Dynamical mixing of planetesimals during Solar System history

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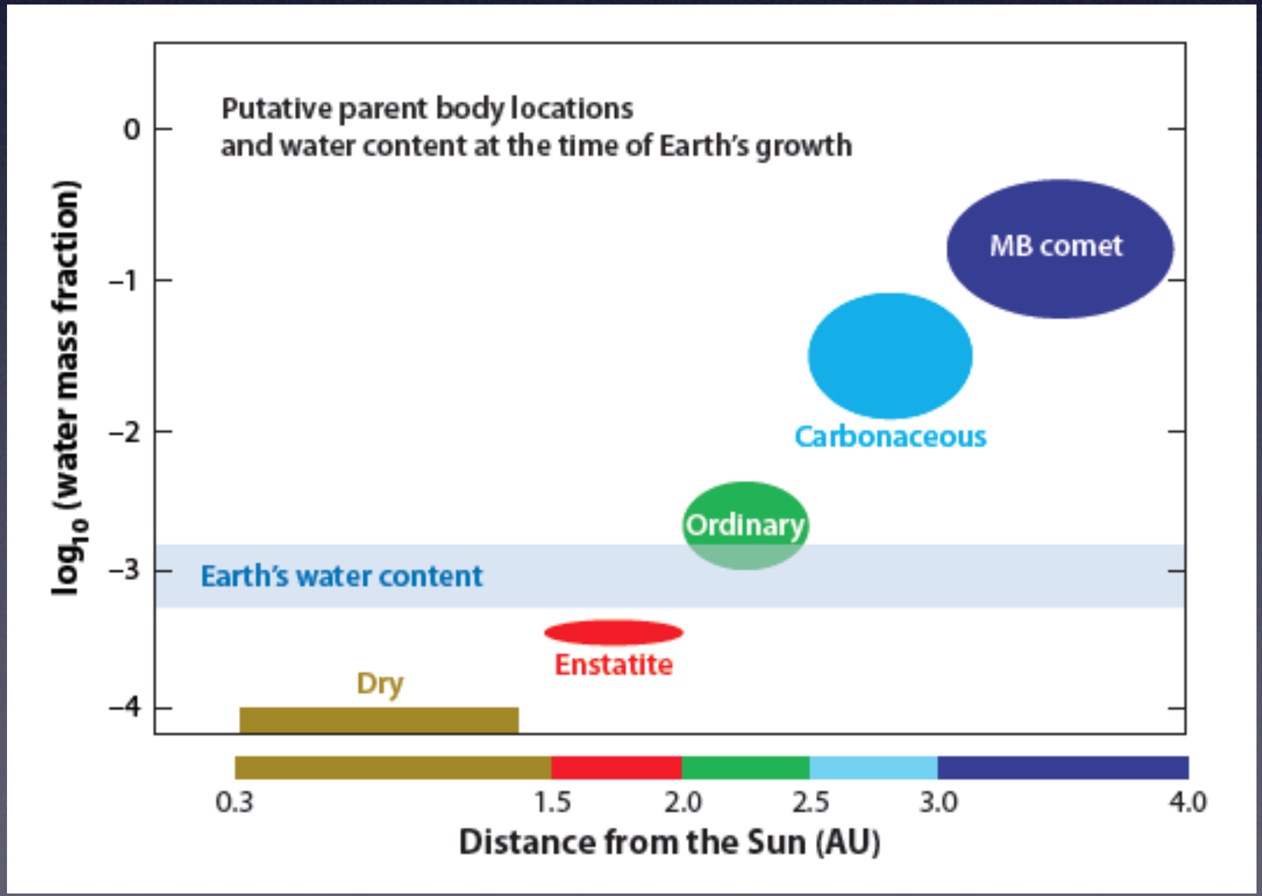
Outline

- Motivation: a few mysteries involving mixing
- Dynamics of particle scattering
- Radial mixing during different phases of Solar System history

Mystery 1: origin of Earth's water

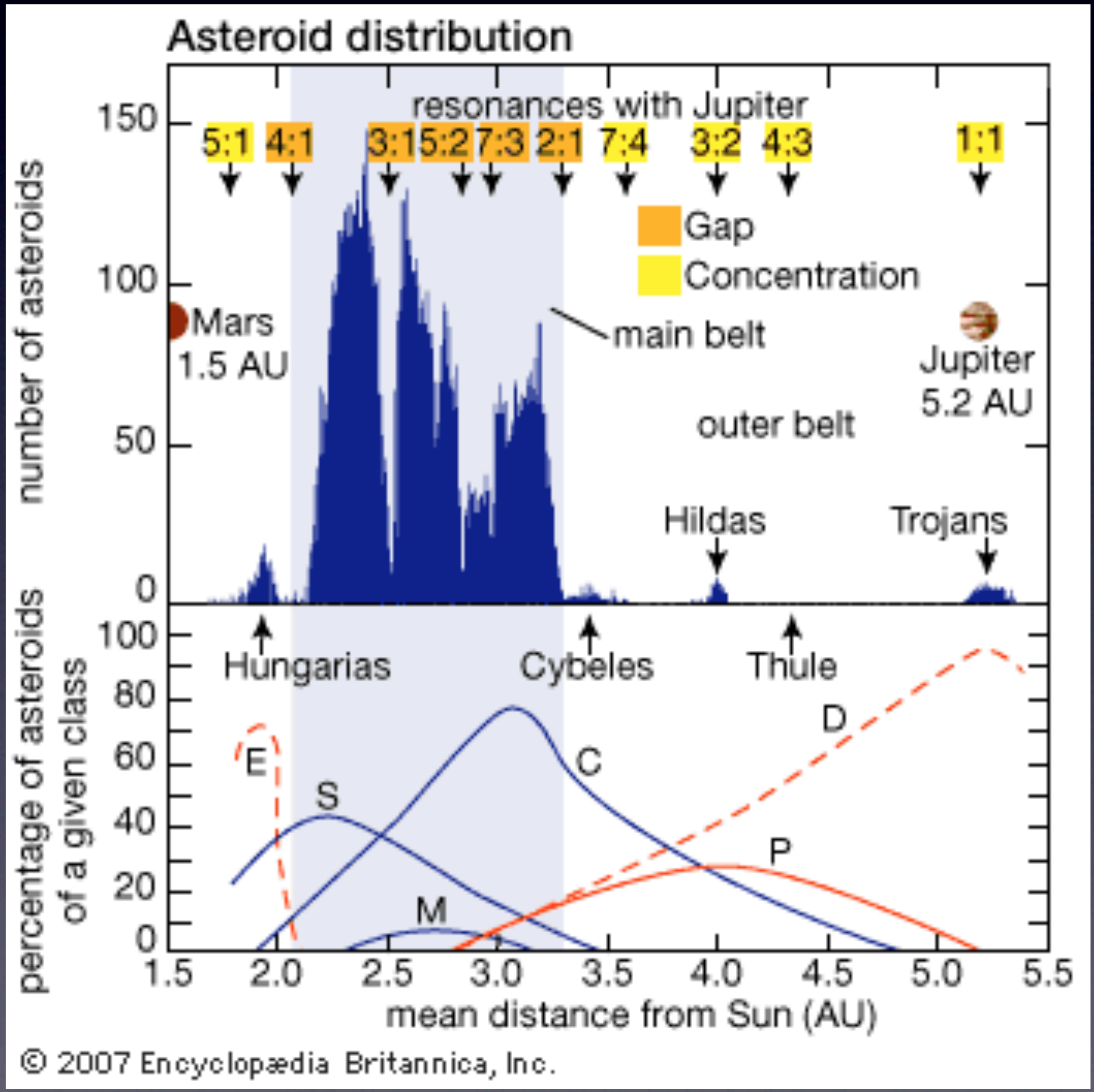
- Terrestrial planet-forming region is thought to have been very dry (Boss 1998, Podolak 2010, ...)
- Earth's water is very good match to carbonaceous chondrites (C-types) from outer belt.



Morbidelli et al 2012

Mystery 2: structure of the asteroid belt

- Many distinct asteroid types on similar orbits
- Large-scale gradient: “primitive” in outer belt, “differentiated” in inner belt



Mystery 3: color structure of Trans-Neptunian objects

- Low-inclination "cold" KBOs are red
- Range of colors among "hot" population
- Origin unknown

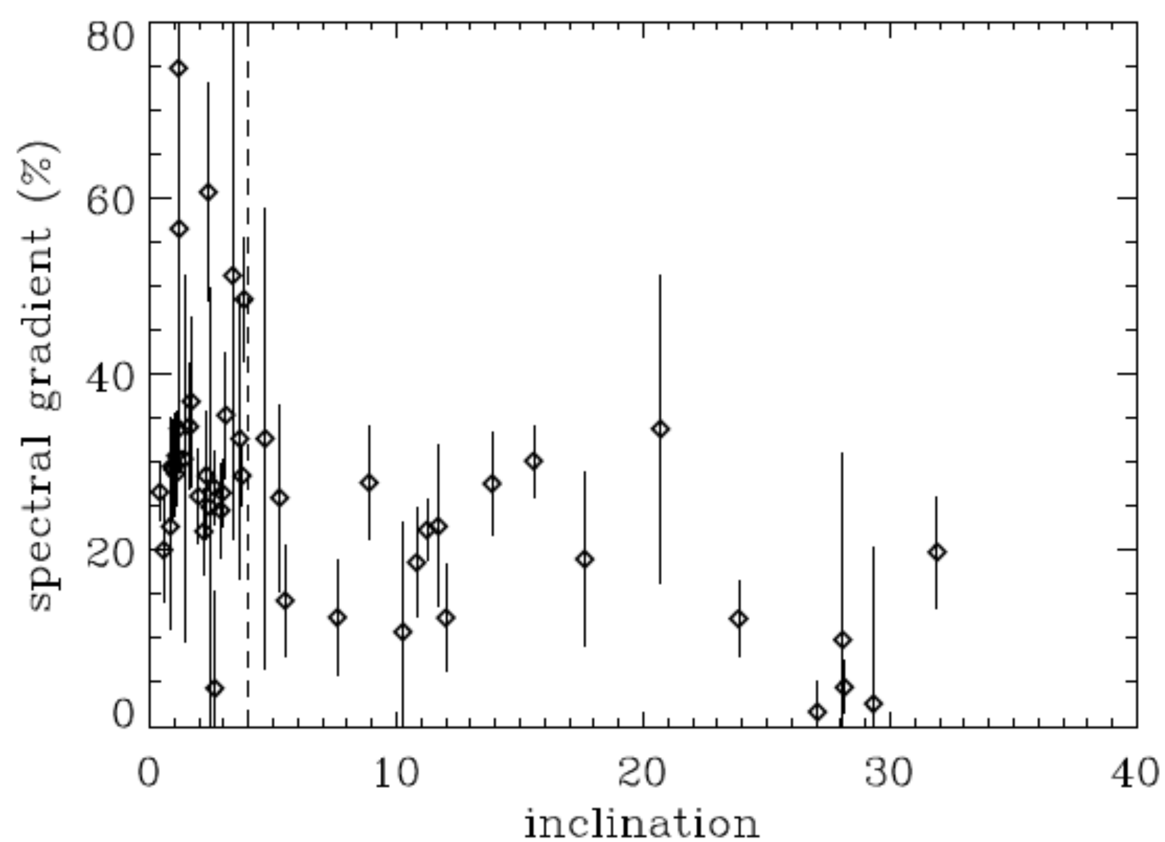


Figure 5: Color gradient versus inclination in the classical Kuiper belt (from [125], using the database in [65]). Color gradient is the slope of the spectrum, in % per 100nm, with 0% being neutral and large numbers being red. The hot and cold classical objects have significantly different distributions of color.

Morbidelli & Brown 2005; Doressoundiram et al 2008

Mystery 4: origin of close-in exoplanets

- At least 30-50% of Sun-like stars have planets with P<100 days and M<20 Earth masses (Mayor et al 2011, Howard et al 2010, 2012, Fressin et al 2013).
- No disk model has that much mass so close to star.

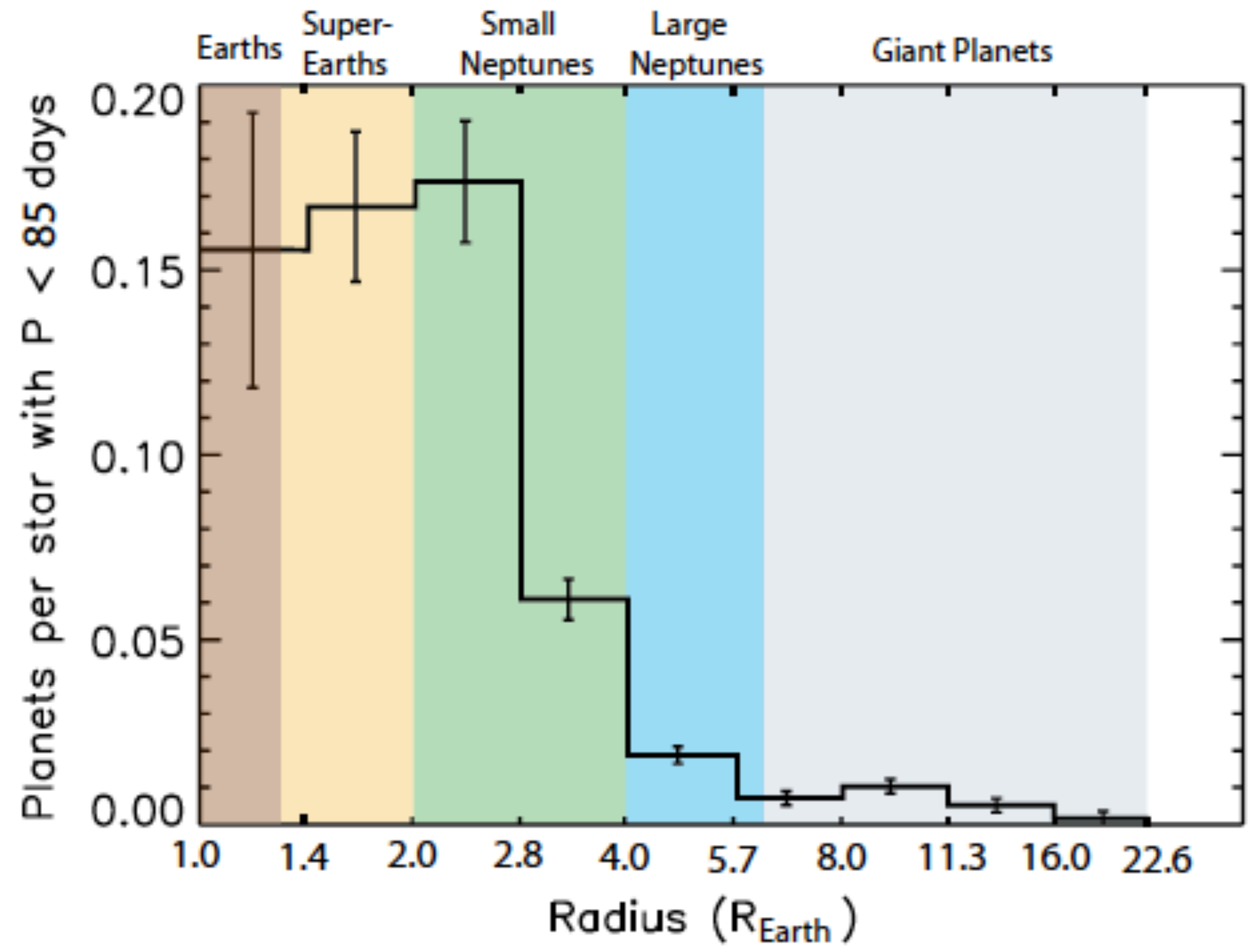
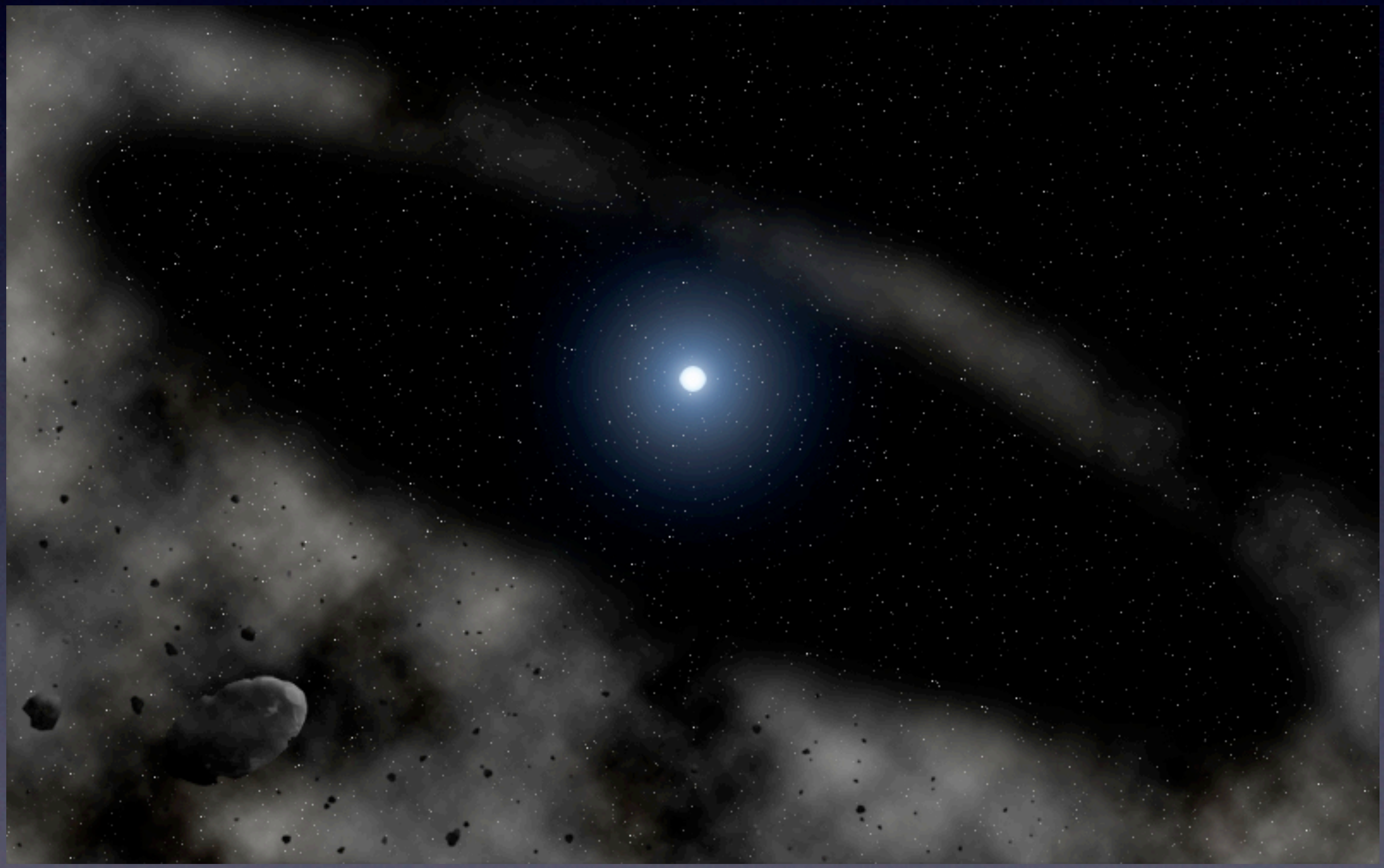


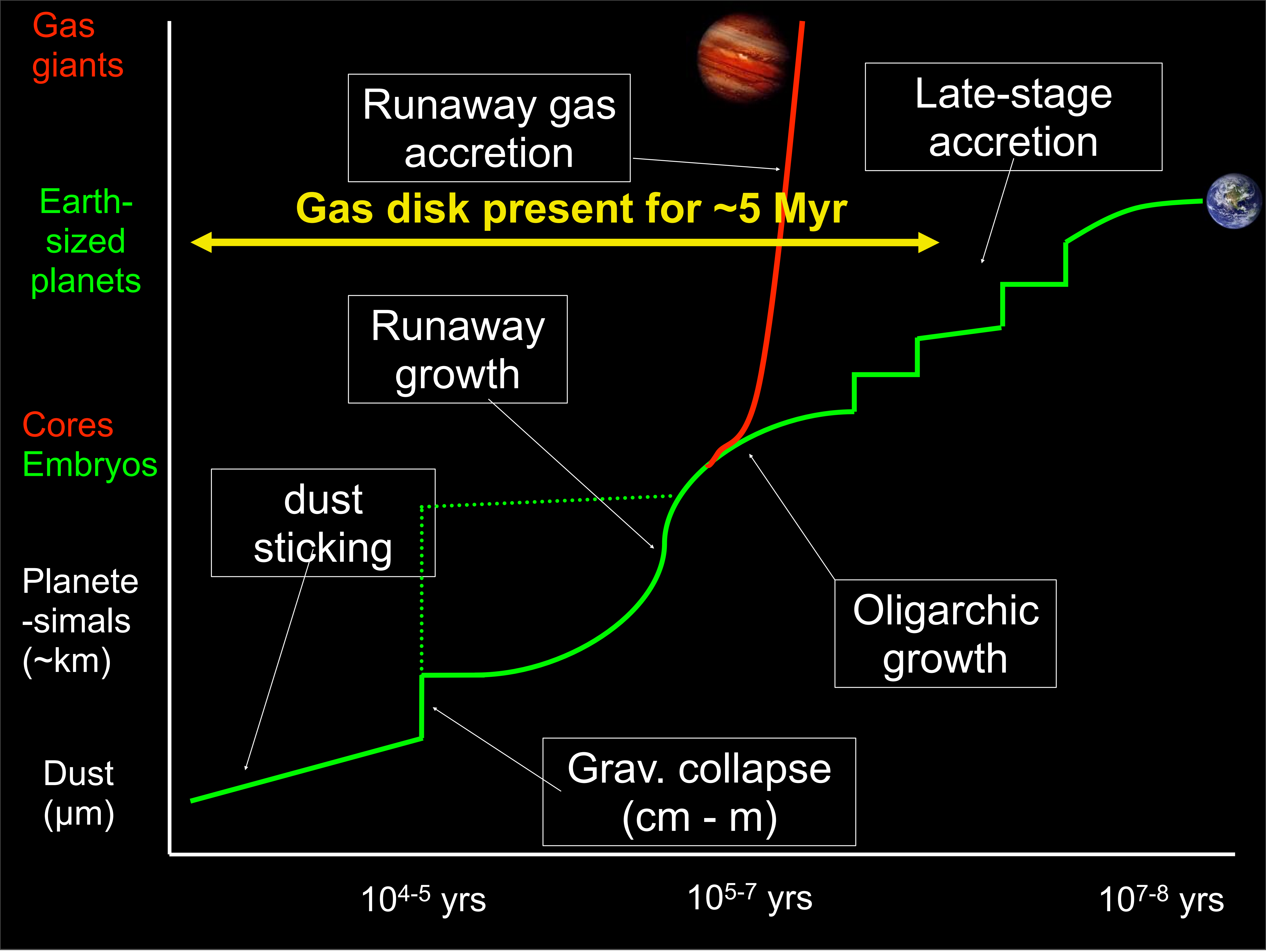
FIG. 7.— Average number of planets per size bin for main sequence FGKM stars, determined here from the Q1–Q6 *Kepler* data and corrected for false positives and incompleteness.

Fressin et al 2013

Mystery 5: the “Vega phenomenon”

- Vega has 2 known dust sources (e.g., Su et al 2013)
    - T~50 K (long-lived)
    - T~150 K (very short-lived)
- Planets in between? (e.g., Bonsor et al 2012)




Gas giants
Earth-sized planets
Cores
Embryos
Planete-simals (~km)
Dust (μm)
Runaway gas accretion
Late-stage accretion
Gas disk present for ~5 Myr
Runaway growth
dust sticking
Oligarchic growth
Grav. collapse (cm - m)
10^{4-5} yrs
10^{5-7} yrs
10^{7-8} yrs

Radial mixing: dust to ~10m

- Inward flow from following pressure gradient of gas
  - Or net flow toward pressure bumps
  - Can get stopped by resonant trapping with planets or embryos
- Turbulent mixing

Radial mixing: planetesimals (10m-100km)

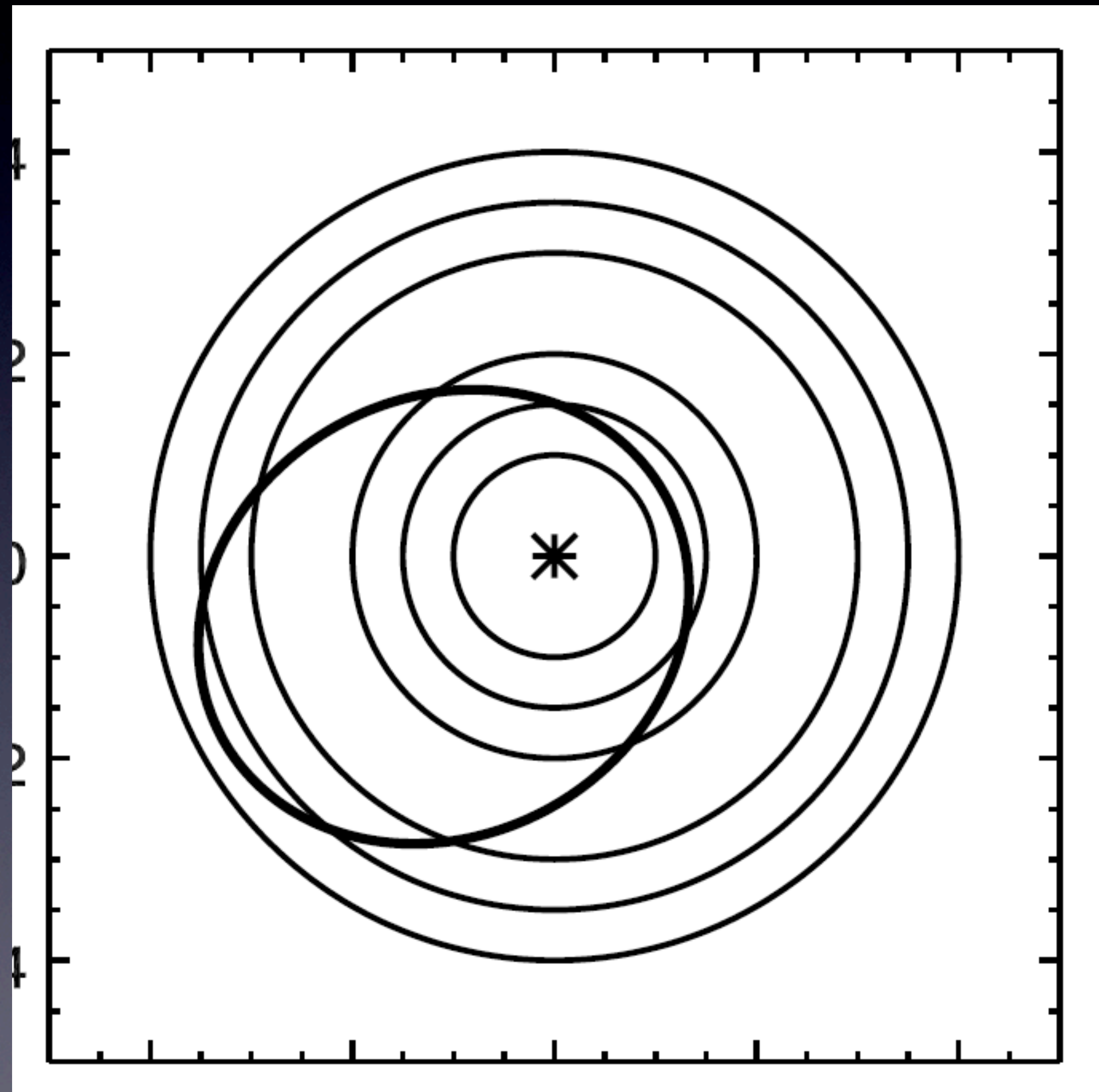
- Inward migration via gas drag
- Turbulent mixing
- Shepherding by embryos/giant planets during gas-driven migration
- Scattering by:
  - Planetary Embryos
  - Giant planets
    - During rapid gas accretion
    - During gas-driven migration (Grand Tack)
    - During planetesimal-driven instability (Nice model)

Radial mixing: planetary embryos (>1000km)

- Type 1 migration: usually inward
- Scattering by
  - other embryos
  - giant planets.

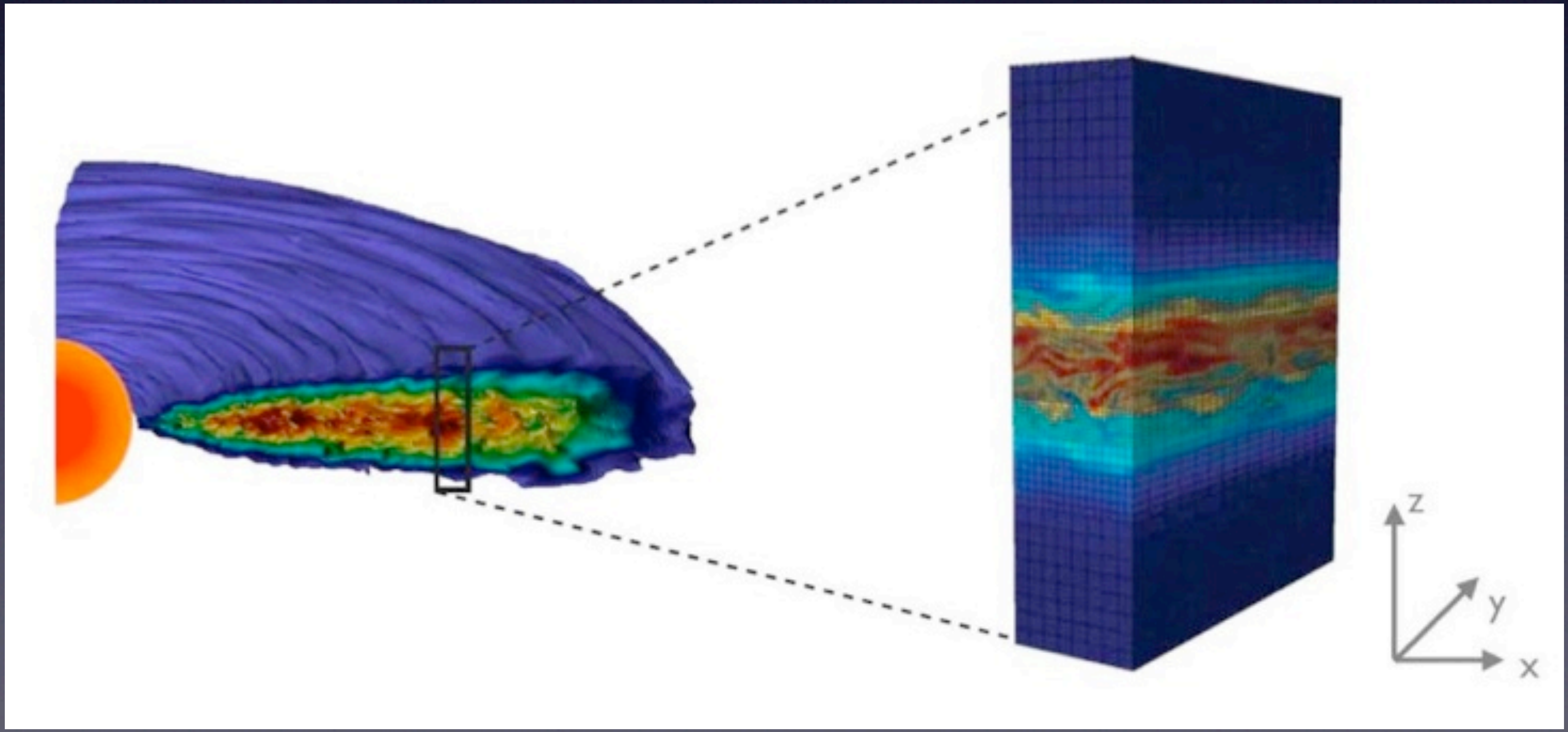
The importance of eccentricity

- For radial mixing to occur, particles need nonzero eccentricities
- Sources: disk turbulence, scattering by larger bodies



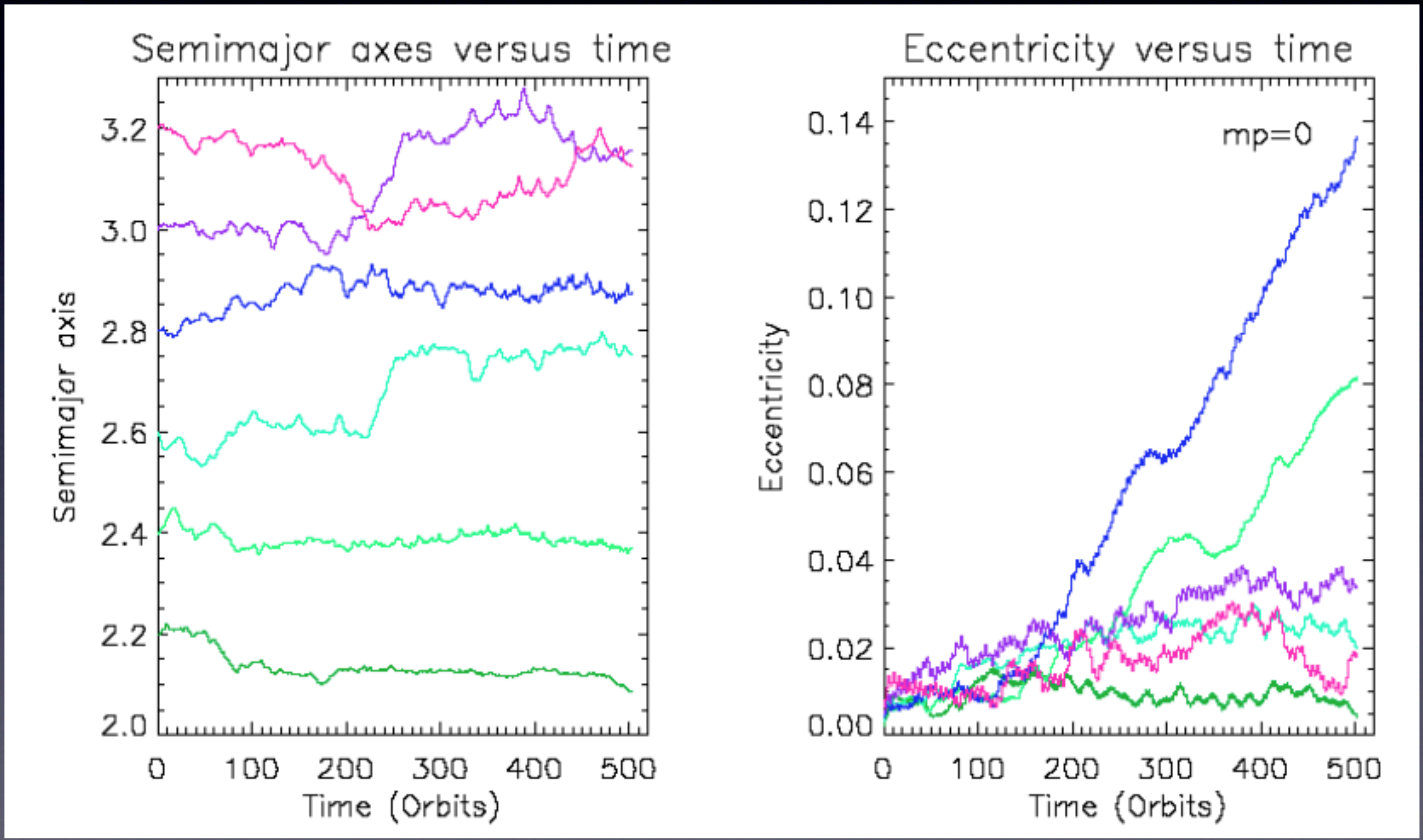
Turbulence

- Turbulence in disks create density fluctuations on a range of size scales
- Density fluctuations perturb bodies in orbit:



credit: Jake Simon

Turbulence causes random walk in planetesimal (and embryo) semimajor axis, increase in eccentricity



Nelson 2005

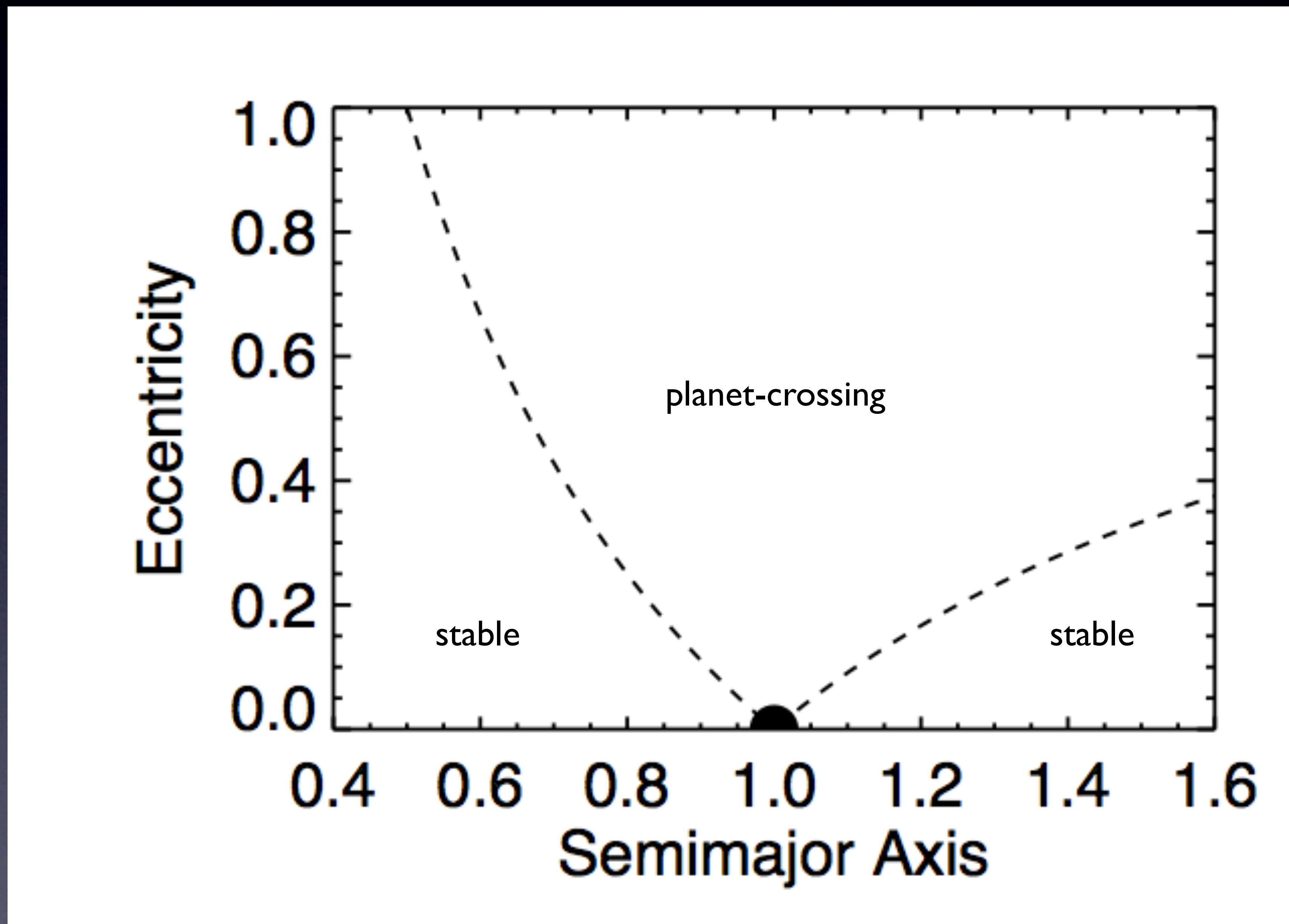
Dynamics of scattering by a large body

- Inside a planet's Hill sphere RH, the planet's gravity is stronger than the star's
- Stability criterion for 2 particle near a large body: ~3.5 RH

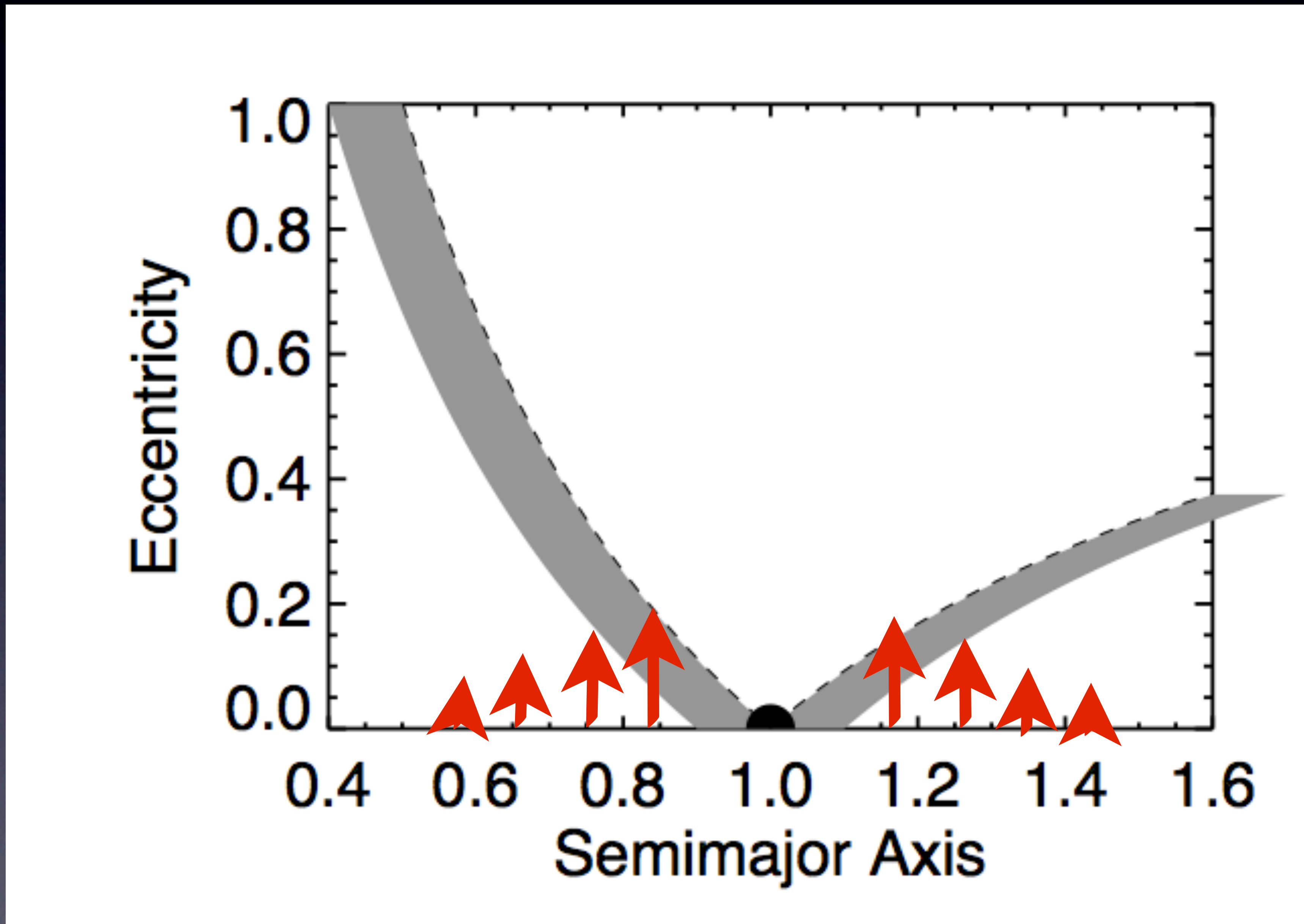
$$R_H = a \left(\frac{M}{3M_*} \right)^{1/3}$$

- Earth: RH~0.01 AU. Each giant planet has RH~1/3 AU

Which particles can be scattered?

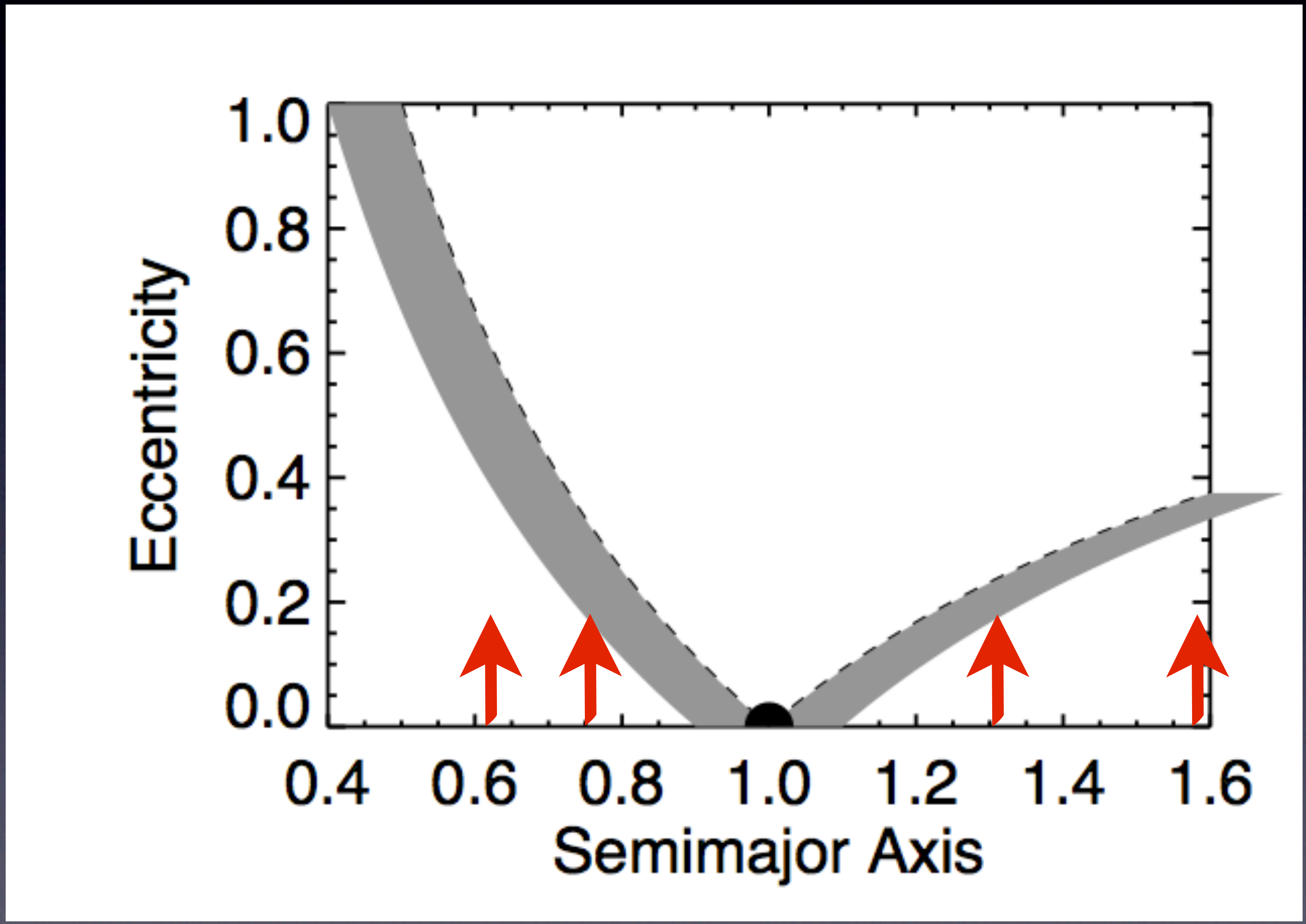


Which particles can be scattered?



Secular forcing

Which particles can be scattered?

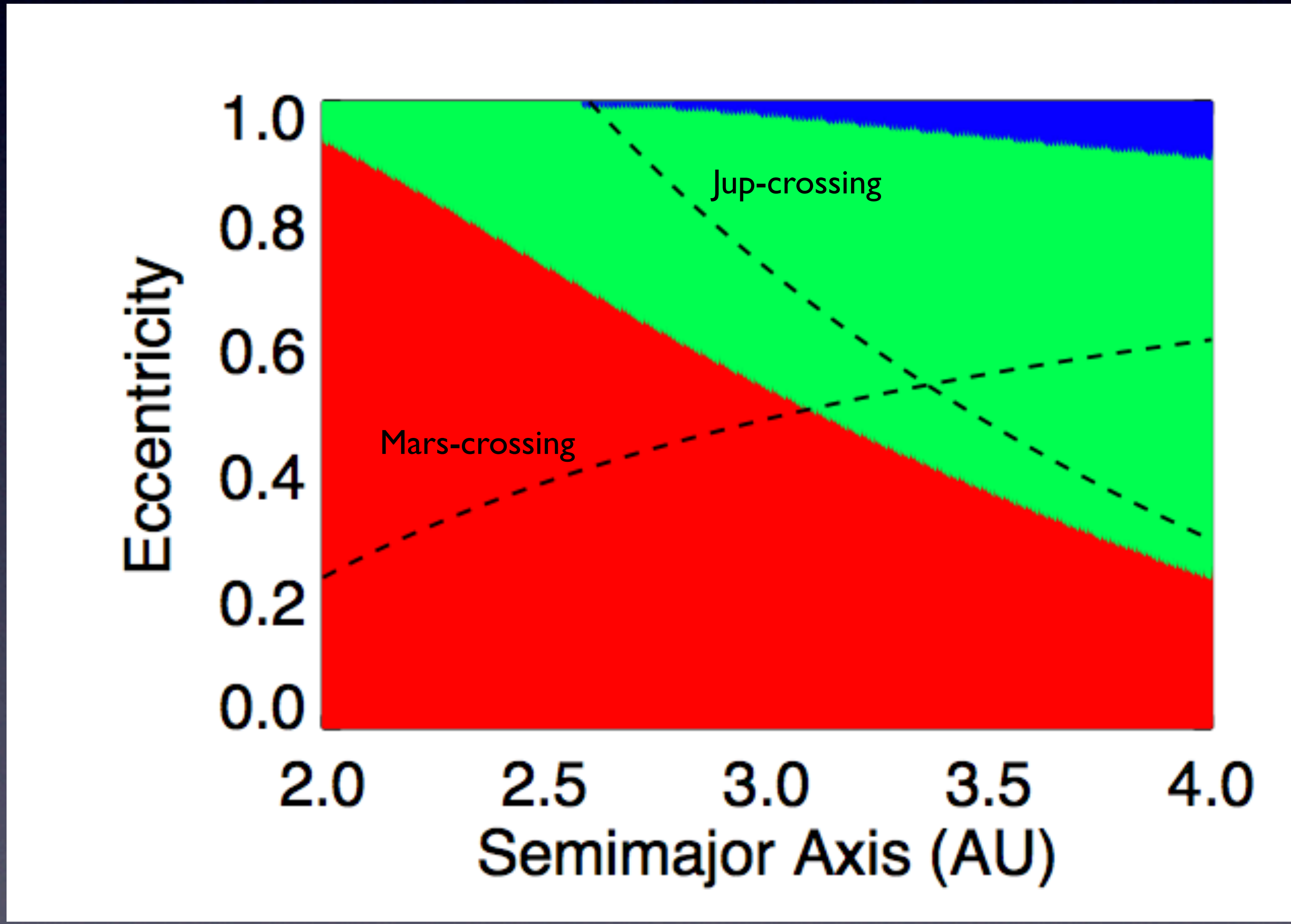


Resonances

Tisserand parameter

$$T_P = \frac{a_P}{a} + 2 \cdot \sqrt{\frac{a}{a_P}(1 - e^2)} \cos i$$

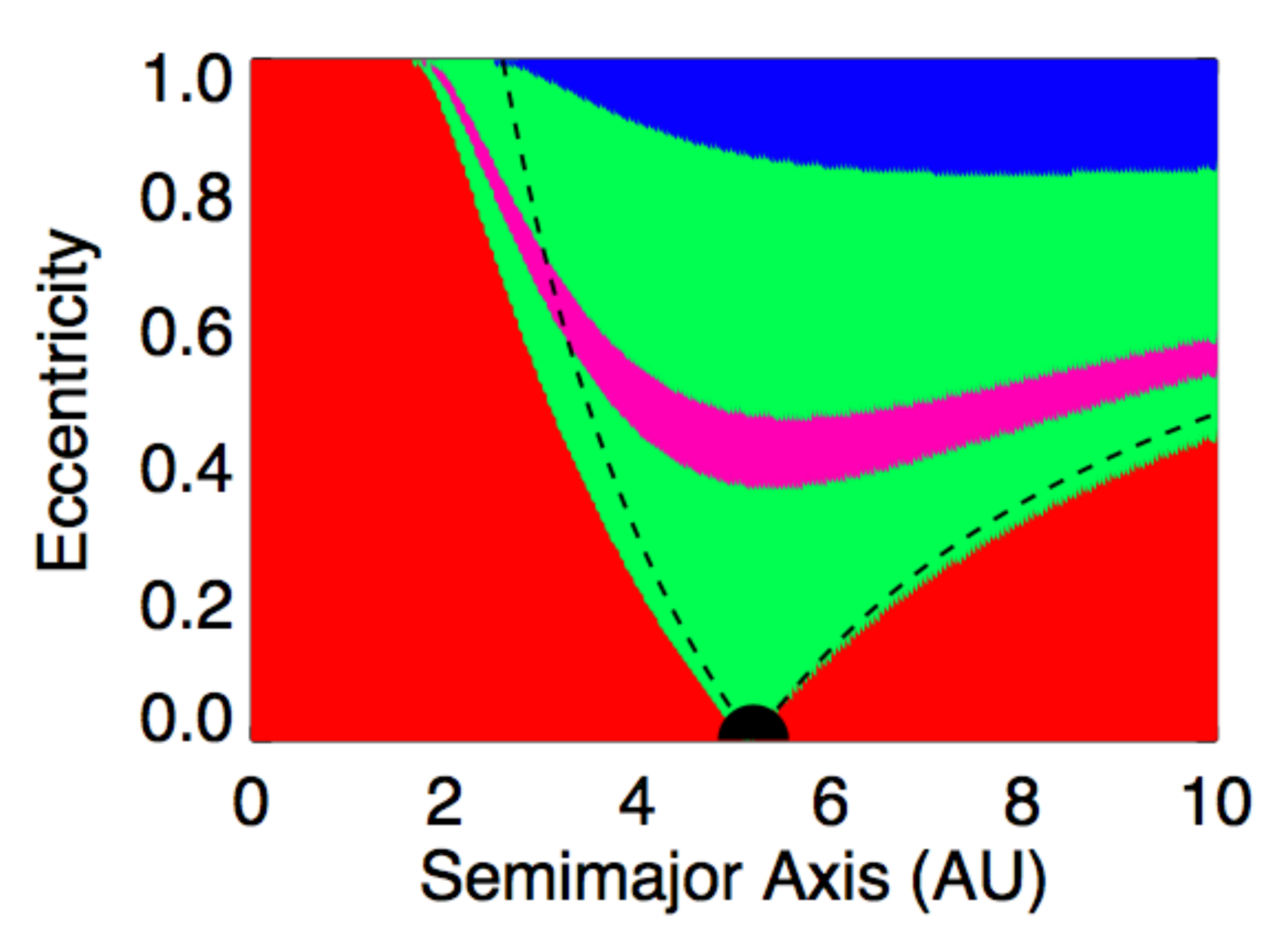
- Conserved quantity during scattering in restricted 3-body problem
- Asteroids have **TJ >3**
- Comets usually have **2<TJ<3**



T differentiates asteroids and comets

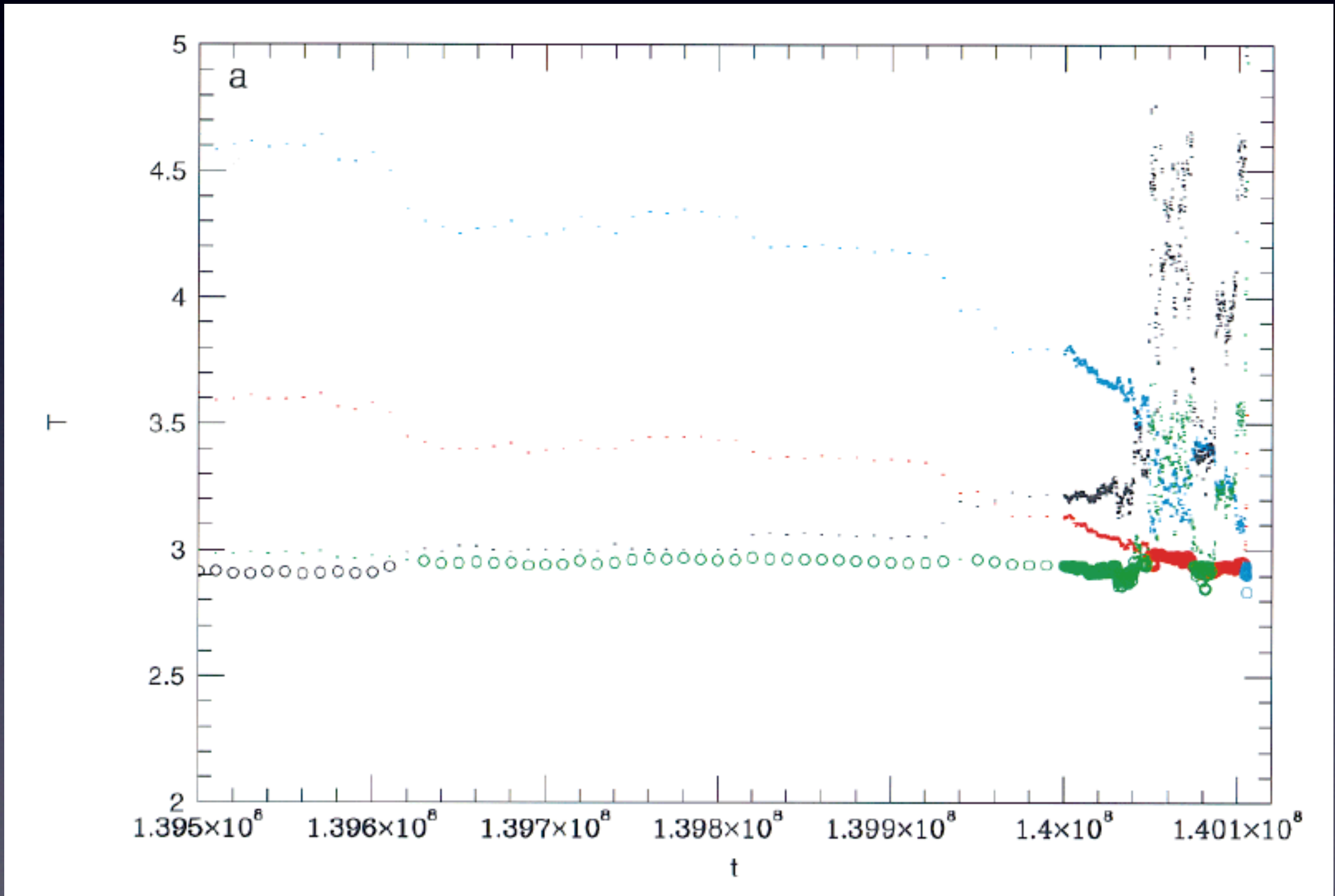
$$T_P = \frac{a_P}{a} + 2 \cdot \sqrt{\frac{a}{a_P}(1-e^2)}\cos i$$

- Asteroids have **TJ >3**
- Comets usually have **2<TJ<3**
- Here, pink is **TJ ~ 2.8**



Example: a comet scattered inward by multiple planets

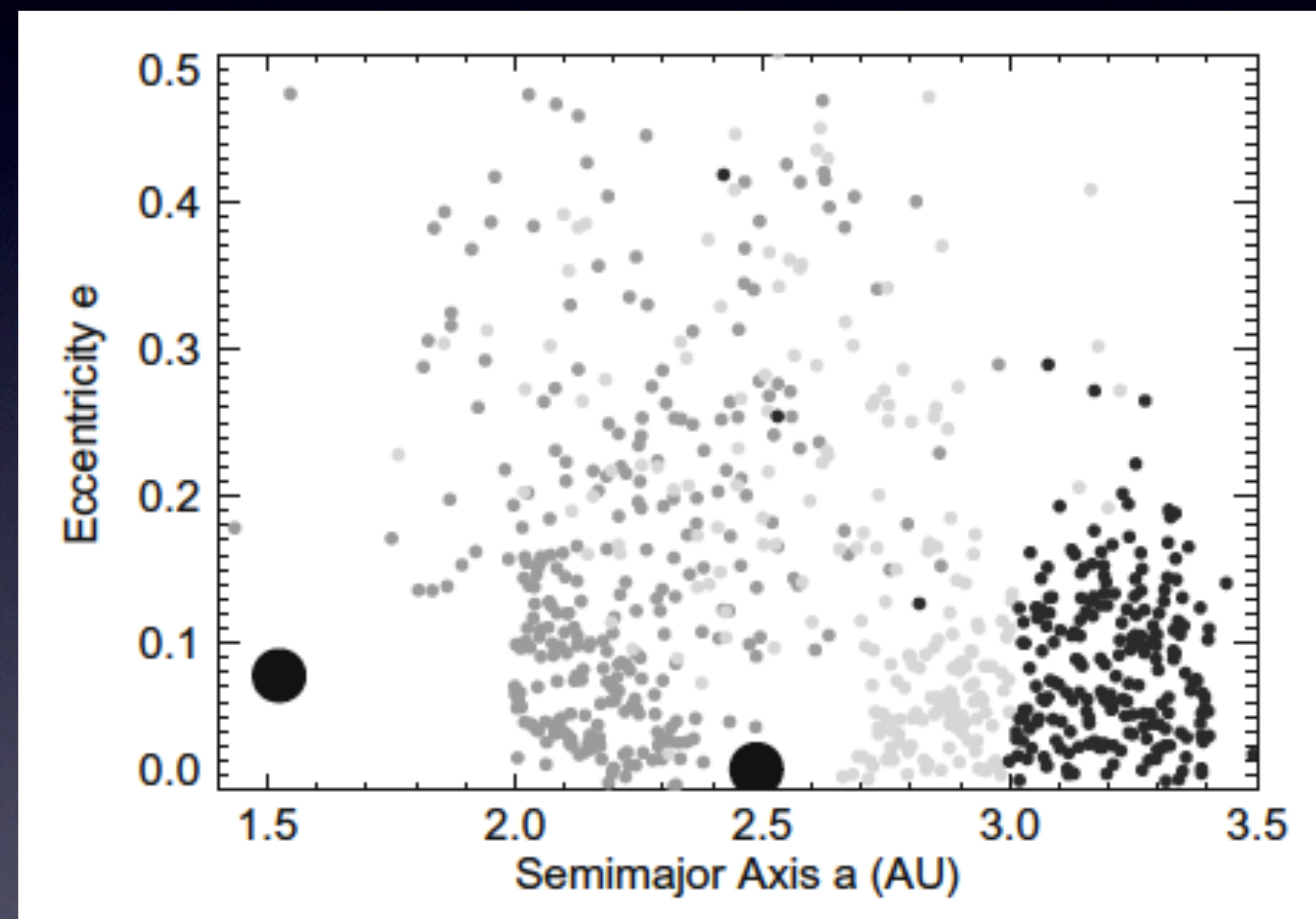
- Tisserand parameter with respect to each planet: **TN**, **TU**, **TS**, **TJ**
- T ~ conserved, (never decreases below initial value)
- Encounters with planets usually at T just below 3



Levison & Duncan 1997

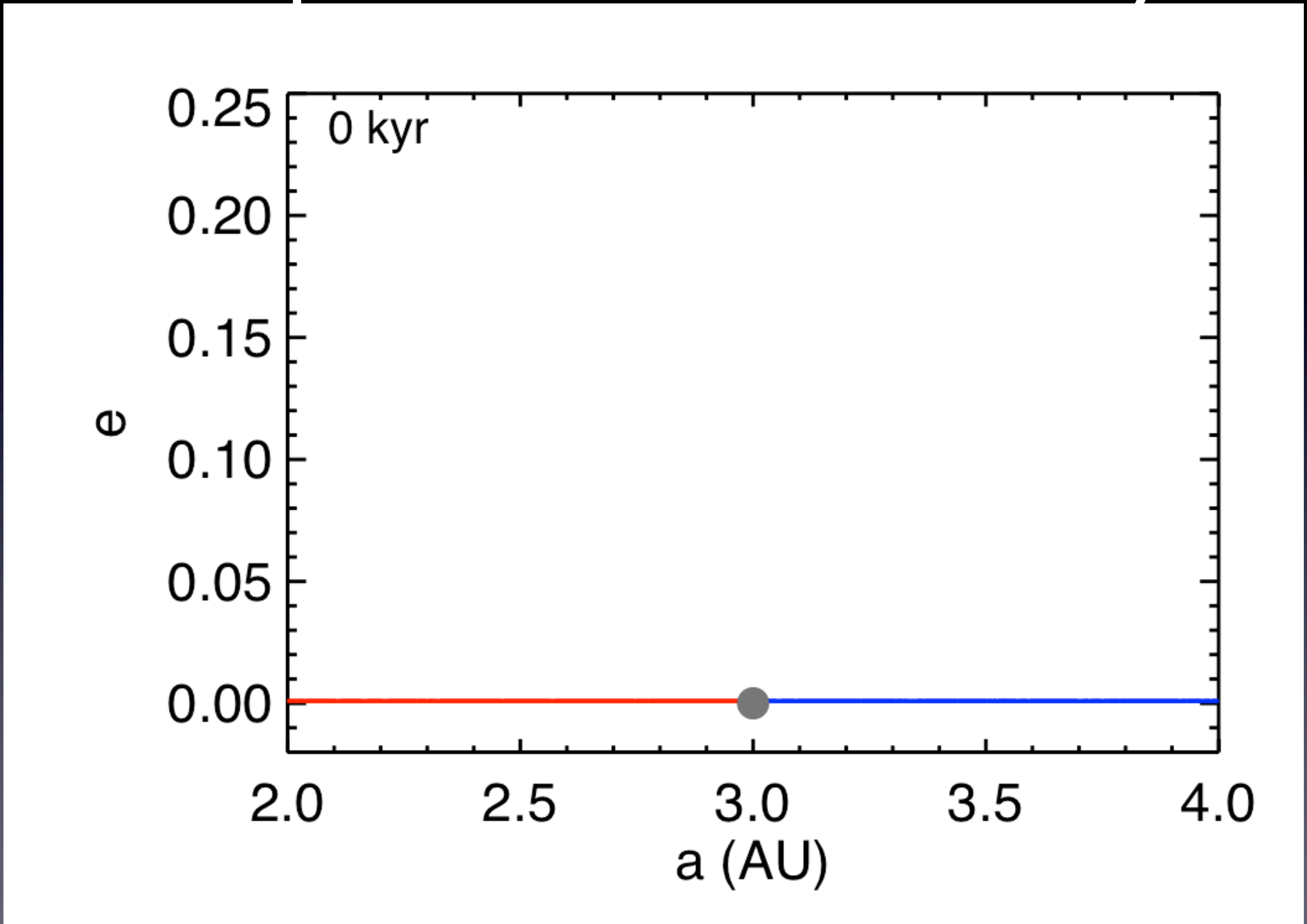
Some examples of radial mixing from scattering by a large body

- 1000 Planetesimals from 2-4 AU
- One planet at 3 AU with M = 0.1, 1, 10 Earth masses

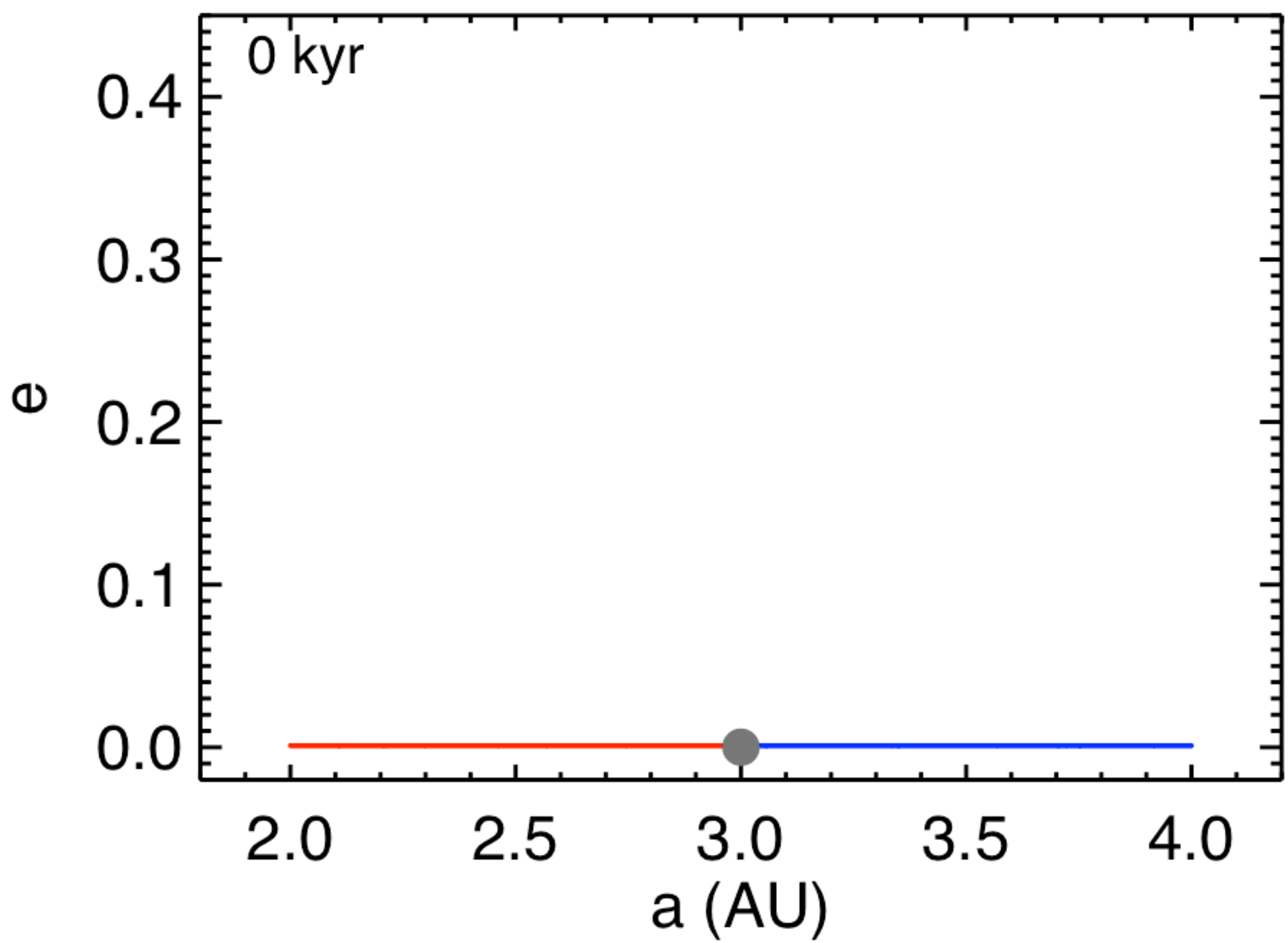


Similar example: Mars-sized embryo in the asteroid belt
(Raymond et al 2009)

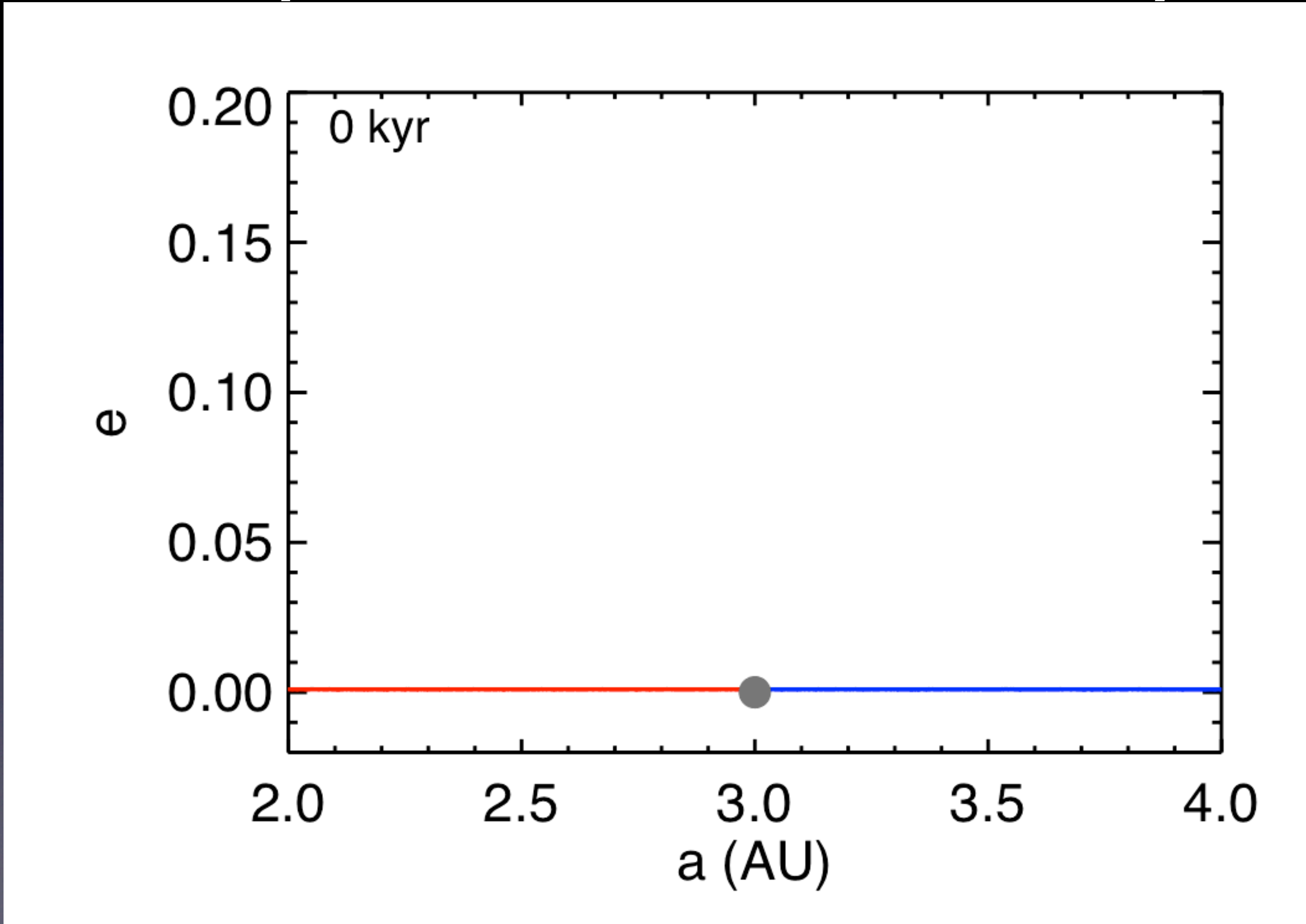
Example 1: Earth-mass embryo



Example 3: 10 Earth-mass embryo

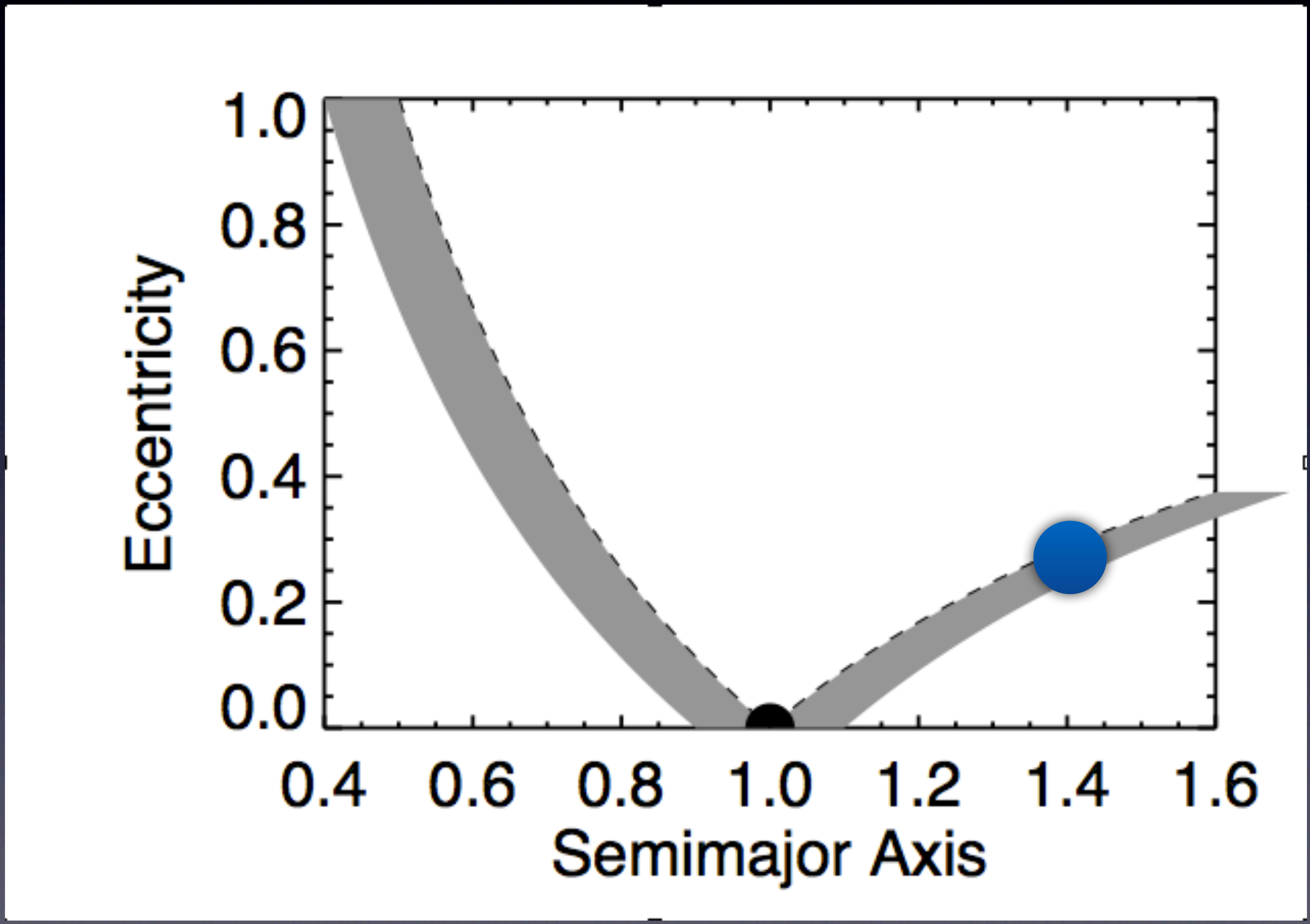


Example 1: Mars-mass embryo



Gas drag

- Headwind from gas causes planetesimals' ecc to decrease quickly, s.m.a. slowly.
- Inward-scattering favored over outward during gas disk phase

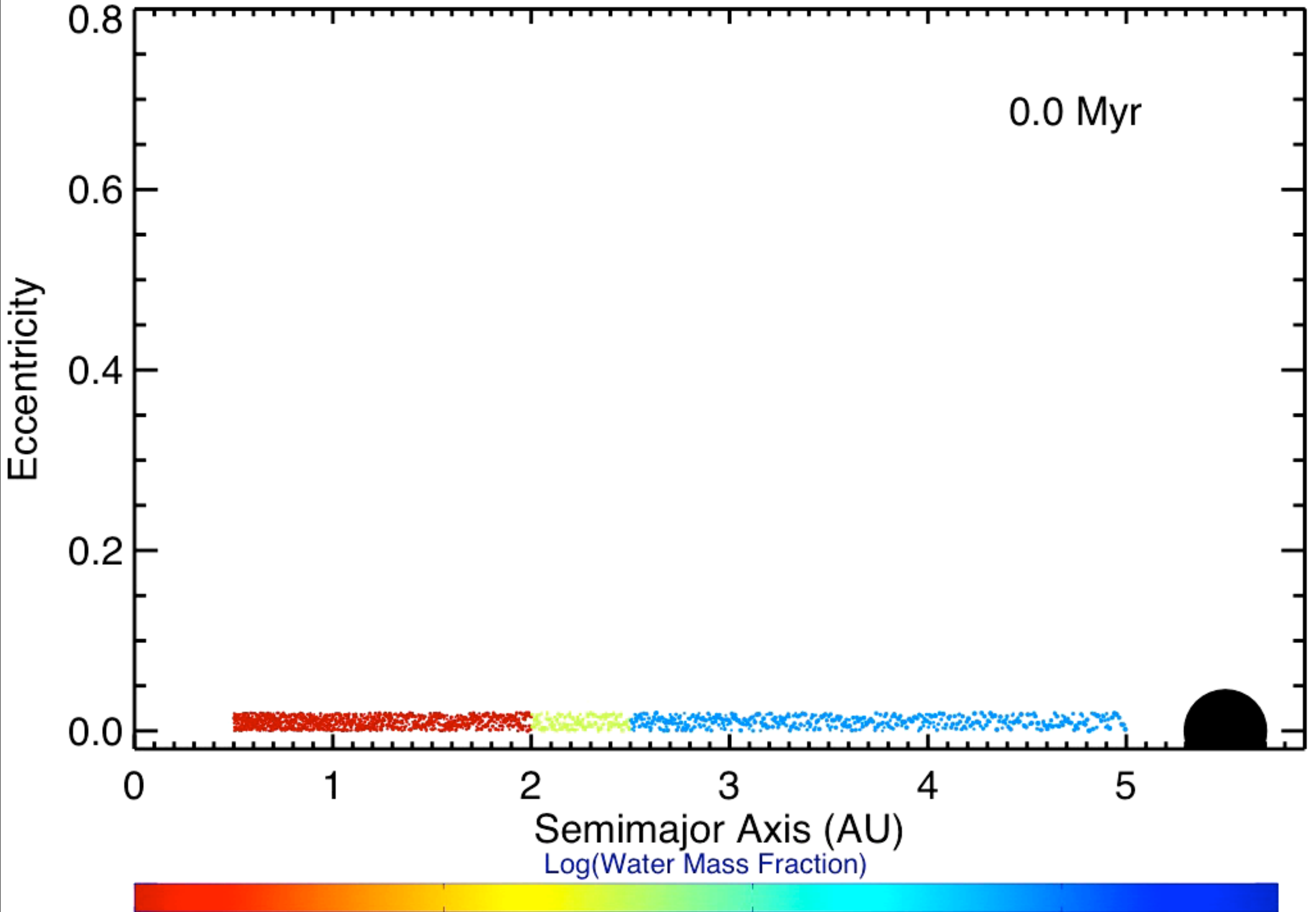


Radial mixing during Solar System history

1. "Standard" terrestrial planet formation
2. Gas-driven (type 2) migration
3. Gas accretion onto giant planets
4. Grand Tack
5. Nice model

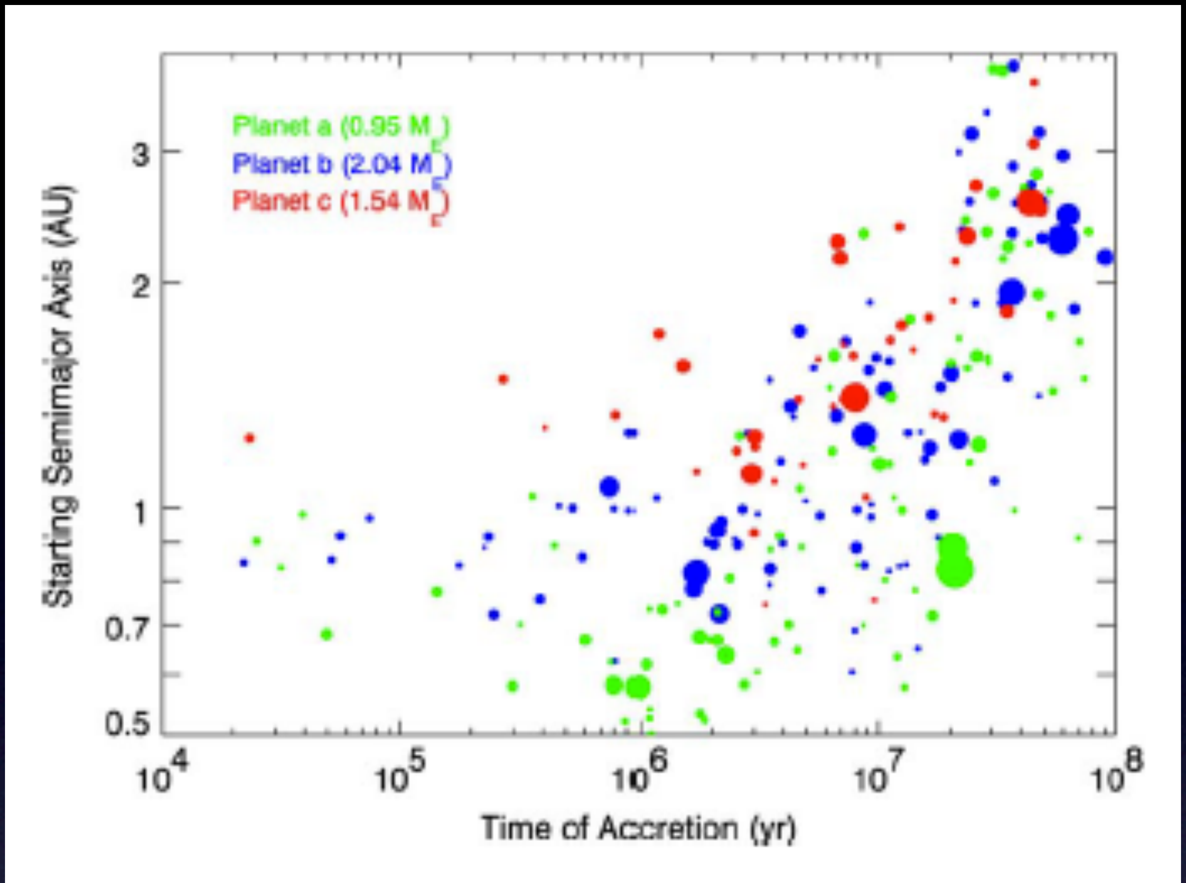
1. "Standard" model of terrestrial planet formation

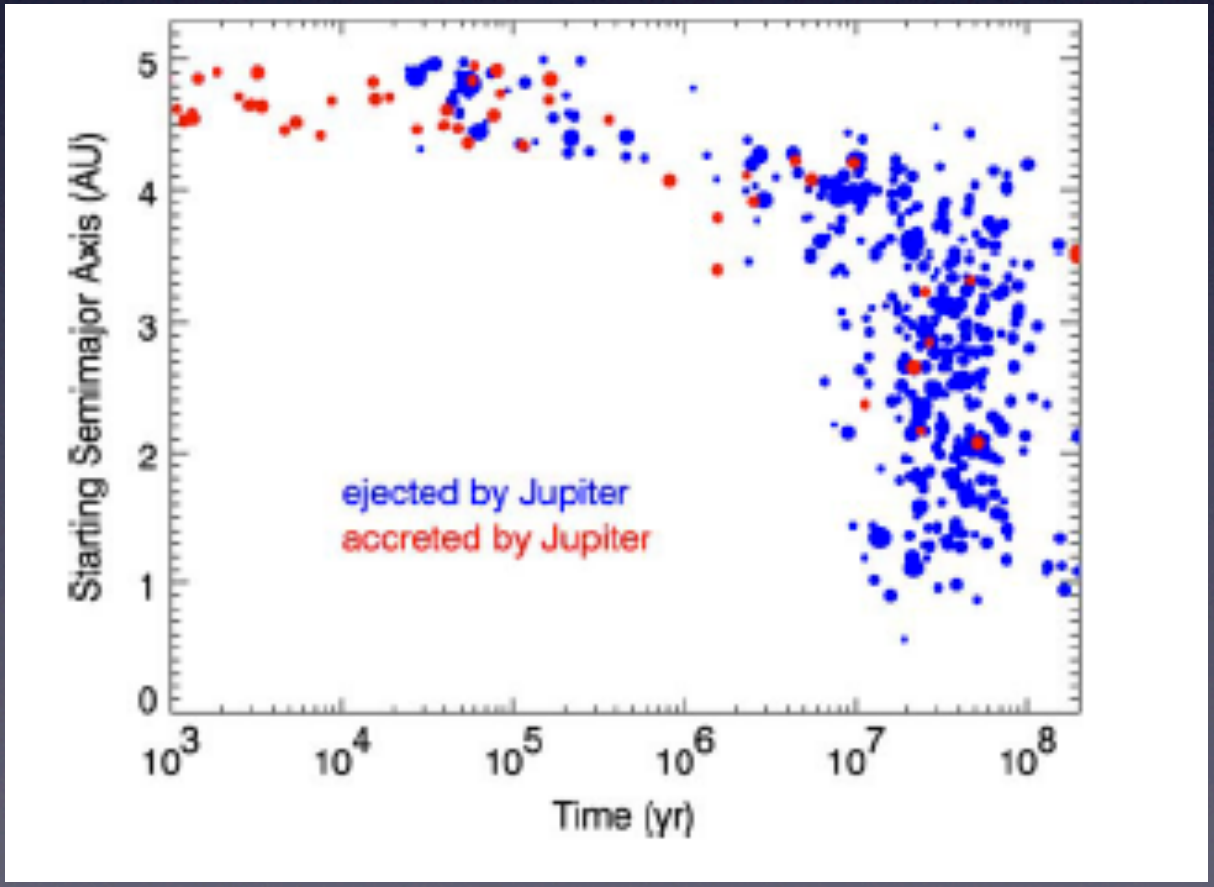
- Jupiter, Saturn on near-current orbits or in pre-Nice orbits
- Embryos and planetesimals throughout inner Solar System



Raymond, Quinn & Lunine 2006

Feeding zones of planets widen, move outward in time



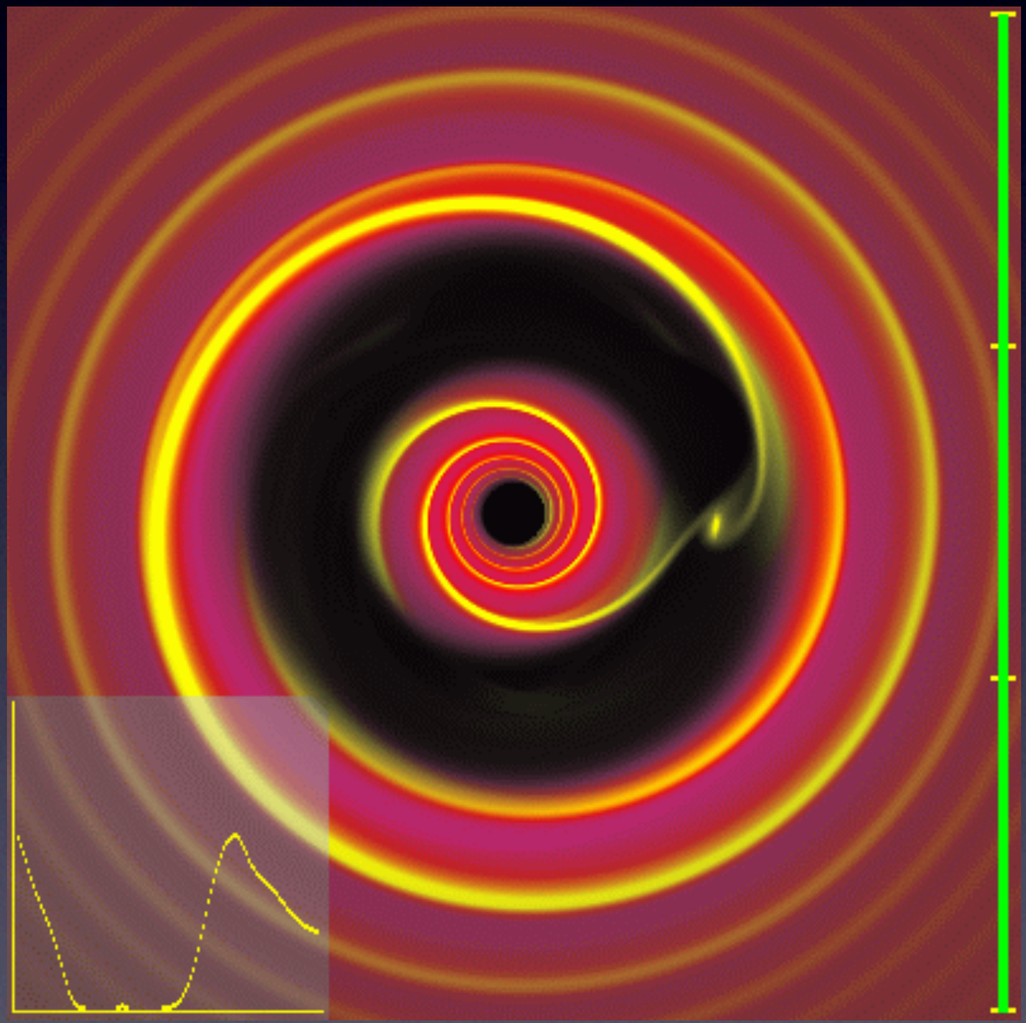


Raymond, Quinn & Lunine 2006

In this case, large-scale mixing through inner Solar System takes ~10 Myr. (This time depends on the initial mass and mass distribution)

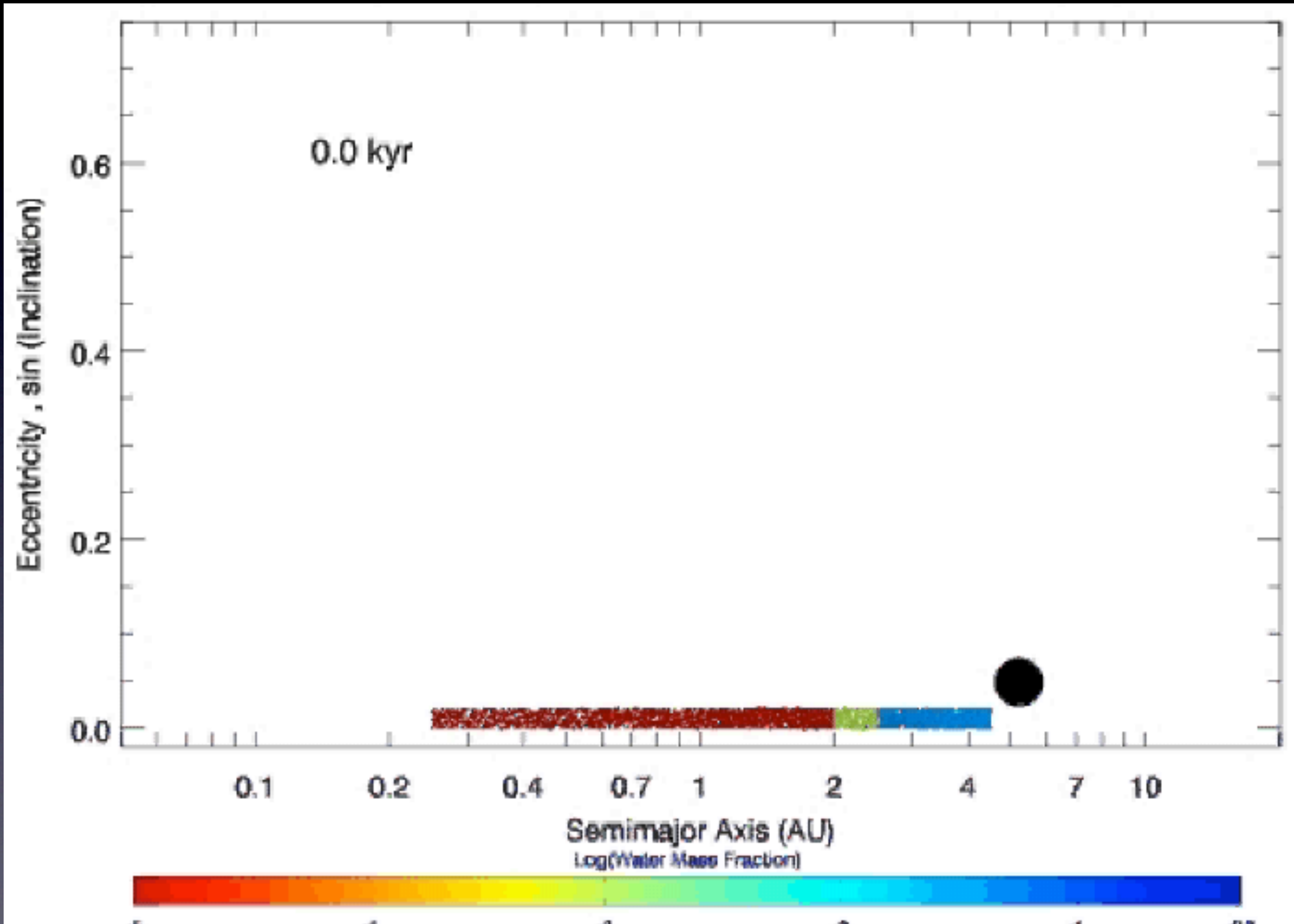
2. Giant planet (type 2) migration

- Gas giant planet carves gap in protoplanetary disk
- Linked to gas' viscous evolution
- Migrates (usually inward) at rate of gas' radial movement



credit: Phil Armitage

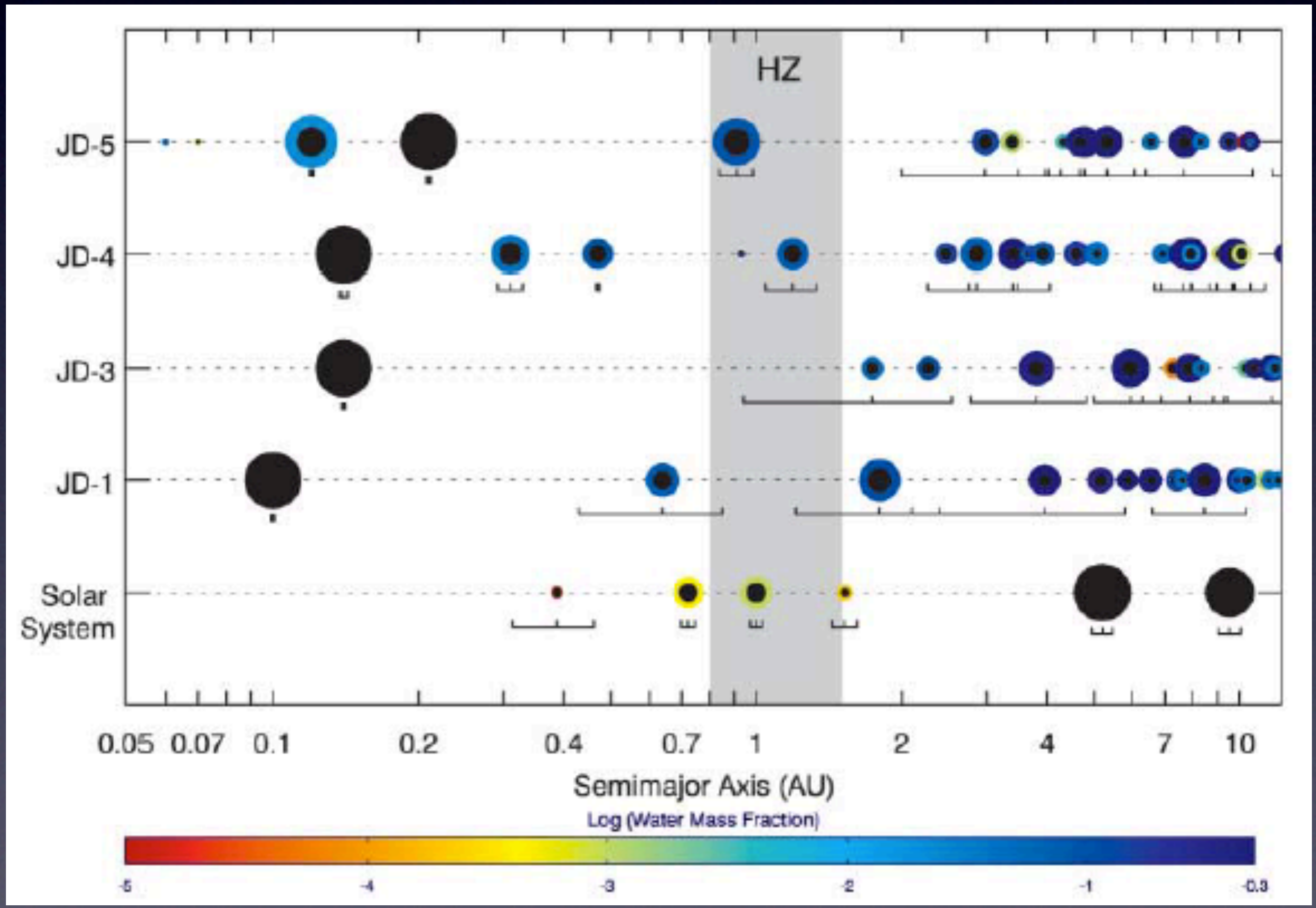
Radial mixing during giant planet migration



Raymond, Mandell & Sigurdsson 2006

Radial mixing with migrating giants

- Shepherding by 3:2 or 2:1 resonances
- Scattering creates large-scale radial mixing: very volatile-rich rocky planets



Raymond, Mandell & Sigurdsson 2006, Science

3. Gas giants' rapid gas accretion

- In core accretion model giant planets undergo rapid phase of gas accretion when core mass ~ envelope mass (Pollack et al 1996, Hubickyj et al 2005, ...)
- Stability criterion (via RHill) depends on mass
- Particles near stability limit destabilized

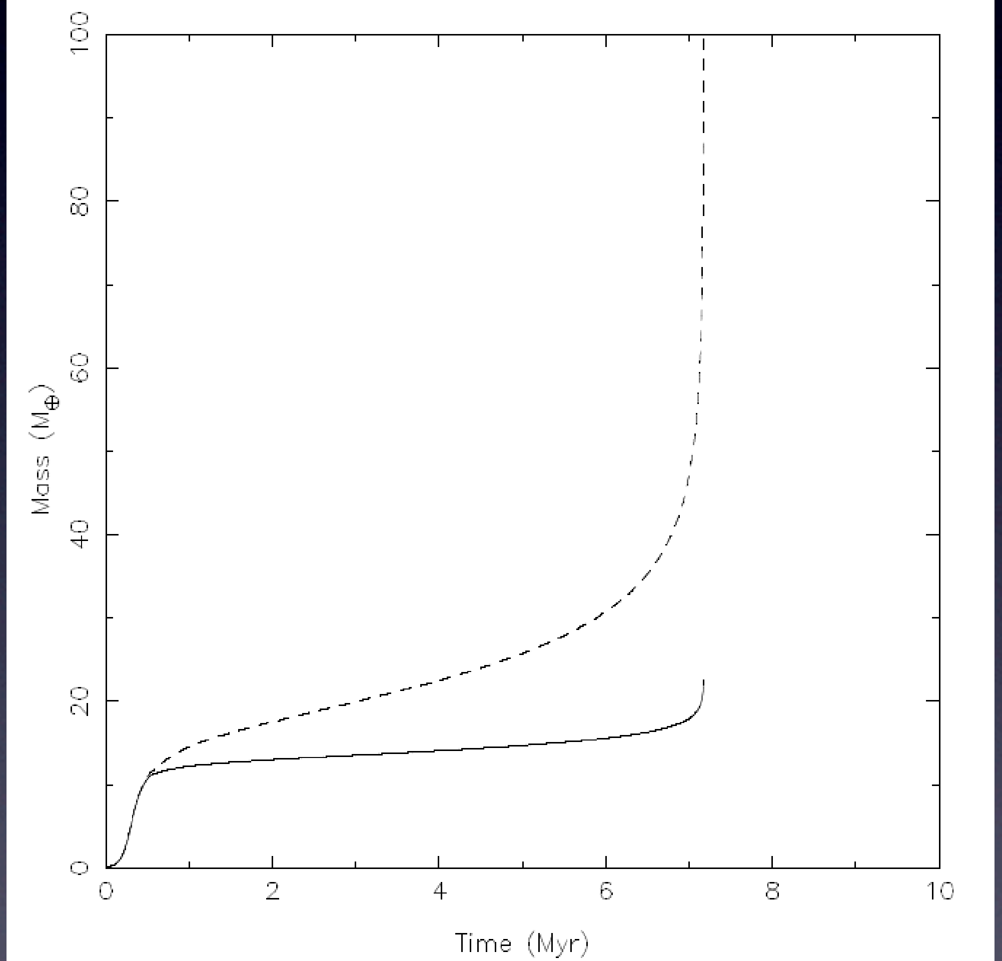
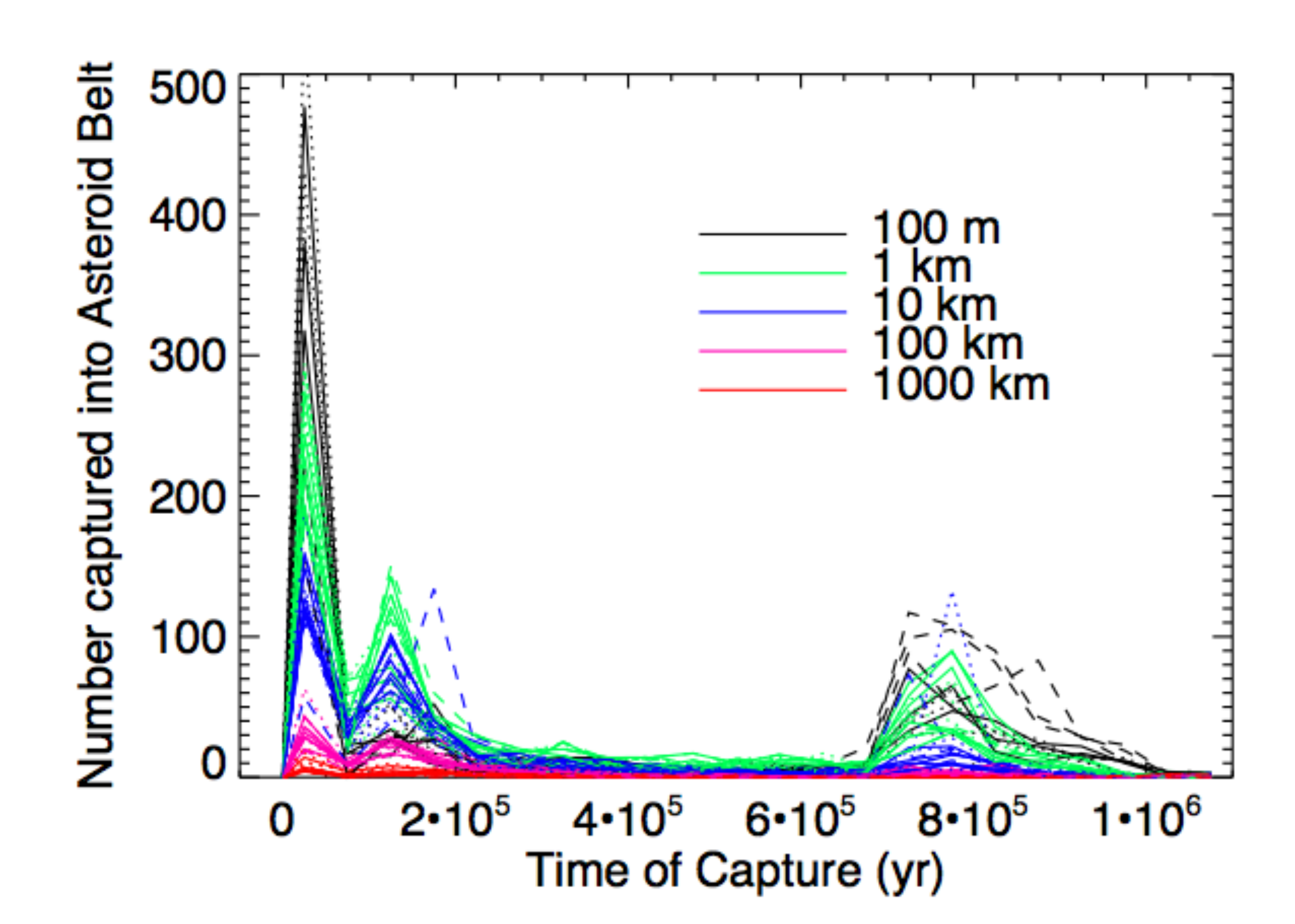


Fig. 1.— Core mass (solid line) and total planet mass (dashed line) for a core fixed in radius at 5 au in a disk with $\sigma_p = 10$ g cm^{-1}.

Rice & Armitage 2003

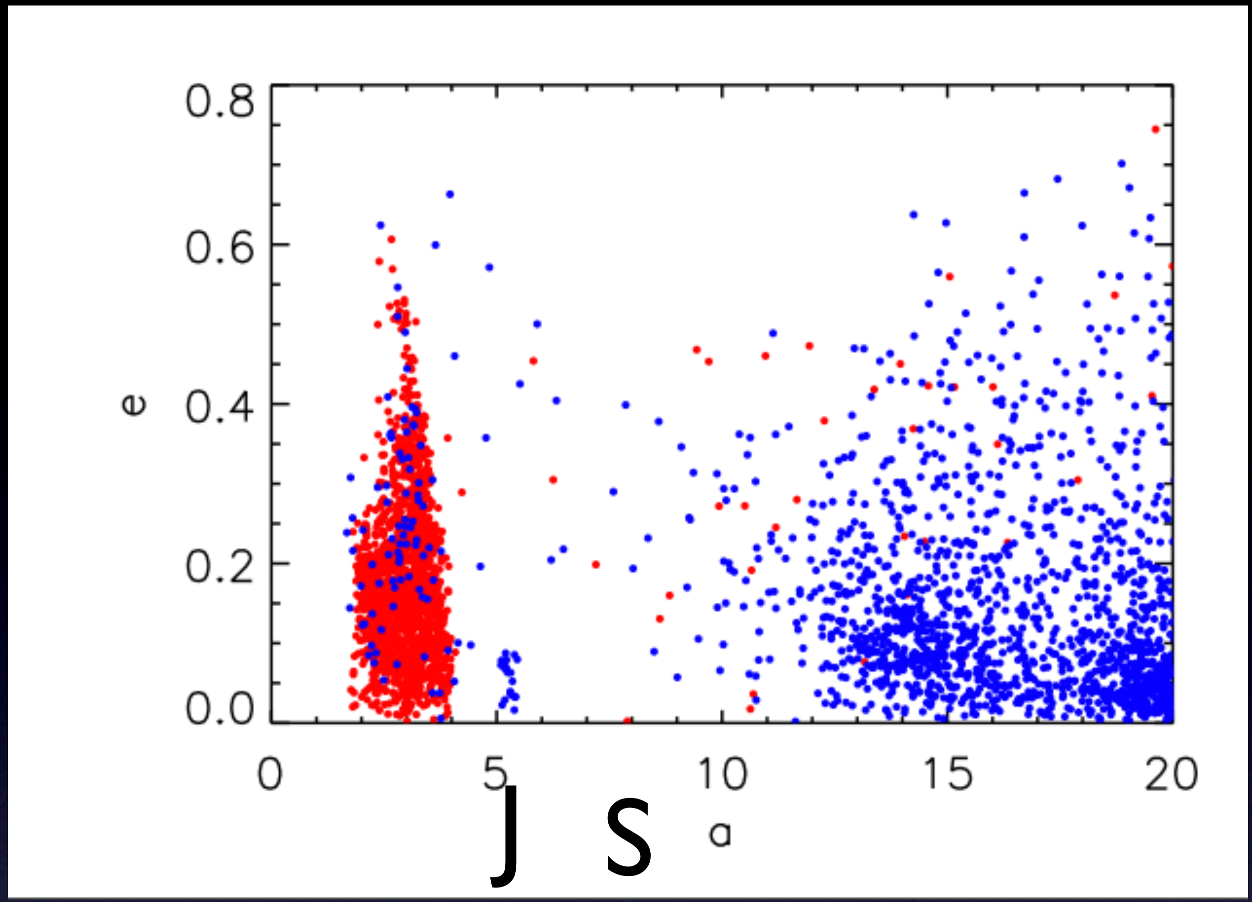
Radial mixing during Jup and Sat's rapid gas accretion

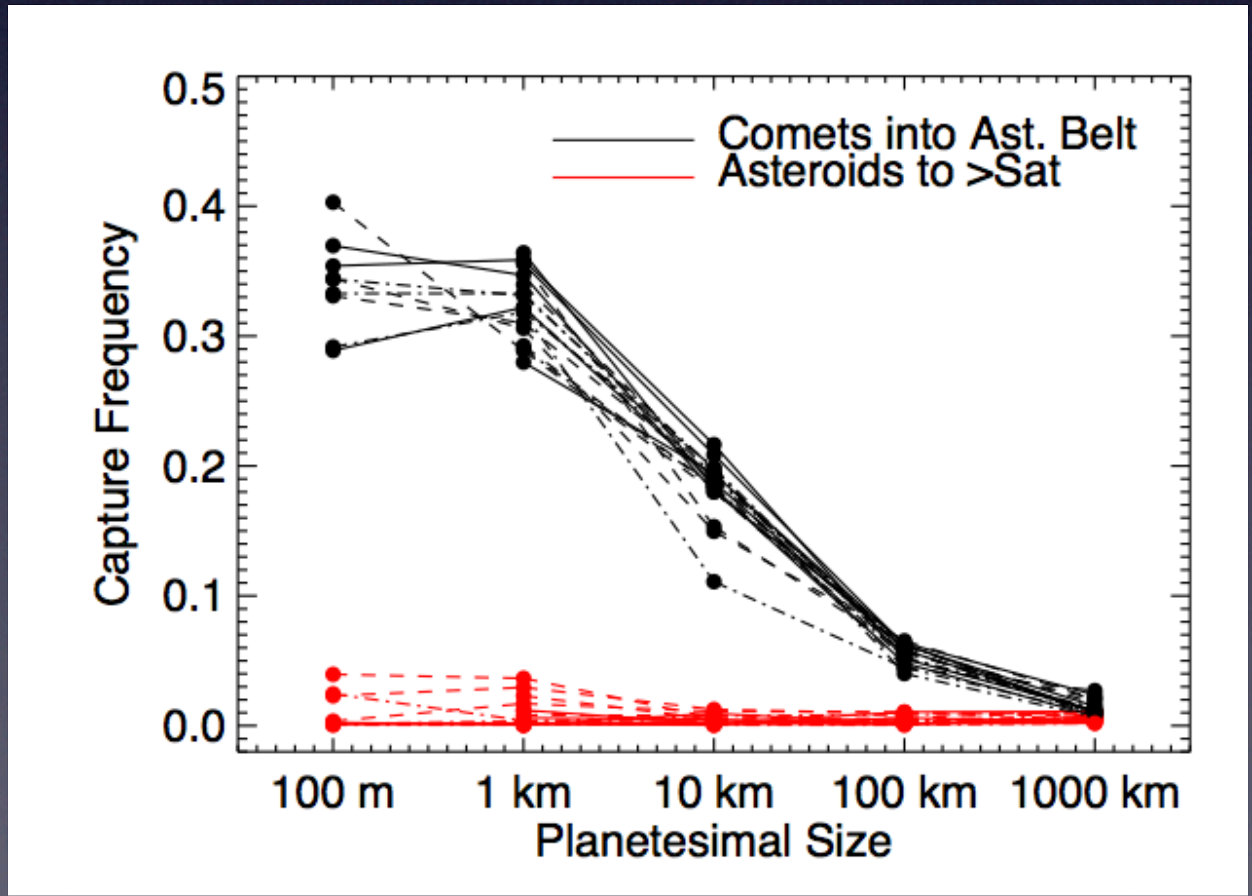
- Experiment: start from Jup and Sat's cores in 3:2 resonance and increase their masses to their current values.
- Jup starts to carve gap in disk, then Sat carves one too.



Raymond et al, never published

- Trans-Jovian bodies implanted into asteroid belt in a size-dependent way
- Some asteroidal bodies scattered out beyond Saturn

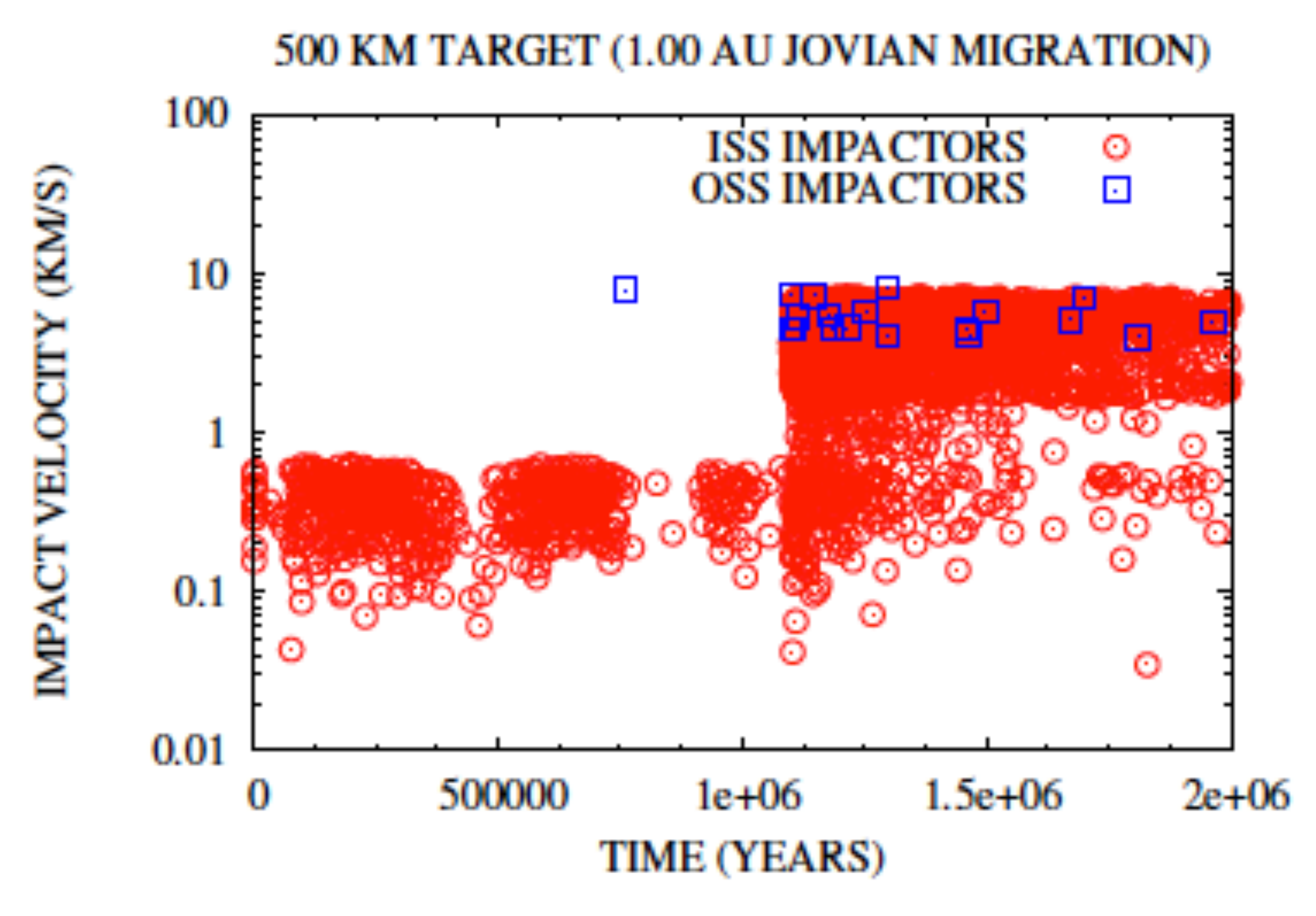




Raymond et al, never published

Jovian Early Bombardment
(Turrini et al 2012)

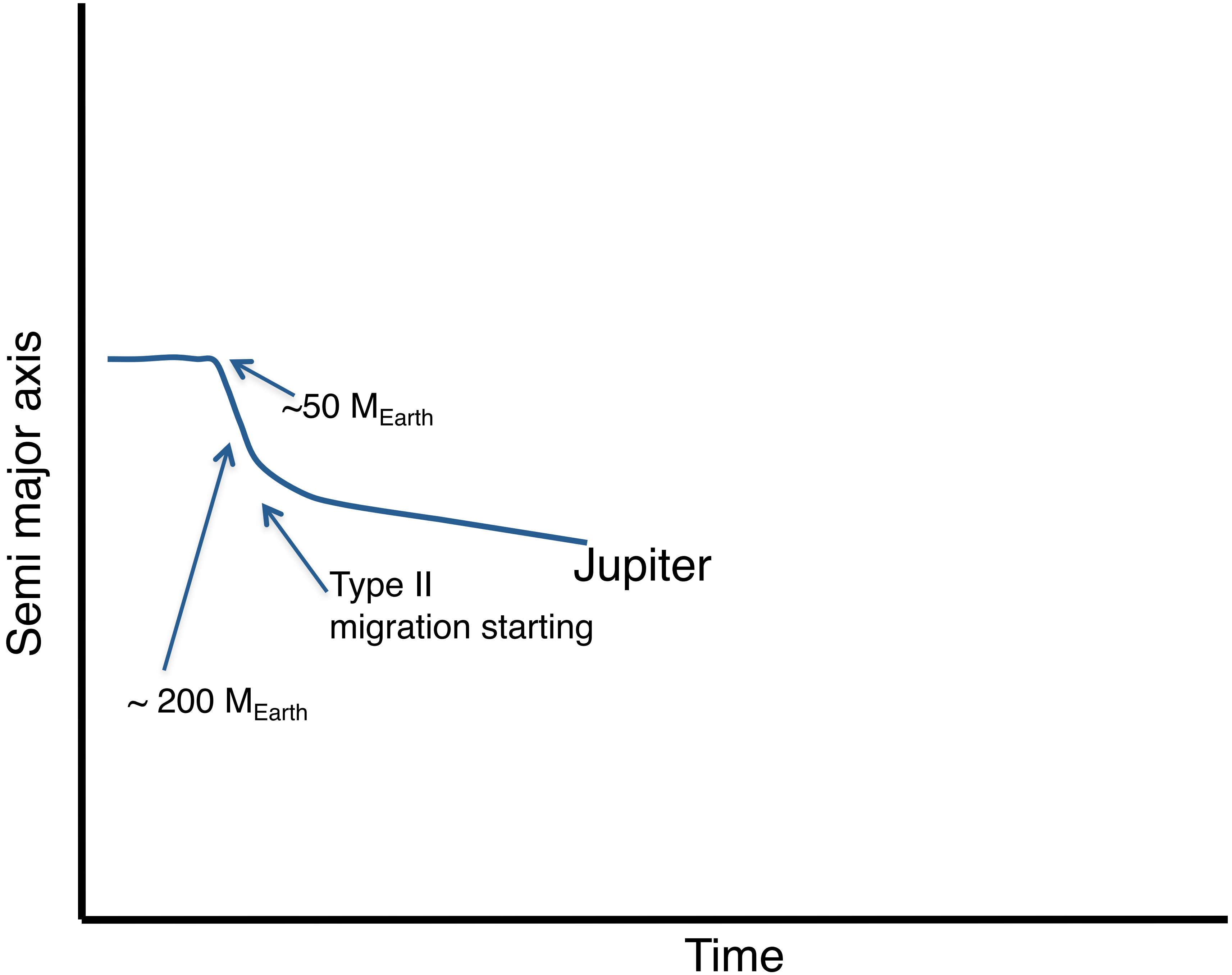
- Jupiter's rapid gas accretion stirs up planetesimal eccentricities
- Increases collision speeds in asteroid belt
- May have caused collisional destruction of bodies up to 200-500 km in size.



Turrini et al 2012

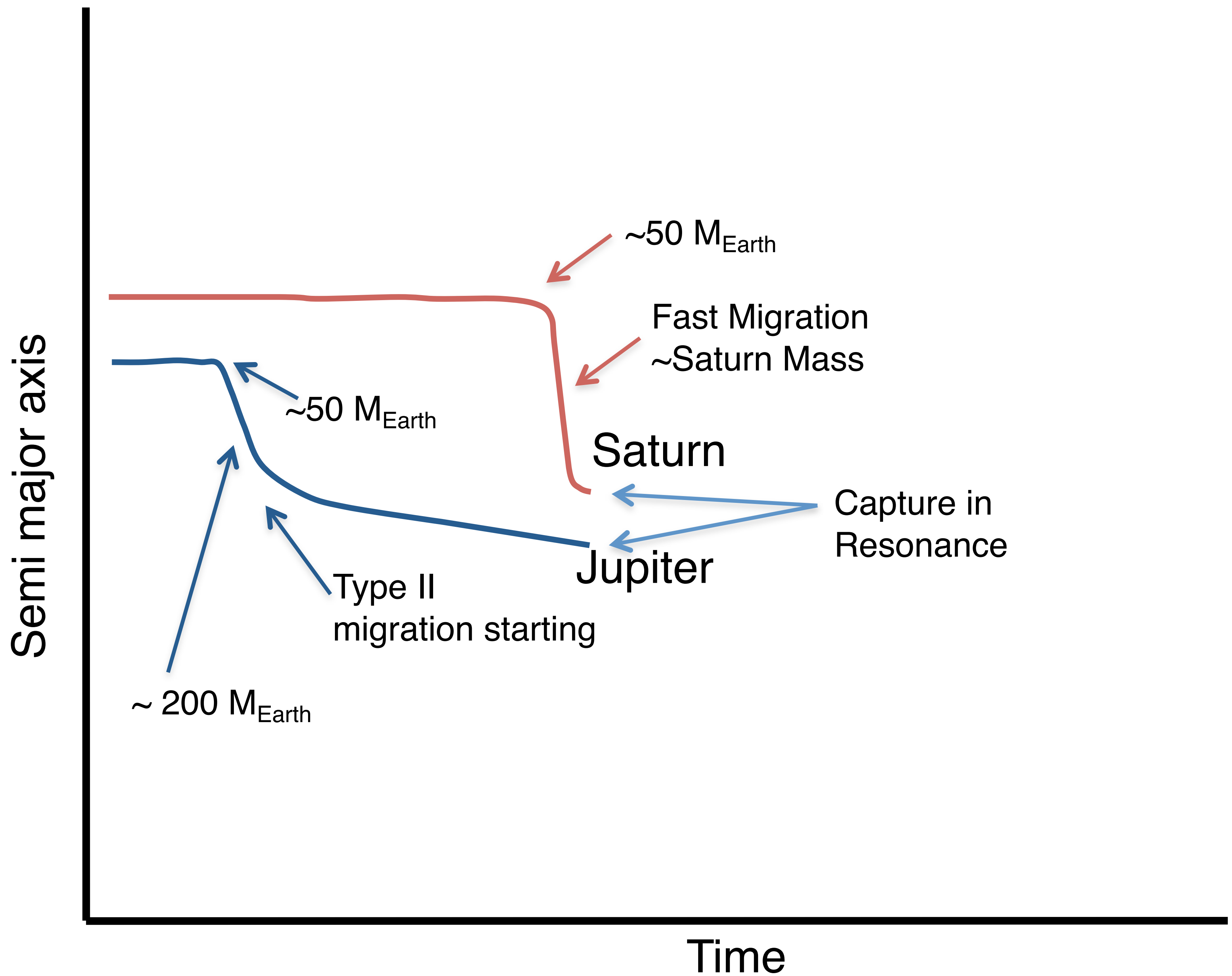
4. The Grand Tack

(Walsh et al 2011)



slide by Kevin Walsh

Jupiter and Saturn in the gaseous disk



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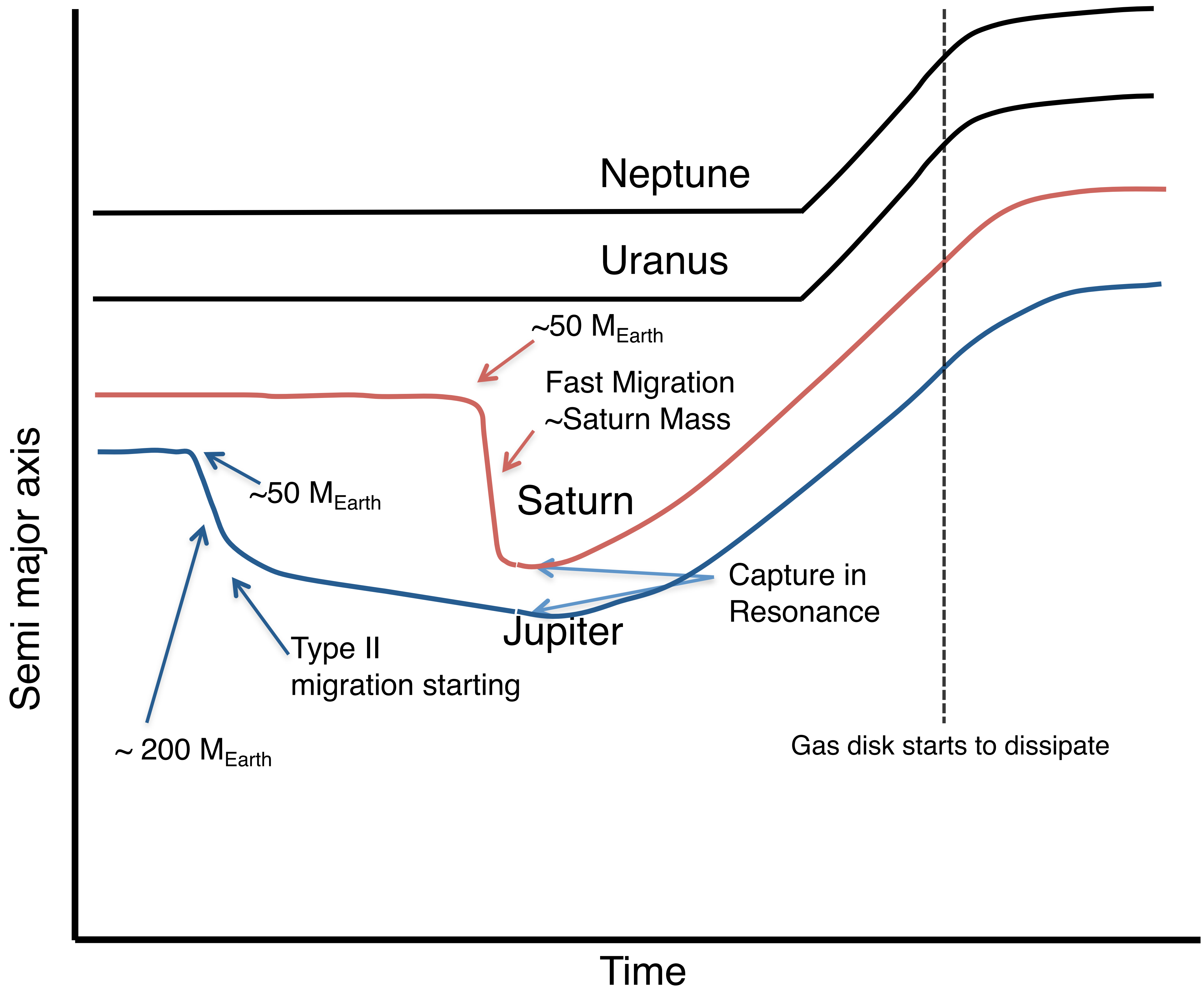
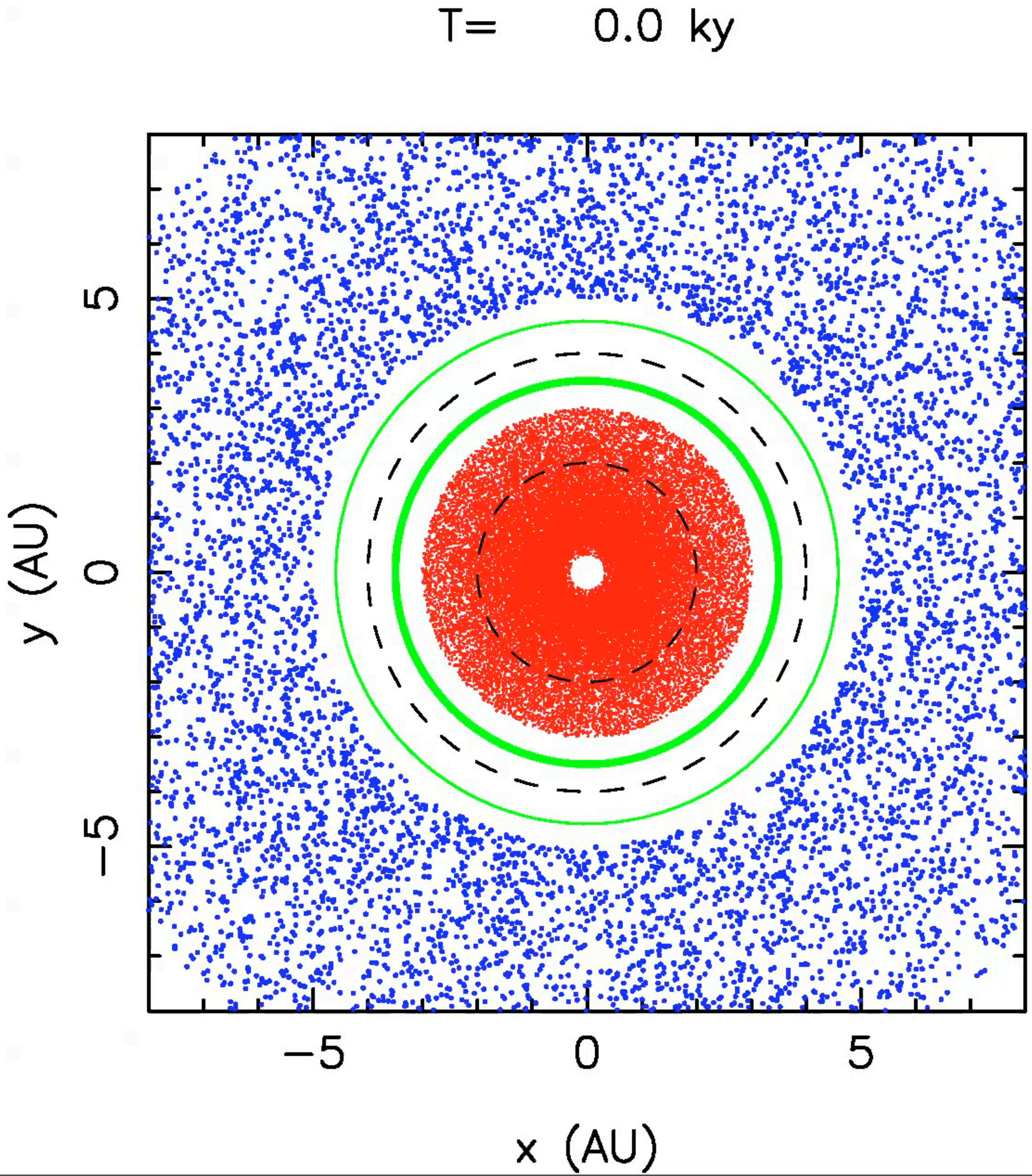
Jupiter and Saturn in the gaseous disk

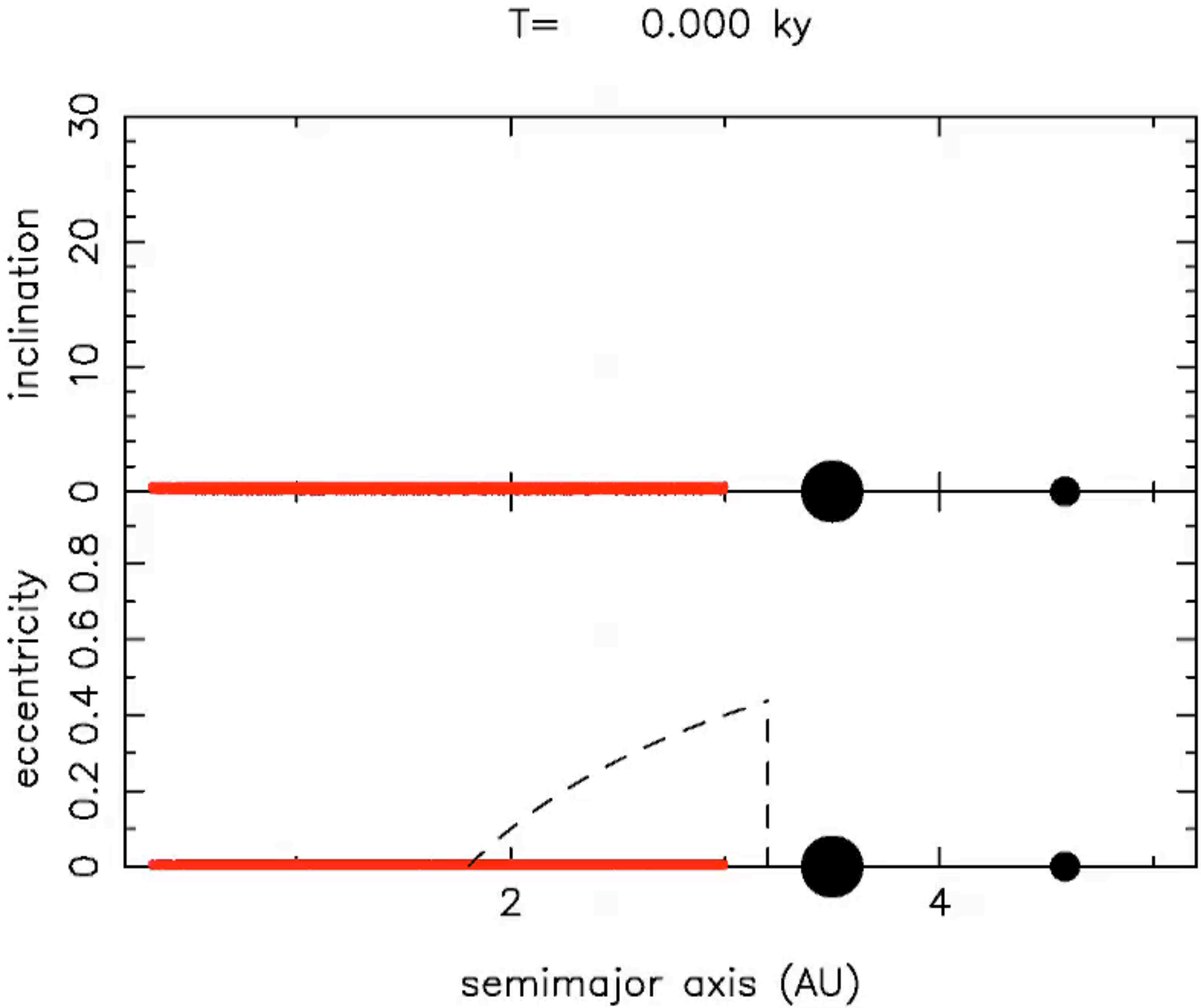


slide by Kevin Walsh

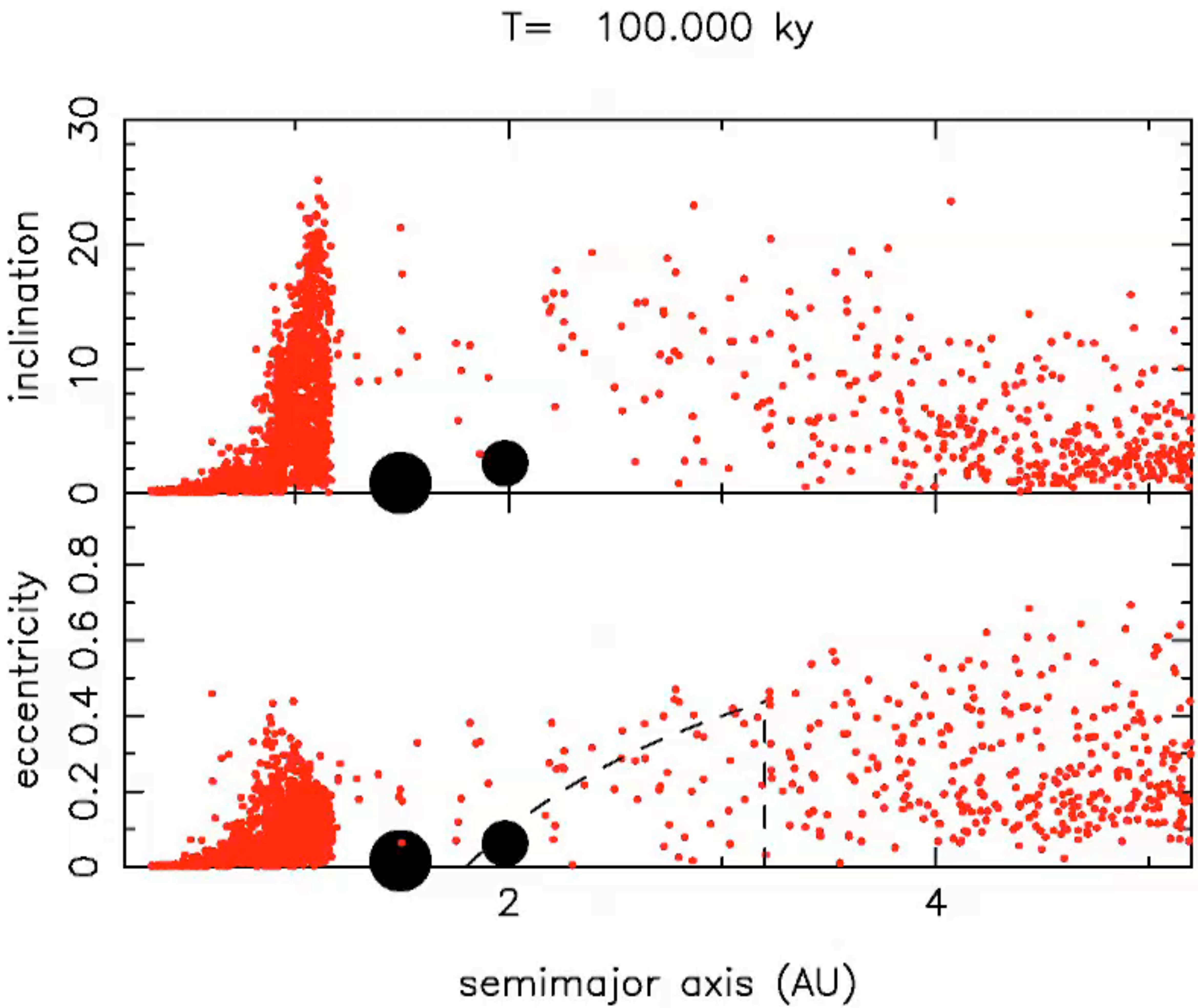
The Grand Tack

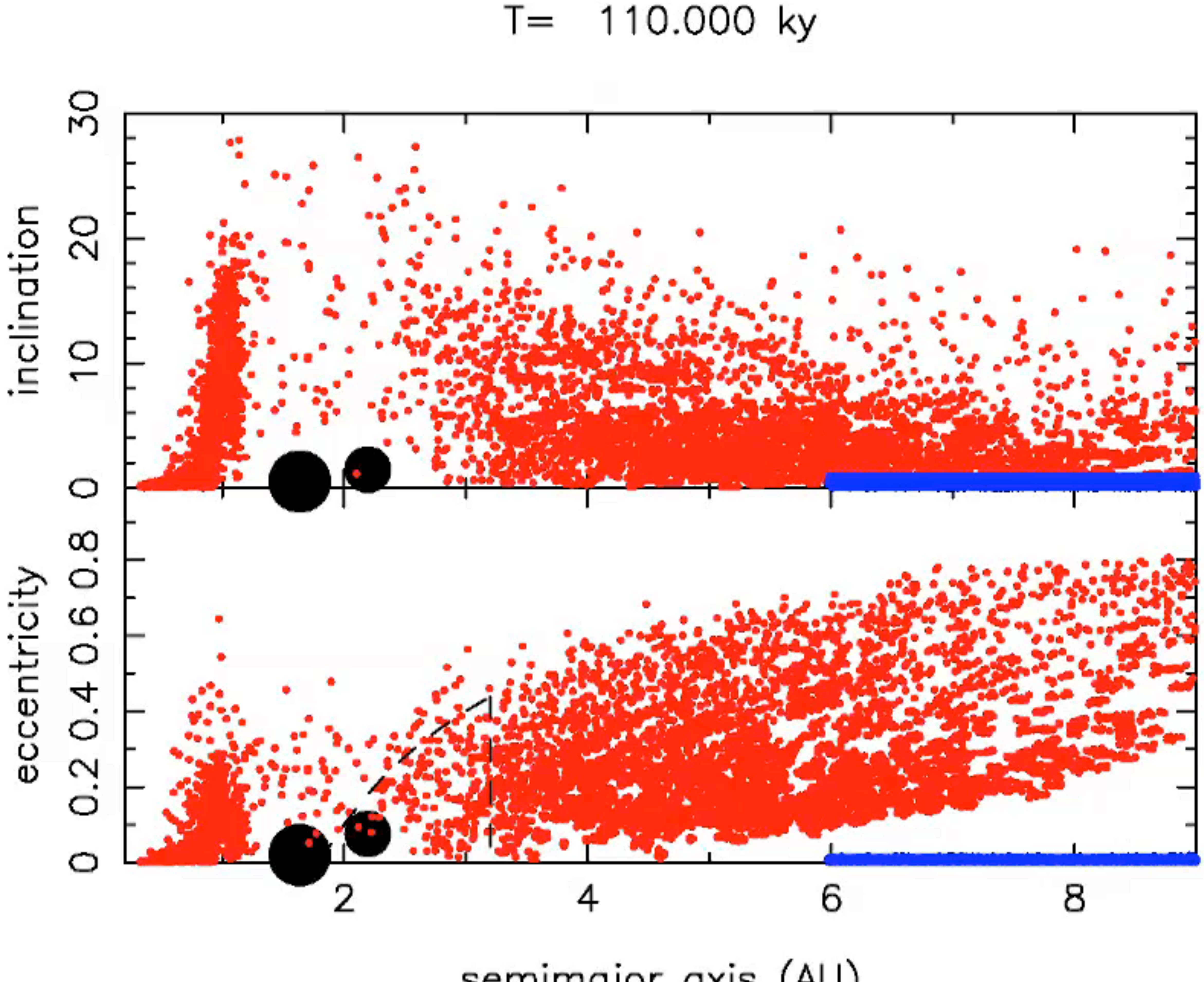
(Walsh et al 2011)



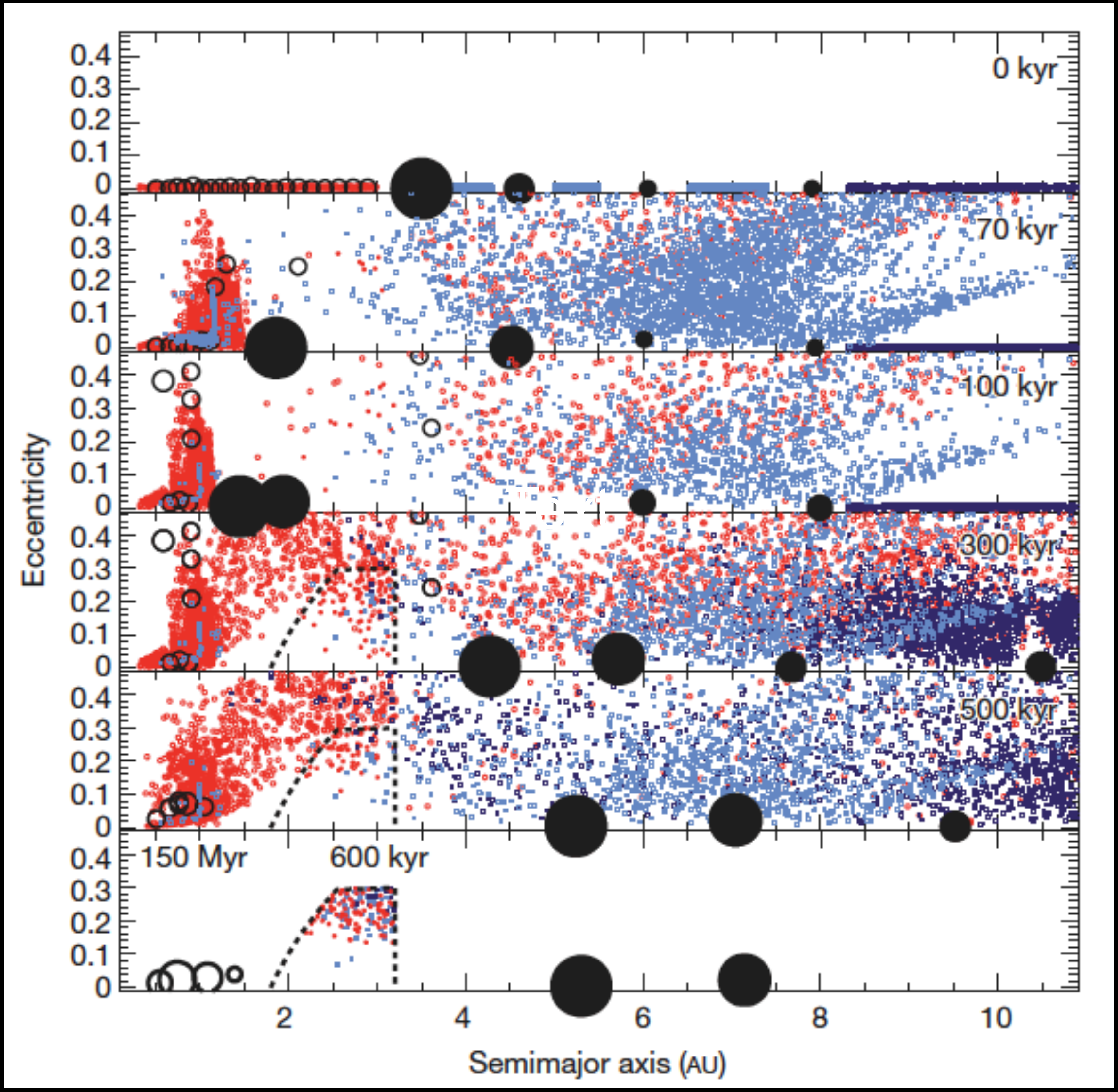


T= 0.000 ky
inclination
30
20
10
0
eccentricity
0.8
0.6
0.4
0.2
0
2
4
semimajor axis (AU)


T= 100.000 ky
inclination
30
20
10
0
eccentricity
0.8
0.6
0.4
0.2
0
2
4
semimajor axis (AU)


T= 110.000 ky
inclination
30
20
10
0
eccentricity
0.8
0.6
0.4
0.2
0
2
4
6
8
semimajor axis (AU)

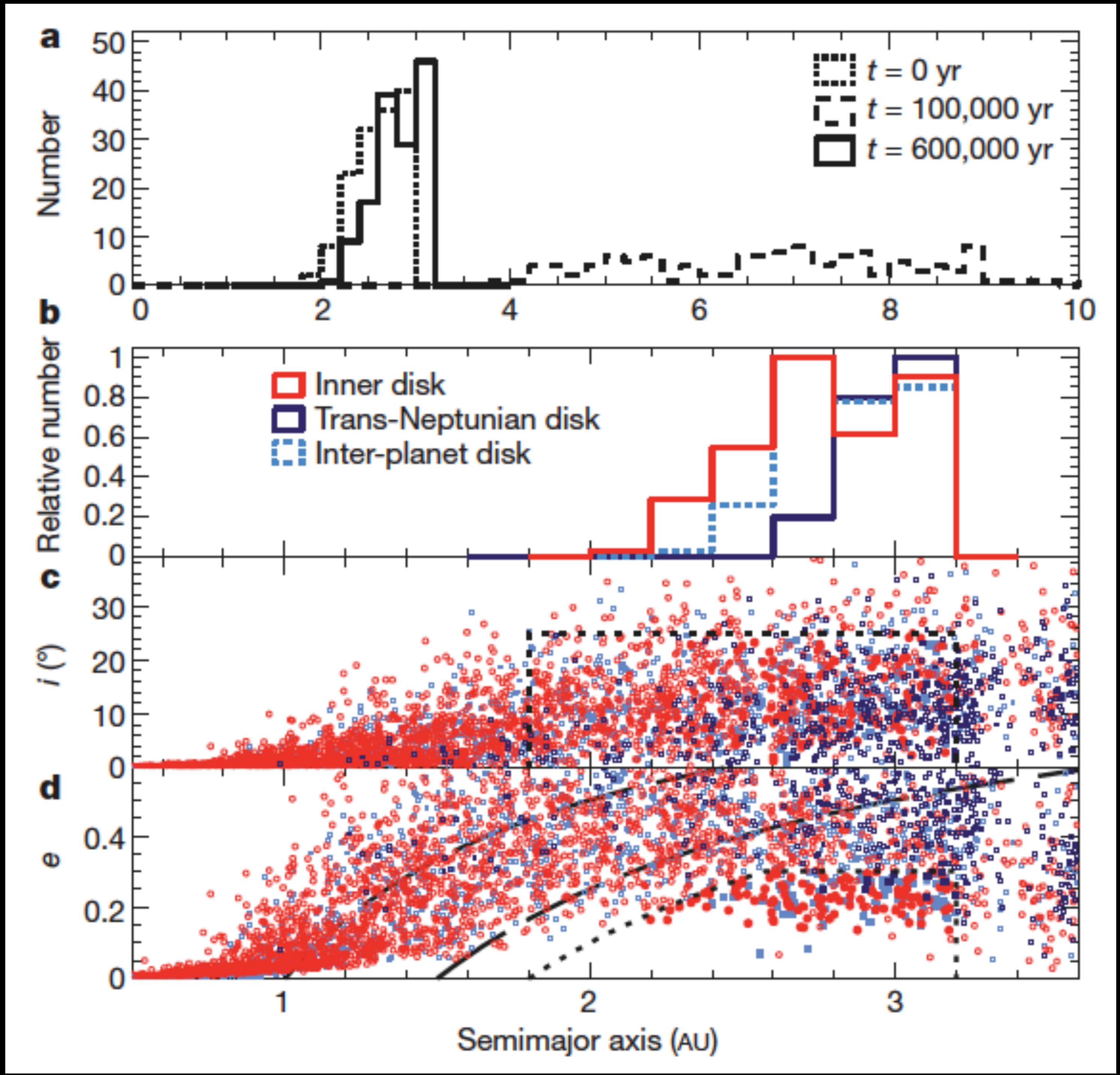
The Grand Tack



Walsh et al 2011, Nature

The asteroid belt

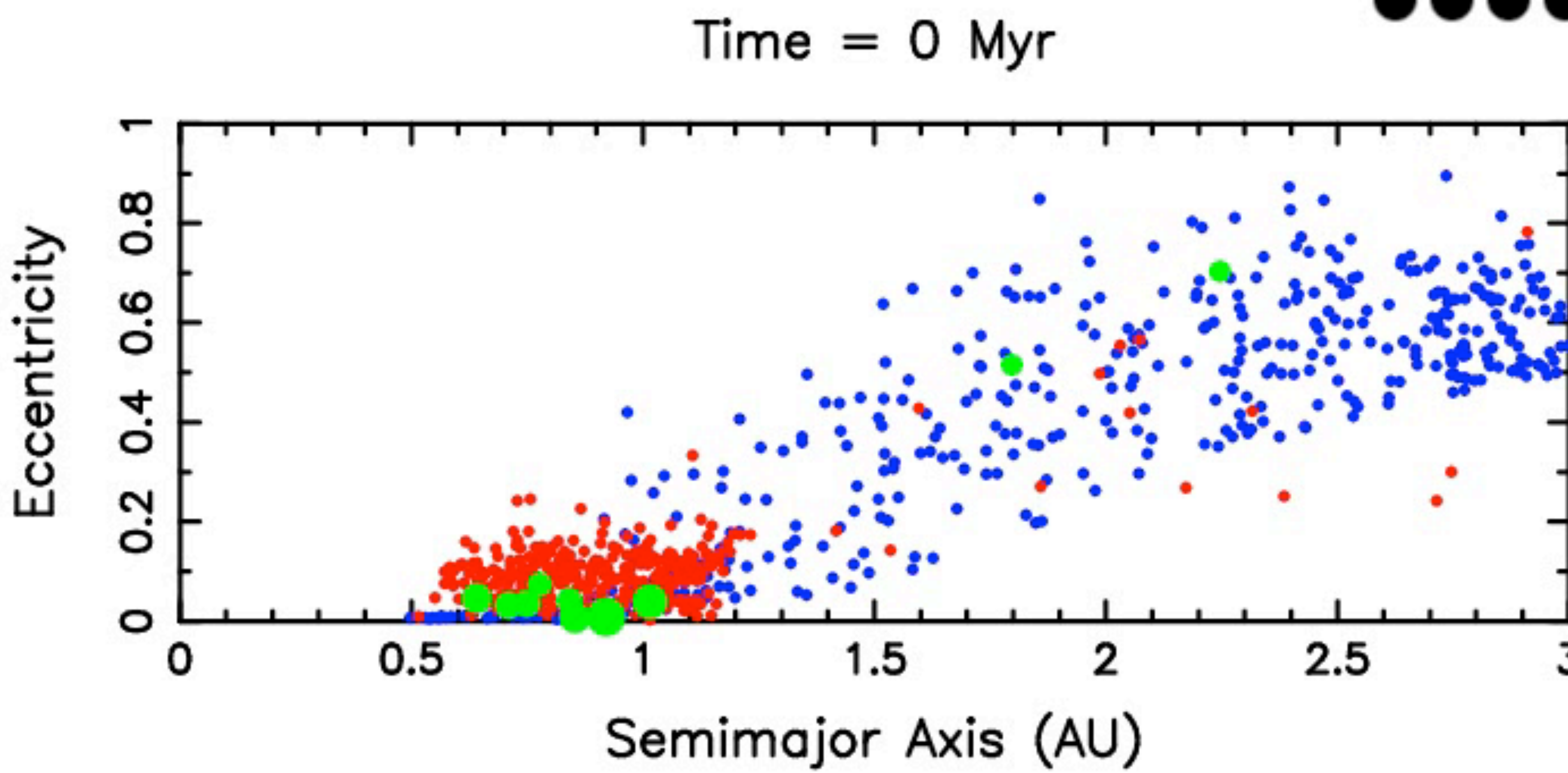
- S-types are scattered out beyond JS then back close to where they started with an efficiency of ~10^{-3}
- C-types are implanted from beyond JS with an efficiency of ~10^{-2}



Walsh et al 2011

Terrestrial planet formation and water delivery in Grand Tack model

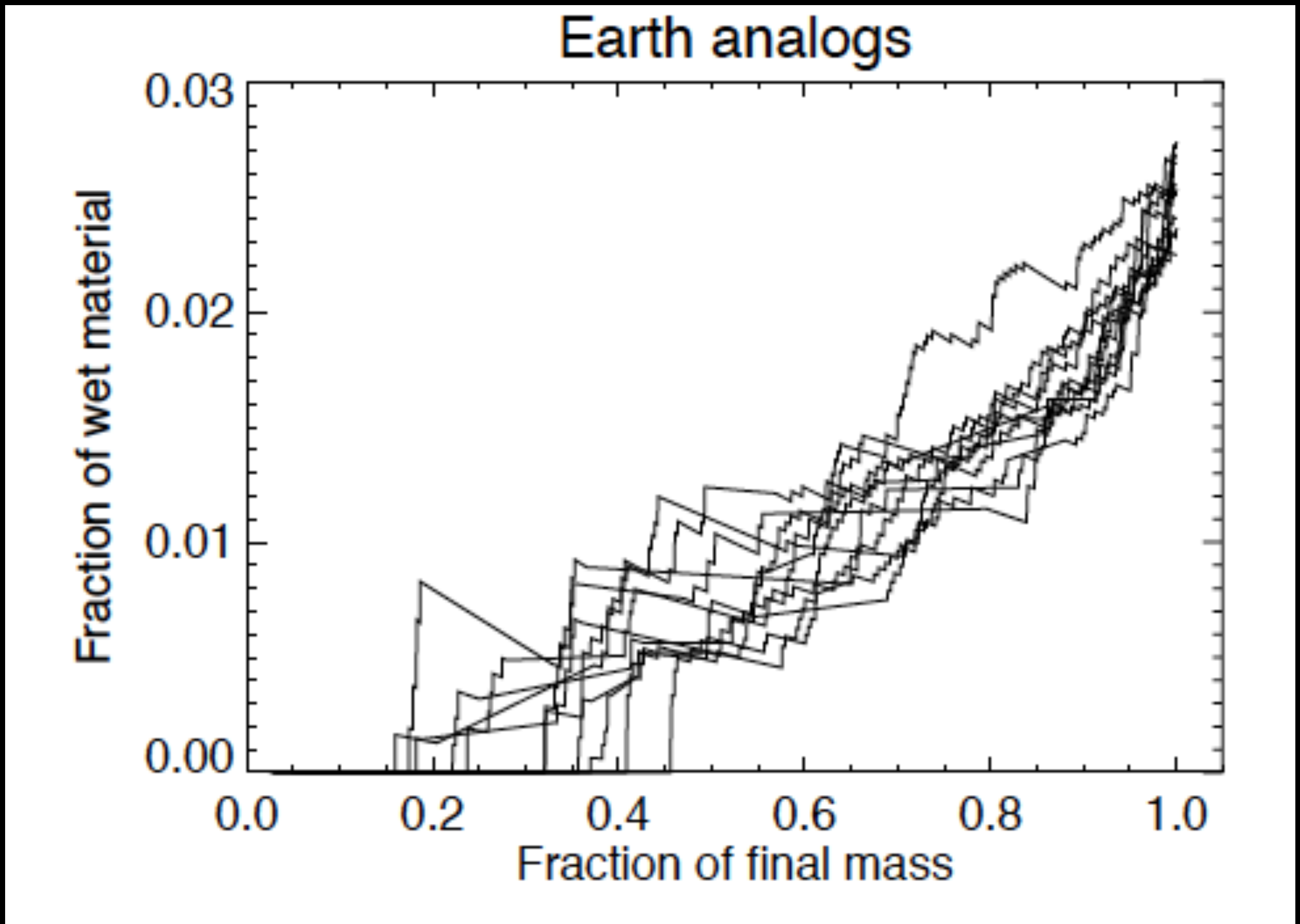
A truncated inner disk plus a tail of high-eccentricity C-type planetesimals



O’Brien et al in prep

Water delivery to Earth analogs

- Wet (C-type) material is mainly accreted late
- Earth typically accretes ~10 oceans of water
  - Earth's current water budget is ~2-10 oceans (Lecuyer et al 1998)
  - Much less than in previous simulations (Morbidelli et al 2000, Raymond et al 2004, 2006, 2009)
- Water mainly delivered by planetesimals, not embryos

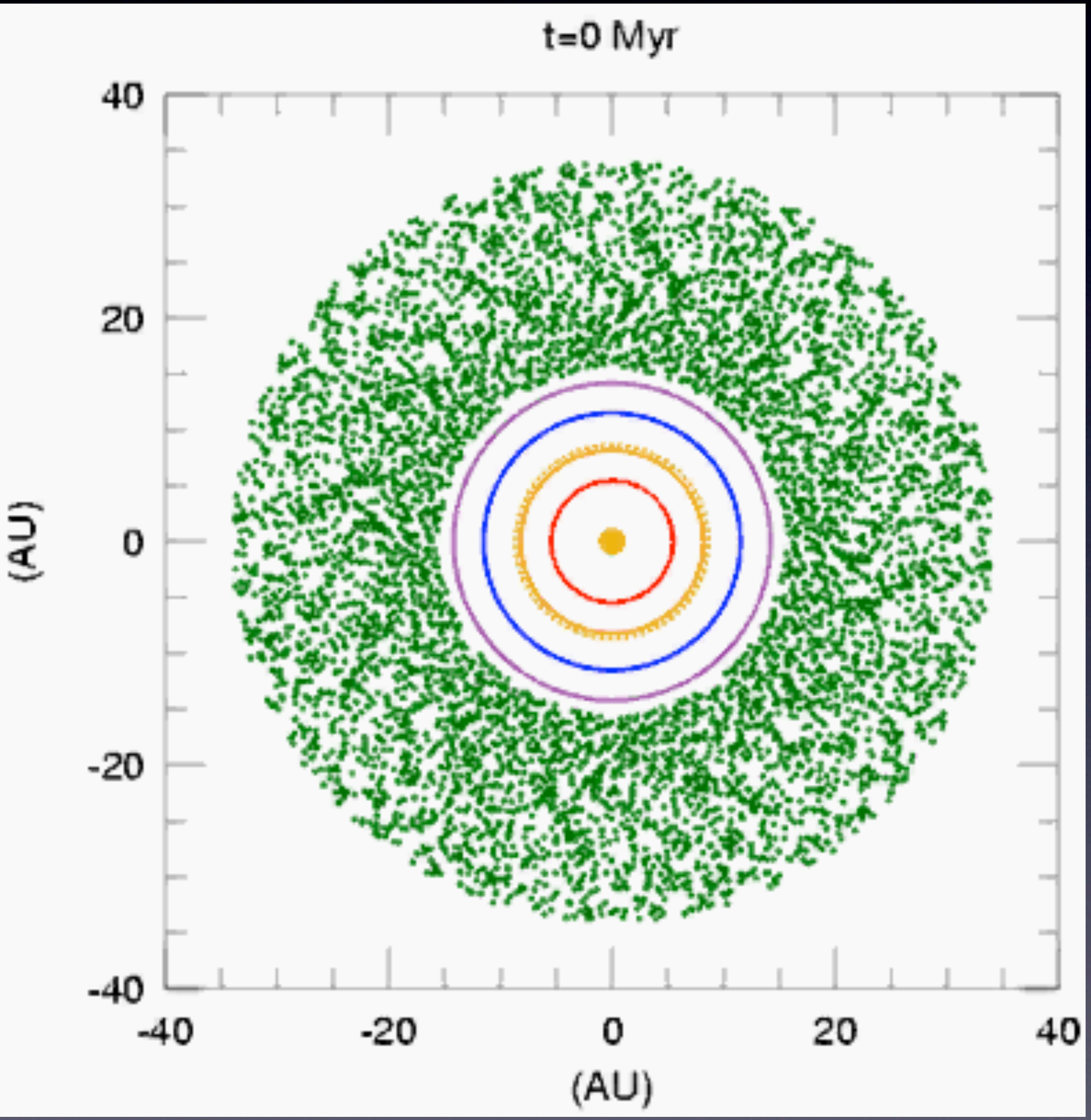


O'Brien et al in prep.

5. The Nice model

(Tsiganis et al 2005, Morbidelli et al 2005, Gomes et al 2005, Morbidelli et al 2010, Batygin & Brown 2010, Levison et al 2011, Nesvorny & Morbidelli 2012, ...)

- Giant planets formed in more compact configuration
- Outer belt of planetesimals (primordial Kuiper belt) survived on larger orbits
- Instability in giant planets triggered late heavy bombardment
- Primitive KBOs captured all over Solar System



Gomes et al 2005

Capture of KBOs in the asteroid belt in the Nice model

(Levison et al 2009)

- red = simulated particles
- green = real asteroids
- black = known D-types

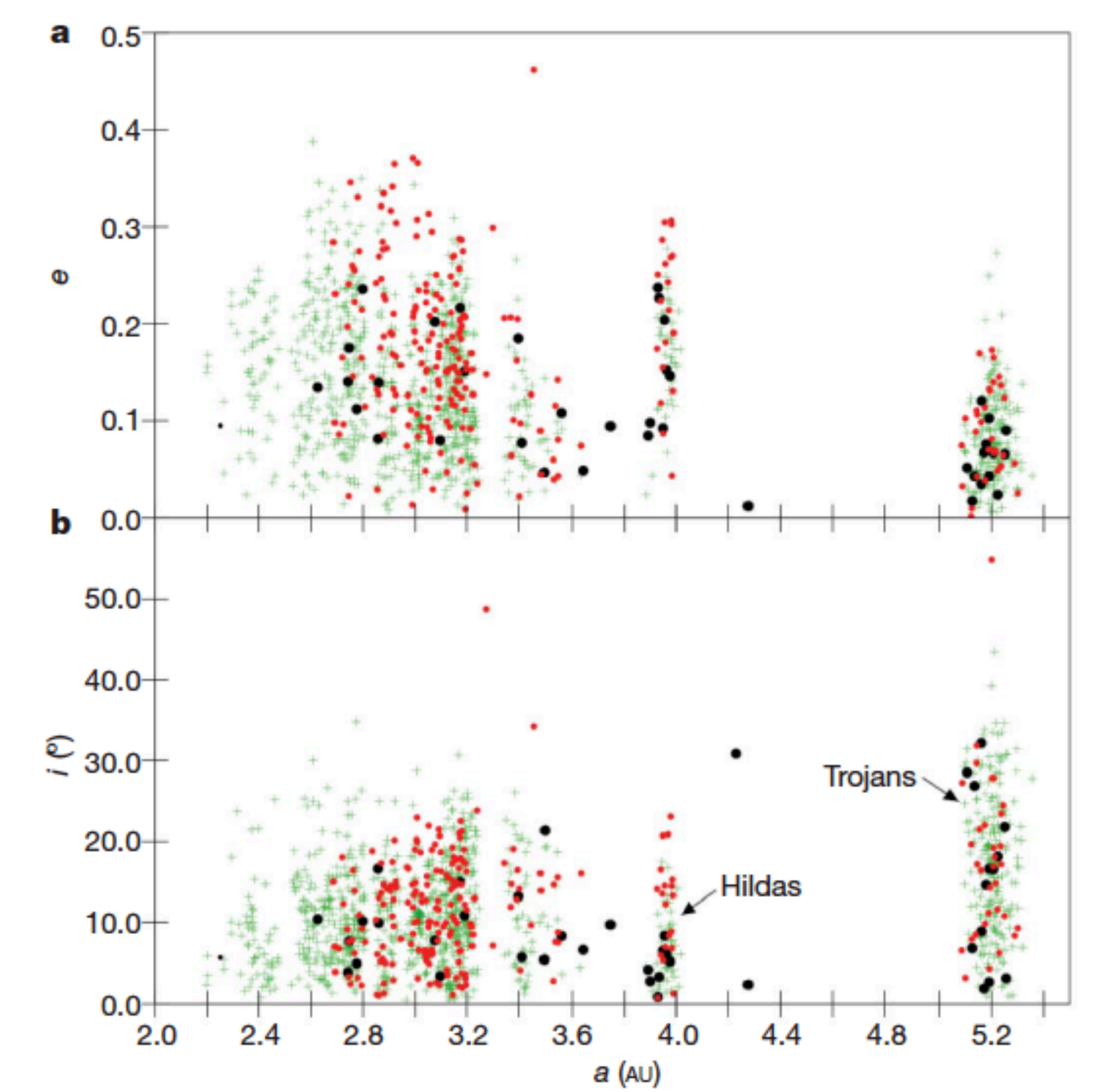
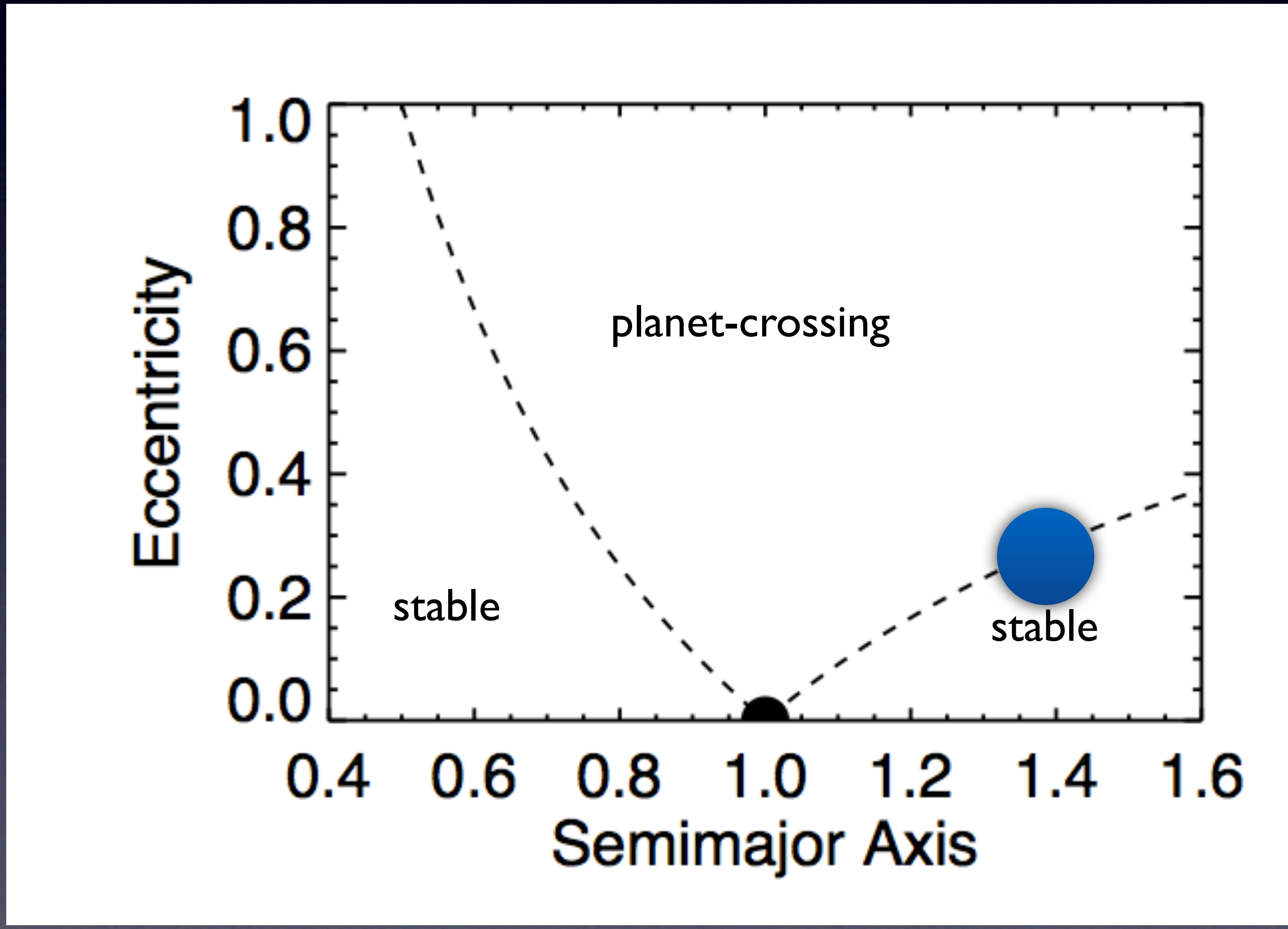


Figure 1 | The orbital element distributions of real and modelled asteroids.

Levison et al 2009

How are particles captured?

- Particles scattered by planets
- Enter inner Solar System on Jup-crossing orbits
- Some particles end up in resonance, where ecc can oscillate
- Jup's orbit changes, resonance moves, particles stranded on stable orbits



- Planetesimals scattered from primordial KB into current-day KB

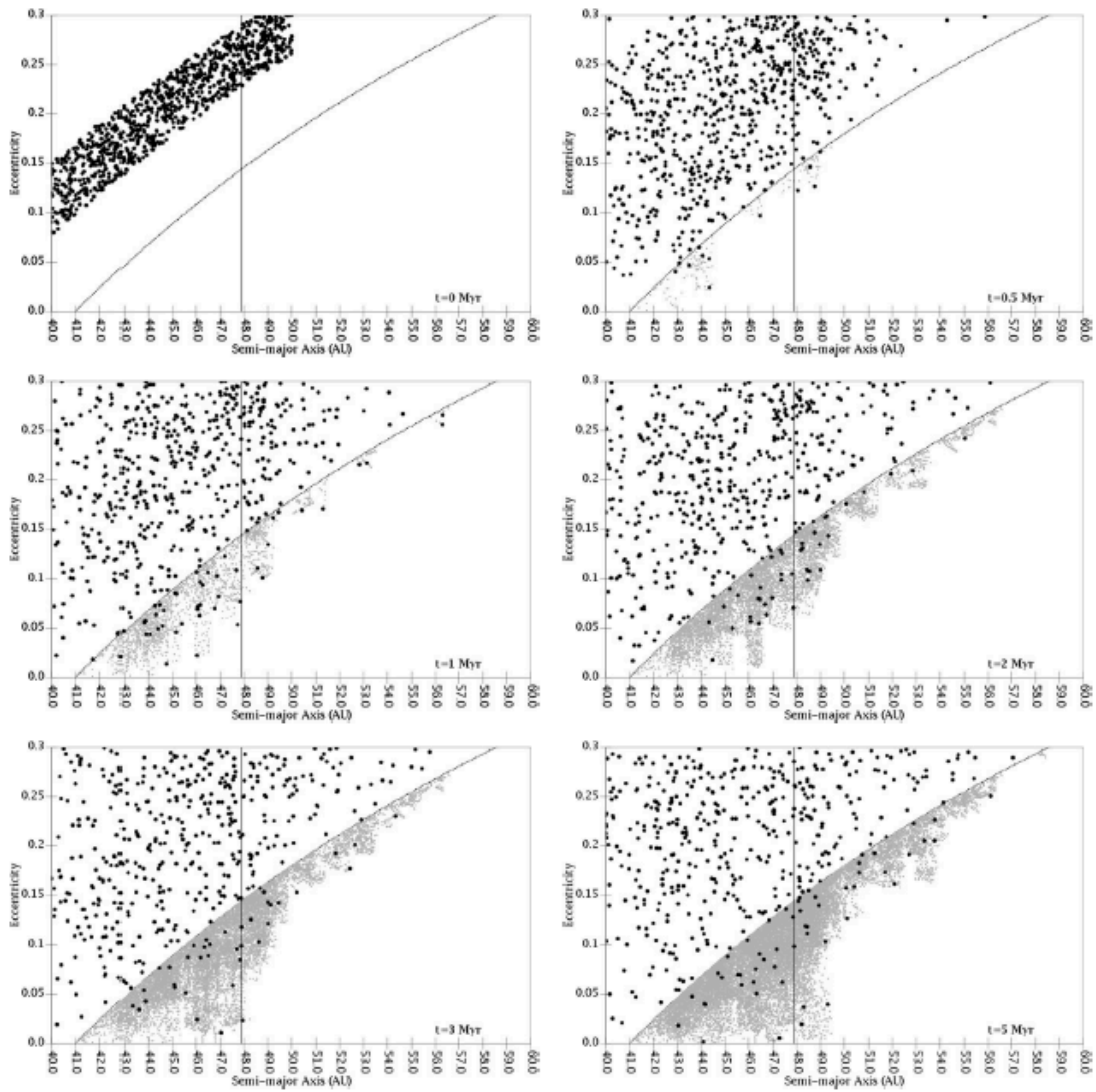


Fig. 3. Evolution of particles undergoing perturbations from Neptune on an eccentric orbit ($a = 30$ AU, $e = 0.2$). The big dots represent the test particles, initially all on Neptune crossing orbits. The solid curve marks $q = 42$ AU and the dotted vertical line the location of the 1:2 MMR with Neptune. The area cumulatively visited by the particles in the $q > 42$ AU region is colored with small gray dots. Time evolves from the top left to the lower right panel. Because of overlapping resonances, particles can evolve into the Kuiper belt and acquire orbits with $e \sim 0$. In addition, the 1:2 MMR is a natural boundary of the visited region.

Levison et al 2008

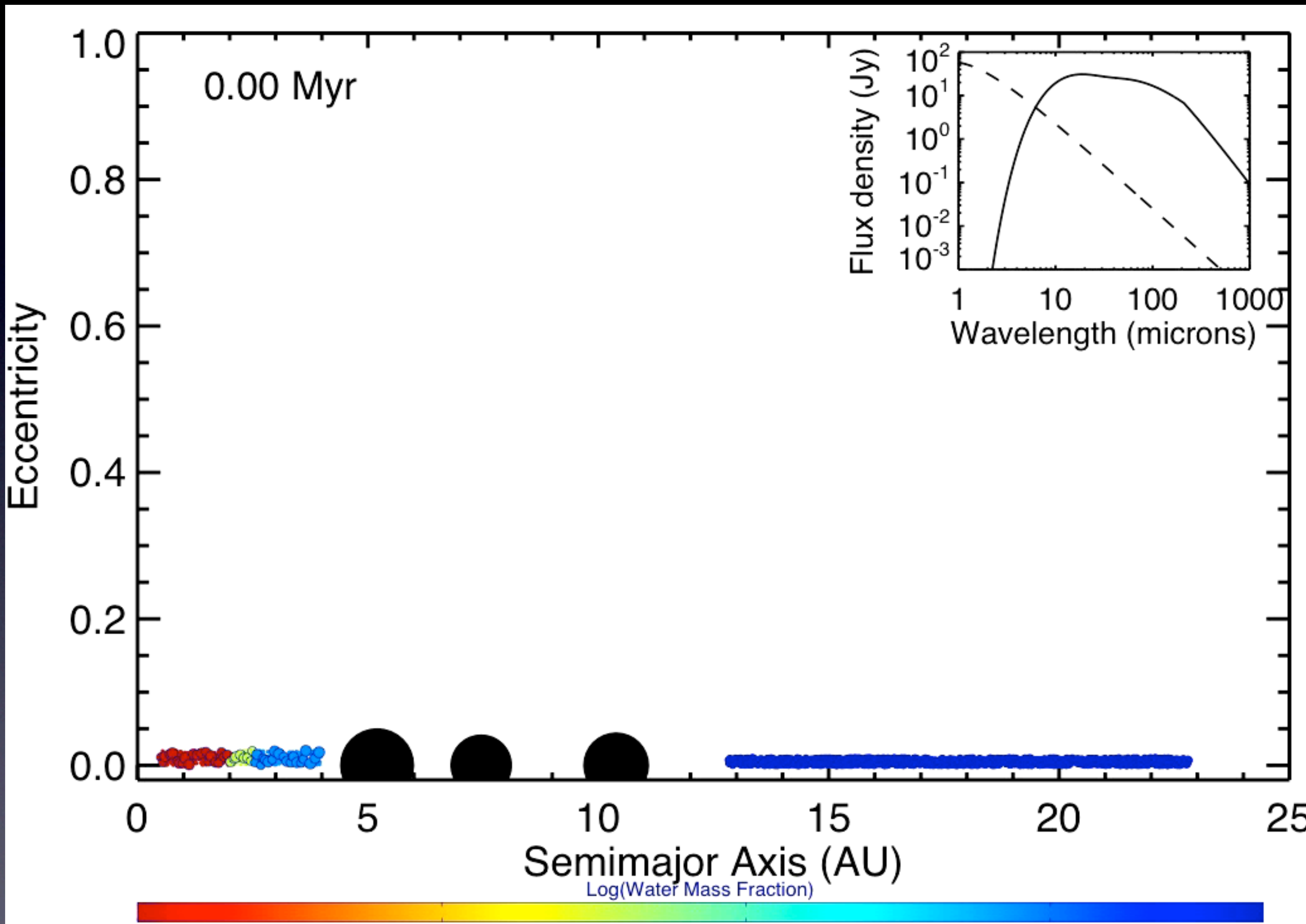
Asteroid belt: contaminated at least 3 times

- During Jup’s rapid gas accretion
- During Jup, Sat’s outward migration (Grand Tack)
- During LHB instability (Nice model)

Kuiper belt: contaminated 2-3 times

- During Jupiter's rapid gas accretion
- During Jup's inward migration
- Radial mixing during Nice model instability

Extreme radial mixing!



Raymond et al 2012