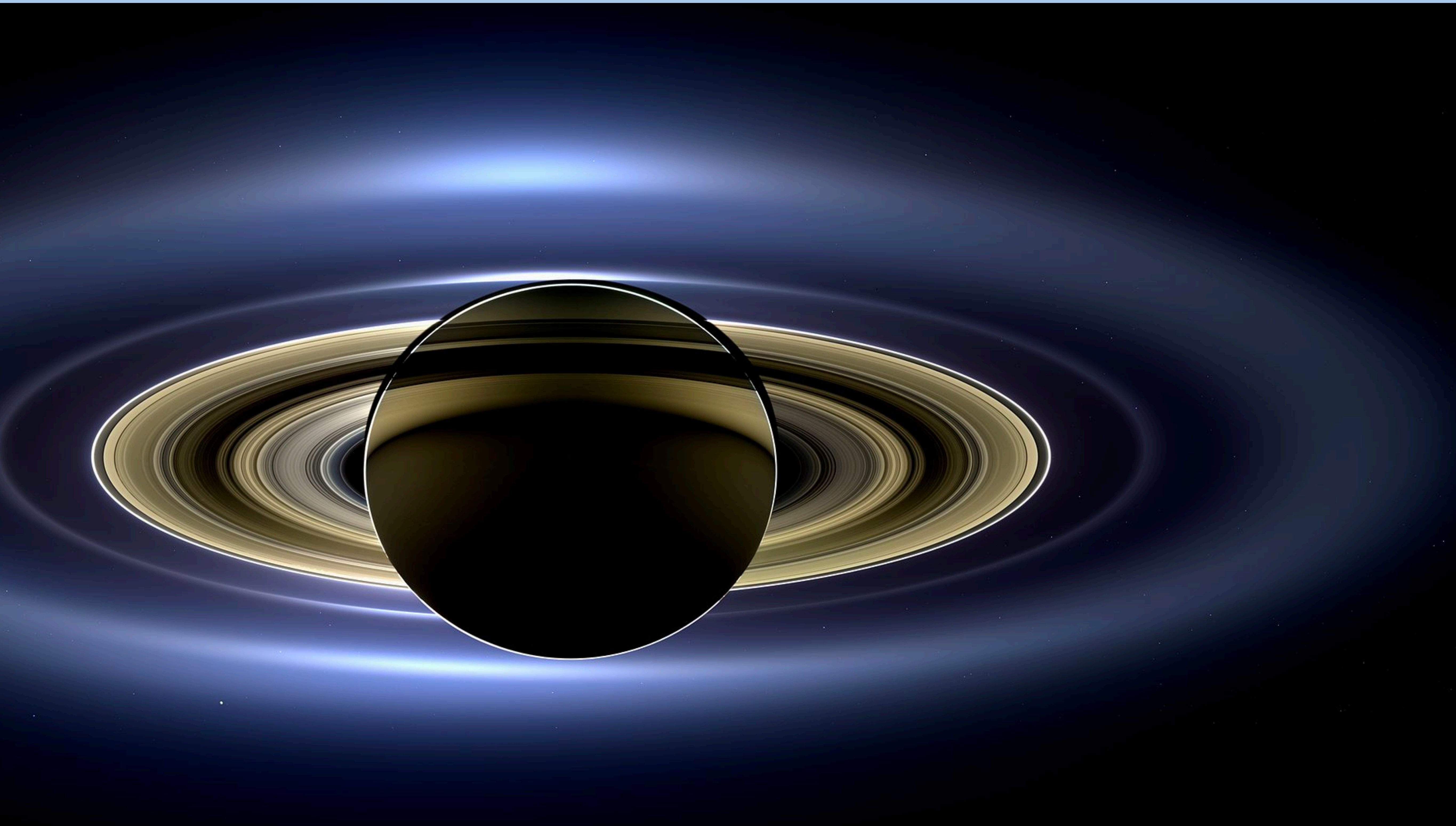
Understanding the spectrum of far away worlds: lessons learned from hot giant planets

Vivien Parmentier — University of Oxford



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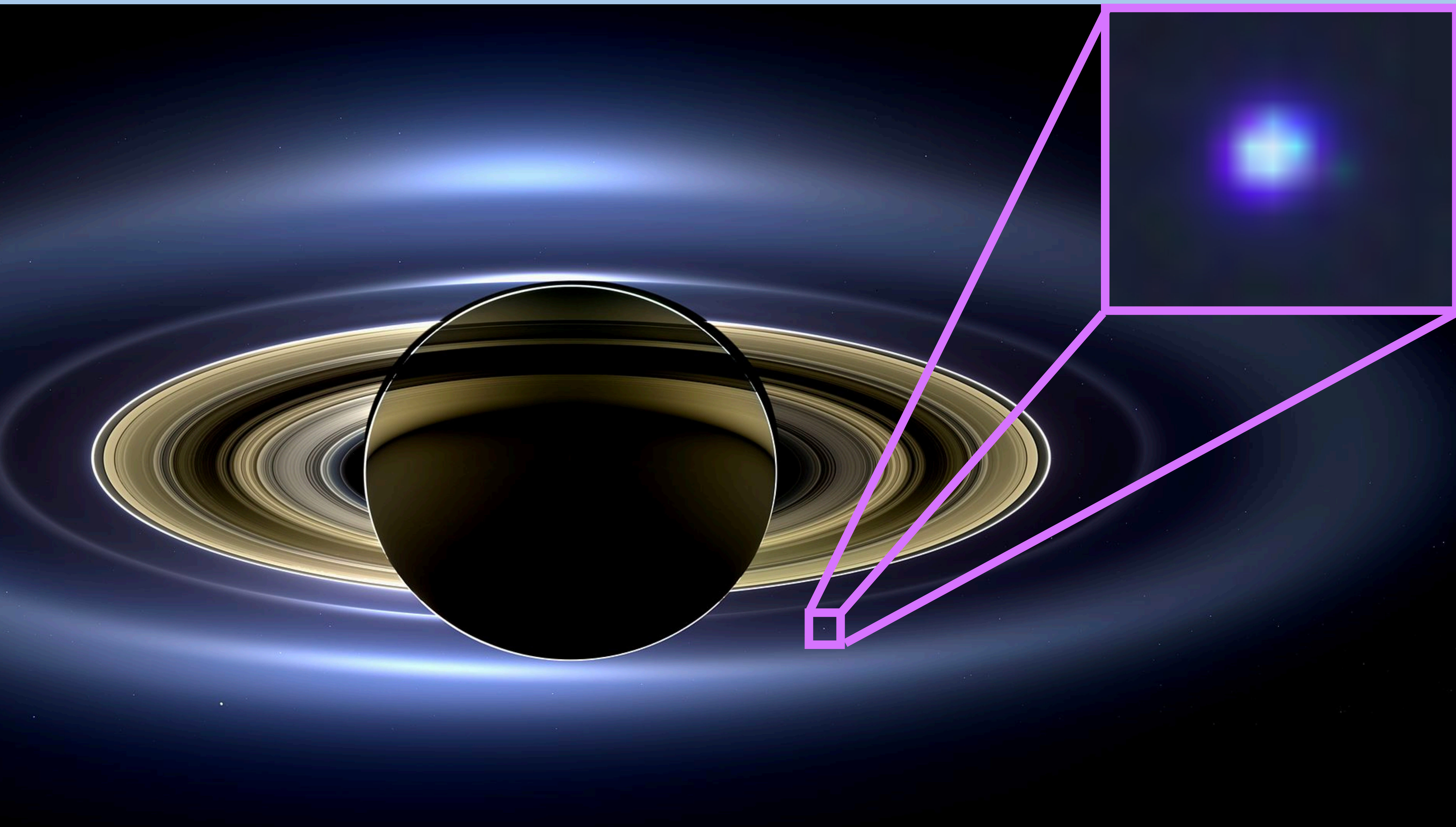
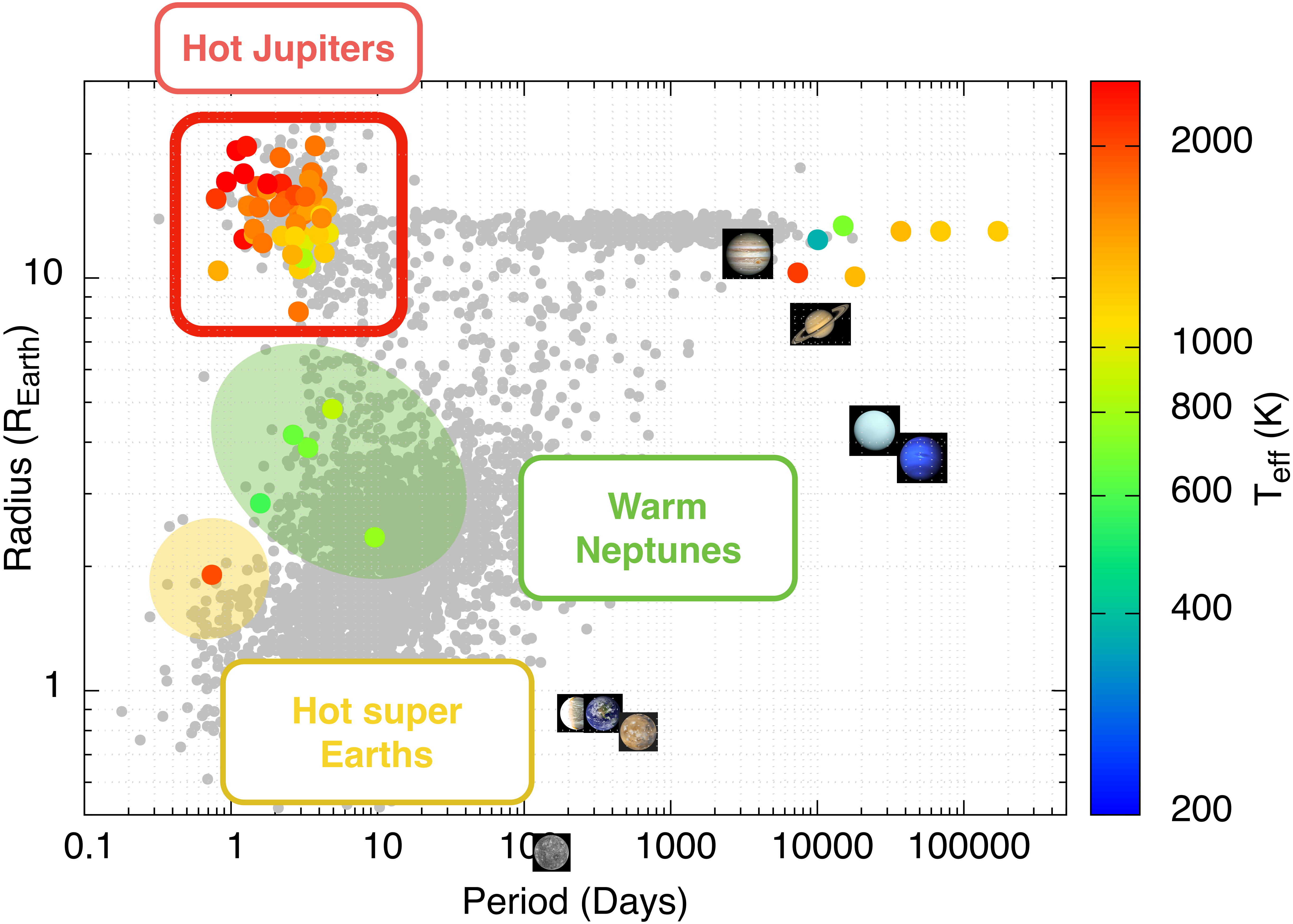


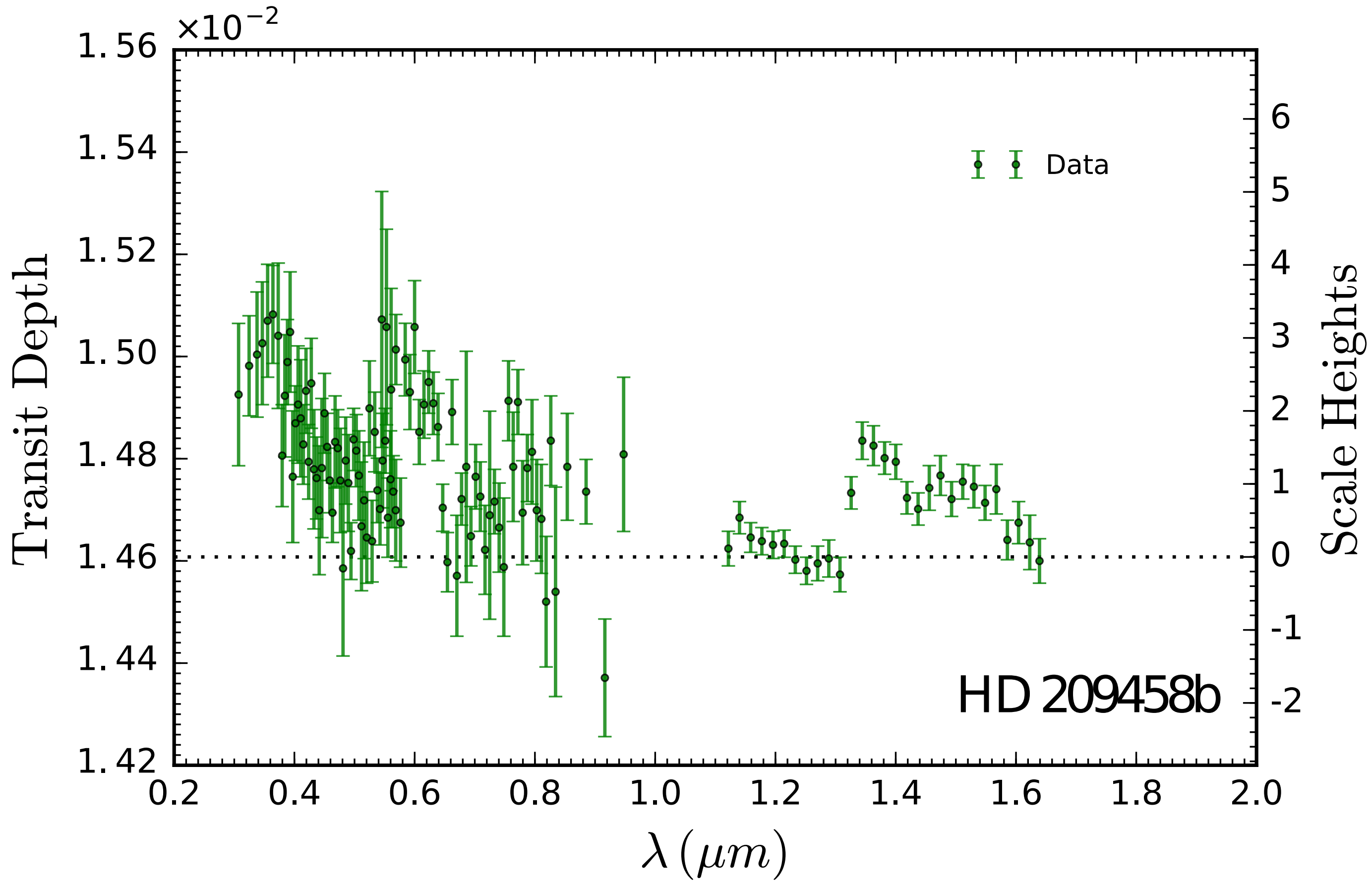
The future of exoplanets : Ariel



Detecting molecules

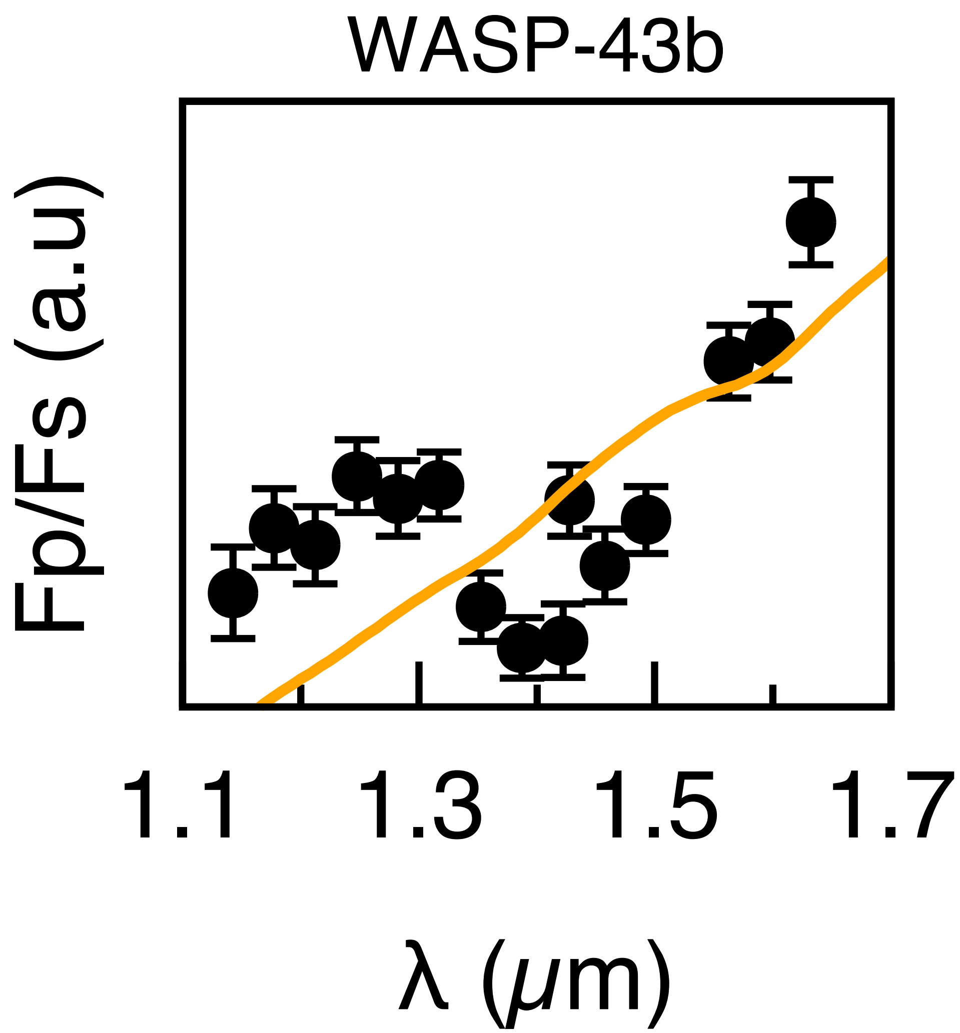
Transmission spectrum

Apparent planet size vs. wavelength
Look for deviation from flat line



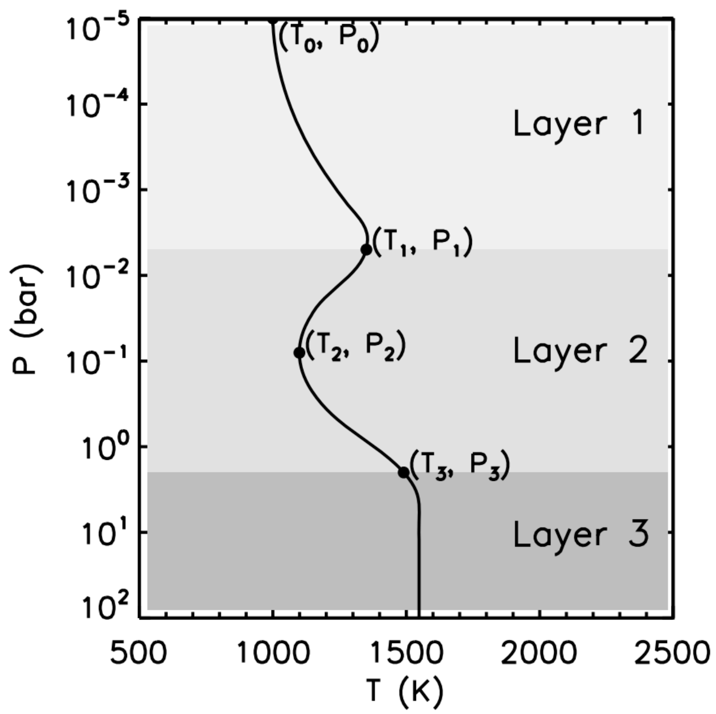
Emission spectrum

Planet's brightness vs. wavelength
Look for deviation from blackbody

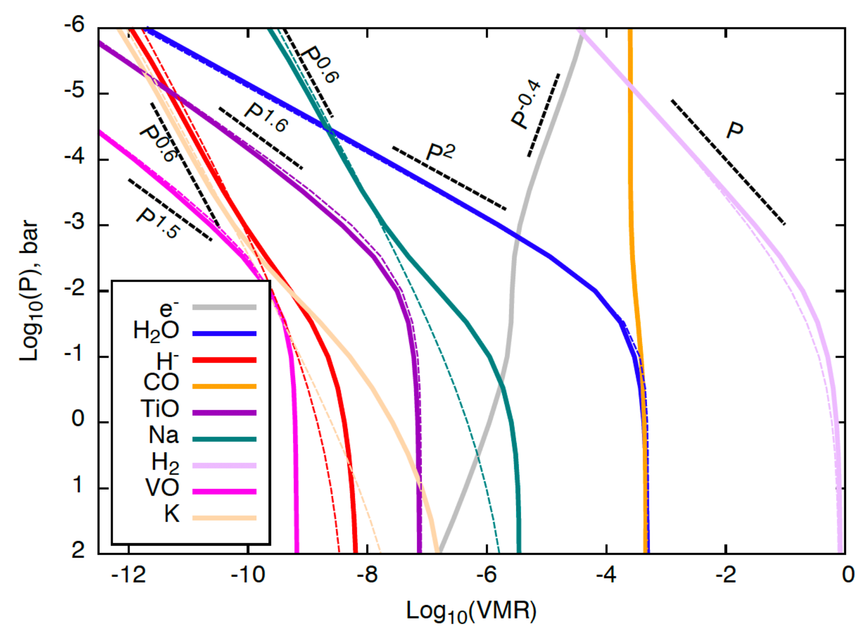


Atmospheric modelling recipe

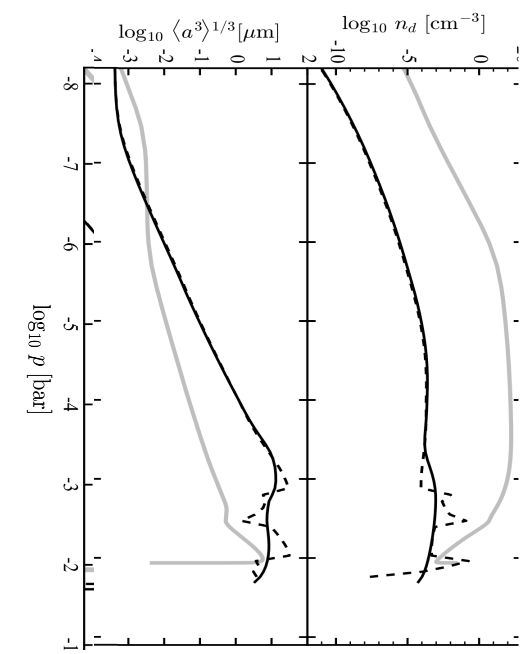
Temperature profile



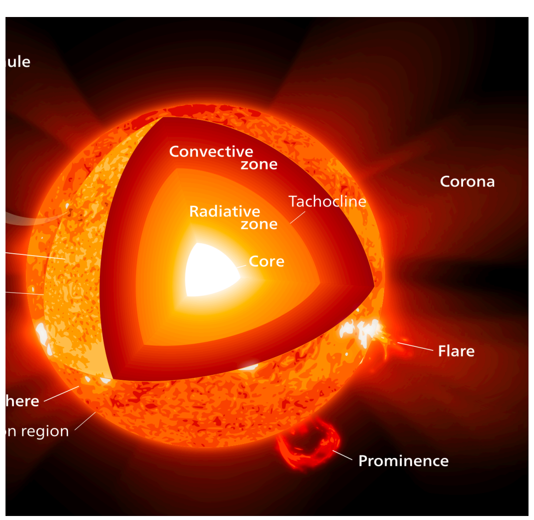
Chemical profile



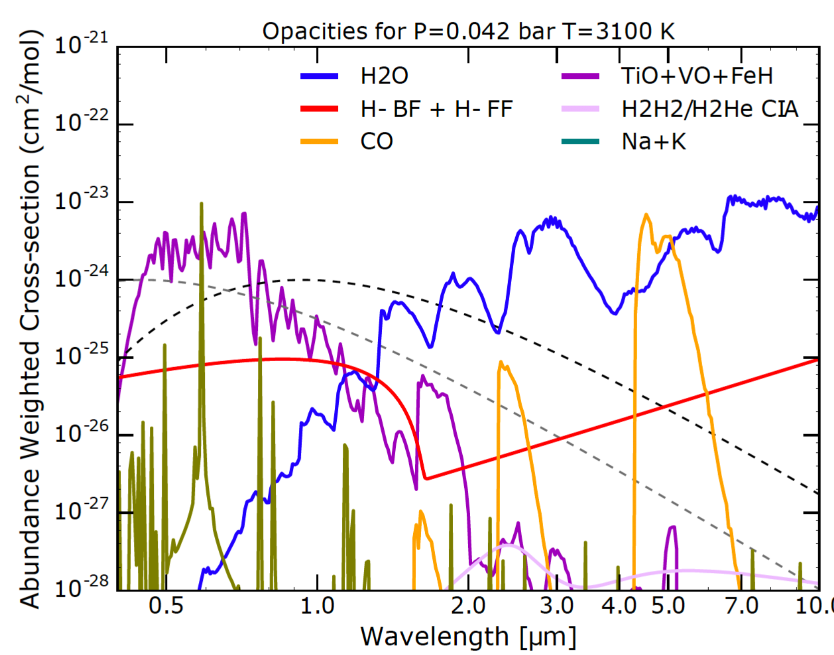
Cloud profile



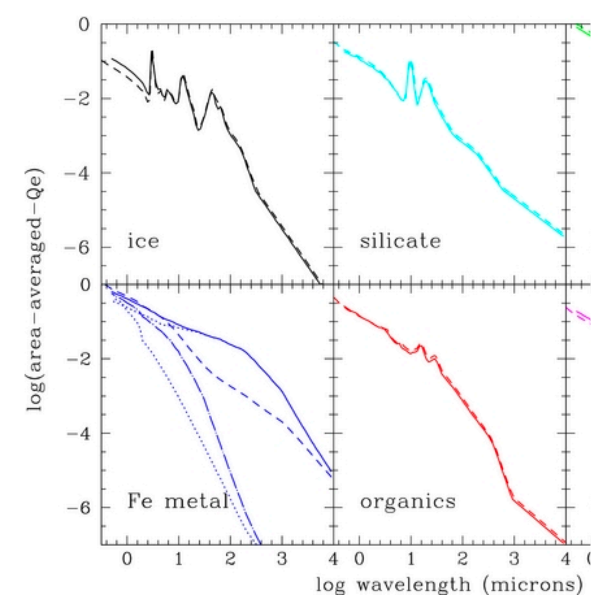
Stellar model



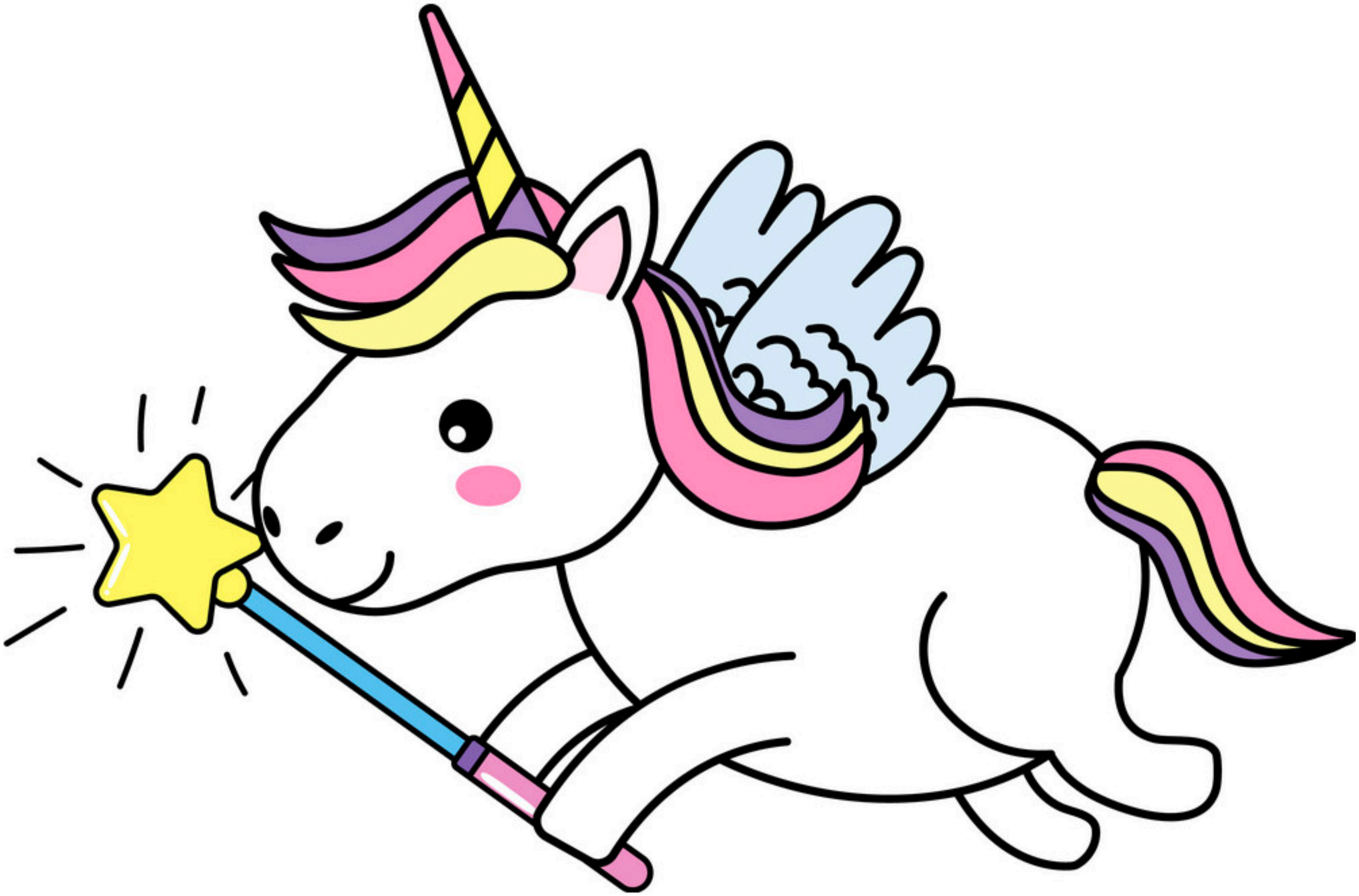
Molecular/atom/ions opacities



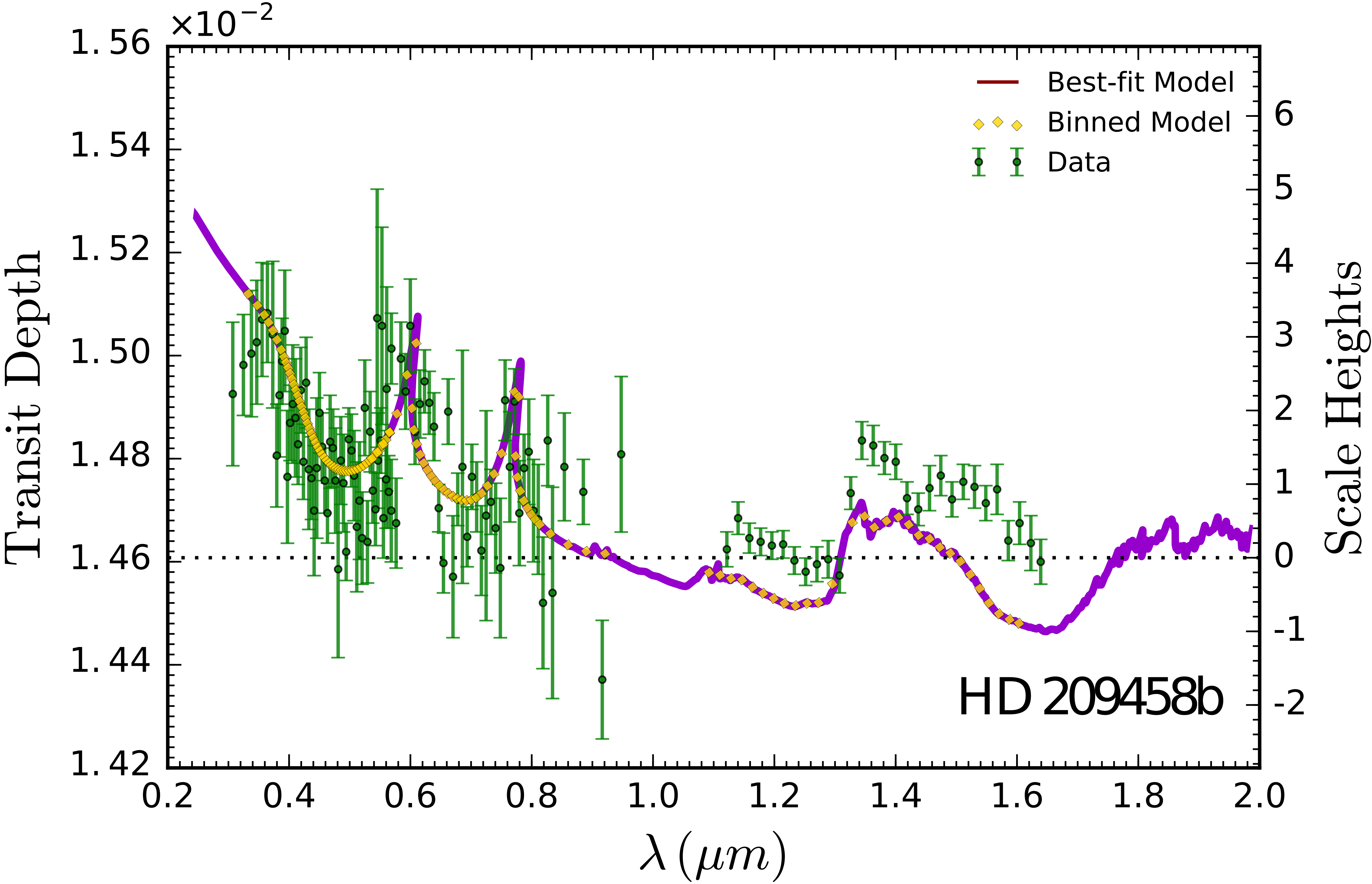
Cloud opacities



Atmospheric modelling recipe



Atmospheric modelling recipe



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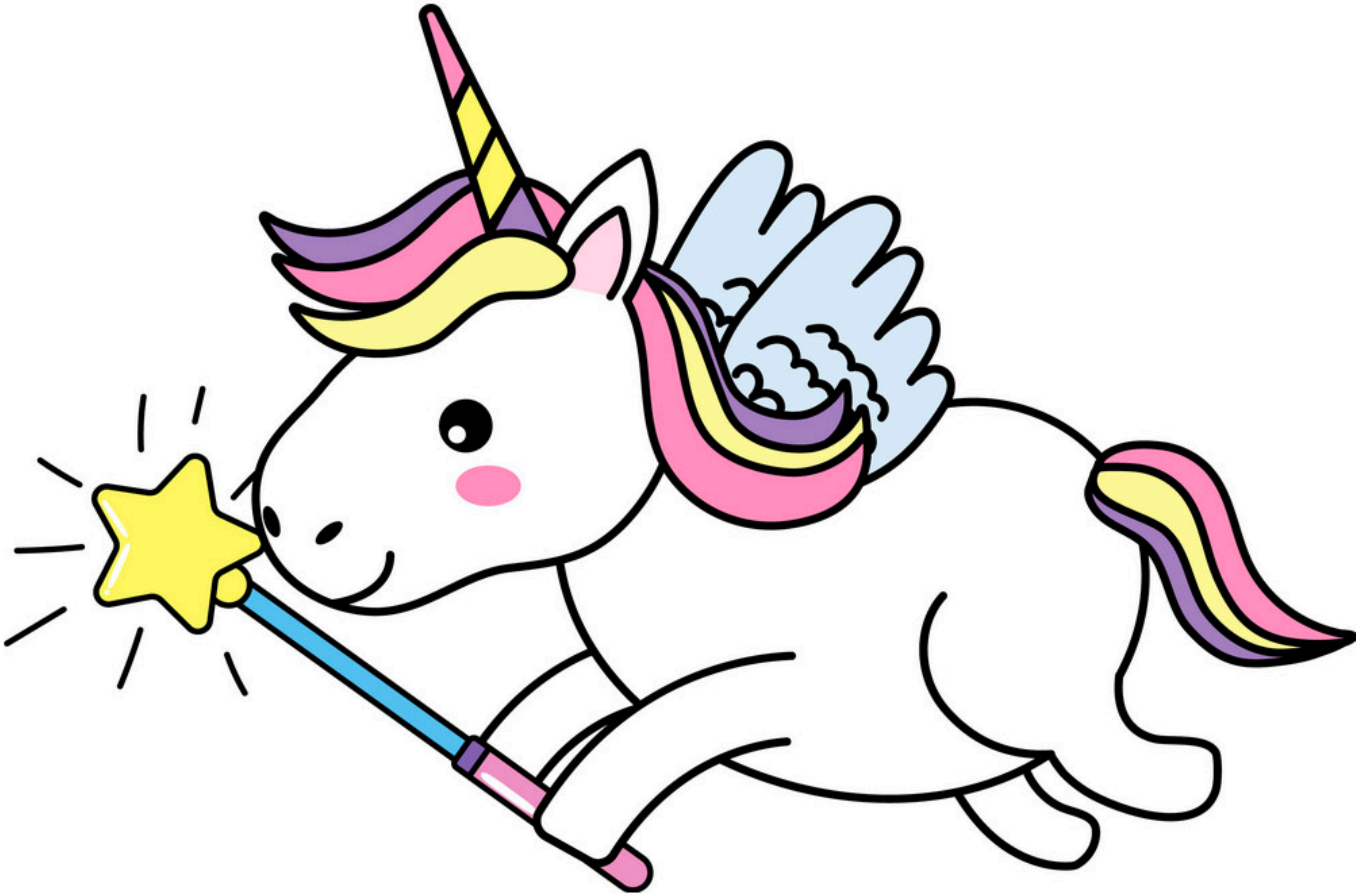
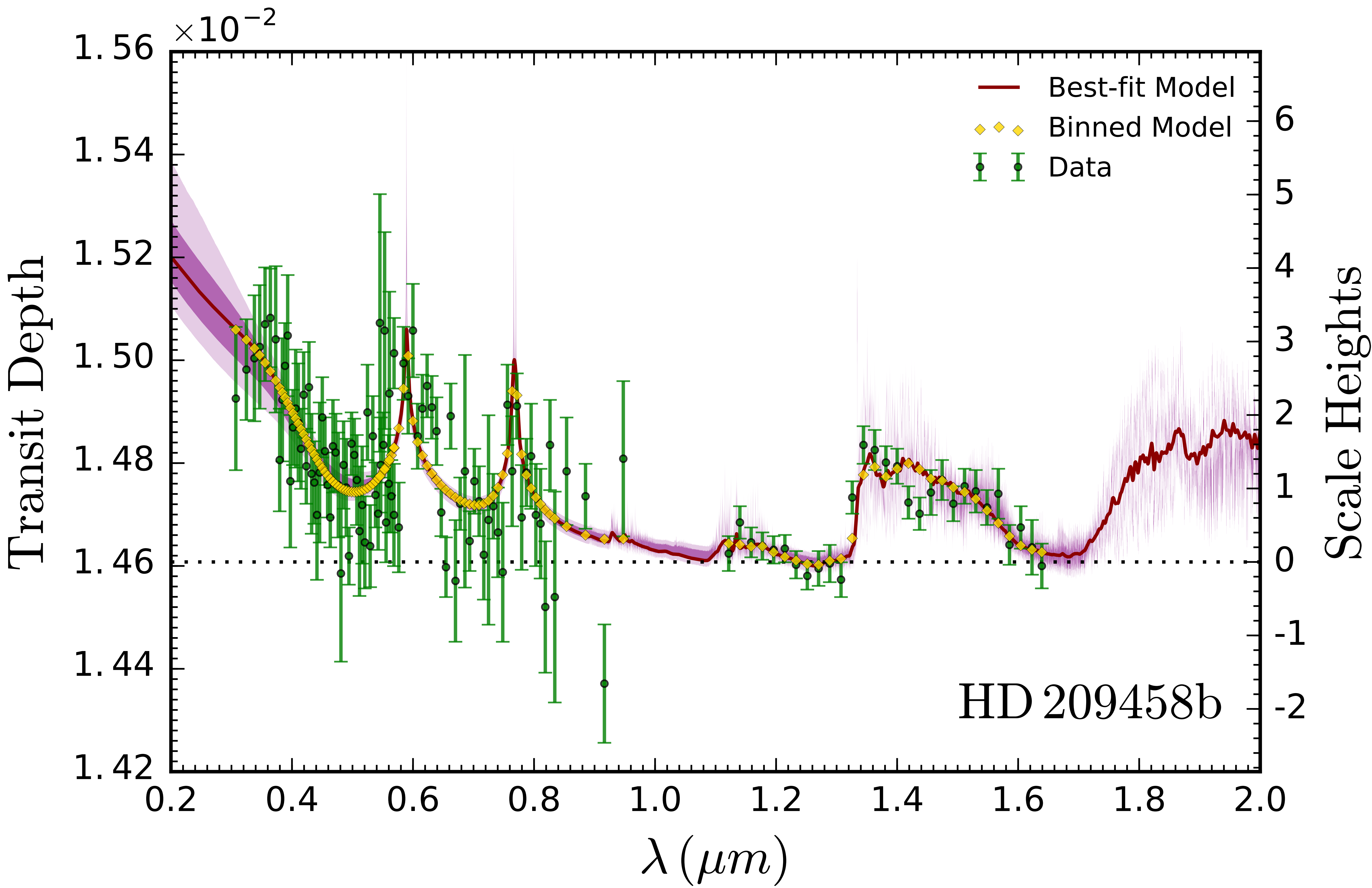
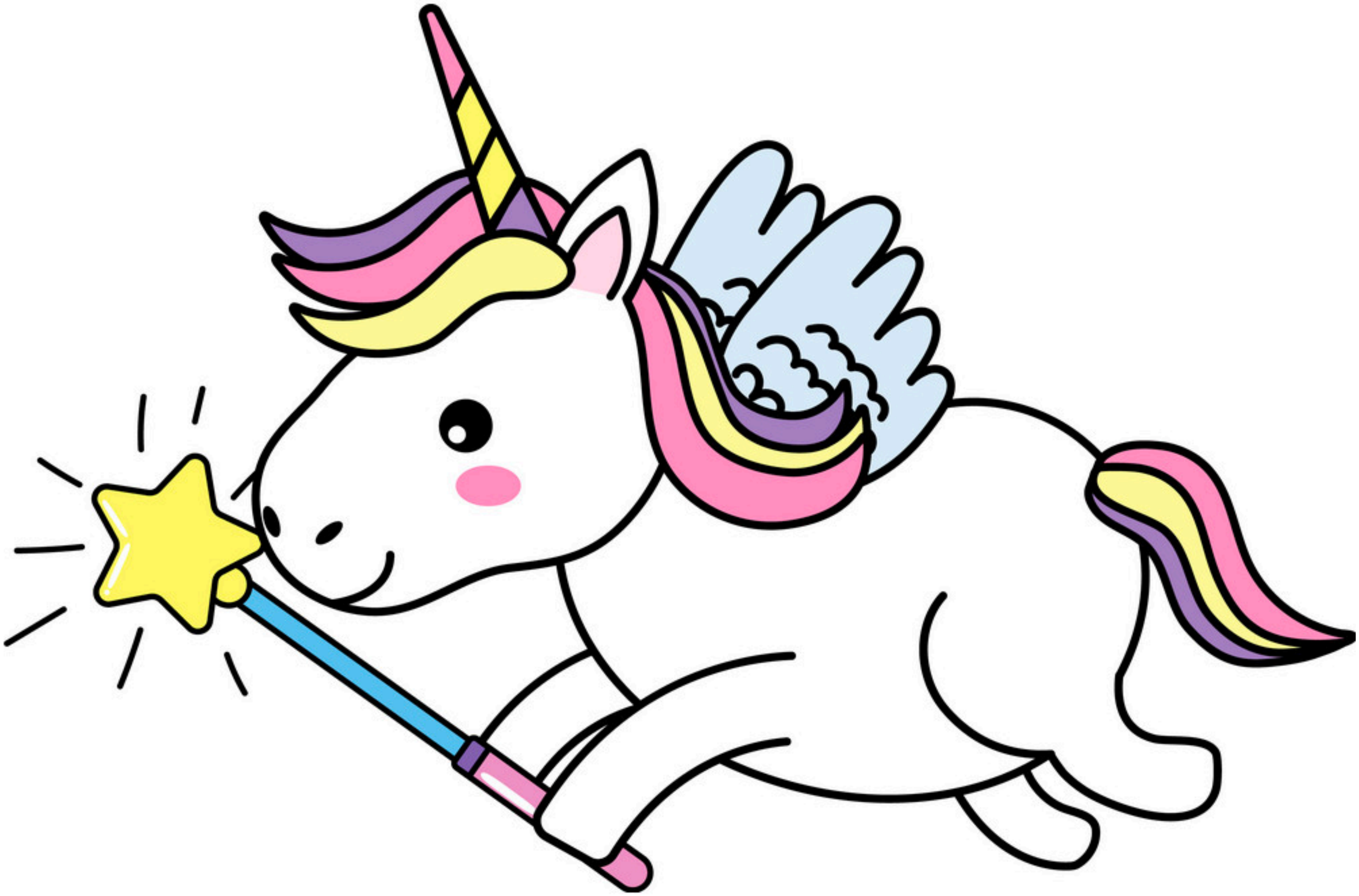


Atmospheric modelling recipe



What is the magic unicorn doing ?



What is the magic unicorn doing ?

*Things** we want with observations we can get*

Nuisance physics we don't want to deal with but have to (blah, star)

$$A = \begin{pmatrix} \frac{\partial(Obs_1)}{\partial(physics_1)} & \frac{\partial(Obs_1)}{\partial(physics_2)} & \cdots & \frac{\partial(Obs_1)}{\partial(physics_n)} \\ \frac{\partial(Obs_2)}{\partial(physics_1)} & \frac{\partial(Obs_2)}{\partial(physics_2)} & \cdots & \frac{\partial(Obs_2)}{\partial(physics_n)} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial(Obs_m)}{\partial(physics_1)} & \frac{\partial(Obs_m)}{\partial(physics_2)} & \cdots & \frac{\partial(Obs_m)}{\partial(physics_n)} \end{pmatrix}$$

Observations we want but can't yet get (will 2020 be the decade JWST launches?)

Things we don't know we want with observations we don't know we need

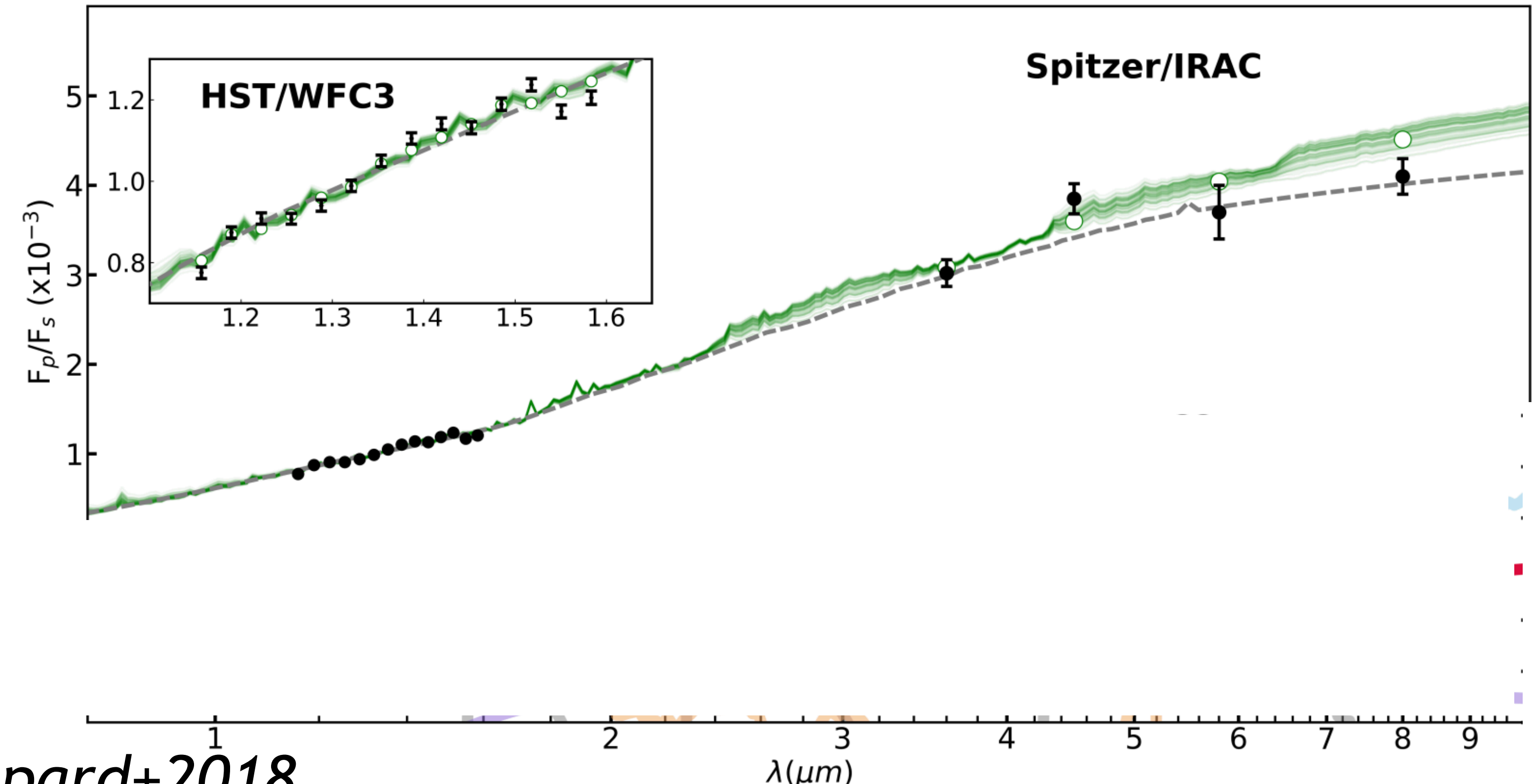
**We often debate what "Things" we want...

$$\vec{Physics} = A^{-1}\vec{Obs}$$

A range of model assumptions

	Less assumptions More parameters		More assumptions Less parameters
Temperature profile	Free Semi-grey	1D Radiative/conv eq. Non-grey	2D/3D radiative/conv eq.
Chemistry	Free chemistry — Choice of species — Vertical profile	Equilibrium Choice of free parameters [M/H], [C/O] others ?	1/2/3D disequilibrium
Clouds	Parametrized Absorbing Grey	Simple equilibrium clouds Scattering, non-grey	Microphysics bin vs. moment ?
Geometry	1D	2D — Lat/long 2D — Limb depth	3D radiative transfer
Stars	Blackbody	1D stellar model	Inhomogeneous stellar model

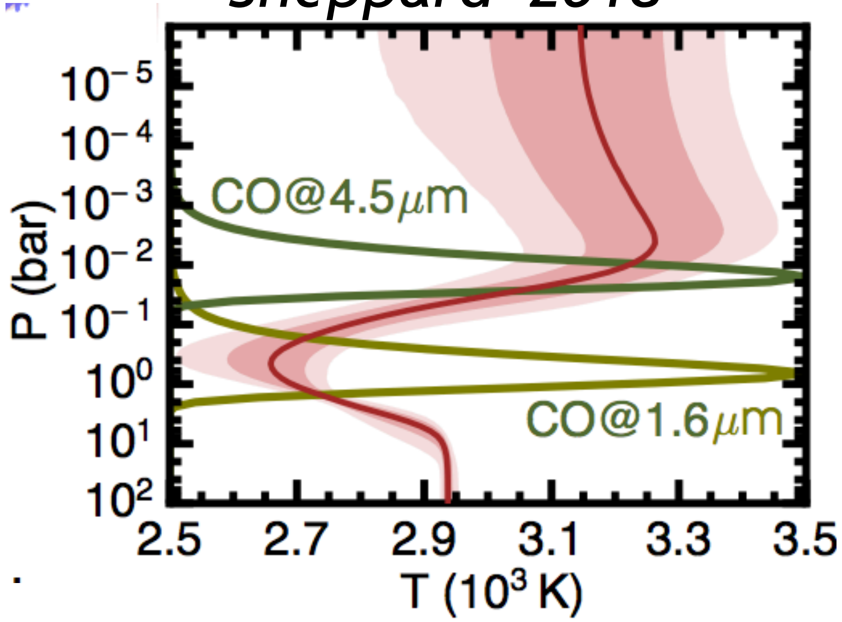
« Free » vs. « self-consistent » thermal and chemistry 1D retrievals



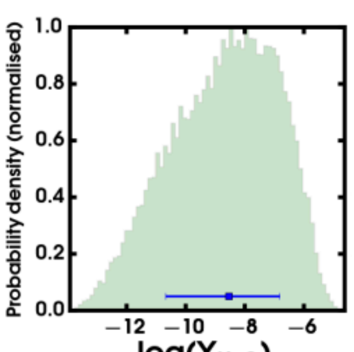
Hot Jupiter
WASP-18b
Teq~2500K

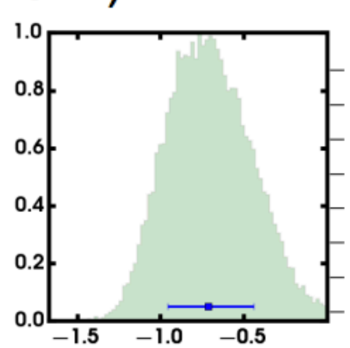
Self-Consistent 1D grid
MCMC interpolation

Sheppard+2018



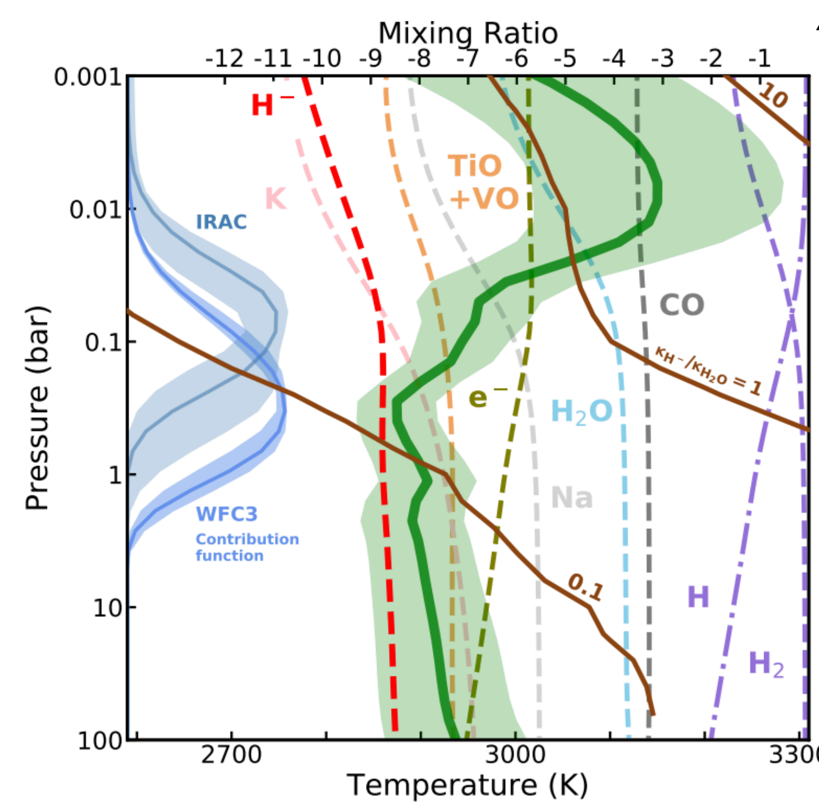
"Free
Retrieval

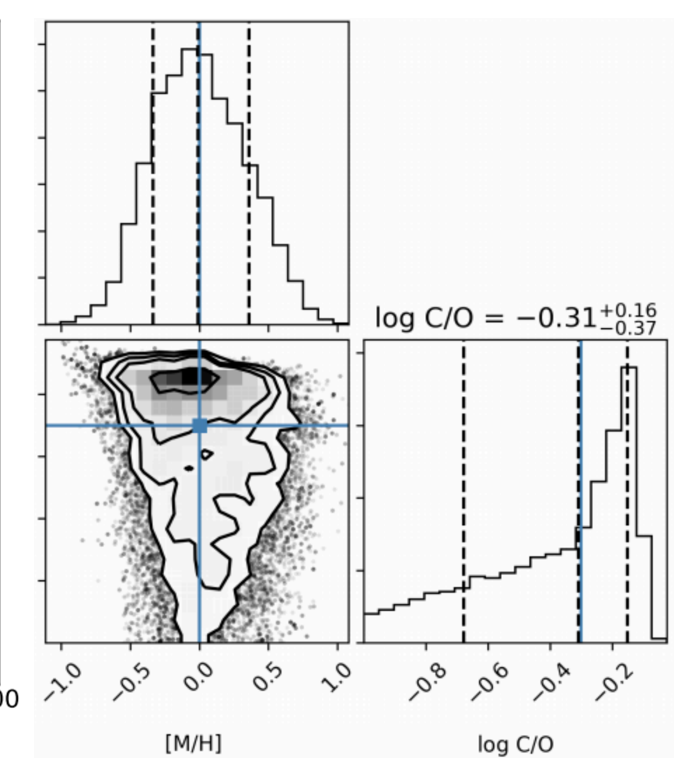




~300x Solar
C/O~1
CO=20% of

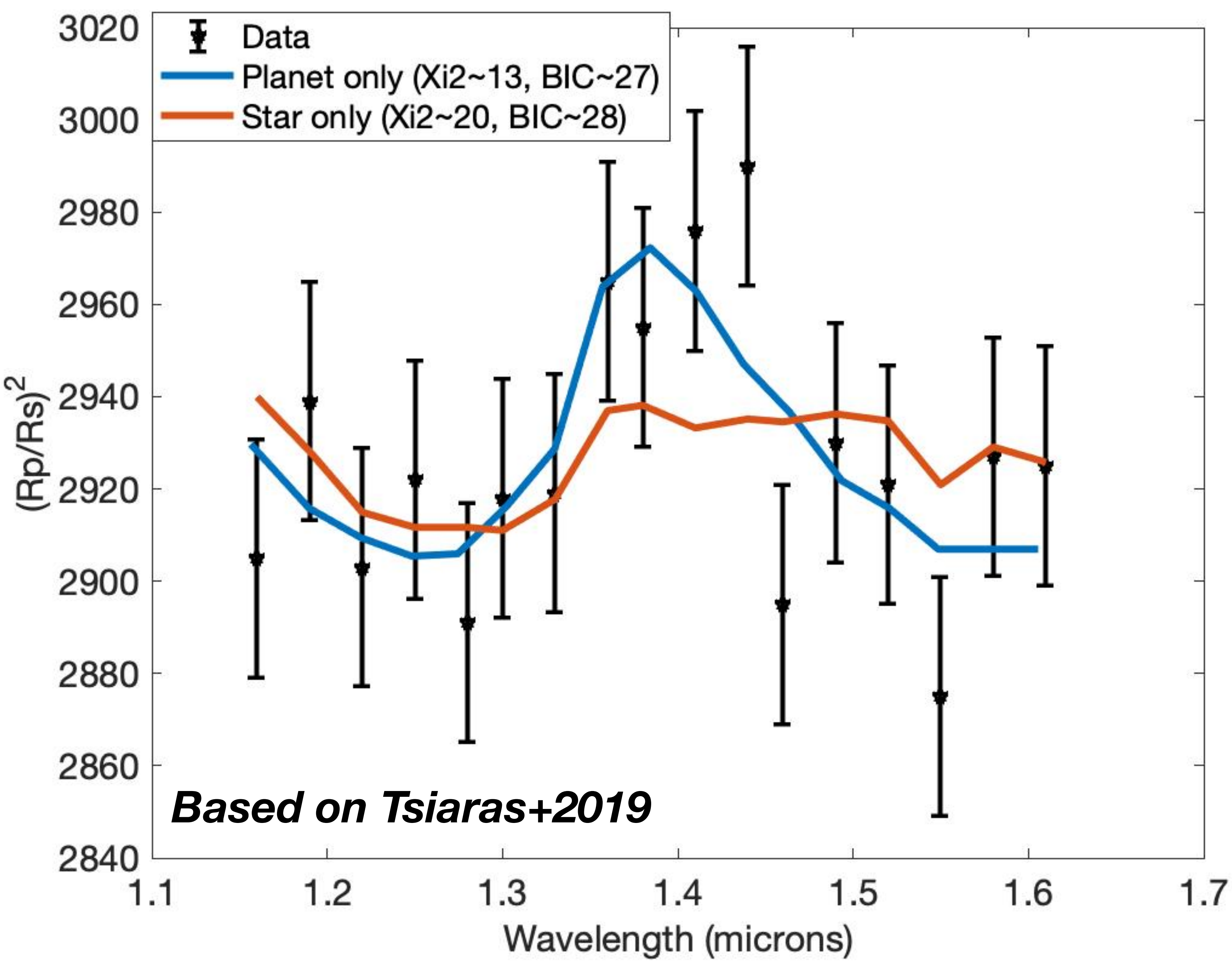
Arcangeli+2018

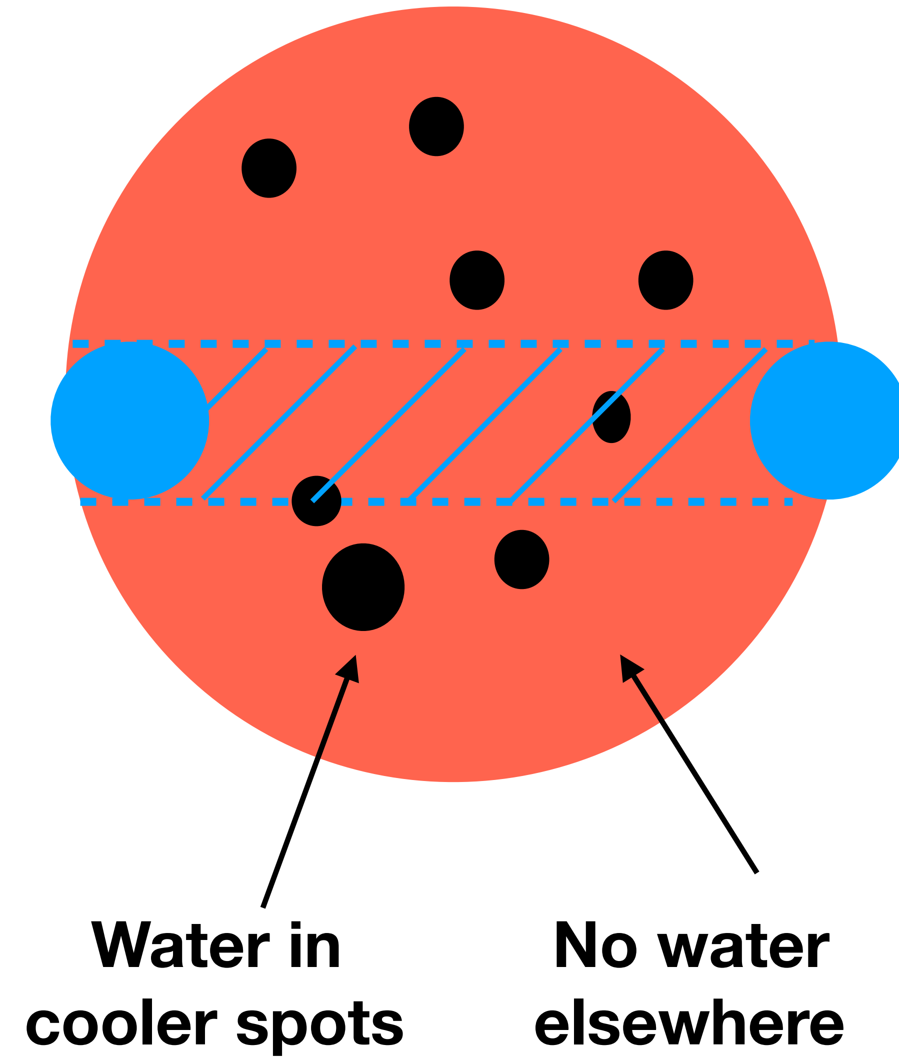




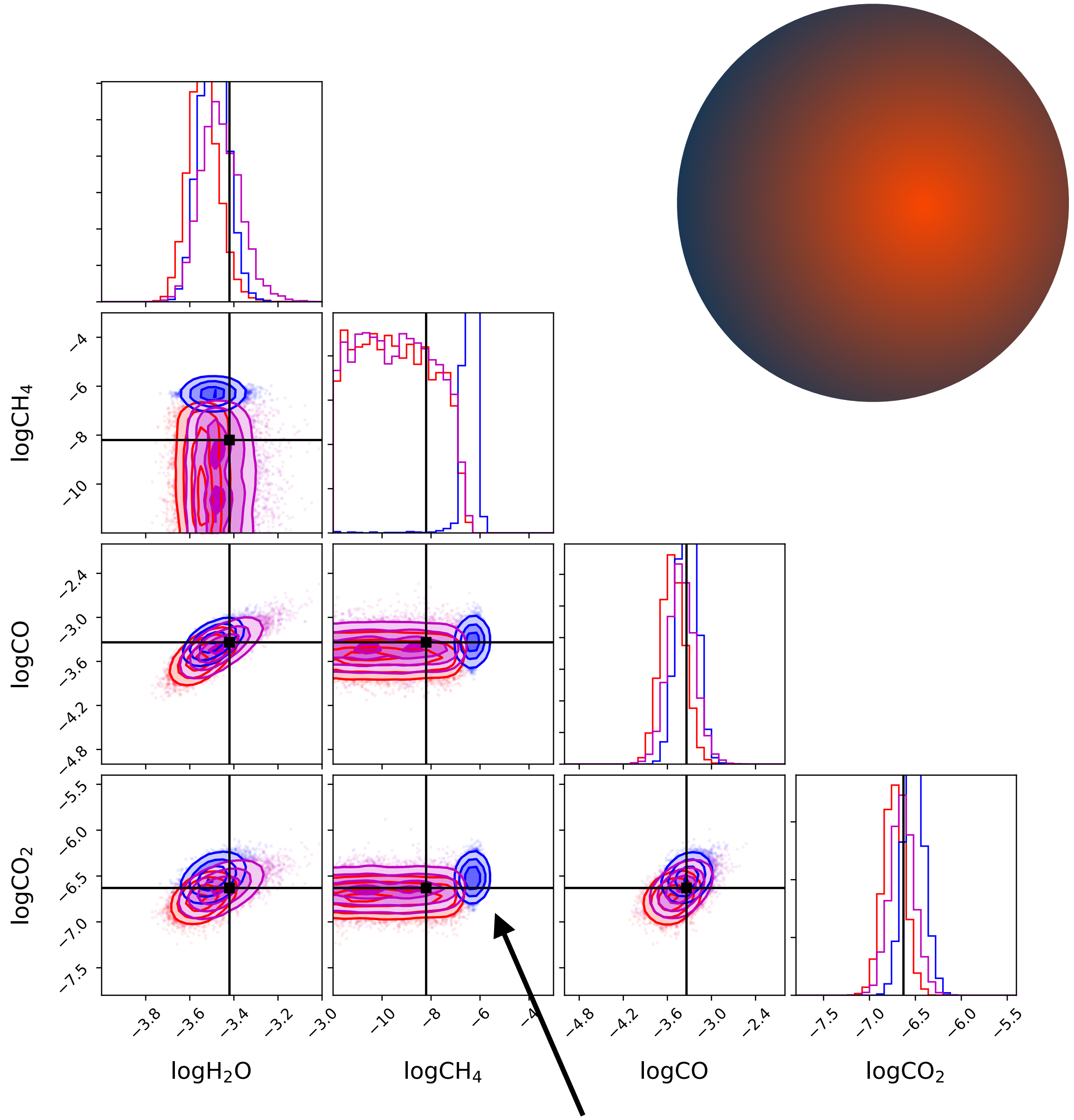
Solar Comp!

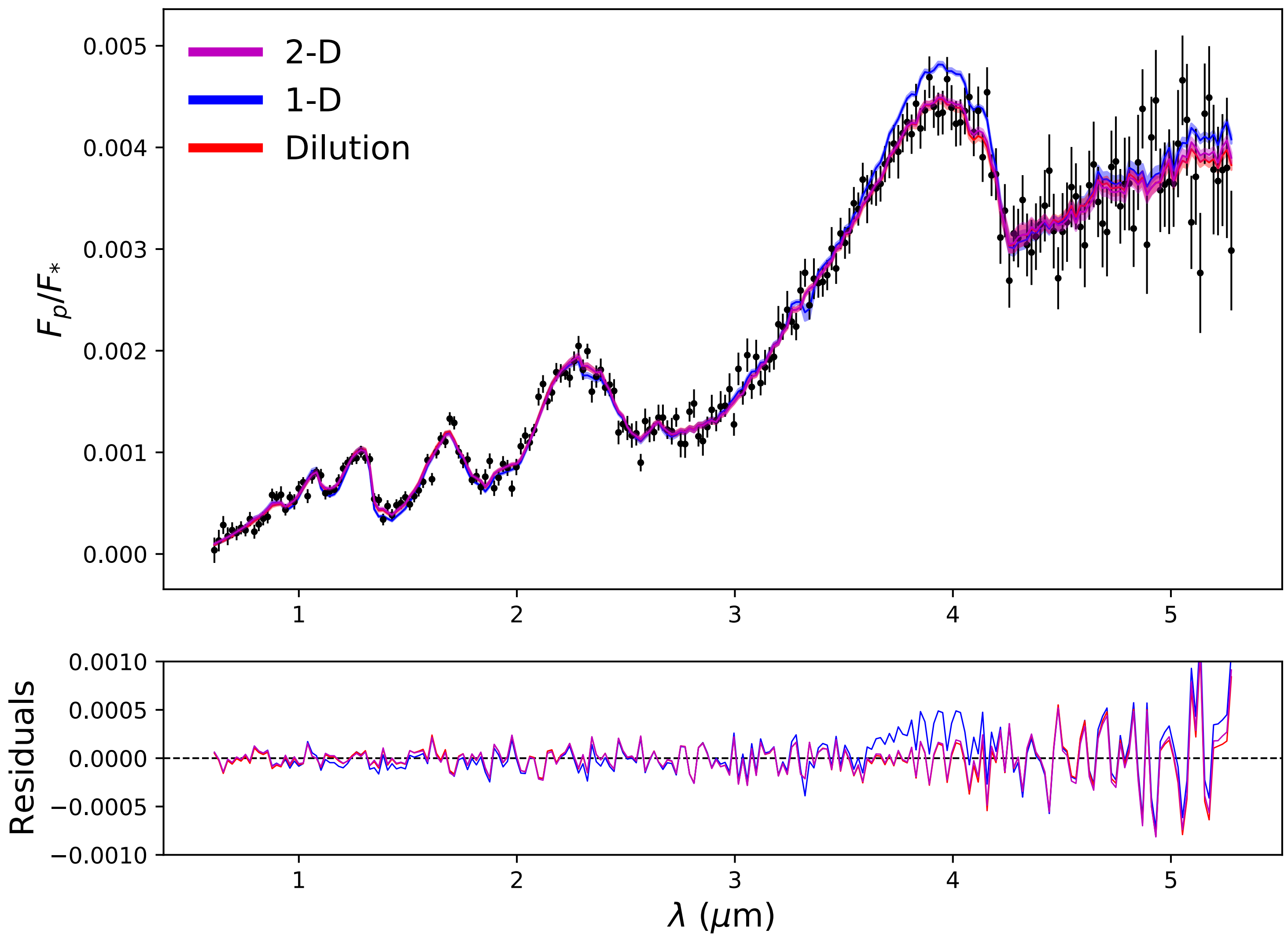
K2-18b: water on a temperature sub-Neptune or in M dwarf starspots ?





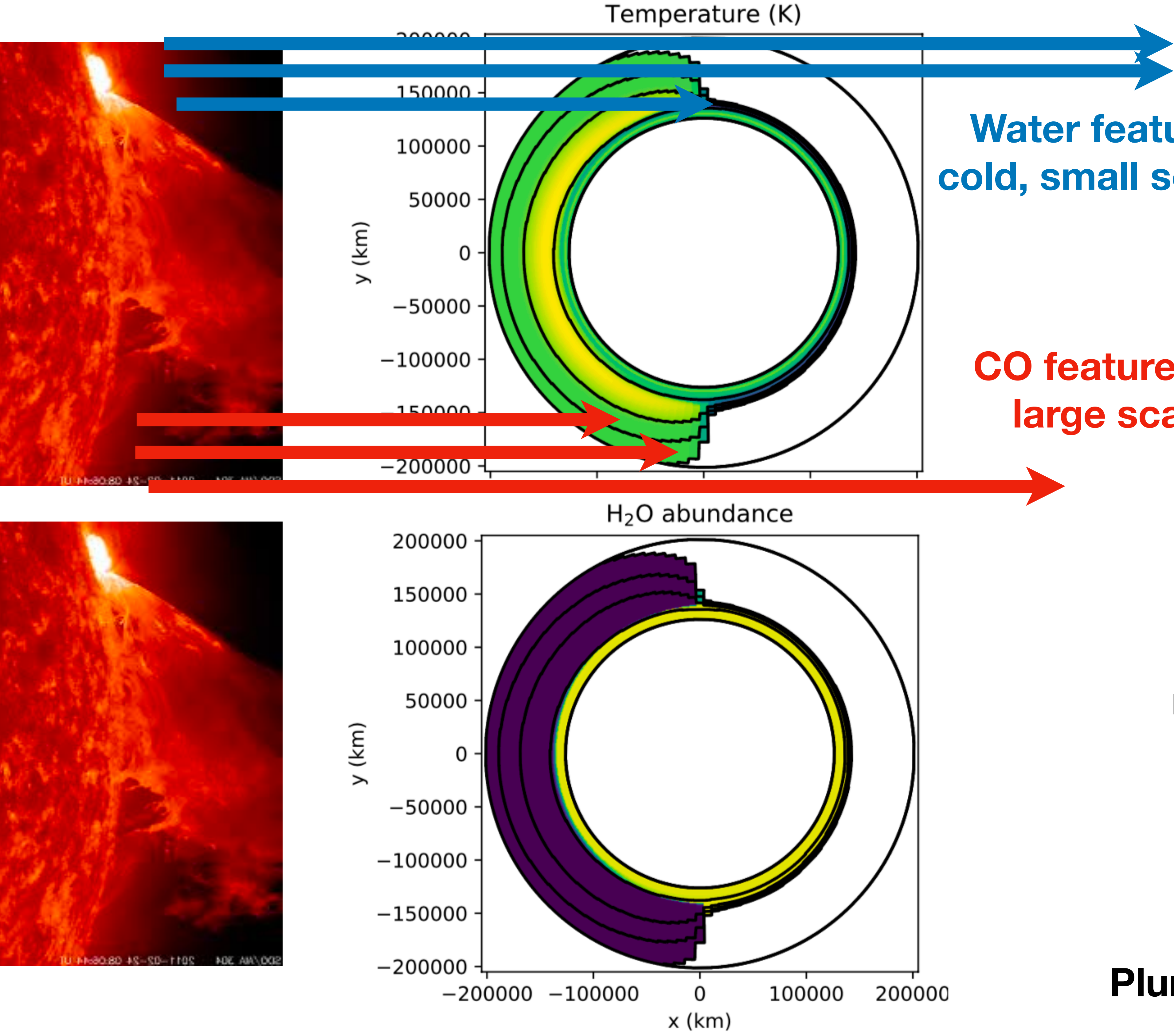
3D effects : non-uniform temperatures in emission



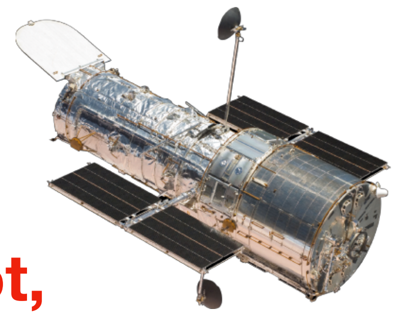


CH4 detection !

3D effects : non-uniform temperatures in transmission



Water feature due to the cold, small scale height gas

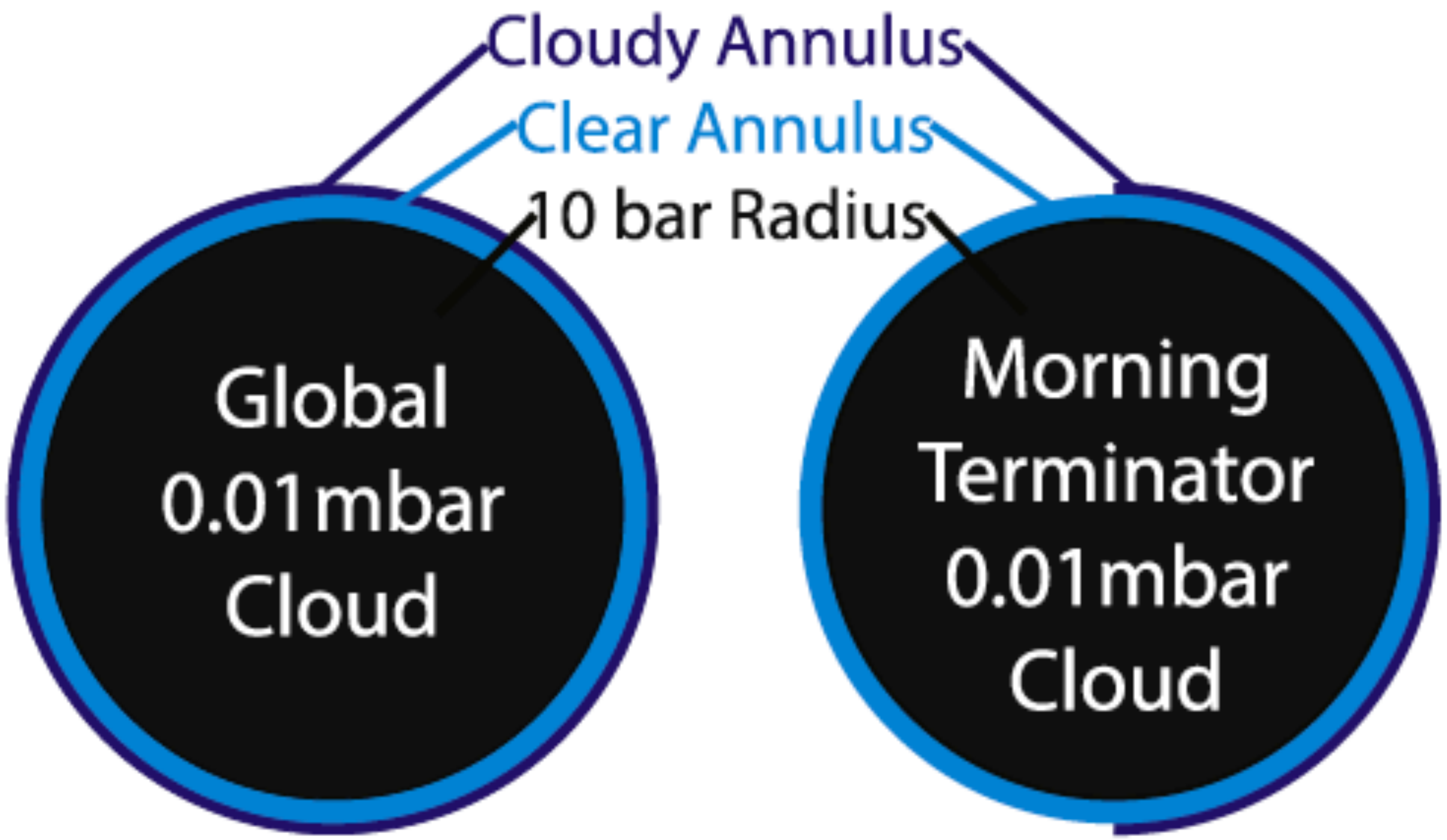


CO feature due to the hot, large scale height gas

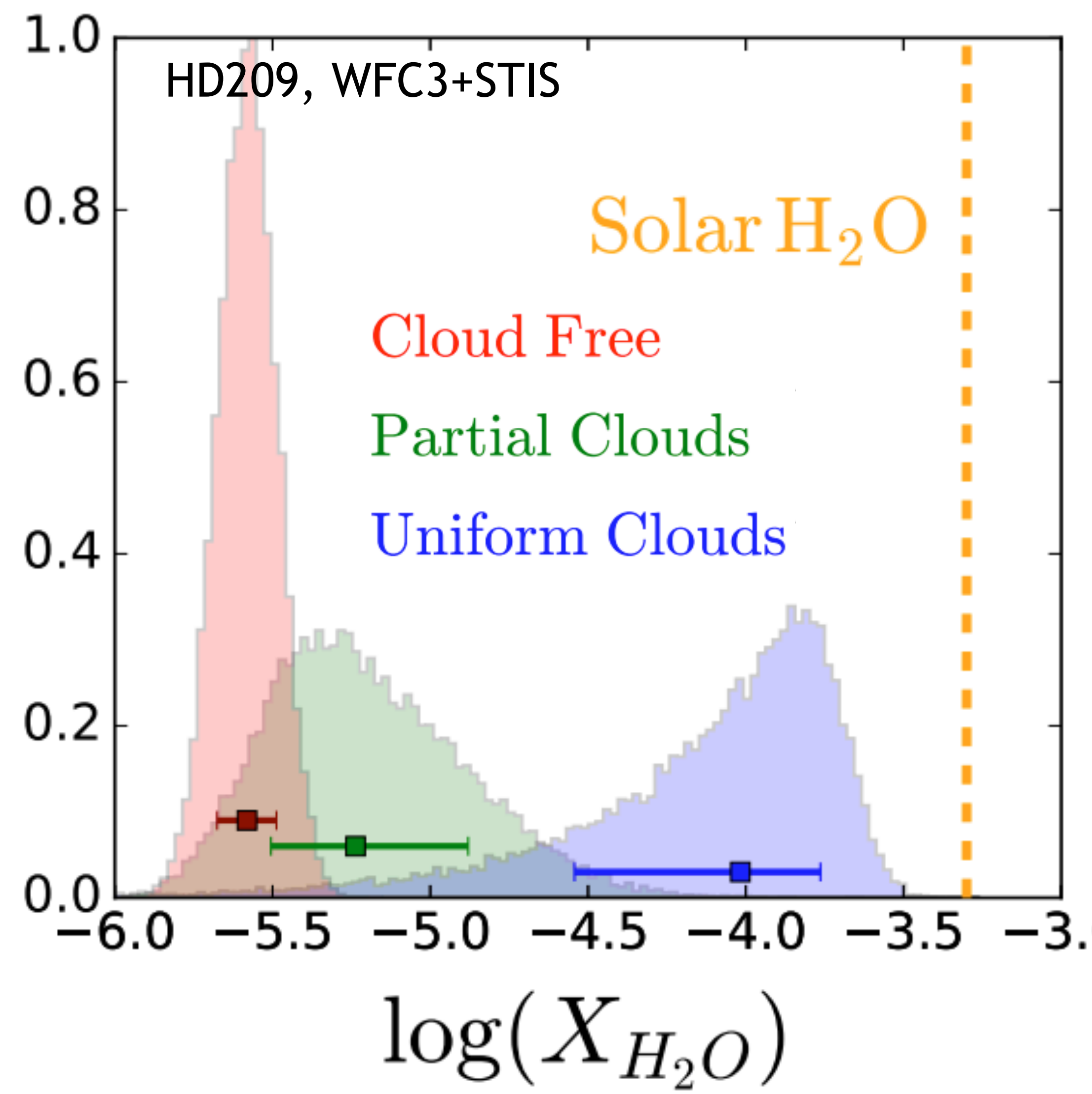
A 1D model would retrieve a carbon to oxygen ratio 100x too large !

Pluriel et al. in prep.

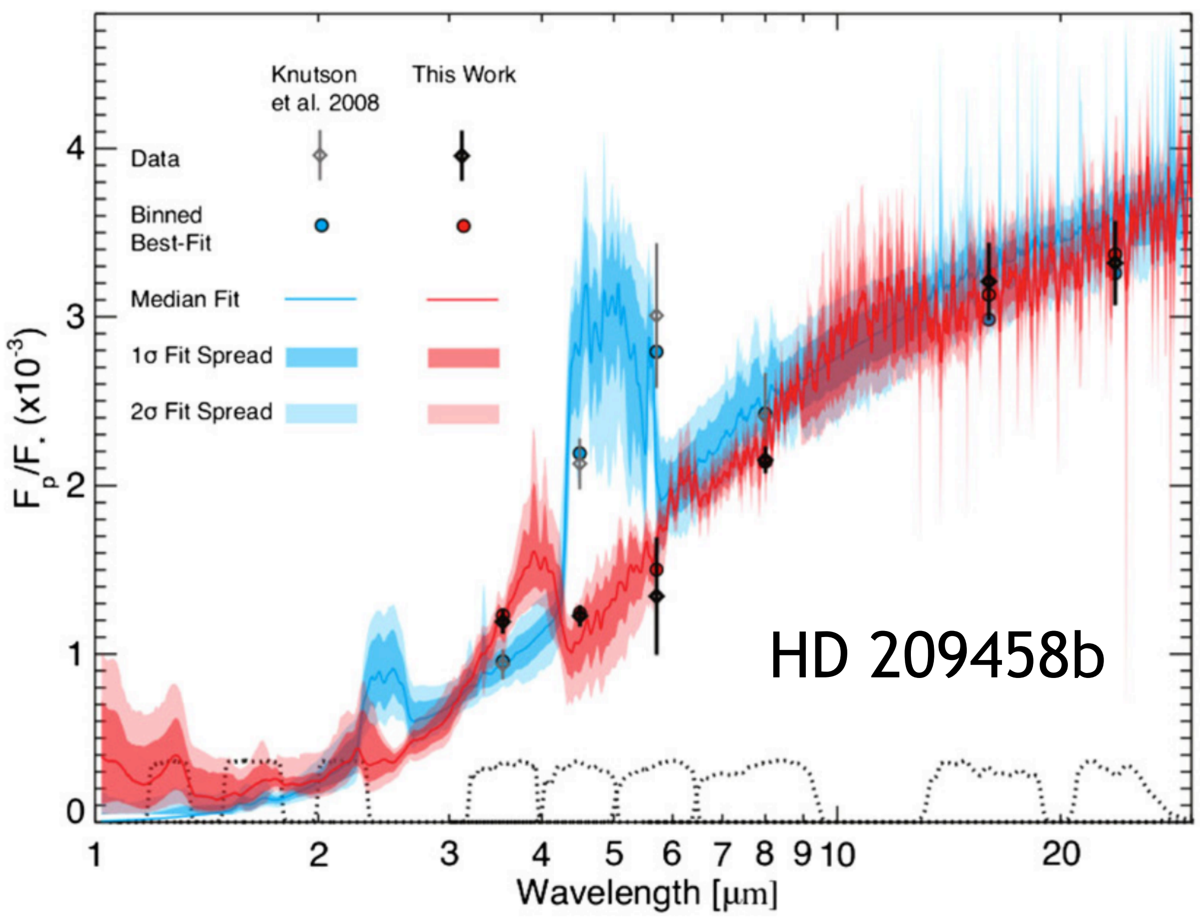
3D effects : non-uniform clouds

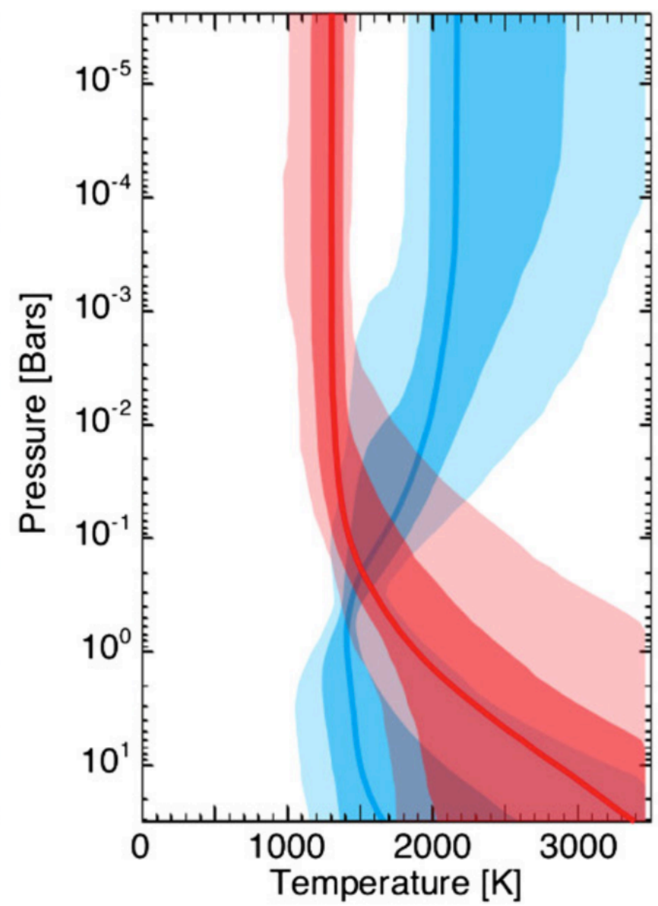


Line & Parmentier 2016; MacDonald & Madhusudhan 2017

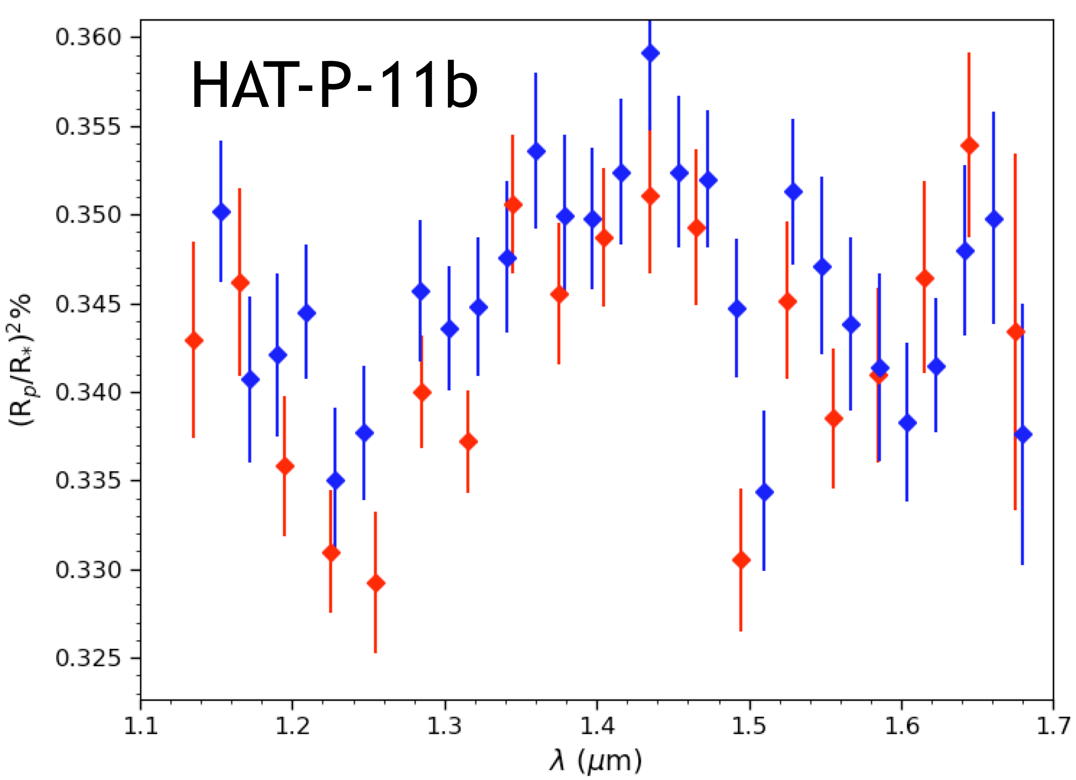


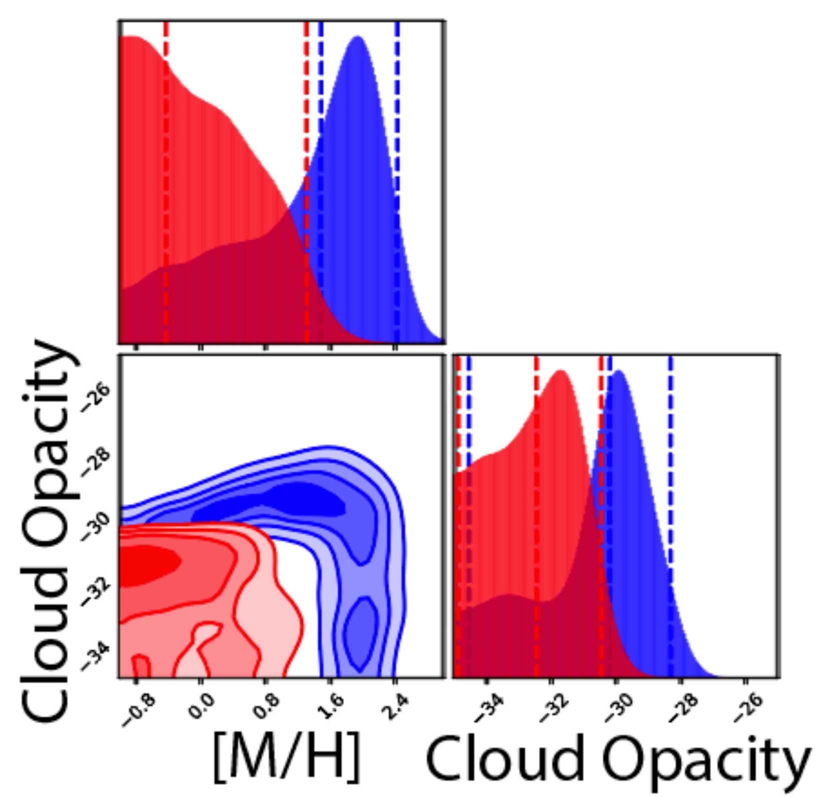
Data analysis — different analysis leads to different conclusions





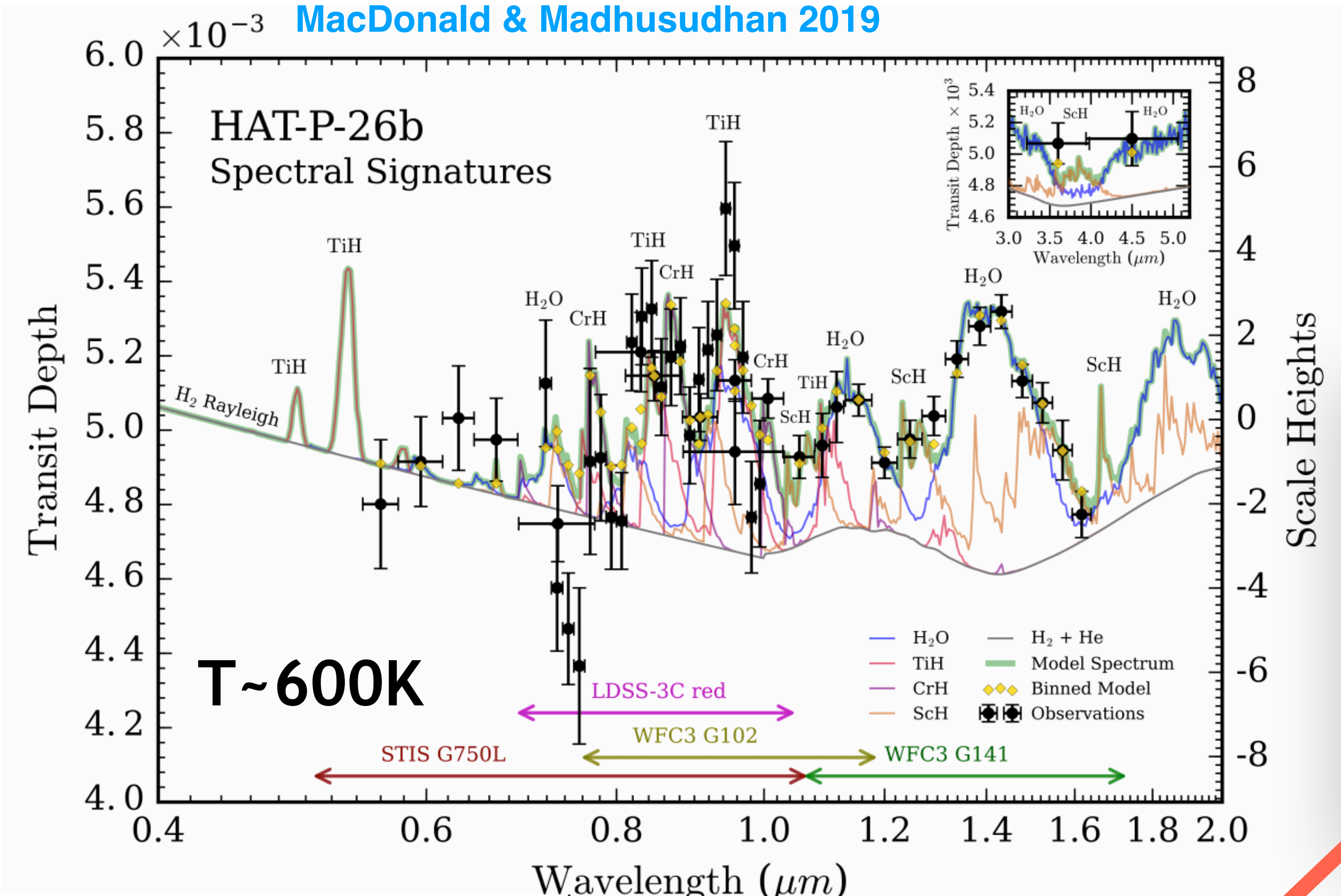
Diamond-Lowe et al.



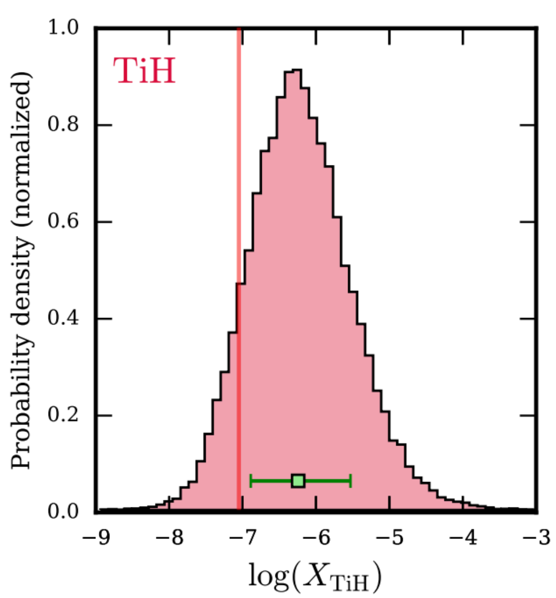


Chachan et al.

Statistical inference: did I really detect this gas ?



Model	Evidence $\ln(\mathcal{Z}_i)$	Best-fit $\chi^2_{r,\min}$	Bayes Factor $\mathcal{B}_{0i}$	Significance of Ref.
Full Chem	352.26	3.55	Ref.	Ref.
No H_2+He	325.59	6.32	3.82×10^{11}	7.6σ
No H_2O	328.12	6.03	3.03×10^{10}	7.2σ
No TiH	347.45	4.08	122	3.6σ
No CrH	351.16	3.54	3.01	2.1σ
No FeH	352.43	3.46	0.84	N/A
No ScH	351.57	3.48	2.00	1.8σ
No ScH or AlO	350.25	3.72	7.44	2.5σ
No M-Oxides	354.08	3.04	0.16	N/A
No M-Hydrides	345.66	3.79	732	4.1σ



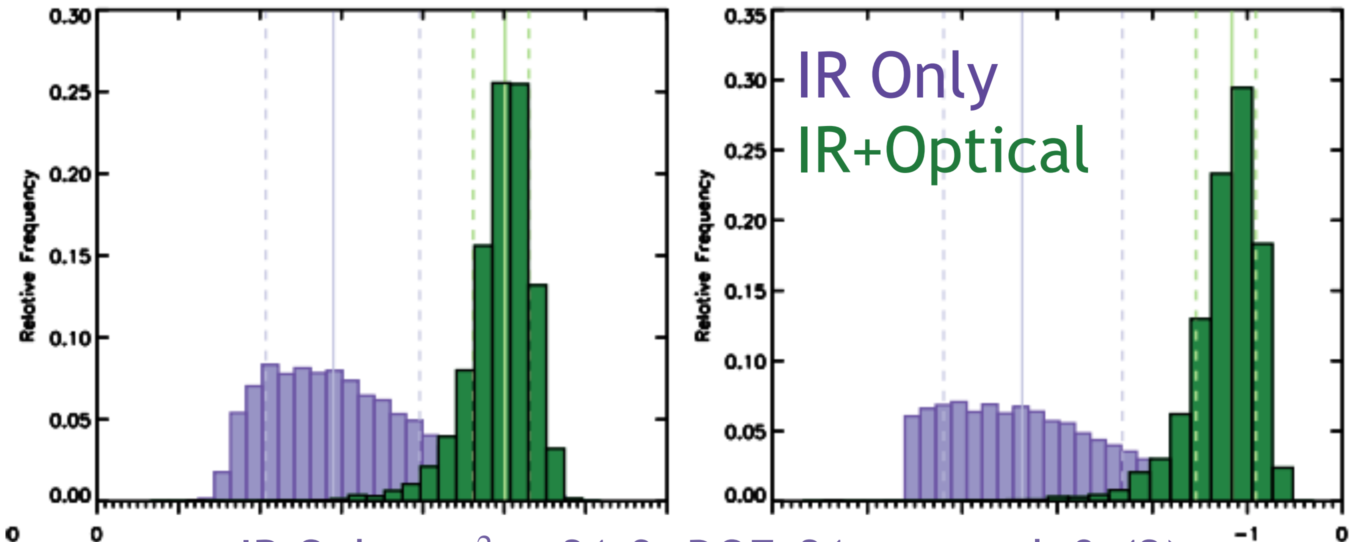
p-value<10-6

Bayesian evidence says that the model with TiH is a significantly better fit !

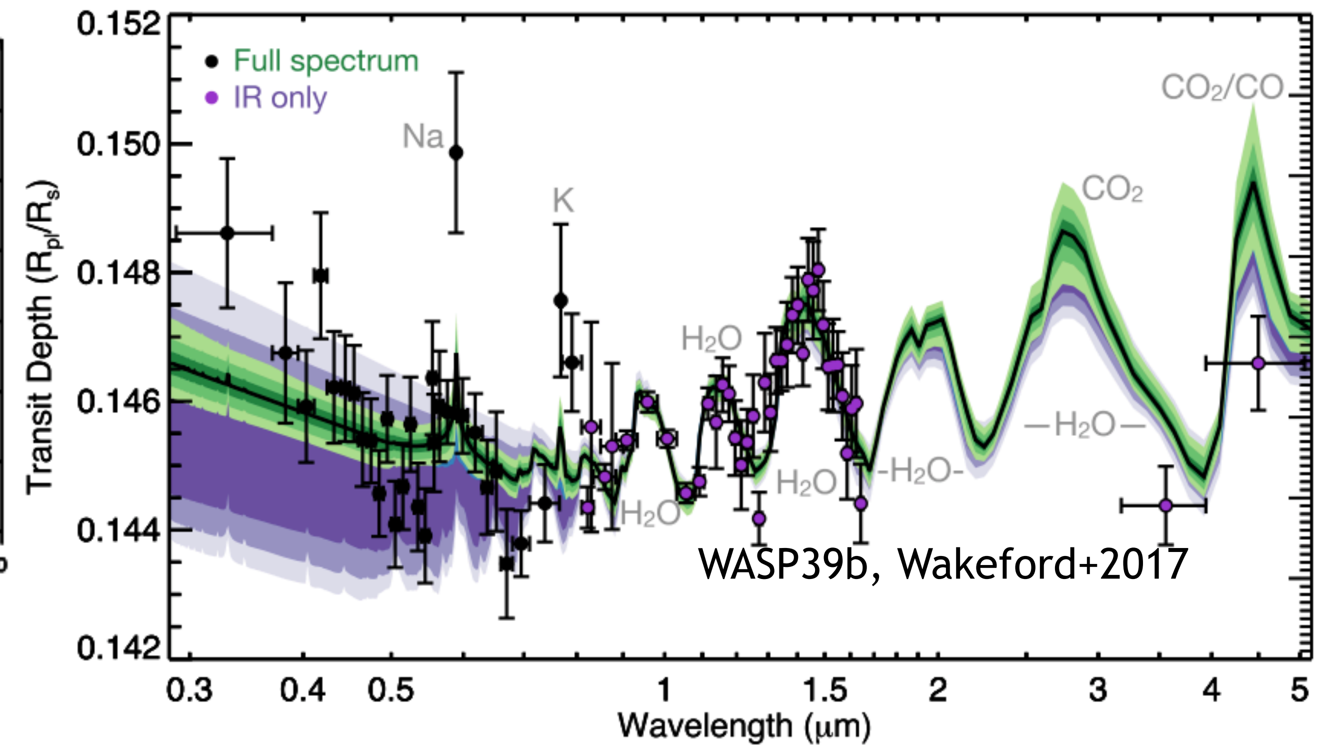
A lot of interesting consequences ! Needs a replenishment of 1 Eros worth of material every 4 years and new physics so that the TiH stays in gaseous form.

If that solution were the real thing, I would have 1 chance over a million to observe a dataset with such a bad Xi2 !

Which data sets to include?

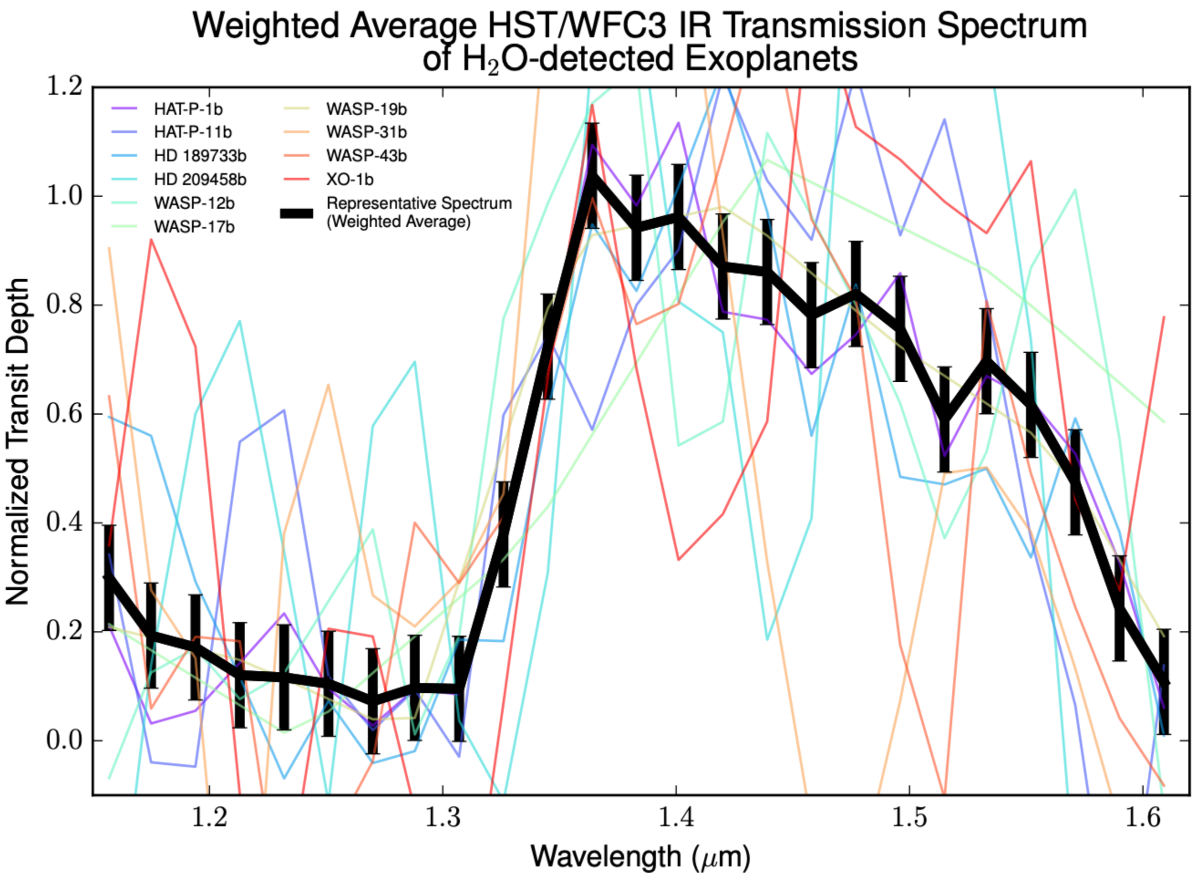


IR Only: χ^2 = 31.9, DOF=31 —> p-val=0.42)
IR+Optical: χ^2 = 88.1, DOF=65 —> p-val=0.03)



Clouds ! Clouds clouds clouds….

We've seen water in almost all planets we looked for it



To first order, the size of the feature does not depend on the water abundance but on the water/cloud abundance.

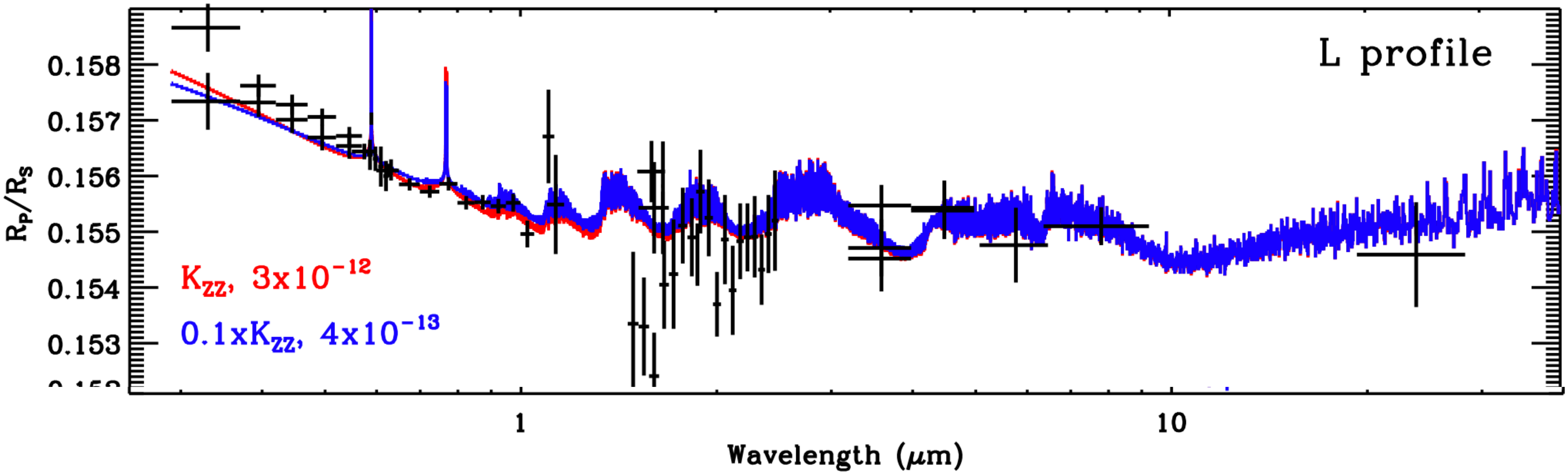
The shape of the feature depends on other factors, such as pressure, but is currently unreliable.

We've seen clouds/hazes in almost all planets when looking for other stuffs.

We can be order-of-magnitude precise on abundances but we can be innacurate because driven by the not-robustly-measured shape of the feature !

Haze ! haze haze haze ….

HD189733b : 1200K planet best fit by hazes ! Even though we don't see any CH4 !



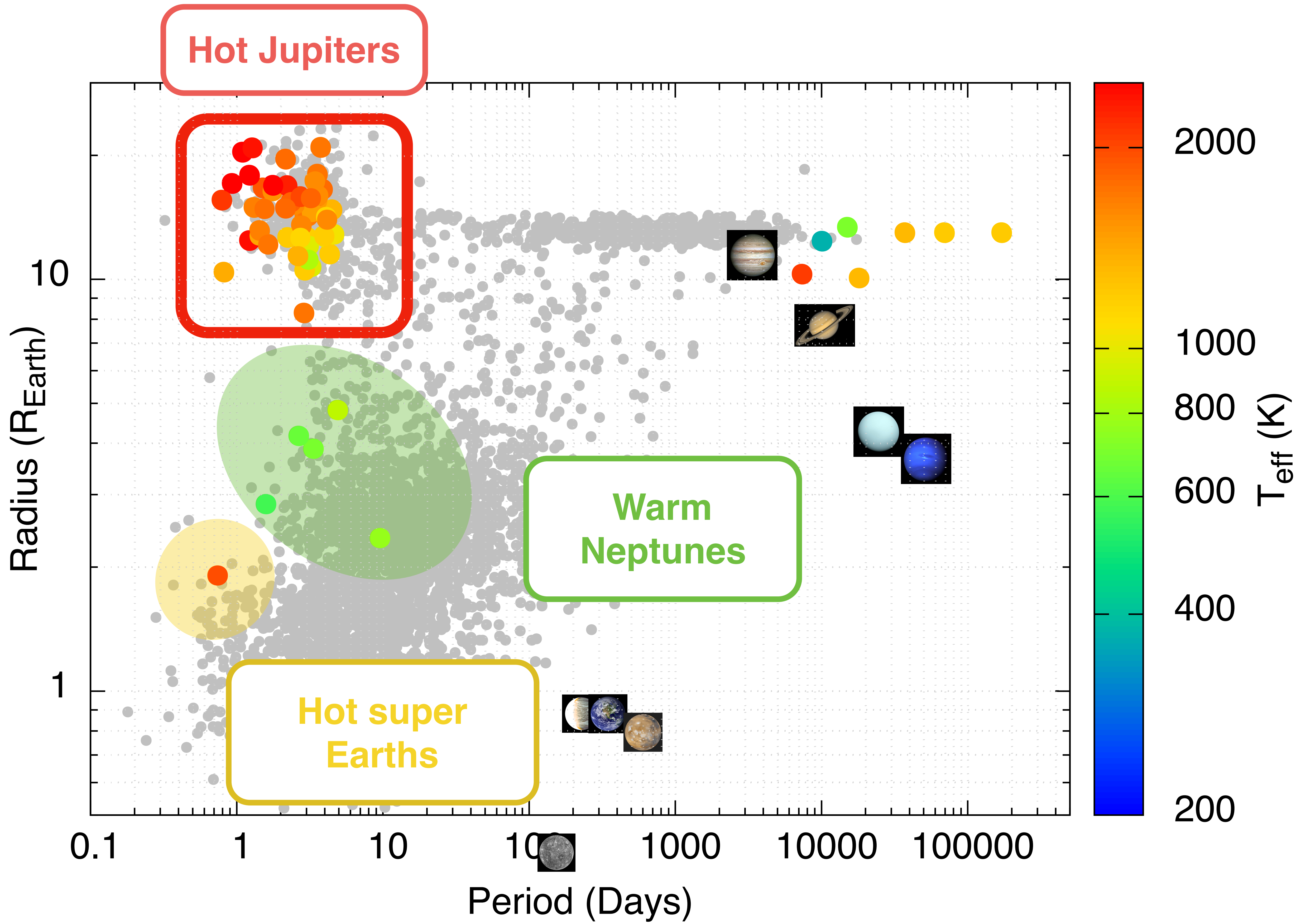
Experiments can form hazes in H2-CO2 mix @ 1500K !

All smaller, cooler guys have some sort fo cloud and hazes

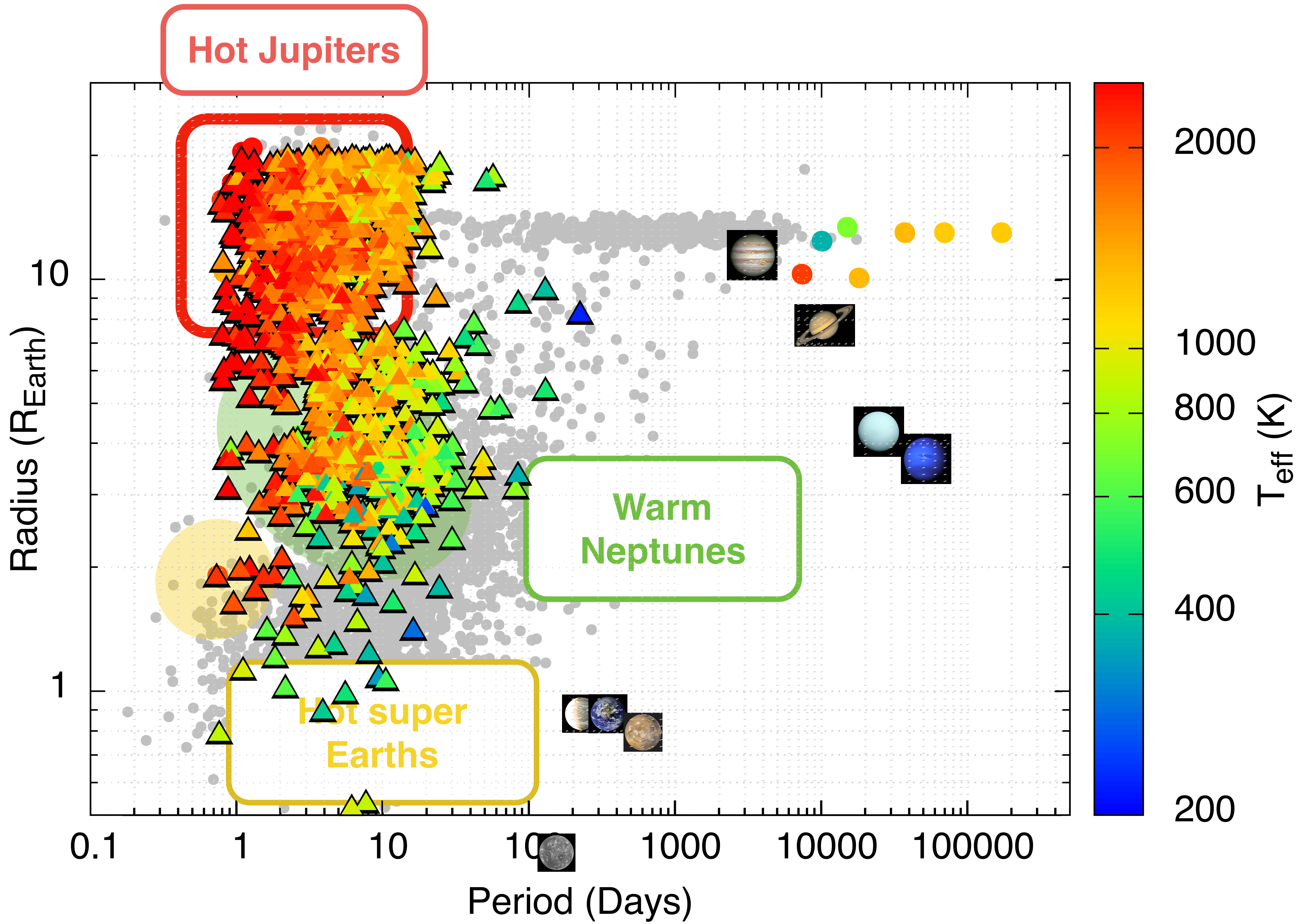
Haze is a pain, and it's not limited to cool planets with CH4 like Titan …

I’m sad now, is there hope ?

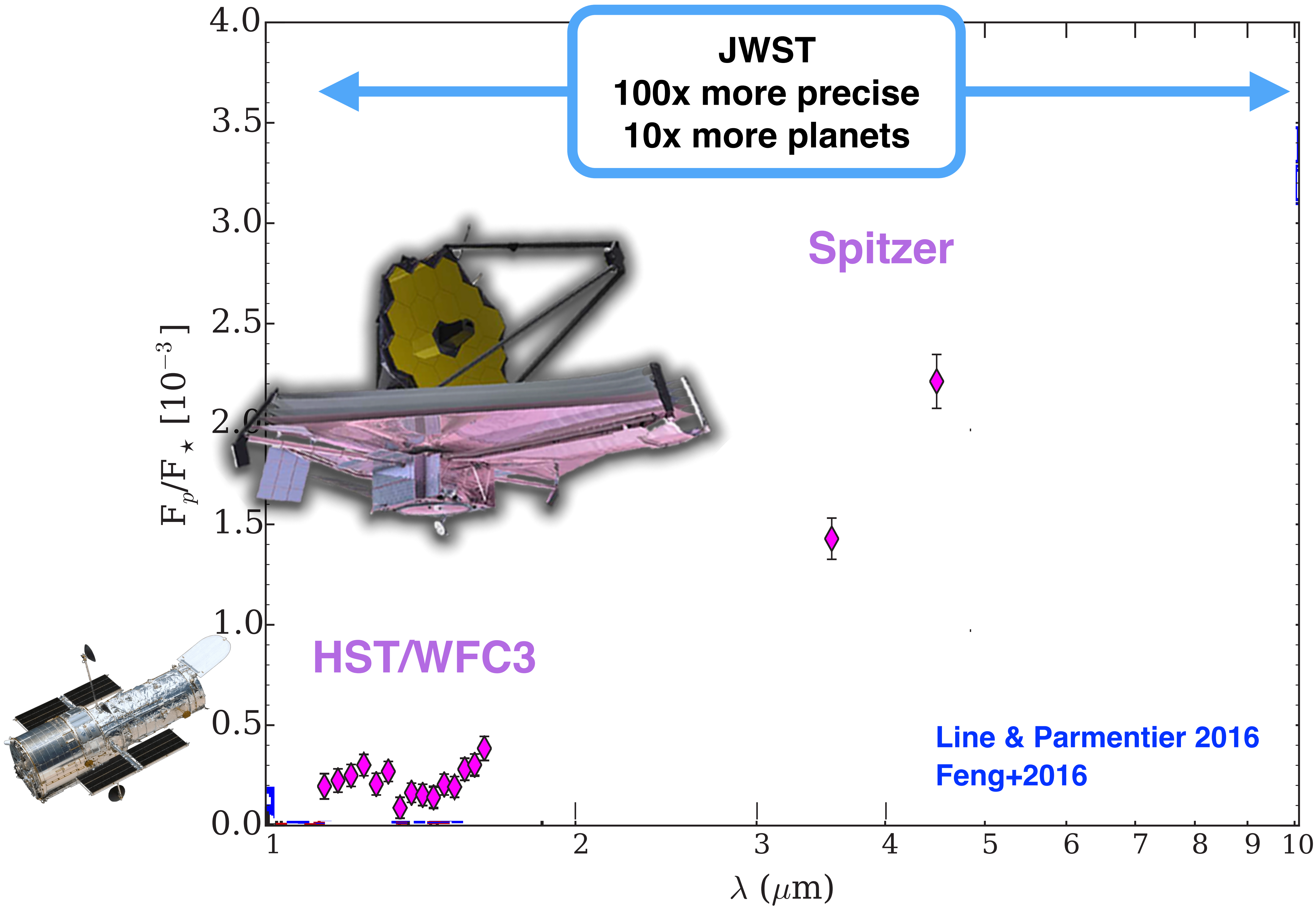
The future of exoplanets : Ariel



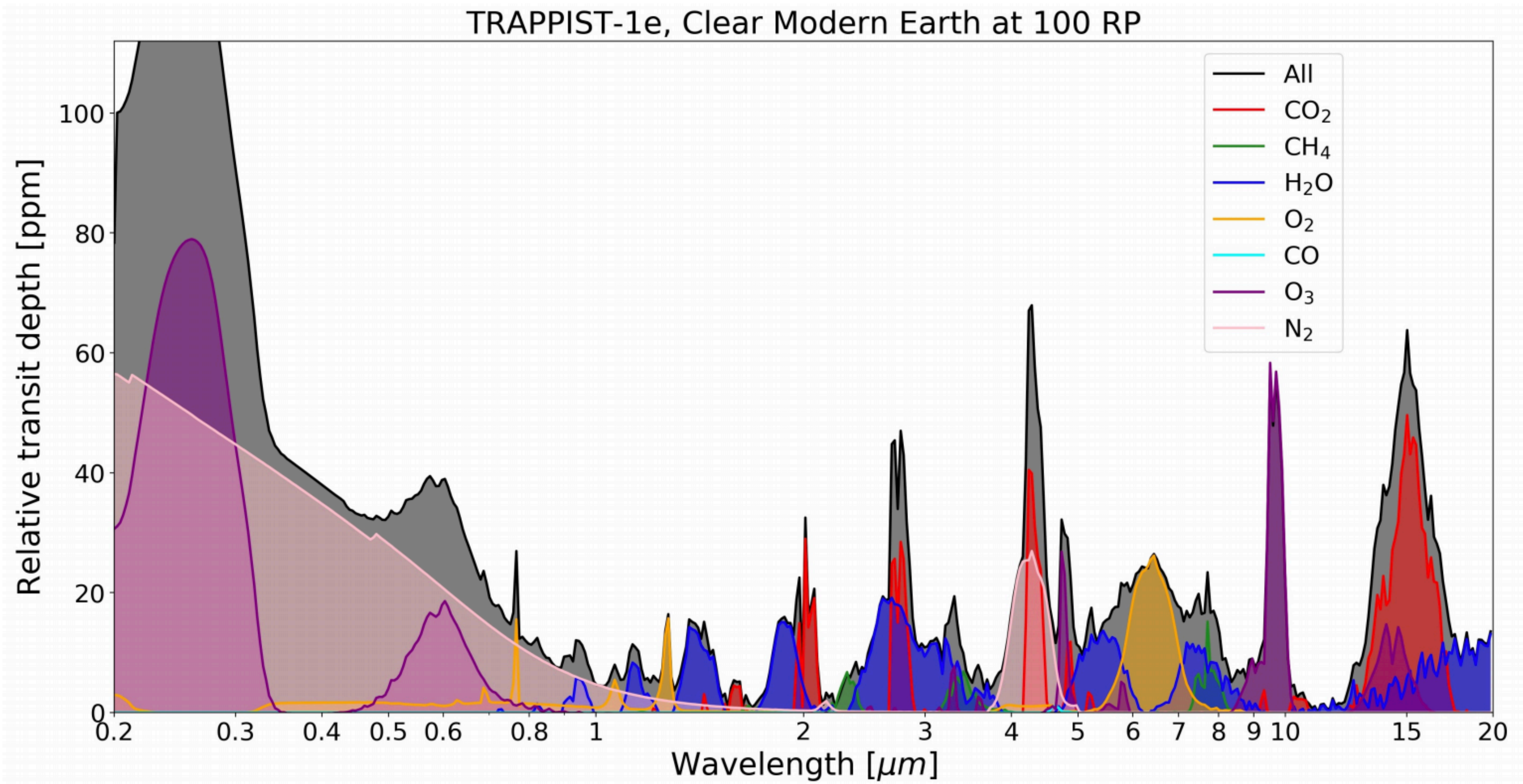
The future of exoplanets : Ariel



The future of exoplanets : JWST

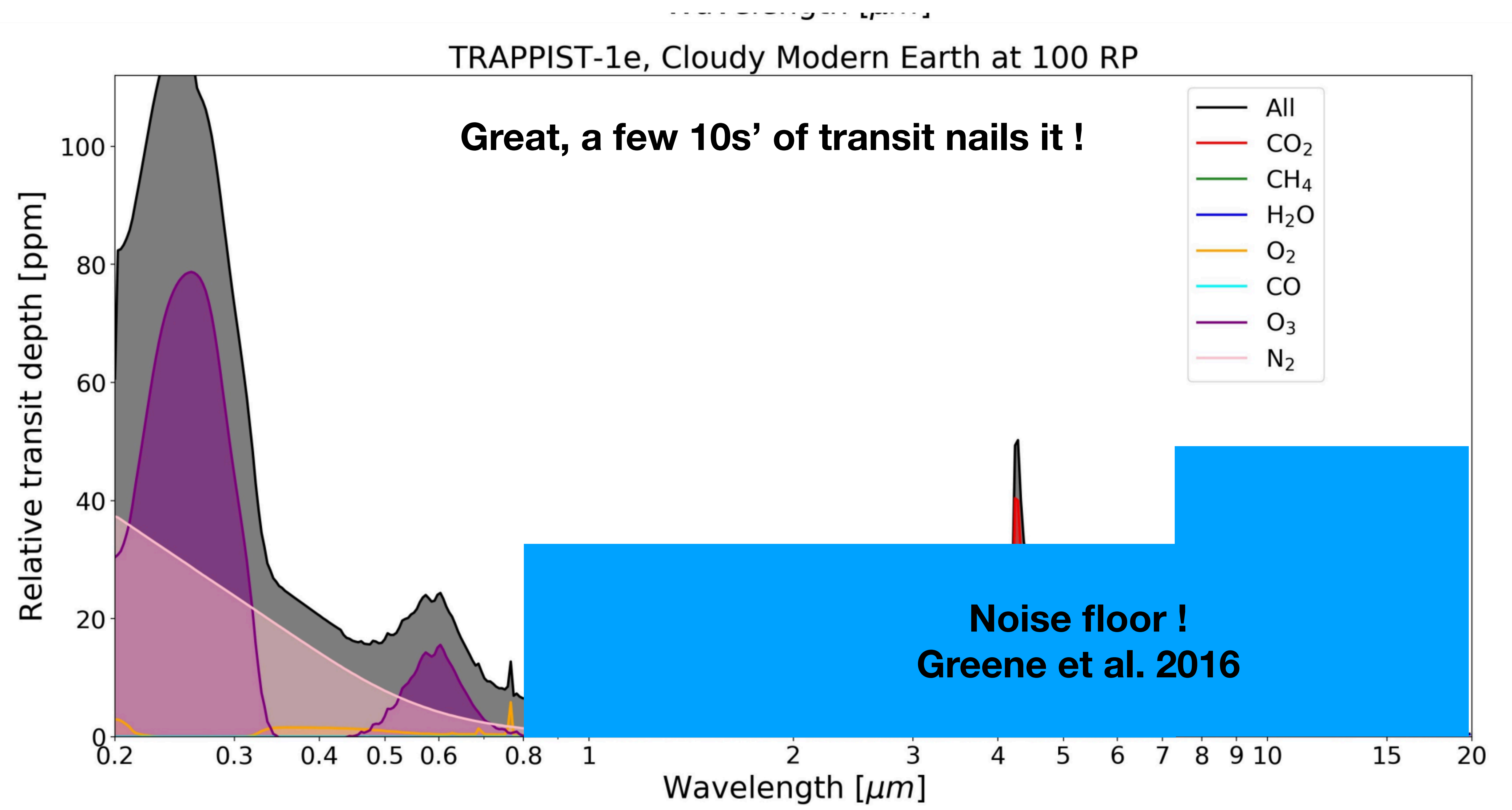


JWST and rocky planets ?



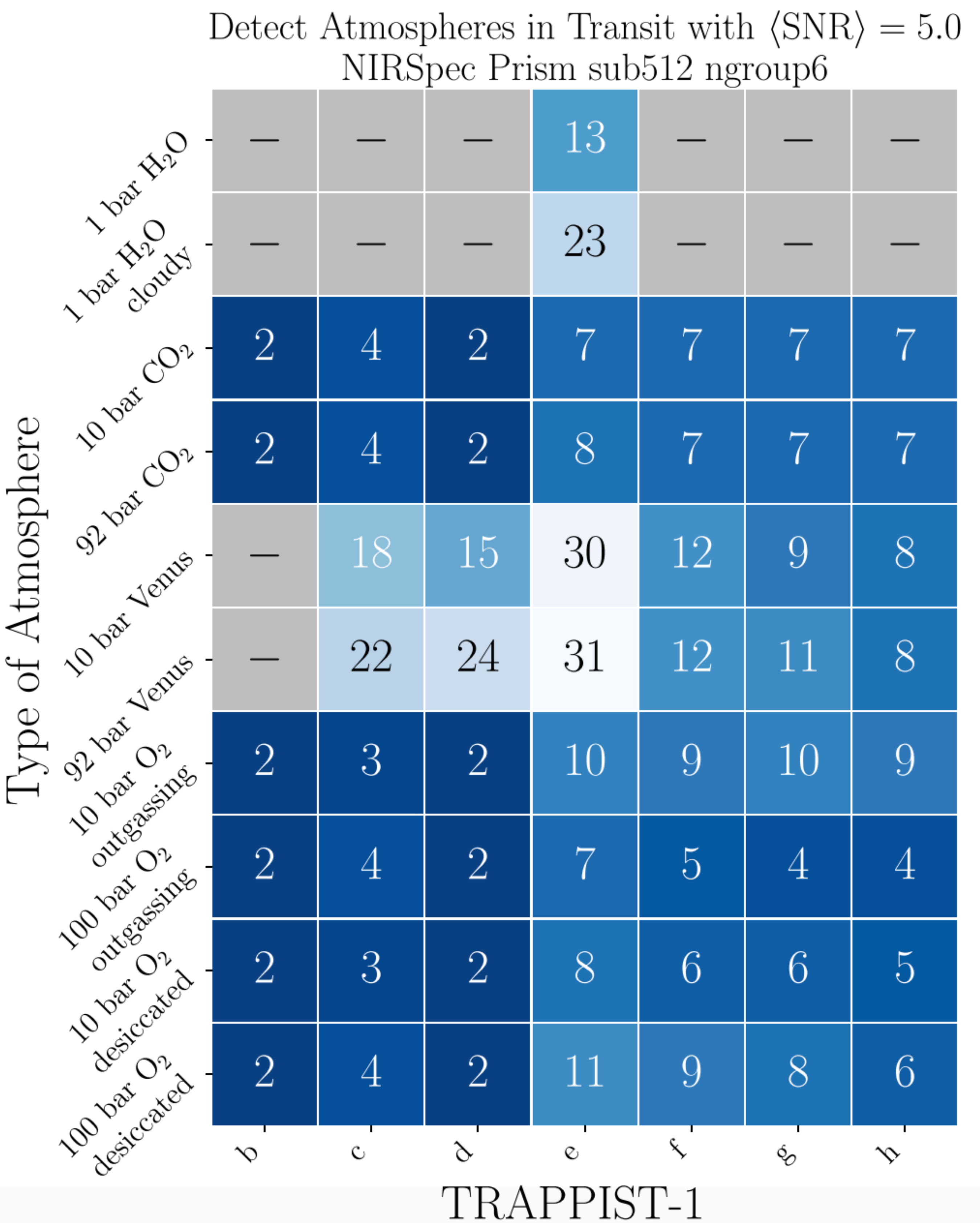
Pidhorodetska et al. 2020

JWST and rocky planets ?



Pidhorodetska et al. 2020

Detecting atmospheres around rocky things

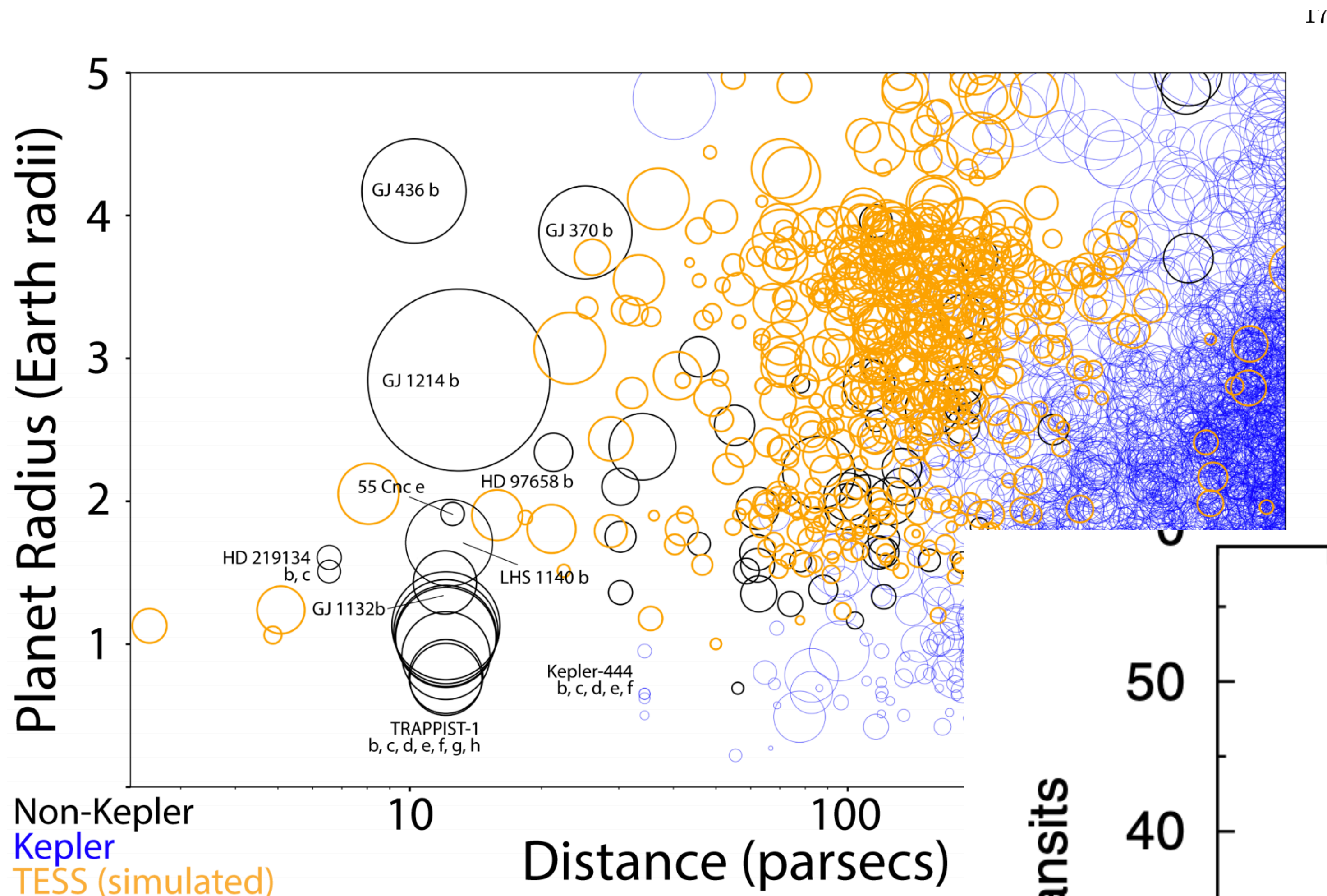


If we're lucky :
Clouds or hazes won't block much of our view and we'll see some CO2

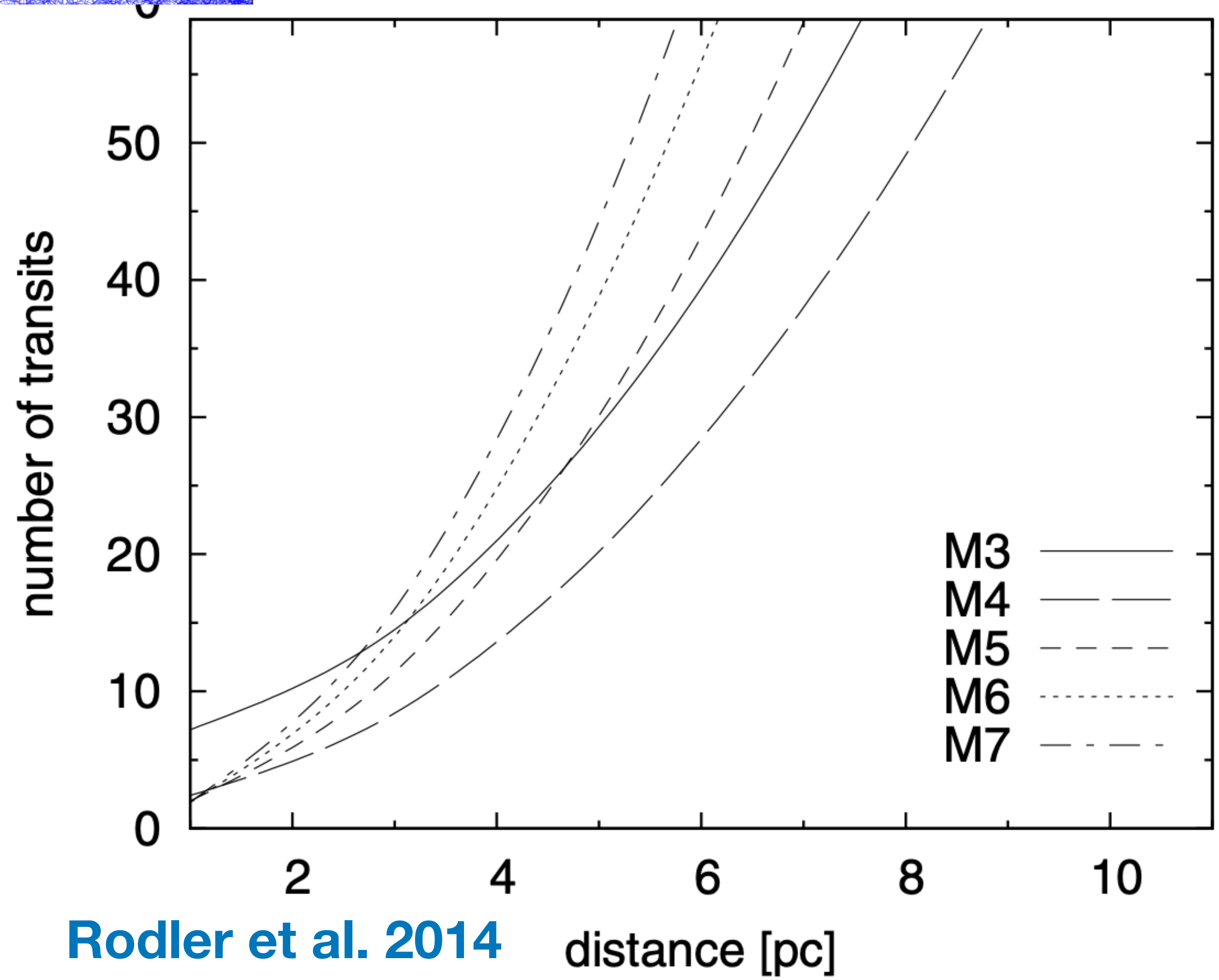
HOWEVER:
it will be extremely hard to quantify abundances, or even total atmospheric pressure (degenerate with cloud pressure level)

Lustig-Yaeger 2019

We likely won't be able to see any O2 is earth-like planet soon



Barclay et al. 2018



Rodler et al. 2014

Questions for rocky exoplanets atmospheric observations

Current status

Most ~50-ish gas planets with atmospheric measurements are ***compatible with physics and solar composition of carbon and oxygen*** +/- 1dex.

Most of these atmospheres are cloudy.

A majority show their ***3D-ness*** in the observations

Expectations

JWST will give us *WAY* better data for the hot planet, so ***we'll see all we got wrong before***, good lessons.

JWST/ARIEL data for rocky stuff will be of similar-ish quality than hot Jupiter now. ***Learn from our mistakes.***

Advices

What's a « detection » ? *Every* retrievals contains model assumptions.

Detection* is much easier than *quantification*. Think what you can do/constrain with detections only.

M dwarfs have water… think about other molecules not present in the star !

Tidally locked rocky planets will be highly 3D ! Always keep that in mind.