ASTR 405
Planetary Systems
Exoplanet Atmosphere II

Fall 2025

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Supplementary Readings: **atmosphere.pdf** on Canvas

Exoplanet Atmospheres by Sara Seager and Drake Deming

Modules

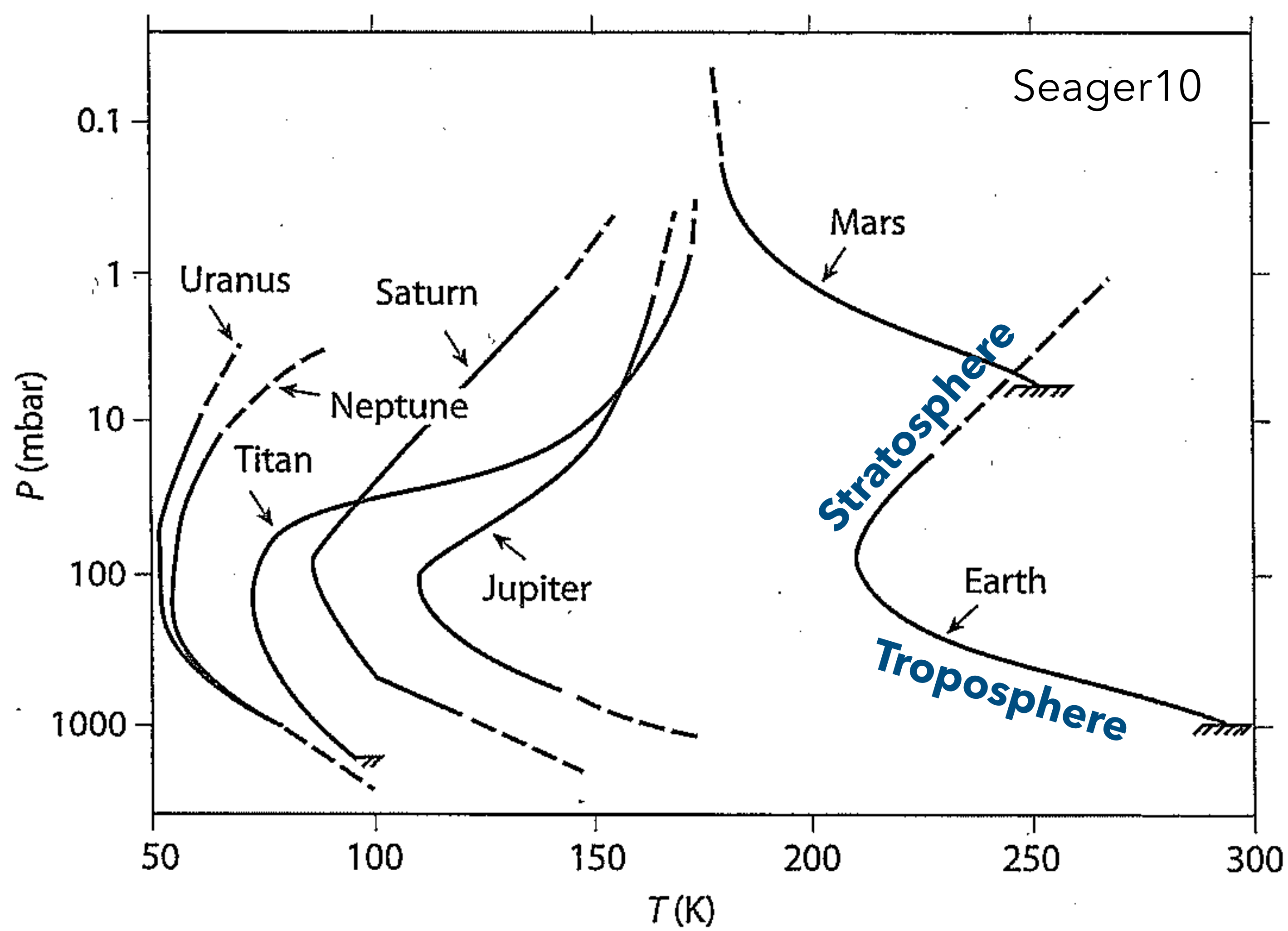
- Part I: Exoplanet Detection Methods
  - Explore the techniques astronomers use to discover planets beyond our solar system
- Part II: Exoplanet Demographics and Planet Formation
  - Investigate the statistical properties of exoplanets and theories of how planetary systems form
- **Part III: Exoplanet Atmospheres, Interiors, and Characterization**
  - **Examine methods for studying the physical properties and compositions of distant worlds**

Module III: Exoplanet Atmospheres, Interiors, and Characterization

- **Exoplanet Characterization**
  - Transmission, emission & phase curves → atmospheric composition, P-T profile
  - Rossiter–McLaughlin effect → spin–orbit angles
- **Atmospheric Physics**
  - Hydrostatic structure and P-T profiles
  - Thermodynamics: convection, lapse rate, and radiative balance
  - <u>Composition and clouds: metallicity, C/O ratio, disequilibrium chemistry</u>
  - <u>Atmospheric loss and the cosmic shoreline</u>
- **Planetary Interiors**
  - Giant planets: phase diagram of hydrogen, central pressure, Hot Jupiter radius inflation
  - Terrestrial planets: heat transport, cooling, and mass–radius relation

Pressure-Temperature (P-T) Profiles

	Earth	Jupiter
Troposphere	Heated from below by sunlight	Heated from below by internal heat
Stratosphere	Heated from above by ozone (UV)	Heated from above by CH_4 + photochemical hazes (UV/IR)



Convective vs Radiative Heat Transport

The adiabatic lapse rate $dT/dz = -g/c_p$ is the temperature gradient a parcel follows when it moves without exchanging heat; comparing it to the environmental gradient tells us if the parcel becomes buoyant (convection) or not.

$$\frac{dT}{dz} < -\frac{g}{c_p} \qquad \text{unstable (convective)}$$

$$\frac{dT}{dz} = -\frac{g}{c_p} \qquad \text{marginally stable}$$

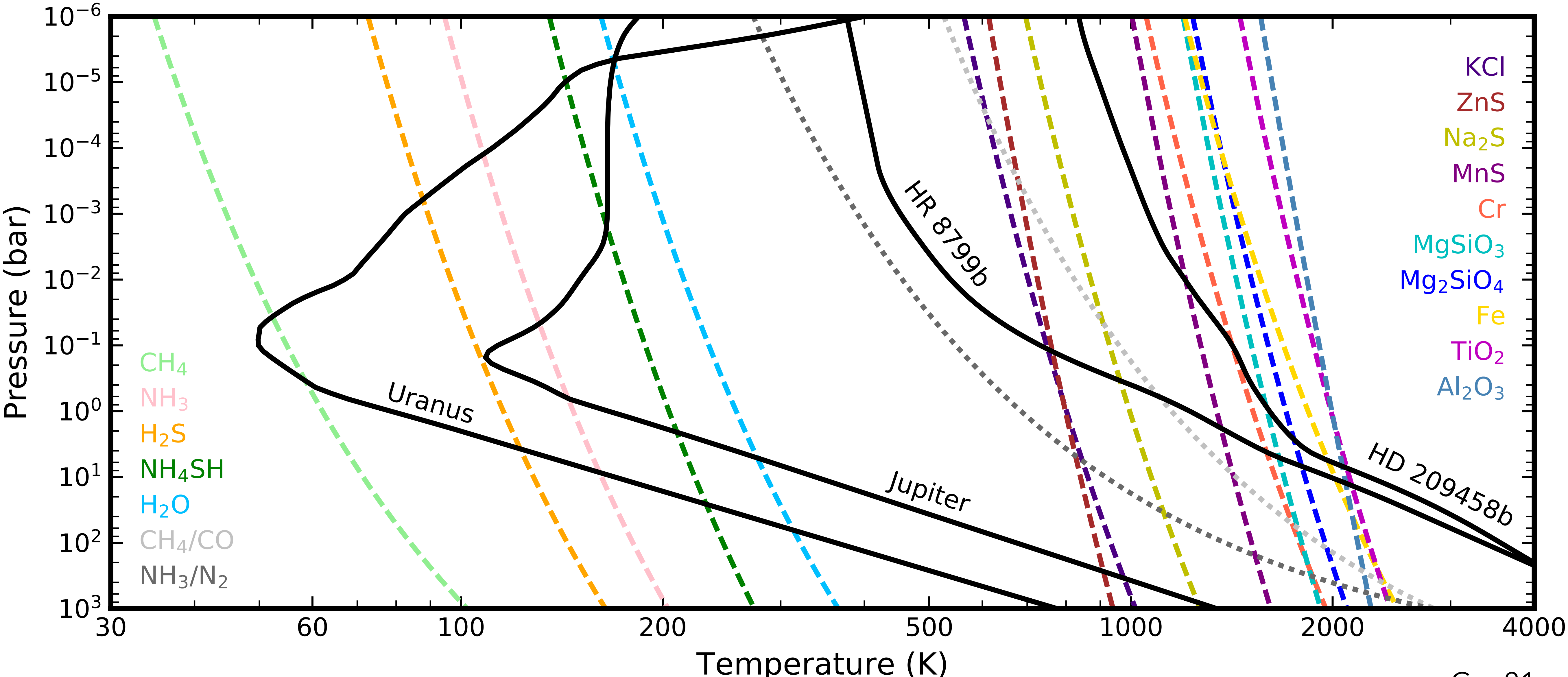
$$\frac{dT}{dz} > -\frac{g}{c_p} \qquad \text{stable (radiative)}$$

Radiative timescale, i.e., how long it takes the atmosphere adjust to a state of radiative equilibrium: $\tau_{\mathrm{rad}} \approx \frac{p}{g}\frac{c_p}{4\sigma T^3}$

Cloud Condensation

Clouds can form in planetary atmospheres where species are thermodynamically favored to undergo a phase transition from vapor to solid phases.

P-T profiles of Solar System giant planets in black lines and exoplanets with condensation curves of various species in dashed lines



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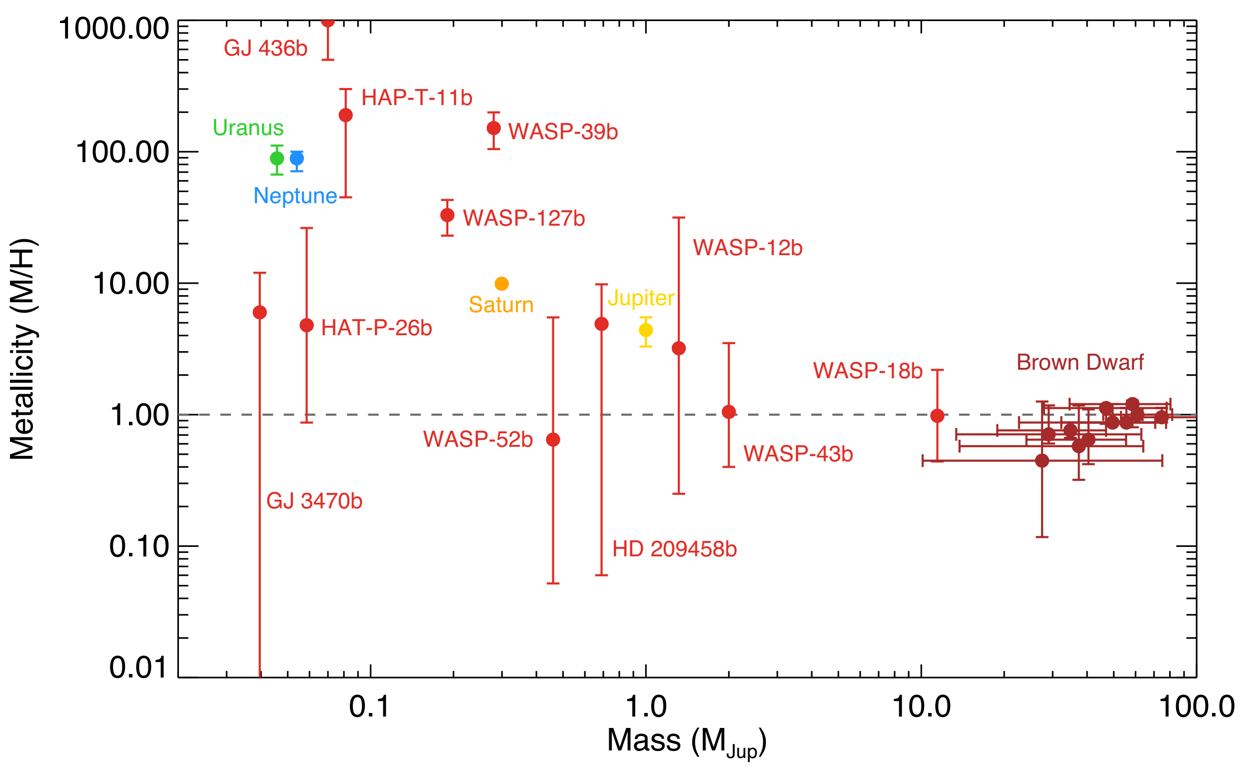
In-Class Activity

Identifying Cloud Species

Atmosphere Composition

- Metallicity (M/H): Measures the abundance of elements heavier than H/He relative to solar. Higher metallicity generally increases the opacity, strengthens molecular features, and may trace how much solid material the planet accreted during formation.

- C/O ratio: Sets the relative amounts of carbon- and oxygen-bearing molecules. provides a chemical "fingerprint" of whether it formed inside or outside the H_2O, CO_2, CO ice lines.



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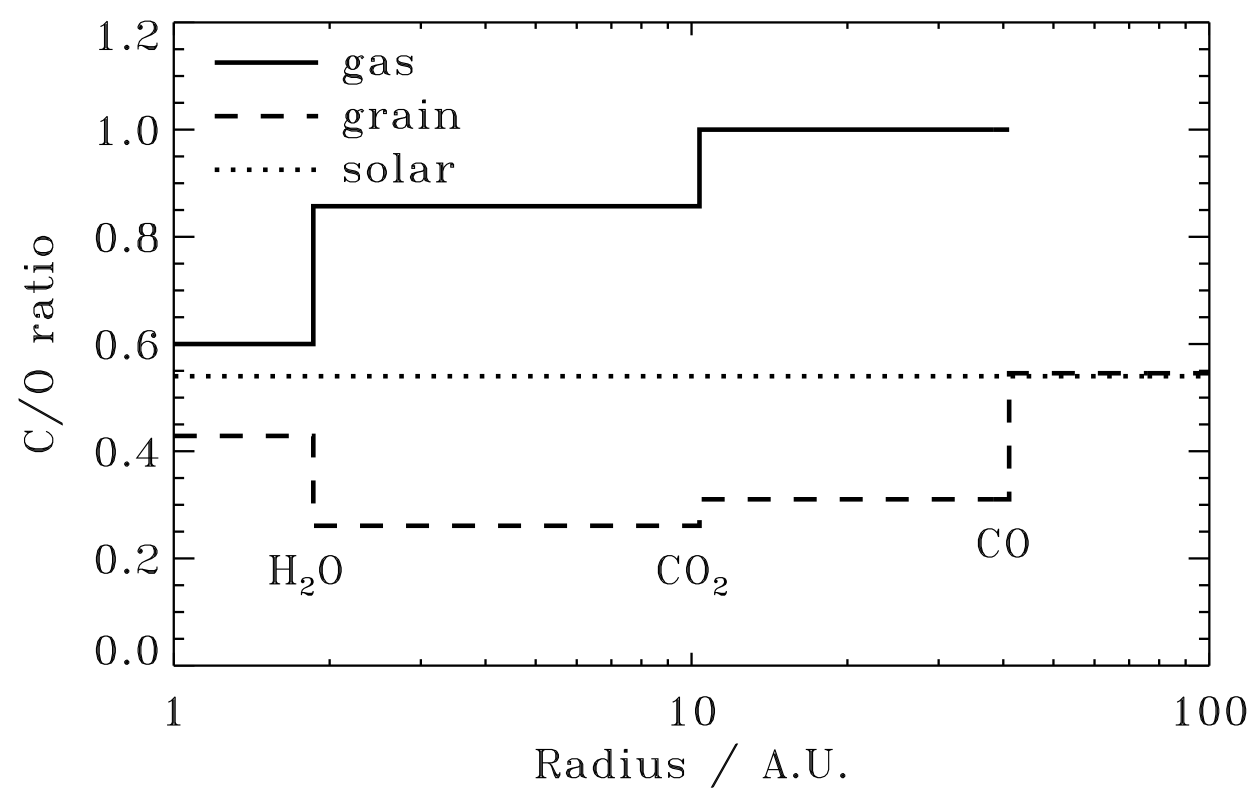

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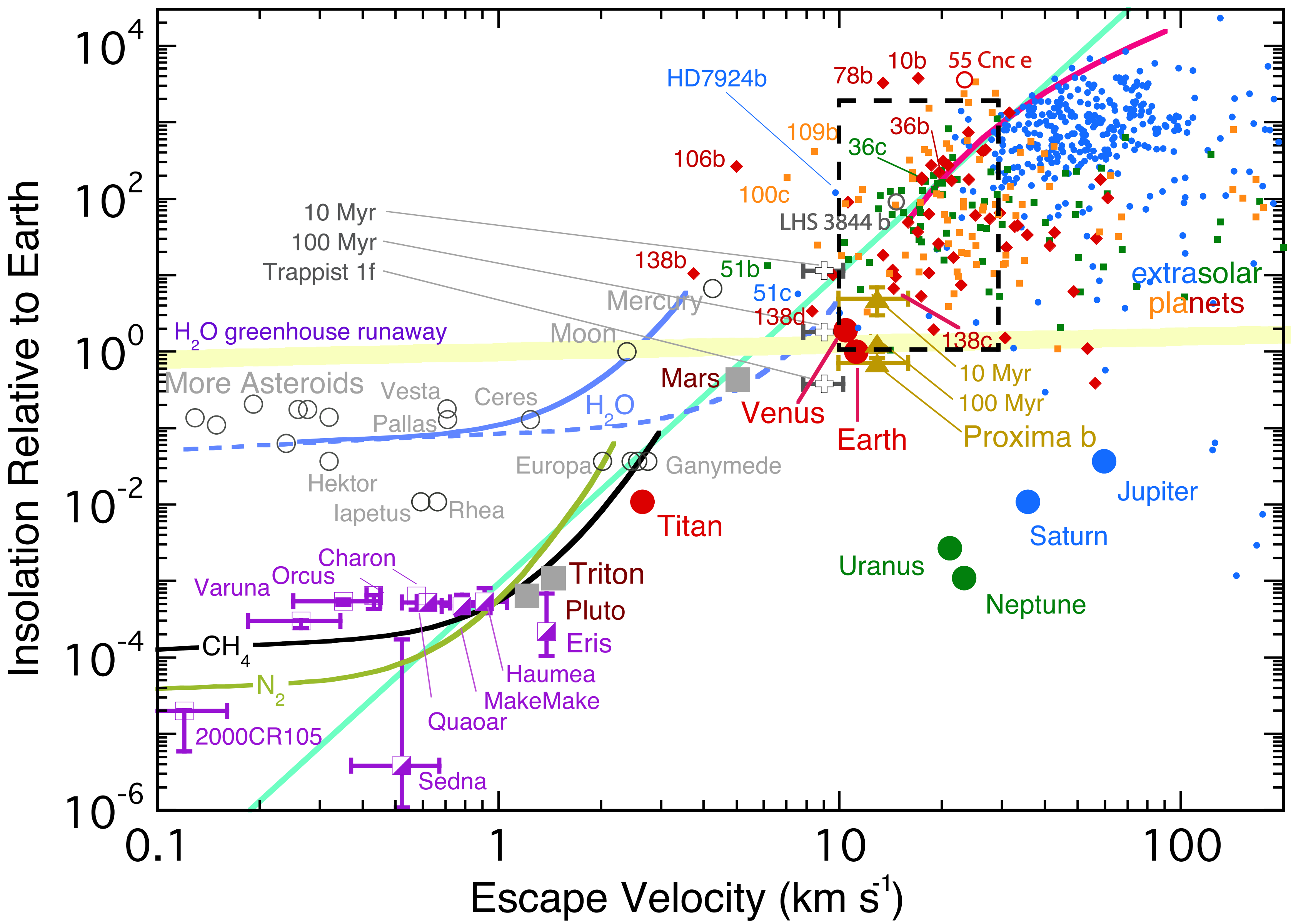
The “Cosmic Shoreline”

The ”cosmic shoreline” is empirically determined level of instellation that planets below a given escape velocity cannot hold onto thick atmospheres. Below is a scatterplot of the level of instellation and escape velocity of various planets and moons in our Solar System and beyond, compared with the **empirical cosmic shoreline (cyan)** and hydrodynamic thermal (energy-limited) escape curves for various species (methane, nitrogen, water in black, gold, blue colored lines).



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