Dynamical evolution of the Solar System

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OUTLINE

I) Summarizing what we know about migration in gas disks

II) Putting the various pieces together into a coherent model of Solar System evolution describing two main phases:

a) in the disk of gas: migration

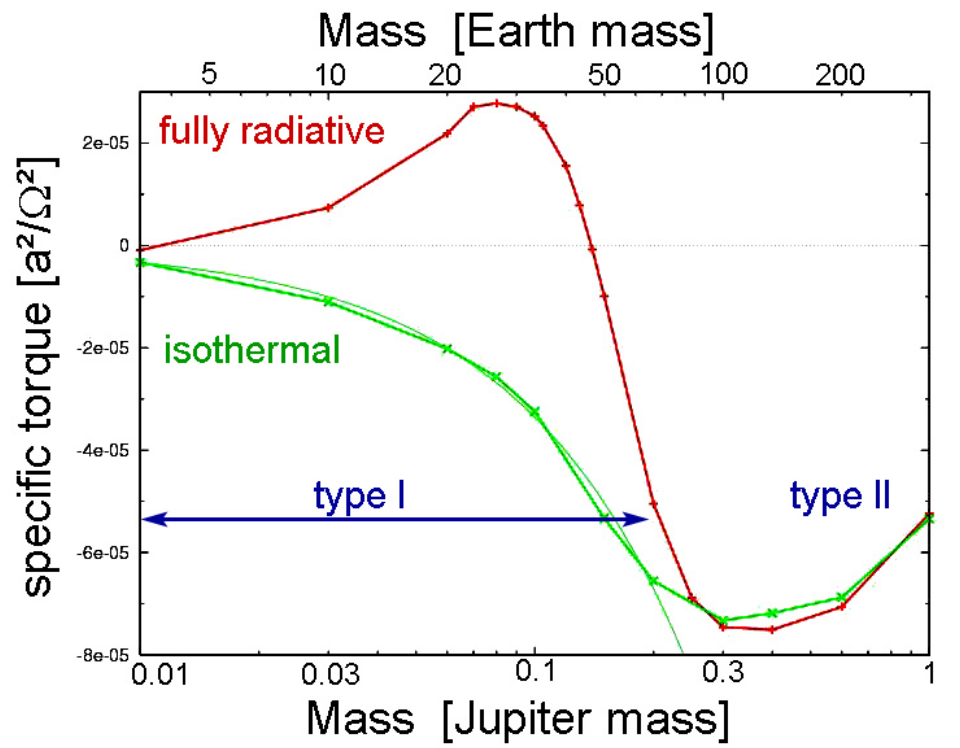
b) after the gas was gone: interactions with planetesimal disk

III) Addressing the origin of the diversity of planetary systems

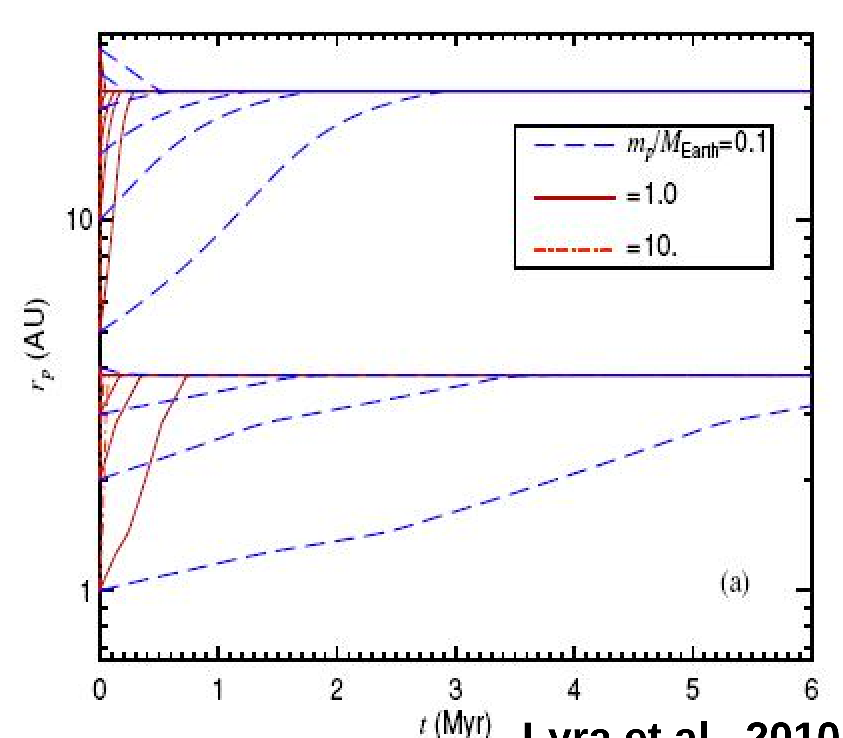
WHAT WE KNOW ABOUT MIGRATION

i) Classical inward type-I migration does not apply to realistic disks

ii) Planetary embryos move to the intermediate region of the disk, where migration is cancelled out. That is where we expect the cores of the giant planets to form, on non-migrating orbits.



Kley and Crida, 2008



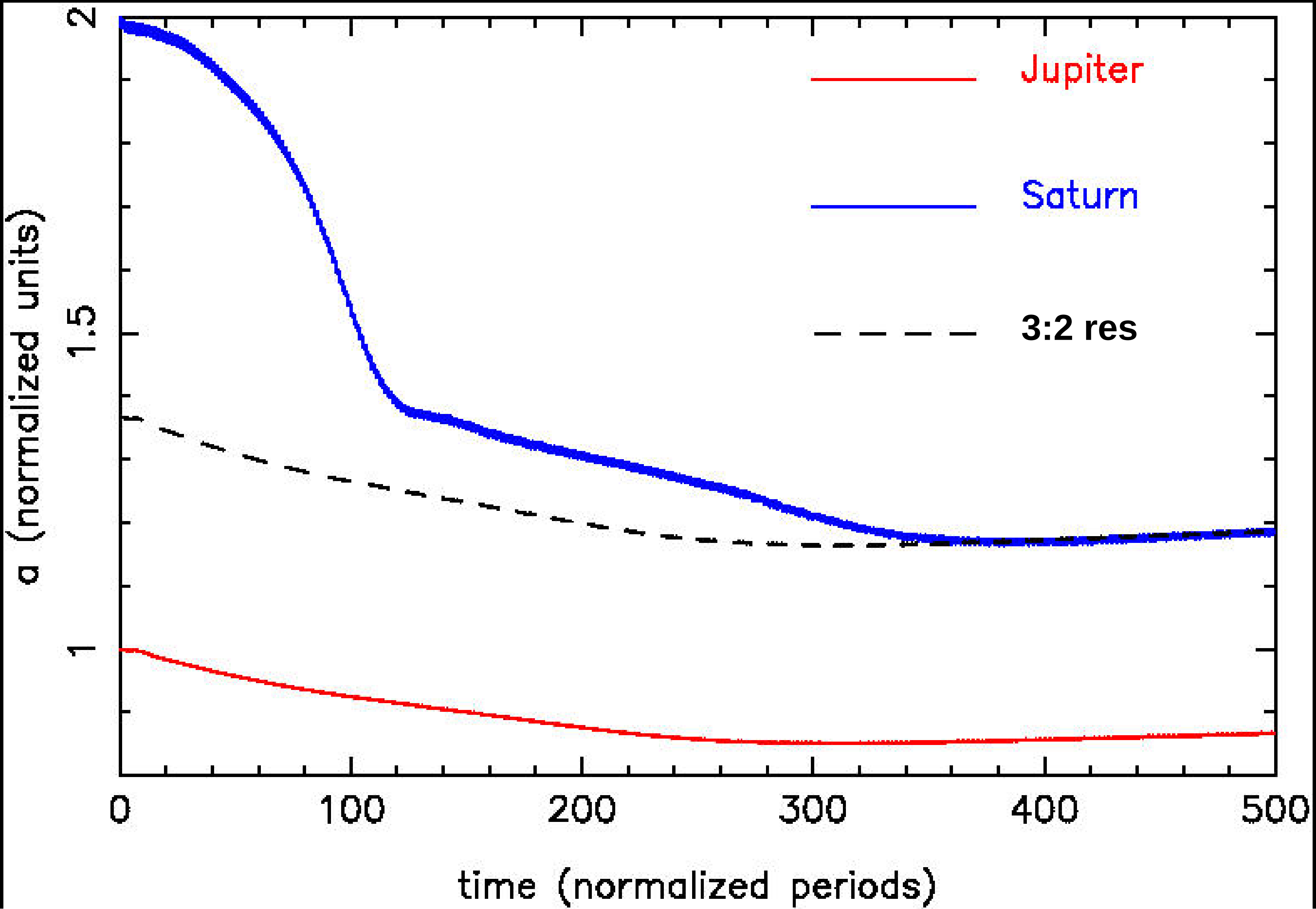
Lyra et al., 2010

iii) Inward migration is resumed when planets exceed 30-50 Earth masses. Thus, Uranus/Neptune don't migrate, Saturn/Jupiter eventually do

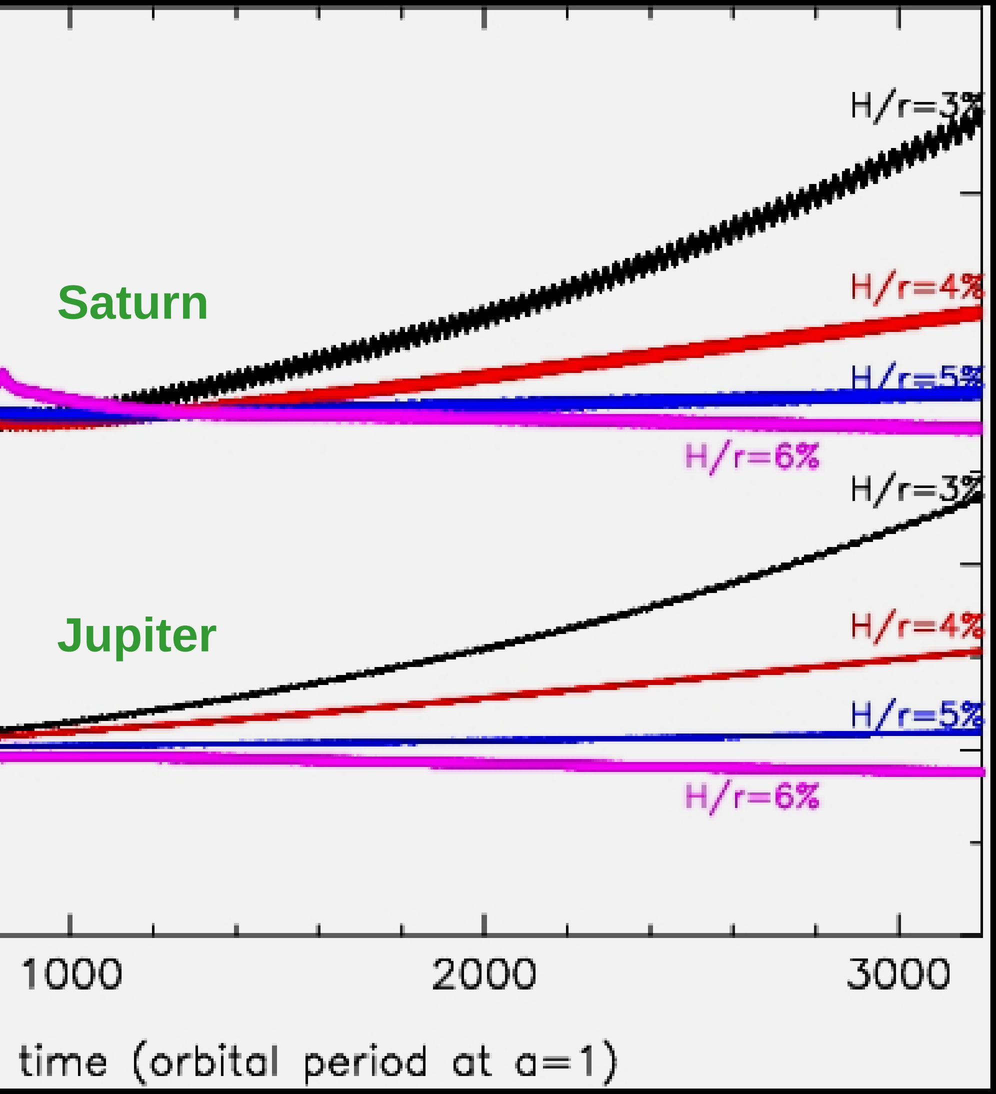
iv) Saturn's mass maximizes migration speed. Possibility of runaway migration (Masset and Papaloizou, 2003)

WHAT WE KNOW ABOUT MIGRATION

V) two-planet (Jupiter-Saturn) migration (Masset and Snellgrove, 2001)



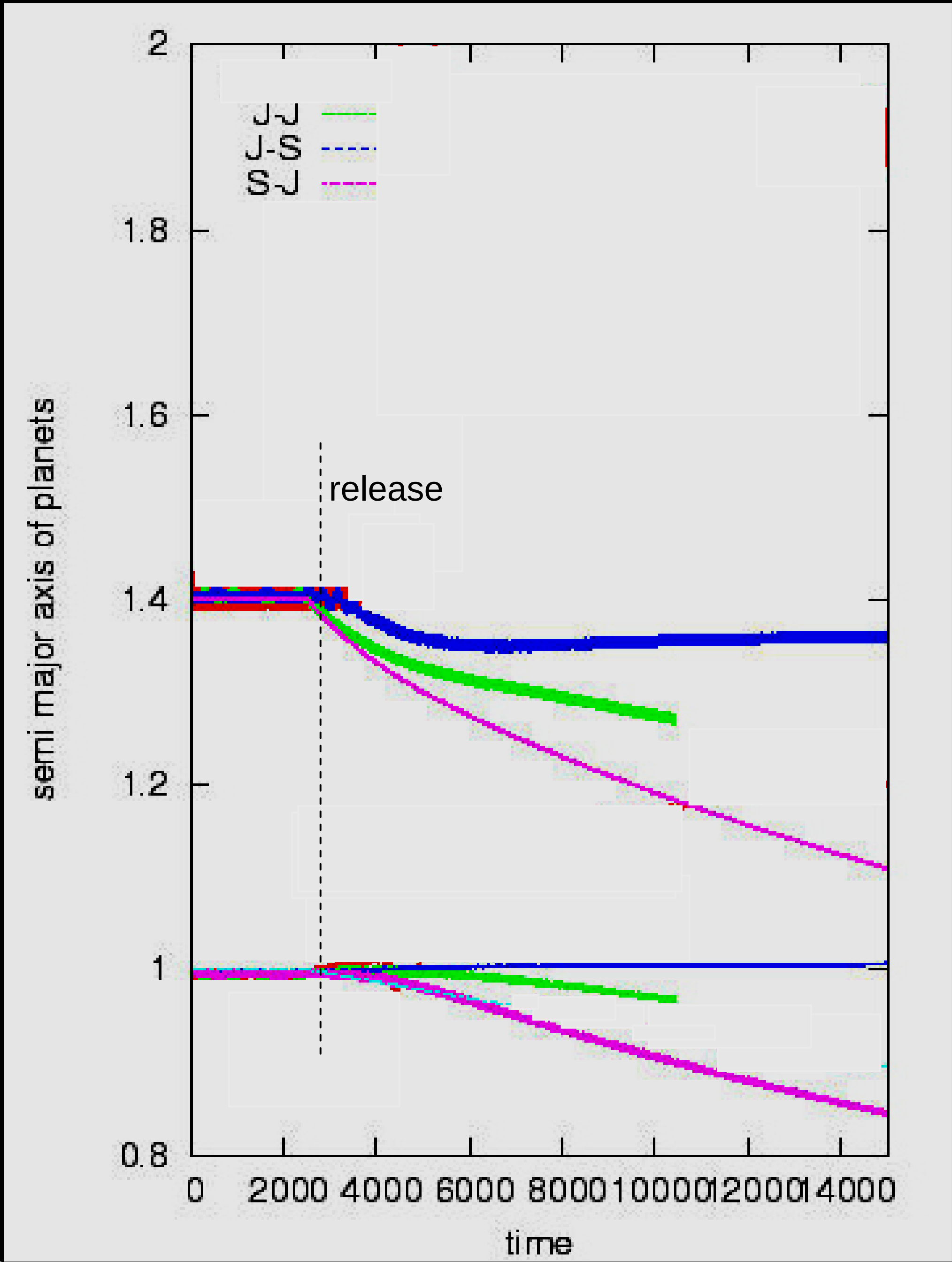
WHAT WE KNOW ABOUT MIGRATION



vi) Once locked in resonance, the evolution of Jupiter and Saturn depends on disk parameters (Morbidelli and Crida, 2007)

WHAT WE KNOW ABOUT MIGRATION

vii) Evolutions with no migration or outward migration are possible ONLY if the outer planet is less massive than the inner one



PUTTING TOGETHER A COHERENT MODEL FOR THE SOLAR SYSTEM

The Jupiter/Saturn mass-ratio seems to be the key to explain why Jupiter is not close to the Sun

However, can Saturn capture Jupiter in resonance if their dynamical evolution is coupled to their accretional evolution?

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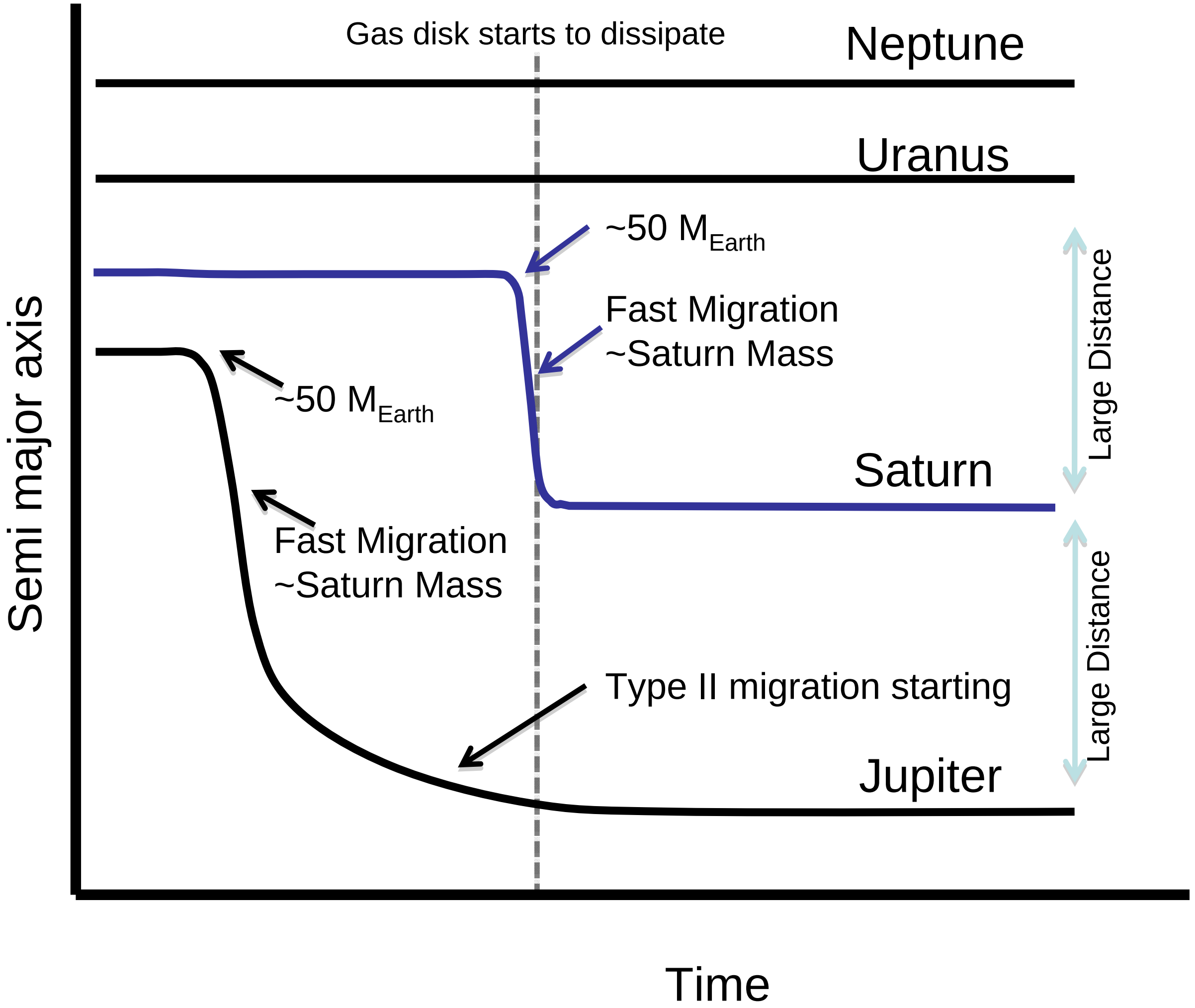
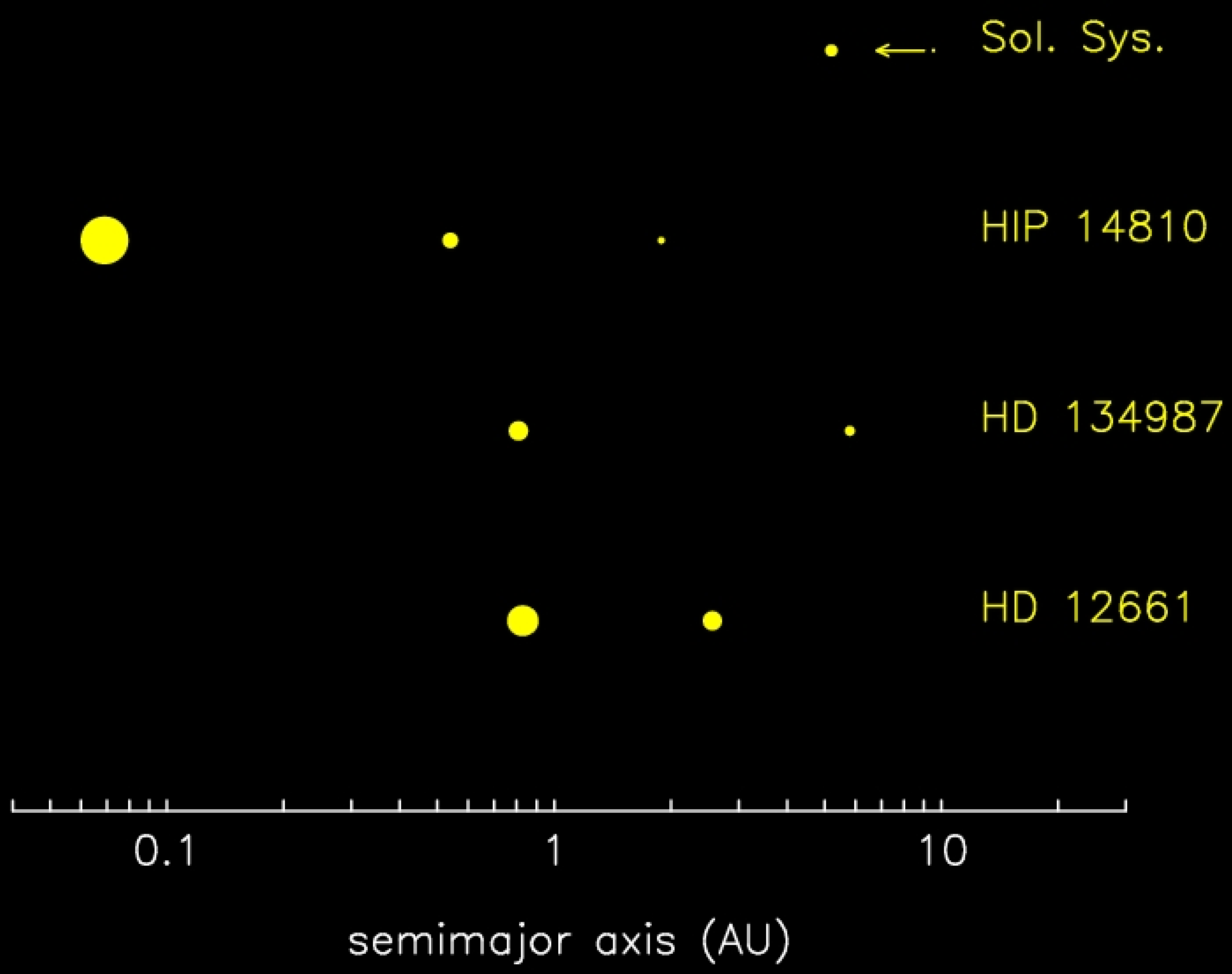


No, if Saturn simply replicates what Jupiter did before

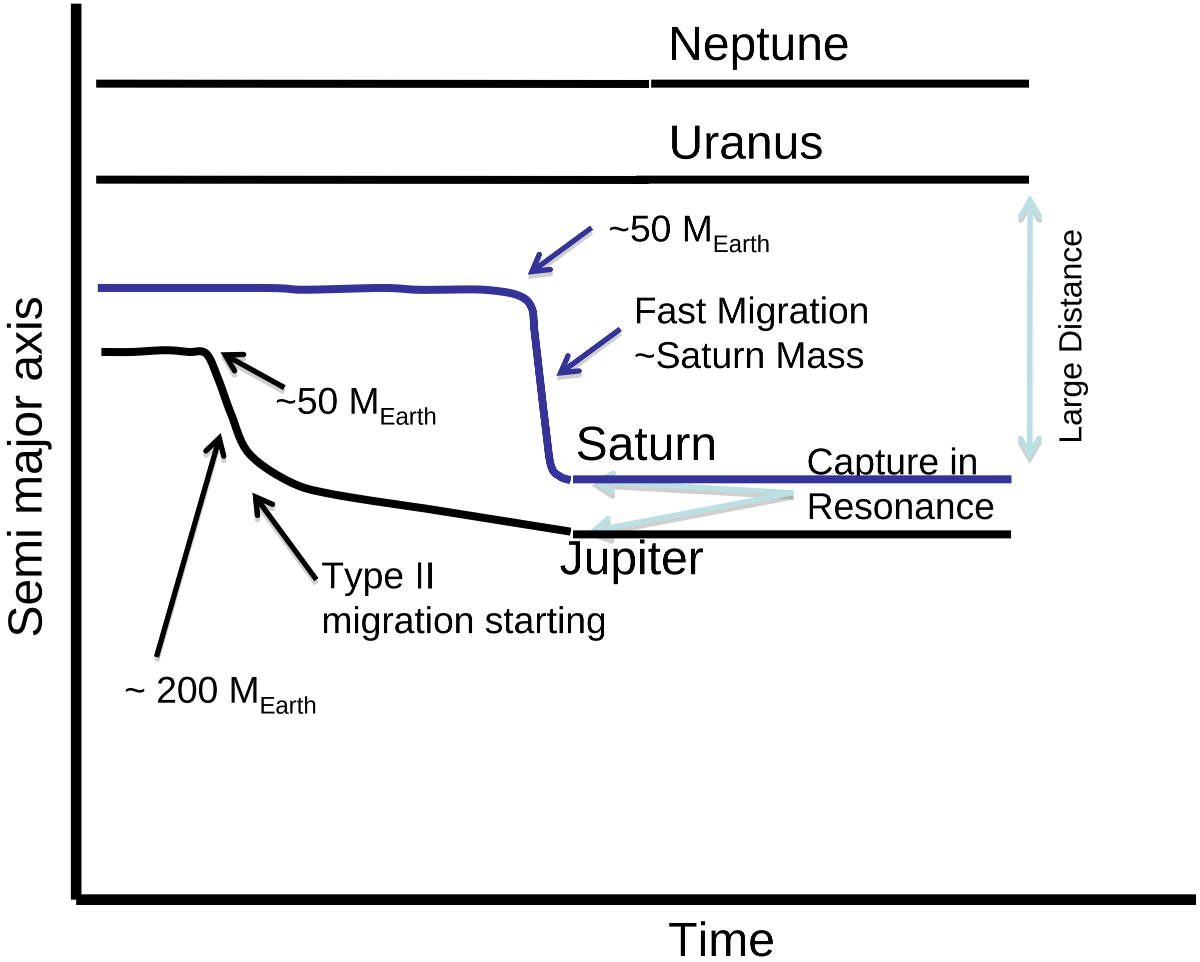
This evolution is incompatible with the structure of the Solar System but may explain some extra-solar systems observed…..

Some planetary systems to scale.....



PUTTING TOGETHER A COHERENT MODEL FOR THE SOLAR SYSTEM

Because Saturn's mass maximizes inward migration speed, Saturn can catch Jupiter if it accretes gas more slowly



This may require an increase in the disk opacity (notice that Saturn's enrichment in heavy elements is 10x Solar, Jupiter's one is 3x Solar)

Case A: no outward migration (inconsistent with current structure)

PUTTING TOGETHER A COHERENT MODEL FOR THE SOLAR SYSTEM

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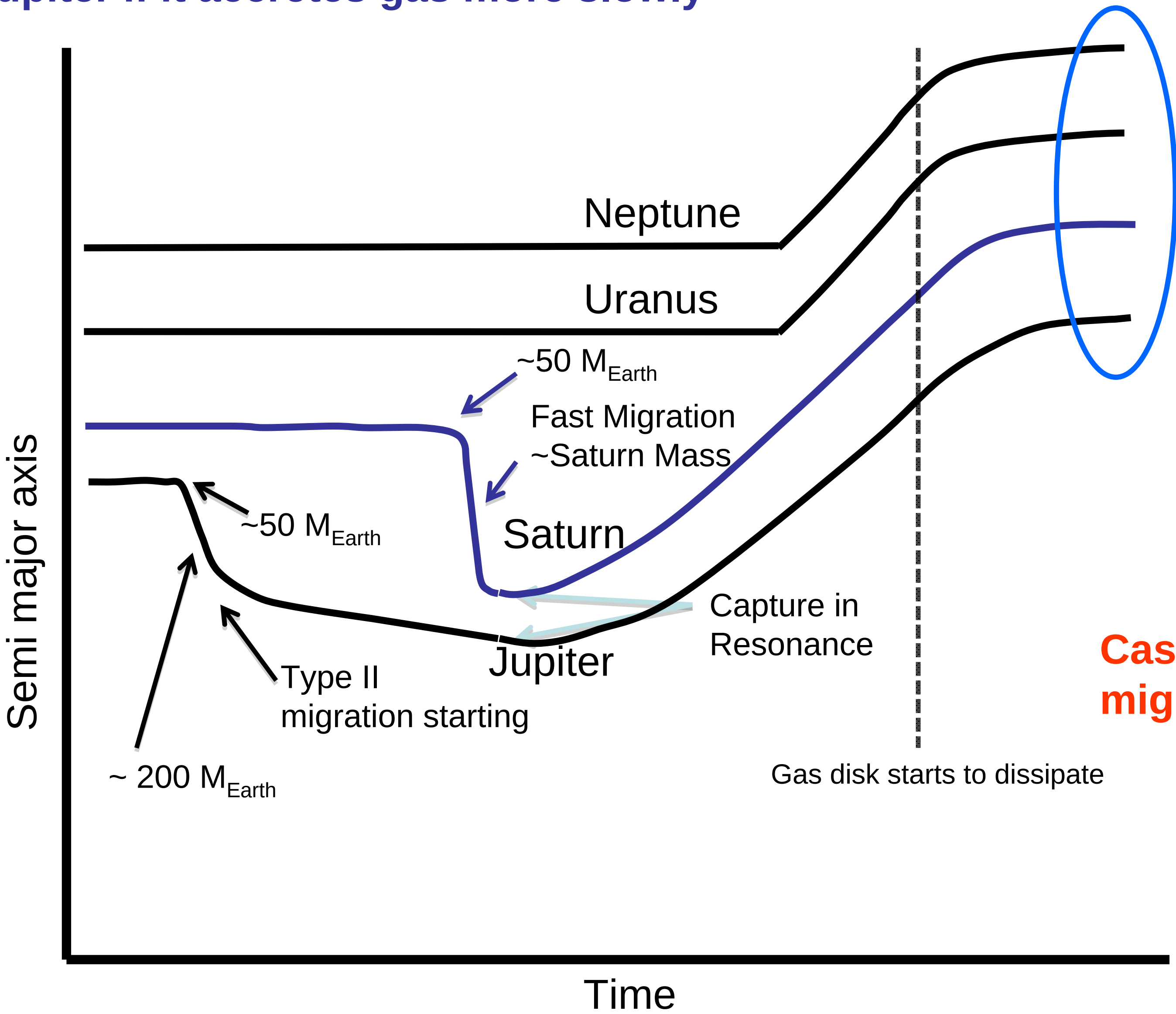


Consistent with the structure of the Solar System via the “Nice model”

Case B: outward migration

PUTTING TOGETHER A COHERENT MODEL FOR THE SOLAR SYSTEM

Is the inward-then-outward migration of Jupiter consistent with the existence of the asteroid belt inside of its current orbit?

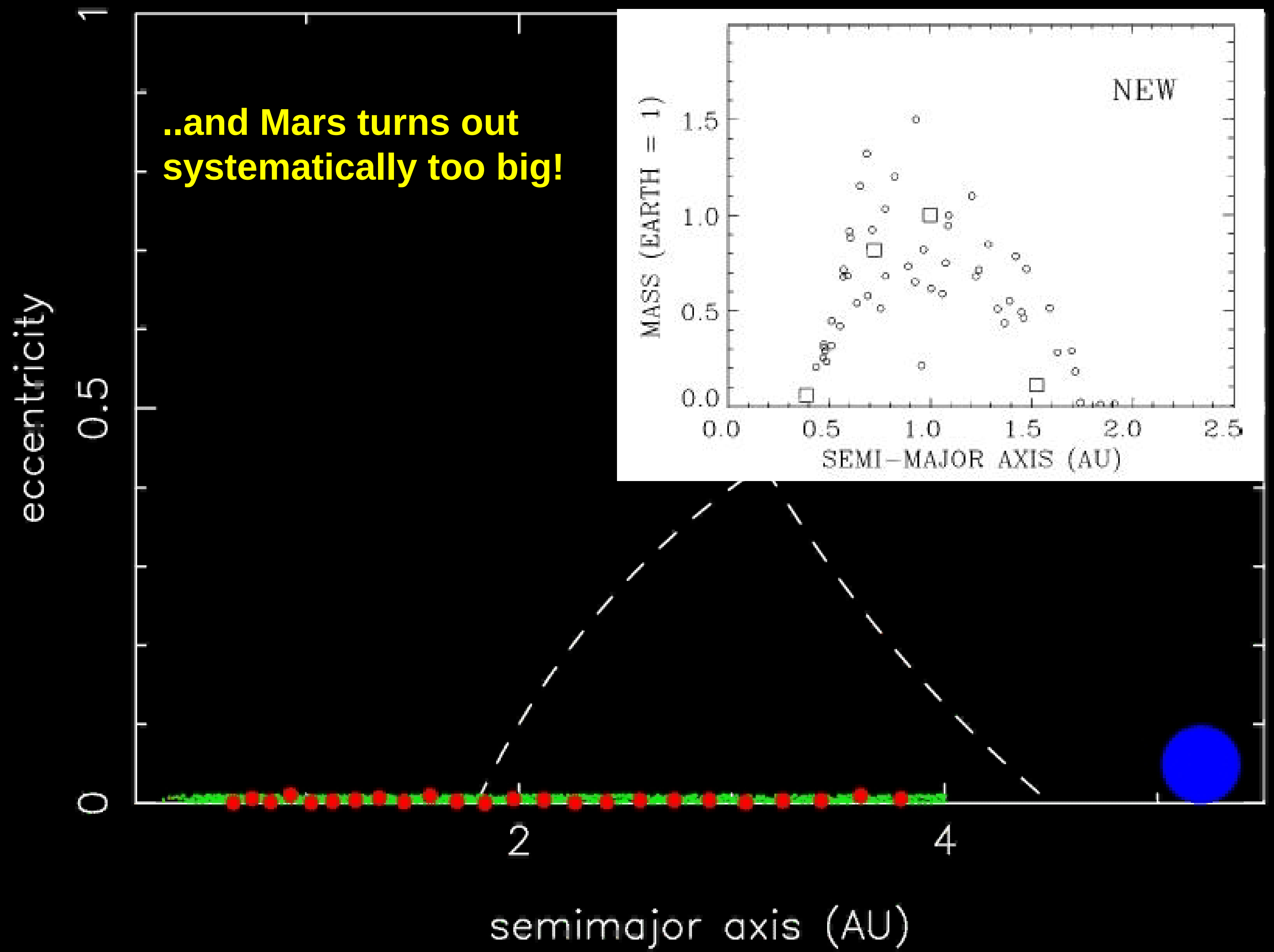
How far inwards did Jupiter go?

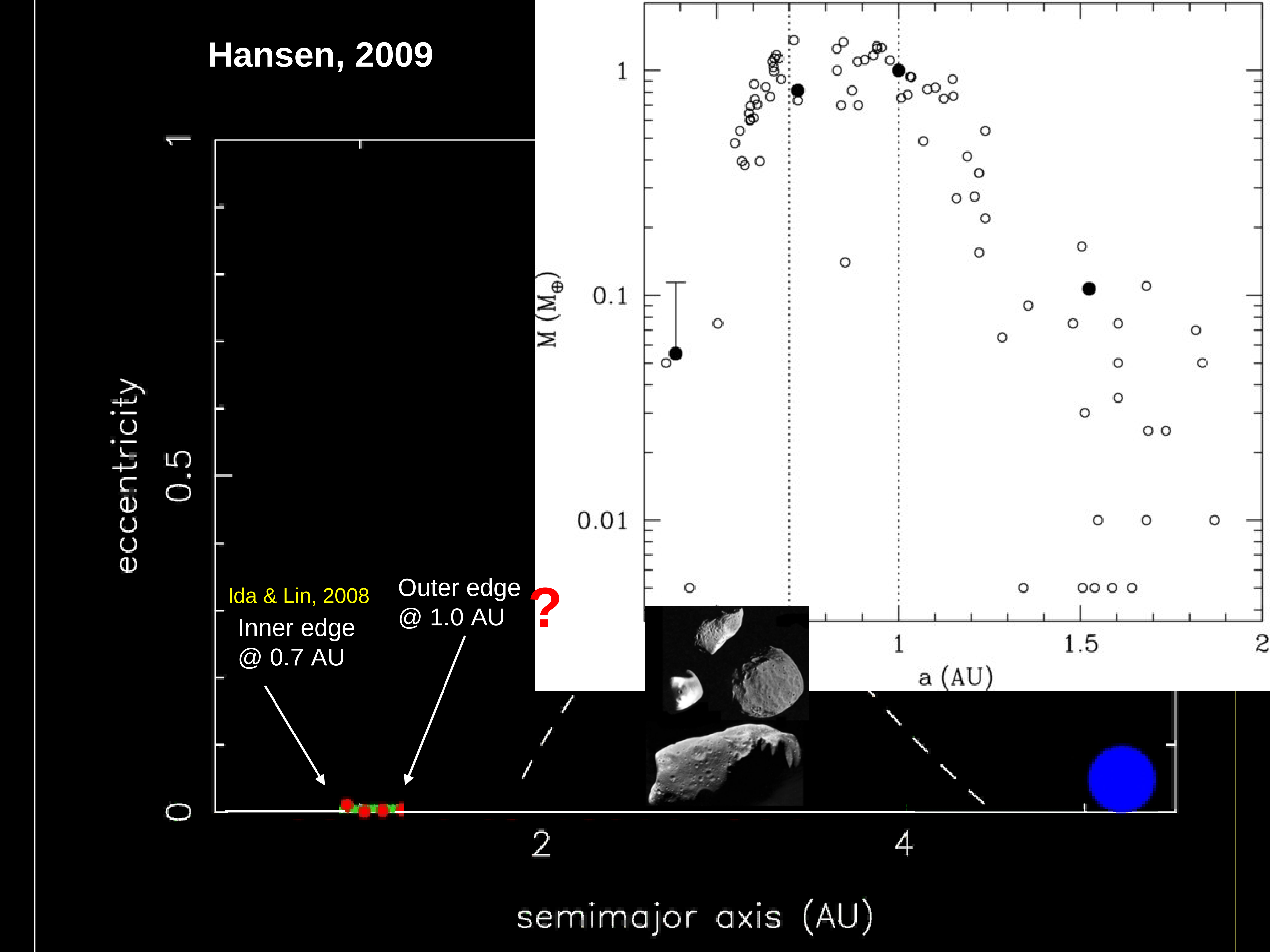
To answer these questions we need to turn to constraints:

TERRESTRIAL PLANETS

ASTEROID POPULATIONS

Simulations of Terrestrial Planets formation, usually start from a disk of planetesimals and planetary embryos, ranging from the Sun to Jupiter's current orbit….

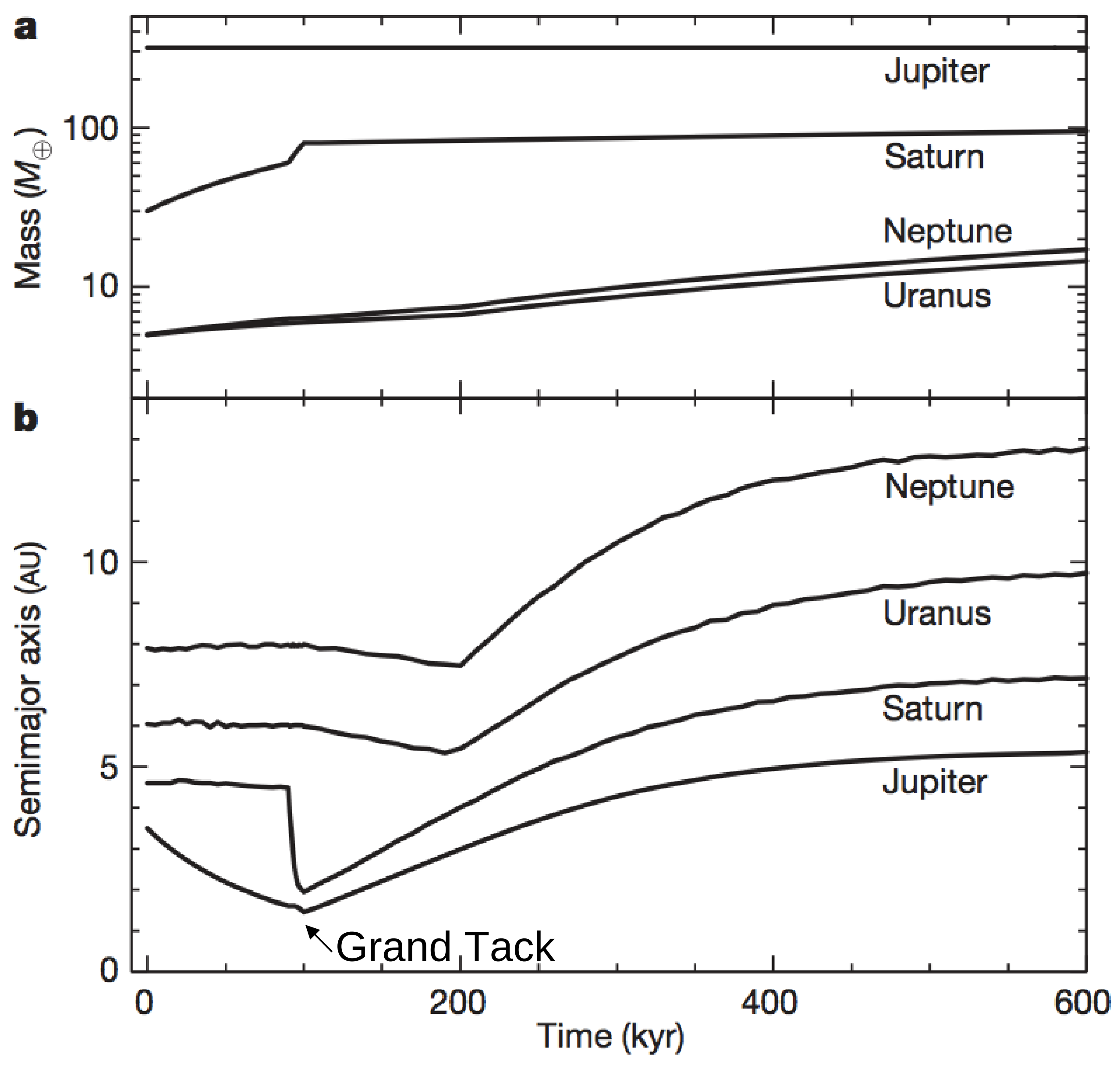


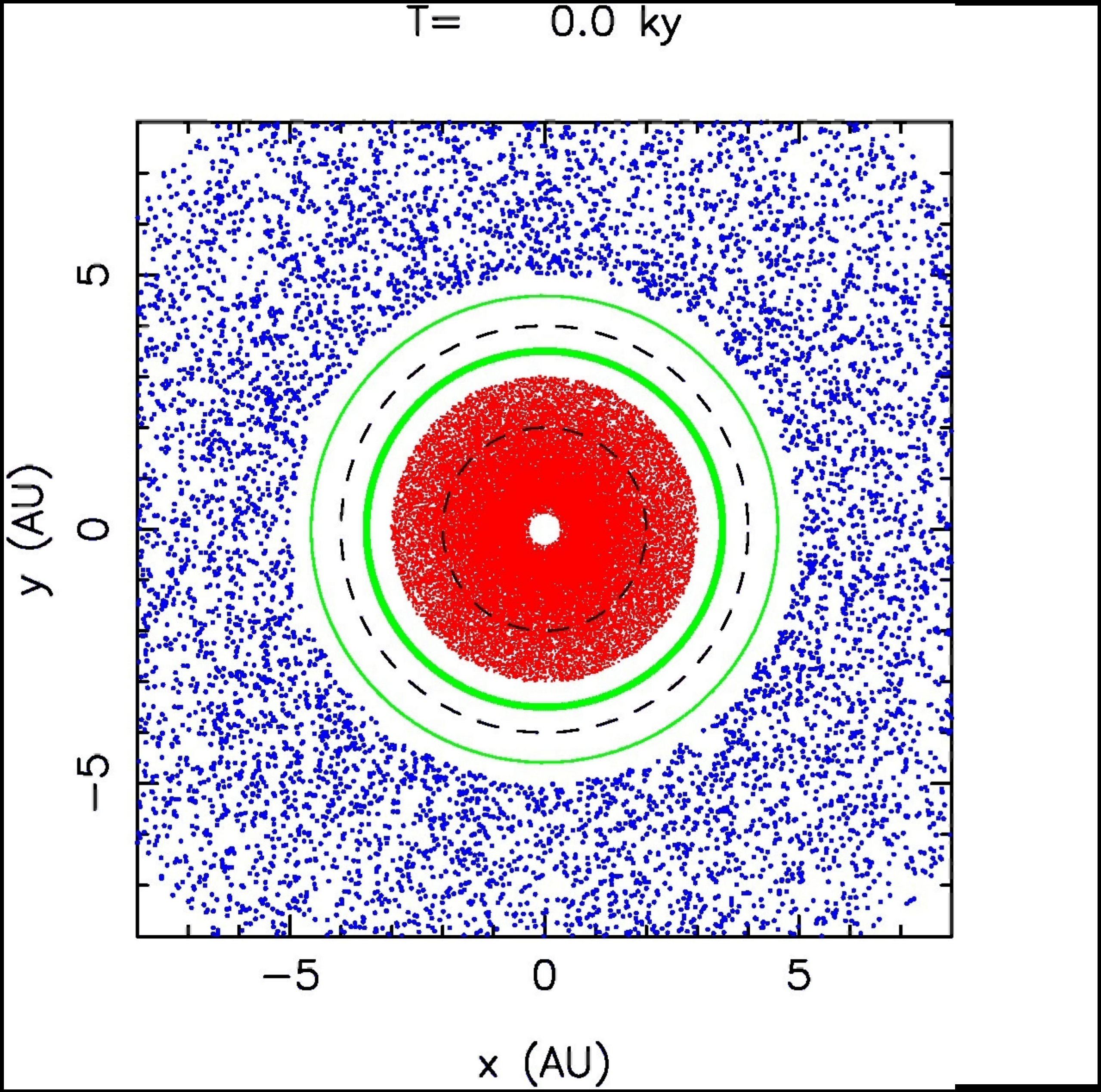


Hansen, 2009
eccentricity
1
0.5
0
Ida & Lin, 2008
Inner edge
@ 0.7 AU
Outer edge
@ 1.0 AU
?
2
4
semimajor axis (AU)
M (M⊕)
1
0.1
0.01
a (AU)
1
1.5
2

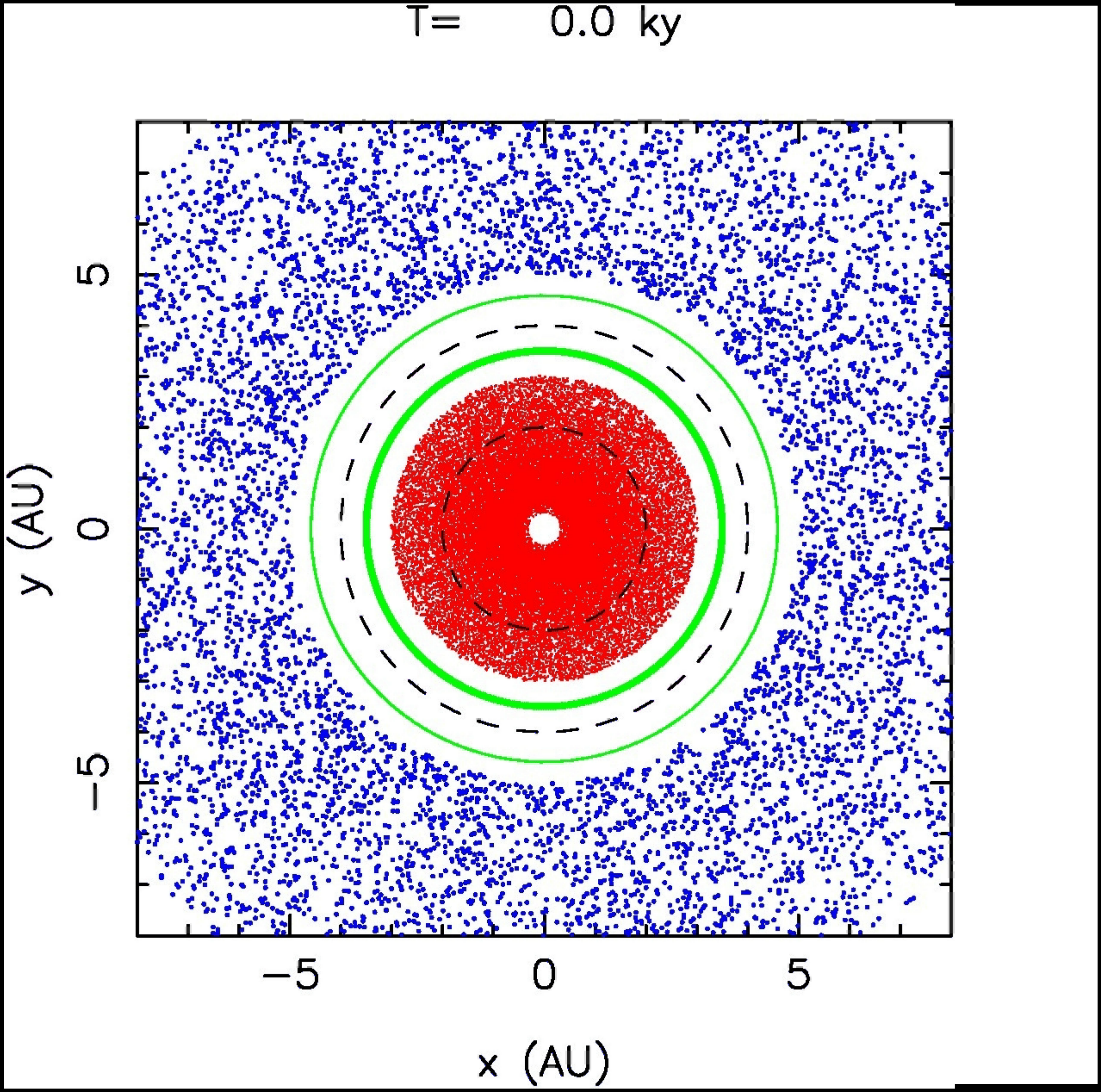
Can the inward-then-outward migration of Jupiter explain this?

We did simulations assuming this evolution scenario, with Jupiter reversing migration at ~1.5 AU





Walsh, Morbidelli, Raymond, O'Brien, Mandell, Nature in press



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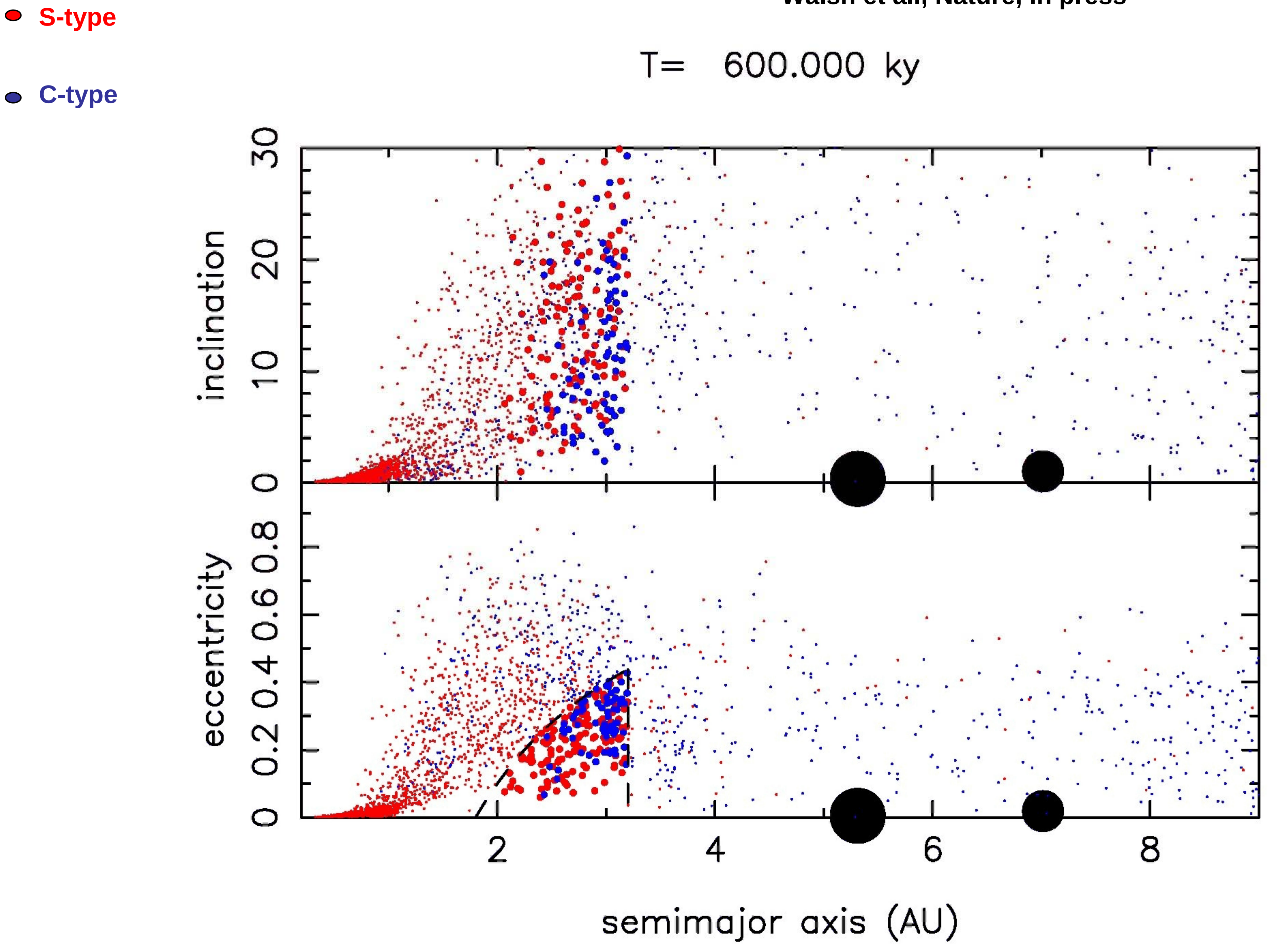
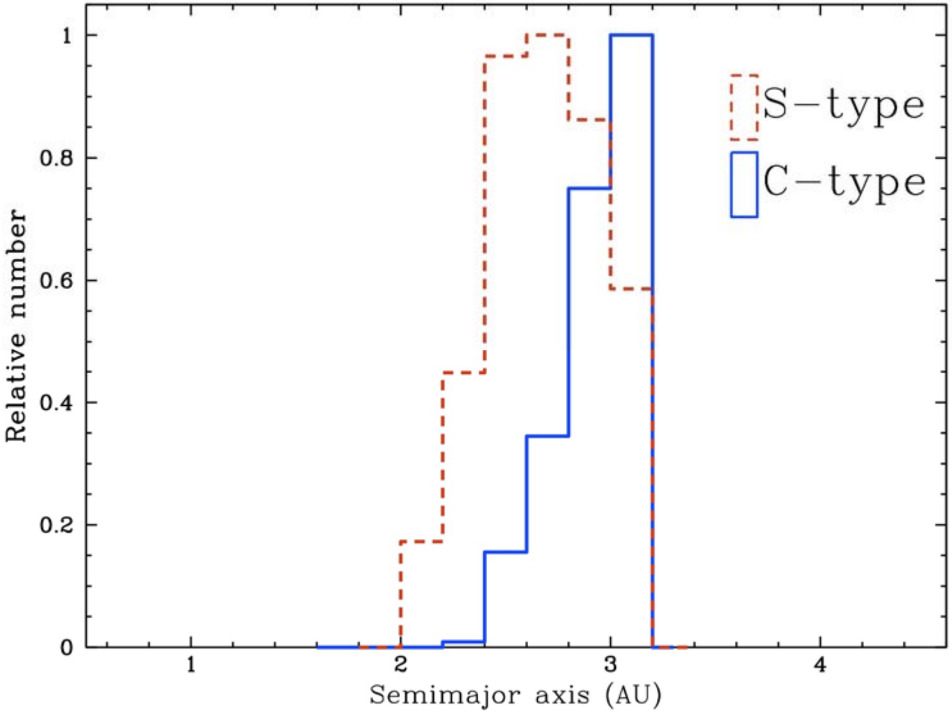
Walsh et al., Nature, in press



Walsh et al., Nature in press

Relative semi major axis distribution of an-hydrous and primitive planetesimals (S and C types) captured in the asteroid belt



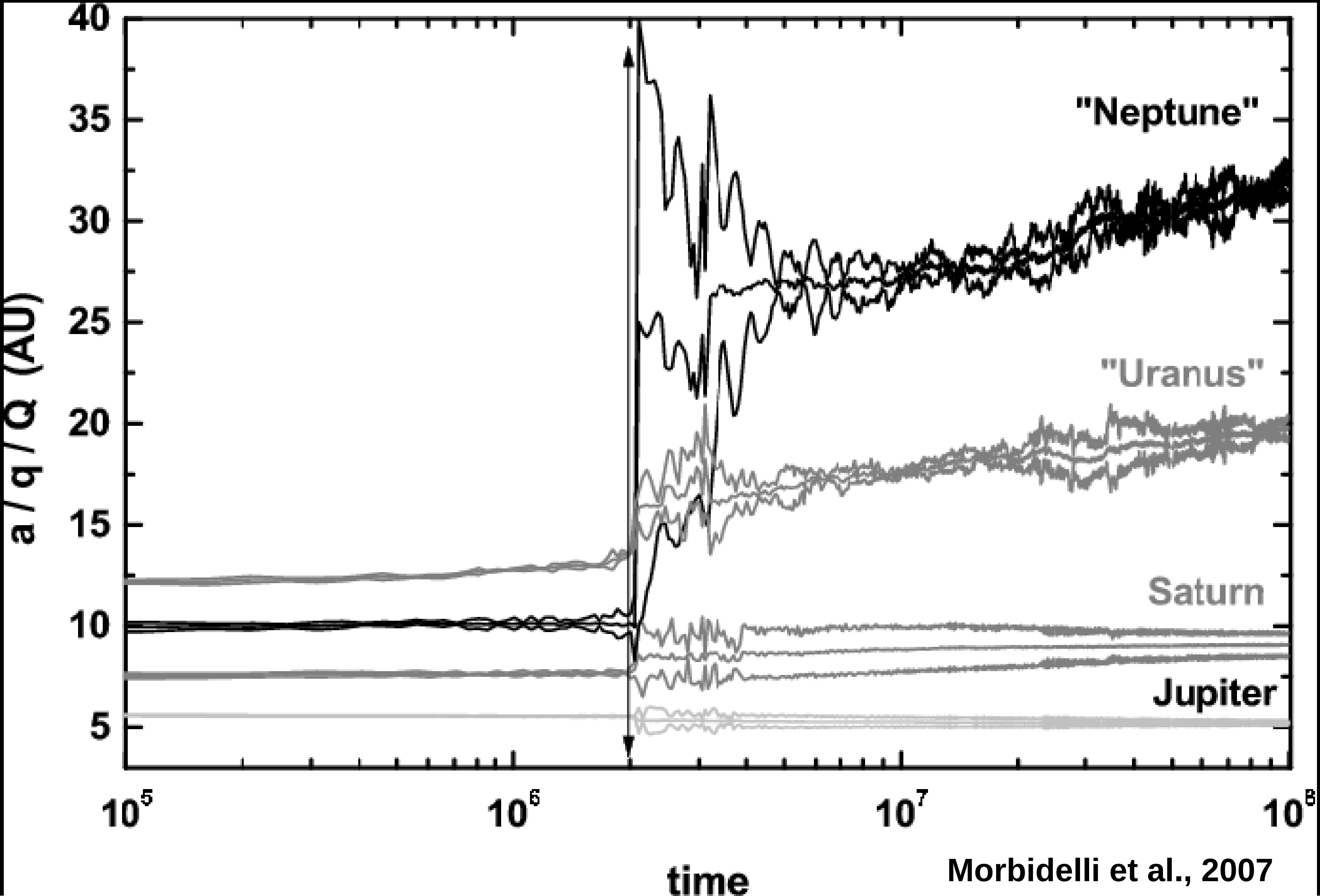
This model explains better than any other the striking dichotomy of physical properties of the asteroid population (i.e. why an-hydrous and primitive asteroids are so different from each other, with the latter being very similar to comets)

After the gas was gone: the evolution of the giant planets in the planetesimal disk

This part was the object of the so-called "Nice model" (Tsiganis, Gomes, Morbidelli, Levison, 2005), but the planetary initial conditions at that time were totally ad-hoc

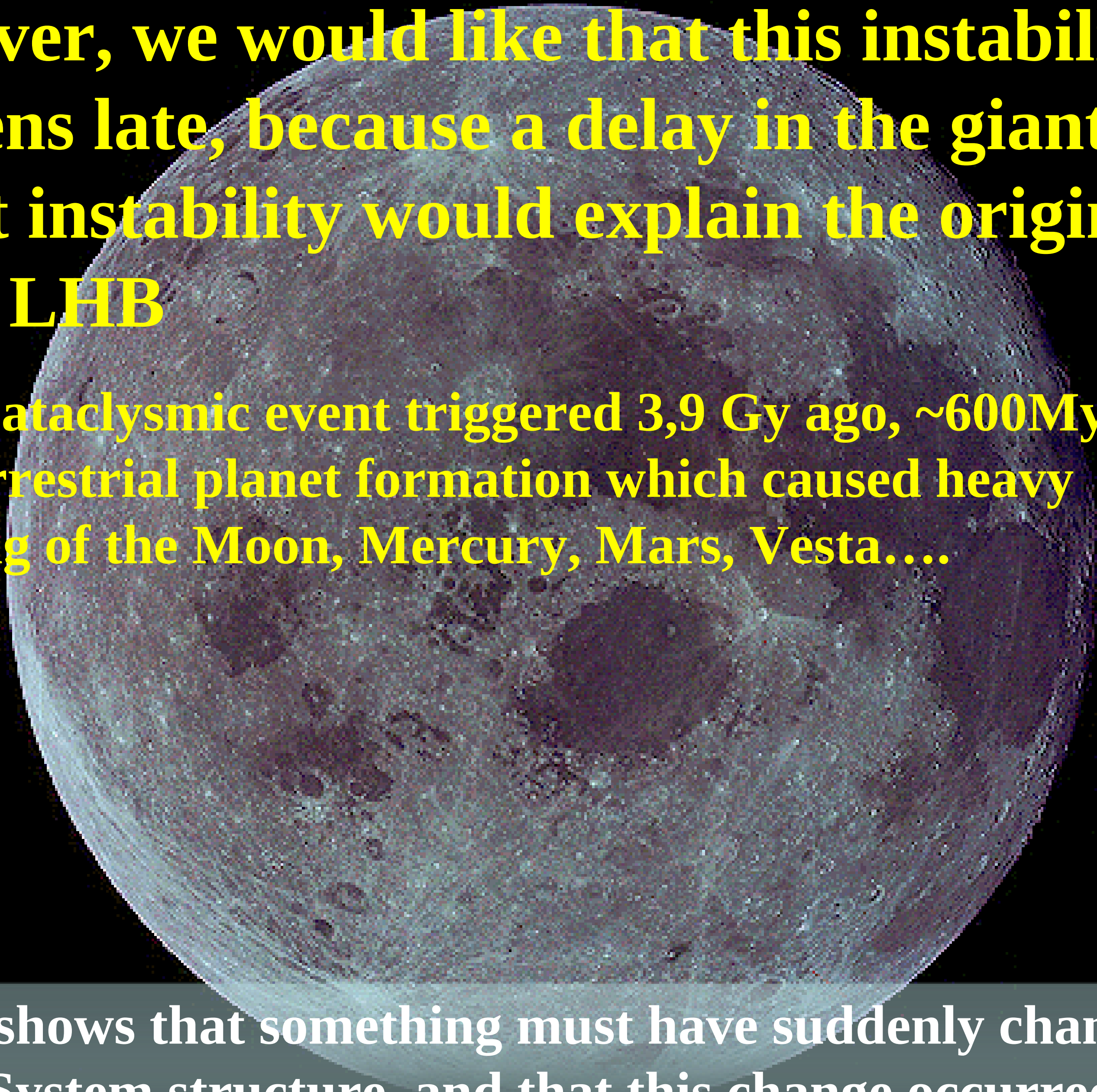
The correct initial conditions for a new Nice-like model should have Saturn and Jupiter in their mutual 2:3 resonance and Uranus and Neptune in resonances with Saturn and with each other

If the planets are embedded in a massive planetesimal disk, they are extracted from their original 4-body resonance and, as soon as this happens, they become unstable. A violent phase, similar to that of the original Nice model, can bring them to final orbits similar to their current ones – see also Batygin and Brown (2010).



However, we would like that this instability happens late, because a delay in the giant planet instability would explain the origin of the LHB

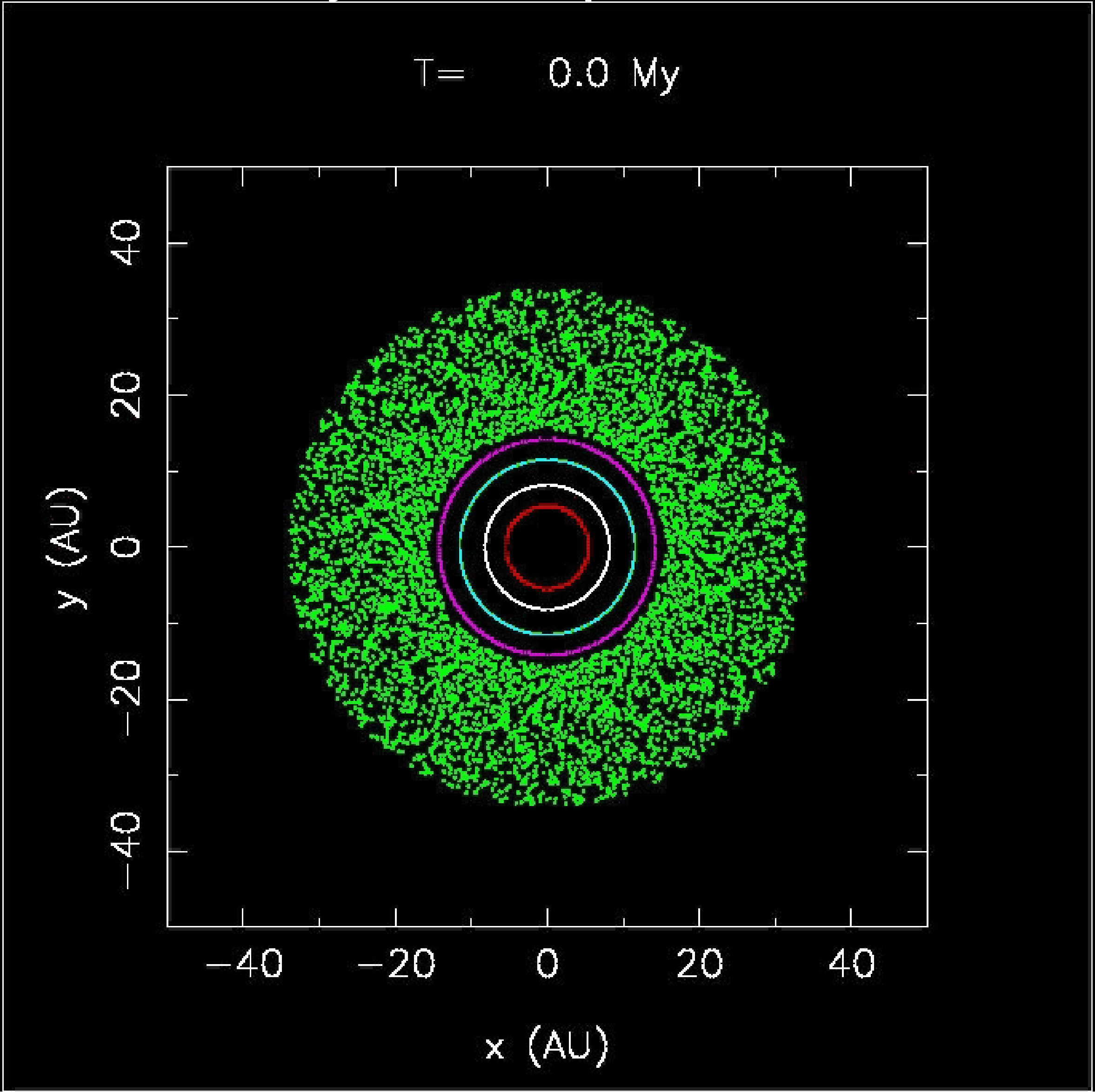
LHB: Cataclysmic event triggered 3,9 Gy ago, ~600My after terrestrial planet formation which caused heavy cratering of the Moon, Mercury, Mars, Vesta….



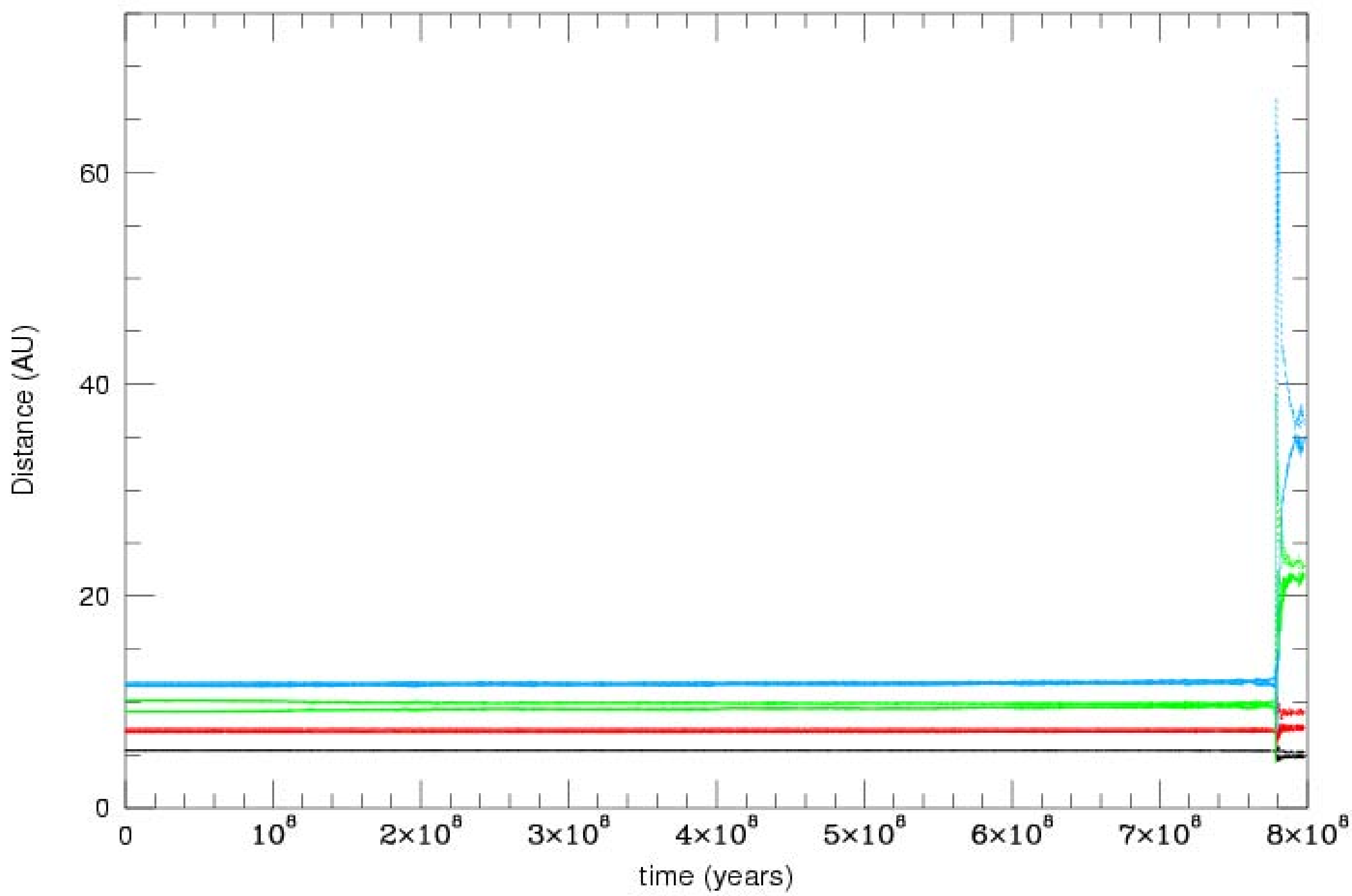
The LHB shows that something must have suddenly changed in the Solar System structure, and that this change occurred late.

The reason why the instability occurs early in the previous simulation is that we embedded the planets in the planetesimal disk.

We believe, though, that the giant planets were not embedded in a planetesimal disk, but rather surrounded by a trans-Neptunian disk, for a lifetime argument

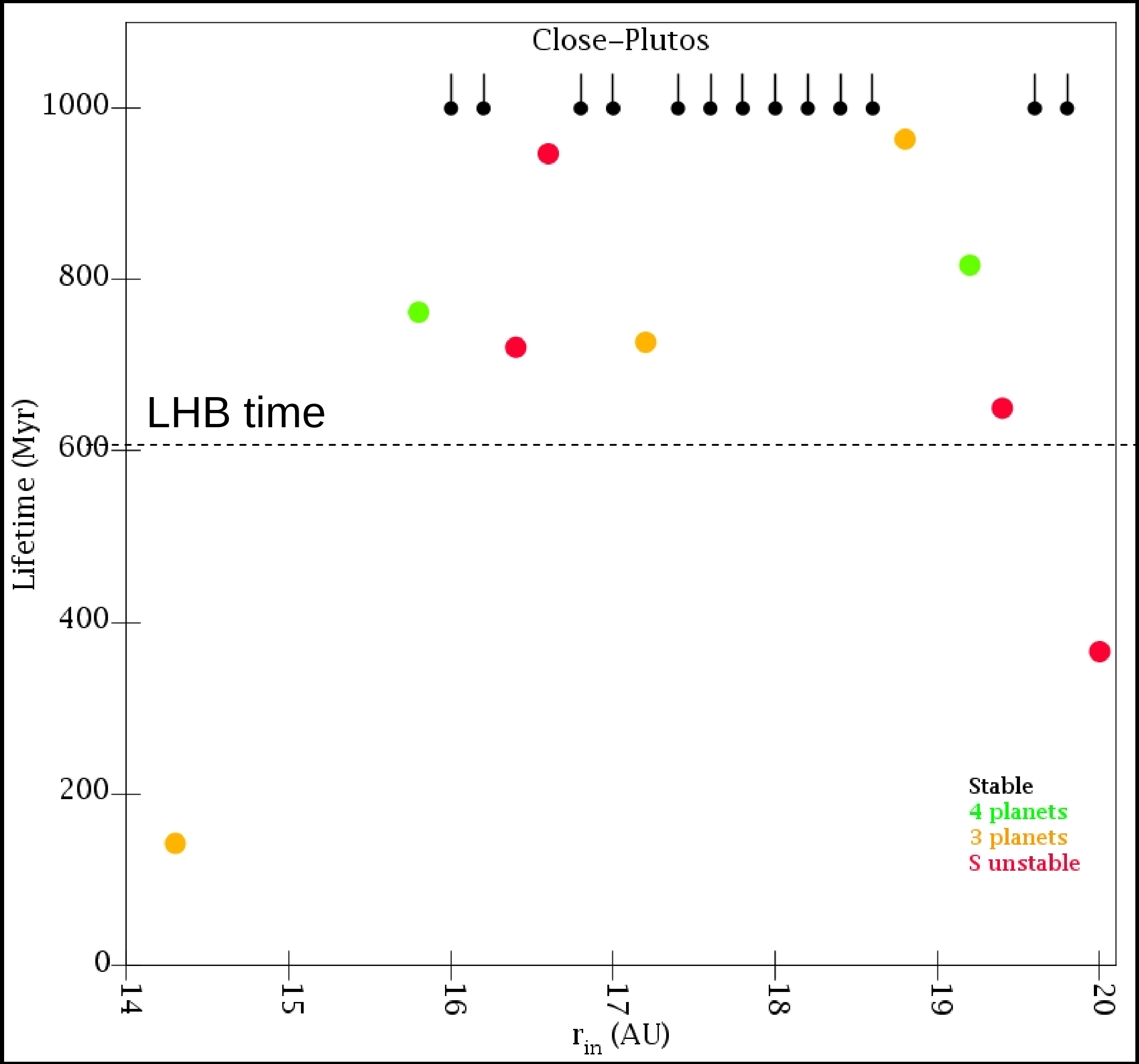


If the disk is trans-Neptunian, the giant planet instability, and the re-arrangement of their orbits can occur at about the LHB time



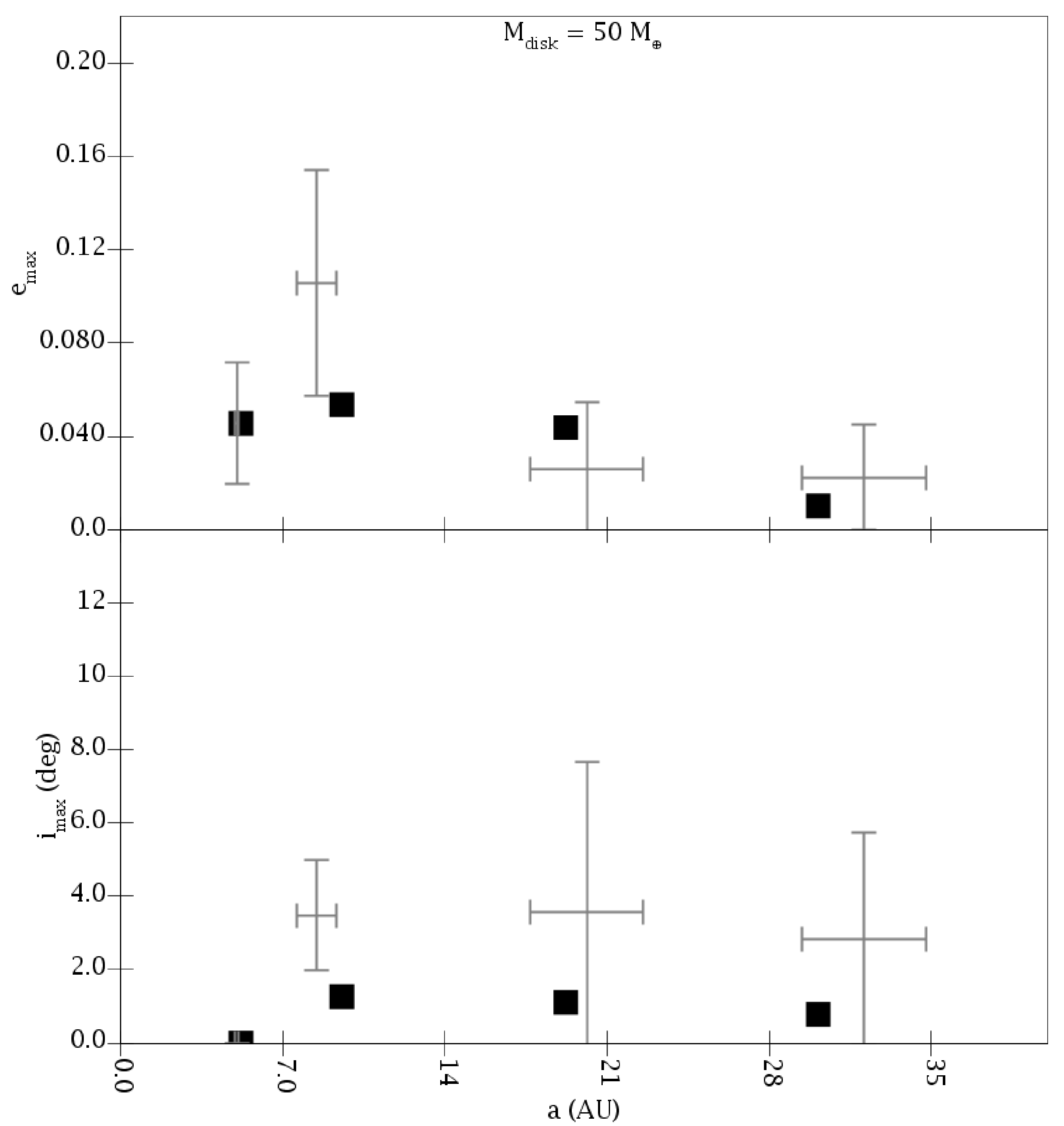
Need to account for disk's self-gravity !!!!

late instabilities occur in a natural way, quite independently of the location of the inner edge of the disk



Levison et al., in preparation

The planets are "saved" in 15-20% of the runs, and when they do their final orbits are pretty good.



CONCLUSIONS ON SOLAR SYSTEM EVOLUTION

By looking carefully to all available constraints, our ambition is to reconstruct as precisely as possible, the past history of the Solar System

Our approach is like that of geologists

So far, we have built a coherent and consistent two-phase scenario of the evolution of the giant planets

•A gas disk phase: no hot Jupiter, although wide range radial migration and “Grand Tack” ; fully resonant, low-e configuration

•A planetesimal-disk phase: global instability; excitation of e, i and secular modes; migration (jump) to current orbits

ON THE ORIGIN OF THE GREAT DIVERSITY OF PLANETARY SYSTEMS

Our model for the evolution of the Solar System highlights few yes/no events that alone can explain most of the diversity that we see

Suppose giant planets form from a system of cores at some equilibrium (i.e. no-migration) radius in the disk and that they grow in mass sequence, from the innermost to the outermost one

First event:

Does the second, lighter planet catch the first one in resonance?

Yes/No

For the Solar System (or OGLE 106-09L) the answer is YES

For HD 12661, HD 134987, HIP14810 the answer is NO

Second event:

Does the second planet eventually grow as massive or more massive than the inner one?

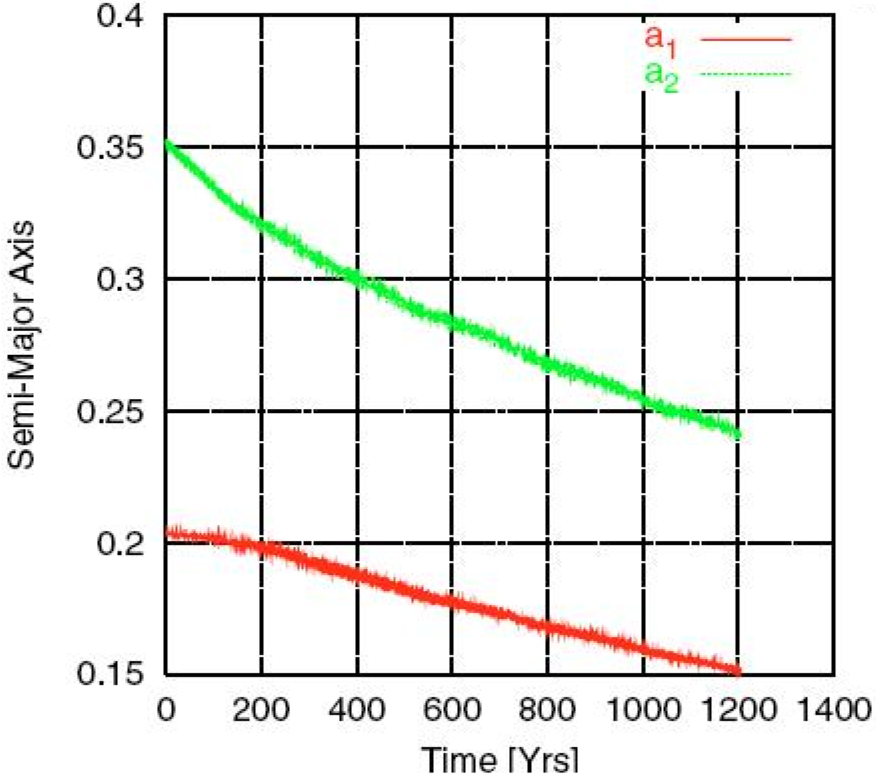
Yes/No

For the Solar System (or OGLE 106-09L) the answer is NO

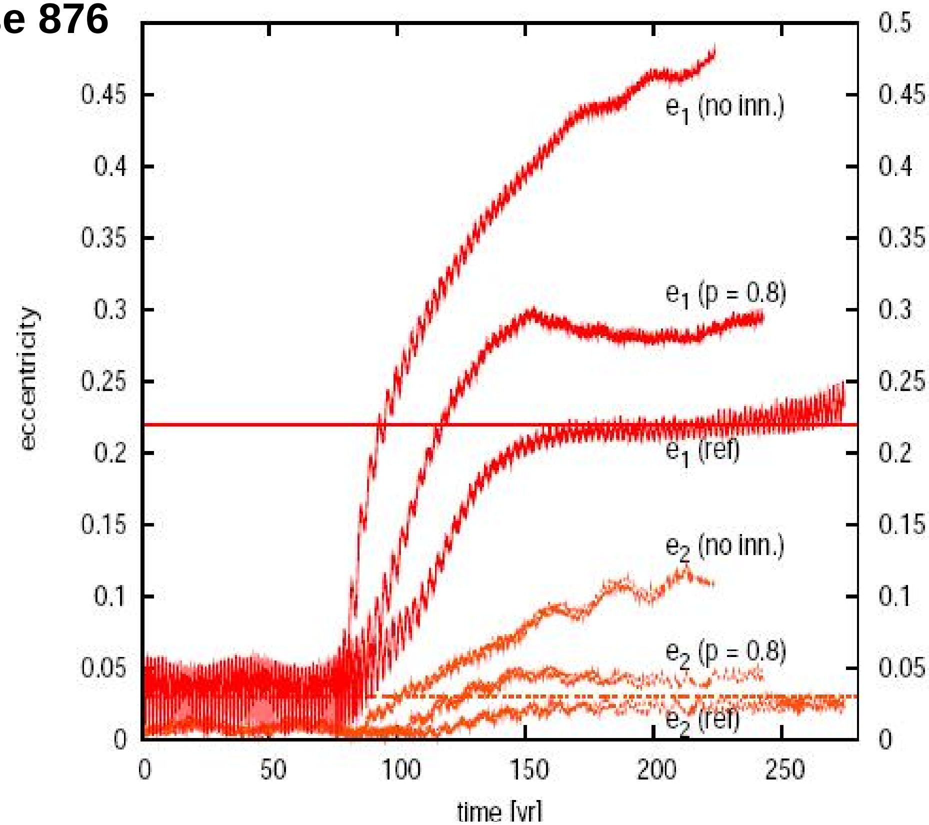
For many/most other systems the answer could be YES

What happens if planets form faster and the outer one has the time to outpass in mass the inner one?

Migration starts again….



Gliese 876



Kley et al. 2004, 2005; Crida et al., 2008

Migration drives the inner, lighter planet to become eccentric

Third event:

Does the eccentricity saturate ?

Yes/No

For the pairs of resonant planets: YES

For single, eccentric planets: NO

CONCLUSIONS

Three events can explain most of the observed diversity: