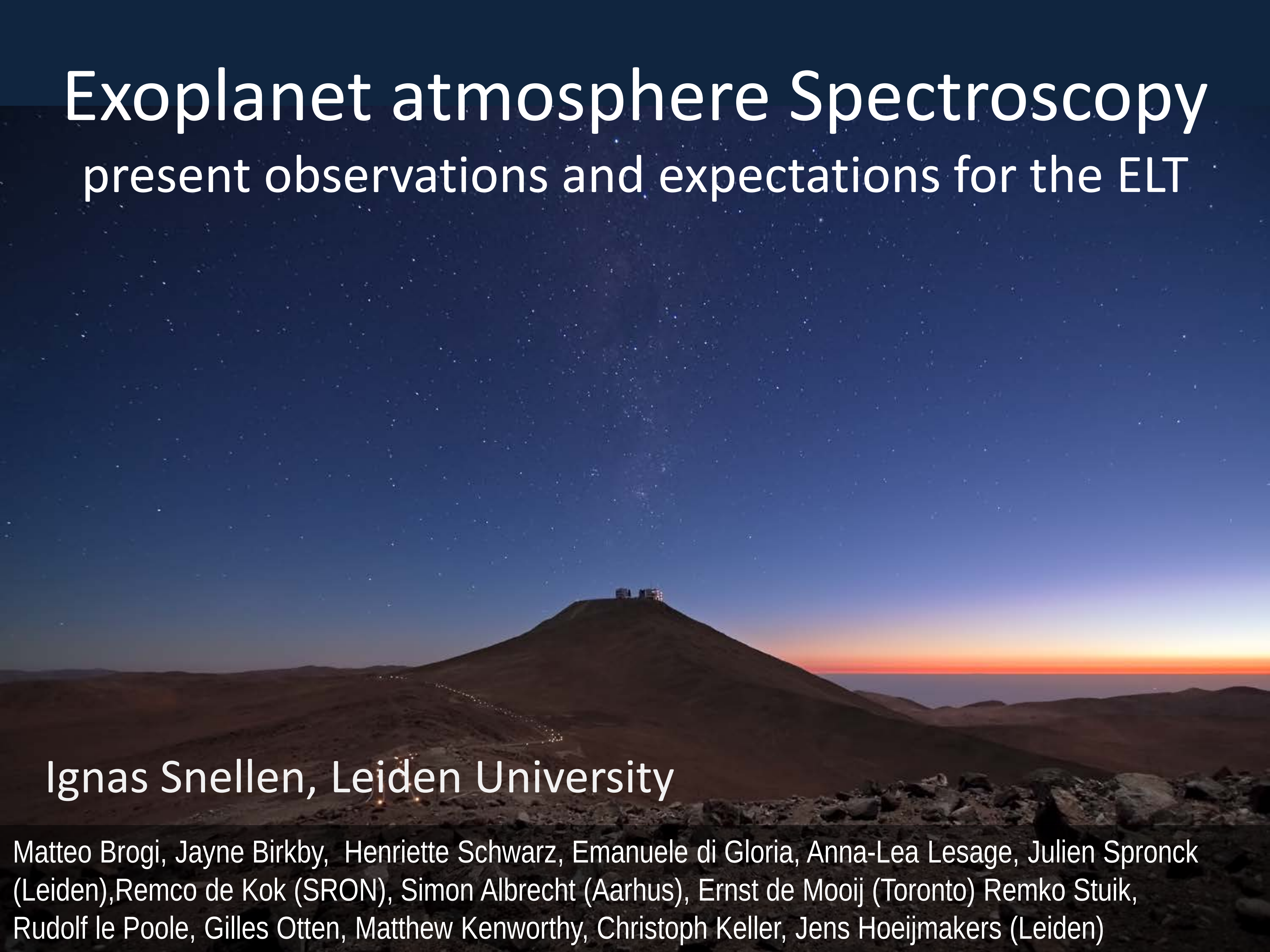
Exoplanet atmosphere Spectroscopy

present observations and expectations for the ELT



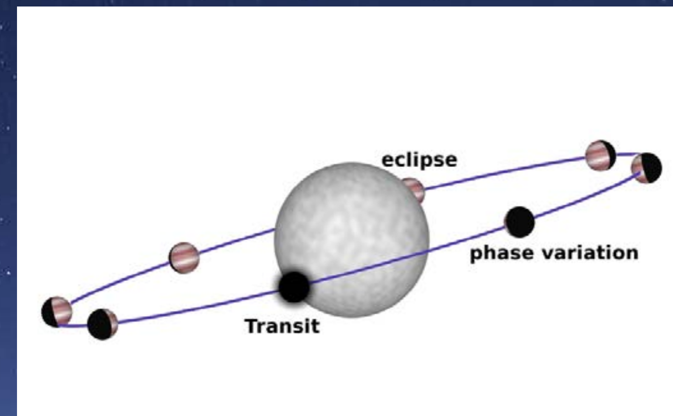
Ignas Snellen, Leiden University

Matteo Brogi, Jayne Birkby, Henriette Schwarz, Emanuele di Gloria, Anna-Lea Lesage, Julien Spronck (Leiden),Remco de Kok (SRON), Simon Albrecht (Aarhus), Ernst de Mooij (Toronto) Remko Stuik, Rudolf le Poole, Gilles Otten, Matthew Kenworthy, Christoph Keller, Jens Hoeijmakers (Leiden)

Challenges for Ground-based Observations

Measure **$<10^{-3-4}$ variations** in flux **as function of λ** over **1-5 hour time scales**

Transits and Secondary Eclipses



Earth Atmosphere:

- Variations in turbulence / seeing
- Variations in absorption & scattering
- Variations in thermal sky emission

Instrumental:

- Variations in gravity vector or field rotation
- Variations in thermal behaviour

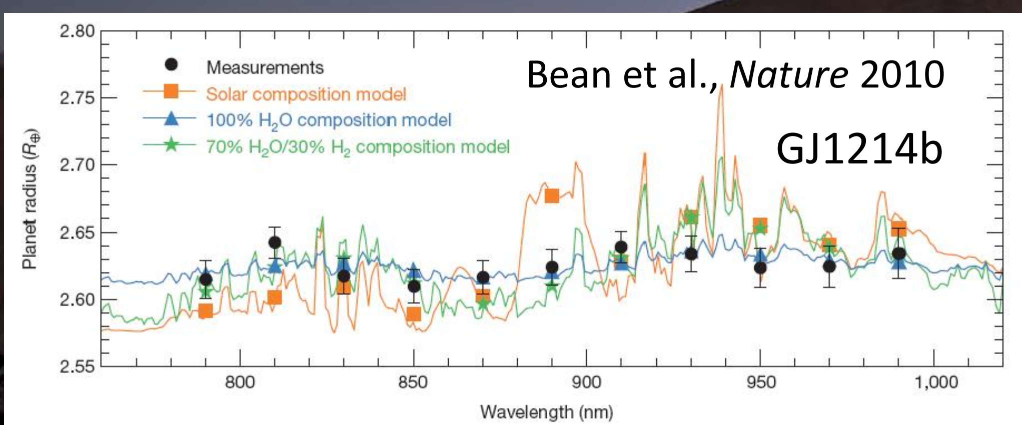
Solutions for Ground-based Observations

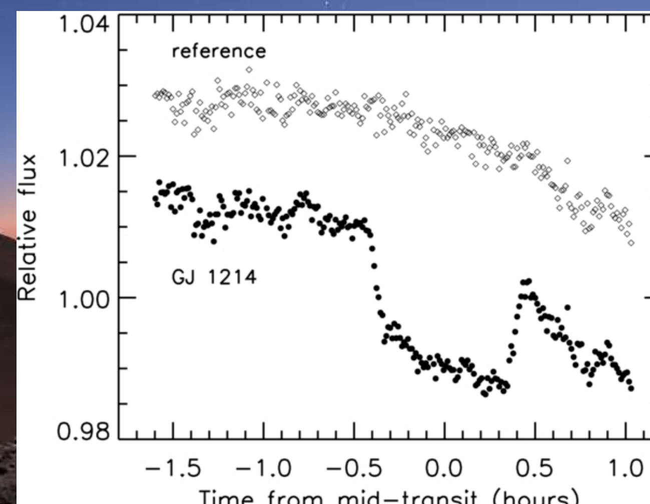
Measure **<10^{-3-4} variations** in flux **as function of λ** over **1-5 hour time scales**

Transits and Secondary Eclipses

<u>Observe target + reference stars simultaneously</u>

- Atmospheric variations similar for target & refs
- Different optical paths through telescope + instruments

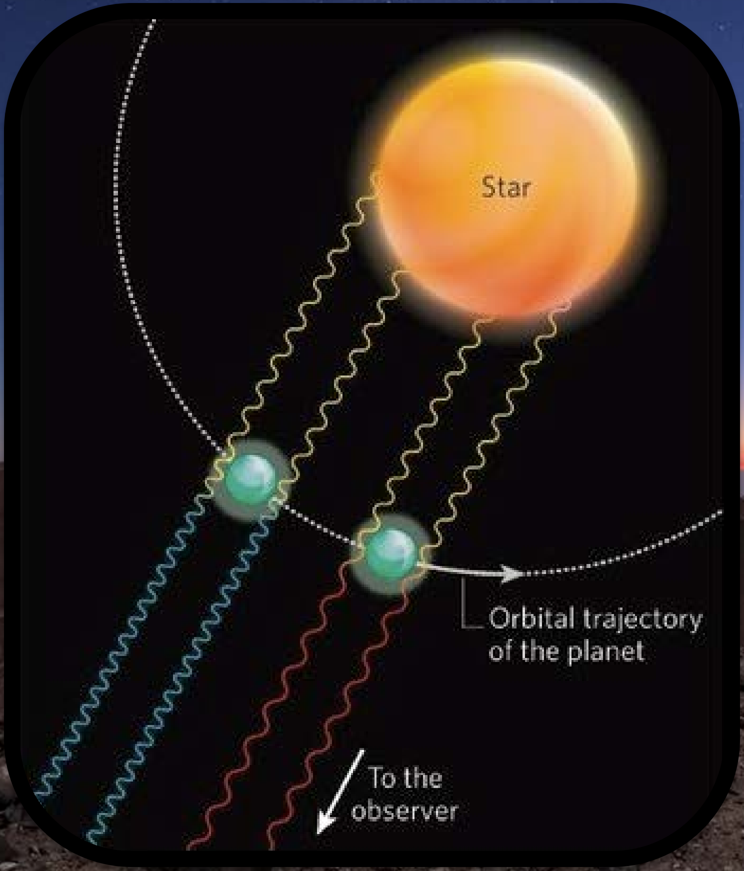


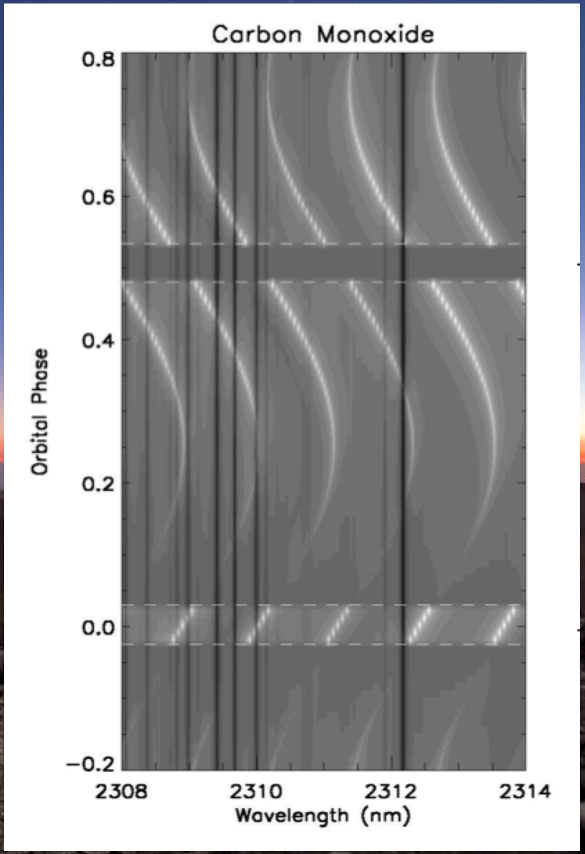


Solutions for Ground-based Observations

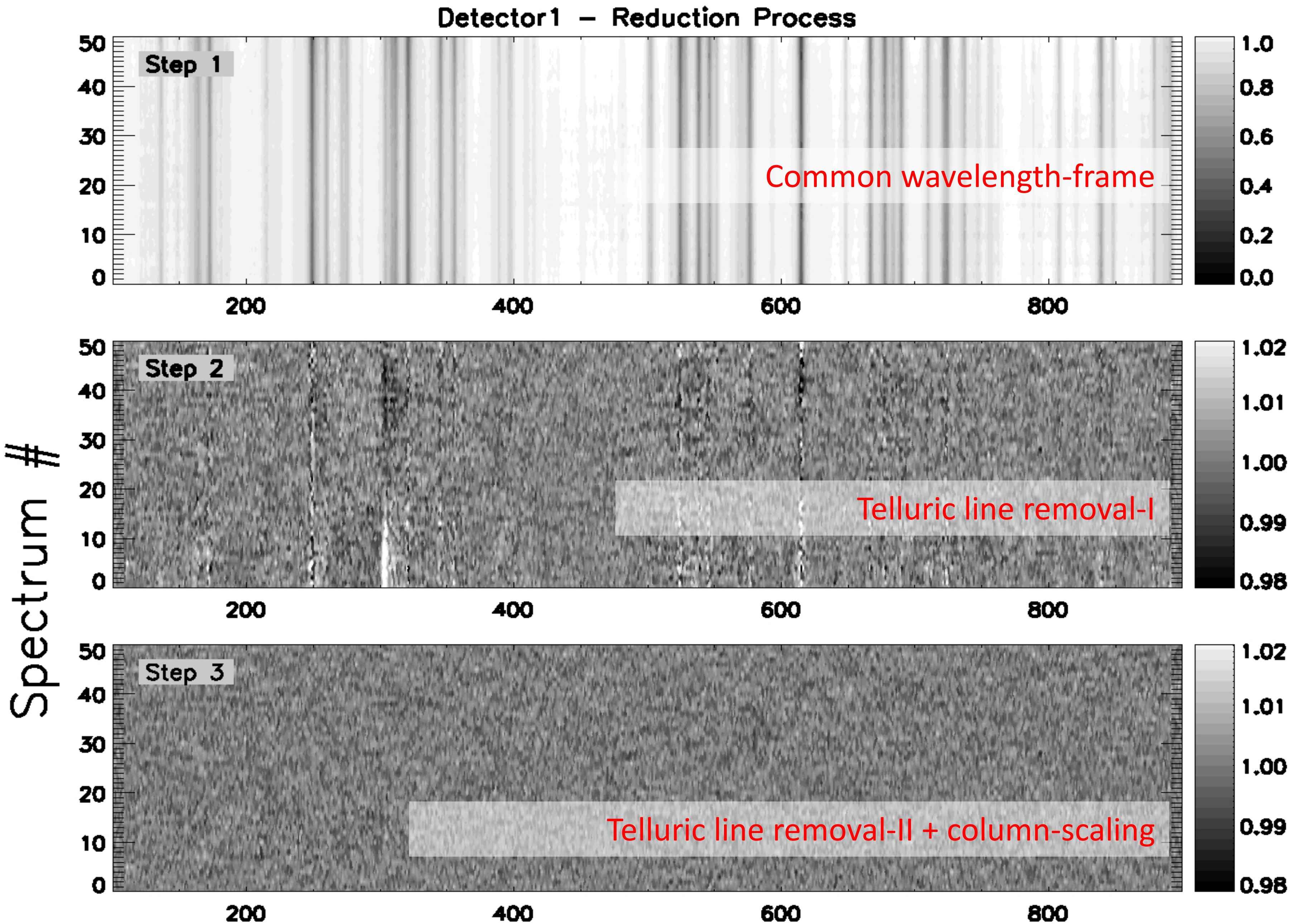
High-Dispersion Spectroscopy (λ/Δλ=100,000)

- Molecular Bands are resolved in tens of individual lines
- Strong Doppler effects due to orbital motion of the planet (upto >150 km/sec)
- moving planet lines can be distinguished from stationary telluric & stellar lines



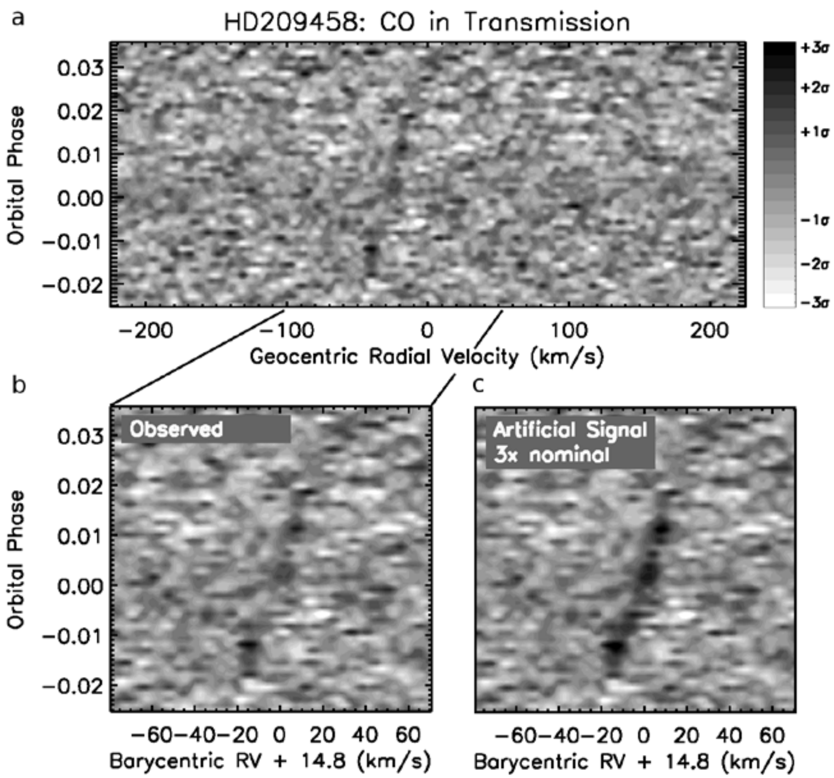


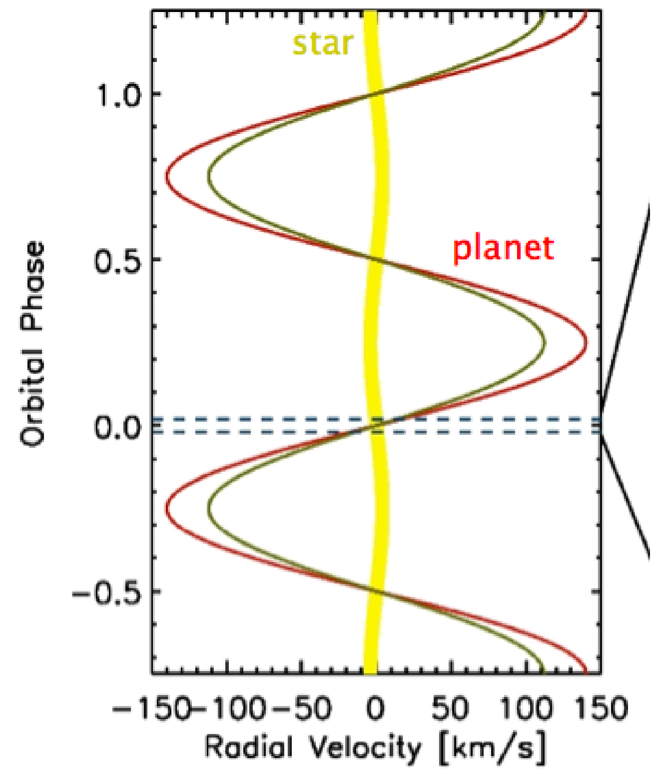
HD209458b in transmission, CO -2.3 um



CO in transmission in HD209458b (CRIRES@VLT)

(Snellen et al. *Nature* 2010)

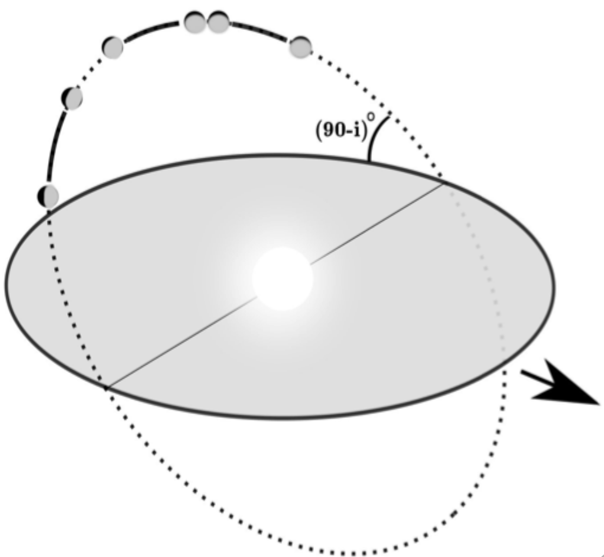




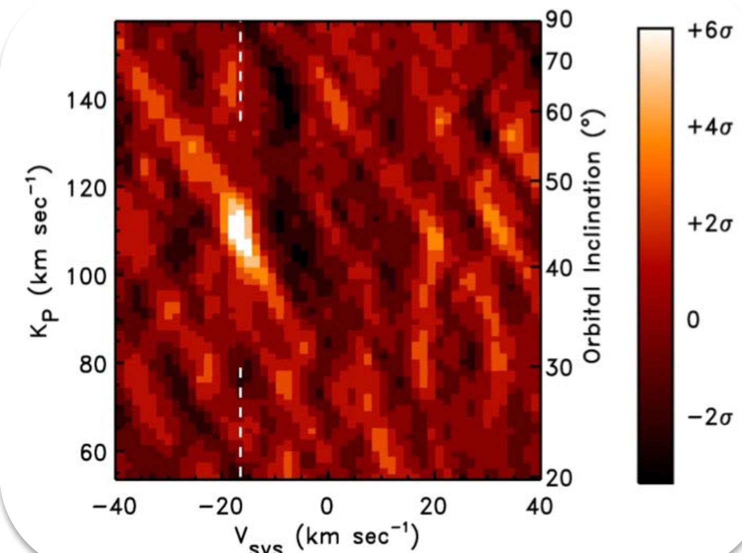
- Reveals planet orbital velocity
- Solves for masses of both planet and star (model independent)
- Evidence for blueshift (high altitude winds?)

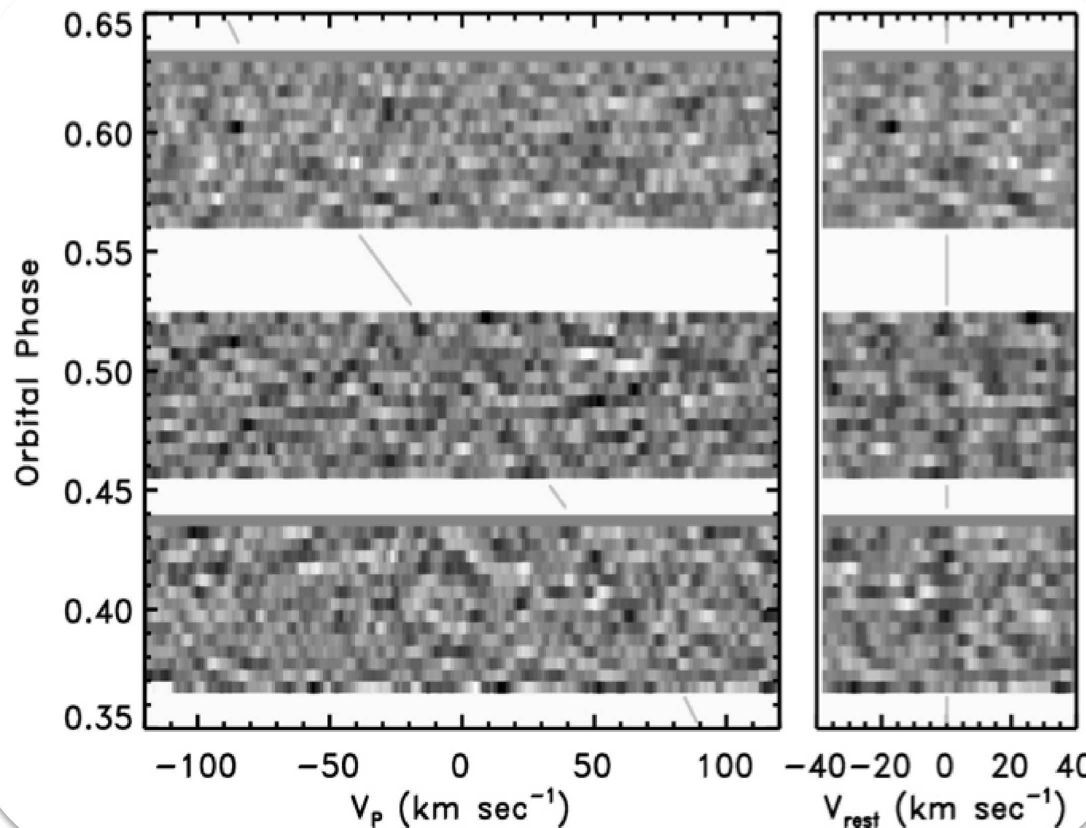
CO in dayside spectrum of tau Bootis b (CRIRES@VLT)

(**Brogi et al. *Nature* 2012 – see also Rodler et al. 2012**)

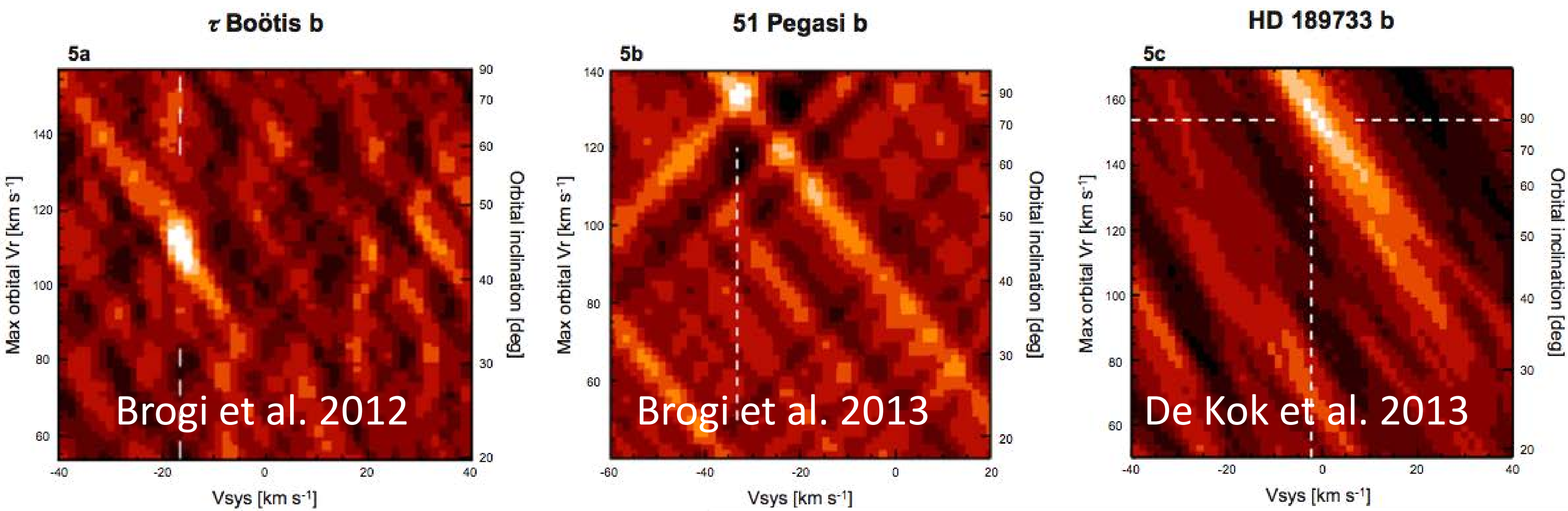


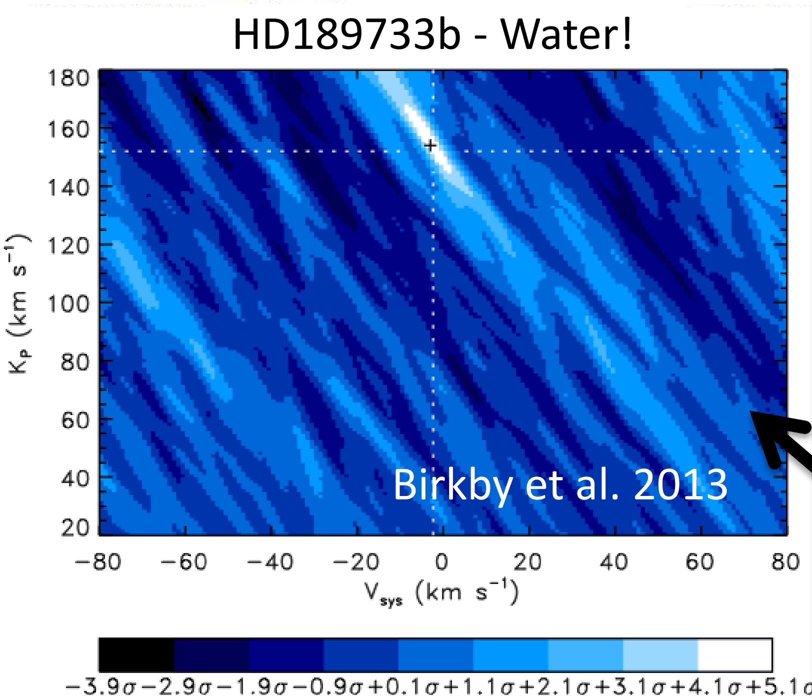
First detection of non-transiting planet→ inclination, mass





CO in dayside spectra of hot Jupiters





CRIRES@VLT Upgrade (2015) →
6x larger wavelength coverage
CO, H2O, CH4, NH3, H3+,…..

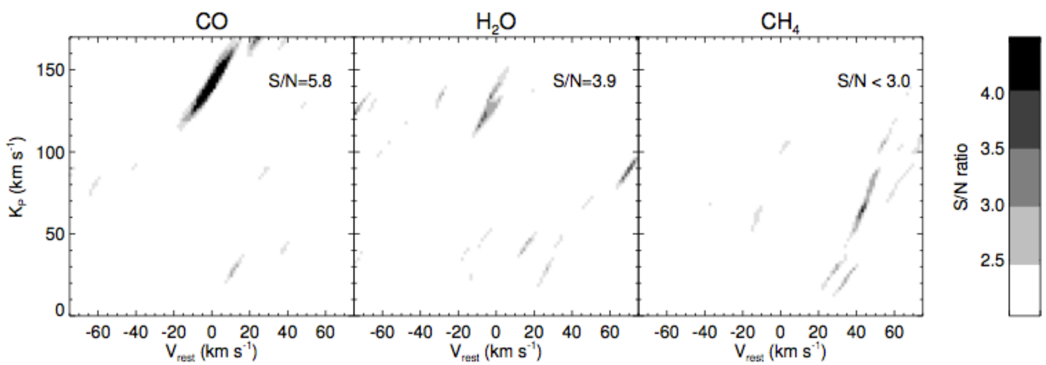
VLT ESPRESSO (Optical → TiO, VO, FeH...)

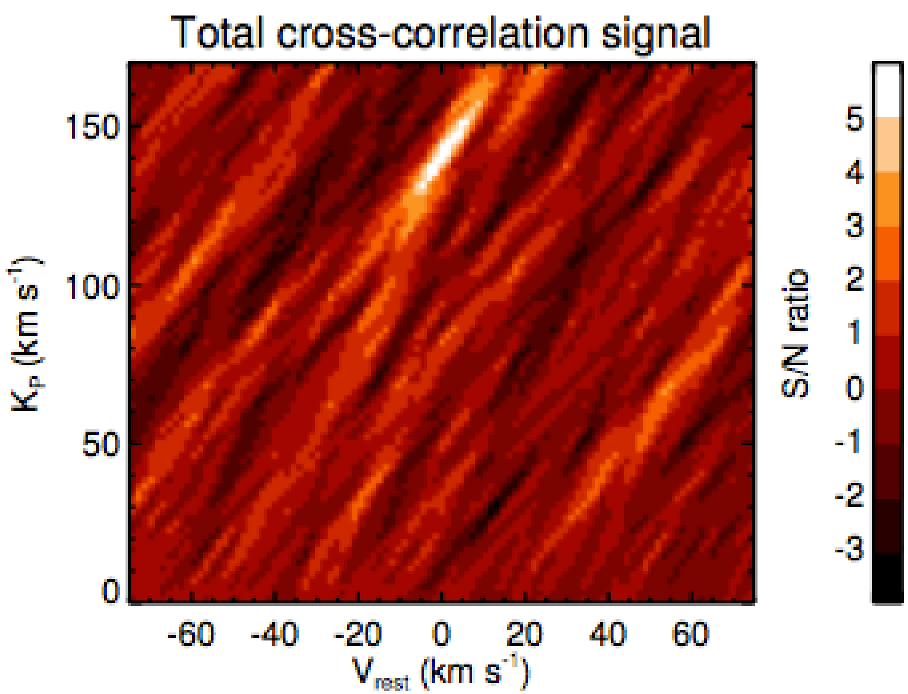
Now also with Keck!
Lockwood et al. 2014

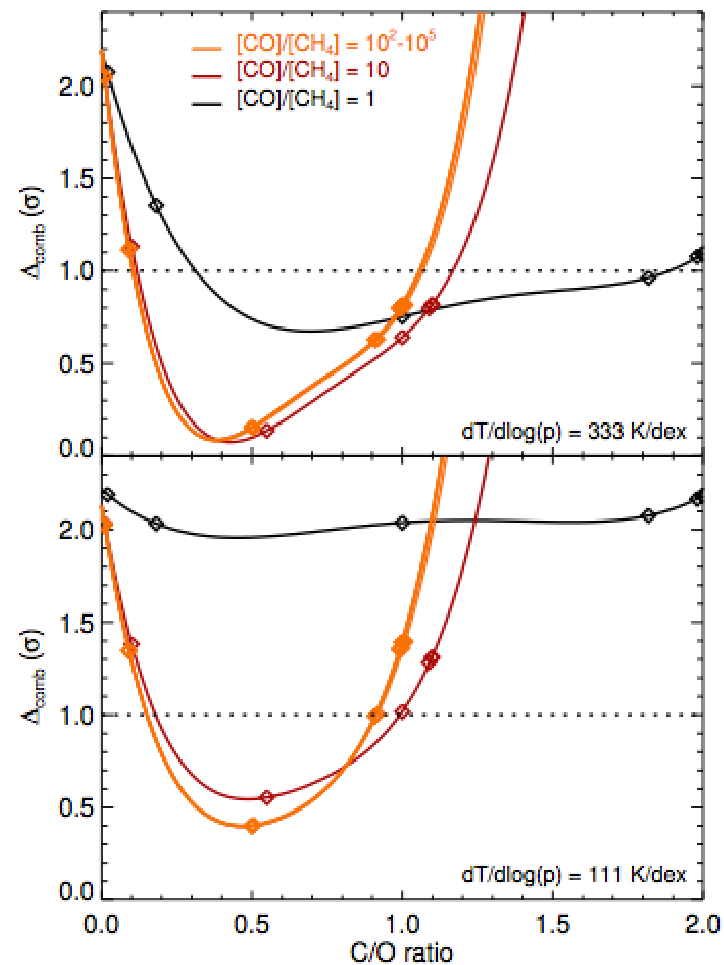
Stepping-stone for the ELTs

Carbon monoxide and water vapour in the atmosphere of the non-transiting exoplanet HD 179949 b*

M. Brogi[1], R. J. de Kok[1,2], J. L. Birkby[1], H. Schwarz[1], and I. A. G. Snellen[1]

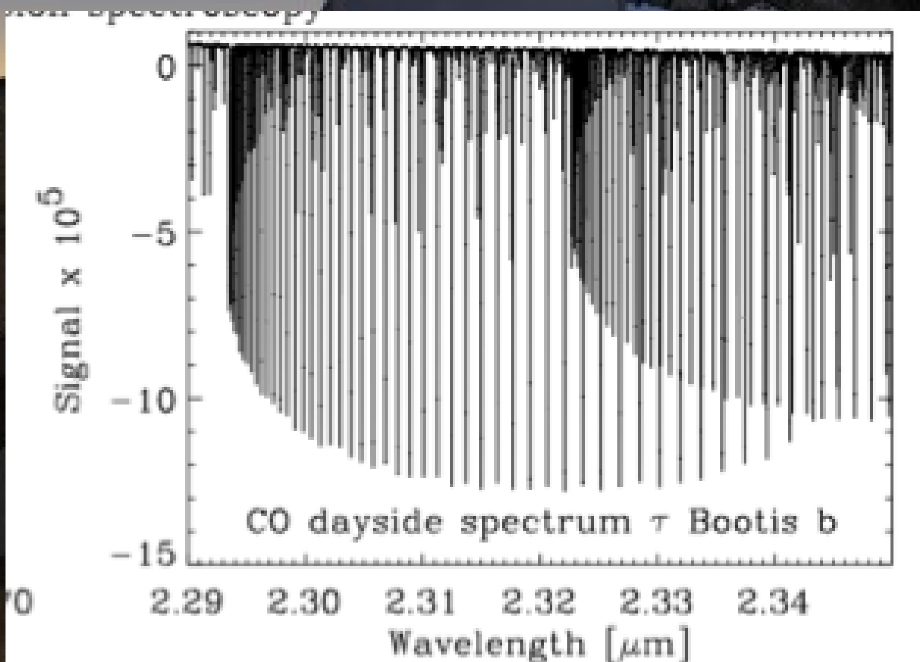


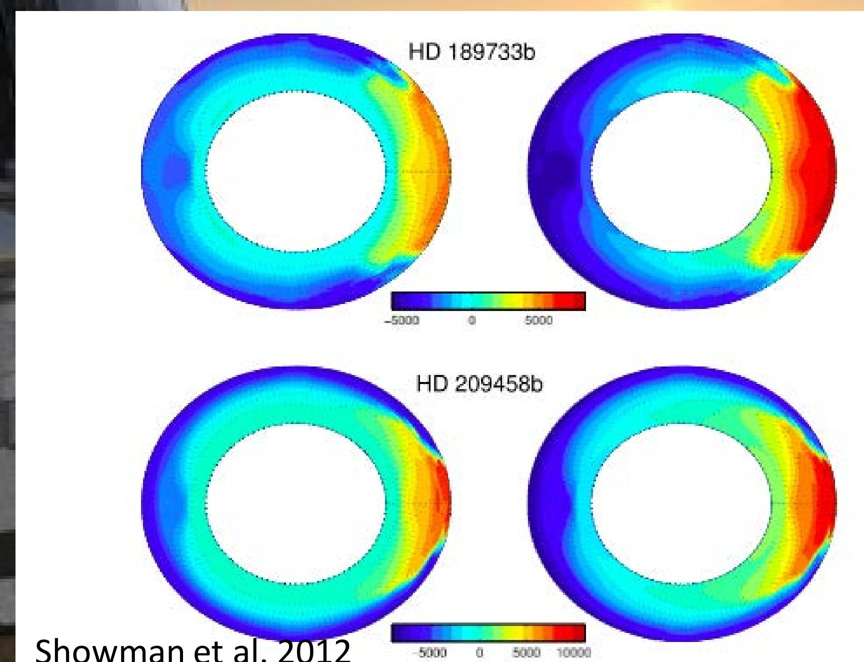




Extremely Large Telescopes

- Orbital inclinations and masses of >100 non-transiting planets
- Detection of the individual lines (instead of cross-correlation) → T/P profile; unambigous detections of inversion layers
- Line broadening → planet rotation and circulation

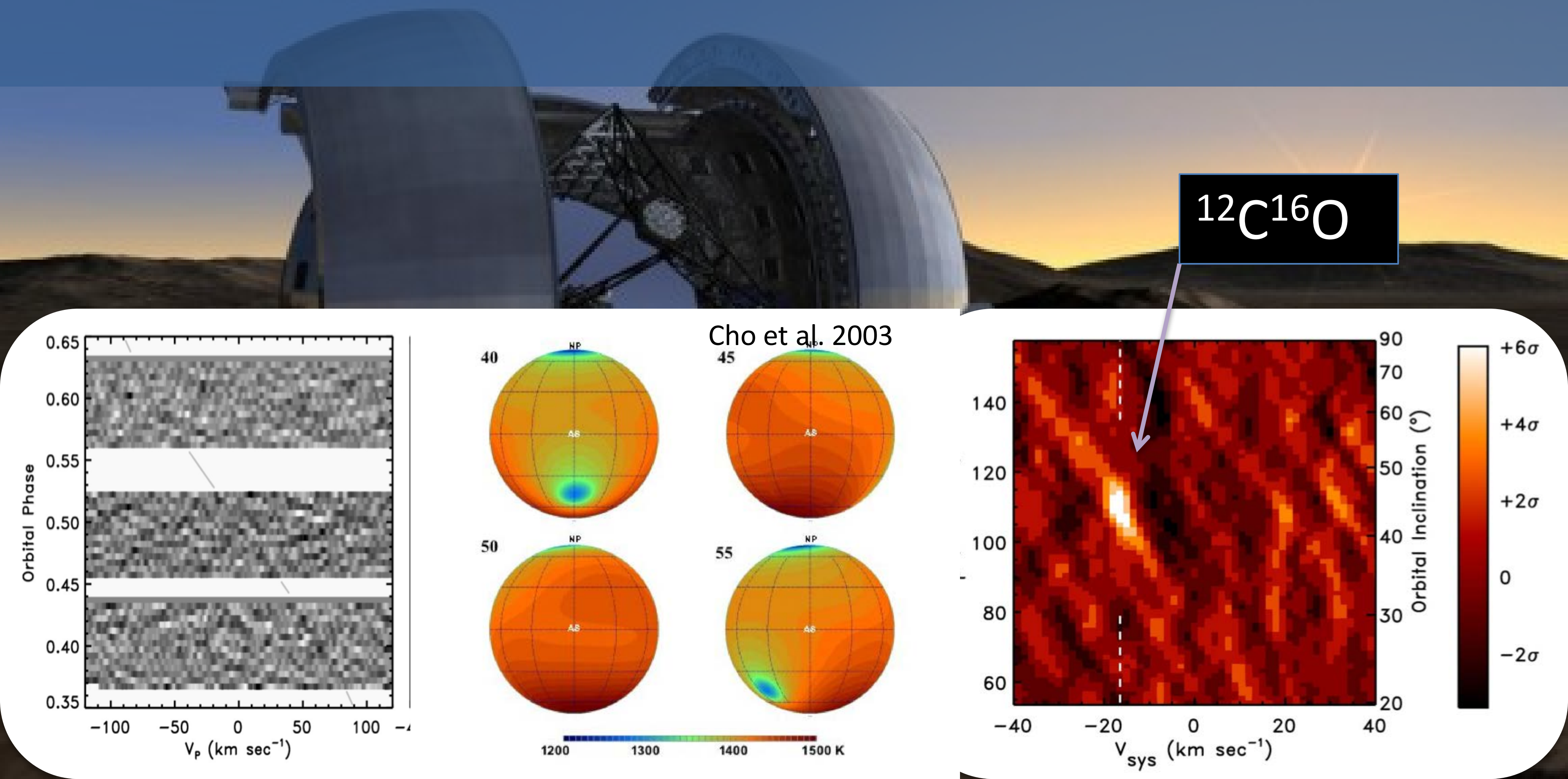




Showman et al. 2012

Extremely Large Telescopes

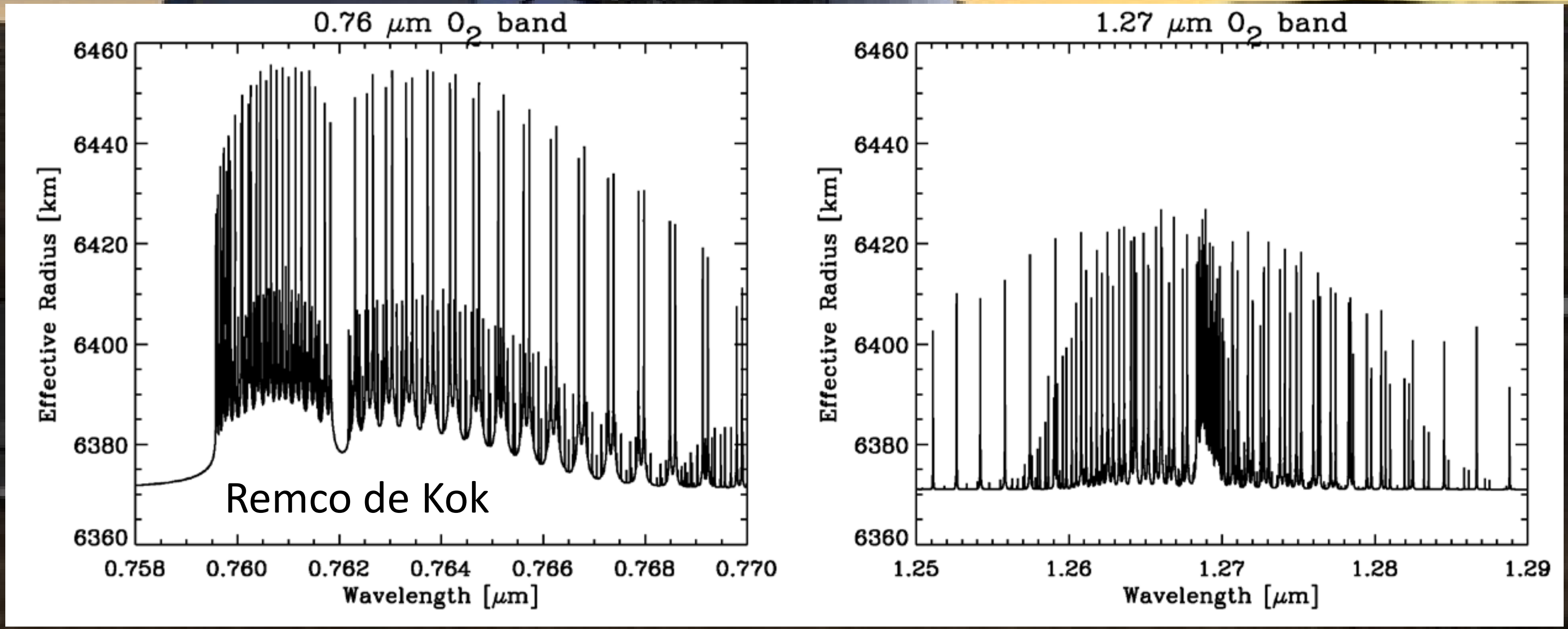
- Molecular spectra (CO, CO2, H2O, CH4) as function of orbital phase
  → photochemistry, T/P versus longitude
- Isotopologues? → evolution of planet atmosphere



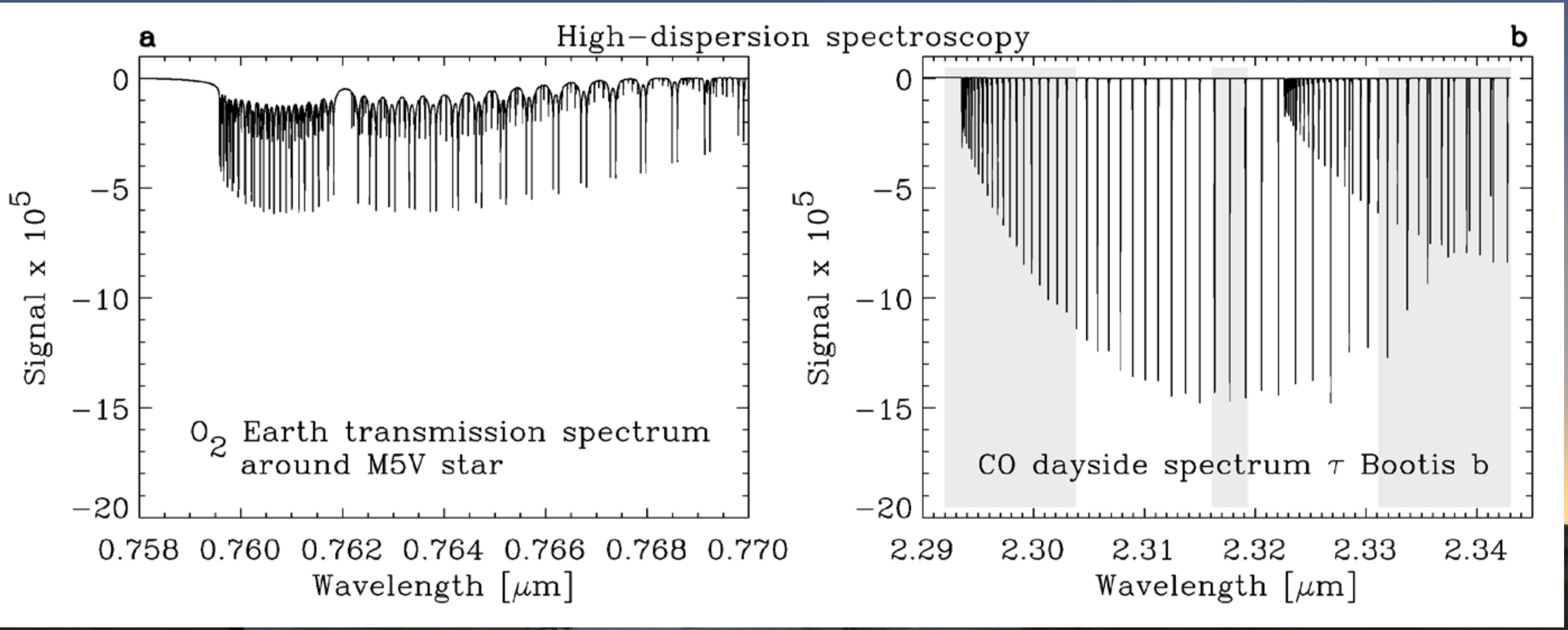
Extremely Large Telescopes

The Ultimate ELT Science Case:
Characterizing twin-Earths

- too high background for 9.6 um Ozone
- O_2 in transmission is possible!



Extremely Large Telescopes



Stellar type	R_* [R_{sun}]	M_* [M_{sun}]	a_{HZ} [au]	Prob [%]	P_{HZ} [days]	Dur. [hrs]	I (η_e=1) [mag]	Line Contrast	SNR σ	Time (yrs)
G0-G5	1.00	1.00	1.000	0.47	365.3	13	4.4 - 6.1	2×10^{-6}	1.1-2.5	80-400
M0-M2	0.49	0.49	0.203	1.12	47.7	4.1	7.3 - 9.1	8×10^{-6}	0.7-1.5	20-90
M4-M6	0.19	0.19	0.058	1.52	11.8	1.4	10.0-11.8	5×10^{-5}	0.7-1.7	4-20

Brightest expected systems

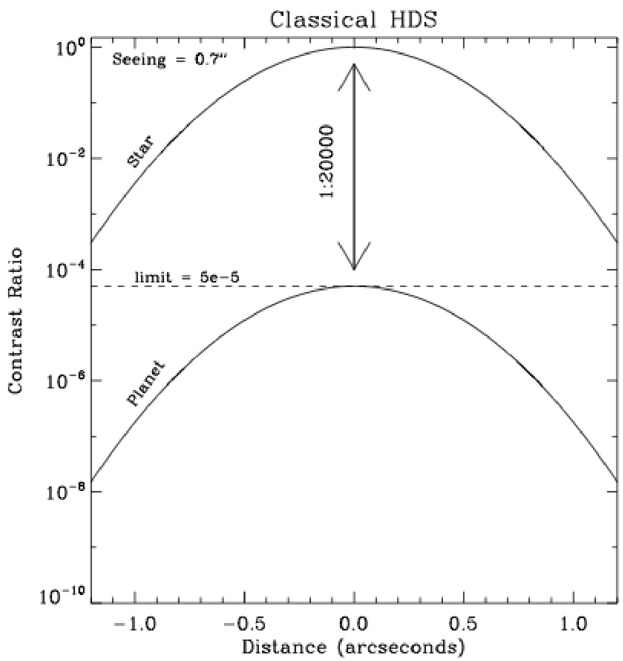
SNR for ELT in 1 transit

Snellen et al. 2013

What about dayside spectroscopy?

Combining High-Dispersion Spectroscopy (HDS) with High Contrast Imaging (HCI)

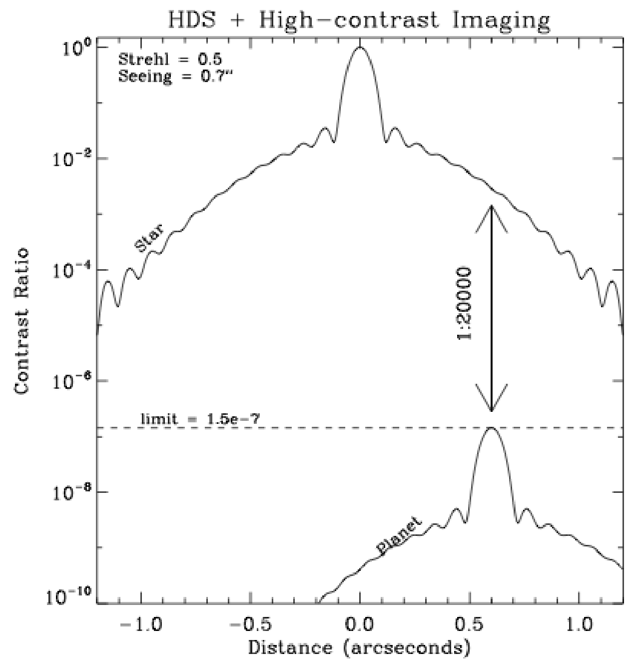
Classical HDS



$$\mathrm{SNR} = \frac{S_{\mathrm{planet}}}{\sqrt{S_{\mathrm{star}} + \sigma_{\mathrm{bg}}^2 + \sigma_{\mathrm{RN}}^2}}$$

Limits: 10^{-5} with VLT

HDS + HCI

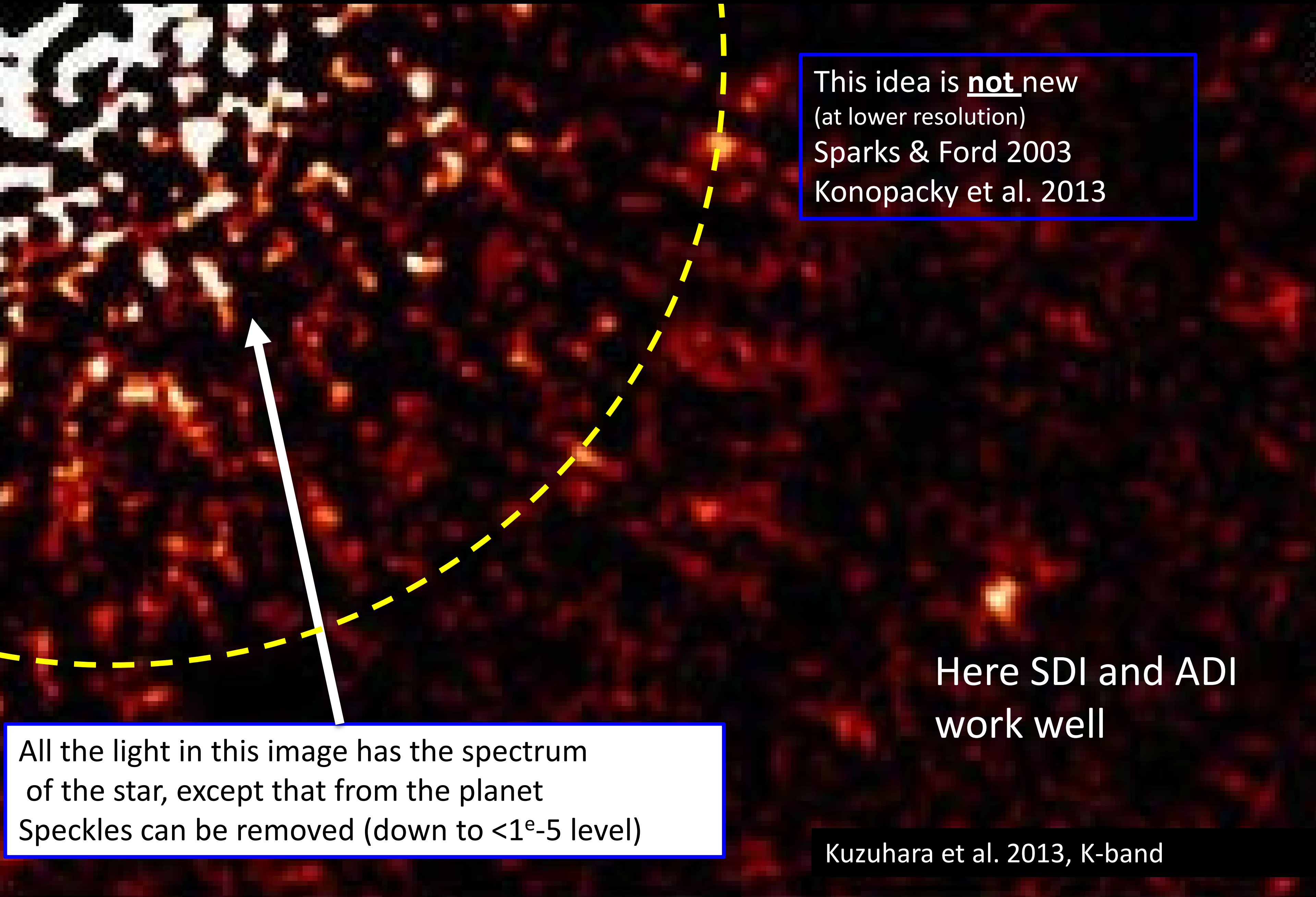


$$\mathrm{SNR} = \frac{S_{\mathrm{planet}}}{\sqrt{S_{\mathrm{star}}/K + \sigma_{\mathrm{bg}}^2 + \sigma_{\mathrm{RN}}^2}}$$

Limits: $10^{-5}/\sqrt{K}$ with VLT

How far can we push this with the ELTs?

Comparison to “classical” high-contrast imaging



This idea is **<u>not</u>** new
(at lower resolution)
Sparks & Ford 2003
Konopacky et al. 2013

All the light in this image has the spectrum
of the star, except that from the planet
Speckles can be removed (down to $<1^{e}$-5 level)

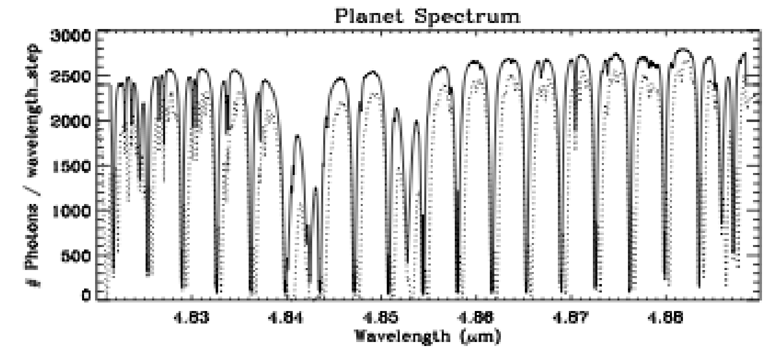
Here SDI and ADI
work well

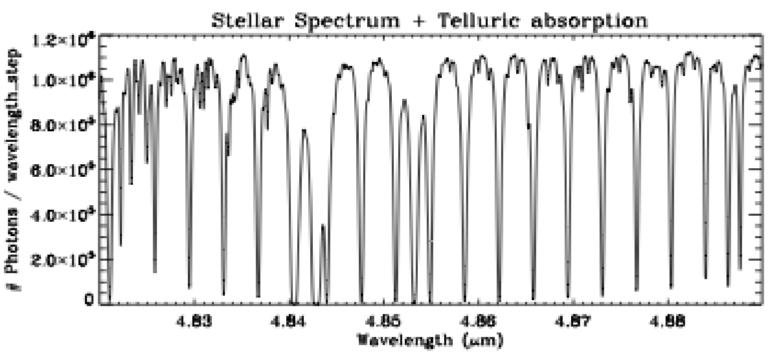
Kuzuhara et al. 2013, K-band

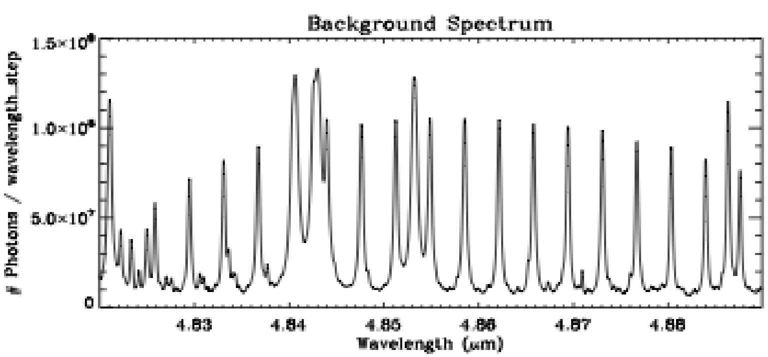
E-ELT simulations - CASE 1

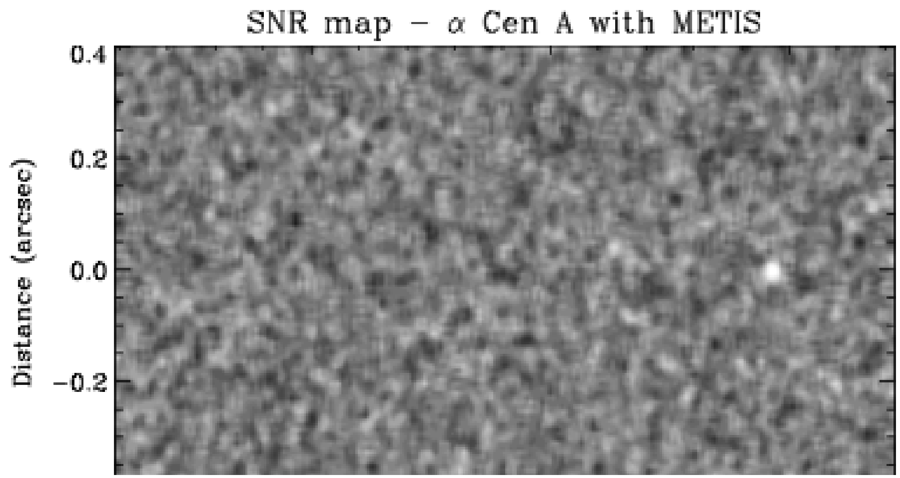
A Super-Earth in the Habitable Zone of Cen A at 4.85 um

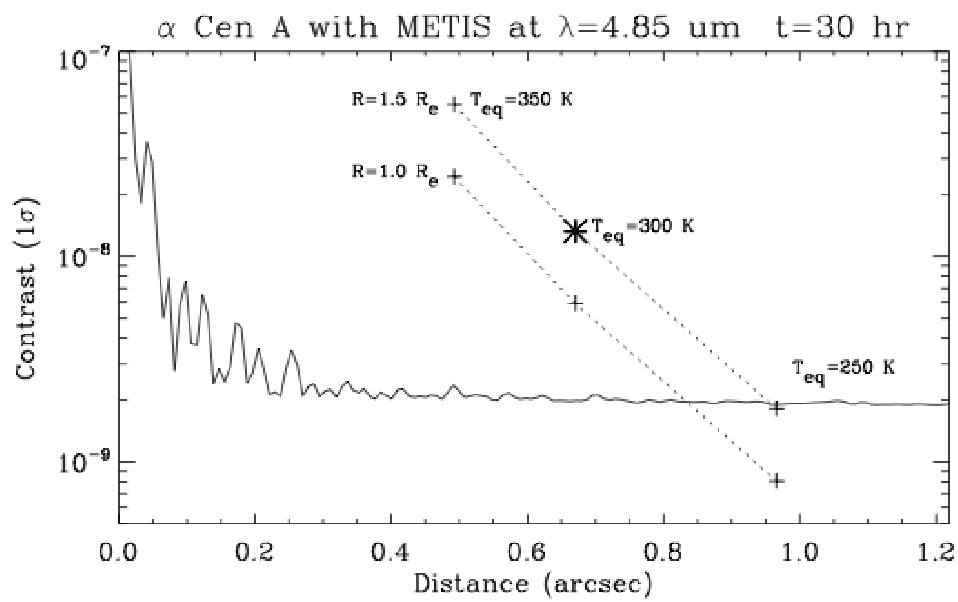
METIS+E-ELT PSF simulation in M-band (Strehl=0.9), baseline METIS set-up. 30 hours Earth-spectrum, T=300 K, 1.5 R_earth.







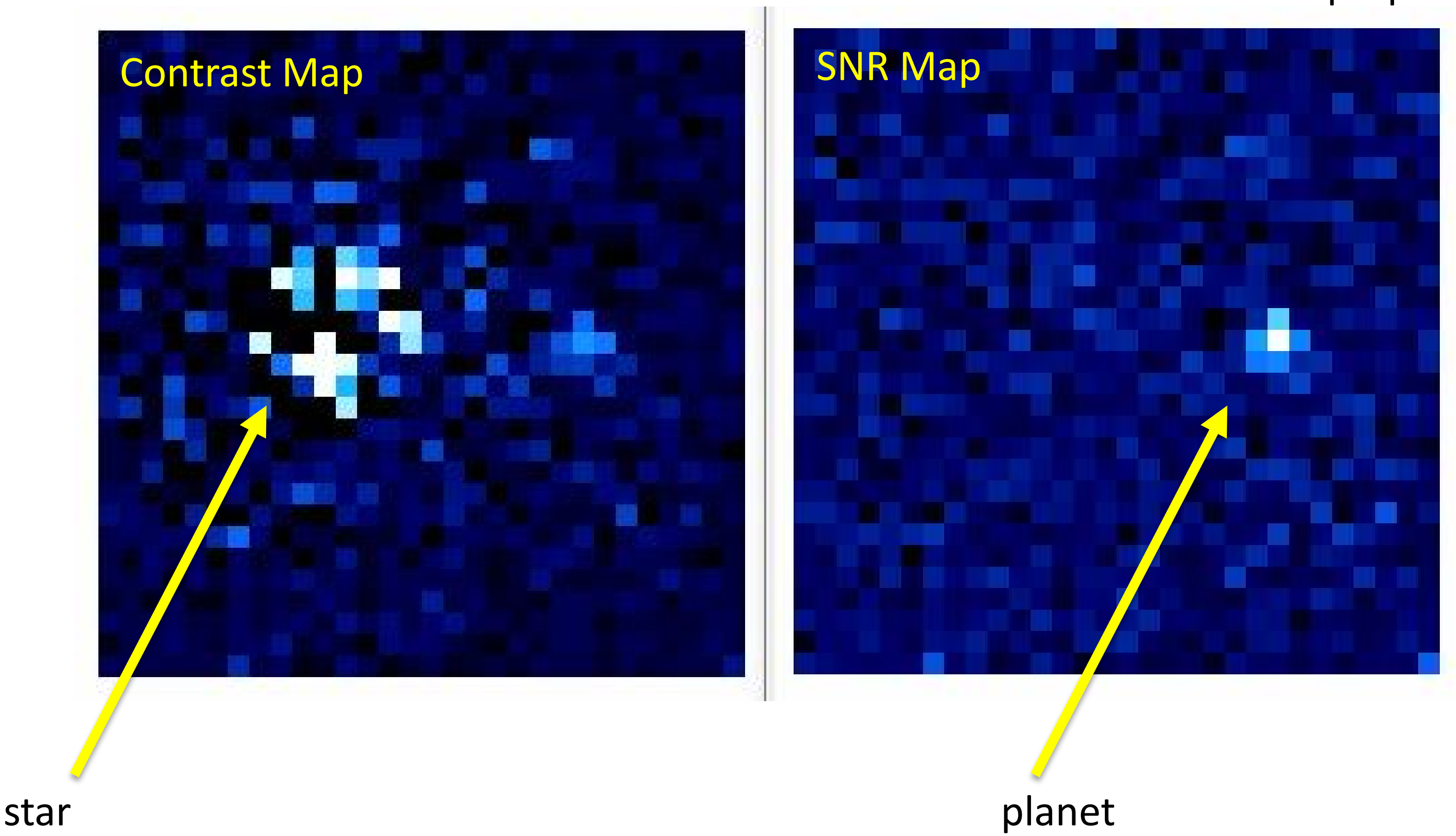




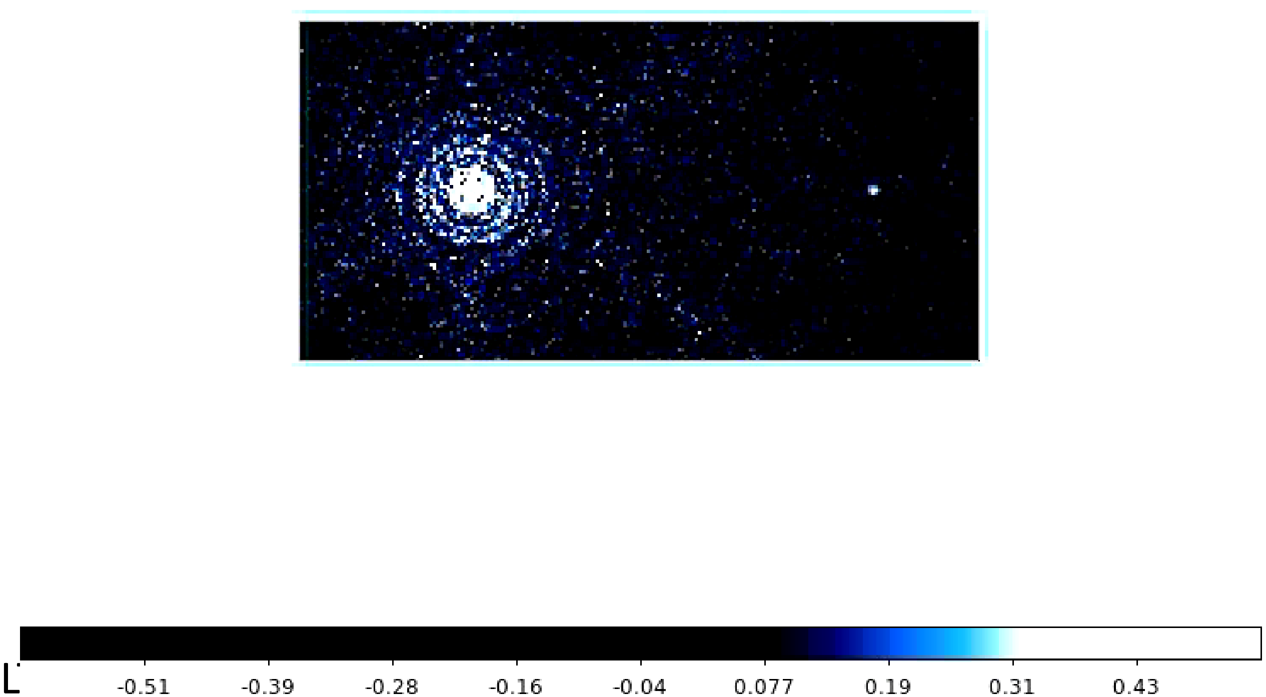
E-ELT simulations - Optical IFU (HIRES/PCS)
CASE 2: A Super-Earth in the Habitable Zone of Proxima

E-ELT (Strehl=0.5), 10 hours, R=100,000, $\Delta\lambda$ = 600 – 900 nm
Earth-spectrum, T=280 K, 2 R_earth.

Snellen et al. In prep



Planet spectrum is a copy of that of the star, but velocity shifted



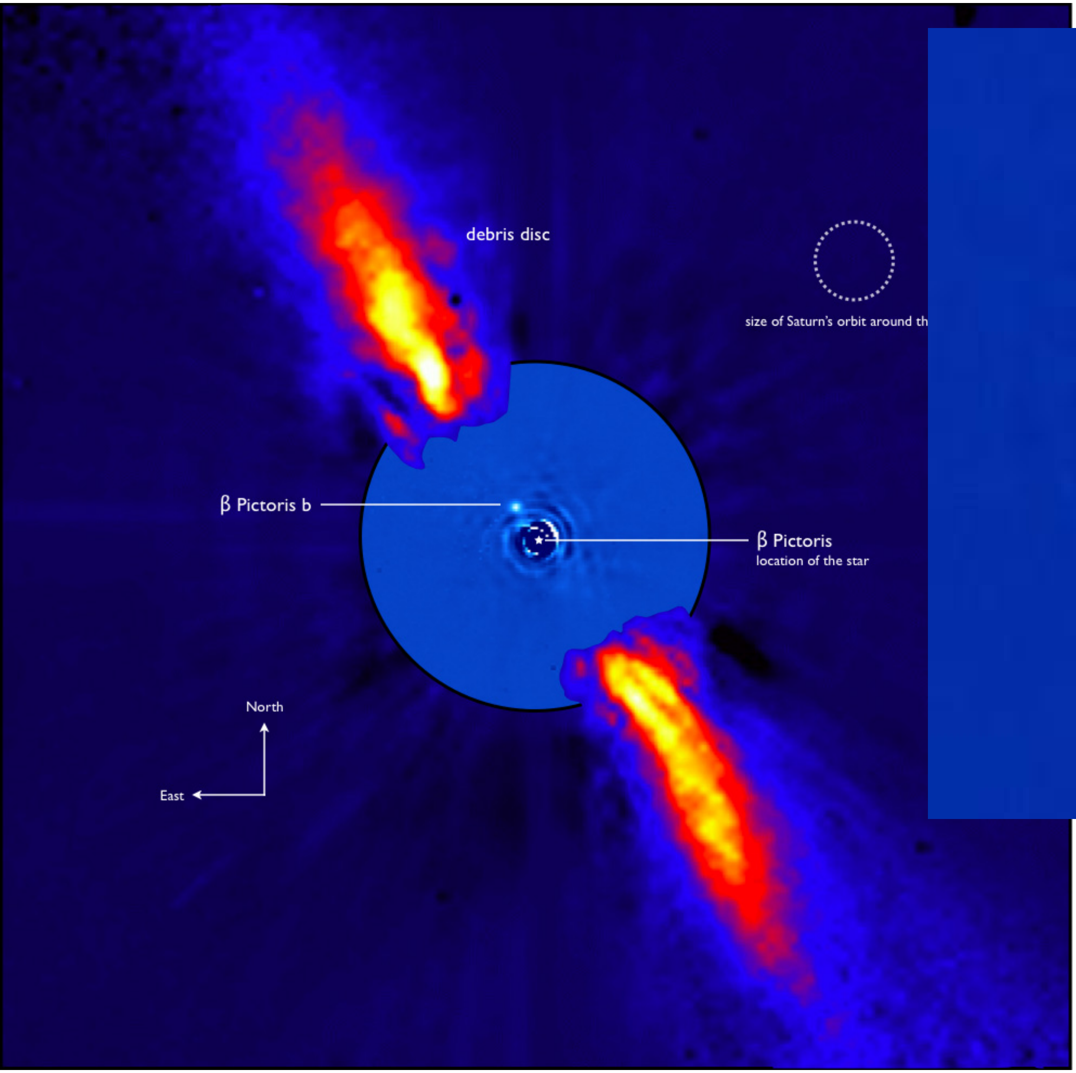
METIS @ E-EL

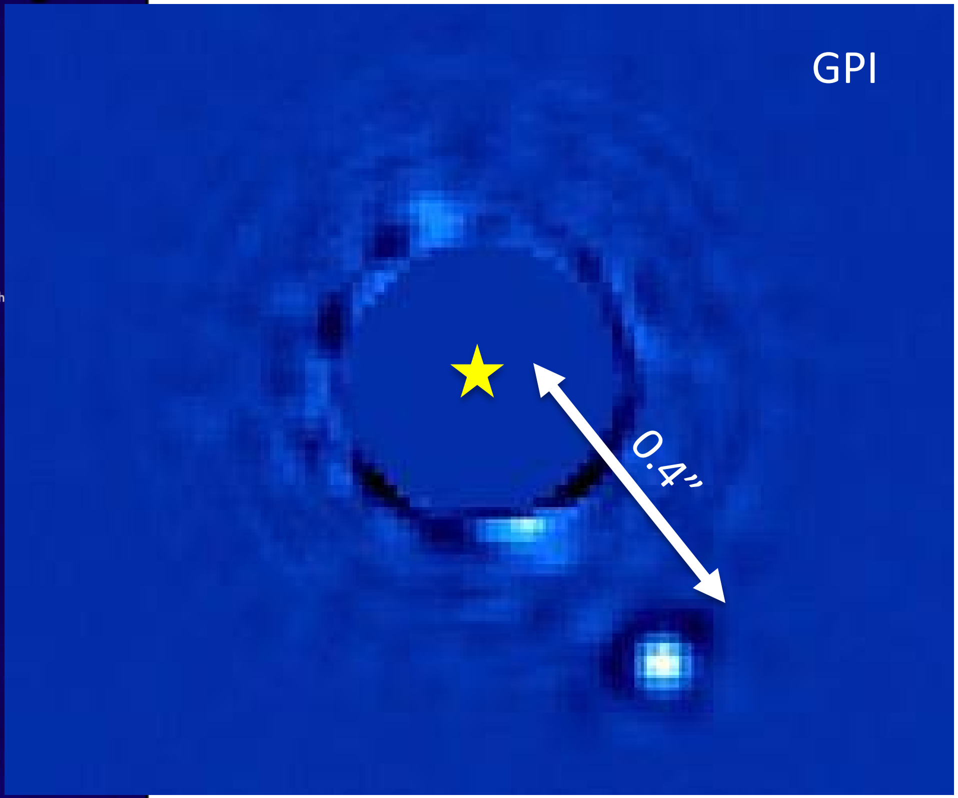
Can we test this with current instrumentation?

Snellen, Brandl, de Kok, Brogi, Birkby, Schwarz

Nature – May 2014

Beta Pictoris b – CRIRES@VLT

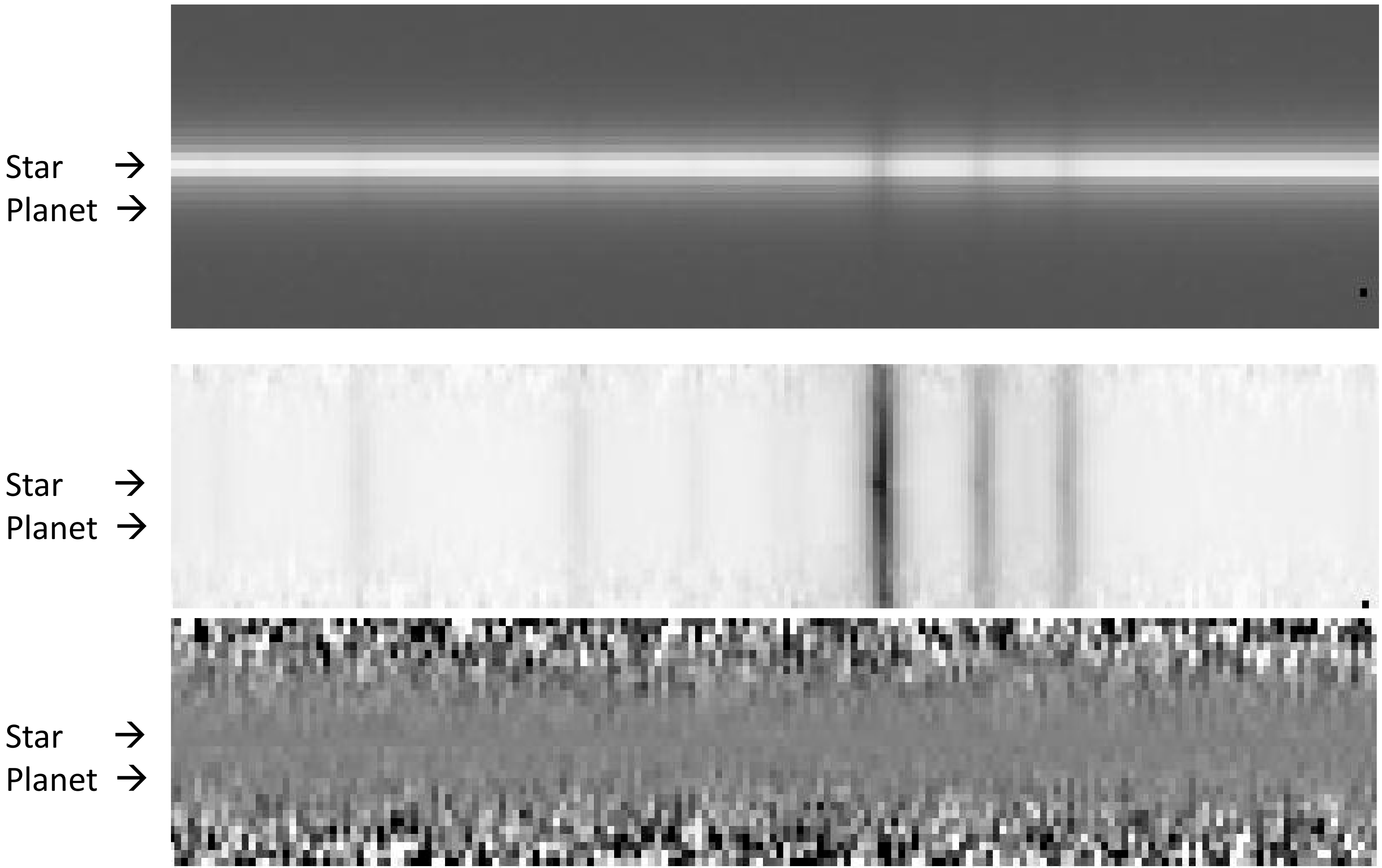




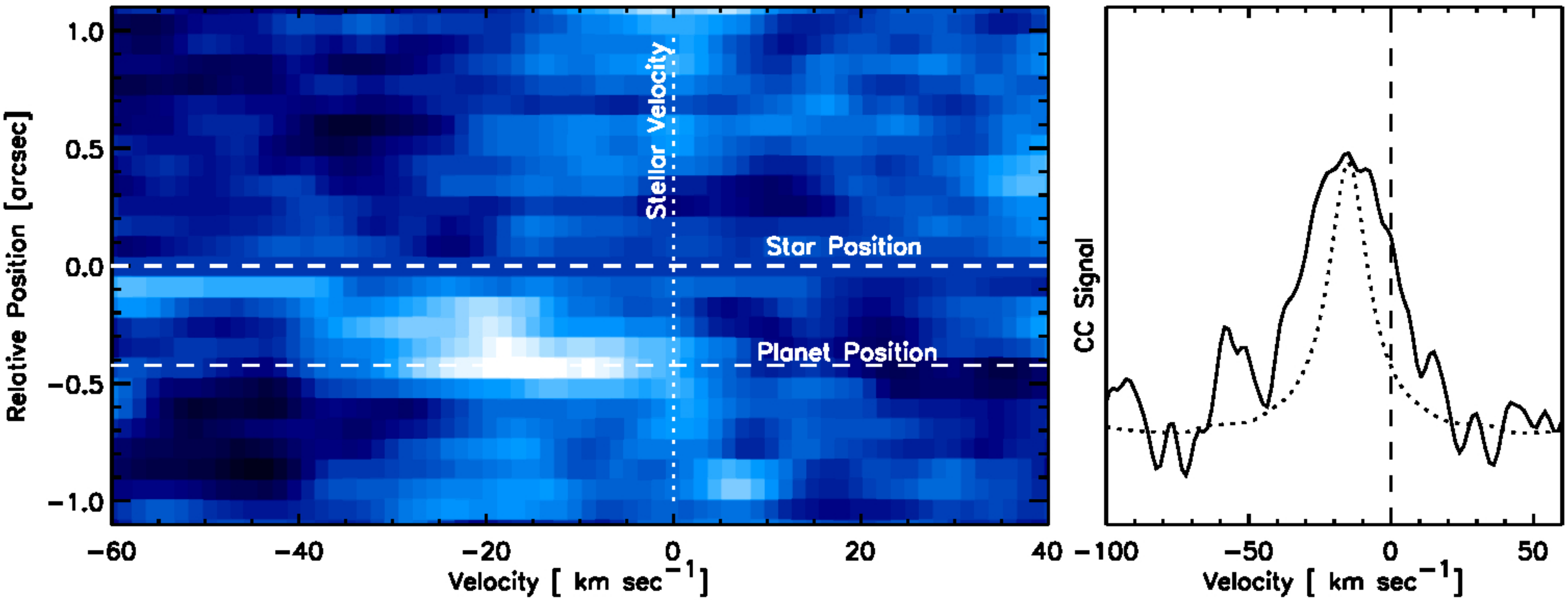
Mass = 11 (+-5) Mjup
Radius ~ 1.65 Rjup
Orbit: 17-20 years

1 hour DDT time (1-1.3” seeing)

22x4x10 seconds



Fast spin of a young extrasolar planet *Snellen et al. - embargoed*



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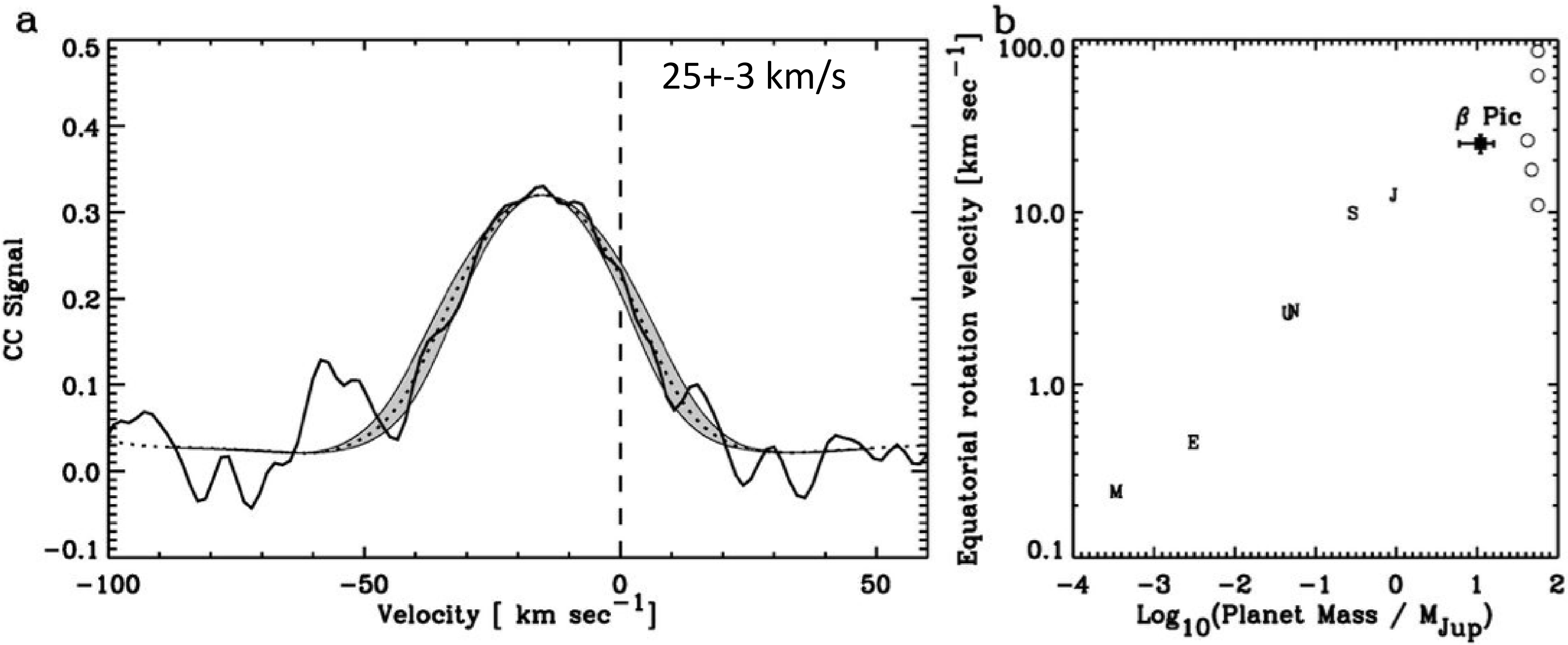
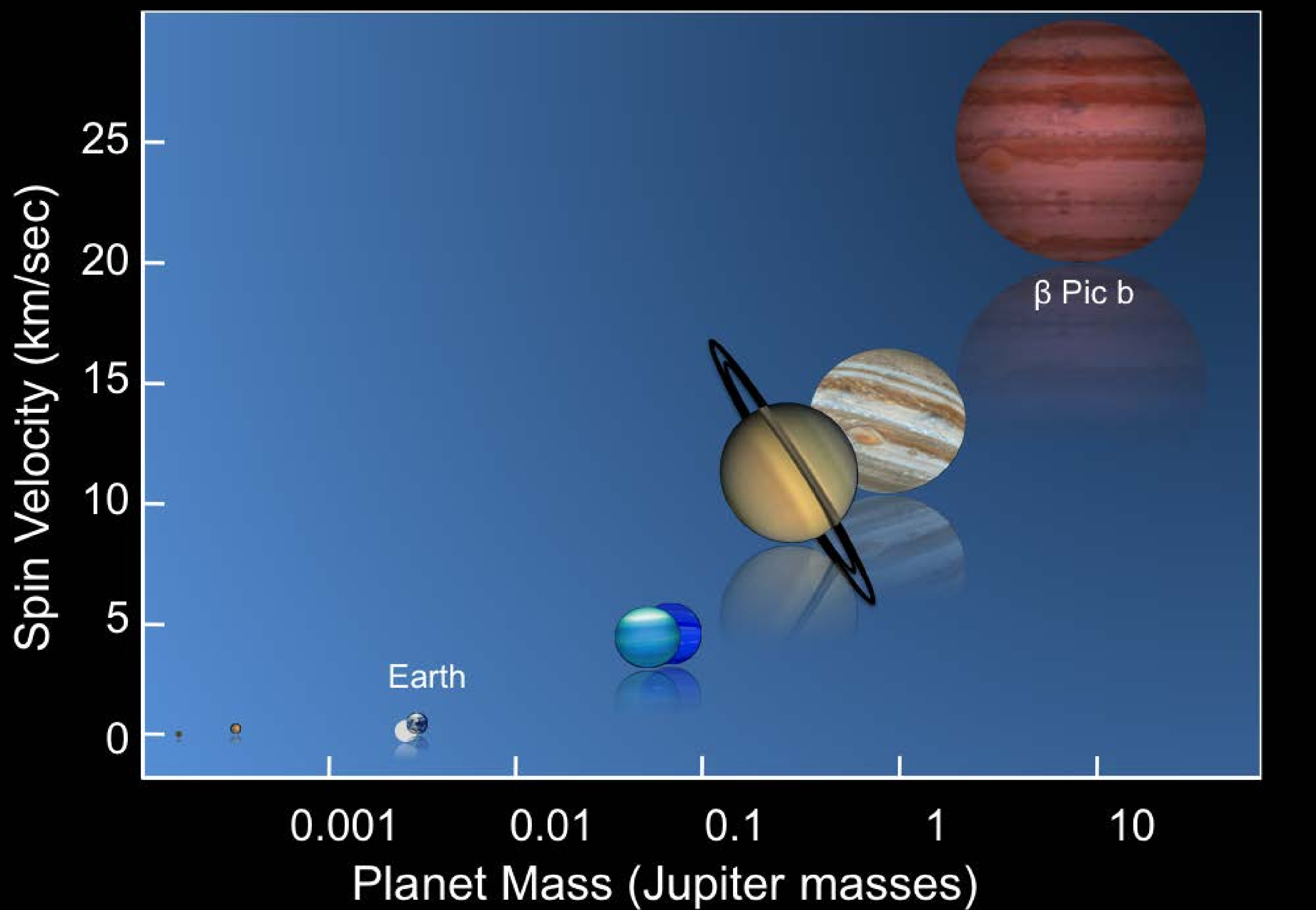


Length of Day on Beta Pictoris b = ~8 hours



Leiden University