

Exoplanets and the search for biological activity

Ignas Snellen, Leiden University



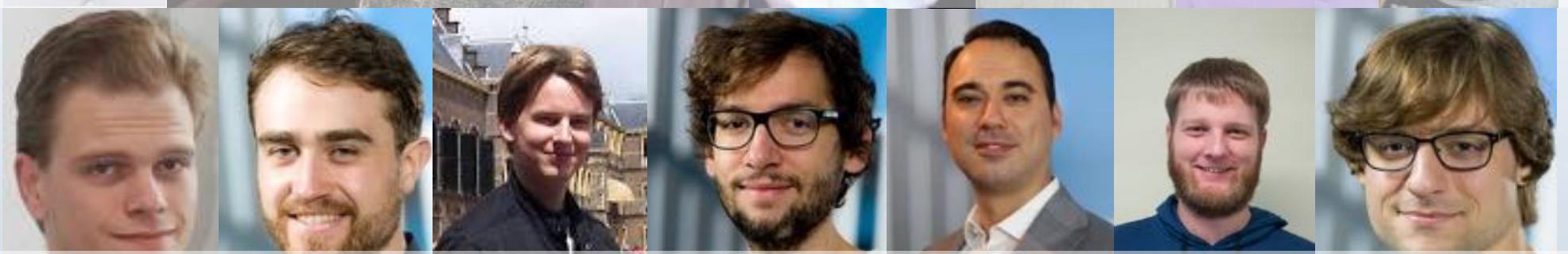
Matteo Brogi, Henriette Schwarz,, Jayne Birkby, Remco de Kok, Simon Albrecht, Remko Stuik, Gilles Otten, Jens Hoeijmakers, Andrew Ridden-Harper, Sebastiaan Haffert, Geert-J. Talens, Javi Alonso, Paul Molliere, Paul Wilson, Patrick Dorval, Dilovan Serindag Yapeng Zhang, Aurelien Wyttenbach, Aurora Kesseli



Thank you – team!



Matteo Brogi Remco de Kok Henriette Schwarz Simon Albrecht Jayne Birkby Vincent Van Eijlen Remko Stuik Ernst de Mooij



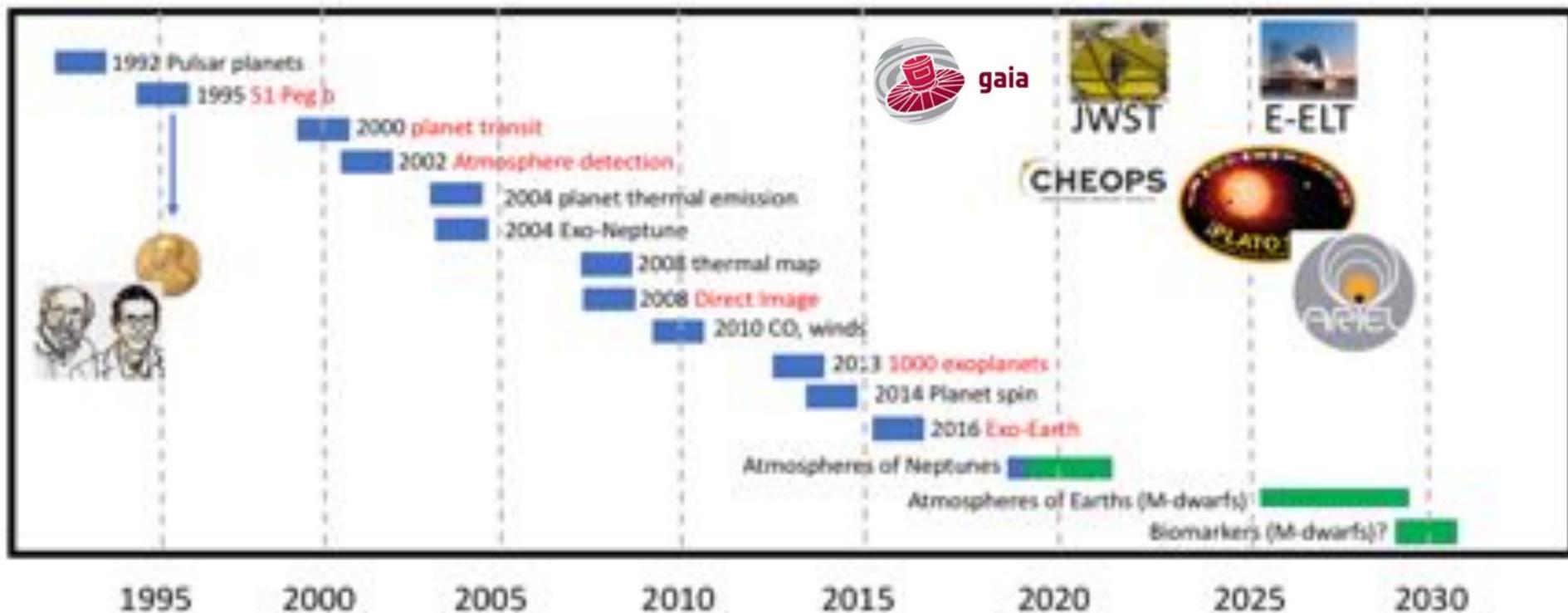
Jens Hoeijmakers Ridden-Harper Gilles Otten Paul Mollière Javi Alonso-Floriano Geert-Jan Talens Sebastiaan Haffert



Anna-Lea Lessage Julien Spronck Aurelien Wyttenbach Dilovan Serindag Aurora Kesseli Patrick Dorval Paul Wilson Yafen Zhang

A Revolution in Exoplanet Research

EXOPLANET REVOLUTION



The place of Earth & our Solar system in the Universe

- How do planets form?
- What ranges of architectures of planetary systems exist?
- How does our Solar System fit into this context?
- Do other life-bearing planets exist?



What we learn from the Solar System

Planets show an immense complexity and diversity

Gas giants:

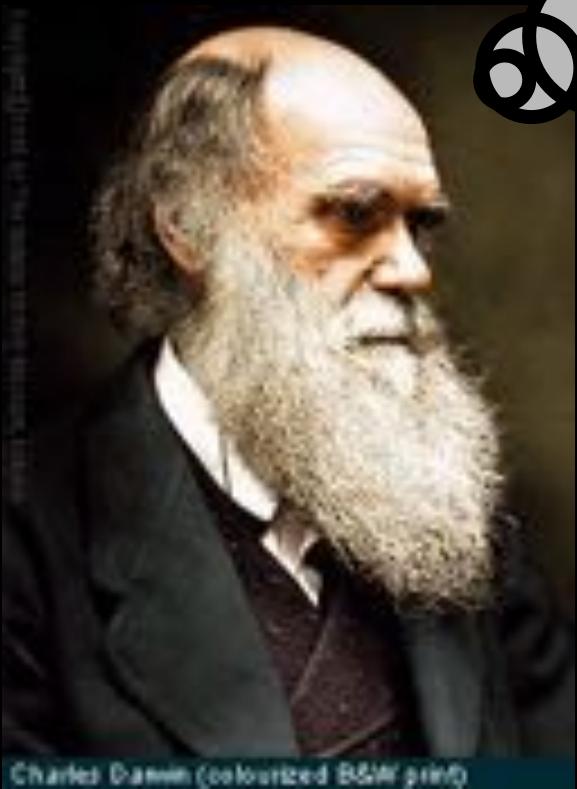
H₂-dominated; clouds; strong zonal flows; storms



Solar system planets show an immense complexity and diversity

Venus	Earth	Mars	Titan
Super-rotating, CO ₂ -based Opaque sulfuric acid clouds	Partially clear, N ₂ -based biotic oxygen	Tenuous CO ₂ varying trace-amount of methane	Very cold, N ₂ - based, opaque methane/ethane clouds

Solar System:



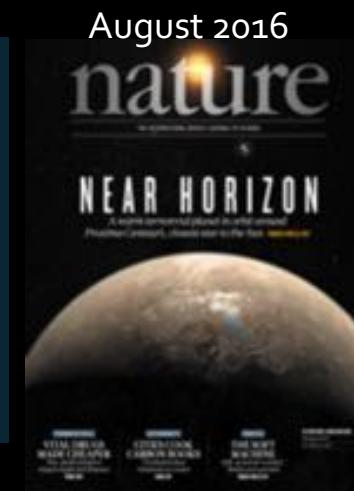
Trying to comprehend Tree of Life
using three animals”

25 years of exoplanet studies

- Thousands of exoplanets found
- Diversity even larger than in Solar System
- 1:10 stars host Jupiter-mass planets
- 1:5 stars host Neptune-mass planets
- Most stars host Earth-mass planets



Milestone: First temperate, rocky planets



Proxima b (Anglada-Escudé et al. 2016); TRAPPIST-1 system (Gillon et al. 2017)

Atmospheric Characterization

1. Does a planet have an atmosphere?
2. What is its climate like?
3. What are the main constituents of the atmosphere? [e.g. H₂, N₂, CO₂?]
4. Do we understand the formation, evolution and current physical & chemical processes in the atmosphere, and geology?
5. Does the planet contain water?
6. Can we detect biosignatures? E.g. O₂, O₃, CH₄?
7. *Are the biosignatures due to biological activity?*

Biosignature: *an effect of biological activity on its environment, detectable at interstellar distances*

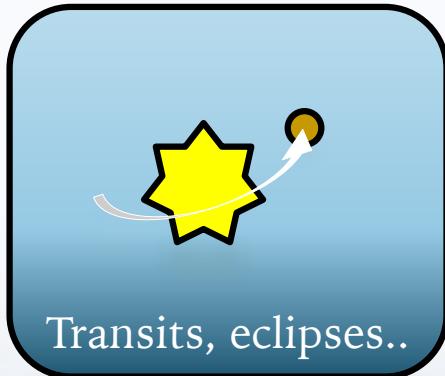
Requirements: *Surface ocean? geological activity? magnetic field?*

Life detection will always require understanding of evolutionary and geophysical context of a planet



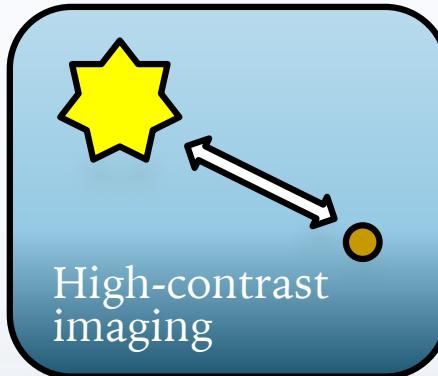
Exoplanet atmosphere observing techniques

Time differential

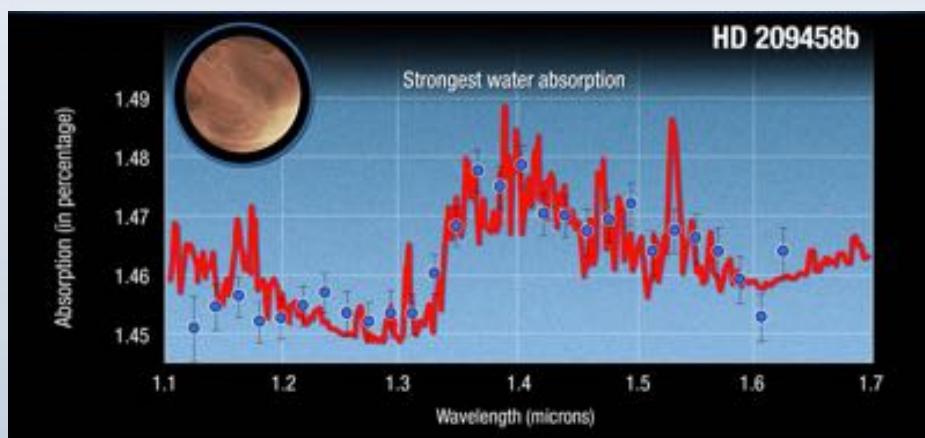


Transits, eclipses..

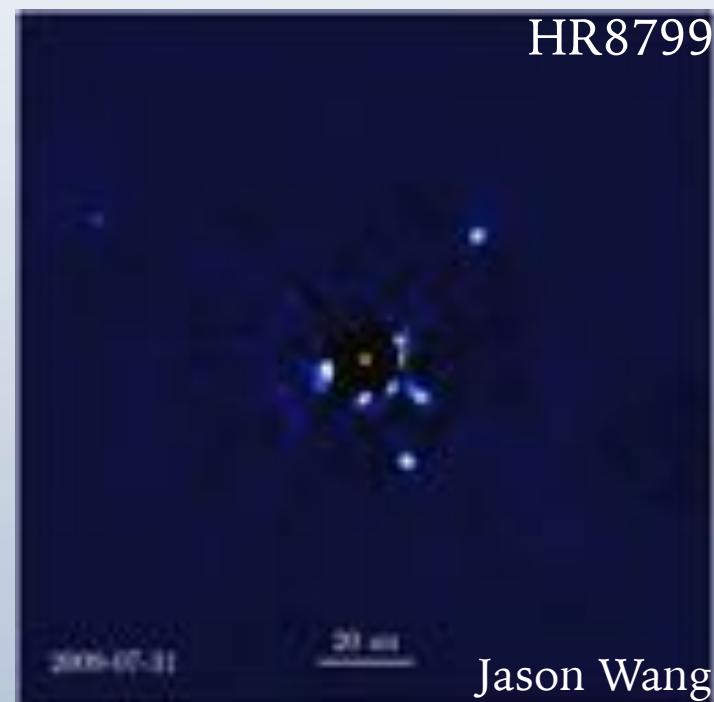
Angular differential



High-contrast imaging

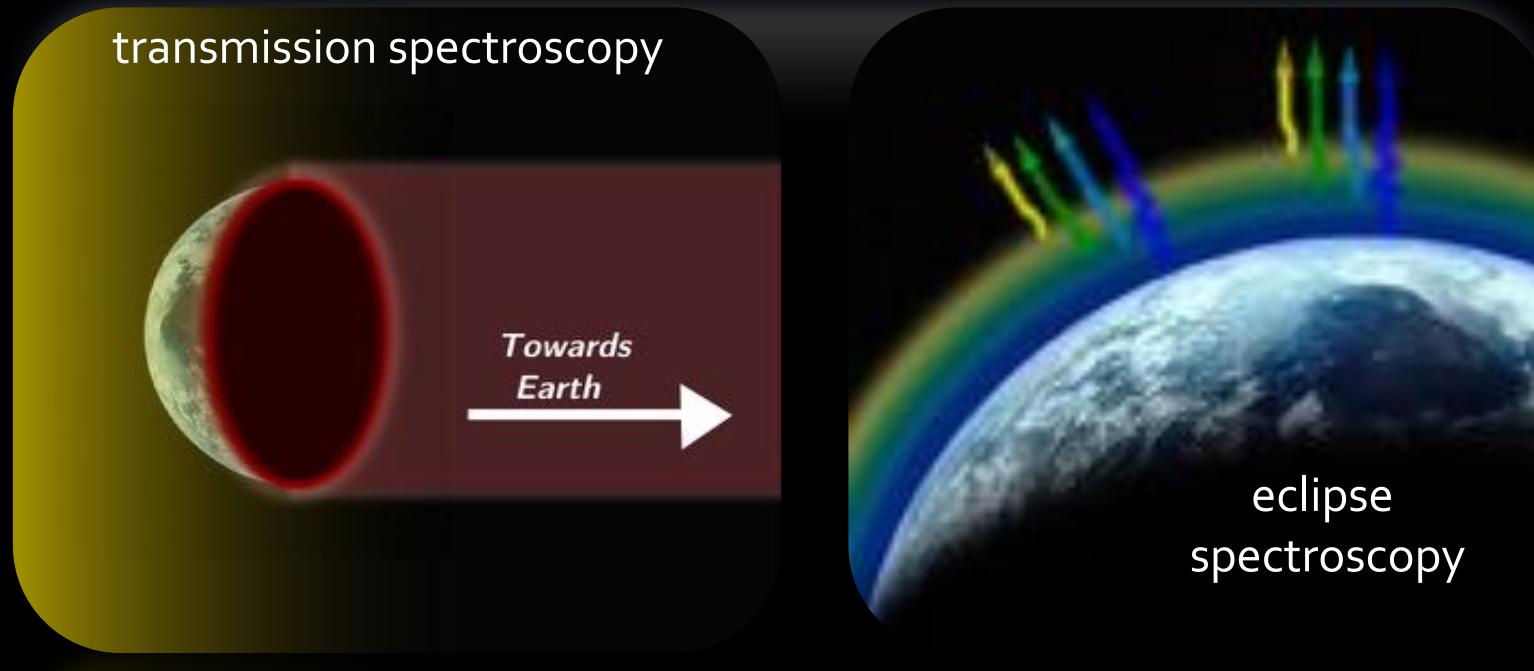
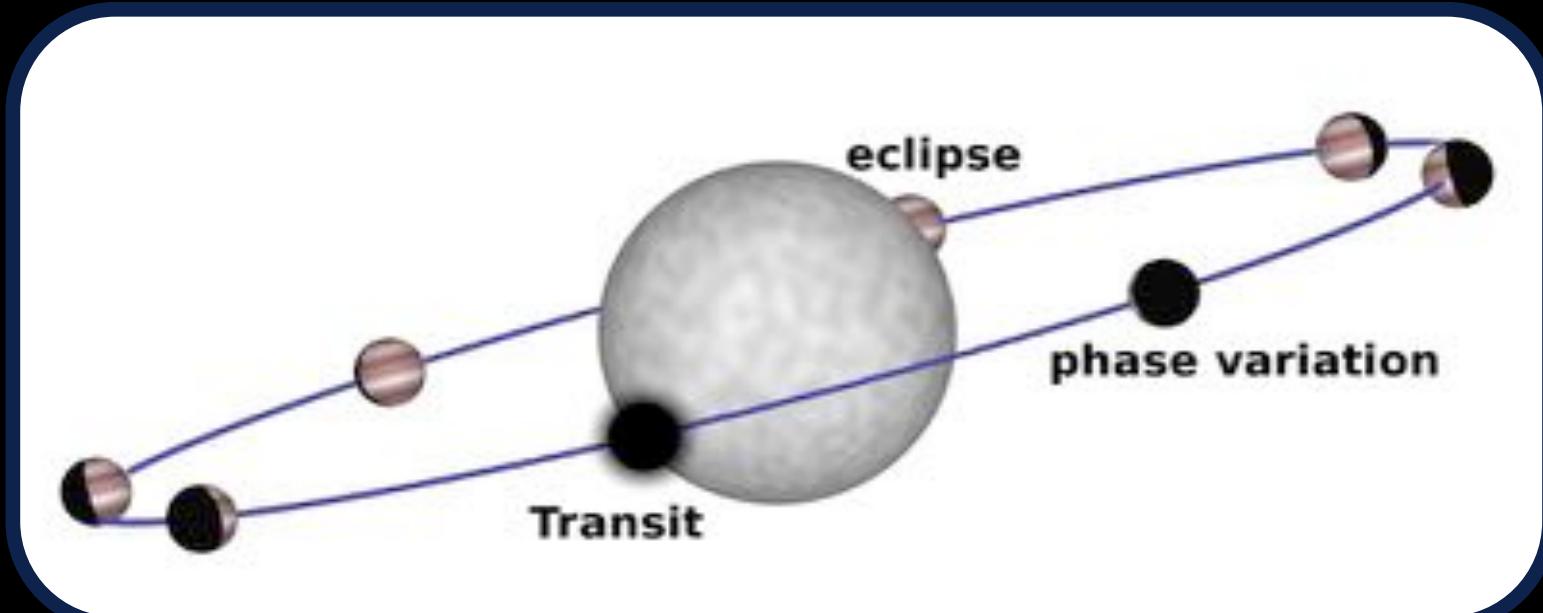


WFC3@HST (Deming et al. 2013)

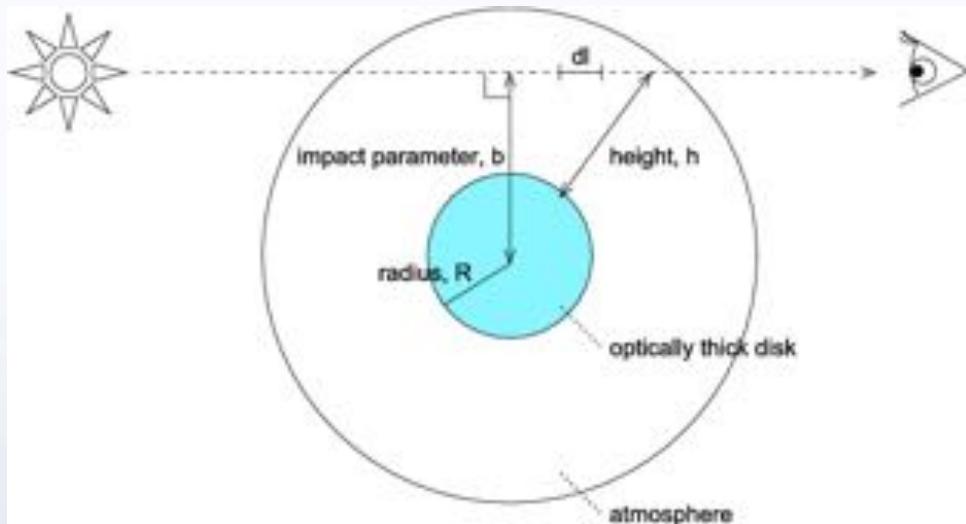


Jason Wang

“time-differential” methods



Transmission spectroscopy

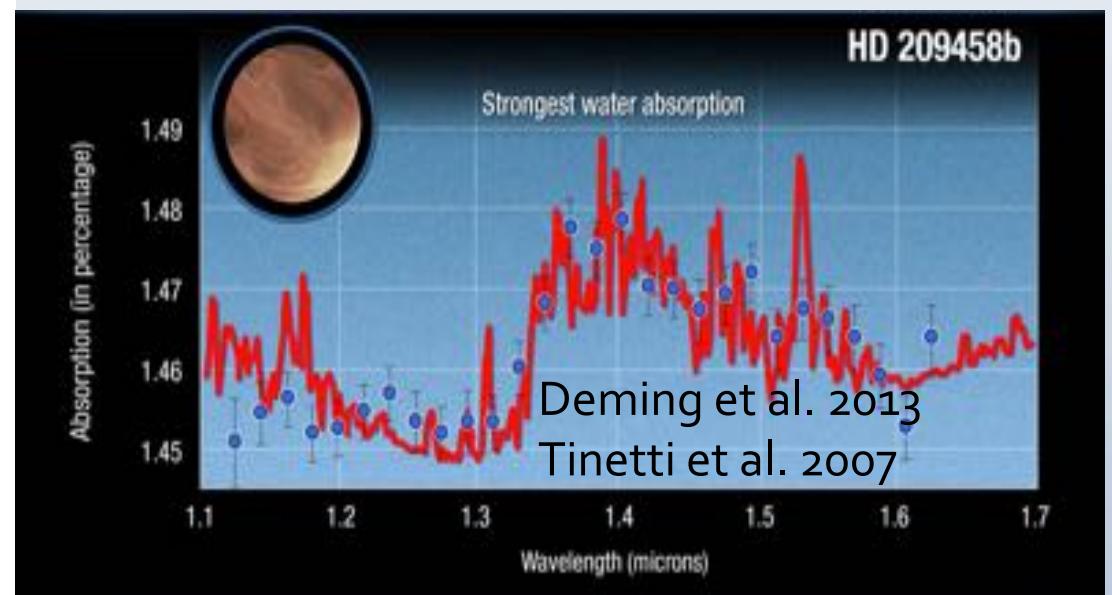
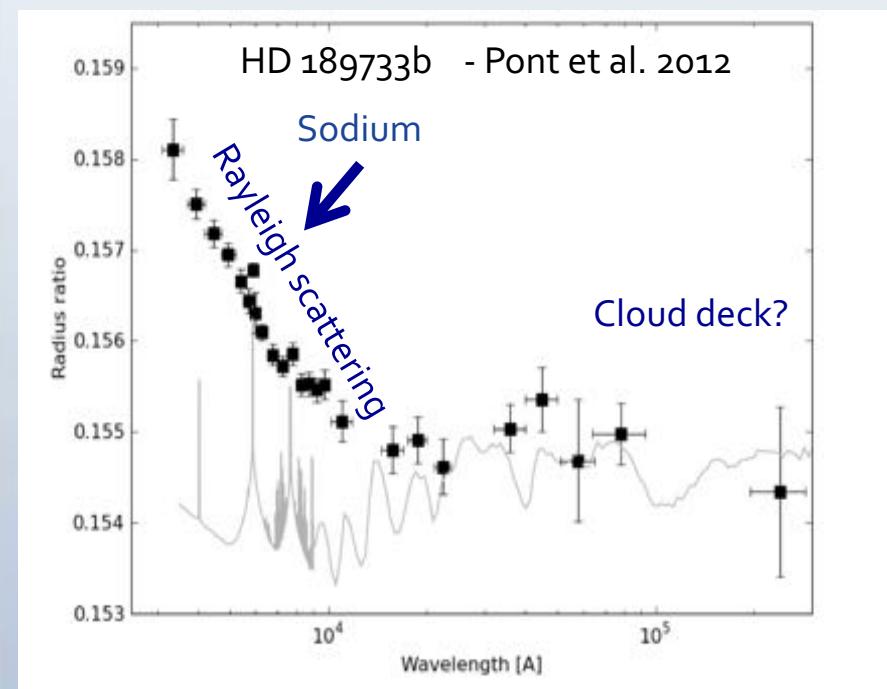


Scale Height,

$$H \sim \frac{T}{\mu g}$$

$$\text{Contrast}, \quad F_c \sim \frac{2 \pi R_p H}{\pi R_s^2}$$

$$H_{\text{HJ}} = \sim 500 \text{ km}, \quad F_c = 10^{-3} \dots 10^{-4}$$



Transmission spectroscopy

What has been observed today?

- ✓ Molecular absorption: CO, H₂O, TiO, (CH₄?, CO₂?)
- ✓ Atomic absorption: Na, K, Fe, Ti
- ✓ Raleigh scattering
- ✓ Hazes/clouds
- ✓ mean particle mass (through H)
- ✓ Global atmospheric winds
- ✓ Mean vertical temperature structure
- ✓ Longitudinal atmosphere structure – Jet streams

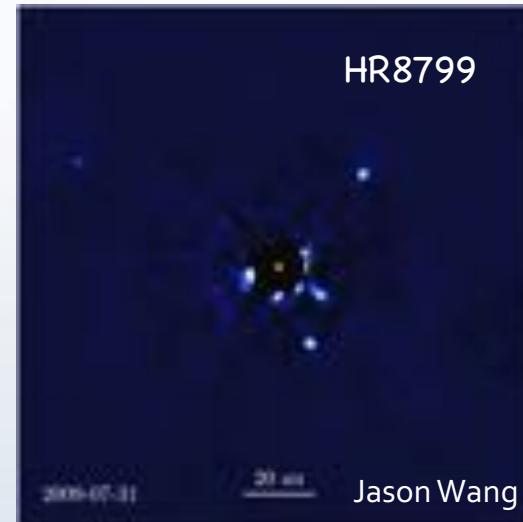
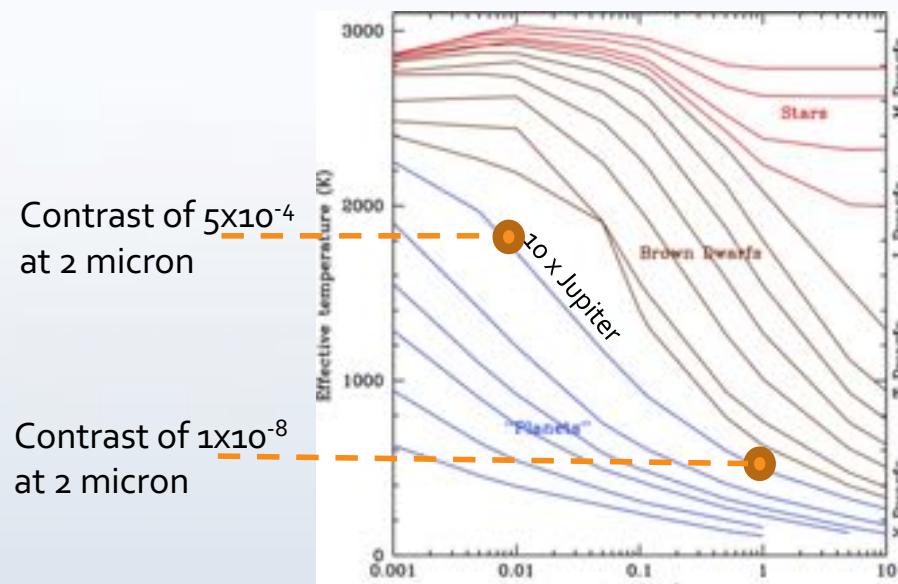
Works best for large, hot
planets transiting small stars –
with light-particle atmosphere

The **Earth** is a small, cool
planet orbiting a large star –
heavy-particle atmosphere

Great future ahead with the JWST

What can we observe today with high-contrast imaging?

Young gas giants on wide orbits are the easiest accessible



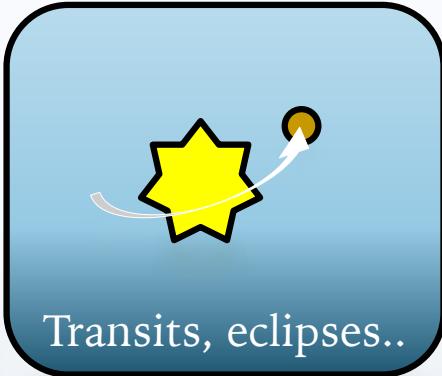
- ✓ Molecular absorption: CO, H₂O, (CH₄?, CO₂?)
- ✓ Clouds cover (variability)
- ✓ Planetary spin
- ✓ Mean vertical temperature structure

Works best for large, hot planets far away from their host stars

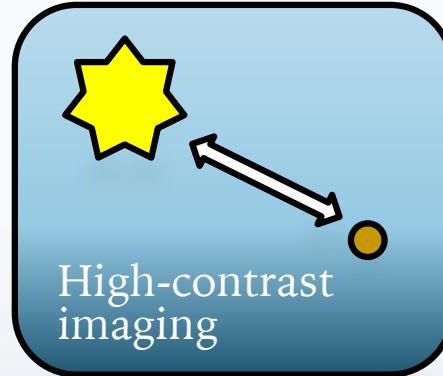
The **Earth** is a small, cool planet orbiting close to its star

Exoplanet atmosphere observing techniques

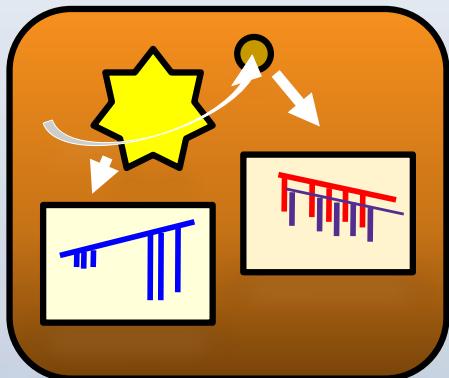
Time differential



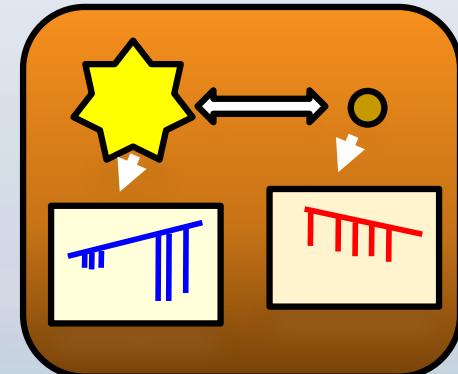
Angular differential



Time + spectral
differential

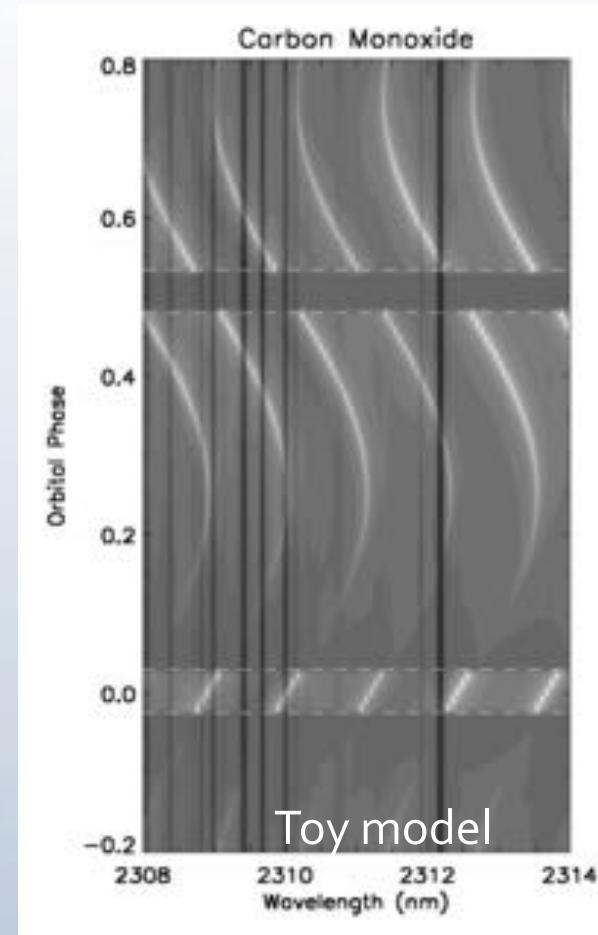
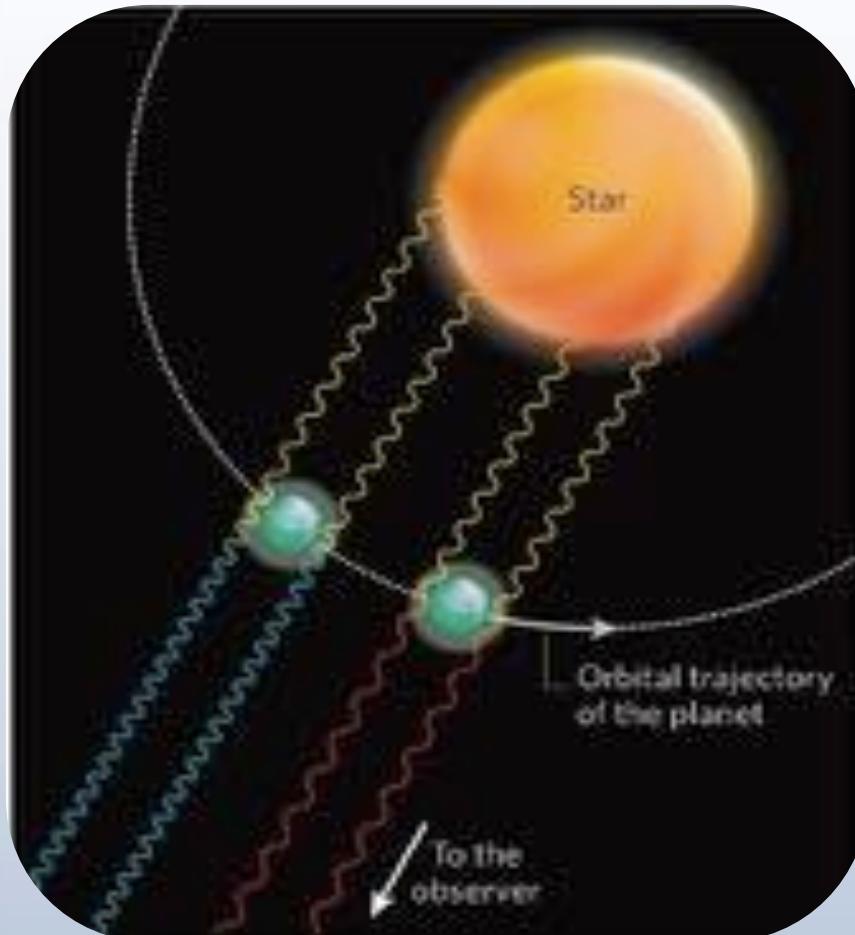


Angular + spectral
differential



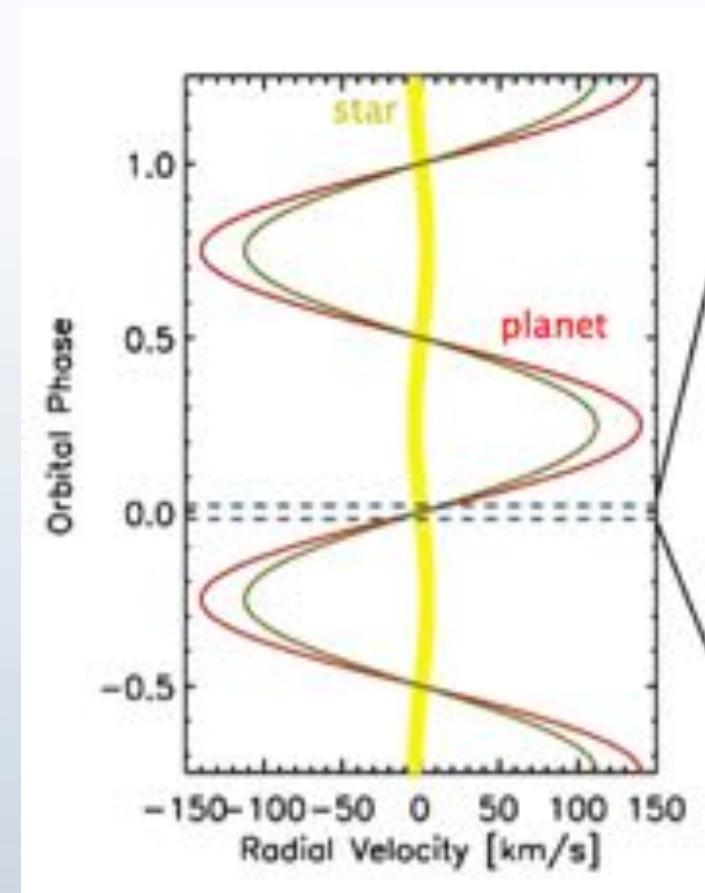
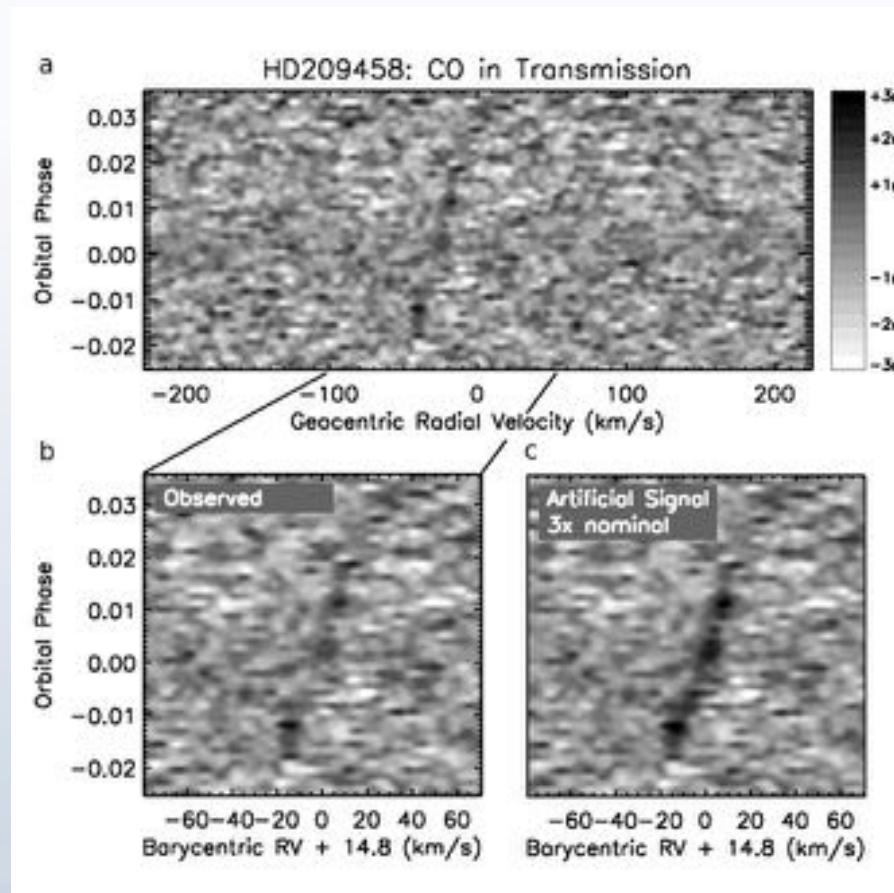
Ground-based High-dispersion spectroscopy

- At $R=100,000$ molecular bands are resolved in tens of individual lines
- Strong doppler effects due orbital motion of the planet (up to >150 km/s).
- Moving planet lines are distinguished from stationary telluric + stellar lines



Snellen et al. *Nature* 2010; Brogi et al. *Nature* 2012; Snellen et al. *Nature* 2014; Nortmann et al. *Science* 2018; haffert et al. *Nature Astr.* 2019

CO in transmission in HD209458b (CRIRES@VLT) (Snellen et al. Nature 2010)

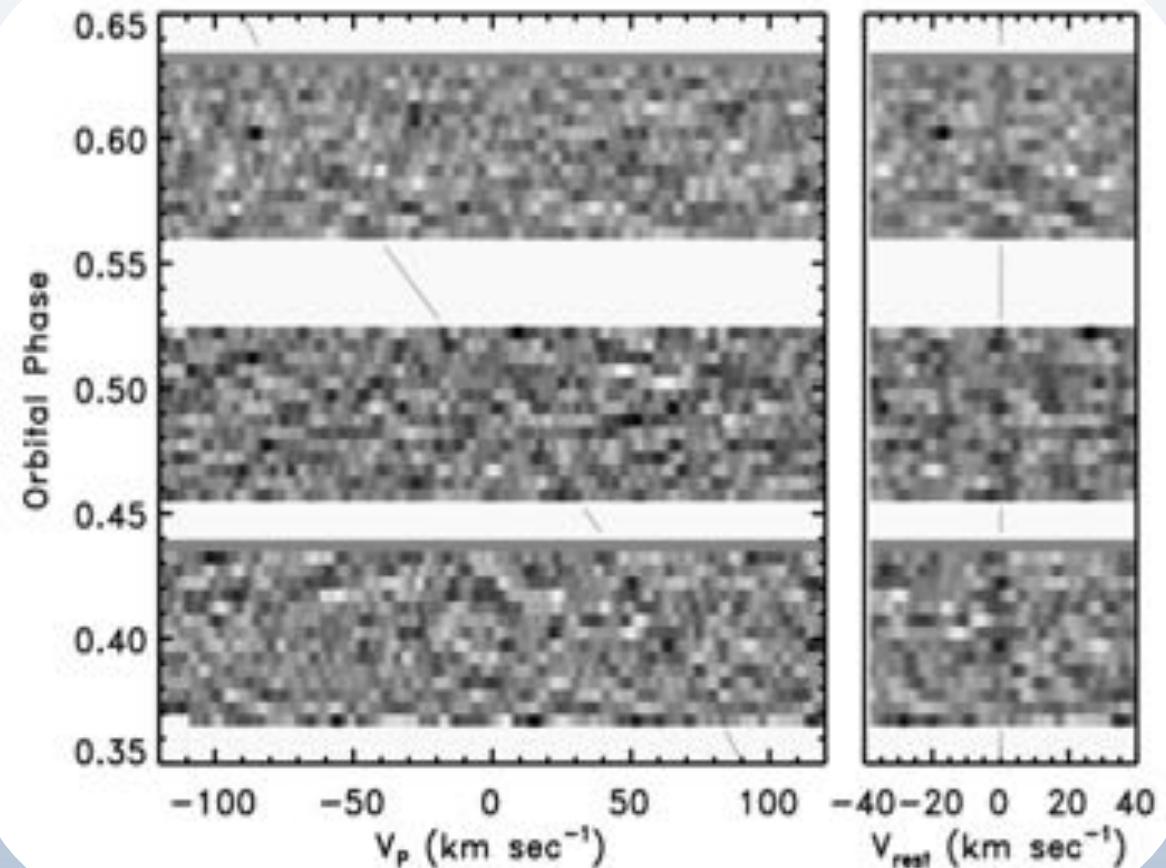
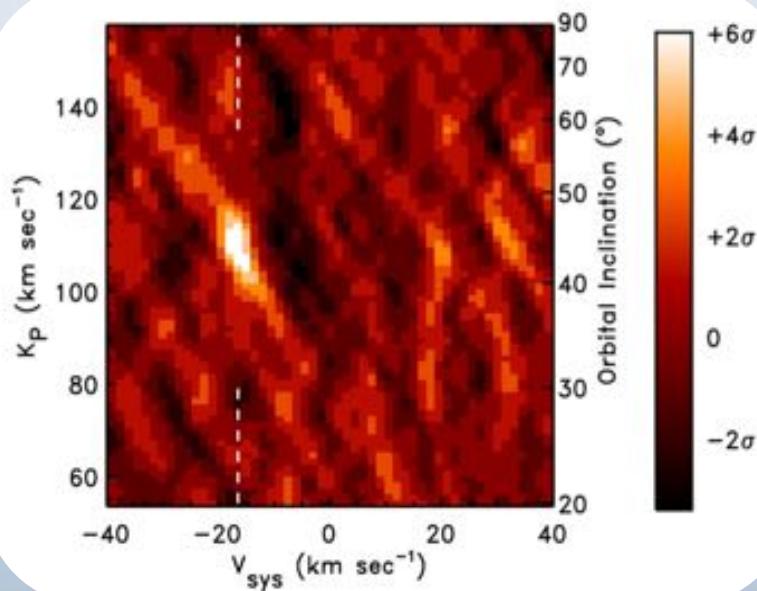


- Reveals planet orbital velocity
- Solves for masses of both planet and star (model independent)
- Evidence for blueshift (high altitude winds?)

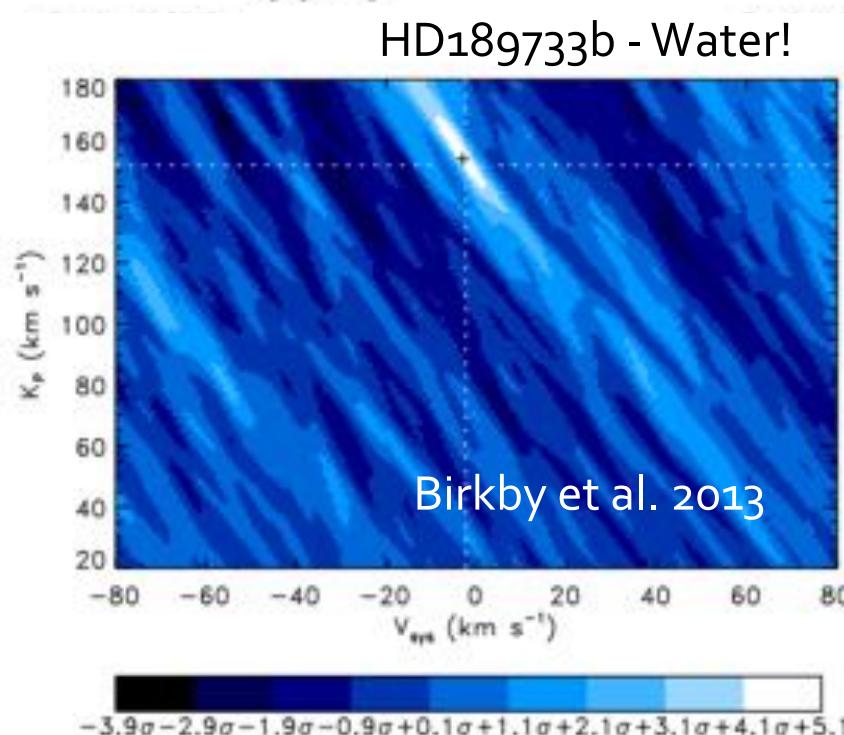
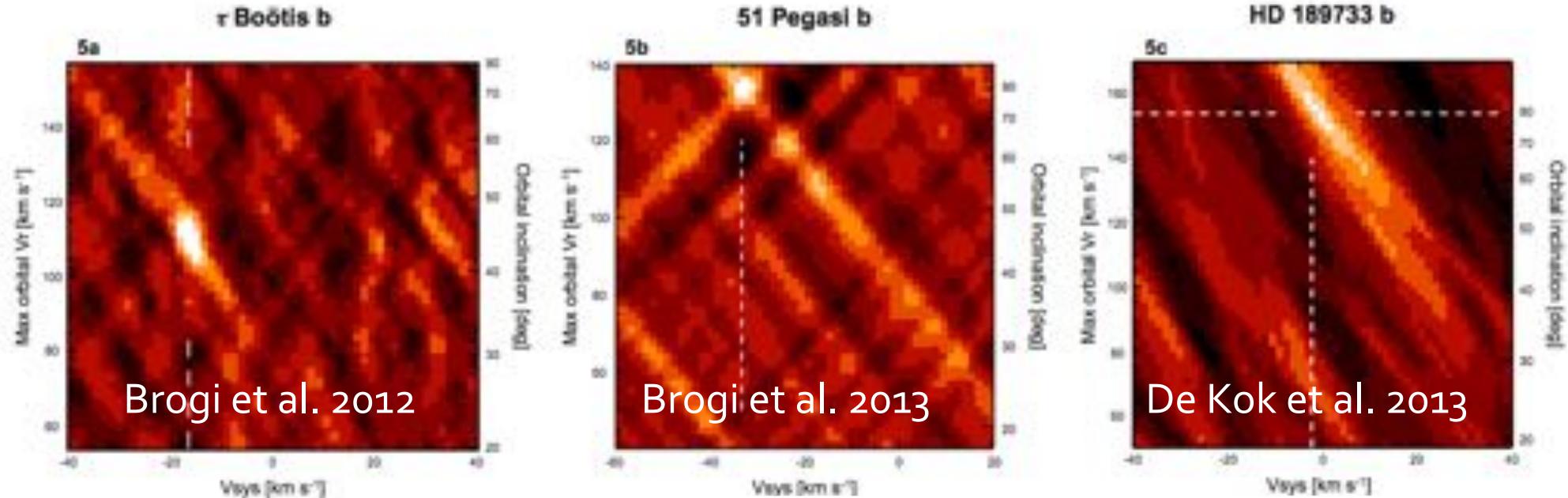
CO in dayside spectrum of tau Bootis b (CRIRES@VLT)

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

First detection of non-transiting
HJ → inclination, mass



CO in dayside spectra of hot Jupiters



CRIRES@VLT Upgrade (2020/Q1)
→
>10x larger wavelength coverage
CO, H₂O, CH₄, NH₃, H₃ +,.....

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

TiO in emission with Subaru

Nugroho et al (2017)

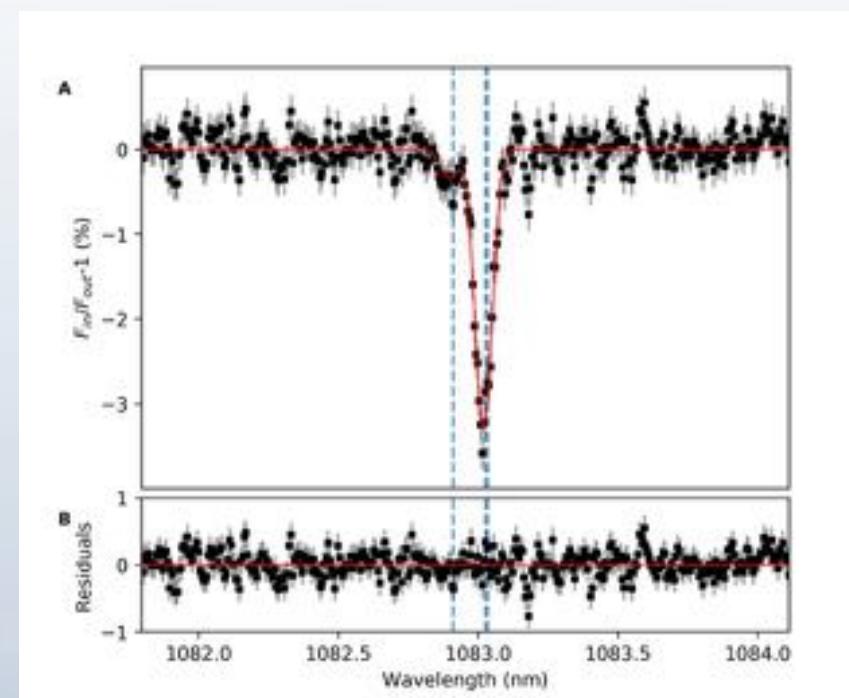
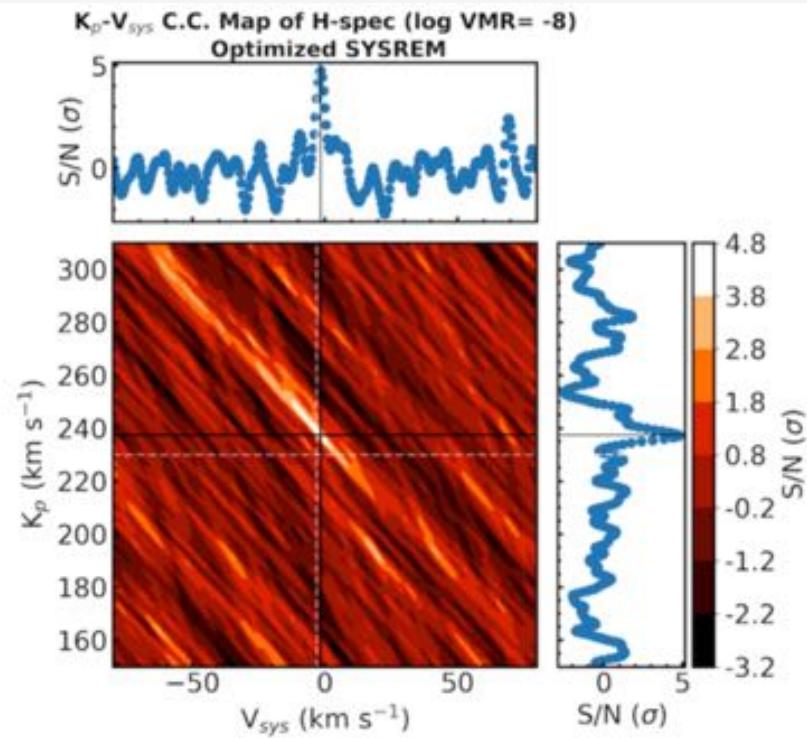
R=160.000

Thermal dayside of WASP-33b

Evaporating atmospheres in helium with CARMENES

Nortmann et al. *Science*, 2018

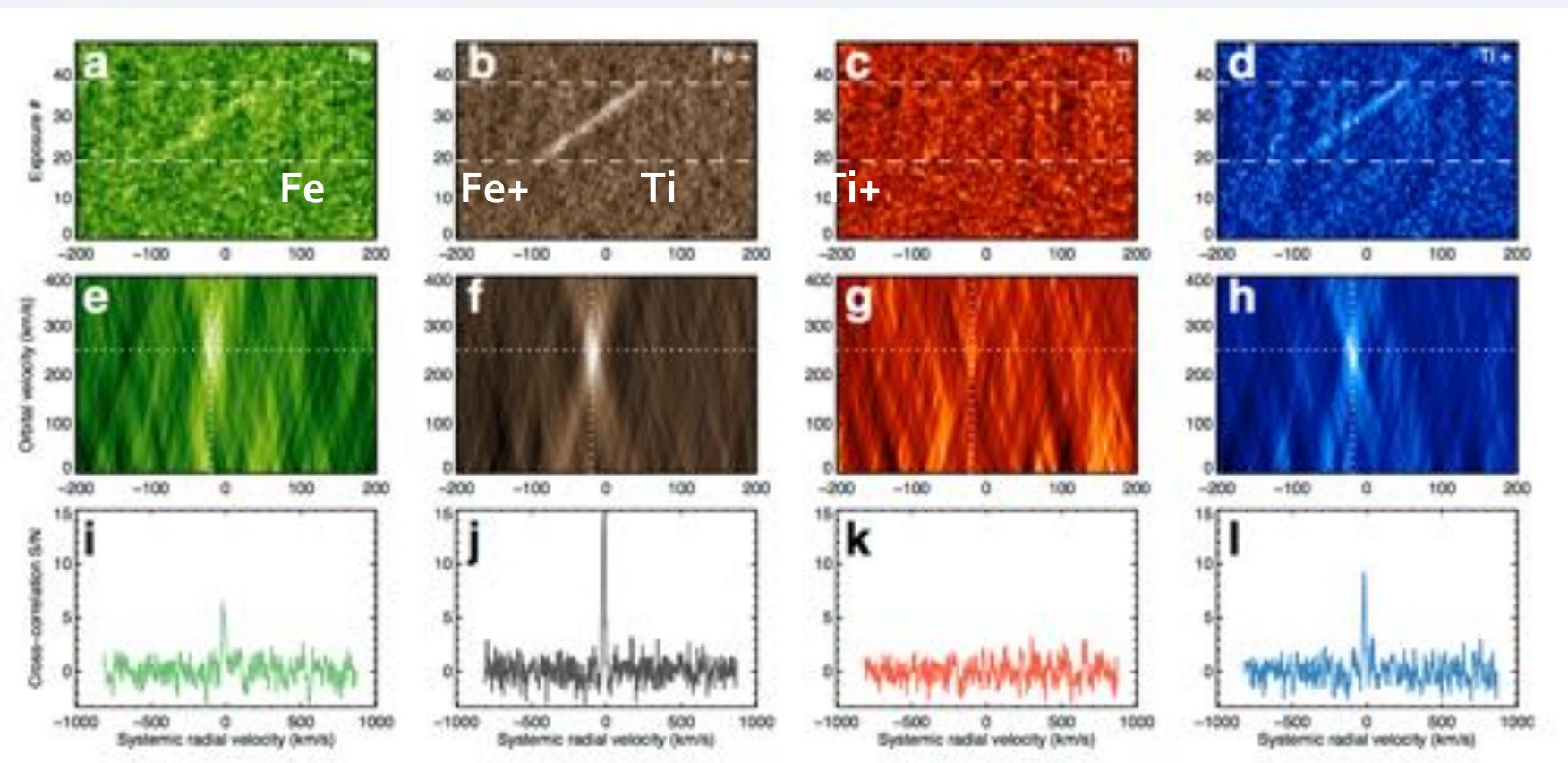
CARMENES spectrograph – WASP-69b



Also: Oklopčić & Hirata 2018; Spake et al. 2018; Salz et al. 2018; Allart et al. 2018; 2019)

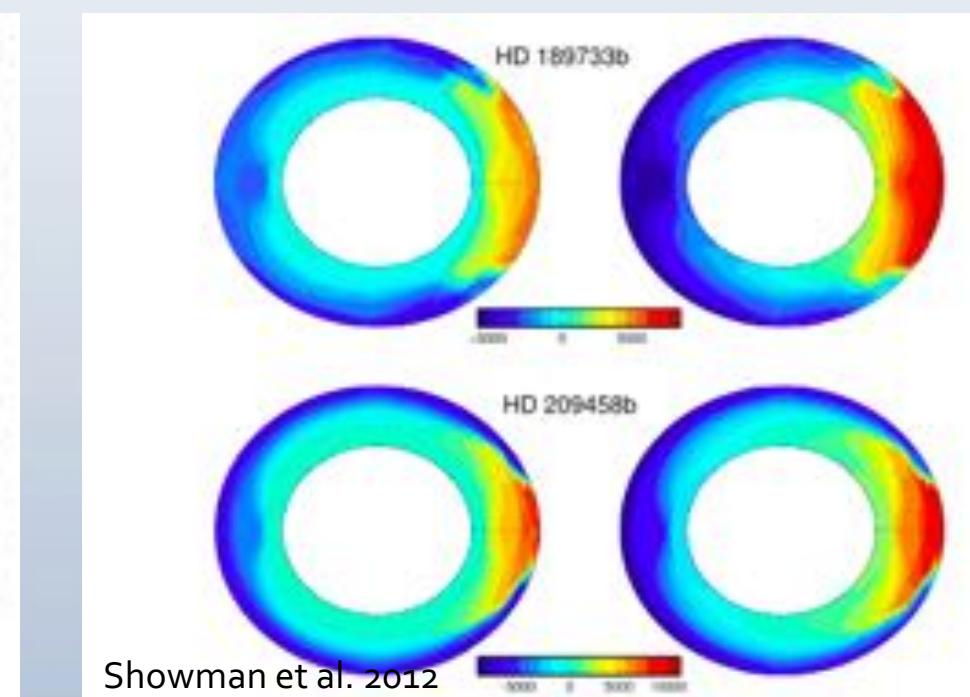
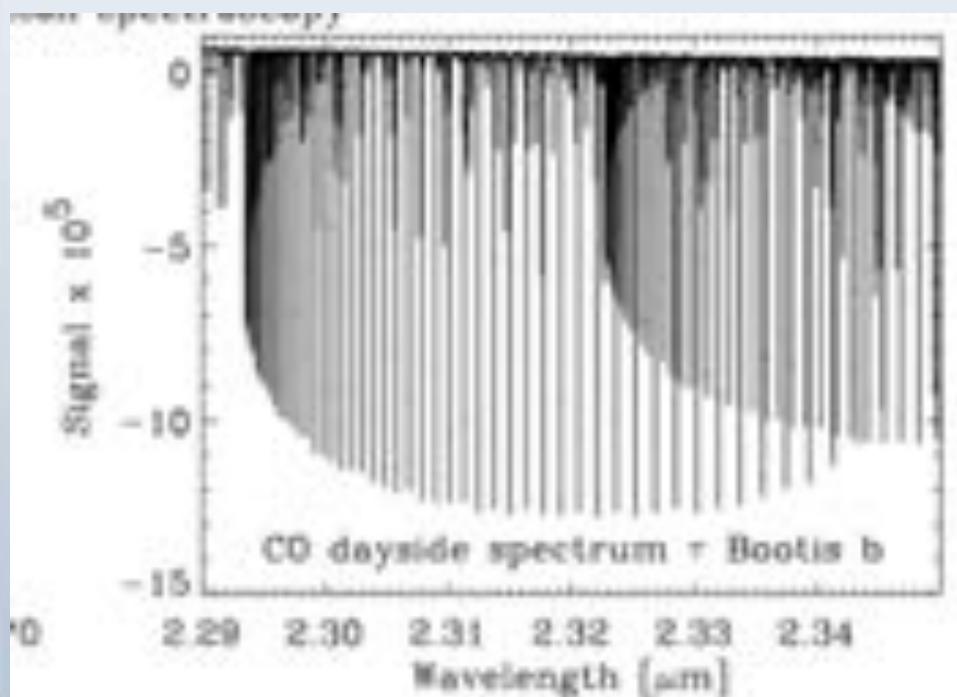
Atomic iron and titanium in the atmosphere of the exoplanet KELT-9b

H. Jens Hoelijmakers^{1,2}, David Ehrenreich¹, Kevin Heng^{2*}, Daniel Kitzmann², Simon L. Grimm², Romain Allart¹, Russell Deitrick², Aurélien Wytténbach¹, Maria Oreshenko², Lorenzo Pino¹, Paul B. Rimmer^{1,4}, Emilio Molinari^{3,6} & Luca Di Fabrizio⁵



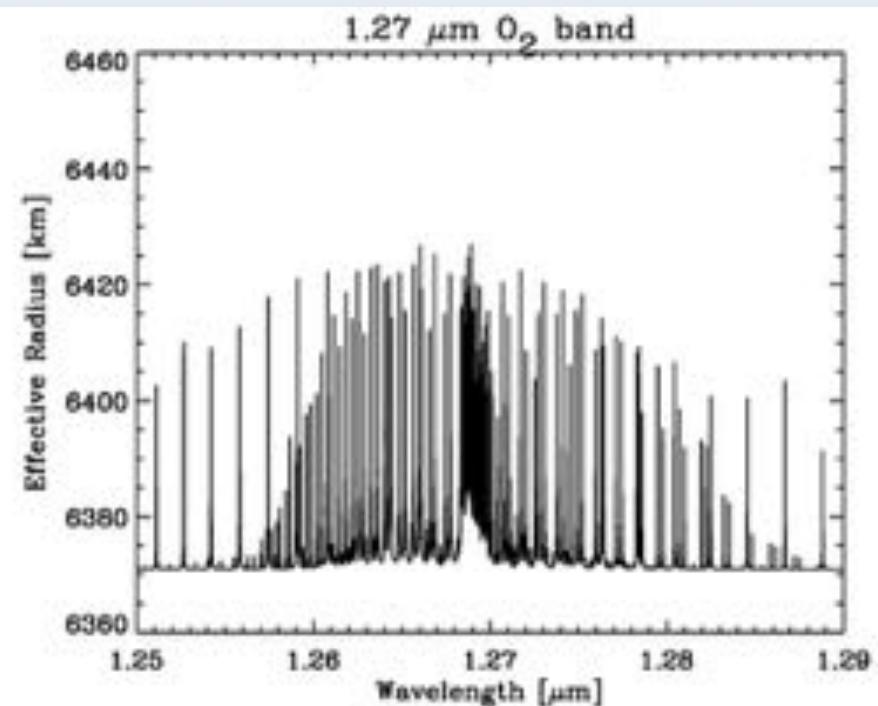
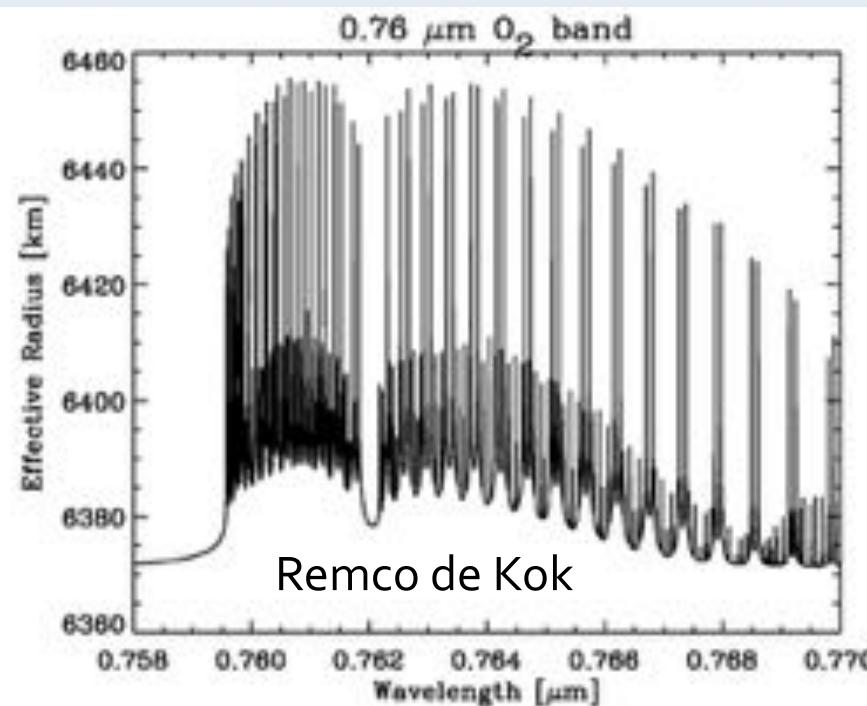
E-ELT science

- Detection of the individual lines (instead of cross-correlation) → T/P profile; unambiguous detections of inversion layers
- Line broadening → planet rotation and circulation
- Molecular spectra (CO, CO₂, H₂O, CH₄) as function of orbital phase → photochemistry, T/P versus longitude
- Isotopologues → evolution of planet atmosphere
(Molliere & Snellen 2019)

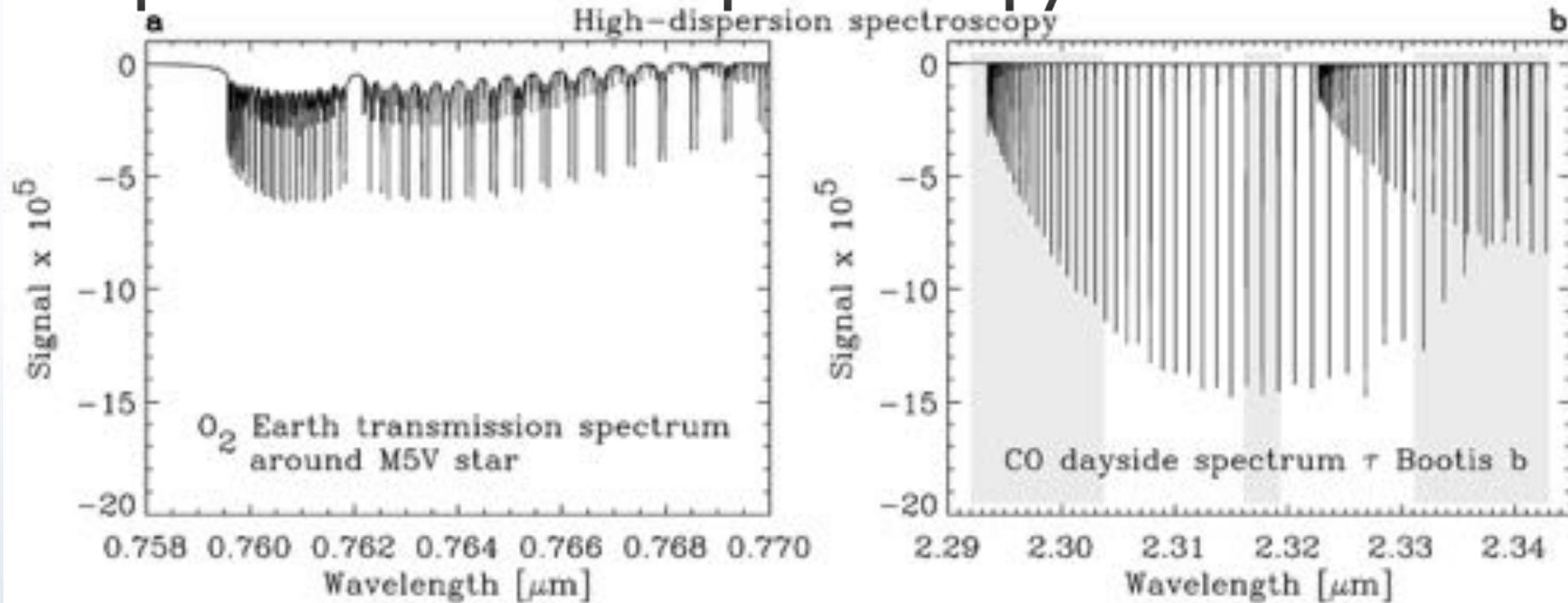


The Ultimate ELT Science Case: Characterizing twin-Earths

- O₂ in transmission is possible!



Optical transmission spectroscopy with the E-ELT



Stellar type	R _* [R _{sun}]	M _* [M _{sun}]	a _{HZ} [au]	Prob [%]	P _{HZ} [days]	Dur. [hrs]	I ($\eta_e=1$) [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

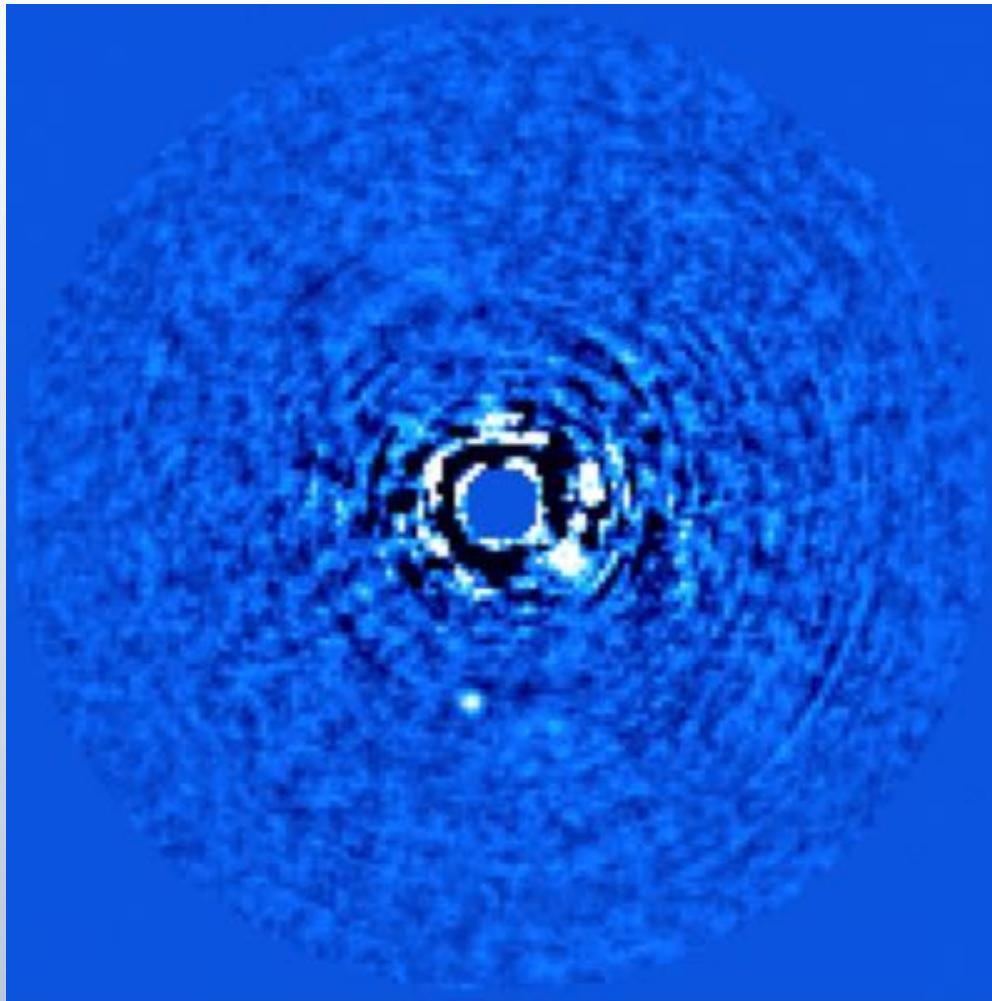
TRAPPIST-1 0.11 0.08 0.021 100% 4.1 1.0 I = 14.0
E-ELT- HIRES J = 11.3

Snellen et al. 2013

Brightest expected systems

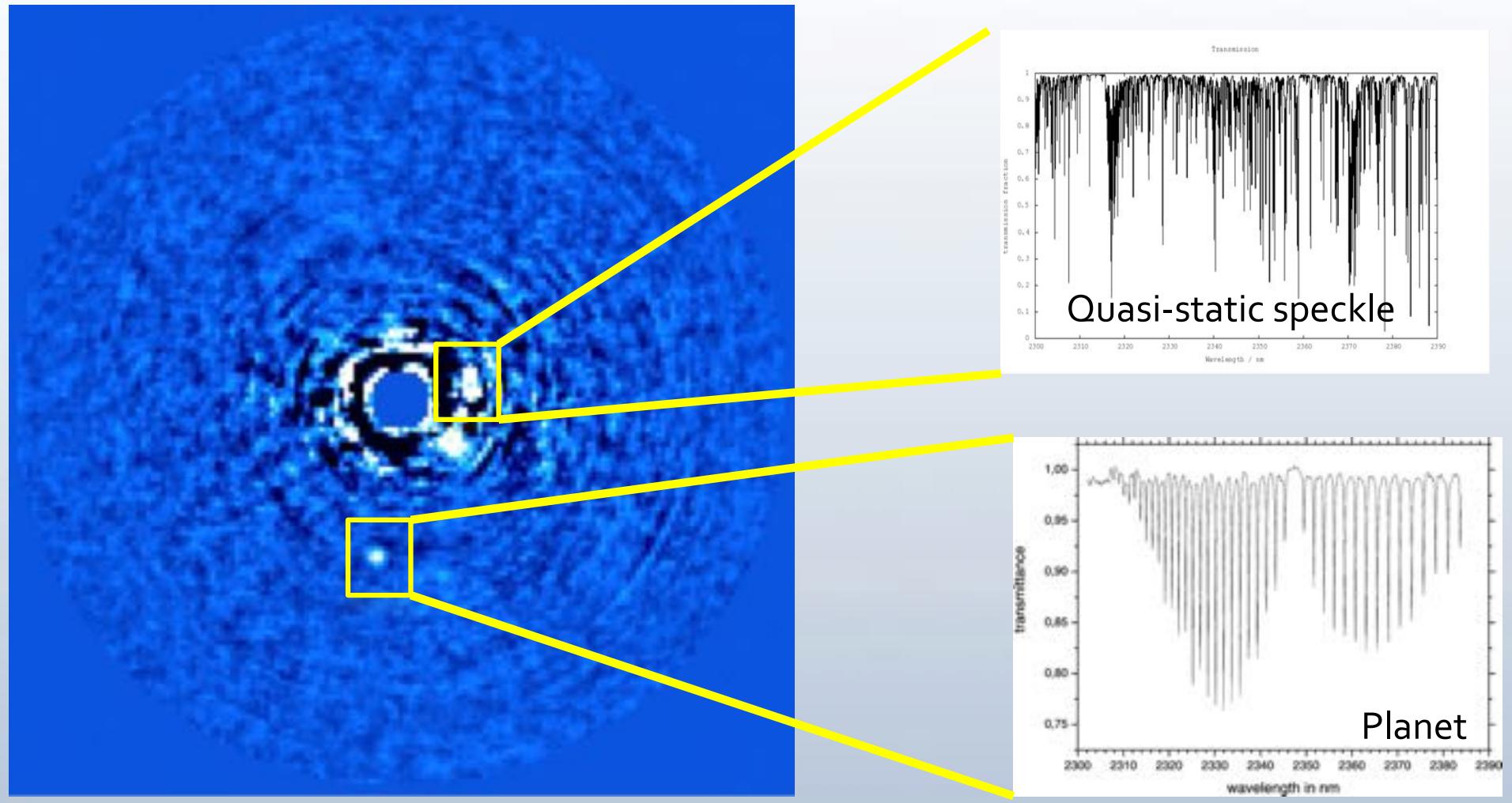
SNR for ELT in 1 transit

High-dispersion spectroscopy + High Contrast Imaging



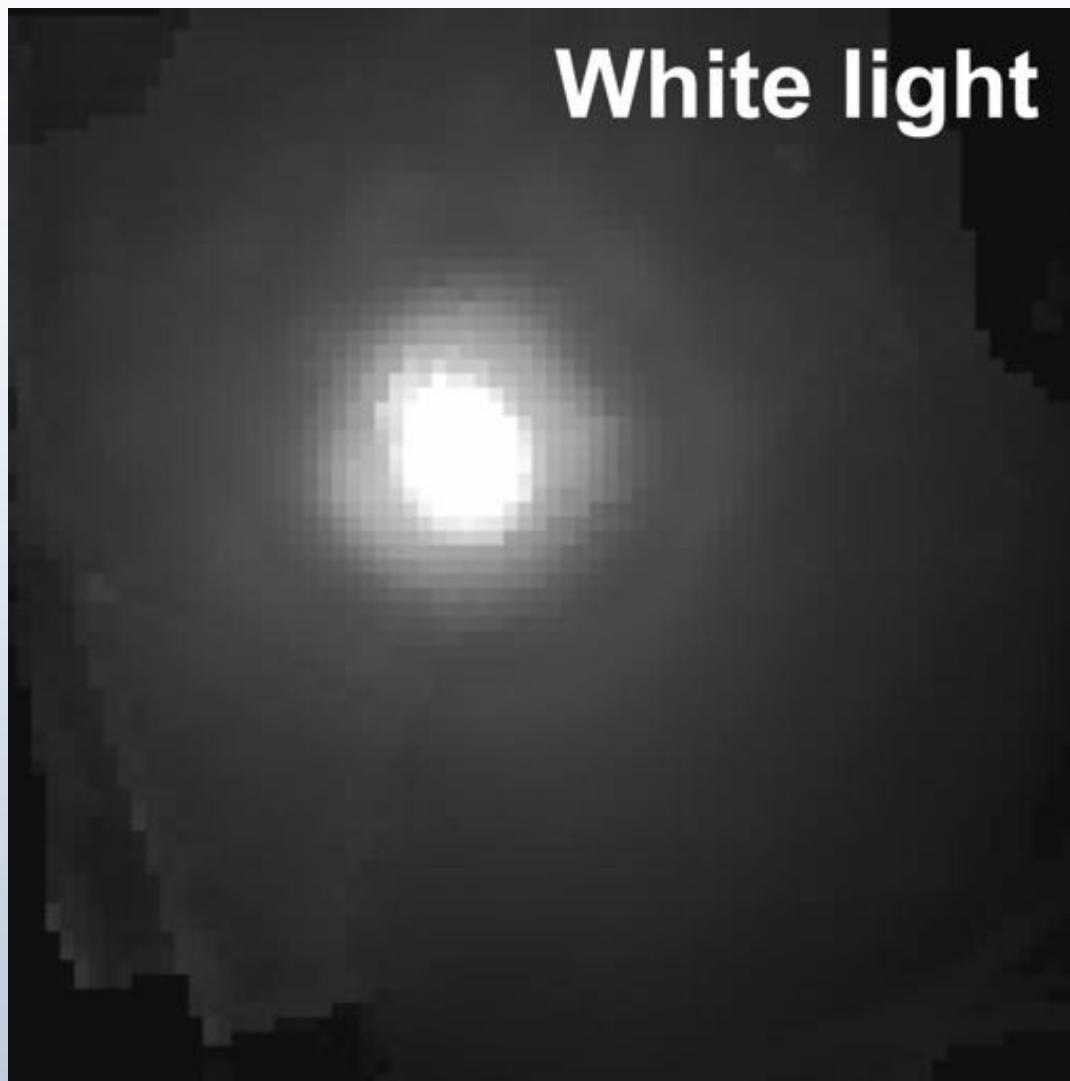
Sparks & Ford 2002
Riaud & Schneider 2007
Snellen et al. 2015
Kawahara et al. 2014
Wang et al. 2016
Konopacky et al. 2013
Lovis et al. 2017
Ruane et al. 2018

High-dispersion spectroscopy + High Contrast Imaging



Low spectral resolution Beta Pictoris with SINFONI ($R=4000$)

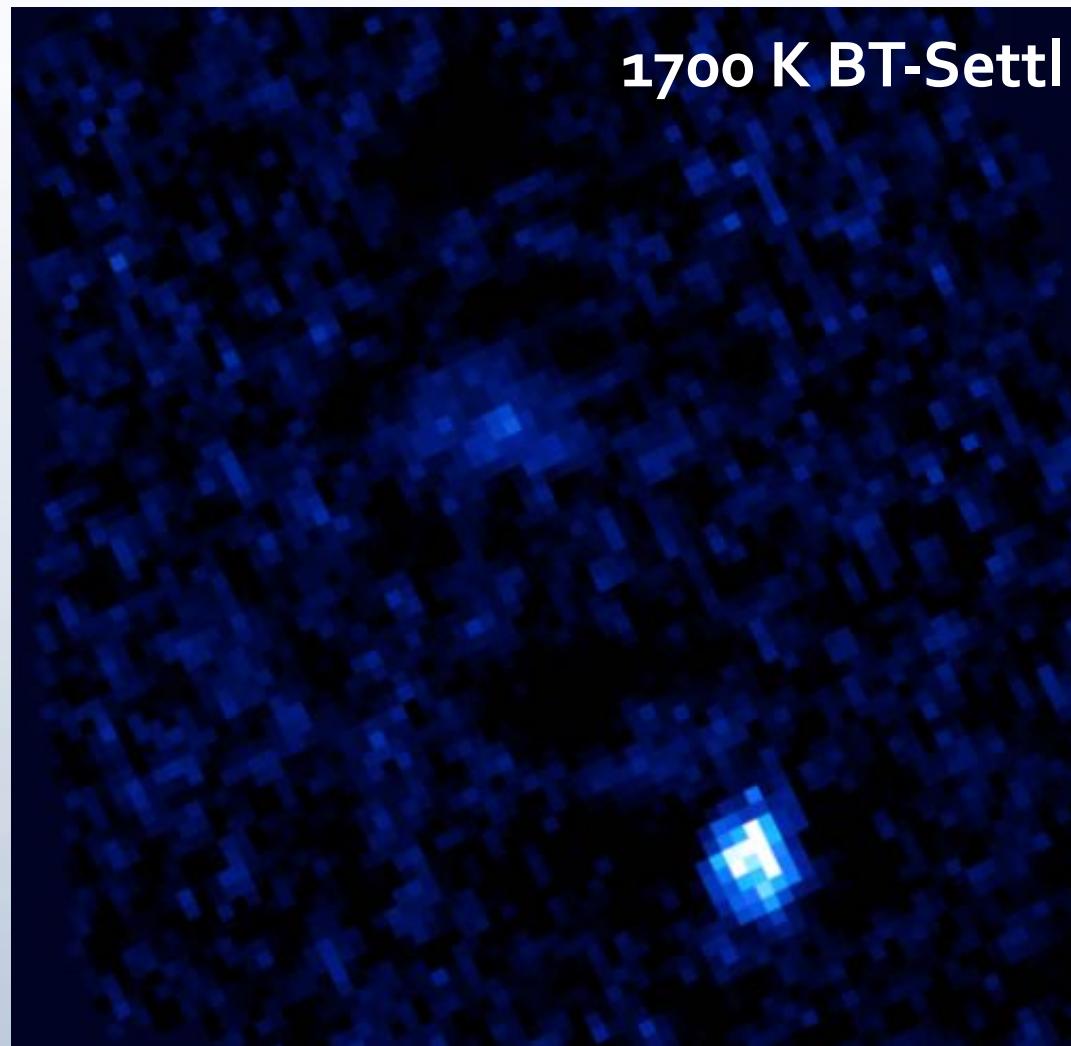
0.8''



Hoeijmakers et al 2018; Raw contrast = 250

Low spectral resolution Beta Pictoris with SINFONI ($R=4000$)

0.8''

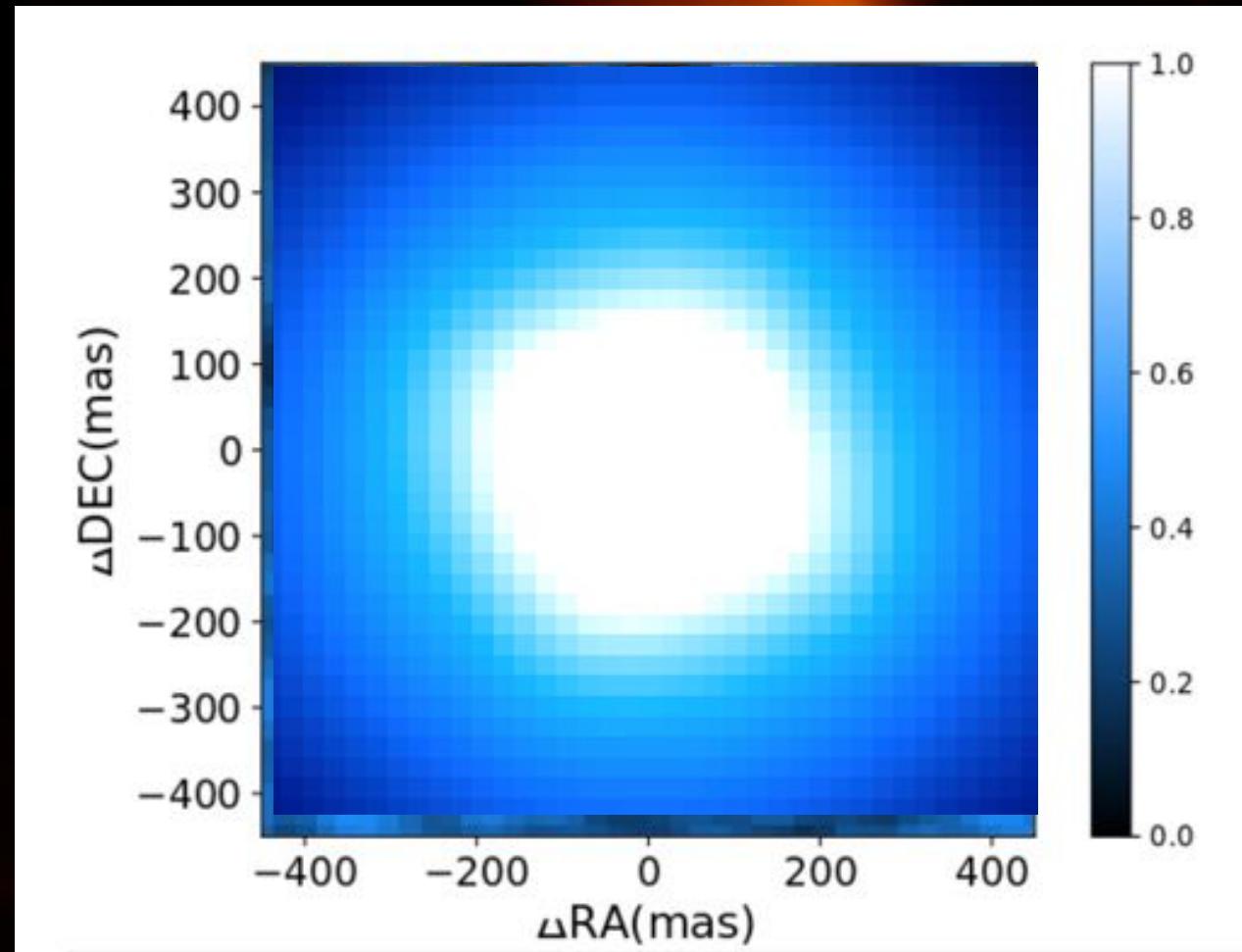


Raw contrast = 250
Final contrast = 100,000

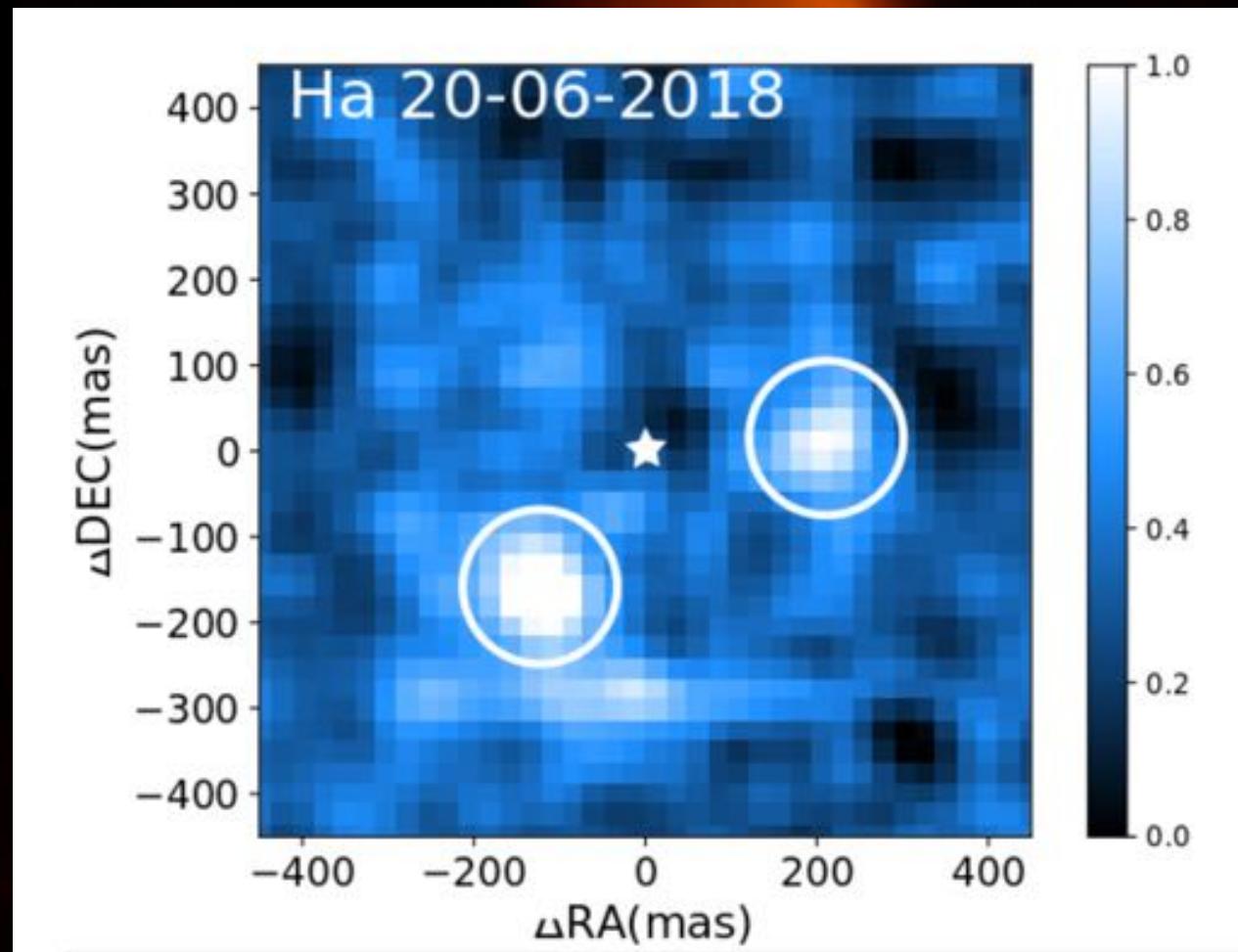
PDS 70: circumstellar disk + planet with SPHERE
(Keppler et al. 2018)



Sebastiaan Haffert et al. Nature Astronomy 2019
MUSE IFU (VLT) – $R = 3000$, moderate AO

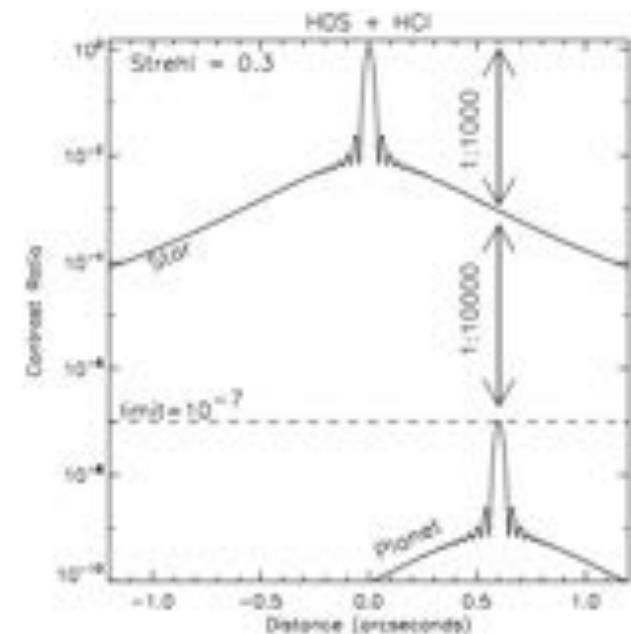
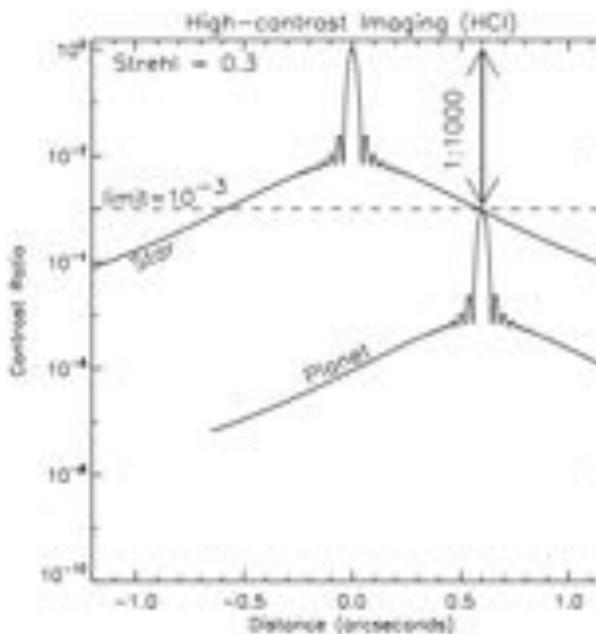
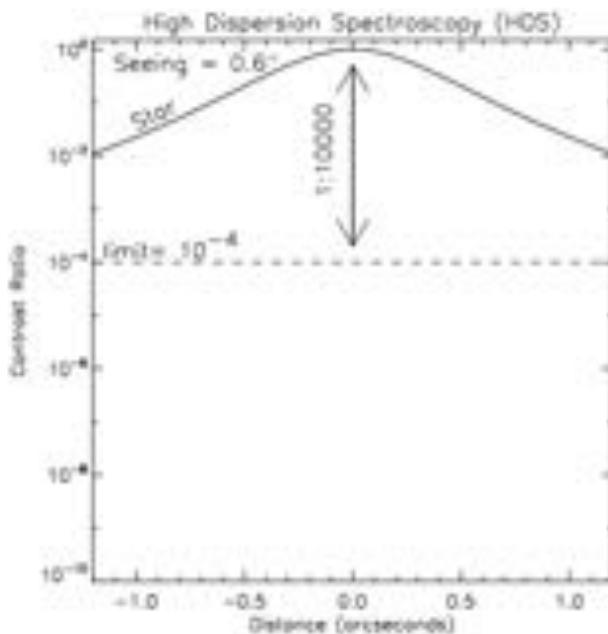


Second planet!



Snellen et al. Nature 2014

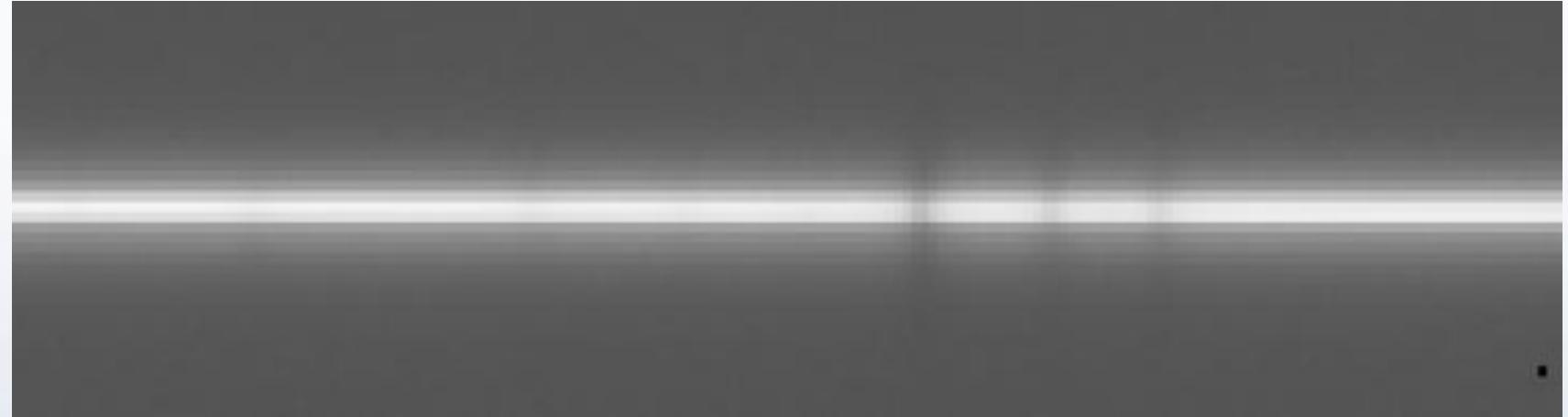
High Dispersion Spectroscopy + high-contrast imaging



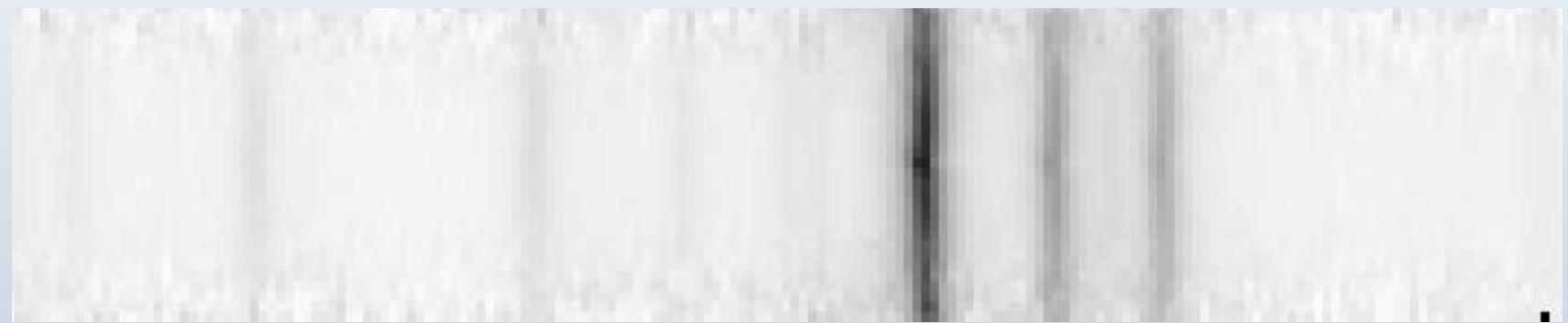
1 hour DDT time (1-1.3" seeing)

22x4x10 seconds

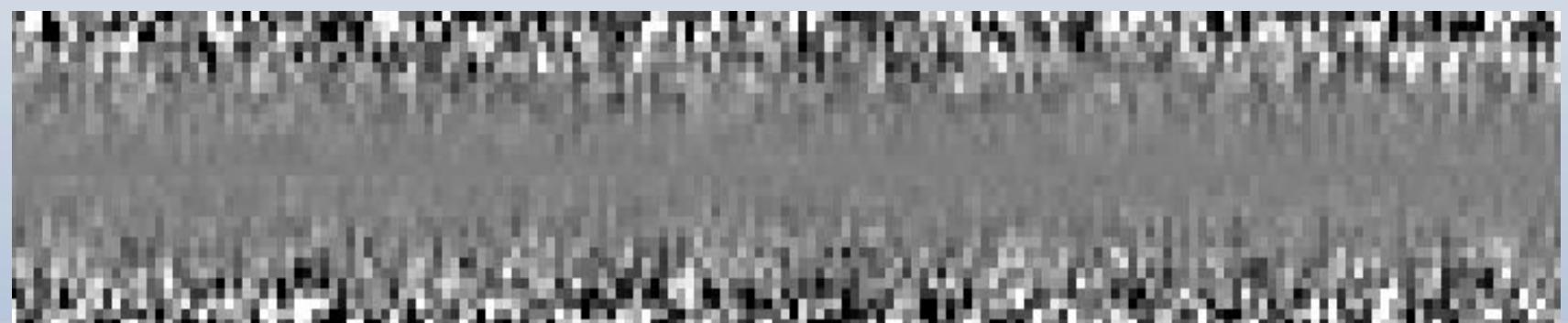
Star →
Planet →



Star →
Planet →

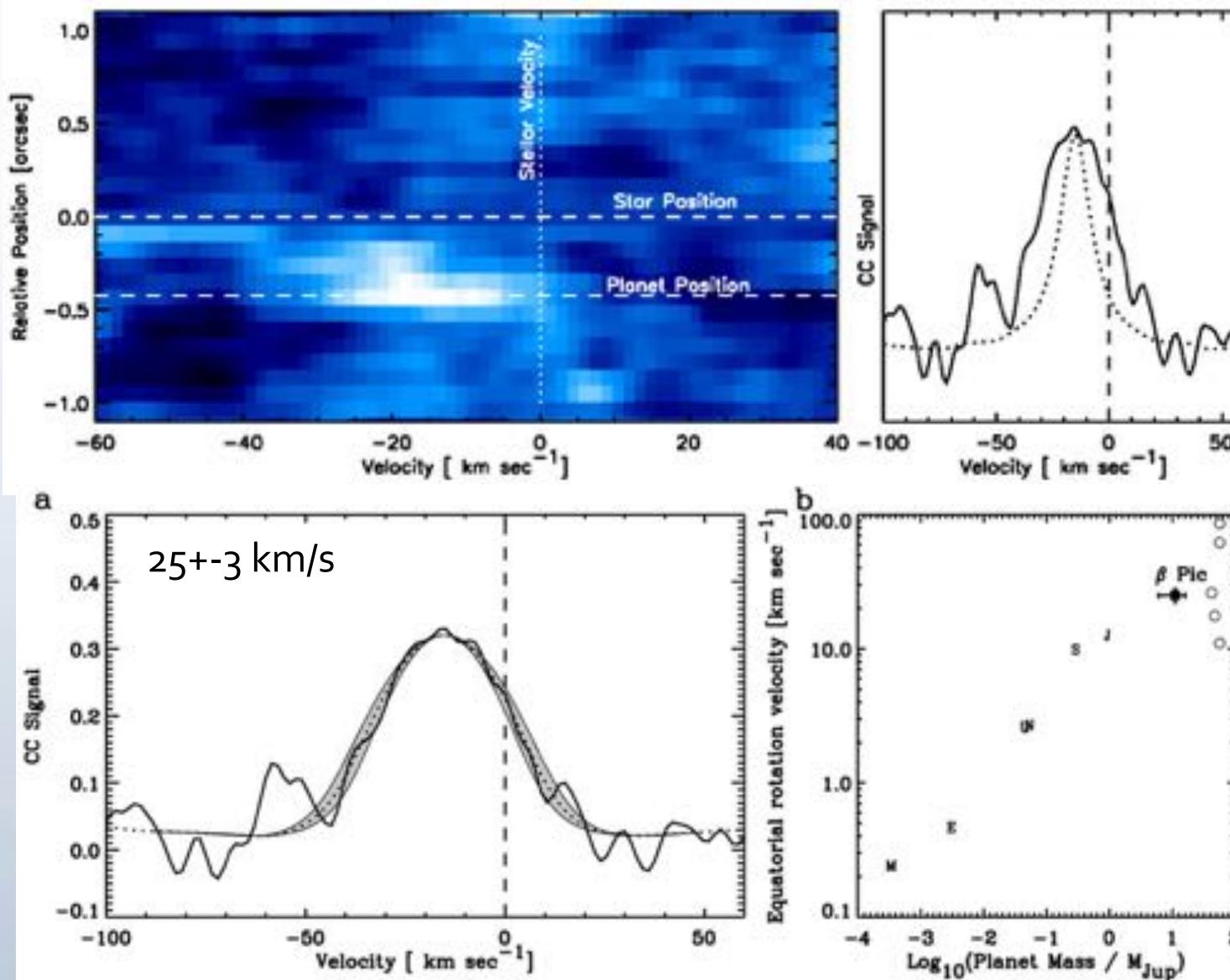


Star →
Planet →

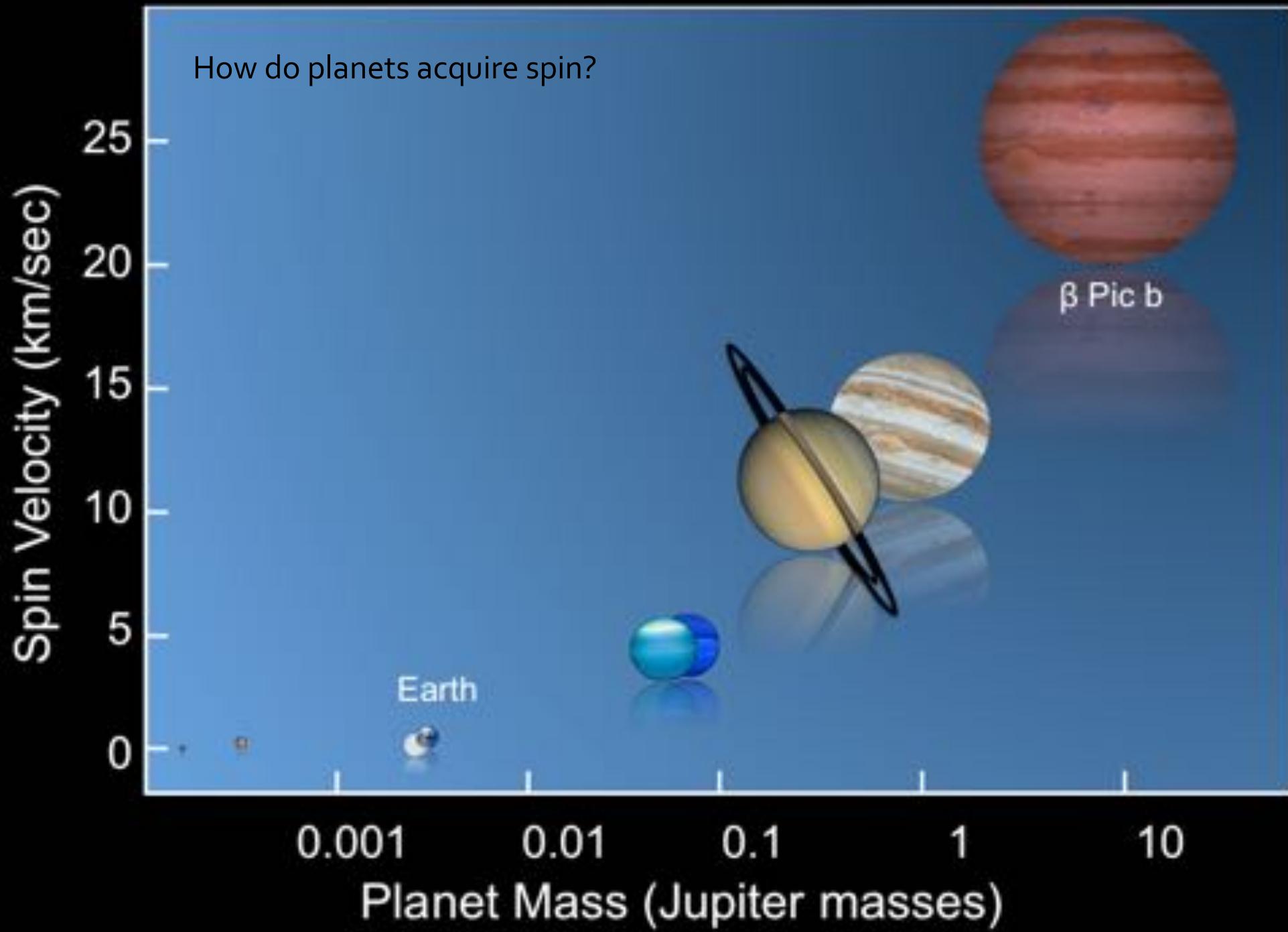


Snellen et al. Nature 2014

High Dispersion Spectroscopy + high-contrast imaging



Length of Day on Beta Pictoris b ~8 hours



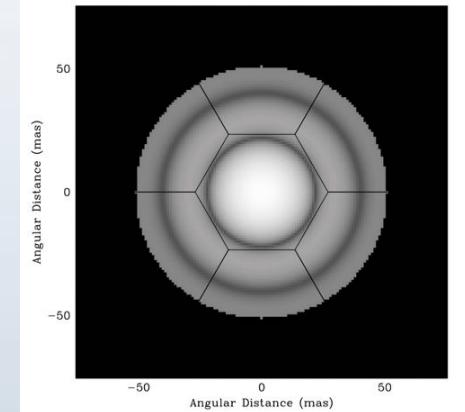
What about detecting molecular oxygen in Proxima b?

Atmospheric characterization of Proxima b by coupling the SPHERE high-contrast imager to the ESPRESSO spectrograph

C. Lovis¹, I. Snellen², D. Mouillet^{3,4}, F. Pepe¹, F. Wildi¹, N. Astudillo-Defru¹, J.-L. Beuzit^{3,4}, X. Bonfils^{3,4}, A. Cheetham¹, U. Conod¹, X. Delfosse^{3,4}, D. Ehrenreich¹, P. Figueira⁵, T. Forveille^{3,4}, J. H. C. Martins^{5,6}, S. P. Quanz⁷, N. C. Santos^{5,8}, H.-M. Schmid⁷, D. Ségransan¹, and S. Udry¹

Proxima b: $F_p/F_* \sim 2 \times 10^{-7}$ at $2\lambda/D$ @ 0.75 μm

- SPHERE XAO upgrade
- coronagraphy
- ESPRESSO IFU mode
- ESPRESSO fiber injection upgrade



Reflected light in 30 nights
O2 in 60 nights

Technology development

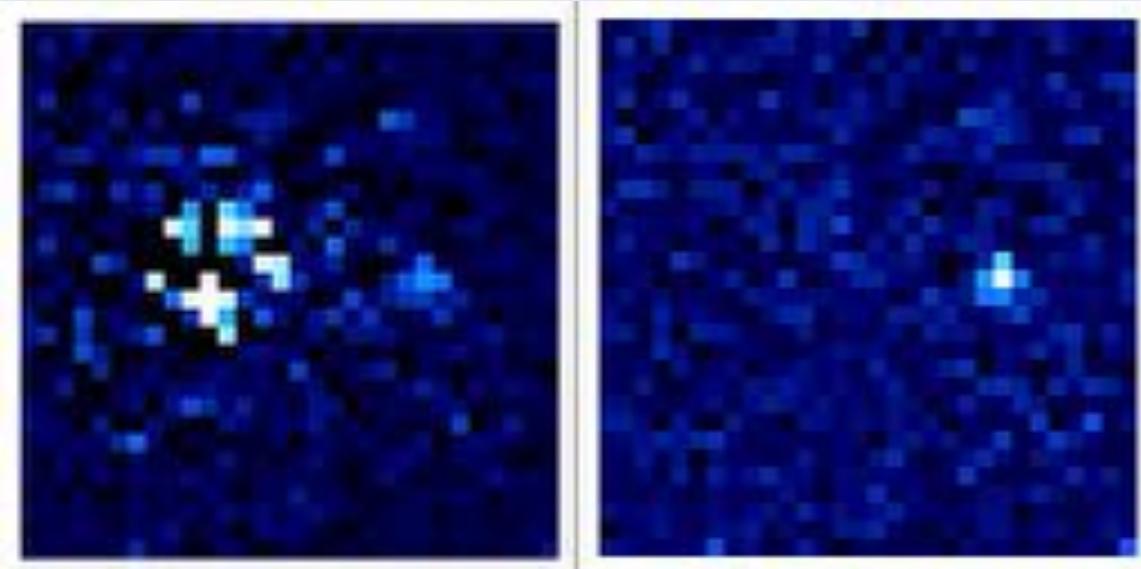
- CRIRES+ (ESO)
- SCExAO + IRD (Subaru JP)
- MagAO-X + RHEA (Magellan USA)
- Keck Planet Imager + Characterizer

RISTRETTO

ESPRESSO/SPHERE is important technology development for HIRES/EPICS ELT

Obs.Time required scales with $D^4 \rightarrow 500x$ faster
Proxima b with HIRES/EPICS@ELT (2030)

0.035''

METIS simulations

