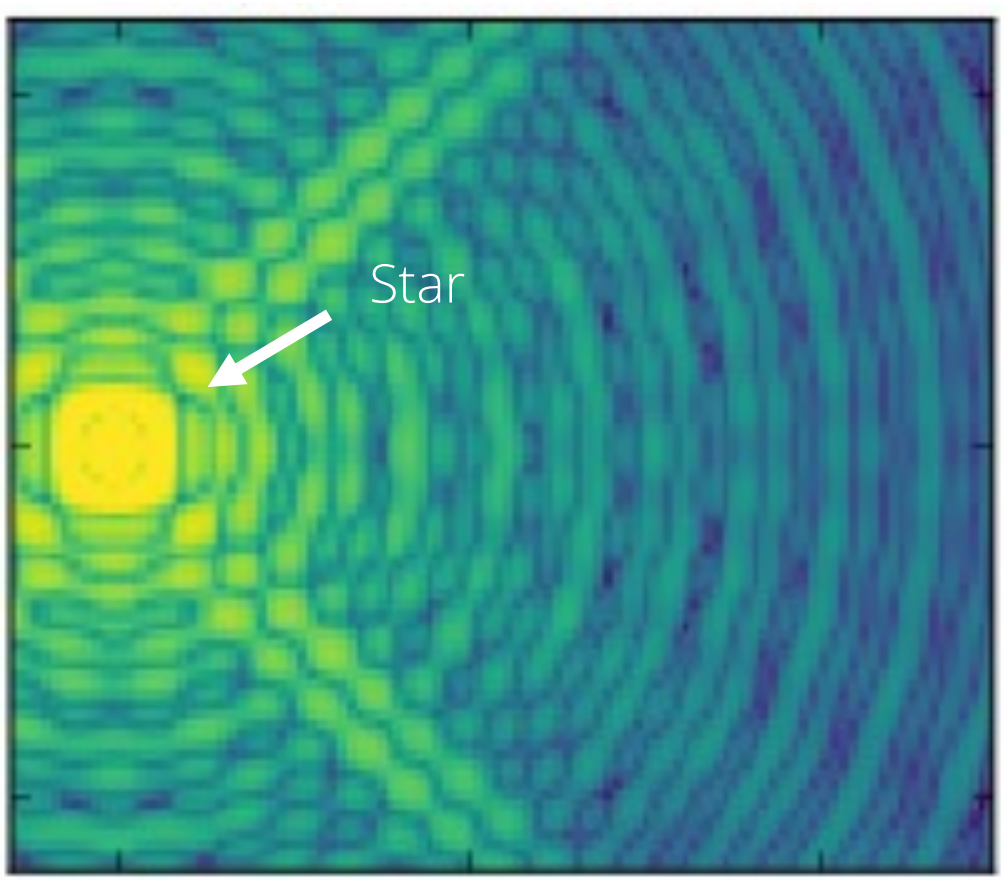


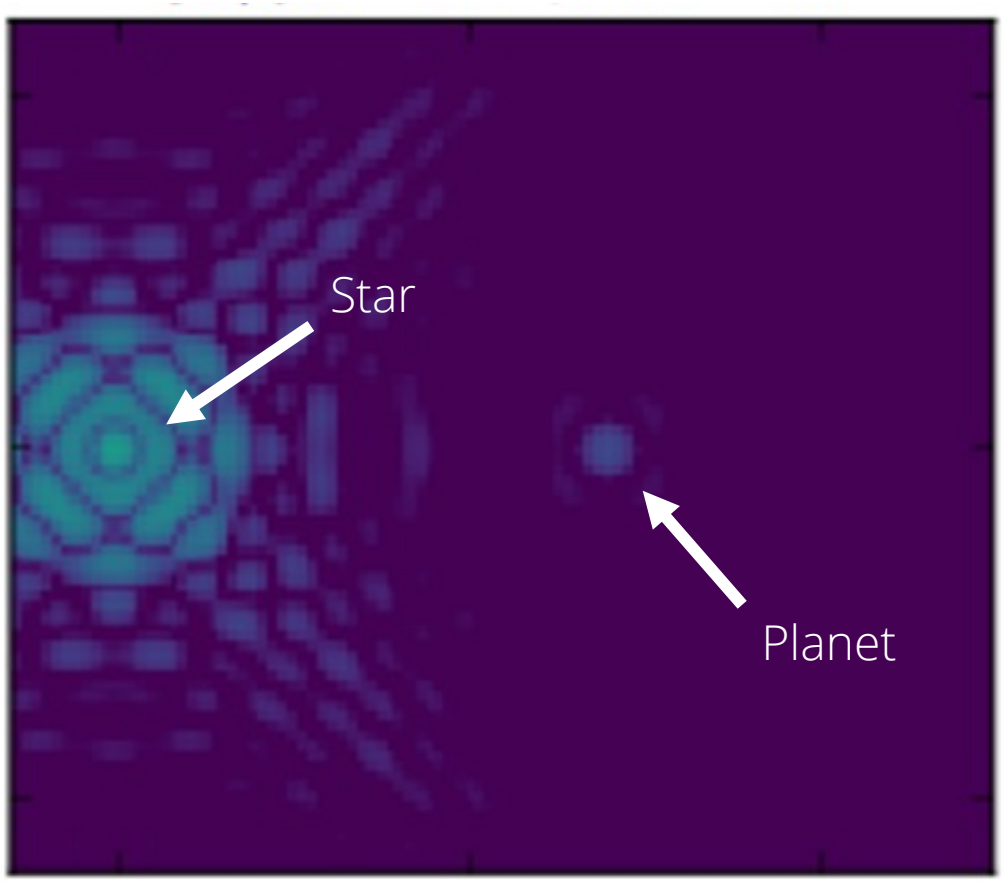
Credit: Rob De Rosa

The Glare of the Star

No Coronagraph

With Coronagraph

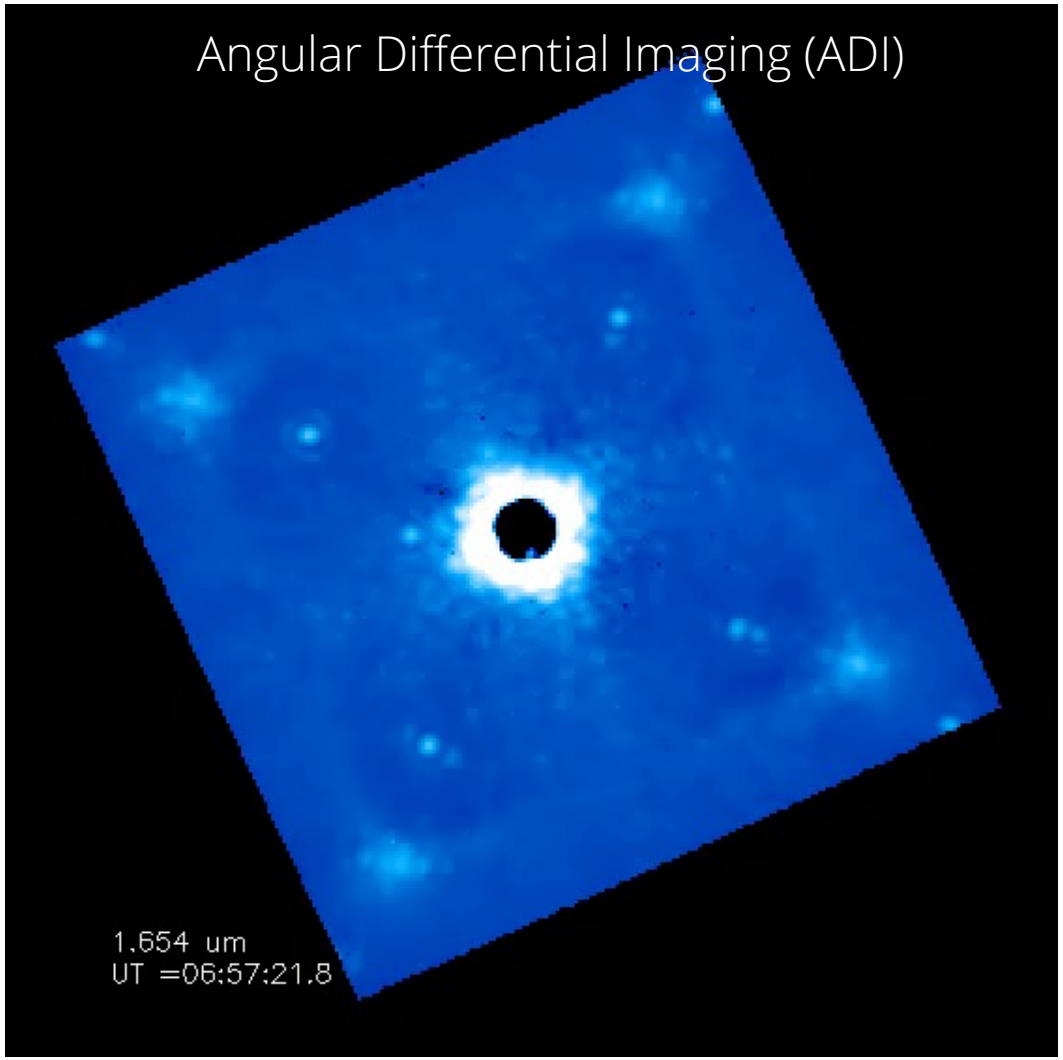




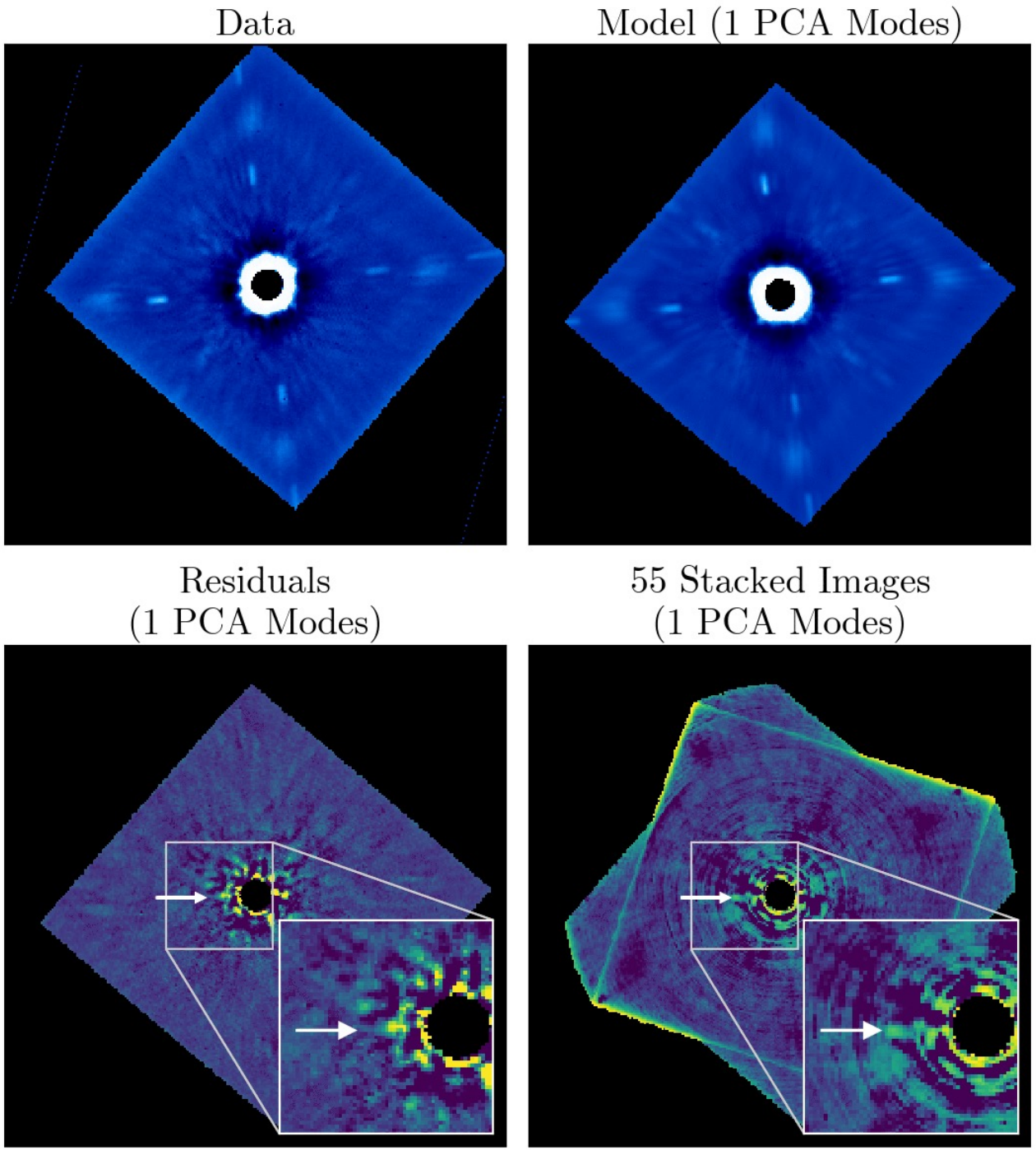
Credit: Rob De Rosa

Stellar PSF Subtraction

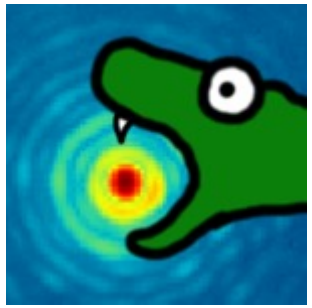
Diversity of Images in Time



Marois+ 2006
Credit: Christian Marois



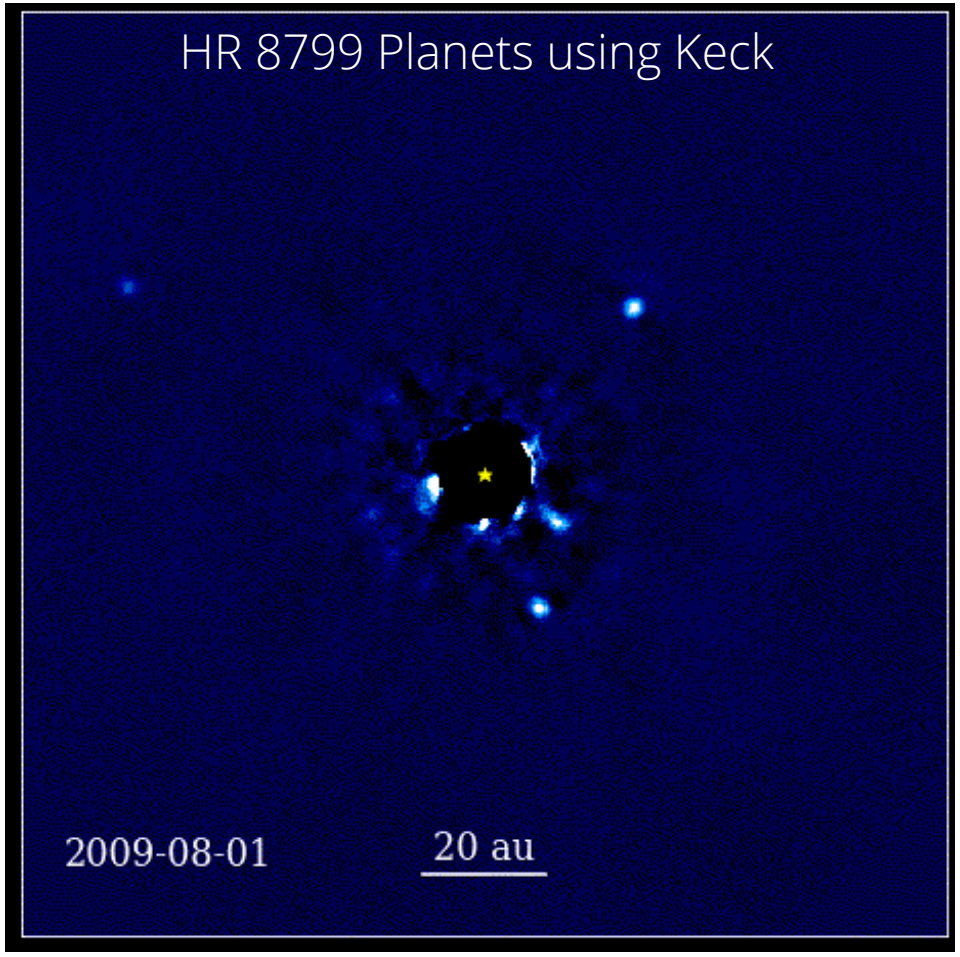
Exoplanet Survey



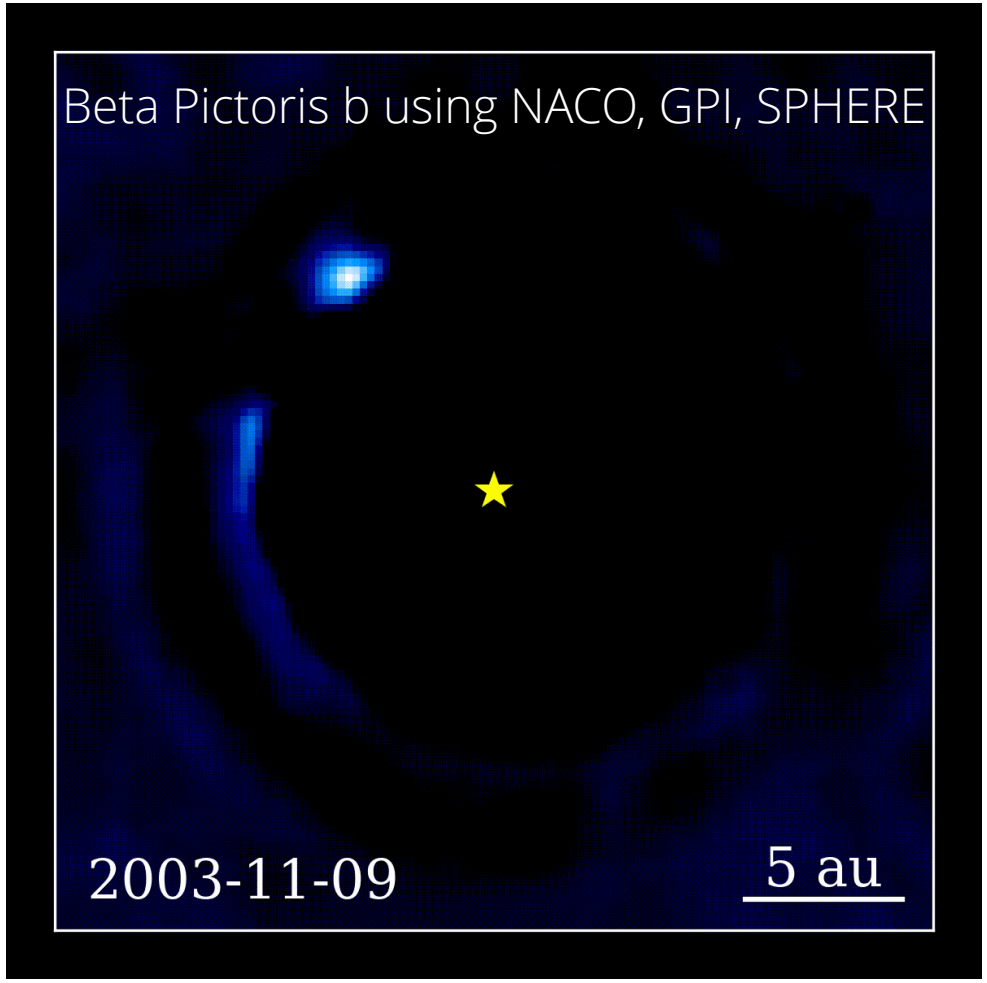
pyKLIP
Wang et al. 2015

See also:
Soummer+ 2012
Amara & Quanz 2012
VIP; Gomez-Gonzalez+ 2017

Images of Exoplanets!



Marois+ 2008, Marois+ 2010,
Konopacky+ 2016, Thompson+ 2023

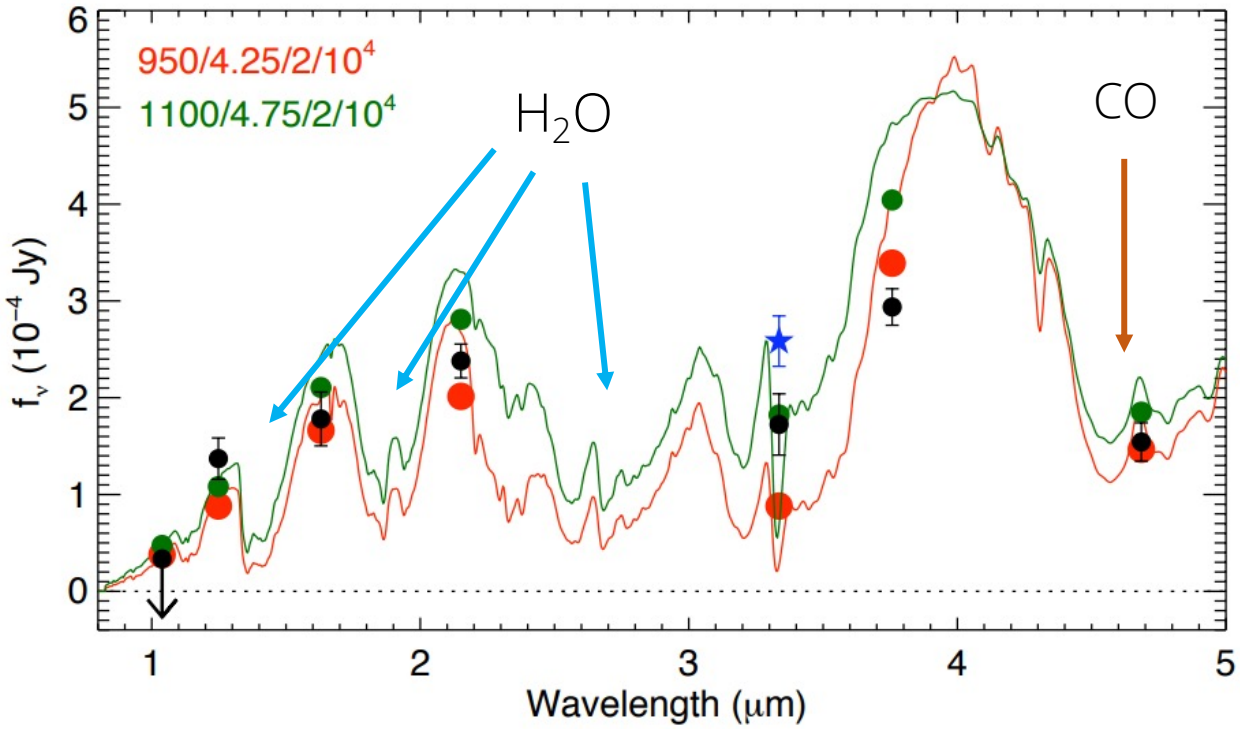


Lagrange+ 2010, Wang+ 2016,
Lagrange+ 2019.

Photometric Constraints

Easiest: Image planets at multiple wavelengths

HR 8799 c



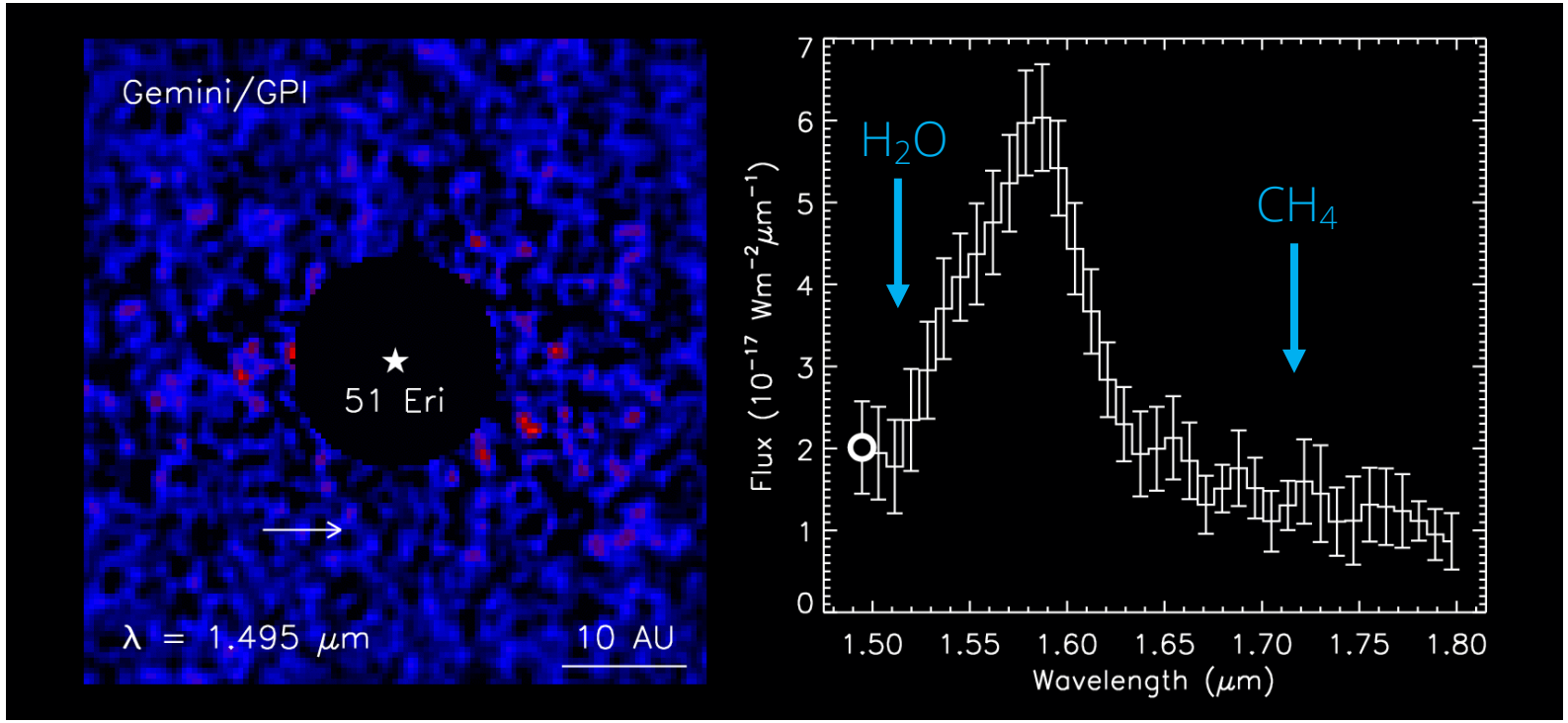
Marley+ 2012, Currie+ 2011, Marois+ 2010
See also: Skemer+ 2014

Low-R Spectra with Integral Field Spectroscopy

Gemini/GPI (Macintosh+ 2014)
VLT/SPHERE (Bezuit+ 2019)
Subaru/CHRAIS (Groff+ 2016)

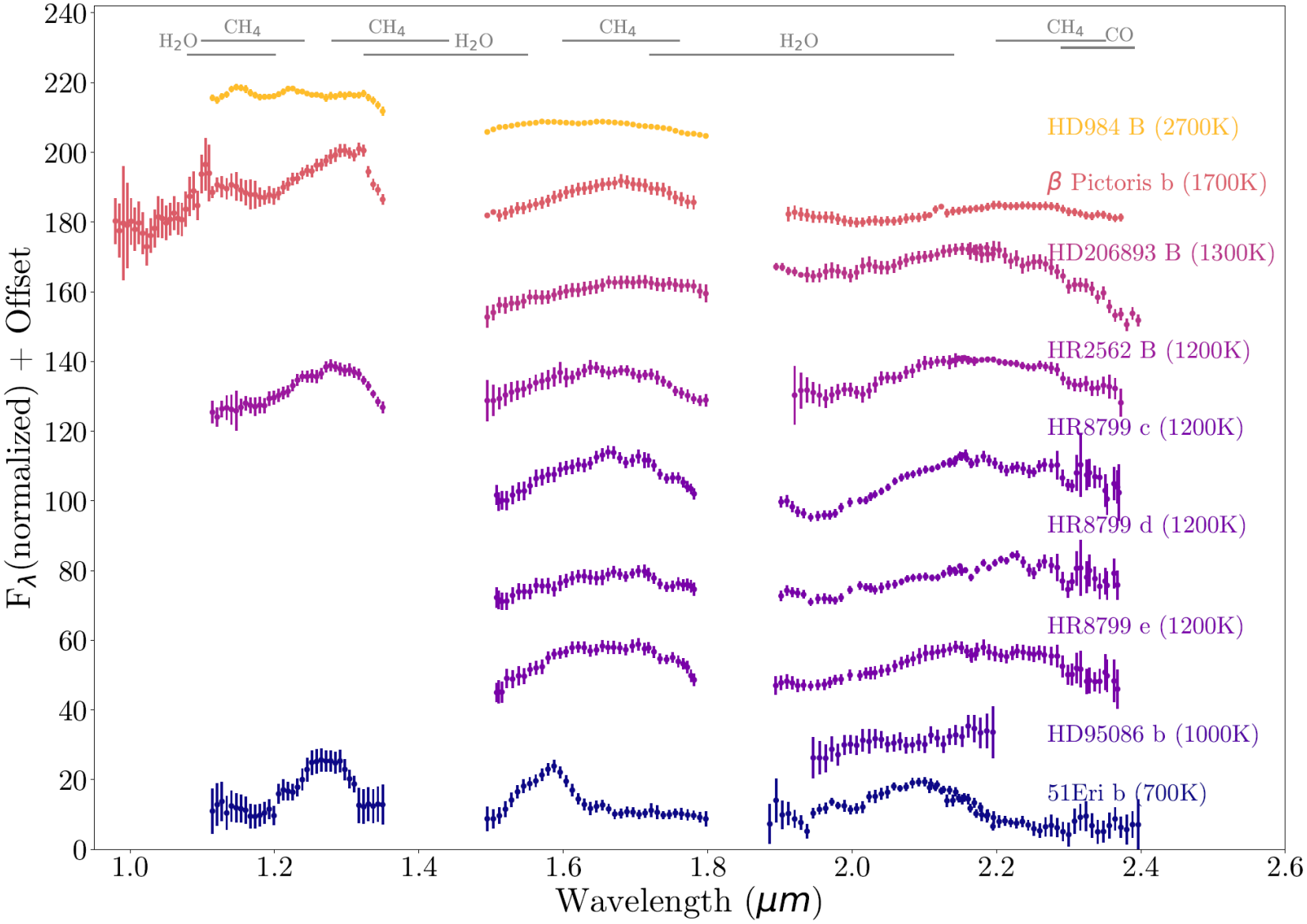
Integral Field Spectroscopy

51 Eri b with GPI
R~50 Integral Field Spectroscopy



Credit: Rob De Rosa
Rajan+ 2017; see also Samland+ 2017

Library of Near IR Low-R Spectra

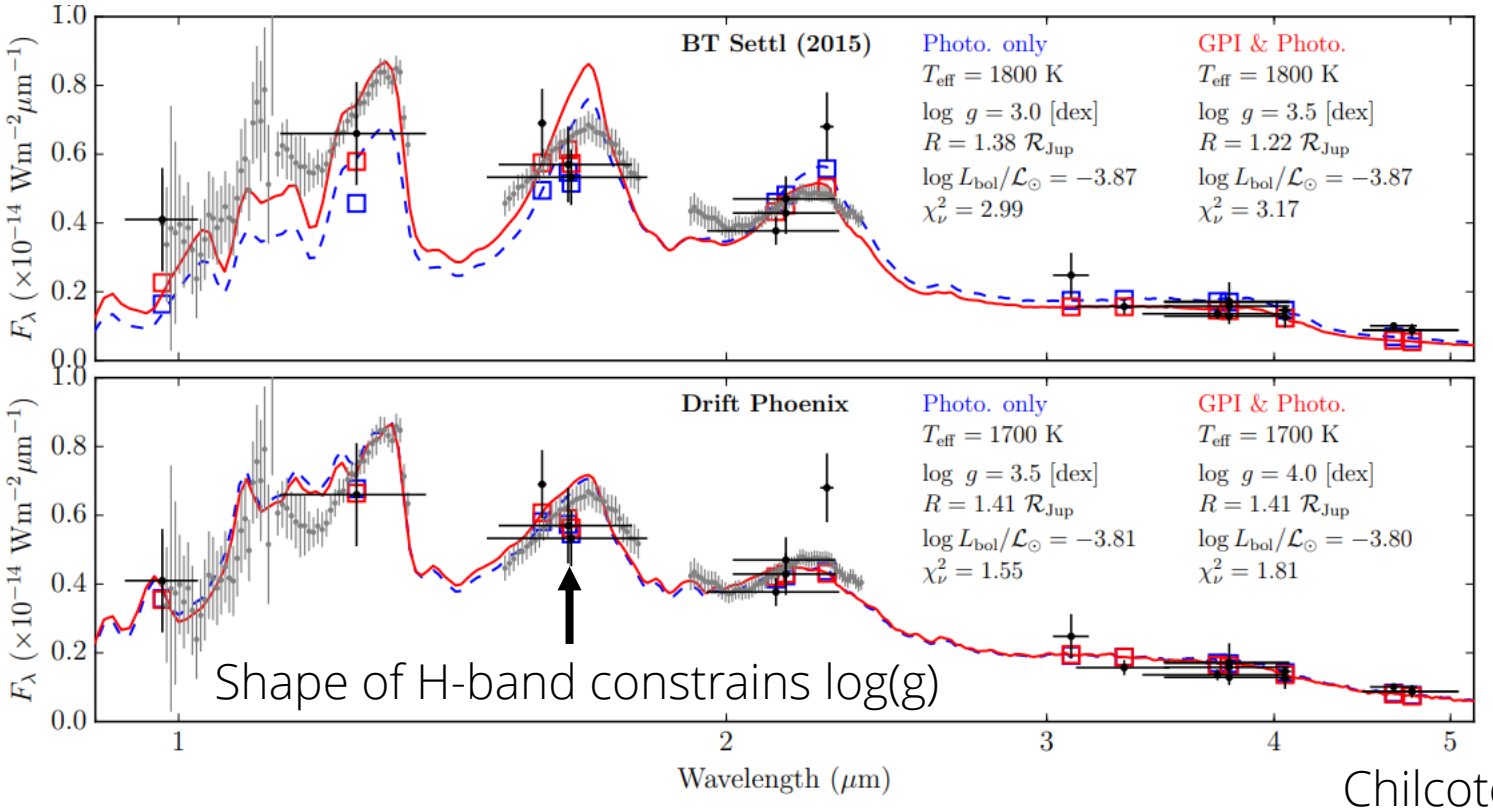


Credit: Julian Rameau/GPI Exoplanet Survey

Bulk Parameters Constrained with Low-R Spectra

Effective temperature, surface gravity, radius to ~10%
Spectra at multiple wavelengths show systematic disagreement with models

Beta Pic b

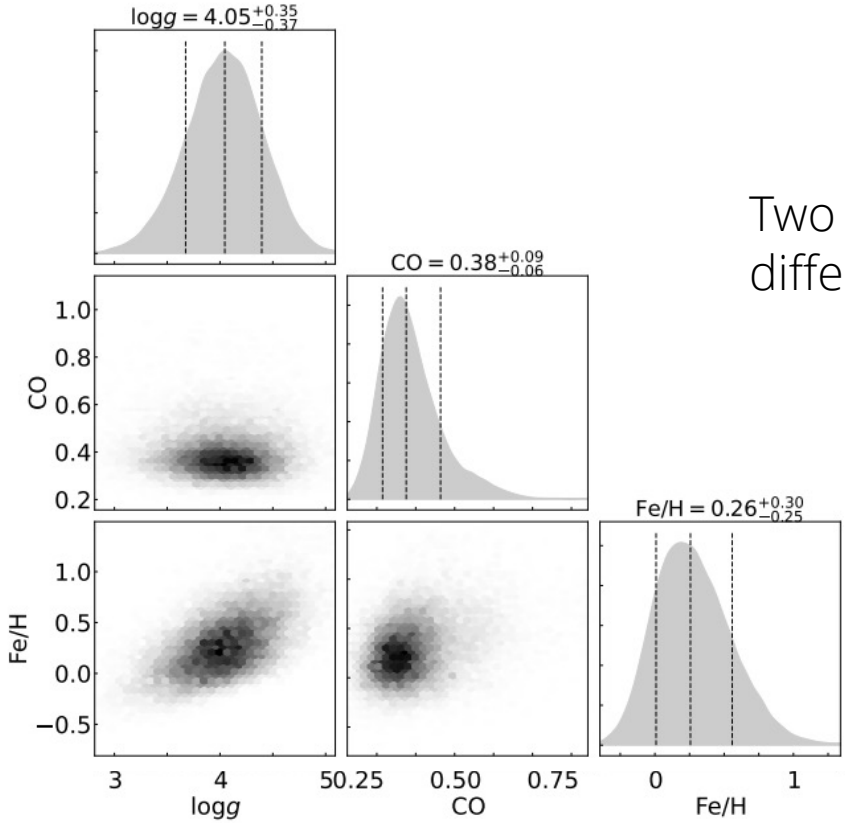


Shape of H-band constrains log(g)

Chilcote+ 2017

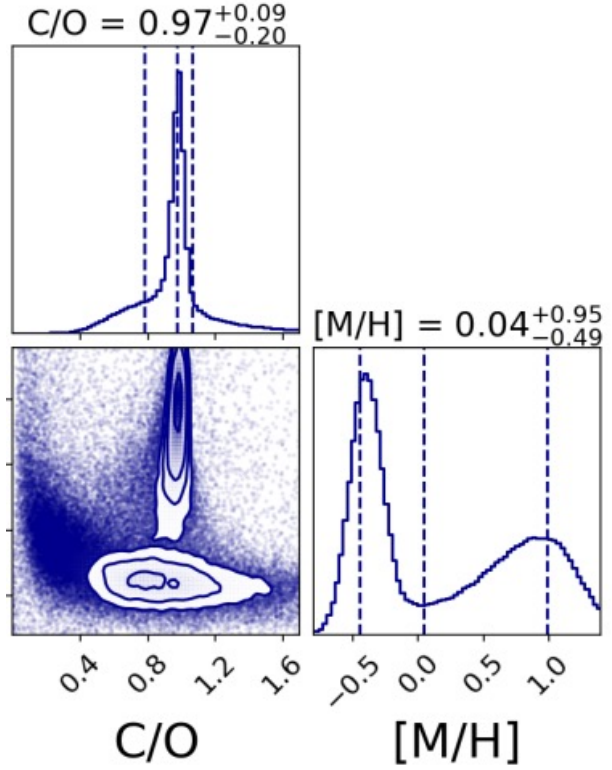
Precise Compositional Measurements Difficult at Low-R

- Depends on model and sensitive to data systematics



Brown-Sevilla+ 2023

Two different models fit to different subsets of 51 Eri b data

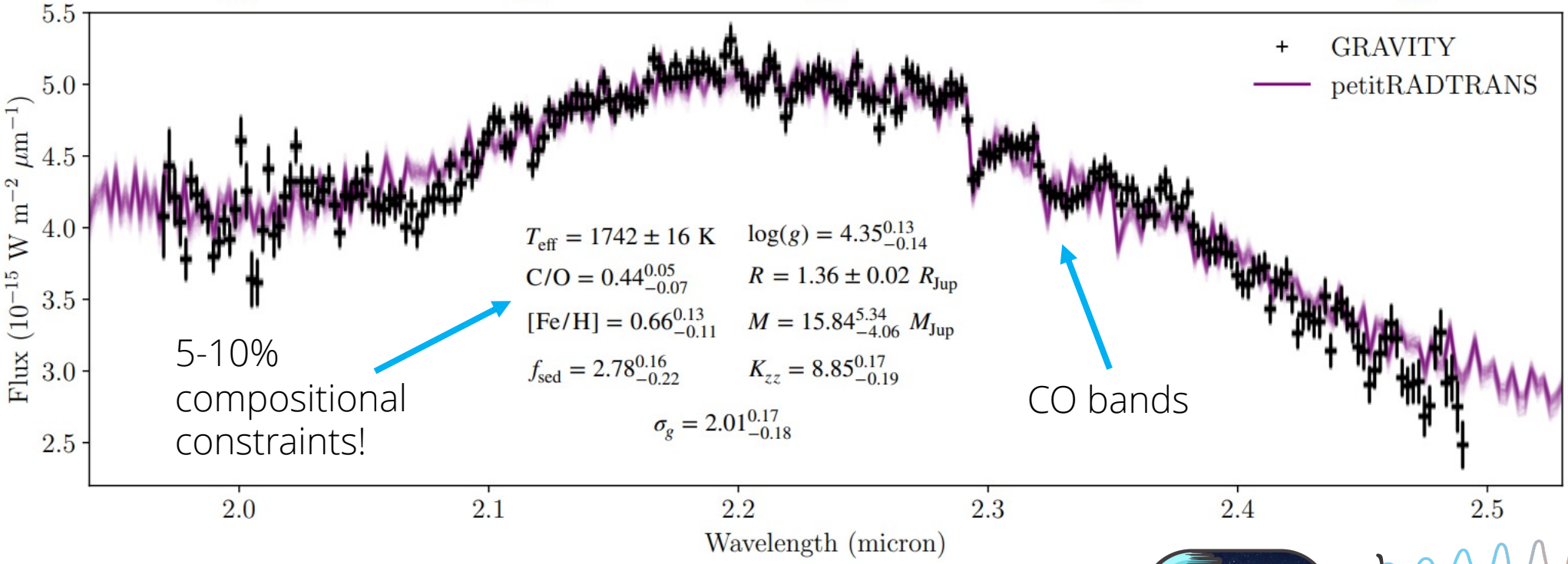


Whiteford+ 2023

Interferometry Can Provide Precise Compositional Constraints

Interferometry uses phases information to filter out noise due to the glare of the star

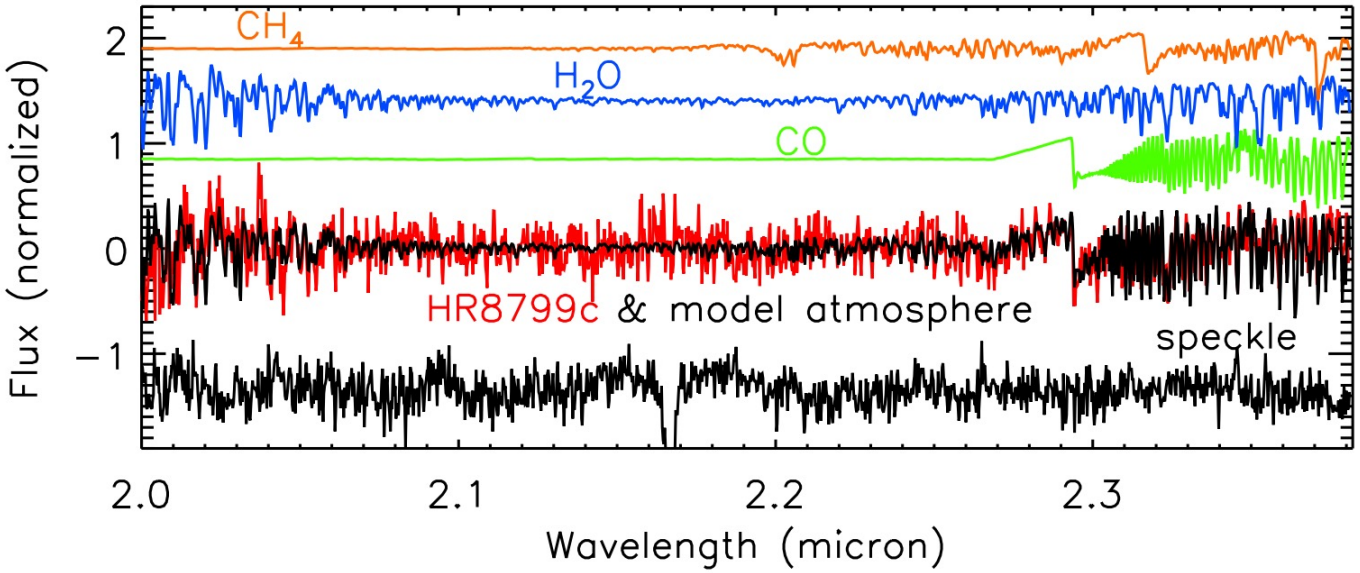
Beta Pic b



GRAVITY Collaboration+ 2020

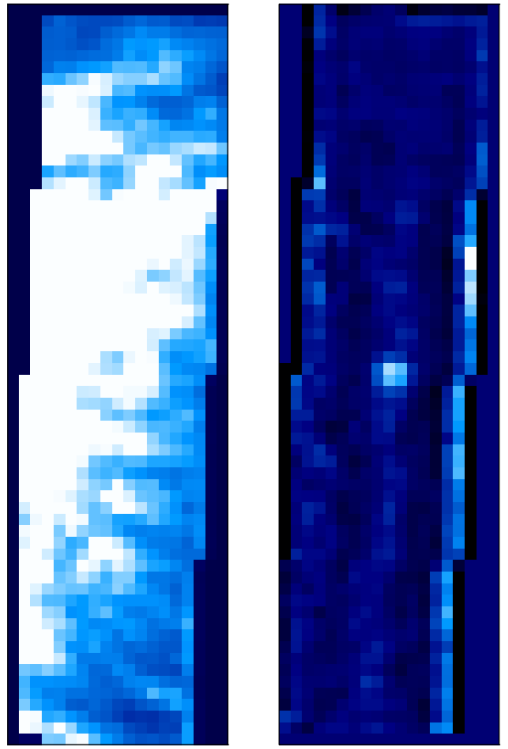
Medium Resolution Spectroscopy (R~1000-10,000)

Resolve individual lines, but not line shapes



Konopacky+ 2013. See also Barman+ 2015

Smaller Field of View
Need to Spectrally Filter out Starlight

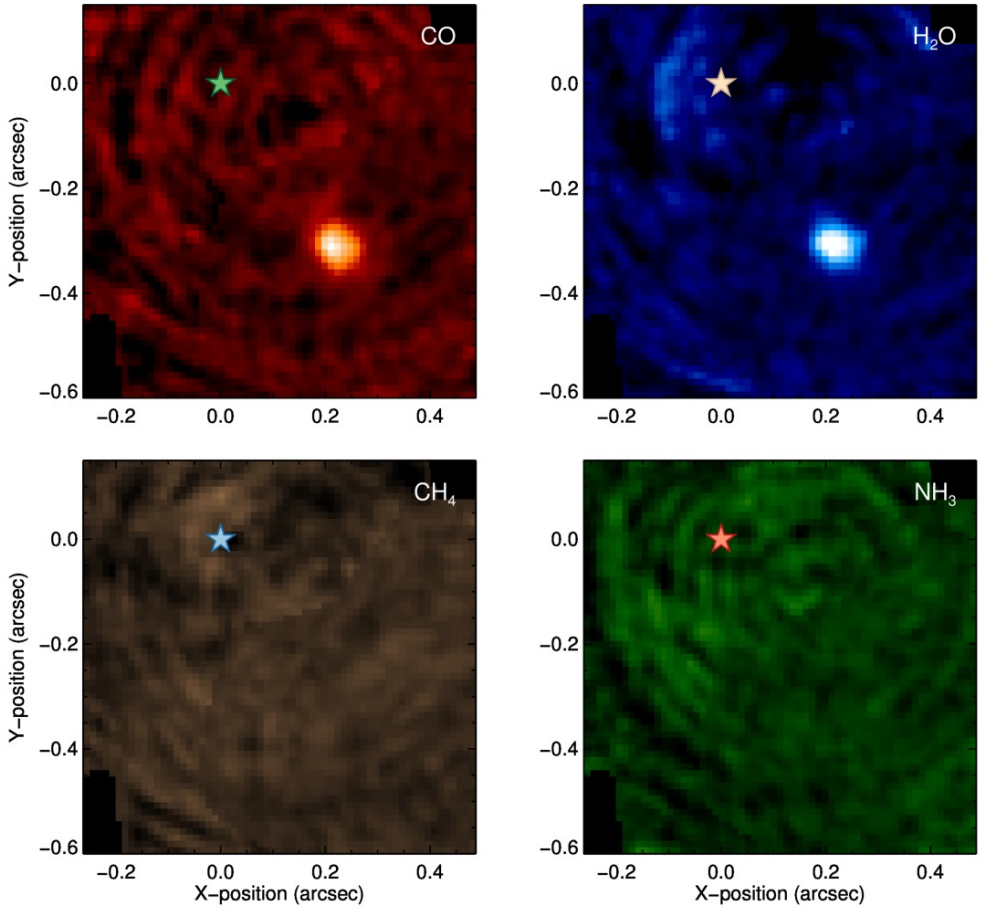


Keck/OSIRIS

Also: VLT/SINFONI, VLT/ERIS, JWST/NIRSPec, JWST/MIRI

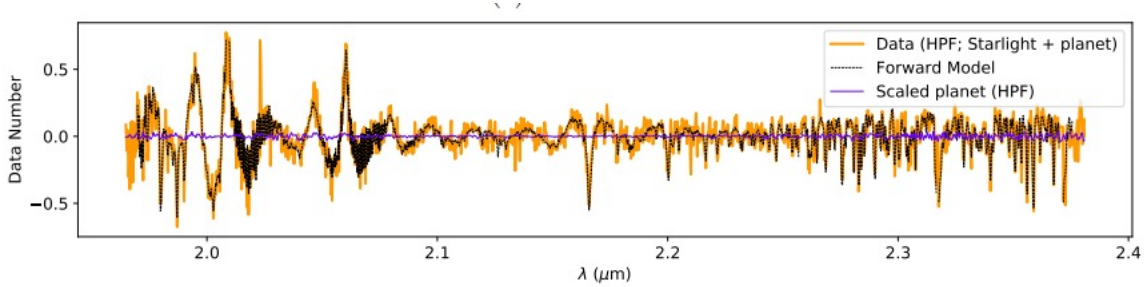
Medium Resolution Enables Detection Through Molecular Templates

Cross-Correlation

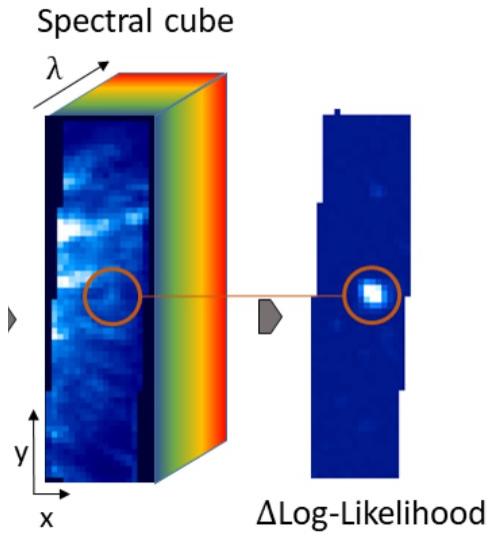


Hoeijmakers+ 2018. See also Petit dit de la Roche+ 2018

Forward Modeling



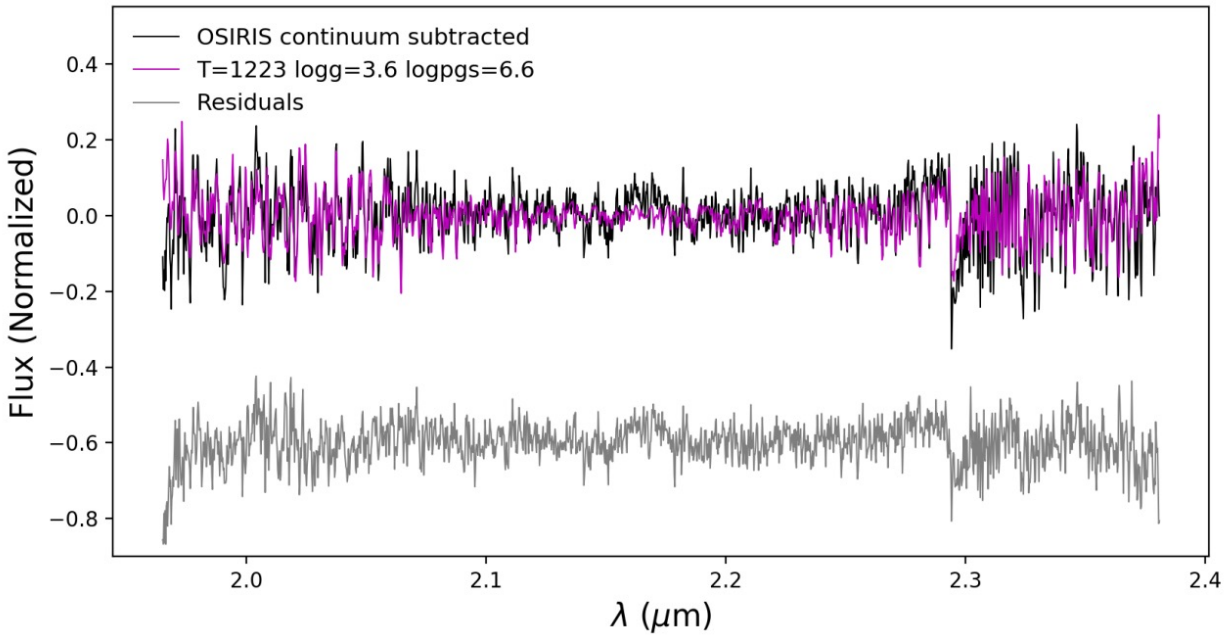
(b) Forward Modeling



Ruffio+ 2019, 2021

Medium Resolution Can Provide Extremely Precise Spectra!

VHS 1256 b: C/O = 0.24 – 0.87 (Model Limited)

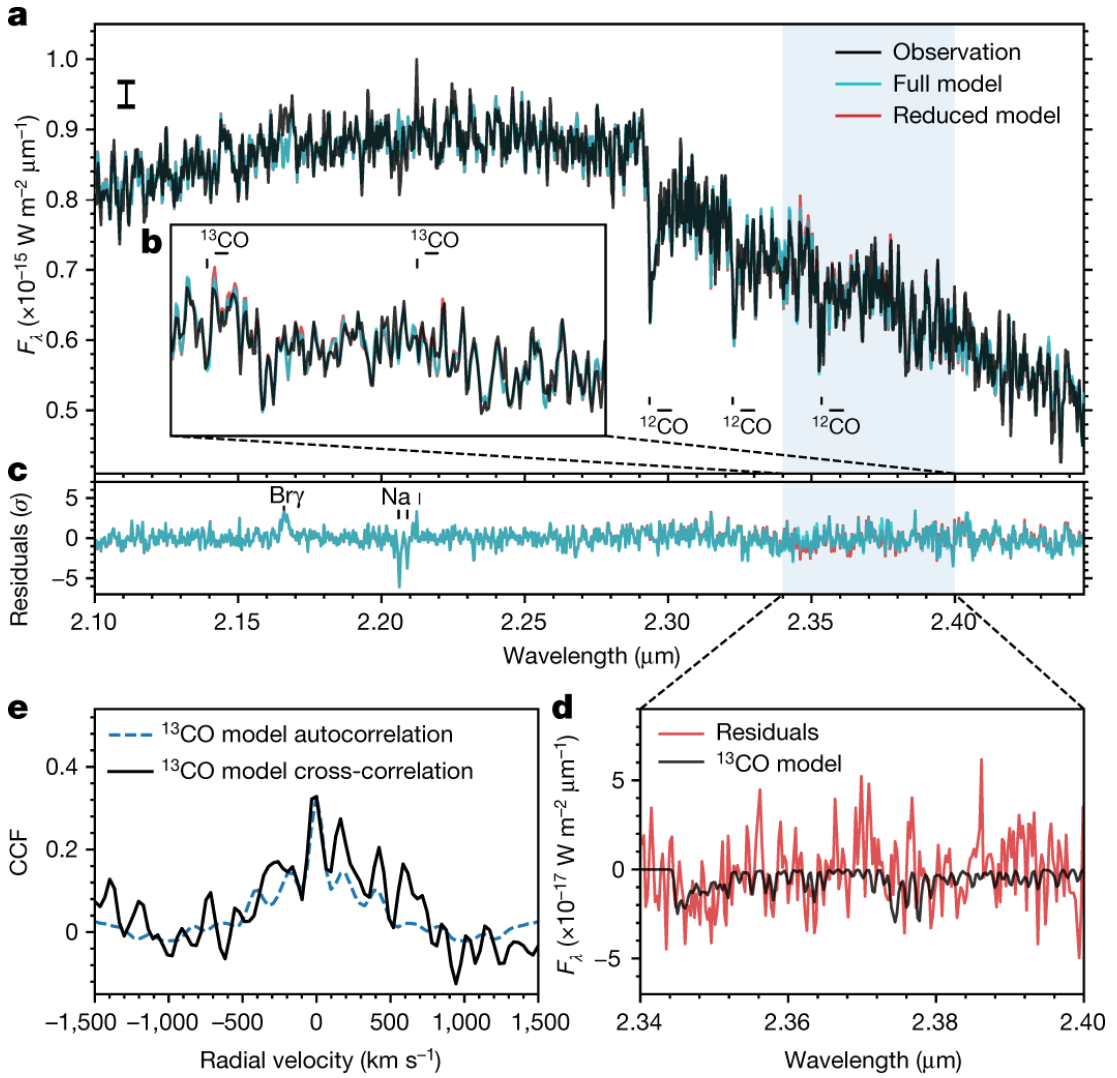


Hoch+ 2022; See also Petrus+ 2022

Need better models!

Especially with upcoming JWST data (see Aarynn Carter's Talk)

TYC 8998-760-1 b: Detection of ^{13}CO

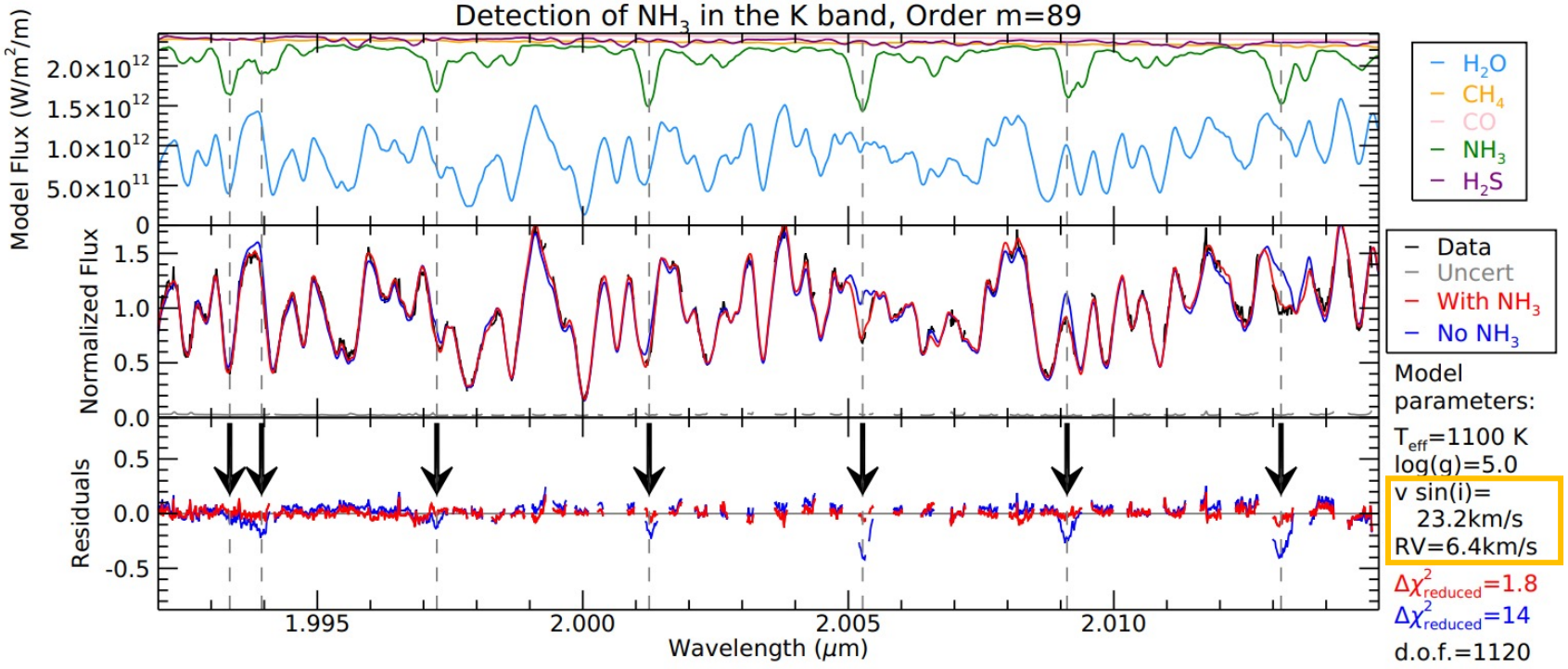


Zhang+ 2021

High-R Spectroscopy

Spectrally Resolve Line Profiles

Example T6 Brown Dwarf



Tannock+ 2022

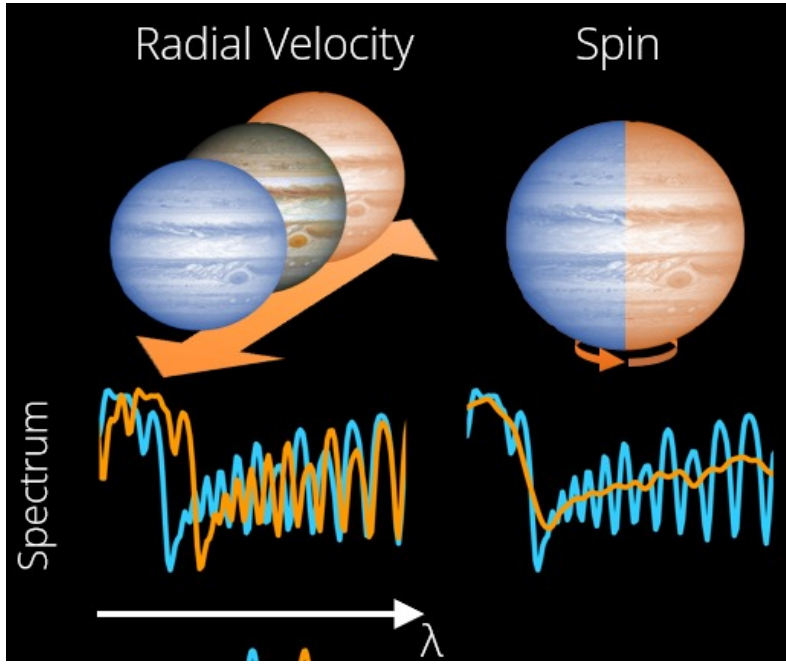
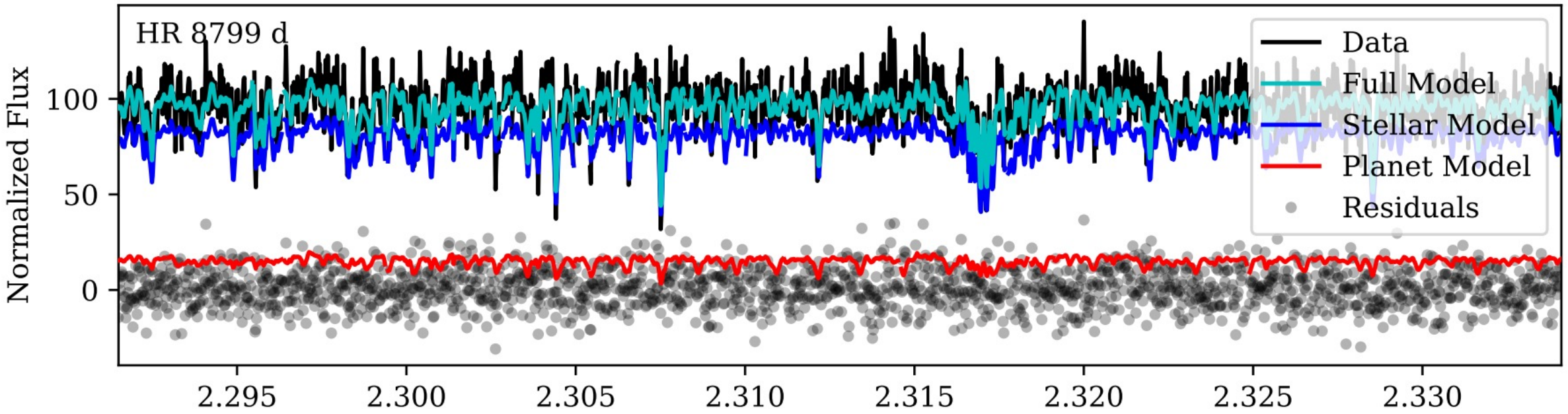


Image Credit: JB Ruffio

Planets Fluxes Are Often in the Noise

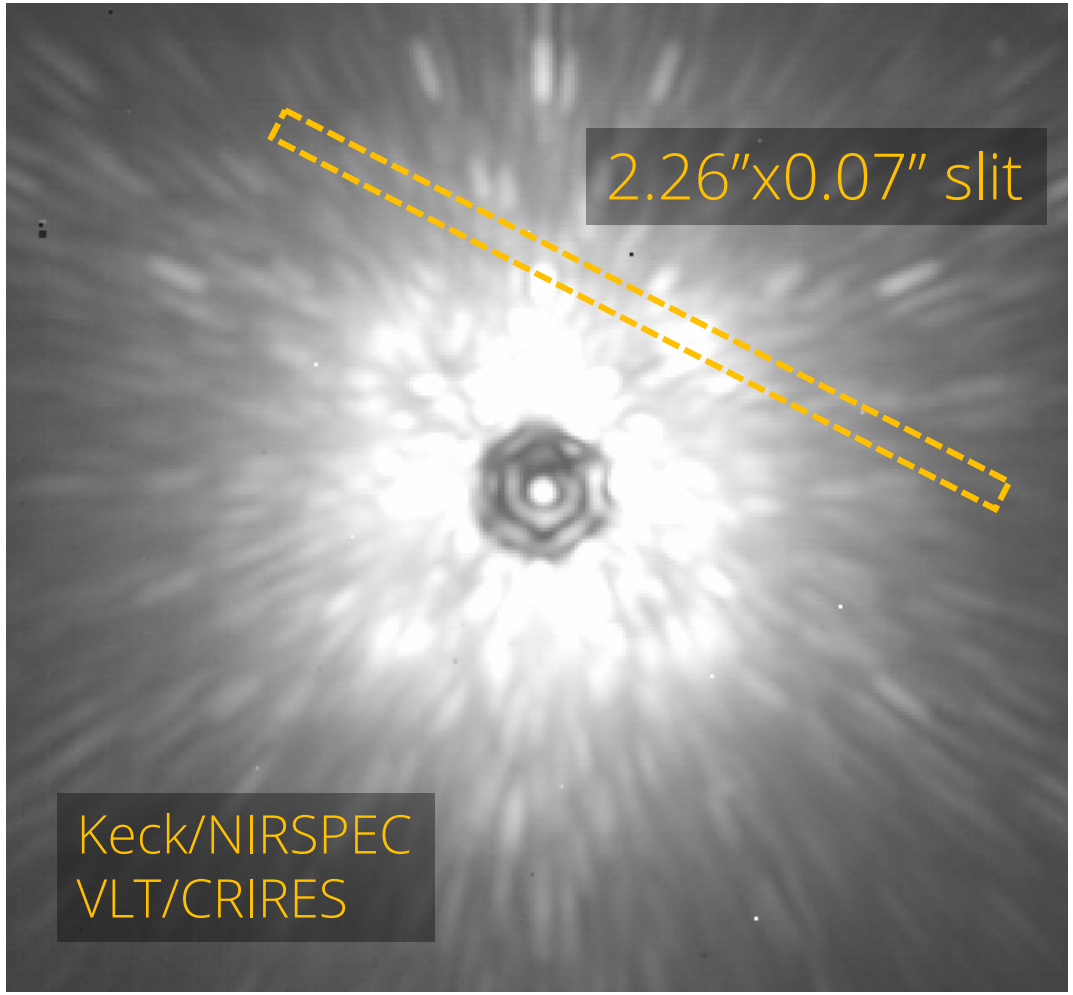
Spectrally Dispersing A Faint Planet Across ~10^4 Channels



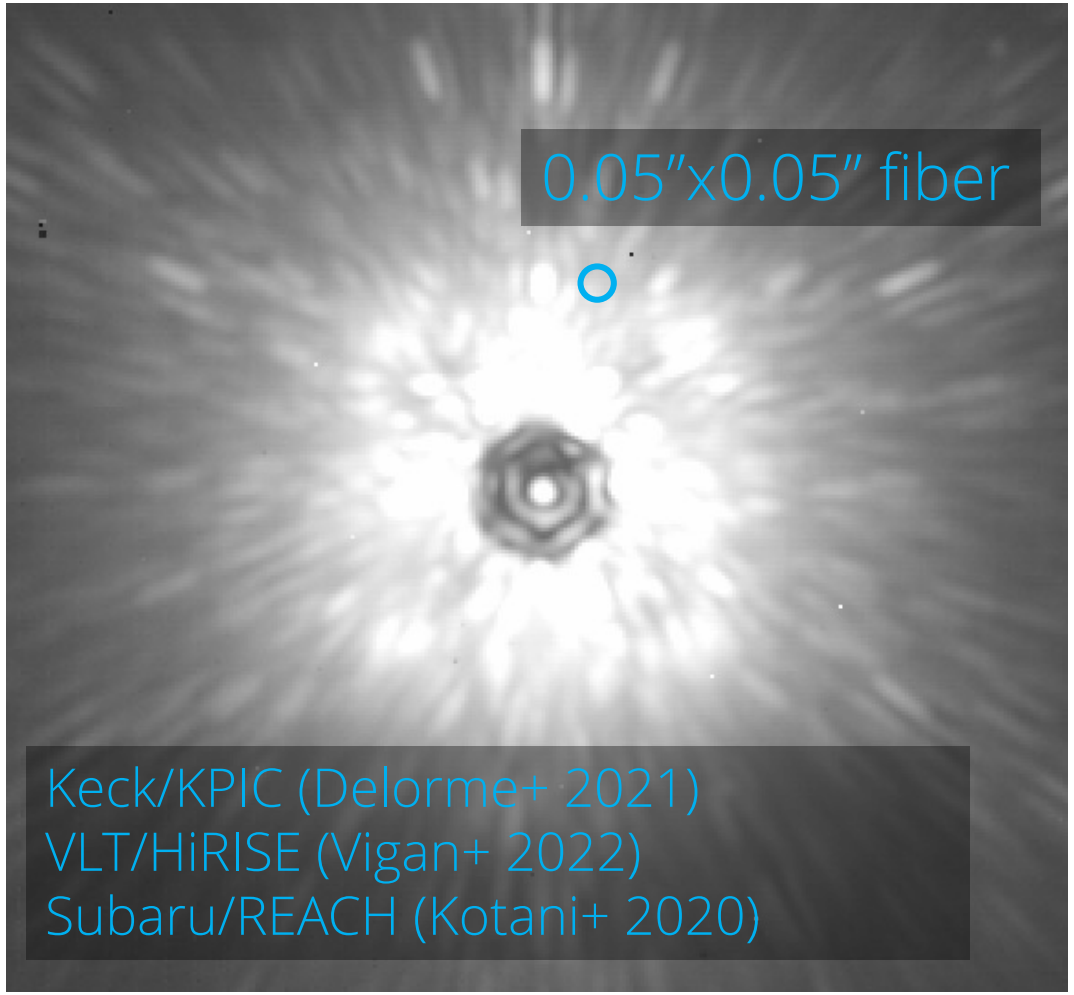
Wang+ 2021

New Generation of Instruments for High-R Spectroscopy

Traditional AO-Assisted High-R Spectrographs use Slits

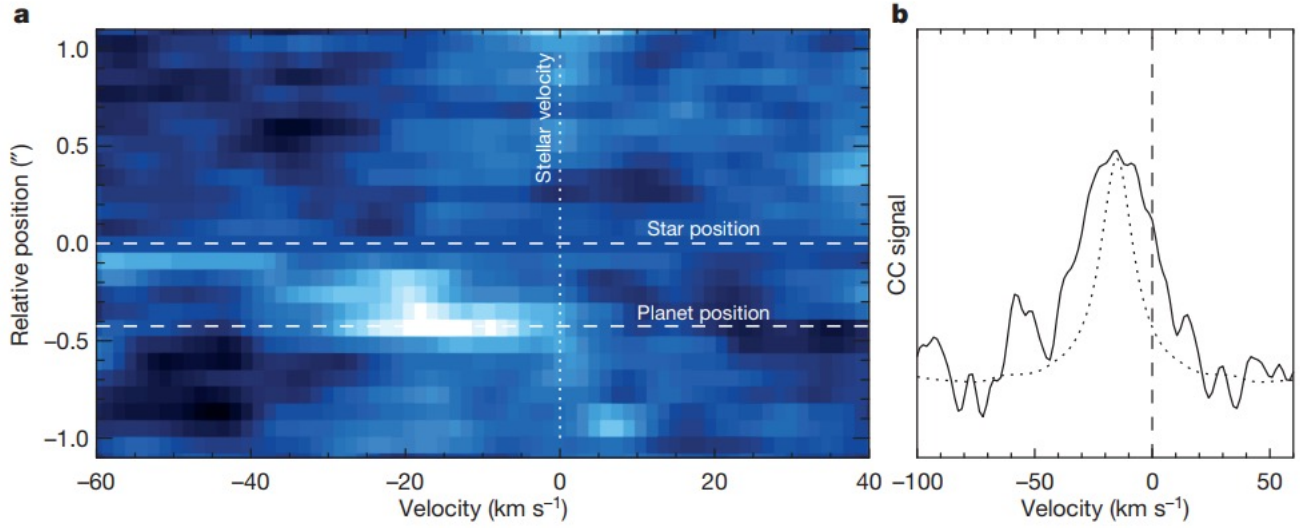


New Exoplanet-focused ones use Single-Mode Fibers



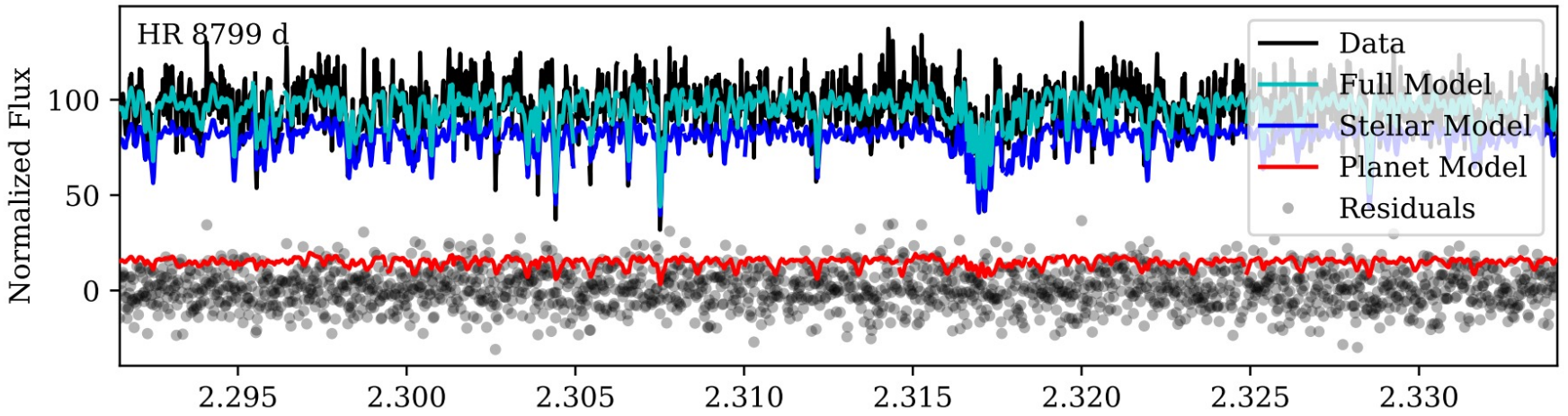
Same Techniques as Medium-R to Detect Planet

Cross-Correlation Detection of Beta Pic b



Snellen+ 2014

Forward Modeling of HR 8799 d

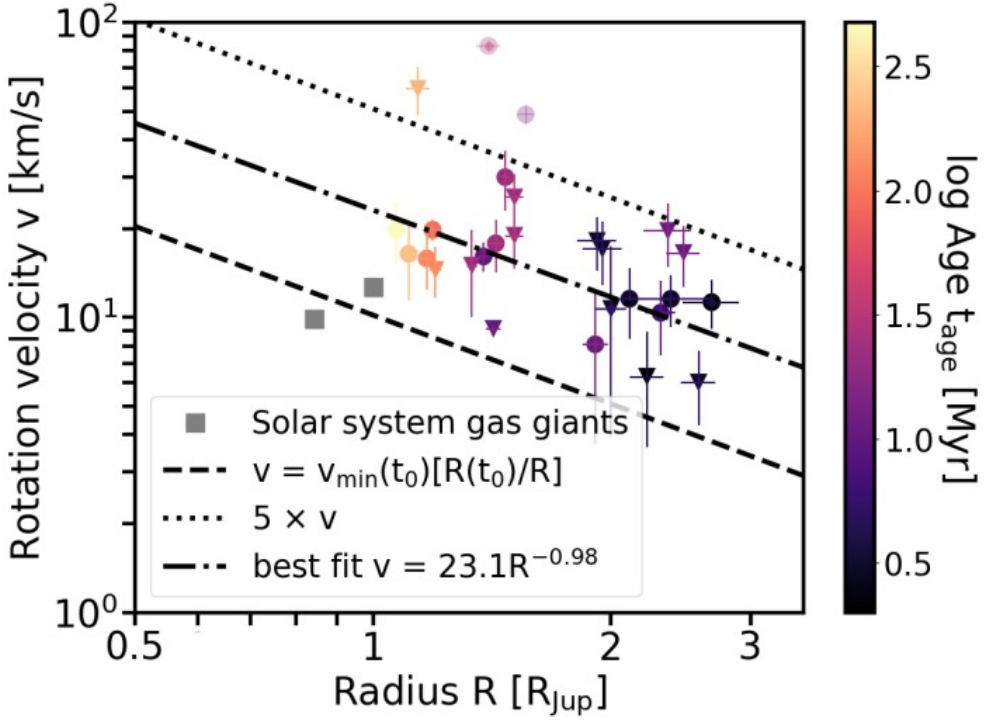


Wang+ 2021

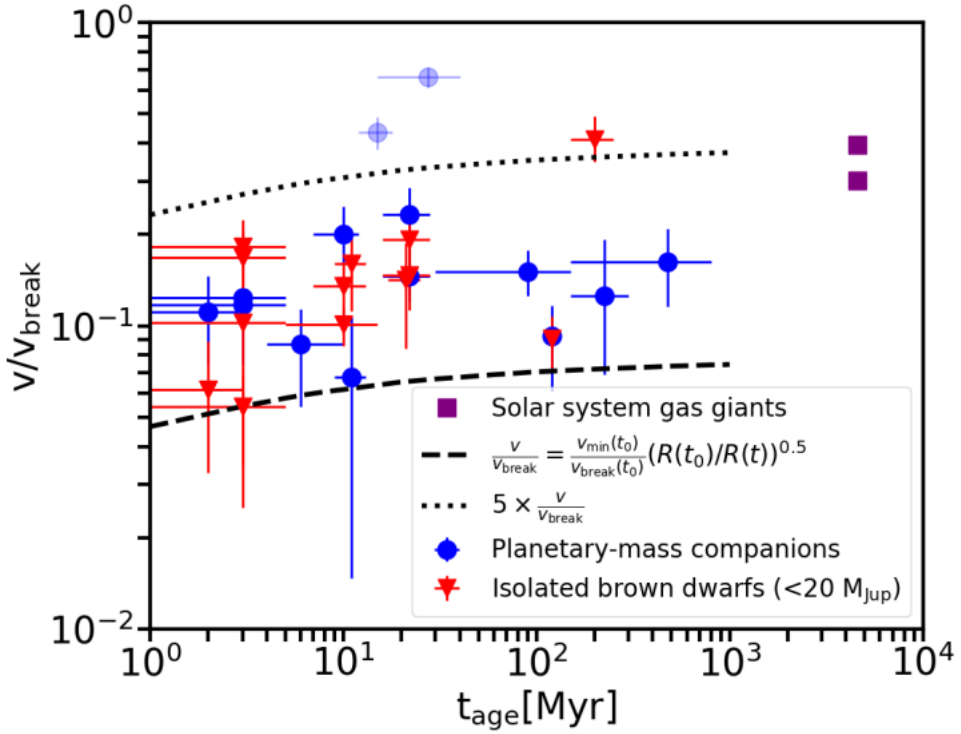
Spin Speeds of Planets From Spectroscopy

Measure vsin(i). Need to assume sin(i)

Consistent with
conservation of angular momentum

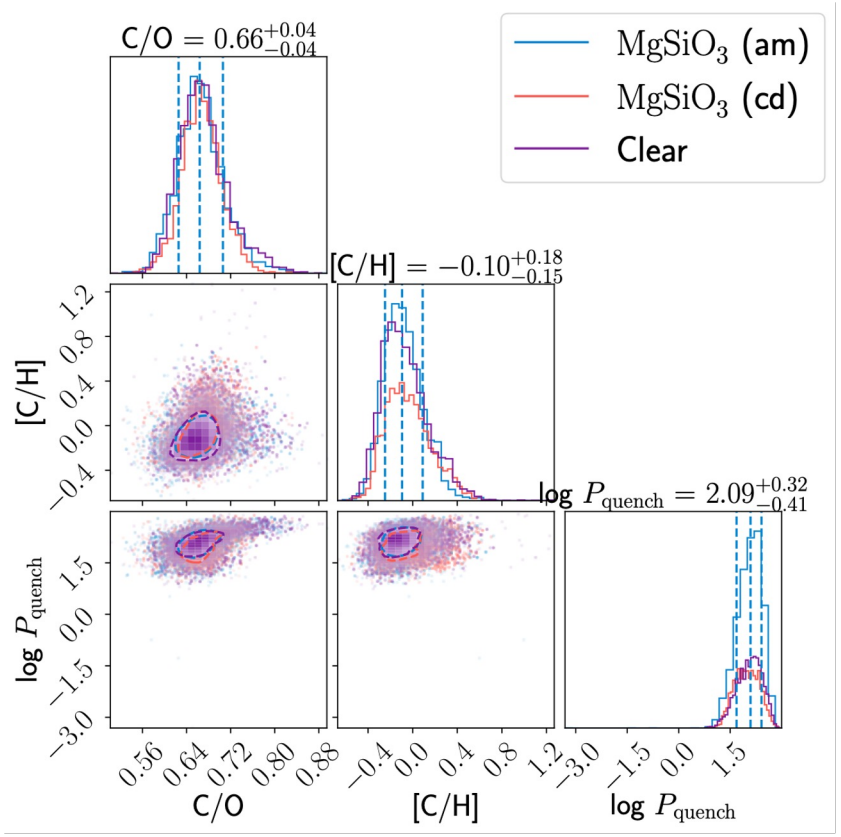


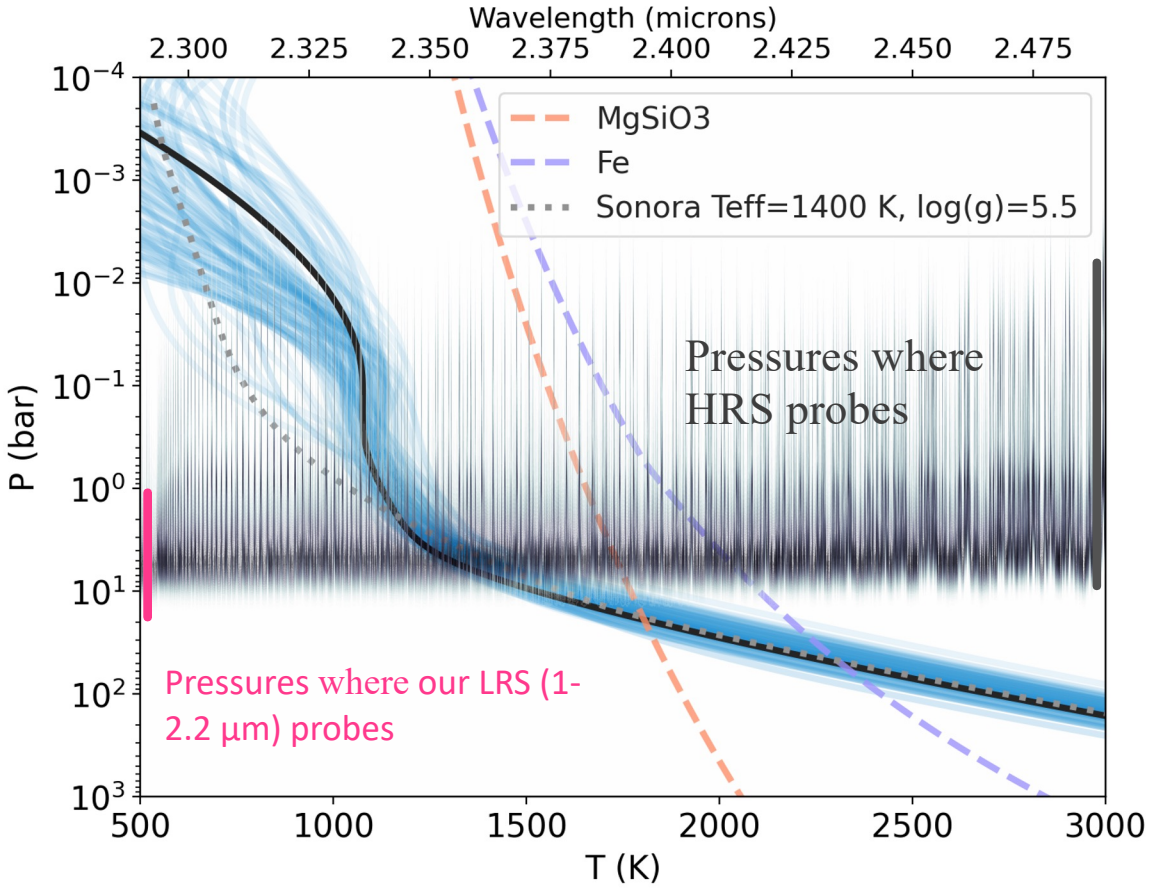
Giant planets spin at ~10% of breakup speed regardless of age
Consistent with picture of magnetic breaking at early times

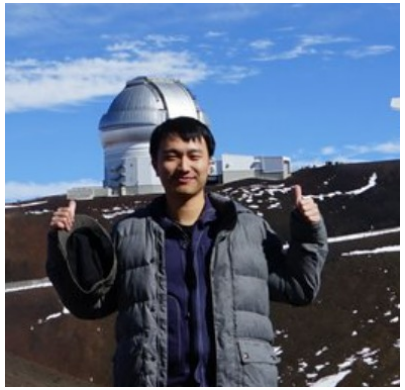


Bryan+ 2020. Also see Bryan+ 2018 and Wang+ 2021

Using Spectral Lines in K-band Allows us to See Above the Clouds







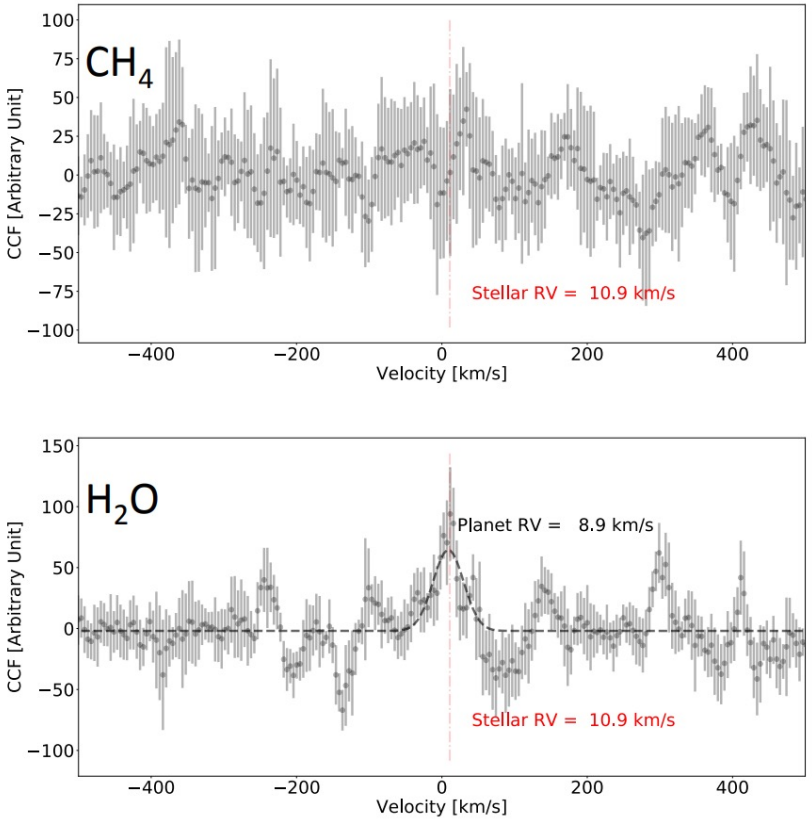
Jerry Xuan+ 2022

petit RADTRANS

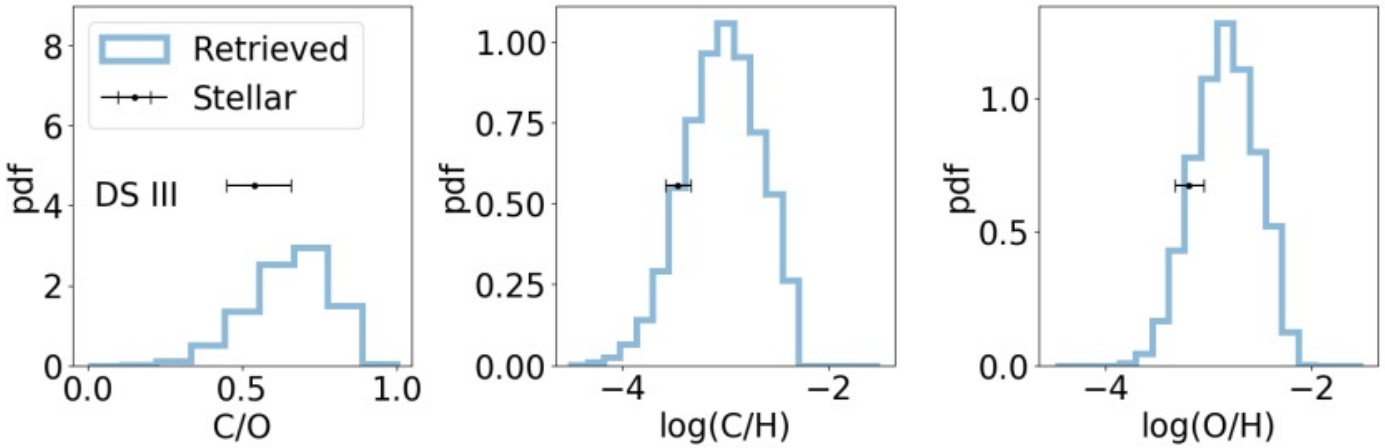
Compositional Measurements at High-R are Just Beginning

HR 8799 c

Methane depleted by 1000x?



Planet has stellar C/O but possibly enriched in metals



Ji Wang+ 2018

Ji Wang+ 2023

Future is Bright for Exoplanet Imaging

Near Term (next 5 years)

- *JWST* 1-15 micron photometry + mid-R spectroscopy (see Aarynn Carter's Talk)
- New Technology from Ground-Based Telescopes (new imagers, High-R, GRAVITY+)

Mid Term (5-10 years)

- Reflected Light Imaging of Gas Giants with *Roman*
- Imaging with ELTs (see Quinn Konopacky Talk)

Long Term (10+ Years)

- Imaging of Terrestrial Planets with ELTs
- Habitable Worlds Observatory (see Shawn Domagal-Goldman Talk)