Water-rich atmospheres under variable XUV: the case of Proxima Centauri b

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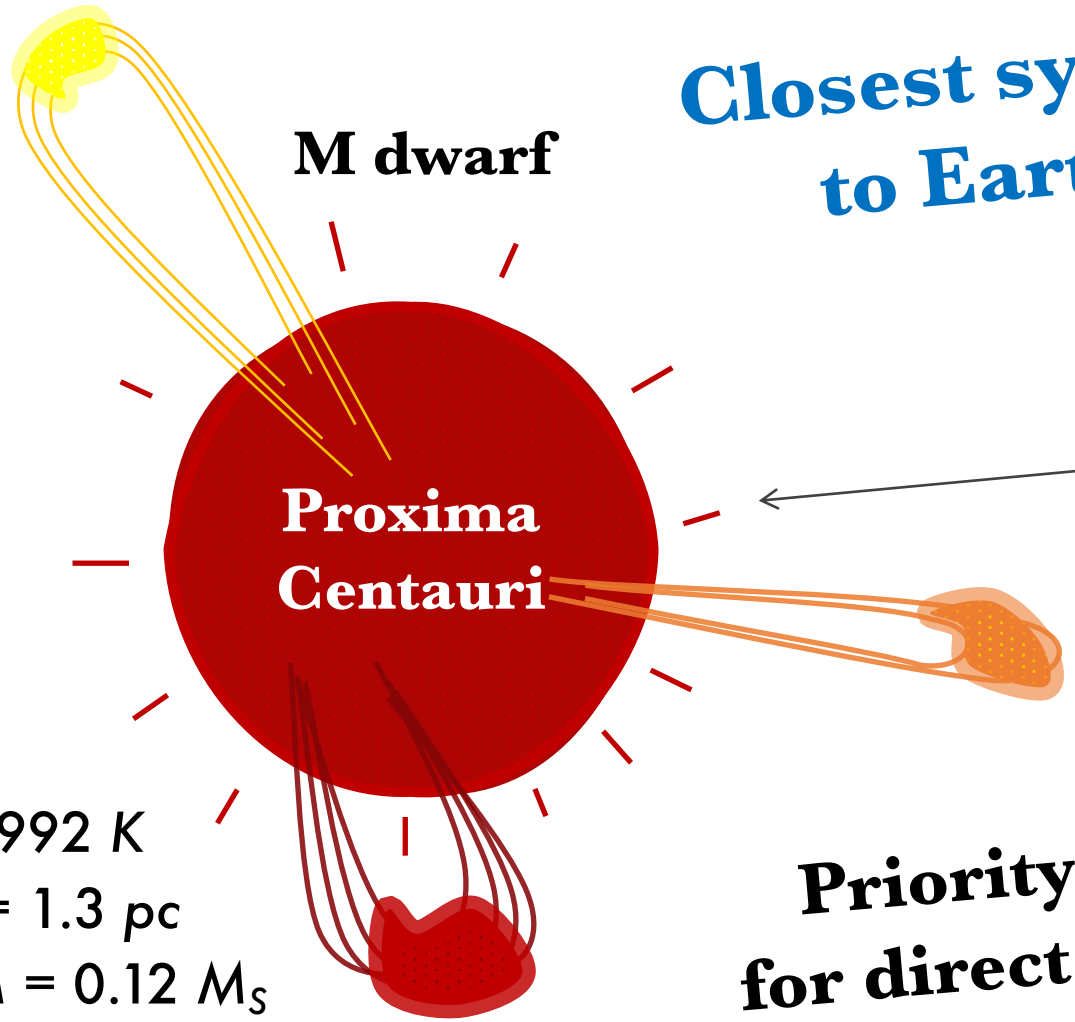
Anglada-Escudé+2016



M dwarf

Proxima Centauri

T = 2992 *K*

D = 1.3 *pc*

M = 0.12 M_S

Closest system to Earth!

d = 0.05 AU

P = 11.2 d

PC b

R ≈ 1 R_E (?)

M = 1.3 M_E

T = 234 *K*

sub-Neptune or super-Earth

(non-transiting)

Priority target for direct imaging a HZ planet.

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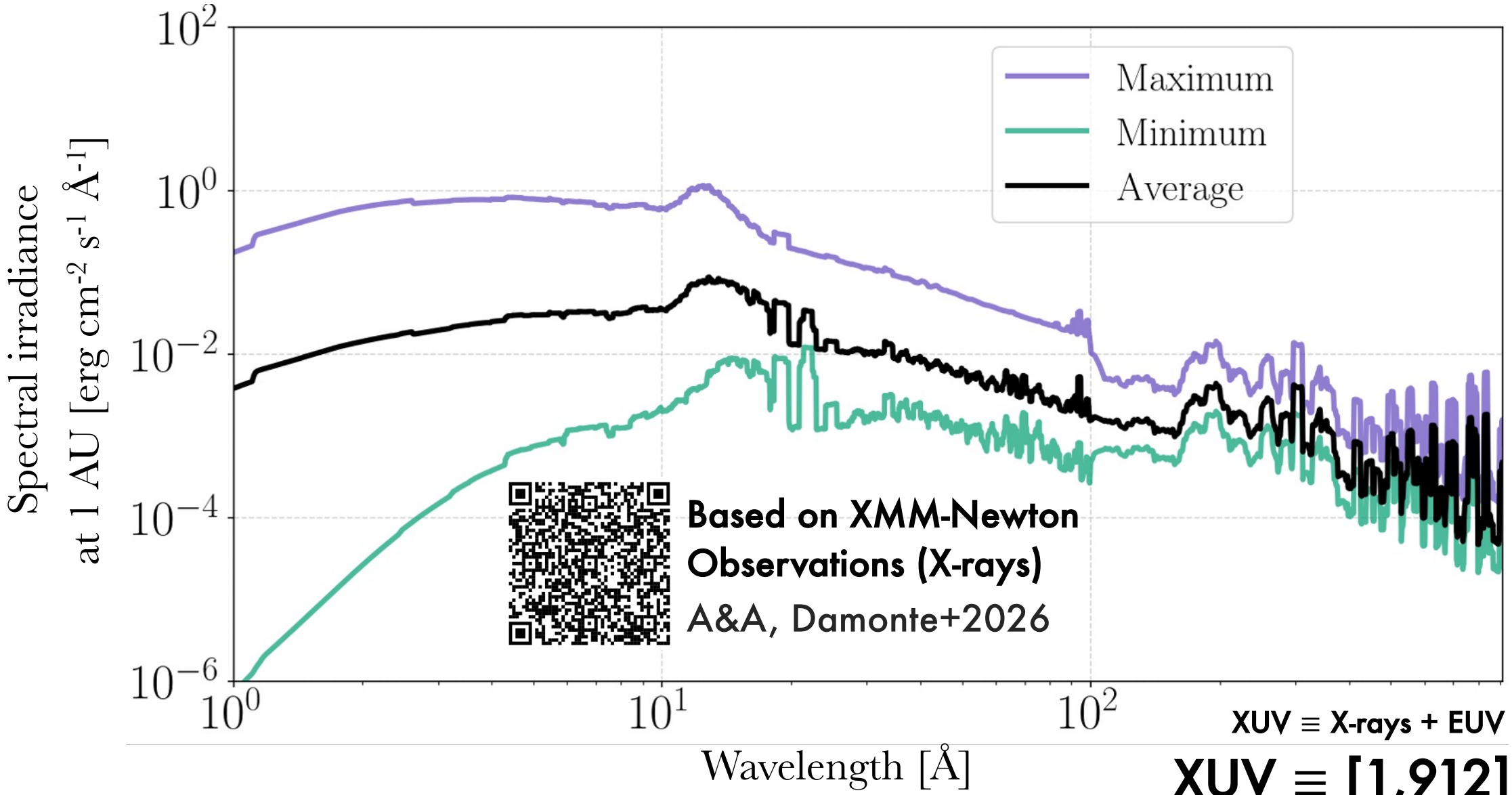
Objectives:

- H_2O upper atmosphere for PCb & planets ↻ cool stars.
- **Chemistry under M dwarf instellation.**
- H_3O^+: diagnostic spectroscopy and energy balance.
- Mass loss rate and long-term evolution of the planet atm.

Prox Cen XUV spectrum at 1 AU



XUV ≡ X-rays + EUV

XUV ≡ [1,912] Å

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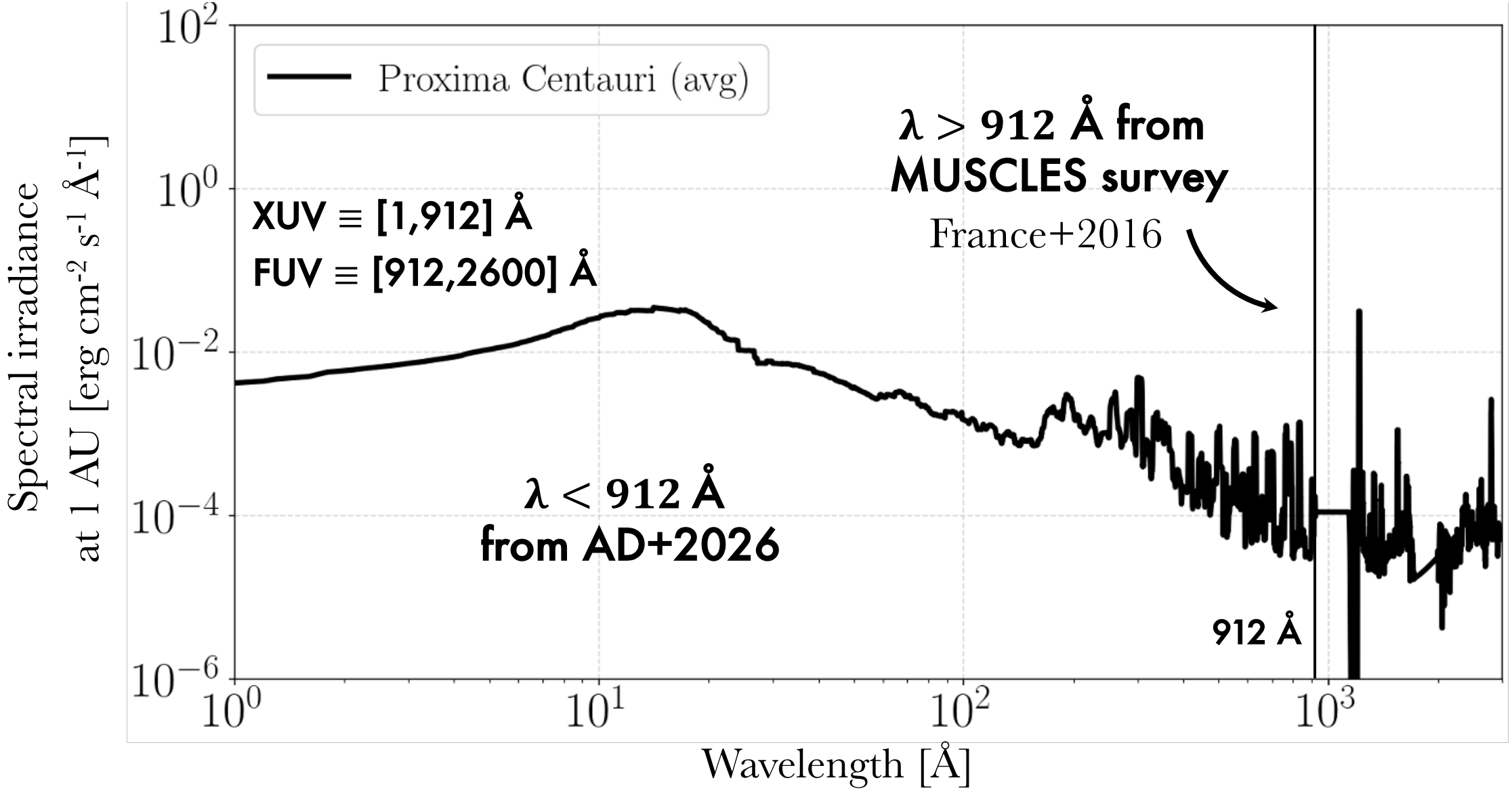
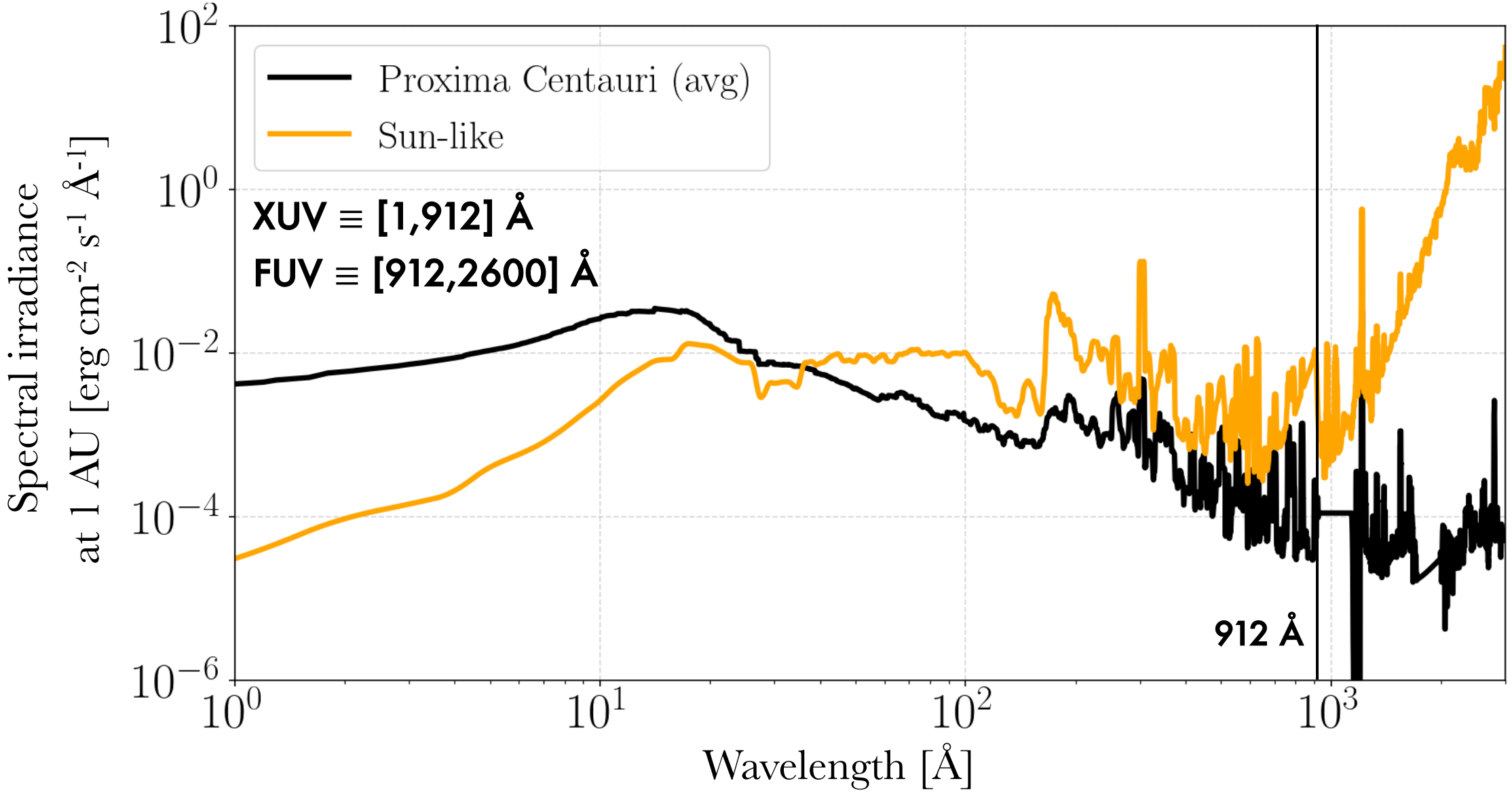
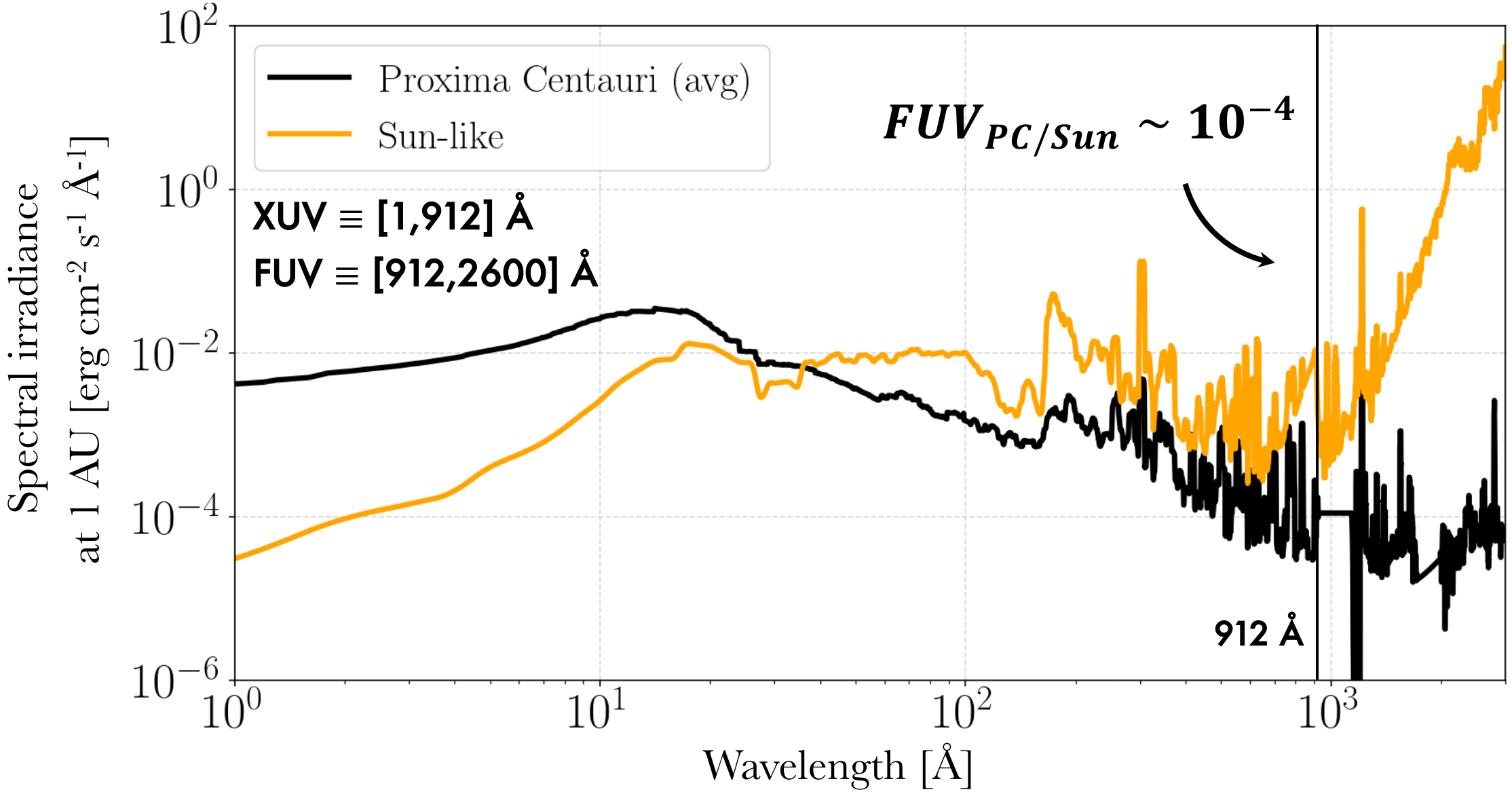
Prox Cen 1–2600 Å spectrum at 1 AU



Prox Cen vs Sun-like spectrum at 1 AU



Prox Cen vs Sun-like spectrum at 1 AU



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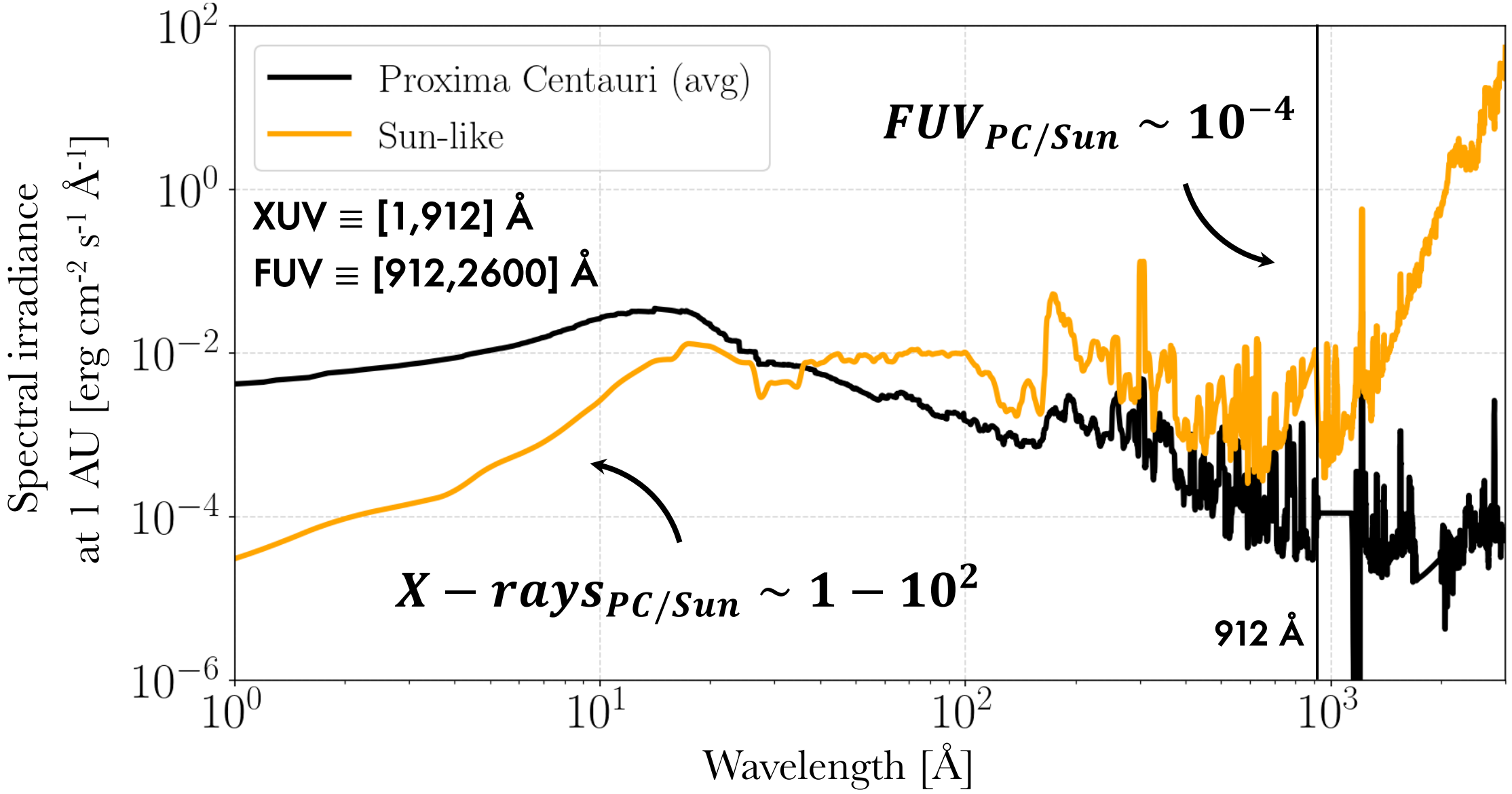
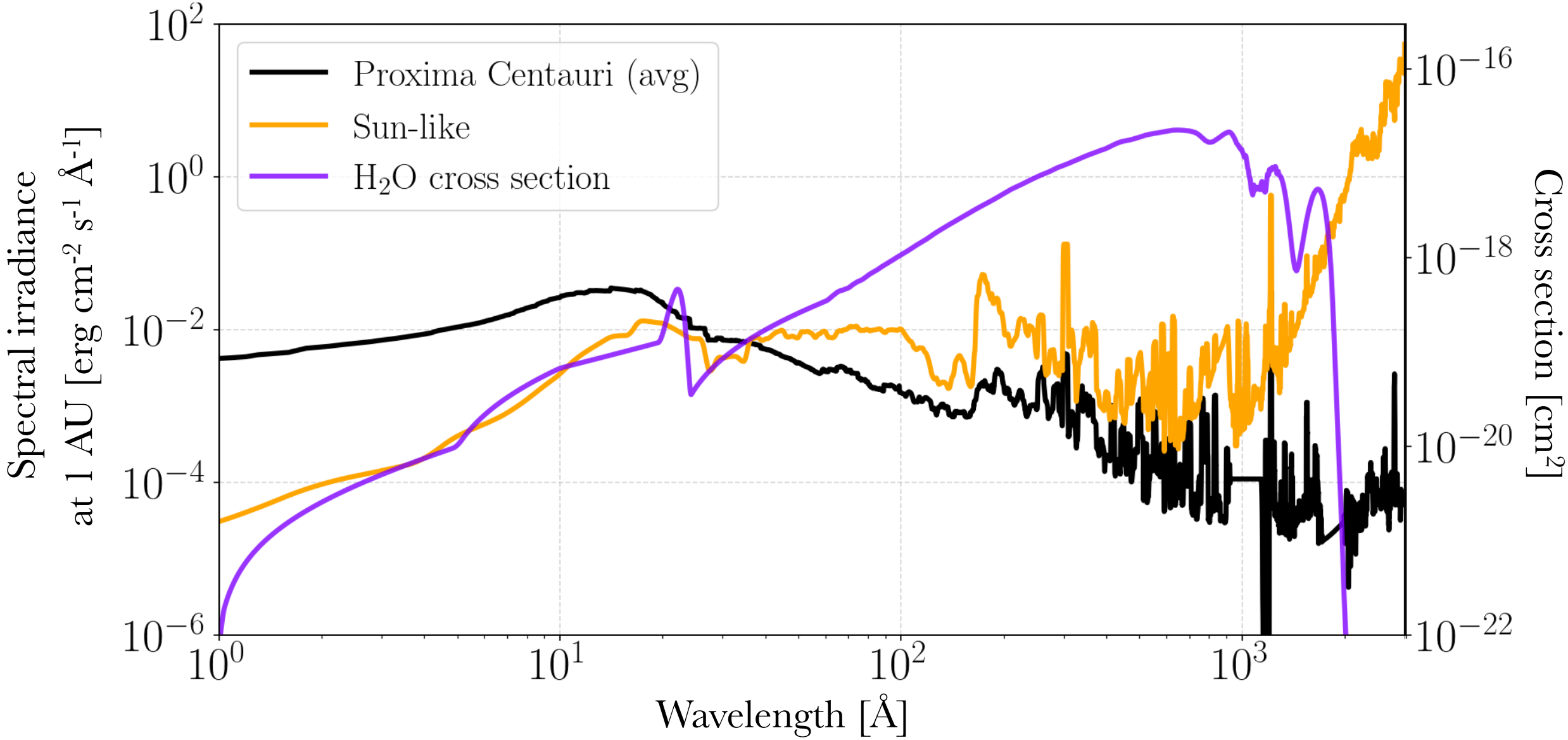
Prox Cen vs Sun-like spectrum at 1 AU



Molecular or ionized atmosphere?



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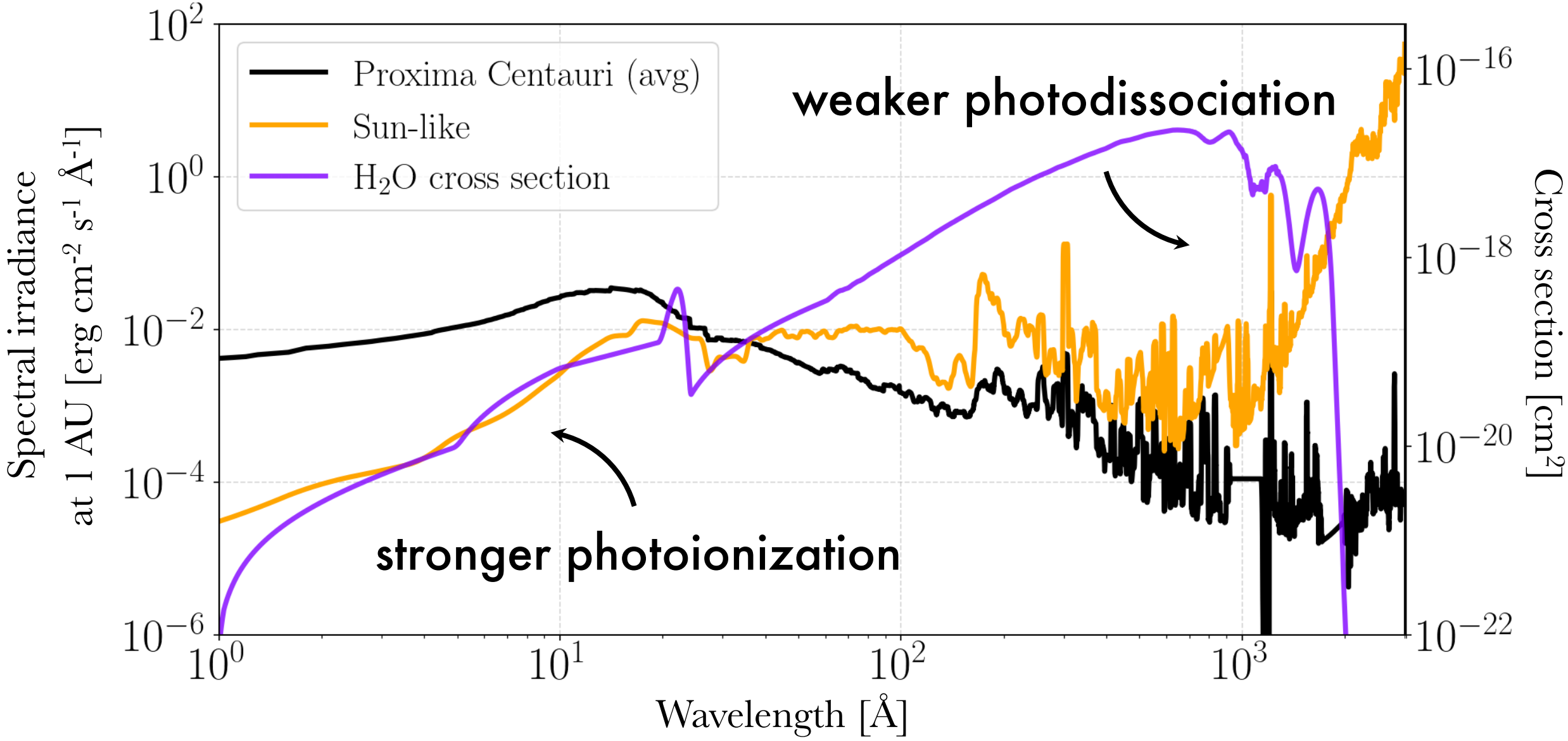
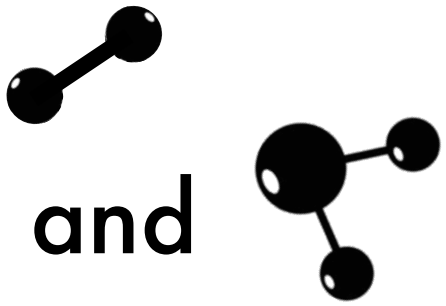
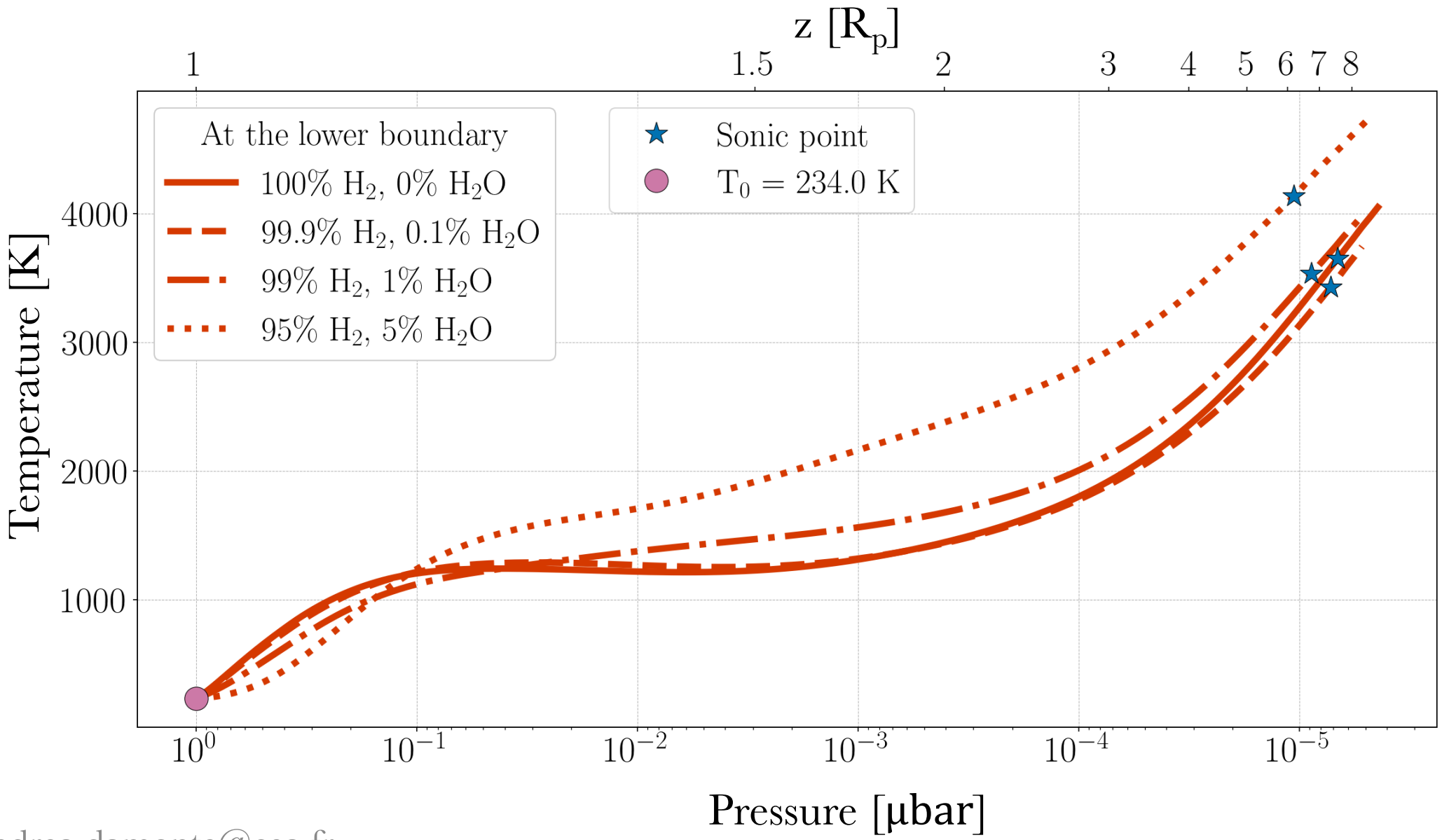


Exoaeronomer (García Muñoz 2025)

- 1D, spherical symmetric, photochemical, hydrodynamical.
- Upper atmosphere from **1 $\mathbf{R_p}$** (1 μbar) to **8 $\mathbf{R_p}$** (1 pbar).
- ~ 50 species: **$\mathbf{H_2}$, $\mathbf{H_2O}$** and derivatives.
  - Lower boundary: ranging **from 100% $\mathbf{H_2}$ to 100% $\mathbf{H_2O}$**.
- ~ 500 reaction channels.



Temperature



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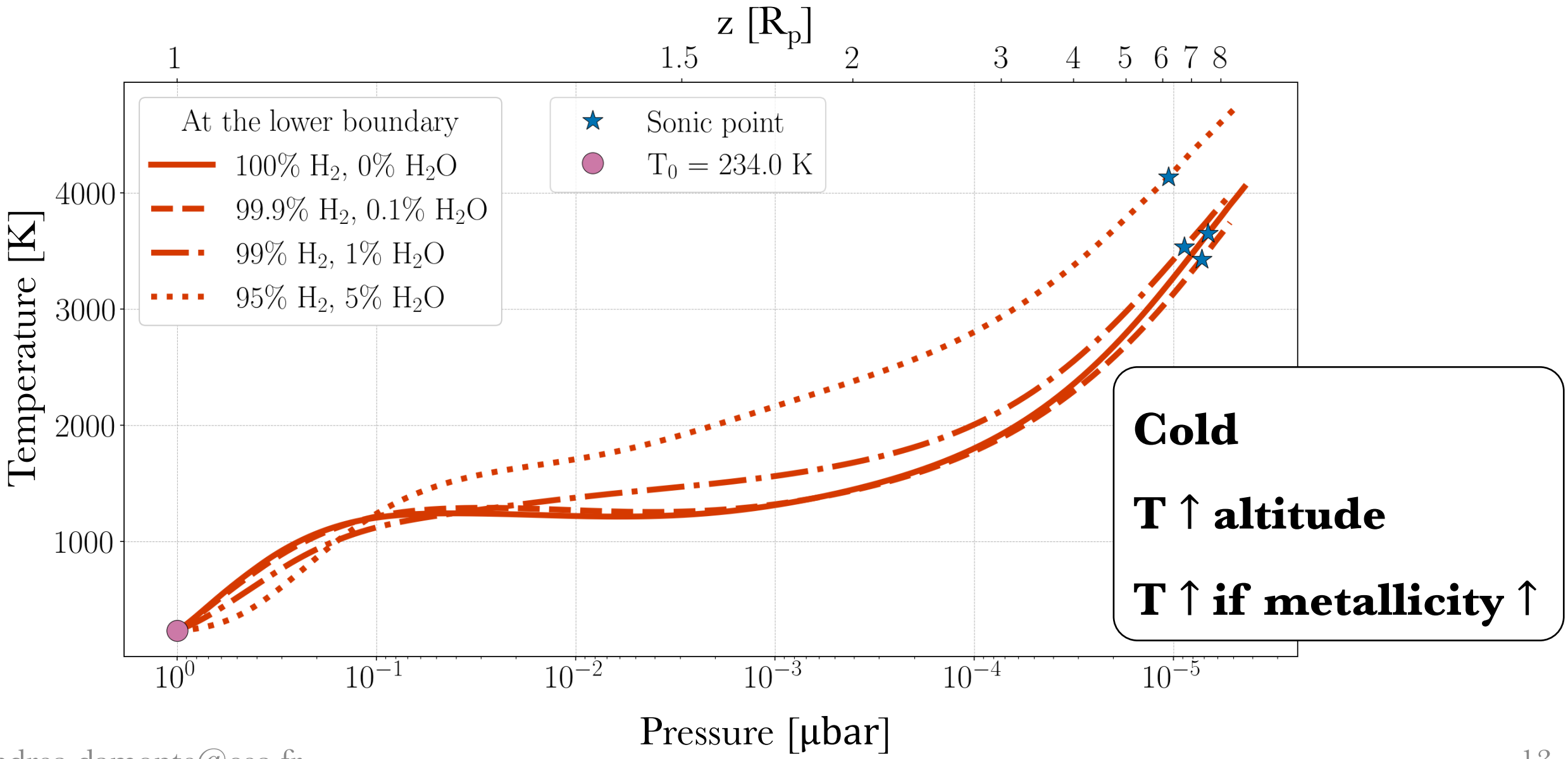


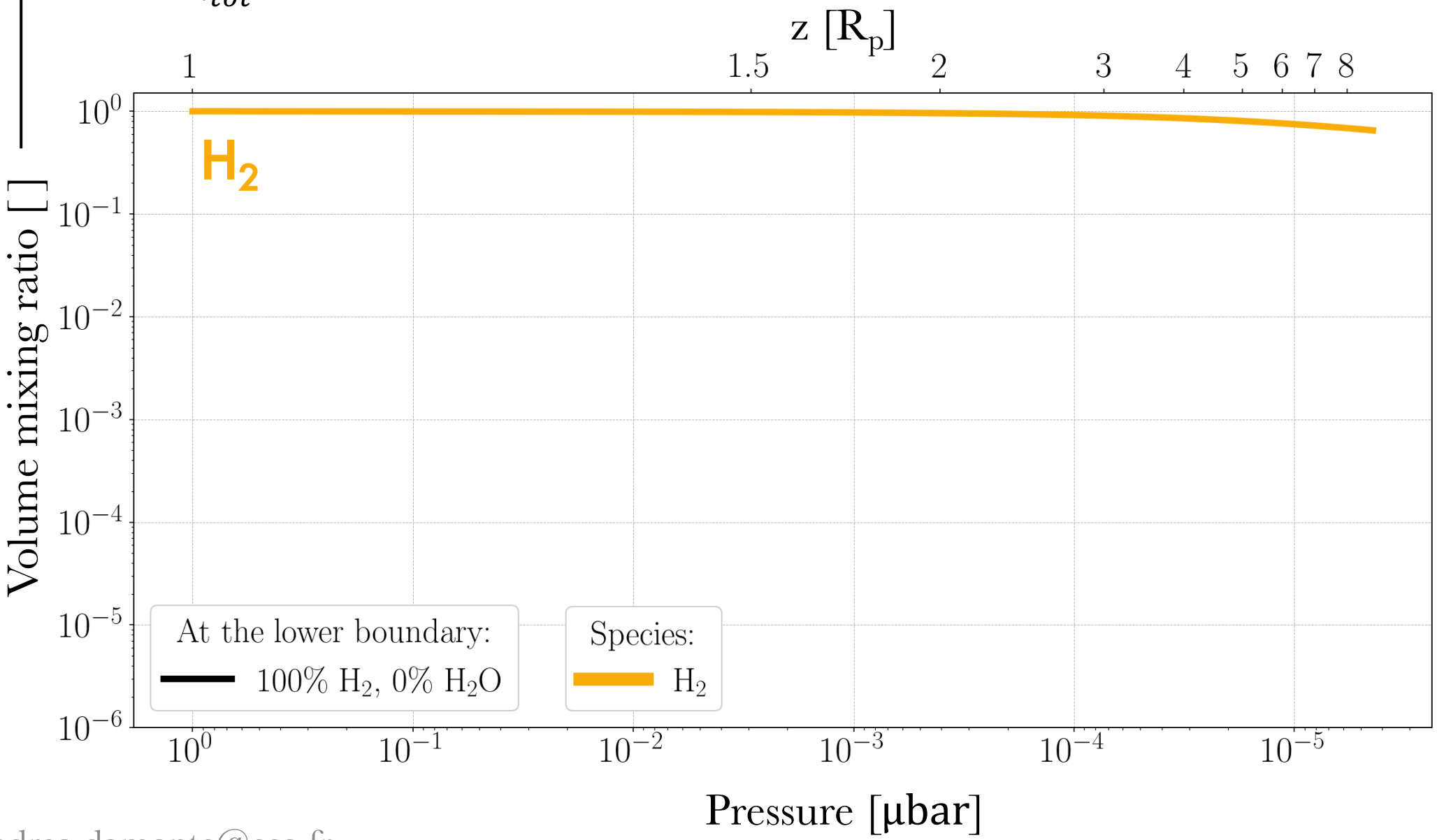
Cold

T ↑ altitude

T ↑ if metallicity ↑

Volume Mixing Ratio

$$X_j = \frac{n_j}{n_{tot}}$$



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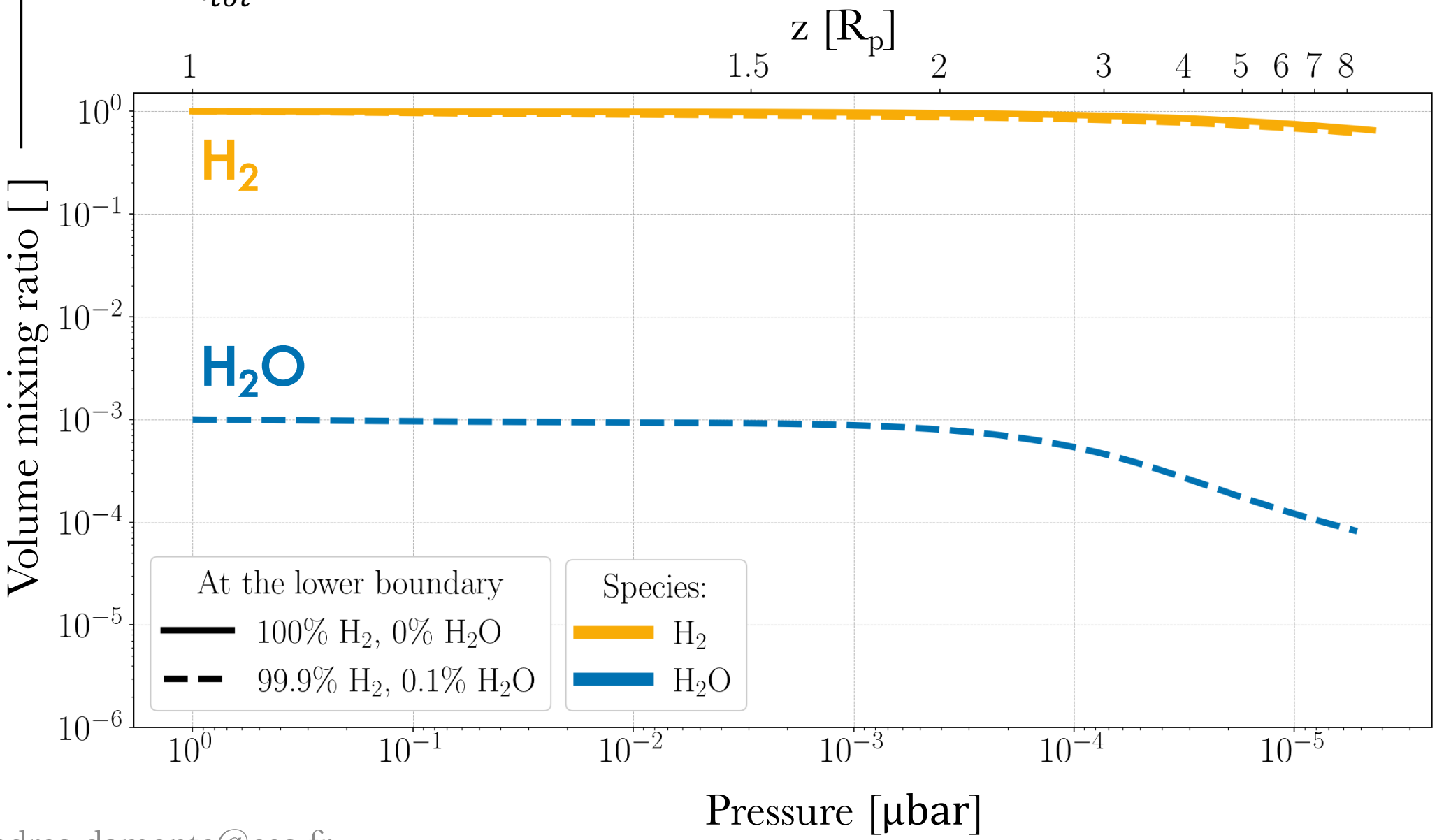

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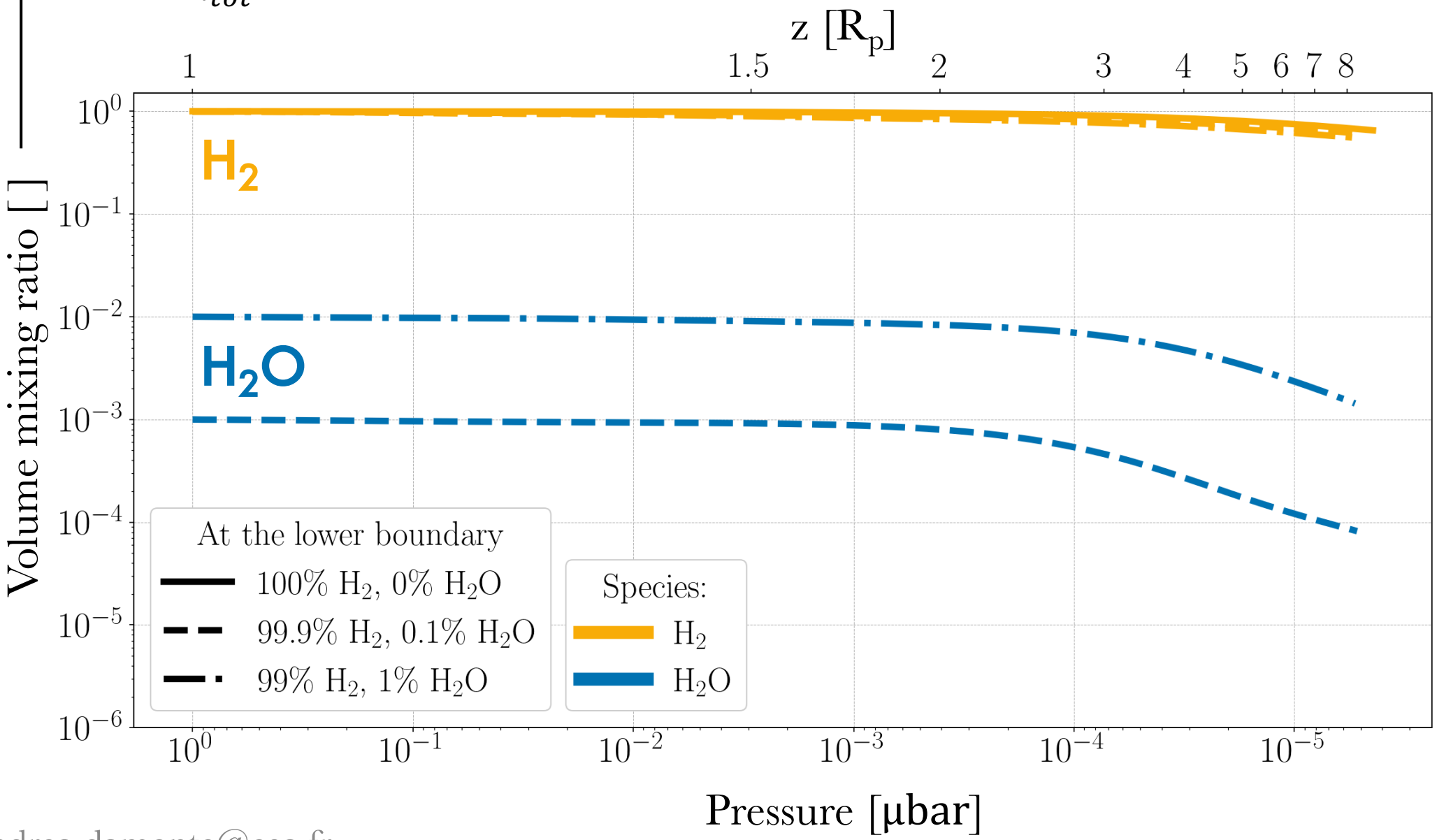

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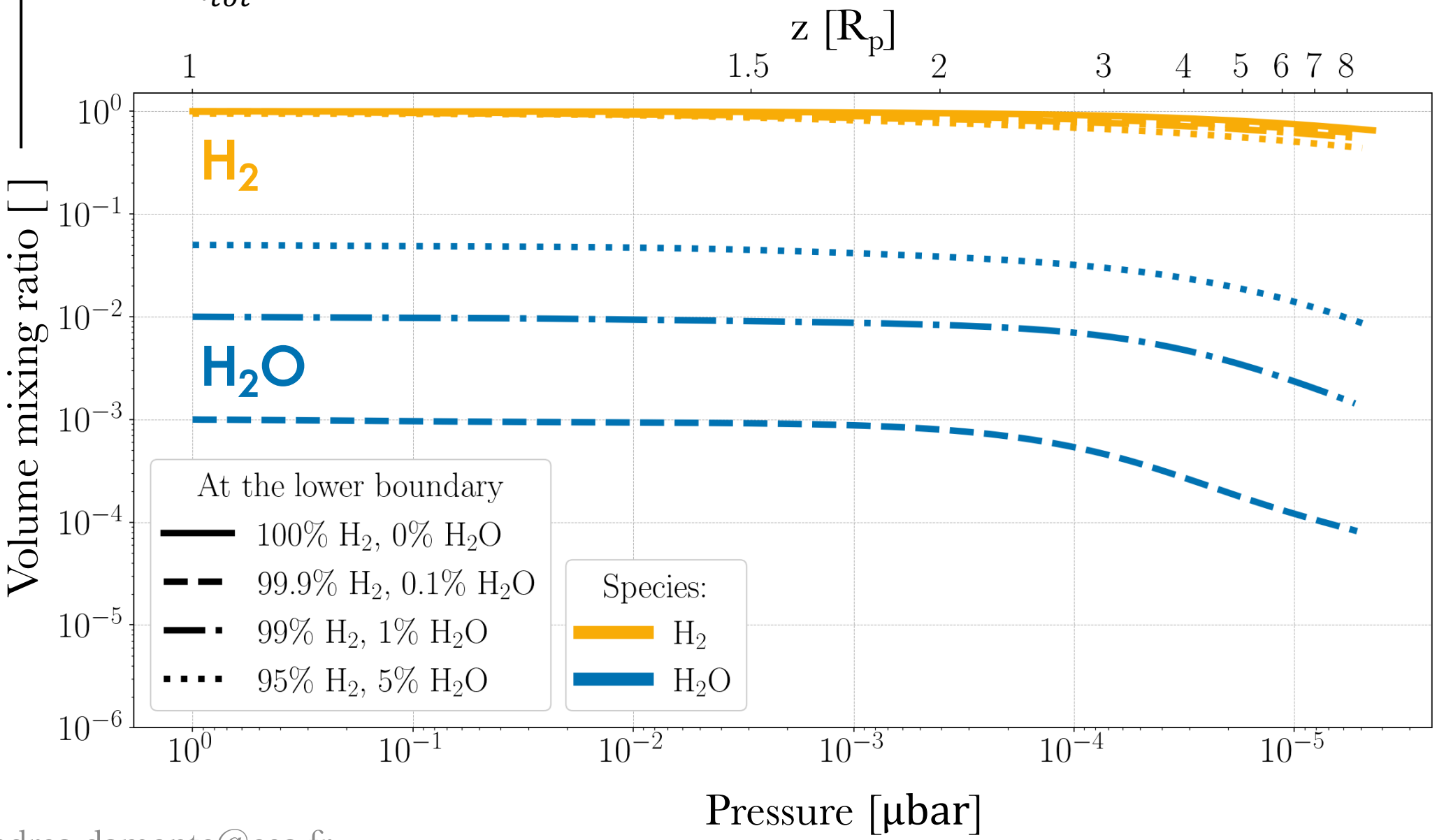

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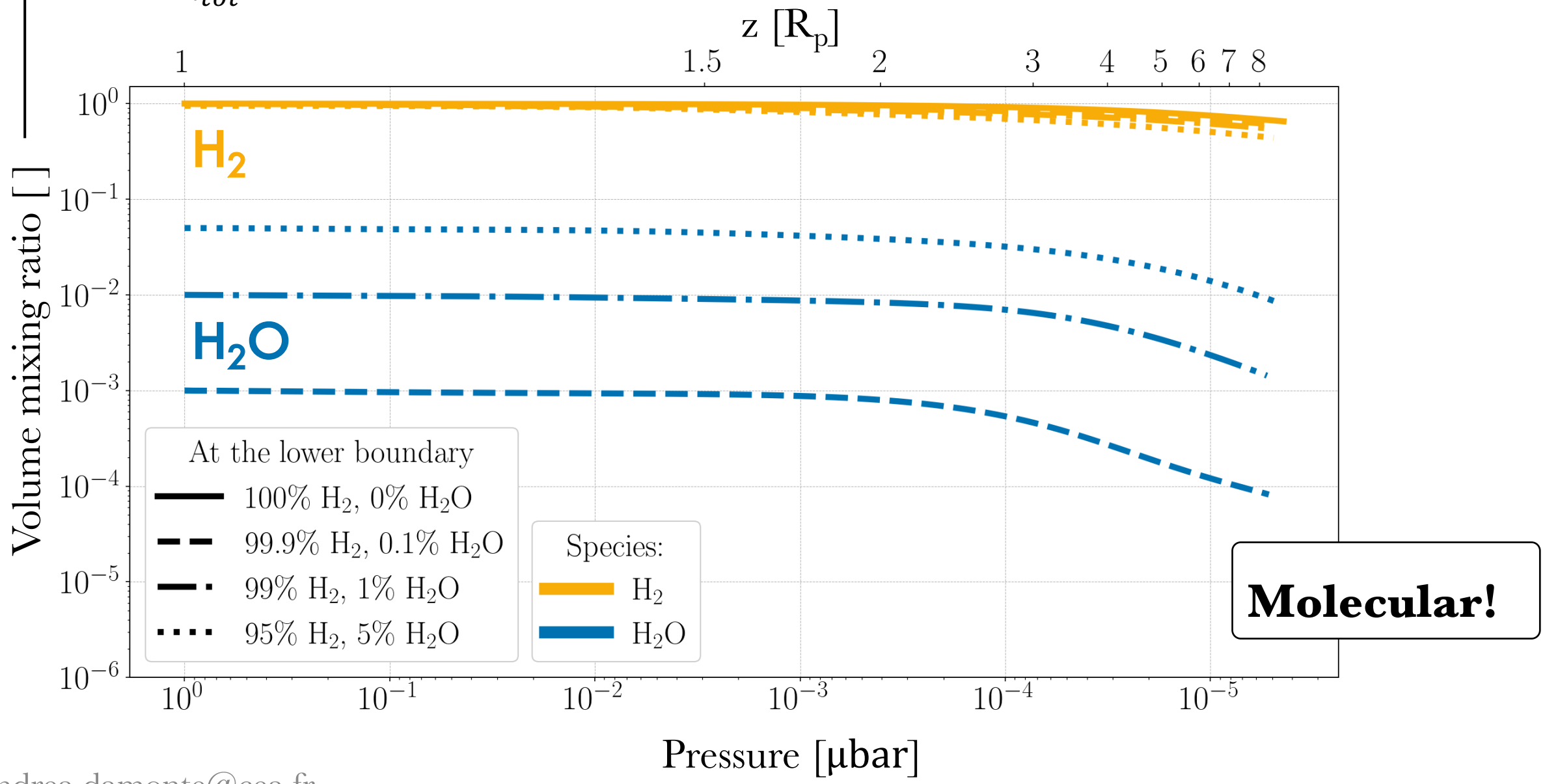
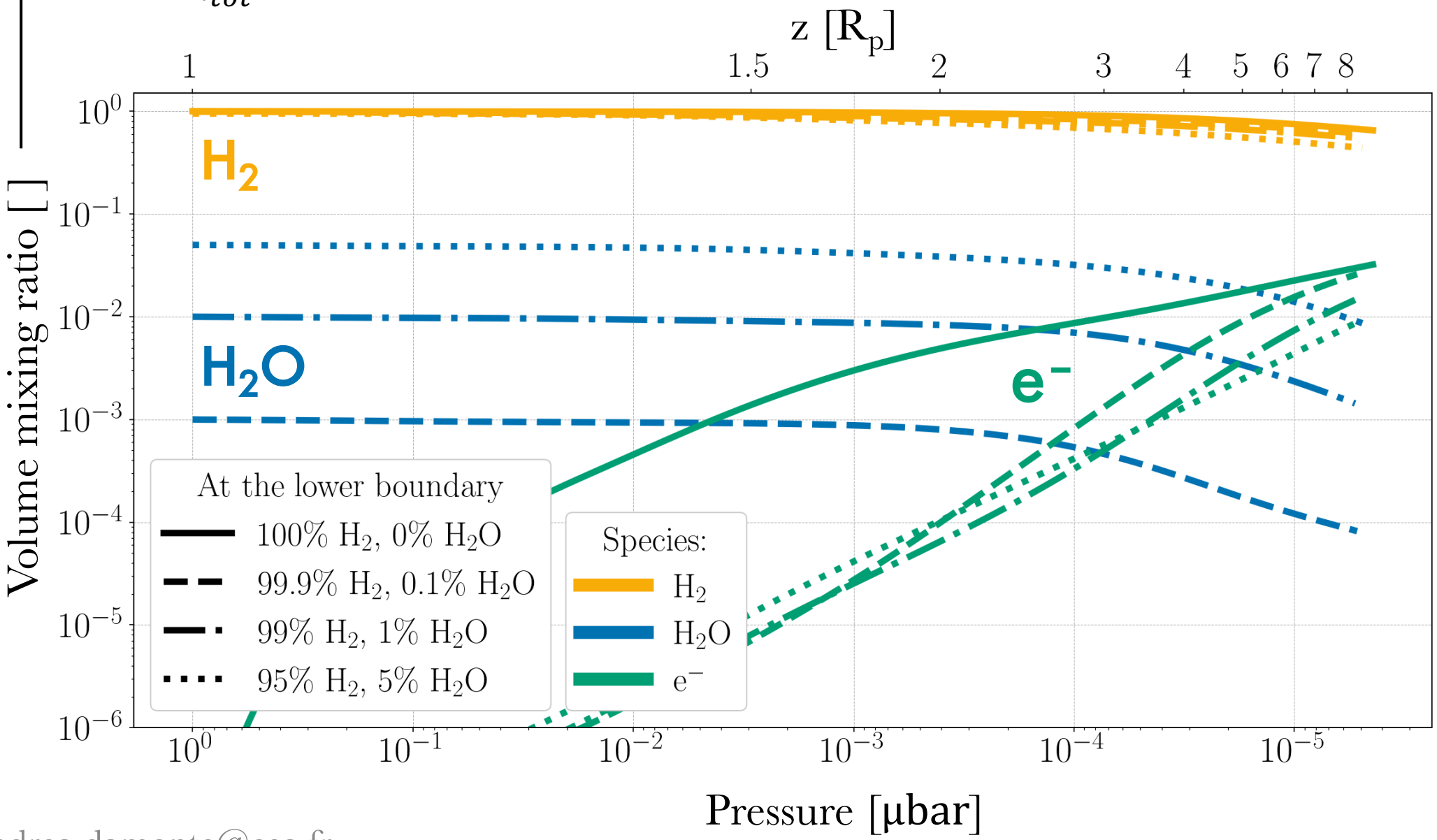


Molecular!

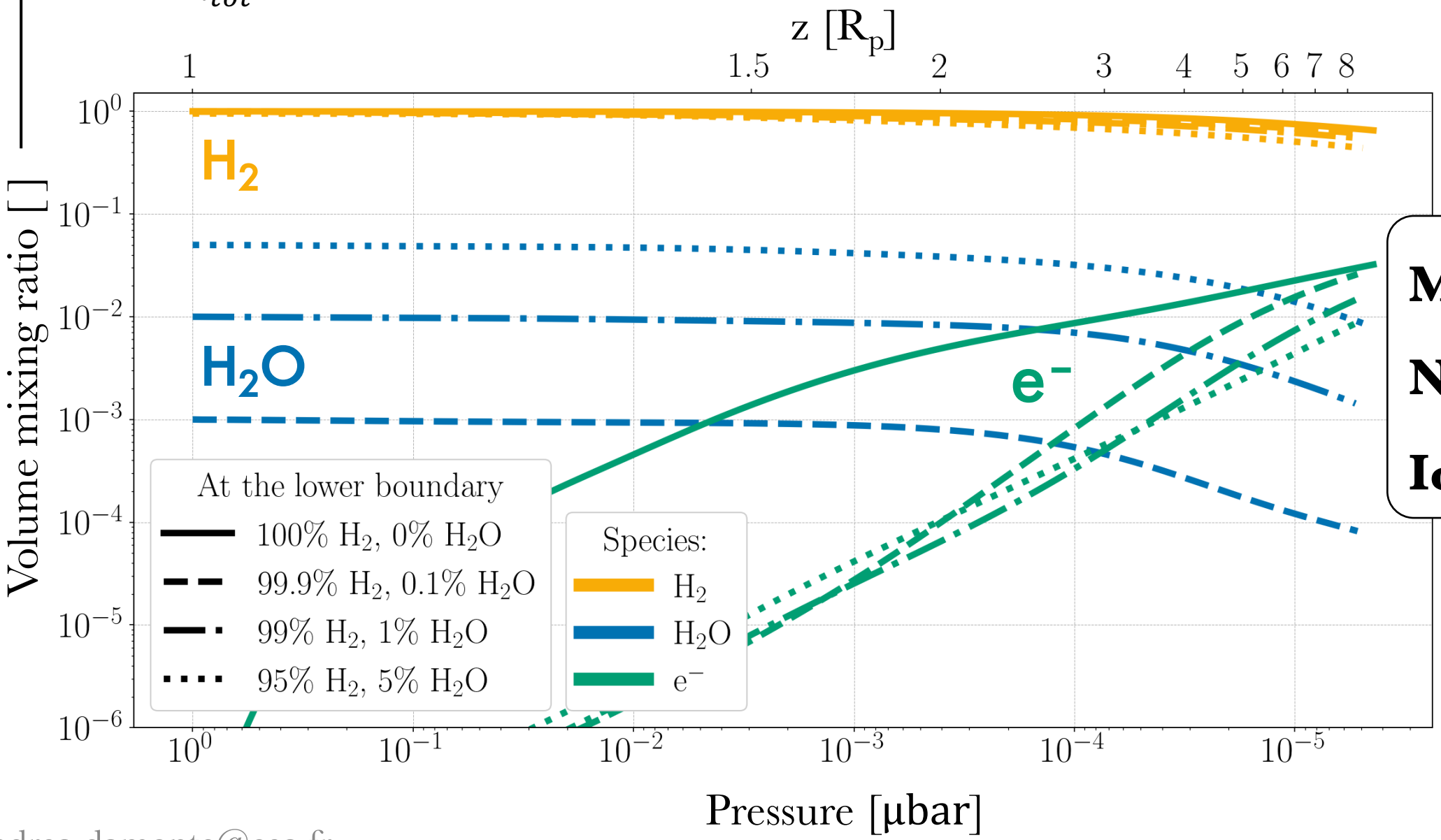
Volume Mixing Ratio

$$X_j = \frac{n_j}{n_{tot}}$$



Volume Mixing Ratio

$$X_j = \frac{n_j}{n_{tot}}$$



Molecular

Neutral

Ions only ↑↑

Transport >> Chemistry

0% H_2O

100% H_2

H_2 is in **chemical disequilibrium** but

net effect!

$$\tau^{H_2}_{transport} \ll \tau^{H_2}_{chemistry}$$

Transport sustains the volume mixing ratios,

chemistry affects ↑↑.

Chemical pathway analysis

We use **PumpKin** (Markosyan+2014) to study the chemical pathways.

- Linear combination of channels
- Effective reactions (longer timescales)
- Easier connection between species

$$\gamma + H_2 \rightarrow e^- + H + H^+$$

$$H_2 + H^+ \rightarrow H + H_2^+$$

$$H_2 + H_2^+ \rightarrow H + H_3^+$$

$$e^- + H_3^+ \rightarrow 3H$$

NET: $3H_2 \rightarrow 6H$

(0% H_2O)

Main pathways for H_2 loss

6 pathways includes more than 50% of all H_2 loss at all altitudes.

Total H_2 loss

20 %

$\gamma + H_2 \rightarrow e^- + H + H^+$

$e^- + H^+ \rightarrow H$

NET: $H_2 \rightarrow 2H$

35 %

$\gamma + H_2 \rightarrow e^- + H + H^+$

$H_2 + H^+ \rightarrow H + H_2^+$

$H_2 + H_2^+ \rightarrow H + H_3^+$

$e^- + H_3^+ \rightarrow 3H$

NET: $3H_2 \rightarrow 6H$

10^{-1} bar

1.1 R_p

30 %

$\gamma + H_2 \rightarrow e^- + H + H^+$

$e^- + H^+ \rightarrow H$

NET: $H_2 \rightarrow 2H$

35 %

$\gamma + H_2 \rightarrow e^- + H + H^+$

NET: $H_2 \rightarrow e^- + H + H^+$

10^{-2} bar

1.4 R_p

35 %

$\gamma + H_2 \rightarrow e^- + H_2^+$

$H_2 + H_2^+ \rightarrow H + H_3^+$

$e^- + H_3^+ \rightarrow 3H$

NET: $2H_2 \rightarrow 4H$

35 %

$\gamma + H_2 \rightarrow e^- + H + H^+$

NET: $H_2 \rightarrow e^- + H + H^+$

10^{-3} bar

1.8 R_p

10 %

$\gamma + H_2 \rightarrow e^- + H + H^+$

NET: $H_2 \rightarrow e^- + H + H^+$

10 %

$\gamma + H_2 \rightarrow e^- + H_2^+$

$H_2 + H_2^+ \rightarrow H + H_3^+$

$e^- + H_3^+ \rightarrow H + H_2$

NET: $H_2 \rightarrow 2H$

65 %

$\gamma + H_2 \rightarrow e^- + H_2^+$

$H_2 + H_2^+ \rightarrow H + H_3^+$

$e^- + H_3^+ \rightarrow 3H$

NET: $2H_2 \rightarrow 4H$

10^{-4} bar

2.6 R_p

At the lower boundary

0% H_2O

100% H_2

10 %

$\gamma + H_2 \rightarrow 2H$

NET: $H_2 \rightarrow 2H$

40 %

$\gamma + H_2 \rightarrow e^- + H_2^+$

$H_2 + H_2^+ \rightarrow H + H_3^+$

$e^- + H_3^+ \rightarrow 3H$

NET: $2H_2 \rightarrow 4H$

10^{-5} bar

5.7 R_p

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1% H_2O

99% H_2

Transport >> Chemistry

H_2O is in **chemical equilibrium** and

$$\tau^{H_2O}_{\text{transport}} \ll \tau^{H_2O}_{\text{chemistry (net)}}$$

Again, transport sustains the volume mixing ratios and chemistry affects ↑↑ in the atm.

$$H_2 + OH \rightleftarrows H + H_2O$$

NET: null cycle

$$H_2 \rightarrow e^- + H_2^+$$

$$H_2 + H_2^+ \rightarrow H + H_3^+$$

$$H_2O + H_3^+ \rightarrow H_2 + H_3O^+$$

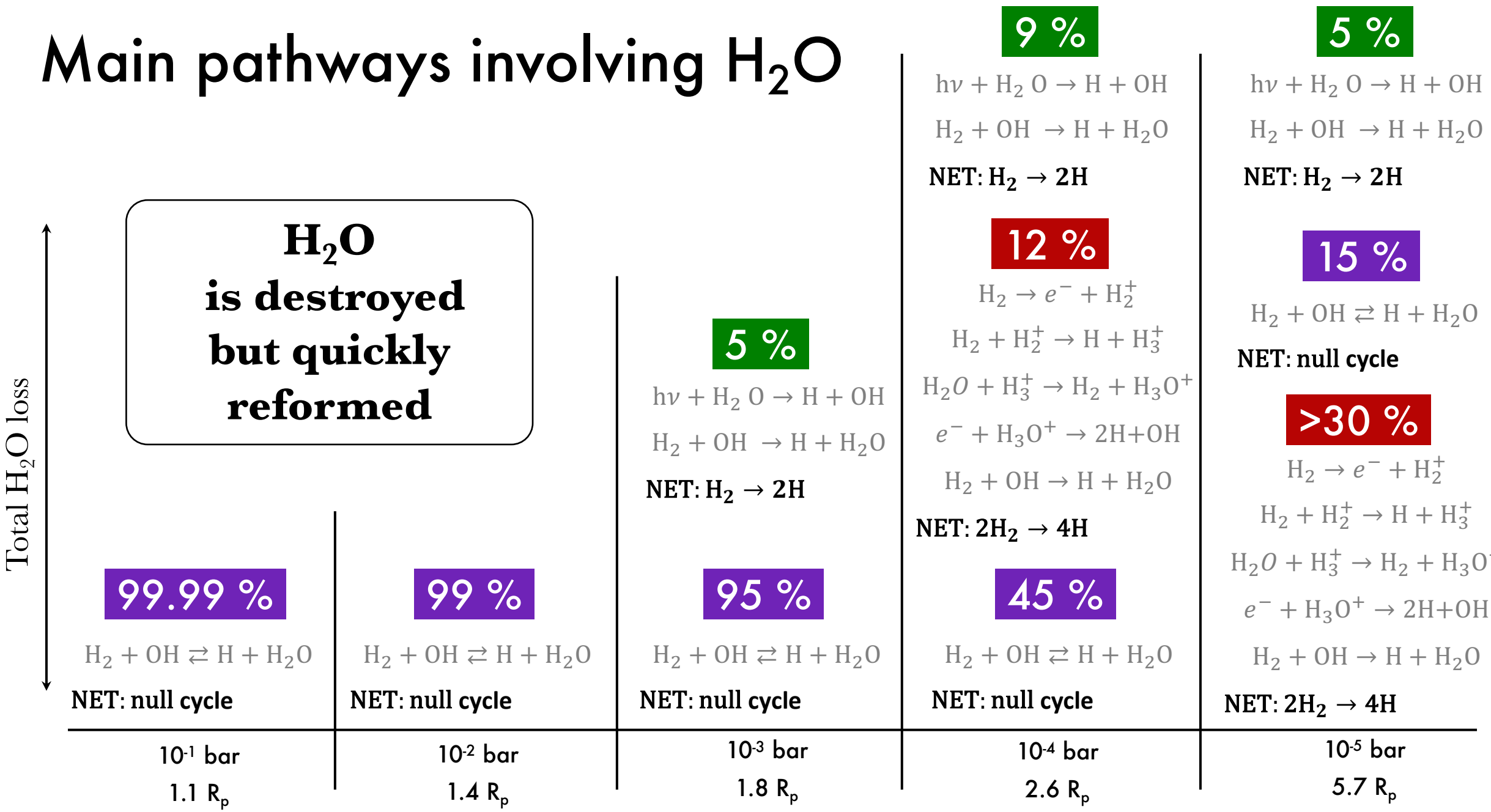
$$e^- + H_3O^+ \rightarrow 2H + OH$$

$$H_2 + OH \rightarrow H + H_2O$$

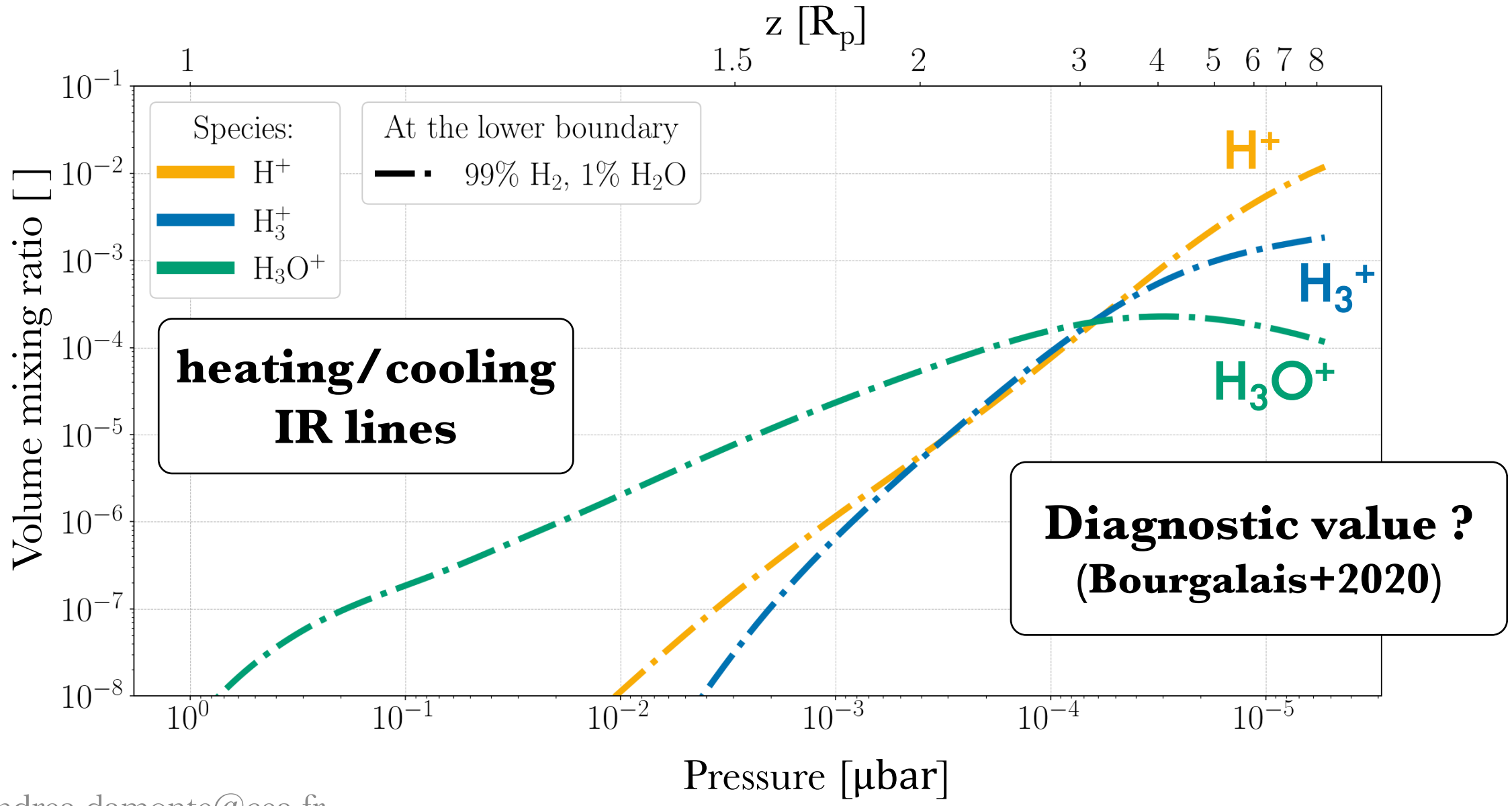
NET: $2H_2 \rightarrow 4H$

No water in the net!

Main pathways involving H_2O



Important ions (H_3^+, H_3O^+) are still appearing ↑↑



Conclusions

- **PCb's H_2 – H_2O** atmosphere is **extended but cold**.
- **Strong transport** and **faint FUV fluxes** render it mostly **molecular**.
- **Fast ion chemistry** assures its **neutrality**.
- H_2O boosts absorption, but transport and **reformation** keep gas molecular.
- **H_3^+**, **H_3O^+** may be important for **cooling** & **IR transmission spectroscopy**.

Plans for the future

- Chemistry for up to **100% of H_2O**.
- Include **He**.
- Role of molecules and ions in **heating/cooling**.
- Effects of **photoelectrons** and **variability**.
- **Mass loss rate** and **long-term** evolution.