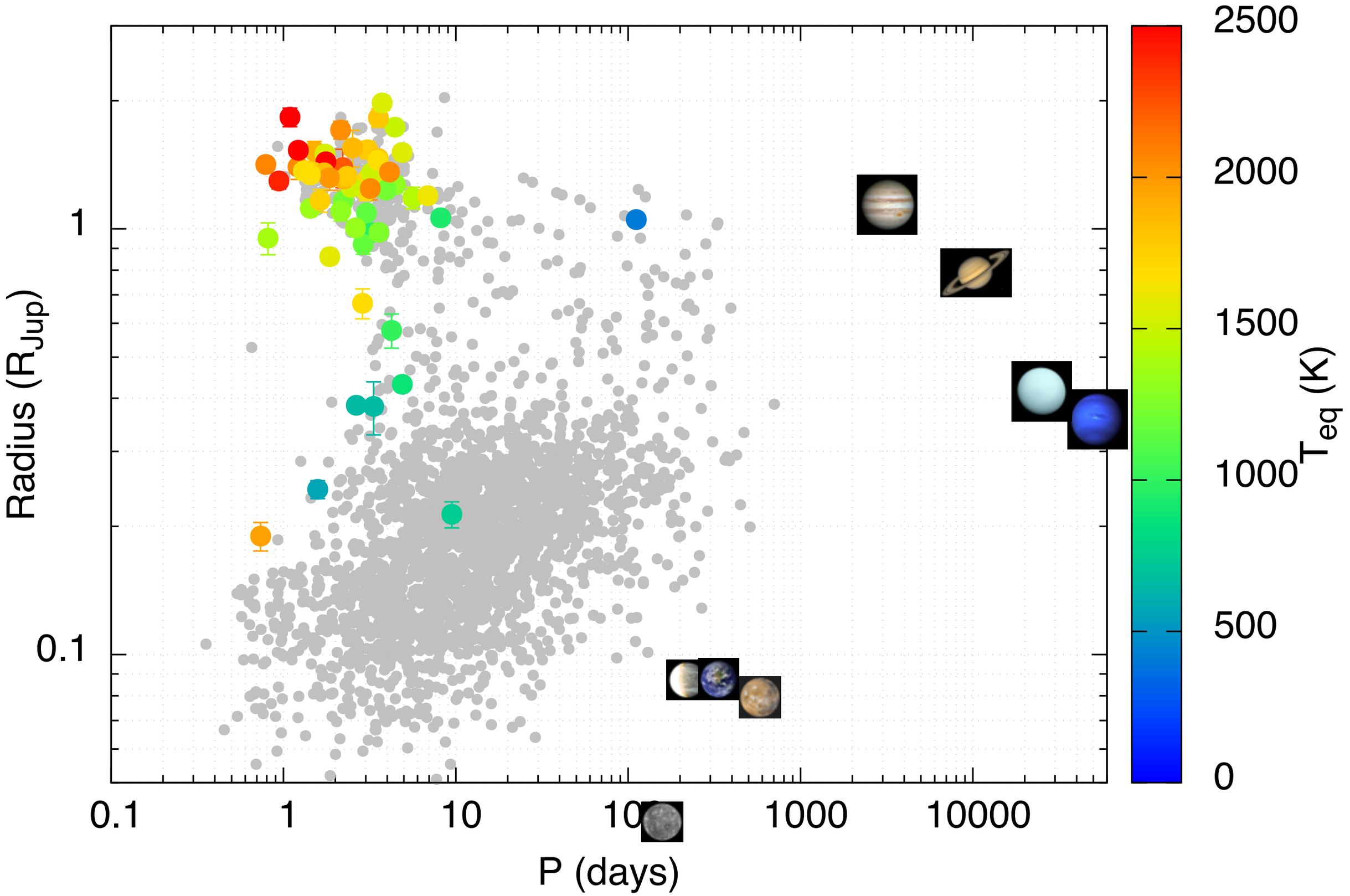
Understanding the complexity of exoplanets atmospheres
from dissociation to condensation in (ultra) hot Jupiters atmospheres.

Vivien Parmentier

Laboratoire d'Astrophysique de Marseille
Soon at the Atmospheric Oceanic and Planetary Physics research group,
Department of physics, University of Oxford

With: Mike R. Line, Jacob L. Bean, Megan Mansfield, Laura Kreidberg, Roxana Lupu, Channon Visscher, Jean-Michel Désert, Jonathan J. Fortney, Magalie Deleuil, Jacob Arcangeli, Adam P. Showman, Mark S. Marley

Atmospheric characterisation from hot Jupiters to super-Earths



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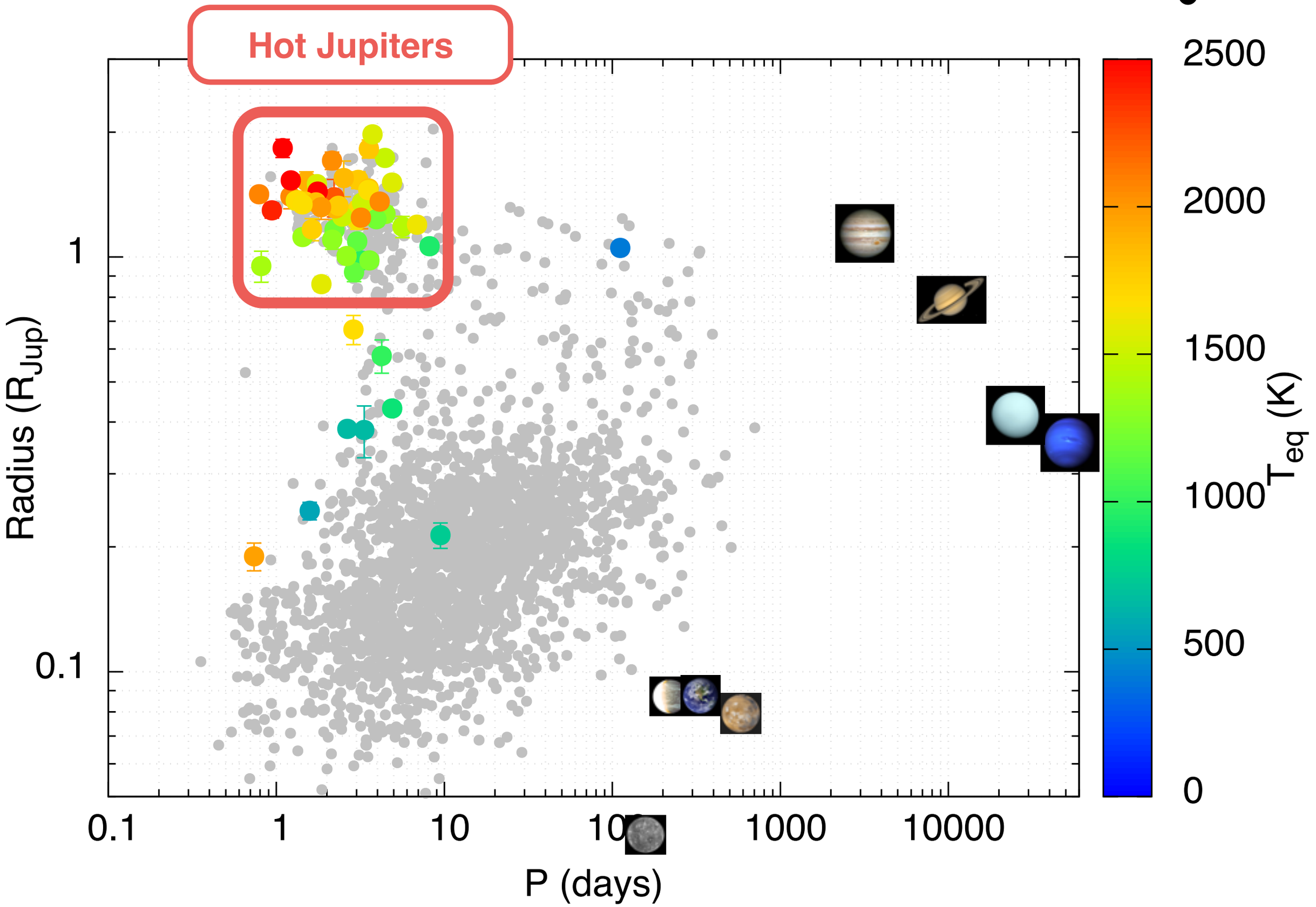

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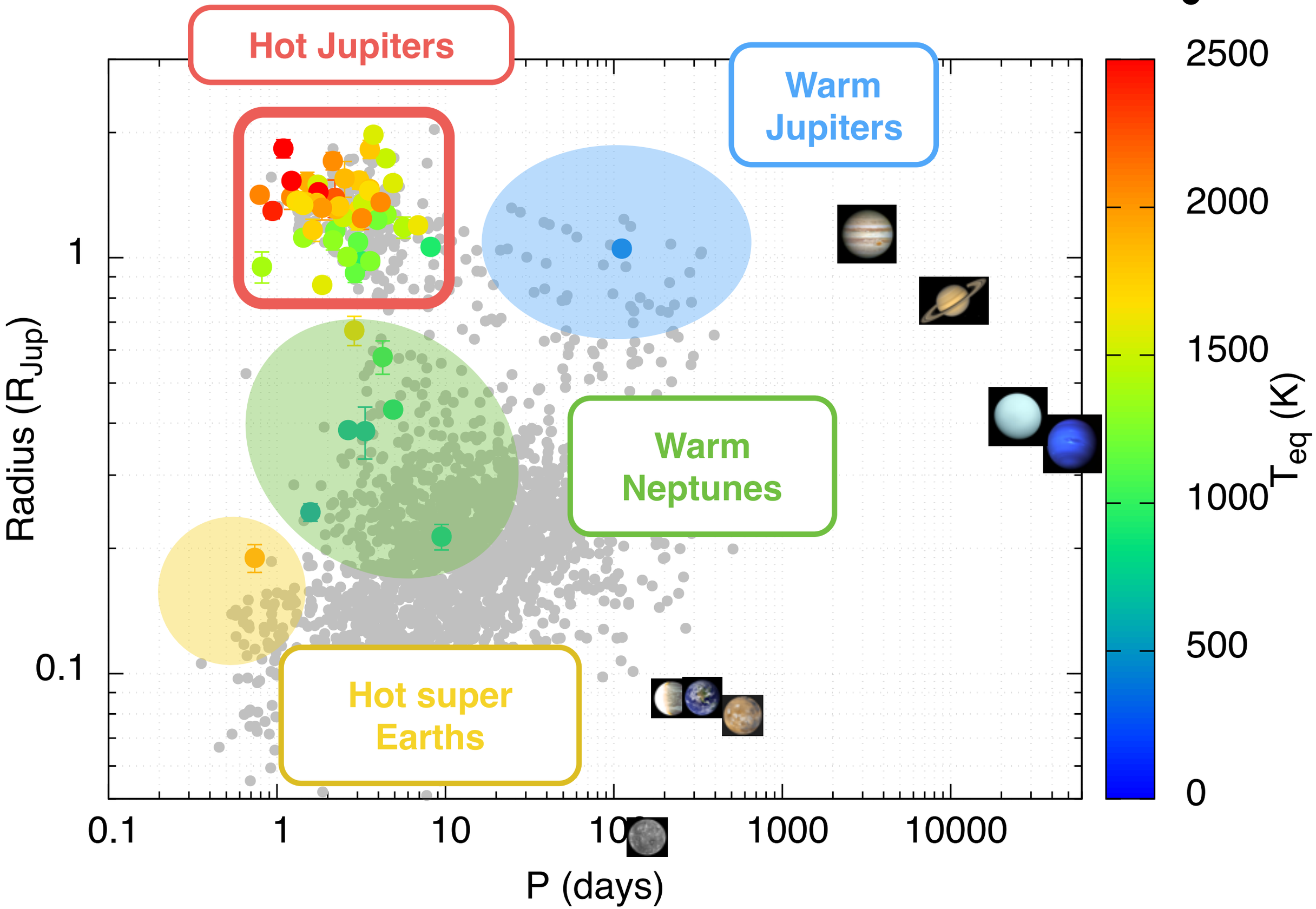

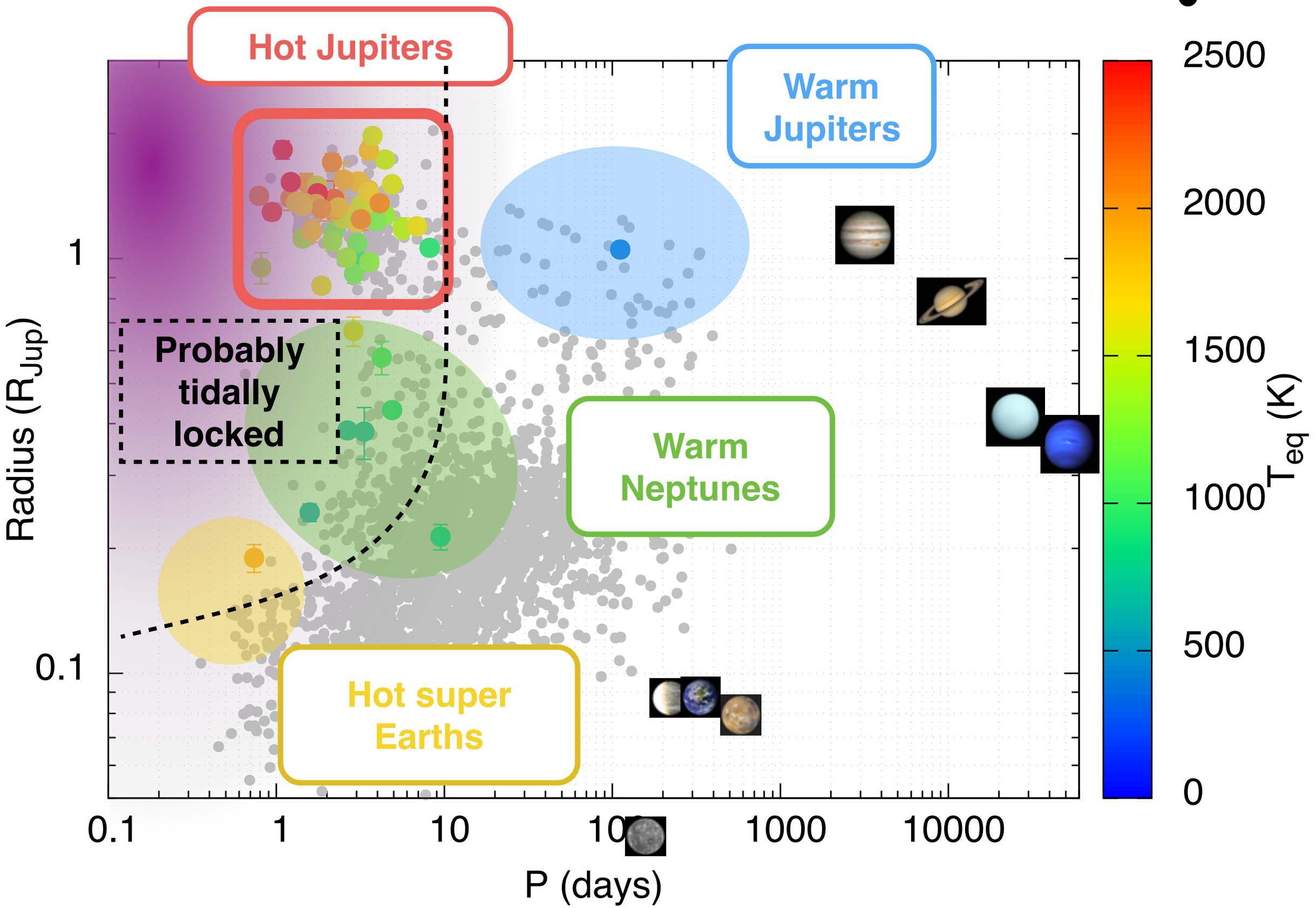
Hot Jupiters
Warm Jupiters
Probably tidally locked
Warm Neptunes
Hot super Earths
Radius (R_Jup)
1
0.1
0.1
1
10
100
1000
10000
P (days)
2500
2000
1500
1000
500
0
T_eq (K)

Seeking answers from exo-atmospheres

What are their physical and chemical properties ?

Energy transport, cloud formation, chemical disequilibrium ?

Now

What are their elemental abundances ?

Are they metal enriched ? What are the relative abundances of C, O, N etc.. ?

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Where is their diversity coming from ?

Inherited from formation ? Or resulting from long-term evolution ?

How planet accretion and formation happens ?

How unique is the solar system ?

+10 years

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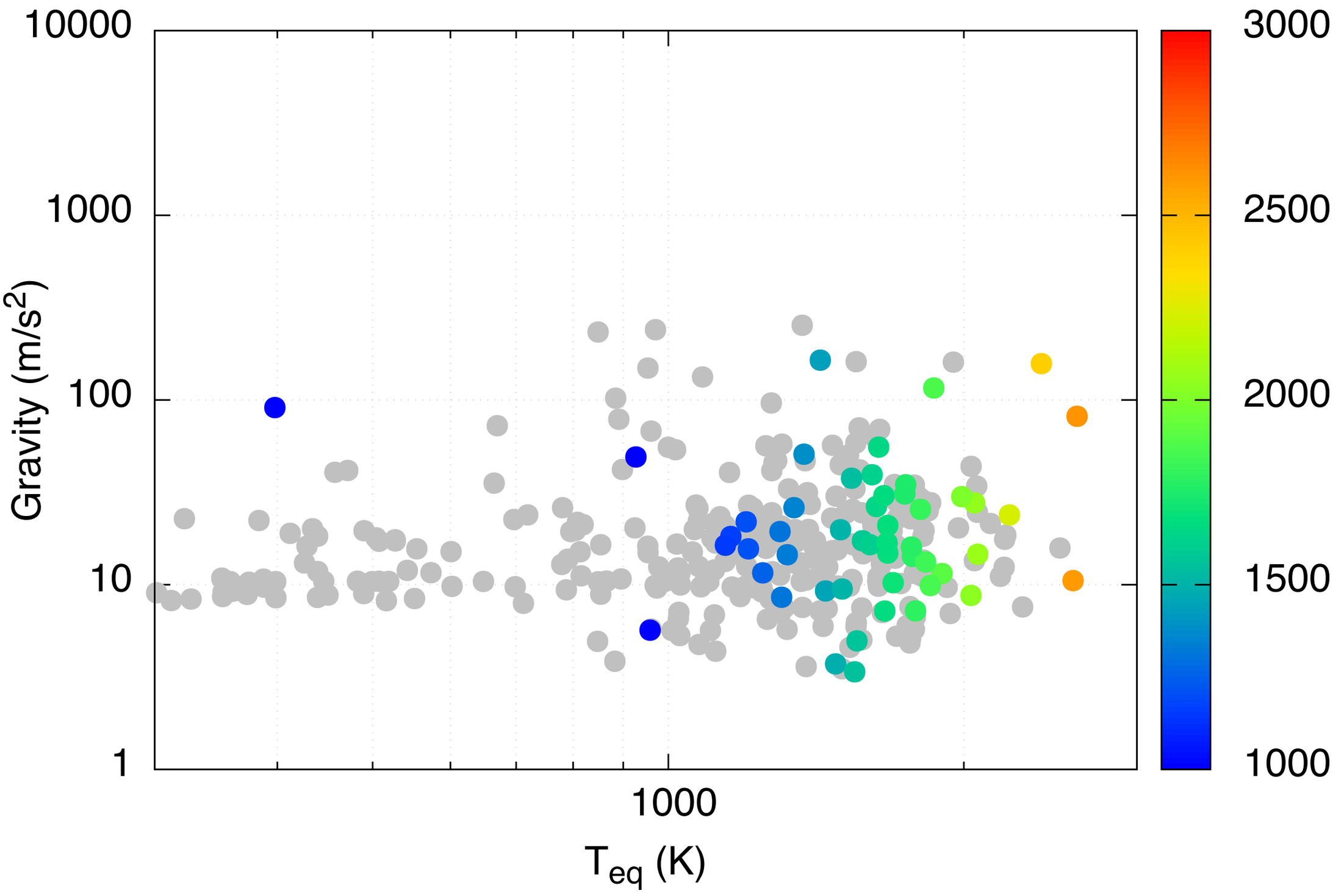
+10 years

What planets are habitable ? Inhabited ?

Will we be able to detect and recognise life ?

+20 years

The peculiar case of « Hot Jupiters »



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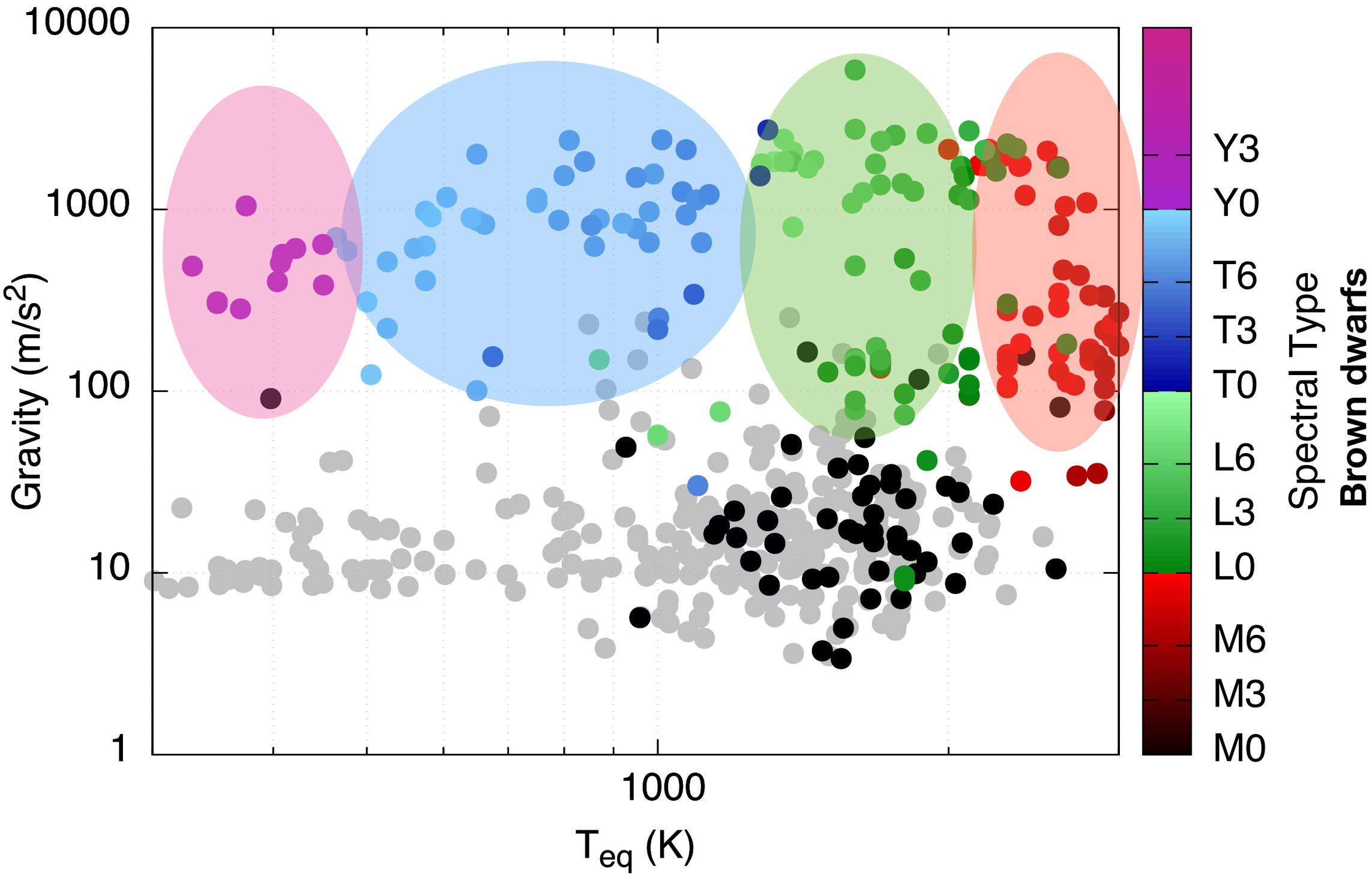

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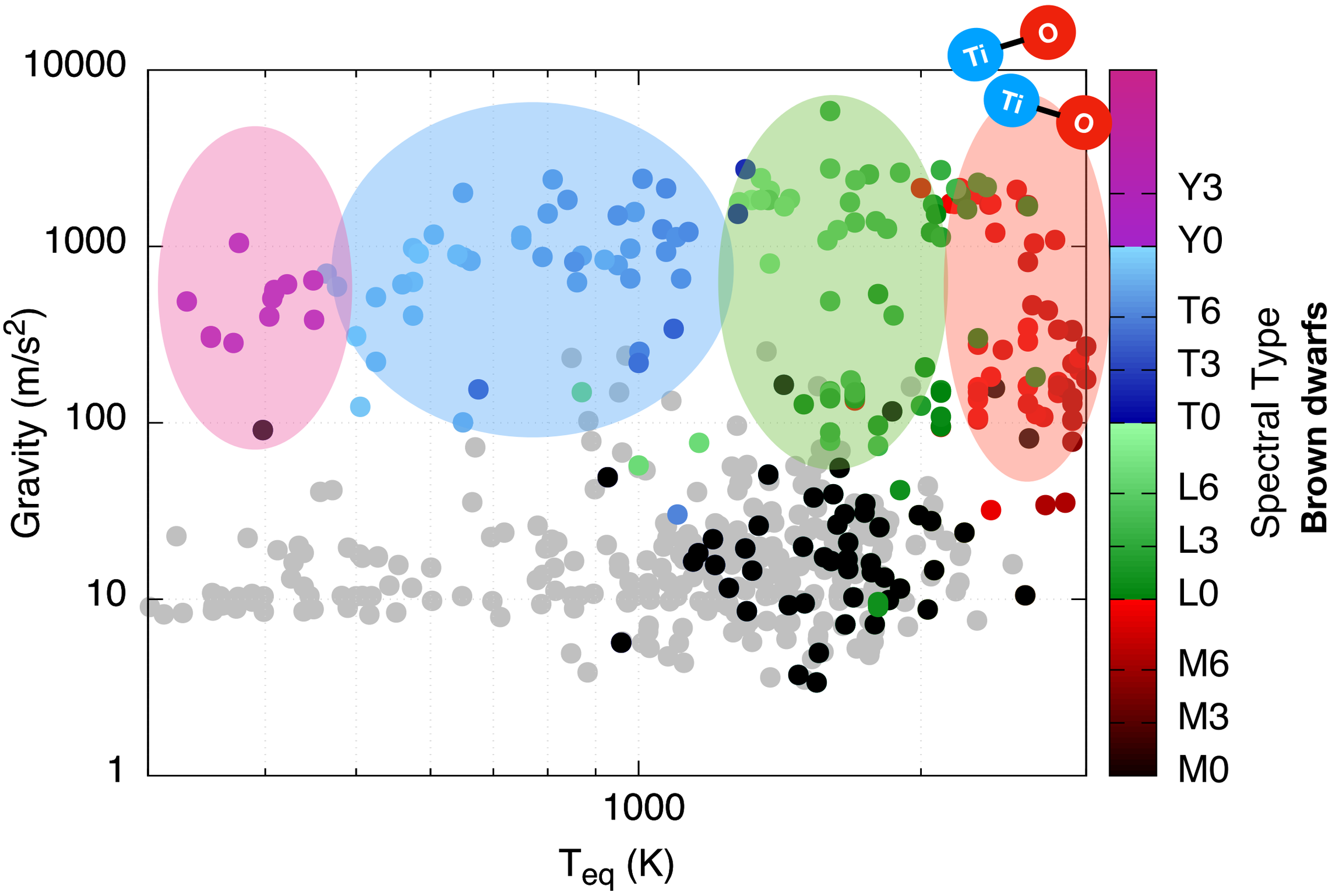

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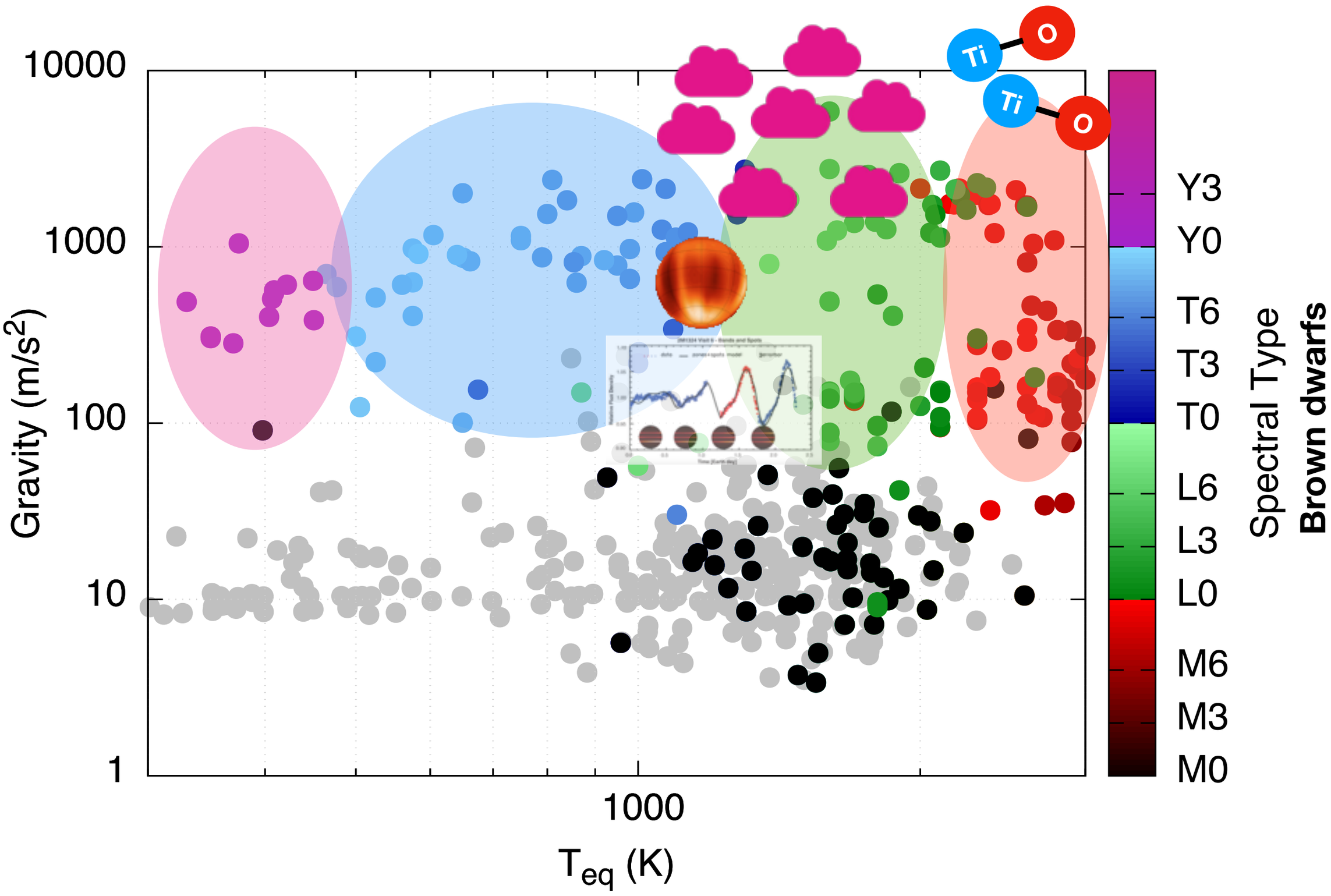

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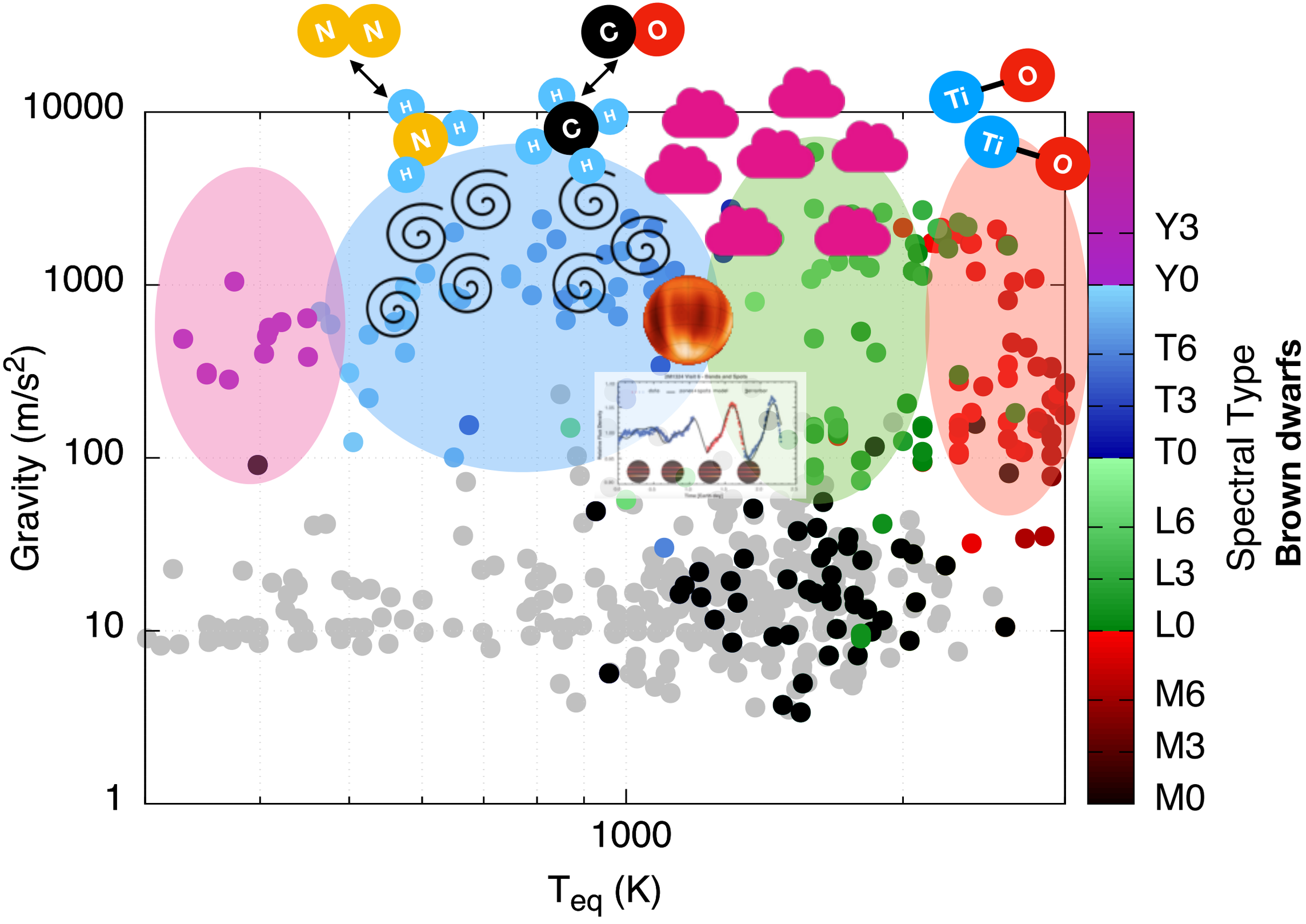

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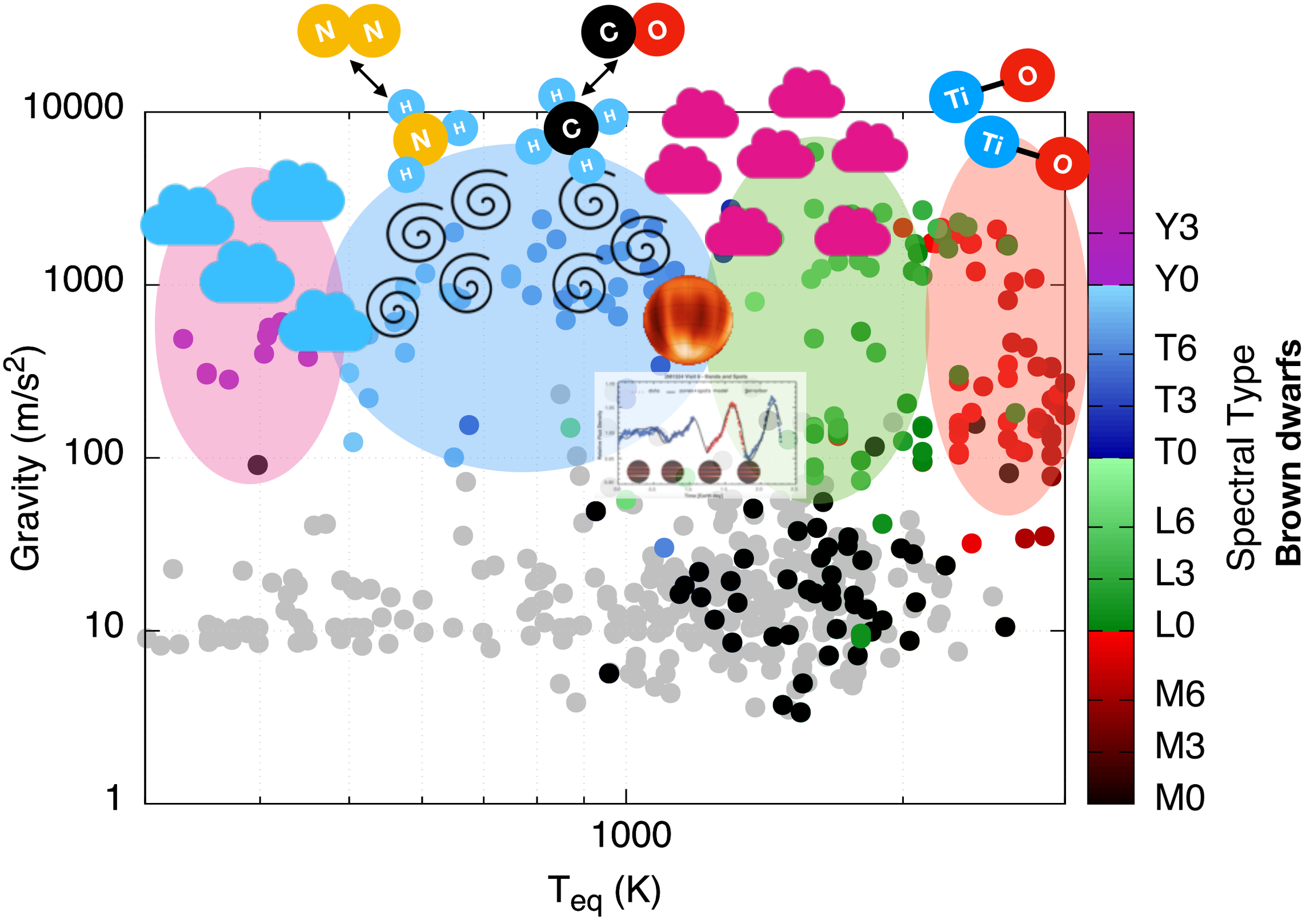

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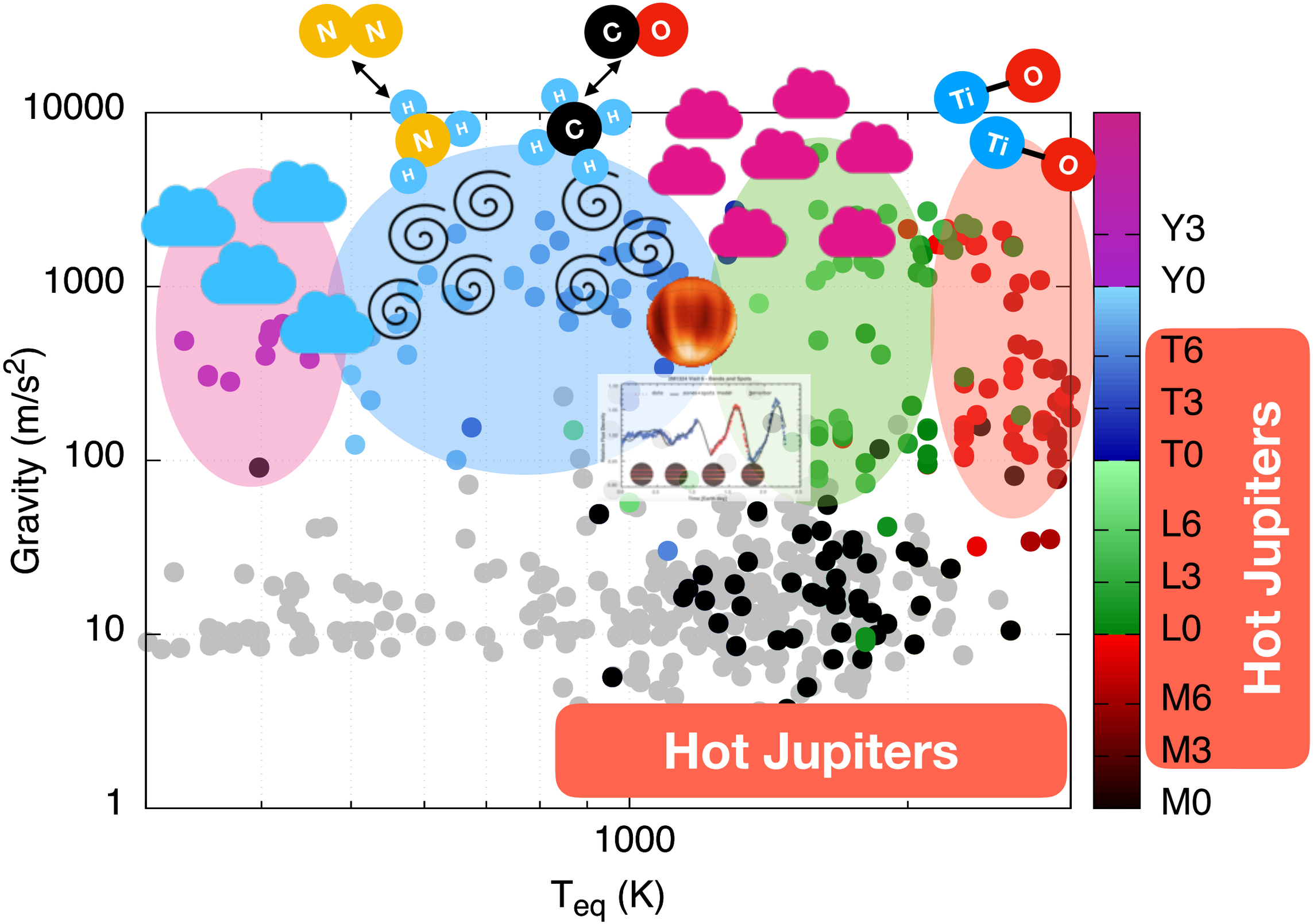
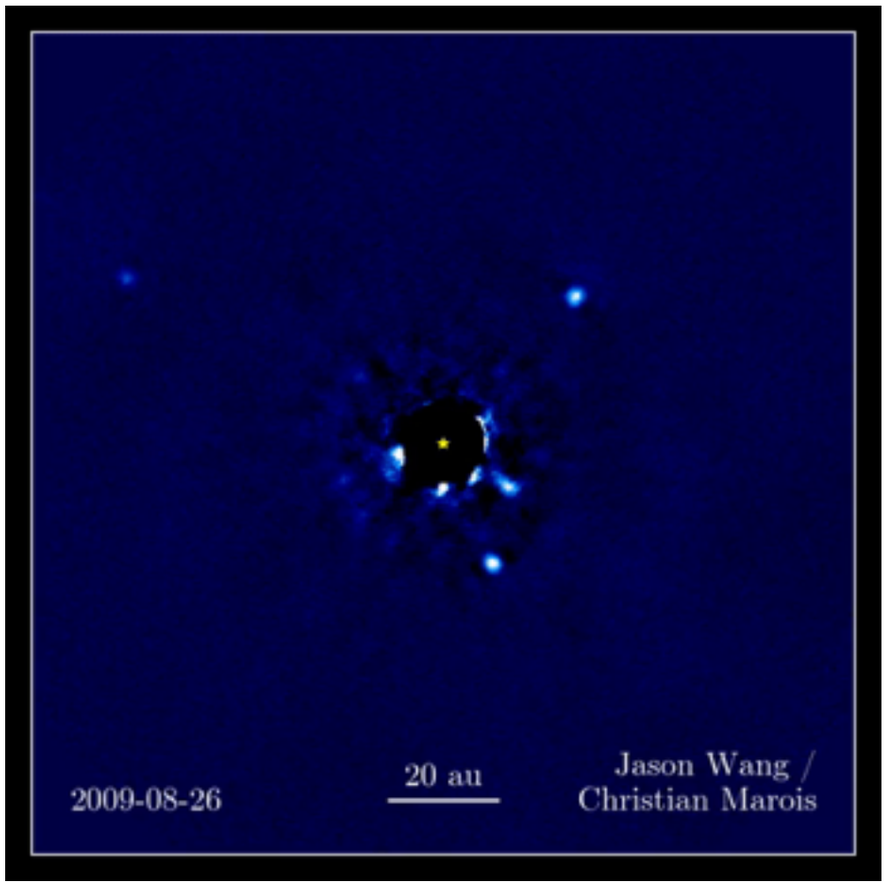


Separating planet and stellar signal

Spatial separation

High angular resolution



Separating planet and stellar signal

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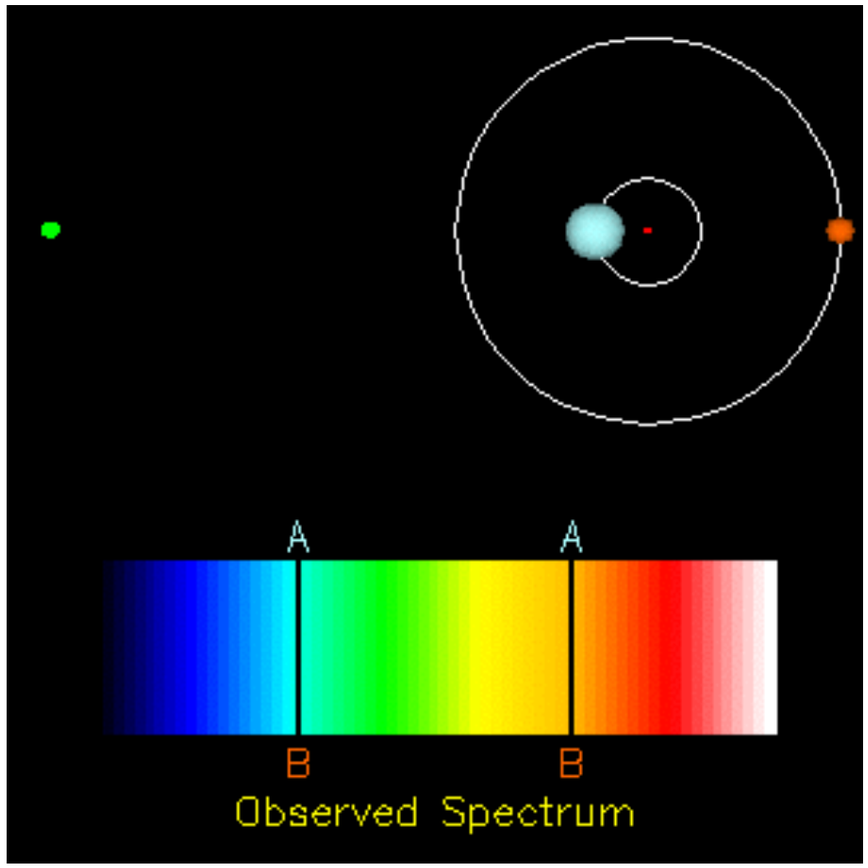
Spectral separation

High spectral resolution



Separating planet and stellar signal

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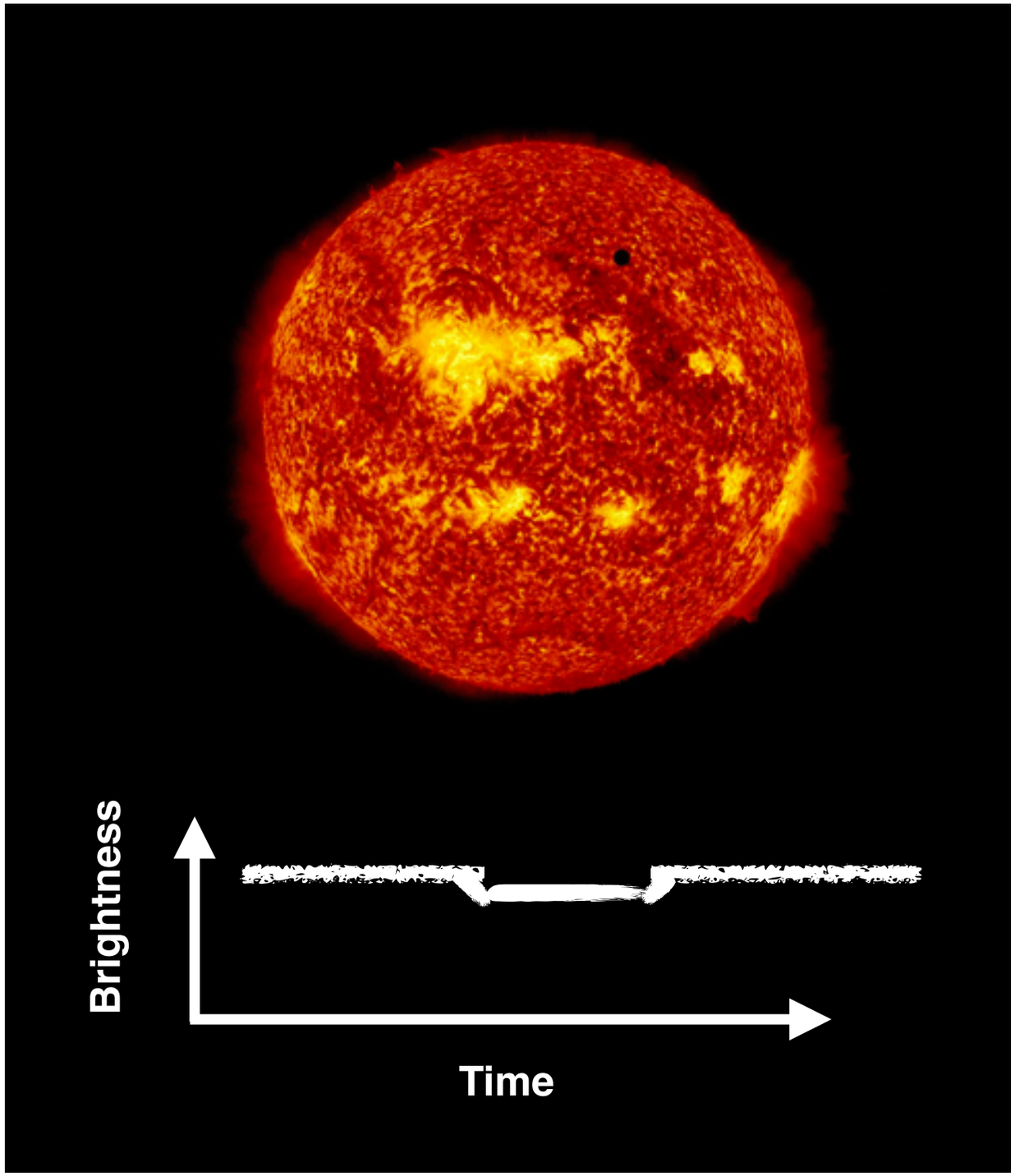
High angular resolution

Spectral separation

High spectral resolution

Temporal separation

High temporal stability



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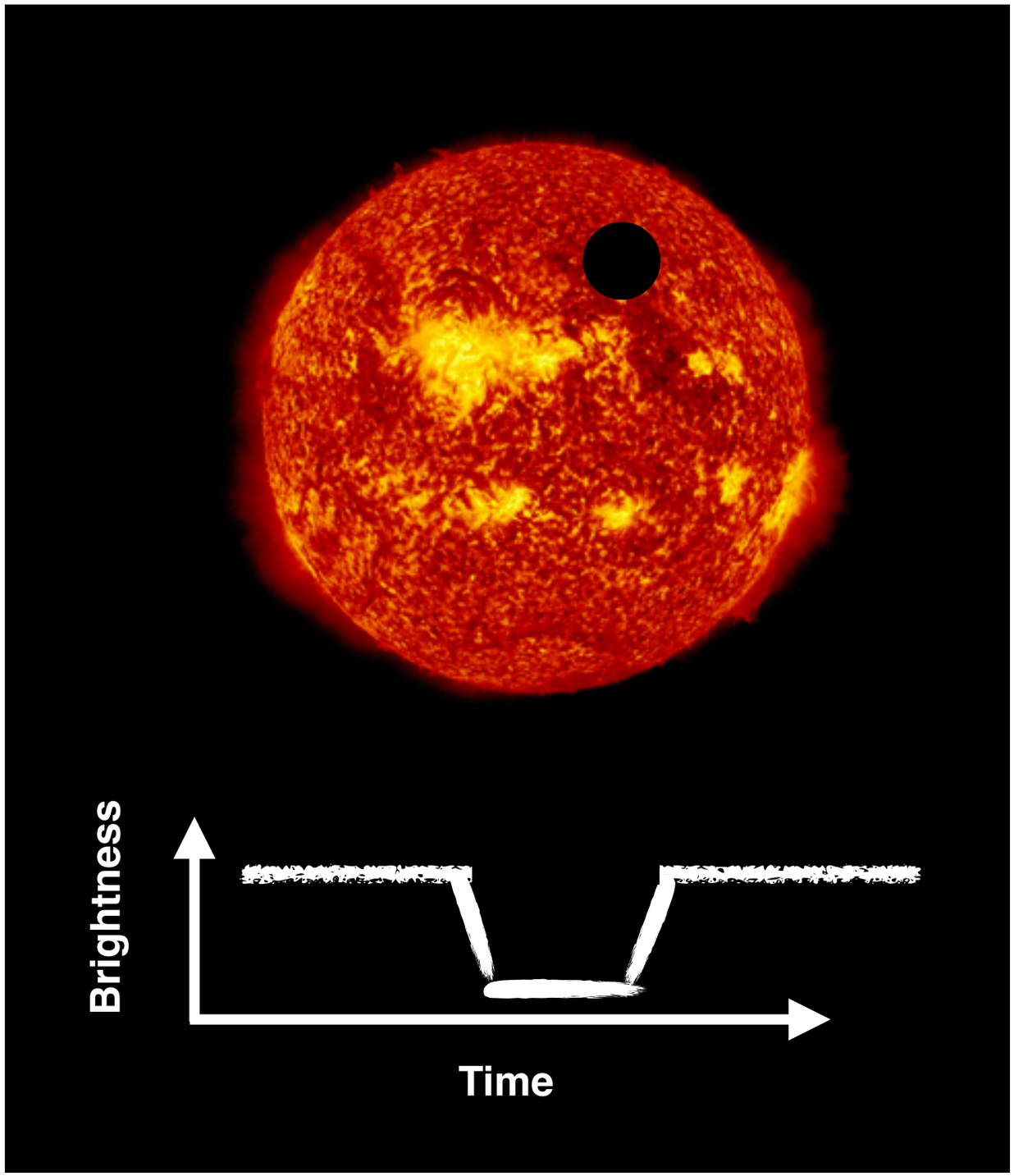
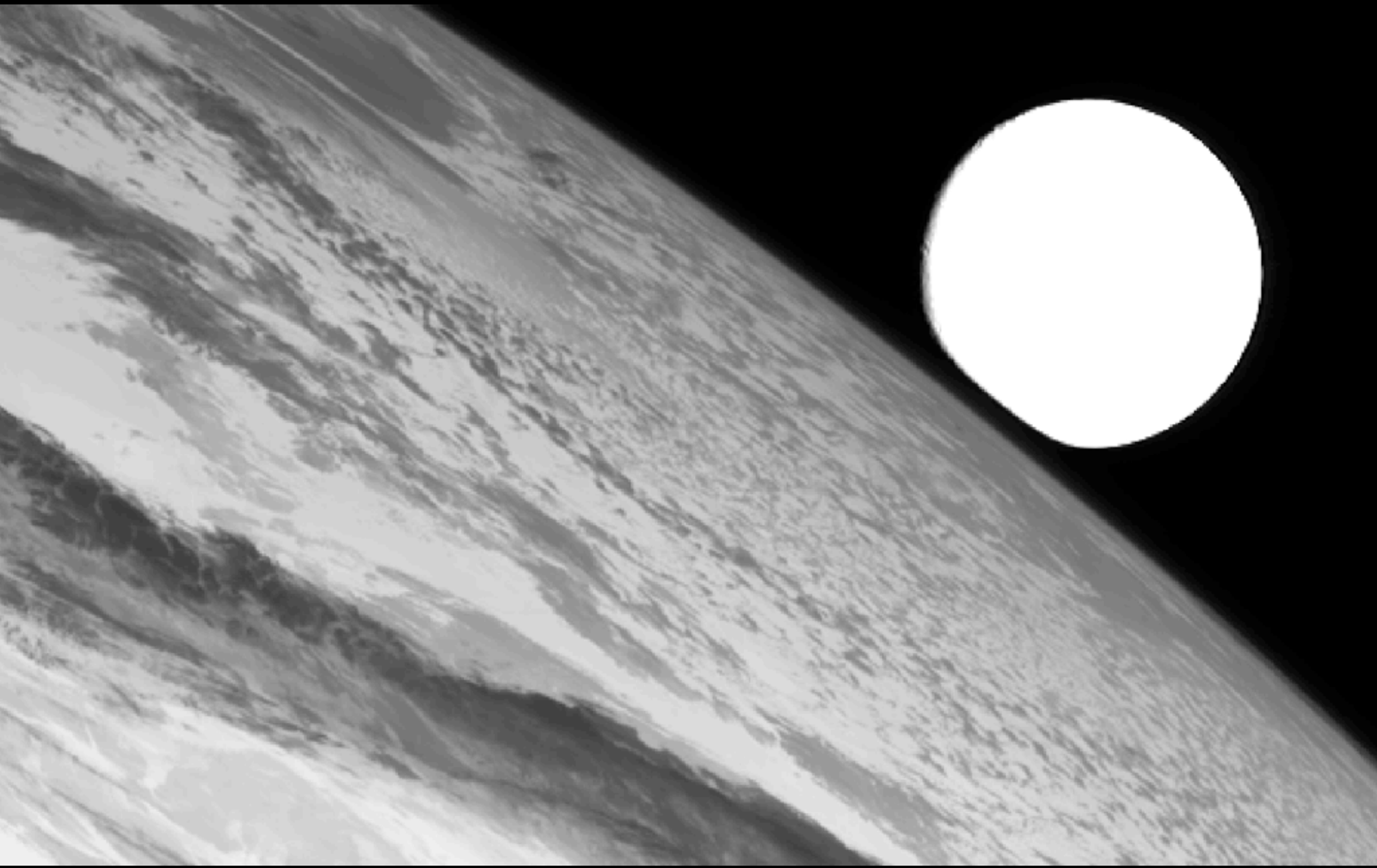


Real color

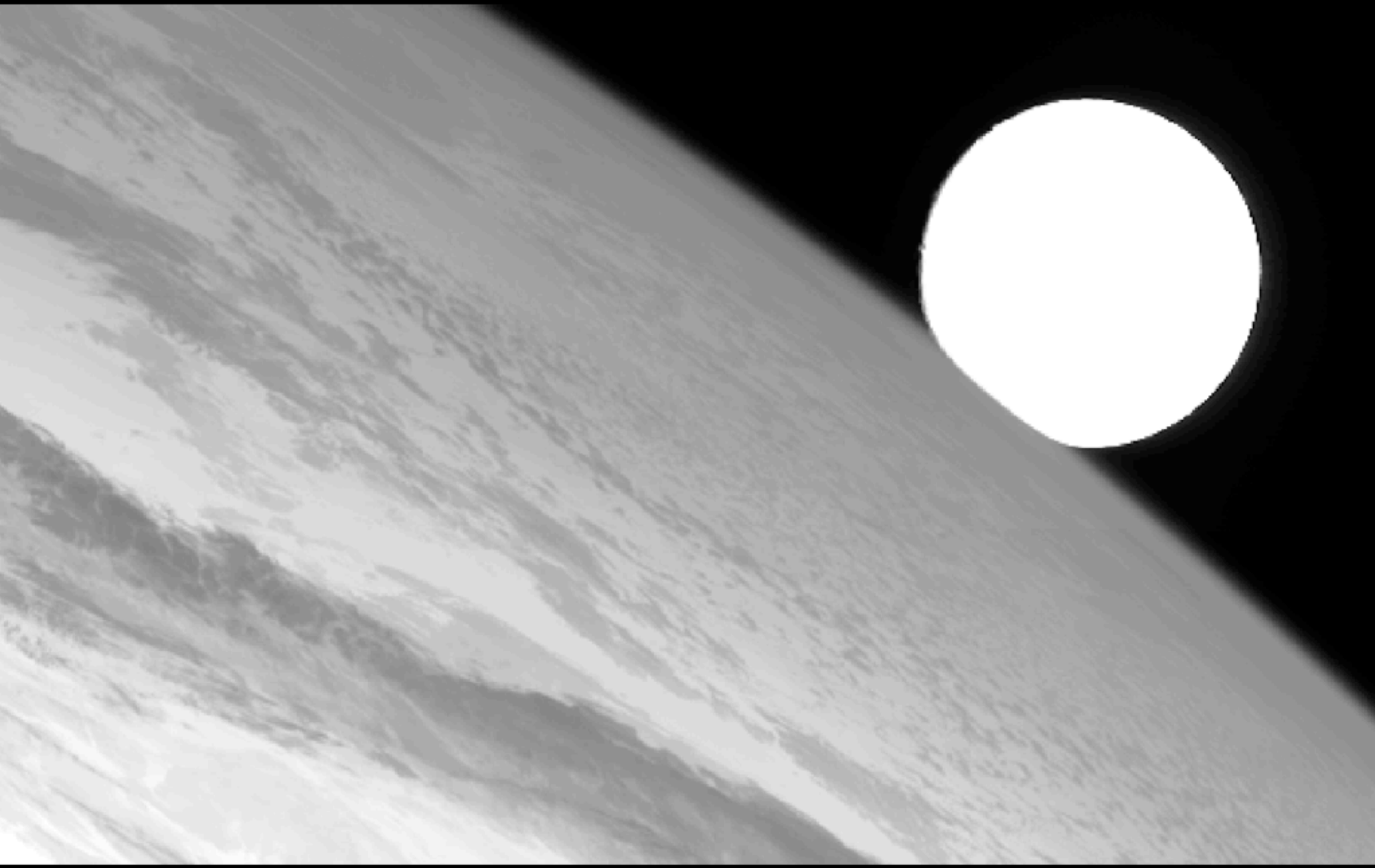
Credit: Himawary/Simon Proud/Vivien Parmentier

8.6 microns



Credit: Himawary/Simon Proud/Vivien Parmentier

9.6 microns — O_3 band



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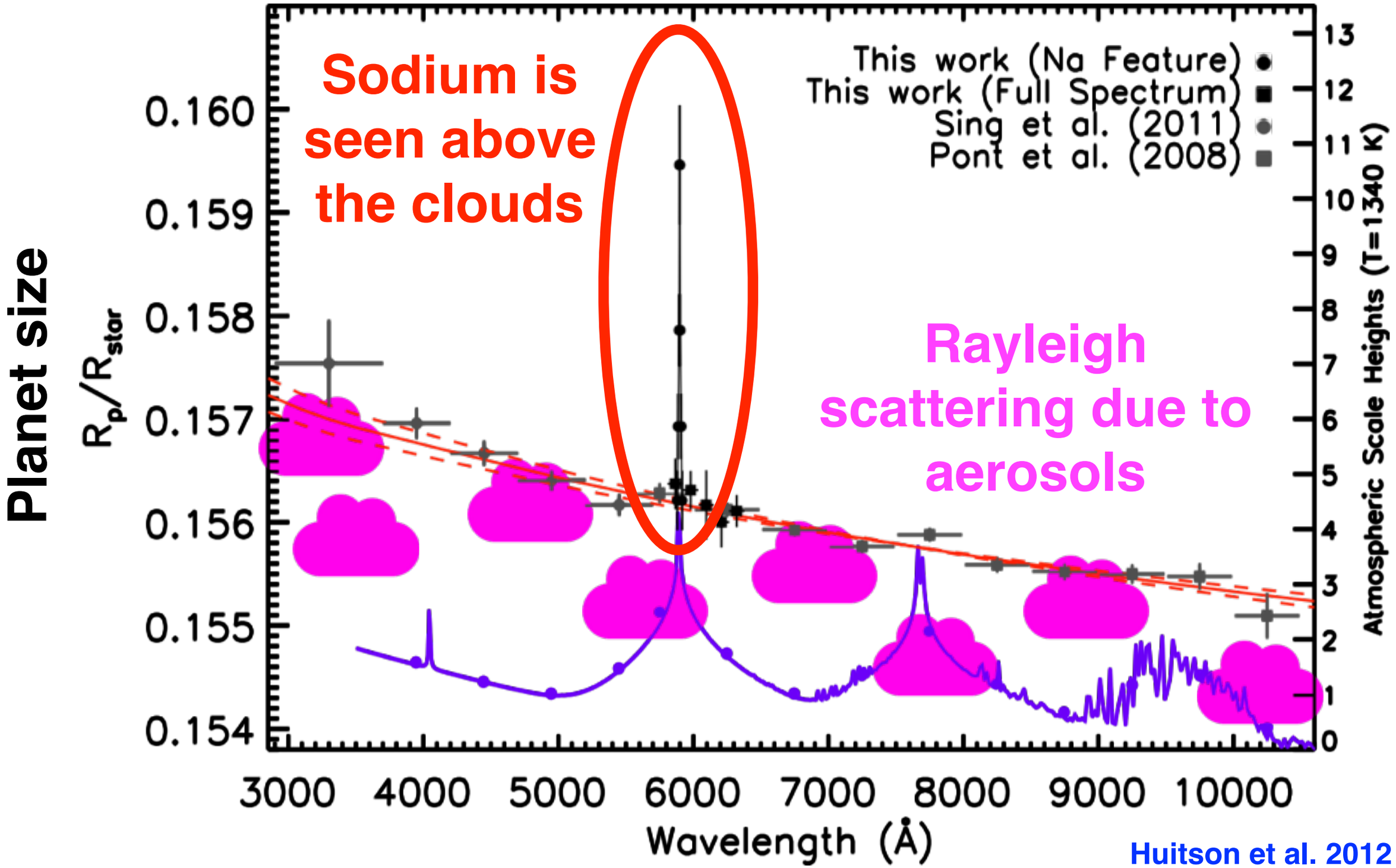
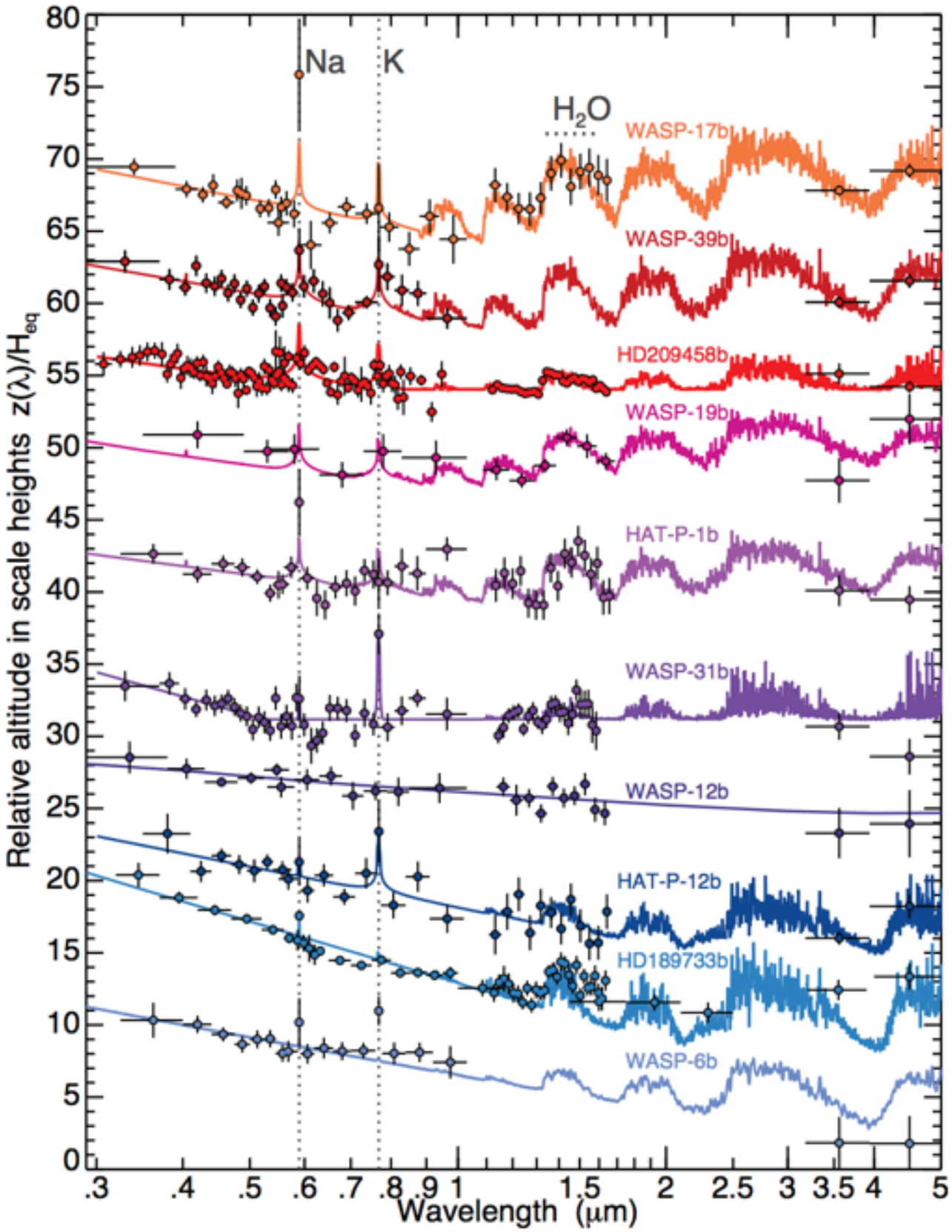

Sodium is seen above the clouds
Rayleigh scattering due to aerosols
This work (Na Feature)
This work (Full Spectrum)
Sing et al. (2011)
Pont et al. (2008)
Planet size
R_p/R_{star}
0.160
0.159
0.158
0.157
0.156
0.155
0.154
Atmospheric Scale Heights (T=1340 K)
13
12
11
10
9
8
7
6
5
4
3
2
1
0
3000
4000
5000
6000
7000
8000
9000
10000
Wavelength (Å)
Huitson et al. 2012
Color

Family portrait



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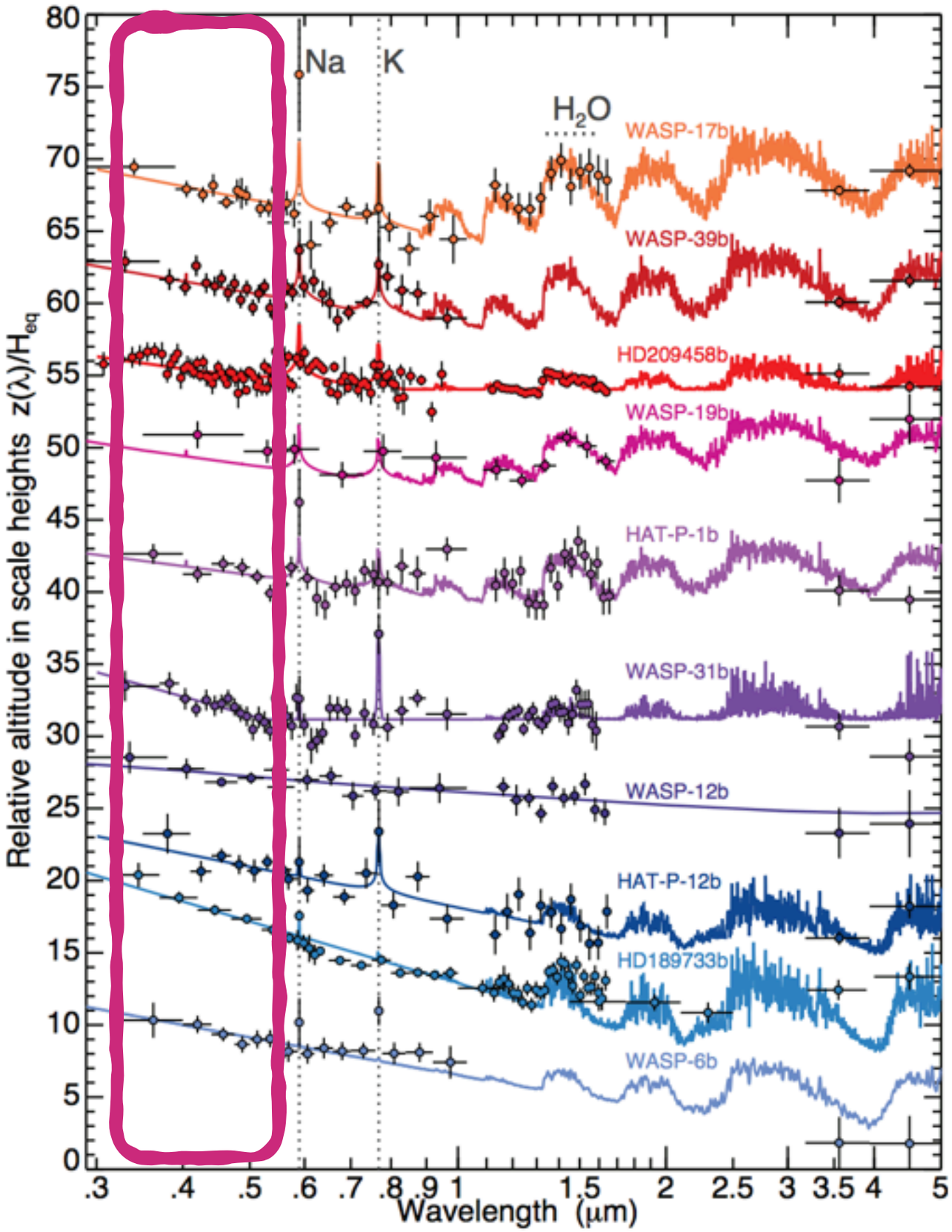
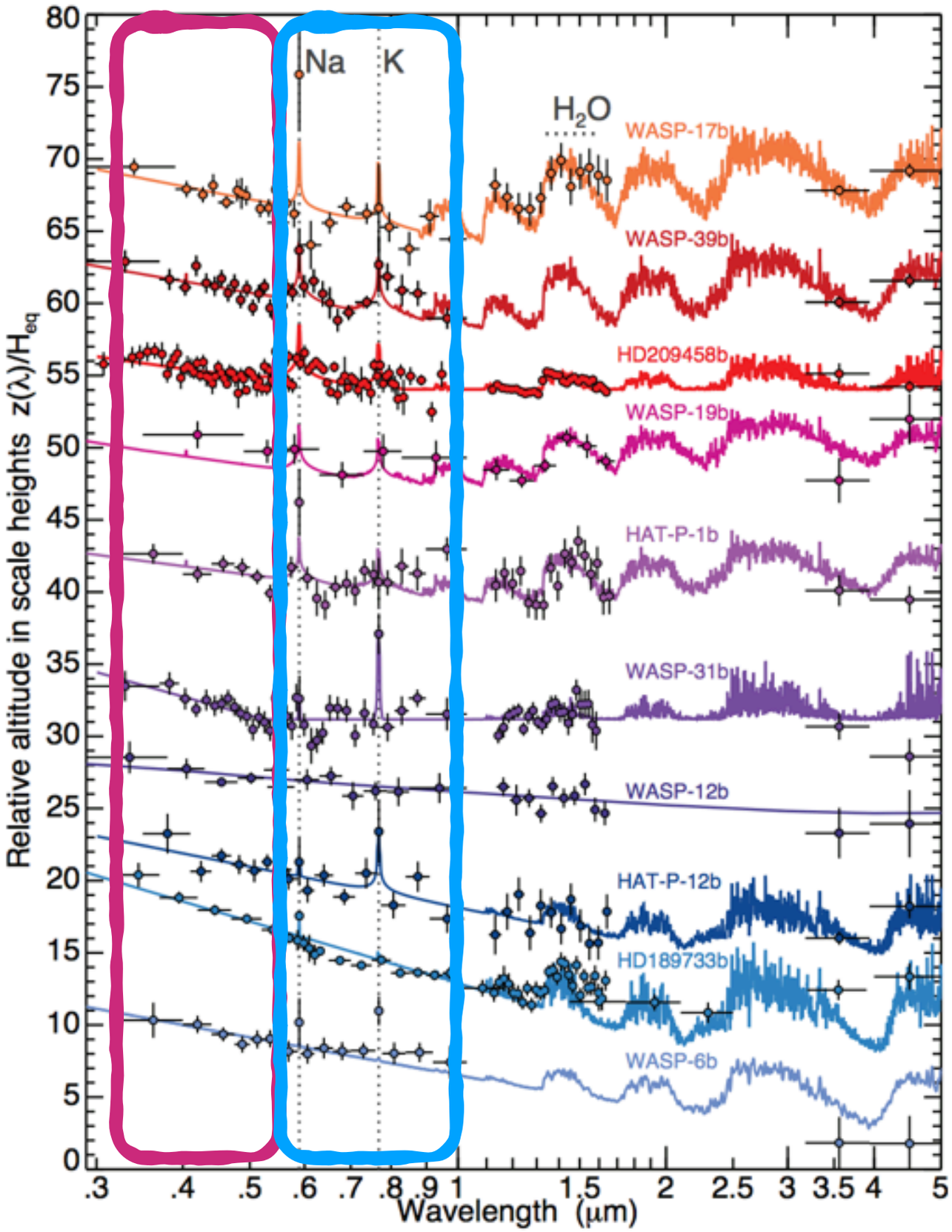


NUV (HST/STIS, Ground-based)

\+ Rayleigh scattering & exosphere

— Stellar activity and clouds

Family portrait



NUV (HST/STIS, Ground-based)
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Optical (HST/STIS, VLT/FORS2)
+ Alkalies, ground base possible
— Stellar activity and clouds

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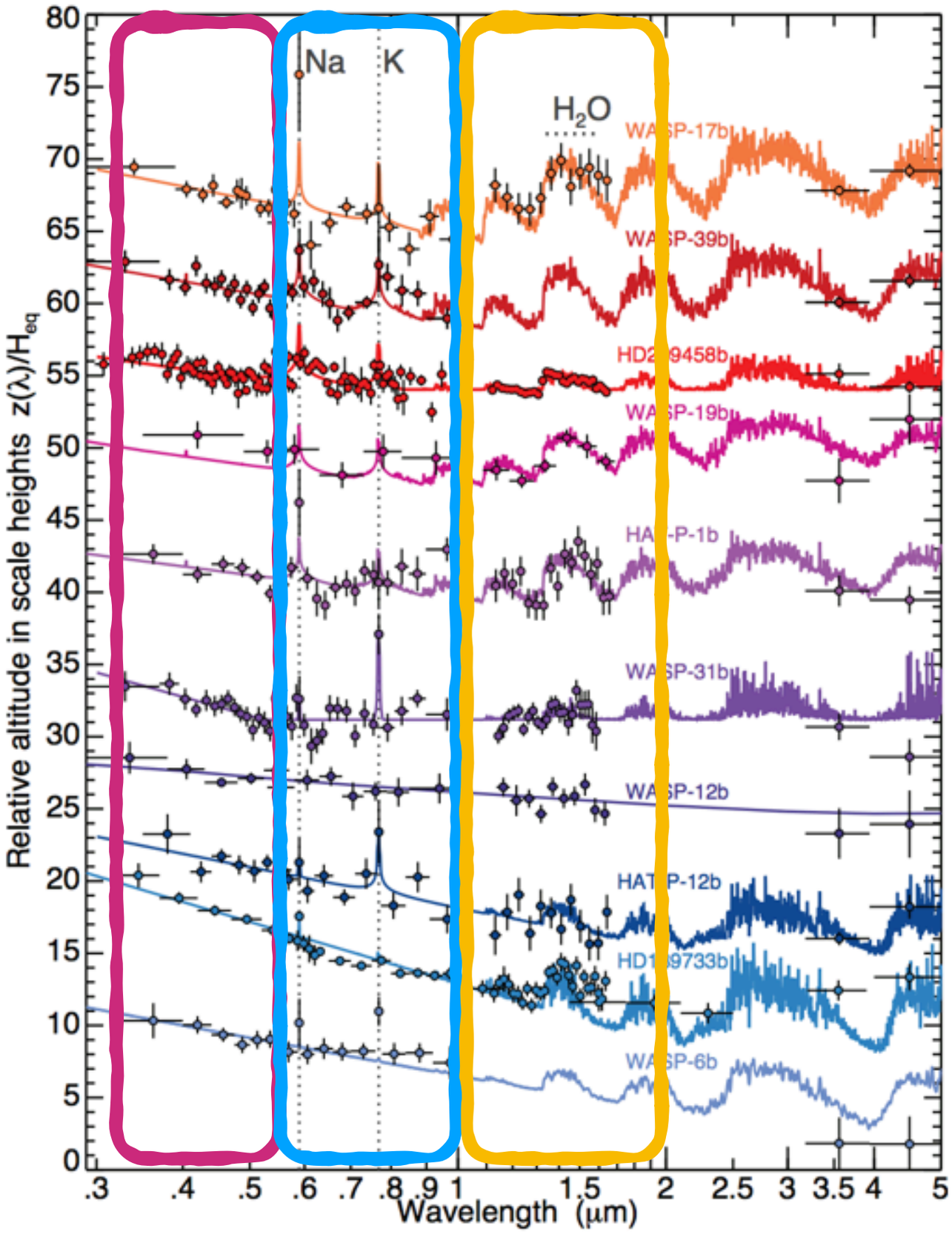

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NIR (HST/WFC3)
+ Water and Methane bands
— Clouds and again clouds

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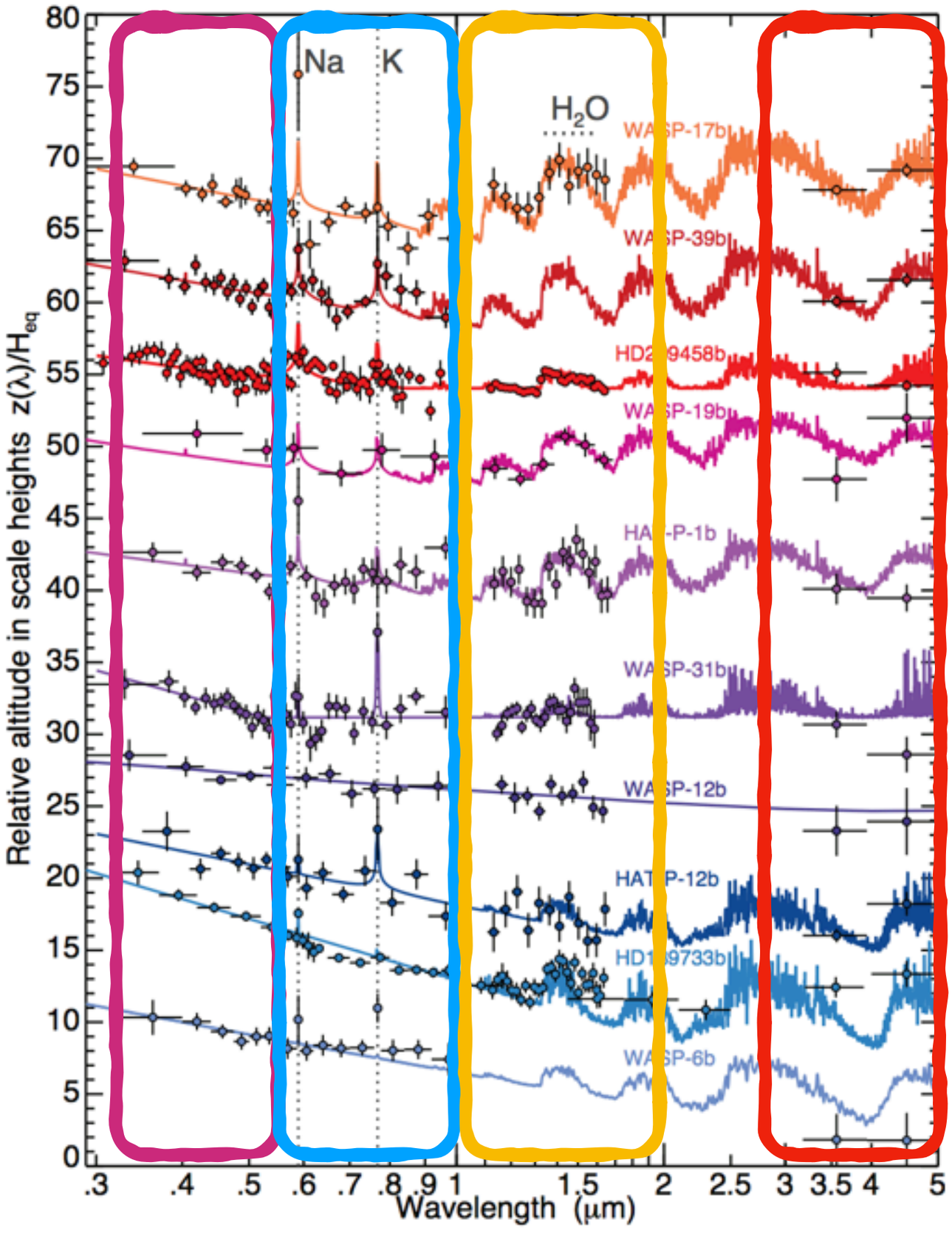

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IR (Spitzer)
+ Water/Methane/CO_2/CO/NH_3 bands
+ Can maybe see through the clouds
— Need to wait for JWST to launch…

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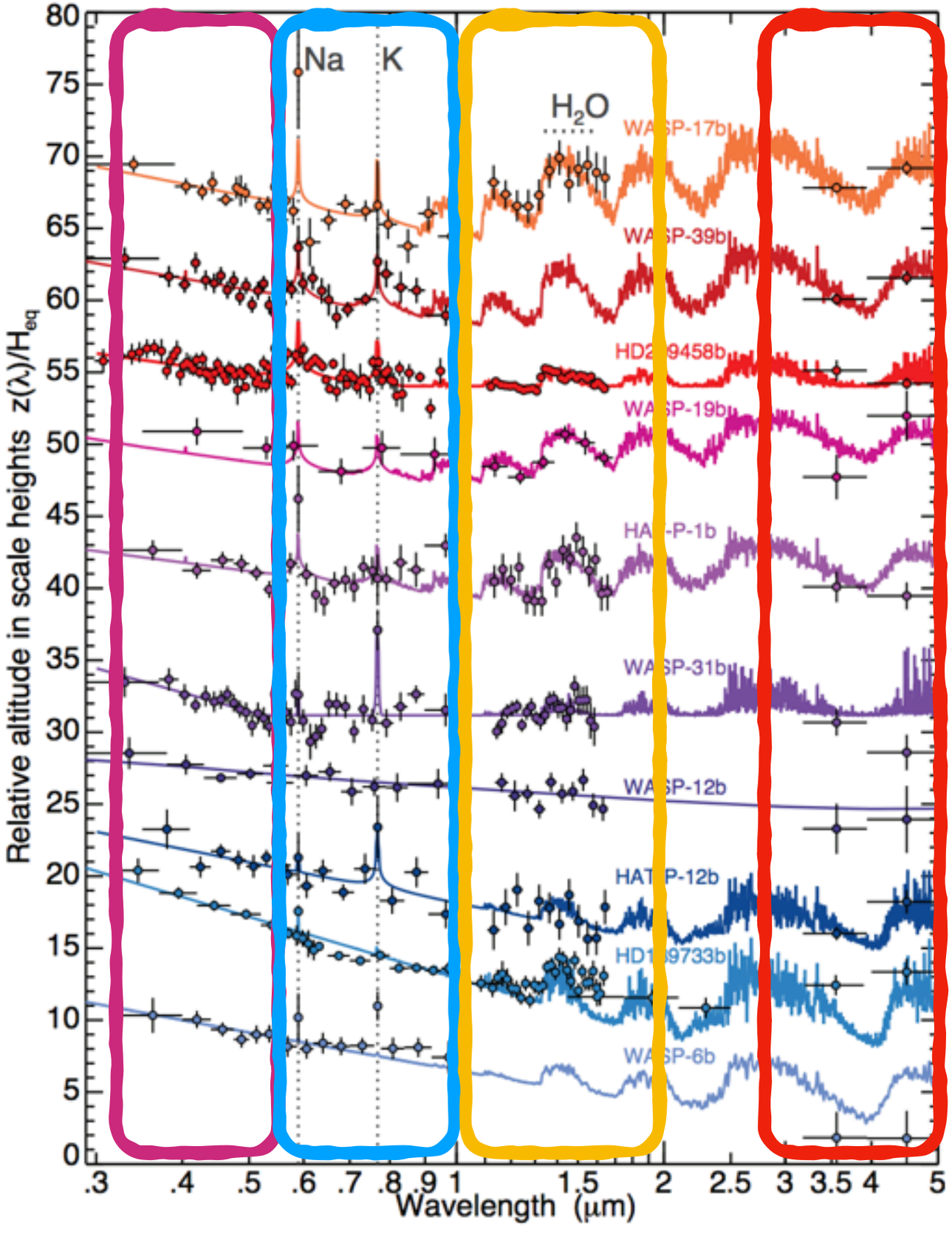

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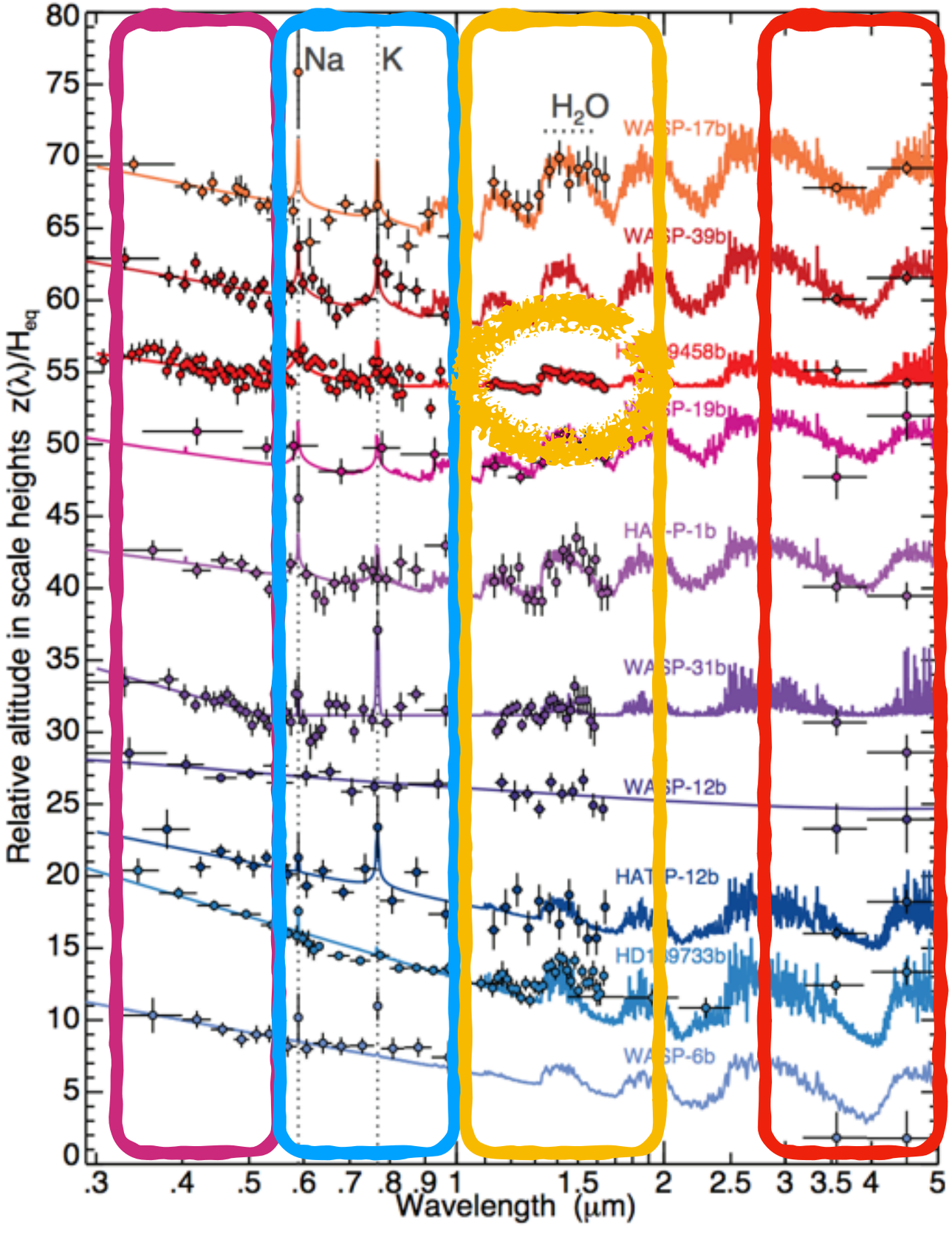
The vast majority of hot Jupiters are somewhat cloudy

Even the hottest ones

Family portrait



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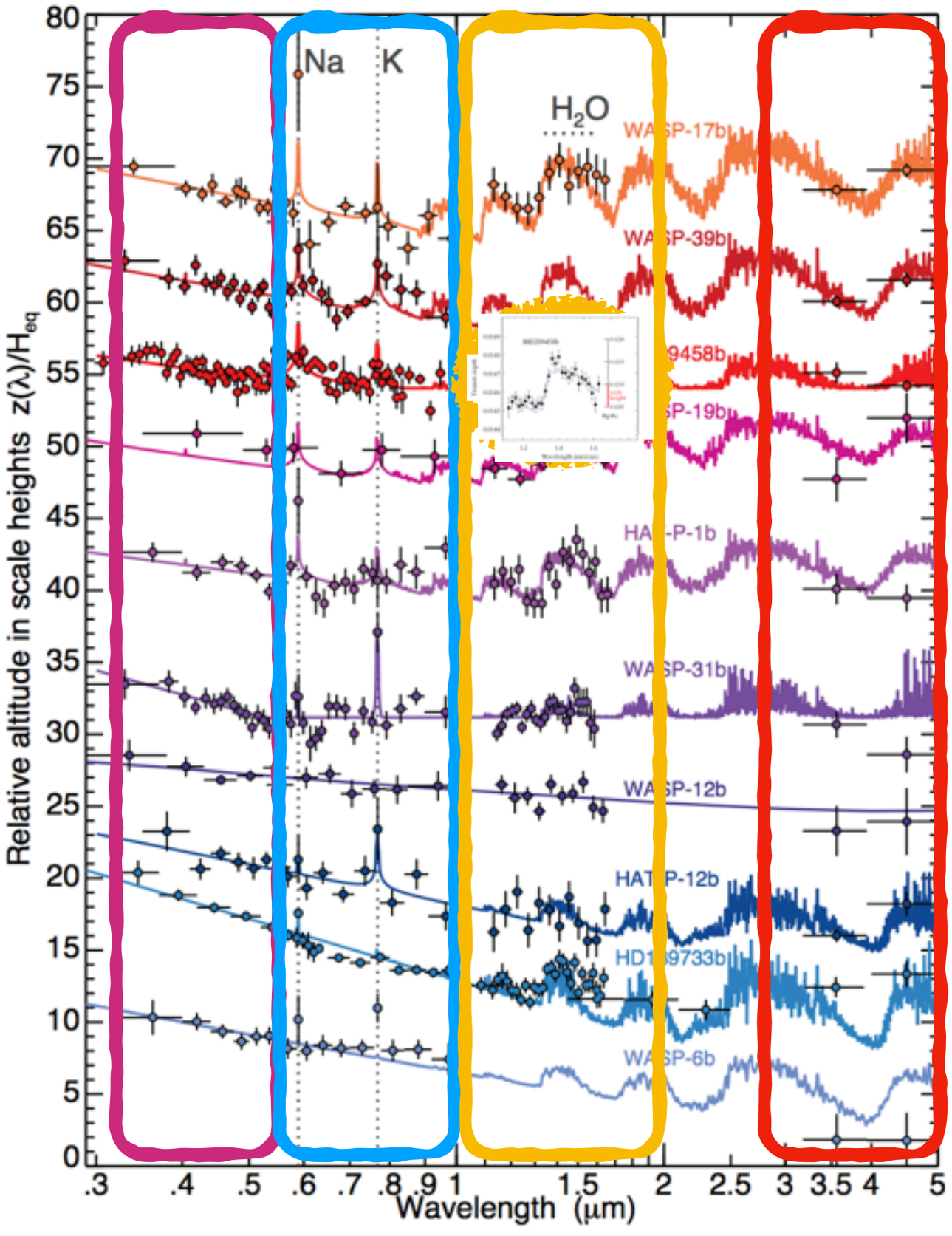

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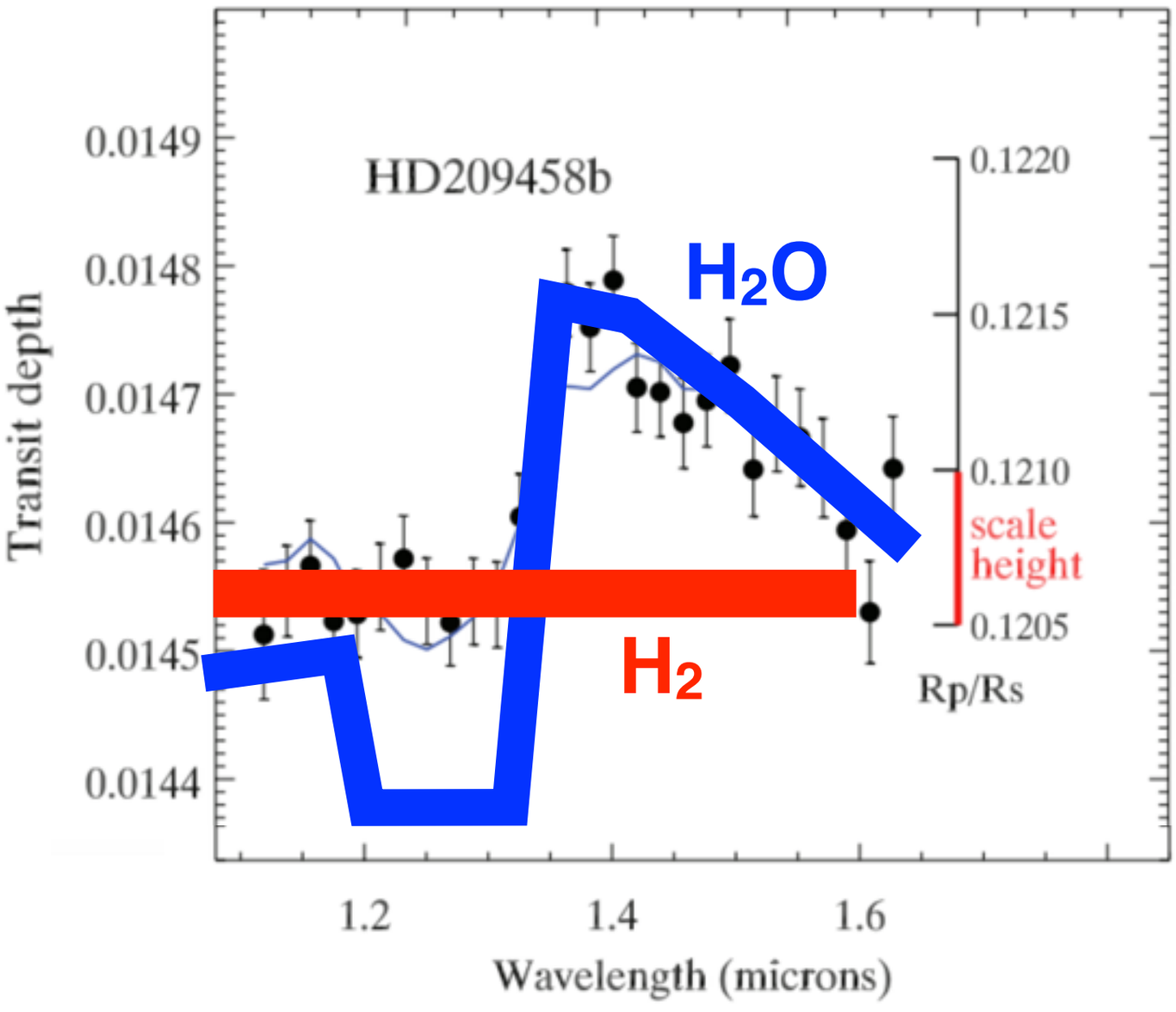
Even the hottest ones

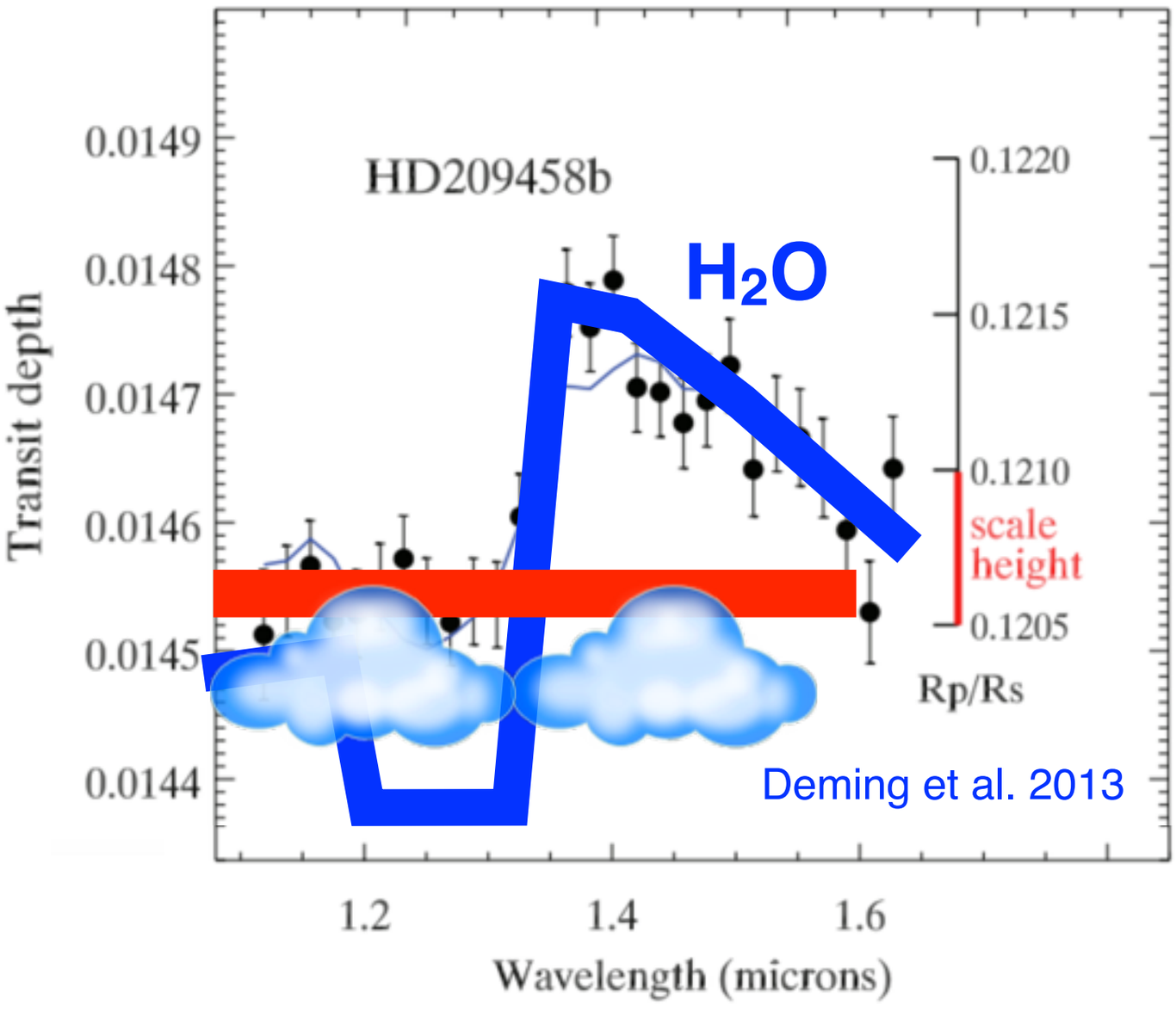
Measuring water abundances with HST/WFC3



Water absorption should look like this unless

…

Measuring water abundances with HST/WFC3



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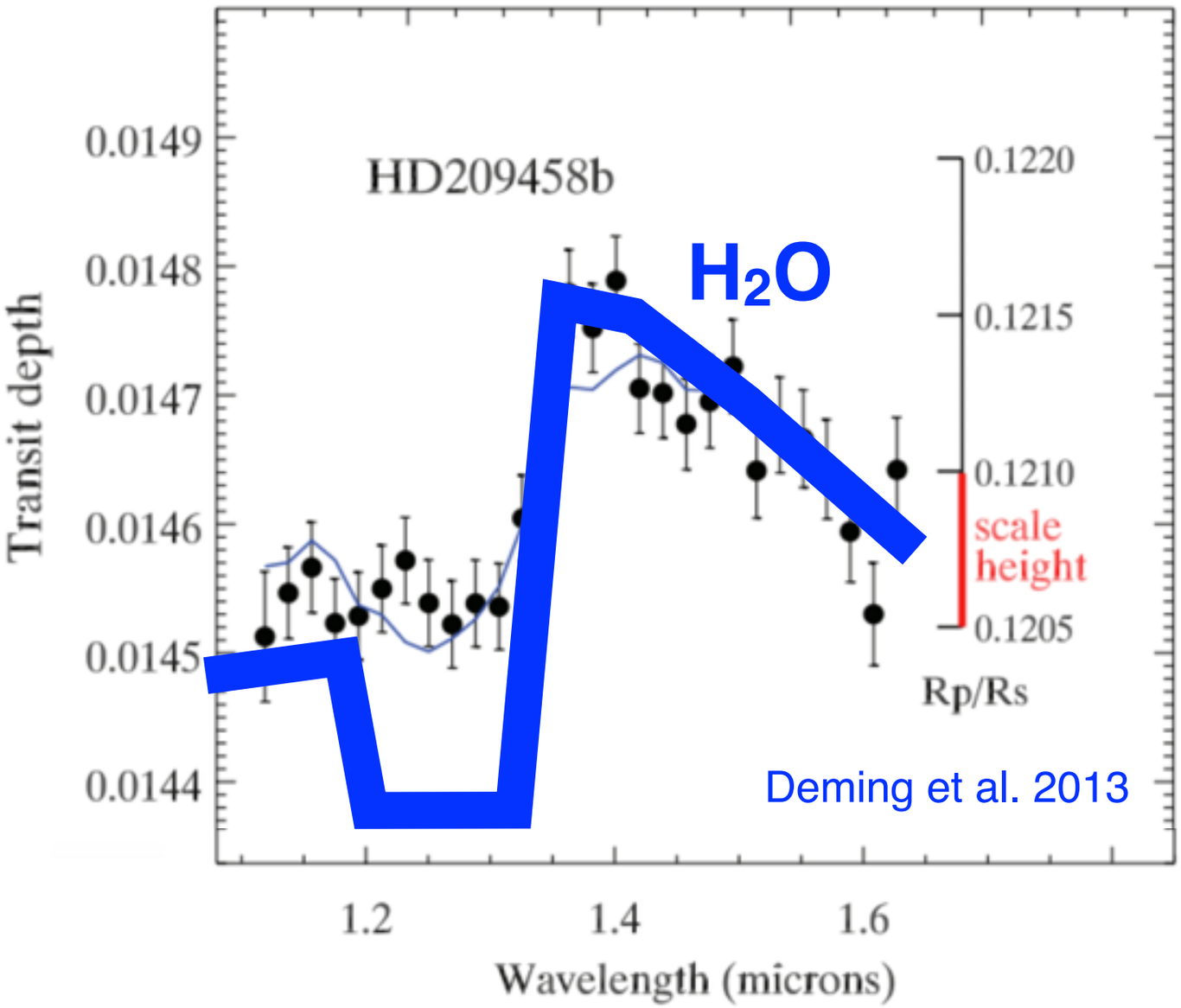
→ it is obscured by H_2
small water abundance

→ it is obscured by clouds
any water abundance

Measuring water abundances with HST/WFC3



Water absorption should look like this unless

…

→ it is obscured by H_2

small water abundance

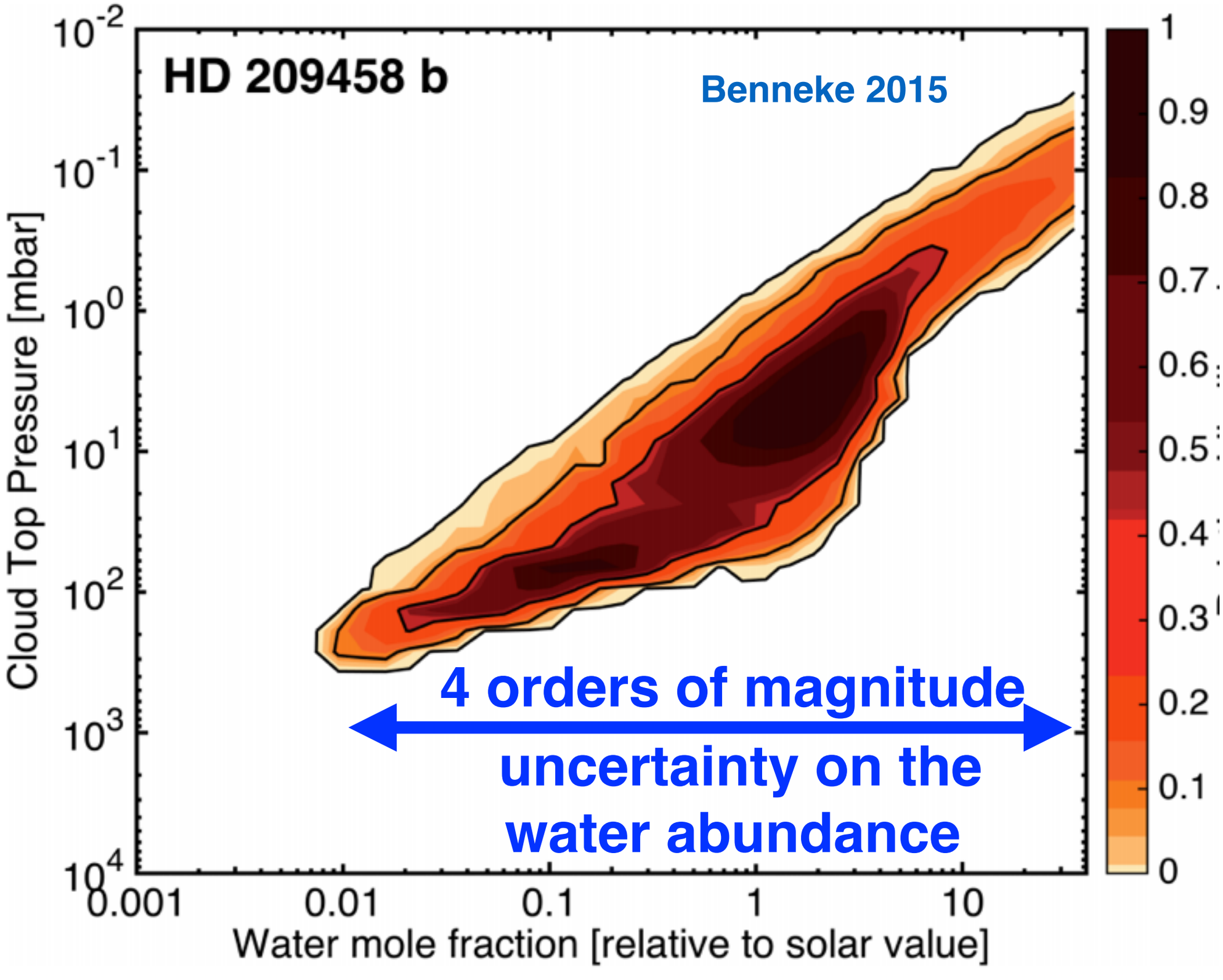
→ it is obscured by clouds

any water abundance

→ molecular weight is large

high water abundance

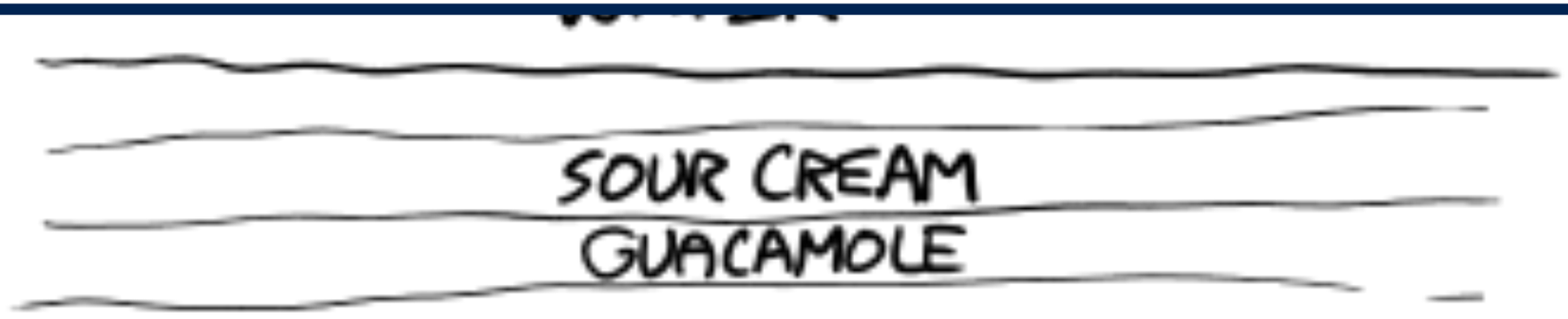
Measuring water abundances with HST/WFC3



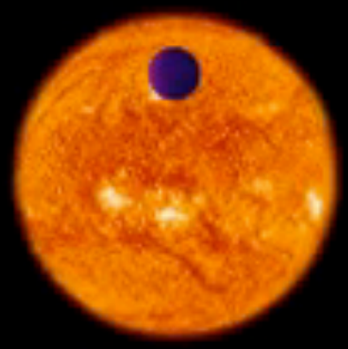
Measuring water abundances with HST/WFC3

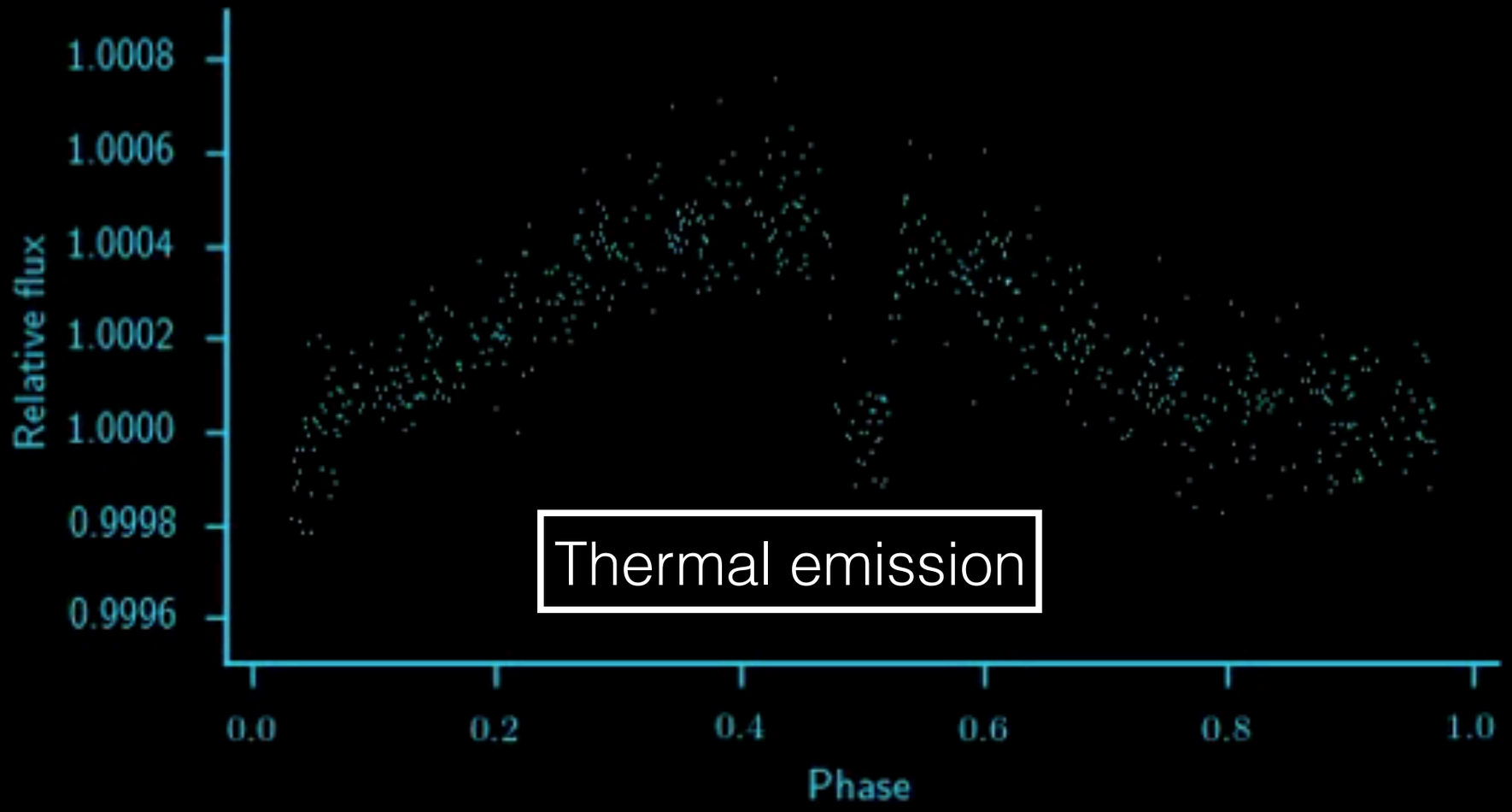
We need to understand clouds to measure compositions !

Problem : we don't even know what they are made of….

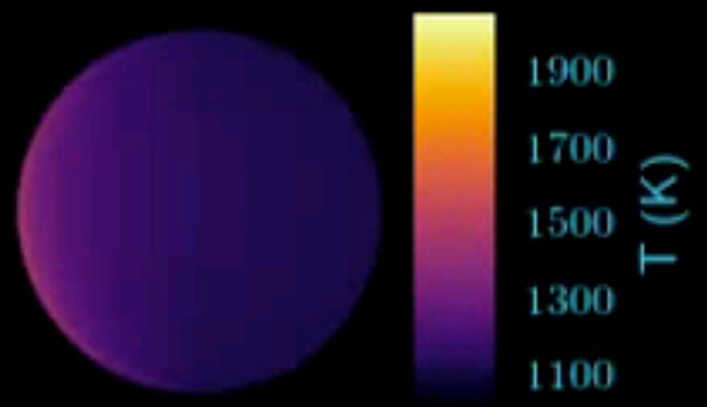


Randall Munroe, XKCD

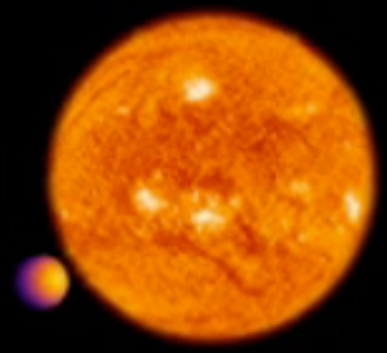


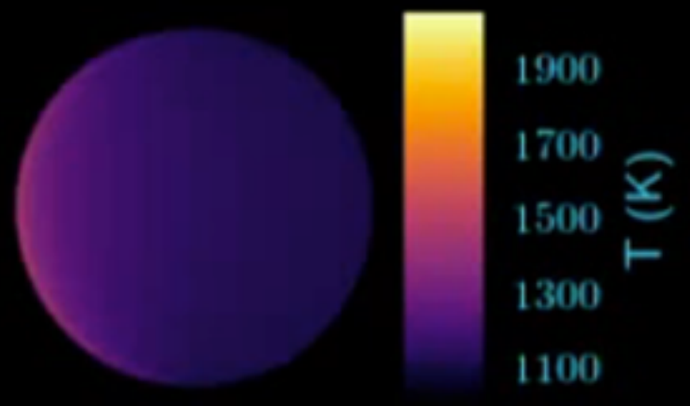


Thermal emission

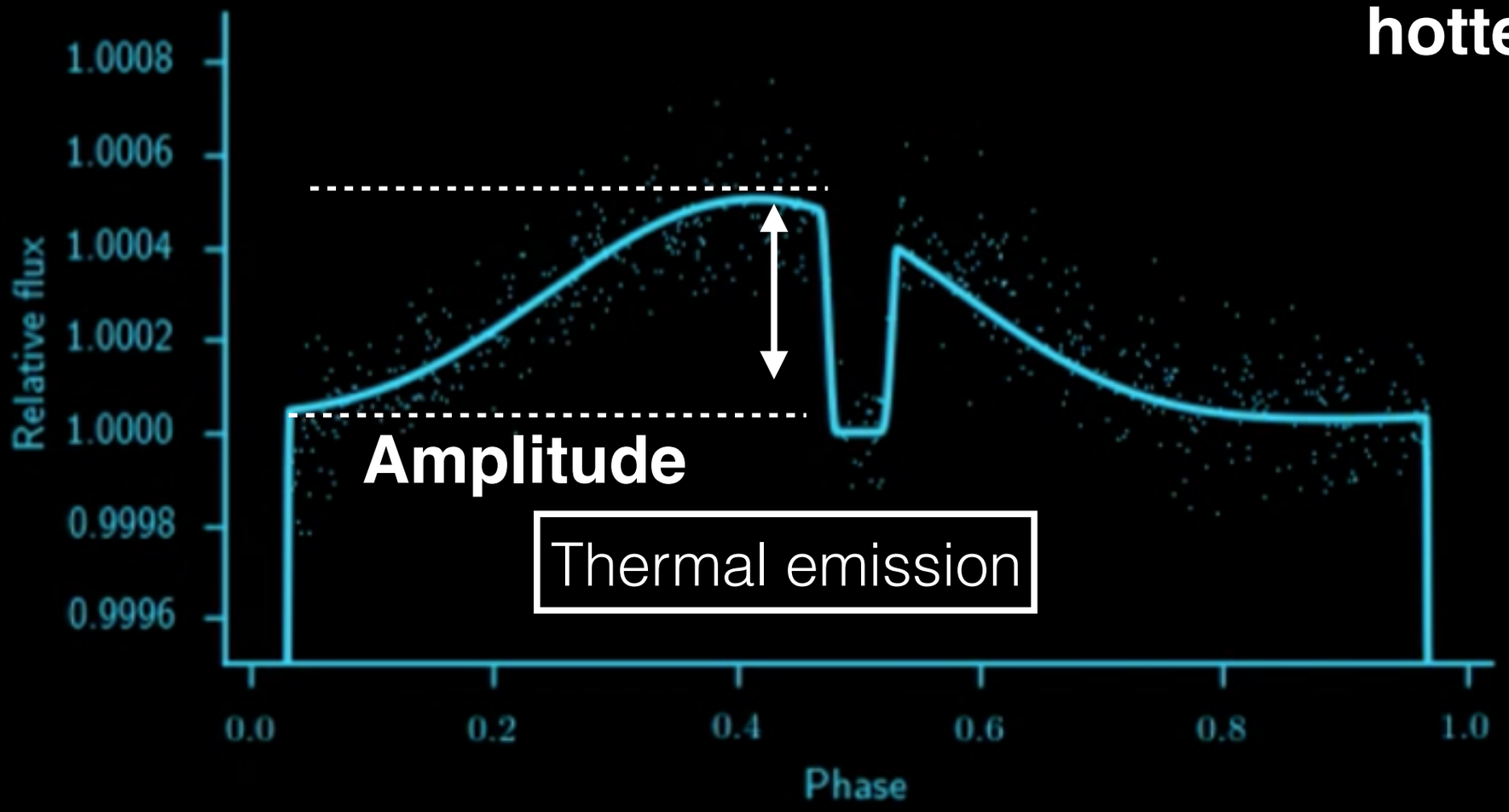


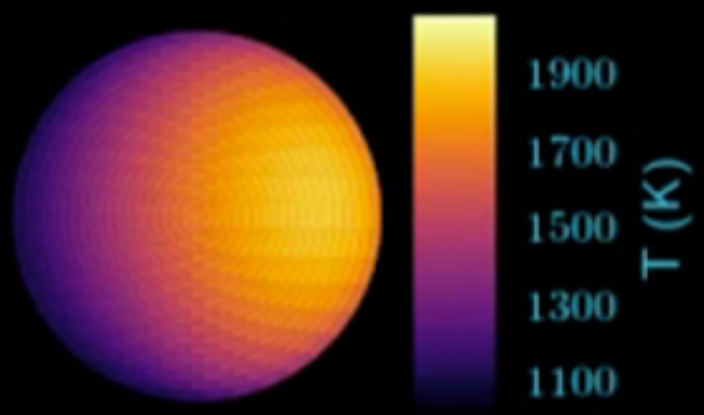
Courtesy Tom Louden





Dayside is ~ 900°C (1620°F) hotter than nightside





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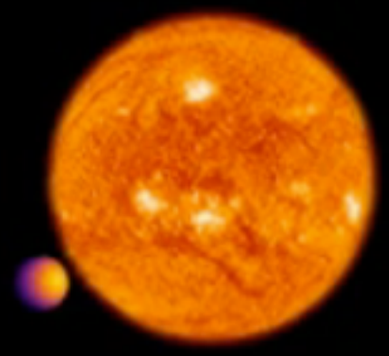
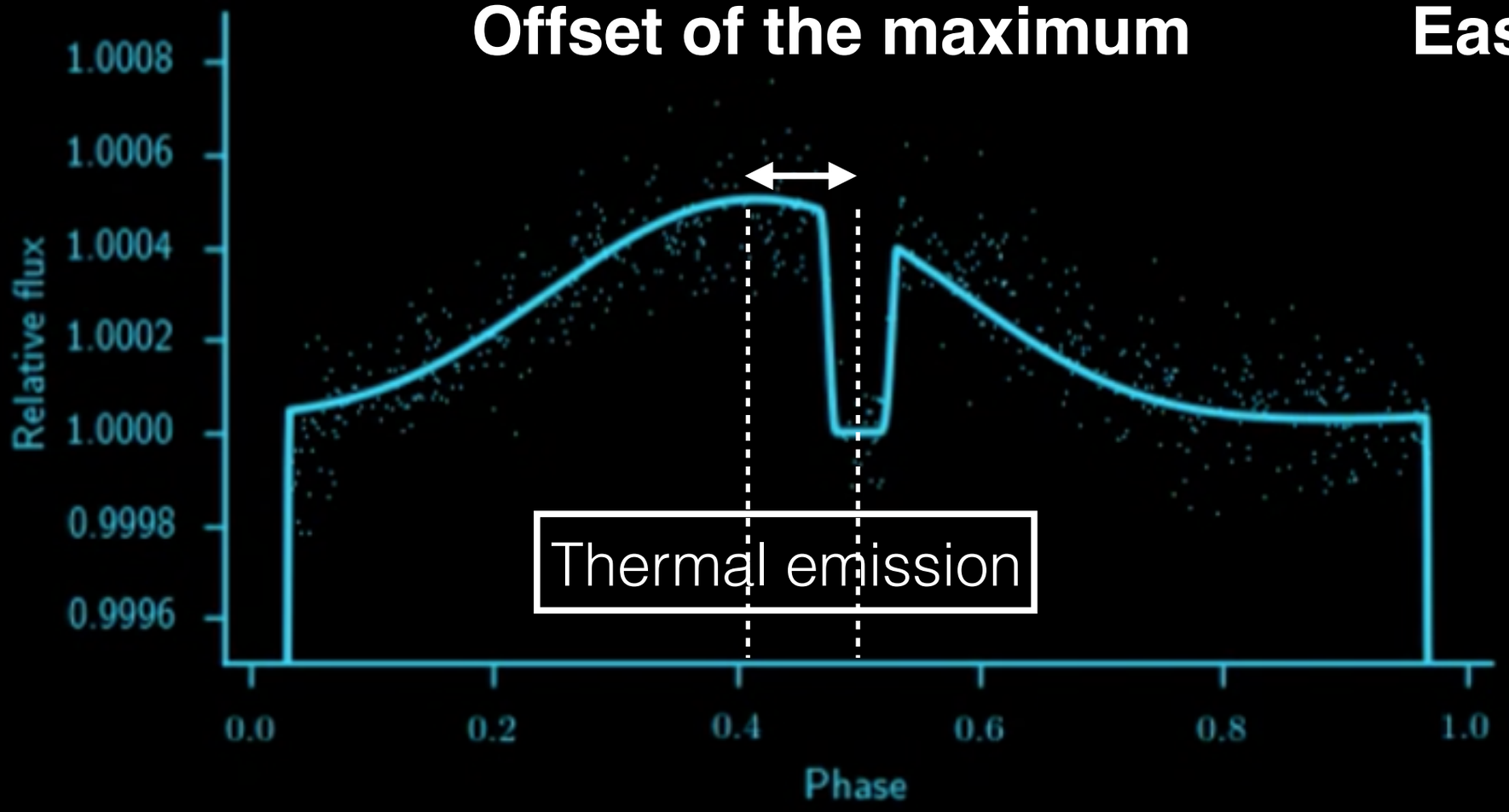
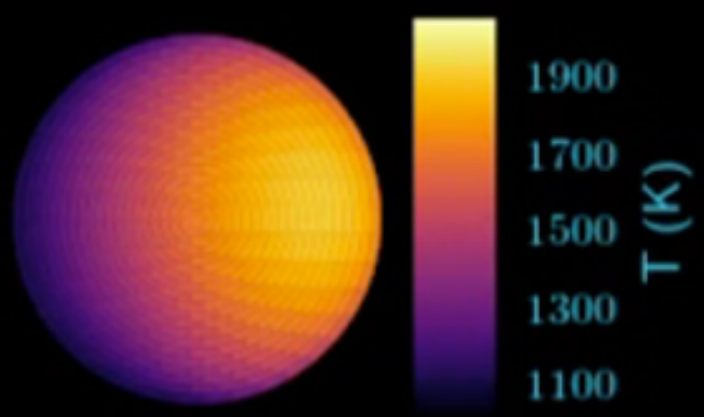


Offset of the maximum

East hotter than west



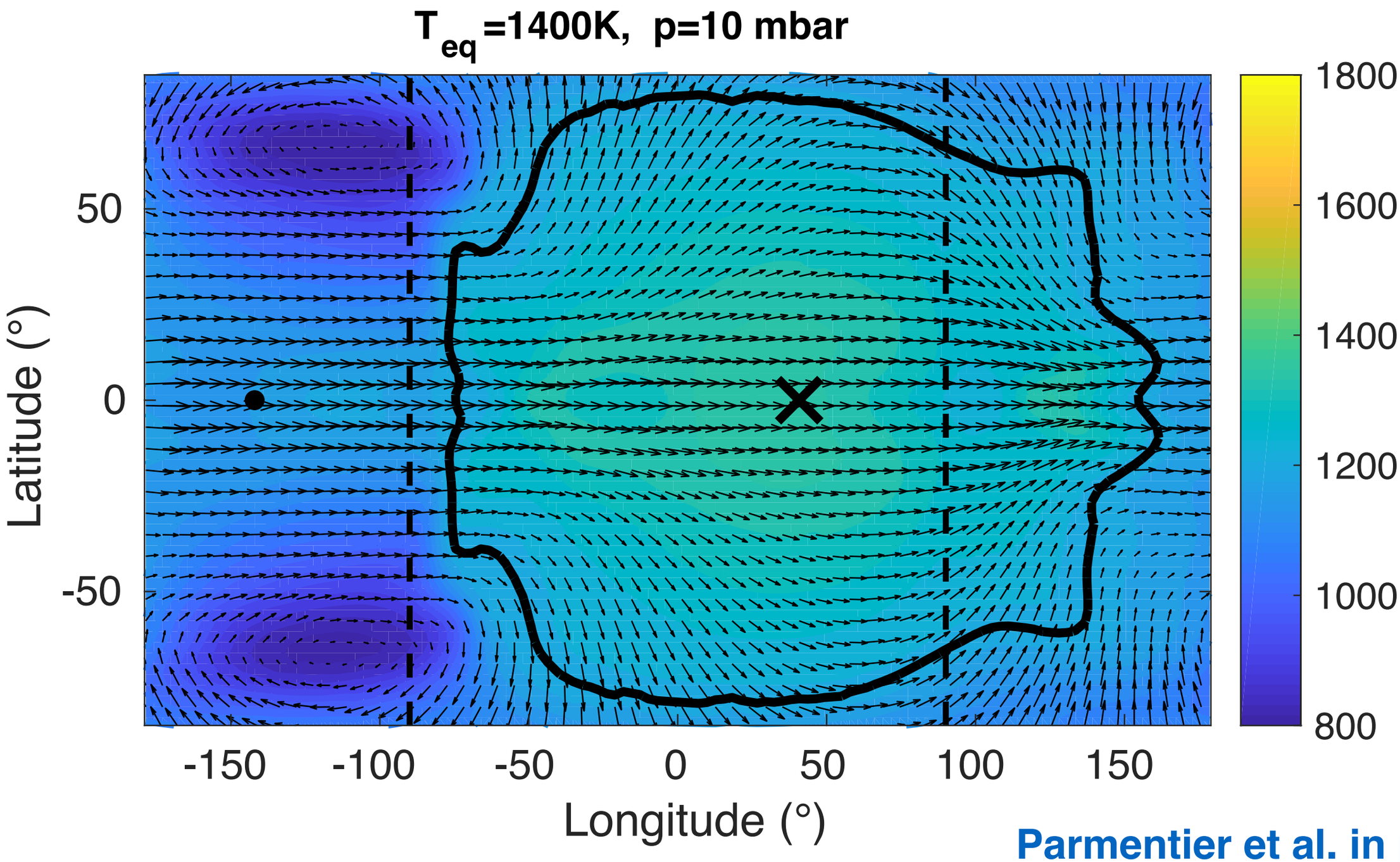


Courtesy Tom Louden

Temperature and clouds of a Hot Jupiter with SPARC/MITgcm

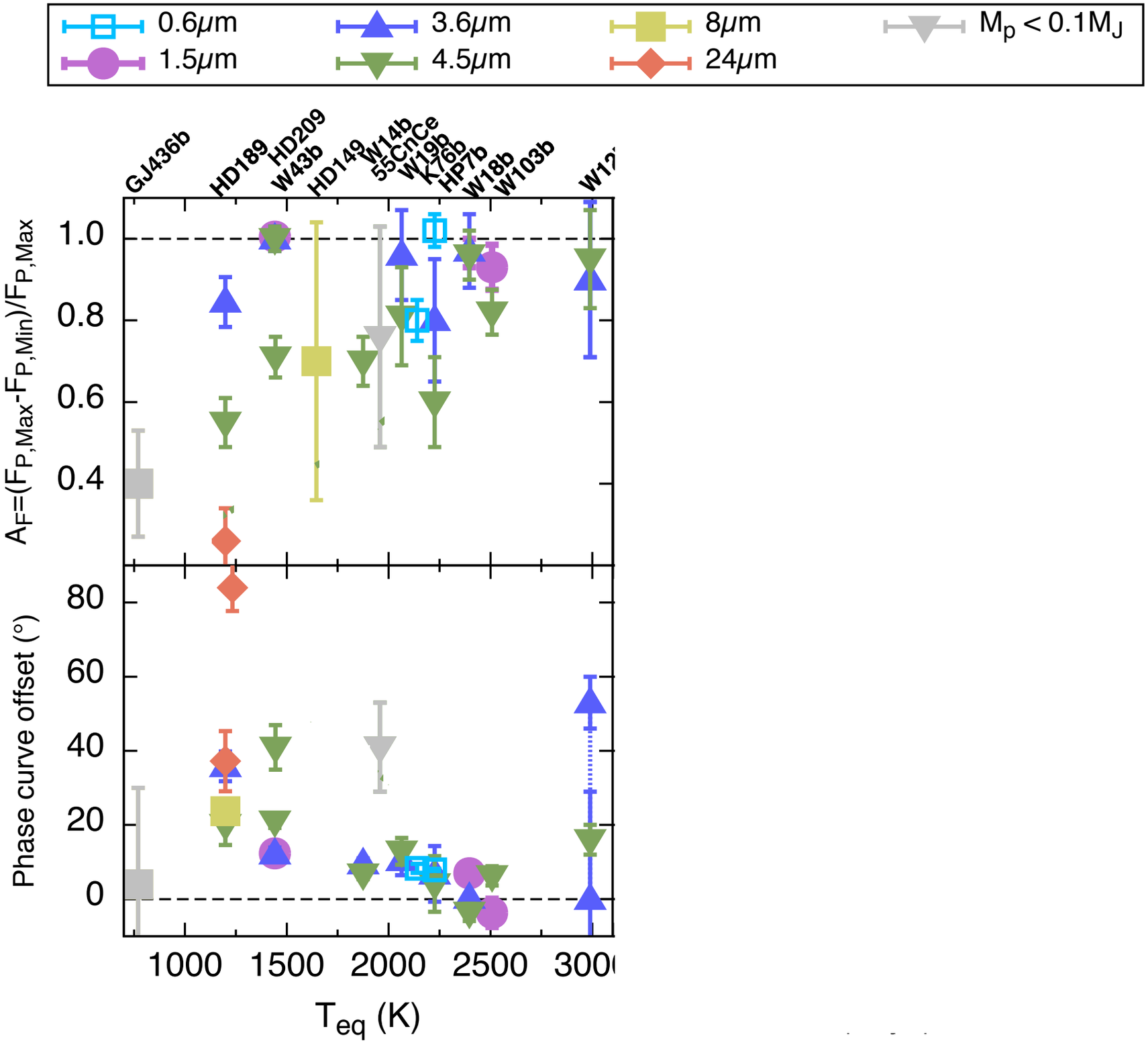
Global Circulation Model **: solves the primitive equation, Euler equation adapted to atmospheres**

SPARC **: solves the radiative energy balance with non-grey, molecular opacities**



Parmentier et al. in prep.

Qualitative vs. quantitative understanding



Parmentier & Crossfield. 2017

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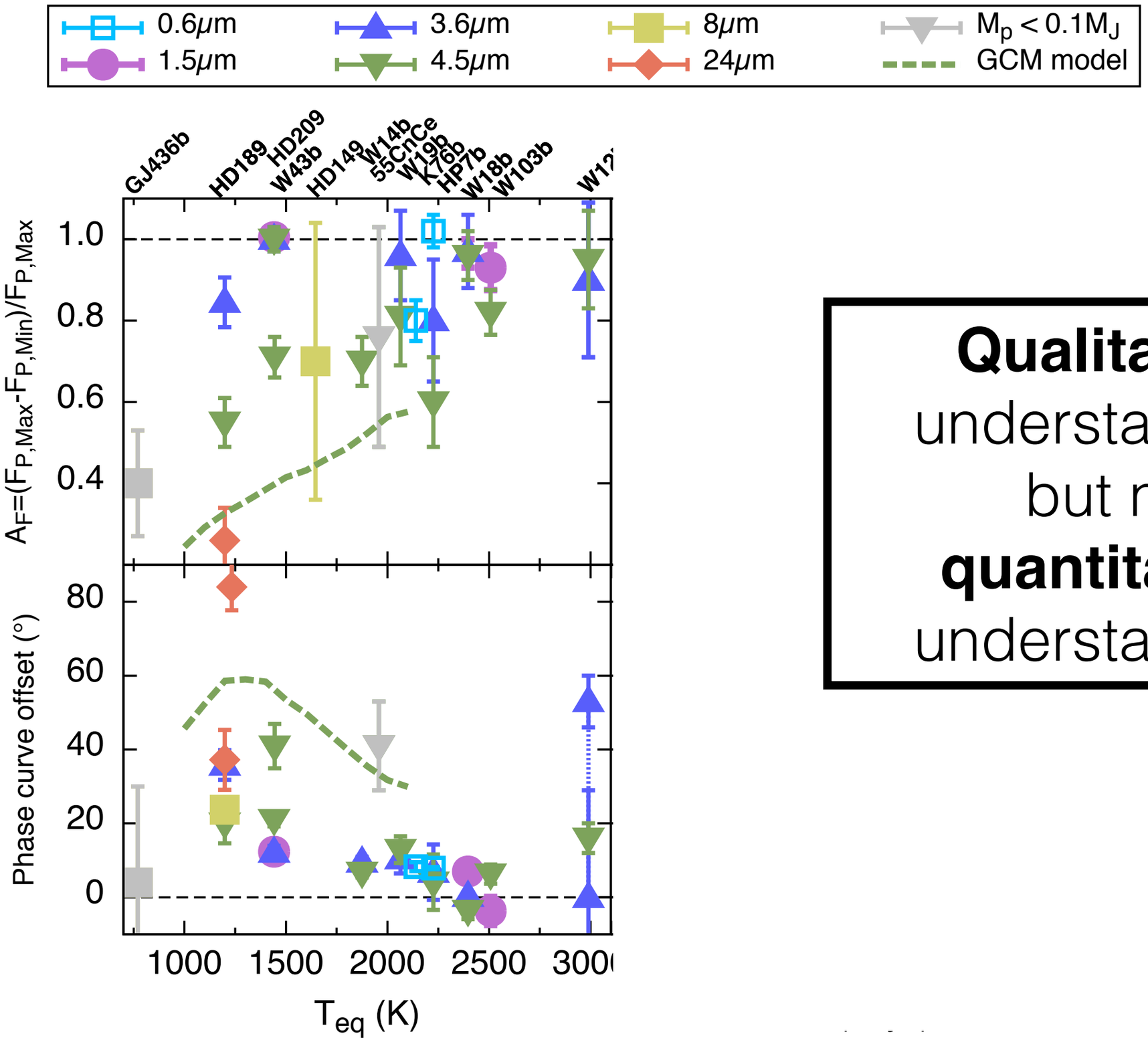
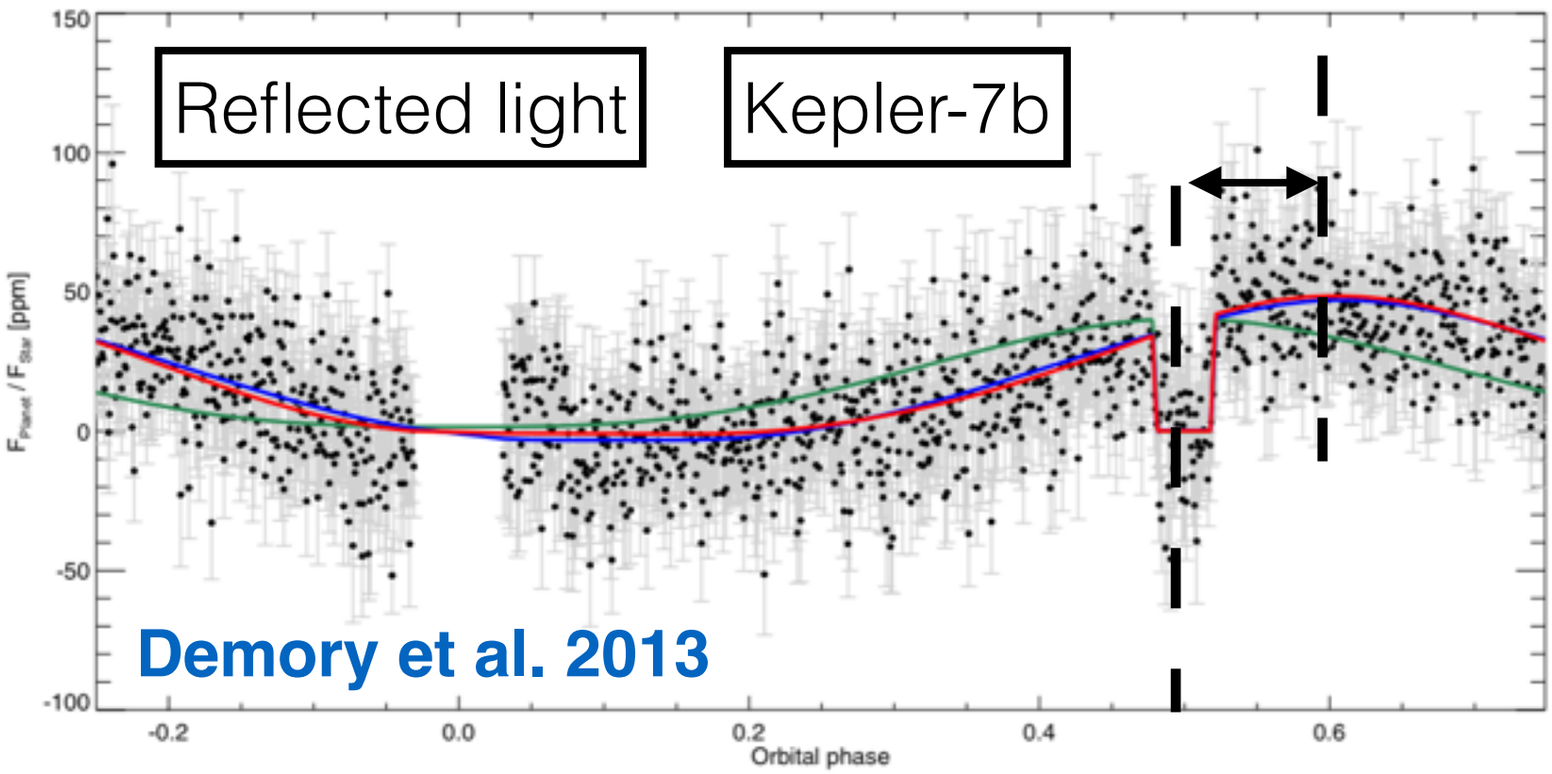


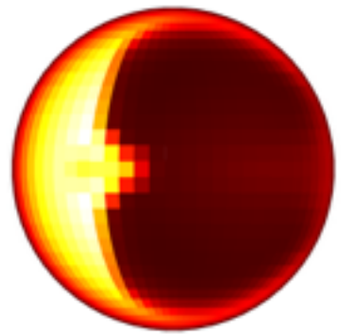
Qualitative understanding but no **quantitative** understanding

Parmentier & Crossfield. 2017

Wavelength dependence of the phase curve

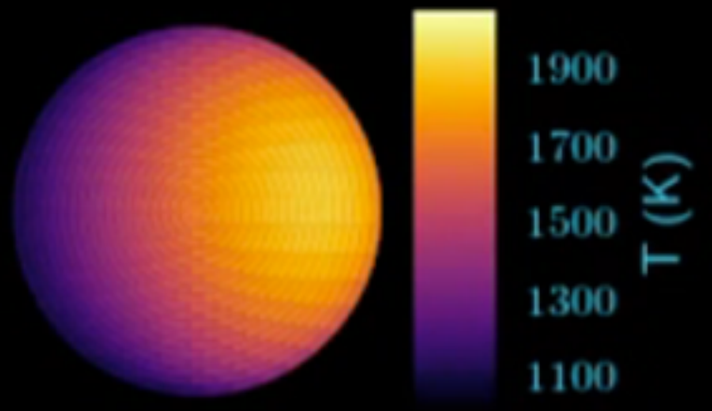


West cloudier than east



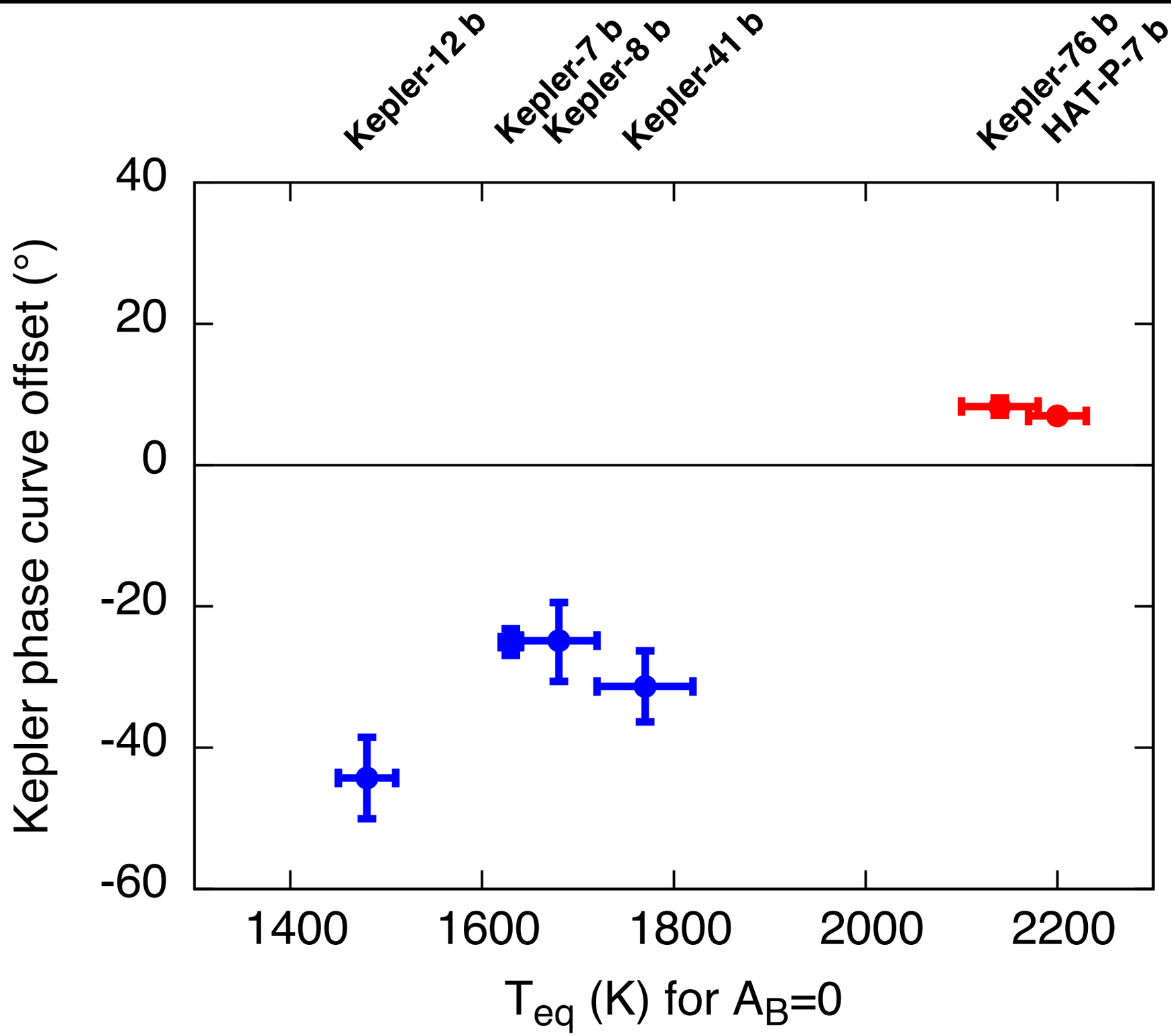
Reflected light phase curve : negative offset

Offset of the maximum



Courtesy Tom Louden

Wavelength dependence of the phase curve



Parmentier et al. 2016

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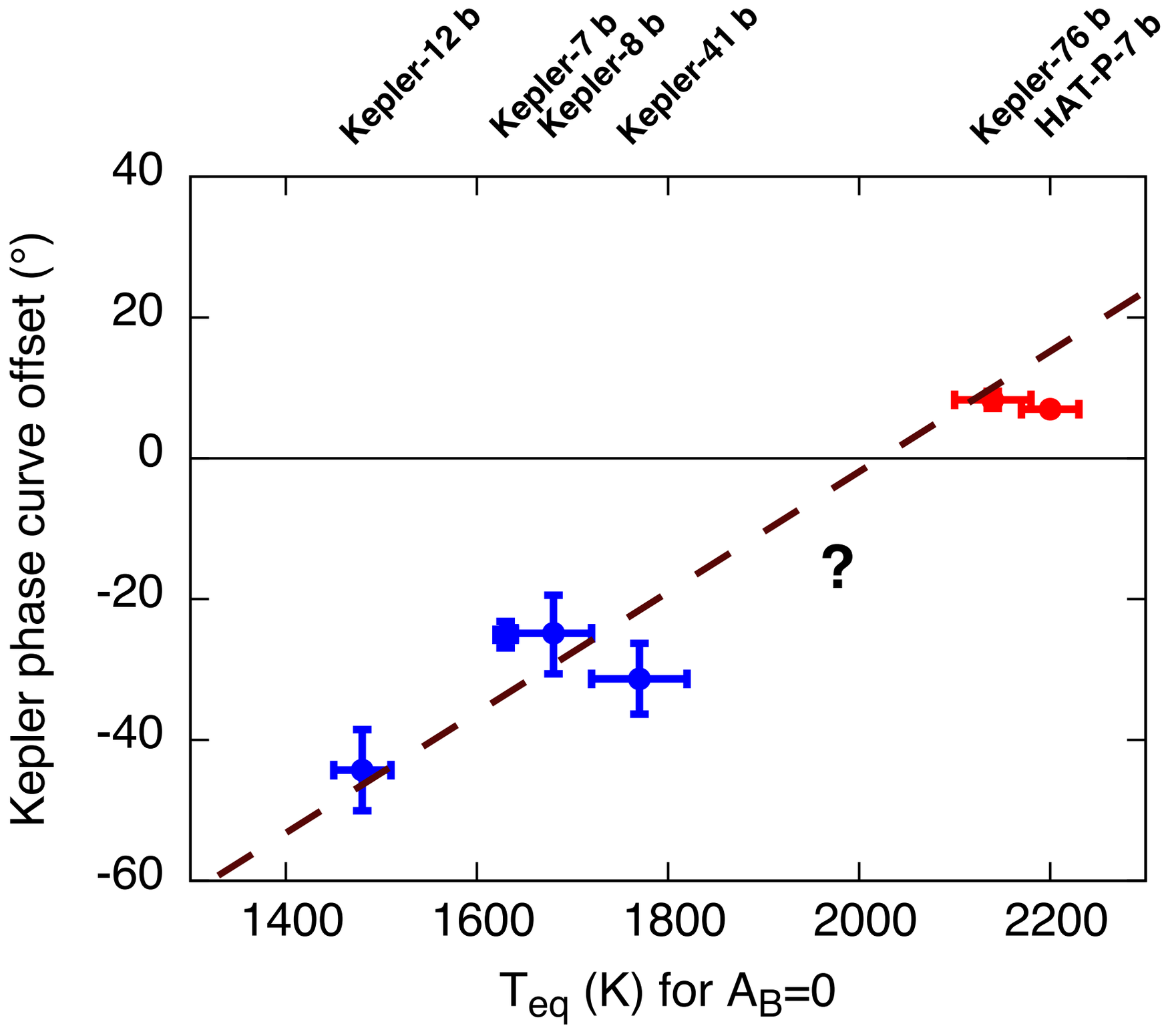

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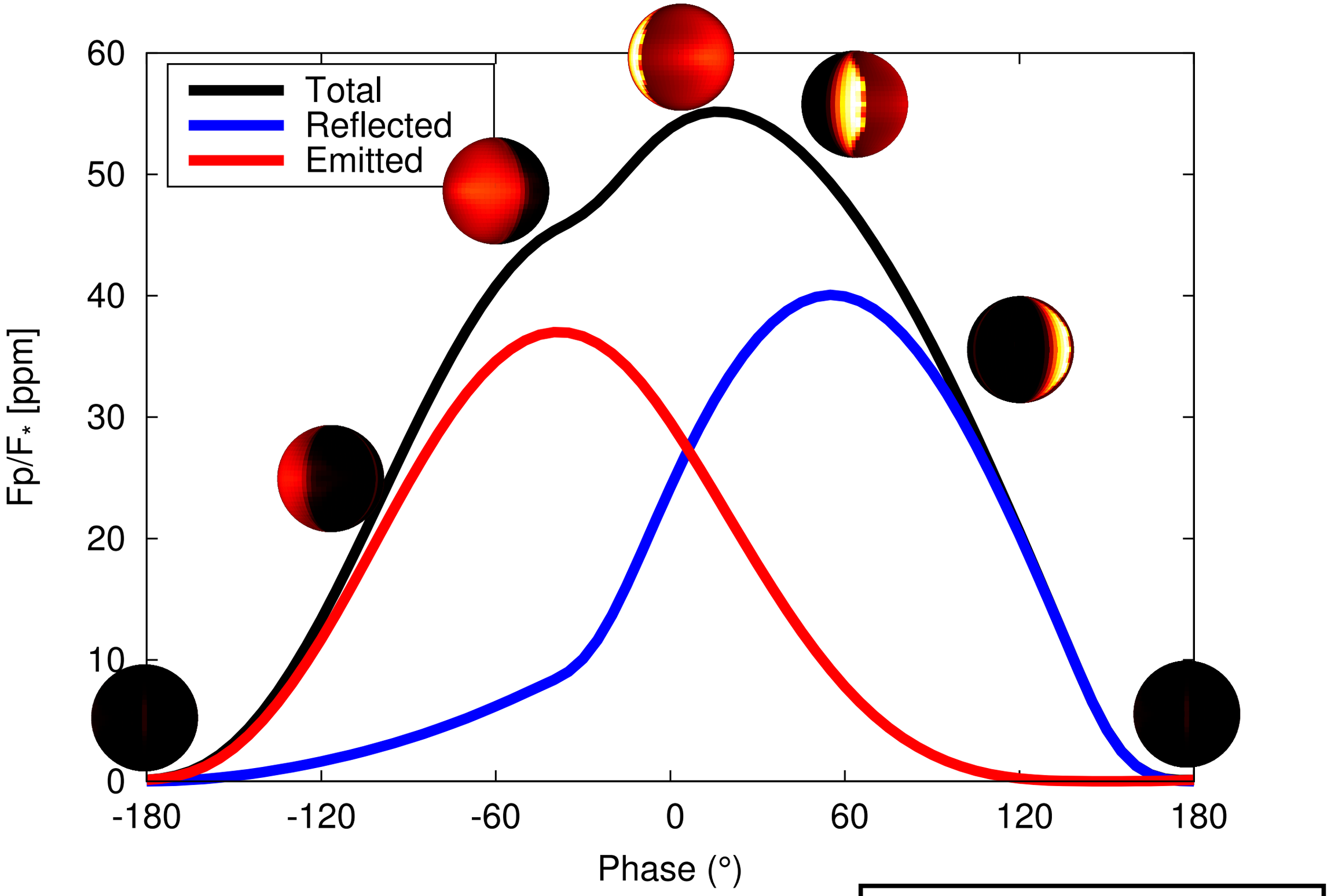
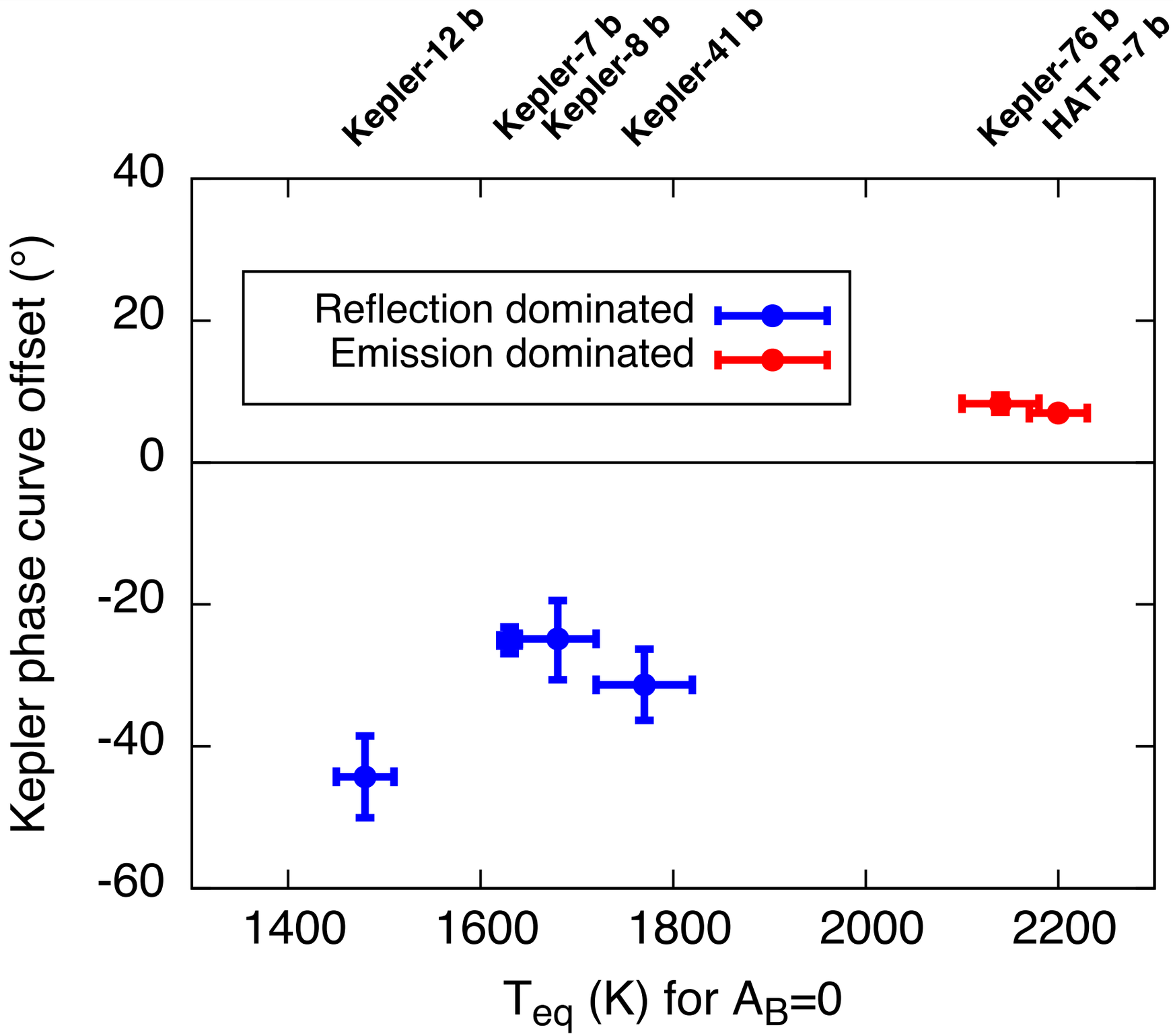


Parmentier et al. 2016

Model: Teq=1900K

Wavelength dependence of the phase curve

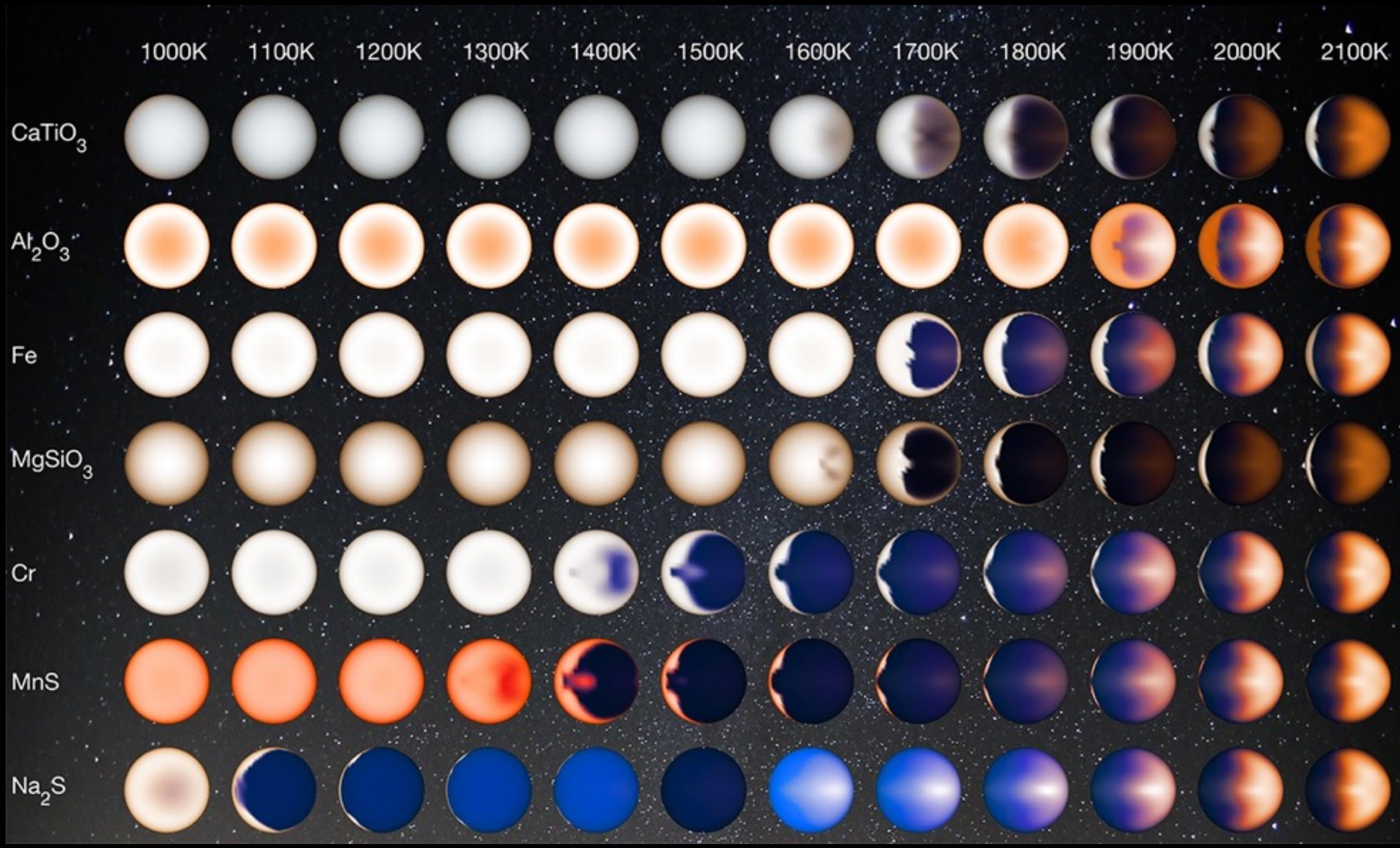


Parmentier et al. 2016

Travel to your nearest Hot Jupiter

Equilibrium temperature

Cloud chemical composition



Parmentier et al. 2016

Hot Jupiter daysides as seen by a human eye

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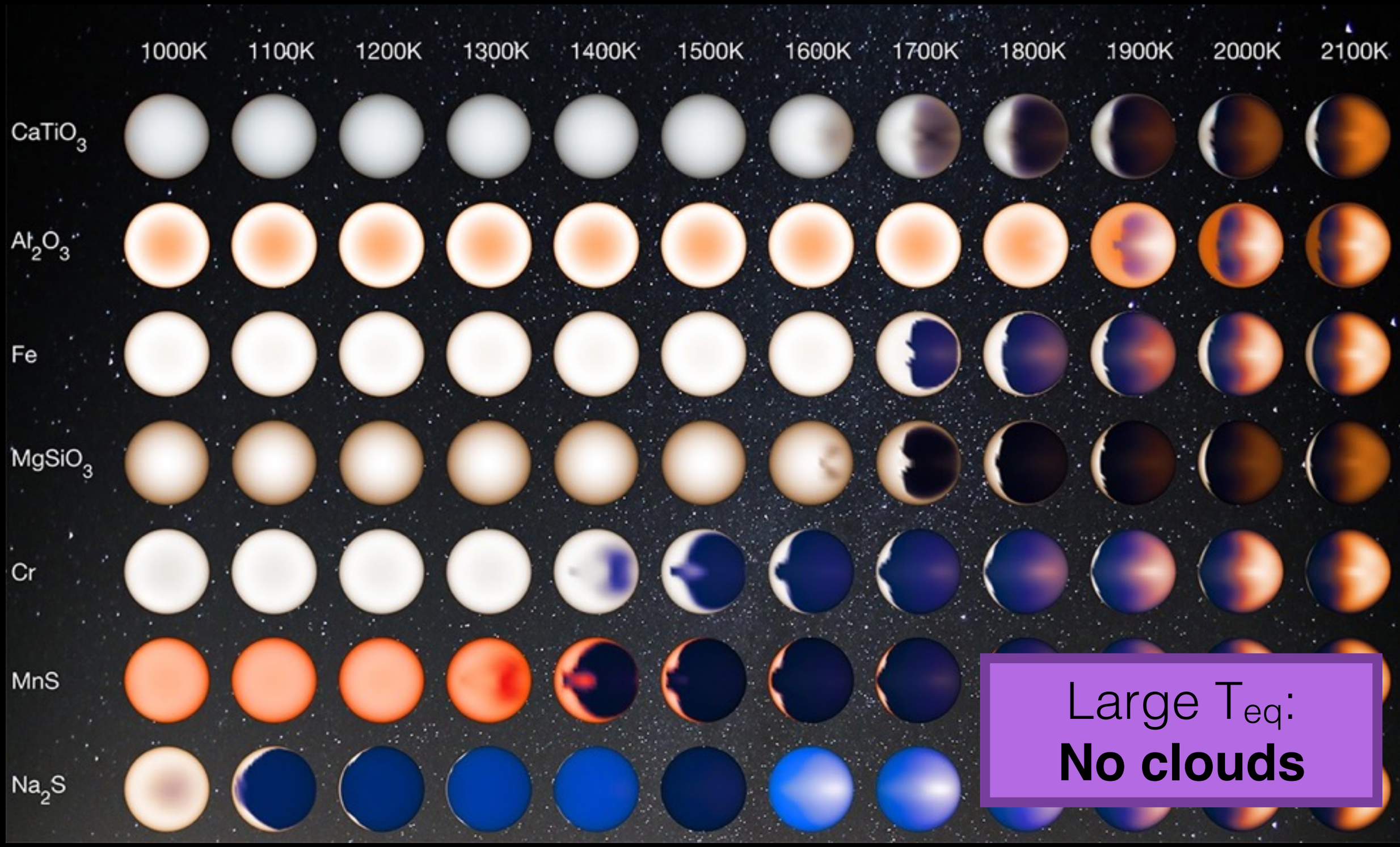

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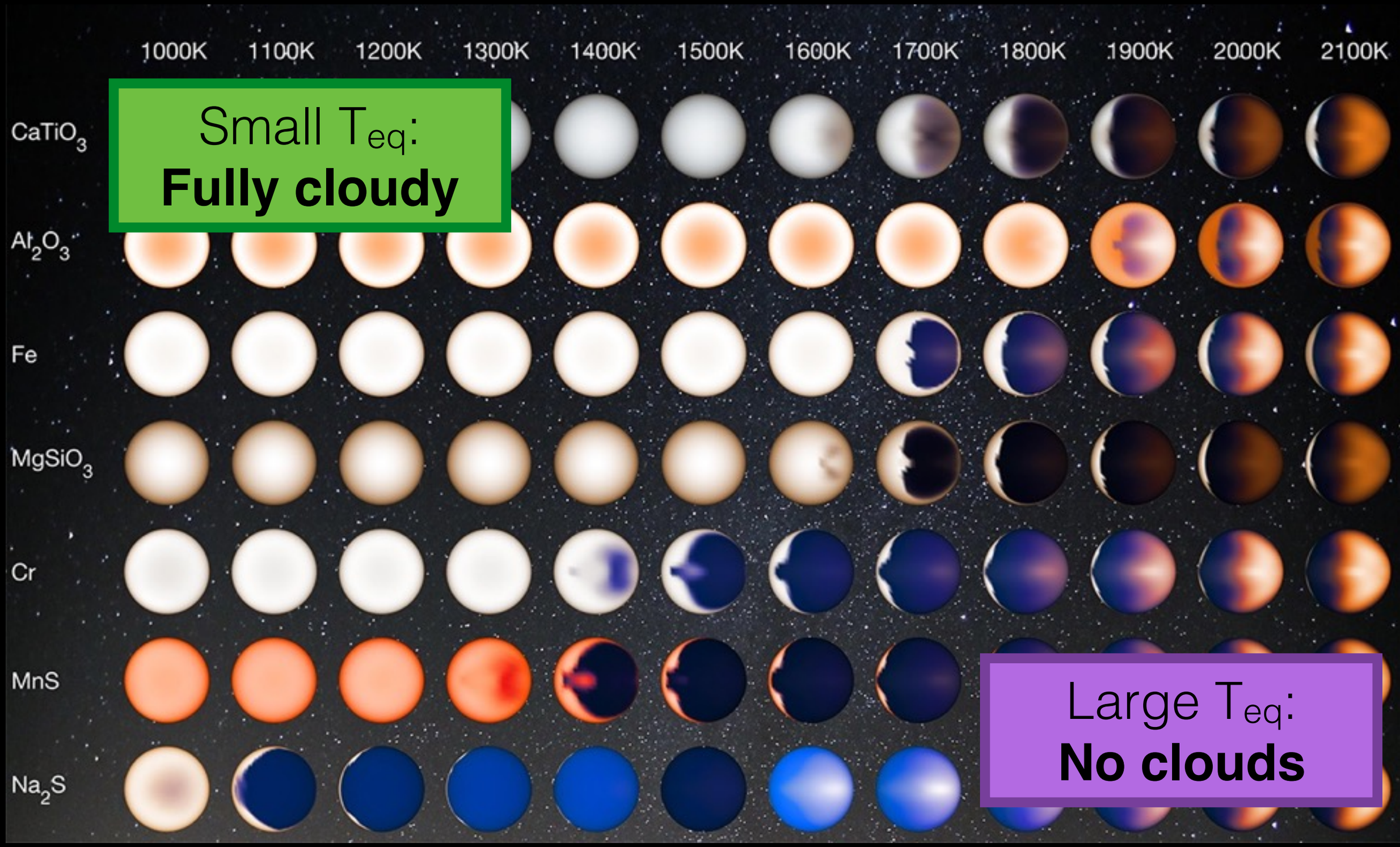

Parmentier et al. 2016

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1000K 1100K 1200K 1300K 1400K 1500K 1600K 1700K 1800K 1900K 2000K 2100K

$CaTiO_3$

Al_2O_3

Fe

$MgSiO_3$

Cr

MnS

Na_2S

Small T_{eq}:
Fully cloudy

Observations:
partially cloudy

Large T_{eq}:
No clouds

Parmentier et al. 2016

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Parmentier et al. 2016

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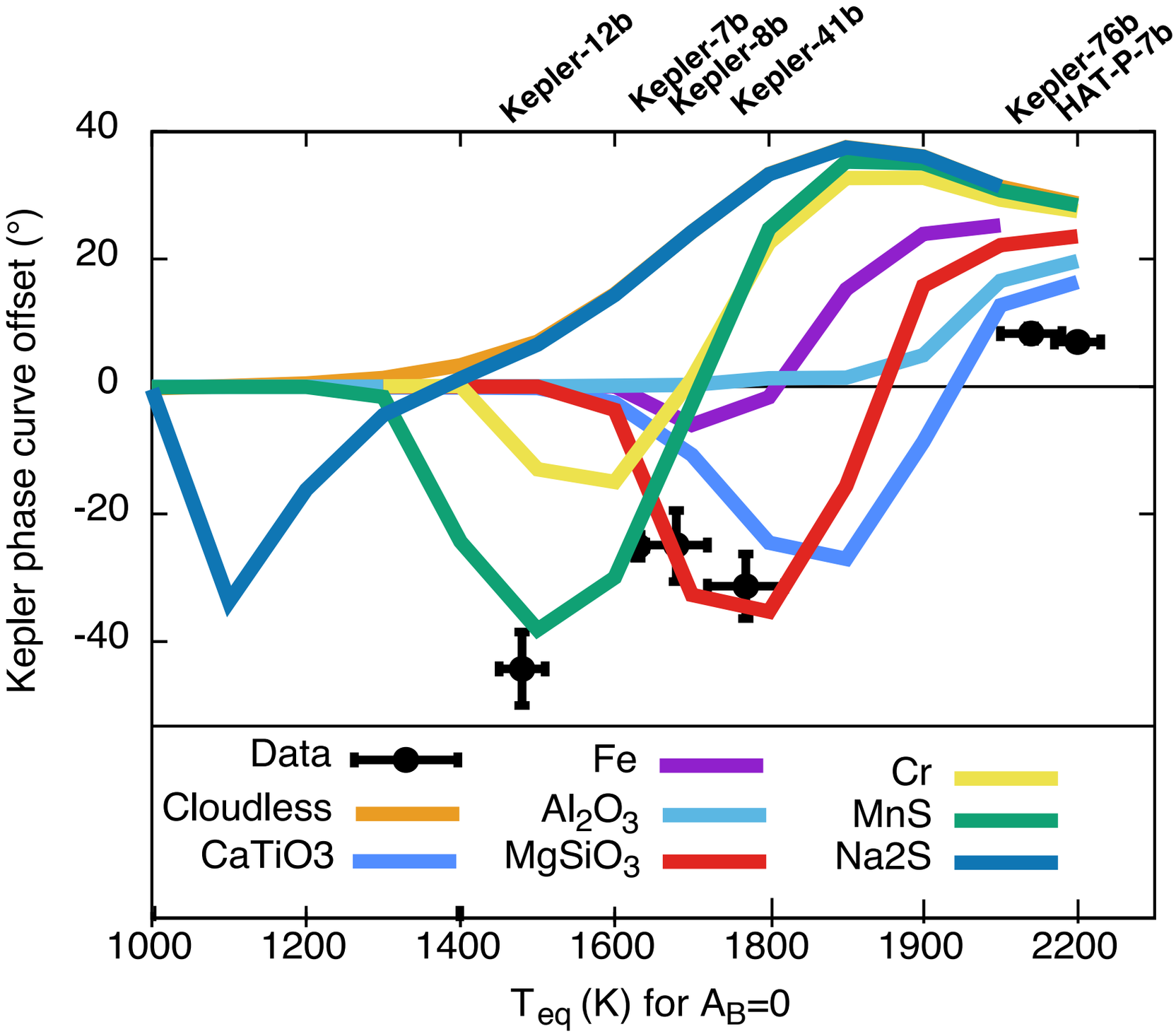
Parmentier et al. 2016

Hot Jupiter daysides as seen by a human eye

A temperature dependent cloud composition ?



Parmentier et al. 2016

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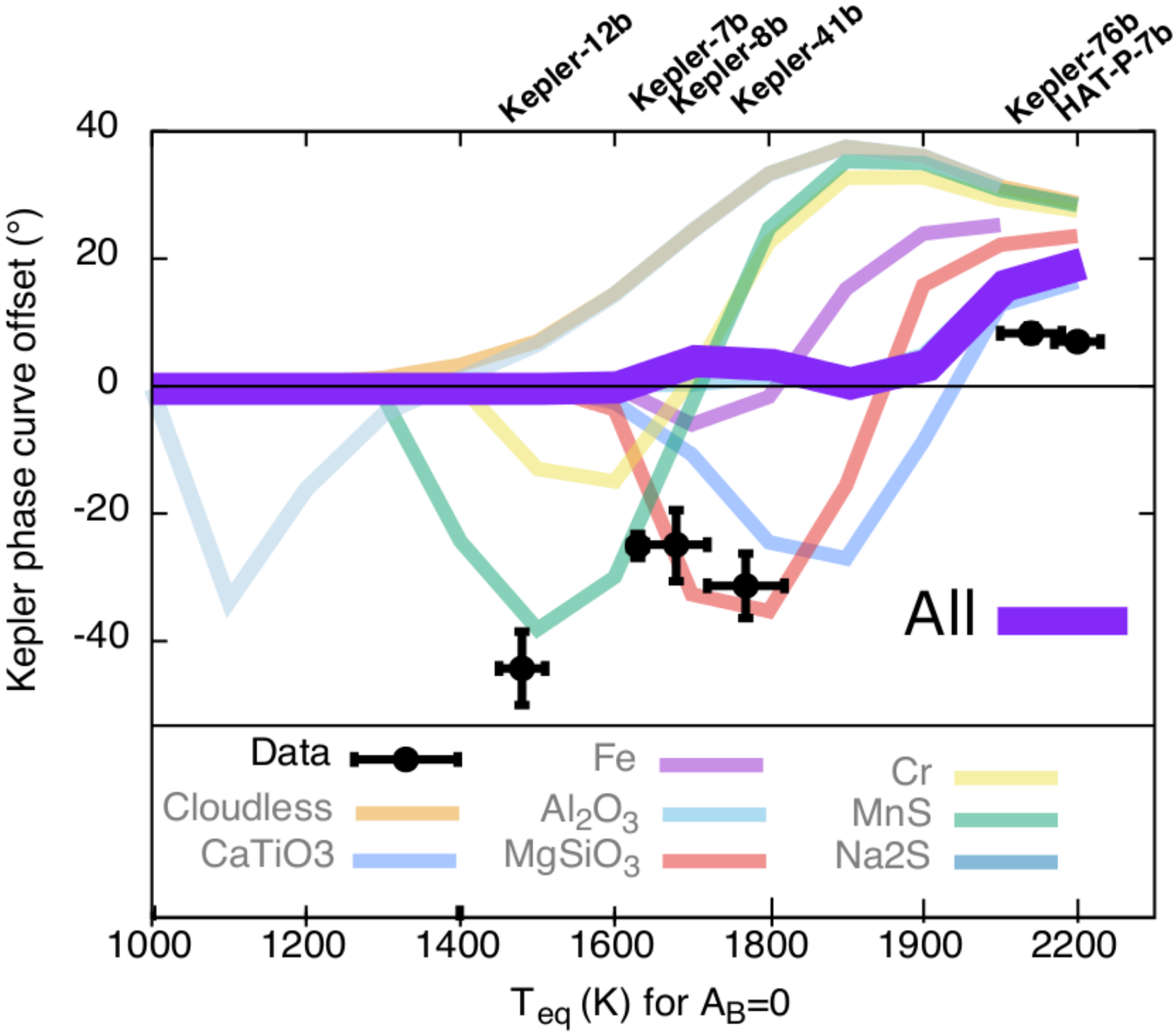

Parmentier et al. 2016

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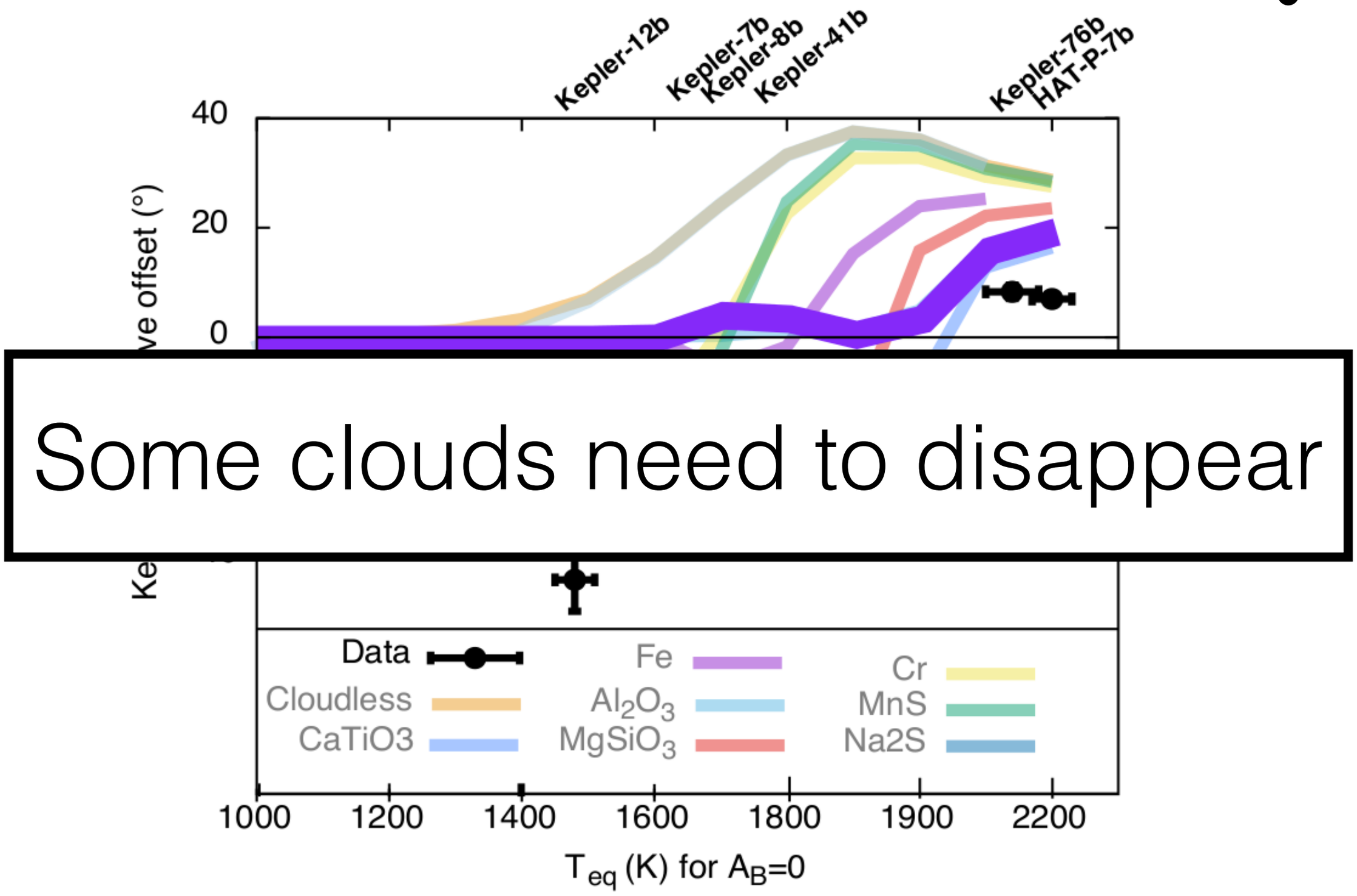
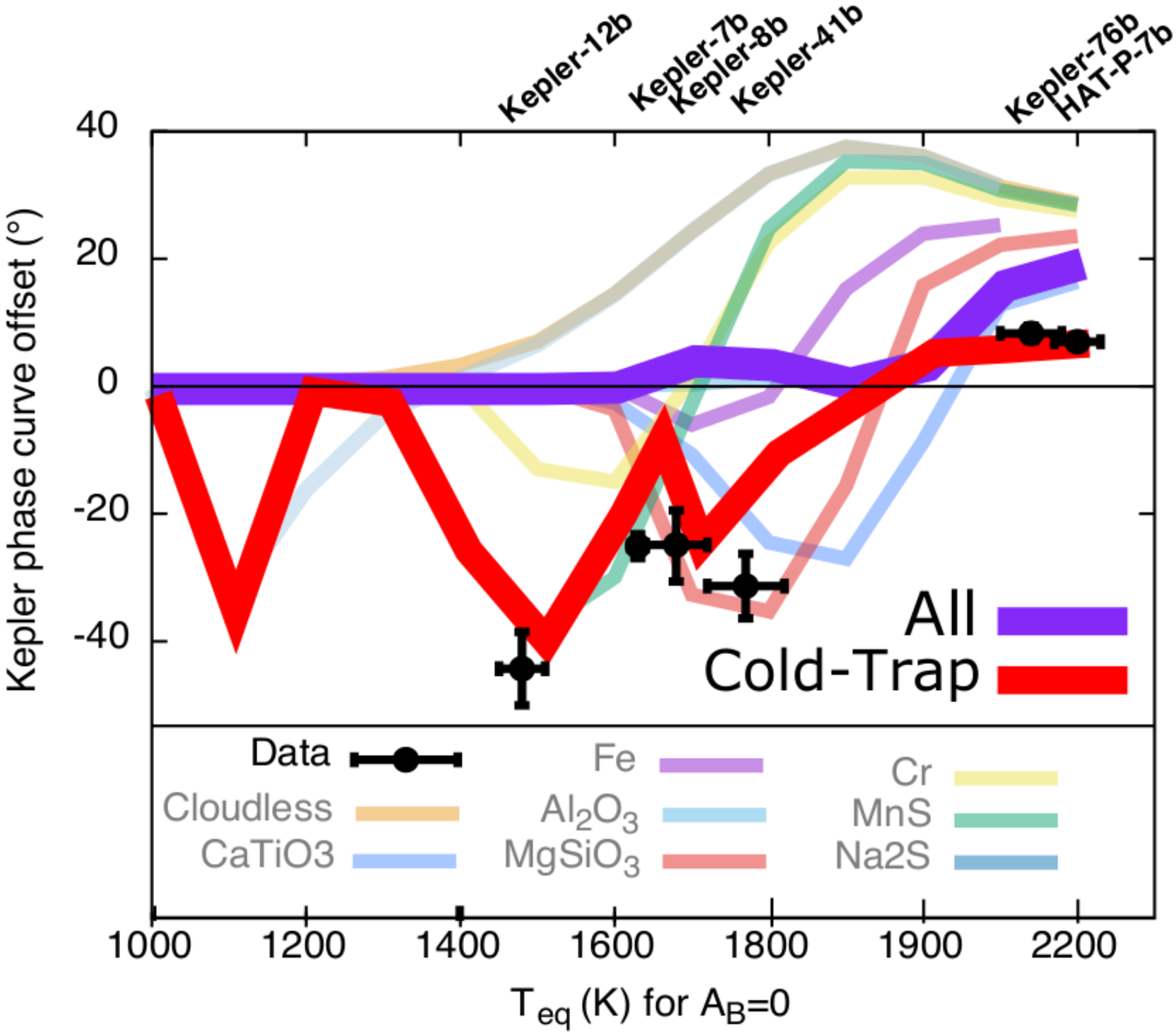


Some clouds need to disappear

Parmentier et al. 2016

A temperature dependent cloud composition ?



Parmentier et al. 2016

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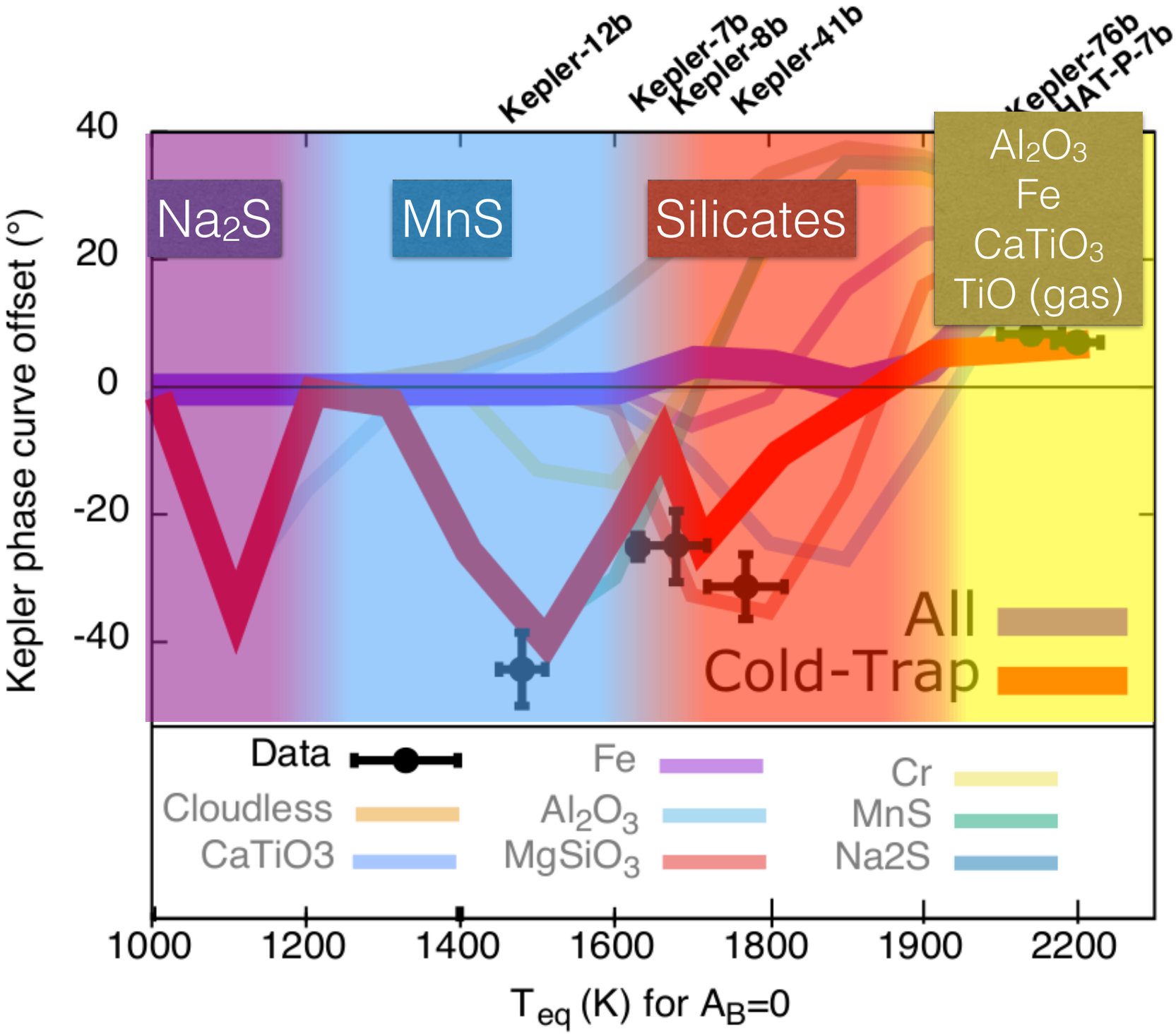
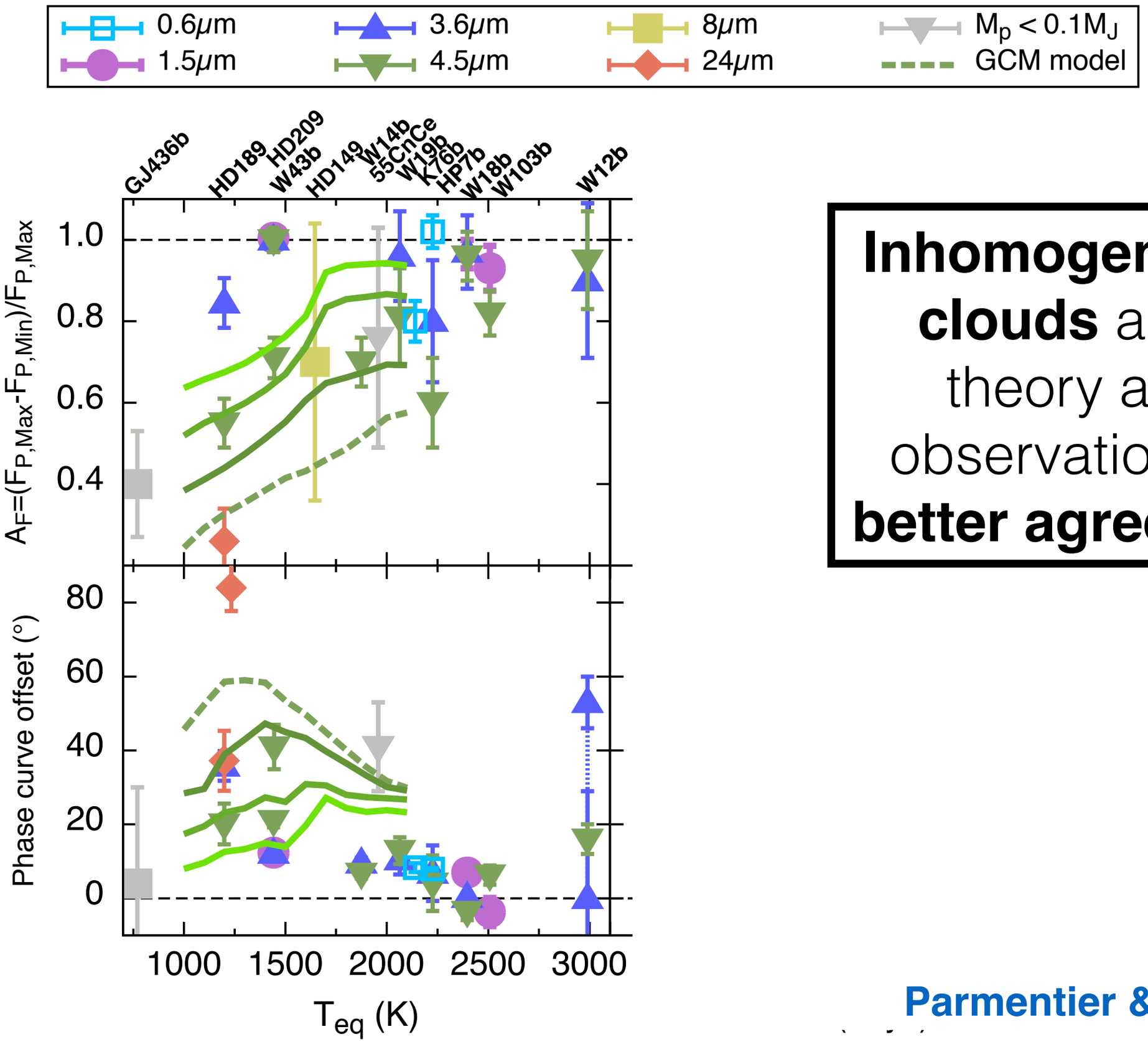


Parmentier et al. 2016

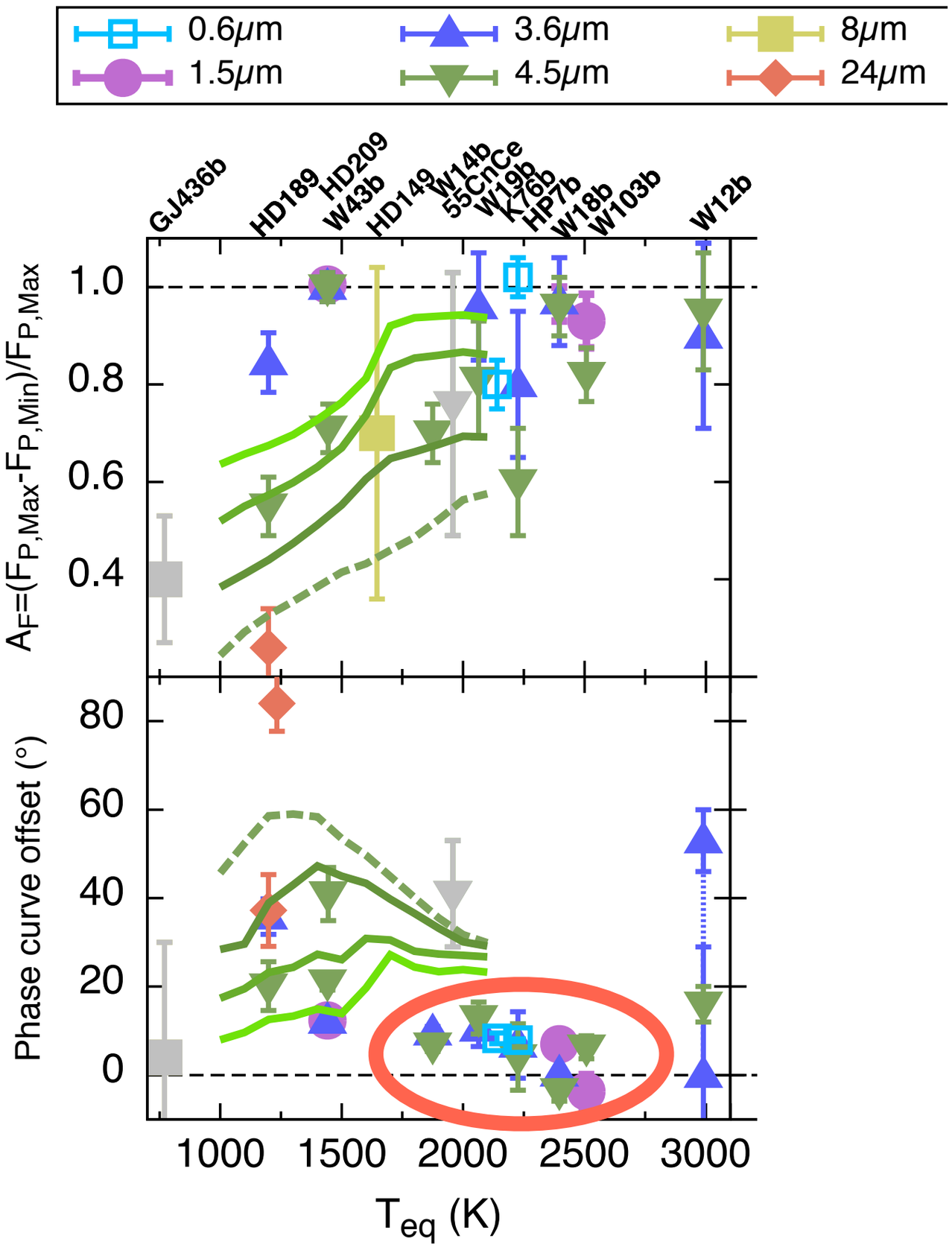
Clouds: when small changes have a big impact



Inhomogeneous clouds allow theory and observations in **better agreement**

Parmentier & Crossfield. 2017

Clouds: when small changes have a big impact



Inhomogeneous clouds allow theory and observations in **better agreement**

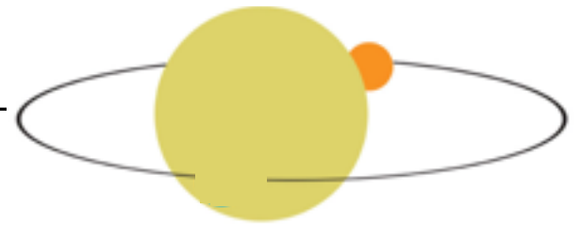
...

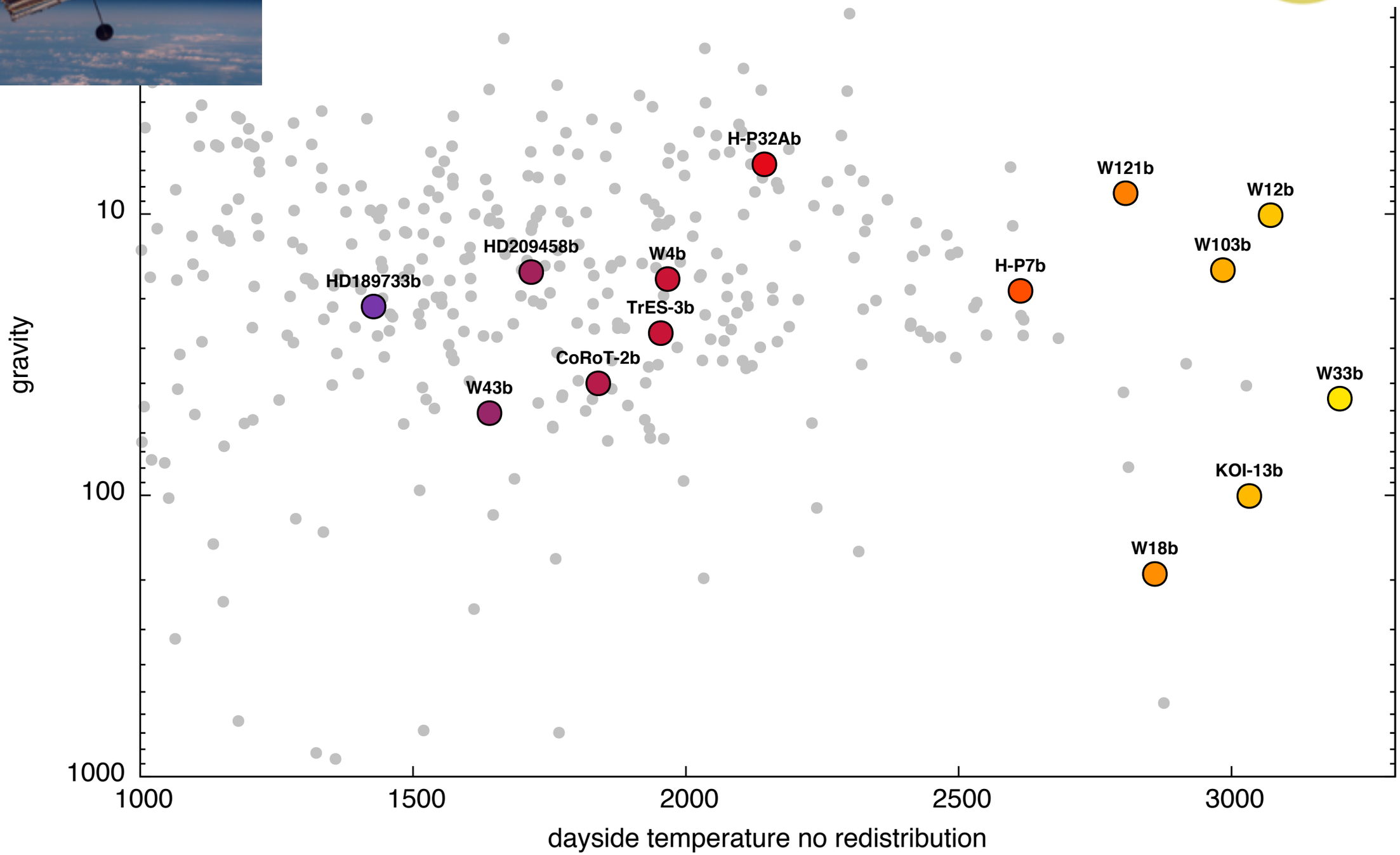
apart for the hottest ones

Magnetic Drag ?

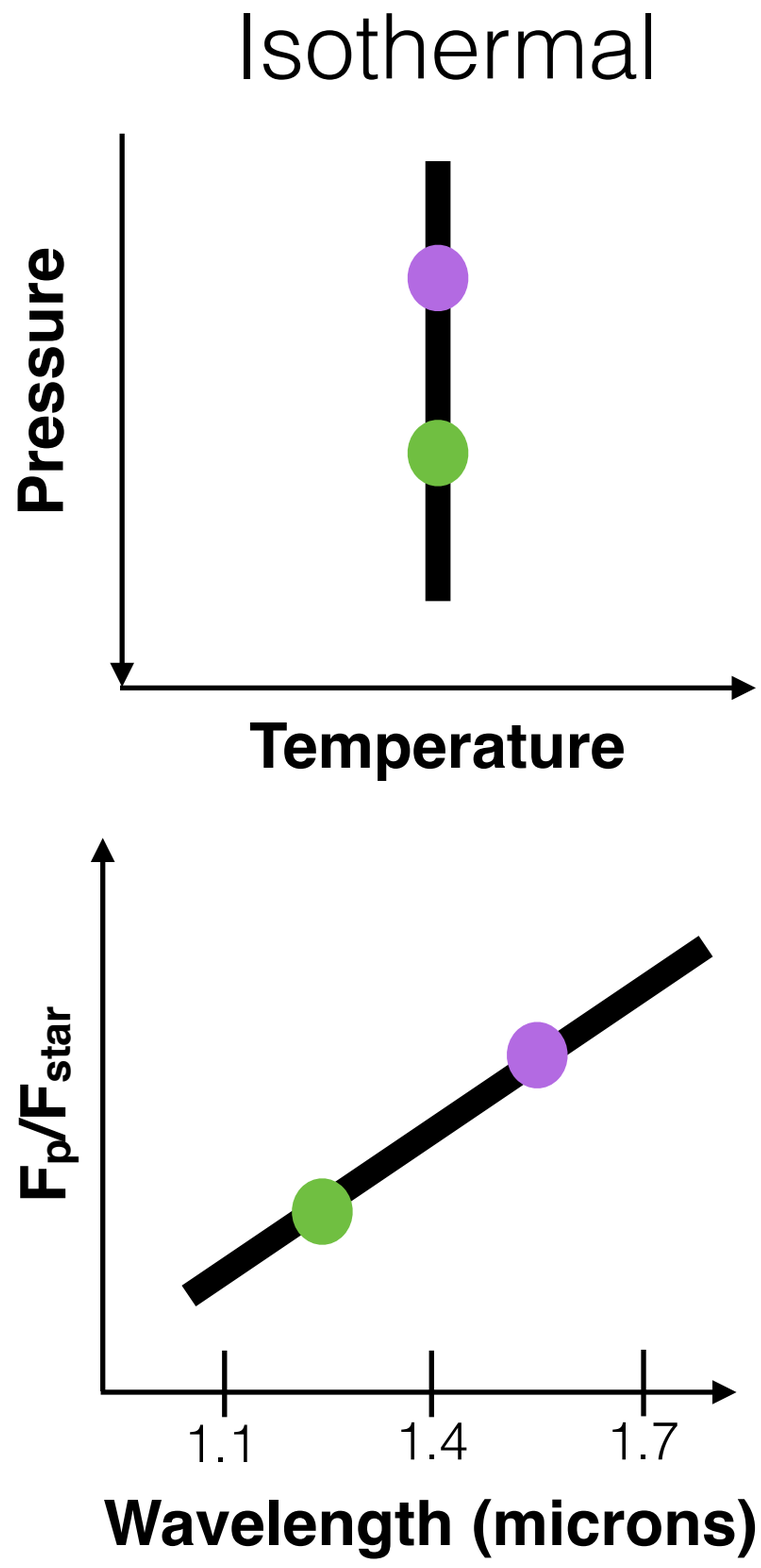
Parmentier & Crossfield. 2017

HST/WFC3 observed 14 planets in secondary eclipse





HST/WFC3 spectroscopy



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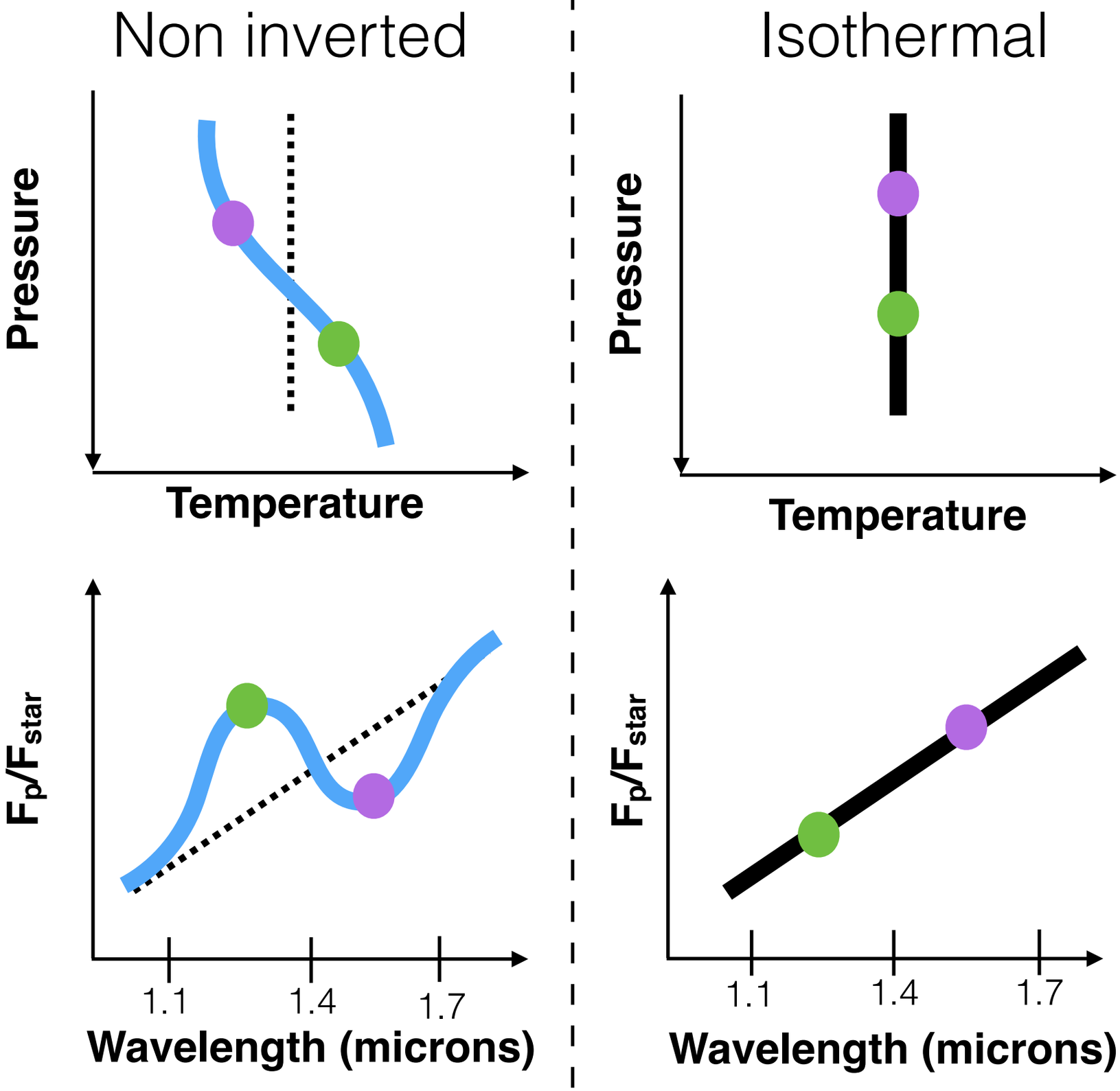

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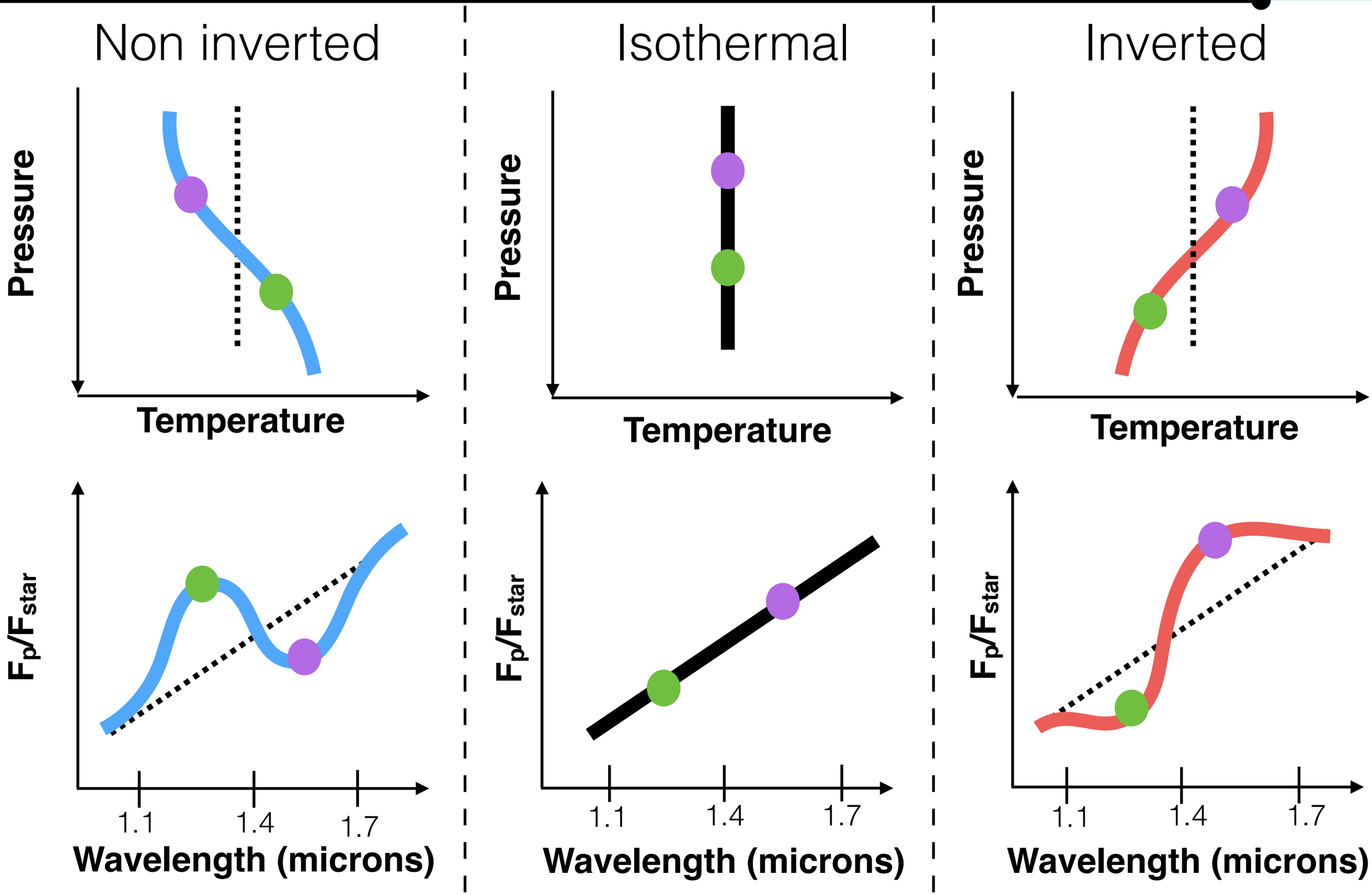
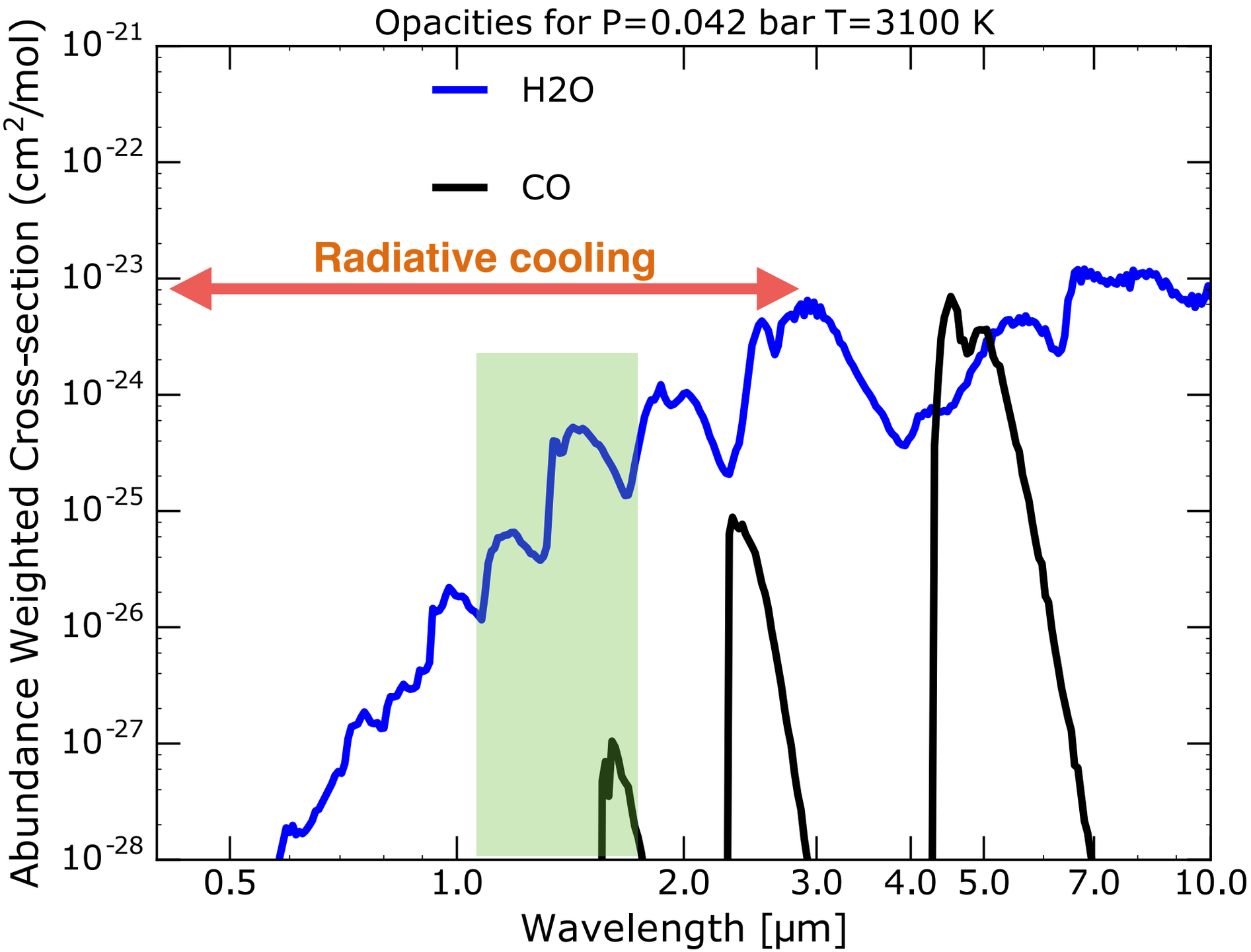


HST/WFC3 spectroscopy: probing water ?



Parmentier+2018

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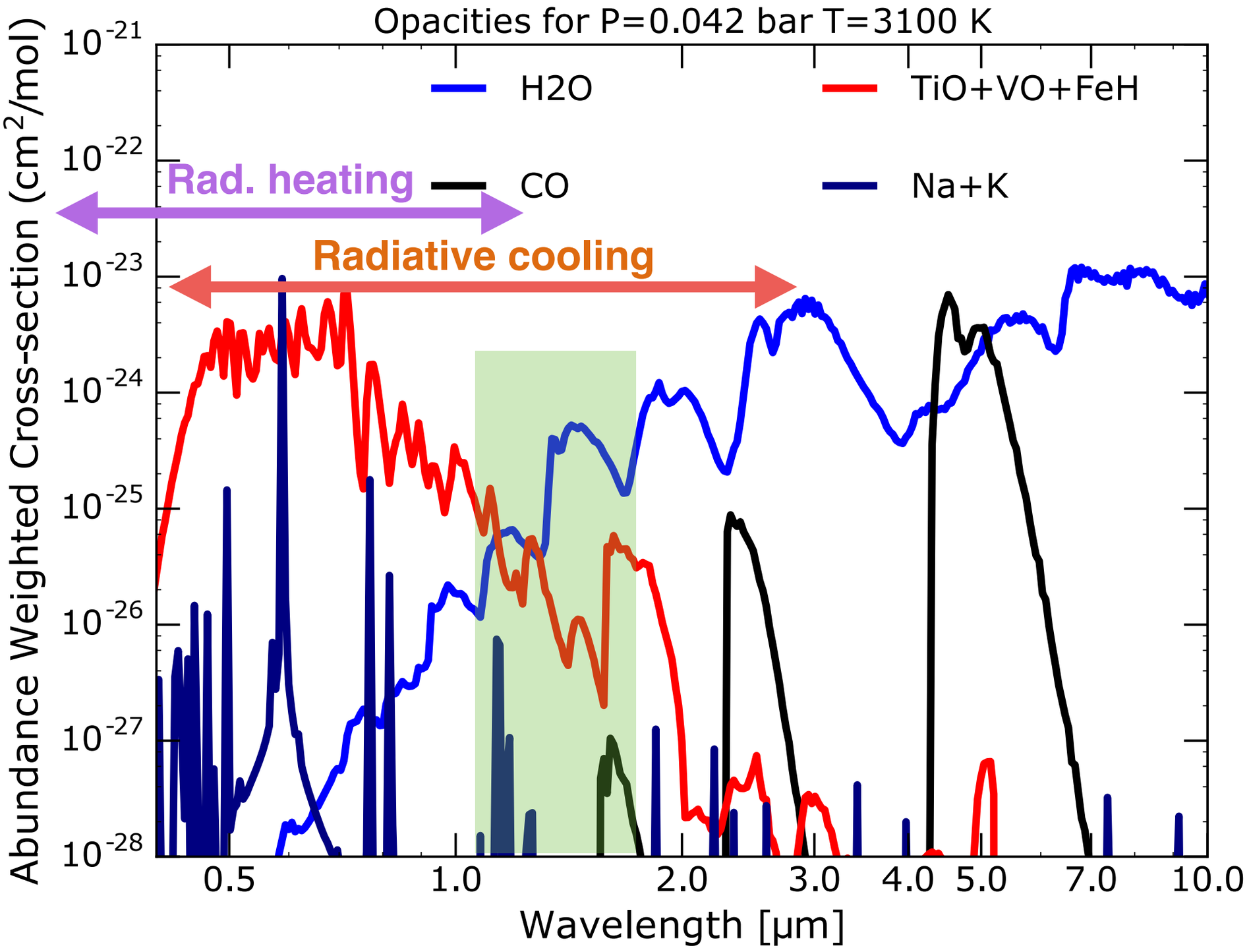

Parmentier+2018 sub.

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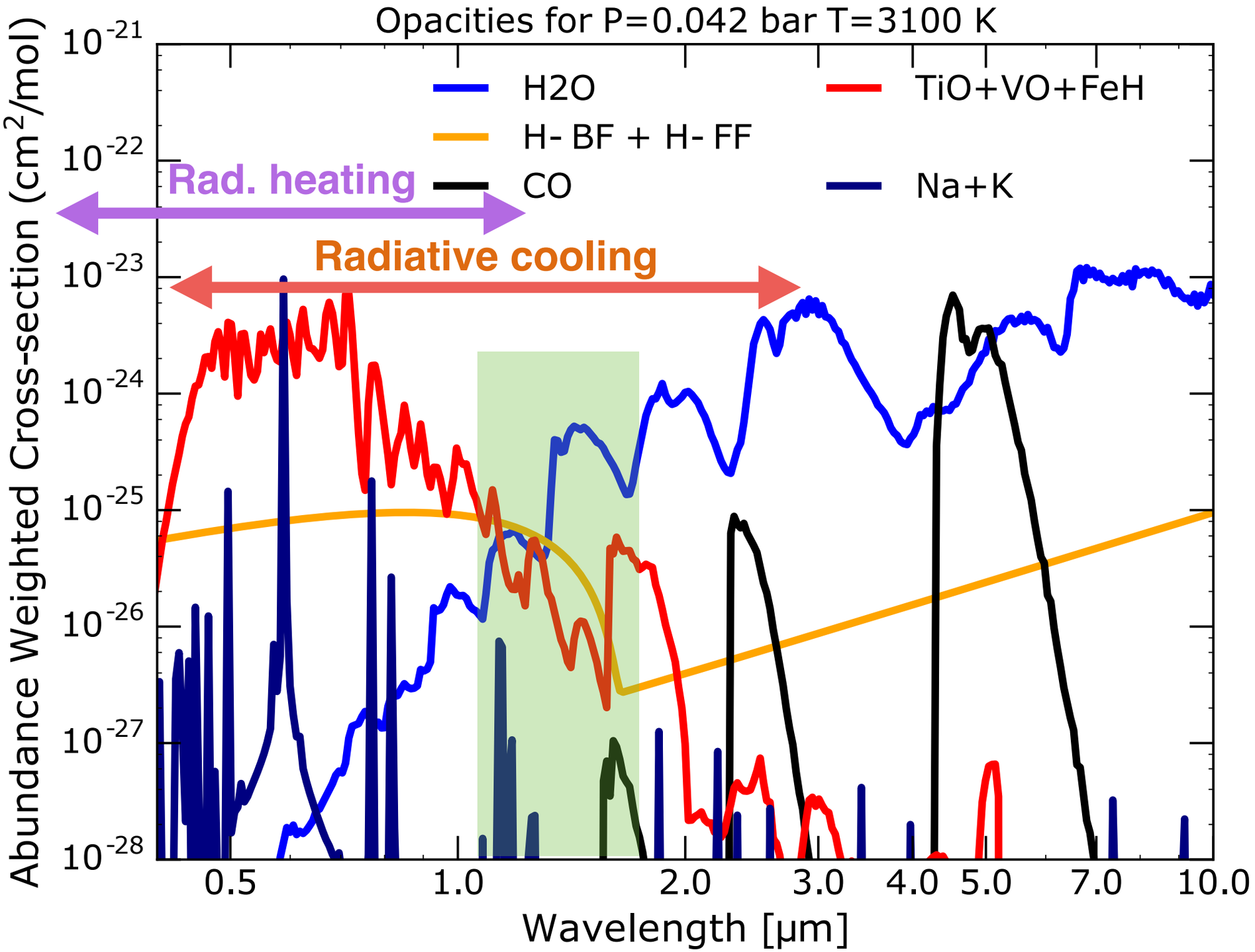

Parmentier+2018 sub.

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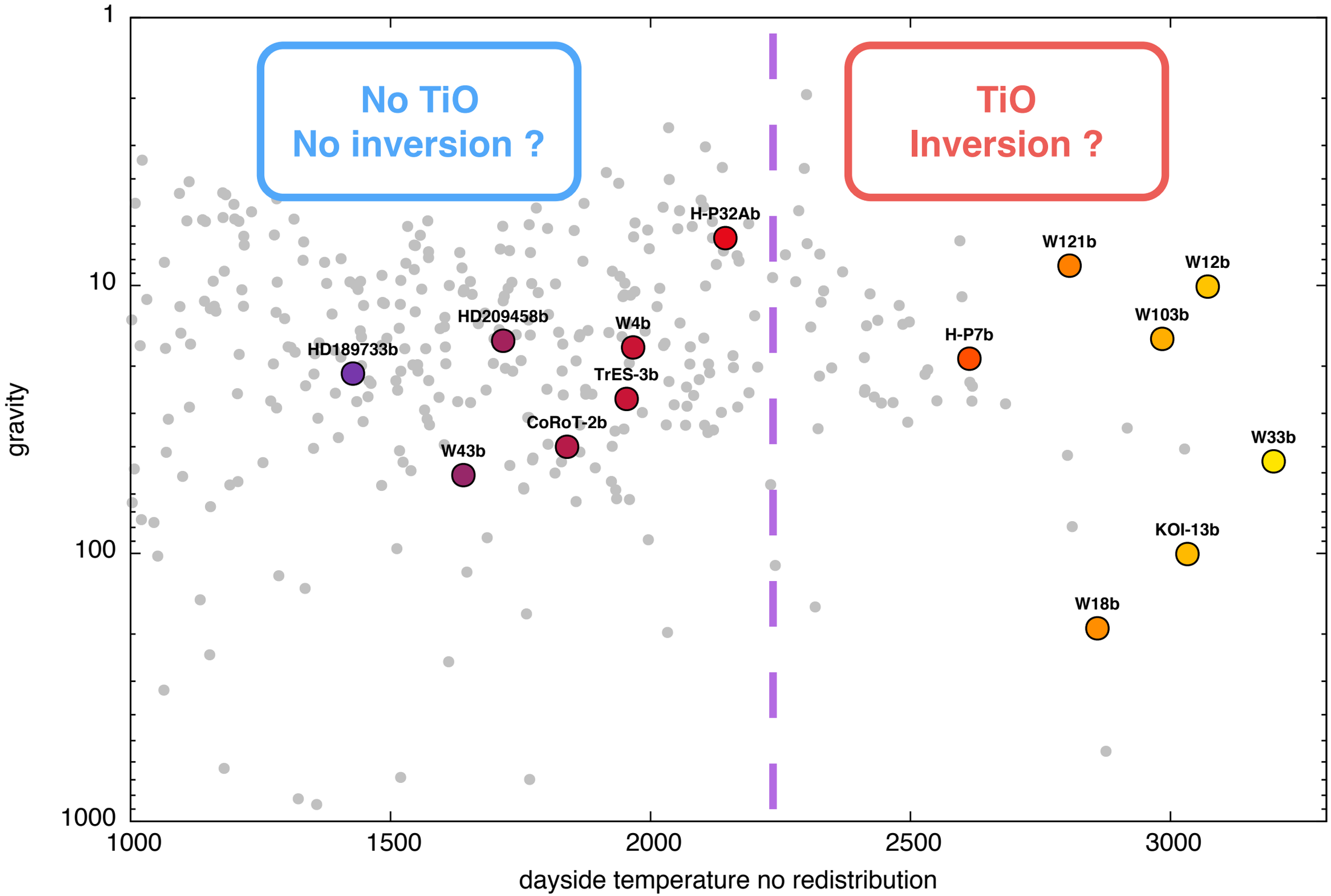
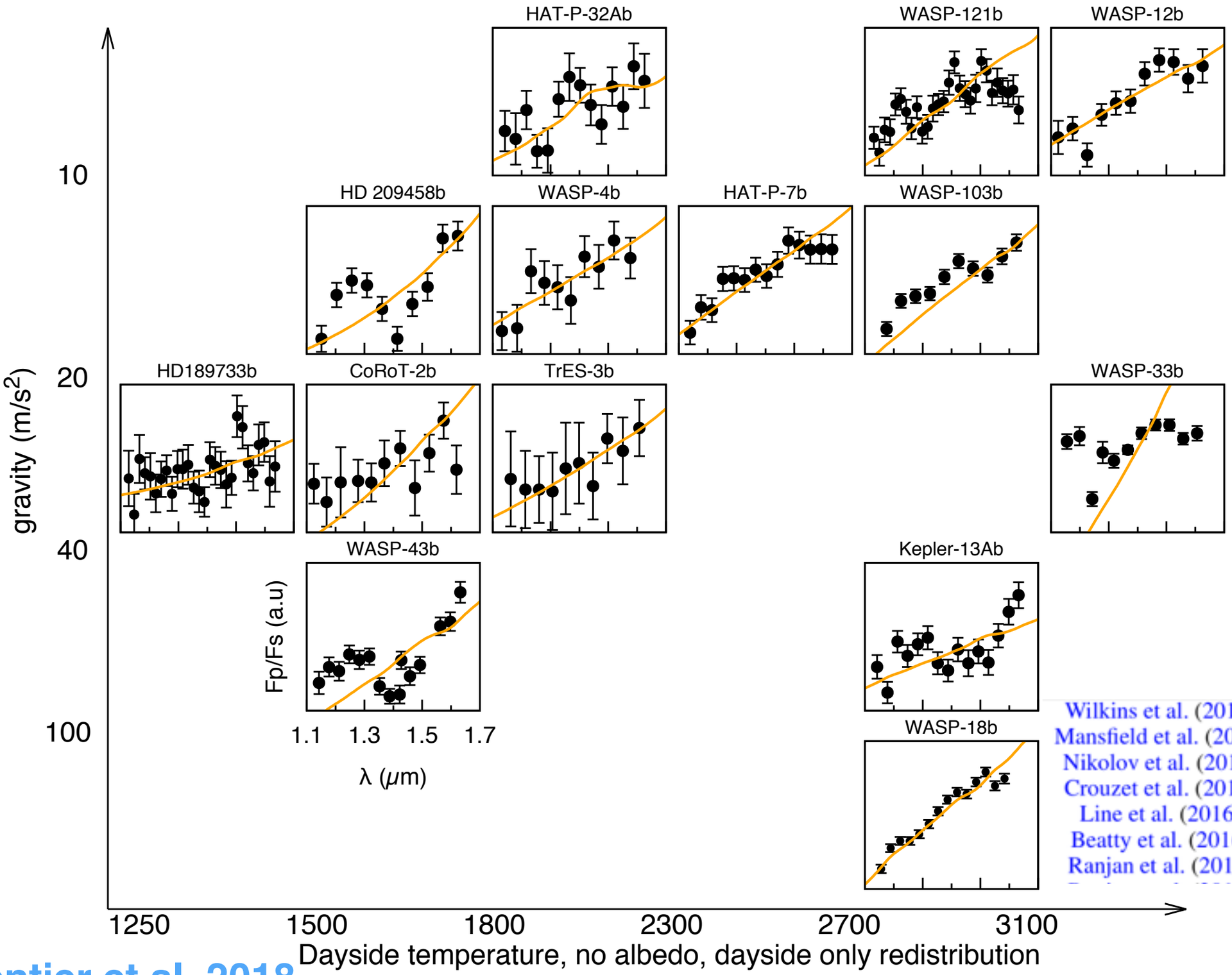


HST/WFC3 observed secondary eclipses



Parmentier et al. 2018

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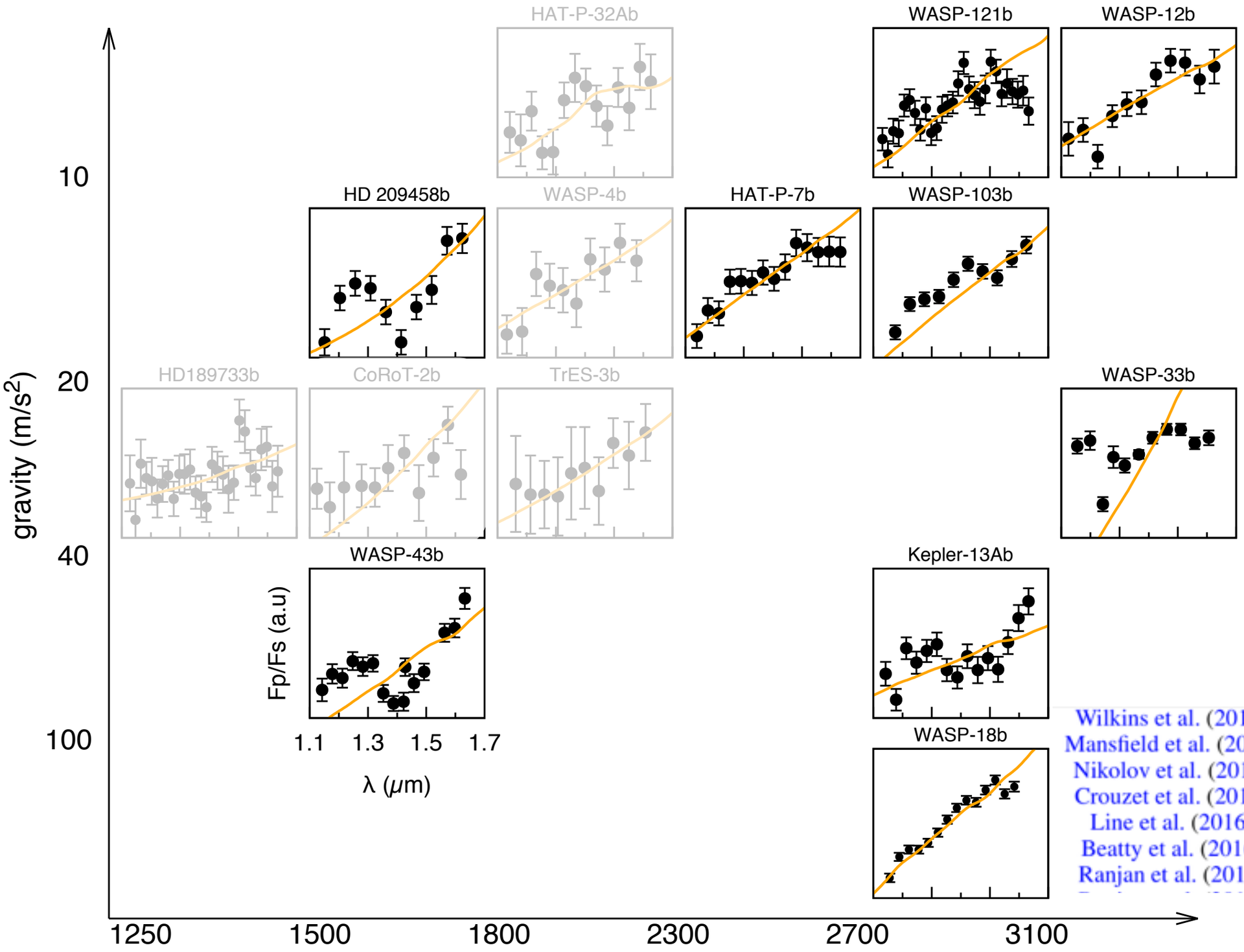

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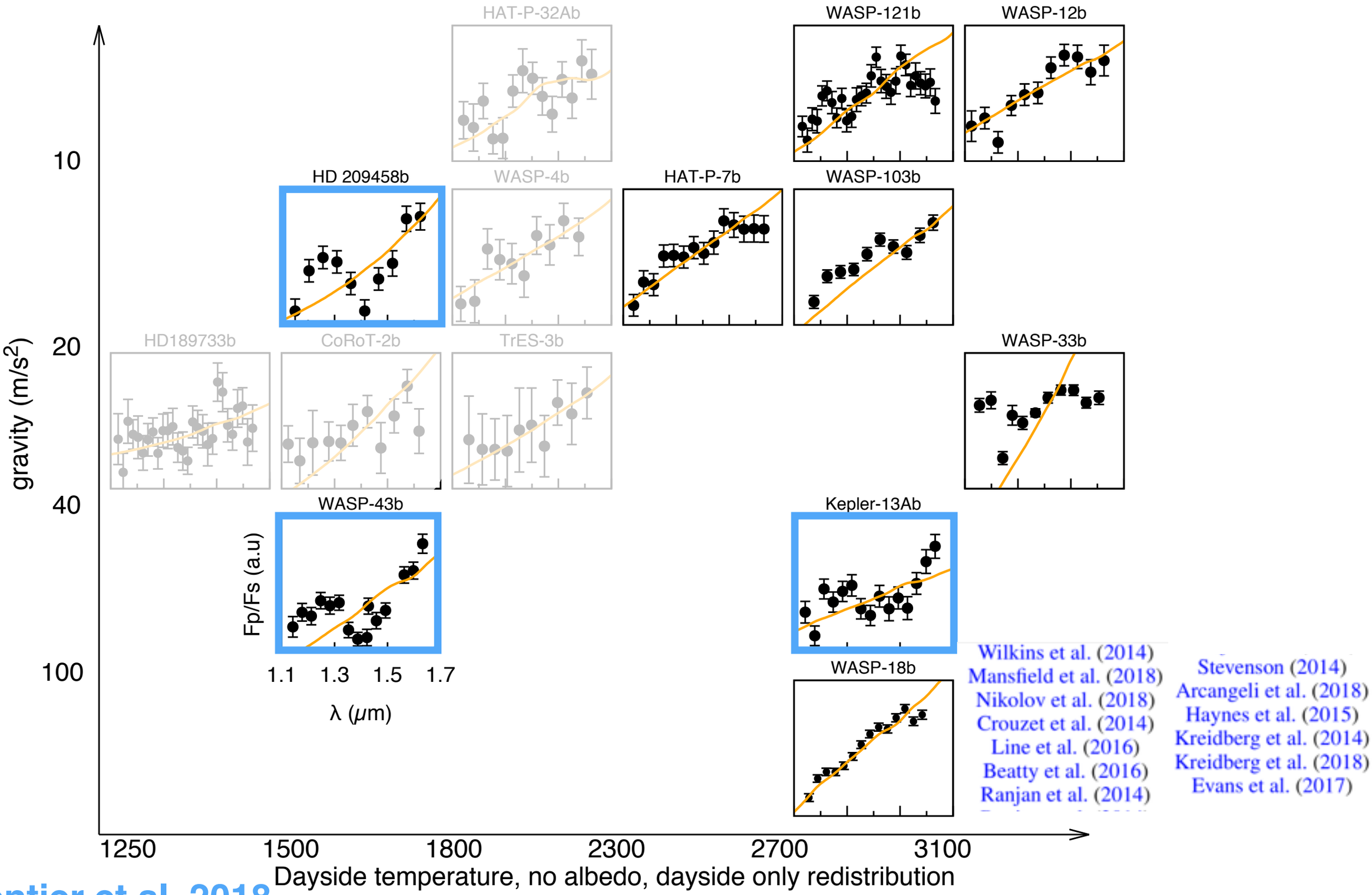

Parmentier et al. 2018

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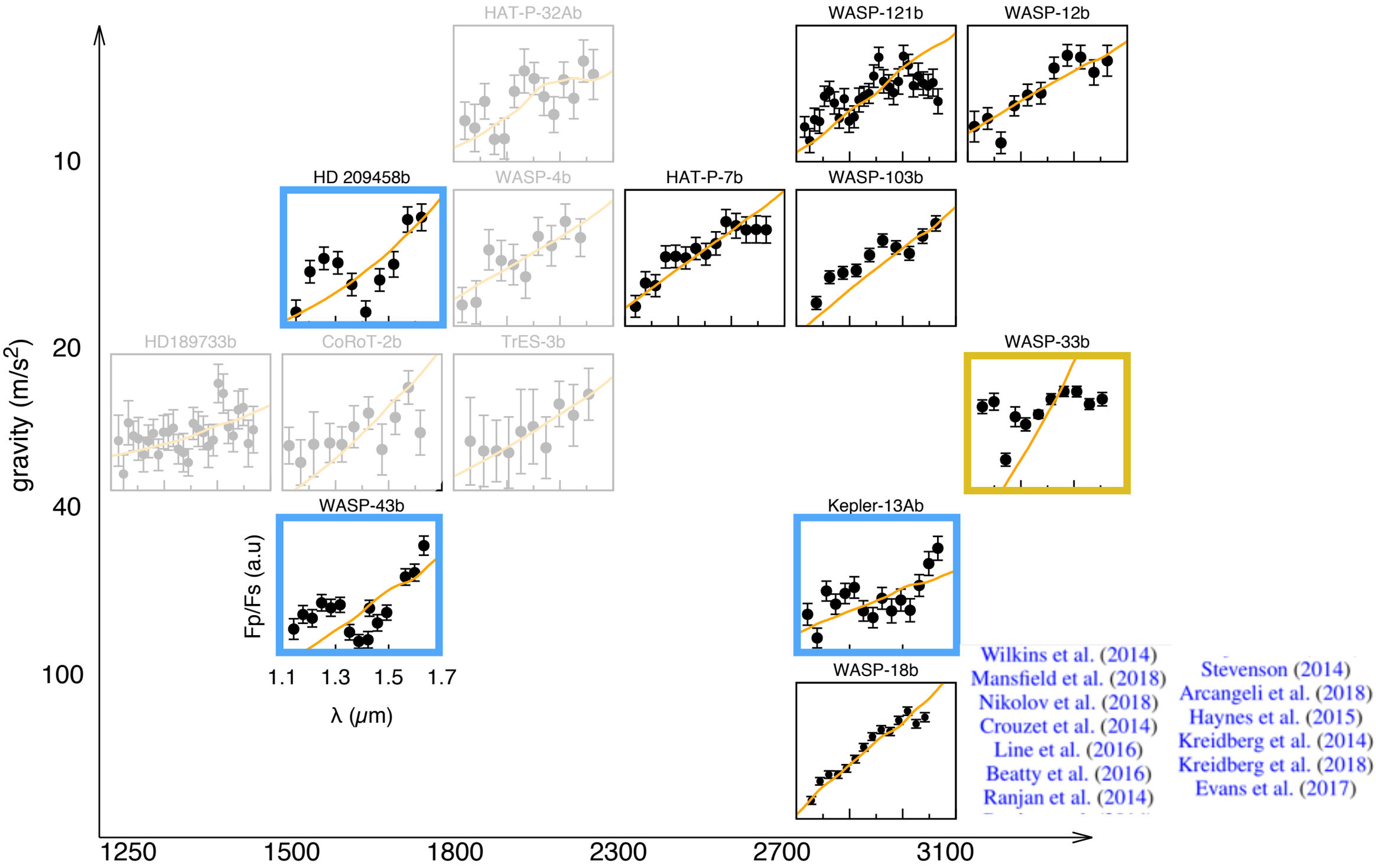

Parmentier et al. 2018

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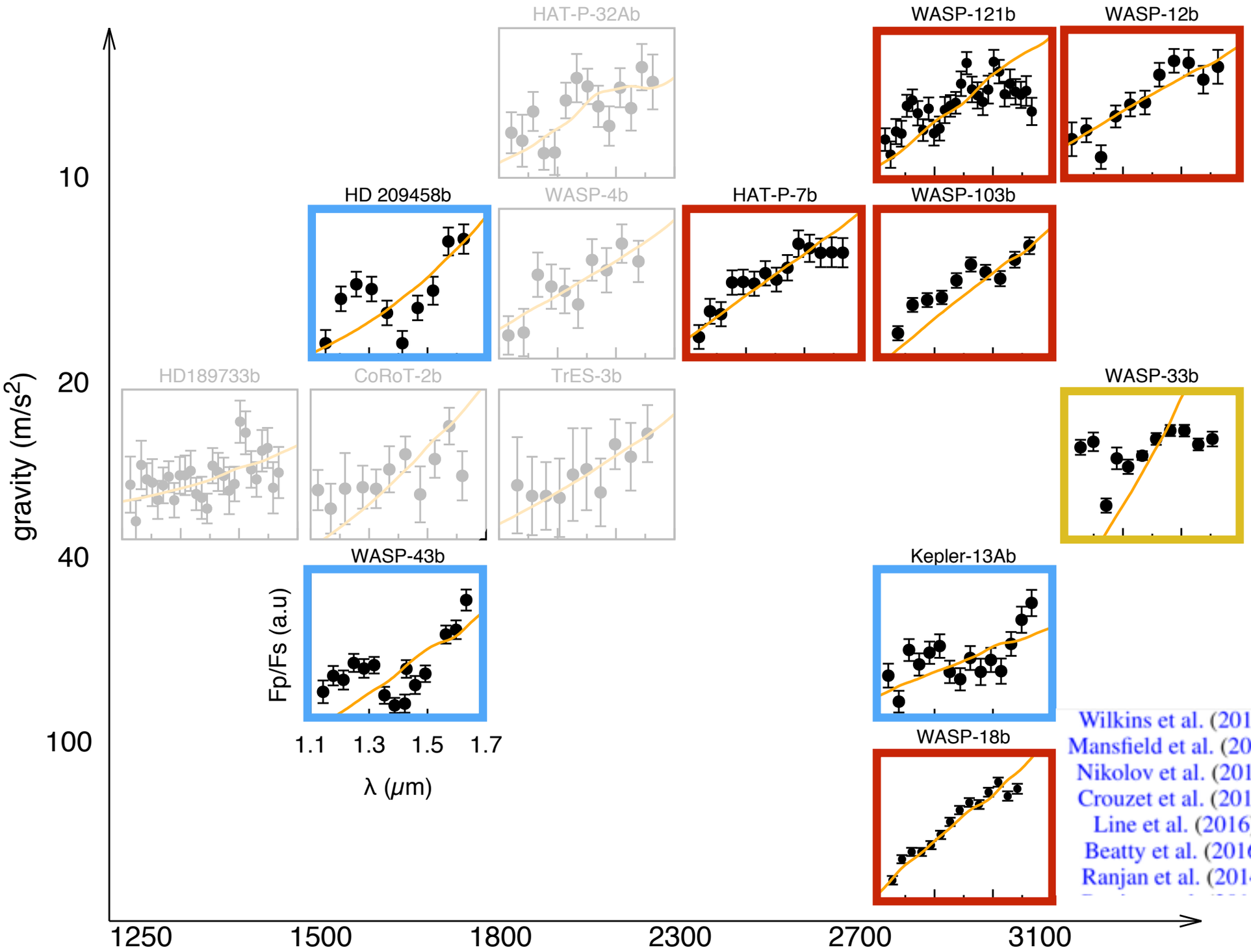

Parmentier et al. 2018

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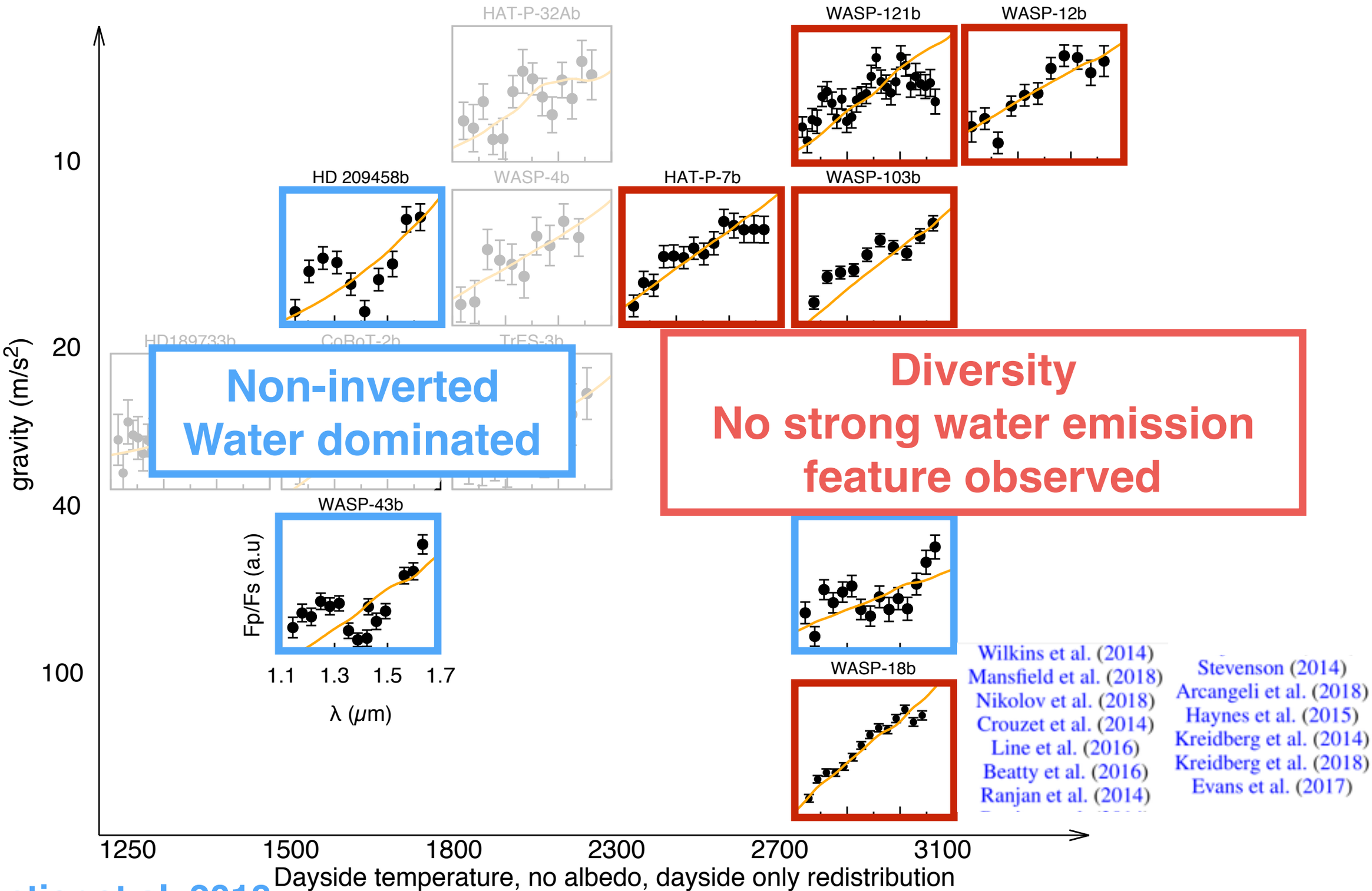

Parmentier et al. 2018

HST/WFC3 secondary eclipses broke most models

How to make water disappear from the HST/WFC3 spectrum ?

Isothermal atmosphere ? Nikolov+2018, Delrez+2018

But this is hard to get ! And Spitzer often shows features

Large C/O ? Madhusudhan+2011 Sheppard+2017

But transmission spectrum shows water !

Another absorber ? Haynes+2015 Evans+2017

But needs unexpected abundance ratio (e.g. VO/H2O>1000x solar, TiO/H2O>10x solar)

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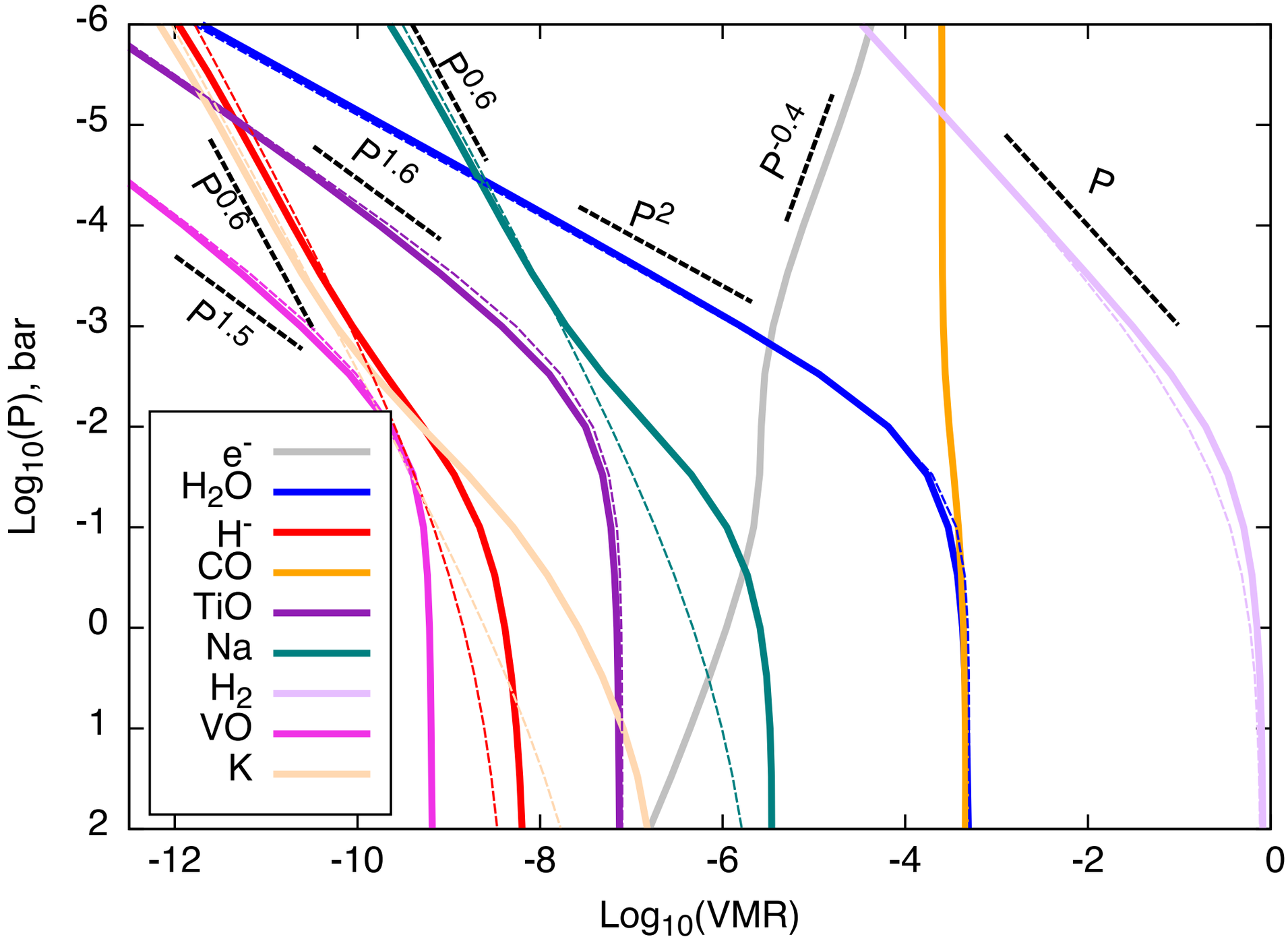
All based on a simple assumption:
abundances are constant with pressure.

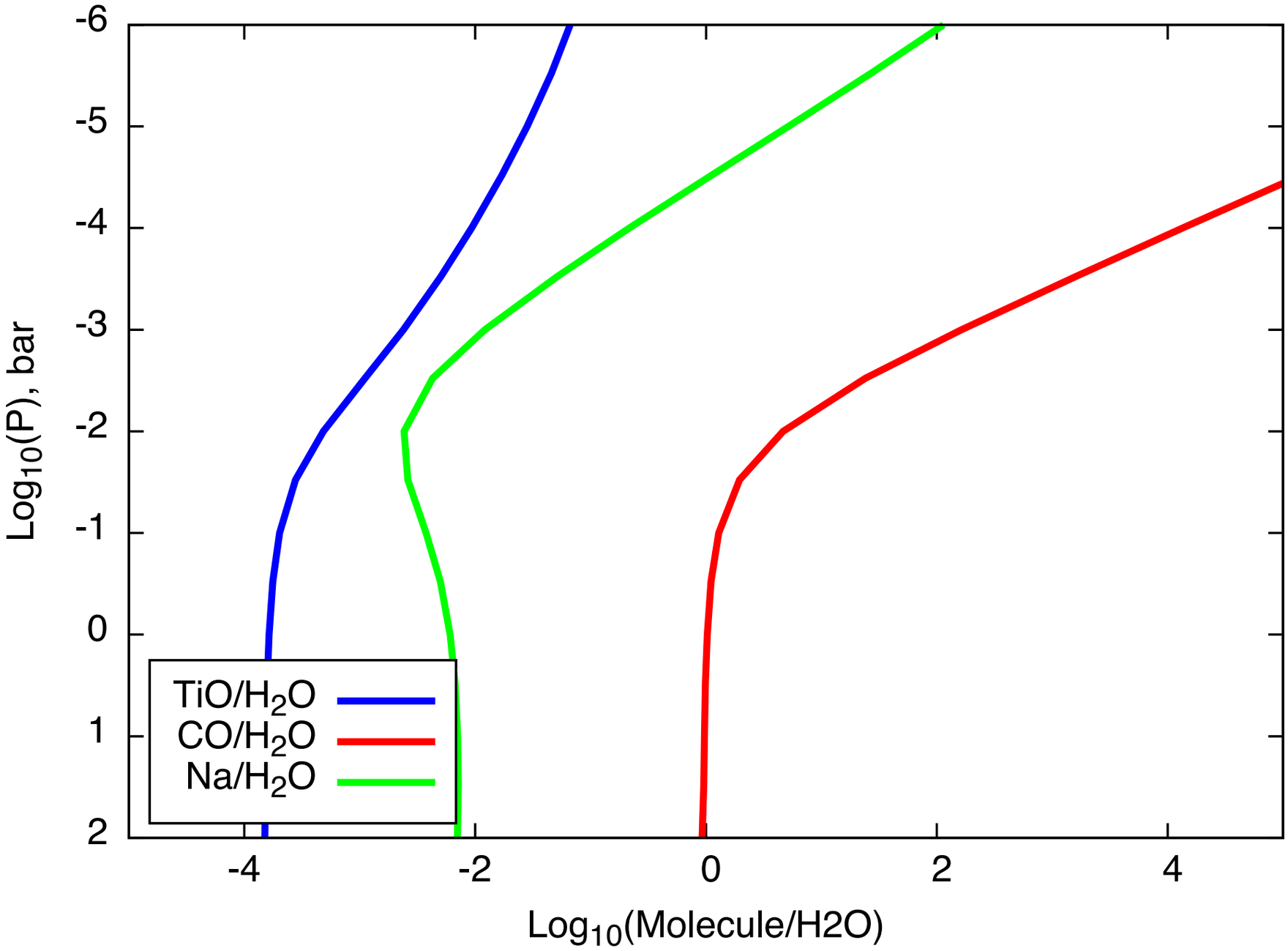
Abundances are NOT constant with pressure…



… apart for CO

Parmentier et al. 2018

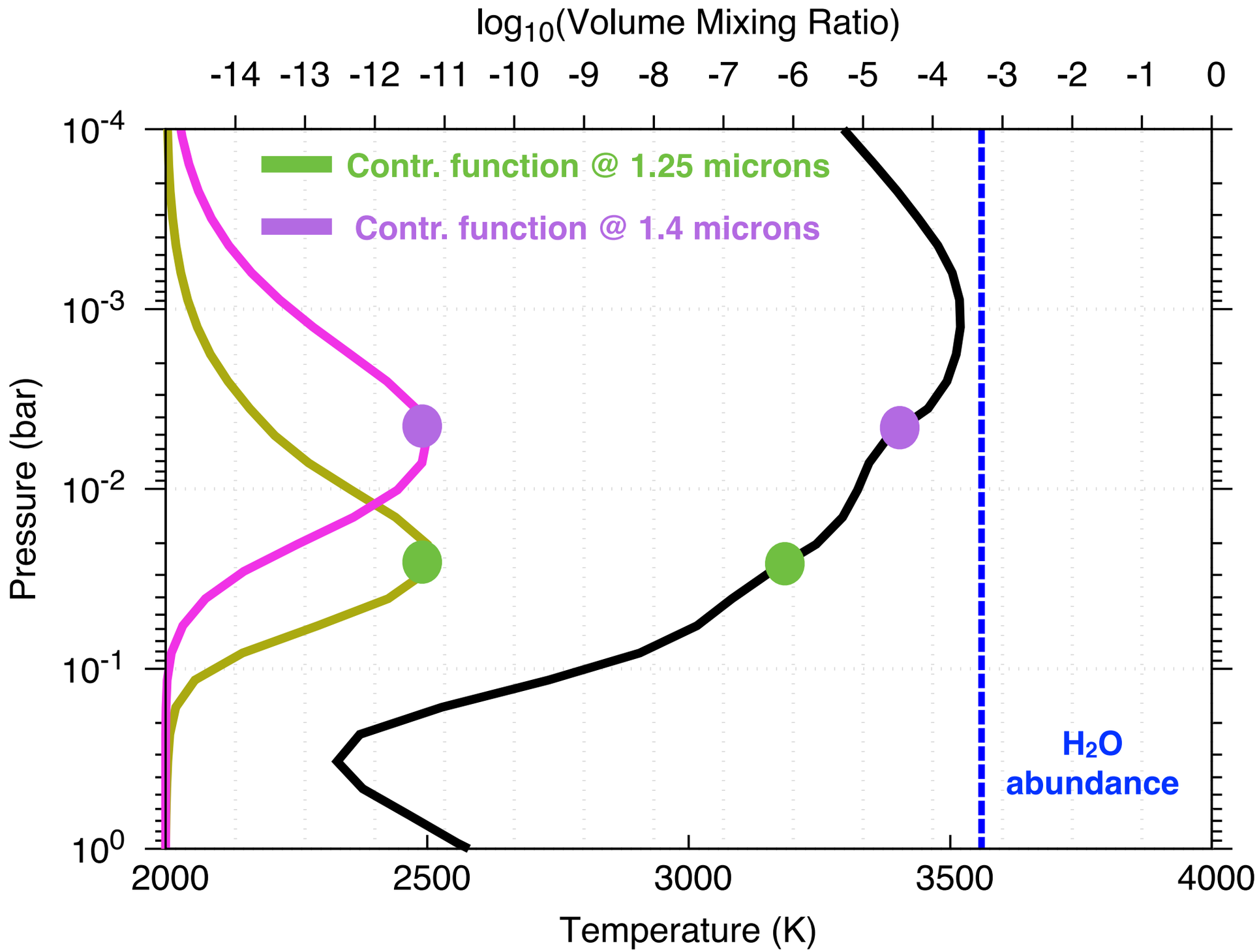
Abundance *ratios* are NOT constant with pressure…



Photospheric pressure and thus photospheric abundance ratios will vary with gravity….

Parmentier+2018

Molecular gradient and H- shape the spectrum



Exemple: WASP-121b

Parmentier+2018 sub.

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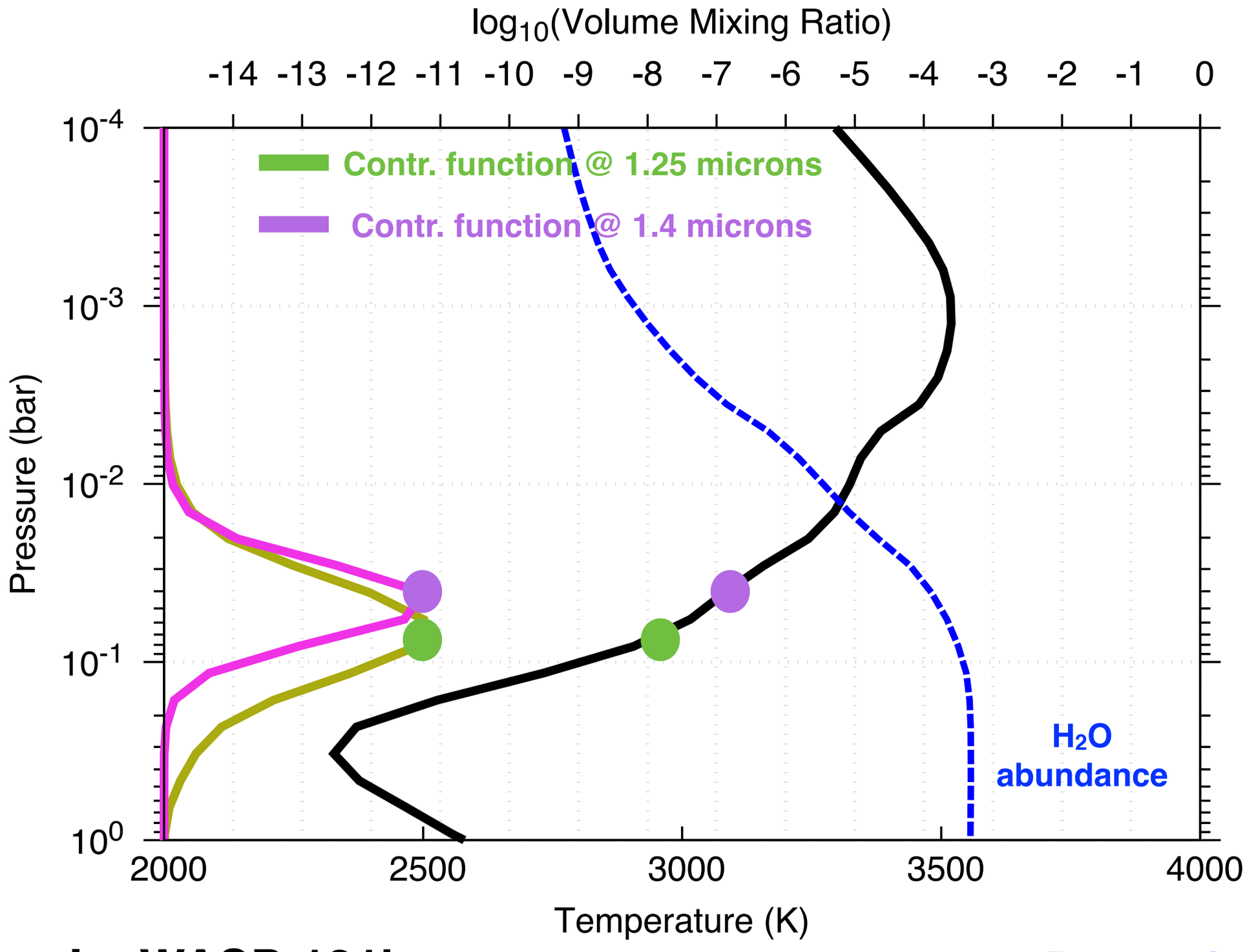

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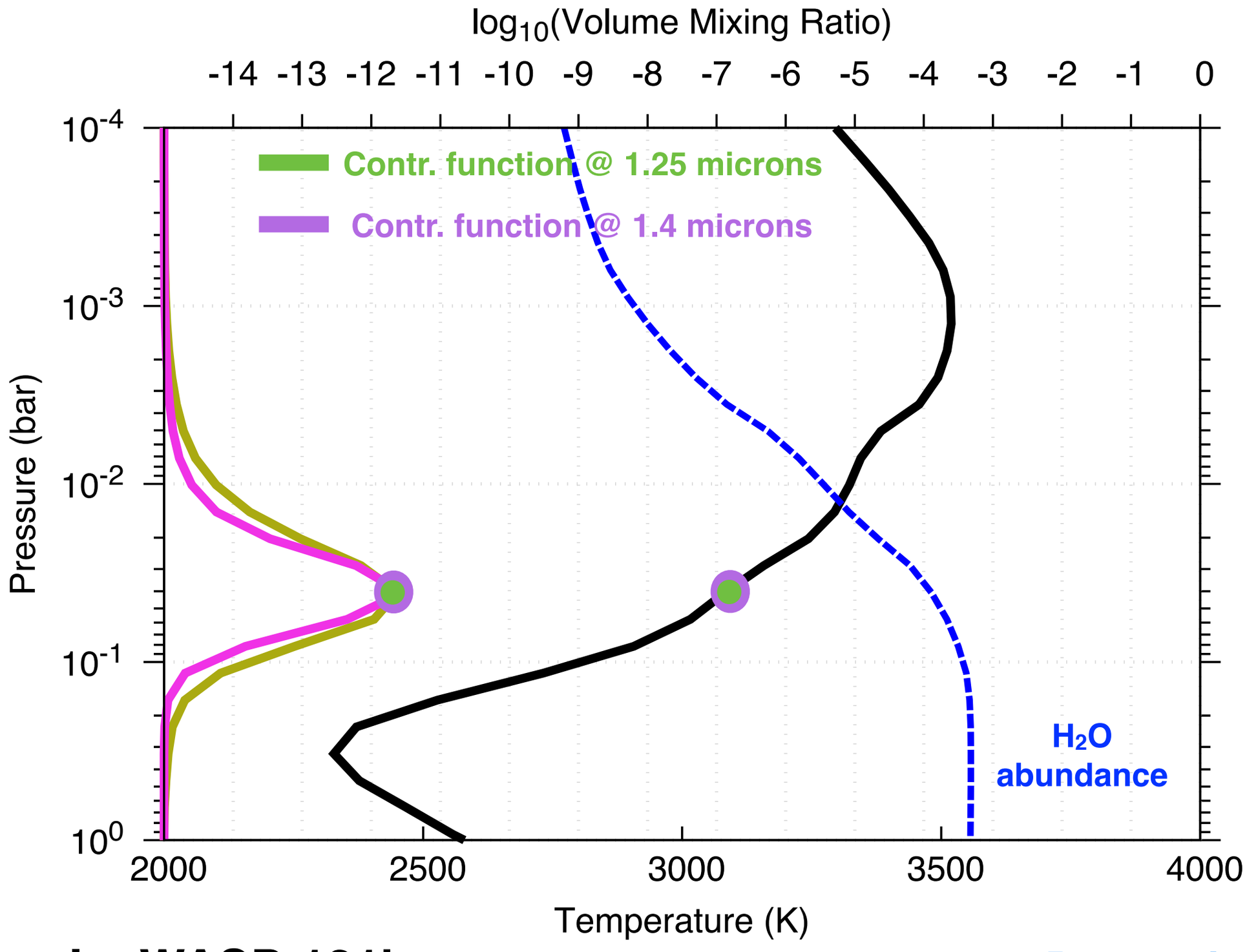

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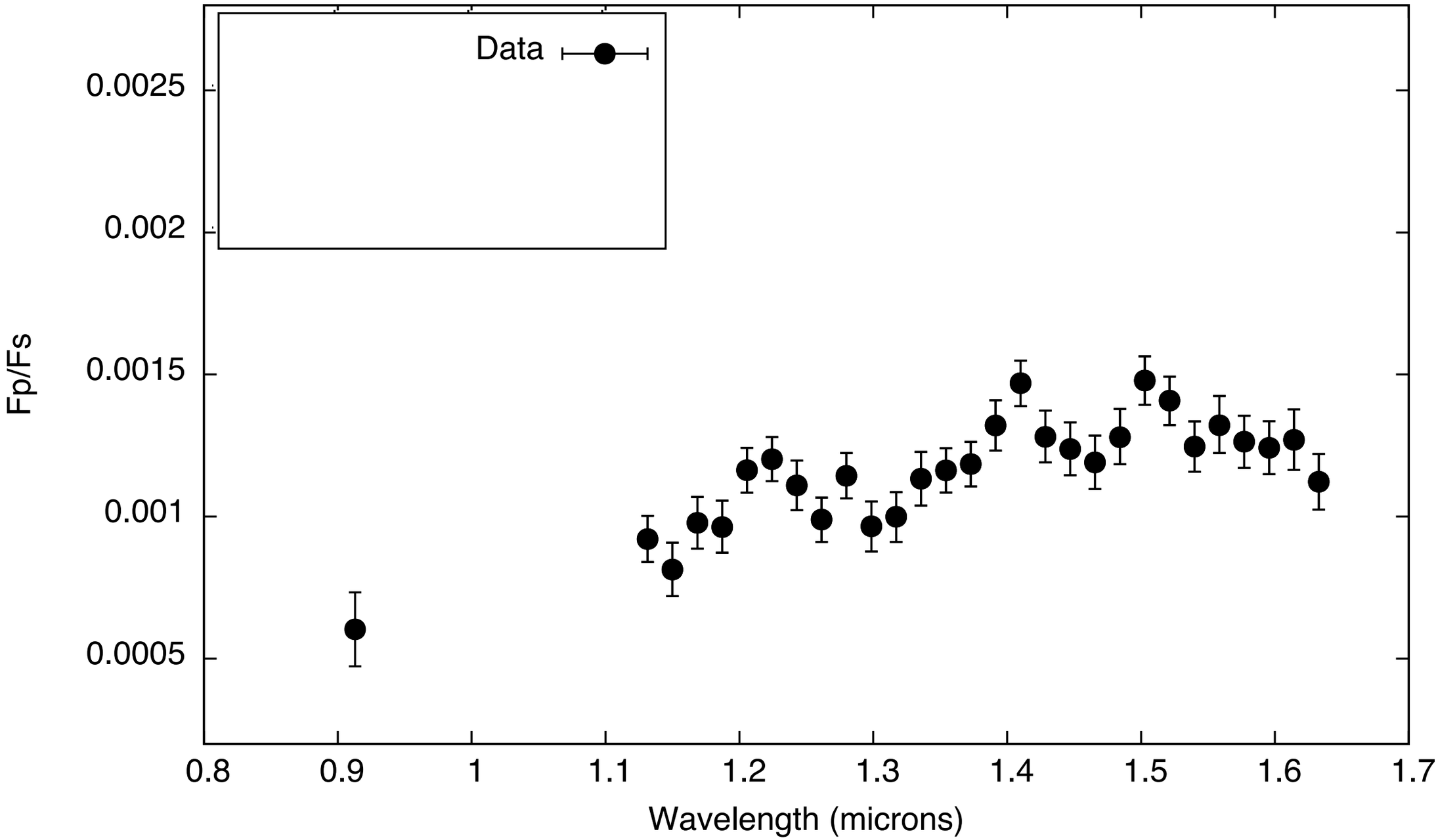

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Models: Parmentier+2018 sub.

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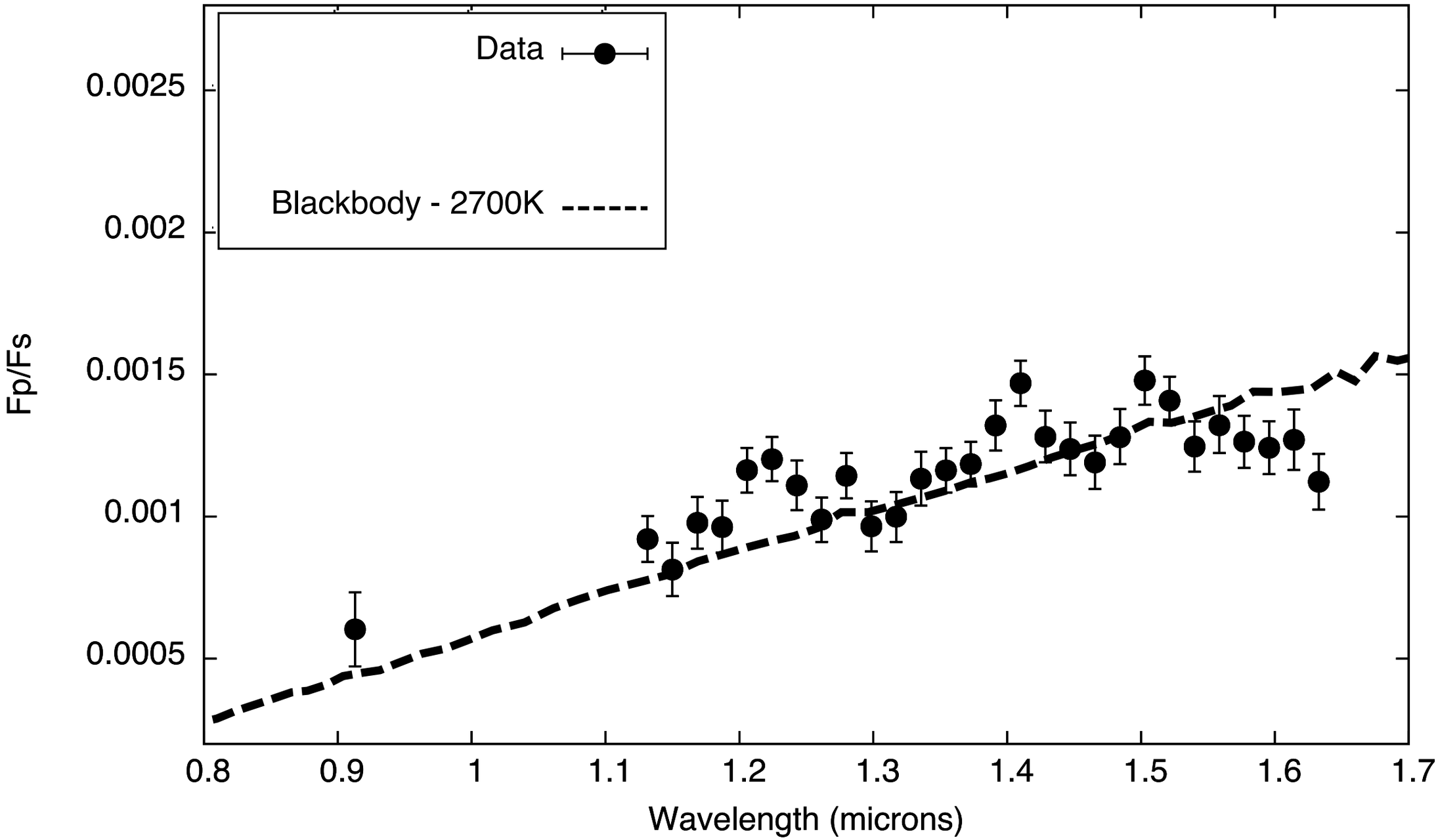

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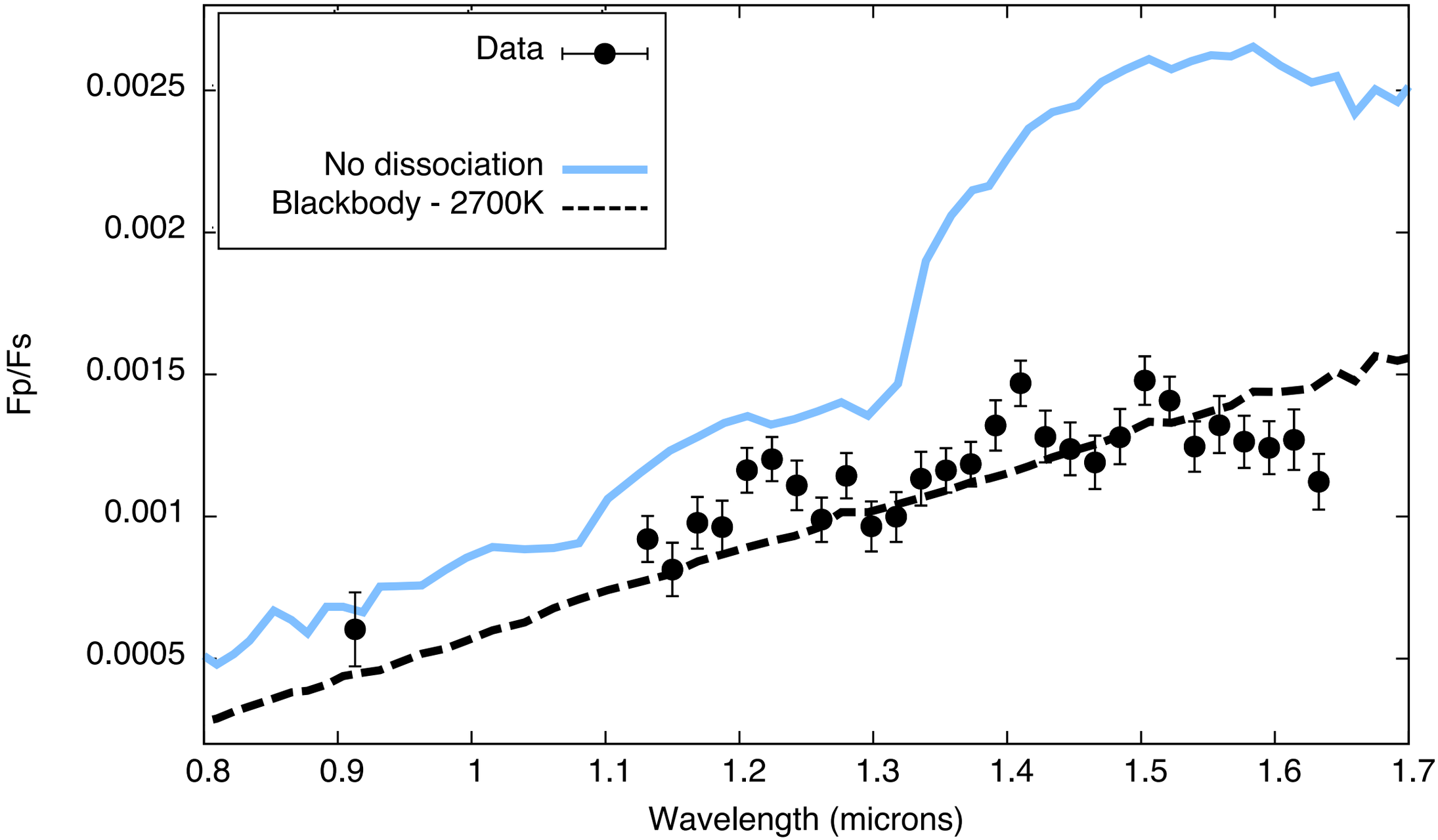

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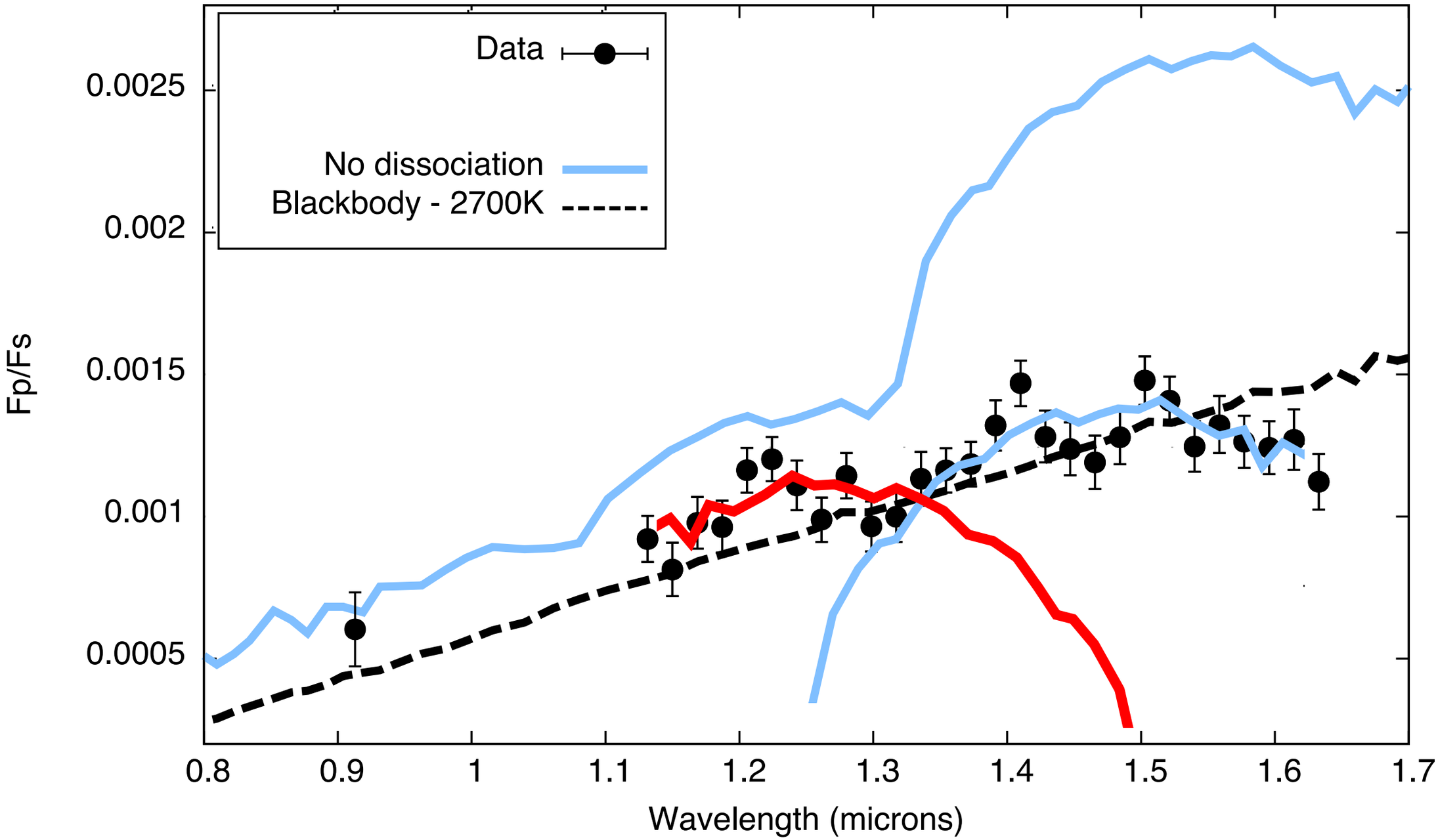

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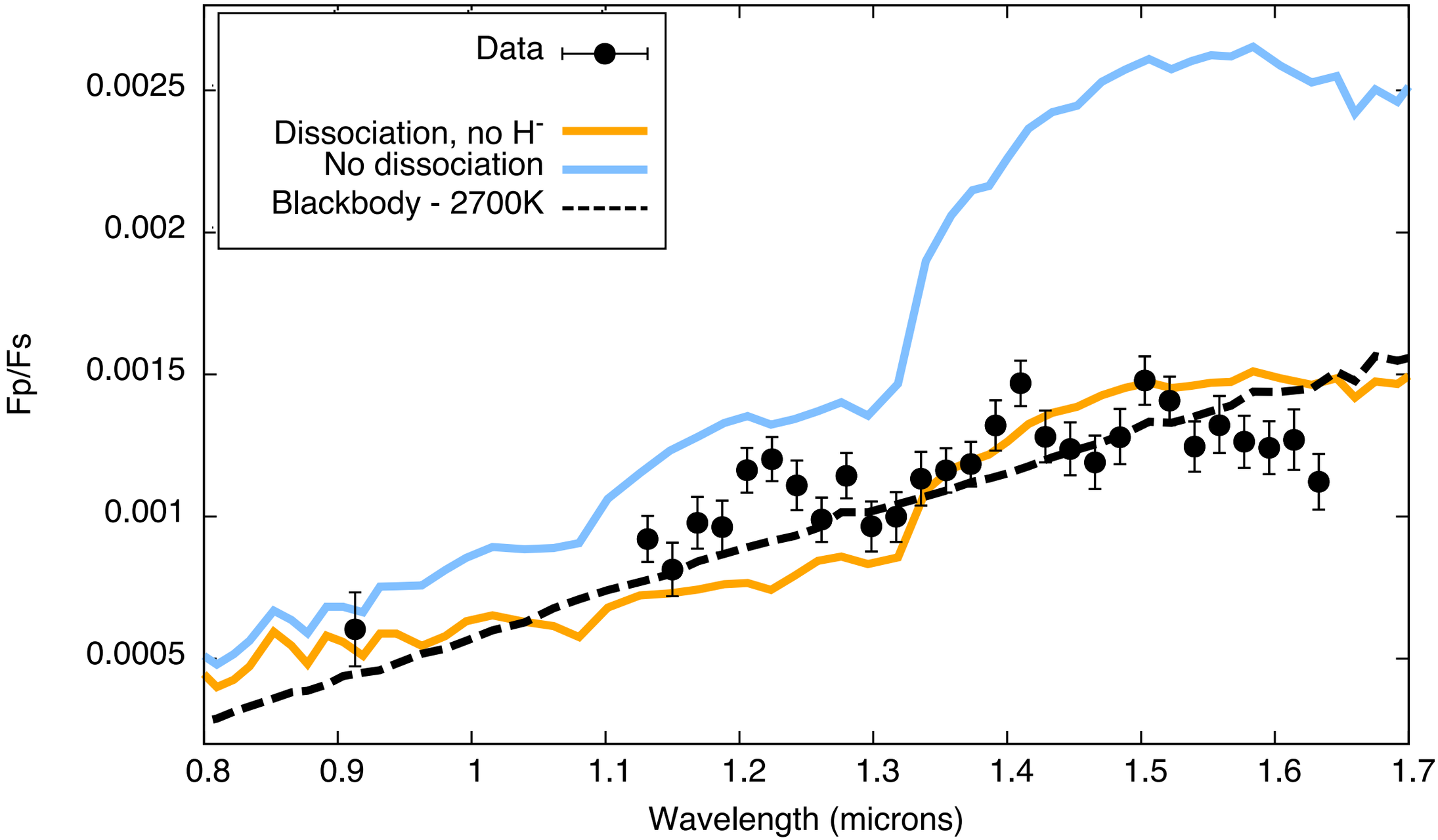

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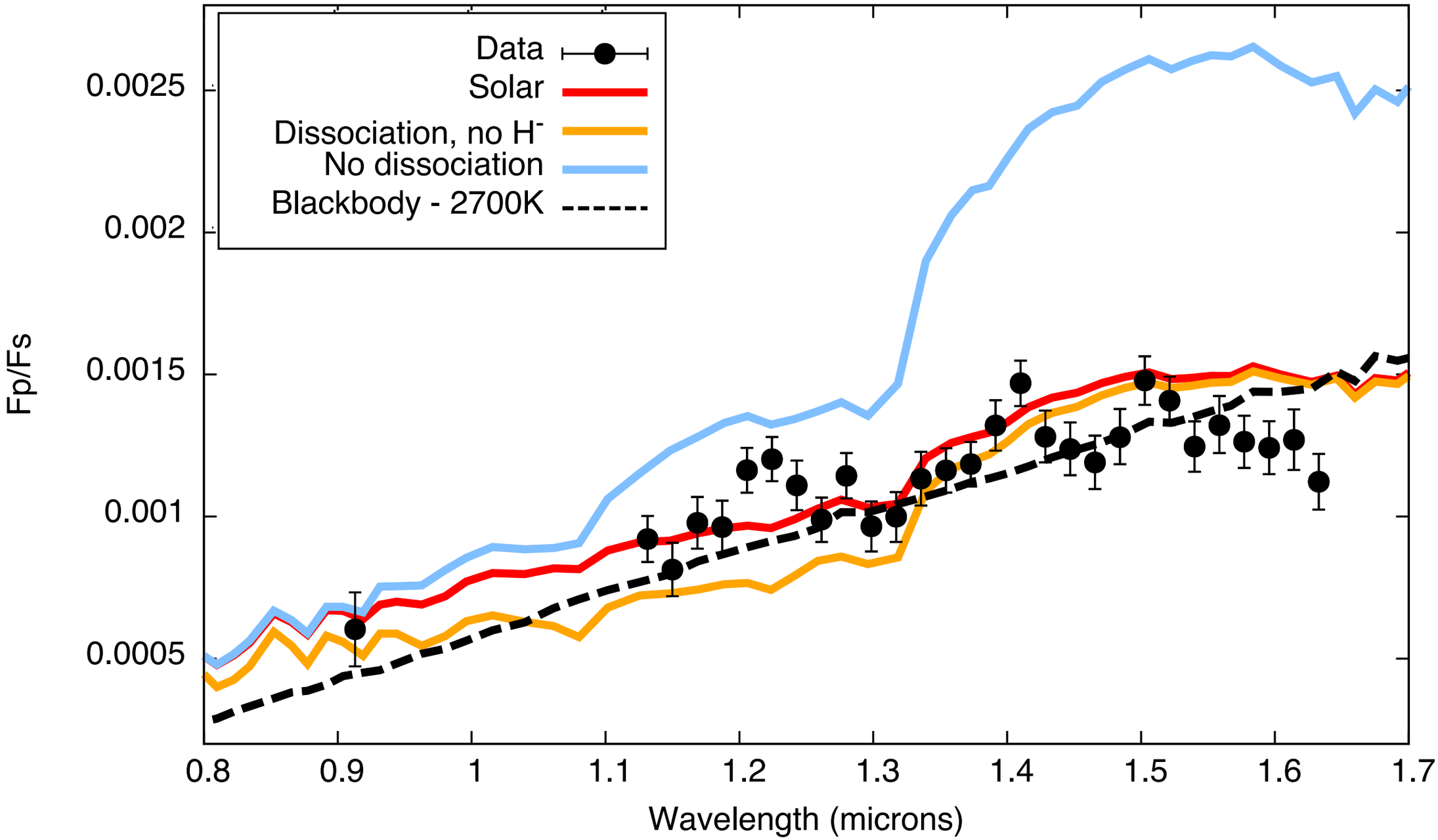
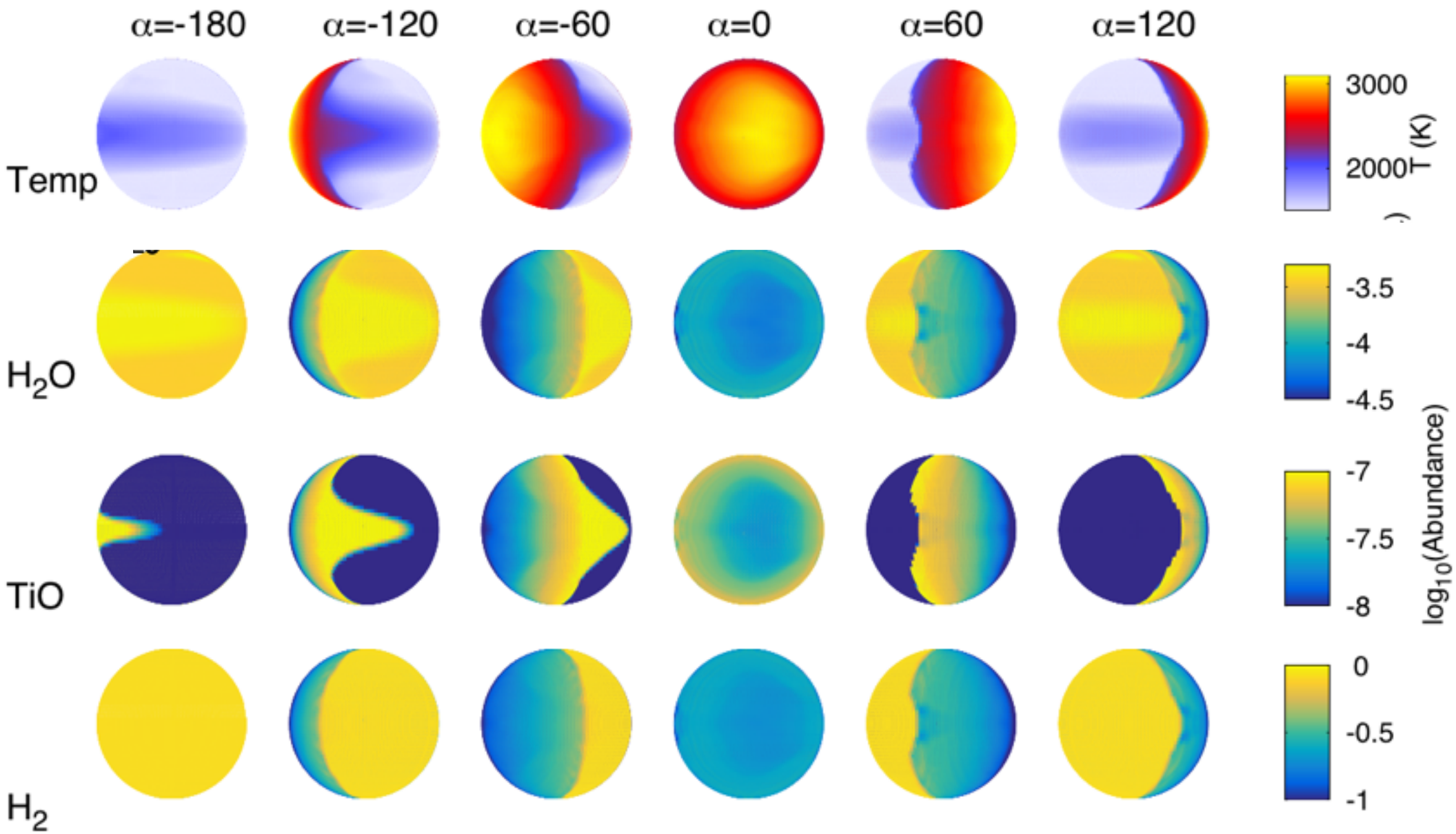


Exemple: WASP-121b

Data: Evans+2017

Models: Parmentier+2018 sub.

2D structure of dissociation

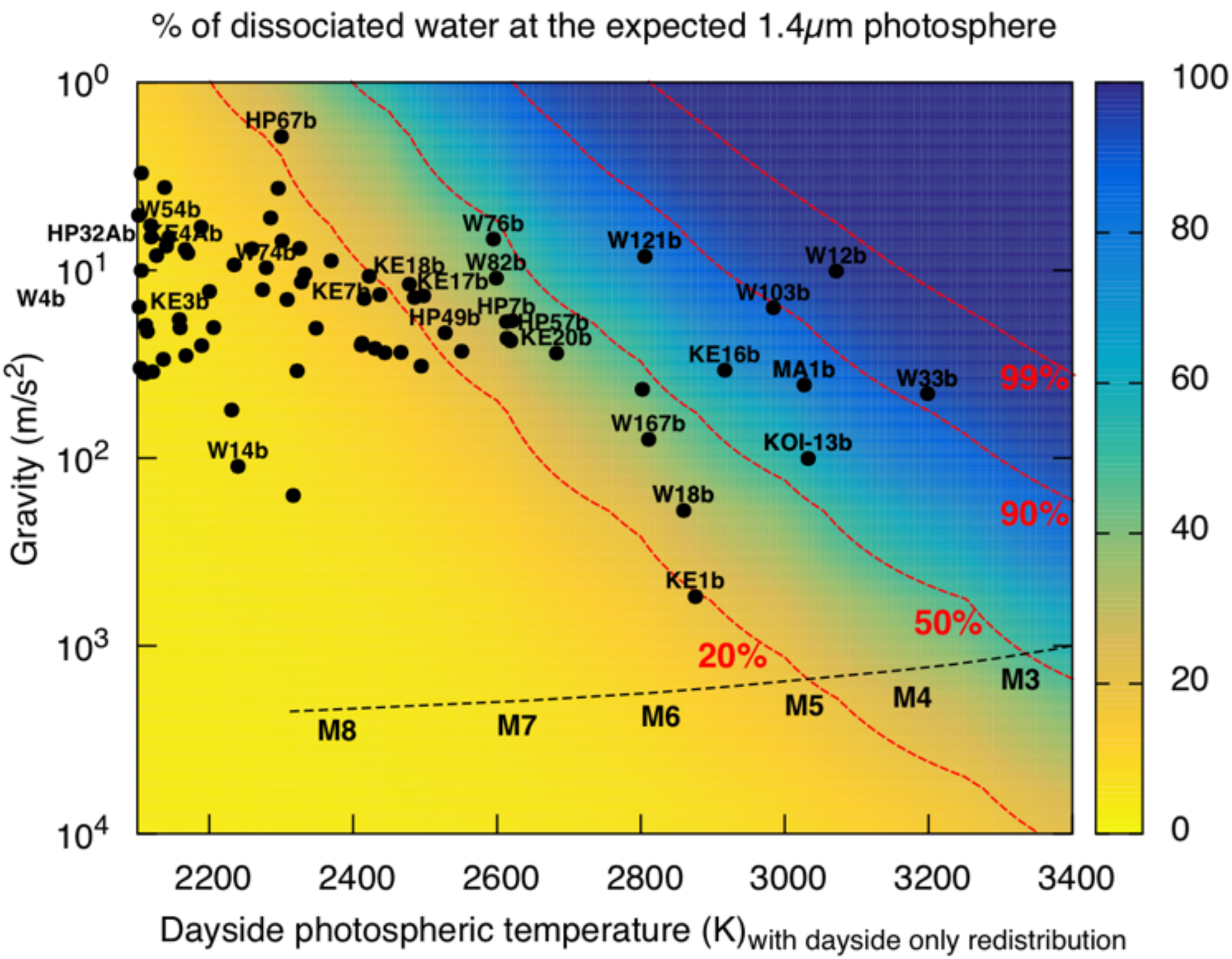


H2 recombination means latent heat transport (e.g. Bell+2016)

Exemple: WASP-121b

Parmentier+2018

The family of Ultra hot Jupiters



Parmentier+2018

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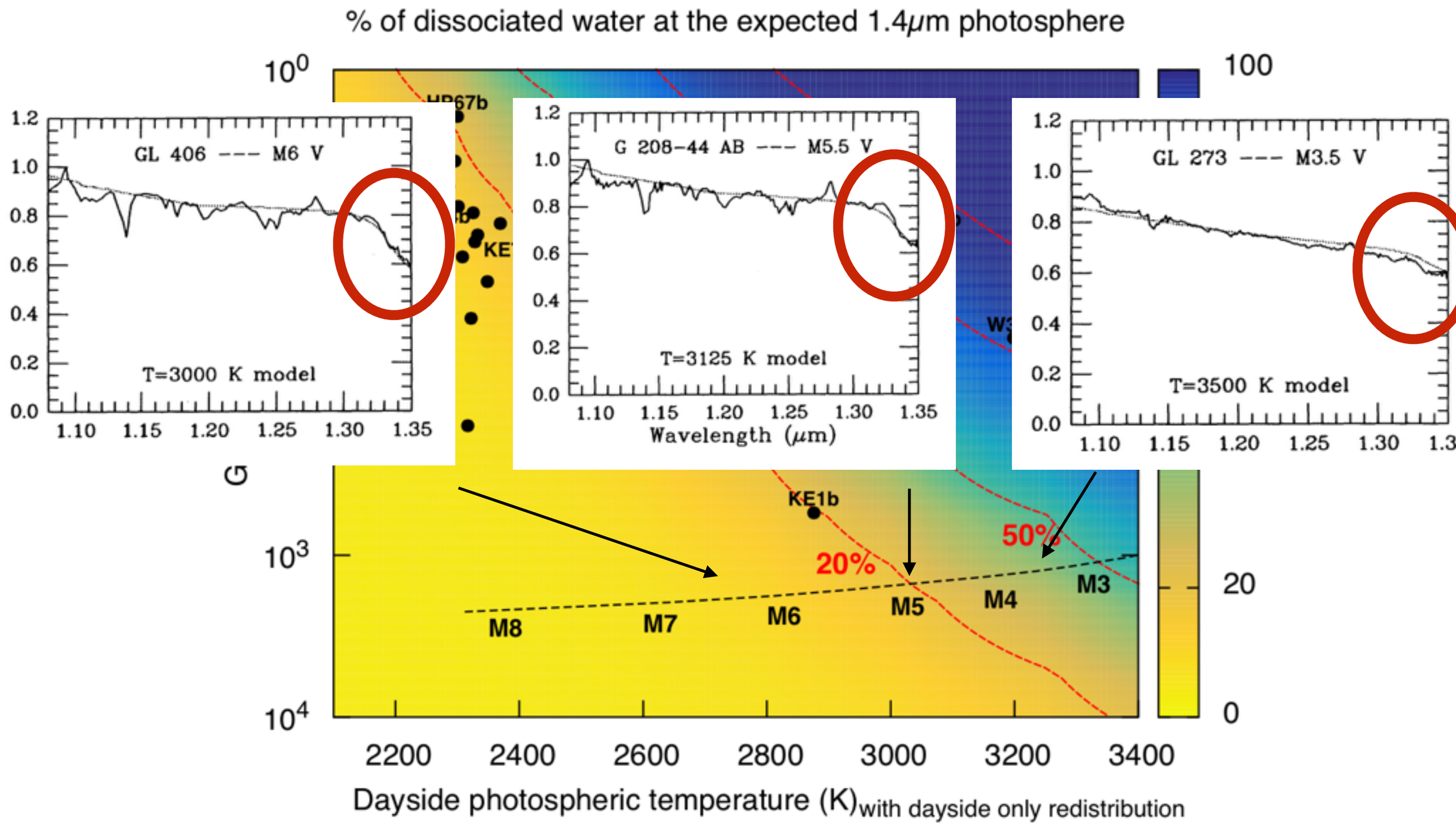

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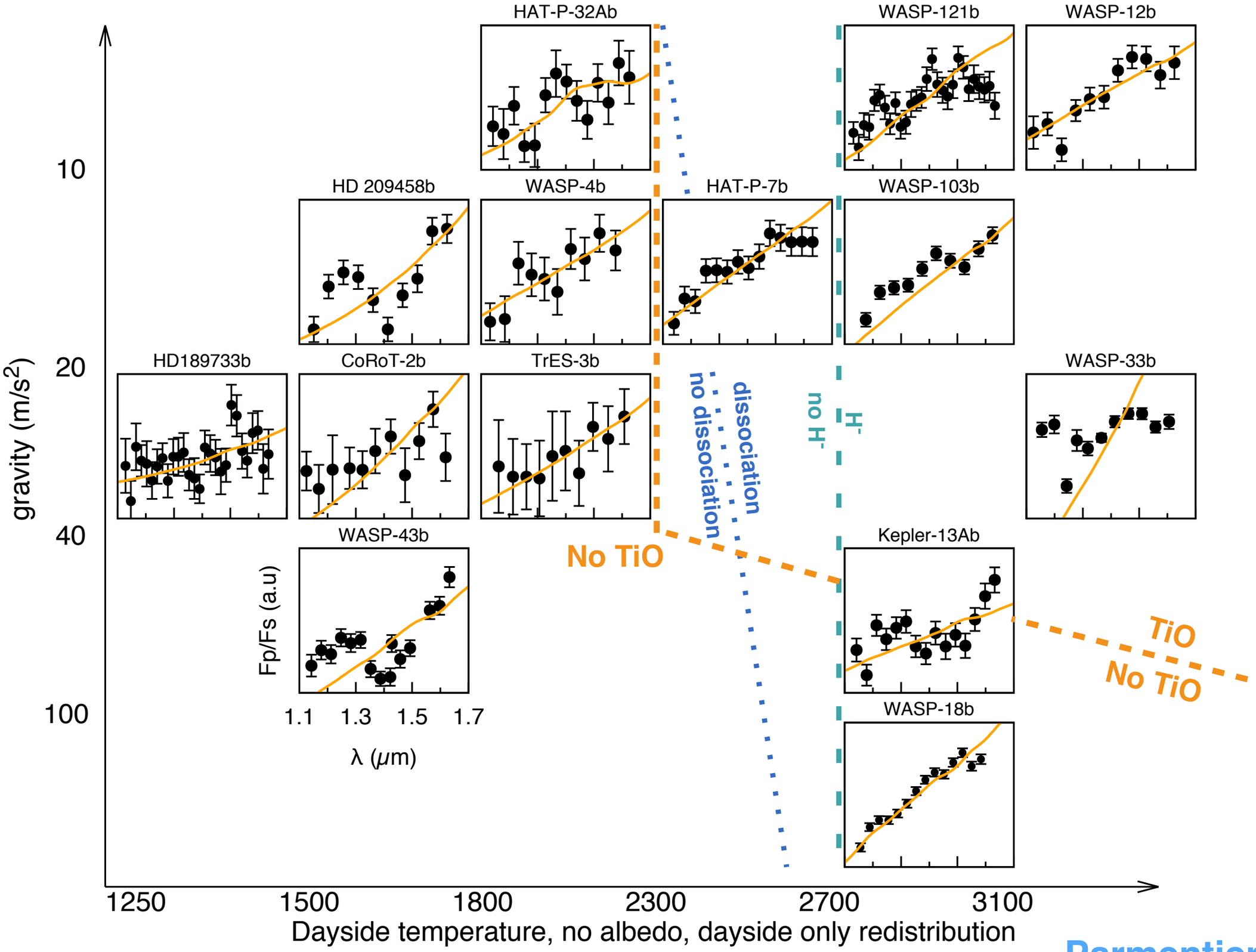

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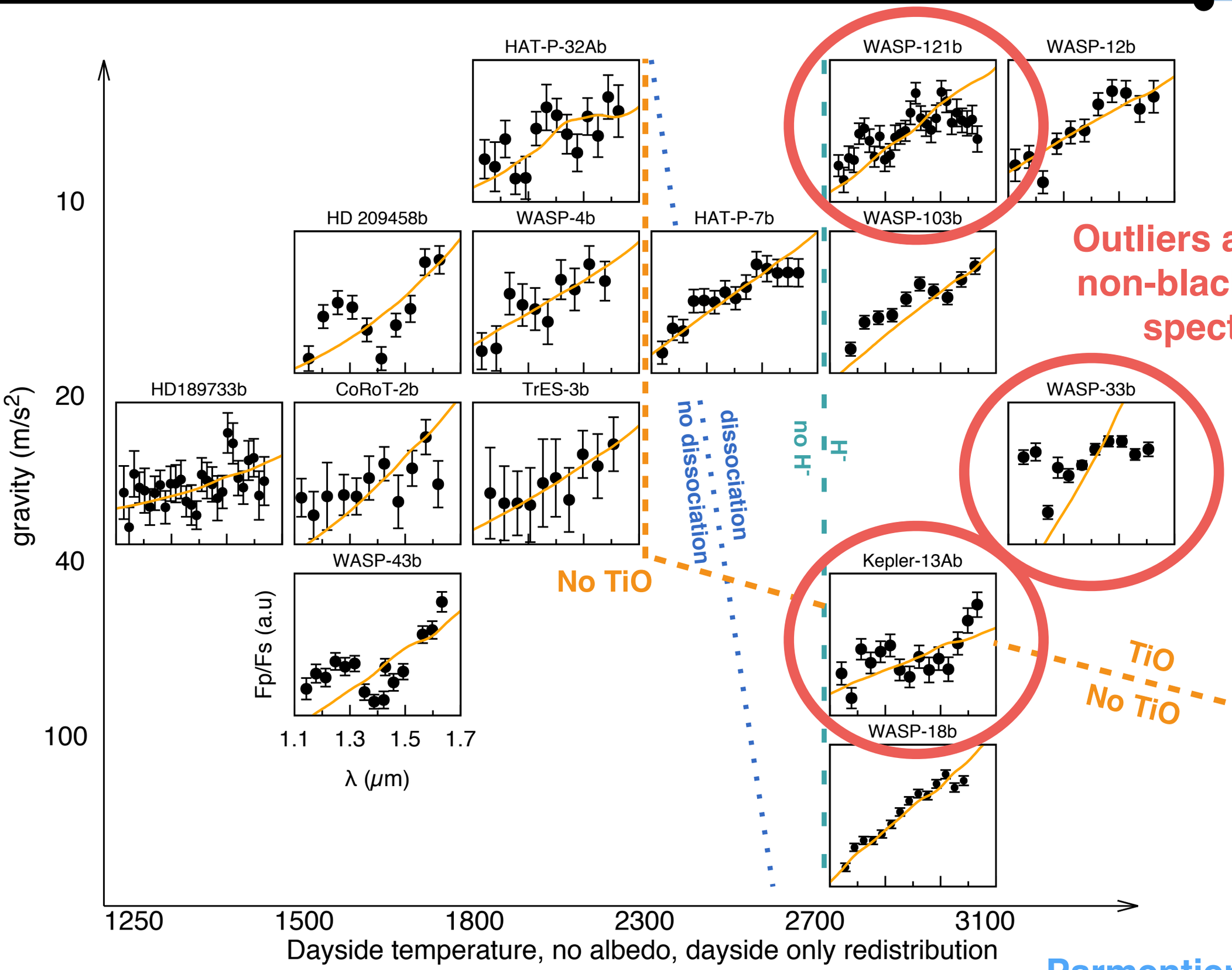

Outliers are the non-blackbody spectra

Parmentier+2018

Now the future…

-> Atmospheres are hard to understand — 3D objects, multi-parameter population

Temperature, rotation, gravity, radius, metallicity, abundance ratio (C/O, Ti/O … etc), magnetic field, planet-star interactions, surface/ocean/ atmosphere/biosphere interactions …

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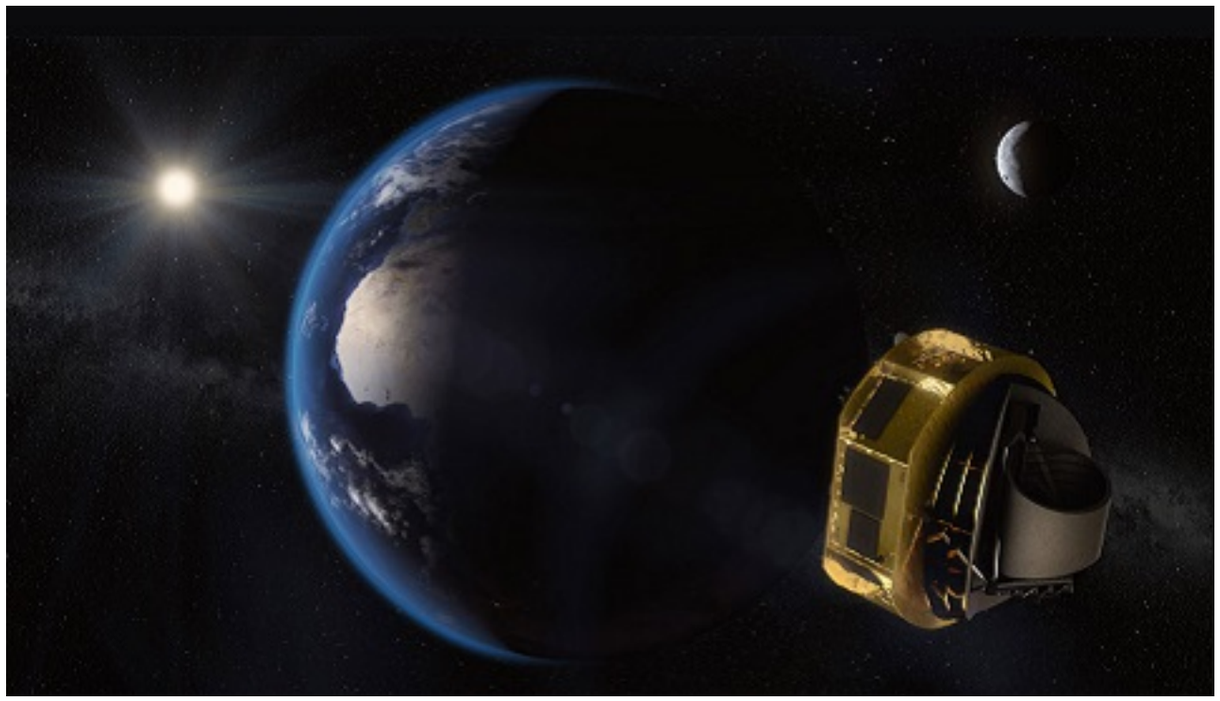

Ariel :
1st Tier : Find the interesting planets by low resolution survey ~1000 among those found by TESS and PLATO
2nd Tier : Spectroscopy on best targets ~100-500
3rd Tier : Full 3D mapping of a few ones~10-50

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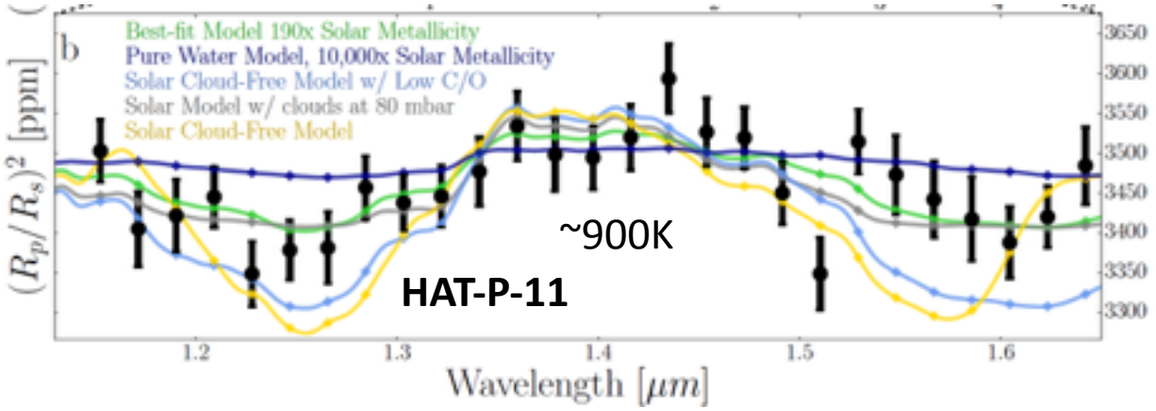
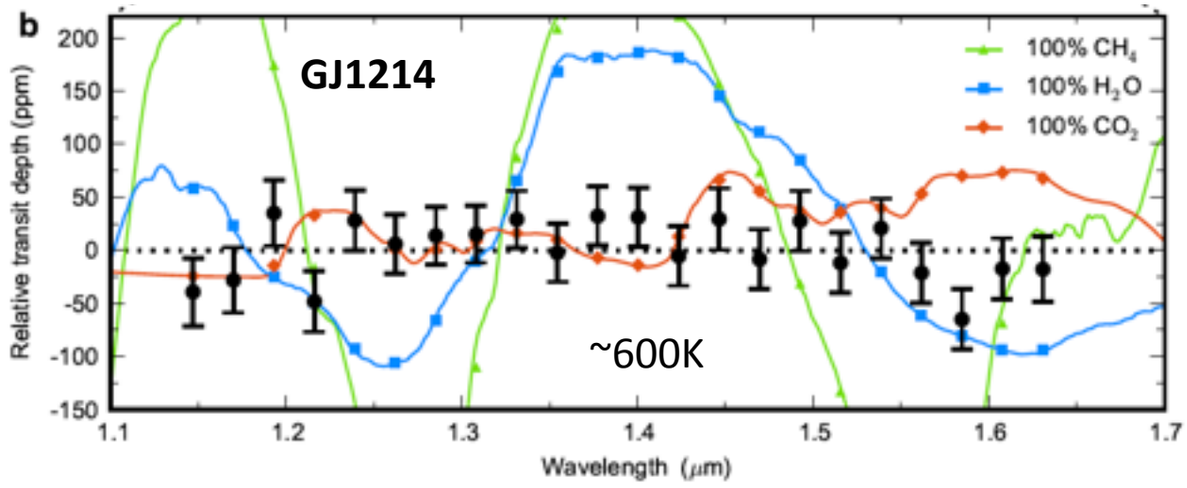
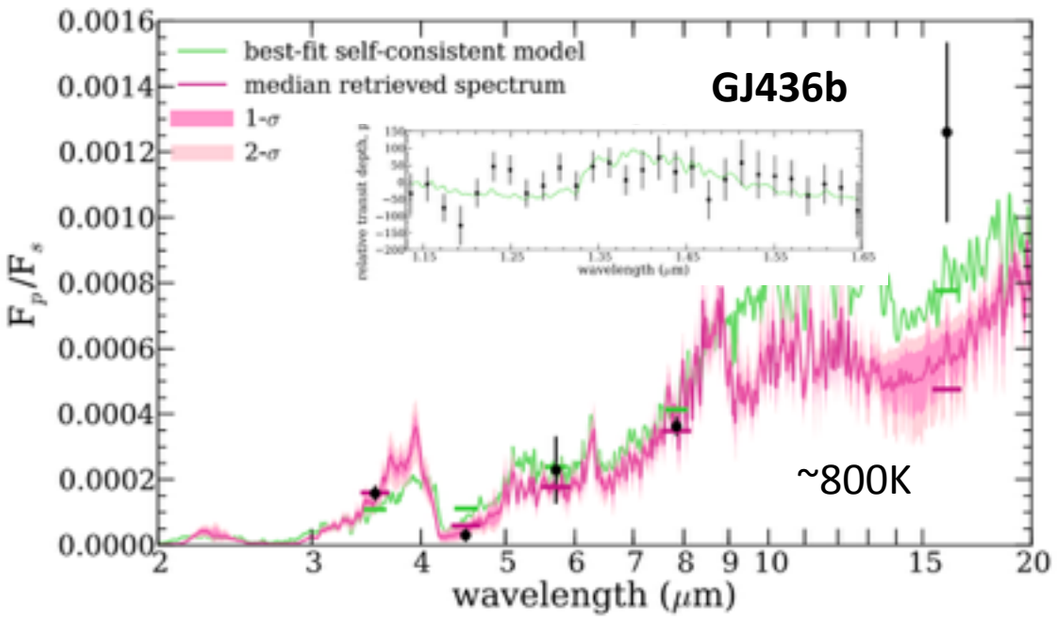
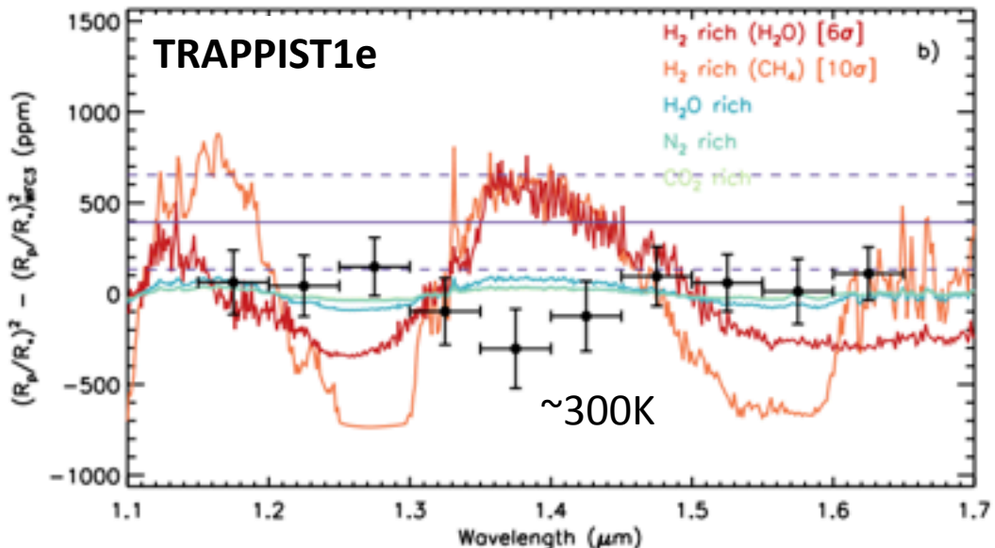
-> Cooler, smaller is harder









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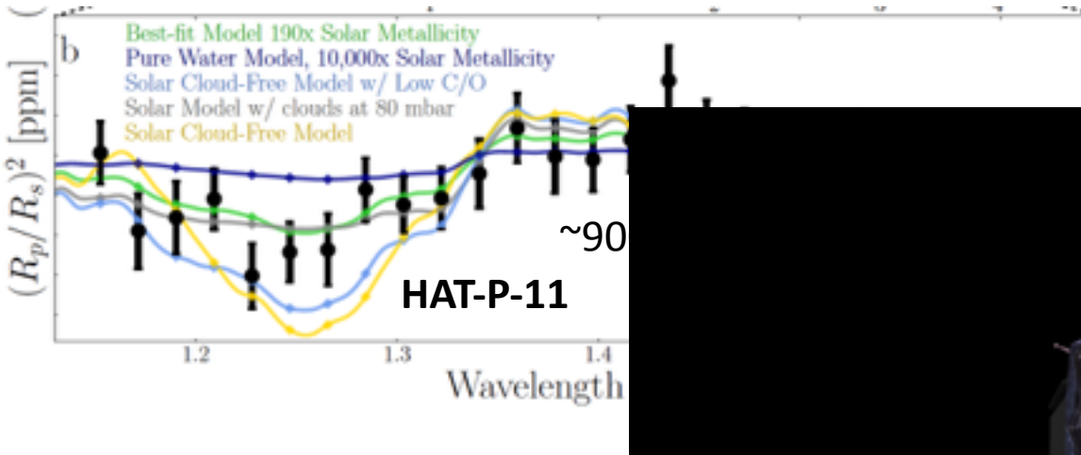
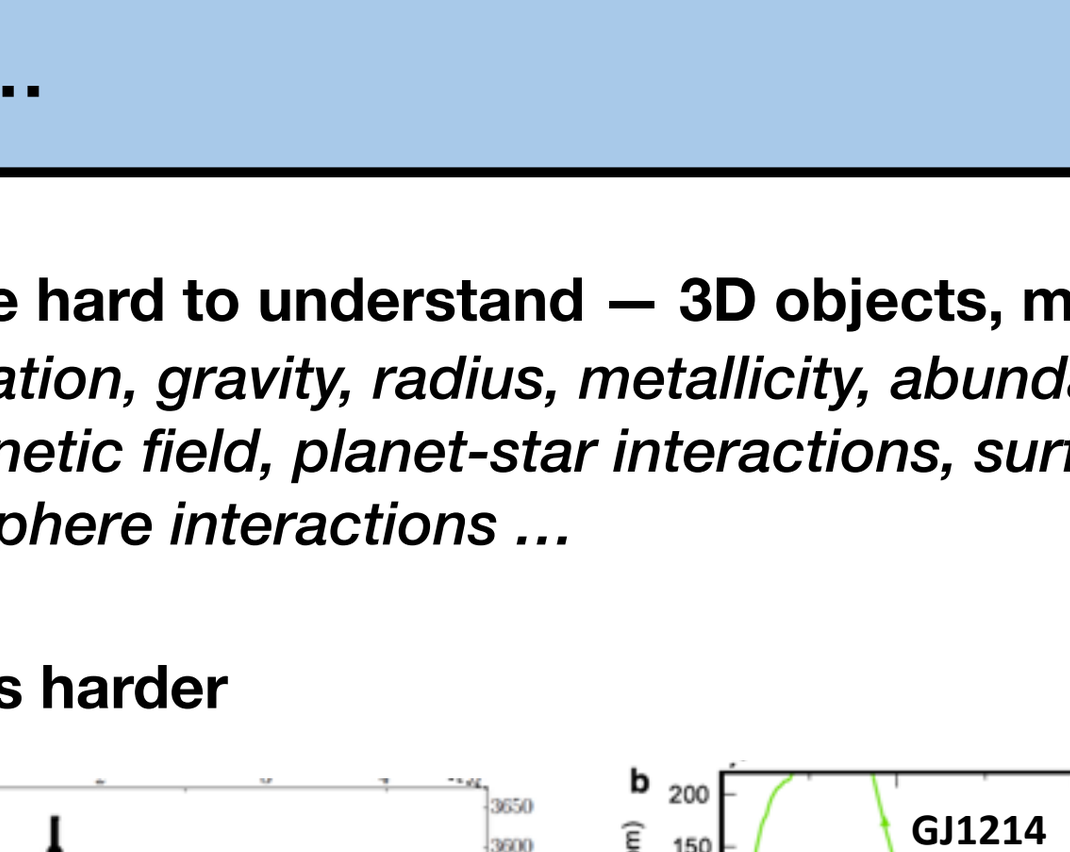
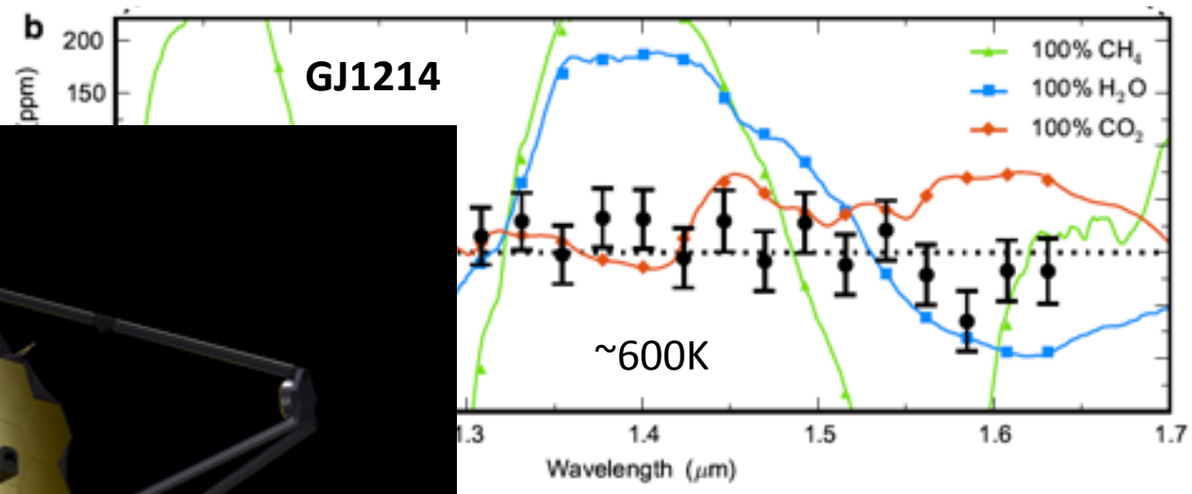
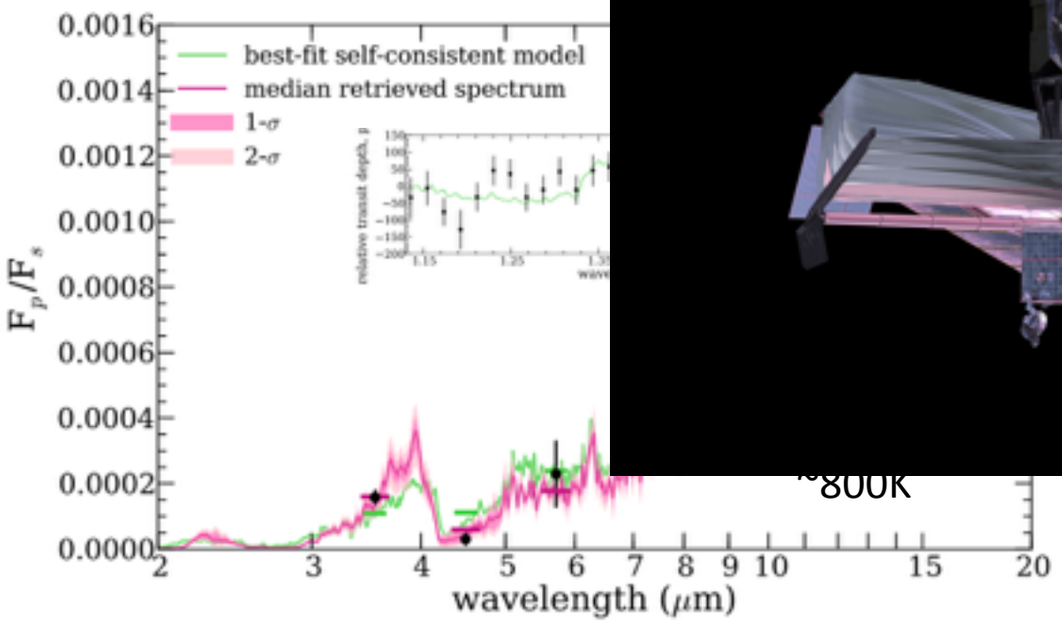
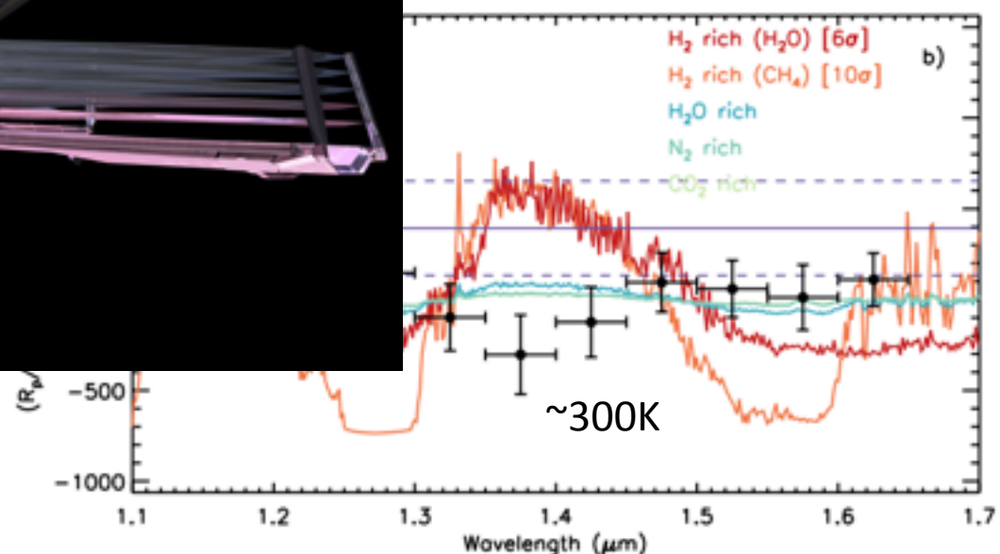






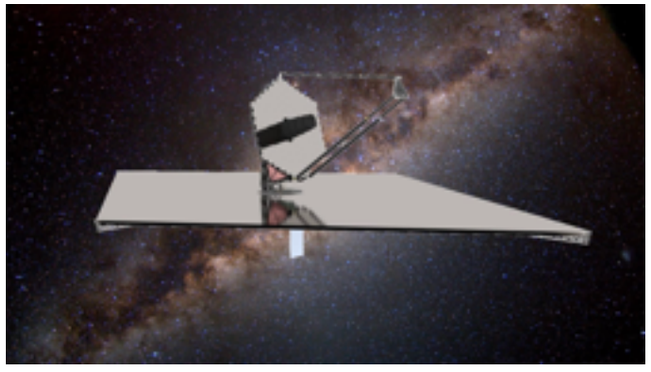




Towards Earth 2.0

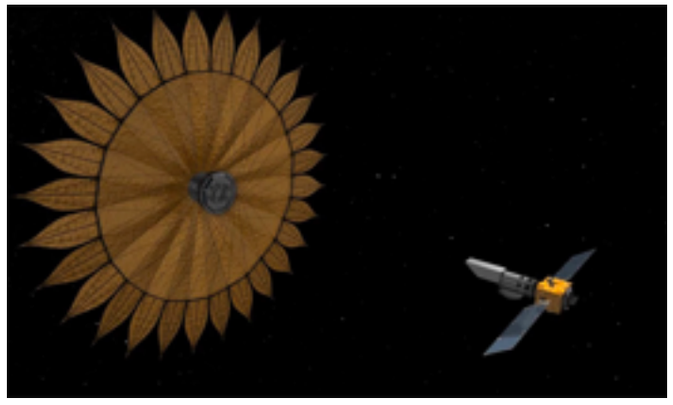
Beyond JWST—The "next next" generation Space Telescopes?

Large UV-Optical-IR Telescope
(LUVOIR-aka, JWST on steroids)



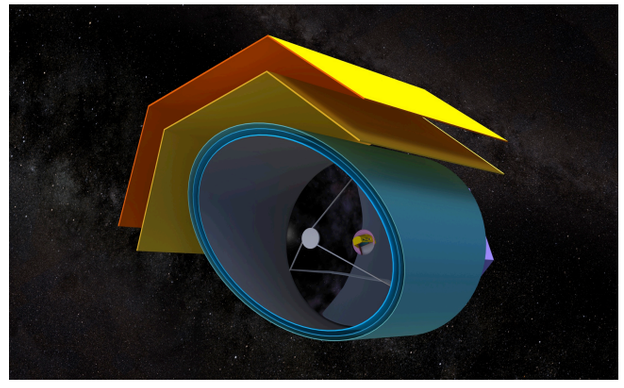
- 8-16 m primary mirror+ coronograph
- 3 science instruments (0.2-2.5 um)
- JWST-like design
- Direct imaging

Habitable Worlds Explorer
(HabEx-StarShade)



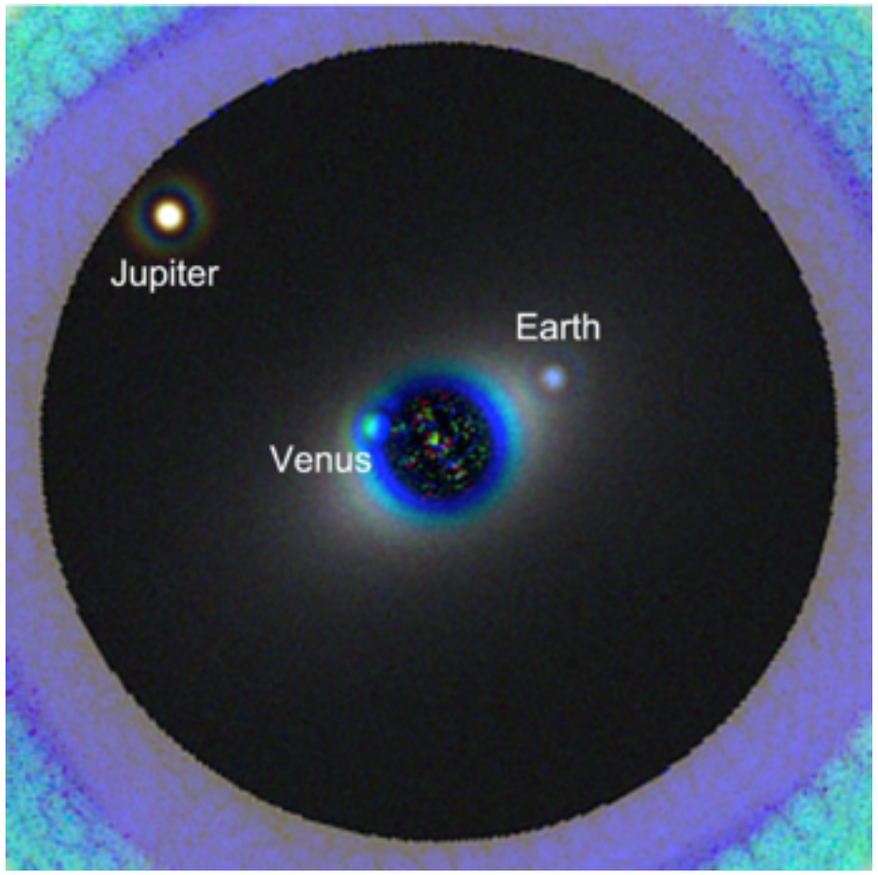
- 4-6 m primary mirror
- Star Shade Coronography
- <~2.5 um
- Direct imaging

Origins Space Telescope
(OST-aka, Spitzer on Steroids)



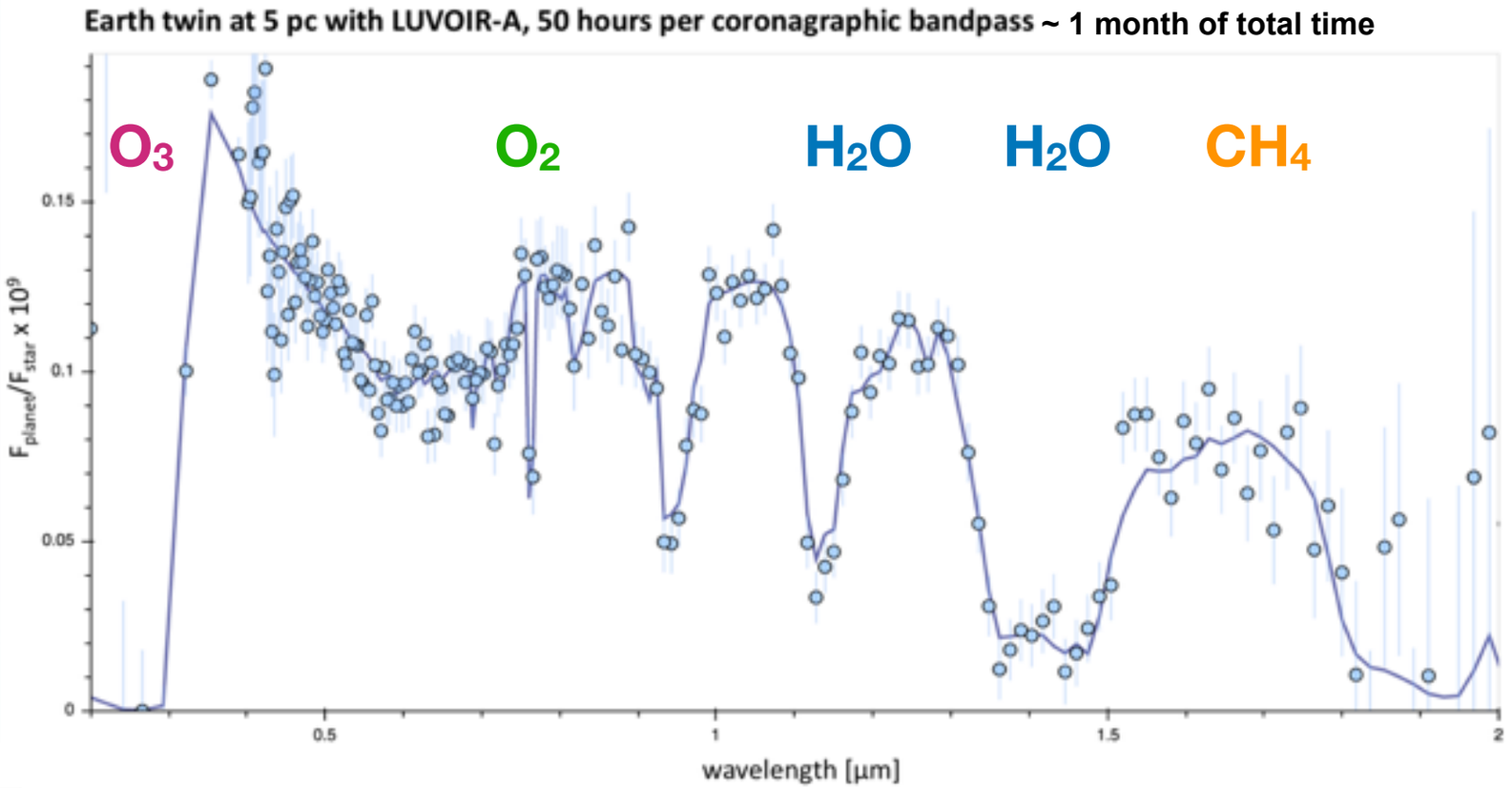
- 5.9 m primary mirror
- 4 science instruments (5-660 um)
- Spitzer-like design
- Minimal deployment
- Transit/Eclipse

Towards Earth 2.0

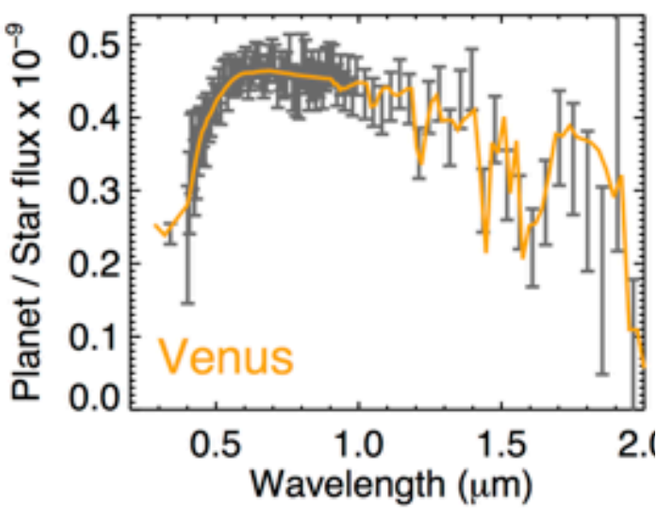


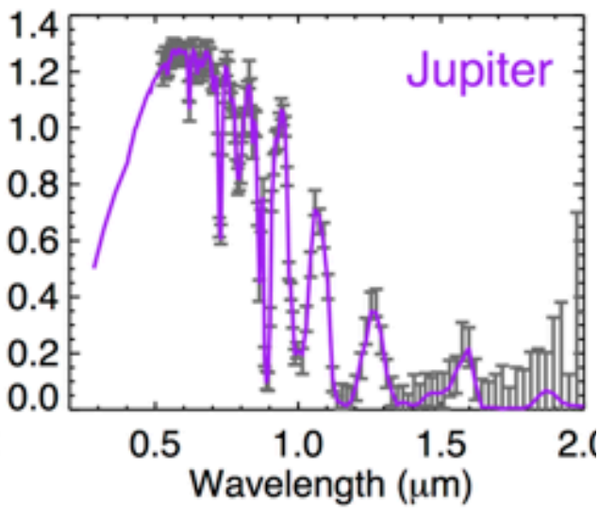
Solar system at 13pc with 12m LUVOIR

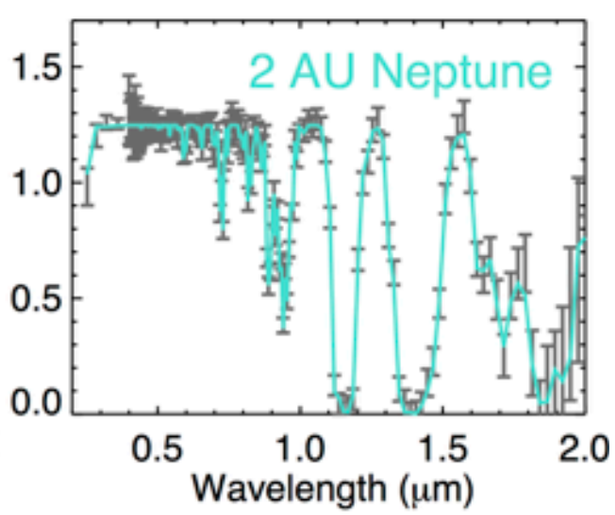
L. Pueyo / M. N'Diaye / A. Roberge

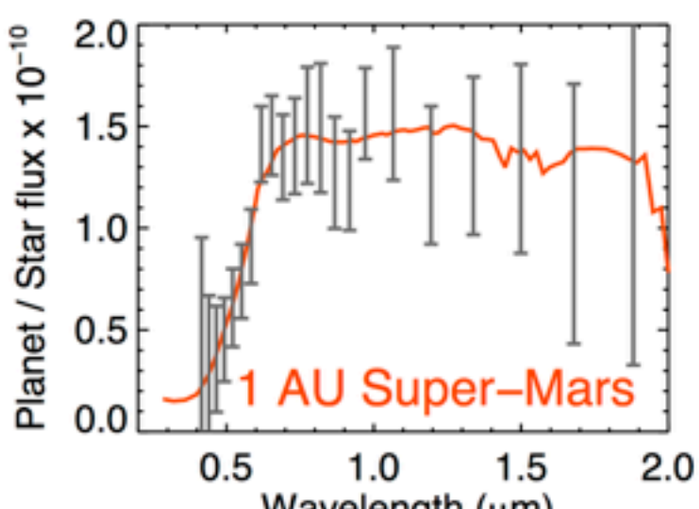


Credit: LUVOIR Tools / Roberge









Conclusions

Atmospheric measurements is the next step in exoplanet characterisation

Reveals planet diversity, informs planet formation and is the best way to search for life.

We need a lot of observations to understand what we see

One method is not enough to get the global view.

Puzzle pieces must be tied together for each planet.

Need of physical understanding backed-up by complex models.

Hot Jupiters are a population spanning a large parameter range.

We should think of them as widely different objects

A handful of planets is not enough to understand the whole population

Cooler, smaller is harder

We need time and ambition to *observe* and *understand* Earth 2.0.

Current population is a good training set to prepare for the sub-Neptune/Super-Earth challenges.