Modeling Atmospheric Chemistry of the Ultra Low Density Exoplanet WASP-193b

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Super-Puff Exoplanet WASP-193b

WASP-193 b's low density challenges standard evolution models; sustaining its inflated radius likely requires deep energy deposition at P>10 bar.

Mass: $0.112^{+0.029}_{-0.034} M_J$ Radius: $1.319^{+0.056}_{-0.048} R_J$

"Cotton candy" density

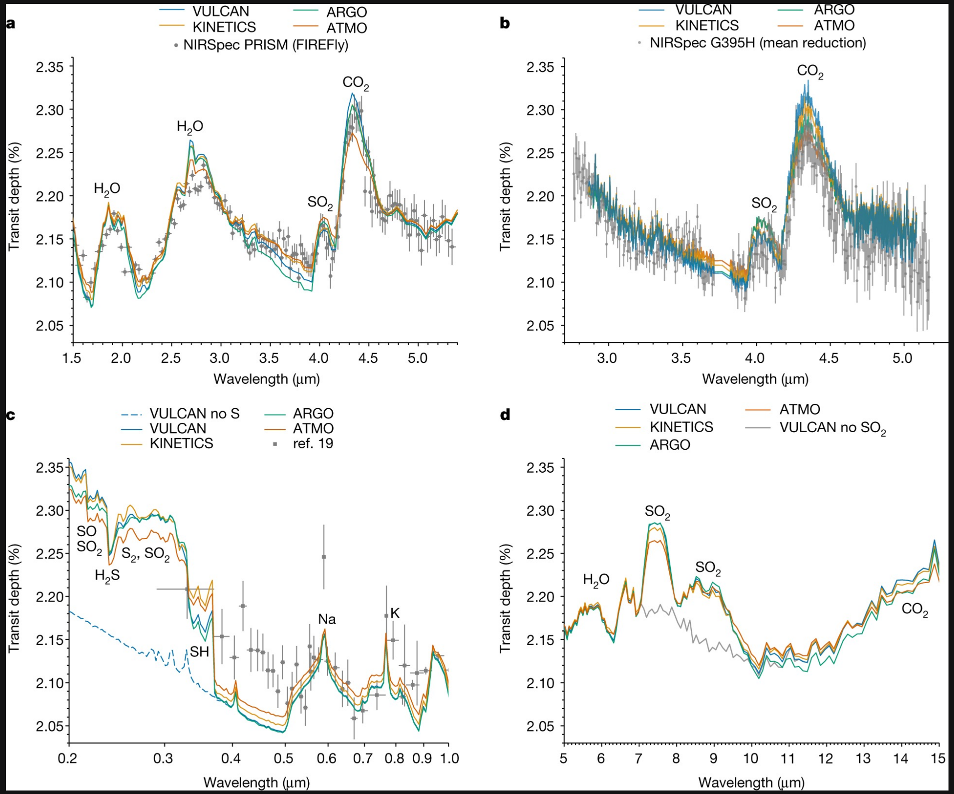
Density: $\mathbf{0.060} \pm 0.019 g \cdot cm^{-3}$

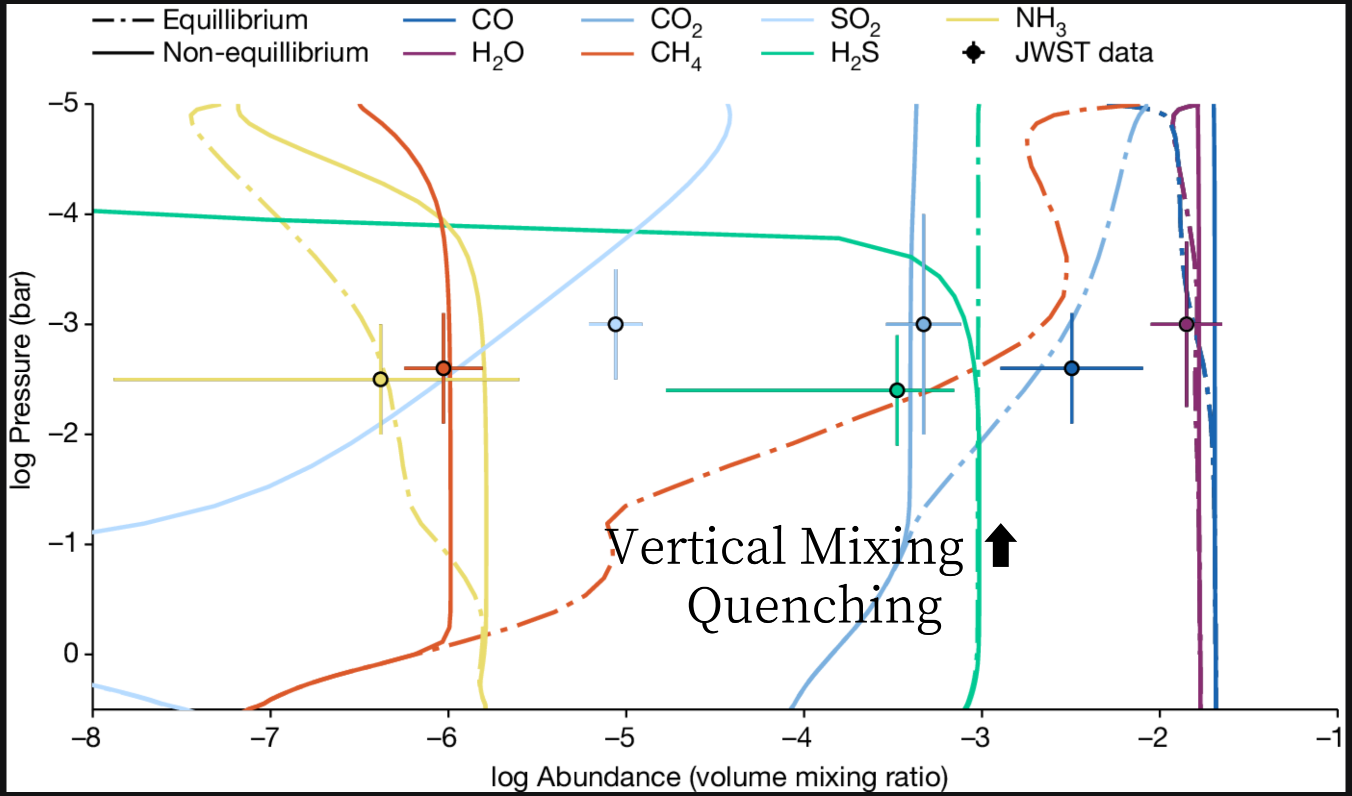
[1] Barkaoui et al. (2024), [2] Yee et al.(2025), [3] Lee & Chiang (2016)

Thermal Structure Controls Chemical Abundance

(Thousands of cases)

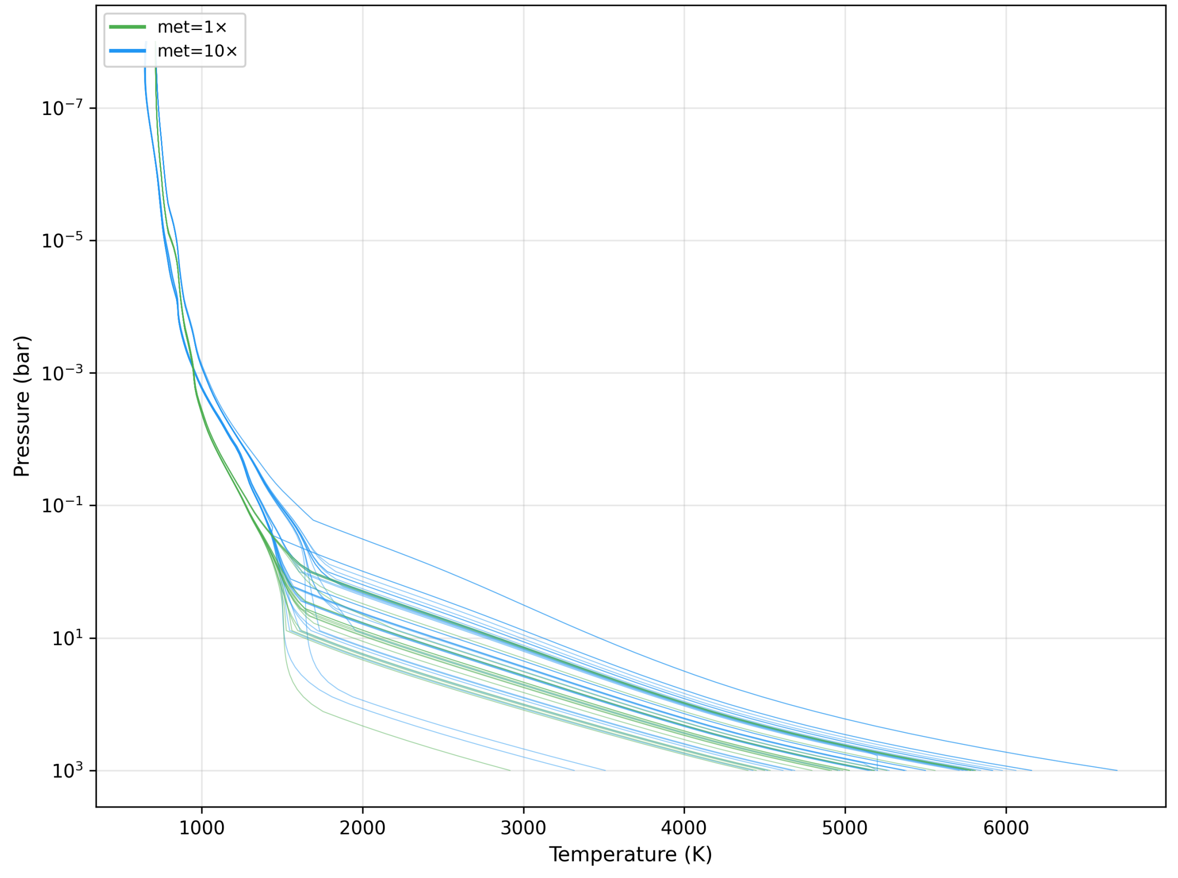
Observational Spectrum ⬅➡ Chemical abundances ⬅➡

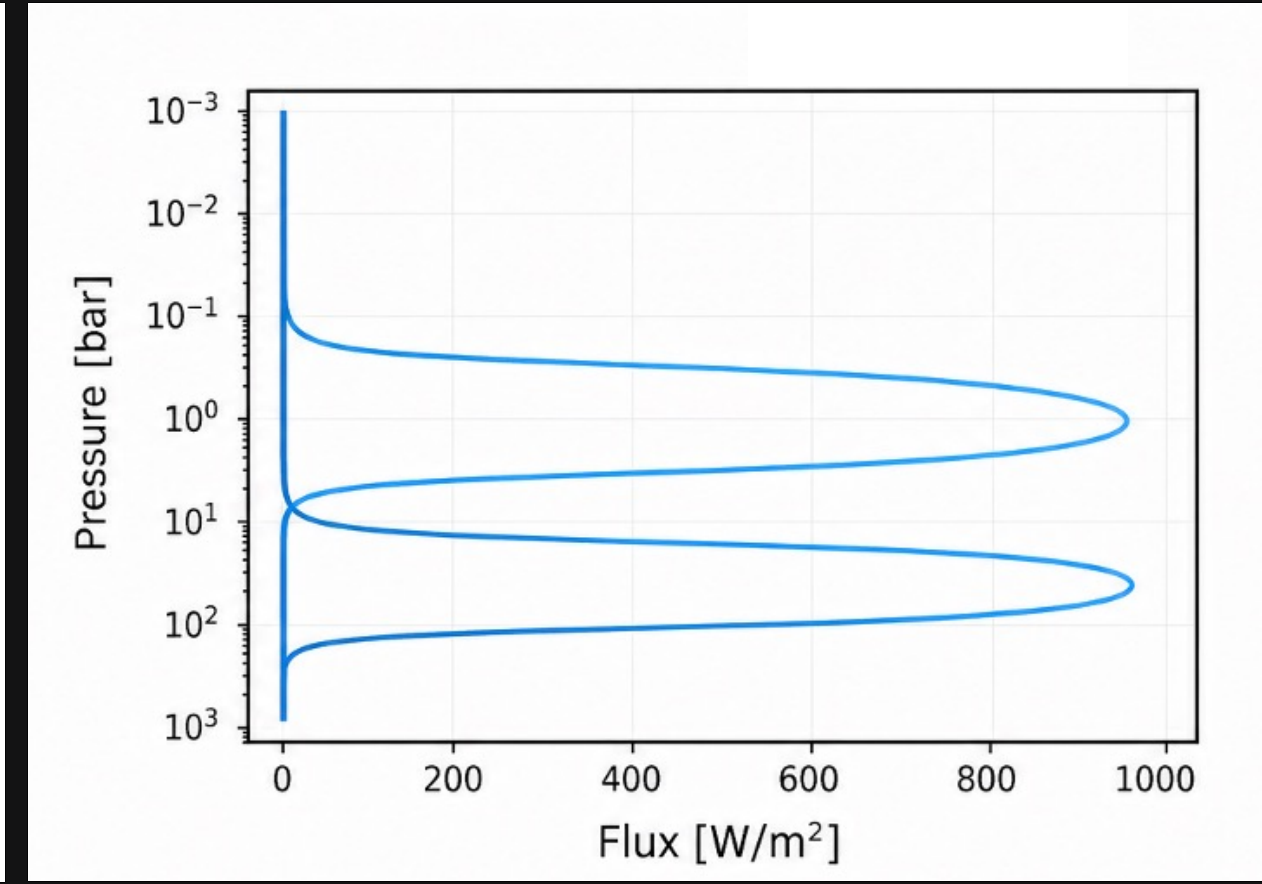




Deep Heating Changes the Thermal Structure

⟺ Temperature-Pressure Profile ⟺ Deep Heating

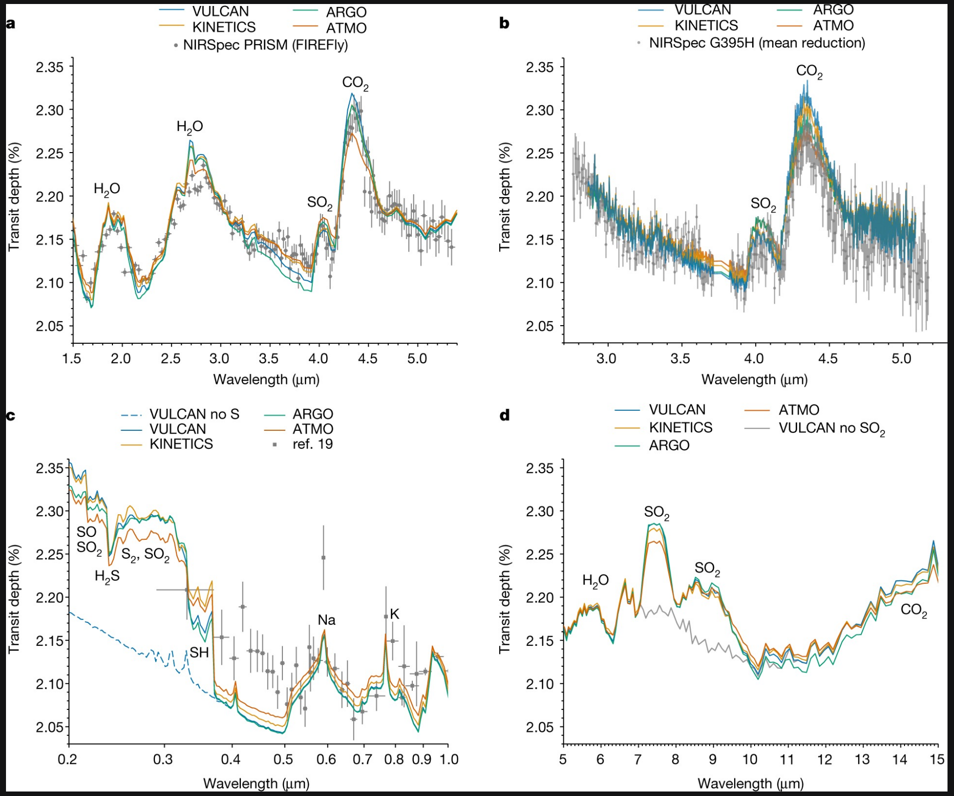


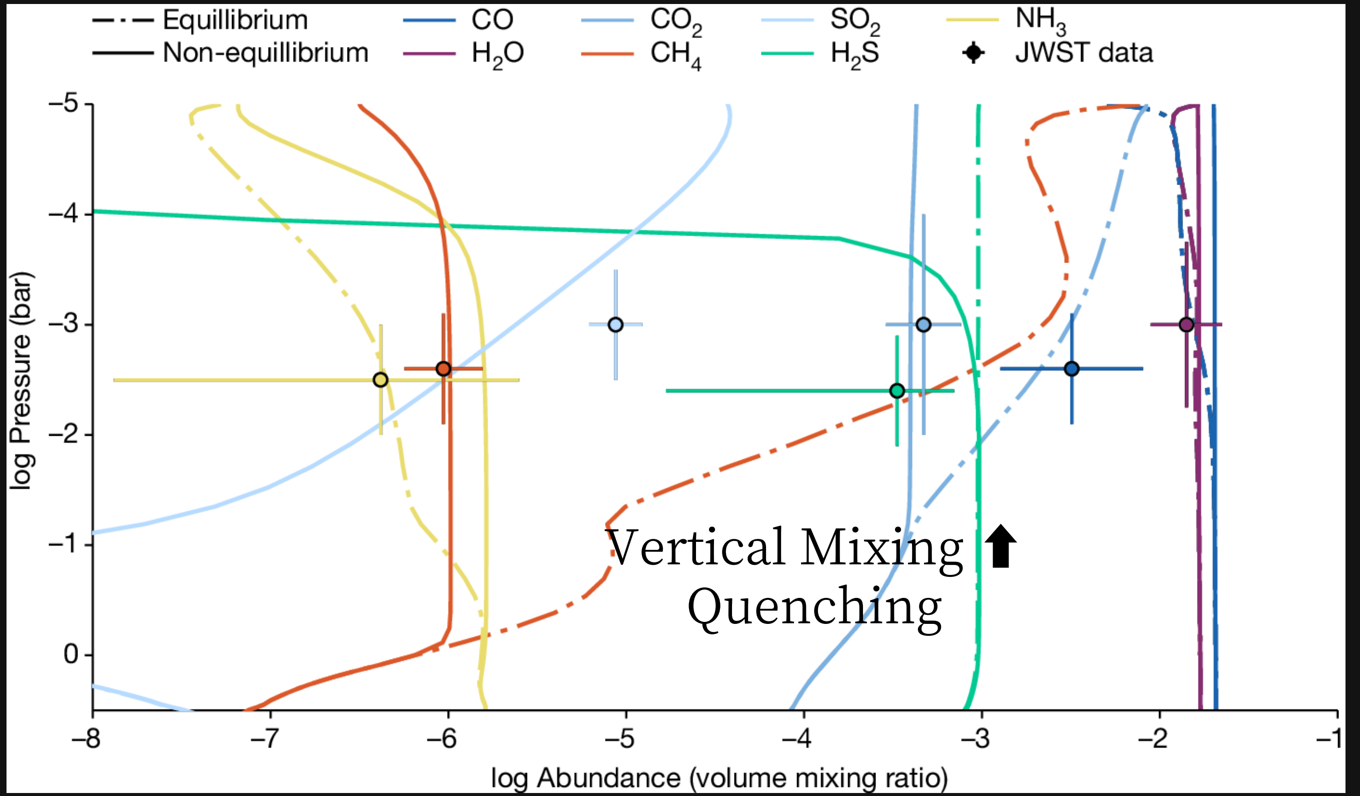


Thermal Structure Controls Chemical Abundance

(Thousands of cases)

Simulation Spectrum ⟺ Chemical abundances ⟺





(Sing et al., 2024, Welbanks et al., 2024 : WASP-107b)

From T_{int} to Heating Deposition

(Sing et al., 2024)

Past approach:

Fixed T-P Profile T_{int}

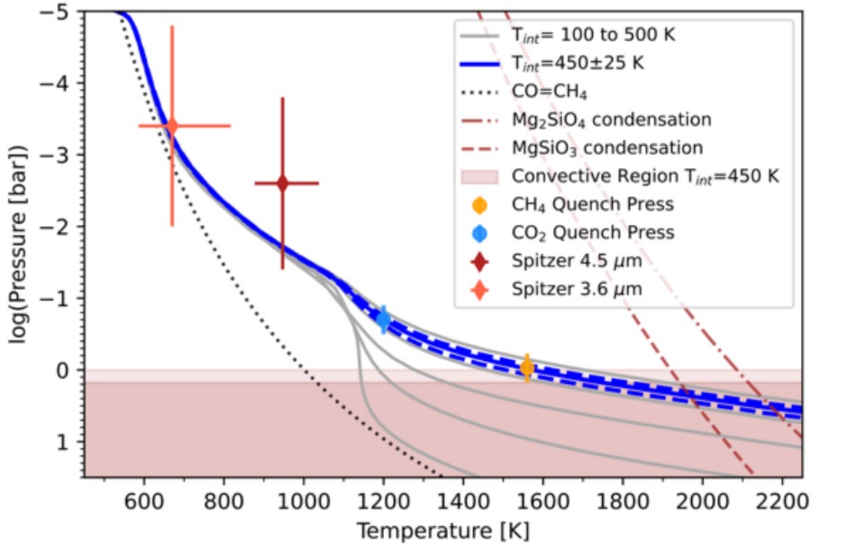
→ Non-EQ chemistry

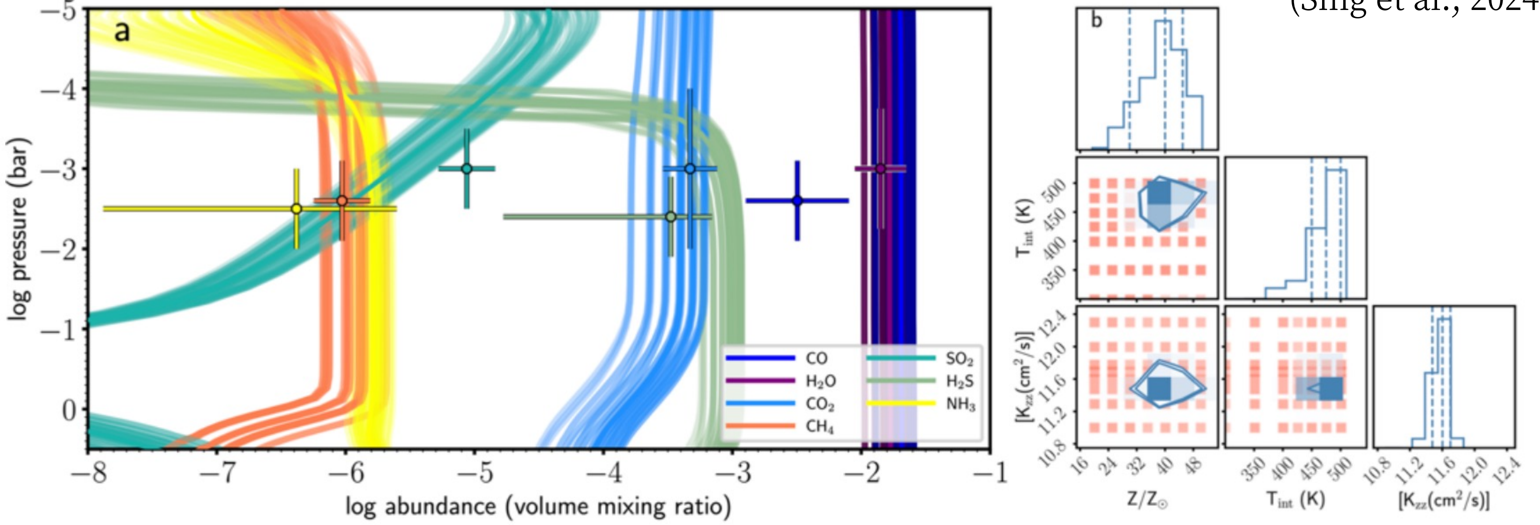
→ Match abundance

This works:

T_{int} & deep heating → Radiation Transfer & chemistry coupled model

→ Understanding the effects on chemistry

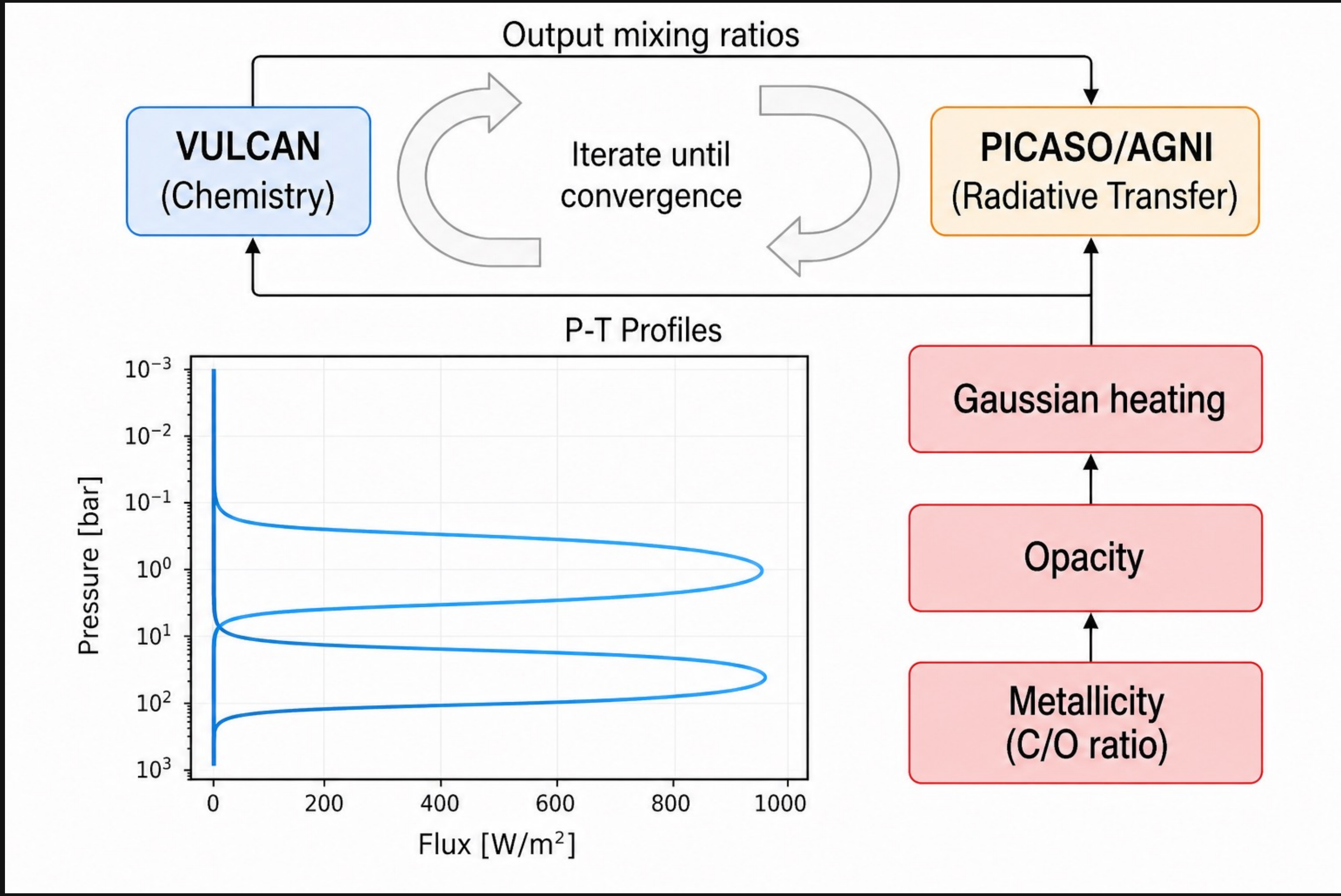




(Sing et al., 2024)

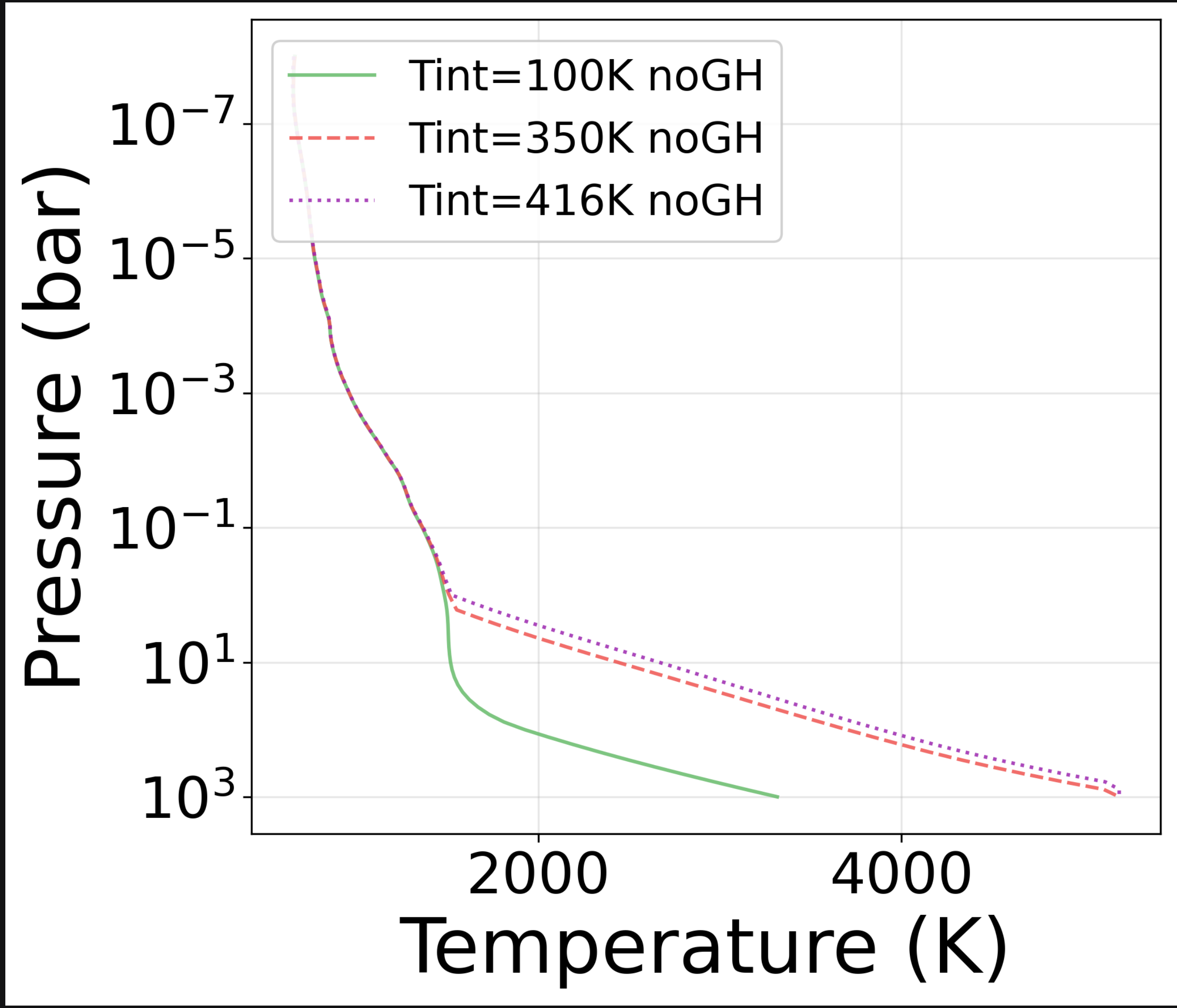
Self-Consistent Radiative–Convective-Chemical Model

Parameter	Grids
Tint	100,350 K
Metallicity	1x,10x solar
C/O ratio	0.55 (solar), 0.8
P_{GH}	1,10,100 bar
Strength q	0.3, 1, 10



From T_{int} to Heating Deposition

Metallicity 10x, C/O ratio 0.8



Tint as a lower-boundary condition

$$F_{int} = \sigma T_{int}^4$$

Tint100K: cold baseline

Tint350K / Tint416K: hotter baselines

(Sing et al., 2024, Welbanks et al., 2024 : WASP-107b)

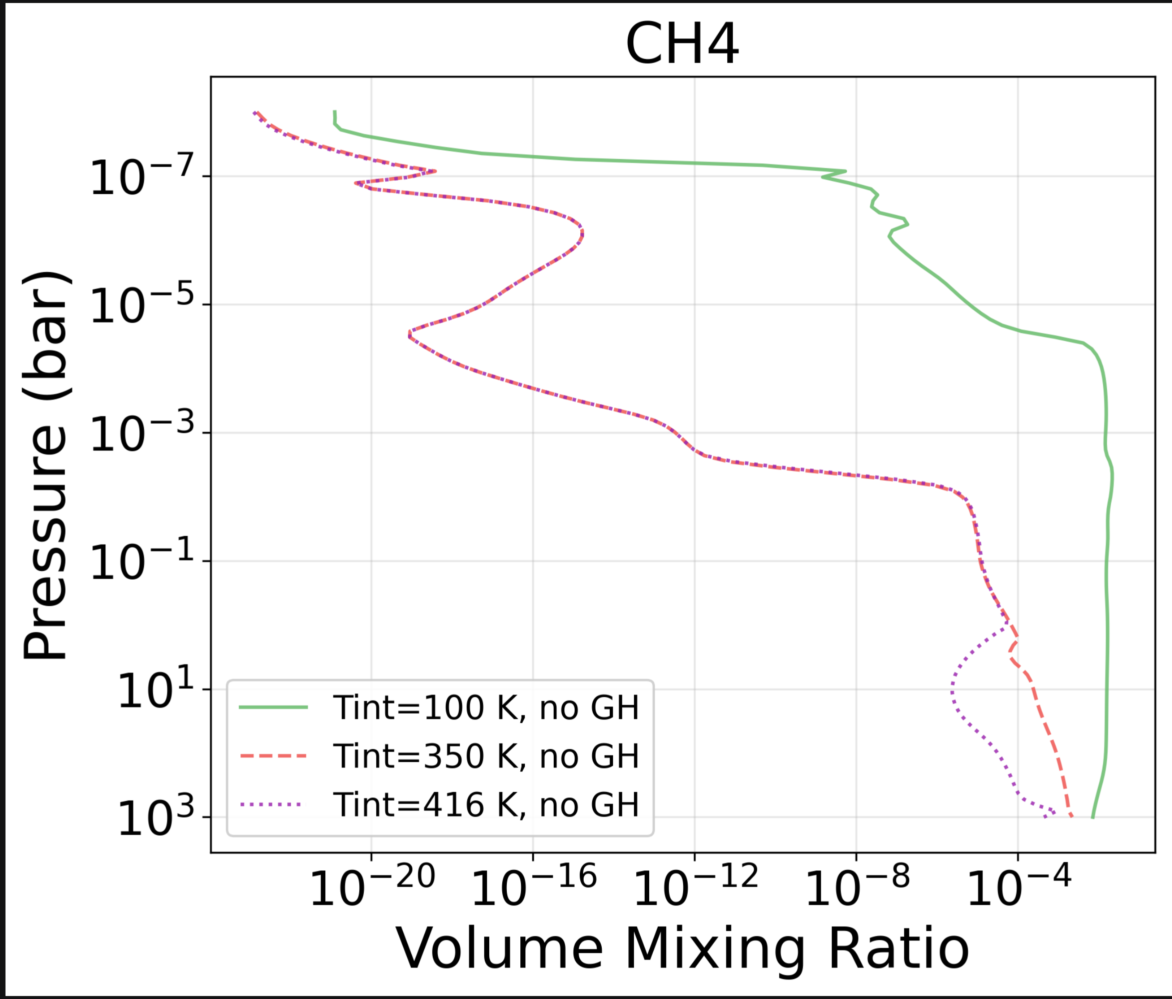
Cool CH_4-rich vs Hot CH_4-poor

CH_4 depletion as a deep thermal tracer:

$$CO + 3H_2 \rightleftharpoons CH_4 + H_2O + Heat$$

Tint100K: Cold baseline, CH_4 rich

Tint350K/416K: Hot deep adiabat, carbon shifts toward CO, CH_4 poor.



(Sing et al., 2024, Welbanks et al., 2024)

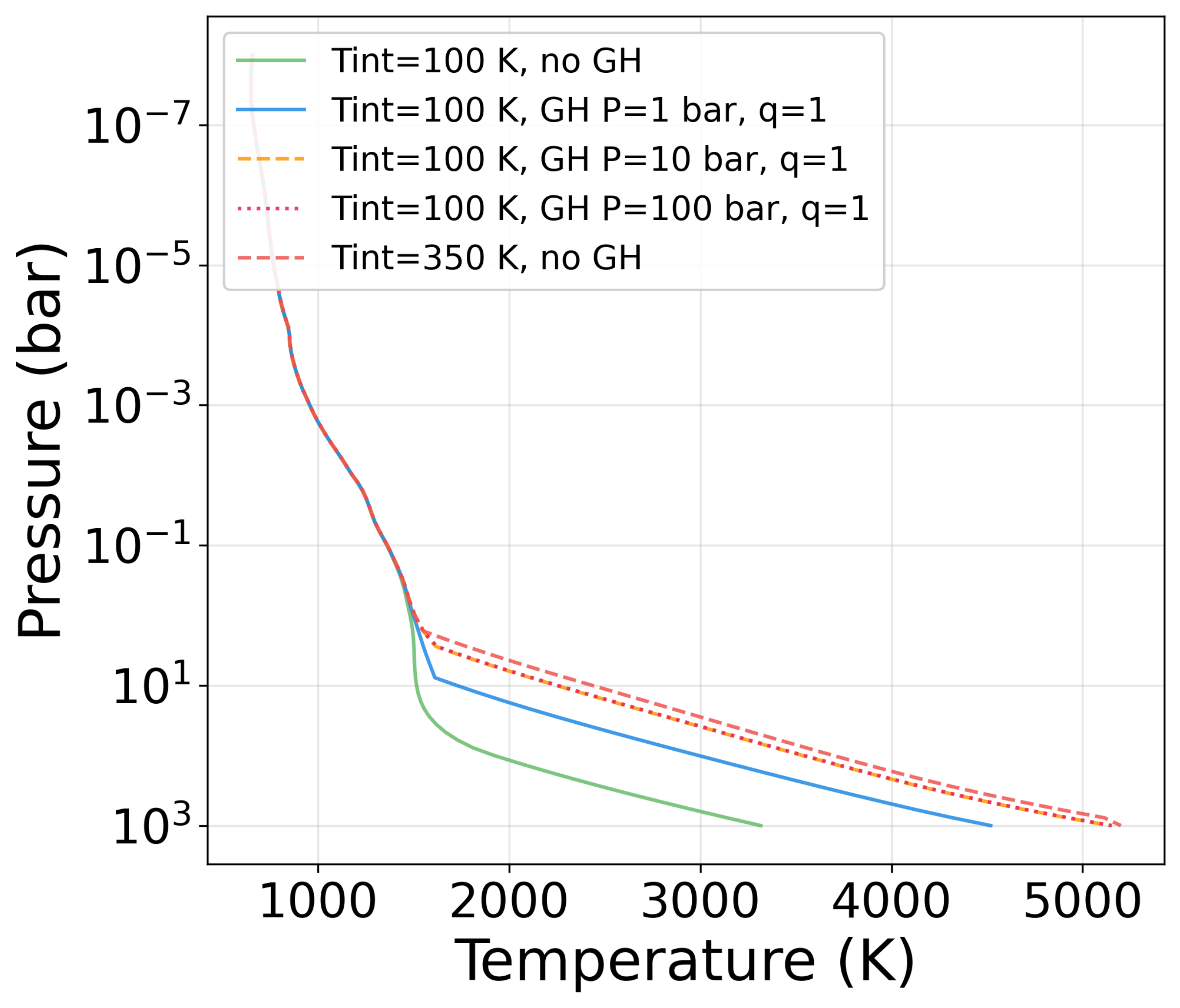
GH Produces a Strong TP Perturbation

Metallicity 10x, C/O ratio 0.8

$$F_{Tint=100K} + F_{GH} \simeq F_{Tint=350K}$$

Tint100K + GH: localized heating warms selected pressure layers

Tint350K noGH:
similar flux, but hotter profile.



GH Produces a Strong TP Perturbation

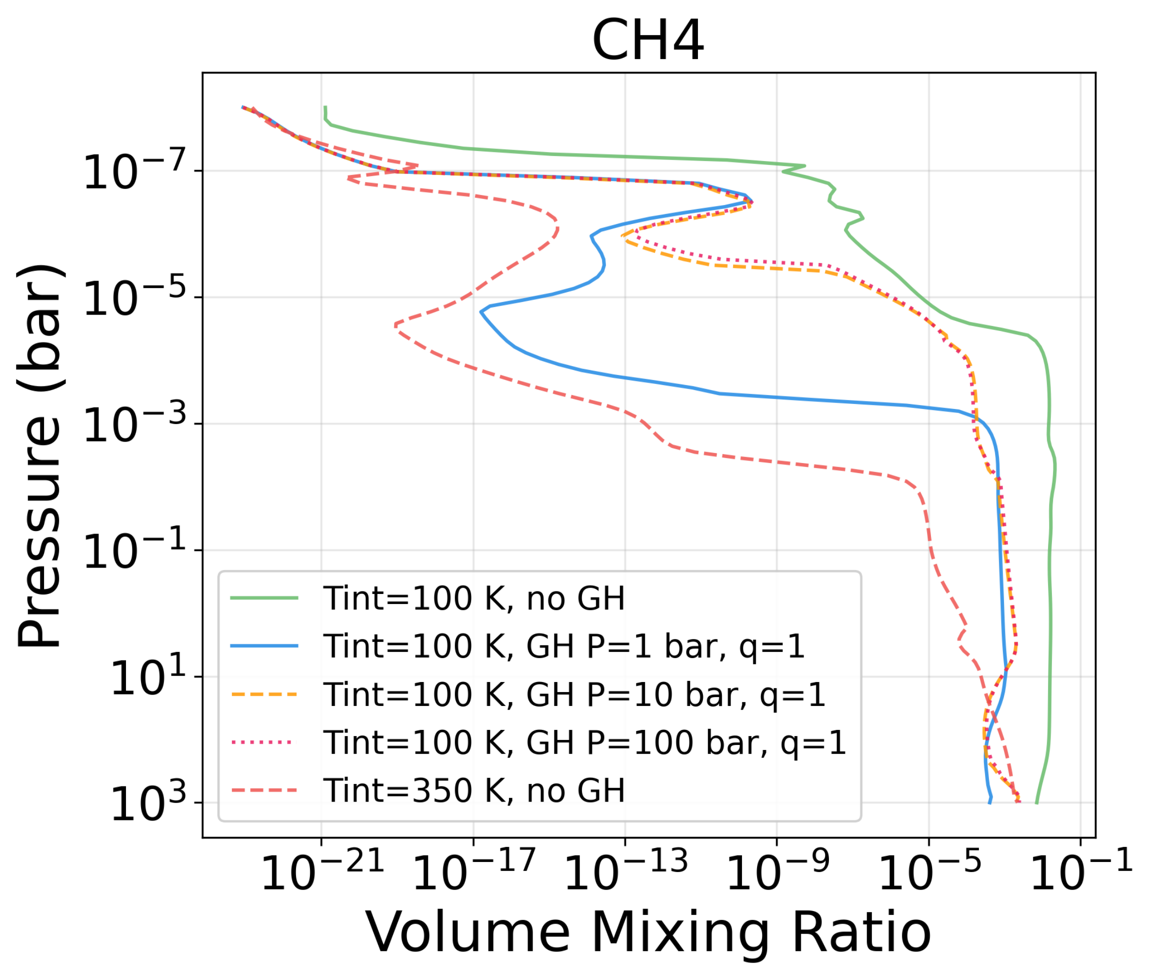
CH_4 depletion as a deep thermal tracer:

$$CO + 3H_2 \rightleftharpoons CH_4 + H_2O + Heat$$

CH_4 Abundance :

$$T_{int}\ 100K > T_{int}\ 100K + GH > T_{int}\ 350K$$

$$GH \neq T_{int}$$



C/O = 0.8 Creates a Cooler and CH_4-Rich Branch

Tint 350K no GH vs Tint 100K GH

C/O ↑ , H_2O , CO_2 opacity ↓⇒T(P) ↓

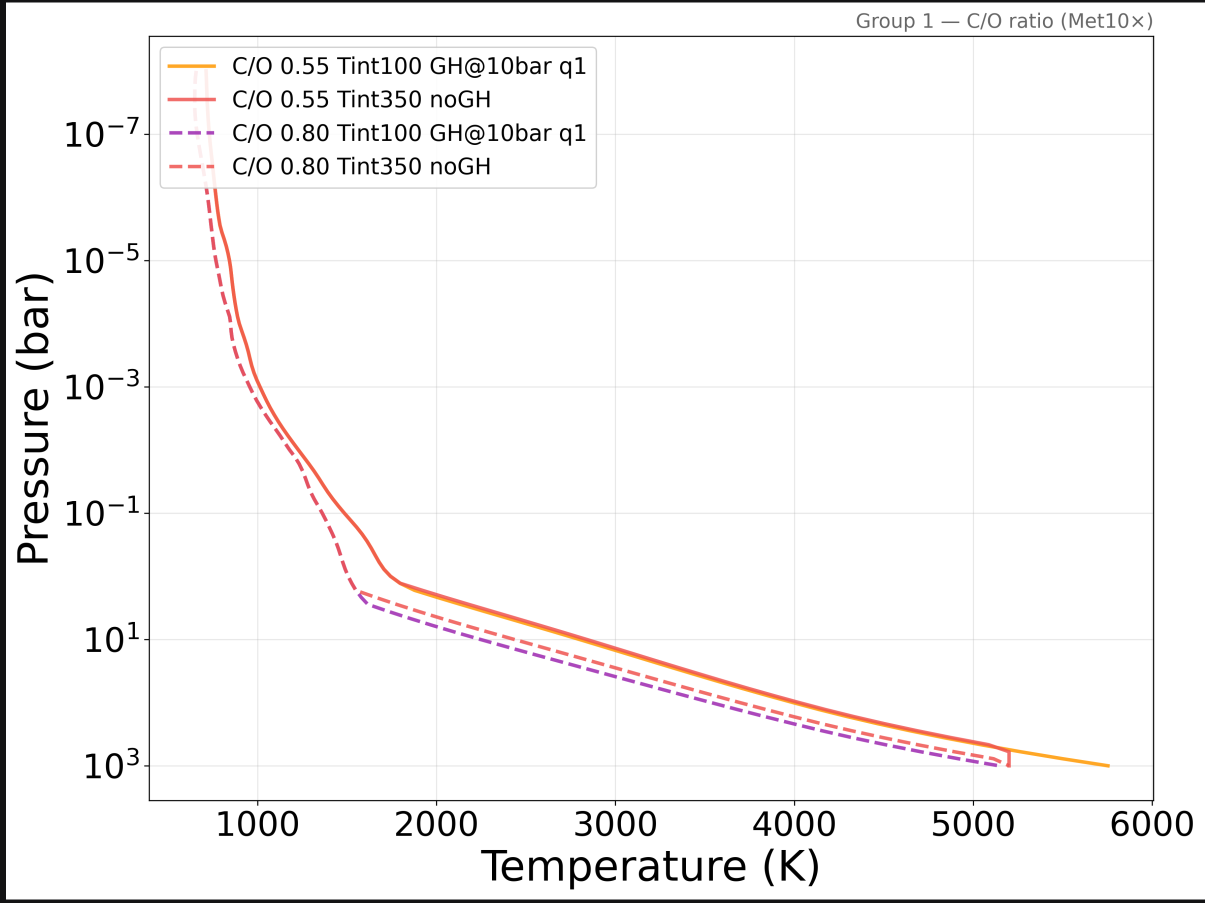
C/O = 0.55:

oxygen-rich → H_2O / CO_2 stronger

C/O = 0.8:

oxygen depleted → H_2O / CO_2 decrease

carbon shifts toward CH_4



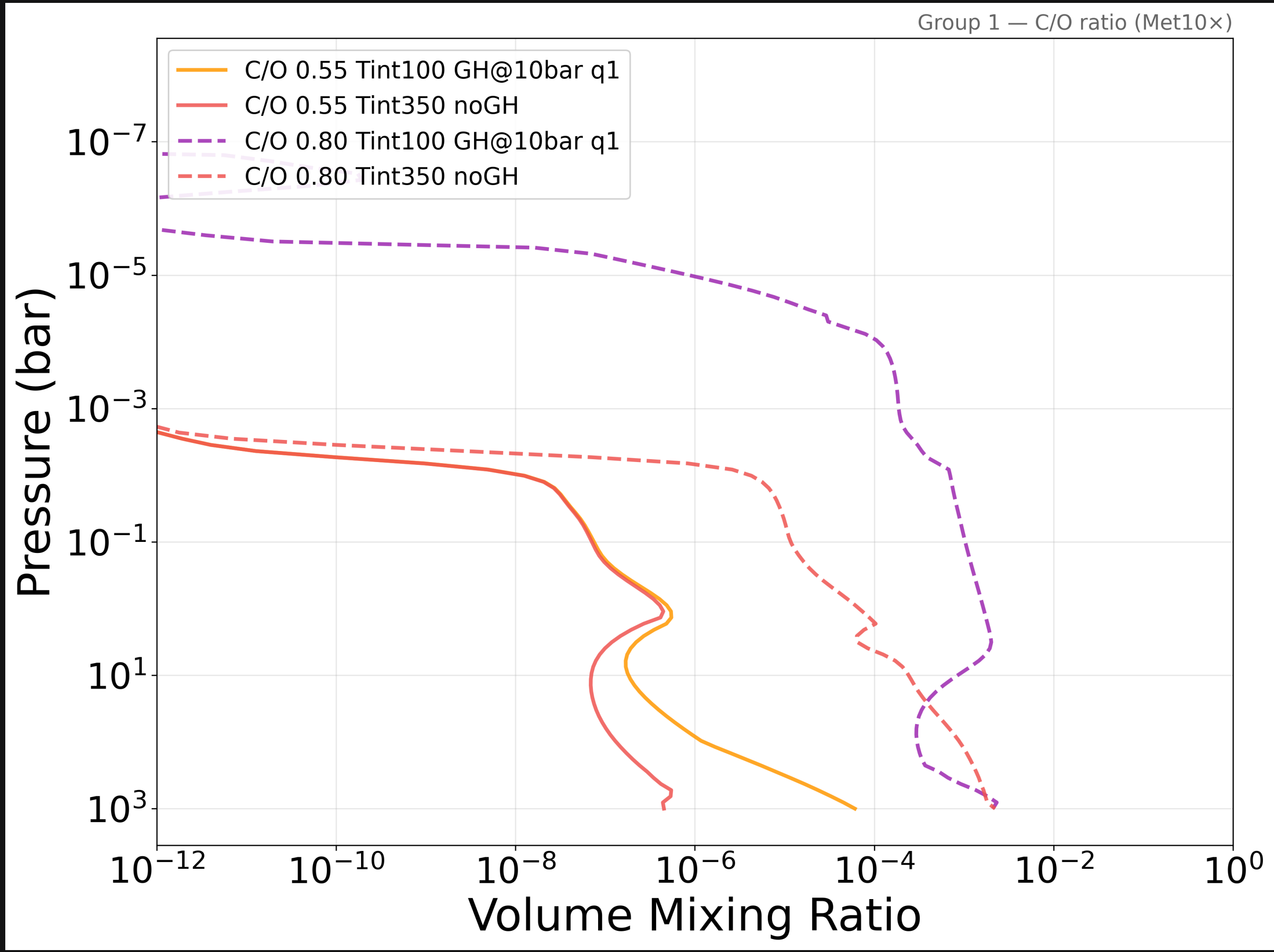
C/O = 0.8 Creates a Cooler and CH_4-Rich Branch

$$CO + 3H_2 \rightleftharpoons CH_4 + H_2O + Heat$$

C/O = 0.55, hot and CH_4 depletion.

C/O = 0.8, cool and CH_4 increase.

$\Delta VMR \simeq$ 3–4 dex



C/O = 0.8 Creates a Cooler and CH_4-Rich Branch

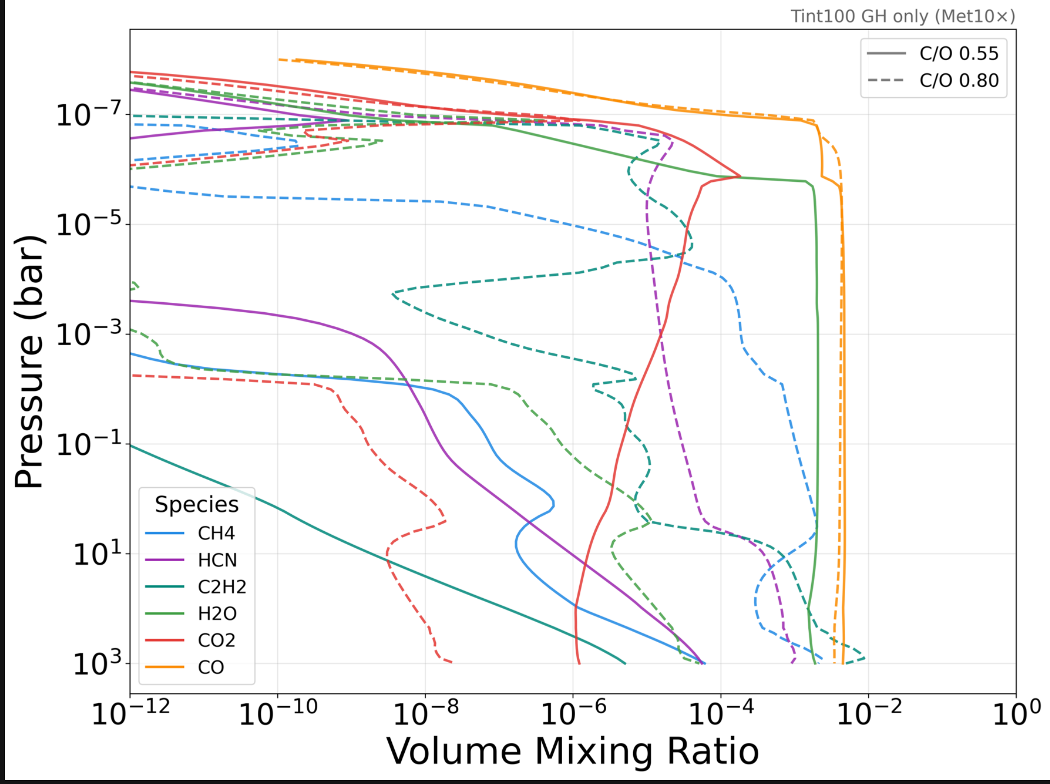
Tint 350K No GH C/O = 0.55 vs 0.8

Pressure	ΔT	CH4 ratio	HCN ratio	H2O ratio	CO2 ratio
0.1 bar	-124K	1.7×10^{2}	1.3×10^{2}	3.3×10^{-2}	4.1×10^{-2}
1 bar	-237K	1.6×10^{2}	2.1×10^{1}	7.2×10^{-2}	9.8×10^{-2}
10 bar	-404K	3.5×10^{3}	6.3×10^{2}	1.5×10^{-3}	1.8×10^{-3}
100 bar	-331K	6.8×10^{3}	8.5×10^{2}	3.4×10^{-4}	4.1×10^{-4}

Tint 100K GH @10bar C/O = 0.55 vs 0.8

Pressure	ΔT	CH4 ratio	HCN ratio	H2O ratio	CO2 ratio
0.1 bar	−124 K	1.4×10^{4}	1.9×10^{3}	3.3×10^{-4}	3.7×10^{-4}
1 bar	−238 K	3.2×10^{3}	4.7×10^{2}	3.0×10^{-3}	3.6×10^{-3}
10 bar	−553 K	4.7×10^{3}	4.0×10^{2}	1.8×10^{-3}	1.9×10^{-3}
100 bar	−458 K	2.4×10^{2}	7.6×10^{1}	8.6×10^{-3}	6.7×10^{-3}

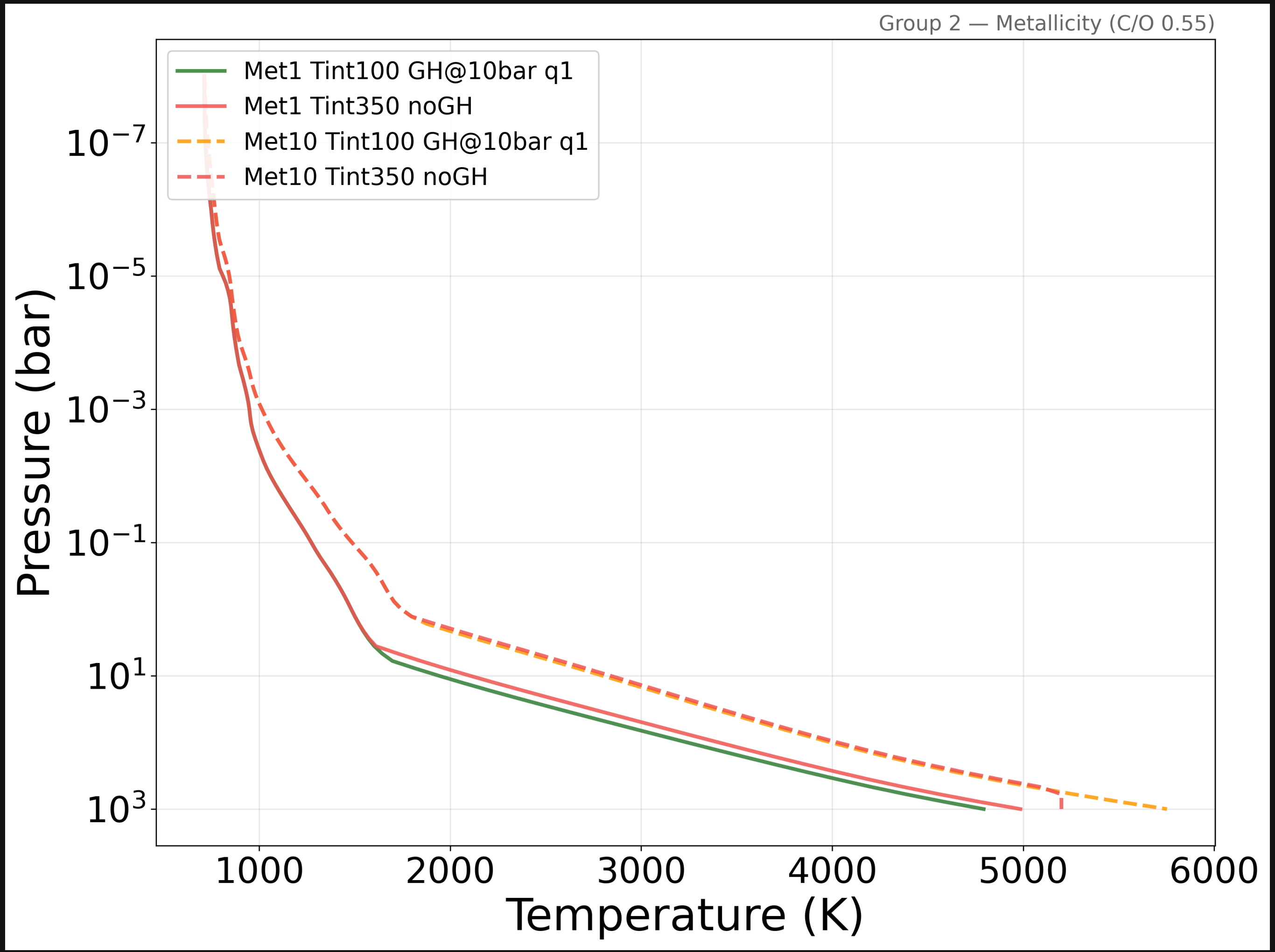
Tint 100K GH @10bar Met 10x



Metallicity 10x Creates a Hot but CH_4-Poor Branch

met $\uparrow \Rightarrow$ IR opacity $\uparrow \Rightarrow$ T(P) $\uparrow$

10× metallicity warms 0.1–100 bar by ~200–850 K.



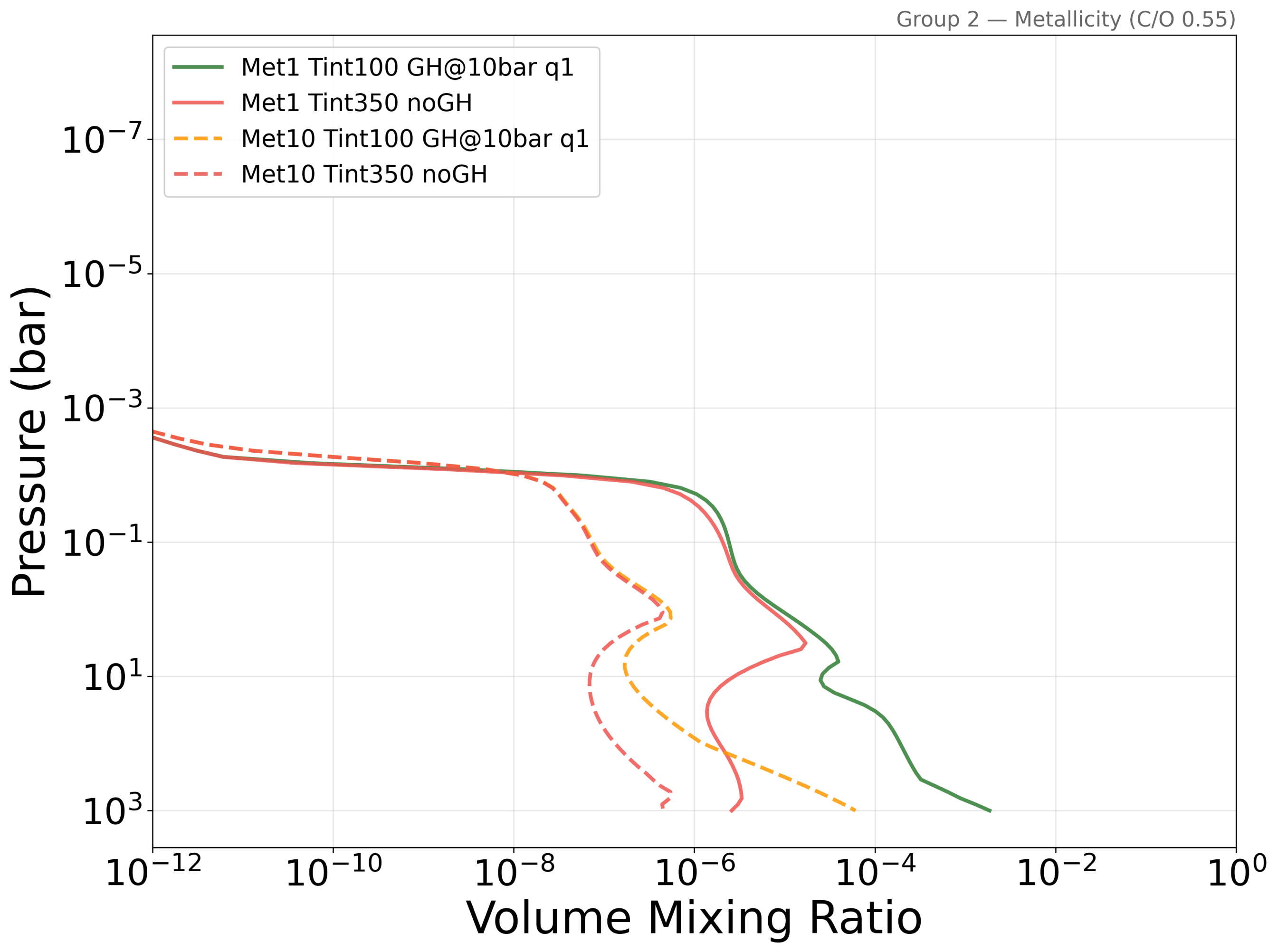
Metallicity 10x Creates a Hot but CH_4-Poor Branch

$$CO + 3H_2 \rightleftharpoons CH_4 + H_2O + Heat$$

Met = 1x, cool and CH_4 remained.

Met = 10x, hot but CH_4 depletion.

$$\Delta VMR \simeq -1\text{–}2 \text{ dex}$$



Metallicity 10x Creates a Hot but CH_4-Poor Branch

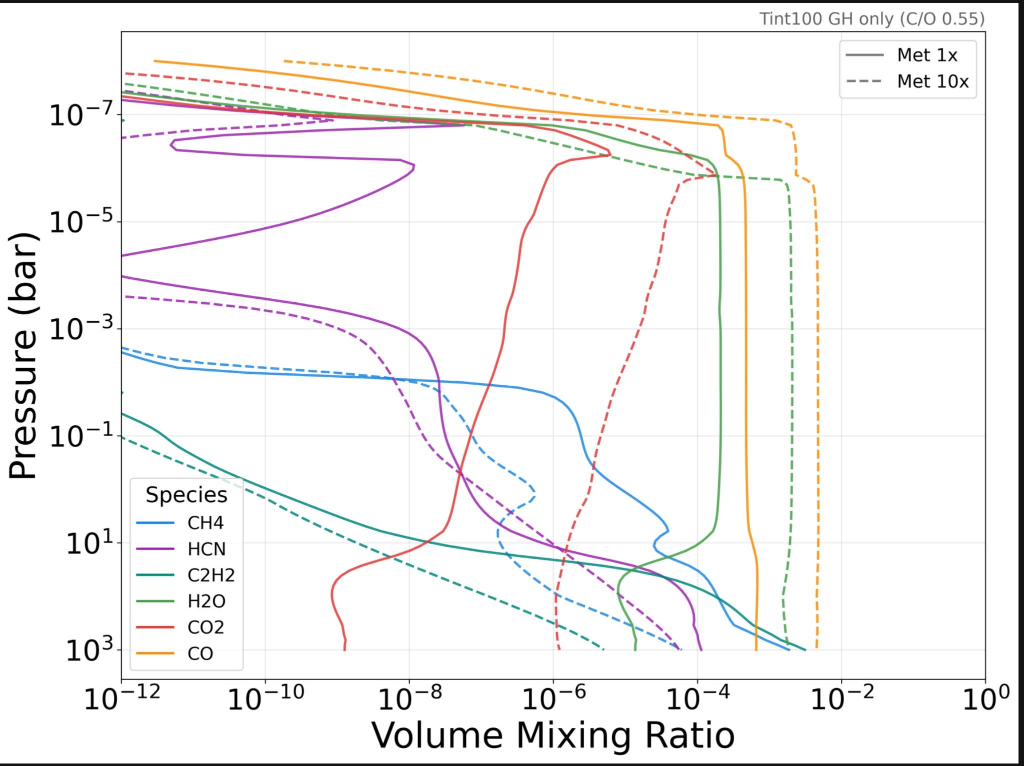
Tint 350K No GH Met = 1x vs 10x

Pressure	ΔT	CH4 ratio	HCN ratio	H2O ratio	CO2 ratio
0.1 bar	+213K	3.5×10^{-2}	1.44	10.0	66.0
1 bar	+263K	6.2×10^{-2}	1.83	10.1	71.5
10 bar	+735K	2.5×10^{-2}	2.08	15.0	108.9
100 bar	+623K	7.0×10^{-2}	0.99	33.1	338.9

Tint 100K GH @10bar Met = 1x vs 10x

Pressure	ΔT	CH4 ratio	HCN ratio	H2O ratio	CO2 ratio
0.1 bar	+213 K	3.1×10^{-2}	0.49	9.8	64.6
1 bar	+263 K	5.9×10^{-2}	1.47	10.2	70.4
10 bar	+857 K	7.1×10^{-3}	1.36	17.8	94.6
100 bar	+754 K	6.6×10^{-3}	0.13	190	1290

Tint 100K GH @10bar CO = 0.55



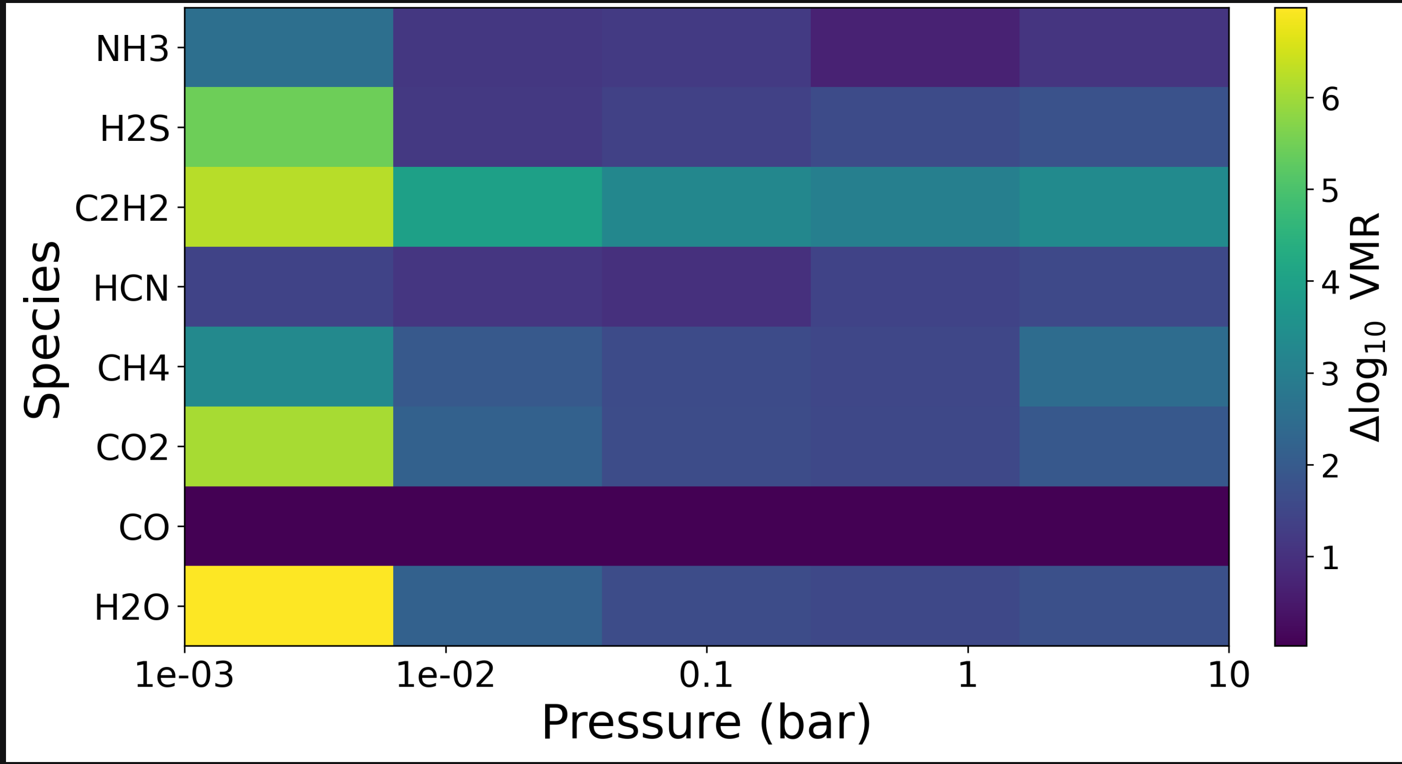
Not only CH_4, Multi-species is needed

$CH_4/\ C_2H_2/\ H_2S$:

deep thermal / quench tracer

CO:

stable carbon reservoir



Conclusion

1. WASP-193 b inflated radius motivates deep energy deposition.

2. Tint and Gaussian heating are not equivalent.

3. Composition reshapes TP through opacity feedback, **Met 10x** warms the atmosphere, while **C/O=0.8** creates a cooler carbon-rich branch.

4. Multi-species chemistry is required:
- CH_4 traces deep thermal/quench state
- CO is a stable reservoir
- C_2H_2/ H_2S provide secondary diagnostics.