IAC Winter School 2016

The Solar System's Early dynamical history :

GRAND TACK & NICE MODEL

UNIVERSITÉ CÔTE D'AZUR

Observatoire de la CÔTE d'AZUR

Aurélien CRIDA

IAC Winter School 2016

a) The GRAND TACK

Jupiter & Saturn's migration

in the gas disk

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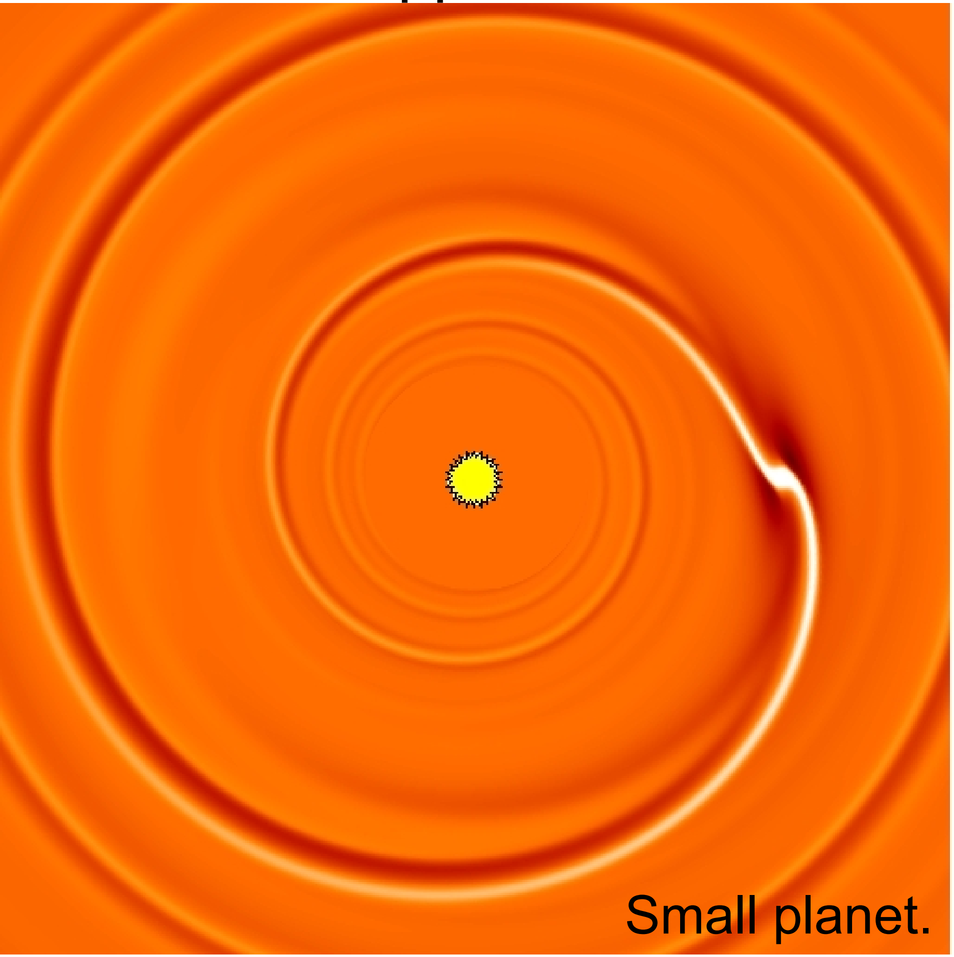
MIGRATION SUMMARY

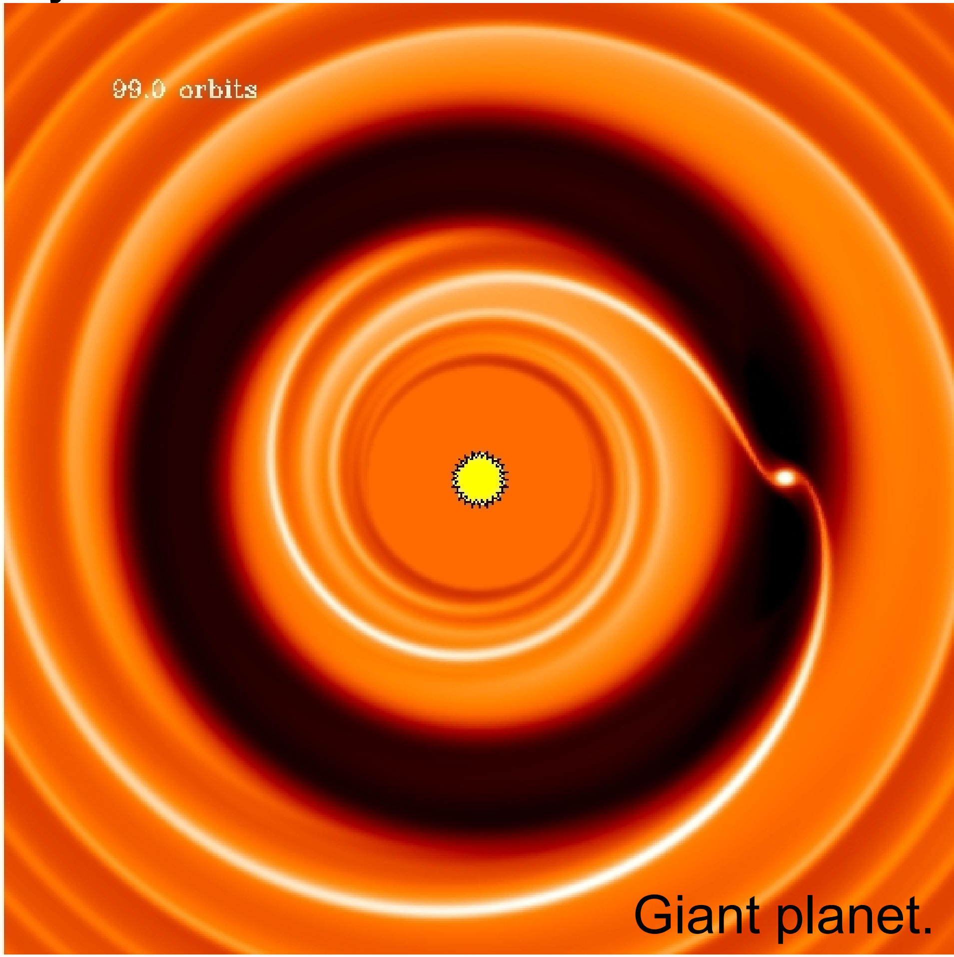
Planet – disk interactions => wake

→ type I migration of small mass planets

→ gap opening and slow inwards migration of giant planets

What happened in the Solar System ?





MIGRATION SUMMARY

Planet – disk interactions => wake

→ type I migration of small mass planets

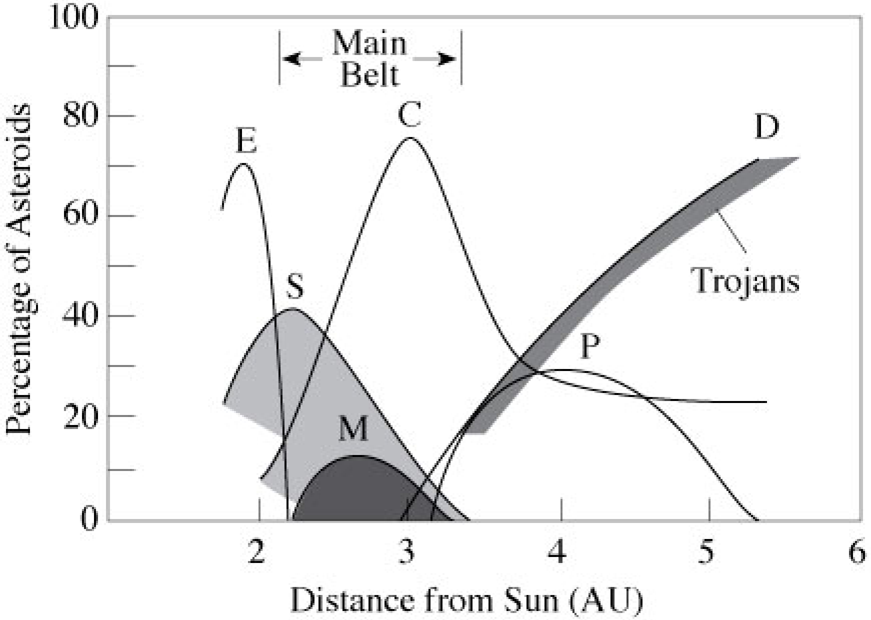
→ gap opening and slow inwards migration of giant planets

What happened in the Solar System ?

<u>Constraints :</u> - small mass of Mars

- existence & structure of the main asteroid and the Kuiper belts.

- present orbits of the giant planets, with non zero *e* and *i* .

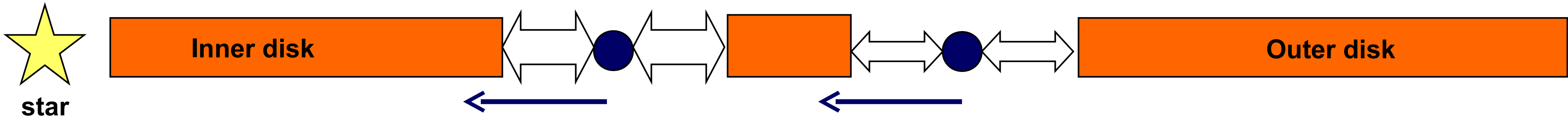


« The properties of the Main Asteroid Belt, between Jupiter and Mars, in particular its quite tight zoning of taxonomic types, show that Jupiter never orbited in this region. »

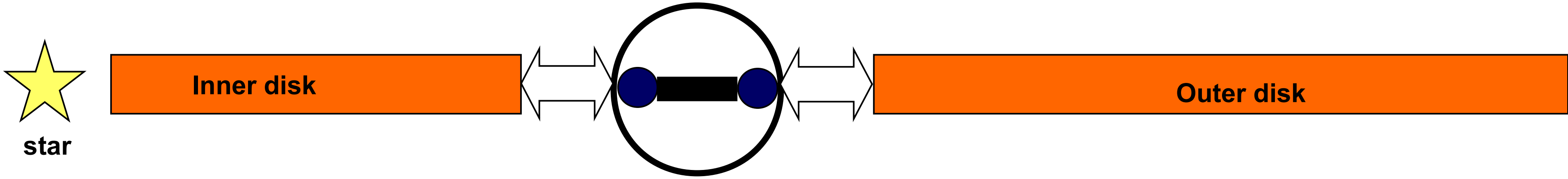
(A. Crida's PhD manuscript, 2006, under the supervision of A. Morbidelli)

MIGRATION in RESONANCE

Two planets in their own gaps migrate in parallel.



Two planets in a same gap approach each other → résonance.



The pair of planet behaves like 1 object in type II migration.

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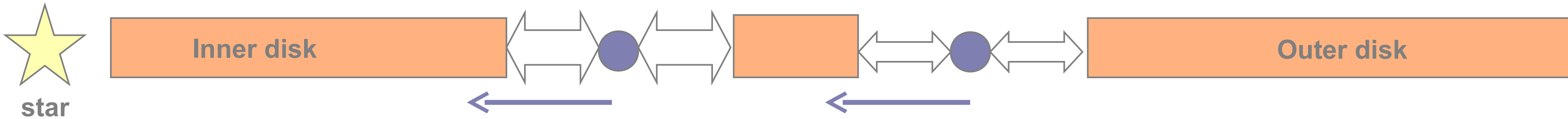

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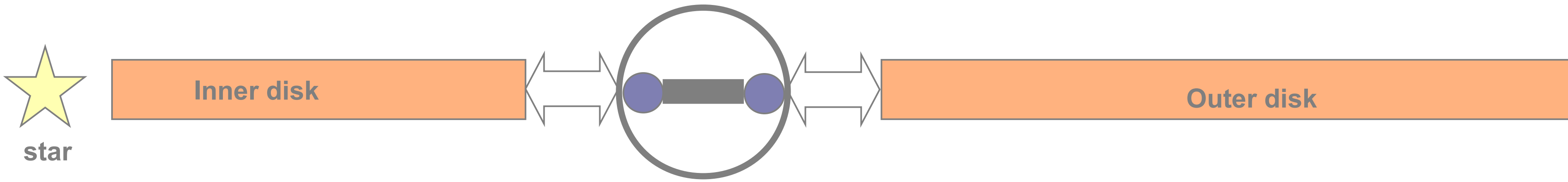

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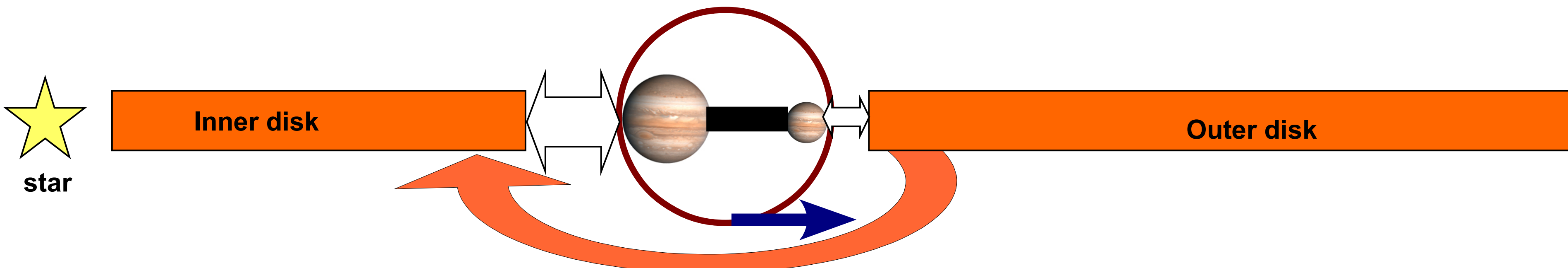
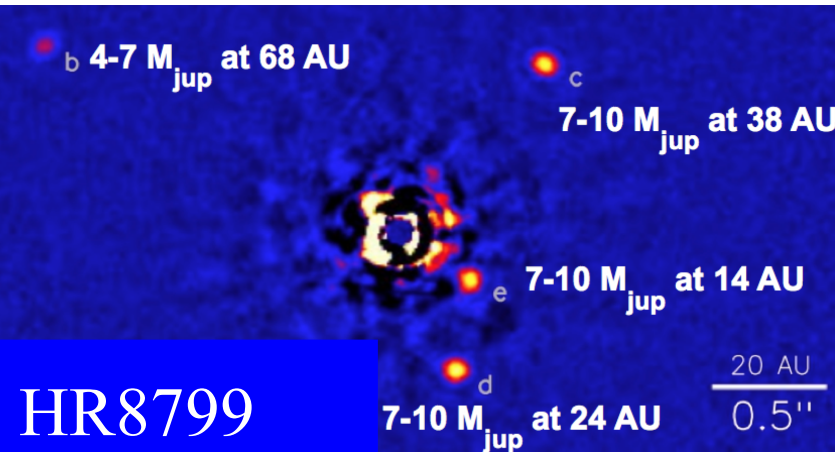
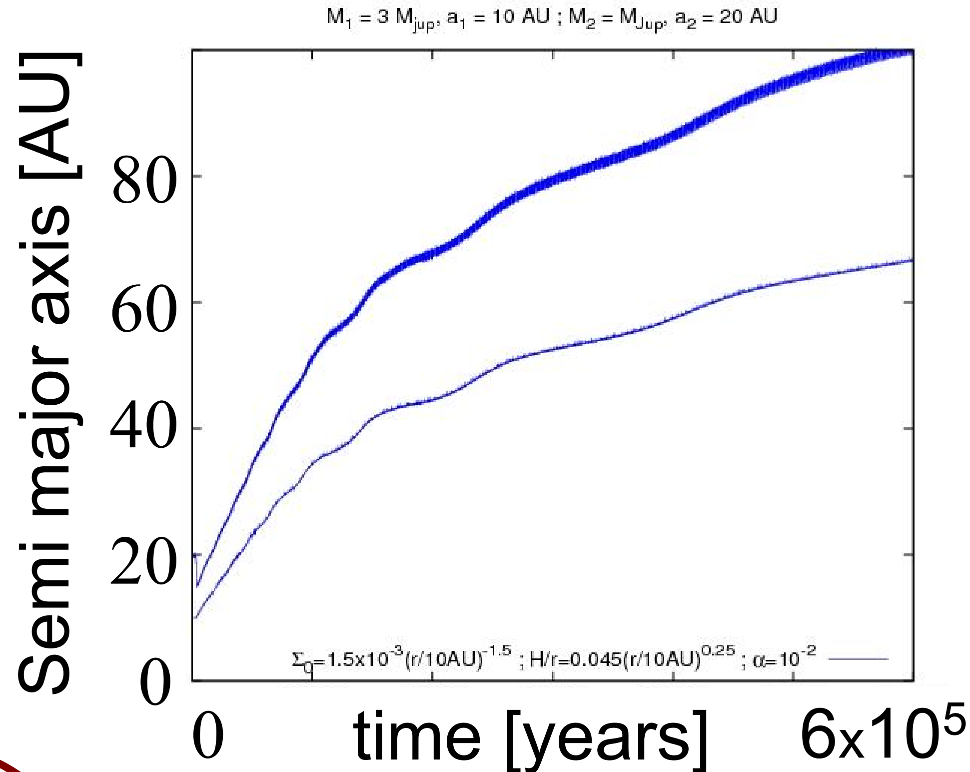


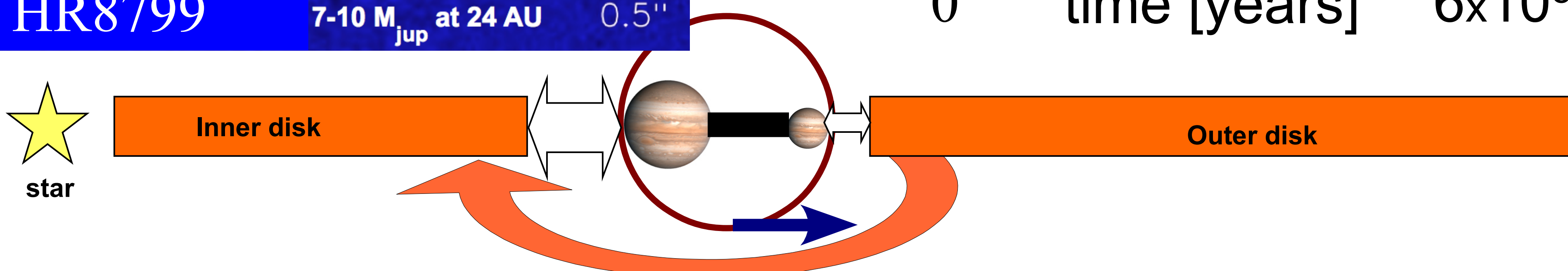
$M_2 < M_1$ => smaller negative torque from outer disk than positive torque from inner disc (Masset & Snellgrove 2001). The pair goes outwards, even if the disc goes inwards.

OUTWARD MIGRATION in RESONANCE

This phenomenon could go on for ever, and explain the cold Jupiters (Crida et al. 2009).





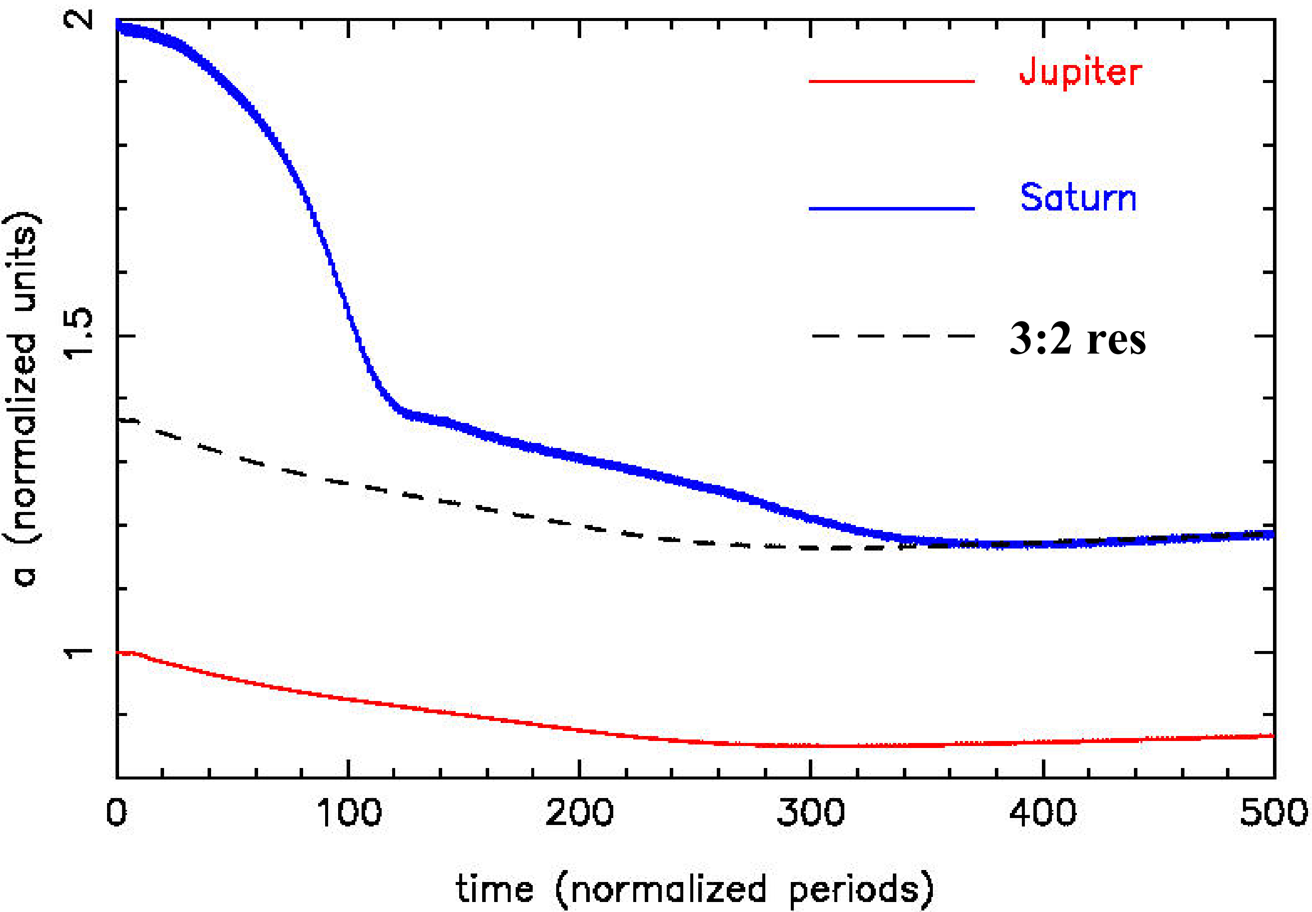


$M_2 < M_1$ => smaller negative torque from outer disk than positive torque from inner disc (Masset & Snellgrove 2001). The pair goes outwards, even if the disc goes inwards.

JUPITER AND SATURN

How to prevent Jupiter from becoming « hot » ?

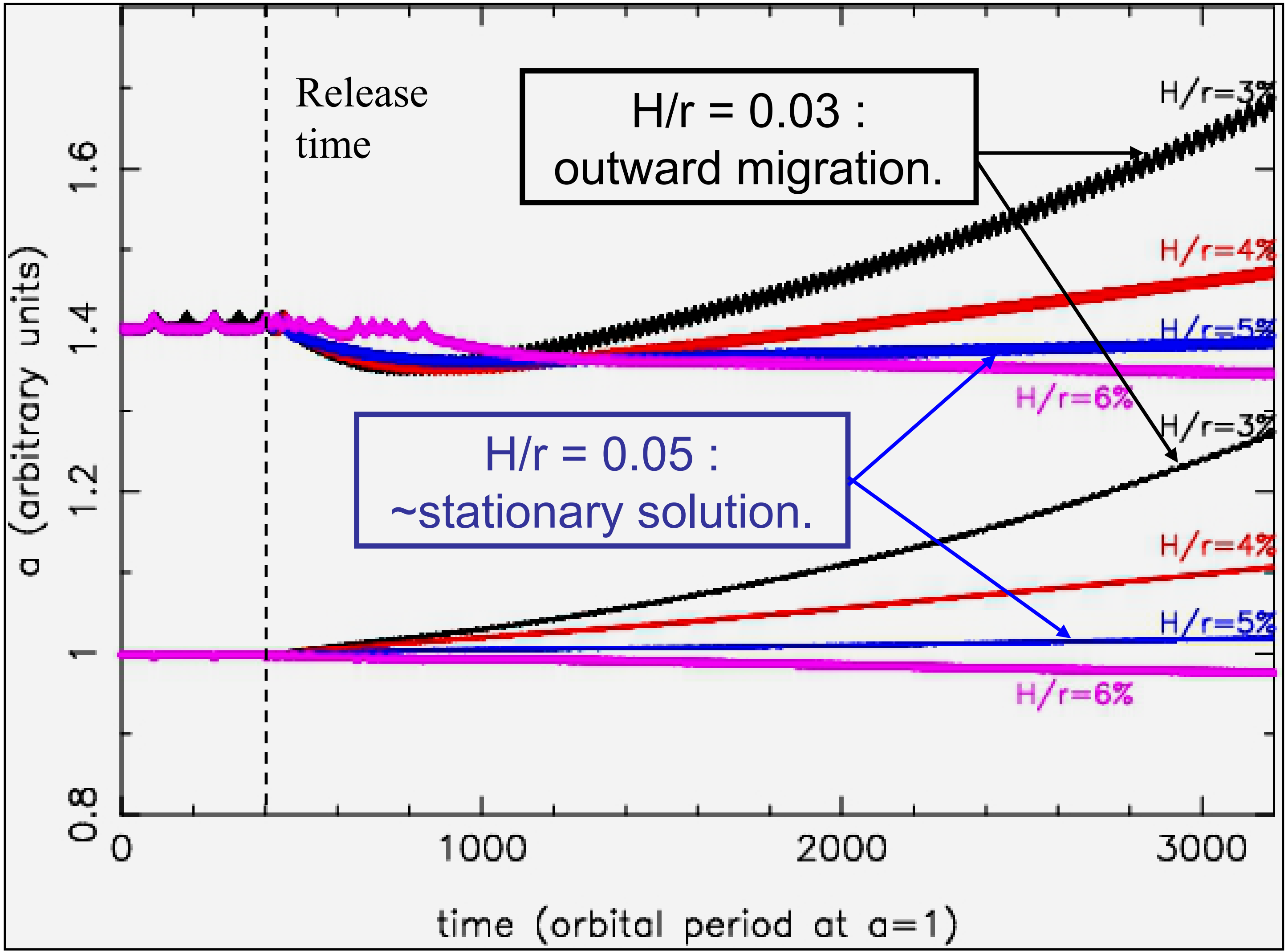
M_{Saturn} =~ $M_{Jupiter}$ / 3 => they can decouple from the disk !



Most likely outcome is a capture in 3:2 resonanceMMR (Pierens & Nelson 2008)

JUPITER AND SATURN

Once in 3:2 MMR, migration speed and direction depends on disk parameters (in particular H/r) (Morbidelli & Crida 2007).



Yes !!!

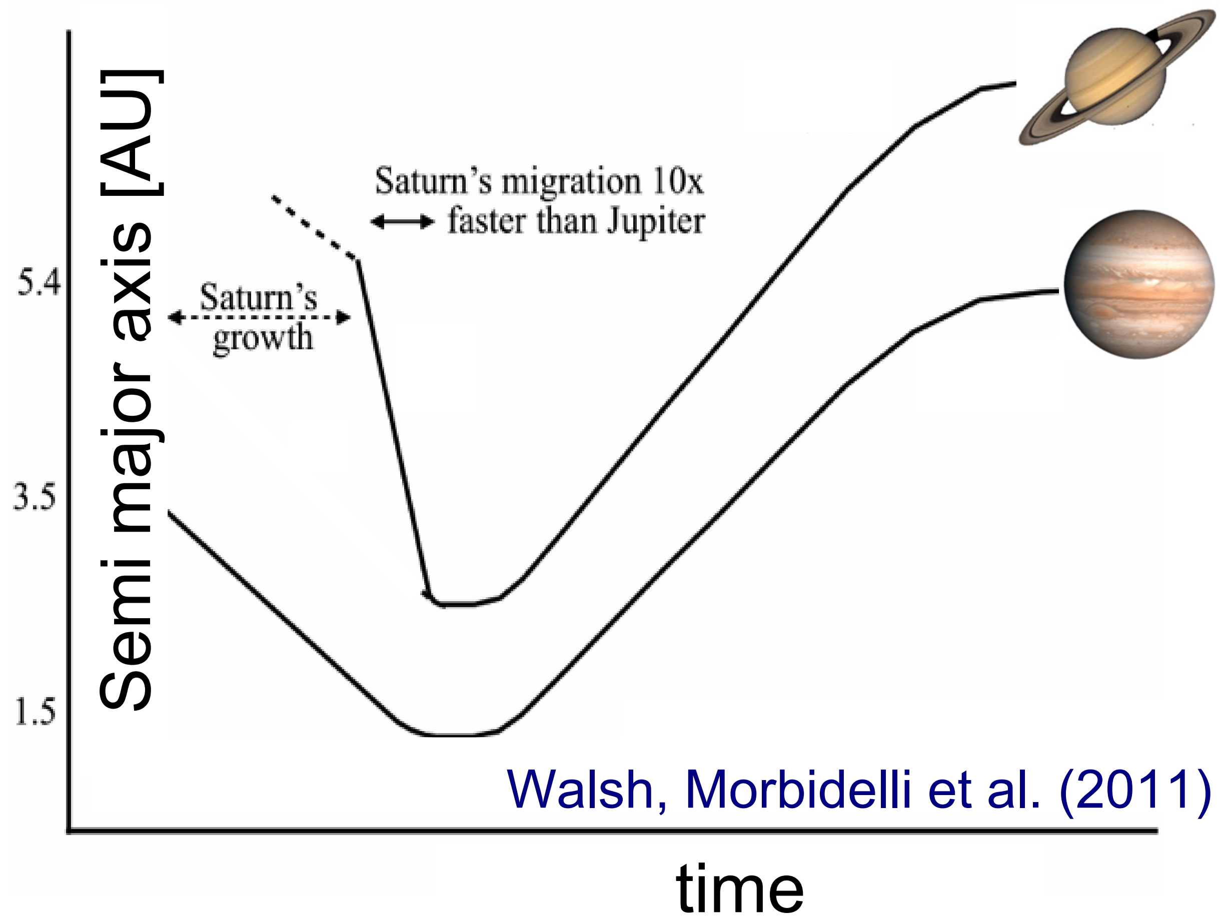
Jupiter & Saturn didn't migrate, I saved the Solar System.

GRAND TACK SCENARIO

1) Jupiter's core grows at the zero-torque migration radius. Jupiter becomes giant, opens a gap, migrates inwards in type II, from ~4-6 AU down to 1.5 AU. → *My thesis is wrong, suggests my advisor !*

2) Saturn's core froms, grows, migrates faster than Jupiter (the migration map has changed), catches up with it in MMR.

3) Jupiter tacks, and the pair of planet migrates outwards, until H/r = 0.05 (hopefully around 5 and 8 AU respectively).



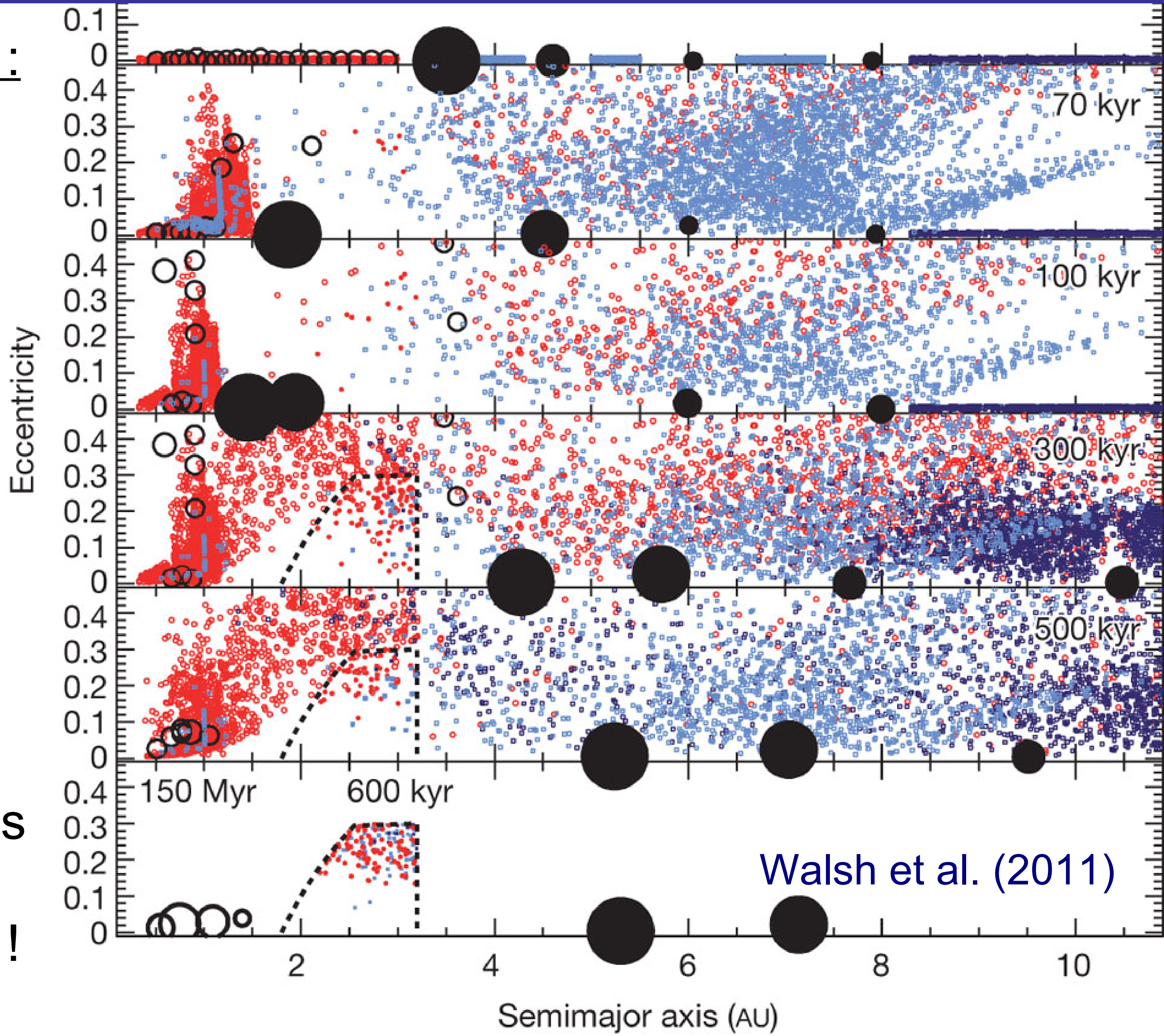
Walsh, Morbidelli et al. (2011)

GRAND TACK SCENARIO

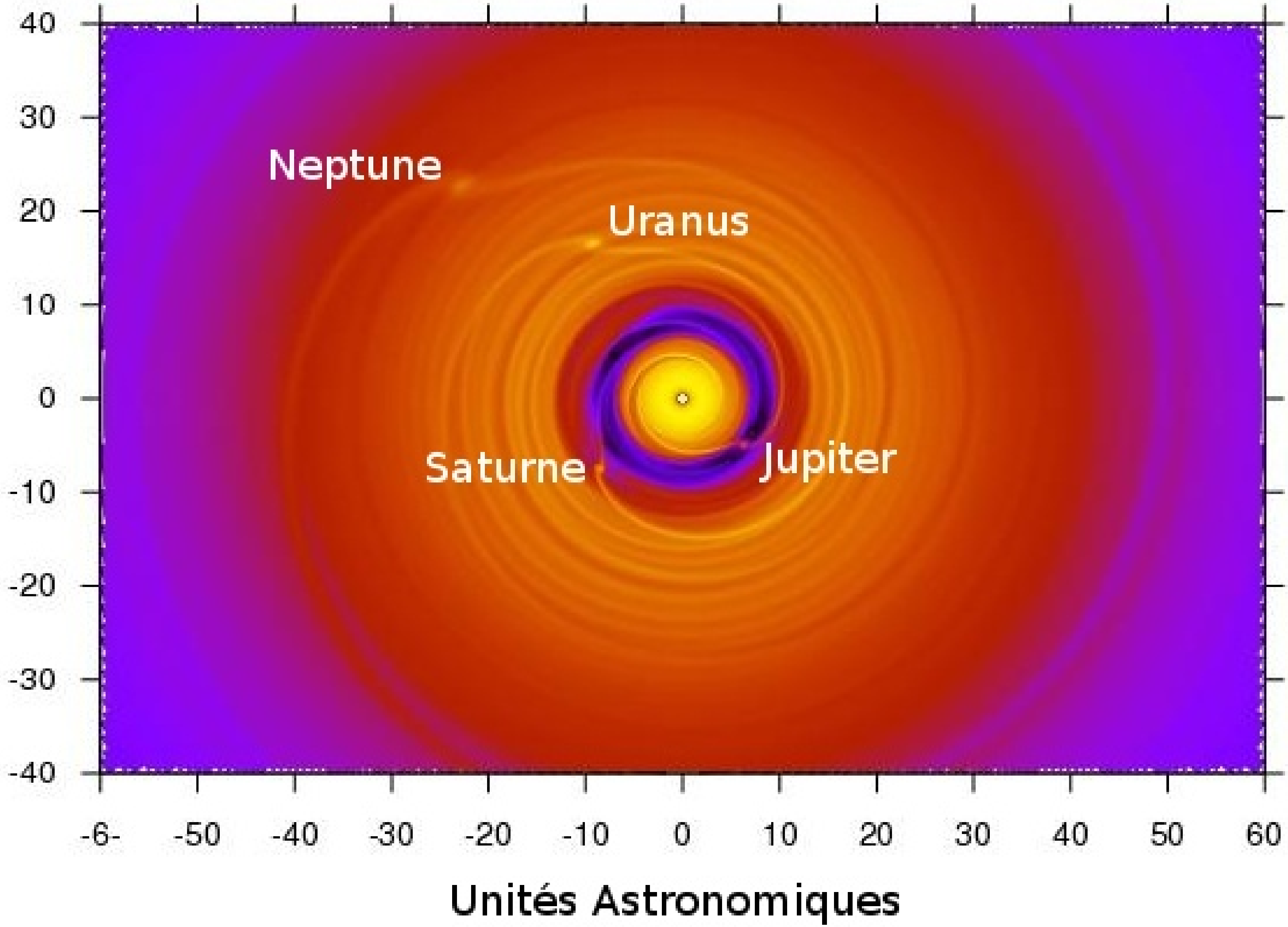
Consequences :

a) The disk of planetesimals and embryos in the terrestrial planets region is truncated at 1 AU.

b) The MAB region is populated with scattered bodies from in and out of the snowline !



MIGRATION IN THE SOLAR SYSTEM



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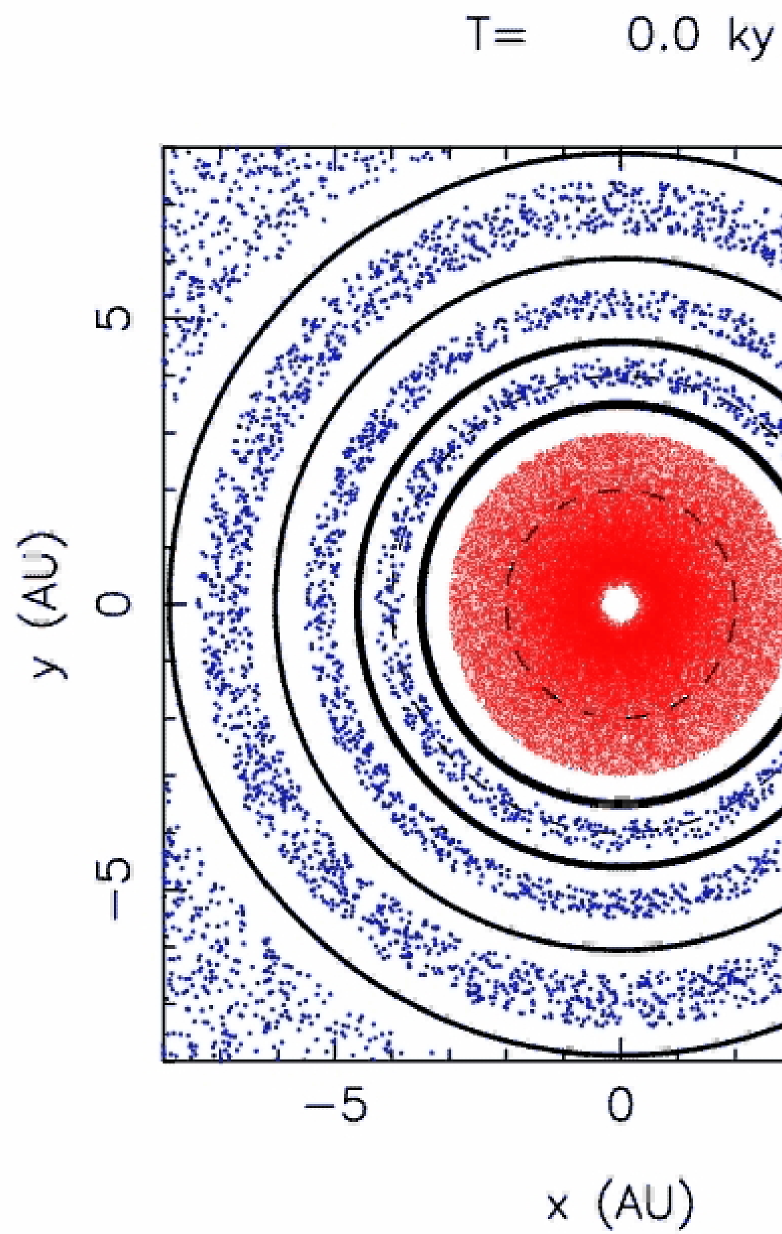
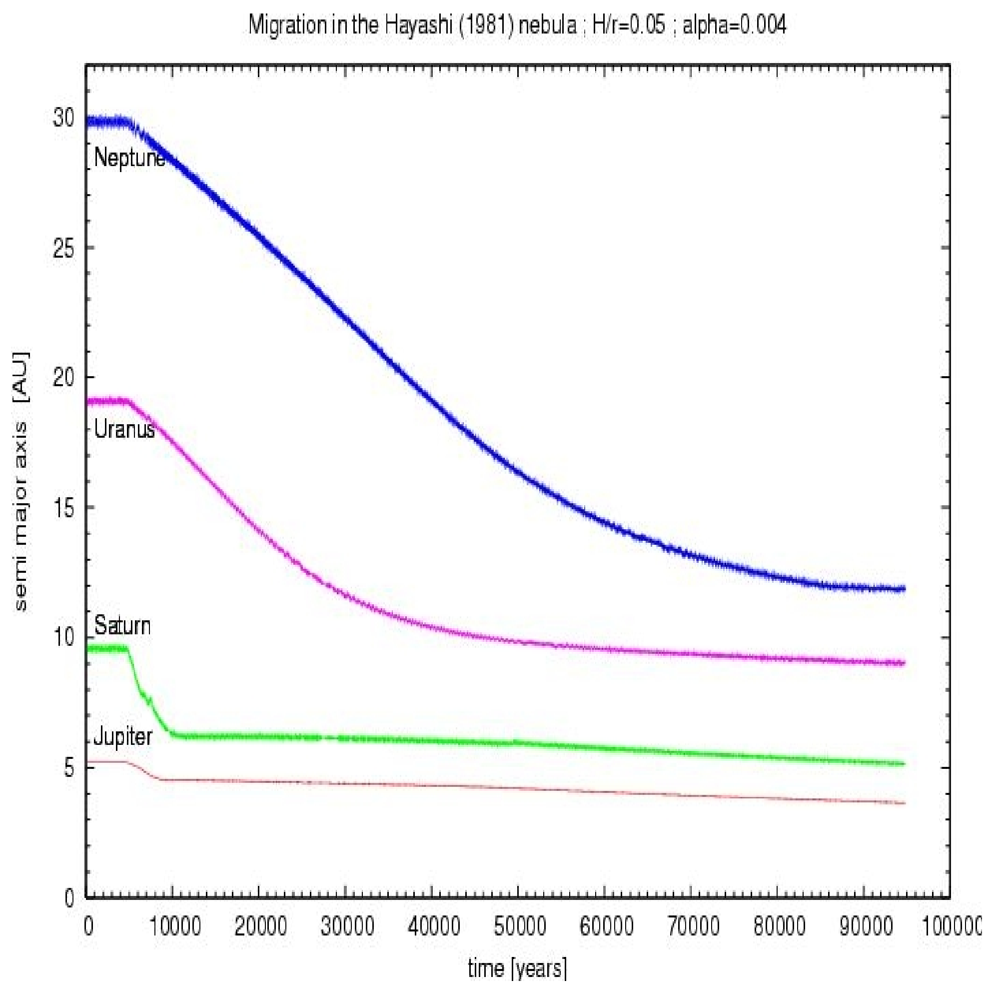
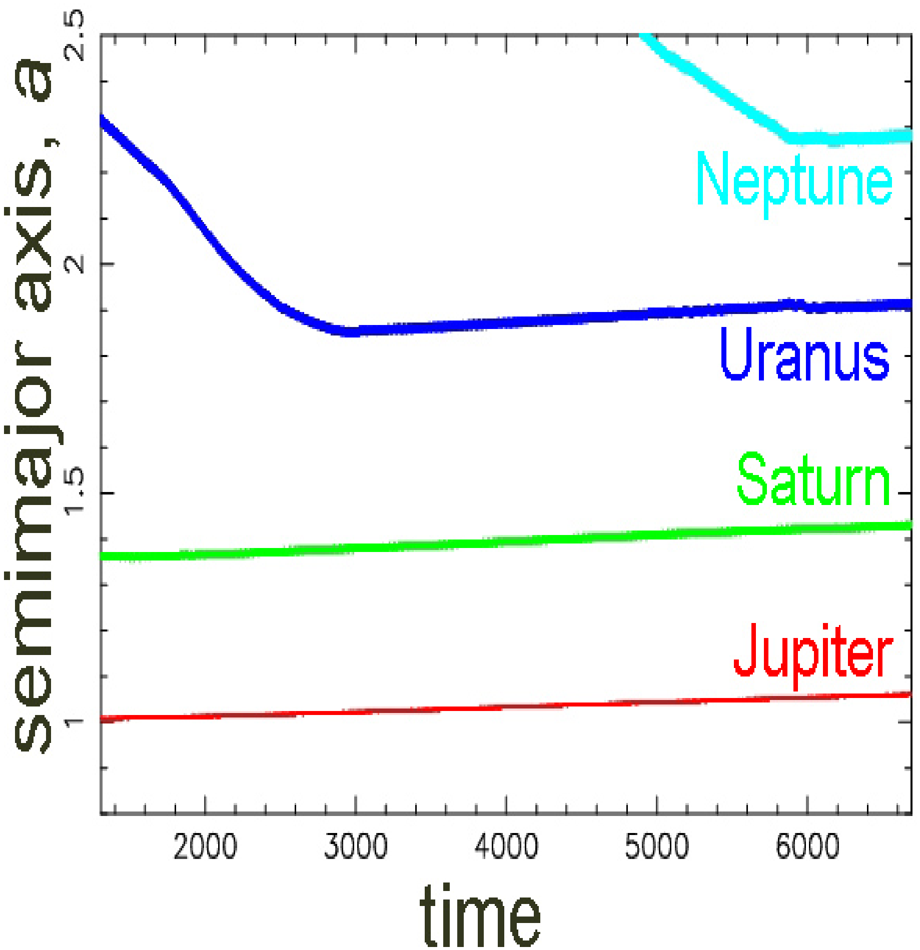


MIGRATION IN THE SOLAR SYSTEM

Whether or not Jupiter and Saturn did a grand tack, the ice giants (Uranus and Neptune) are trapped in mean motion resonance as well...





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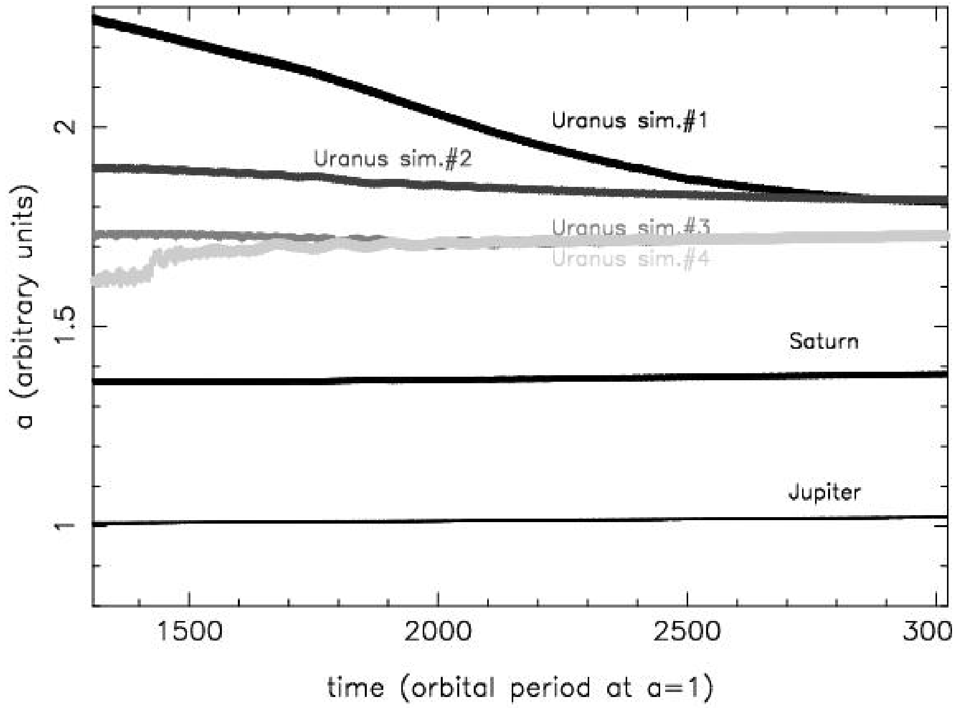
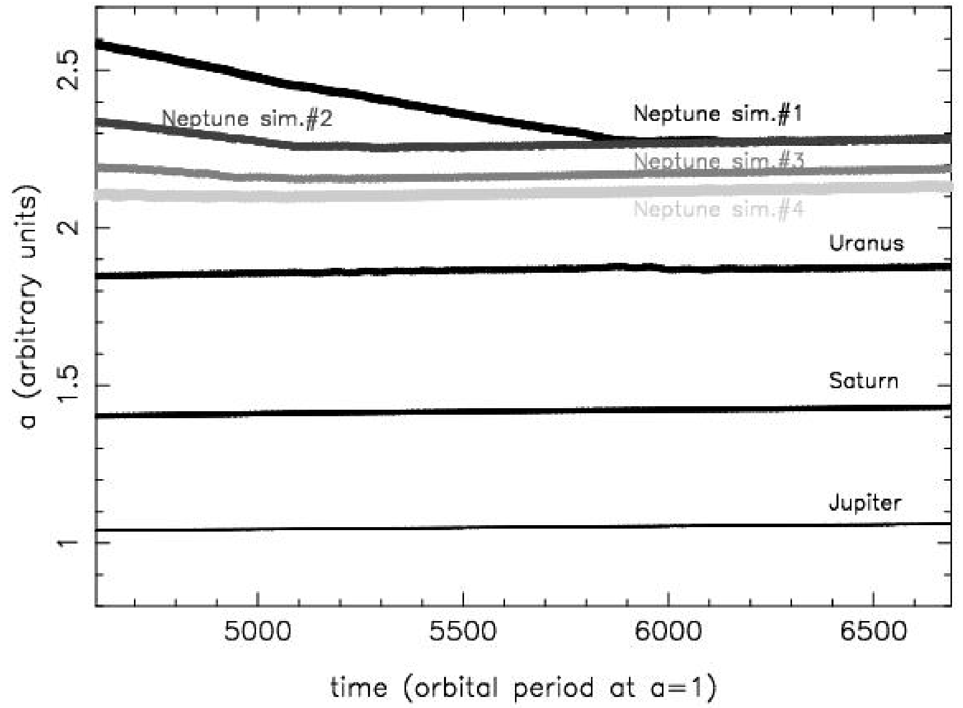




<u>Possible configurations :</u>

J:S in 3:2, S-U in 3:2 or 4:3, U-N in 4:3, 5:4 or 6:5.

→ 6 possible configurations. (ex : J:S:U:N in 12:8:6:5)

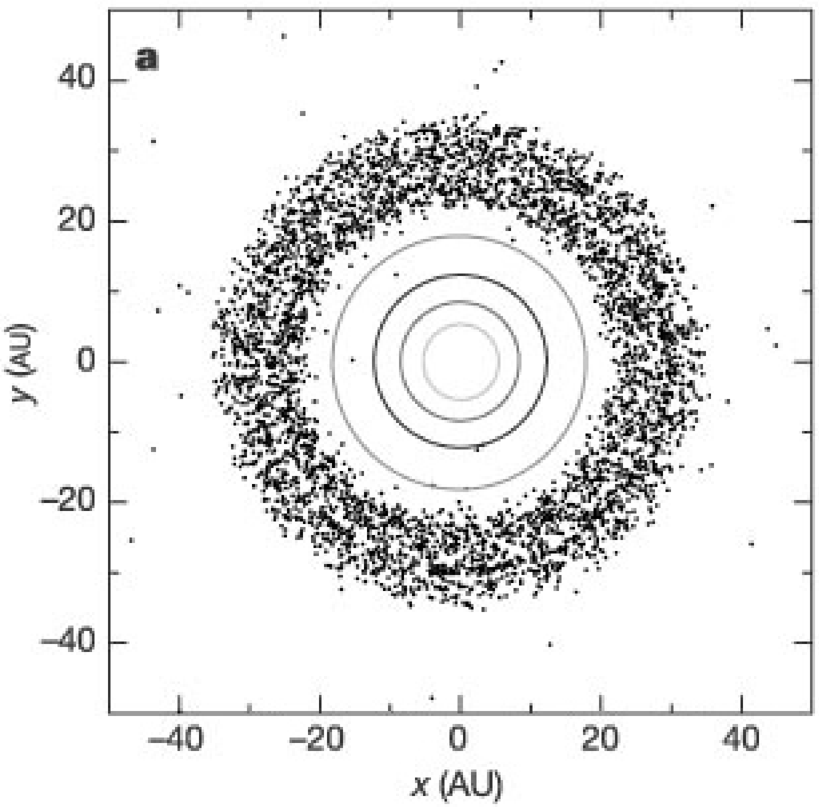
4 unstable in a few Myrs, 2 stable for more than 100 Myrs.

(Morbidelli, Tsiganis, Crida, Levison, Gomes, 2007)

MIGRATION IN THE SOLAR SYSTEM

We are left with a favourable situation
for the formation of the terrestrial planets,
and the giant planets are in a strange, compact configuration.

What next ?



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b) The NICE MODEL

global instability in the giant planets' architecture

after dispersal of the gas disk

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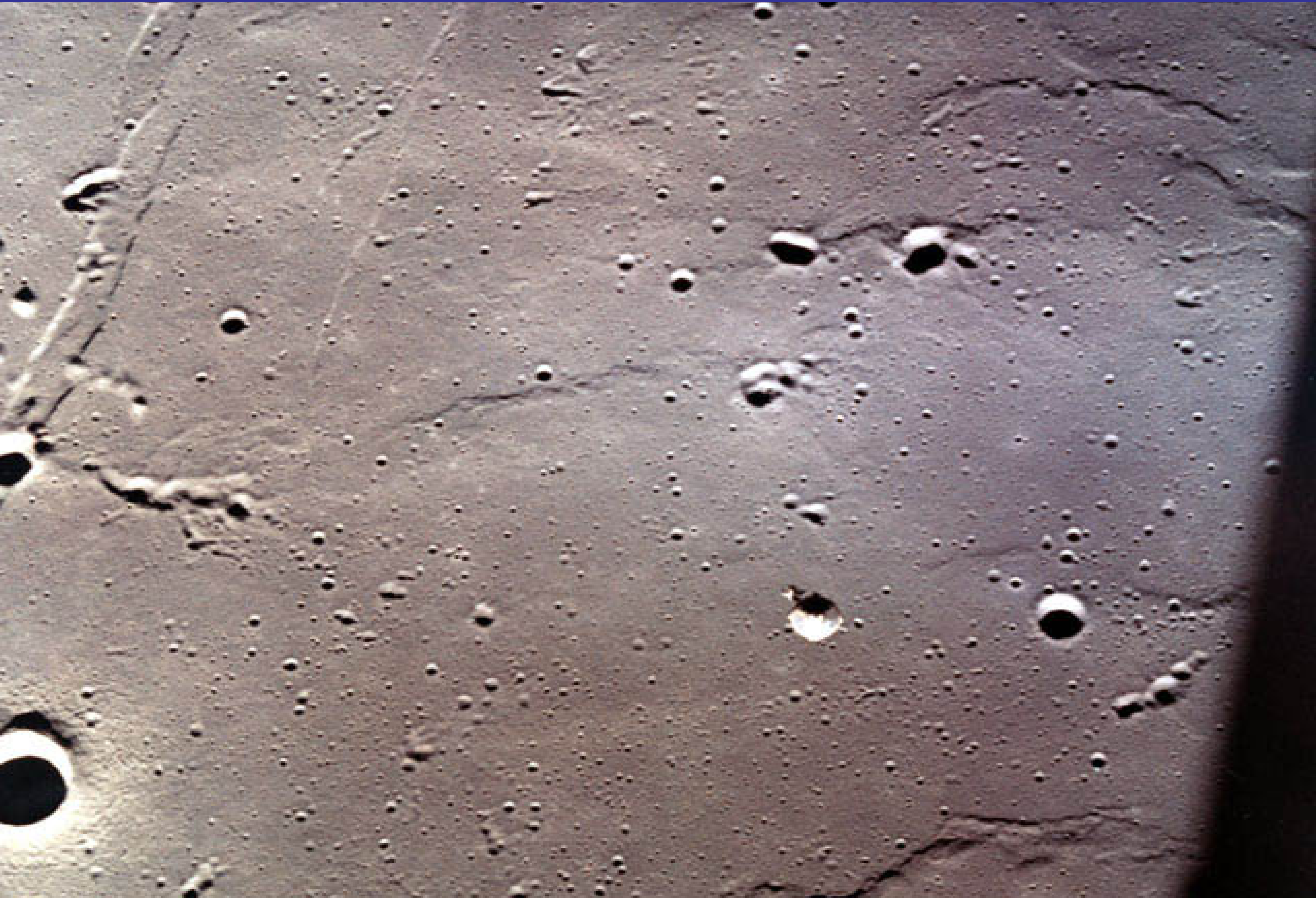
A LATE HEAVY BOMBARDMENT ?

"LUNA"

A LATE HEAVY BOMBARDMENT ?



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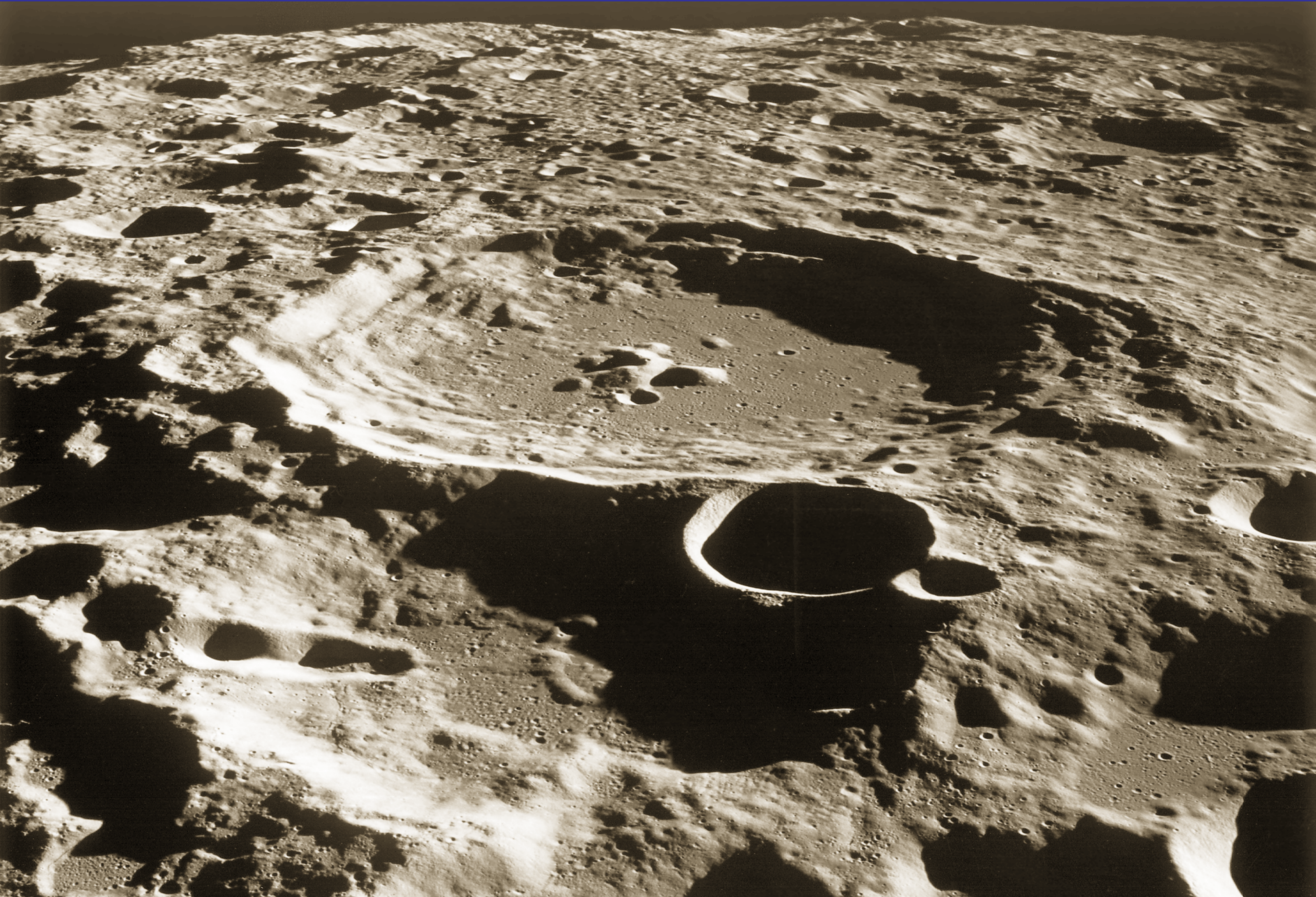
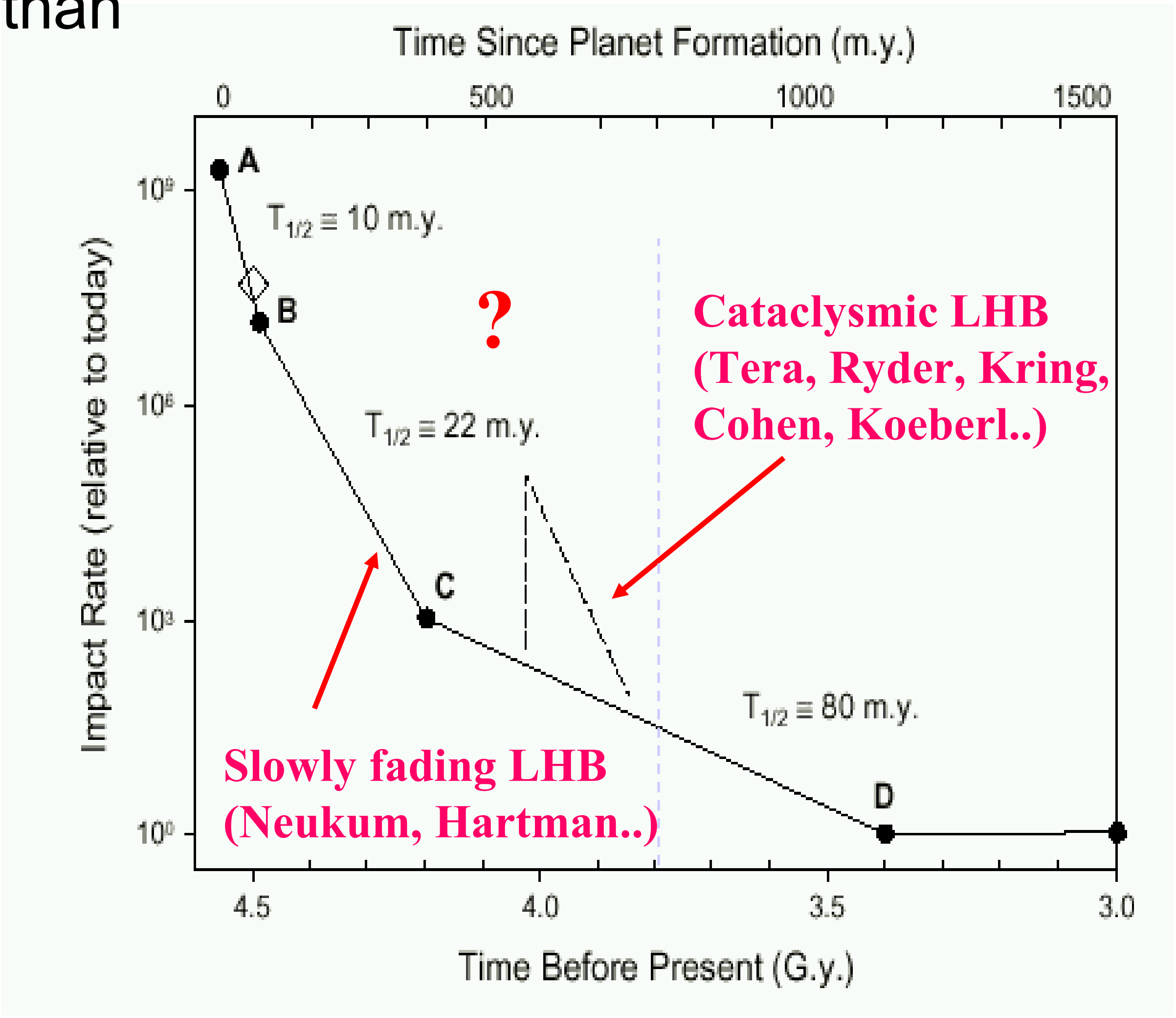


A LATE HEAVY BOMBARDMENT ?

The Moon's bombardment was much more intense ~3,8 Giga years ago than now.

Problem: what was its temporal evolution ? Monotonic decrease, or possible peaks ?



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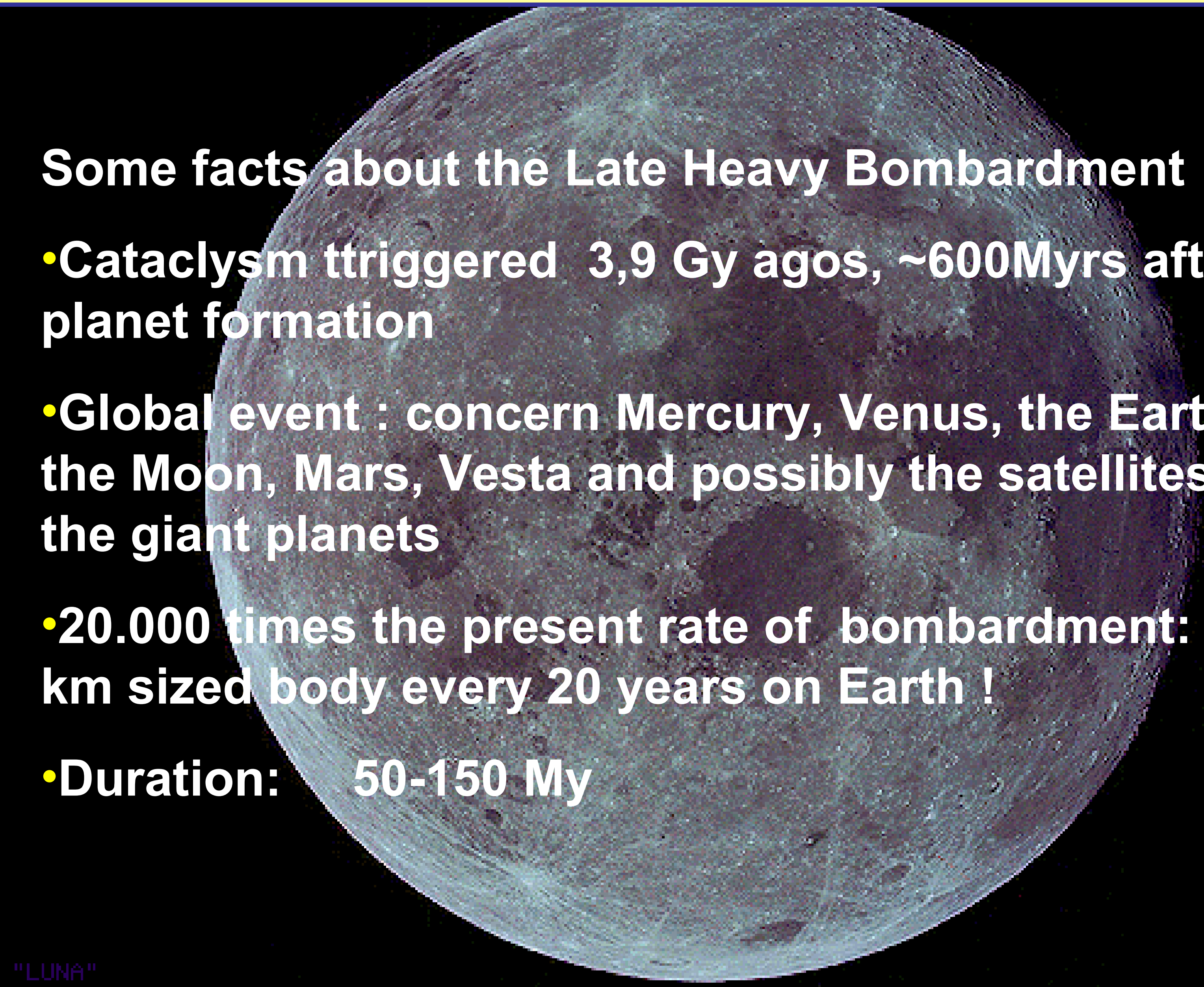


Some facts about the Late Heavy Bombardment :

- **Cataclysm ttriggered 3,9 Gy agos, ~600Myrs after planet formation**
- **Global event : concern Mercury, Venus, the Earth, the Moon, Mars, Vesta and possibly the satellites of the giant planets**
- **20.000 times the present rate of bombardment: a km sized body every 20 years on Earth !**
- **Duration: 50-150 My**

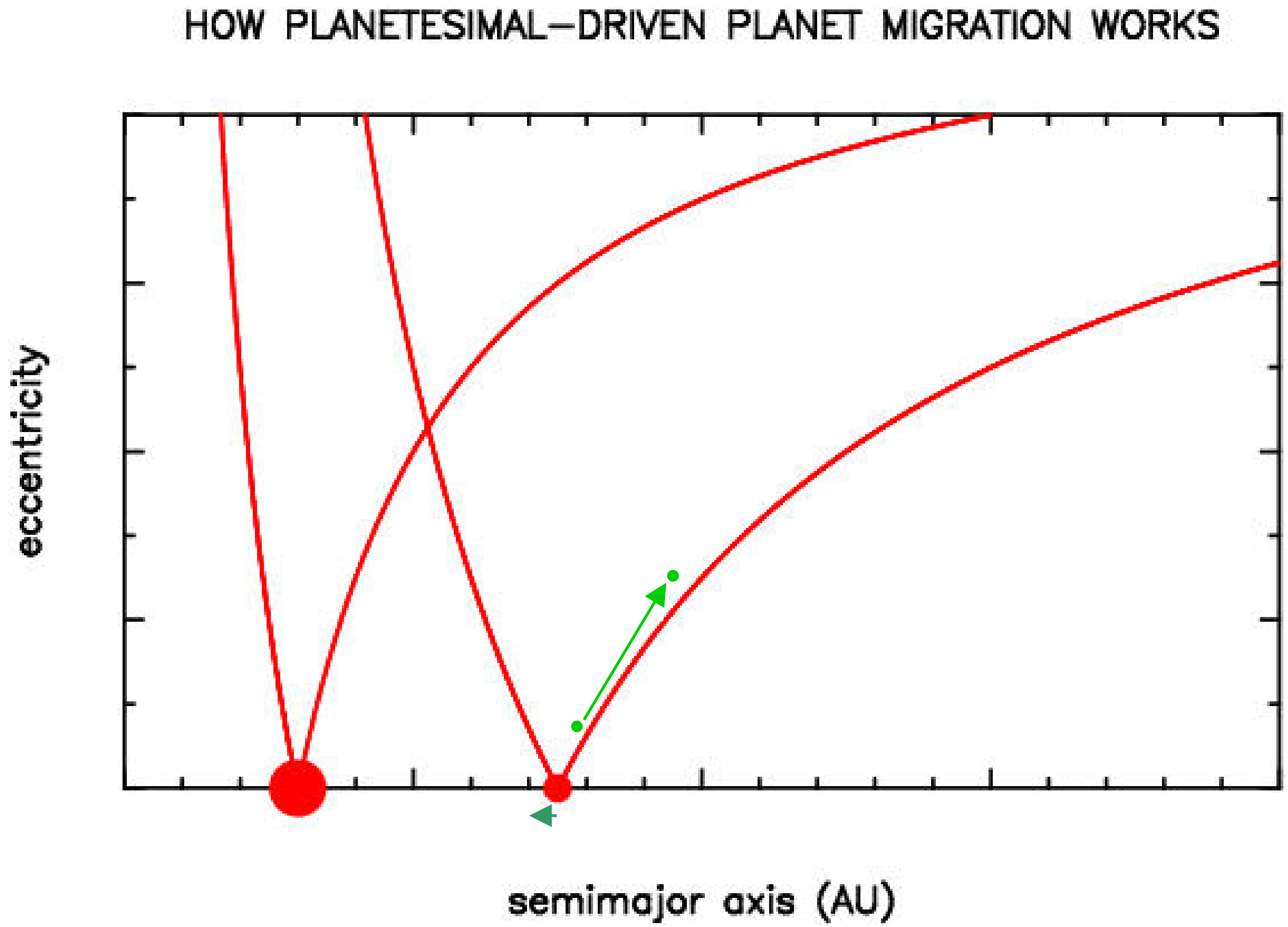
A LATE HEAVY BOMBARDMENT ?

Such a cataclysmic bombardment cataclysmique is only possible if a reservoir of small bodies, which remained stable for ~600 My, becomes suddenly unstable.

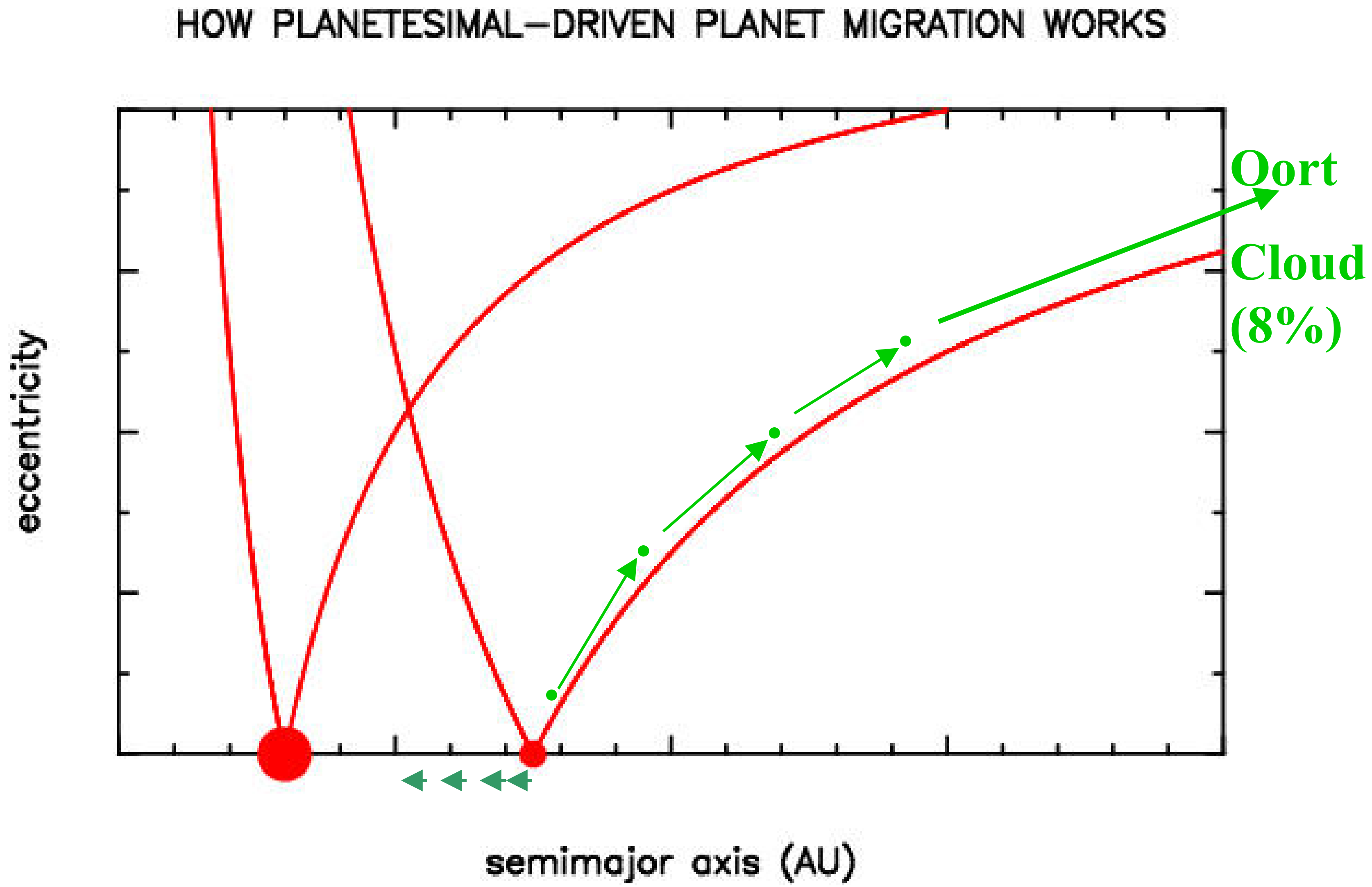
This is only possible if there is a change in the orbital structure of the giant planets.

How can the planets move, migrate, after the gas disapeared ?

PLANETESIMALS DRIVEN MIGRATION



PLANETESIMALS DRIVEN MIGRATION



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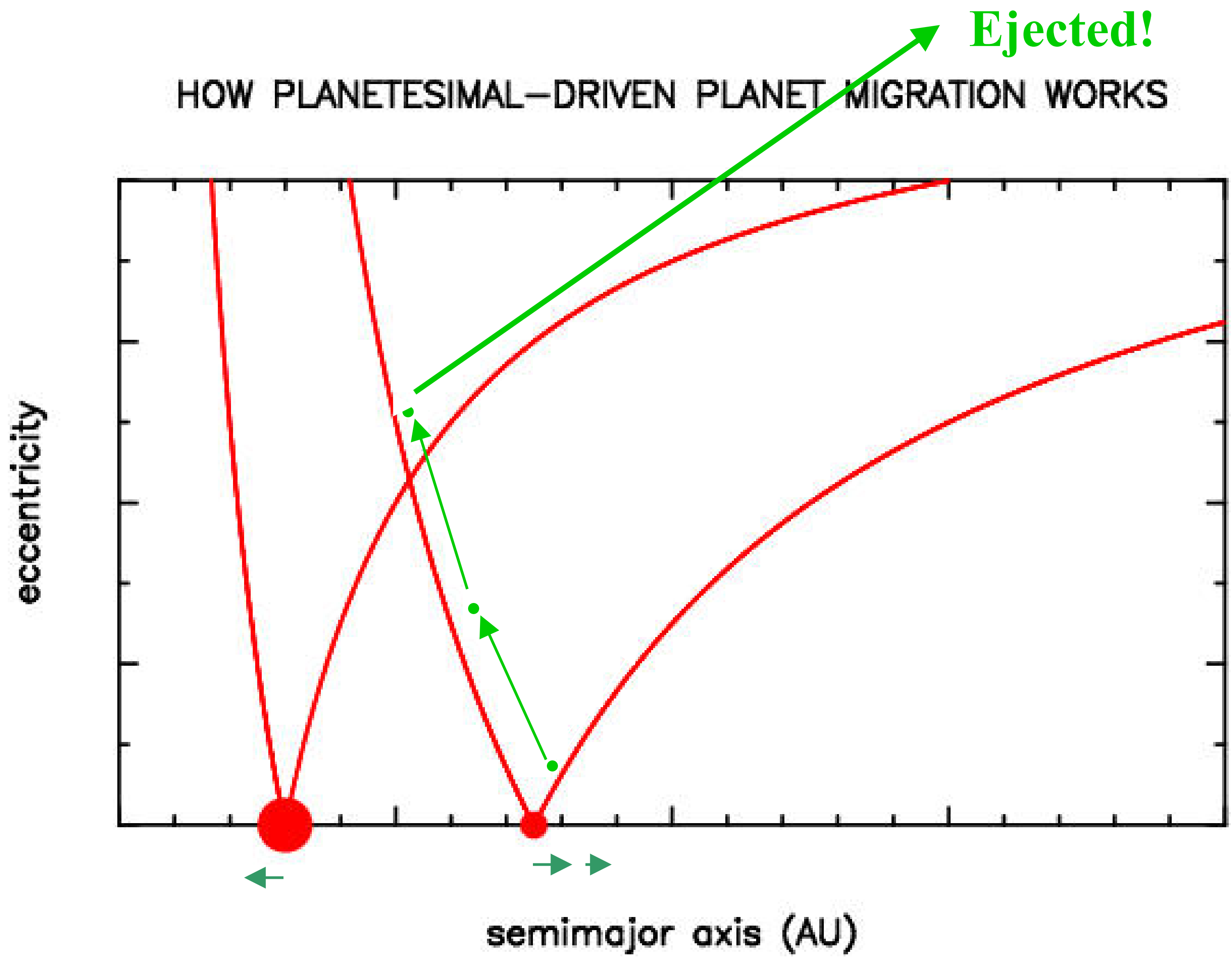
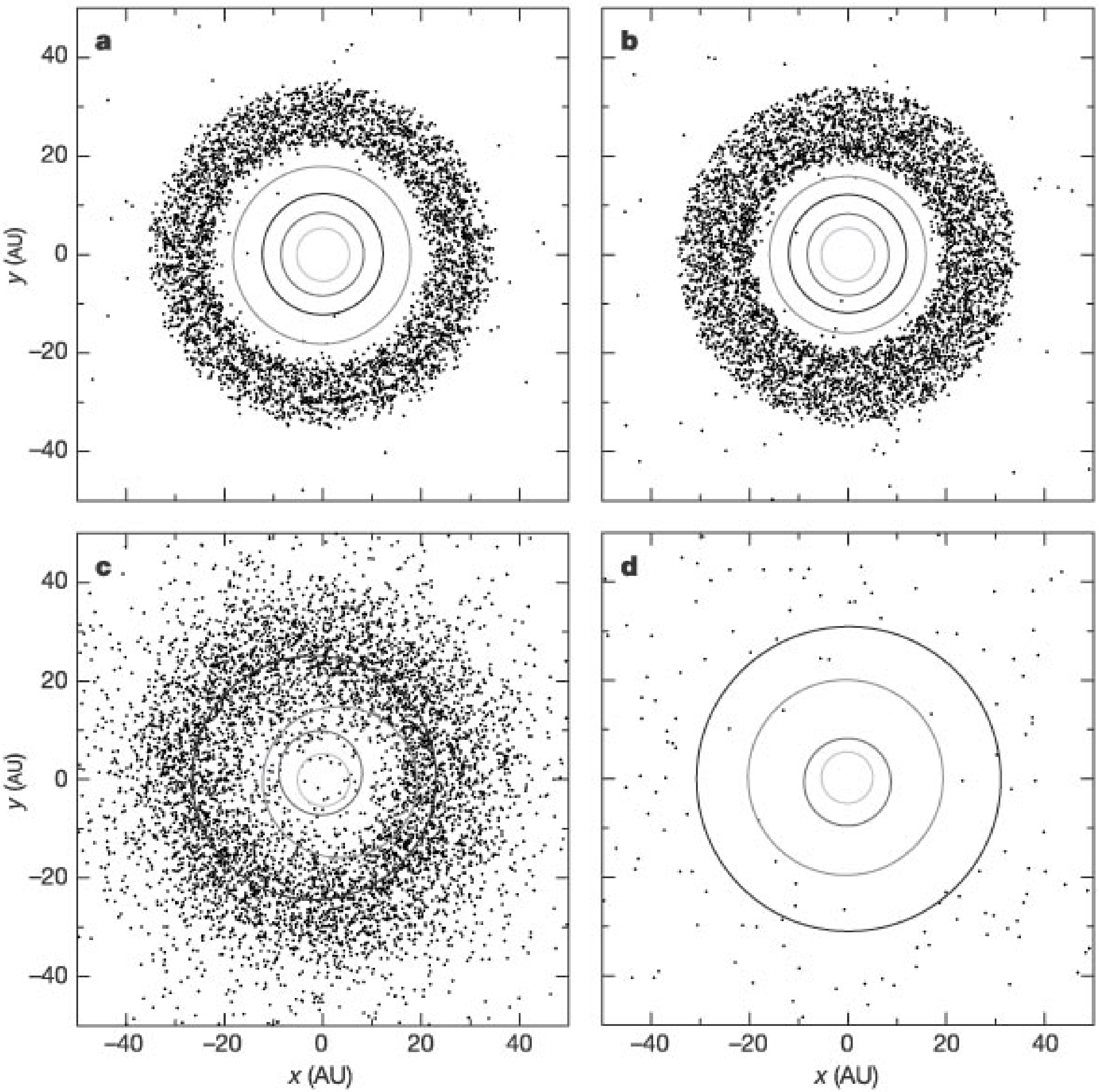


The NICE MODEL



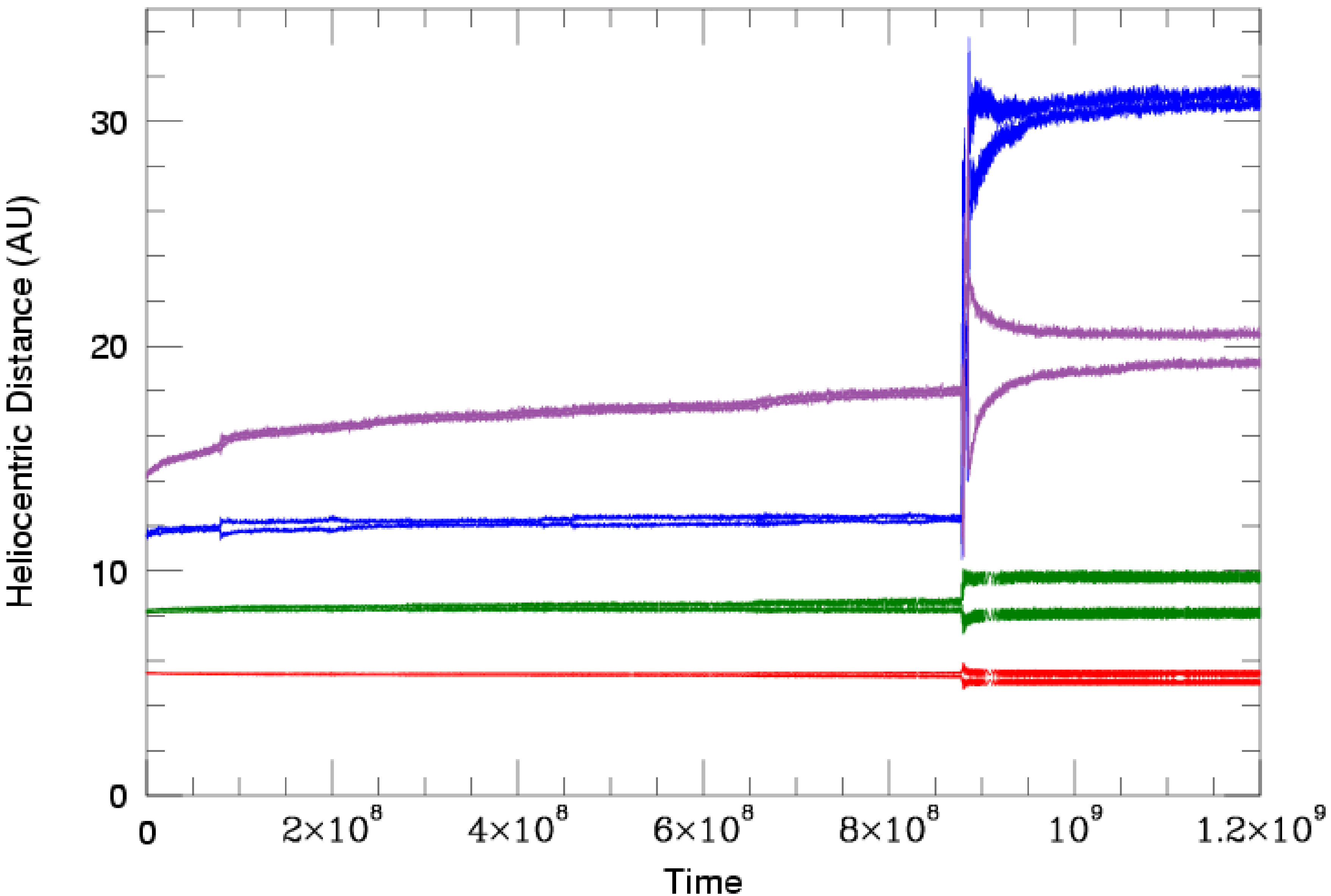
First, slow migration. Jupiter inwards, Saturn, Uranus & Neptune outwards.

When Jupiter & Saturn enter in 2:1 Mean Motion Resonance, their eccentricities rise suddenly.

It destabilises the whole system, and the process runs away.

Result ?

The NICE MODEL



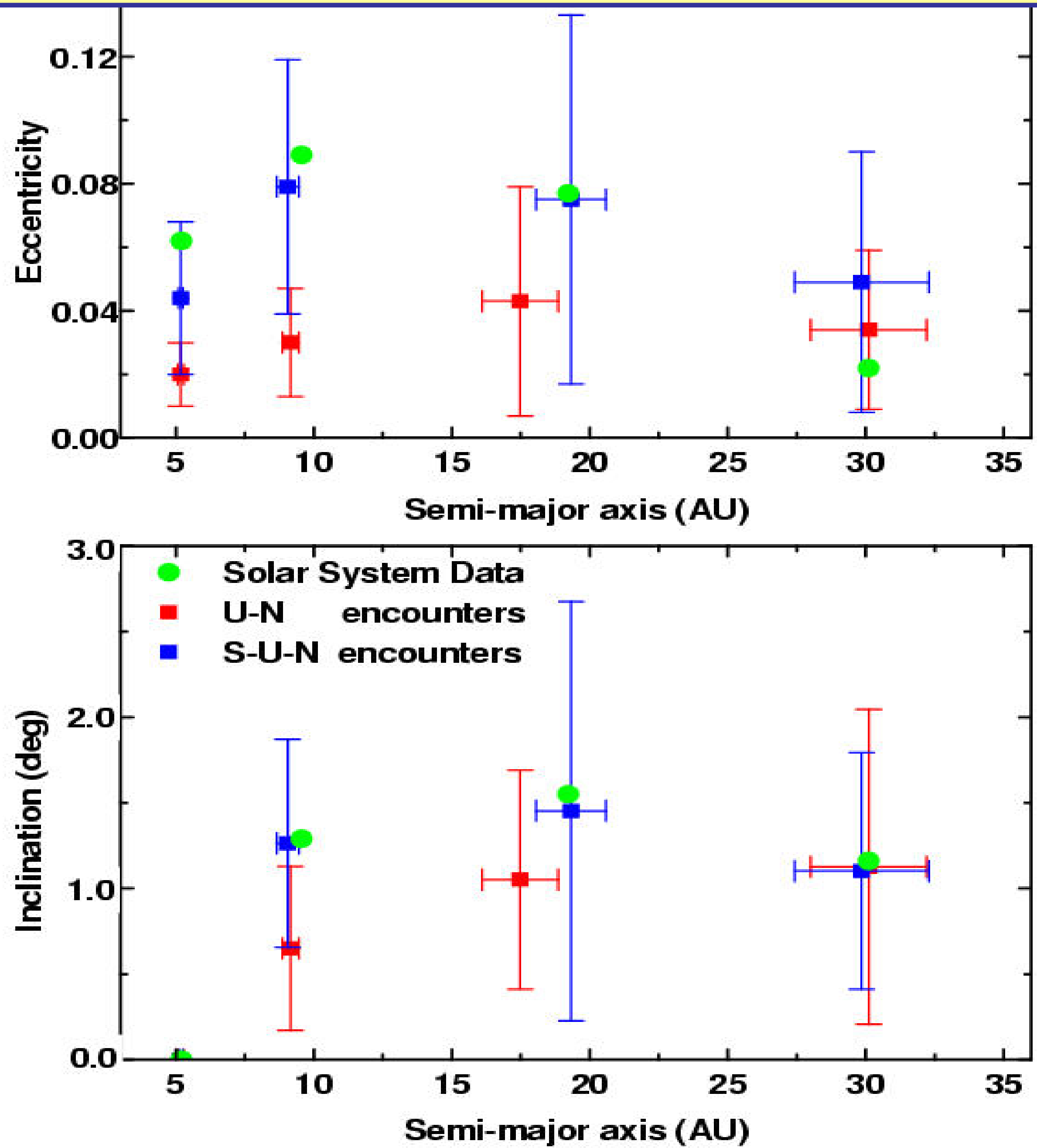
K. Tsiganis, R. Gomes, A. Morbidelli, H.F. Levison 2005. *Nature, 435, 459*

The NICE MODEL

Two strengths:

I: Explanation of the present orbits of the giant planets (semi-major axes, eccentricities, and inclinations) starting from <u>circular</u> orbits.

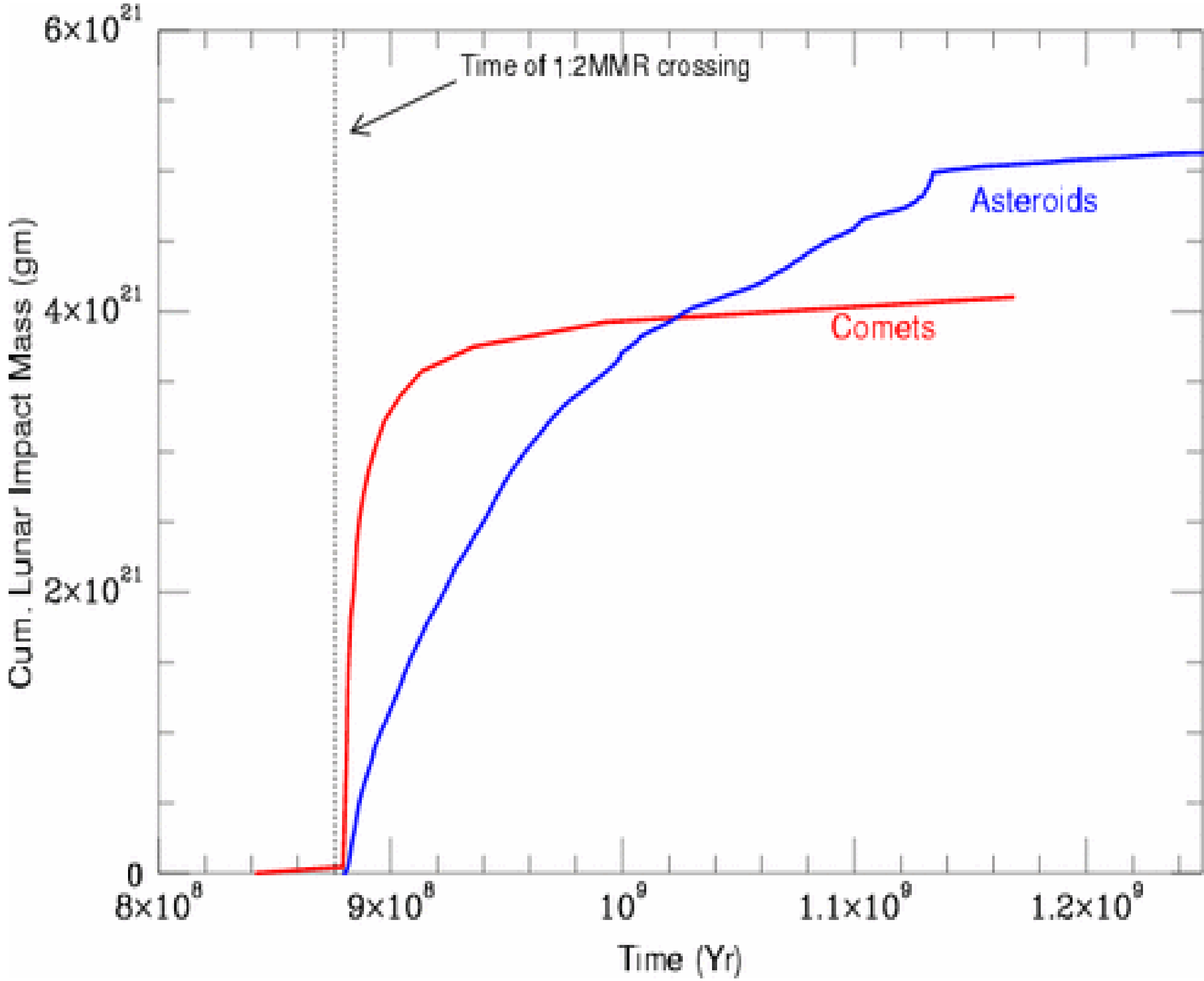
K. Tsiganis, R. Gomes, A. Morbidelli, H. Levison 2005. *Nature, 435, 459*



The NICE MODEL

II: A cometary and asteroidal late bombardment, of the good magnitude compared to craterization constraints on the Moon.

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



The NICE MODEL

Are there other consequences of this global instability ?

Yes !

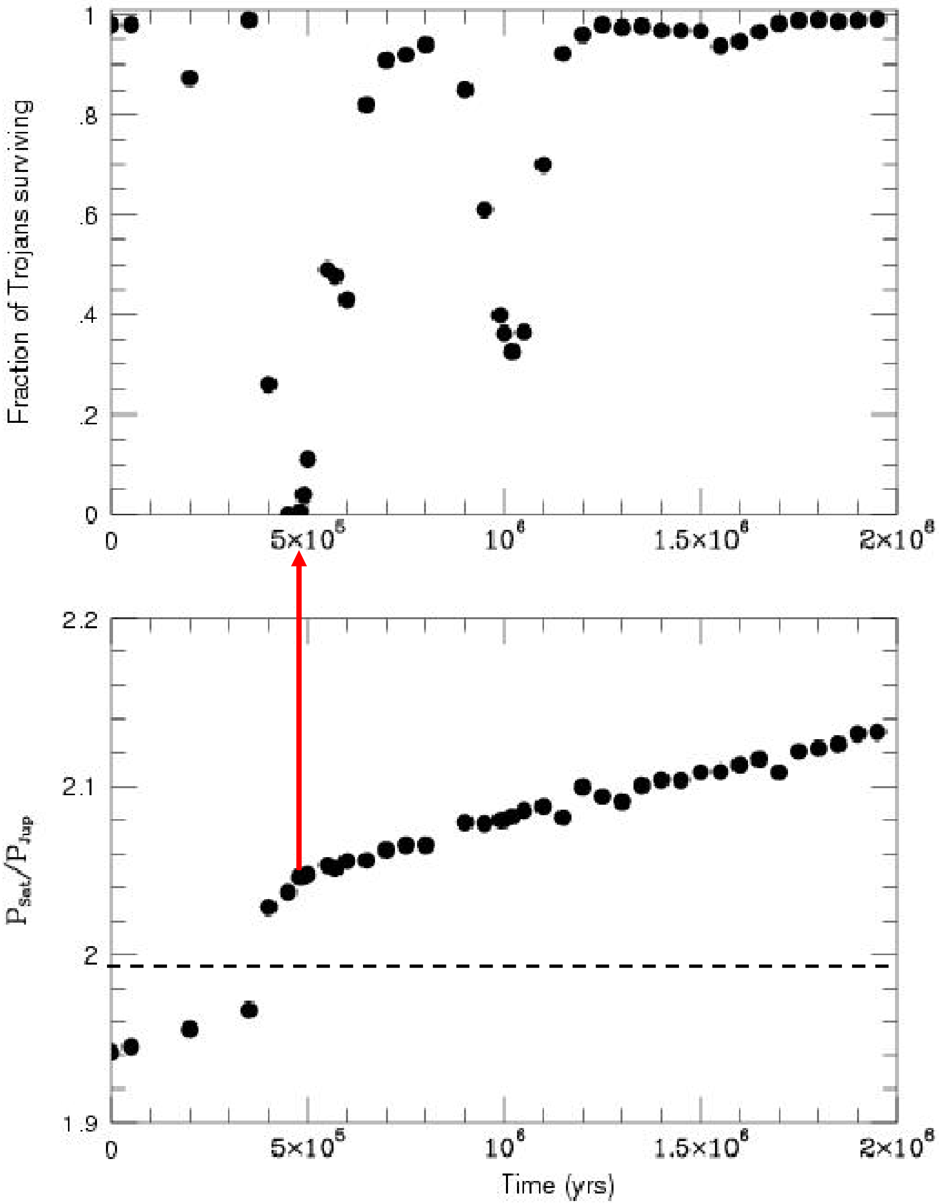
1) Jupiter's trojans

2) Irregular satellites of the giant planets

3) formation and structure of the Kuiper Belt

...

JUPITER's TROJANS



At the moment of the 2:1 MMR crossing between Jupiter and Saturn, no trojan asteroid can survive. They are all lost in the instability. But we see them now...

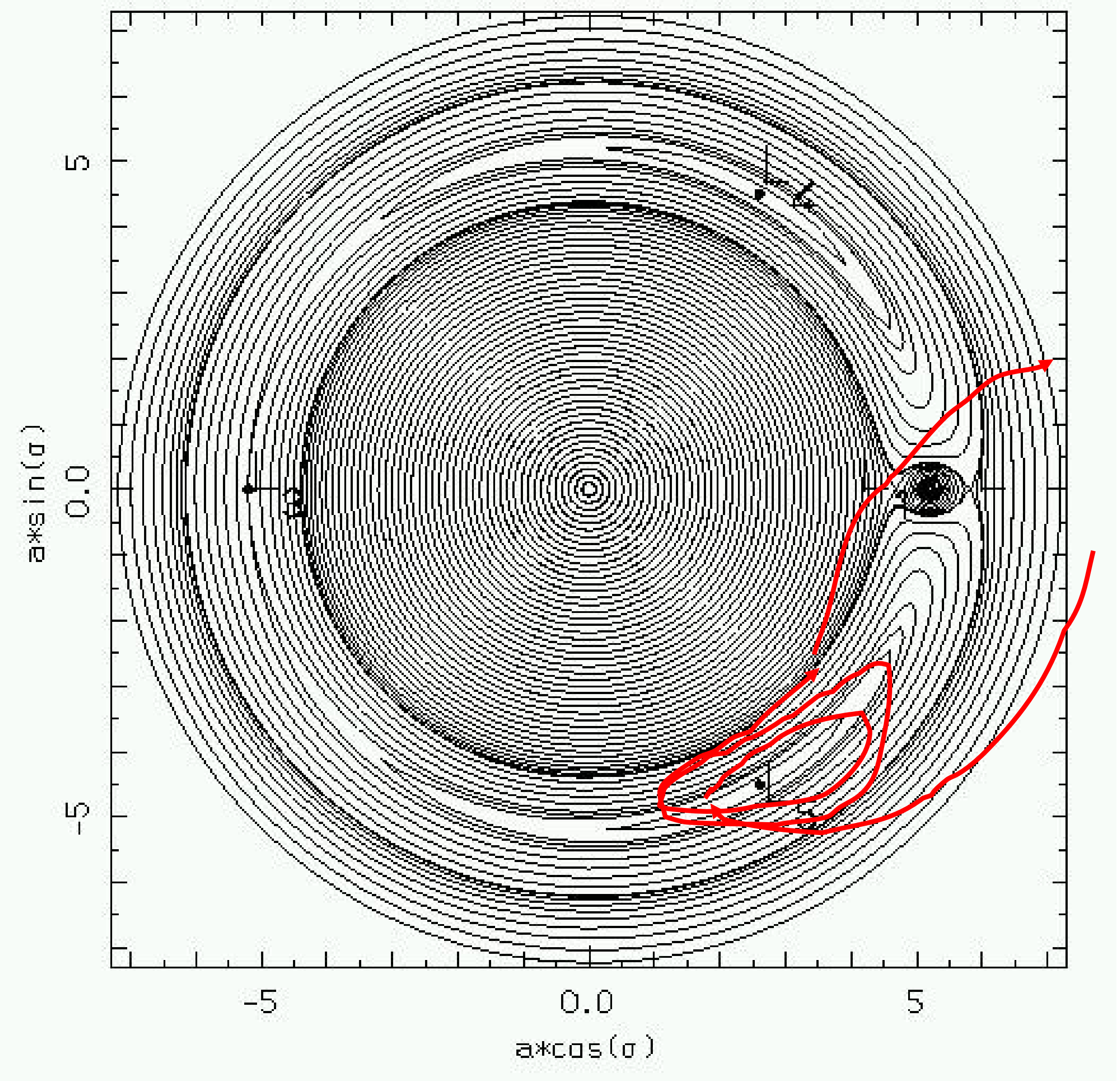
Problem !

JUPITER's TROJANS

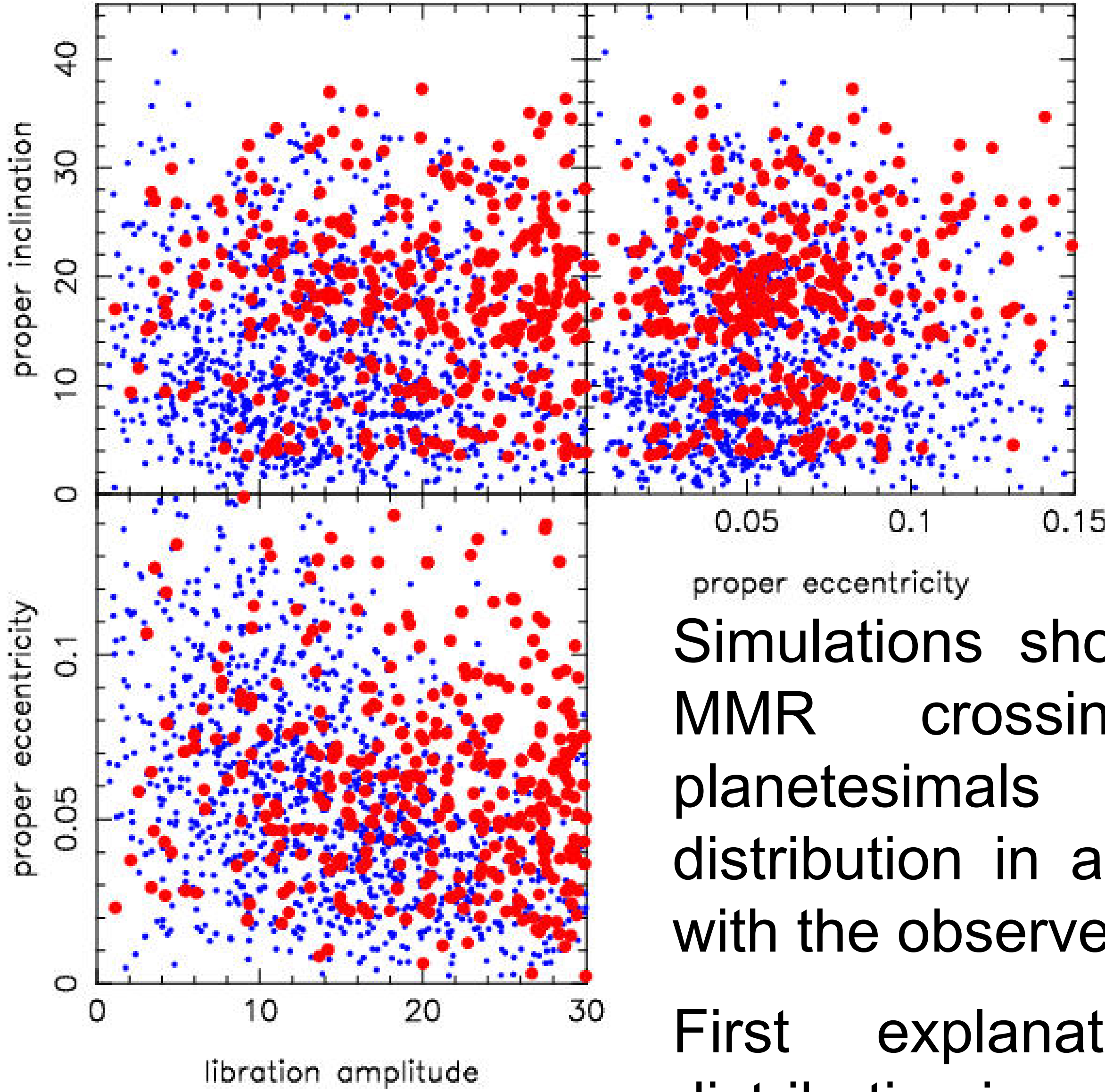
Solution :

If the trojans' zone is open, the pre-existing trojans can leave, but new ones can come. This region would always be populated during the instability, by planetesimals passing by...

In the end, the zone closes again, and planetesimals are captured.



JUPITER's TROJANS



Simulations show that, during the 2:1 MMR crossing, a fraction of planetesimals is captured, whose distribution in a, e, i agrees quite well with the observed one.

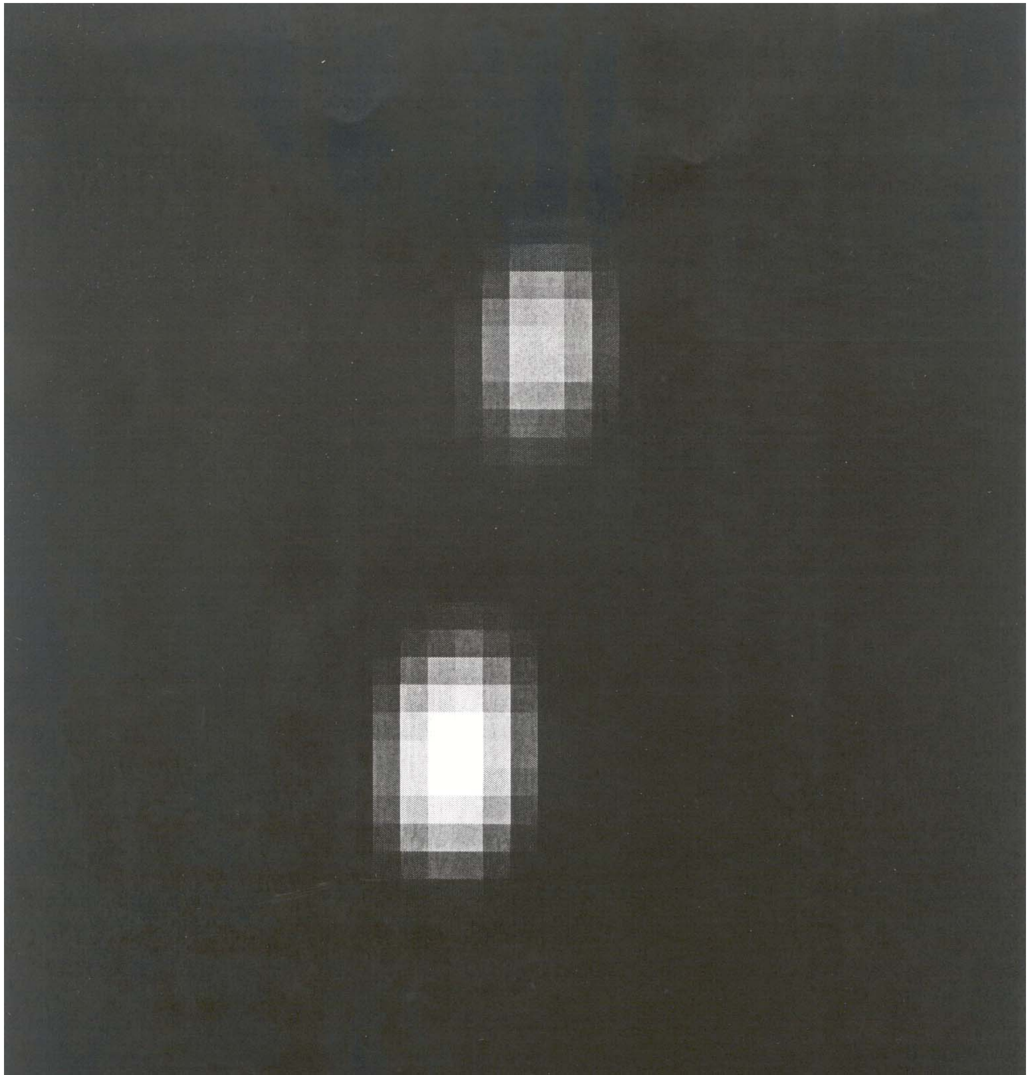
First explanation for the broad distribution in e and i of the trojans.

A.Morbidelli, H.Levison, K.Tsiganis, R.Gomes 2005. *Nature*, 435, 462.

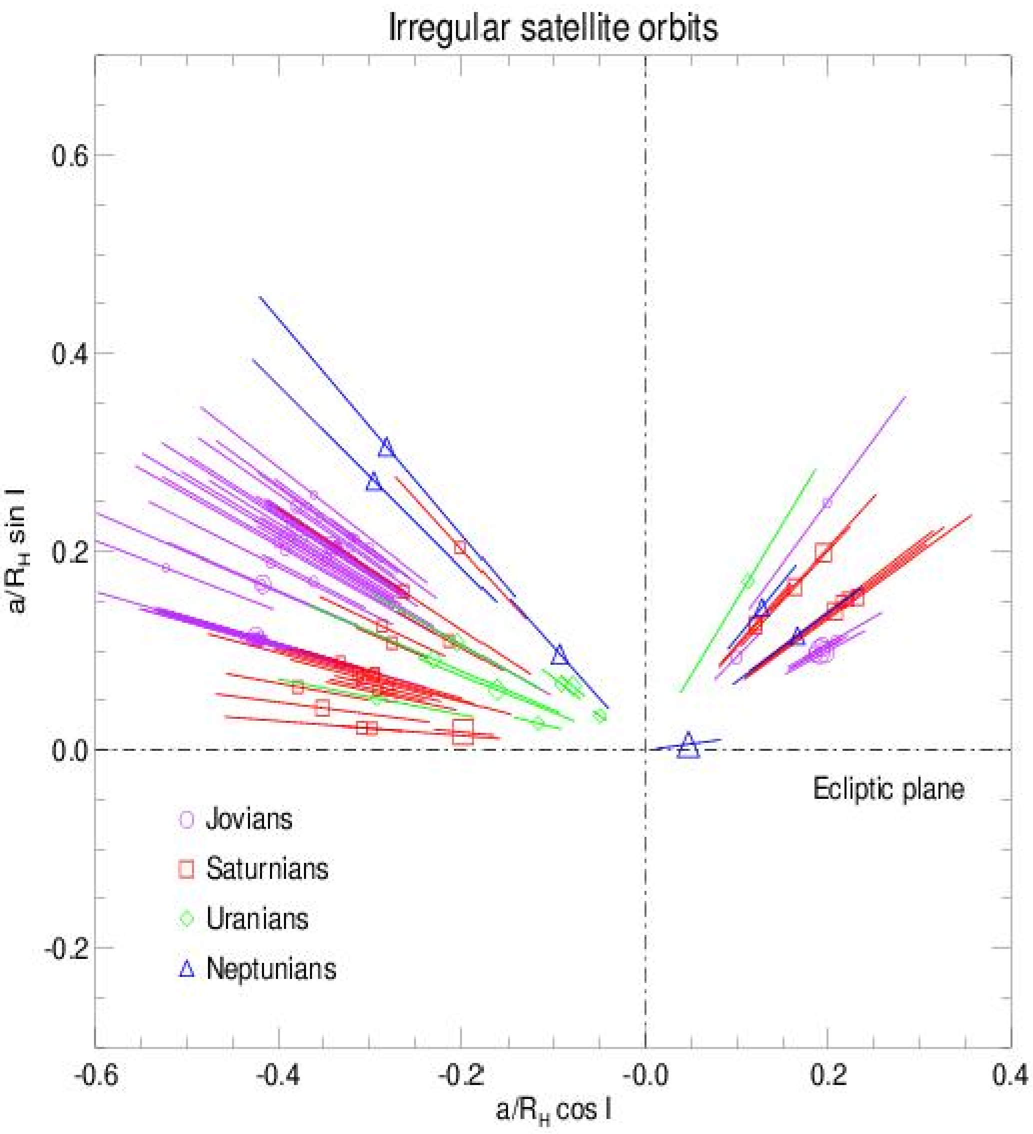
JUPITER's TROJANS

NB : The density of the binary trojan Patroclos is only 0,8g/cm^3, smaller than that of asteroids, but identical to that of Kuiper Belt objects...

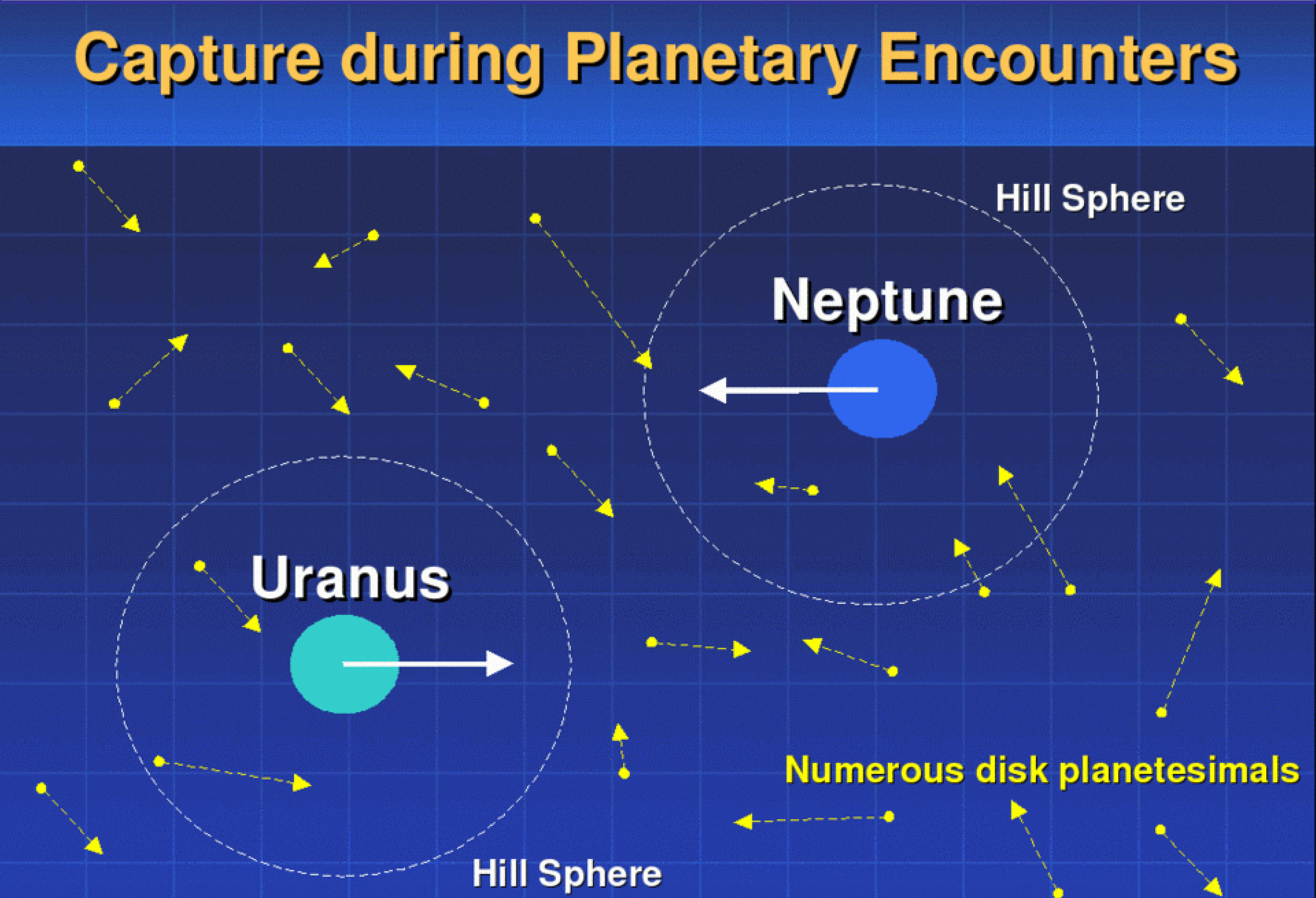
(Marchis et al., 2005)



IRREGULAR SATELLITES

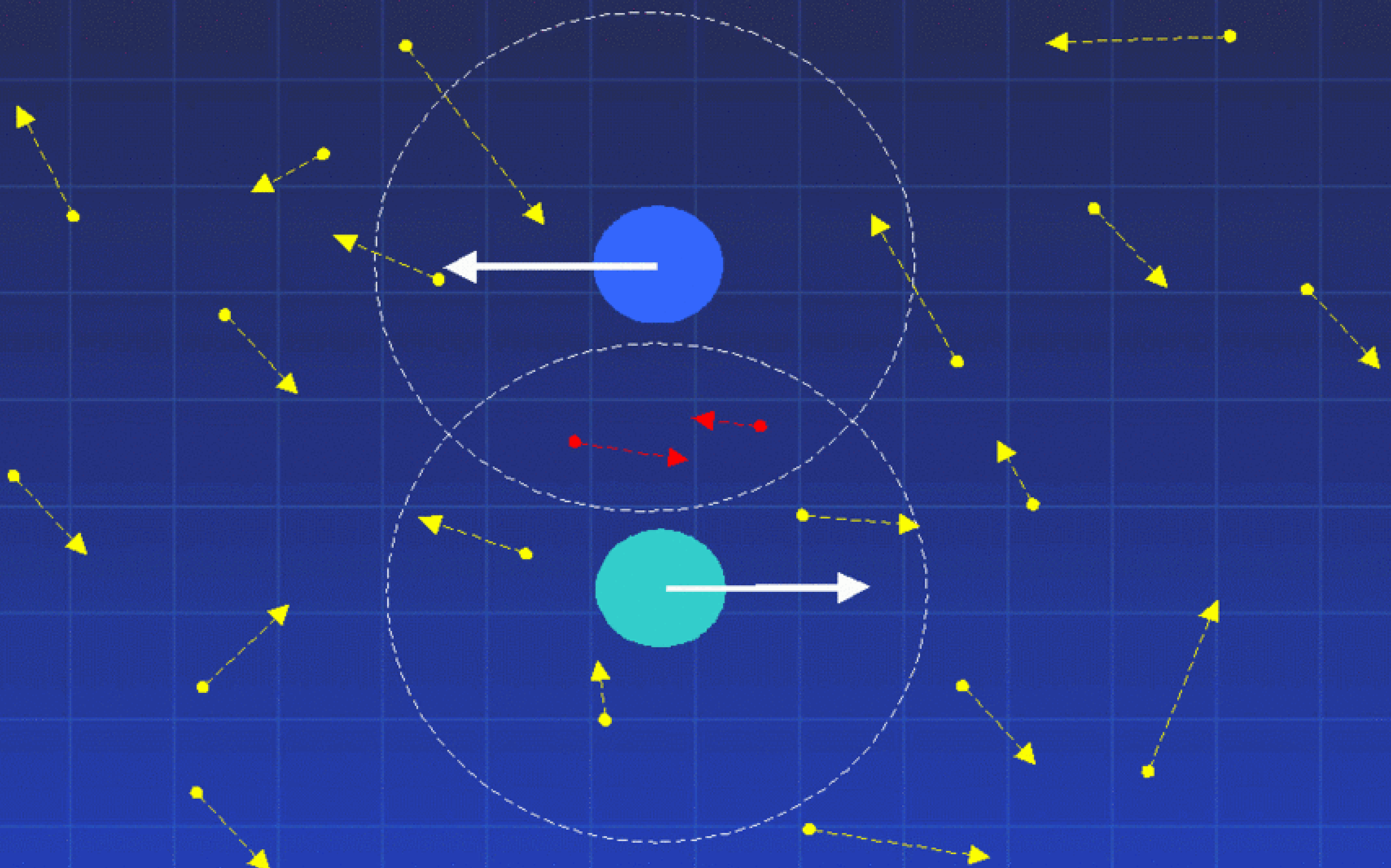


IRREGULAR SATELLITES



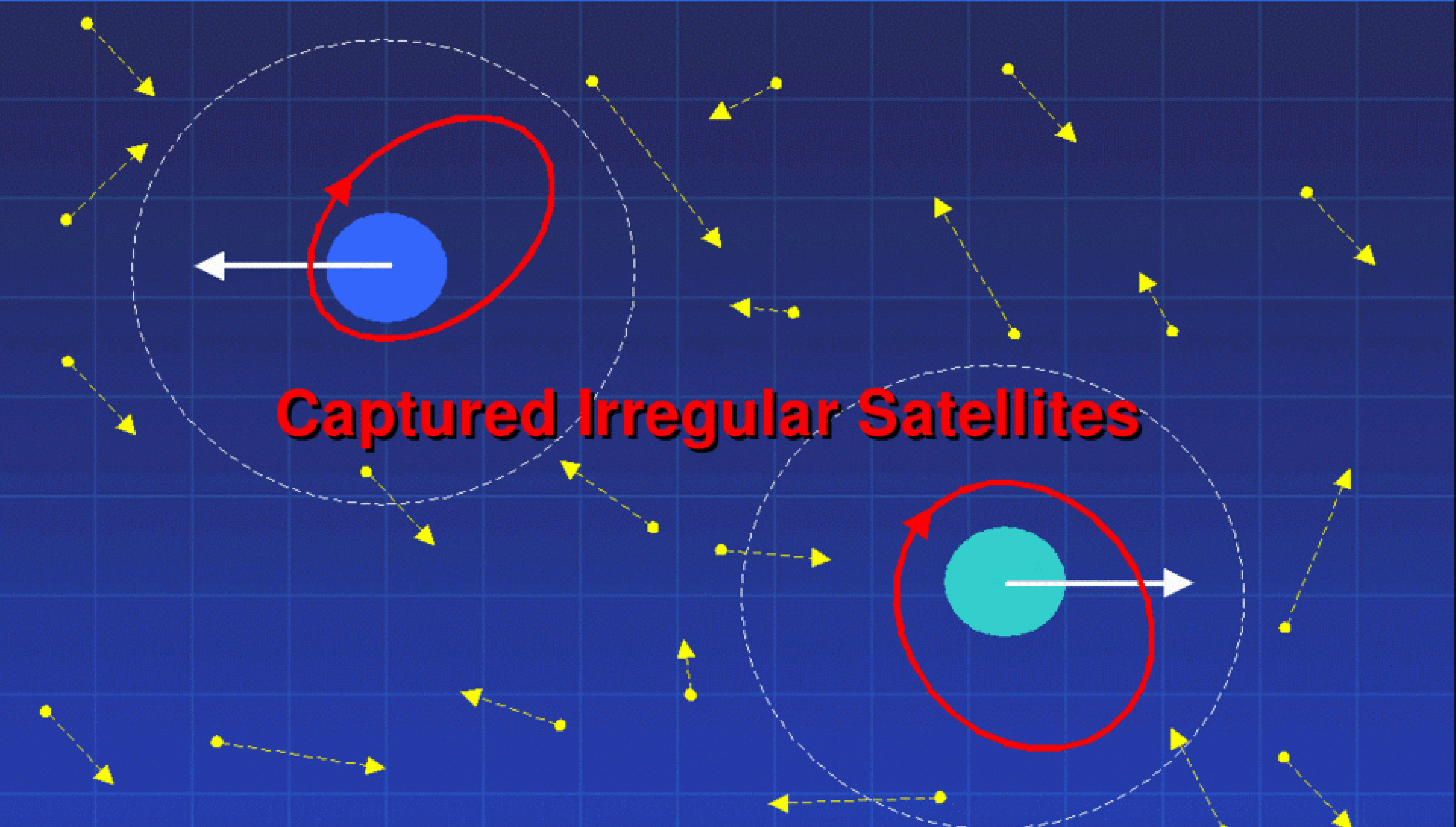
IRREGULAR SATELLITES

Capture during Planetary Encounters

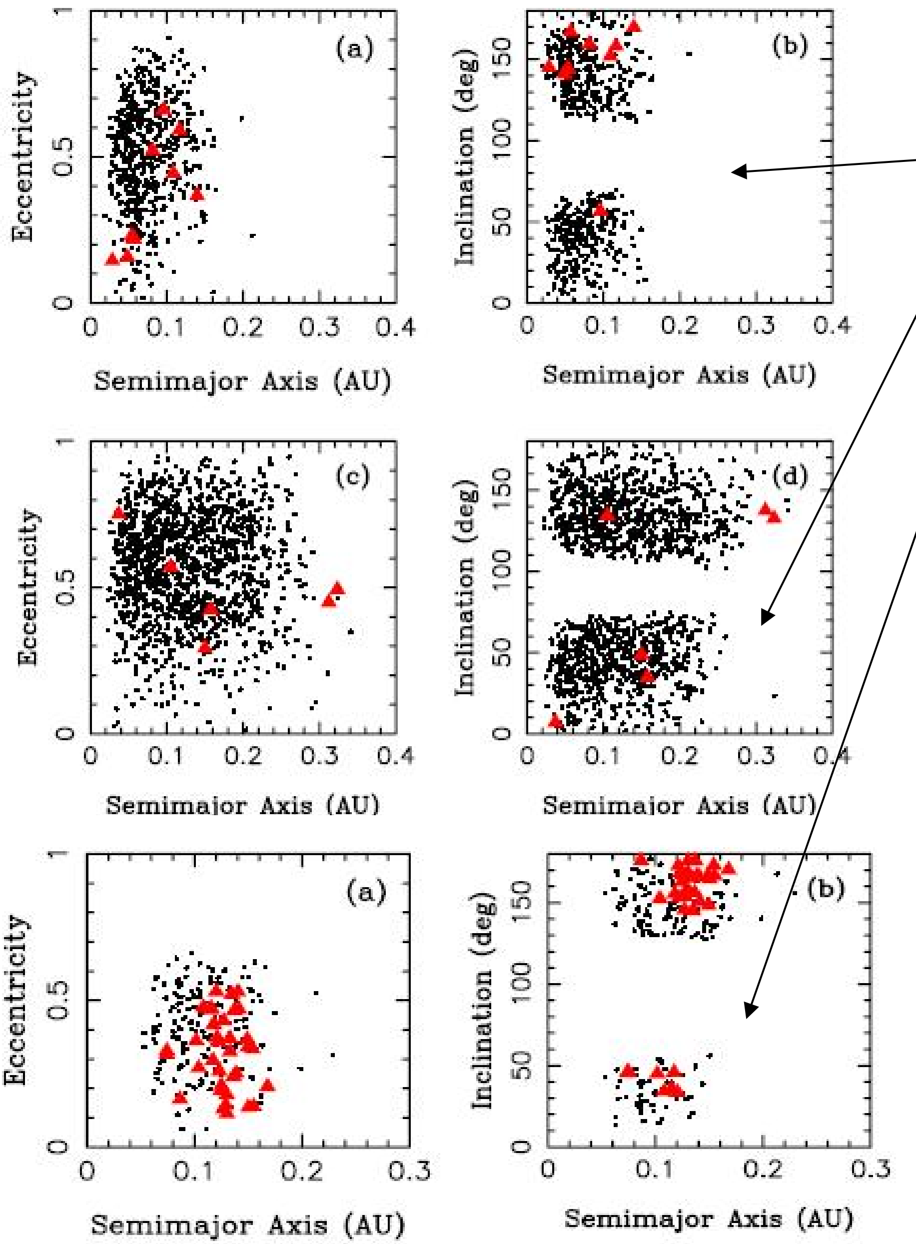


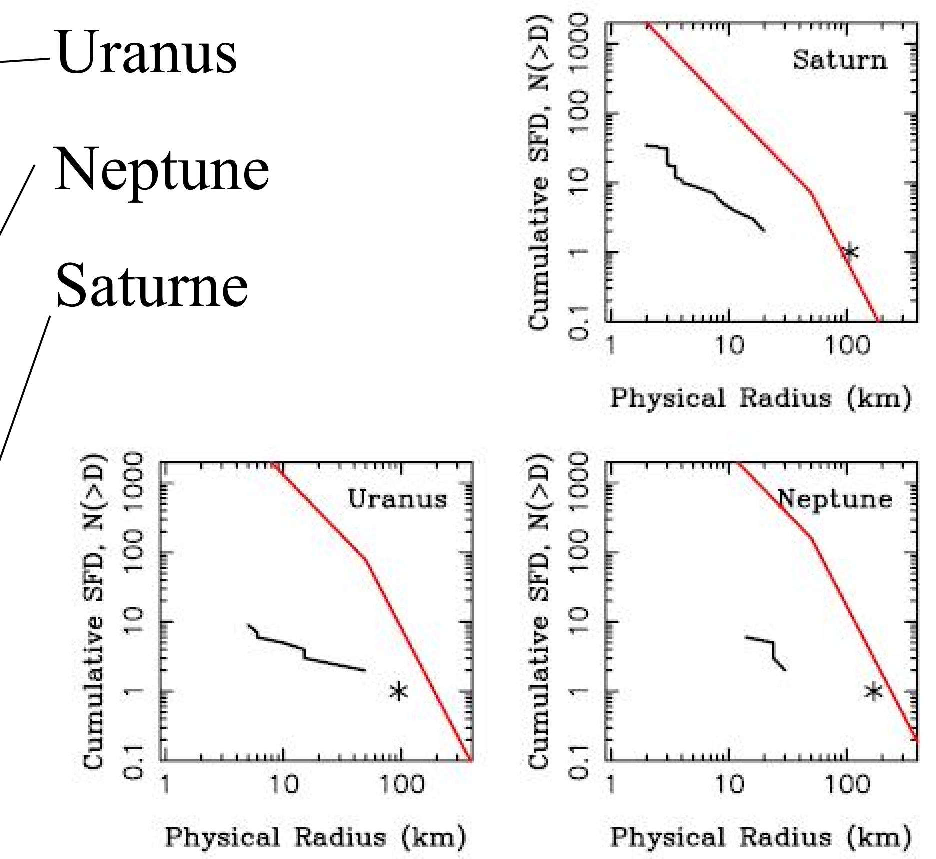
IRREGULAR SATELLITES

Capture during Planetary Encounters



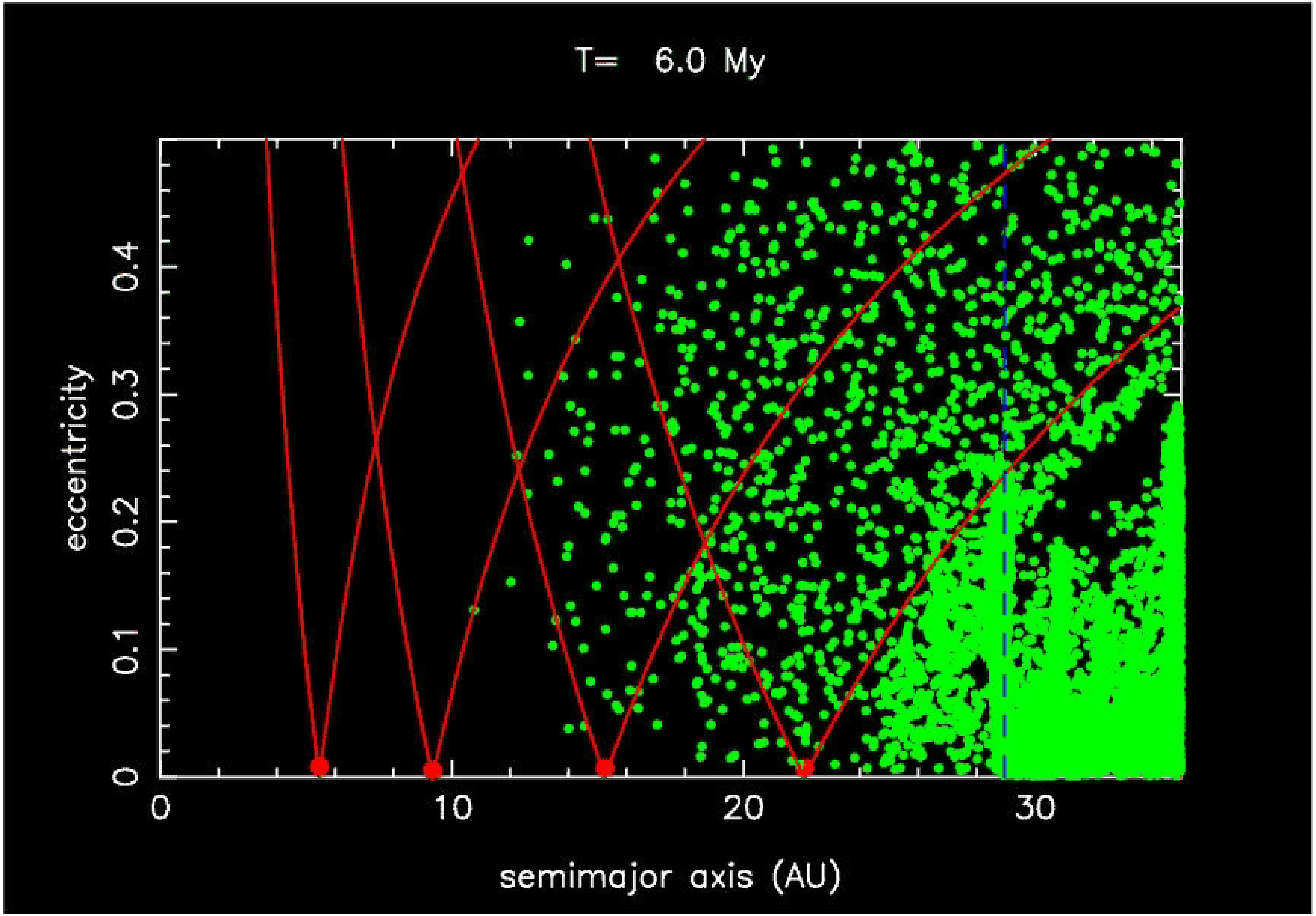
IRREGULAR SATELLITES





Origin of the irregular satellites of Saturn, Uranus and Neptune
(Nesvorny et al., 2007)

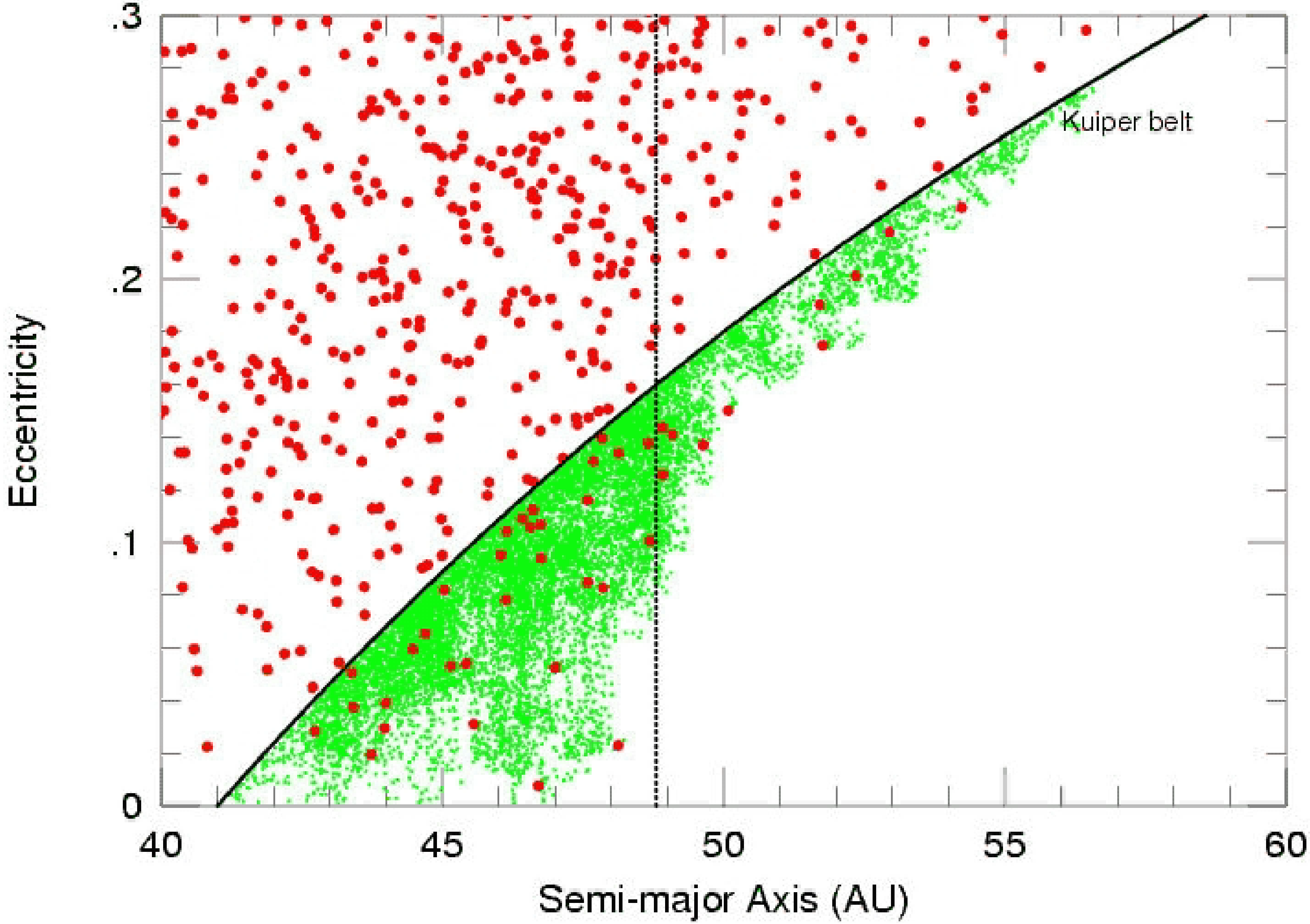
KUIPER BELT ORIGIN



KUIPER BELT ORIGIN

During the outward migration of Neptune, planetesimals are pushed into the Kuiper Belt region, upto 48 AU, the 2:1 MMR with Neptune.

$e_{neptune}$=0.2, fixed



KUIPER BELT ORIGIN

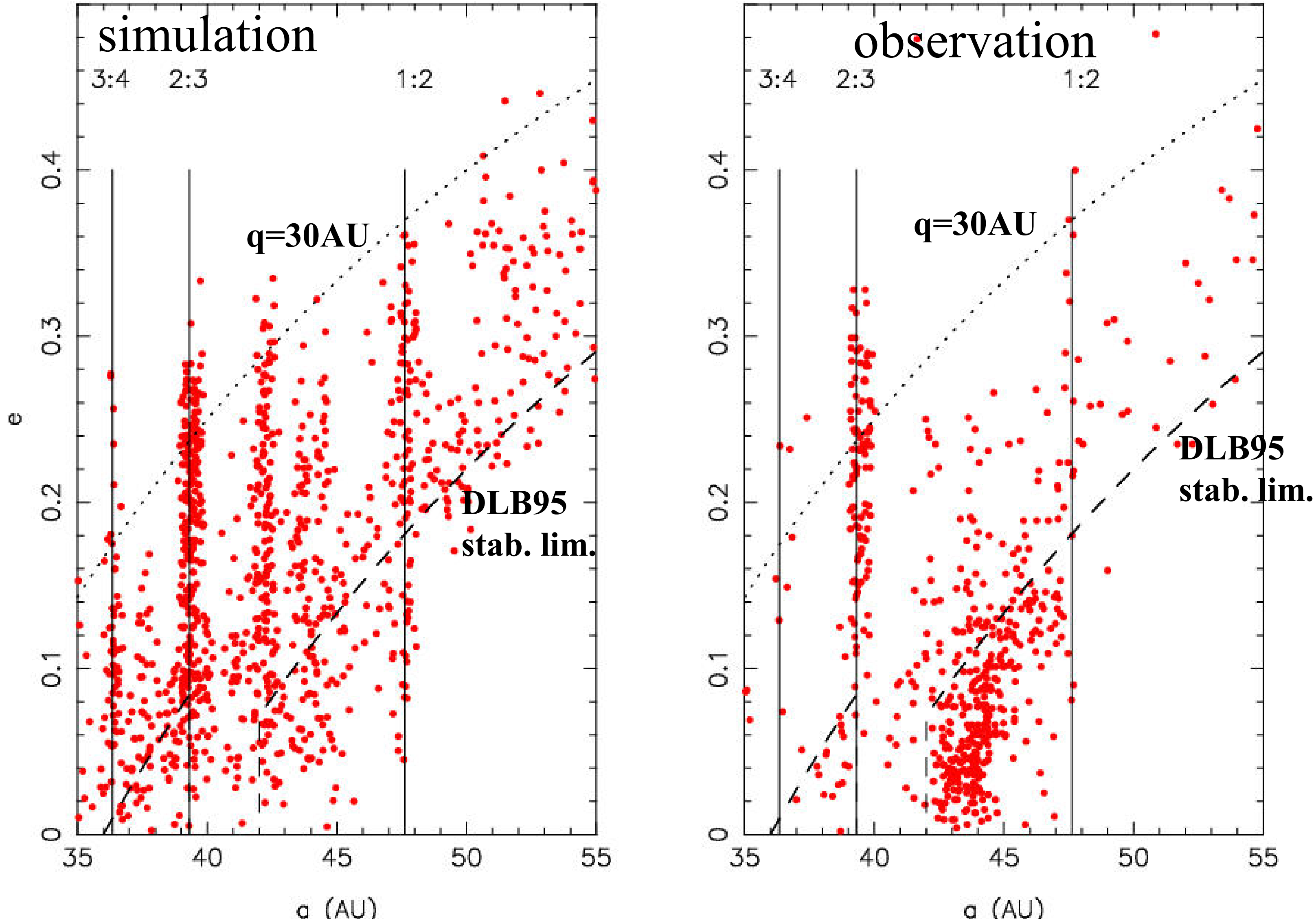
In total, ~30 objects out of simulated 30,000 are captured in the classical belt. Given that the initial mass of the planetesimal disk is ~35 Earth masses in the Nice model, we account for about 0.03-0.05 Earth masses in the Kuiper belt.

About right, provided that collisional erosion was not important. This implies that the size distribution was similar to the current one, but scaled `up' by a factor ~ 1,000.

1,000 Plutos in the primordial planetesimal disk!

KUIPER BELT ORIGIN

The distribution in the (a,e) plane is quite well reproduced
(Levison et al. 2010?).

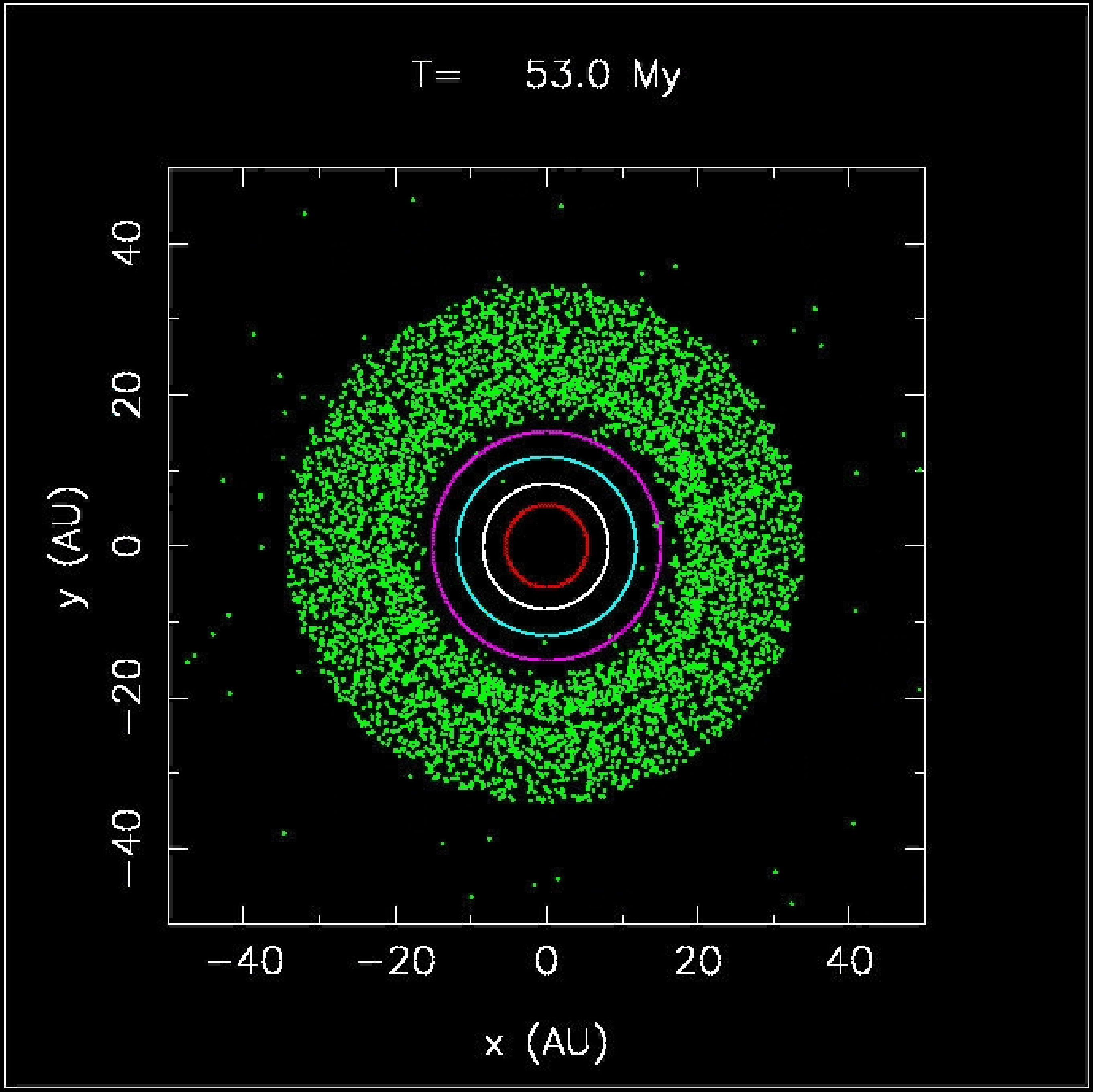


KUIPER BELT ORIGIN

Although the distribution obtained in the simulations is admittedly not perfect, the 'Nice' model reproduces the structure of the Kuiper belt at an unprecedented level.

It explains:

- Edge of the classical belt
- Characteristic (a,e) distribution
- Inclination distribution
- Correlations between inclination and physical properties
- Existence of an extended scattered disk
- Orbital distribution in the main resonances
- Mass deficit of the Kuiper belt


T= 53.0 My
40
20
0
−20
−40
y (AU)
x (AU)

GRAND TACK = in then out migration of Jupiter & Saturn in the gas disk.
→ shapes the asteroid belt
→ explains the small mass of Mars.

NICE MODEL = global instability the outer planets, after the gas disk is gone.
→ present orbits of the giant planets, Kuiper Belt, irregular satellites, trojans, LHB...

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