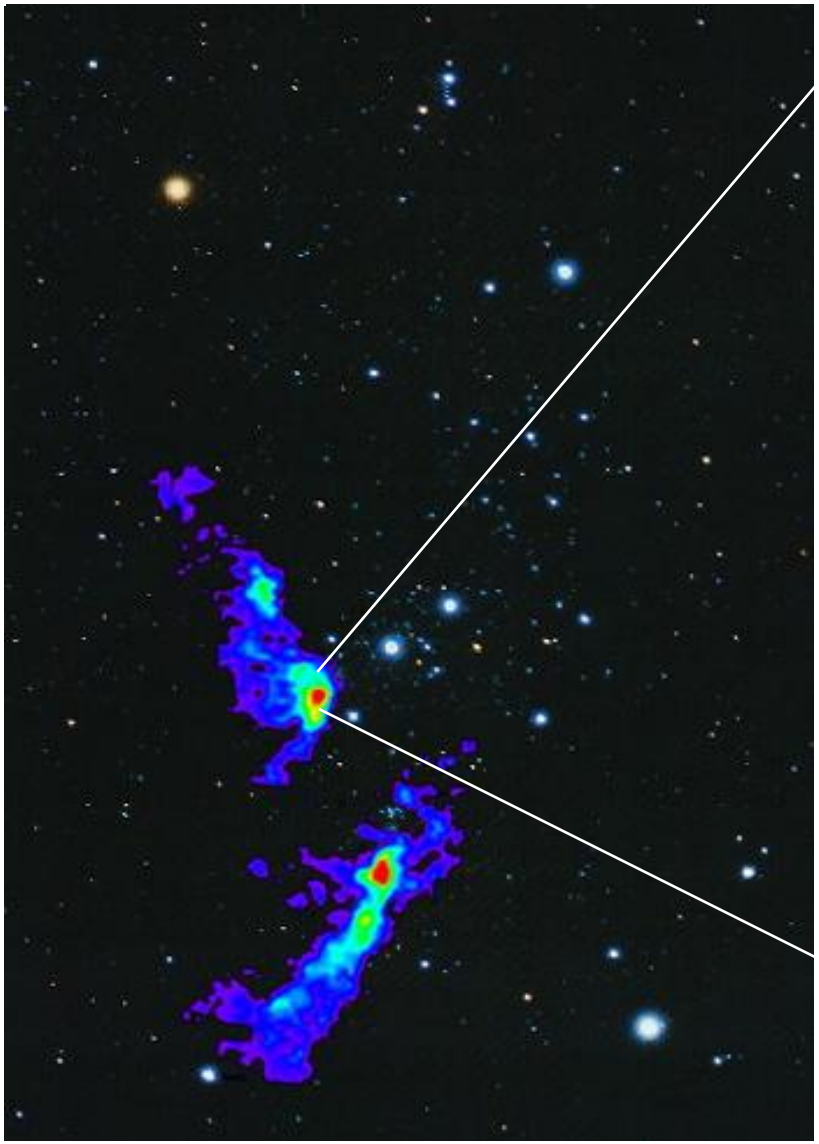
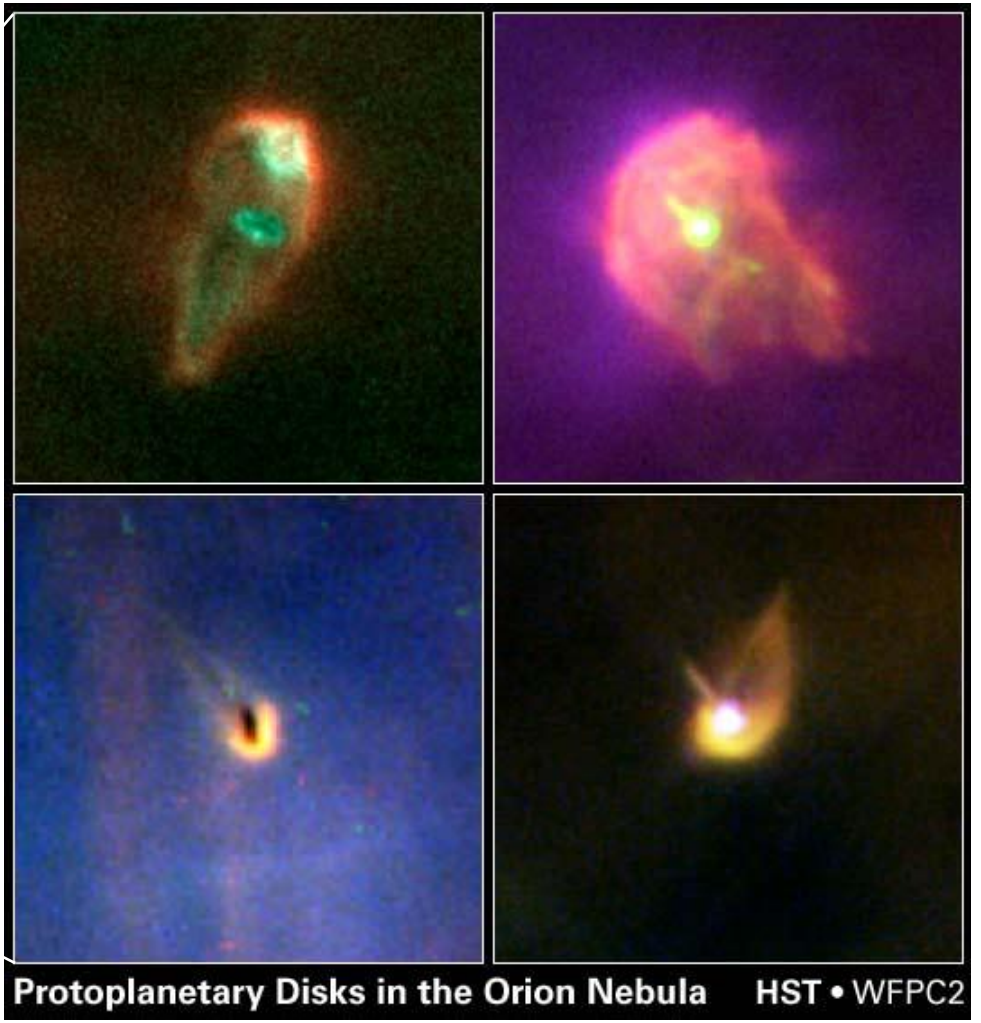
Accumulation of Envelopes of Gas Giant Planets

Masahiro IKOMA

(Tokyo Institute of Technology, Japan)

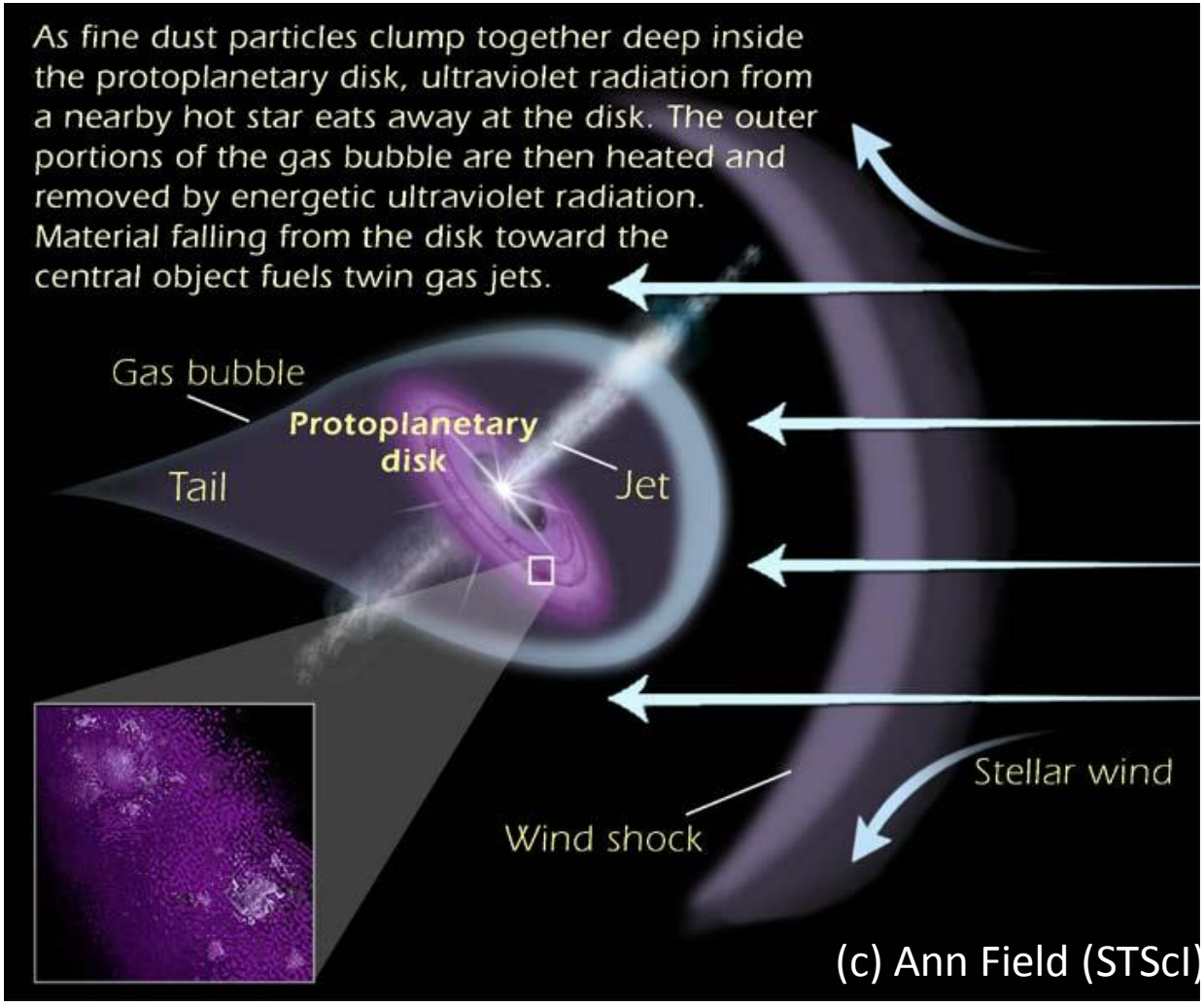
Birth of Stars and Planets





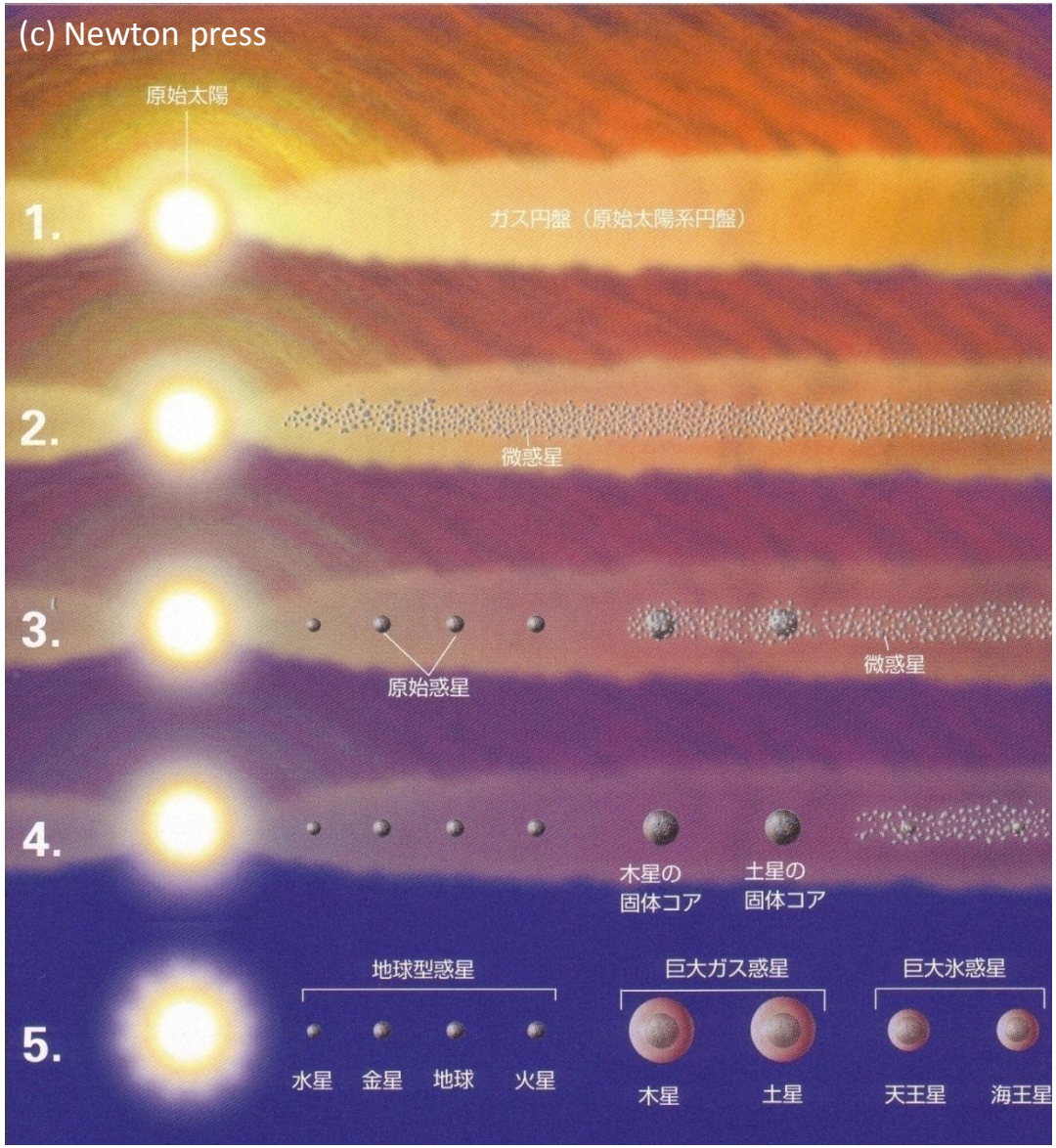
Circumstellar “Protoplanetary Disks”





Standard Picture of Solar-System Formation

Hayashi et al. (1985)



protoplanetary disk

agglomeration of dust grains

planetesimals

coalescence of planetesimals

planetary embryos

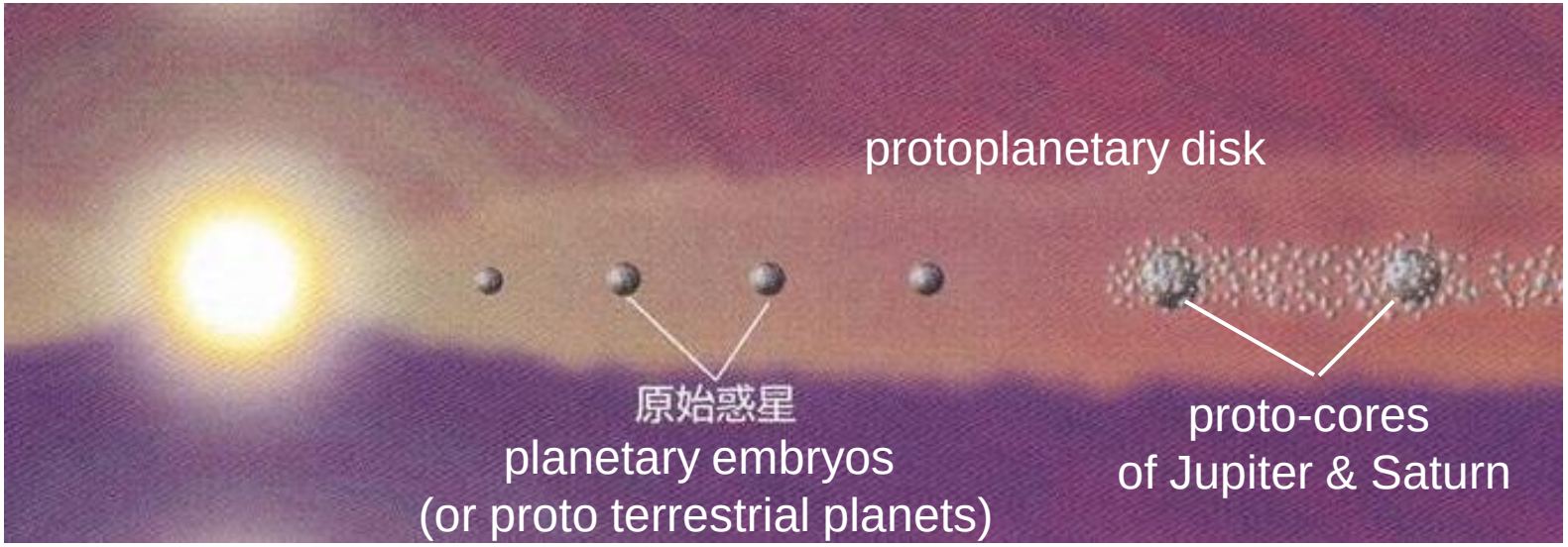
further bombardment of planetesimals
and/or giant impacts between embryos

terrestrial planets
+ gas giants' cores

disk-gas capture
dissipation of the disk gas

present Solar System

Protoplanets Embedded in a Protoplanetary Disk



Today's topic:

What happens on a protoplanet embedded in a protoplanetary disk?

… related to issues about

- **Formation of gas giant planets**
- Origin of the atmospheres and oceans of terrestrial planets

Outline

- Properties of the atmospheres of protoplanets embedded in the protoplanetary disks
- Onset of runaway gas accretion and critical core mass
- Application to the formation of Jupiter and extrasolar gas giant planets



Properties of the atmosphere

Sensitivities of atmospheric mass to several quantities

Two characteristic radii

Bondi radius

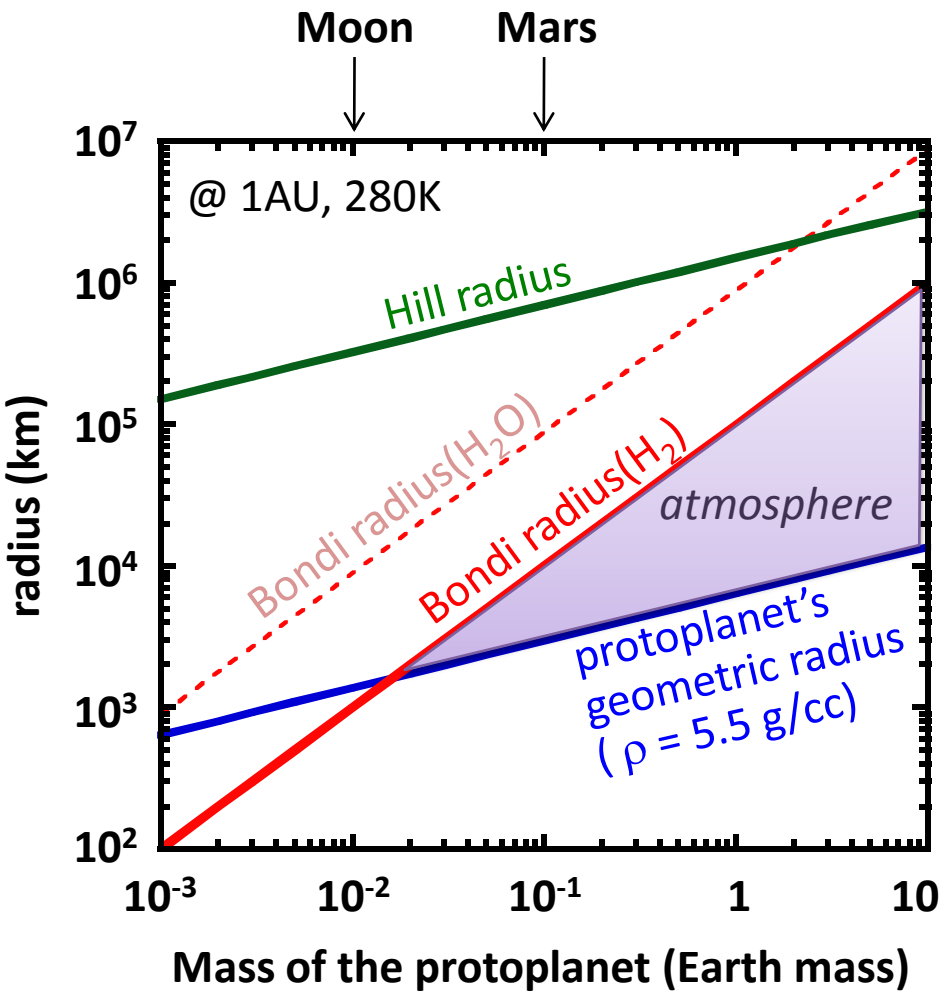
The planet's gravity dominates gas' thermal motion.

$$R_{\mathrm{B}} \approx \frac{GM_p \mu m_{\mathrm{H}}}{kT}$$

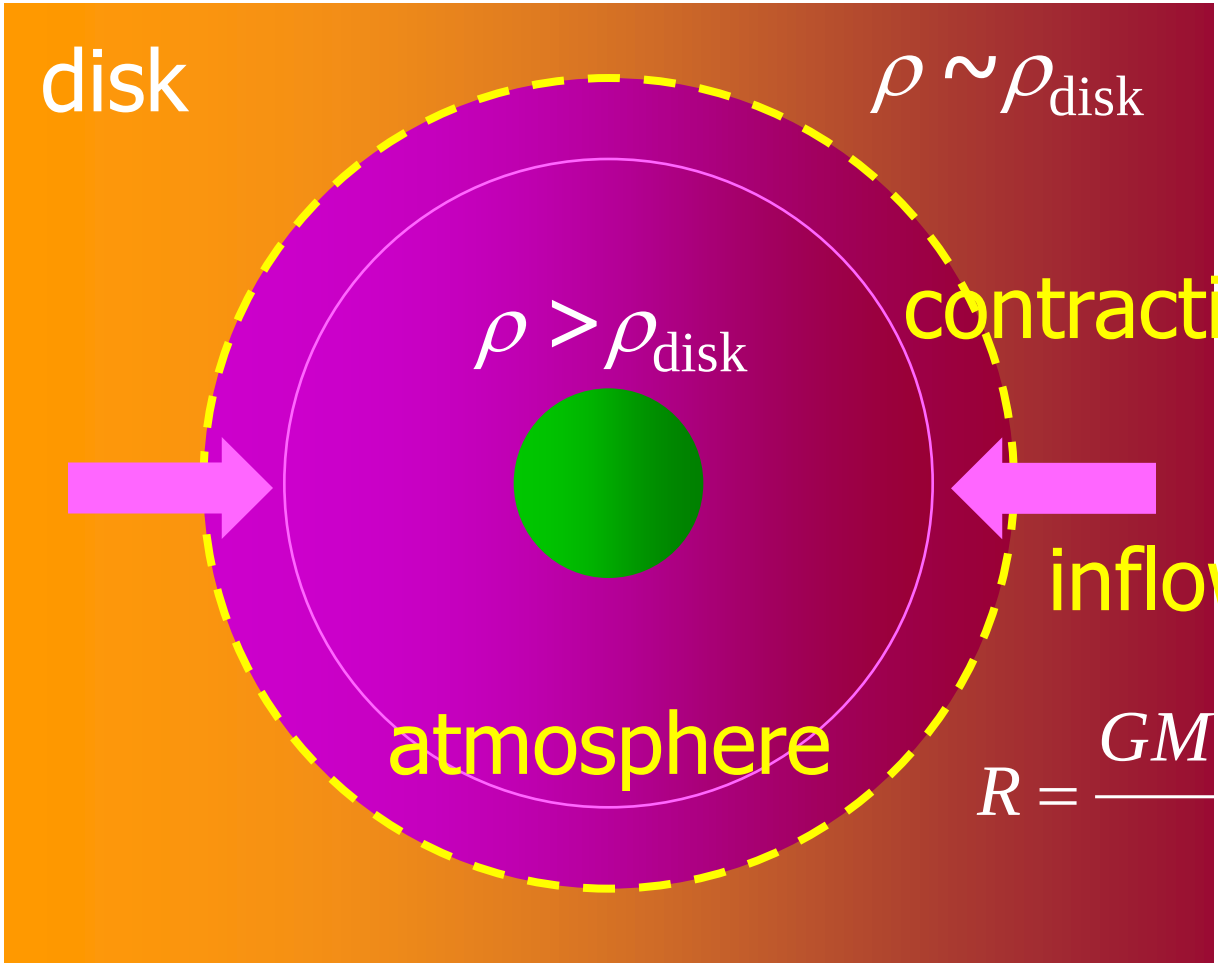
Hill radius

The planet's gravity dominates the central star's gravity.

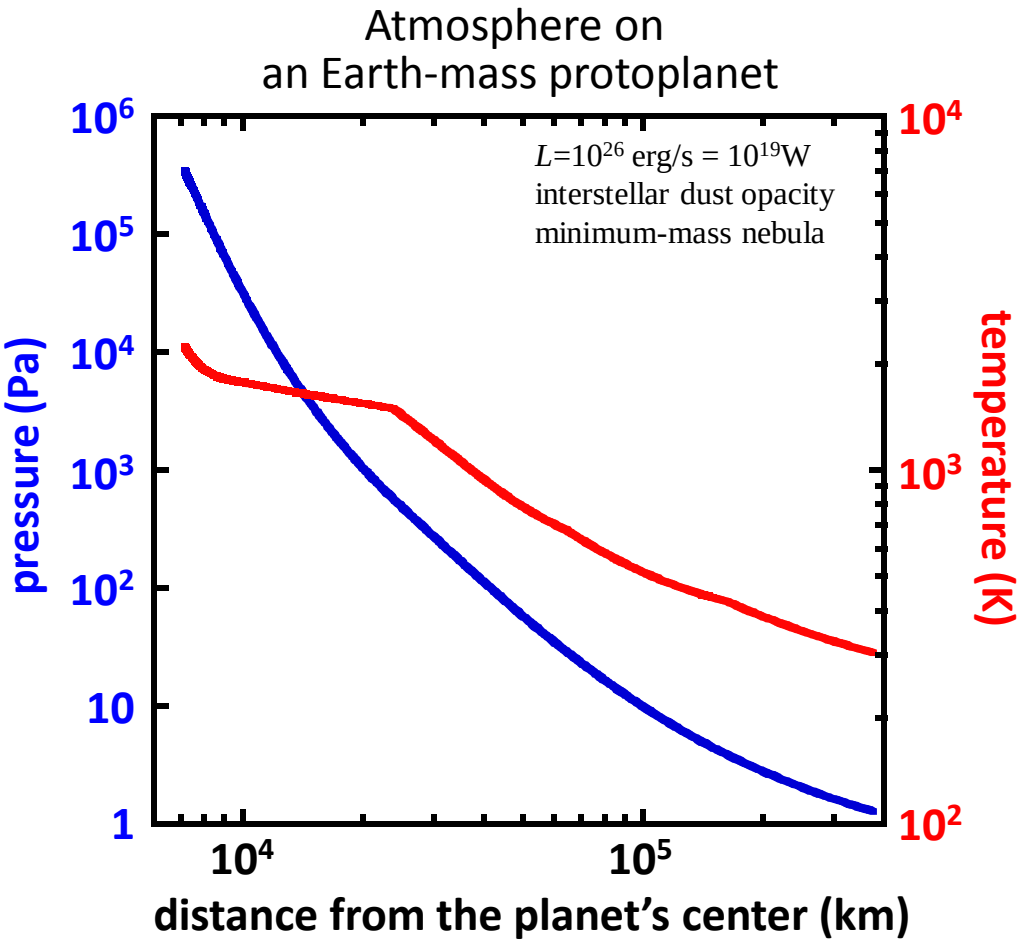
$$R_{\mathrm{H}} \approx \left(\frac{M_p}{M_*} \right)^{1/3} a$$



Accumulation of the Atmosphere: Concept



Typical Structure of the Atmosphere

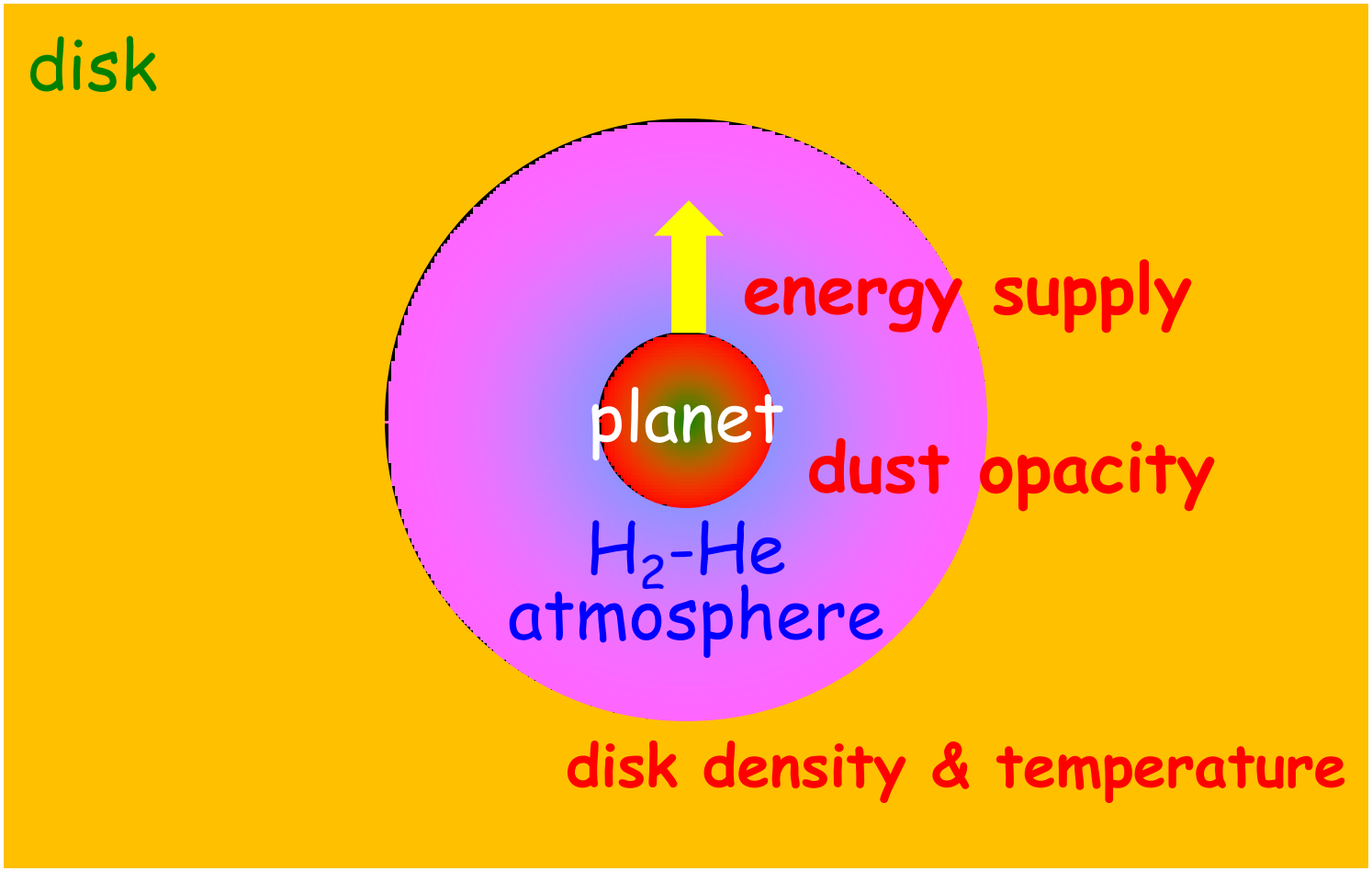


- Pressure and temperature become higher toward the surface of the planet.
- **High temperature at the bottom** due to the strong blanketing effects
- **Extended structure** due to high temperature and low molecular weight

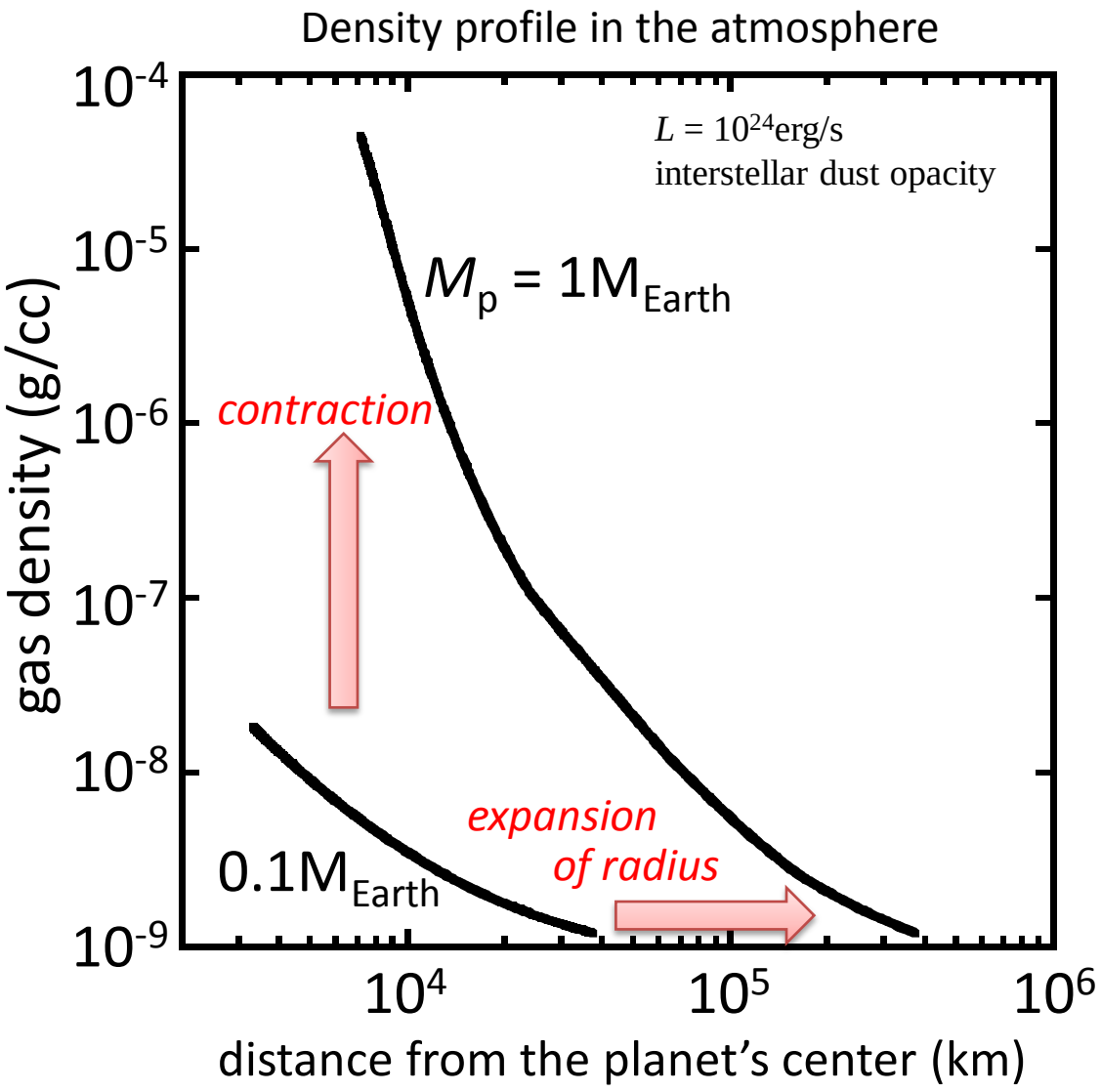
… scale-height: $H \equiv \frac{kT}{\mu m_{\mathrm{H}}} \frac{1}{\mathrm{g}}$

cf. H ~ 10km for current atmosphere

Parameters for Atmospheric Structure

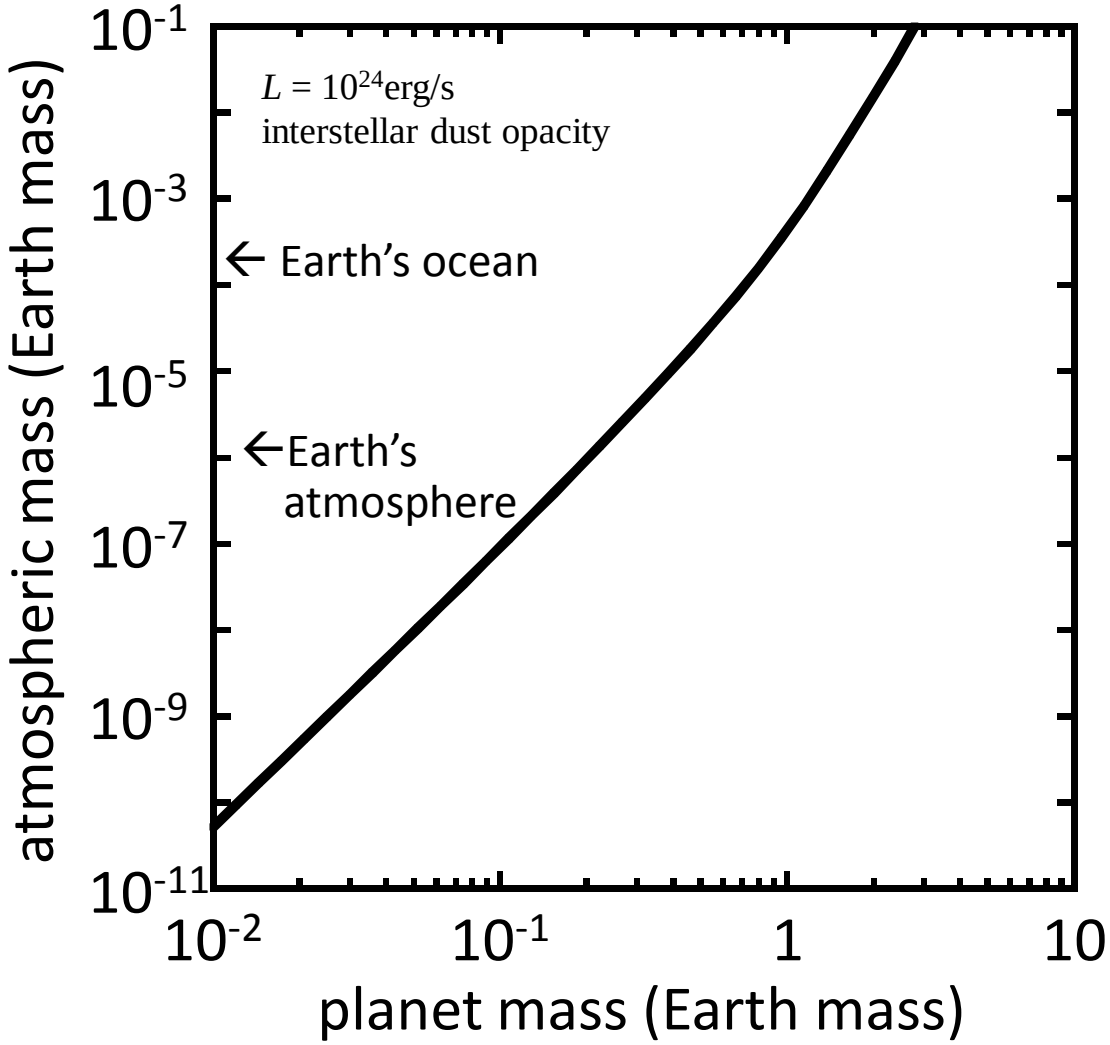


Atmospheric Mass: Sensitivity to Planet's Mass



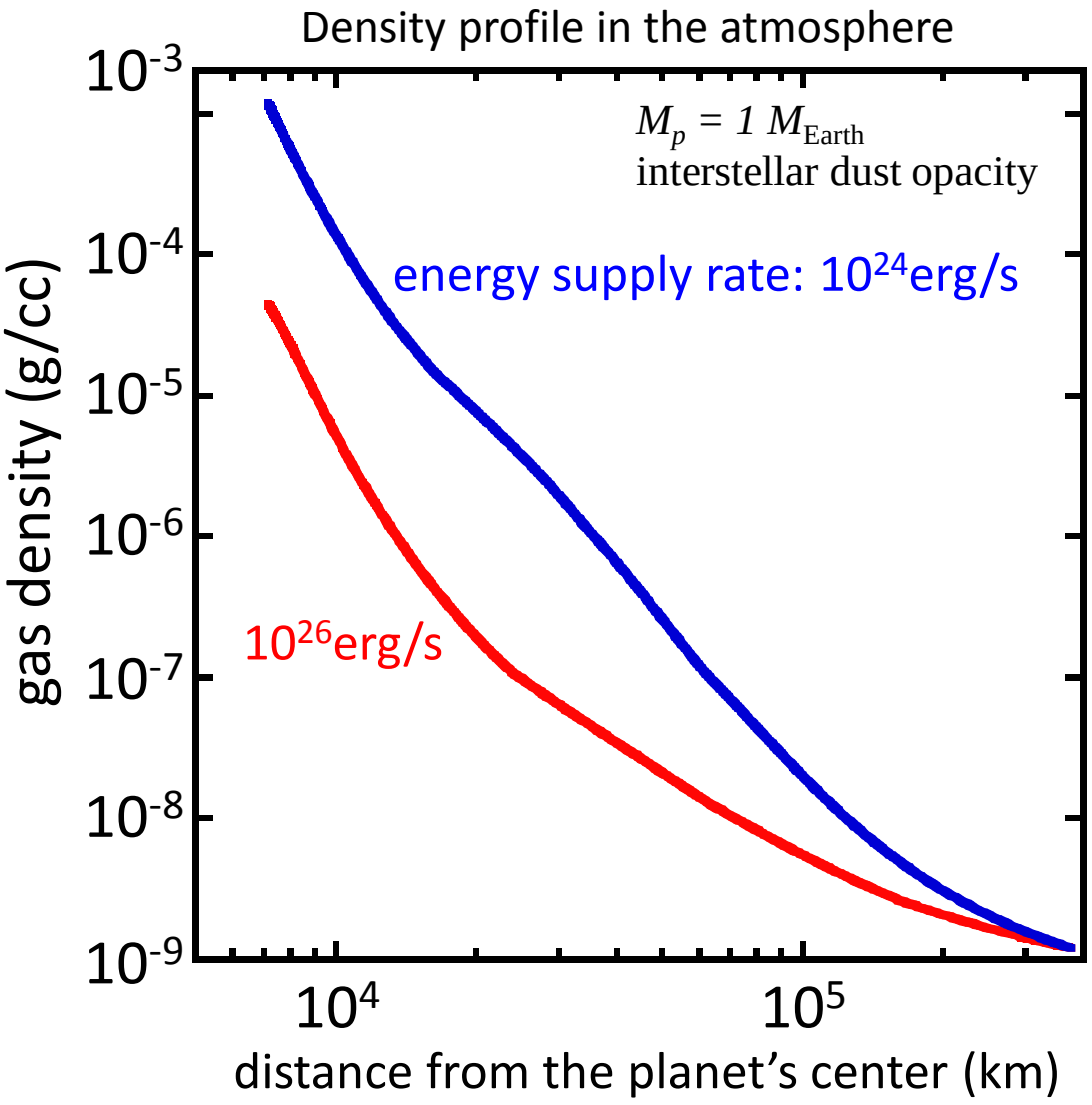
- Gas density becomes higher toward the surface of the planet
- The atmospheric mass increases with planet mass for two reasons:
  - (1) The outer radius (Bondi or Hill radius) expands, because of increases in planet's mass.
  - (2) The atmosphere contracts because of enhancement of gravity, which results in an increase in density.

Atmospheric Mass: Sensitivity to Planet's Mass



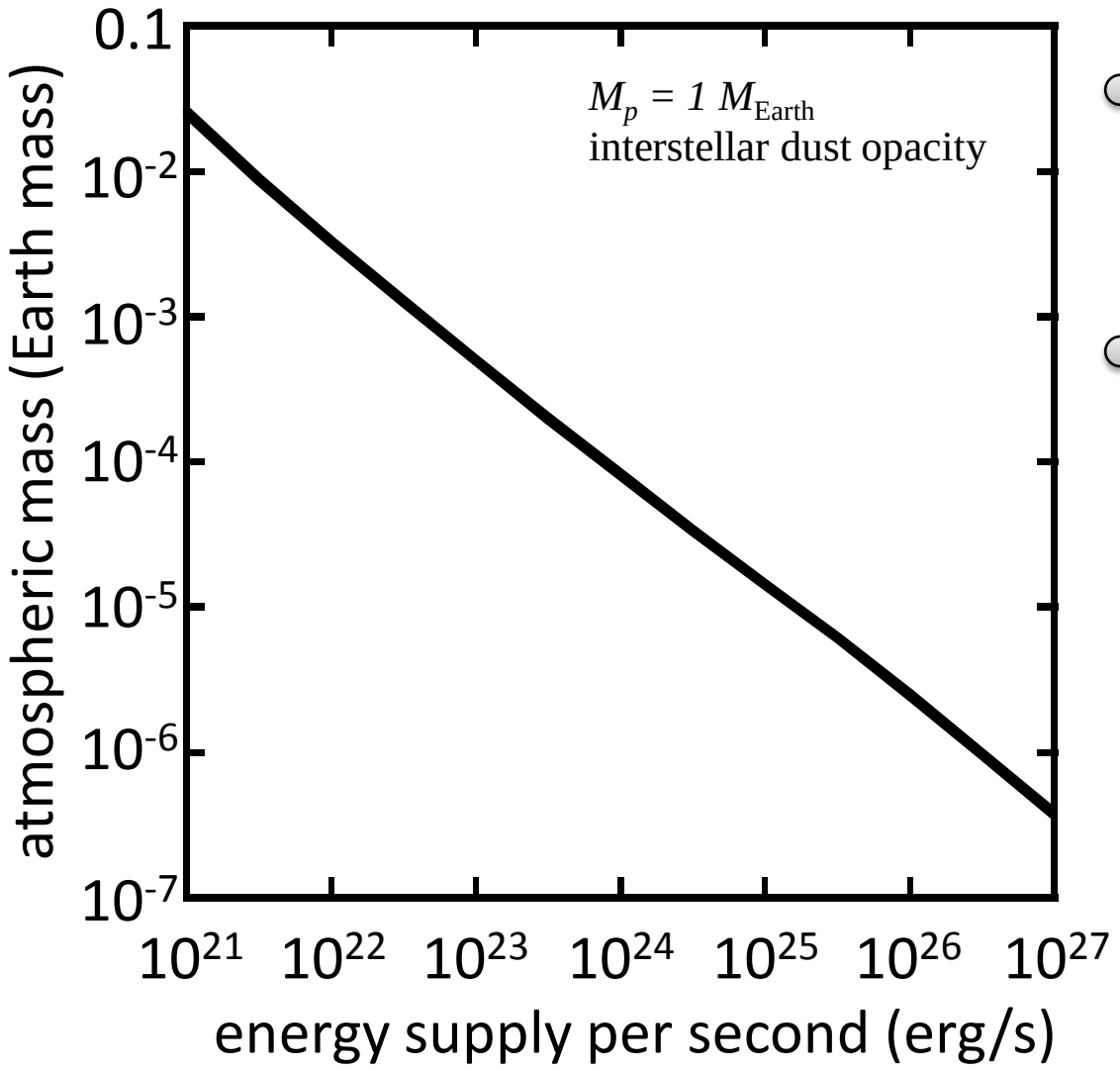
- **The atmospheric mass depends strongly on the planet mass**: the former increases by more than 3 order of magnitude, as the latter increases by a factor of 10.

Atmospheric Mass: Sensitivity to Energy Supply



- A large energy supply pushes the atmosphere outward. The atmosphere becomes tenuous as the amount of energy supply increases.

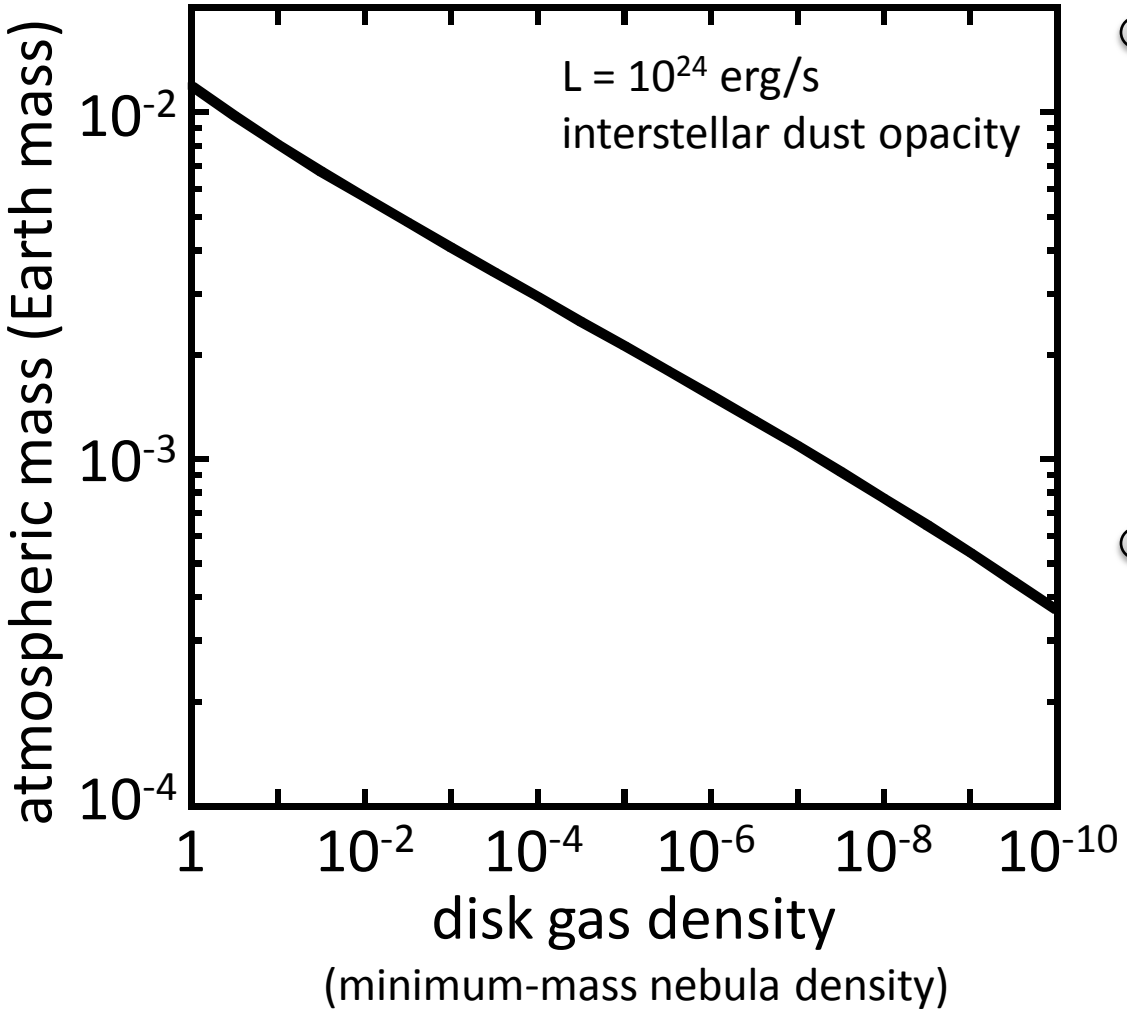
Atmospheric Mass: Sensitivity to Energy Supply



- Atmospheric mass increases almost linearly with decreasing energy supply rate.
- The sensitivity to opacity is almost the same, because *L* and κ appear in the equation in the form of κL:

$$\frac{dT}{dr} = -\frac{3\rho}{16\pi acr^2T^3}\kappa L$$

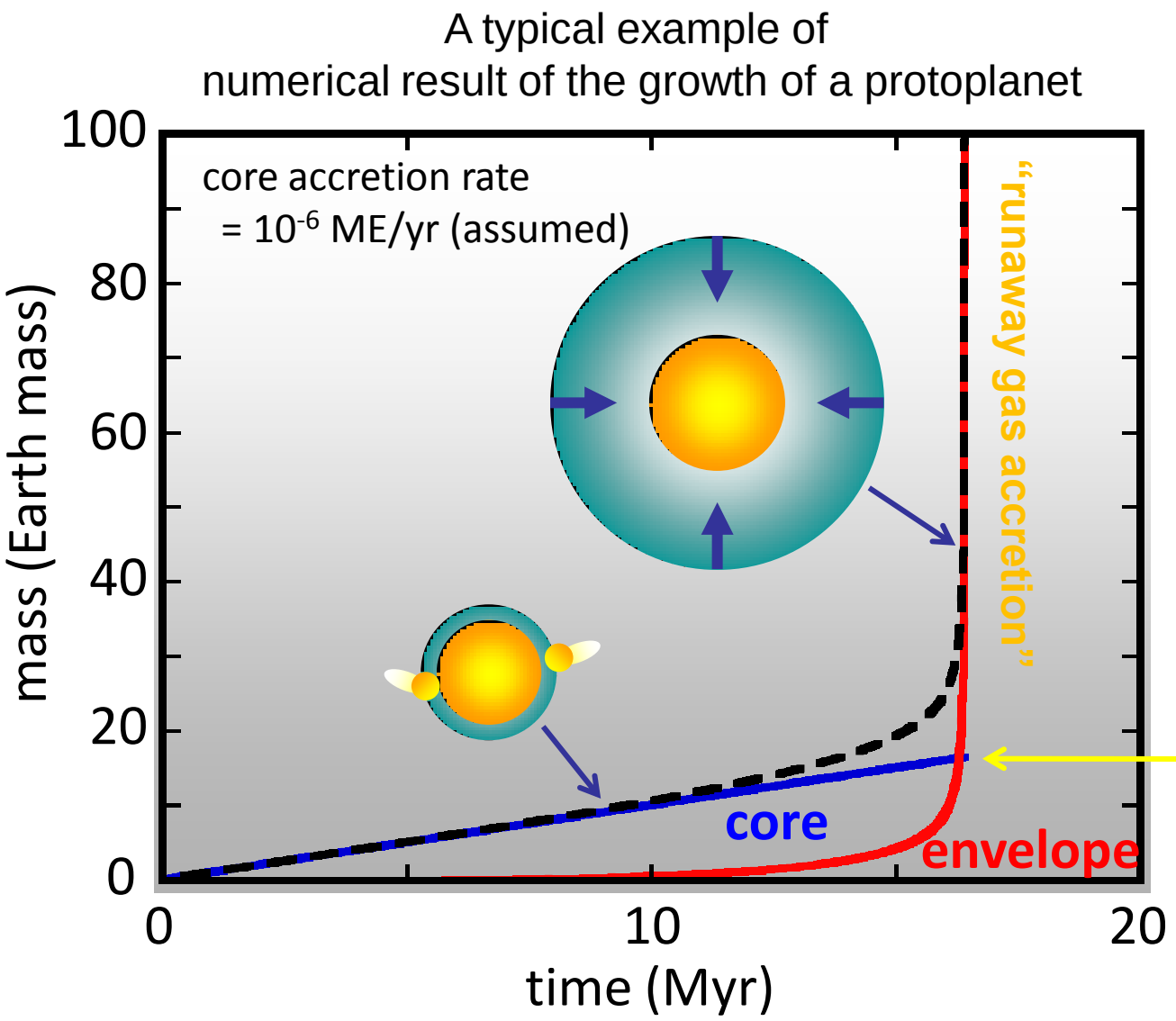
Atmospheric mass: Sensitivity to Disk-gas Density



- The atmospheric mass depends **very weakly on the disk-gas density**—A 10-order-of-magnitude decrease in disk-gas density yields only a decrease in the atmospheric mass by a factor of 100.
- However, this is not the case in cases of disk-gas densities high enough to make the atmosphere wholly convective (Ikoma et al. 2001).

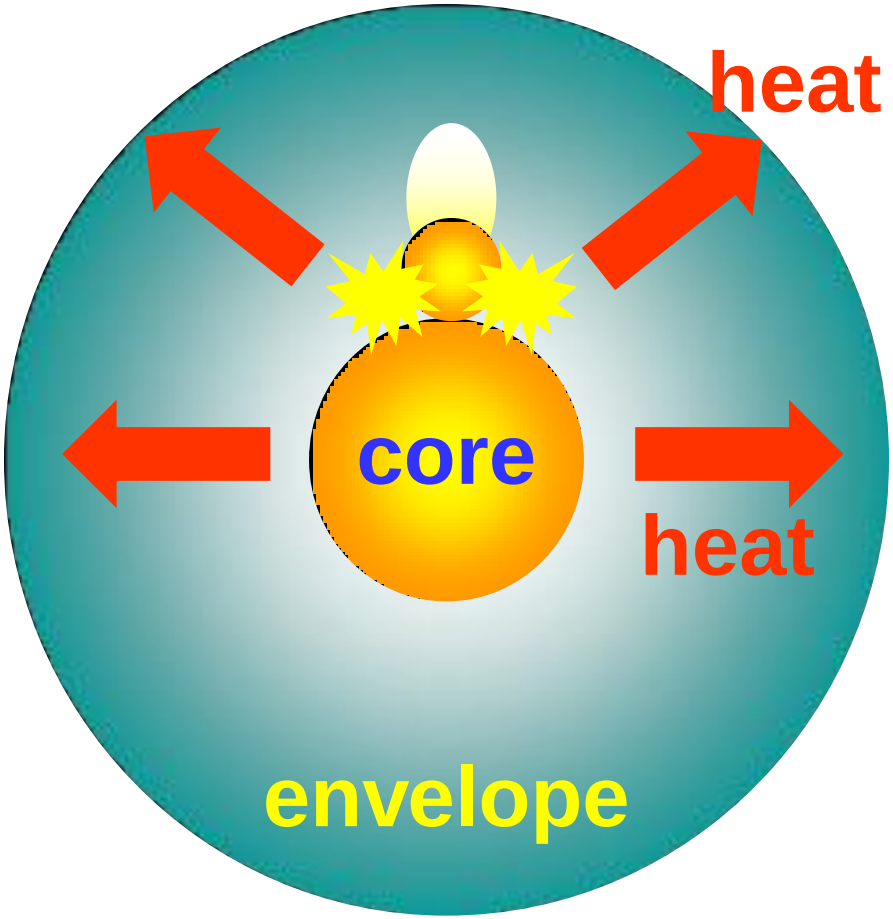
Onset of Runaway Gas Accretion and Critical Core Mass

Accumulation of Gas Giant's Envelope



- Significant accretion of disk gas ("runaway gas accretion") occurs almost suddenly when the core mass reaches a certain critical value.

Energy sources

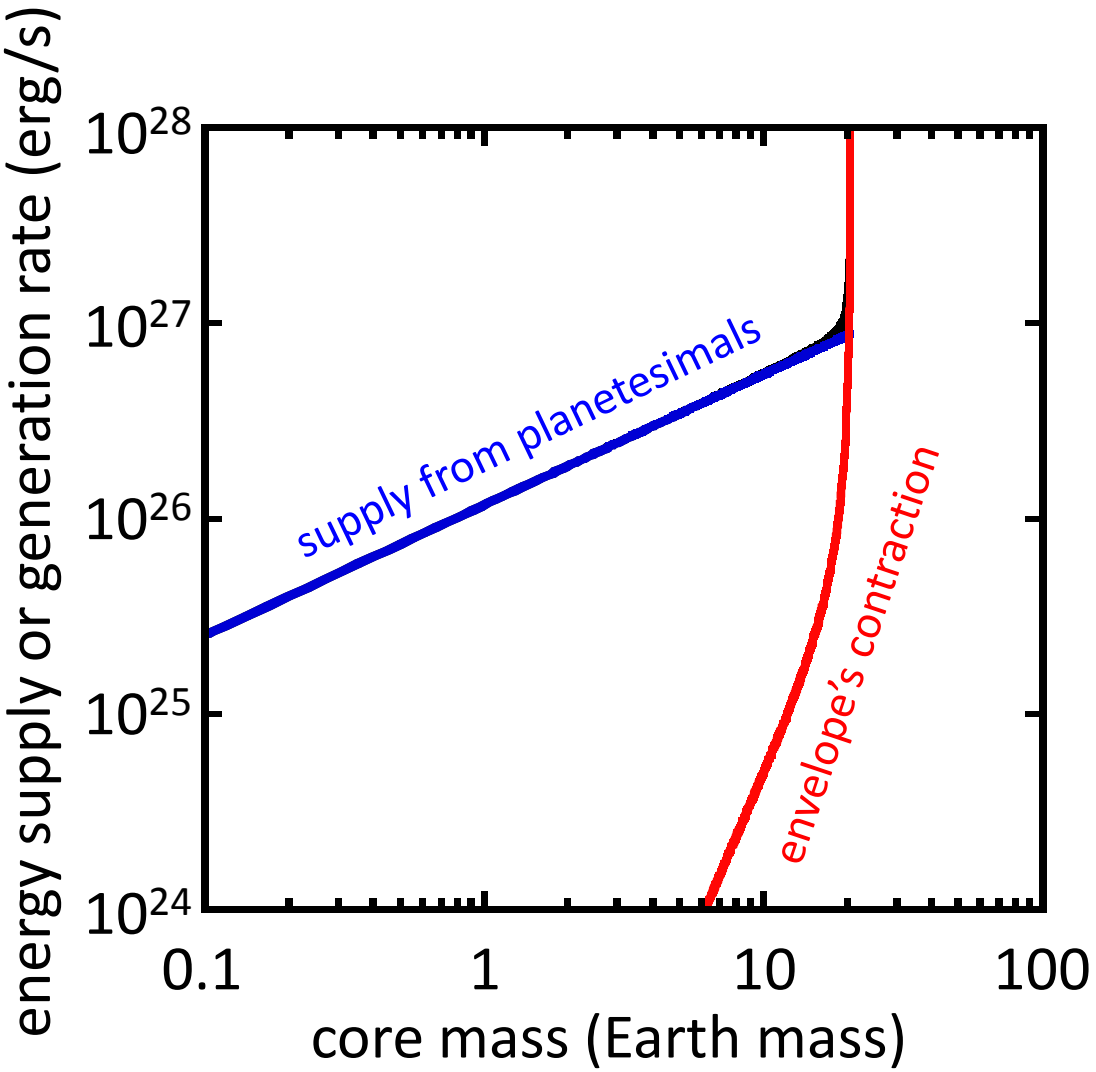


- For hydrostatic structure to be stable, energy must be supplied to the envelope.
- One energy source is the kinetic energy of **incoming planetesimals**.

$$\approx \frac{GM_{\text{core}}}{R_{\text{core}}} \times \dot{M}$$

- Another energy source is the gravitational energy of the envelope itself which is released due to the **contraction of the envelope**.

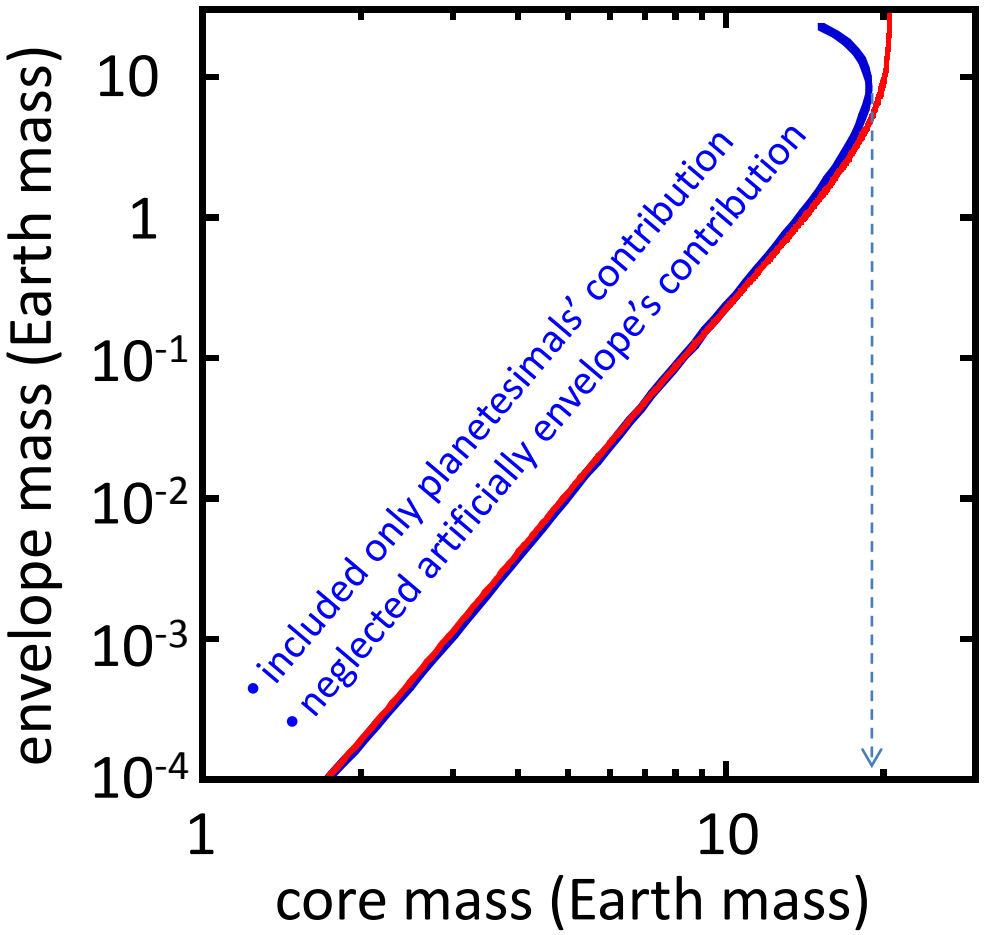
What happens around critical core mass



- When the core mass is small, the amount of supply from planetesimals is much larger than gravitational energy release due to the contraction of the envelope.
- Around the critical core mass, the contribution of the envelope contraction becomes dominant suddenly.

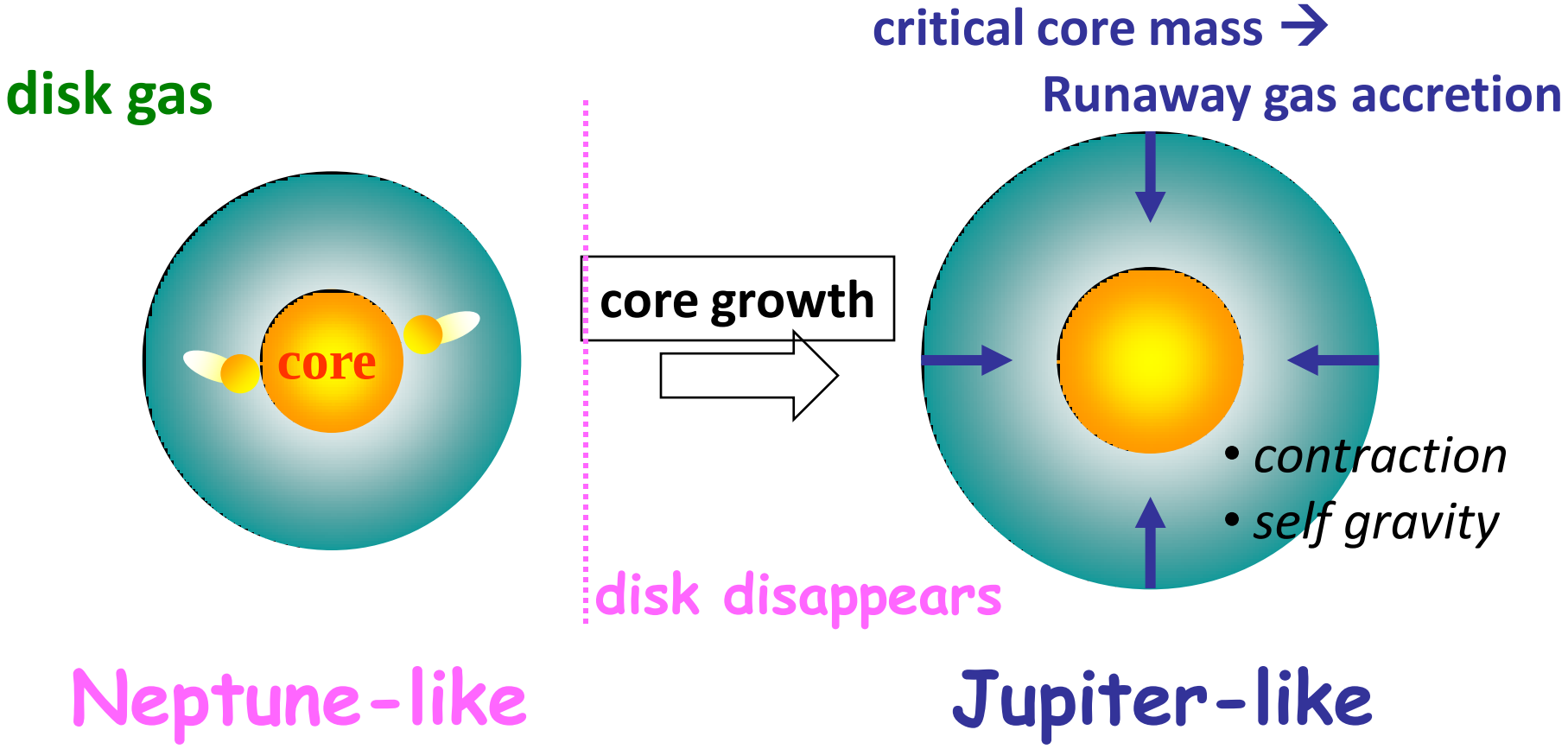
What happens around critical core mass

core-envelope mass relation

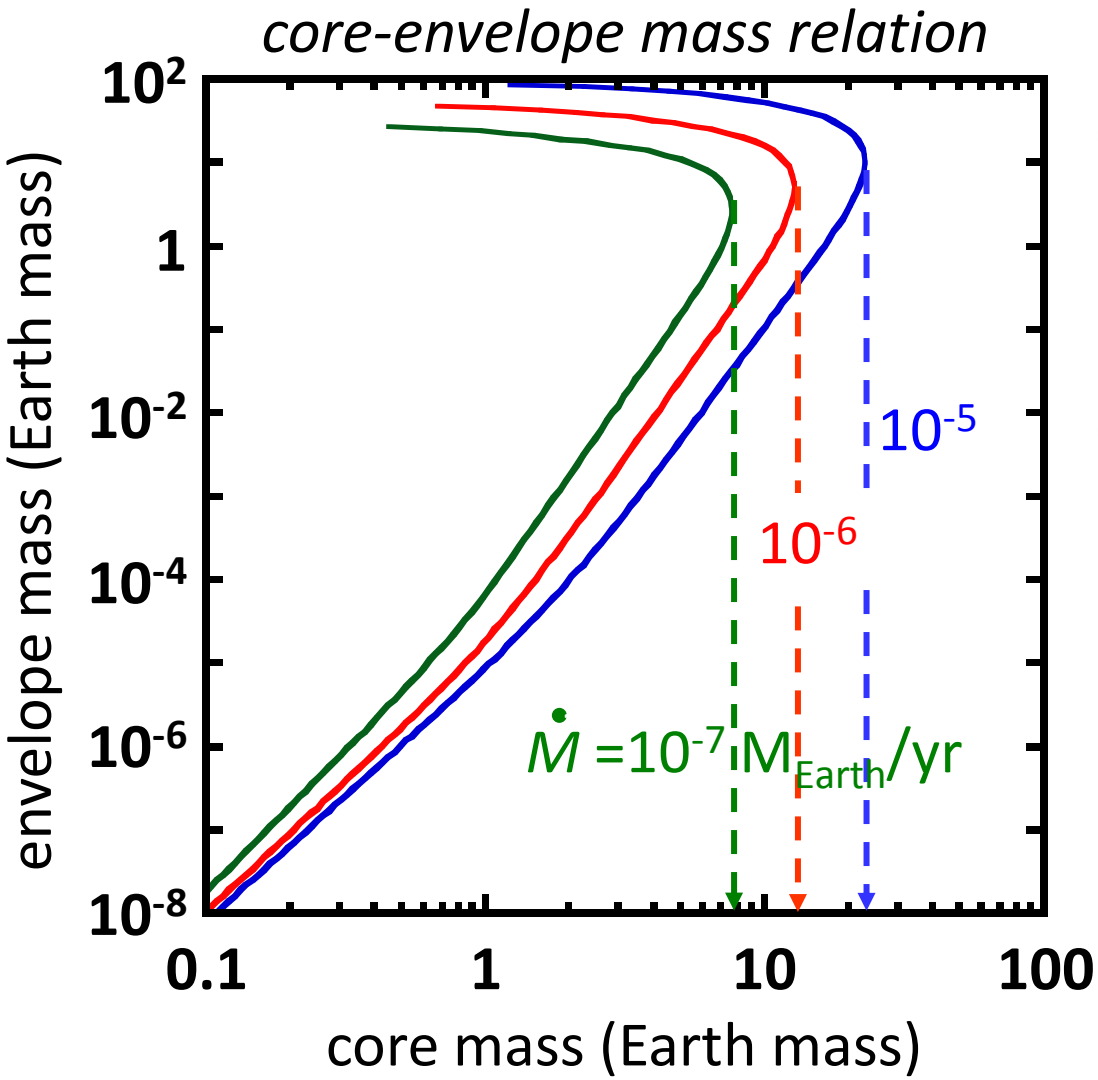


- If you simulate the structure of the envelope by neglecting energy generation due to envelope contraction artificially, you find a maximum value of the core mass beyond which no purely hydrostatic solution exists (blue curve). This is the mathematical definition of the critical core mass.

Formation of a gas giant

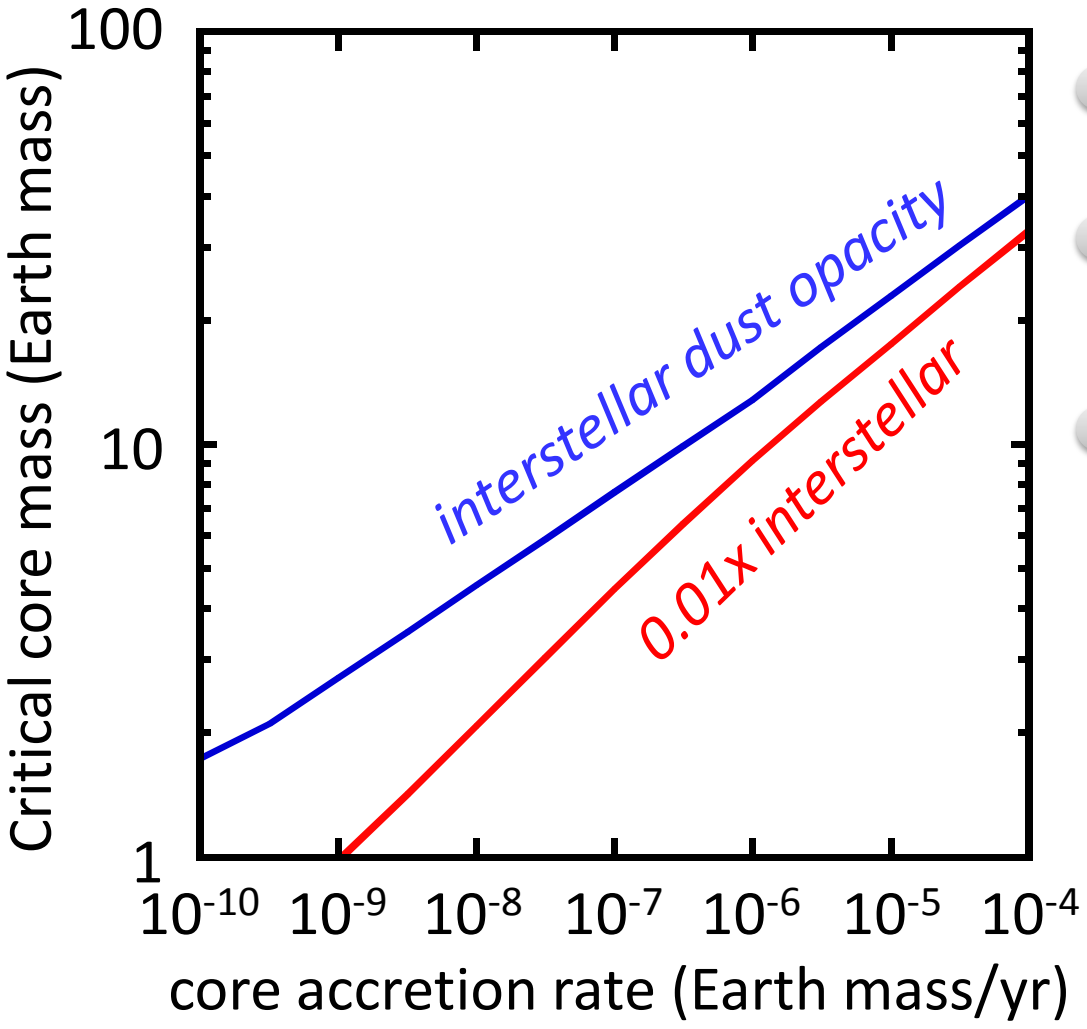


Critical core mass: sensitivity to core accretion rate



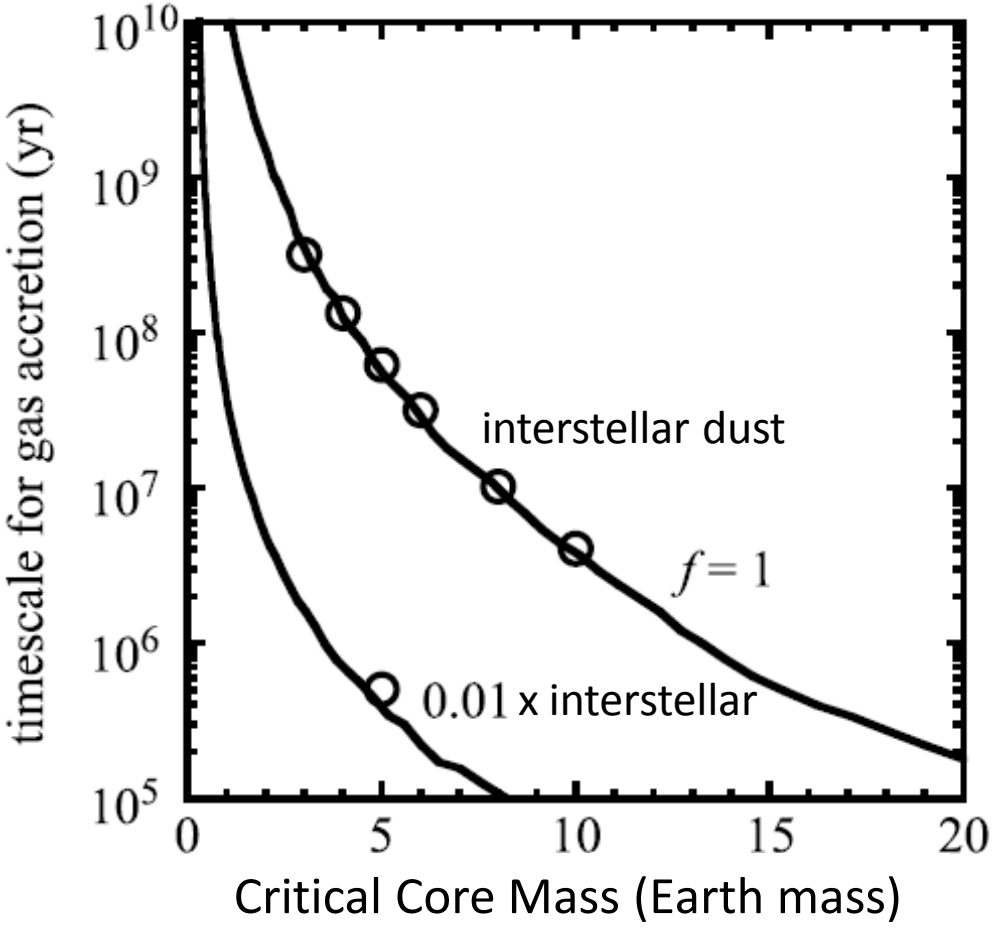
- At a given core mass, the envelope mass decreases as the core accretion rate increases.
- The critical core mass is larger for higher core accretion rates.

Critical core mass: sensitivity to core accretion rate and grain opacity



- Critical core mass increases with core accretion rate.
- Critical core mass increases with grain opacity.
- However, the dependences are rather weak.

Growth Timescale after Critical Core Mass



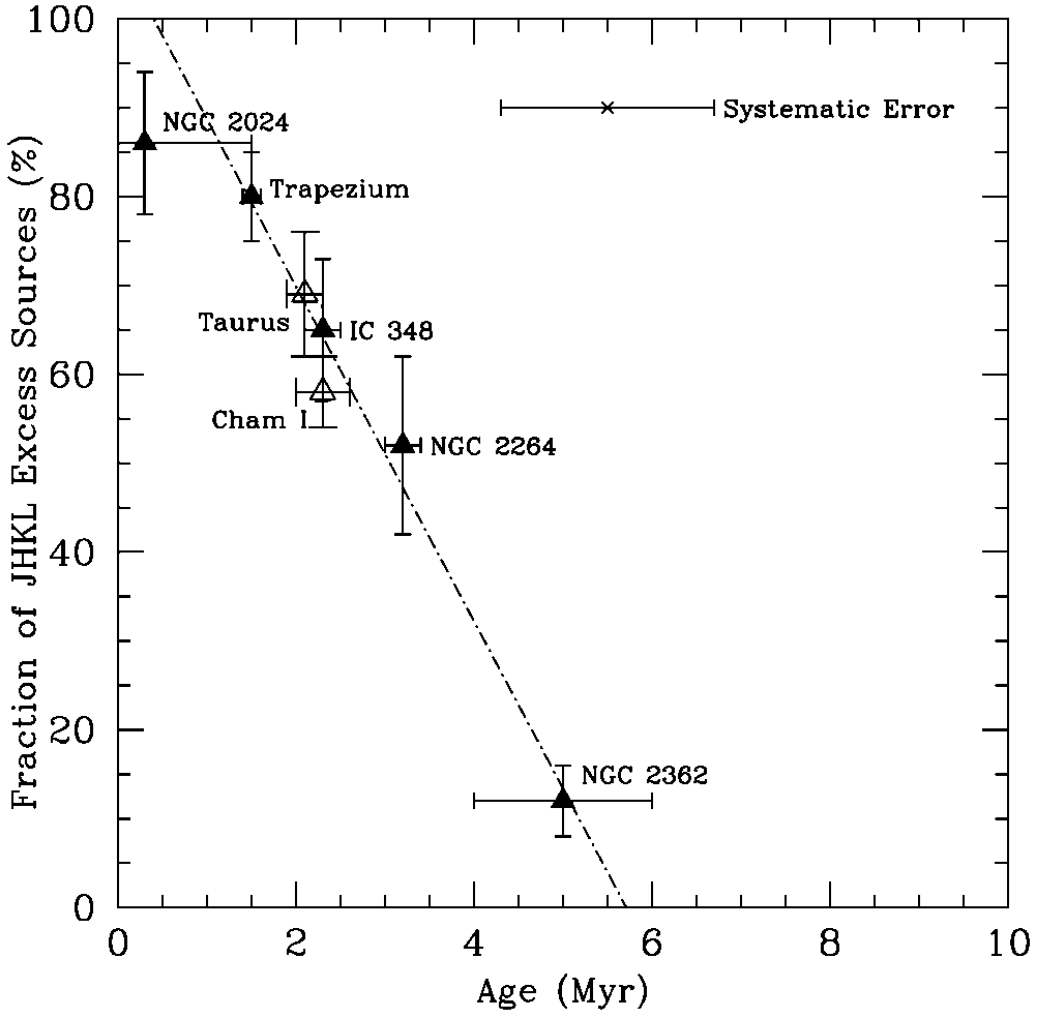
Ikoma & Genda (2006)

- The times required for the core to capture a significant amount of disk gas are longer for smaller critical core masses.
- The dependence is quite strong: $\log t \propto -3.5 \log M_c$.

Application to the Formation of Gas Giant Planets

Jupiter and extrasolar planets

Constraints on gas giant formation: Disk's lifetime

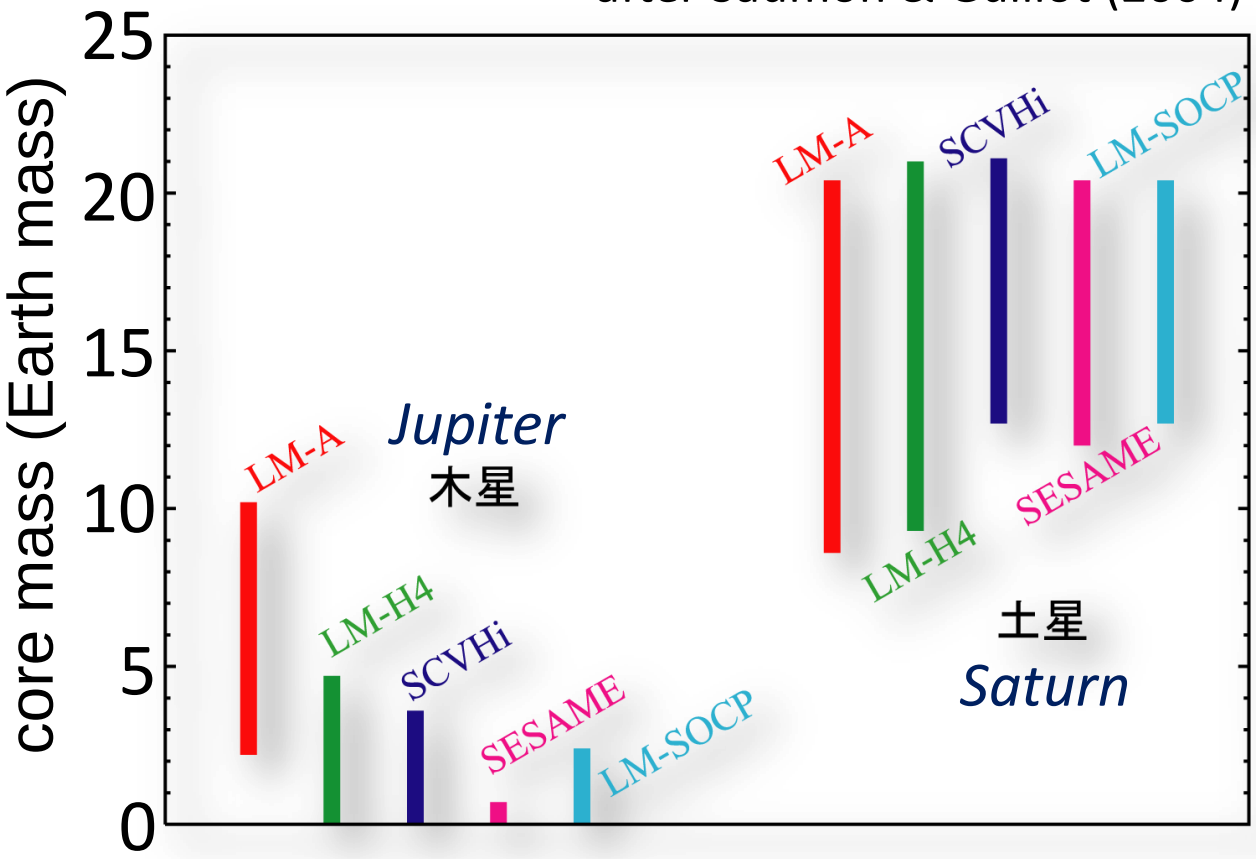


Haisch et al. (2001)

- Infrared observations of young stars suggest that **disk gas disappears in several million years**
- Gas giants must be formed within the lifetime of disk gas, namely, in several million years.

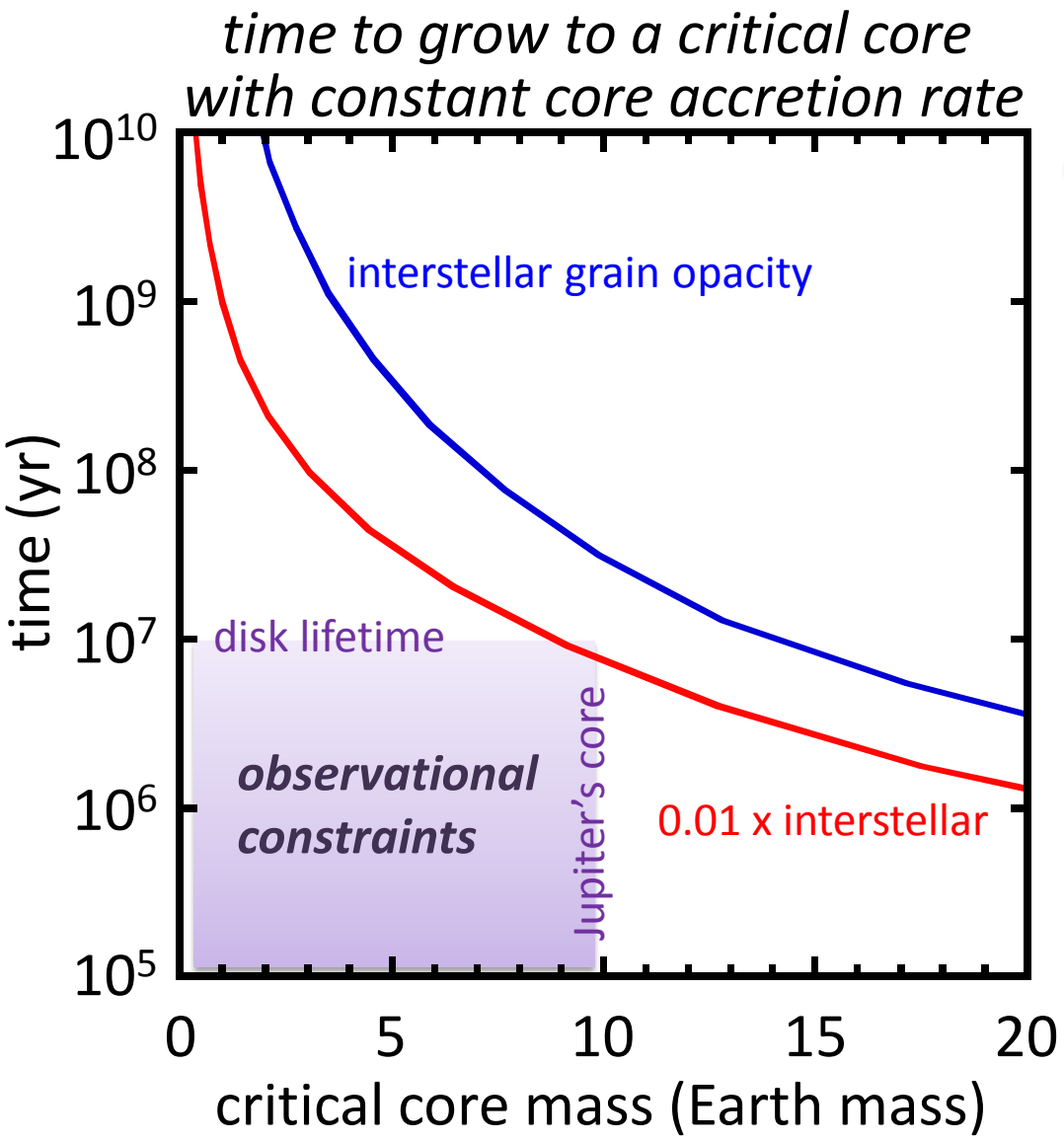
Constraints on gas giant formation: Cores of Jupiter & Saturn

after Saumon & Guillot (2004)



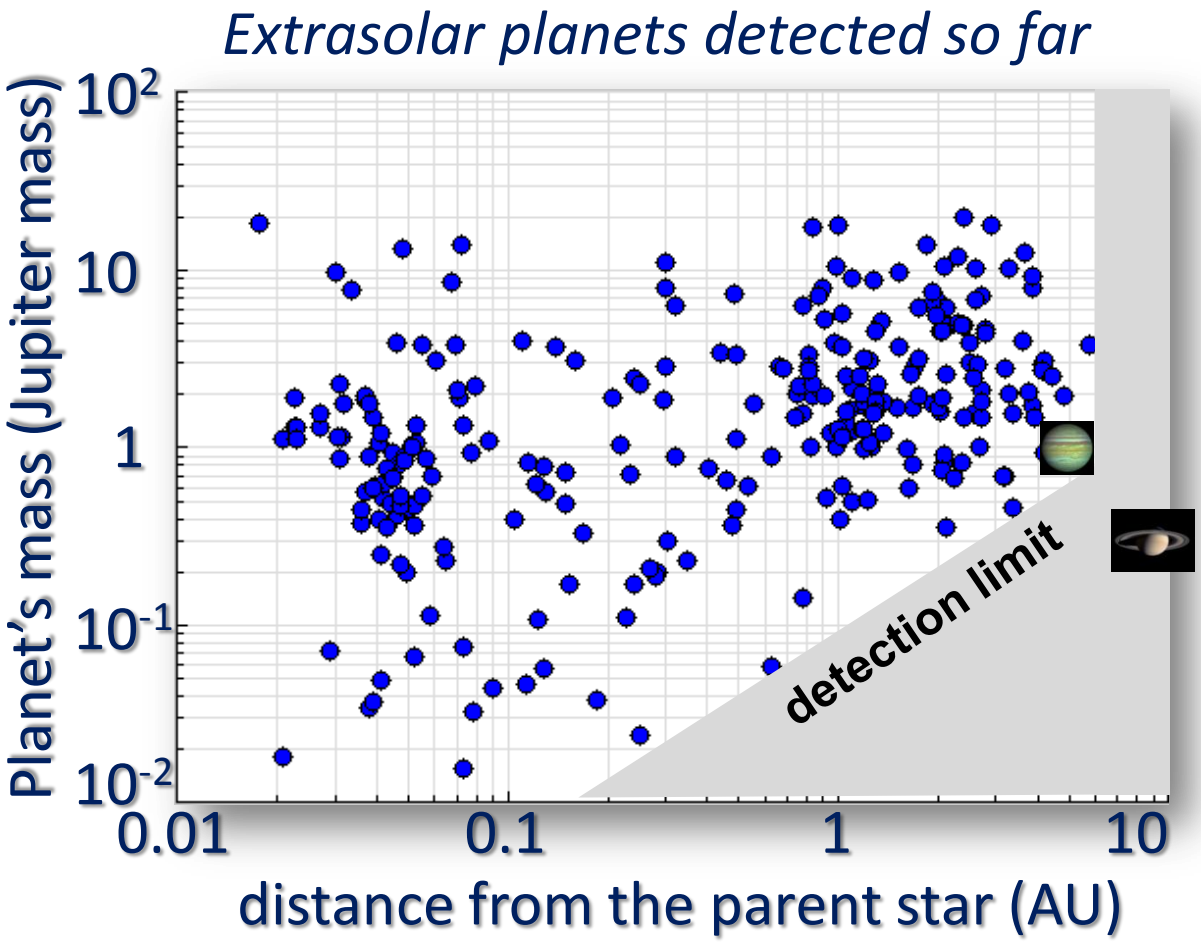
- The interiors of Jupiter & Saturn are inferred by making models that reproduce the values of gravitational moments from observations.
- Recent models suggest the existence of a small core inside Jupiter, less than 10 Earth masses.

Difficulty in Jupiter's Formation



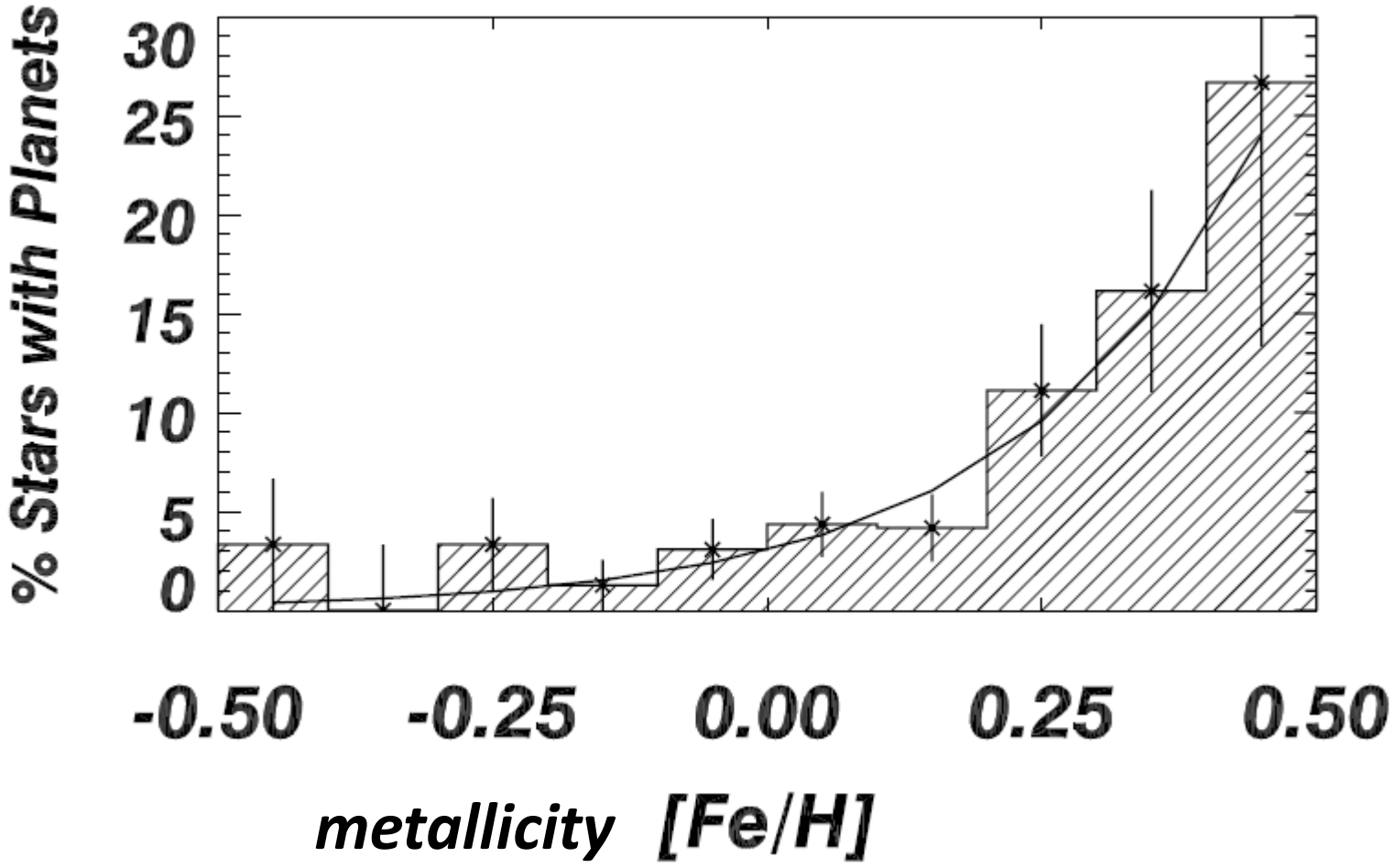
- The time to grow to a critical core decreases with critical core mass, which makes the problem difficult to be solved.

Extrasolar Gas Giants

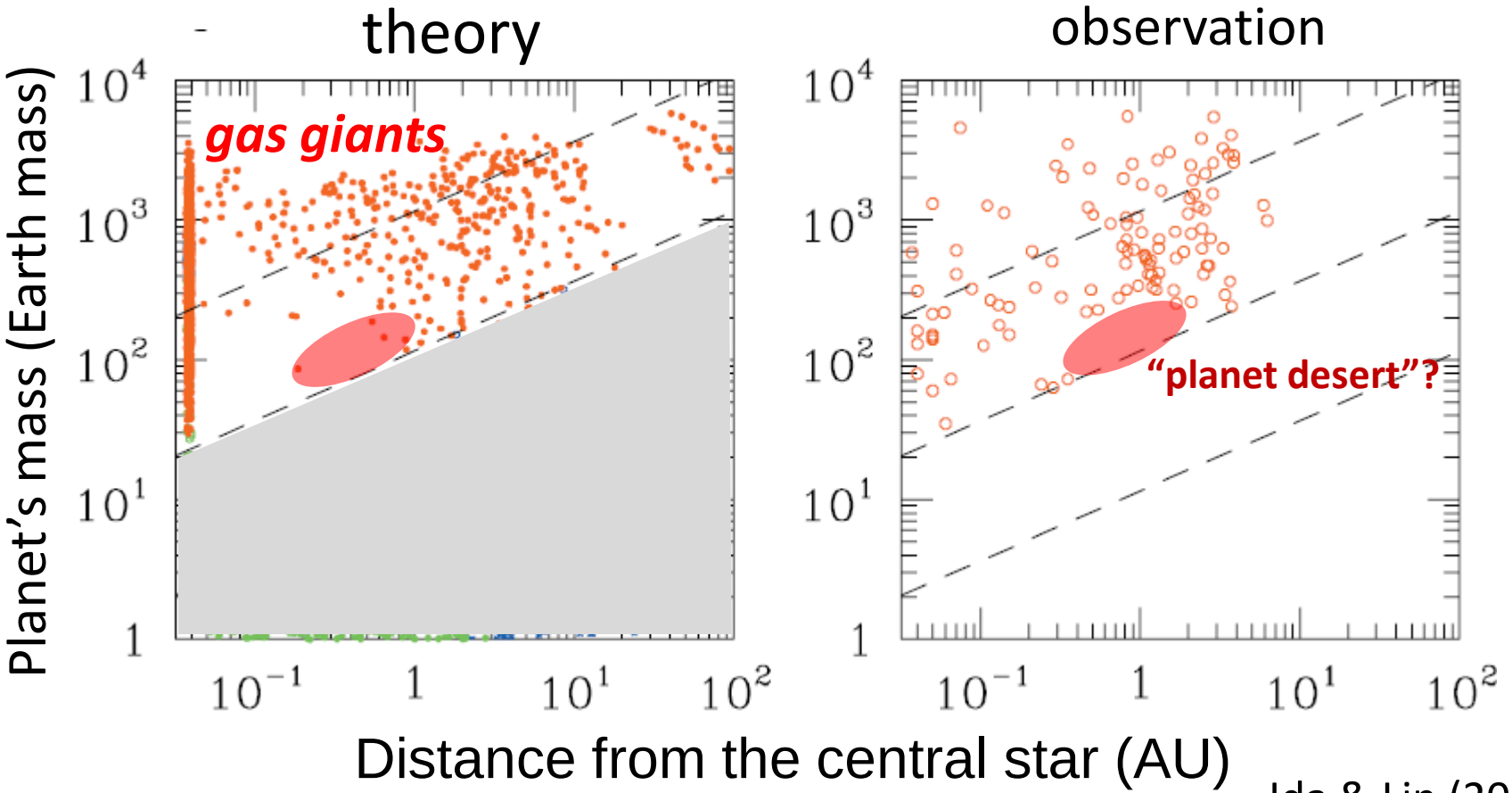


- Plenty of gas giants have been detected around other stars.
- The existence of many hot Jupiters indicates that planets migrate toward their parent star. The migration occurs due to the exchange of angular momentum between the planet and the disk.
- The difficulty in forming Jupiter might not be too bad!

Validity of the theory of gas giant formation



Validity of the theory of gas giant formation

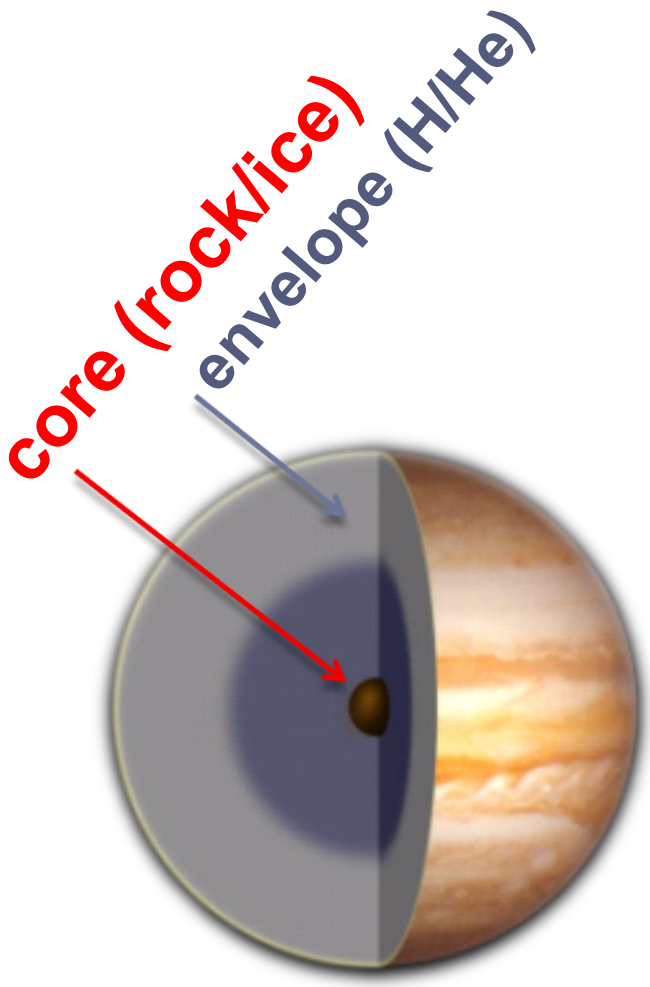


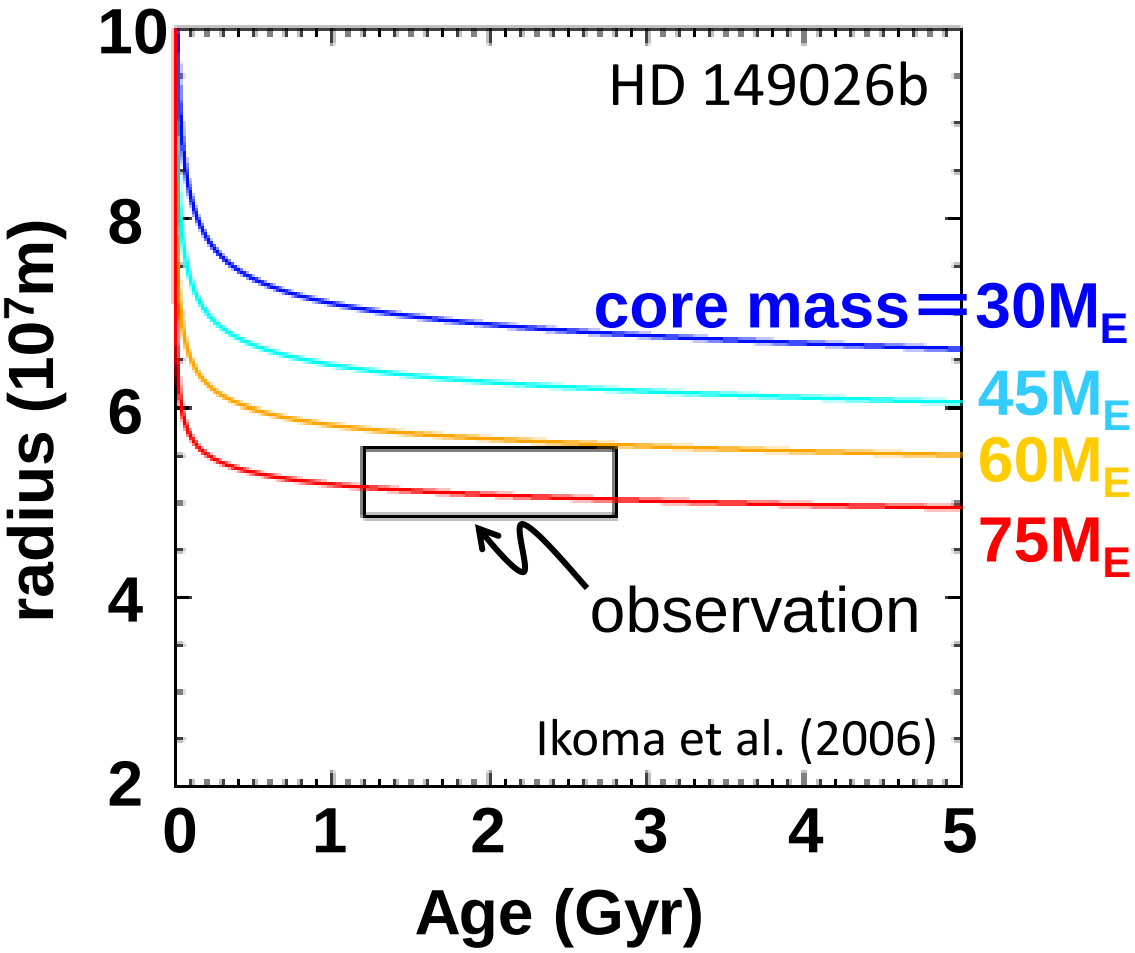
Ida & Lin (2004)

Present theories of planet formation can account for

- **the diversity of planets on the mass-period plane**
- **the existence of a cavity ("planet desert") on that plane (?)**

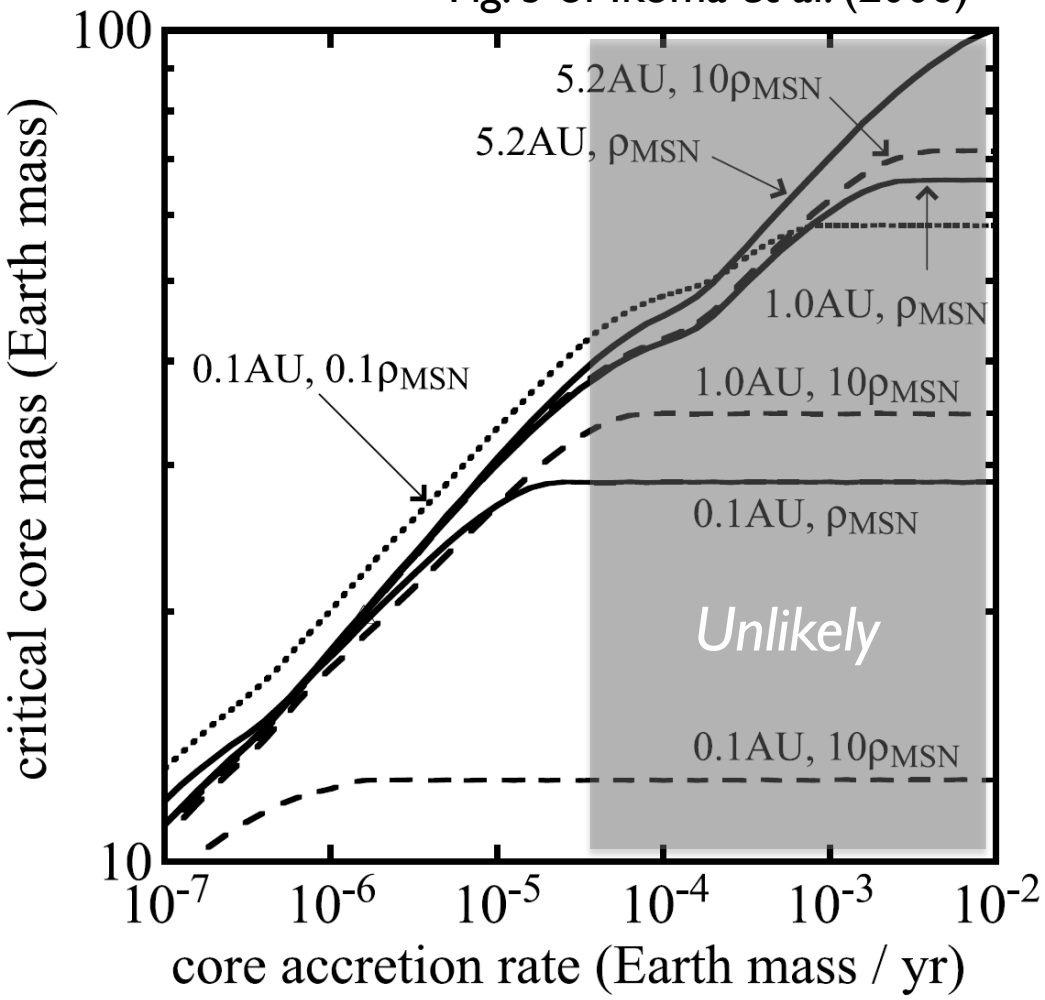
A Huge Core in a Recently Detected Gas Giants





Critical Core Mass

Fig. 3 of Ikoma et al. (2006)



- It is quite hard for such a massive core to be formed without starting runaway gas accretion.

Diversity of Planetary Metallicity

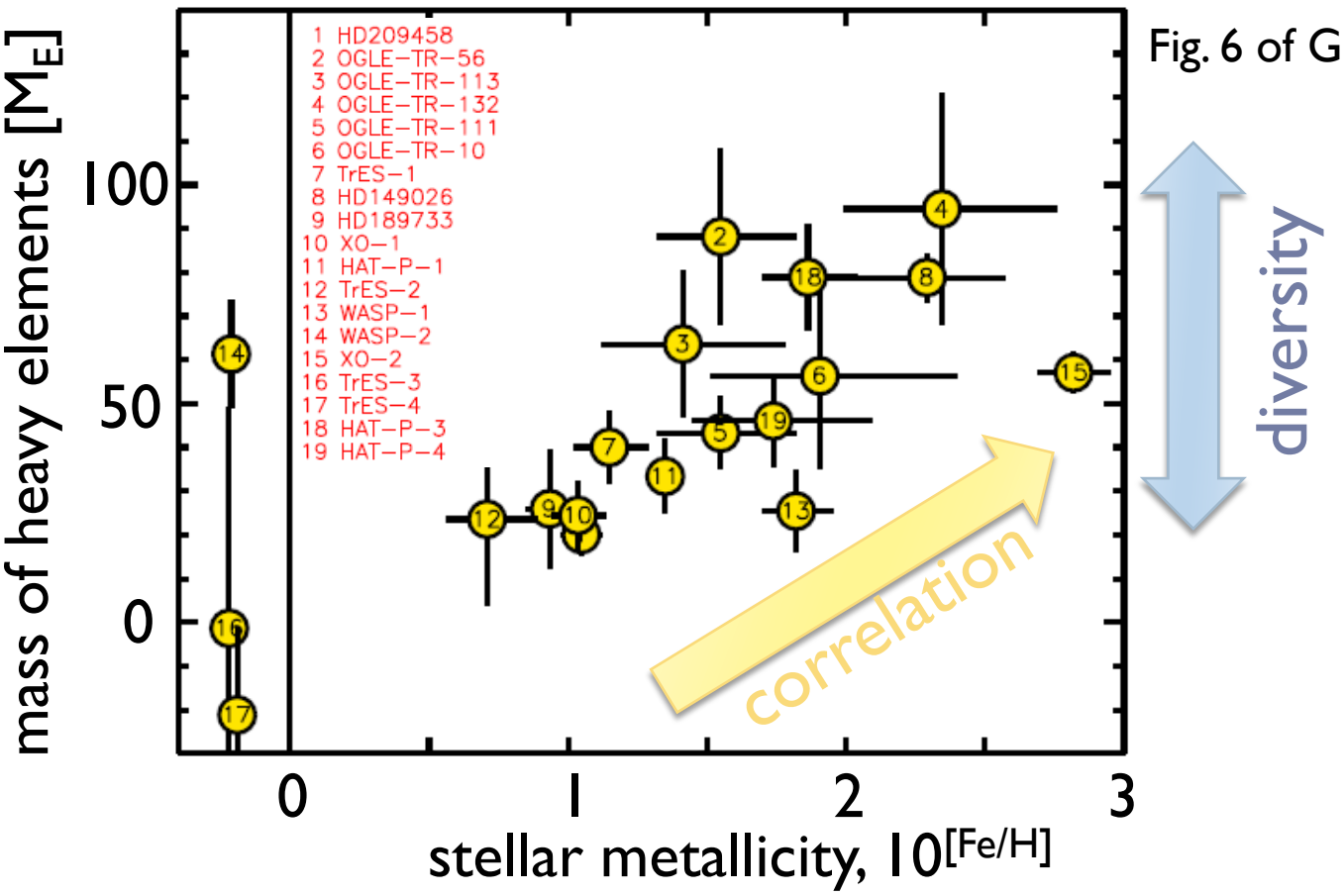


Fig. 6 of Guillot (2007)

What are the origins of such much heavy elements?

Summary

- A protoplanet embedded in the protoplanetary disk captures the disk gas to form an atmosphere.
- If the protoplanet (i.e., proto-core) grows to a certain critical mass (critical core mass), runaway disk-gas accretion happens to form a gas giant planet.
- This formation model is successful in explaining the diversity in mass and orbit of extrasolar planets and, maybe, the existence of Jupiter and Saturn far from the Sun.
- However, a simple consideration based on the theory is unable to account for large amounts of heavy elements in transiting gas giants.

