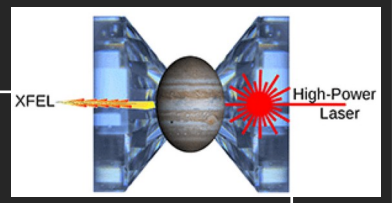


On the possibility of phase separation in the H-He-H_2O system in the ice giants

M. Cano, N. Nettelmann, N. Tosi DLR Berlin, SP5-2, FOR 2440

image: NASA/JPL

General key questions

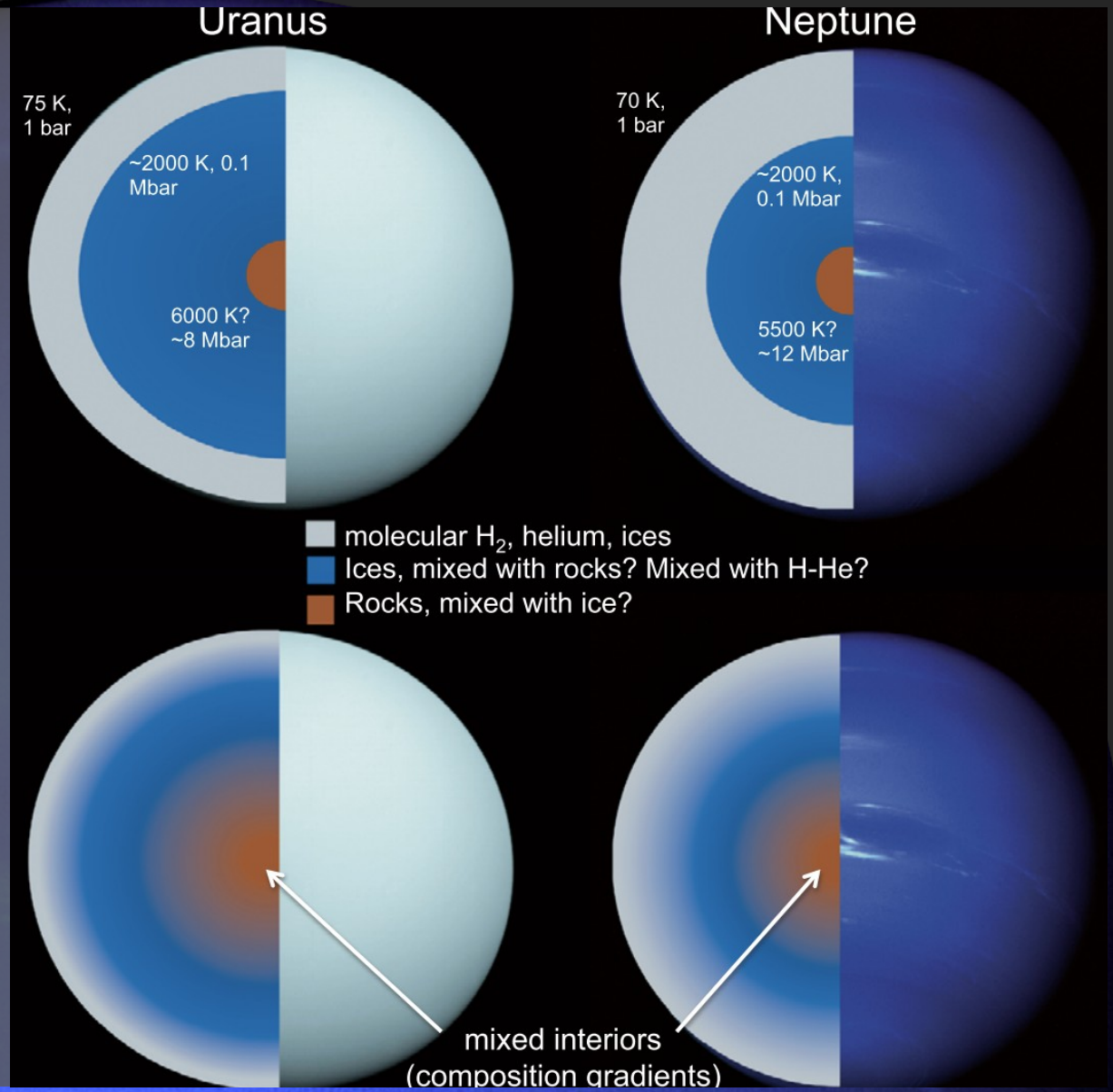
- Are Uranus and Neptune similar in internal structure?
- What is their bulk composition? (ice : rocks : H/He)
- Why Uranus so faint? Or Neptune so luminous?
- Why did they not become gas giants?
- Thermal evolution: mixing, settling, phase separation, inhibited convection?

Structure models - traditional approach

- Available observational constraints: mass, radius, gravitational field, rotation rate, atmospheric temperature

- Outcome of modelling efforts:
  - Several layers of different composition - gas, ices and rock
    (Hubbard & MacFarlane 1980, Podolak et al. 1991, Hubbard et al. 1995, Helled et al 2011, Nettelmann et al. 2013)

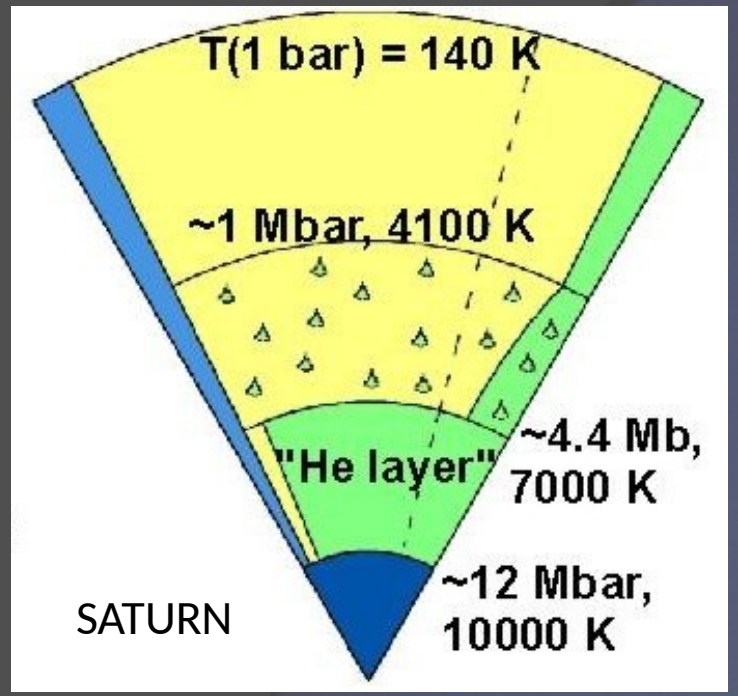
- Why is structure like this? crucial: equations of state and phase diagrams



Helled et al. 2020

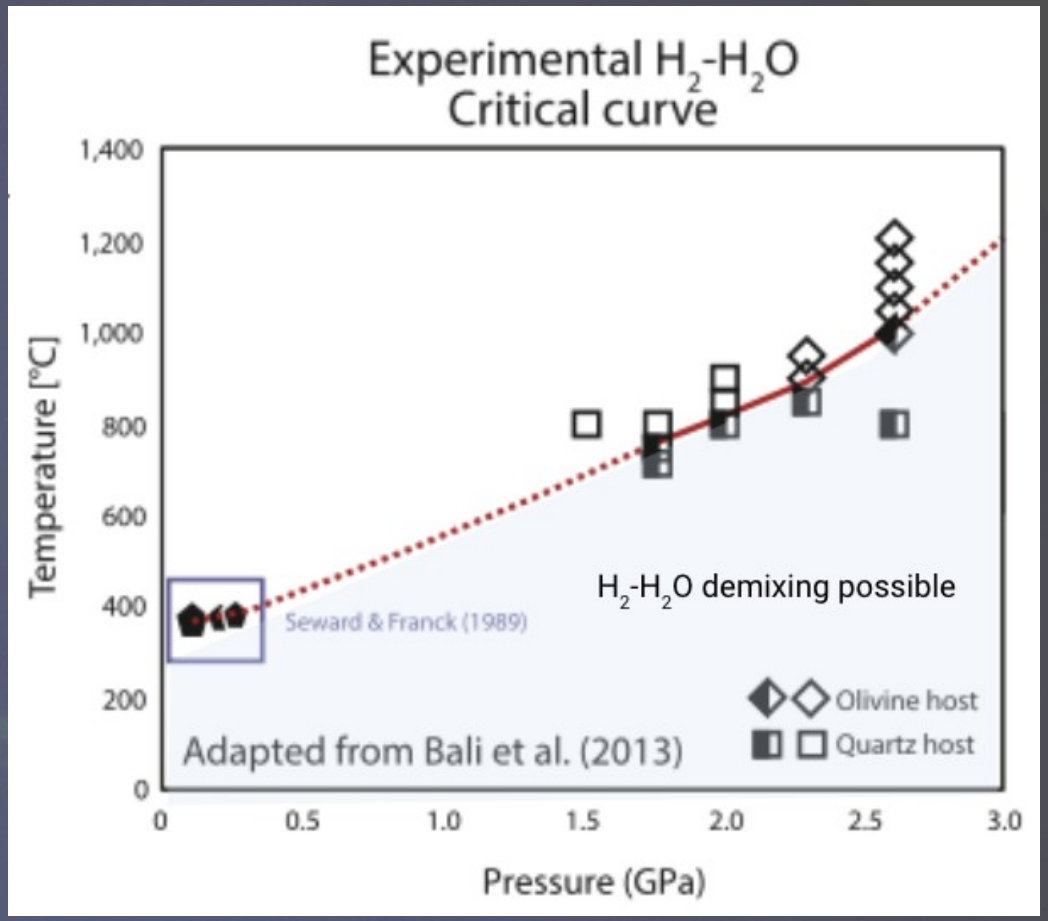
Why phase separation?

H-He demixing in Jupiter and Saturn



Fortney & Hubbard 2003, Püstow et al 2016, N. Nettelmann

H_2-H_2O demixing in Uranus and Neptune

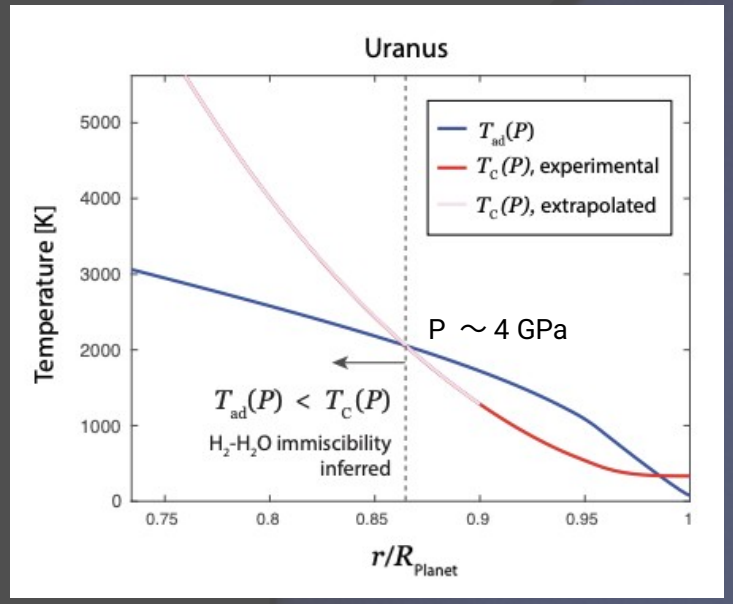


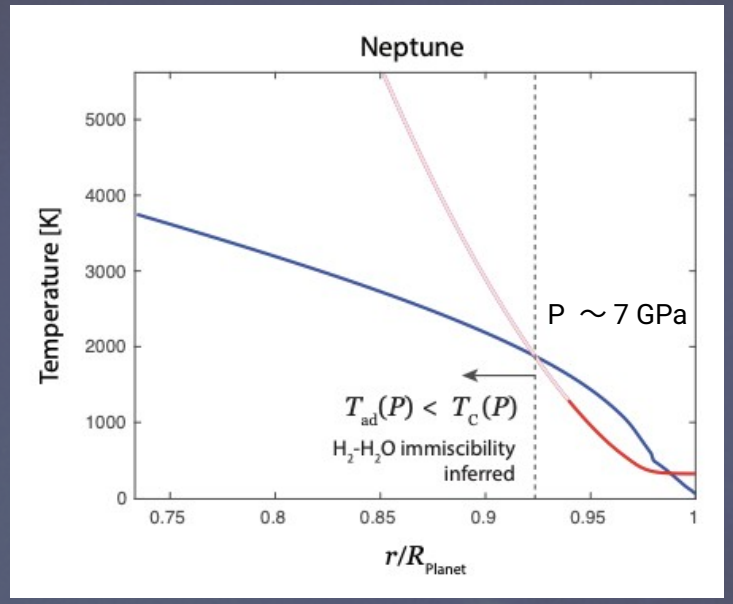
Bailey & Stevenson 2021

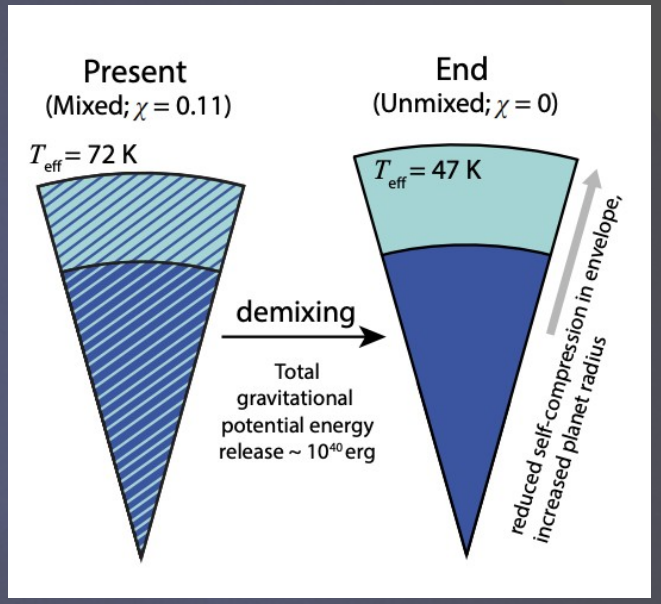
Bailey & Stevenson 2021 find…

Temperature deep in ice giants may be below the critical temperature, suggesting immiscibility of hydrogen and water.

However: conclusion based on extrapolation



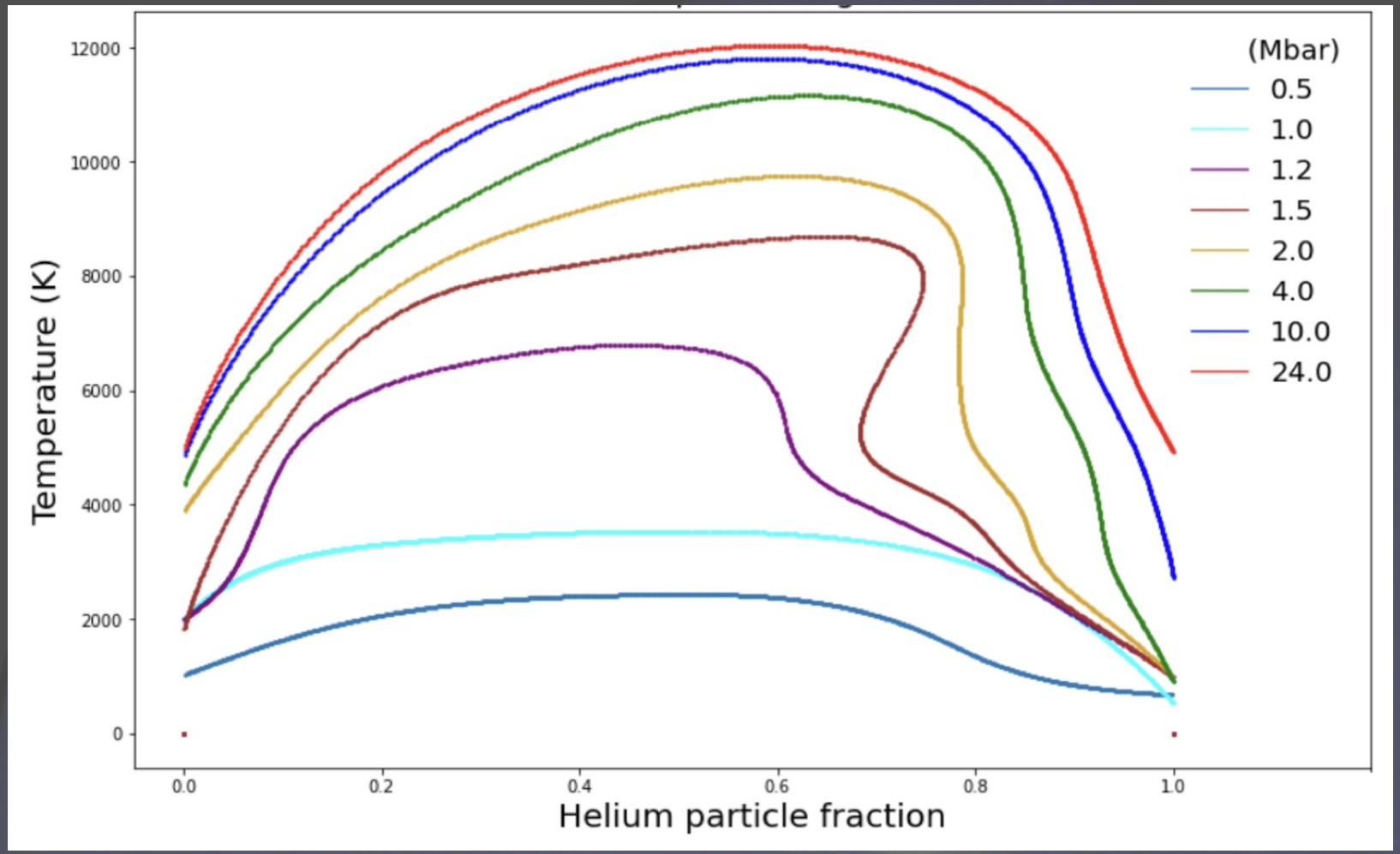




Find: H_2-H_2O demixing explains layered structure and could slow down Neptune's cooling rate.
Different states of H_2-H_2O demixing can account for difference in heat fluxes between U. and N.

Phase diagrams: H-He

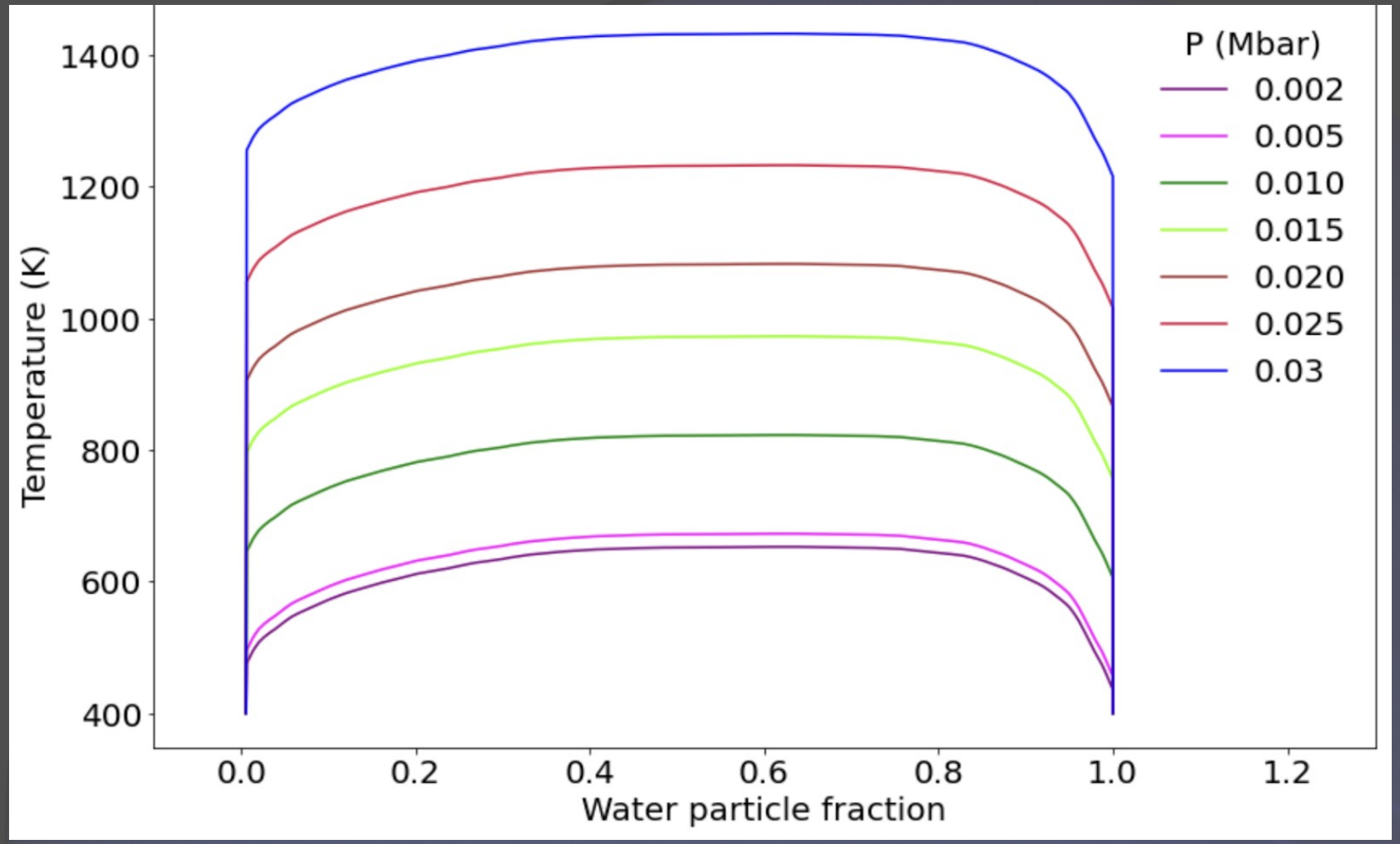
Schöttler & Redmer 2018



Demixing curves $T_{dmx}(P, x_{He})$ provide the maximum temperature below which phase separation occurs

Phase diagrams: H_2-H_2O

Seward & Franck 1981, Bali et al. 2013, Bailey & Stevenson 2021



Provide demixing curves $\mathbf{T_{dmx}(P, x_{H2O})}$

Equations of state

H/He-EOS (Chabrier & Debras 2021)

H_2O-EOS (AQUA, Haldemann et al. 2020)

$$T_{adiabat}(P, x_{He}, x_{H2O})$$

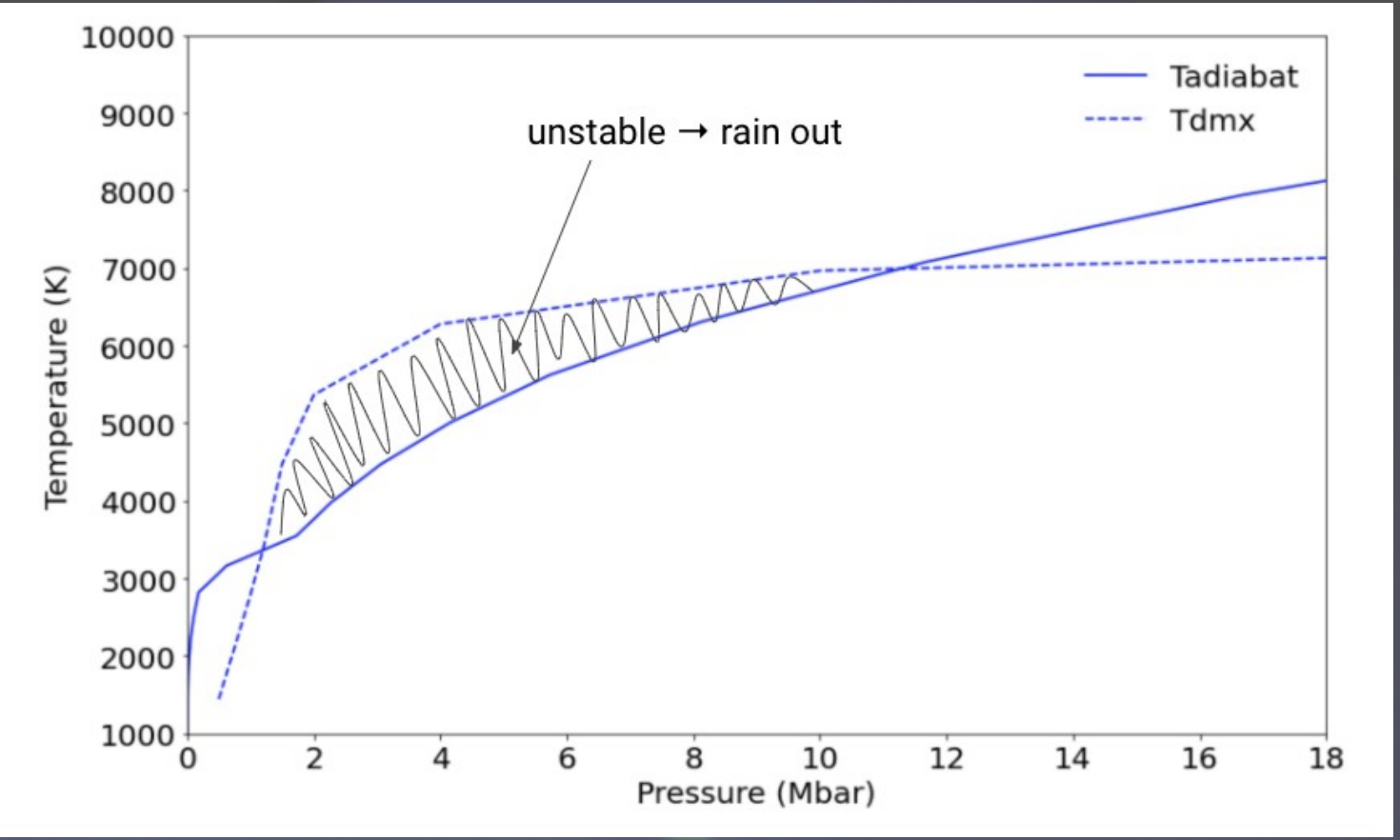
Computed adiabatic temperature profiles assuming the additive volume rule for various mixtures of H-He and H_2-H_2O using equations of state at specific T_{1bar}

Example of EOS for H-He mixture

	log_T	log_P	log_rho_H	log_rho_He	log_S_H	log_S_He	log_rho_mix	log_S_ideal_mix	log_S
0	2.0	-6.00	-5.615400	-5.31748	-1.16135	-1.45088	-5.551656	0.001929	-1.209933
1	2.0	-5.95	-5.565400	-5.26748	-1.16435	-1.45382	-5.501656	0.001929	-1.212829
2	2.0	-5.90	-5.515400	-5.21748	-1.16737	-1.45678	-5.451656	0.001929	-1.215744
3	2.0	-5.85	-5.465400	-5.16748	-1.17041	-1.45977	-5.401656	0.001929	-1.218679
4	2.0	-5.80	-5.415400	-5.11748	-1.17347	-1.46277	-5.351656	0.001929	-1.221632
...	...	...	...	...	...	...	...	...	...
15686	5.5	4.80	0.987771	1.40342	-1.00284	-1.52120	1.068377	0.001929	-1.084923
15687	5.5	4.85	1.025450	1.43747	-1.00792	-1.52677	1.105592	0.001929	-1.089933
15688	5.5	4.90	1.062650	1.47106	-1.01293	-1.53228	1.142328	0.001929	-1.094873
15689	5.5	4.95	1.099410	1.50424	-1.01787	-1.53773	1.178625	0.001929	-1.099745
15690	5.5	5.00	1.135730	1.53707	-1.02276	-1.54312	1.214490	0.001929	-1.104566

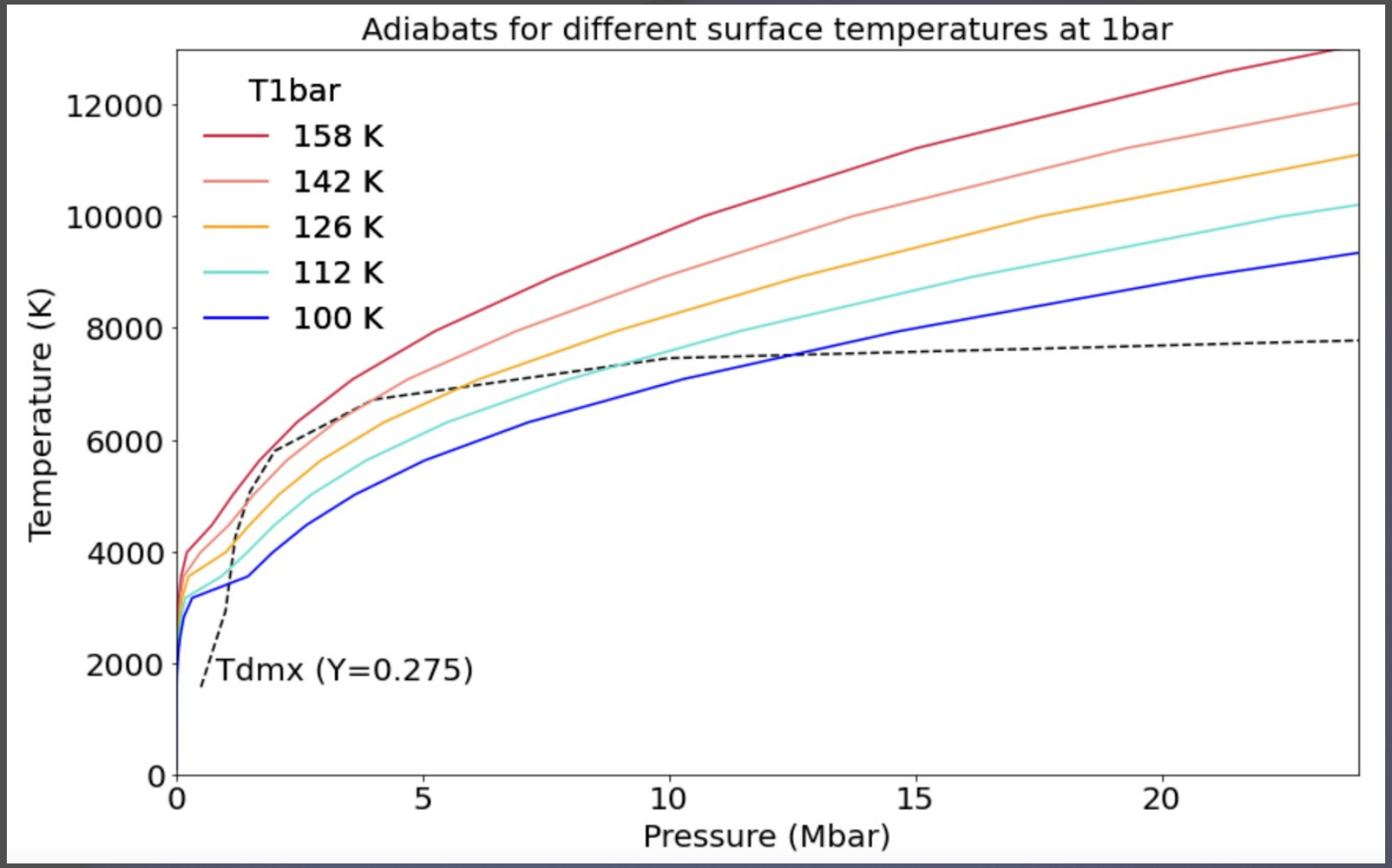
Immiscibility: $T_{adiabat} < T_{dmx}$

H/He for Y=0.220

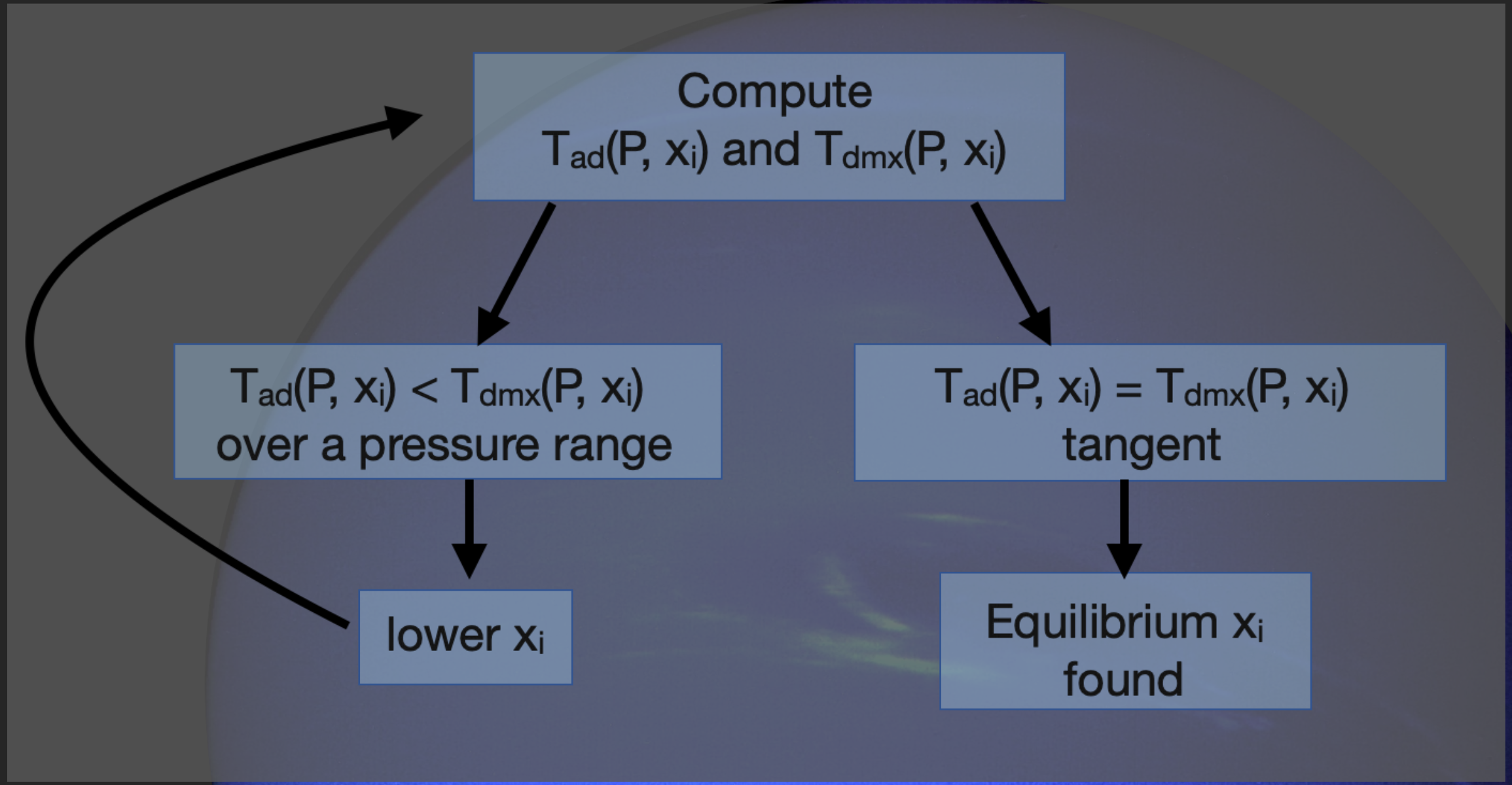


Aim: obtain **local equilibrium** abundances of He and H_2O, yielding the predicted H/He and H_2/H_2O composition in the atmosphere

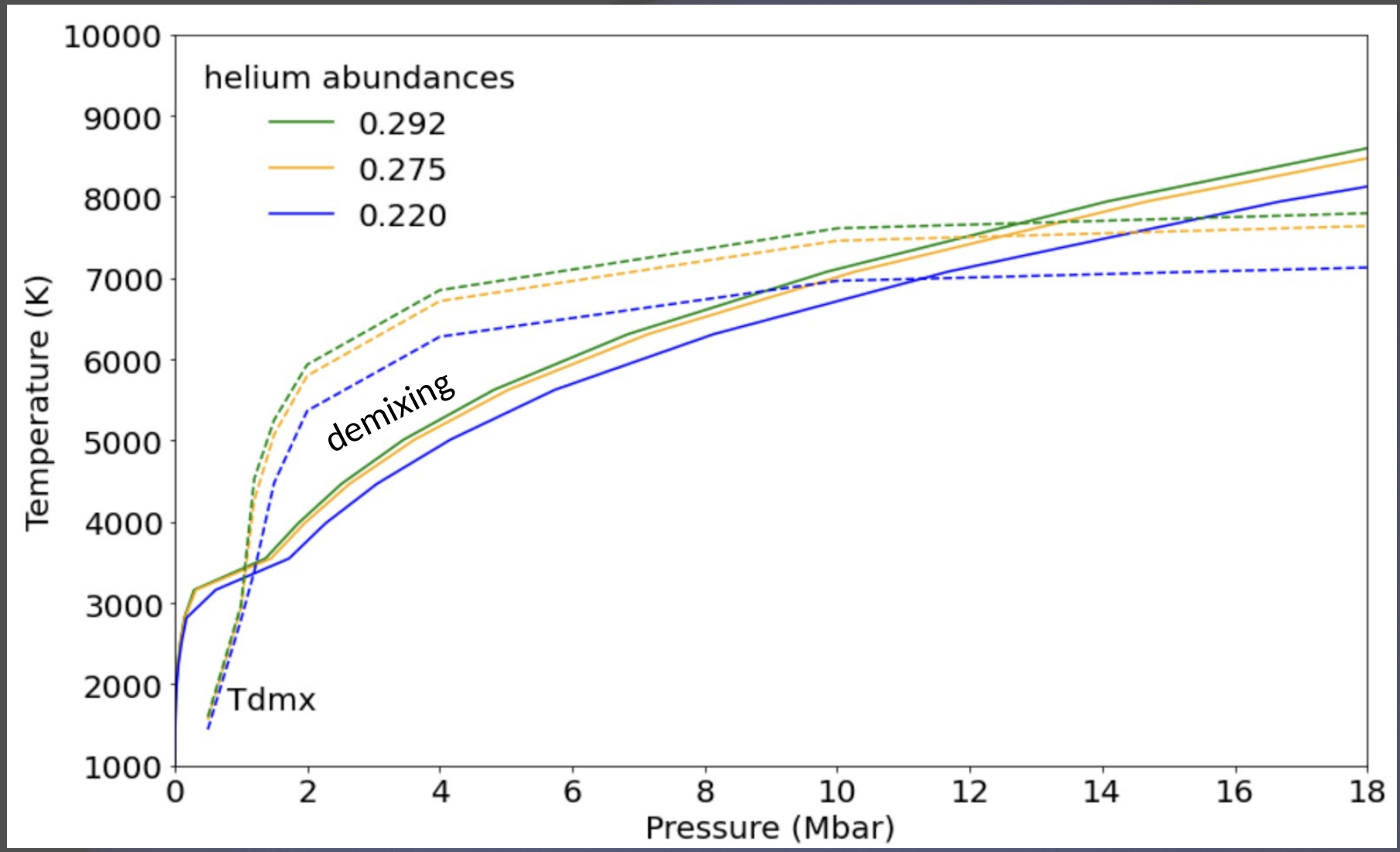
Adiabats


Adiabats for different surface temperatures at 1bar
T1bar
158 K
142 K
126 K
112 K
100 K
Tdmx (Y=0.275)
Temperature (K)
Pressure (Mbar)
0
2000
4000
6000
8000
10000
12000
0
5
10
15
20

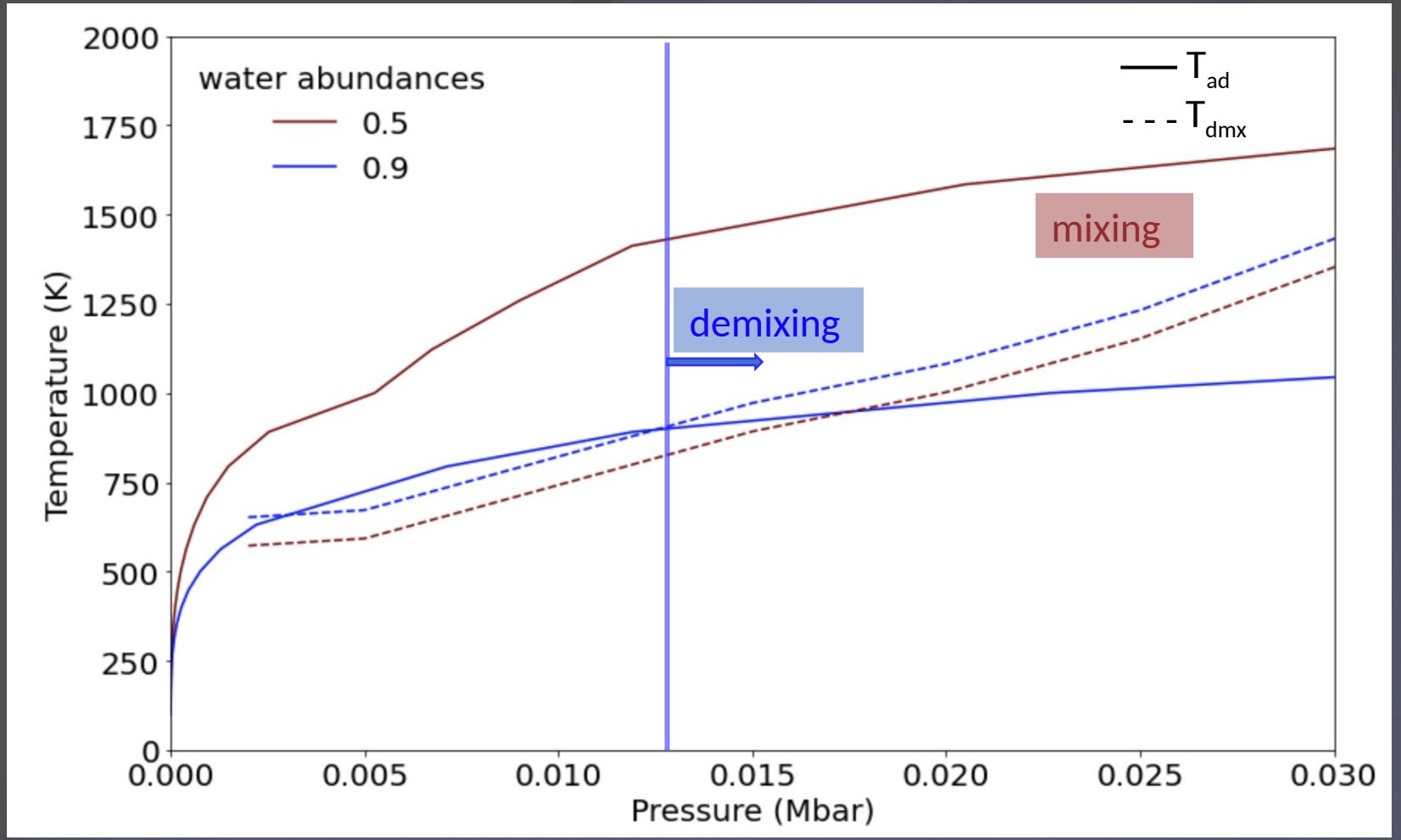
Finding equilibrium abundances



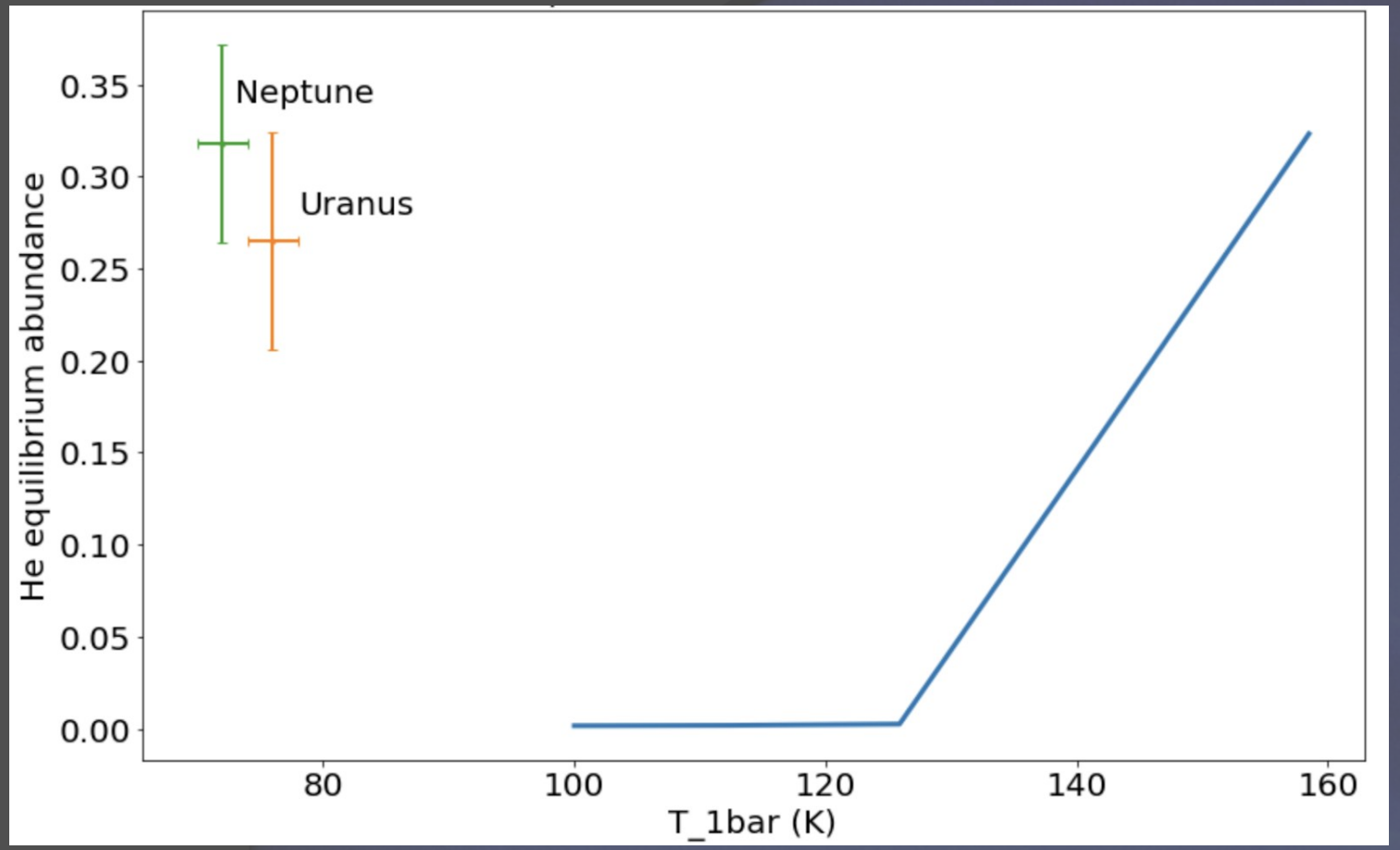
Finding equilibrium abundances H-He

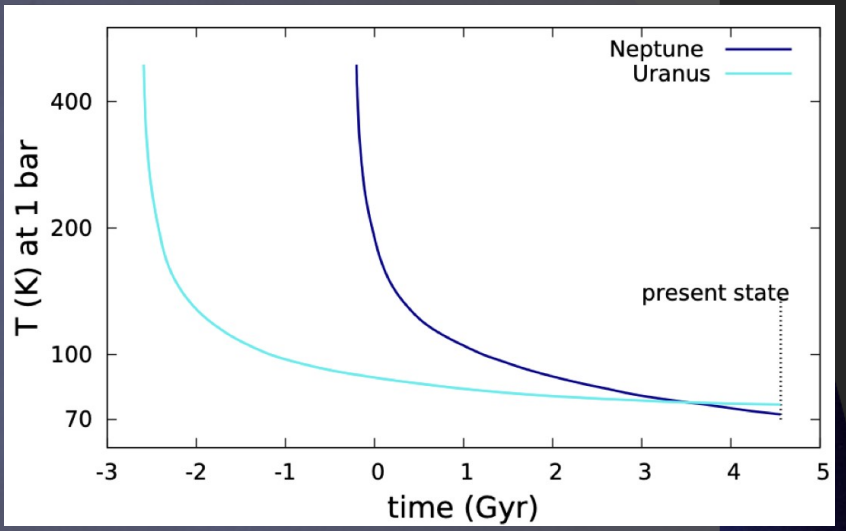


Finding equilibrium abundances H_2-H_2O



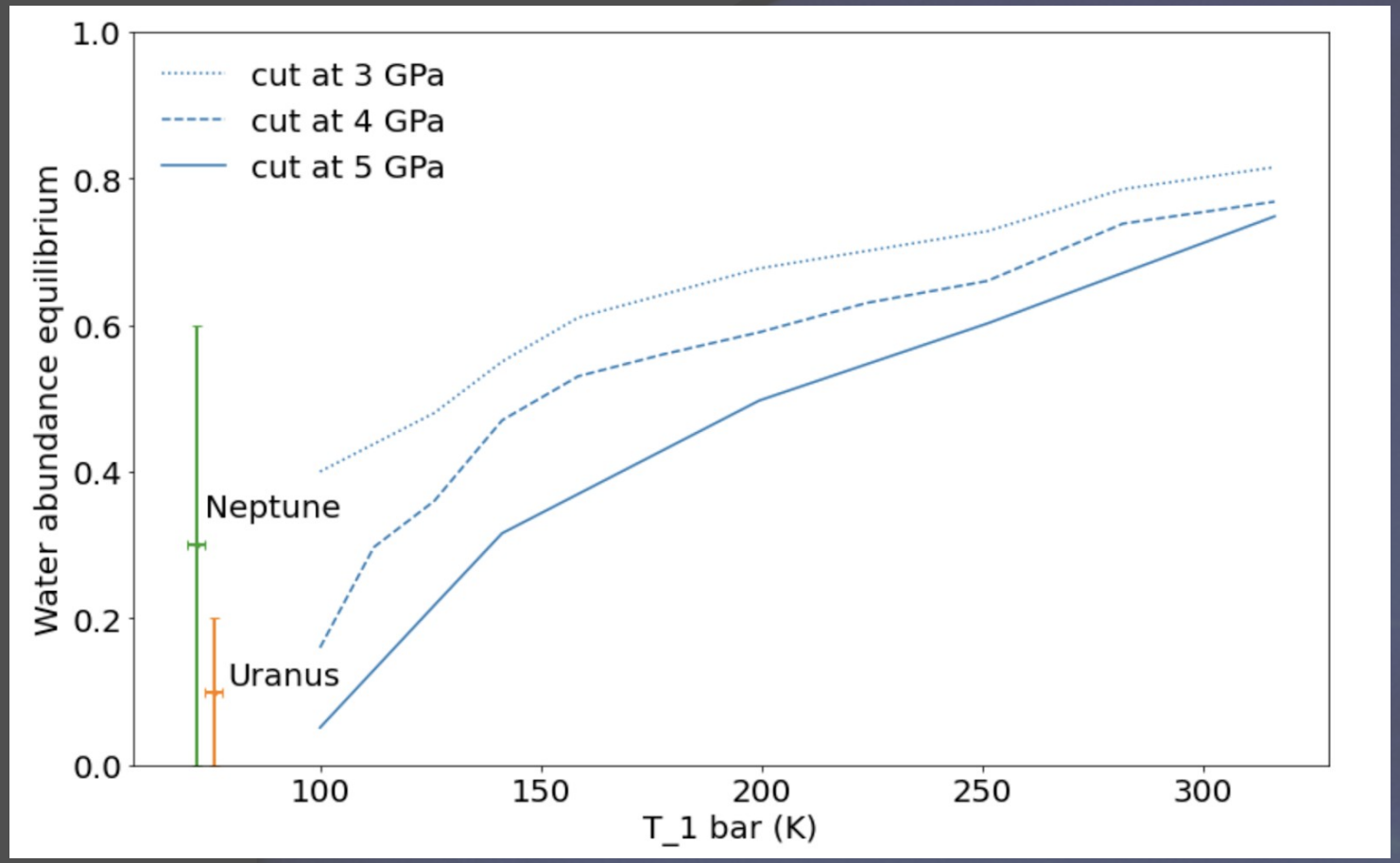
Results: equilibrium abundance He

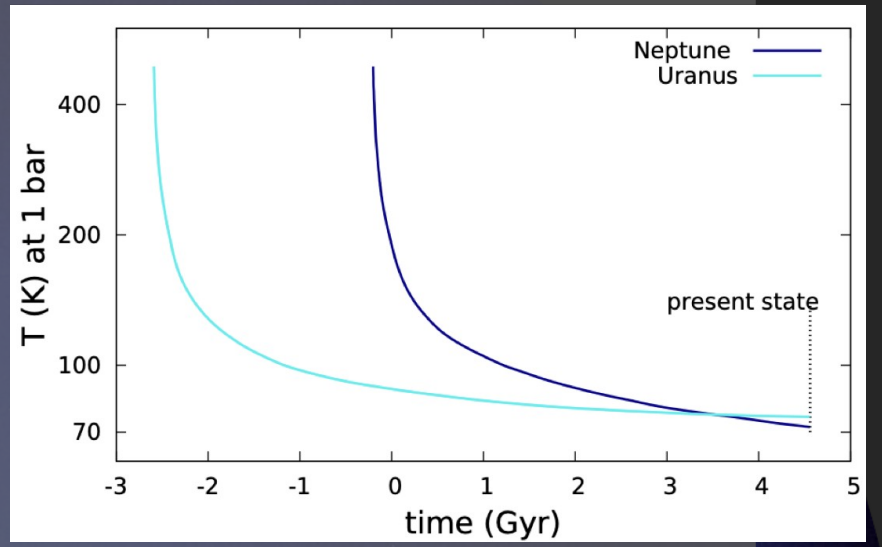




Nettelmann, N., Helled, R., Fortney, J. J., & Redmer, R. (2013)

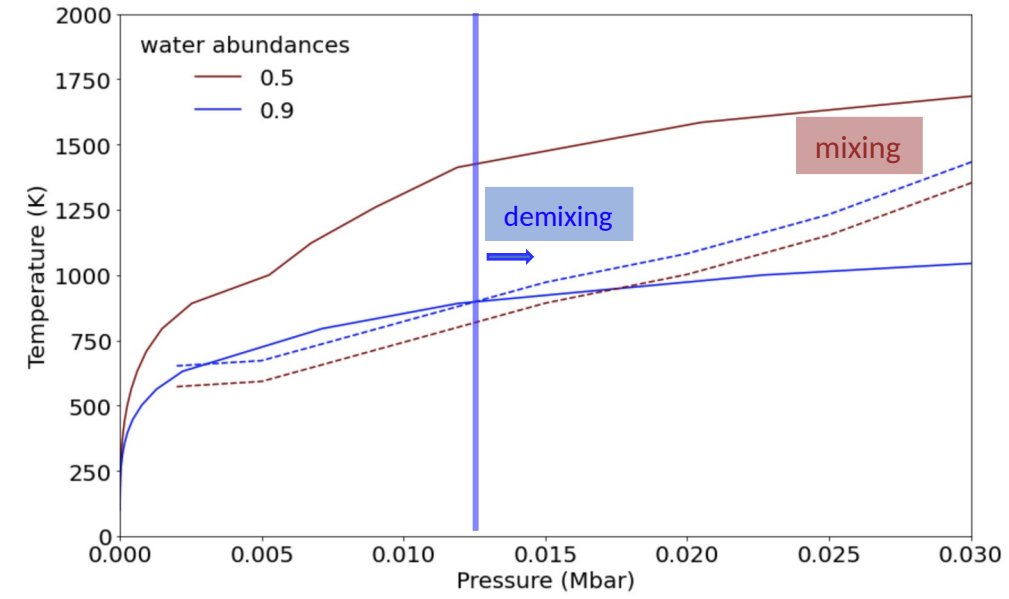
Results: equilibrium abundance H_2O

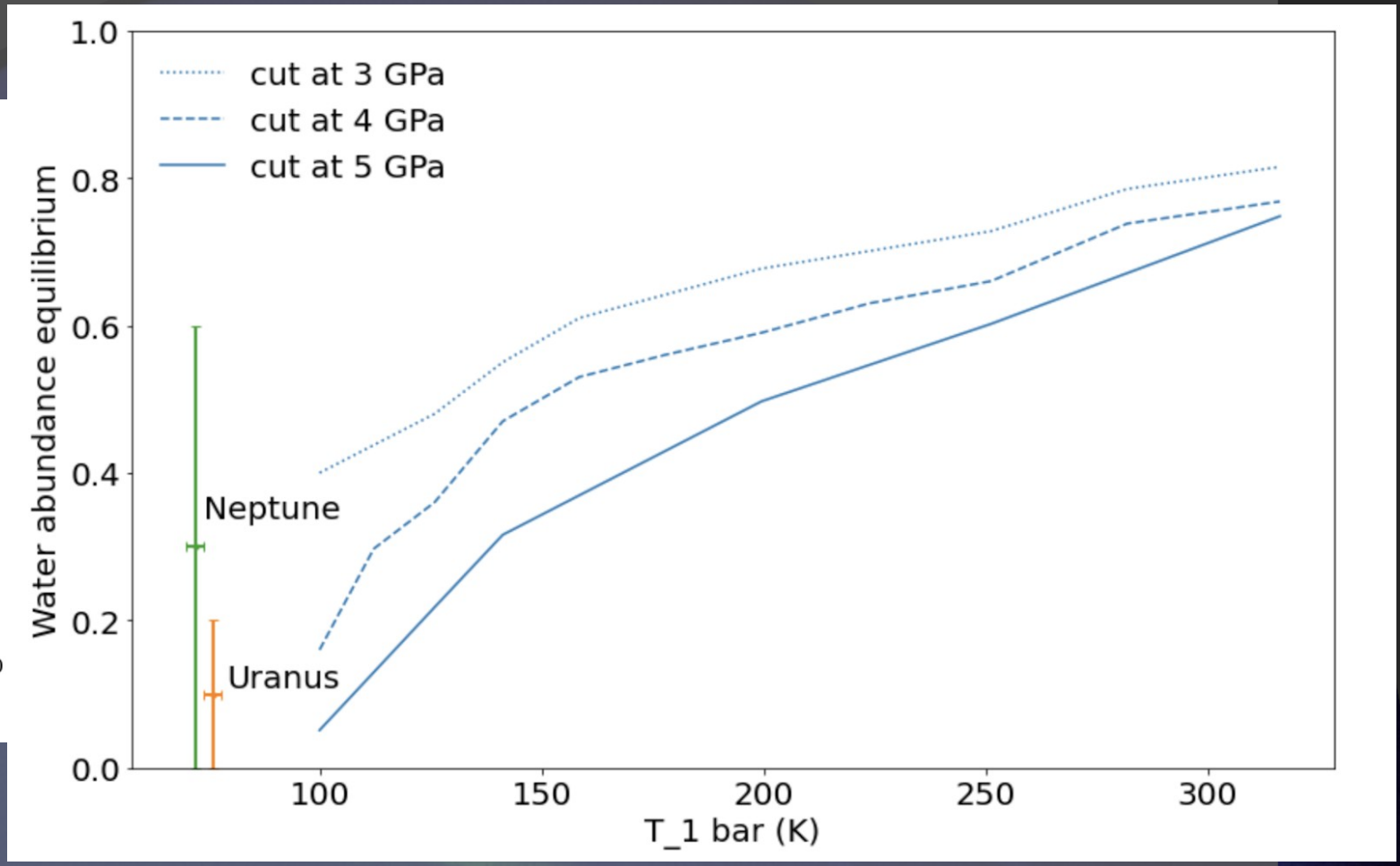




Nettelmann, N., Helled, R., Fortney, J. J., & Redmer, R. (2013)

“Cut-off” & extrapolation





Summary & Outlook

- Procedure so far allows the estimation of the atmospheric He and H_2O abundance in the ice giant atmospheres upon cooling
- Current results imply that demixing of H_2-H_2O started before H-He phase separation and also early in the evolution of the planets, which may have influenced their current thermal budget considerably
- Next steps:
  - Obtain cooler adiabats for T_{1bar} for Uranus and Neptune ~ 75 K
  - Apply phase diagram for H_2-H_2O for higher pressures as data becomes available
  - Apply mass conservation to find inner edge of demixing region
- Combine H-He-H_2O
- We aim to build interior structure and evolution model which takes into account the role of phase separation