



Image credit: ESA

From Hot gas giants to cooler exo-Earths

A pioneering spectral survey of exoplanet atmospheres

Nikolay Nikolov
Johns Hopkins University

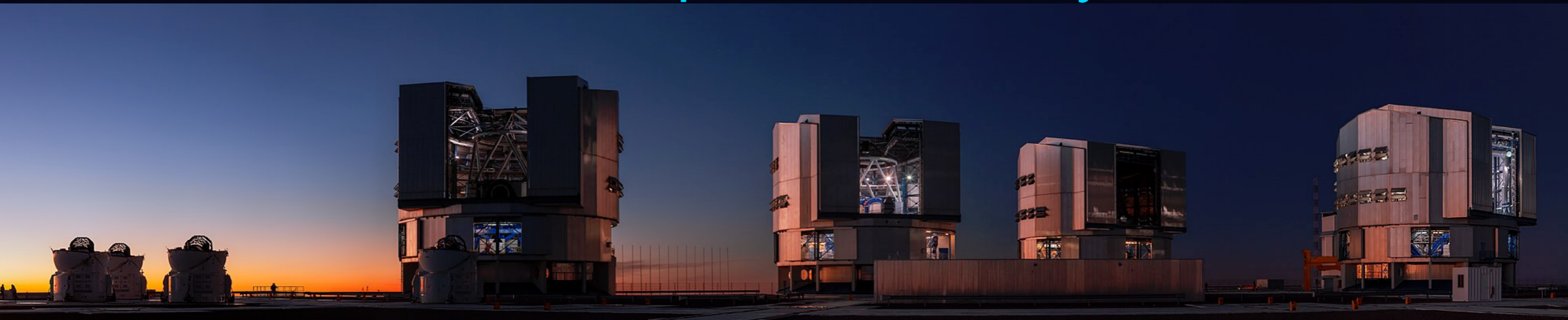
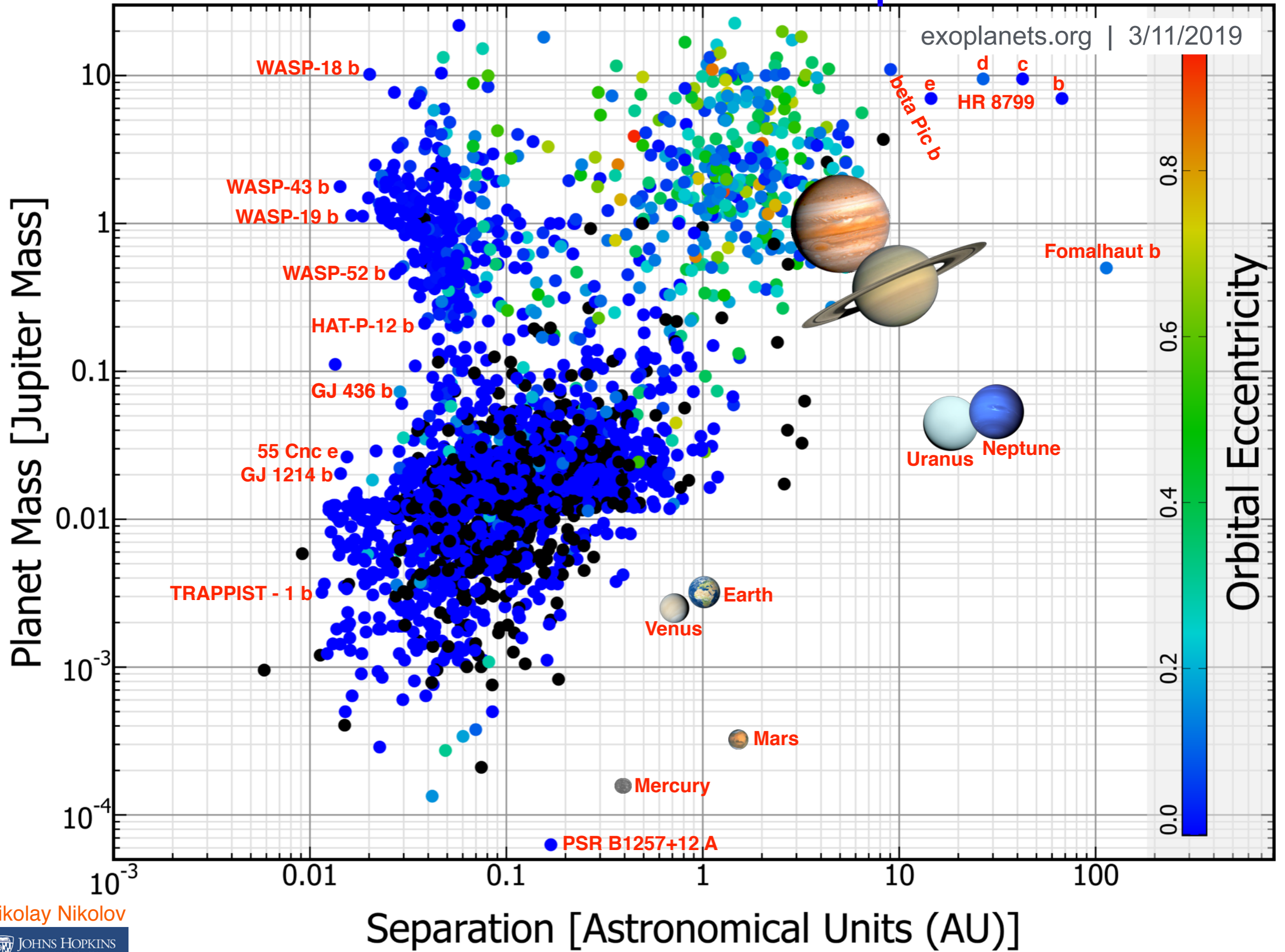


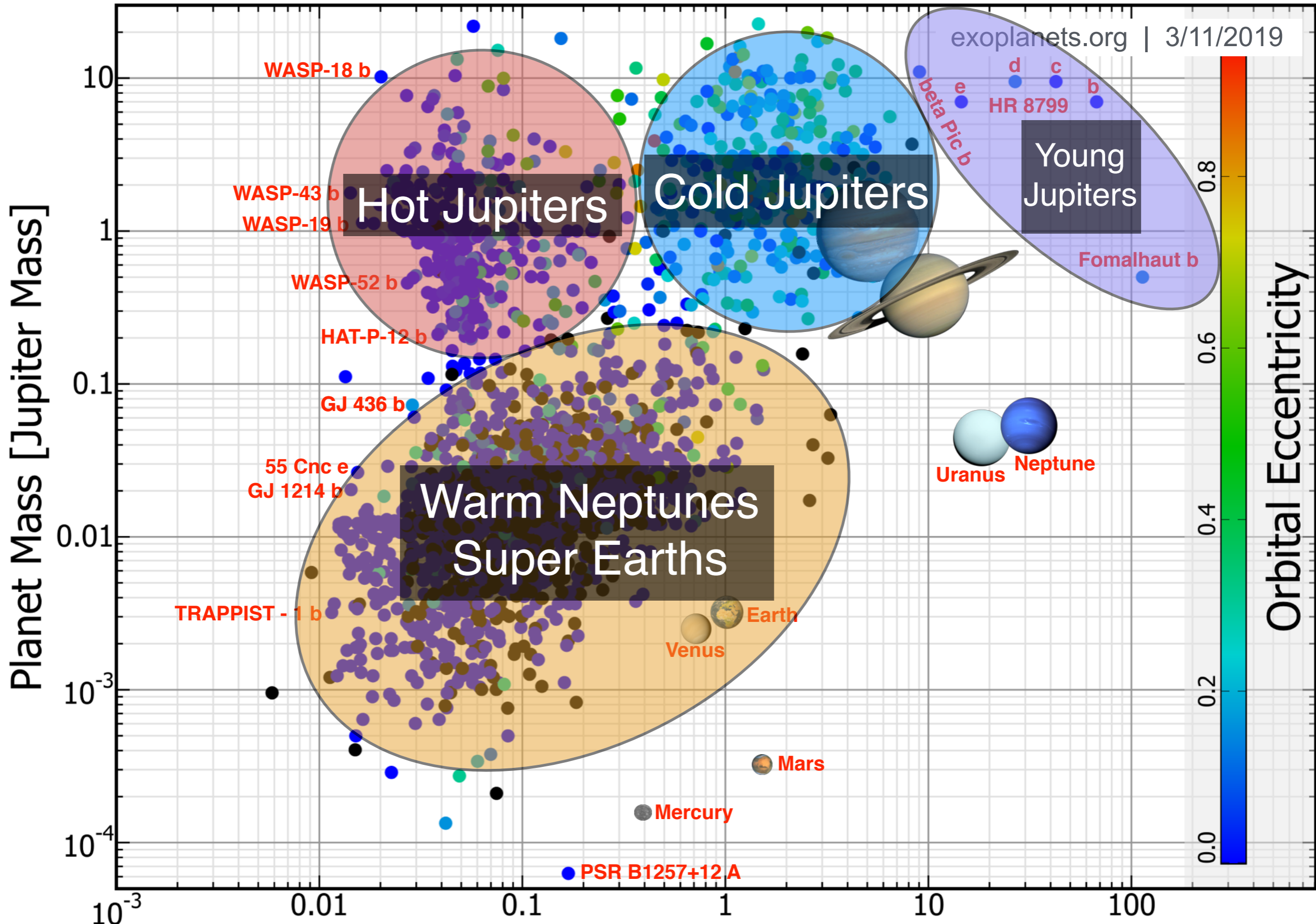
Image credit: Babak Tafreshi, ESO Ambassador

Outline

- **Introduction: exoplanets**
- **Why atmospheric characterization of transiting exoplanets and how ?**
- **Exoplanet science with FORS2**
- **Conclusions and how to improve FORS2 ?**

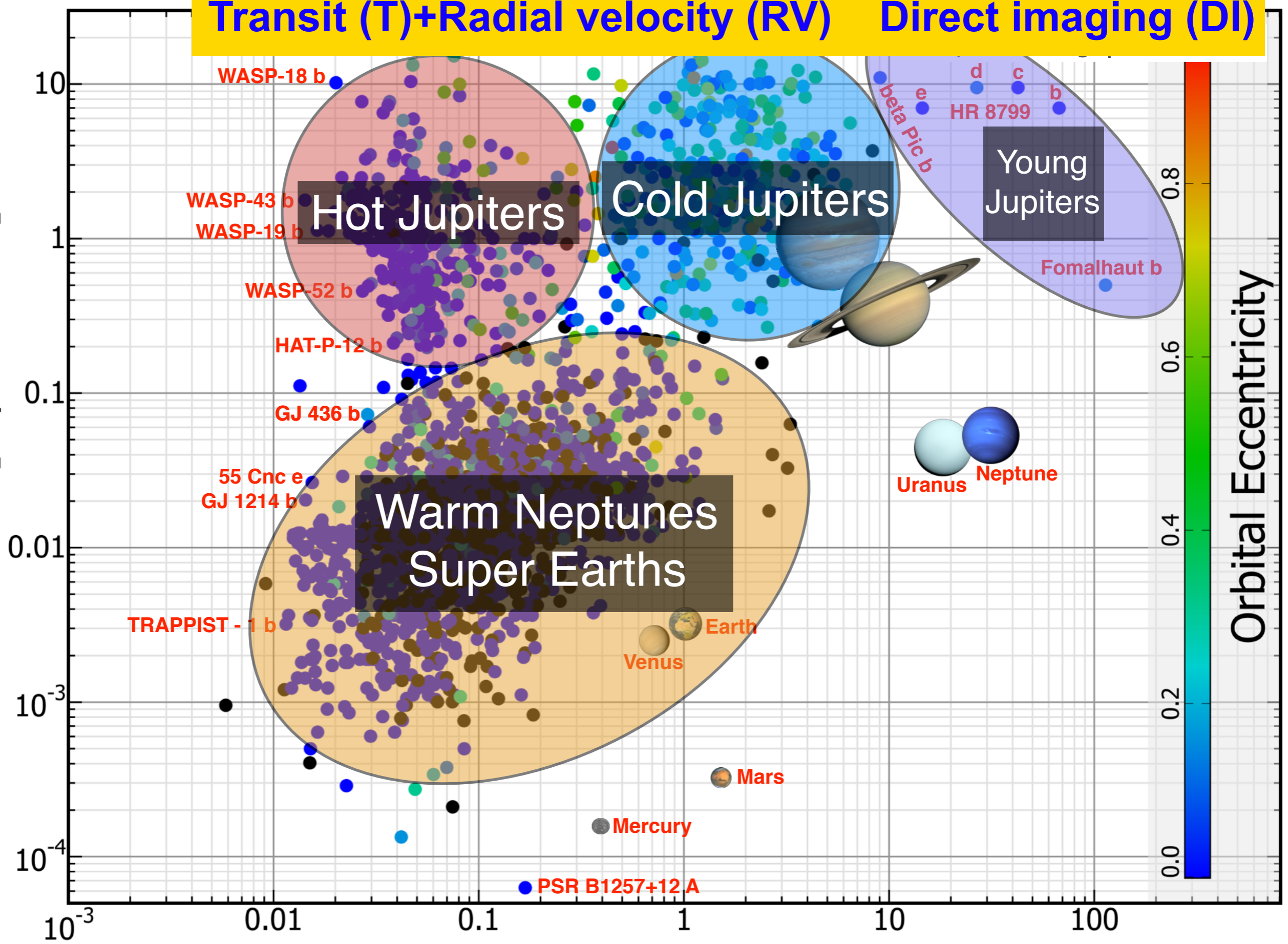
All exoplanets known to date





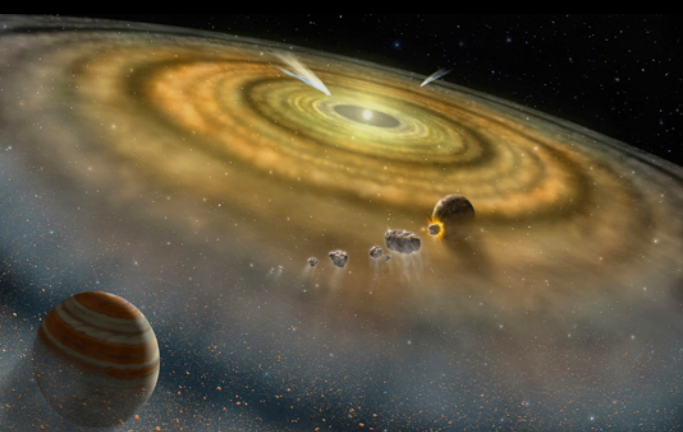
Transit (T)+Radial velocity (RV) Direct imaging (DI)

Planet Mass [Jupiter Mass]



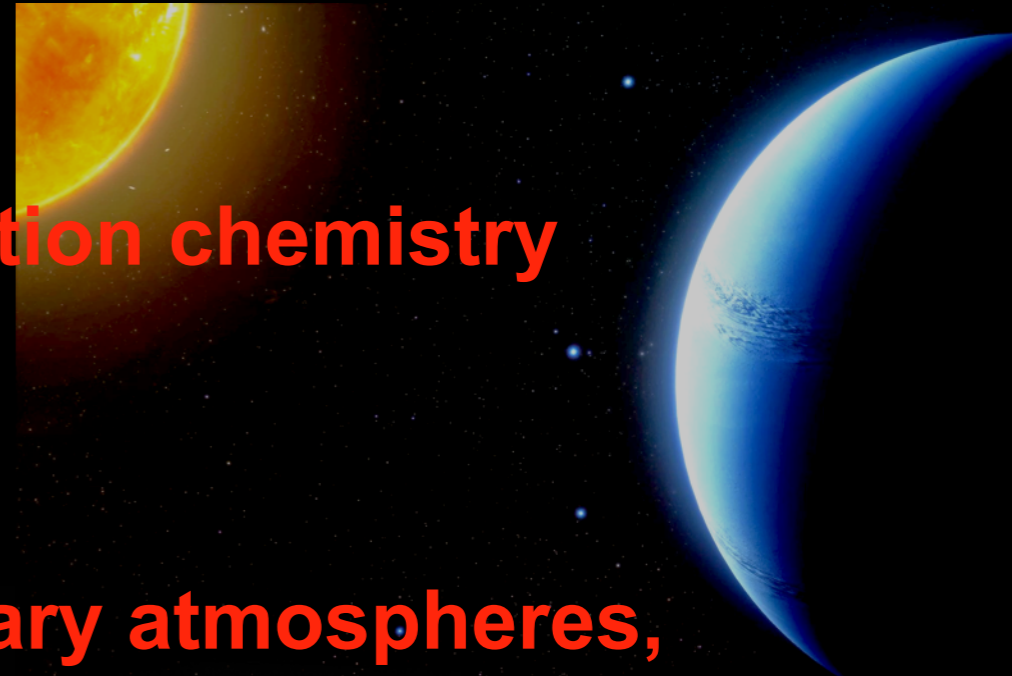
Separation [Astronomical Units (AU)]

Major Exoplanet Science Questions

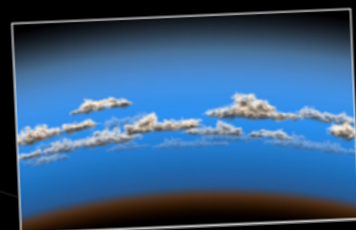
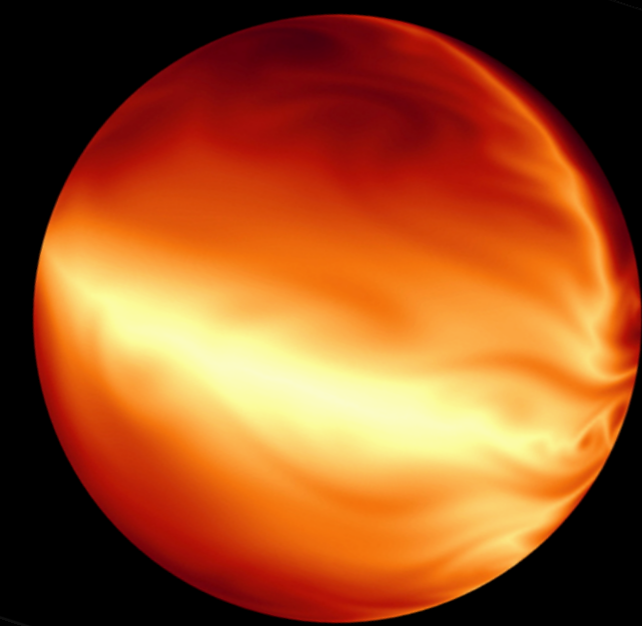


- Link composition & abundances to formation:
Absolute abundances (Na, H₂O, ...)

- Clouds & hazes:
**Occurrence, Condensation chemistry
Photochemistry?**



- Spectra of super-Earths:
**Primordial and secondary atmospheres,
formation**



Exoplanet Atmosphere Characterization

Method Advantage	Transits	Direct Imaging	Radial Velocity
Close-in planets	✓		✓
Wide separations		✓	
Bright targets	✓	✓	✓
M_p , precision	✓ 2-3%	✓ 20-30%	✓ $M_p \sin(i)$
$R_p(\lambda)$	✓		
$F_p(\lambda, \Phi)$	✓	✓	
P, i, a	✓	✓ ?	✓
Atmo composition	✓	✓	✓
Clouds/hazes	✓	✓	
Thermal profiles	✓	Temperature	
Stratospheres	✓		✓
Thermospheres	✓		
Exospheres	✓		
Escape	✓		
Dynamics, Winds	✓	Dynamics	✓
Photochemistry	✓	Chemistry	

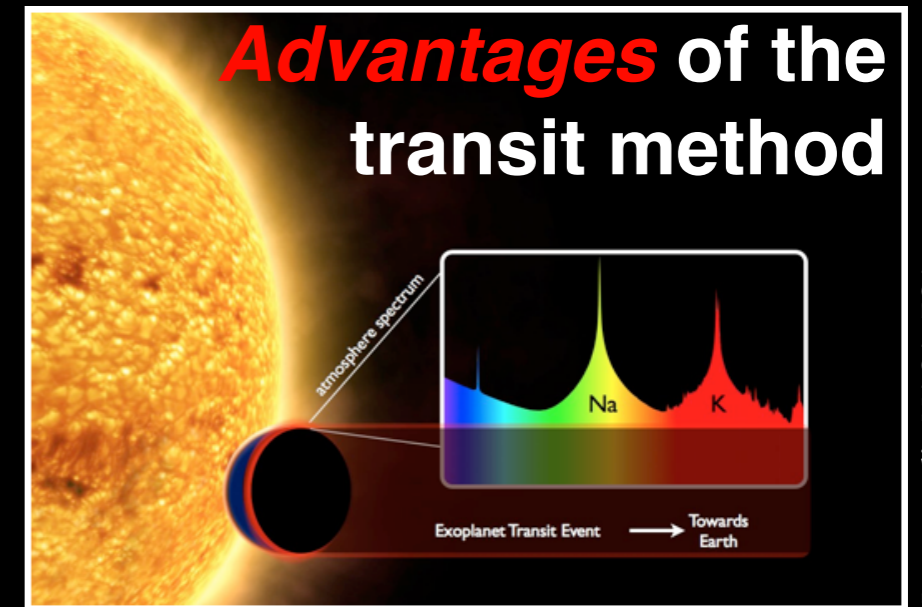
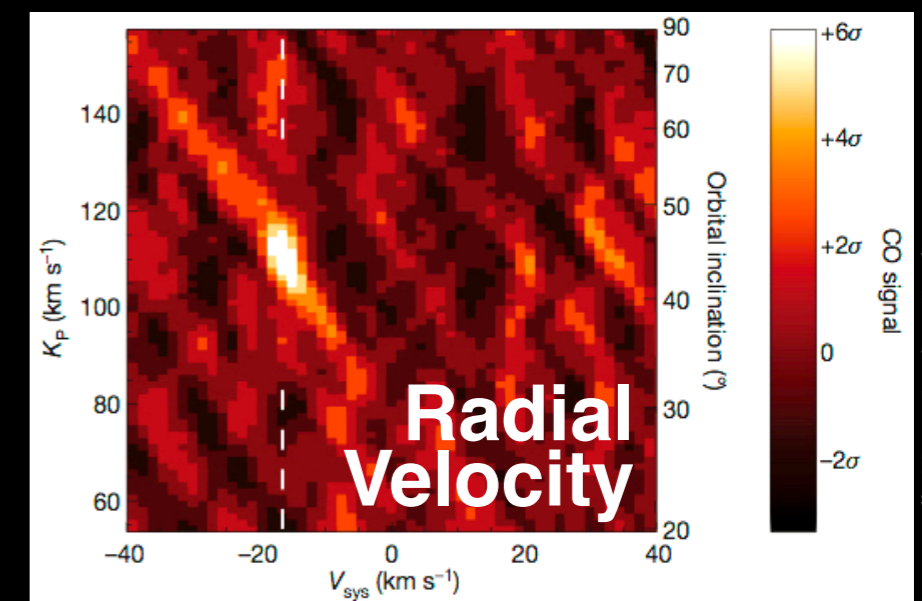
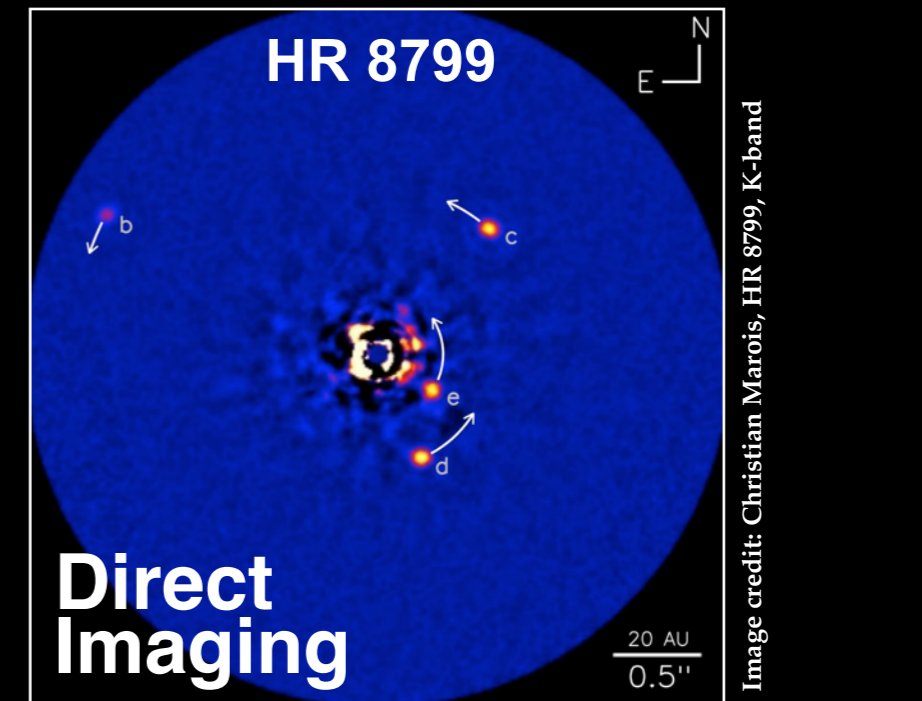
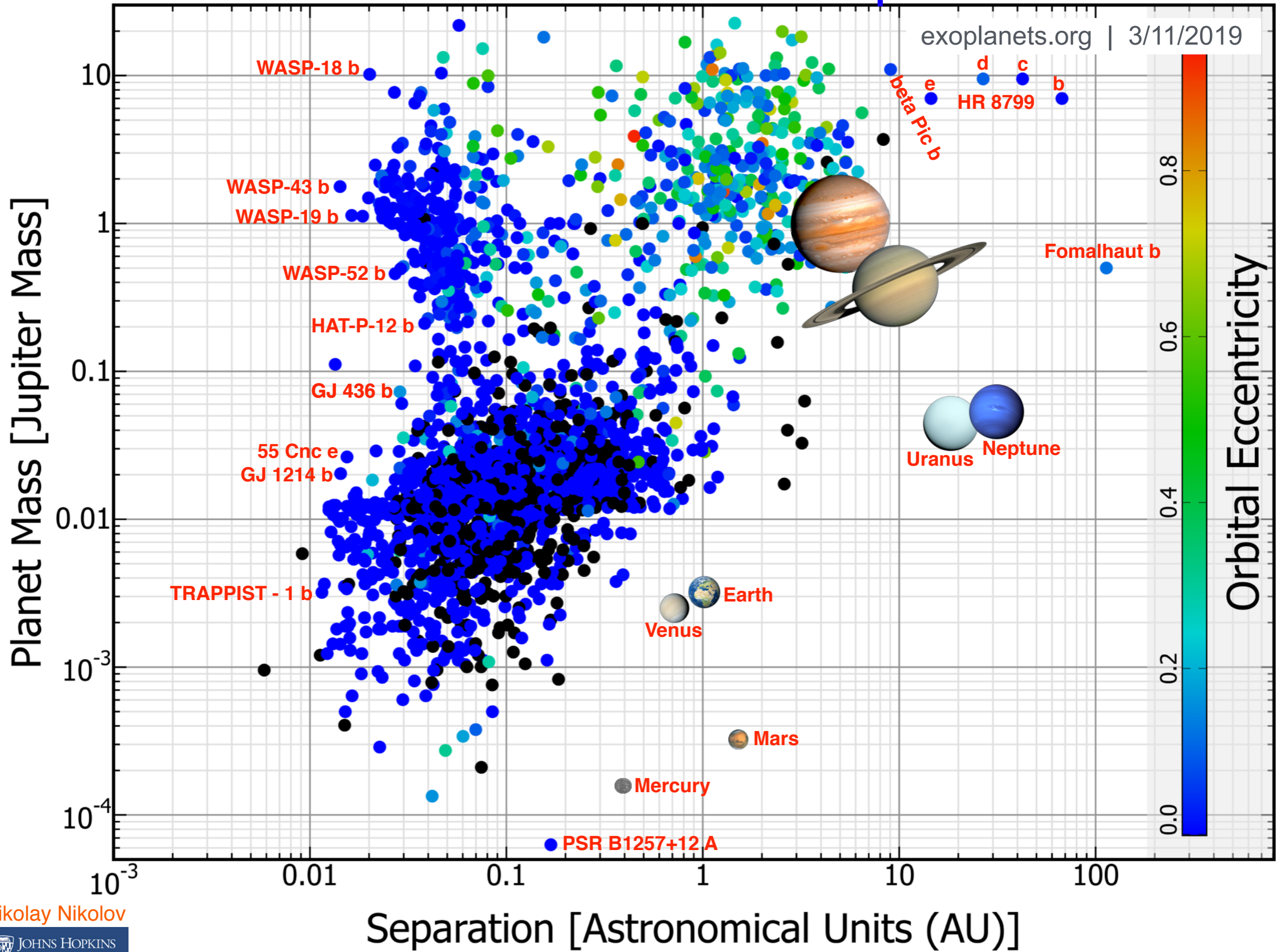


Image credit: NASA, ESA
D. Sing, University of Exeter



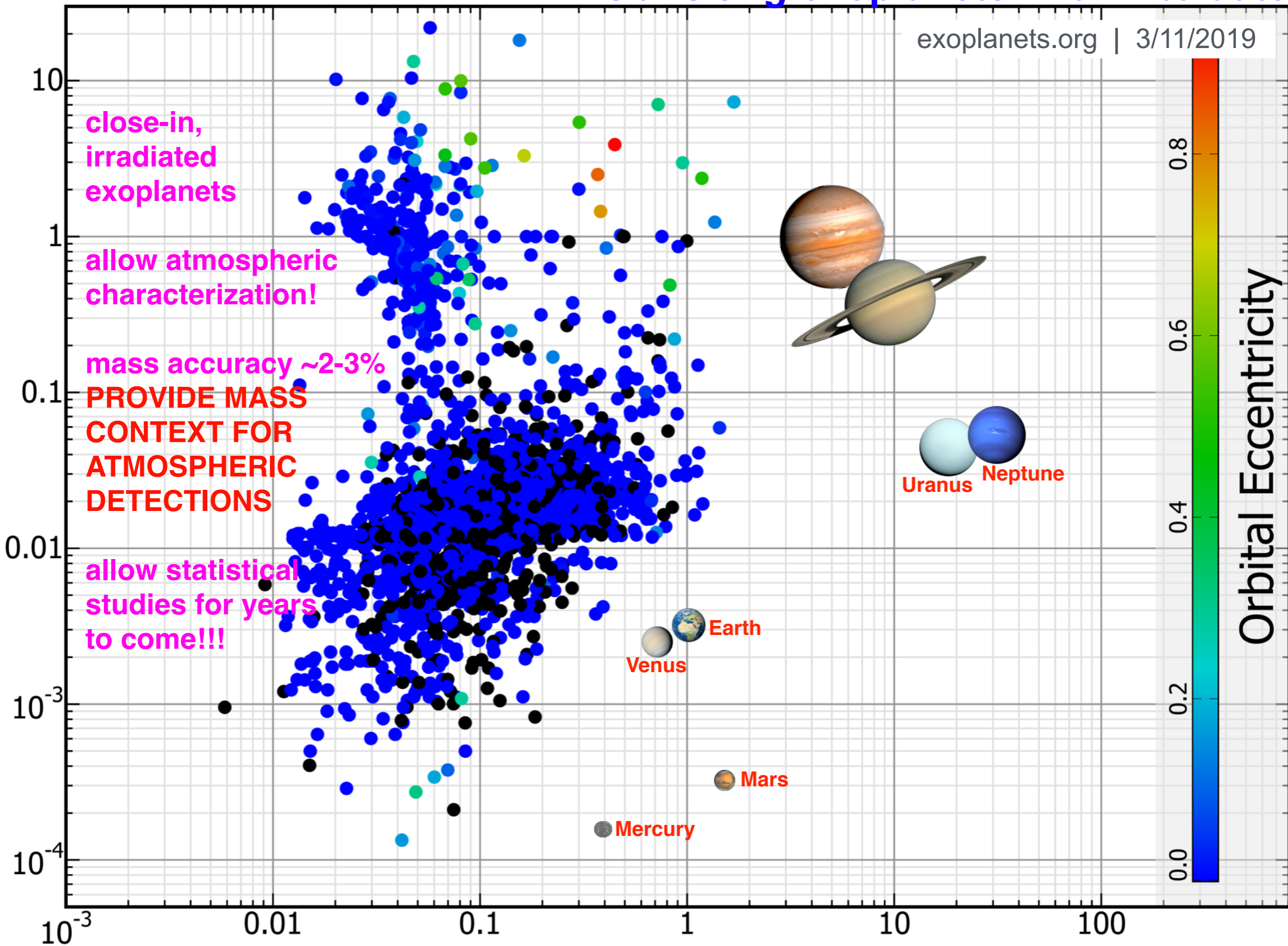
All exoplanets known to date



All transiting exoplanets known to date

exoplanets.org | 3/11/2019

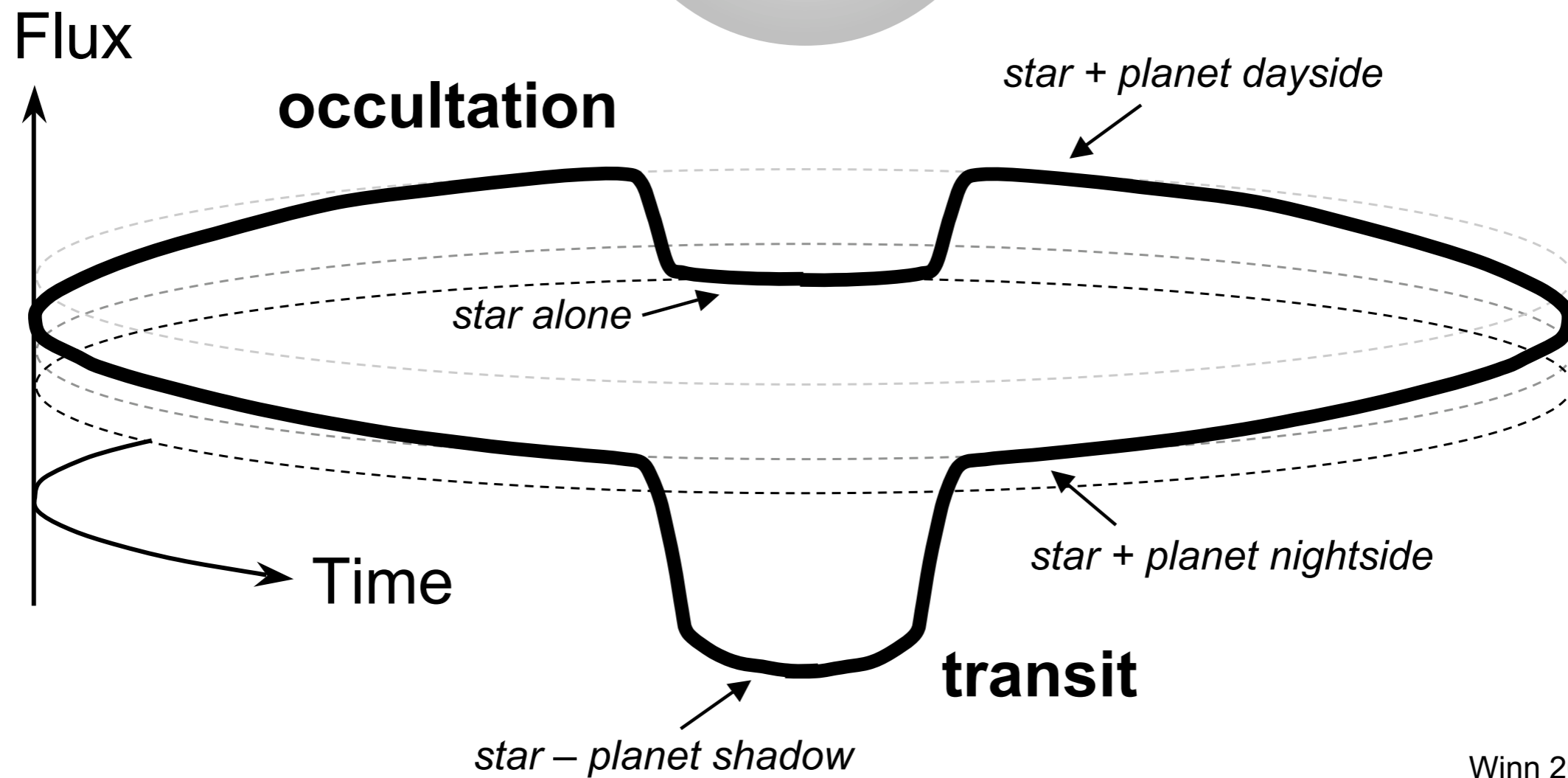
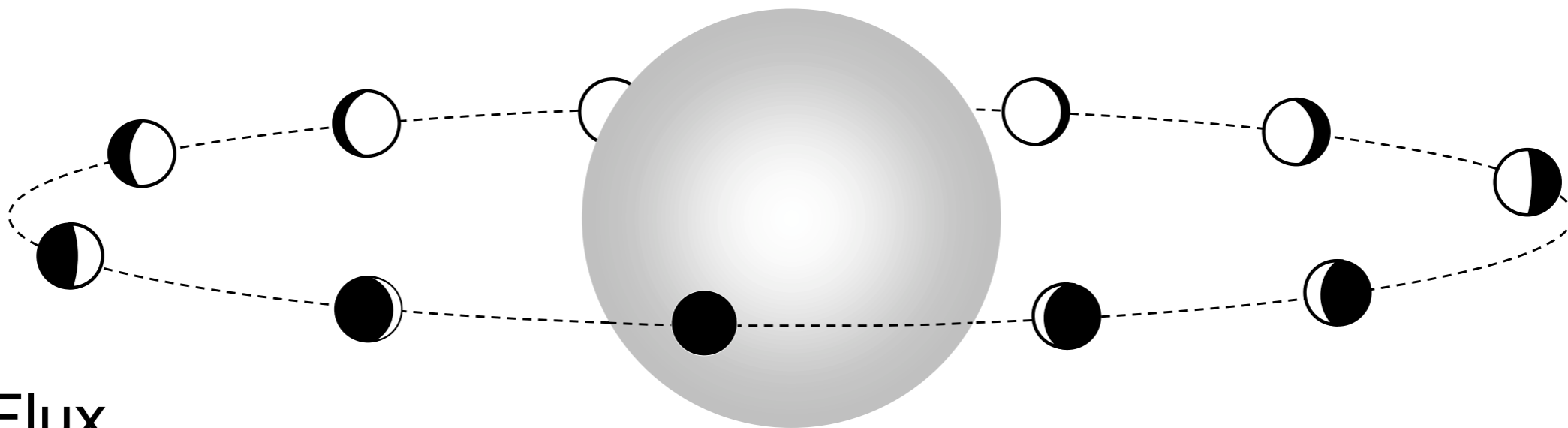
Planet Mass [Jupiter Mass]



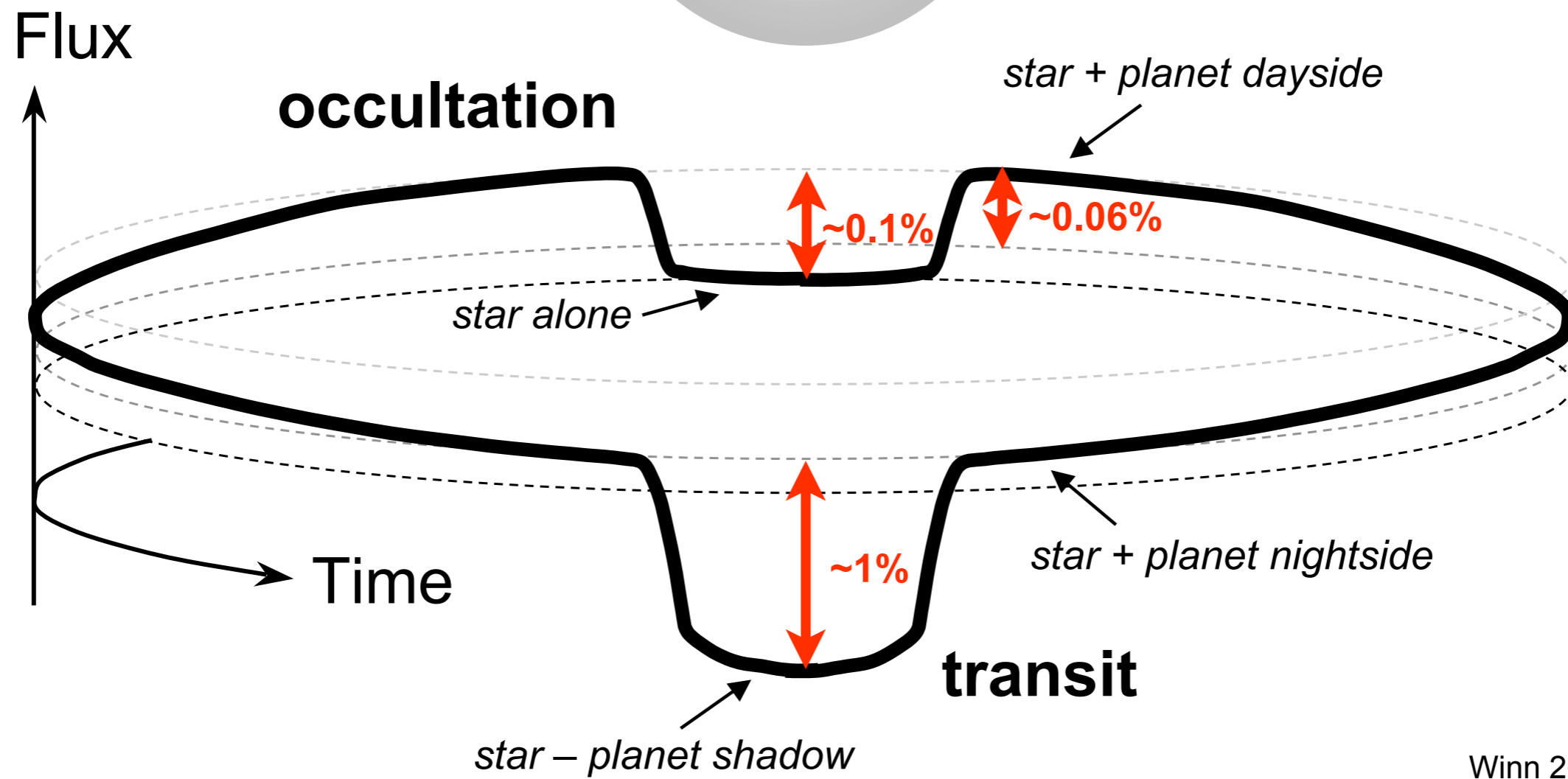
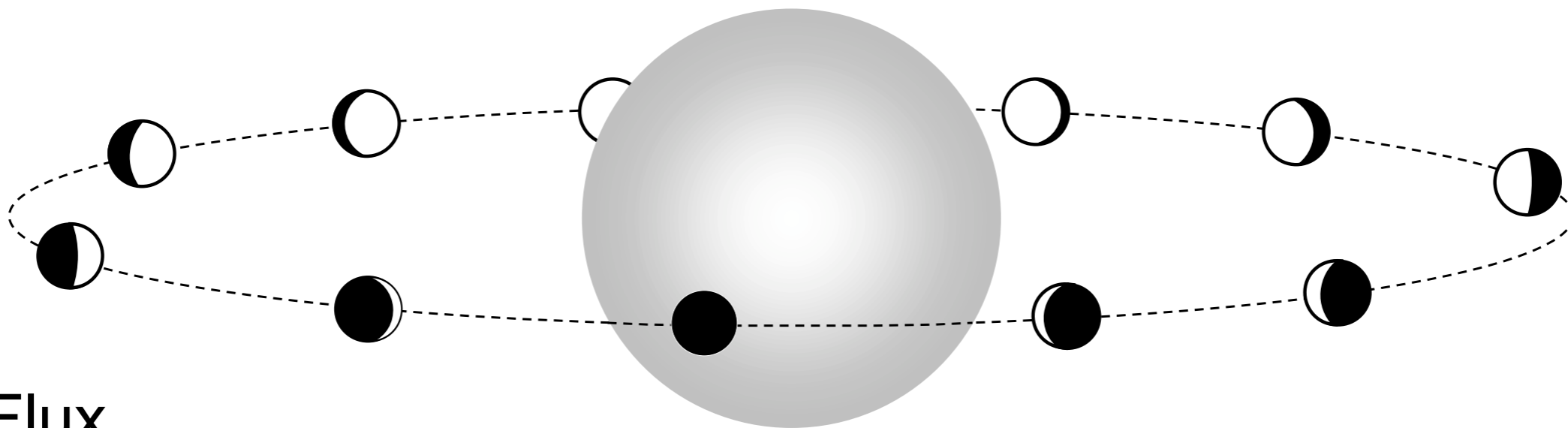
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Nikolay Nikolov





Winn 2010



Winn 2010

Hot Jupiters atmospheric models 1D

What might irradiated gas giant exoplanets look like?

Forward Models

Solar composition

Chemical equilibrium

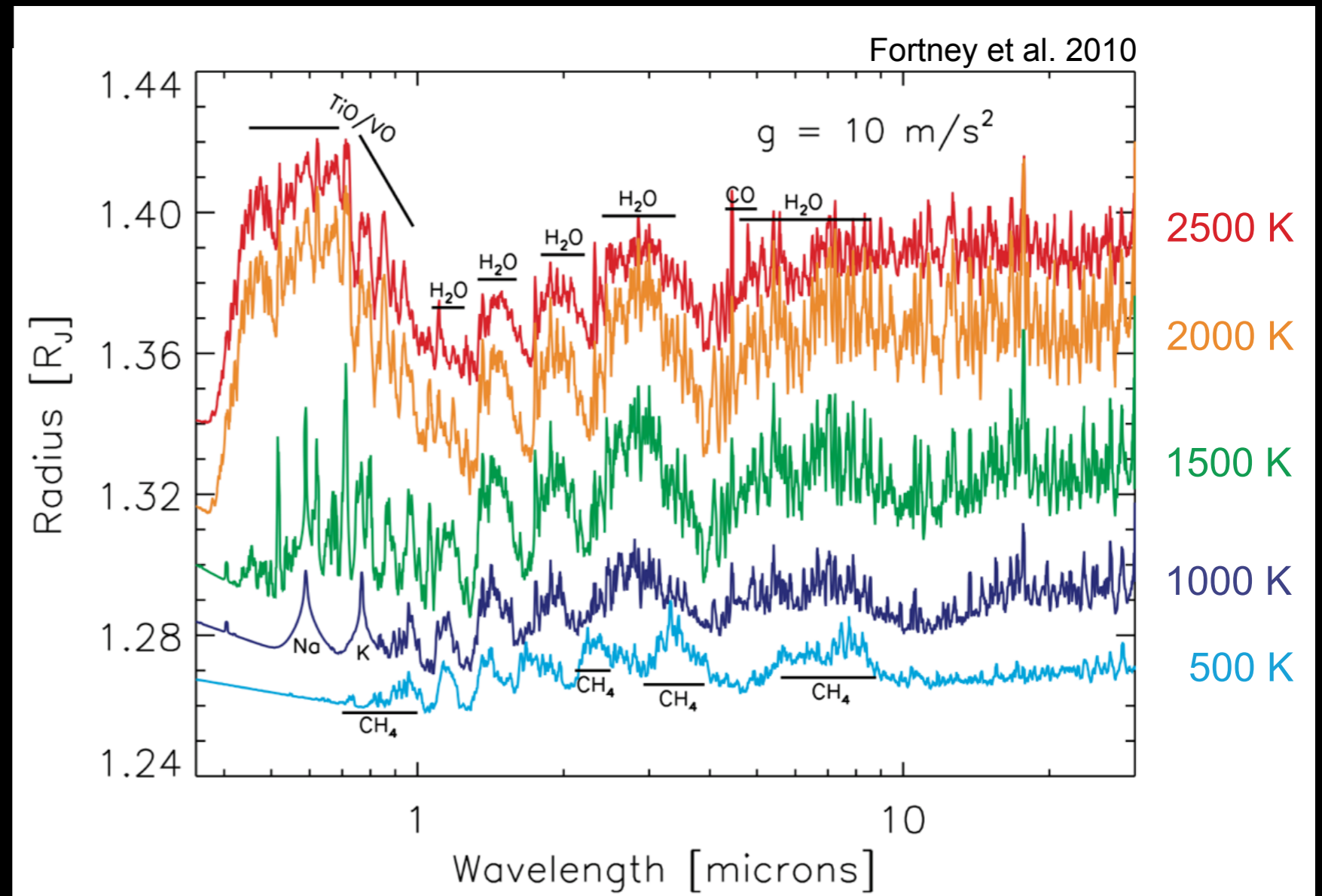
Radiative transfer

H₂ Na K

H₂O dominant

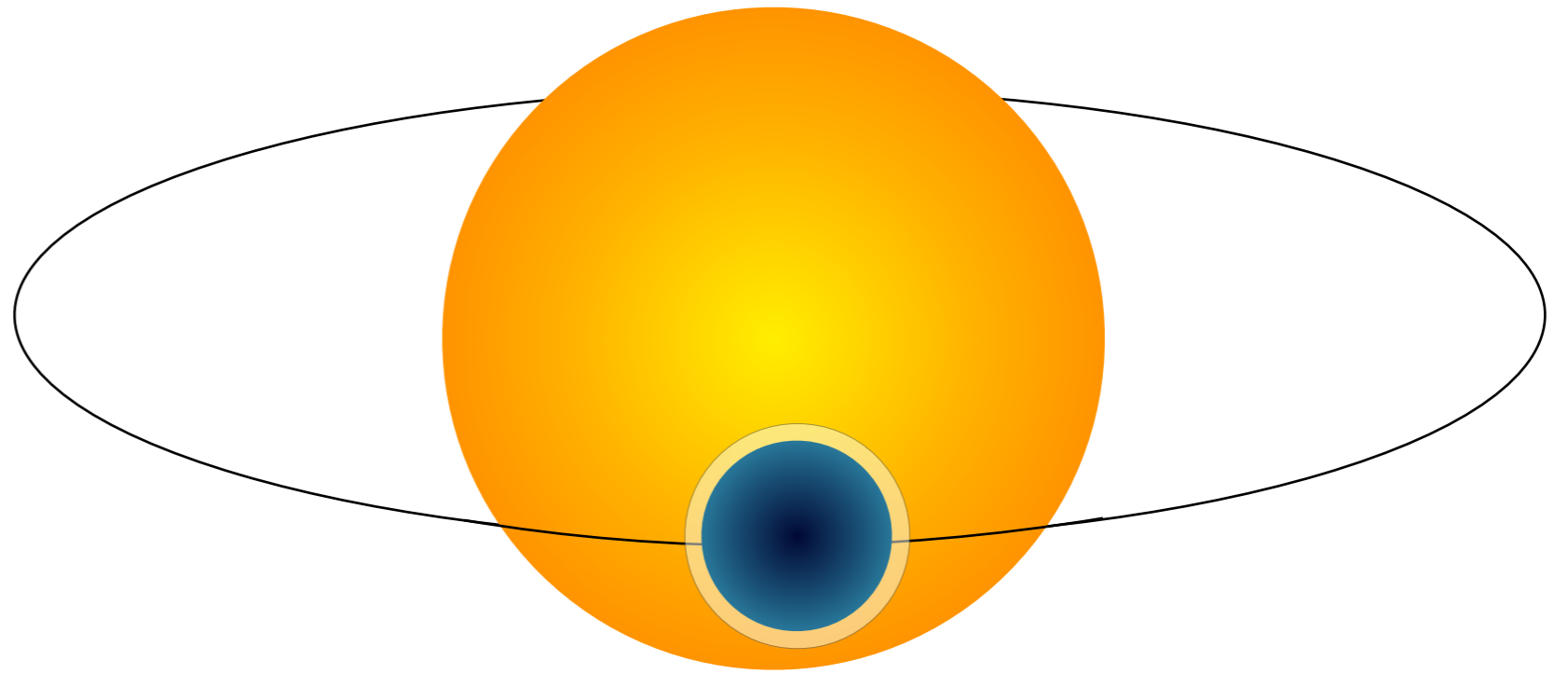
CO hotter atmospheres

CH₄ cooler atmospheres

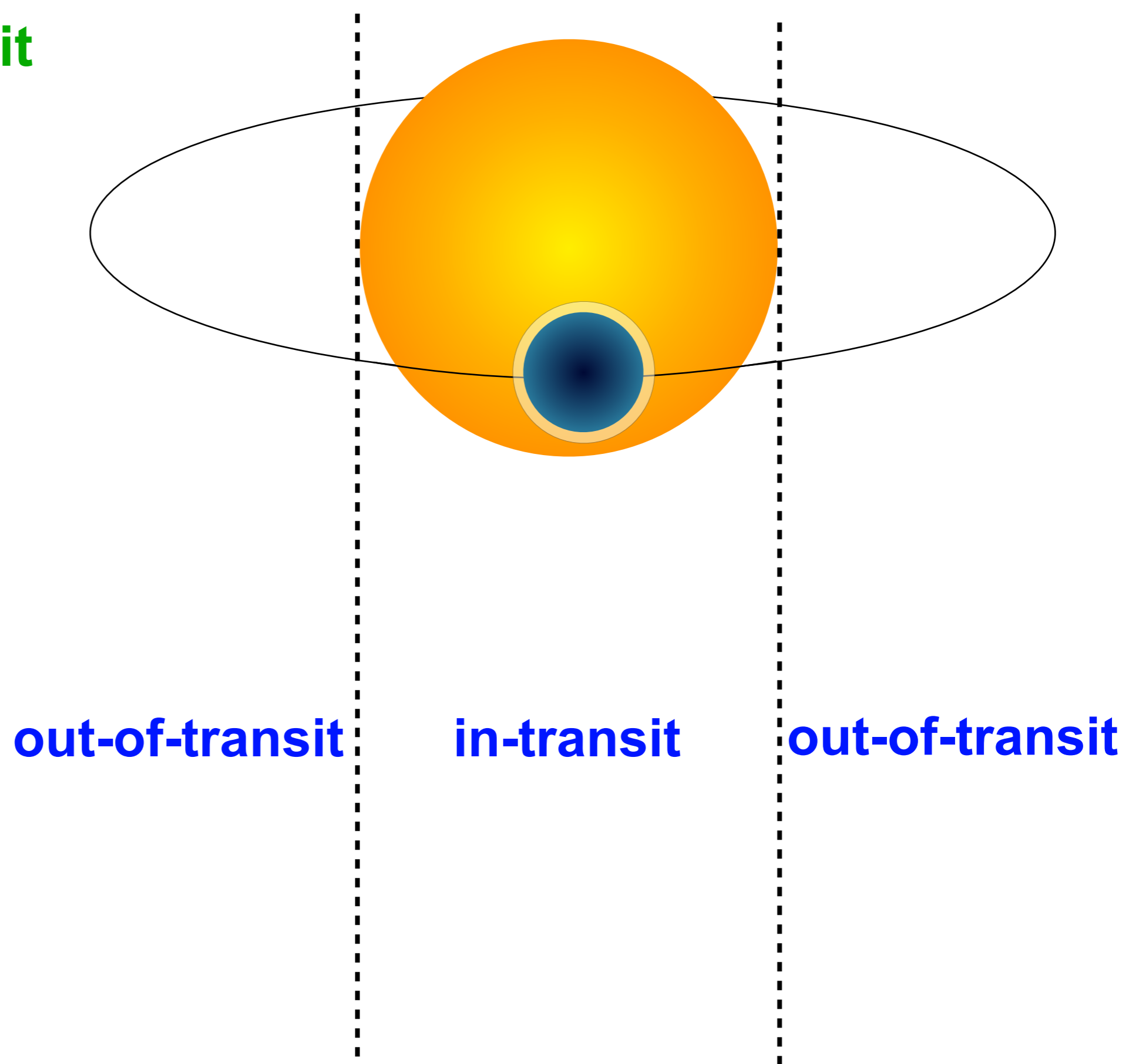


Clouds- very dependent on T-P profiles

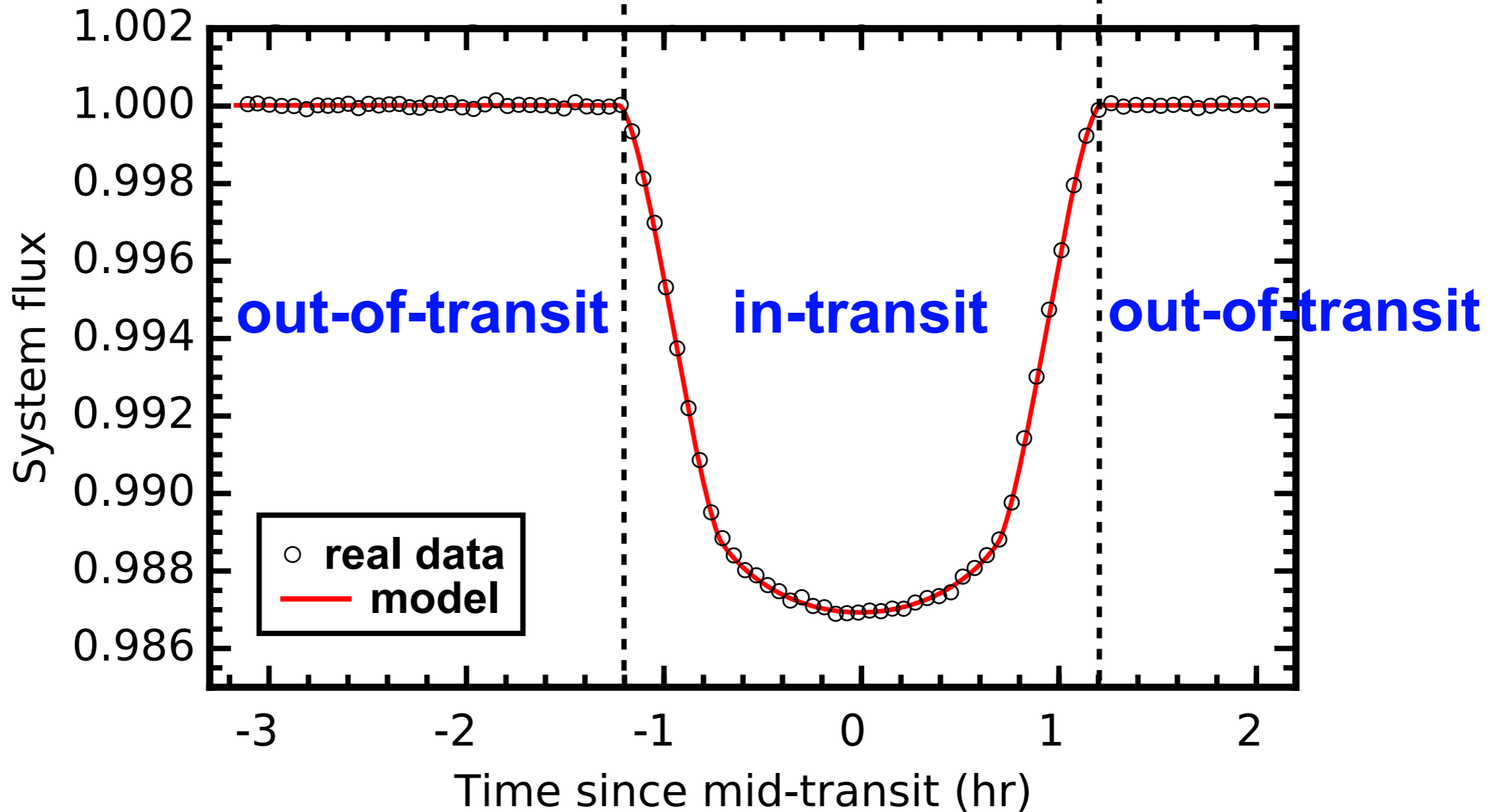
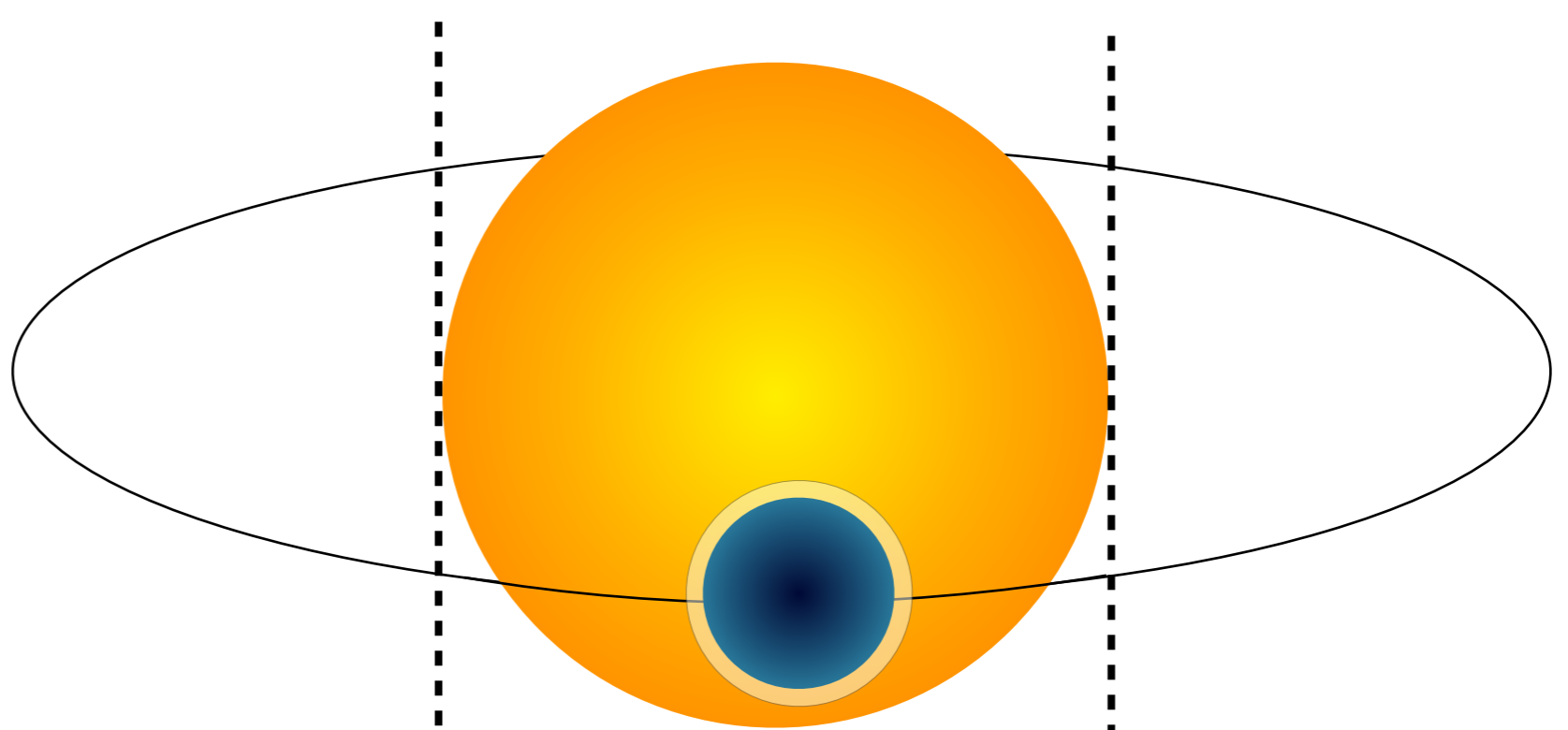
How does transit spectroscopy work ?



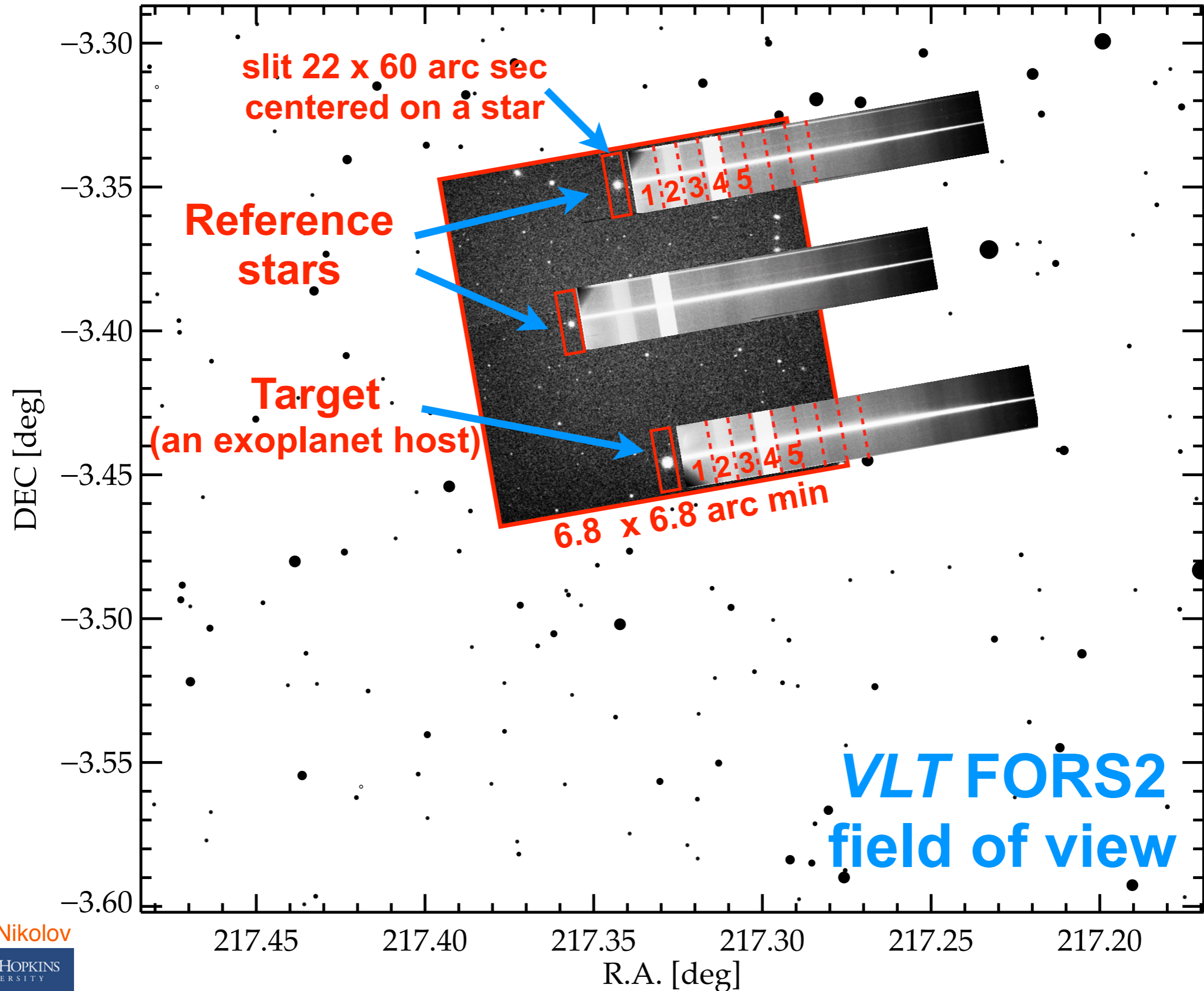
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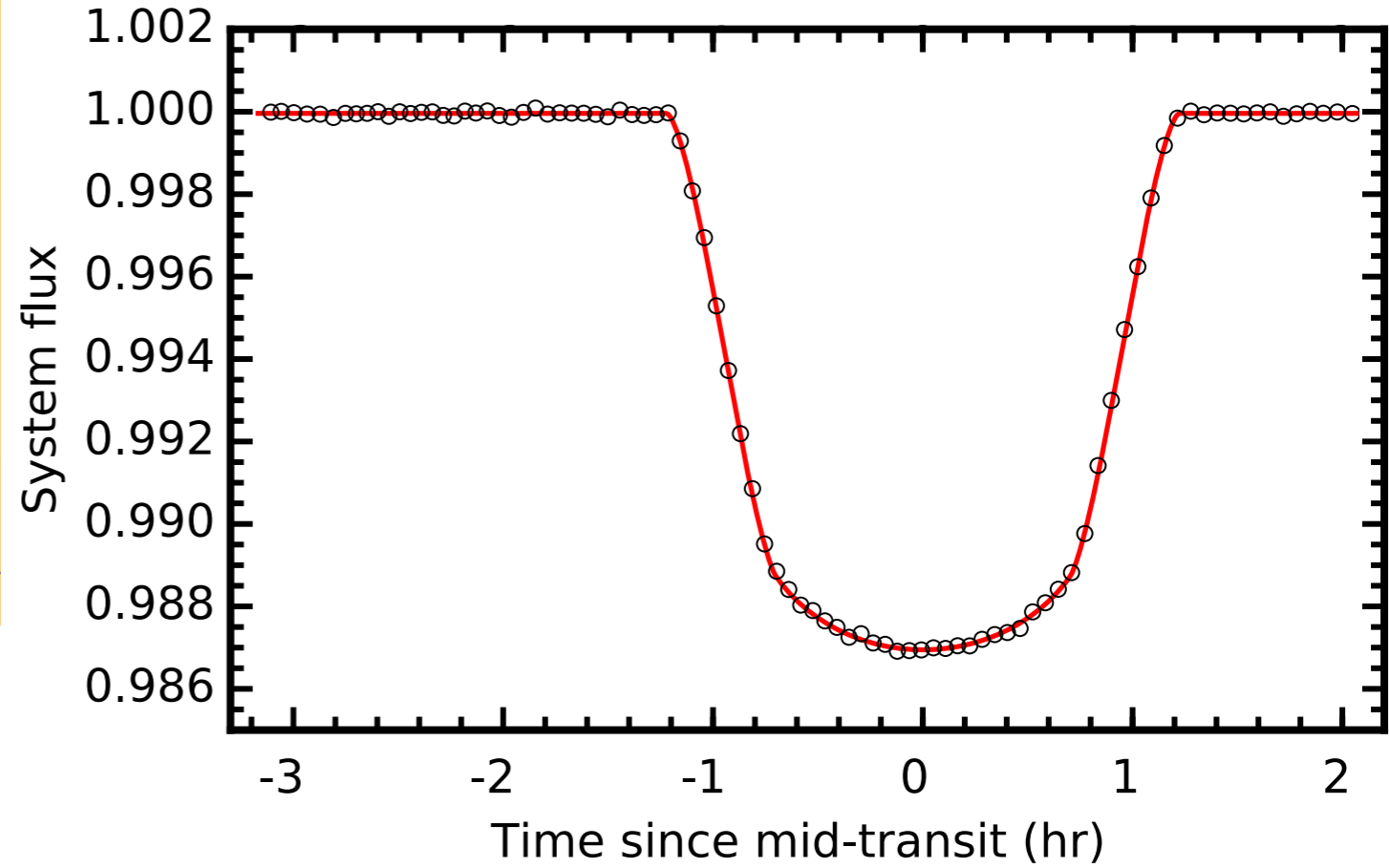
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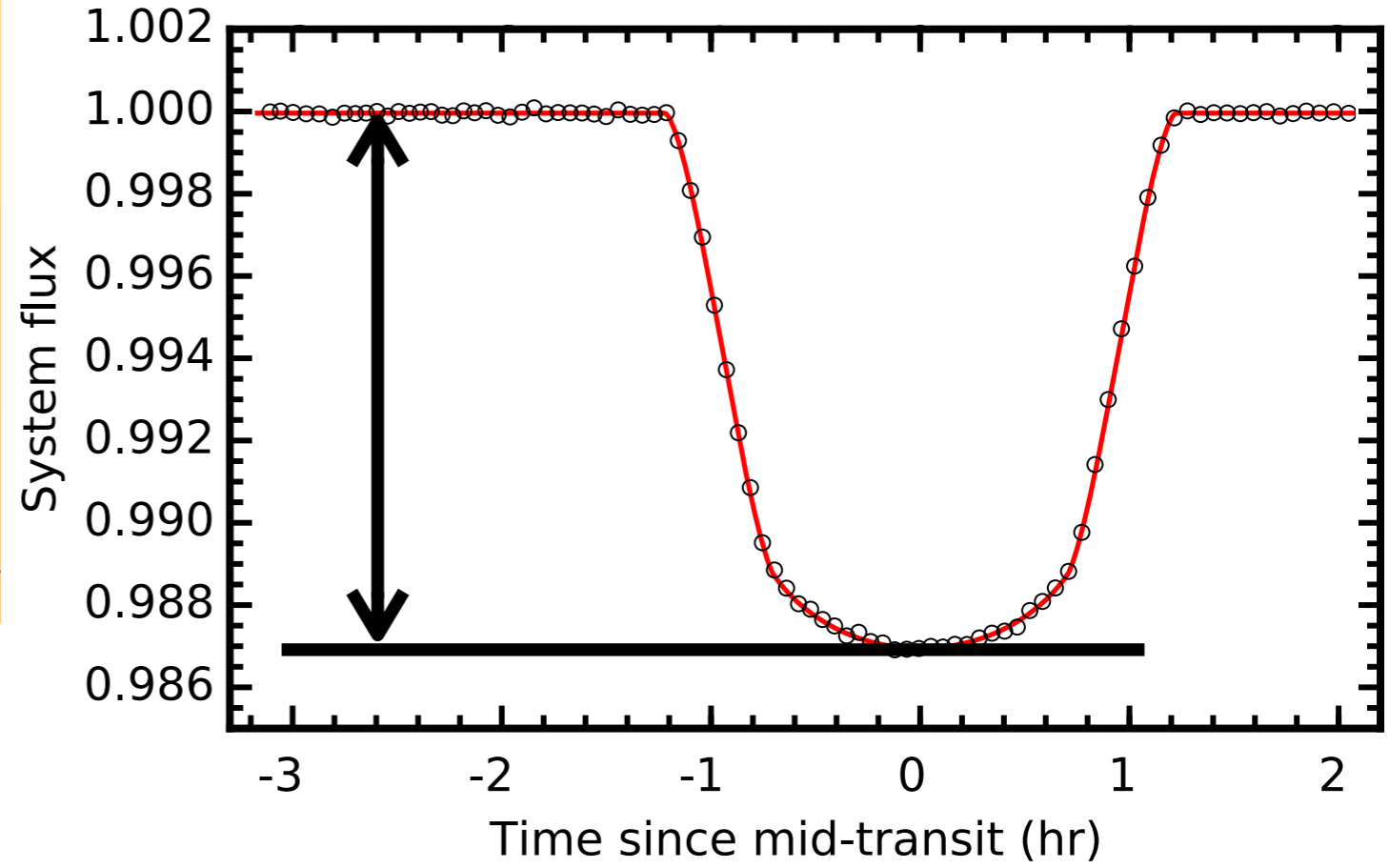
From the ground: multi-object spectroscopy



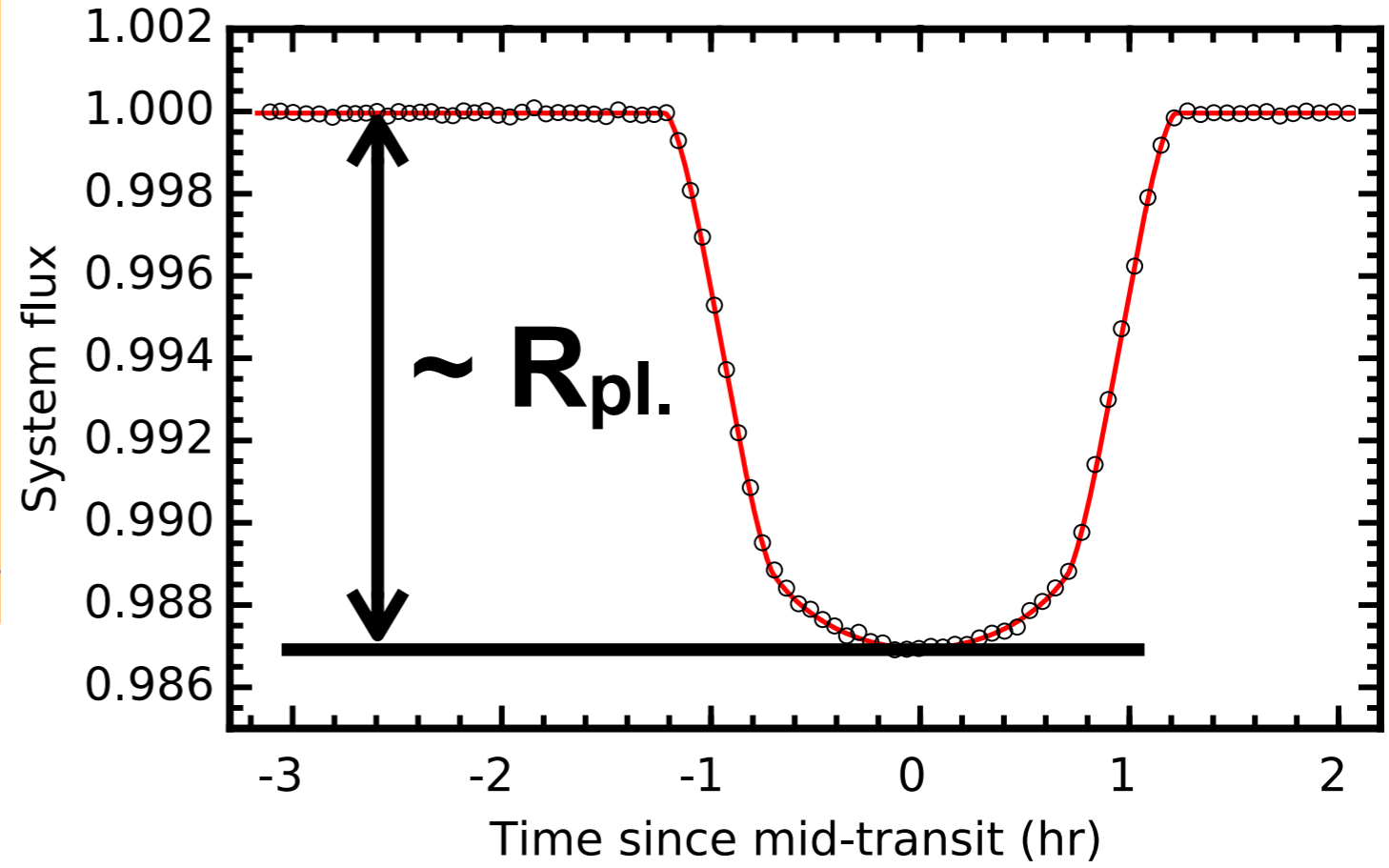
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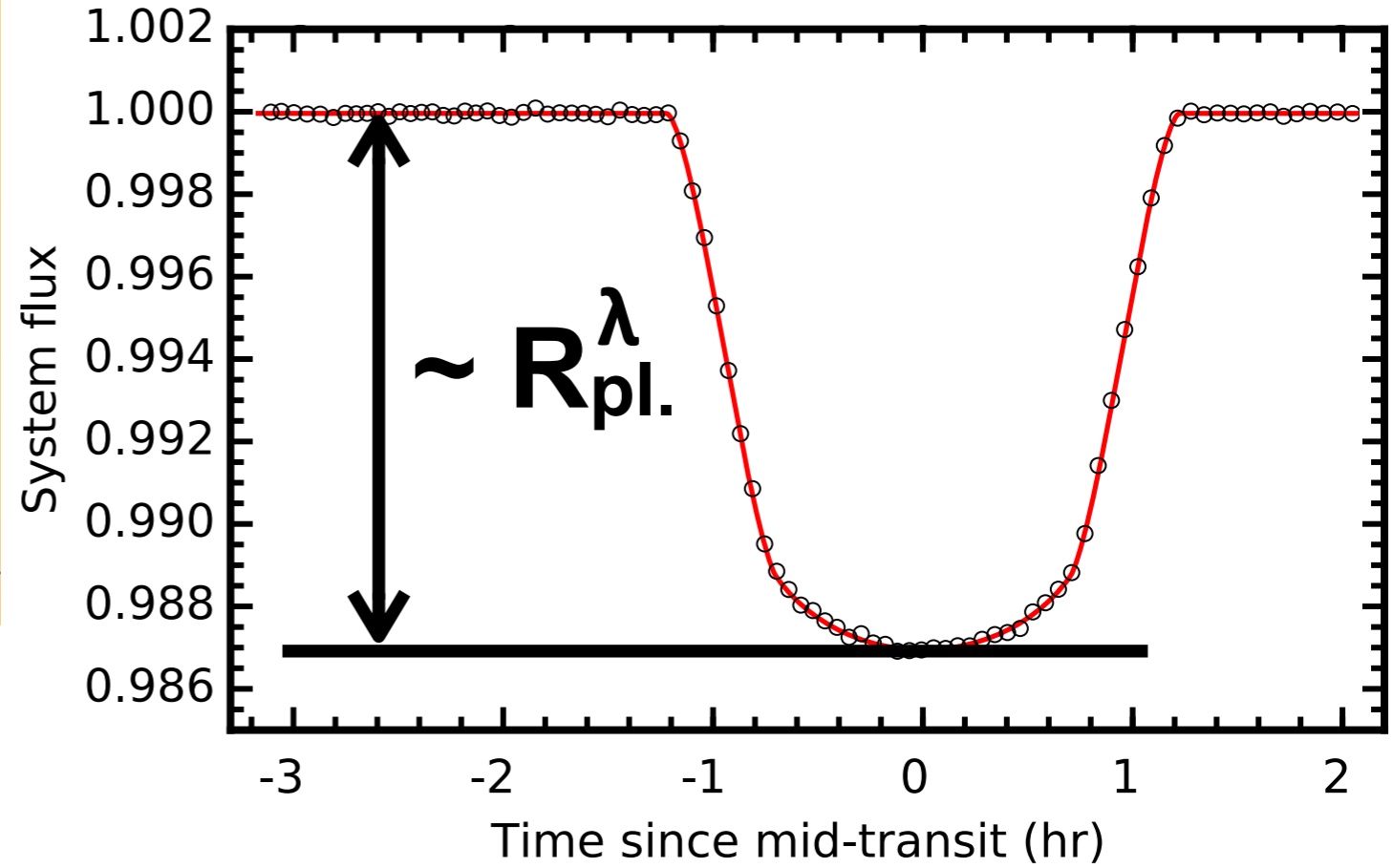
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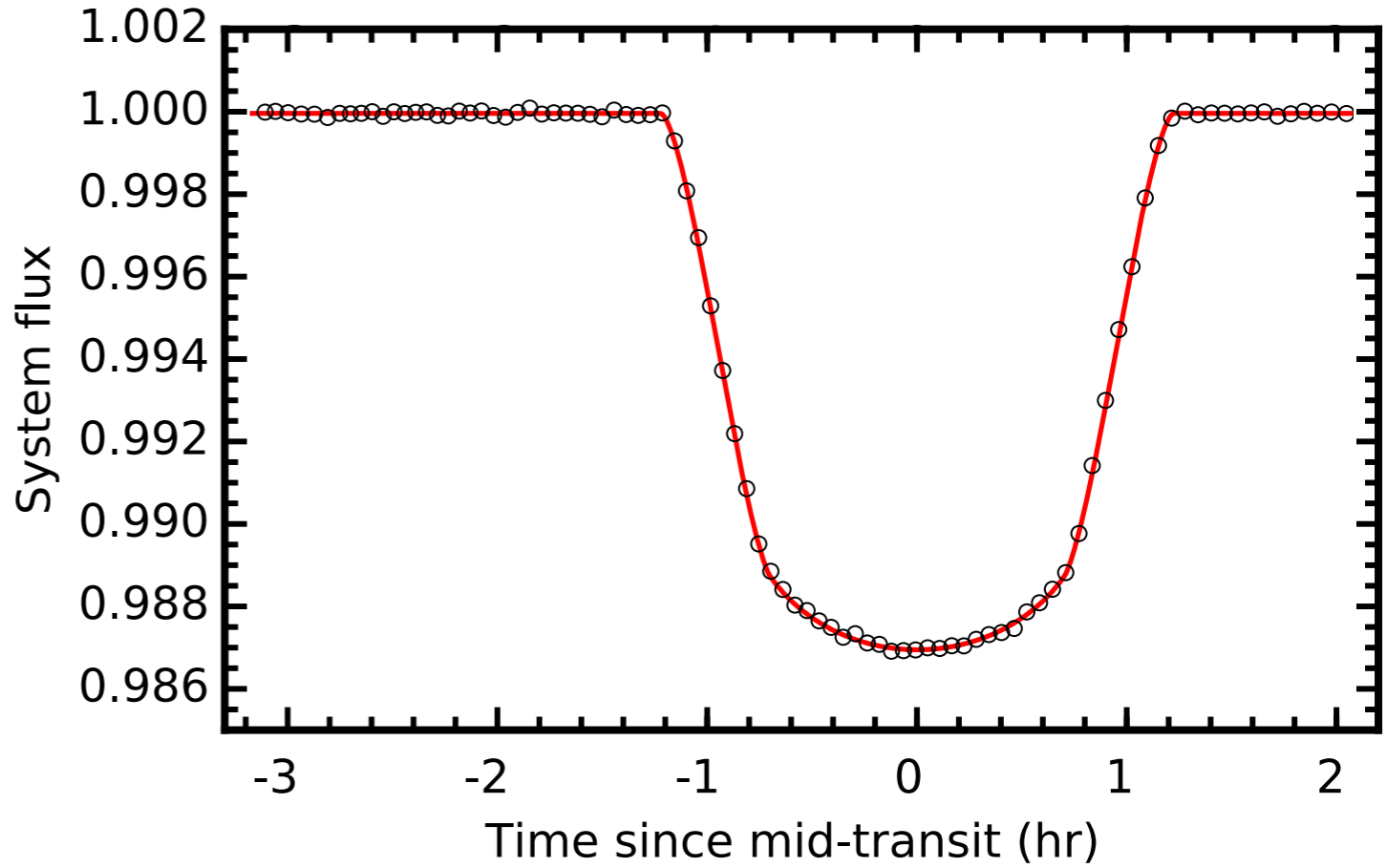
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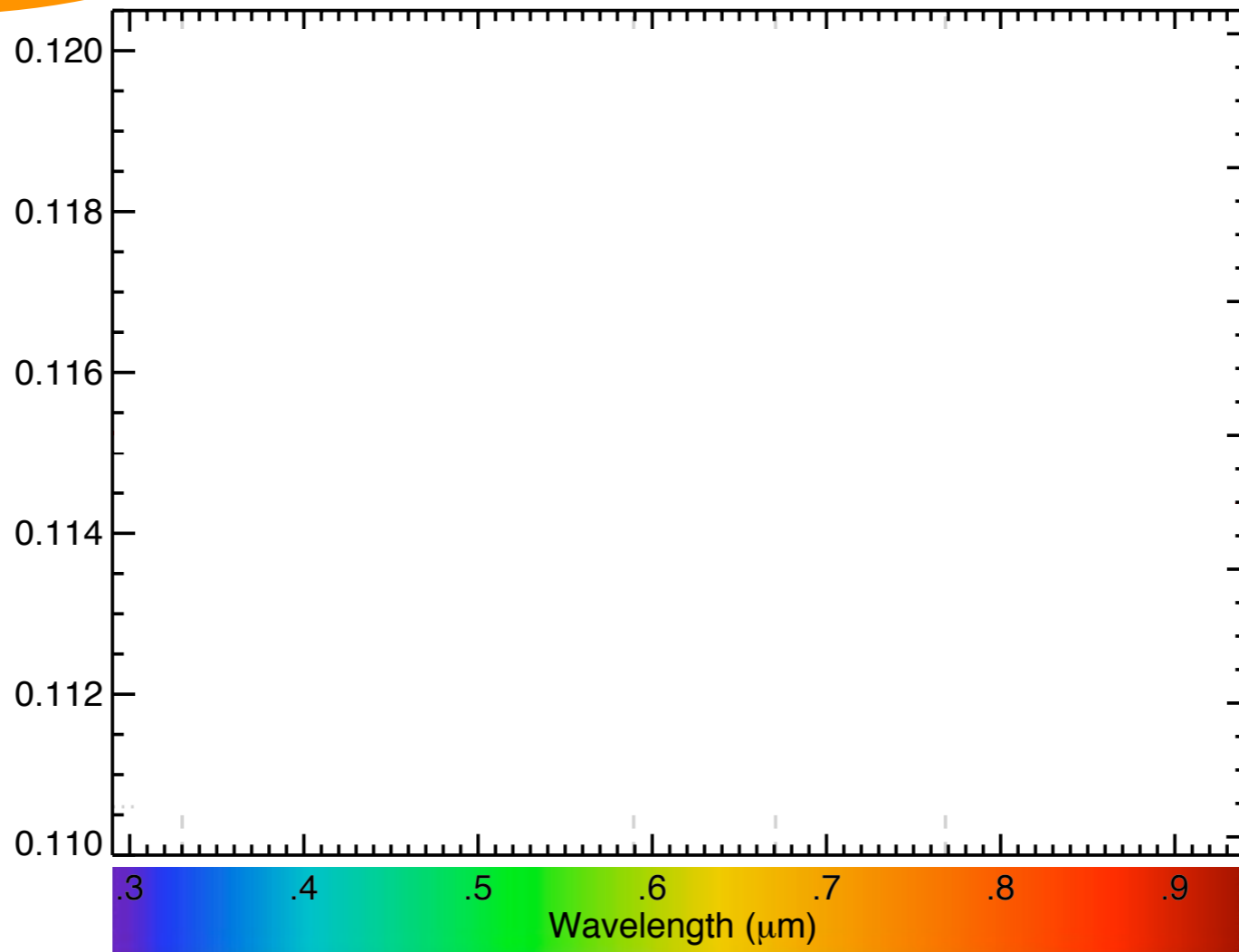
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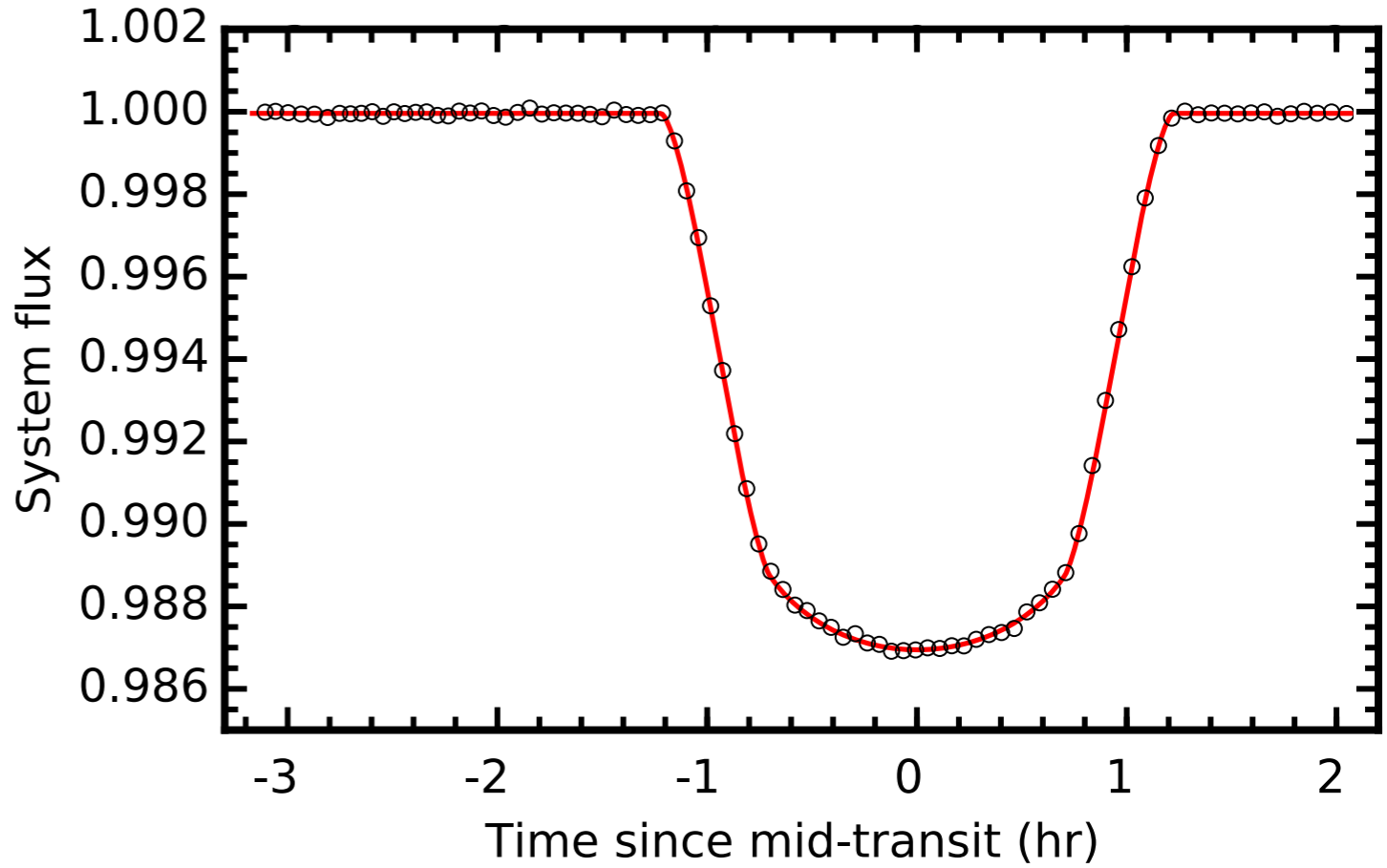
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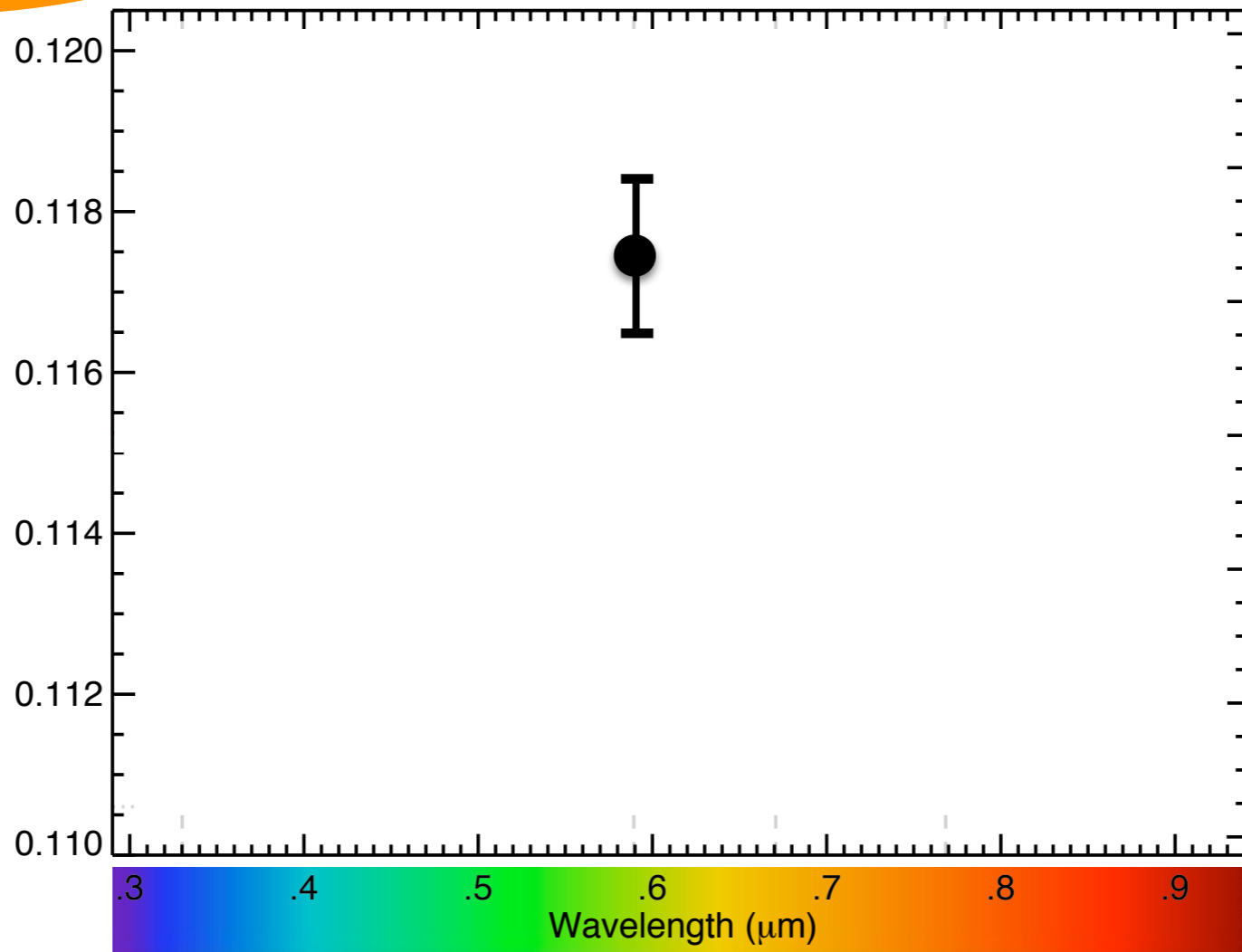
$R_{pl.}$



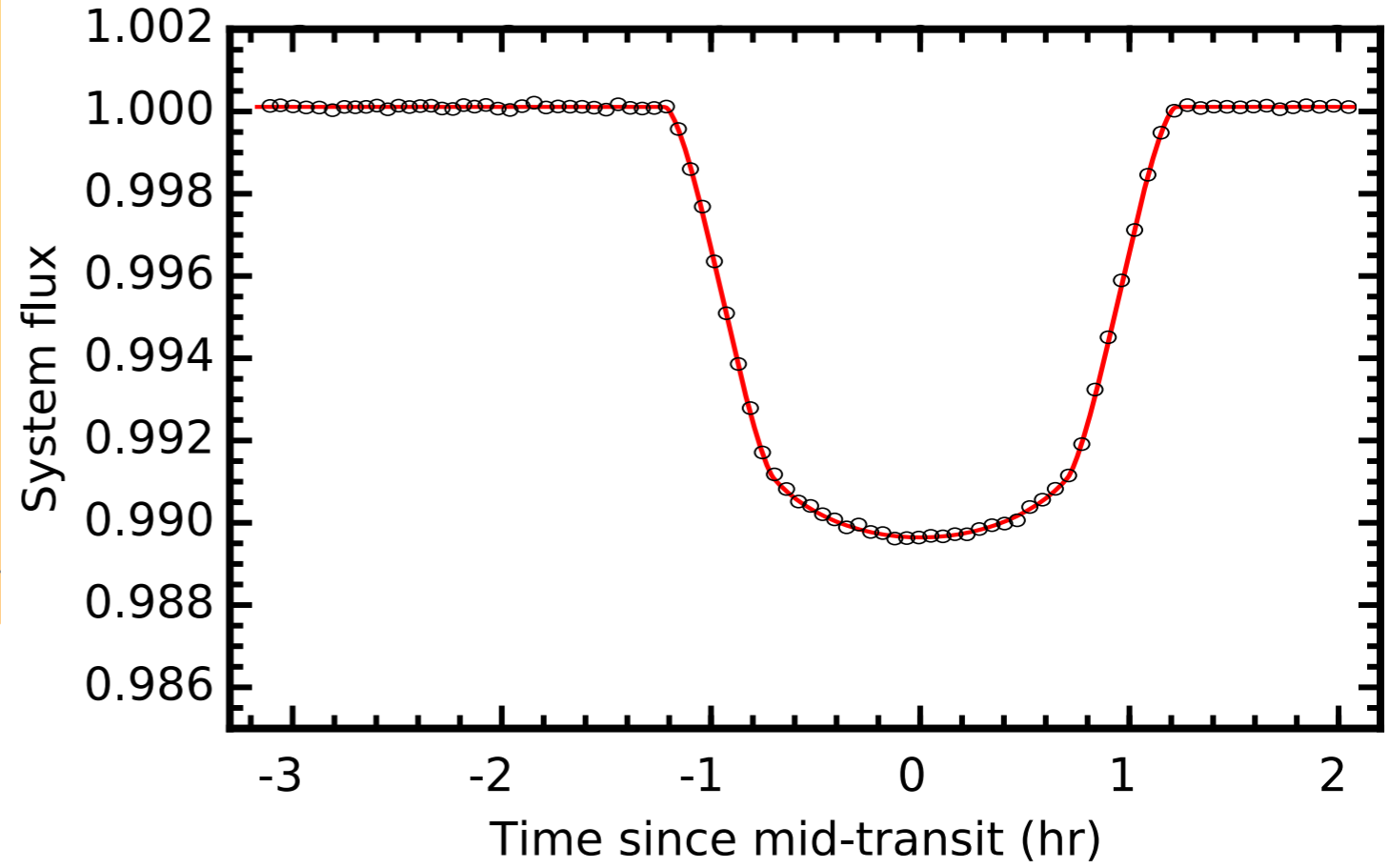
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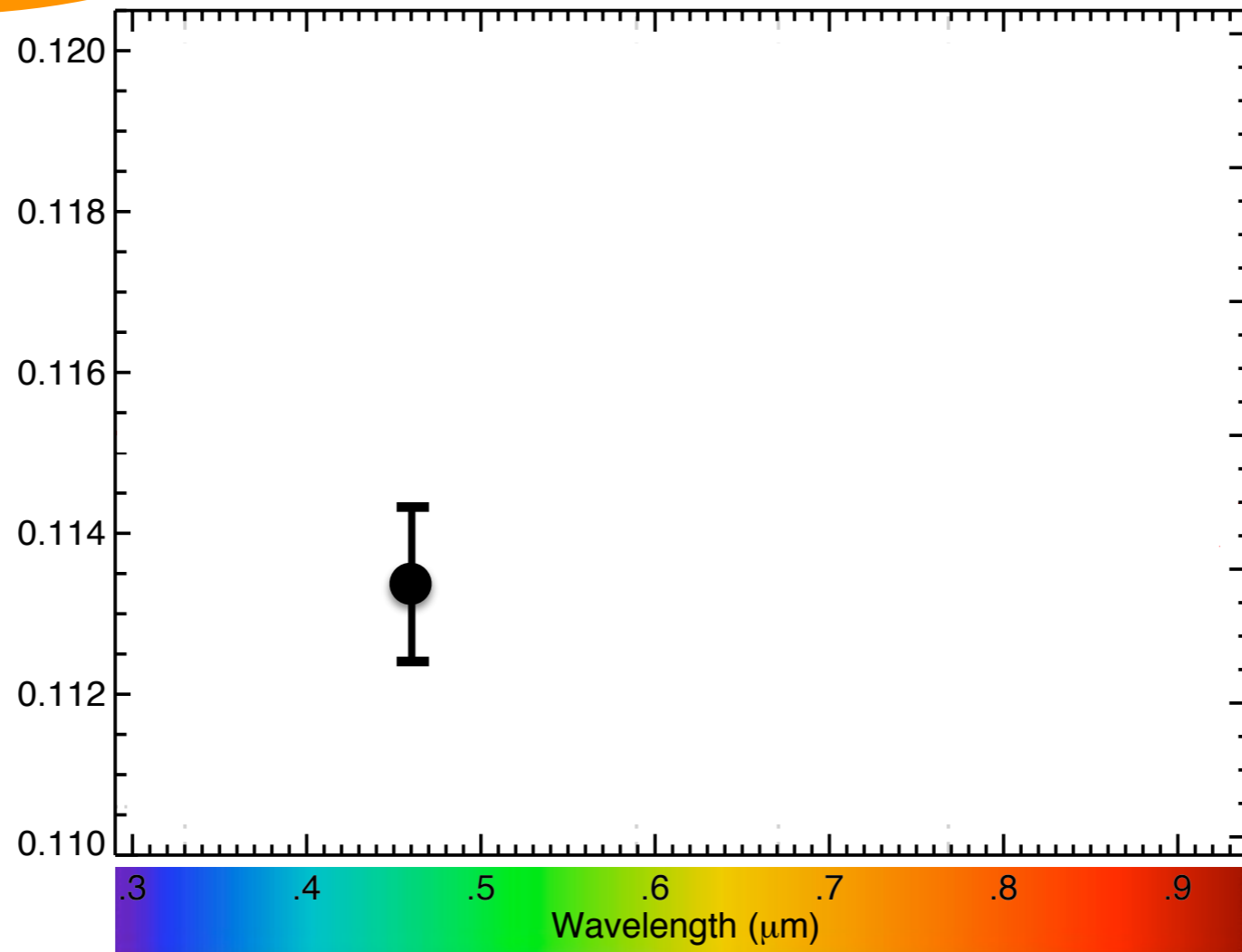
$R_{pl.}$



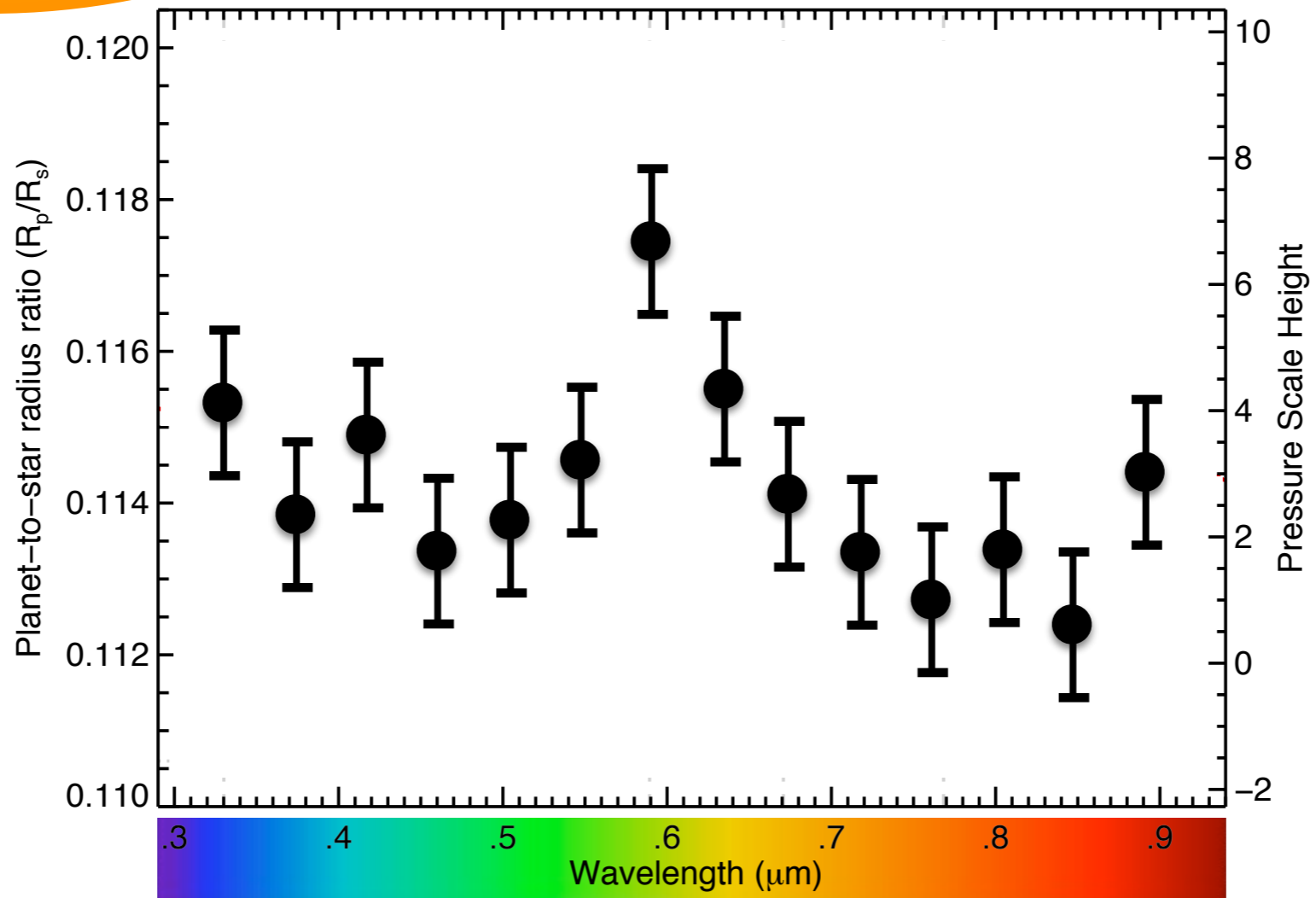
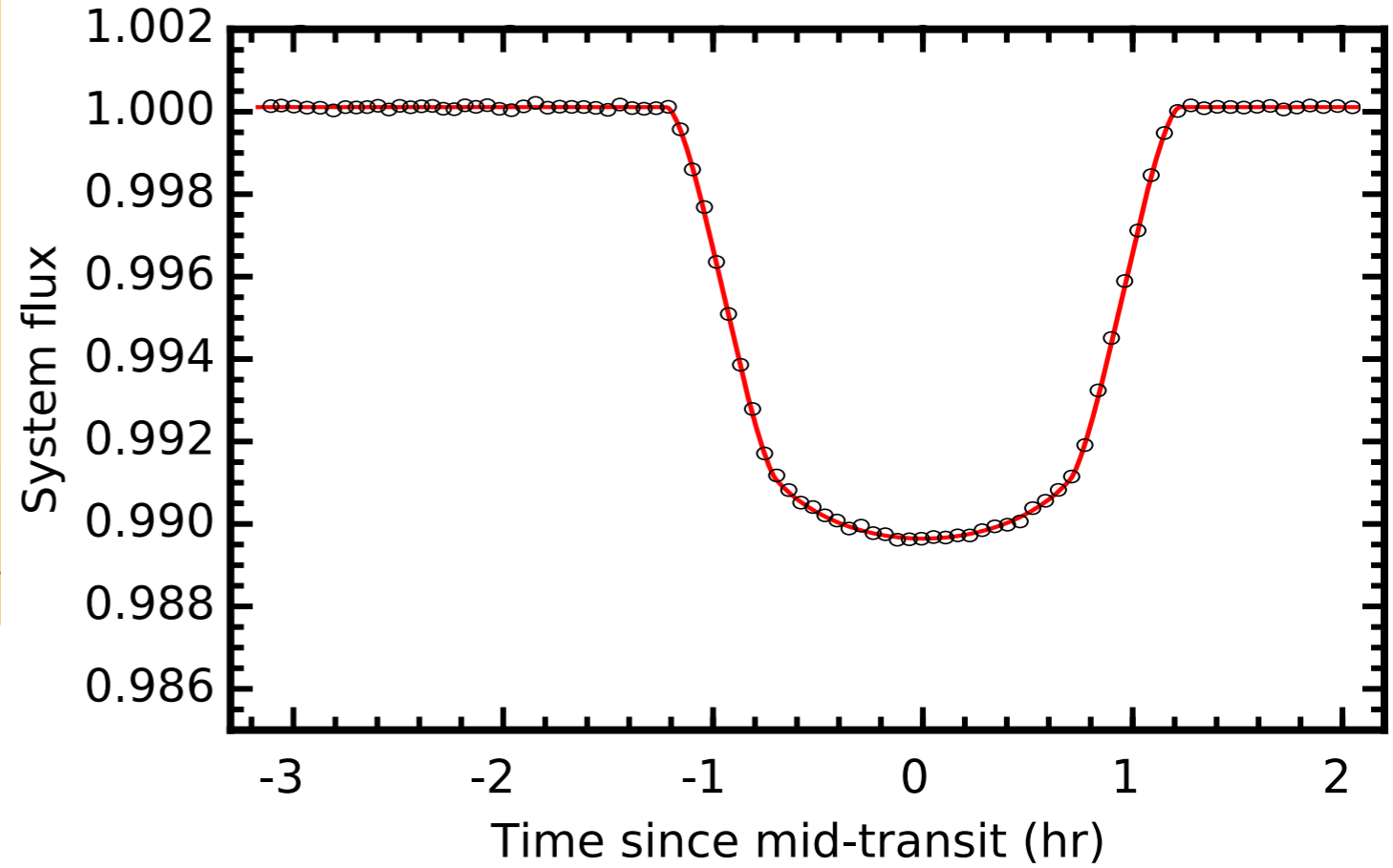
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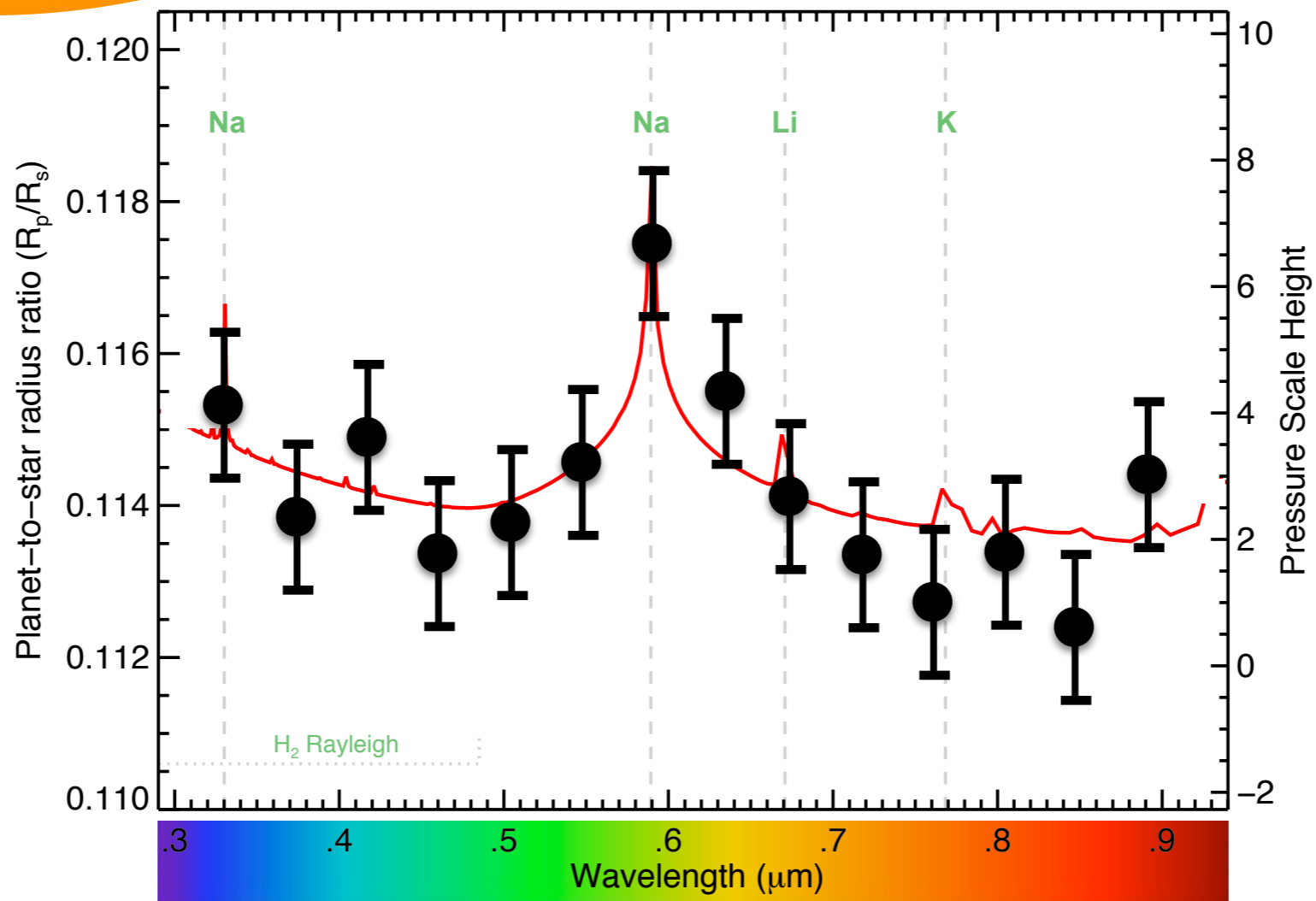
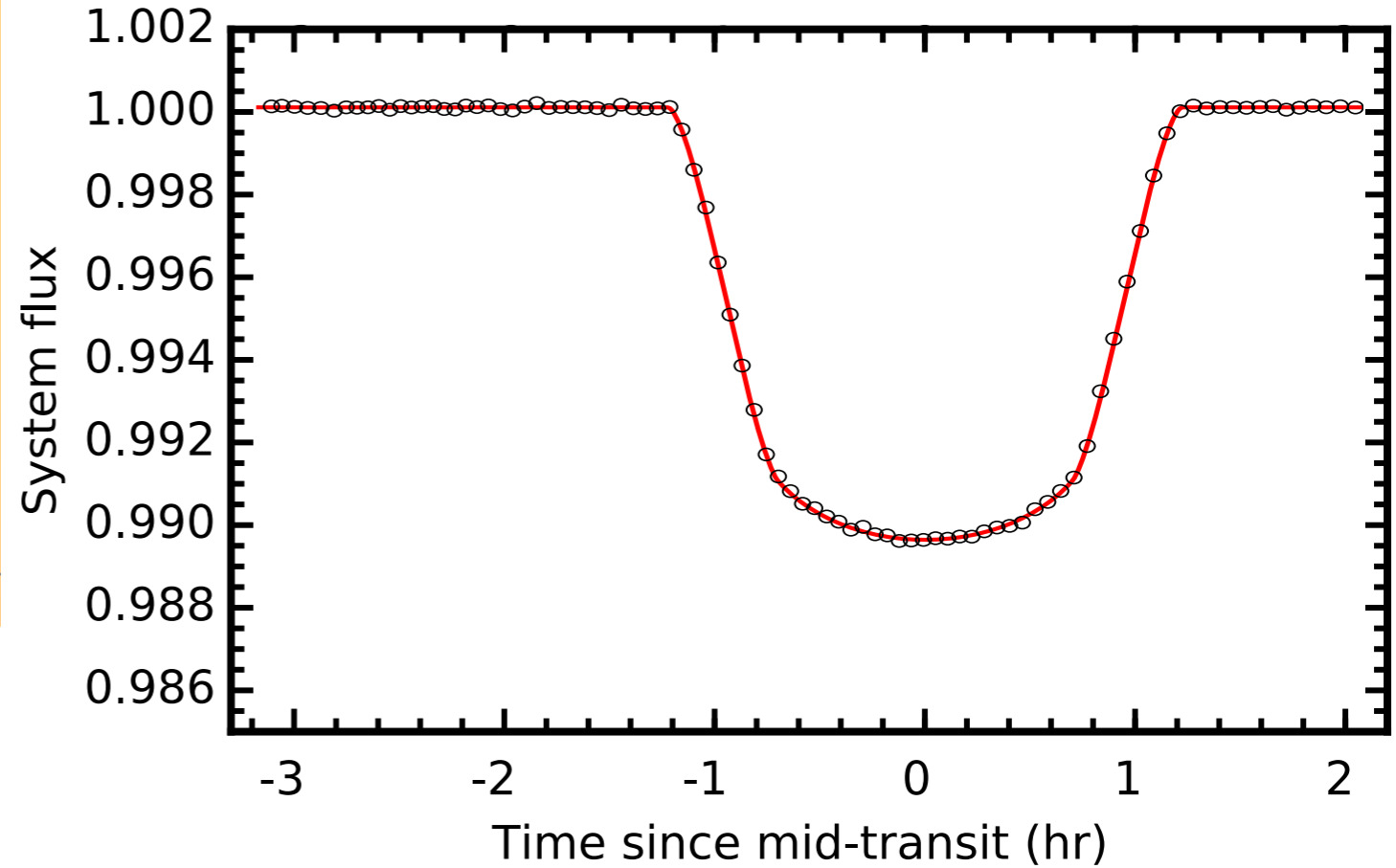
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How does transit spectroscopy work ?



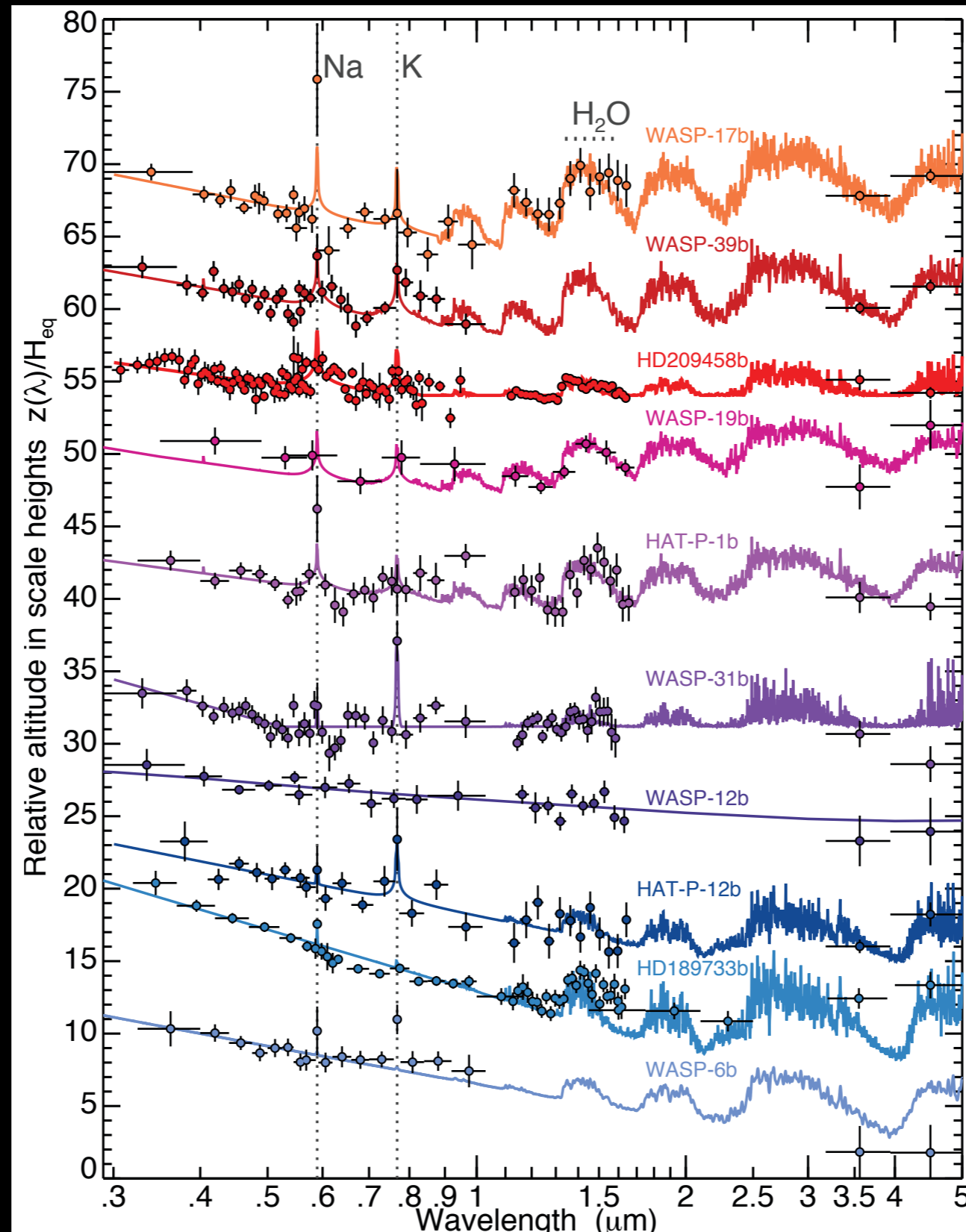
Few Hot Jupiters should be completely clouded out

Strong Features

**Clouded Features
need
High-Res**

**Rayleigh scattering
aerosols clear in
IR**

**only a handful
of exoplanet
spectra - still
unable to establish
correlations !!!**



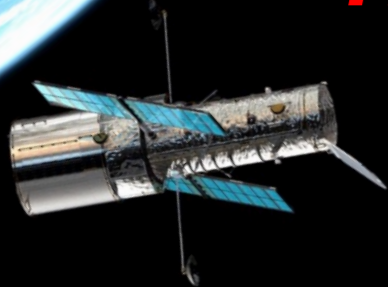
Clear-ish Skies

Cloud Decks

Strong Aerosols

Sing, Fortney, Nikolov et al. (2016, *Nature*)

Need VLT and HST for Scattering and correlations



***HST* still plays a leading role in the exploration of exoplanet atmospheric diversity**

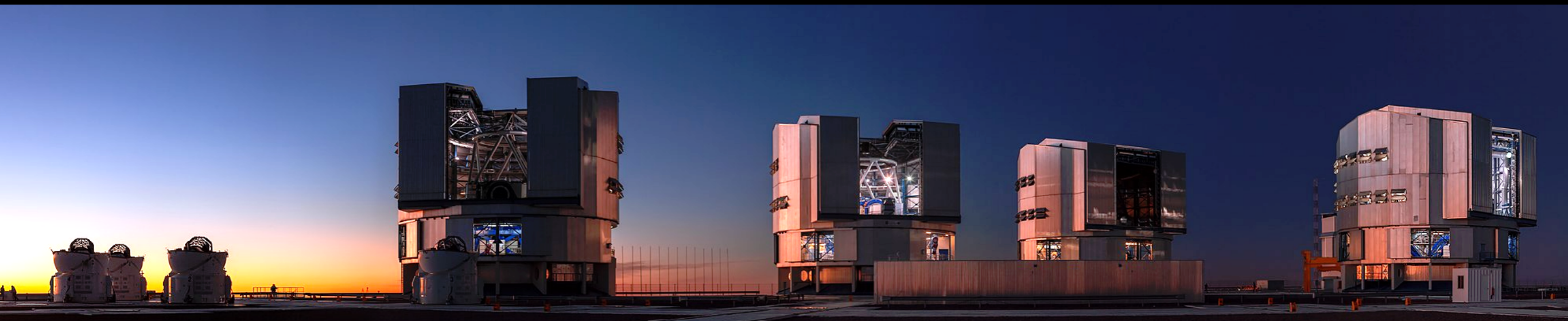
Comparative VLT FORS2 survey (**38hrs, PI Nikolov**)

Large VLT FORS2 transmission survey (**212hrs, PI Nikolov**)

Large *HST* spectral survey (**120 orbits, PI Sing**)

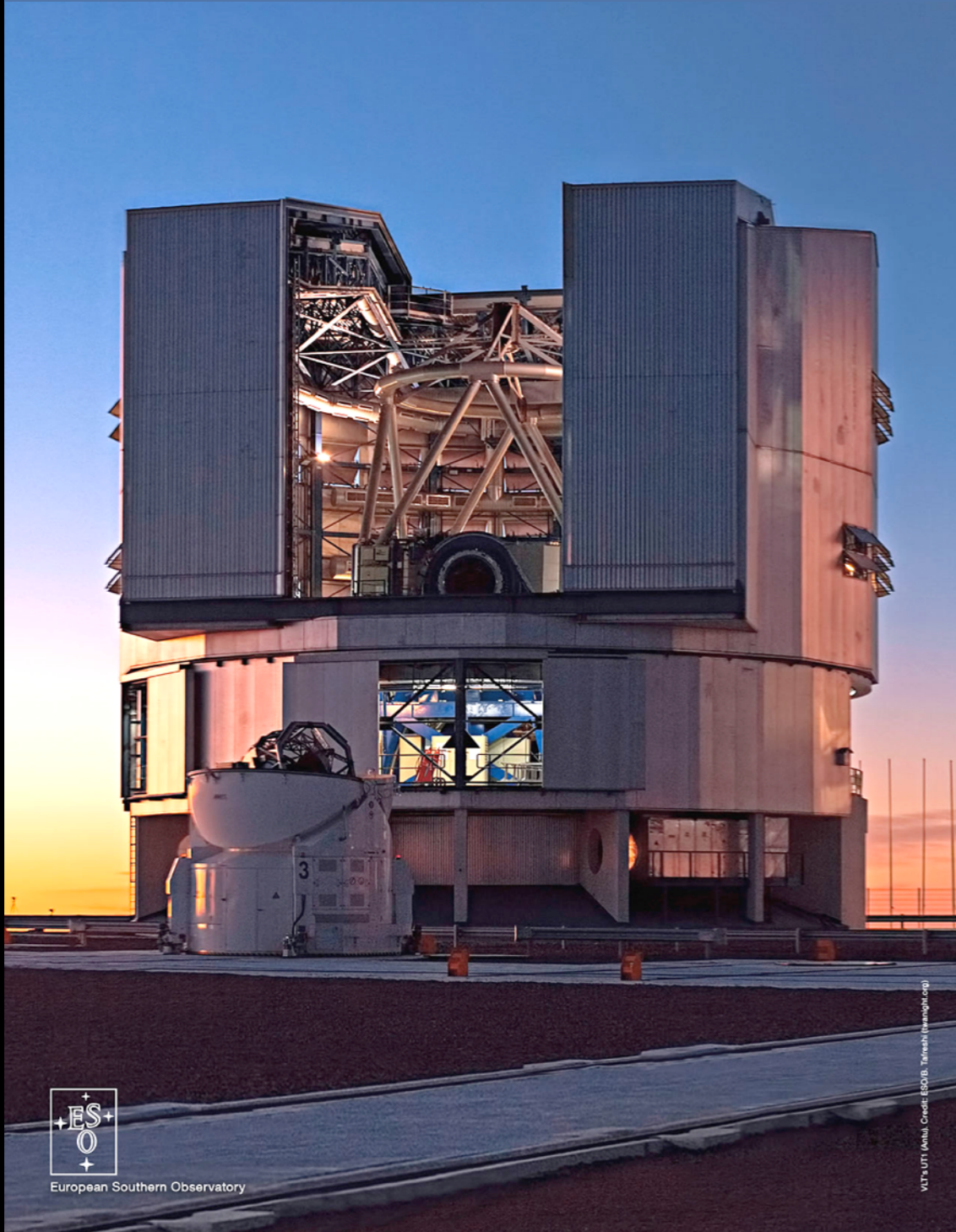
HST PanCET (**500 orbits, PIs Sing & Lopez Morales**)

Significant progress from the ground too, notably with the *Very Large Telescope* (FORs2 and CRiRES)

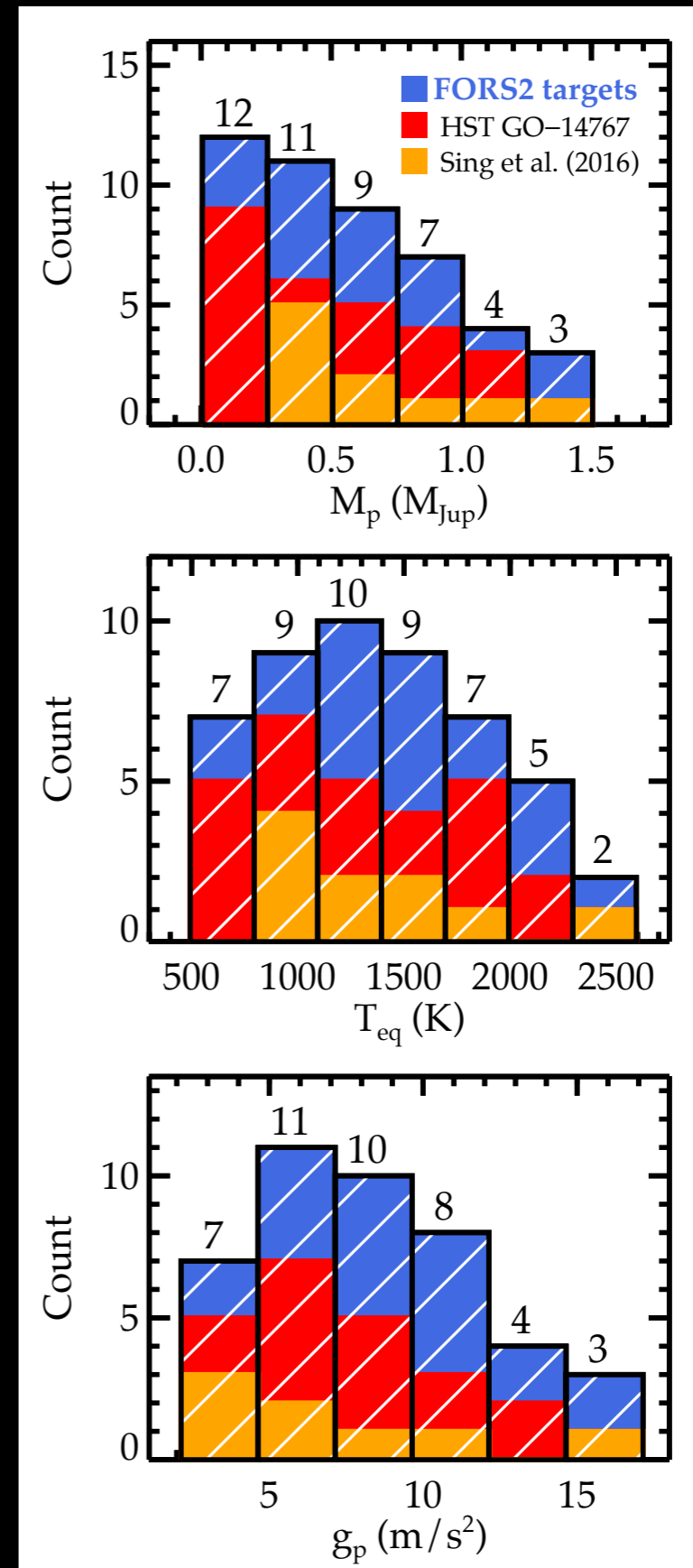


Introducing the *first large-scale ground-based, exploratory transmission spectral survey* of 20 transiting exoplanets

212hr on the VLT FORS2 started in P99, PI Nikolov



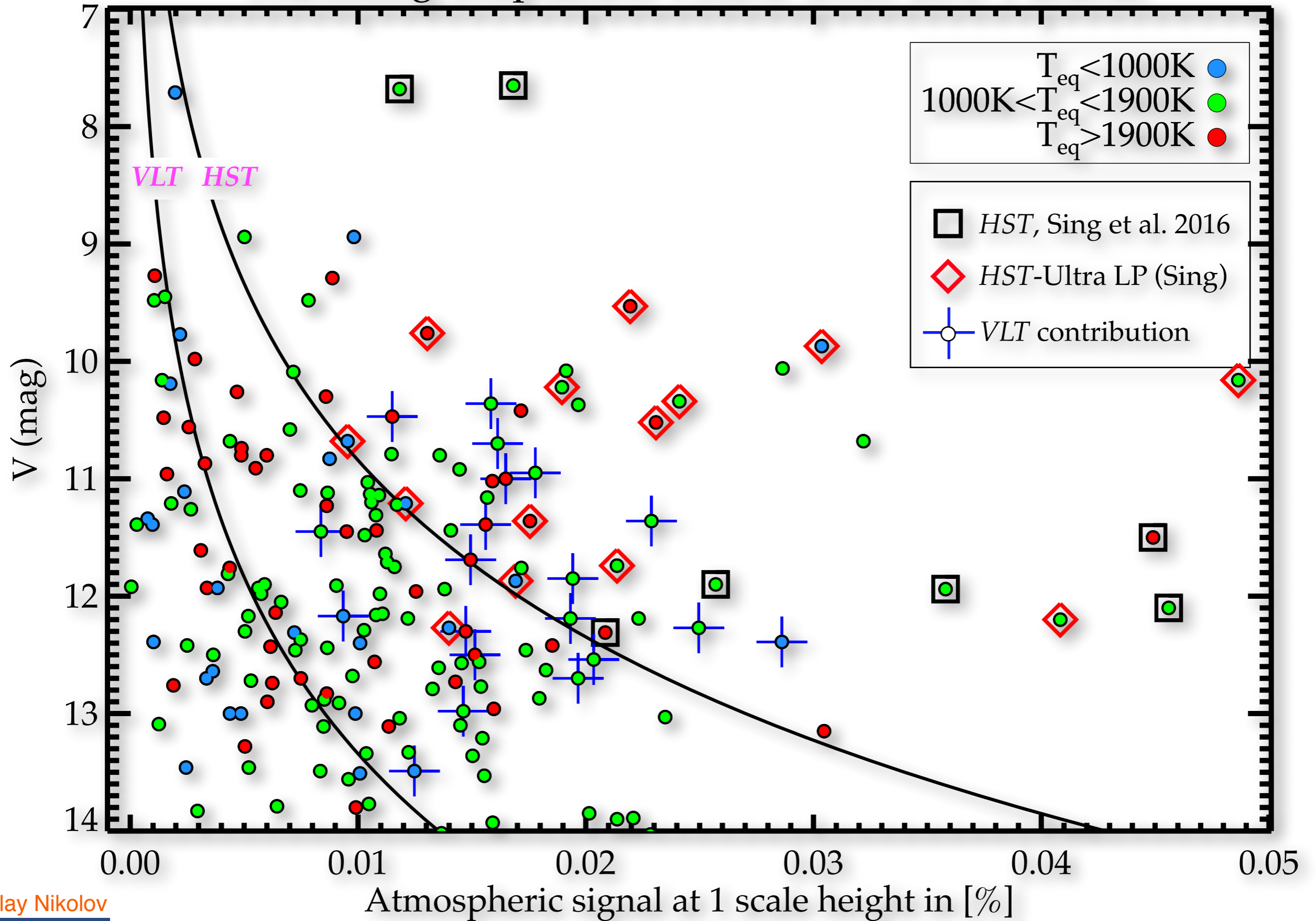
VLT's VTI, Alouat, Credit: ESO/D. Tereshkin/naospia.org



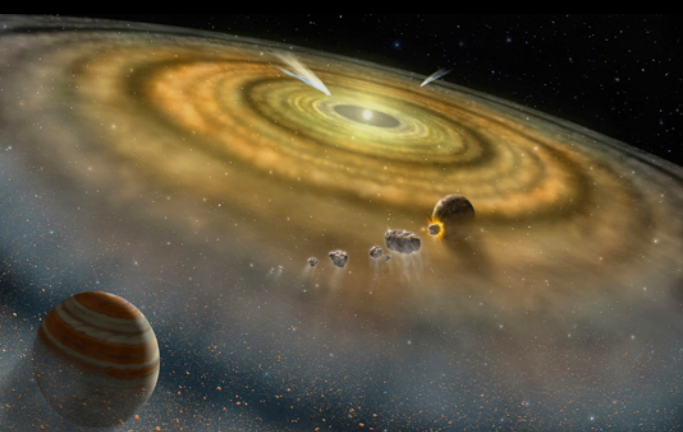
Nikolay Nikolov



Transiting exoplanets visible from ESO Paranal

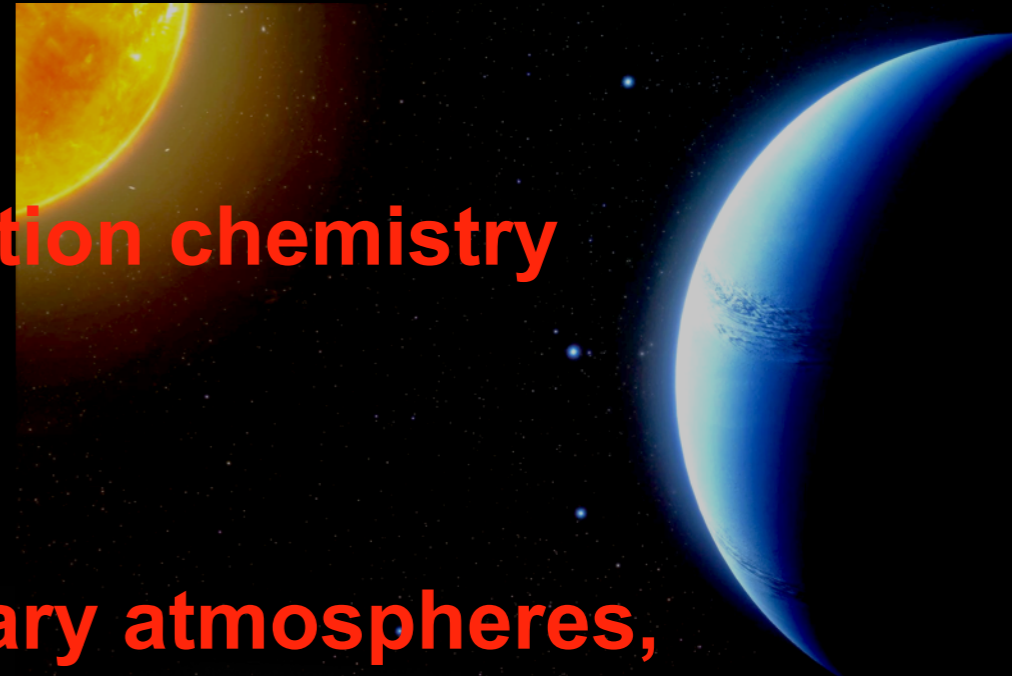


Major Exoplanet Science Questions

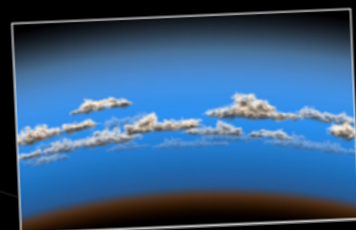
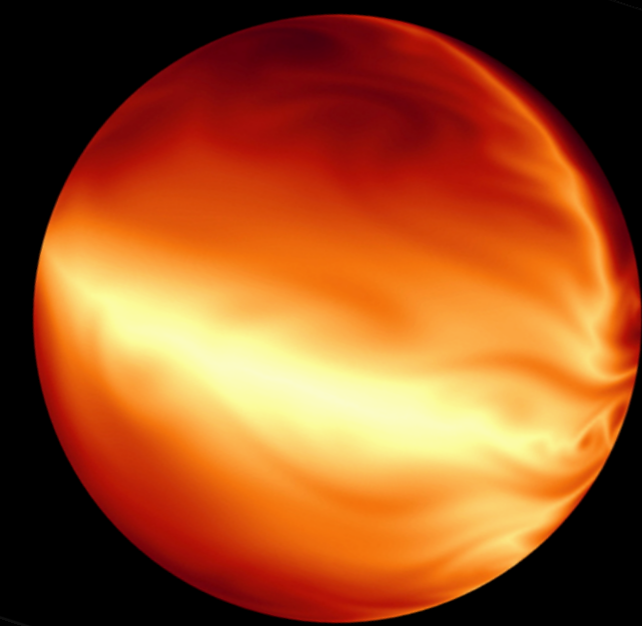


- Link composition & abundances to formation:
Absolute abundances (Na, H₂O, ...)

- Clouds & hazes:
**Occurrence, Condensation chemistry
Photochemistry?**



- Spectra of super-Earths:
**primordial and secondary atmospheres,
formation**

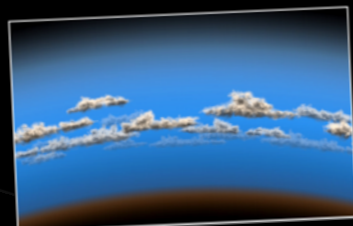


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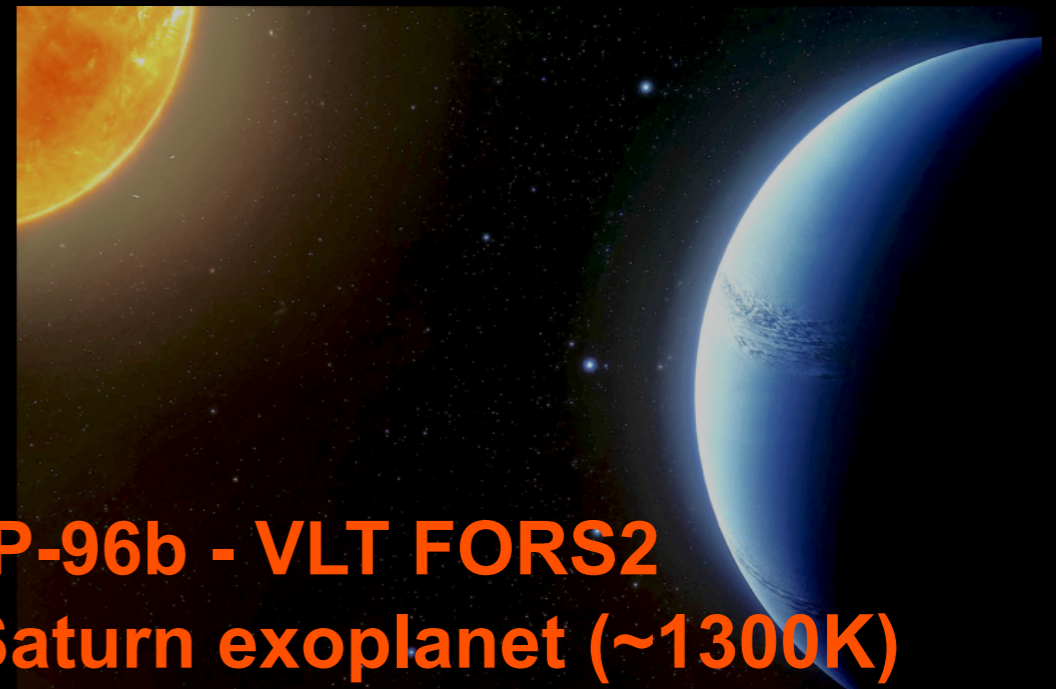
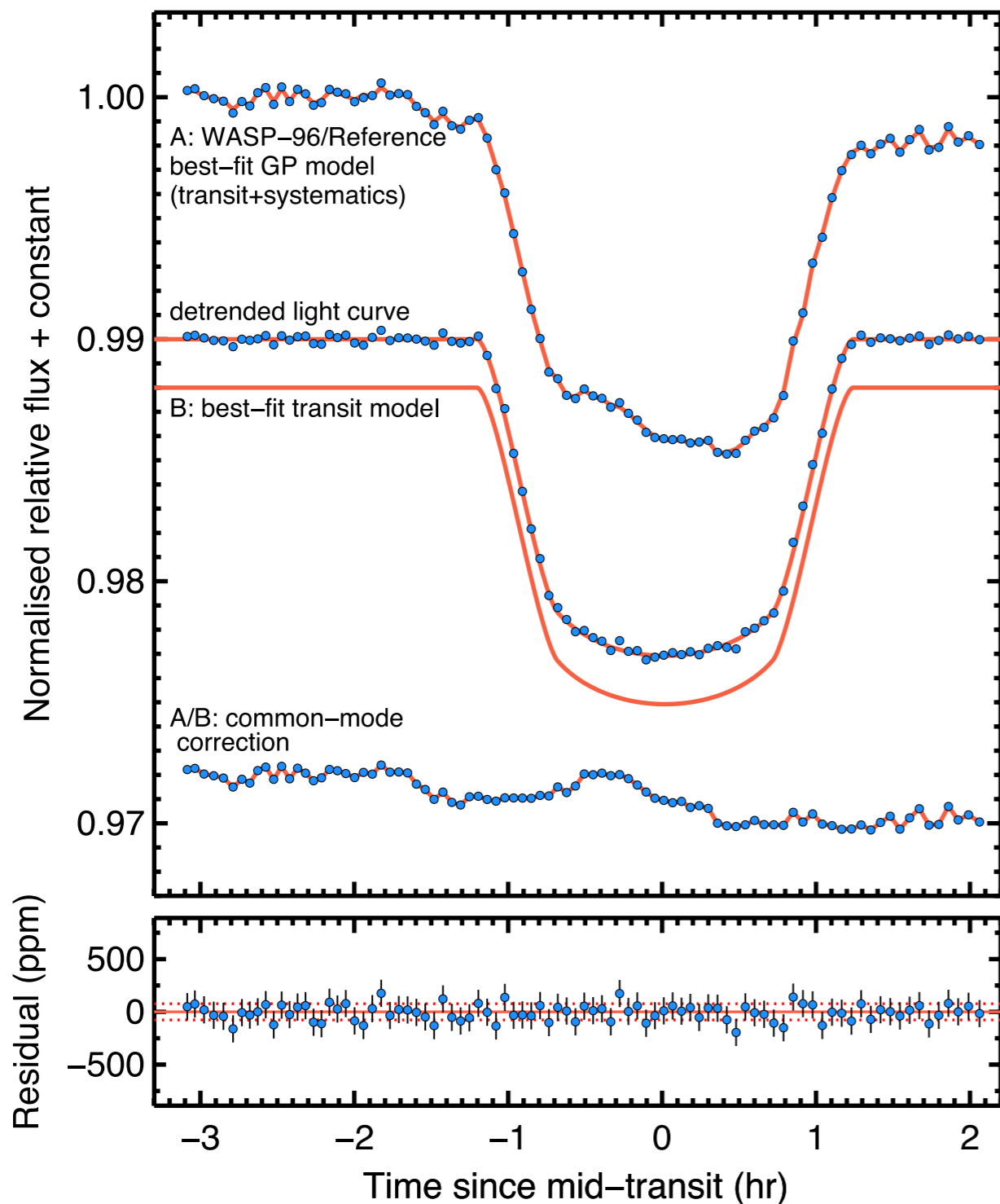
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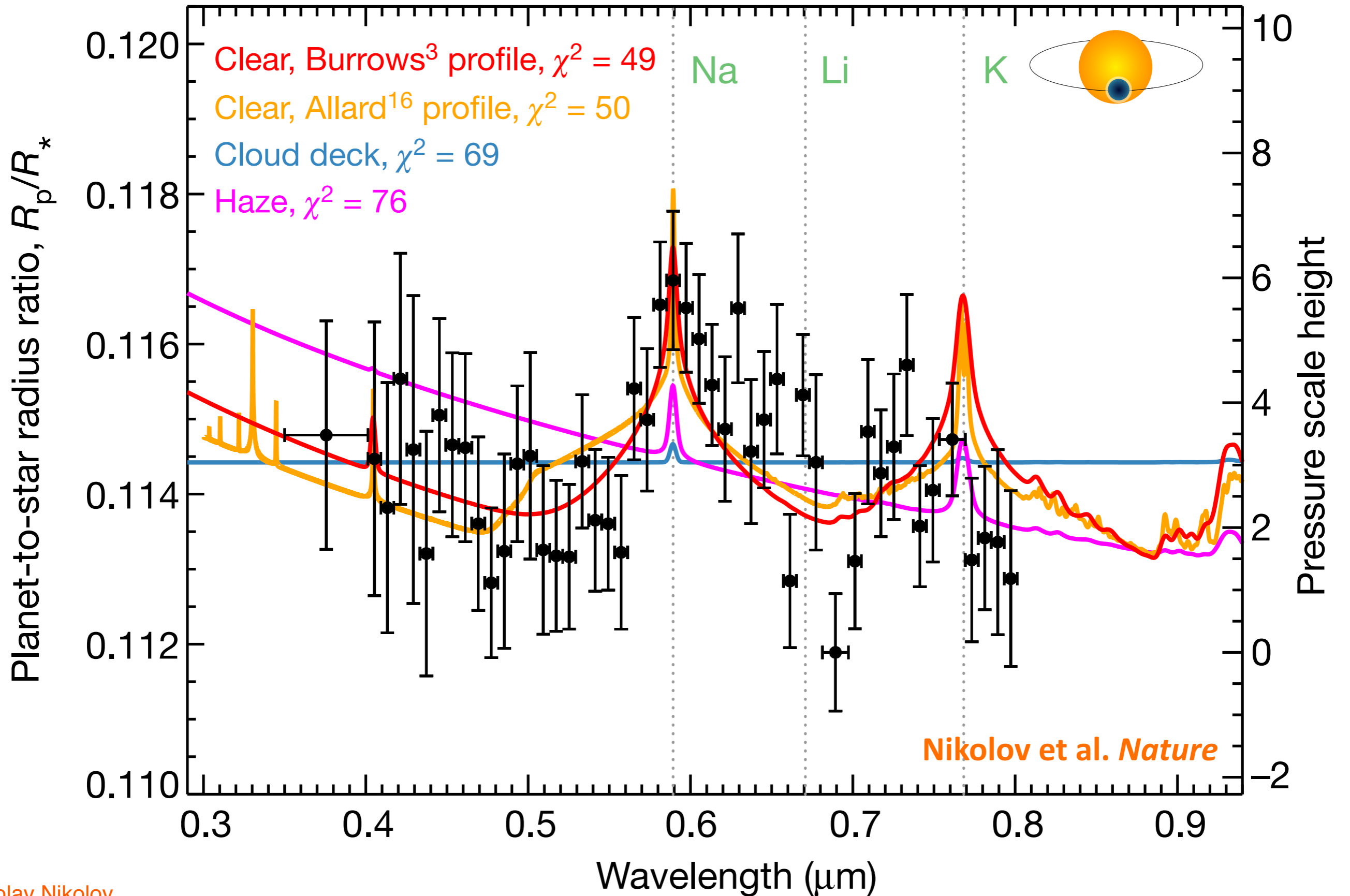
Absolute abundances and link with planet formation



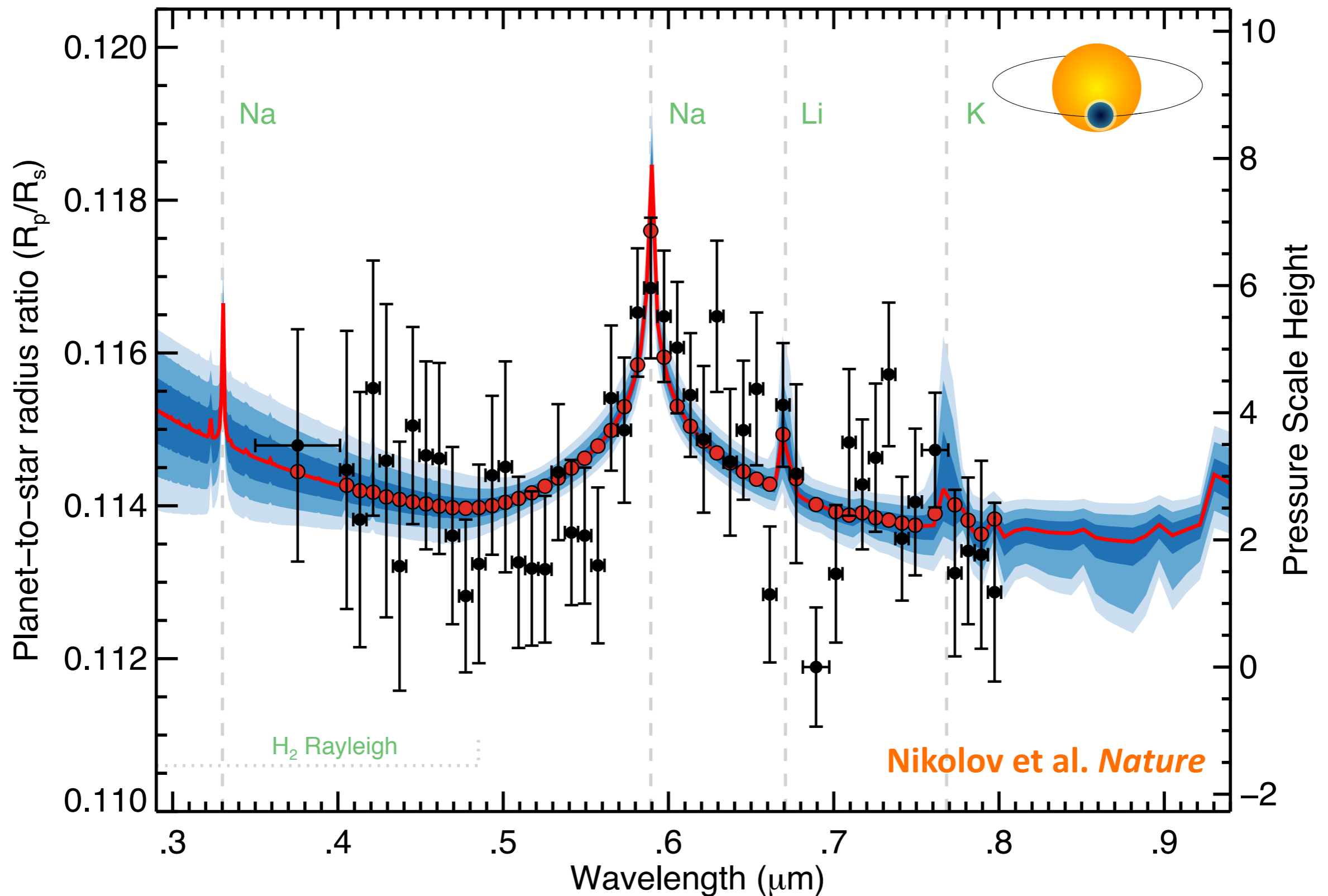
WASP-96b - VLT FORS2
Hot Saturn exoplanet (~1300K)
Large VLT FORS2 program (212hrs)

**part of a large exploratory survey
from hot gas giants to
cooler exoEarths**

**orbiting a quiet star:
 $\log(R_{H\&K}) \sim -5$**

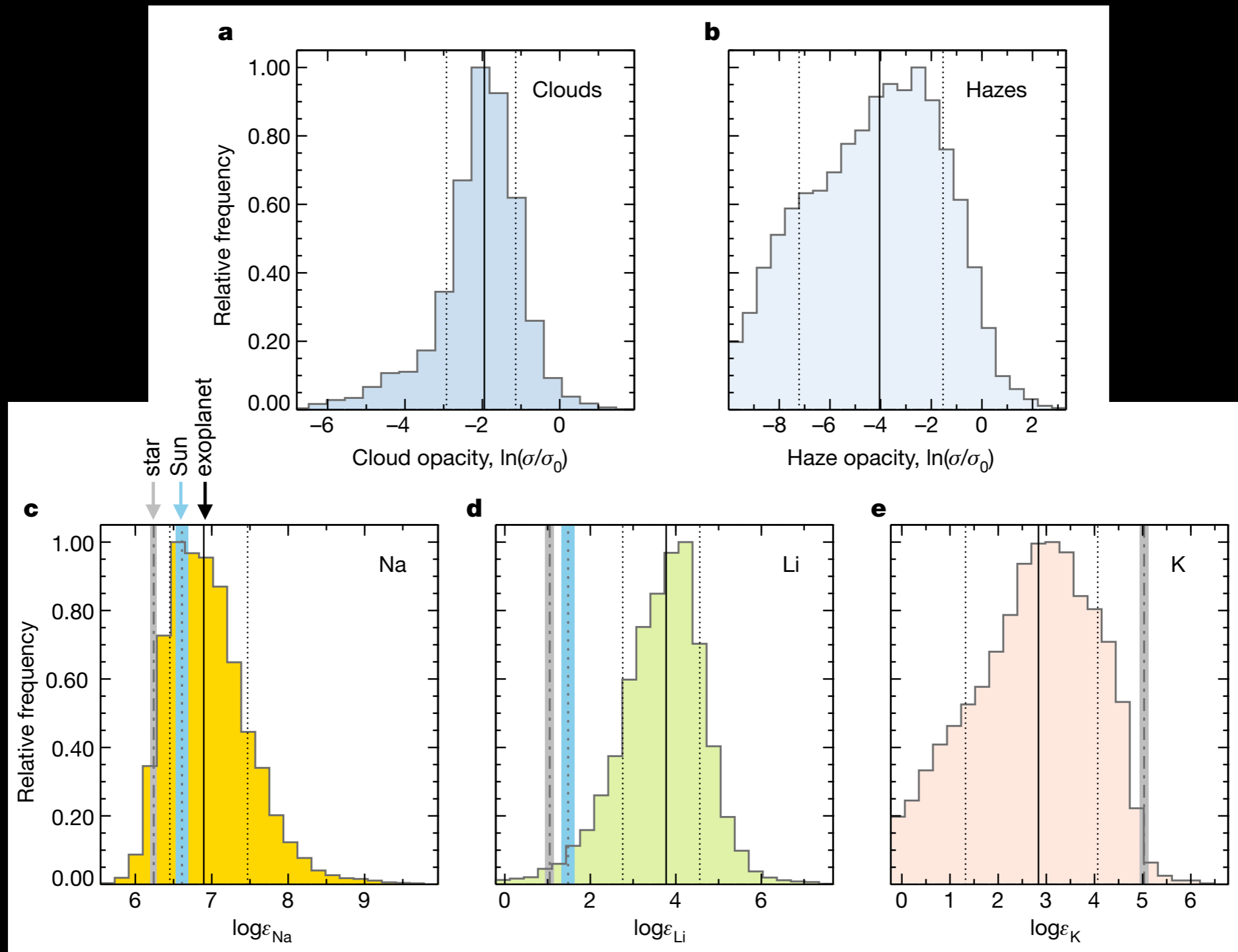


Detection of a *pressure-broadened* sodium line with VLT FORS2

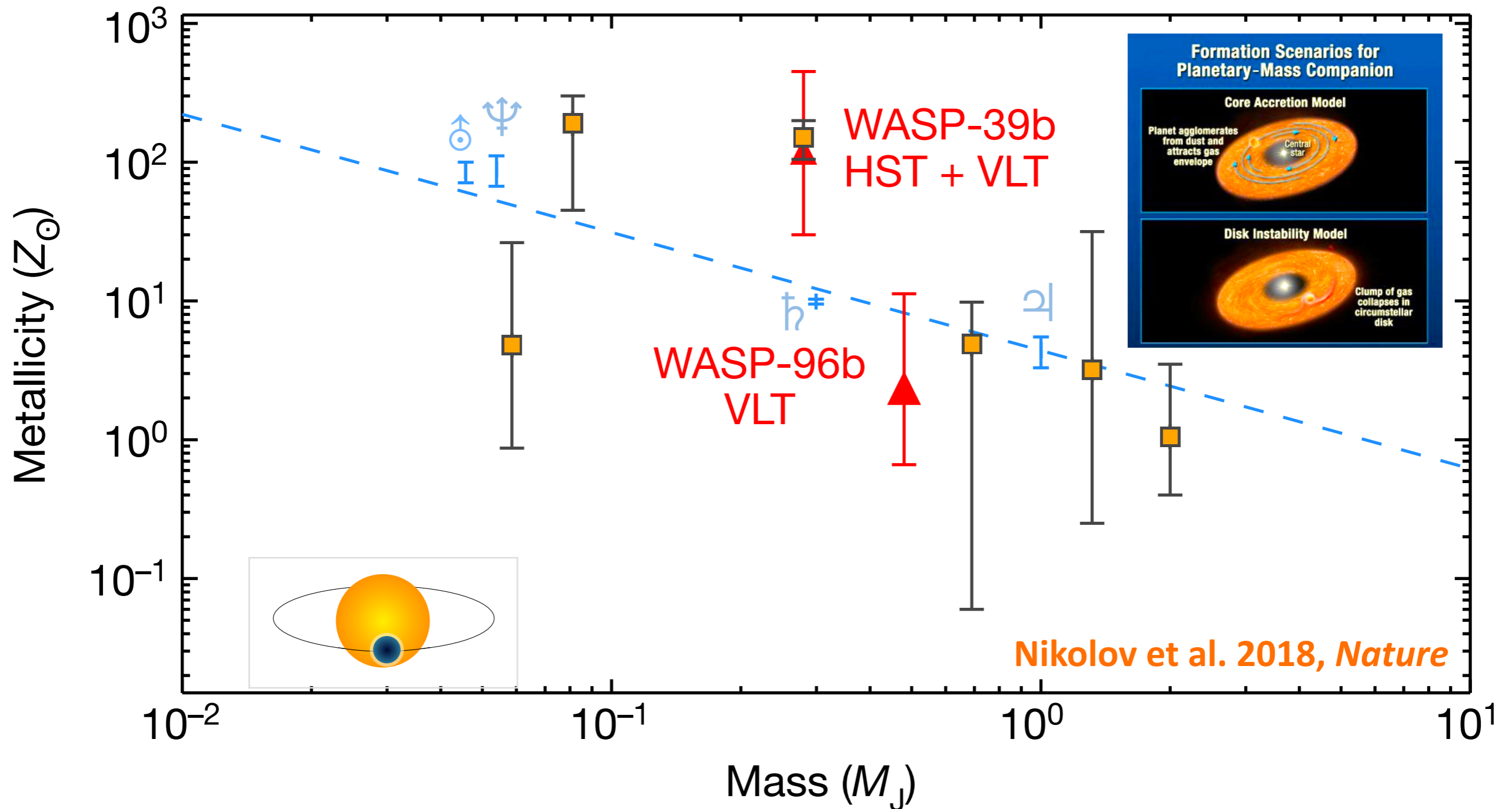


**WASP-96b - “hot Saturn” with a cloud-free atmosphere
a benchmark for the exoplanet field, found with FORS2**

Blue-optical transmission spectra are the only way to constrain ABSOLUTE abundances for exoplanets

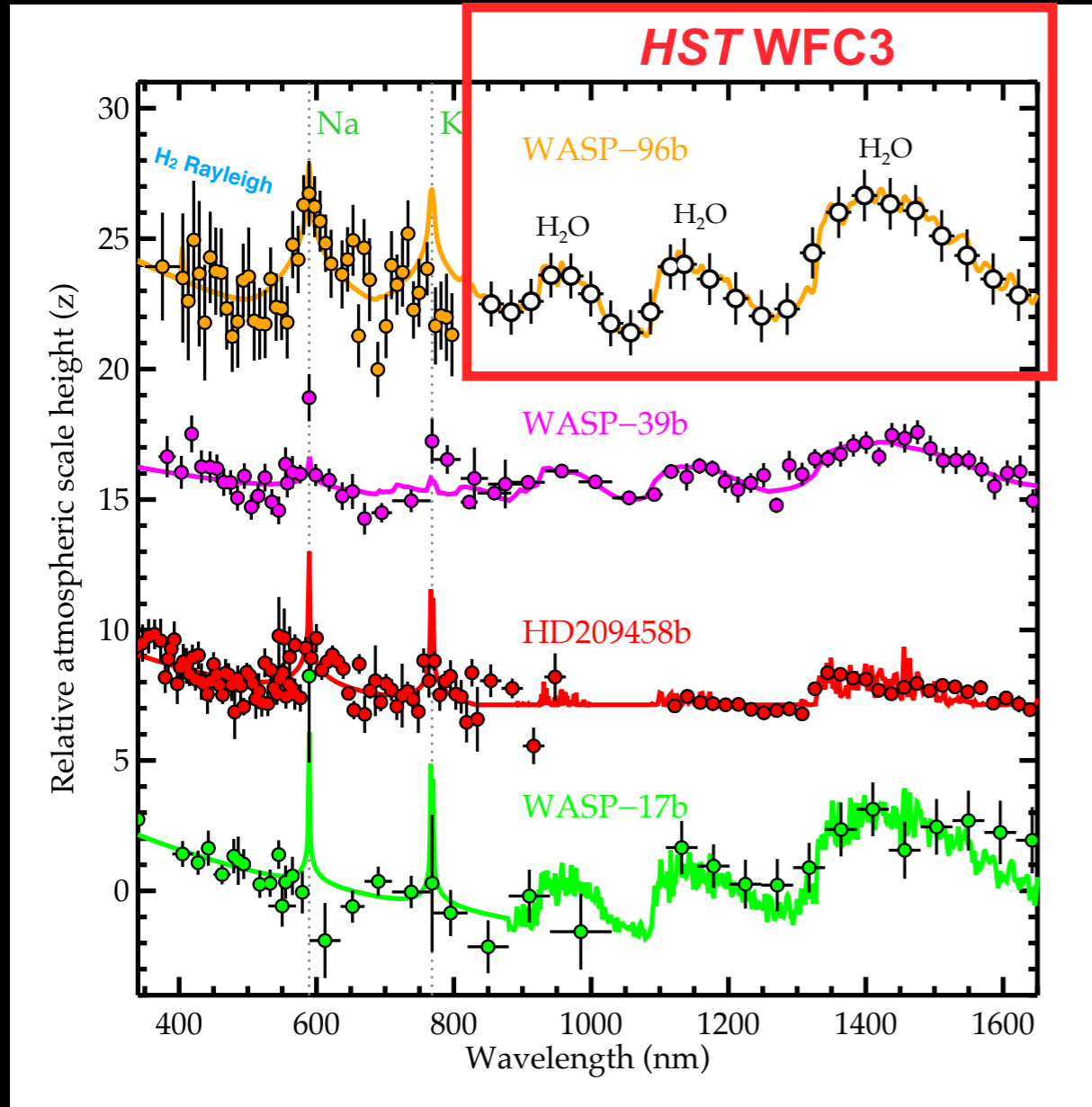


Constraining constituent: CH_4 H_2O Na



Next on WASP-96b: Linking exoplanet atmospheric metallicity with planet formation

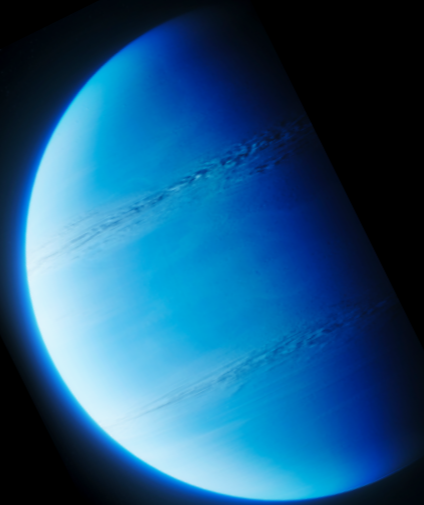
top four cloud-free exoplanet atmospheres



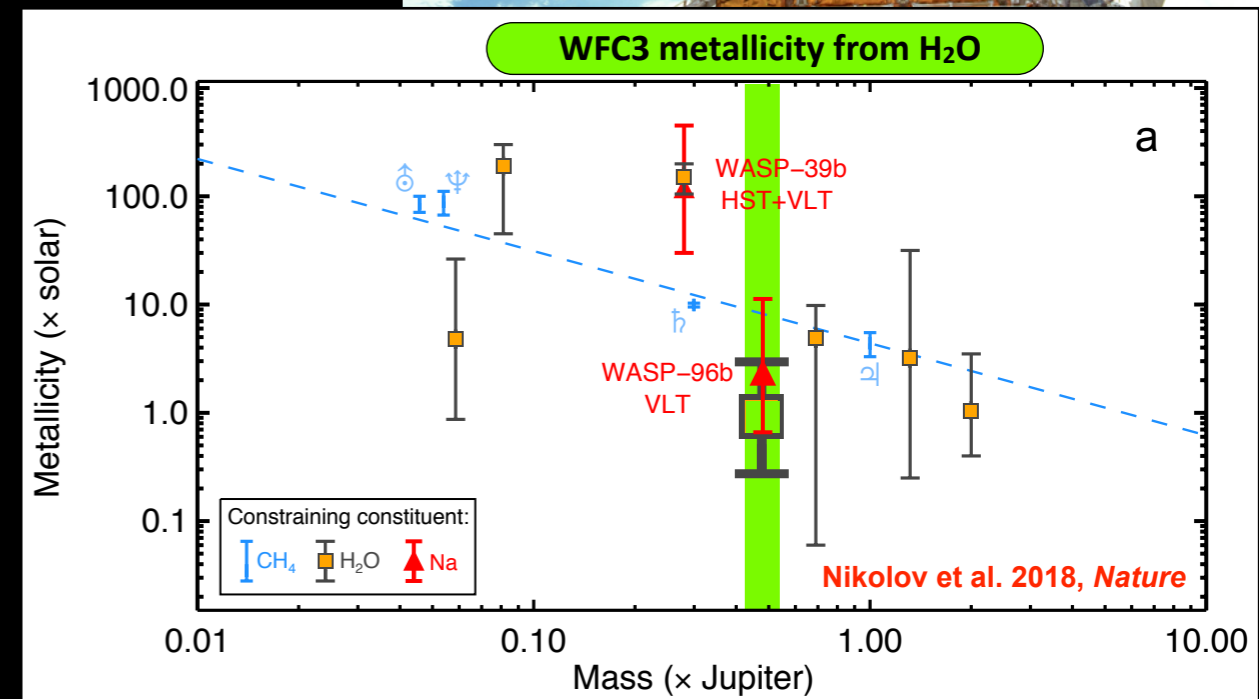
compare metallicity from Na and H₂O
feedback for future missions: **JWST & ARIEL**

Hubble Space Telescope

Search for H₂O in WASP-96b
PI Nikolov, 10 orbits

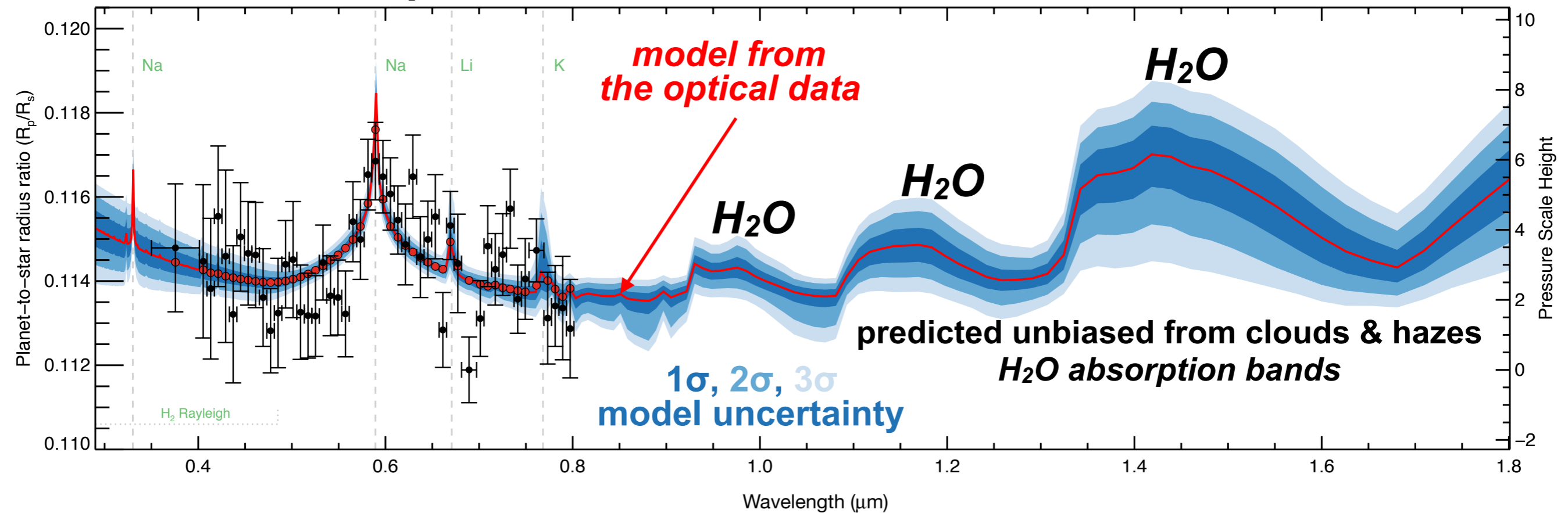


artist's impression of WASP-96b



WASP-96b has become a standard for the field and key target for JWST

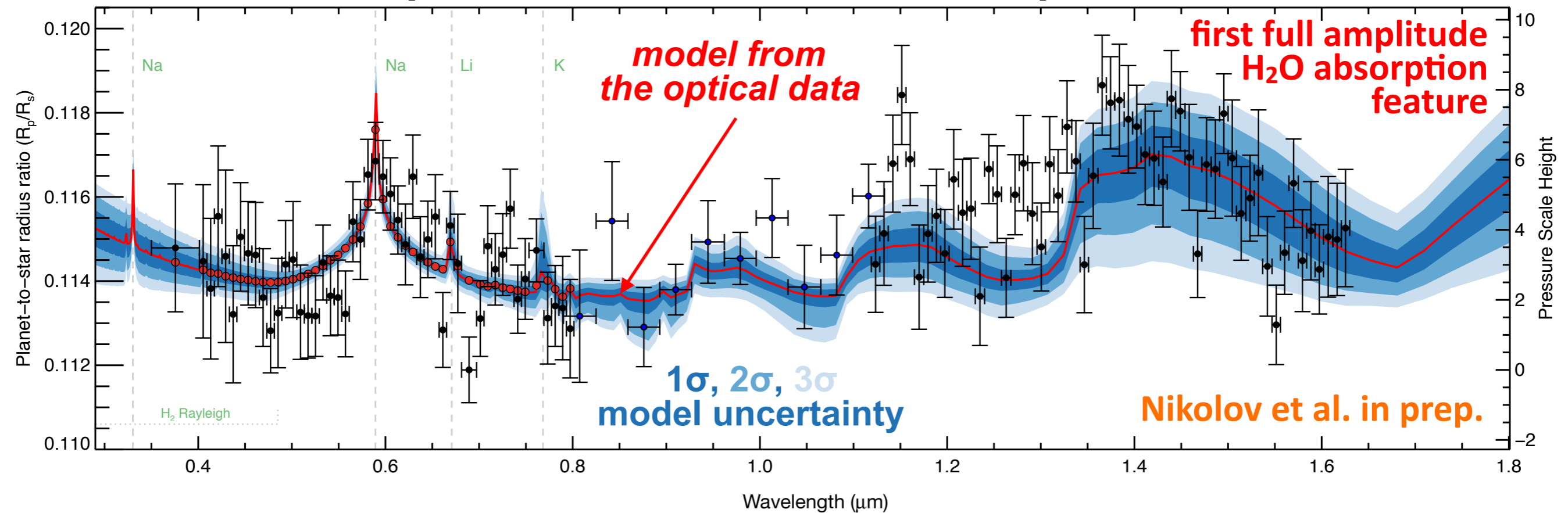
VLT FORS2 spectrum



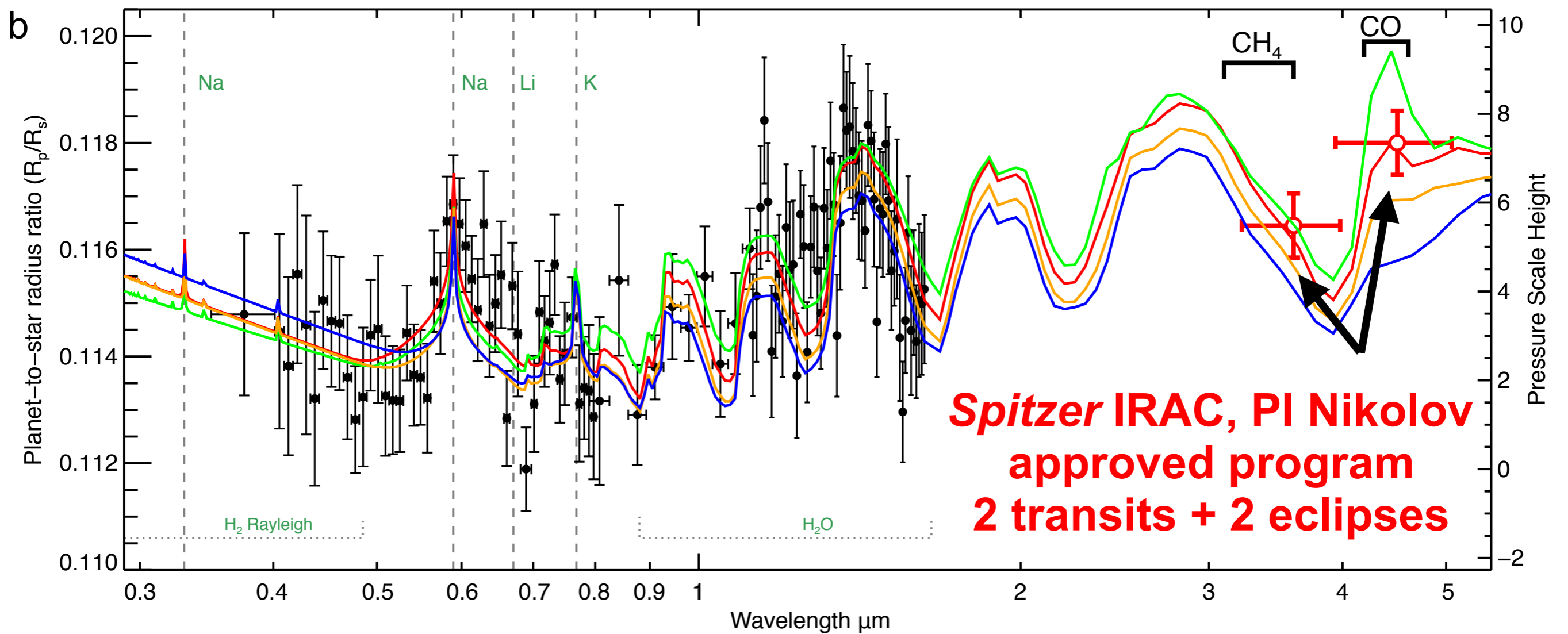
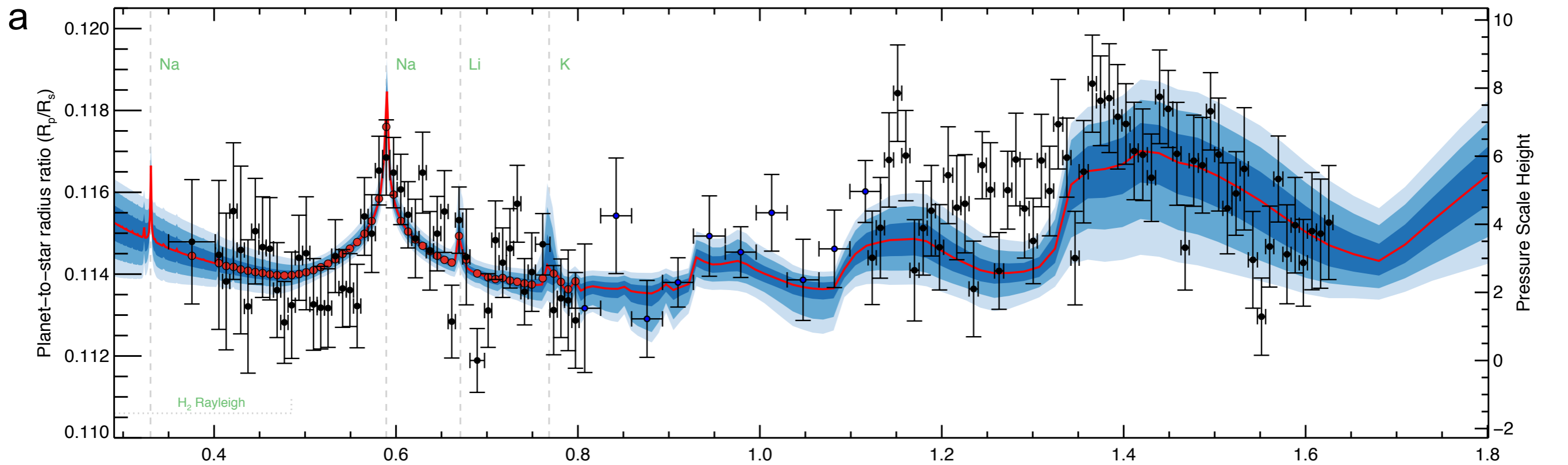
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VLT FORS2 spectrum

HST WFC3 spectrum

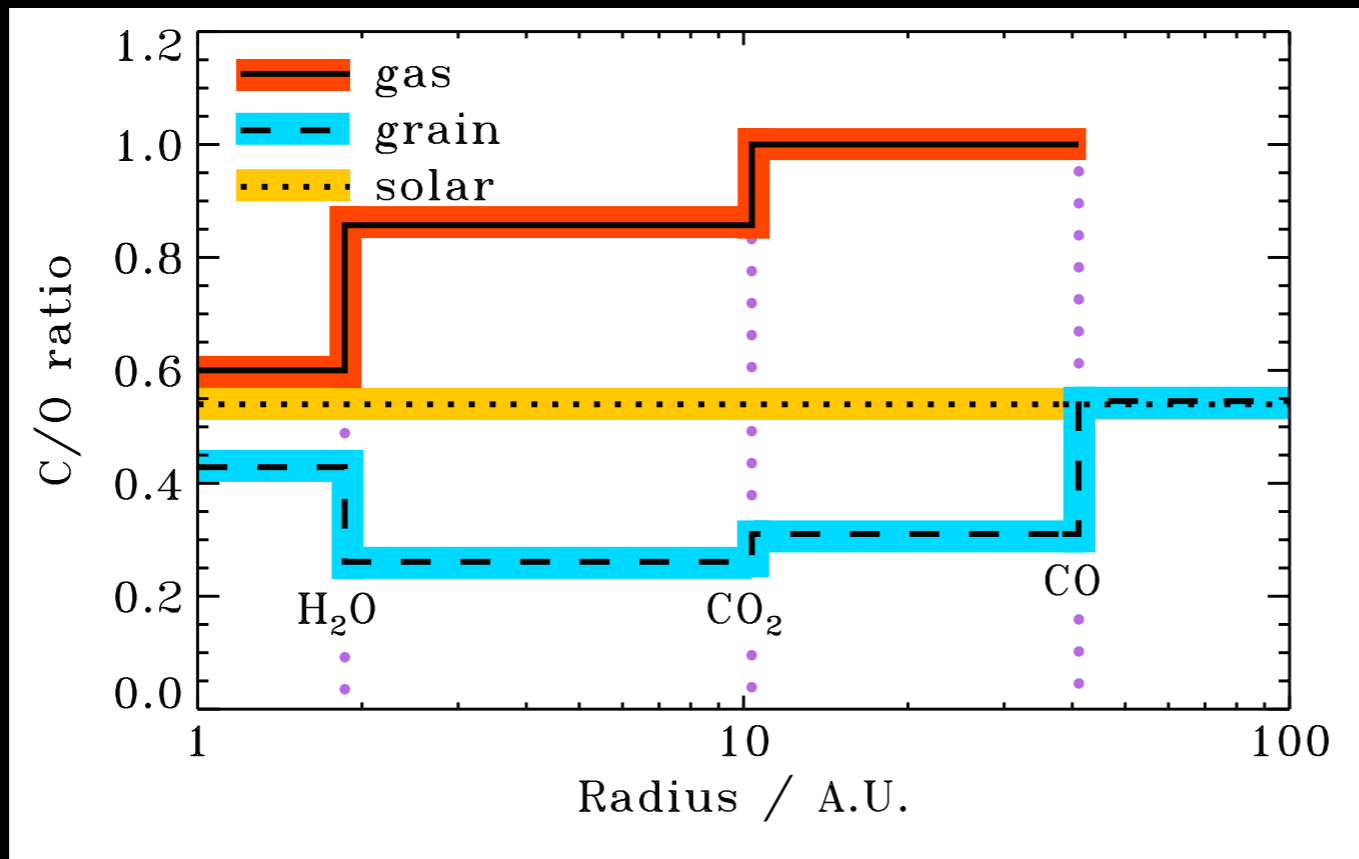
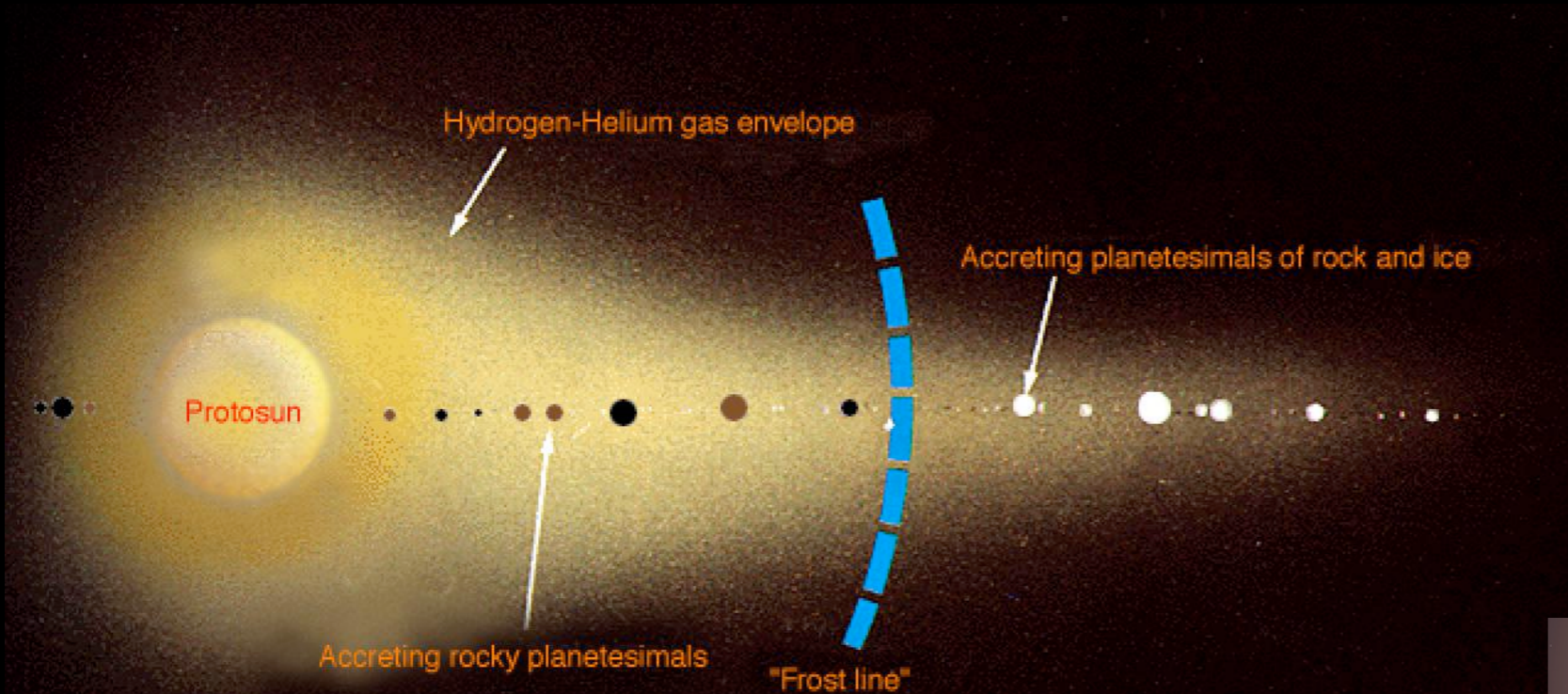


a cloud-free atmosphere identified from an exploratory exoplanet survey with FORS2

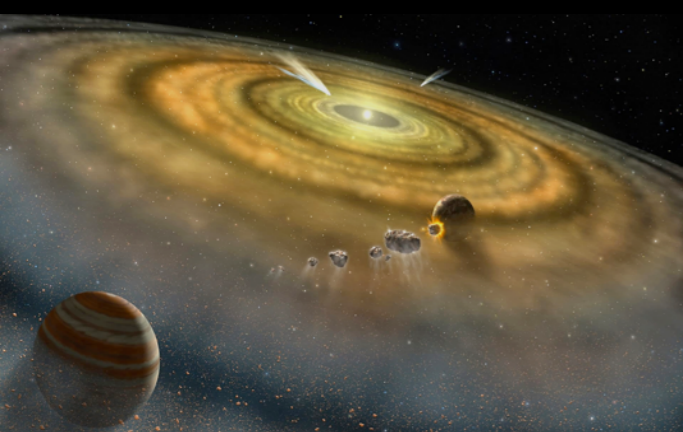


Next on WASP-96b:

Measuring exoplanet temperature and C/O ration - link with formation

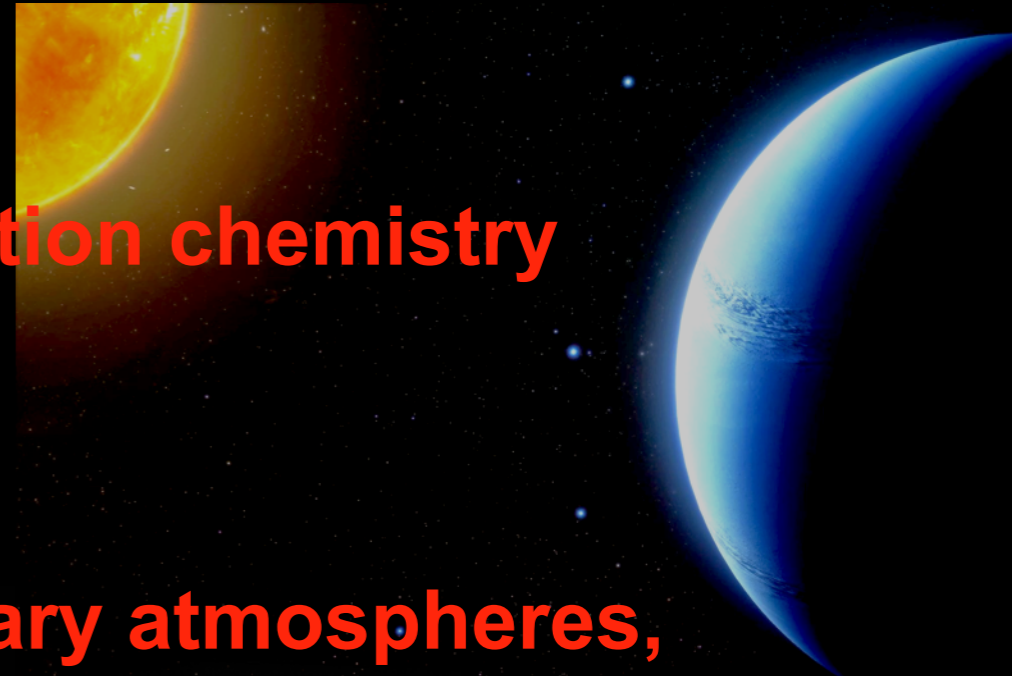


Major Exoplanet Science Questions

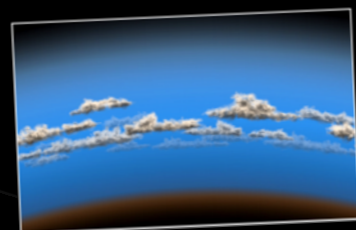
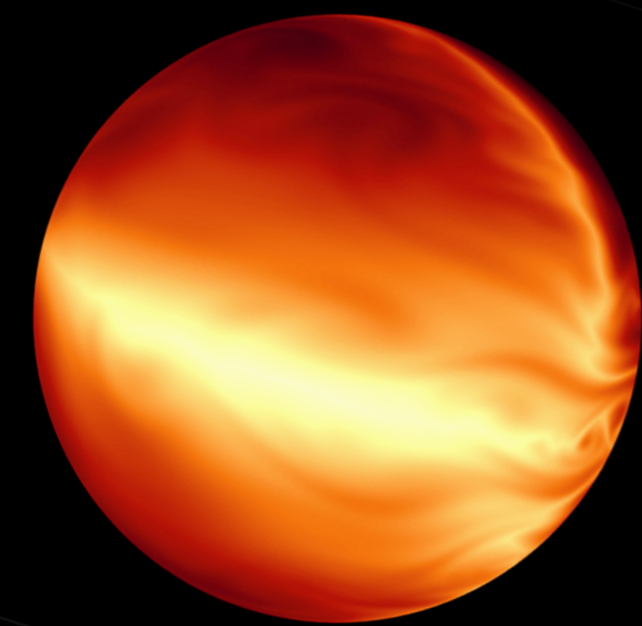


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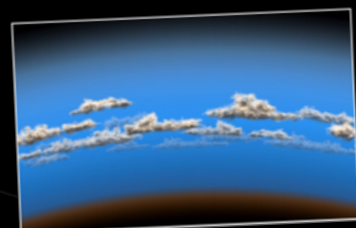
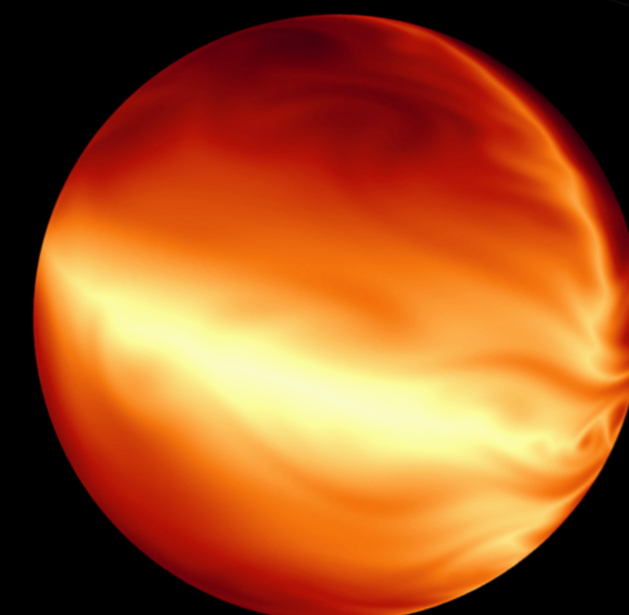
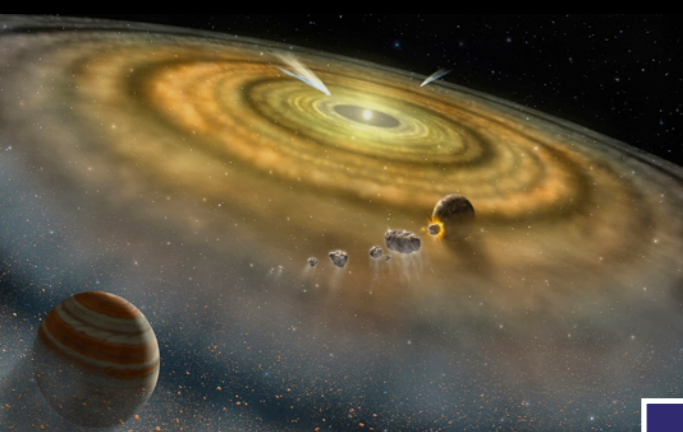


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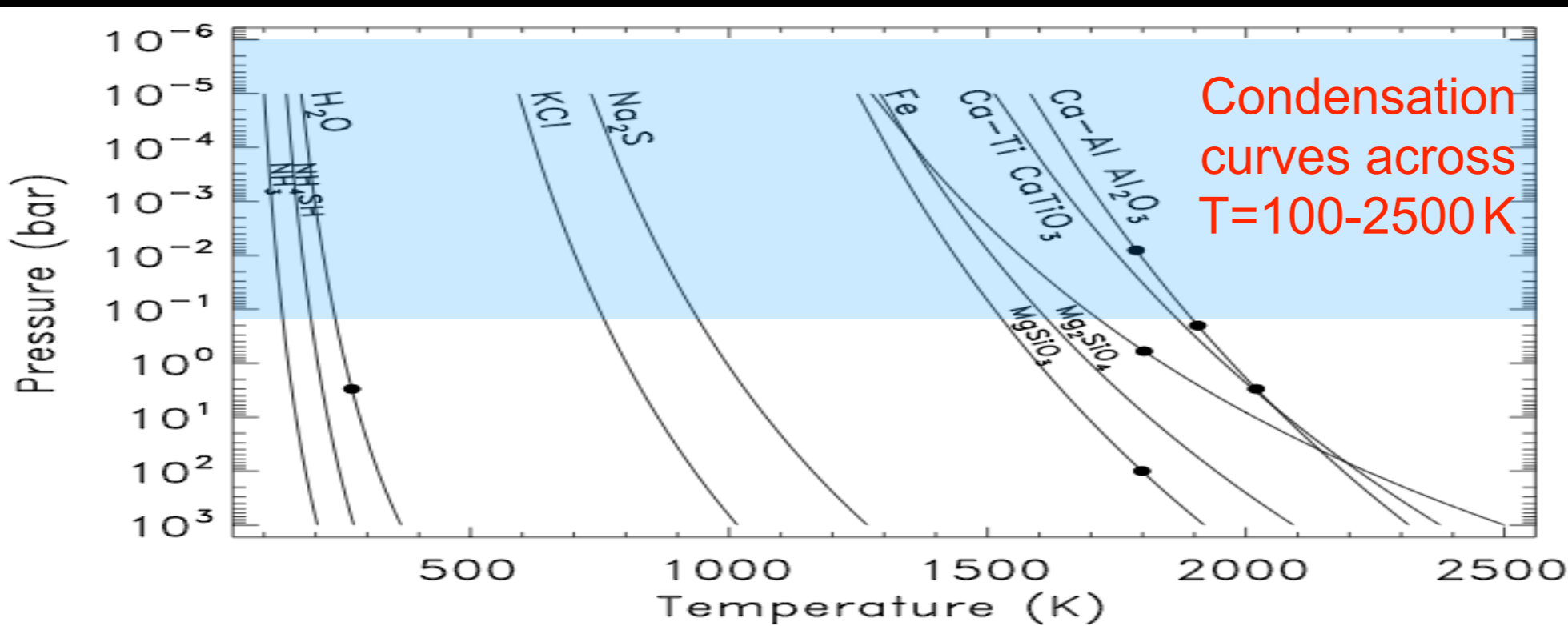
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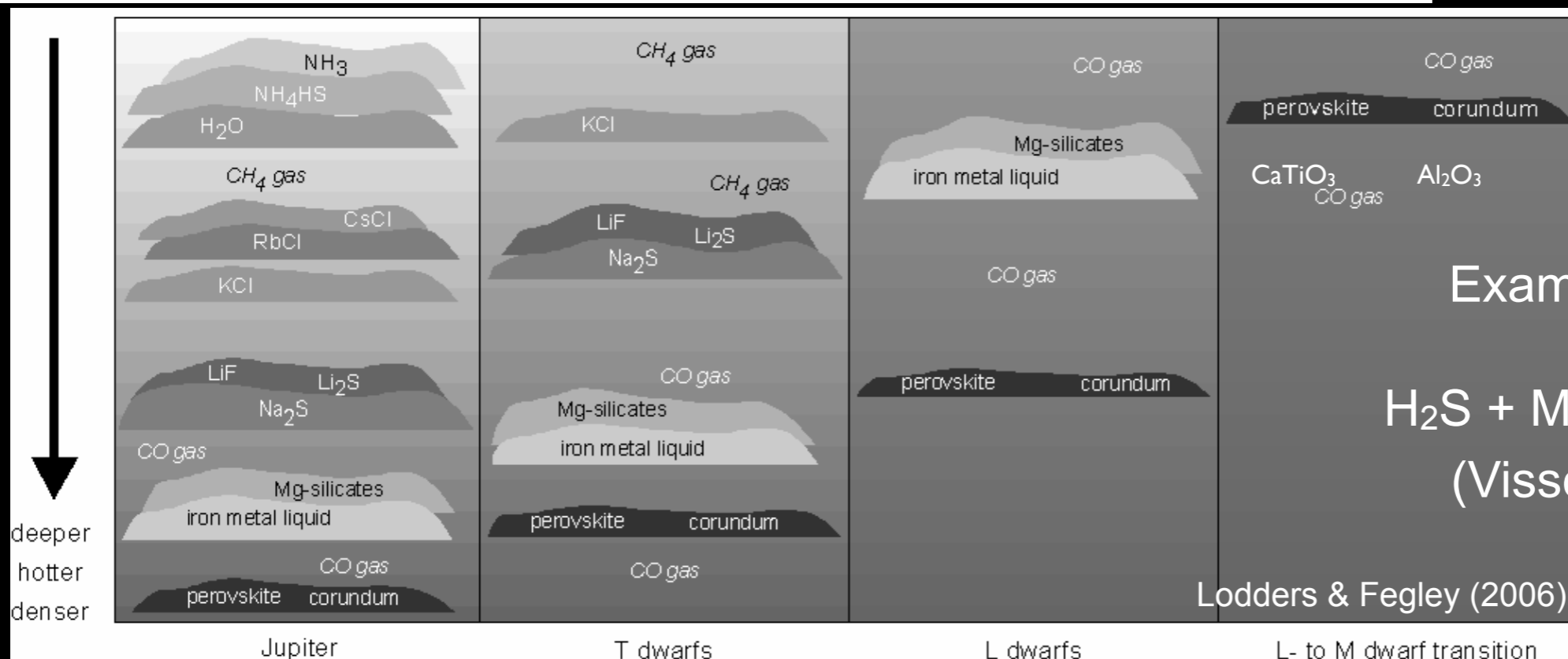


Depending on conditions: exotic refractory species at high T and alkali sulphides, chlorides and water at low T

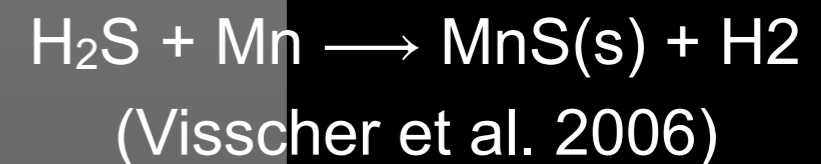


wide range of reactions depending on T, p and composition

not all clouds condense from the gas to a solid or liquid phase

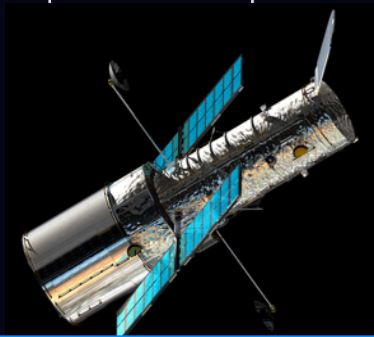


Example (solid MnS):

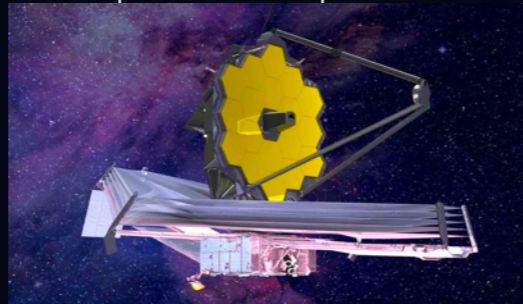


Lodders & Fegley (2006)

Telescopes for exoplanet atmospheric characterization: need of optical spectrographs (such as FORS2)



HST optical & IR

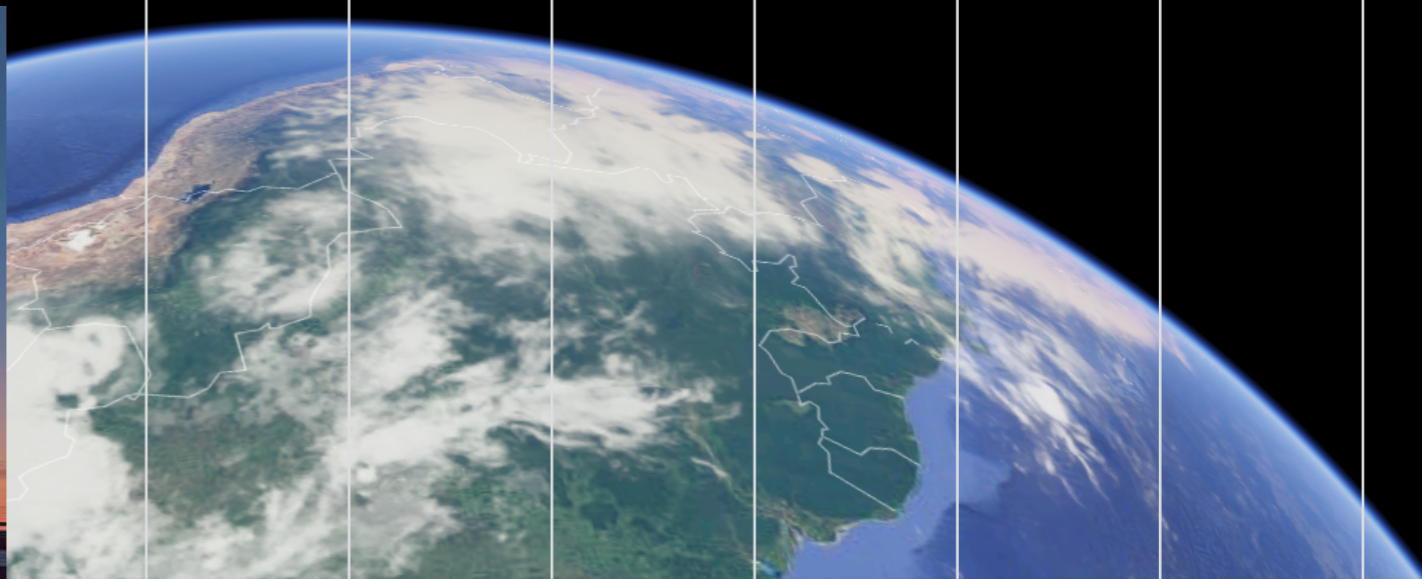


JWST: near- and mid-IR



ARIEL: IR spectra & optical photometry: the first large-scale exoplanet survey

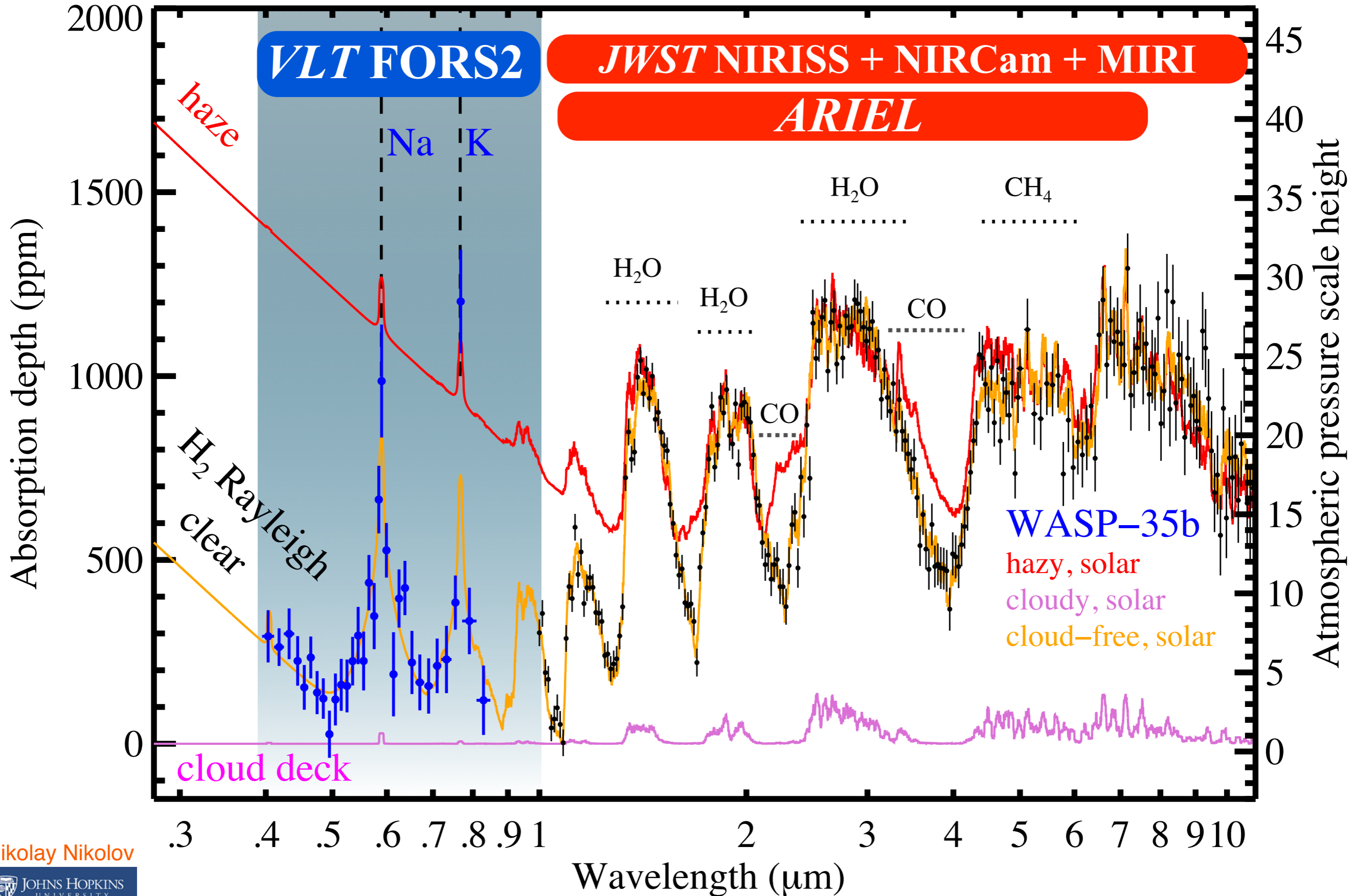
18	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
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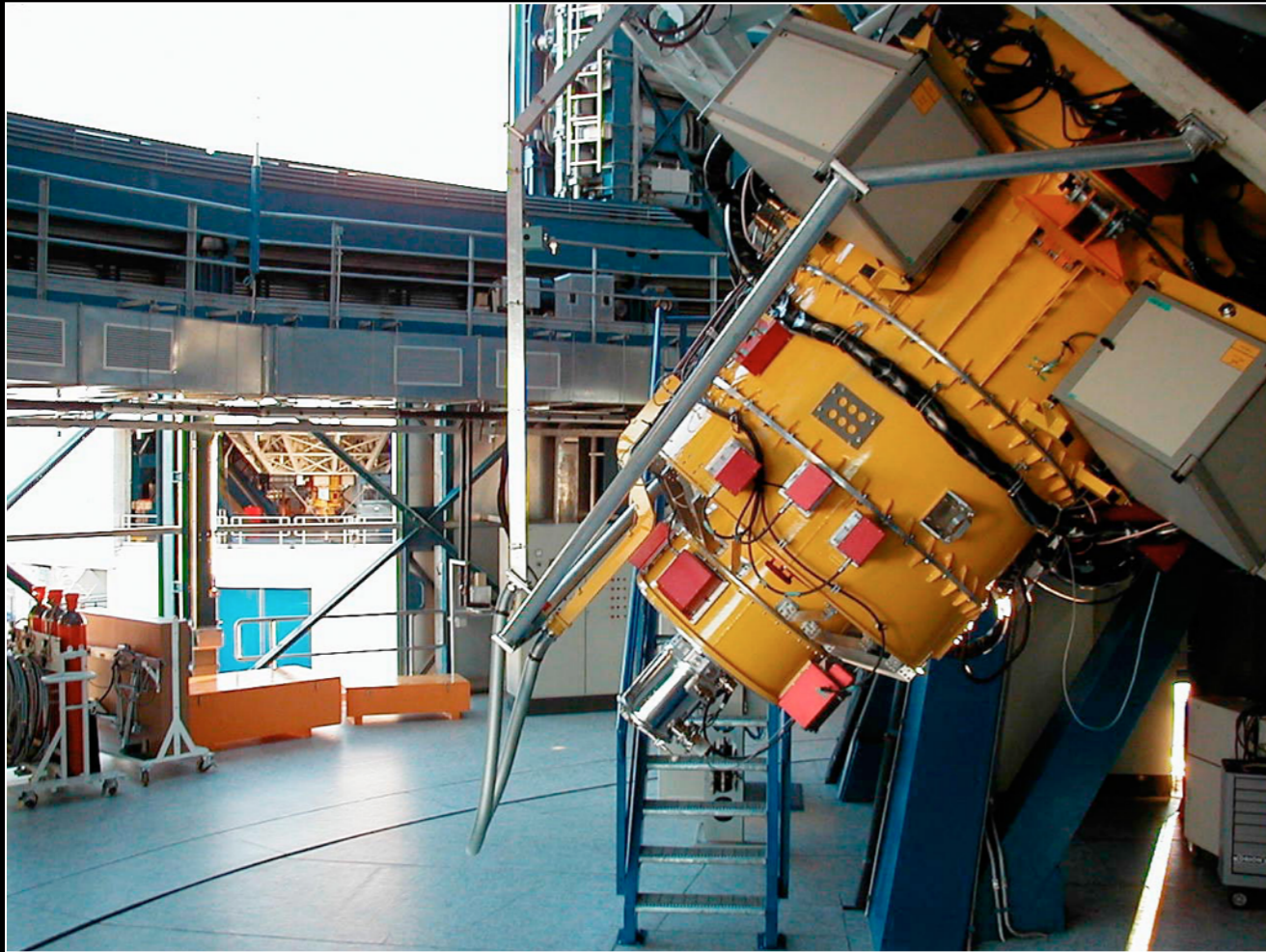
VLT FORS2: can fill JWST/ARIEL wavelength gap with highly-complementary optical spectra enabling absolute abundances and metallicities

Characterize cloud-free, cloudy and hazy exoplanet atmospheres

Optical spectrographs: distinguish *clear* from *cloudy* and *hazy* atmospheres and enable absolute abundances for **JWST & ARIEL**



The first comparative ground-based followup of exoplanets with atmospheric features detected with HST



Multi-object spectroscopy (MOS)

**35 hr on VLT FORS2
Oct 2015 - Apr 2016
(PI Nikolov)**

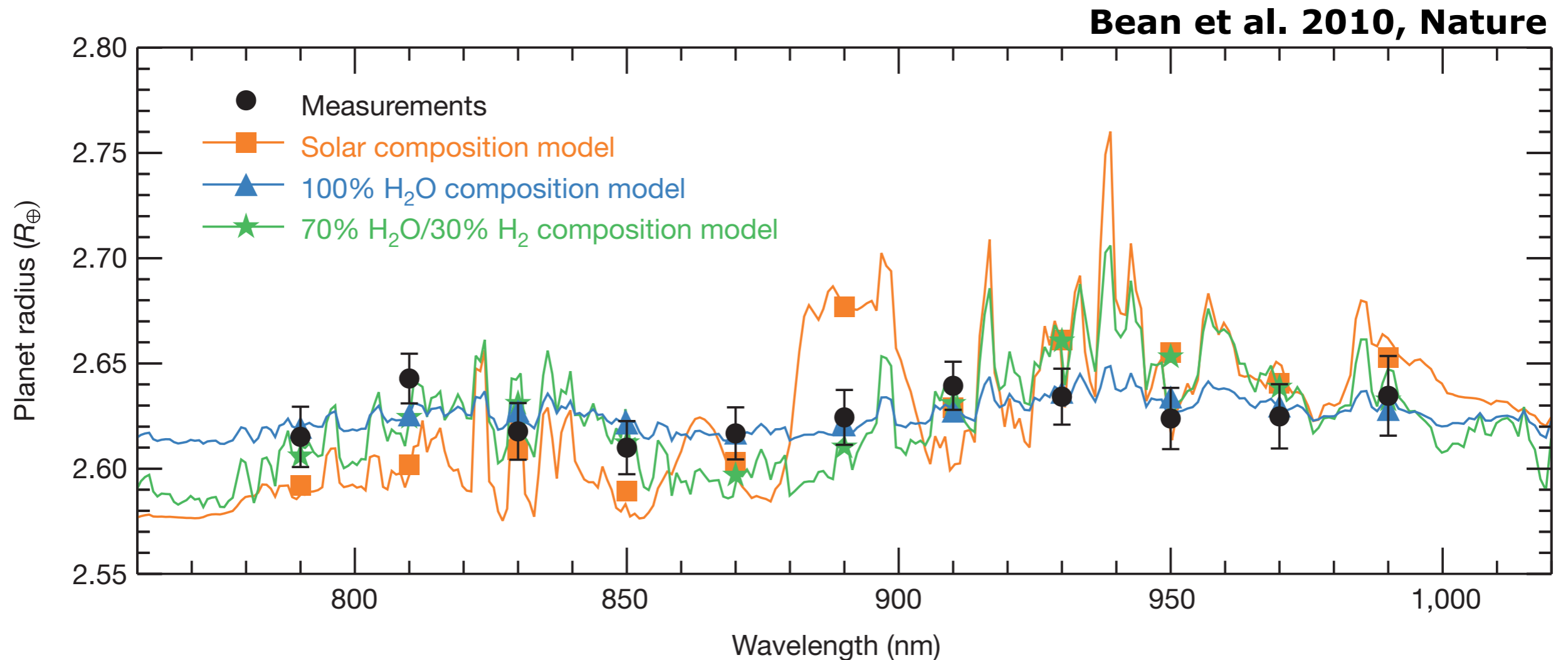
**target list: WASP-6b, WASP-31b,
WASP-39b**

**2 transits for each exoplanet at
low ($R \sim 600$) resolution:**

**blue: GRIS 600B
red: GRIS 600RI**

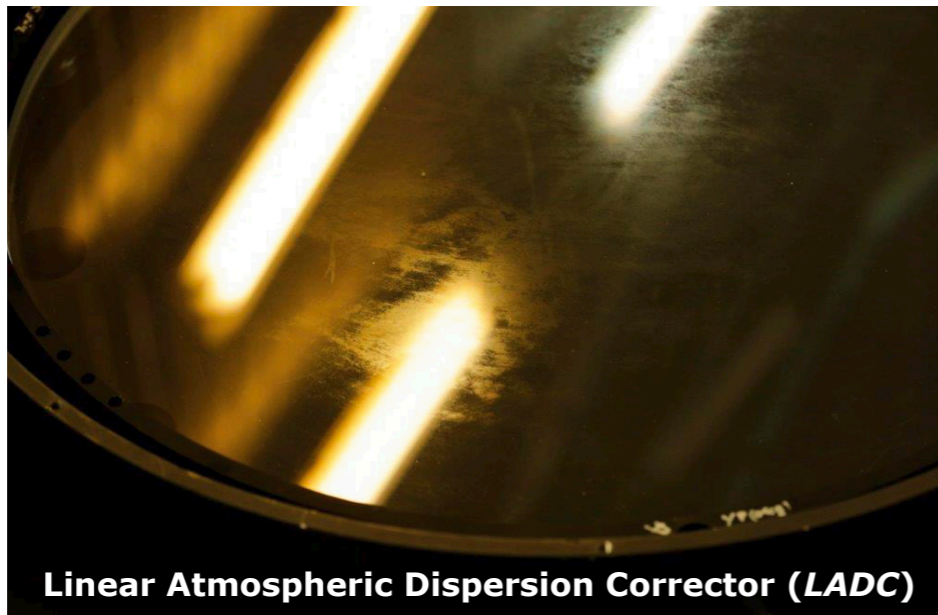


Motivation: feasibility of low/medium resolution transmission spectroscopy from the ground



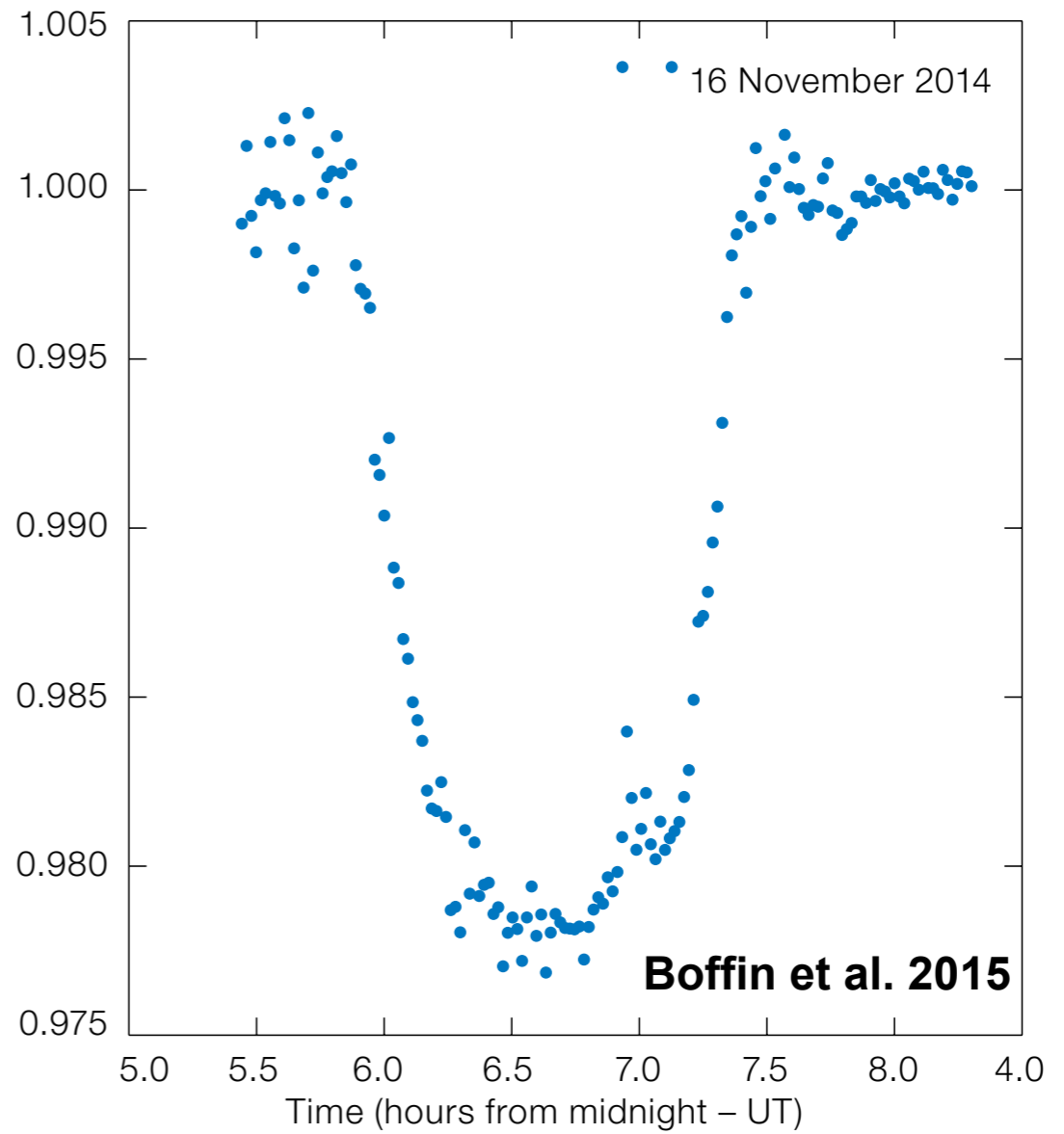
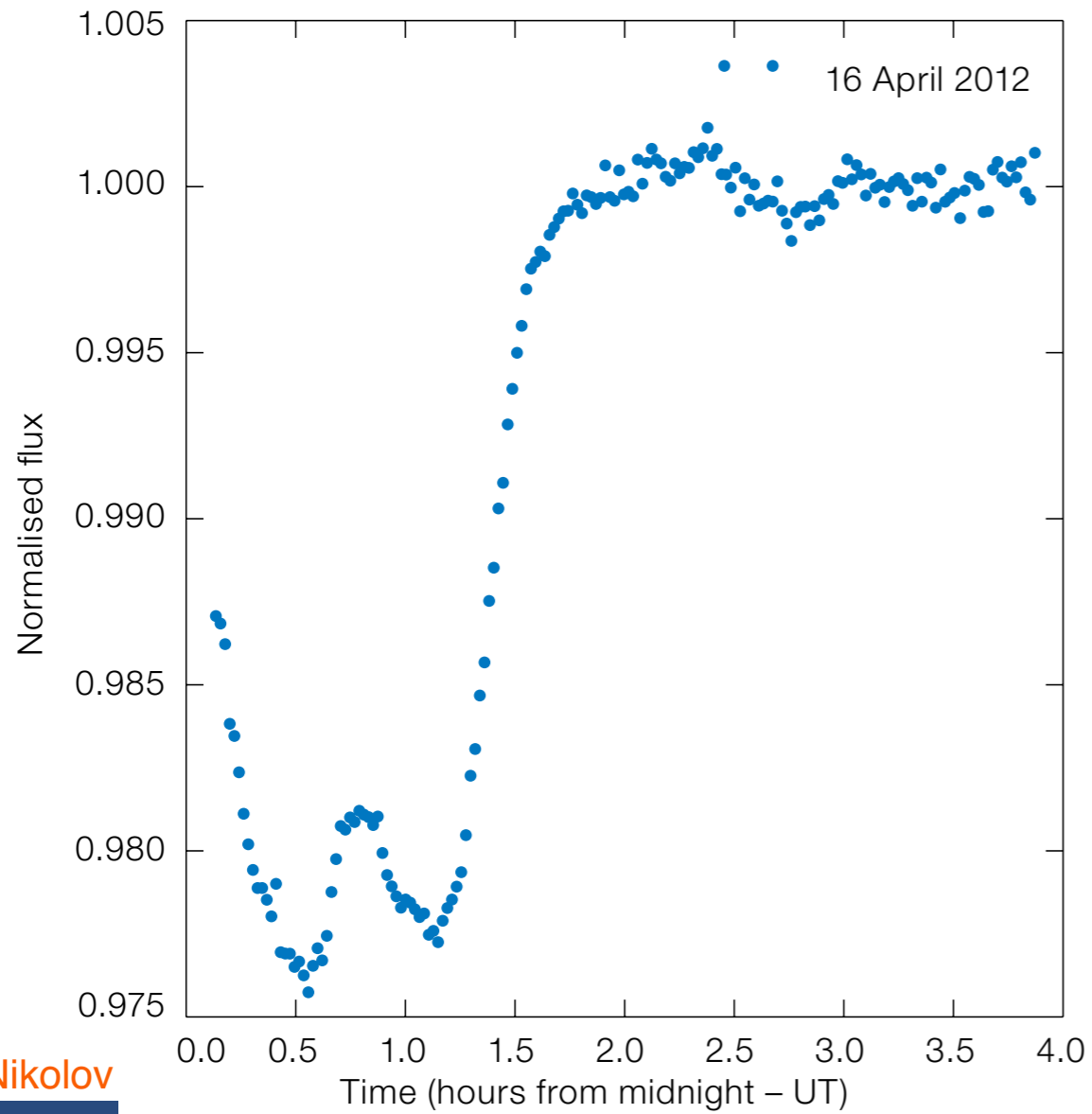
Multi-object spectroscopy with six comparison stars in $6.8' \times 6.8'$

GJ1214b must have water-dominated or cloudy atmosphere

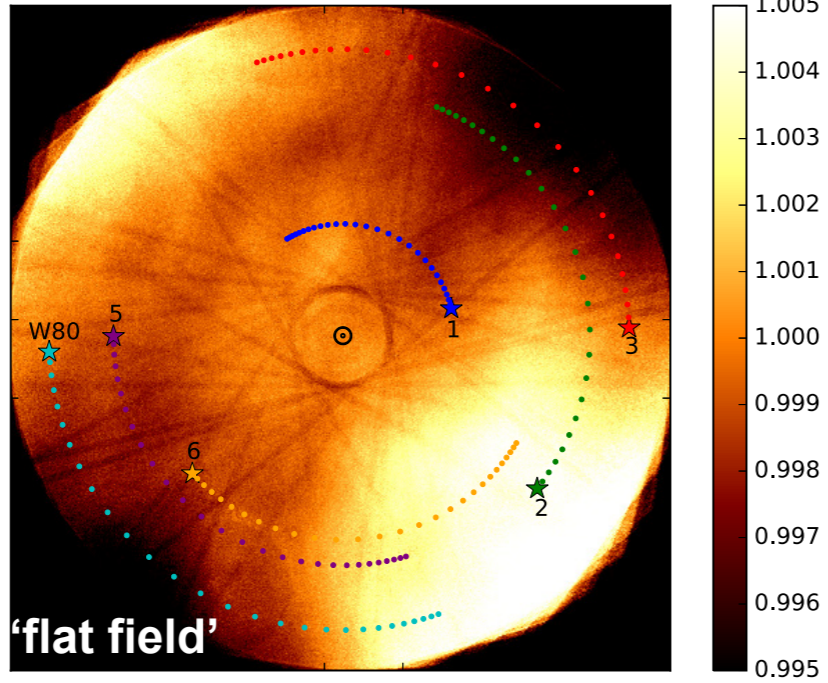


Before coating removal

After coating removal

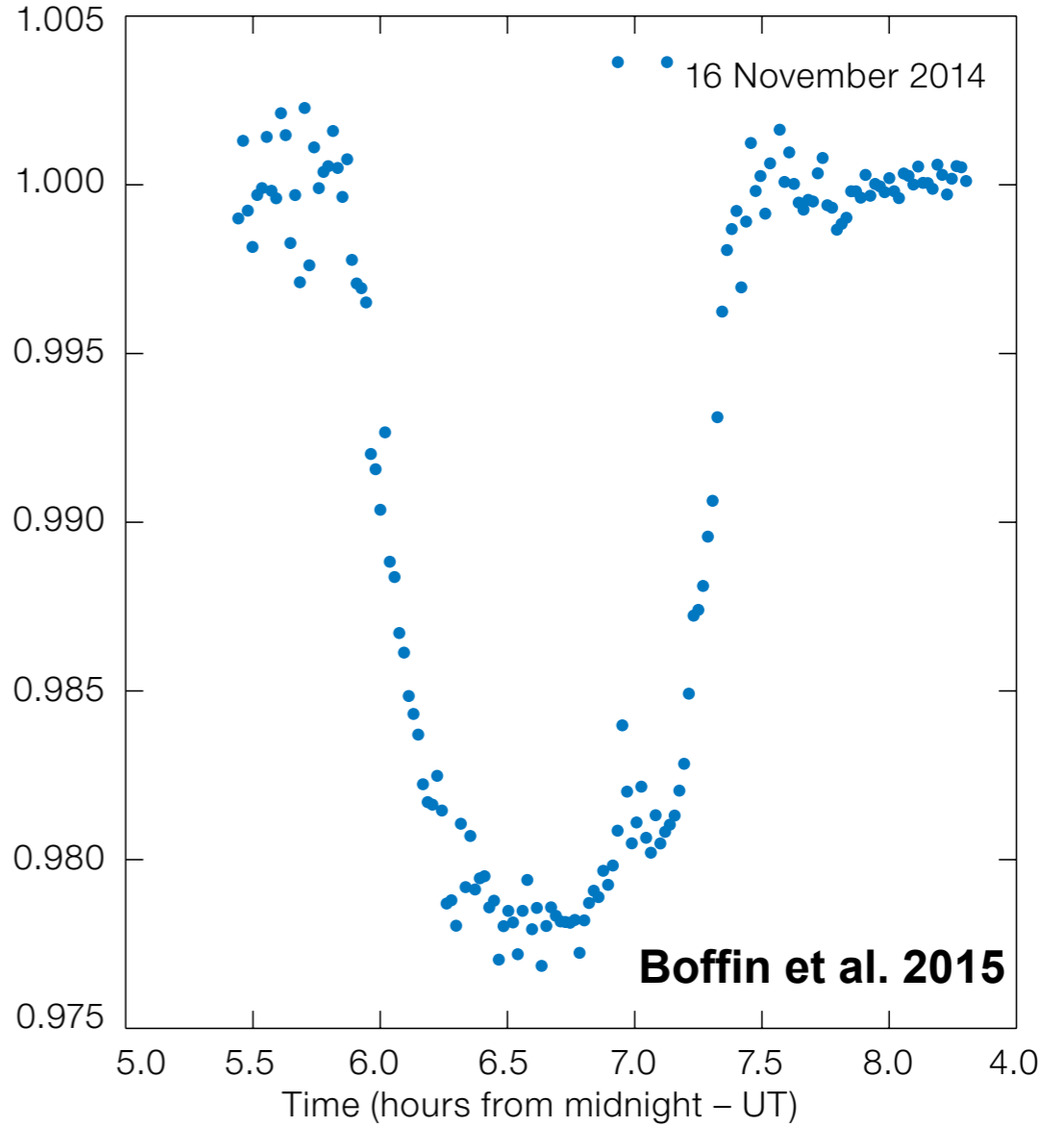
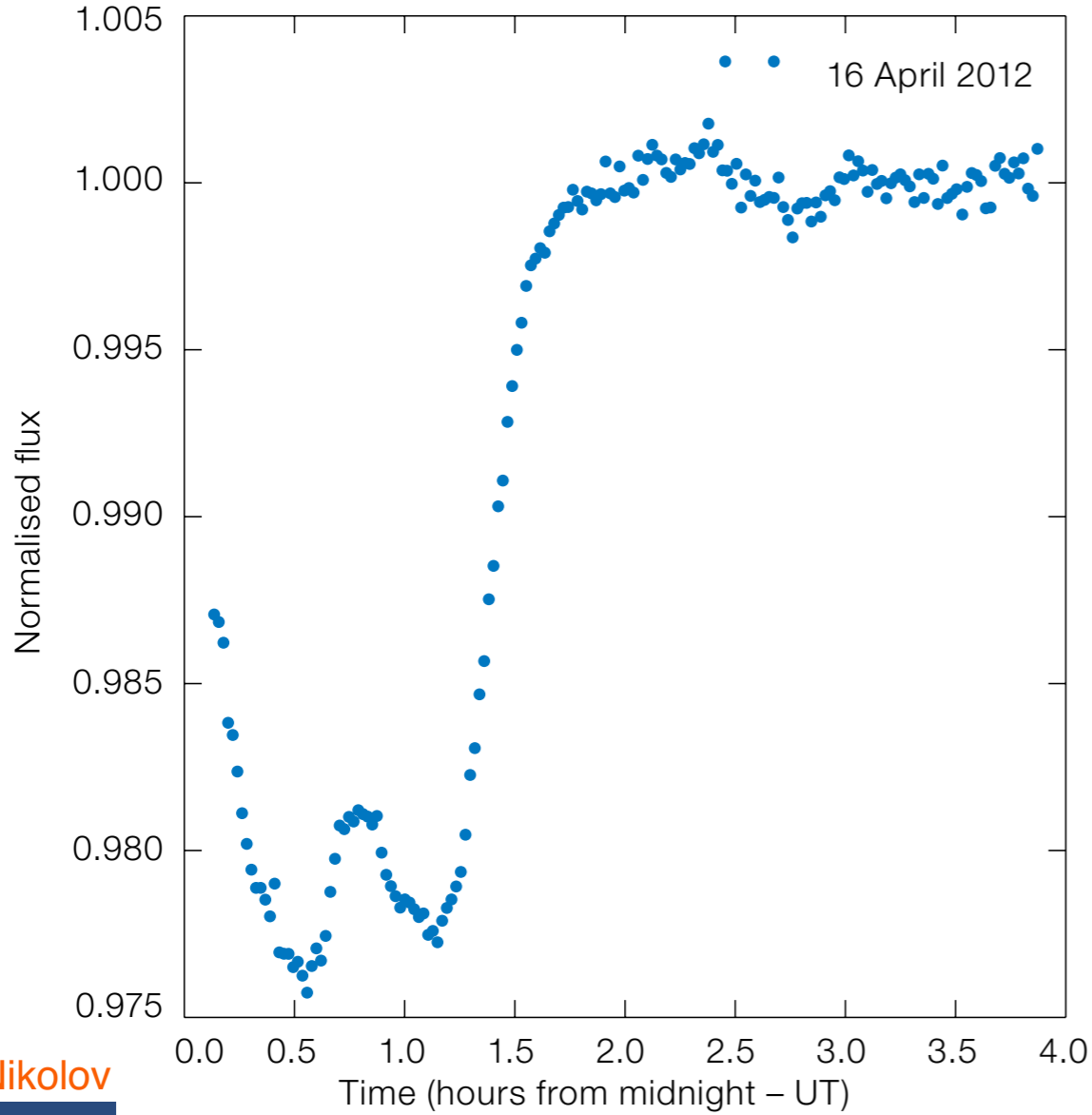


Sedaghati et al. 2017



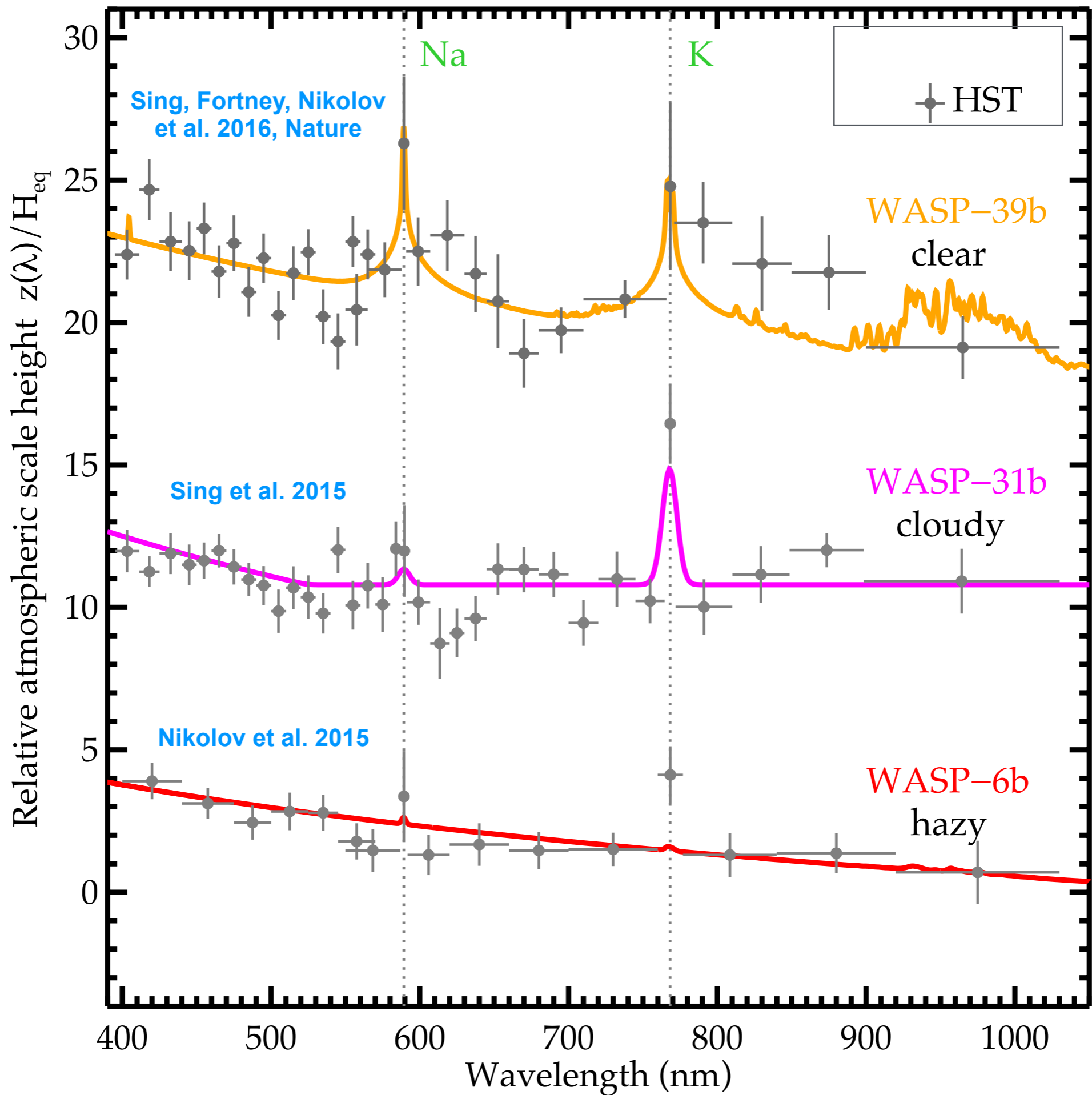
Before coating removal

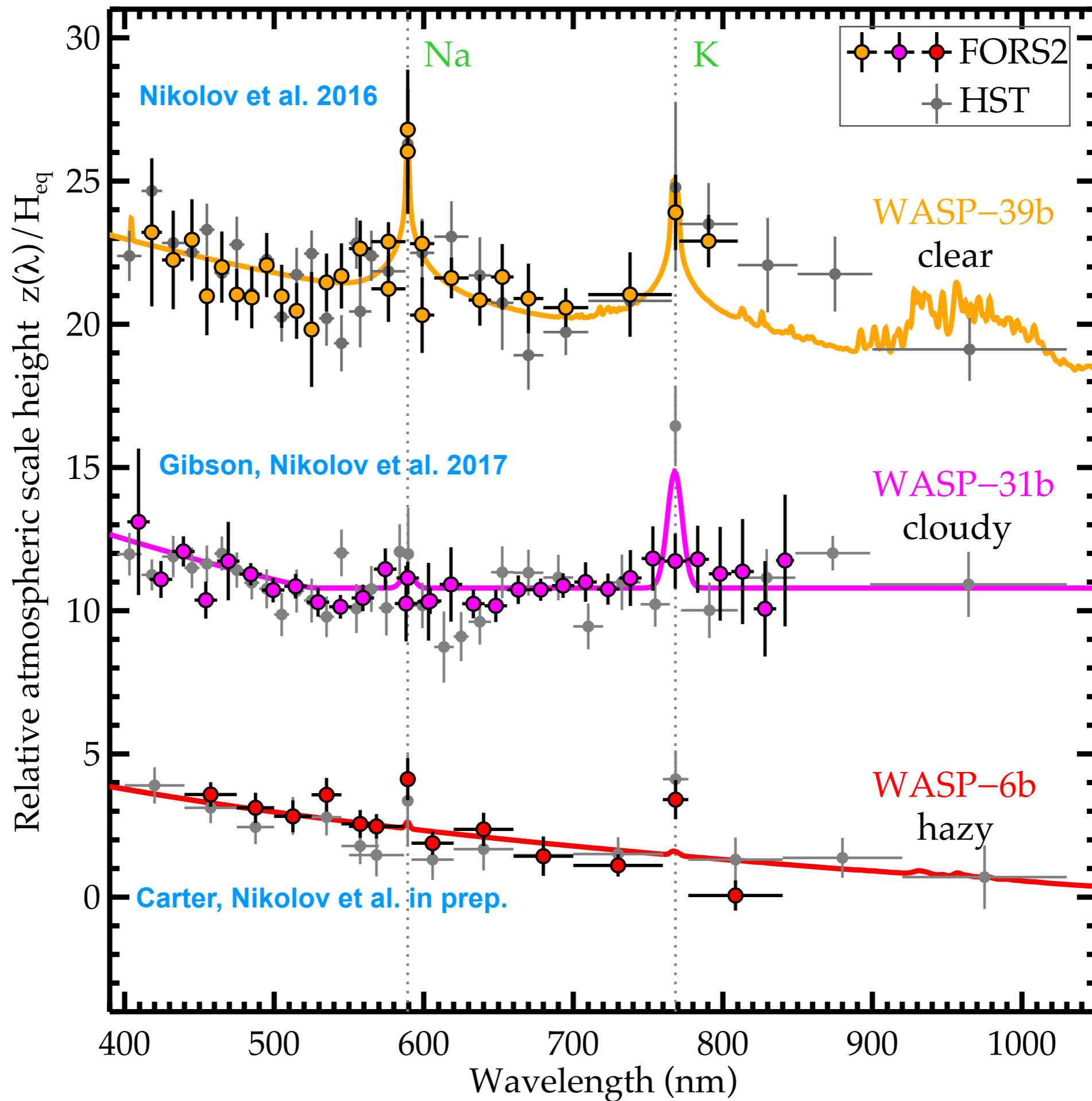
After coating removal

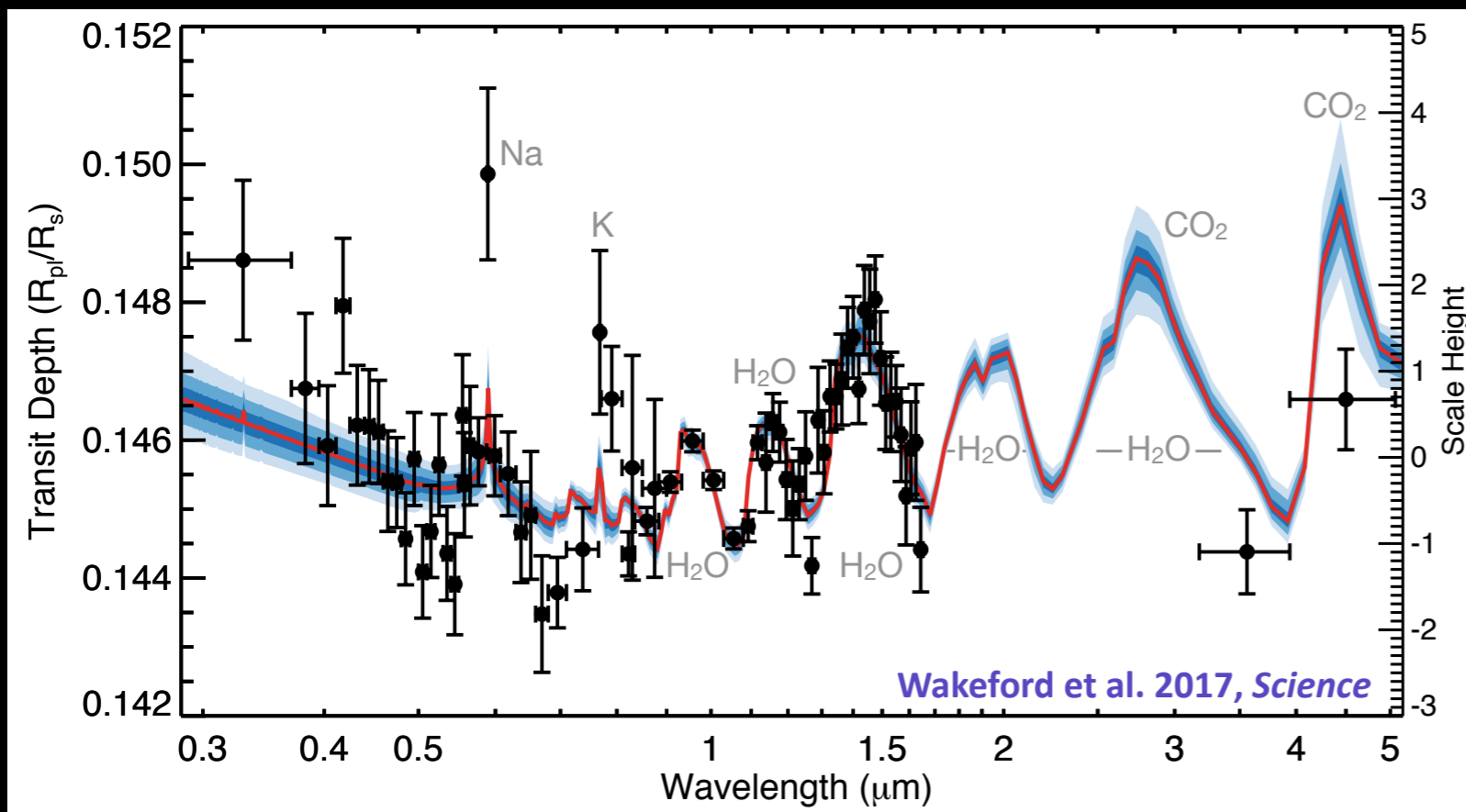


Nikolay Nikolov

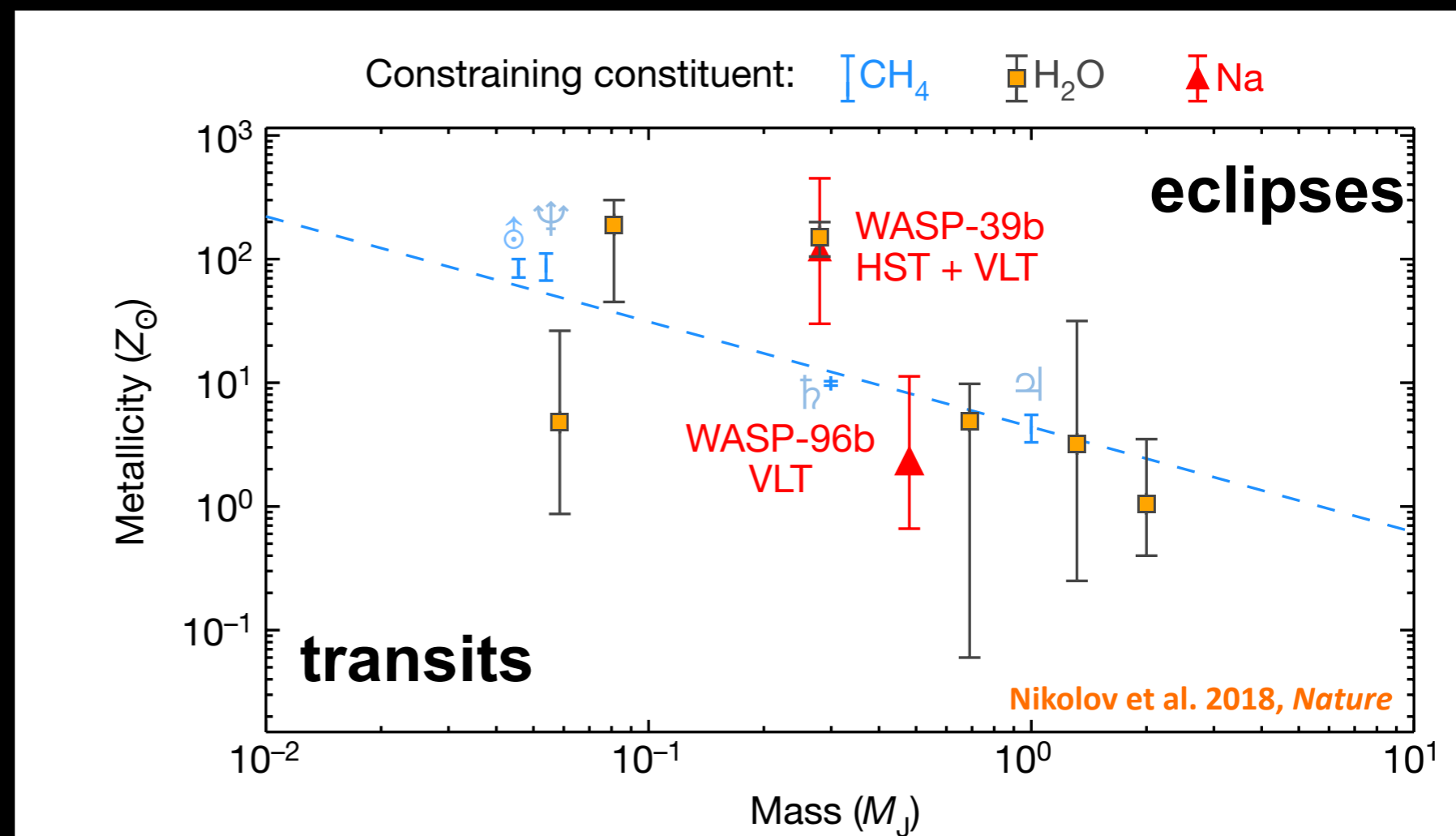




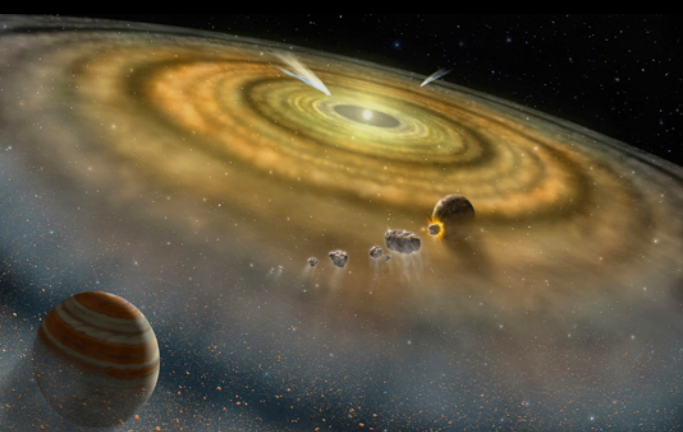




Optical spectroscopy is necessary to constrain abundances, C/O and metallicity

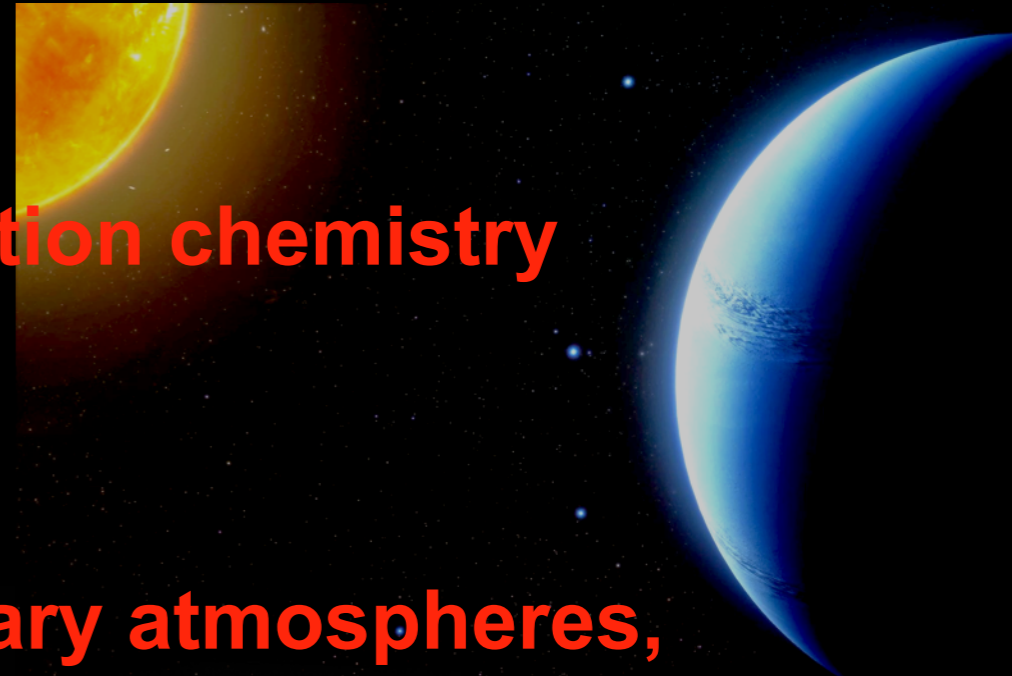


Major Exoplanet Science Questions

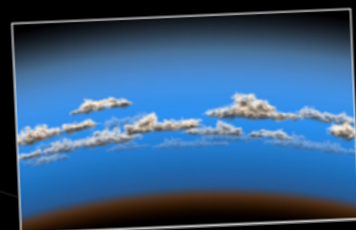
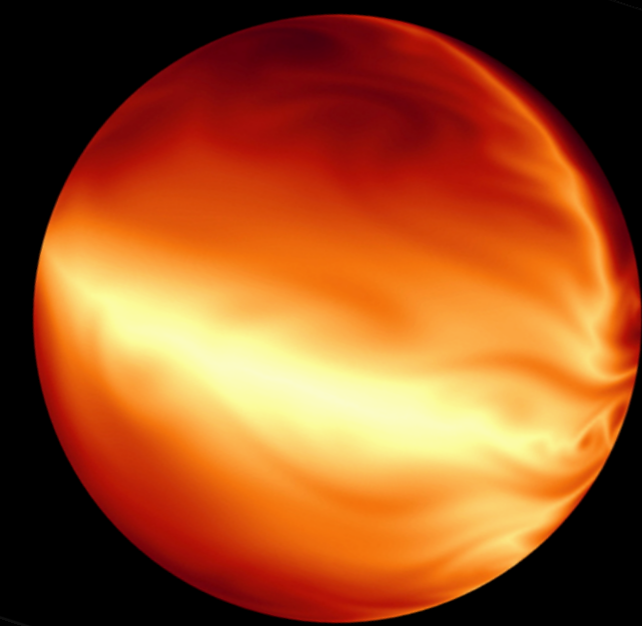


- Link composition & abundances to formation:
Absolute abundances (Na, H₂O, ...)

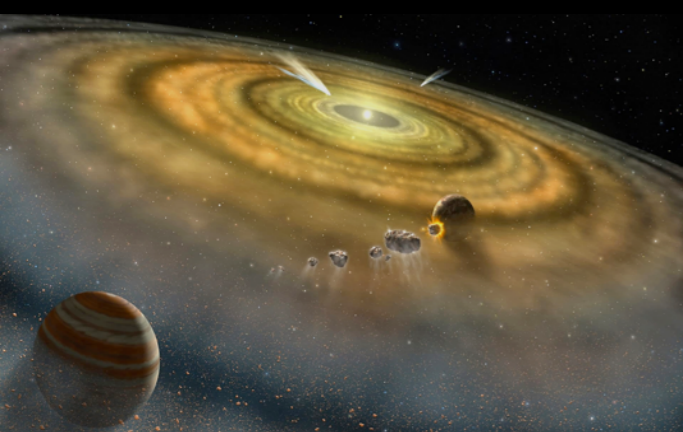
- Clouds & hazes:
**Occurrence, Condensation chemistry
Photochemistry?**



- Spectra of super-Earths:
**Primordial and secondary atmospheres,
formation**

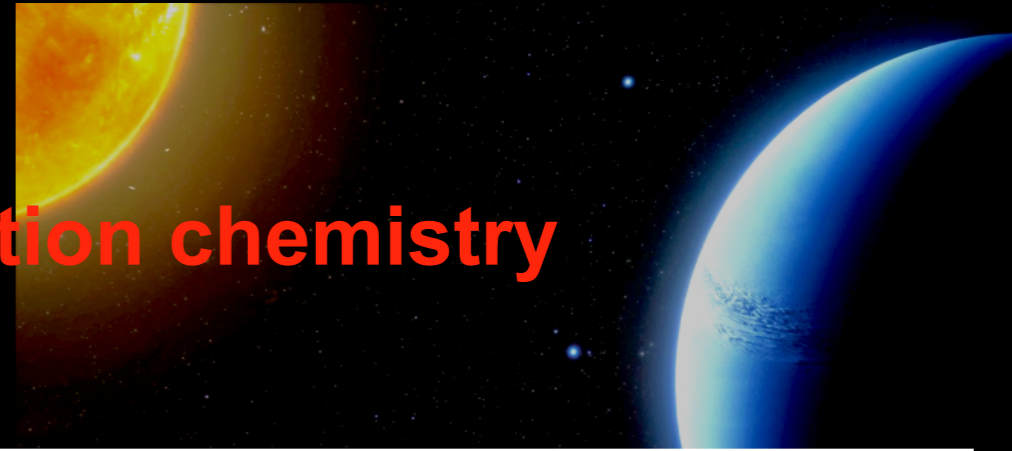


Major Exoplanet Science Questions

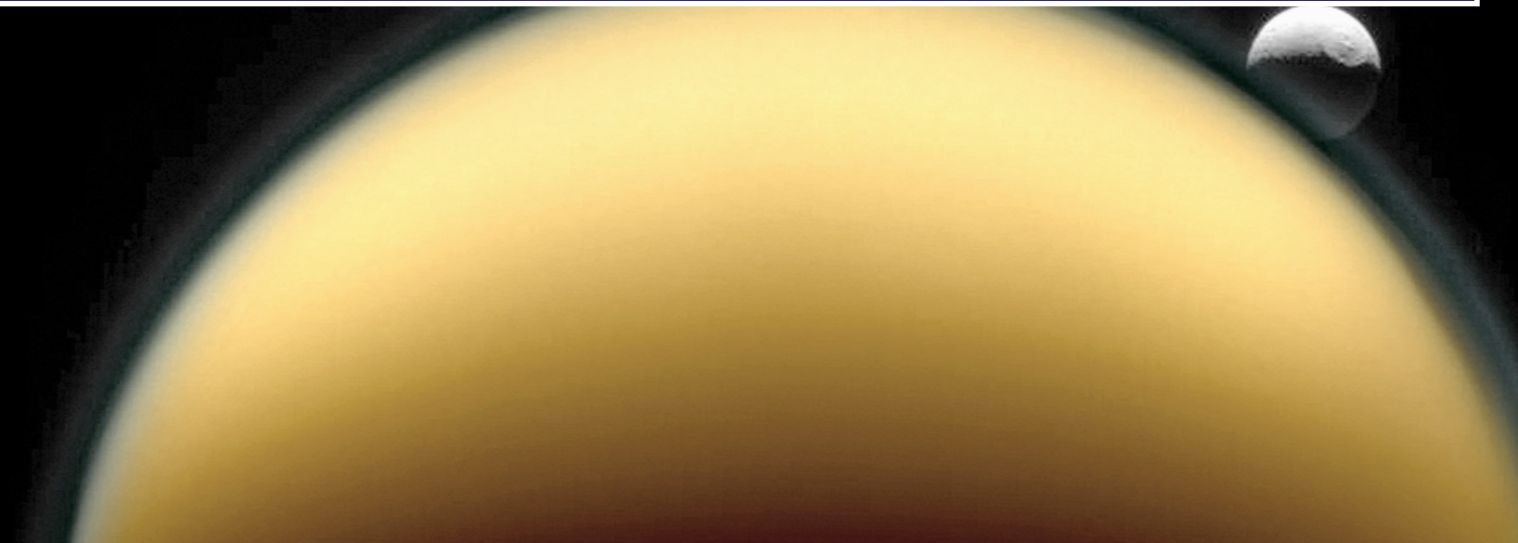
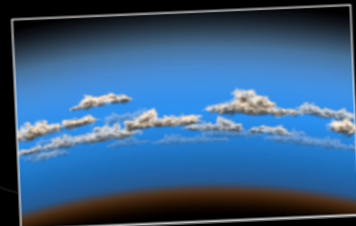
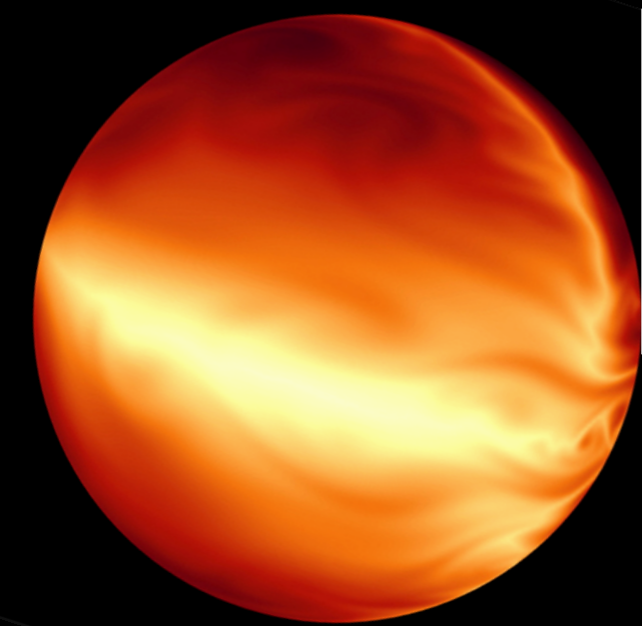


- Link composition & abundances to formation:
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**Occurrence, Condensation chemistry
Photochemistry?**

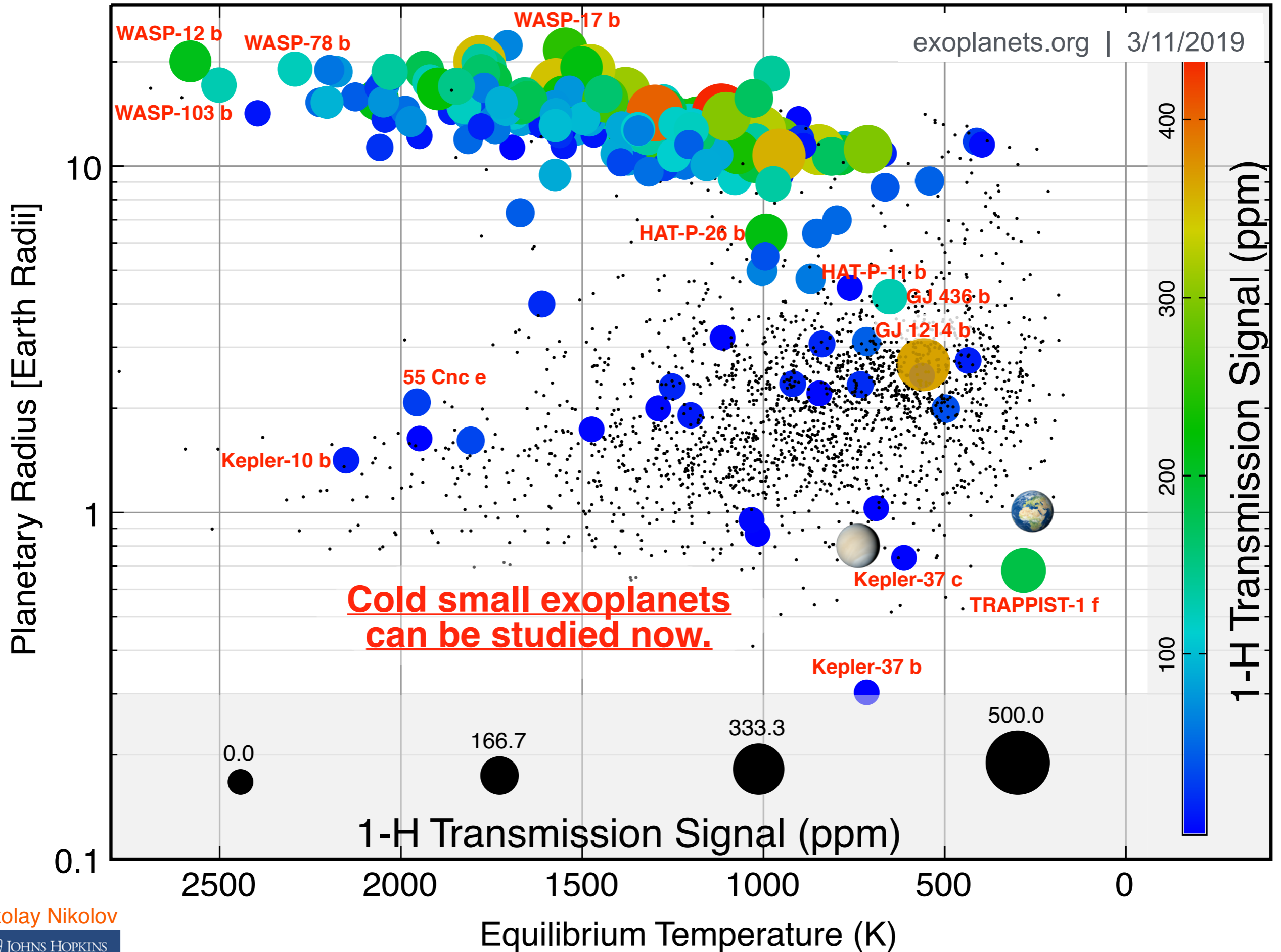


- Spectra of super-Earths:
**Primordial and secondary atmospheres,
formation**

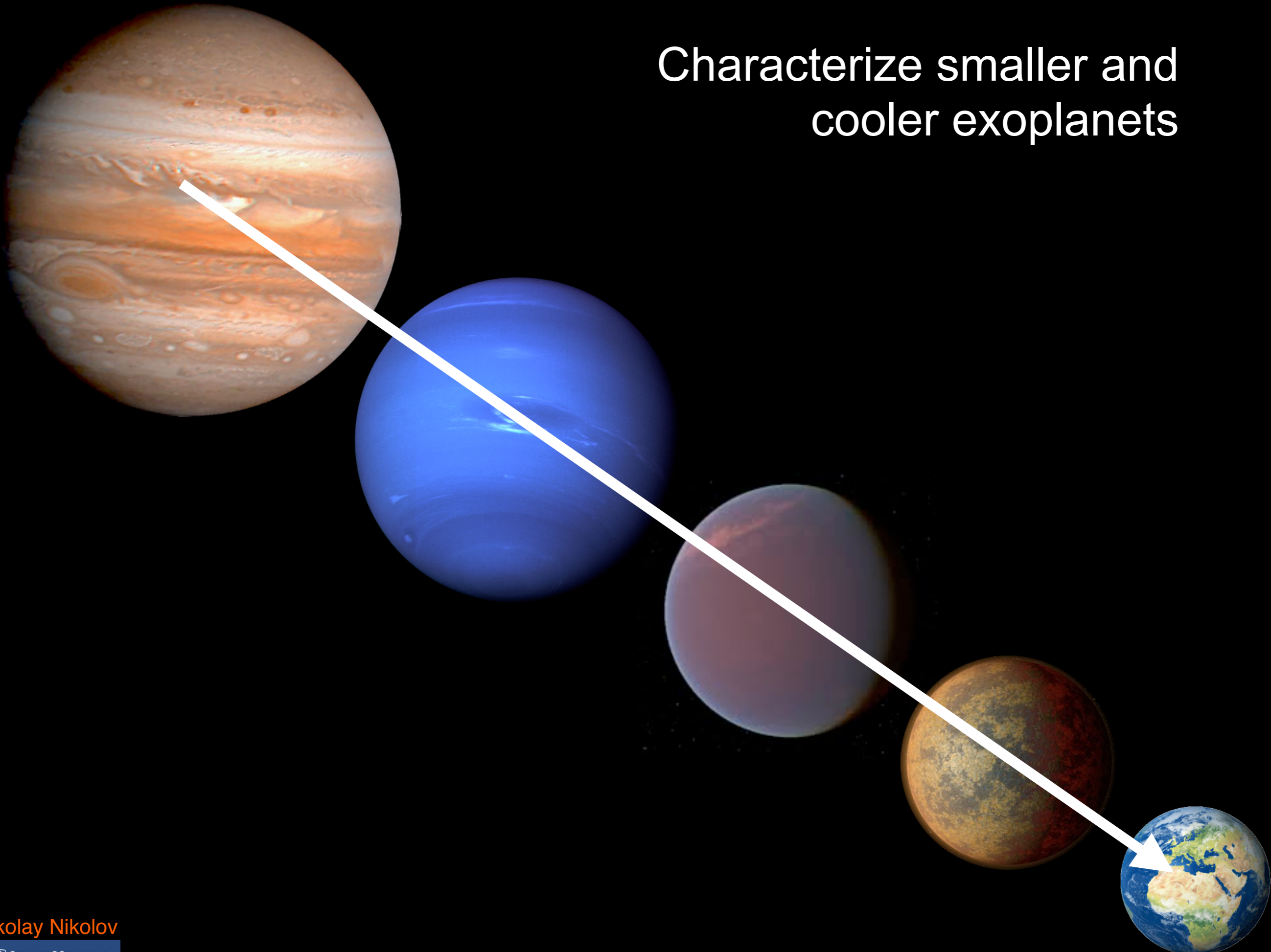


assuming H-rich atmosphere

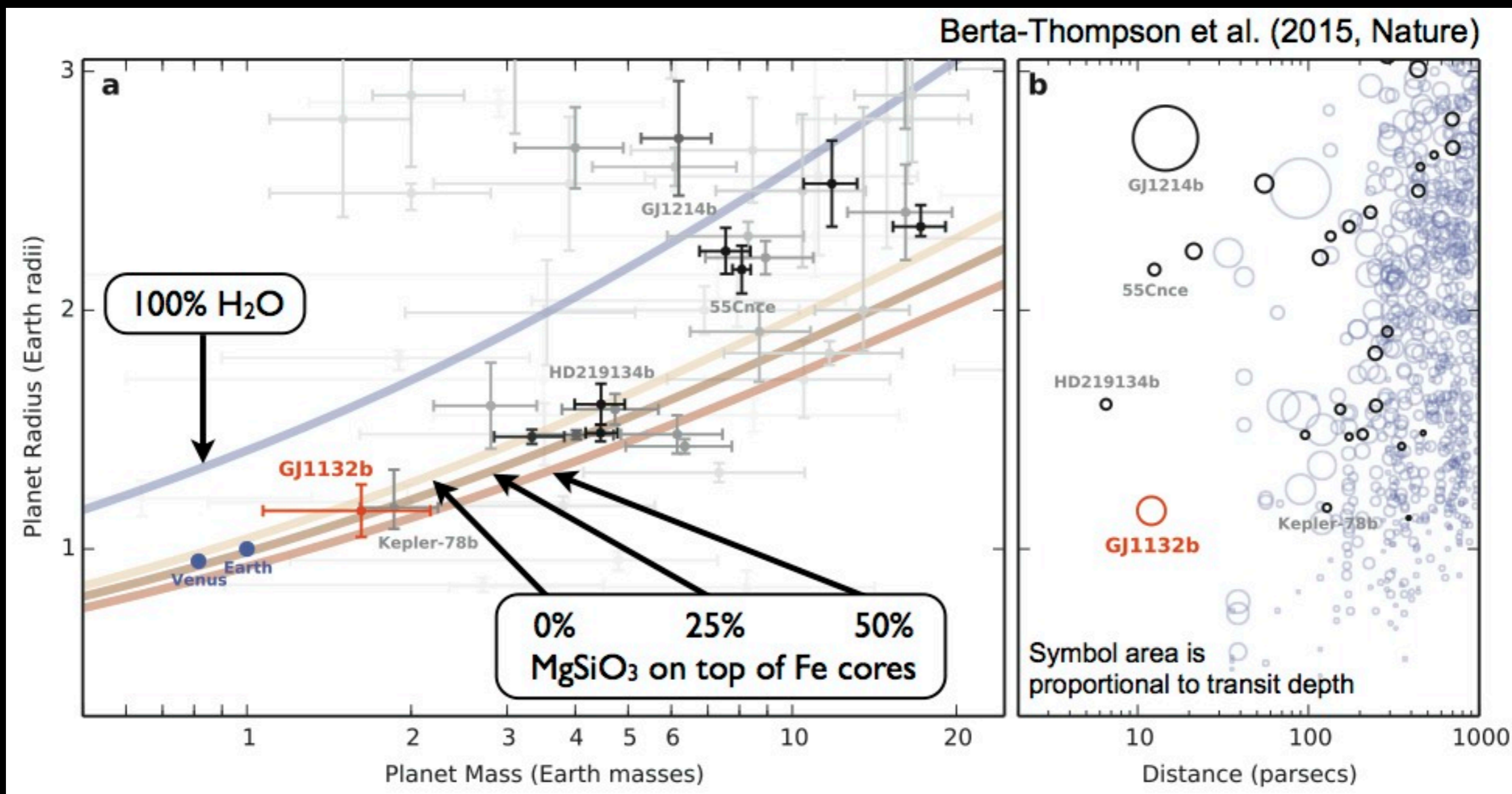
exoplanets.org | 3/11/2019



Characterize smaller and cooler exoplanets

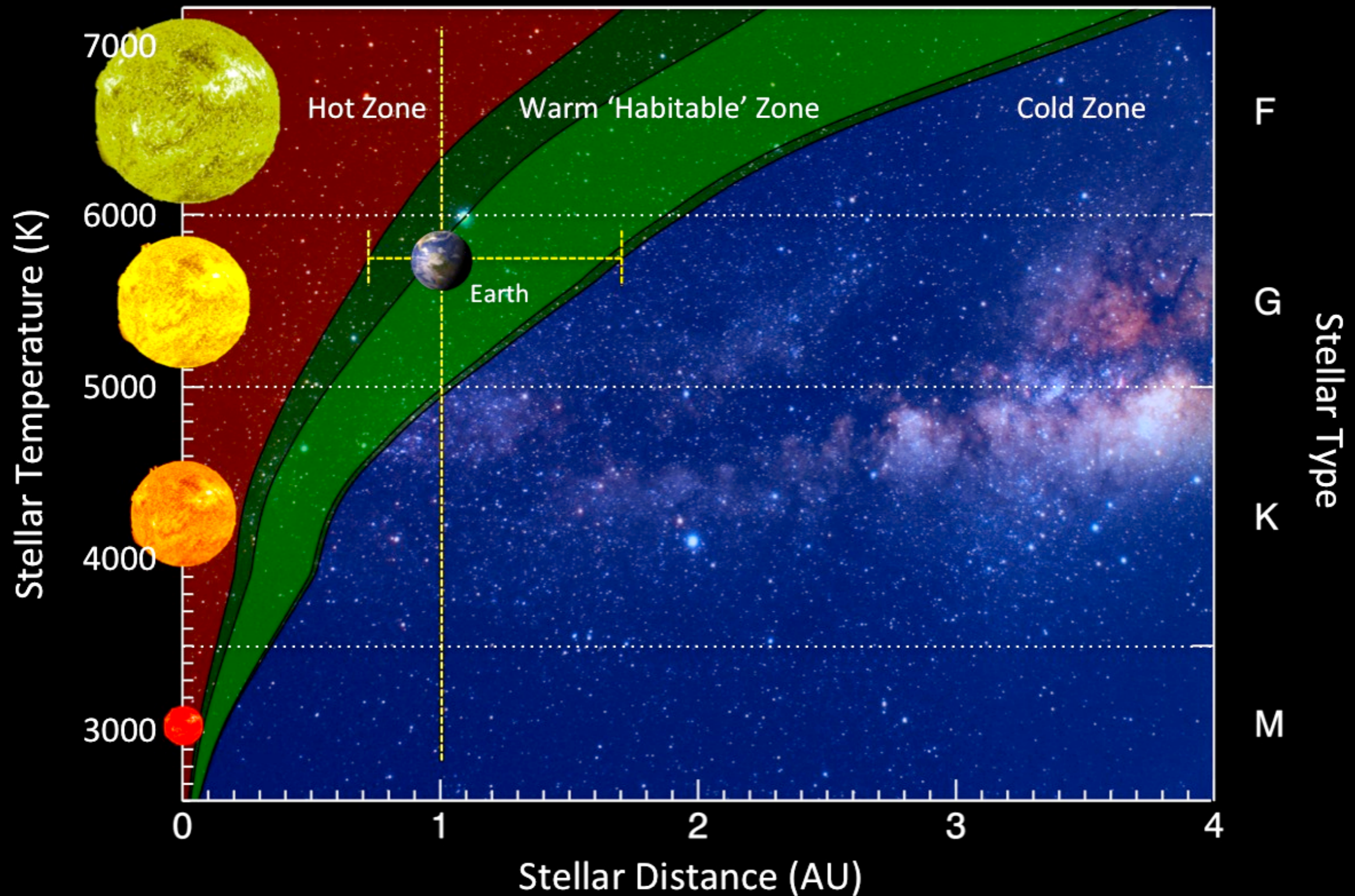


Search for primordial H-rich atmosphere of the M-dwarf GJ 1132b - Venus-mass exoplanet



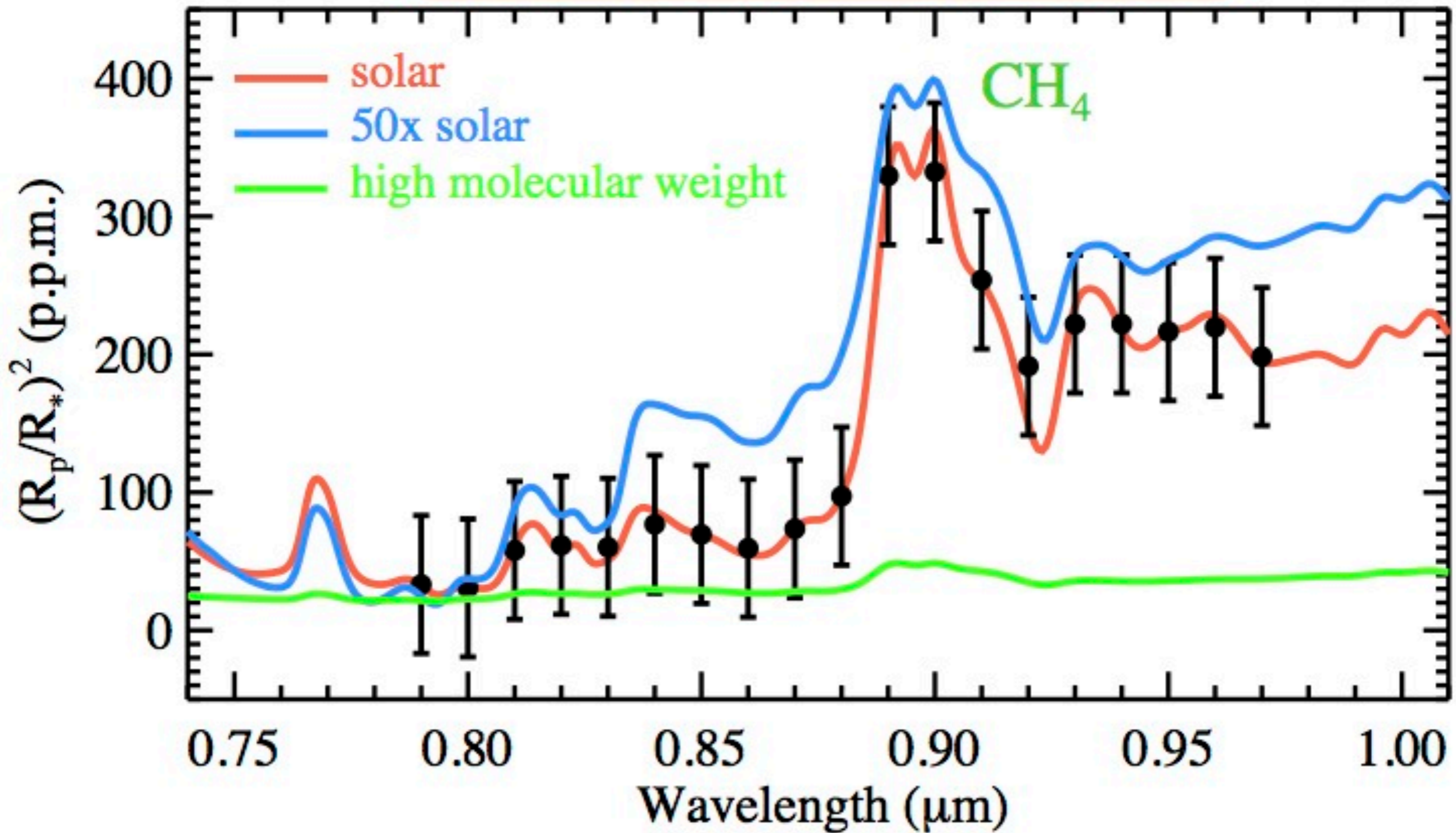
atmospheric characterisation of GJ-1132b is a part of my large VLT FORS2 program

Habitable Zone of Main Sequence Stars

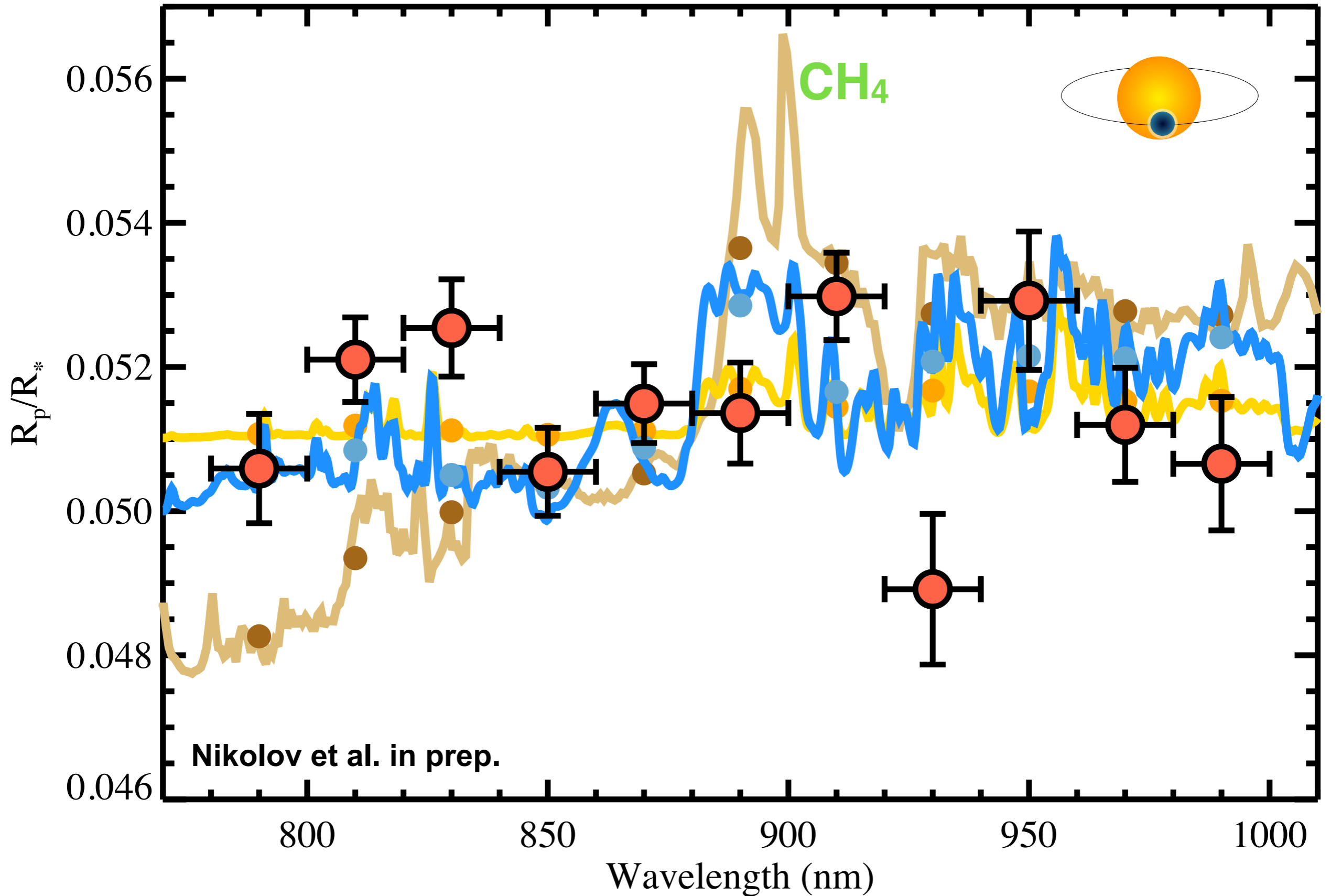


GJ1132b with

VLT FORS2 GRIS600z



GJ1132b - Venus mass exoplanet



ruled out H/He atmosphere for "exo-Venus" GJ 1132b

How to improve FORS2 for transits

Detectors:

- CCD with higher blue optical QE (planned by ESO)
- reduced cosmetics - minimise light curve systematic errors
- faster read-out - more time on the target

Grisms:

- GRIS 600B, 600RI and 600z - best for transmission spectroscopy
- need for higher sensitivity and flatter throughputs
- need for Na, K and Li grisms at higher resolution (e.g. GRIS1200)

Mechanical stability:

- need an instrument that is gravity neutral

Telescope improvements:

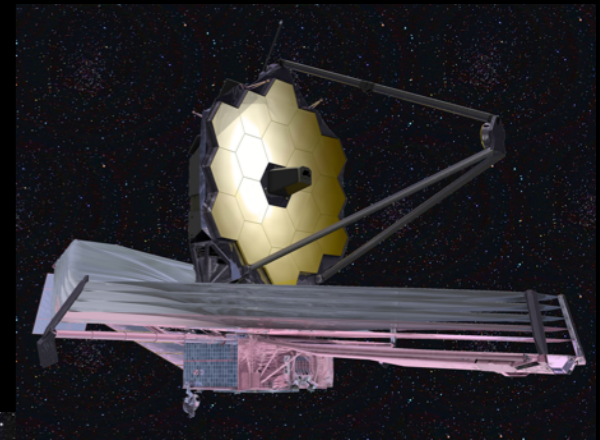
- improve rotator positioning, e.g. around small zenith distances
- LADC cleaning/monitoring system, e.g. nearUV flats, piezo-clean

Instrument field of view:

- wider field of view - enable bright targets with suitable comparison stars (Magellan IMACS - 27' v FORS2 6.8'x6.8')

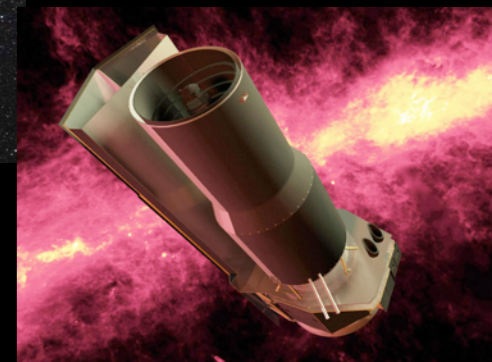
Conclusions

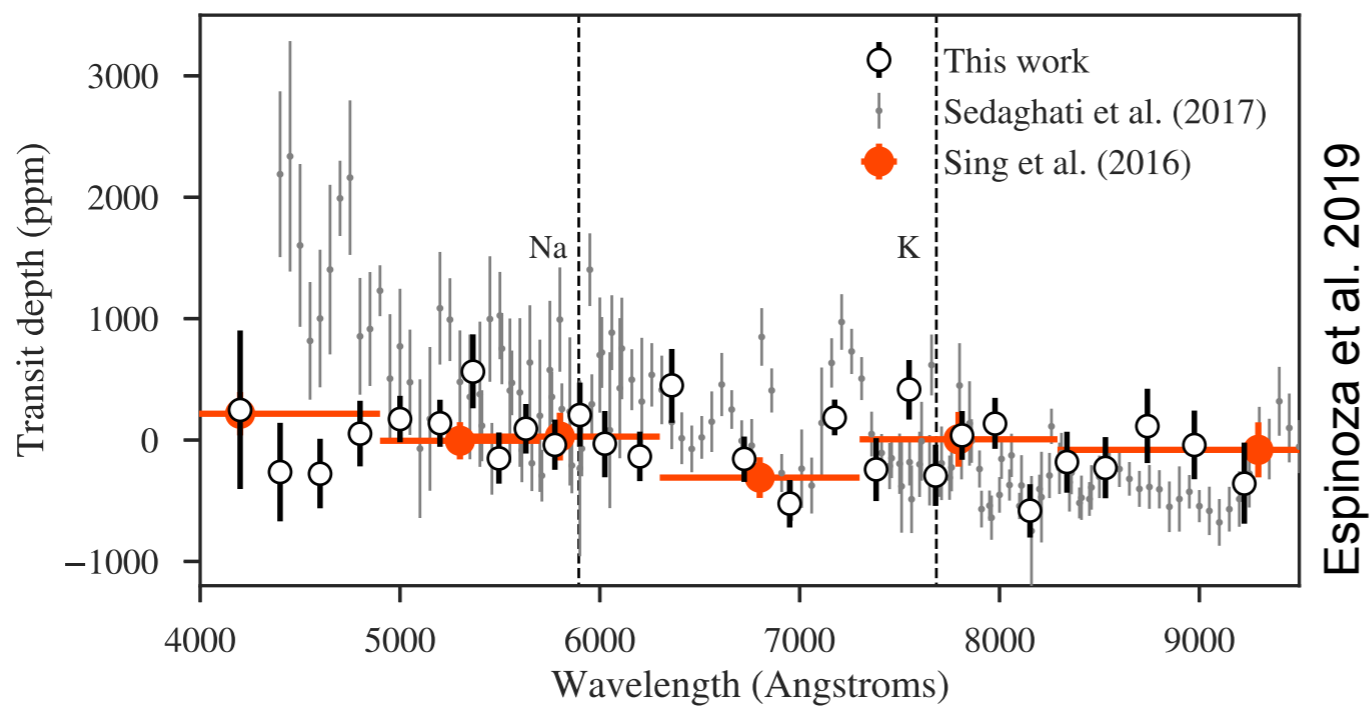
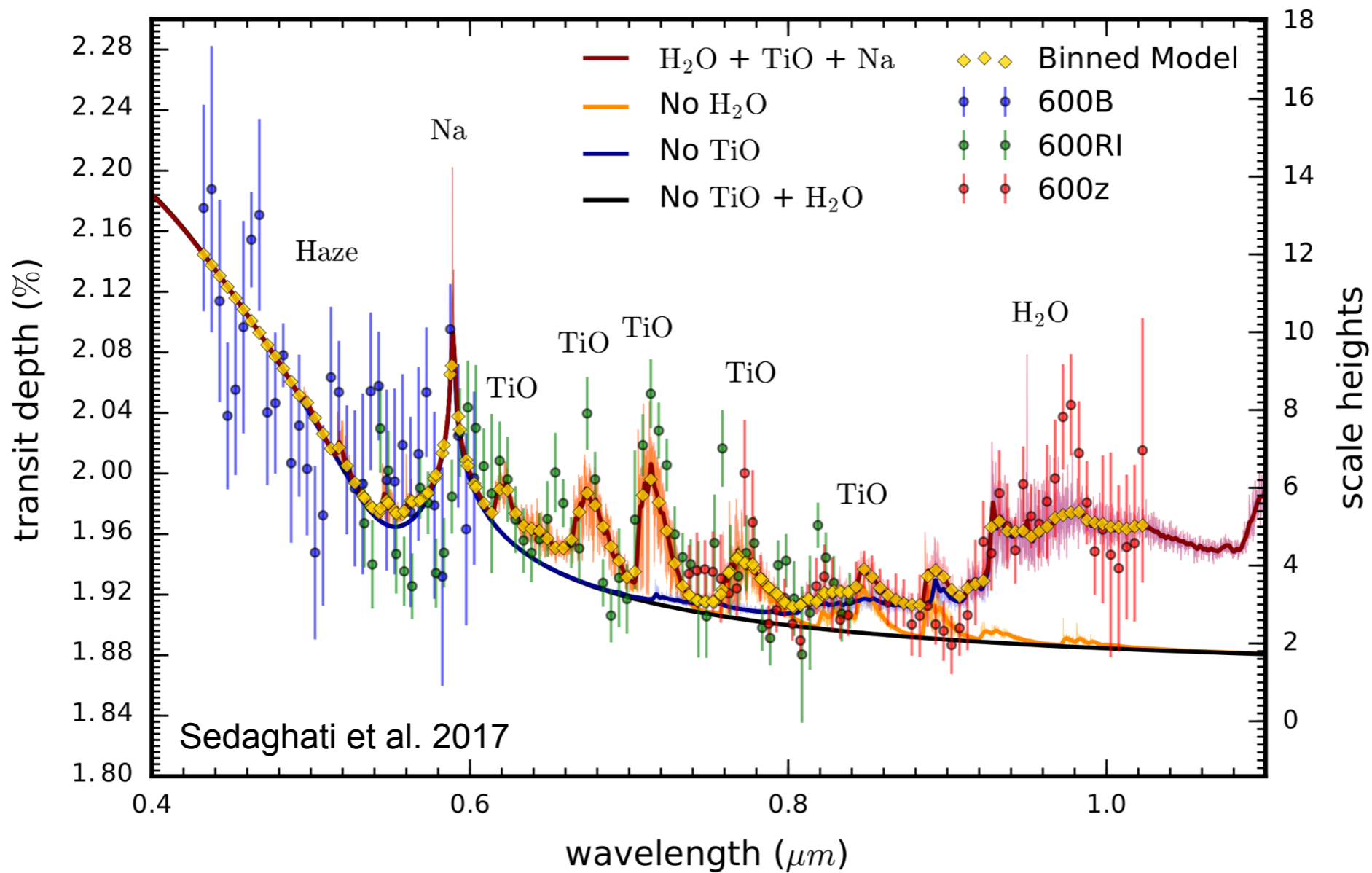
Exoplanets are very diverse



Still have not fully explored Hot Jupiters
Hot Neptunes and super-Earth are just starting

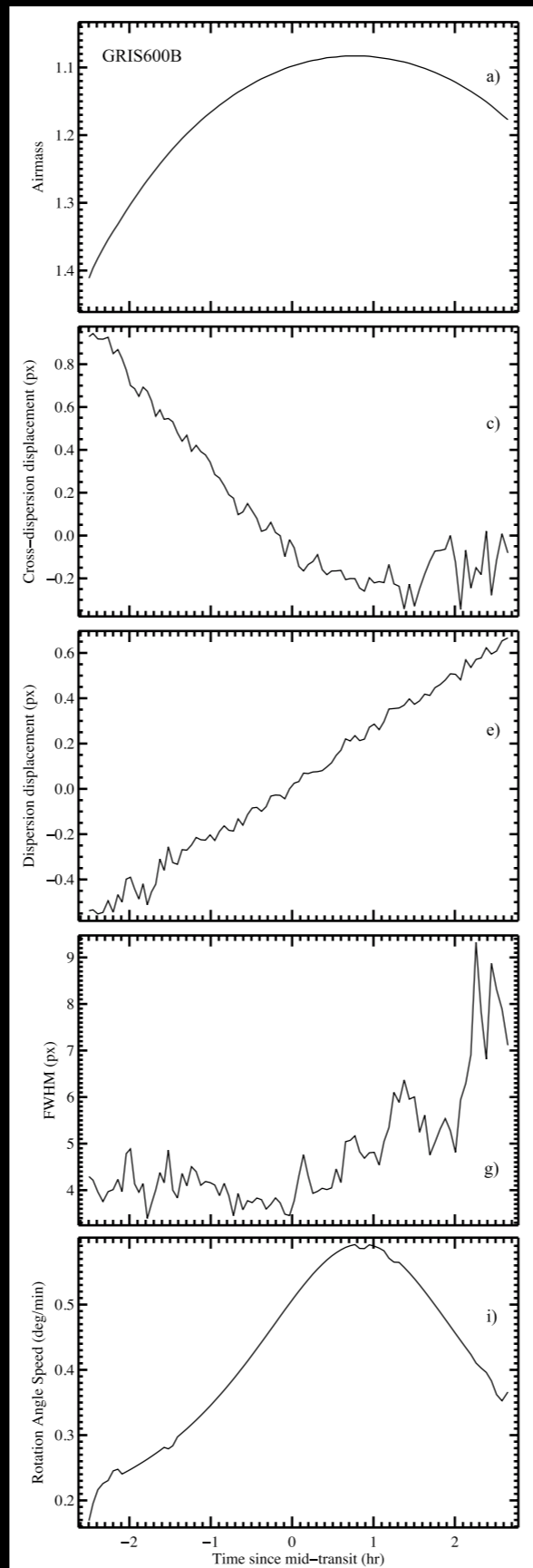
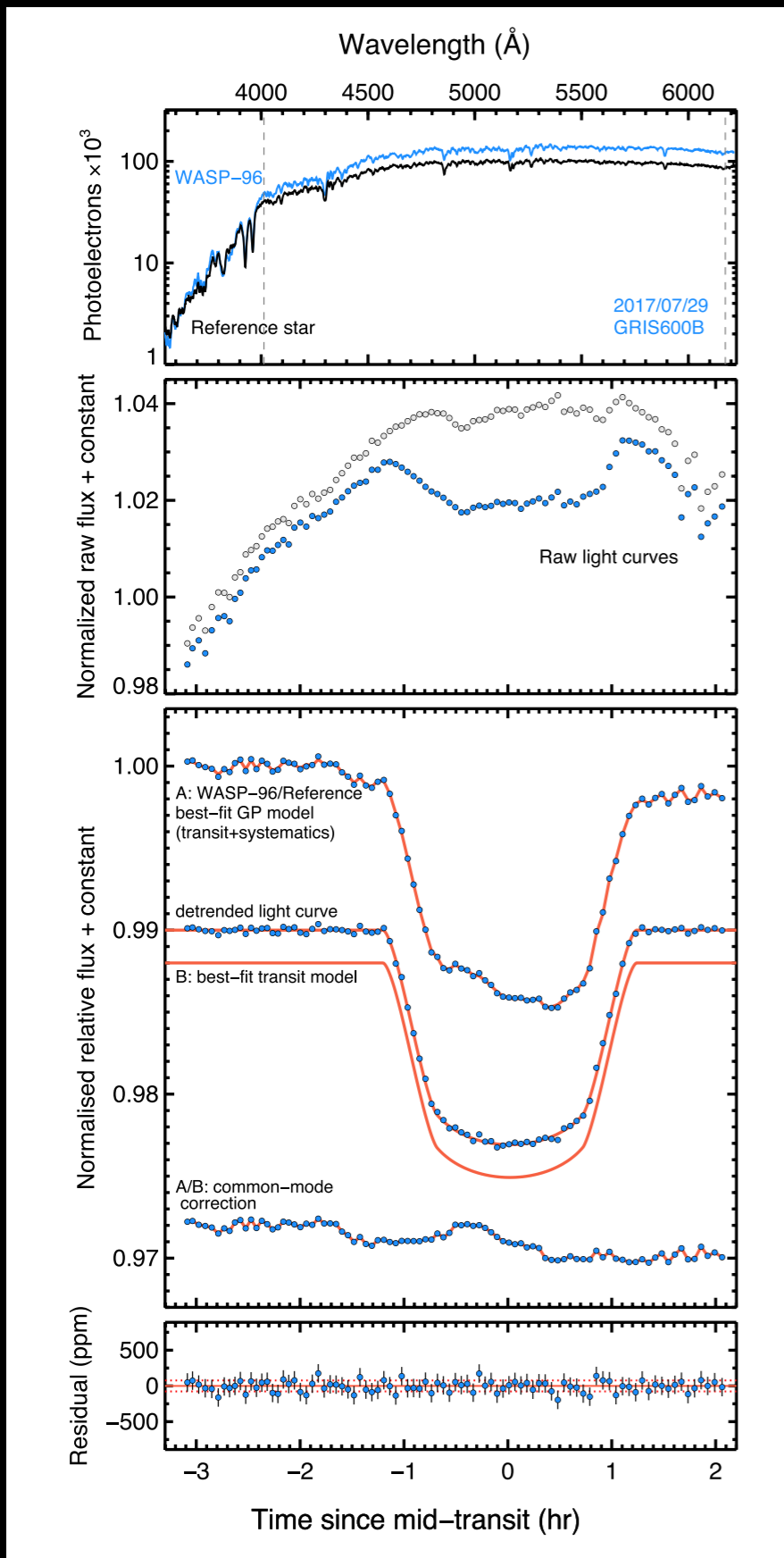
VLT & JWST will play a key role
for understanding the planet population



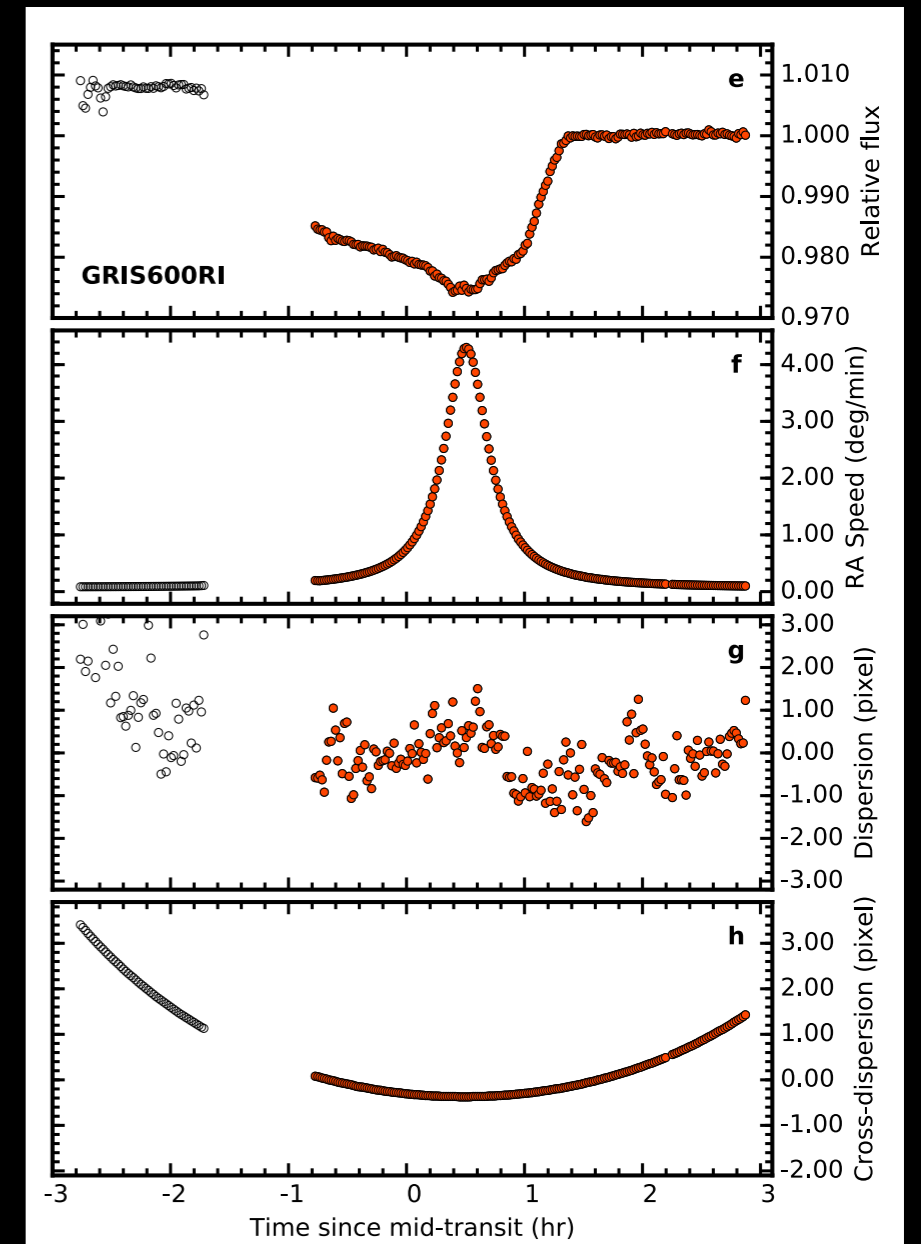


WASP-96b

Nikolov et al. 2018b



WASP-25b



Nikolay Nikolov