News and Reminders

Homework 6 (last one!) - due Monday (Dec. 2)

No more reading quizzes!

JC 8 - Monday (Dec. 2)

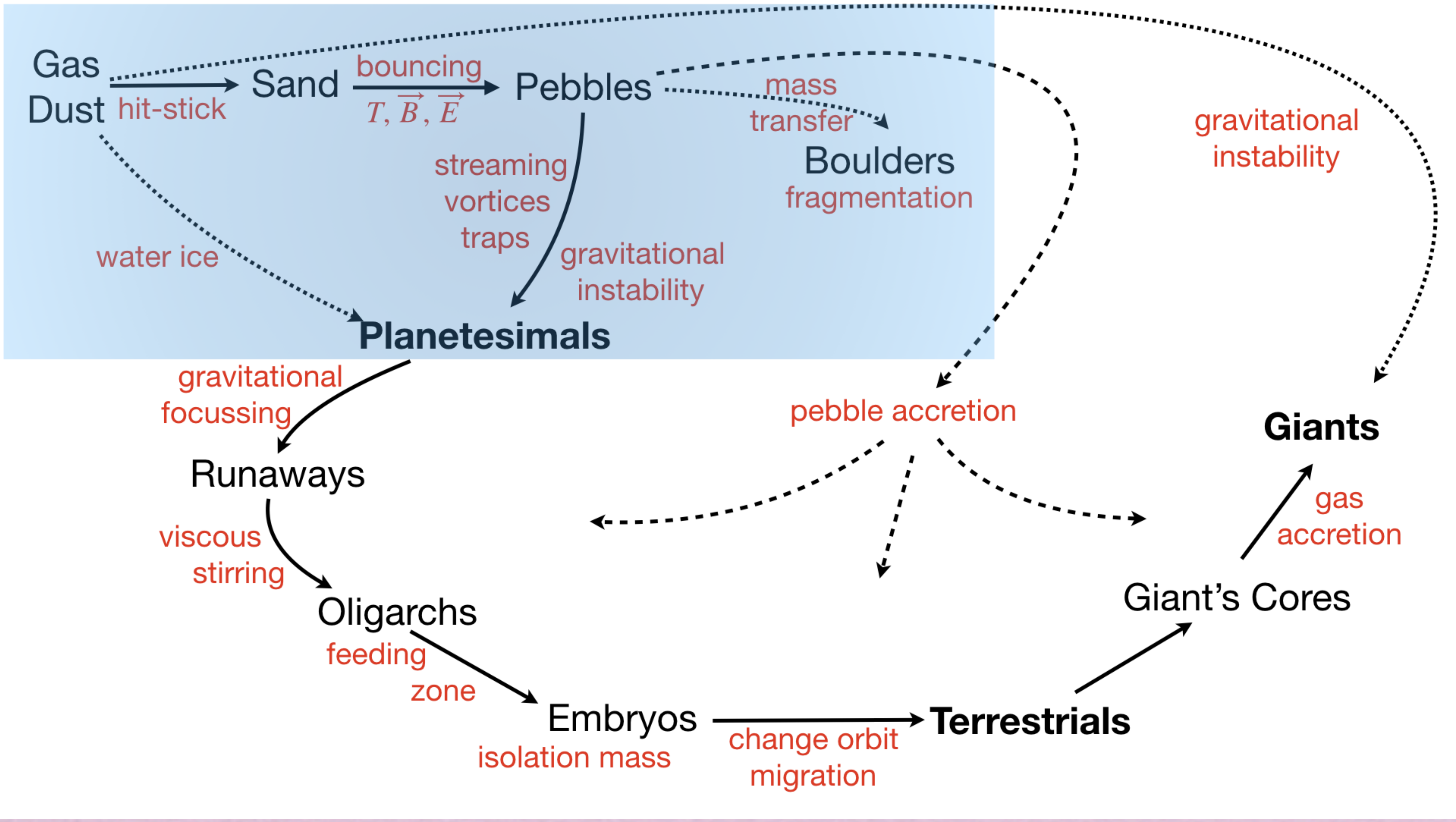
End of semester proposal due dates:

- Proposal due: Monday, Dec. 2
- Proposal review: Wednesday, Dec. 4
- Proposal review write-ups: Monday, Dec. 9

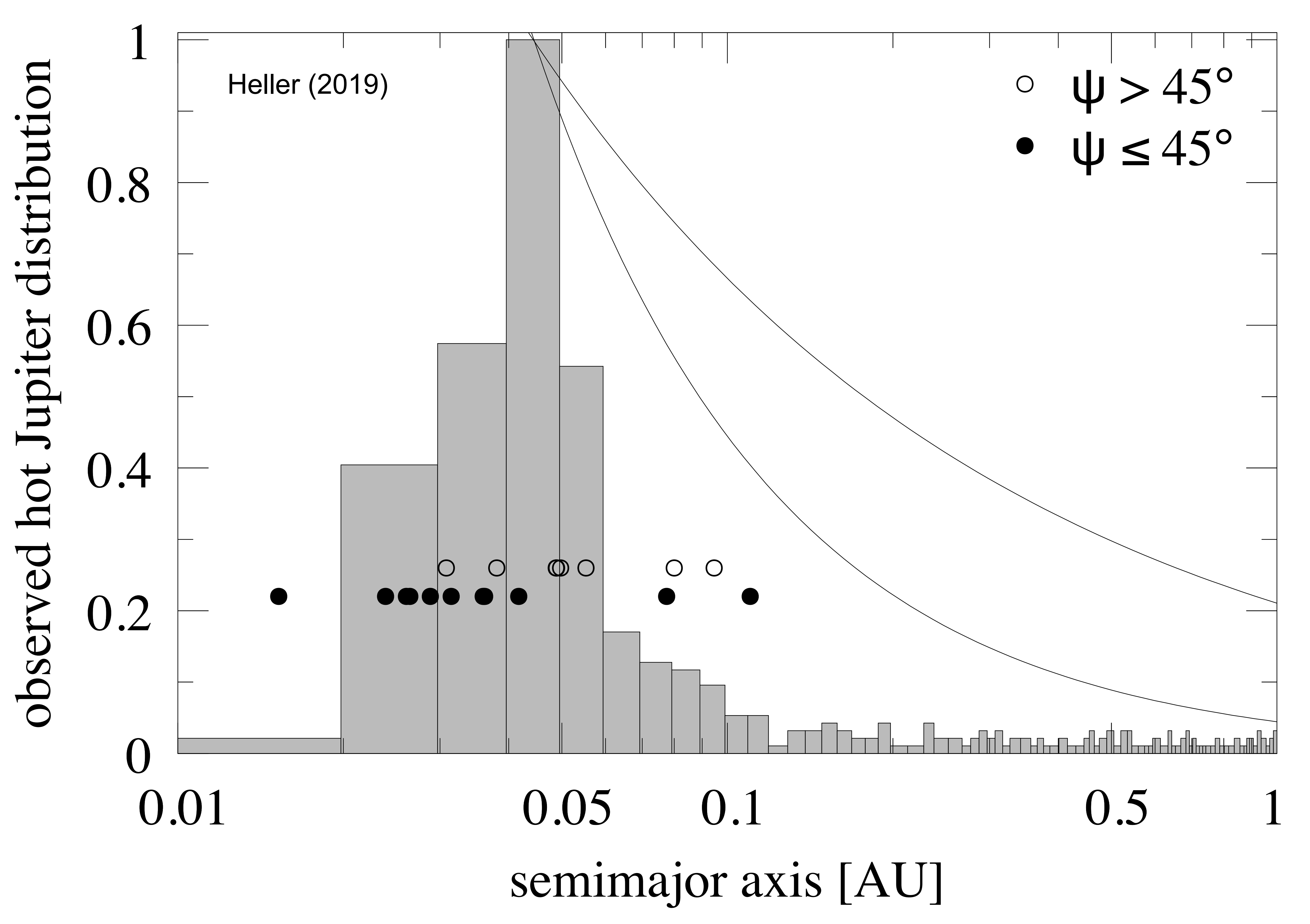
Bonus topics: email me your suggestions by end of today

Please complete the **course evaluations**

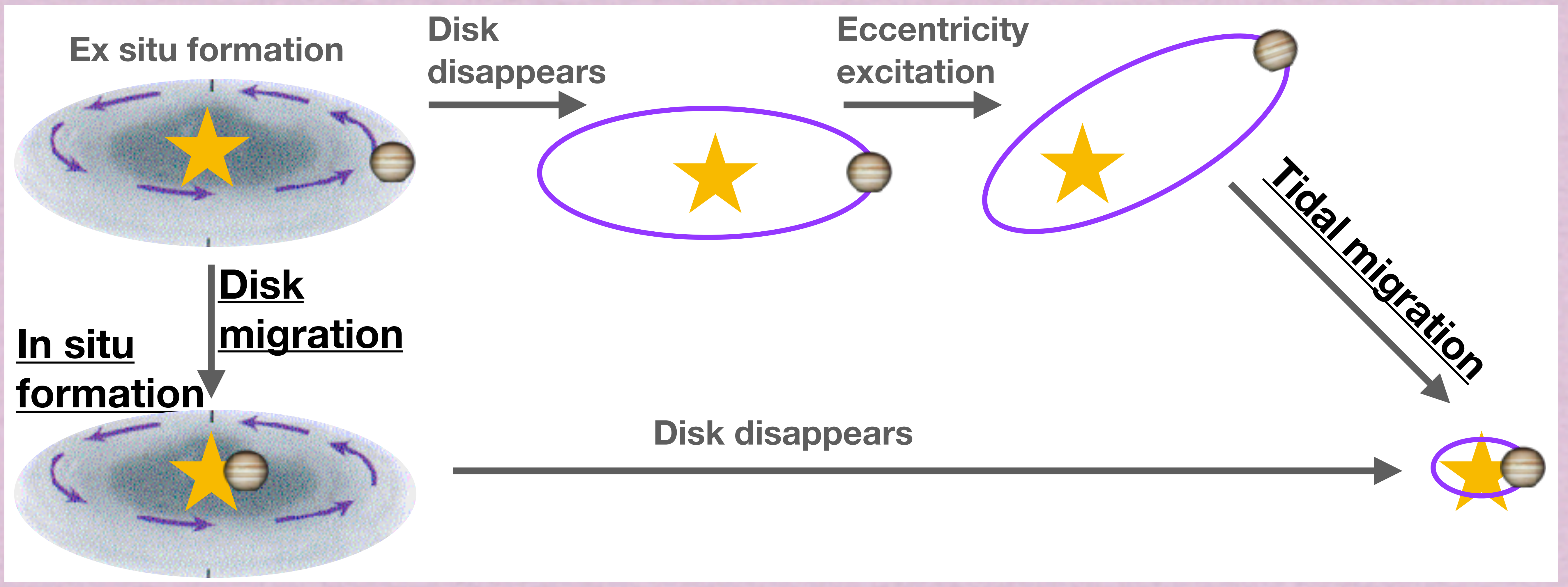
Planet Formation Summary



Considerations from Observations of Exoplanets

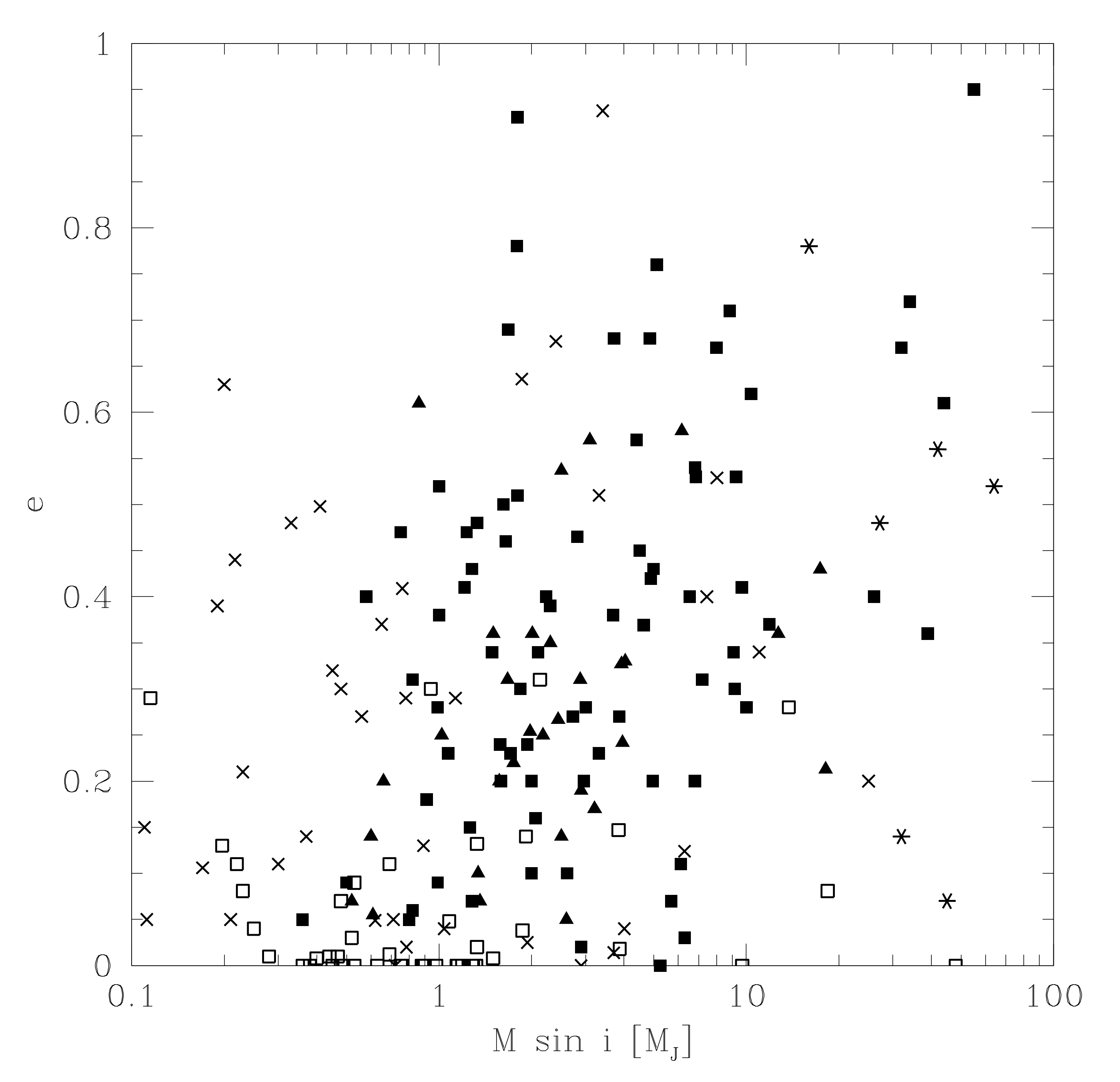


Considerations from Observations of Exoplanets



What might happen to a system initially like the SS, if a gas giant migrates in to become a hot Jupiter?

Considerations from Observations of Exoplanets



Gas Disk Migration

Planets exchange angular momentum with the disk, giving rise to torques on the planets.

Torque is generally expected to be negative -> planets lose angular momentum to the disk and drift towards the star.

For gas interior to the planet orbit

- Increase in $\Delta v_{\parallel}$ means decrease in *j*

- *The gas loses angular momentum*
- *The planet gains angular momentum*

- Planet moves outwards
- Gas moves inwards (gas is repelled from the planet)

For gas exterior to the planet orbit

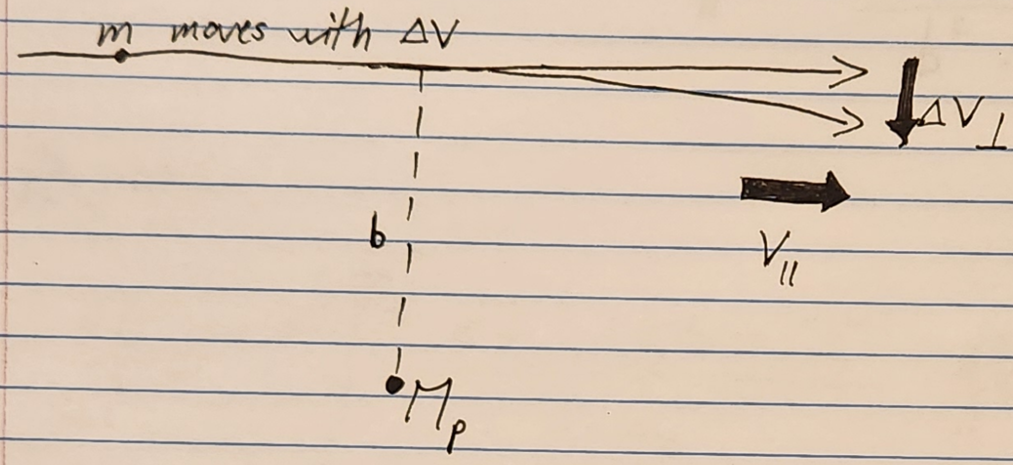
- Decrease in $\Delta v_{\parallel}$ means increase in *j*

- *The gas gains angular momentum*
- *The planet loses angular momentum*

- Planet moves inwards
- Gas moves outwards (gas is repelled from the planet)

Gas disk migration:

Impulse approximation:



ΔV: velocity of gas relative to planet

$$F_\perp = \frac{G m M_p}{b^2}\left(1+\left(\frac{vt}{b}\right)^2\right)^{-3/2}$$

$$\Delta V_\perp = \int_{-\infty}^{\infty} \frac{F_\perp}{m}\, dt = \frac{2GM}{bV}$$

but $\Delta V_\perp$ does not change the angular momentum, only $V_\parallel$ does.

conservation of energy:

$$\Delta V^2 = \Delta V_\perp^2 + \left(\Delta V - \Delta V_\parallel\right)^2$$

for small deflection angles:

$$\Delta V_\parallel \approx \frac{1}{2\Delta V}\left(\frac{2GM_p}{b\,\Delta V}\right)^2$$

Angular momentum change:

$$\Delta L = a \times \Delta V = a\,\Delta V_{\parallel} = \frac{2G^2 M_p^2 a}{b^2 \Delta V^3}$$

Torque:

$$\tau = \frac{dL}{dt} = -\int_0^{\infty} \frac{8G^2 M_p^2 a \Sigma}{9\Omega_p^2} \frac{db}{b^4}$$

for interaction with gas outside the planet's orbit.

Integral diverges, so let's integrate from b_{min} to ∞ instead.

$$\Rightarrow \quad \tau = \frac{-8}{27} \frac{G^2 M_p^2 a \Sigma}{\Omega_p^2 b_{min}^3}$$

$\tau \propto M_p^2$ $\Rightarrow$ more massive planets migrate faster

~~Mig. ...~~

$$T_{mig} = \left(\frac{1}{L}\frac{dL}{dt}\right)^{-1} \sim 1\ \text{Myr for } 1M_\oplus \text{ or } 0.2\ \text{Myr for } 1M_J$$

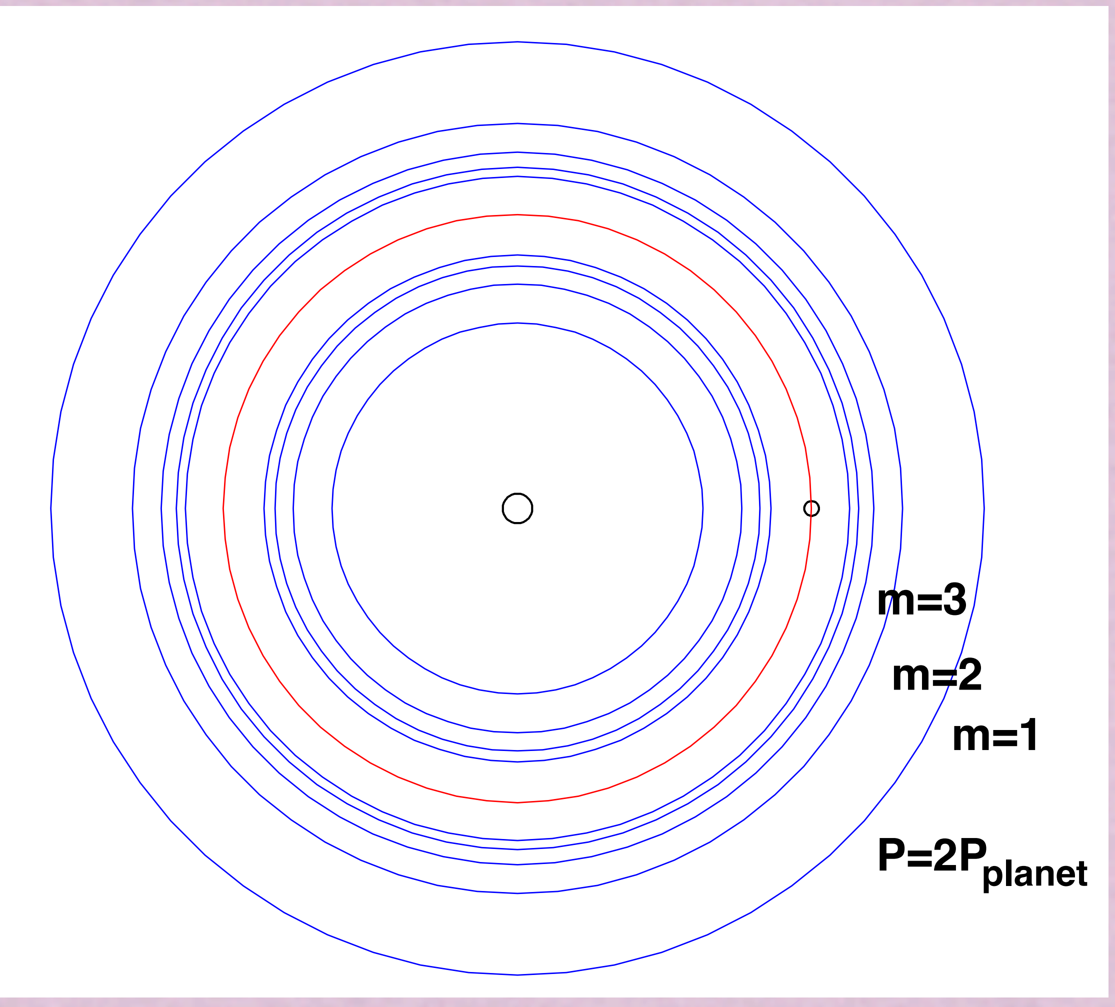
$$\propto \frac{M_p}{M_p^2} \propto \frac{1}{M_p}$$

Gas Disk Migration

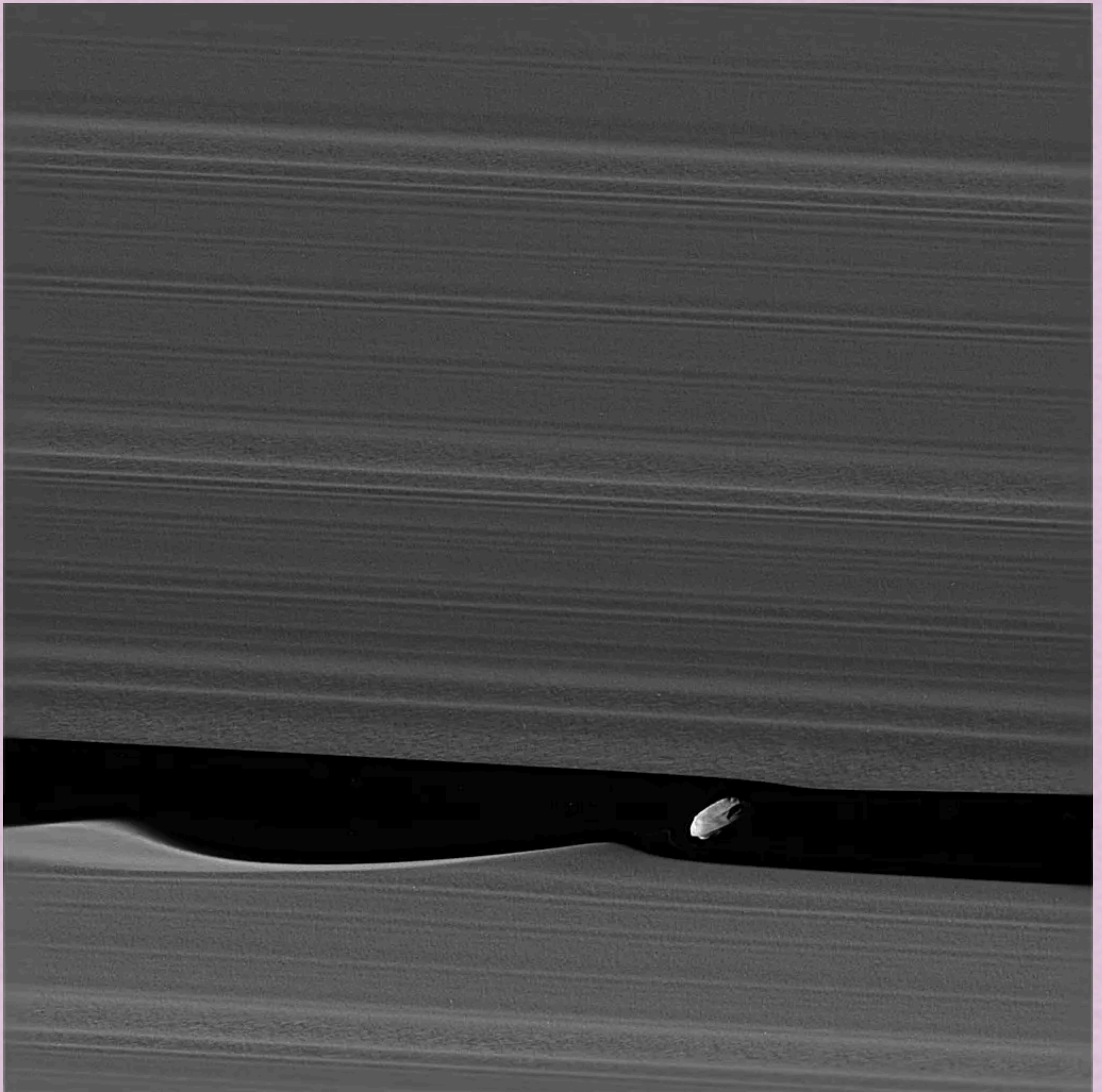
$$m(\Omega - \Omega_p) = \begin{cases} \kappa & \text{Inner Lindblad Resonance} \quad \Omega = \Omega_p + \kappa/m \\ 0 & \text{Corotation} \quad \Omega = \Omega_p \\ -\kappa & \text{Outer Lindblad Resonance} \quad \Omega = \Omega_p - \kappa/m \end{cases}$$

Location of Lindblad resonances

$$r_{L\pm} = r_p \left(1 \pm \frac{1}{m}\right)^{2/3}$$



A gap-opening body in a disk

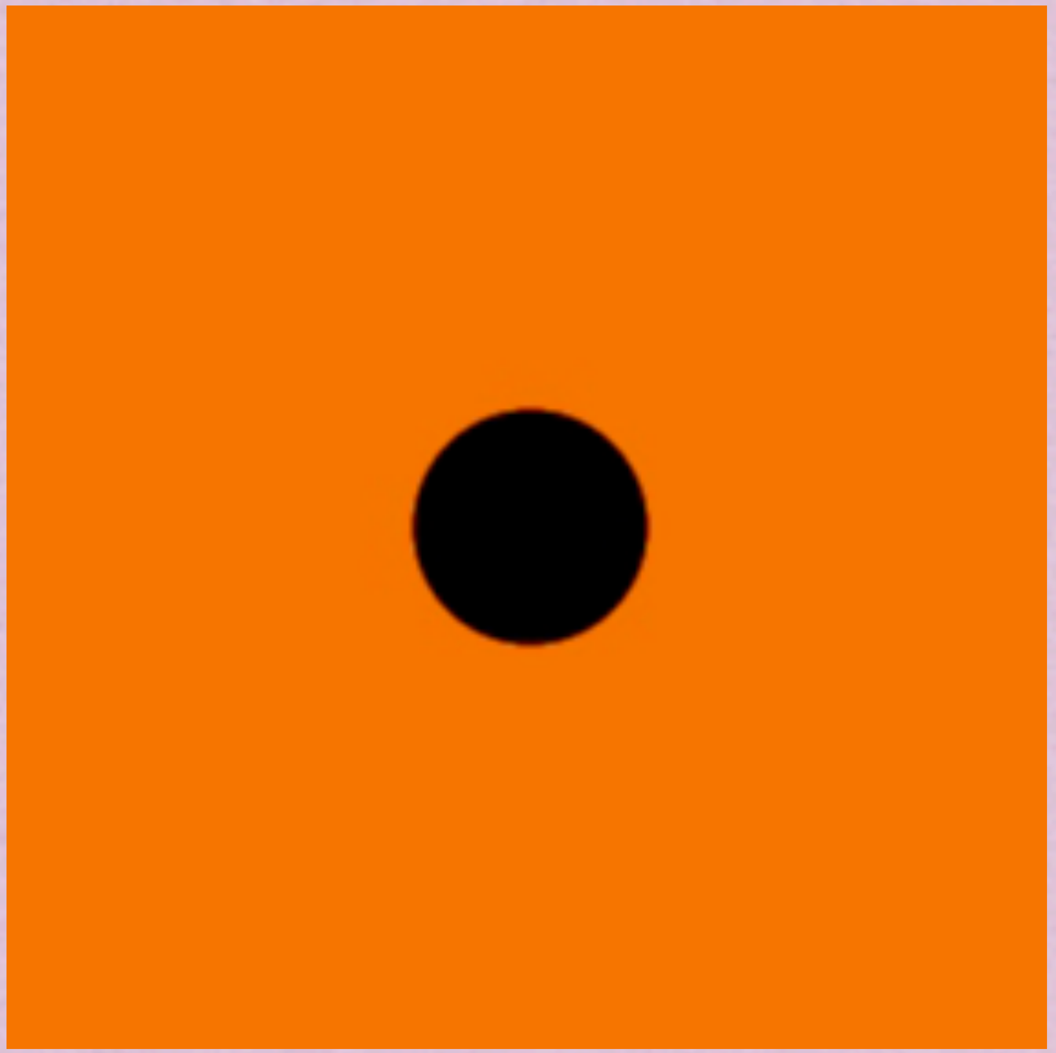


Type I Migration

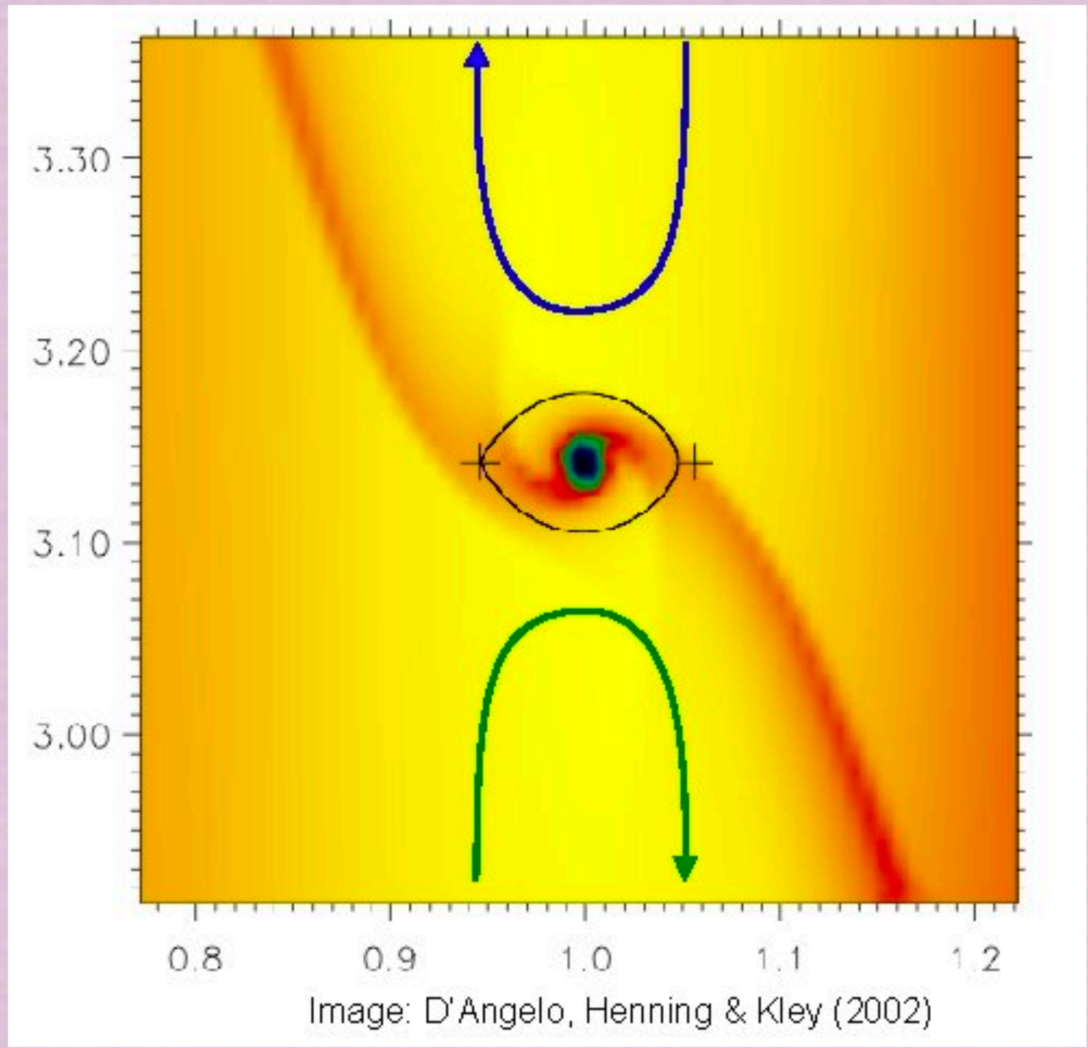
A lower-mass planet doesn't perturb the disk very much -> Type I migration

Lindblad torques act on the planet
Numerical simulations find that the net torque is always negative -> inward migration

Fast: a 10 MEarth planet at 5 AU drifts into the star in 10 000 years!
-> too fast to allow giant planet formation
-> Neptune would have been ingested by the Sun.



The material leading the planet pulls it ahead and makes it gain angular momentum. The trailing material brakes the planet making it lose angular momentum.

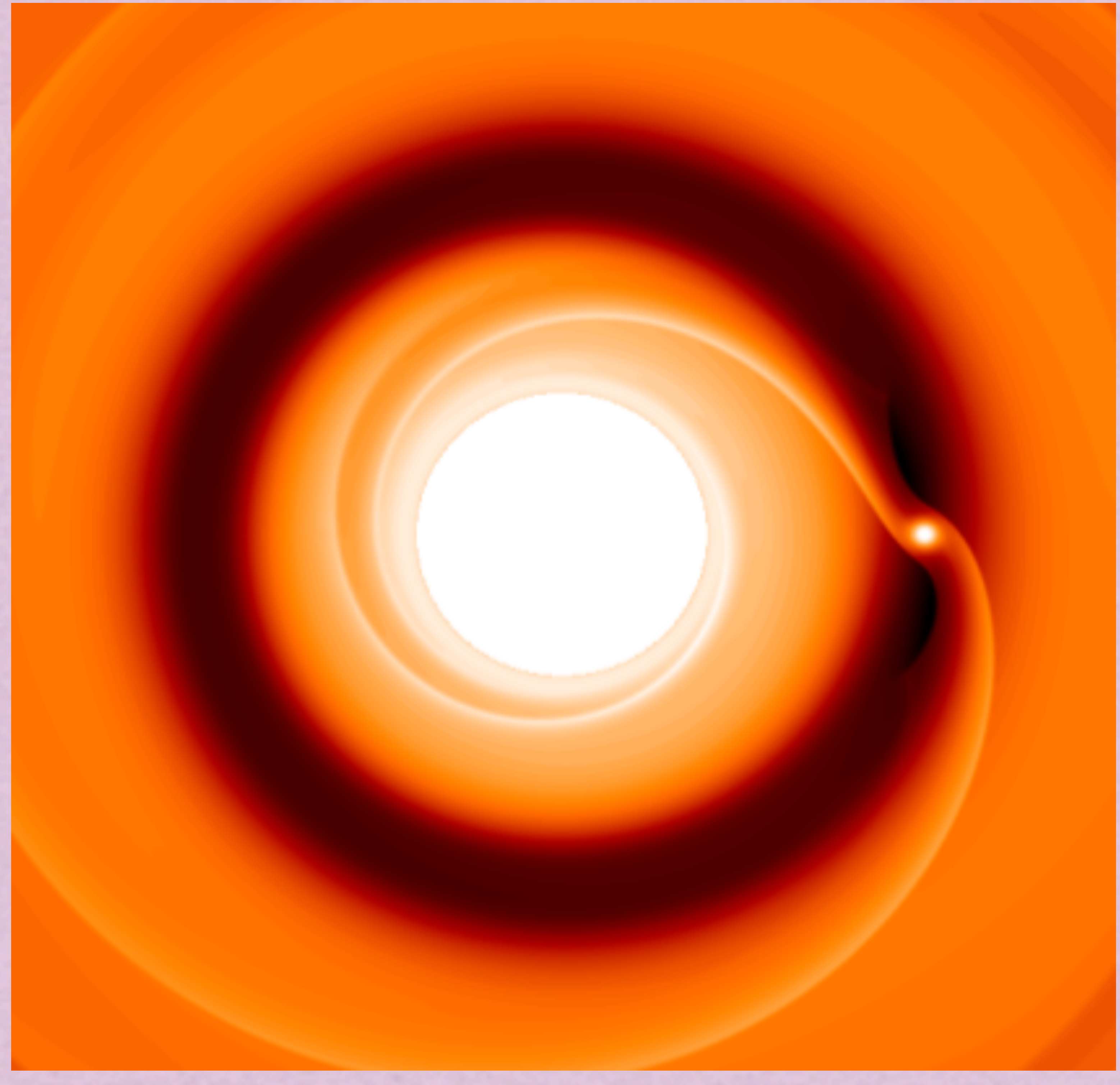


Type II Migration

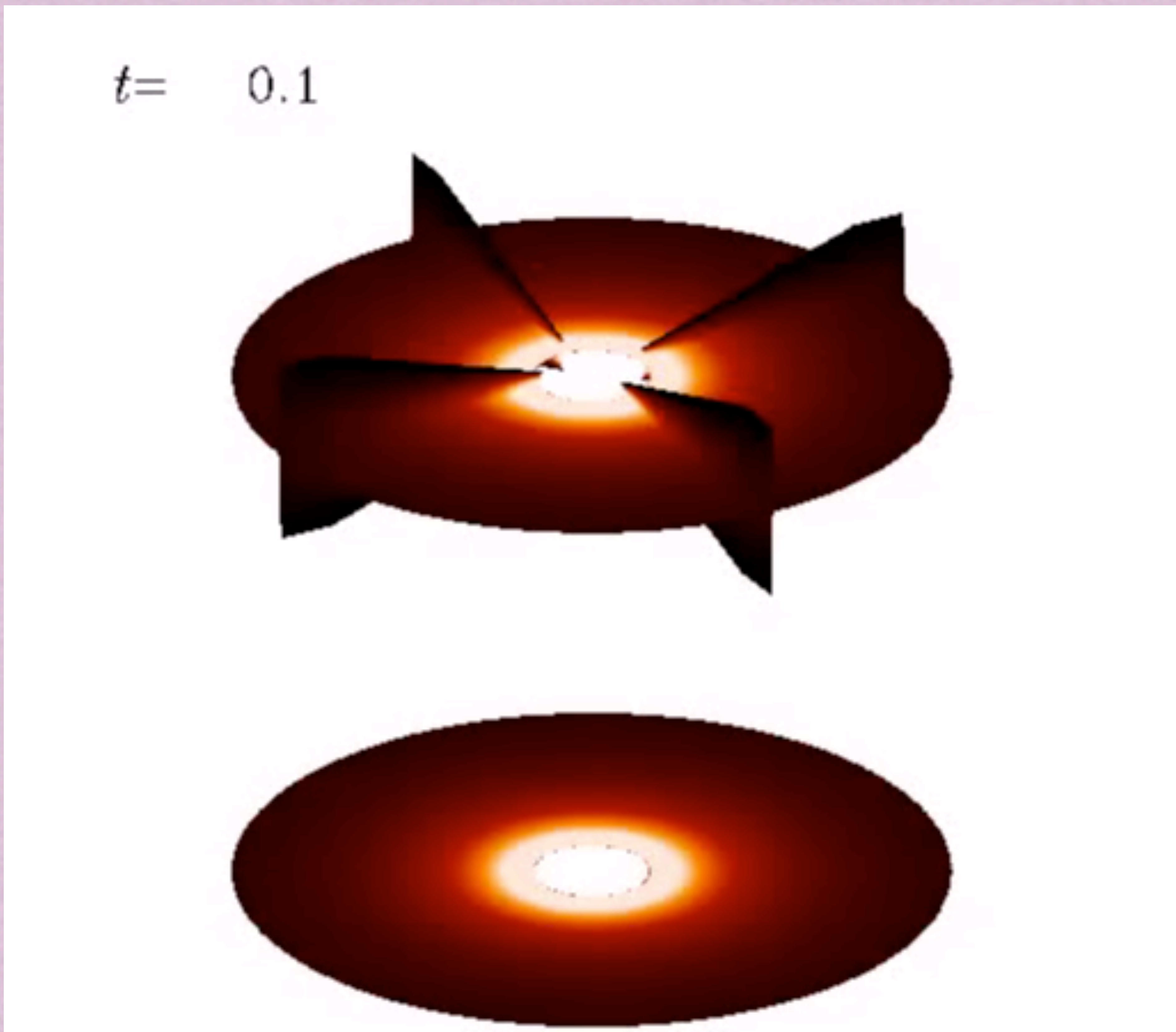
High-mass (~Saturn-mass +) planets can clear a gap in the disk.
This ends Type I migration and allows Type II to take over.

Two conditions necessary for gap formation:

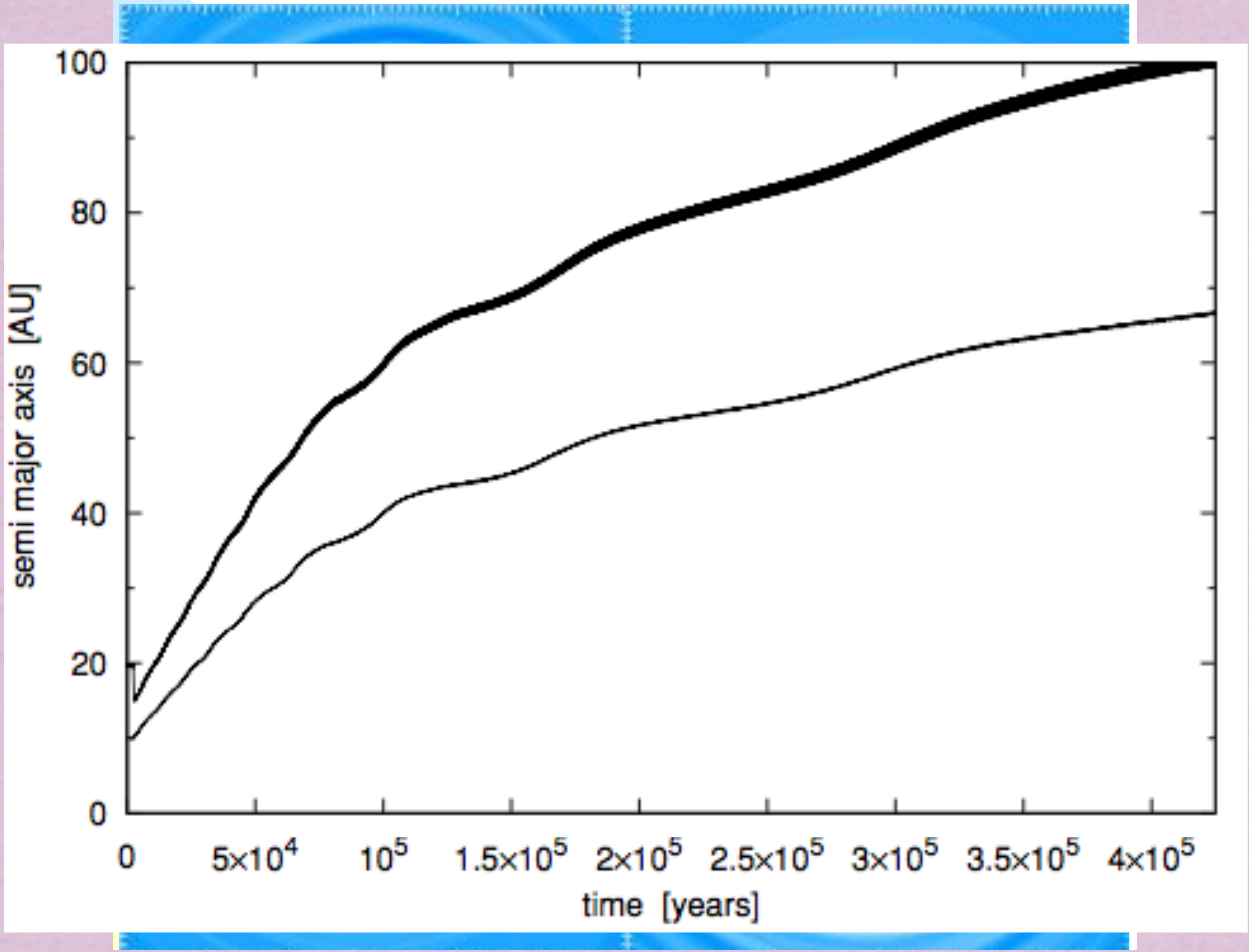
1) the Hill sphere of the planet needs to be comparable to the thickness of the gas disk
2) tidal torques must be able to remove gas from the gap region faster than viscosity can fill the gap back in



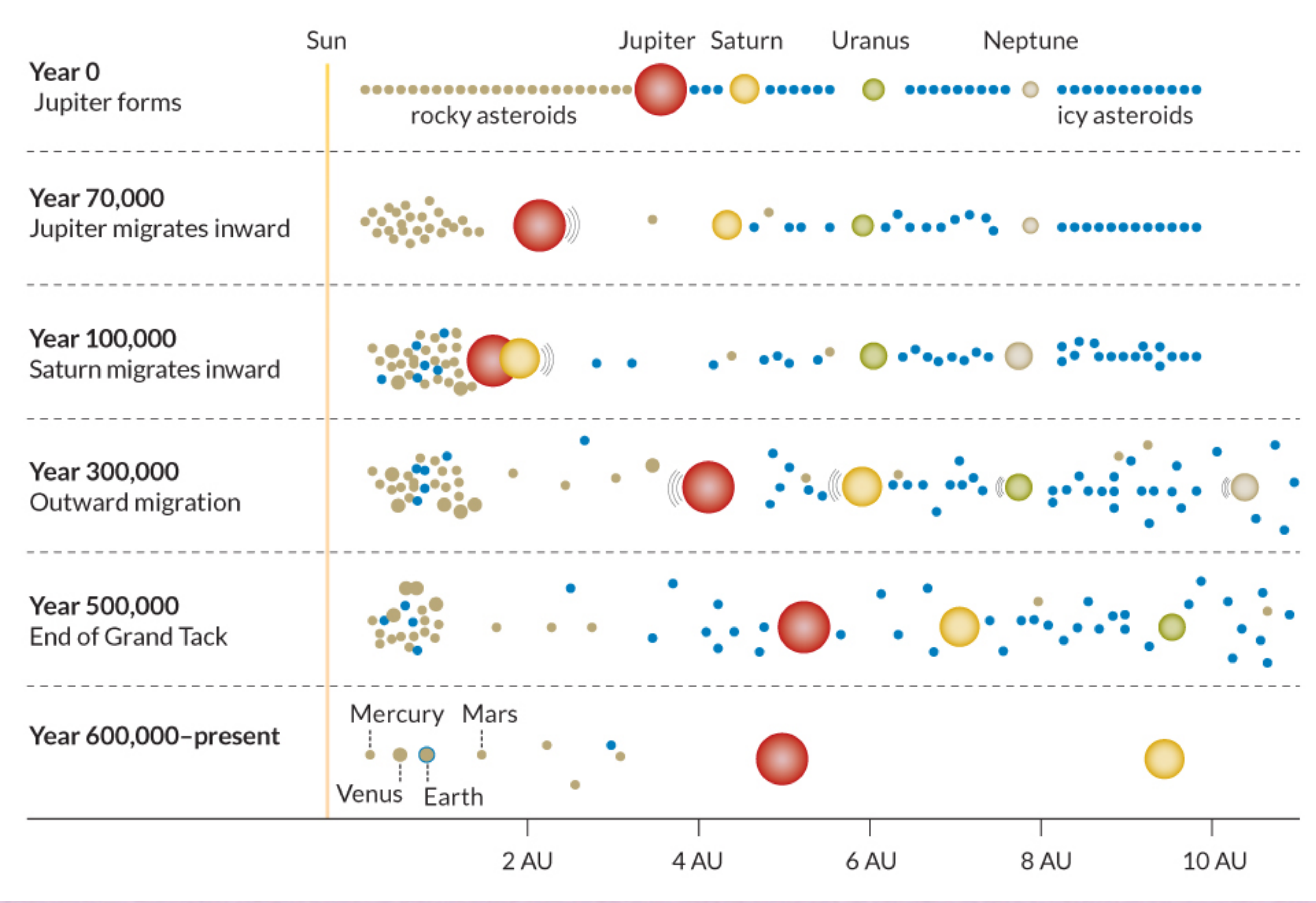
Type II Migration



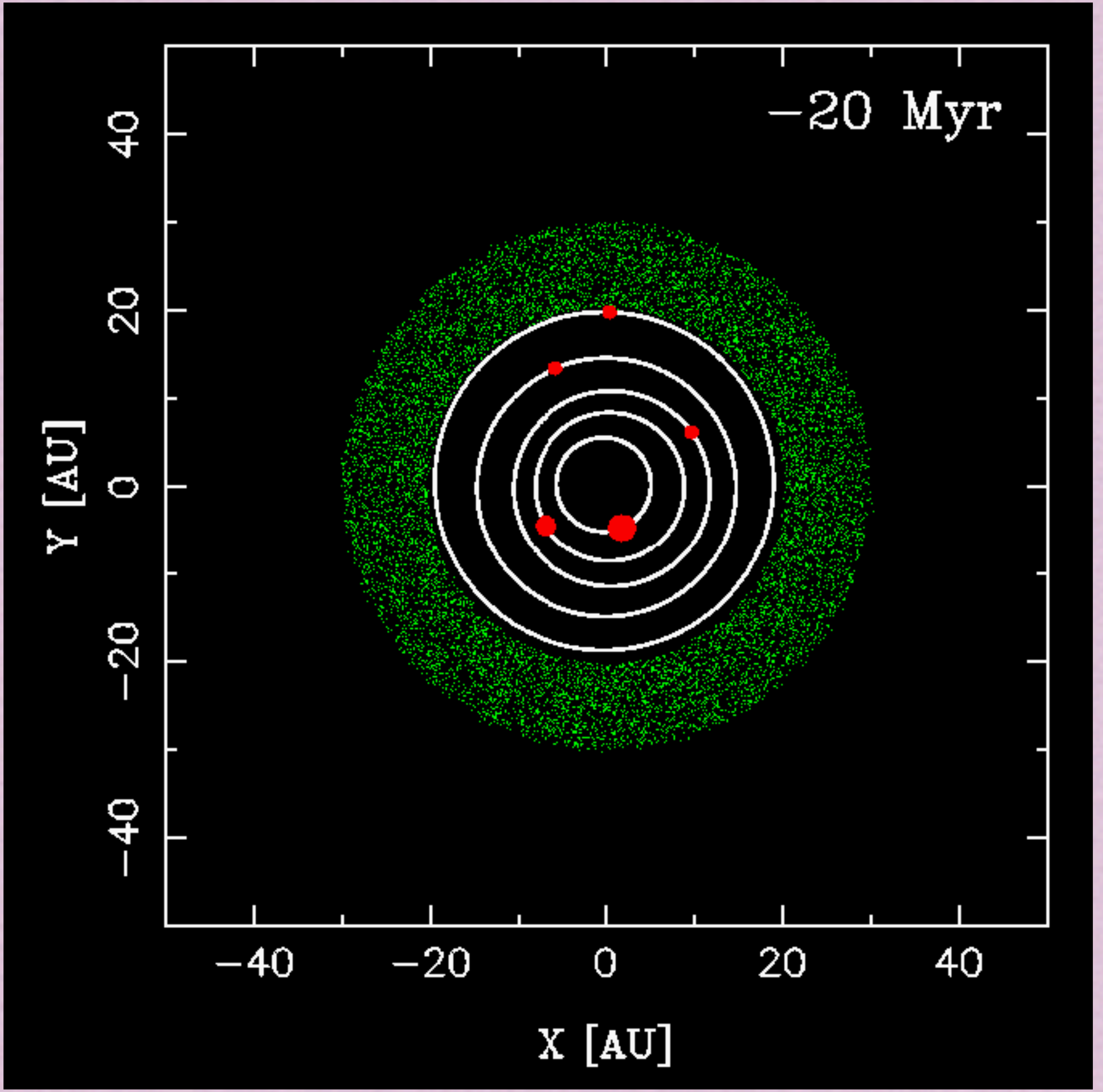
Planet Migration



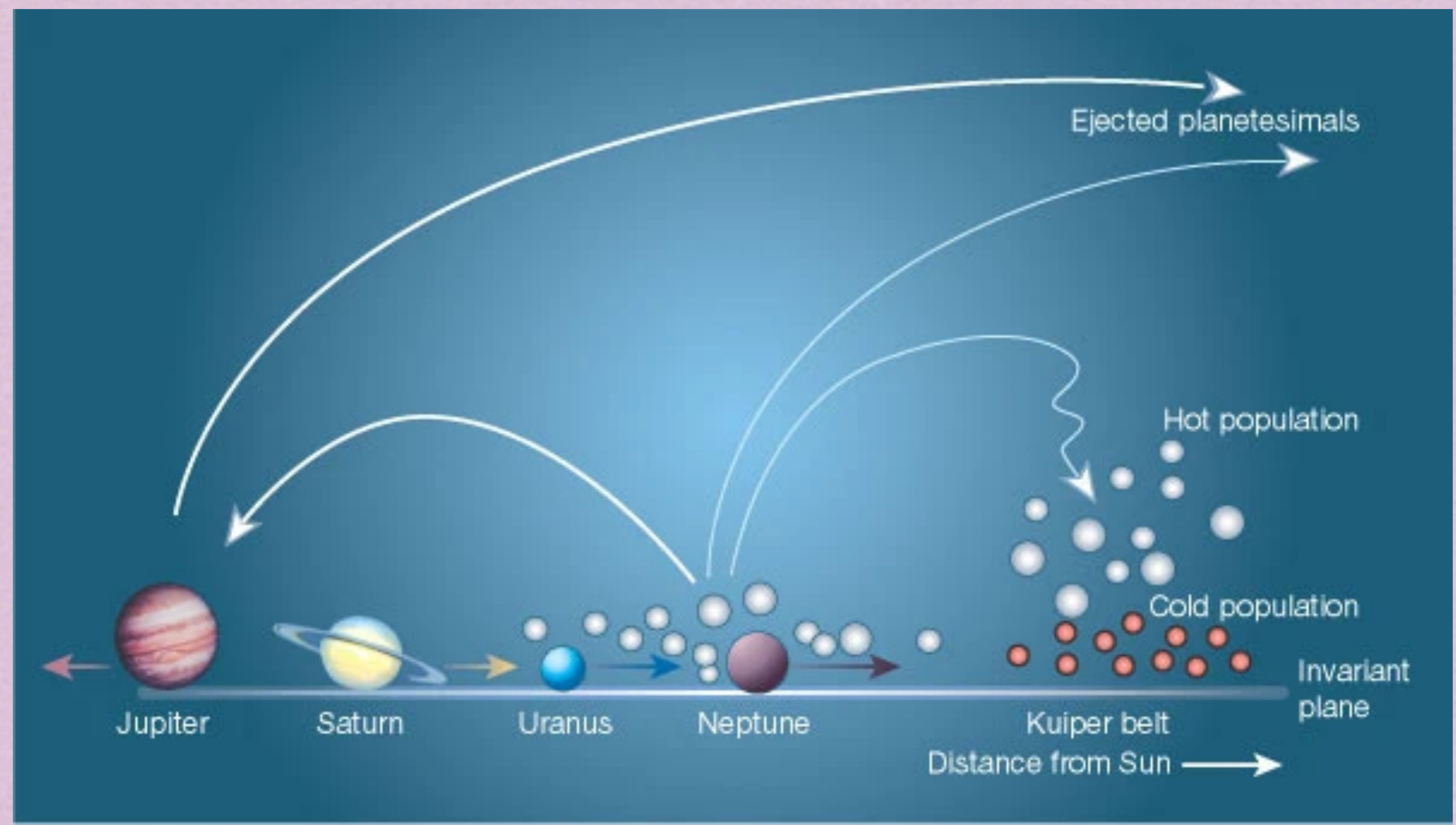
"Grand Tack" Model



“Nice” Model



"Nice" Model



Ejected planetesimals
Hot population
Cold population
Invariant plane
Jupiter
Saturn
Uranus
Neptune
Kuiper belt
Distance from Sun