Solar System evolution and the diversity of planetary systems

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HELMHOLTZ ALLIANCE: Planetary Evolution and Life

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

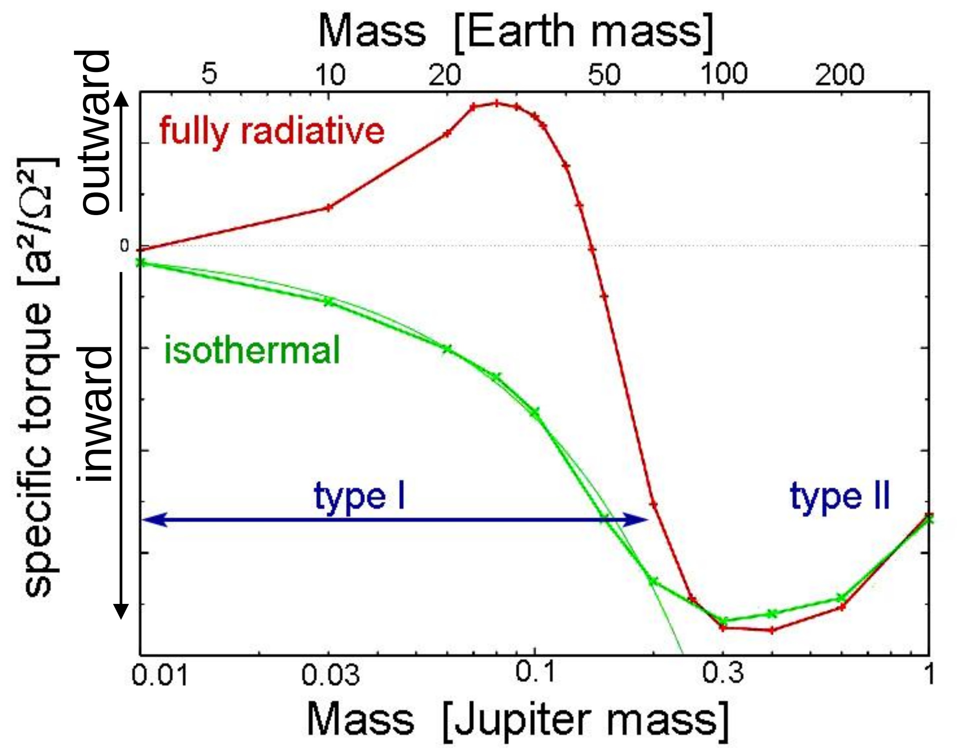
b) after the gas was gone: interactions with planetesimal disk

III) Addressing the origin of the diversity of planetary systems

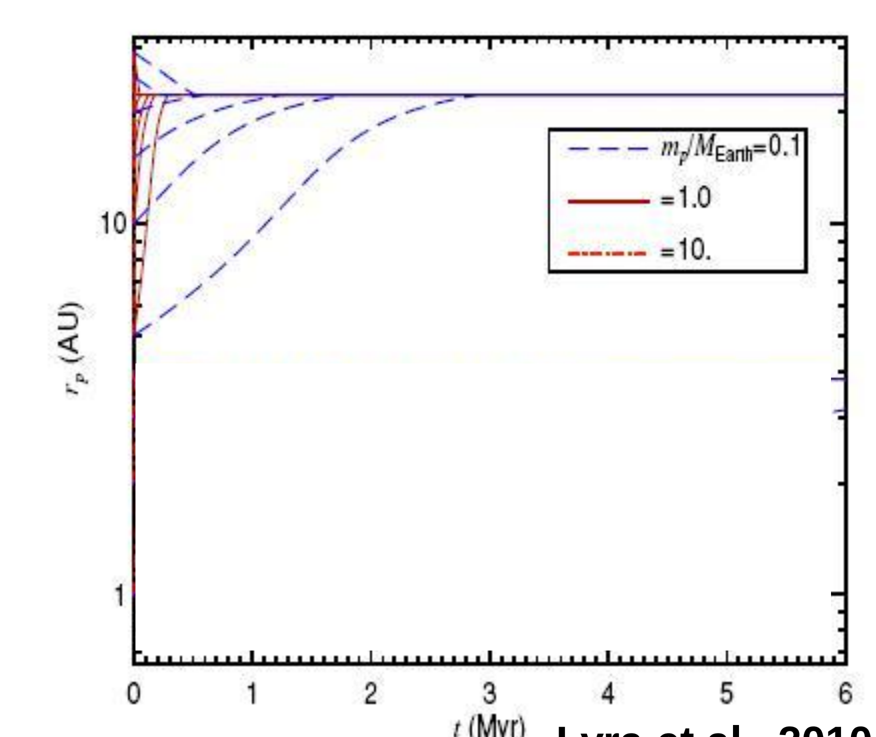
WHAT WE KNOW ABOUT MIGRATION

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



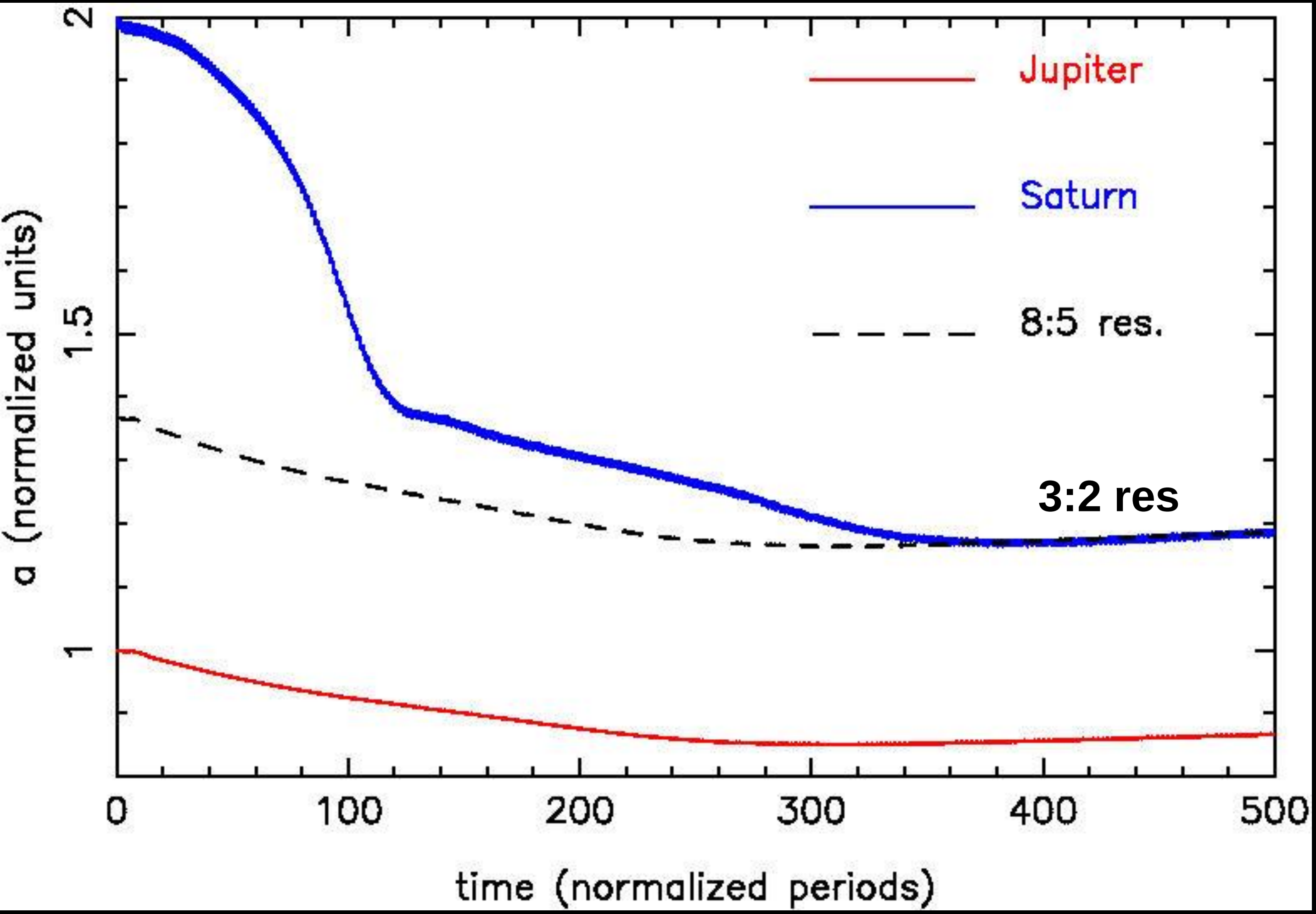
Lyra et al., 2010

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)

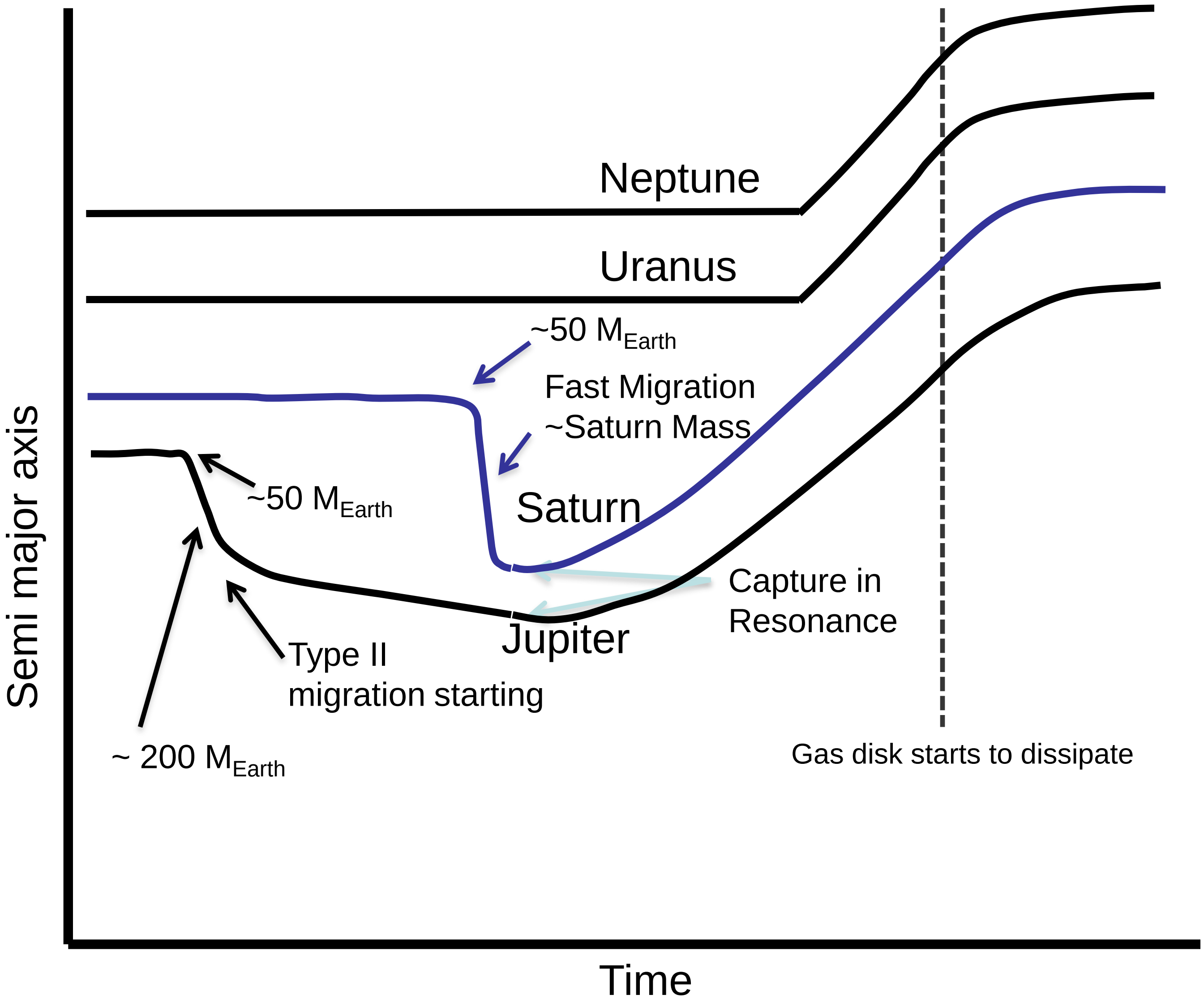
WHAT WE KNOW ABOUT MIGRATION

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



Works only if the outer planet is less massive than inner one. Ideal mass ratio 1:2 – 1:4
(Morbidelli & Crida, 2007)

PUTTING TOGETHER A COHERENT MODEL FOR THE SOLAR SYSTEM



Explains why we don't have a Hot Jupiter is the Solar System

PUTTING TOGETHER A COHERENT MODEL FOR THE SOLAR SYSTEM

Is there any evidence for the inward-then-outward migration of Jupiter?

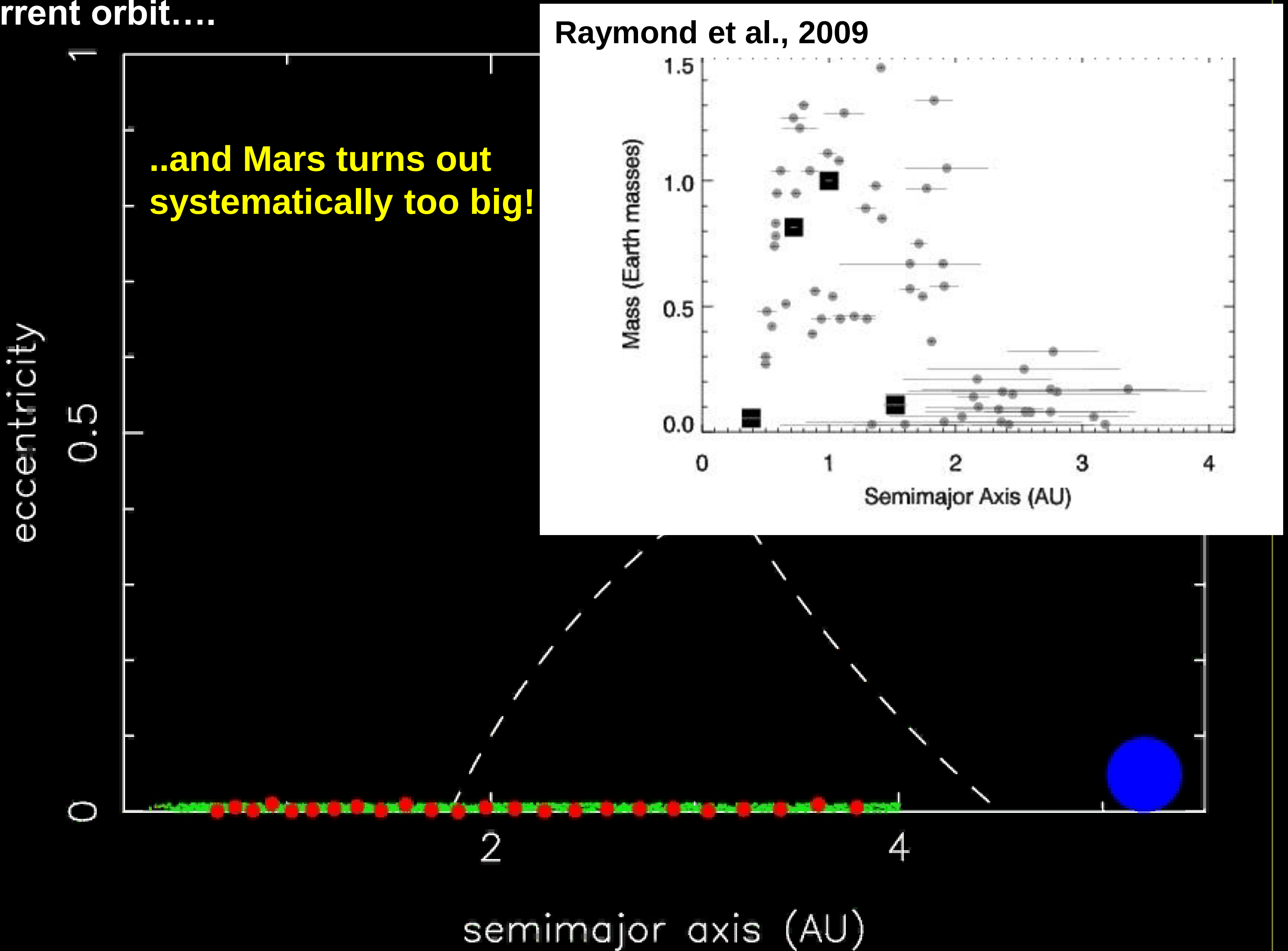
How far inwards did Jupiter go?

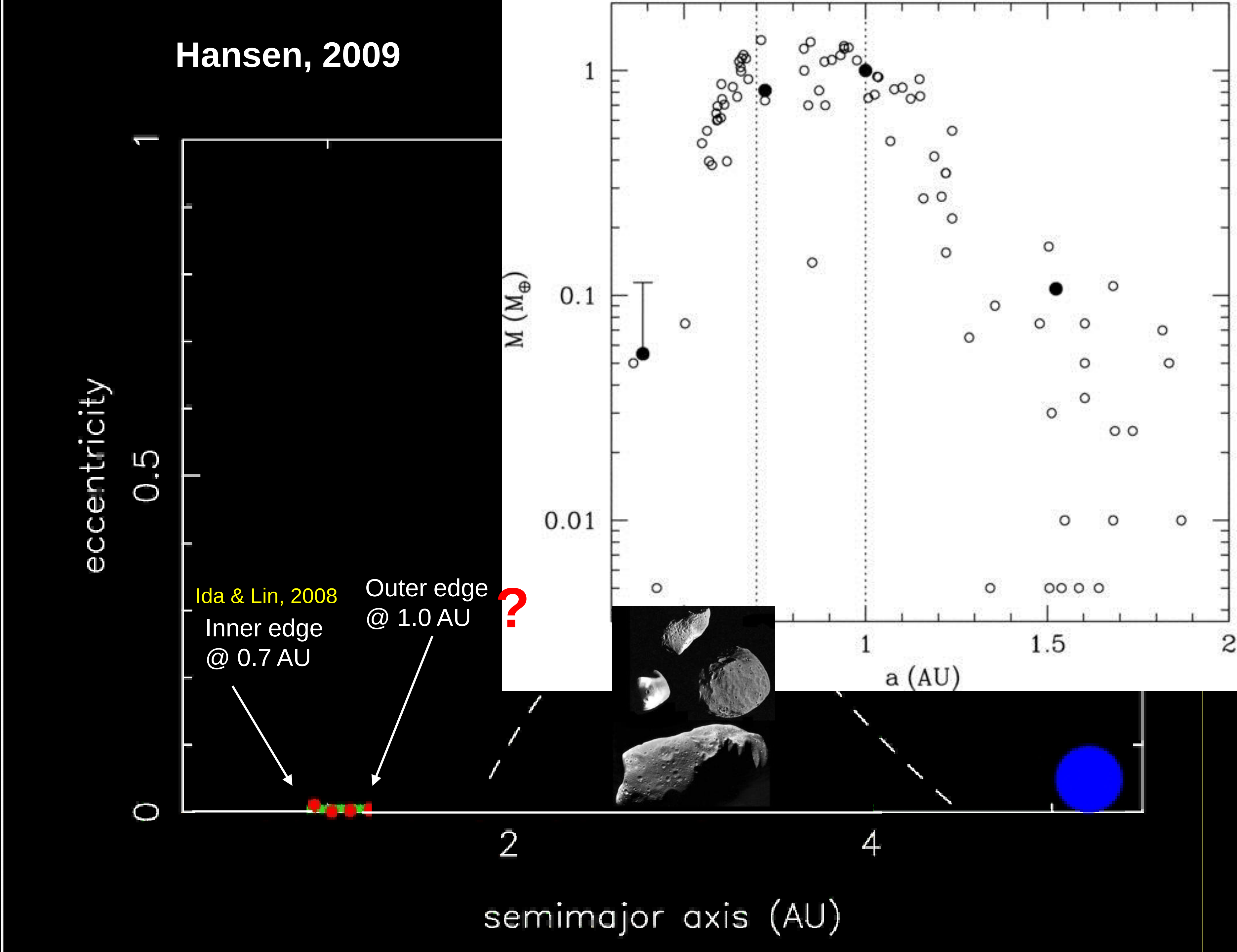
To answer these questions we need to turn to constraints:

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….

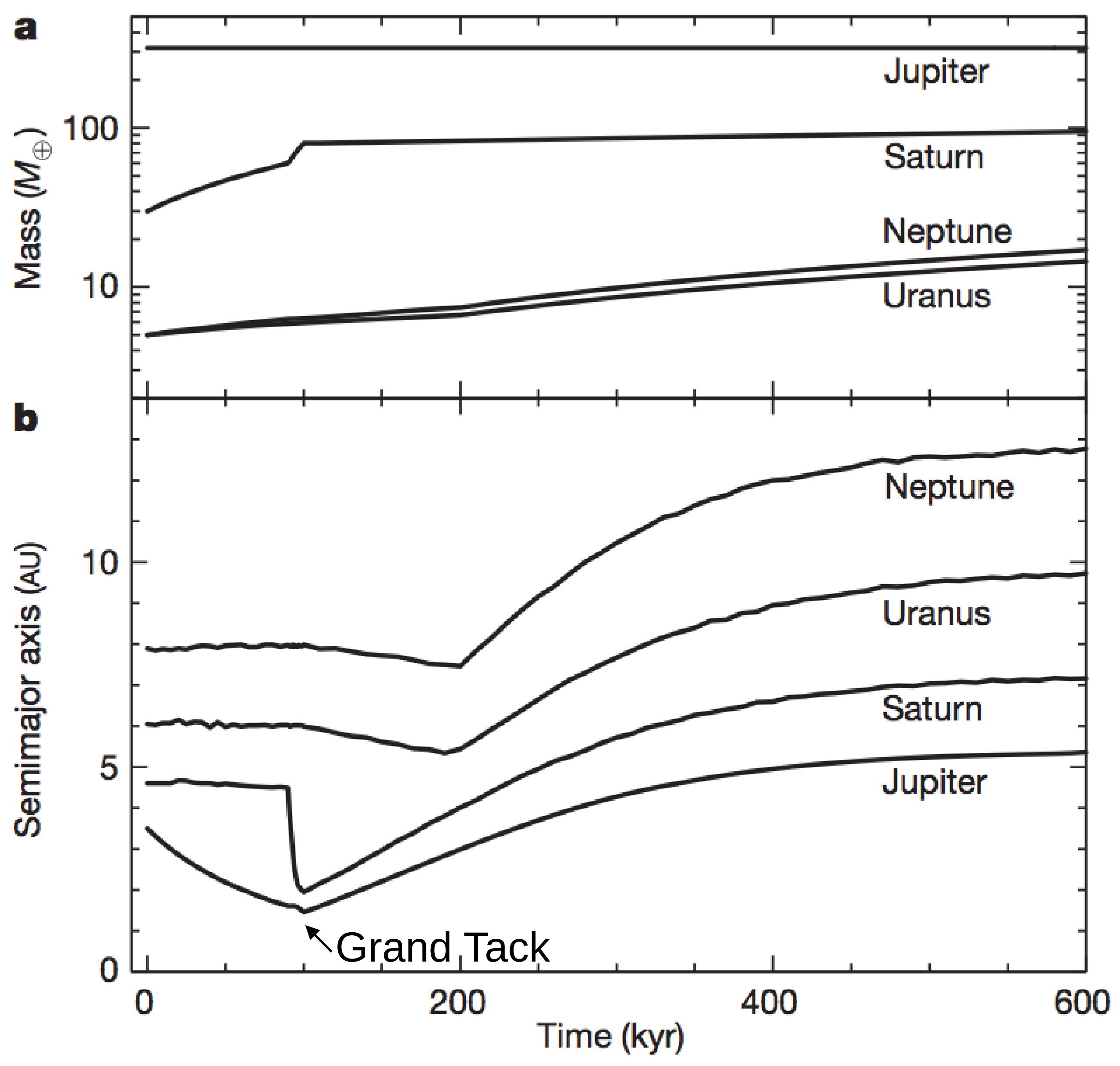


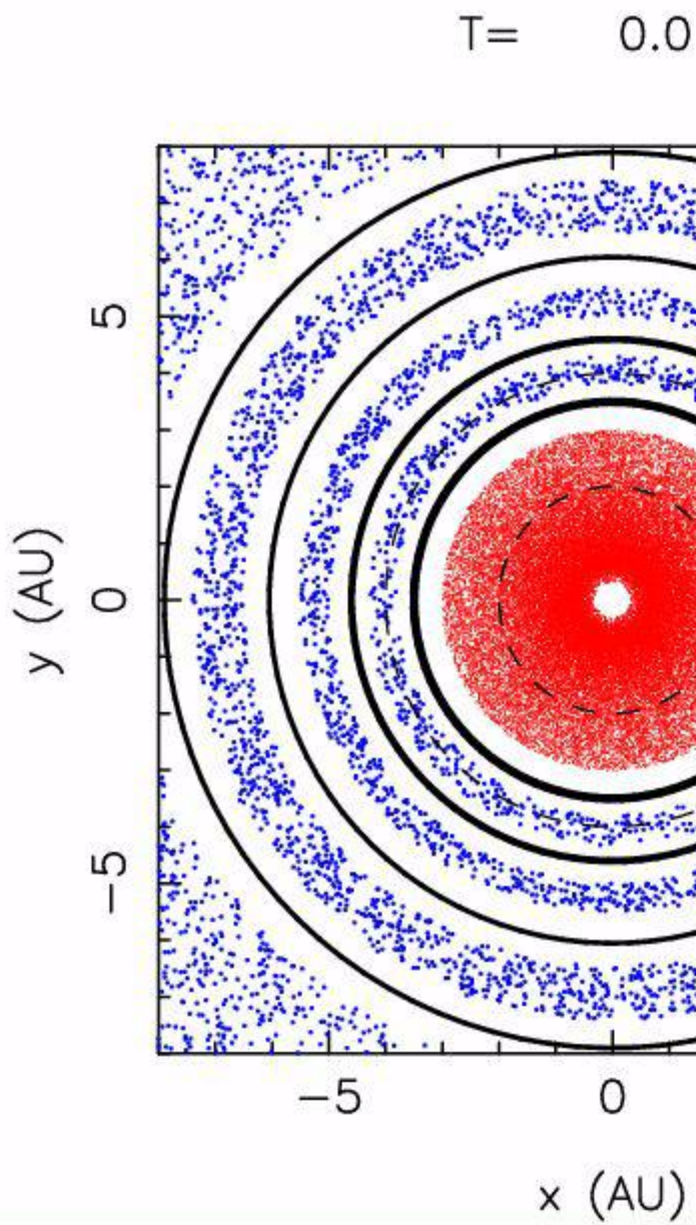


Hansen, 2009
eccentricity
0
0.5
1
semimajor axis (AU)
2
4
Ida & Lin, 2008
Inner edge
@ 0.7 AU
Outer edge
@ 1.0 AU
?
M ($M_\oplus$)
0.01
0.1
1
a (AU)
1
1.5
2

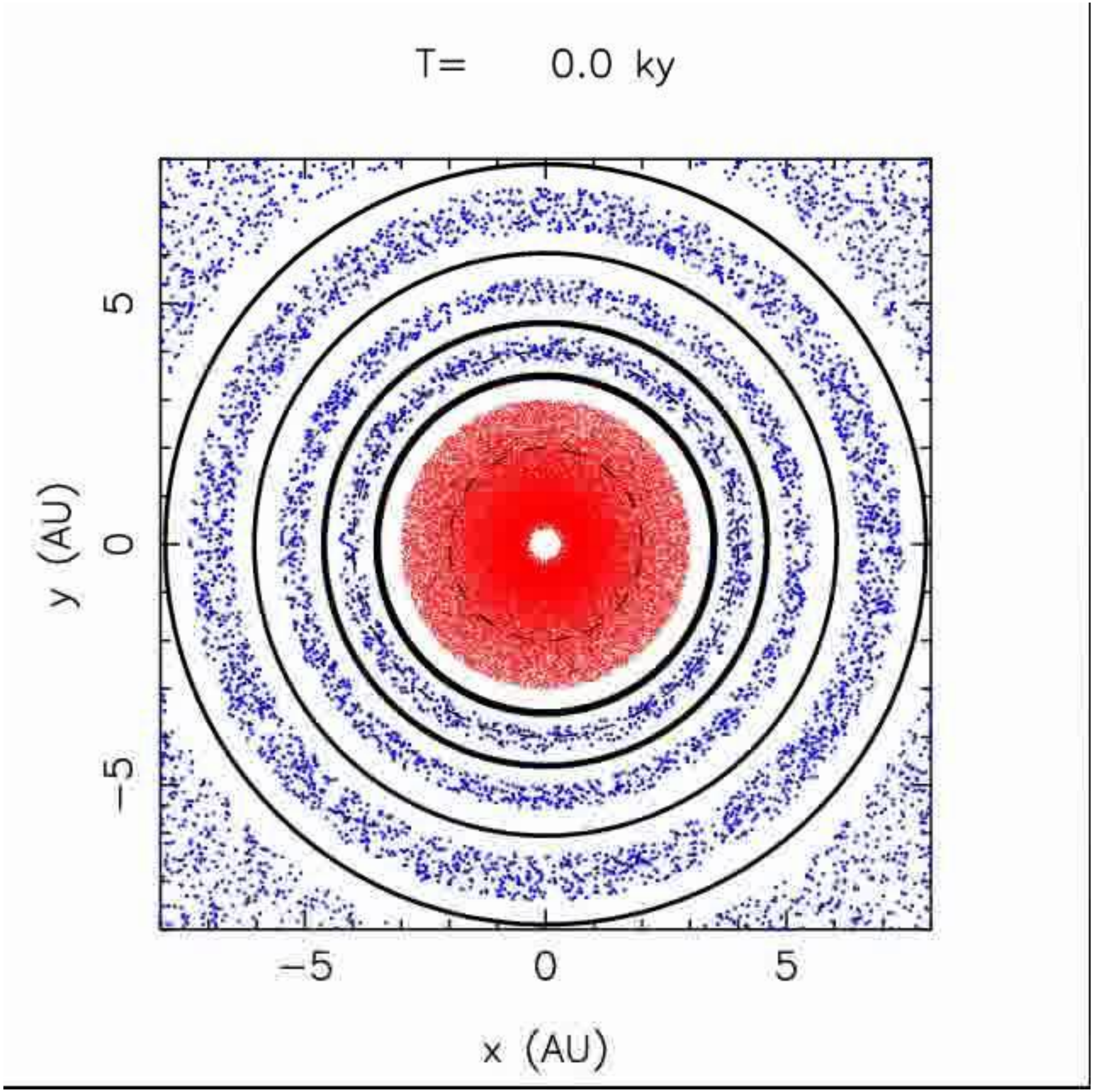
Can the inward-then-outward migration of Jupiter explain this?

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





Walsh, Morbidelli, Raymond, O'Brien, Mandell, Nature, 2011

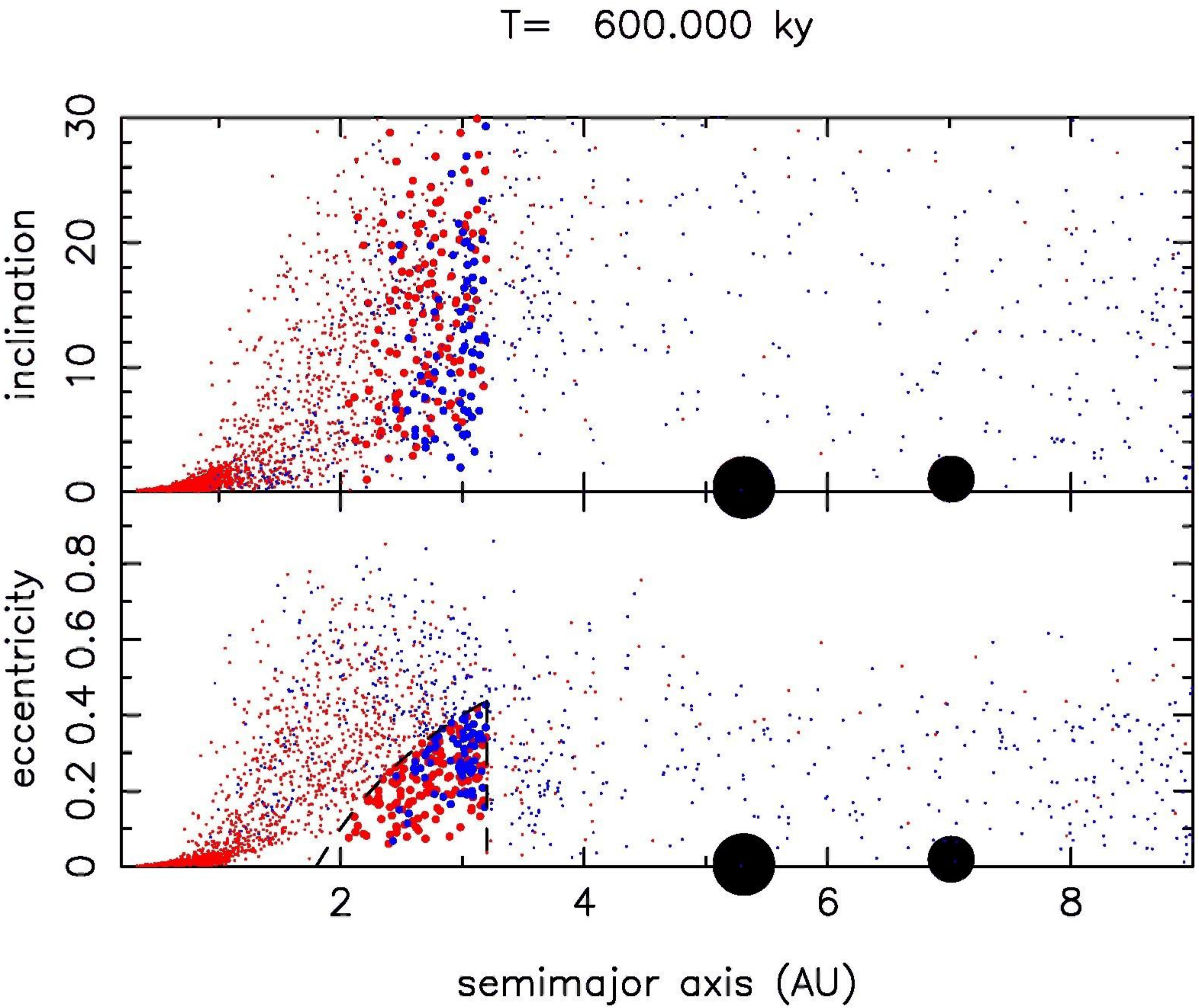


Walsh, Morbidelli, Raymond, O'Brien, Mandell, Nature, 2011

S-type

C-type

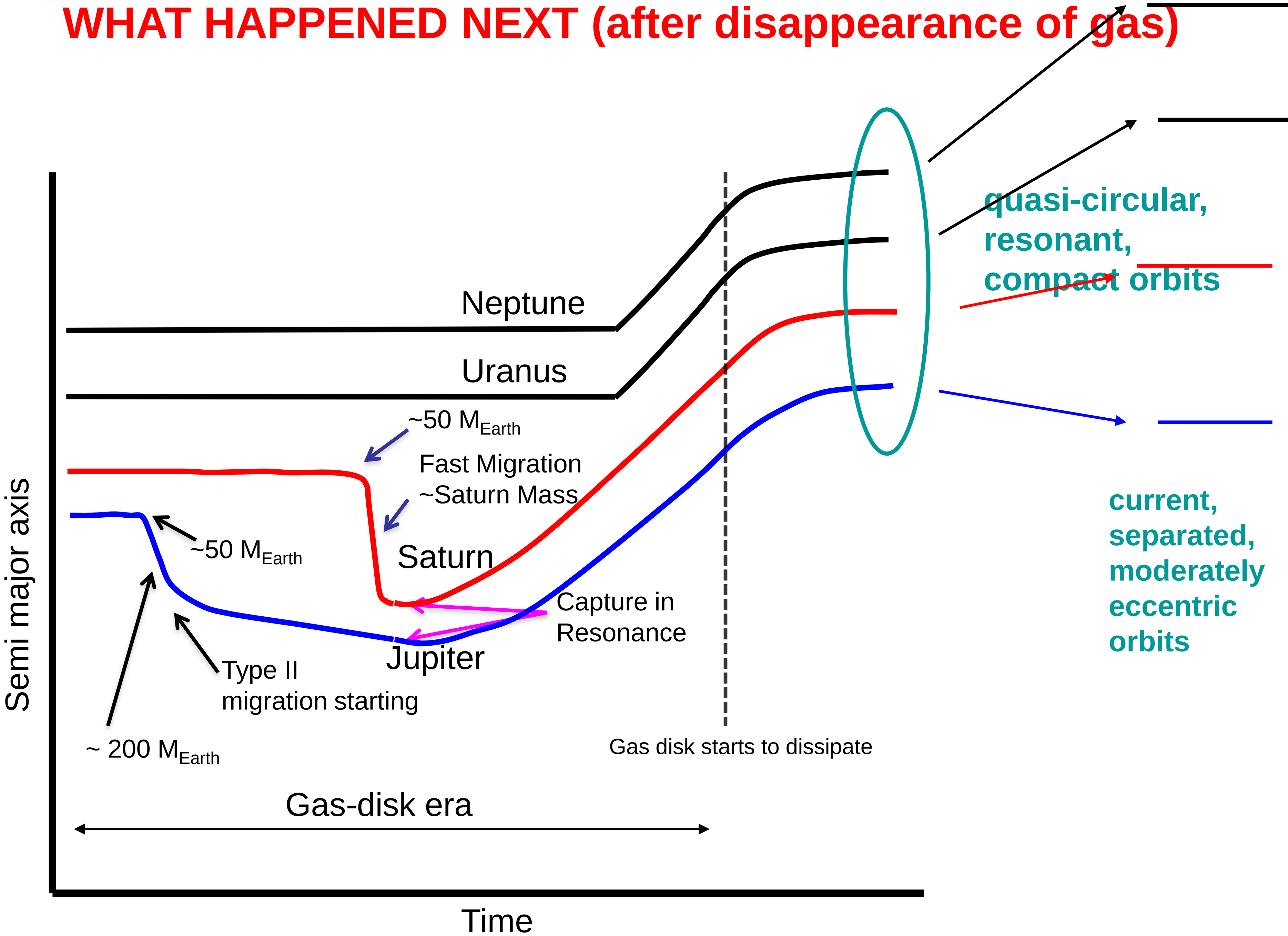
Walsh et al., 2011



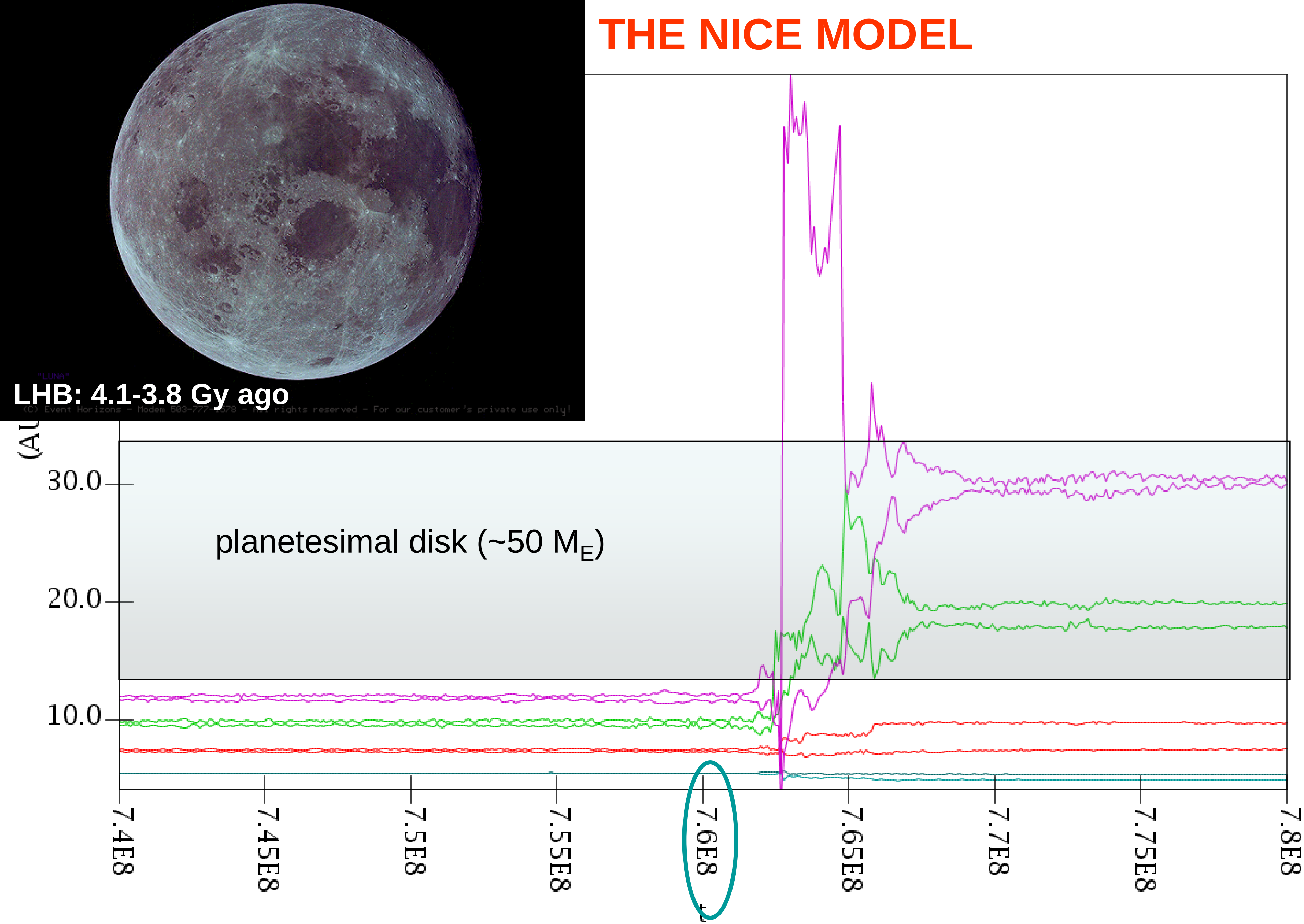
Three reasons to believe the Grand tack scenario

1. It explains why Jupiter is not in the inner ~AU region of the Sun, unlike many extra-solar giant planets
2. It explains the small mass of mars and its extremely short accretion timescale
3. It explains the structure of the asteroid belt in terms of:
   - Orbital distribution
   - Mass deficit
   - Dichotomy of the asteroid spectral/physical types

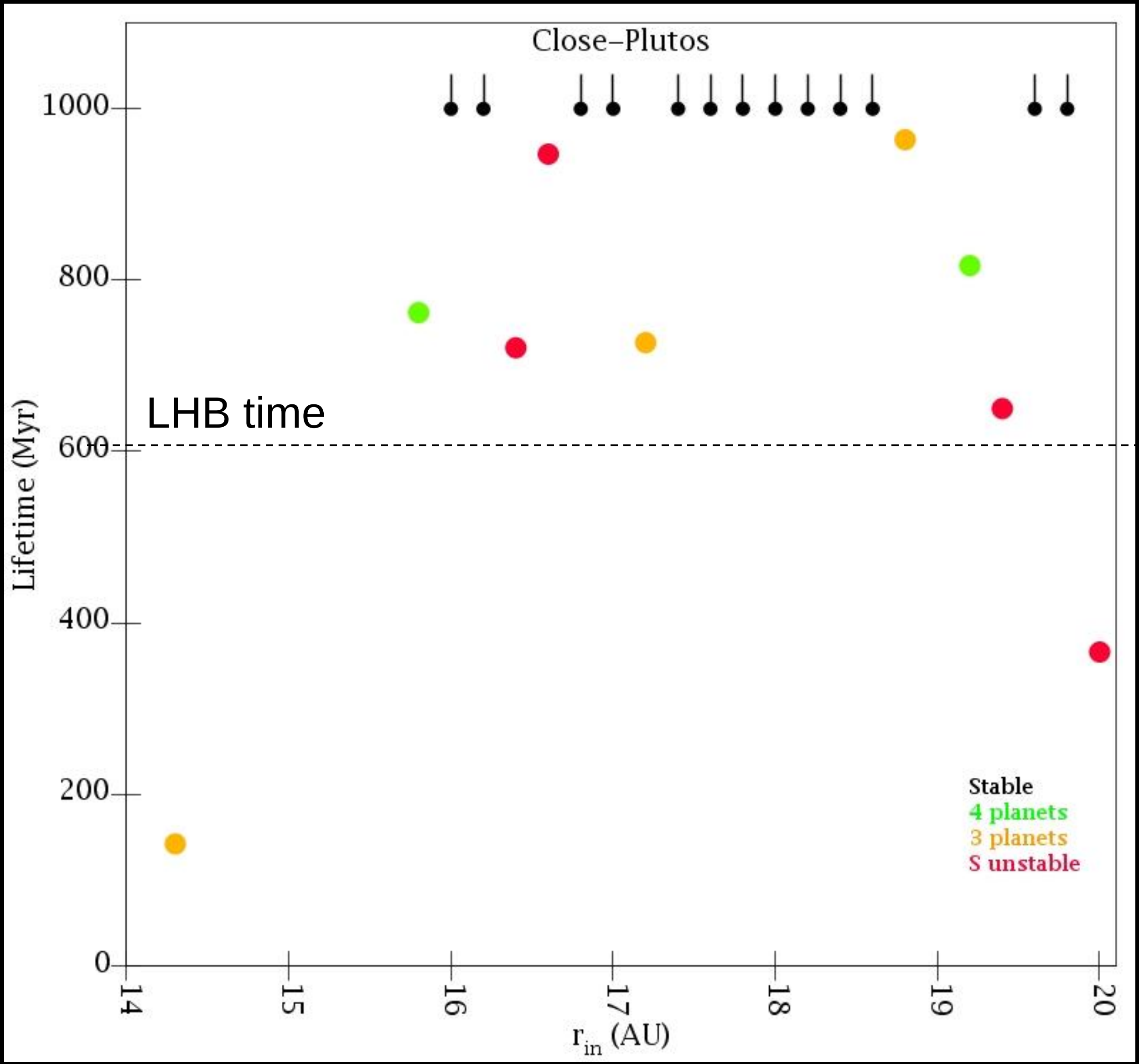
WHAT HAPPENED NEXT (after disappearance of gas)



THE NICE MODEL

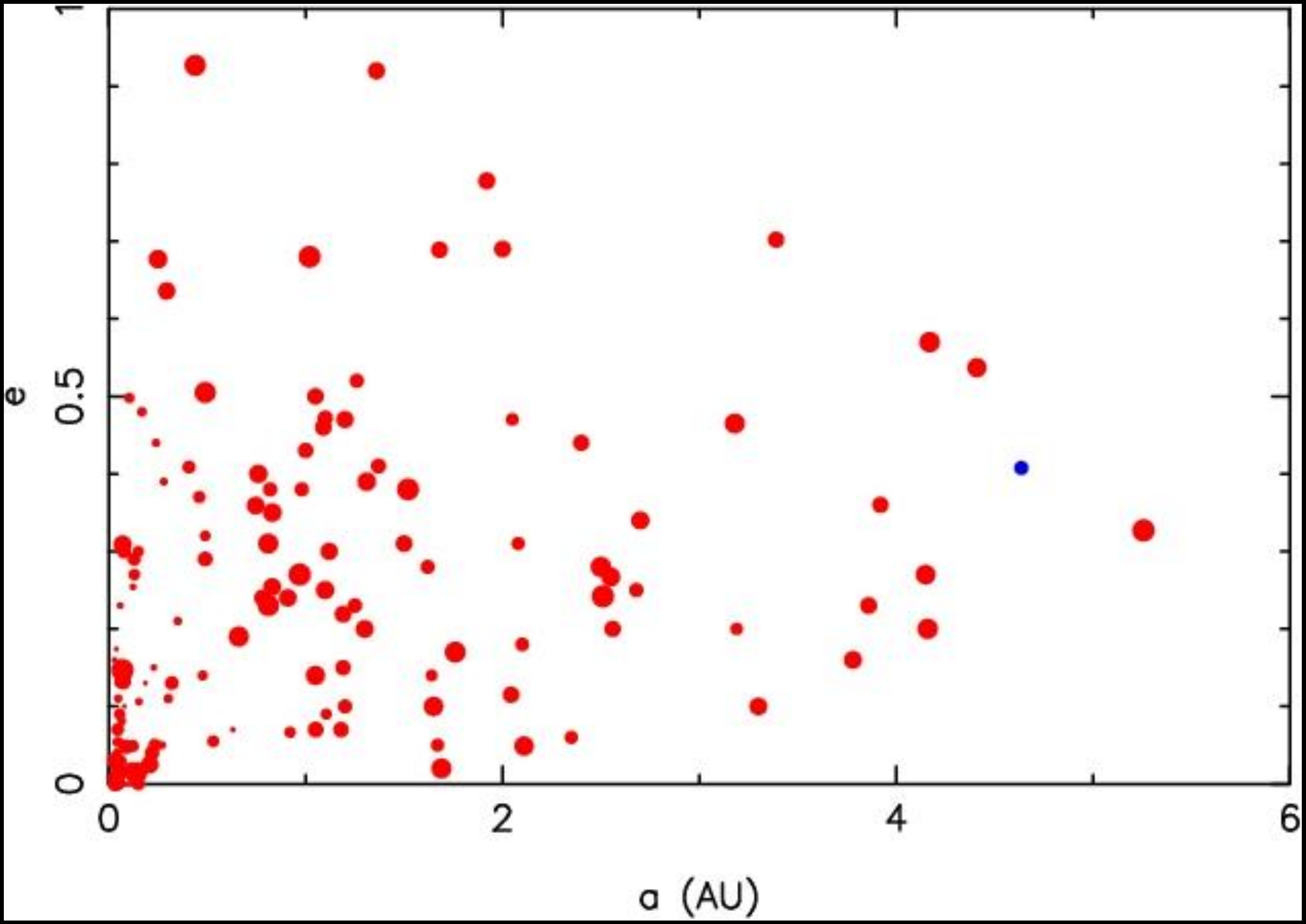


If the disk self-gravity is taken into account, late instabilities occur in a natural way, quite independently of the location of the inner edge of the disk

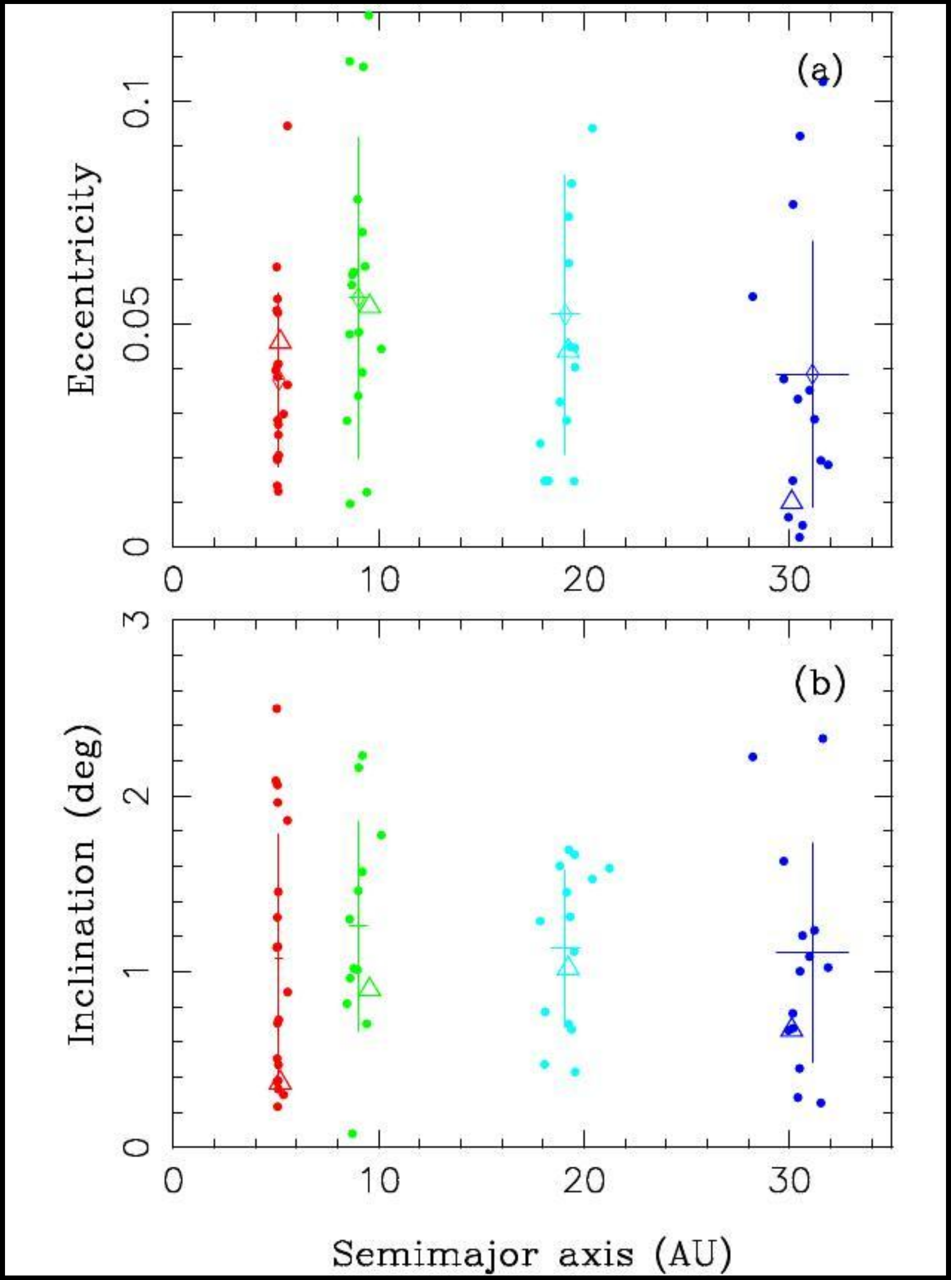


Levison et al., 2011

Nice-model simulations exhibiting Jupiter-Saturn encounters leave Jupiter on an orbit that looks like those of some exo-planets far from their star!



All planets are "saved" in 10-15% of the runs, and when they do their final orbits are pretty good.



Nesvorny and Morbidelli, 2012, AJ in press.

The result improves if one postulates the existence of 3 Uranus-like planets, of which one was ejected (Nesvorny and Morbidelli, 2012)

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; but no Jupiter-Saturn encounters**

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

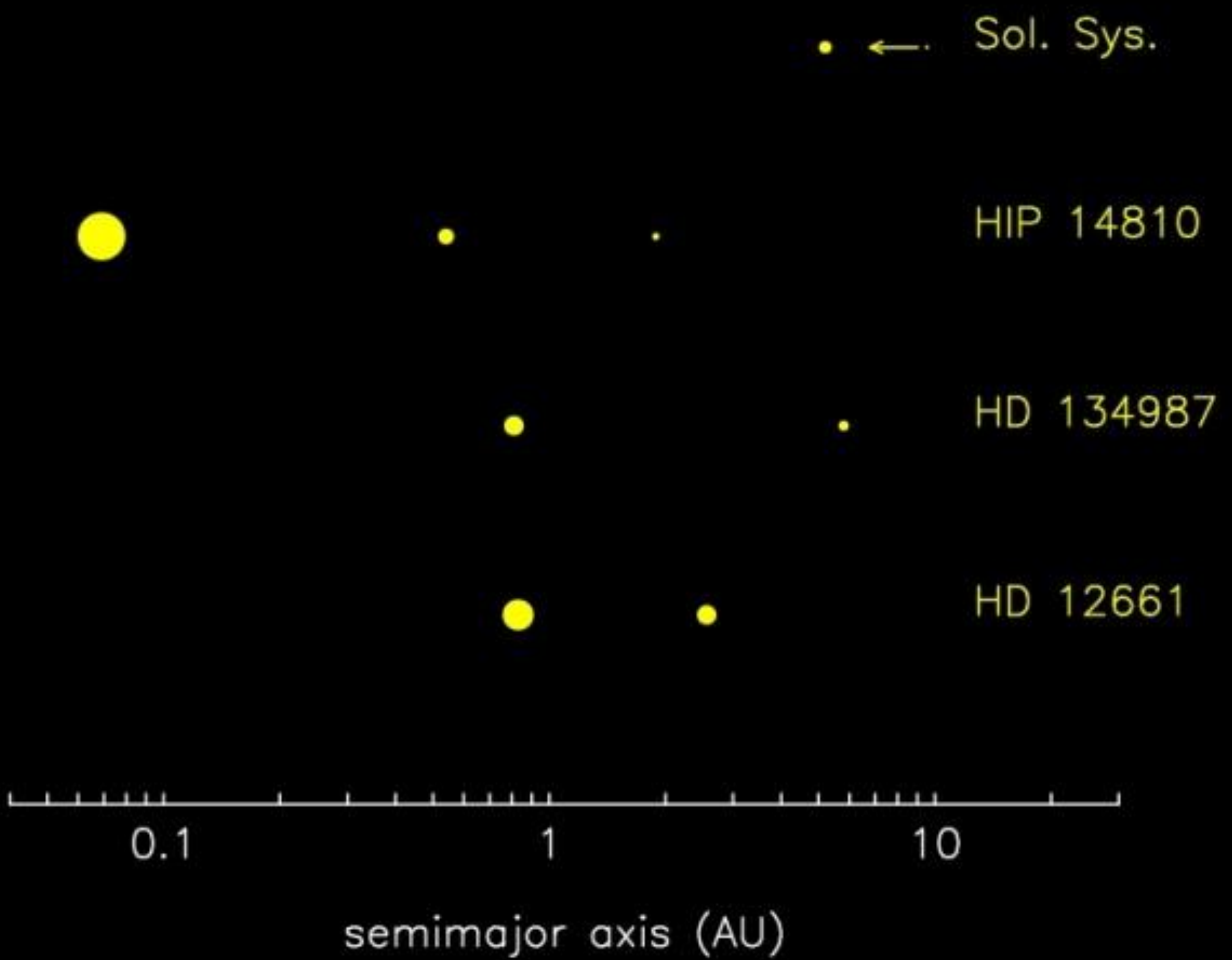
First event:

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

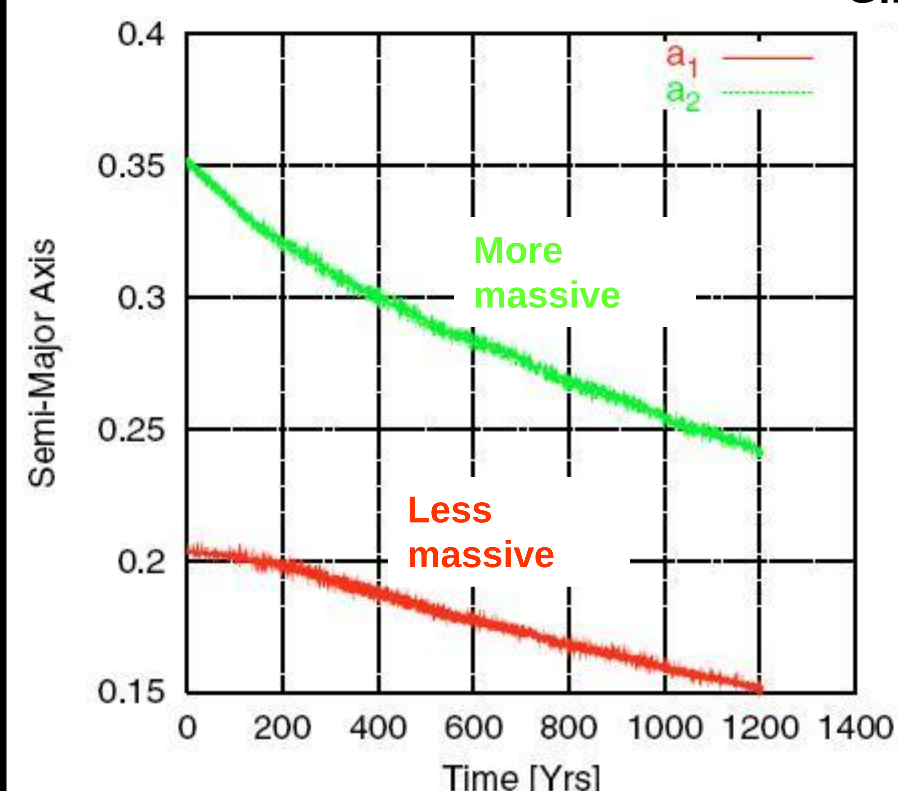
For the Solar System (or OGLE 106-09L) the answer is NO

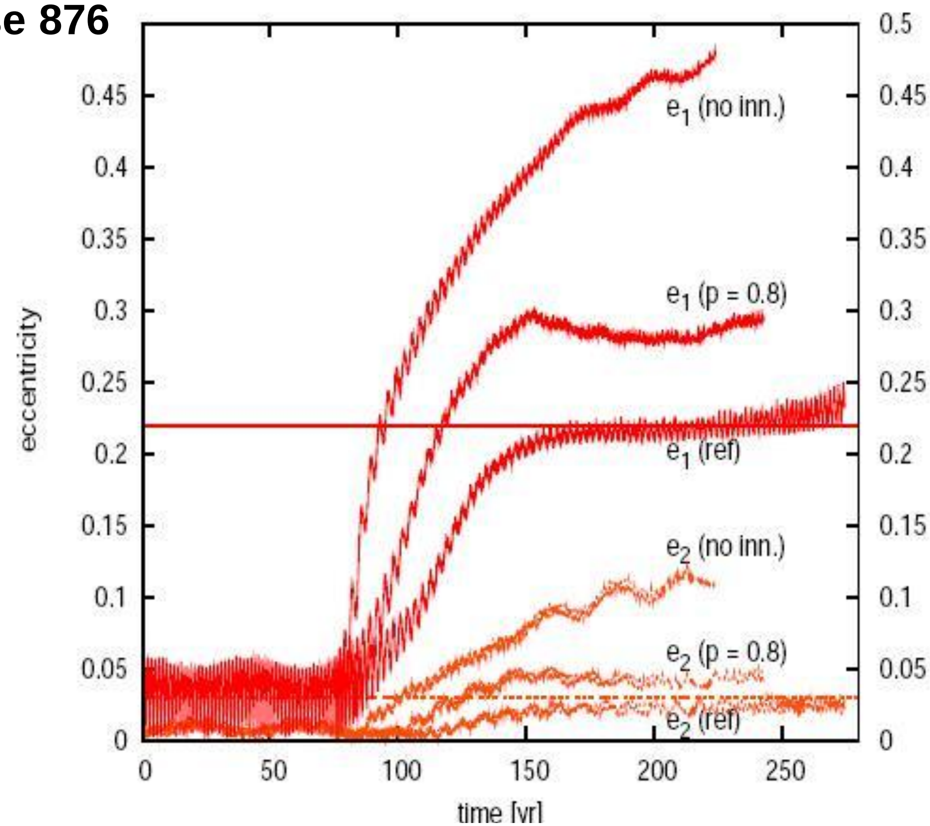
For many/most other systems the answer could be YES

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:

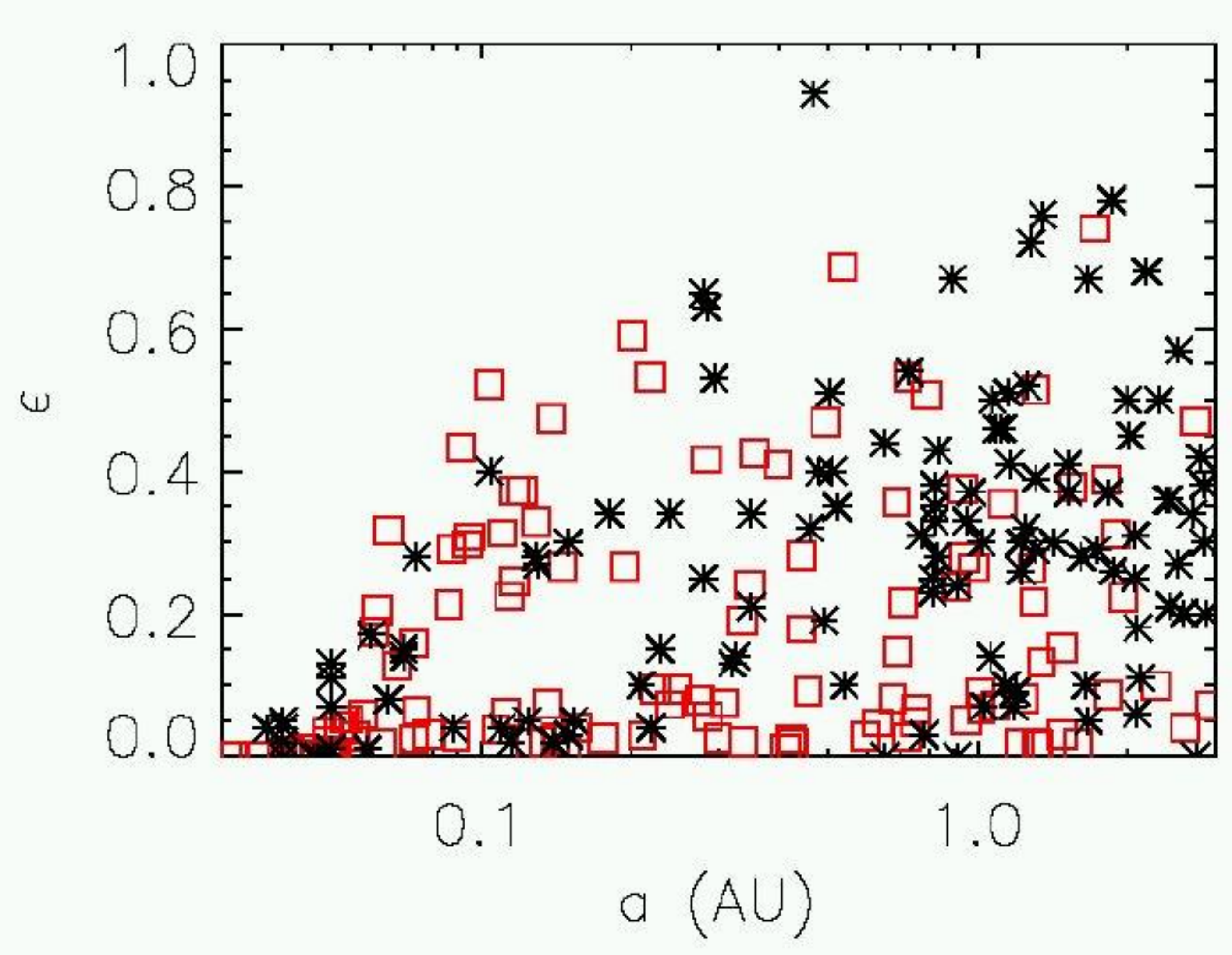
Does the eccentricity saturate ?

Yes/No

For the pairs of resonant planets: YES

For single, eccentric planets: NO

Unsaturated eccentricity growth for migrating planets leads to instability. This 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.

CONCLUSIONS

Three events can explain most of the observed diversity:

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

- **NO** → **HD 12661& Co.**
- **YES** → **Does the second planet eventually grow as massive or more massive than the inner one?**
  - **NO** → **Solar System**
  - **YES** → **Does the eccentricity saturate ?**
    - **NO** → **Eccentric single planets**
    - **YES** → **resonant pairs (Gliese 876)**

For more discussion see my chapter “Dynamics of Planetary Systems” available on AstroPH