The Importance of Moist Convection Inhibition for Planets in the Habitable Zone

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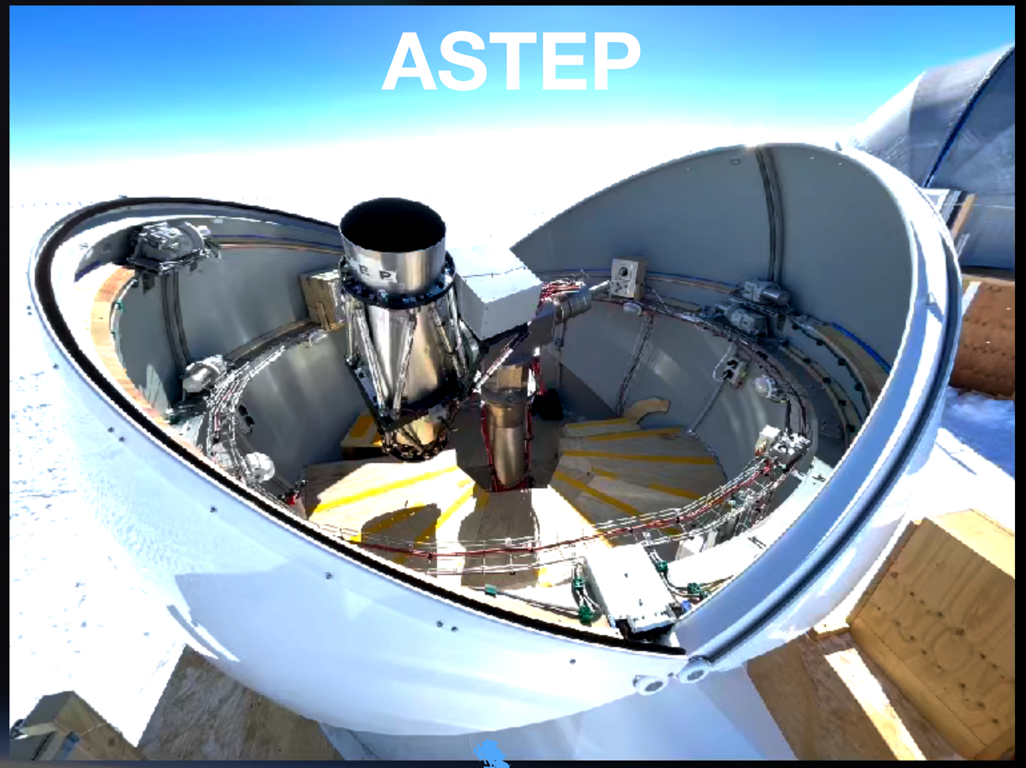
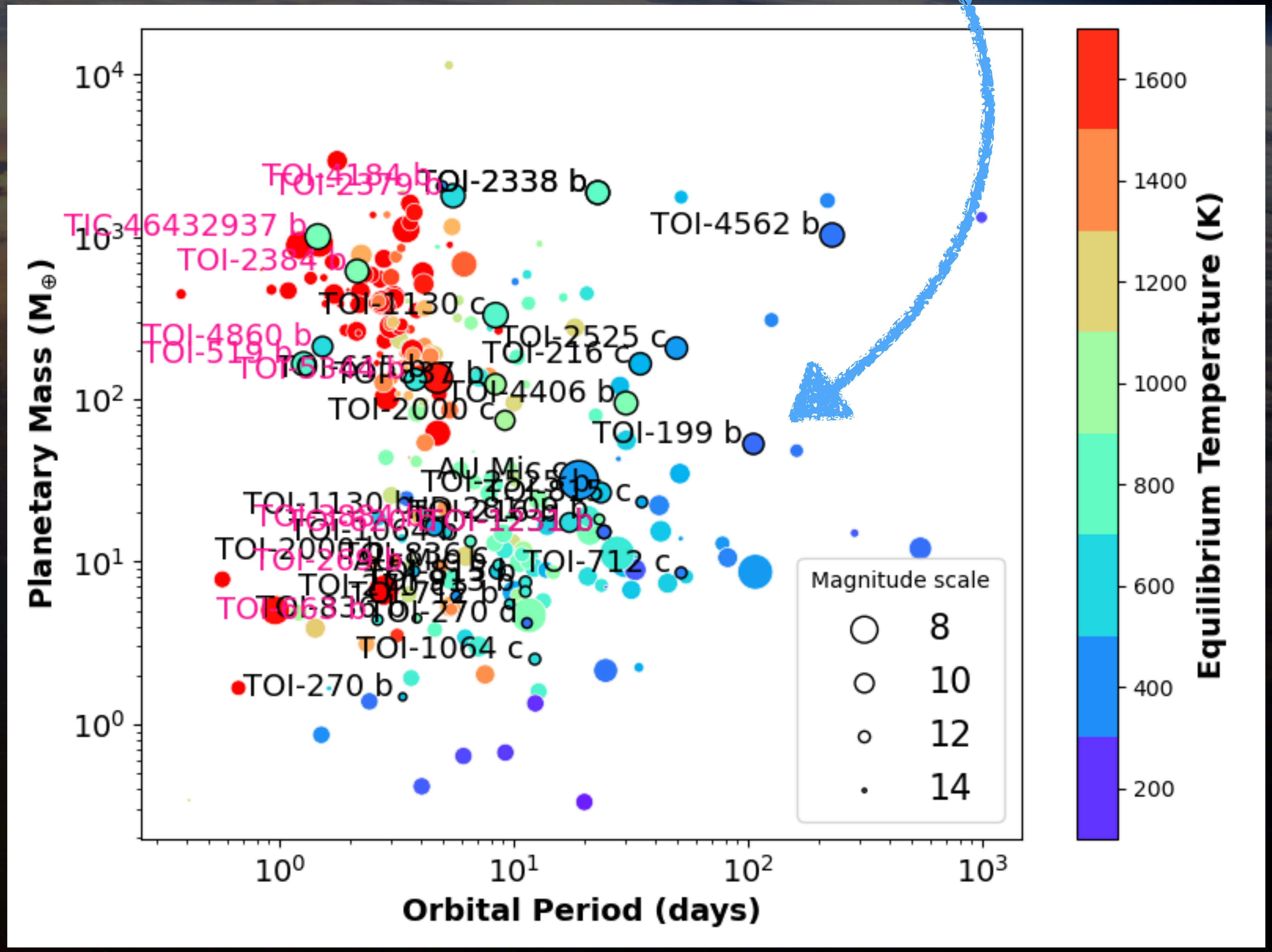
Planets in the Habitable Zone

- Will come in all kinds of masses, radii, compositions
  - Earth-like planets, with an H_2O ocean and 1 bar of N_2 and O_2
  - Earth-like planets, with vastly different atmospheres (and perhaps an H_2O ocean)
  - Super-Earths (with perhaps an H_2O ocean)
  - Mini-Neptunes (with perhaps an H_2O ocean)
  - Ice giants (with perhaps an H_2O ocean)
  - Gas giants & brown dwarfs

- Their atmospheres too
  - Different masses and extent:
    - No atmosphere
    - Optically thin to moderately thick atmosphere
    - Abyssal atmosphere
  - Different compositions:
    - Light (with a significant amount of hydrogen)
    - Moderately heavy (with e.g., N_2 or CO_2)





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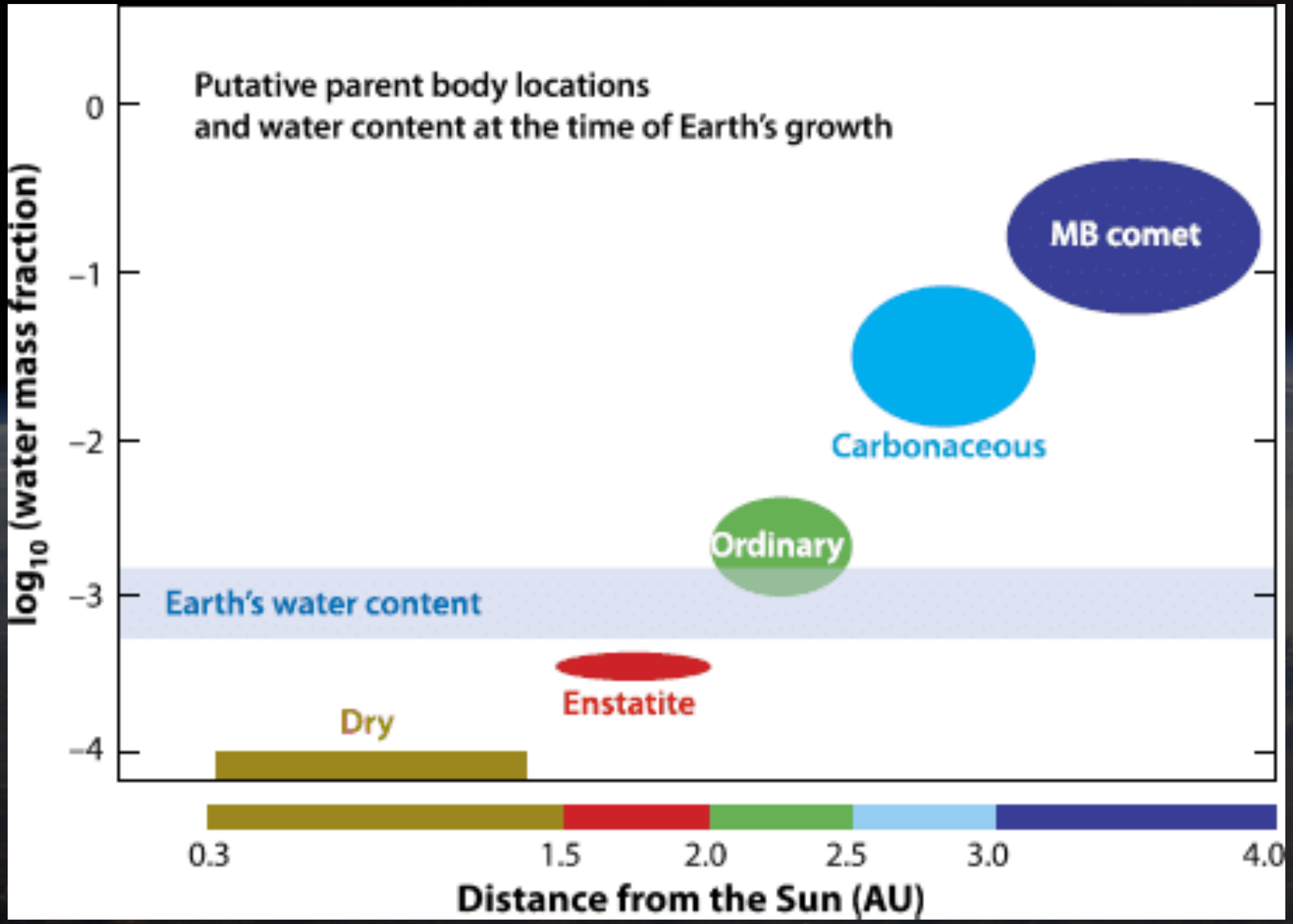
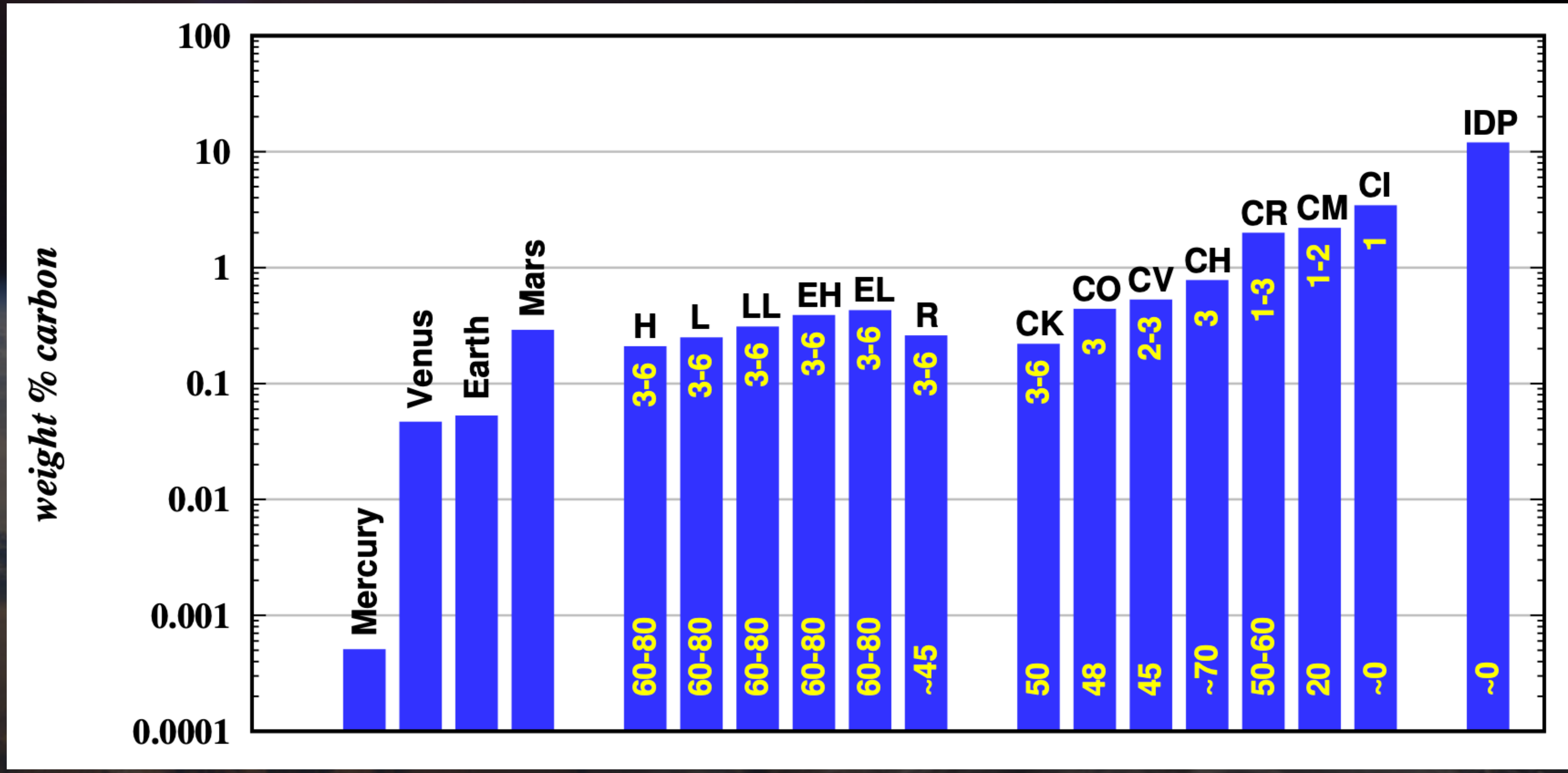
The Earth is dry, carbon-poor and with no molecular hydrogen



Morbidelli et al. (2012)



Gail & Trieloff (2017)

	Geosphere	Hydrosphere	Atmosphere
	Units alongside elements	**Units alongside elements**	**ppm**
Hydrogen	0.15 wt% in water, hydrocarbons and as H_2	10.7 wt%	0.5–1.0 as H_2, variable as H_2O
Helium	8 ppb	7.2 ppt	5.2
Lithium	20 ppm	0.18 ppm	zero

For comparison, 10% = 100 000 ppm, 10 000 000 ppb and 10 000 000 000 ppt.

Gluyas et al. (2024)

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Planets in the HZ could be rich in H_2O and H_2

- Different stellar properties
- Different planet masses
- Stochasticity in planet formation models
- Prevalence of H_2O and H_2 in disks
- Existence of super-puffs

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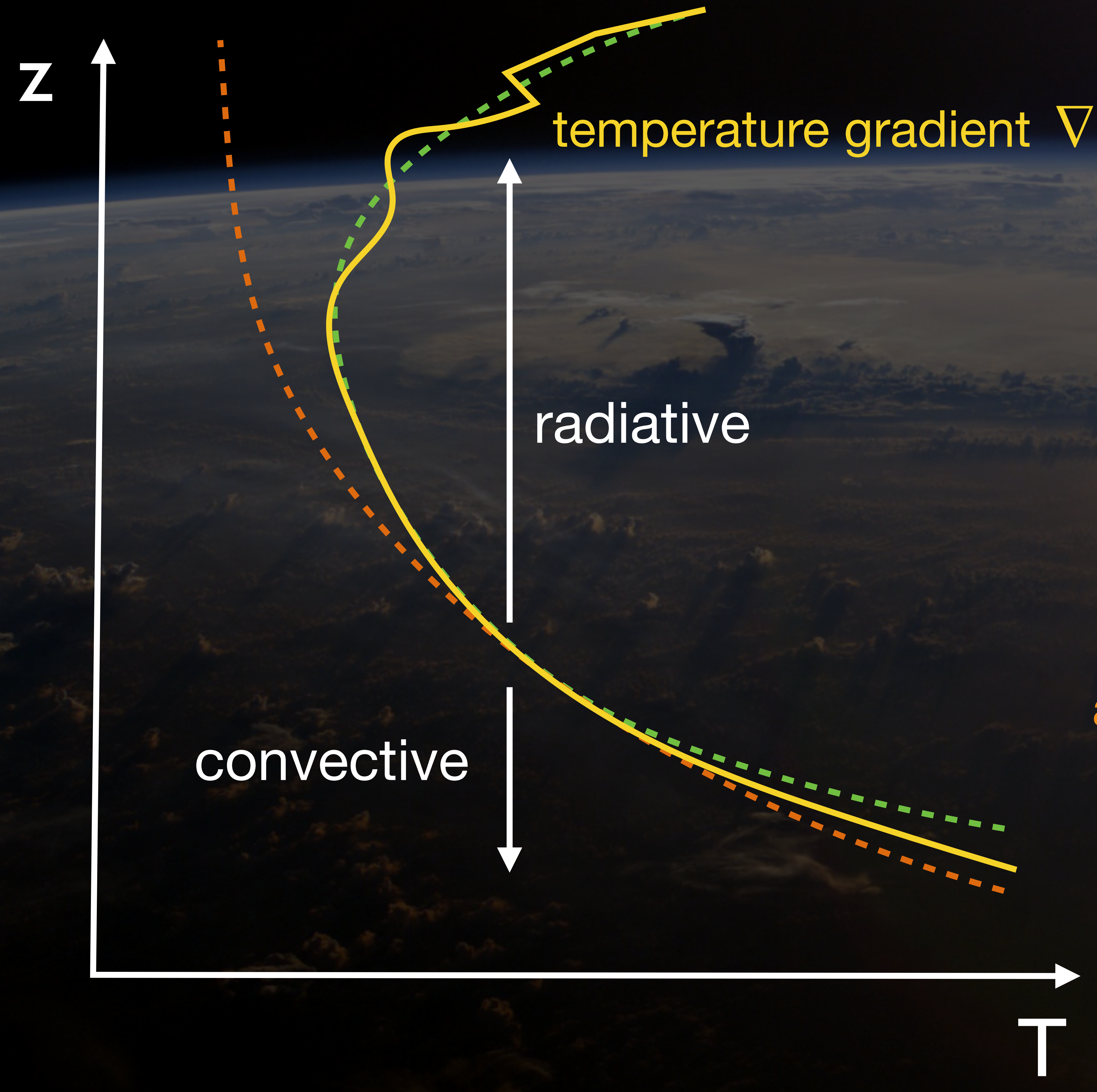
H_2O condensation & atmospheric properties



radiative equilibrium solution $\nabla_{\rm rad} \equiv \left(\frac{d\log T}{d\log P}\right)_{\rm radiative}$

temperature gradient $\nabla_T \equiv \left(\frac{d\log T}{d\log P}\right)$

adiabatic solution $\nabla_{\rm ad} \equiv \left(\frac{\partial\log T}{\partial\log P}\right)_S$

including latent heat $\nabla_{\rm moist} \equiv \nabla_{\rm dry}\left(\frac{1-\frac{\lambda\rho K}{\mu P}\frac{\partial m_1}{\partial P}}{1+\frac{\lambda\rho}{c_P}\frac{\partial m_1}{\partial T}}\right) < \nabla_{\rm dry}$

Convective instability

Heat transport is generally modeled using a simple Schwarzschild criterion

The medium is convective if:

$$\nabla_{\rm ad} \leq \nabla_T^\star < \nabla_T \leq \nabla_{\rm rad}$$

where $\nabla_T \equiv \dfrac{d\ln T}{d\ln P}$,

$\nabla_{\rm ad}$ and $\nabla_{\rm rad}$ are the adiabatic and radiative gradients, respectively.

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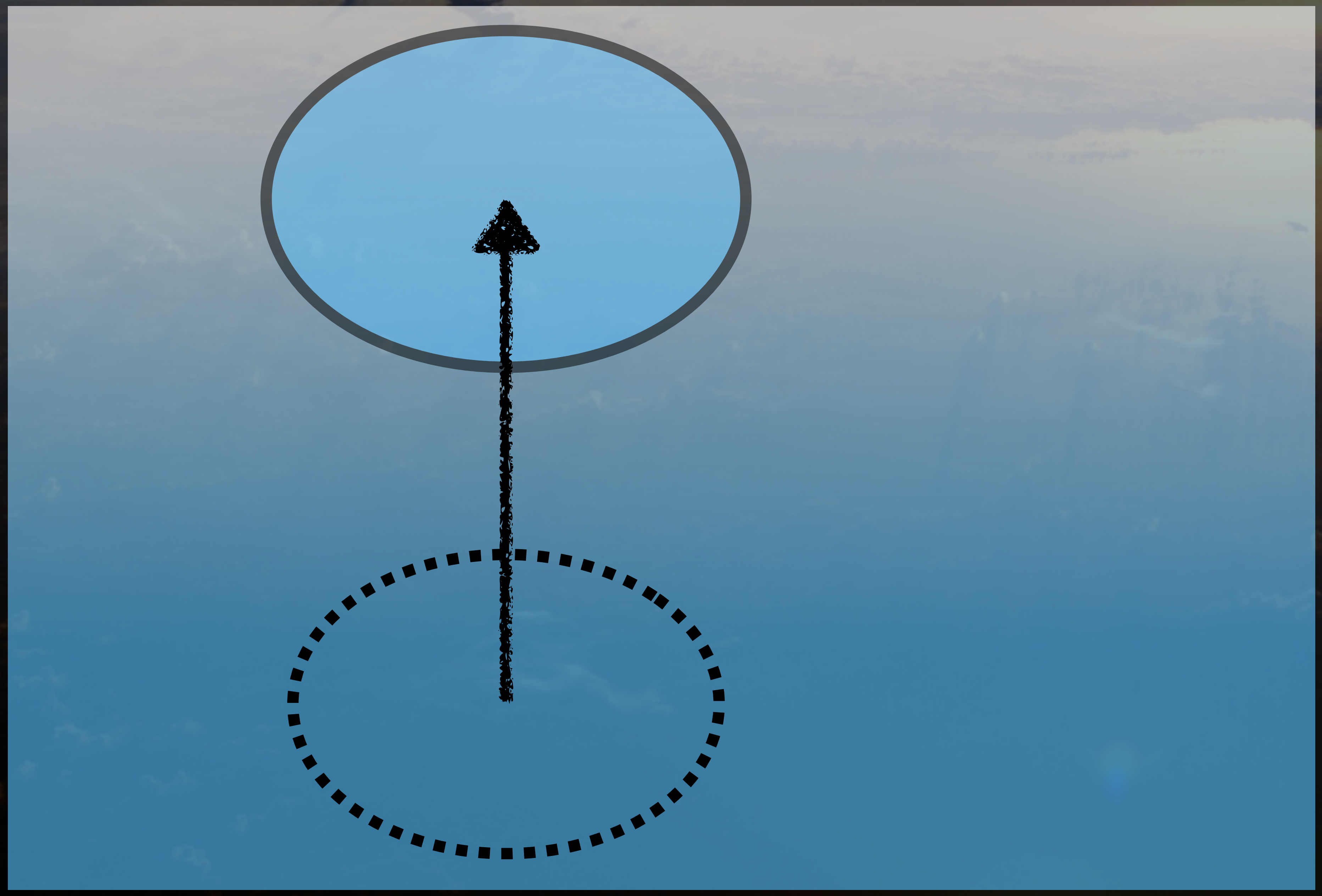
Convective instability: Ledoux criterion

In the presence of a mean molecular weight gradient ∇_μ, the Ledoux criterion applies

The medium is convective if:

$$\nabla_{\rm ad} \quad \leq \quad {\color{red}\nabla_T^\star} \quad < \quad \nabla_T + \nabla_\mu \quad \leq \quad \nabla_{\rm rad} + \nabla_\mu$$



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where $\nabla_T \equiv \dfrac{d\ln T}{d\ln P}$, $\nabla_\mu \equiv \dfrac{d\ln \mu}{d\ln P}$

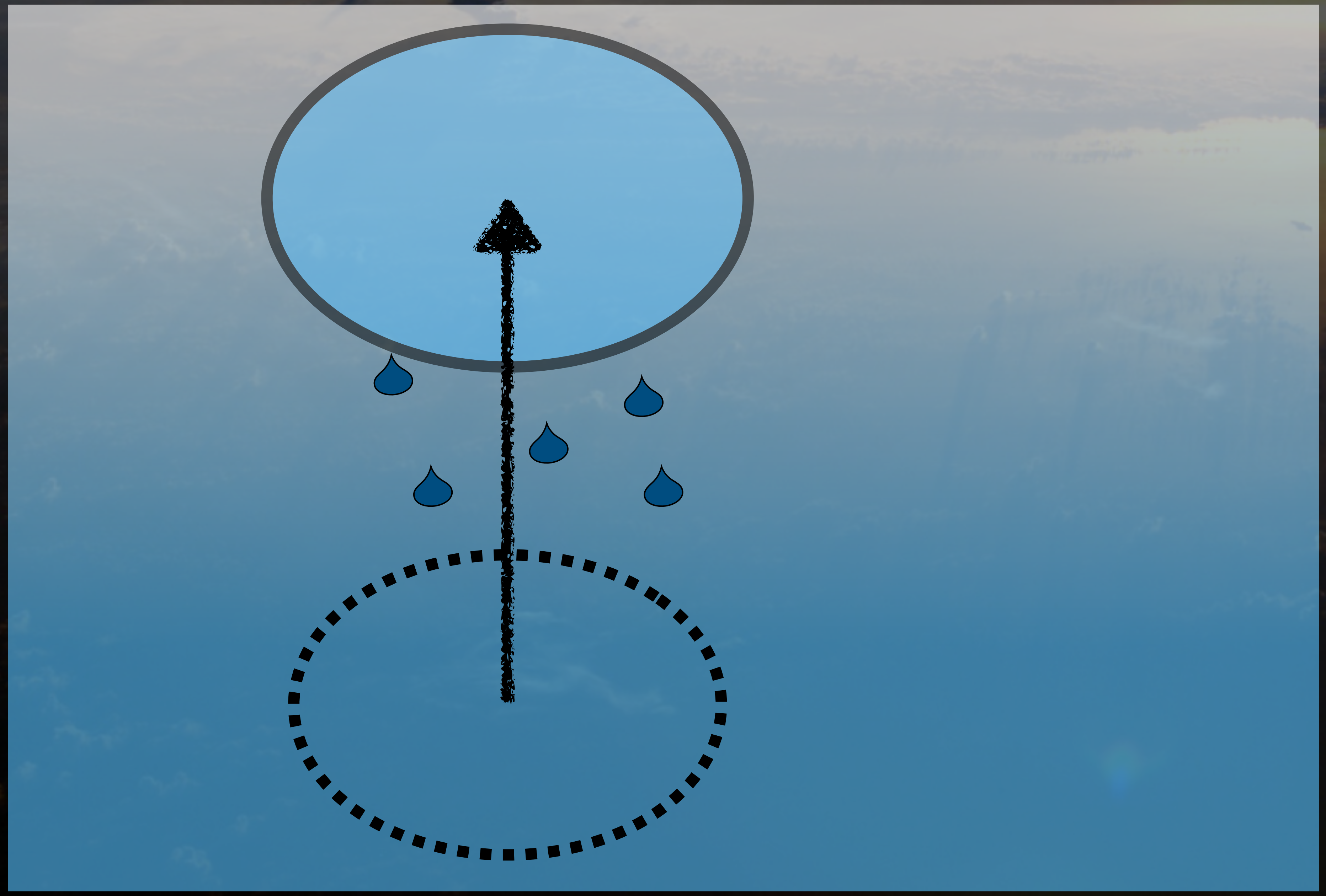
$\nabla_{\rm ad}$ and $\nabla_{\rm rad}$ are the adiabatic and radiative gradients, respectively.

Convective instability w/ condensation

In the presence of condensation, the mean molecular weight gradient ∇_μ, then depends on how the humidity changes with pressure.

The medium is convective if:

$$\nabla_T^\star + \nabla_\mu^\star \quad < \quad \nabla_T + \nabla_\mu$$



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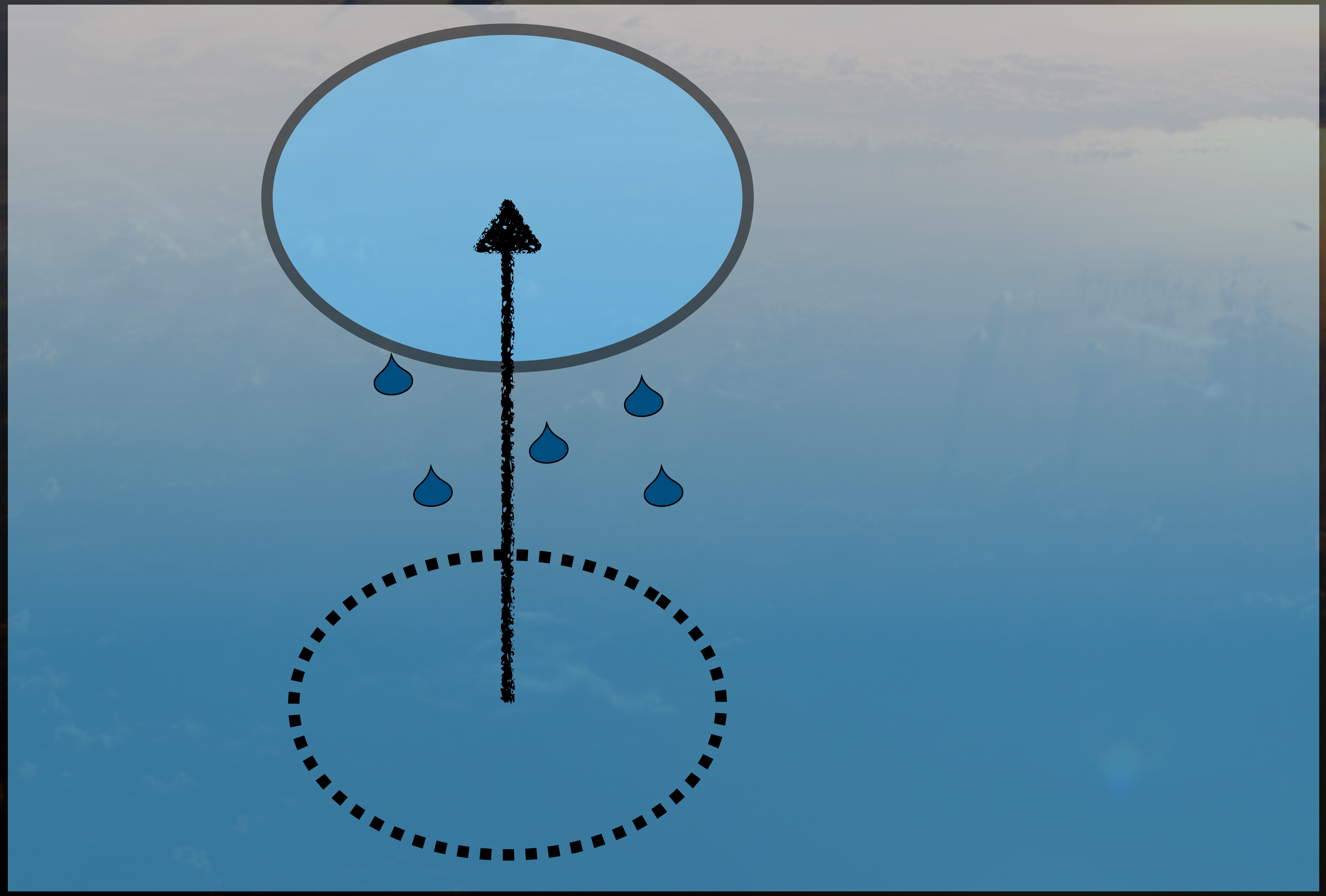

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Assuming saturation, the molecular weight gradients are set by the Clausius-Clapeyron relation:

$$\nabla_\mu = \varpi f(\beta \nabla_T - 1)$$

$$\nabla_\mu^\star = \varpi f(\beta \nabla_T^\star - 1)$$

where:
f is the mass mixing ratio of condensable species
$\varpi \sim 1$ for hydrogen atmospheres is related to the mass ratio of condensable to uncondensable species
$\beta \equiv L/RT \sim 20$ is the ratio of the latent heat to the thermal energy

Guillot (Science 1995)

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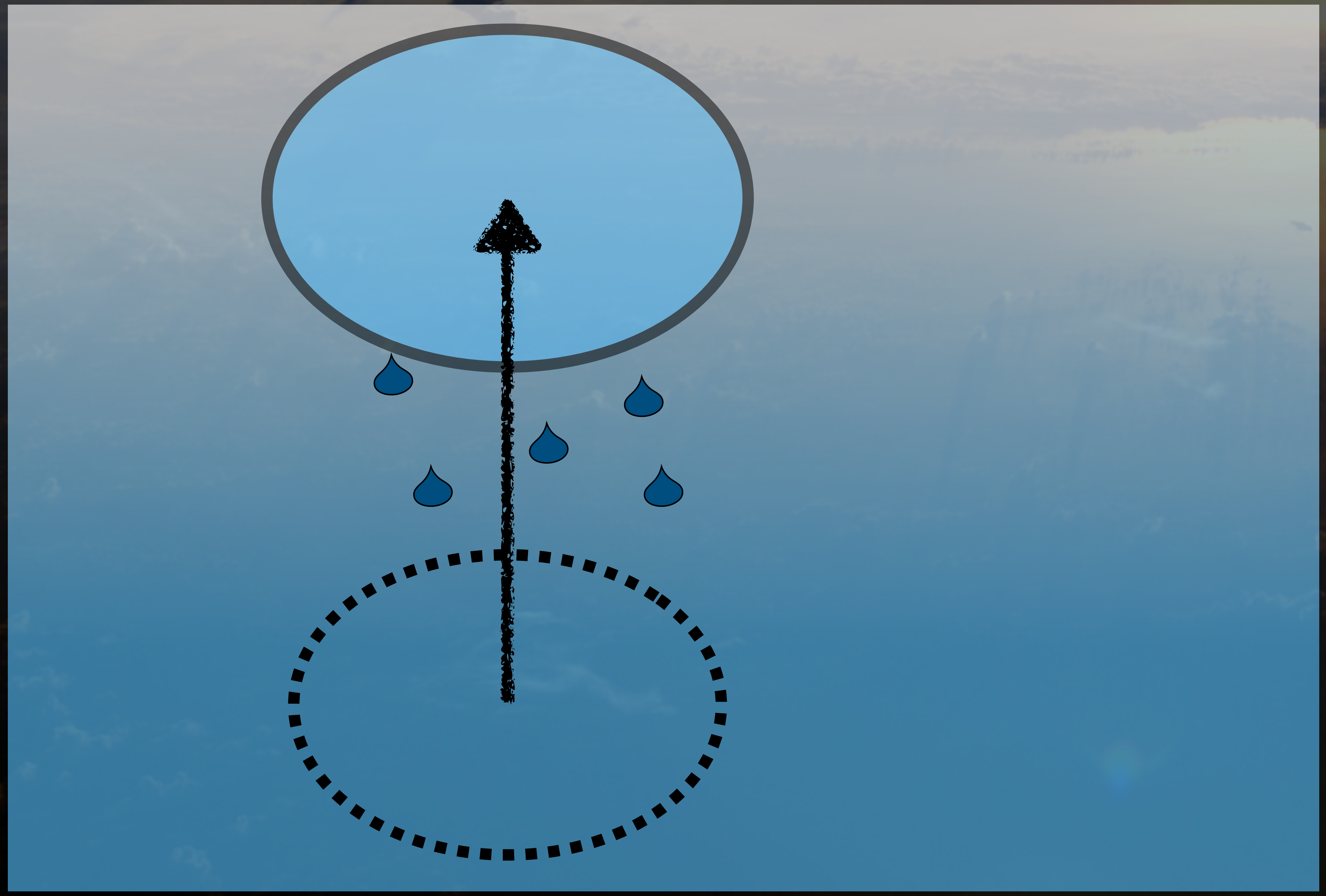
$$\nabla_T^\star + \varpi f(\beta\nabla_T^\star - 1) \quad < \quad \nabla_T + \varpi f(\beta\nabla_T - 1)$$



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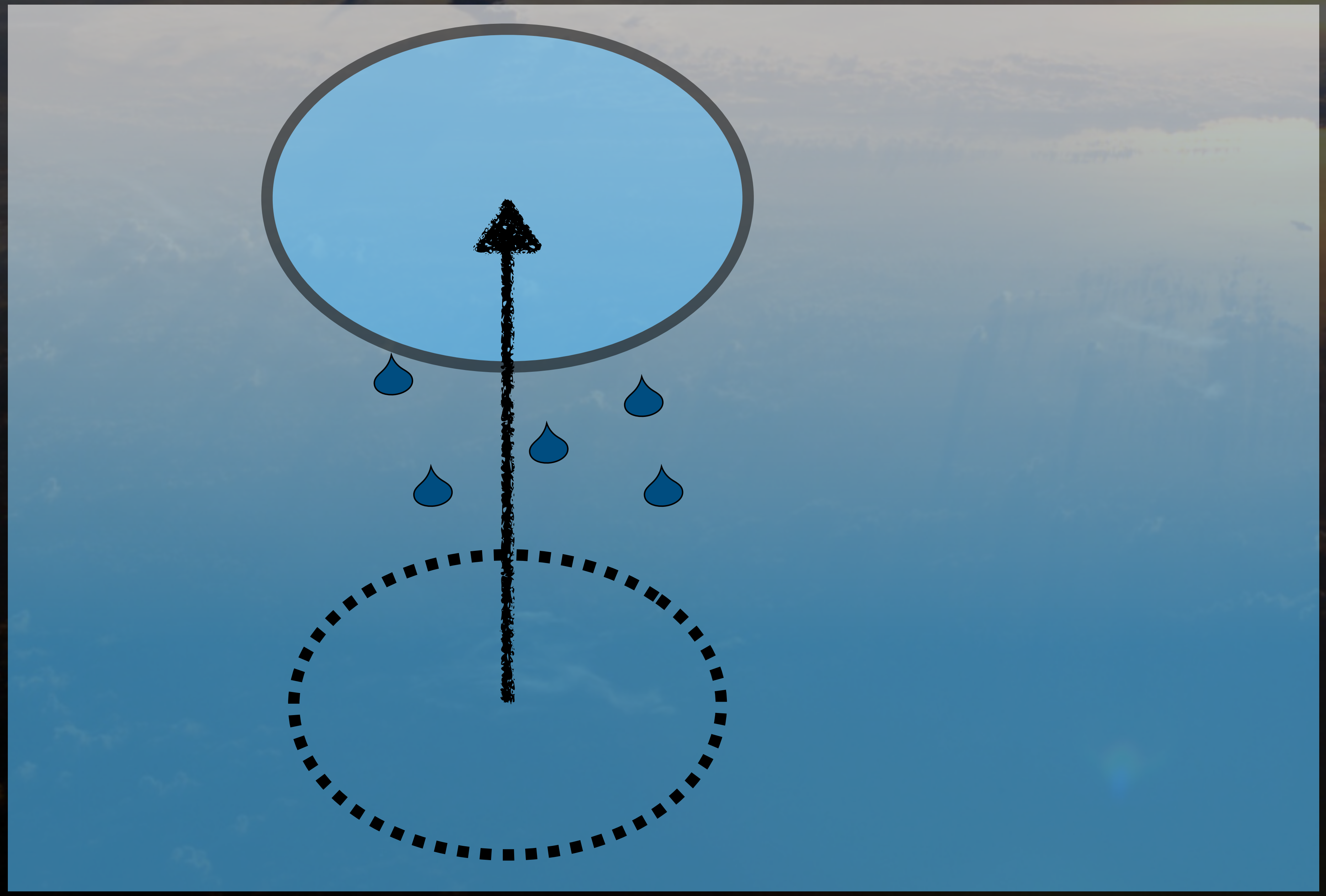
$$(\varpi f \beta - 1)\nabla_T^\star - \varpi f \quad < \quad (\varpi f \beta - 1)\nabla_T - \varpi f$$



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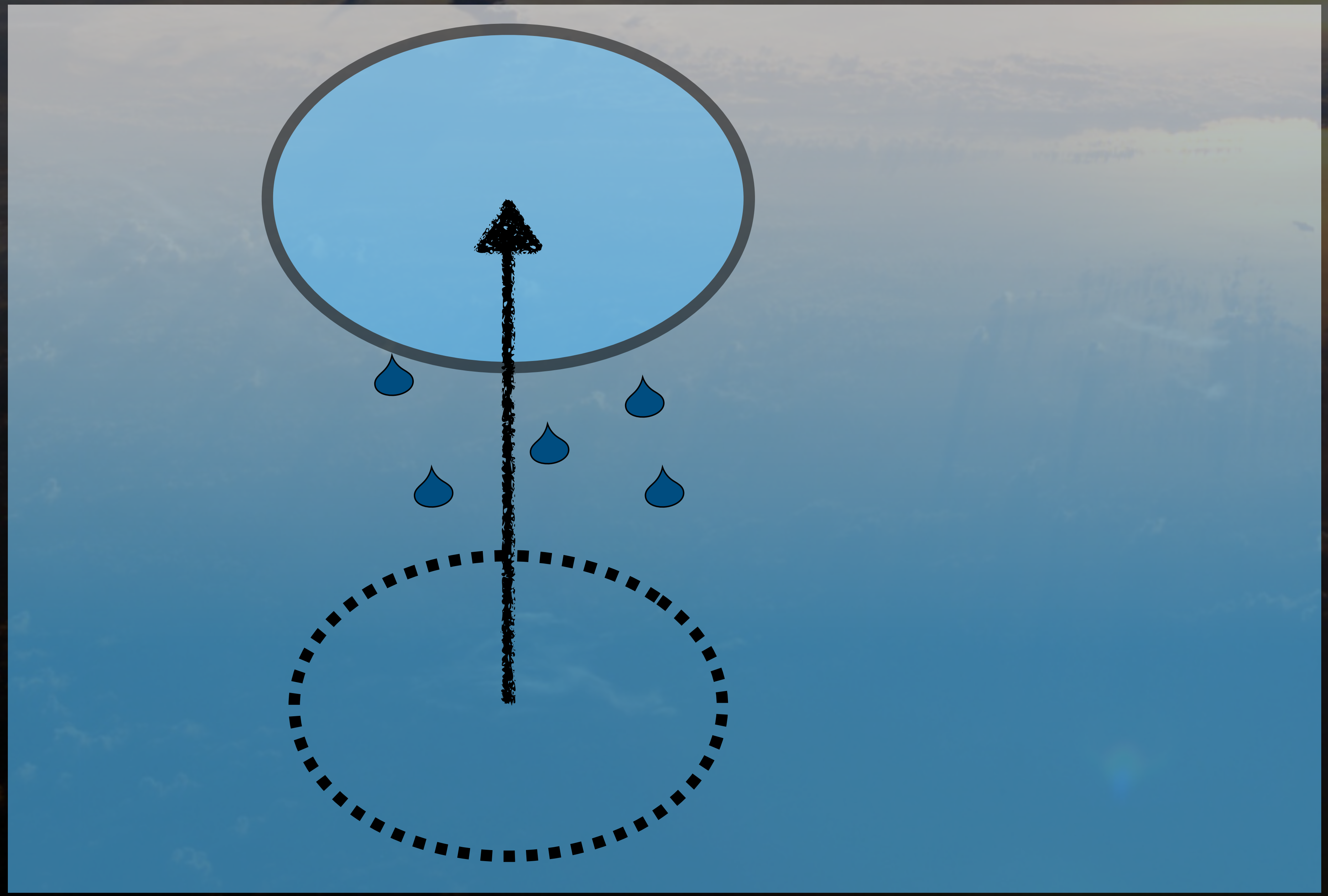
Convective instability w/ condensation

In the presence of condensation, the mean molecular weight gradient ∇_μ, then depends on how the humidity changes with pressure.

The medium is convective if:

$$(1 - \varpi\beta f)(\nabla_T - \nabla_T^\star) > 0$$



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Moist convection inhibition

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$$(1 - \varpi\beta f)(\nabla_T - \nabla_T^\star) > 0$$

1 for Jupiter
-0.5 for Earth

β=L/RT~20

mass mixing ratio
of condensing species

This ***never*** occurs if: $f > f_0 \equiv \dfrac{1}{\varpi\beta}$

→ Enrichments in: $H_2O \gtrsim 10 \times \odot$
$CH_4 \gtrsim 40 \times \odot$

Leconte et al. (2017) further demonstrate that double-diffusive convection is also inhibited

Guillot (Science 1995)

Moist convection inhibition: cases

- In Uranus & Neptune, due to CH_4 condensation
  - Guillot (1995), Ge et al. (2024), Clément et al. (2024)
- In Jupiter & Saturn
  - Linked to H_2O condensation, possibly: Li & Ingersoll (2017), Hyder et al. (2024)
  - Linked to helium rain: Markham & Guillot (2024)
- In K2-18b
  - Leconte et al. (2024)
- In Earth-like planets with a water ocean and a hydrogen atmosphere
  - If the ocean temperature is >300K: Seeley & Wordsworth (2025)
- In magma-ocean planets
  - Markham, Guillot & Stevenson (2023)

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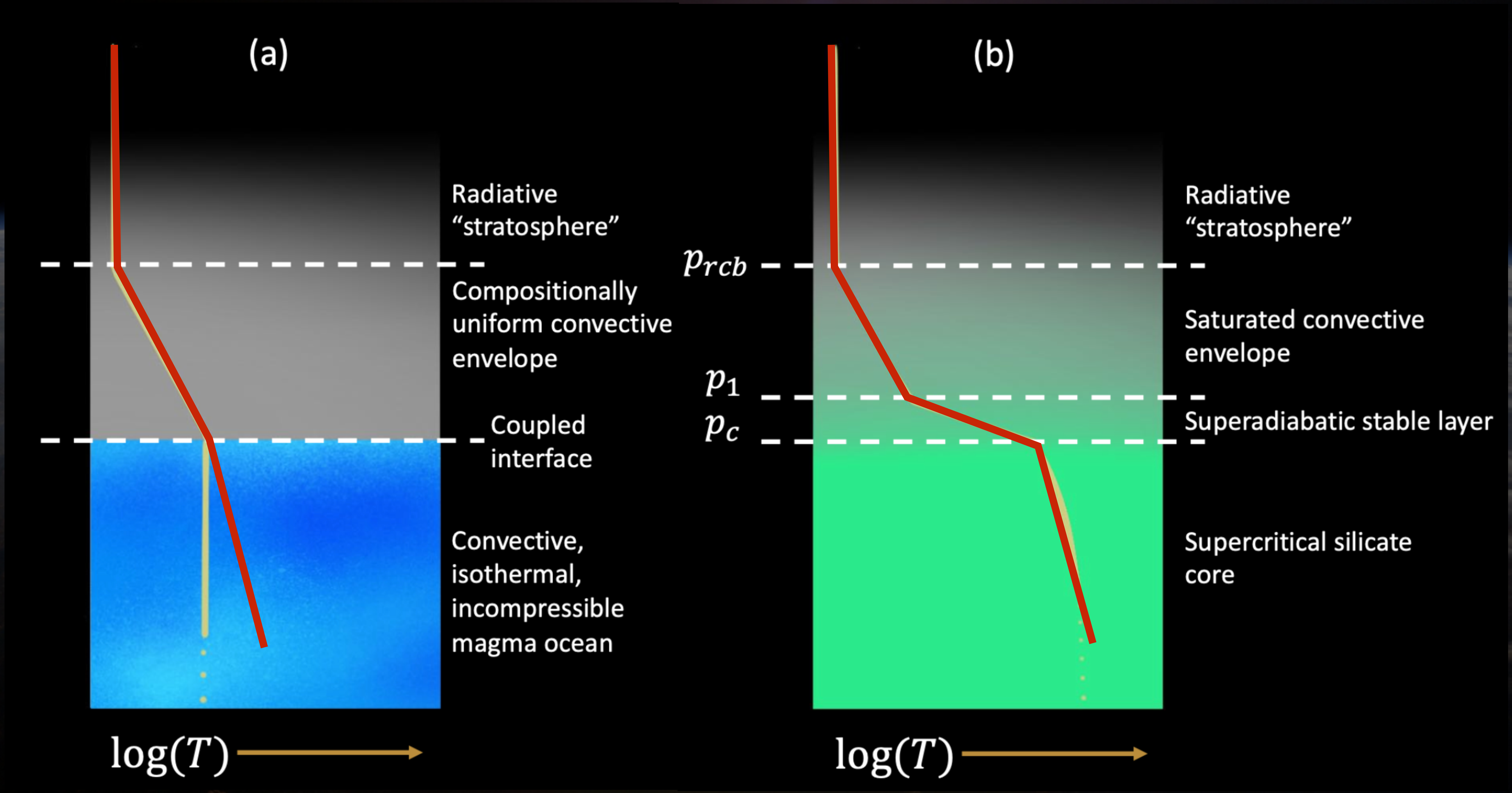
Moist convection inhibition: consequences

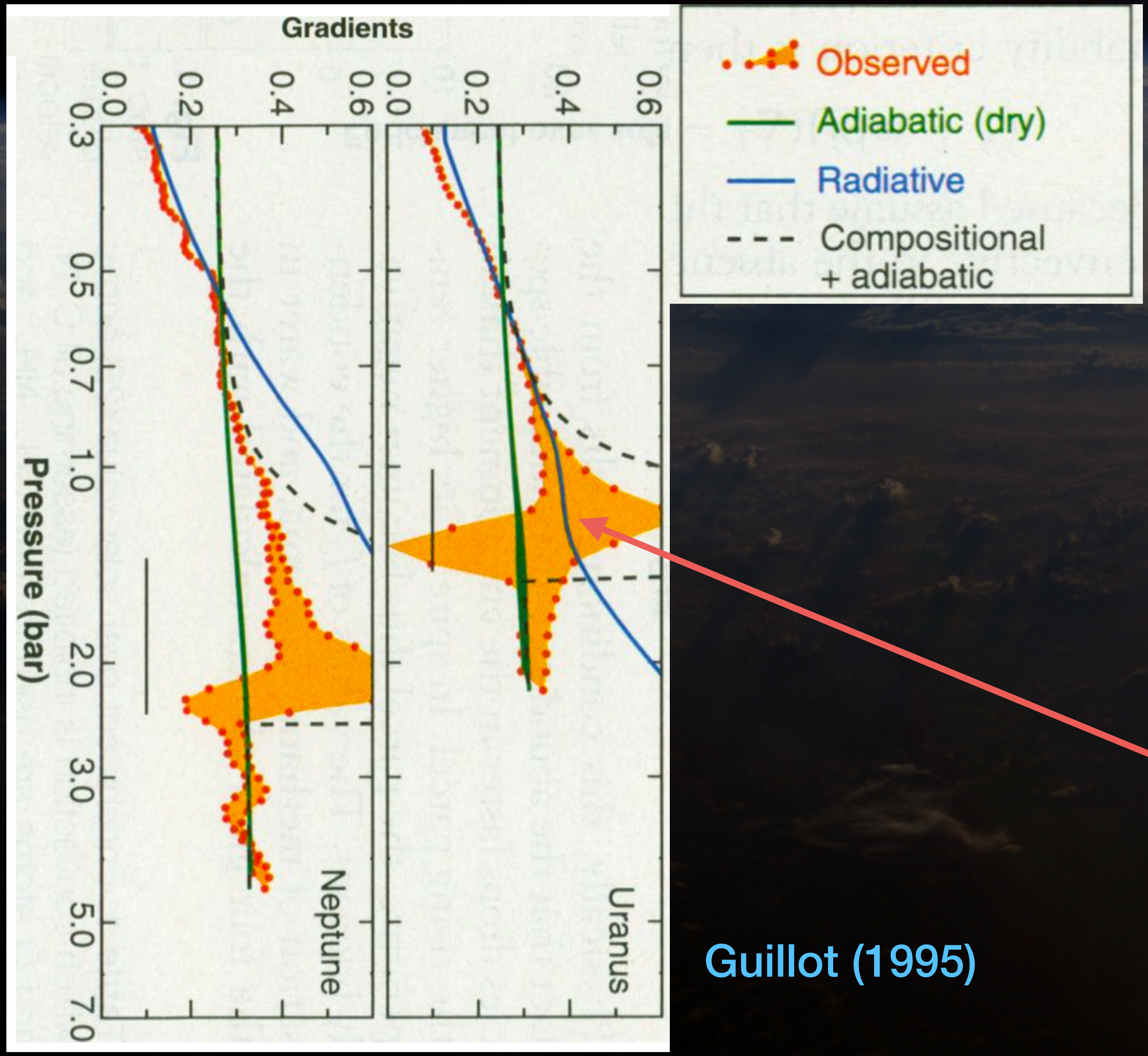


Markham, Guillot & Stevenson (2022)
(see also Leconte et al. 2017)

Moist convection inhibition: consequences

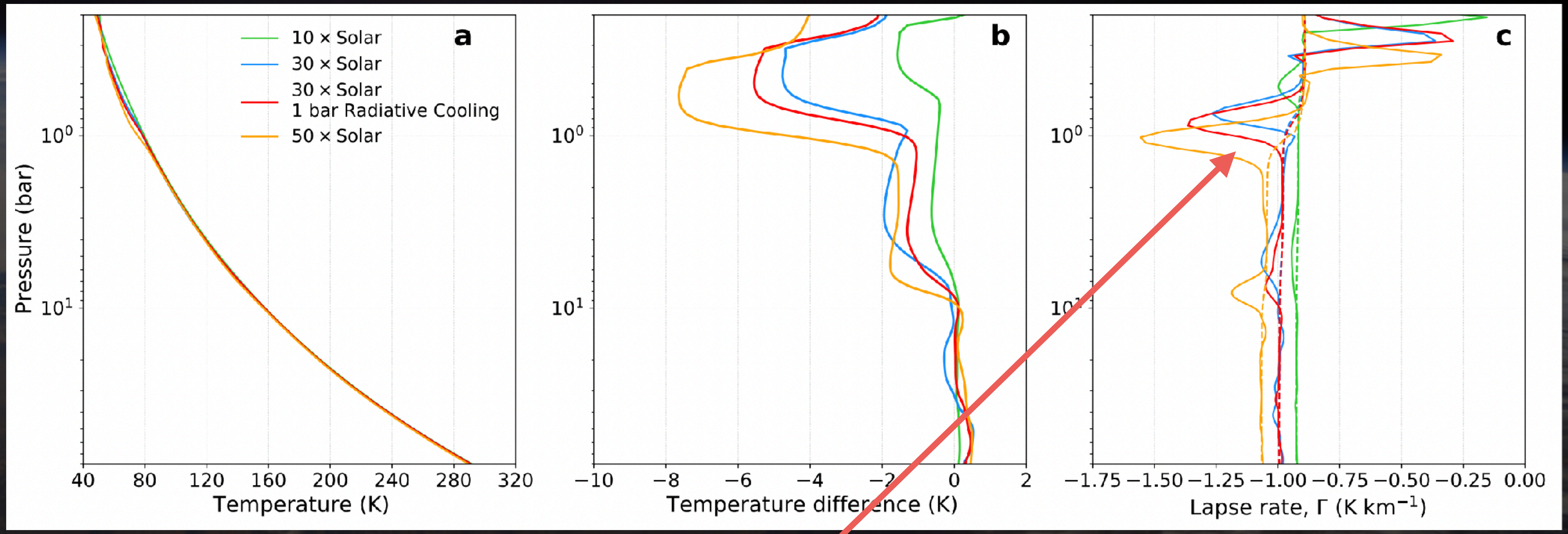
In Uranus and Neptune (CH_4 condensation)

From Voyager 2 radio occultations:



Guillot (1995)

From cloud ensemble simulations:



Ge et al. (PSJ, 2024)

superadiabaticity

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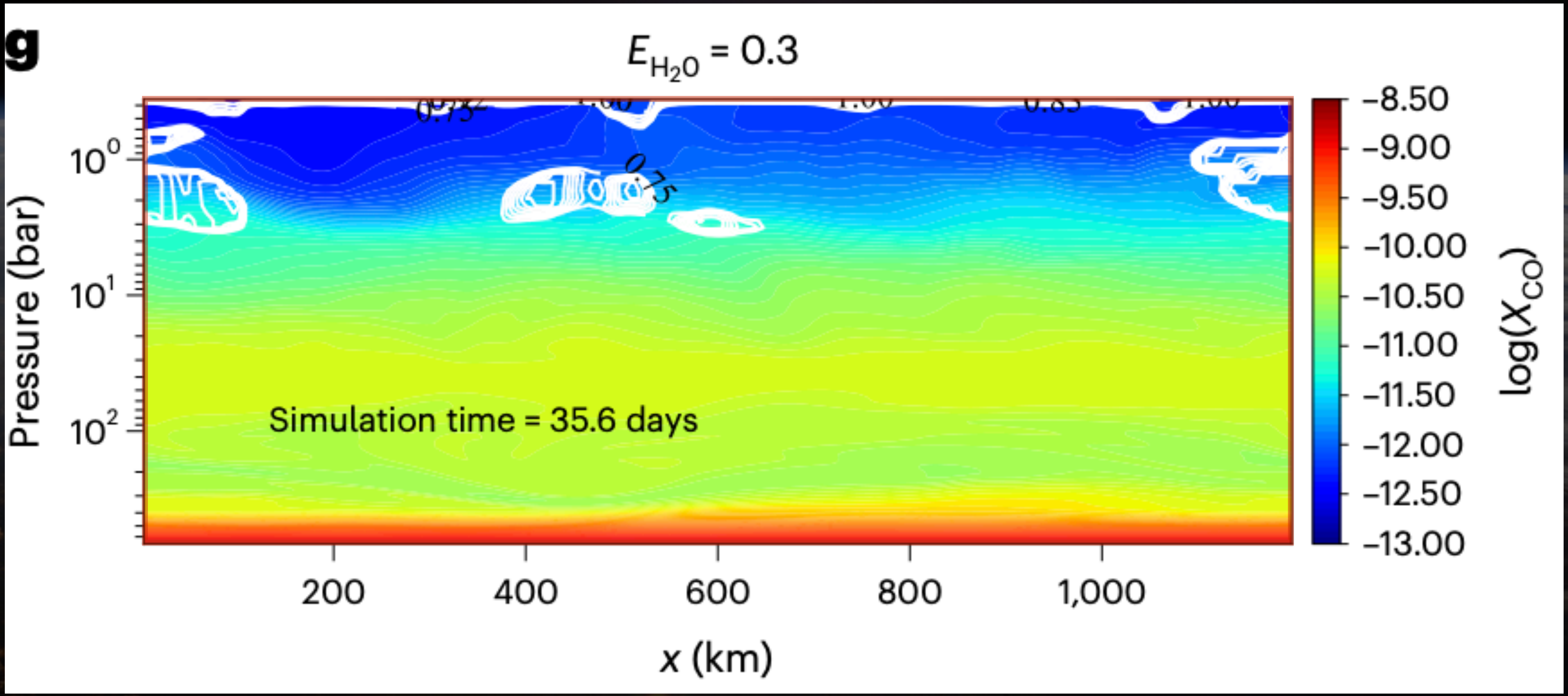
Moist convection inhibition: consequences

In Jupiter (H2O condensation & atmospheric CO abundance)



Hyder et al. (2025)

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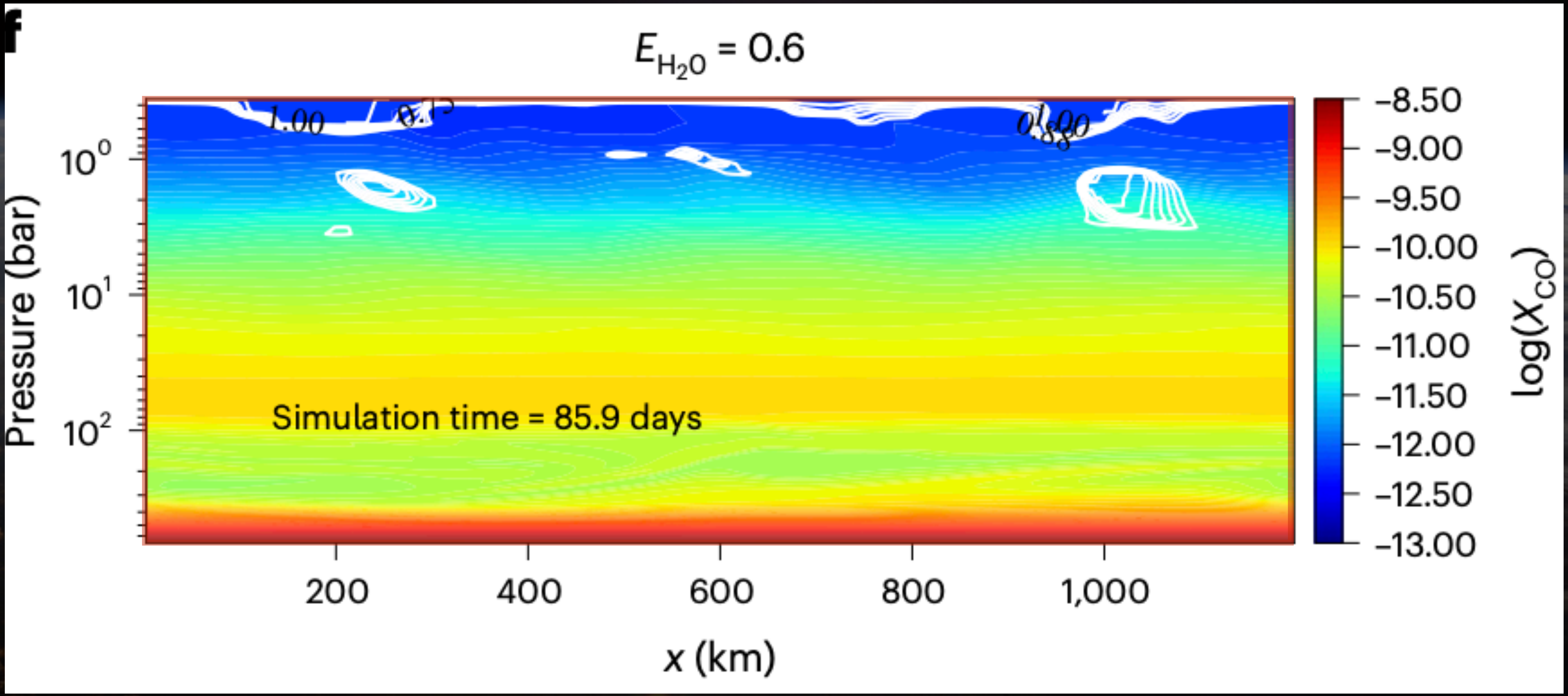

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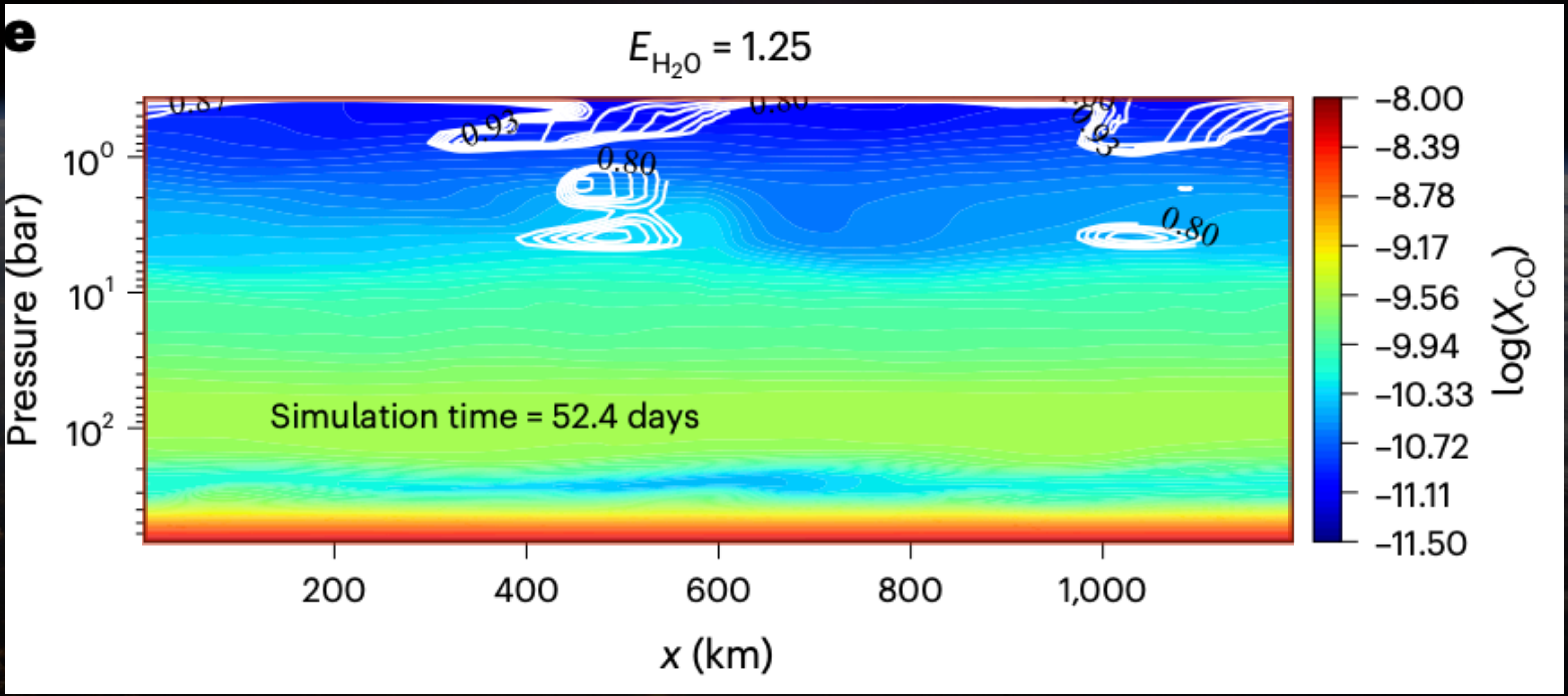

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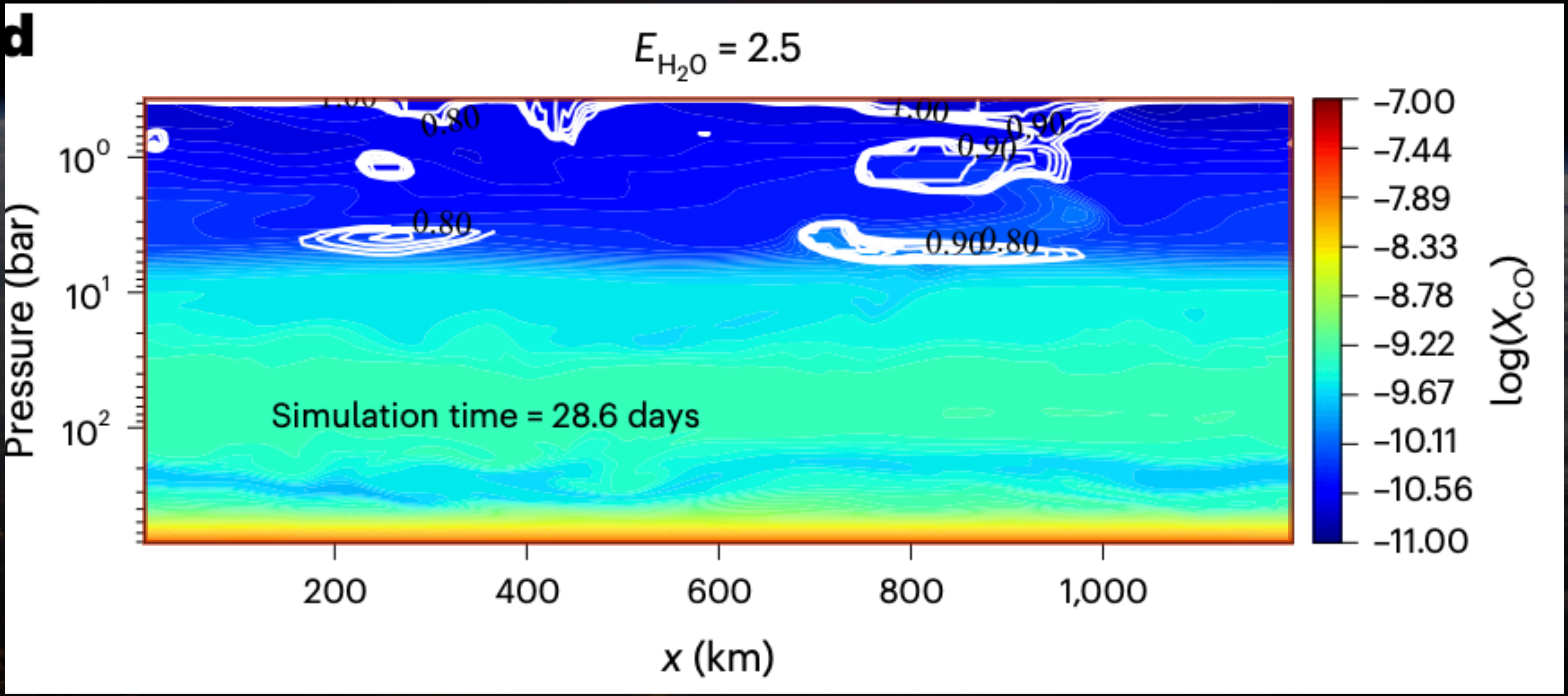

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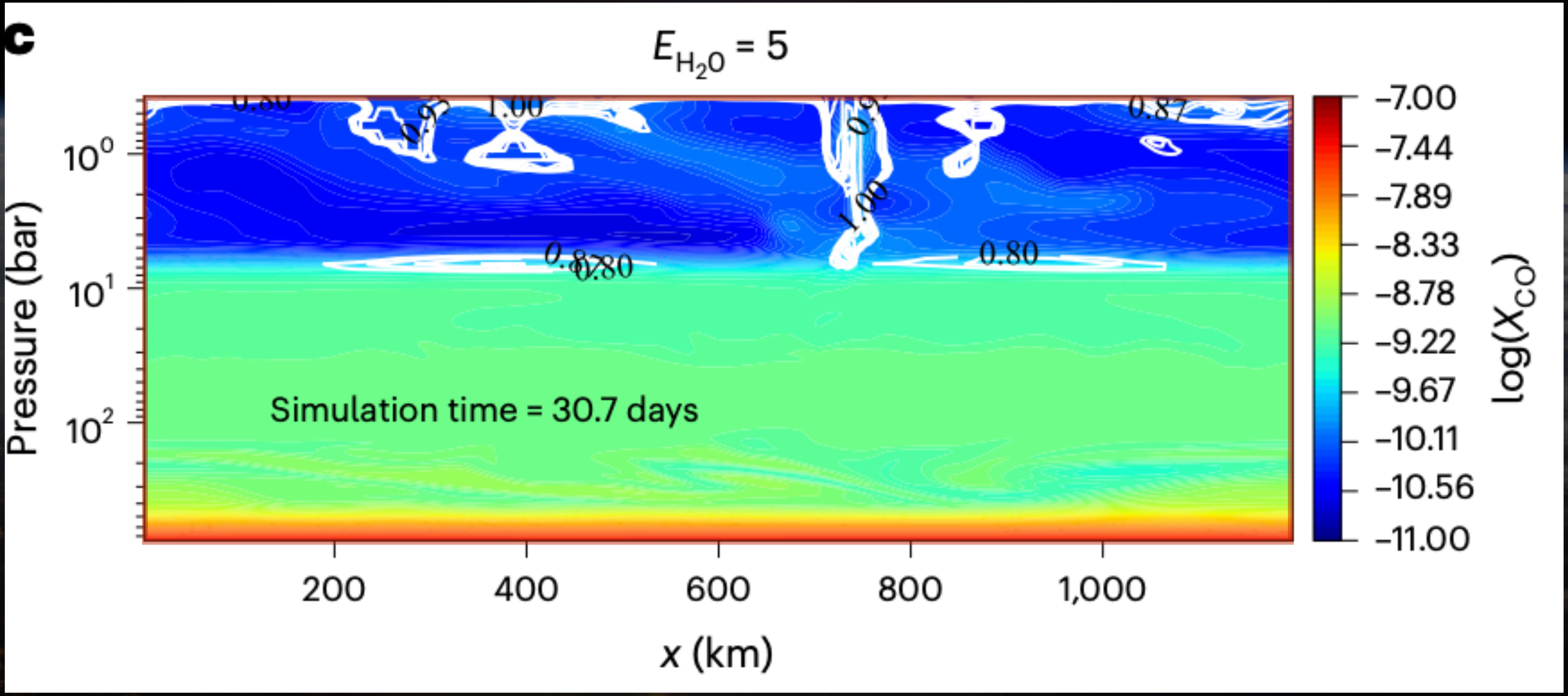

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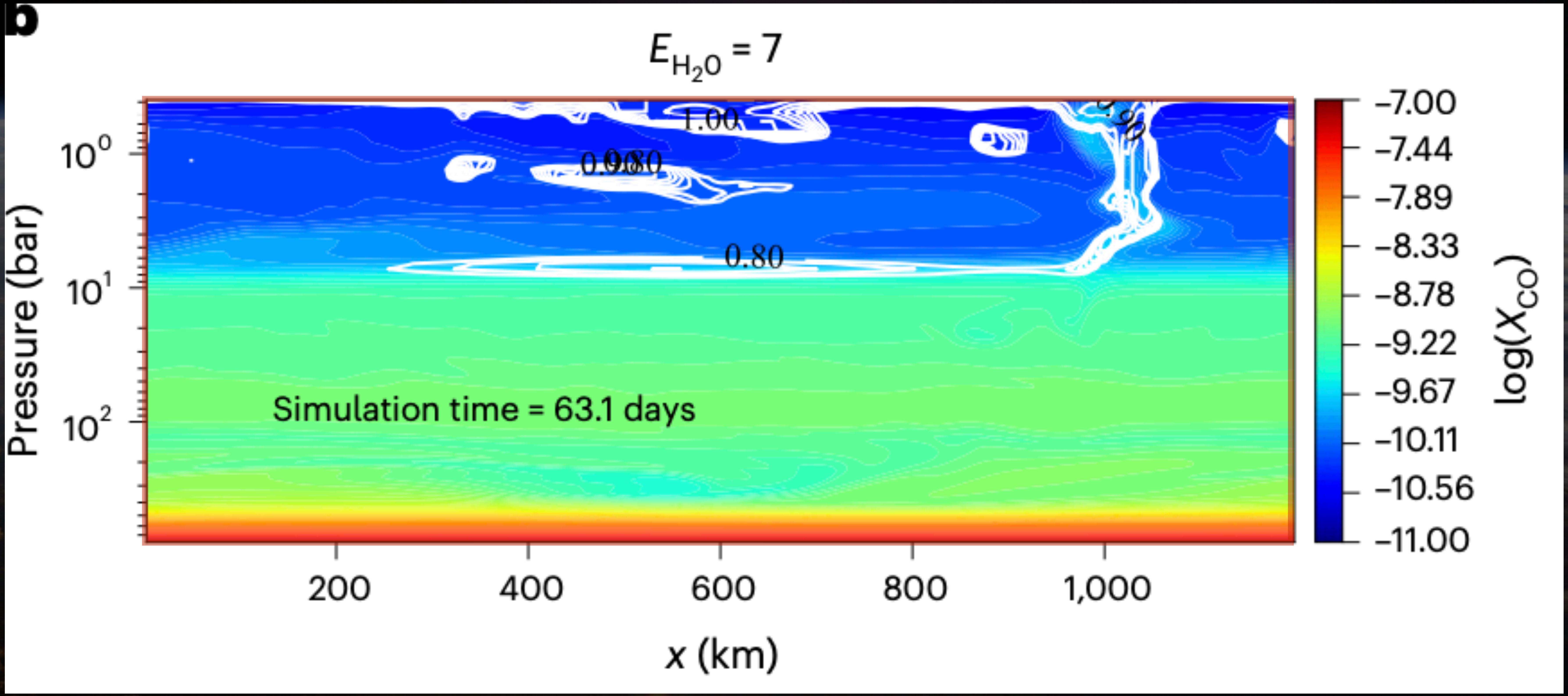

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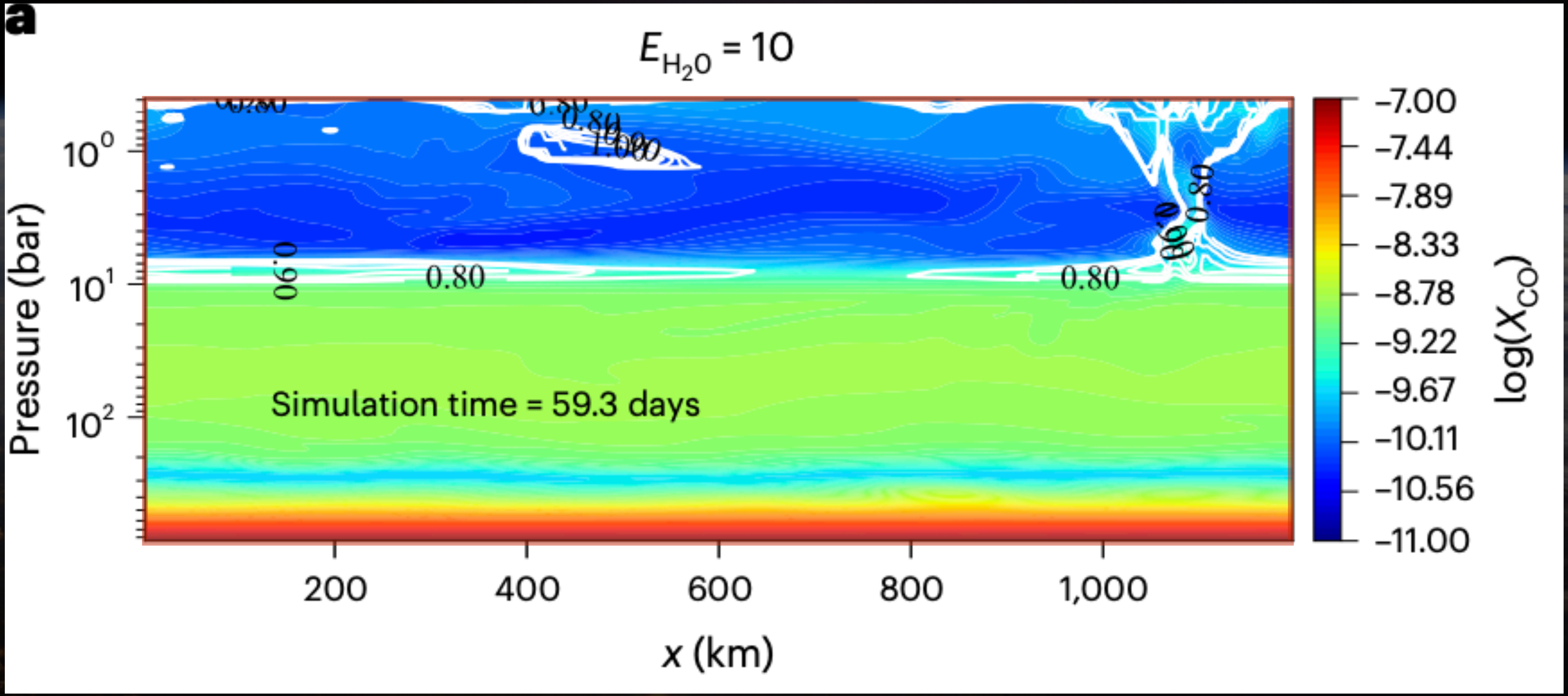
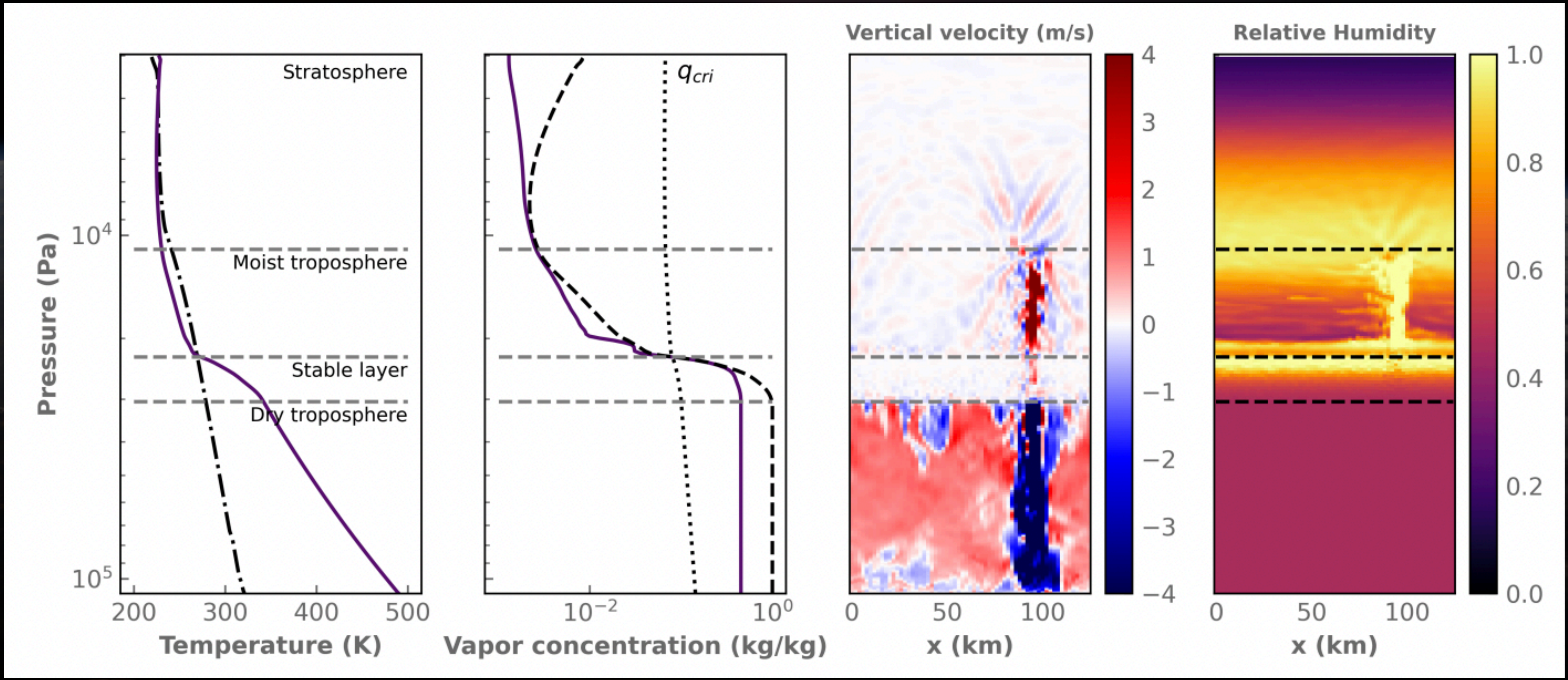


Hyder et al. (2025)

Moist convection inhibition: consequences

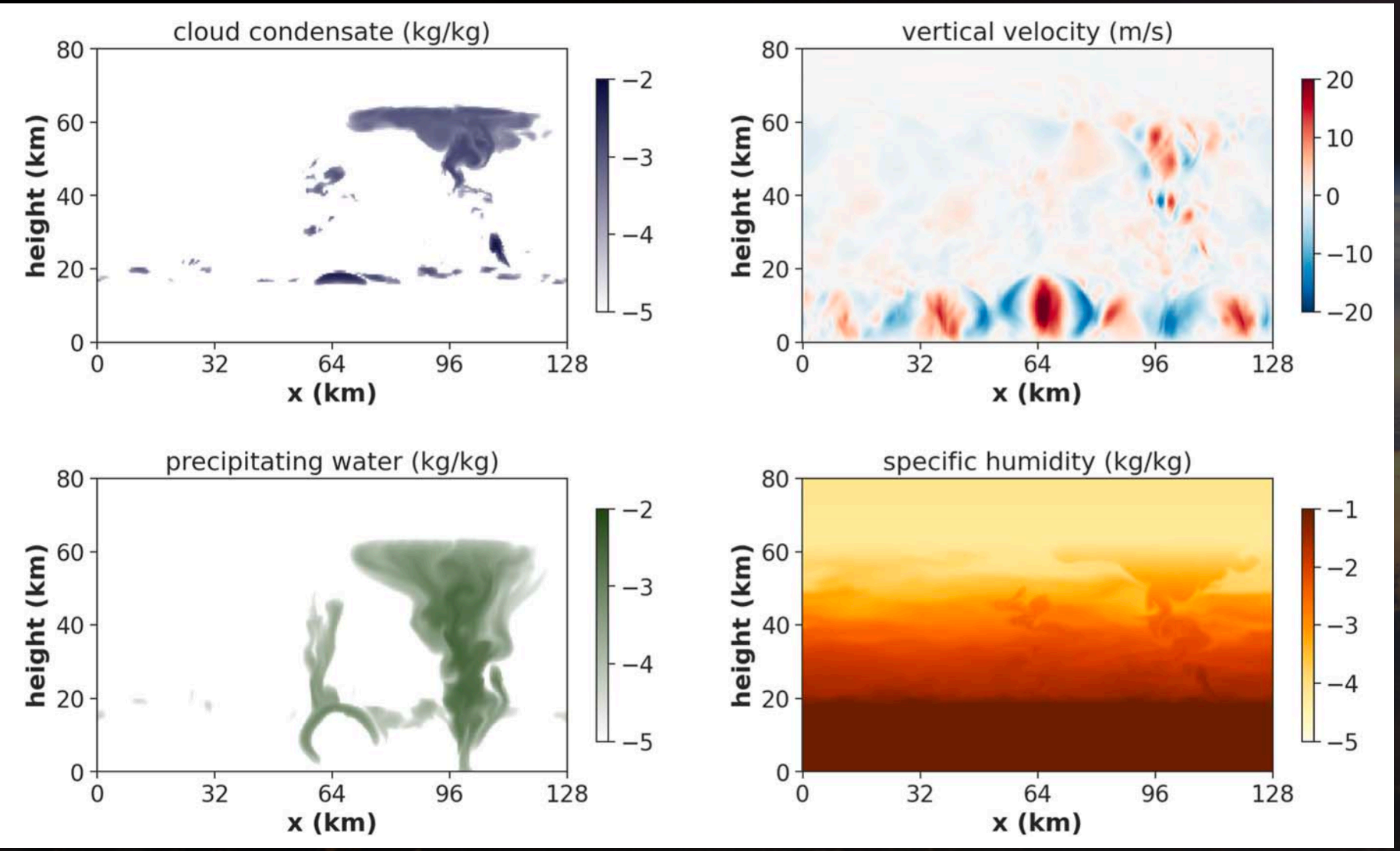
In exoplanet K2-18b (H_2O condensation)



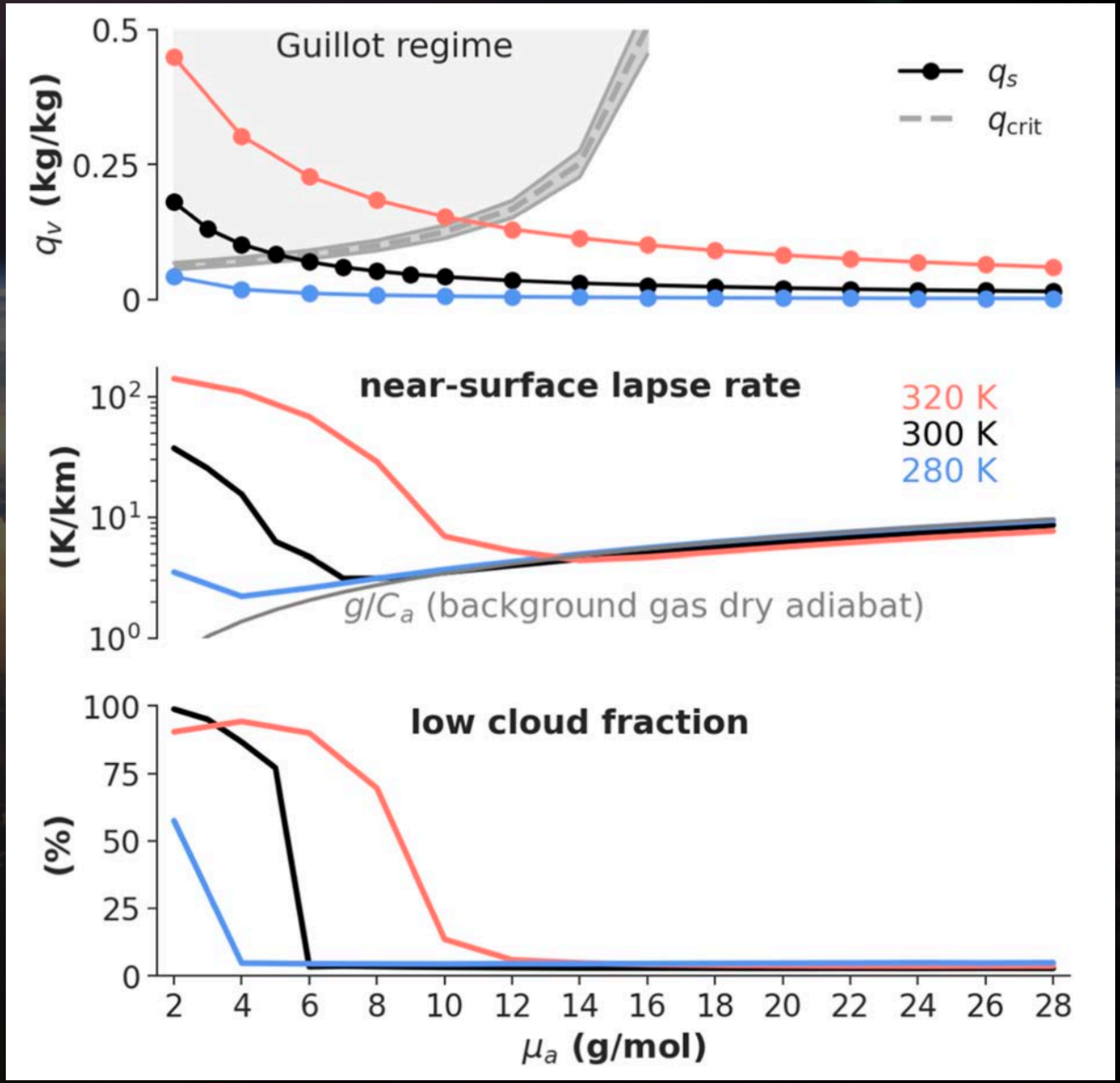
Leconte et al. (2024)

Moist convection inhibition: consequences

In Earth-like planets with H_2O ocean



Seeley & Wordsworth (2025)



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Moist convection inhibition & PLATO

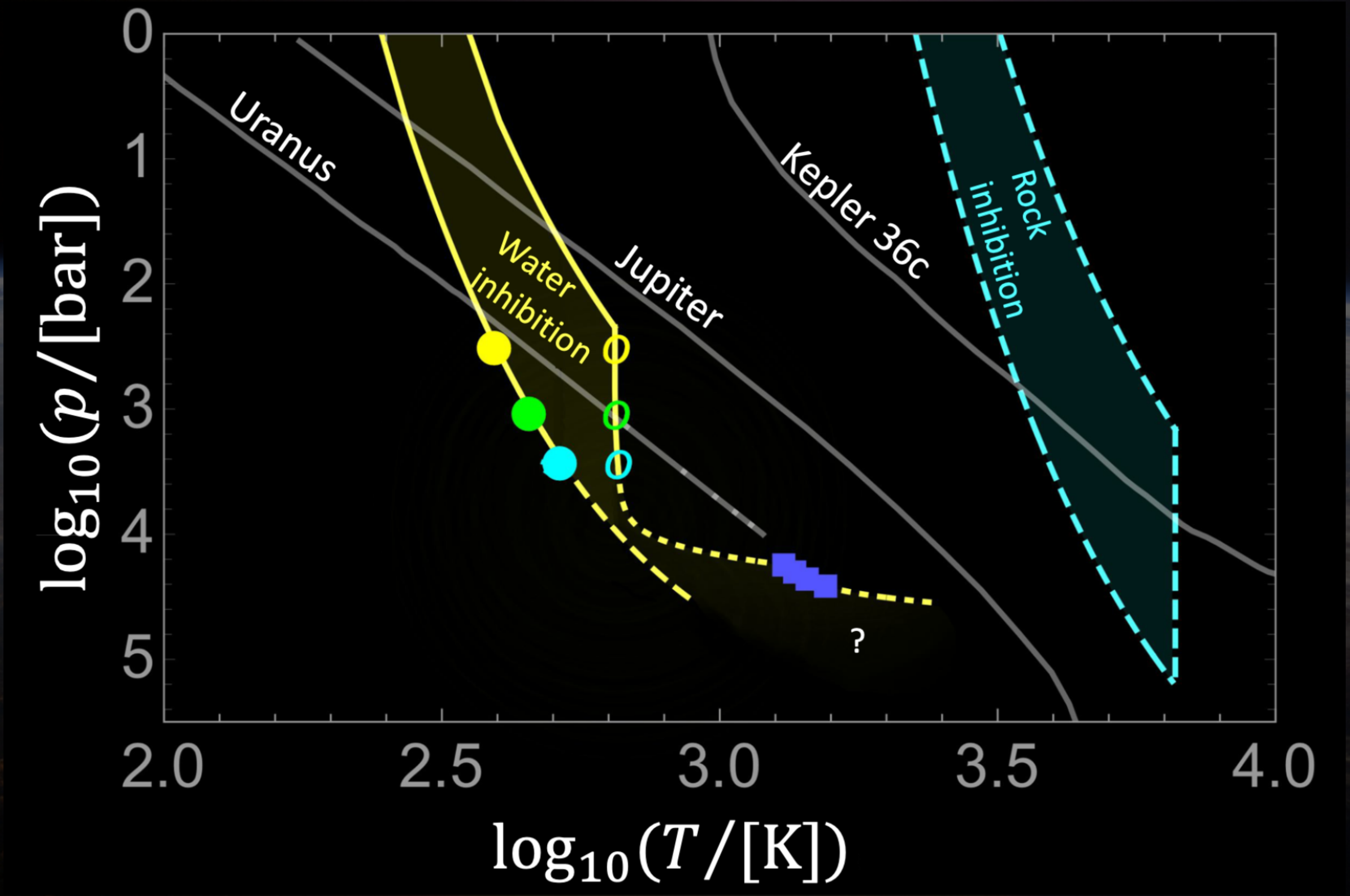
- This will yield slower cooling, higher internal temperatures
  - Will modify inferred bulk abundances
  - Very difficult to check against composition degeneracies, particularly in small planets
    - Age information may be a game changer but this is to be quantified
    - Problem yet to be tackled with evolution models in the context of WP116100

- Testing this requires observations of enriched exoplanetary atmospheres
  - Constraints on disequilibrium species abundances
  - Linking bulk and atmospheric compositions.
  - Long-period temperate planets (w/ water condensation) are especially interesting

- Characterizing planets in the HZ is essential
  - With water condensation & inhibition, convection becomes very intermittent
  - We will need many targets & many observations!


Dome ASTEP West 2023-05-27 LT 12:00

Moist convection inhibition: location



Markham, Guillot & Stevenson (2022)