Interior (bulk) Compositions and the Importance of Measured Masses and Connection to Atmospheres

Leslie Rogers
University of Chicago
larogers@uchicago.edu

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Where is the dividing line between a planet's interior and the atmosphere?

Interior:

$P > P_0$ ~10 to 10^3 bar

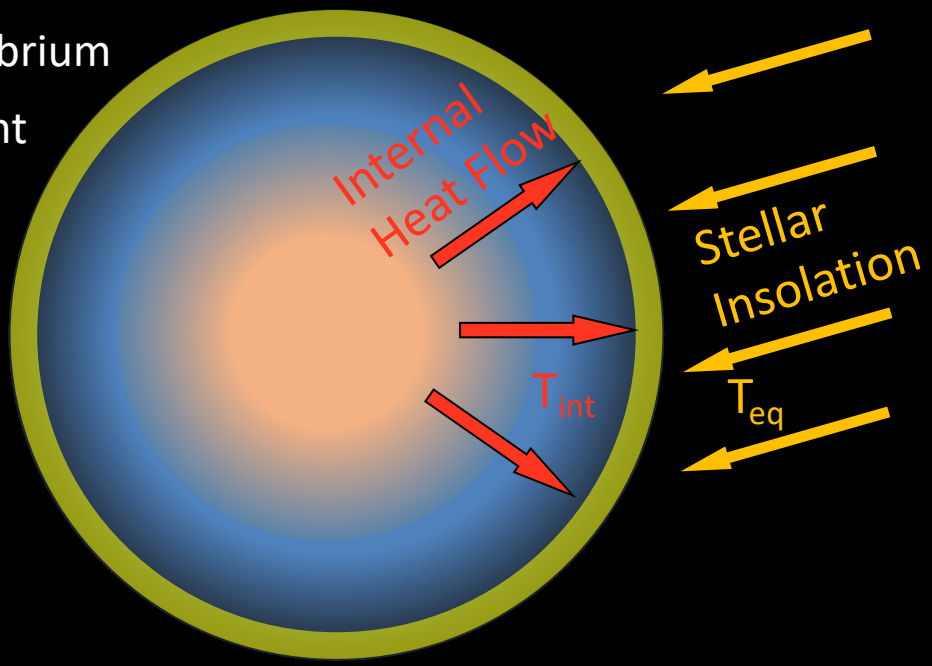
Optically Thick

Nearly Isotropic/Thermalized Radiation

Local Thermal Equilibrium

m(r), r, g not constant

Non-ideal gas EOS



Atmosphere:

$P < P_0$ ~ 10 to 10^3 bar

Includes Optically Thin

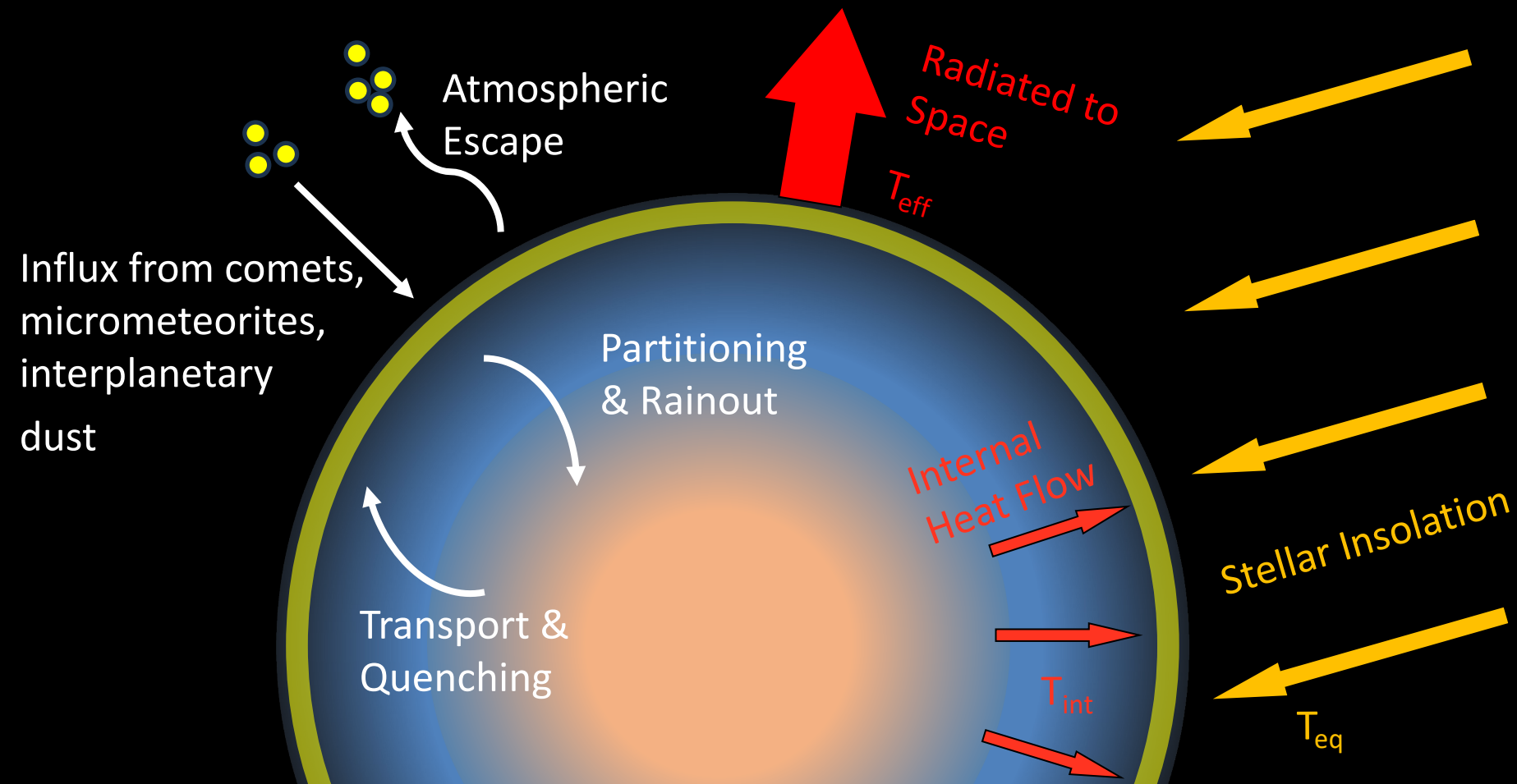
Plane parallel, $\Delta r/R << 1$

Constant logg

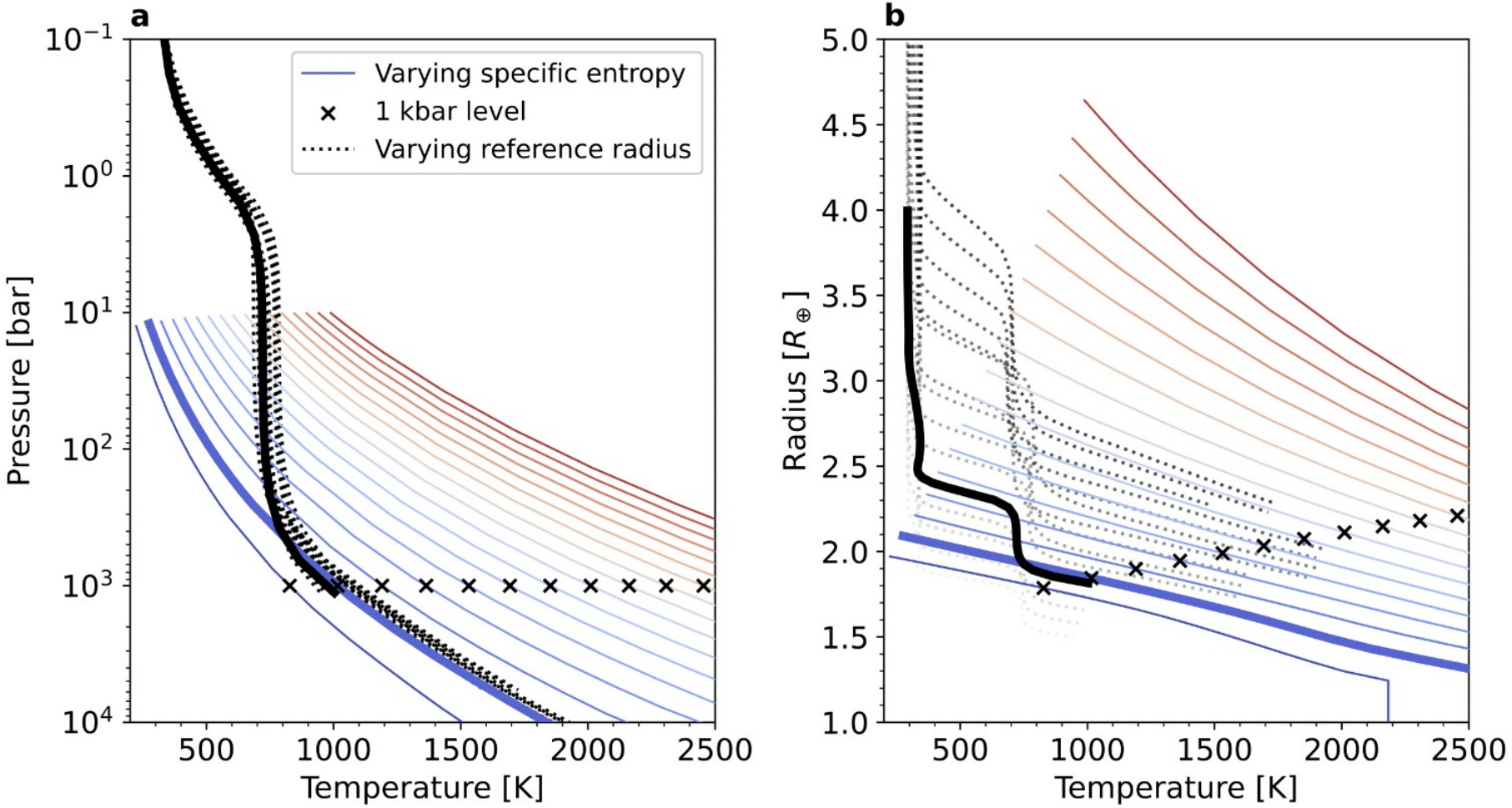
Ideal gas

(mostly/typically)

Physical Processes Connecting Atmospheres and Interiors

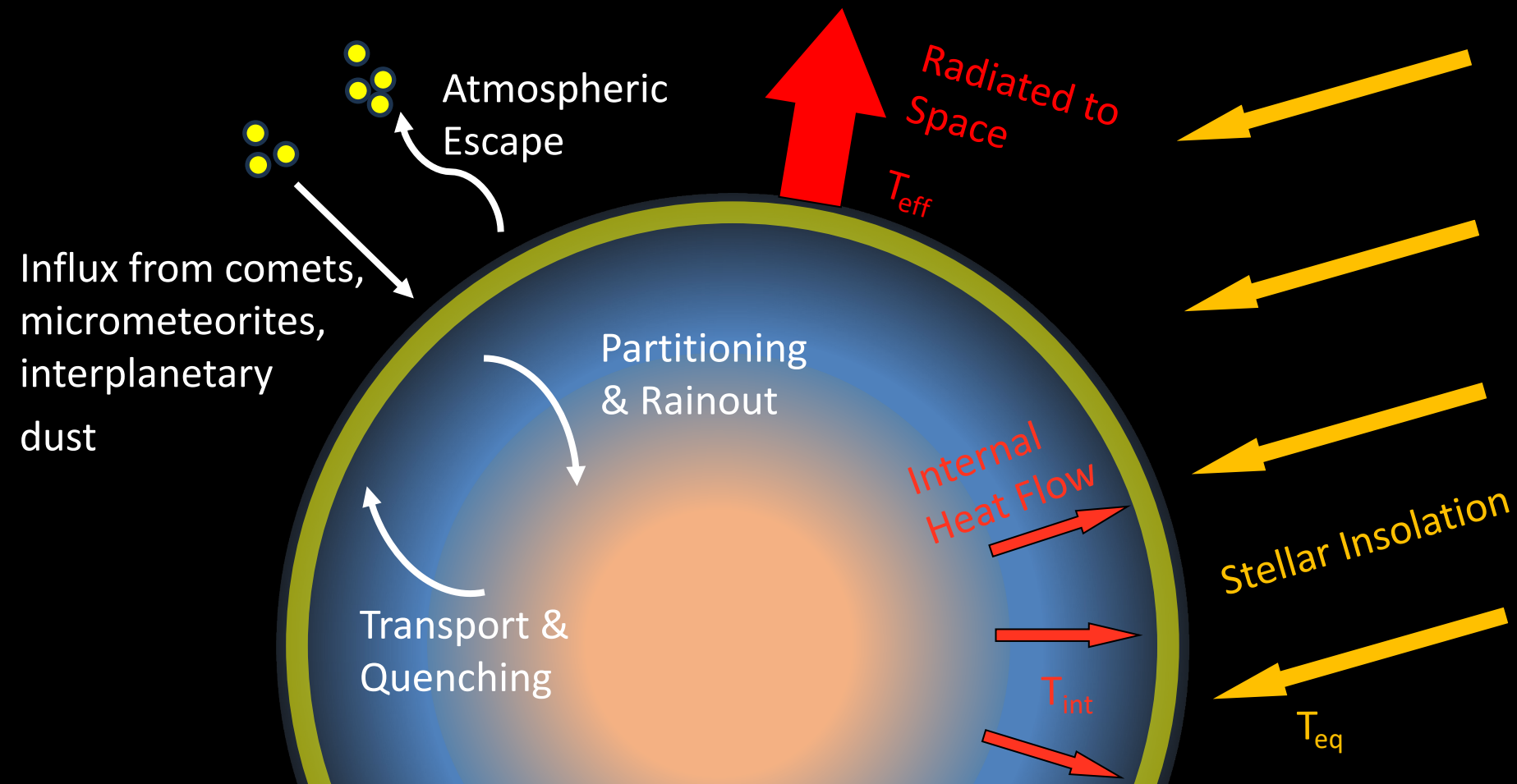


Matching Conditions (r, T, P, Fluxes) at the Top of Interior and Bottom of Atmosphere Models

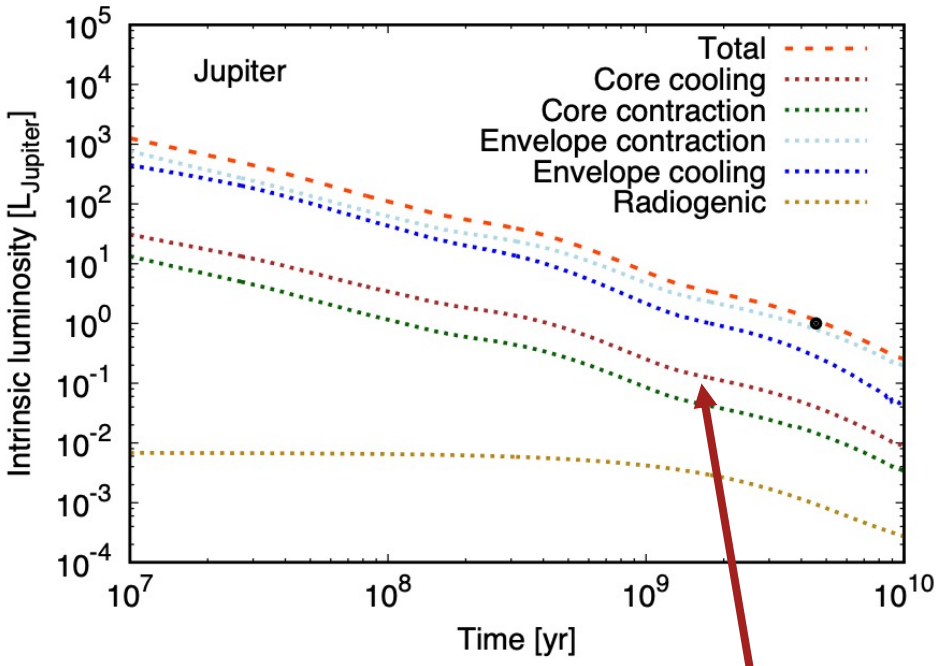


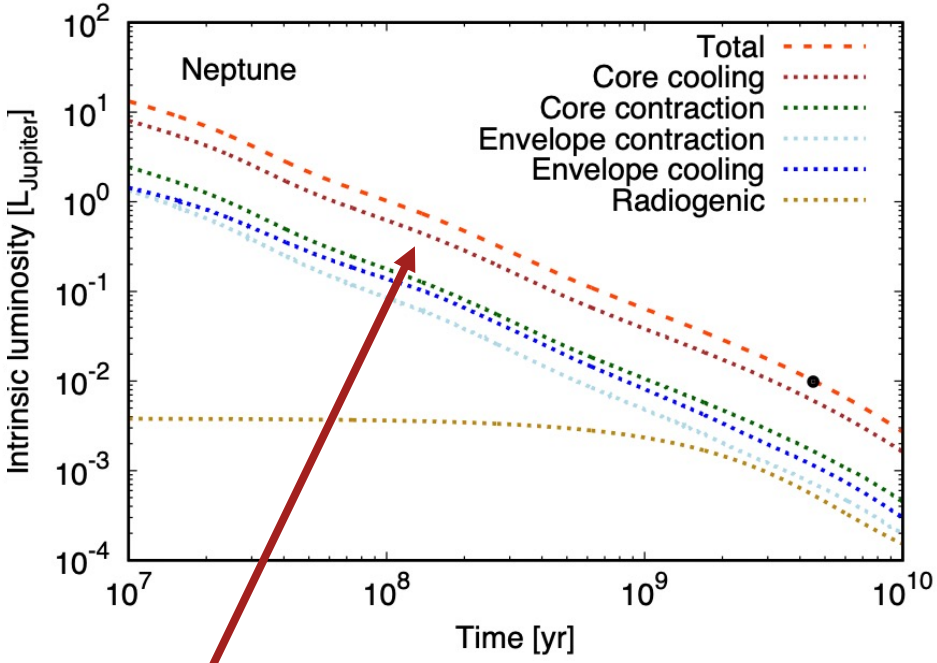
Piaulet et al. (2023): planet model for a mass of 2.36 $M_\oplus$, a H_2/He mass fraction of 3%

Physical Processes Connecting Atmospheres and Interiors



Atmosphere Radiates to Space
Bulk Interior Contributes Thermal Inertia



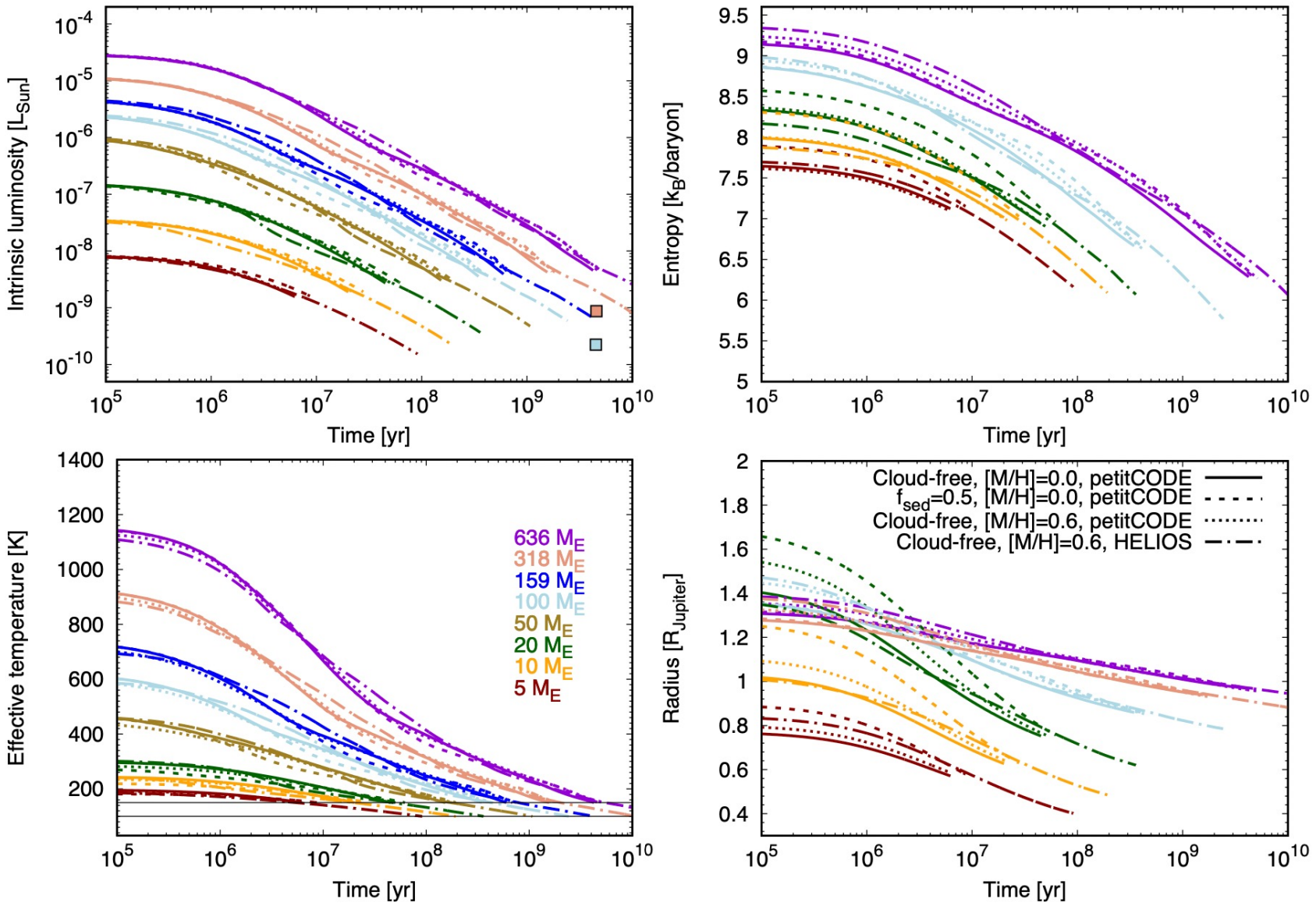


Core Contributions especially important
for lower-mass core-dominated planets

Thermal Evolution sensitive to detailed interior structure
(e.g., presence of thermal boundary layers)

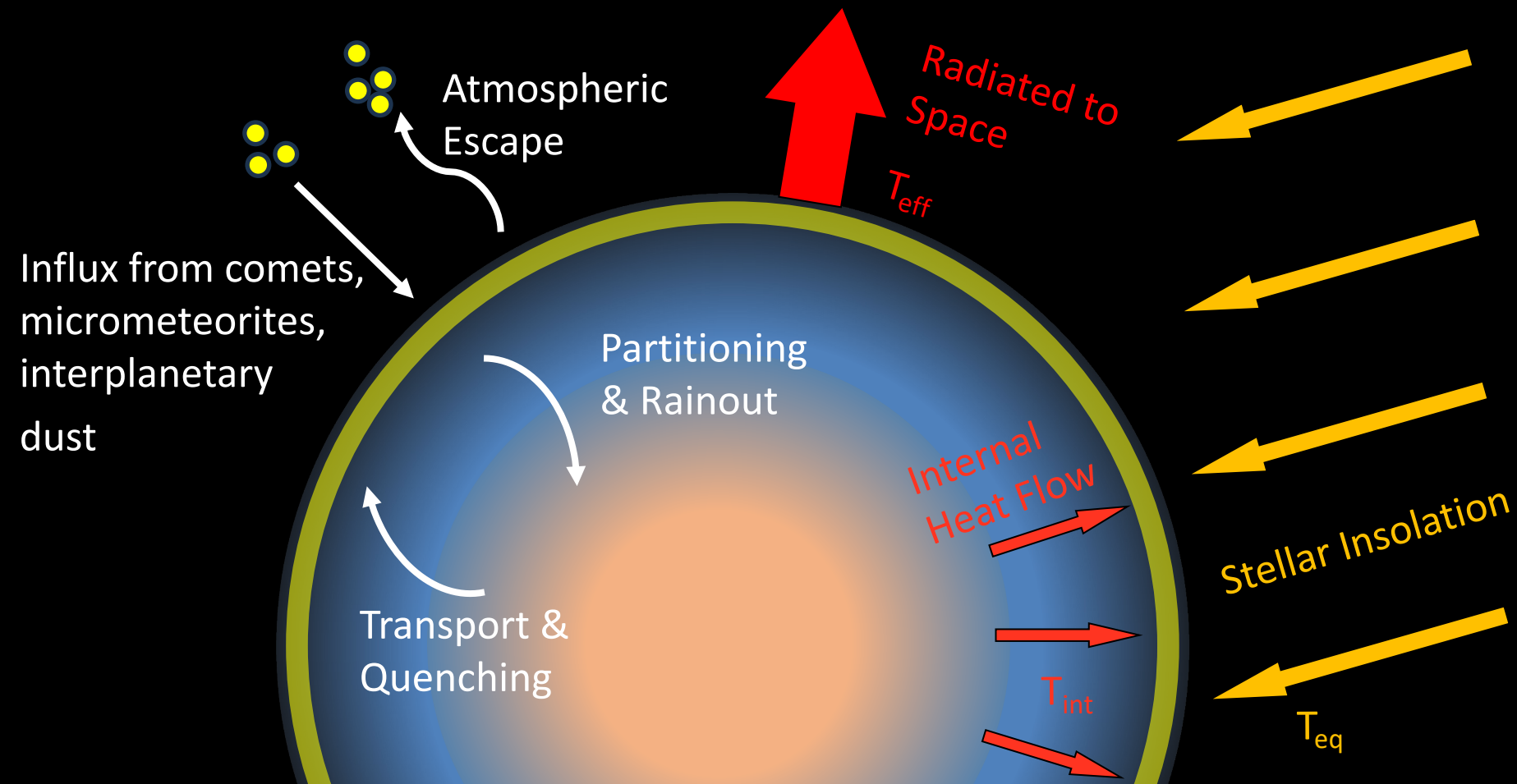
Linder et al. (2019)

Atmosphere Affects Planet Cooling Rate

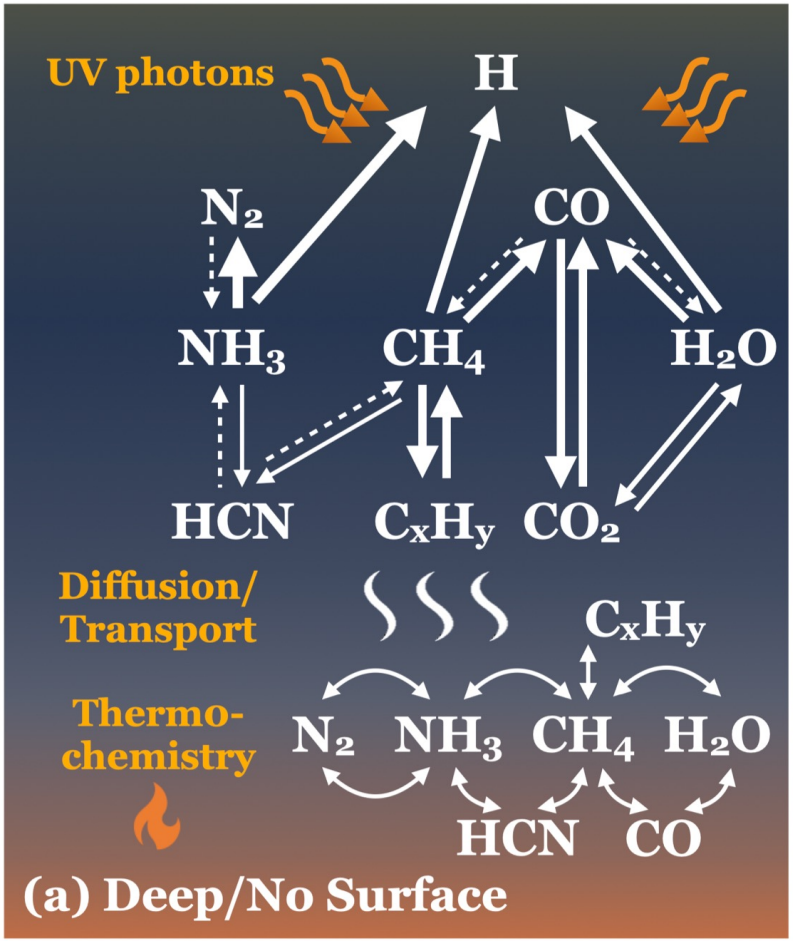


Linder et al. (2019)

Physical Processes Connecting Atmospheres and Interiors

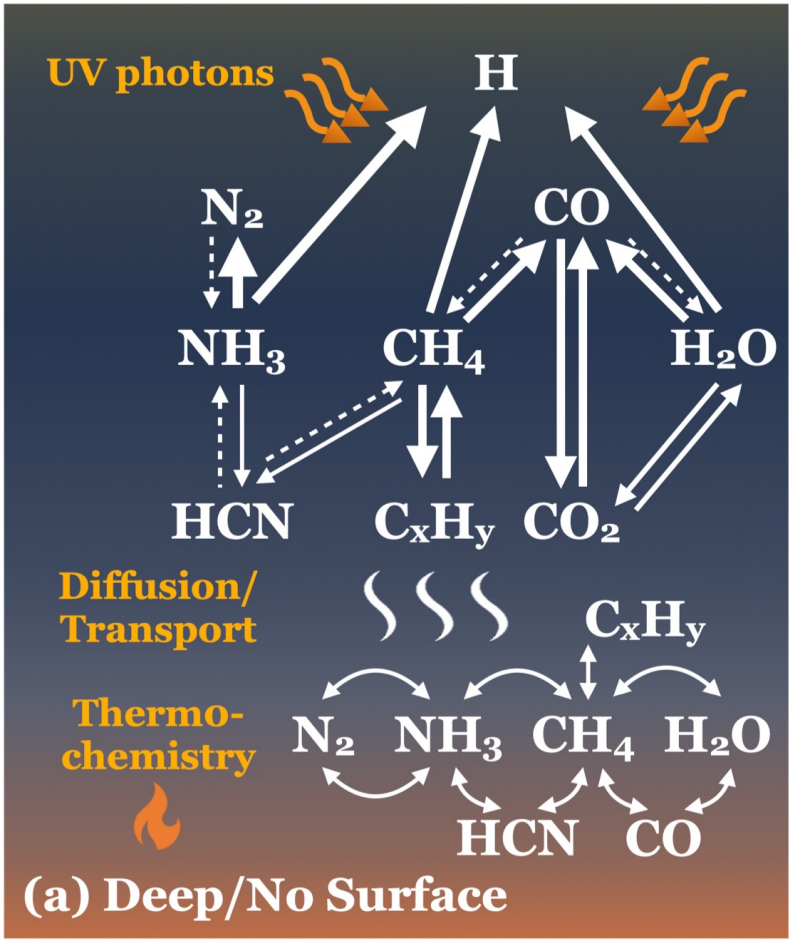


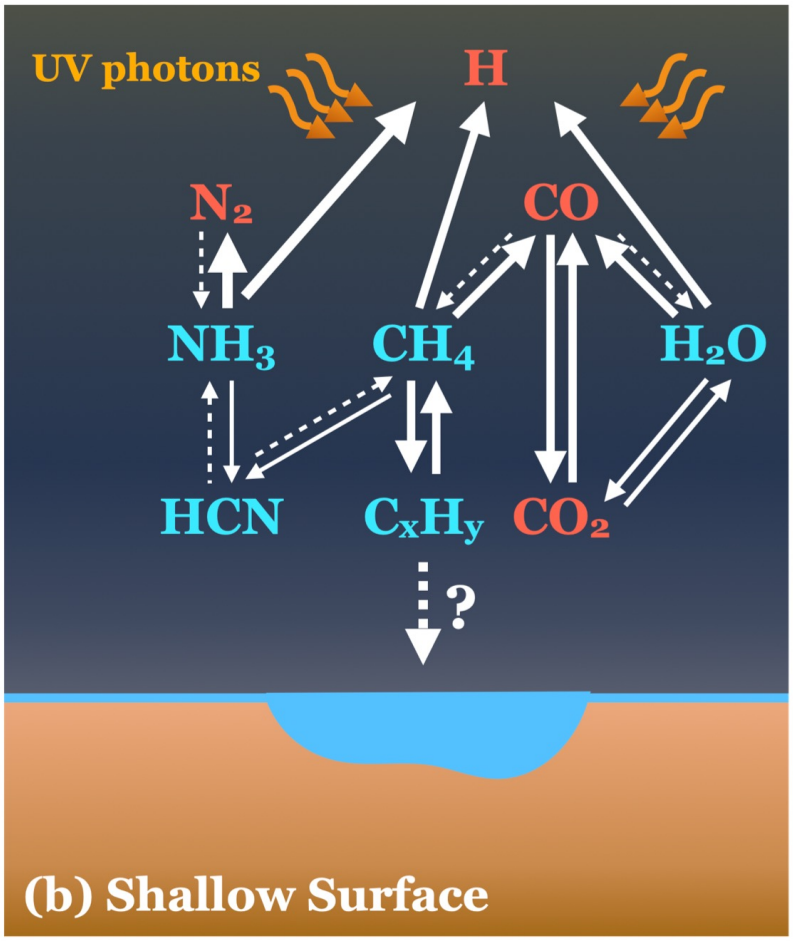
Atmospheric Species Indicative of Surface Pressure:
Importance of Thermochemical Recycling



Yu et al. (2021)

Atmospheric Species Indicative of Surface Pressure:
Importance of Thermochemical Recycling

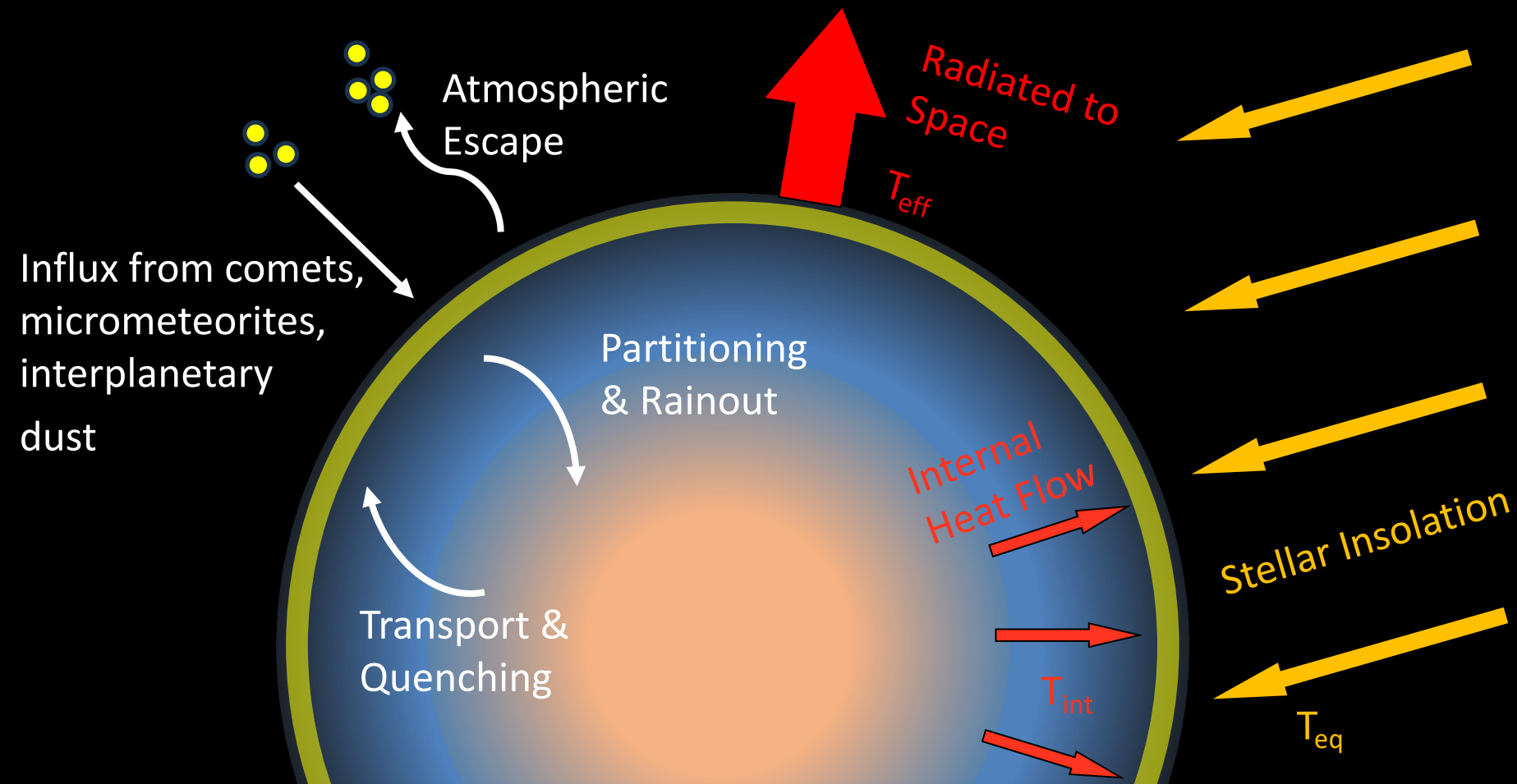




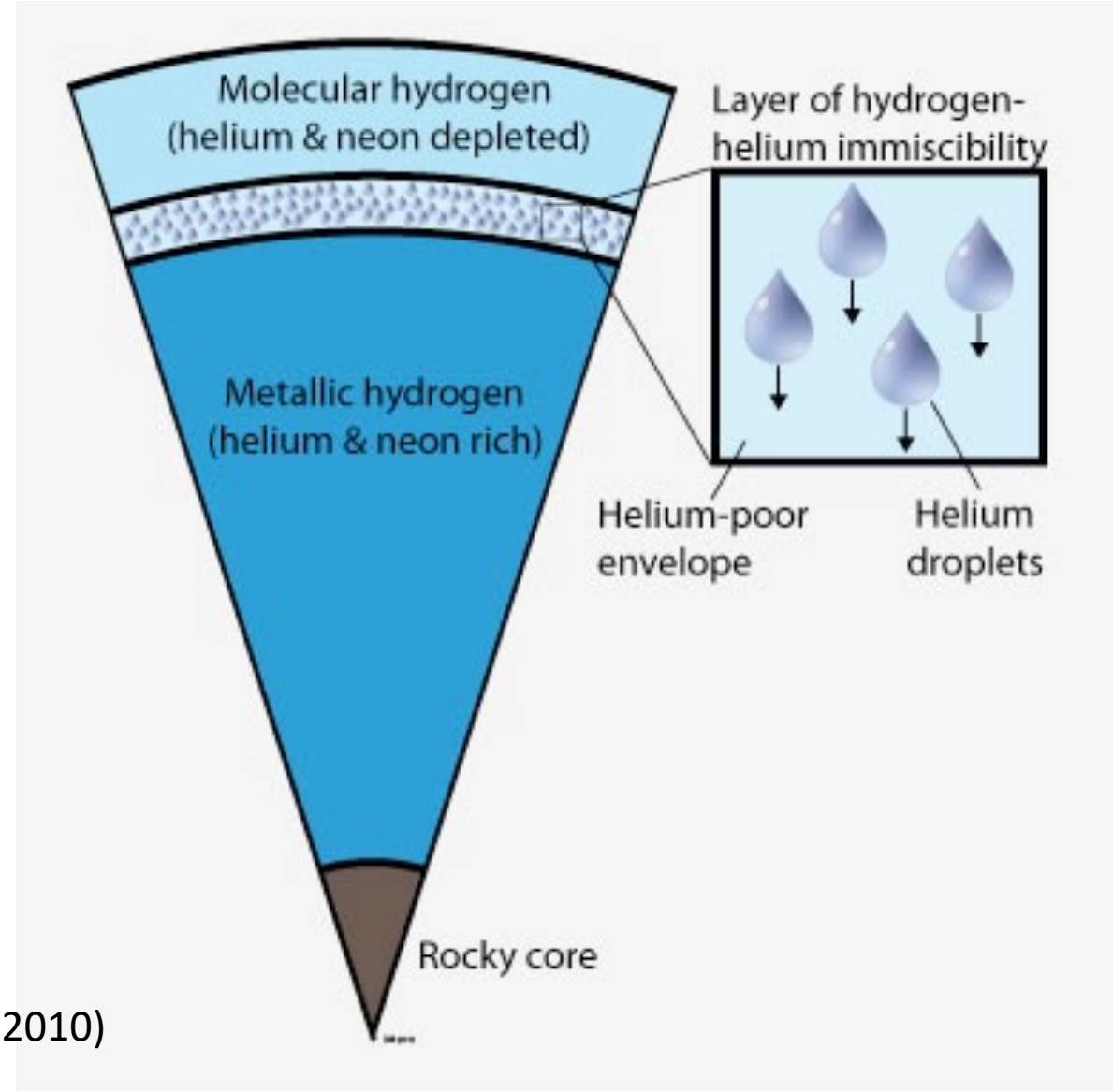
Red Increased Abundance
Blue decreased abundance
(compared to "no surface" case)

Yu et al. (2021)

Physical Processes Connecting Atmospheres and Interiors



Partitioning of Species Between the Interior & Atmosphere:
Neon Depletion in Jupiter's Atm

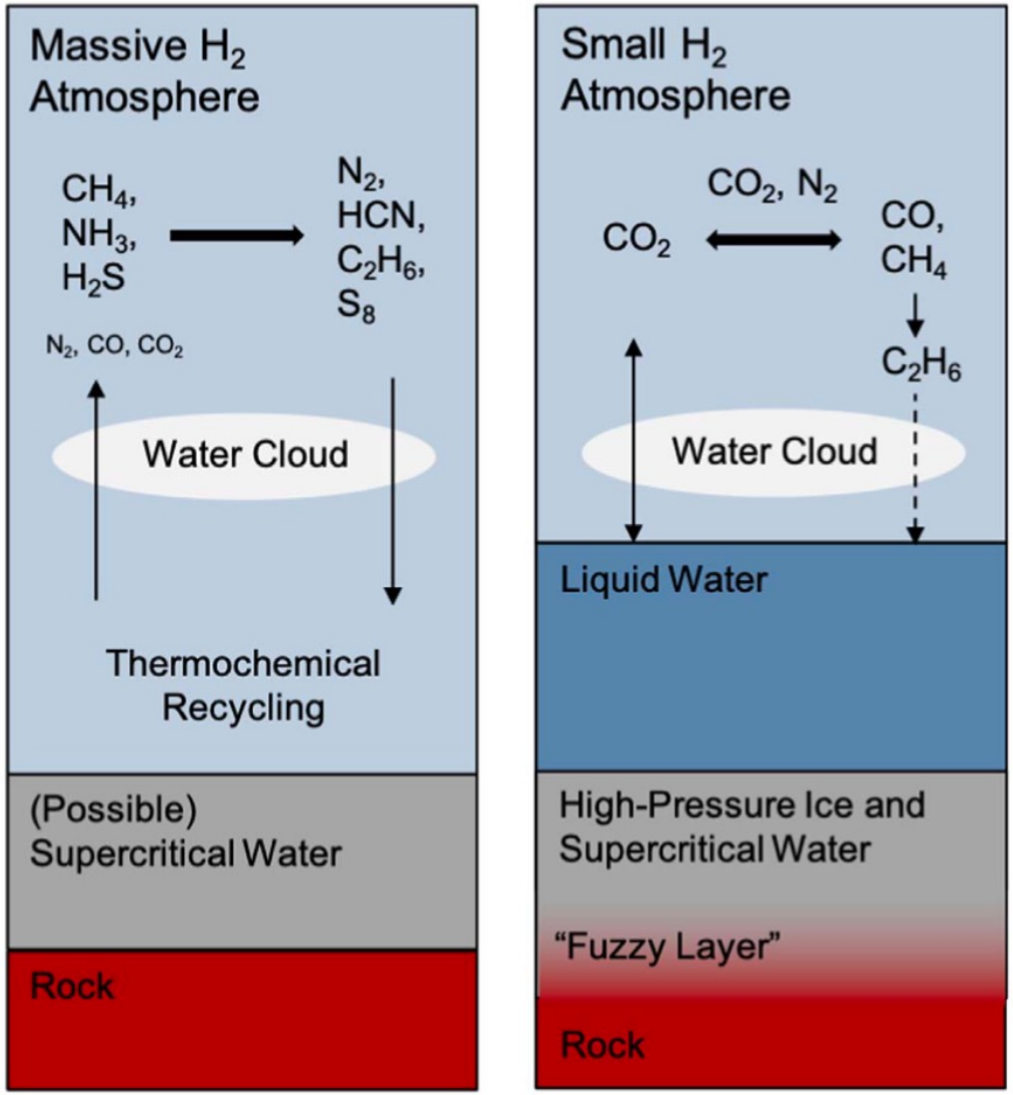


Wilson & Militzer (2010)

Partitioning of Species Between the Interior & Atmosphere:
Solubility Equilibria to find Shrouded Oceans

Temperate Planets

CH_4 and NH_3 dominant C and N gases due to thermochemical recycling

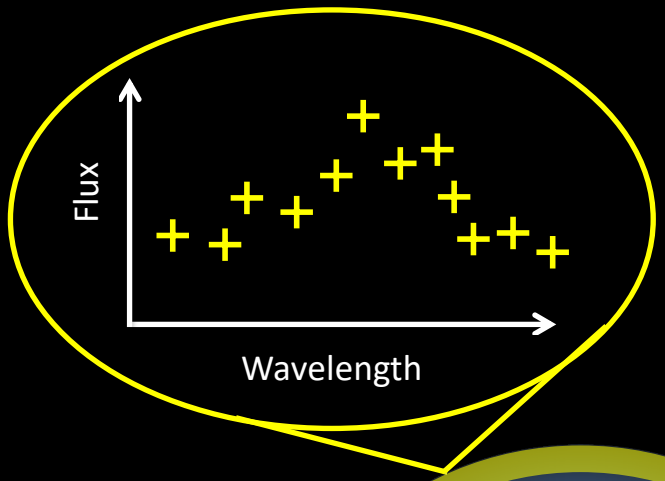


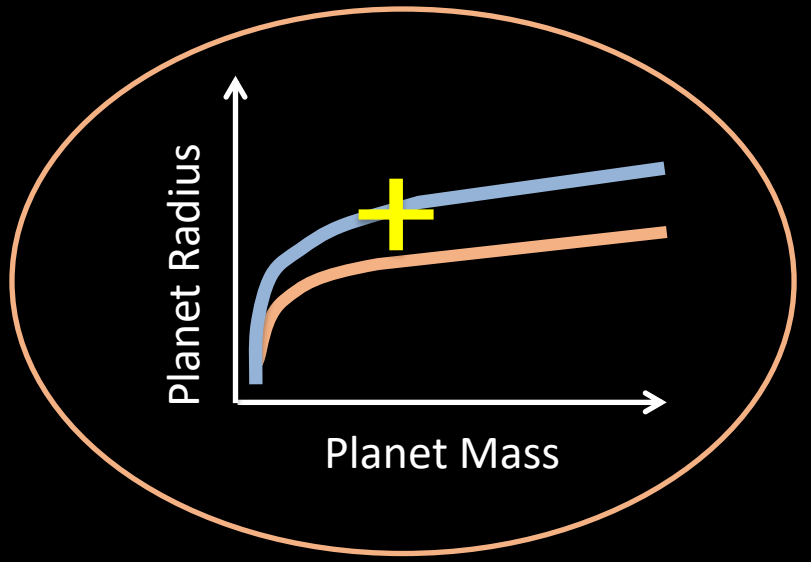
CO_2 and N_2 dominant C and N gases.

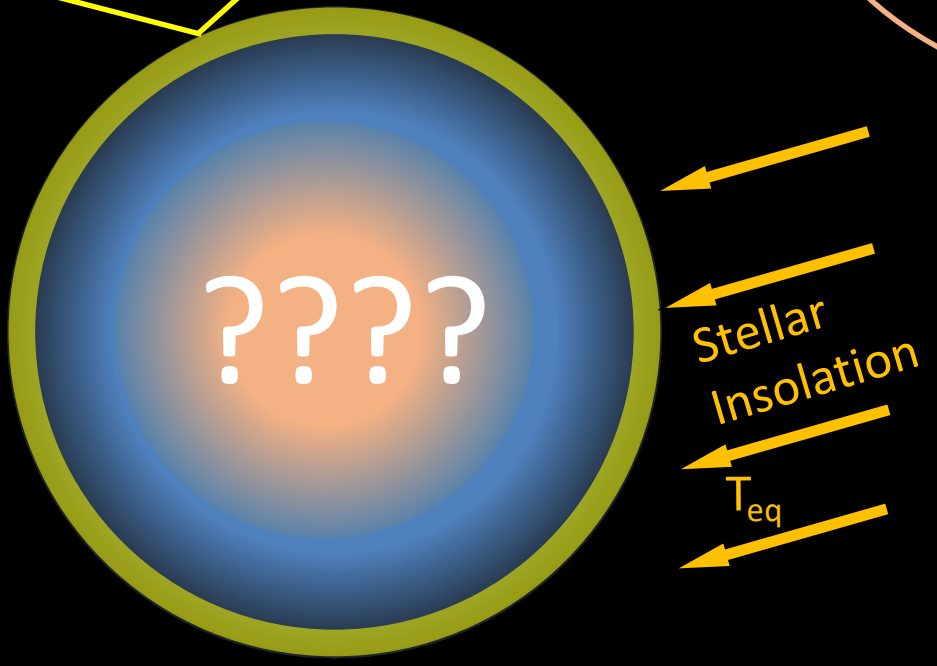
NH_3 is depleted by dissolution into the liquid-water ocean

Hu et al. (2021)

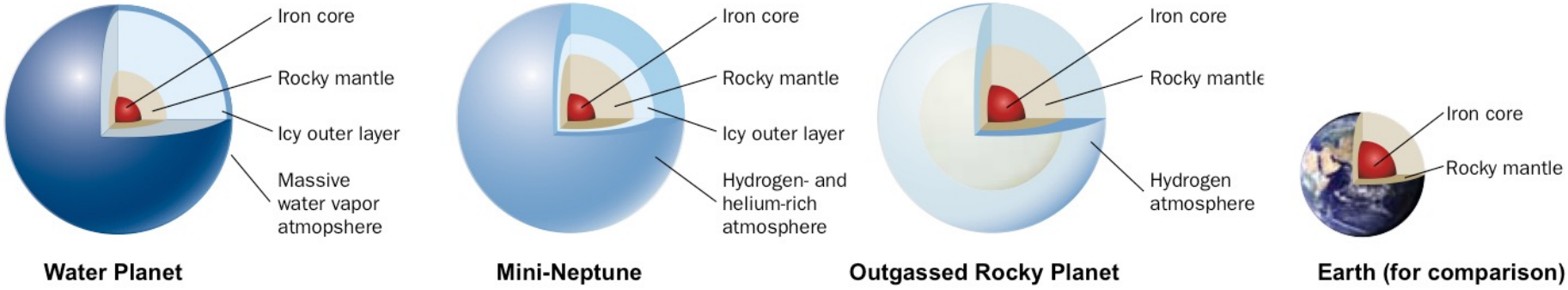
Combining Insights from Planet Atmosphere Observations and Mass-Radius Measurements when Interpreting Planets







A Range of Bulk Compositions are Consistent with a Planet Mass and Radius (especially for sub-Neptunes)

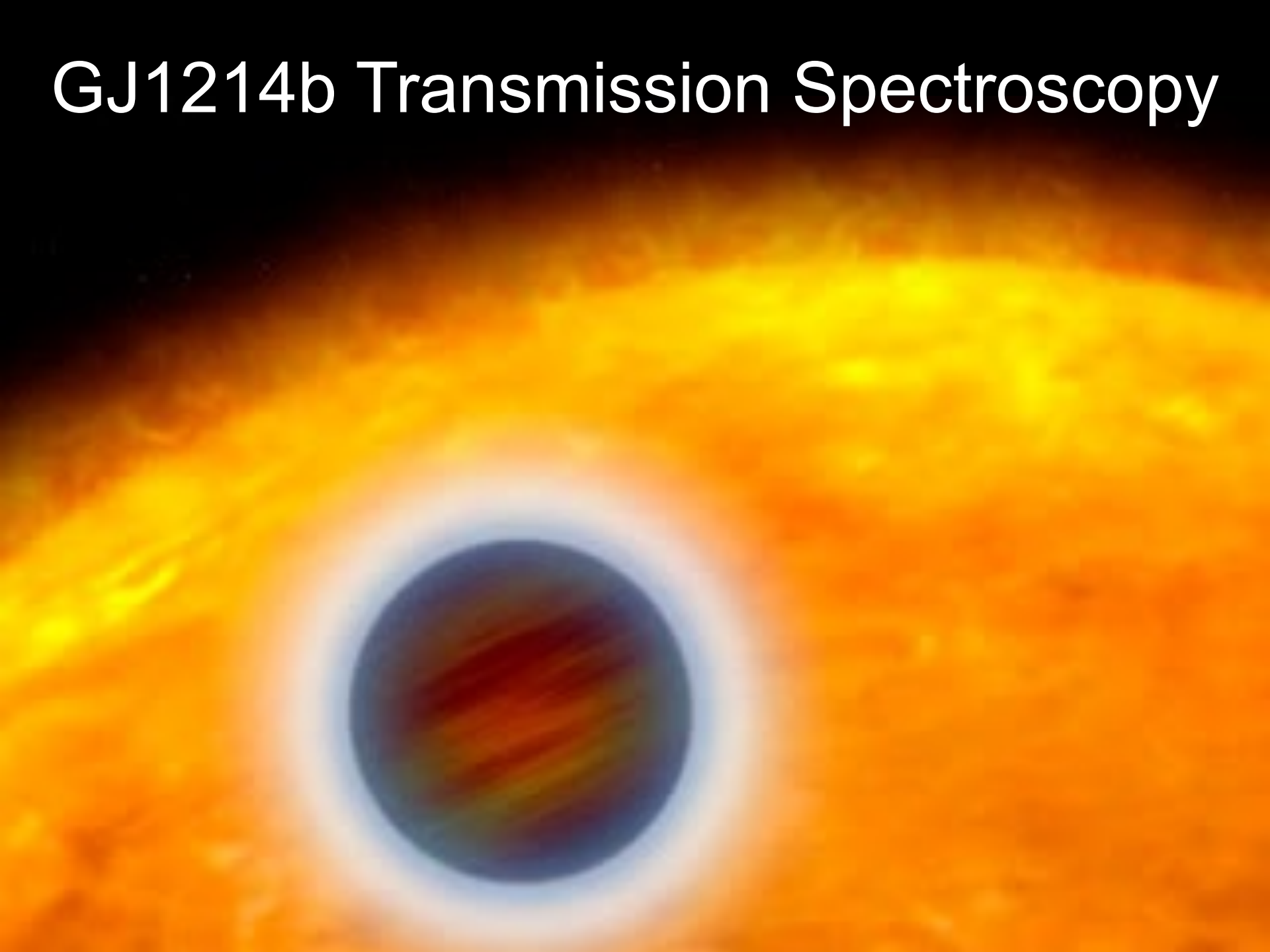


Composition scenarios for the sub-Neptune-size planet GJ1214b (6.5 M_E, 2.7 R_E) that are all consistent with the measured planet mass and radius. (Rogers & Seager, 2010)

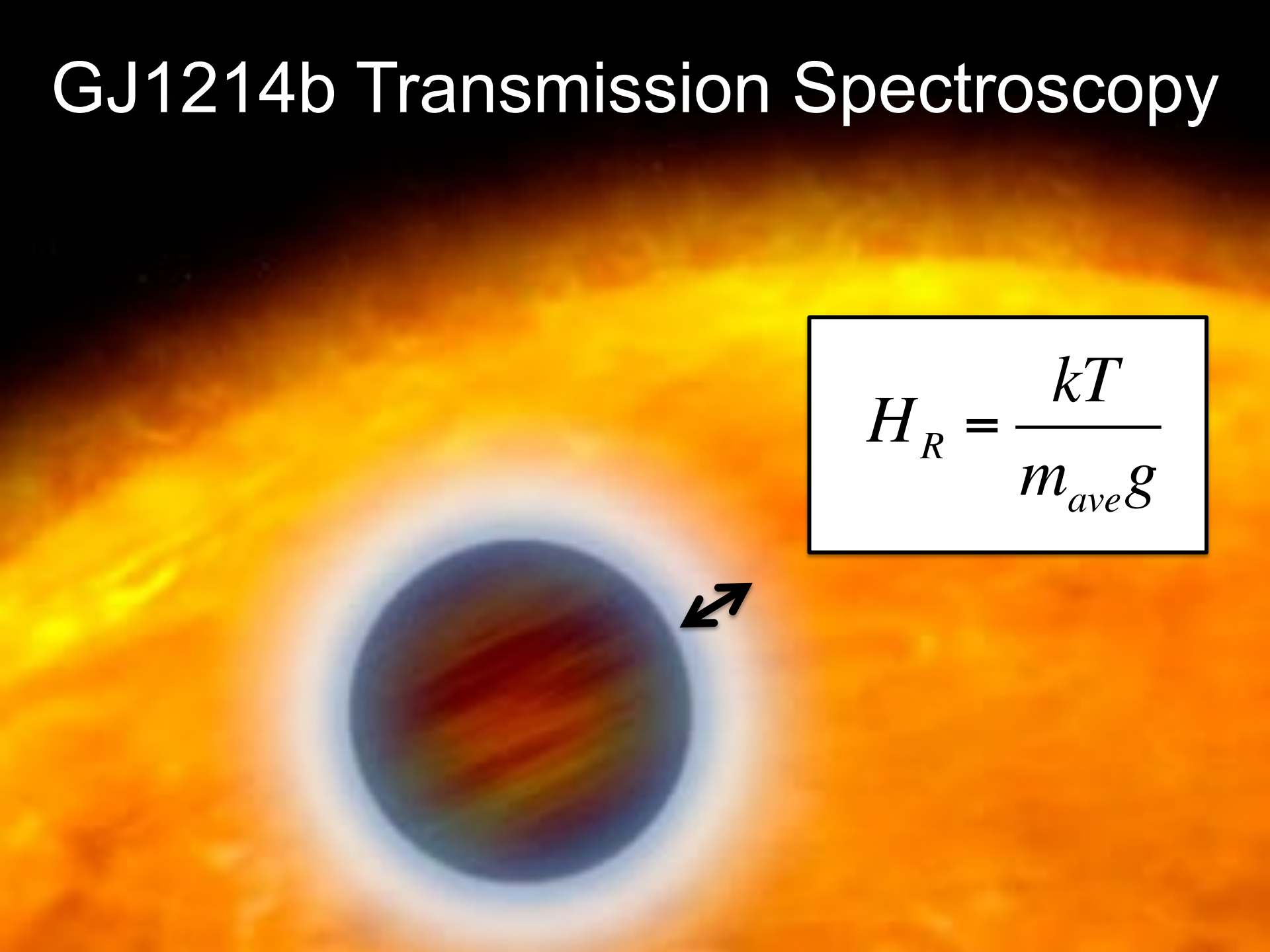
Challenge:

Since water is intermediate in density between H/He and rock, the fraction of a planet's mass in water is poorly constrained by measurements of the planet's mass and radius (e.g., Adams et al., 2008; Rogers & Seager, 2010a,b).

GJ1214b Transmission Spectroscopy

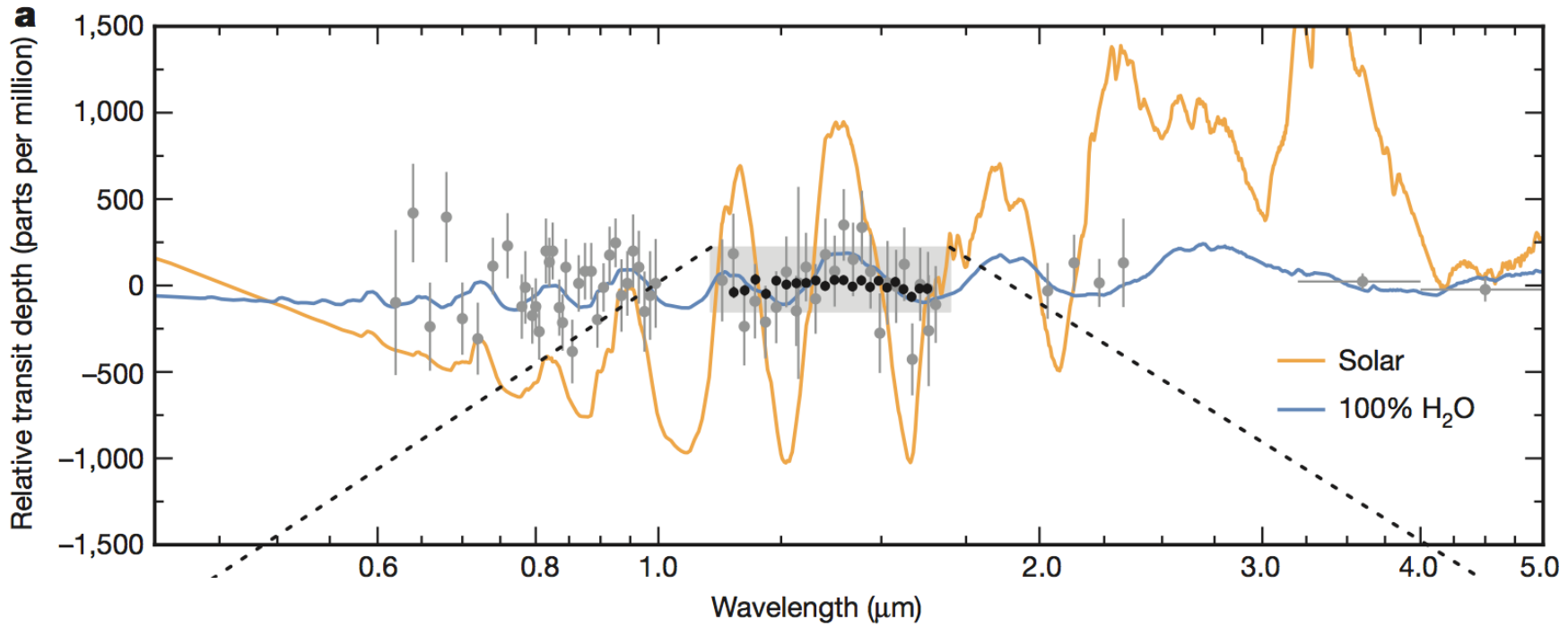


GJ1214b Transmission Spectroscopy



$$H_R = \frac{kT}{m_{ave}g}$$

GJ1214b Transmission Spectroscopy

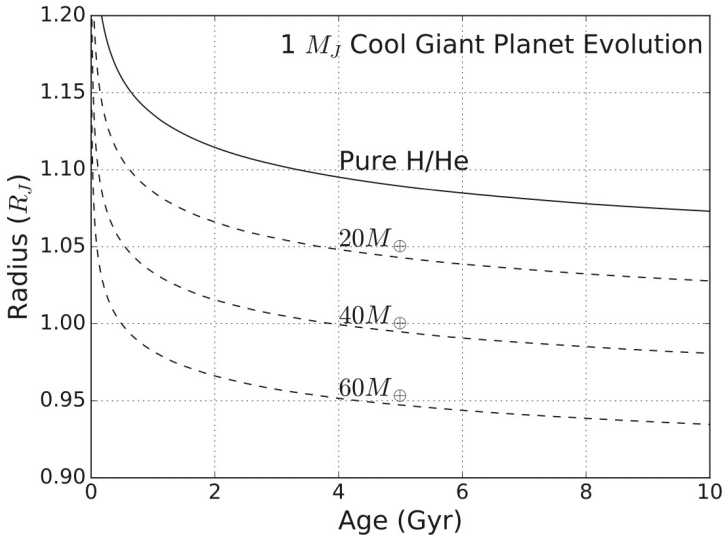


Kreidberg et al. (2014)

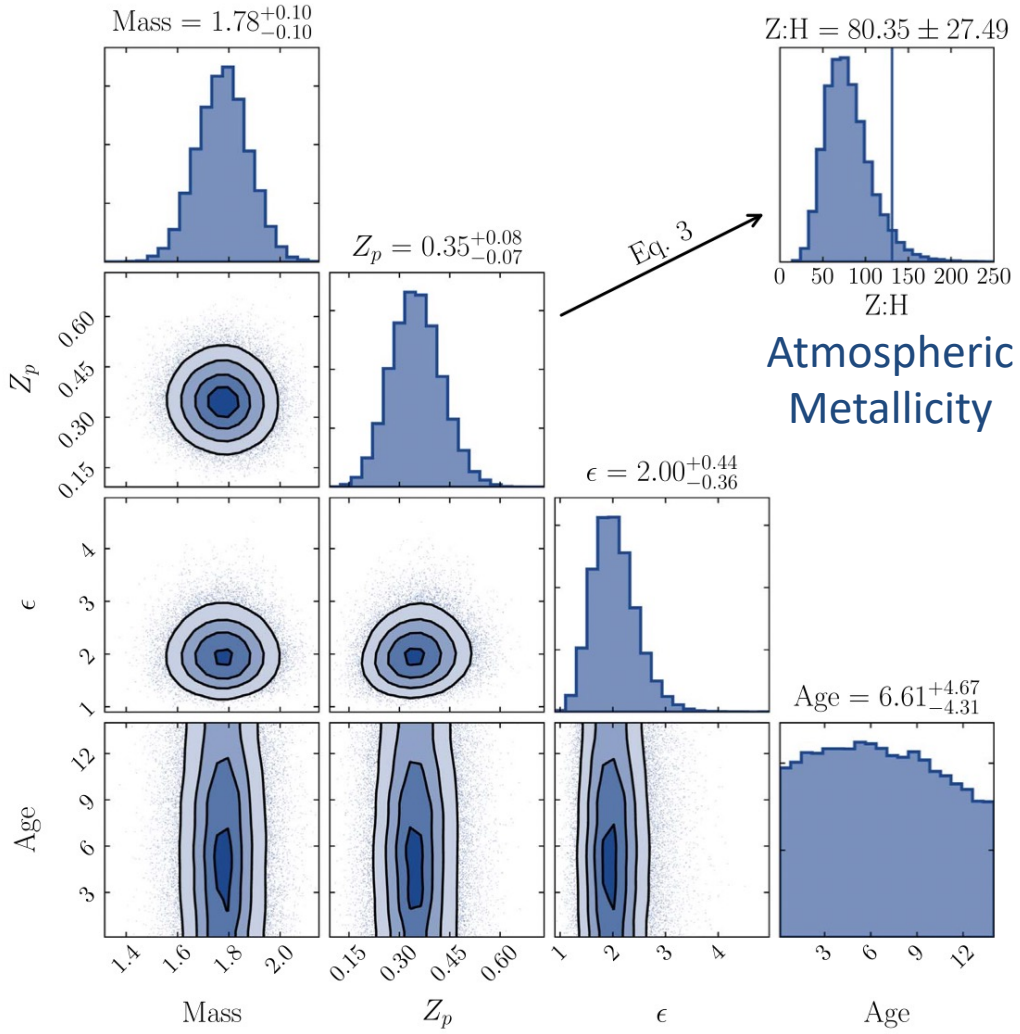
Interior Structure Inform Atmospheres: Bulk Metallicity Sets an Upper Limit on Atm Metallicity

WASP-43 b
$M_p = 1.78 \pm 0.10\ M_{Jup}$
$R_p = 0.93\ 0.08\ R_{Jup}$
$T_{eq} = 1379$ K

Retrieval Fitting Interior Structure Models to Measured M_p, R_p, age, T_{eq}



Thorngren & Fortney (2019)



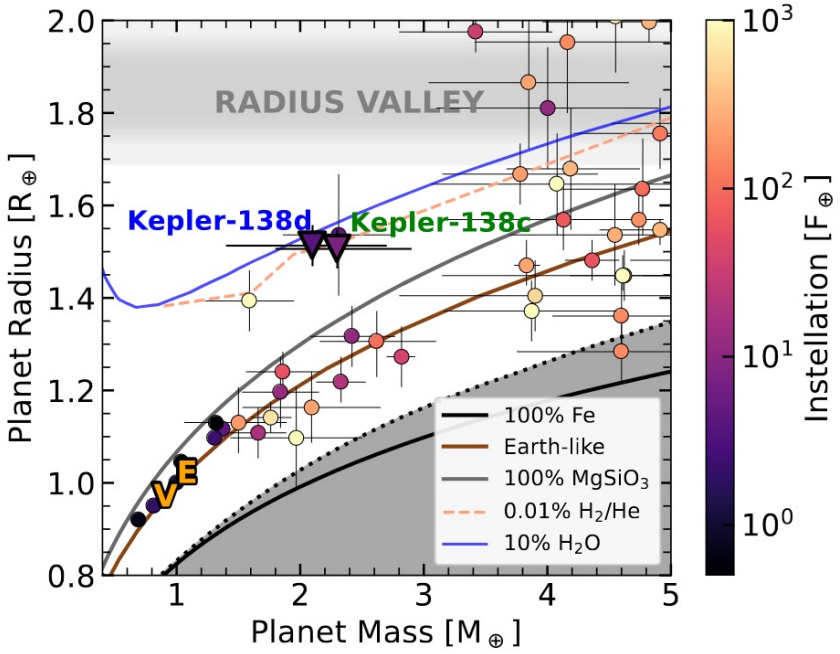
Atmospheric Metallicity

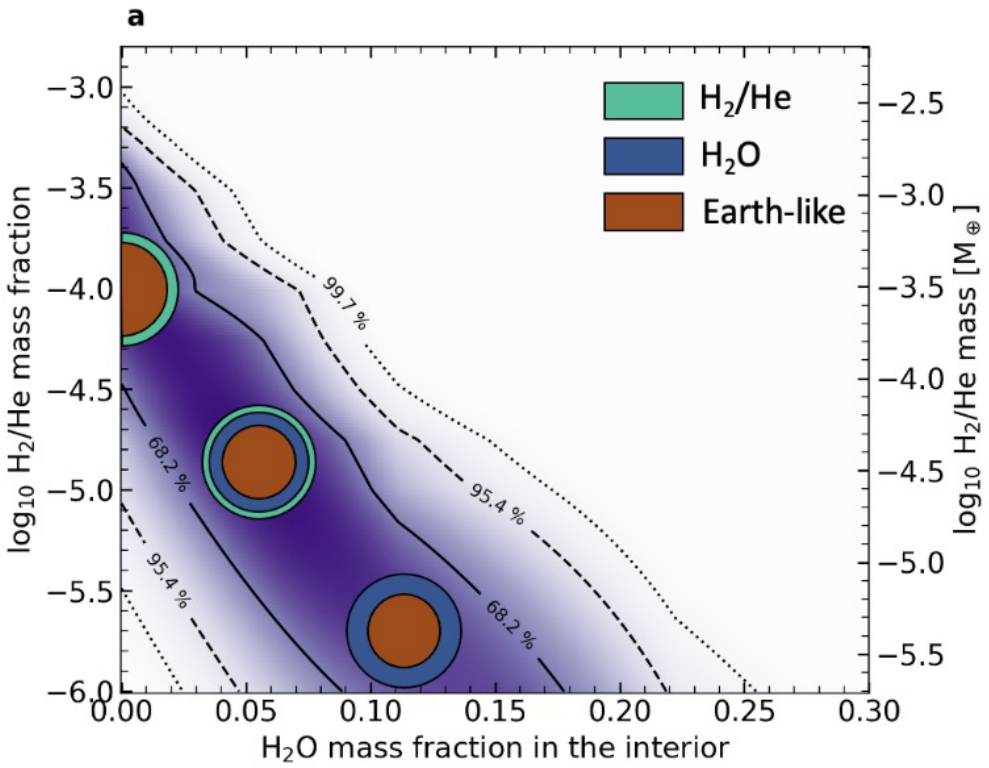
Planet Mass | Bulk Metallicity | Heating Efficiency | Age

Planet Mass measurements are needed…

- To constrain planet compositions, distinguishing terrestrial planets from water-rich planets and mini-Neptunes.
- To assess the planet's thermal evolution (e.g., intrinsic heat flux, thermal profile).
- To determine the planet's surface gravity (log g), which facilitates the retrieval of abundances from atmospheric spectra.
- To assess atmospheric loss rates.
- To understand the interactions of the planet with other bodies in the system.
- Because mass is one of the most fundamental properties of any astrophysical body!

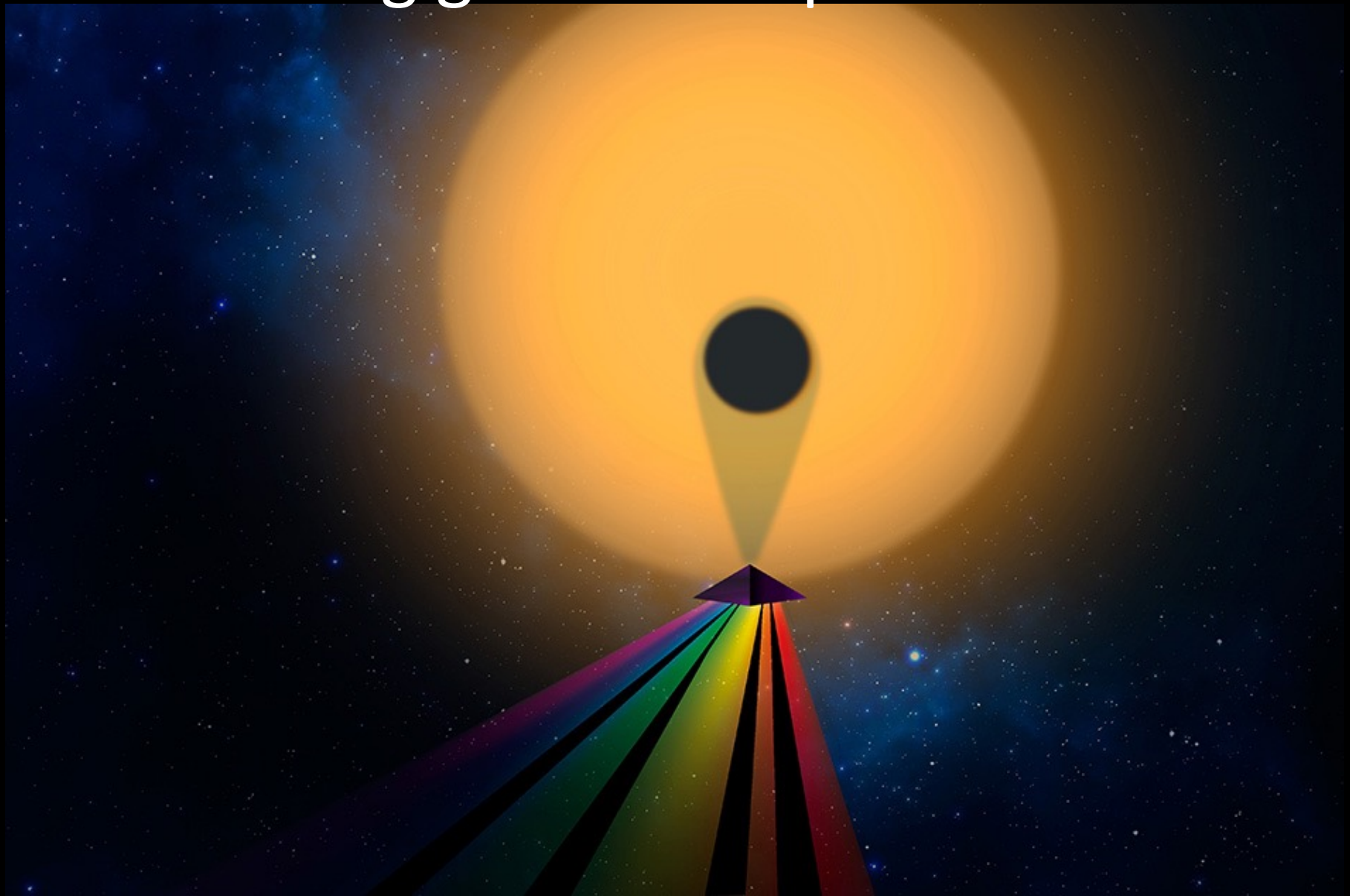
Mass measurements are needed to constrain planet compositions



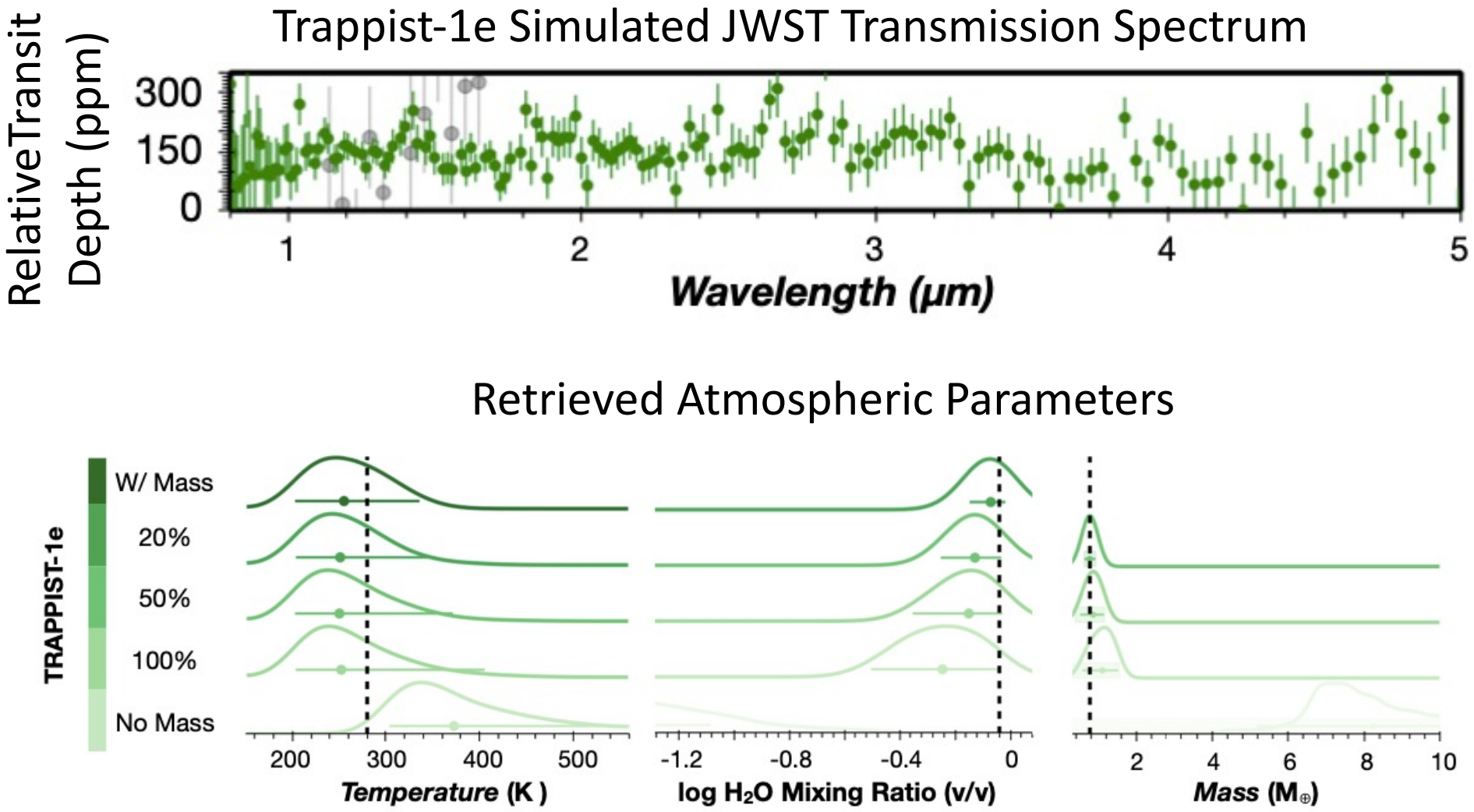


Piaulet et al. (2023): Evidence for the volatile-rich composition of Kepler-138d

Mass measurements are needed to constrain log g for atmosphere retrievals.

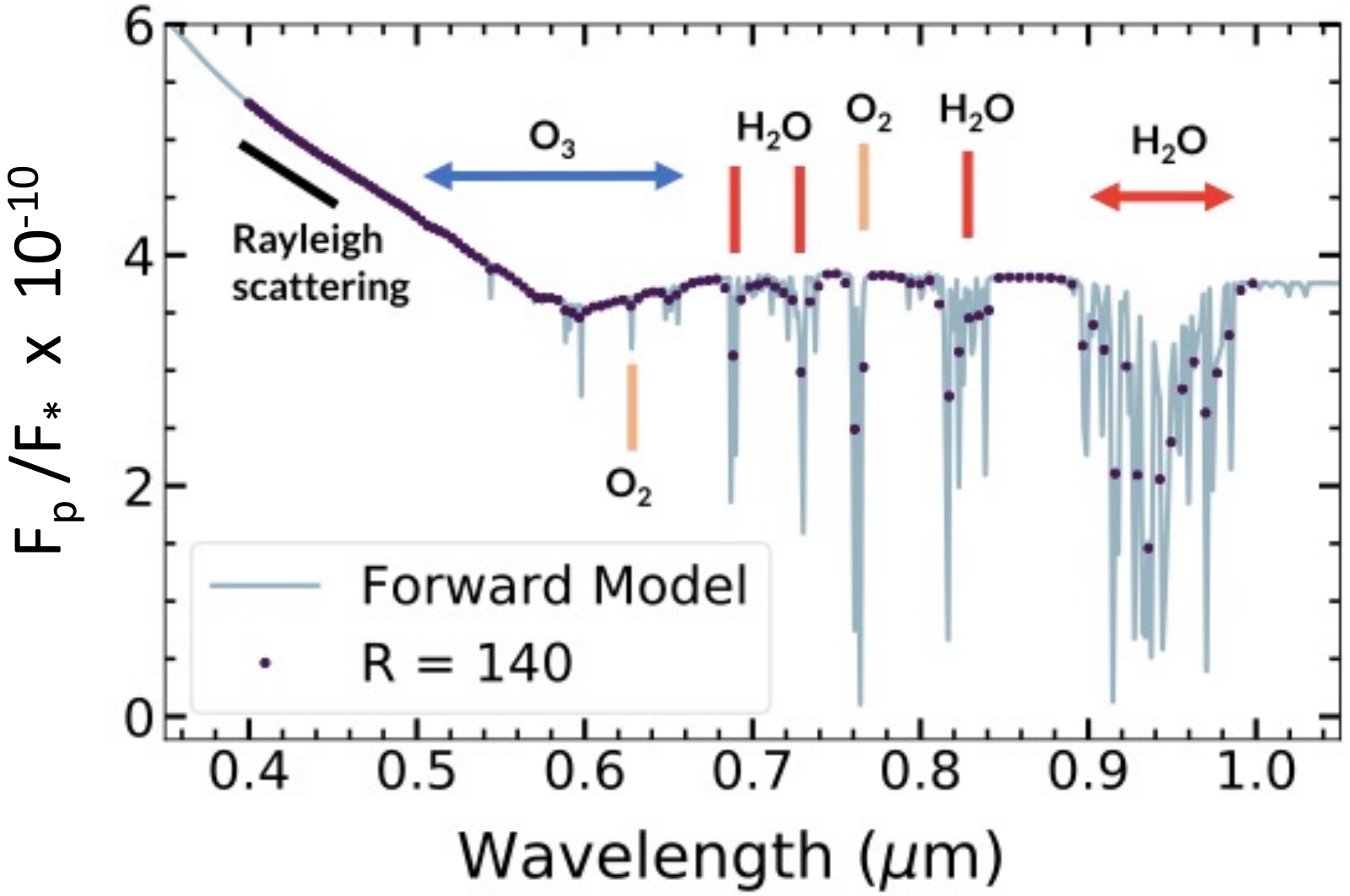


Mass measurements are needed to constrain log g for atmosphere retrievals – transit transmission



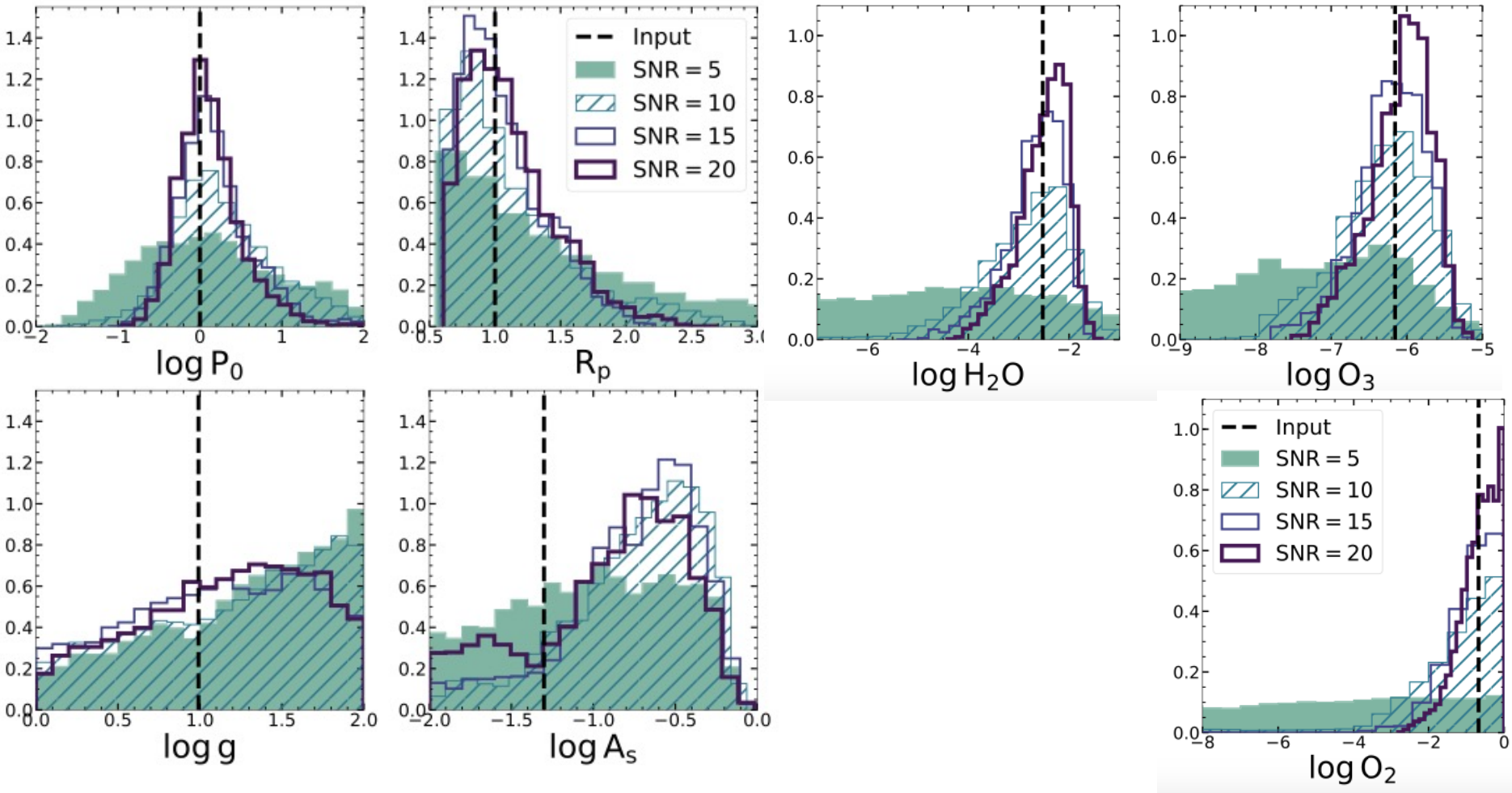
Batalha et al. (2020)

Mass measurements are needed to constrain log g for atmosphere retrievals – reflected light imaging



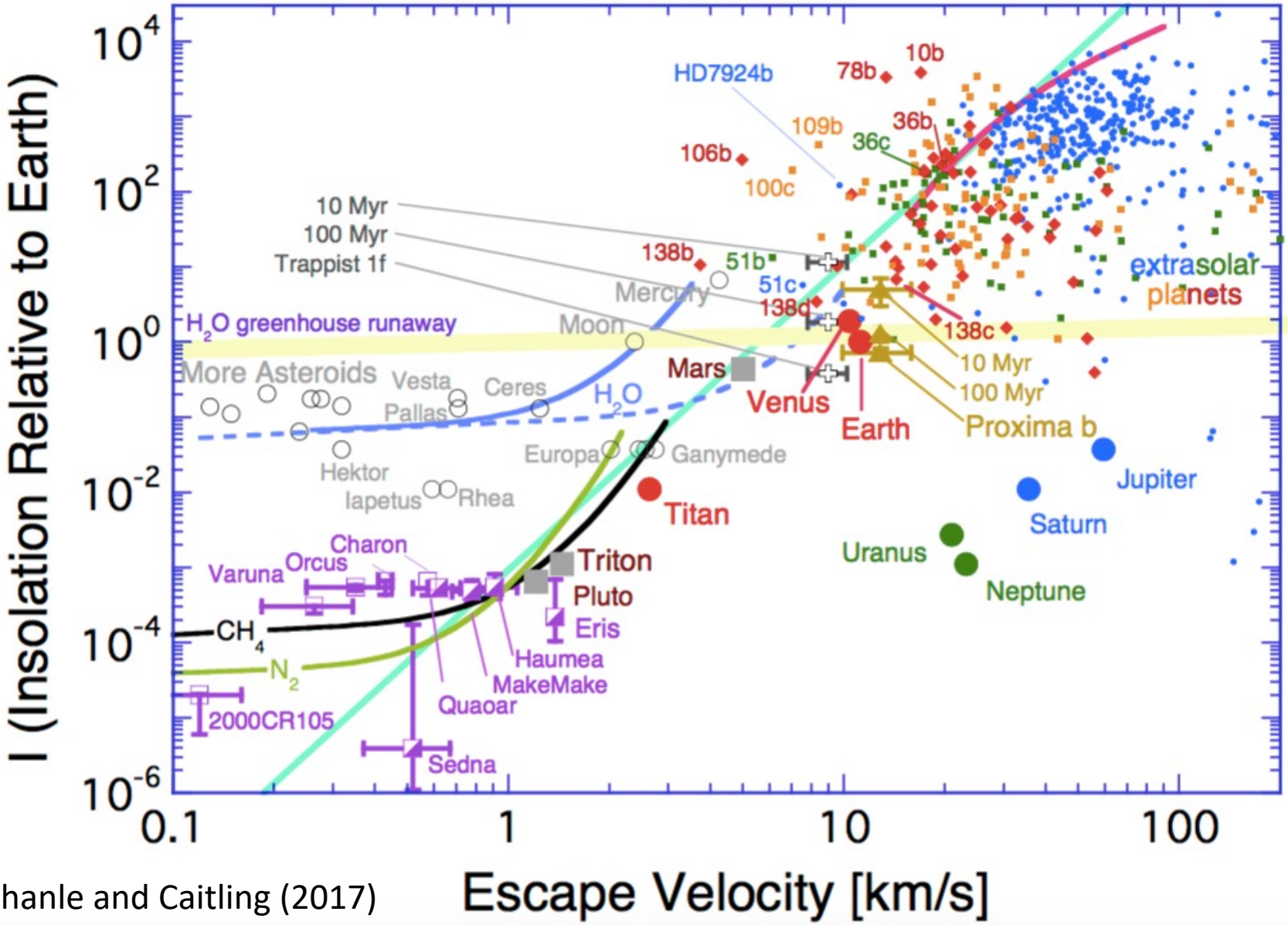
Feng et al. (2018)

Mass measurements are needed to constrain log g for atmosphere retrievals – reflected light imaging



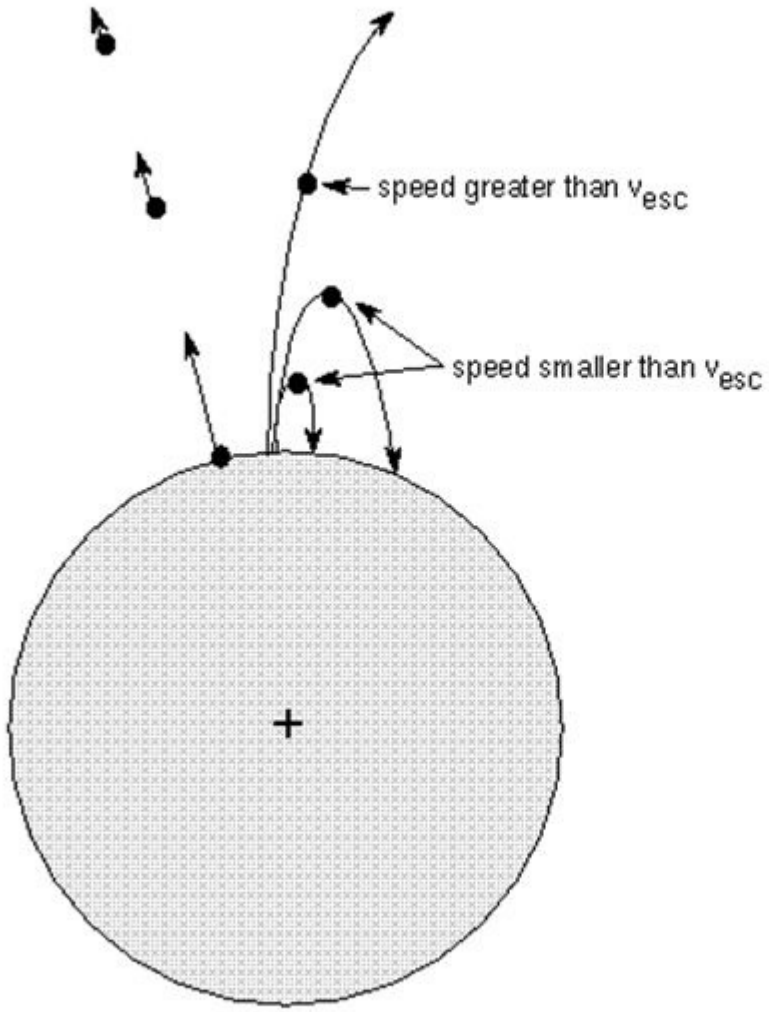
Feng et al. (2018)

Mass measurements are needed to assess atmospheric mass loss rates.



Zhanle and Caitling (2017)

Escape Velocity, v_{esc}

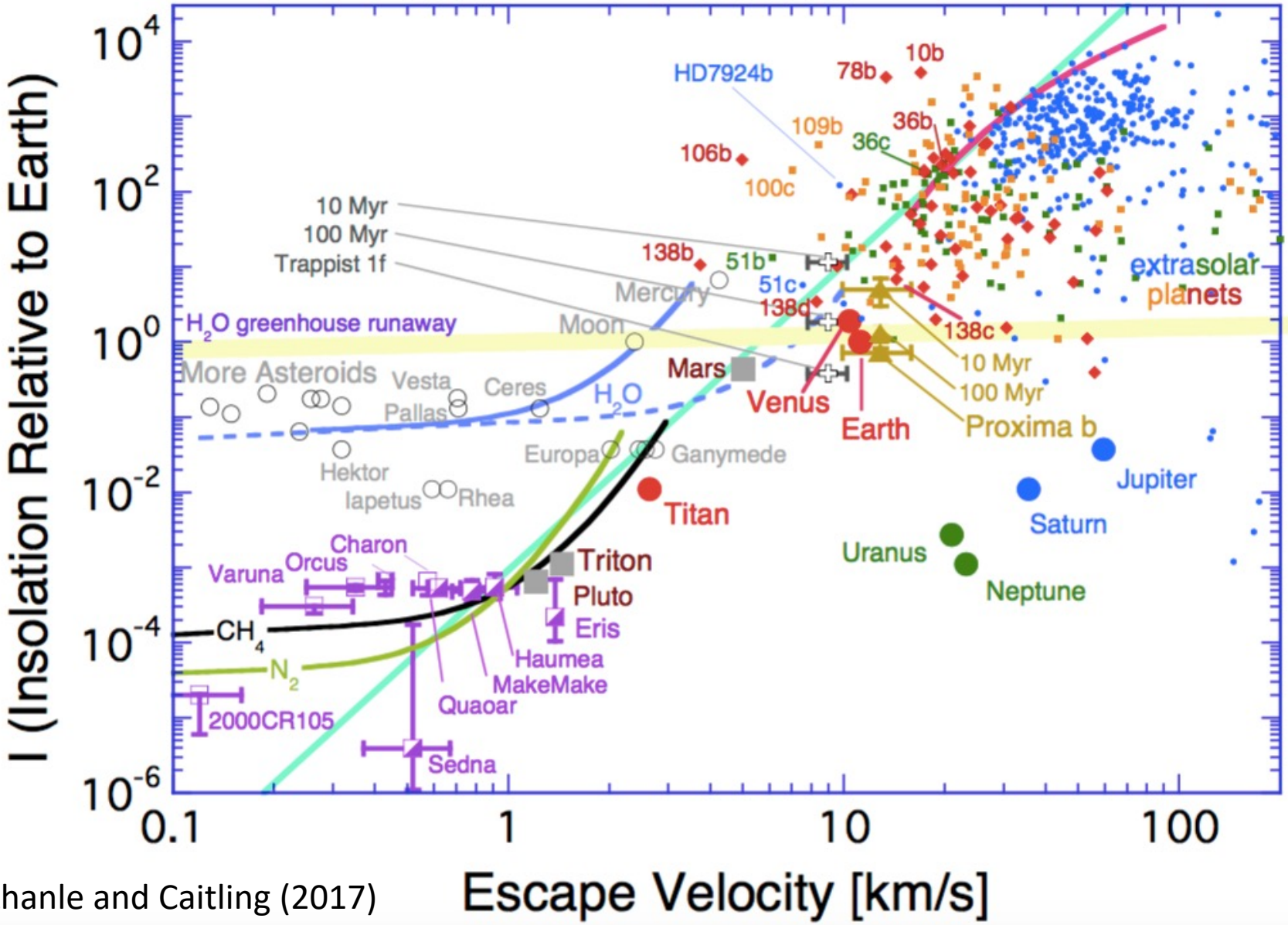


Escape velocity depends on the gravitational potential of the planet

$$\frac{1}{2}mv^2 = \frac{GMm}{r}$$

$$v_{escape} = \sqrt{\frac{2GM}{r}}$$

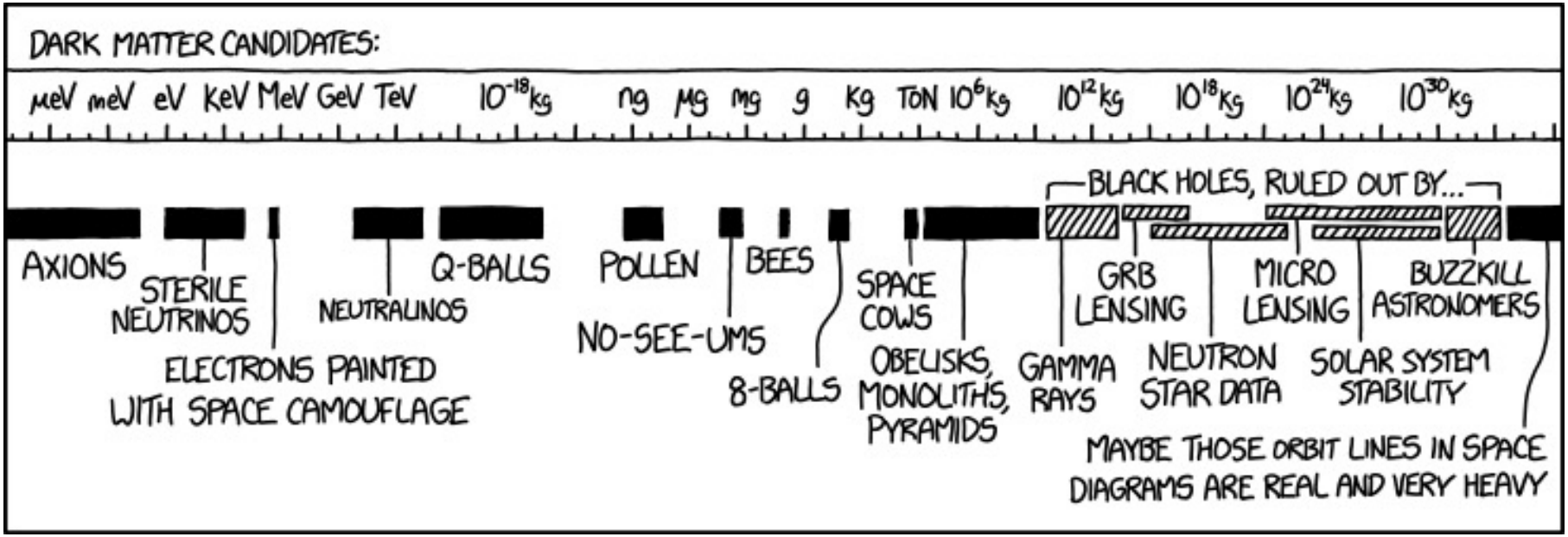
Mass measurements are needed to assess atmospheric mass loss rates.



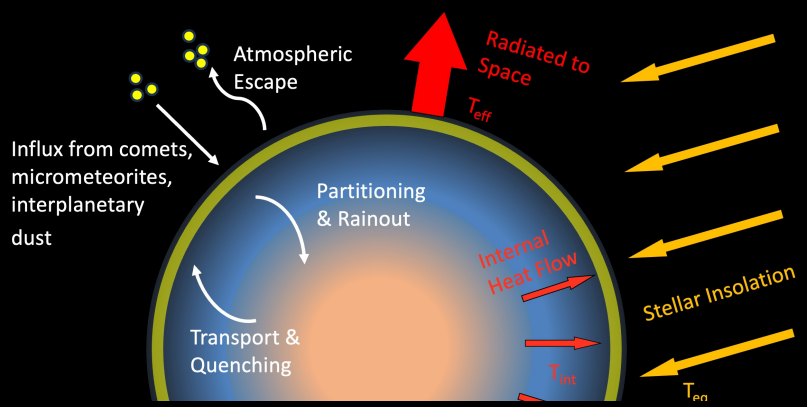
Zhanle and Caitling (2017)

Mass measurements are needed to understand the planets' interactions with the rest of its system.

Mass measurements are needed since mass is a fundamental property of any astrophysical body.

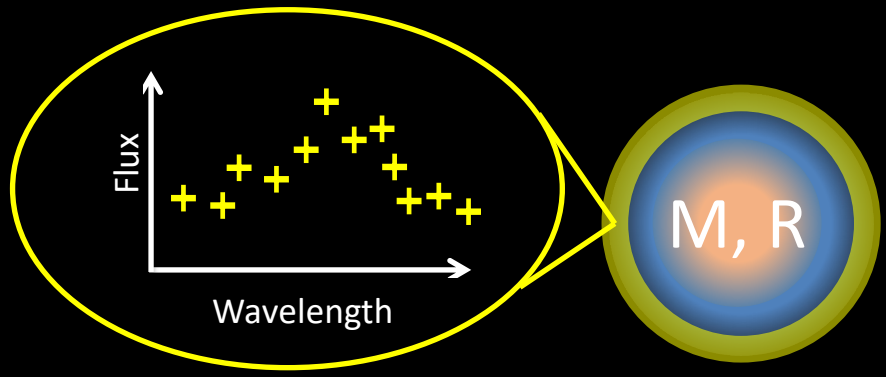


https://xkcd.com/2035/



Physical Processes Connecting Interiors and Atmospheres

Combining Insights from Planet Atmosphere Observations and M-R Measurements



- Constrain planet compositions
- Assess the planet's thermal evolution
- log g for atmospheric retrieval
- Assess atmospheric loss rates
- Planet Context in the system
- Fundamental property

The Importance of Planet Mass Measurements