ASTR 405
Planetary Systems
Exoplanet Interiors: Giant Planets

Fall 2025

Prof. Jiayin Dong

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

Giant Planet Interior Structure and Thermal Evolution by Fortney et al.

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
    - Composition and clouds: metallicity, C/O ratio, disequilibrium chemistry
    - Atmospheric loss and the cosmic shoreline
- **Planetary Interiors**
    - <u>Giant planets: phase diagram of hydrogen, central pressure, Hot Jupiter radius inflation</u>
    - Terrestrial planets: heat transport, cooling, and mass–radius relation

Phases of H/He in Giant Planets

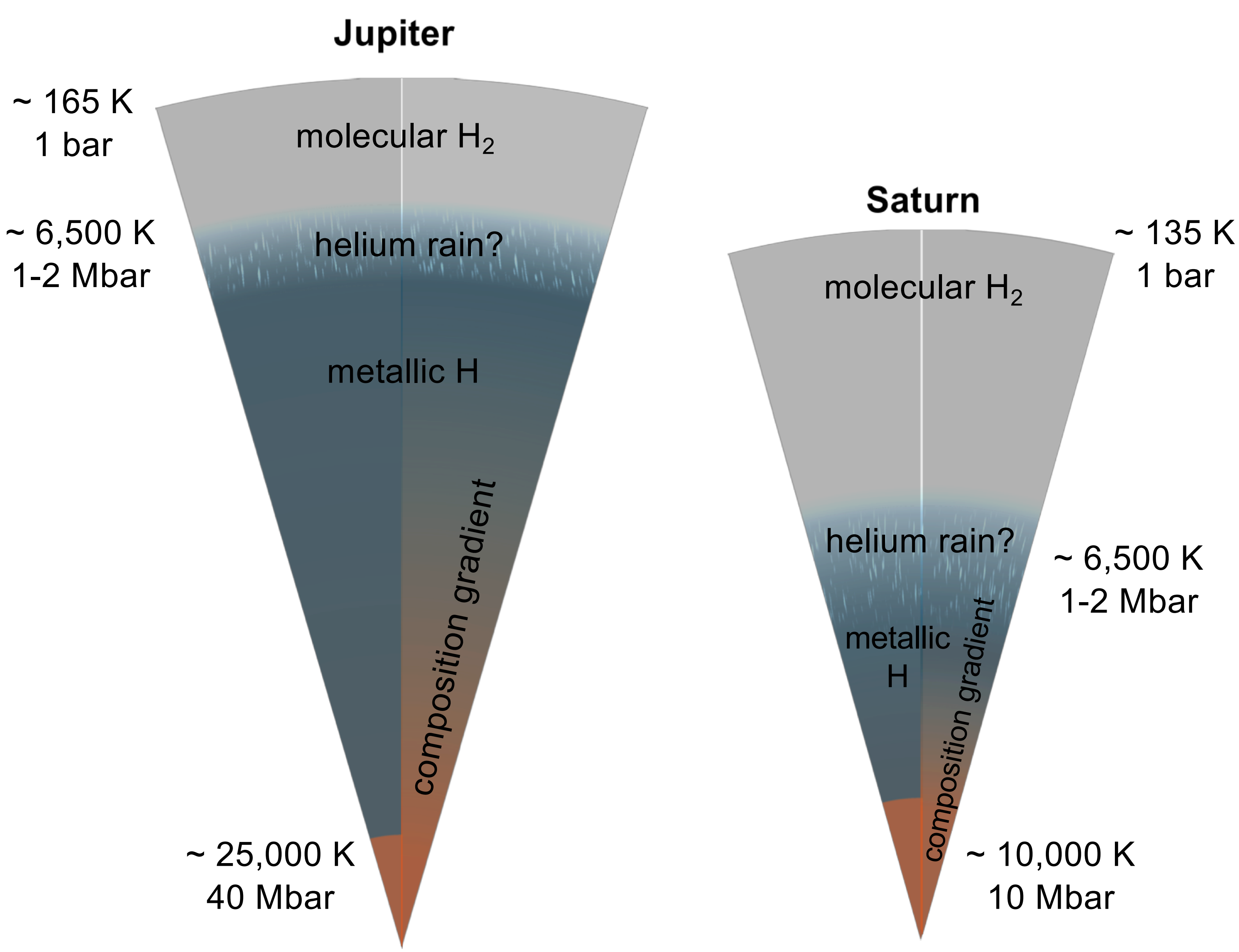
Giant planet interiors are made primarily of H and He, with a central heavy-element core (rock/ice/metals).

- **Hydrogen Phases (H)**
  - Molecular Hydrogen (H_2) in the upper envelope behaves as a gas in the atmosphere but becomes a dense fluid as pressure increases with depth.
  - Metallic Hydrogen (H^+) in the deep interior at high pressure ($\gtrsim$ 1 Mbar)
- **Helium Phases (He)**
  - Helium (He) remains neutral in planet interiors because it is much harder to ionize (two electrons).
- **H/He Mixture Phases:** Giant planets have outer layers of molecular He-H_2, a deep interior of metallic H^+ where He becomes immiscible and forms He droplets ("helium rain"), and at still higher pressures the He-H^+ mixture becomes fully miscible again within a uniform metallic fluid.

Interior Structures

Jupiter and Saturn

Gravity measurements on Jupiter (Juno) and Saturn ring seismology (Cassini) have greatly improved our understanding of giant planet interiors, revealing that both Jupiter and Saturn possess extended, **"fuzzy" diluted cores** rather than compact ones.

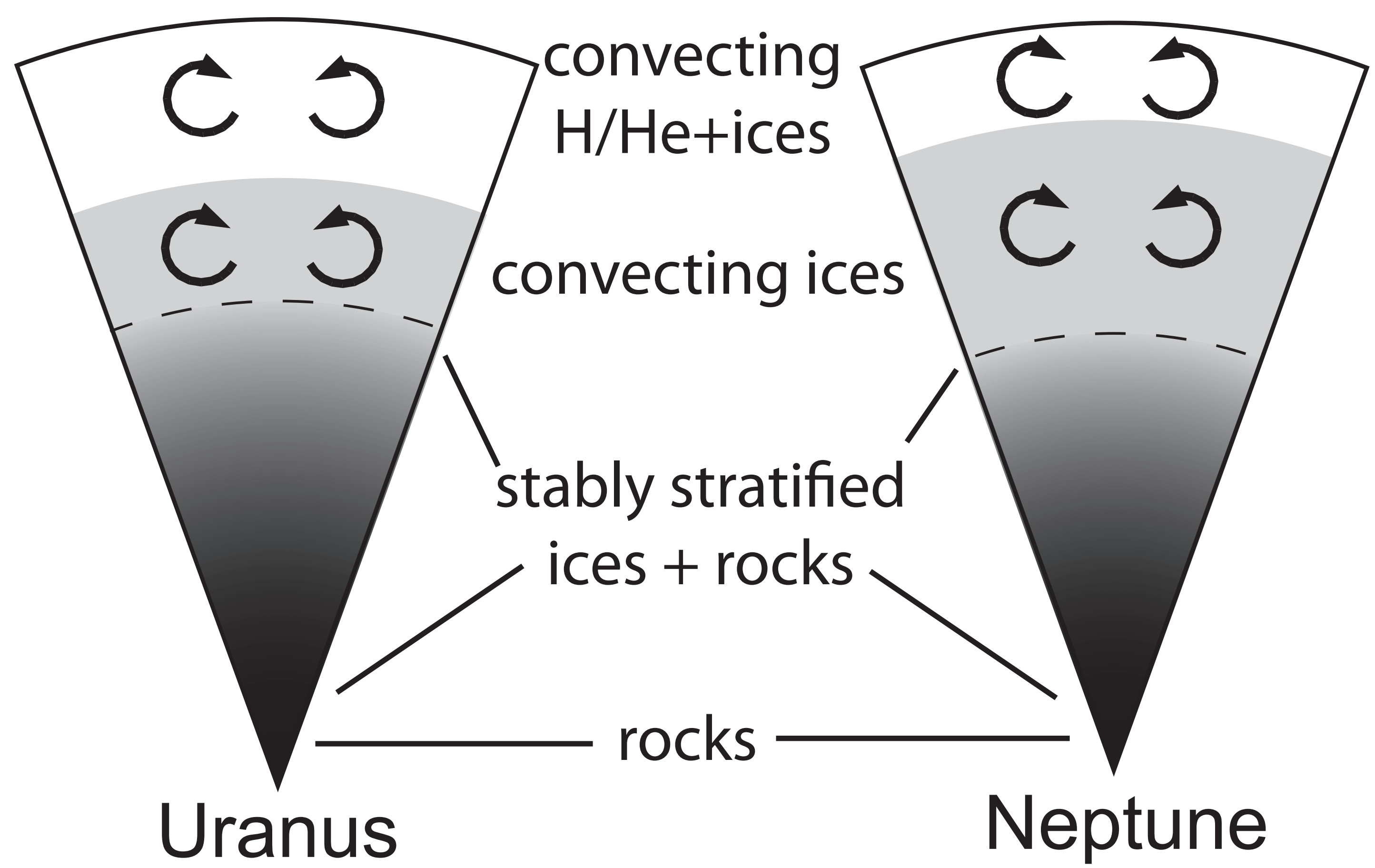


Credit: J. Fortney

Interior Structures

Uranus and Neptune

- Interiors of Uranus (~14.5 $M_\oplus$, 4 $R_\oplus$) and Neptune (~17 $M_\oplus$, 3.9 $R_\oplus$) are poorly known. Only a single Voyager 2 flyby; gravity data are limited, so interior structure is highly uncertain.
- Possibly Layered Composition: Thin H/He envelope, overlying a deep layer of hot, dense *ices* (H_2O, CH_4, NH_3; likely as a superionic, conducting fluid), above a mixed ice/rock interior.



Credit: J. Fortney

Central Pressure

Recall that hydrostatic equilibrium can be expressed as

$$\frac{dp}{dr} = -\rho g = -\rho \frac{Gm}{r^2} \quad .$$

Note that the mass of any given sheet of the planets can be written as $dm = \rho 4\pi r^2 dr$. Substituting in for dr, we can express hydrostatics equilibrium as

$$\frac{dp}{dm} = -\frac{Gm}{4\pi r^4} \quad .$$

The pressure must decrease as the mass coordinate increases. I.e., the pressure must increase as the mass coordinate decreases, going toward the center of the planet.

In-Class Activity

Calculating Central Pressures of Giant Planets

Equations of Planetary Structure

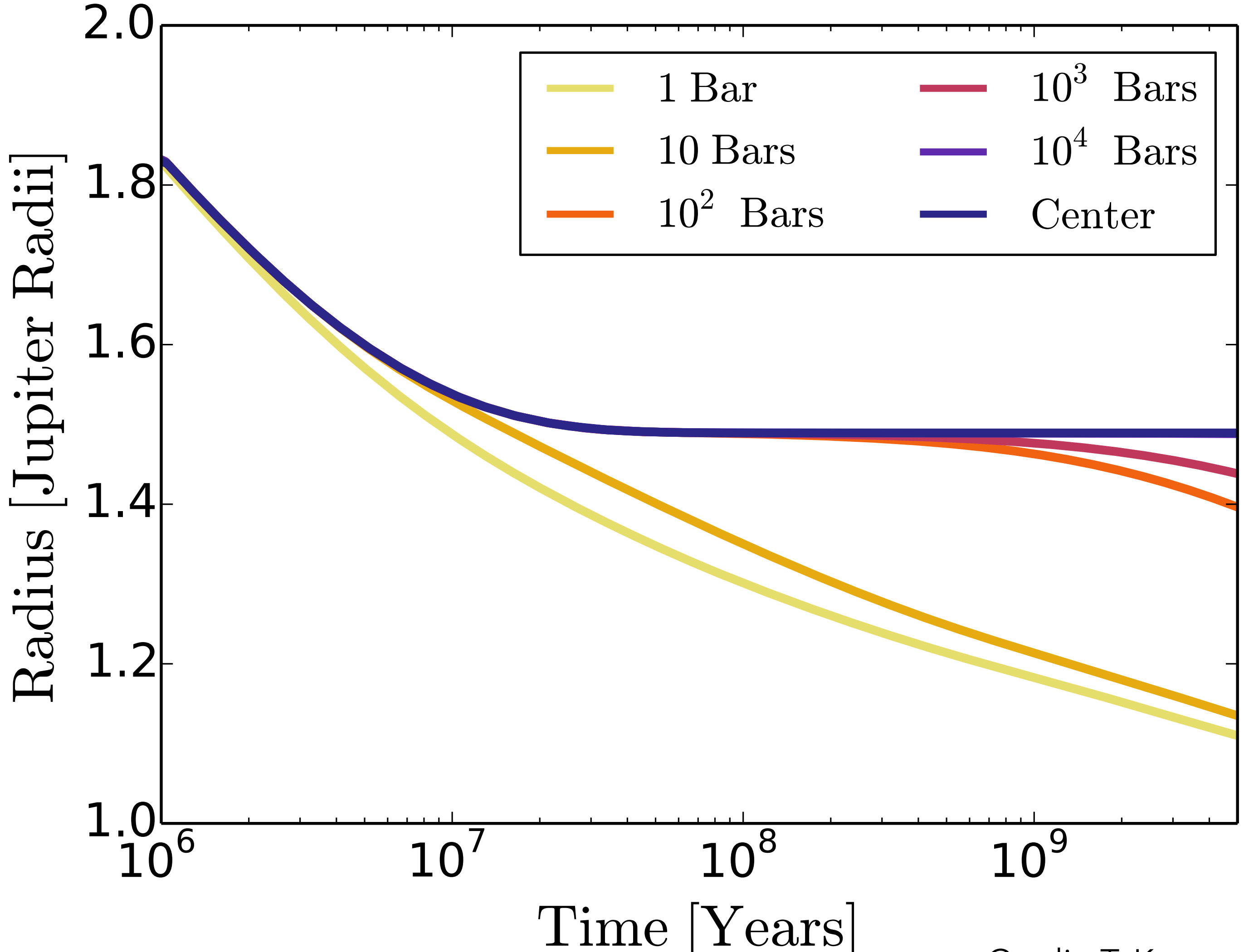
Five equations fully represent the internal structure of a planet. These are the equations of planetary structure, which are equivalent to the equations of stellar structure but without including nuclear burning.

1. Mass conservation: $\dfrac{dm}{dr} = 4\pi r^2 \rho$
2. Hydrostatic equilibrium: $\dfrac{dp}{dm} = -\dfrac{Gm}{4\pi r^4}$
3. Energy conservation: $\dfrac{dL}{dm} = \epsilon_{\mathrm{grav}} = -T\dfrac{dS}{dt}$, where L is the outgoing luminosity at mass coordinate and S is the entropy, the loss of which drives gravitational cooling ϵ_{grav} and contraction.
4. Energy transport: $\dfrac{dT}{dm} = -\dfrac{GmT}{4\pi r^2 p}\nabla$, where $\nabla = d\ln T / d\ln p$
5. Equation of state: $\mathrm{EOS}(P, \rho, T, \mathrm{composition})$

Radius Evolution

Young, newly formed planets have their cooling dominated by gravitational energy loss, with a cooling luminosity of $L \sim -dE_g/dt$. We can scale this expression to derive a characteristic Kelvin-Helmholtz (thermal) timescale

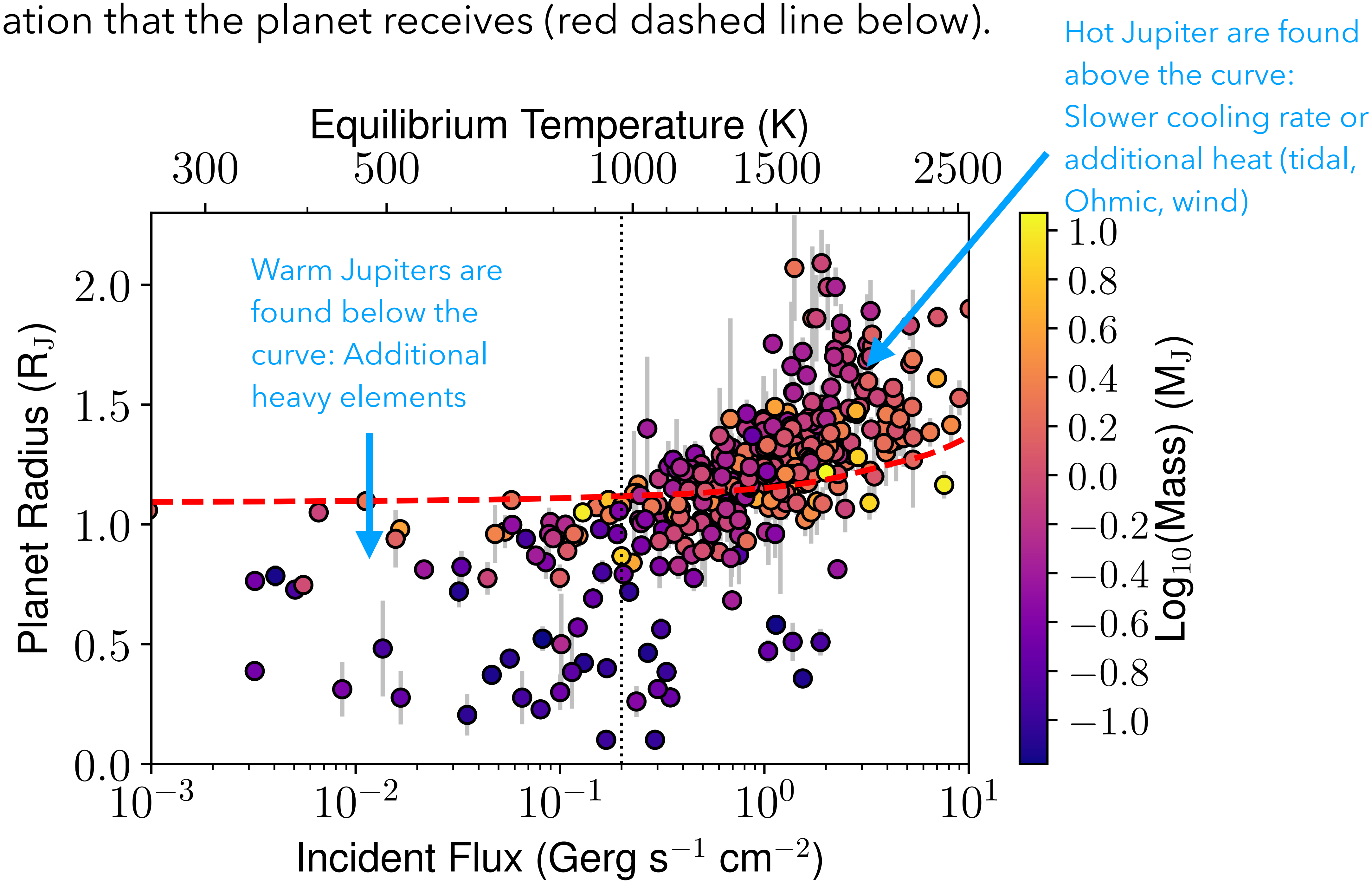
$$\tau_{\rm KH} \sim \frac{E_g}{L} \sim \frac{GM_p^2}{R_p L}$$



Credit: T. Komacek

Radius Inflation of Hot Jupiters

Many hot Jupiters have radii larger than expected from solving the equations of planetary structure, even including an additional atmospheric heating term due to the instellation that the planet receives (red dashed line below).



Credit: D. Thorngren