

Tracing Uranus and Neptune Formation with Disequilibrium Species

T. Briand¹, V. Hue¹, O. Mousis², T. Cavalié^{3,4}, T. Benest Couzinou¹,
A. Schneeberger⁵, and M. D.Hofstadter⁶

1. Aix-Marseille Université, CNRS, CNES, Institut Origines, LAM, Marseille

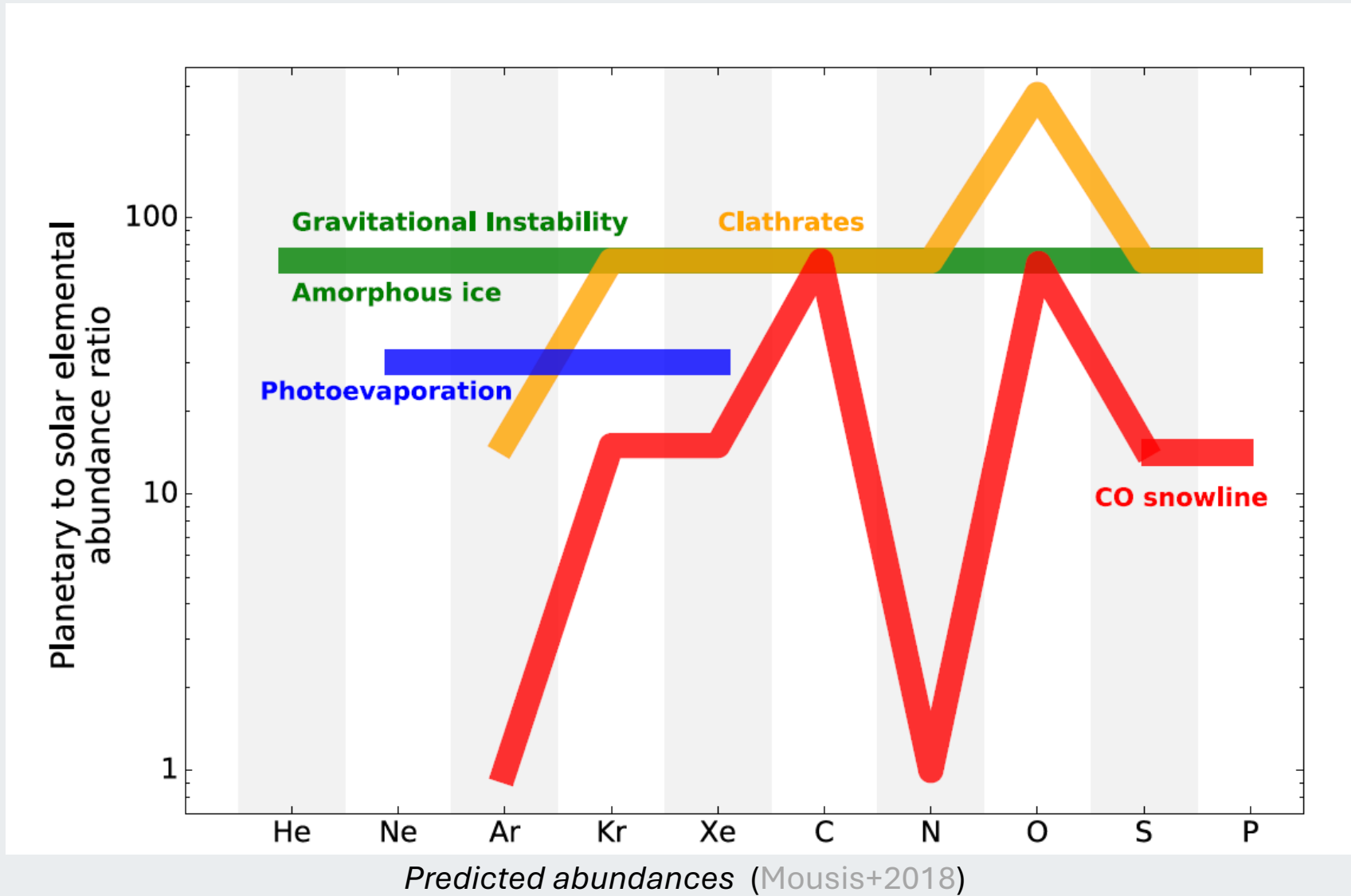
2. Solar System Science and Exploration Division, Southwest Research Institute, 1301 Walnut St, Ste 400, Boulder, CO, USA

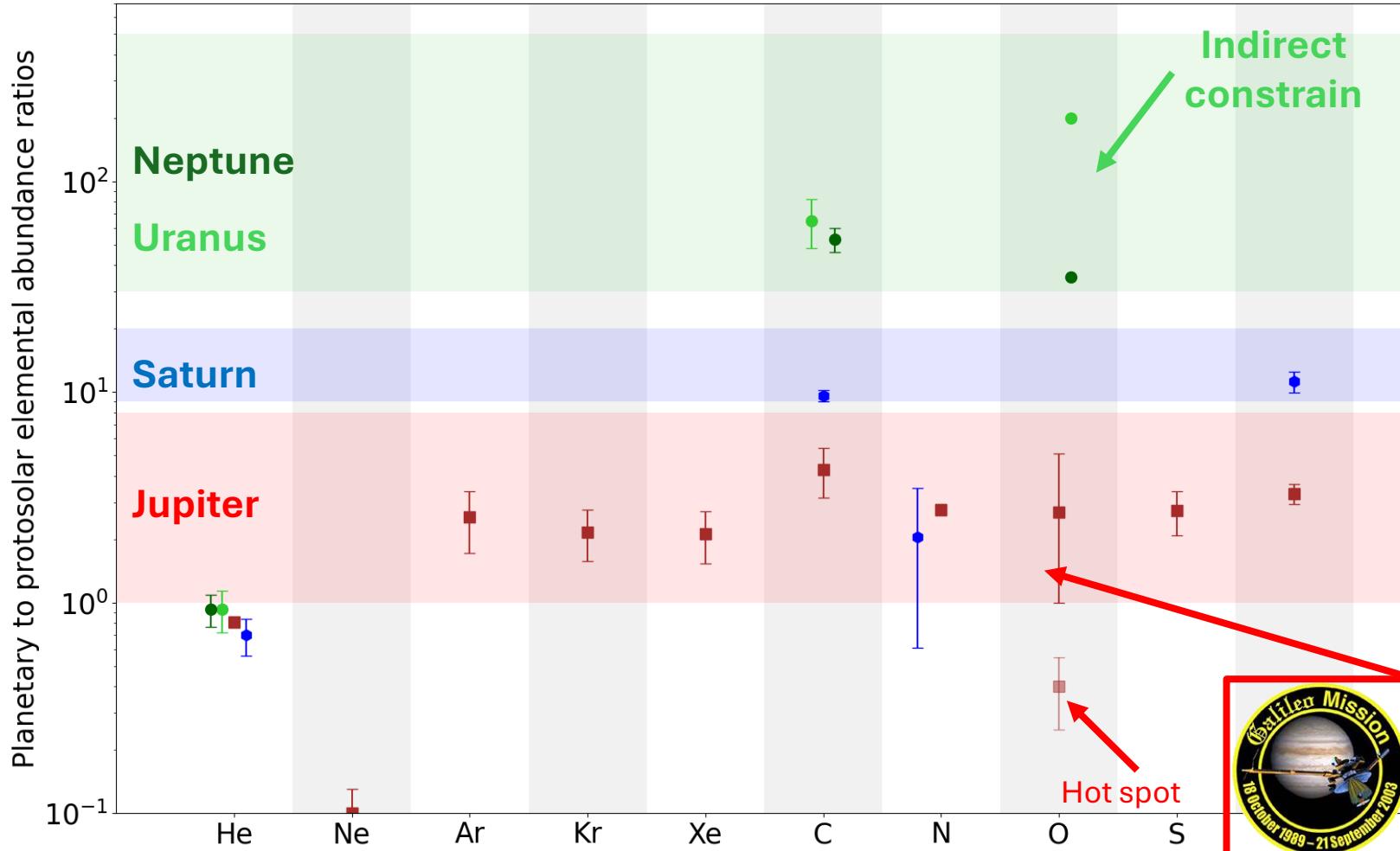
3. Laboratoire d'Astrophysique de Bordeaux, Univ. Bordeaux, CNRS, B18N, allée Geoffroy Saint-Hilaire, 33615 Pessac

4. LIRA, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, Université Paris Cité, 5 place Jules Janssen, 92195 Meudon, France

5. Astronomy & Astrophysics Section, School of Cosmic Physics, Dublin Institute for Advanced Studies, 31 Fitzwilliam Place, Dublin D02 XF86, Ireland

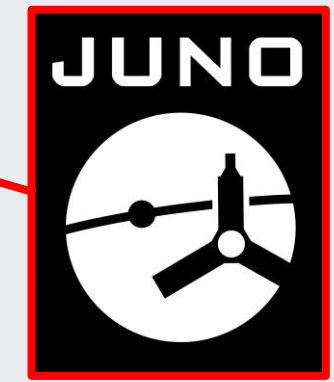
6. Space Science Institute, 4765 Walnut Street, Suite B, Boulder, CO, USA

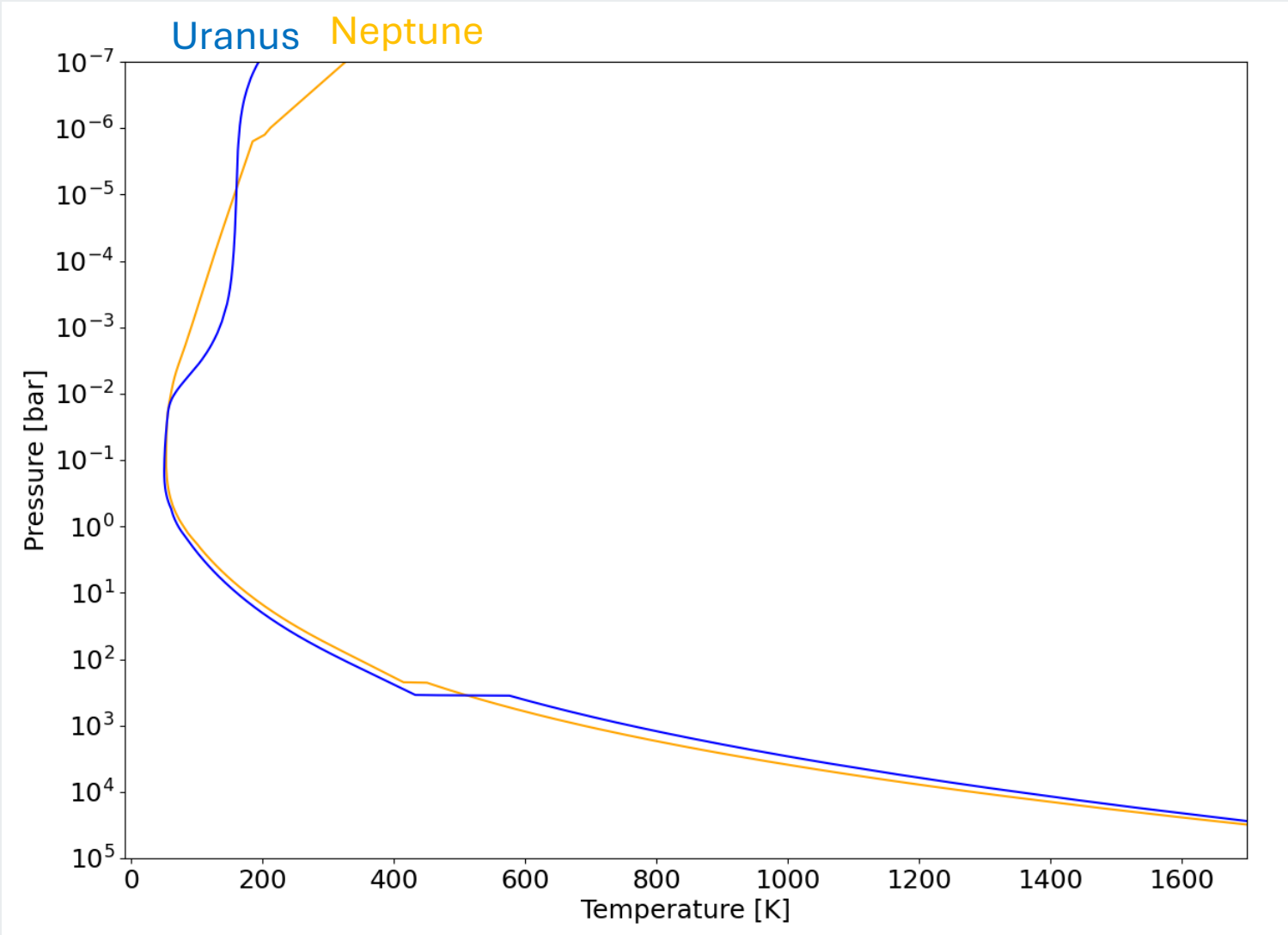


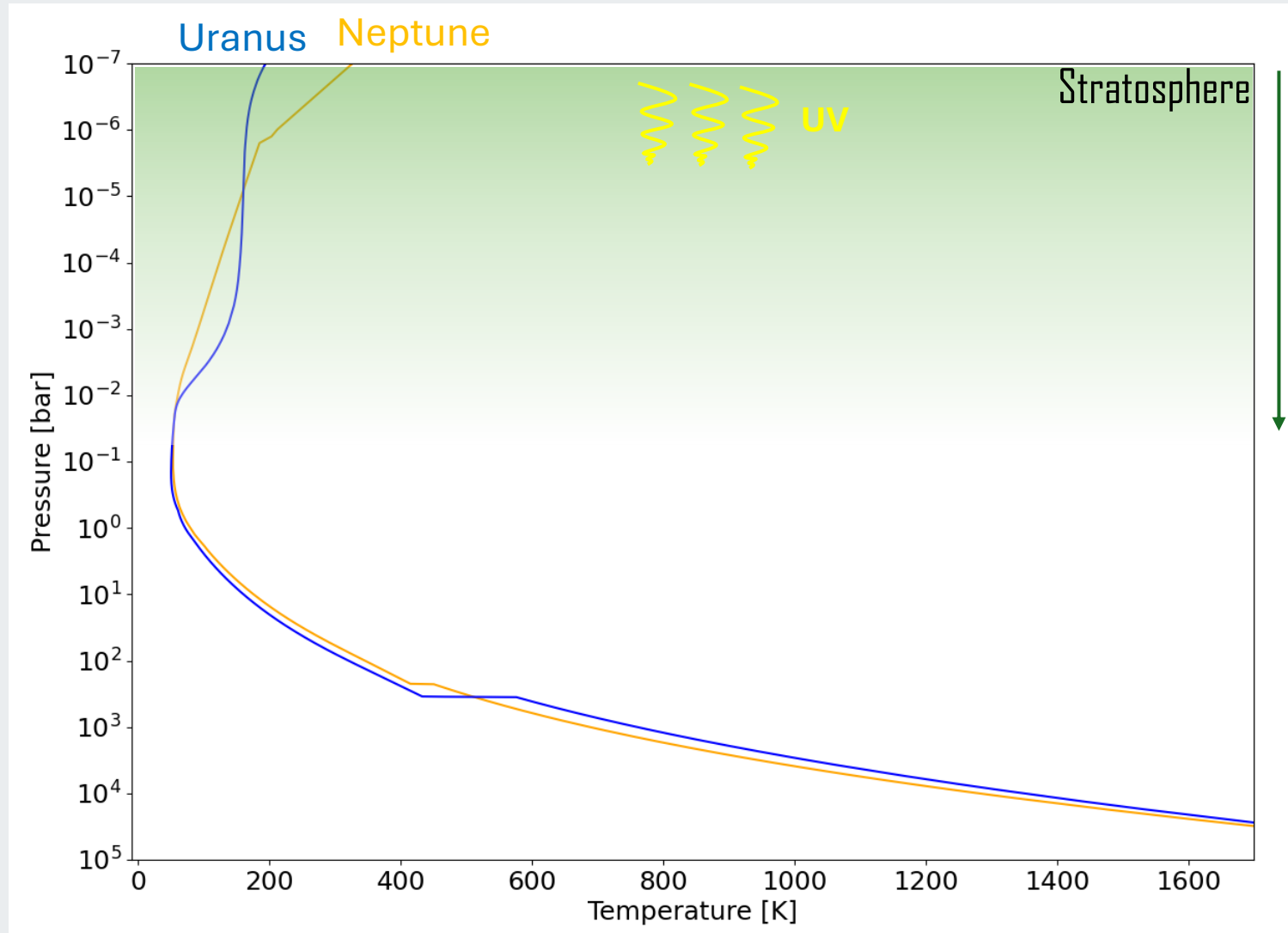


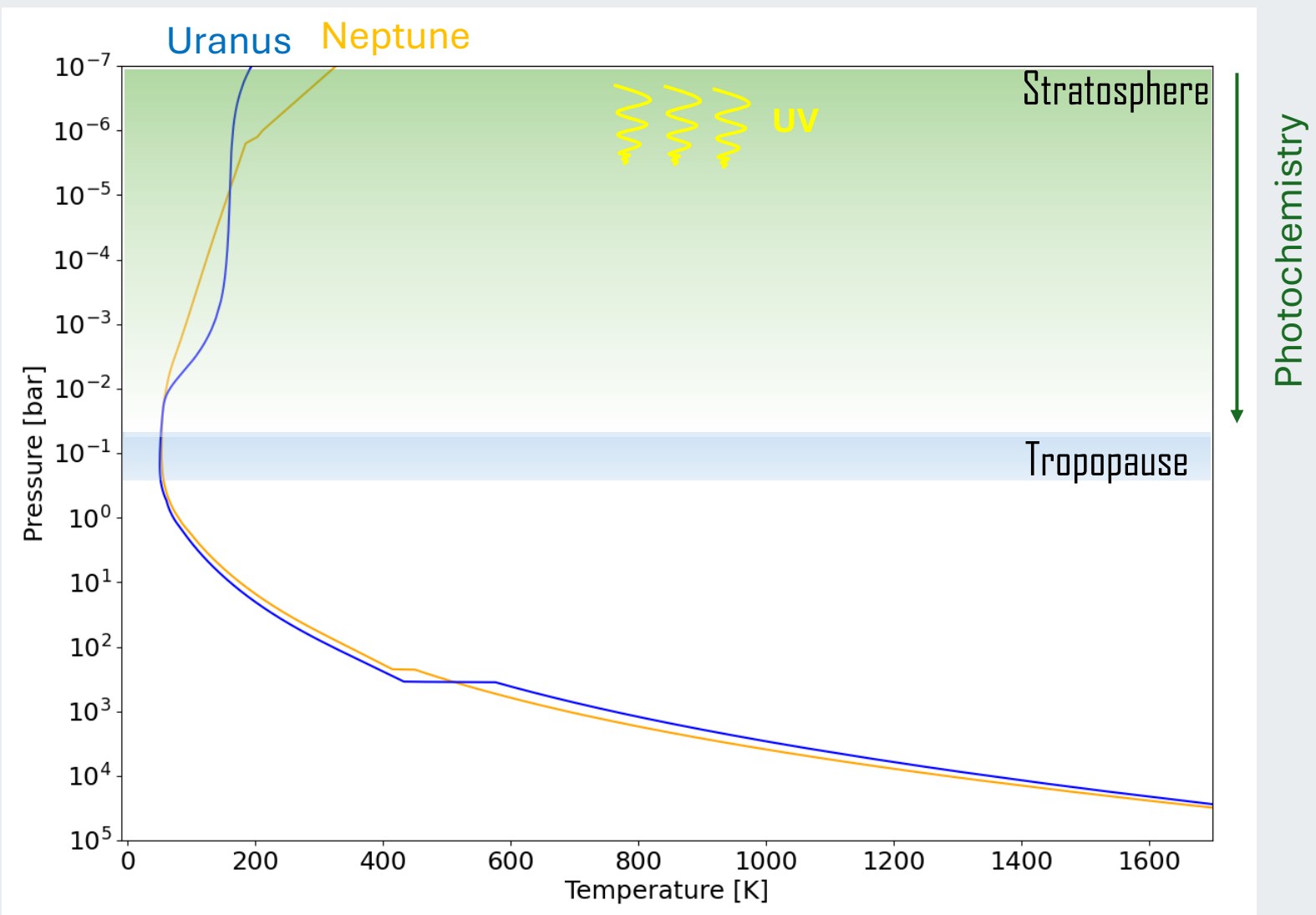
Observed abundances (updated from Mousis+2018)

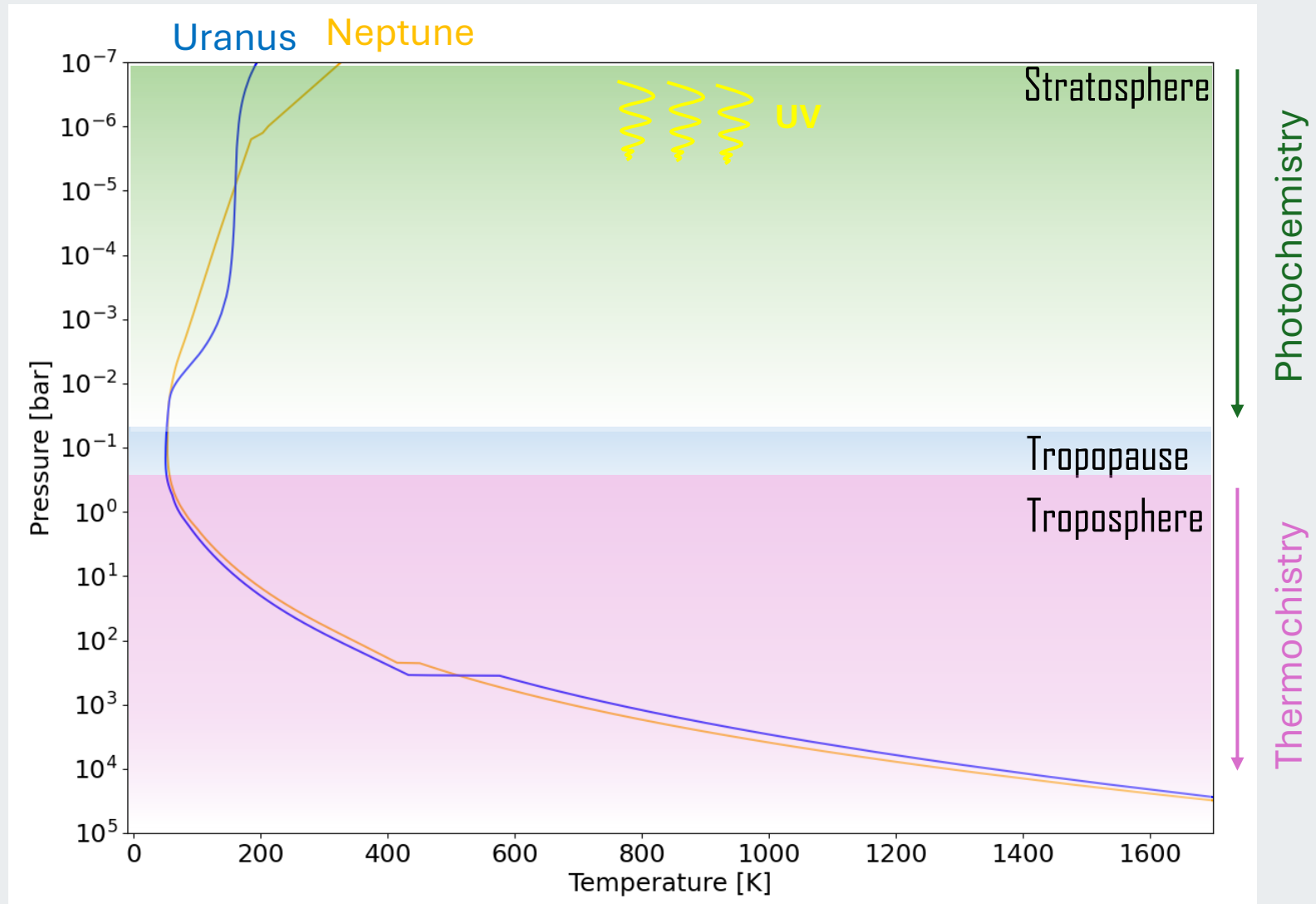
- Single Voyager 2 flyby late 80s
- **Uranus Orbiter and Probe (UOP)** mission 2040s ?

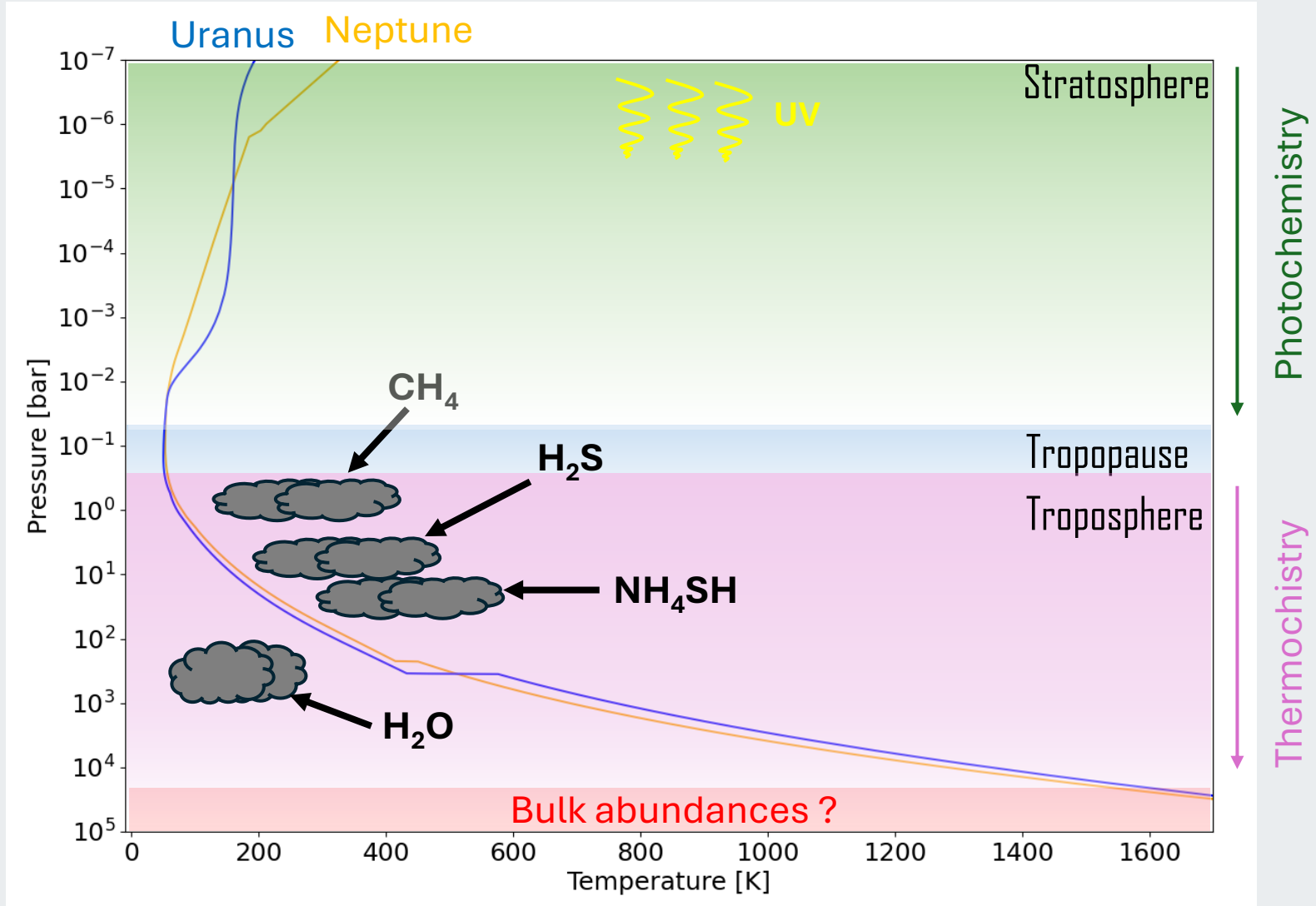


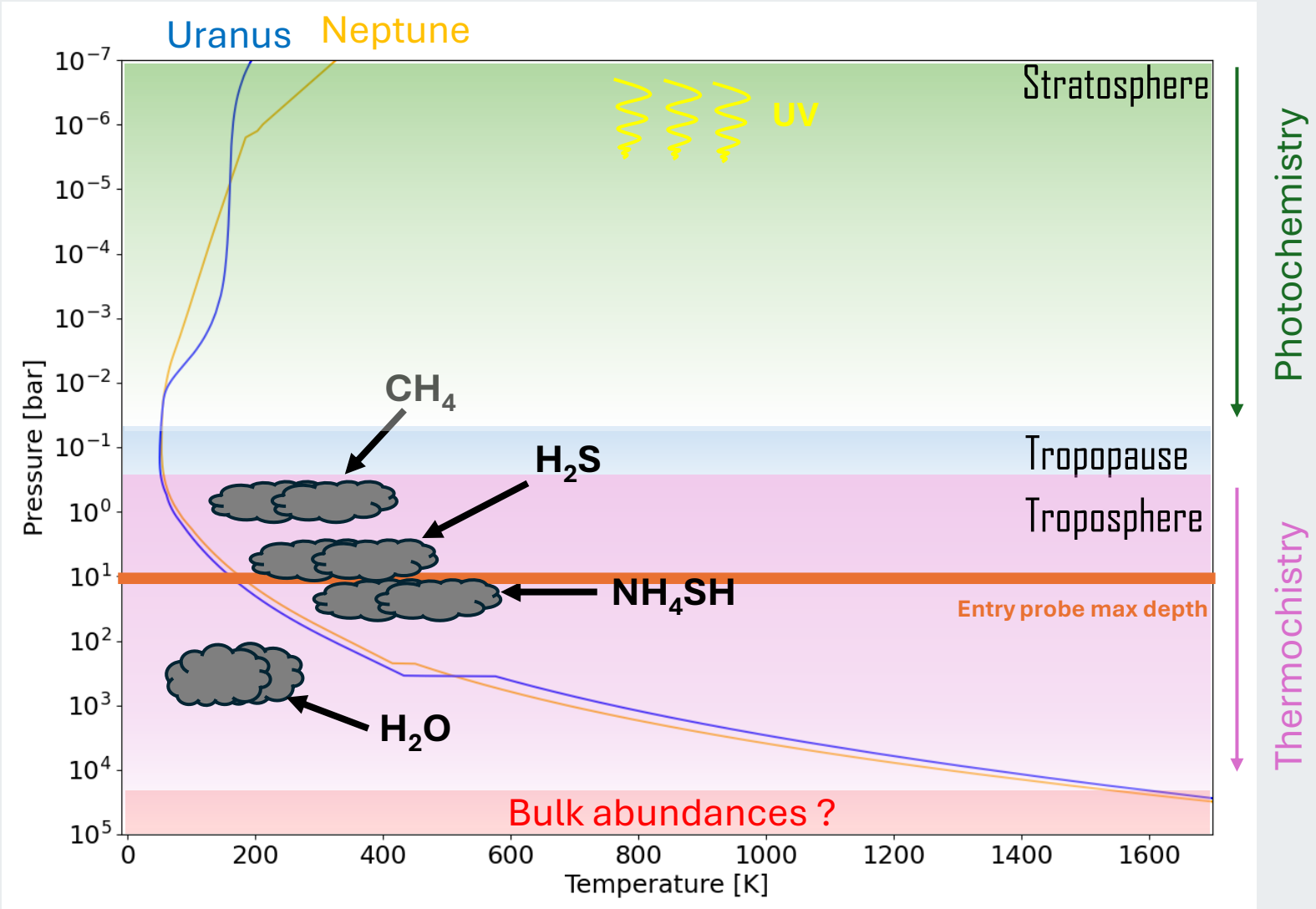


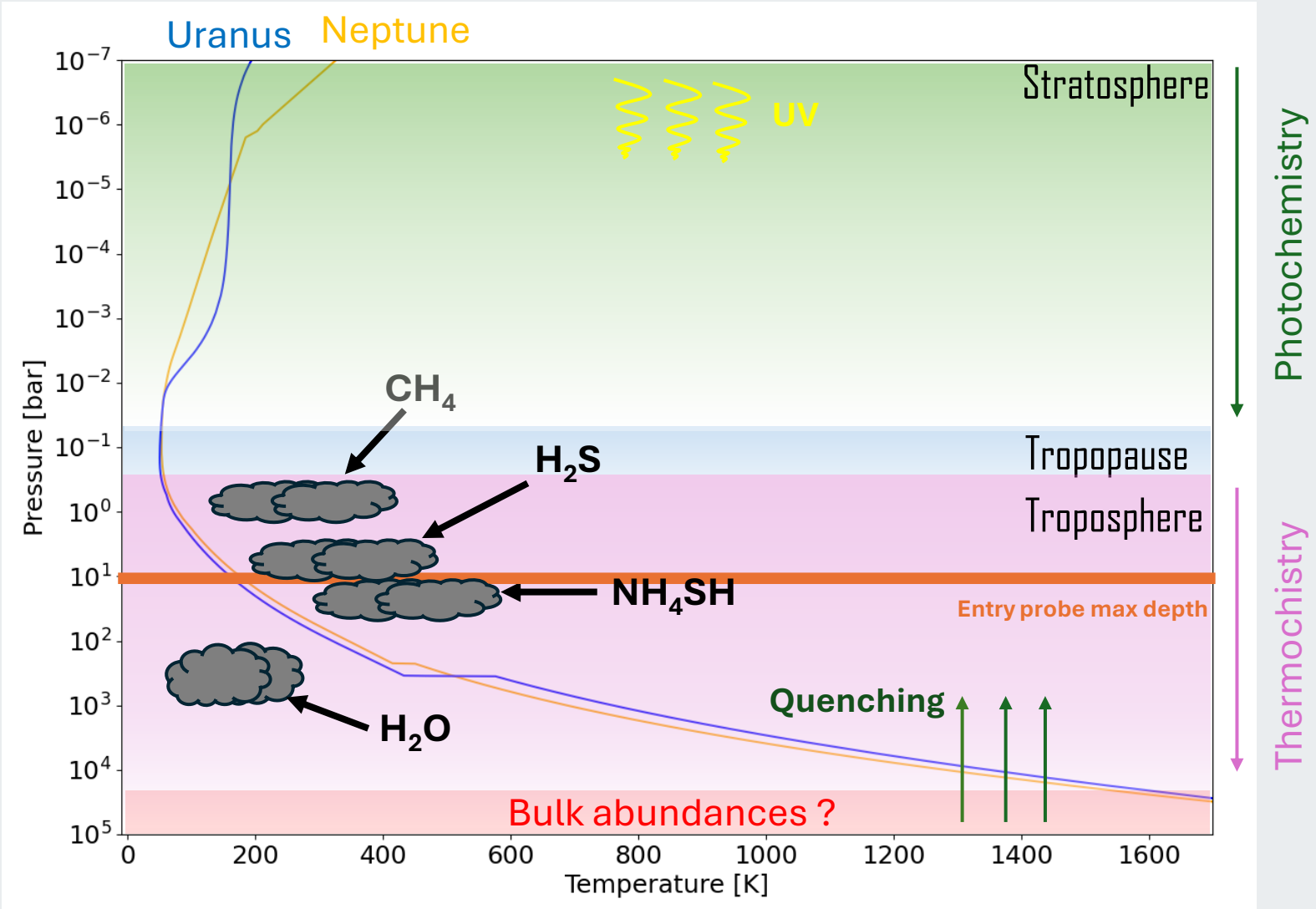


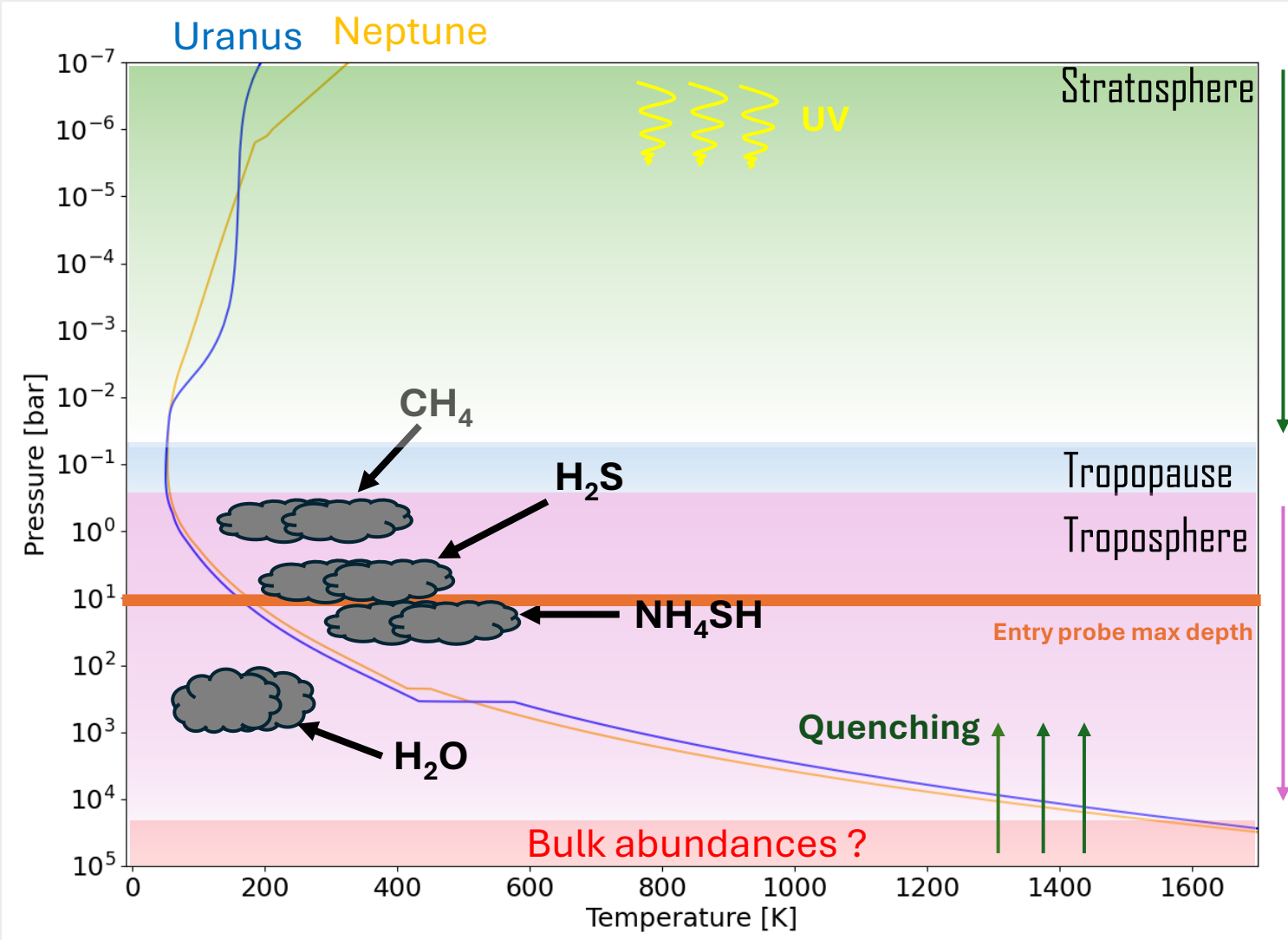




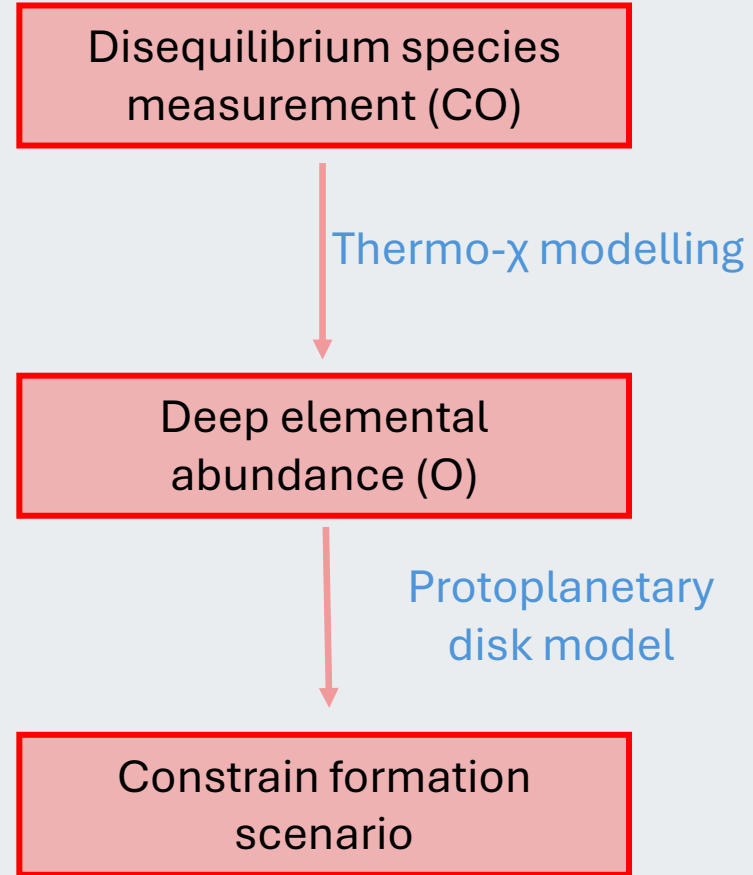


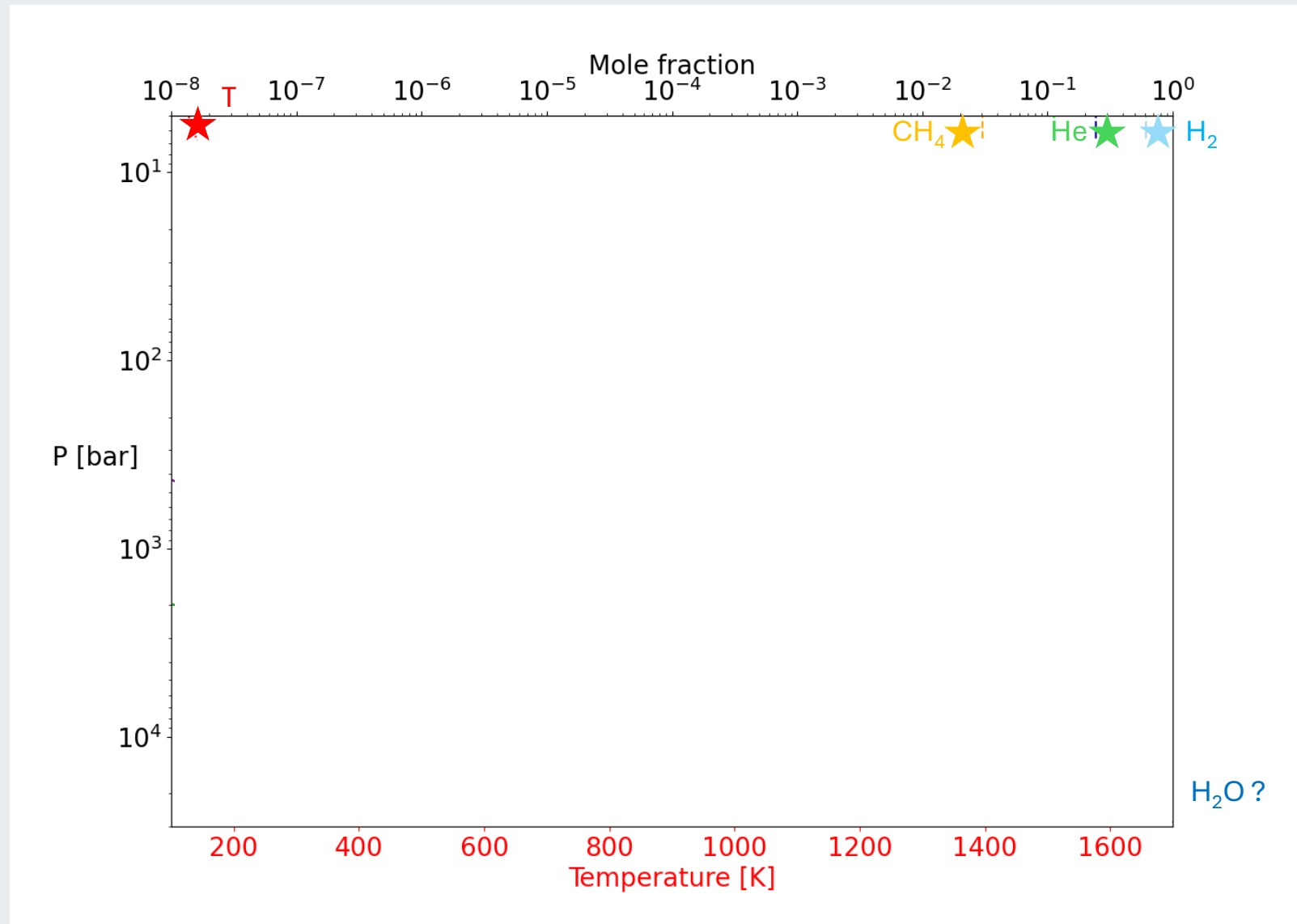


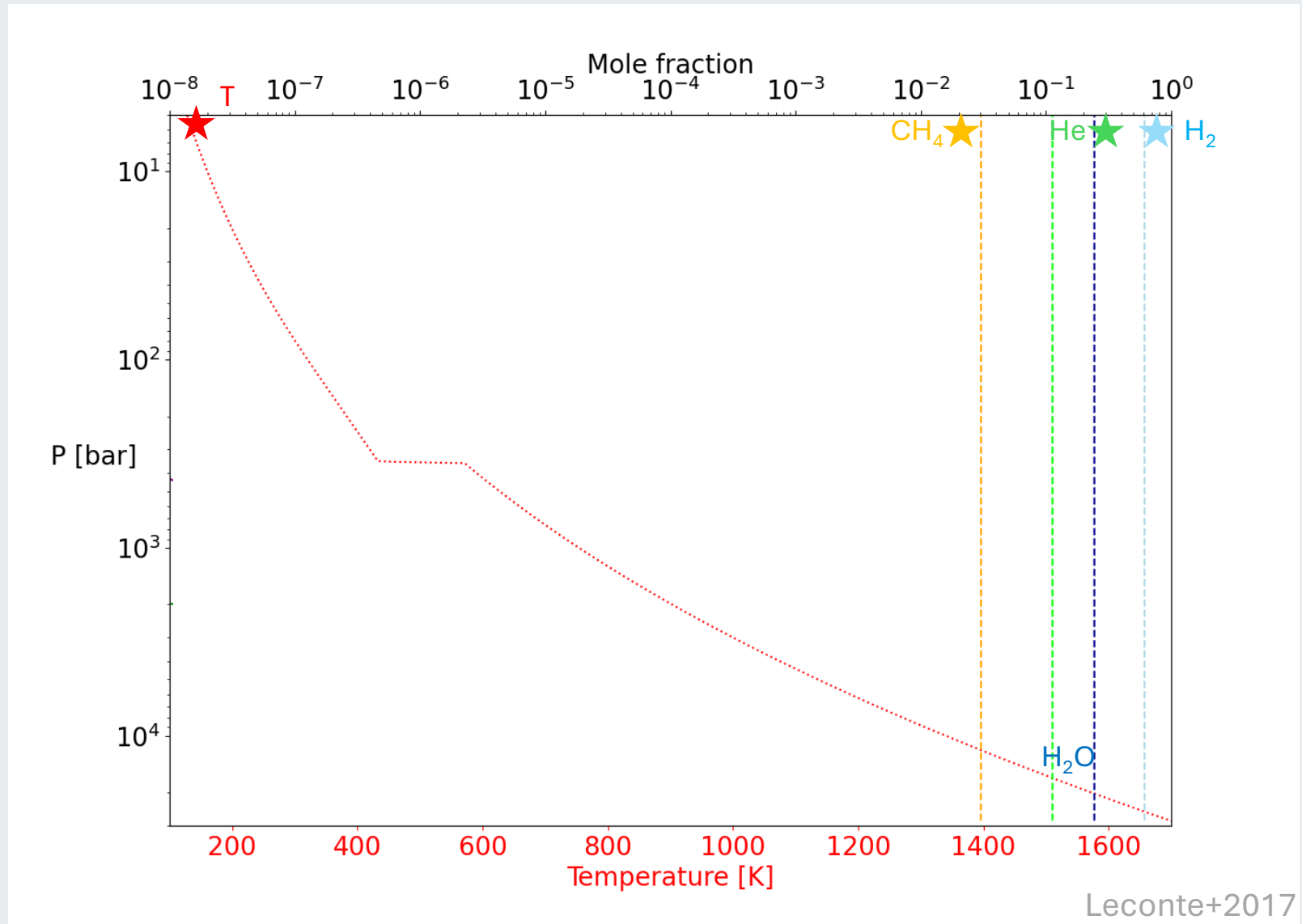




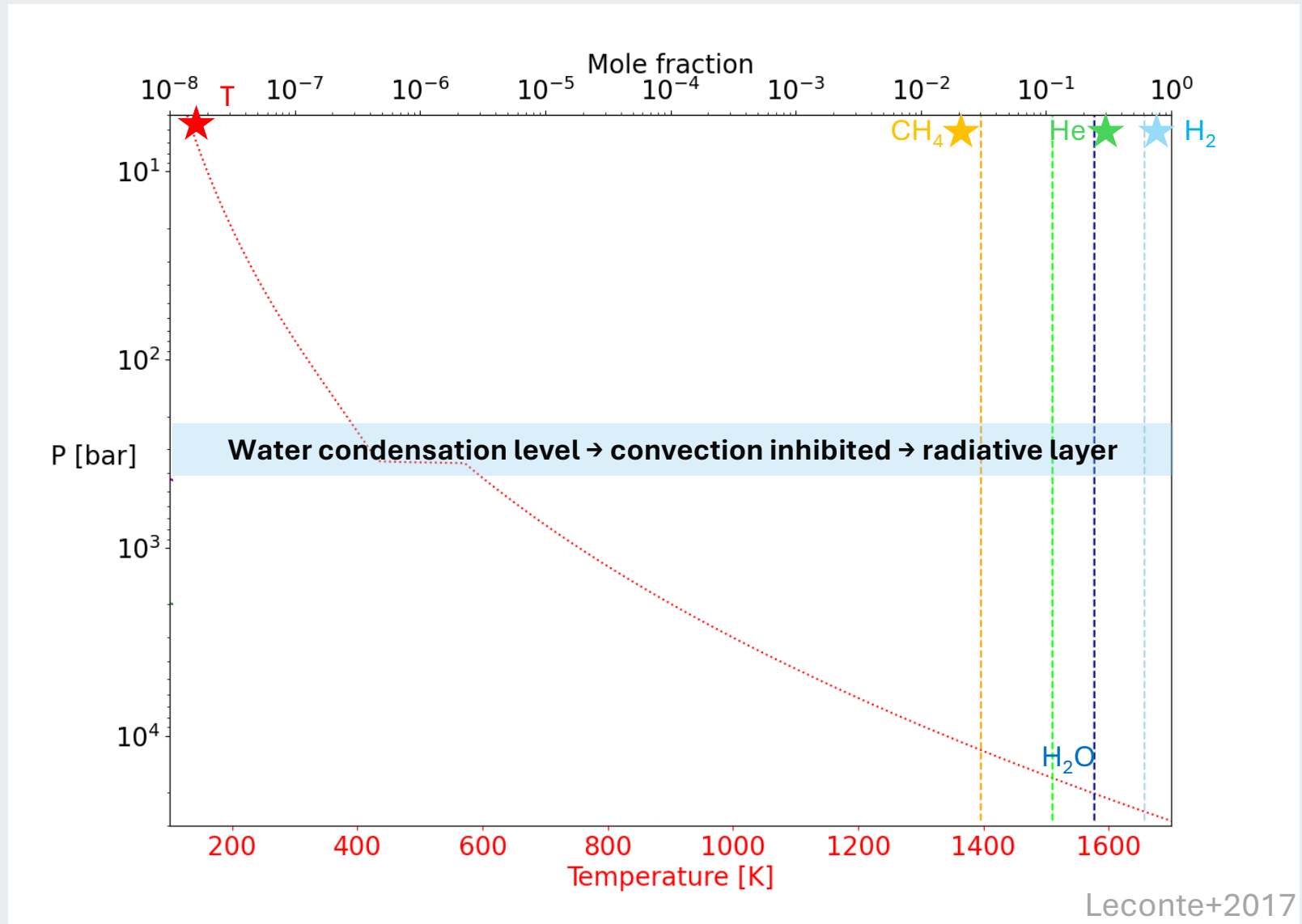
Scope of the project :

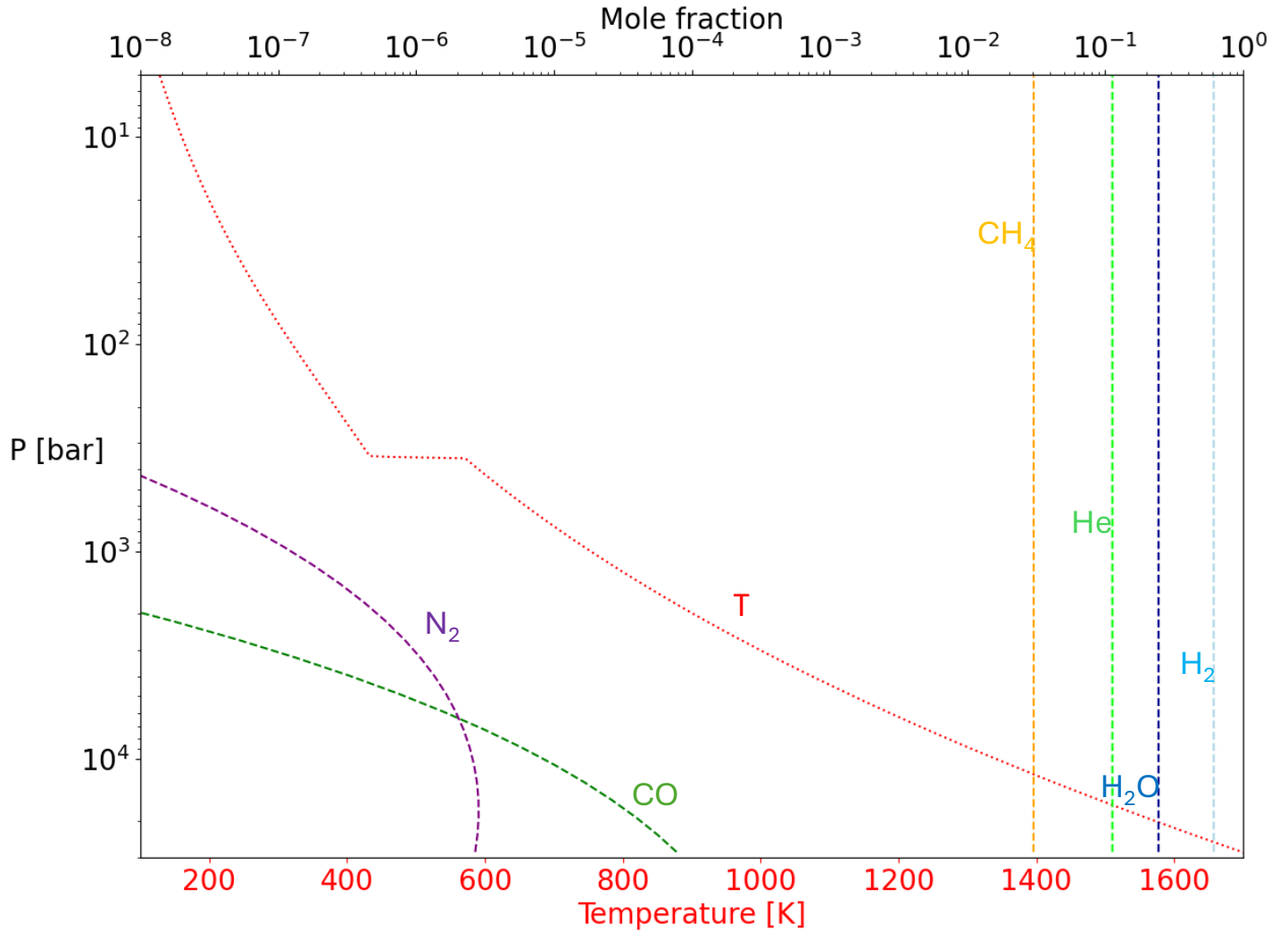






Leconte+2017



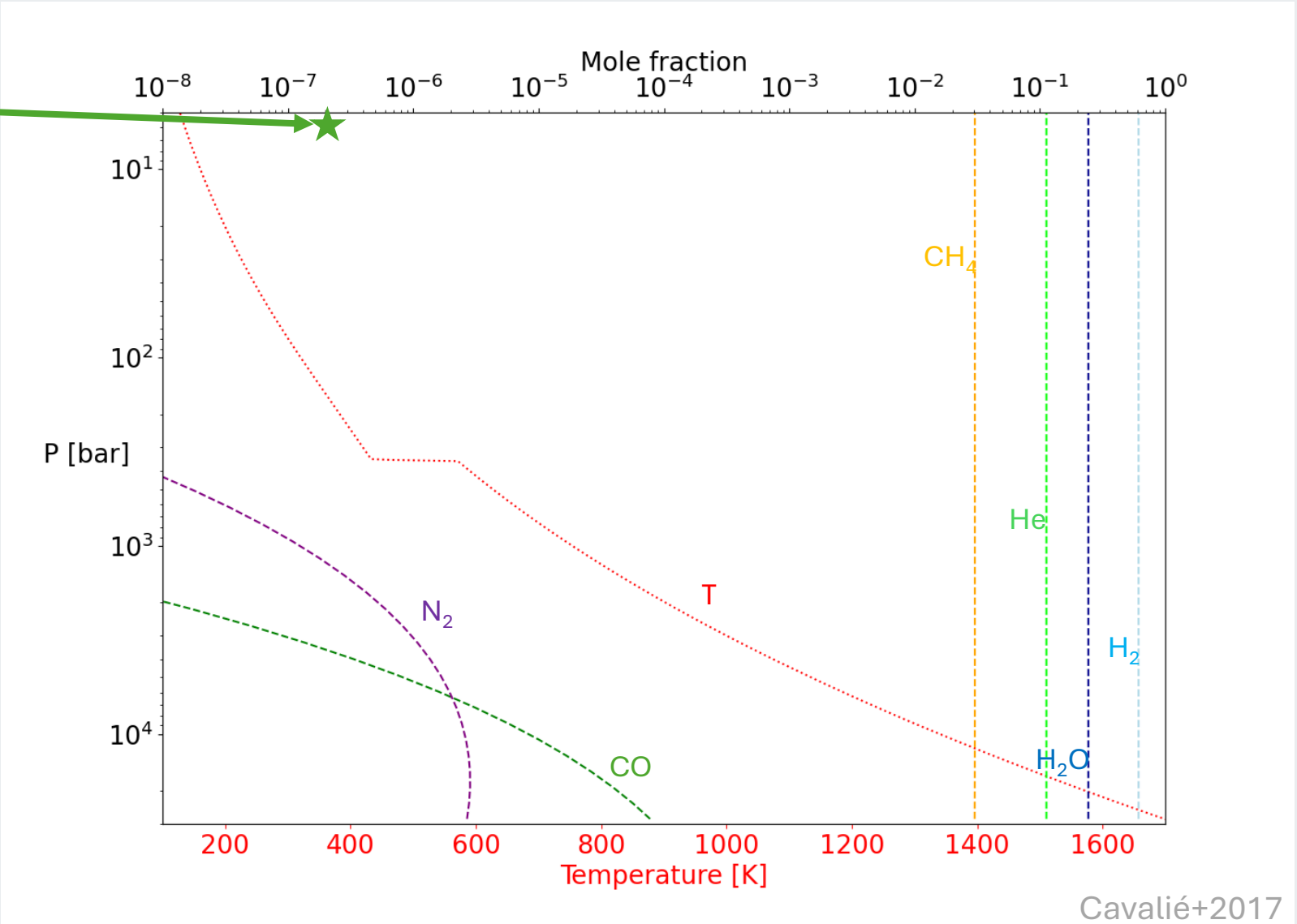


Cavalié+2017

In the deep atmosphere
Thermochemical equilibrium holds
 $\text{CO} + 3\text{H}_2 \rightleftharpoons \text{CH}_4 + \text{H}_2\text{O}$

In the upper atmosphere
 Measured CO abundance
 → Target of the model

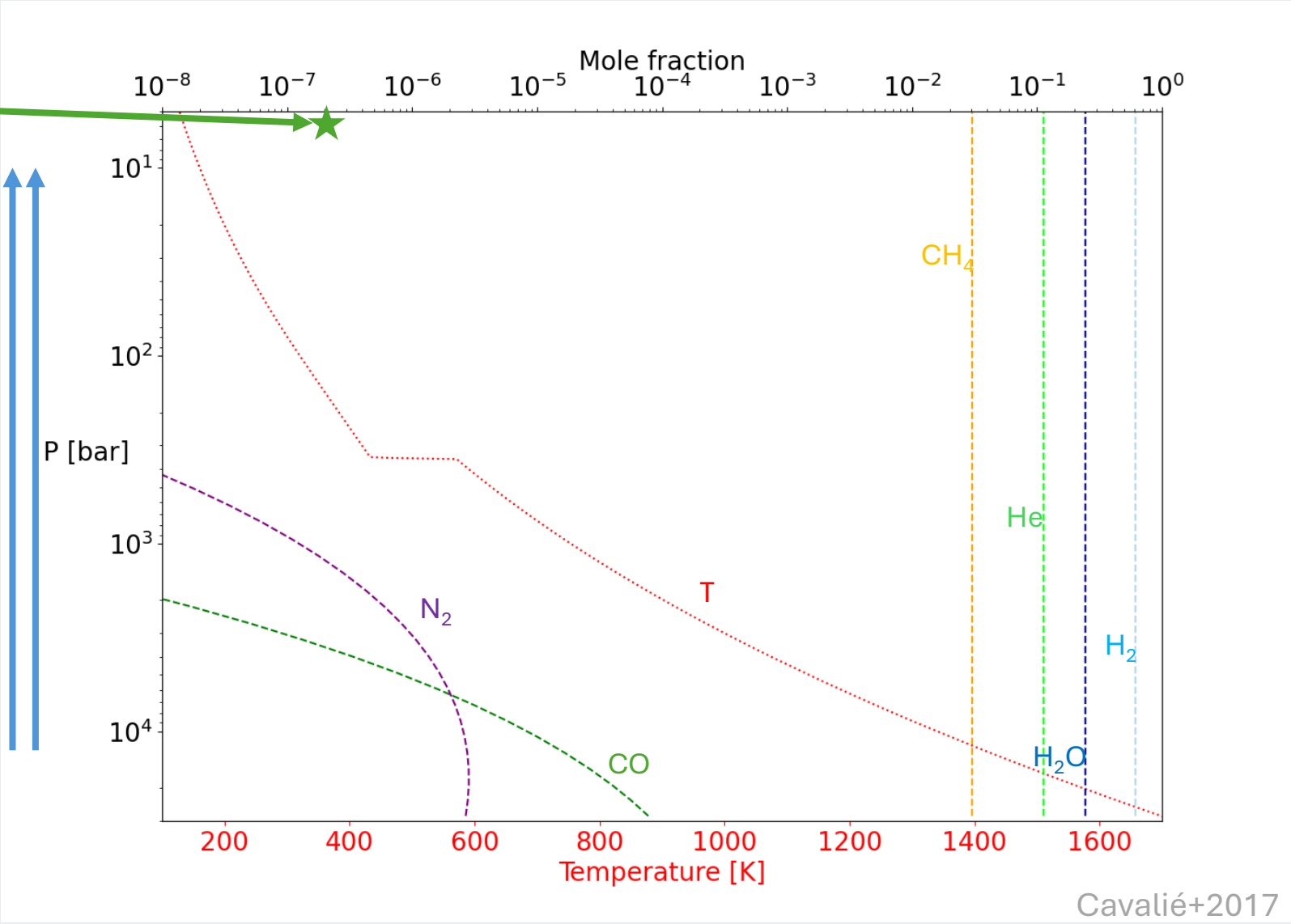
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 Free parameter K_{zz}

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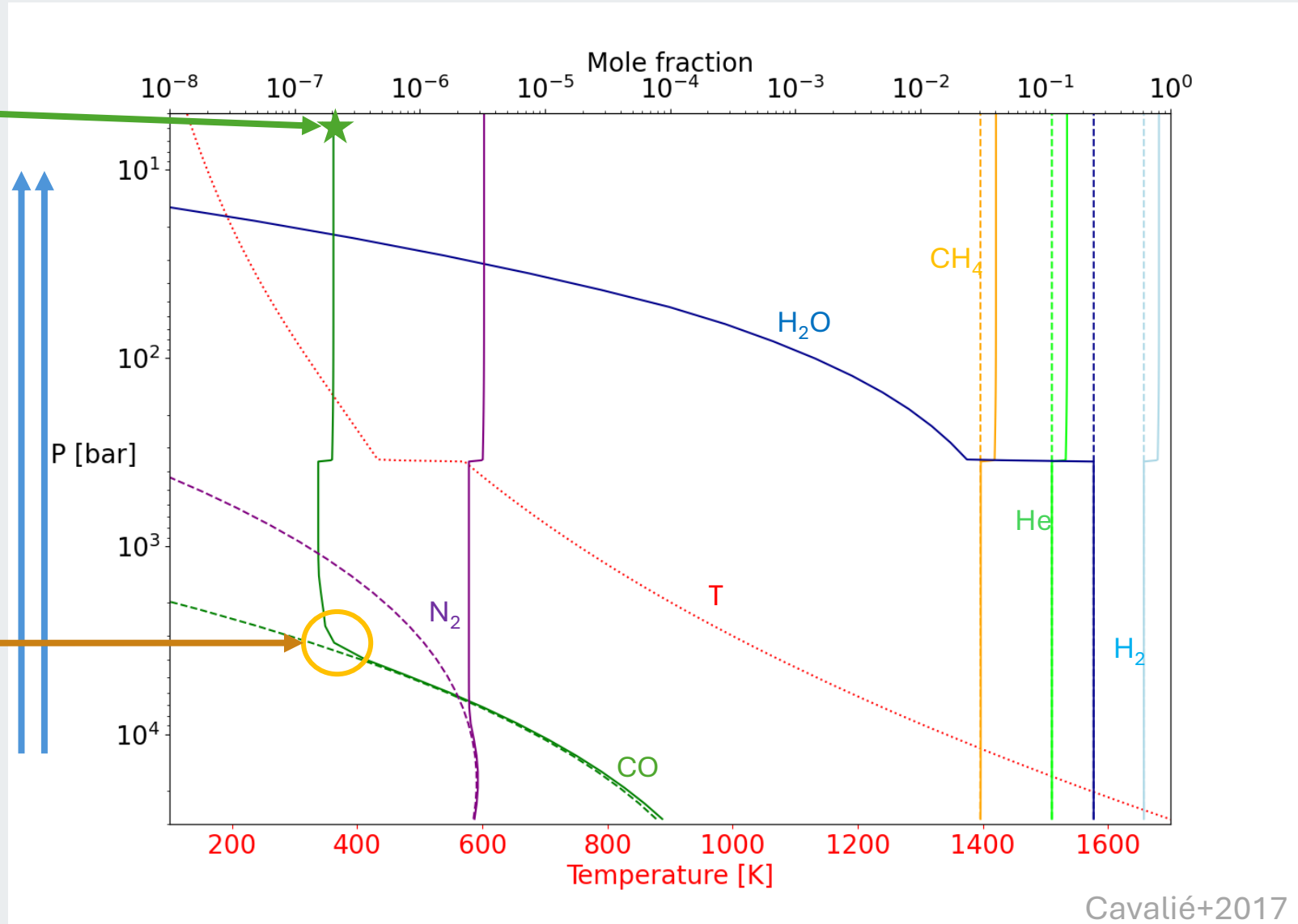
Cavalié+2017

In the upper atmosphere
 Measured CO abundance
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Vertical transport processes
 Free parameter K_{zz}

Quenching level
 Abundances leave equilibrium when :
 $\tau_{transport} < \tau_{chemistry}$

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 Thermochemical equilibrium holds
 $CO + 3H_2 \rightleftharpoons CH_4 + H_2O$



Cavalié+2017

- Predicts the vertical profile of species from :

- ★ Deep elemental abundances

- A temperature profile
 - A chemical network
 - A vertical mixing efficiency profile (K_{zz})

Accounting for uncertainties → error bar on deep oxygen abundance (O/H ratio)

- Simplified physics, more complete chemistry

- Takes advantage of disequilibrium species

- Solves the continuity equation (1D) :

$$\frac{\partial n_i}{\partial t} = P_i - L_i - \frac{\partial \Phi_i}{\partial z}$$

Concentration Production Loss Flux (vertical transport)

→ Chemical scheme : network of **reversible** reactions w/ **parametrized kinetics**

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➤ C/H/O/N schemes :

- Venot+2020 : 108 species – 1906 reactions (full)
44 species – 542 reactions (reduced)
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➤ Uncertainty propagation (MC) :

- **Modify all (forward) reaction rates simultaneously**

$$k_f'(T) = \exp[k_f(T) + \ln(F(T)) \times \epsilon]$$

Modified rate Nominal rate Uncertainty factor Random draw from std normal distribution

- Compute $k_r'(T)$ from $k_f'(T)$
- Run **1000 times**, store results

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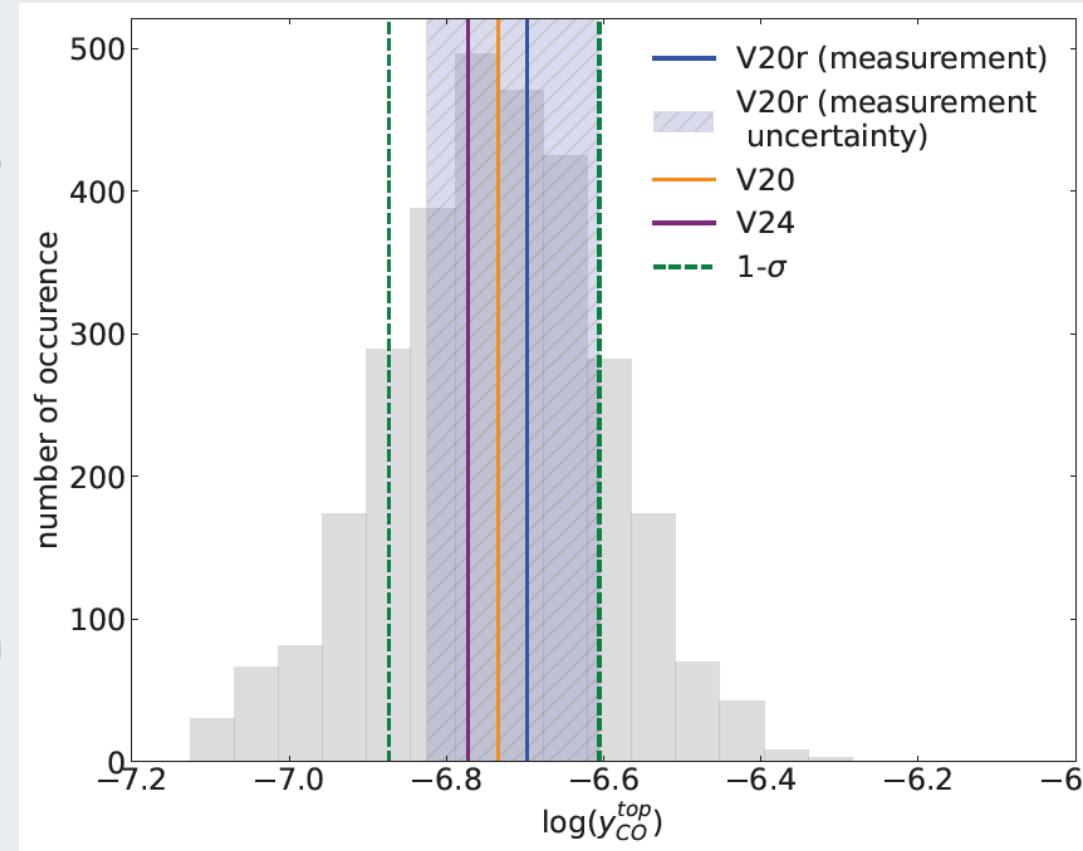
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Modified rate (blue arrow) = $k'_f(T)$
 Nominal rate (orange arrow) = $k_f(T)$
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- **Feedback on O/H uncertainty**



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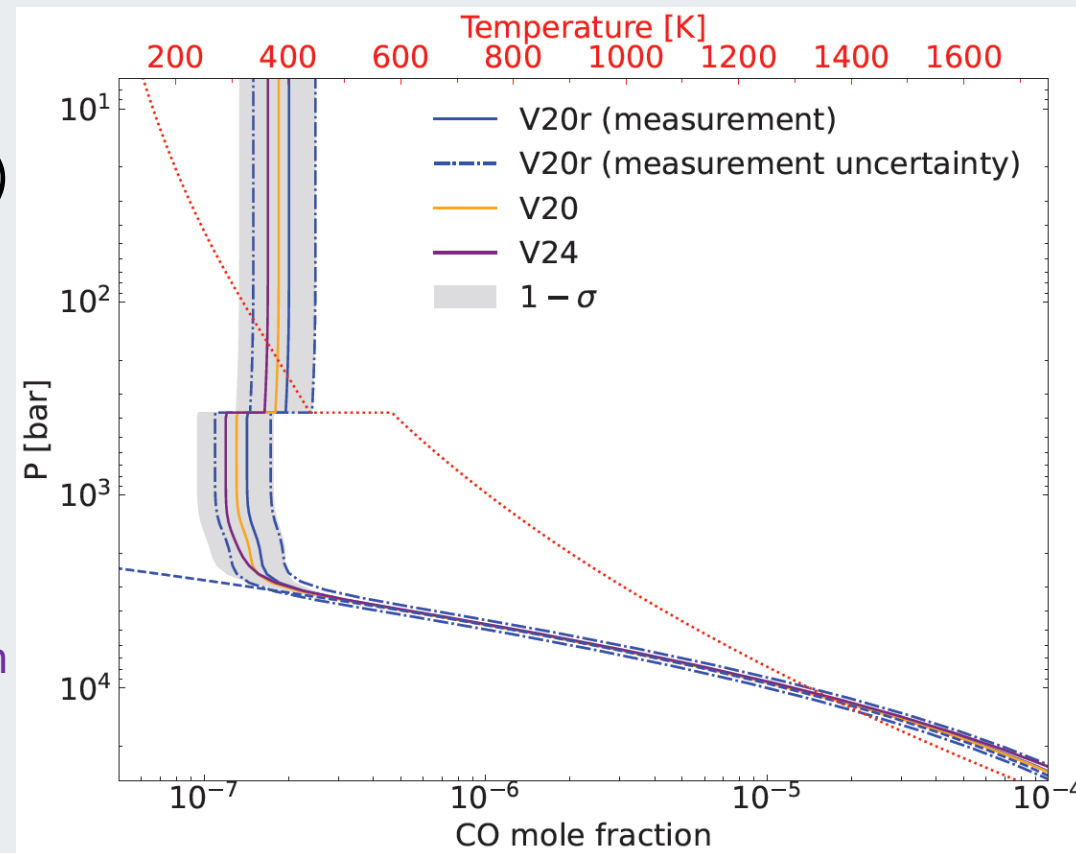
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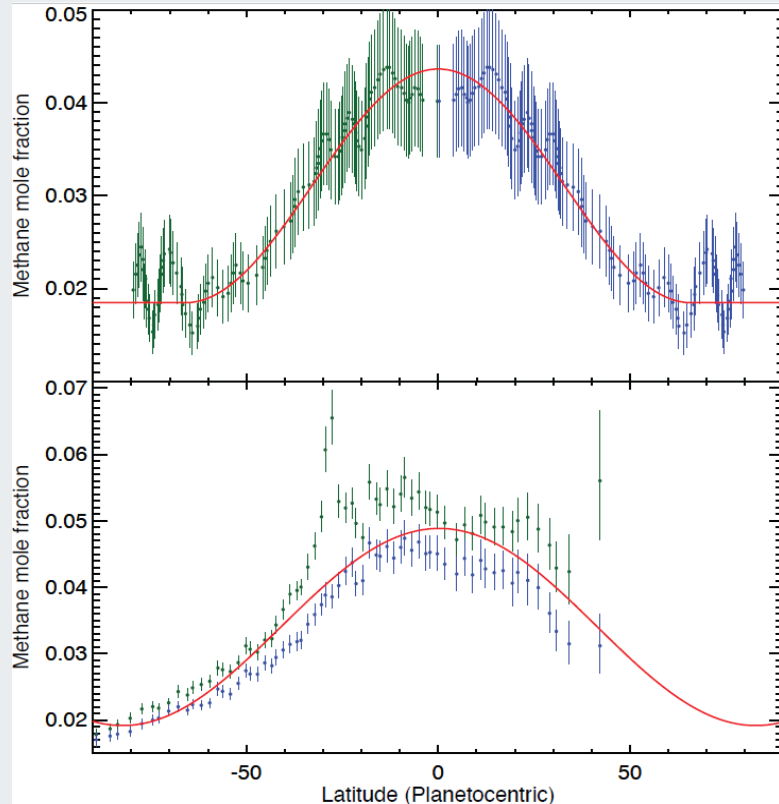
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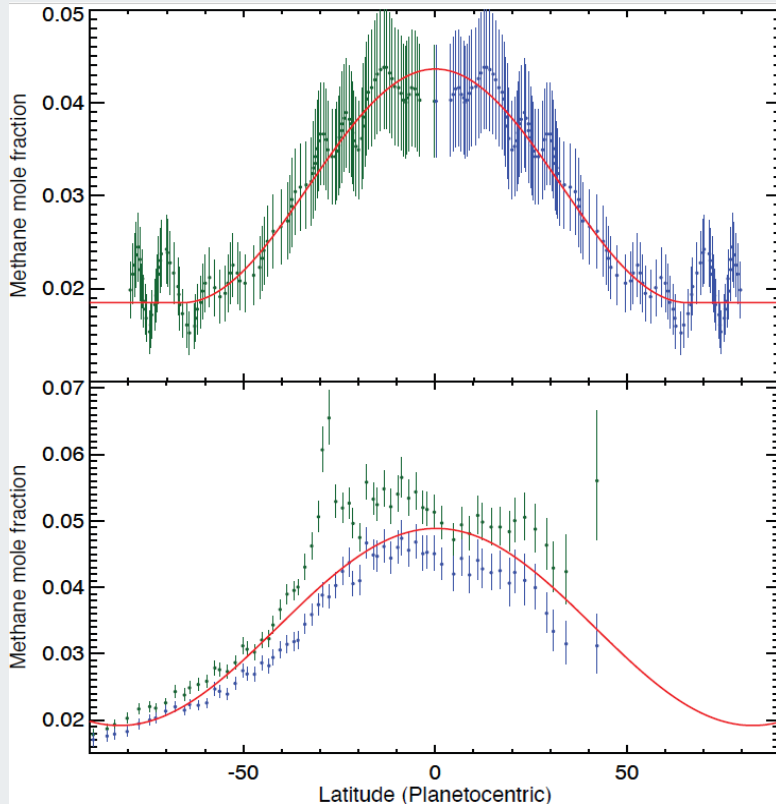


→ Proceed with V20r

- Meridional temperature structure :
 - $y_{CH_4}^{top}$: **obs.** equator (~4%) → pole (~2%) depletion

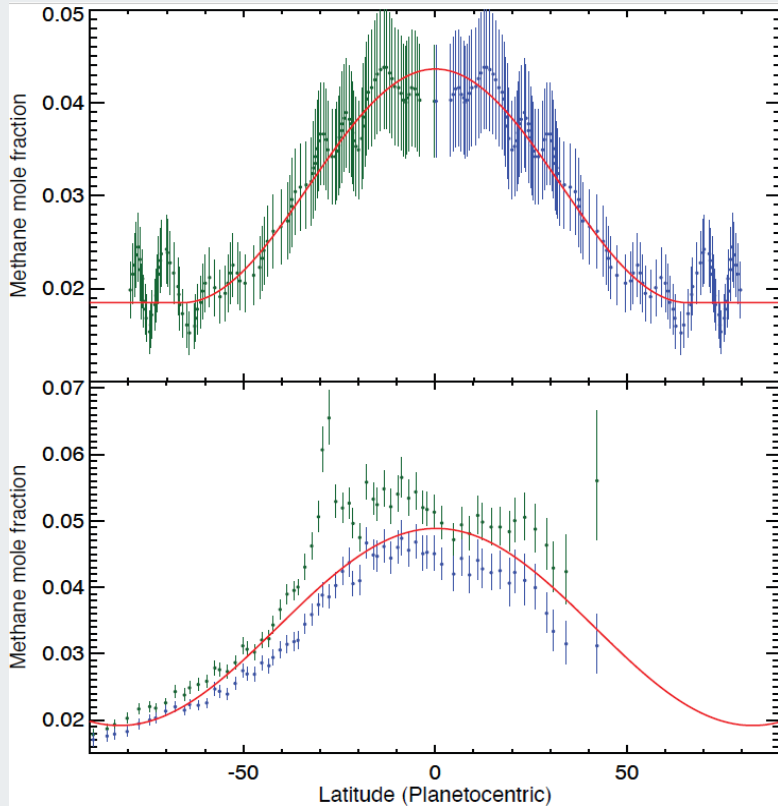


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 - T^{top} : **radiative-convective model**
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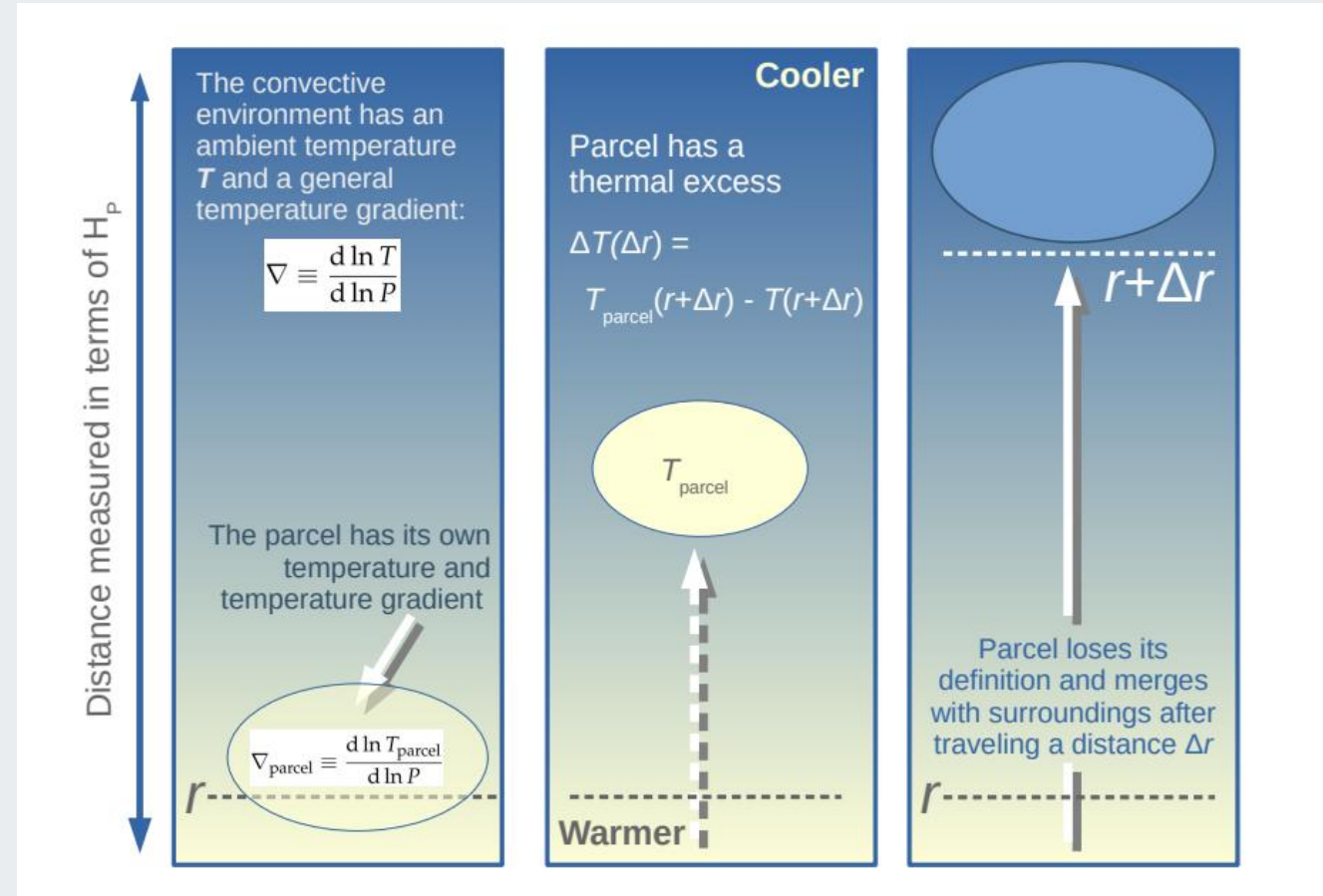
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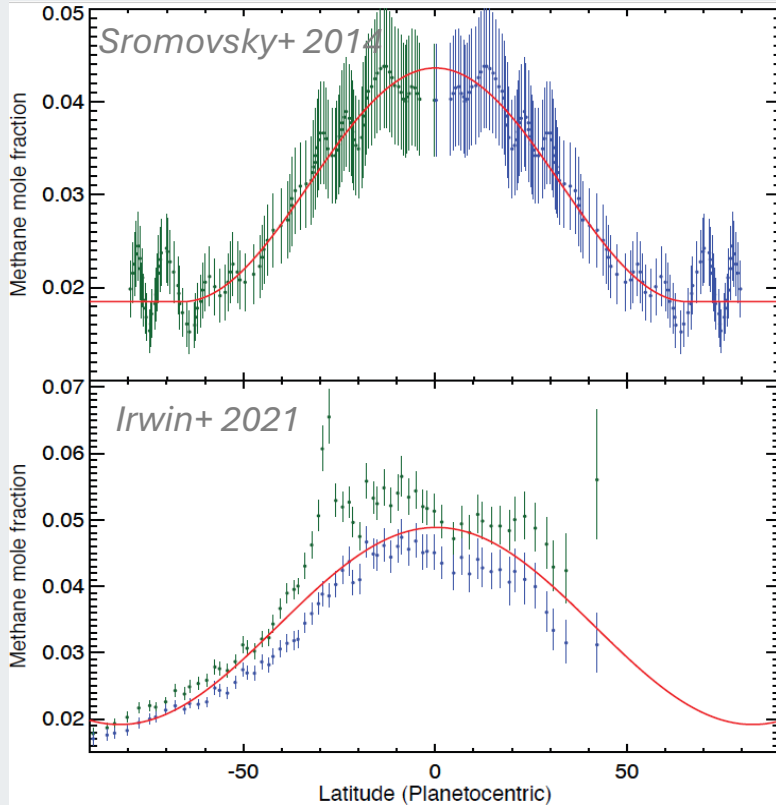
➤ Meridional transport (K_{zz}) :

- Typically estimated by MLT

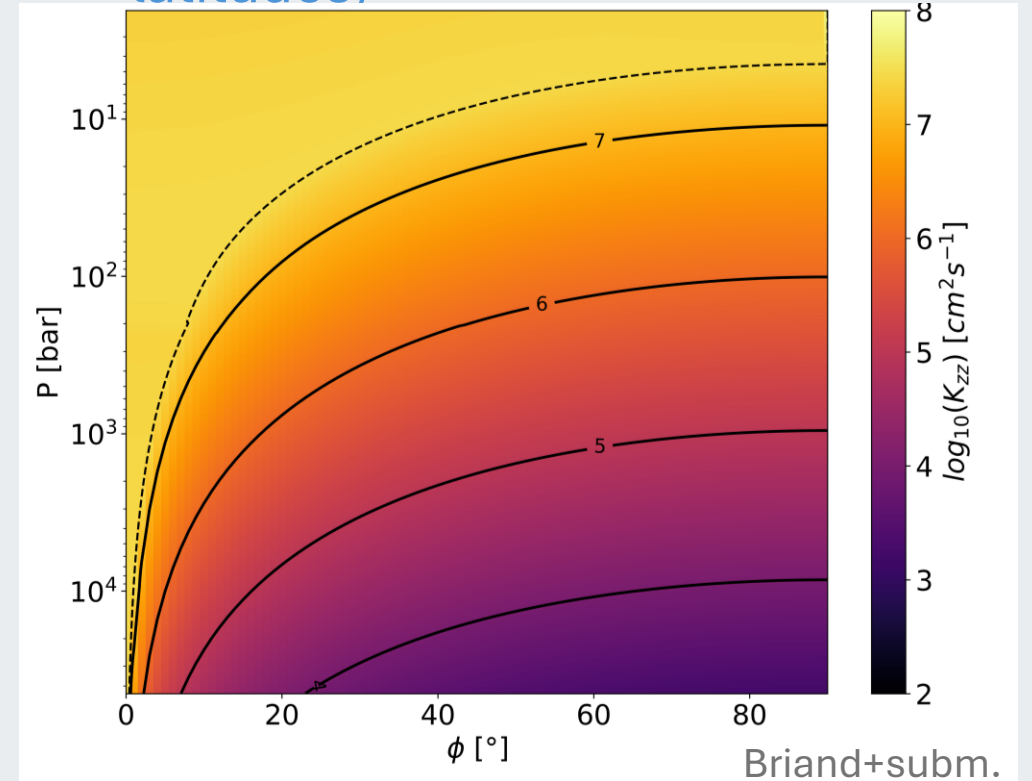


Joycee+2023

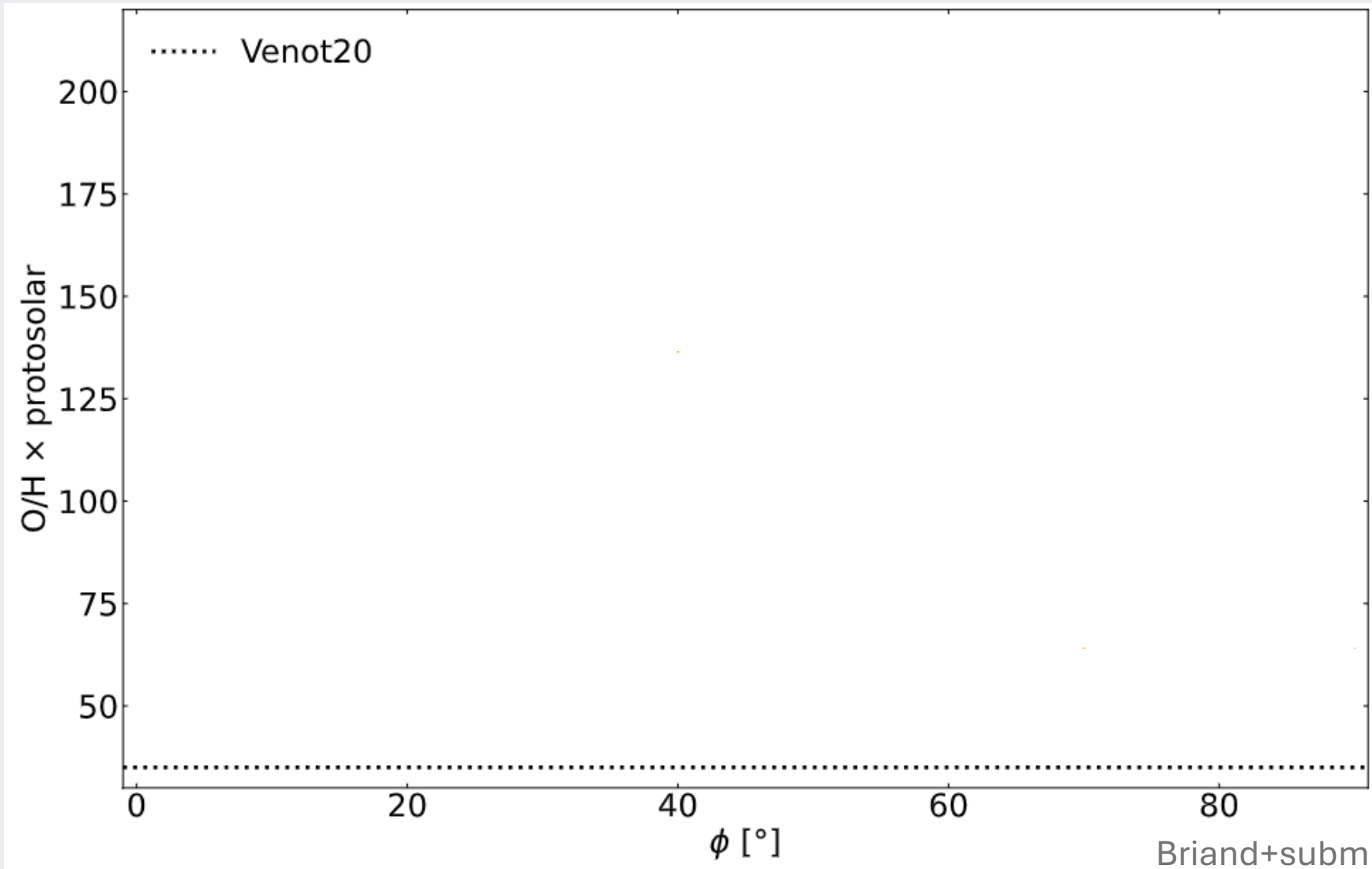
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 - Typically estimated by MLT
 - Wang+2015 formulation : **rotation inhibits convection (mid-to-high latitudes)**

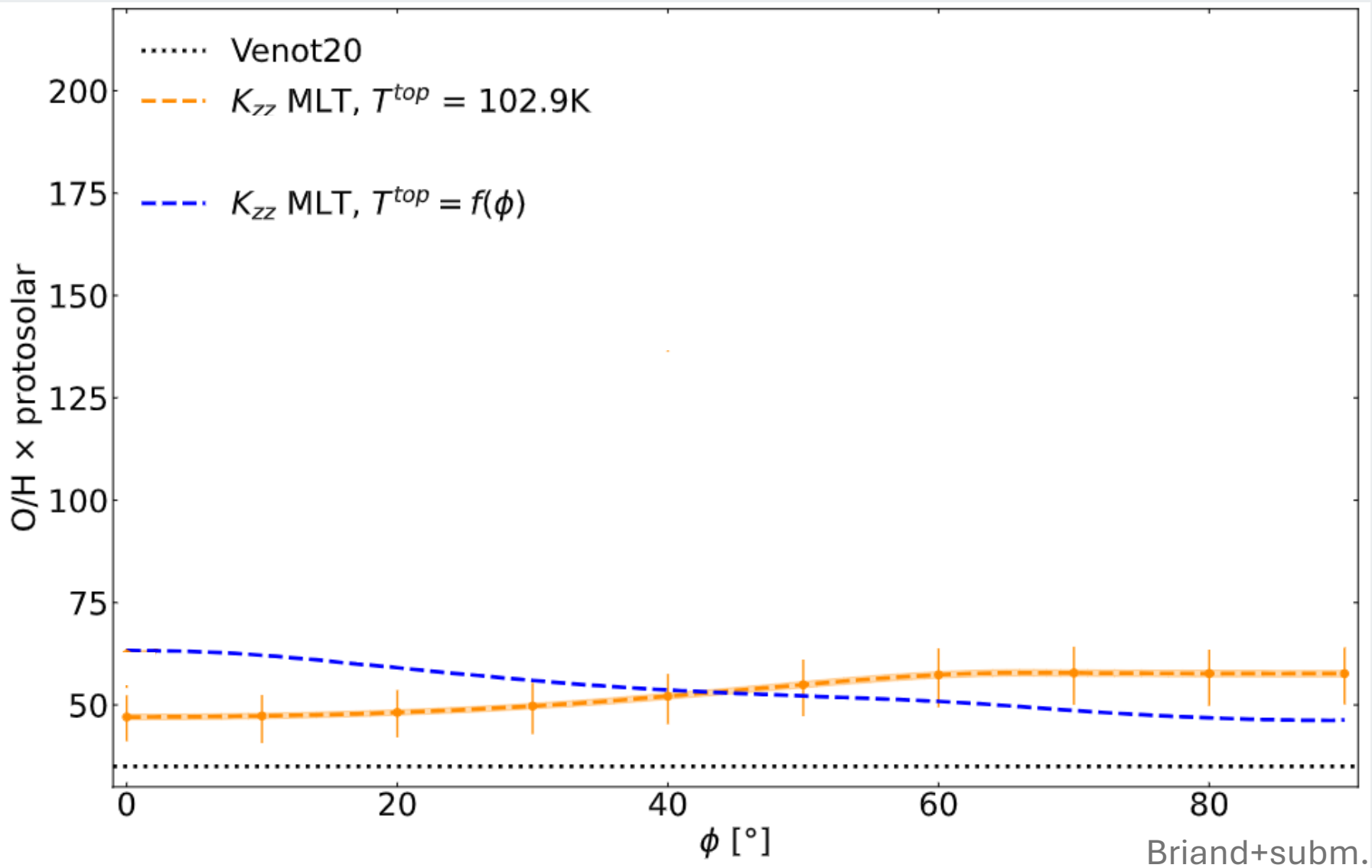


→ Idea : At each latitude, find the O/H ratio that fits the **observed y_{CO}^{top}** in the planet (*disk-averaged value*)



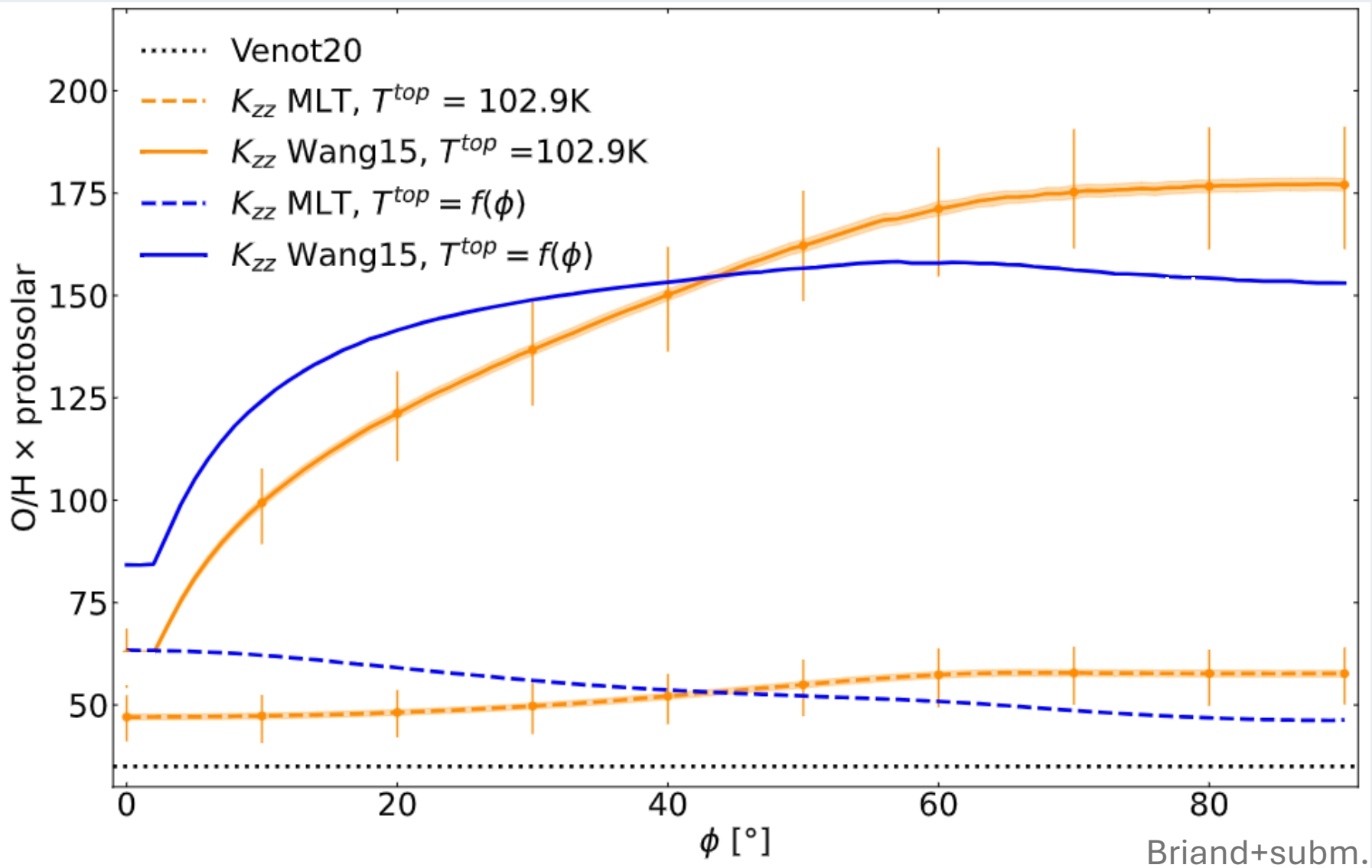
$y_{CO}^{top} = 5.6 \pm 0.2 \text{ ppb}$
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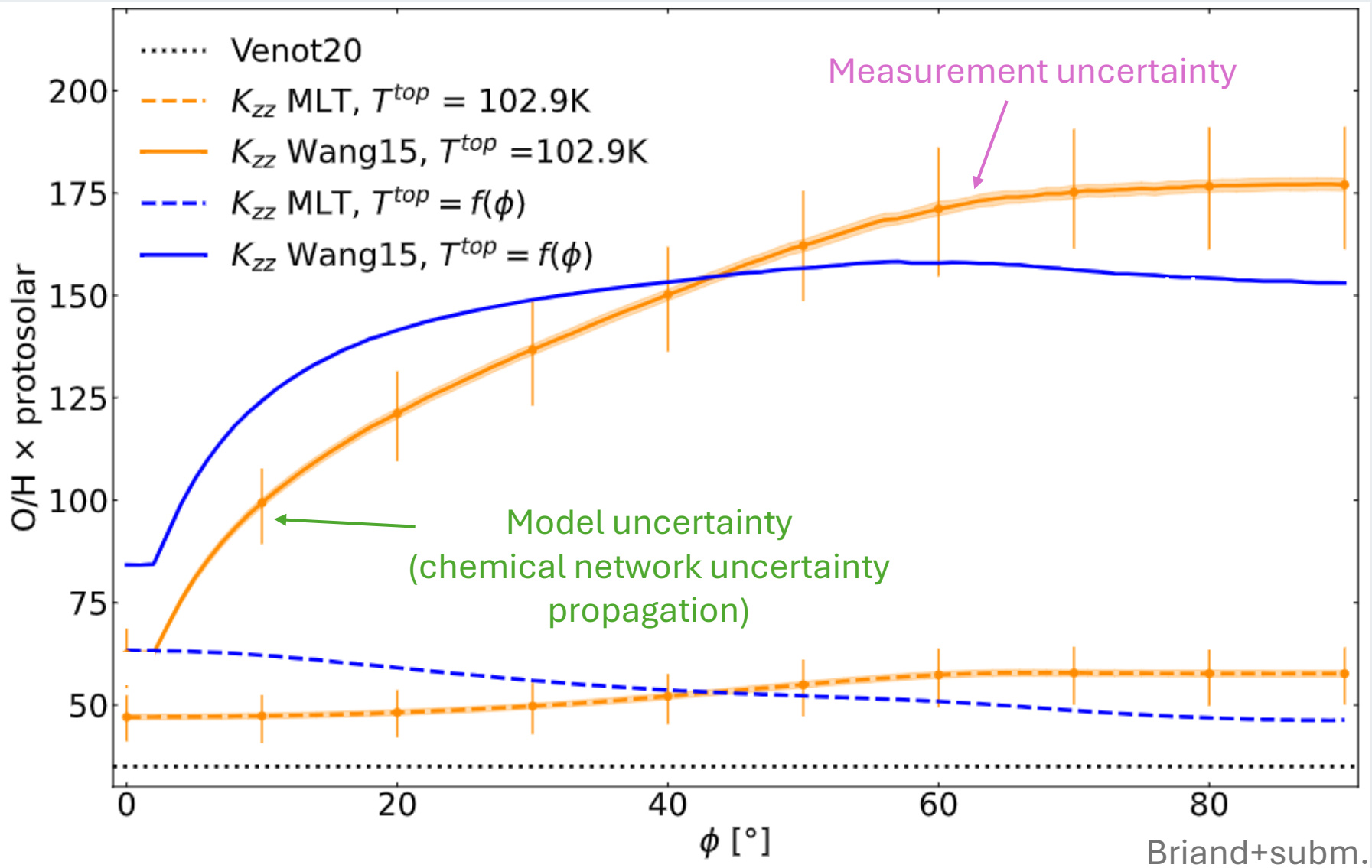
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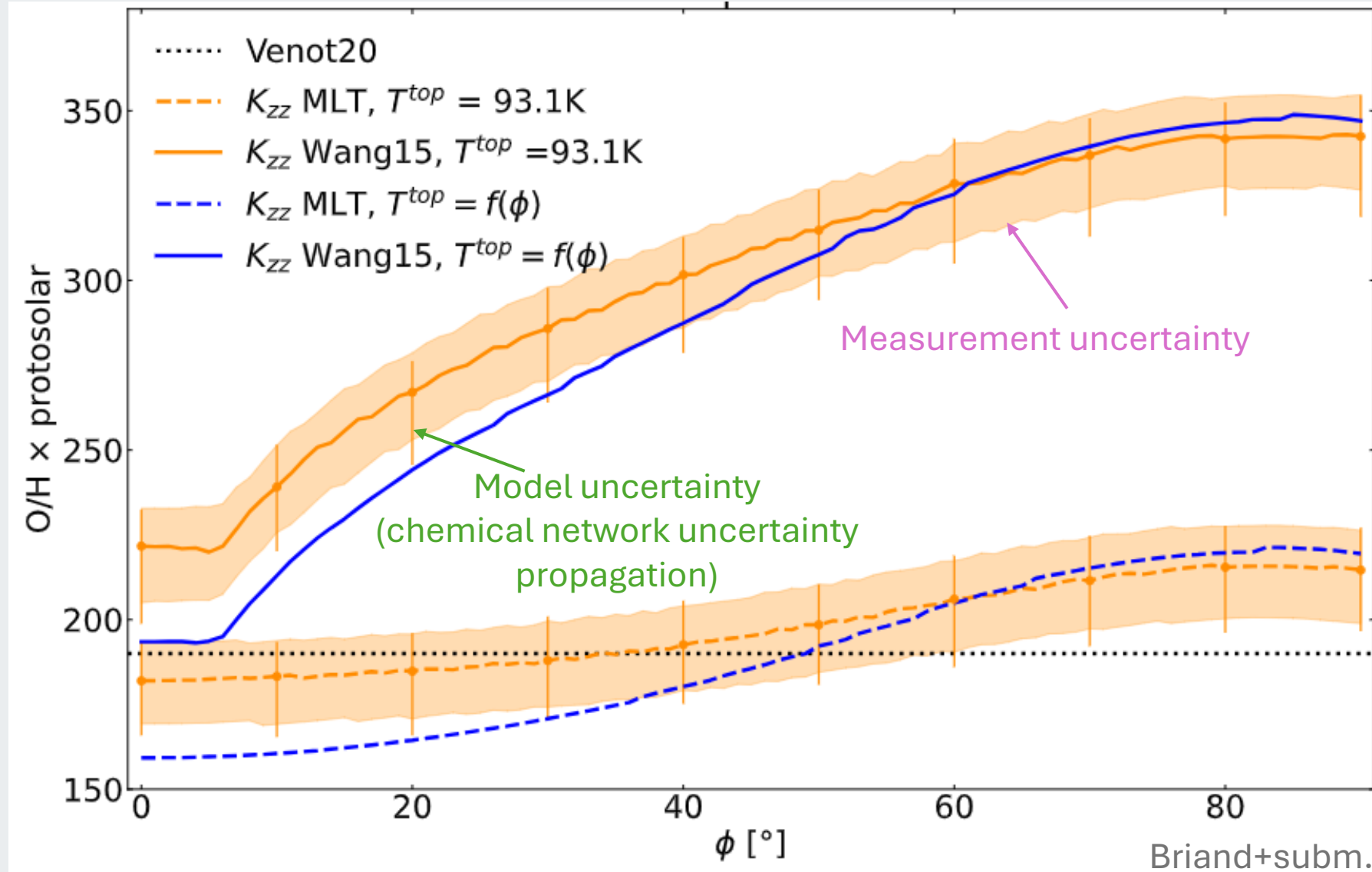
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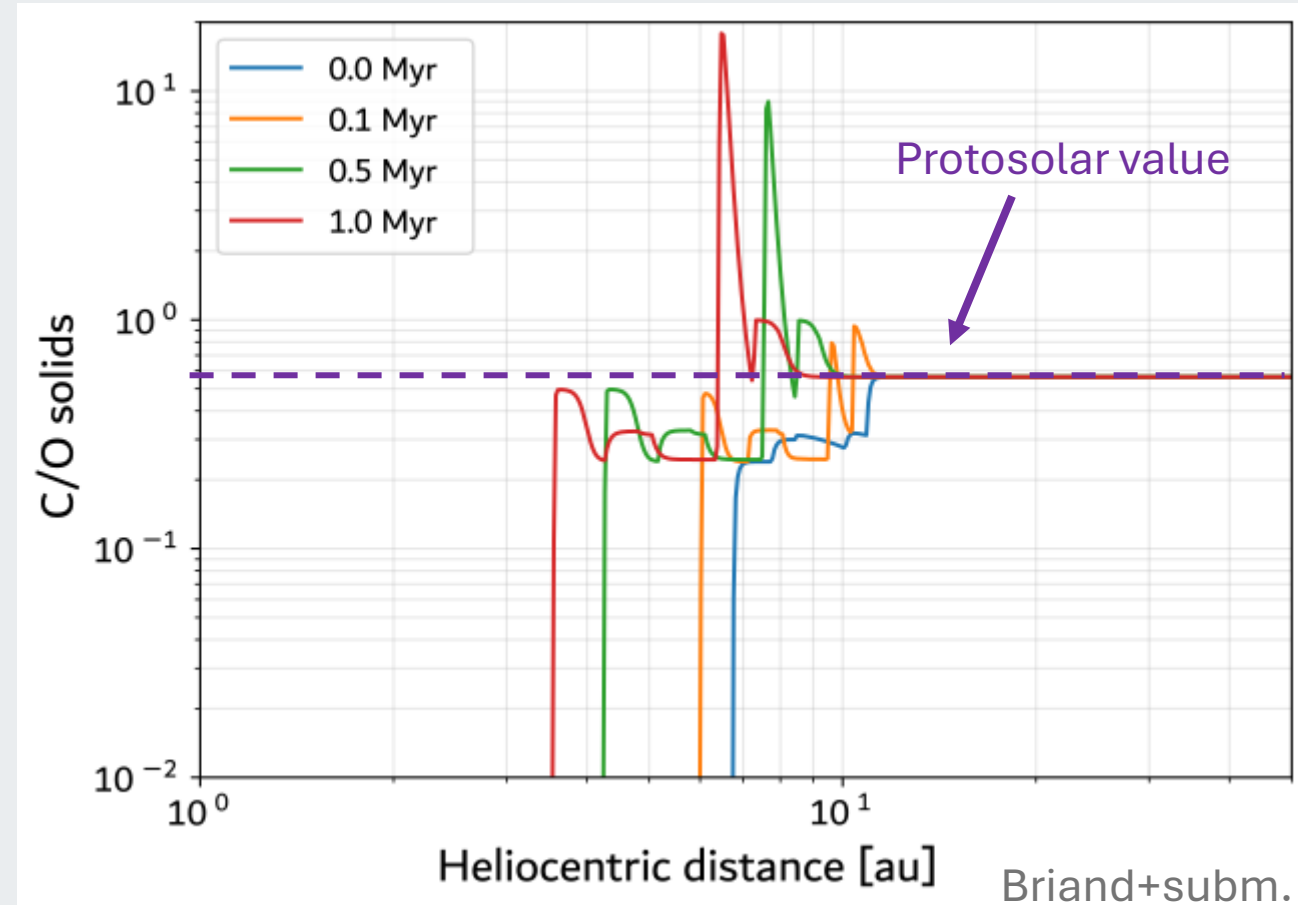
Results - Neptune



$y_{CO}^{top} = 0.2 \pm 0.05$ ppm
 Moreno+2017

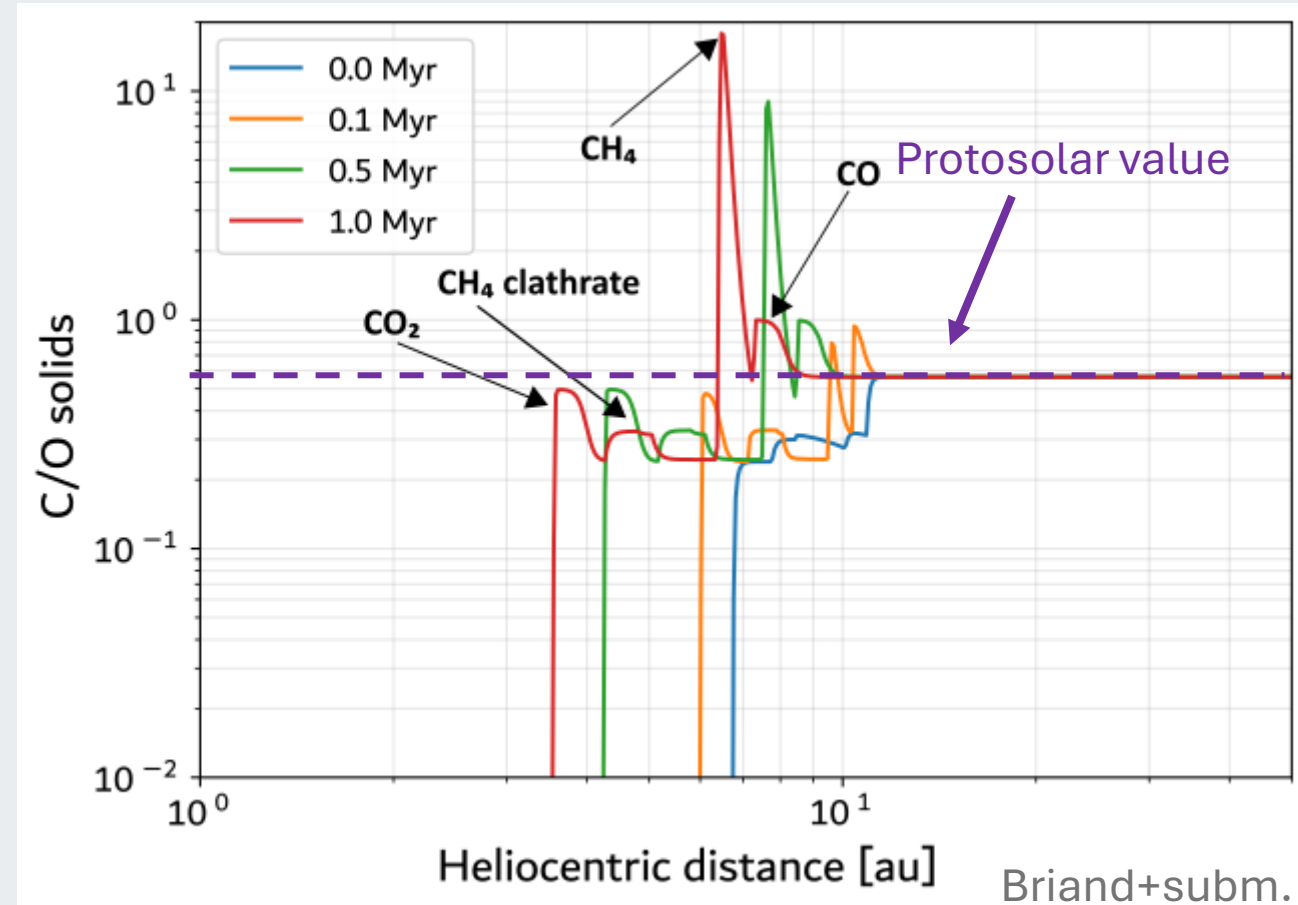
→ Compare O/H & C/H latitudinal range \Rightarrow compute C/O ratio

- PPD evolution model (Schneeberger+2023) tracks transport of solids through the disk.



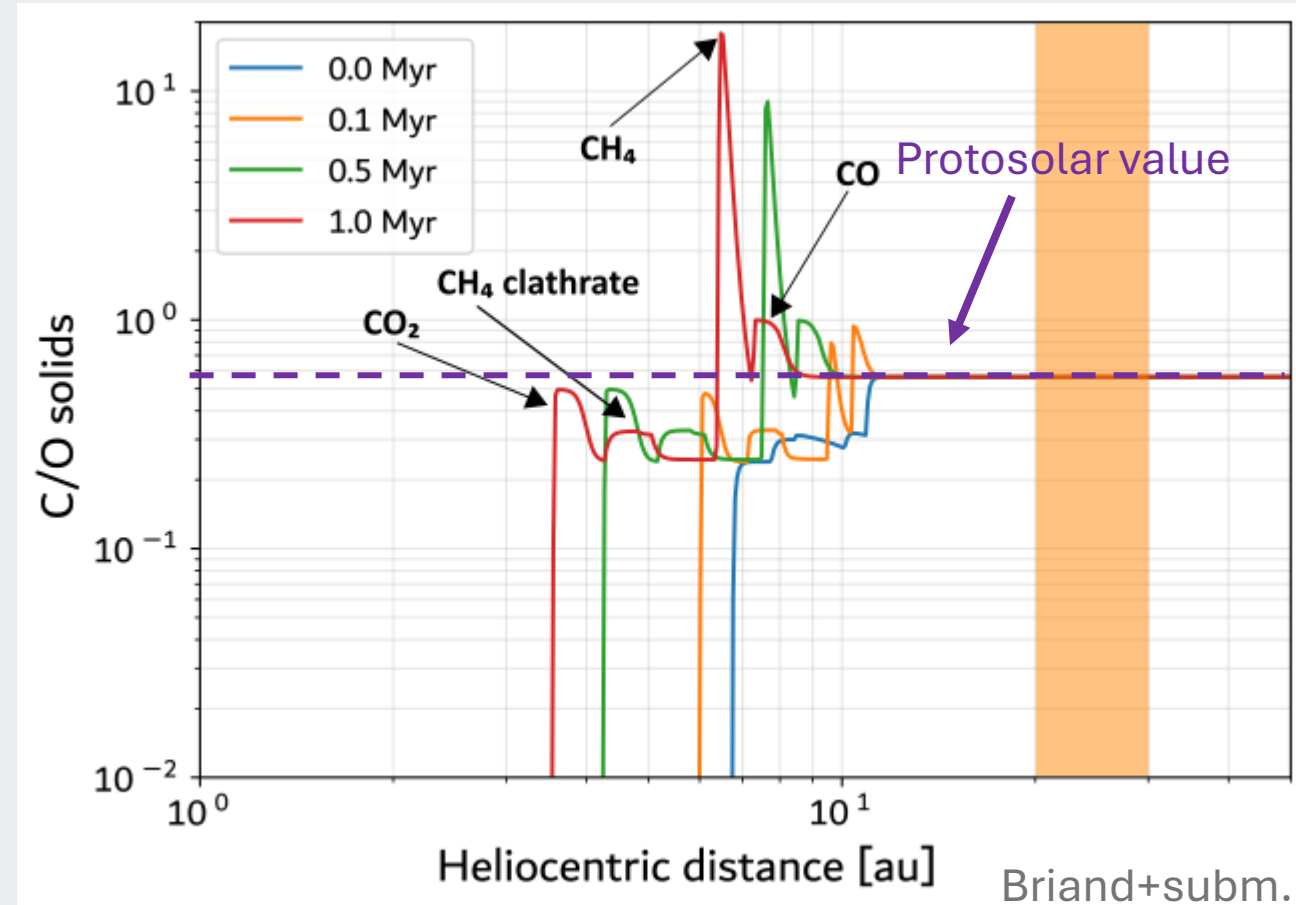
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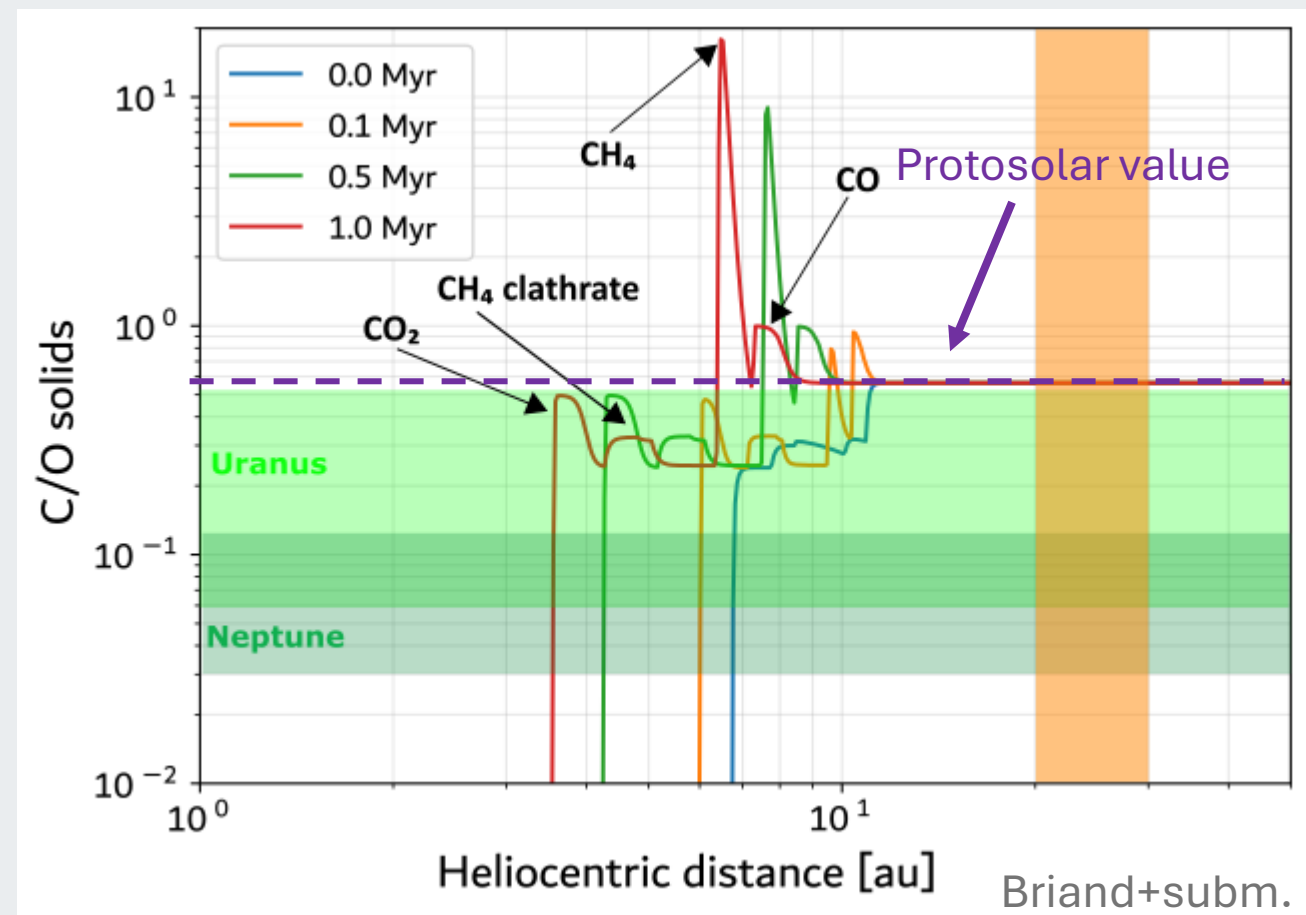
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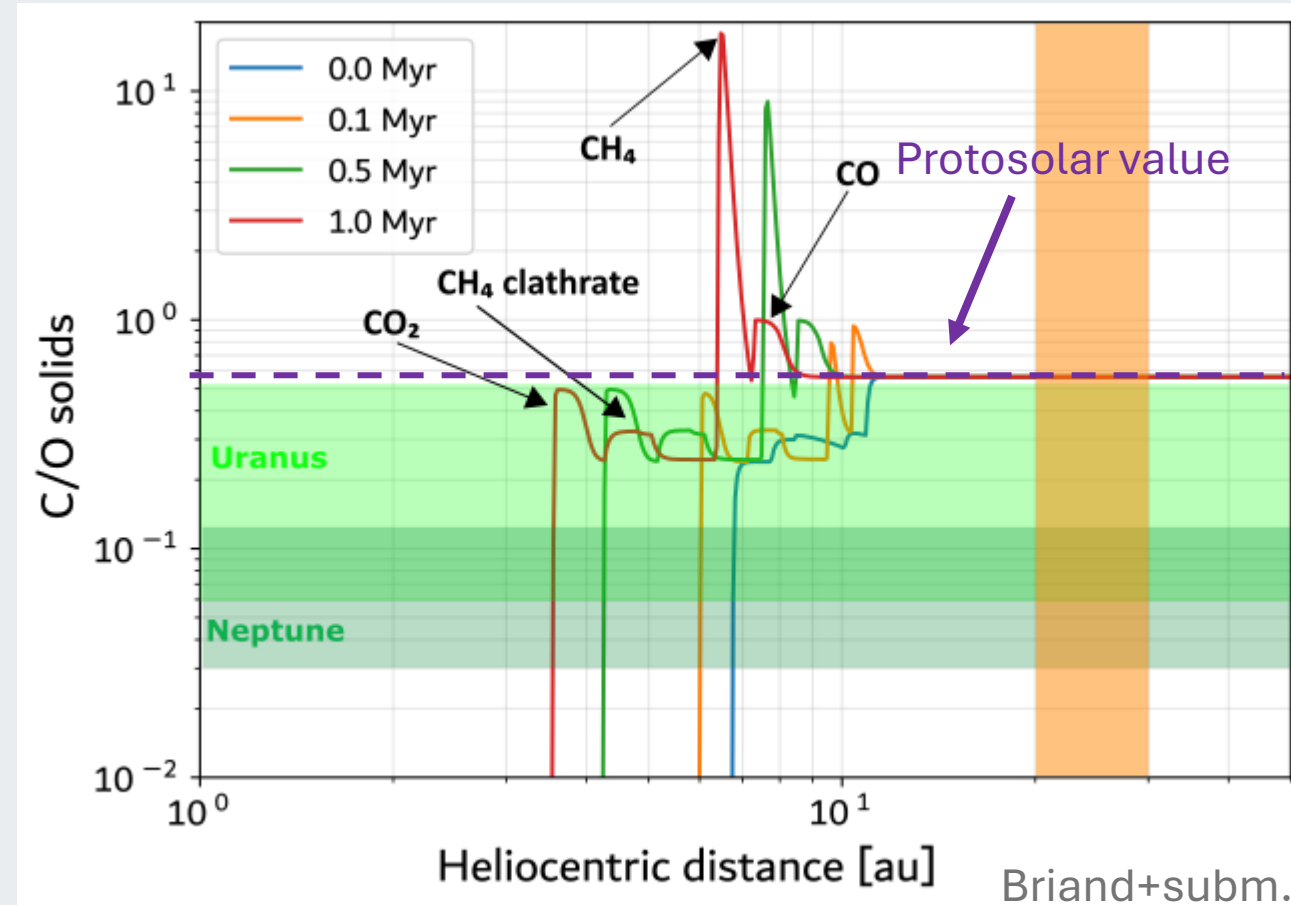
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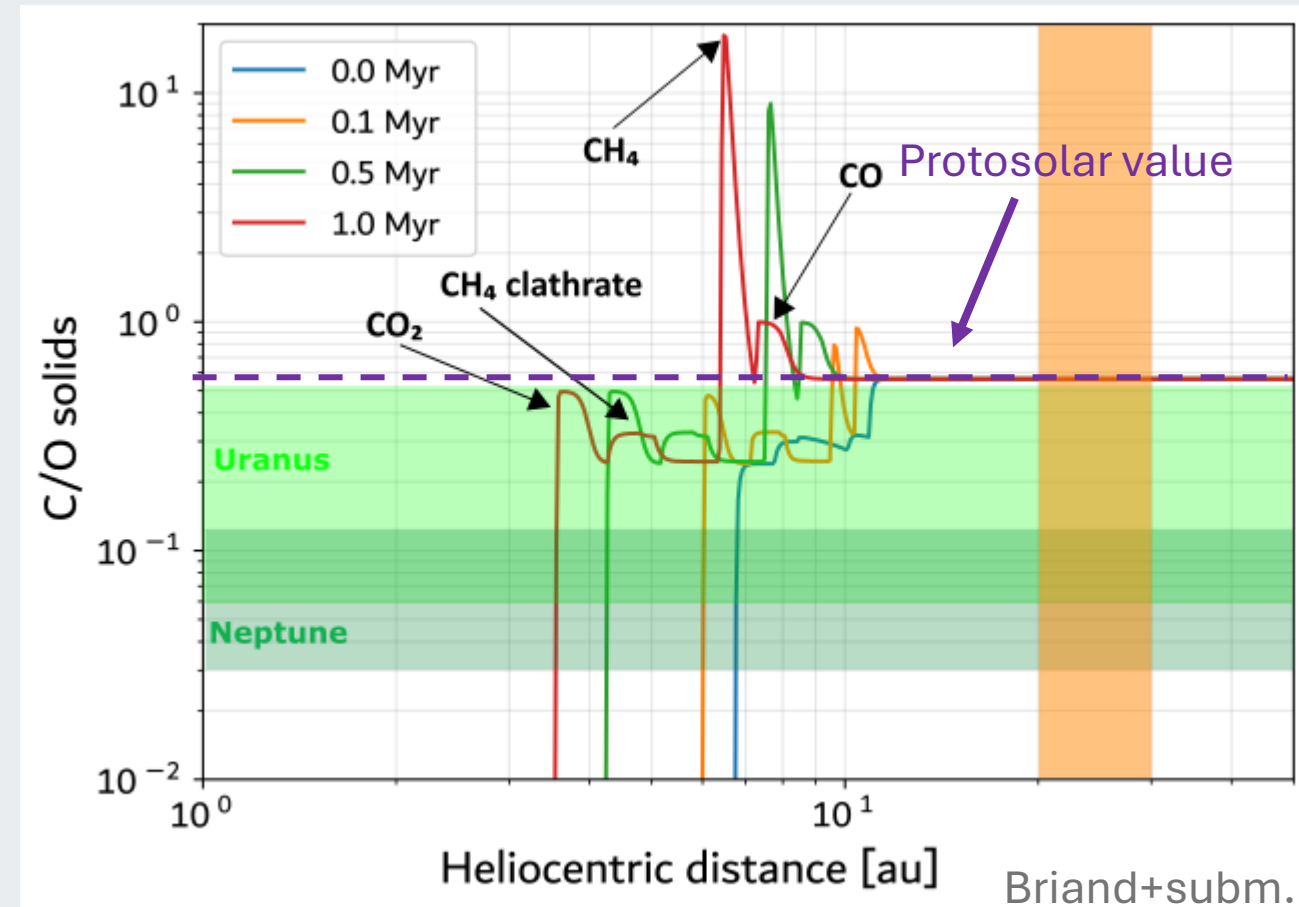
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- PPD evolution model (Schneeberger+2023) tracks transport of solids through the disk.
- Uranus : C/O consistent with protosolar value
- Neptune : C/O subsolar
- Both planet equatorial C/O are most likely different given similar transport properties, possibly supporting different formation pathway



- ✓ Disequilibrium species measured in the upper troposphere (few bars) can constrain the chemical composition of the deep atmosphere ($\sim 10^4$ bars).
 - ✓ Meridional variations need to be considered. The widely use yet poorly constrained K_{zz} is the key parameter in the model and rotation can be crucial to compute it.
 - ✓ C/O ratios in Uranus and Neptune are supporting of different formation pathways or different K_{zz}
 - ✗ Lacking K_{zz} constrains : (i) inhibited-convection layers ; (ii) rotating diffusion-less turbulence regime hard to probe experimentally ; (iii) effect of magnetic field
- See Briand et al. (submitted)
- Incomming : Couple recent spatially-resolved CO obs+ rotating convection lab experiments to constrain meridional K_{zz} variation