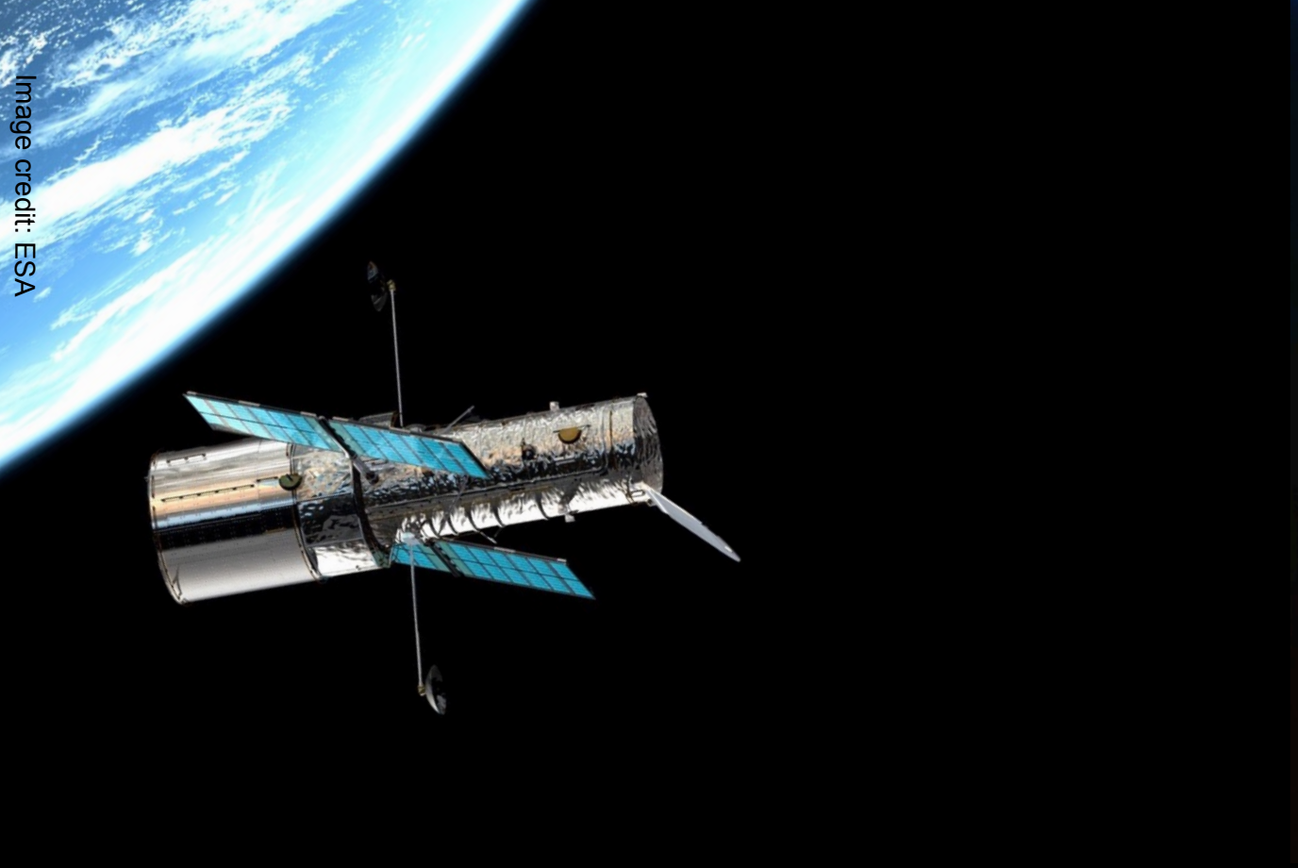


Image credit: ESA

From Hot gas giants to cooler exo-Earths

A pioneering spectral survey of exoplanet atmospheres

Nikolay Nikolov

Johns Hopkins University

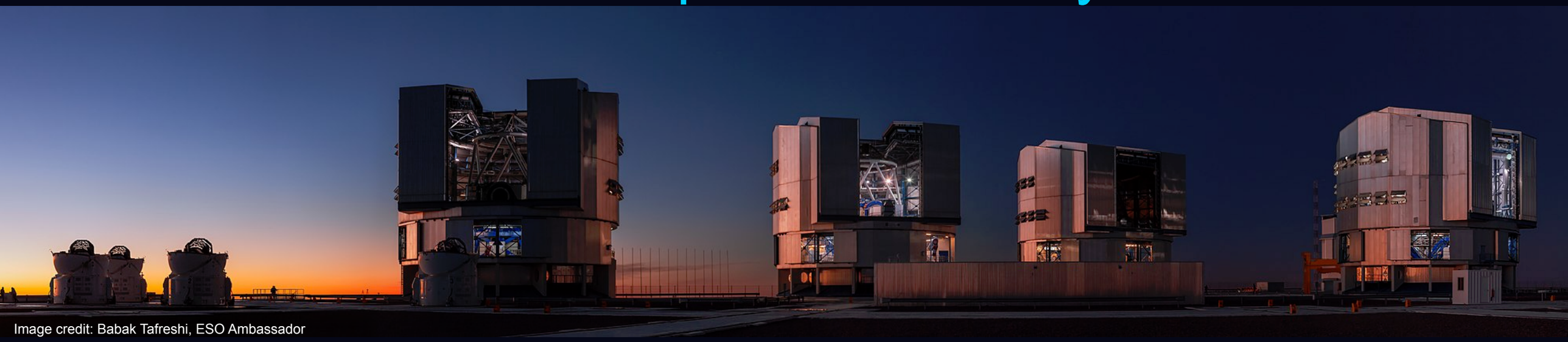


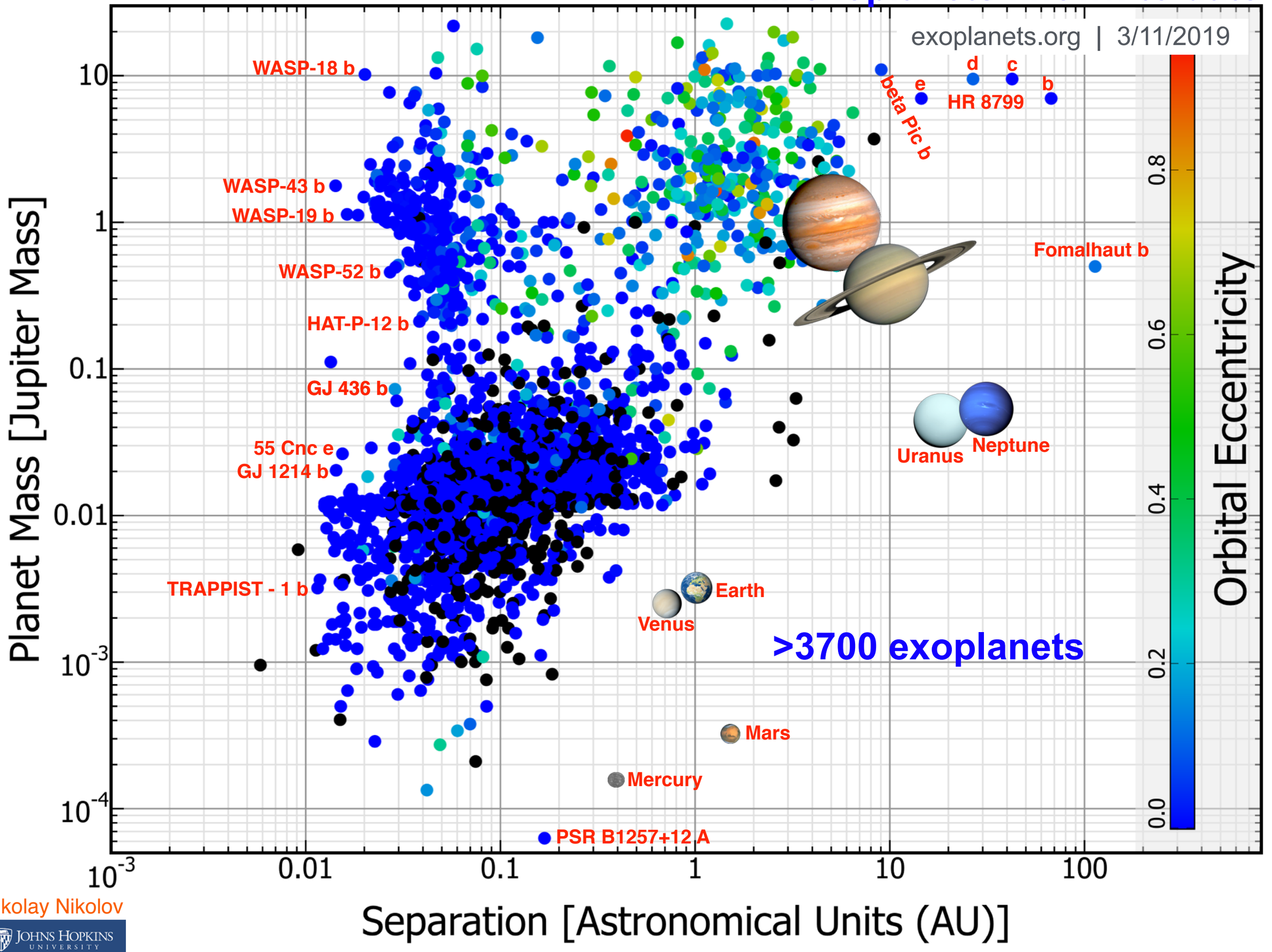
Image credit: Babak Tafreshi, ESO Ambassador

Outline

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

Nikolay Nikolov
JOHNS HOPKINS UNIVERSITY

All exoplanets known to date



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exoplanets.org | 3/11/2019

Hot Jupiters

Cold Jupiters

Young Jupiters

Warm Neptunes
Super Earths

WASP-18 b
WASP-43 b
WASP-19 b
WASP-52 b
HAT-P-12 b
GJ 436 b
55 Cnc e
GJ 1214 b
TRAPPIST - 1 b

beta Pic b
e
d
c
b
HR 8799
Fomalhaut b

Uranus
Neptune
Earth
Venus
Mars
Mercury
PSR B1257+12 A

>3700 exoplanets

Planet Mass [Jupiter Mass]

10
1
0.1
0.01
10^{-3}
10^{-4}

Separation [Astronomical Units (AU)]

10^{-3}
0.01
0.1
1
10
100

Orbital Eccentricity

0.0
0.2
0.4
0.6
0.8

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

Hot Jupiters

Cold Jupiters

Young Jupiters

Warm Neptunes
Super Earths

WASP-18 b
WASP-43 b
WASP-19 b
WASP-52 b
HAT-P-12 b
GJ 436 b
55 Cnc e
GJ 1214 b
TRAPPIST - 1 b

beta Pic b
e
d
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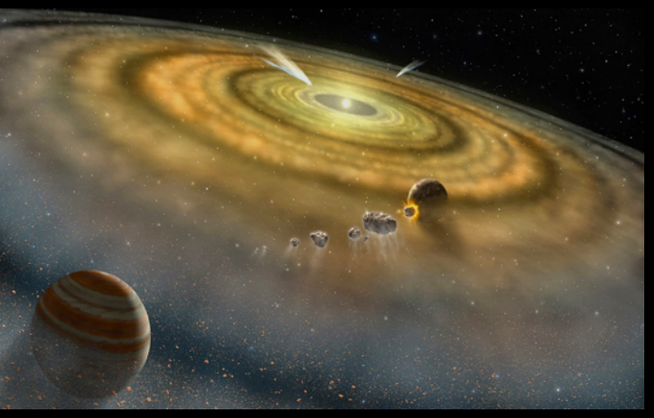
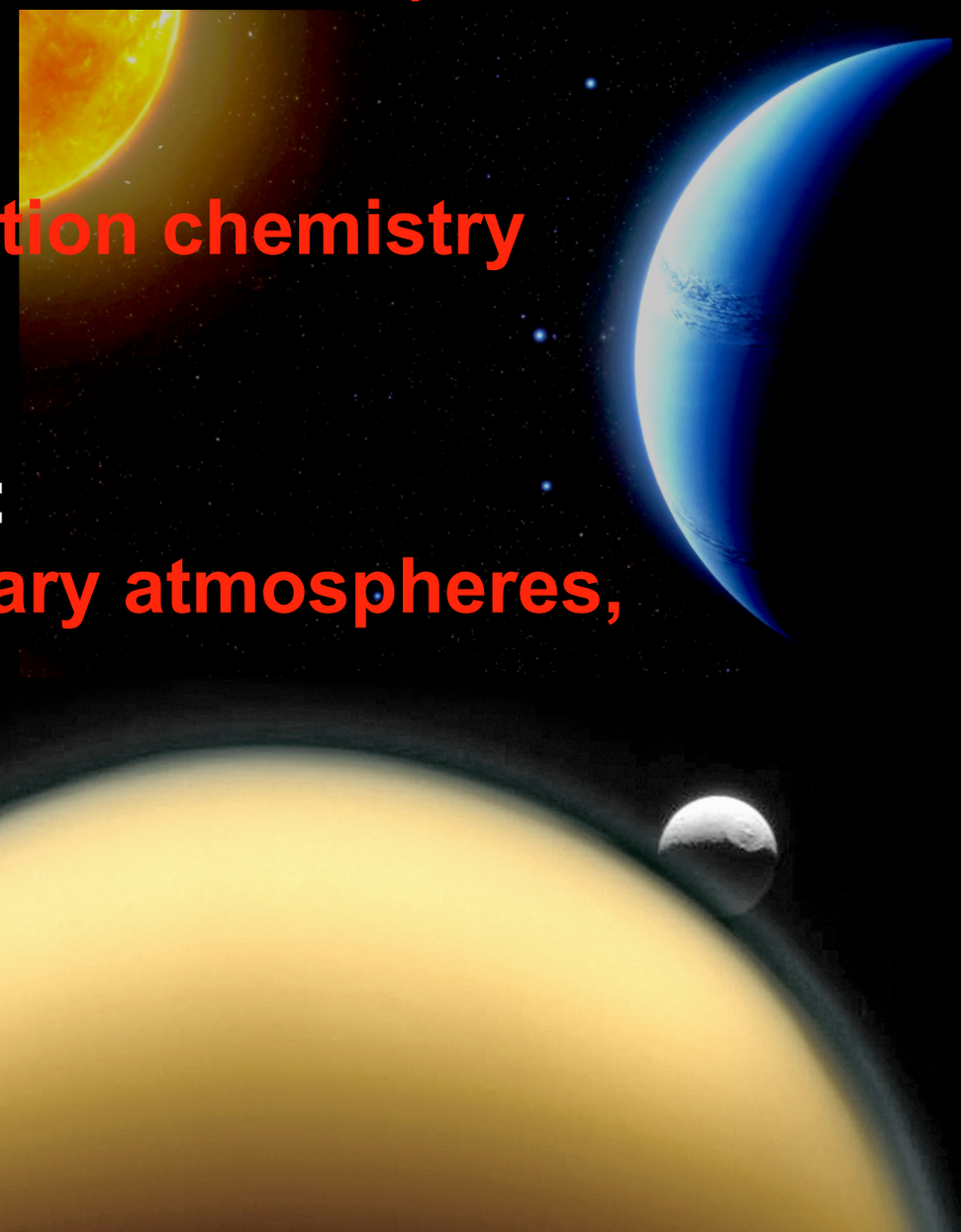
Major Exoplanet Science Questions

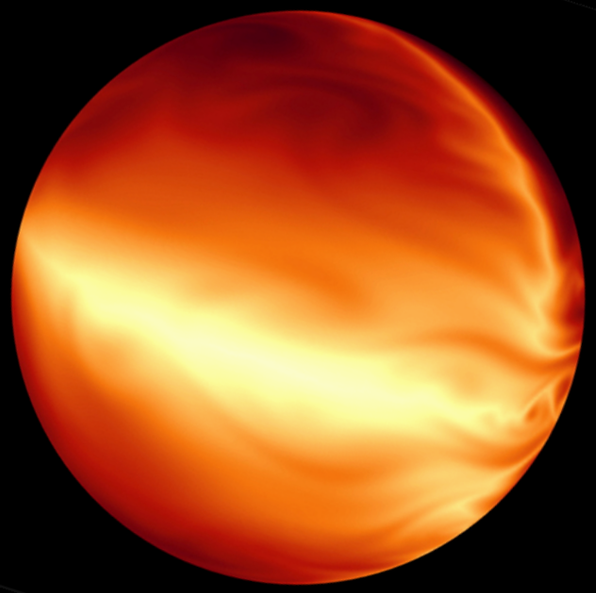


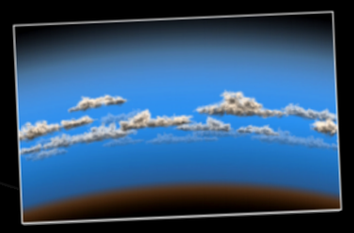
- **Link composition & abundances to formation:**
  Absolute abundances (Na, H_2O, …)

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



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





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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*	

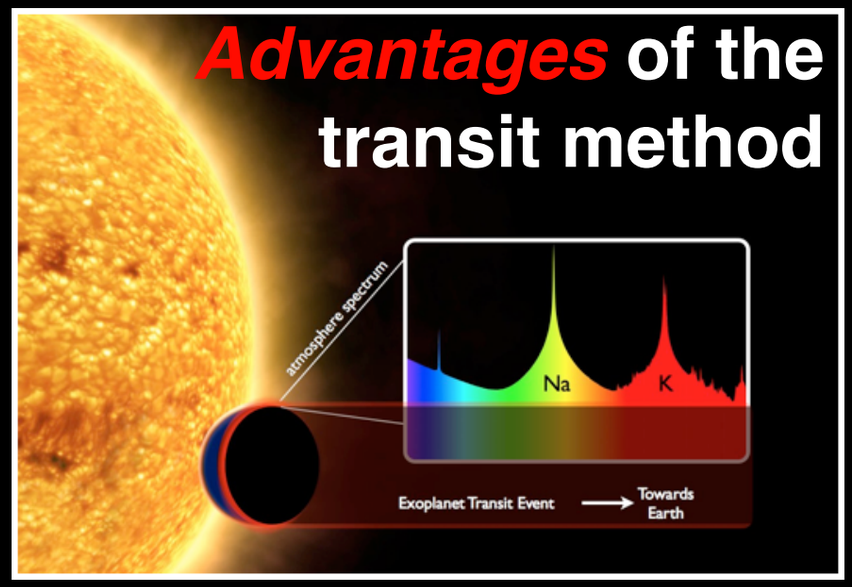


Image credit: NASA, ESA
D. Sing, University of Exeter

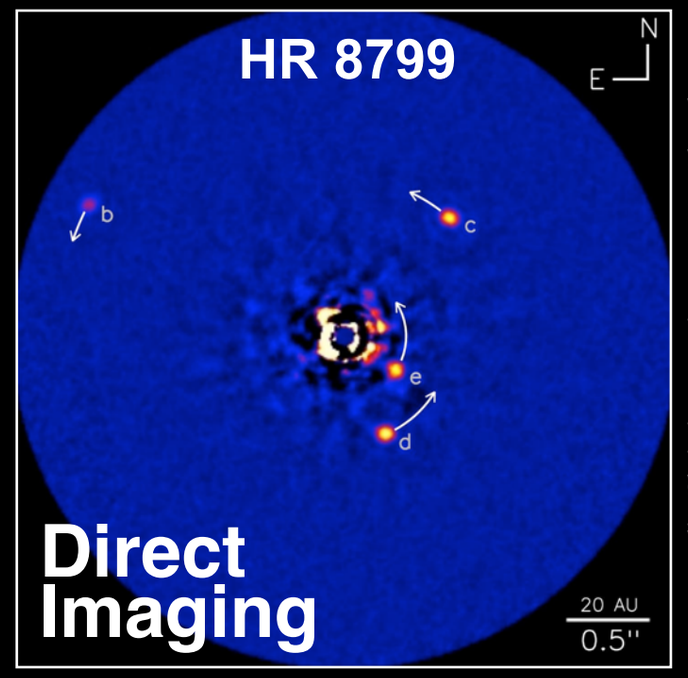


Image credit: Christian Marois, HR 8799, K-band

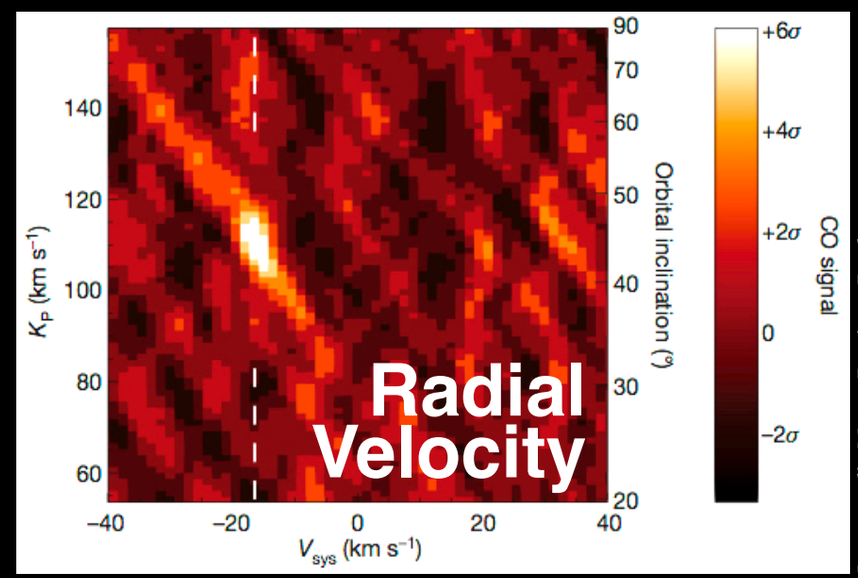
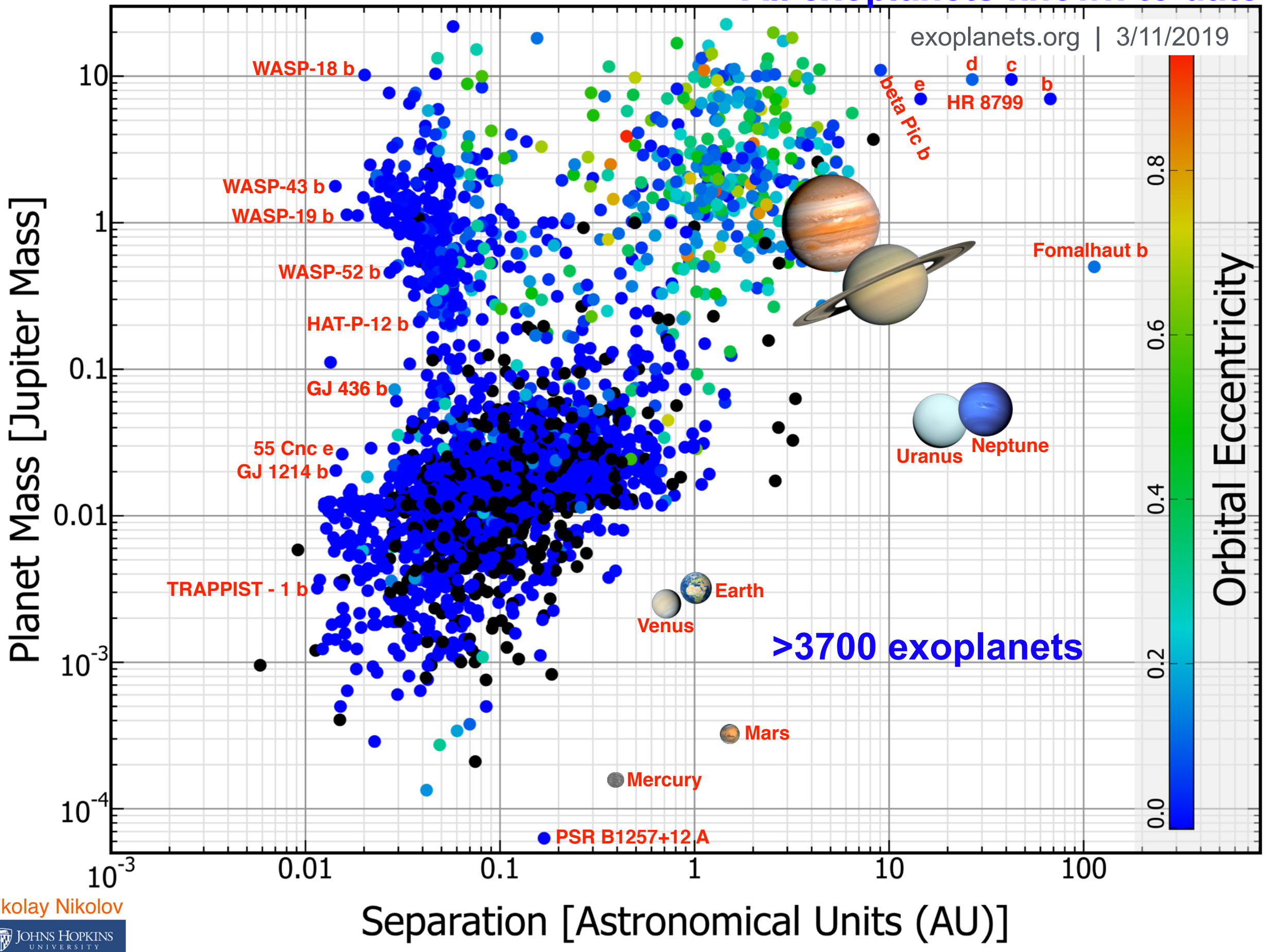


Image credit: Matteo Brogi, tau Boo b

All exoplanets known to date



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All *transiting* exoplanets known to date

exoplanets.org | 3/11/2019

close-in, irradiated exoplanets

allow atmospheric characterization!

mass accuracy ~2-3%
PROVIDE MASS CONTEXT FOR ATMOSPHERIC DETECTIONS

allow statistical studies for years to come!!!

Uranus
Neptune
Earth
Venus
Mars
Mercury

Planet Mass [Jupiter Mass]

10
1
0.1
0.01
10^{-3}
10^{-4}

10^{-3}
0.01
0.1
1
10
100

Separation [Astronomical Units (AU)]

Orbital Eccentricity

0.0
0.2
0.4
0.6
0.8

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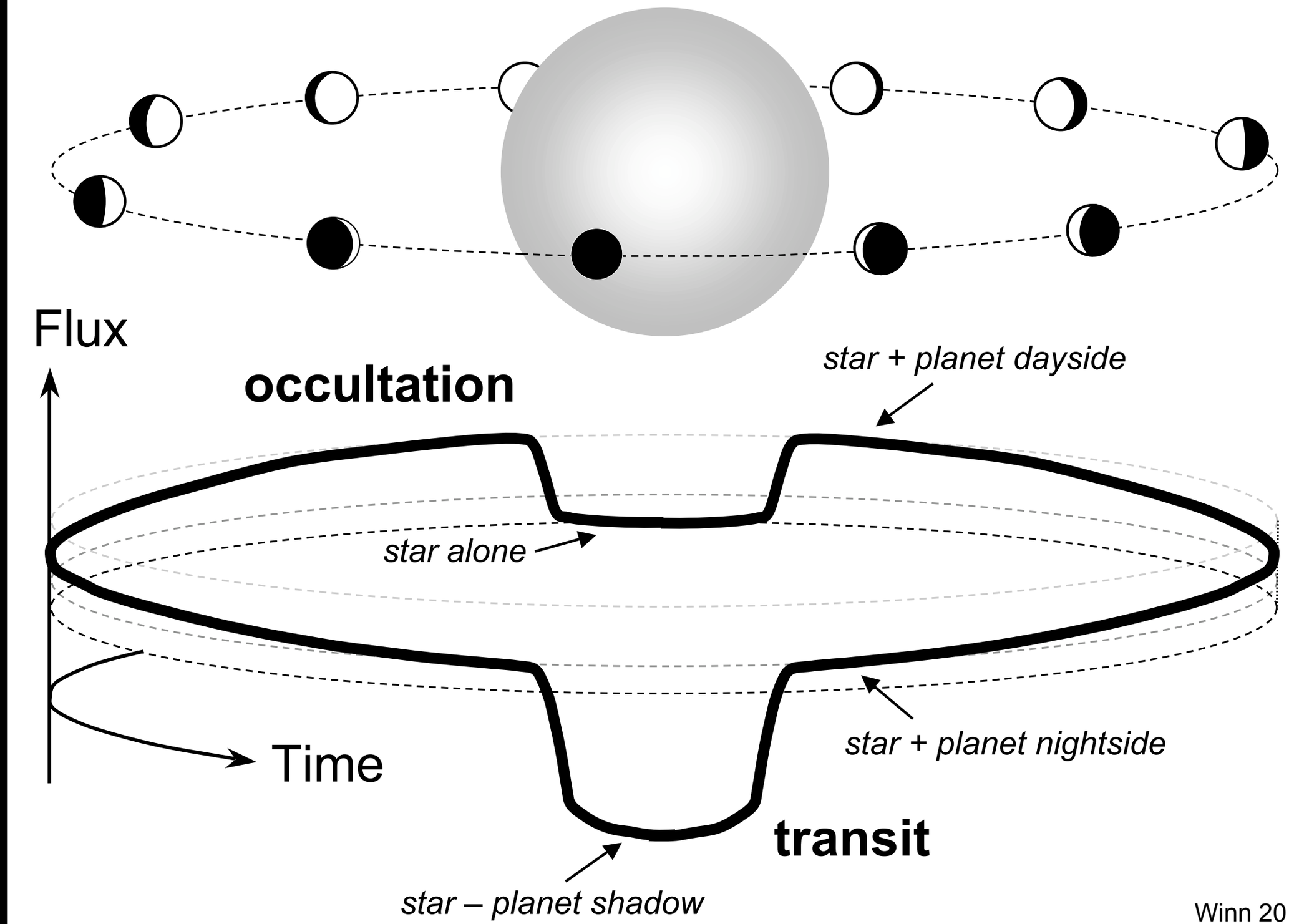
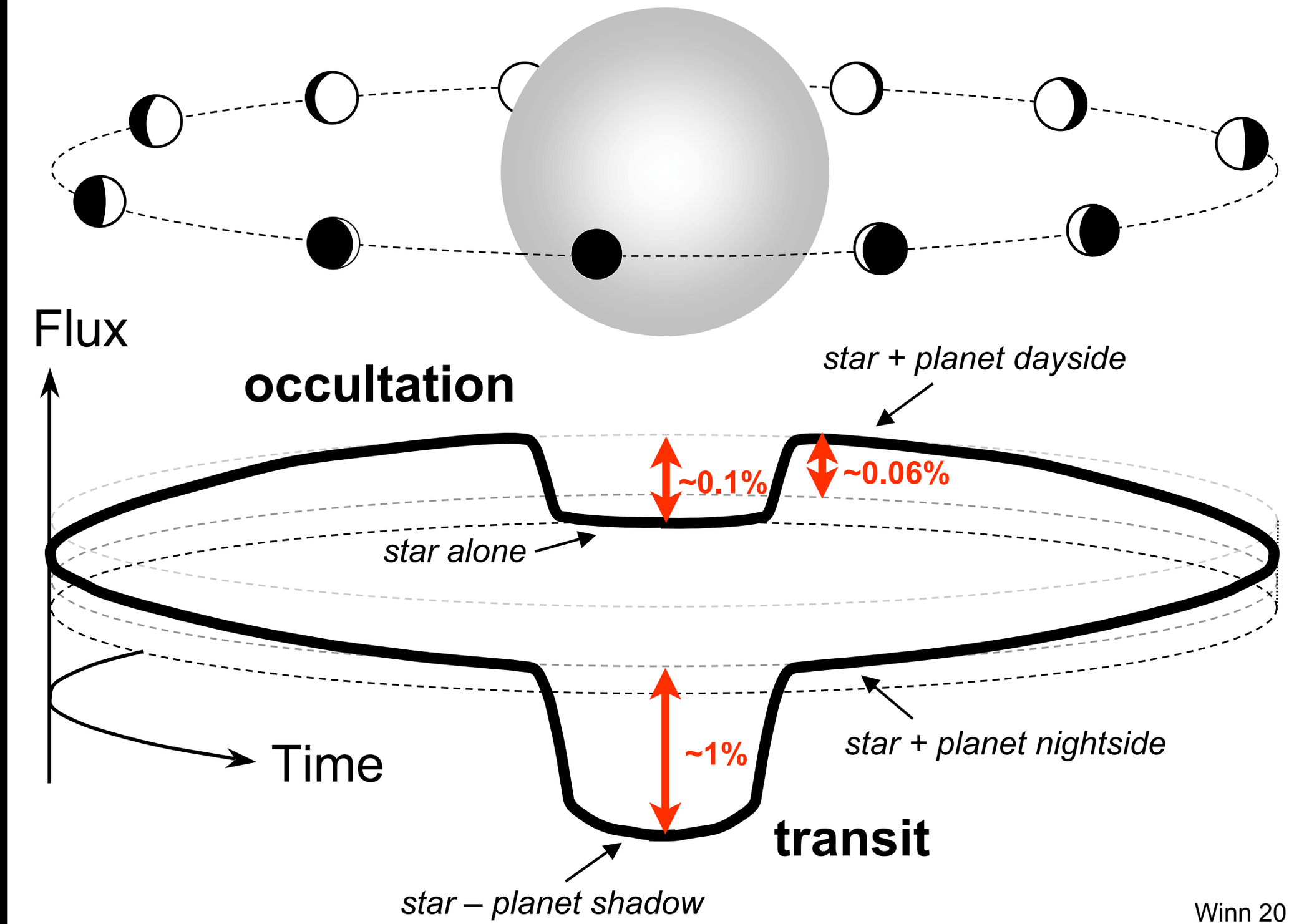

Flux
occultation
star + planet dayside
star alone
Time
star + planet nightside
transit
star – planet shadow
Winn 2010


Flux
occultation
star + planet dayside
~0.1%
~0.06%
star alone
Time
~1%
star + planet nightside
transit
star – planet shadow
Winn 2010

Hot Jupiters atmospheric models 1D

What might irradiated gas giant exoplanets look like?

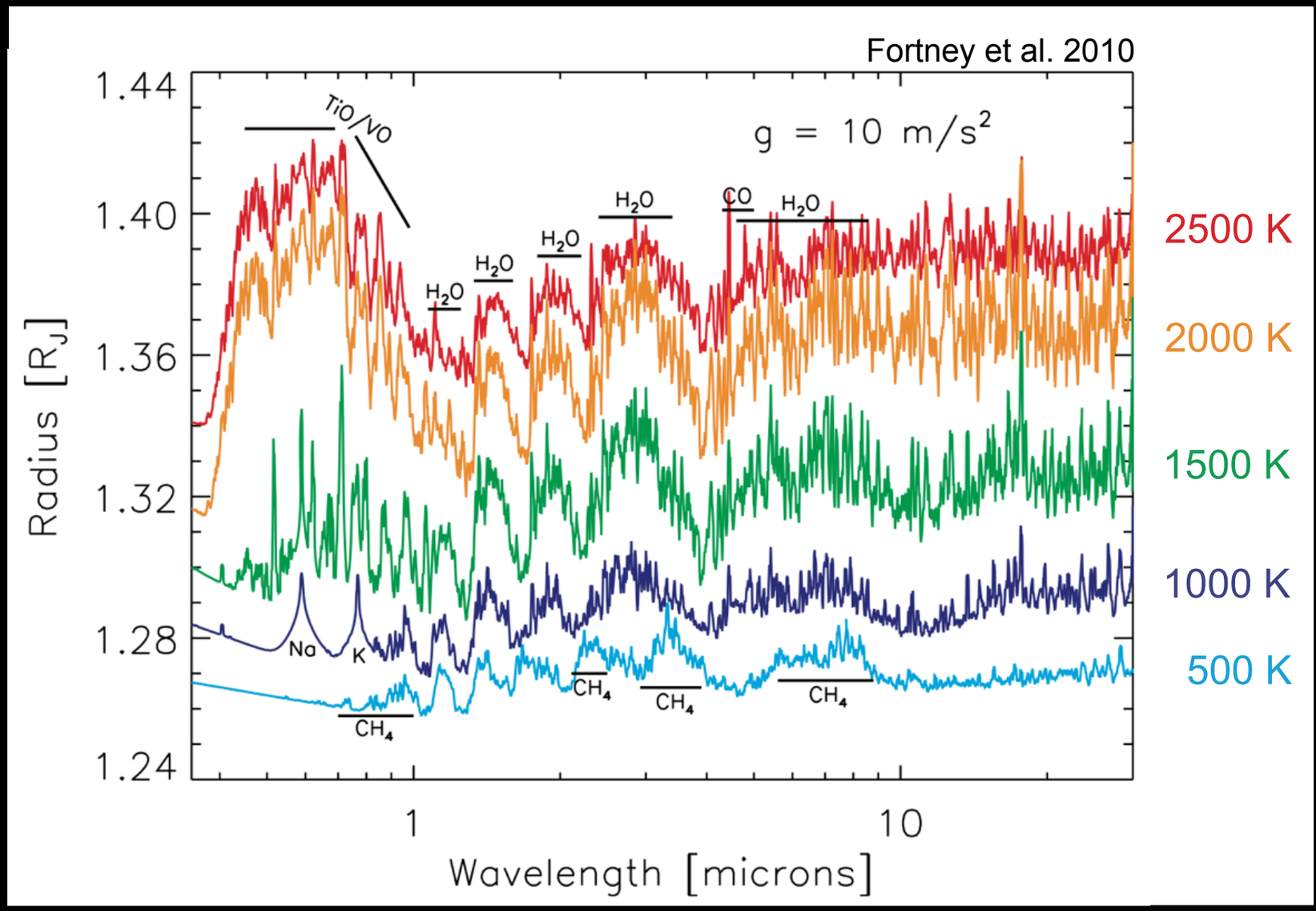
Forward Models

Solar composition

Chemical equilibrium

Radiative transfer

- H_2 Na K
- H_2O dominant
- CO hotter atmospheres
- CH_4 cooler atmospheres



Clouds- very dependent on T-P profiles

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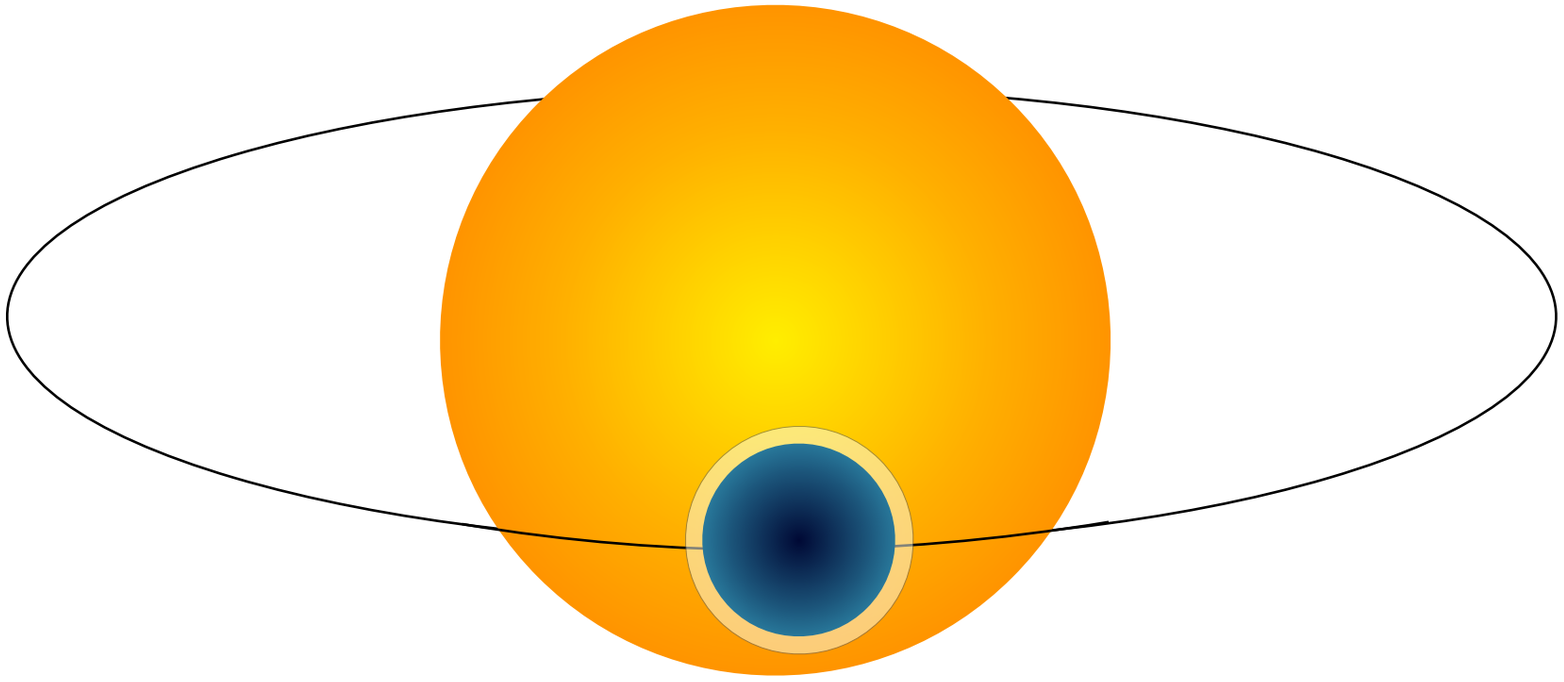
How does transit spectroscopy work ?



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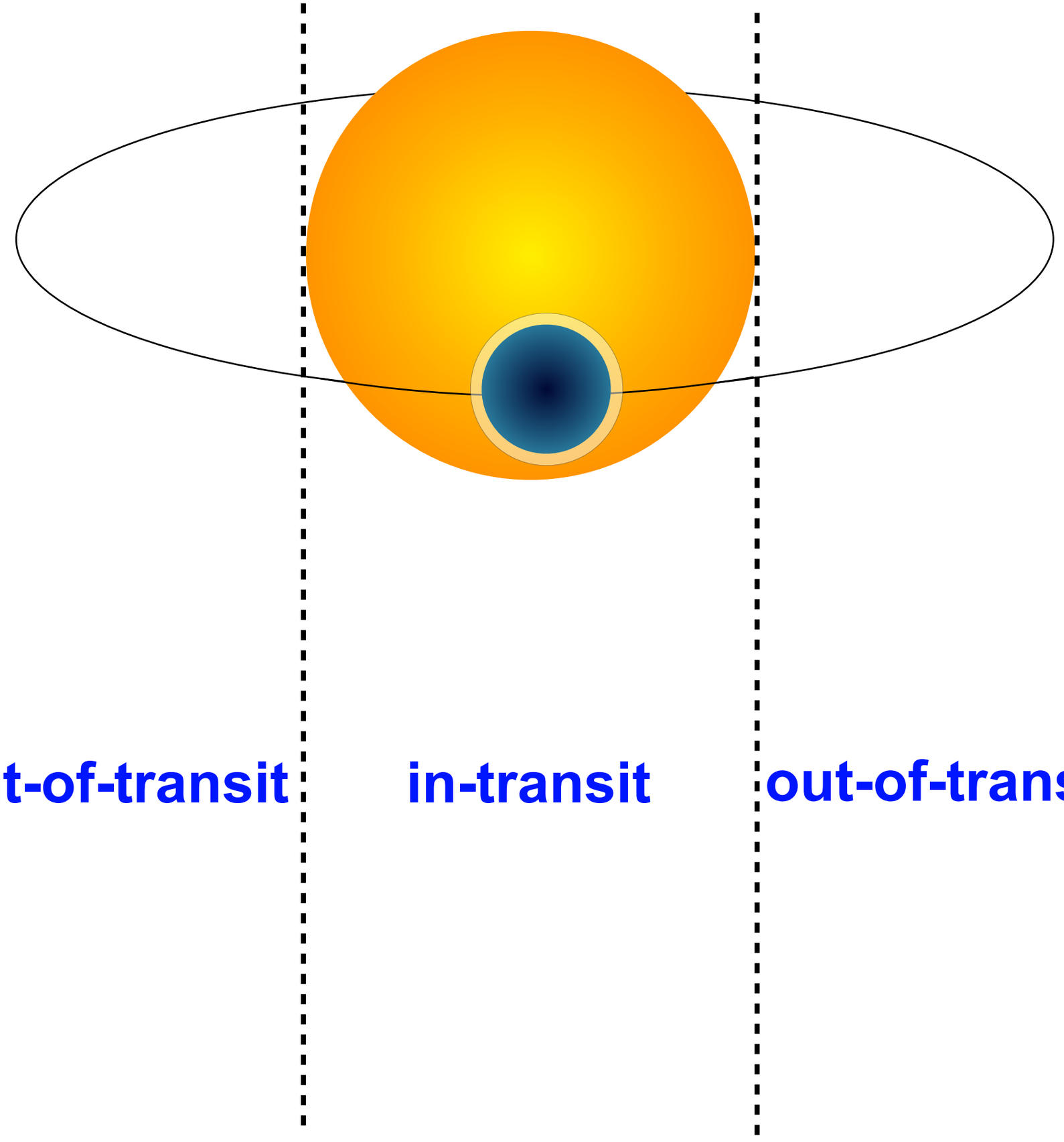

out-of-transit

in-transit

out-of-transit

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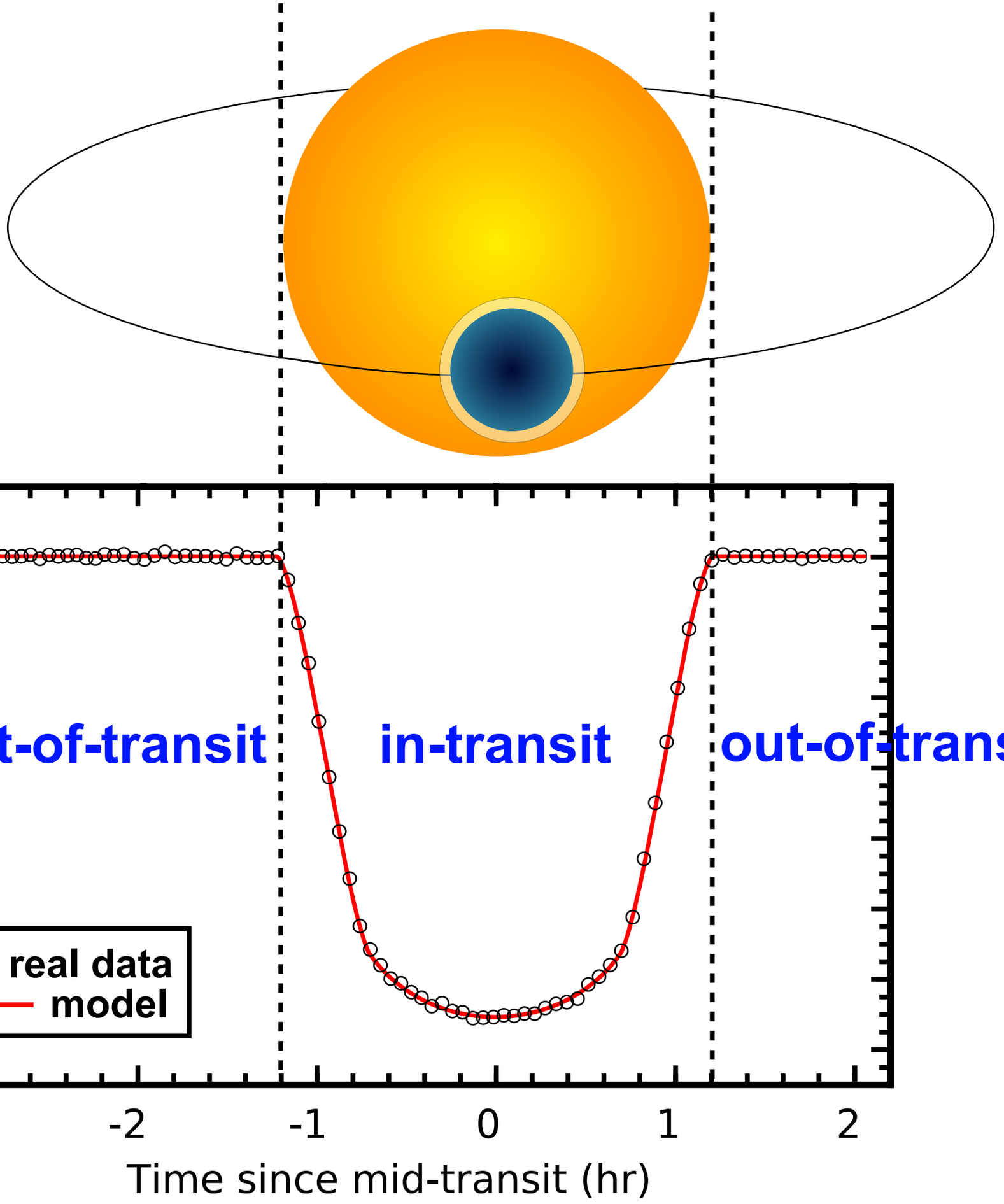
How does transit spectroscopy work ?



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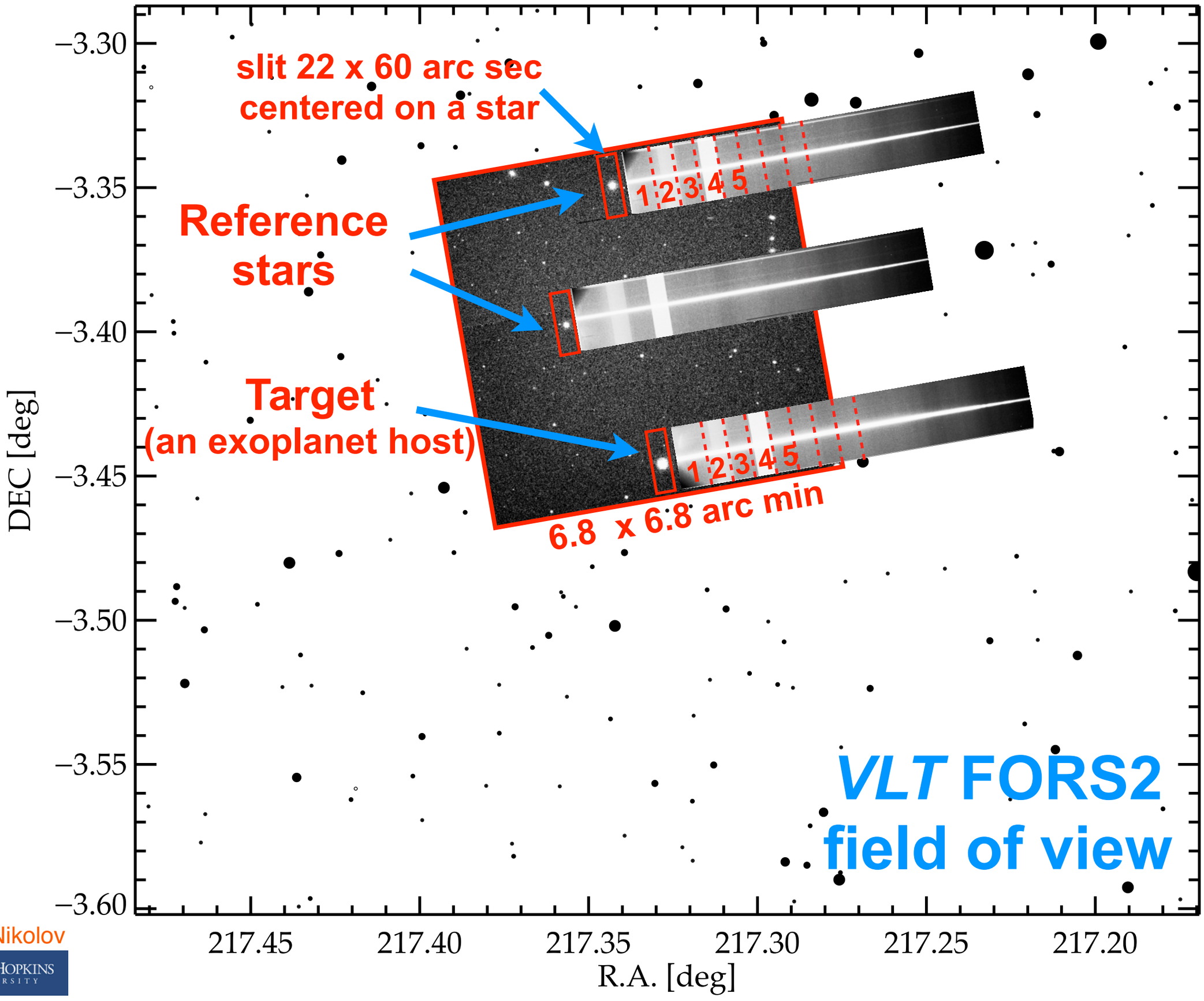
From the ground: multi-object spectroscopy



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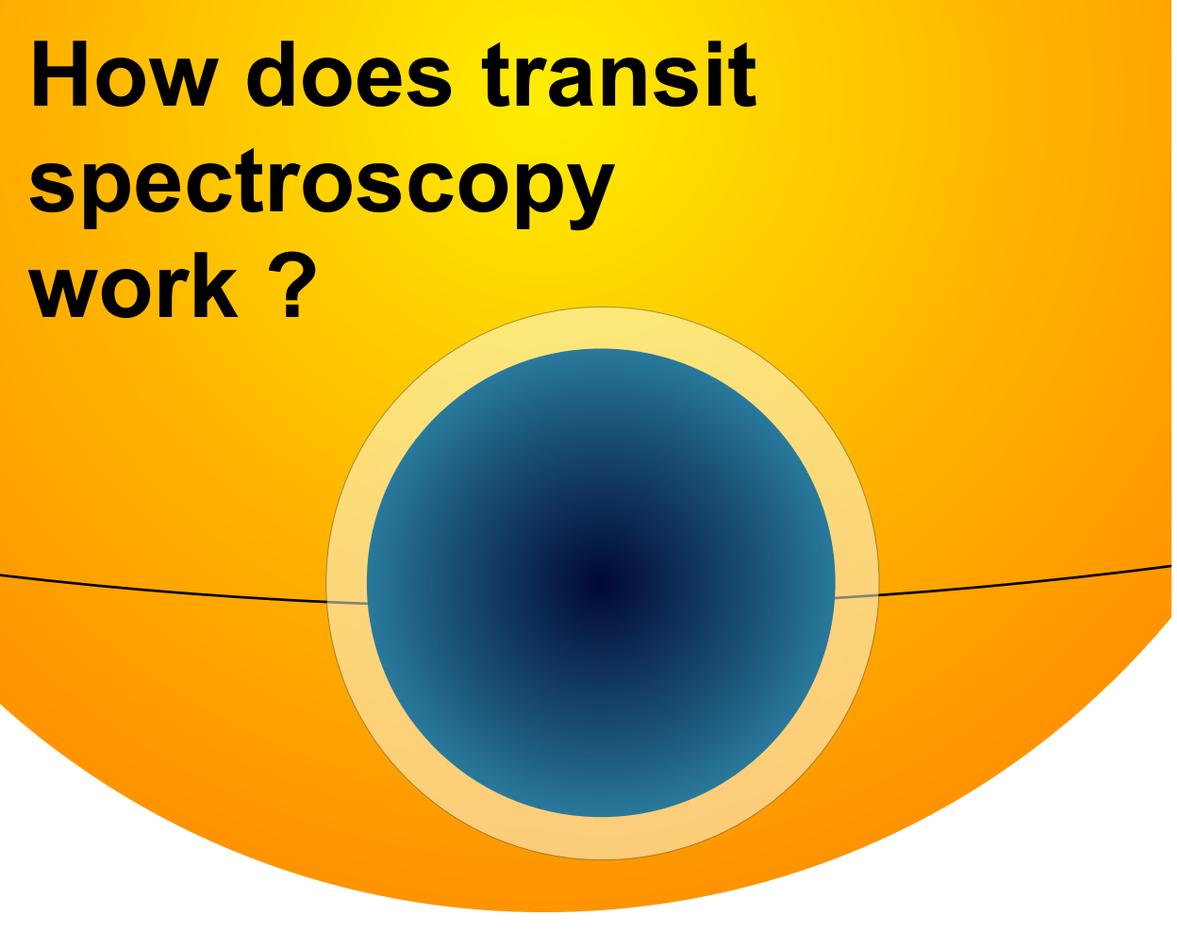

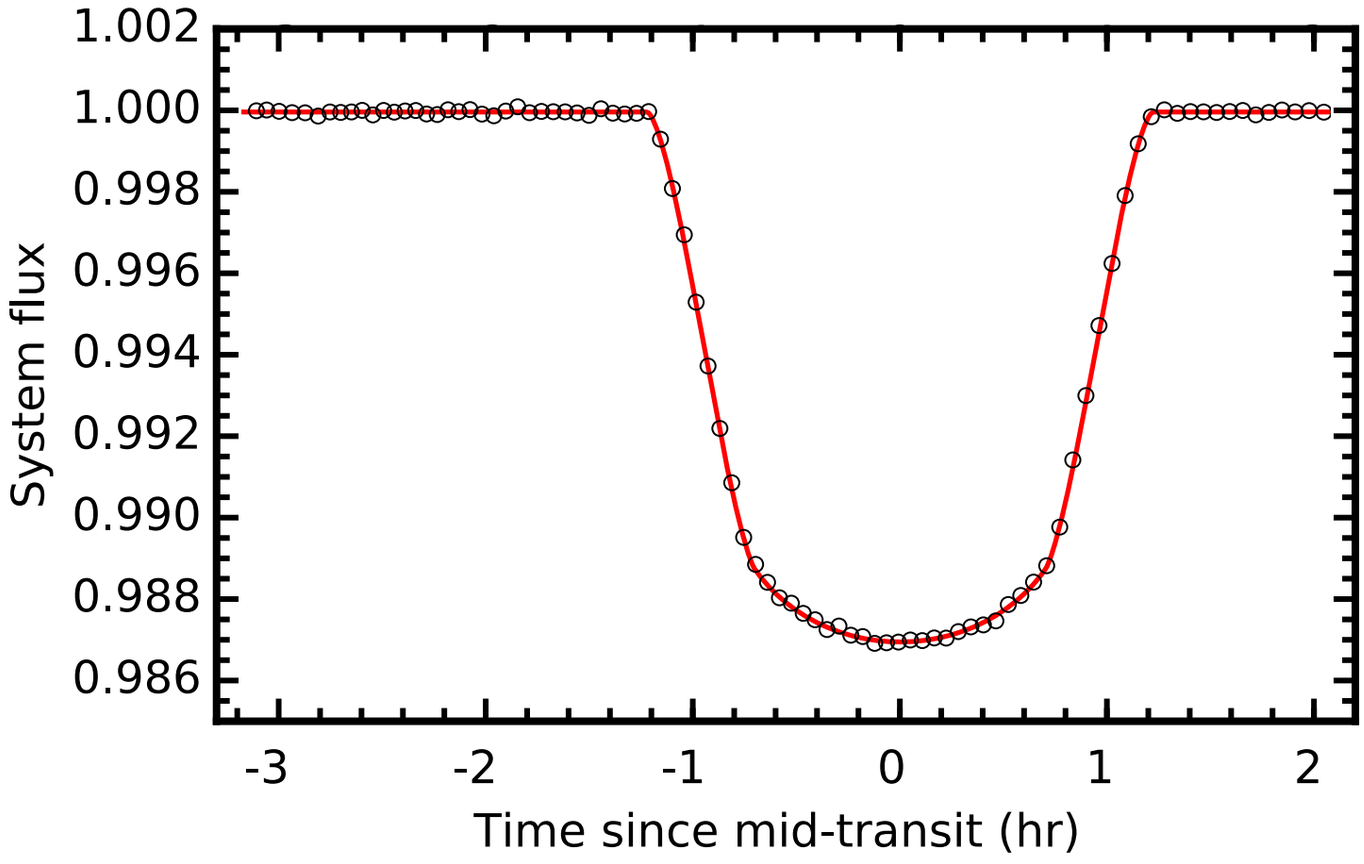

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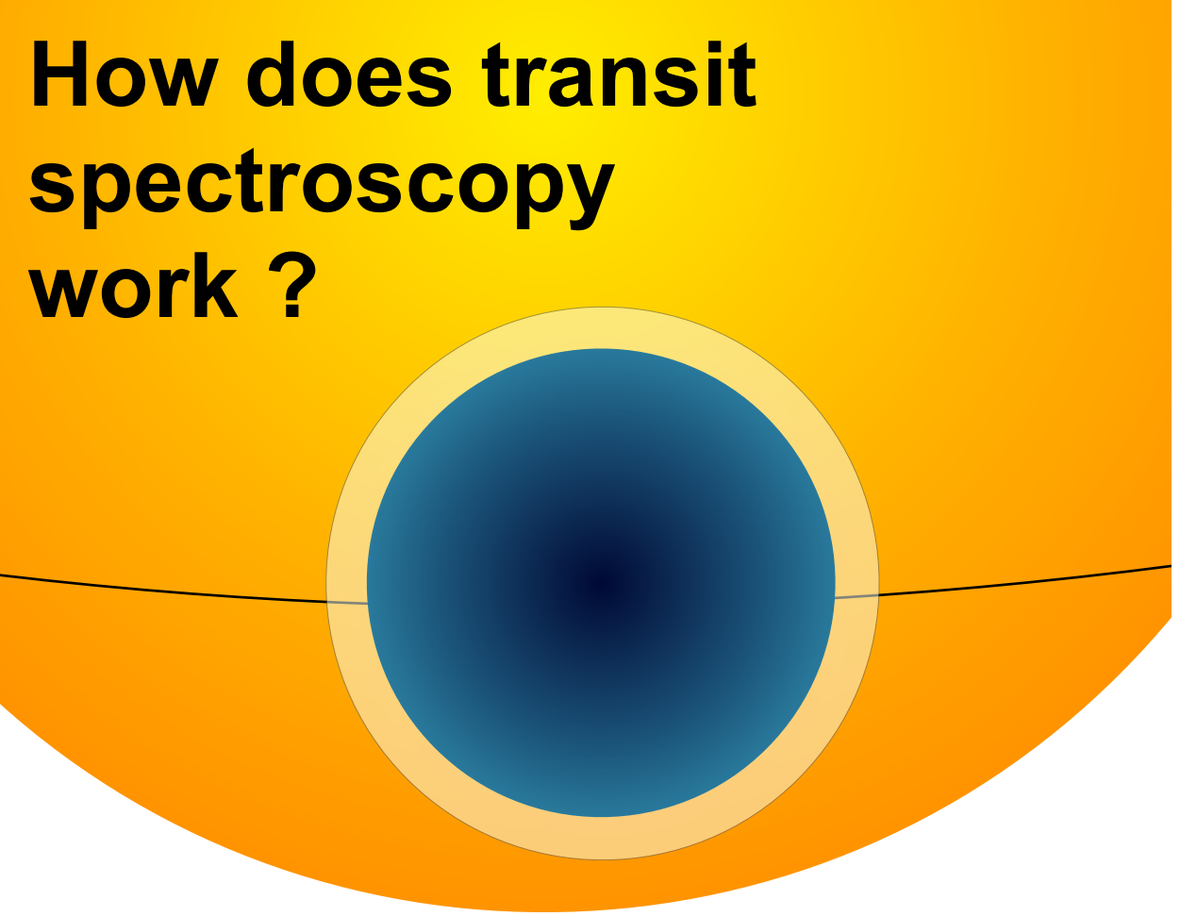

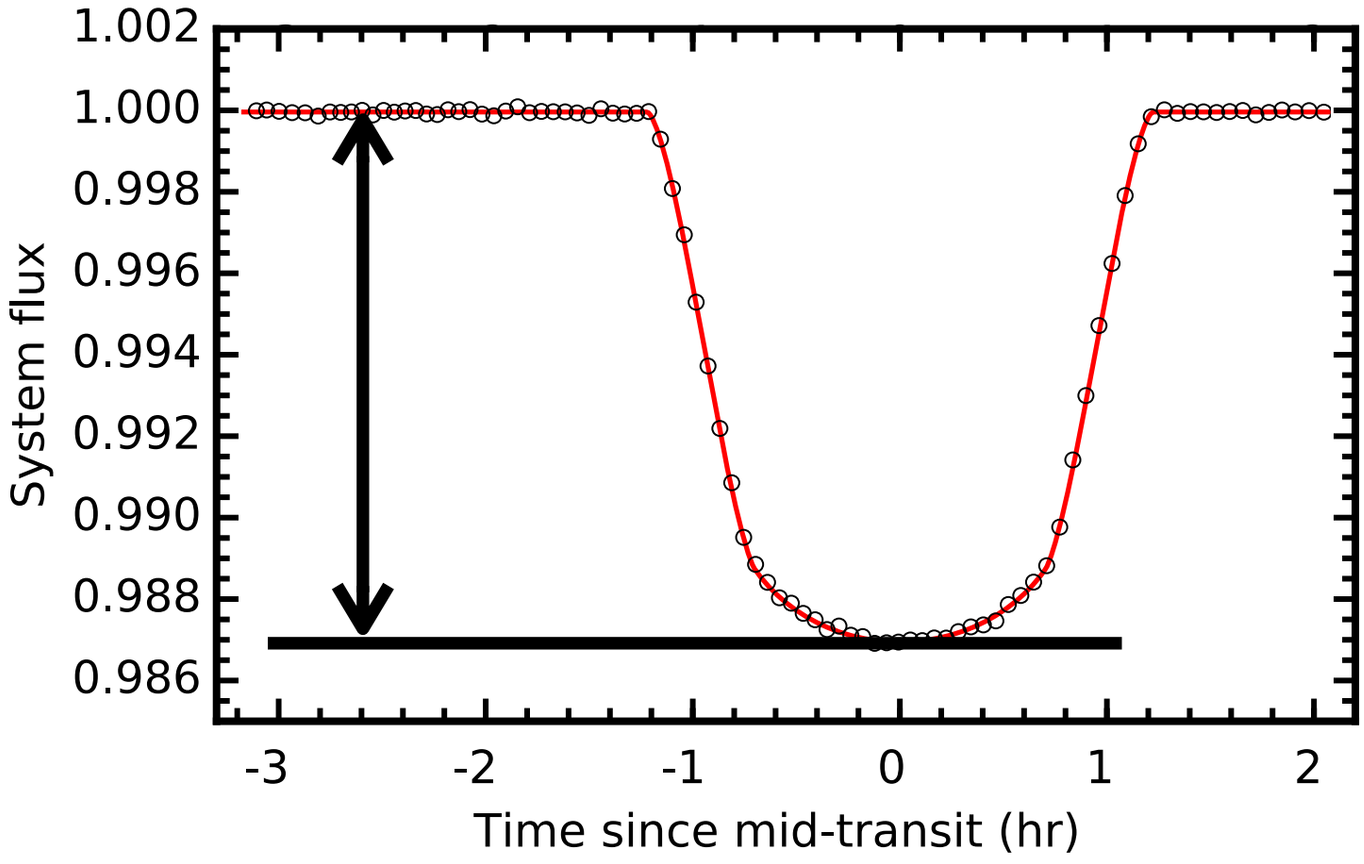

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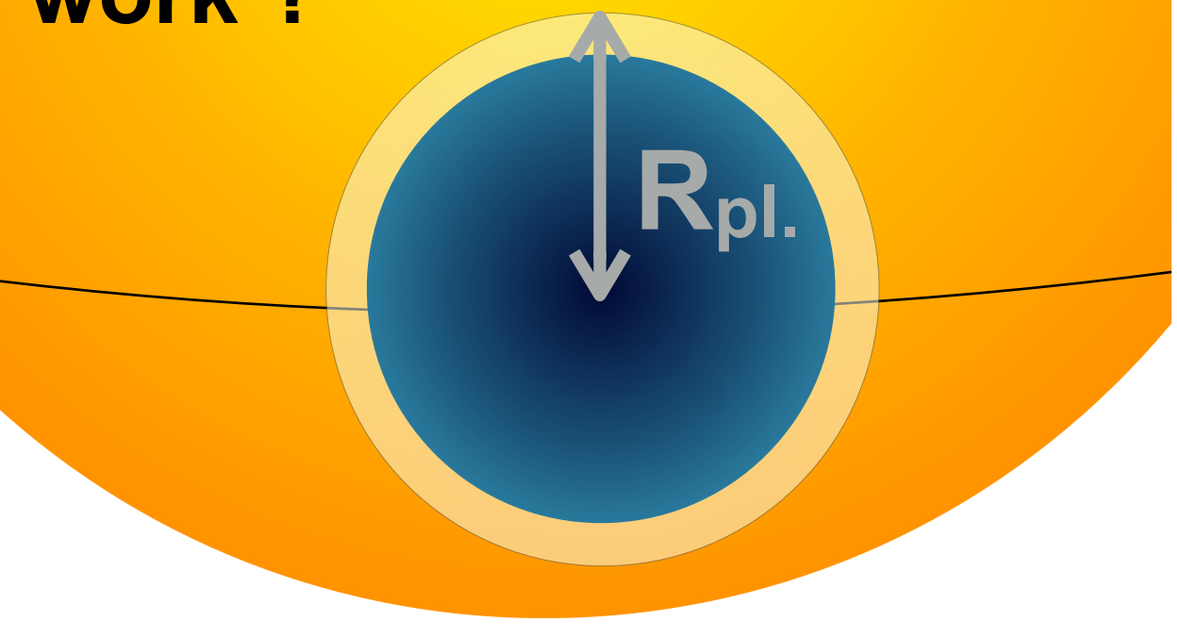

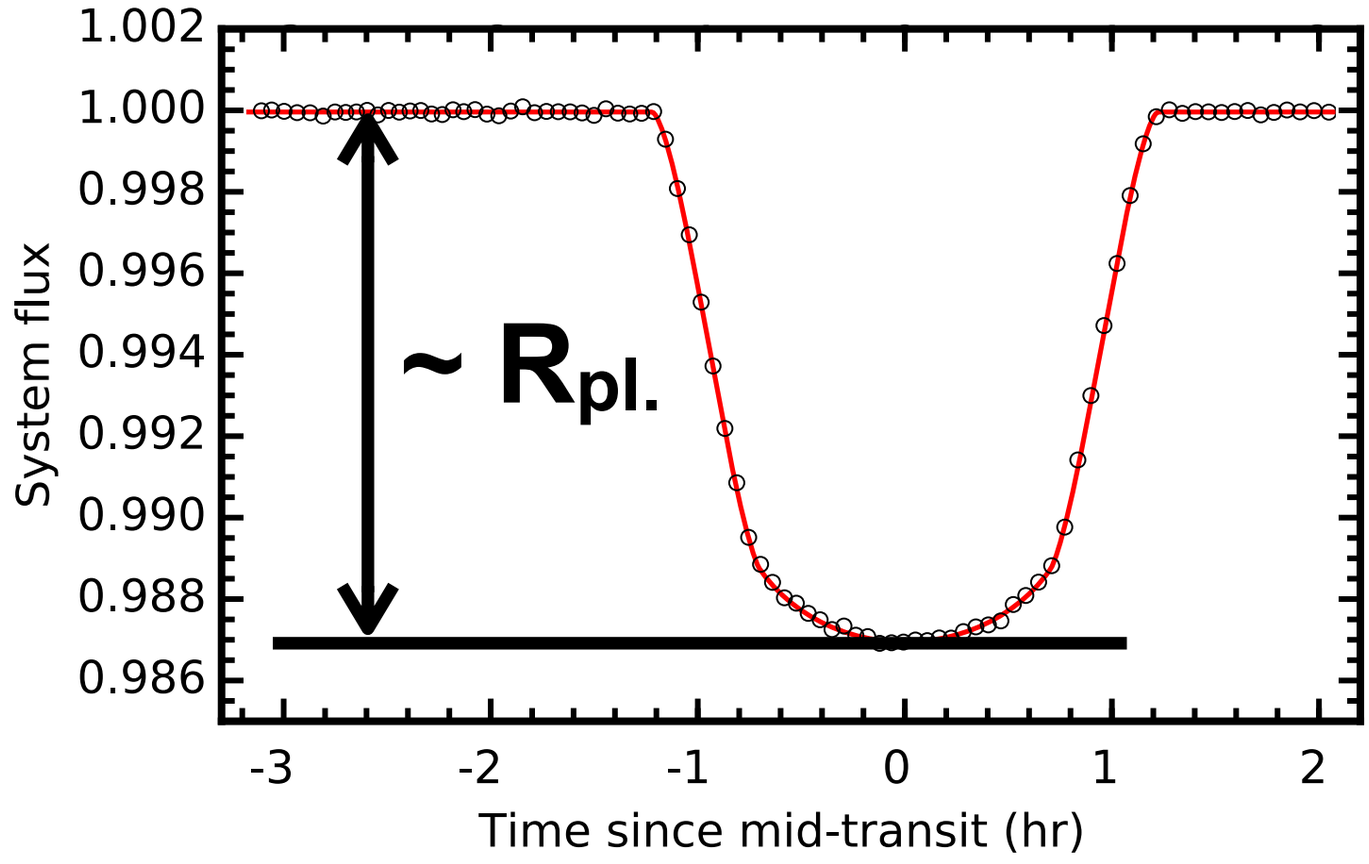

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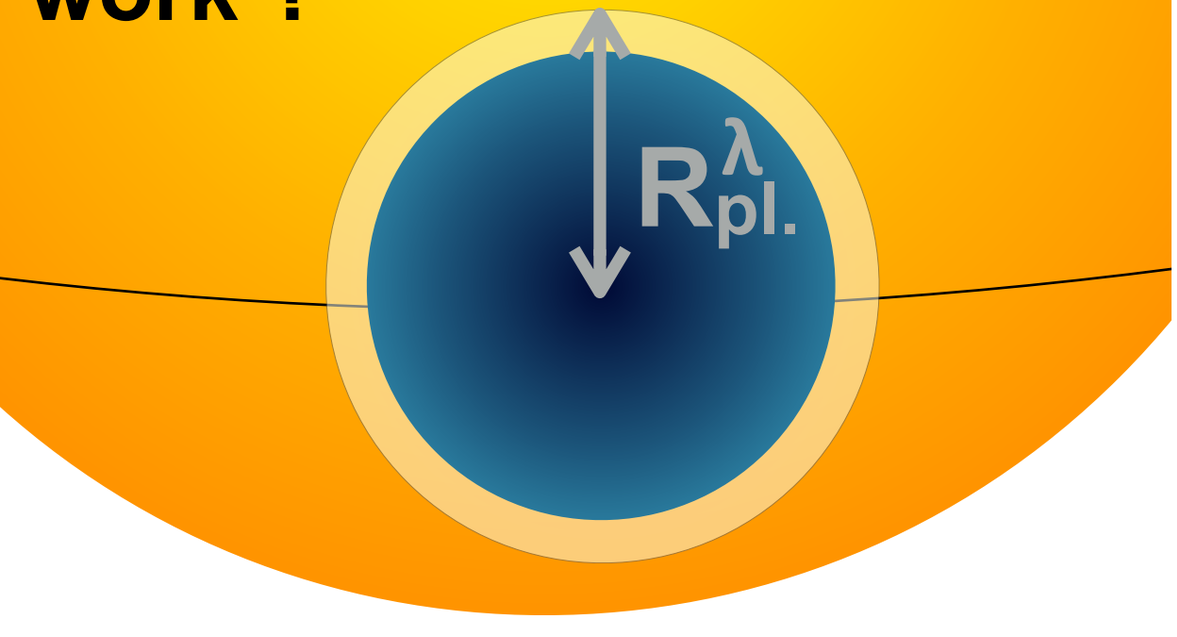

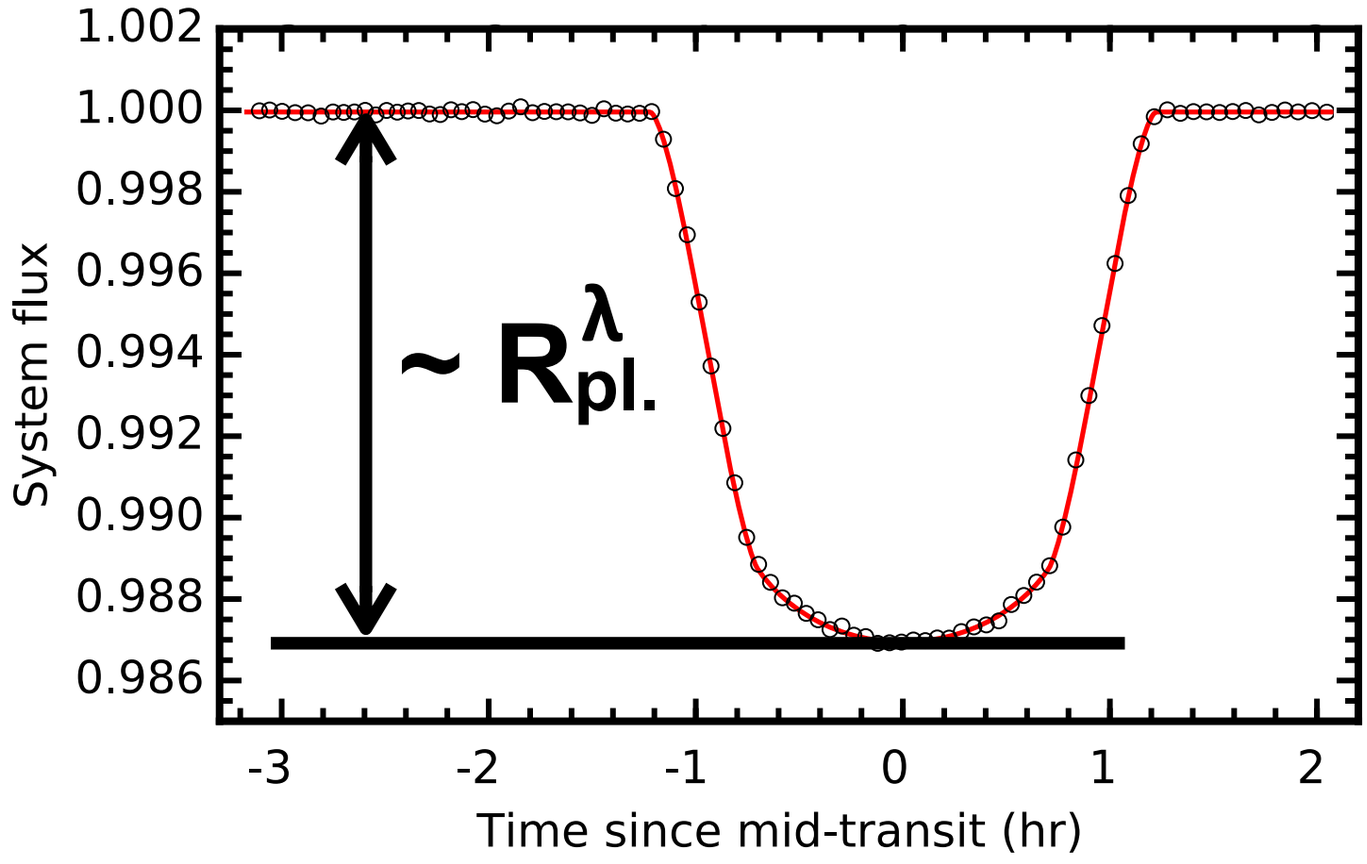

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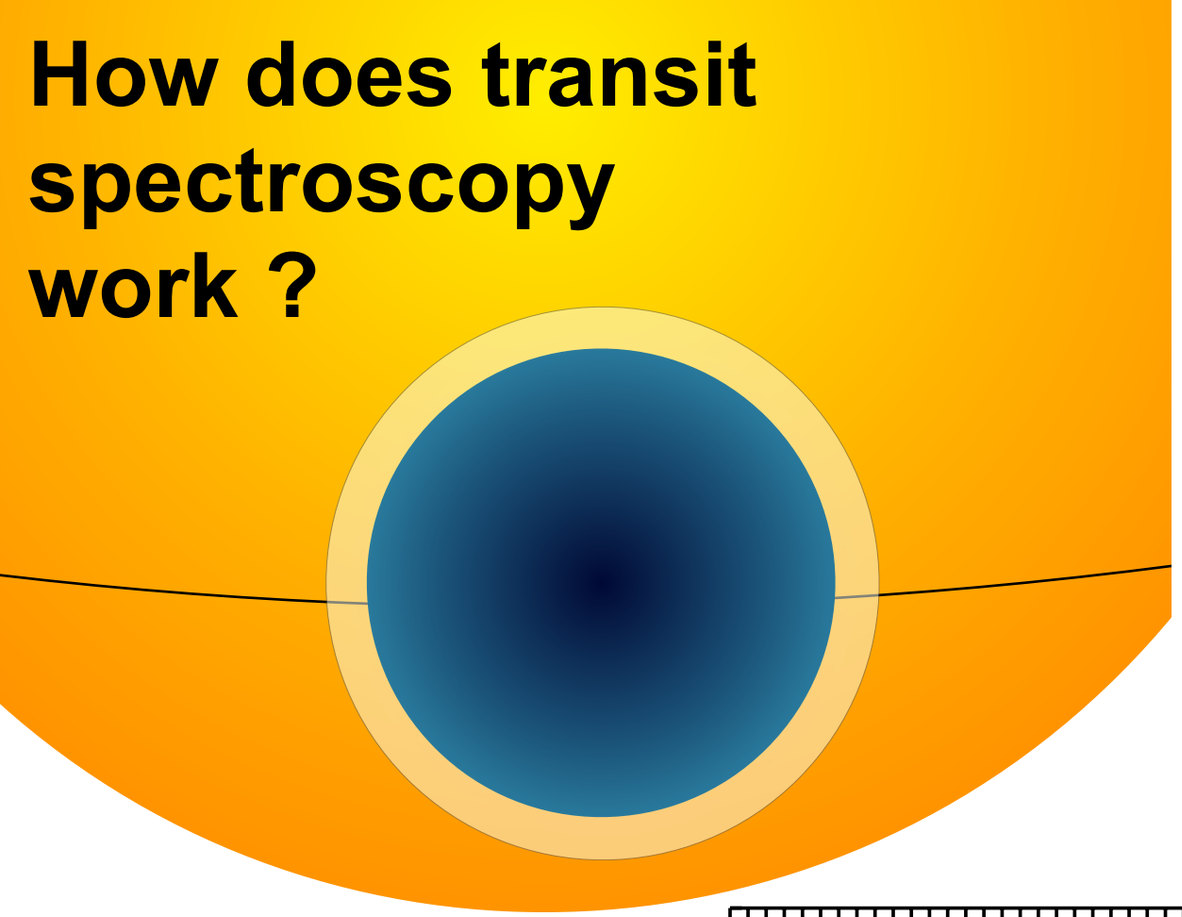

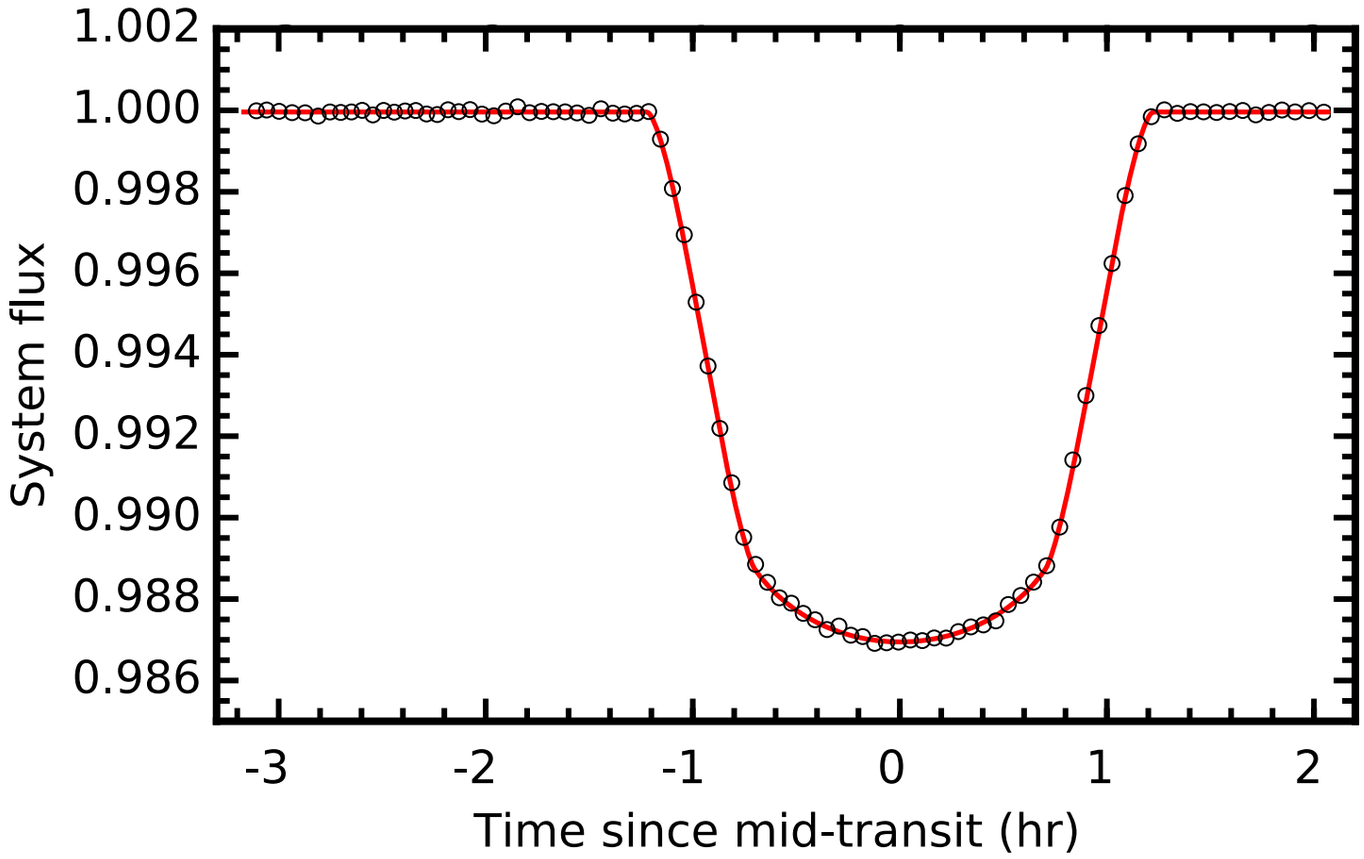

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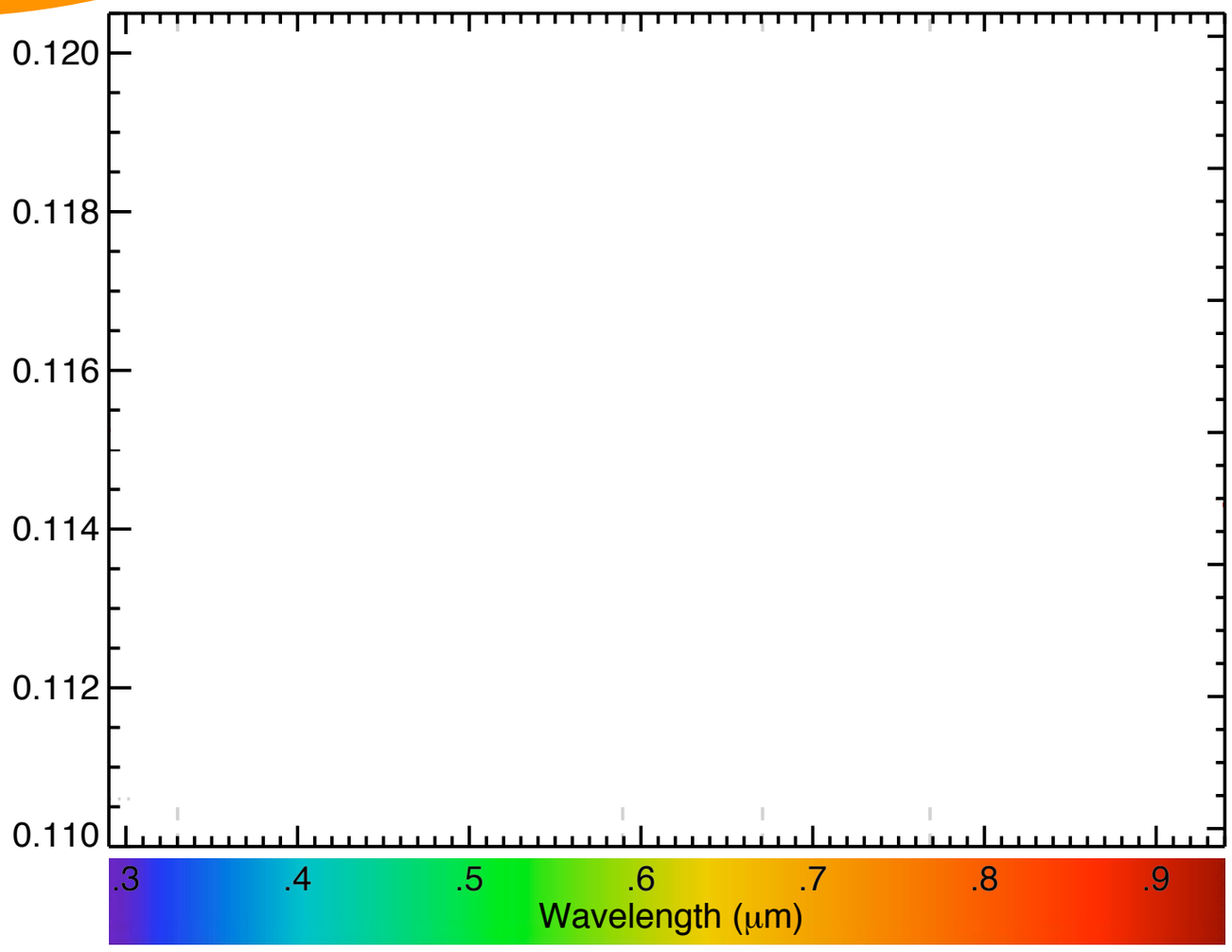

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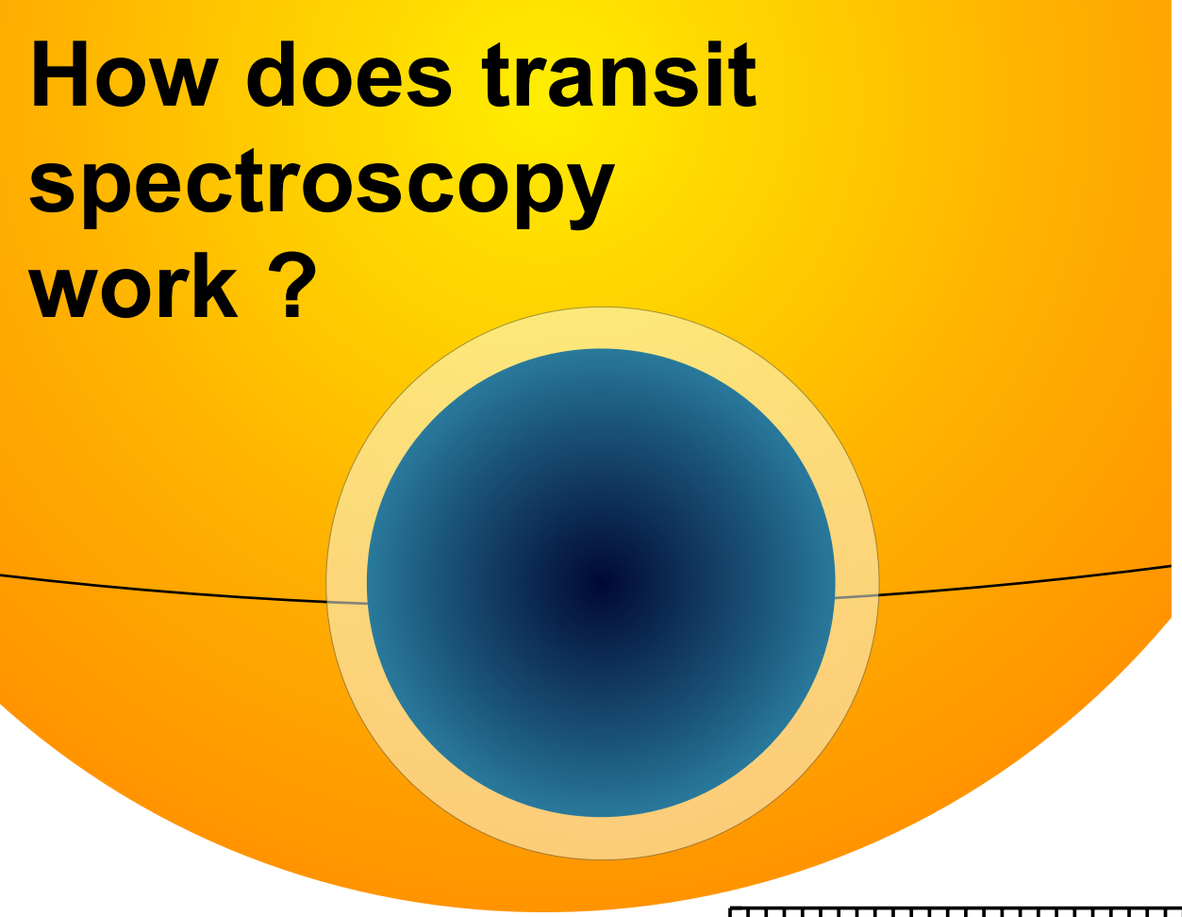

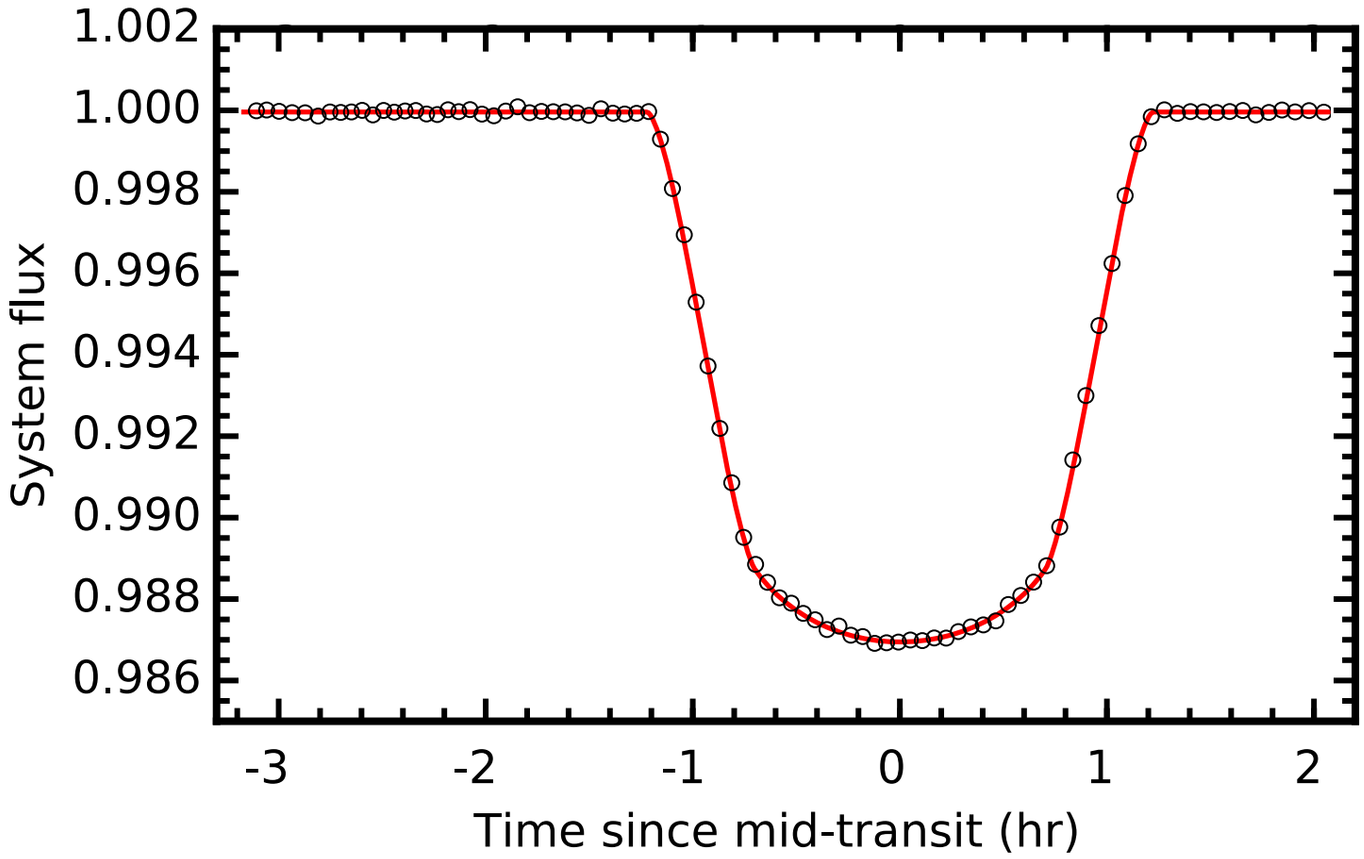

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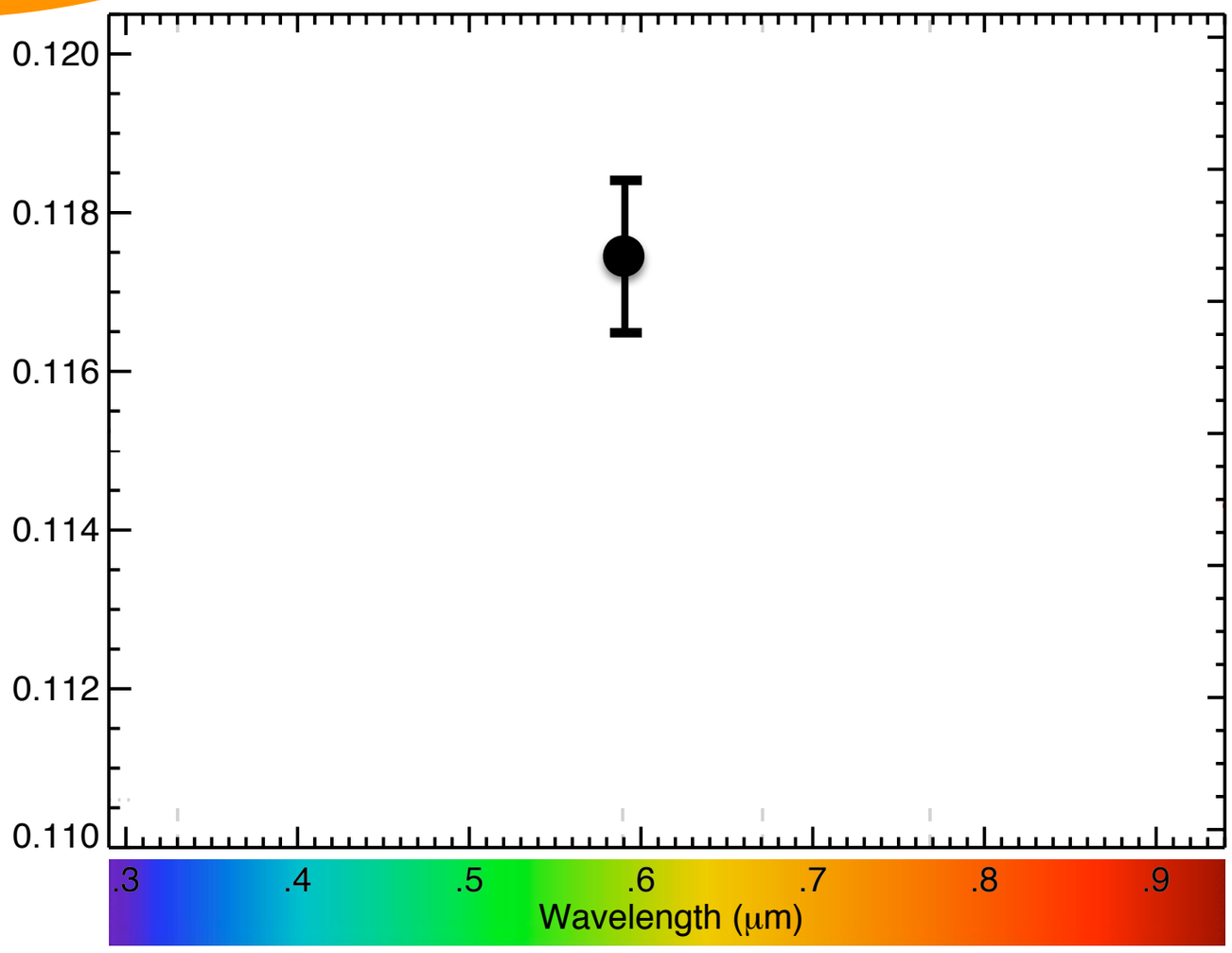

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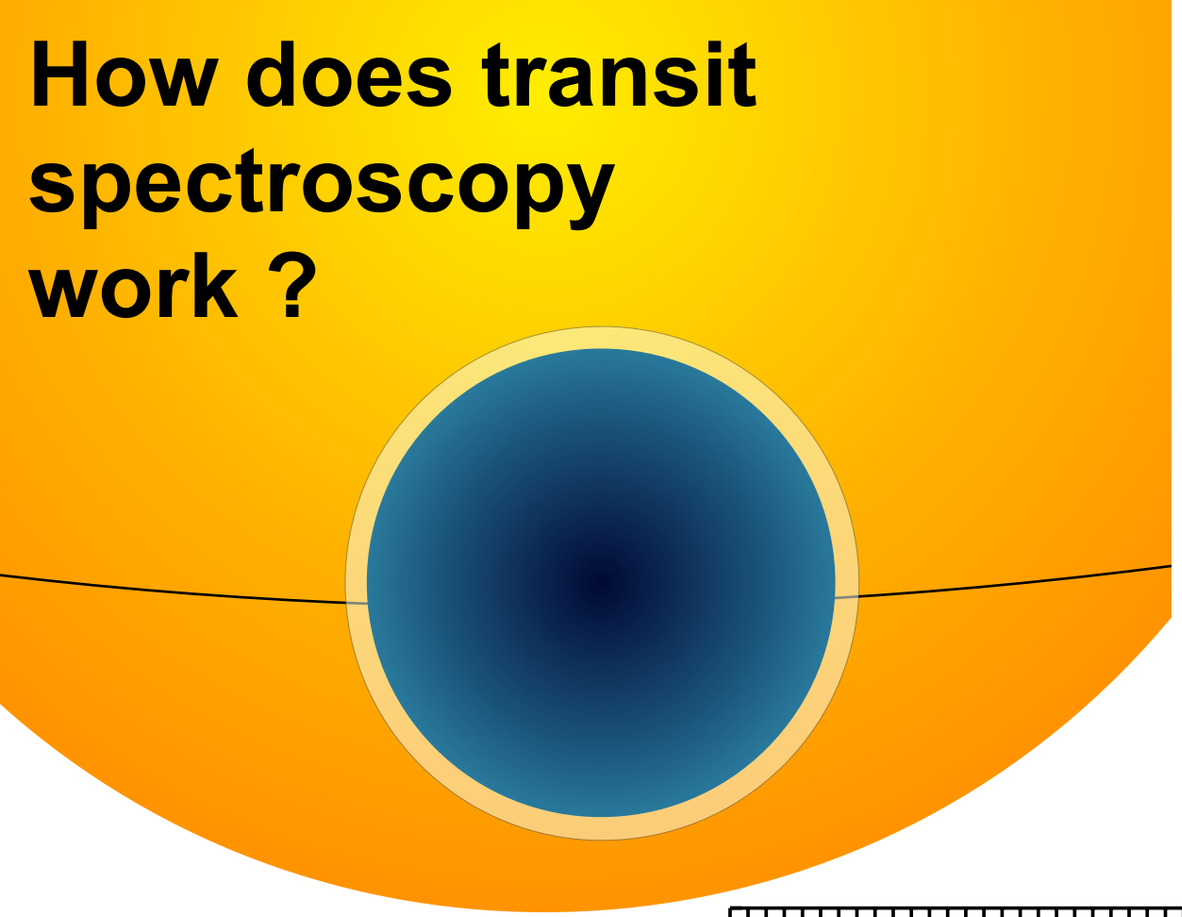

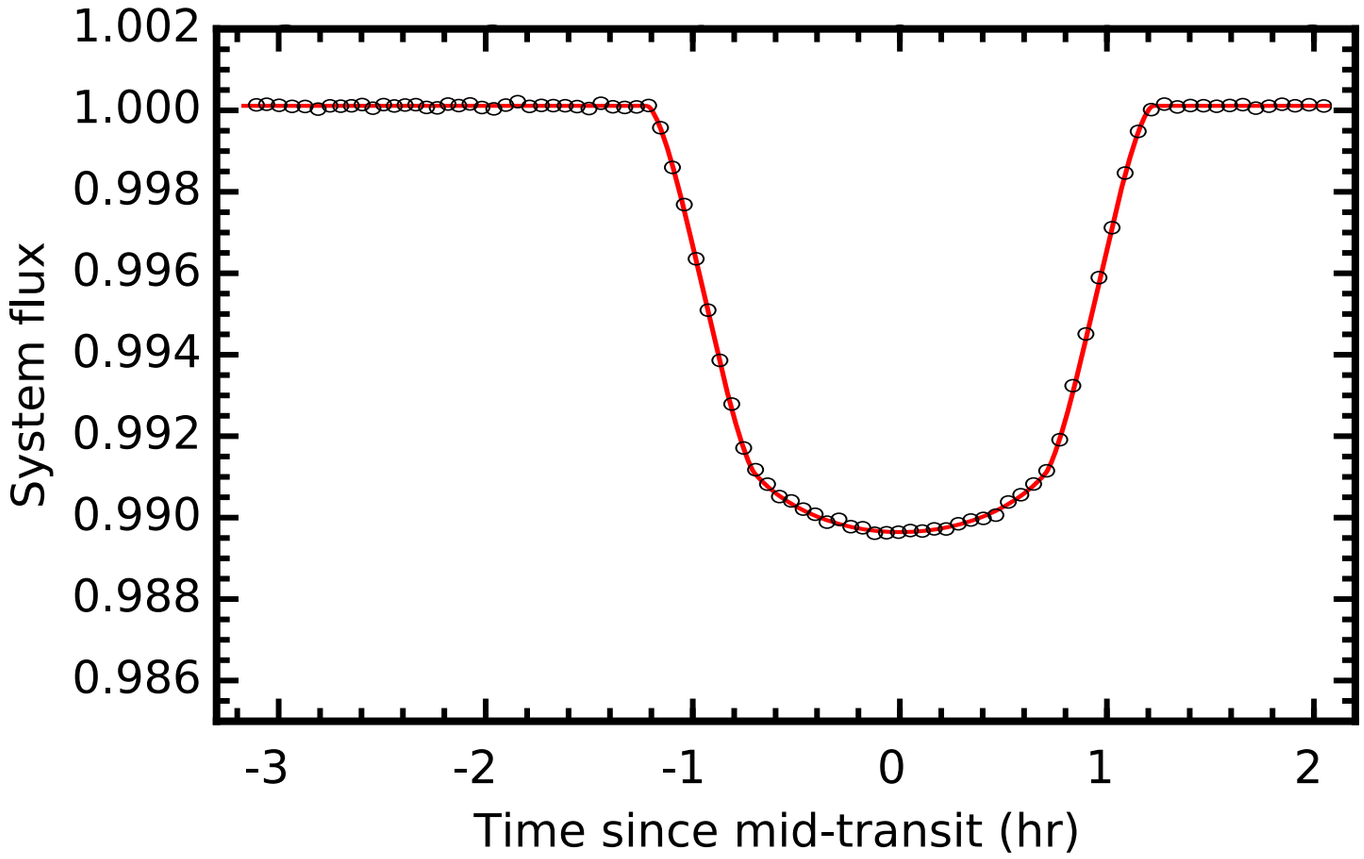

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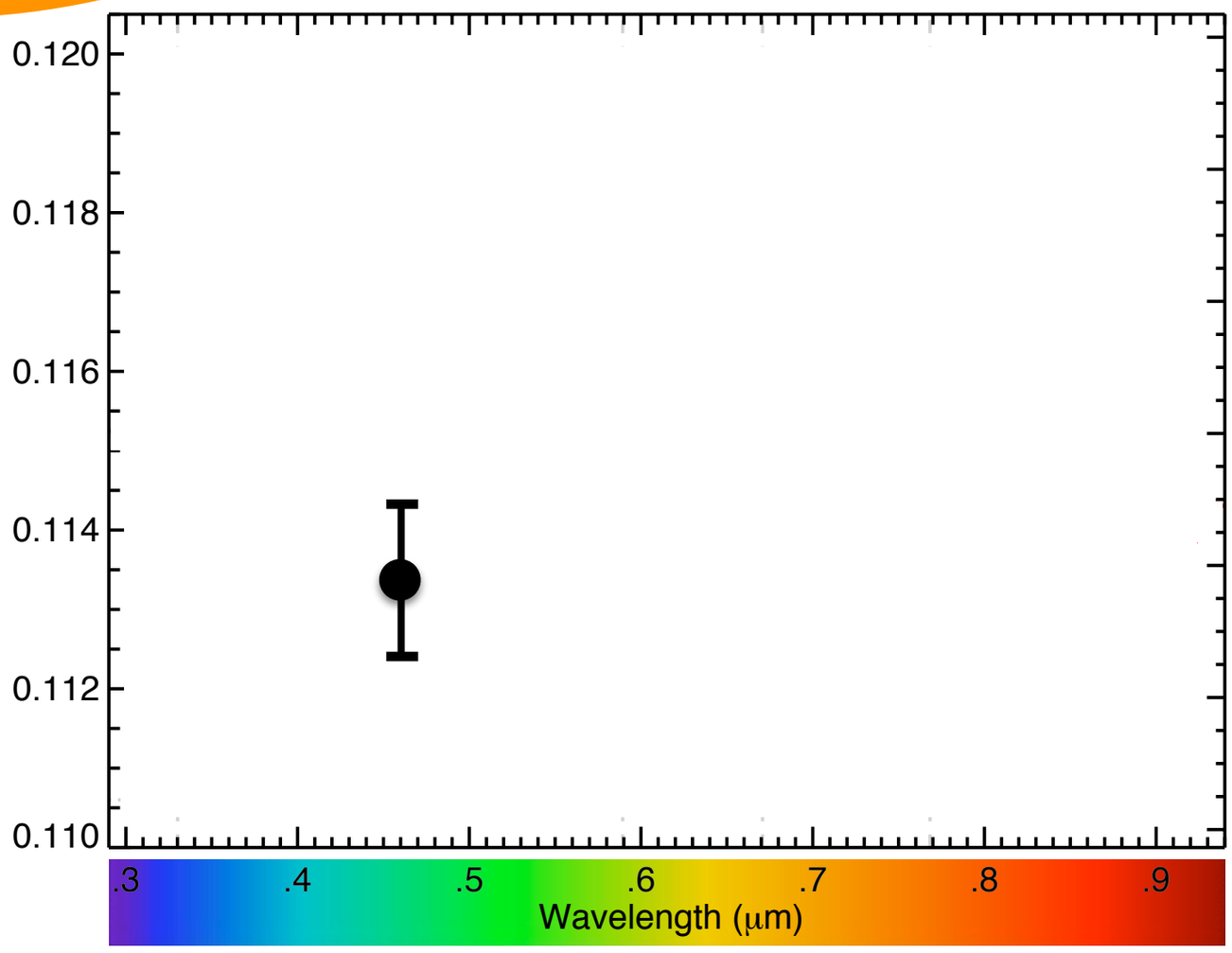

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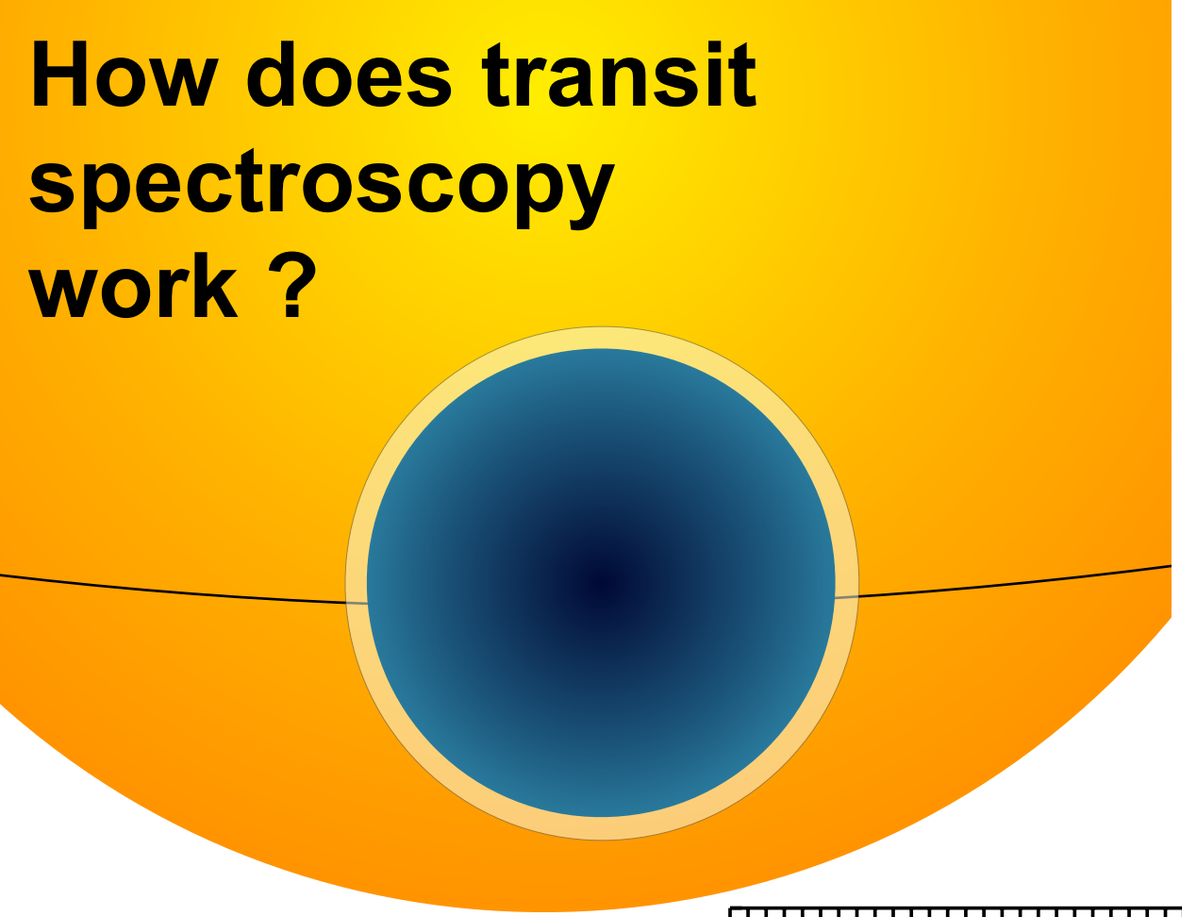

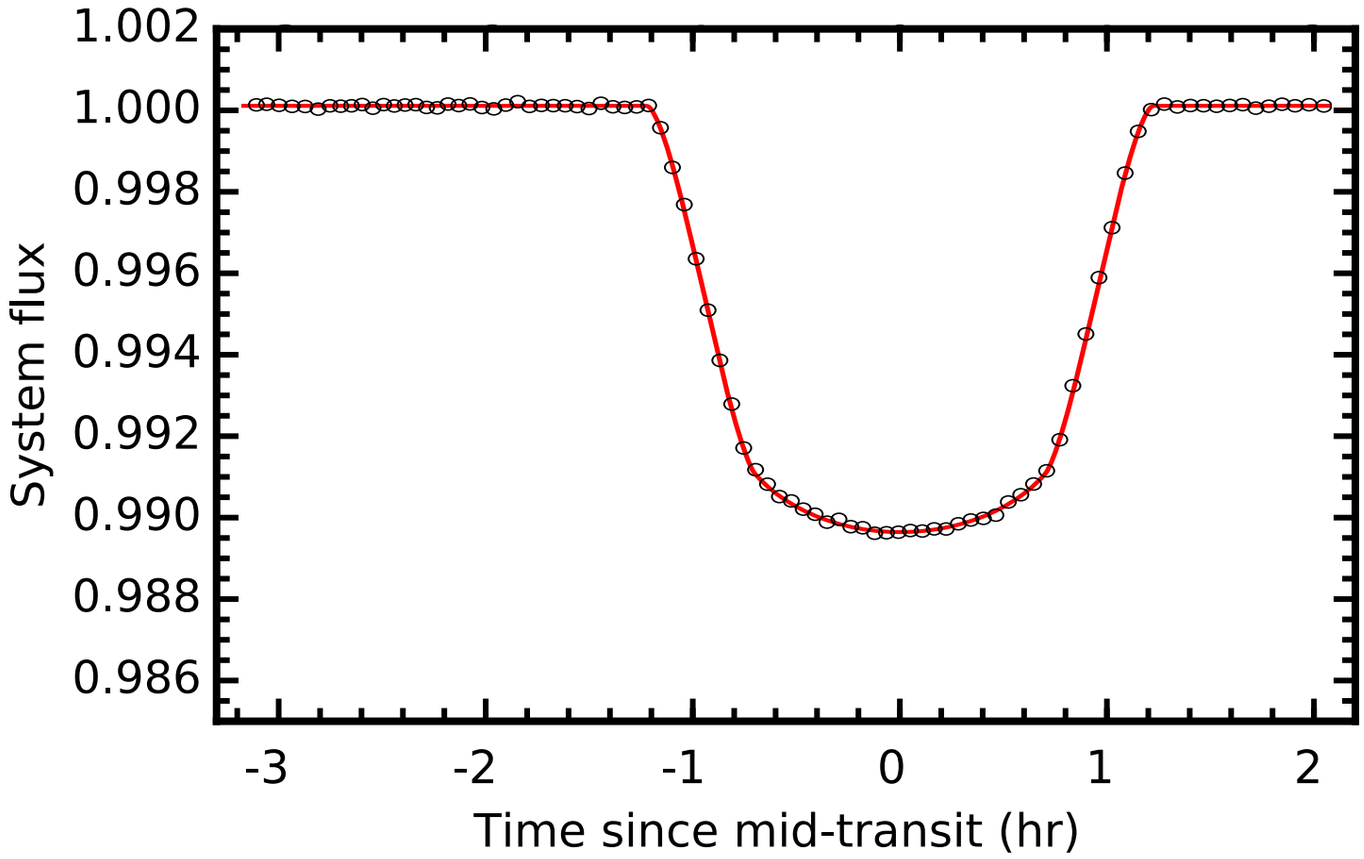

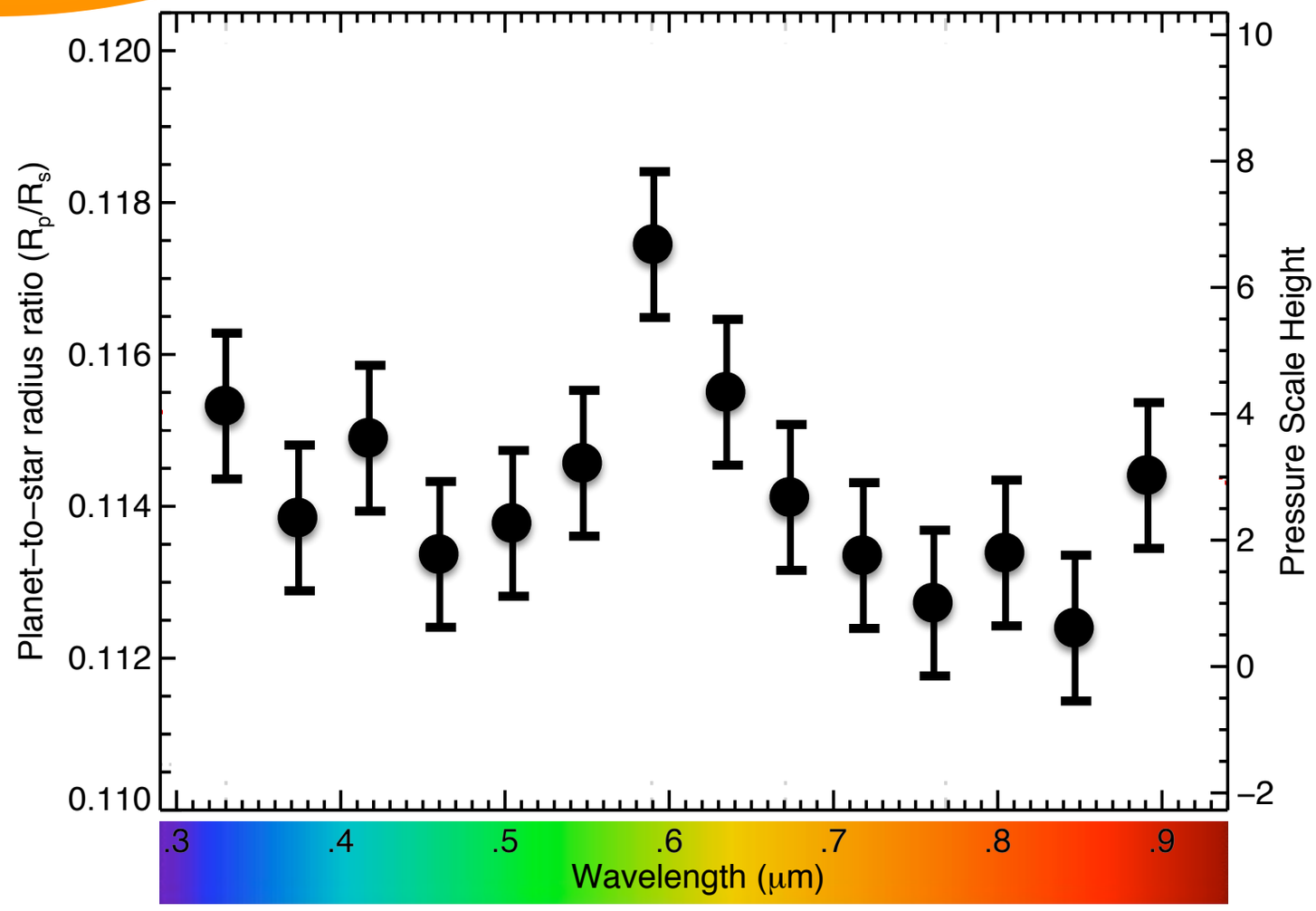

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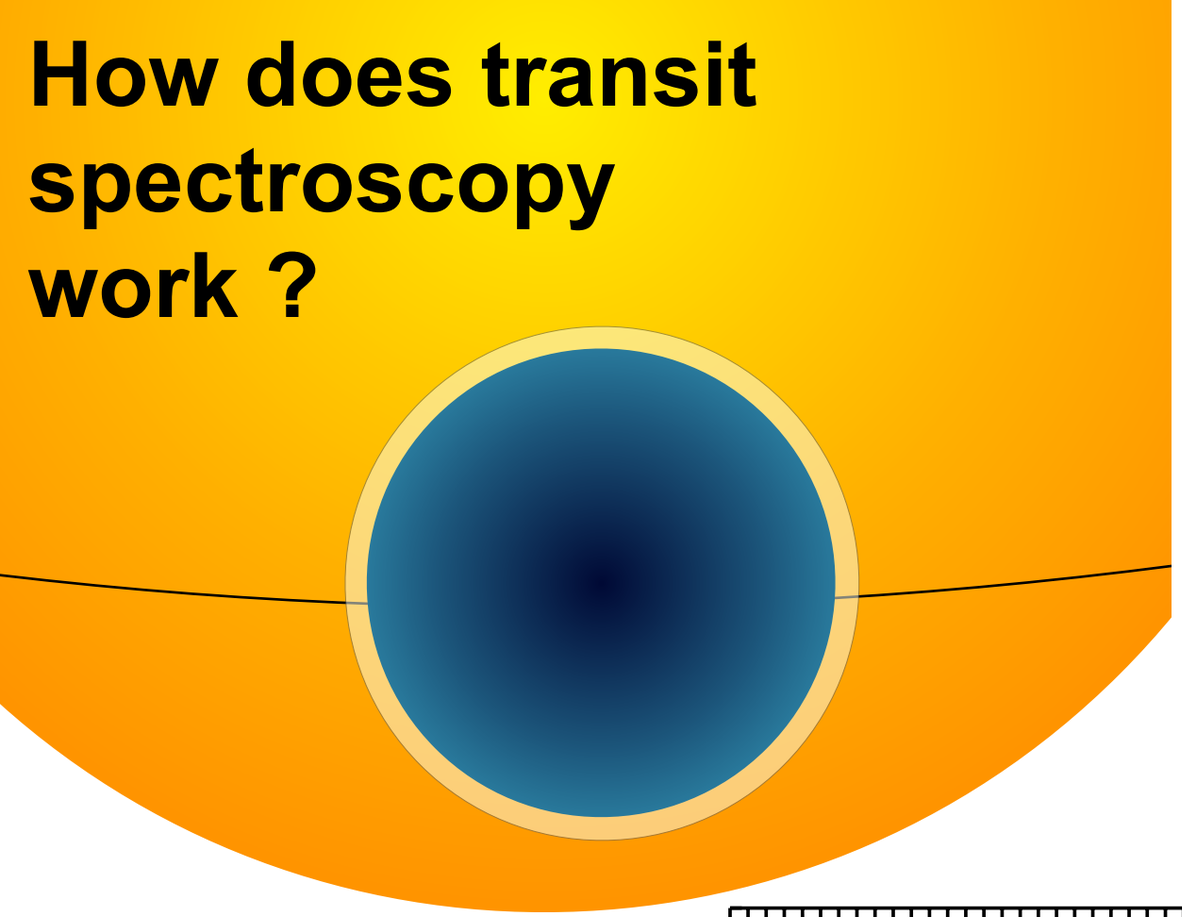

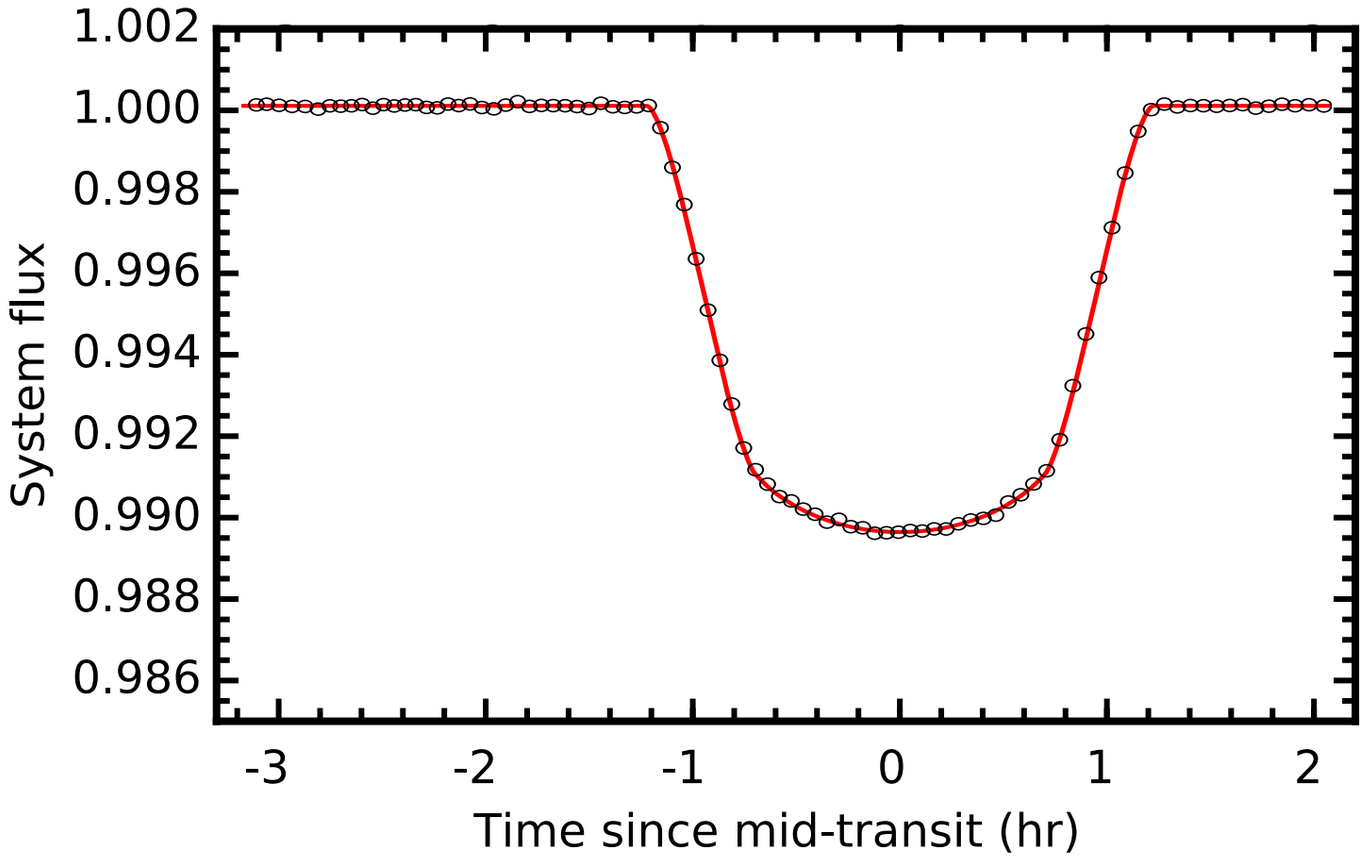

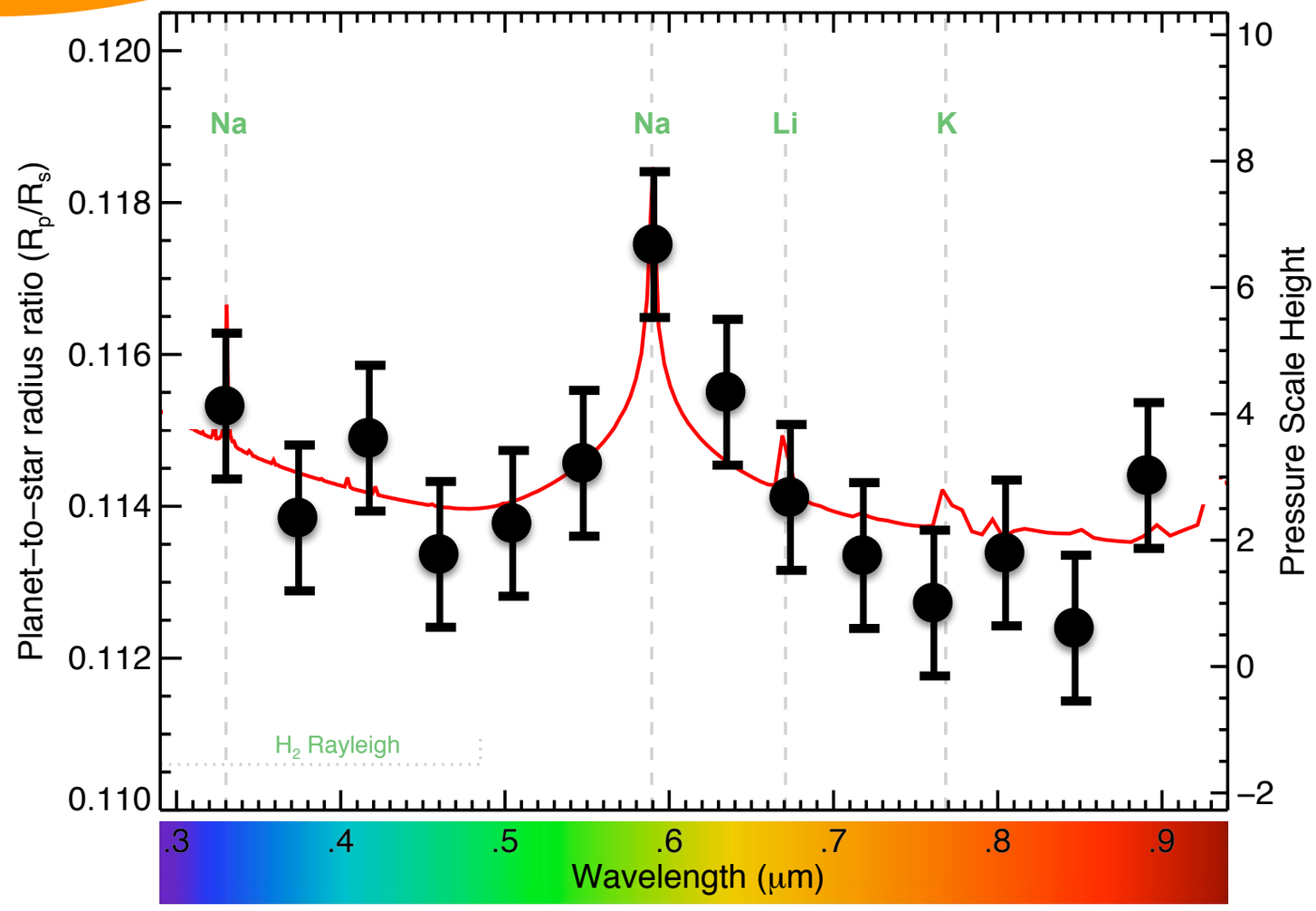

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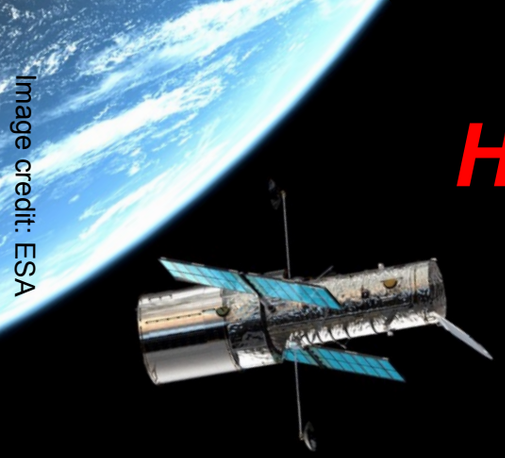


HST still plays a leading role in the exploration of exoplanet atmospheric diversity

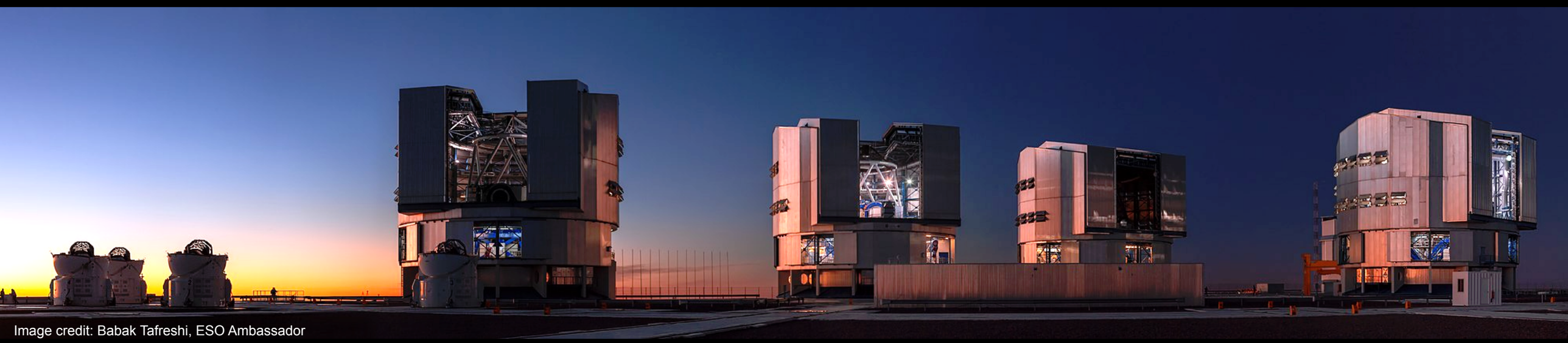
Comparative VLT FORS2 survey (**38hrs, PI Nikolov**)

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

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

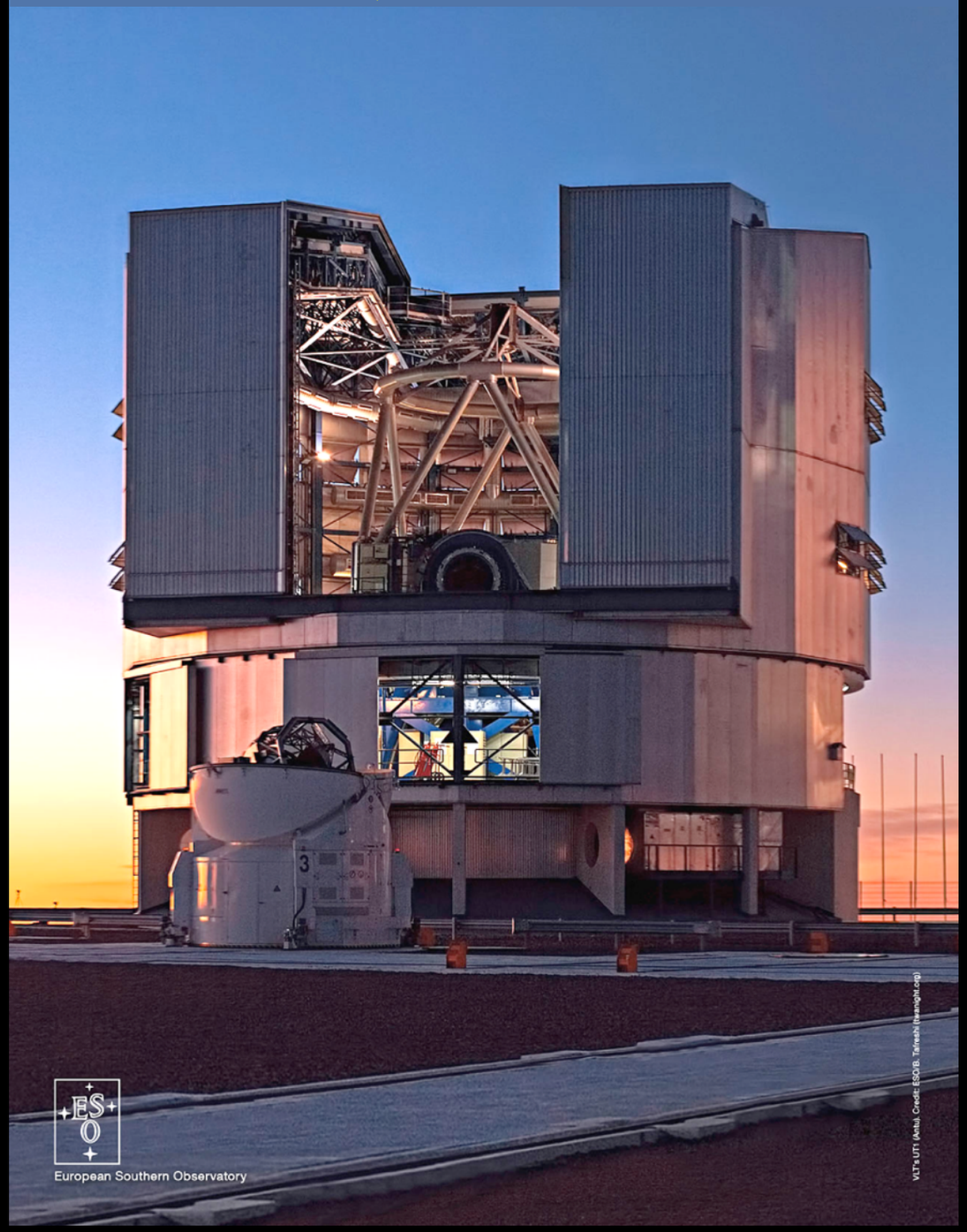
HST PanCET (**500 orbits, PIs Sing & Lopez Morales**)

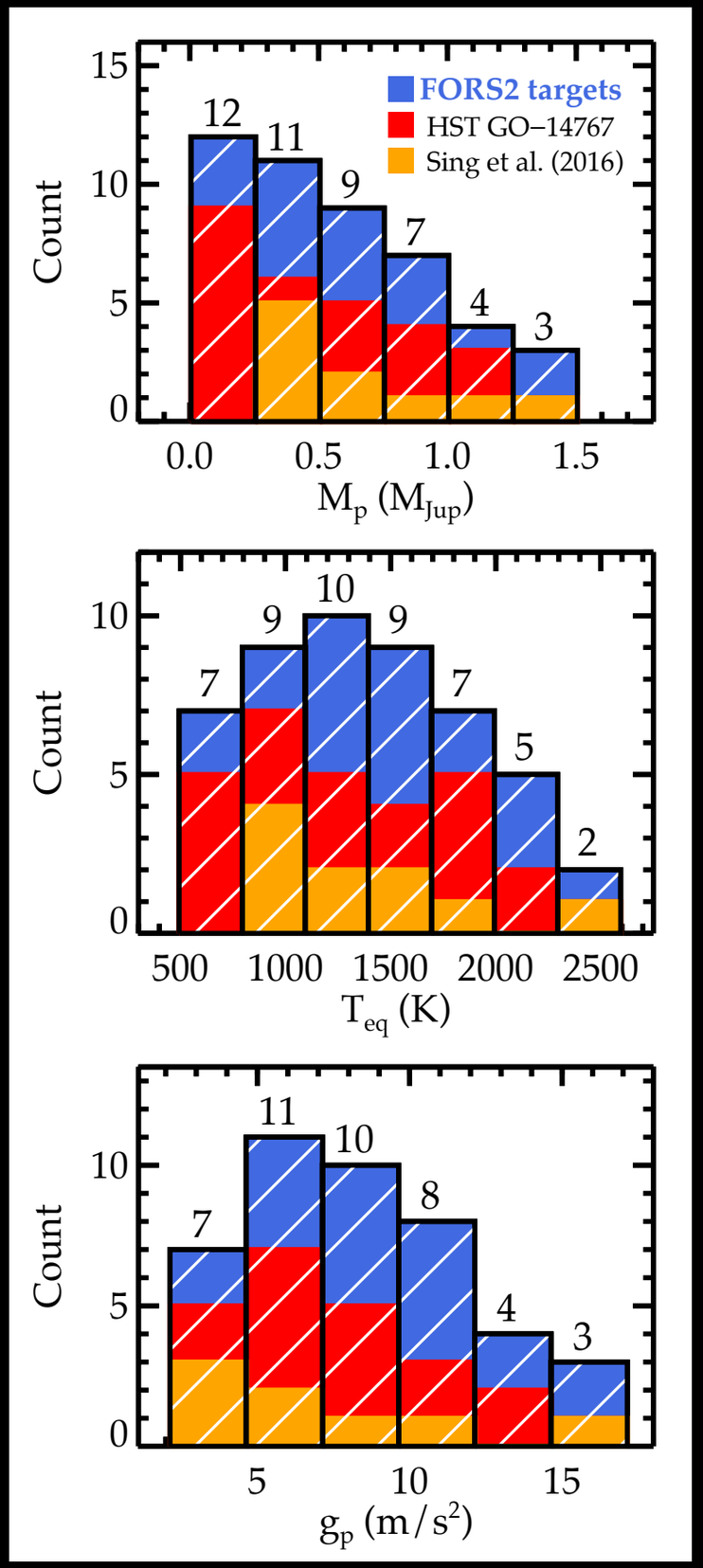
Significant progress from the ground too, notably with the *Very Large Telescope* (FORS2 and CRIRES)



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





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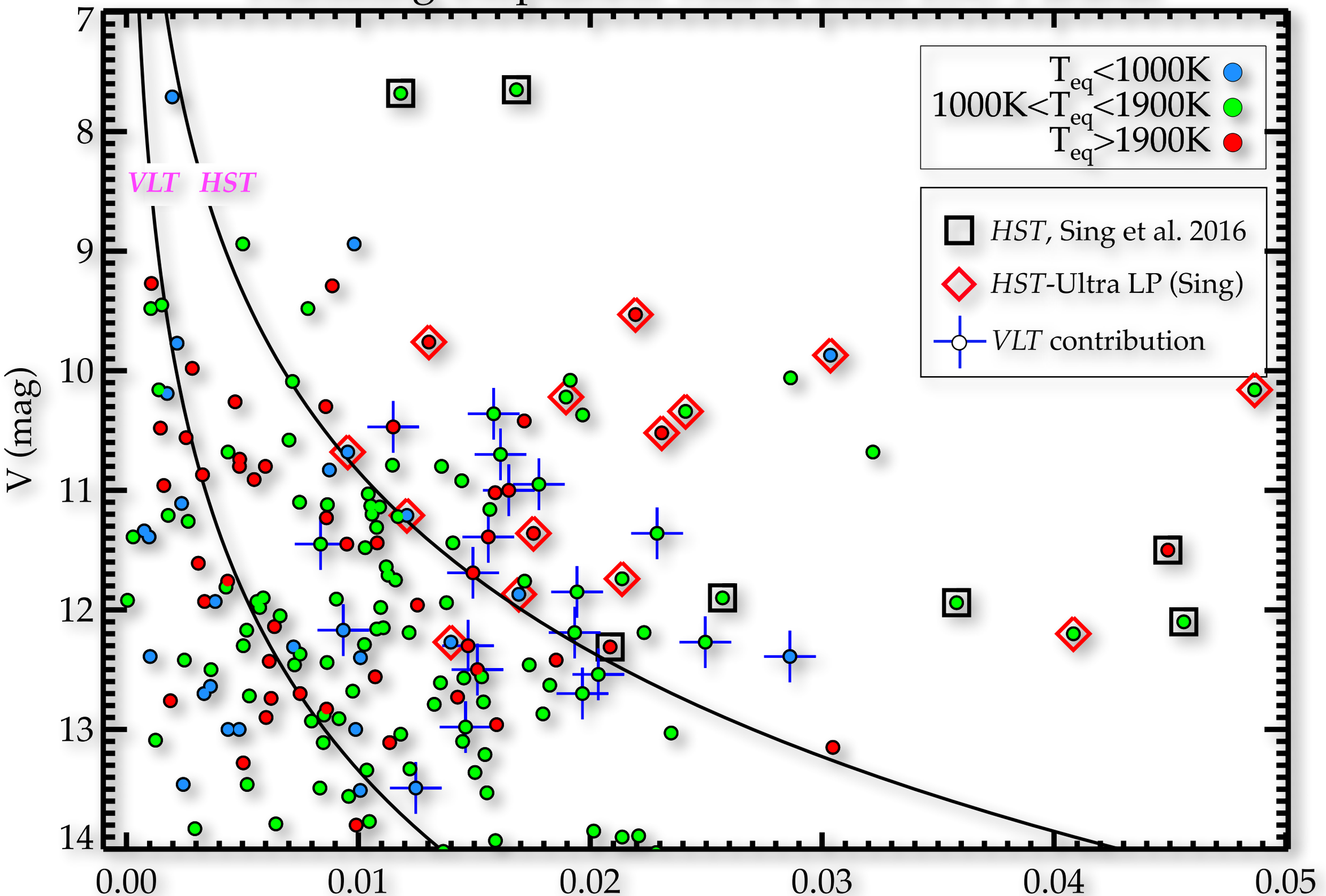
Transiting exoplanets visible from ESO Paranal



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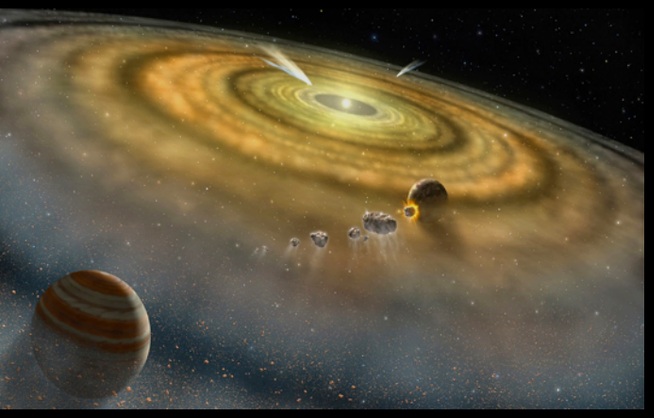
Major Exoplanet Science Questions



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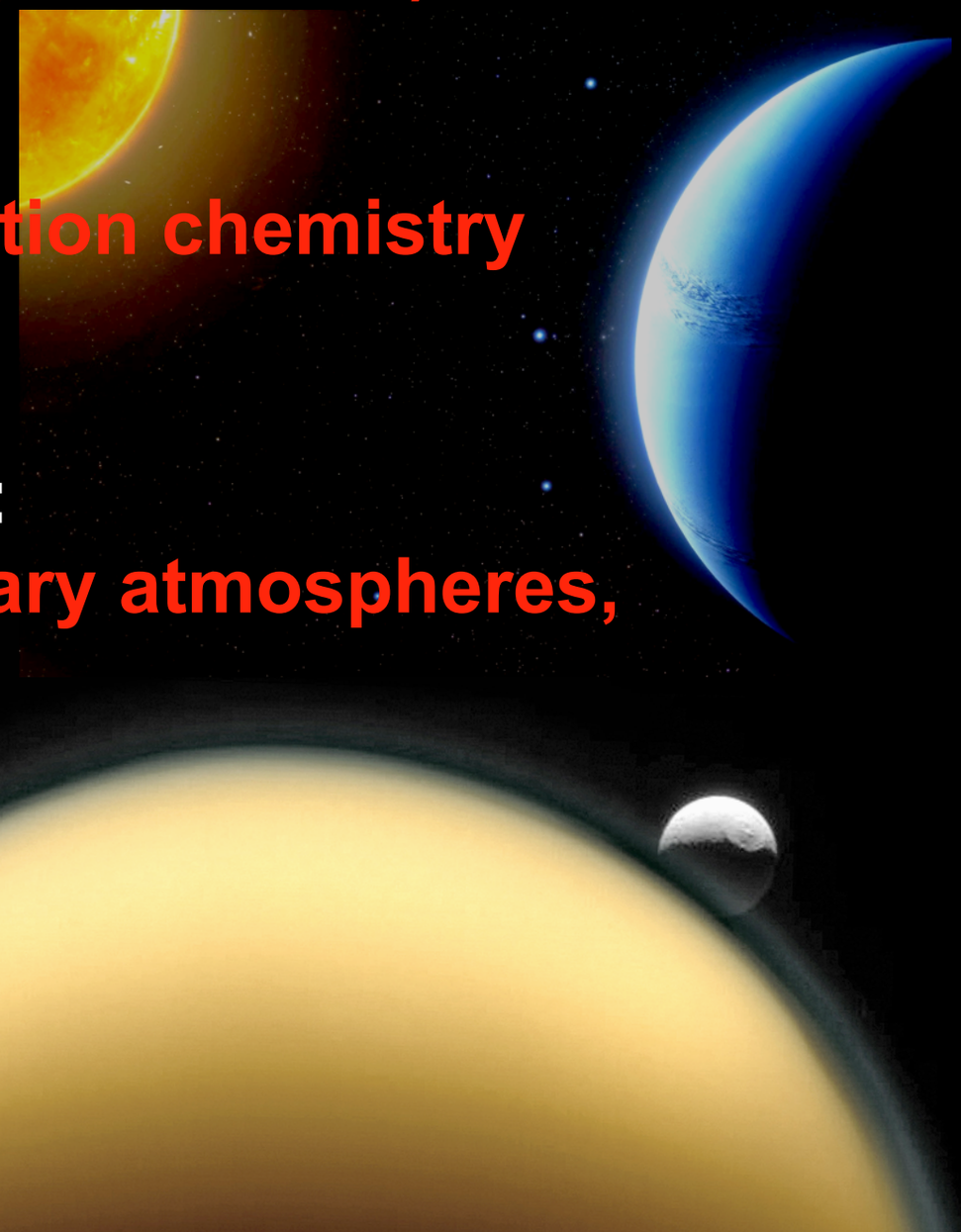
- **Clouds & hazes:**
  Occurrence, Condensation chemistry
  Photochemistry?



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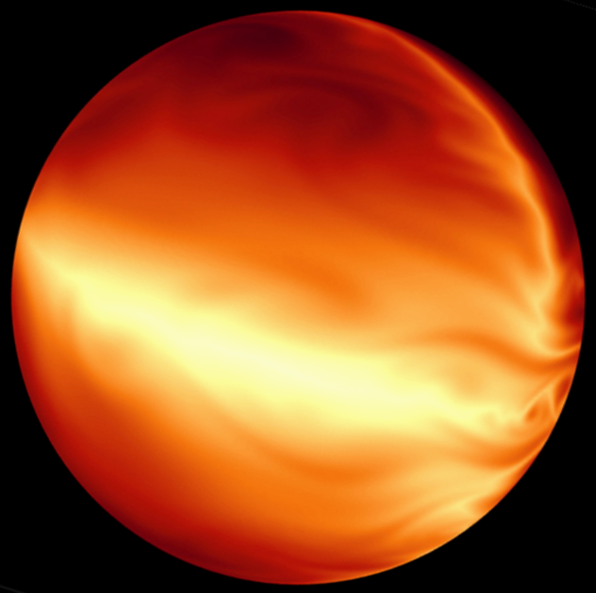
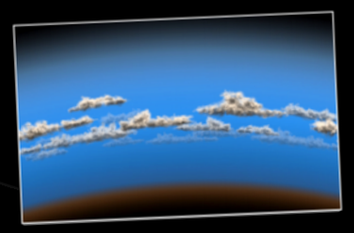
  primordial and secondary atmospheres, formation





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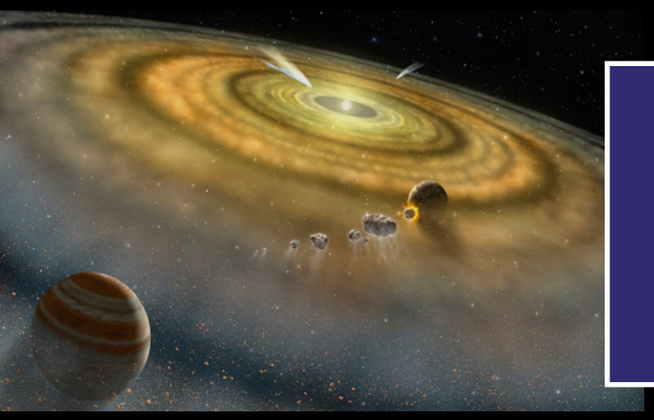

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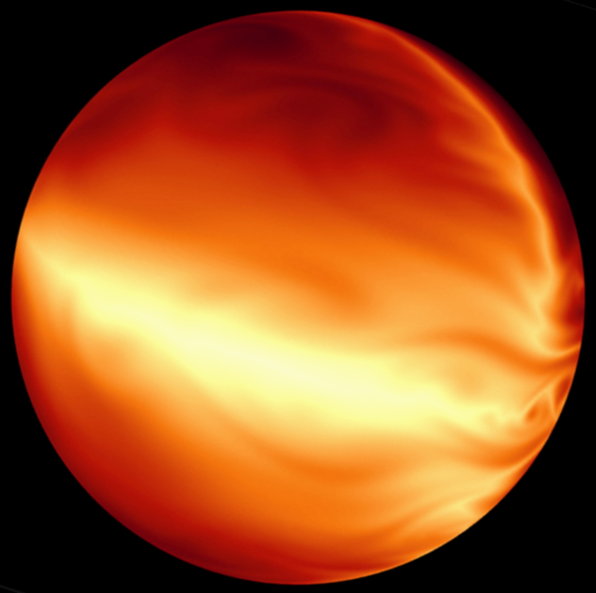

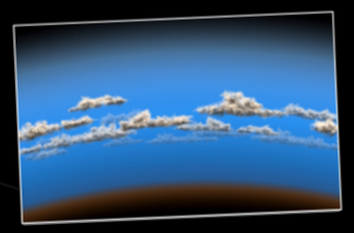

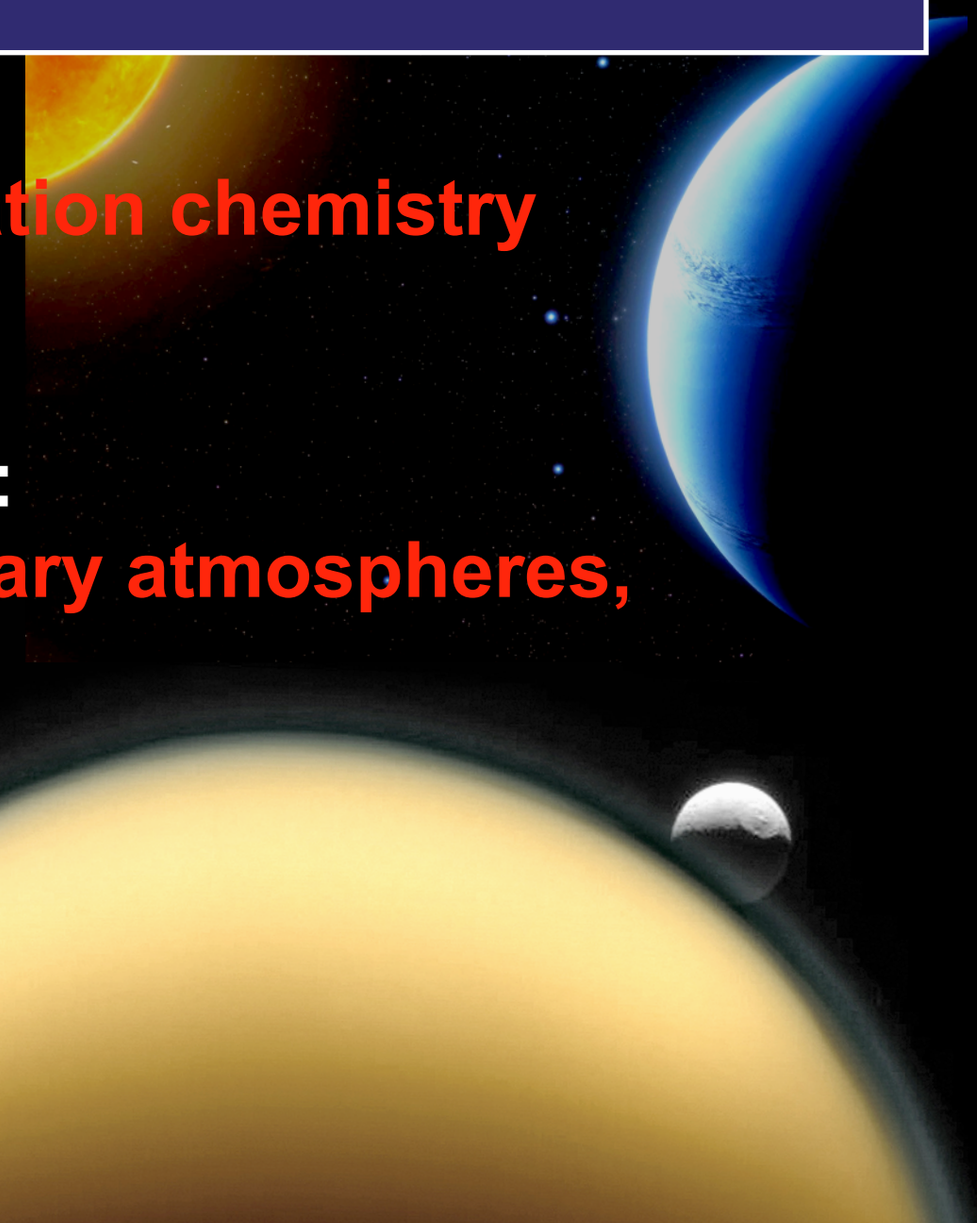

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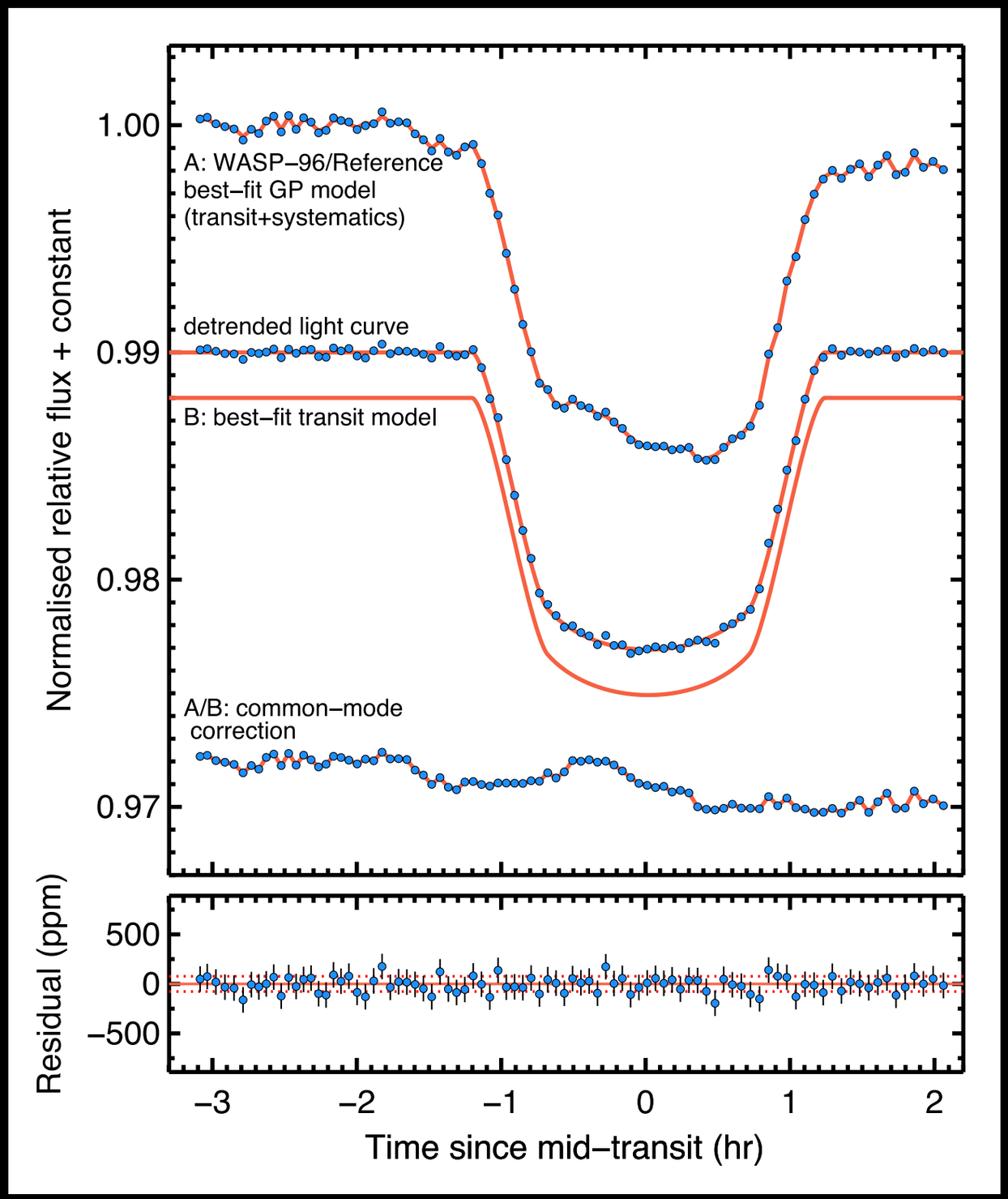
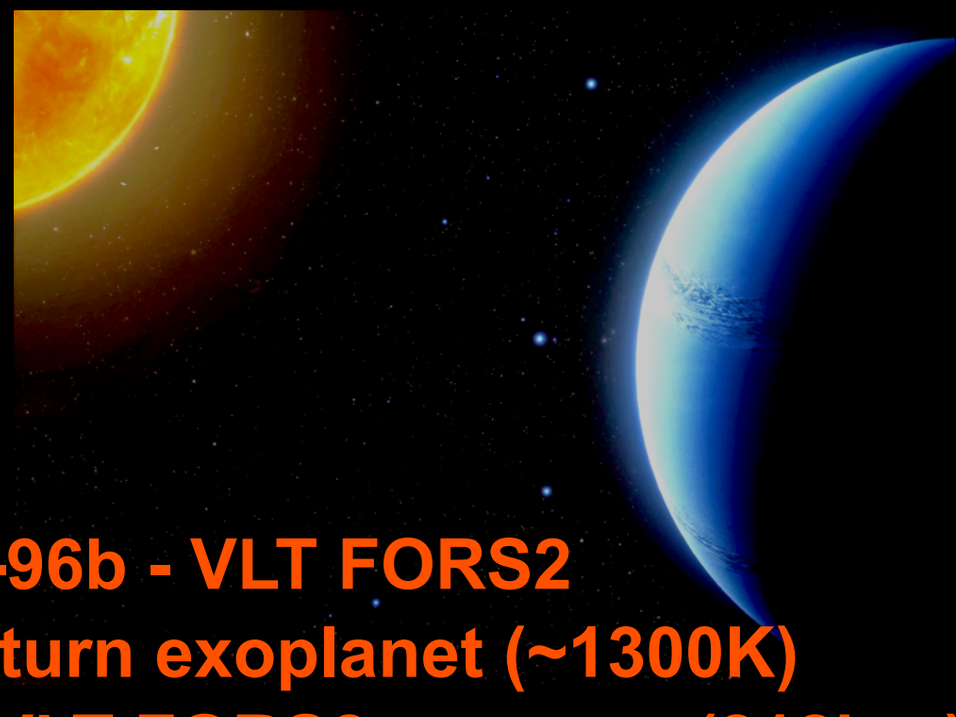
Absolute abundances and link with planet formation



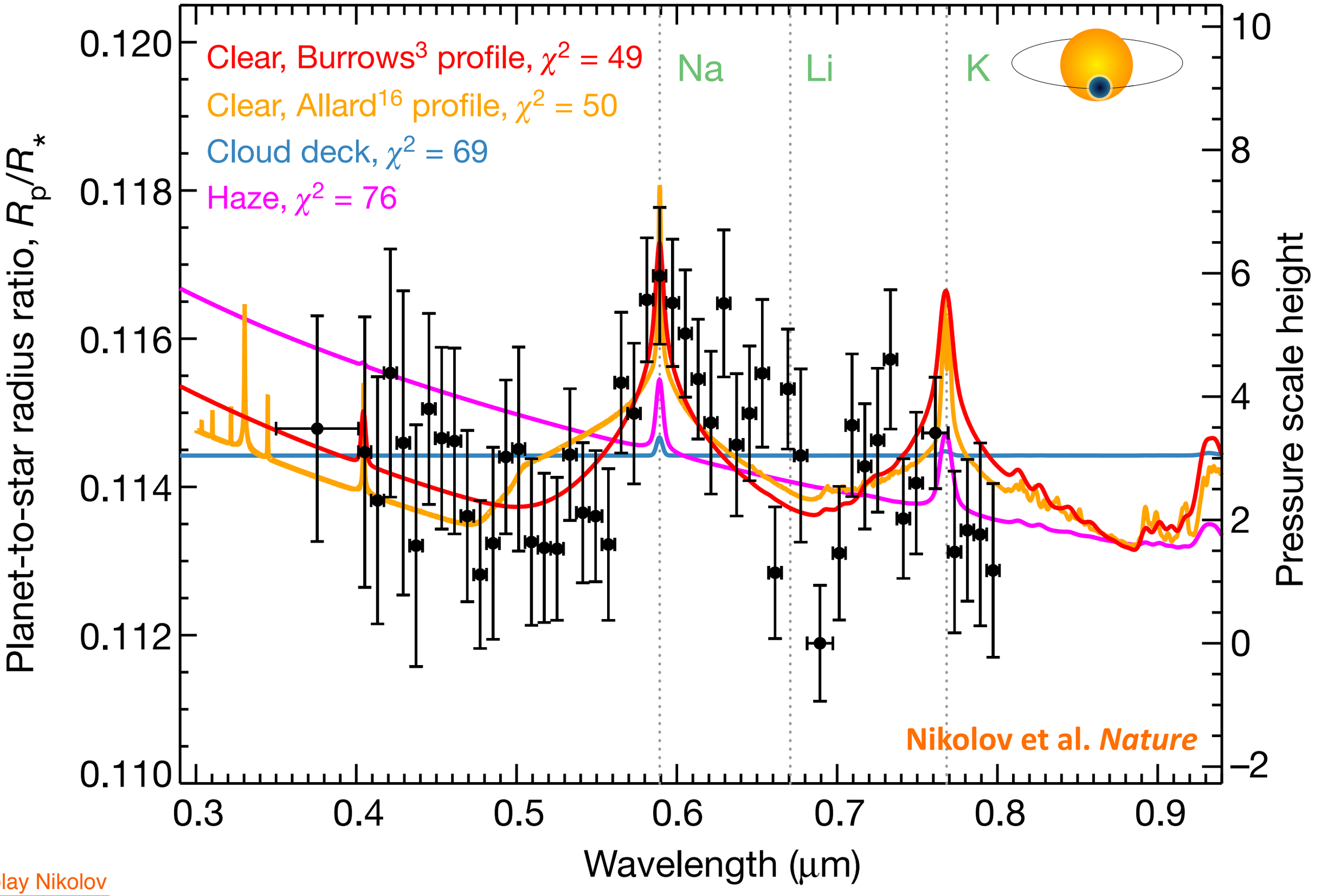
Nikolov et al. 2018, *Nature*



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) ~ -5



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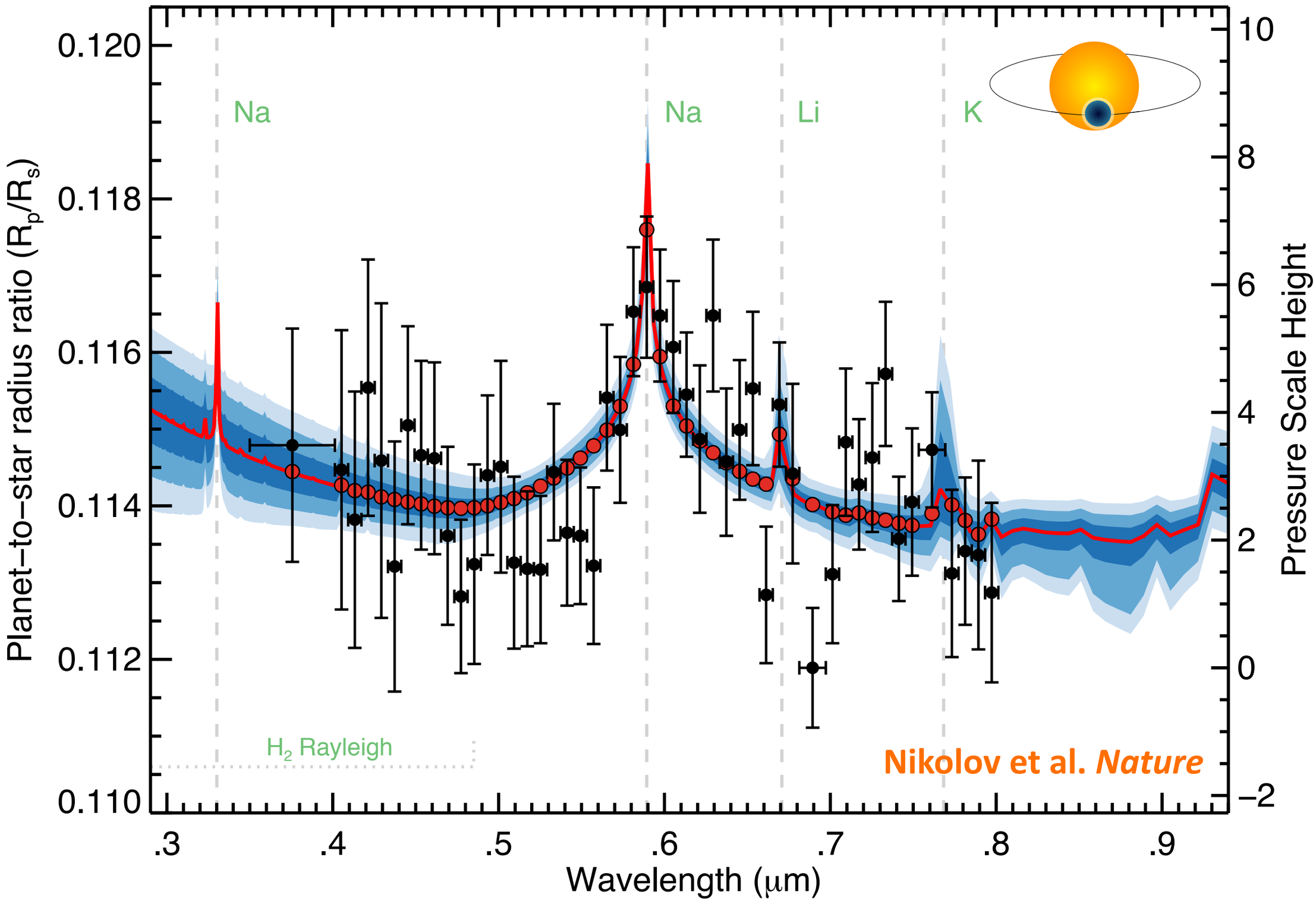
Detection of a *pressure-broadened* sodium line with VLT FORS2



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

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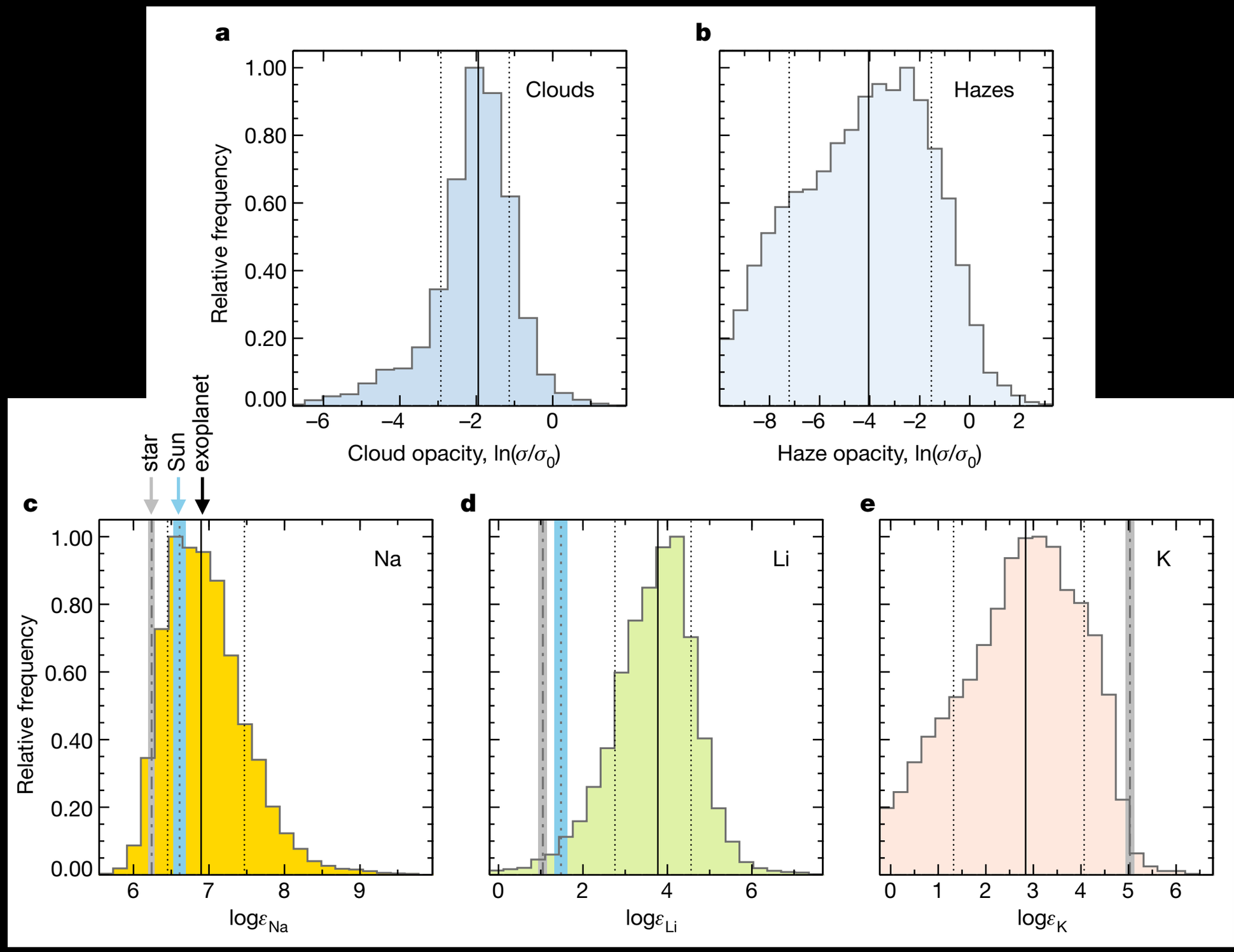
Blue-optical transmission spectra are the only way to constrain ABSOLUTE abundances for exoplanets



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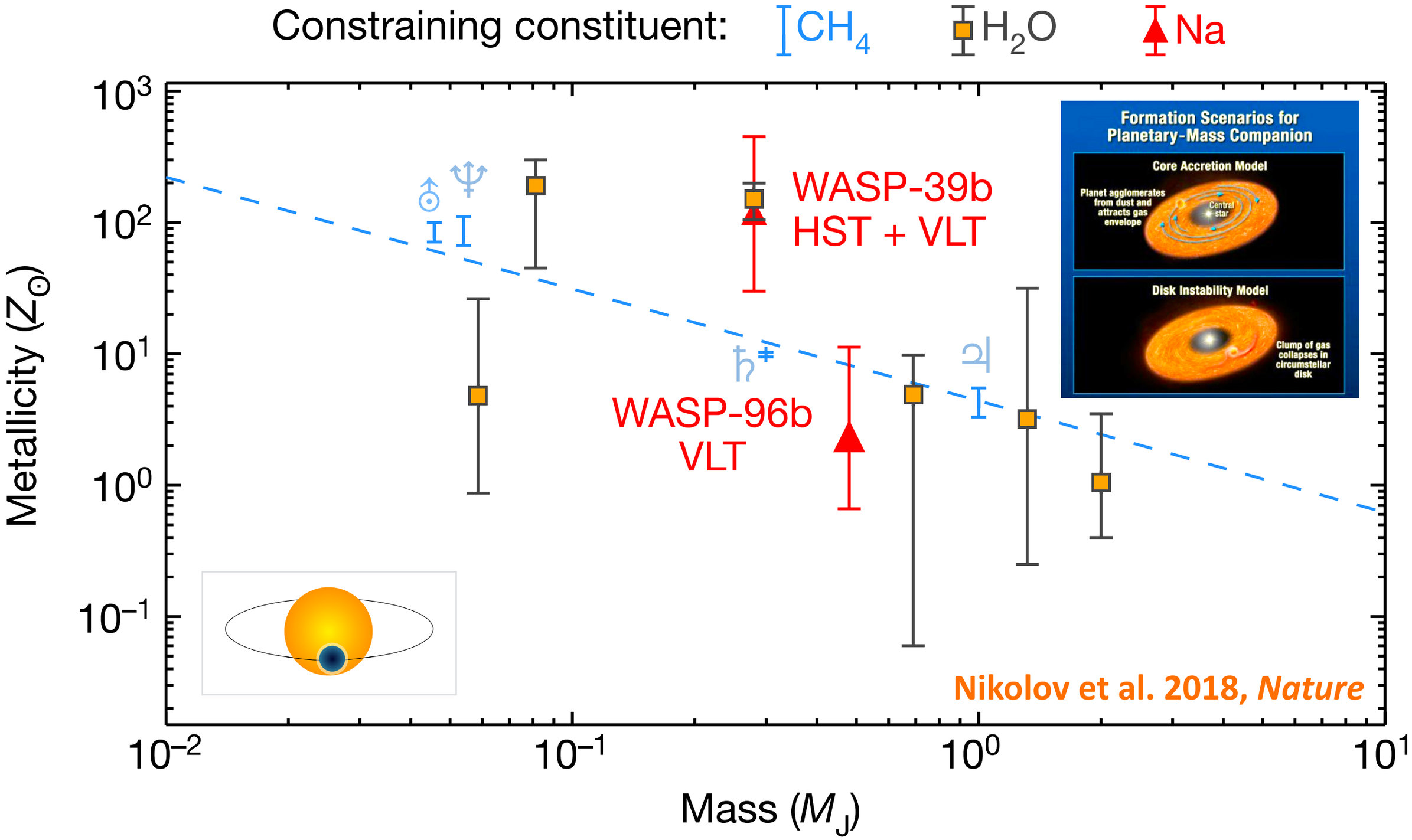

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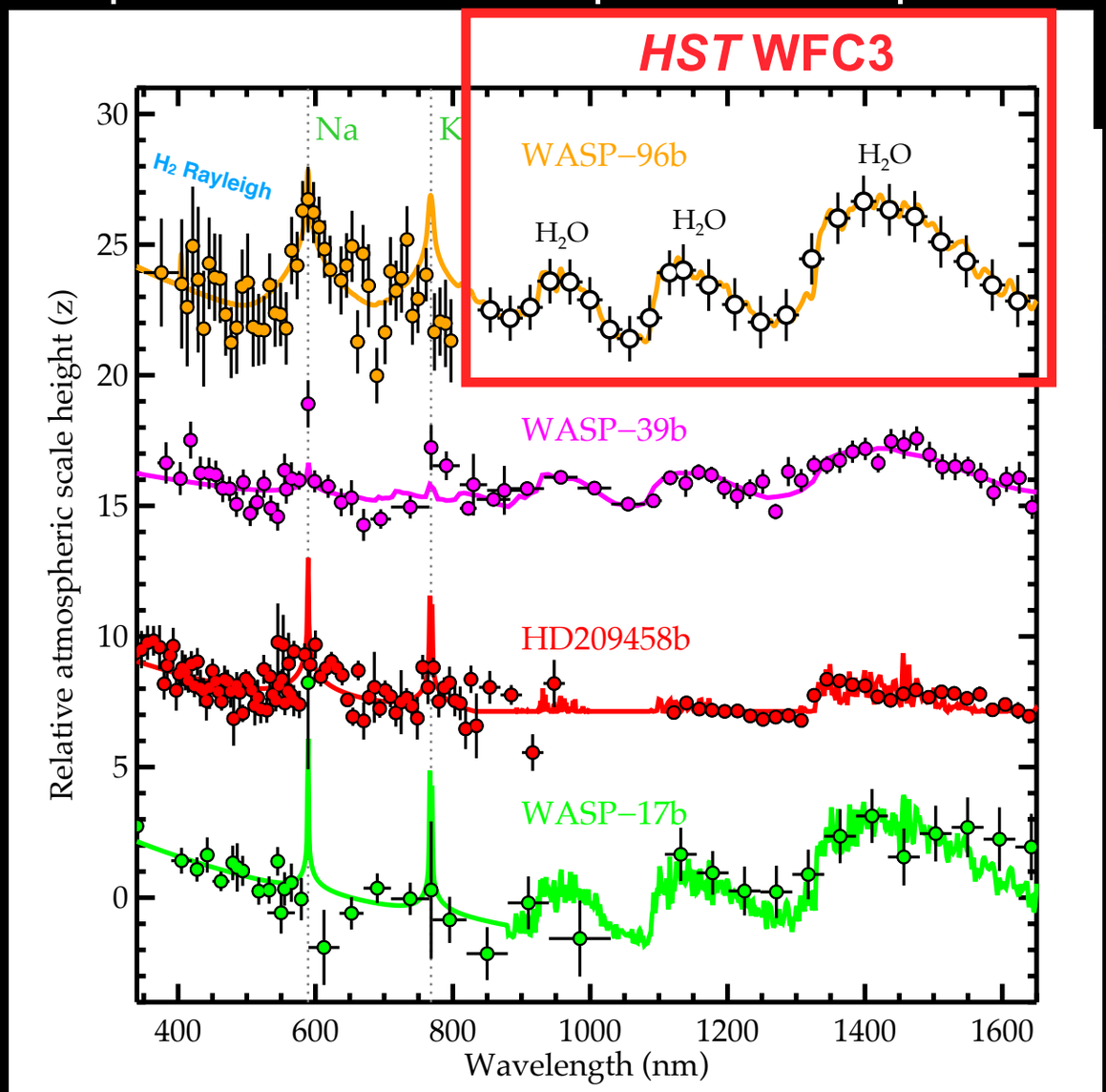
Core accretion predicts metal-enriched atmospheres

Next on WASP-96b:

Linking exoplanet atmospheric metallicity with planet formation

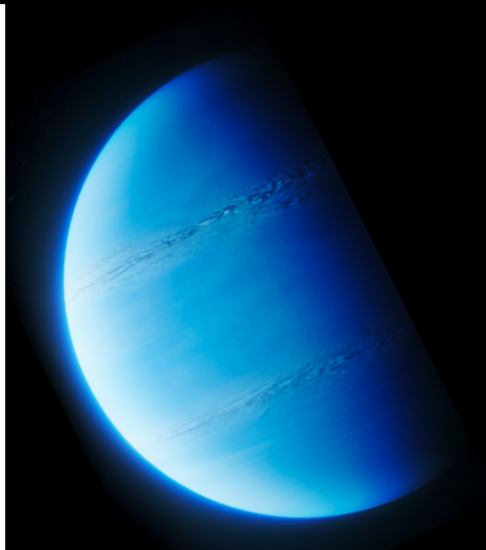
top four cloud-free exoplanet atmospheres



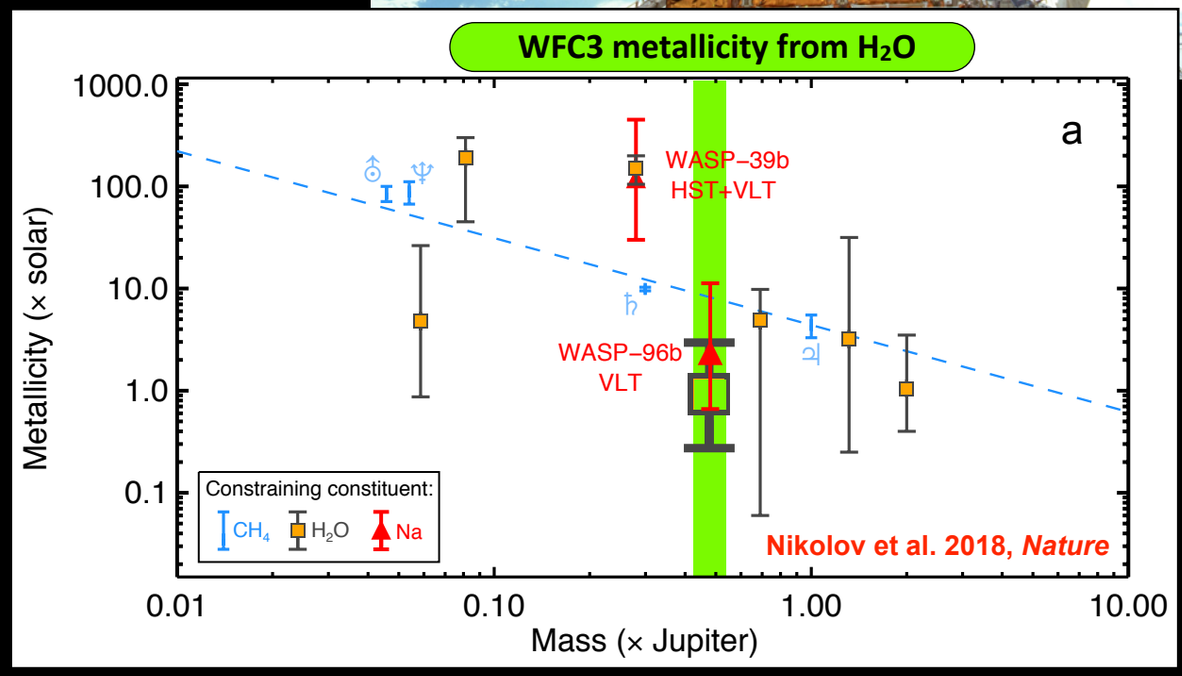
Hubble Space Telescope

Search for H_2O in WASP-96b

PI Nikolov, 10 orbits



artist's impression of WASP-96b



compare metallicity from Na and H_2O feedback for future missions: *JWST & ARIEL*

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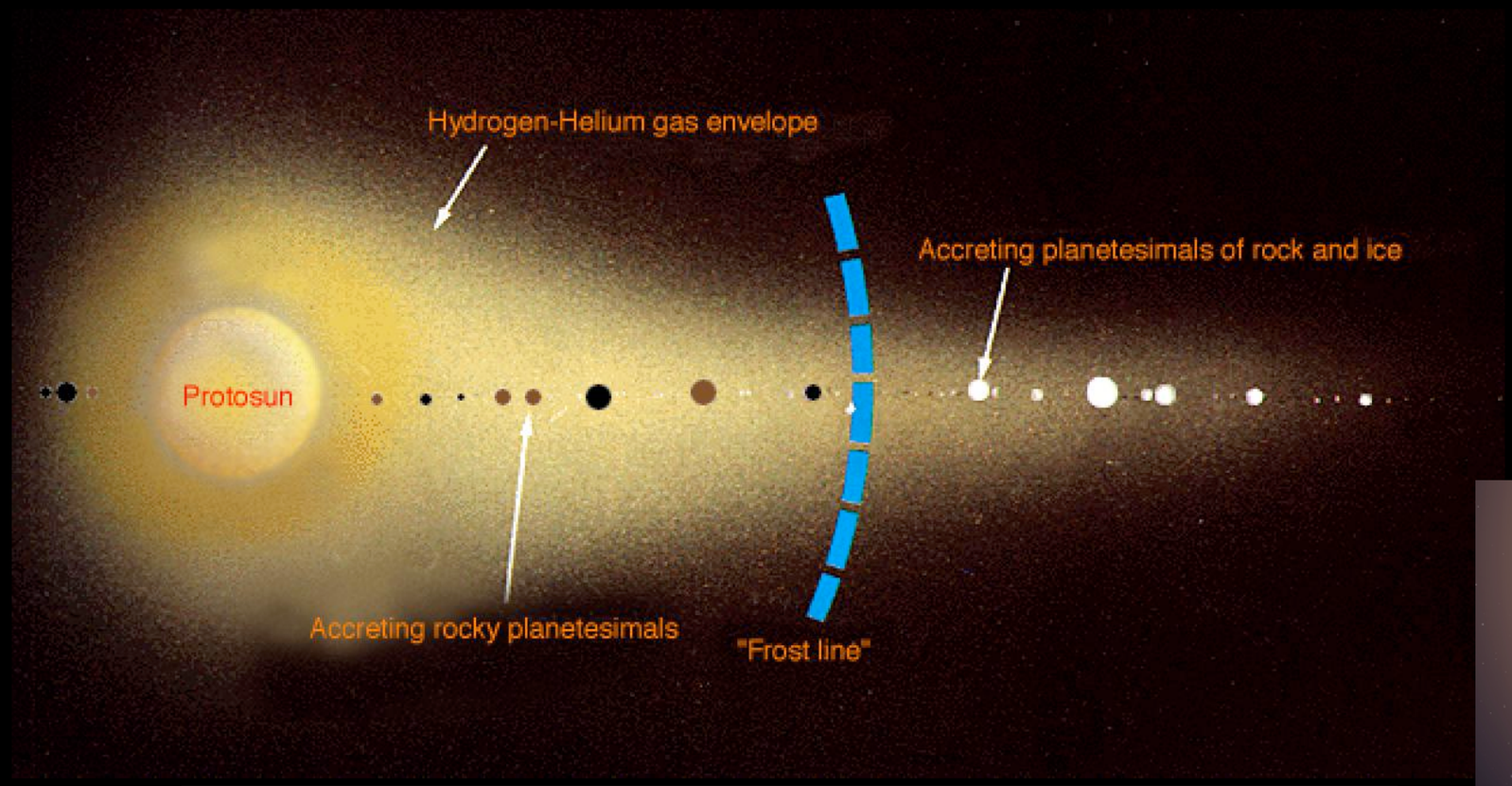
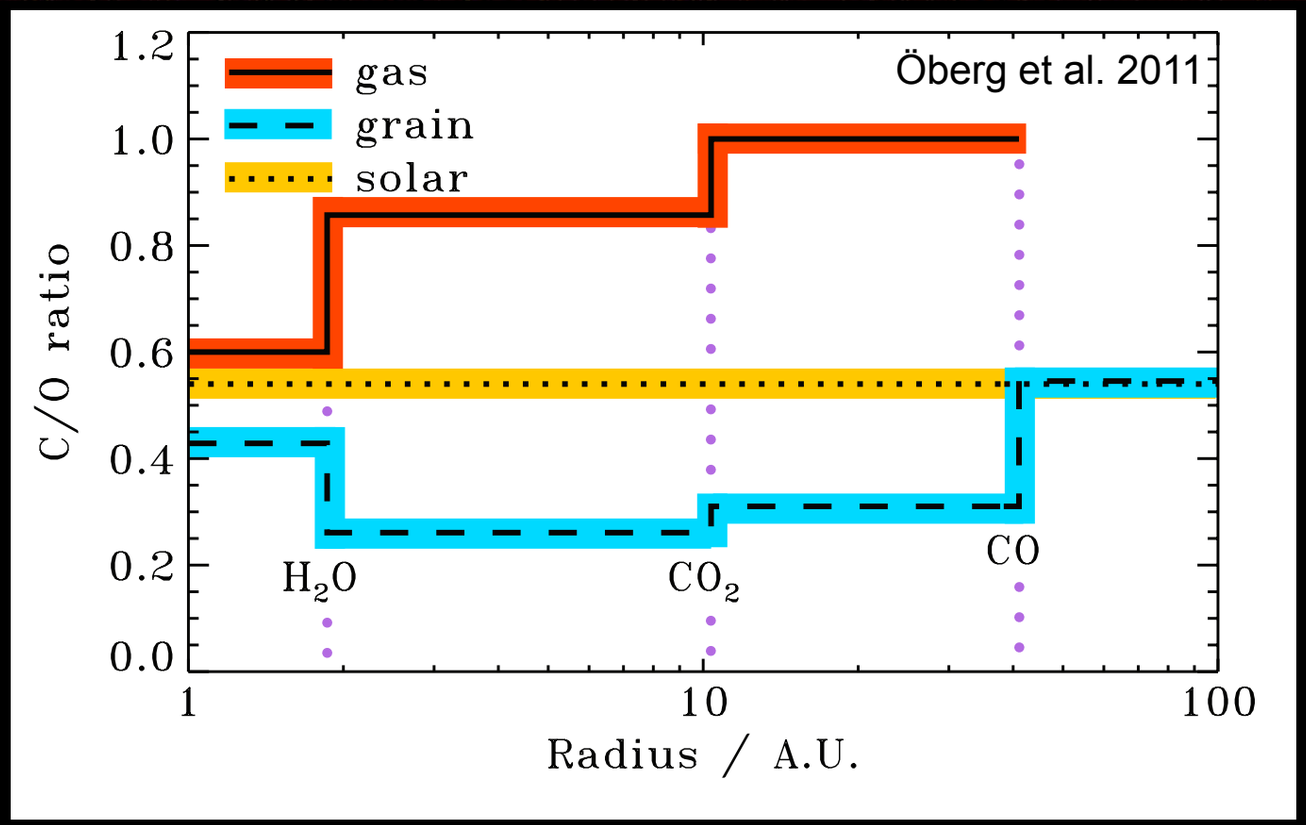
Next on WASP-96b:

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



SPITZER SPACE TELESCOPE



solar value, C/O = 0.56

carbon-rich, C/O > 0.56
outside the snow line

oxygen-rich, C/O < 0.56
inside the snow line

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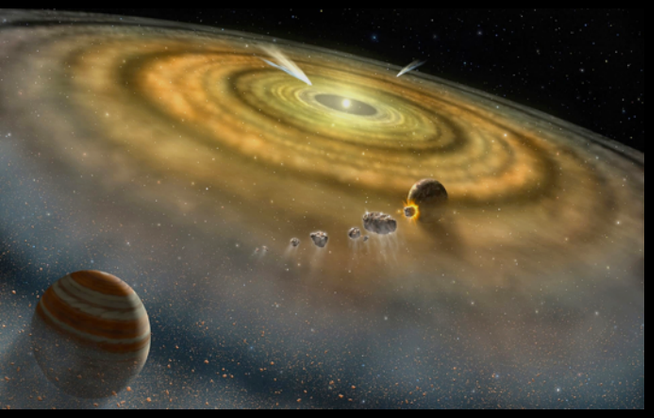

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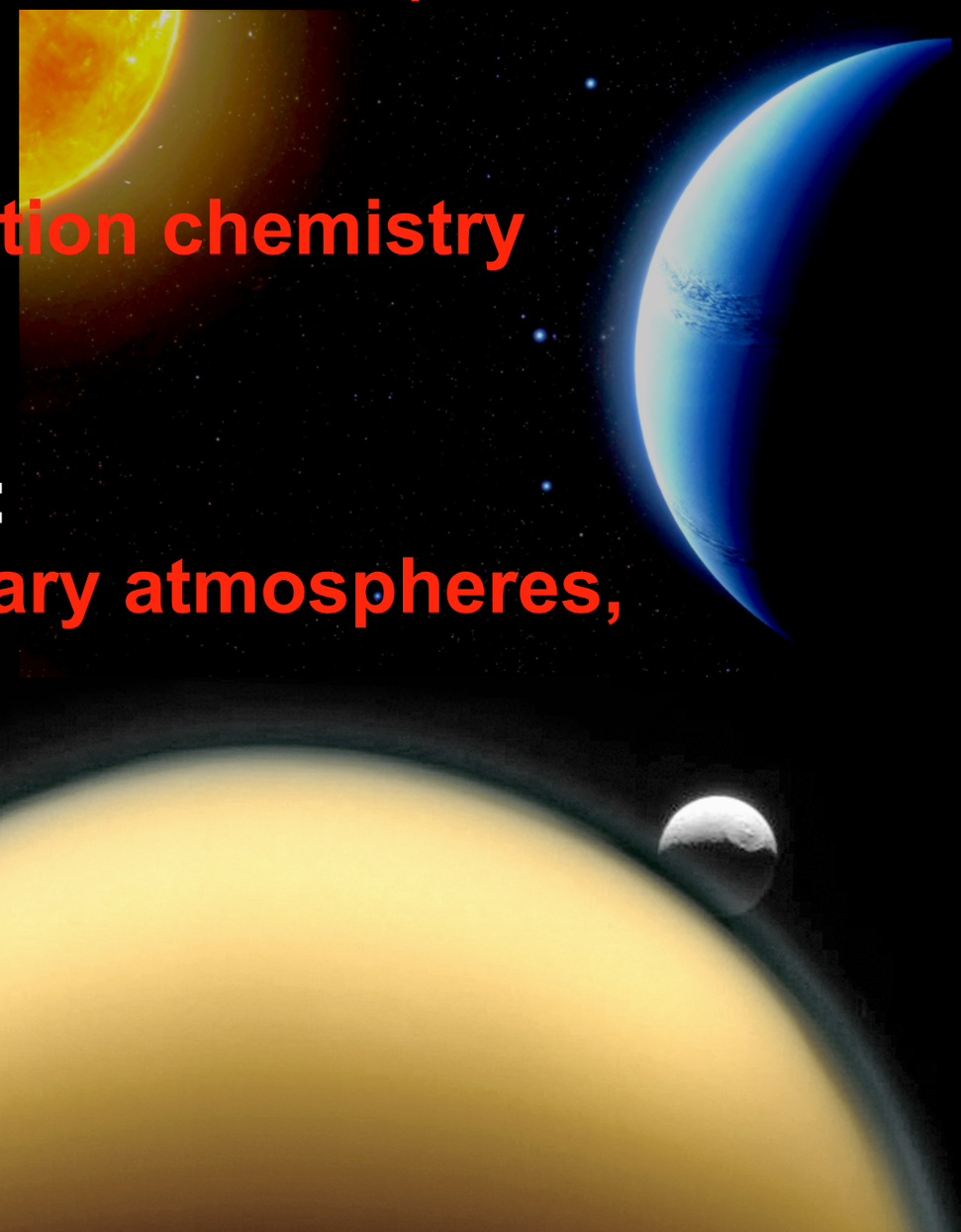

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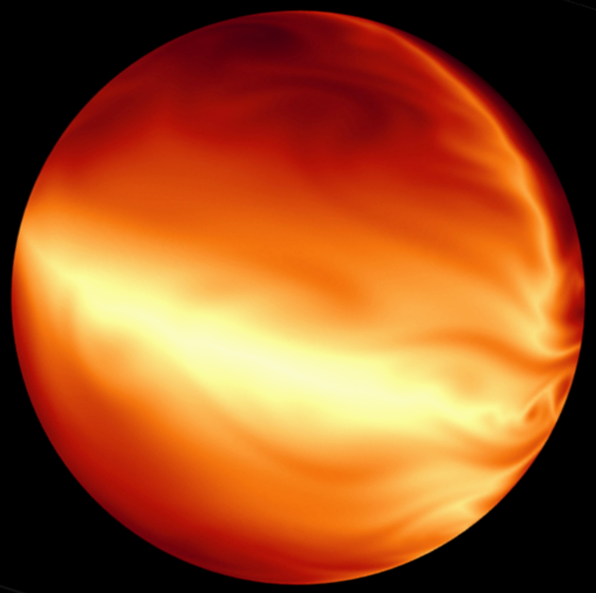

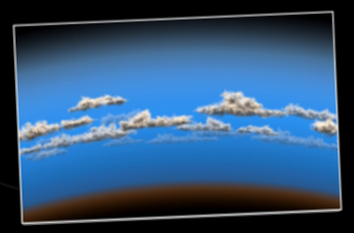

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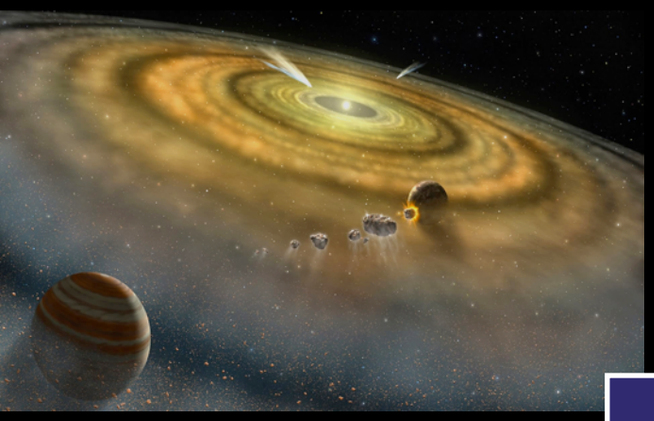
Major Exoplanet Science Questions



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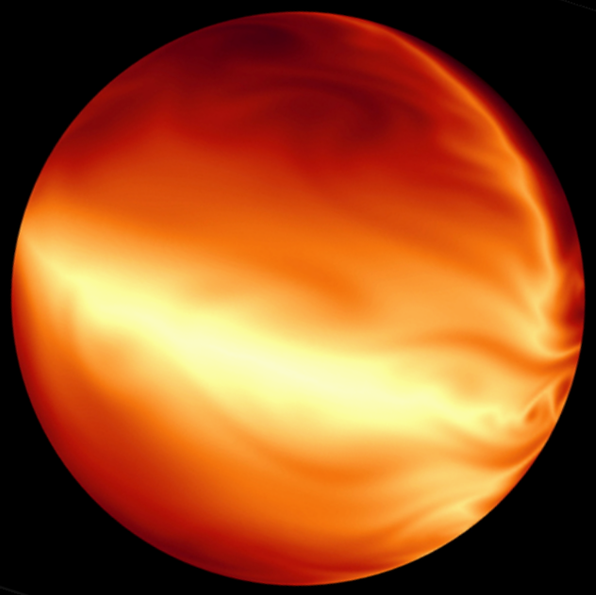

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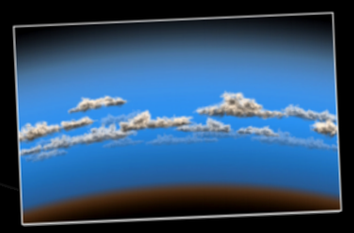

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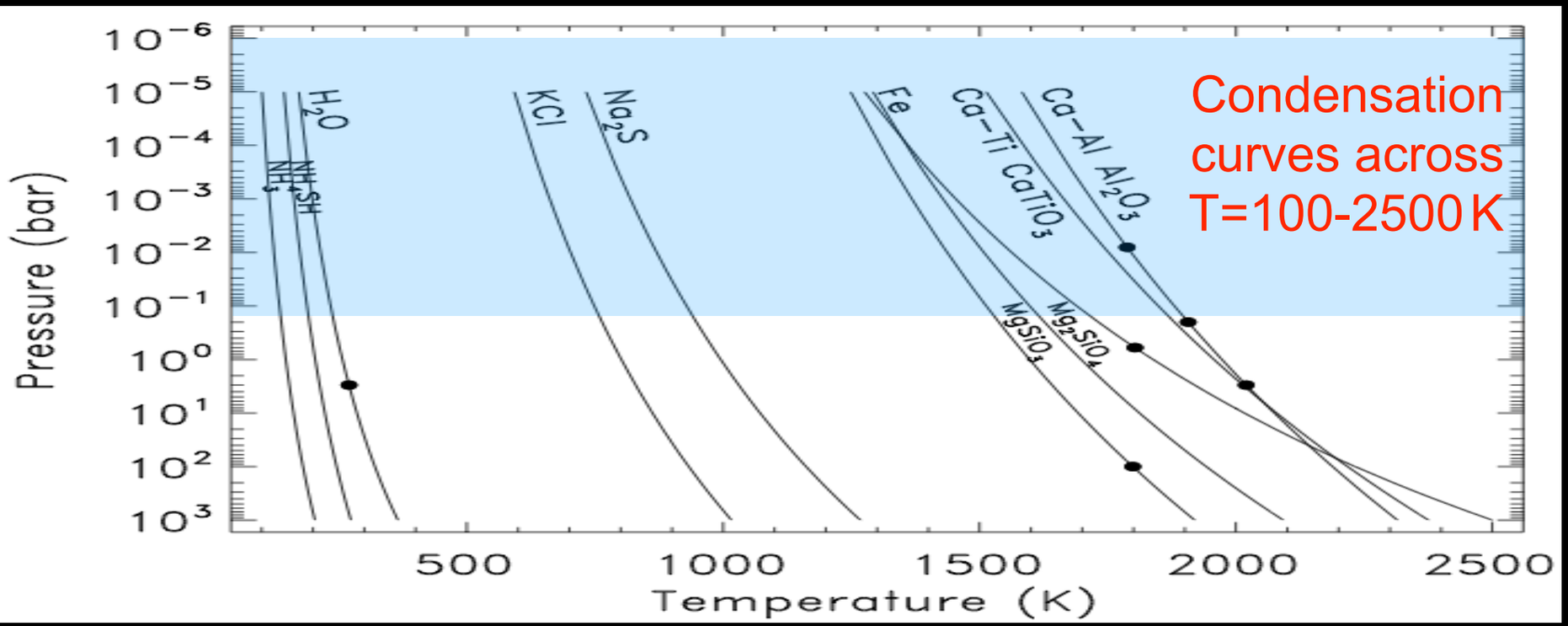
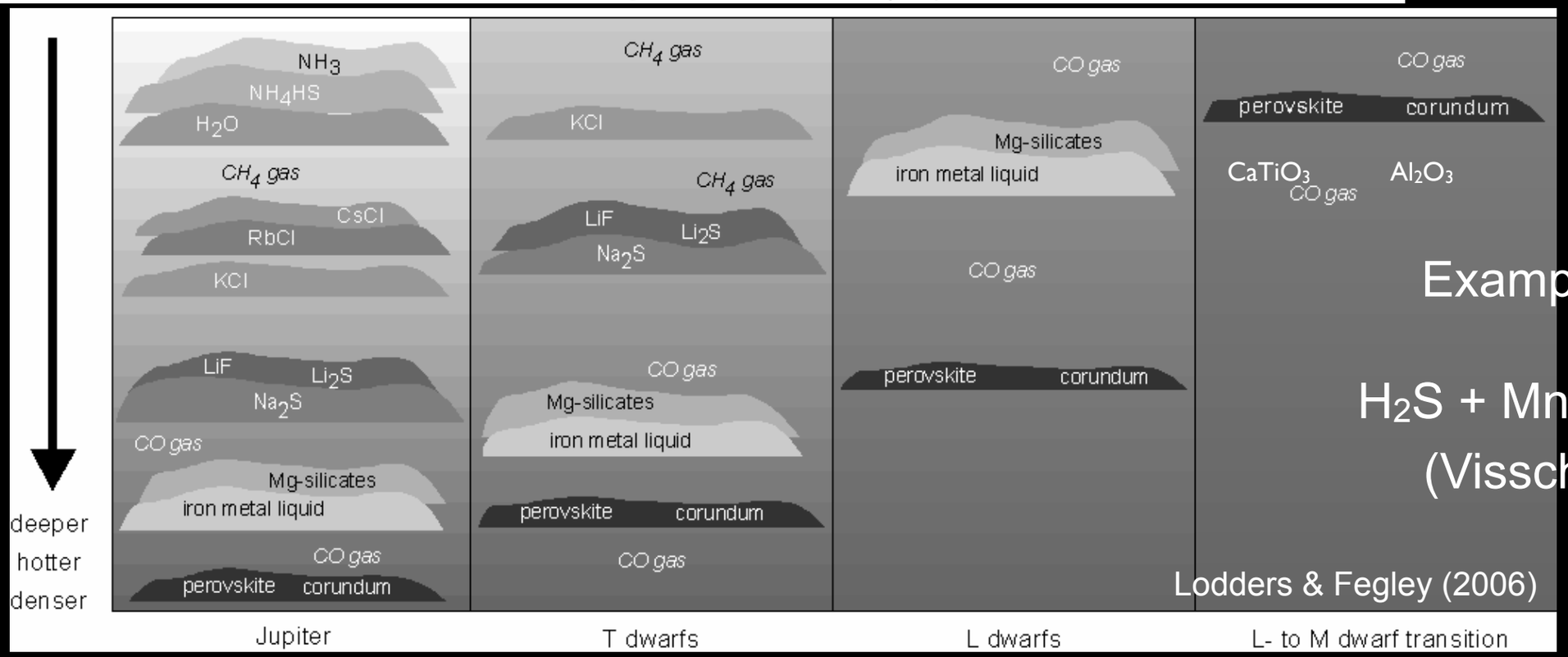
Depending on conditions: exotic refractory species at high T and alkali sulphides, chlorides and water at low T



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):

$H_2S + Mn \longrightarrow MnS(s) + H2$

(Visscher et al. 2006)

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200 K | 500-1300 K | 1300-2400 K | < 3000 K

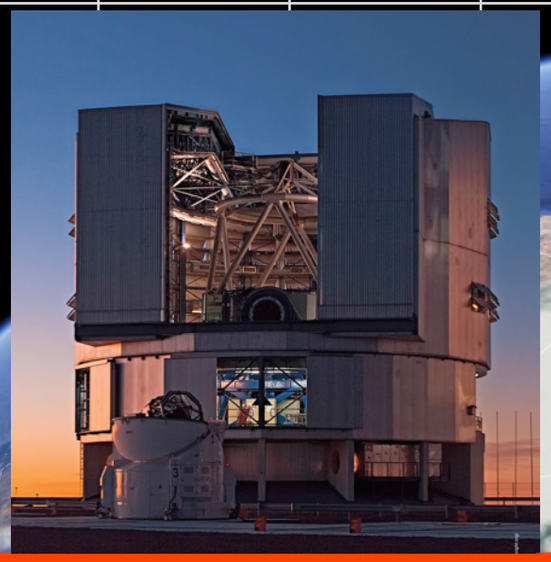
Telescopes for *exoplanet atmospheric characterization: need of optical spectrographs (such as FORS2)*

HST optical & IR ?

JWST: near- and mid-IR ?

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

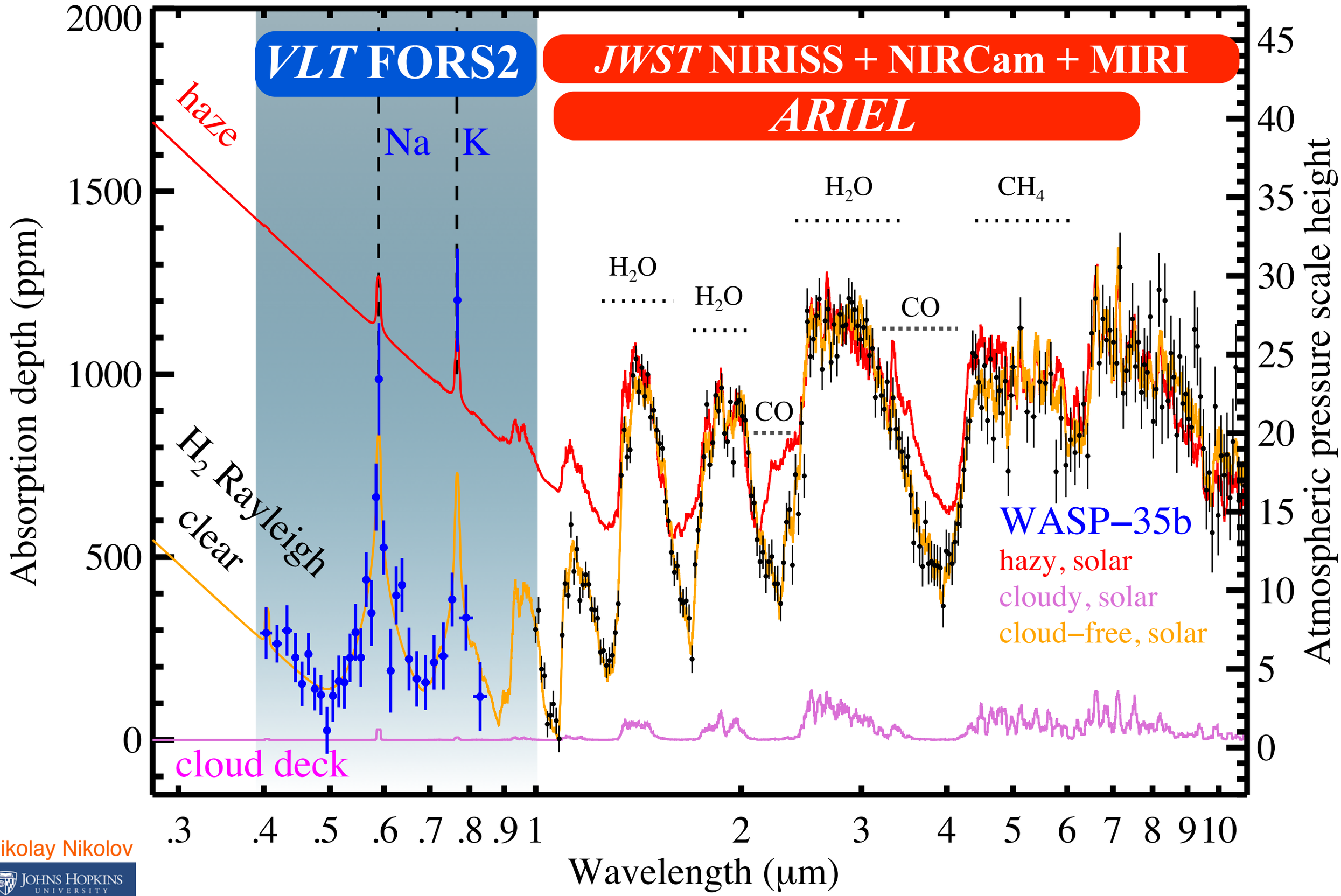
18 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031



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*



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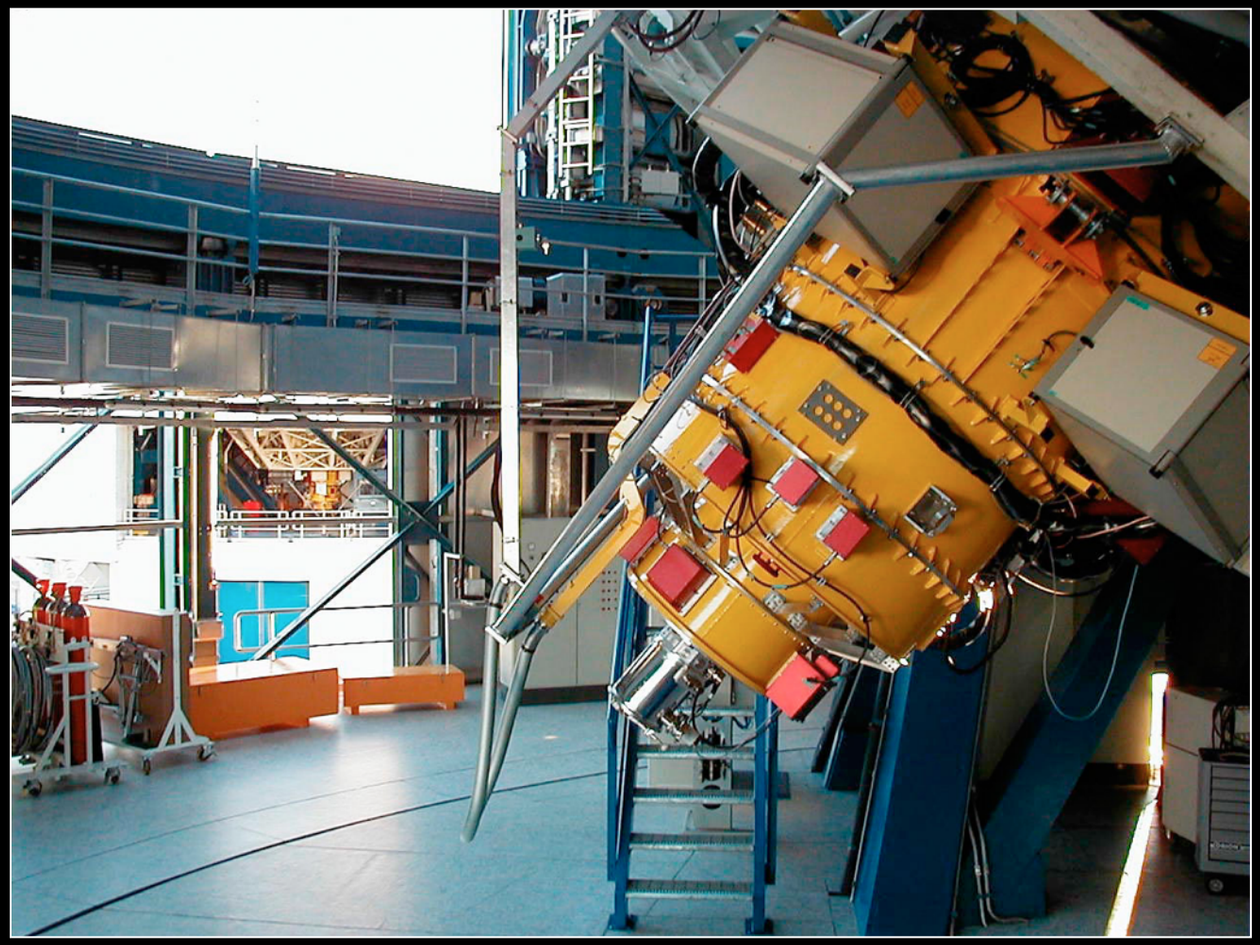
The first comparative ground-based followup of exoplanets with atmospheric features detected with HST



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~600) resolution:

blue: GRIS 600B
red: GRIS 600RI

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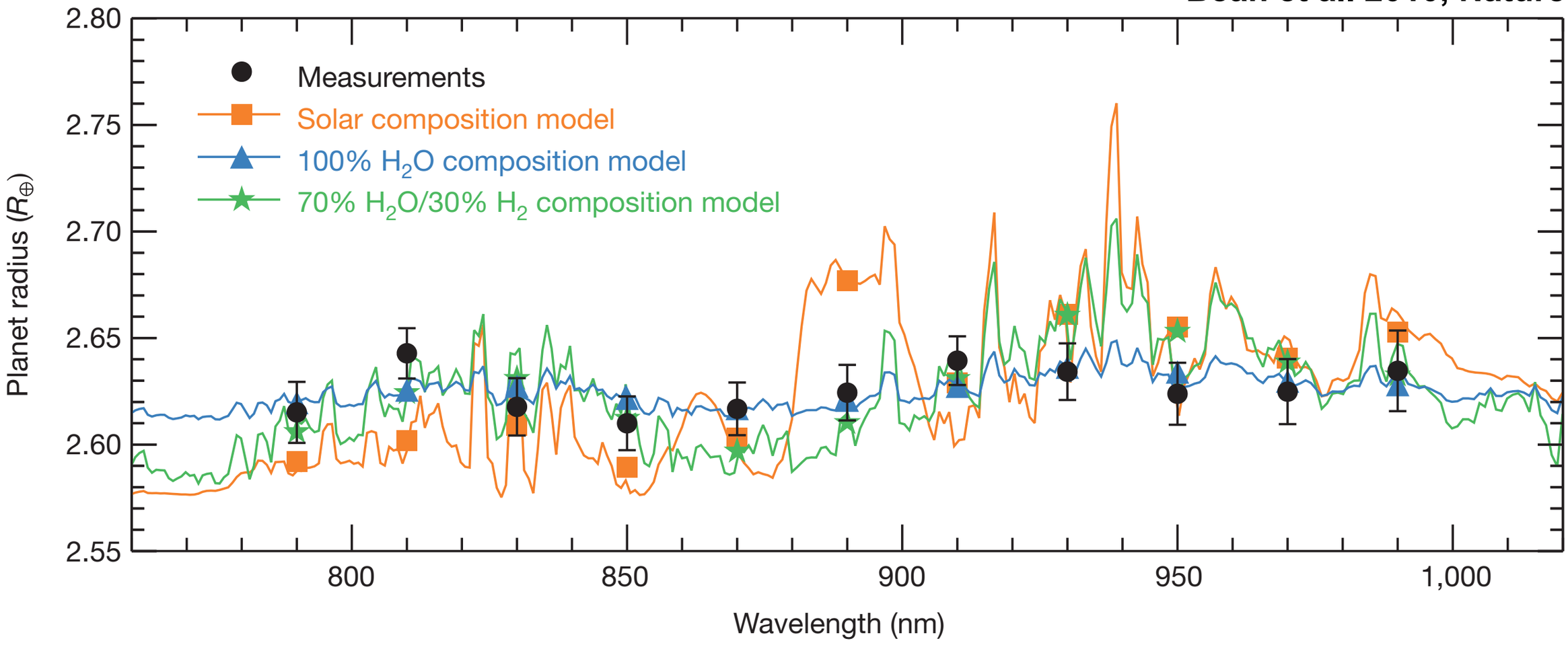
Motivation:
feasibility of low/medium resolution transmission spectroscopy from the ground

Bean et al. 2010, Nature



Multi-object spectroscopy with six comparison stars in 6.8’ x 6.8’

GJ1214b must have water-dominated or cloudy atmosphere

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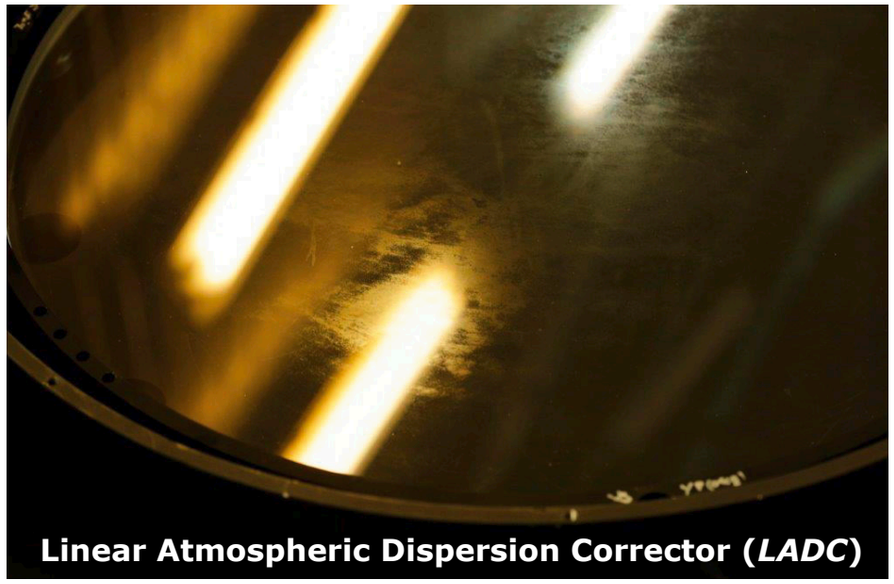
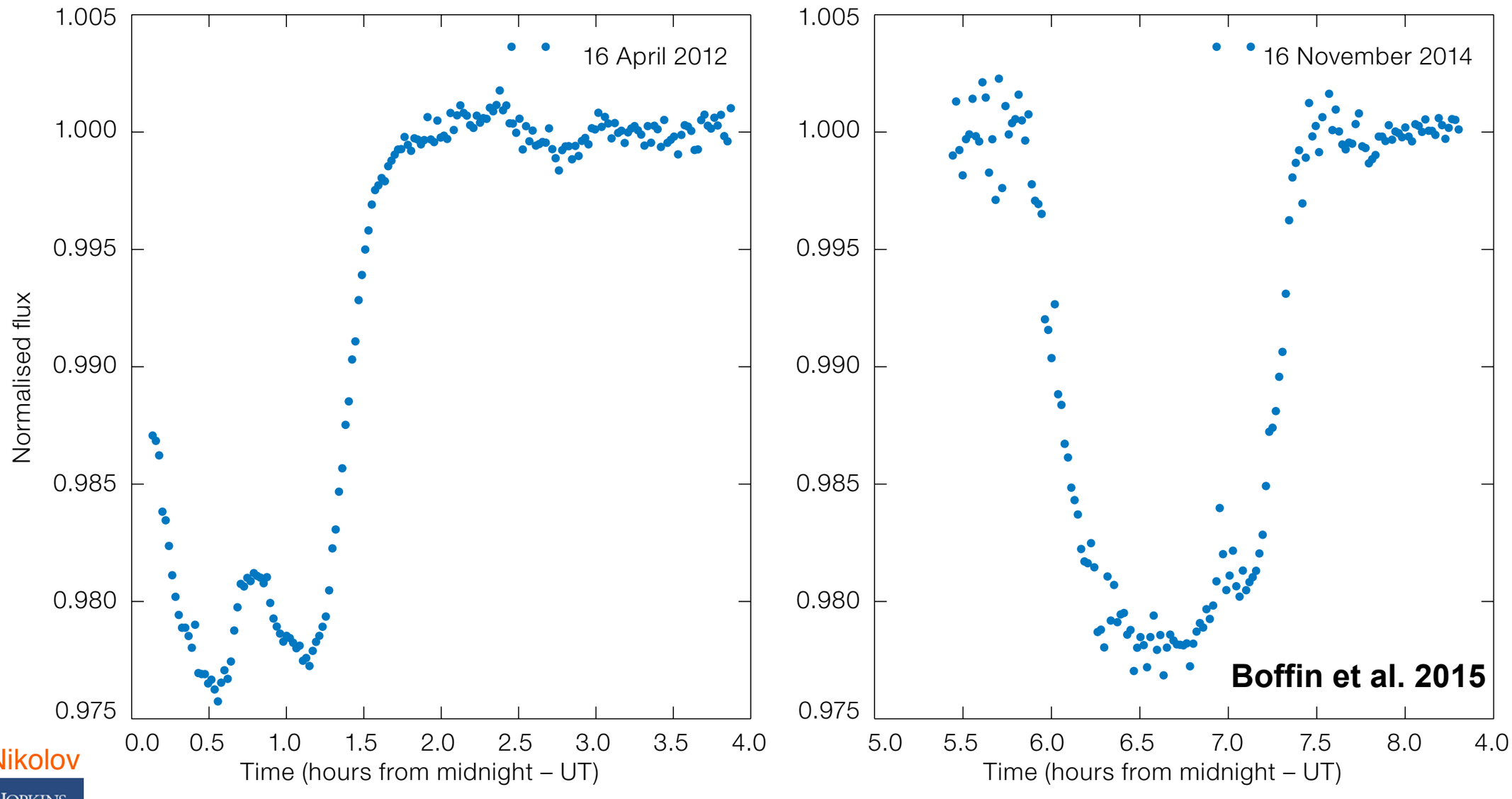


Before coating removal **After coating removal**



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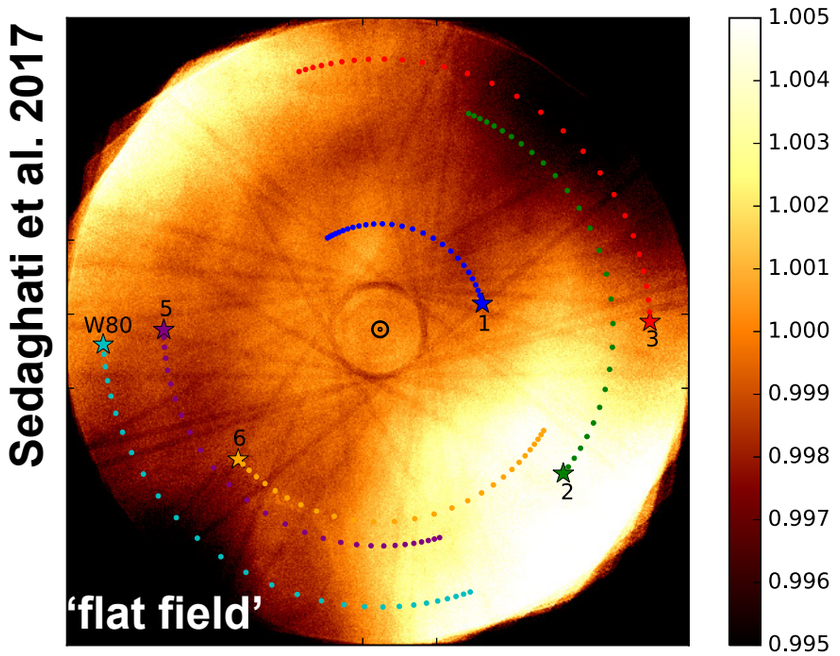

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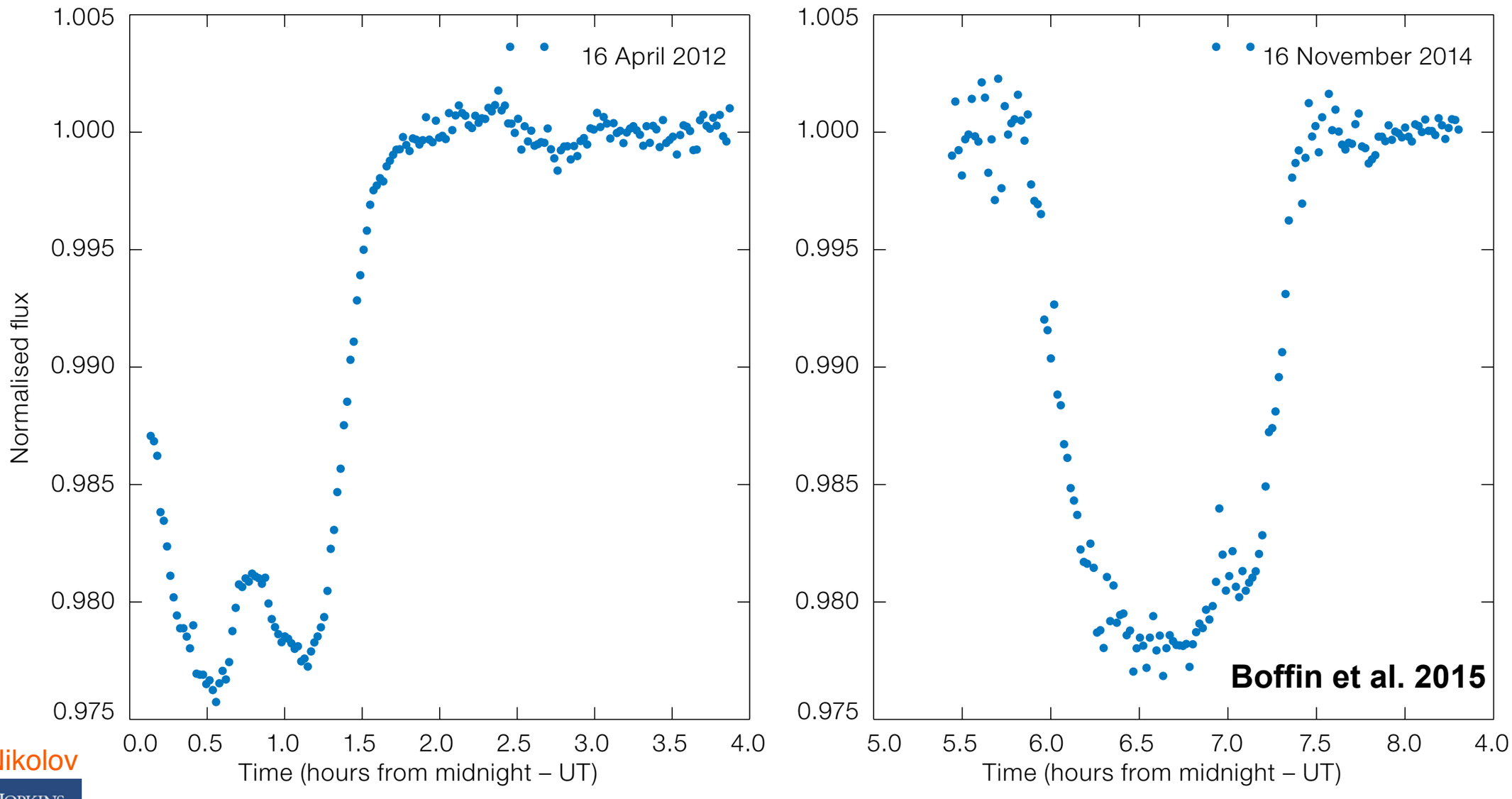

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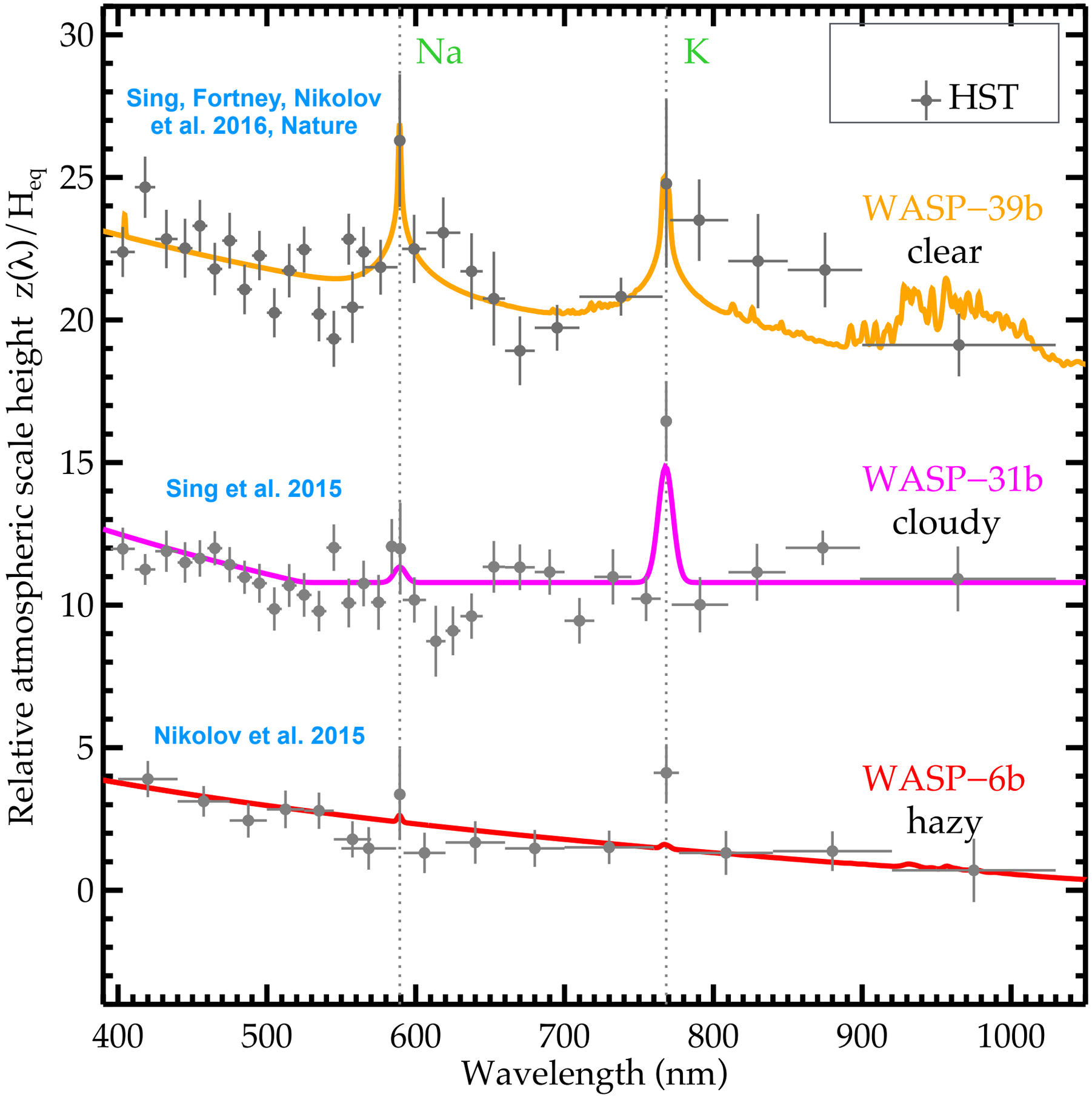

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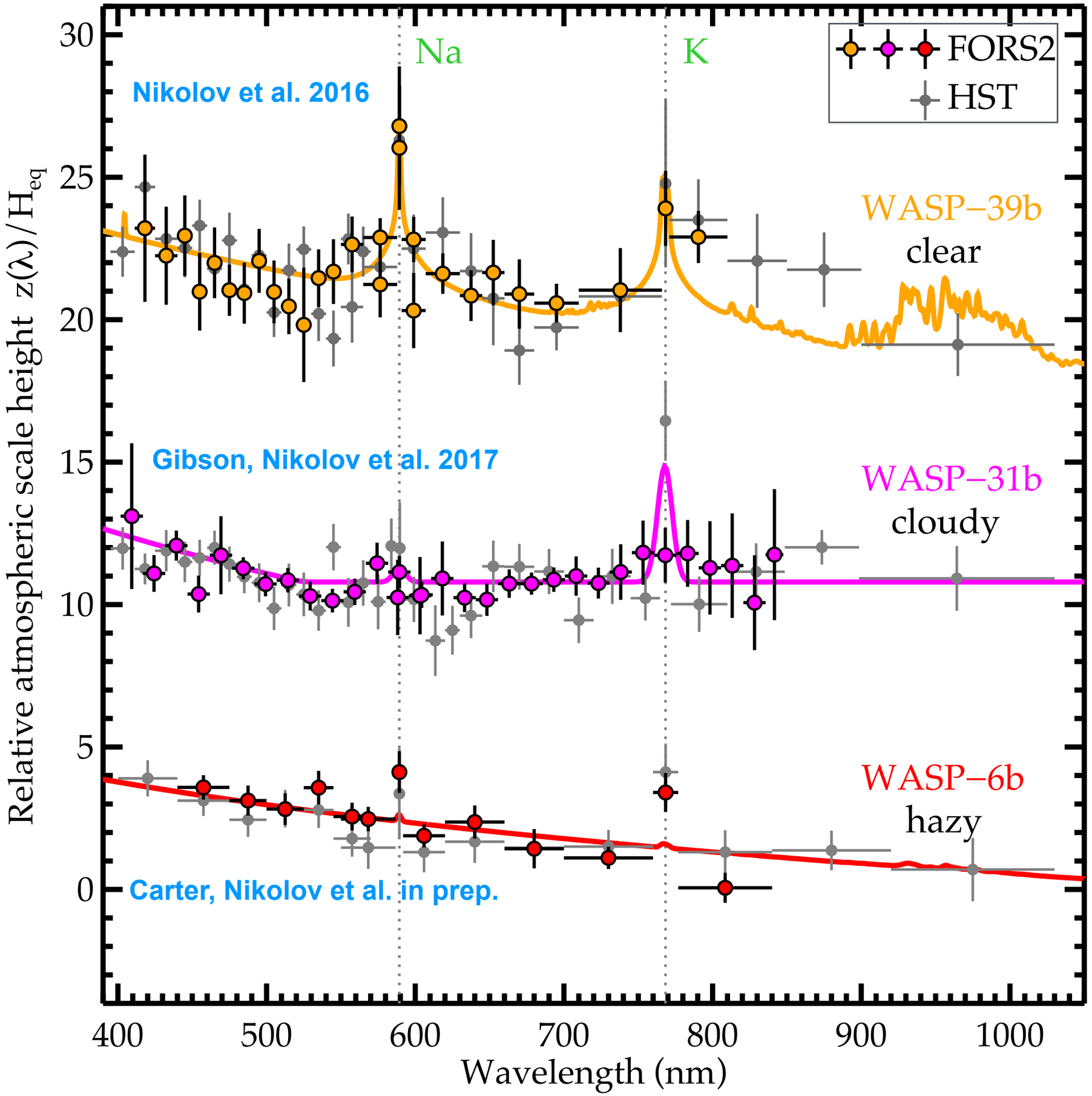

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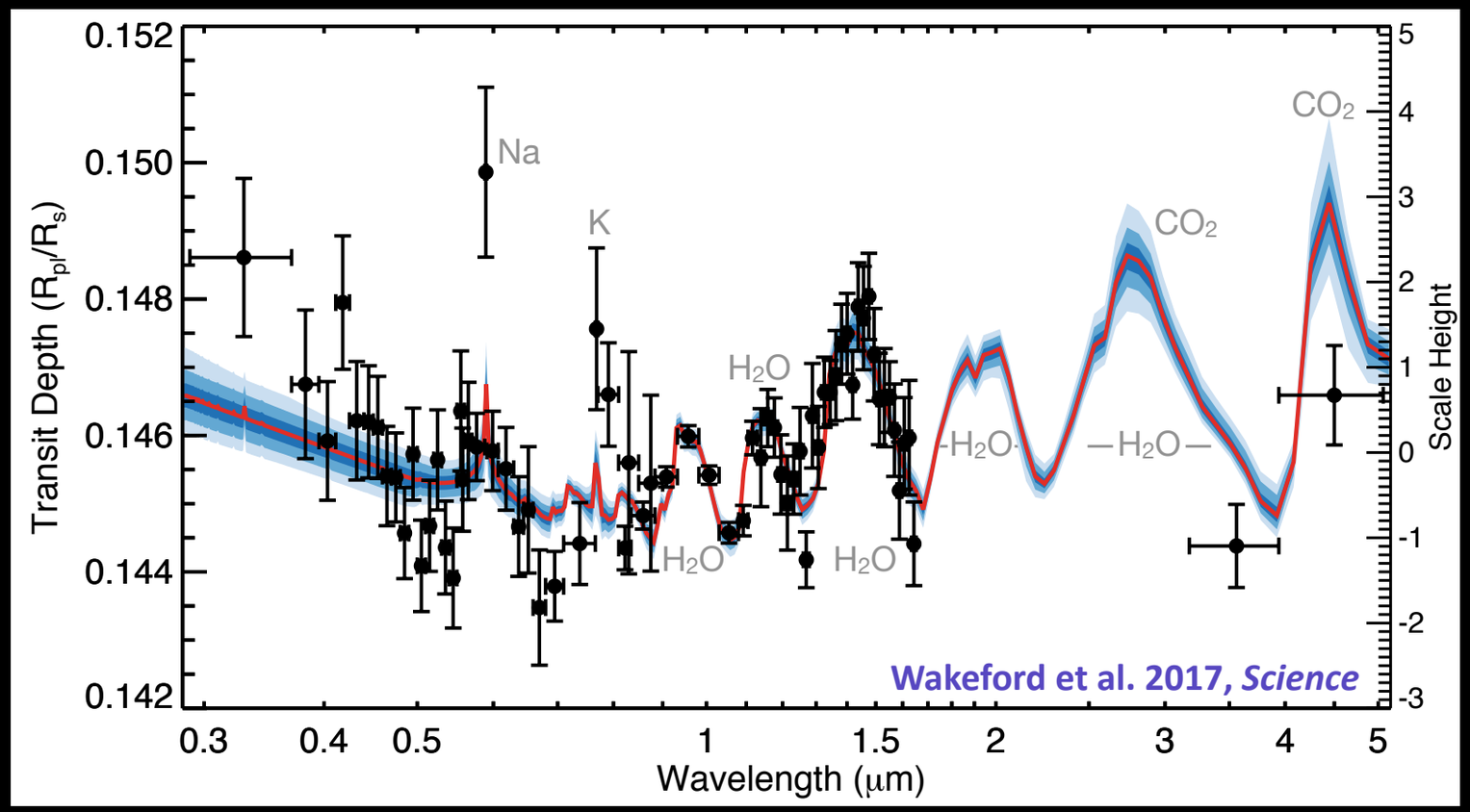
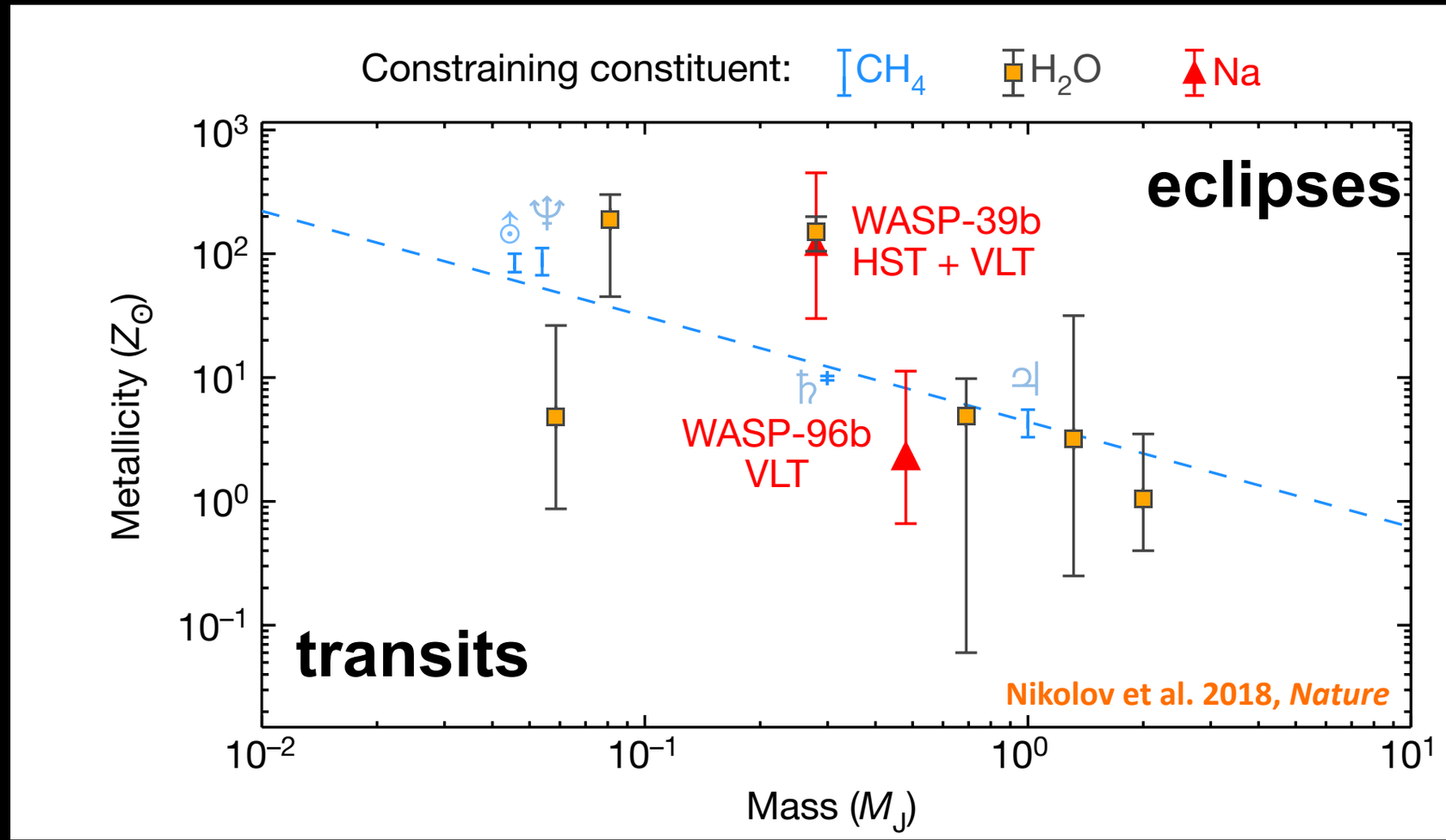


Optical spectroscopy is necessary to constrain abundances, C/O and metallicity



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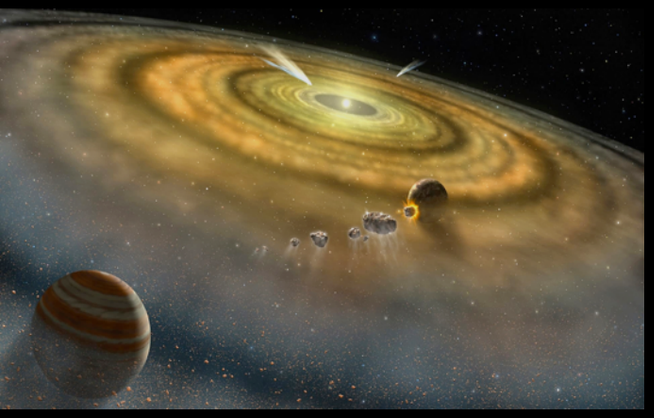

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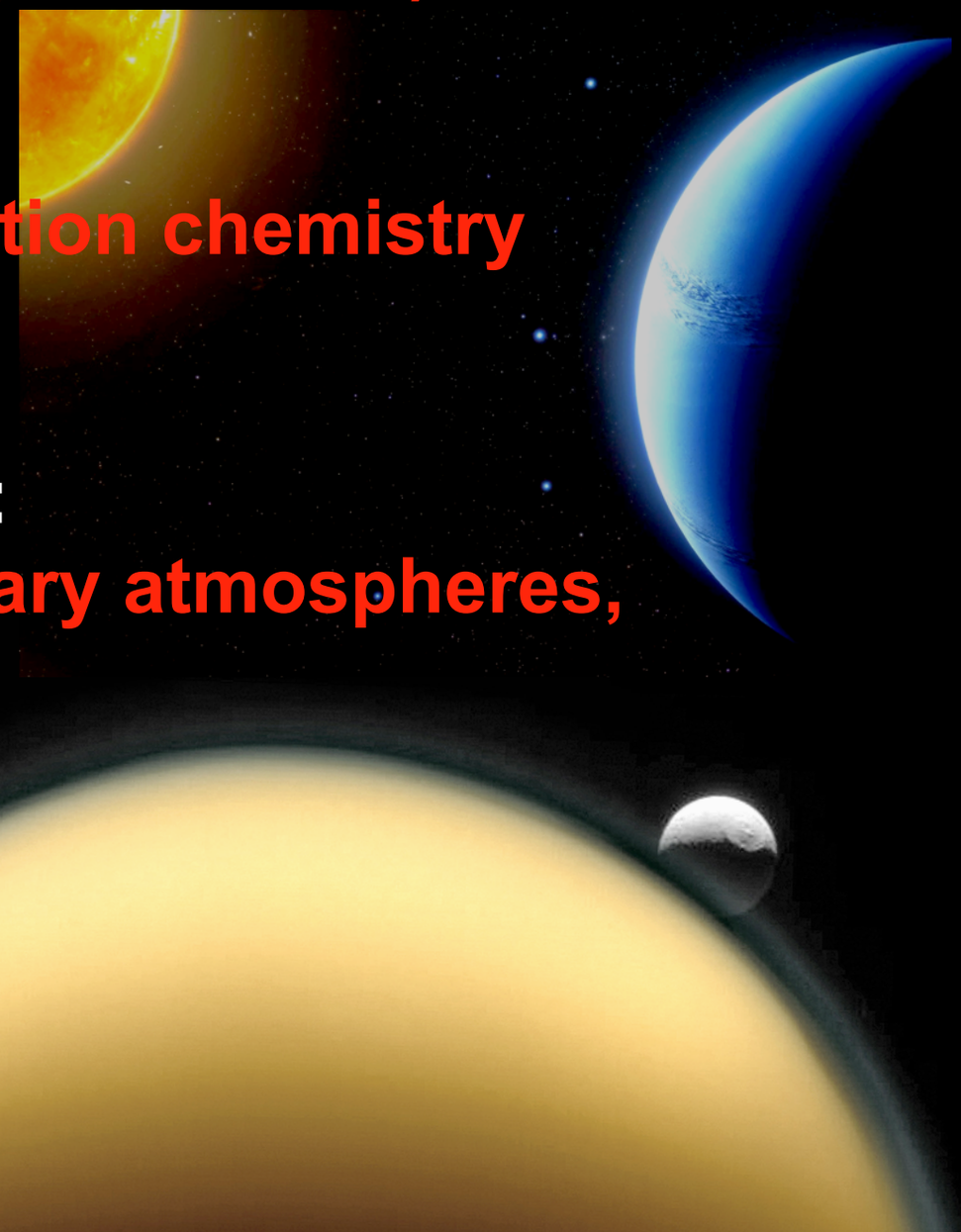

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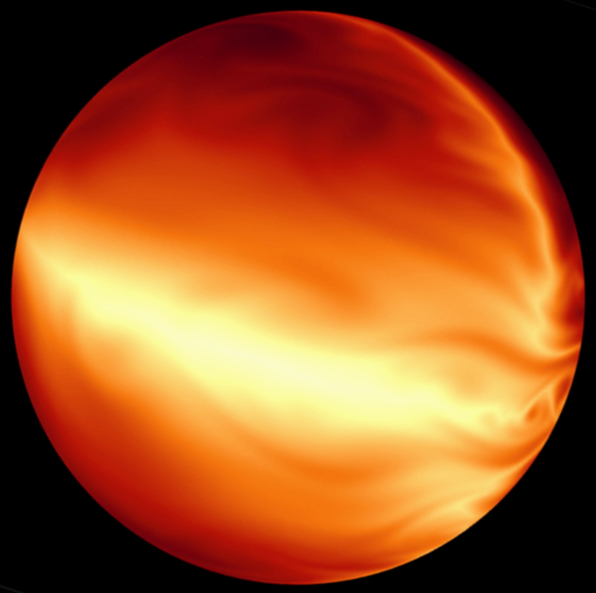

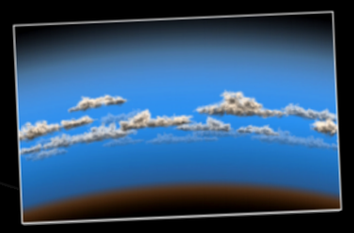

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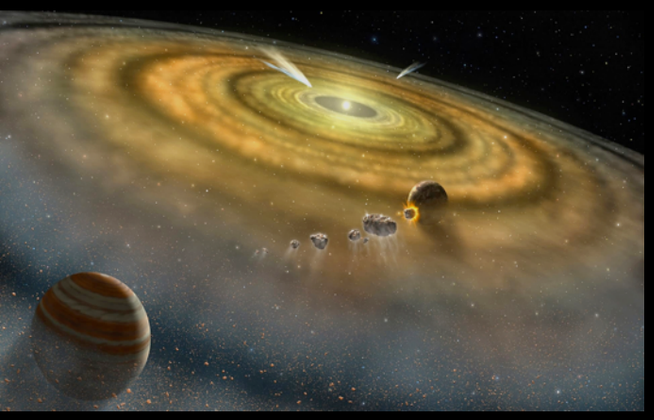

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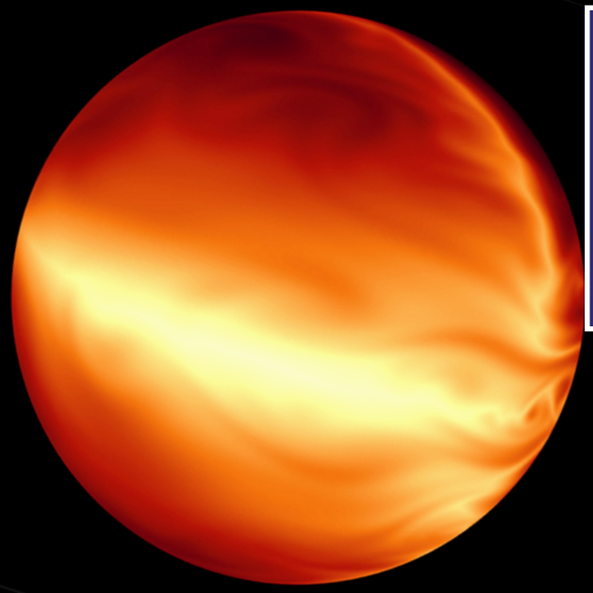

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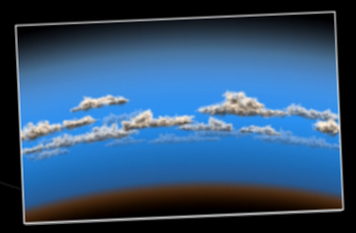

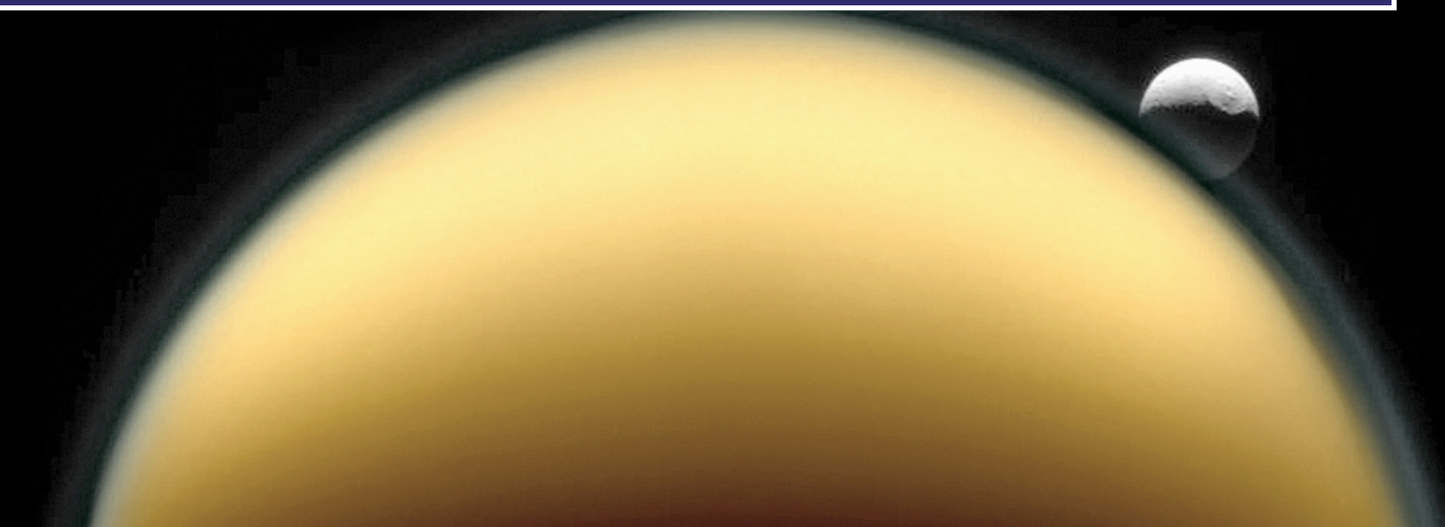

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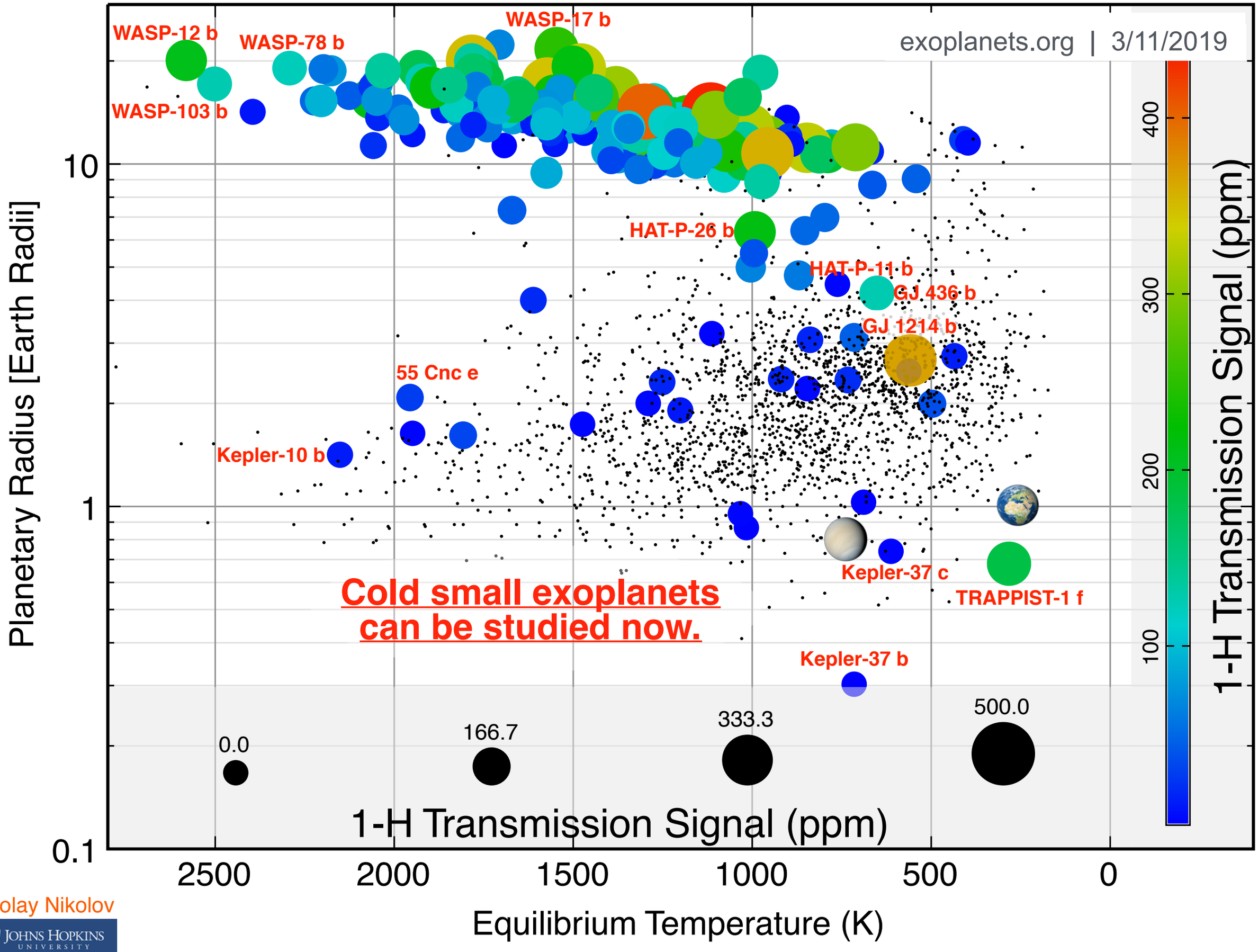
assuming H-rich atmosphere



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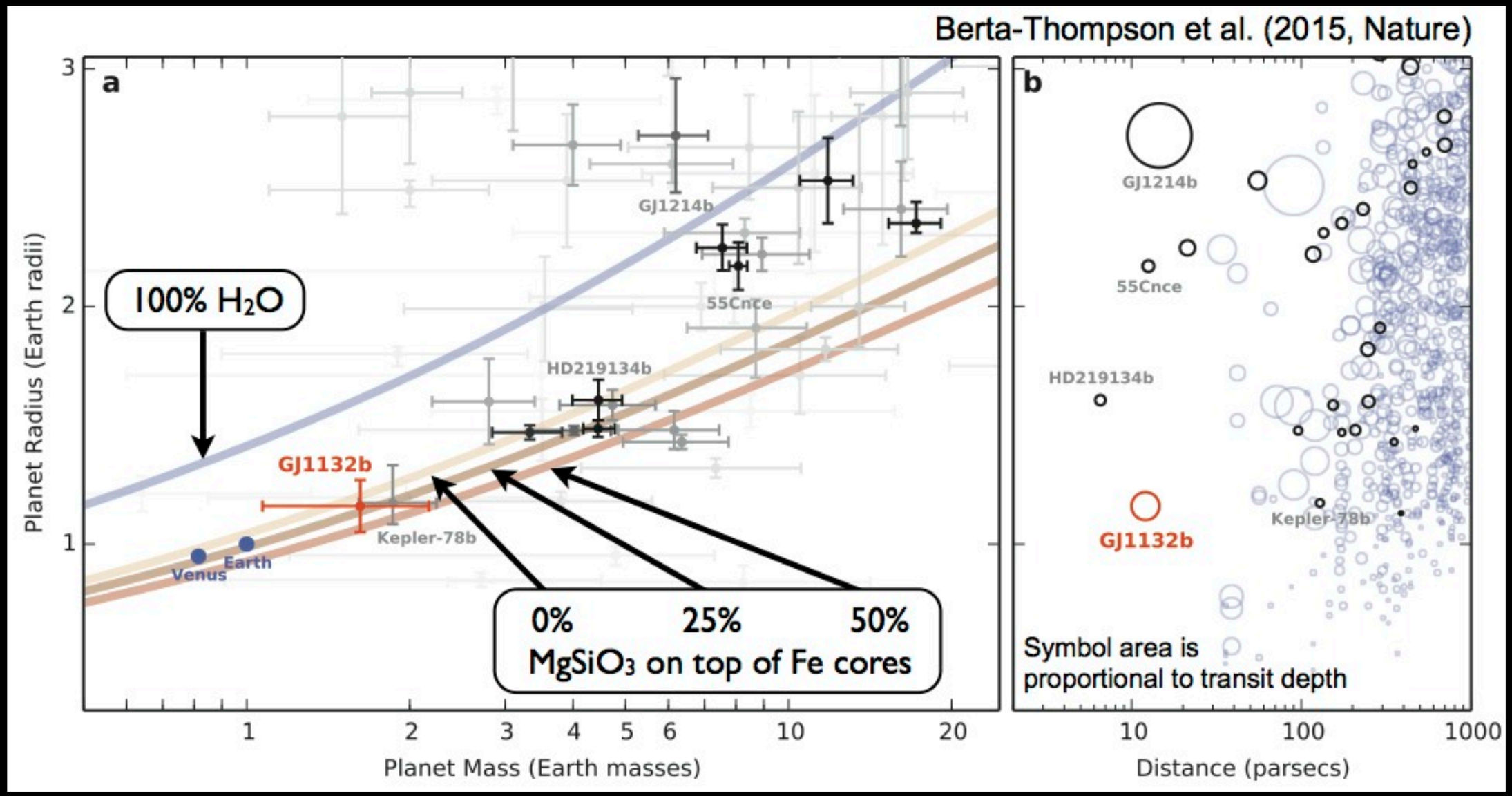
Search for primordial H-rich atmosphere of the M-dwarf *GJ 1132b* - Venus-mass exoplanet



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

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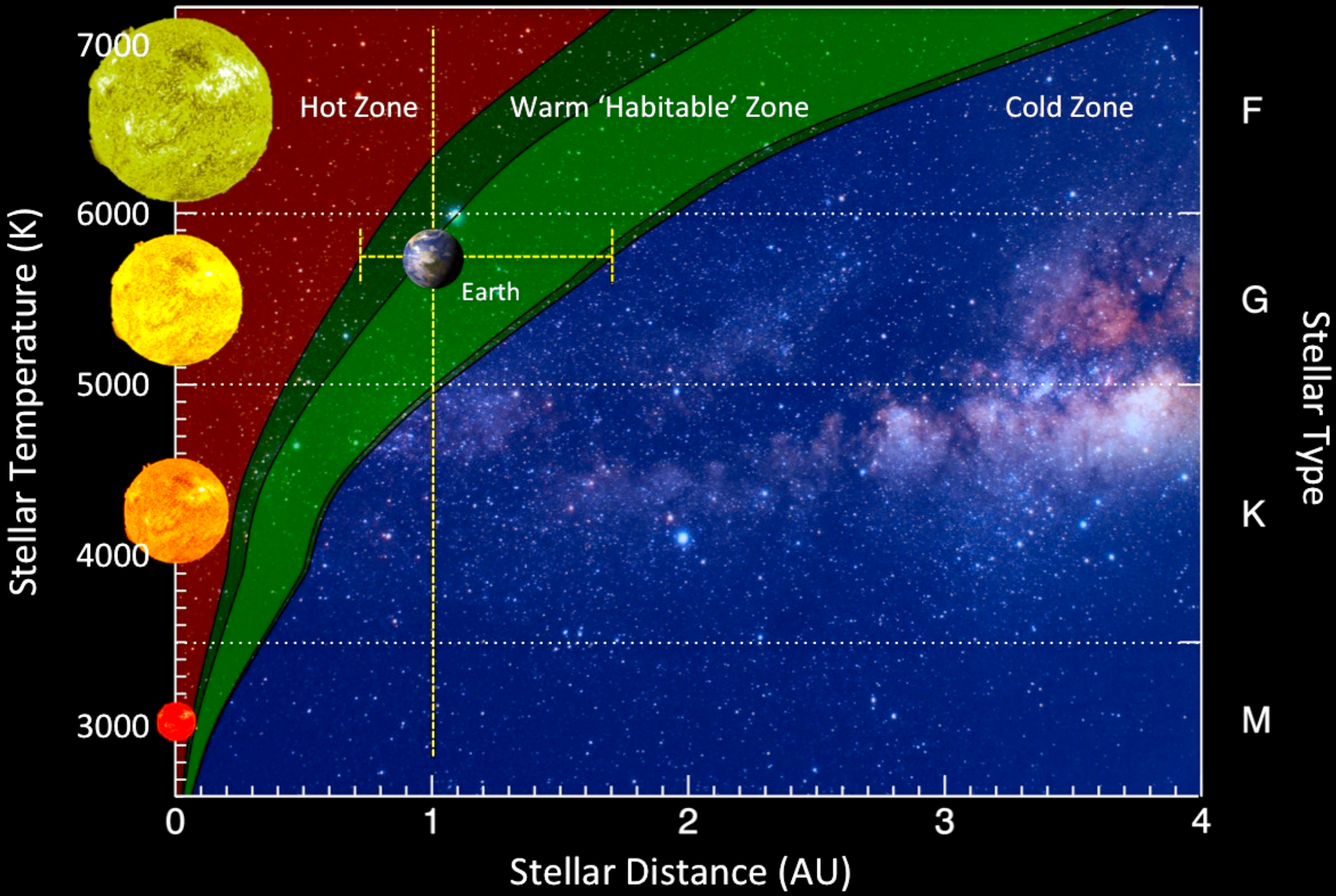
Habitable Zone of Main Sequence Stars



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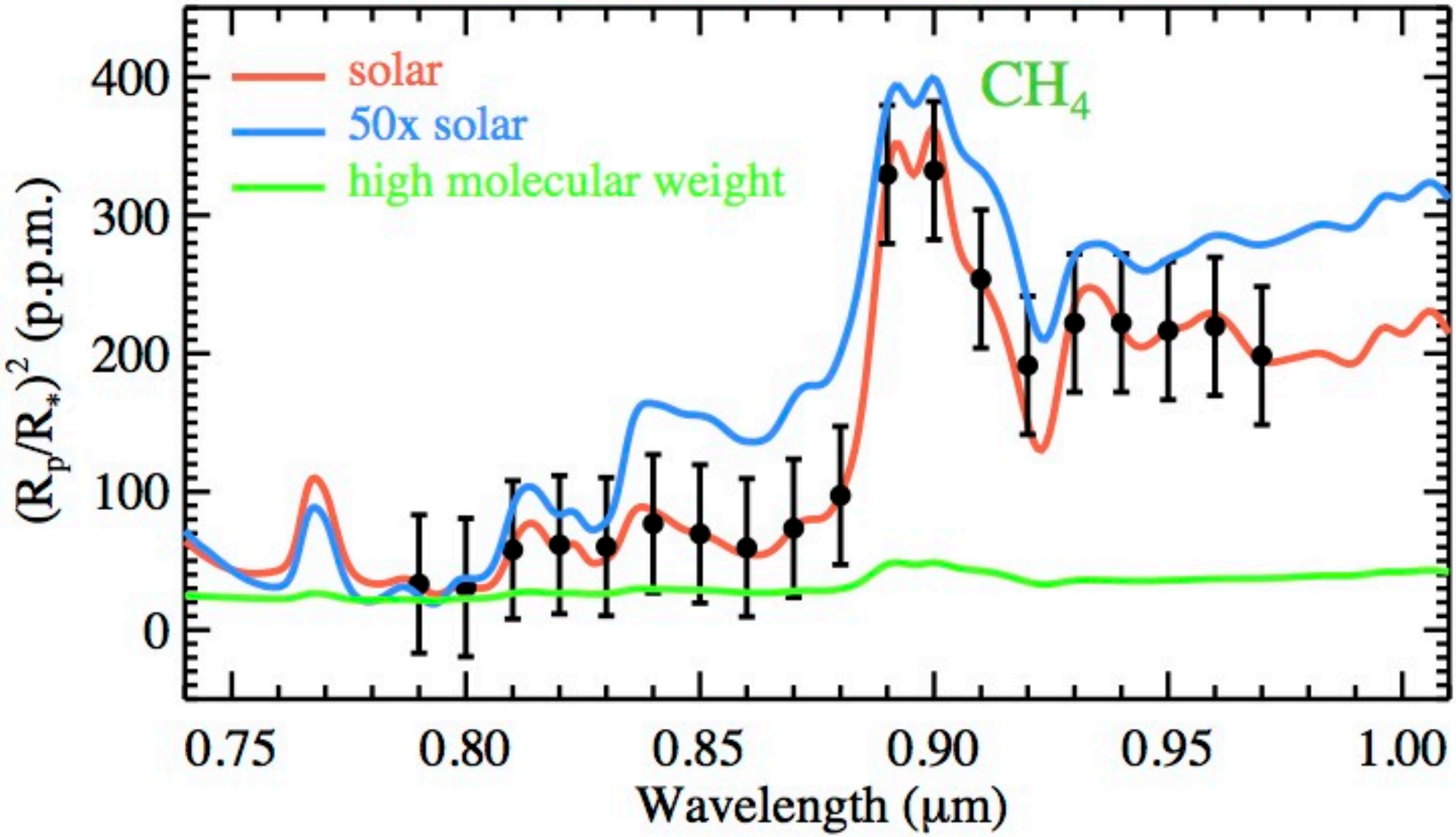
GJ1132b with *VLT* FORS2 GRIS600z



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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’)

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