


Late stages in the evolution of the Solar System



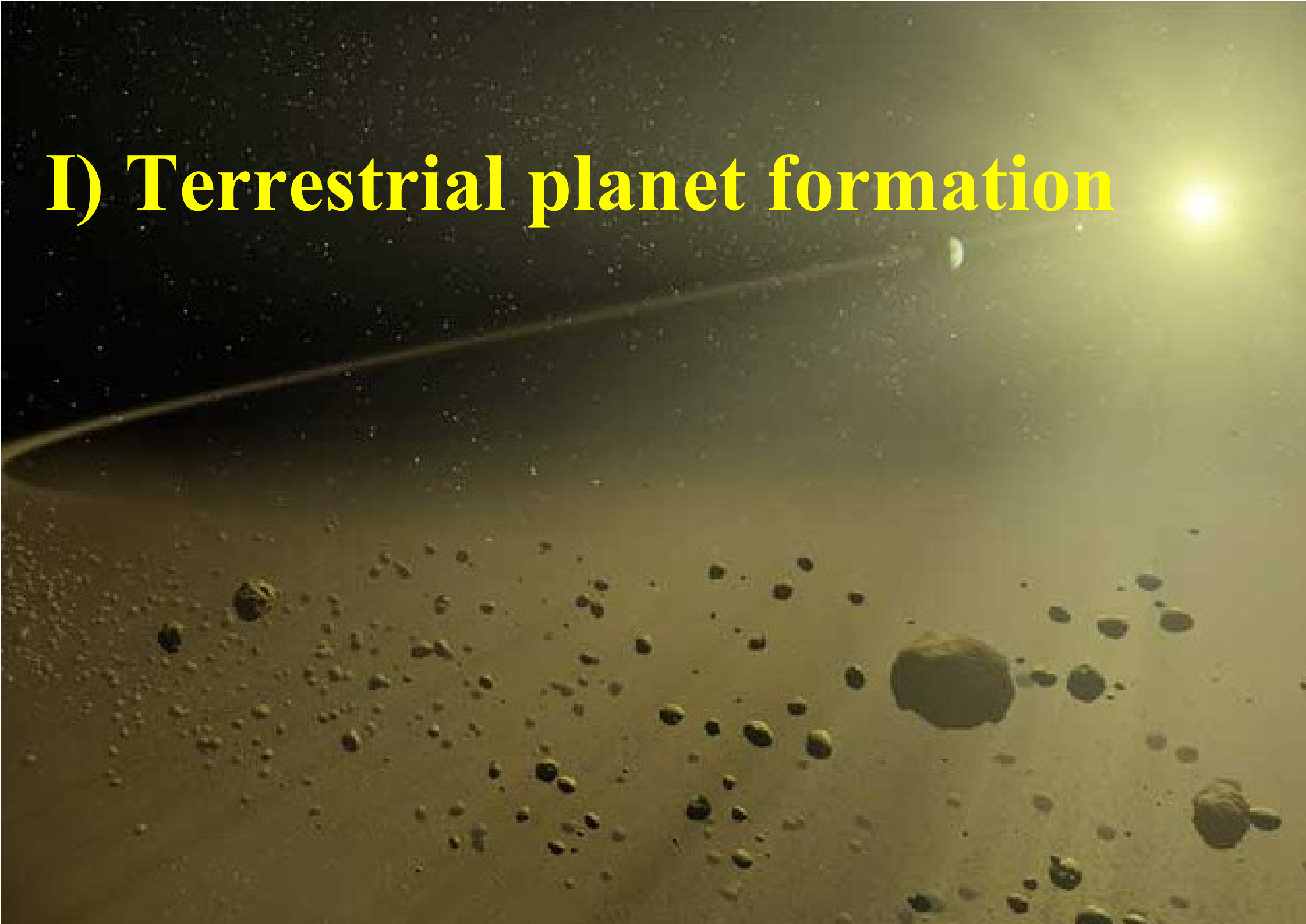
A. Morbidelli (OCA, Nice, France)

OUTLINE

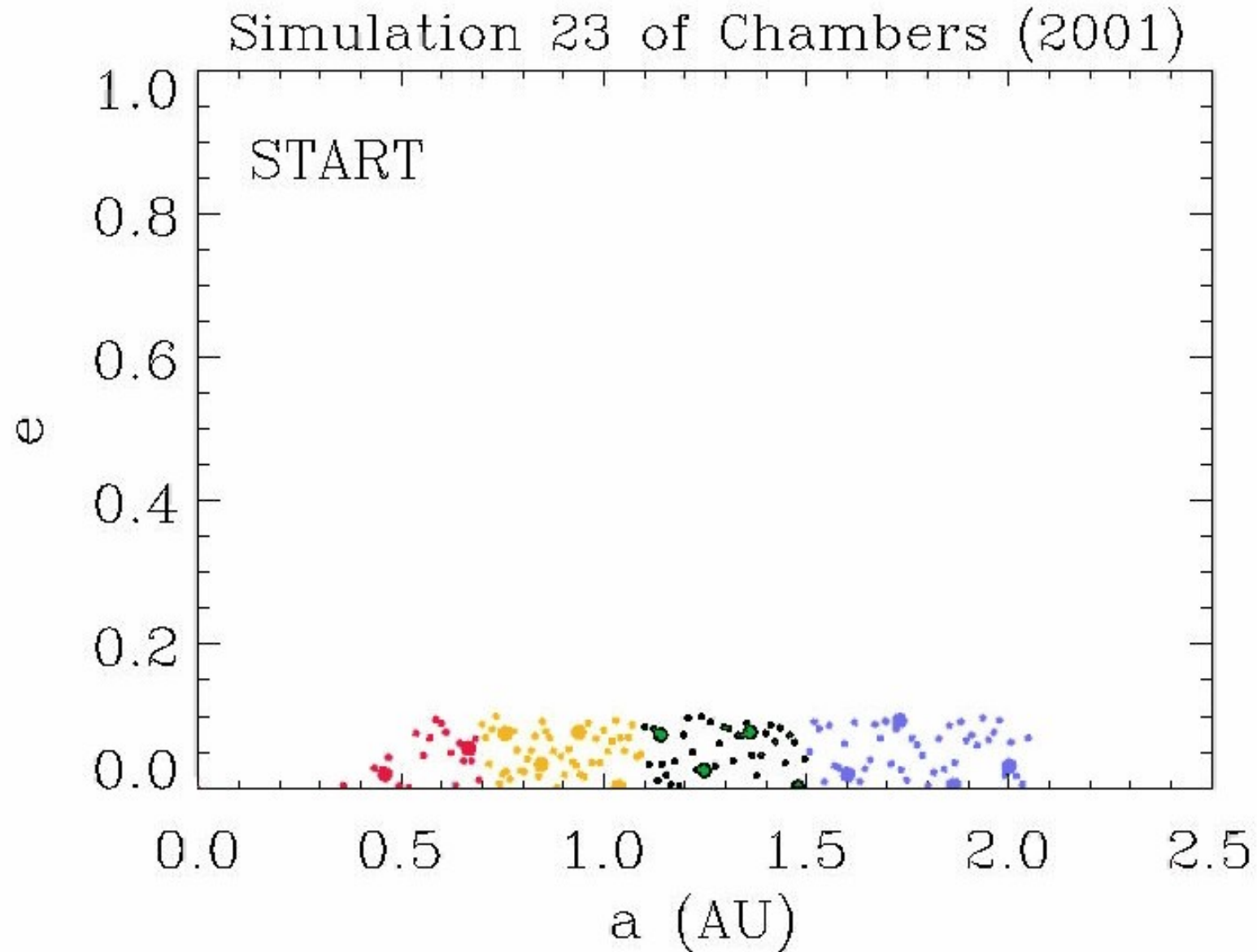
Late = after the gas disappeared

- **Terrestrial planet formation**
- **Giant planets migration due to a planetesimal disk**
- **Late instabilities: the Late Heavy Bombardment**

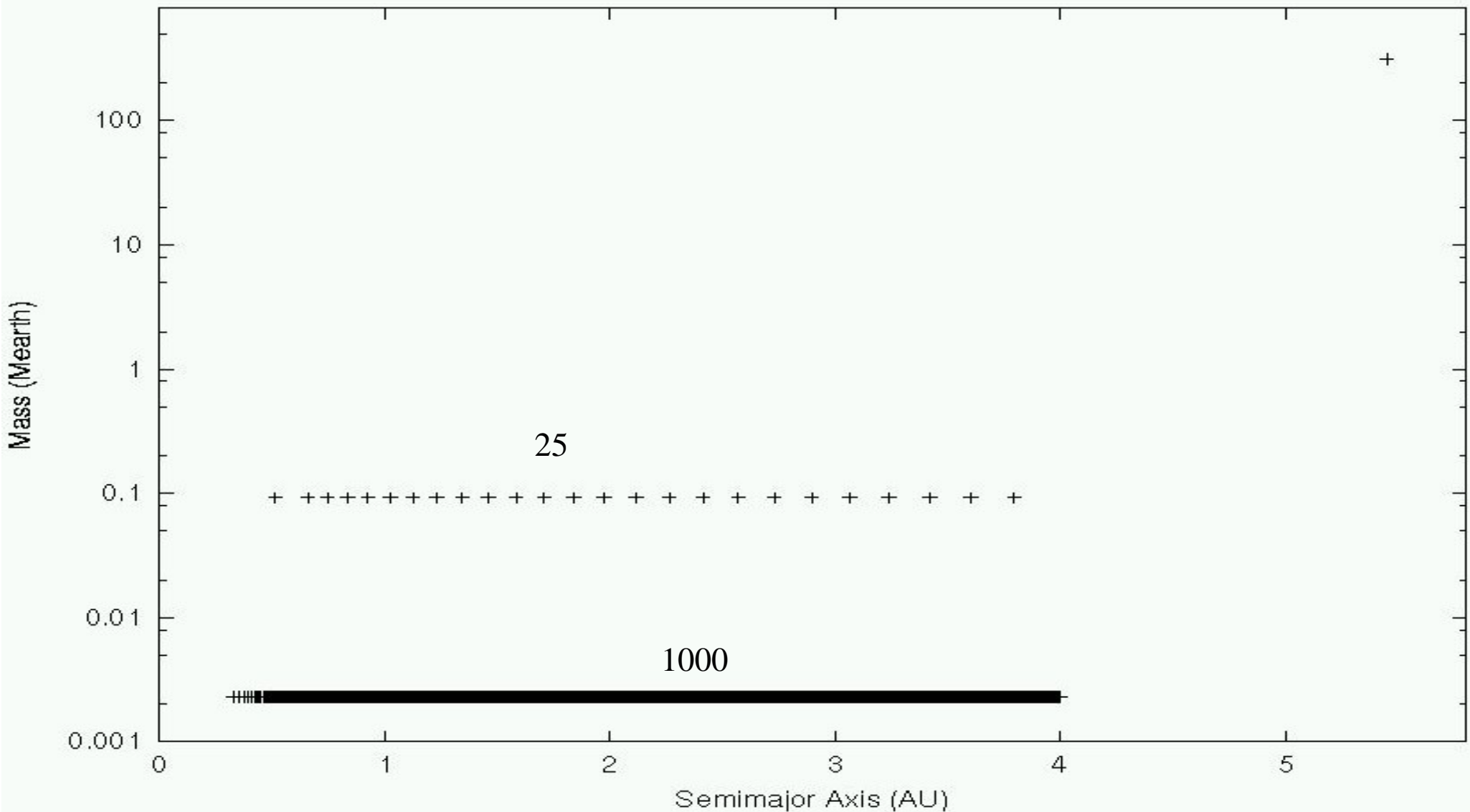
I) Terrestrial planet formation



`Classical' model of terrestrial planet accretion: from embryos in the 0.5-2.0 AU zone.



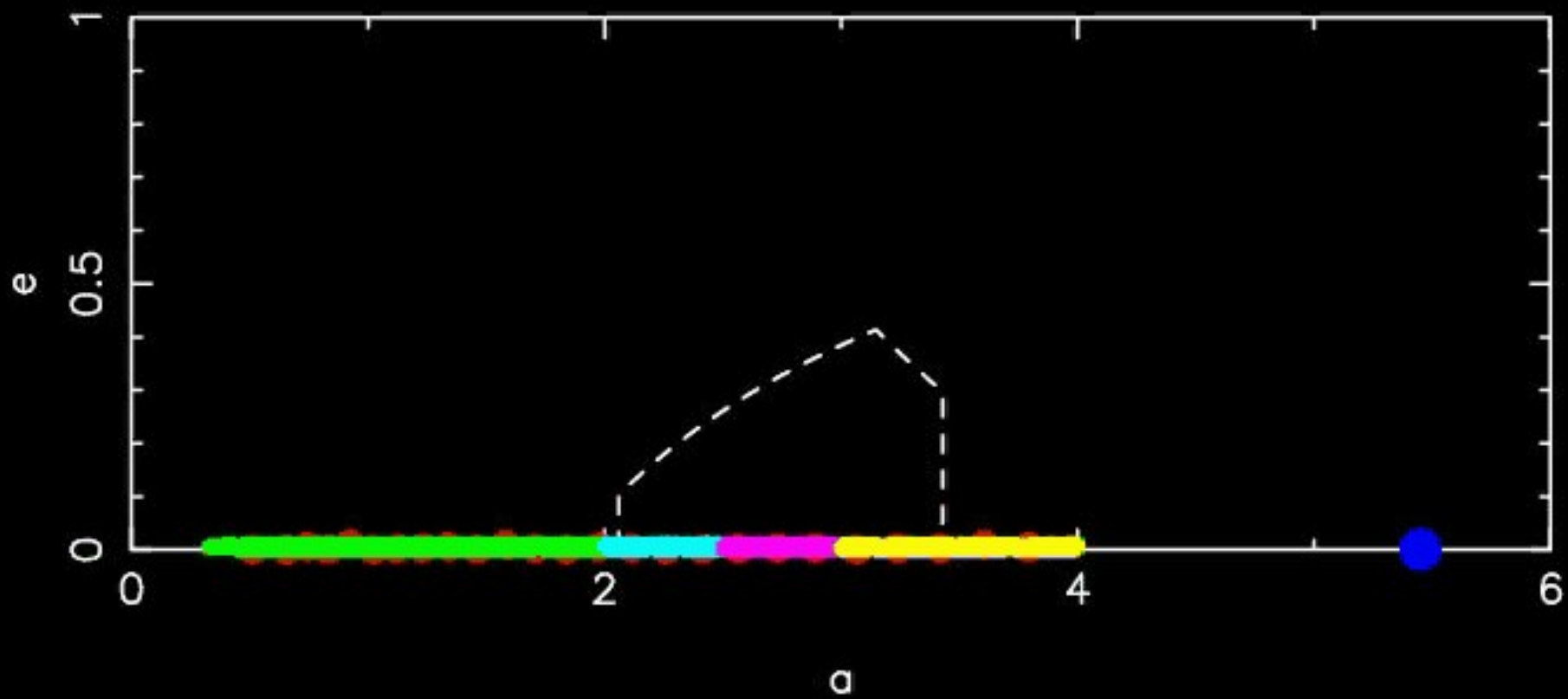
Looking for solutions for the e/i/timescale problem: Pushing dynamical friction



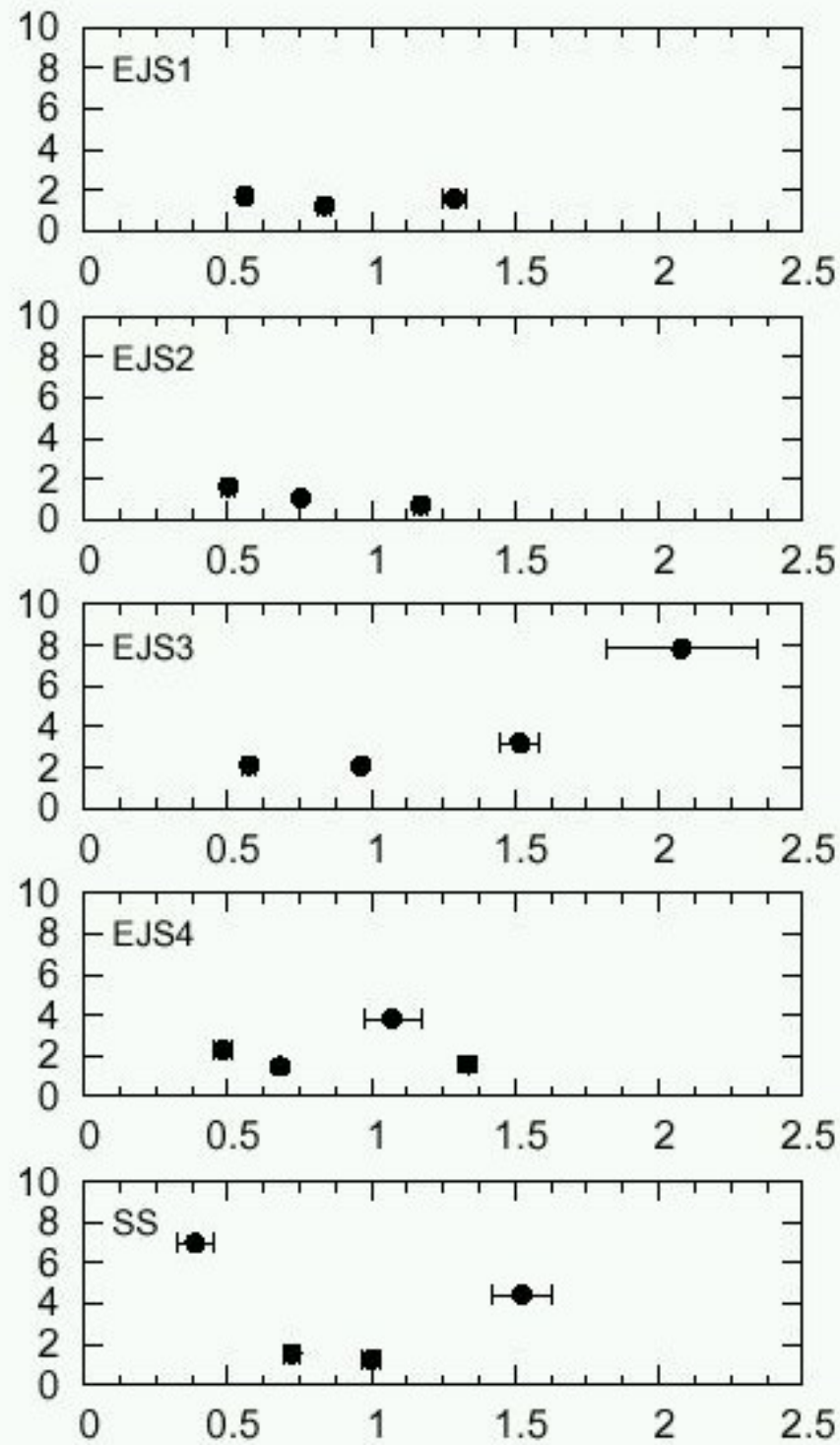
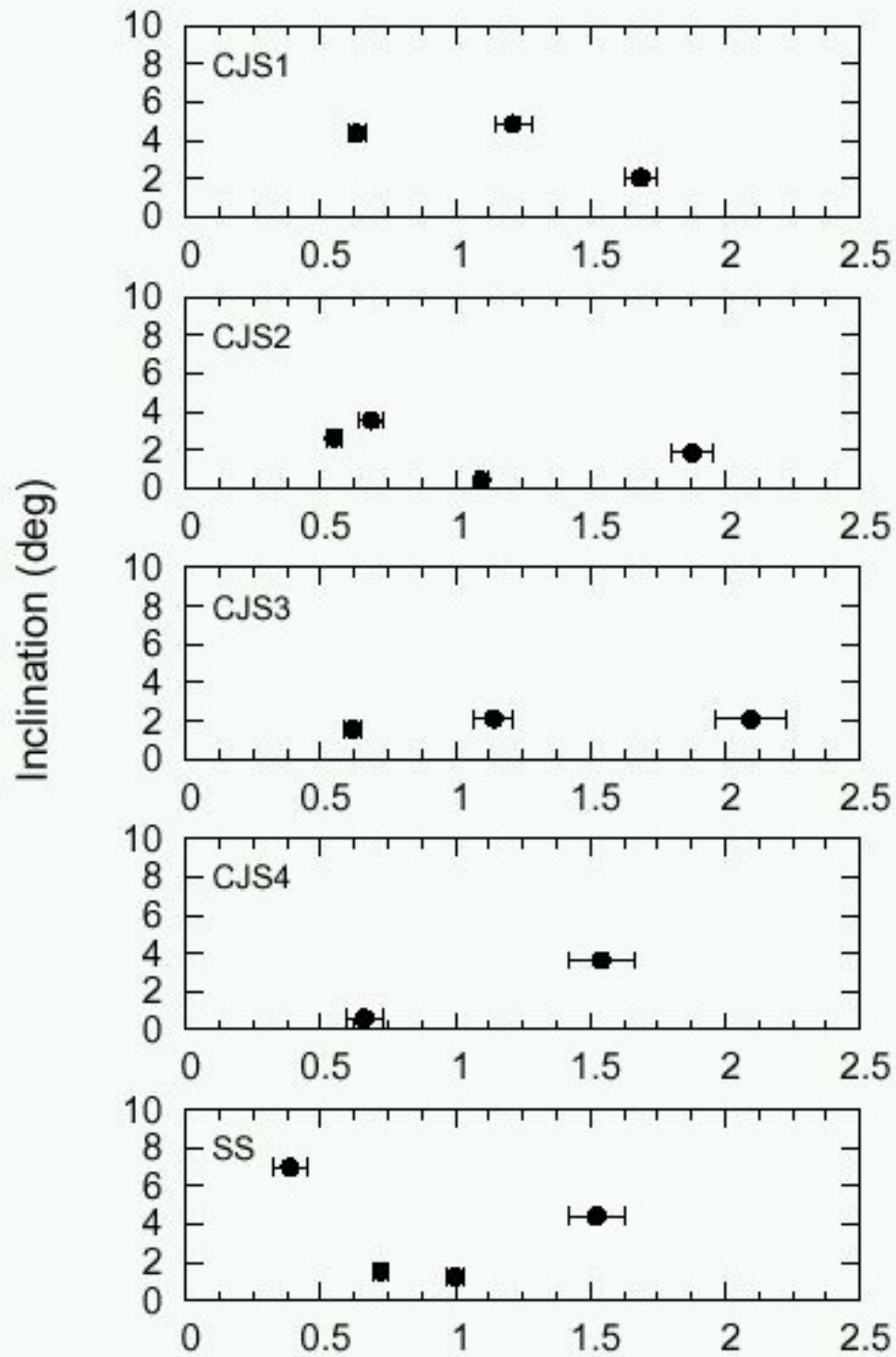
New simulations: O'Brien, Morbidelli, Levison, 2006
4 simul. with circular Jup. & Sat. and 4 with giant planets on current orbits

O'Brien et al. (2006)

Time = 0.00E+00 Myr



ObML06



Semimajor Axis (AU)

ObML06

Quantifying orbital excitation

AMD

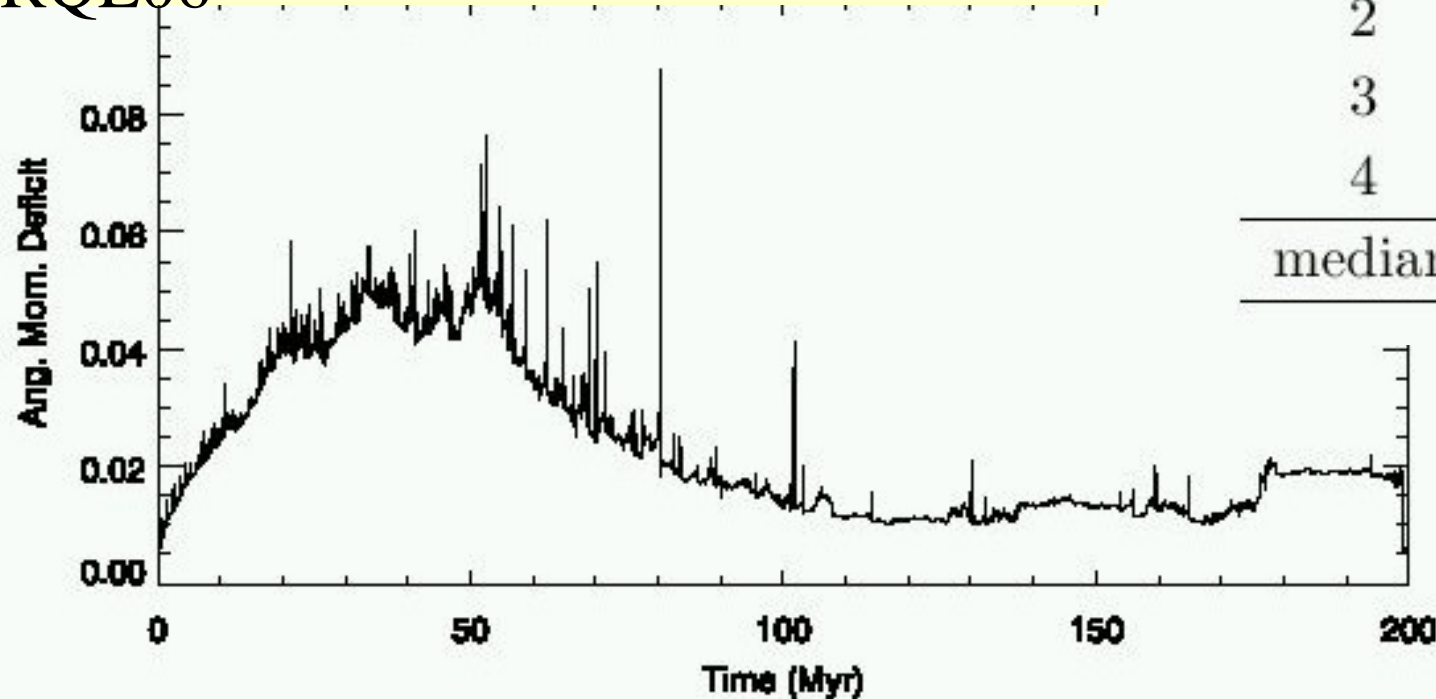
$$= \frac{\sum_j m_j \sqrt{a_j(1 - e_j^2)} \cos i_j - \sum_j m_j \sqrt{a_j}}{\sum_j m_j \sqrt{a_j}}$$

ObML06

Angular Momentum Deficits

	S_d (CJS)	S_d (EJS)
1	-0.0034	-0.00077
2	-0.0013	-0.00049
3	-0.0026	-0.0026
4	-0.0051	-0.0013
median	-0.0030	-0.0010

RQL06



$$\text{AMD}_{\text{chambers}} = -0.007$$

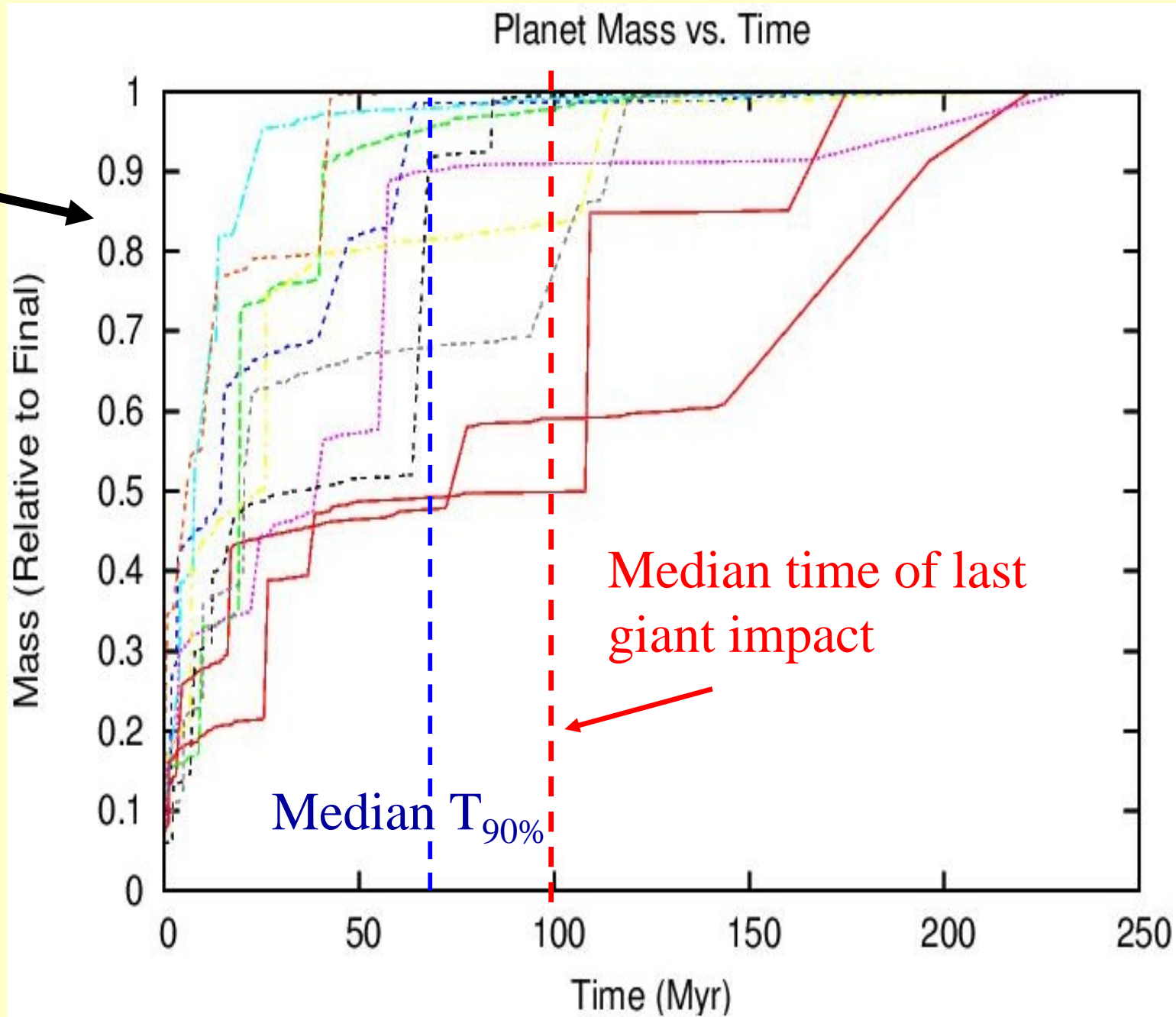
$$\text{AMD}_{\text{ss}} = -0.0018$$

Timescales....

ObML06 for simulations with Circ. Jup. & Sat.

Median $T_{90\%}$ and time of last impact decrease to 40 Myr and 31 Myr in simulations with eccentric Jup. & Sat.

($T_{90\%}$ of Chambers 2001 was 125 Myr)



Origin of material incorporated into the planets

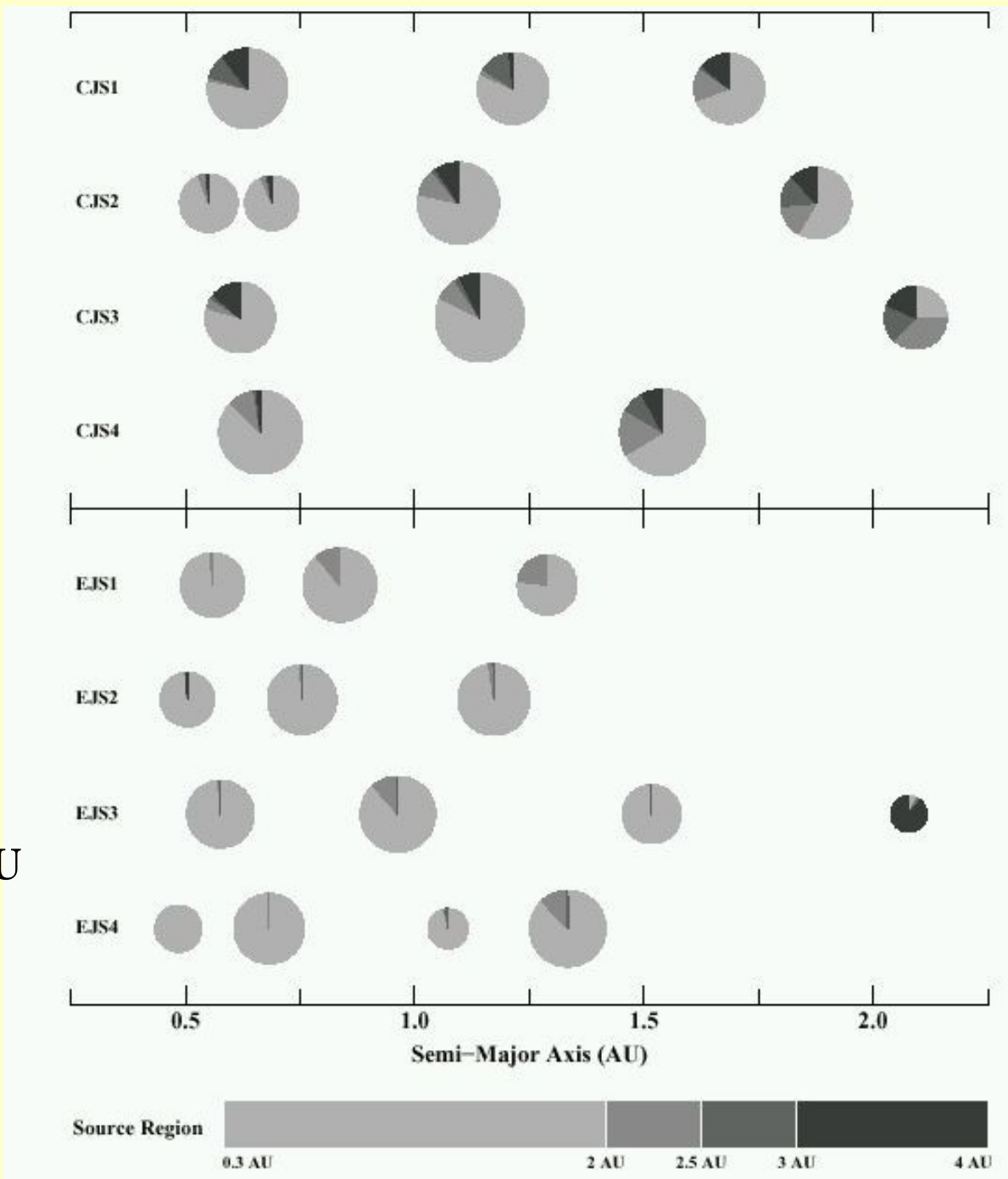
ObML06

Circular JS case

15% of planetary mass accreted from beyond 2.5 AU, 75% of which from embryos

Eccentric JS case

No material accreted from > 2.5 AU

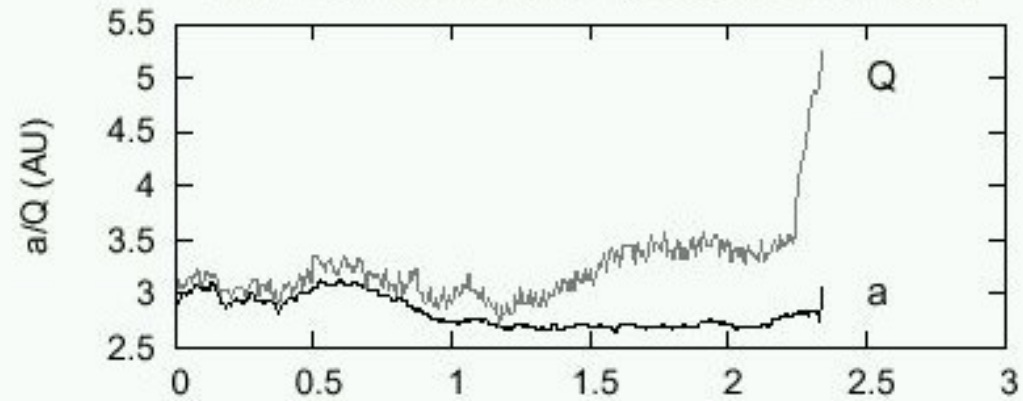


**Why these differences
between the circular and
the eccentric cases?**

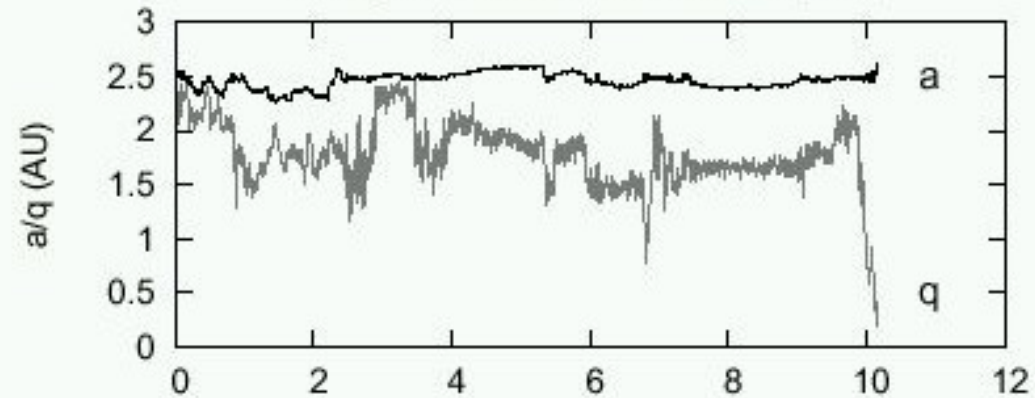
**The answer is in
resonance strength**

**So, was Jupiter circular or
eccentric? ...difficult to
say...**

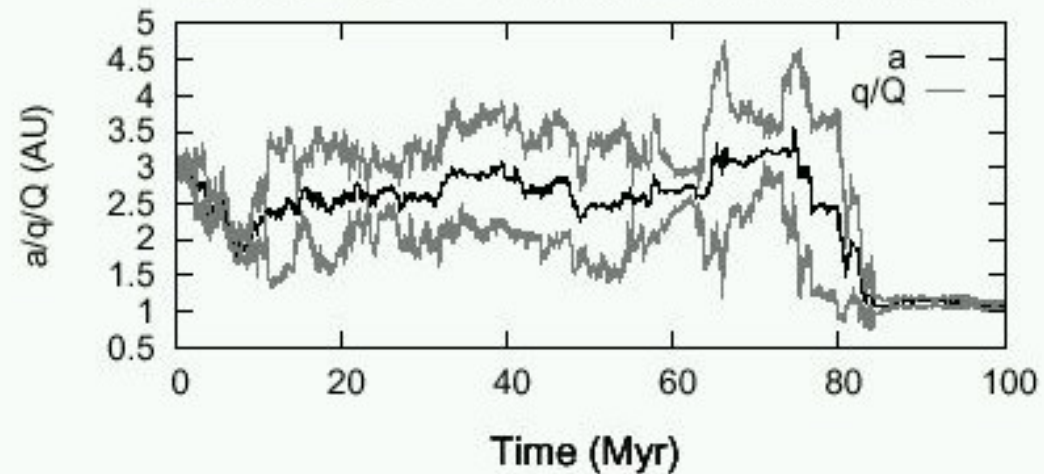
Embryo Enters 5:2 and is Ejected by Jupiter (EJS)



Embryo Enters 3:1 and Hits Sun (EJS)



Embryo Migrates to Terrestrial Planet Region (CJS)

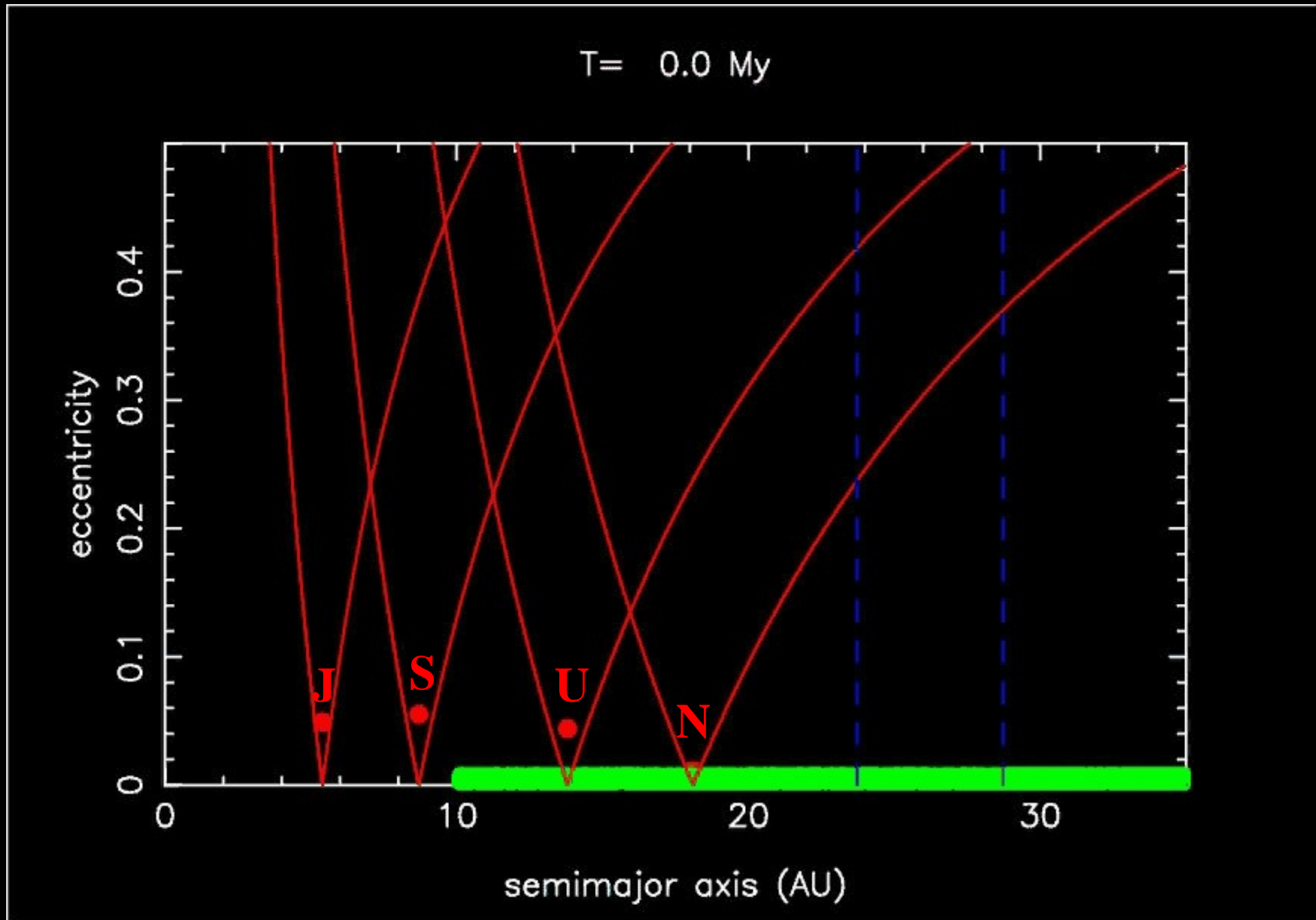


II) Giant planet migration due to a planetesimal disk

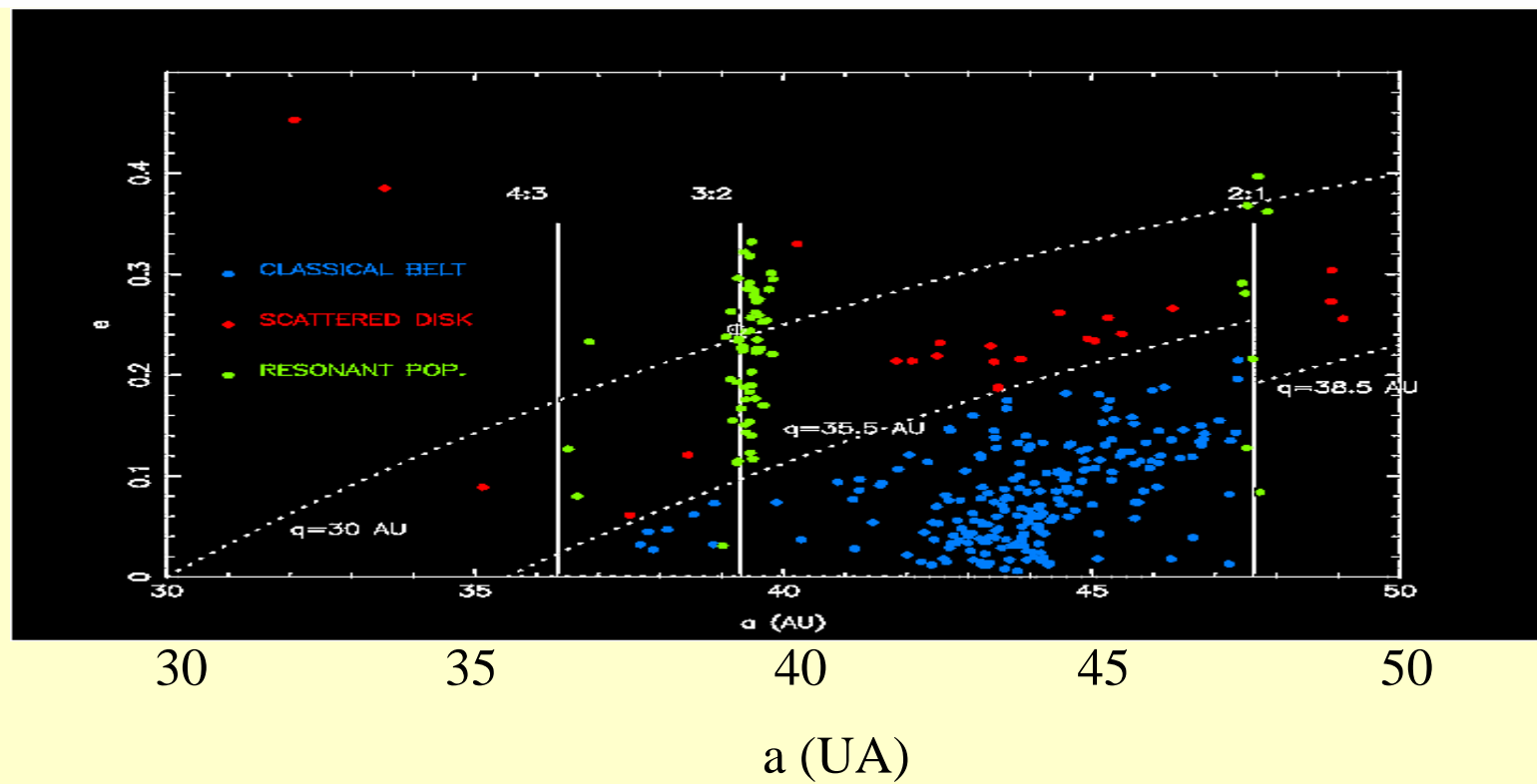
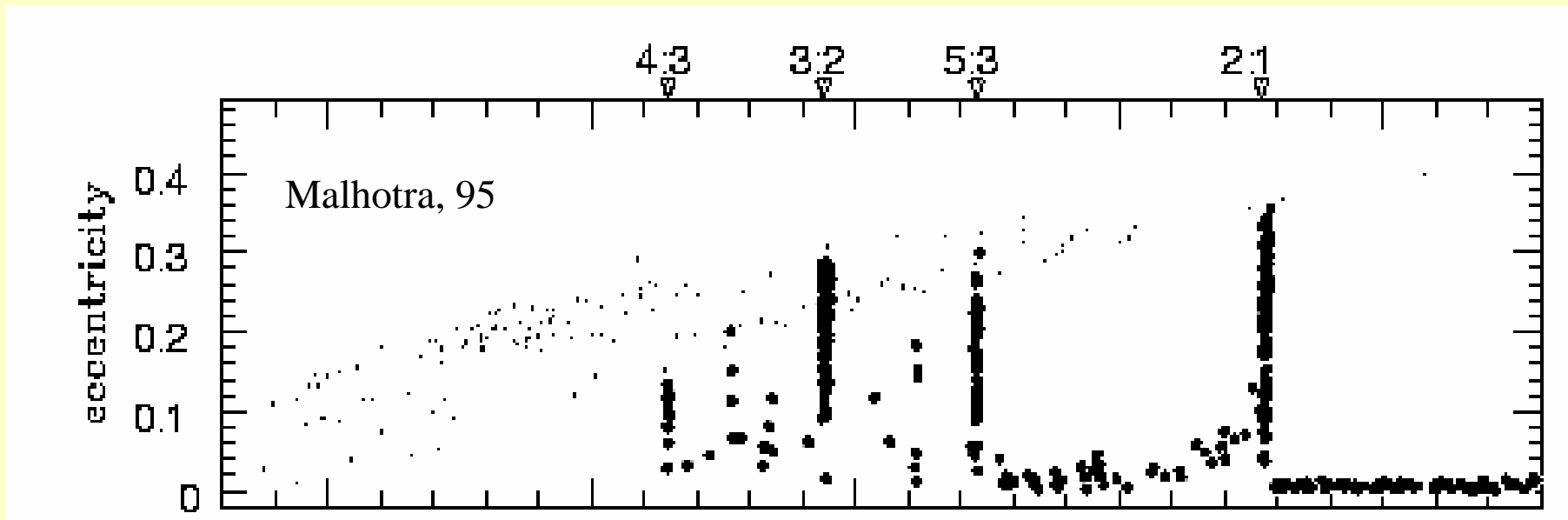


Migration direction: Our Solar System case.

Fernandez and Ip (1980); Malhotra (1993, 1995)



Evidence for planet migration: The Kuiper belt

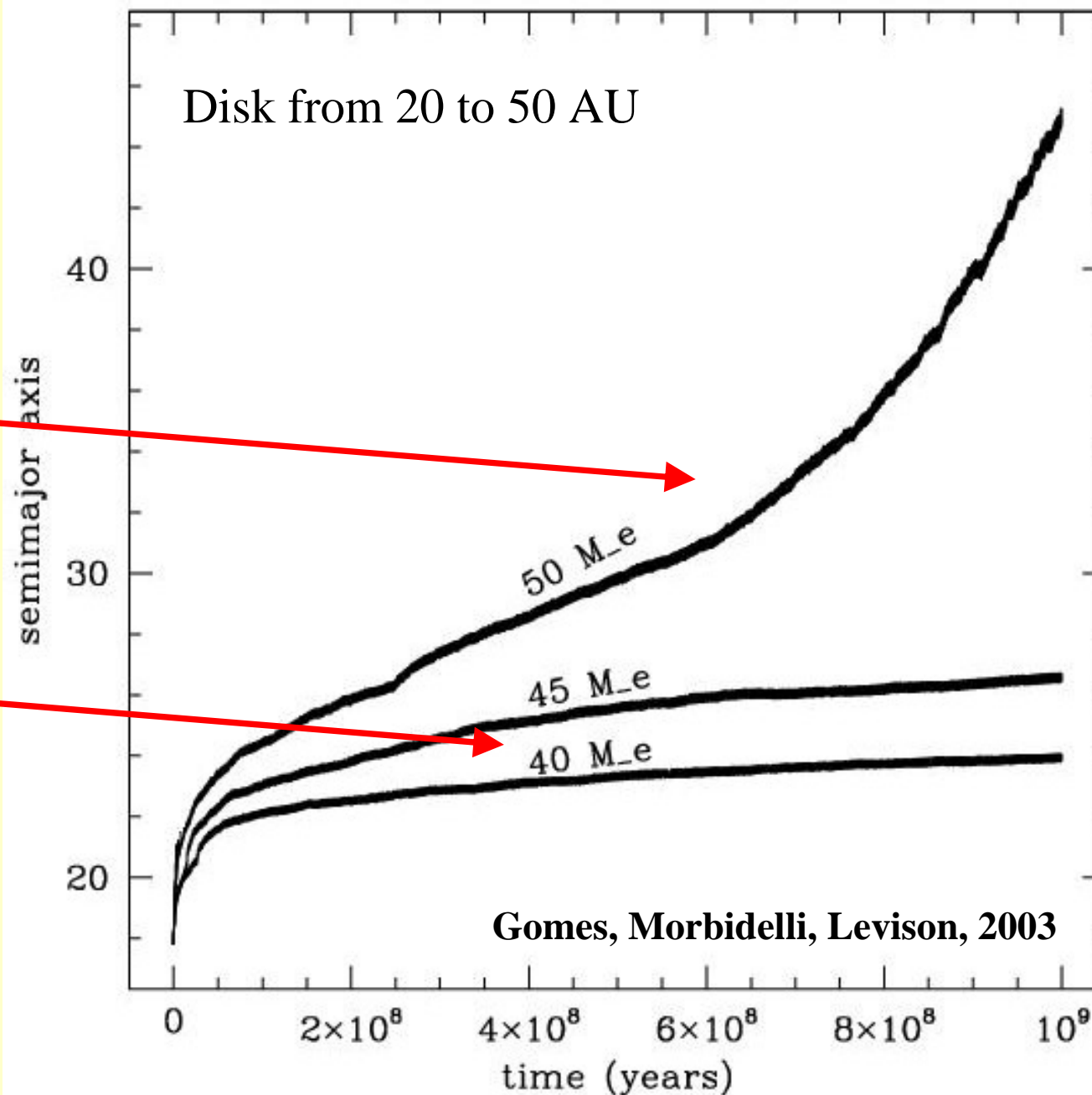


Why did Neptune stop at 30 AU?

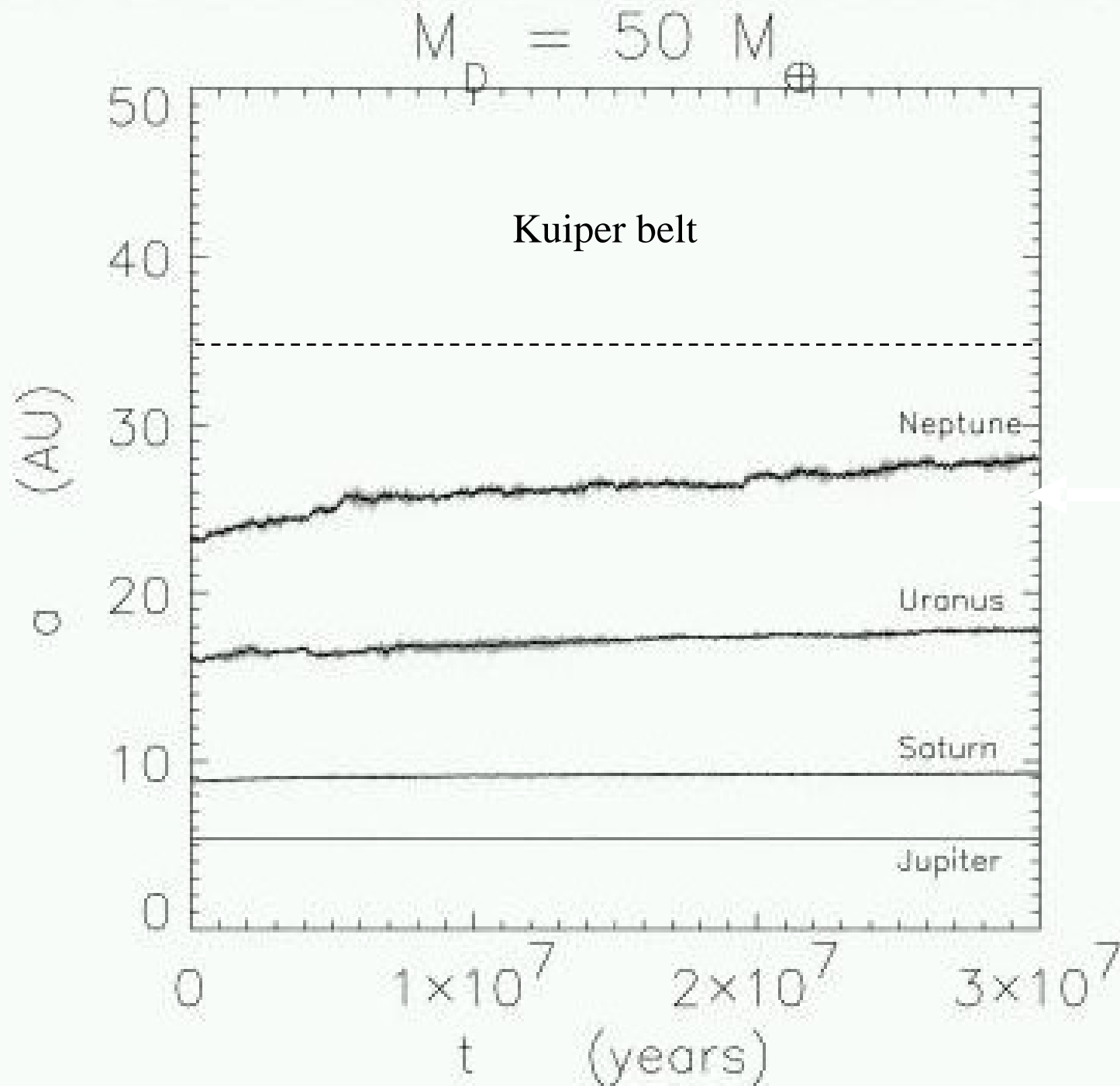
The migration mode depends on the disk's surface density:

runaway

damped



Hahn and Malhotra (1999) solution

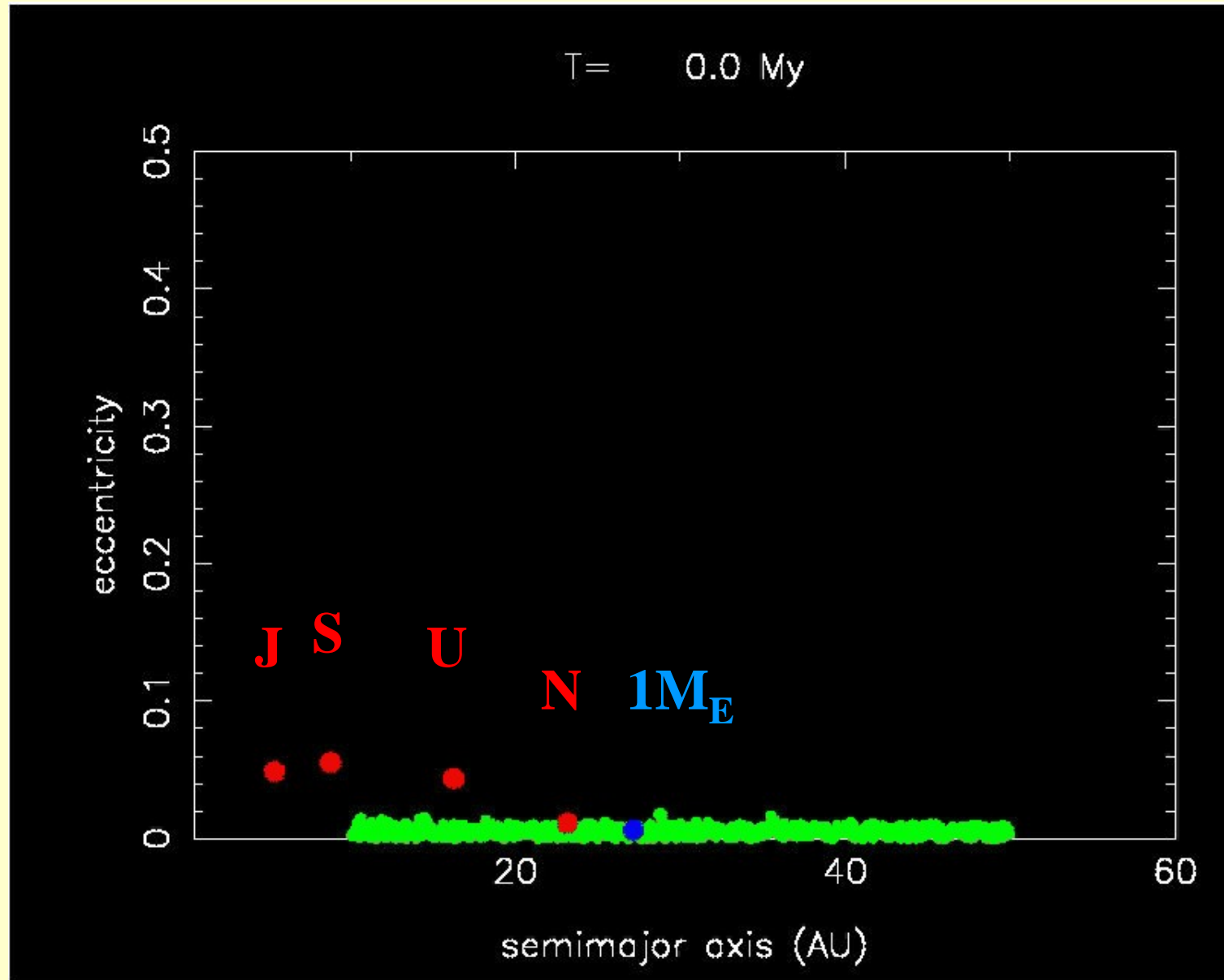


**A massive
Kuiper belt
($\sim 15 M_E$) would
remain beyond
 $\sim 35 \text{AU}$!**

**The current
mass is $< 0.1 M_E$**

Dynamical mass depletion of the Kuiper belt

Gomes, Morbidelli, Levison (2004)



Simulation as in Hahn and Malhotra (1999) but with a half massive disk and one Earth mass embryo

GENERAL IMPLICATION

It is not possible to deplete the belt by ejecting most of its objects to Neptune-crossing orbit* otherwise Neptune would have migrated well beyond 30 AU !

***unless the belt was $<5 M_E$ from the beginning – not enough to grow the KBOs**

The collisional grinding of the Kuiper belt does not seem to work either (Gomes et al., 2004; Kenyon and Bromley, 2004)

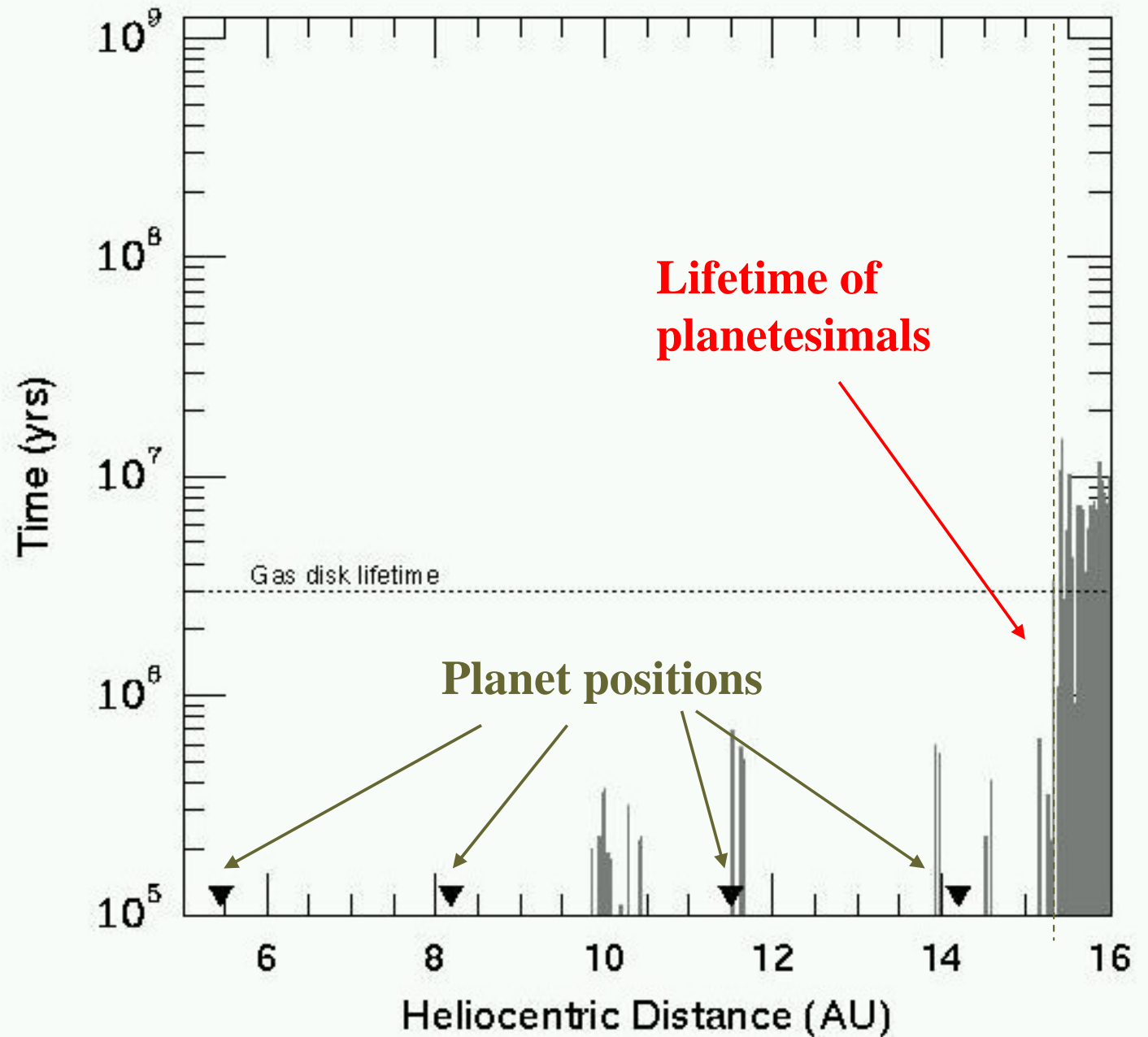
Thus, Gomes (2003) - Levison & Morbidelli (2003) proposed that the disk was truncated at $\sim 30 - 35$ AU. The KBOs had to form within this limit and be transported outward, during Neptune's migration.

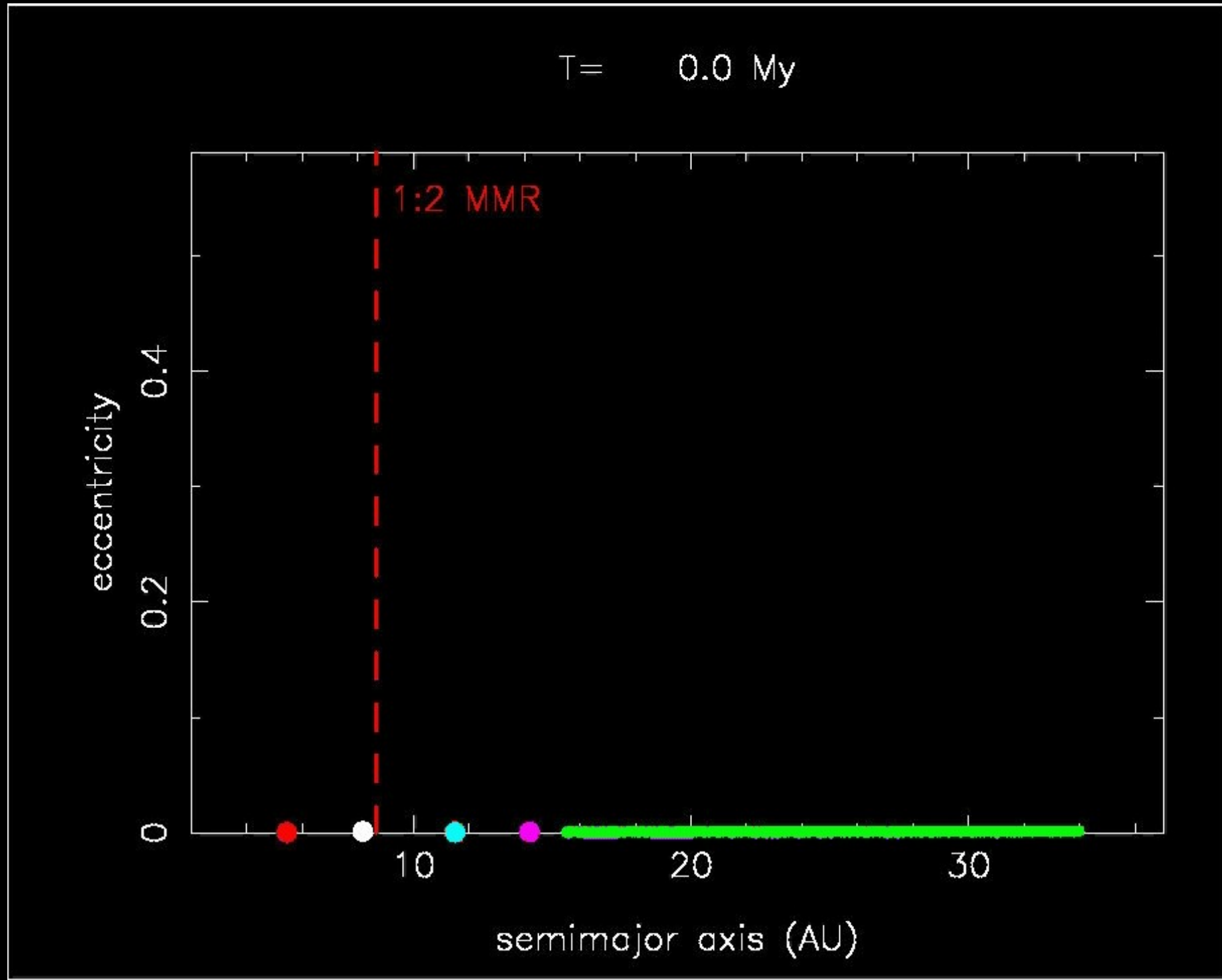
III) Late instabilities : the Late Heavy Bombardment

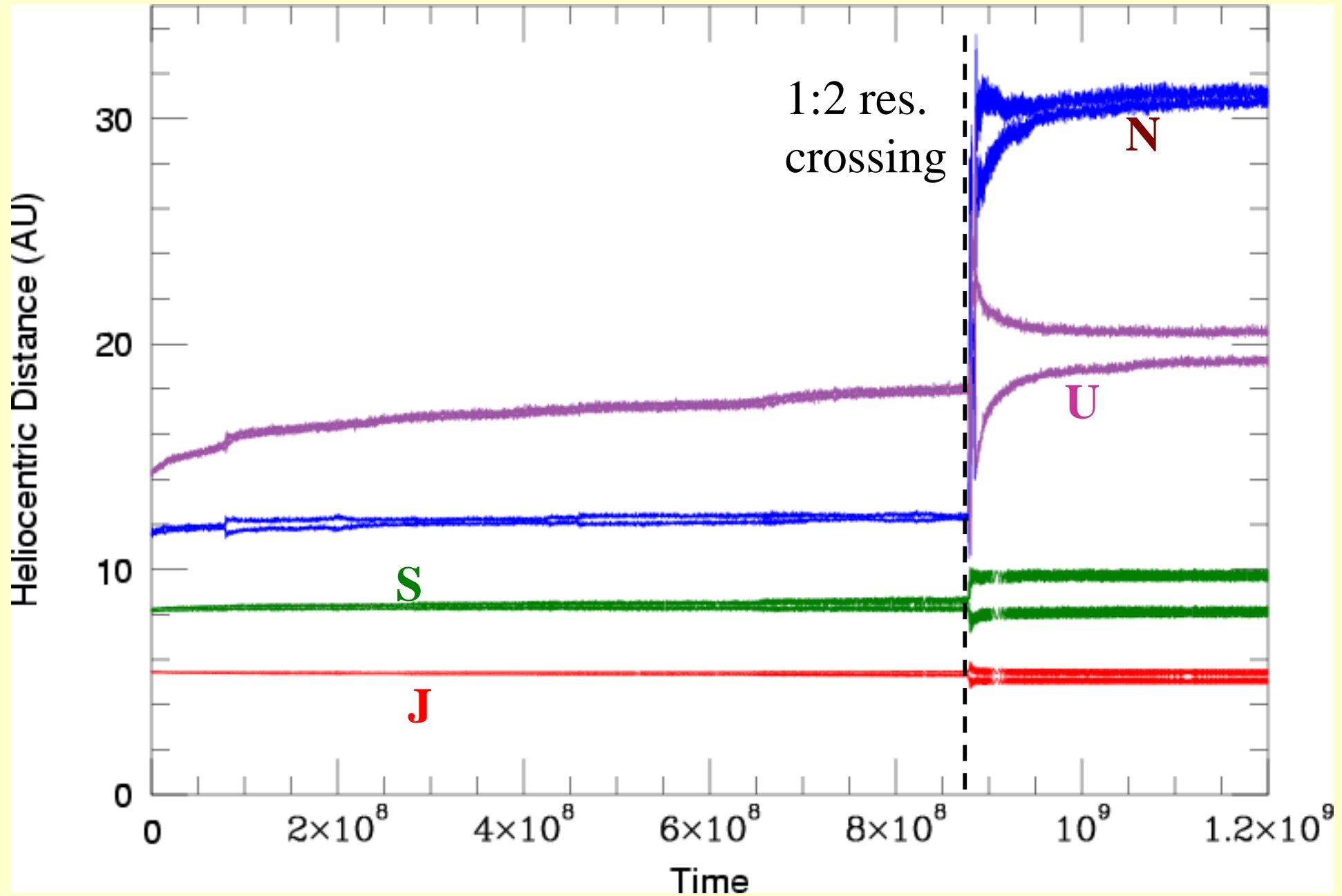


In all previous simulations, migration started immediately because planetesimals were placed in very unstable regions.

However, at the end of the gas-disk phase, planetesimals should be only where the lifetime is longer than the nebula dissipation time







We argue that this is the solution of the problem of the Origin of the Late Heavy Bombardment

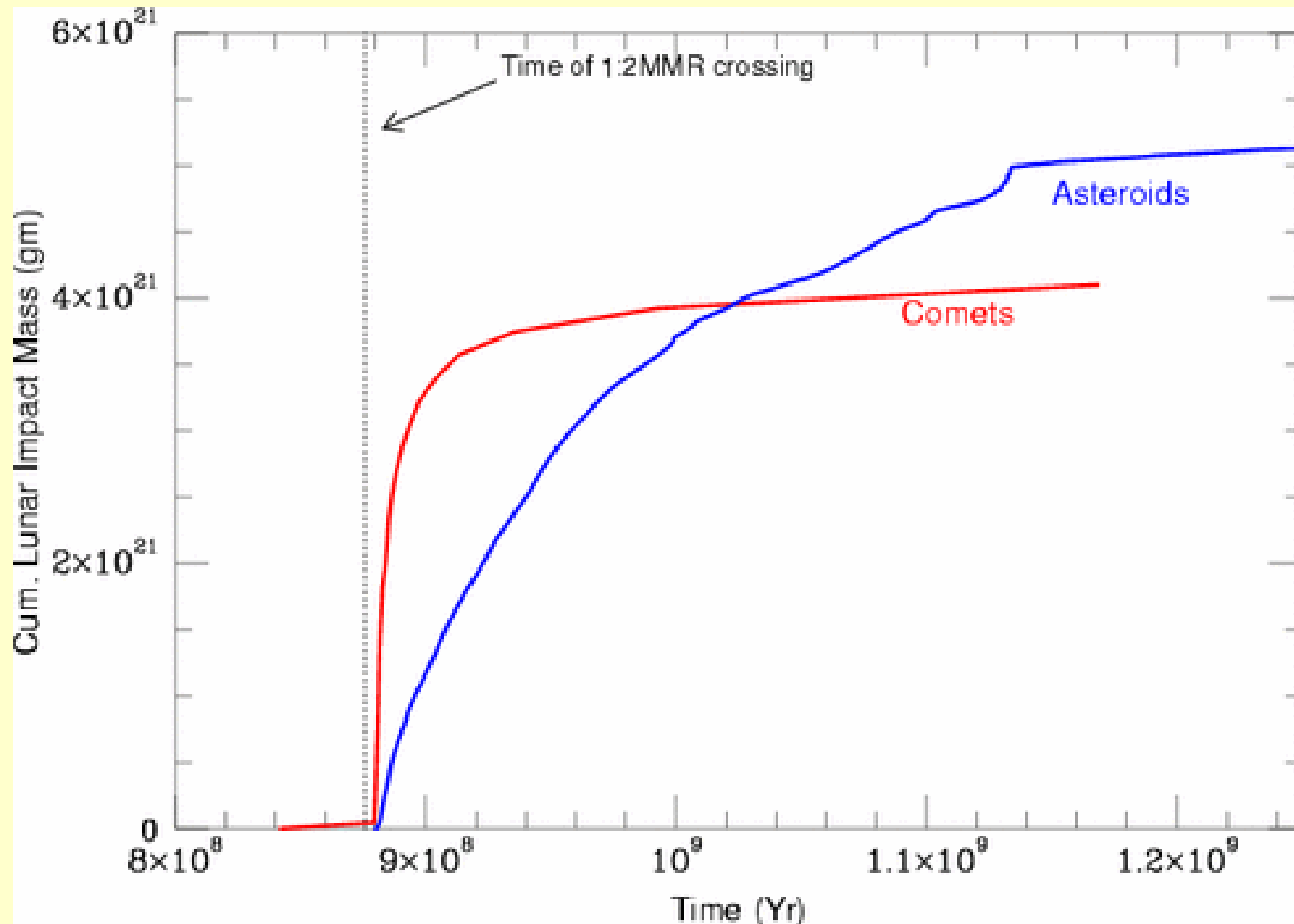
A few facts on the LHB:

- Cataclysmic event triggered 3,9 Gy ago, ~600My after terrestrial planet formation
- Global event: traces found on Mercury, Venus, Earth, Mars, Vesta....., possibly on giant planets satellites
- 20.000x the current bombardment rate: 1 km object impacting the Earth every 20 years!
- Duration: 50-150 My

Two strengths of our LHB model.

I: We explain a late heavy bombardment, with magnitude and duration consistent with crater constraints

R. Gomes et al. 2005. *Nature*, 435,466

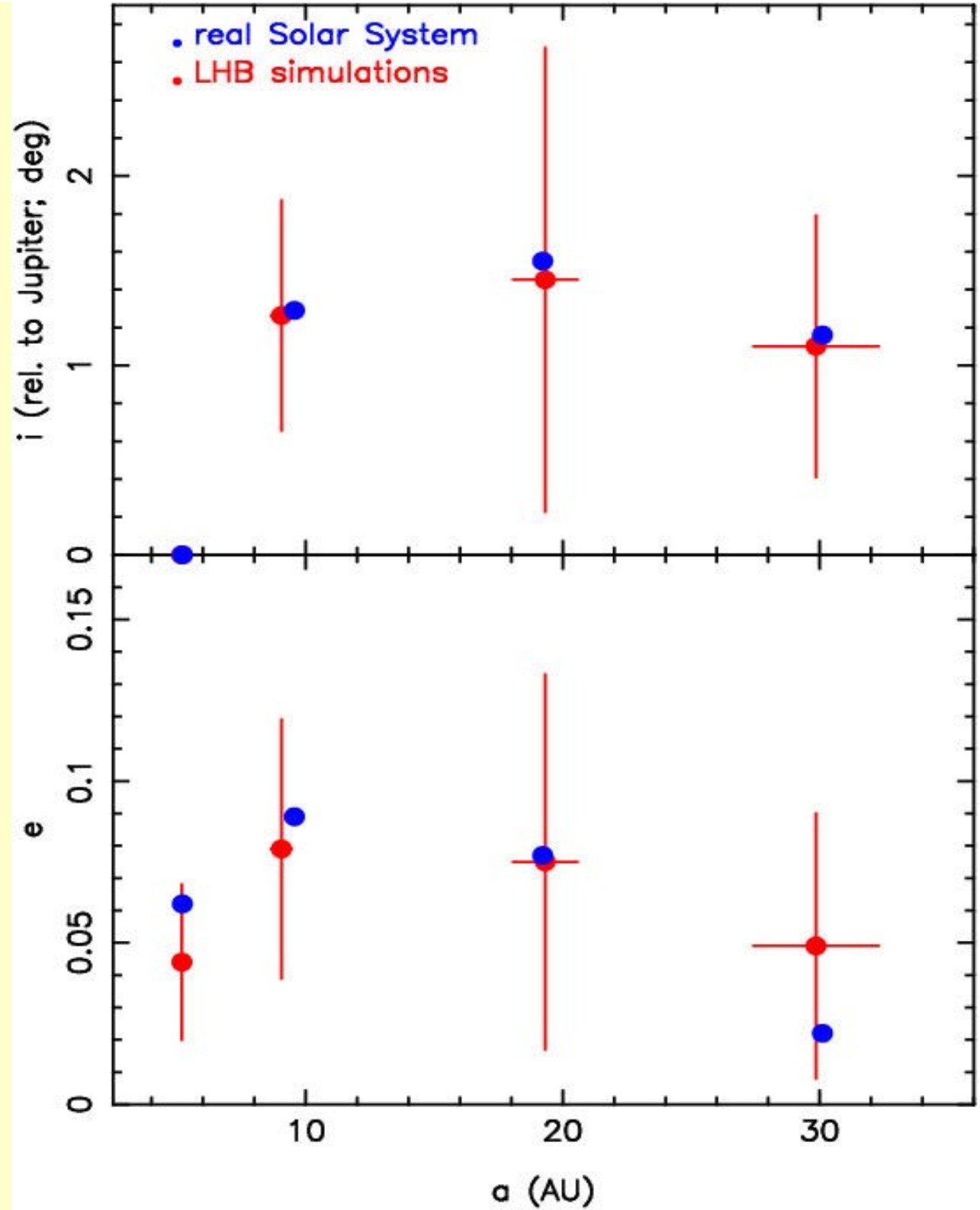


Asteroids dominated the LHB signature: Kring and Cohen 2002, Strom et al. 2005:

II: We explain the current orbits of the giant planets: their semi major axes, eccentricities and inclinations

K. Tsiganis, R. Gomes, A. Morbidelli, H.F. Levison 2005.
Nature, 435, 459

We also explain the distribution of Jupiter Trojans (see Morbidelli, Levison, Tsiganis, Gomes 2005)

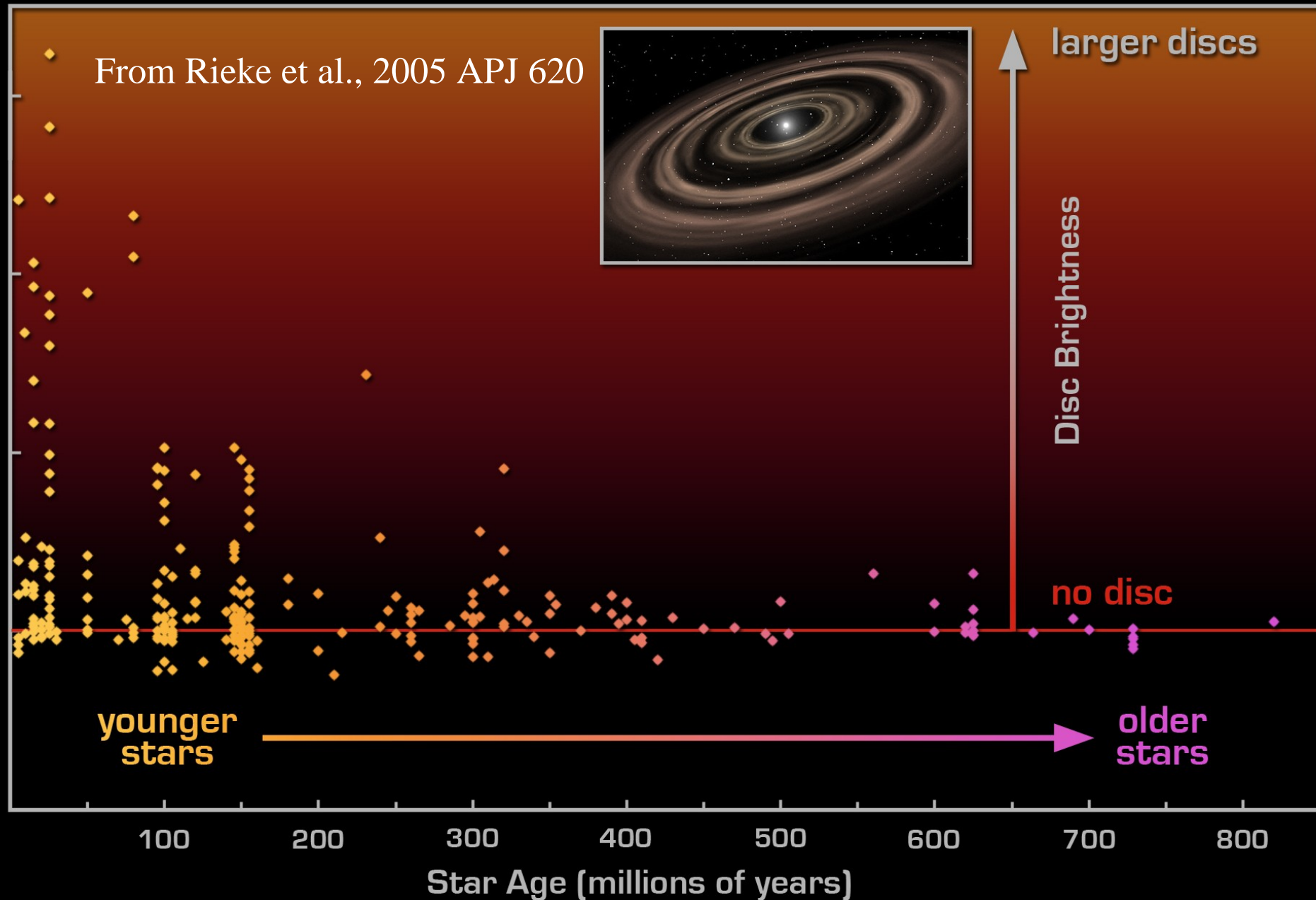


Conclusions

When the gas disk is dissipated, the Solar System is not done yet

- Terrestrial planet formation continues for about ~40 My**
- Giant planets migrated, driven by planetesimals continues for ~600 My**
- The Late Heavy Bombardment marks a big reorganization of the Solar System's structure, which led to the System that we know today.**

LATE PLANET INSTABILITIES



might be quite generic, explaining the IR excess observed for main sequence stars

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