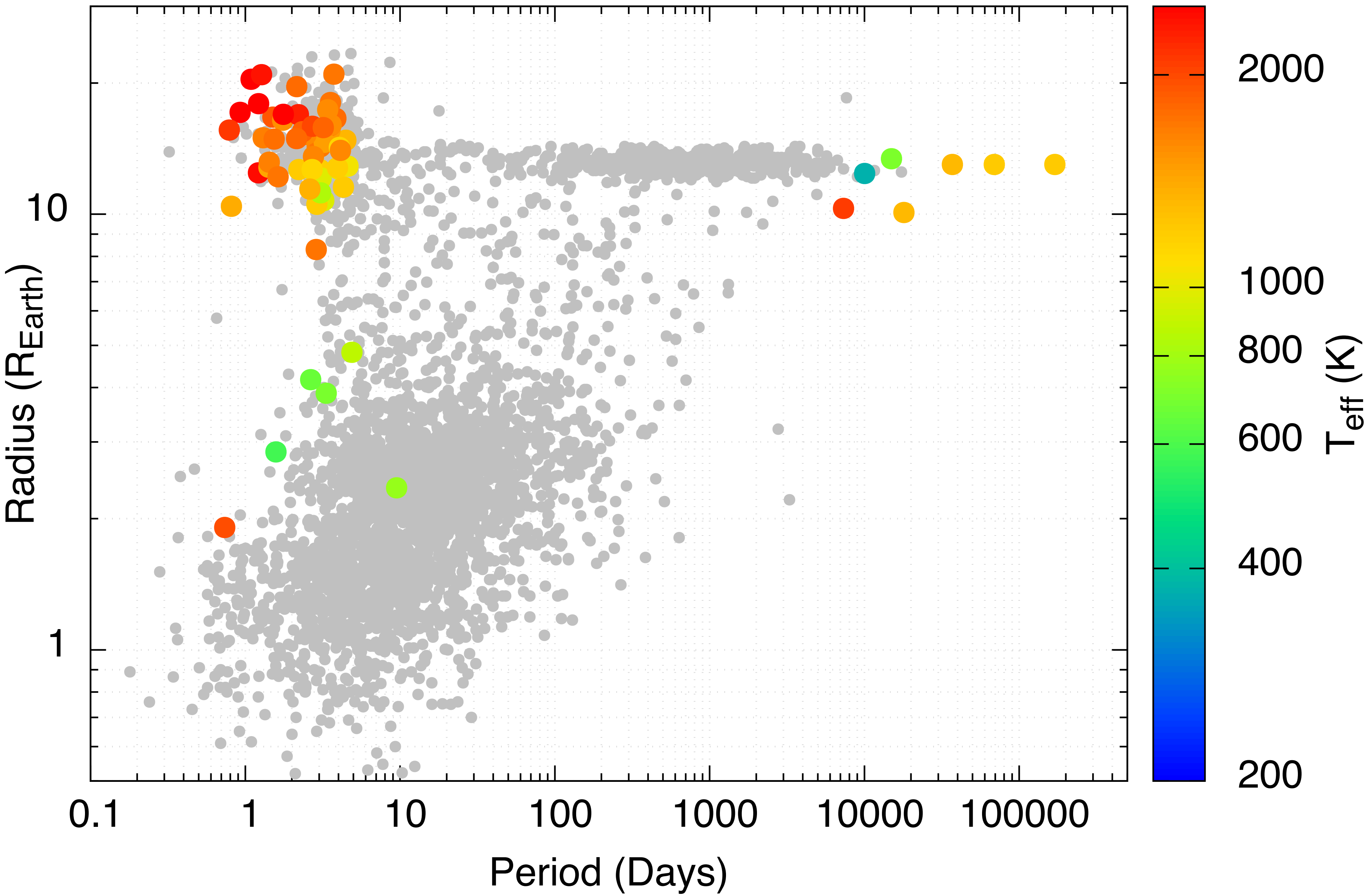
Ariel & the 3D planets

Vivien Parmentier — University of Oxford



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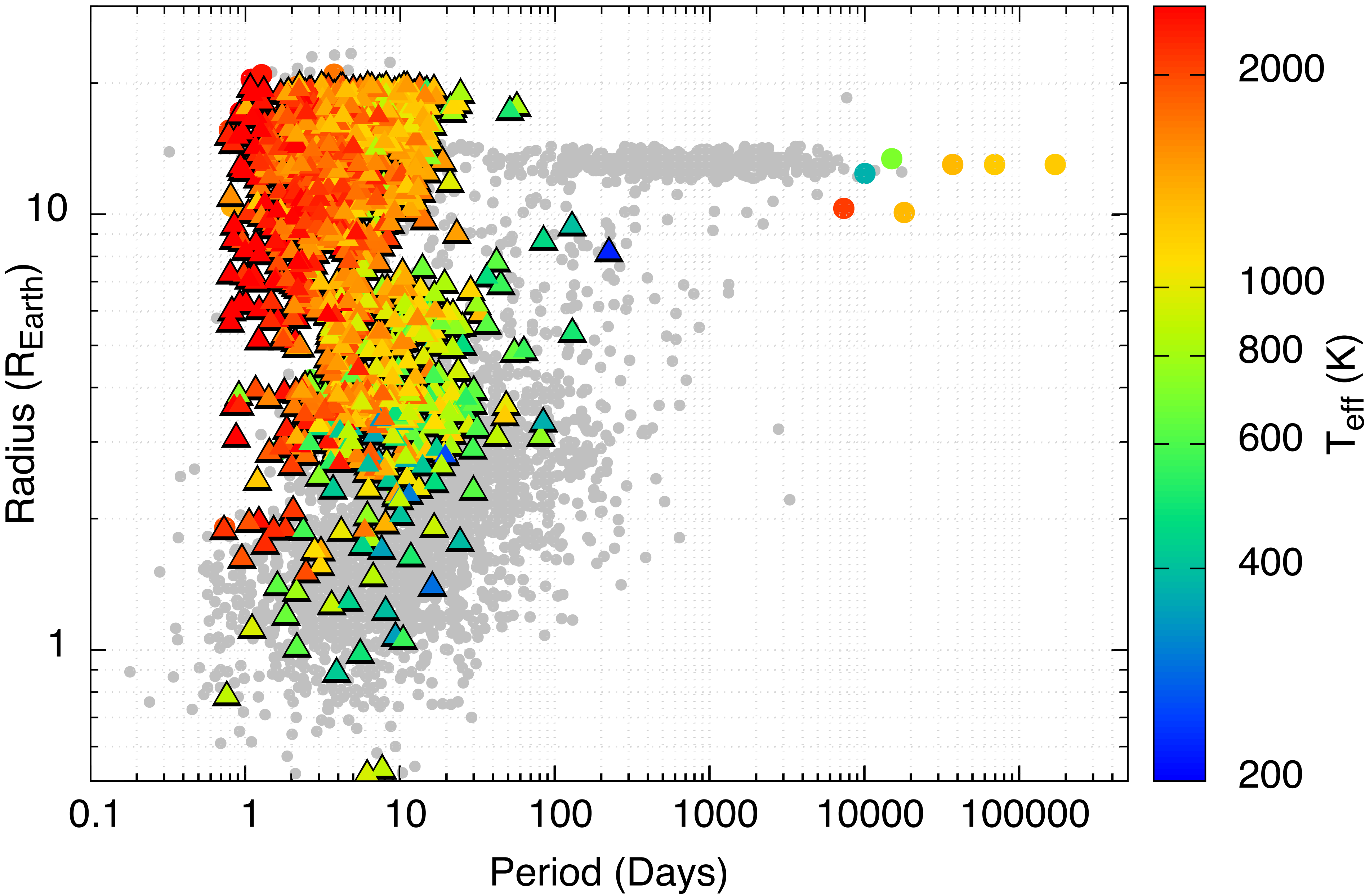

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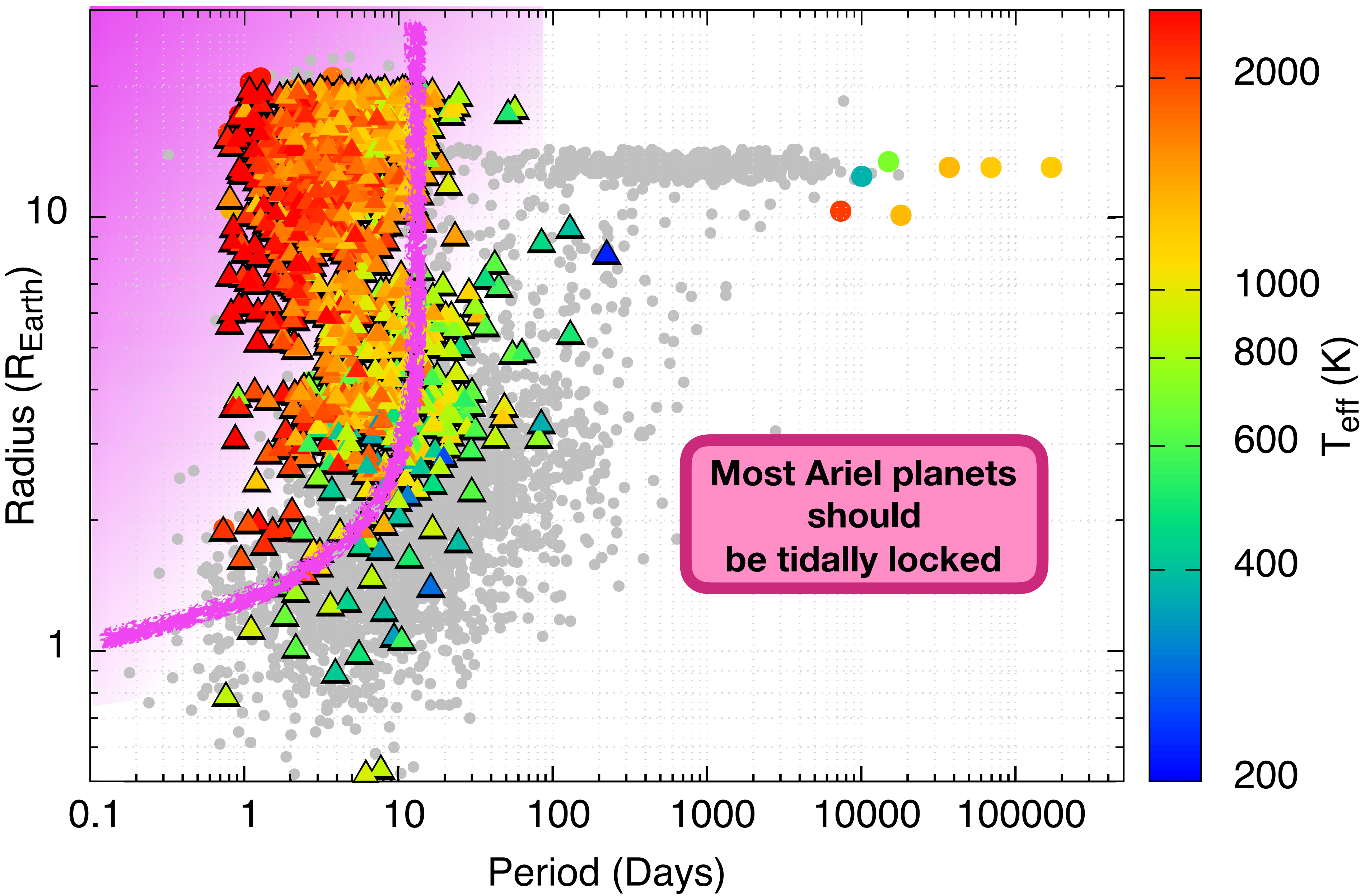
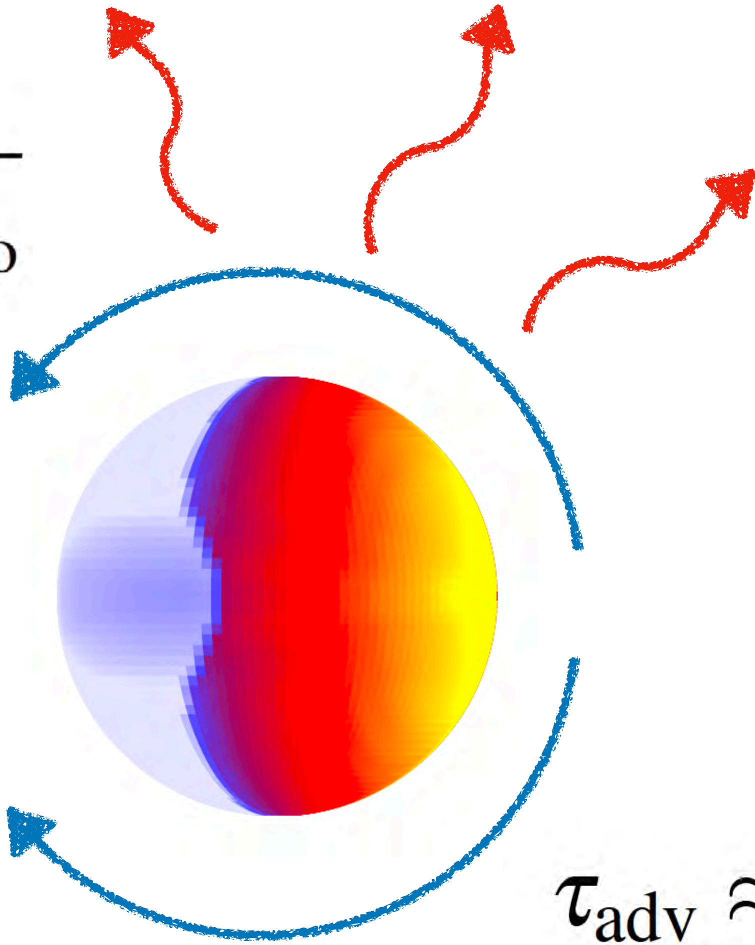


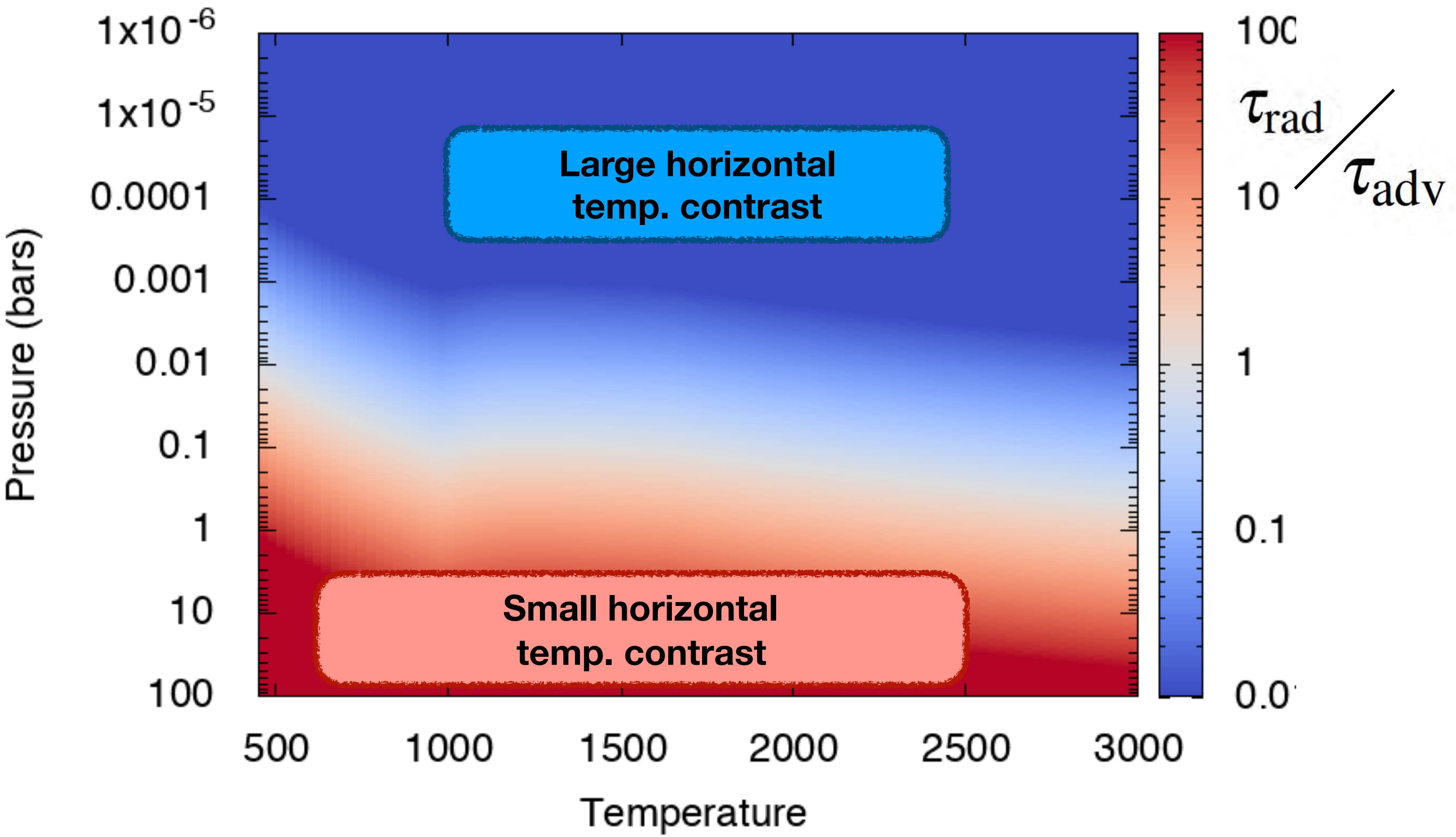
Tidally locked planets in 3D

$$\tau_{\mathrm{rad}} \approx \frac{P_{\mathrm{photo}}}{g} \frac{c_{\mathrm{p}}}{4\sigma T^3_{\mathrm{photo}}}$$

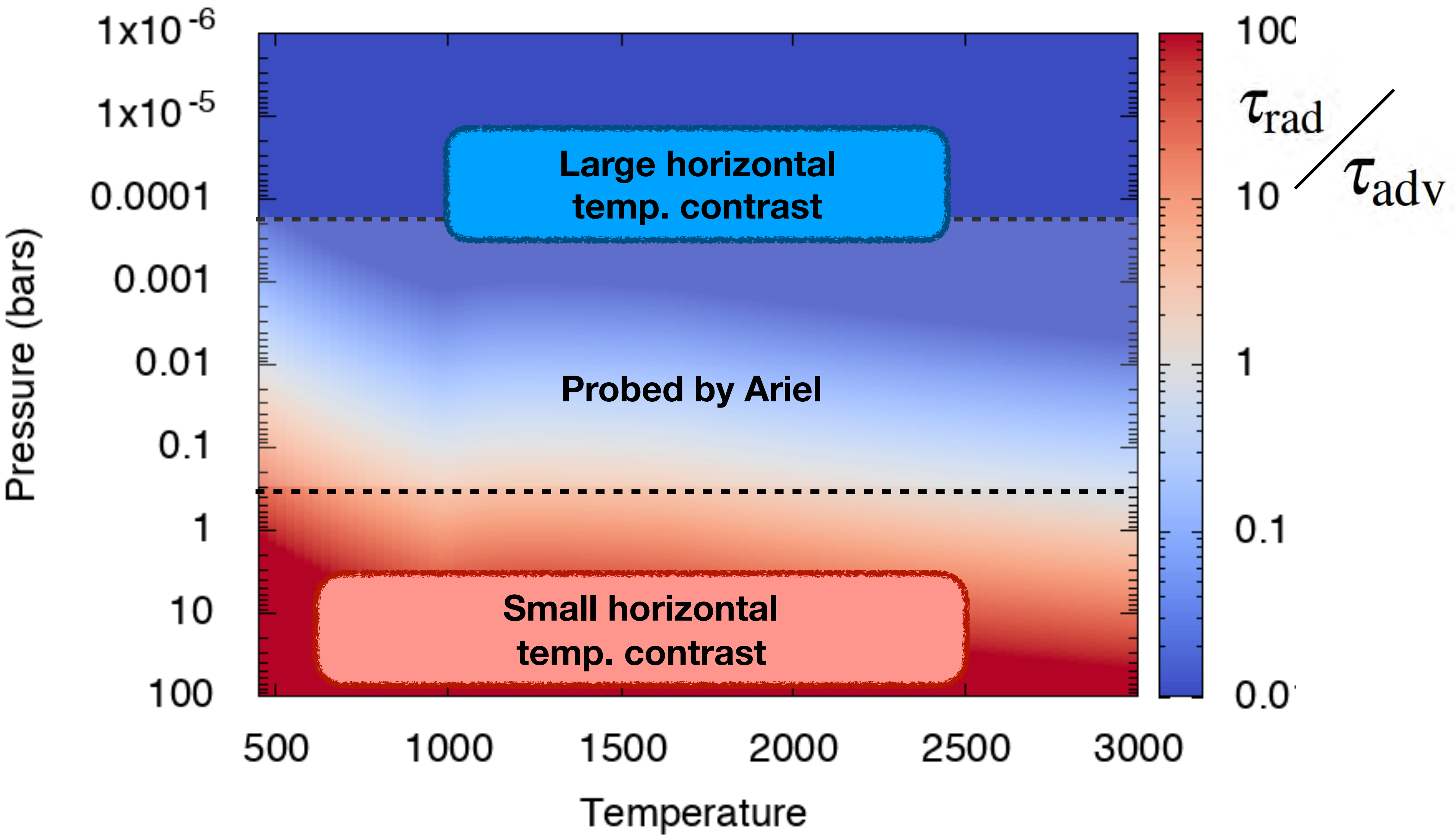


$$\tau_{\mathrm{adv}} \approx \frac{R_{\mathrm{p}}}{U_{\mathrm{jet}}}$$

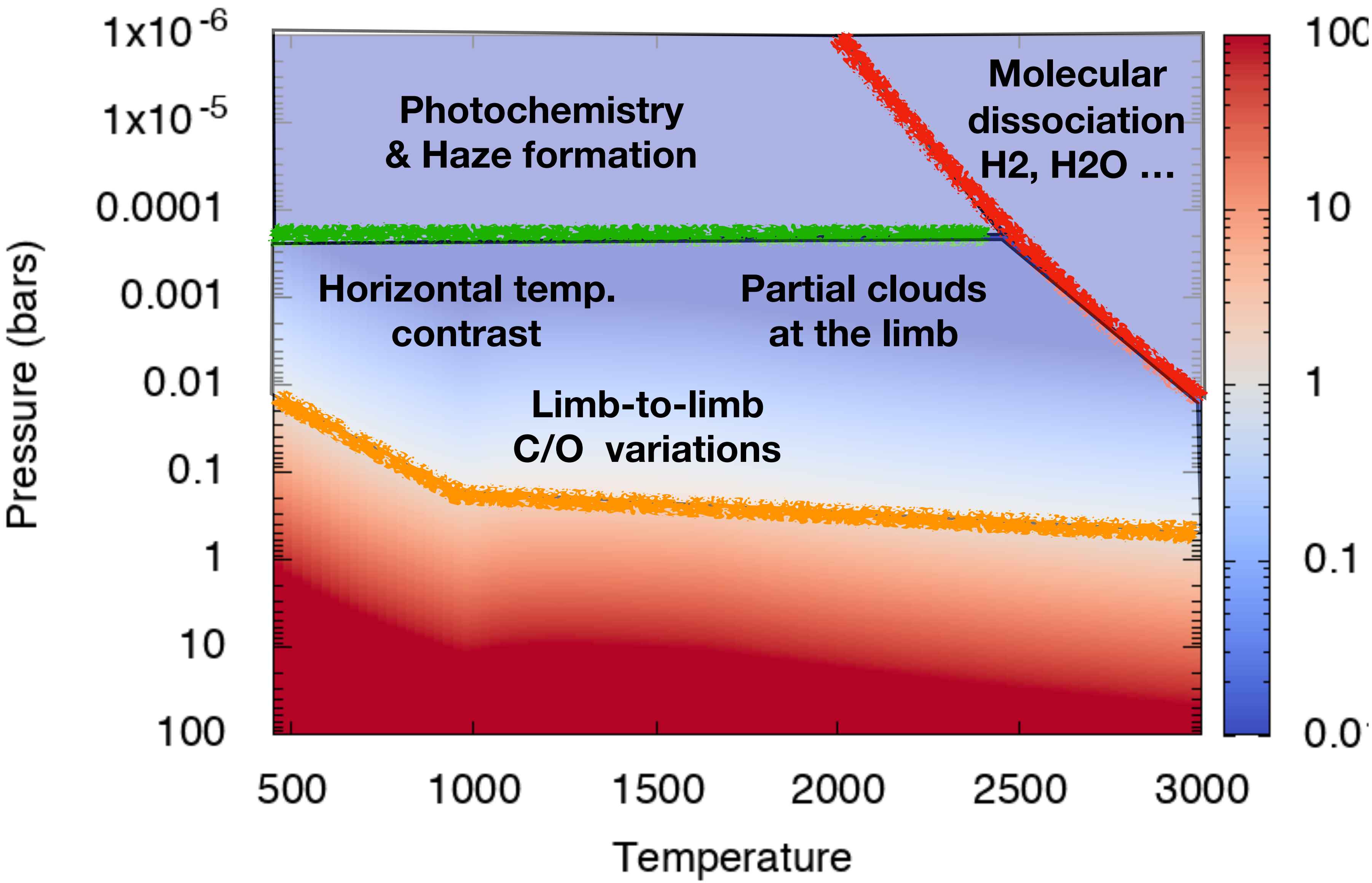
Horizontal homogeneities : causes



Horizontal homogeneities : causes



Horizontal homogeneities : causes



Why does this matter ? After all, we just want the abundances !

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

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

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

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

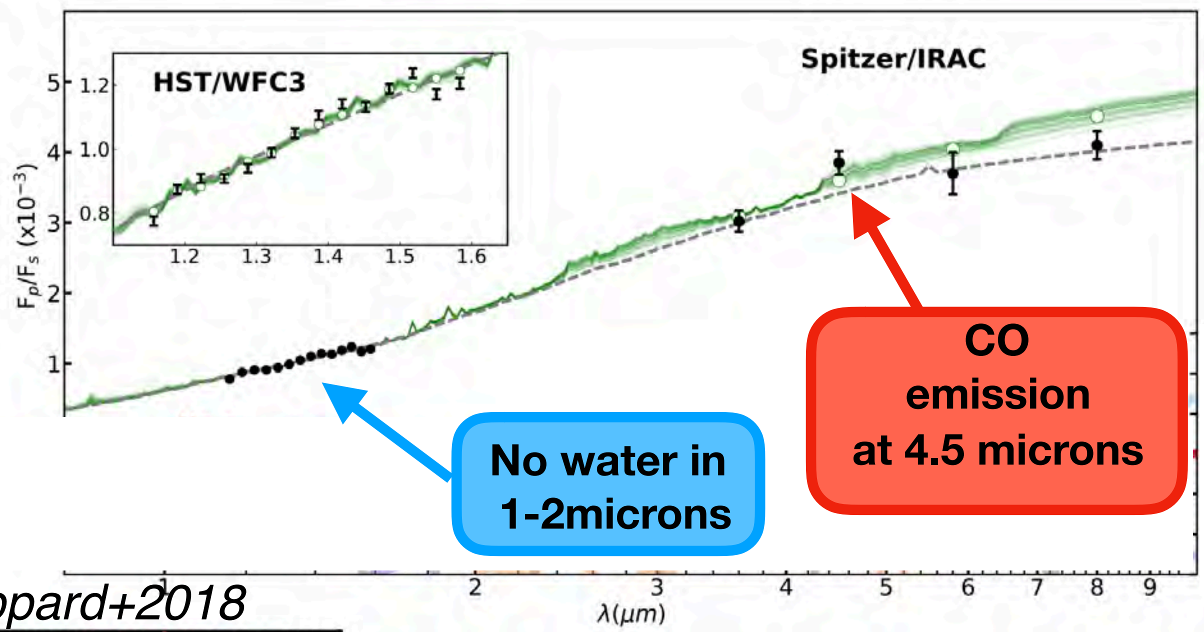
**We often debate what "Things" we want…

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

A range of model assumptions

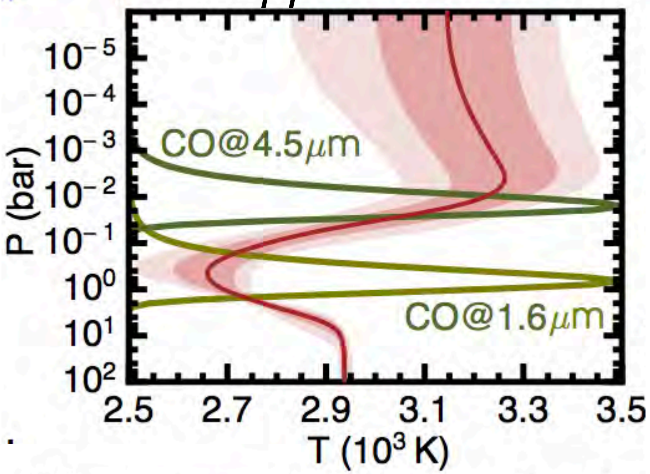
	Less assumptions More parameters		More assumptions Less parameters
Temperature profile	Free Semi-grey	1D Radiative/conv eq. Non-grey	2D/3D radiative/conv eq.
Chemistry	Free chemistry — Choice of species — Vertical profile	Equilibrium Choice of free parameters [M/H], [C/O] others ?	1/2/3D disequilibrium
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

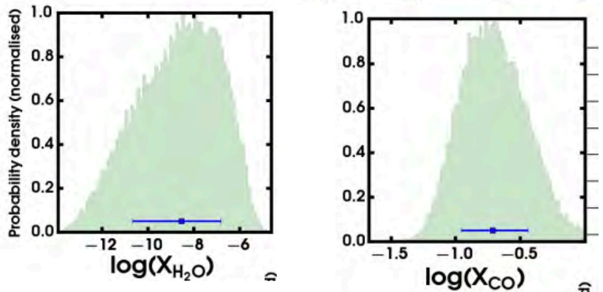


Hot Jupiter
WASP-18b
Teq~2500K

Sheppard+2018



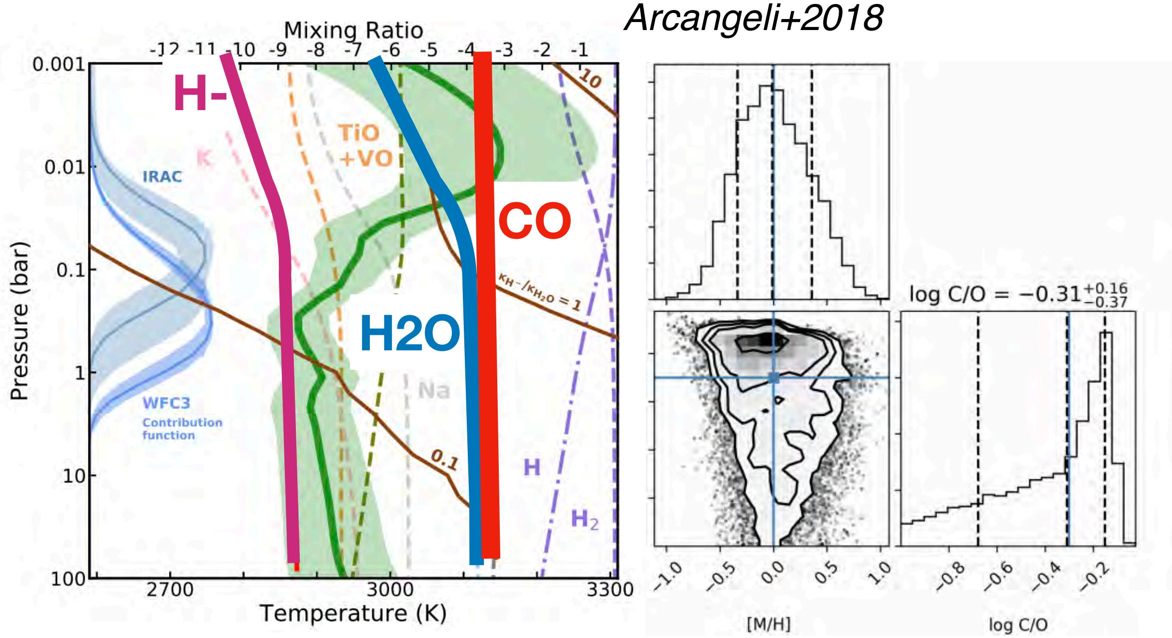
Free Retrieval



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

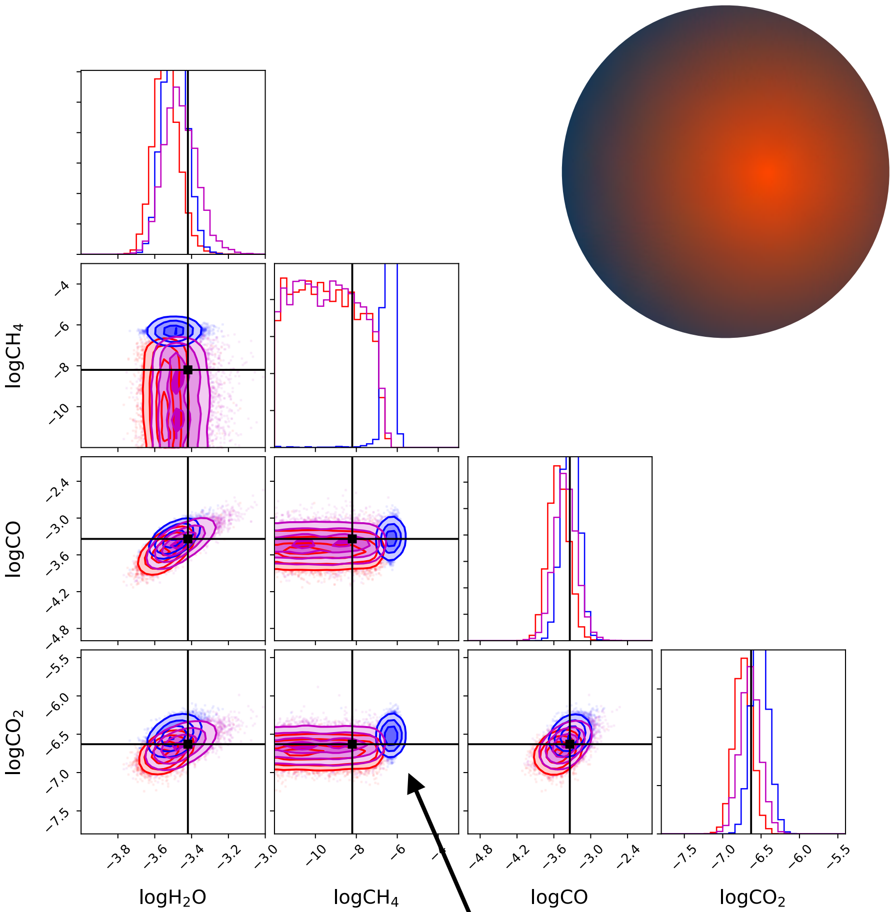
Self-Consistent chemistry

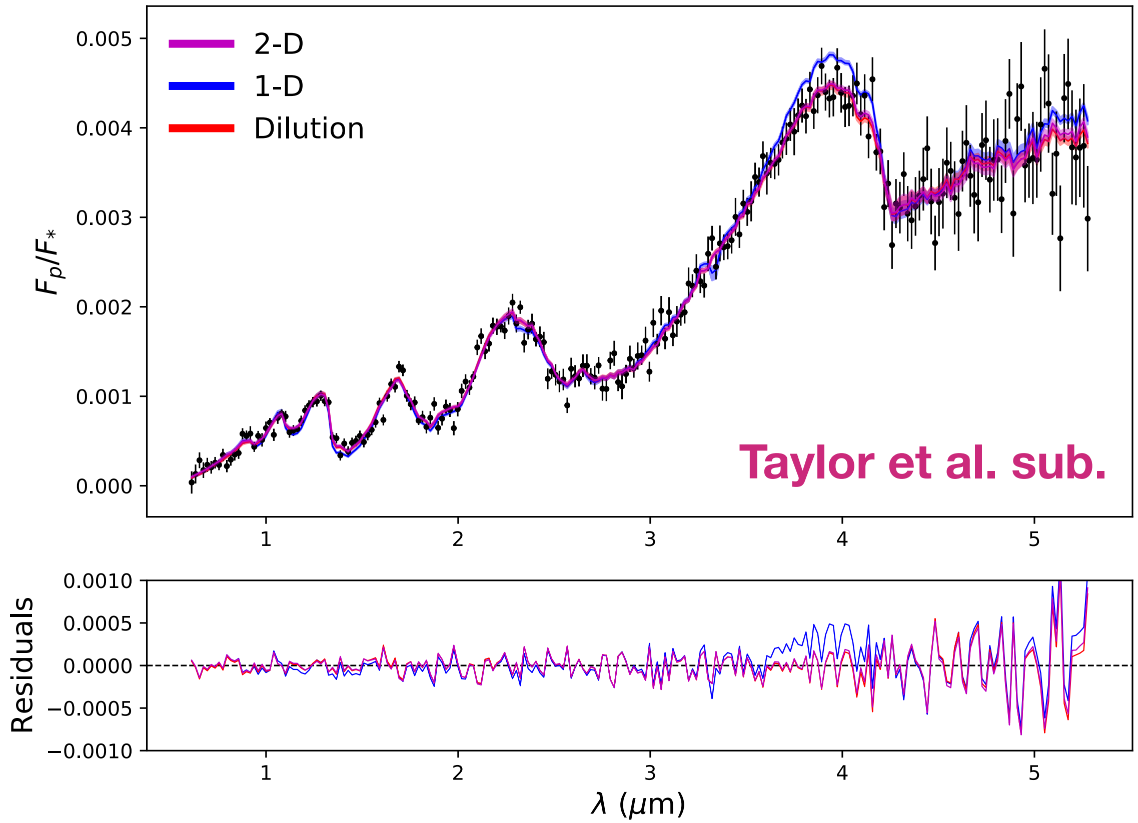
Arcangeli+2018



Solar Comp!

3D effects : non-uniform temperatures in emission



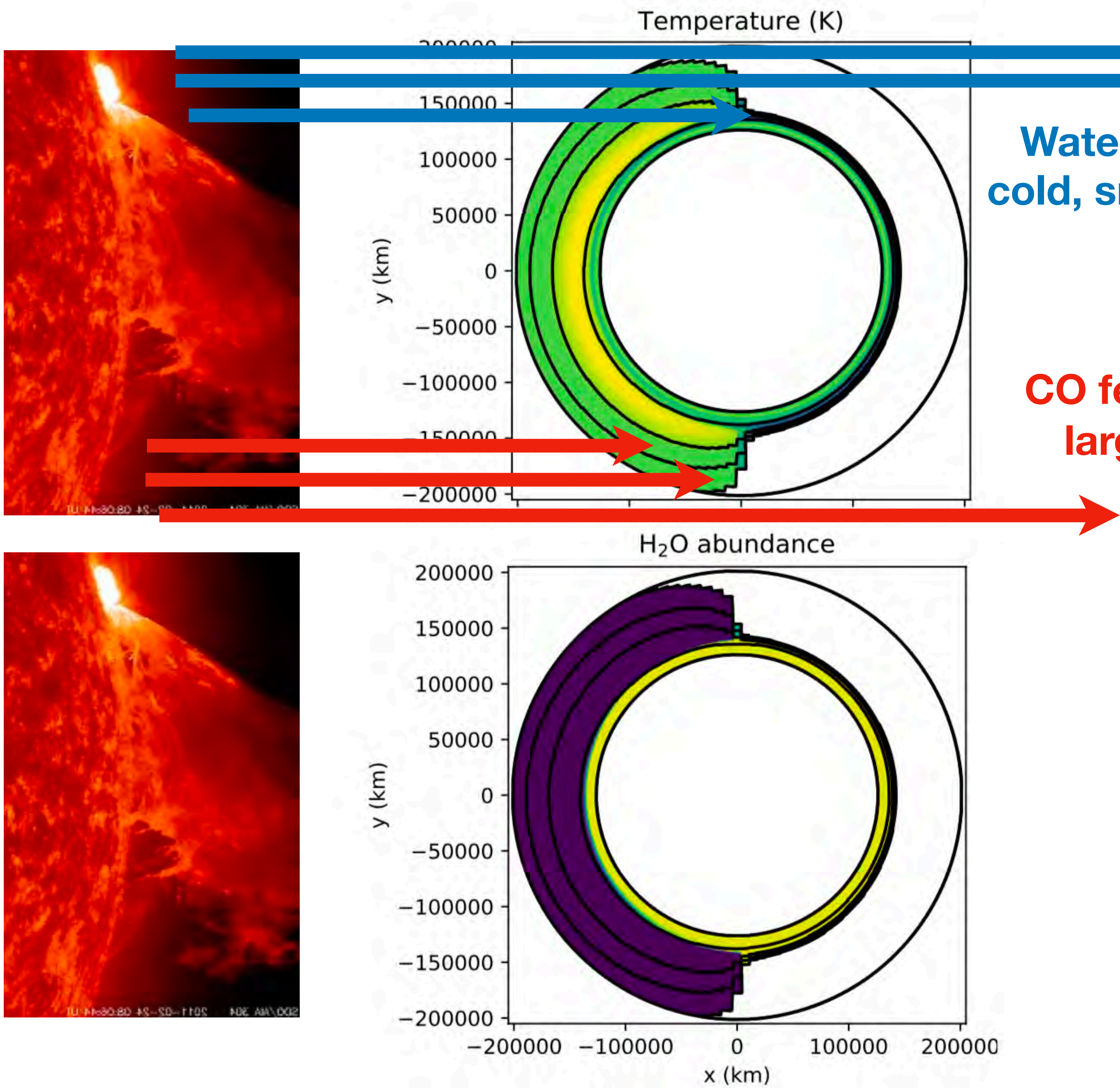


CH4 detection !

See Jake Taylor's poster !

The more molecules you add to the retrieval, the more likely you'll make a spurious detection to compensate for the lack of 3D-ness

3D effects : non-uniform temperatures in transmission



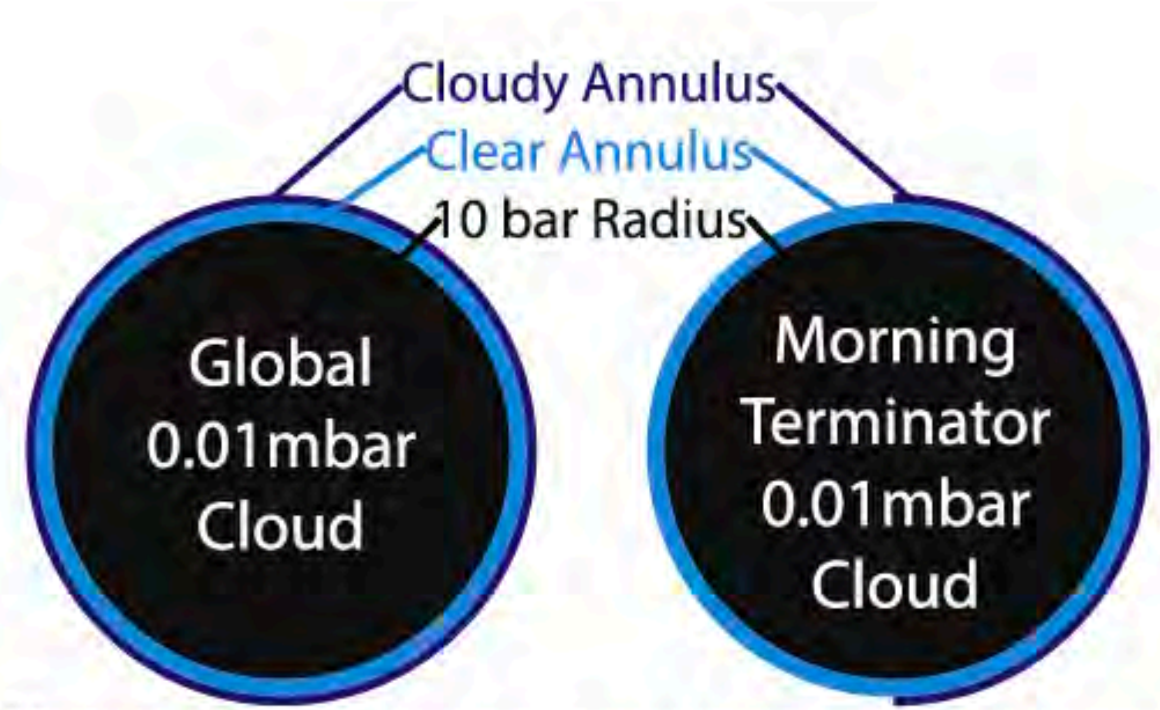
Water feature due to the cold, small scale height gas

CO feature due to the hot, large scale height gas

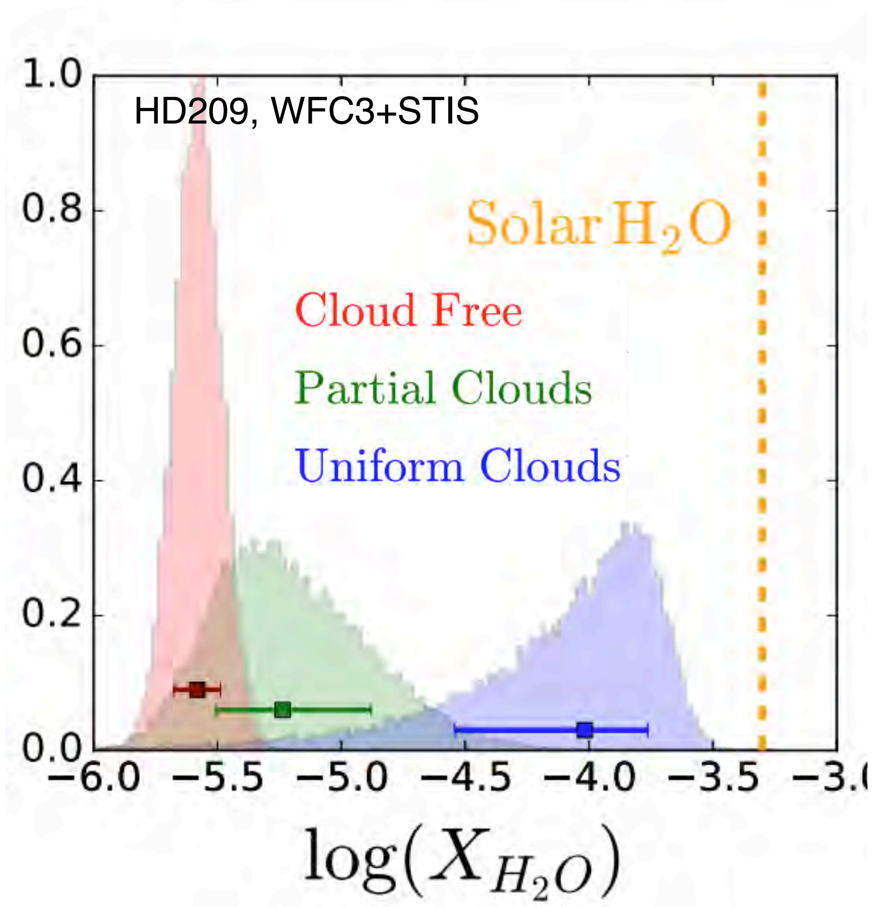
A 1D model would retrieve a carbon to oxygen ratio 100x too large !

Pluriel et al. in prep.

3D effects : non-uniform clouds

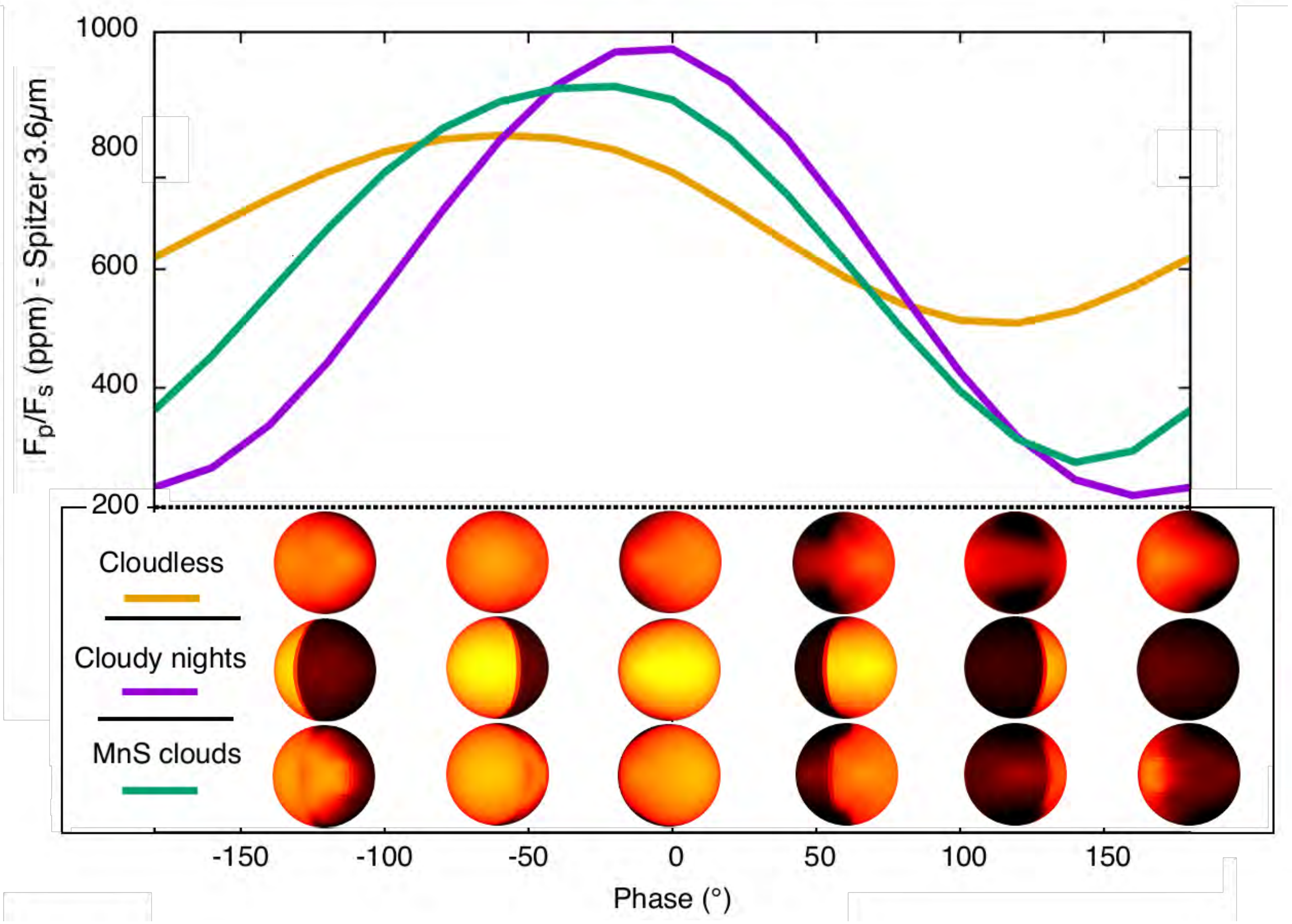


Line & Parmentier 2016; MacDonald & Madhusudhan 2017



We are precise, but not necessarily accurate !

3D effects : cloudy phase curves



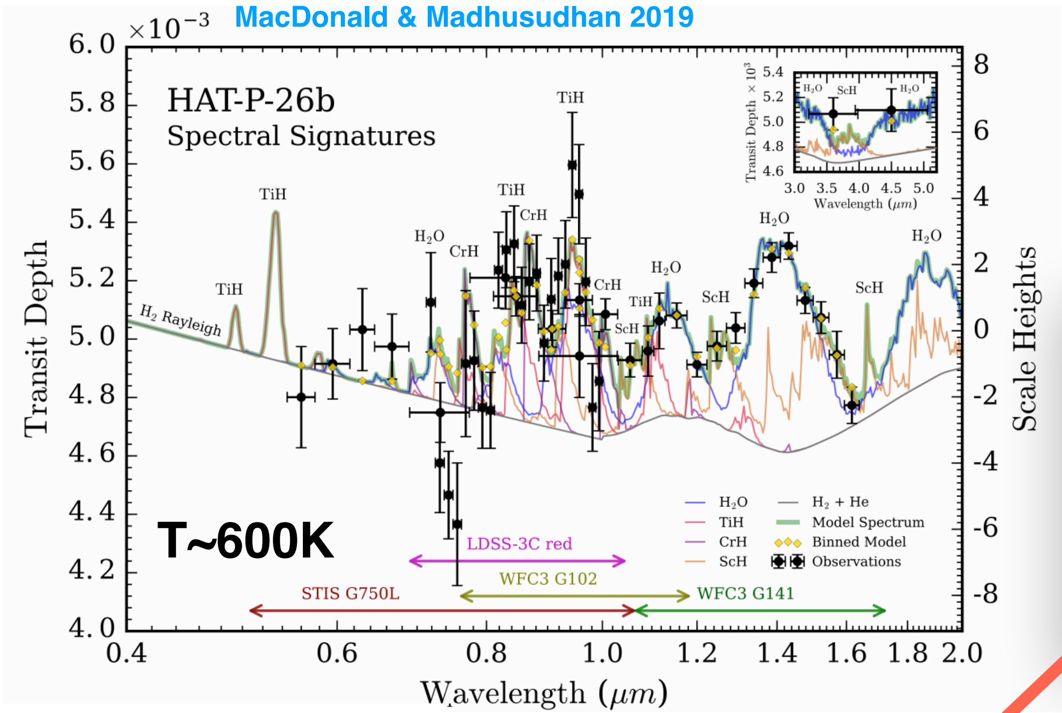
The phase curve offset does not correspond to the hot spot shift !

Clouds really matter for phase curves…

Venot et al. 2020 on ArXiV today !

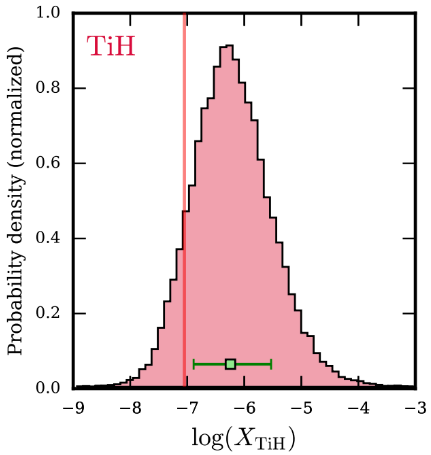
Parmentier et al. 2020 in prep.

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

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

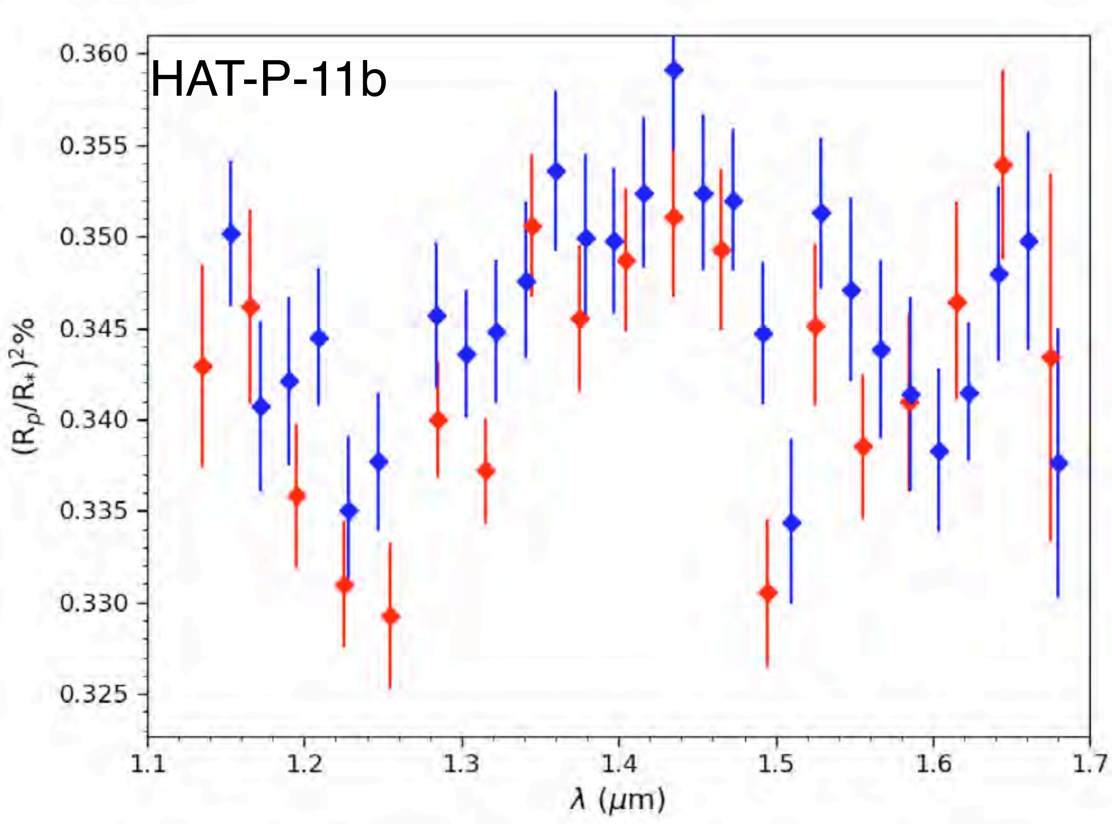


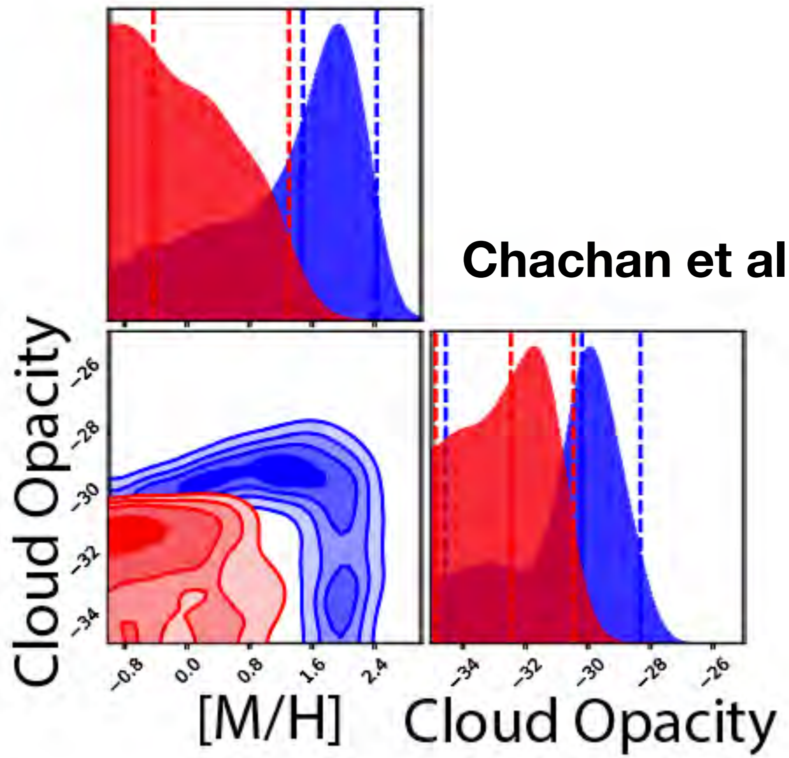
p-value<10-6

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 !

Data analysis — different analysis leads to different conclusions





Chachan et al.

Current inferences often based on the shape of the spectrum — which is not very robust — rather than the size of the features

That can lead to good precisions but bad accuracy !

Conclusions

Current status

Detection is (kind of) easy, quantification is hard !

It's easy to get precise but not accurate solutions !

What do we need ?

Better priors on what the planets might look like !

Theoretical work — ***but we are probably not smart enough to anticipate the complexity***

Observations : ***JWST will give us the 3D understanding we need !***

ESPRESSO et al. can follow the lines during the transit !

Ariel

What will be a robust Ariel spectrum signature for all planets, ***even the low SNR ones ?***

What conclusions can we make from it ?

How do we make sure that we are precise *AND* accurate ?