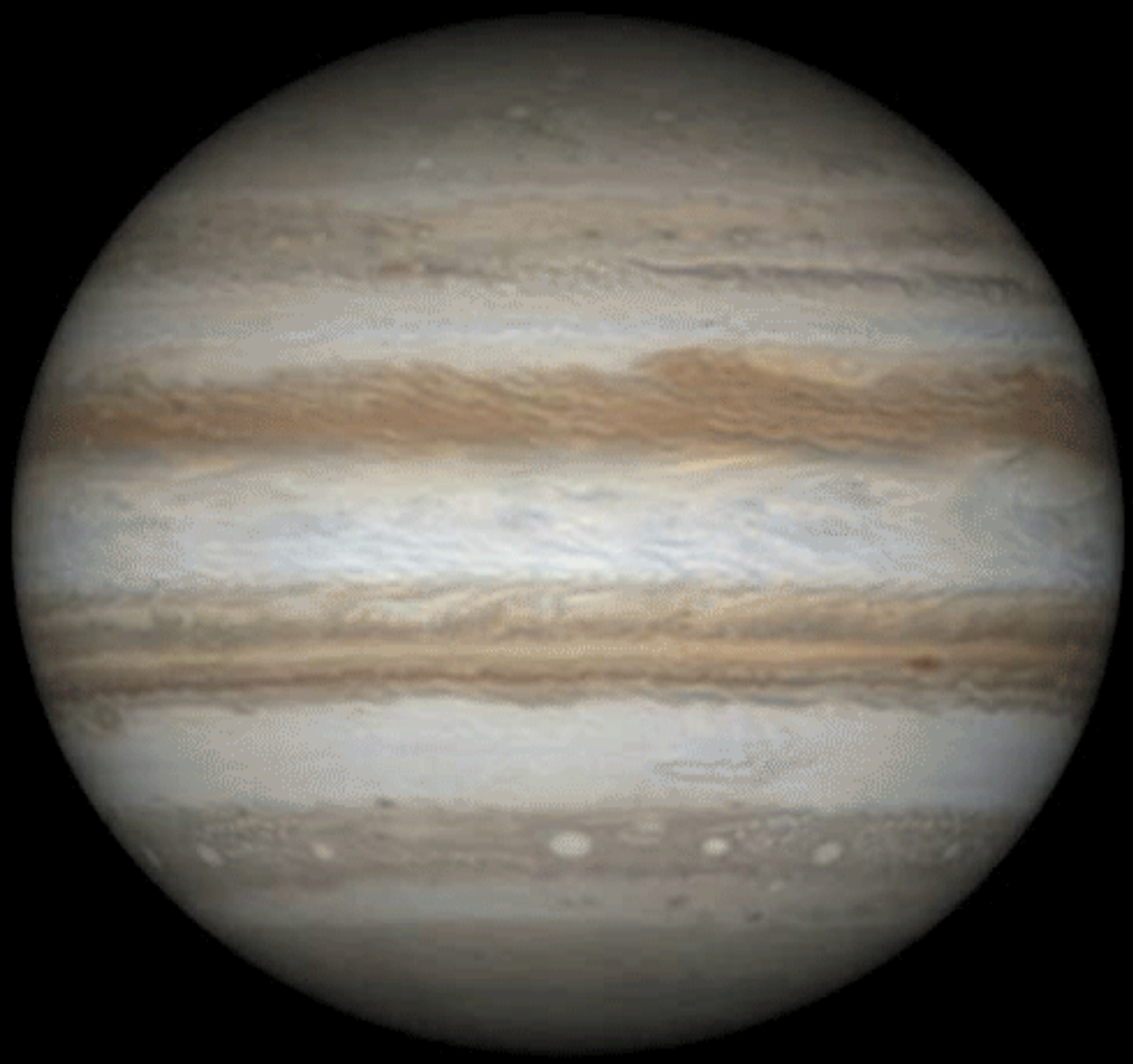
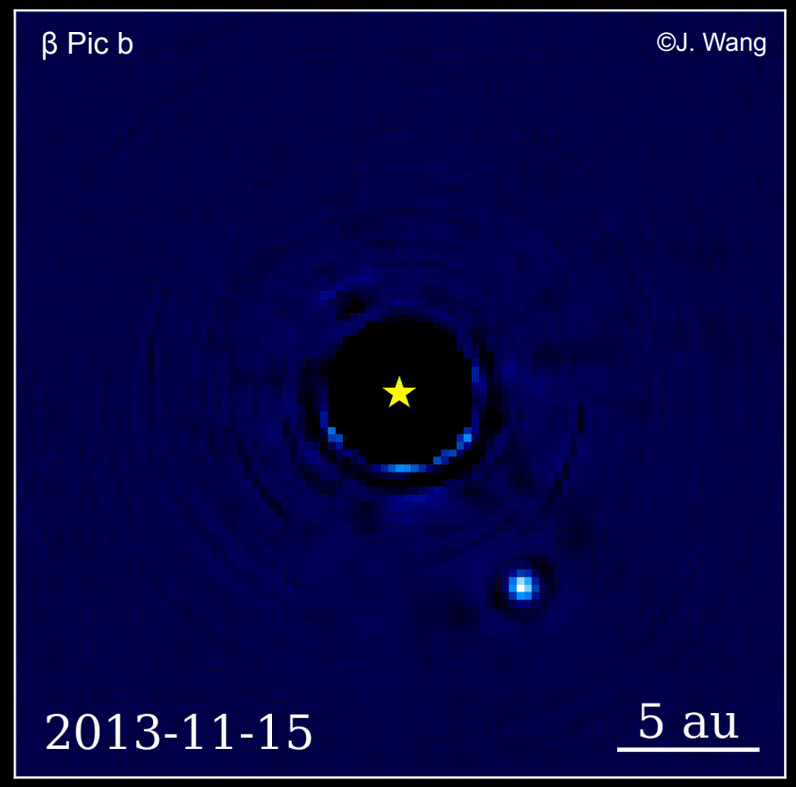
Combining High Spatial and High Spectral Resolution to Find and Characterize Young Planets



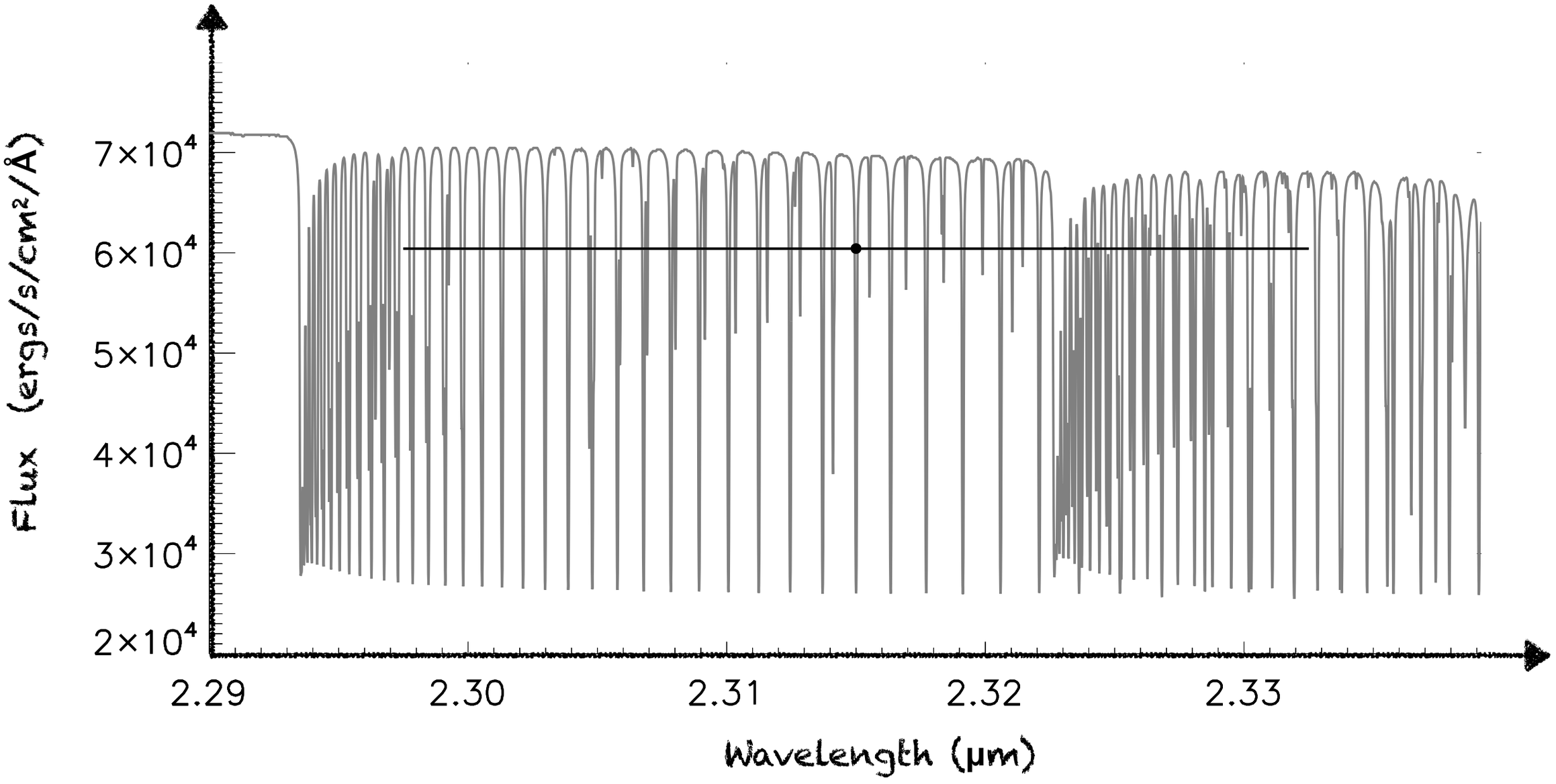


Prof Jayne Birkby
University of Oxford

A high resolution spectrum contains lots of information

Hubble Space Telescope
R=30

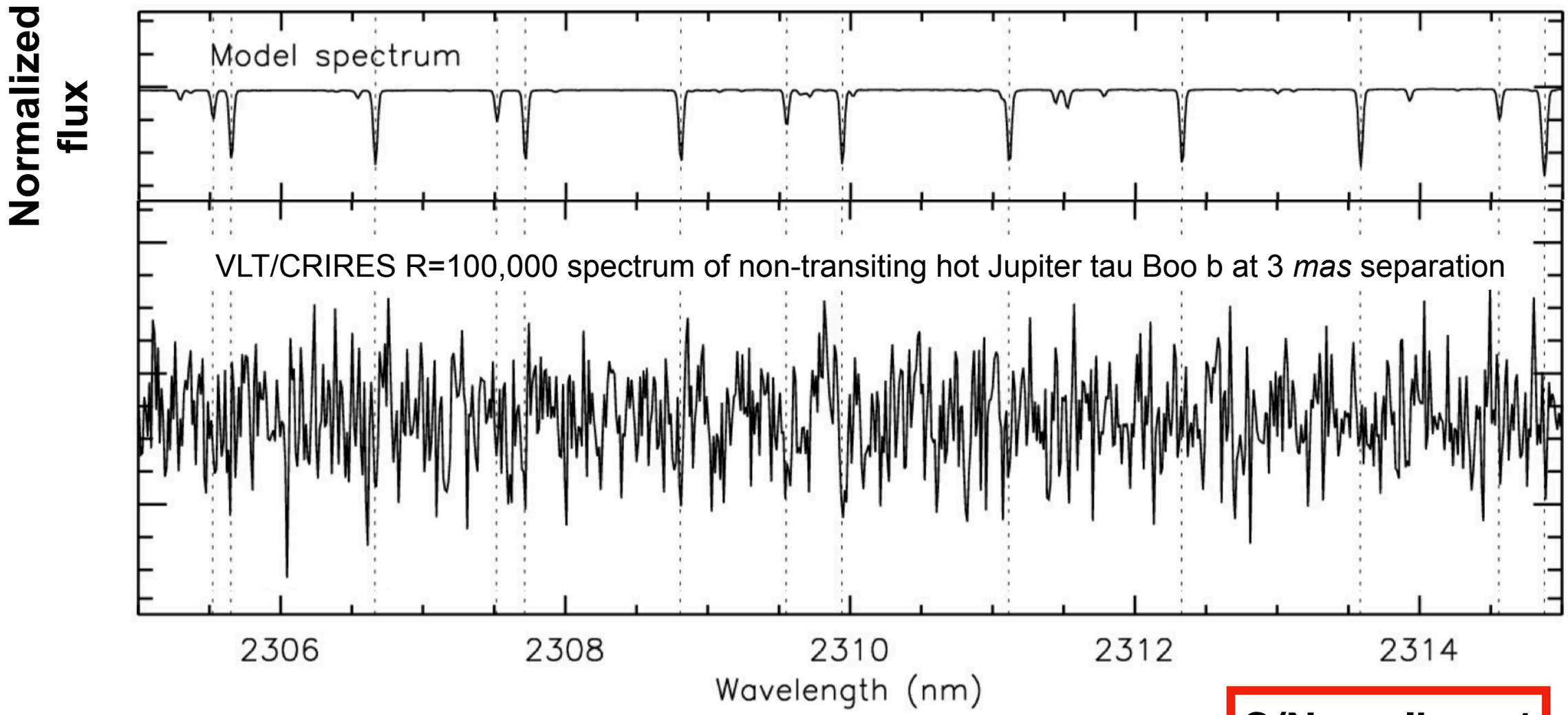
Ground-based Telescopes (e.g. VLT, ELTs)
R=100,000



Model of carbon monoxide spectrum in a hot Jupiter atmosphere

Birkby 2018

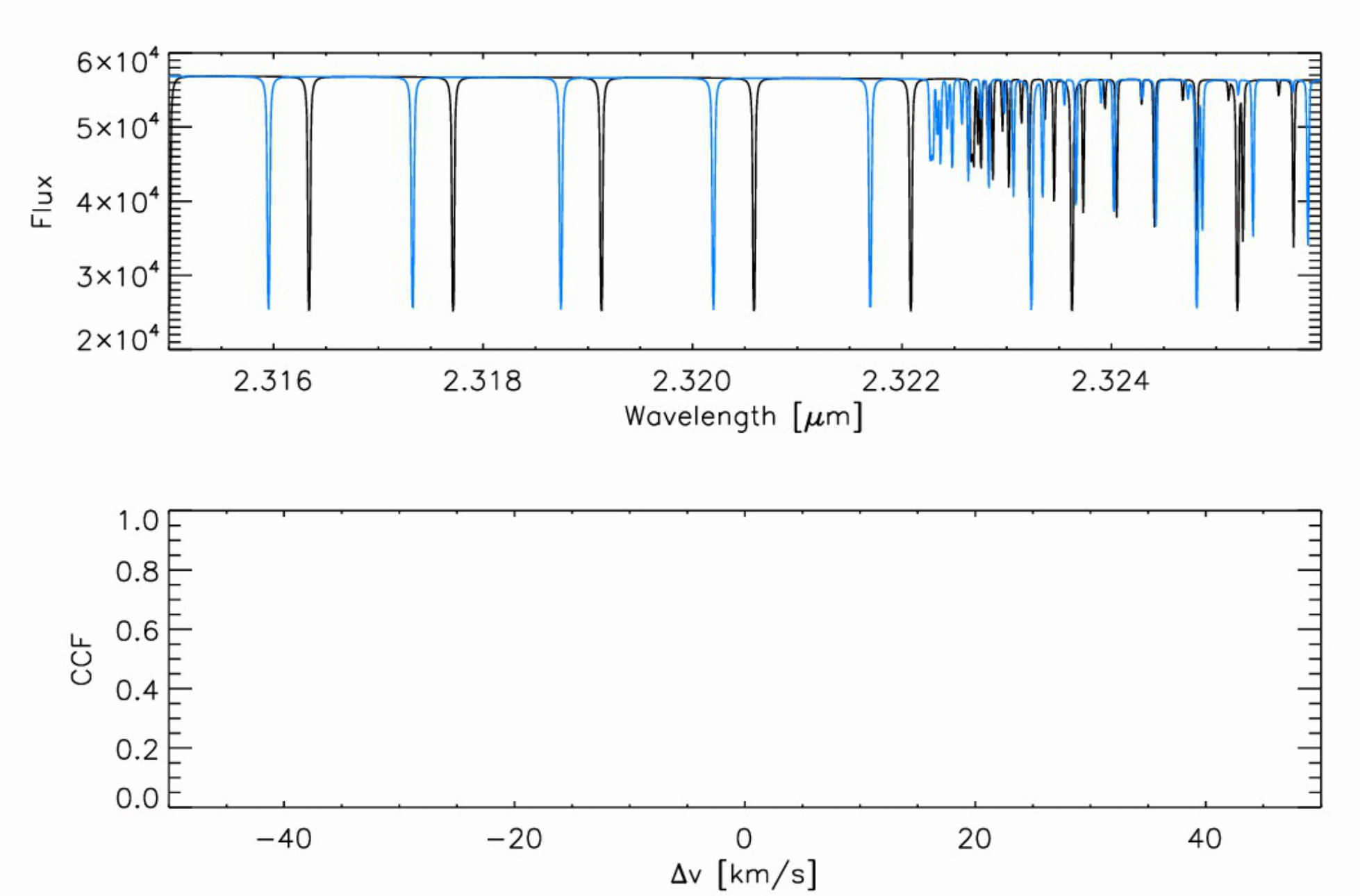
Extracted high resolution planet spectrum is noisy



S/N per line ~1

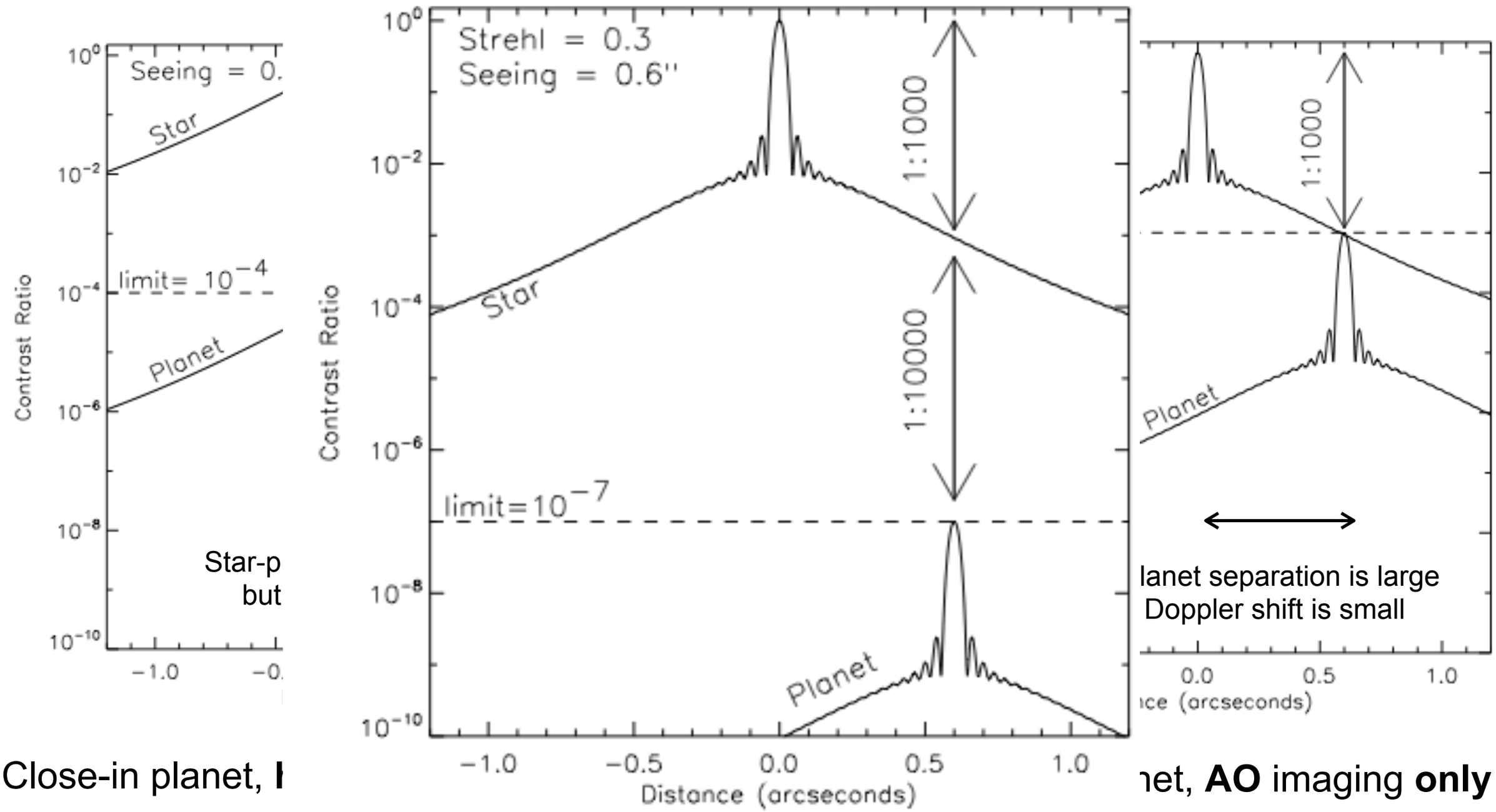
Brogi et al. 2012

Cross-correlation sums up all the signal from each line in the planet spectrum



Reaches contrast ratios ~1x10^{-4}, but relies on the planet Doppler-shifting significantly during the observations

Use spatial separation of *wide orbit* planet to disentangle its spectrum from bright companion and Earth's atmosphere

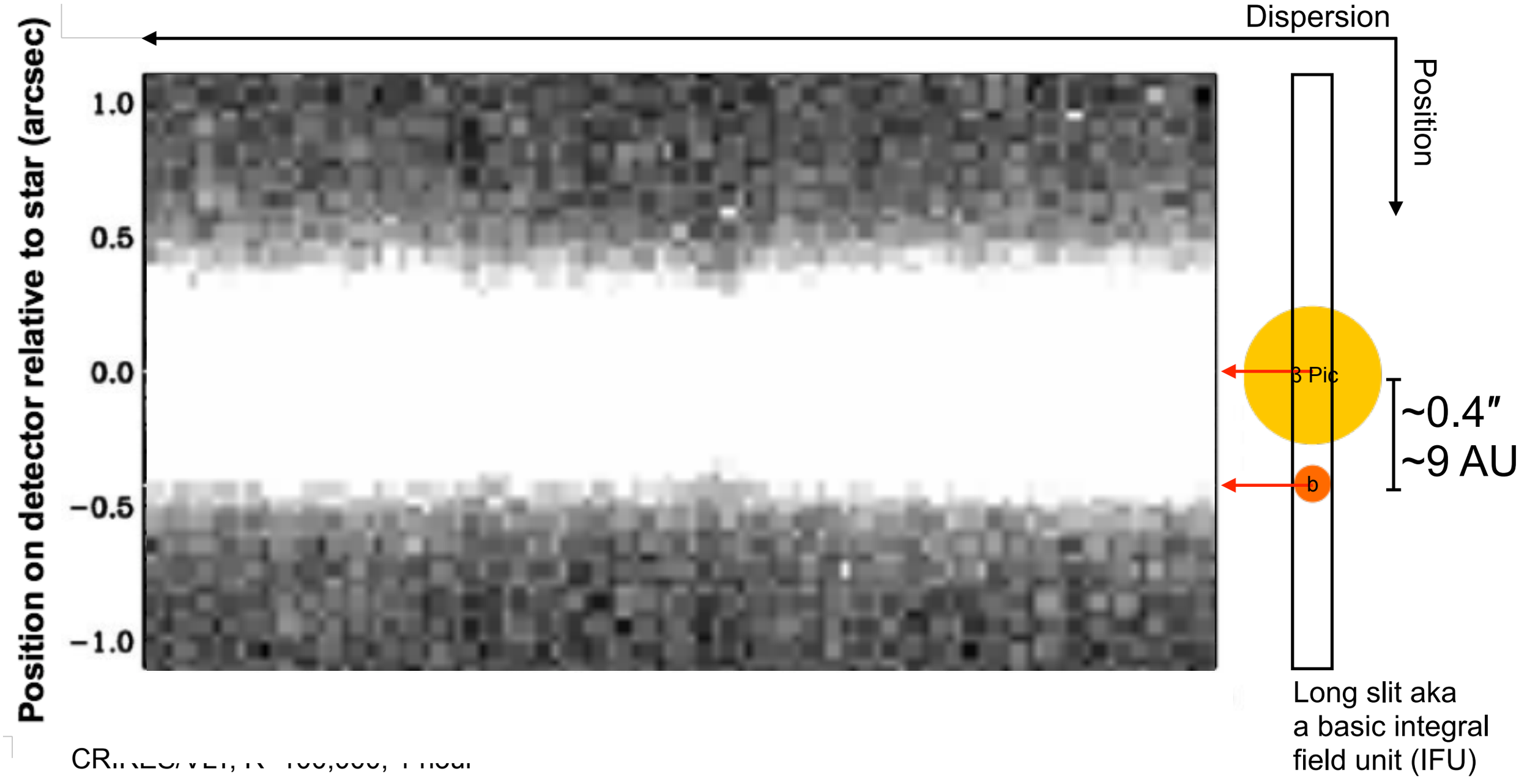


Close-in planet, **I** …net, **AO** imaging **only**

Wide orbit planet, high-res spectroscopy ***plus*** AO imaging

Snellen, de Kok, Birkby et al. 2015

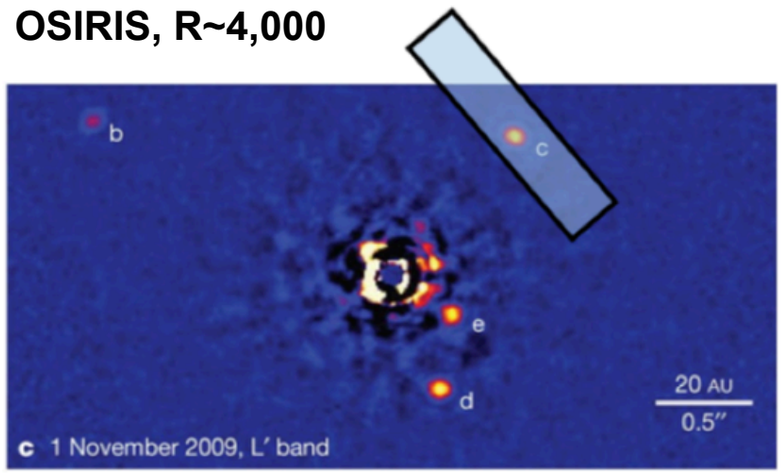
Star and tellurics dominant but identical everywhere, planet emission storngly localized and uniquely different



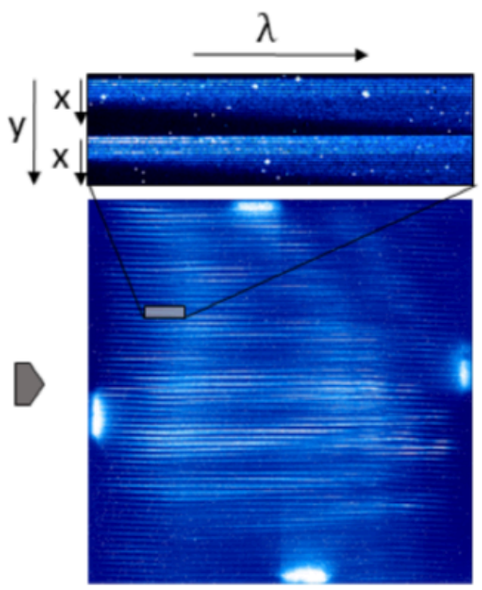
Carbon monoxide in the directly-imaged giant planet β Pic b

Snellen, Brandl, de Kok, Brogi, Birkby et al., *Nature,* 2014

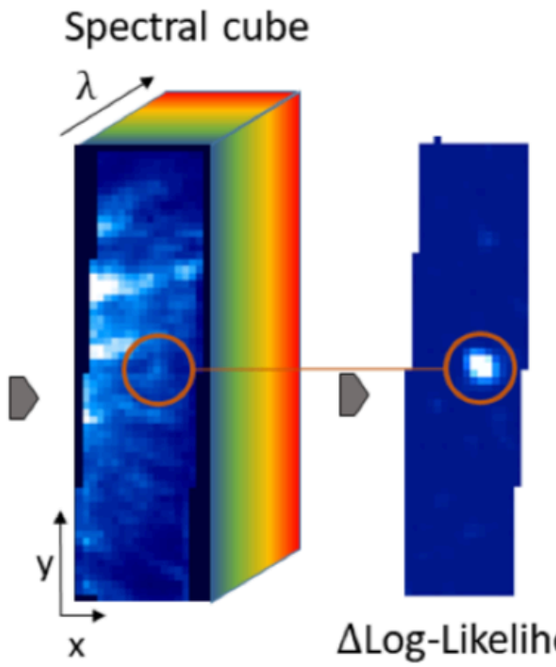
Even moderate resolution direct imaging spectra can provide constraints on C/O and measure radial velocities



HR 8799 (Marois et al. 2010)

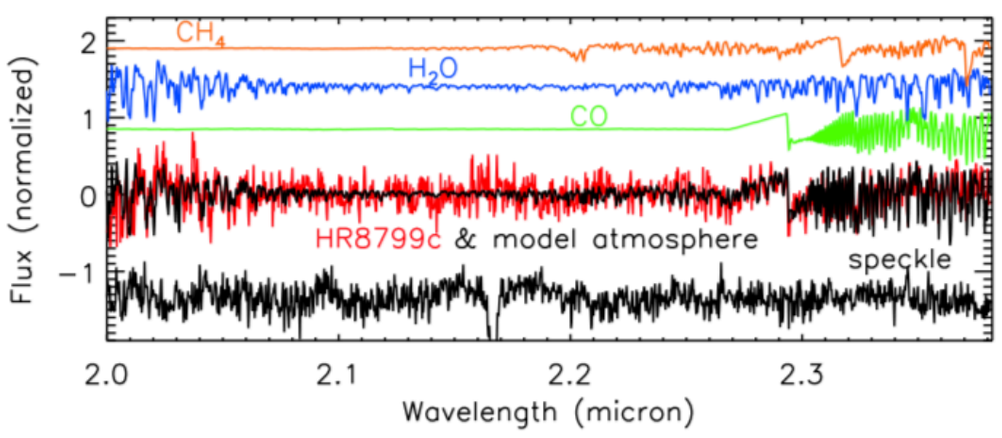


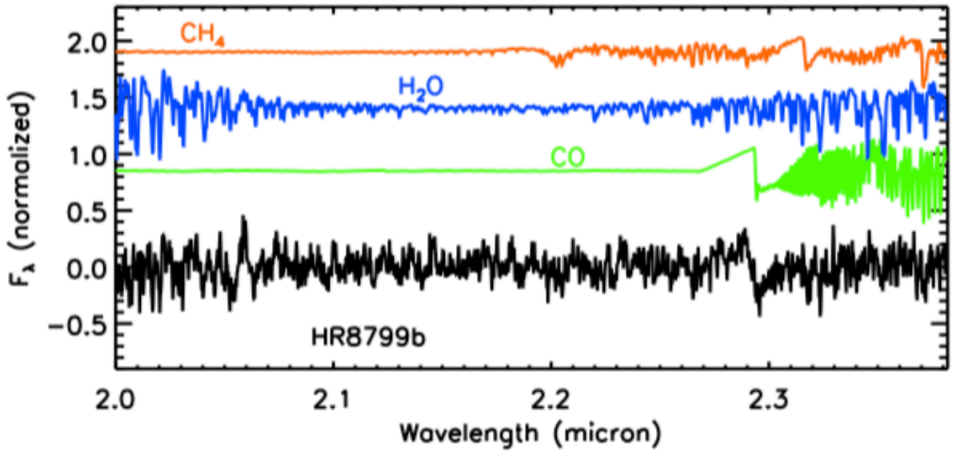
OSIRIS raw data

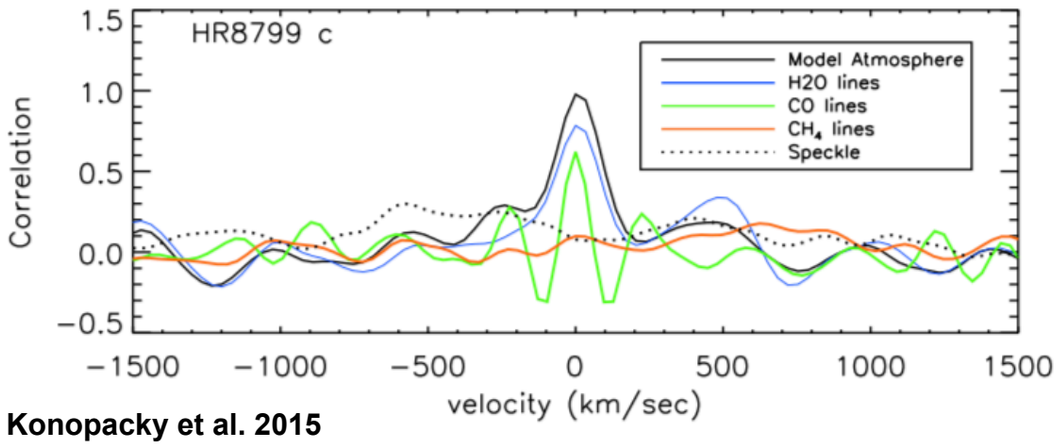


ΔLog-Likelihood

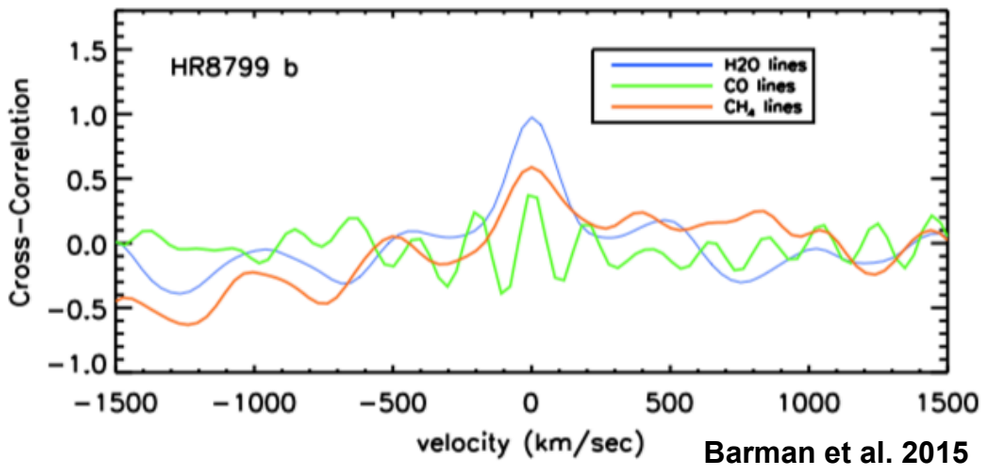
Ruffio et al. 2019





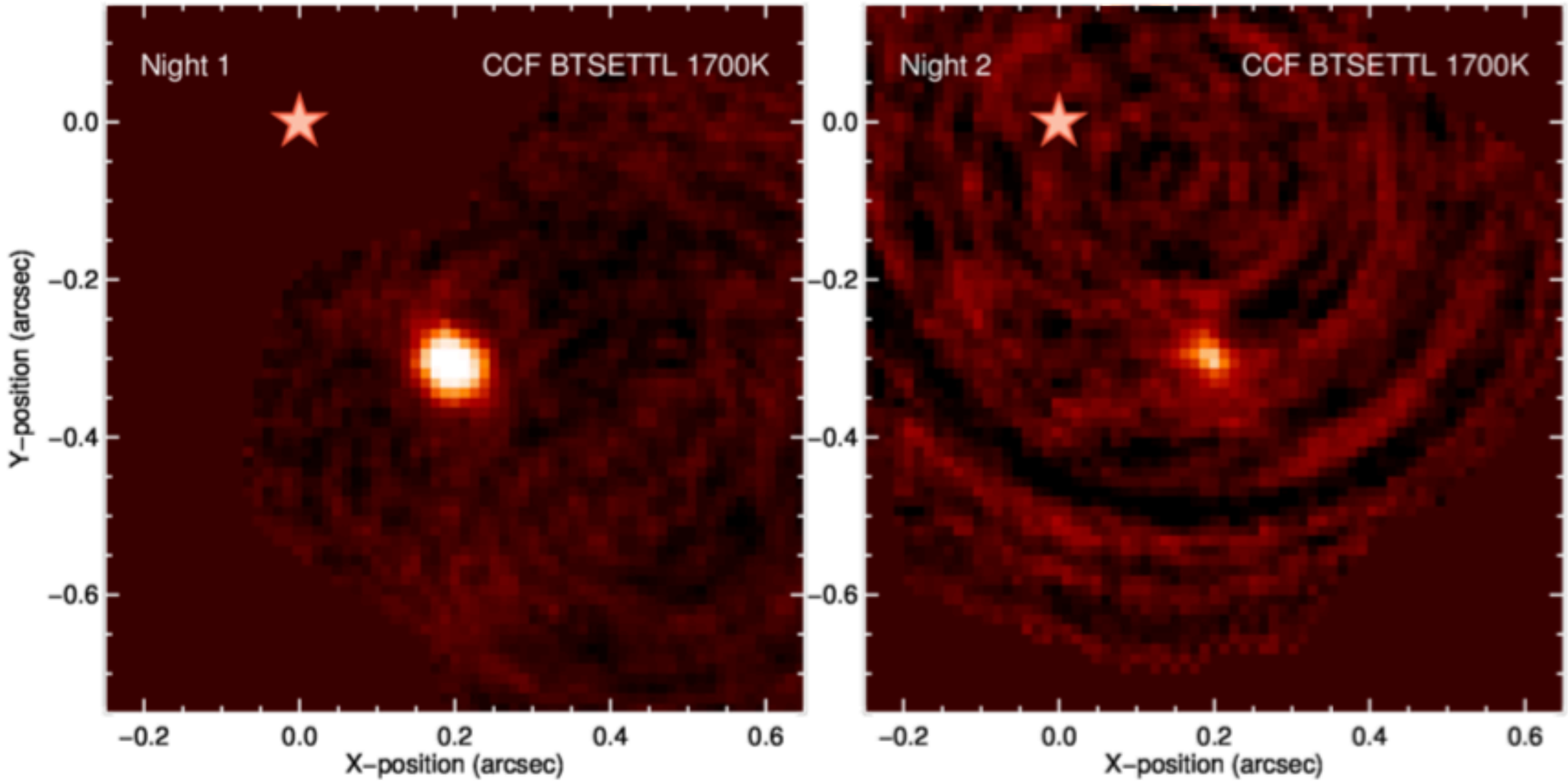


Konopacky et al. 2015



Barman et al. 2015

Molecule mapping with integral field spectrographs can detect planet without prior knowledge of location

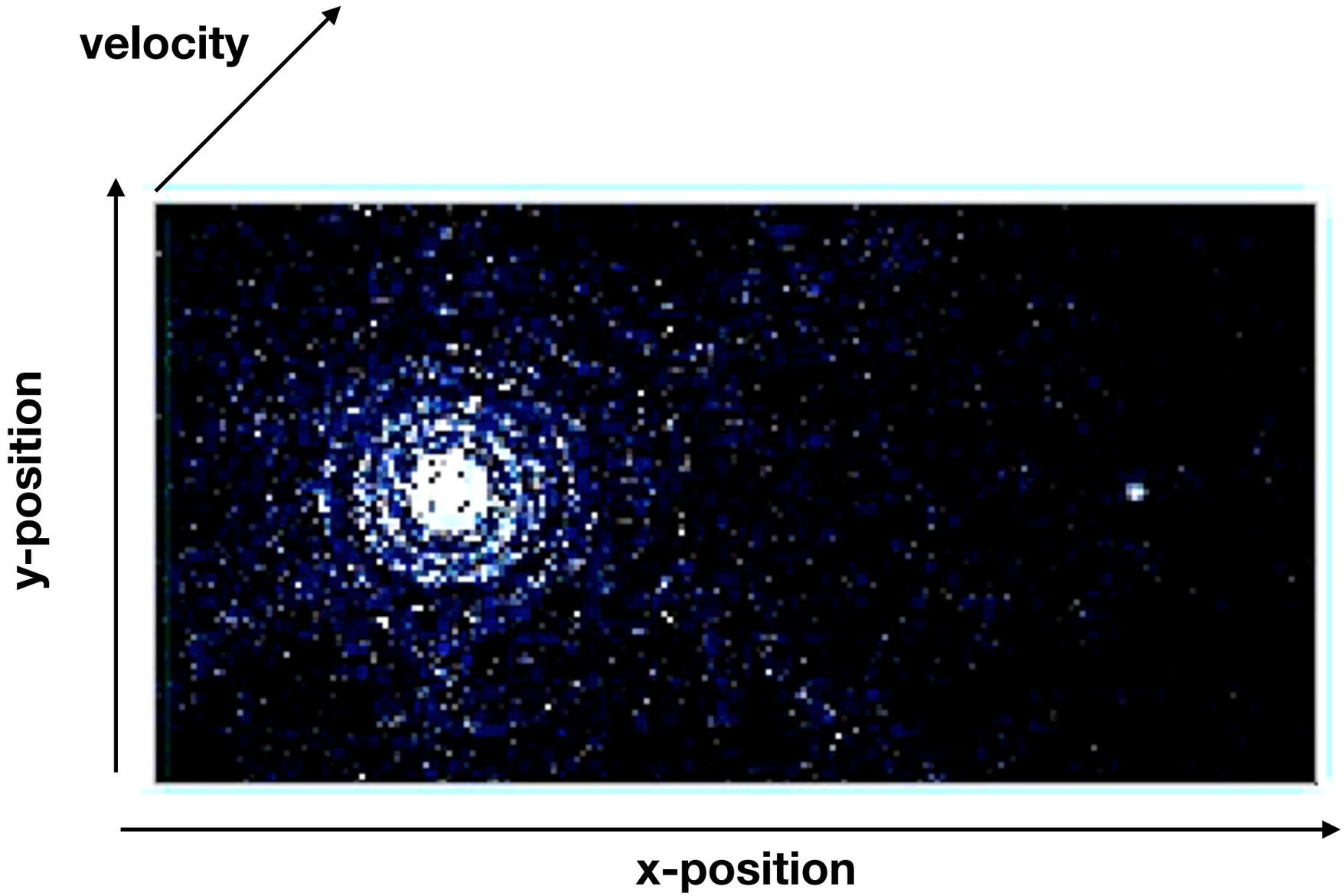


White light images of β Pic b from SINFONI/VLT integral field spectrograph using standard direct imaging post-reduction techniques

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

ELT molecule map for Proxima b

(simulated for METIS)



Snellen, de Kok, Birkby et al. 2015

Key O2 biomarker in the optical where planets reflect light

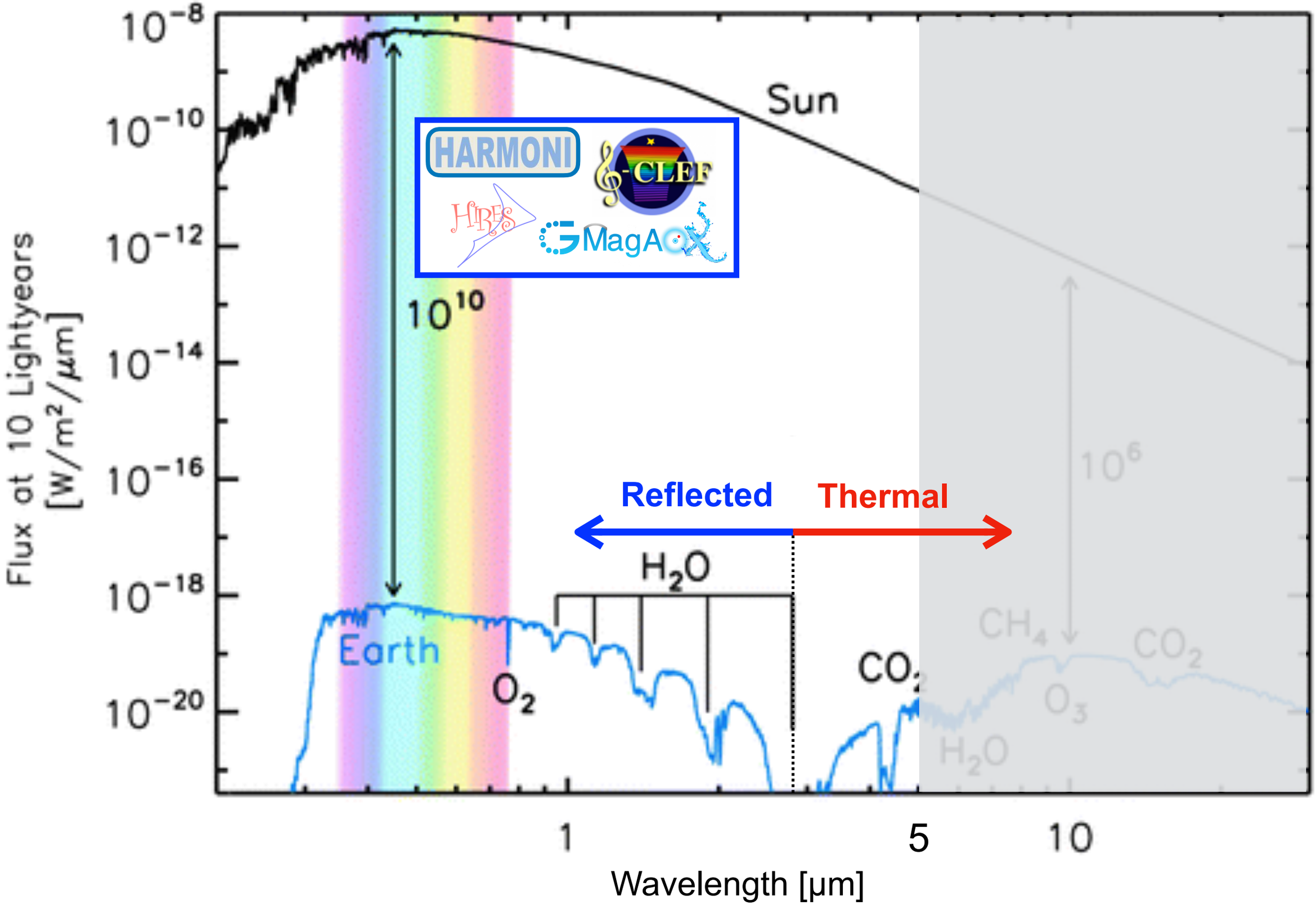


Figure credit: Sarah Rugheimer & Tyler Robinson in Domagal-Goldman et al. 2016

We need ~4 nights @ELT to unambiguously detect oxygen in the atmosphere of the nearest rocky exoplanet

100 m

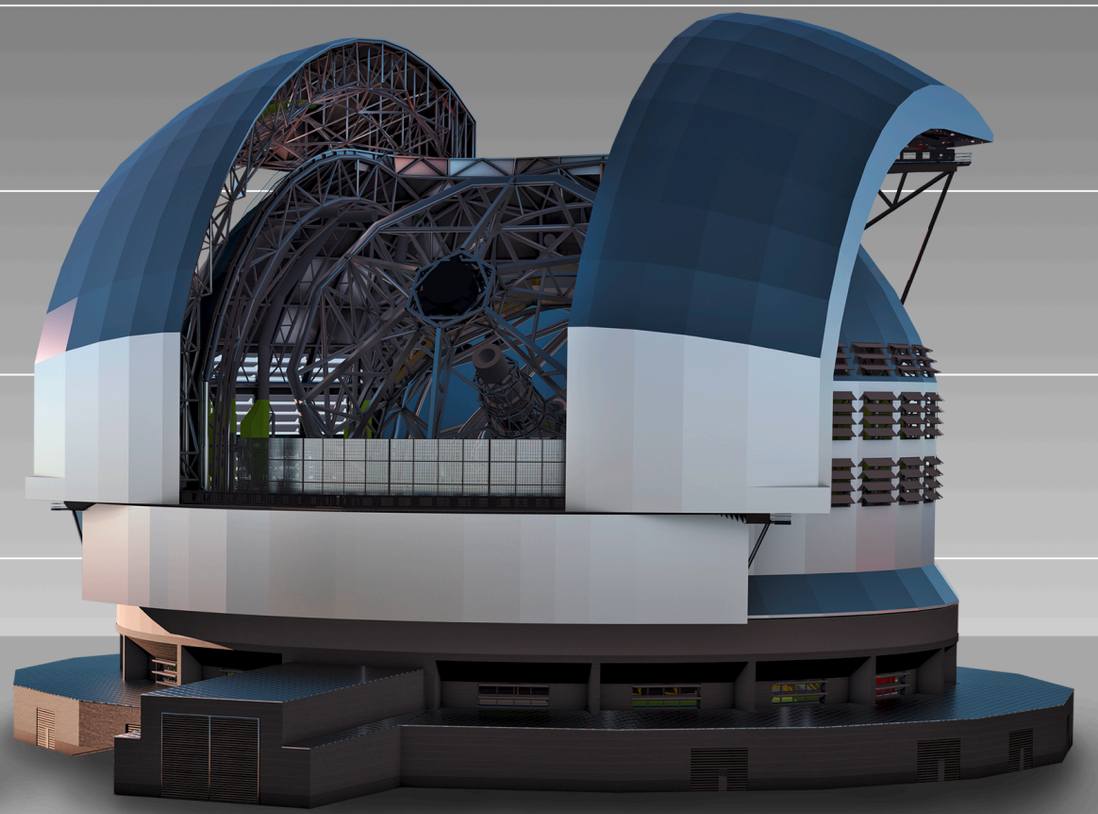
80 m

60 m

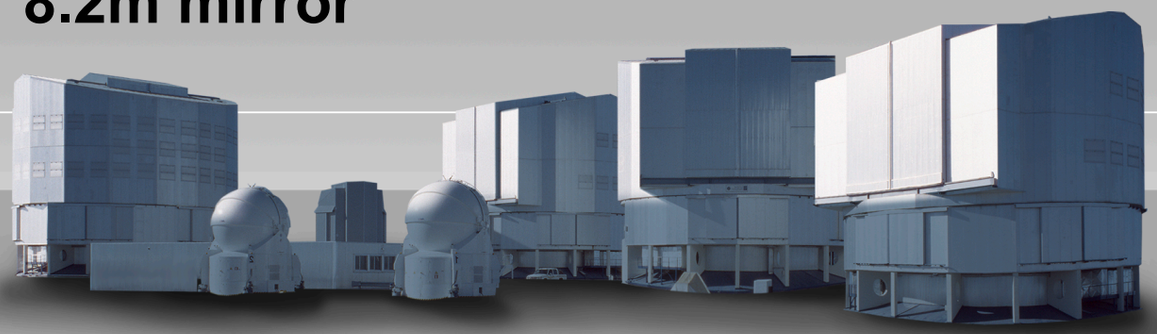
40 m

20 m

39m mirror



8.2m mirror



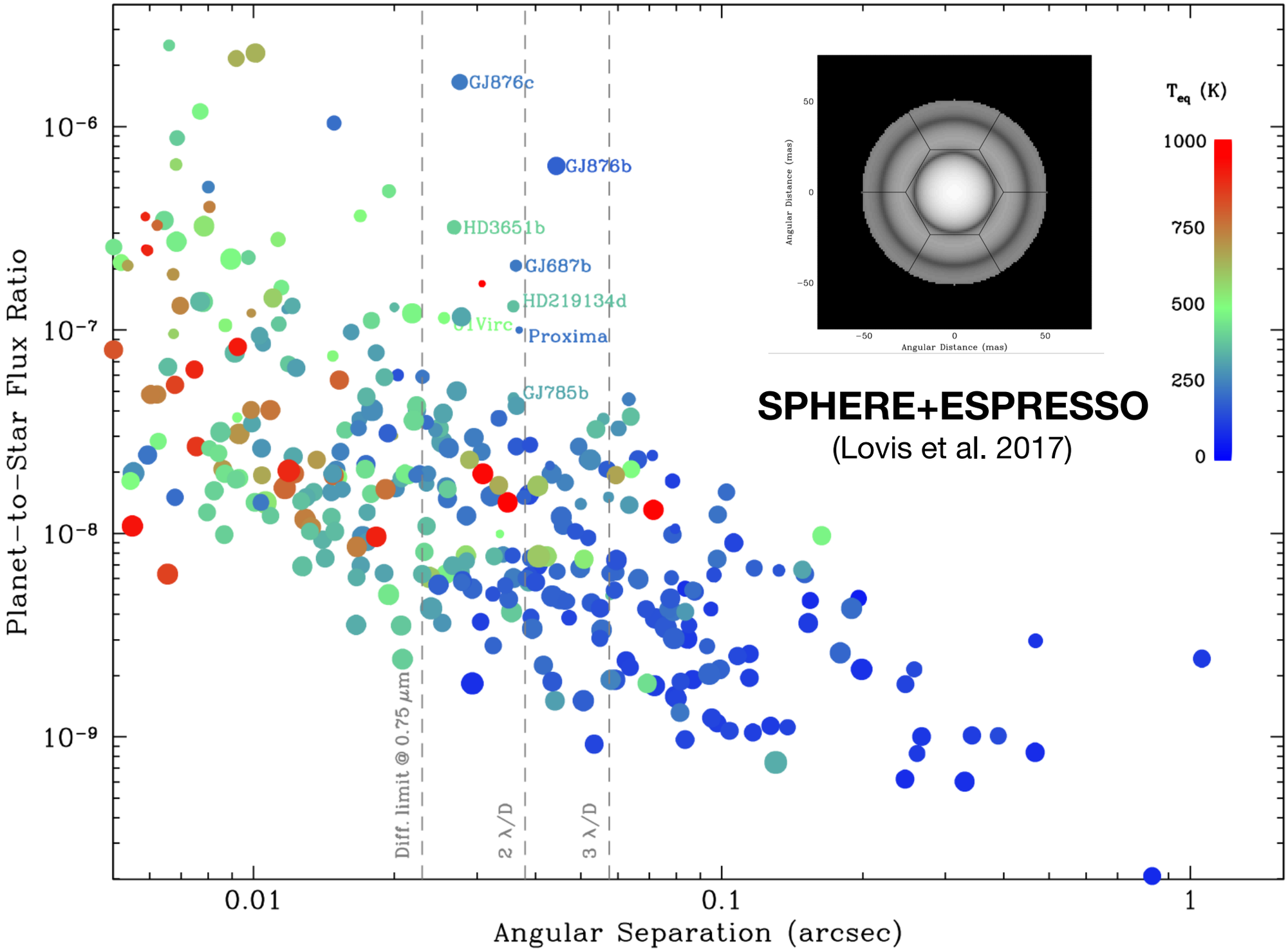
Very Large Telescope

Extremely Large Telescope

First light expected 2027

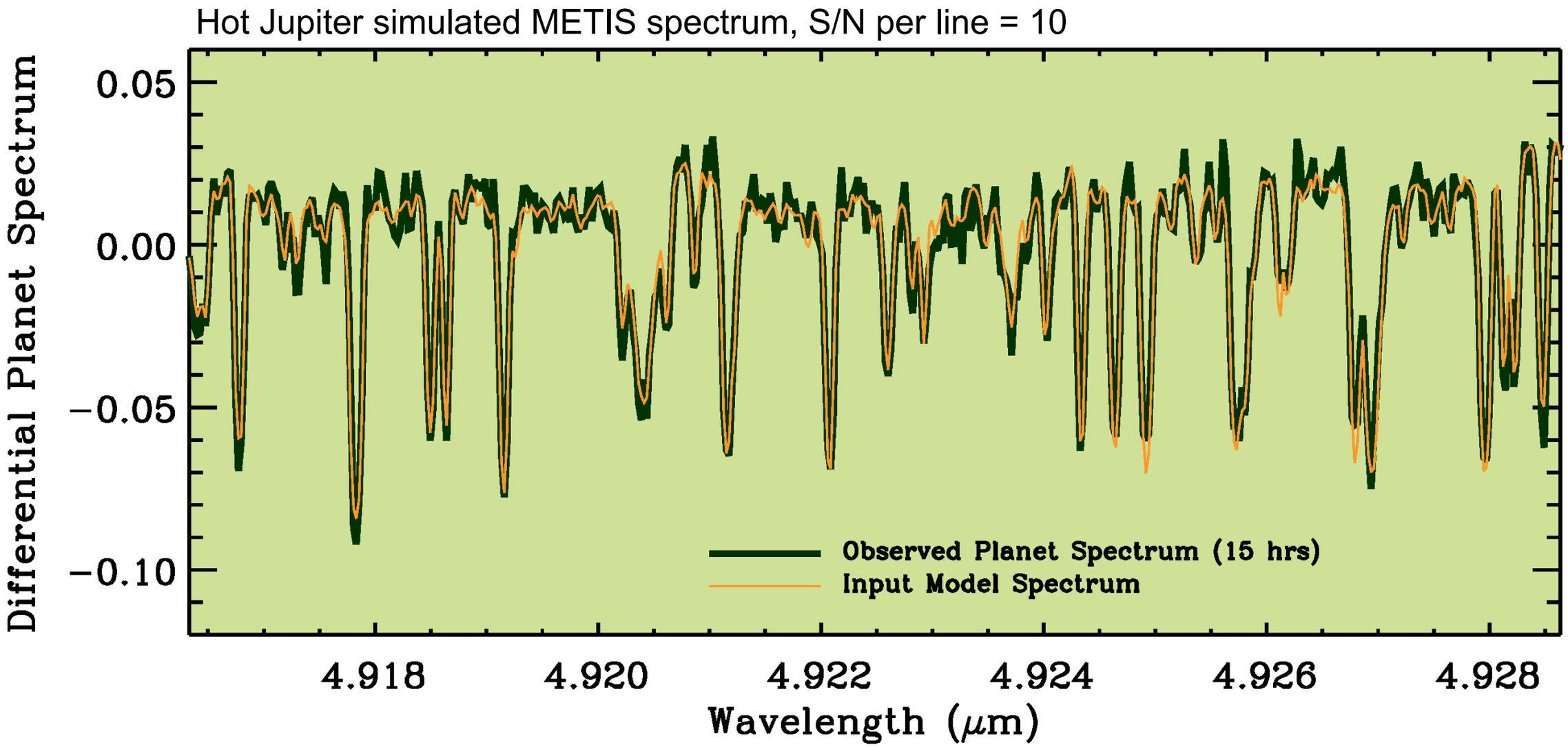
Snellen, de Kok, Birkby et al. 2015

Temperate worlds are accessible in reflected light with molecule mapping



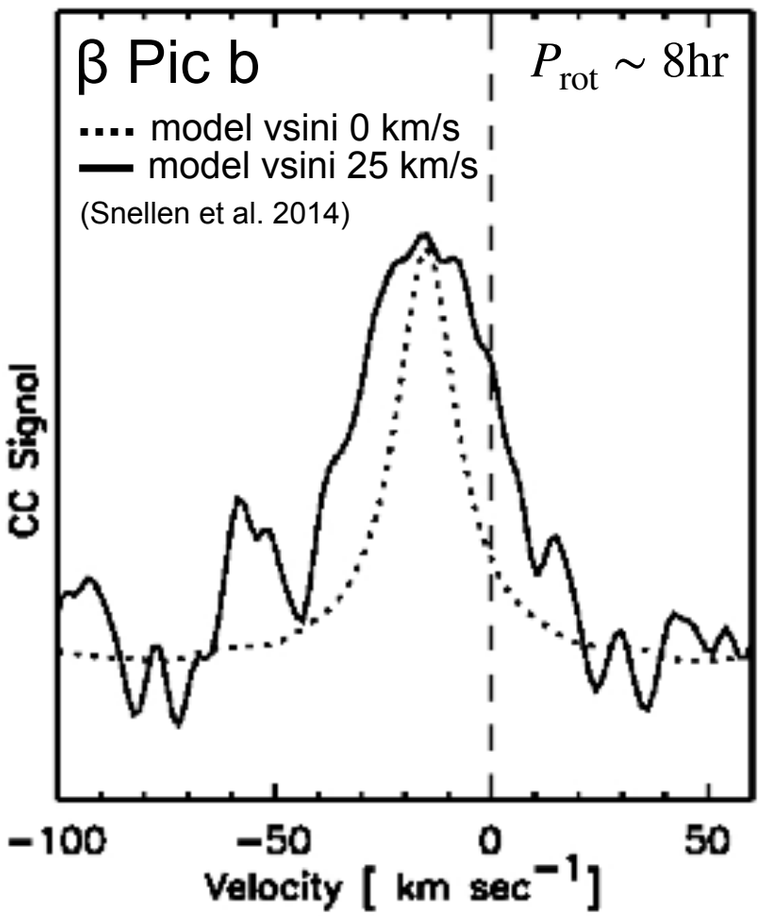
Lovis et al. 2016

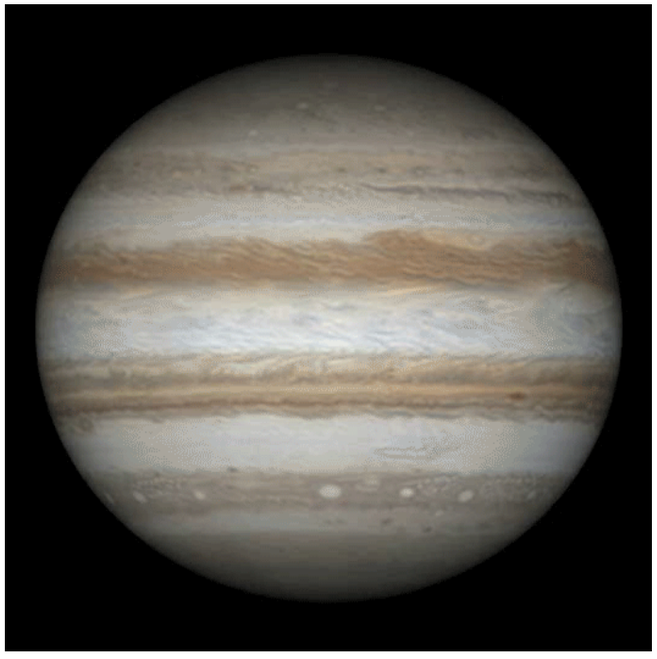
ELTs will provide sufficiently high S/N high resolution spectra to model the exoplanet atmosphere directly

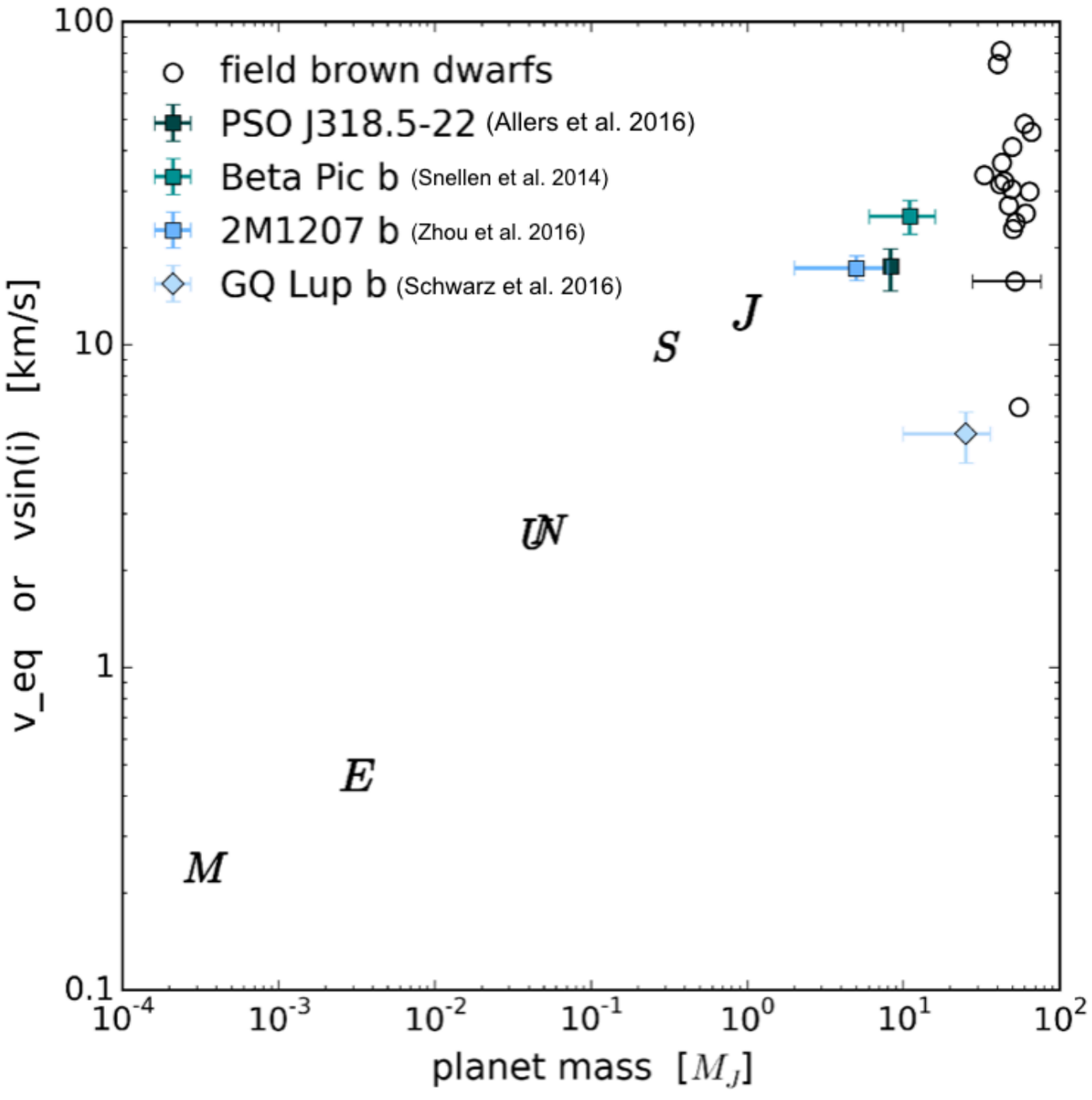


I.A.G. Snellen, METIS Science Document

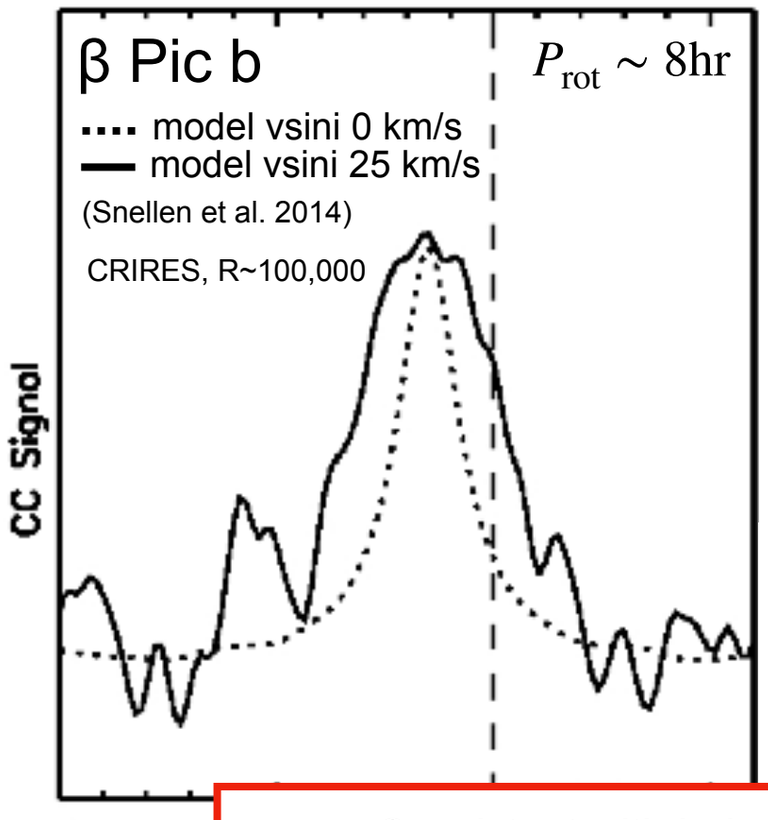
High resolution spectroscopy accessed a new fundamental parameter: exoplanet rotation rate

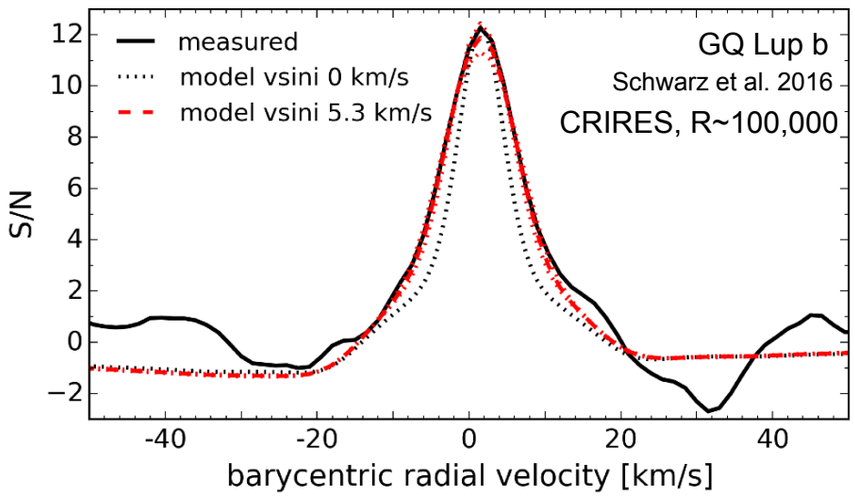


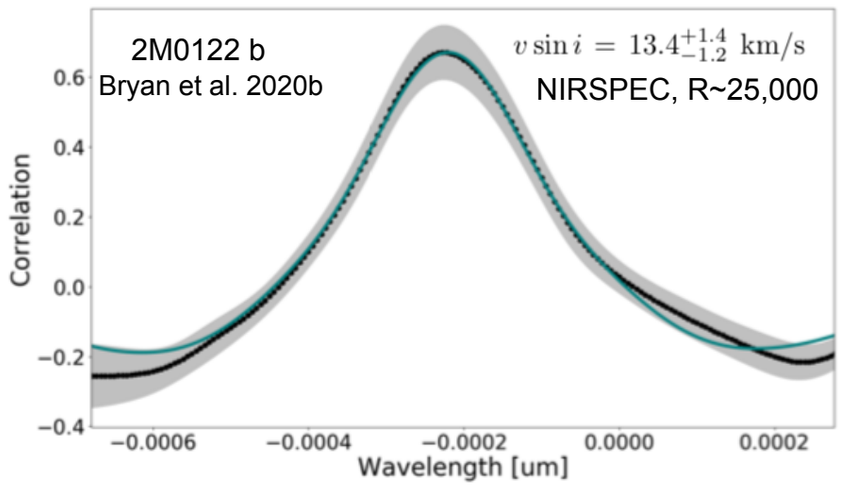


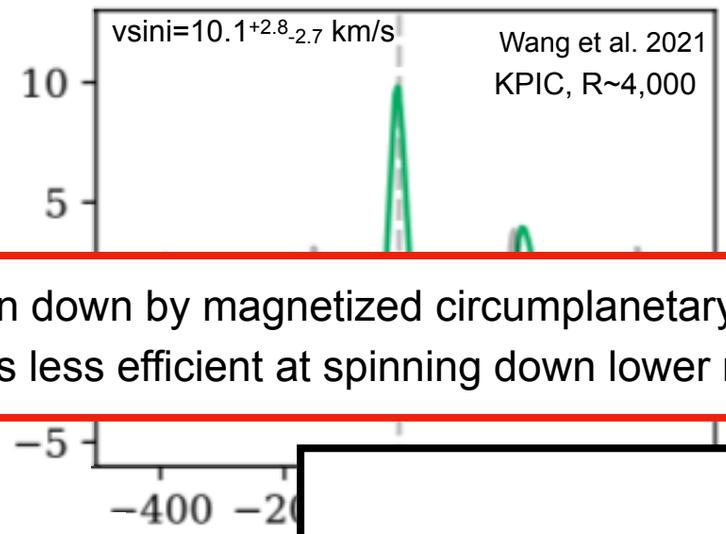


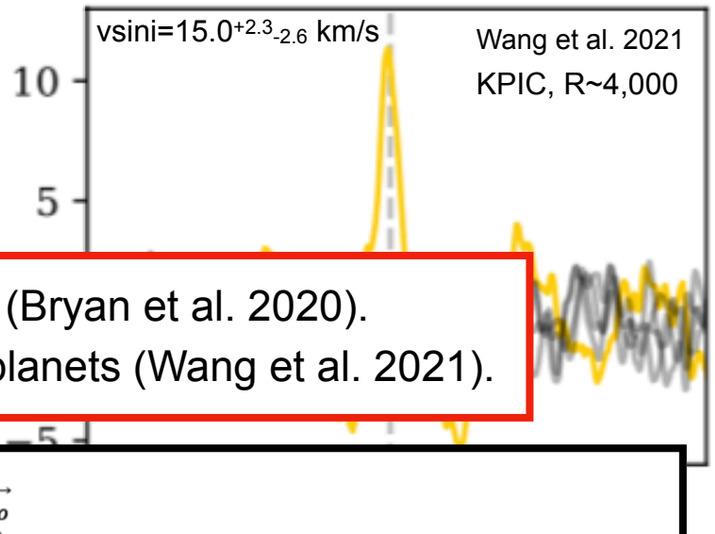
High resolution spectroscopy accessed a new fundamental parameter: exoplanet rotation rate



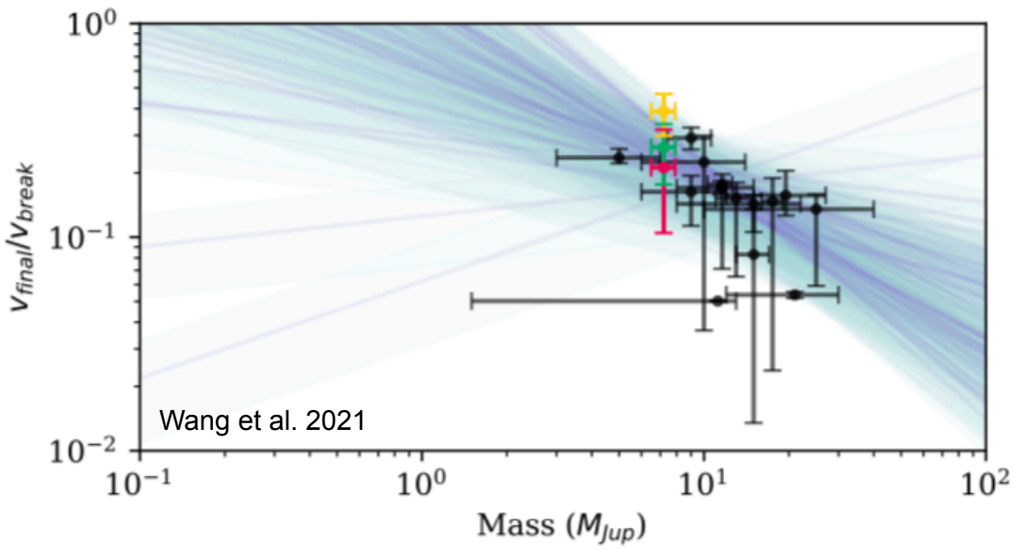


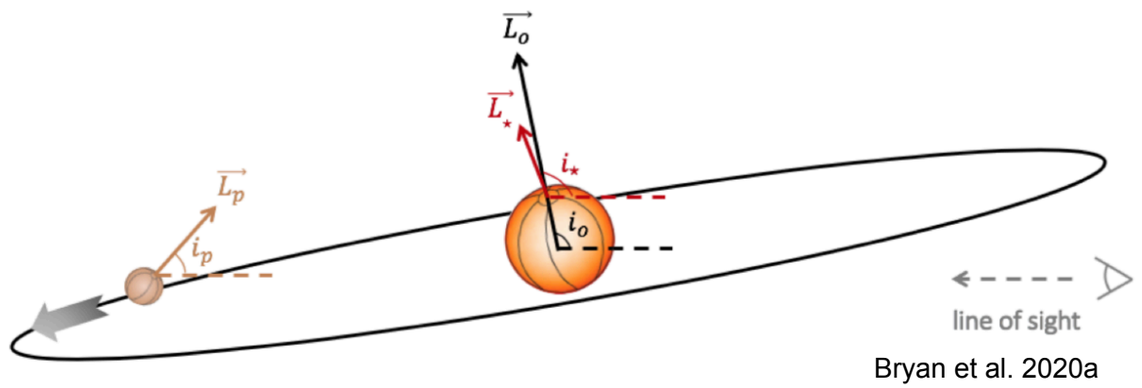






Consistent with being spun down by magnetized circumplanetary disks (Bryan et al. 2020).
Magnetic braking at early times is less efficient at spinning down lower mass planets (Wang et al. 2021).

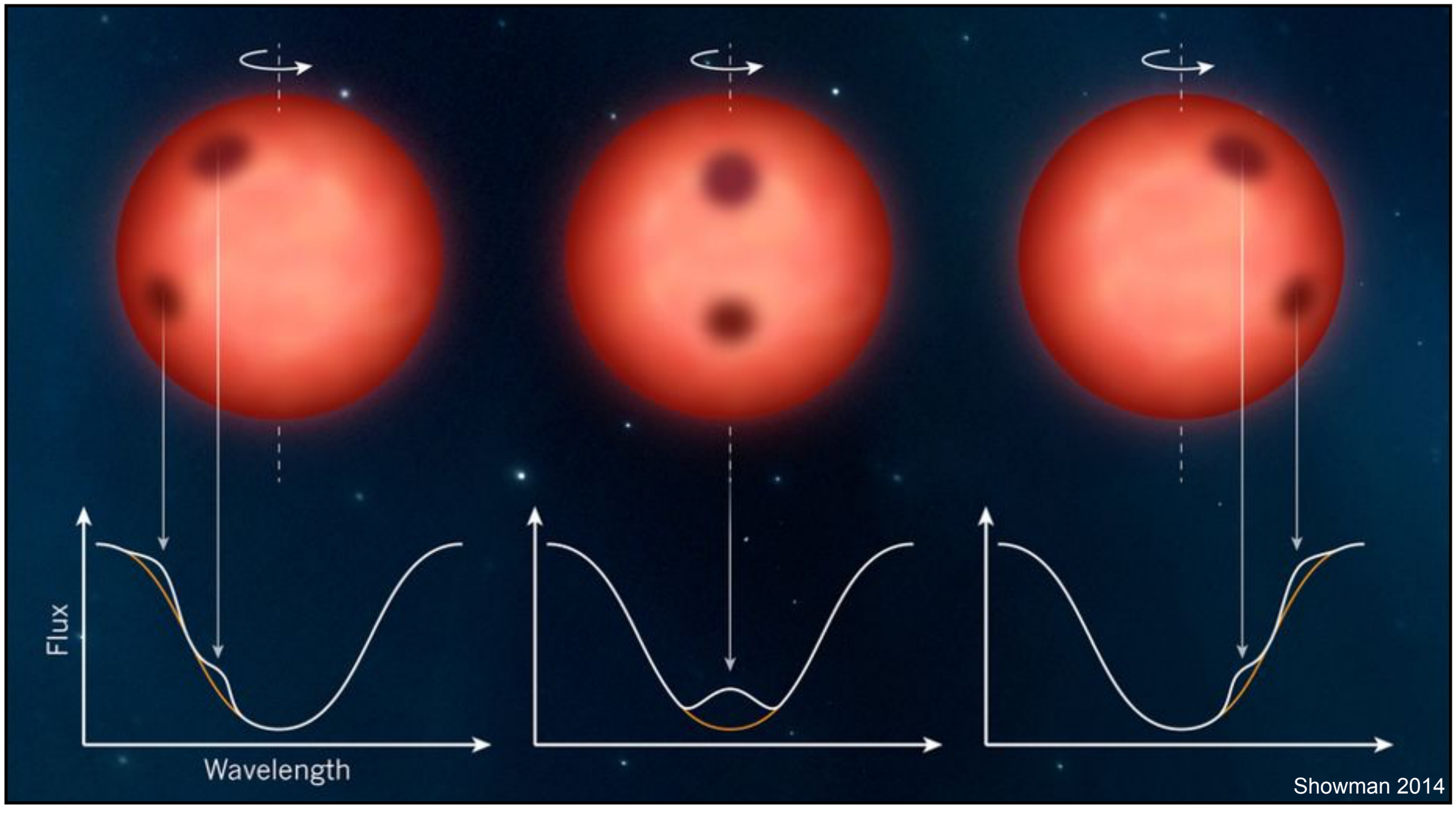




Bryan et al. 2020a

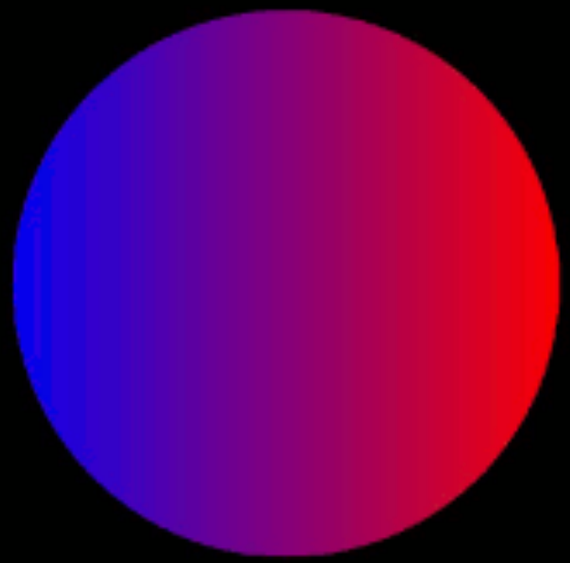
With true period from photometric variability and vsini from spectroscopy, oblqiuities can be solved in full.

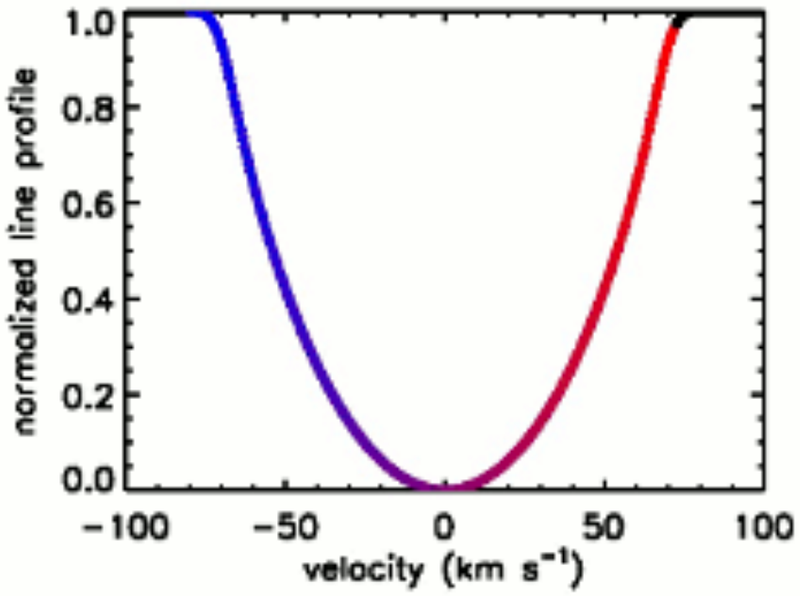
Potential to map exoplanet features with Doppler imaging



Exocartography possible with HRS+HCI in the ELT era

Line profiles altered by storms

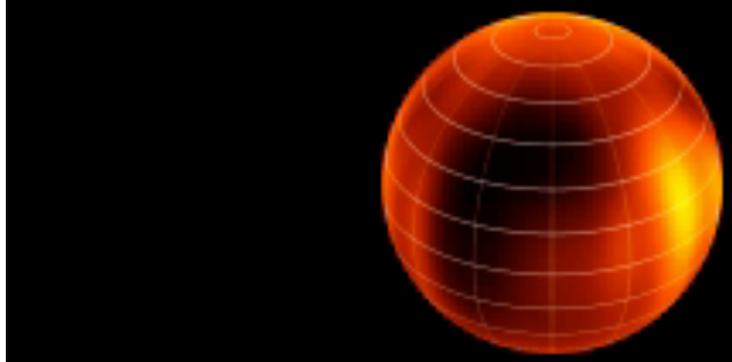


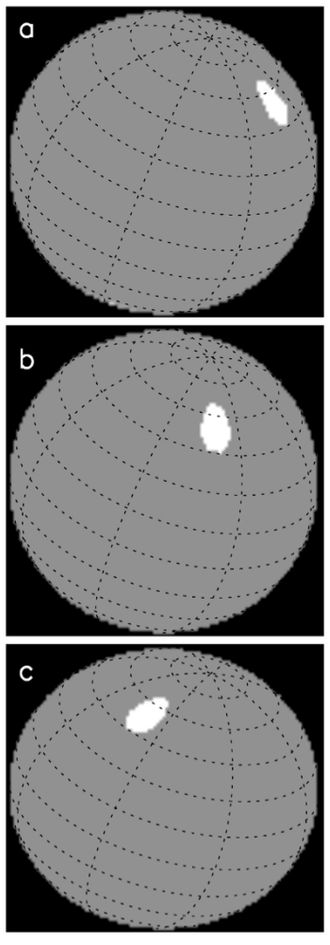


© Marshall Johnson http://www.as.utexas.edu/~mjohnson

Global weather map of brown dwarf from CRIRES/VLT

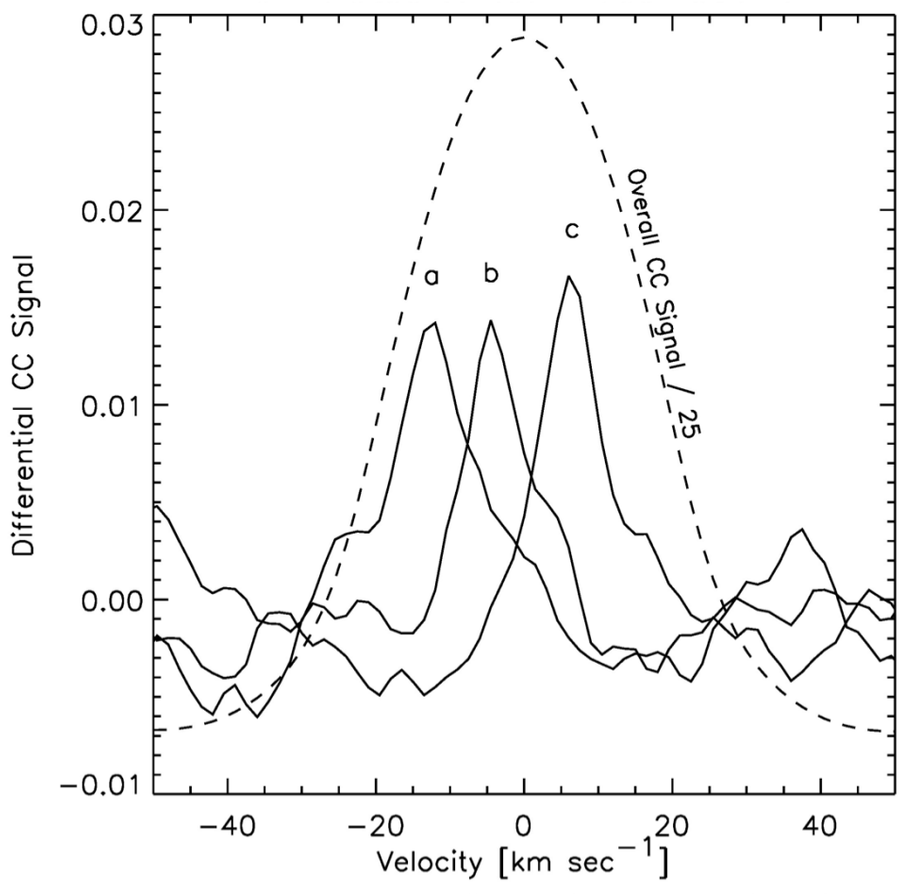
Crossfield et al. 2014





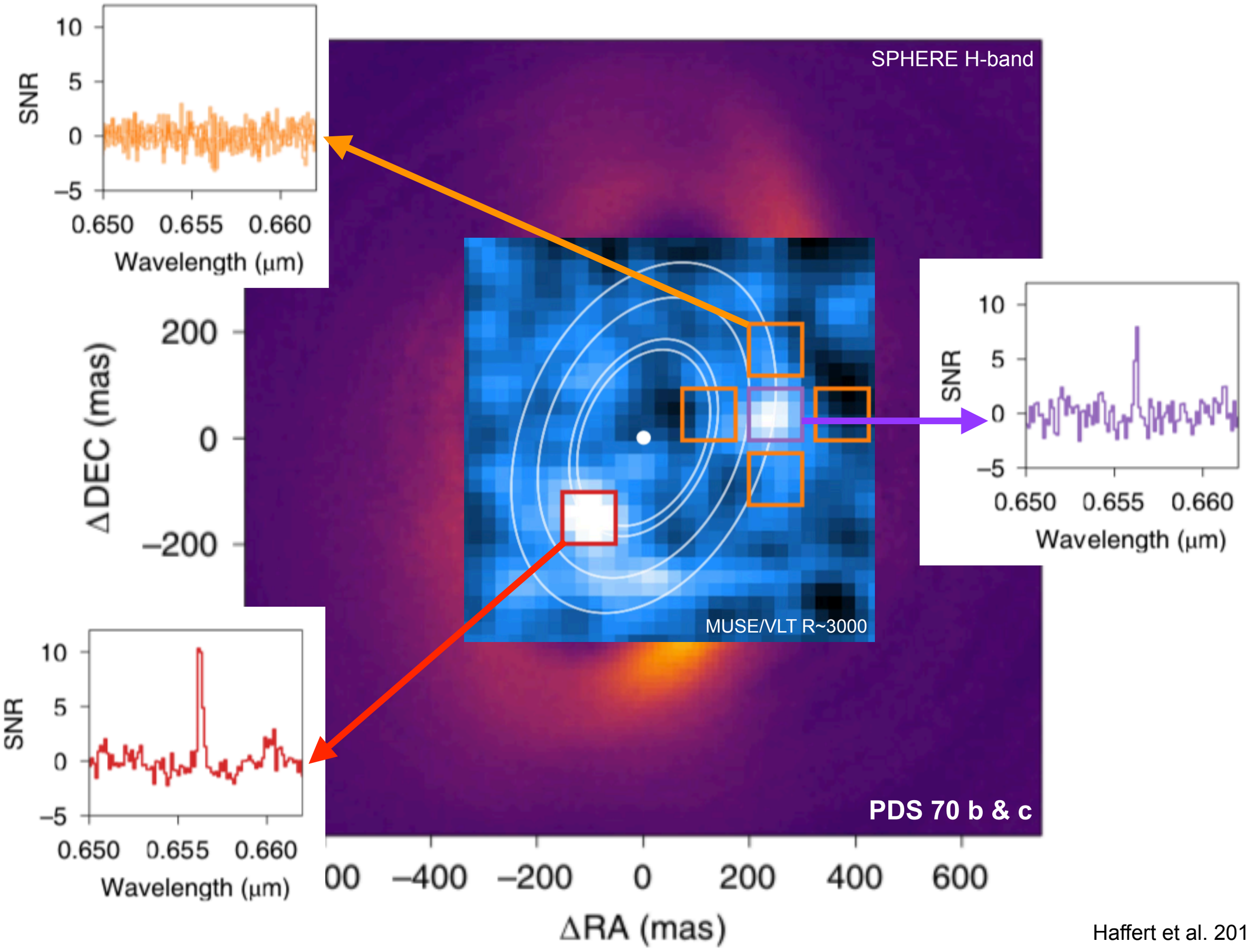
Mapping surface of β Pic b with E-ELT

(twice as efficient as VLT BDs)



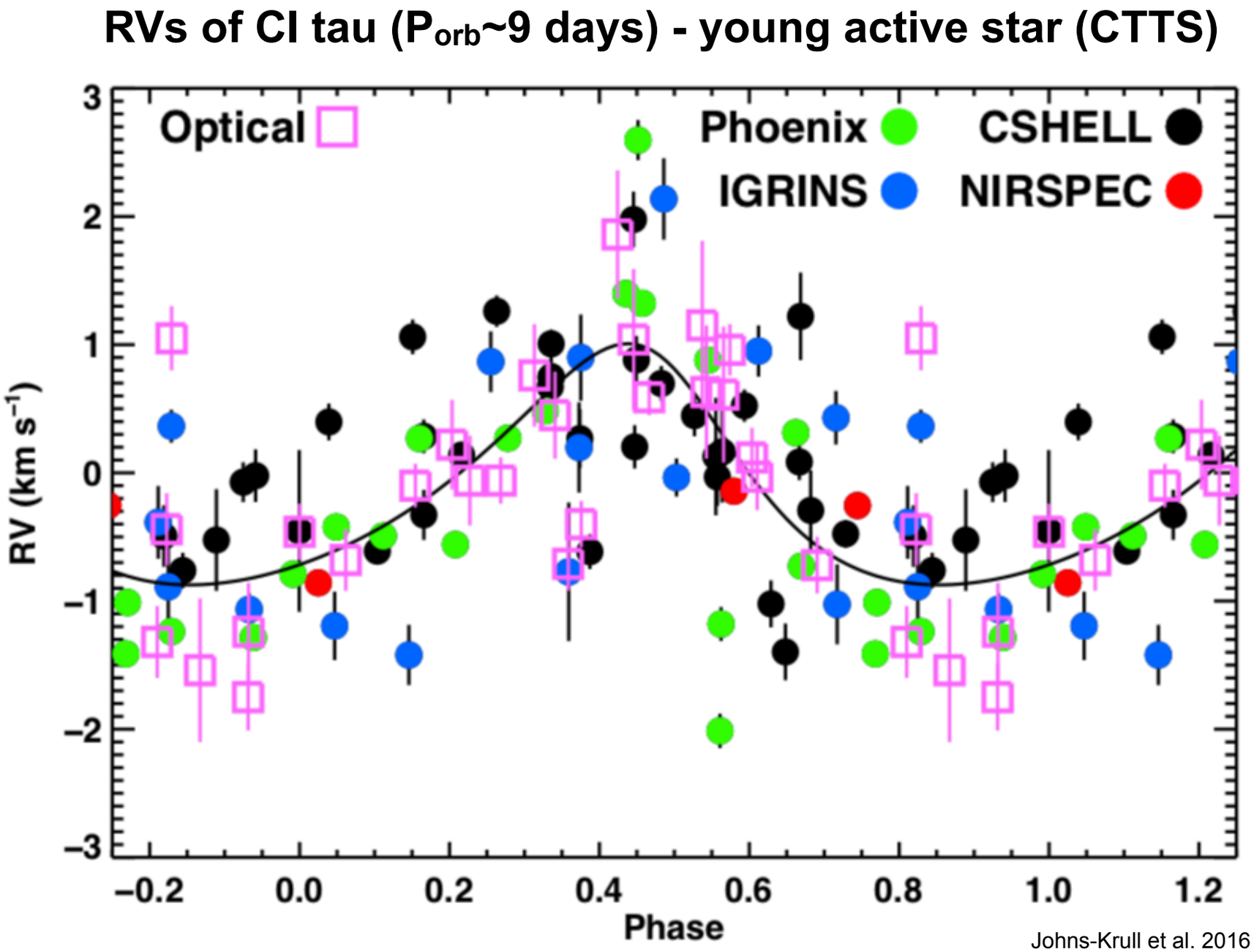
Snellen, Brandl, de Kok, Brogi, Birkby et al. 2014

High-Resolution Spectral Differential Imaging (HRSDI) reveals accretion via Hα emission



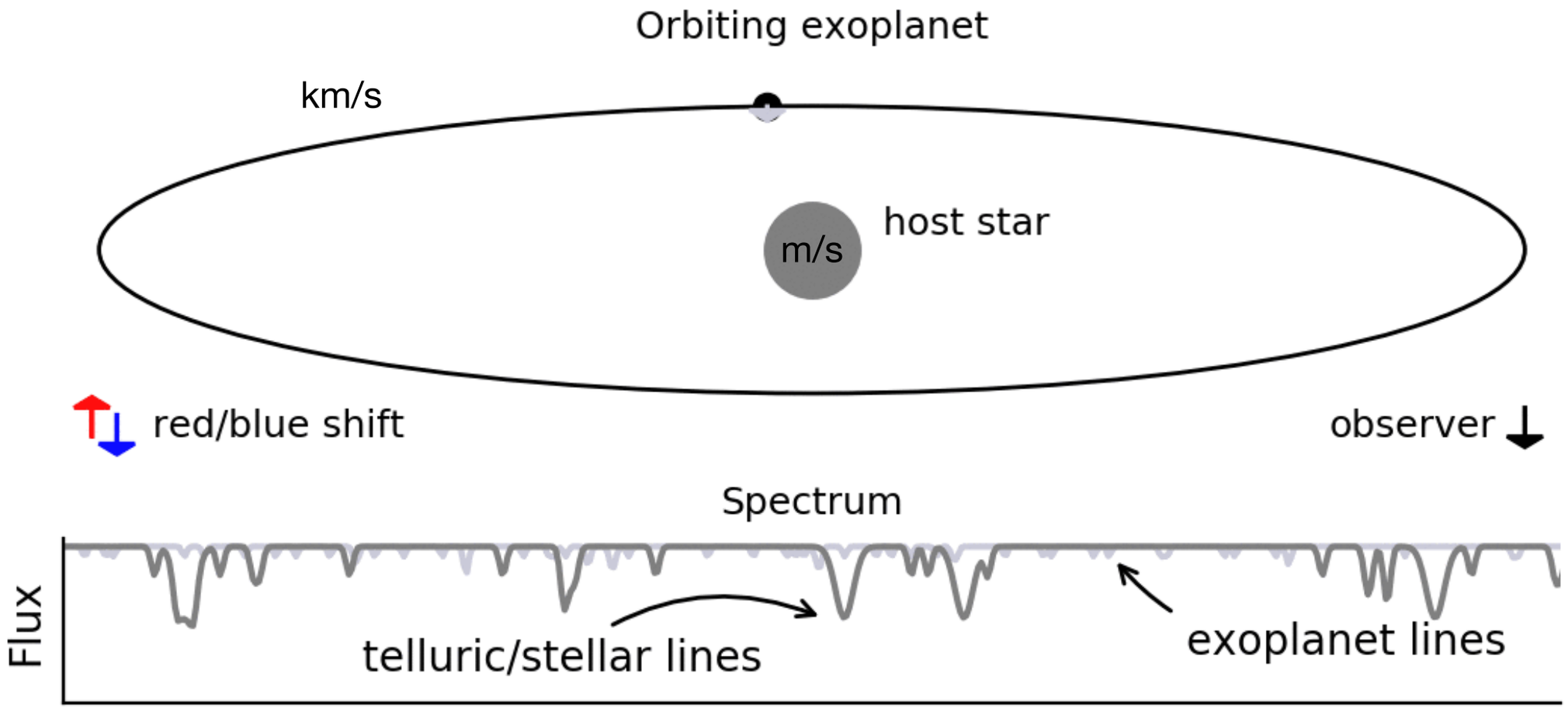
Haffert et al. 2019

Young stars are active which makes RVs difficult



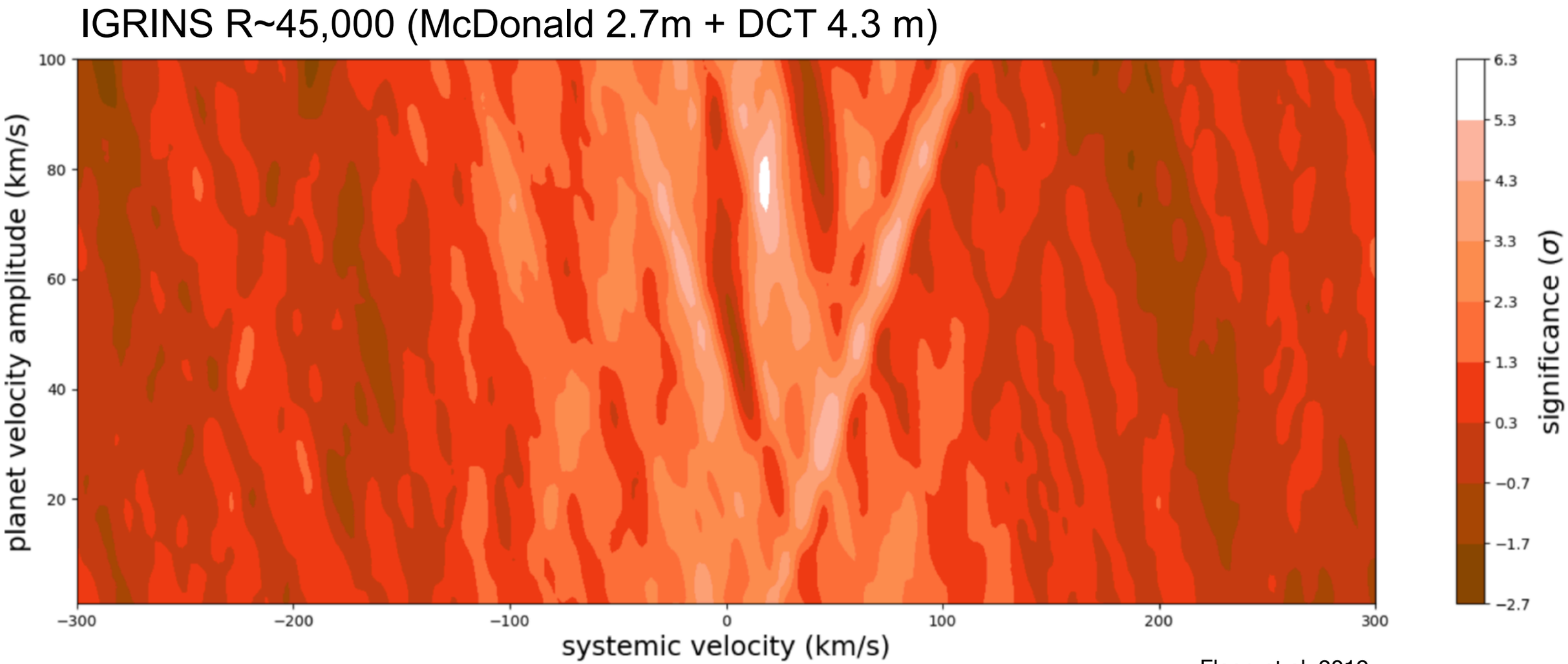
Johns-Krull et al. 2016

We use the large radial velocity of the planet to disentangle its spectrum from its almost stationary host star



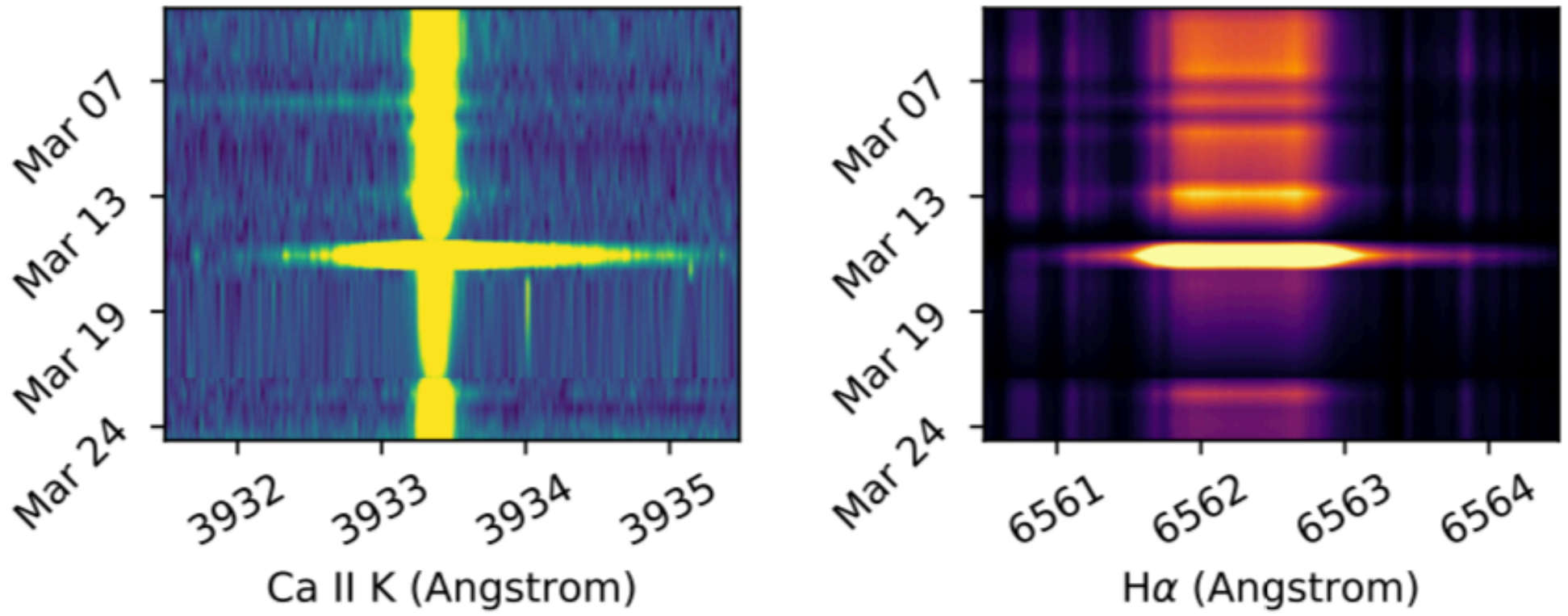
Annimation by Lennart van Sluijs

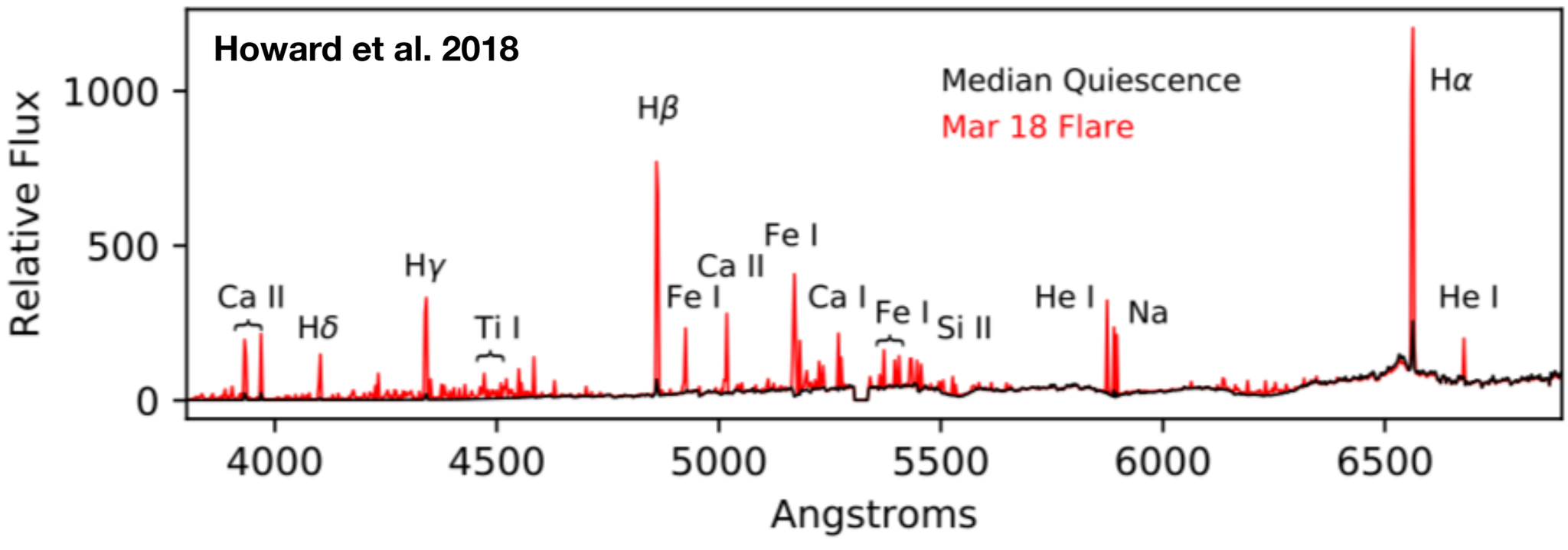
CO detected in the 2 Myr old planet CI tau b indicating a hot start model



Flagg et al. 2019

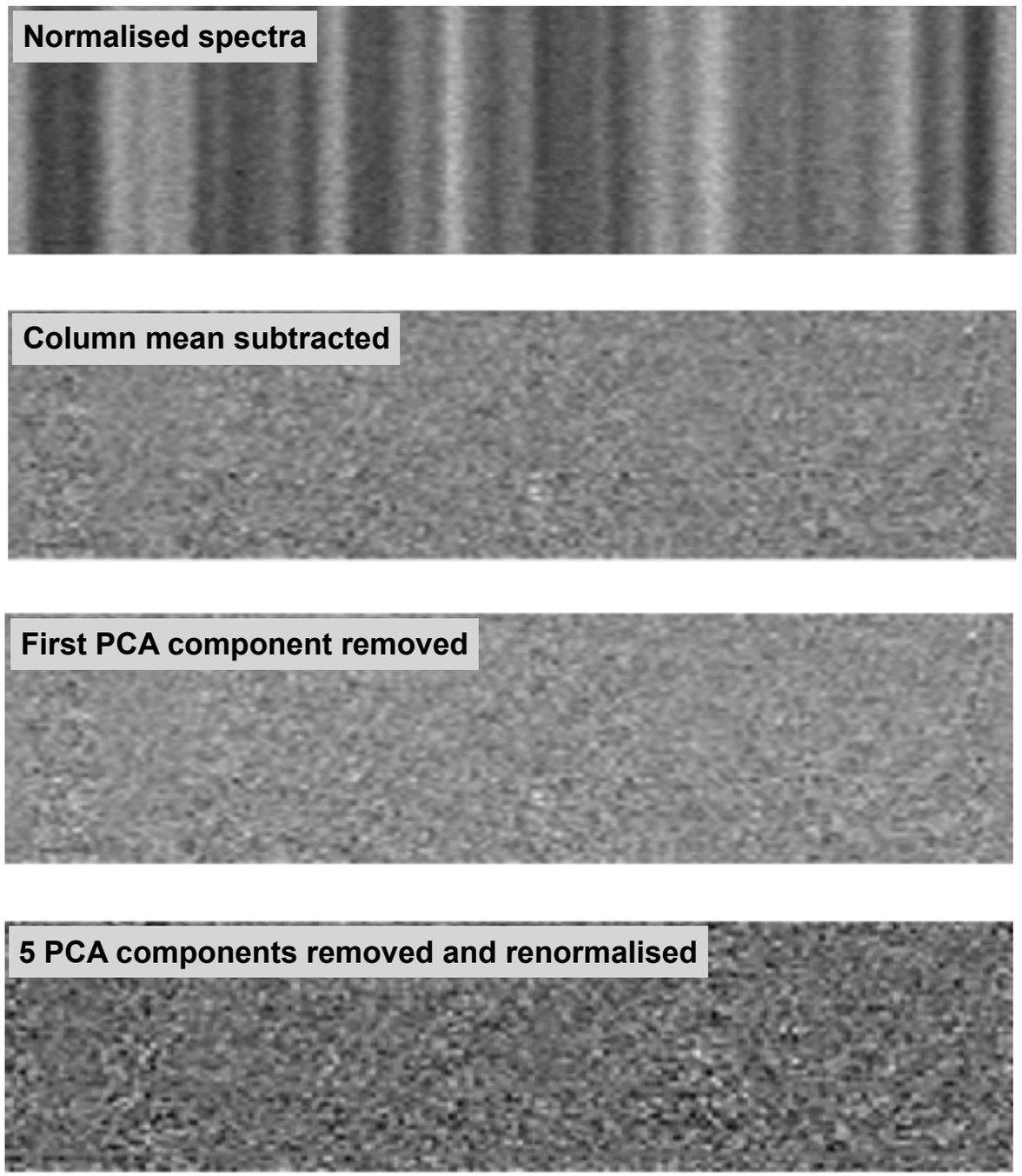
Are flares and stellar activity a problem for high resolution studies?





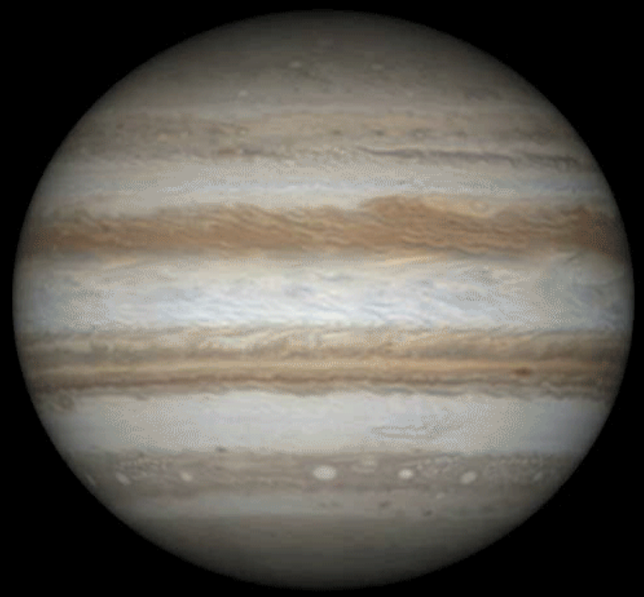
Simple simulation of super flare in M-dwarf spectral sequence shows star can be mostly removed

Quiescent



Spectra from Pale Red Dot Campaign on HARPS

Stapper, Birkby in prep.



Take home messages

- High resolution spectroscopy **combined** with high contrast imaging is a powerful tool to find and characterize (young) exoplanets.
- **Molecule mapping** operates down to R~3,000, giving information about **atmospheric composition** and **3D orbital solution.**
- At higher resolutions it measures planet **rotational velocity** and with the ELTs has the potential to **map** their storms and features.
- HRS+HCI with **ELTs** is our avenue this decade to study **oxygen** and **biomarkers** in the **nearests rocky exoplanets**.

jayne.birkby@physics.ox.ac.uk **https://users.ox.ac.uk/~phys2149** **@jaynebirkby**