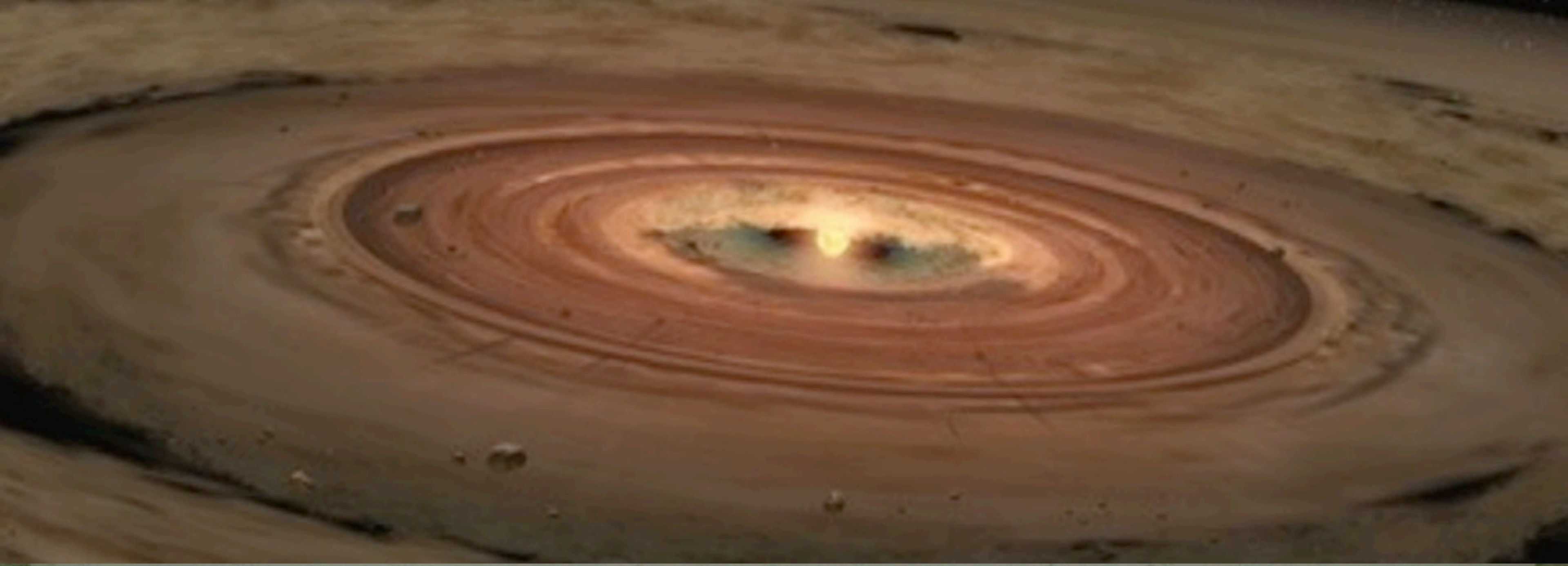
Planet Formation

Munan Gong

Outline

- Terrestrial planets: from planetesimals
- Gas Giants: Core accretion VS Gravitational instability
- Planet migration: Type I & Type II
- Exoplanets and future work



Dust -> Planetesimals -> Protoplanets(embryos) -> Planets

~μm ~km ~1000km

(Chris & Konstantin)

-Terrestrial planets

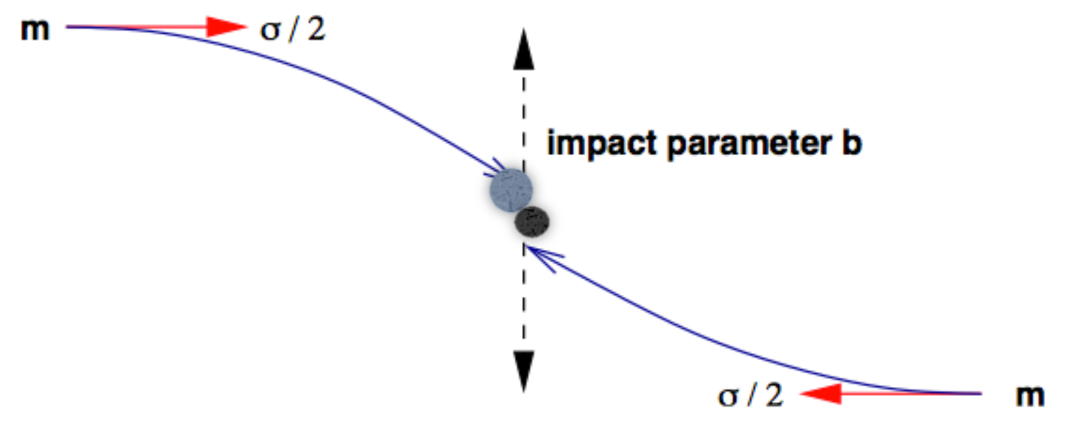
$R_E \sim 6000$km

-Gas giants (also GI)

$R_J \sim 10R_E$, $M_J \sim 300M_e$

Planetesimals -> Protoplanets

- For ~km sized planetesimal, gravitational focused collisions begin to dominates.



The cross section for collision

$$\Gamma^2 = \pi R_s^2 \left(1 + \frac{v_{esc}^2}{\sigma^2}\right)$$ F_G Gravitational focusing factor

Orderly growth -> Runaway growth

- The growth rate of a big planetesimal in a swarm of small ones:

$$\frac{dM}{dt} = \frac{1}{2}\Sigma_p \Omega \pi R_s^2 \left(1 + \frac{v_{esc}^2}{\sigma^2}\right)$$

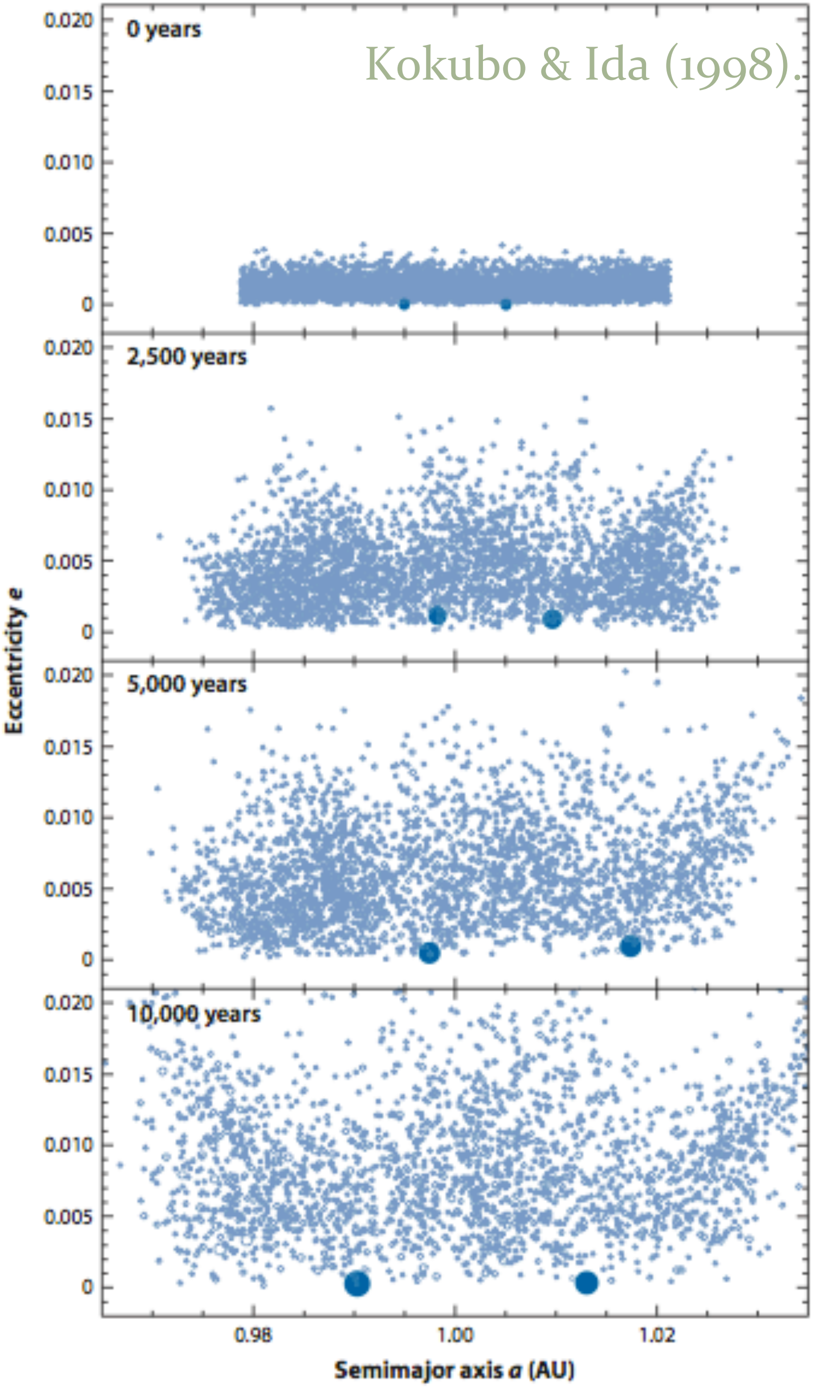
- Small ones: $F_G \sim 1$

$$\frac{1}{M}\frac{dM}{dt} \propto \frac{R_s^2}{M} \propto M^{-1/3}, \;\; R_s \propto t$$

- Big ones: $F_G \sim (v_{esc} / \sigma)^2$

$$\frac{1}{M}\frac{dM}{dt} \propto M^{1/3}\frac{1}{\sigma^2}$$

The relative growth rate is an increasing function of mass: big bodies grow even faster.



Kokubo & Ida (1998).

3D N-body simulation, accretion

0 yr: 2 planetesitmals 2 times more massive than others.

2,500 yr: Runaway growth
These 2 objects accrete quickly, and their mass increases exponentially.

5,000 yr: Oligarchic growth
Large bodies stars to stir up the eccentricity of the small ones in their vicinity, and grows slower. This “oligarchy” embryos competes for the remaining materials.

10,000 yr: Isolation mass
The embryos consumed all the materials in their feeding zone, and stops to grow. The masses of embryos grow by a factor of 200, and planetesimals by a factor of 2.

Stir up the isolated embryos

- Isolation mass

$$M_{iso} = \frac{8}{\sqrt{3}}\pi^{3/2}C^{3/2}M_*^{-1/2}\Sigma_p^{3/2}a^3$$

  - MMSN at 1AU

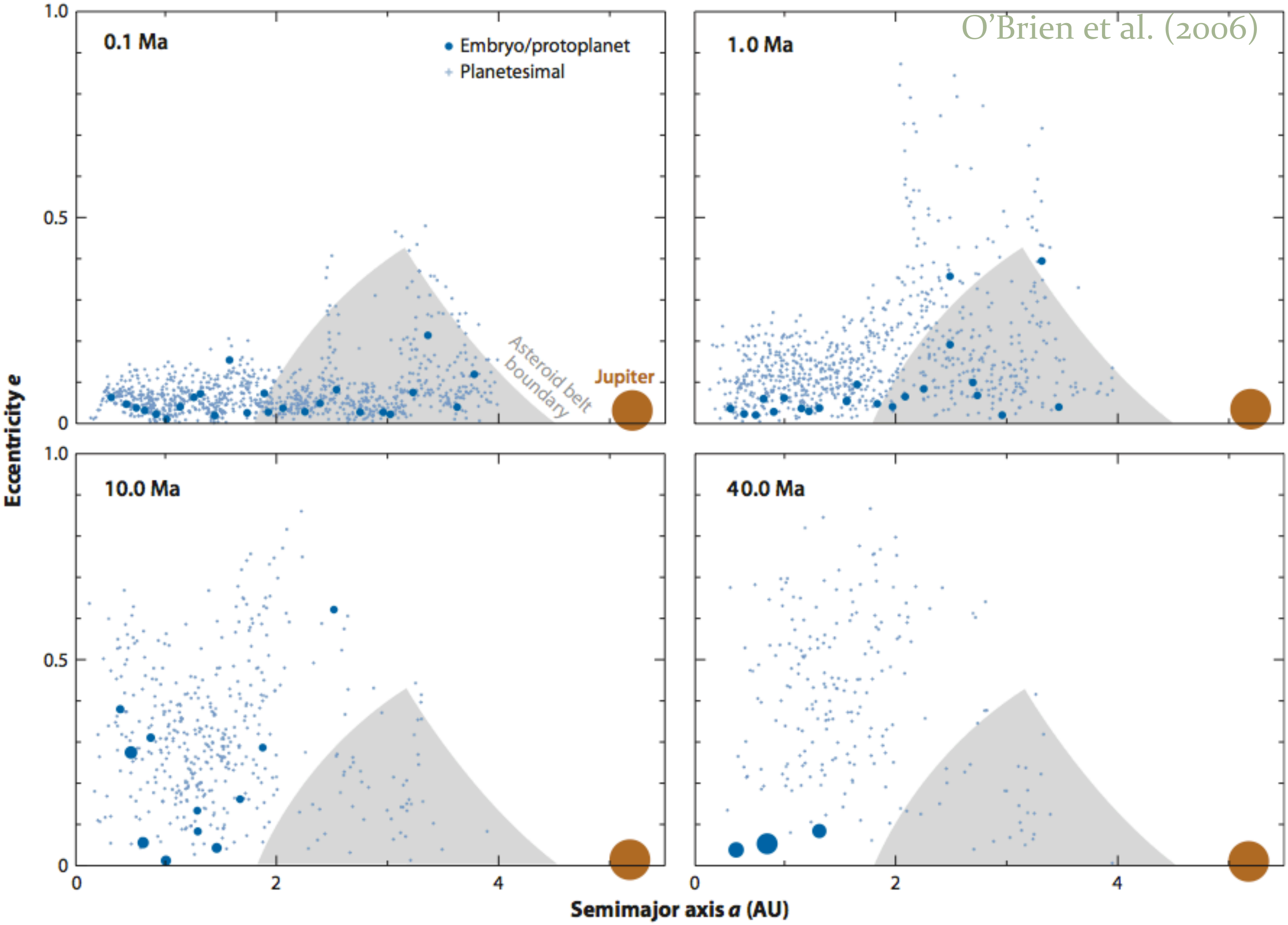
$$M_{iso} \sim 0.07M_E$$

  - Requires 3-4 times of solid density of MMSN at 5AU to form the core of Jupiter we see today

$$M_{iso} \sim 9M_E$$

- Stirring up embryos: the presence of gas giant
  - By definition, the gas giants must be fully formed by the time the gas is removed from the disk, i.e., well before the formation of the terrestrial planets is complete.

3D N-body simulation, earth size planets can be formed < 2AU, in ~40 Myr



Summary of simulation

- Pros
  - Collisions of embryos are frequent: formation of moon.
  - The accretion timescale ~30–100 Myr, agrees with the timescale of Earth accretion deduced from radioactive chronometers .
  - Embryos are ejected form the asteroid belt. Can explain the mass deficit of the asteroid belt and the large orbital eccentricity and inclination of asteroids.
- Cons
  - Cannot produce the small mass and short formation timescale(comparable to embryos) of Mars.

The Grand Track

- Walsh et al. built their model on previous hydrodynamical simulations that showed that the migration of Jupiter can be in two regimes:
    - When Jupiter is the only giant planet in the disk, it migrates inward (Lin & Papaloizou 1986).
    - But when Jupiter is paired with Saturn, both planets typically migrate outward, locked in a 2:3 mean motion resonance .

$$\text{Mean motion resonance:}$$

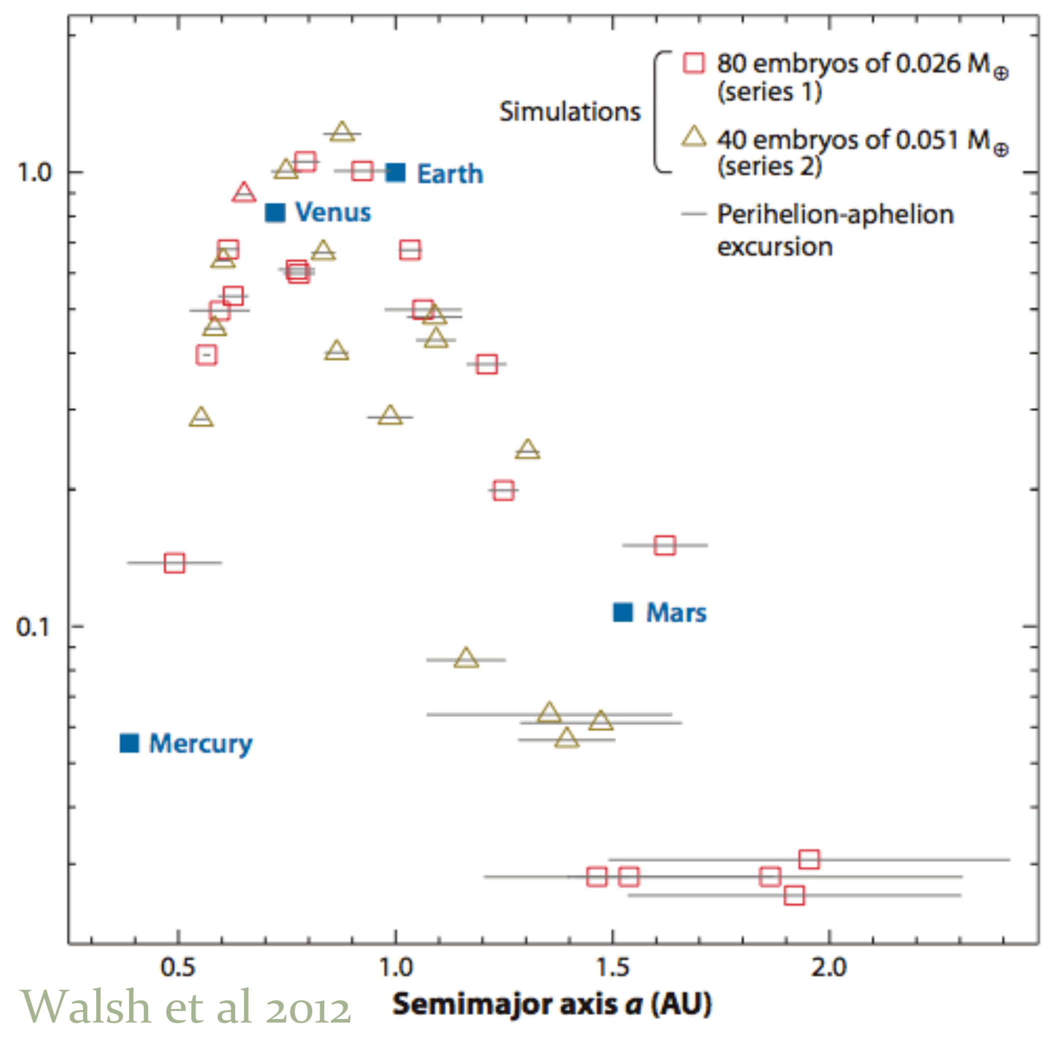
$$\frac{T_1}{T_2} = \frac{m}{n}$$

3D N-body simulation, artificial force on Jupiter and Saturn

A reversal of Jupiter's migration at 1.5 AU

Mass ratio of terrestrial planets can be systematically reproduced.

Mars: Stopped accreting when the Jupiter migrate in and disk truncate at 1 AU, and it is later scattered out by earth's embryo.



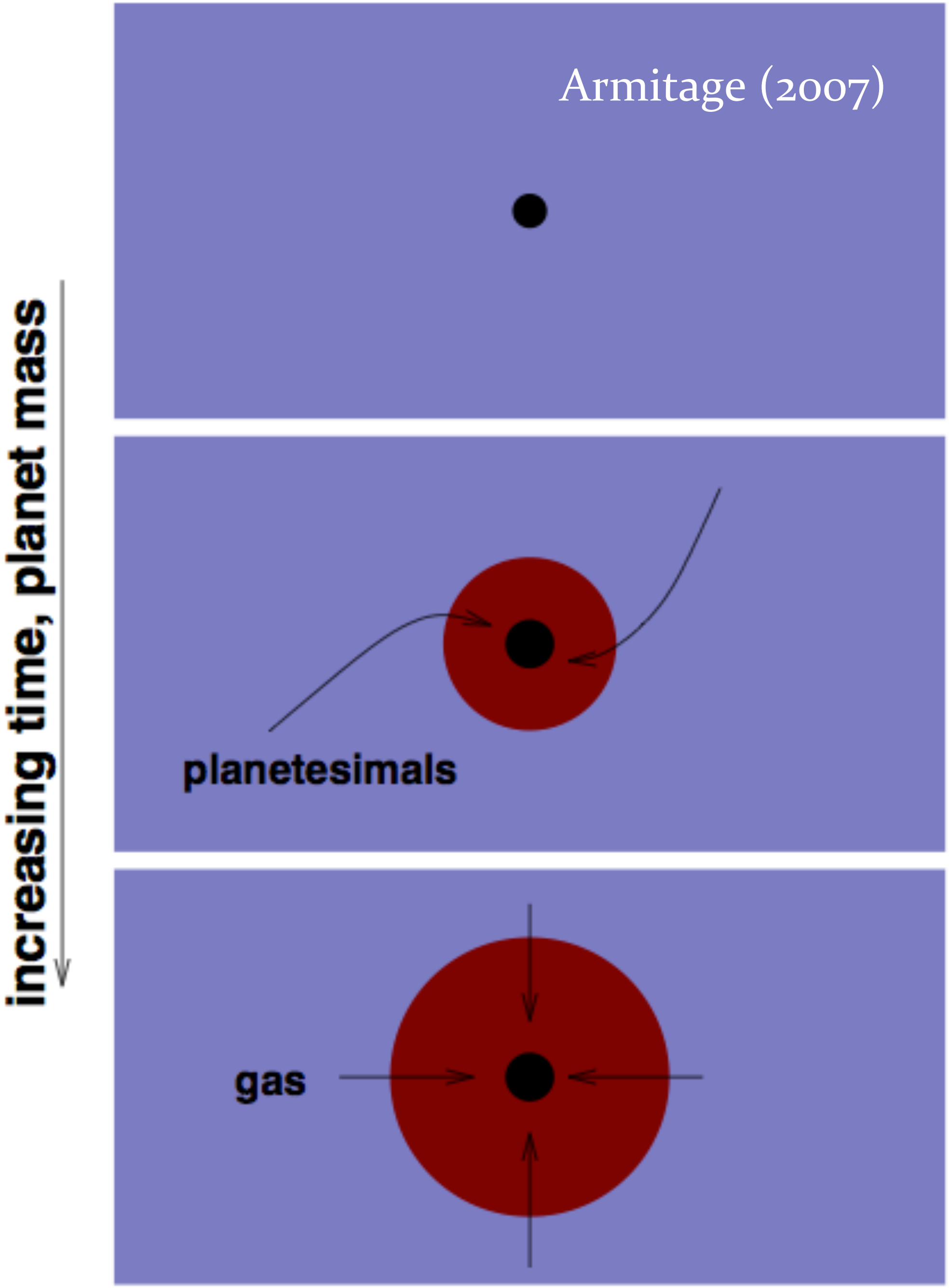
Walsh et al 2012

Gas giants: Core accretion VS. GI

- Core accretion (down to top)
  - The core of gas giants is assembled similar to terrestrial planets, and then the gas envelope was accreted.
  - Current dominant theory
- Gravitational instability (top to down)
  - Massive protoplanetary disk collapses directly to form massive planets.
  - Tends to form massive exo-Jupiters and brown dwarfs at large radii.

Core accretion

- A core formed
- It be came massive enough to hold on a significant envelope(in hydrostatic equilibrium). Luminosity mainly from infalling planetesimals.
- When the atmosphere's mass exceeds roughly the core mass, the atmosphere cannot maintain hydrostatic equilibrium and collapses(core accretion instability), leads to rapid gas accretion and the birth of a gas giant.

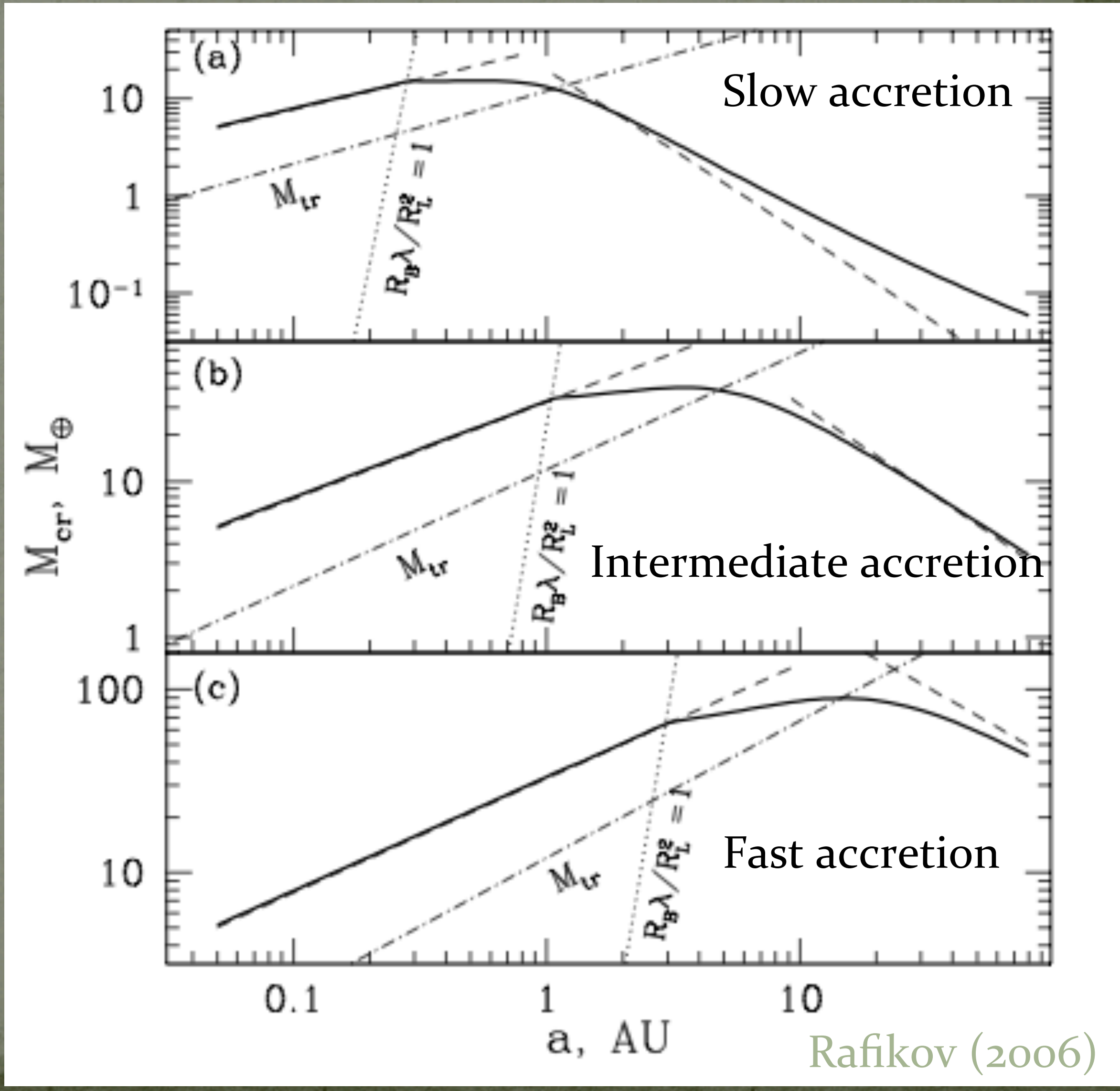

Armitage (2007)

Critical mass

Ikoma, Nakazawa & Emori (2000)

$$\frac{M_{crit}}{M_E} \approx 12 \left(\frac{\dot{M}_{core}}{10^{-6} M_E yr^{-1}} \right) \left(\frac{\kappa_R}{1 cm^2 g^{-1}} \right)$$

- Fast growth is at the expanse of a larger final core mass. M_{cr} ~20-40M_E >> M_{iso}
  - A very low opacity, M_{cr}~5M_E
  - Uncertainty of disk structure
- In situ formation of hot Jupiter is unlikely
  - M_{cr}~5M_E, not enough amounts or refractory material in inner disk, and takes a long time to form.
  - Gap formation becomes important at 0.2-0.5M_{cr}



Rafikov (2006)

GI – Disk fragmentation (Wendy)

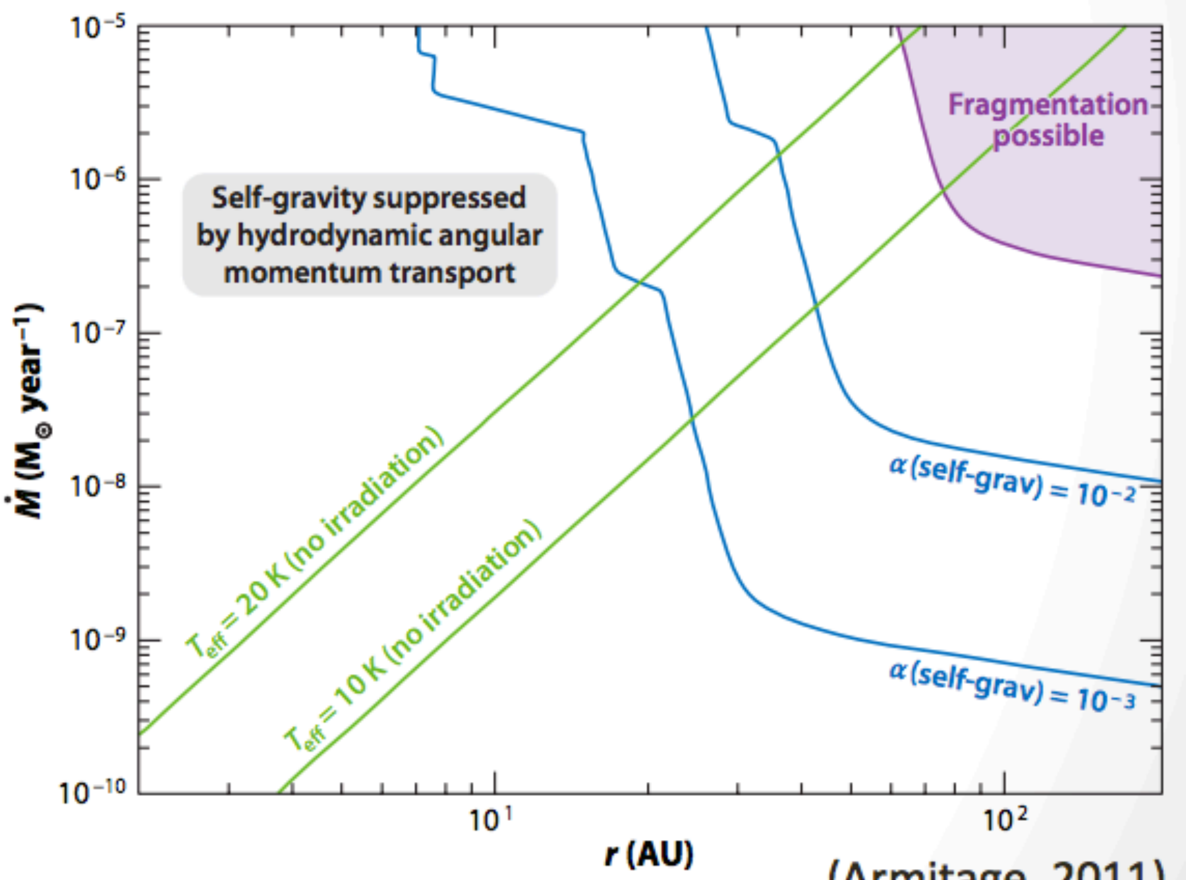
- Q value

$$Q \equiv \frac{c_s \Omega}{\pi G \Sigma} < Q_{\rm crit} \simeq 1$$

- Cooling timescale

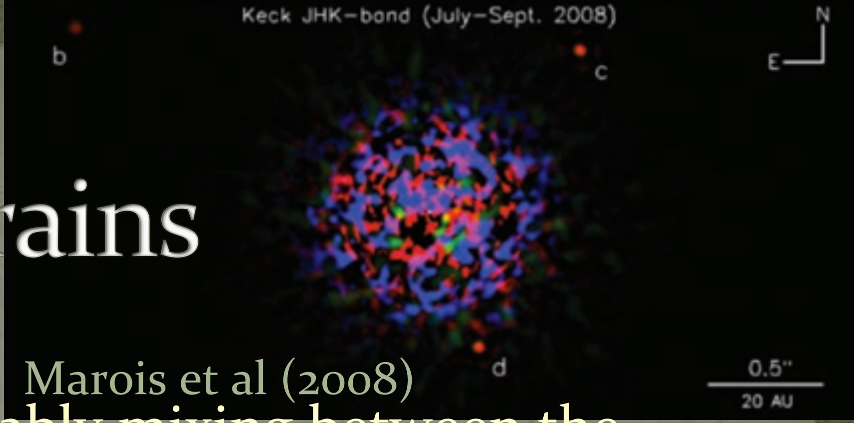
$$t_{\rm cool} \lesssim 5\ \Omega^{-1}$$

- Since fragmentation occurs at large radii (50-100AU) and early times, a large reservoir of mass is typically available locally and the likely outcome of fragmentation would be very massive planets or brown dwarfs
  - Can they migrate in?



(Armitage, 2011)

Observational constrains



Marois et al (2008)

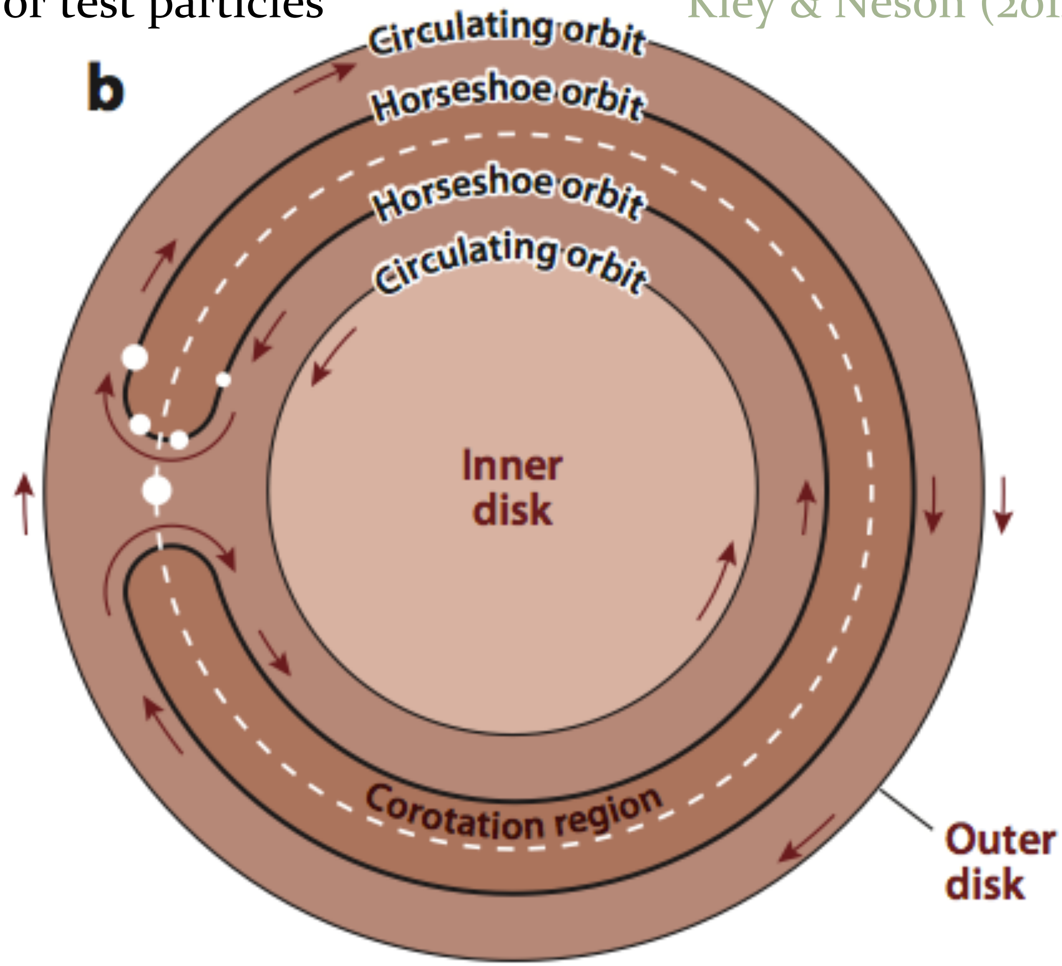
- Solar system
  - Jupiter's core mass < $5M_E$? Probably mixing between the core and the atmosphere after formation, uncertain parameters of core accretion, indirect observation of core mass and uncertain assumptions about Jupiter's atmosphere…
    - NASA's JUNO mission: expected to Jupiter arrival at 2016
  - Timescale to form Neptune is too long?
    - Probably not in situ formation
- Exoplanets
  - Core accretion consistent with observed correlation of planet frequency with host metallicity
    - Biased by radial velocity and transiting survey
  - The HR 8799 system with ~$15M_J$ planets at 24, 38, 68 AU?
    - Need future direct imaging of planets to test where there is a second population of massive planets in outer radii with different host metallicity distribution

Migration: Type I

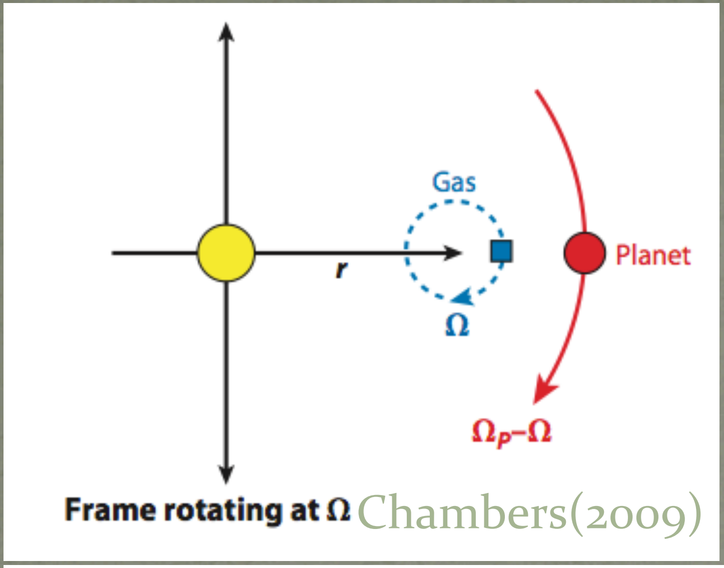
- Exterior to planet's orbit
  - Planet loses angular momentum to the gas, and tend to migrate inward. Gas will be repelled from the planet
- Interior to planet's orbit
- Sign of torque depends on which dominates
  - A subtle second order effect
- Horseshoe orbit
  - Closed orbit in the absence of viscosity
  - In real disk, co-rotation torque depends on viscosity and cooling

For test particles

Kley & Neson (2012)



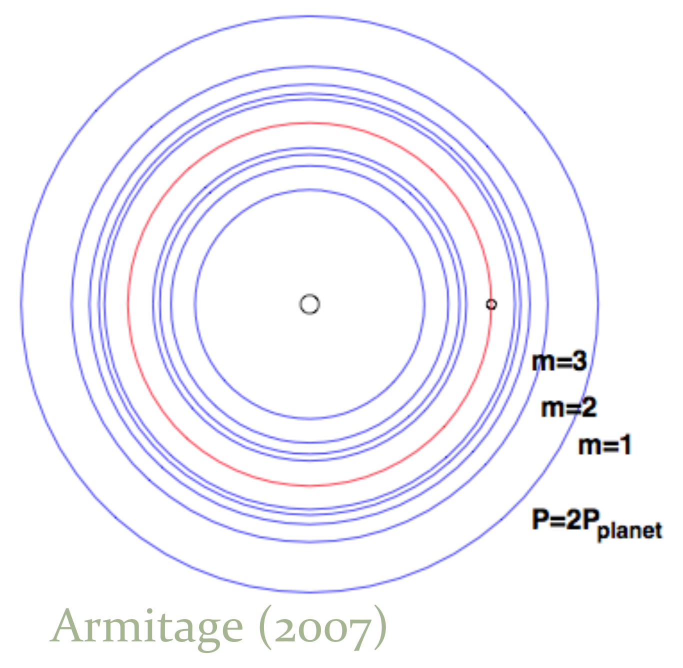
In real disk of gas: Linblad resonance



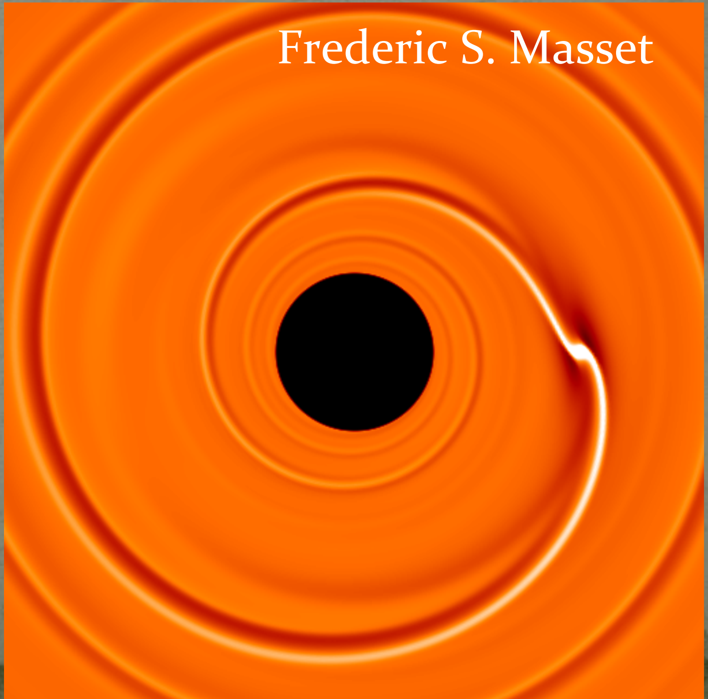
Chambers(2009)

- Resonance: Locations where planet have strong perturbation on gas and exchange angular momentum

$$\Omega_p - \Omega = \Omega_{epicycle}$$



Armitage (2007)



Frederic S. Masset

Timescale for type I migration

- In isothermal disk with smooth surface density distribution, under linear theory, the planet migrates inward in a short timescale. A 5 M_E core at 5AU:

$$\tau_{I,LR} \sim 0.5 Myr, \ \tau_I \propto M_P^{-1}$$

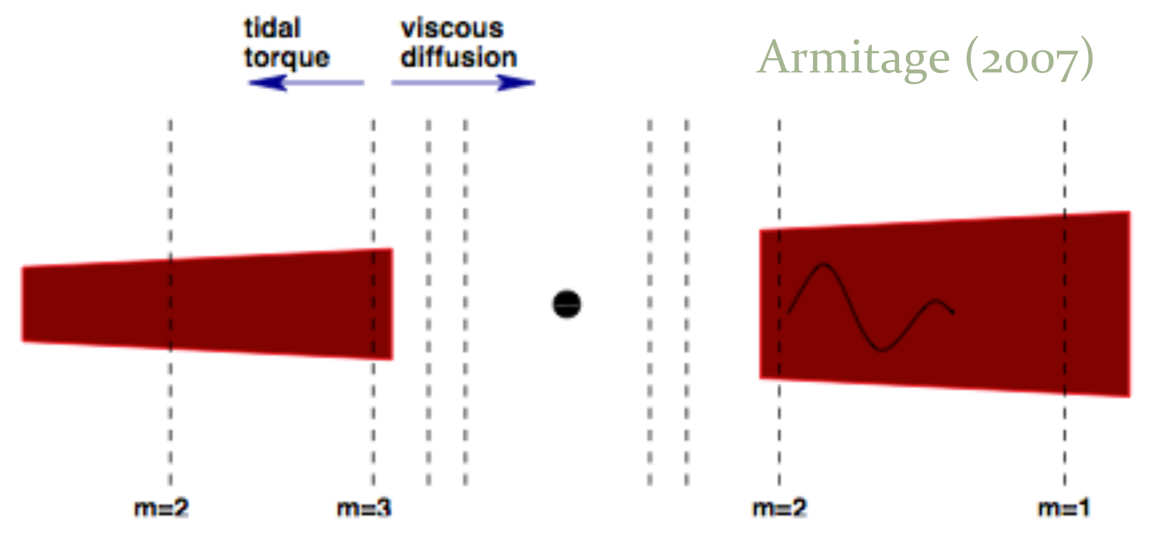
- However, it may be far from the truth. The sign and rate of migration is actually poorly understood
  - Poor understanding of disk structure, and migration sensitively depends on subtle physics
  - Torque on co-rotation orbits depends on viscosity and cooling time
  - Even simulations cannot include all the physics: radiative transfer, opacity, steep surface density gradient at the dead zone, magnetic field…

Migration: Type II

- A gap can be opened if the planet is massive enough that the timescale for opening a gap is smaller than the timescale to refill it by viscous diffusion

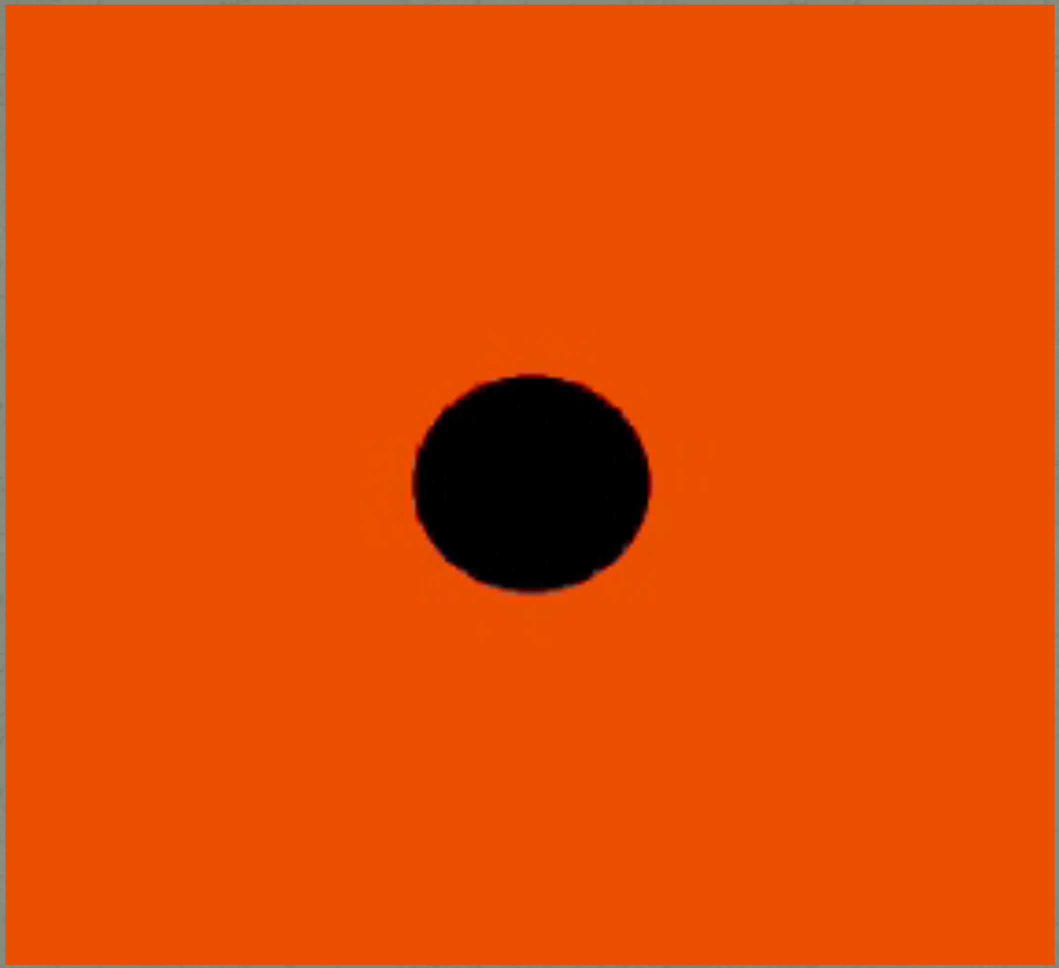
$$q \gtrsim \left(\frac{c_s}{r_p \Omega_p} \right)^2 \alpha^{1/2}.$$

- Jupiter mass planet should be massive enough to open a gap, and Saturn mass is close to the critical mass



Armitage (2007)

Gap opening of type II migration



Timescale for type II migration

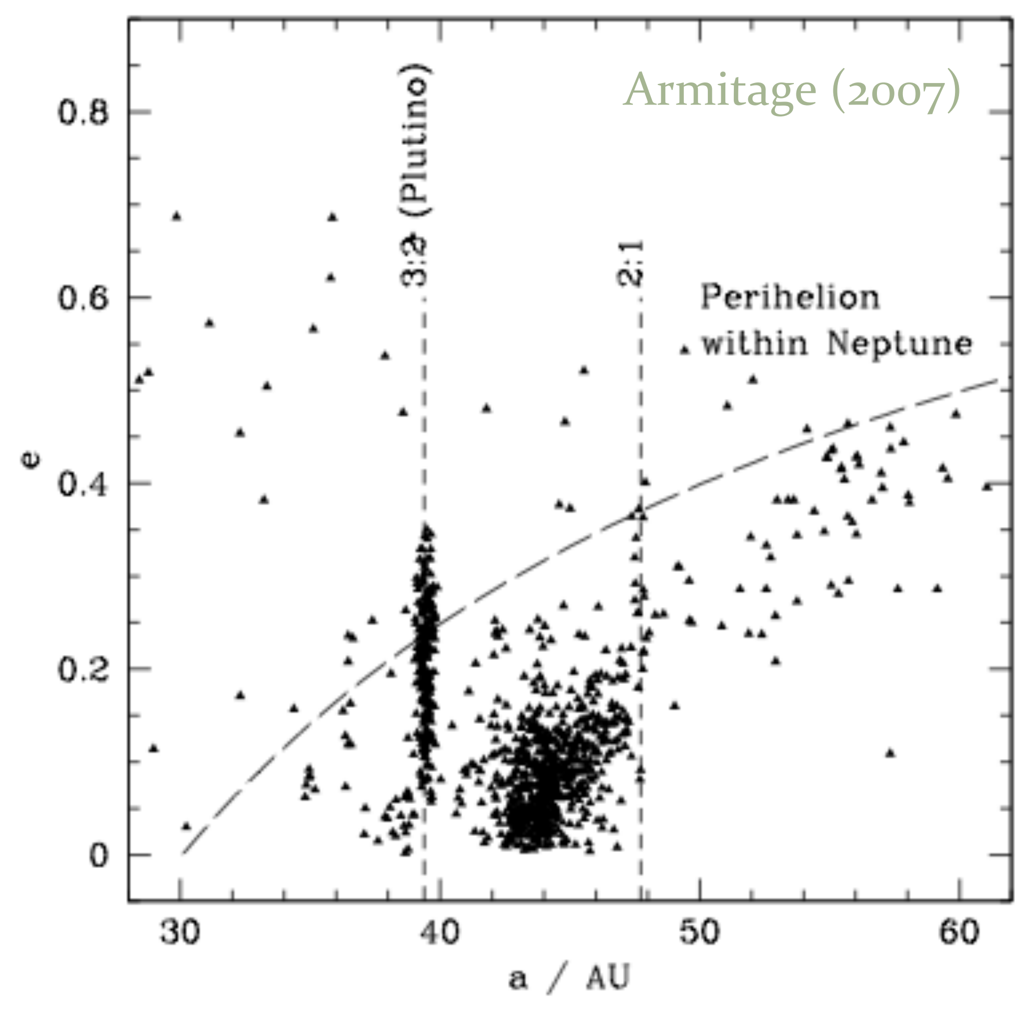
- The planet migrates at the same rate that gas moves viscously through the disk(inward at small radii and outward at large radii). If the planet approaches either edge of its gap, the resulting torque imbalance acts to return the planet toward the middle of the gap.
- Timescale typically longer than type I migration. h/r=0.05, α=0.01, at 5AU: ~0.5 Myr

$$\tau_0 = \frac{2}{3\alpha}\left(\frac{h}{r}\right)_p^{-2}\Omega_p^{-1}.$$

- Uncertainties
  - Simulations show that planets are able to accrete gas via tidal streams that bridge the gap, and this will exert substantial torque
  - Partial gap opening of Saturn size planets: type III?
  - Two gaps overlap: Jupiter and Saturn

Observational evidence for migration

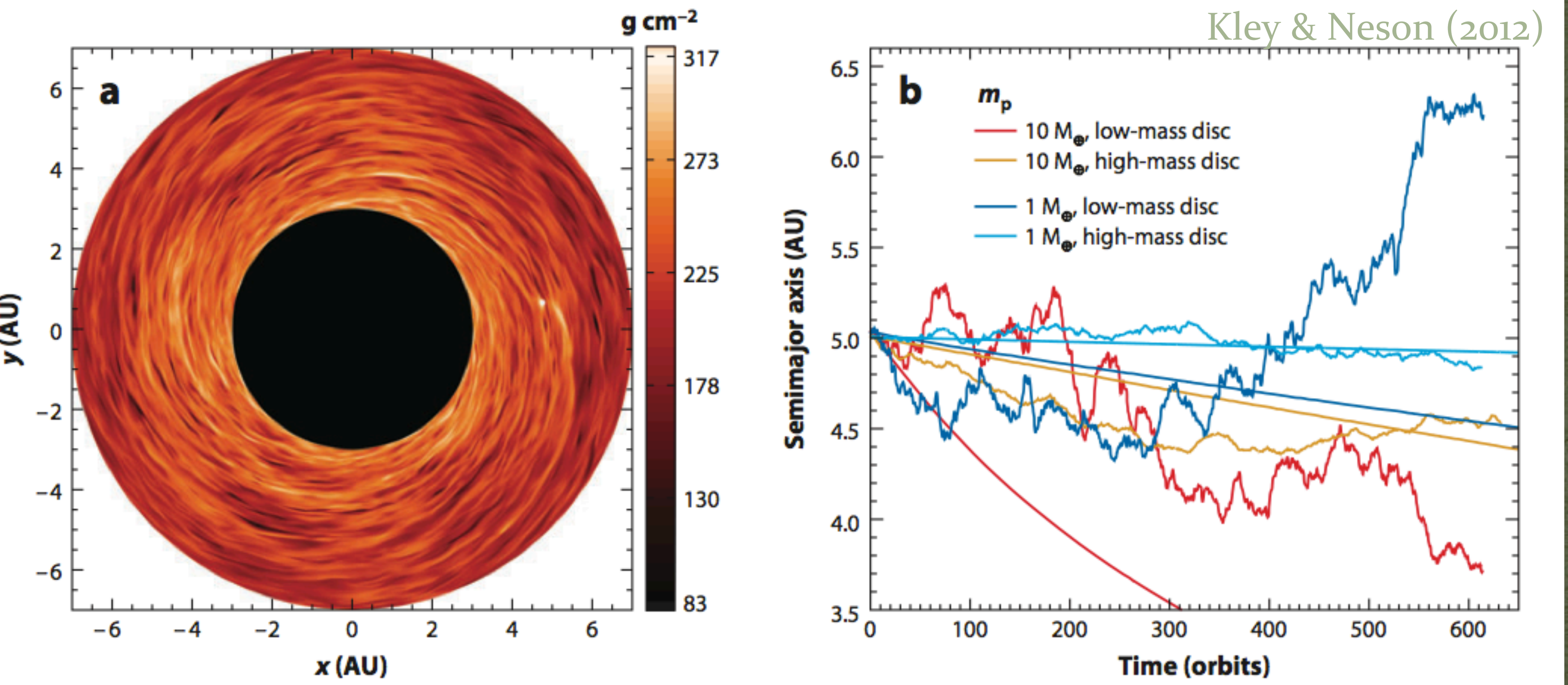
- Hot Jupiters
- The outward migration of Neptune
  - Pluto in highly eccentric orbit
  - Existence of a large population of KBOs in 3:2 resonance



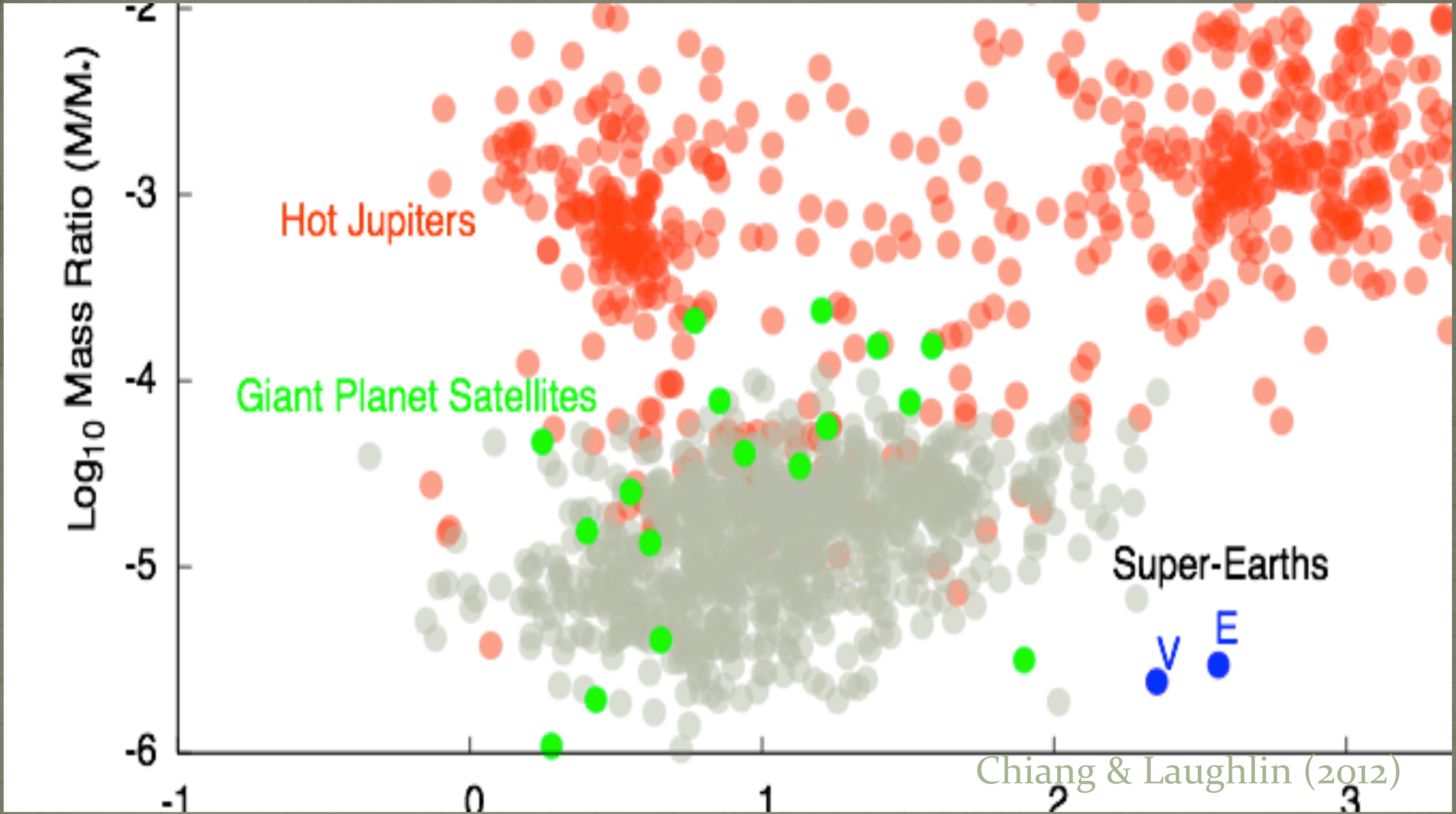
Armitage (2007)

Stochastic migration

Kley & Neson (2012)



Exoplanets



Chiang & Laughlin (2012)

- Diverse planet systems
- Statistical trends
- Future: mm/sub-mm high resolution direct imaging of disks and exoplants with ALMA

Summary

- Terrestrial planets: from planetesmals
  - Relative clearer than gas giant formation because mainly gravitational in the absence of gas (?)
- Gas Giants: Core accretion VS Gravitational instability
  - Uncertainties of core mass, formation timescale
- Planet migration: Type I & Type II
  - Poorly understood because of the uncertainties of disk structure
  - However, can be very important for dynamical interaction, and planets can probably from far from where we see them today
  - A main uncertainty in planet formation theory
- Exoplanets and future work
  - Well understanding of individual physics & Statistical trends of exoplanets
  - Disk observation and direct imaging of planet: ALMA

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