Key aspects of the evolution of the of the Solar System: a few hints to understand the diversity of planetary systems

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OUTLINE

I) The evolution of the giant planets in the gas disk

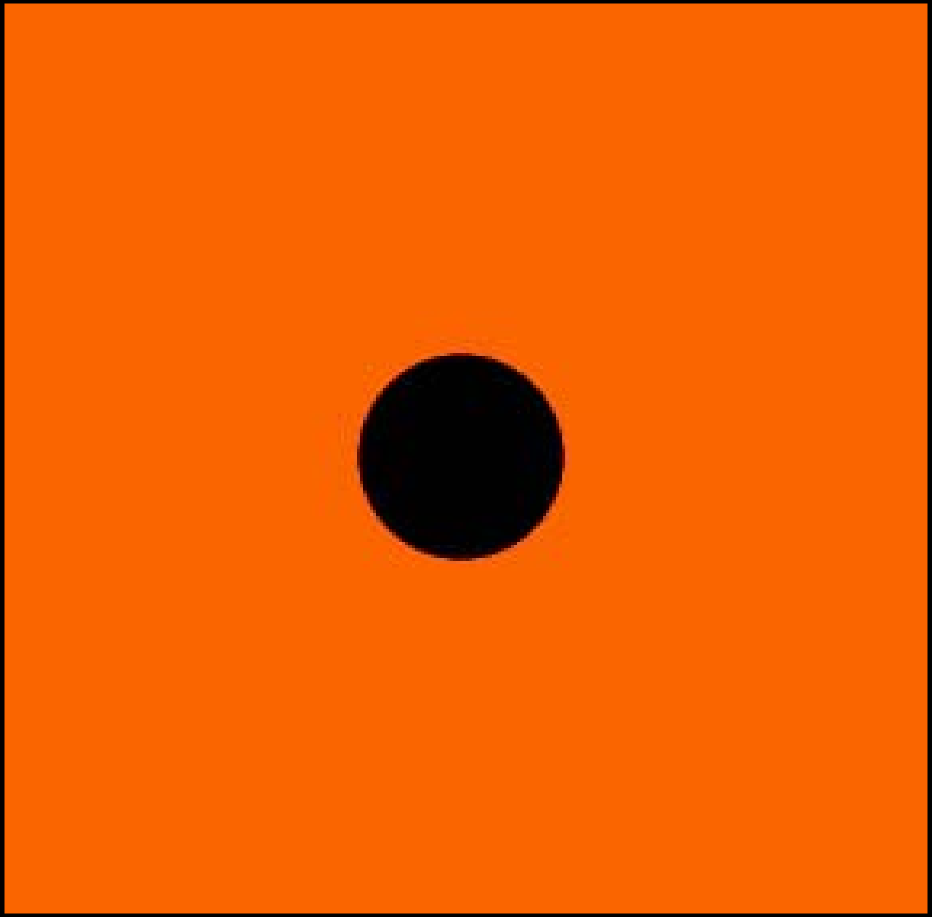
II) After the gas was gone: the evolution of the giant planets in the planetesimal disk

III) The Solar System as a debris disk

IV) Constraining the actual evolution of the giant planets from the orbits of the terrestrial planets and of the asteroid belt

Every time we identify a combination of parameters that set the specific evolution of our Solar System, we discuss how the planetary system would have evolved if the said parameters had had different values

I) The evolution of the giant planets in the gas disk

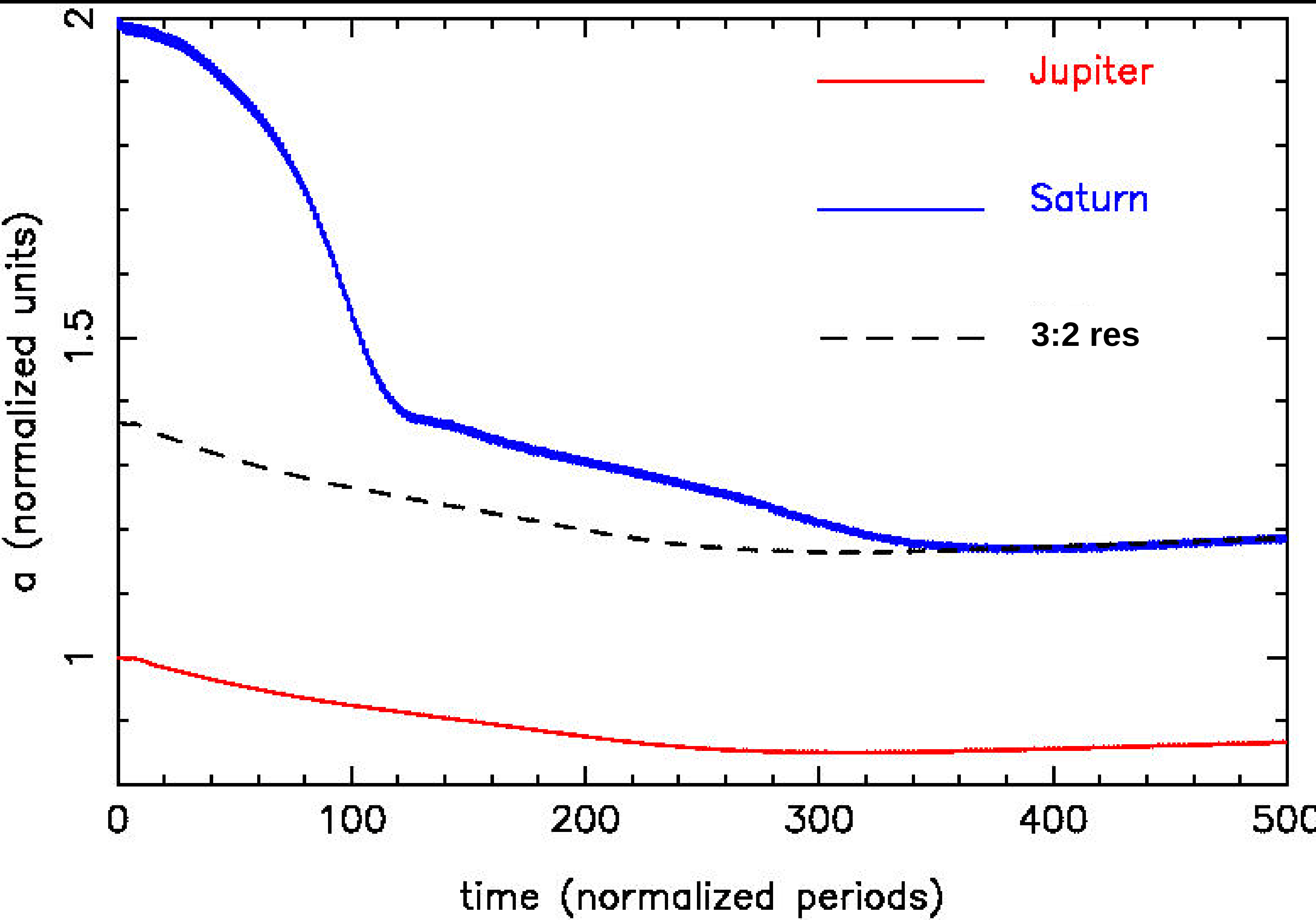


Type II migration:
Lin & Papaloizou, 1986

Type II migration explains the origin of the Hot Jupiters (Lin et al., Nature, 1996)

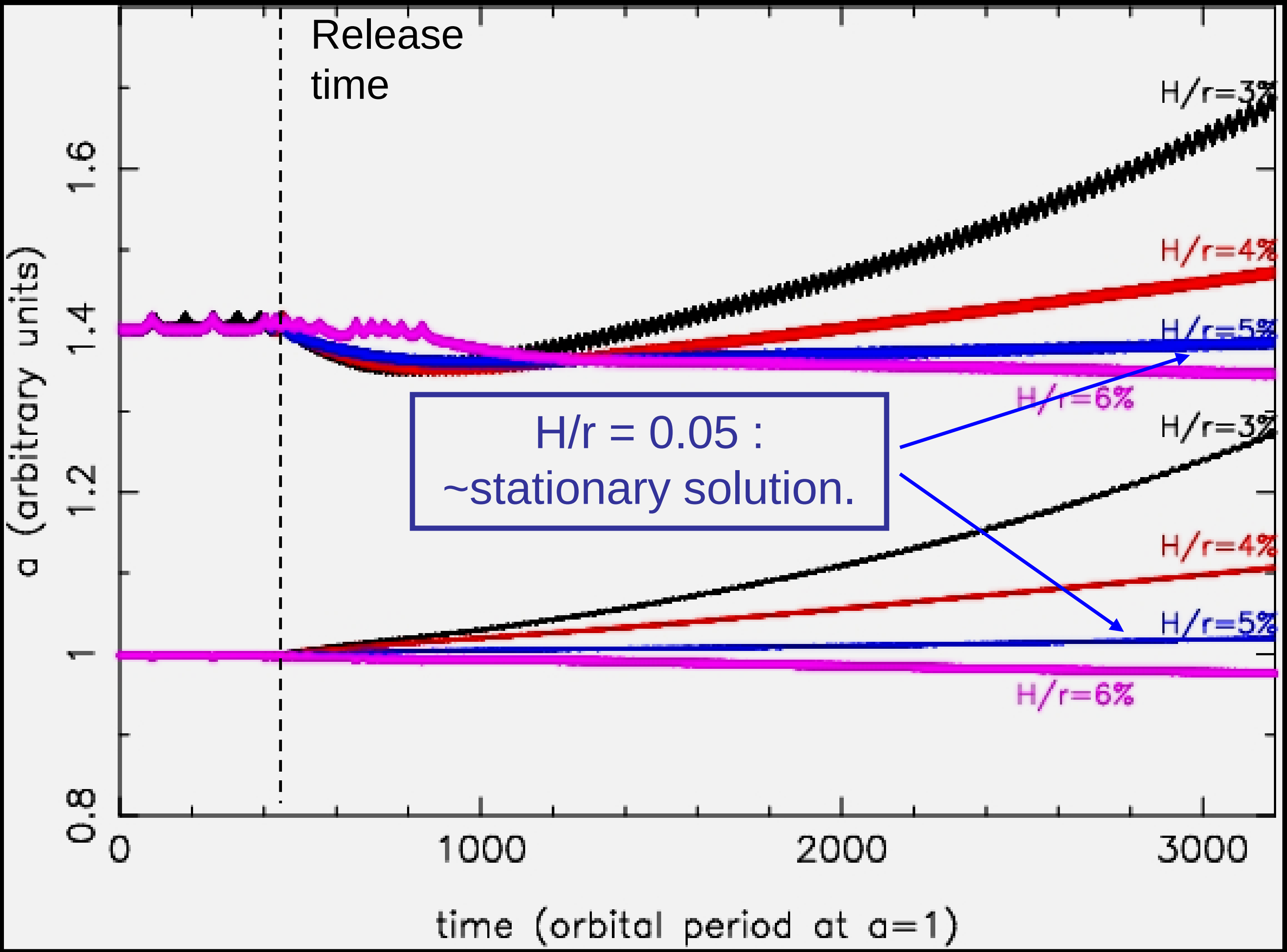
But we don't have a Hot Jupiter here, so what happened?

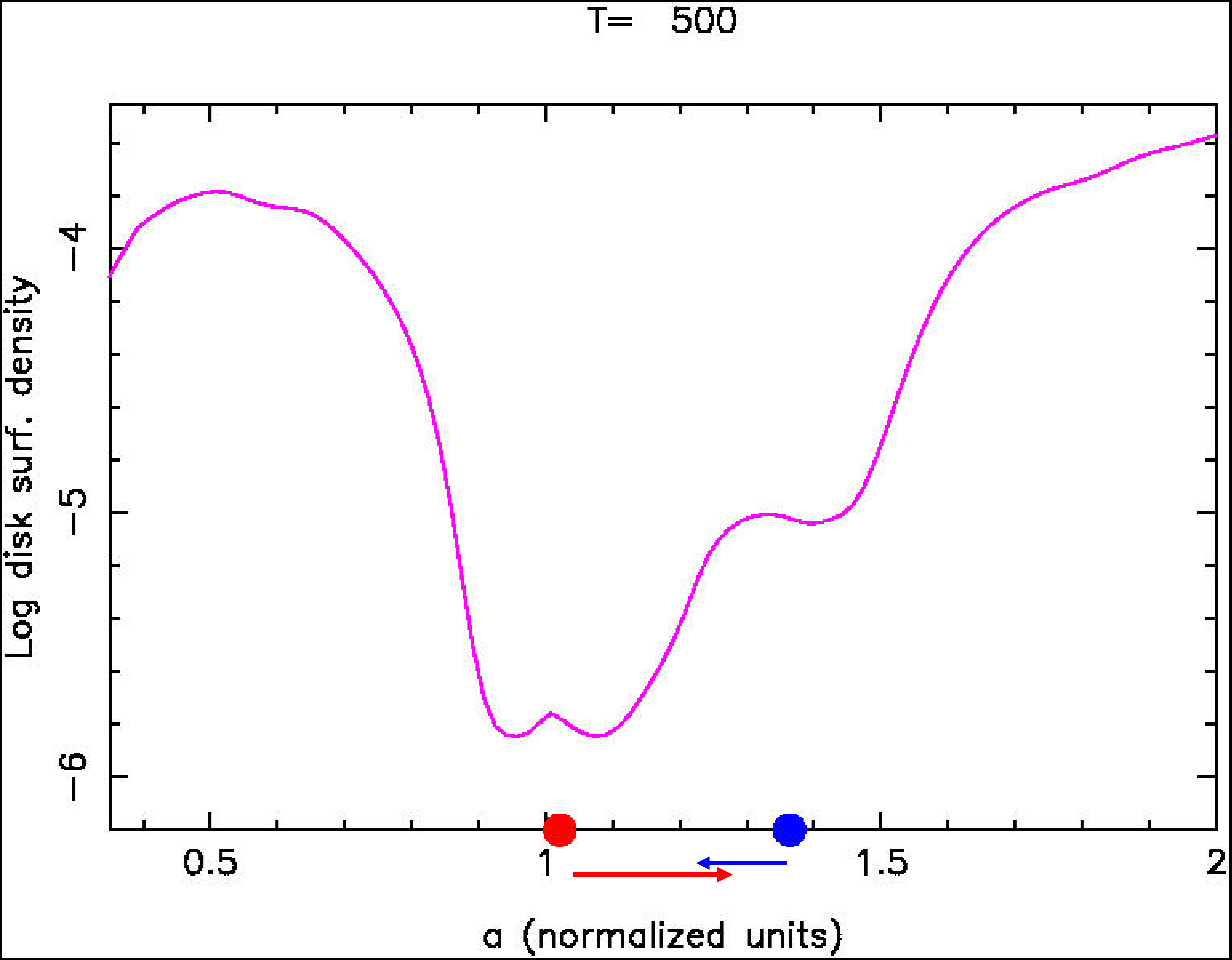
Masset and Snellgrove, 2001



Morbidelli and Crida, 2007 and –particularly- Pierens and Nelson, 2008, showed that the capture of Jupiter and Saturn in their 3:2 resonant is robust

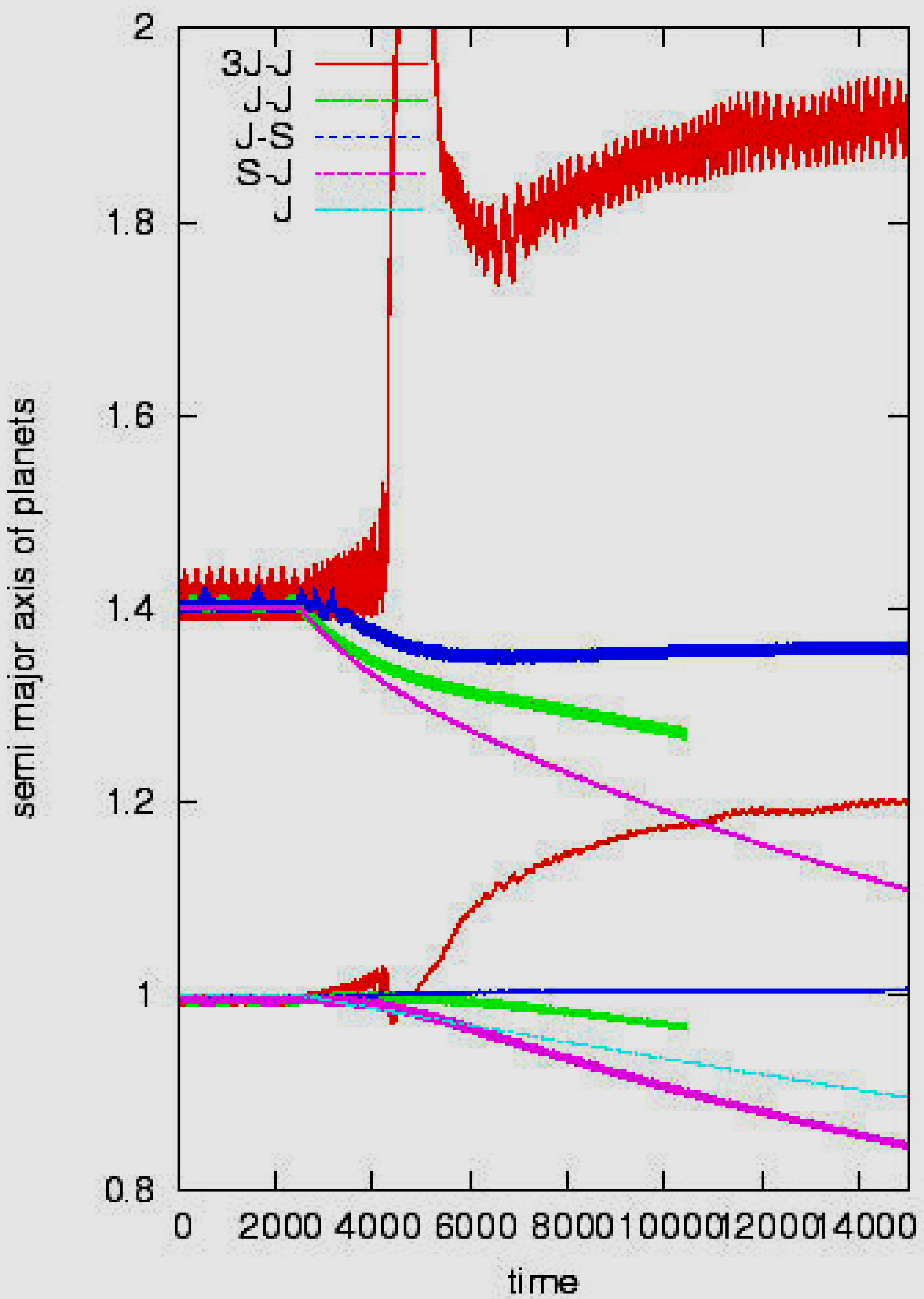
Once locked in resonance, the evolution of Jupiter and Saturn depends on disk parameters (Morbidelli and Crida, 2007, Icarus, 2007)



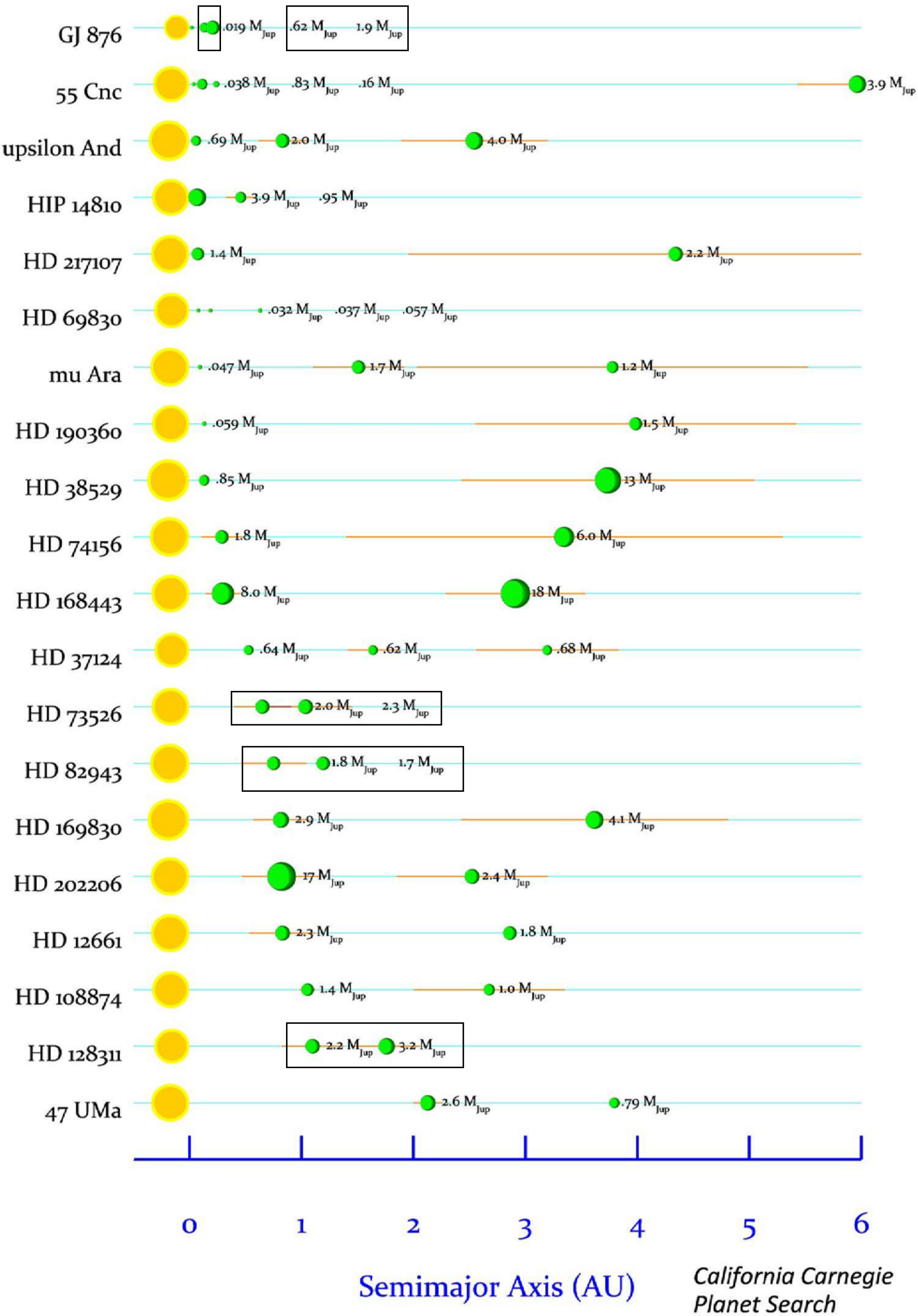


T= 500
Log disk surf. density
−4
−5
−6
0.5
1
1.5
2
a (normalized units)

This mechanism works ONLY for a mass ratio close to Jupiter/Saturn, and if the planets are sufficiently close (relative to their masses).



20 Known Multi-Planet Systems



The outer planet should accrete gas faster than the inner planet and eventually become the more massive one.

Why then Saturn is lighter than Jupiter?

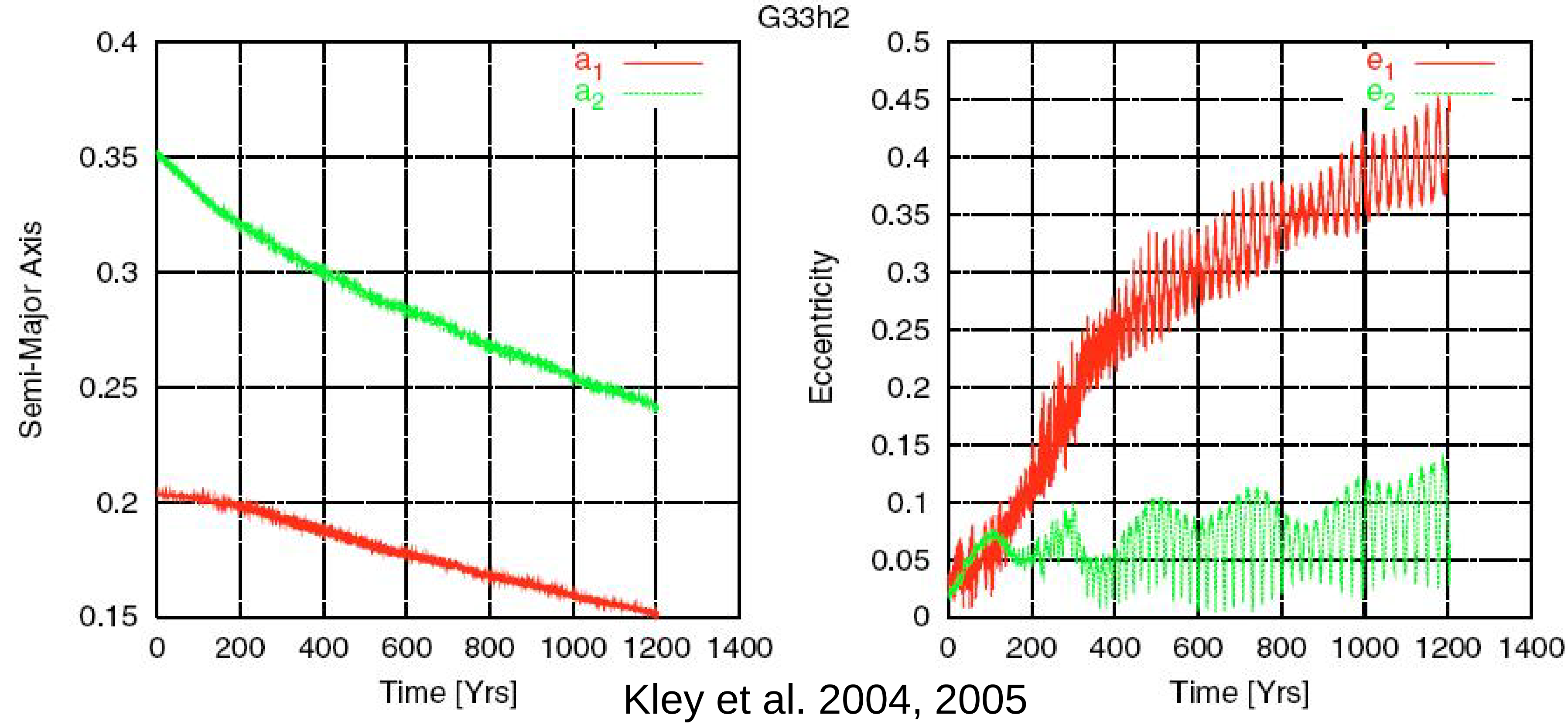
Late formation (close to disk disappearence)?

Consistent with metal enrichment in Jupiter atmosphere (Guillot) and with the « small » masses of Uranus and Neptune.

Consistent with the low metallicity of the Sun

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

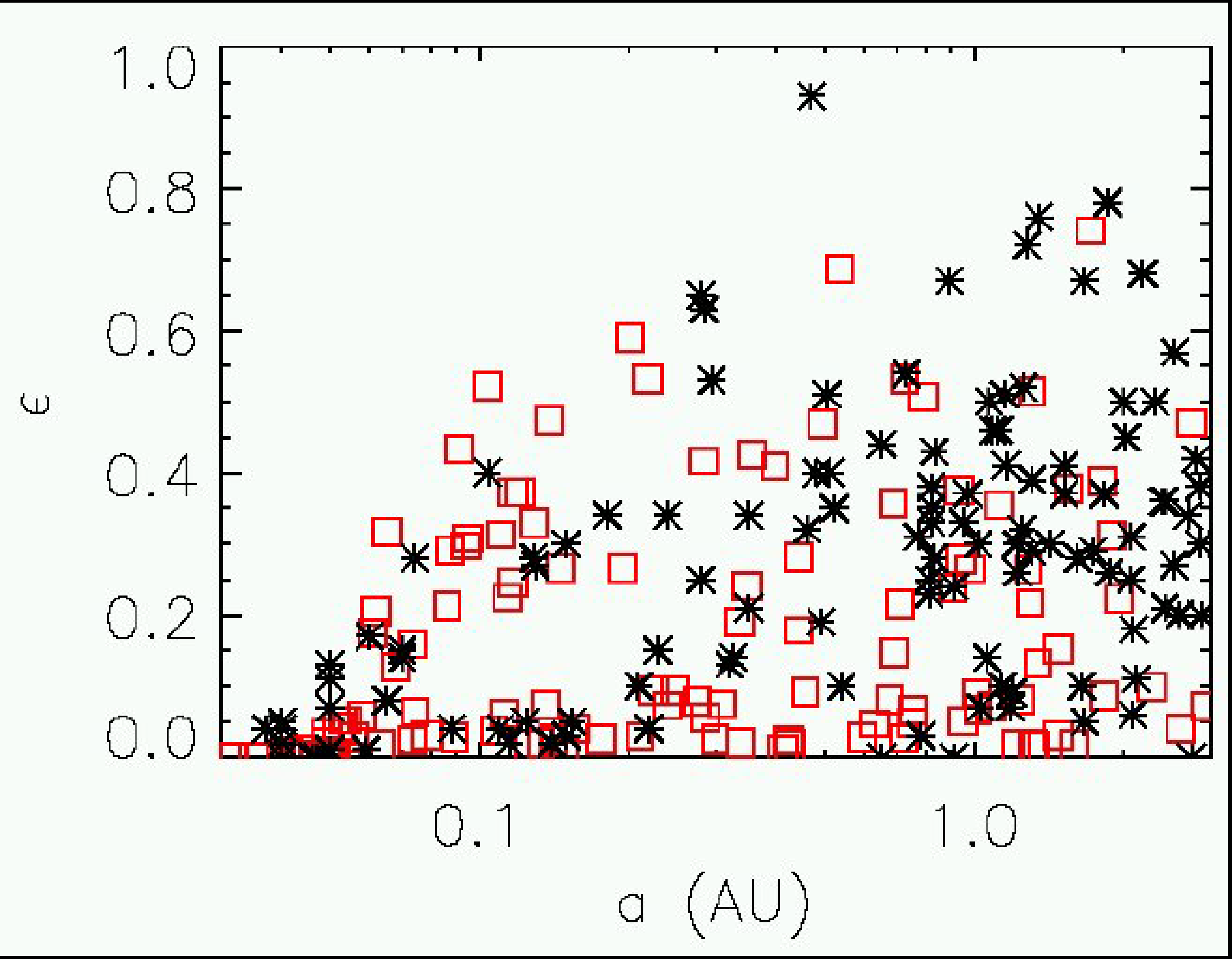
Migration starts again….



Kley et al. 2004, 2005

Migration drives the inner, lighter planet to become very eccentric -> this can lead to an instability which ejects one planet and leaves the other one on an orbit very elliptic and close to the star…..

Close encounters between migrating planets is considered the best mechanism to explain the distribution of eccentricities and semi major axes of extra-solar planets.



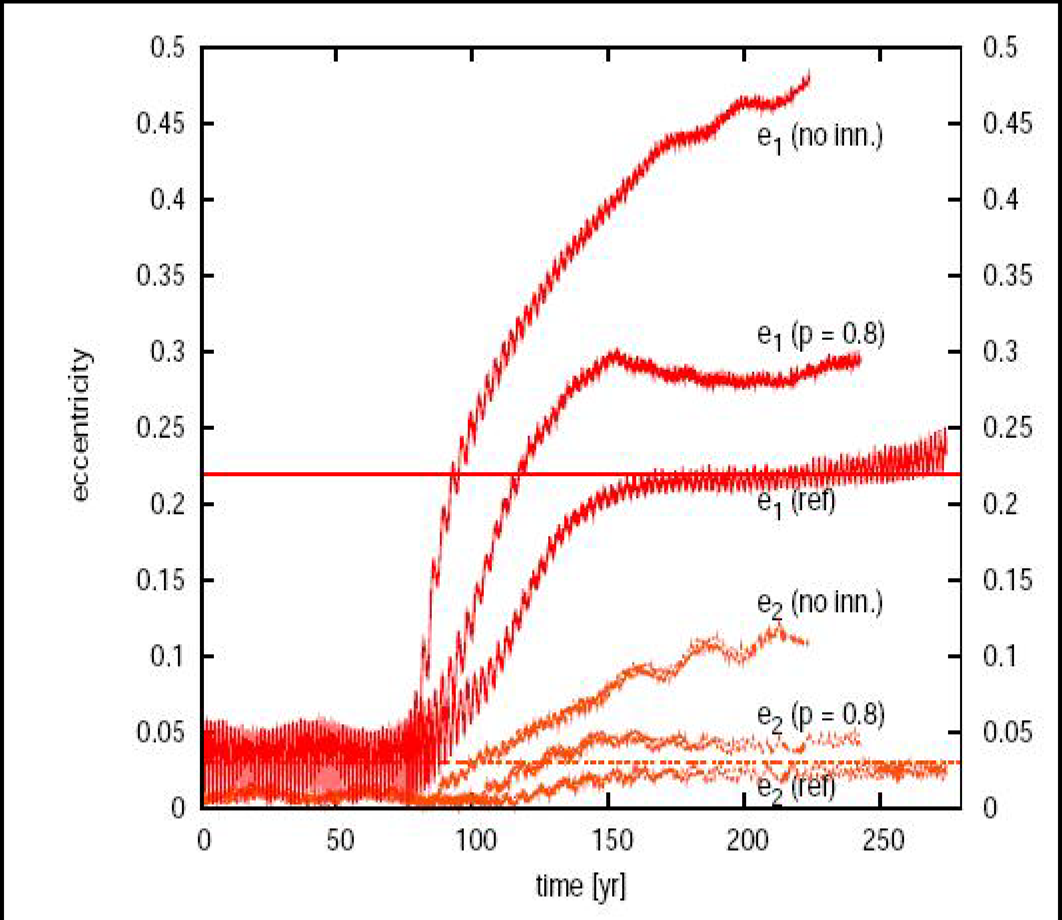
Moorhead et Adams, 2005

See also:

Juric et Tremaine, 2008; Chatterjee et al., 2008; Ford et Rasio, 2008; Veras et al., 2009.

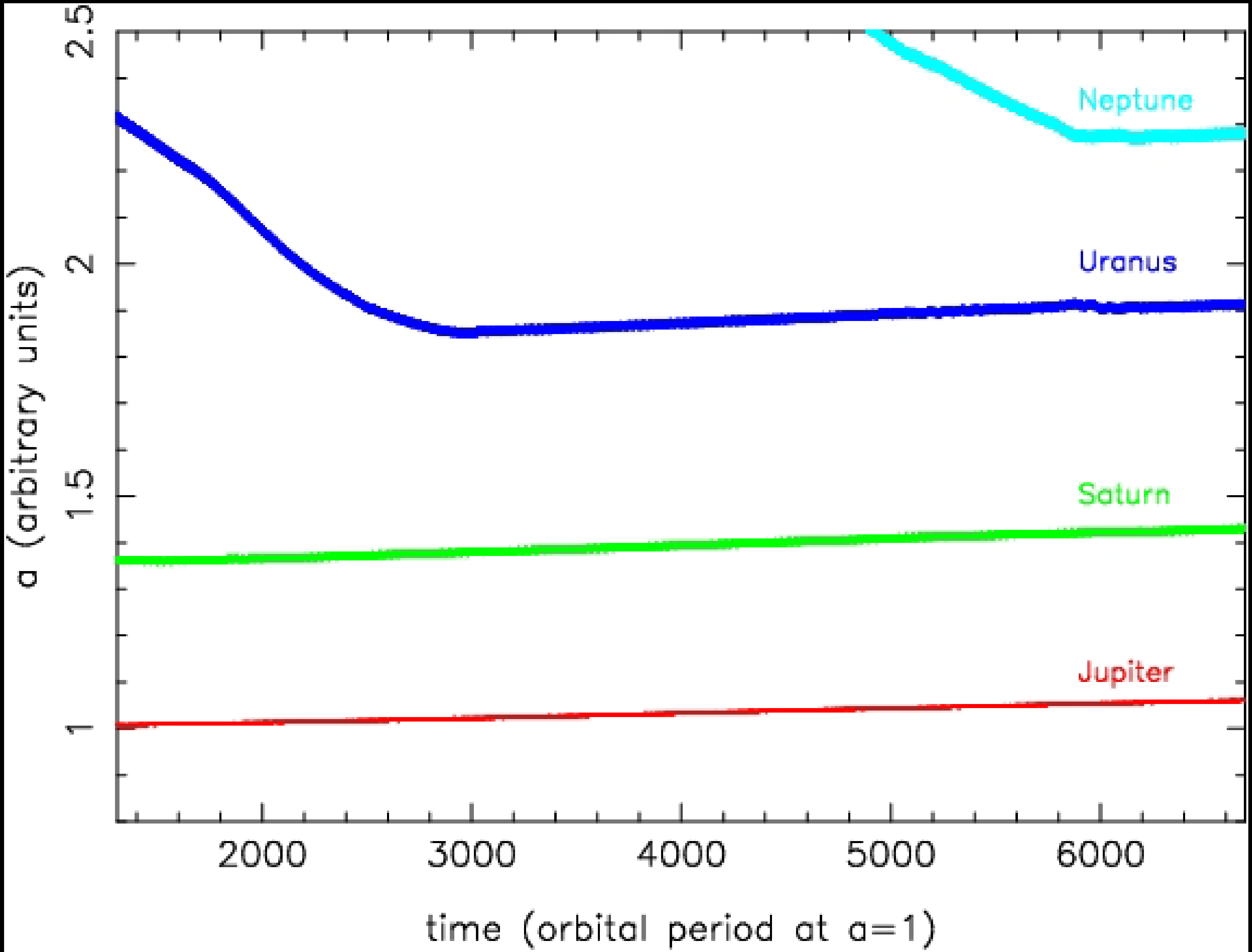
… except if the disk inside the orbit of the inner planet remains relatively massive (which depends on planet masses and disk viscosity).

In this case the inner planet eccentricity saturates (Crida et al., 2008). This explains the stable resonant pairs of planets observed (Gliese etc.)

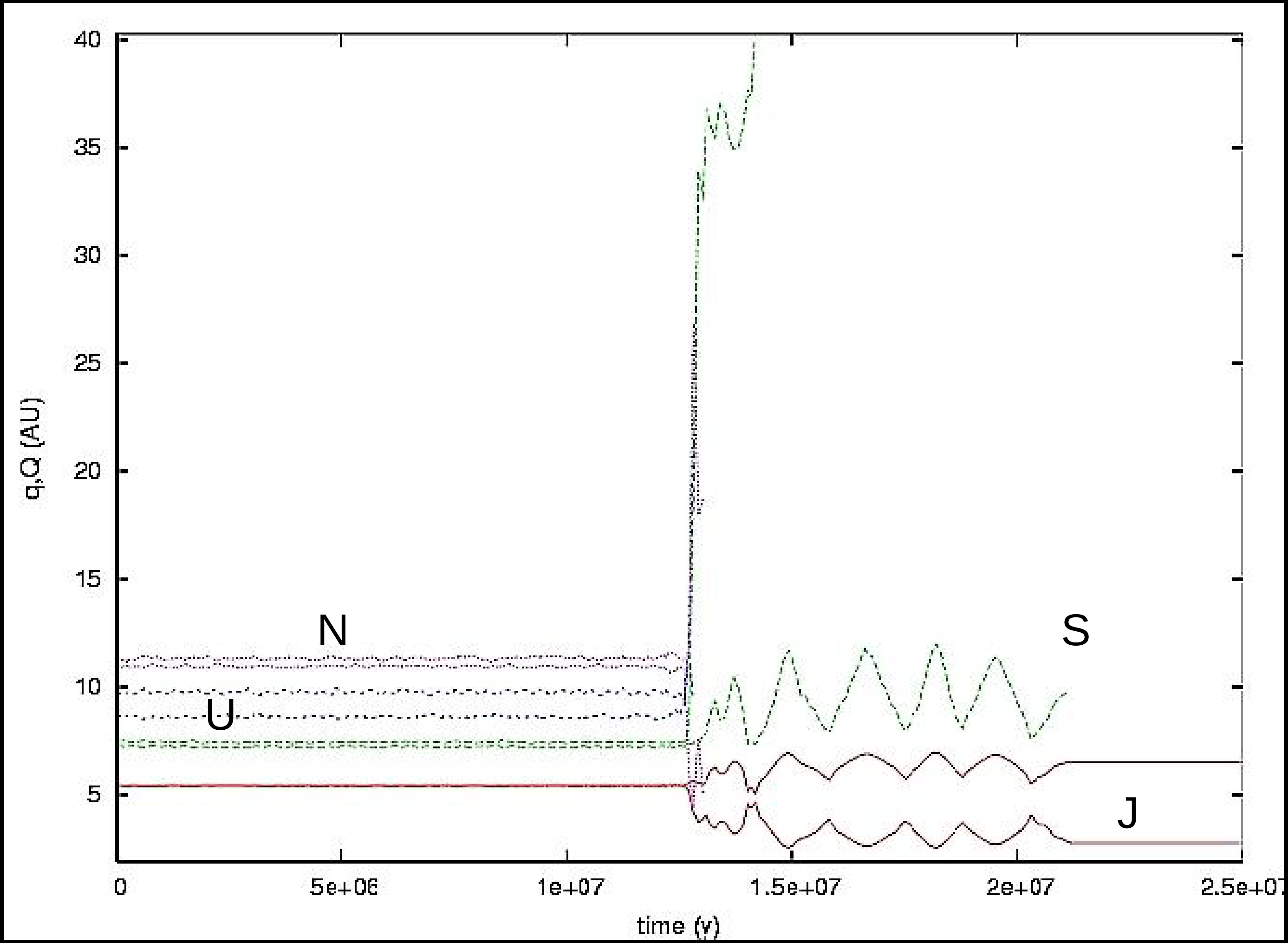


BACK TO THE SOLAR SYSTEM

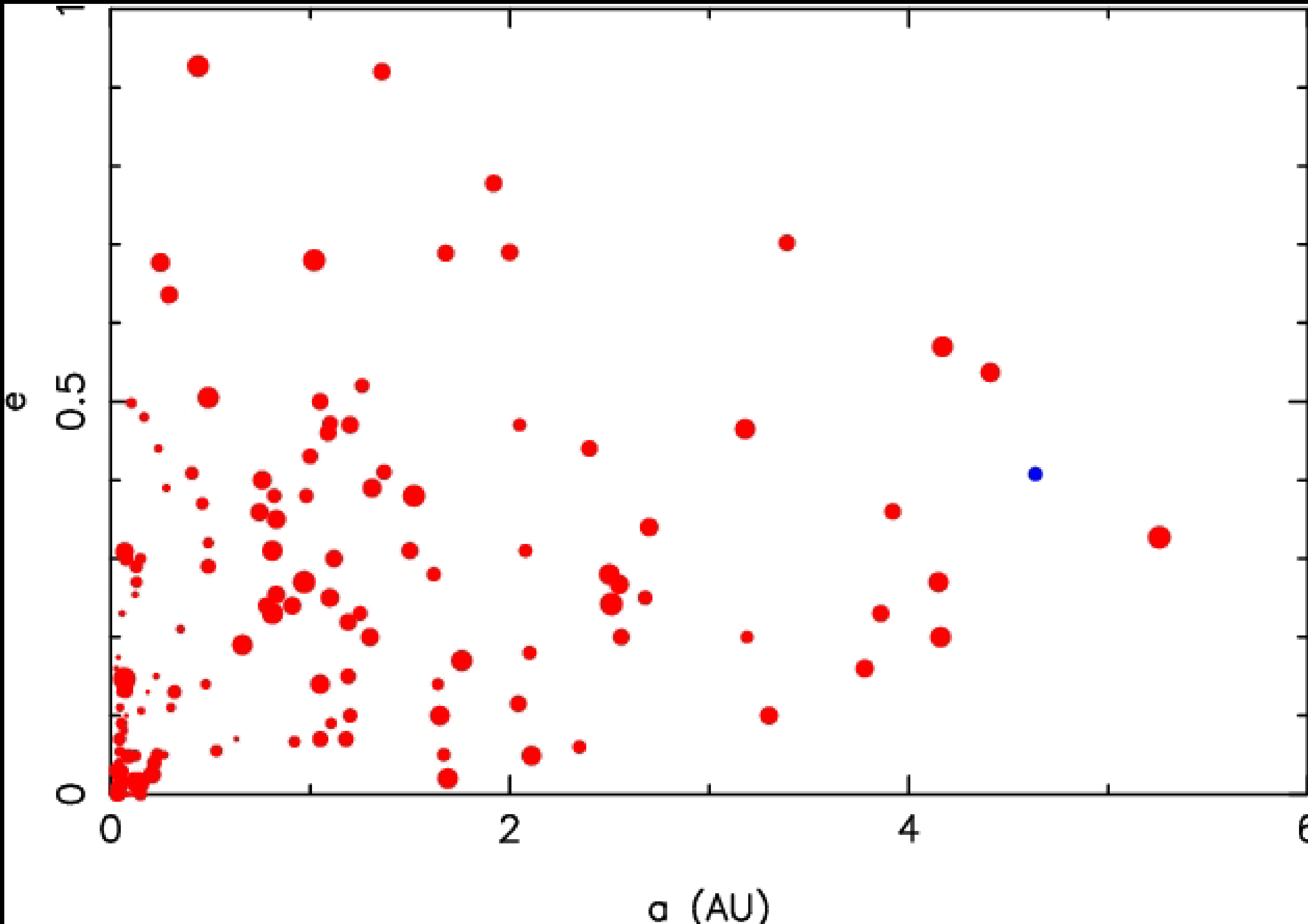
Once Jupiter and Saturn are blocked in their 3:2 resonance, Uranus and Neptune, which migrate by type I migration, have to be trapped in resonances with Saturn and with each other (Morbidelli et al., 2007)



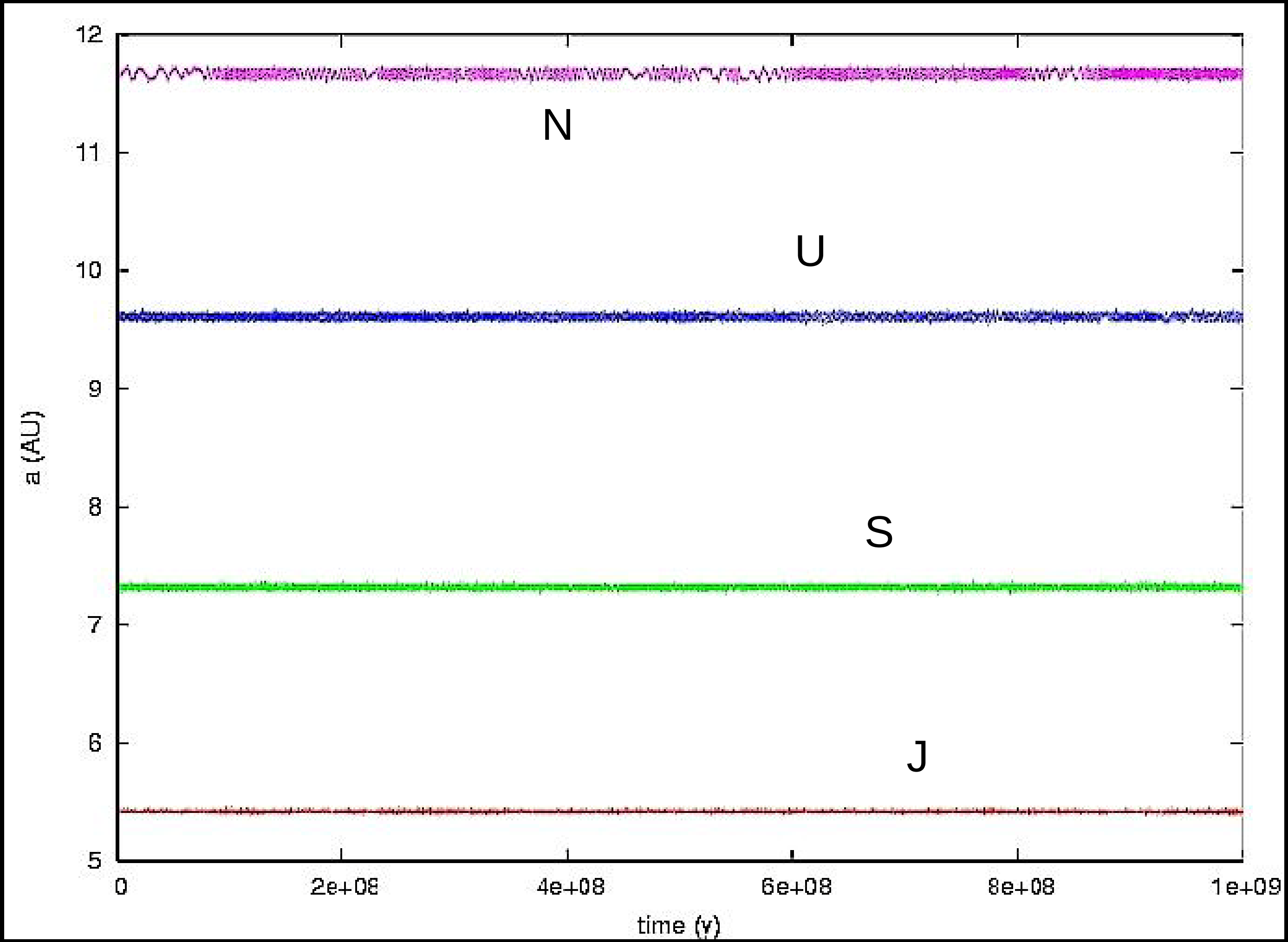
We have found 6 possible configurations. Four of them, those with planets too close to each other, become rapidly unstable as soon as the gas disk dissipates, leading to the ejection of most planets and leaving Jupiter on an excited orbit…..



….that looks like those of some exo-planets far from their star!



The 2 solutions with the widest orbital separations remain stable also after the disappearance of the gas disk (and in absence of planetesimals).

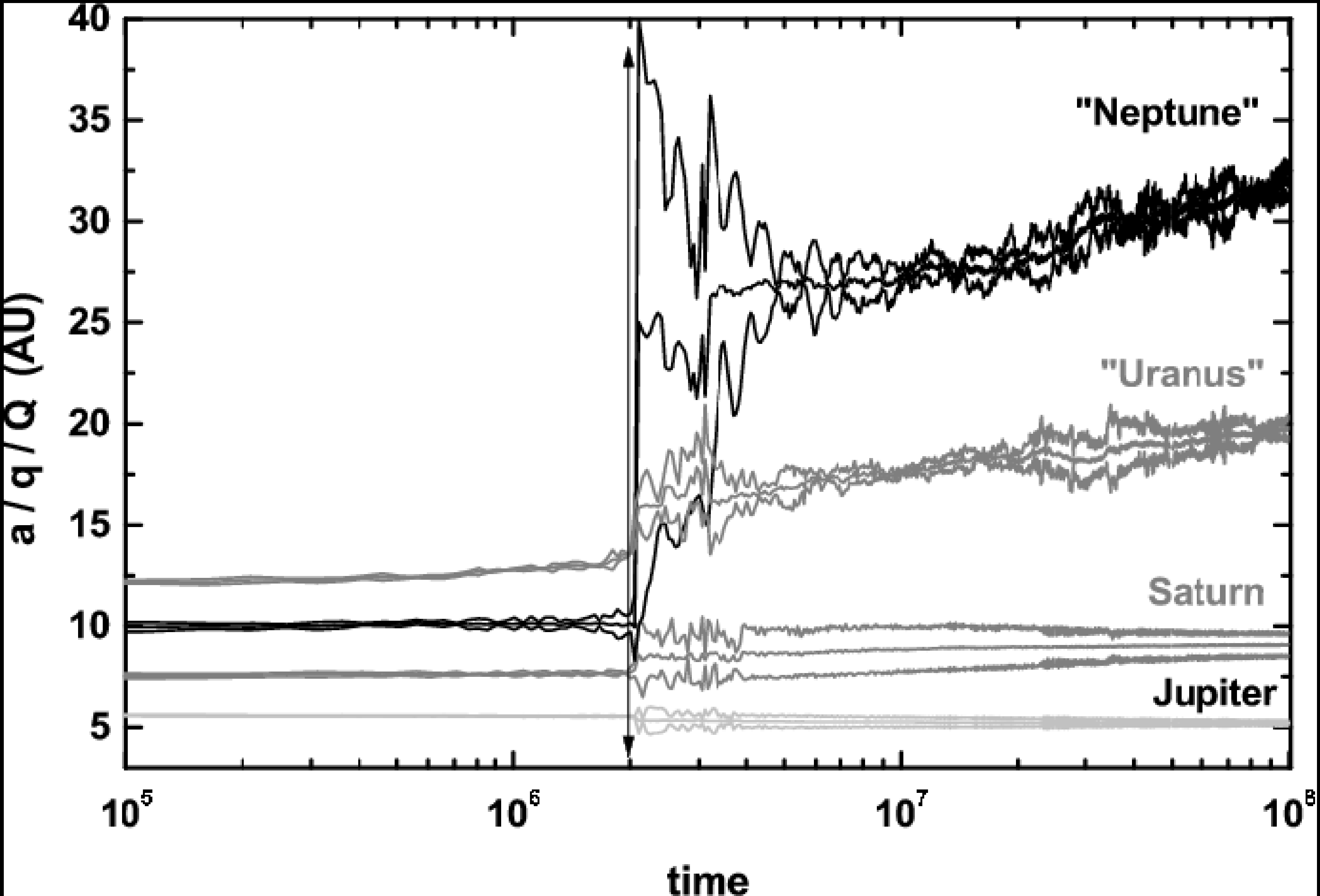


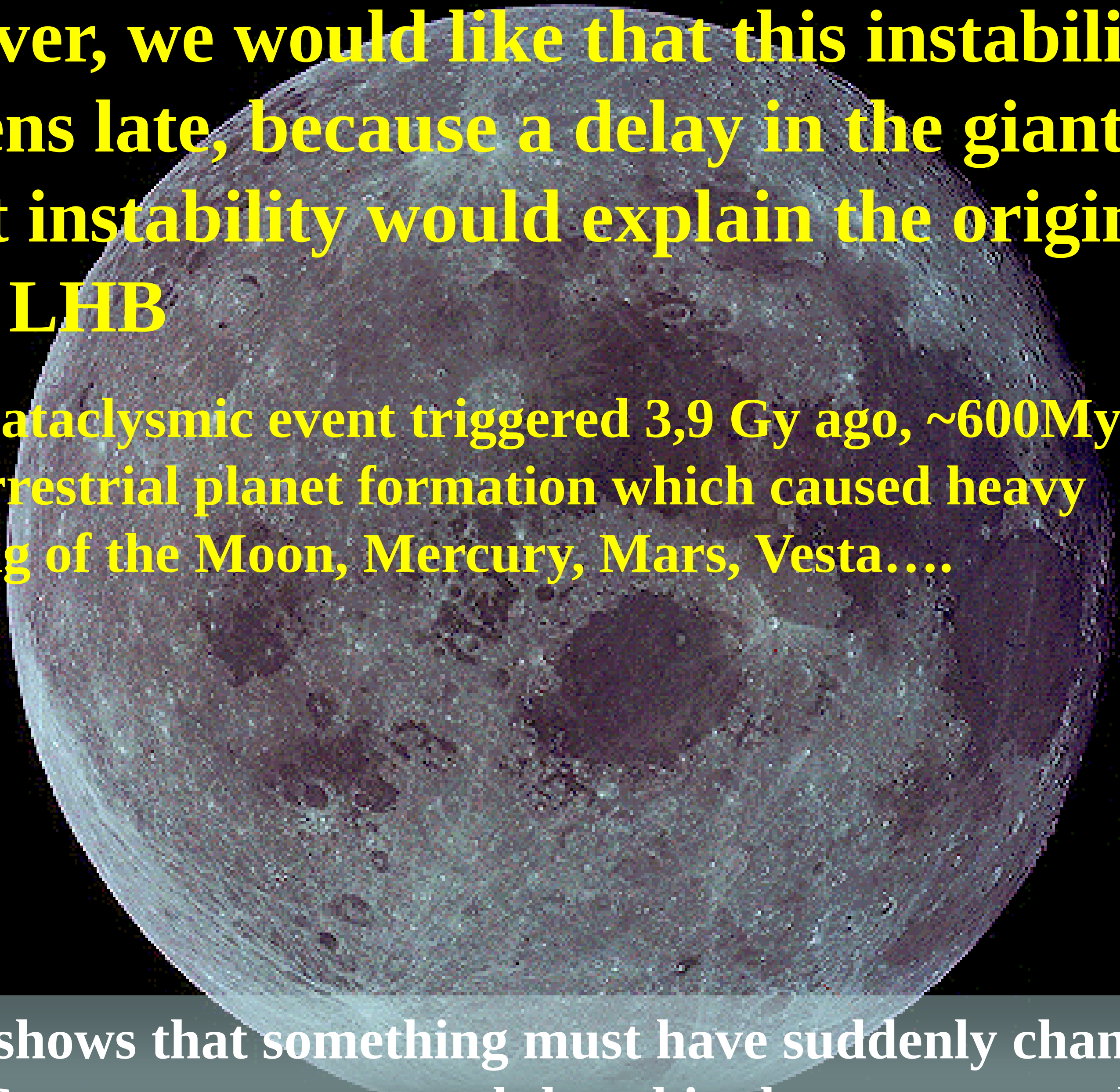
II) After the gas was gone: the evolution of the giant planets in the planetesimal disk

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 stable configurations found in the hydro-dynamical simulations should be the correct initial conditions for a new Nice-like model (Morbidelli et al., 2007)

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, brings them to final orbits similar to their current ones





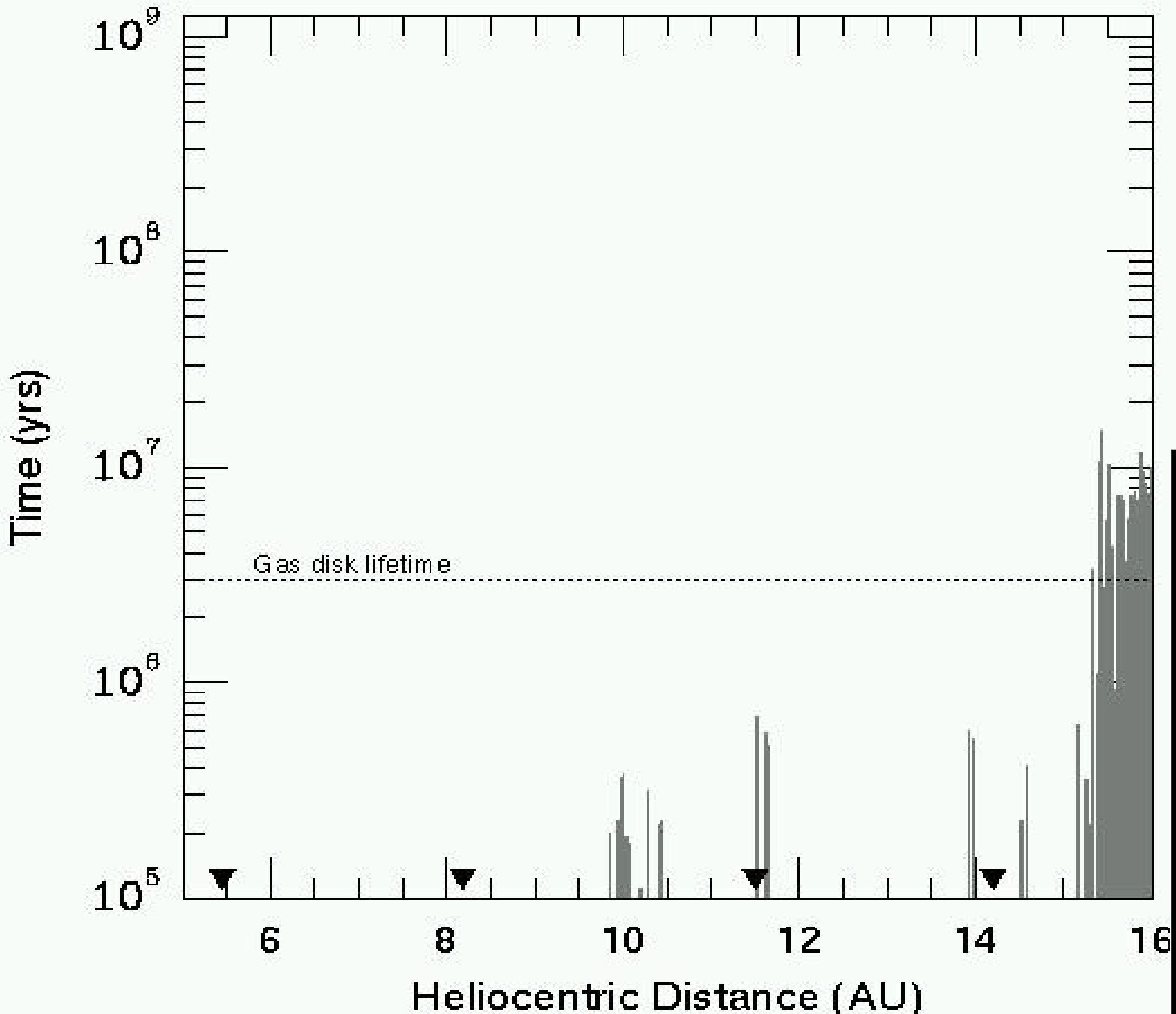
However, we would like that this instability happens late, because a delay in the giant planet instability would explain the origin of the LHB

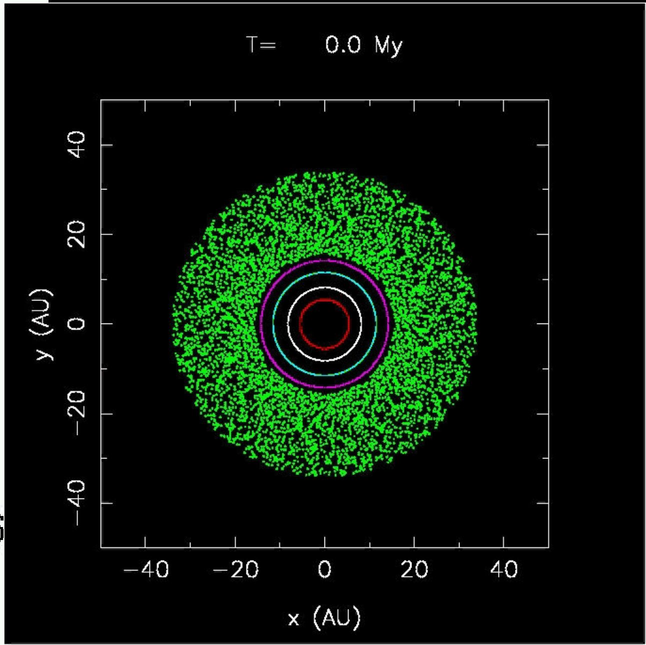
LHB: Cataclysmic event triggered 3,9 Gy ago, ~600My after terrestrial planet formation which caused heavy cratering of the Moon, Mercury, Mars, Vesta….

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

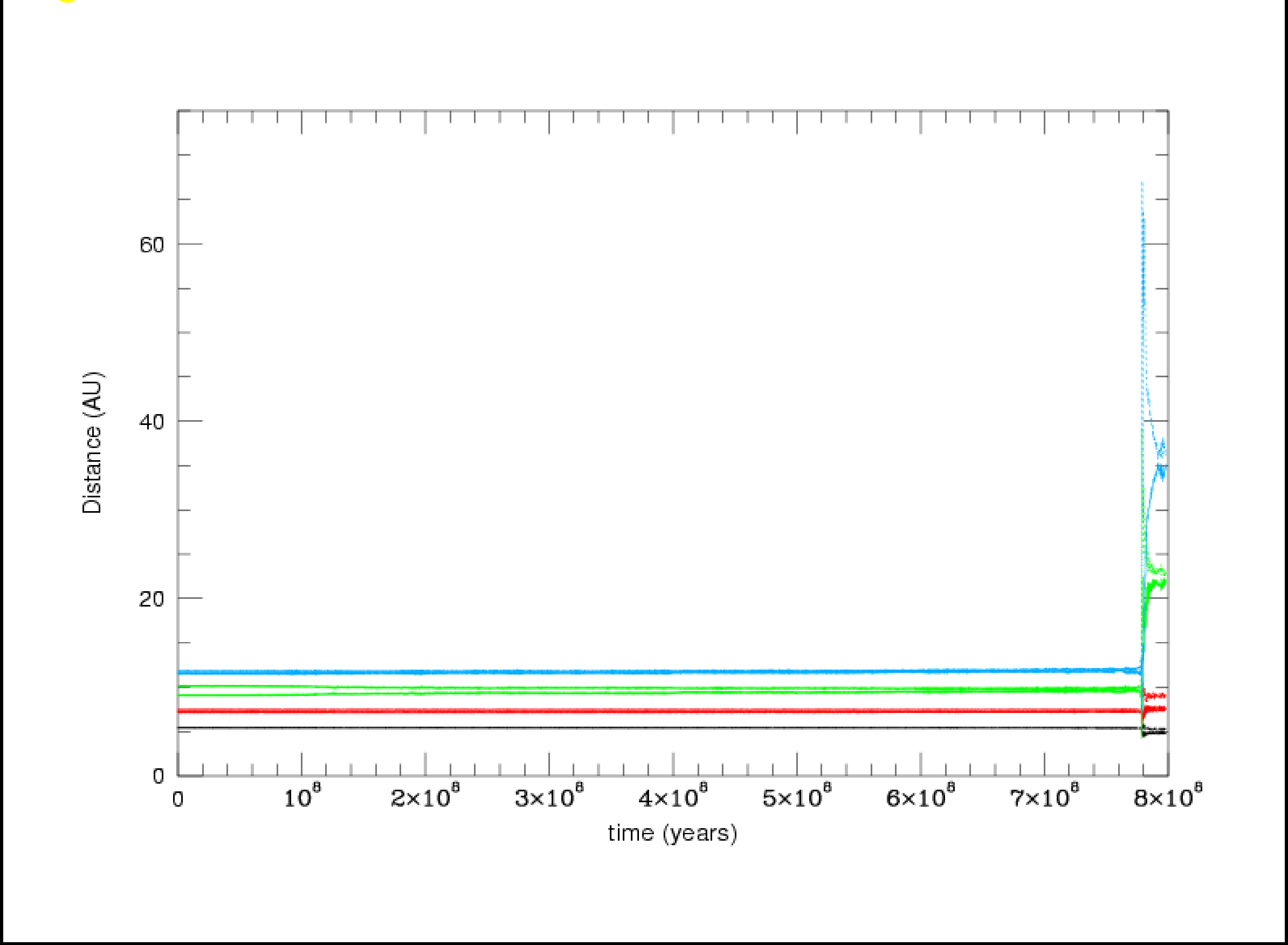
The reason why the instability occurs early in the previous simulation is that we embedded the planets in the planetesimal disk.

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





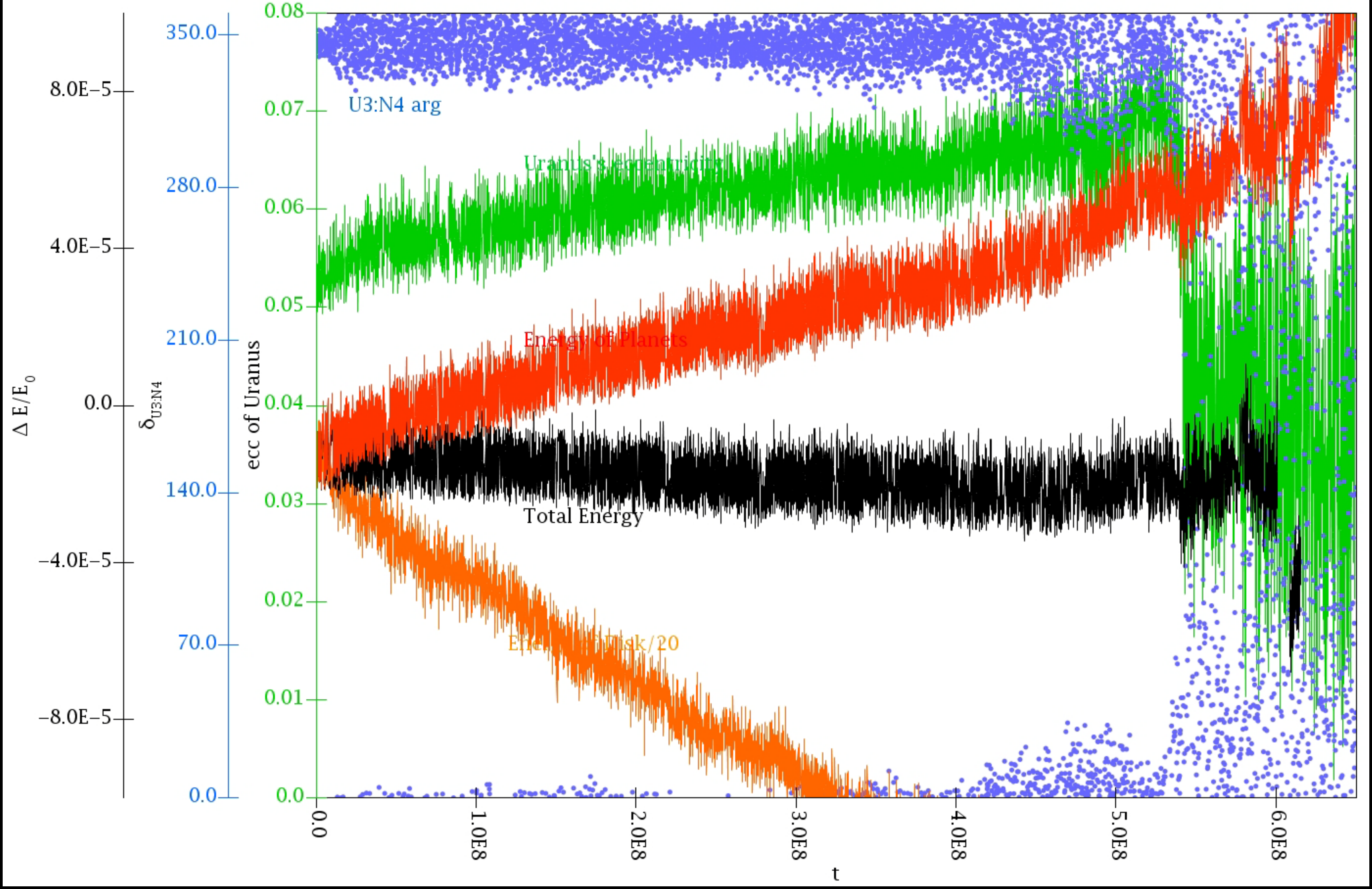
If one tunes the location of the inner disk, the giant planet instability, and the re-arrangement of their orbits can occur at about the LHB time



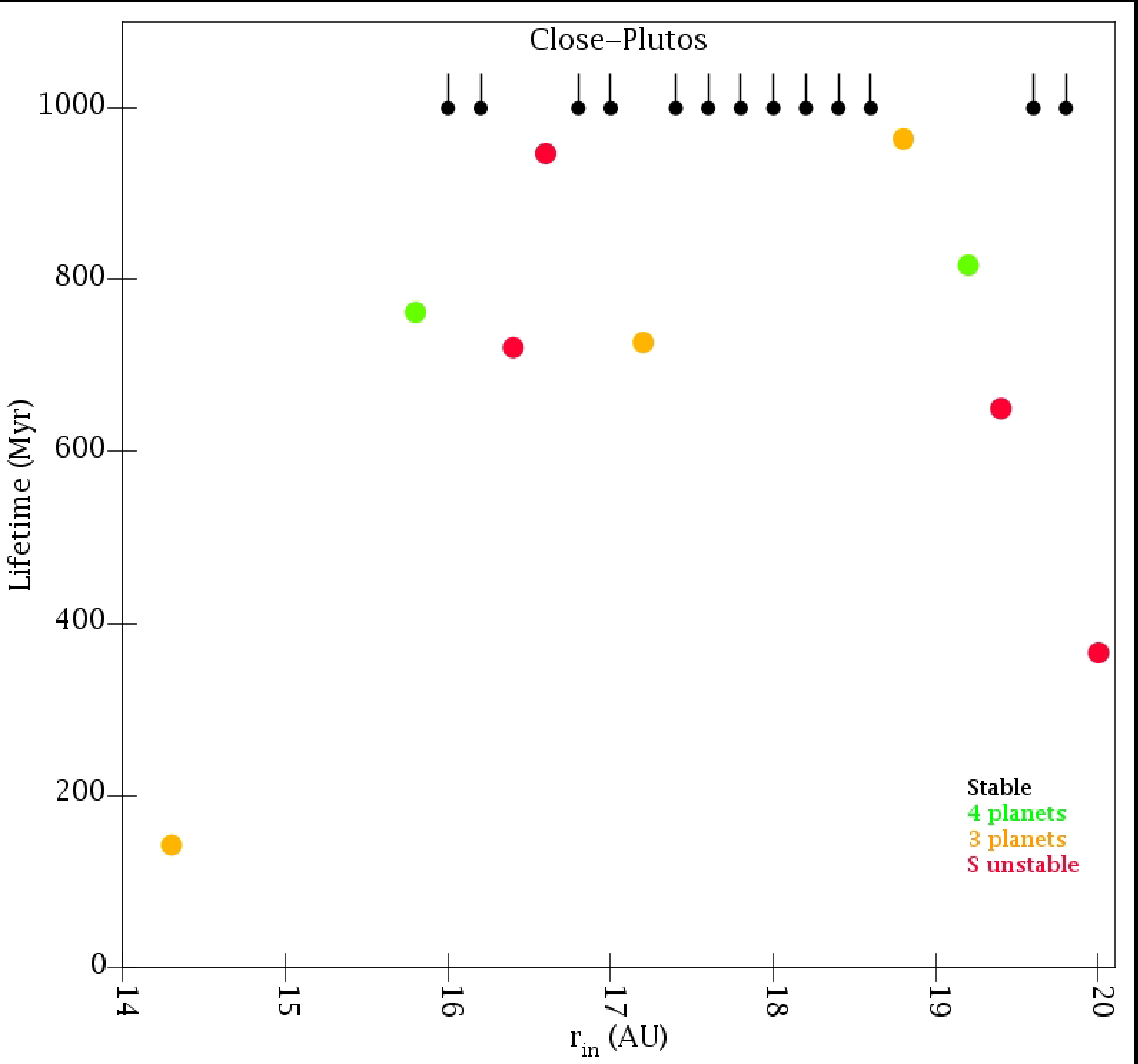
But one needs to tune it REALLY WELL!!!!

A self-gravitating trans-Neptunian planetesimal disk…..

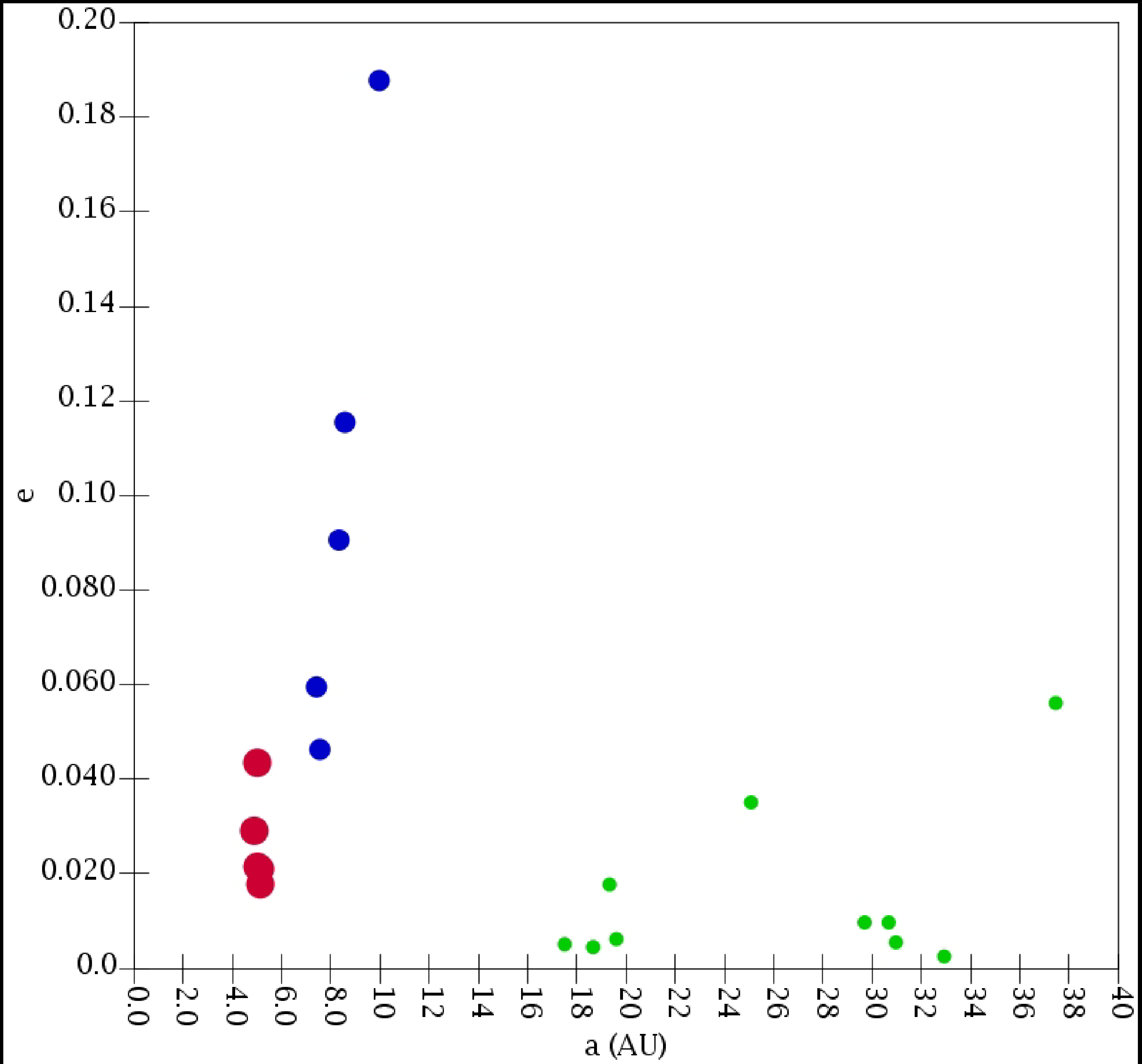
(Levison et al., in preparation)



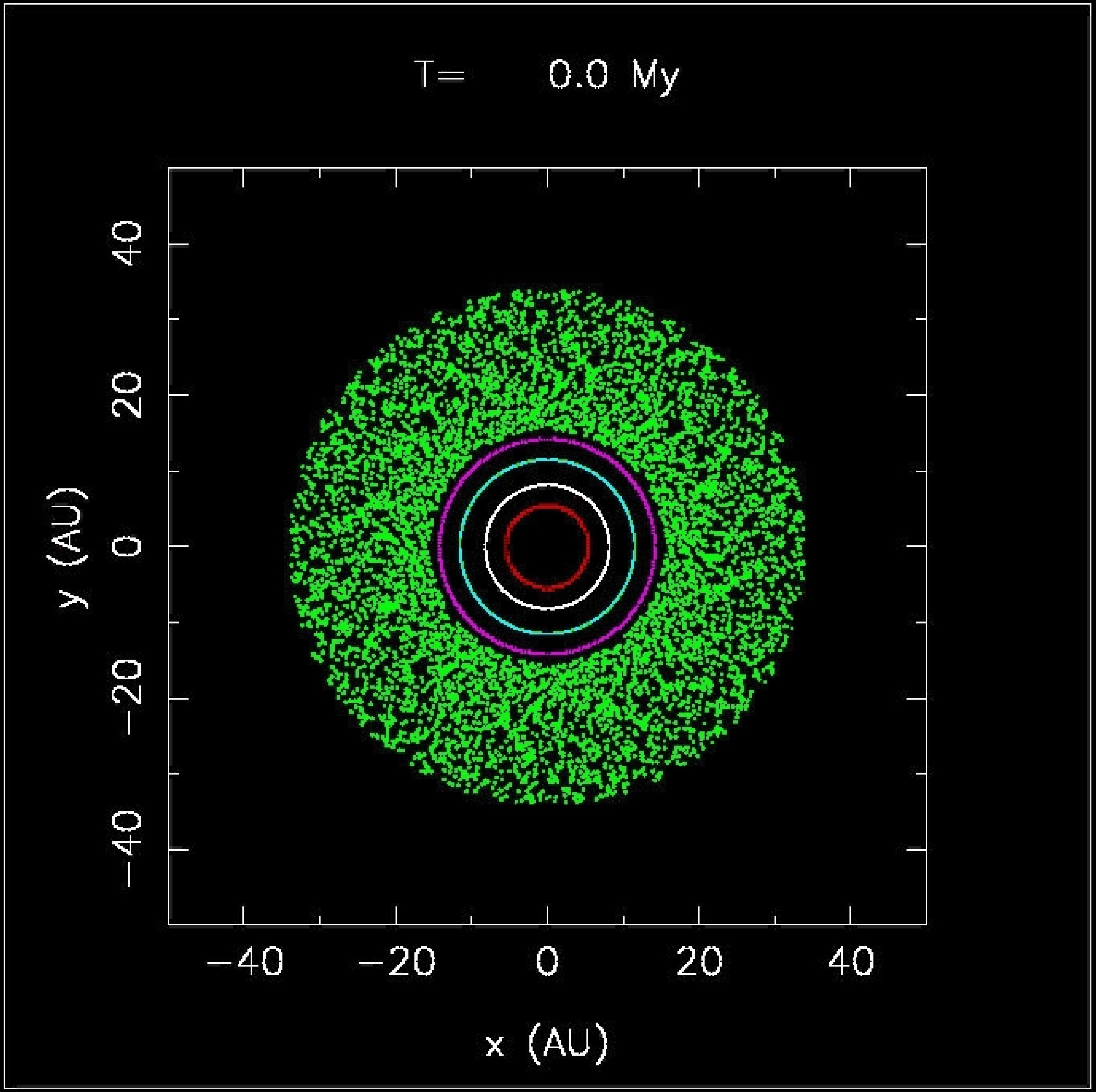
….leads in a natural way to late instabilities, quite independently of the location of the inner edge of the disk



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



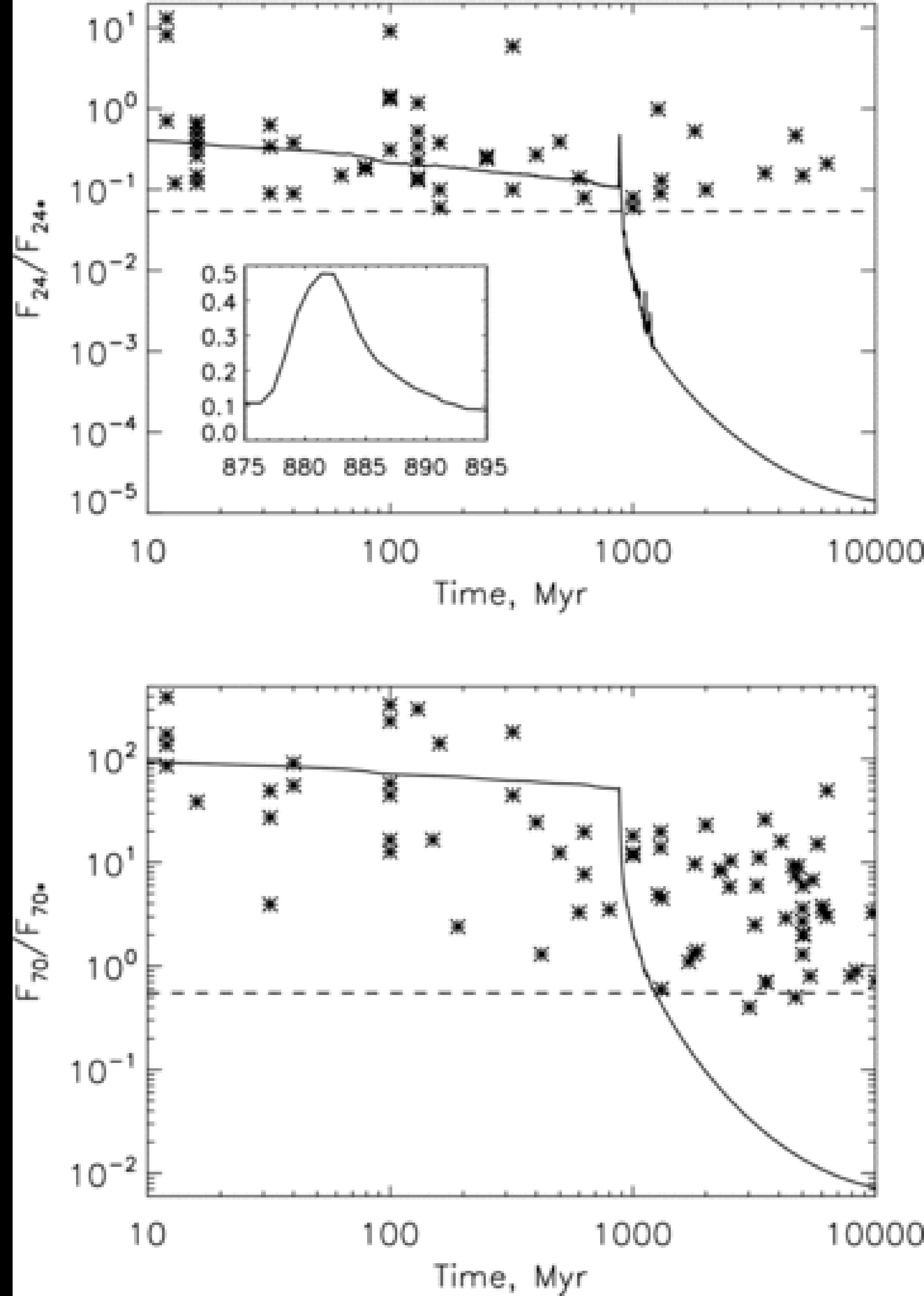
III) The Solar System as a debris disk

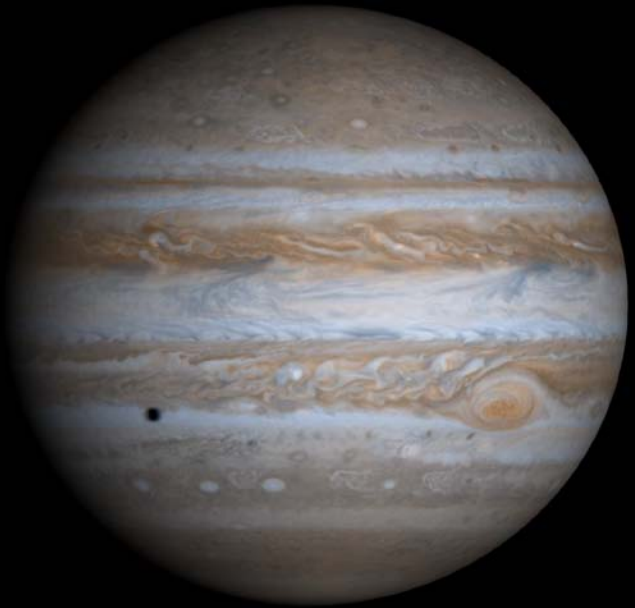


We have computed the "brightness" of the solar system as a debris disk throughout its history according to the LHB model (Booth et al., 2009).

Prior to the LHB the Solar System was a "typical" debris disk. The disk disappeared at the LHB type due to the dynamical depletion of the trans-Neptunian population.

Such rapid dynamical clearing should occur at most for 15% of the systems.

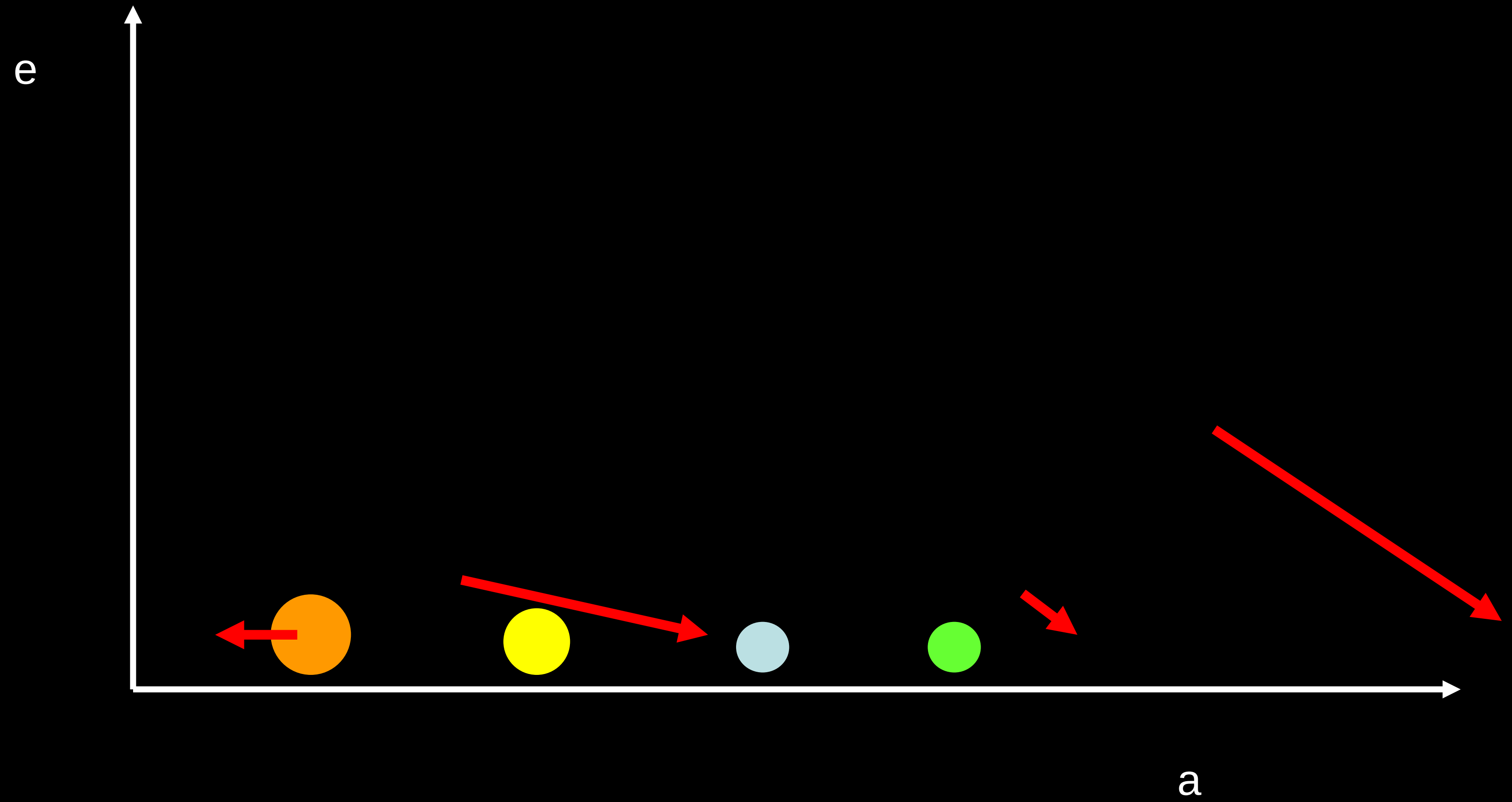





IV) Constraining the giant planets evolution after the trigger of their instability

Two possible evolutions from instability:

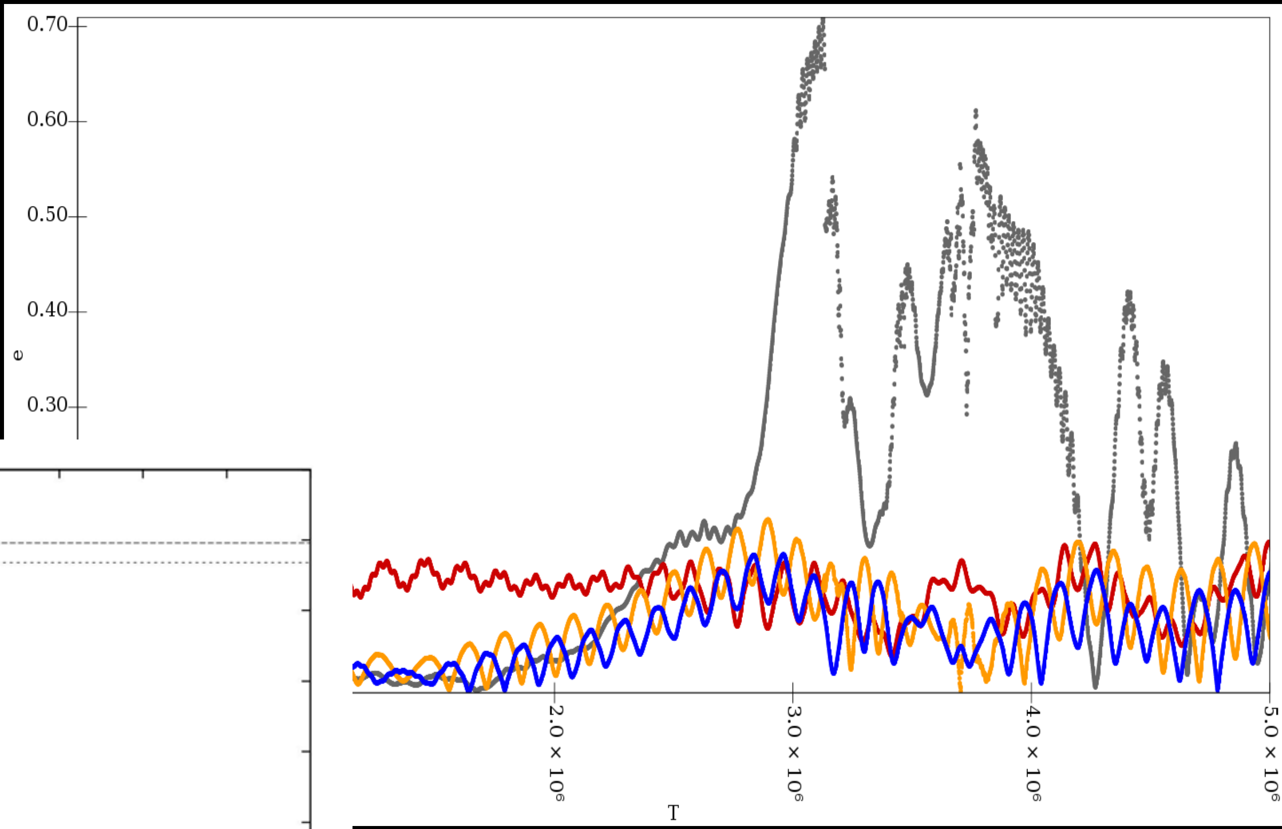
I) The divergent evolution of Jupiter and Saturn is dominated by planetesimal-driven migration

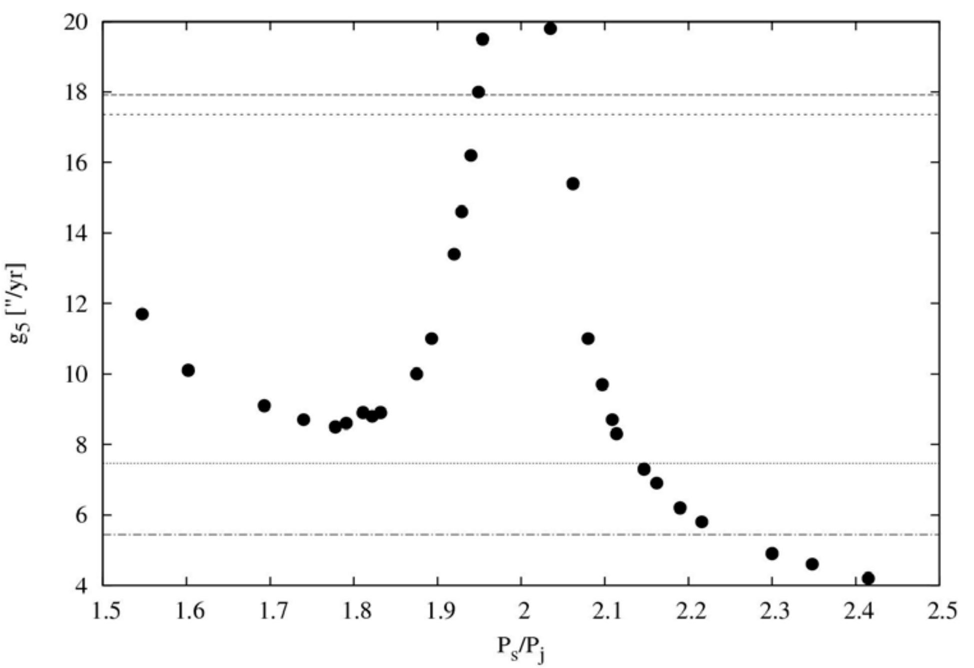


Typical timescale for Jupiter-Saturn separation: 10My

The divergent migration of Jupiter and Saturn drives secular resonances across the terrestrial planets region and the asteroid belt.
If this migration takes as long as a few My, this:

i) Makes the terrestrial planets too eccentric or even unstable

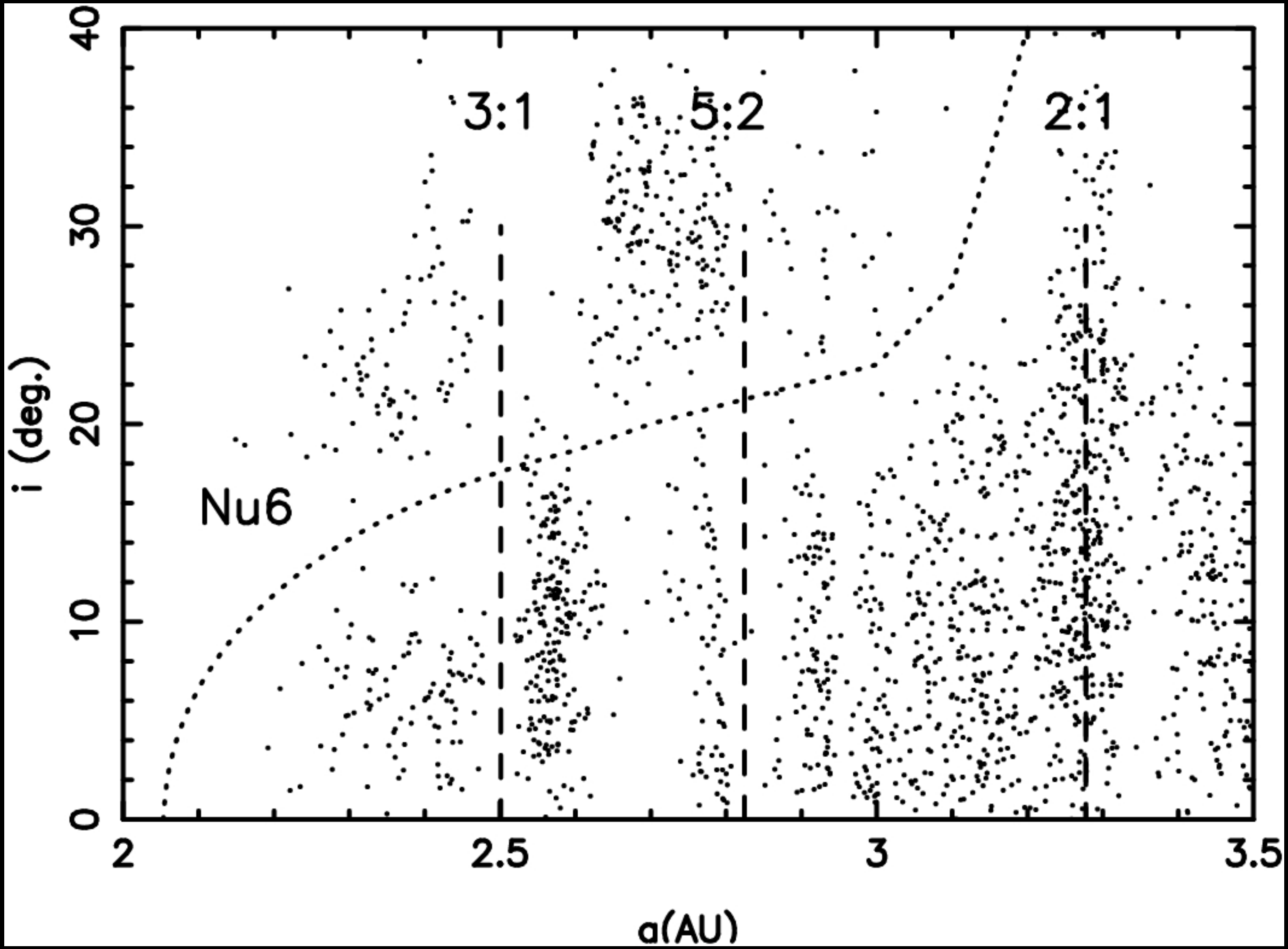




Brasser et al., 2009

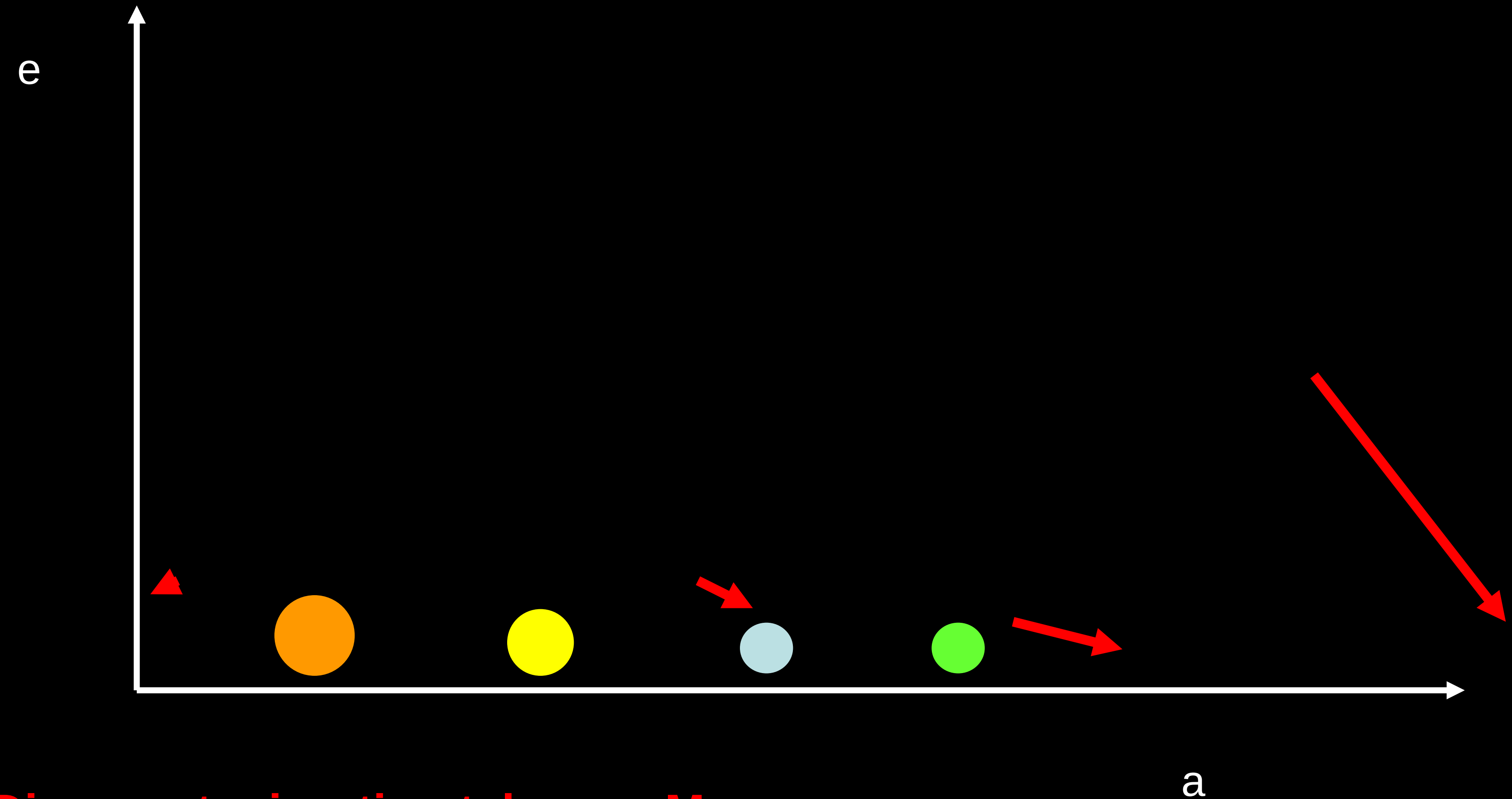
The divergent migration of Jupiter and Saturn drives secular resonances across the terrestrial planets region and the asteroid belt.
If this migration takes as long as a few My, this:

ii) Gives the asteroid belt a really weird orbital distribution



Two possible evolutions from instability:

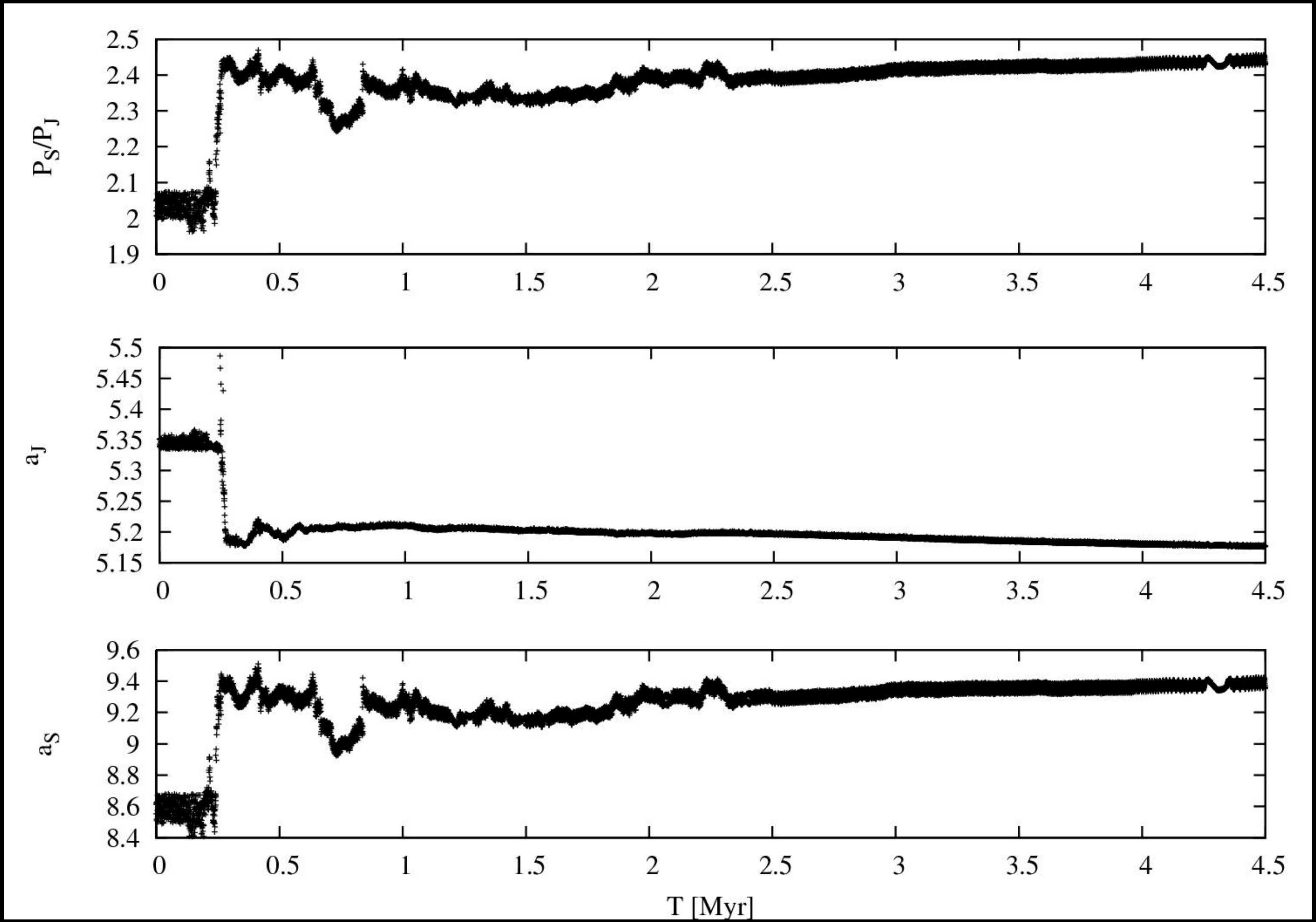
II) The divergent evolution of Jupiter and Saturn is dominated by encounters with Uranus or Neptune



Divergent migration takes << My

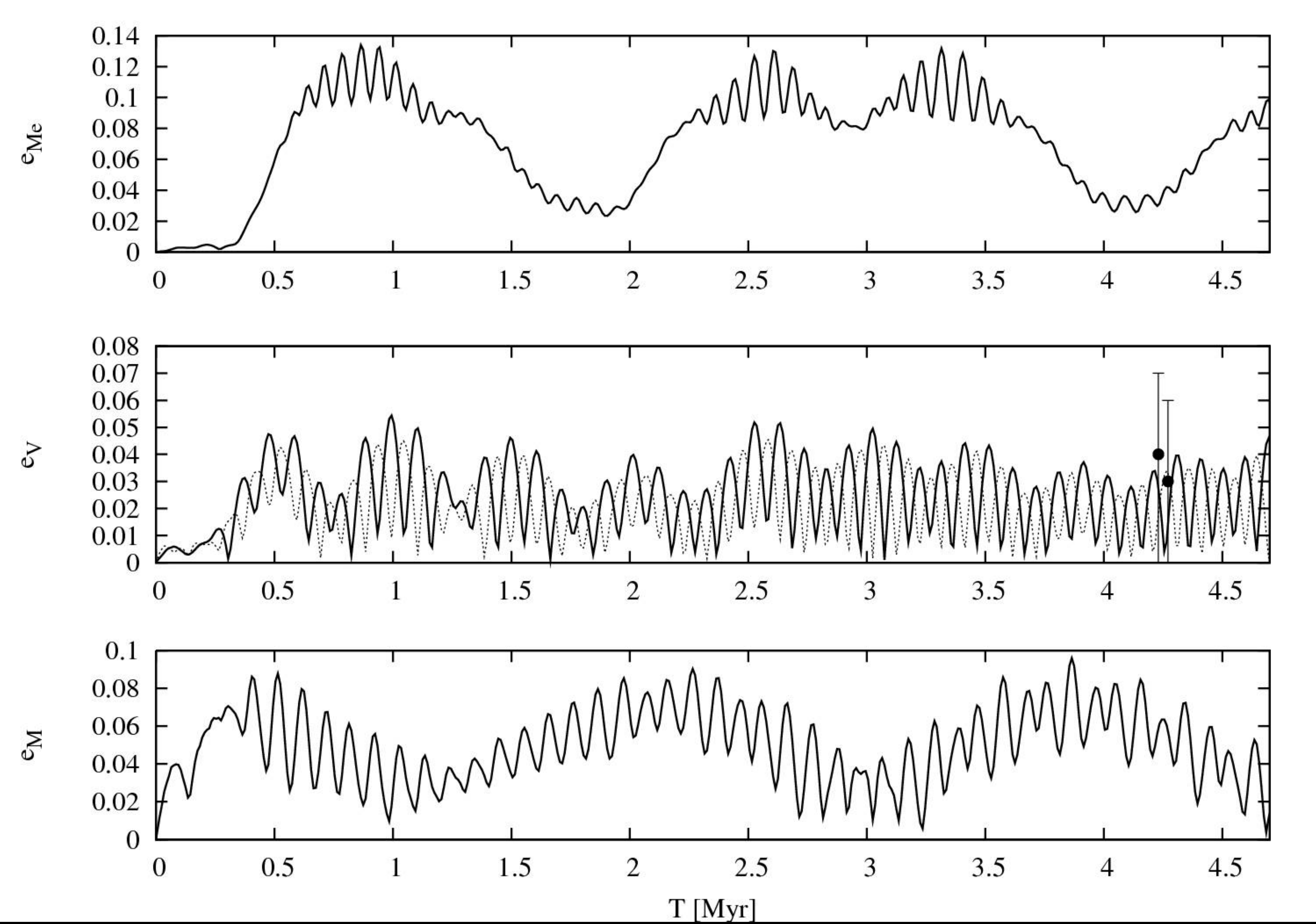
This kind of evolution occurs in ~10% of the successful runs in the original Nice model and > 50% of those of the " new" Nice model

Example of Jumping-Jupiter evolution

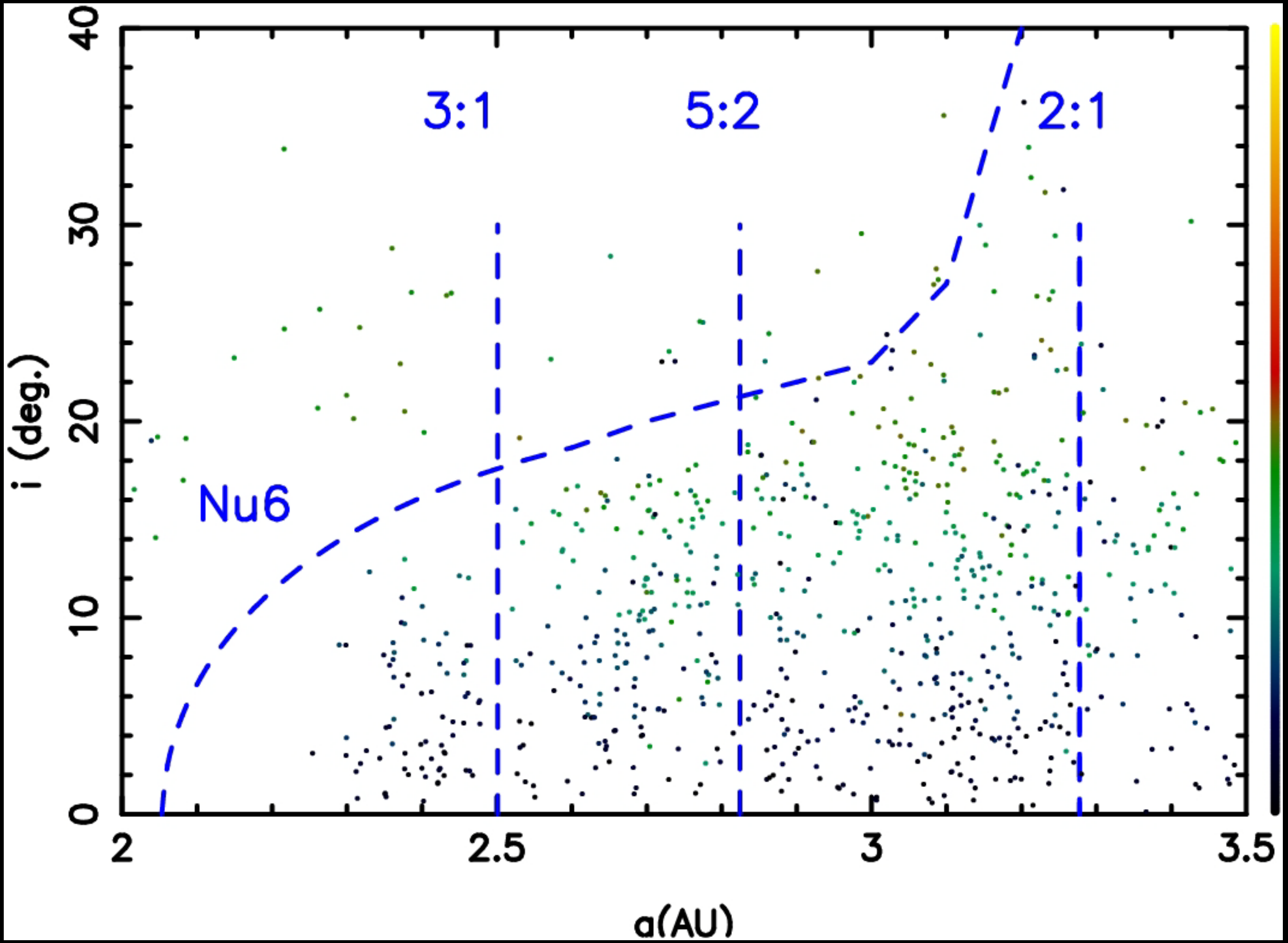


Nesvorny et al. (2007) argued that Jupiter-Uranus encounters did occur, otherwise only Saturn, Uranus and Neptune (NOT Jupiter) should have irregular satellites

If the "jump" is large enough, then the secular resonance sweep too fast to have a disruptive effect (Brasser et al., 2009)



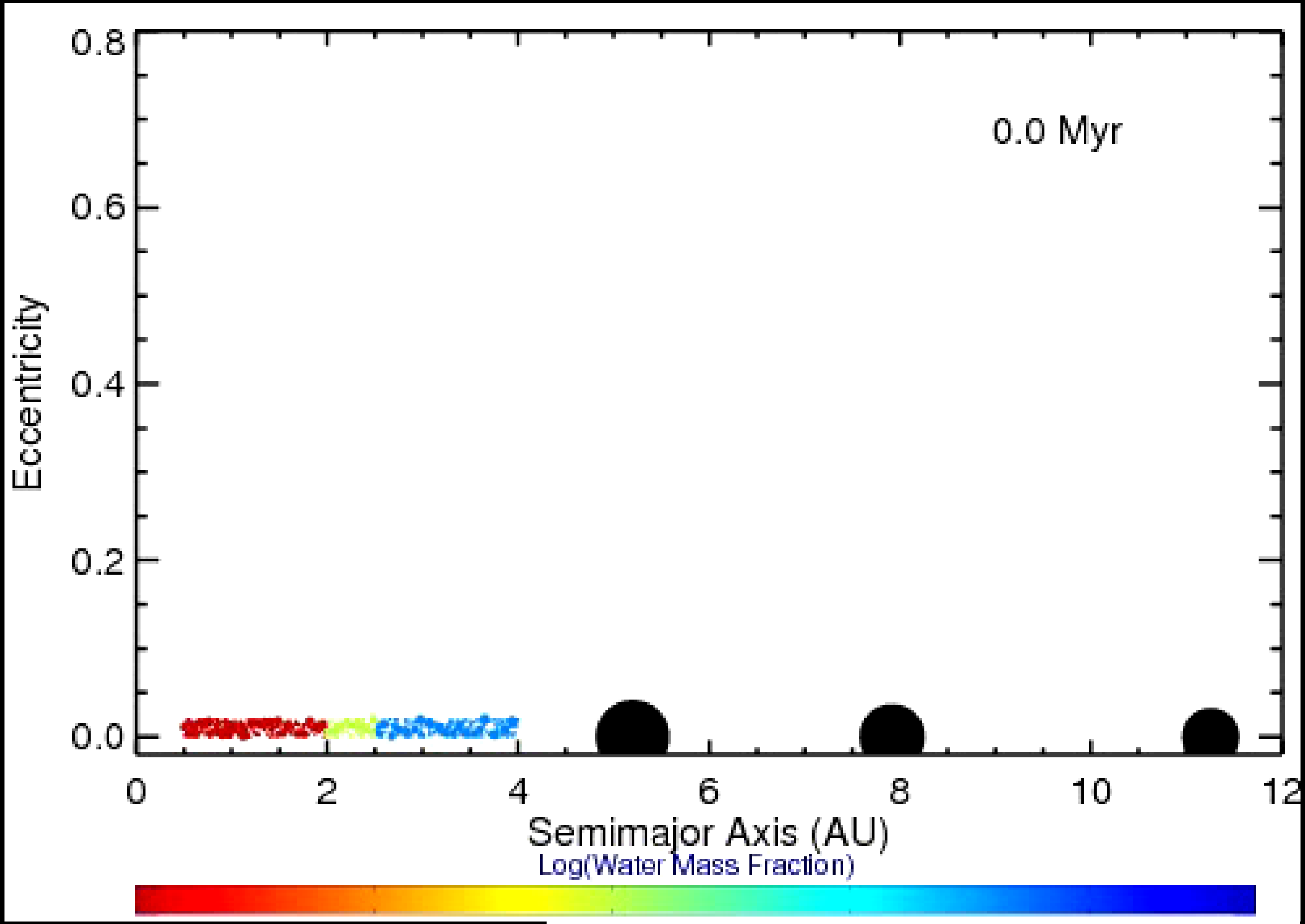
…the same is true for the asteroid belt



•In our solar system the terrestrial planets remained on cold orbits, thanks to the jumping-Jupiter evolution…

•…but in other systems they might be excited by the subsequent orbital evolution of the giant planets

•If the giant planets undergo a violent orbital instability, the terrestrial planet system is violently shaken as well



Raymond and Armitage, in prep.

CONCLUSIONS

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

We consider ourselves "Celestial geologists"

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

•A gas disk phase: fully resonant, low-e configuration; no hot Jupiter

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

The current structure of the Solar System depends on specific fortuitous features/events (Saturn did not grow more massive than Jupiter, the 4 giant planets were not too close to be violently unstable, the planetesimal disk was truncated small…).

If any of these features had happened to be different, the resulting planetary system would have been largely different

Dynamics are rich enough to generate spontaneously the great diversity of planetary system that we observe