Extrasolar Planets and their atmospheres

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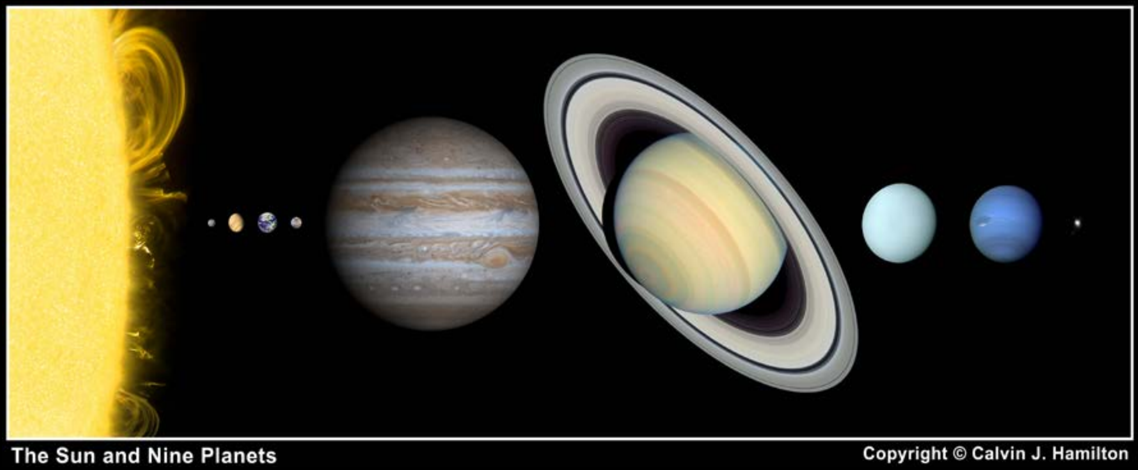
The Sun and Nine Planets
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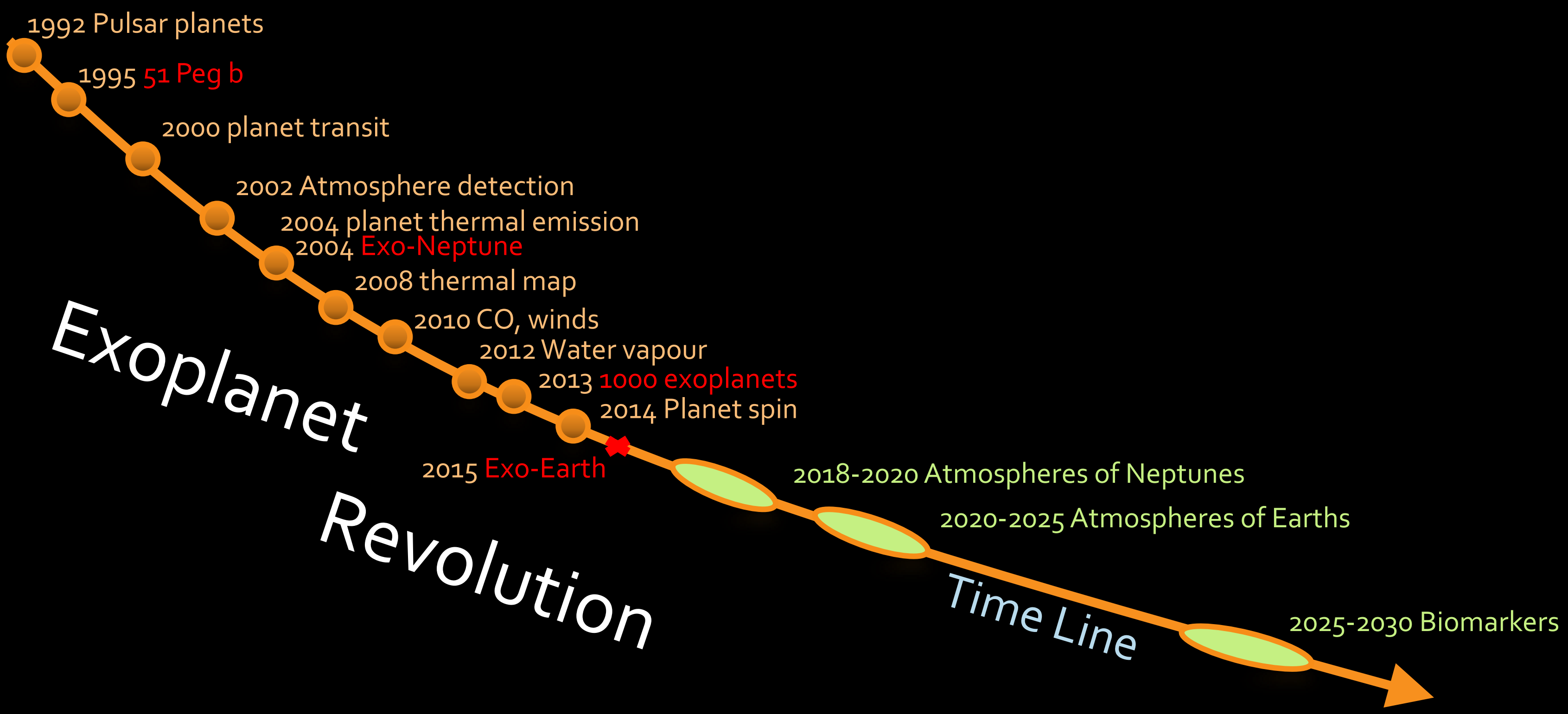

1992 Pulsar planets
1995 51 Peg b
2000 planet transit
2002 Atmosphere detection
2004 planet thermal emission
2004 Exo-Neptune
2008 thermal map
2010 CO, winds
2012 Water vapour
2013 1000 exoplanets
2014 Planet spin
2015 Exo-Earth
2018-2020 Atmospheres of Neptunes
2020-2025 Atmospheres of Earths
2025-2030 Biomarkers
Exoplanet
Revolution
Time Line

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

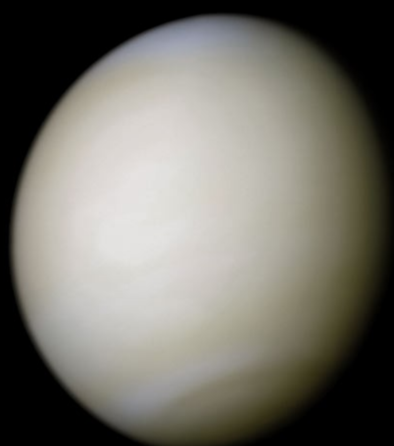
Gas giants:

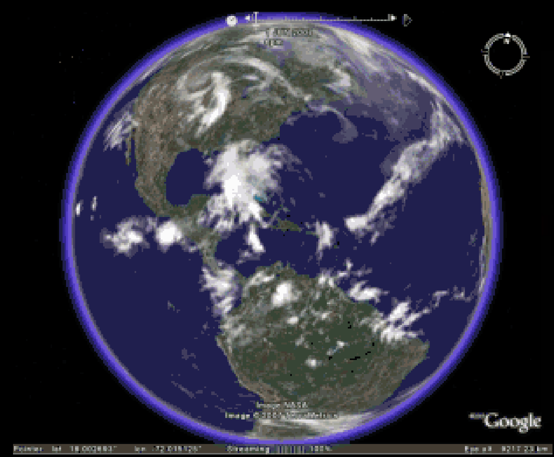
H_2-dominated; clouds; strong zonal flows; storms

What we learn from the Solar System

Planets show an immense complexity and diversity

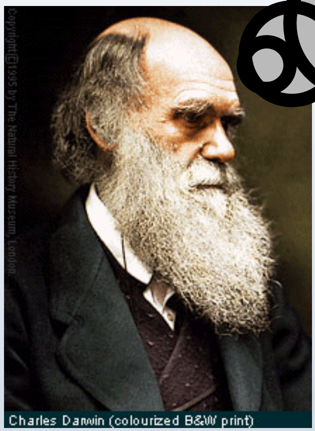
Rocky planets: secondary atmospheres – very diverse





Super-rotating, CO_2 based Opaque sulfuric acid clouds	**Partially clear, N_2-based Biotic oxygen**	**Tenuous CO_2 Varying trace-amount of methane**

Solar System:



"Trying to comprehend **Tree of Life** using three animals"

Exoplanet studies shows that diversity is much larger:

- Hot Jupiters
- super-Earth & mini-Neptunes
- Gas giants at large orbital distances (>100 AU)

Exoplanet challenge

You visit

You dig and drill

in situ measurements

Understanding planets

- Body’s mass, size
- Composition of atmosphere surface
- Rotation period, oblateness
- Gravity field, magnetic field, seismic data
- Sample return
- Laboratory data → behaviour of materials
- Quantum mechanical calculations

Exoplanets

- Possible
- hard
- Very difficult?
- Impossible!

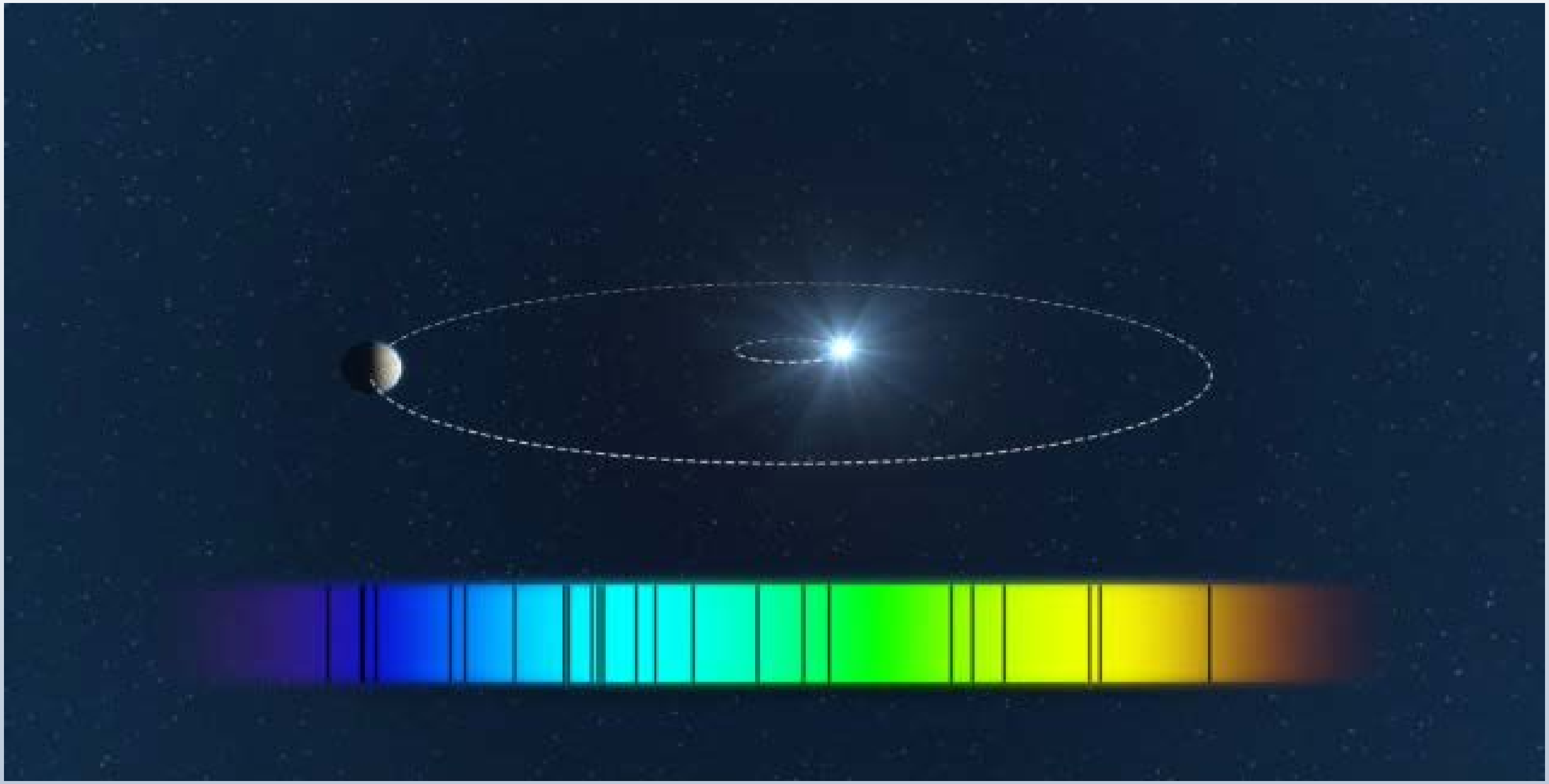
The place of Earth & our Solar system in the Universe

Understanding planet **atmospheric processes** and their **evolutionary histories** is crucial for unambiguously identifying **extraterrestrial life**

Finding Exoplanets

Techniques to find exoplanets

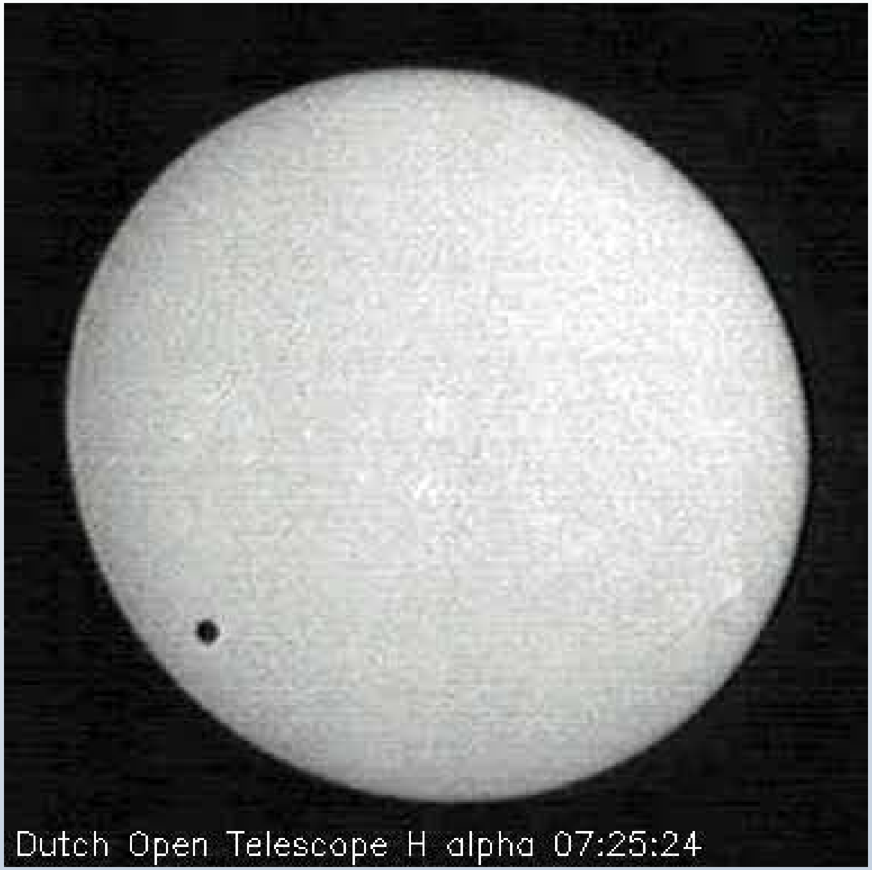
- **Radial Velocity Technique**
- Measures the reflex motion of the host-star around the center of mass
- Very successful. Hundreds of planets found

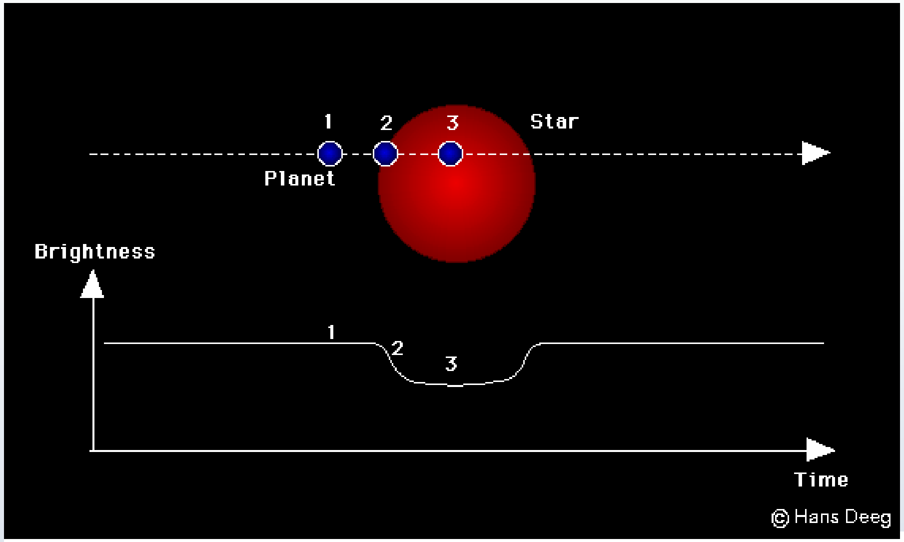


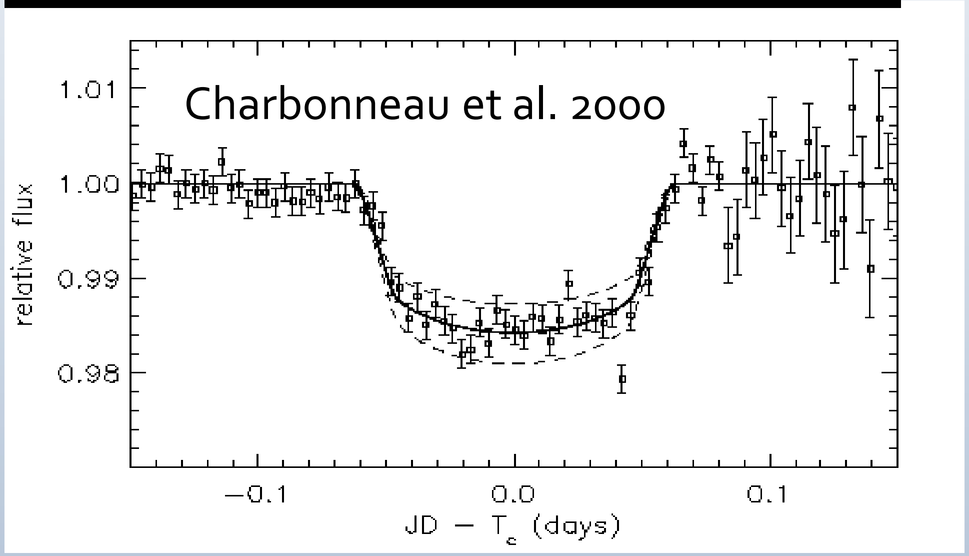
Techniques to find exoplanets

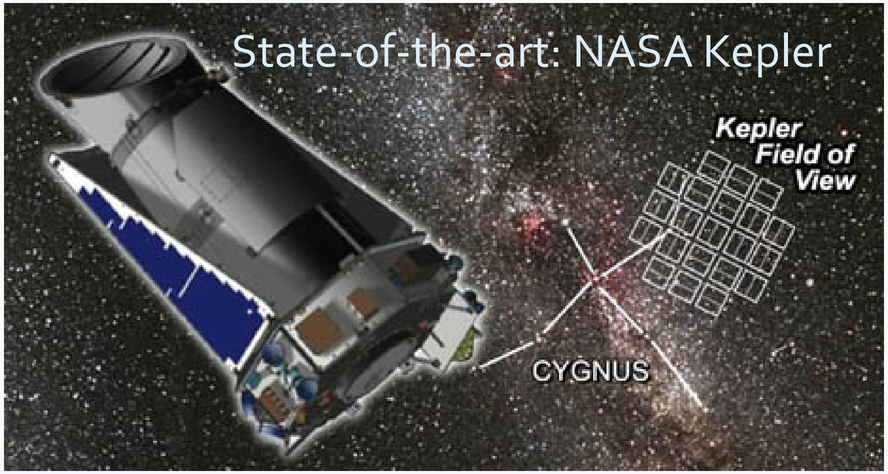
- **Transit technique**

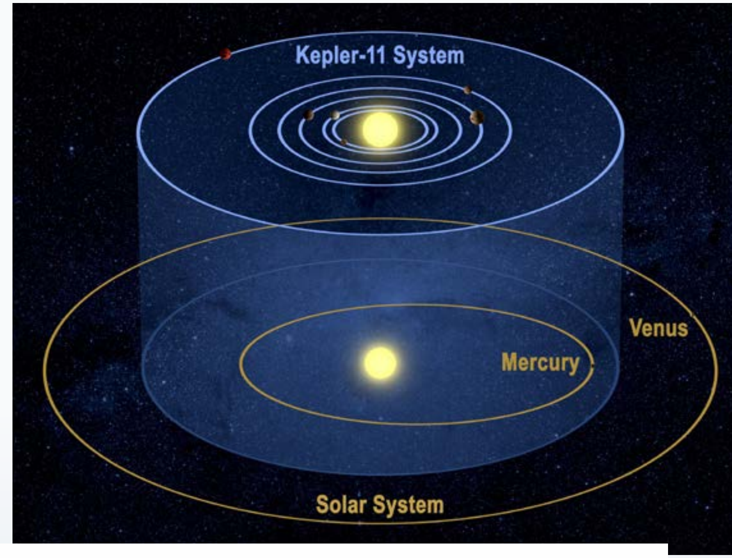
If lucky, planet can be seen to move in front of stellar disk

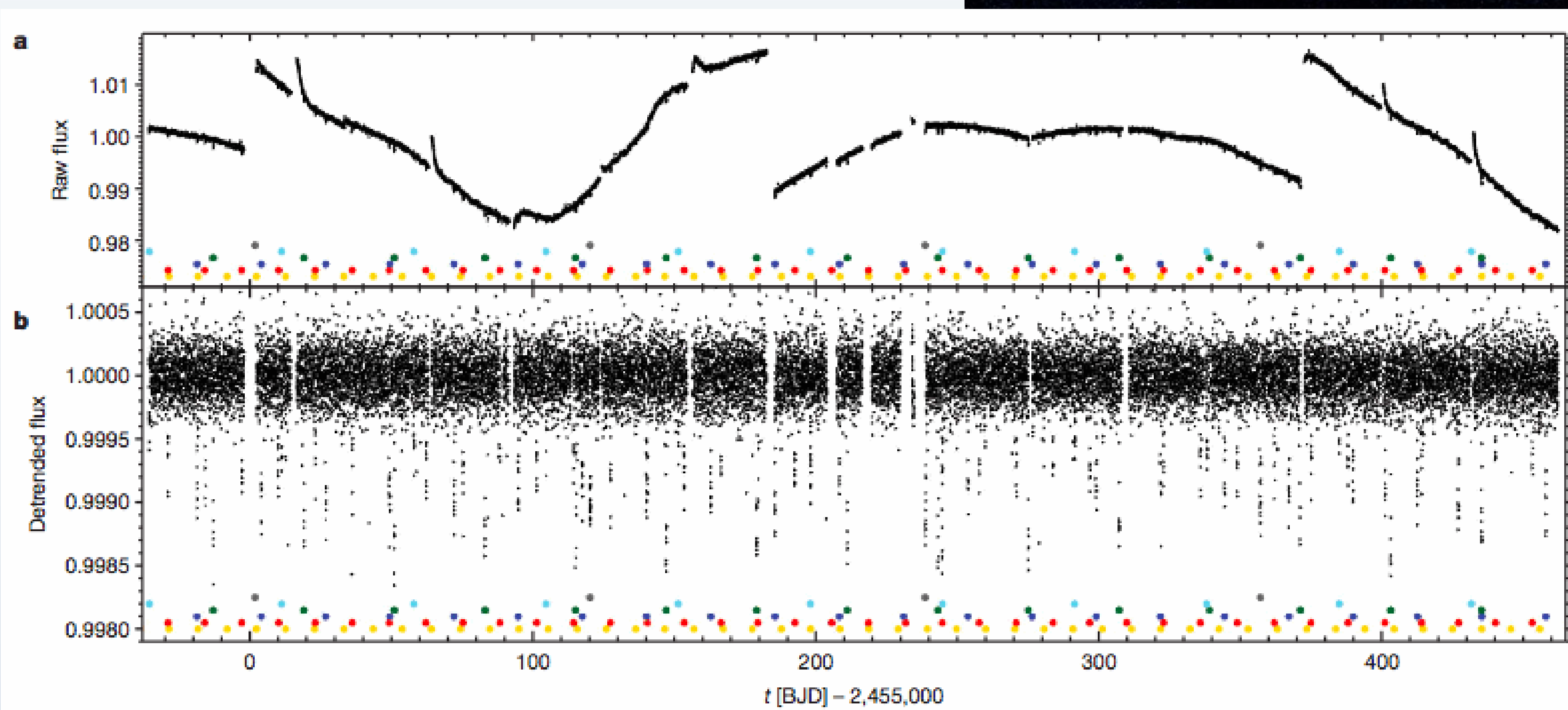












Upcoming missions: NASA TESS (2018); ESA PLATO (2024)

Techniques to find exoplanets

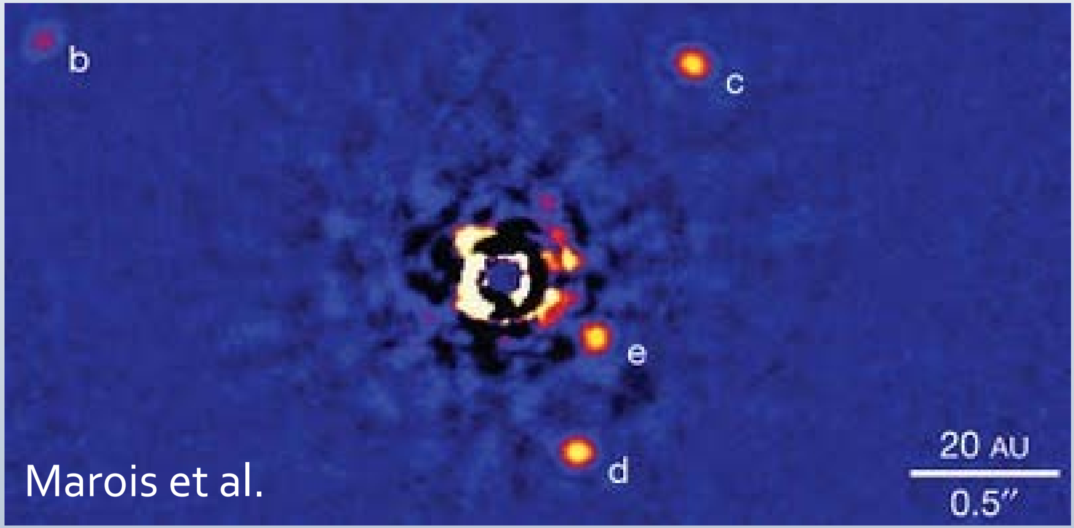
- **High Contrast imaging**

→ Approach theoretical PSF with adaptive optics

→ Alter (part of) PSF with coronagraphy

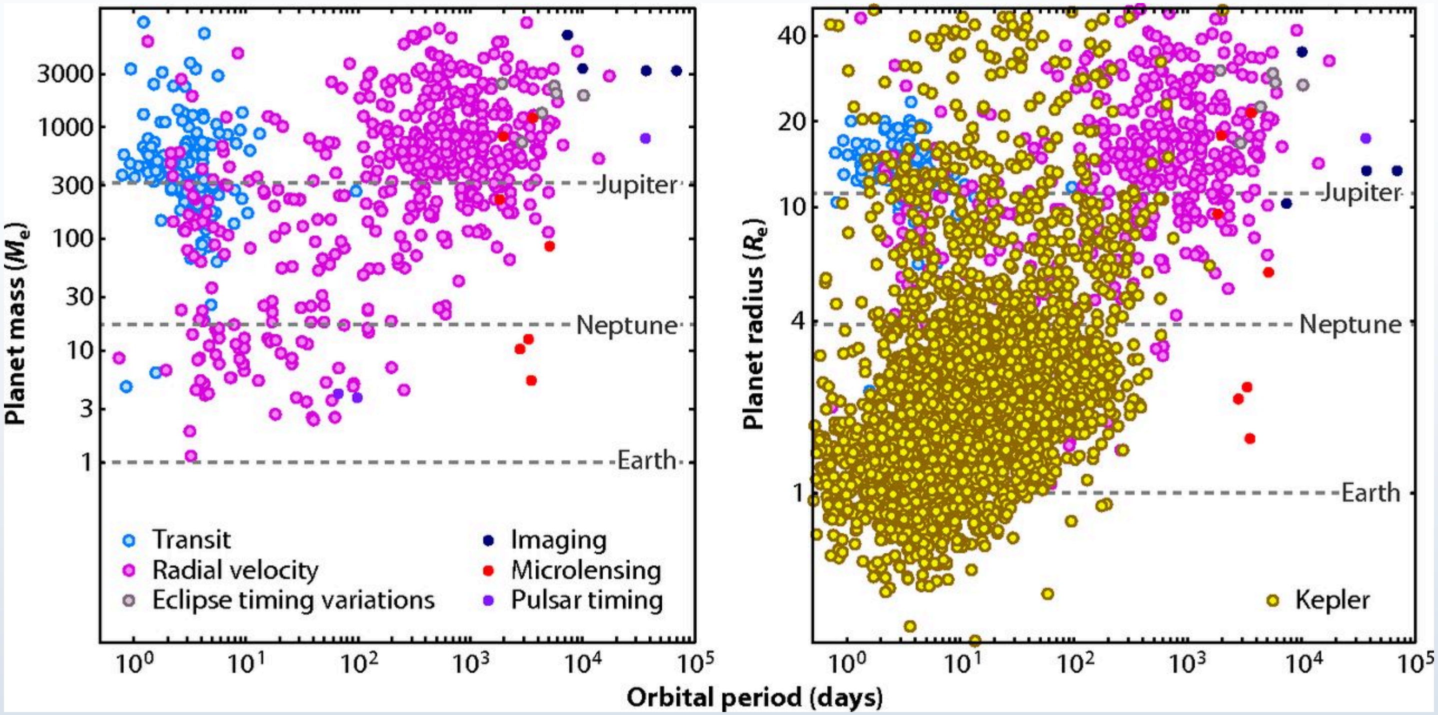
→ Smart algorithms to remove starlight

- Up to now restricted to young, massive, self-luminous planets at large orbital distances



Marois et al.

Exoplanet population



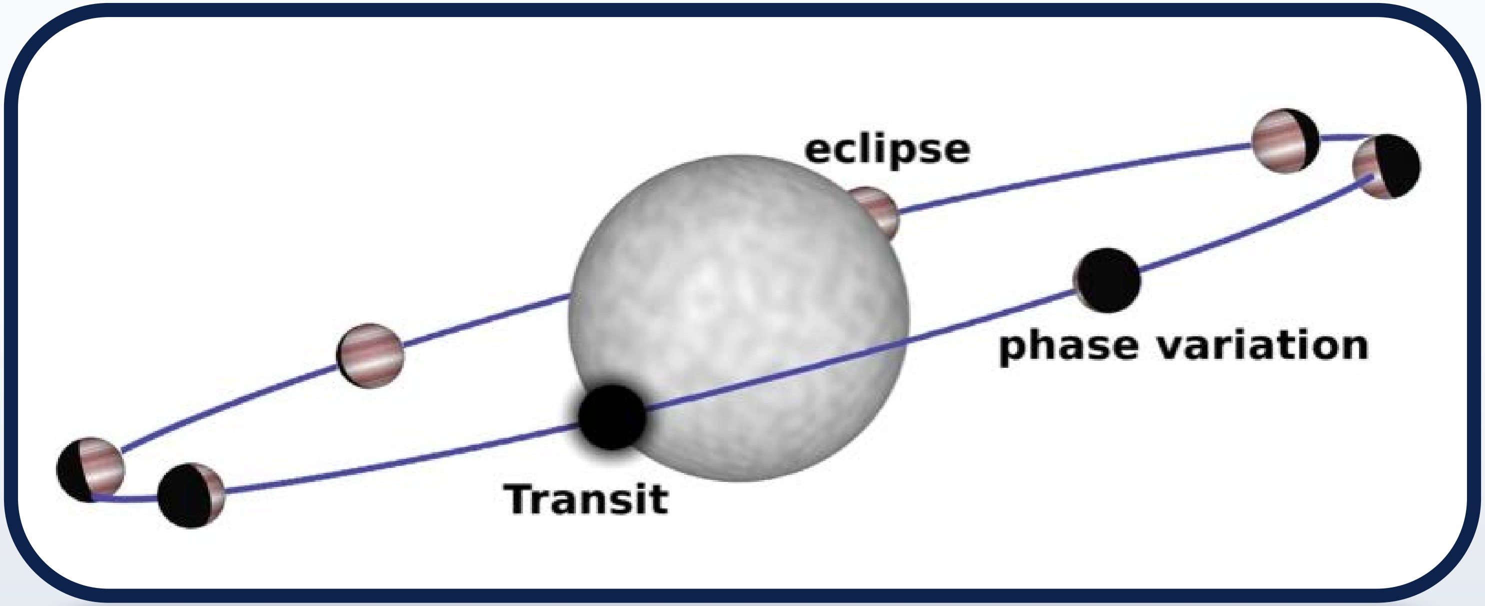
1 in 10 stars has a Jupiter-mass planet

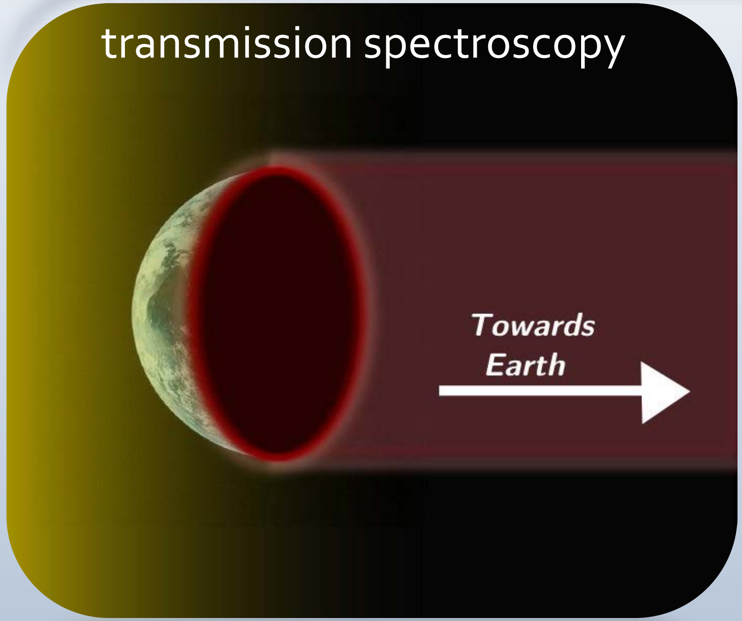
1 in 3 stars has a Neptune-mass planet

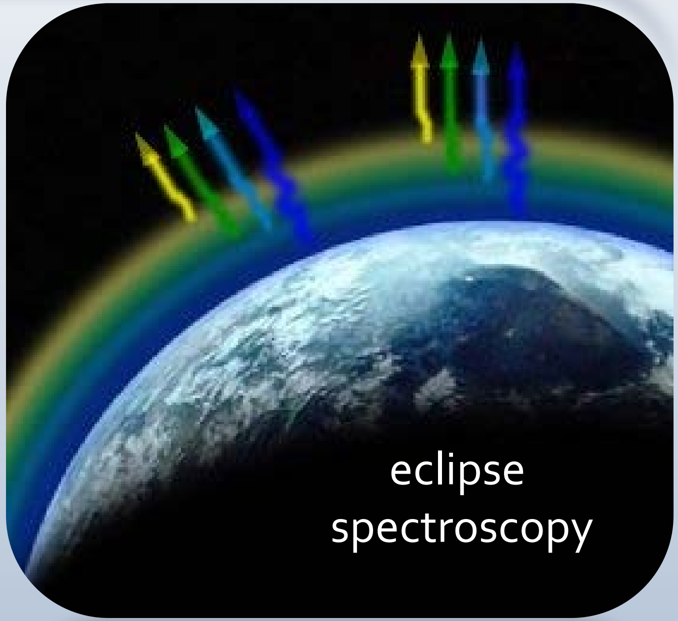
Most of the stars have an Earth-mass planet

Atmospheric Characterization

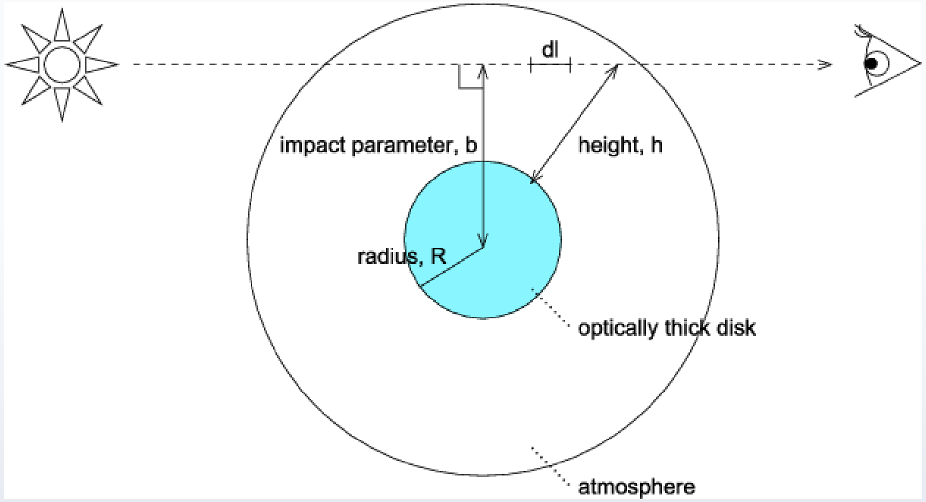
Exoplanet atmospheres







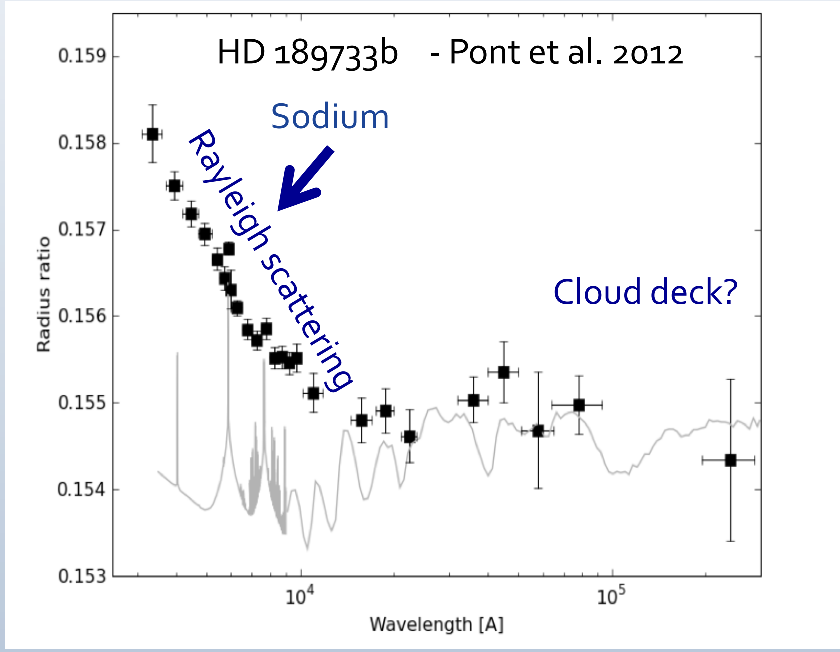
Transmission spectroscopy

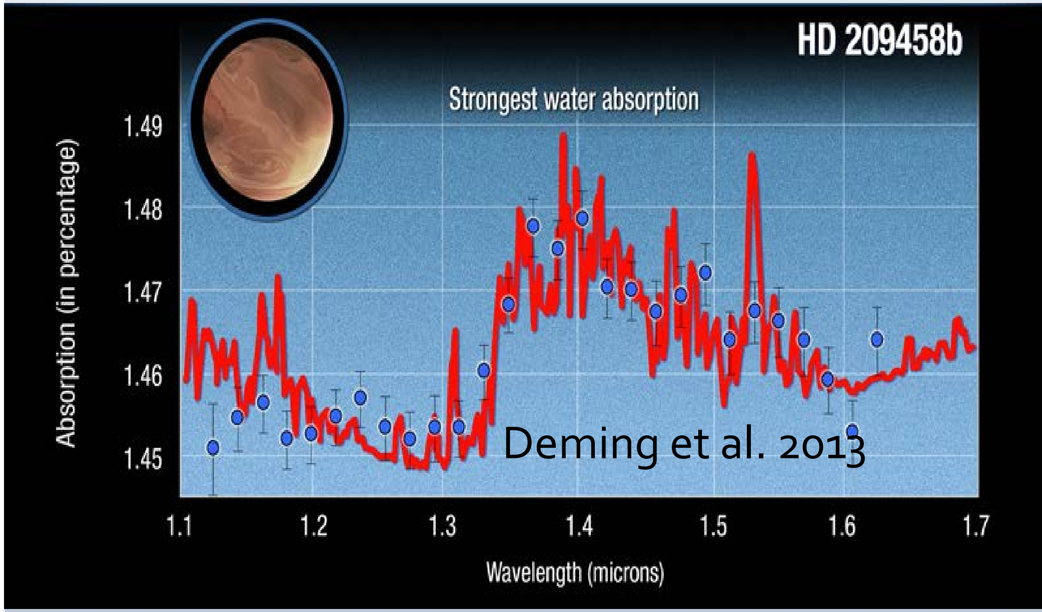


Scale Height, $H \sim \frac{T}{\mu g}$

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

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

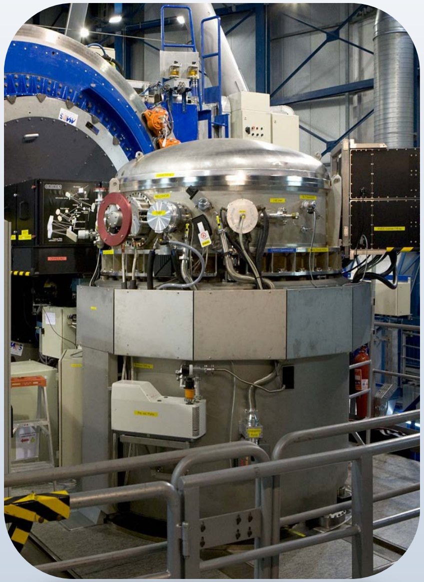


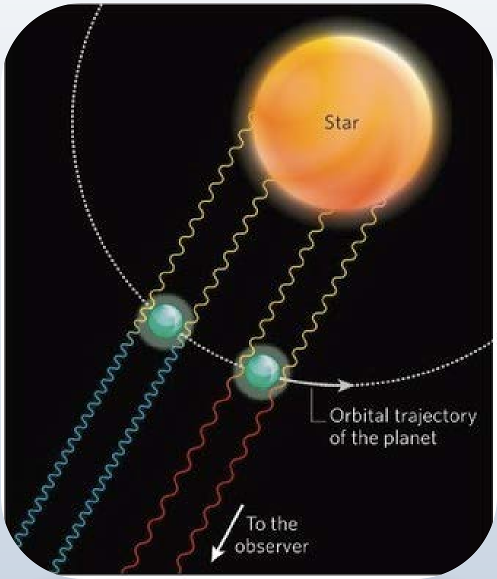


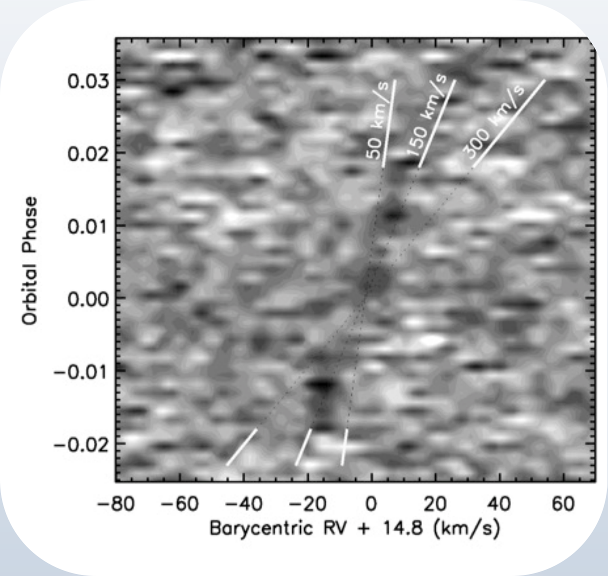
Expertise - Leiden Exoplanet Group

Unique capabilities of ground-based instruments

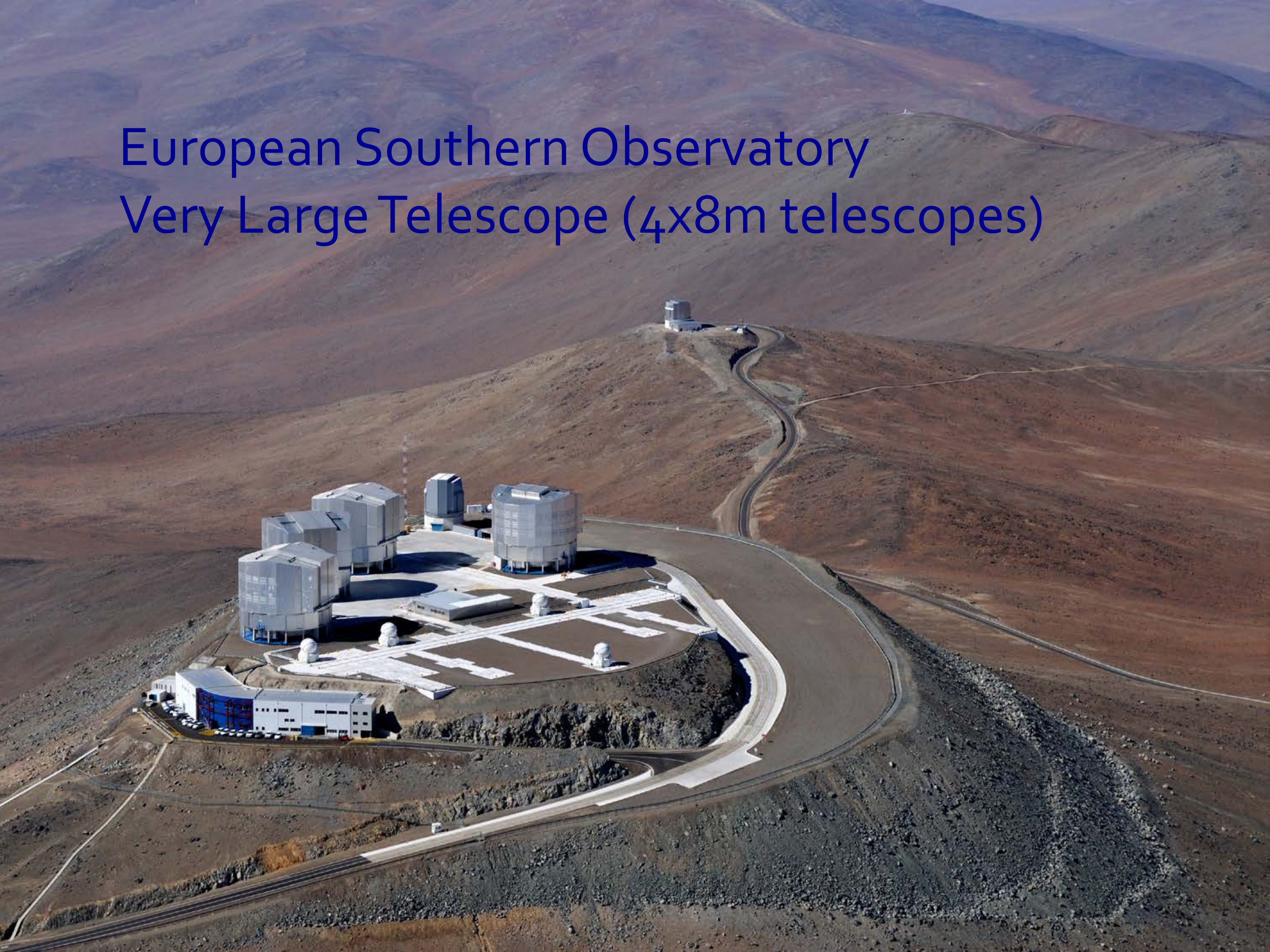
- Telescopes have enormous light-gathering power
- High spectral resolution
- Flexibility





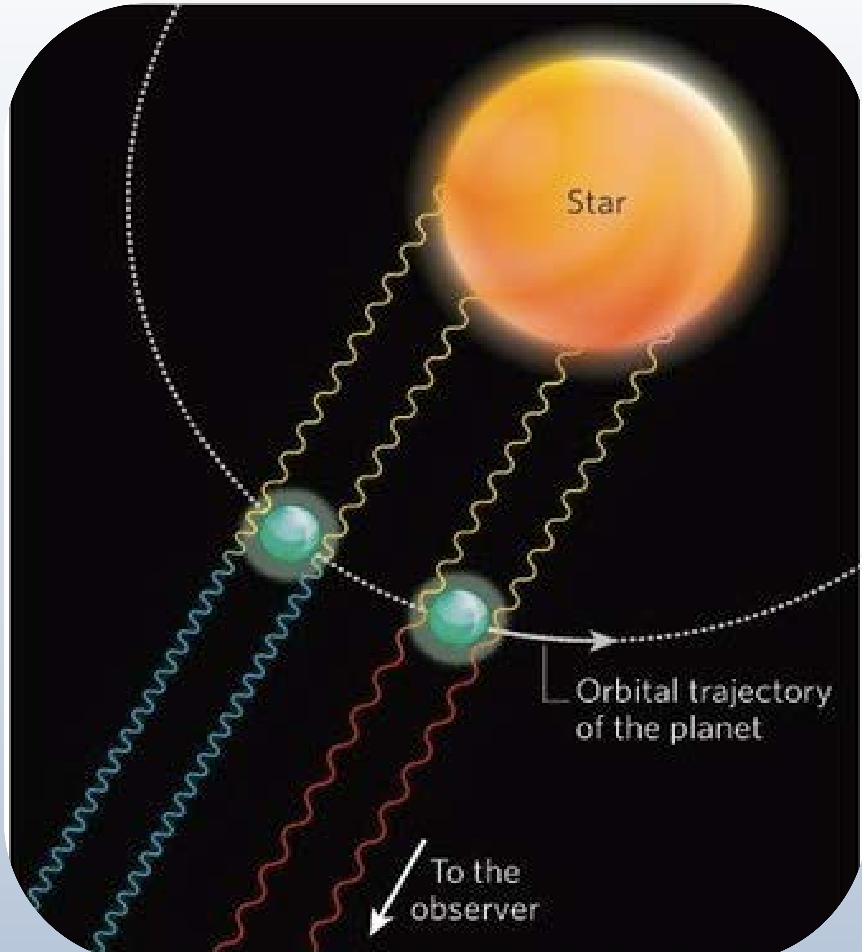


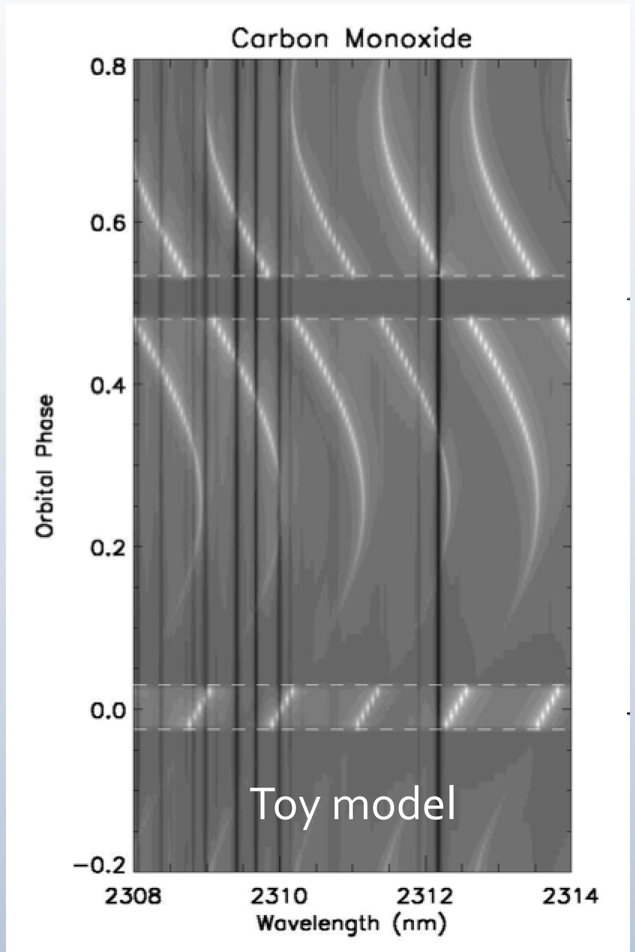
Snellen et al. 2008; De Mooij & Snellen 2009; Snellen et al. ***Nature*** 2009; Albrecht et al. ***Nature*** 2009; Snellen et al. ***Nature*** 2010; Brogi et al. ***Nature***, 2012, Snellen et al. ***Nature*** 2014


European Southern Observatory
Very Large Telescope (4x8m telescopes)

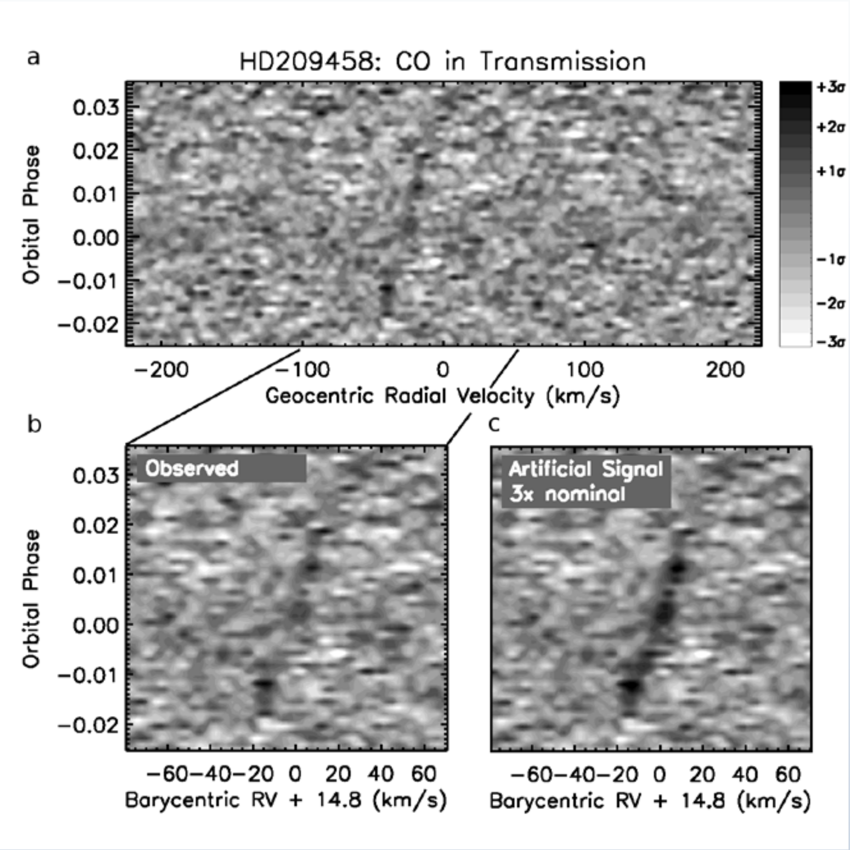
Ground-based High-dispersion spectroscopy

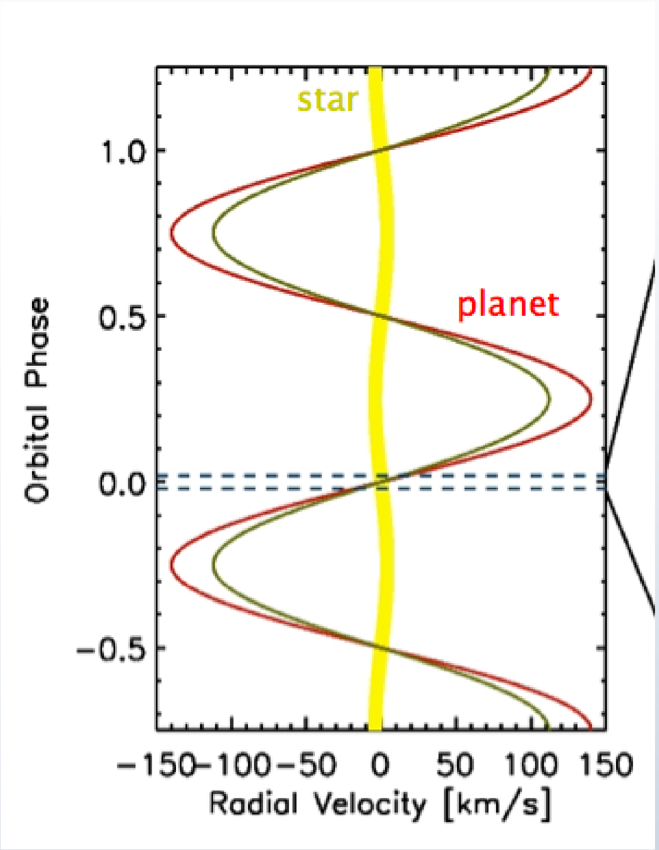
- At R=100,000 molecular bands are resolved in tens of individual lines
- Strong doppler effects due orbital motion of the planet (up to >150 km/s).
- Moving planet lines can be distinguished from stationary telluric + stellar lines





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

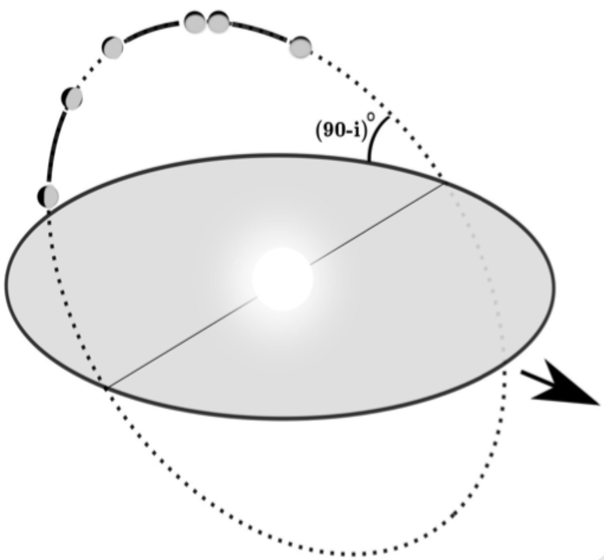




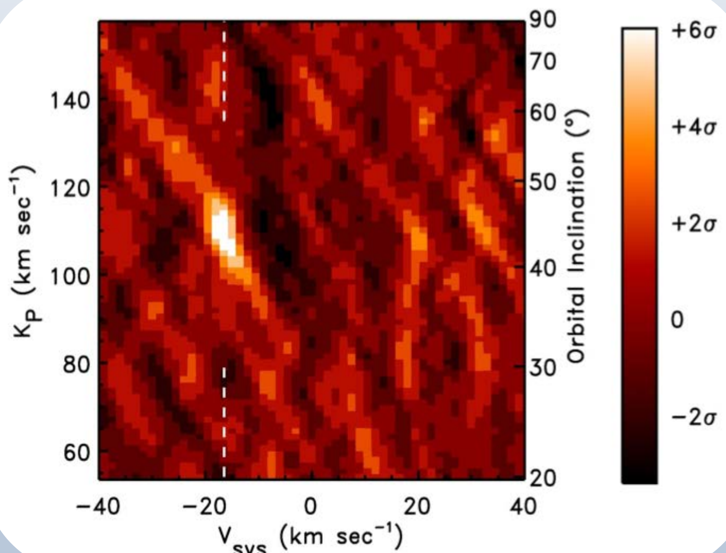
- Reveals planet orbital velocity
- Solves for masses of both planet and star (model independent)
- Evidence for blueshift (high altitude winds?)

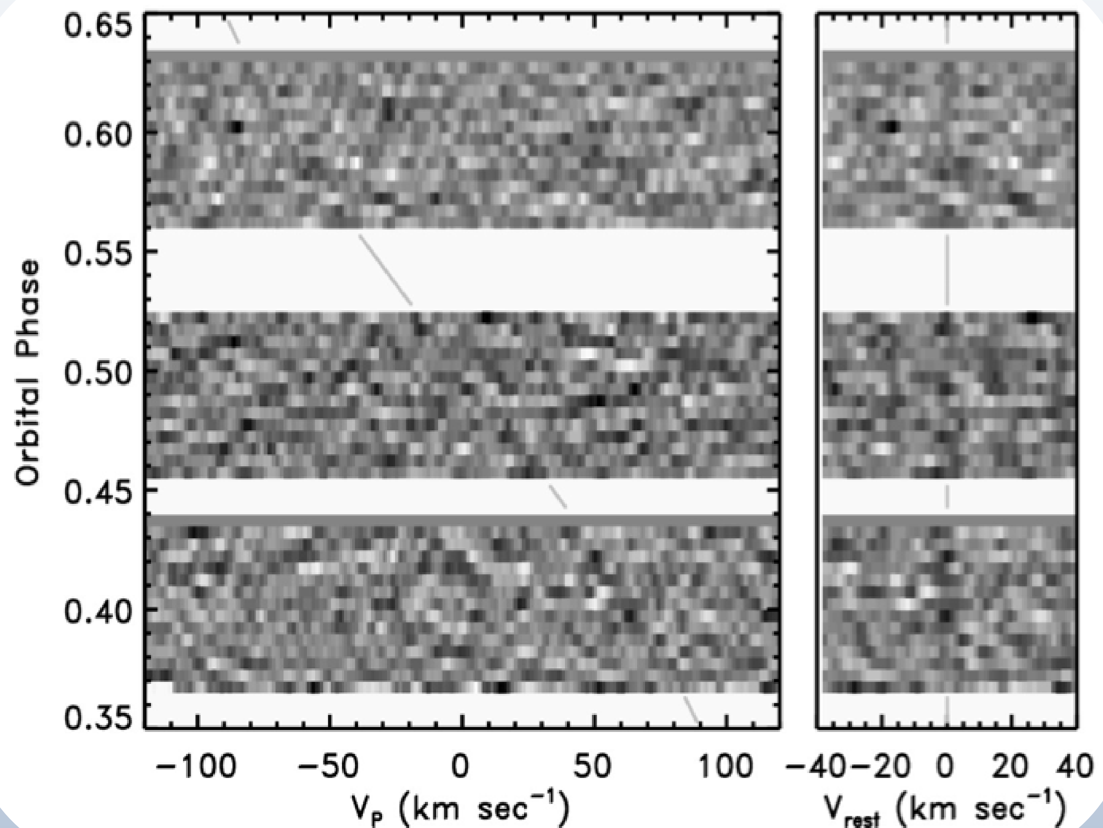
CO in dayside spectrum of tau Bootis b (CRIRES@VLT)

(Brogi et al. Nature 2012)

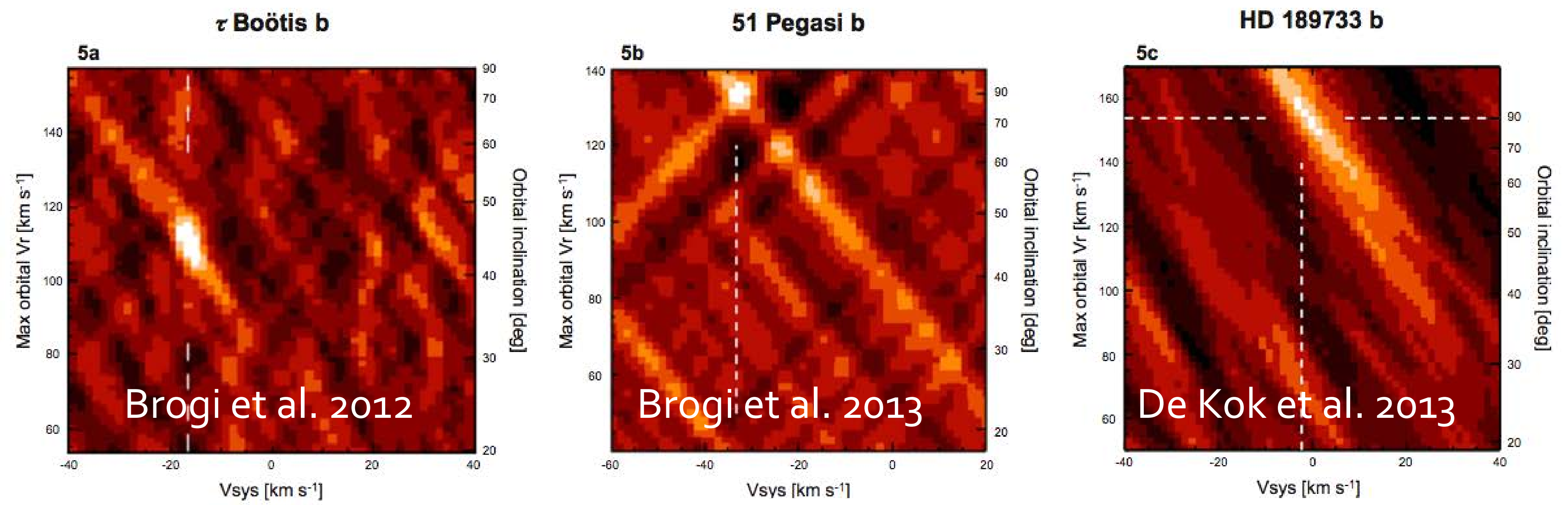


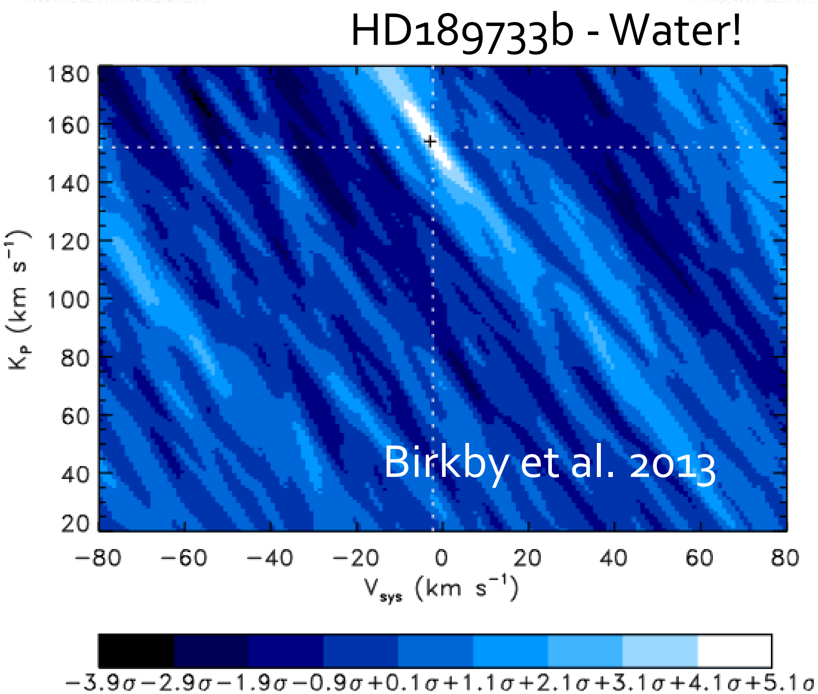
First detection of non-transiting planet→ inclination, mass





CO in dayside spectra of hot Jupiters



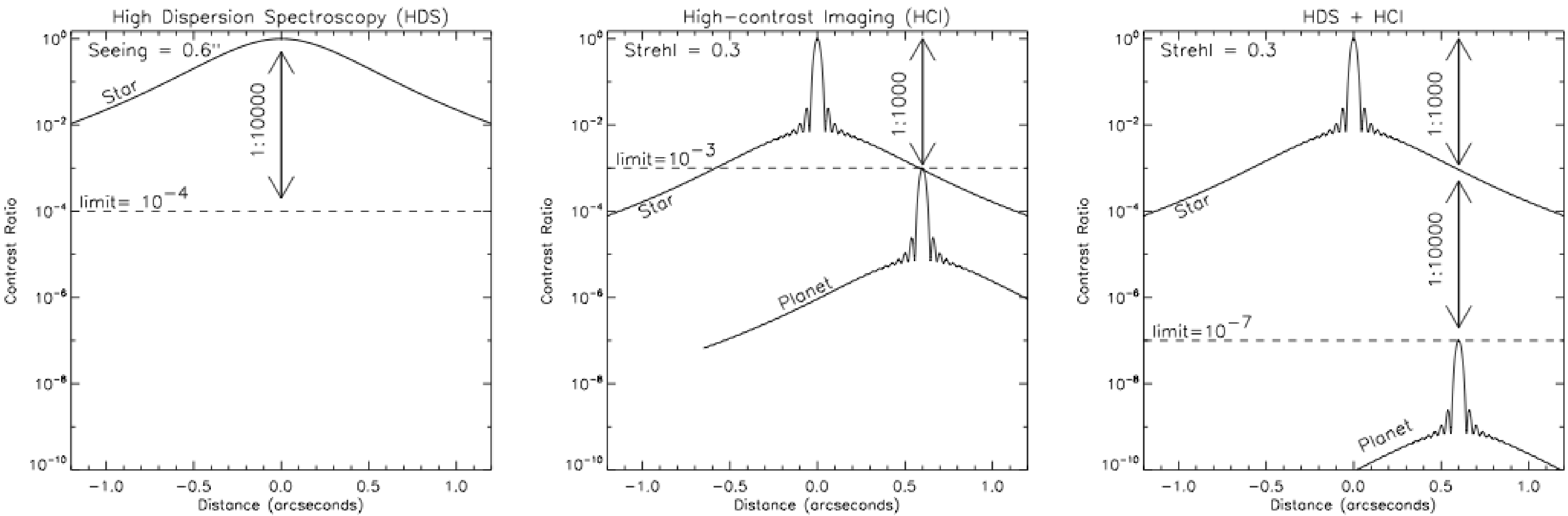


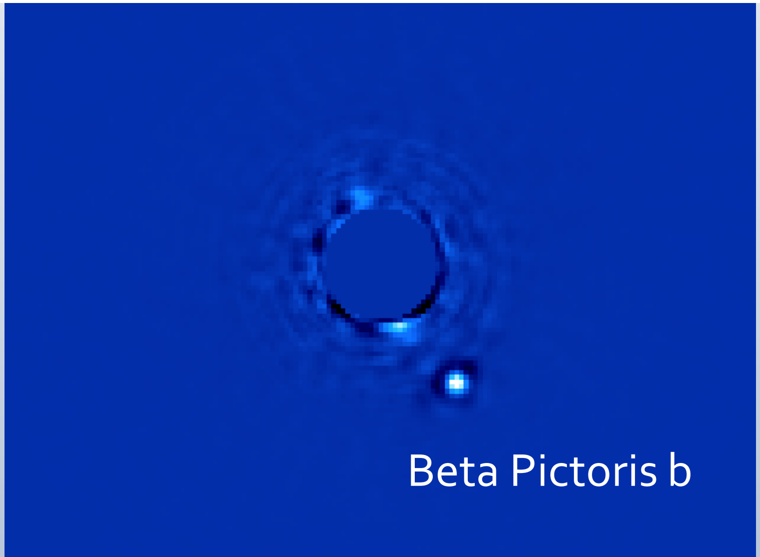
CRIRES@VLT Upgrade (2017) → 20x larger wavelength coverage
CO, H2O, CH4, NH3, H3+,.....

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

Snellen et al. Nature 2014

High Dispersion Spectroscopy + high-contrast imaging

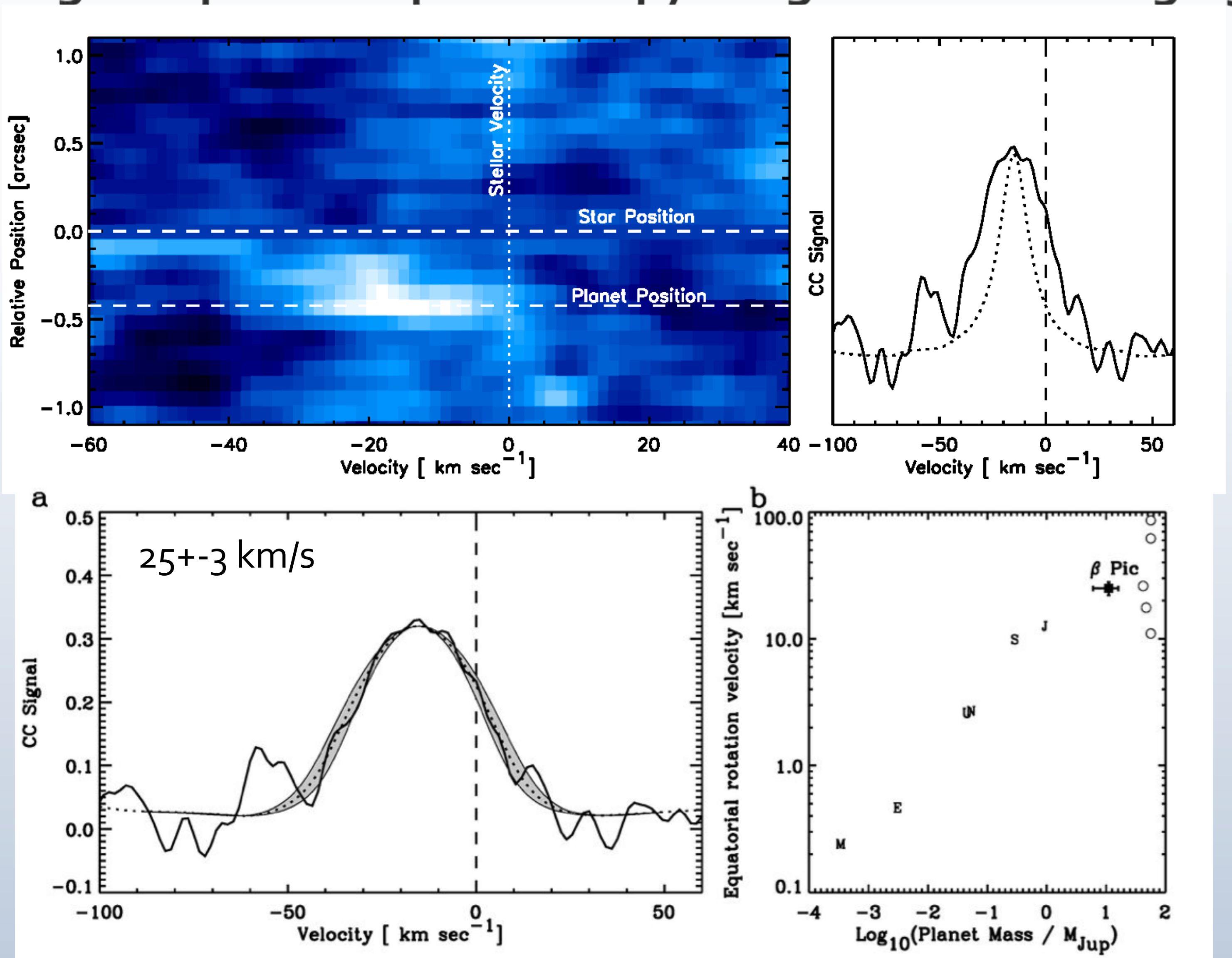




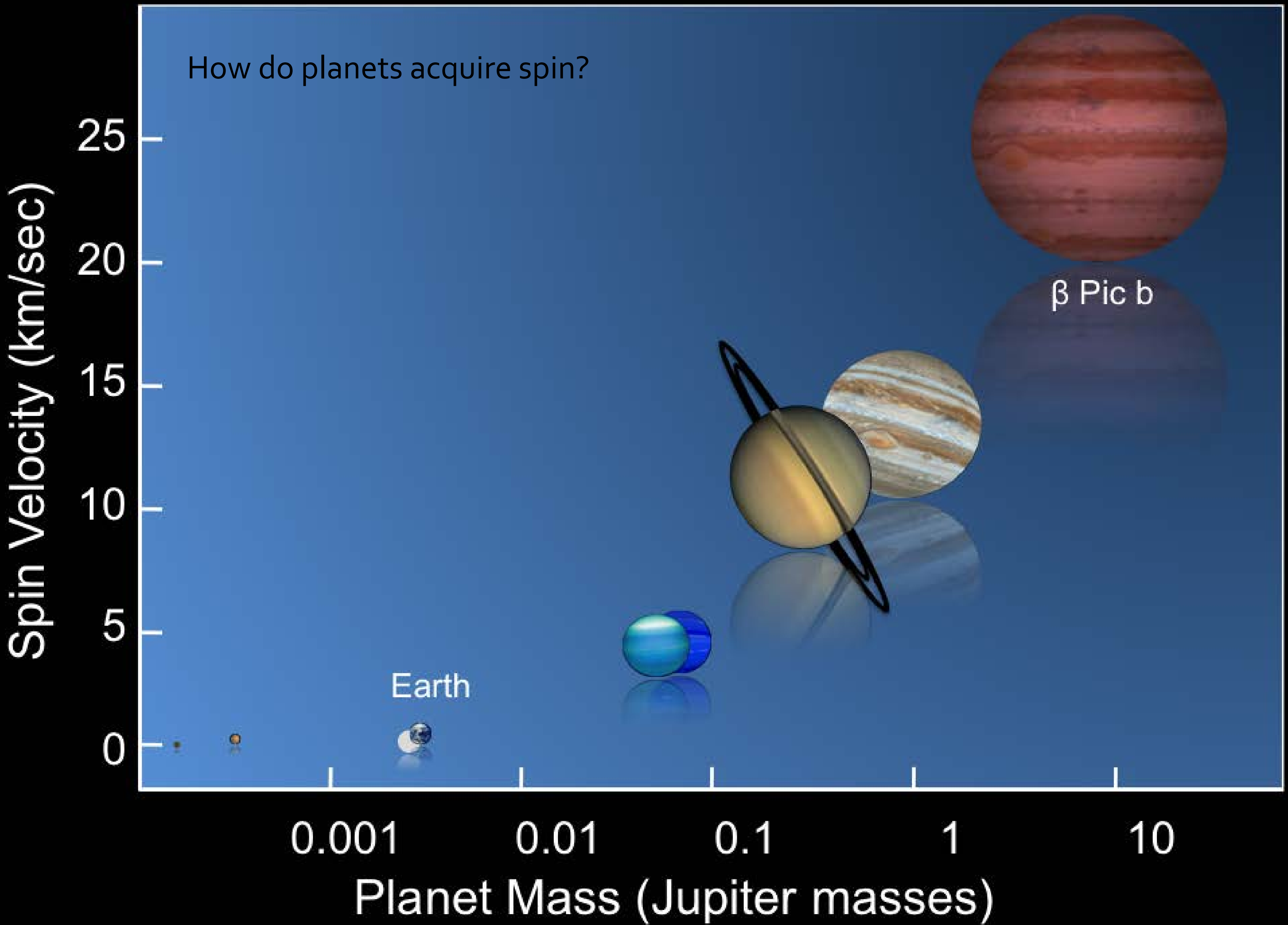
Mass = 11 (+-5) Mjup
Radius ~ 1.65 Rjup
Orbit: 17-20 years

Snellen et al. Nature 2014

High Dispersion Spectroscopy + high-contrast imaging



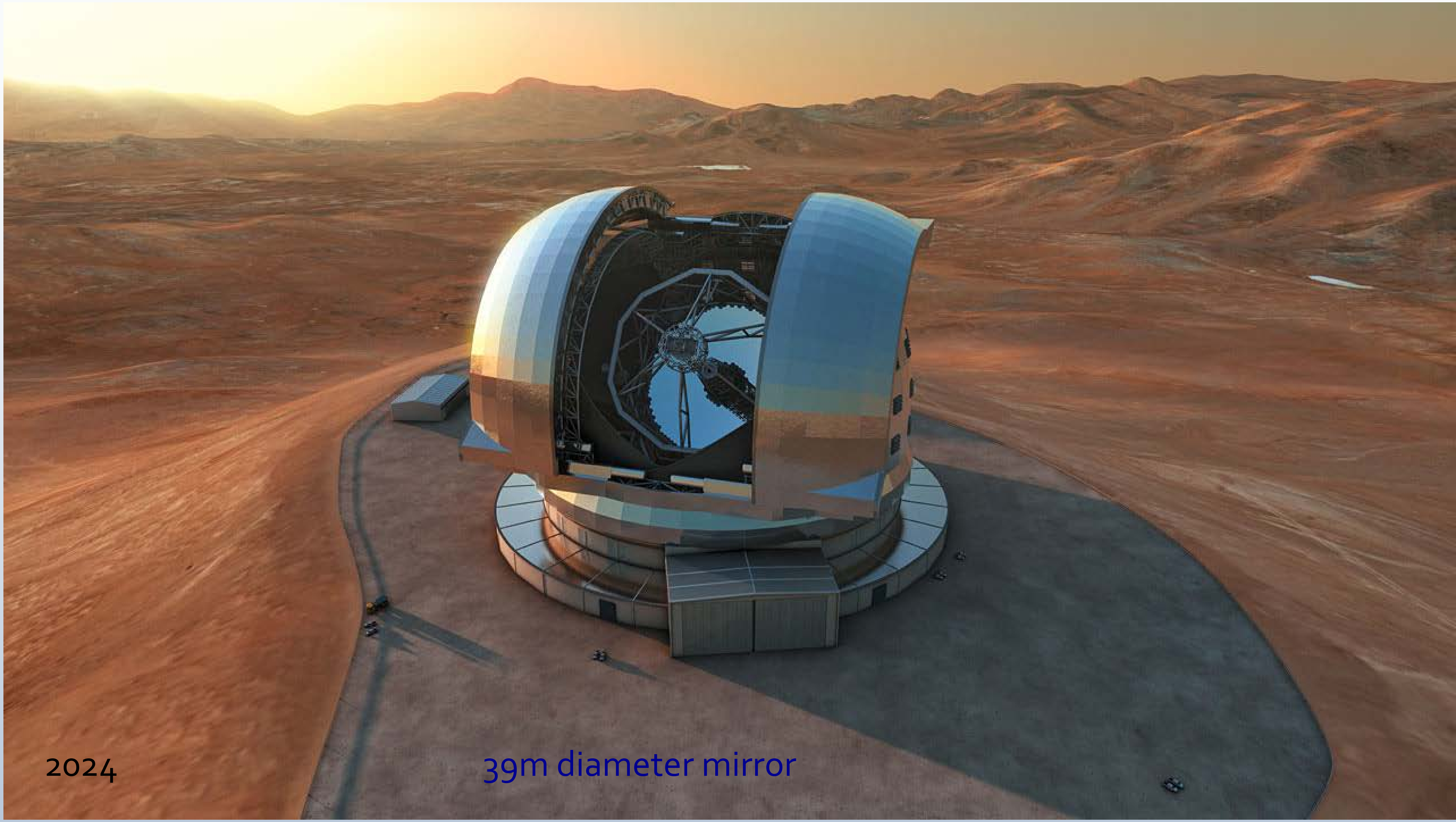
Length of Day on Beta Pictoris b ~8 hours



Leiden University

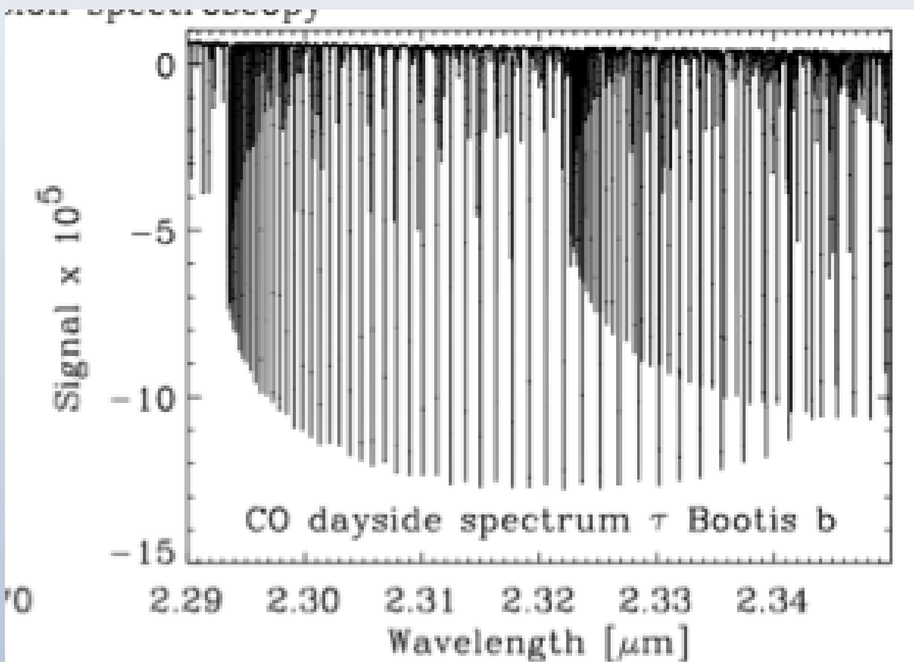
Towards characterization of Earth-like planets

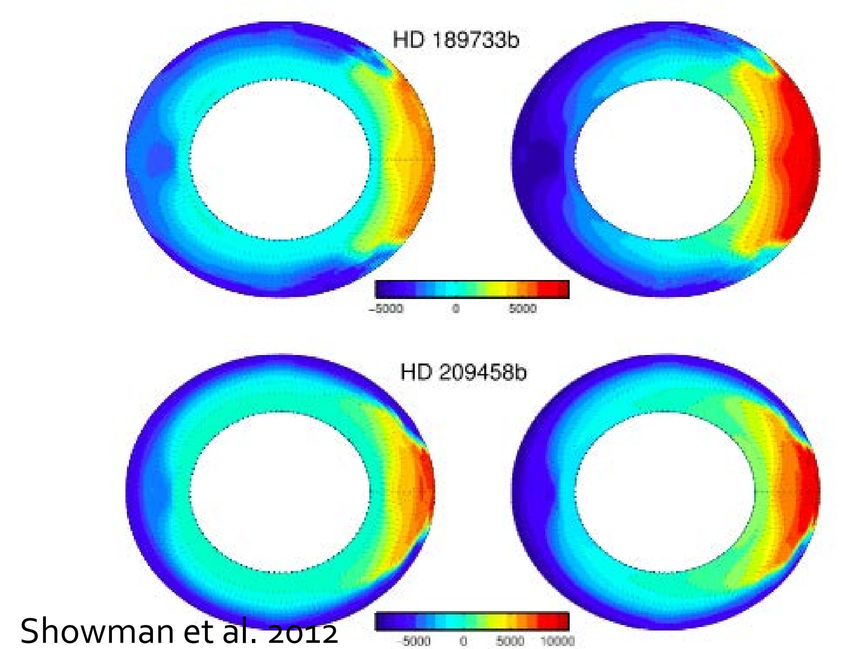
The European Extremely Large Telescope



E-ELT science

- Detection of the individual lines (instead of cross-correlation) → T/P profile; unambigous detections of inversion layers
- Line broadening → planet rotation and circulation
- Molecular spectra (CO, CO_2, H_2O, CH_4) as function of orbital phase → photochemistry, T/P versus longitude
- Isotopologues → evolution of planet atmosphere

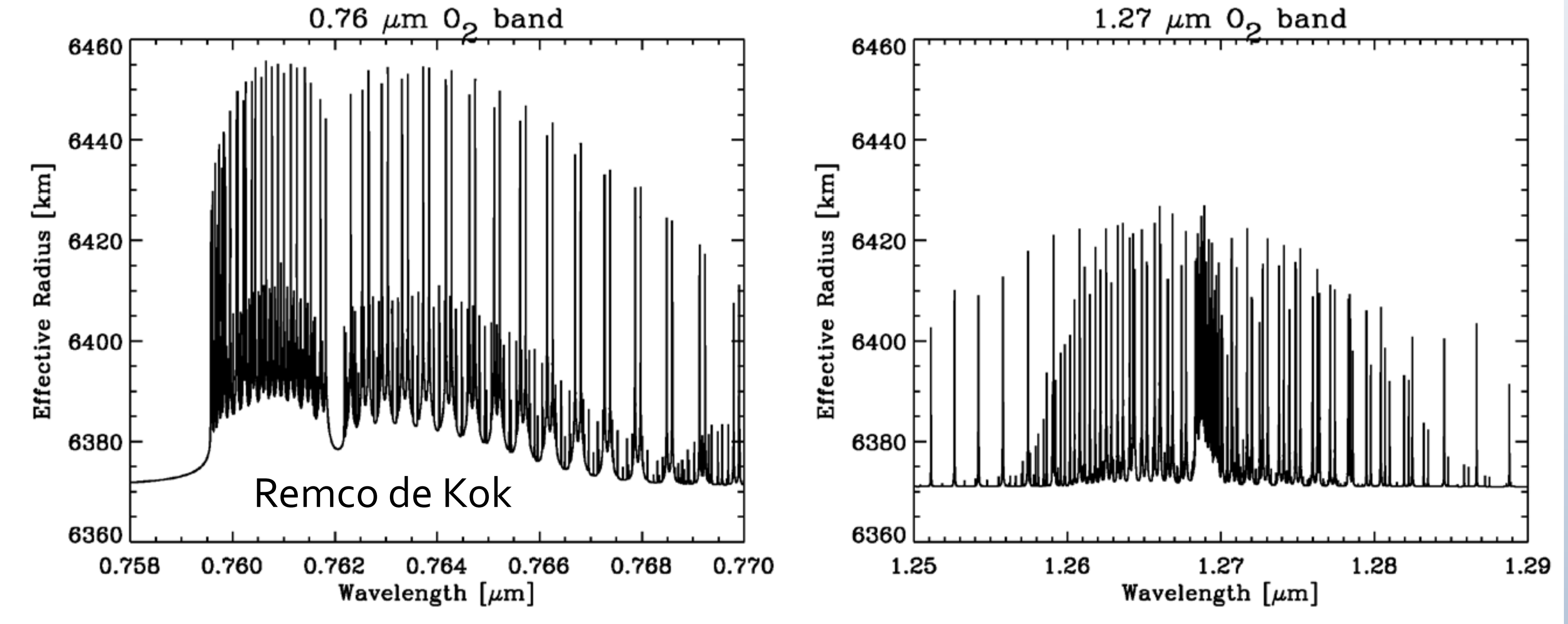




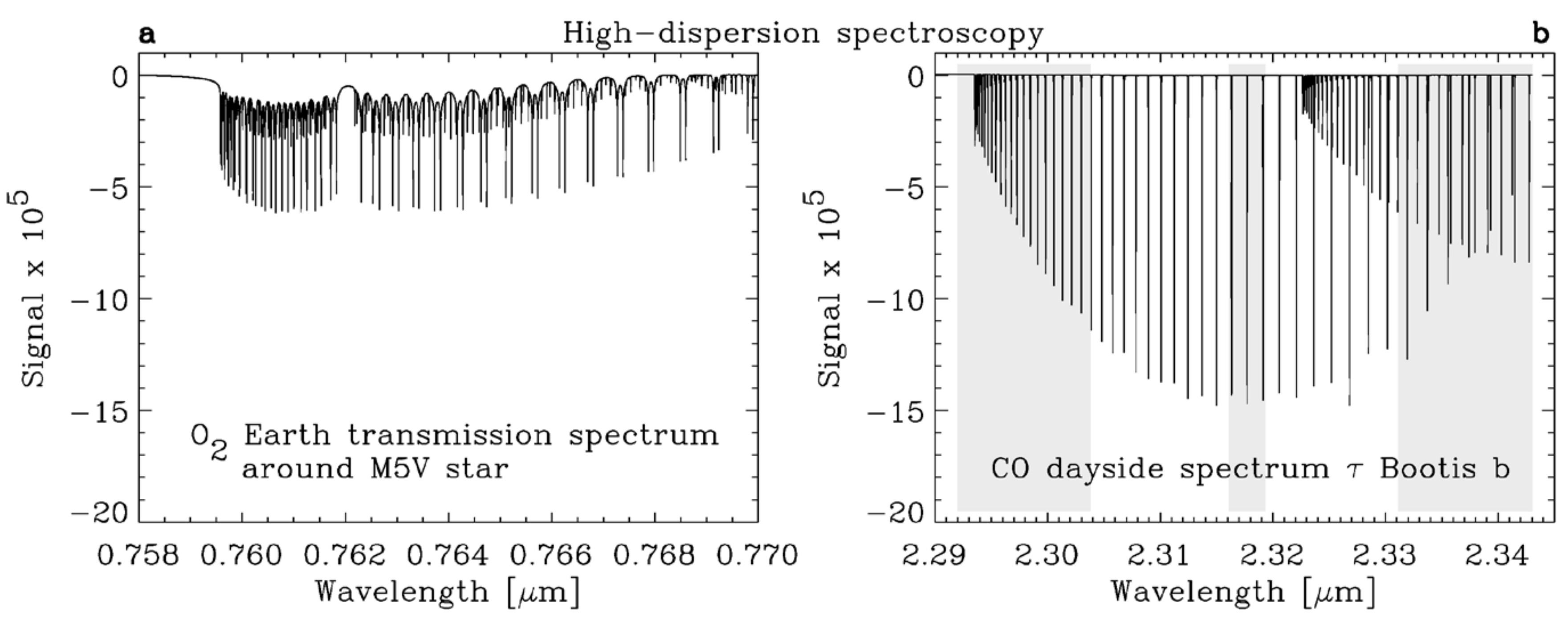
Showman et al. 2012

The Ultimate ELT Science Case: Characterizing twin-Earths

- Too high background for 9.6 um Ozone
- O2 in transmission is possible!



Optical transmission spectroscopy with the E-ELT



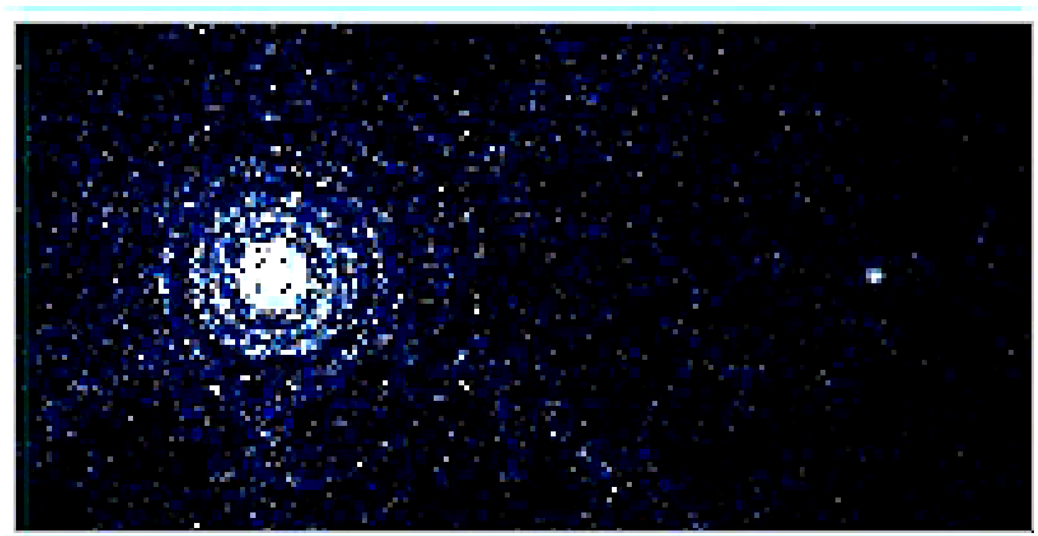
Stellar type	R_* $[R_{sun}]$	M_* $[M_{sun}]$	a_{HZ} [au]	Prob [%]	P_{HZ} [days]	Dur. [hrs]	I (η_e=1) [mag]	Line Contrast	SNR σ	Time (yrs)
G0-G5	1.00	1.00	1.000	0.47	365.3	13	4.4 - 6.1	2×10^{-6}	1.1-2.5	80-400
M0-M2	0.49	0.49	0.203	1.12	47.7	4.1	7.3 - 9.1	8×10^{-6}	0.7-1.5	20-90
M4-M6	0.19	0.19	0.058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

Snellen et al. 2013

Brightest expected systems

SNR for ELT in 1 transit

METIS@E-ELT simulations



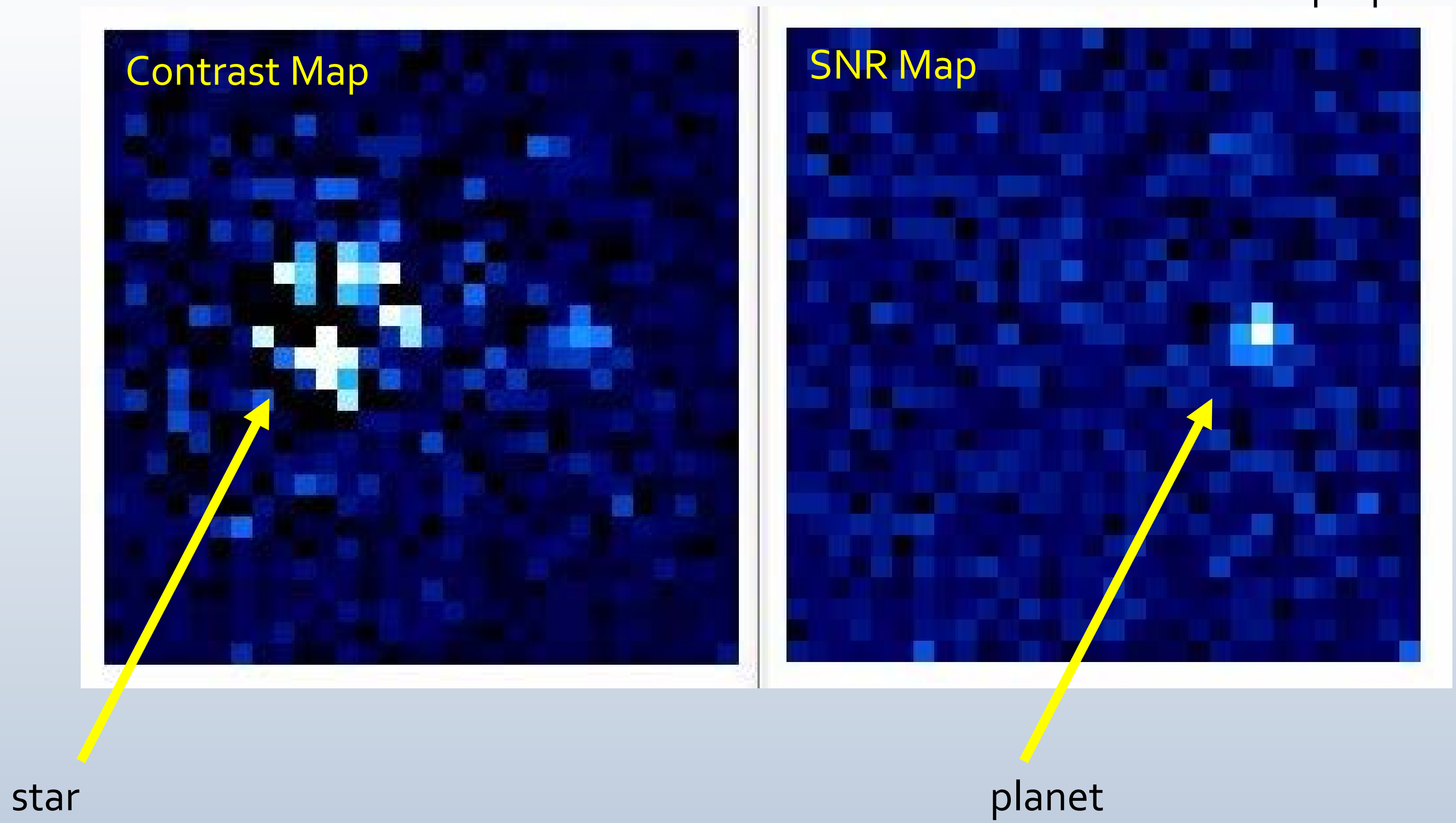
Rocky planet in the habitable zone of Alpha Centaurus A

METIS @ E-ELT, Snellen et al.2015.

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

SUMMARY

→ Exoplanets are everywhere

→ We can study atmospheres hot/warm gas giants now [molecular gases, circulation, rotation]

→ First generation of instruments on E-ELT allows study of Earth-like planets (2025)

→ Technical development → 2nd generation of instruments will allow study of biomarker gases (>2030)

Thank You