Atmospheres: Magma-hydrogen interactions in sub-Neptunes

William Misener
PhD Candidate
UCLA Department of Earth, Planetary, and Space Sciences

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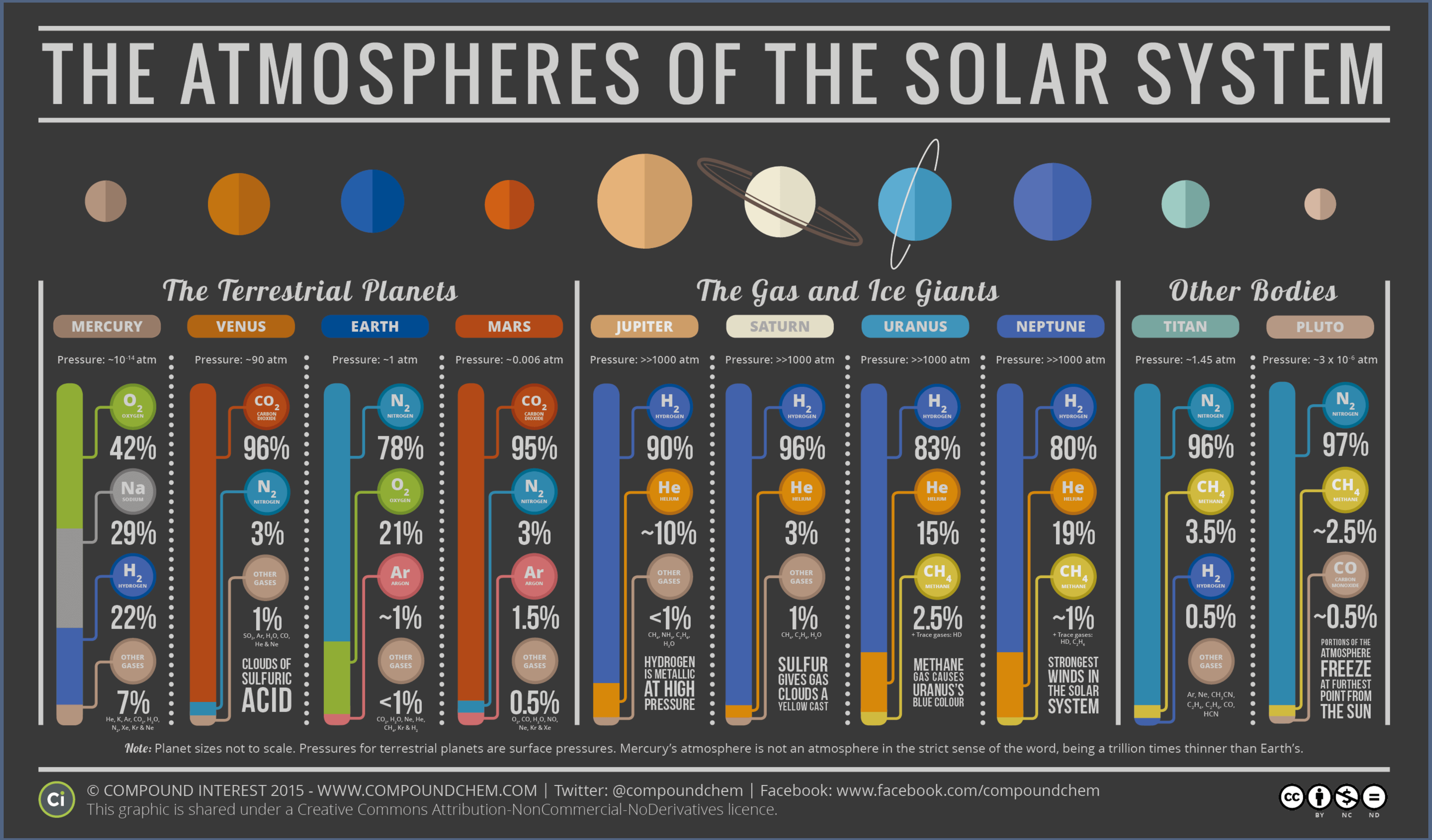
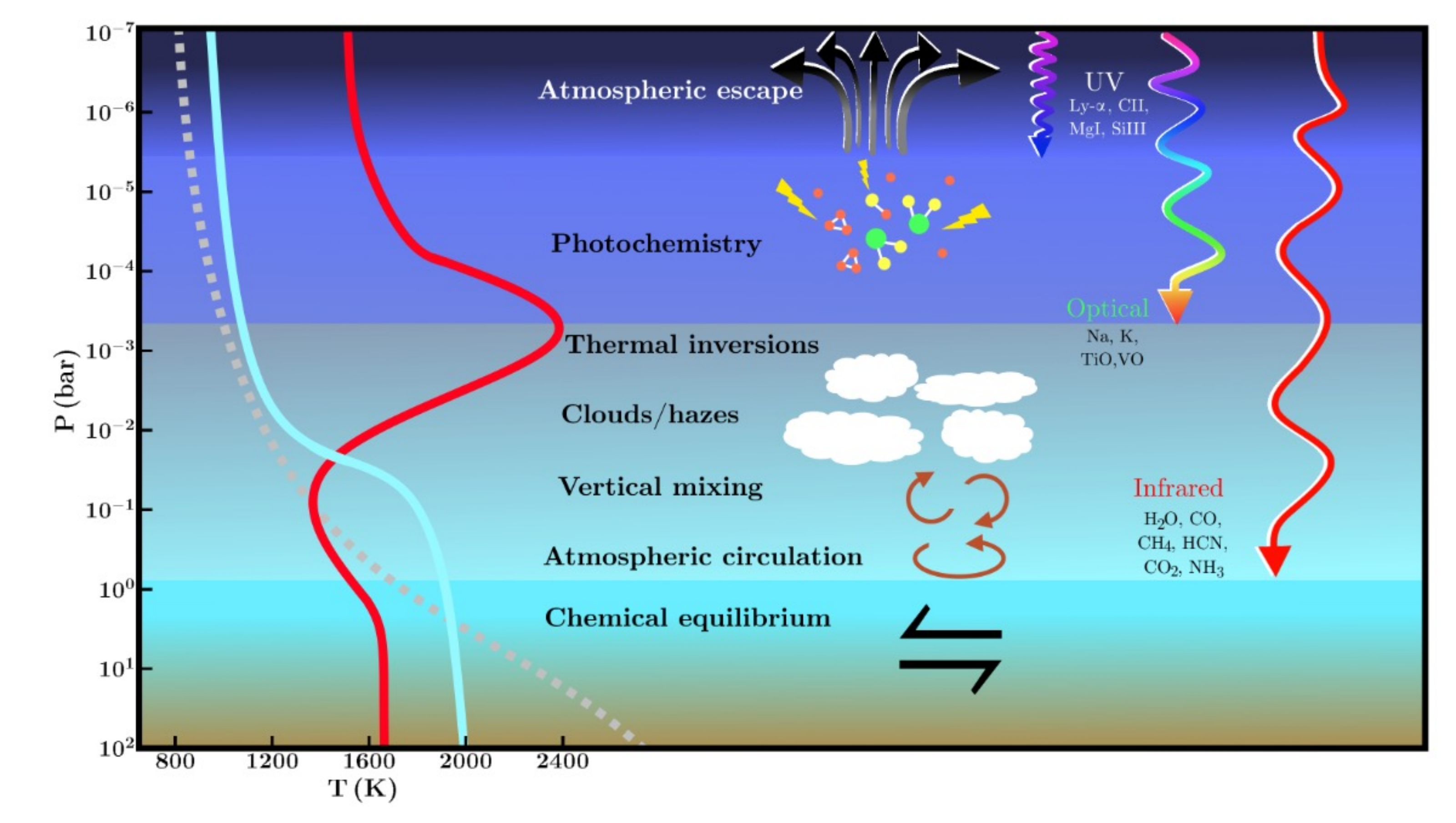
willmisener.com

UCLA
Planet Formation Group
Department of Earth, Planetary, and Space Sciences

Atmospheres: The Solar System

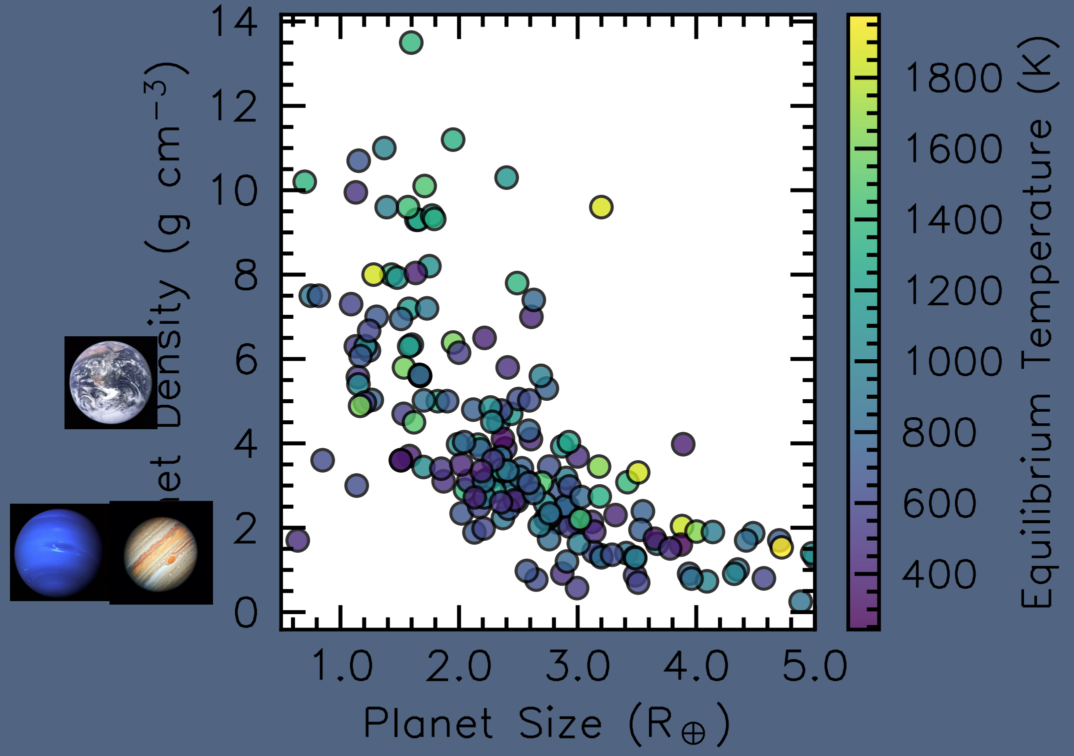


Atmospheres: The Basics

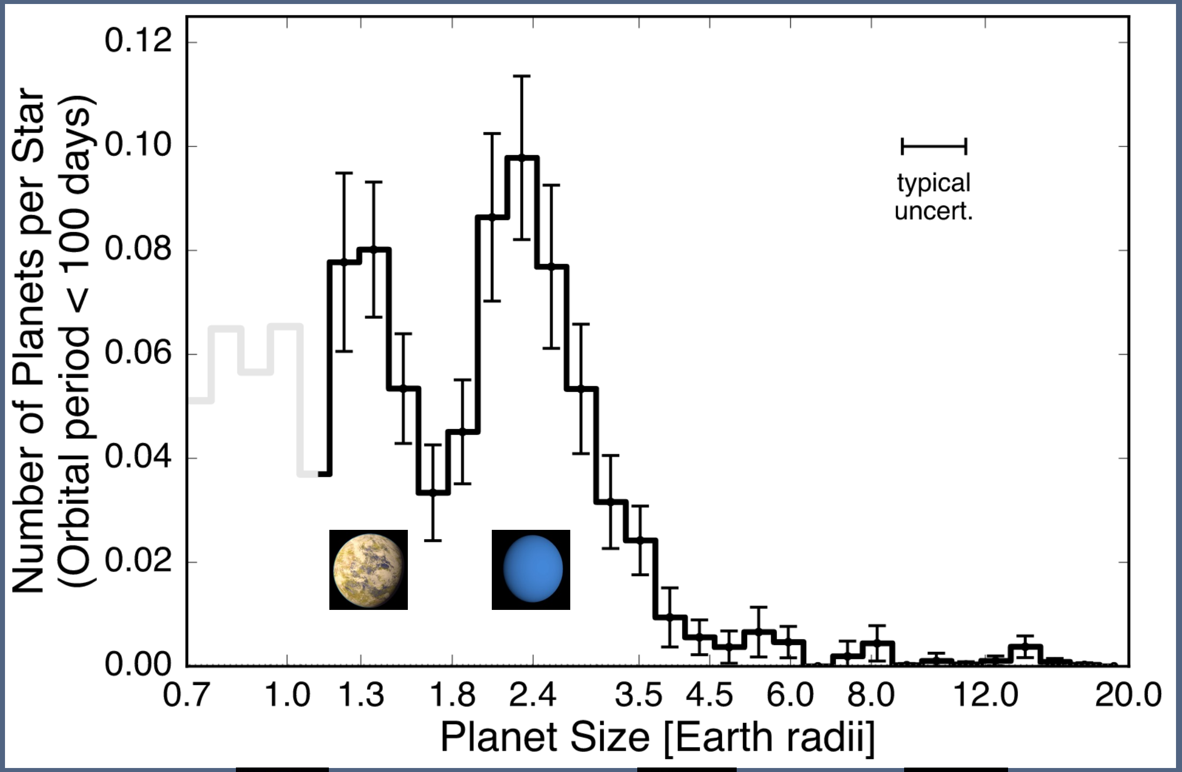


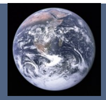
Madhusudhan (2019)

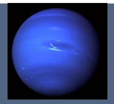
How to find an atmosphere: bulk properties

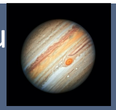


Courtesy J. Rogers (UCLA)





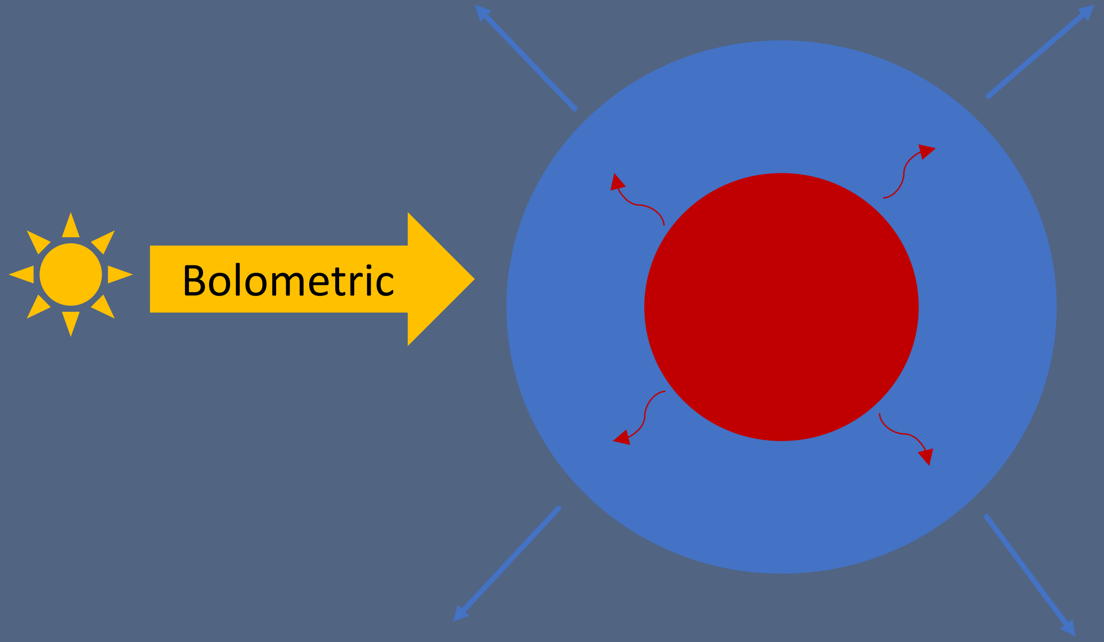




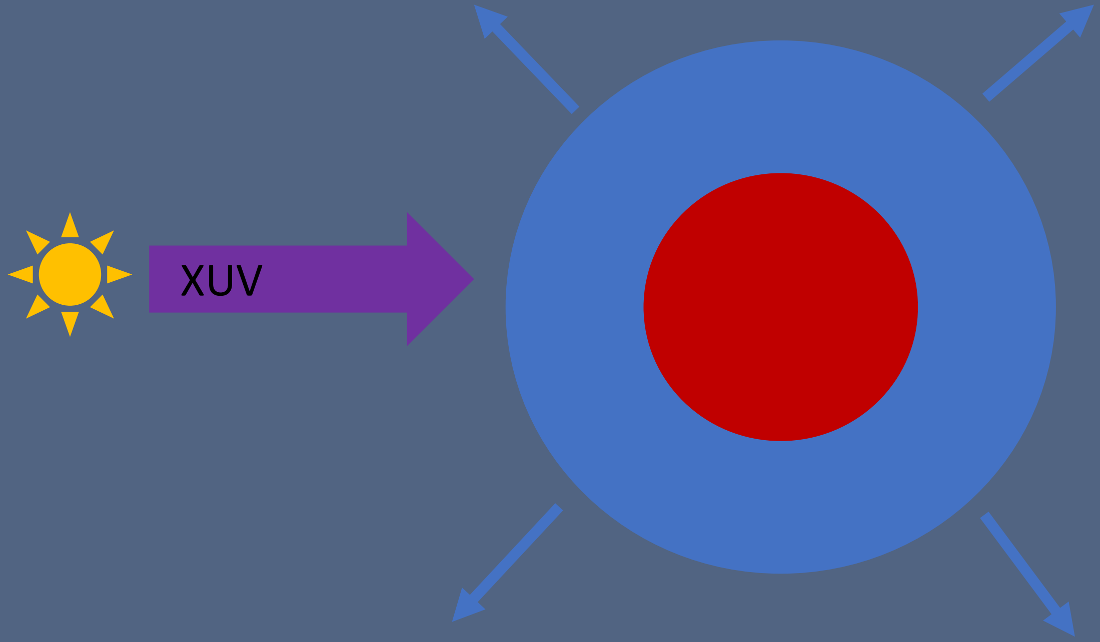
Fu … al. (2017)

Atmospheric Escape: Two mechanisms

Core-powered mass loss

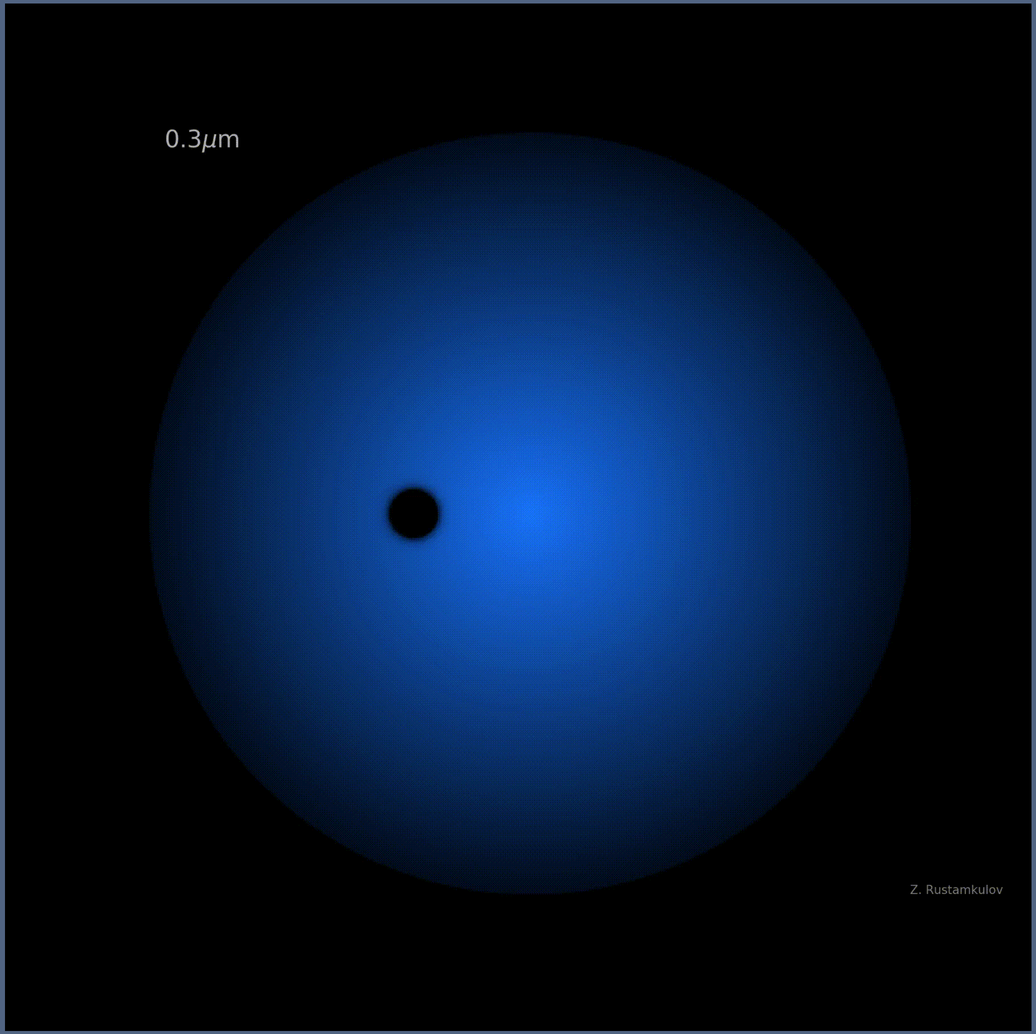


Photoevaporation

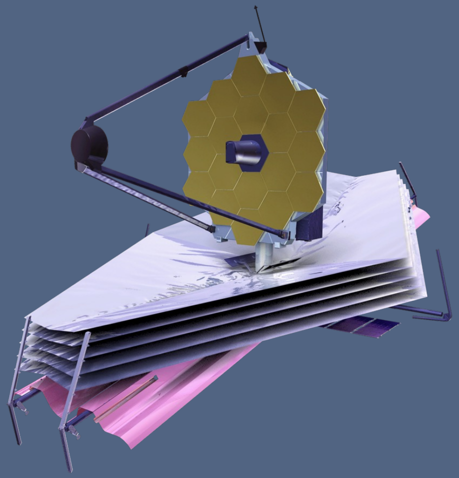


See e.g. Owen & Jackson (2012), Ginzburg et al. (2016), Owen & Wu (2017), Gupta & Schlichting (2019), Rogers et al. (2021), Owen & Schlichting (2023)

How to find an atmosphere: transit spectroscopy

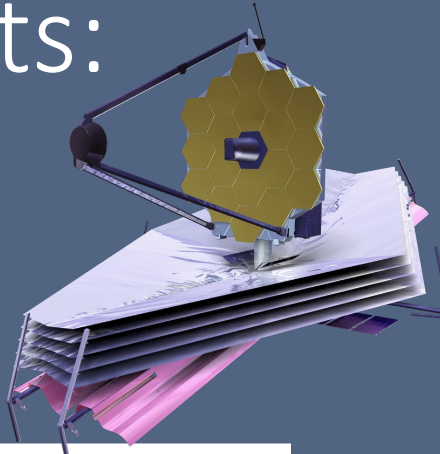


Courtesy Z. Rustamkulov (JHU)

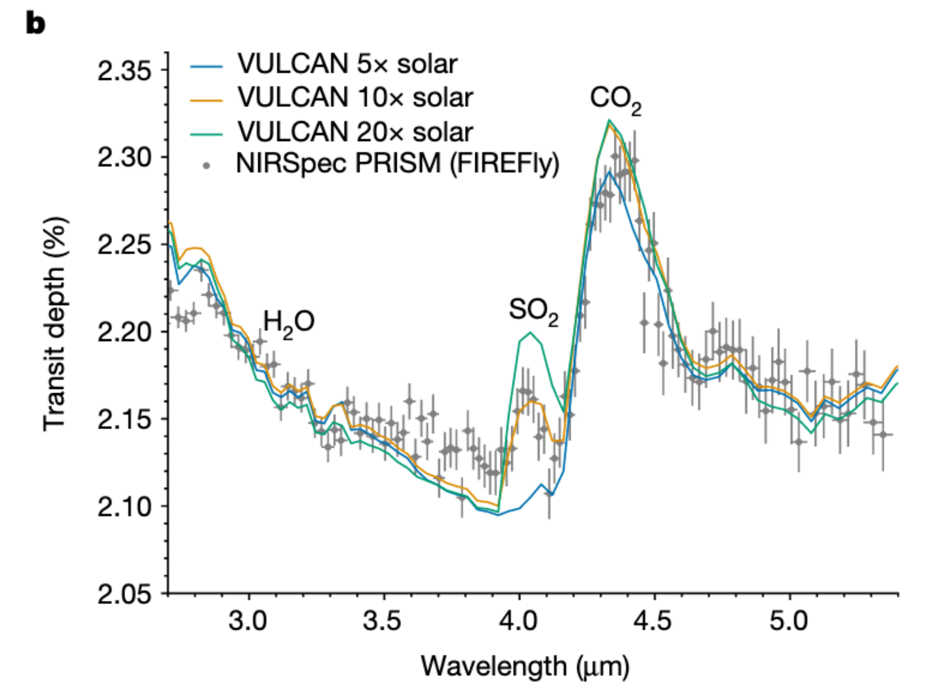


=> composition of upper atmosphere

Hot Jupiter atmospheric measurements: long-awaited physics

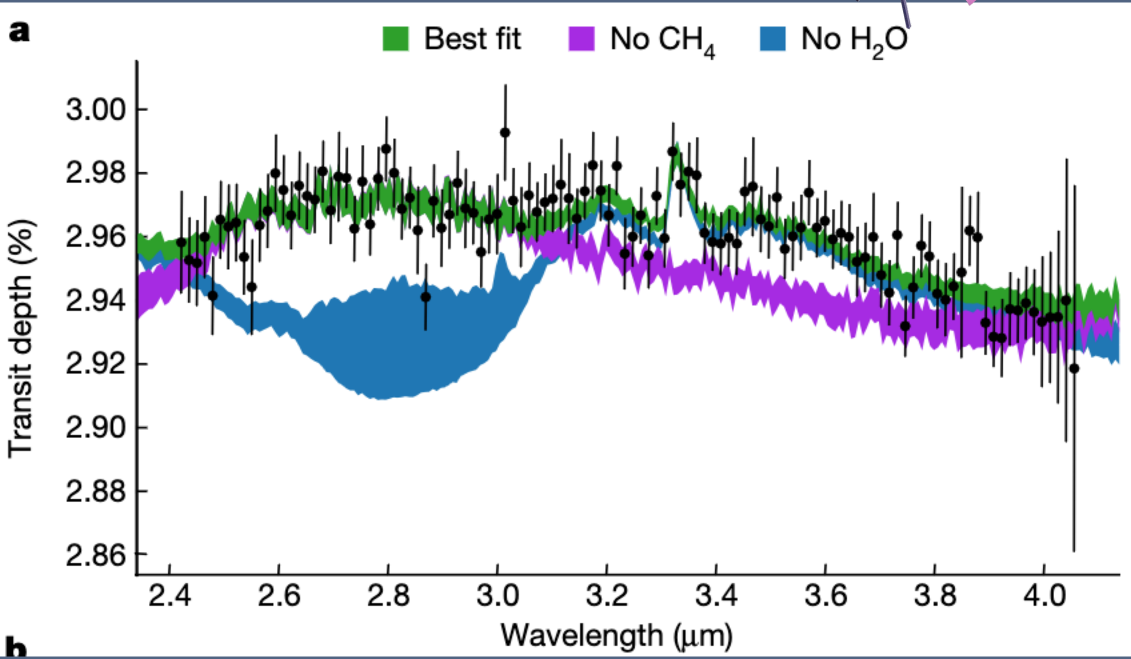


Photochemistry



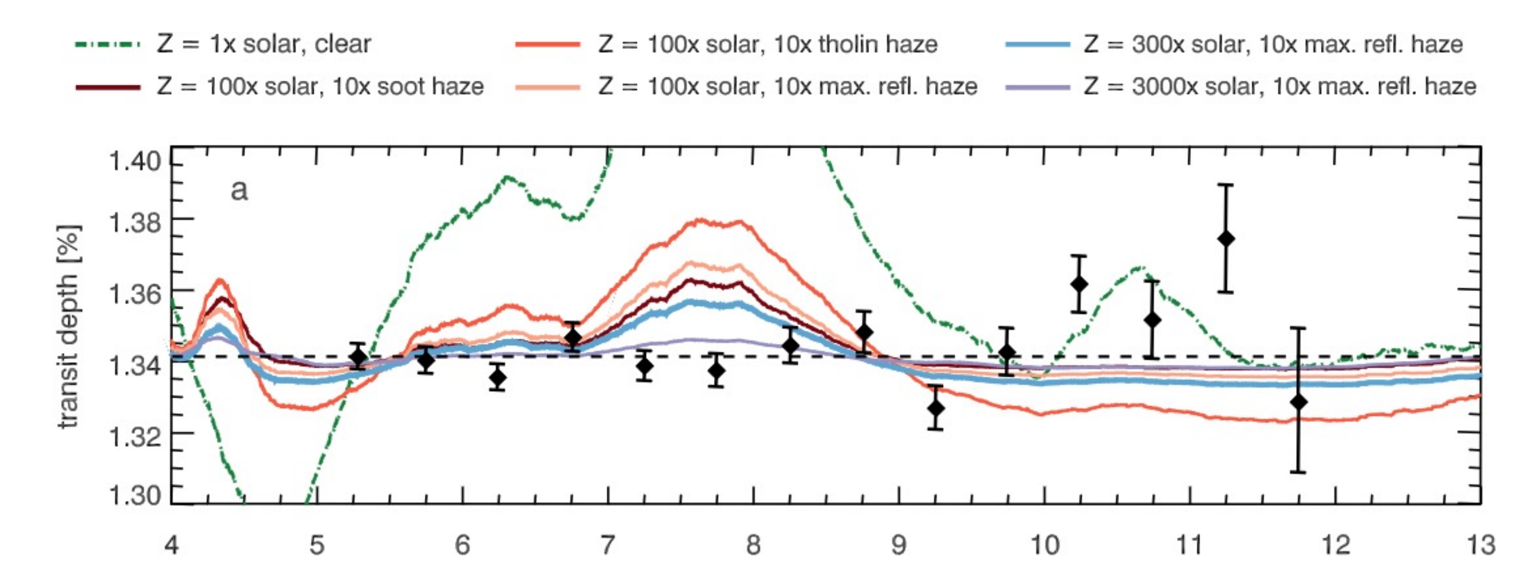
Tsai et al. (2023)

Methane



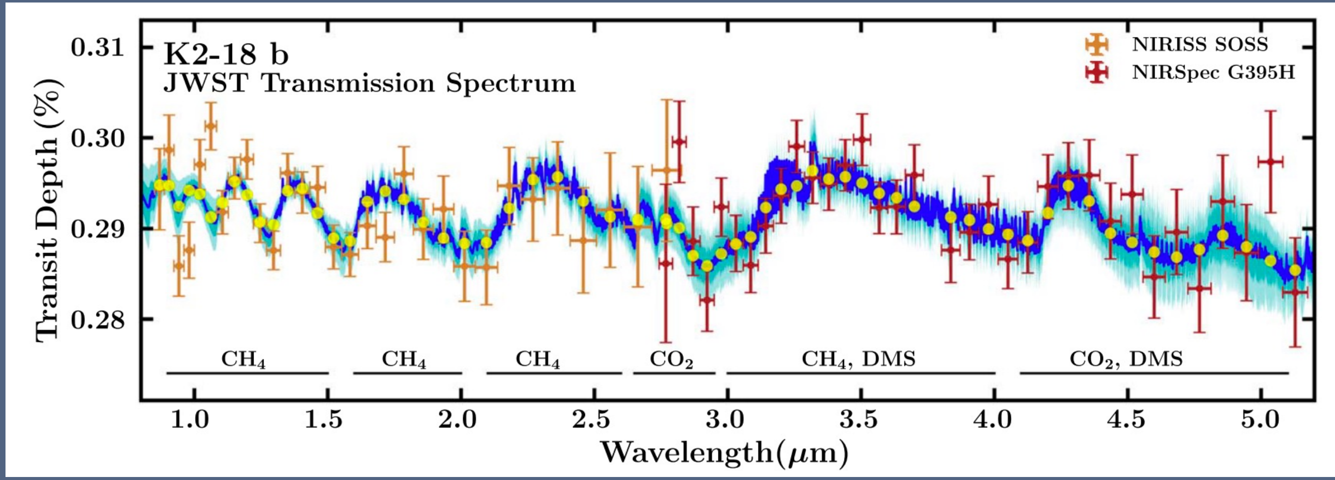
Bell et al. (2023)

Sub-Neptune atmospheric measurements: the future is now

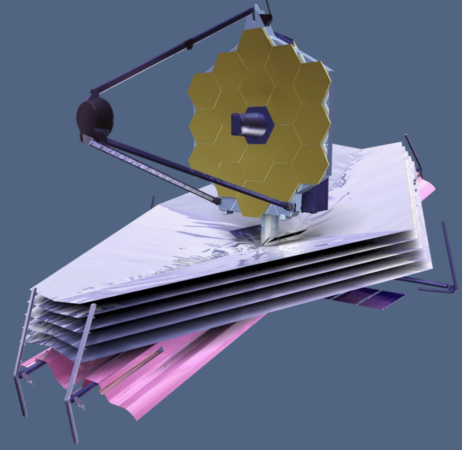


Wavelength (microns)

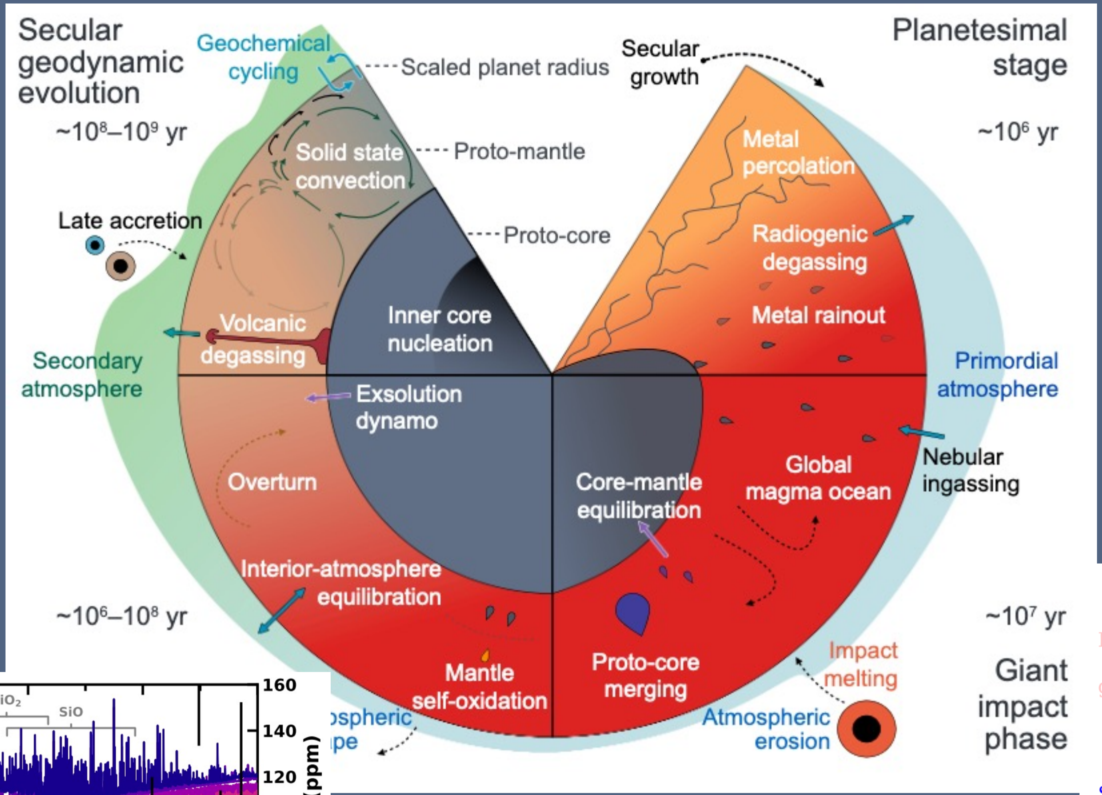
Kempton et al. (2023)



Madhusudhan et al. (2023)



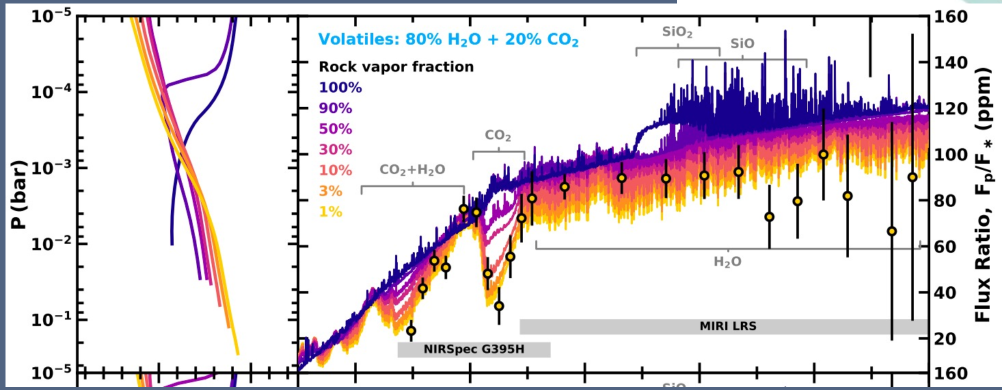
Small planet atmospheric models



Lichtenberg et al. (2022)

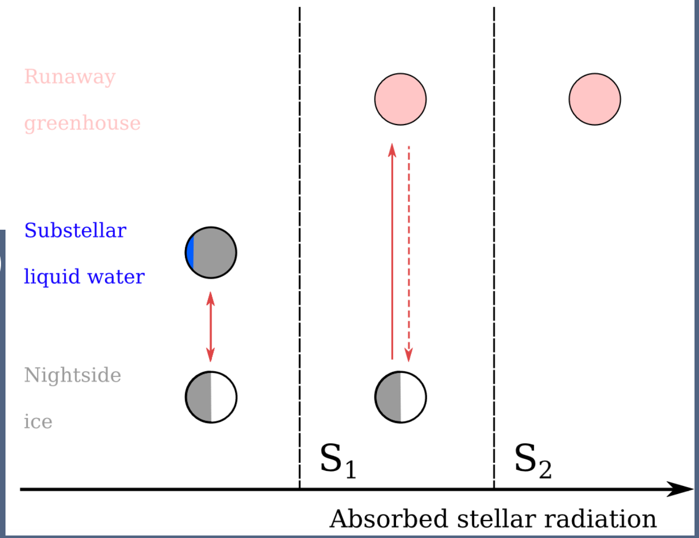
Rock vapor atmospheres

Piette et al. (2023)

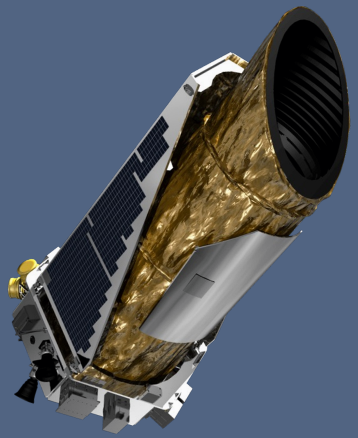


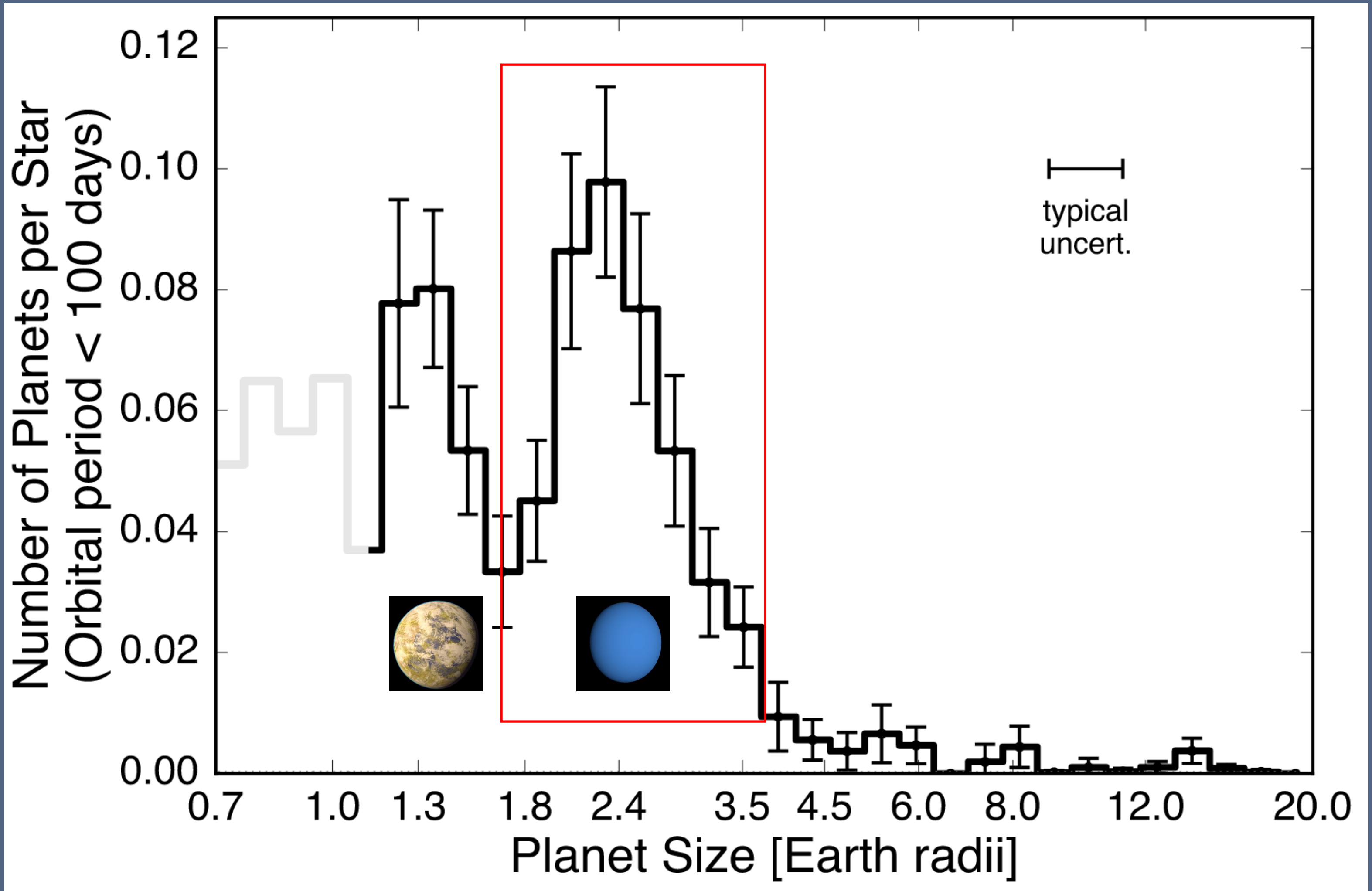
Tidal locking and liquid water

Ding & Wordsworth (2020)

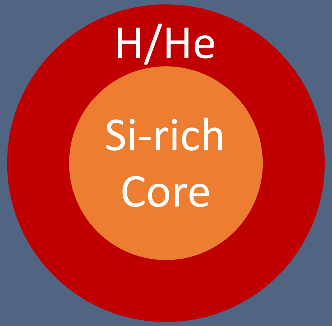


Sub-Neptunes: the key to unlock planetary interiors

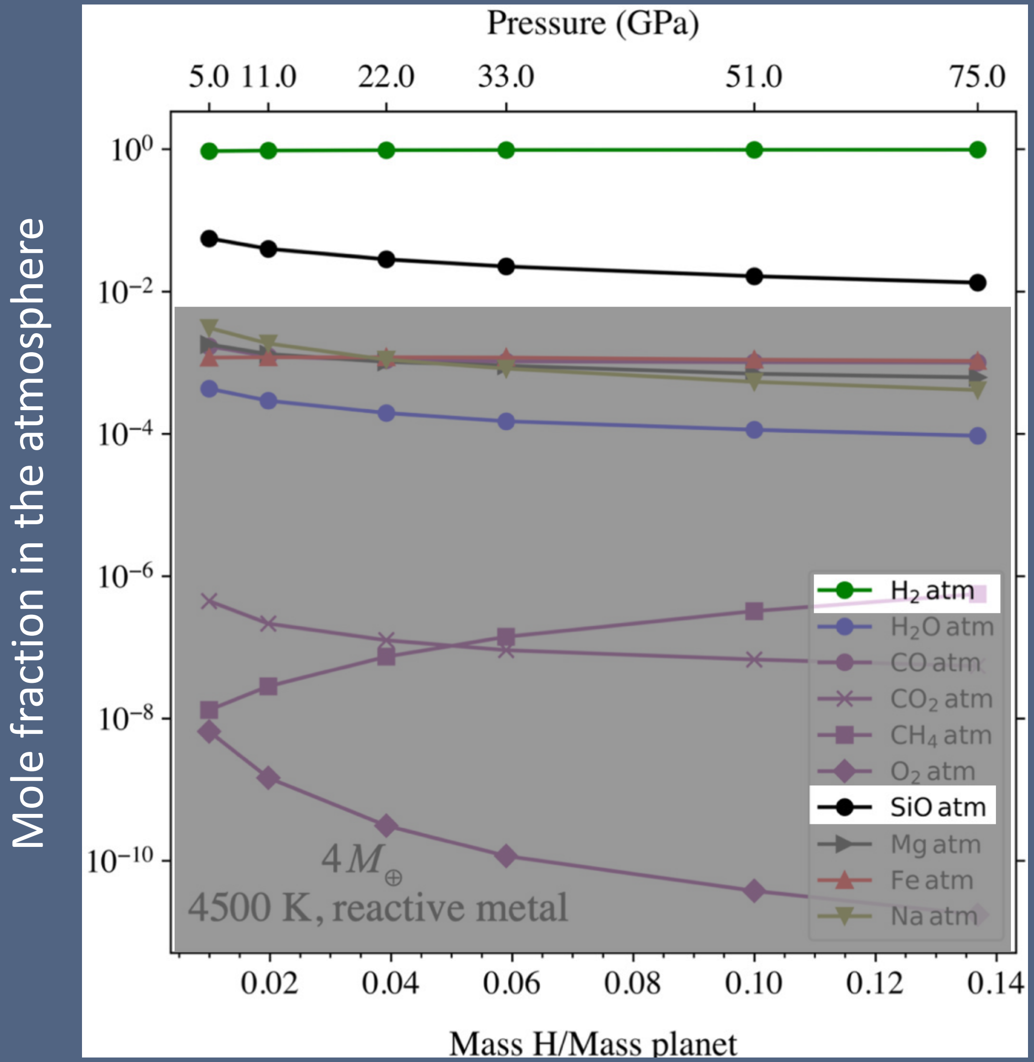




Fulton et al. (2017)

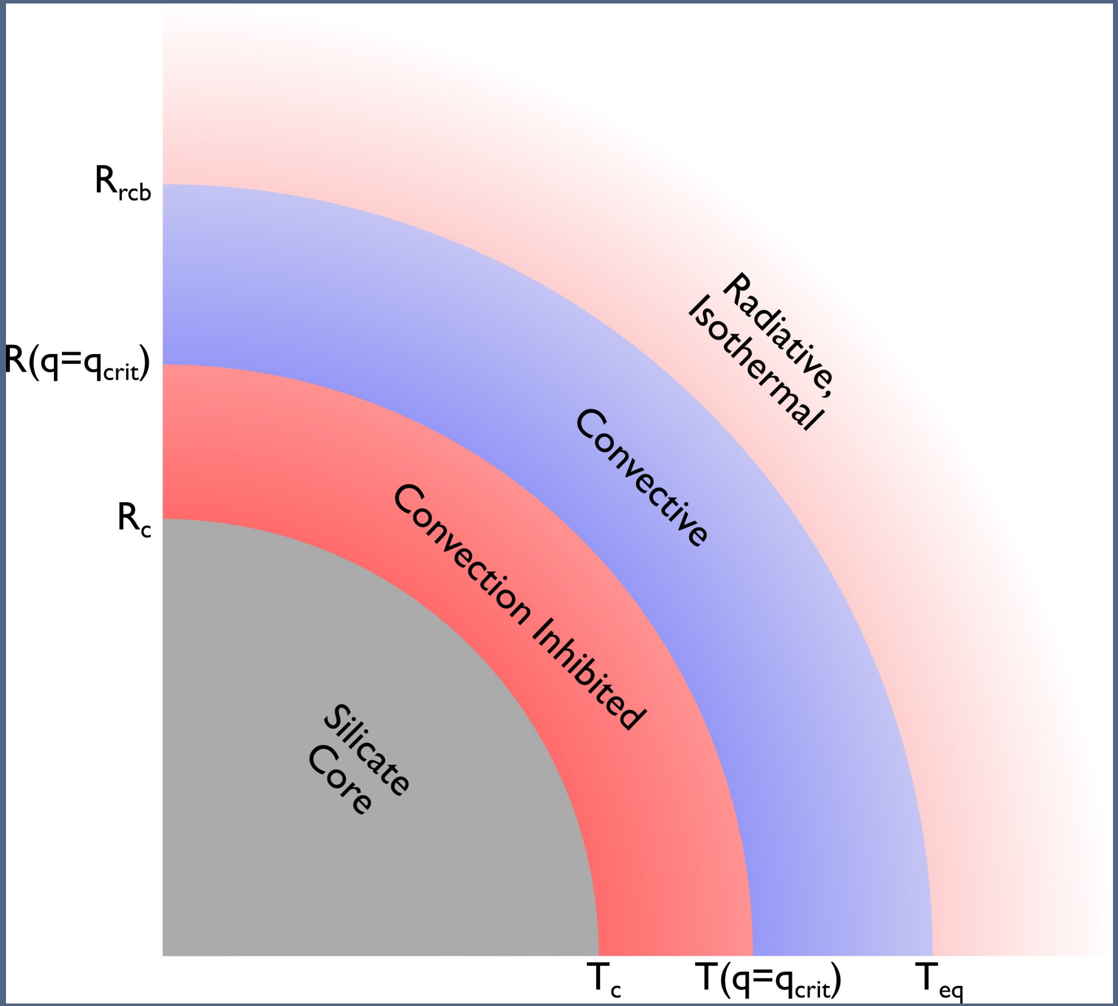


Magma components stable at equilibrium at the base of sub-Neptune atmospheres



Schlichting & Young (2022)

Atmospheric Composition Influences Structure



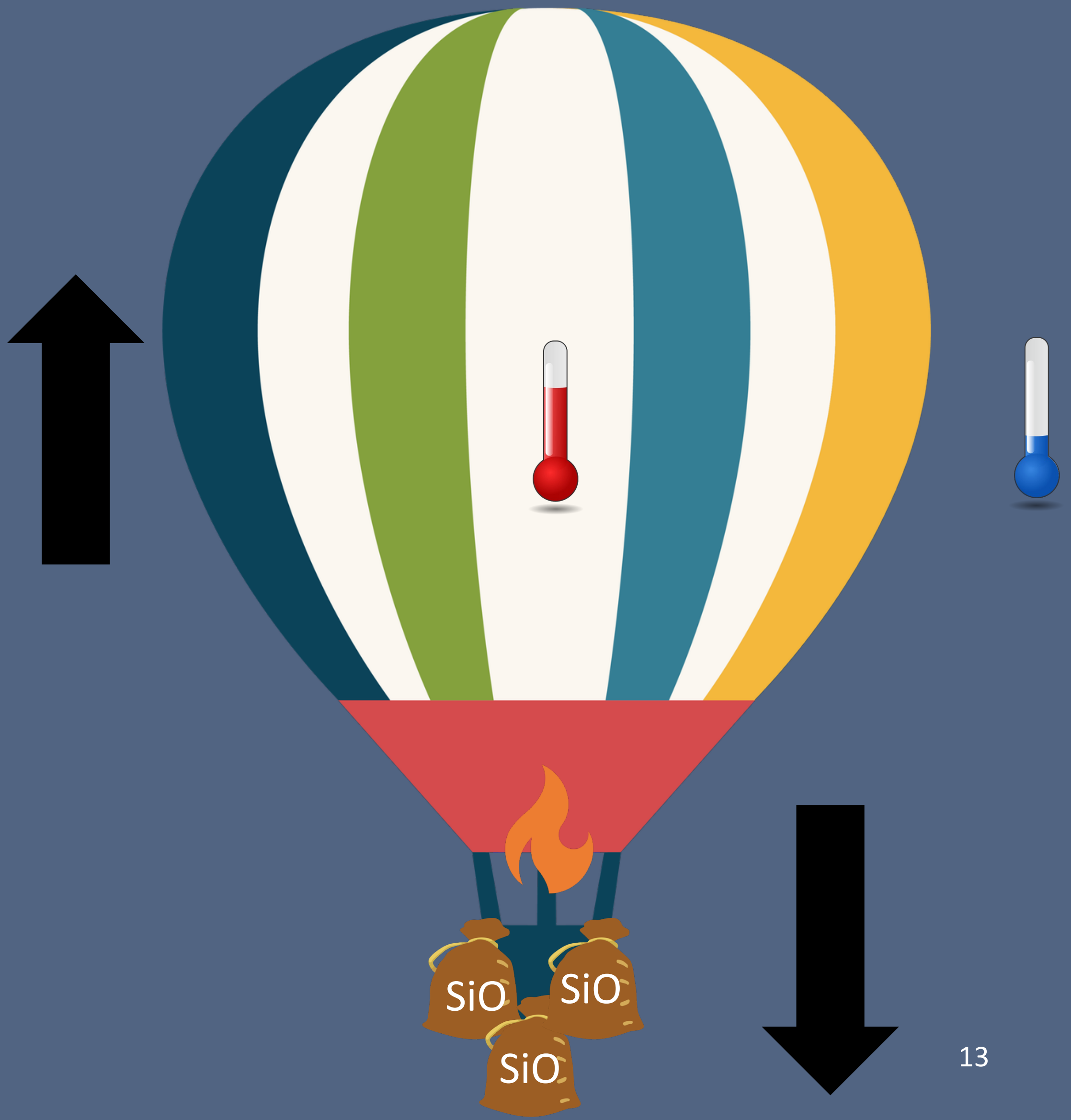
Misener & Schlichting (2022)

- Significant quantities of heavy condensables in light gas can inhibit convection (Guillot 1995)
  - Induces a non-convective layer once mass mixing ratio, *q*, exceeds a critical value
- Previous studies focused on Solar System planets and relatively volatile species
- Same arguments apply to silicate vapor

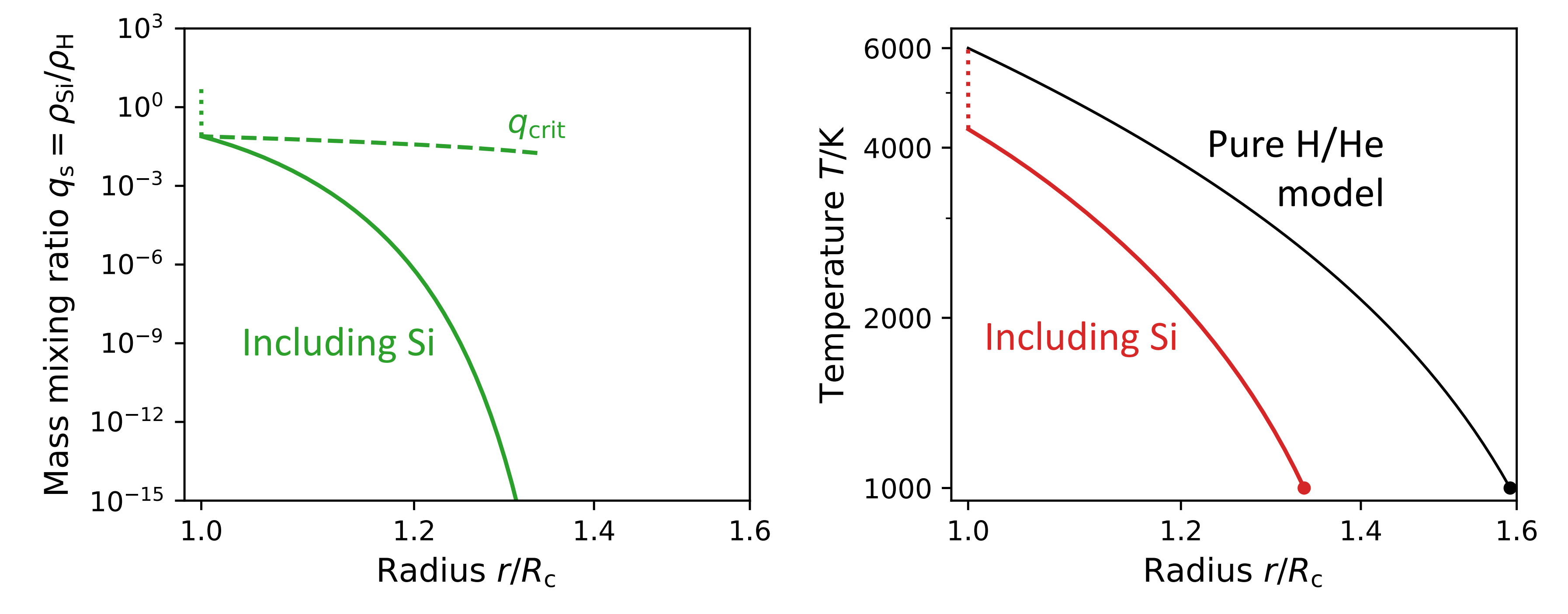
Why is convection inhibited?

- Convection with constant composition: deeper parcels are hotter, so lower density than surroundings if lifted
- If sufficient condensable present: lifted parcel has higher density than new surroundings due to large mean molecular weight, μ
  - Quantified by critical value of mass mixing ratio, q_{crit}

$$q_{\mathrm{crit}} = \frac{1}{\left(1 - \frac{\mu_{\mathrm{H}}}{\mu_{\mathrm{sv}}}\right) \frac{\partial \ln P_{\mathrm{svp}}}{\partial \ln T}}$$



Silicates alter atmospheric profile



Misener & Schlichting (2022)

Hydrogen-silane-water reactions

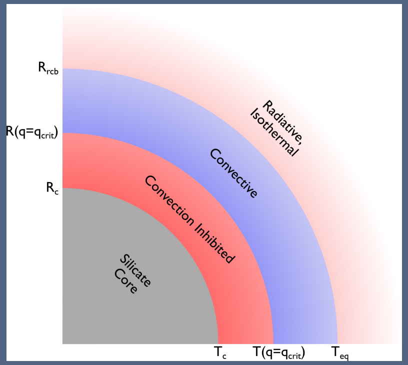
- Misener & Schlichting (2022) has only one reaction: congruent evaporation of SiO_2 (from Visscher & Fegley 2013)
- New work (Misener, Schlichting, & Young 2023, in press): Include chemical equilibrium of three reactions at all levels in the atmosphere:

$$SiO_{2\,(liq.)} \rightleftharpoons SiO_{\,(g)} + 0.5\, O_{2\,(g)}$$

$$H_{2\,(g)} + 0.5\, O_{2\,(g)} \rightleftharpoons H_2O_{\,(g)}$$

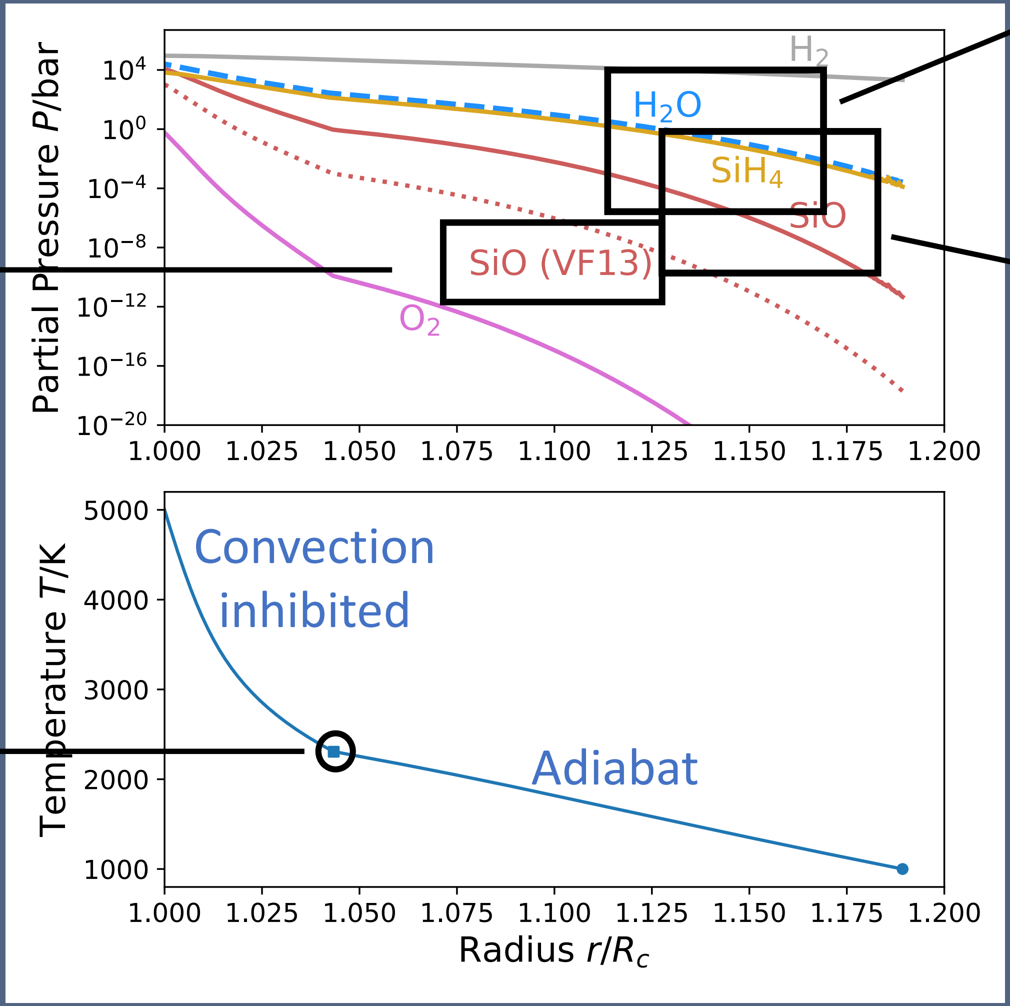
$$3\, H_{2\,(g)} + SiO_{\,(g)} \rightleftharpoons SiH_{4\,(g)} + H_2O_{\,(g)}$$

Hydrogen-silane-water atmospheres



Si atmosphere content much higher than previous model

Transition to non-convective zone: T ~ 2400 K



Misener, Schlichting, and Young (2023)

H_2O and SiH_4 in lockstep

SiH_4 dominates SiO over most of atmosphere

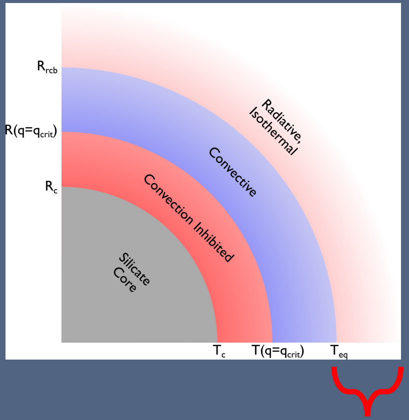
$$SiO_{2\,(liq.)} \rightleftharpoons SiO_{(g)} + 0.5\,O_{2\,(g)}$$

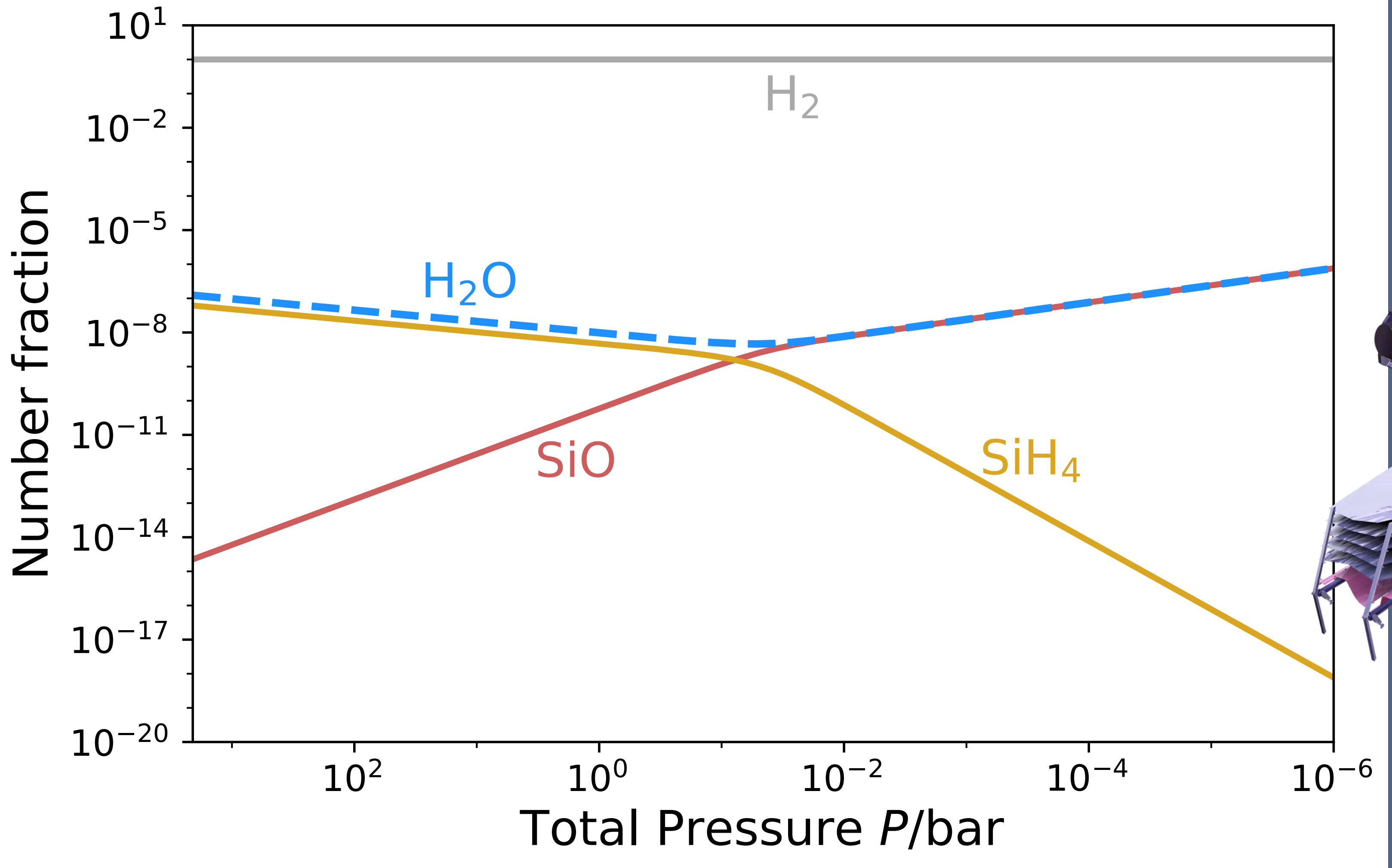
$$H_{2\,(g)} + 0.5\,O_{2\,(g)} \rightleftharpoons H_2O_{(g)}$$

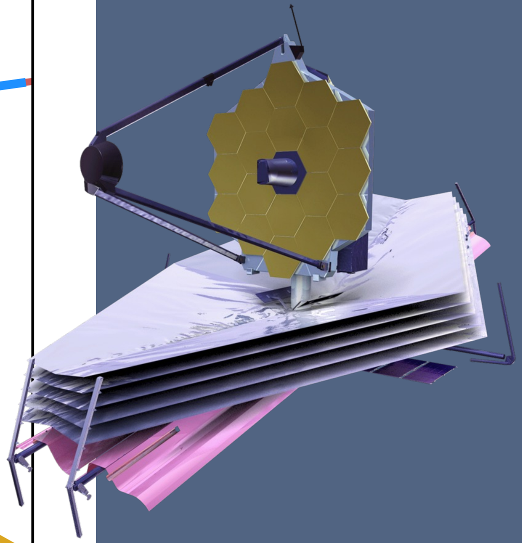
$$3\,H_{2\,(g)} + SiO_{(g)} \rightleftharpoons SiH_{4\,(g)} + H_2O_{(g)}$$

$$\text{[Net]}\ SiO_{2\,(liq.)} + 4\,H_{2\,(g)} \rightleftharpoons SiH_{4\,(g)} + 2\,H_2O_{(g)}$$

SiO-SiH_4: a window into the interior



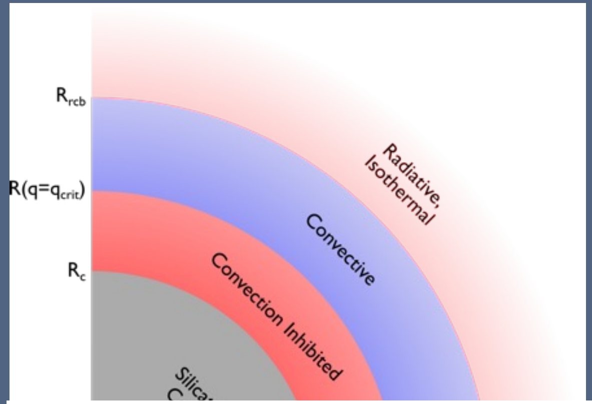


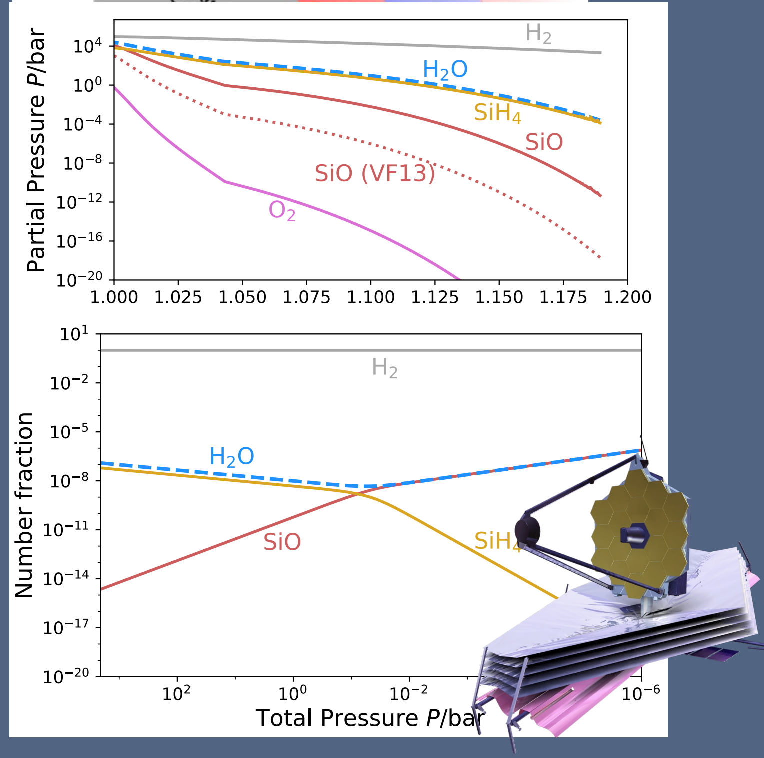


Misener, Schlichting, and Young (2023)

Conclusions

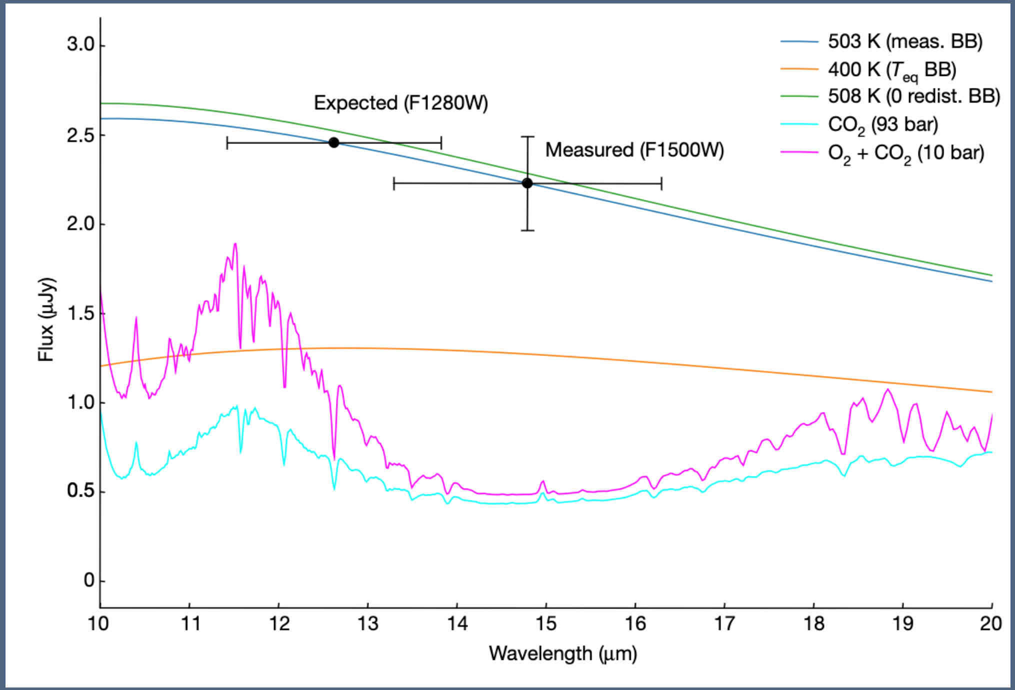
- Silicate vapor can inhibit convection deep in sub-Neptune atmospheres
  - Alters the planet's thermal profile and radius
- Reactions between outgassed species and H atmosphere can produce significant H_2O and SiH_4
  - Pulls more Si out of interior than previously appreciated
- Signatures of interior-atmosphere interactions potentially observable in upper atmosphere



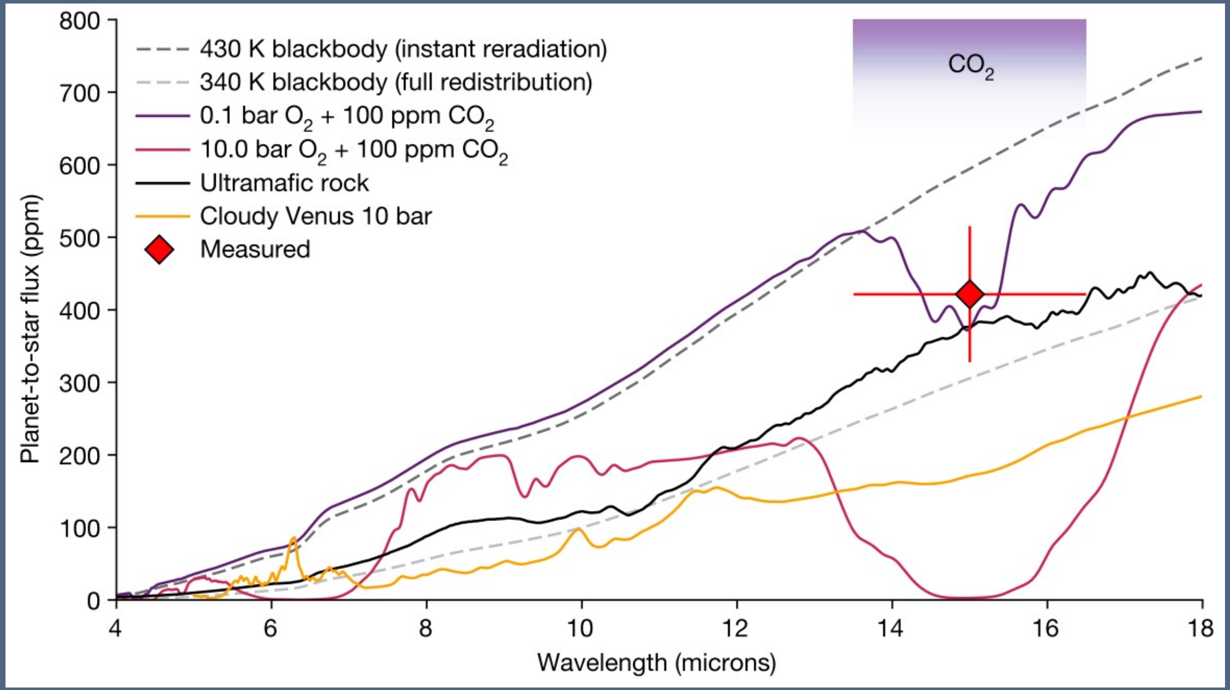


Misener, Schlichting, & Young (2023), *MNRAS*, in press, arxiv: 2303.09653

Terrestrial planet atmospheric measurements: so far so airless

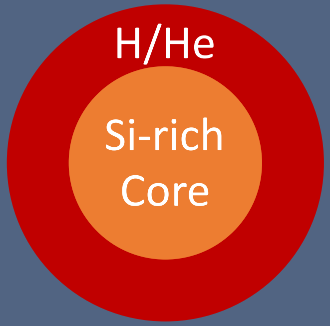


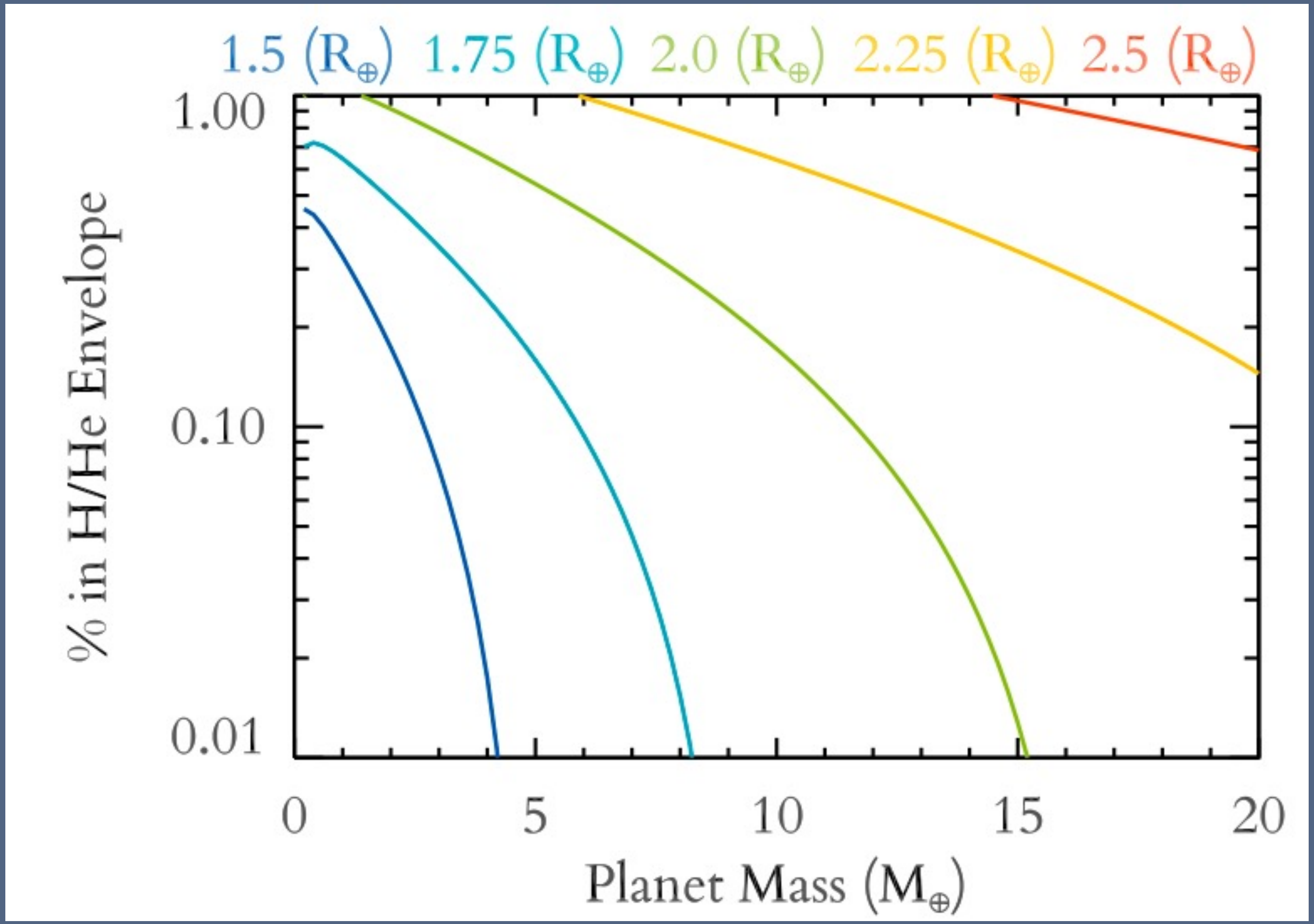
Greene et al. (2023)



Zieba et al. (2023)

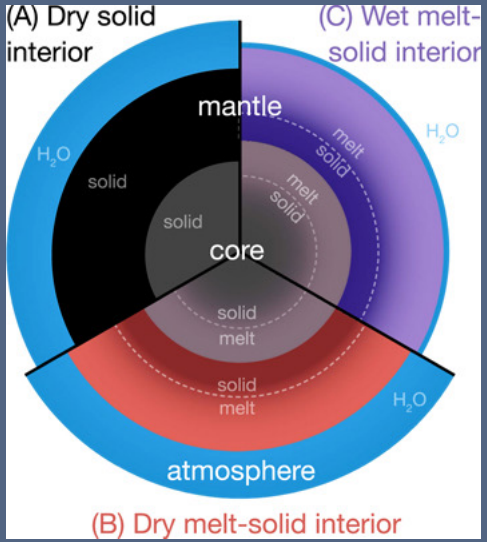
Models of sub-Neptune envelope evolution assume pure H/He



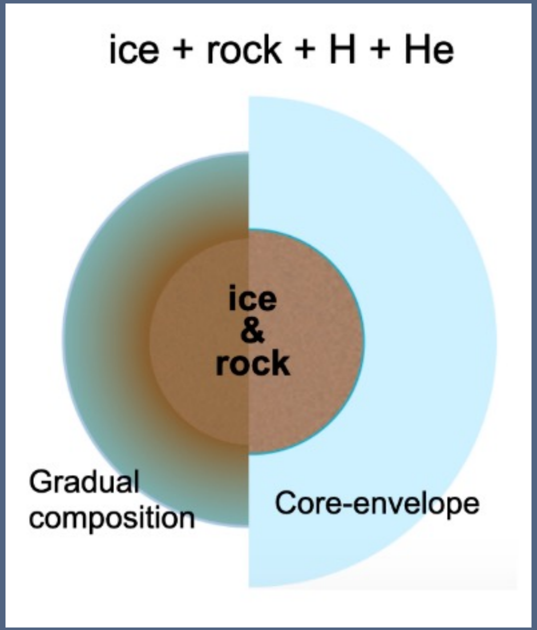


Lopez & Fortney (2014)

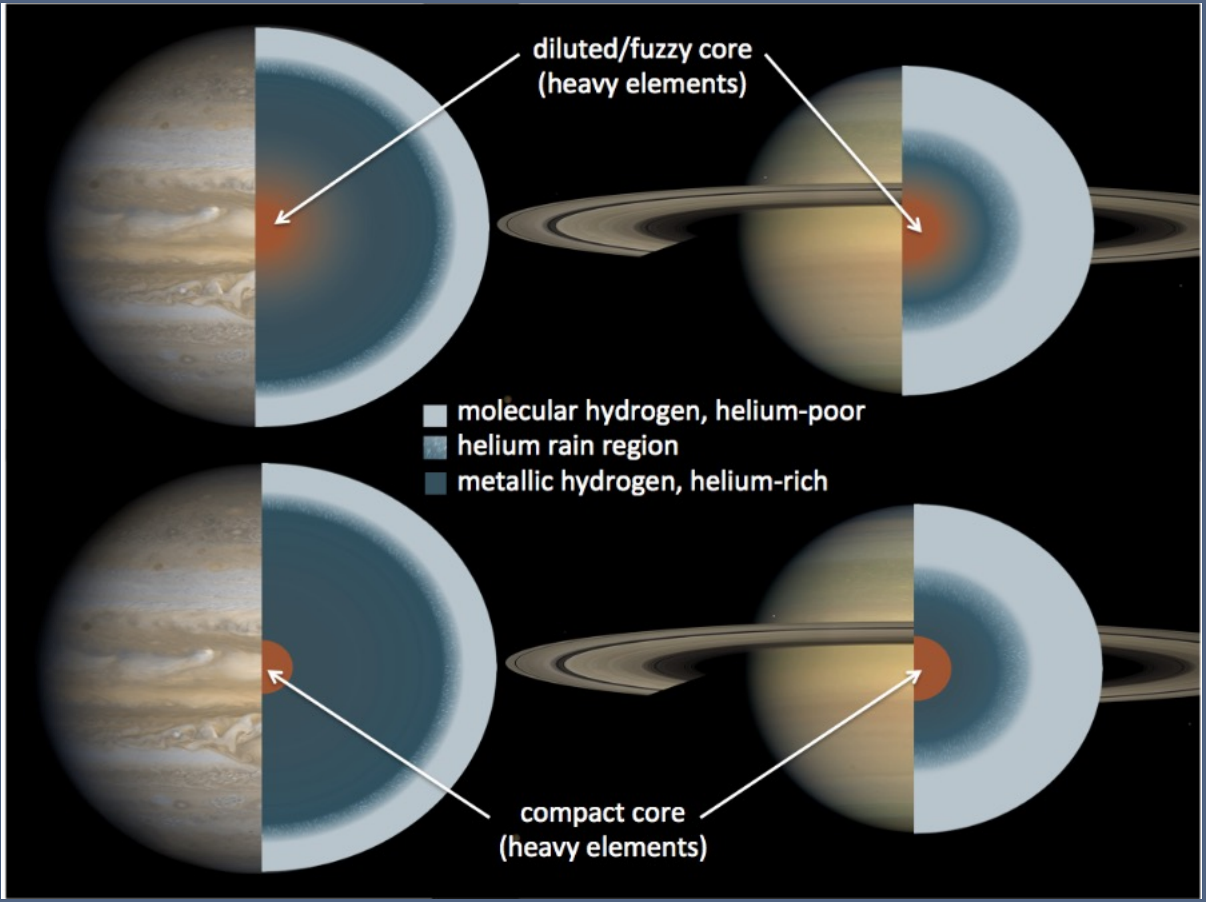
Interactions between planetary layers: probably important



Dorn & Lichtenberg (2021)



Vazan et al. (2022)

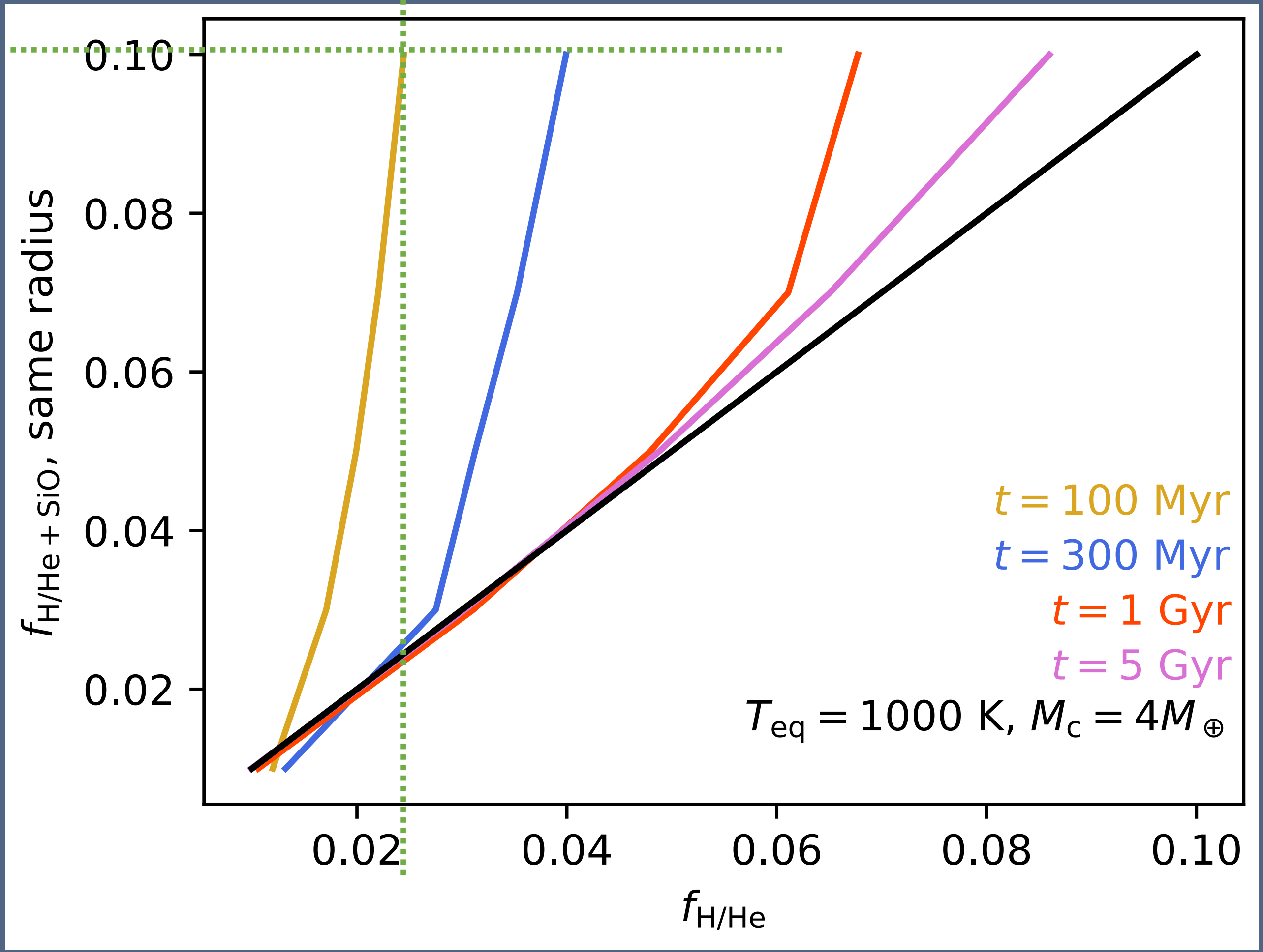


Helled (2019)

Extra: Inferred mass fractions altered by SiO vapour

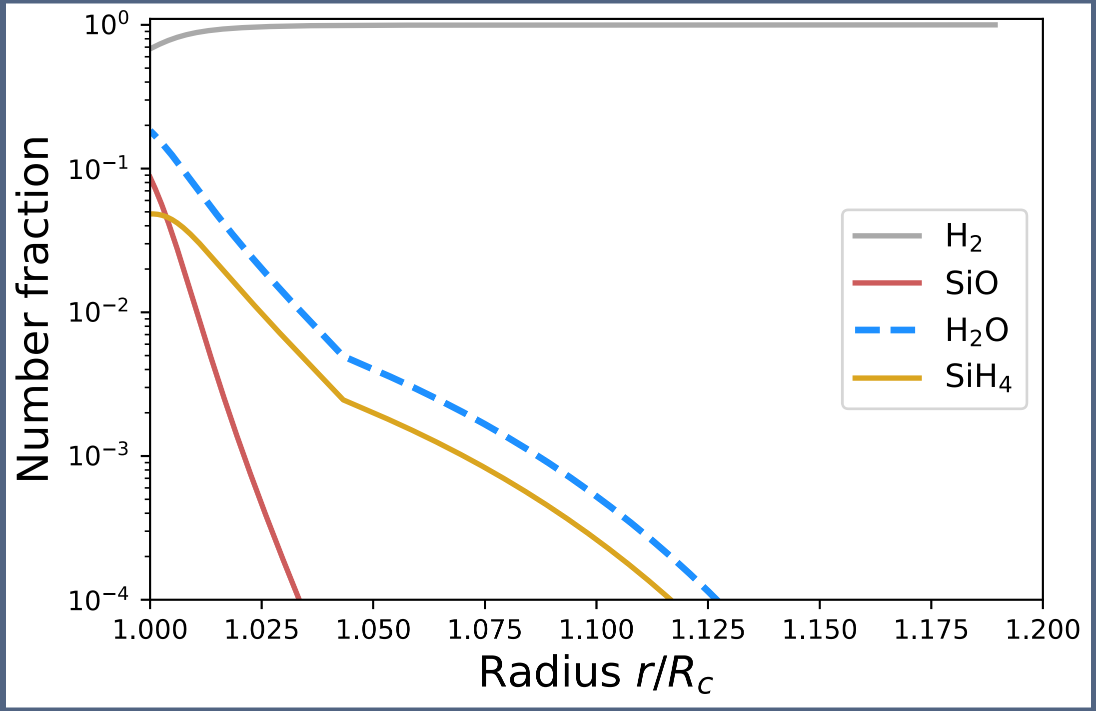
Looks like f=2.5% based on radius

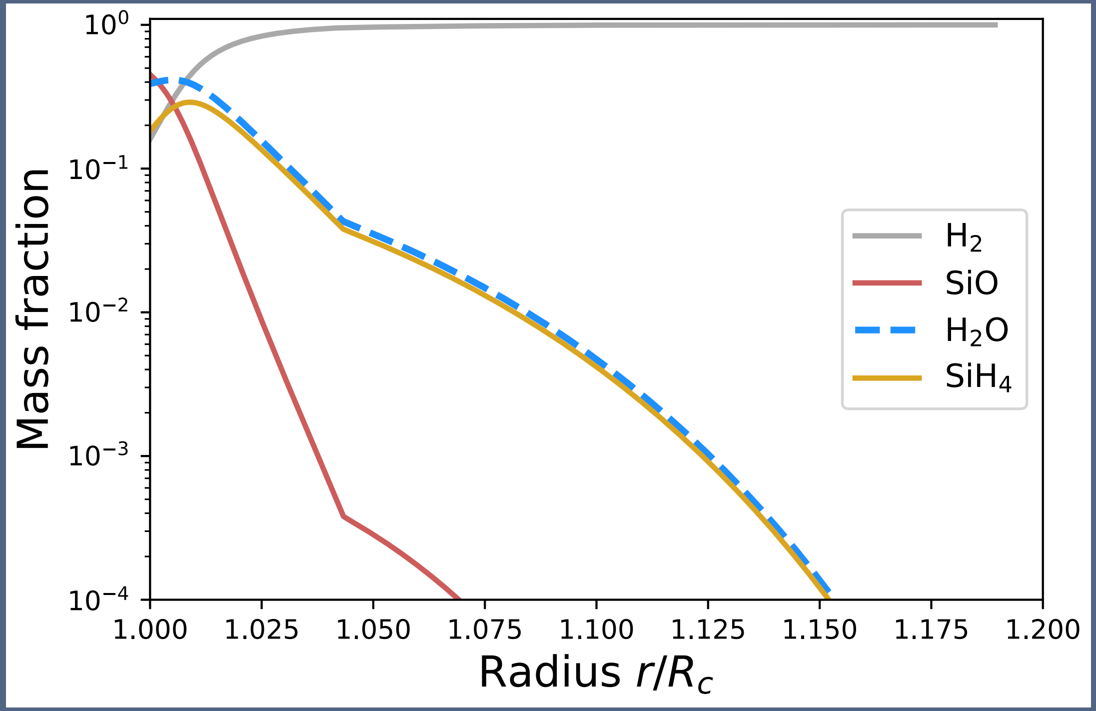
Same radius:
10% if SiO considered!



Misener & Schlichting (2022)

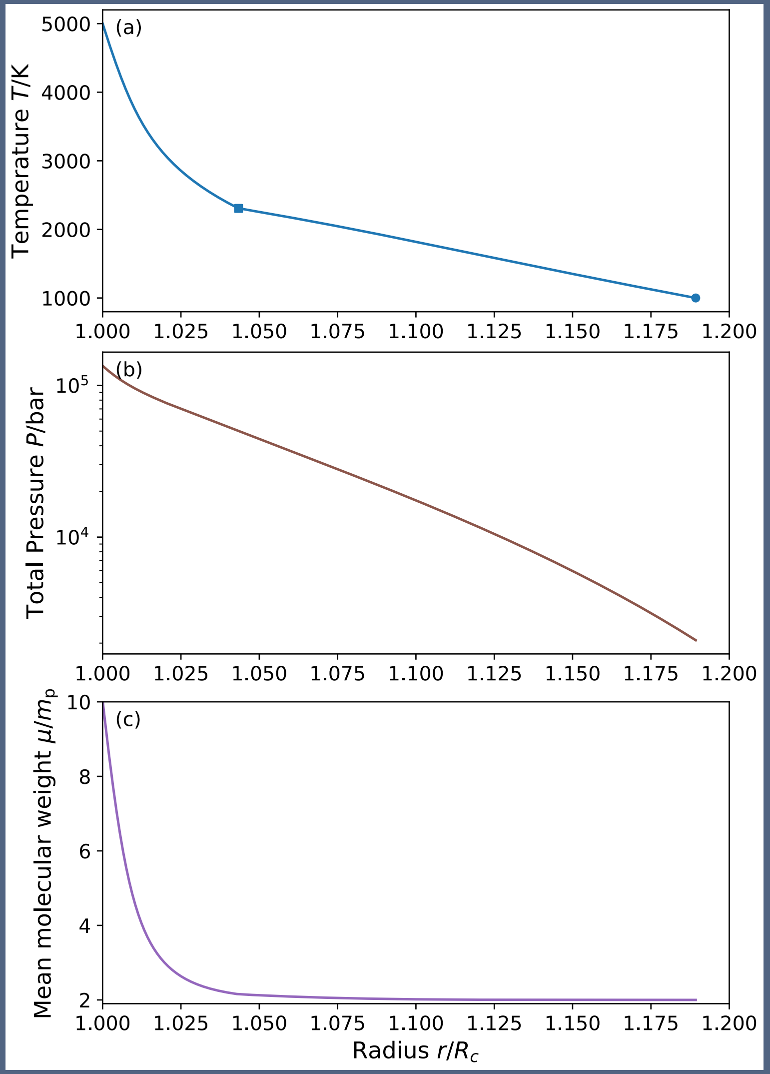
Extra: Alternate views of silane atmospheres





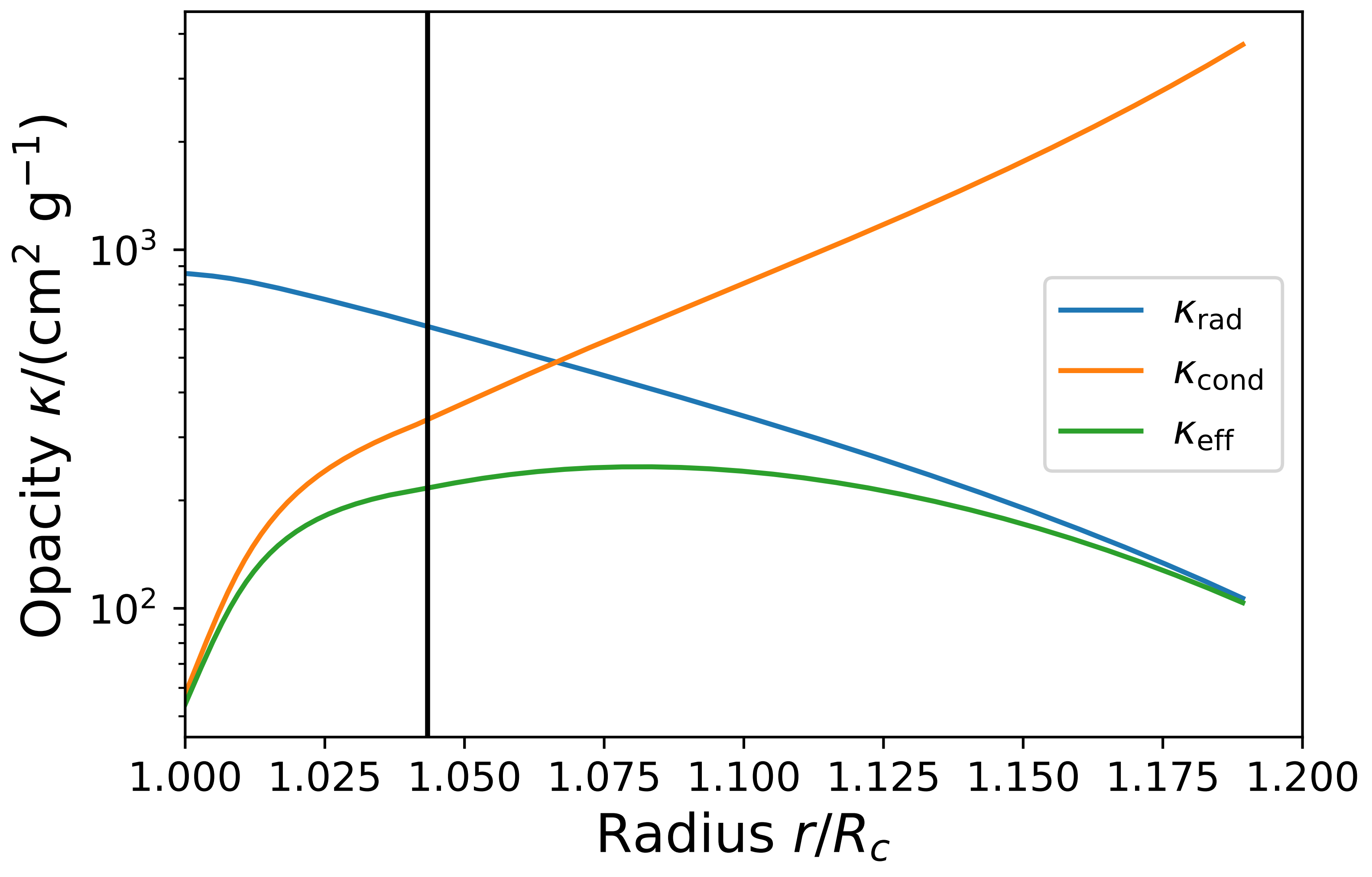
Misener, Schlichting, and Young (2023)

Extra: atmospheric profile



Misener, Schlichting, and Young (2023)

Extra: conduction vs. radiation



Misener, Schlichting, and Young (2023)