ASTR 405
Planetary Systems
Giant Planet Formation

Fall 2025

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Supplementary Readings: **formation.pdf Section III C** on Canvas

Lecture Notes on the Formation and Early Evolution of Planetary Systems by Armitage

Module II: Exoplanet Demographics and Planet Formation

- **Protoplanetary Disks:** Gas–dust disks around young stars; evolve on Myr timescales, set the initial conditions for planet formation

- **Dust, Pebbles, and Planetesimals:** Dust grains stick → pebbles (mm–cm); rapid drift & instabilities lead to km-scale planetesimals

- **<u>Planet Formation: Terrestrial and Giant Planets</u>**

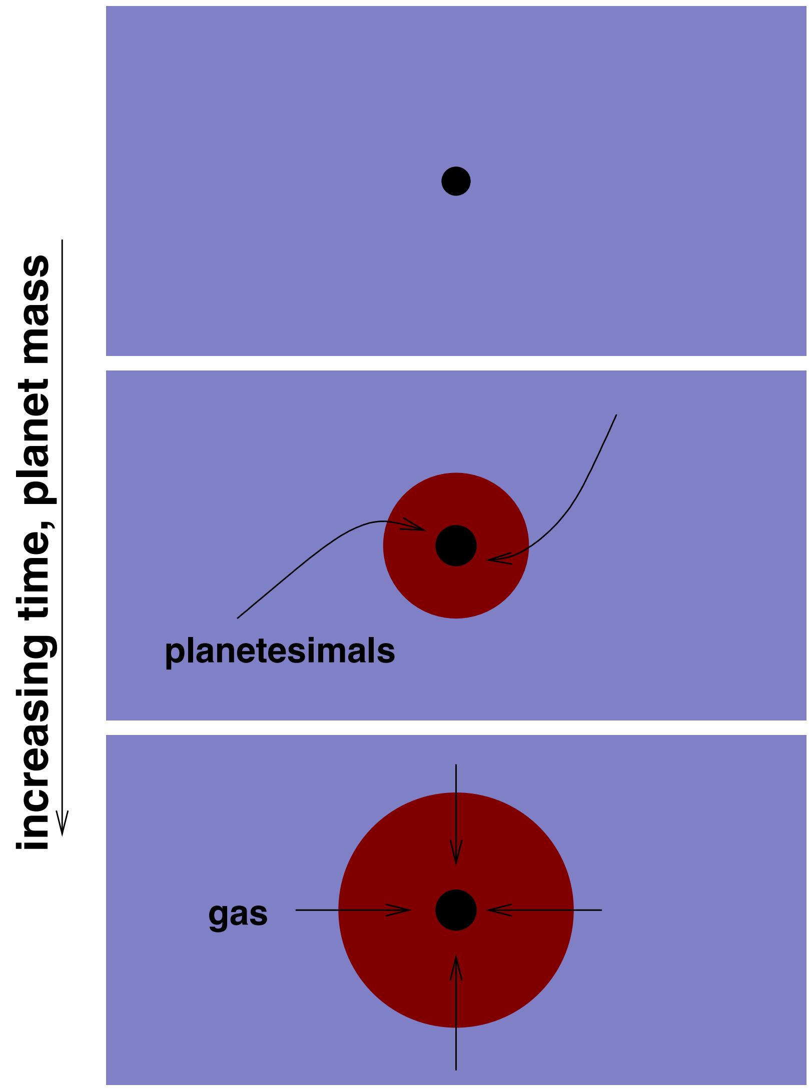
  Terrestrials: runaway/oligarchic growth → embryos → giant impacts

  <u>Giants: ~10 $M_\oplus$ cores accrete gas before disk dispersal or via disk instability</u>

- **Evolution of Planetary Systems:** Migration, resonances, and instabilities sculpt exoplanet architectures

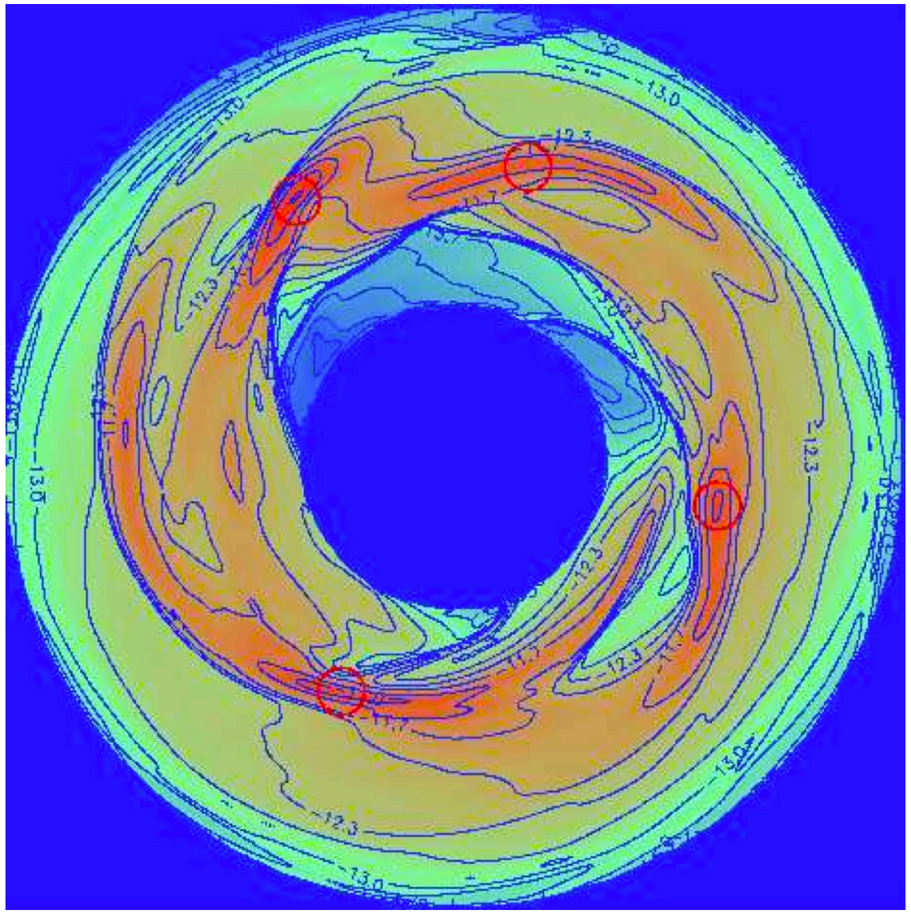
Two Proposed Giant Planet Formation Mechanisms

Core Accretion: gradual buildup of solid cores followed by runaway gas accretion



Credit: Armitage

Gravitational Instability: rapid fragmentation of a self-gravitating disk into bound clumps



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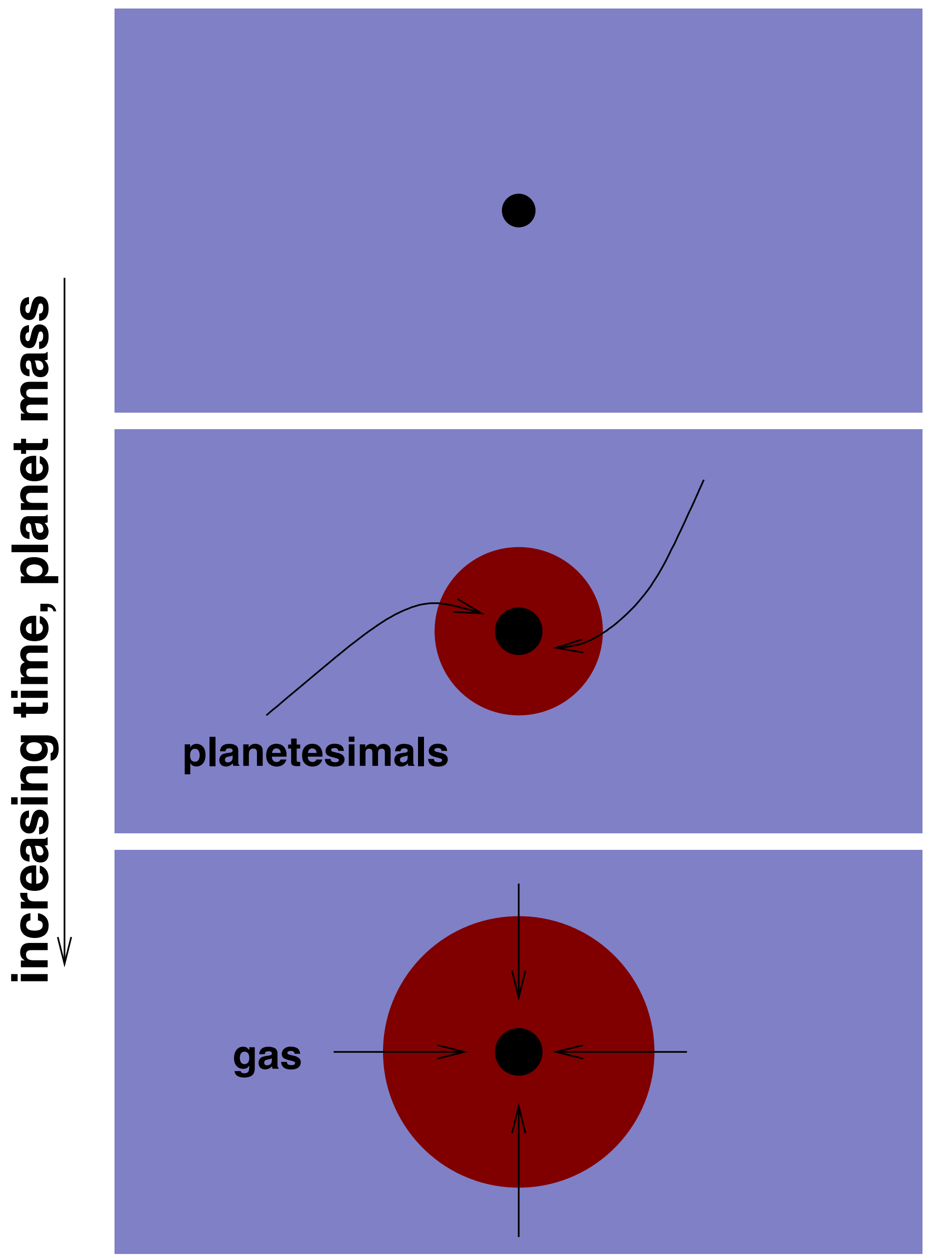
Giant Planet Formation via <u>Core Accretion</u>



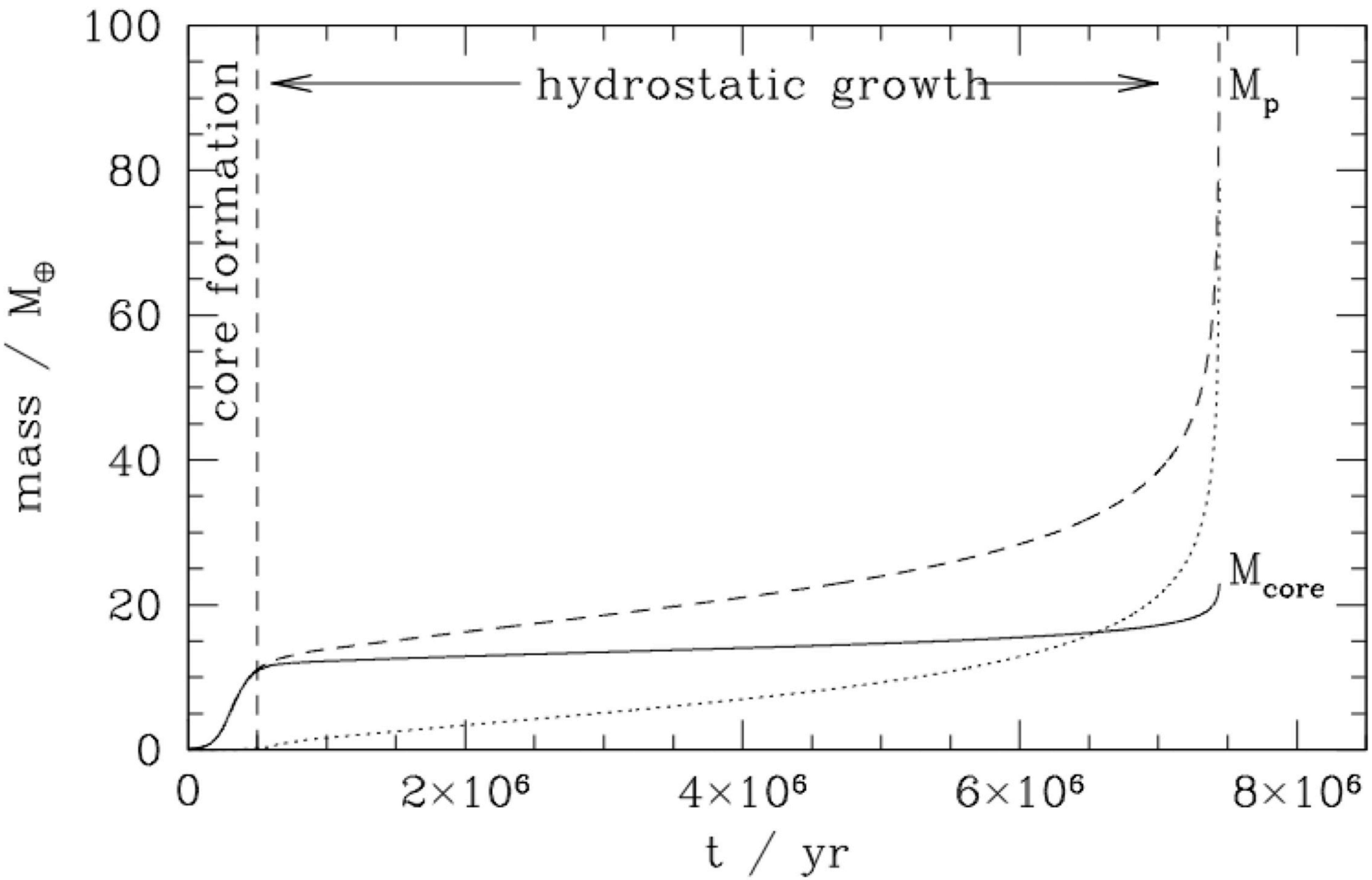
Credit: Armitage

Protoplanet assembles a solid core of 5+ Earth masses, by same processes as formation of terrestrial planets.

As core grows, gravity binds an envelope of disk gas that is in hydrostatic equilibrium. Envelope grows as heat is lost.

As $M_{env} \sim M_{core}$, the envelope can no longer maintain hydrostatic equilibrium → collapse and runaway gas accretion form a giant planet.

Giant Planet Formation via Core Accretion



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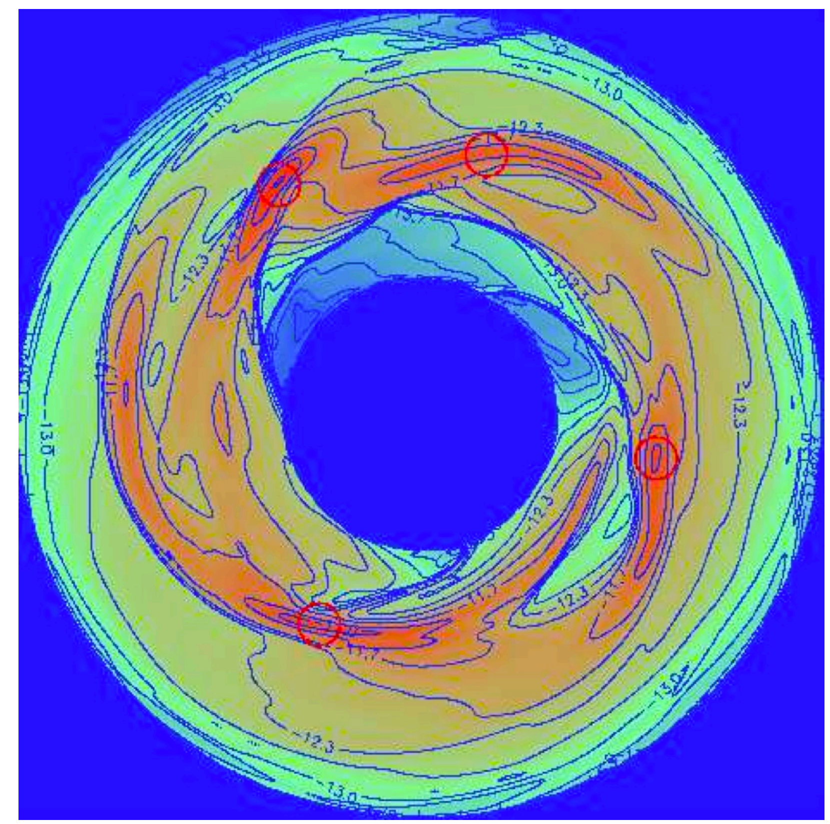
Giant Planet Formation via Gravitational Instability

- A sufficiently massive and/or cold gas disk is gravitationally unstable.
- Gravitational instability of a disk is only possible if the Toomre Q parameter is low:

$$Q \equiv \frac{c_s \Omega}{\pi G \Sigma} \lesssim 1$$

where where c_s is the sound speed in a gas disk of local surface density Σ.



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Giant Planet Formation via <u>Gravitational Instability</u>

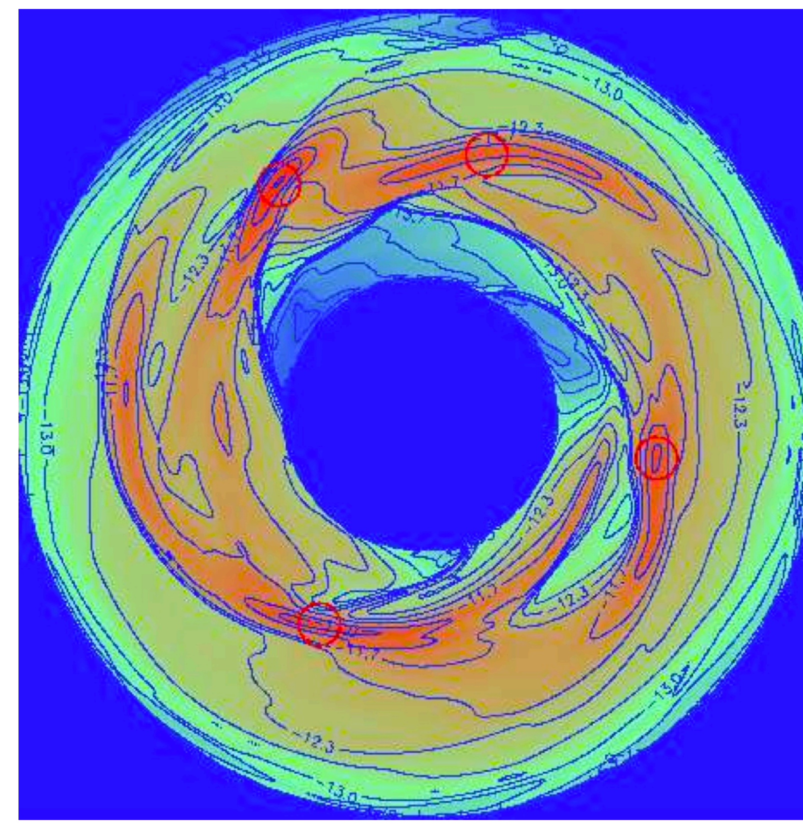
- A second, **important** criterion for gravitational collapse to form a planet (rather than just a gas and dust clump) is that the collapsing clump be able to cool on a timescale shorter than the free-fall timescale:

$$\tau_{\rm cool} < \tau_{\rm ff}$$

- Gammie (2001) shows

$$\tau_{\rm cool} = \frac{E_{\rm int}}{F_{\rm rad}} = \frac{c_s^2 \Sigma}{2\sigma T^4} \ ,$$

which is the ratio of internal thermal energy per unit area to the radiative energy loss per unit time per unit area.



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In-Class Activity

Forming Hot Jupiters In-Situ