# Extrasolar Planets & the search for Extraterrestrial life

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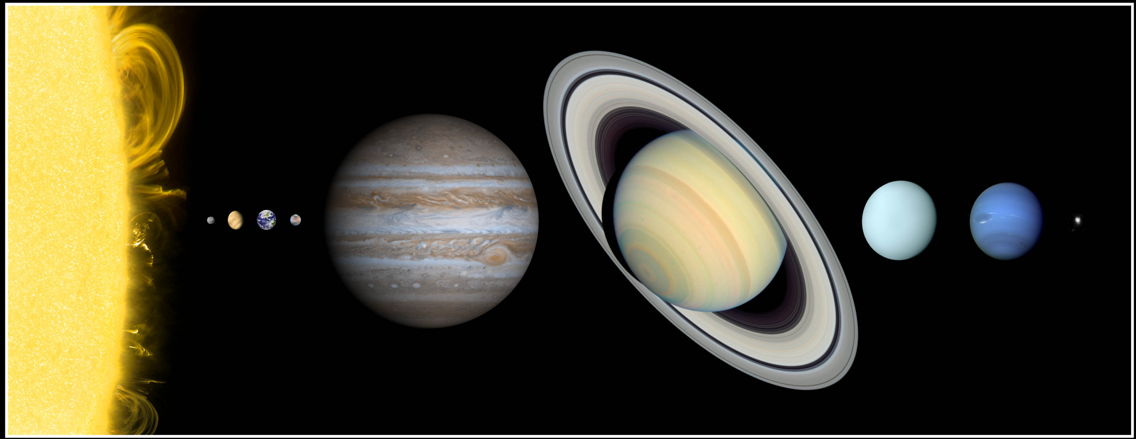
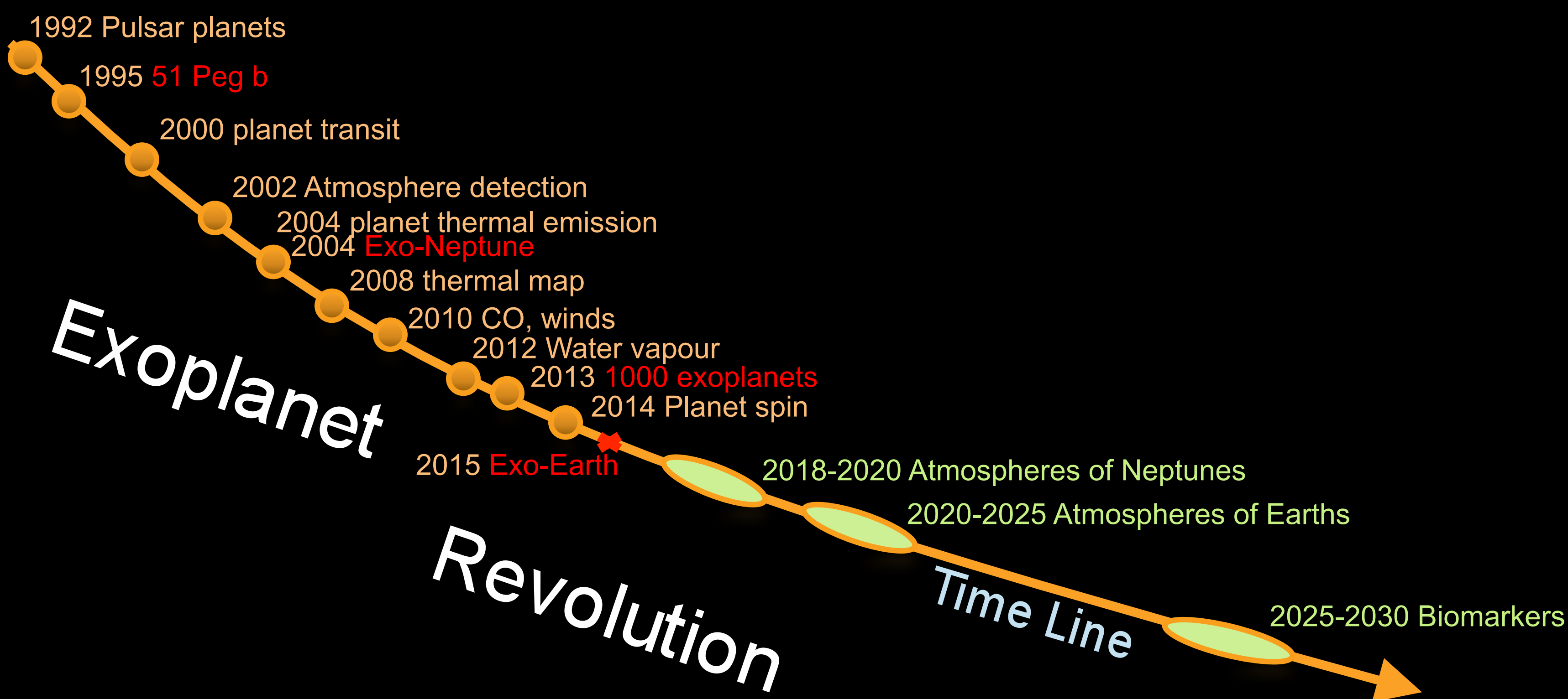
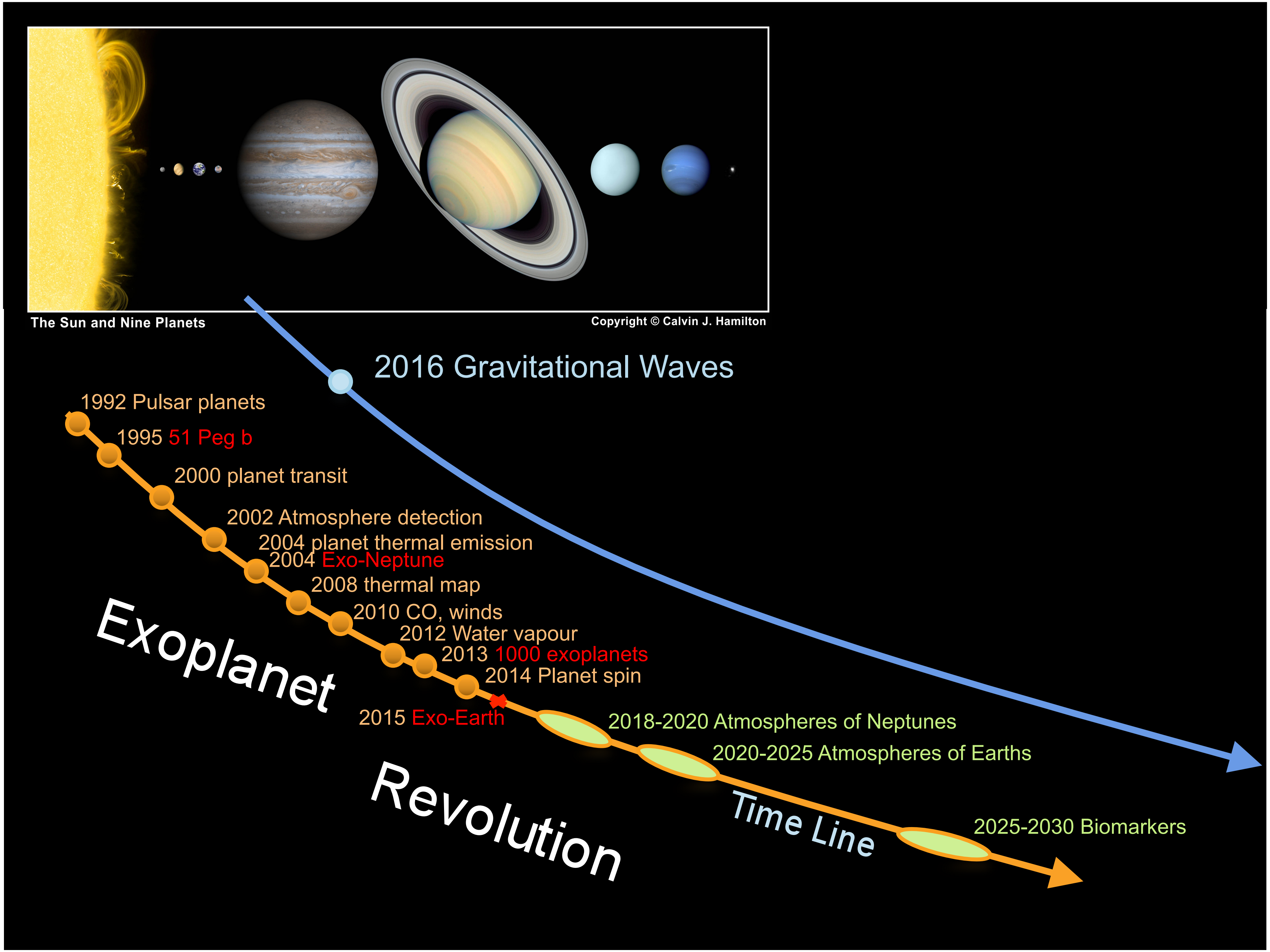


The Sun and Nine Planets







The Sun and Nine Planets
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2016 Gravitational Waves
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

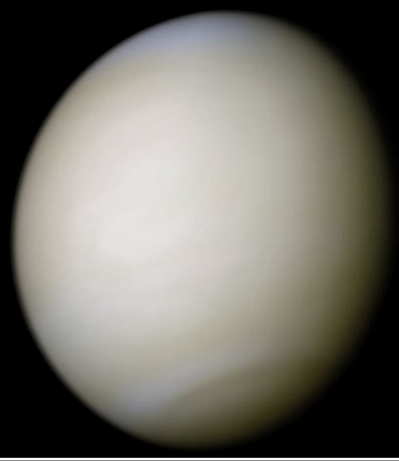
**Gas giants**:

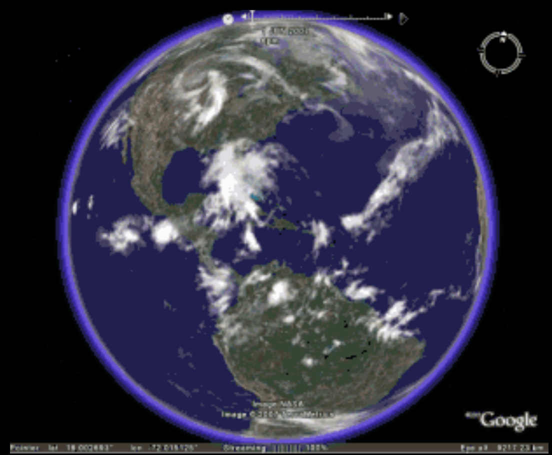
H2-dominated; clouds; strong zonal flows; storms

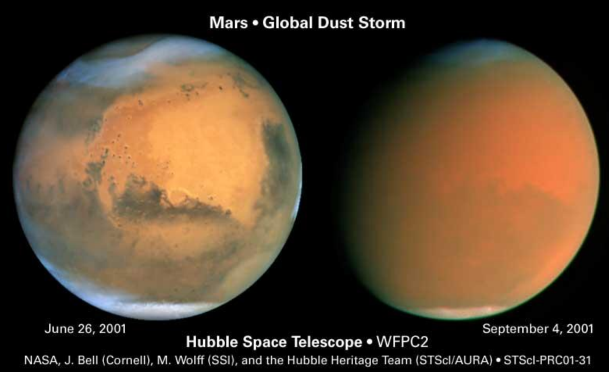
# What we learn from the Solar System

Planets show an immense complexity and diversity

**Rocky planets**: secondary atmospheres – very diverse

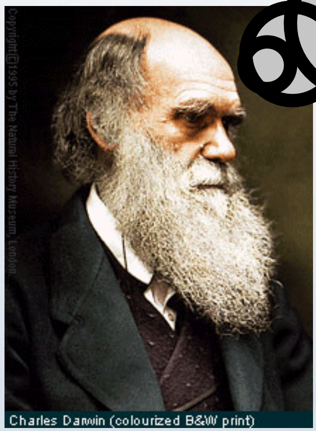







| | | |
|---|---|---|
| **Super-rotating,<br>$CO_2$ based<br>Opaque sulfuric acid clouds** | **Partially clear,<br>$N_2$-based<br>Biotic oxygen** | **Tenuous $CO_2$<br>Varying trace-amount of methane** |

## 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

| Exoplanets |
| --- |
| Possible |
| hard |
| Very difficult? |
| Impossible! |

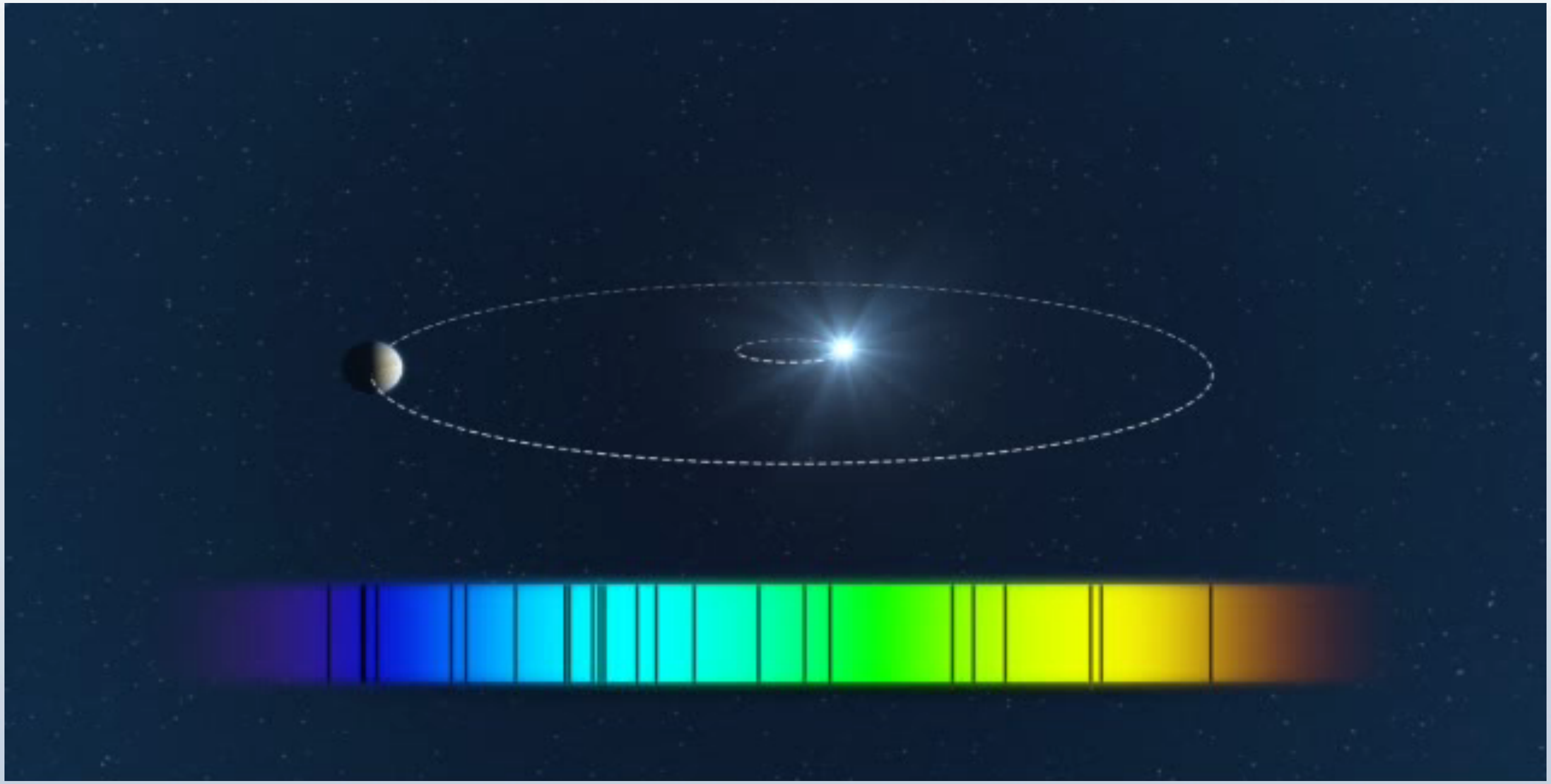
# The place of Earth & our Solar system in the Universe

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

# Finding Exoplanets

# Techniques to find exoplanets

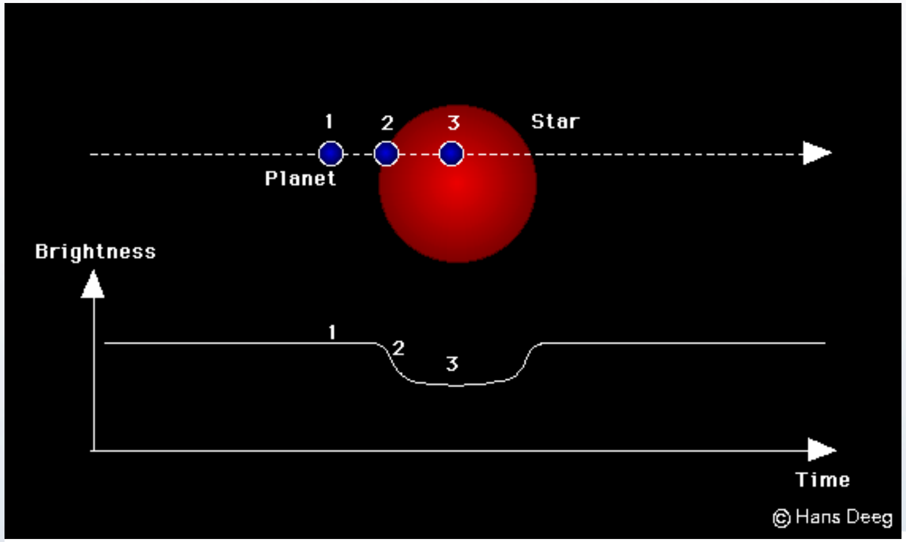
- **Radial Velocity Technique**
- Measures the reflex motion of the host-star around the center of mass
- Very successful. Hundreds of planets found

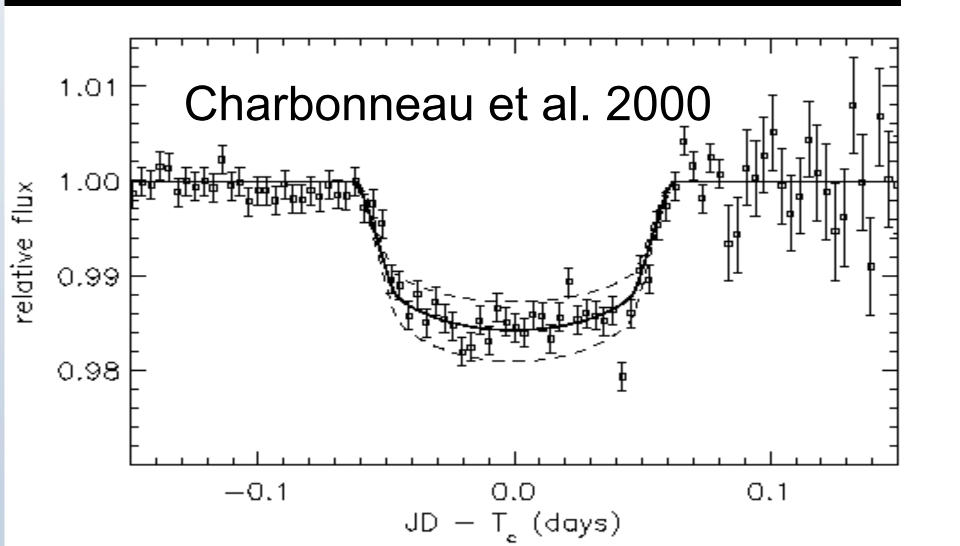


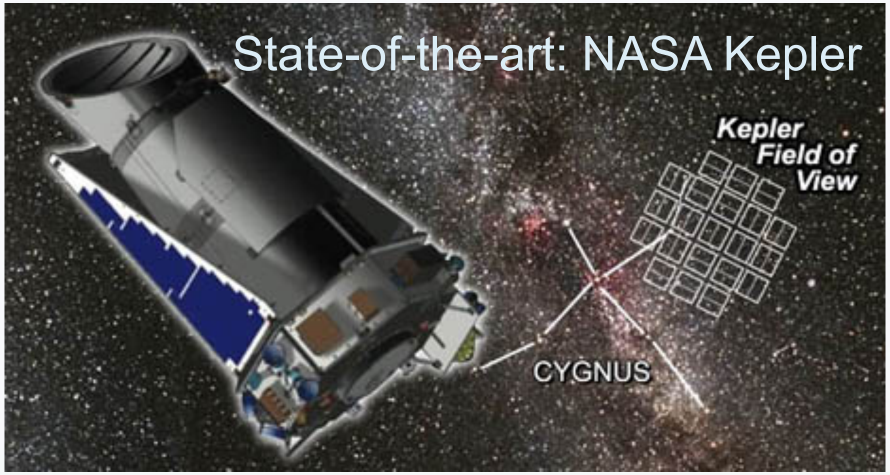
# Techniques to find exoplanets

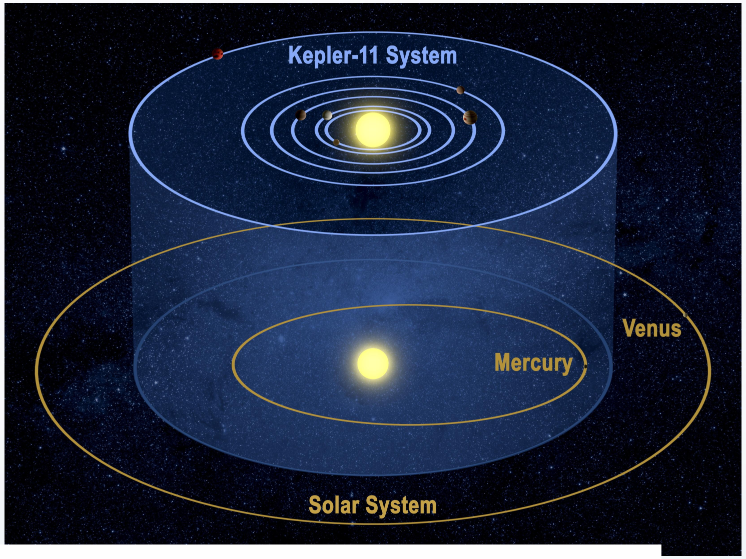
- **Transit technique**

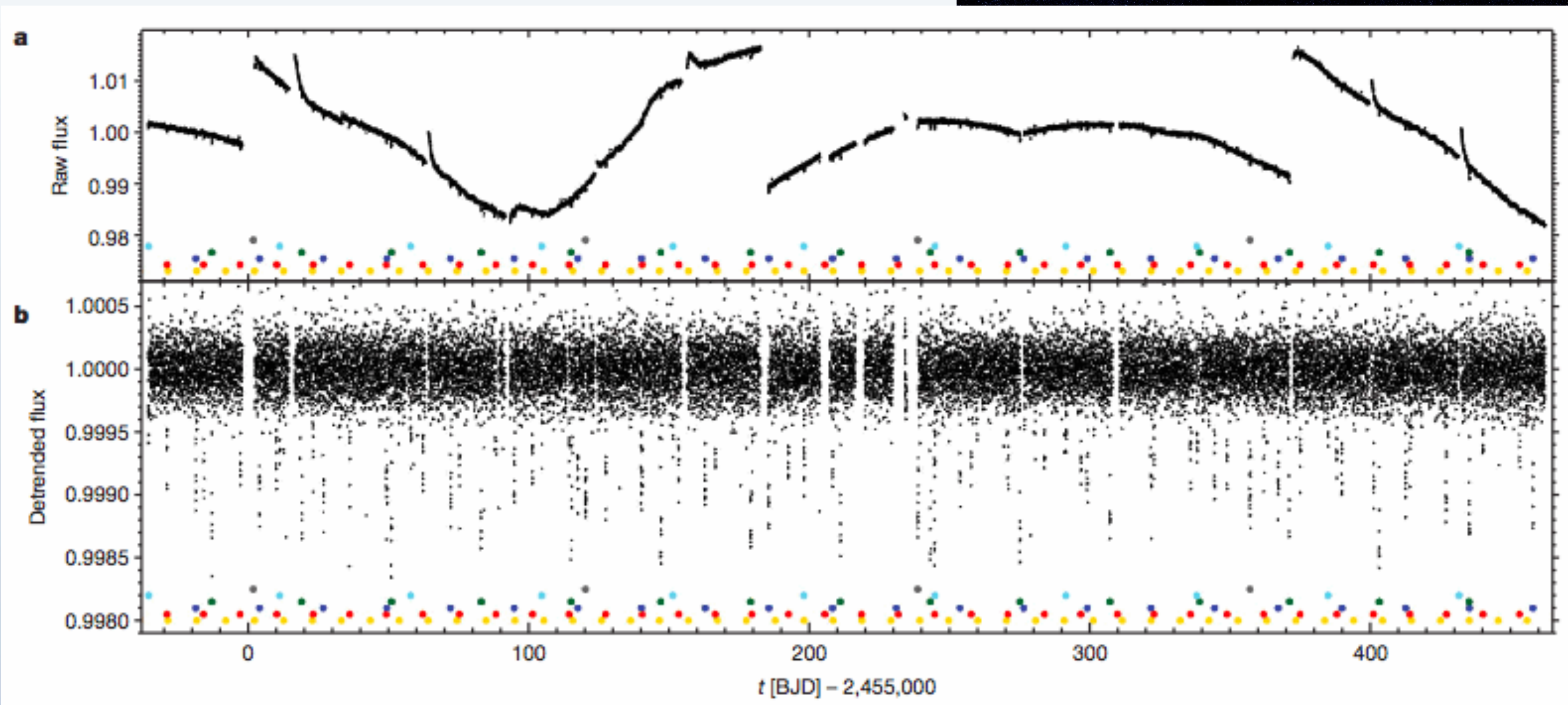
If lucky, planet can be seen to move in front of stellar disk




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

# Techniques to find exoplanets

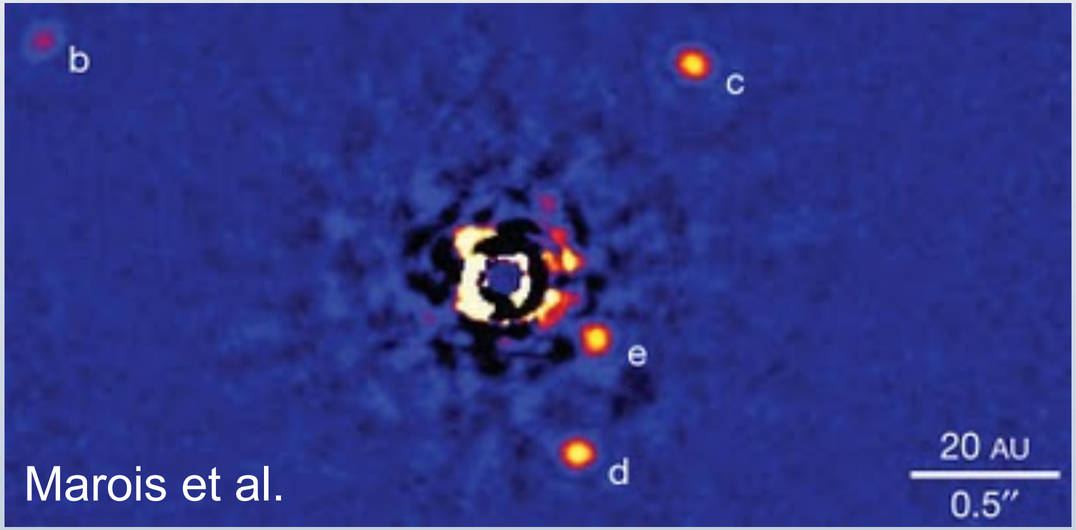
- **High Contrast imaging**

→ Approach theoretical PSF with adaptive optics

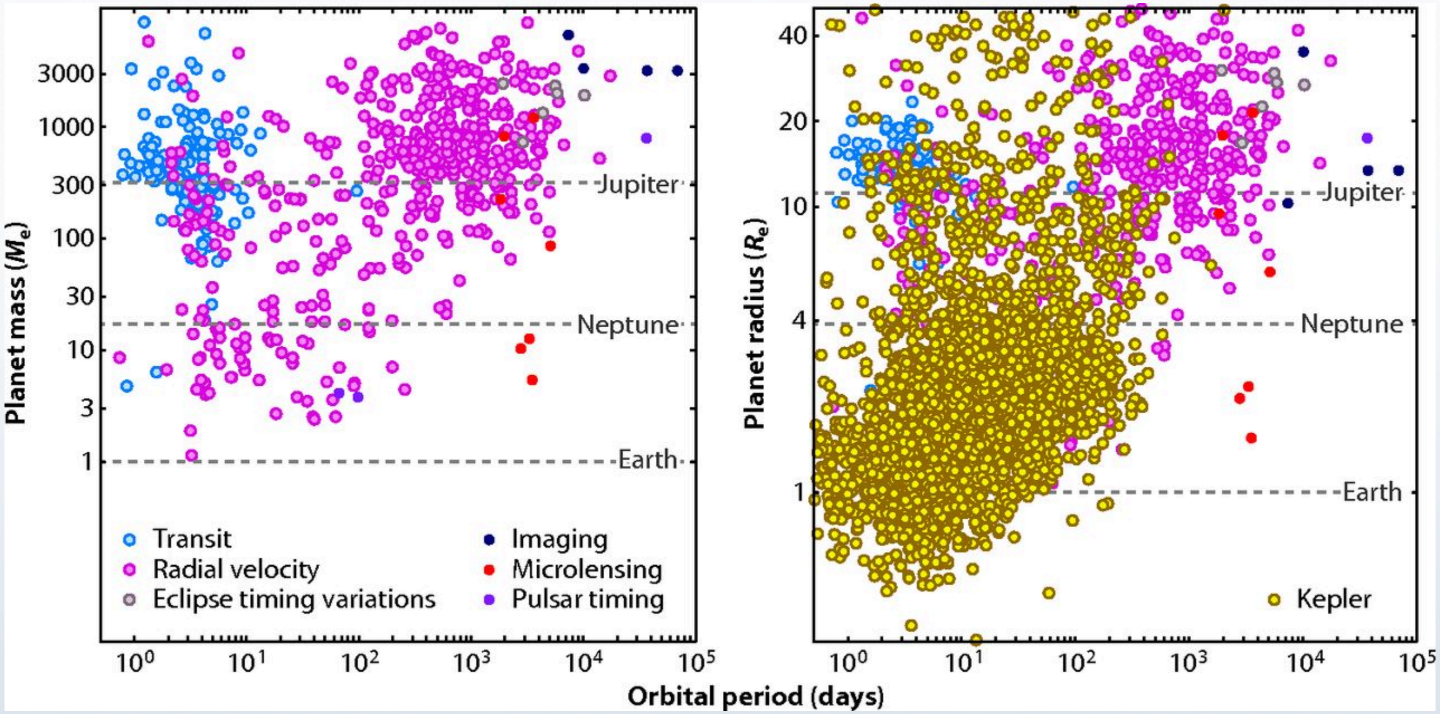
→ Alter (part of) PSF with coronagraphy

→ Smart algorithms to remove starlight

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



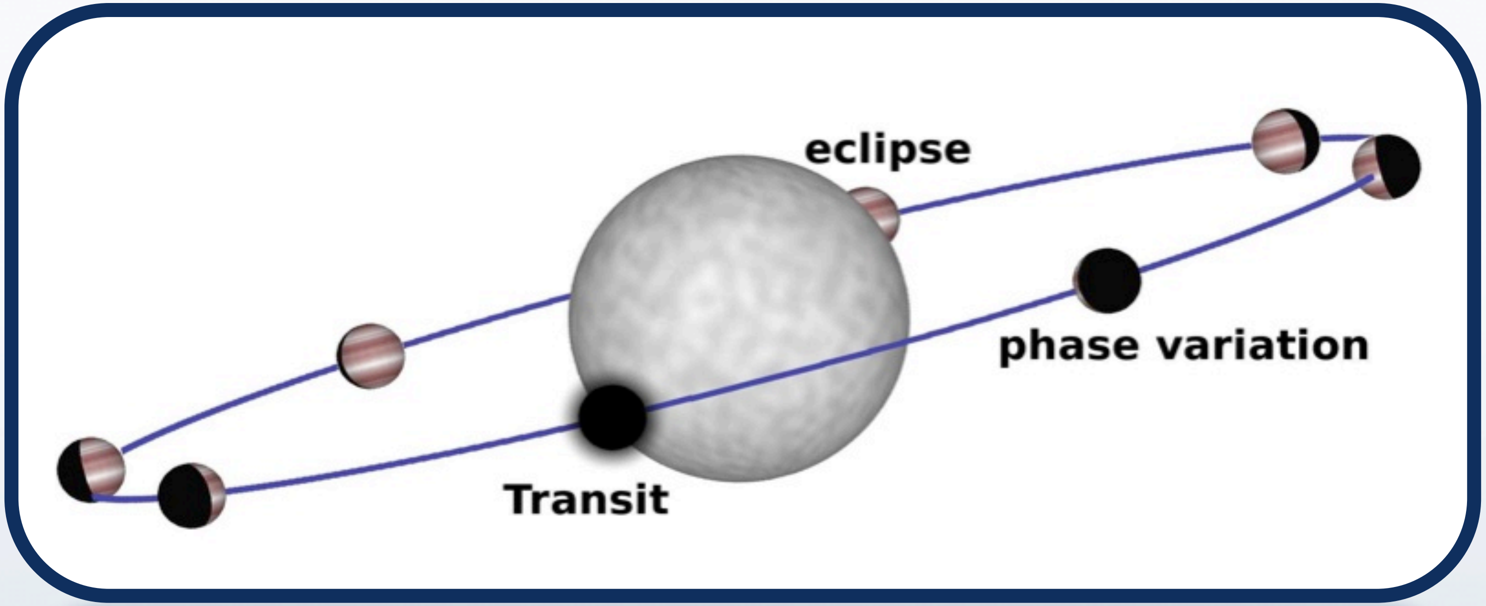
# Exoplanet population

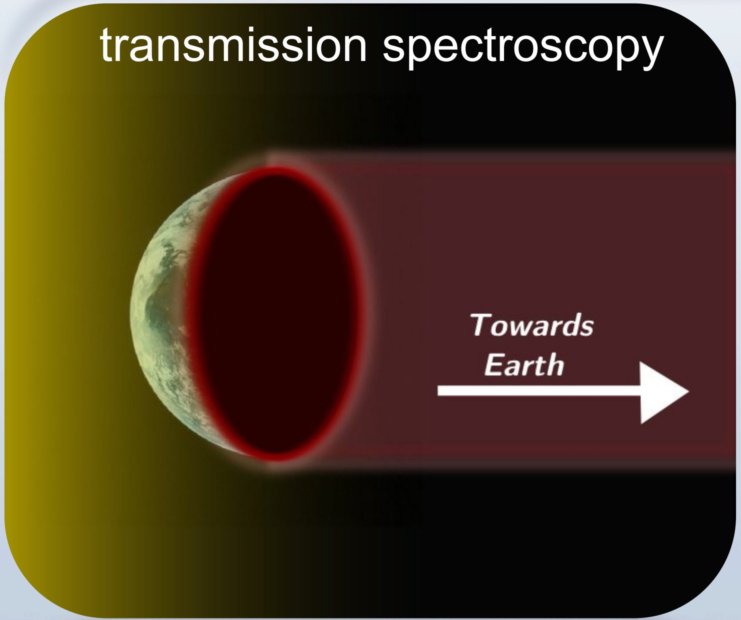


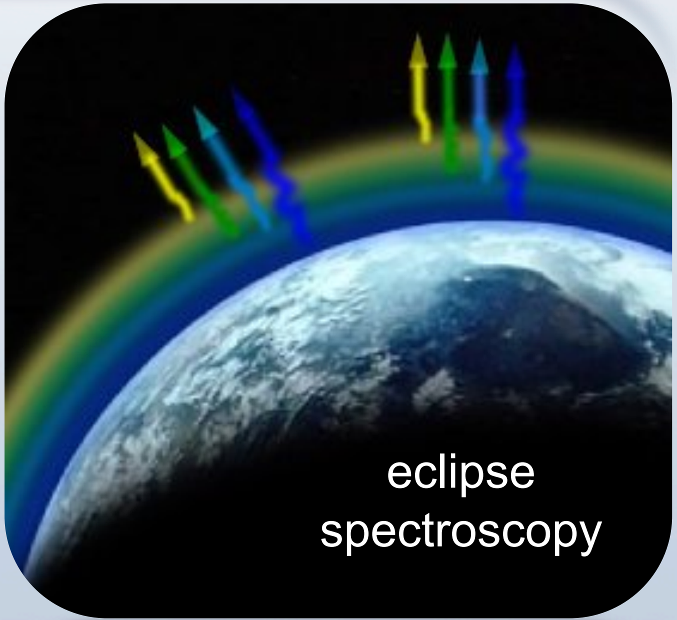

1 in 10 stars has a Jupiter-mass planet
1 in 3 stars has a Neptune-mass planet
Most of the stars have an Earth-mass planet

# Atmospheric Characterization

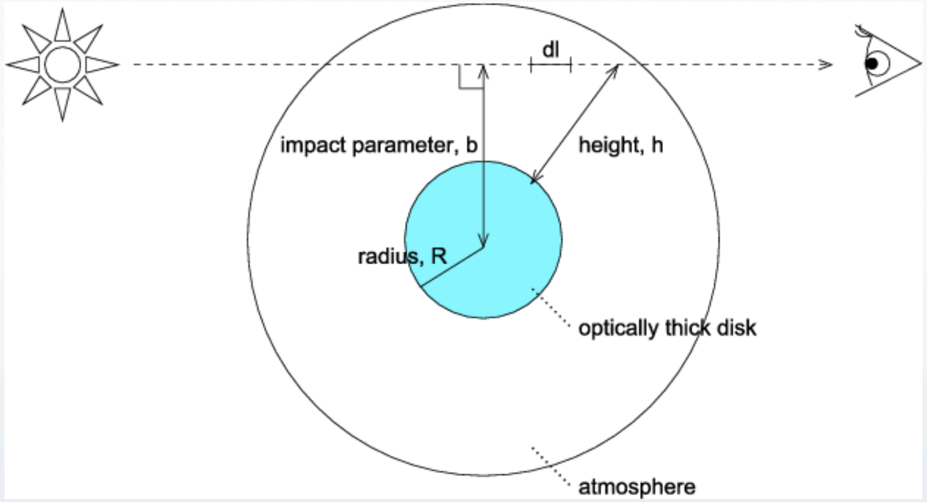
# Exoplanet atmospheres



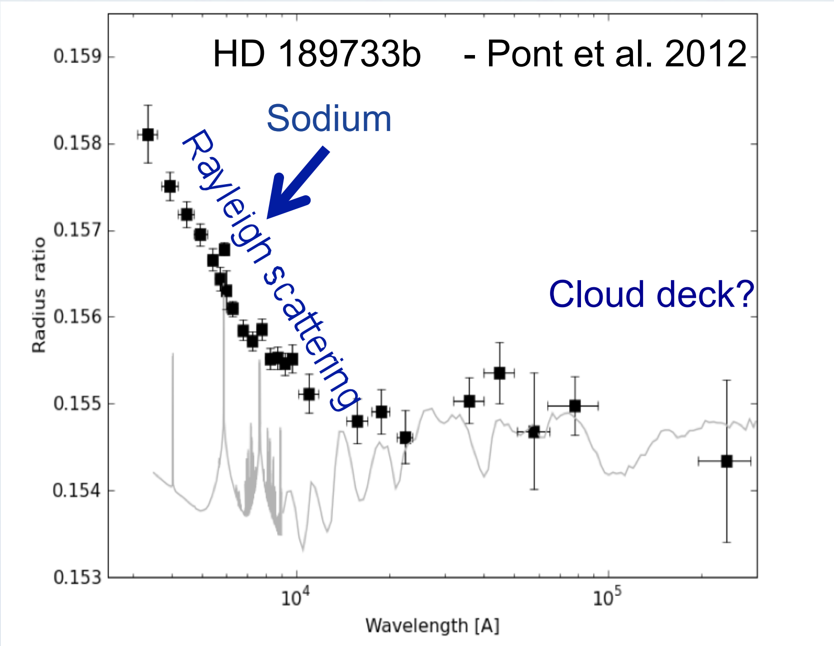
# Transmission spectroscopy

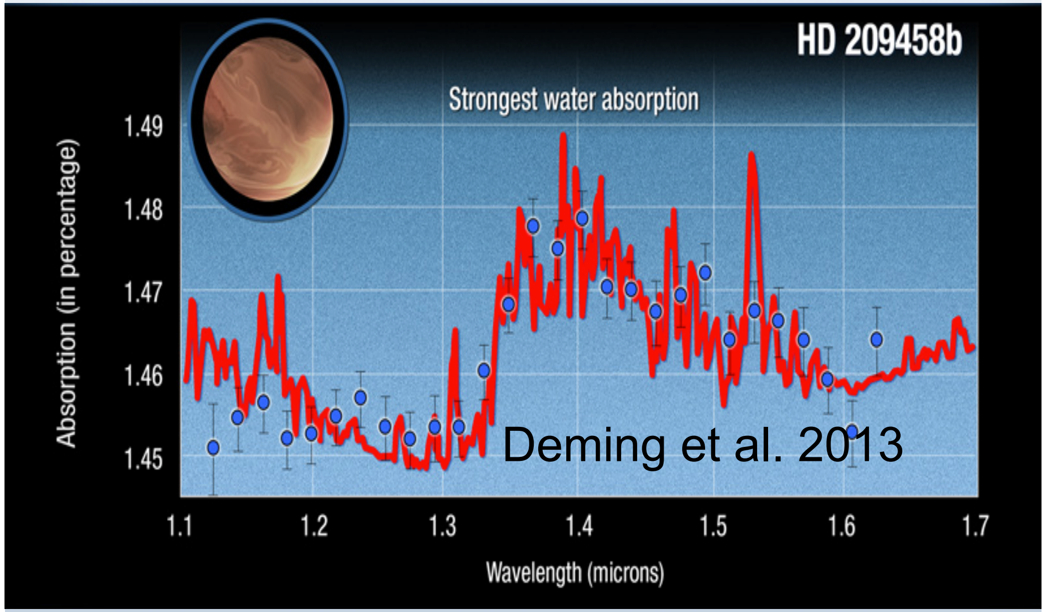



Scale Height, $H \sim \frac{T}{\mu g}$

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

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

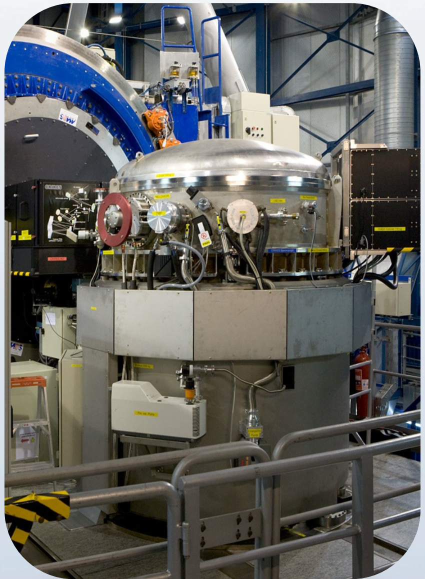


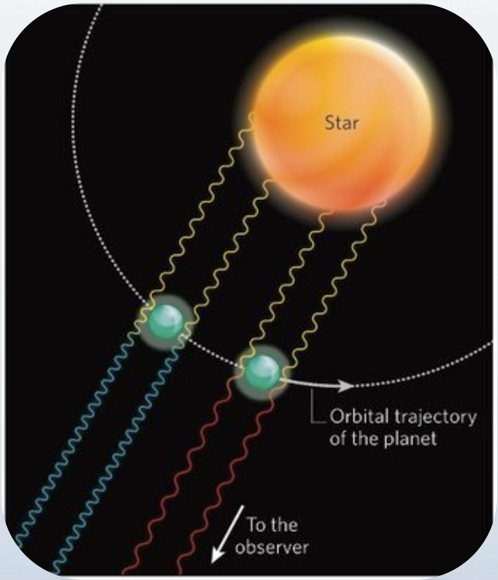



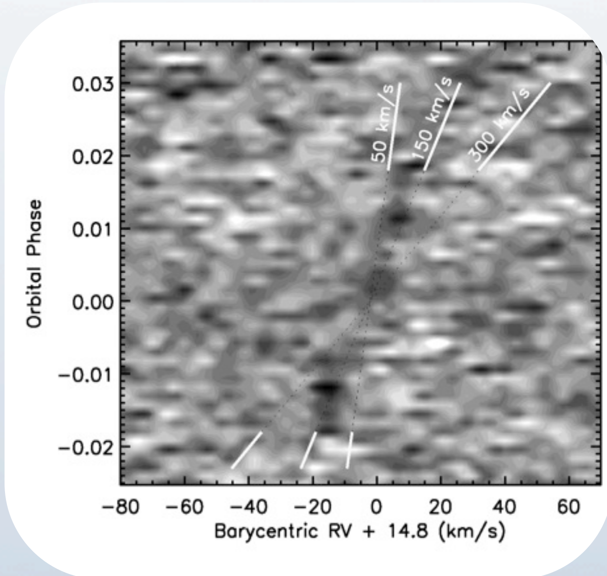
# Expertise - Leiden Exoplanet Group

## Unique capabilities of ground-based instruments

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





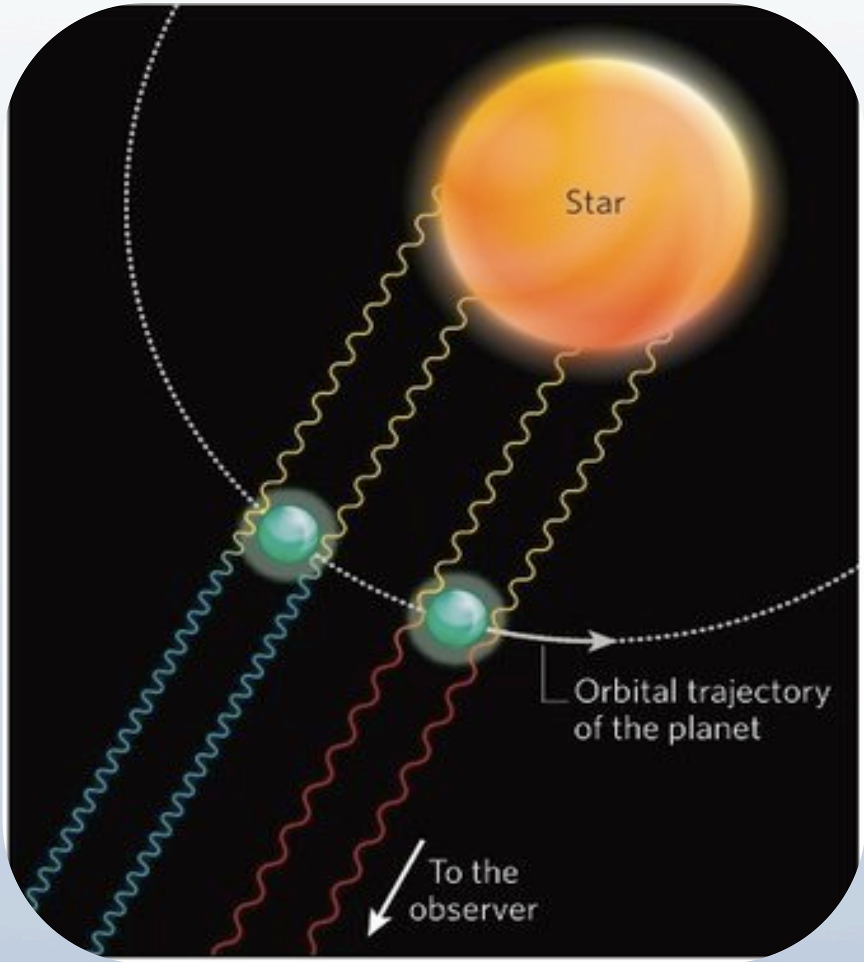

Snellen et al. 2008; De Mooij & Snellen 2009; Snellen et al. ***Nature*** 2009; Albrecht et al. ***Nature*** 2009; Snellen et al. ***Nature*** 2010; Brogi et al. ***Nature***, 2012, Snellen et al. ***Nature*** 2014

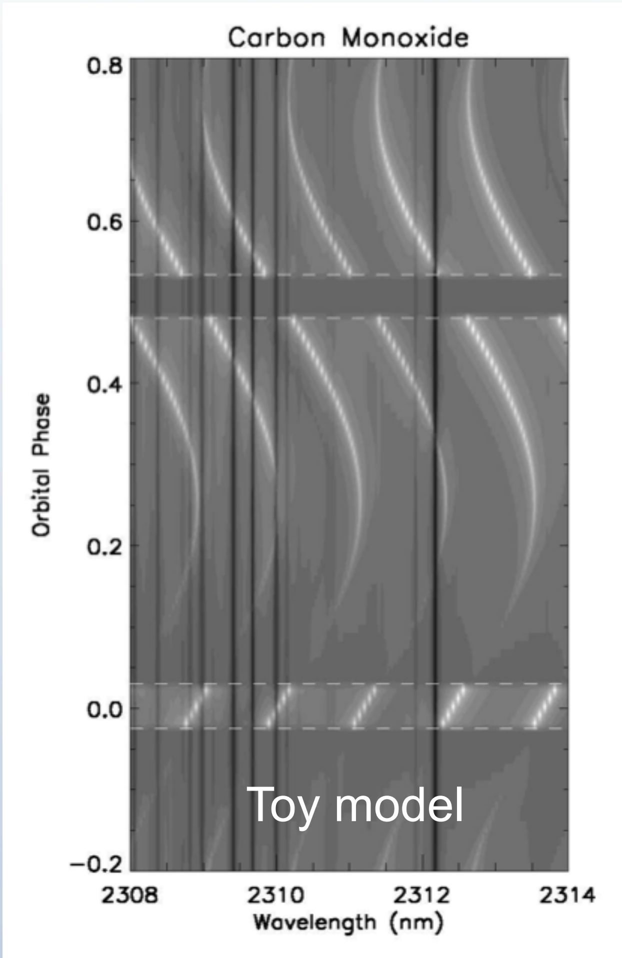
Snellen et al. 2008; De Mooij & Snellen 2009; Snellen et al. ***Nature*** 2009;


European Southern Observatory
Very Large Telescope (4x8m telescopes)

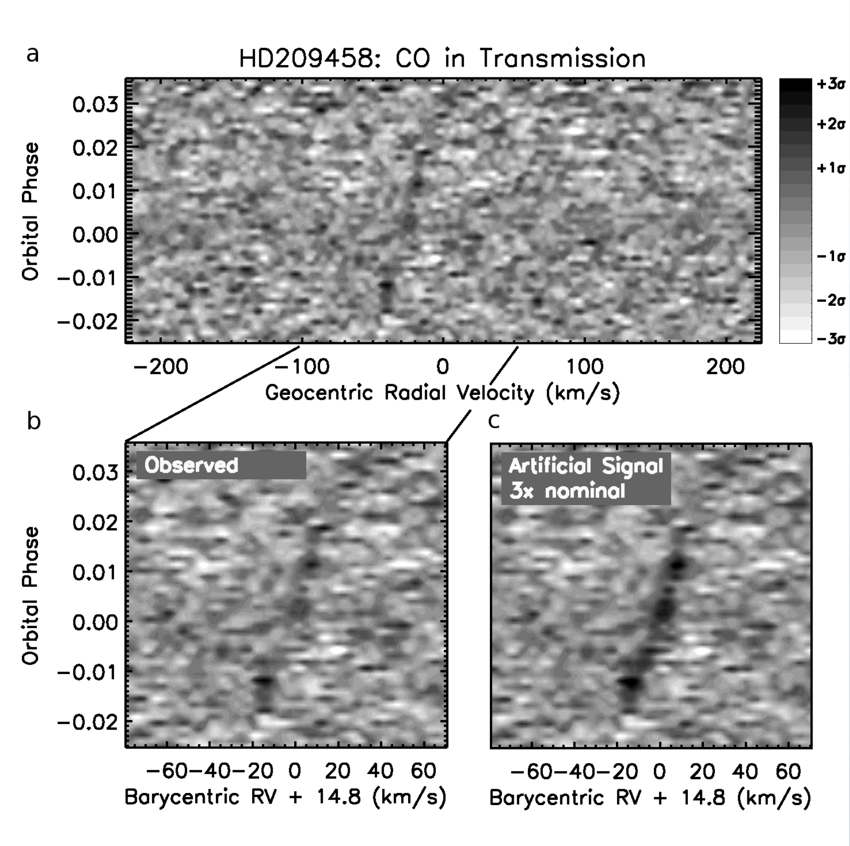
# Ground-based High-dispersion spectroscopy

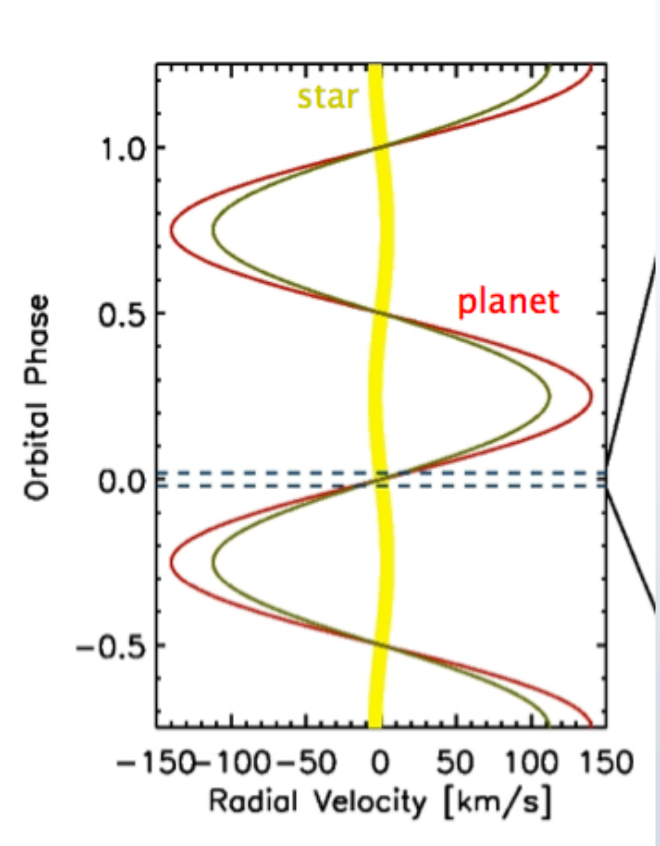
- At R=100,000 molecular bands are resolved in tens of individual lines
- Strong doppler effects  due orbital motion of the planet (up to  >150 km/s).
- Moving planet lines can be distinguished from stationary telluric + stellar lines



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



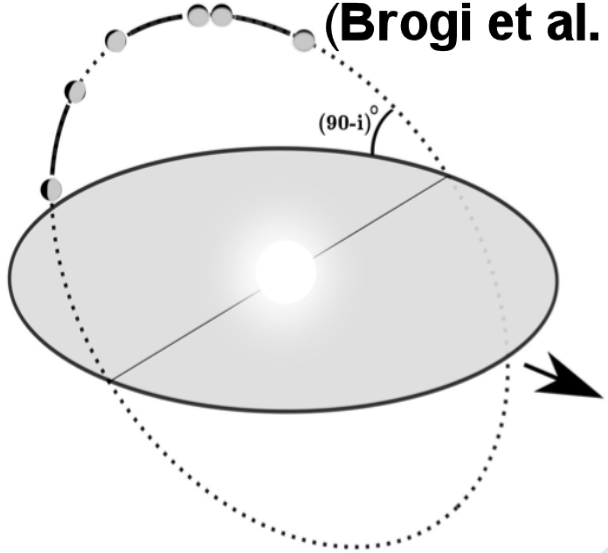



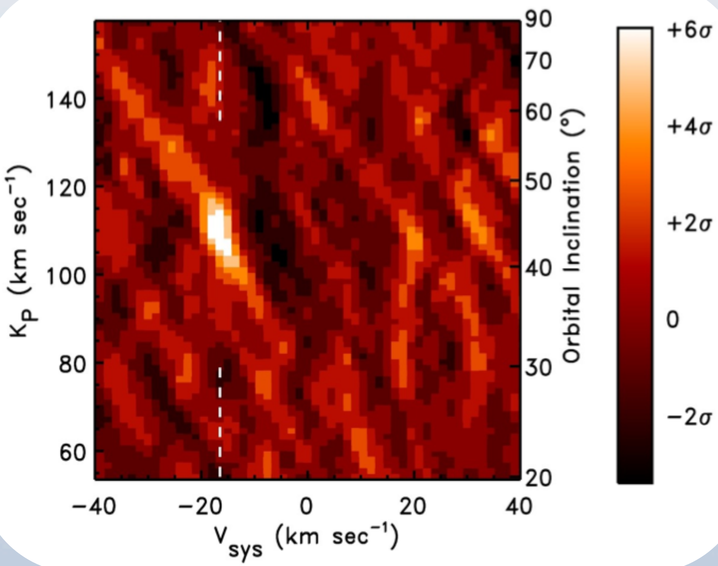

- Reveals planet orbital velocity
- Solves for masses of both planet and star (model independent)
- Evidence for blueshift (high altitude winds?)

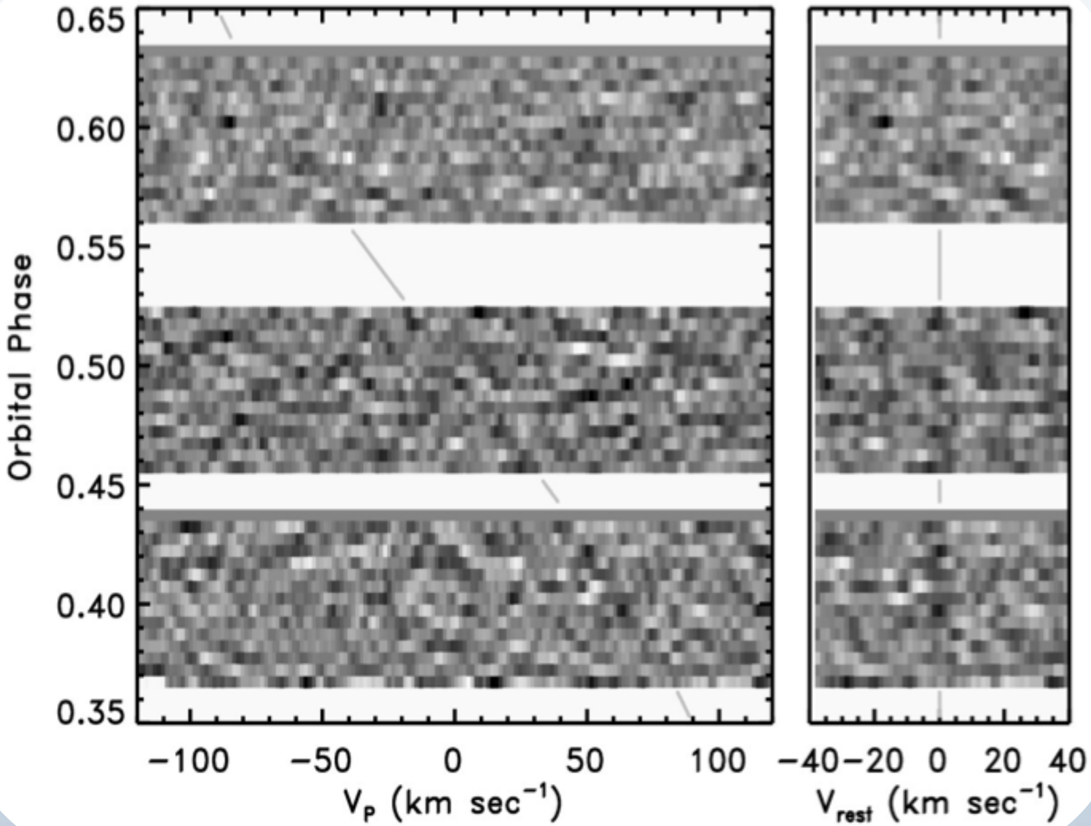
# CO in dayside spectrum of tau Bootis b (CRIRES@VLT)

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

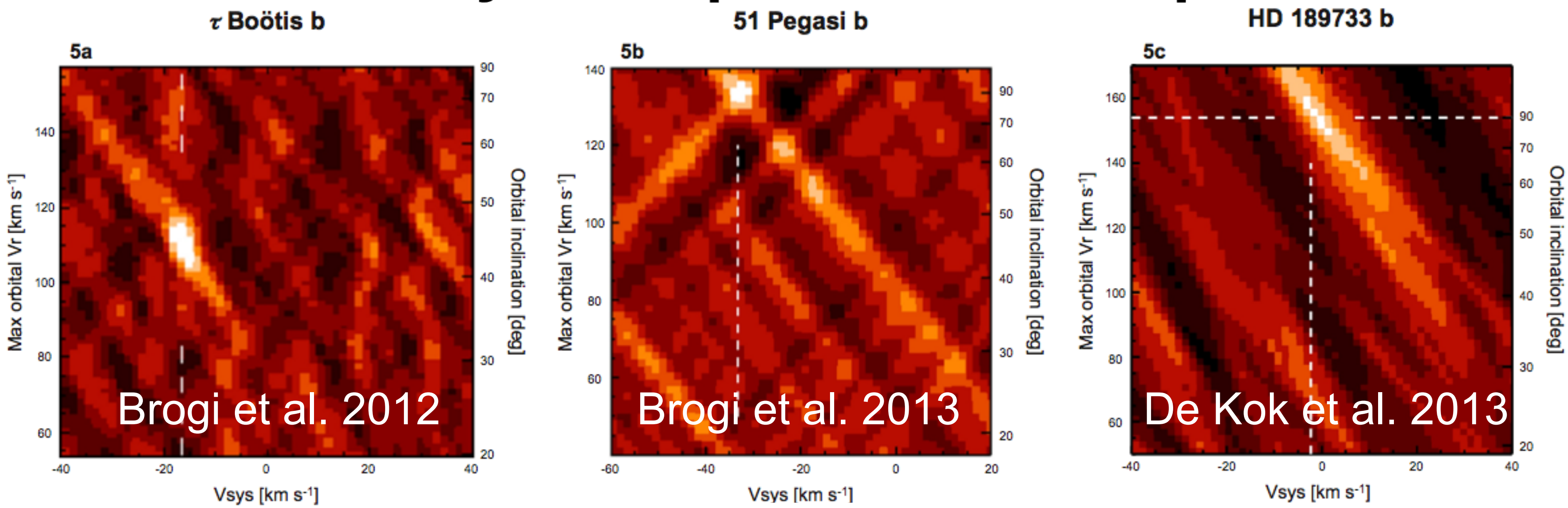
First detection of non-transiting planet→ inclination, mass

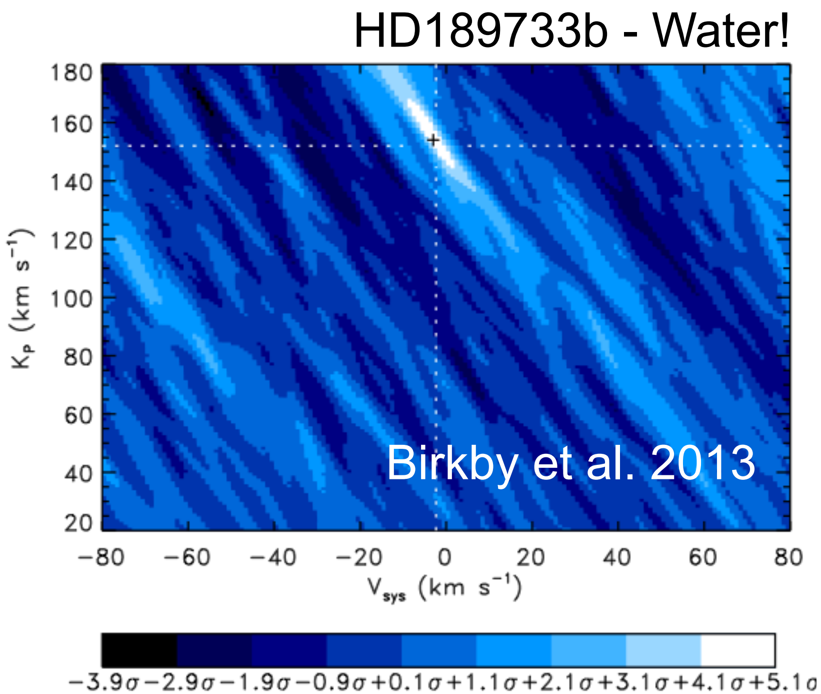


# CO in dayside spectra of hot Jupiters



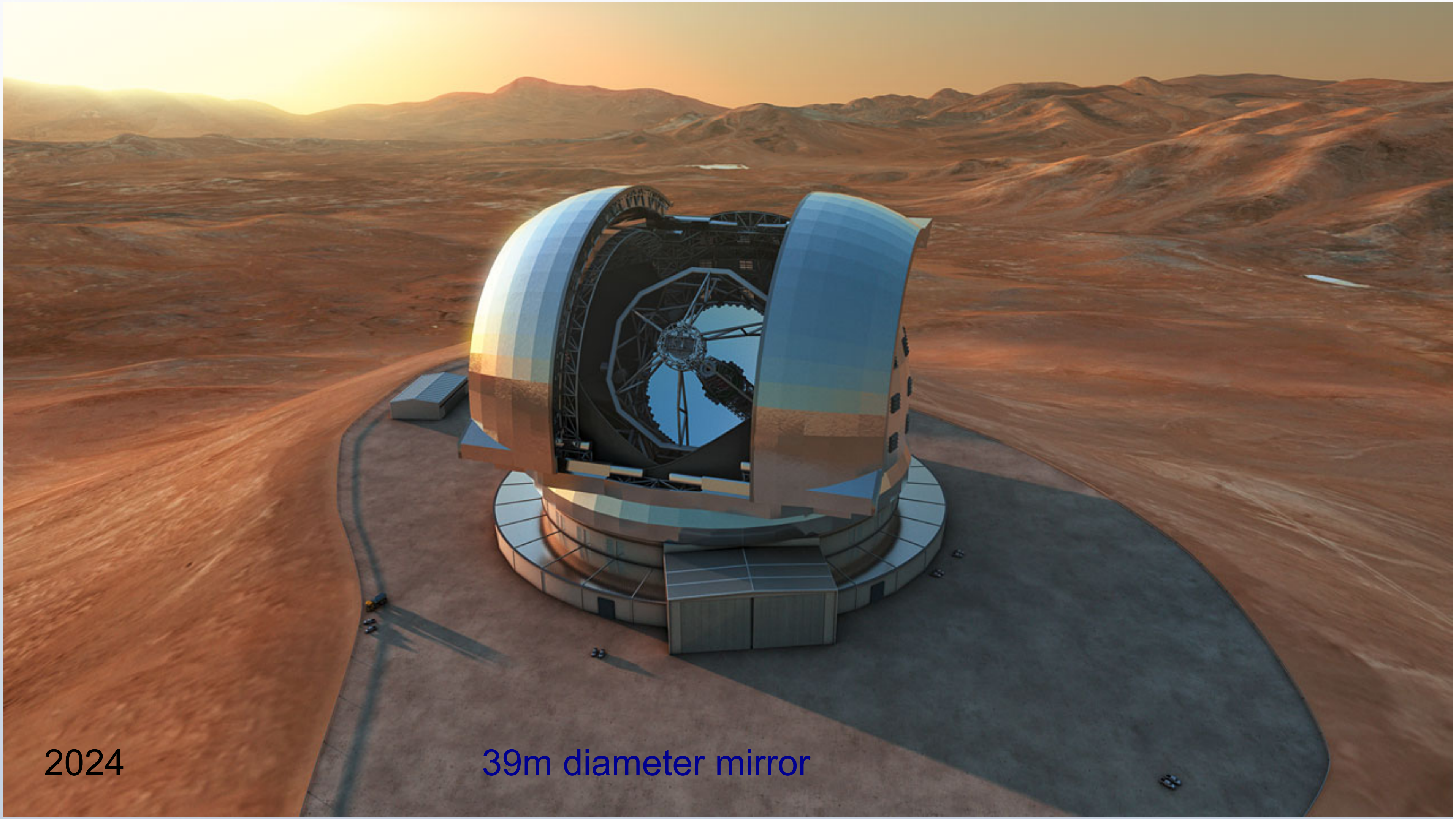




CRIRES@VLT Upgrade (2017) → 6x larger wavelength coverage CO, H2O, CH4, NH3, H3+,…..

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

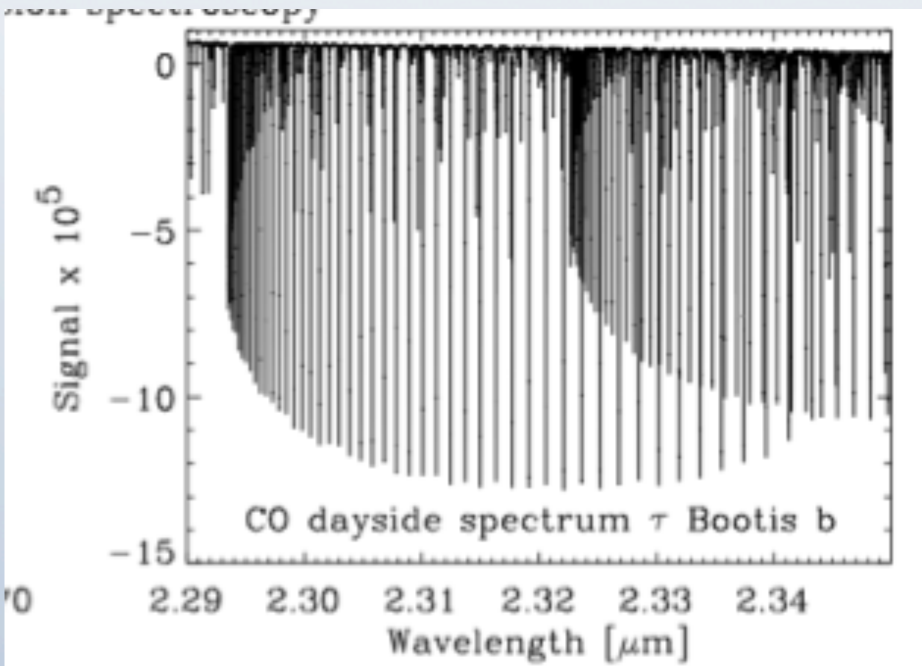
# Towards characterization of Earth-like planets

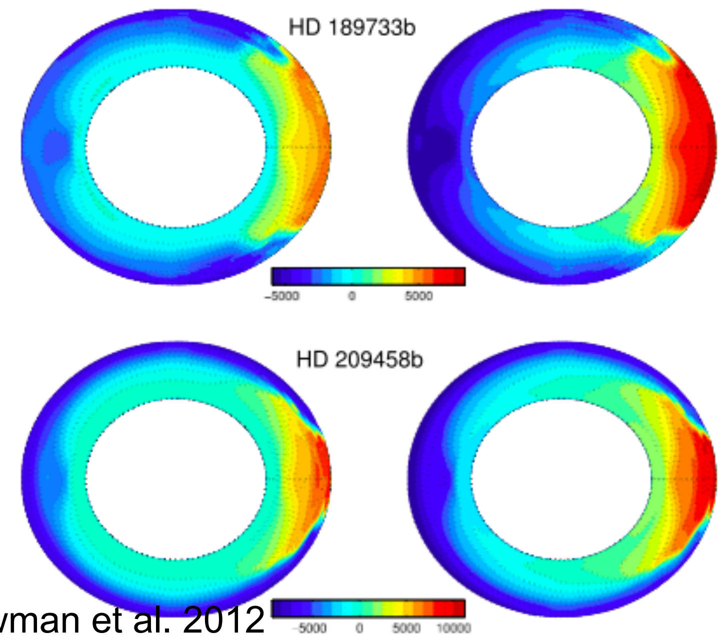
## The European Extremely Large Telescope



# 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, CO2, H2O, CH4) as function of orbital phase → photochemistry, T/P versus longitude
- Isotopologues → evolution of planet atmosphere

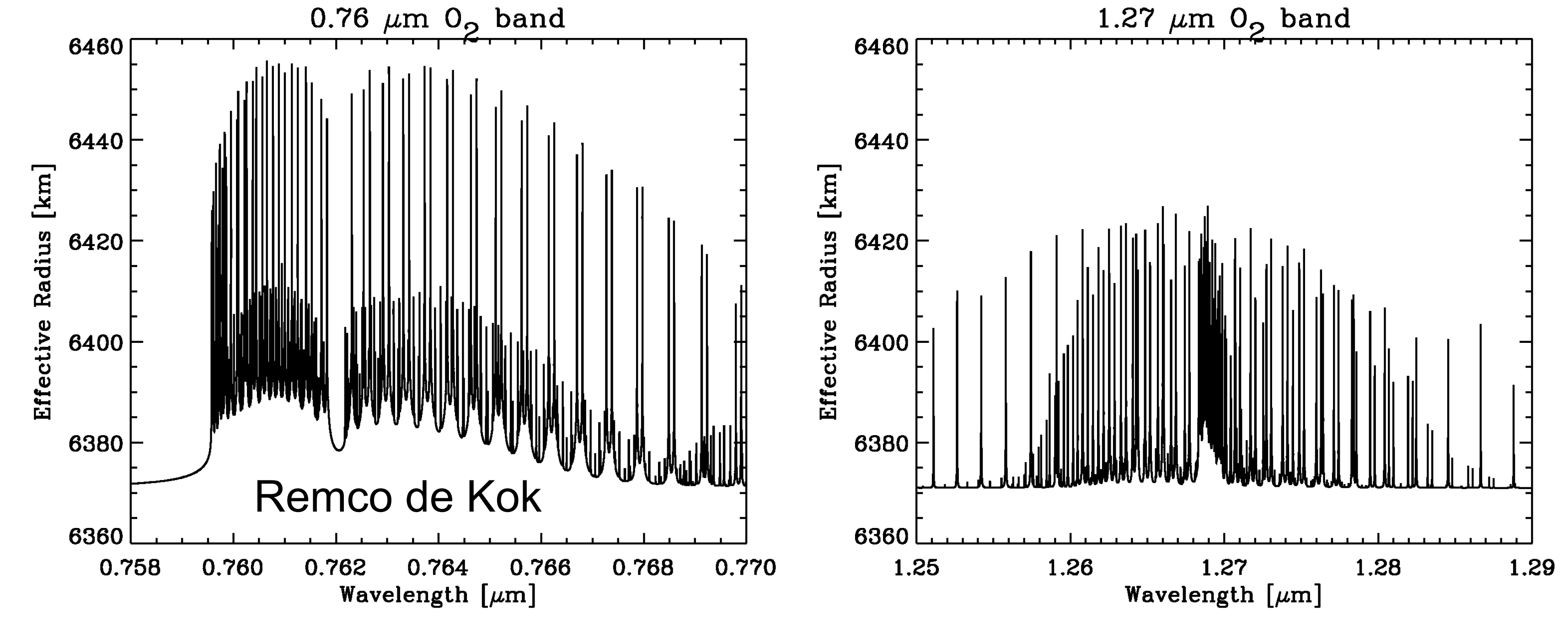


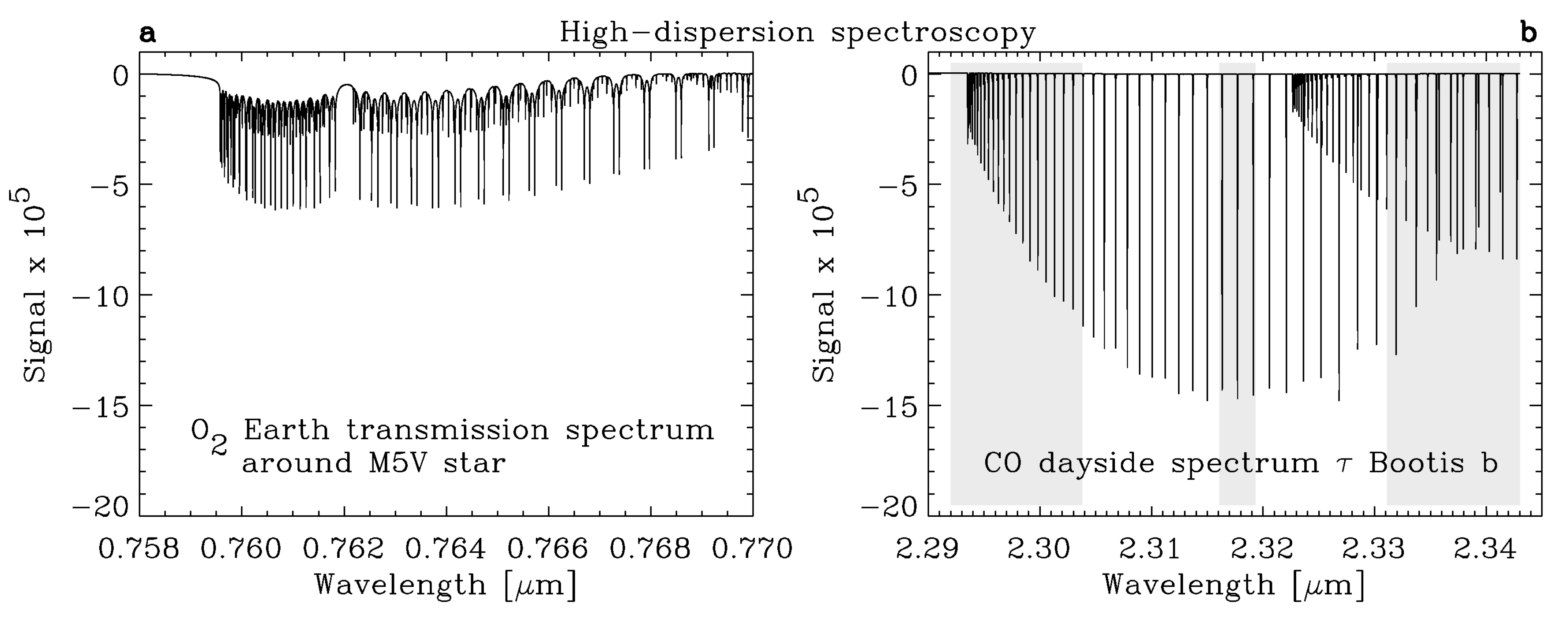

Showman et al. 2012

# 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 ($\eta_e$=1) [mag] | Line Contrast | SNR $\sigma$ | Time (yrs) |
|---|---|---|---|---|---|---|---|---|---|---|
| G0-G5 | 1.00 | 1.00 | 1.000 | 0.47 | 365.3 | 13 | 4.4 - 6.1 | $2\times10^{-6}$ | 1.1-2.5 | 80-400 |
| M0-M2 | 0.49 | 0.49 | 0.203 | 1.12 | 47.7 | 4.1 | 7.3 - 9.1 | $8\times10^{-6}$ | 0.7-1.5 | 20-90 |
| M4-M6 | 0.19 | 0.19 | 0.058 | 1.52 | 11.8 | 1.4 | 10.0-11.8 | $5\times10^{-5}$ | 0.7-1.7 | 4-20 |

Snellen et al. 2013

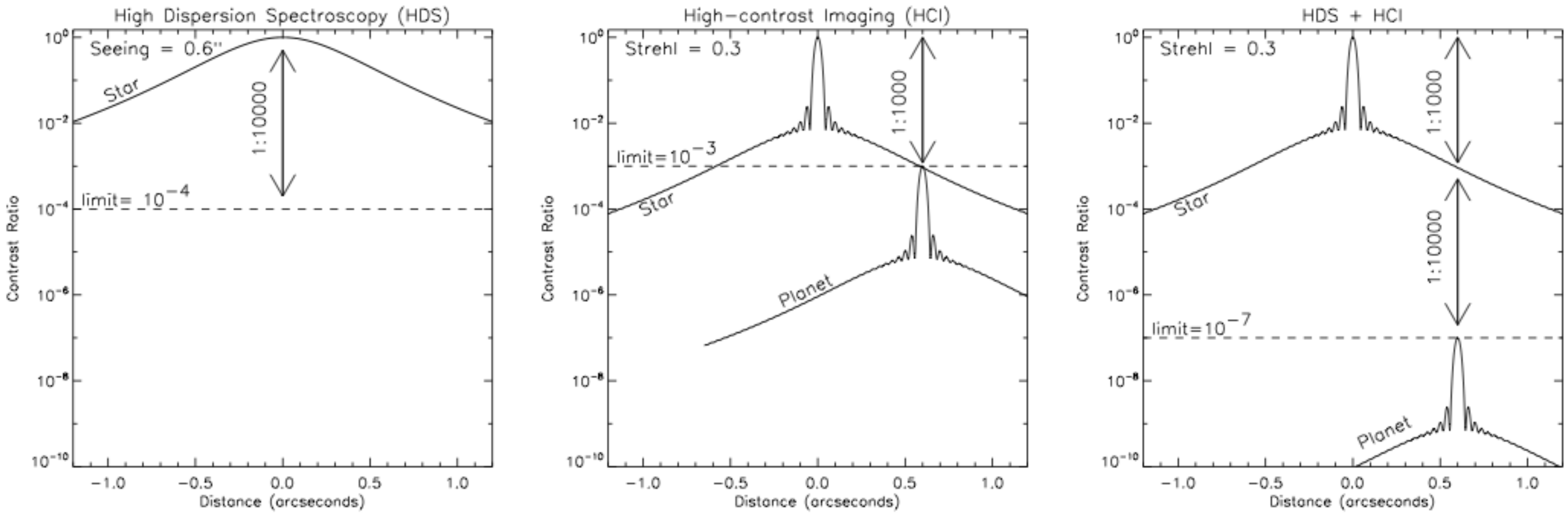
Brightest expected systems

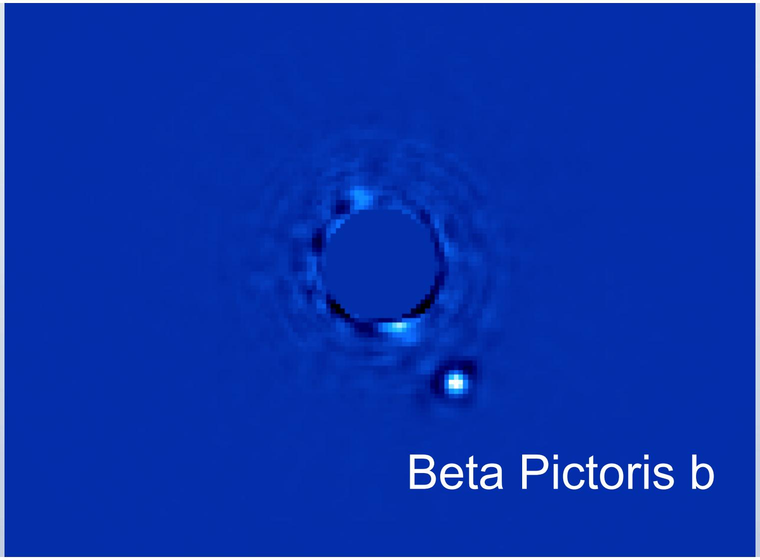
SNR for ELT in 1 transit

# A new technique

# Snellen et al. Nature 2014

## High Dispersion Spectroscopy + high-contrast imaging

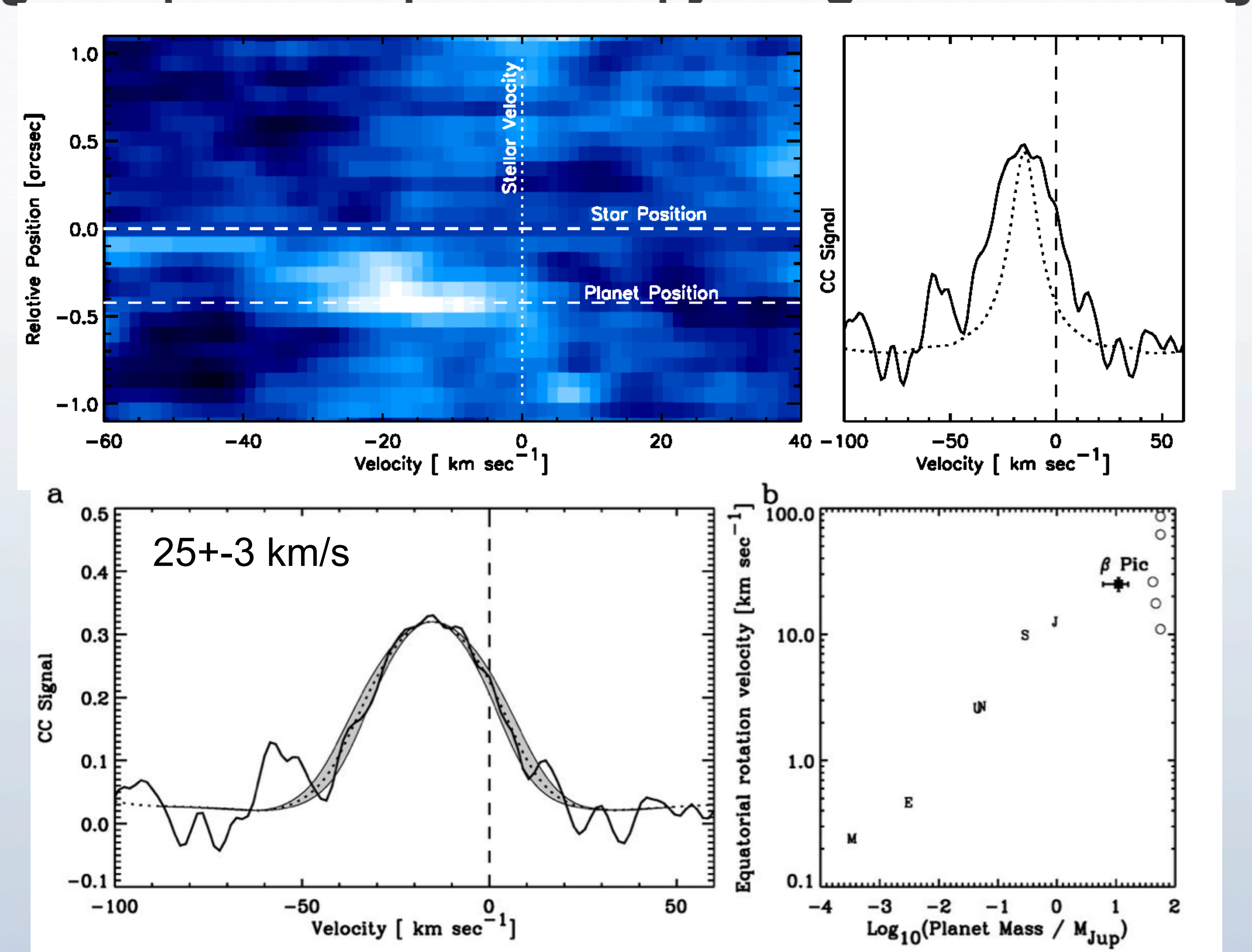


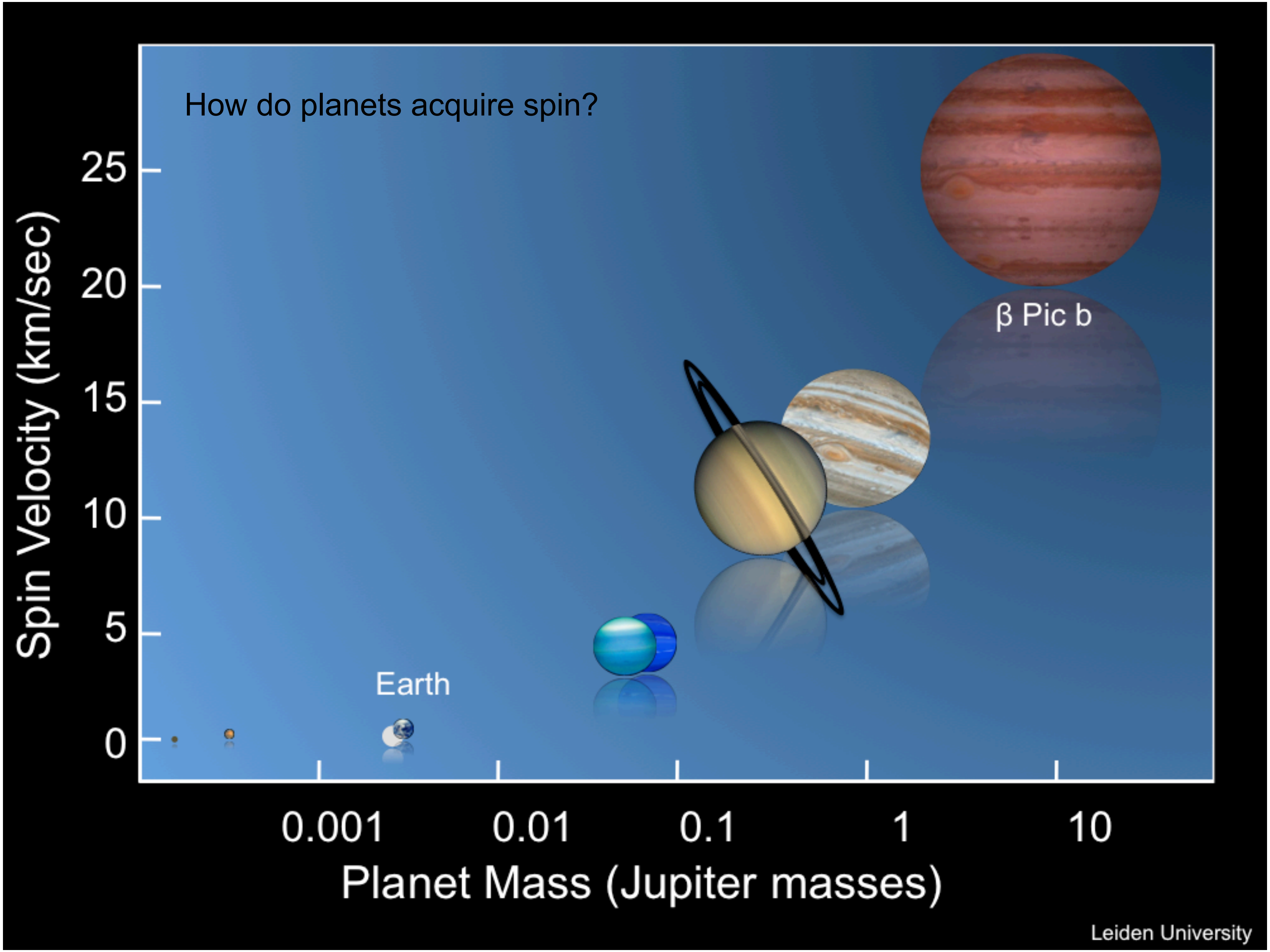

Mass = 11 (+-5) Mjup
Radius ~ 1.65 Rjup
Orbit: 17-20 years

# Snellen et al. Nature 2014

## High Dispersion Spectroscopy + high-contrast imaging

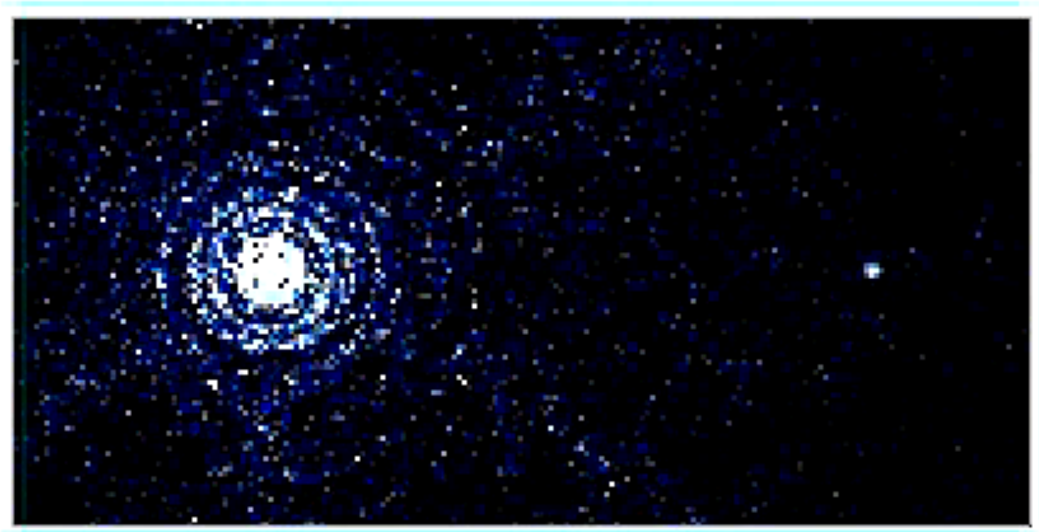



Length of Day on Beta Pictoris b ~8 hours



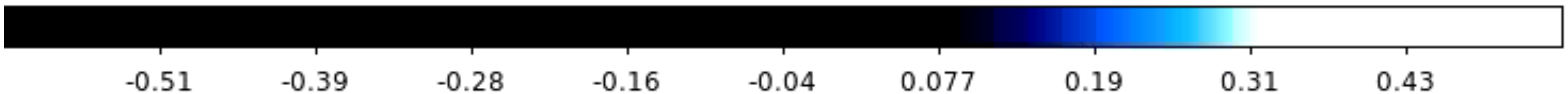
How do planets acquire spin?
β Pic b
Earth
Spin Velocity (km/sec)
25
20
15
10
5
0
0.001
0.01
0.1
1
10
Planet Mass (Jupiter masses)
Leiden University

# METIS@E-ELT simulations



Rocky planet in the habitable zone of Alpha Centaurus A

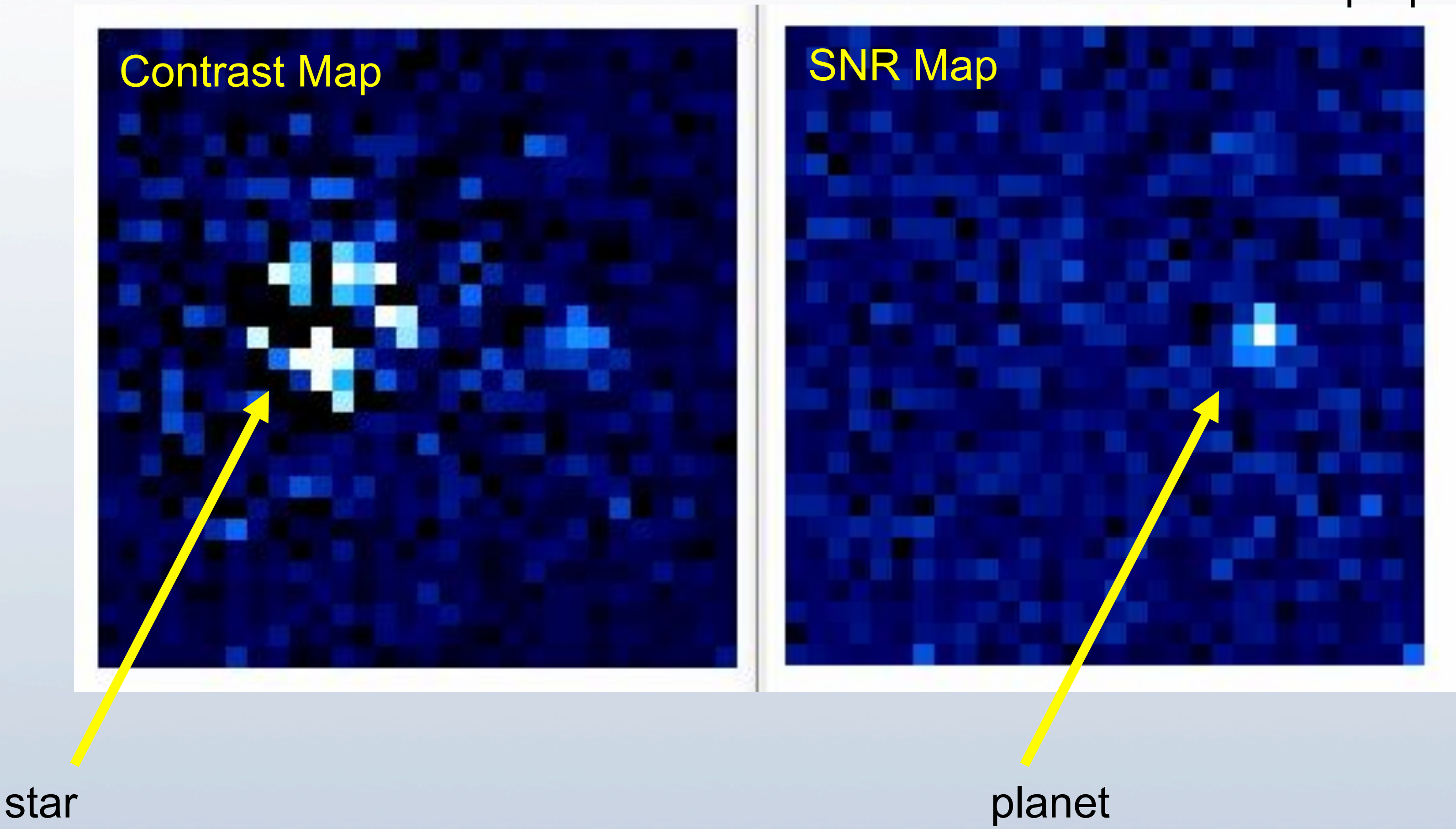
METIS @ E-ELT, Snellen et al.2015.



# 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