# The NICE MODEL

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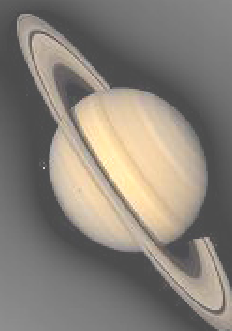
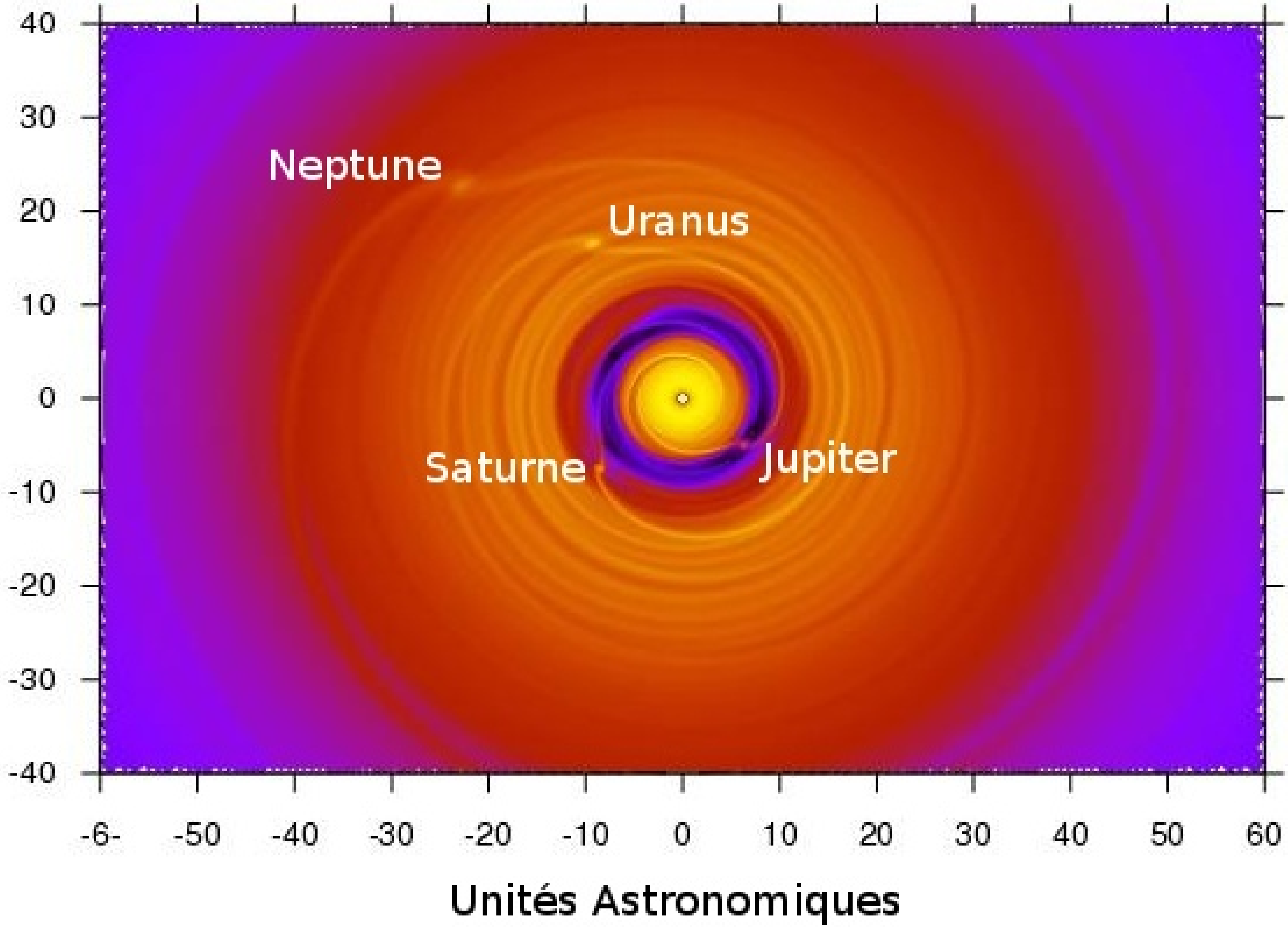


Aurélien CRIDA

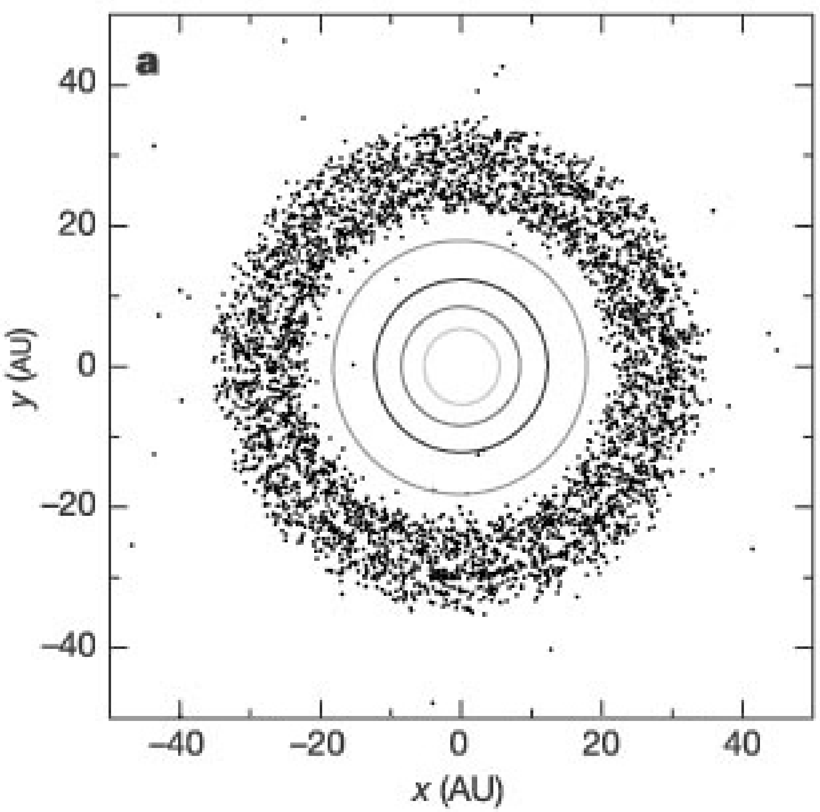
# MIGRATION in the SOLAR SYSTEM



# MIGRATION in the SOLAR SYSTEM

**Once the gas disk is dissipated, Jupiter, Saturn, Uranus and Neptune are in a resonant, compact (between 5 and 15 AU) configuration, on circular orbits, and there remains a dense belt of planetesimals outside.**

**It is not the case now...**



# A LATE HEAVY BOMBARDMENT ?

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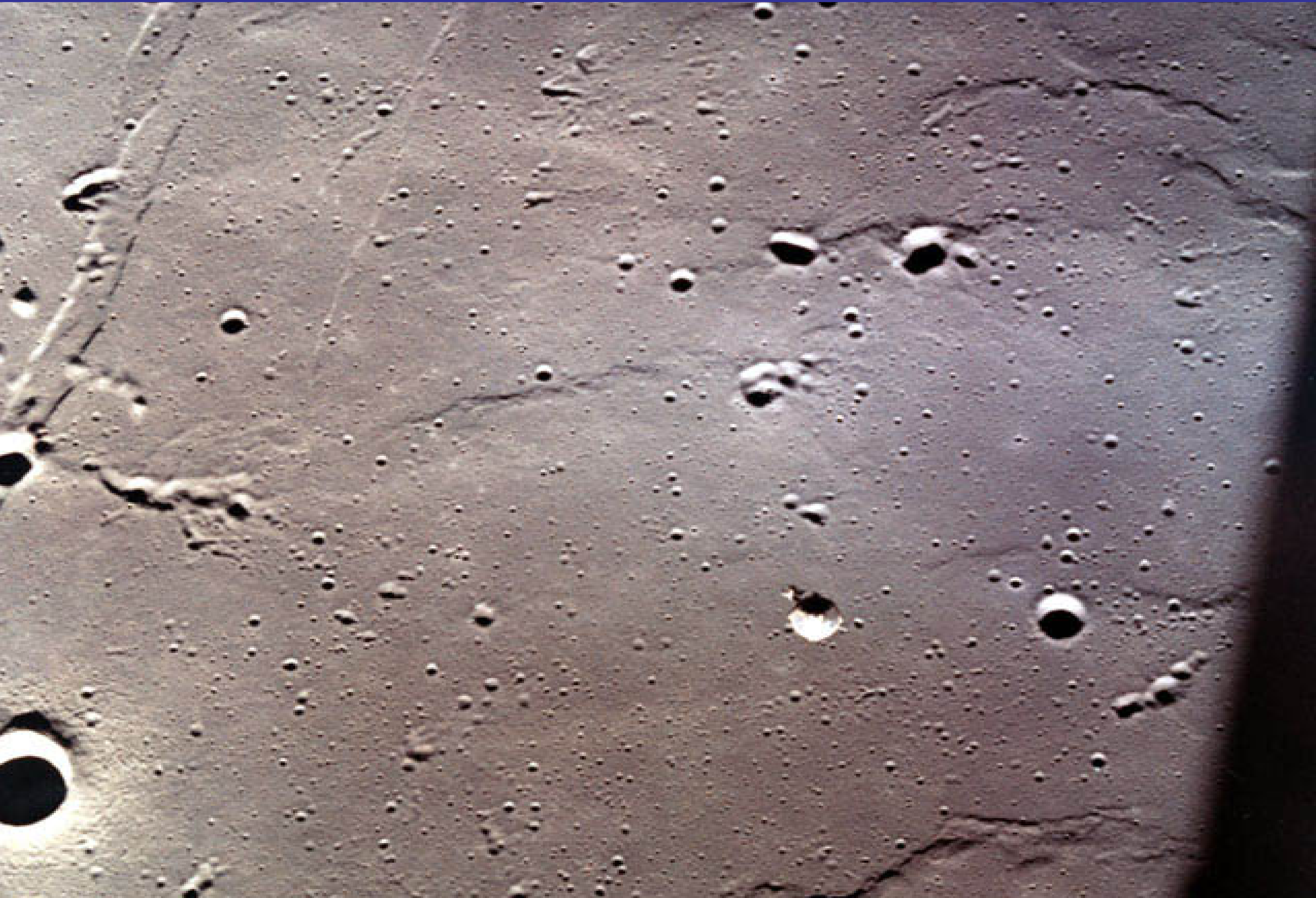

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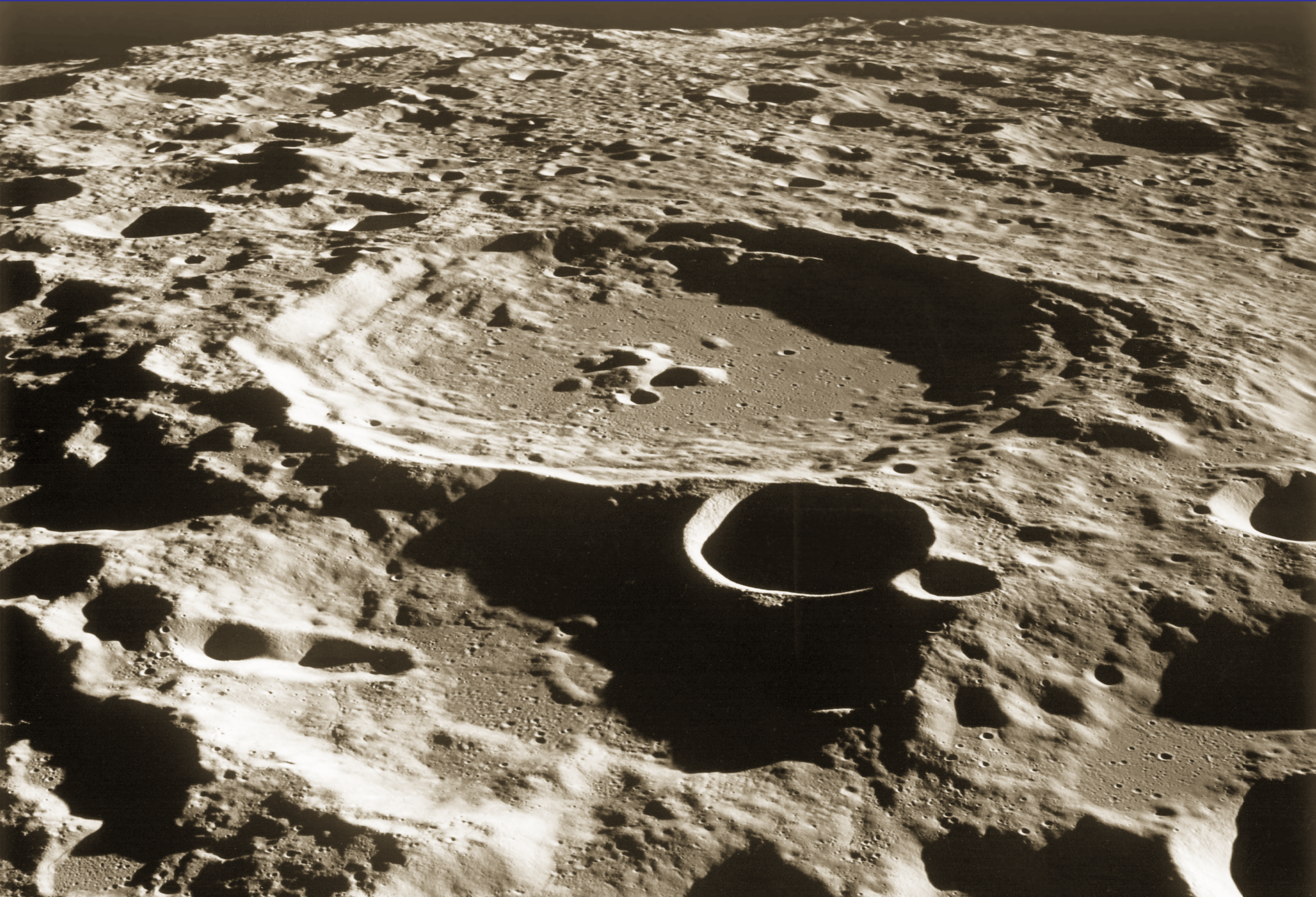
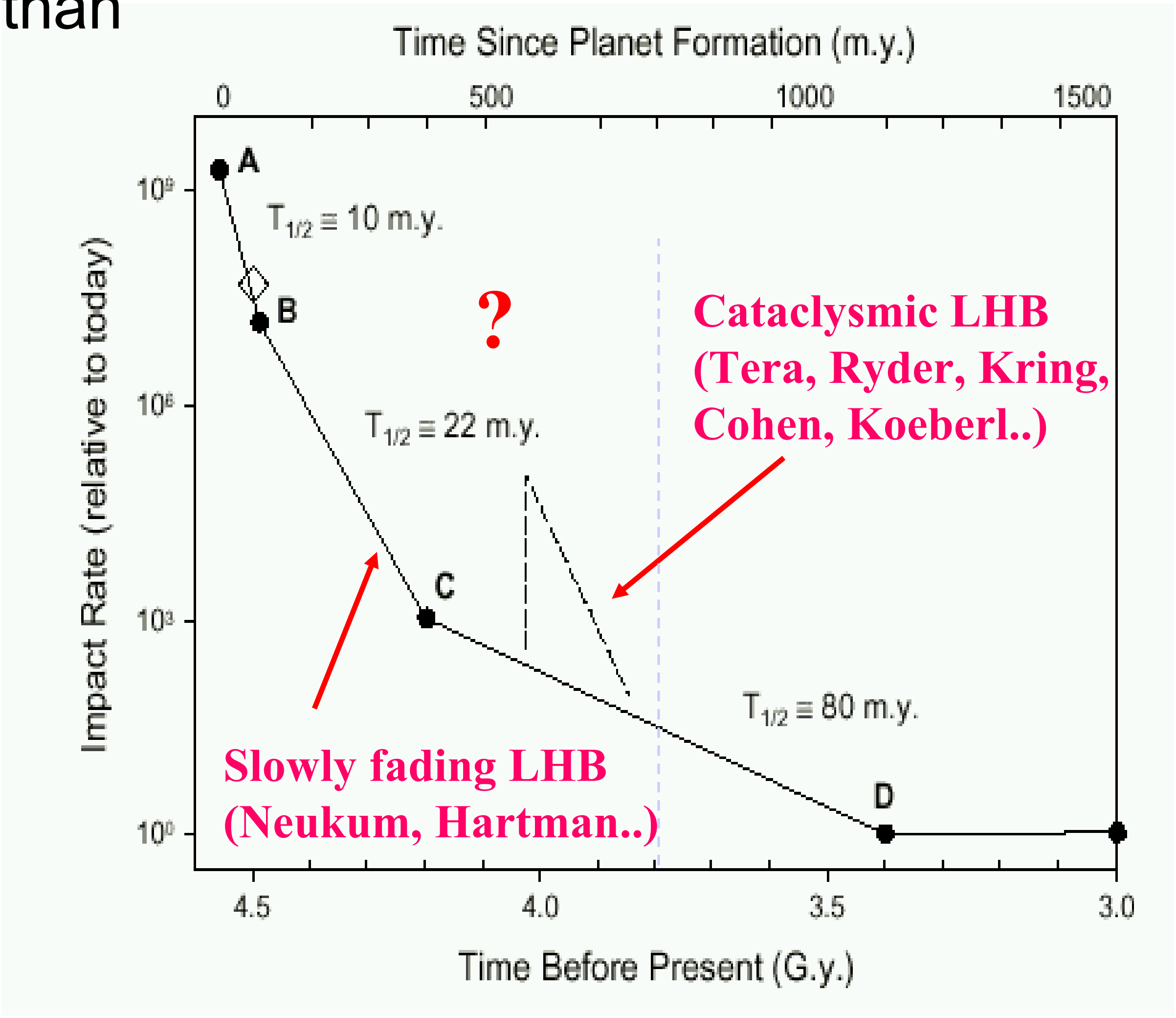


# A LATE HEAVY BOMBARDMENT ?

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 ?



# A LATE HEAVY BOMBARDMENT ?

## Evidence for a cataclysm ~4.0-3.8 Gy ago:

**The ages of the rocks collected on the Moon cluster at ~3.9-3.8 Gy, and rocks older than 4 Gy are extremely rare.**

**Suggests a disastrous sudden and short-lived cratering episode about 3.9 Gy ago, which distroyed all primoridal rocks, resetting their ages (Tera et al., 1974)**

## Counter-argument:

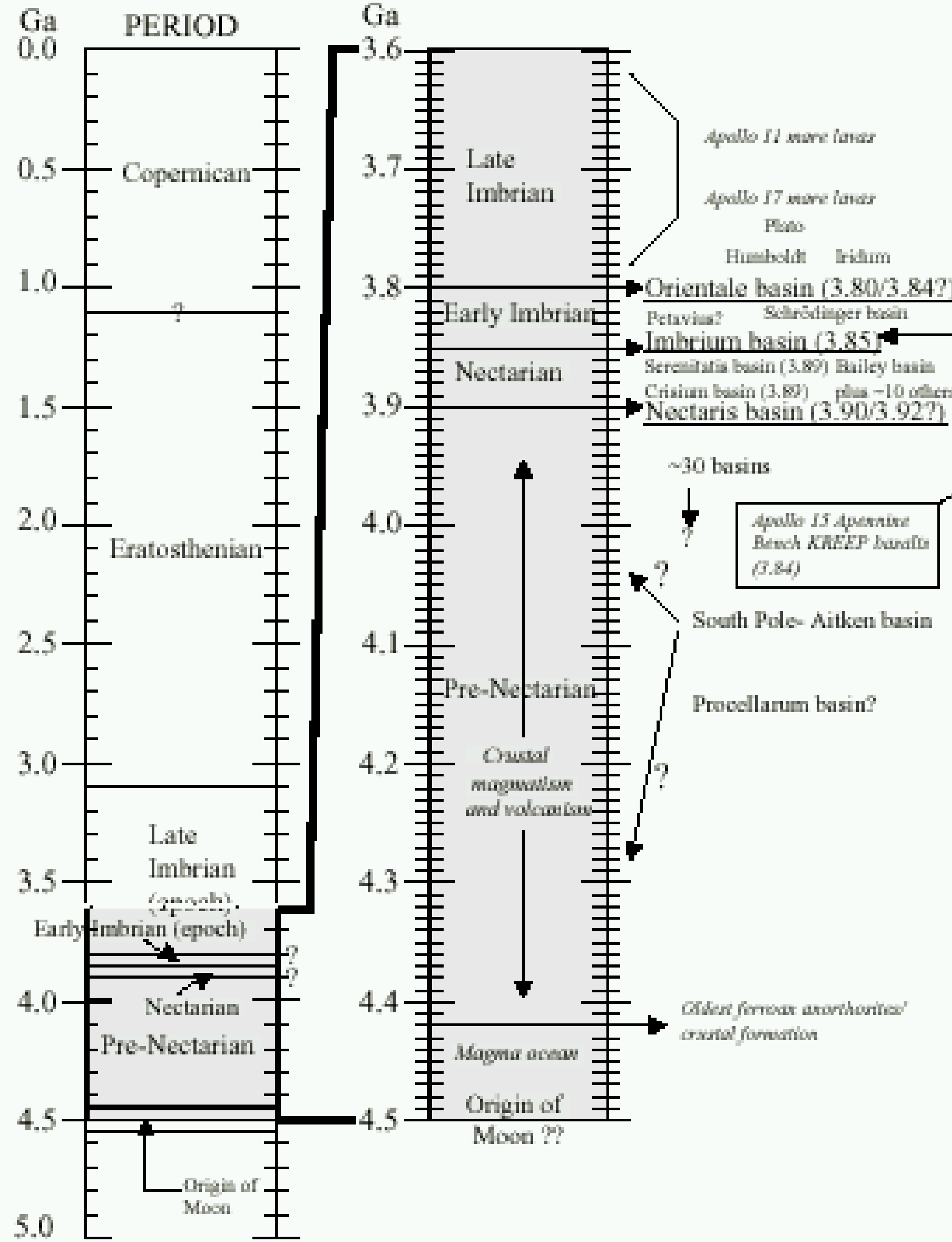
**A very heavy, time declining, bombardment, could produce the same effect (Hartung, 1974; Hartmann, 1975, 1980, Grinspoon, 1989)**

# Evidence for a cataclysm ~4.0-3.8 Gy ago:

The ages of many basins (impact features > 200km) cluster in the 3.9-3.8 Gy period (Wilhelms, 1987; Ryder, 1994)

# Counter-argument:

Basins datations are fooled because collected samples are dominated by Imbrium ejecta (Haskin, 1998). Only Imbrium is dated.



# A LATE HEAVY BOMBARDMENT ?

**Evidence for a cataclysm ~4.0-3.8 Gy ago:**

The amount of siderophile elements on the ancient highlands suggest that the amount of interplanetary mass accumulated by the Moon in the 4.4-3.9 Gy period is about the same of that required to form the basins in the 3.9-3.8 Gy period (5 $10^{21}$g), 20 times less than suggested by models with a declining bombardment from the time of formation

**Counter-argument:**

It critically depends on the assumed composition of the early impactors. Was it the same as that of the current meteorites?

# A LATE HEAVY BOMBARDMENT ?

**Evidence for a cataclysm ~4.0-3.8 Gy ago:**

On Earth, the oldest minerals are more than 4 Gyr old,

but the oldest full rock is only 3.8 Gyr (Isua, Greenland).

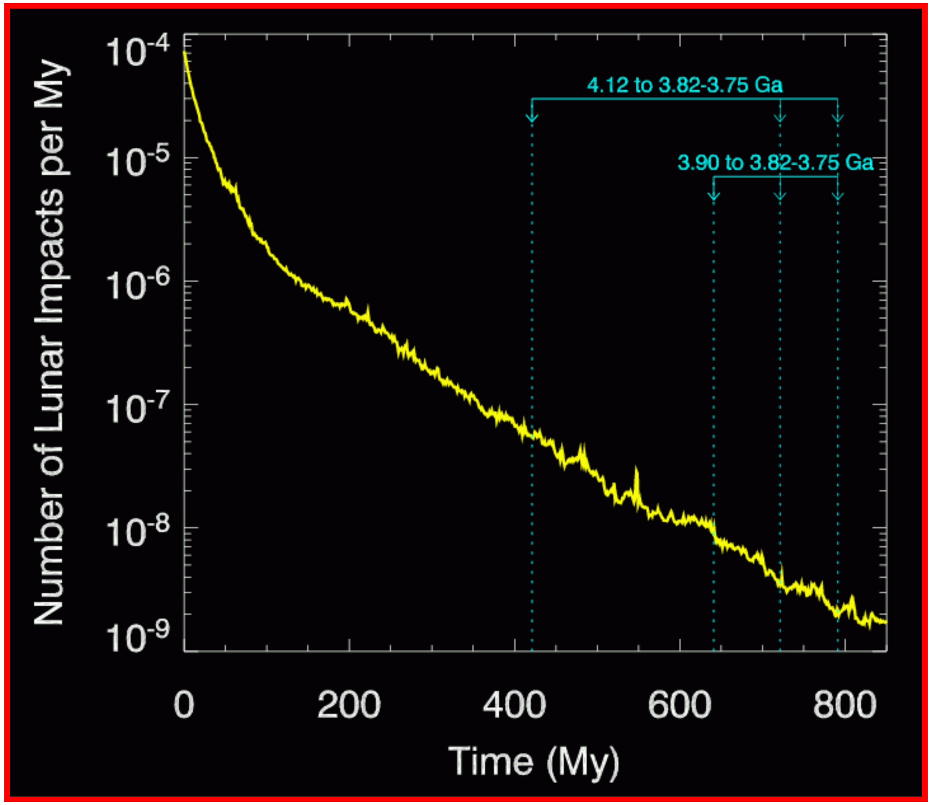
Was the surface reprocessed 3.9 Gyr ago ?

**Counter-argument:**

Plate tectonics may have swallowed older rocks.

# A LATE HEAVY BOMBARDMENT ?

DECAY RATE OF POST-PLANET FORMATION POPULATION




Nectaris, Serenitatis, Imbrium and Orientale Basins:

If formed between 3.90 < $t$ < 3.82-3.75 Gy, the total mass of the Post planet-formation population had to be ~5-8 $M_{EARTH}$

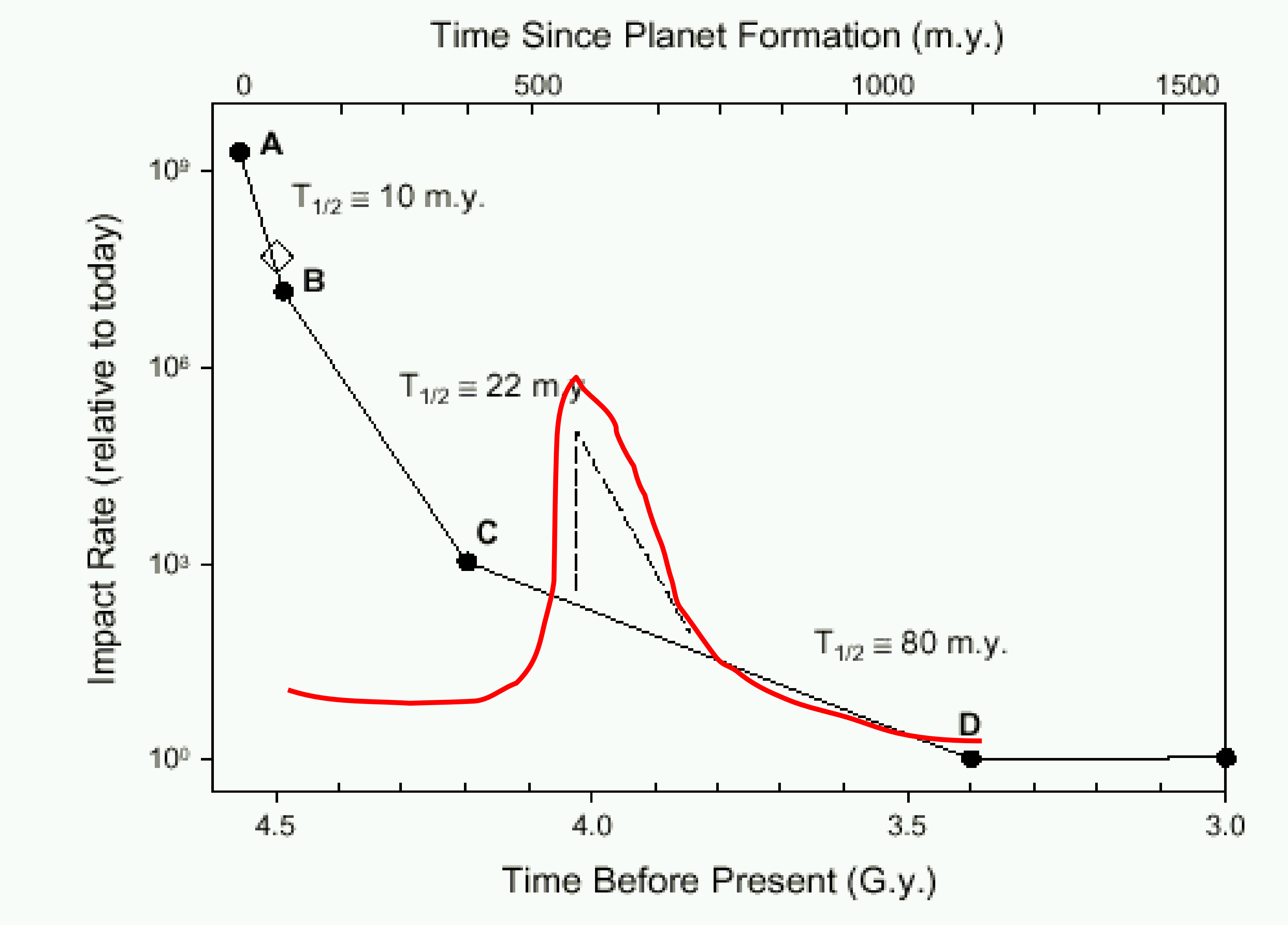
If formed between 4.12 < $t$ < 3.82-3.75 Gy, the total mass had to be at least 0.7 $M_{EARTH}$

Collisional erosion increases both values by a factor of 20!

**Declining Bombardment Model is Unrealistic for LHB!**

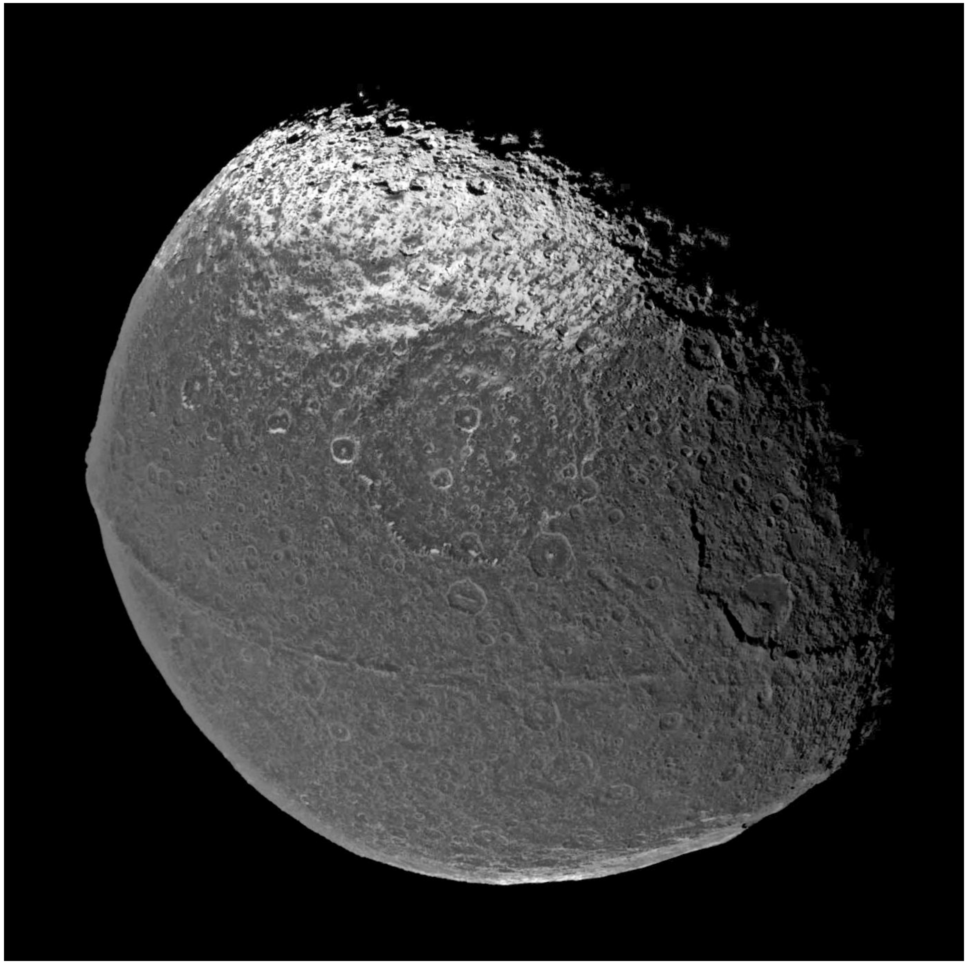
From Bottke et al., Icarus, 2006.

# A LATE HEAVY BOMBARDMENT ?



# A LATE HEAVY BOMBARDMENT ?

**A key issue: did the LHB concern also the outer solar system?**



Iapetus suffered a Heavy Bombardment (> 100x the current bombardment integrated over the age of the solar system: Zahnle et al.)

Was this bombardment late?
It seems so :

Ejecta blankets from basins overlap the equatorial ridge which should have formed at 200-800 My (Castillo et al., Icarus, 2007). Moreover, the satellite crust could not have retained basins before 100 My.

# A LATE HEAVY BOMBARDMENT ?

**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**

"LUNA"

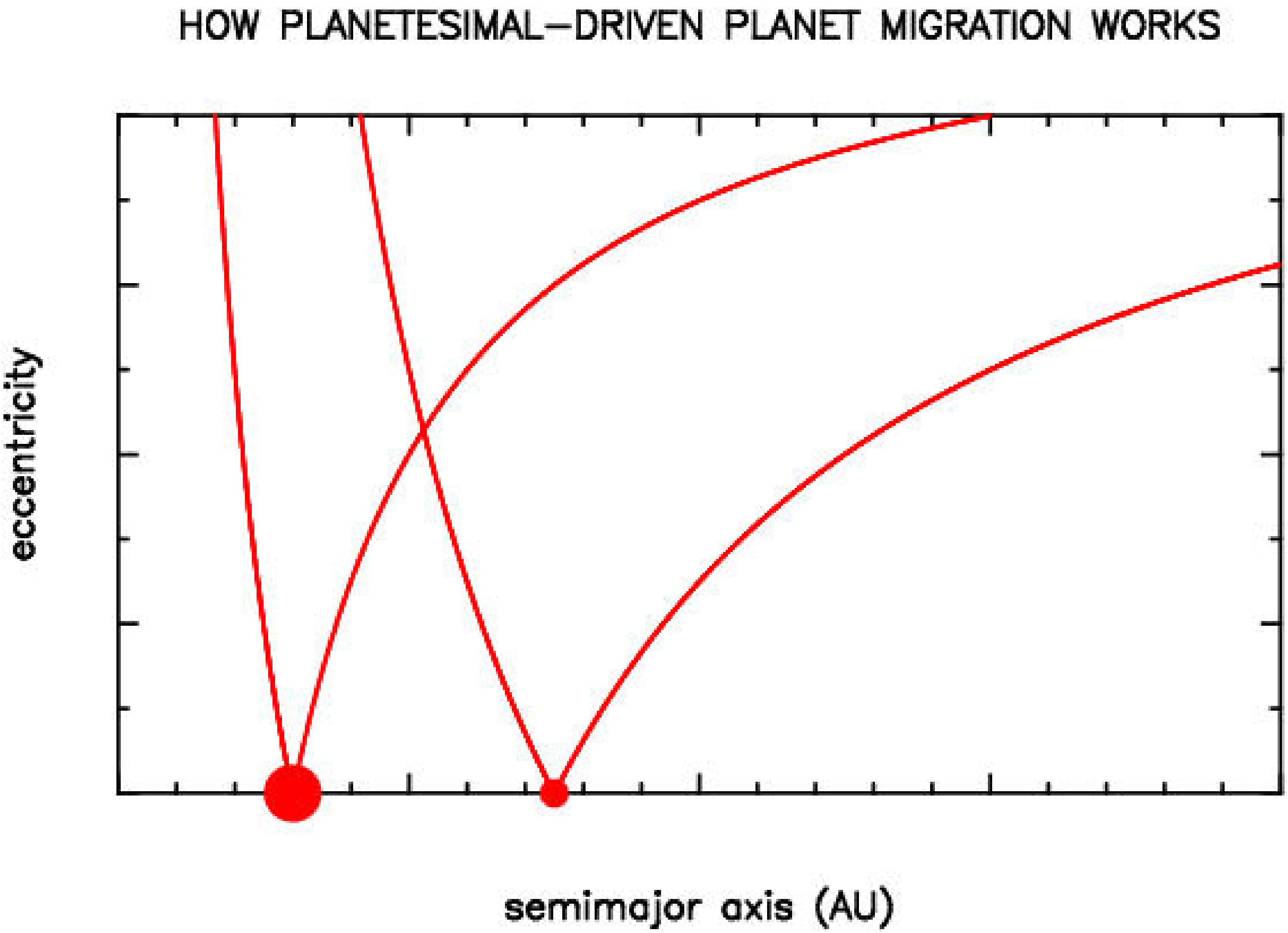
# A LATE HEAVY BOMBARDMENT ?

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 thge planets move, migrate, after the gas disapeared ?

# PLANETESIMALS DRIVEN MIGRATION



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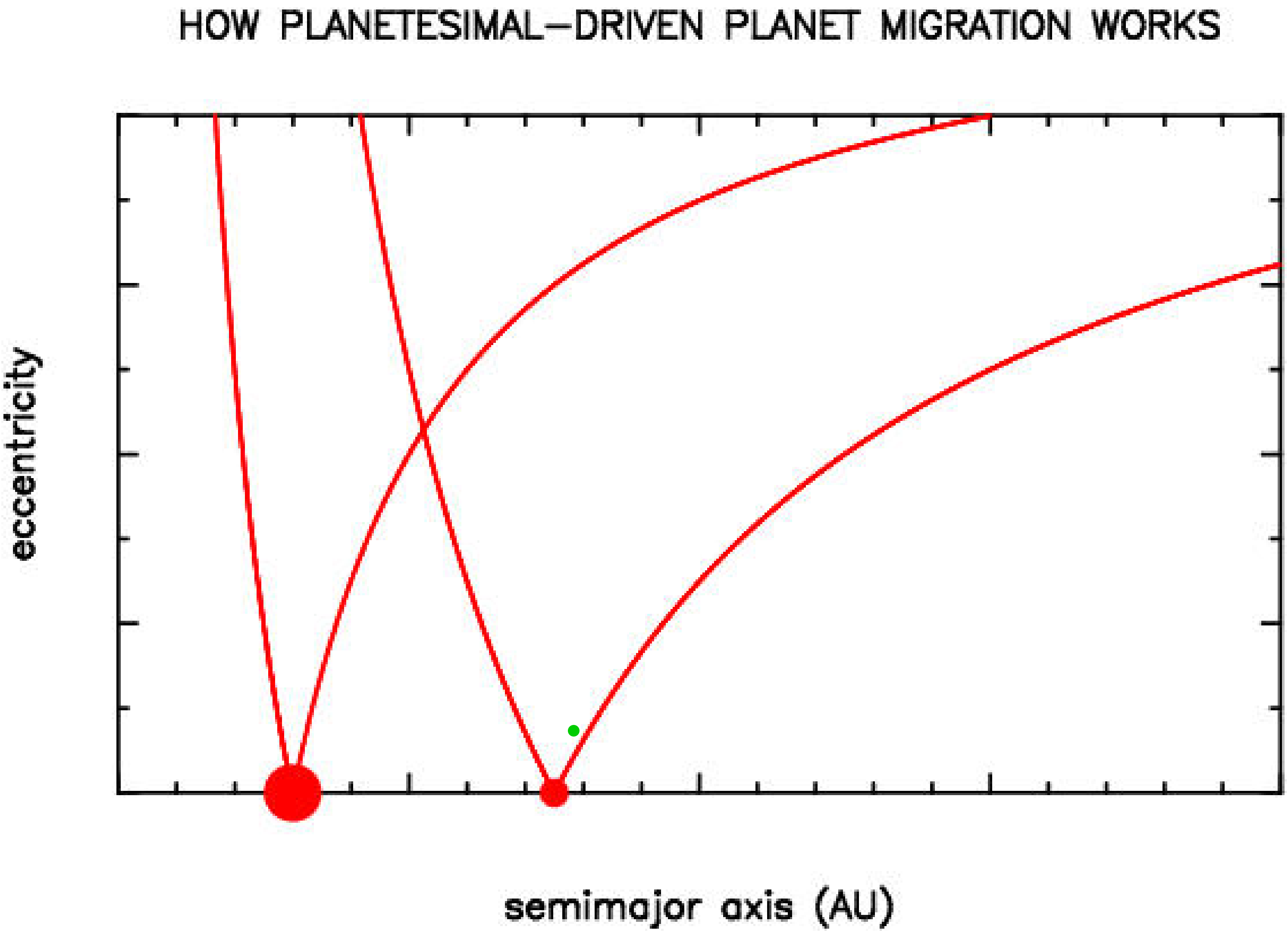

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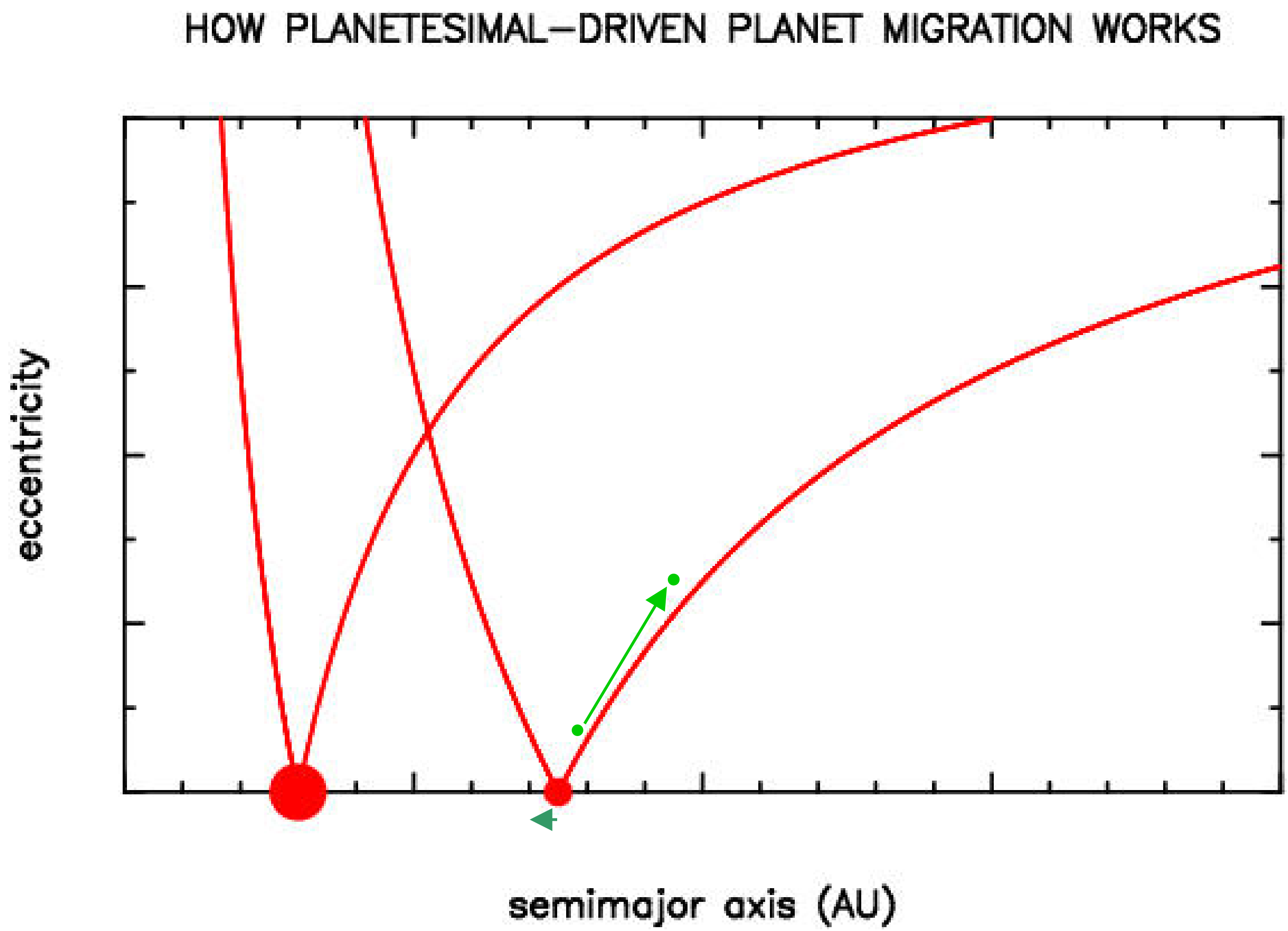

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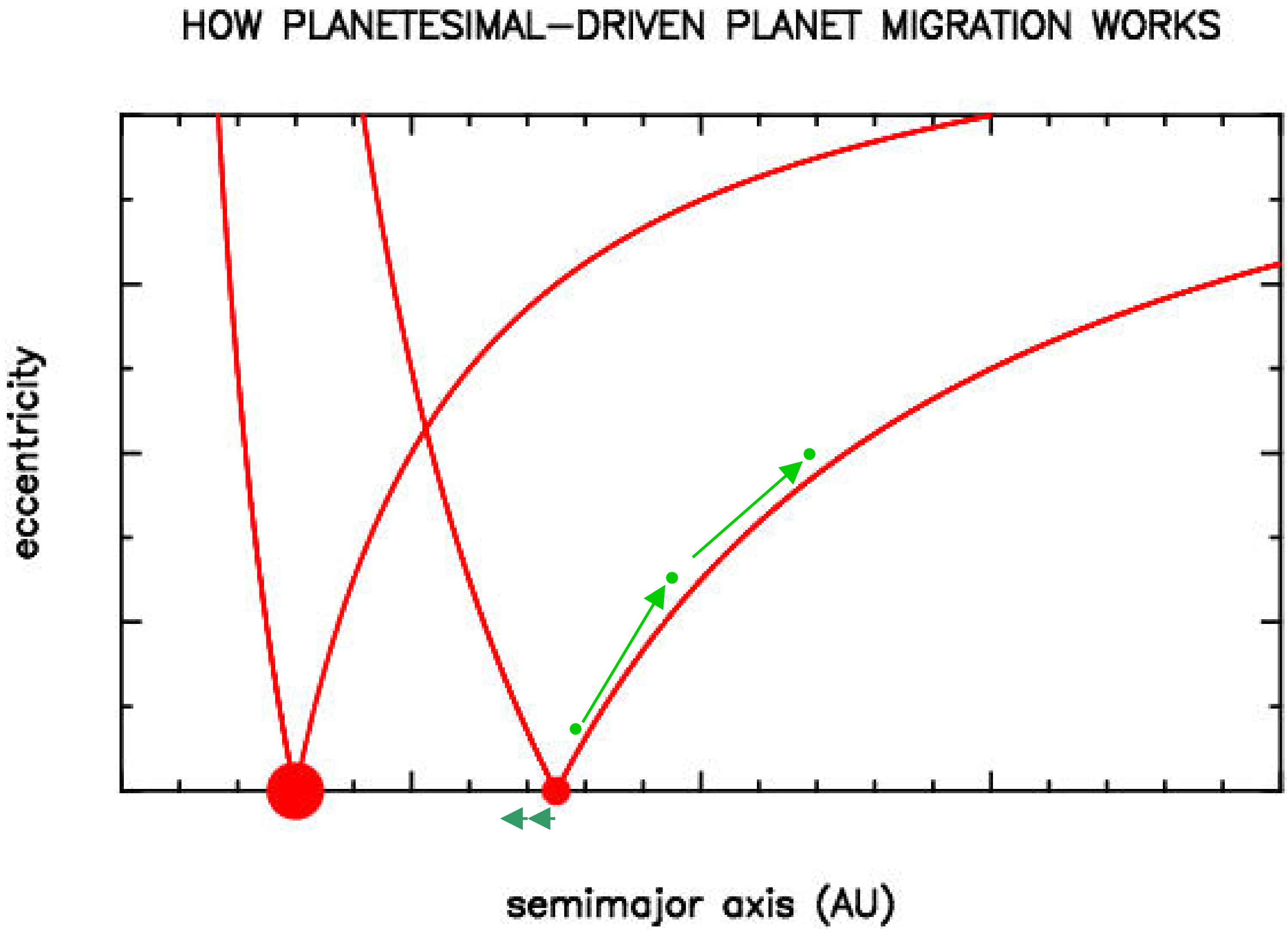

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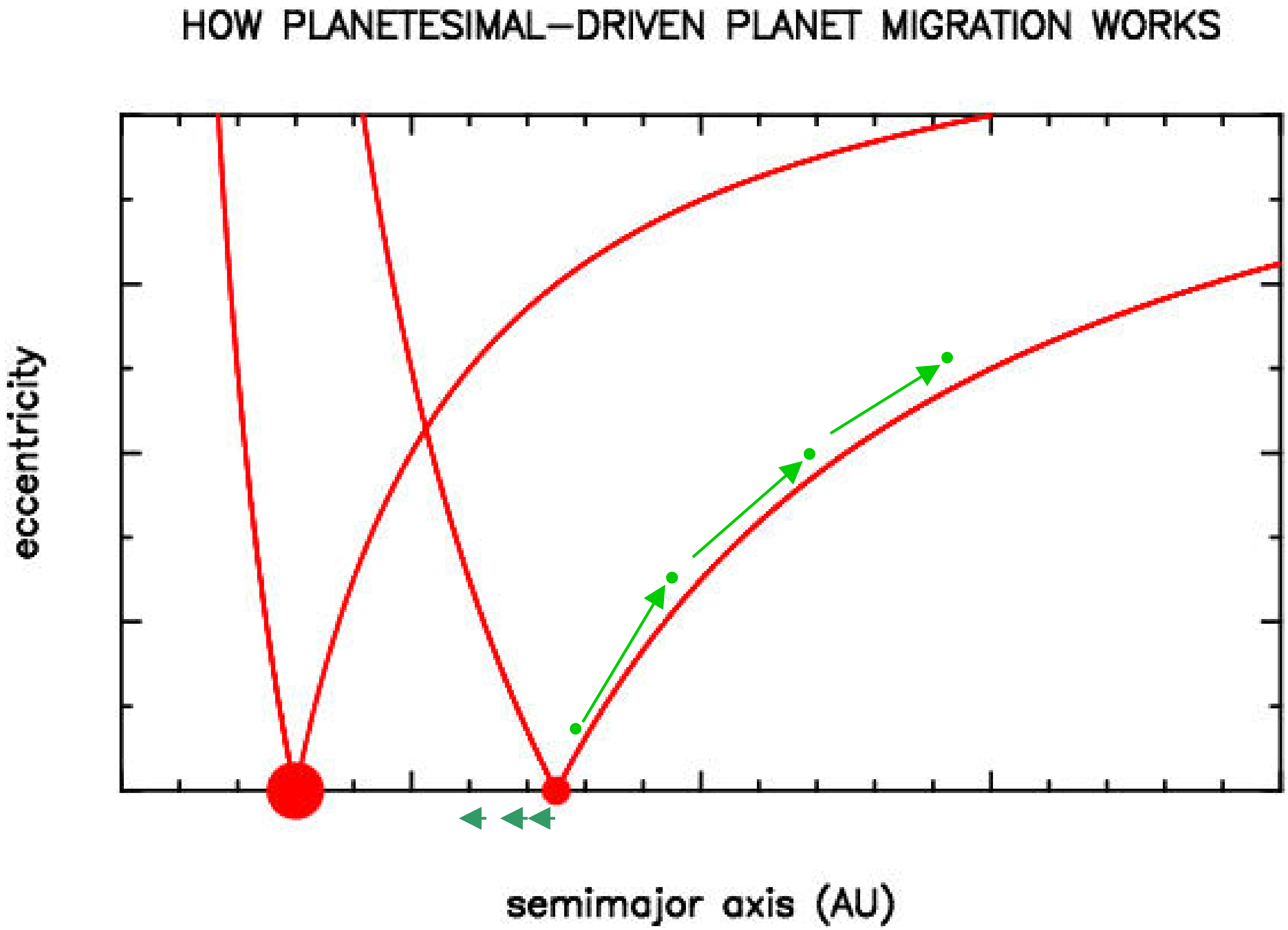

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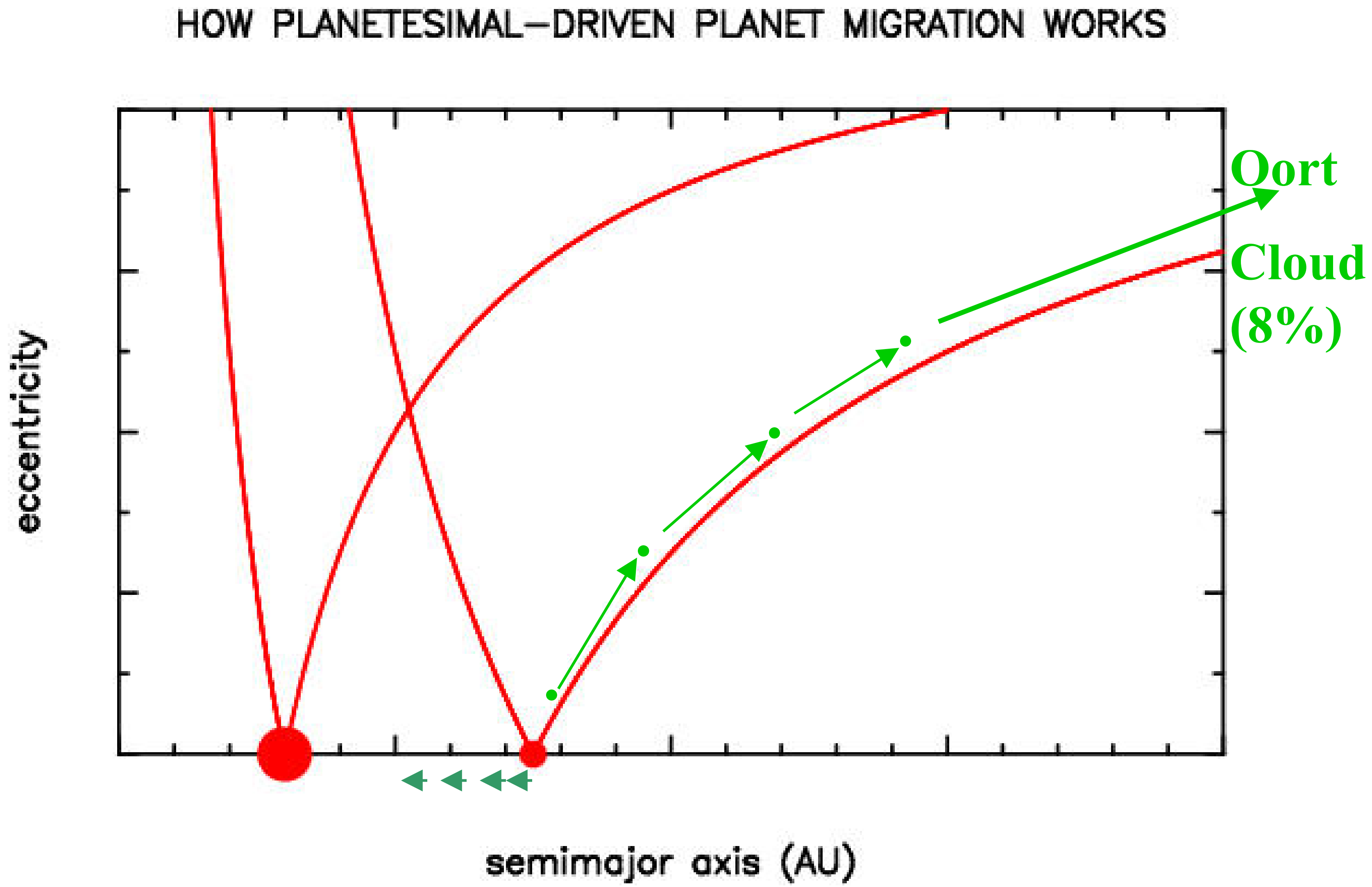

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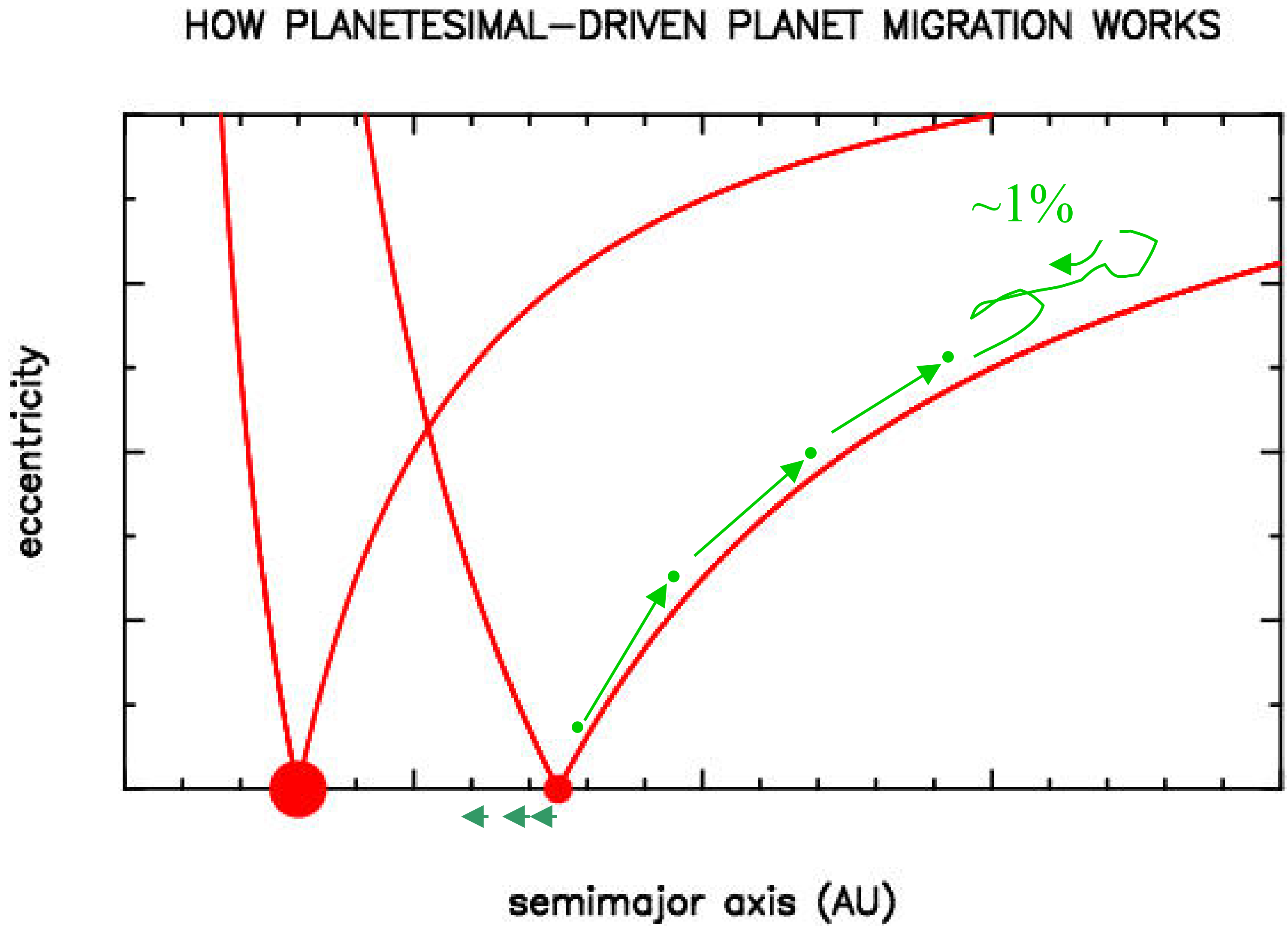

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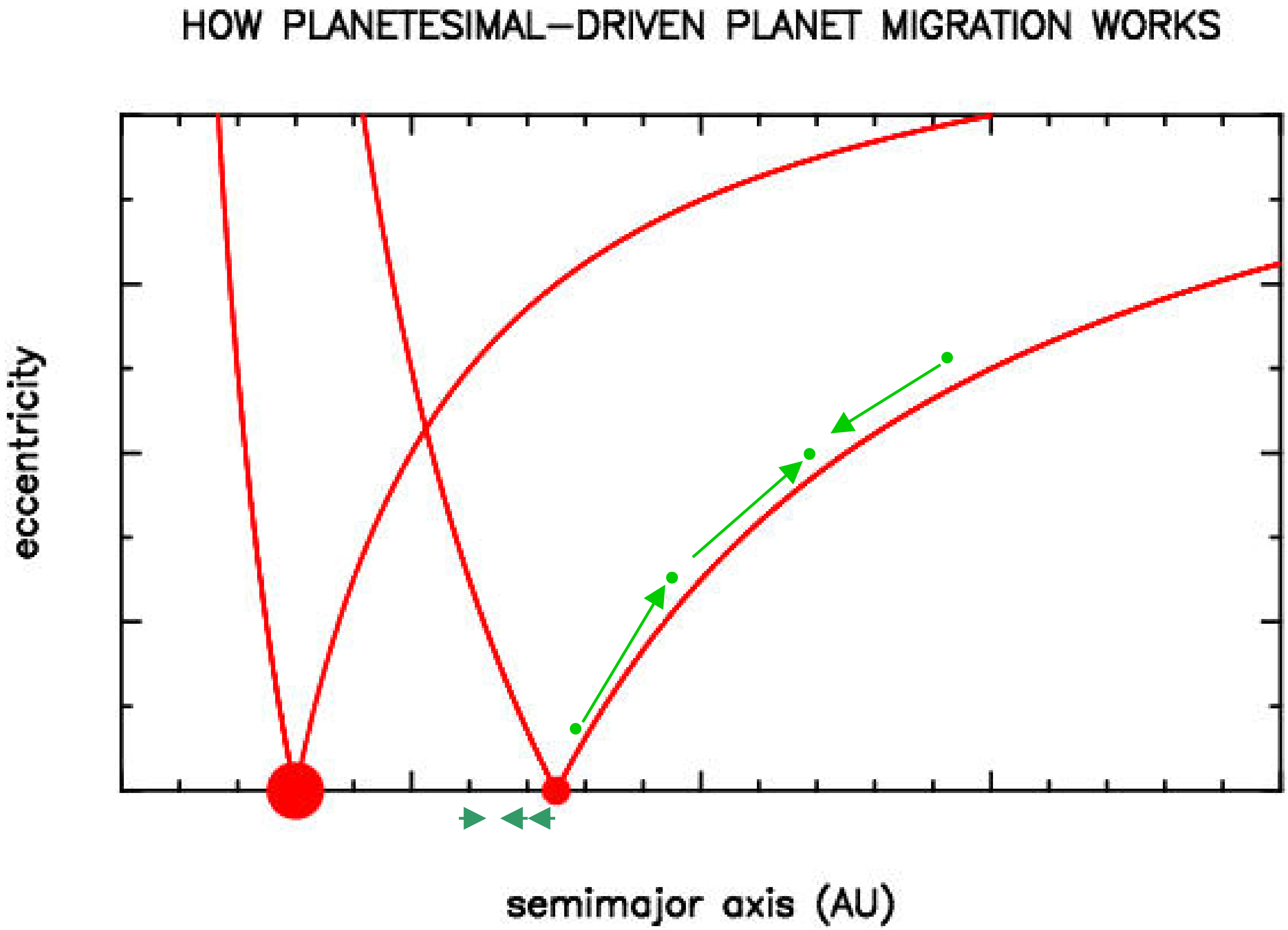

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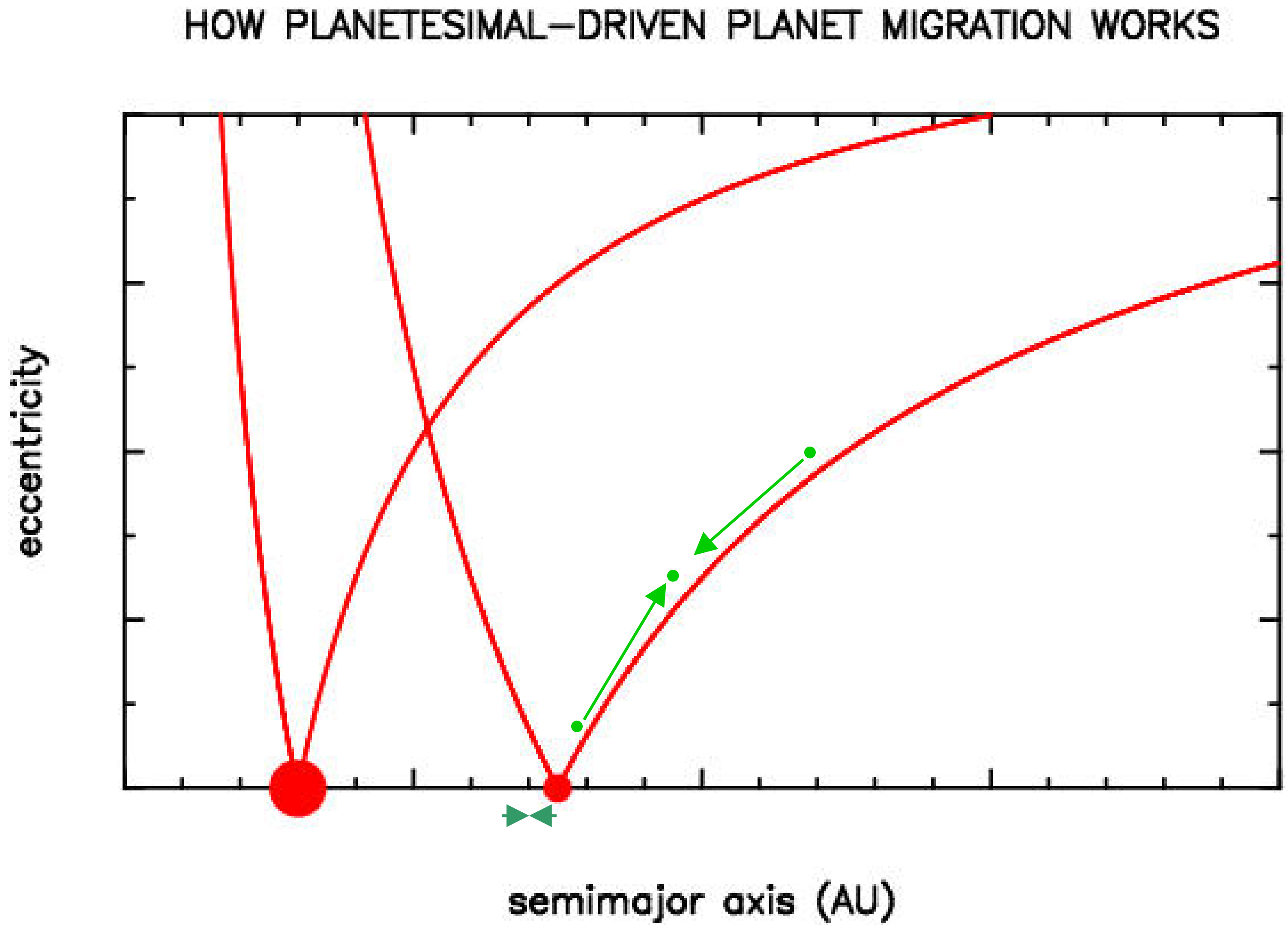

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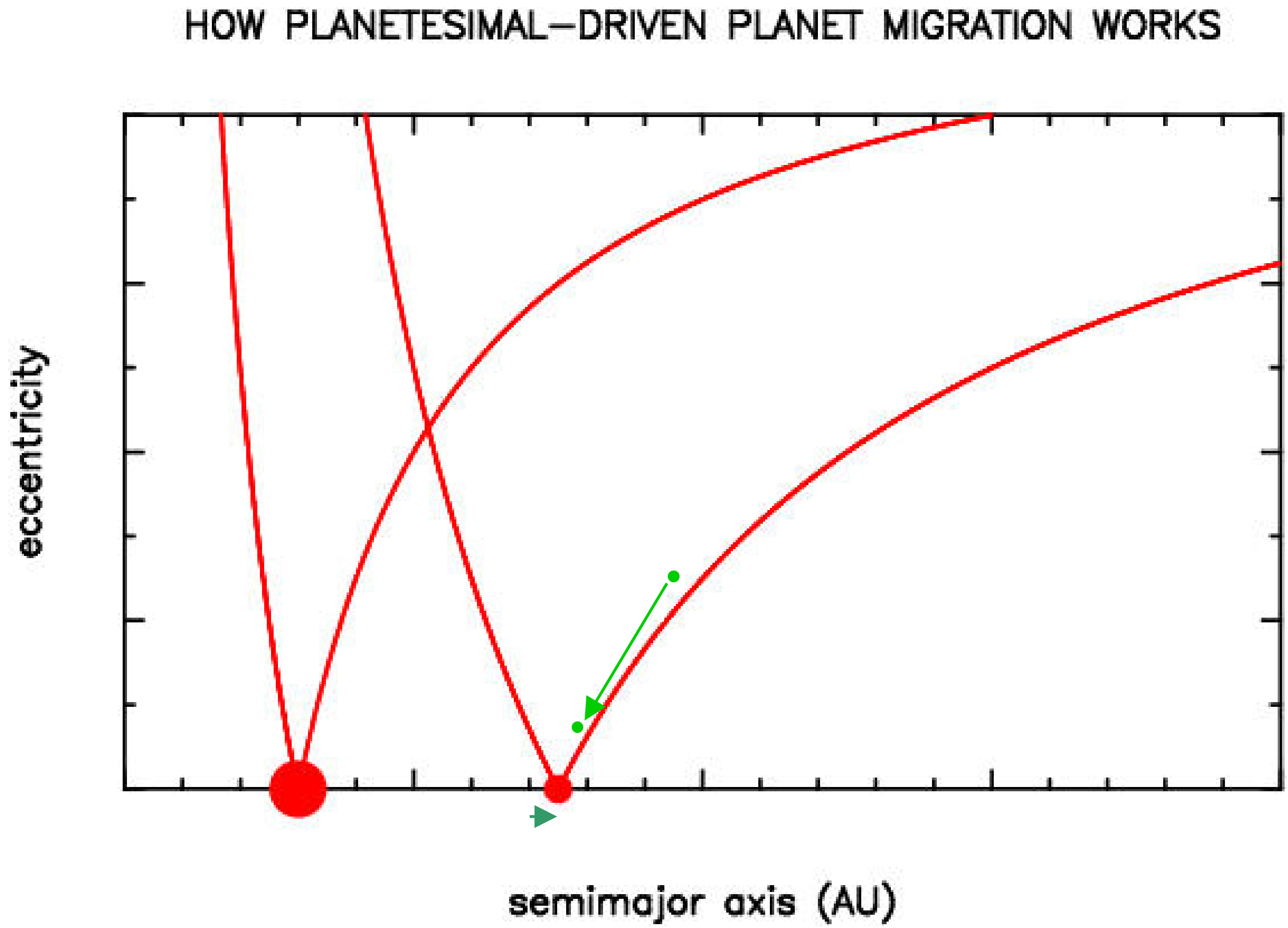

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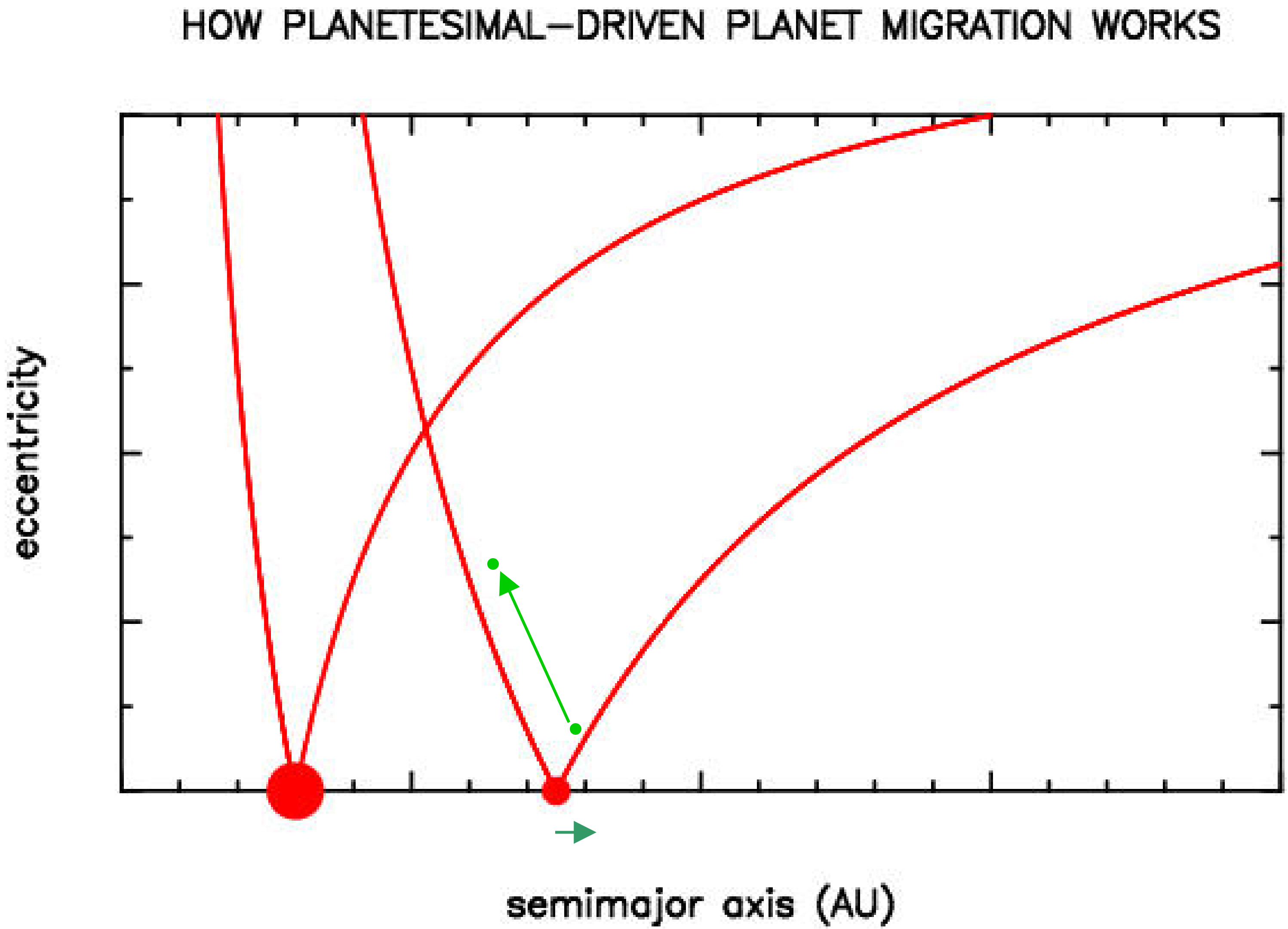

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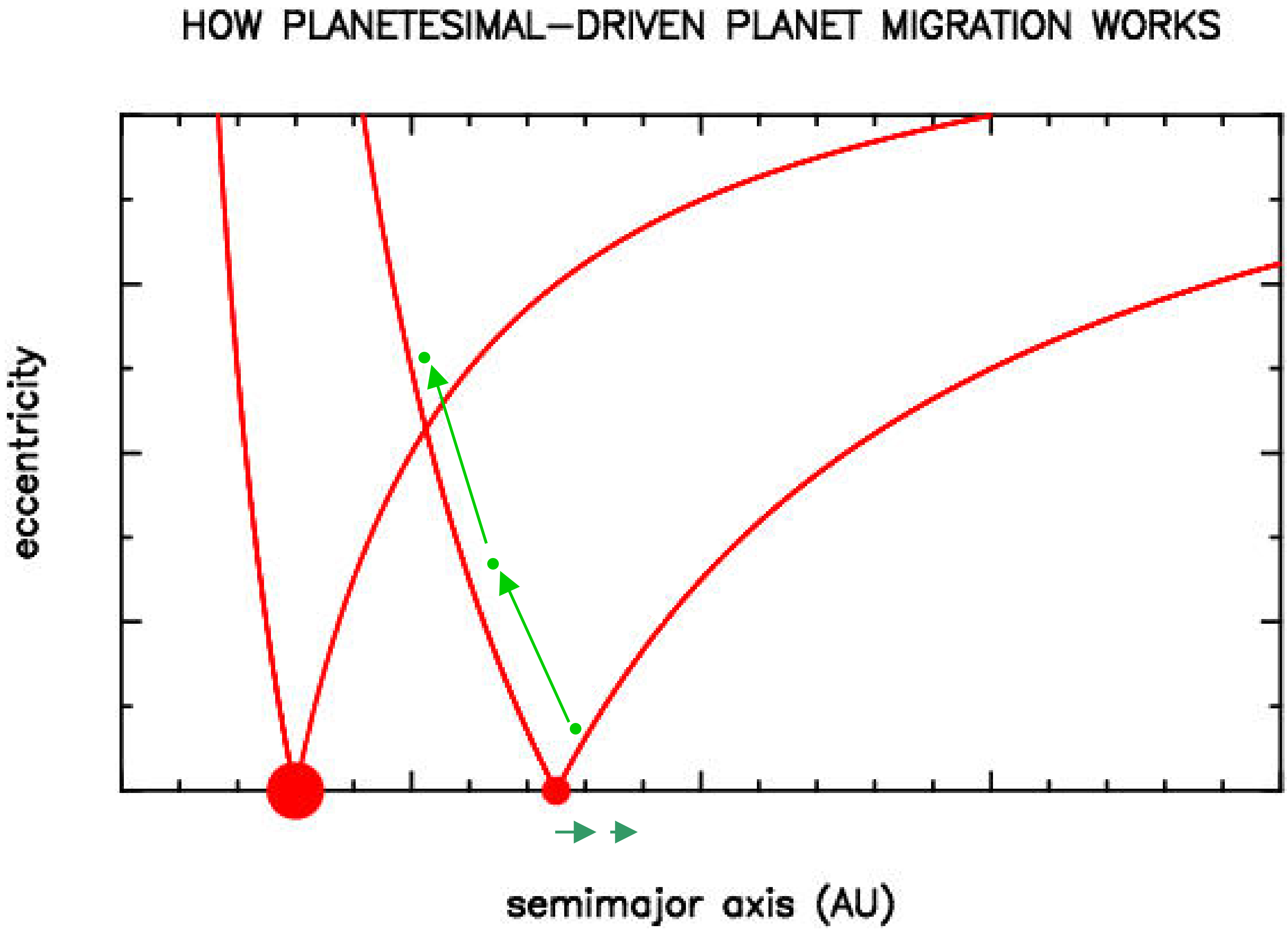

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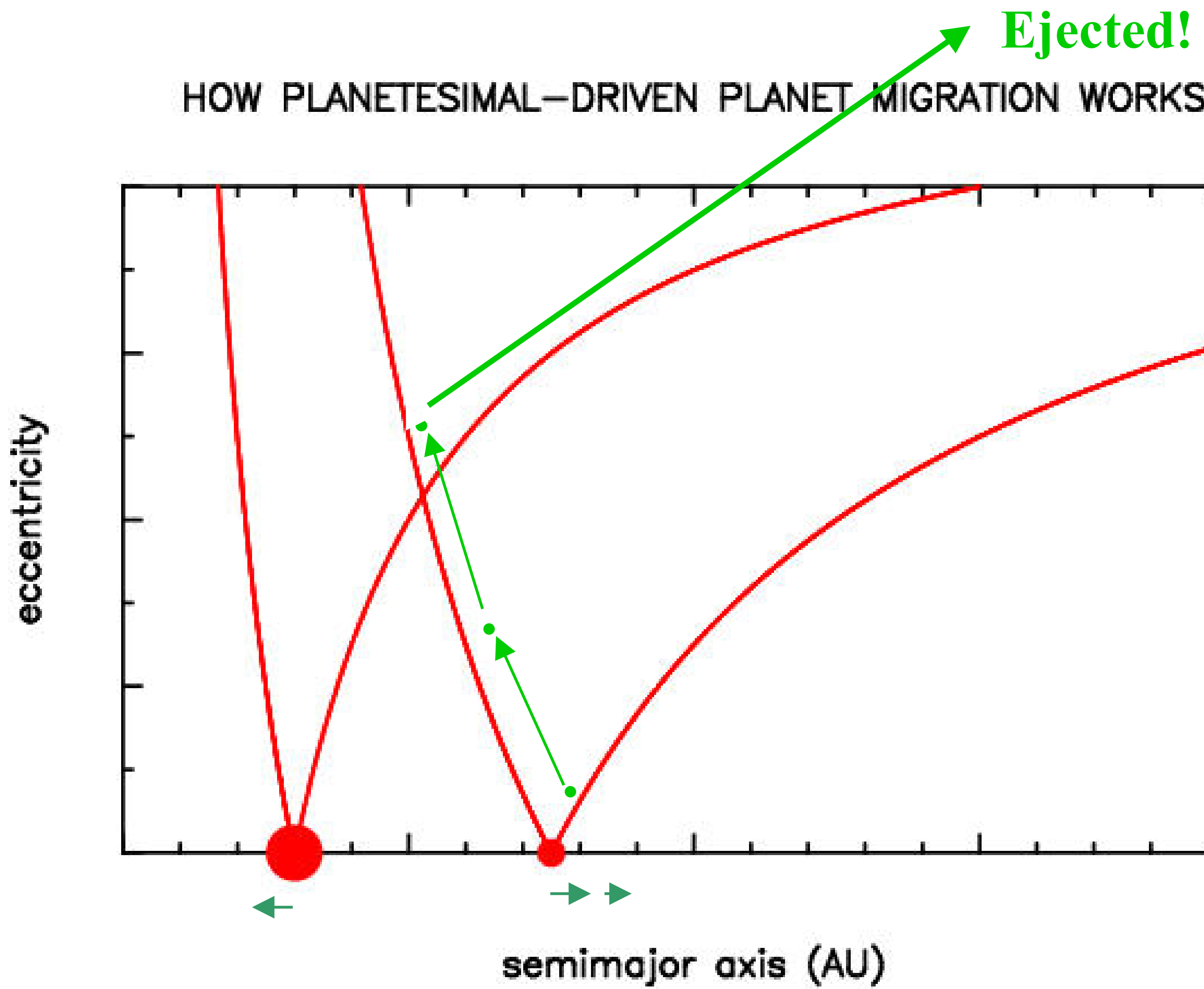
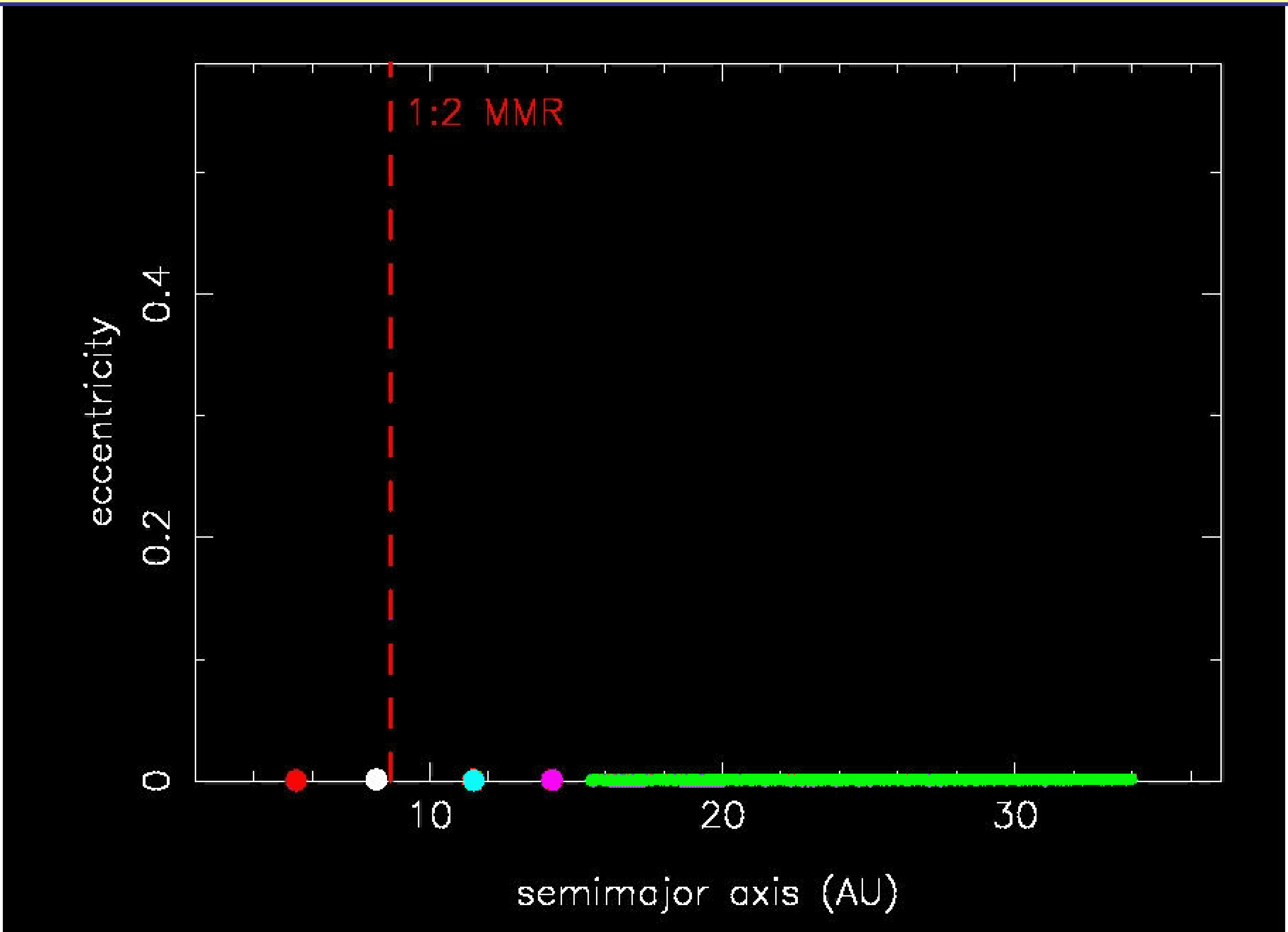
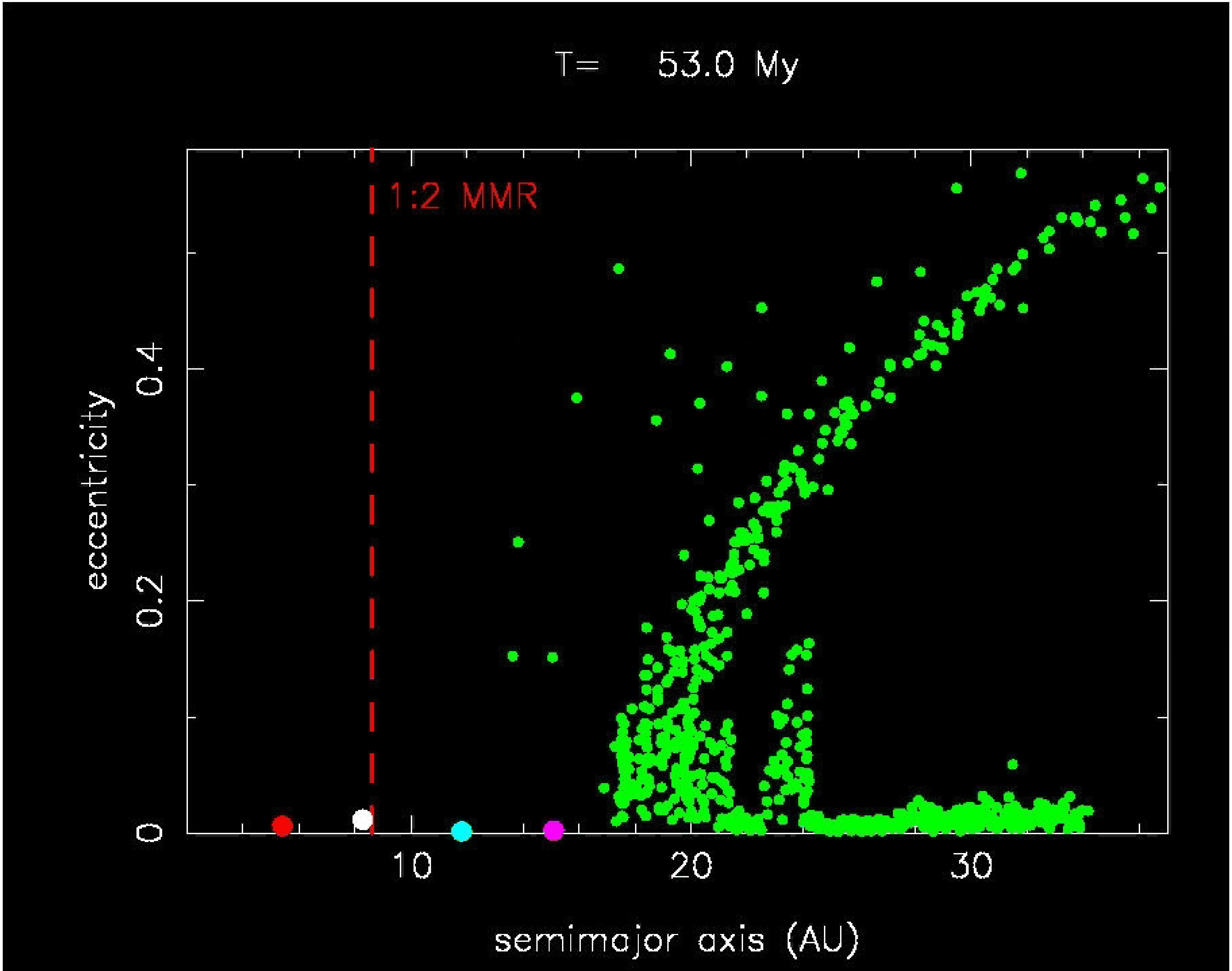
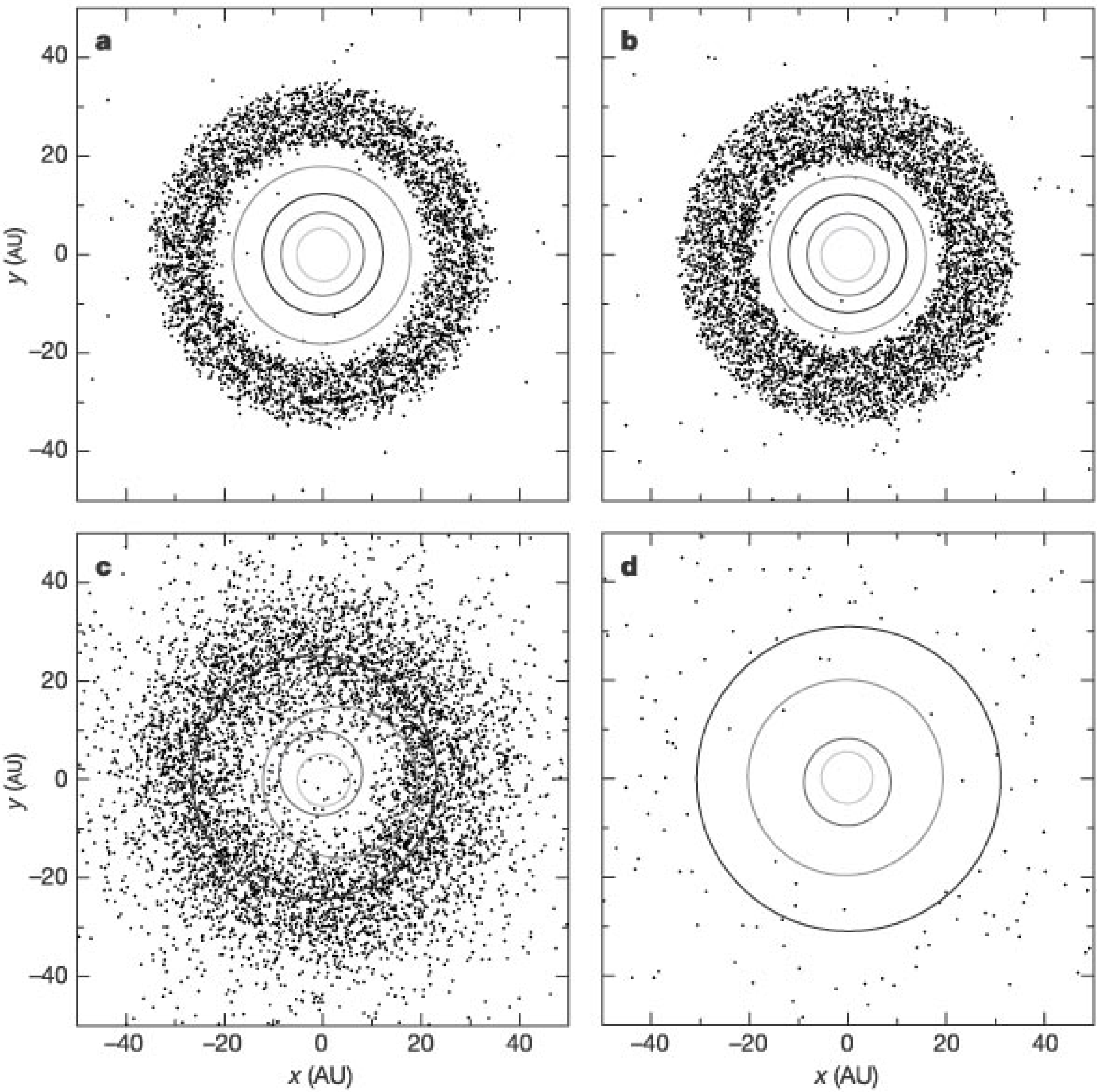


# The NICE MODEL




T= 53.0 My
1:2 MMR
eccentricity
0
0.2
0.4
10
20
30
semimajor axis (AU)

# The NICE MODEL



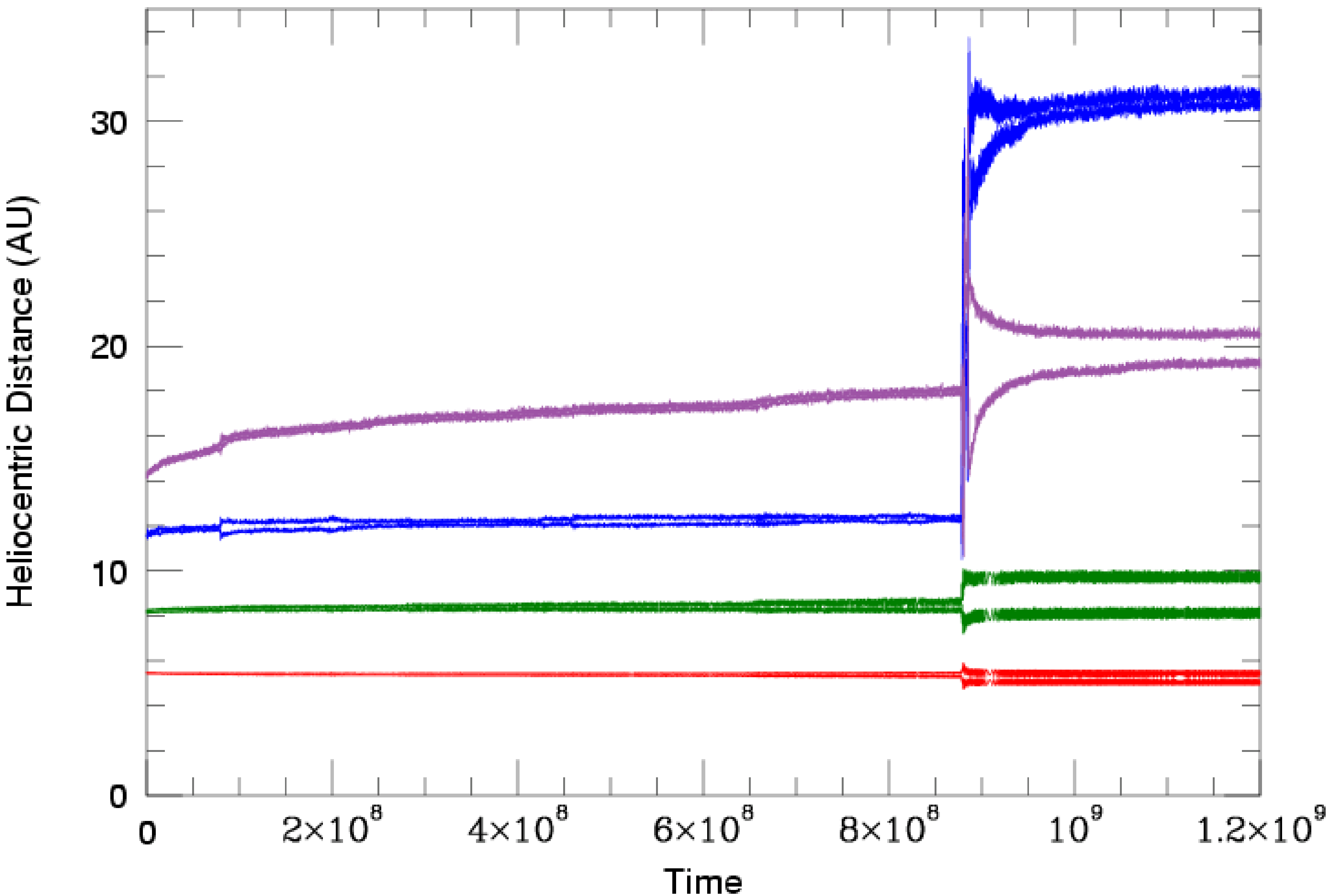

First, slow migration. Jupiter inwards, Saturn, Uranus & Neptune outwards.

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



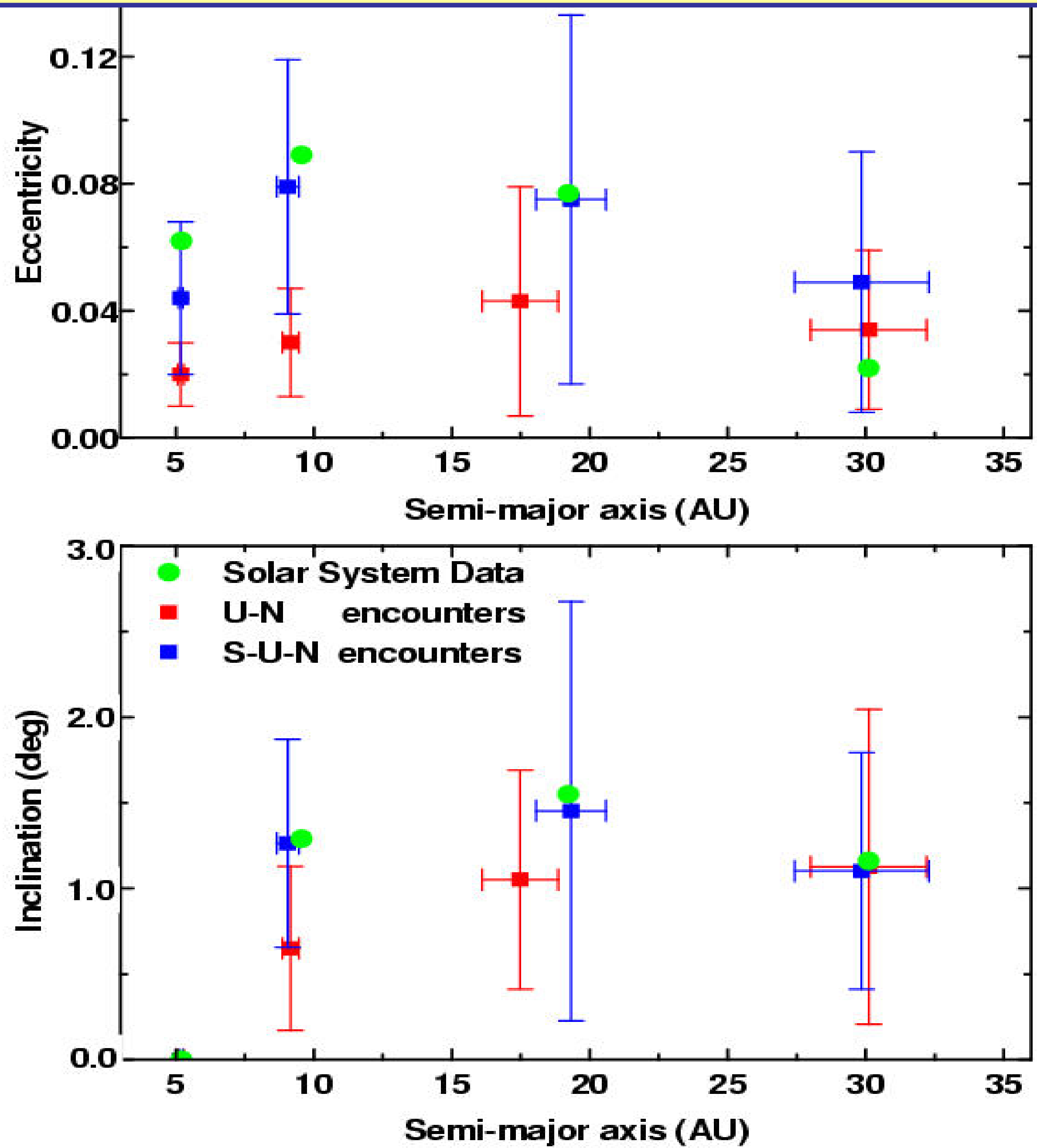

K. Tsiganis, R. Gomes, A. Morbidelli, H.F. Levison 2005. *Nature, 435, 459*

# 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***



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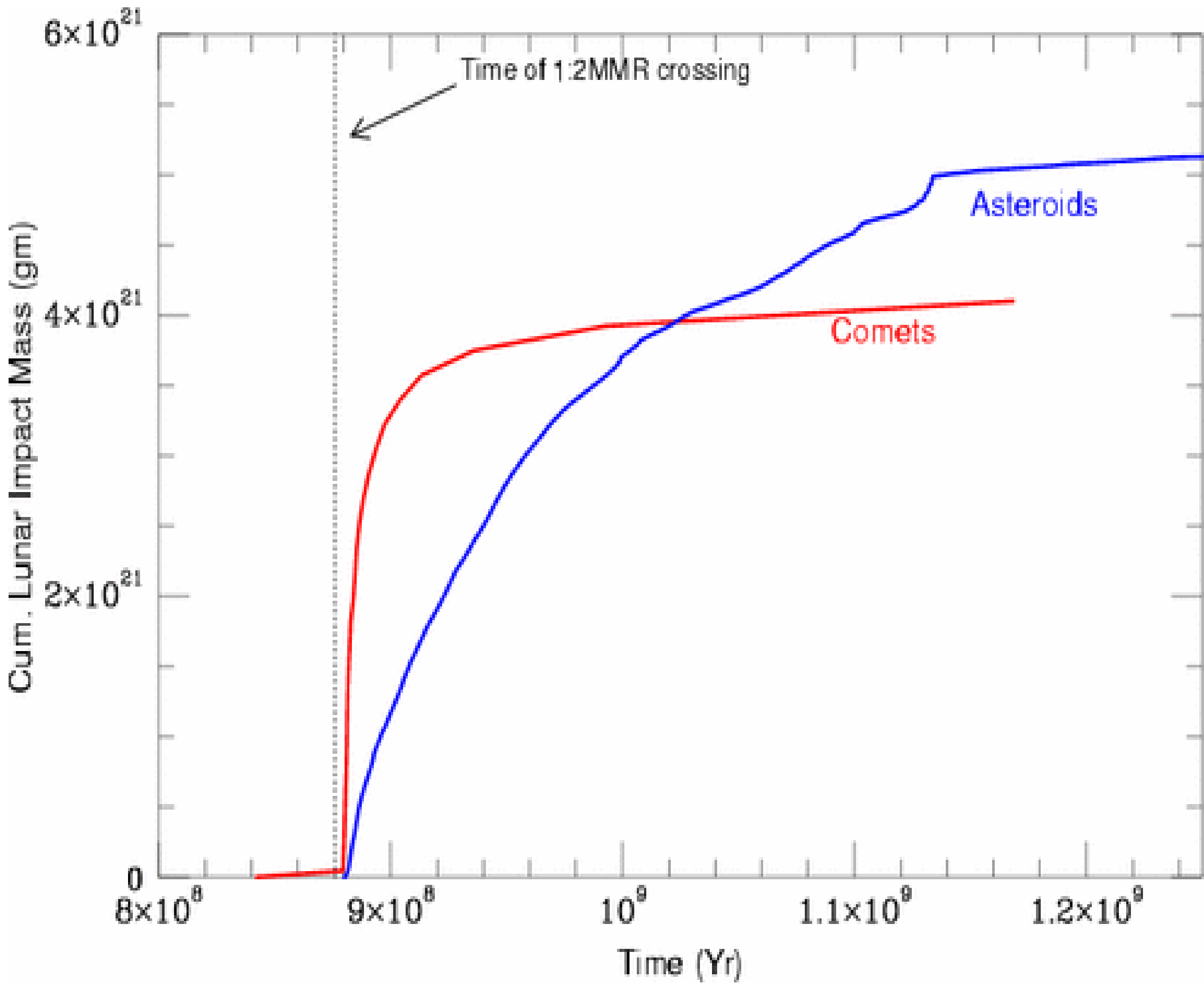
**II: A cometary and asteroidal late bombardment, of the good magnitude compared to craterization constraints on the Moon.**

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



# The NICE MODEL

Are there other consequences of this global instability ?

Yes !

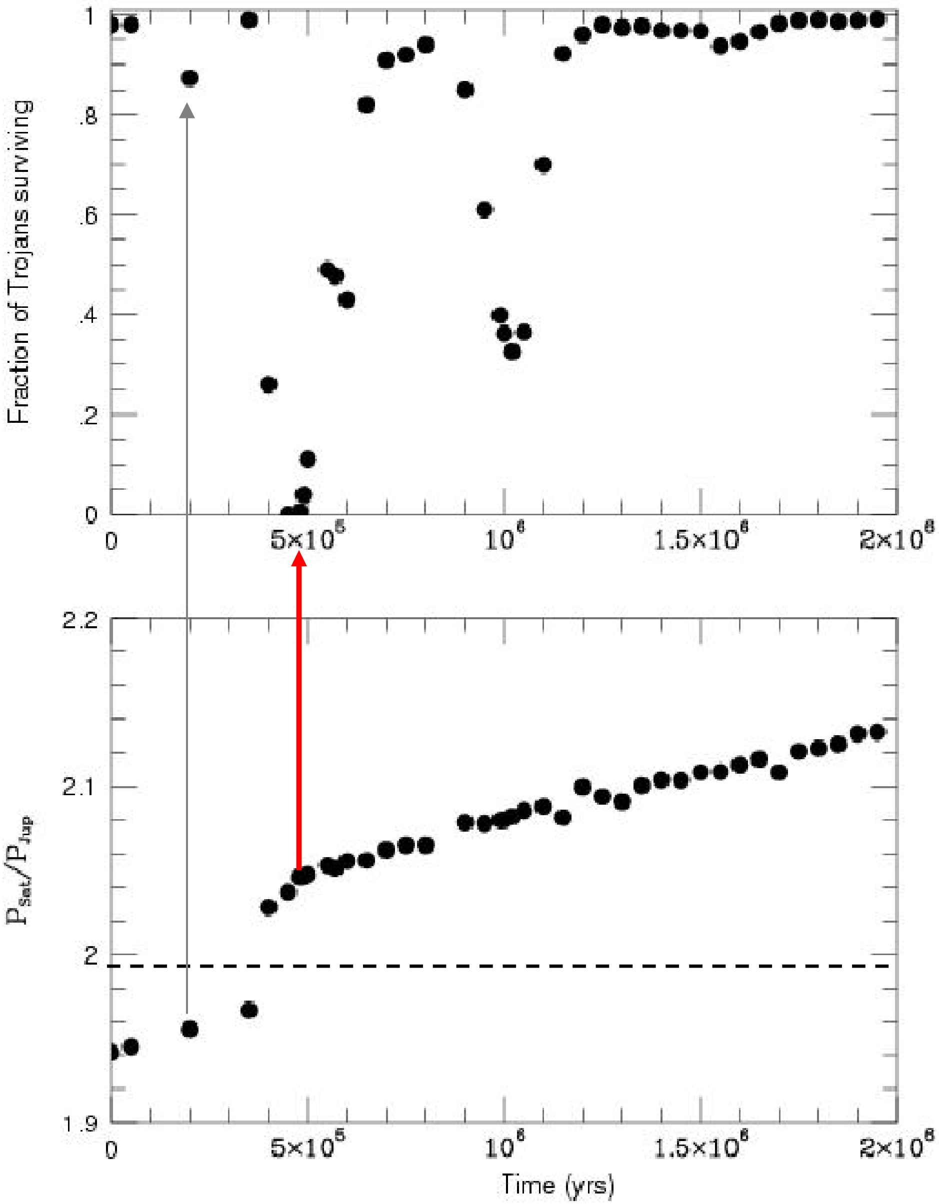
1) Jupiter's trojans

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 ca&n suurvive. They are all lost in the instability. But we see them now...

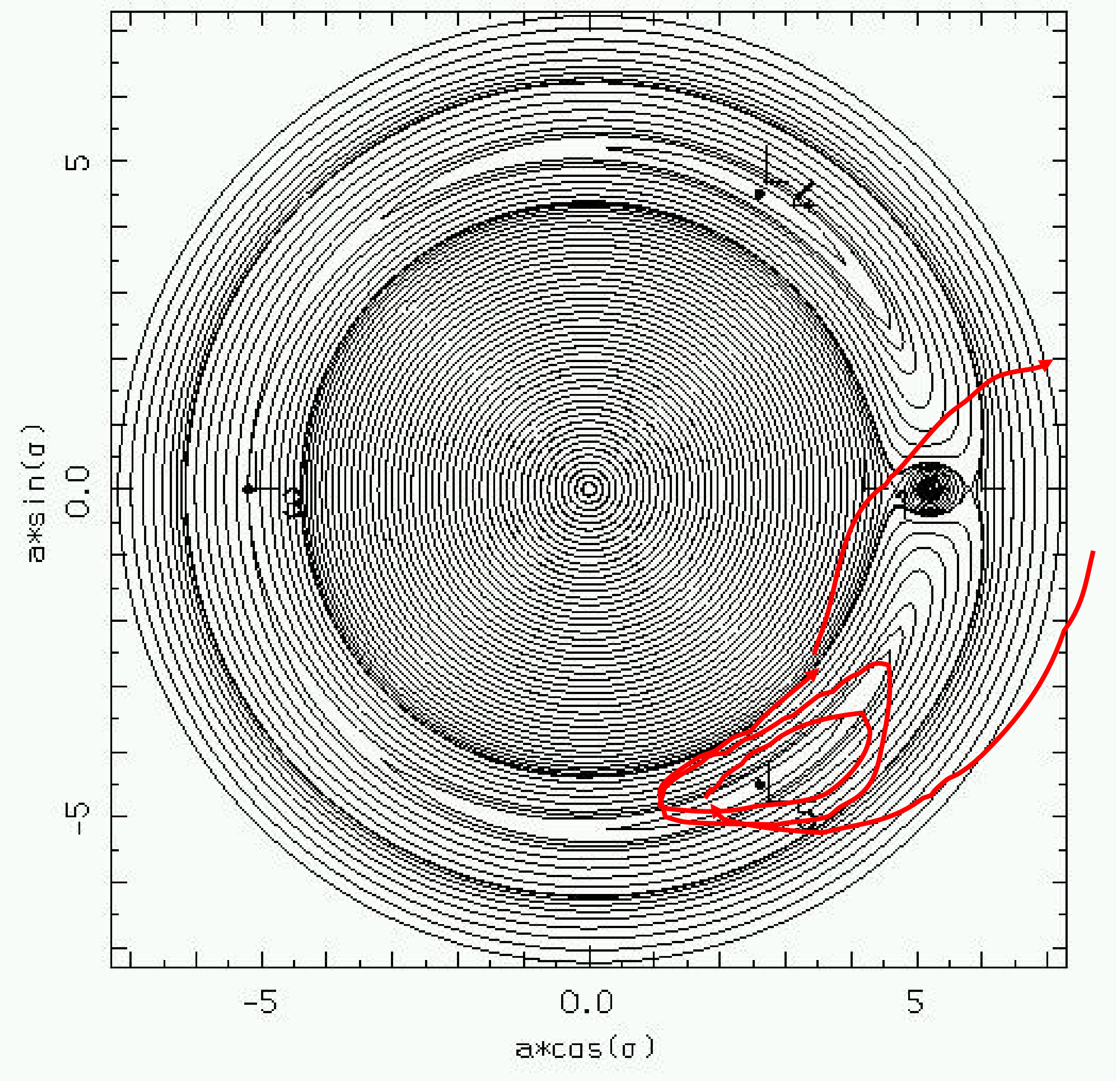
Problem !

# JUPITER's TROJANS

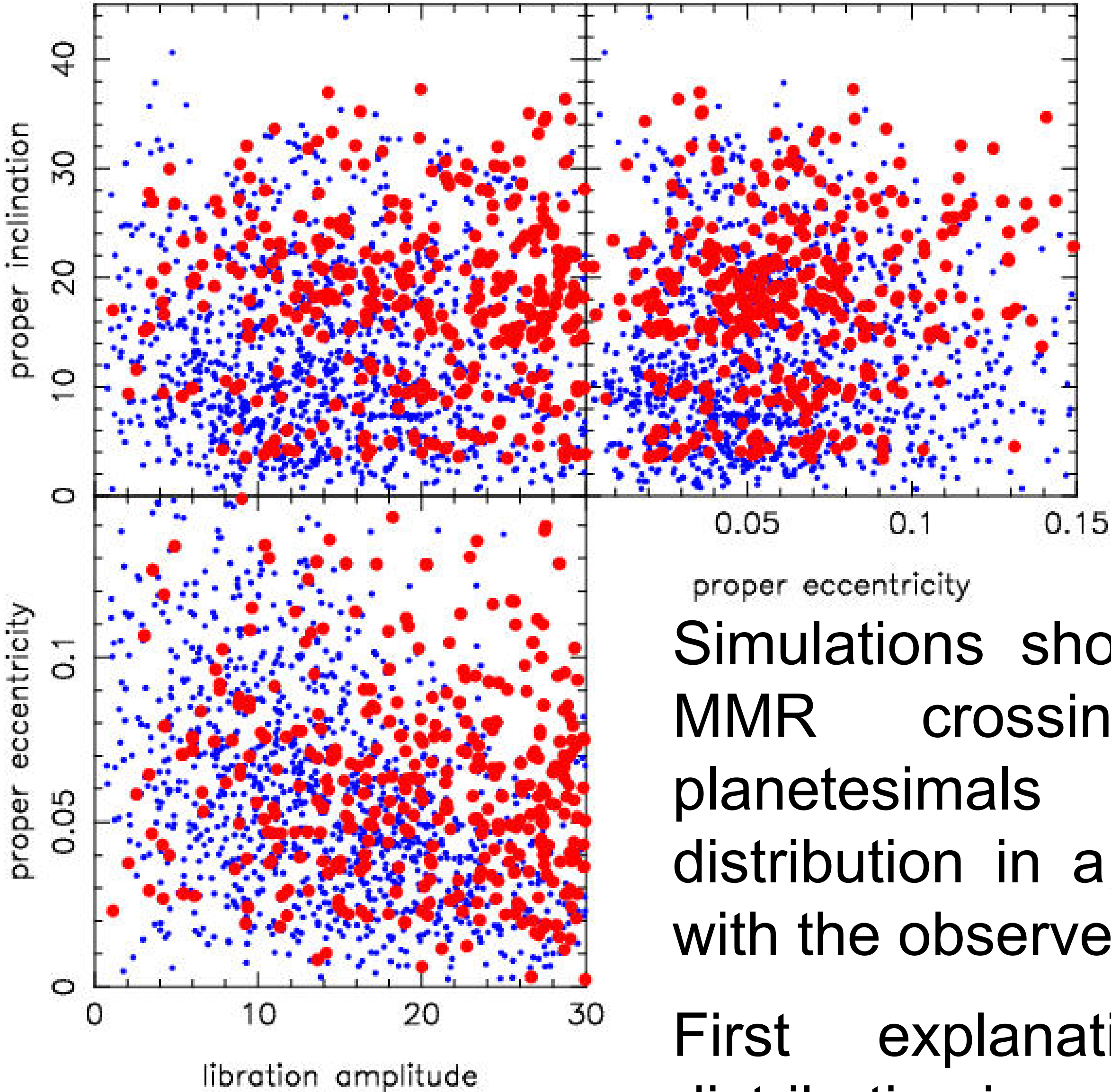
Solution :

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.

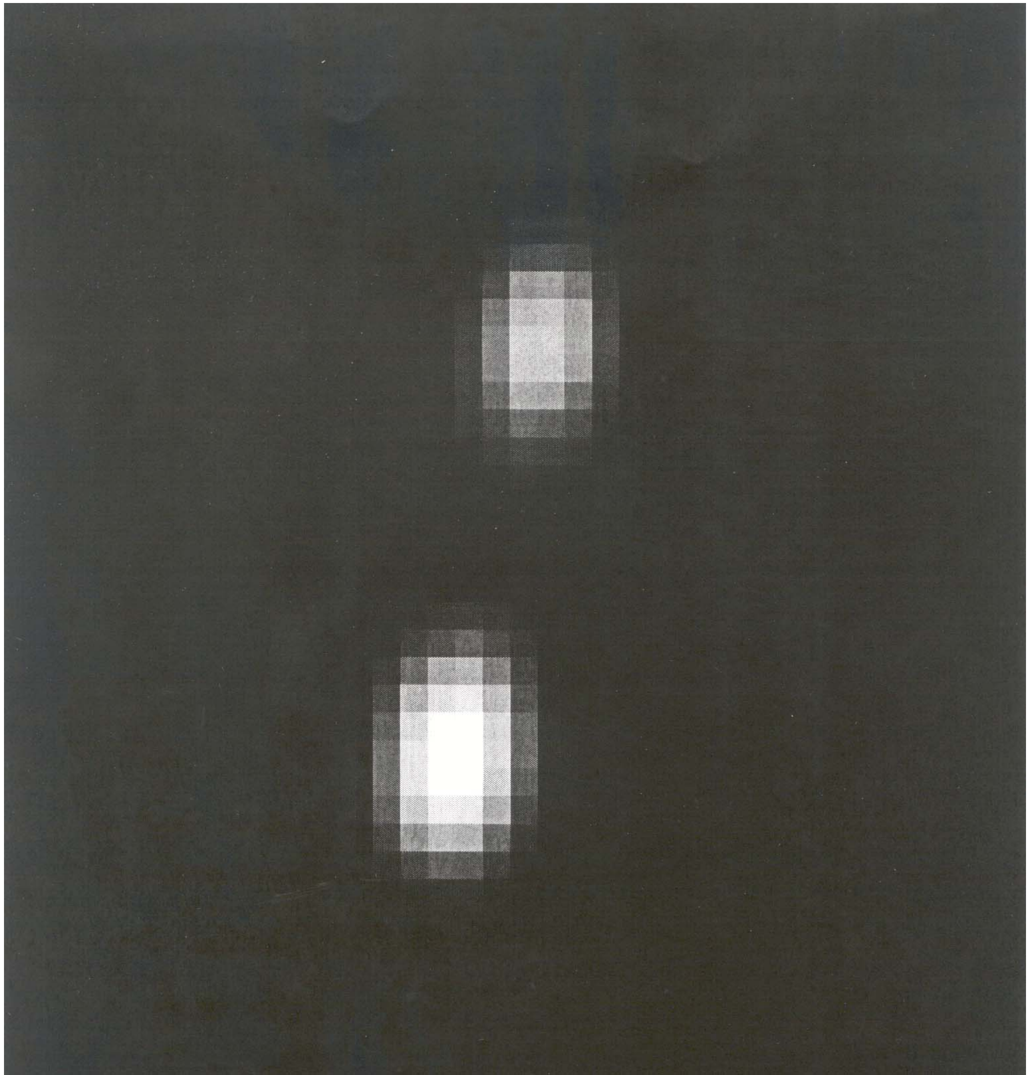
First explanation for the broad distribution in e and i of the trojans.

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

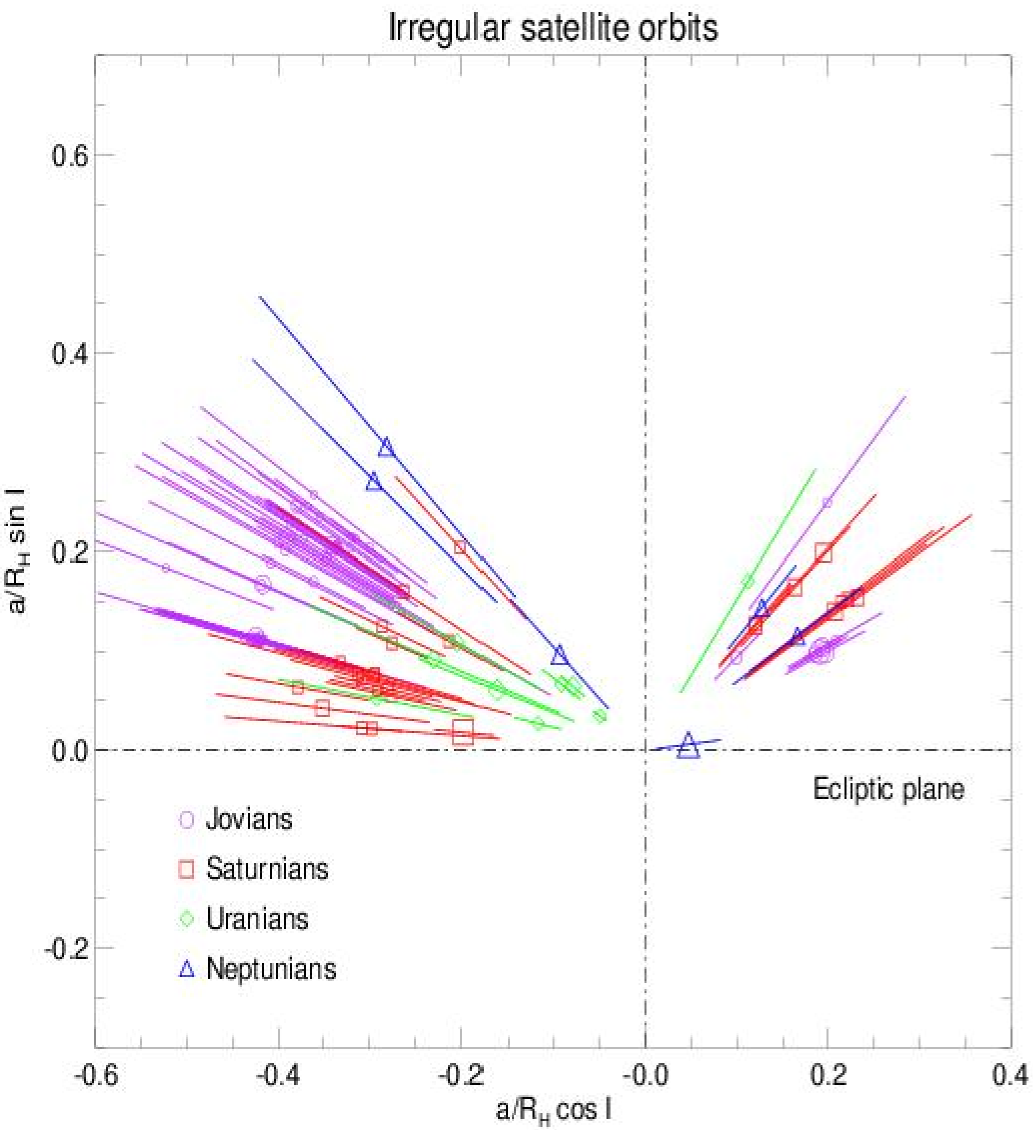
# JUPITER's TROJANS

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



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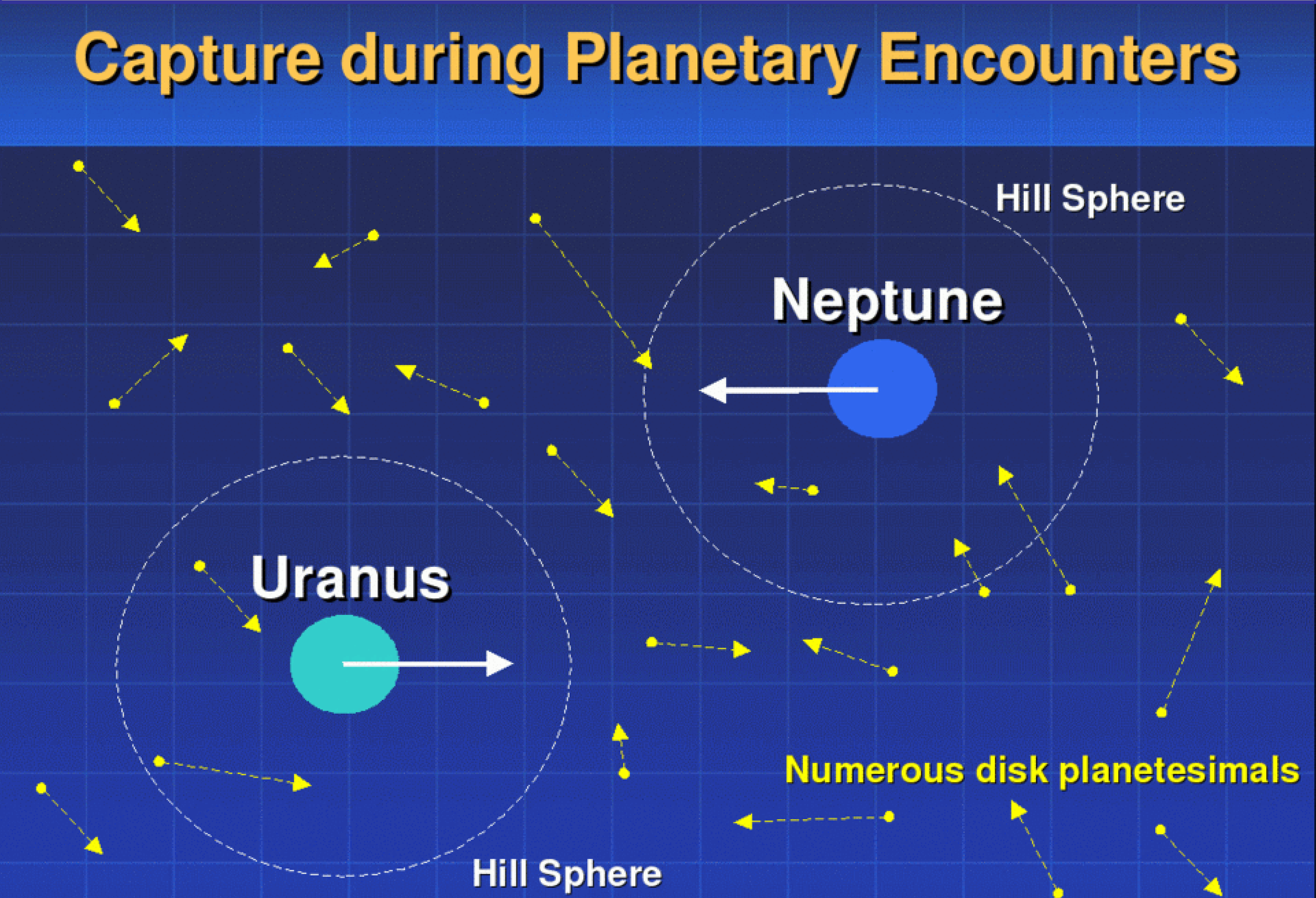
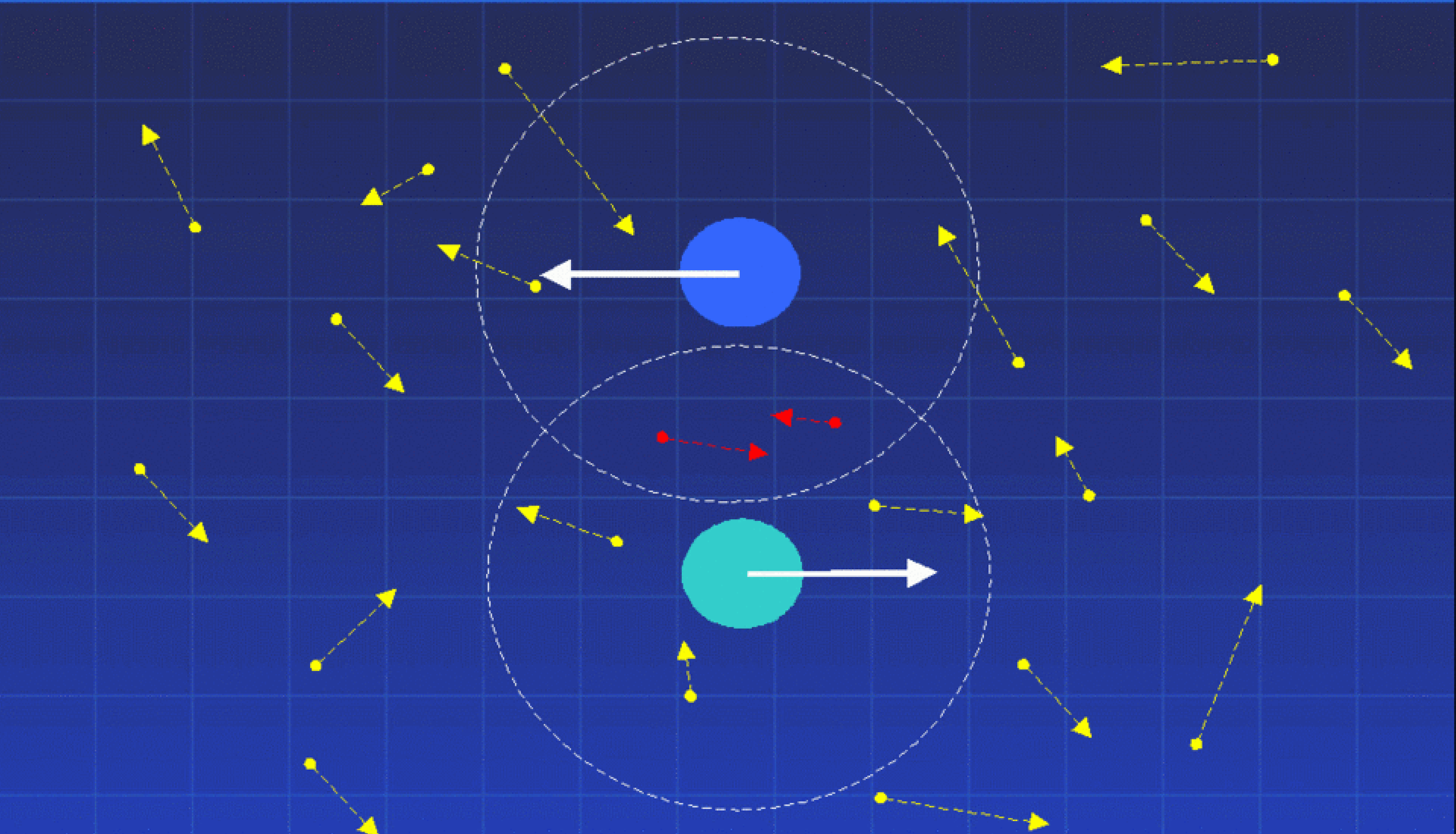


# IRREGULAR SATELLITES

## Capture during Planetary Encounters



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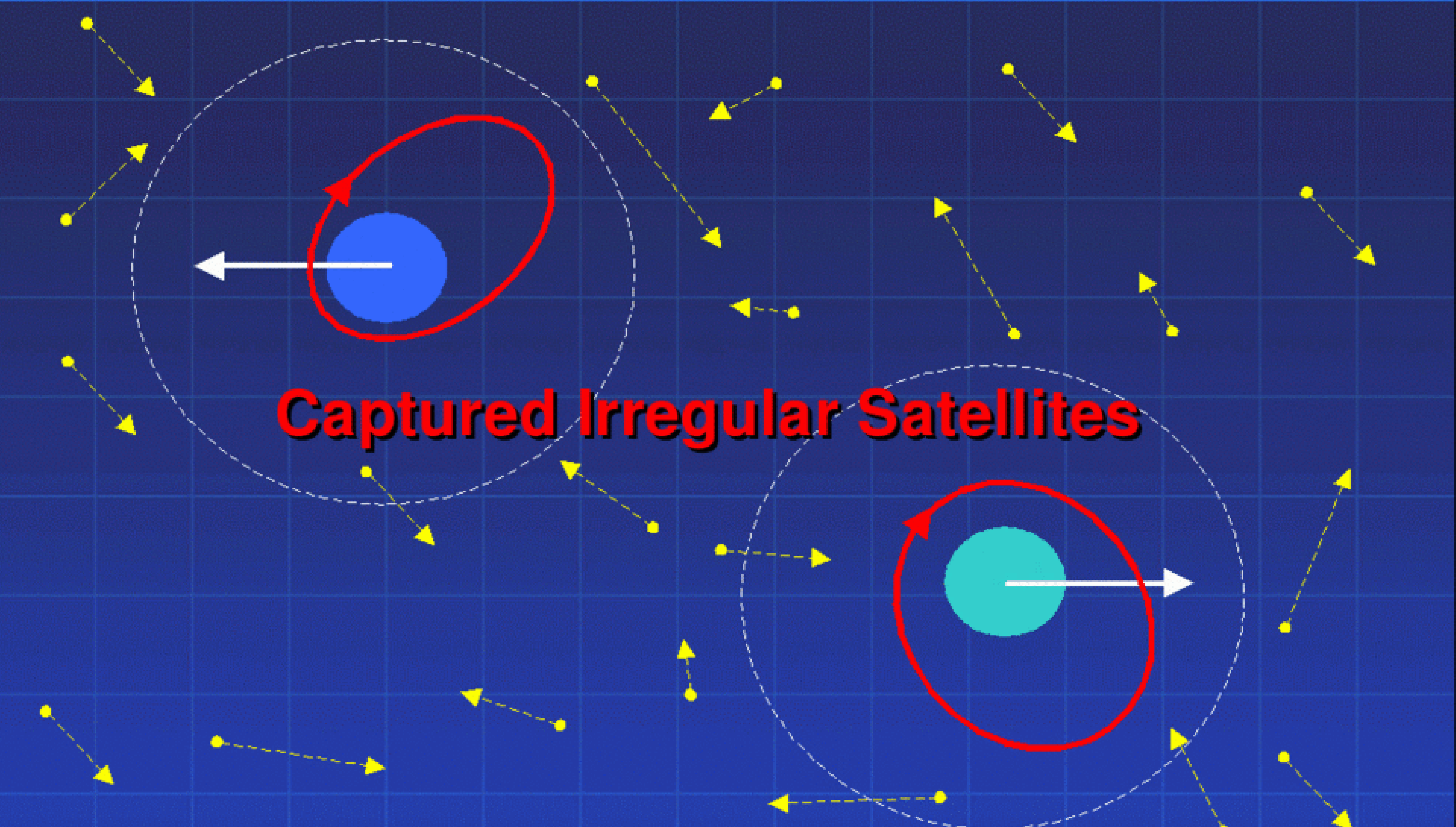

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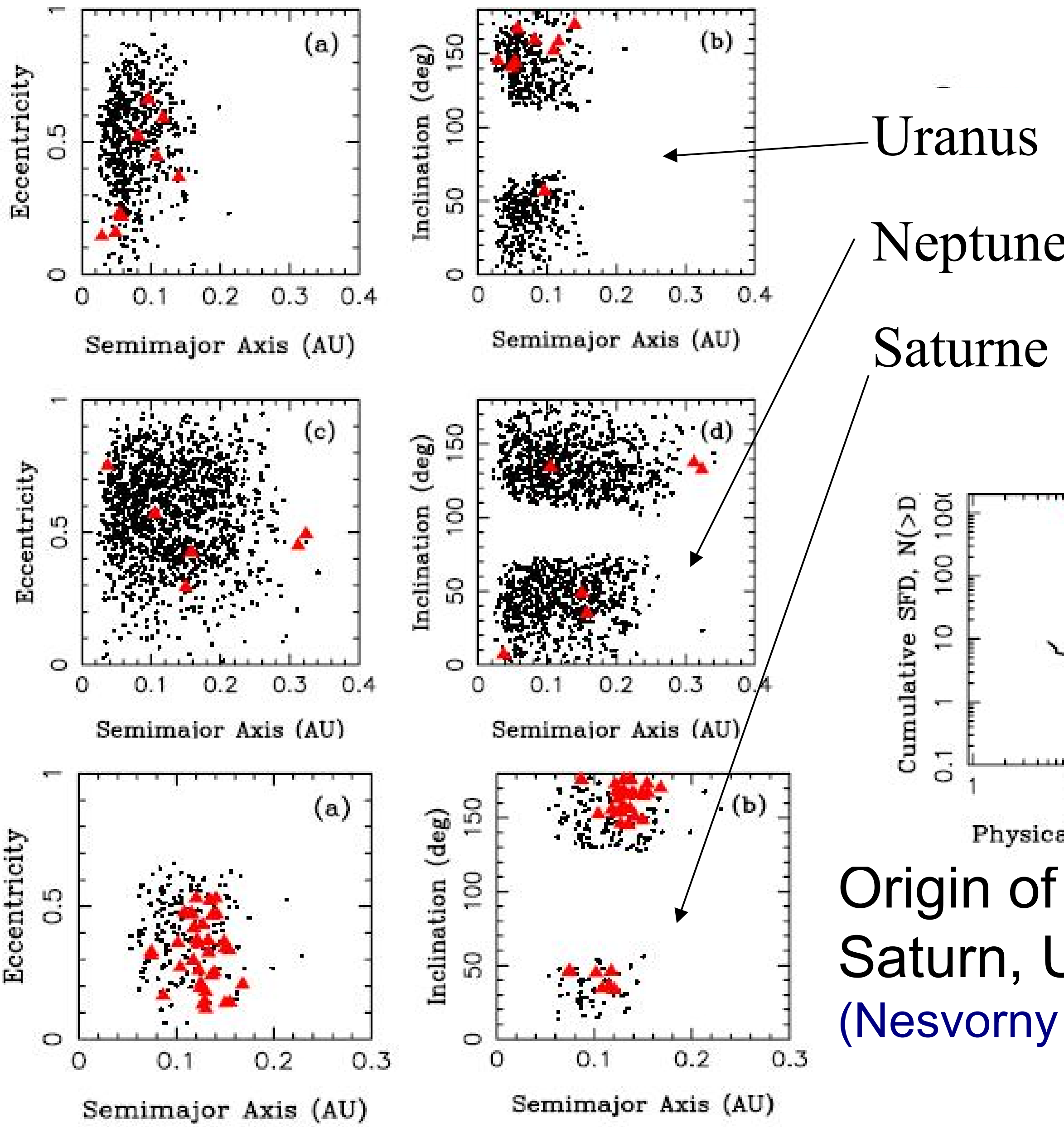
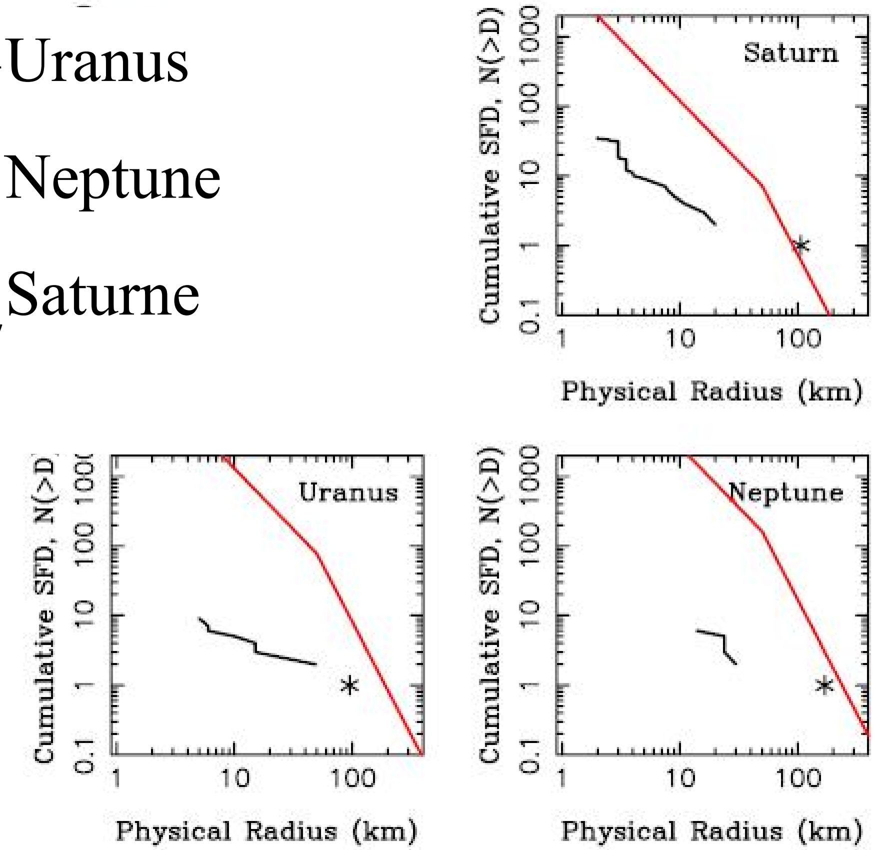
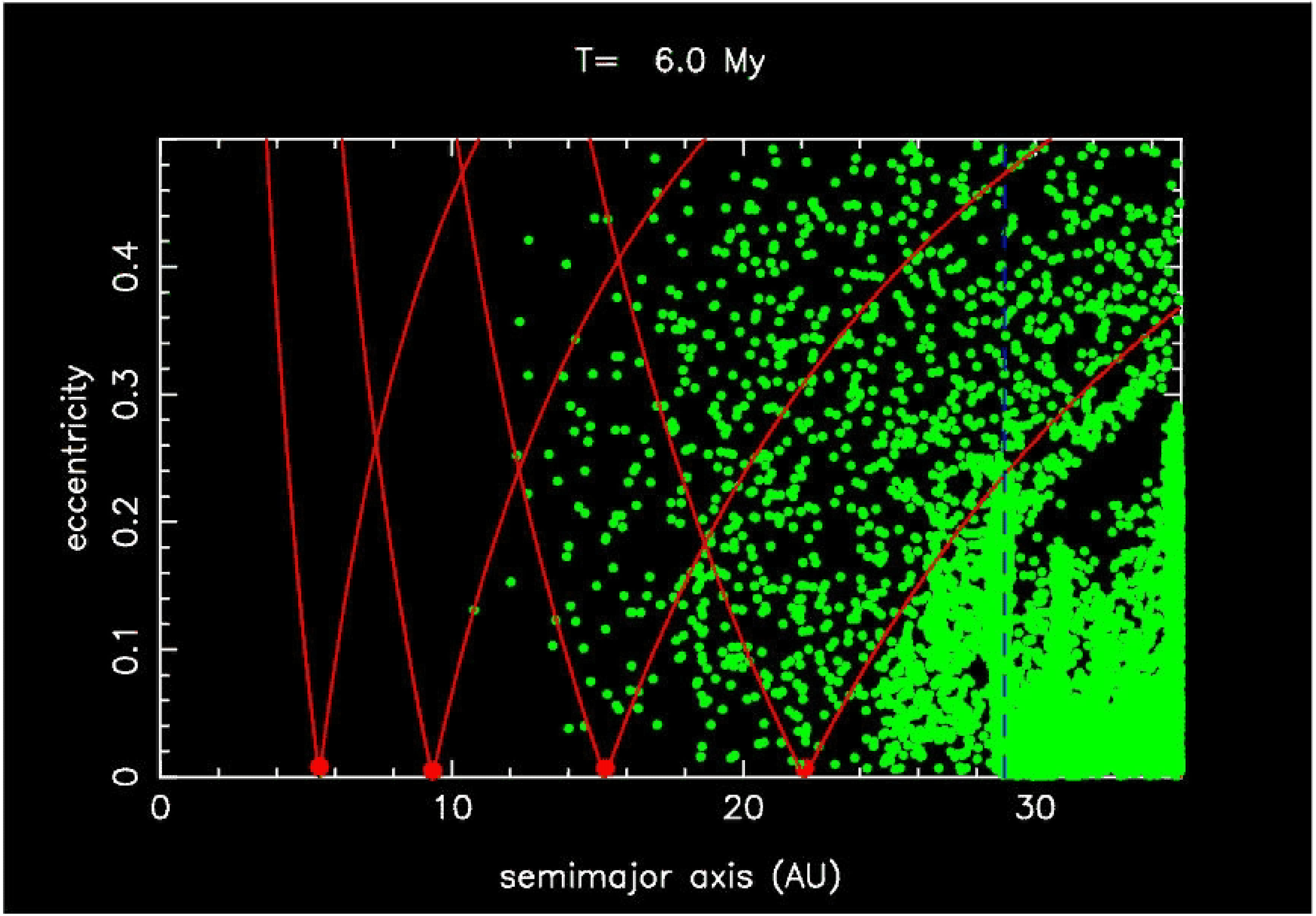



Origin of the irregular satellites of Saturn, Uranus and Neptune

(Nesvorny et al., 2007)

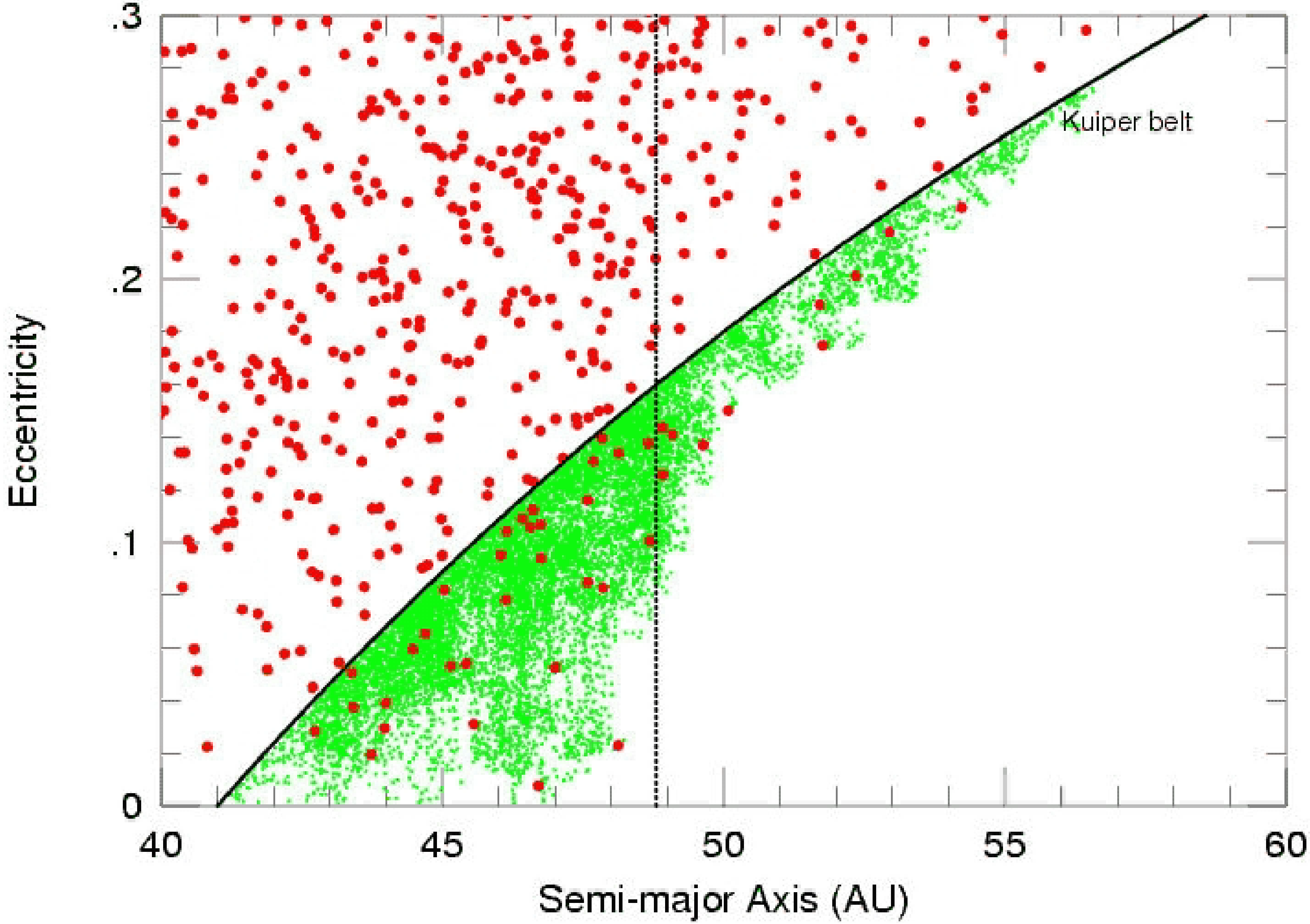
# KUIPER BELT ORIGIN



# KUIPER BELT ORIGIN

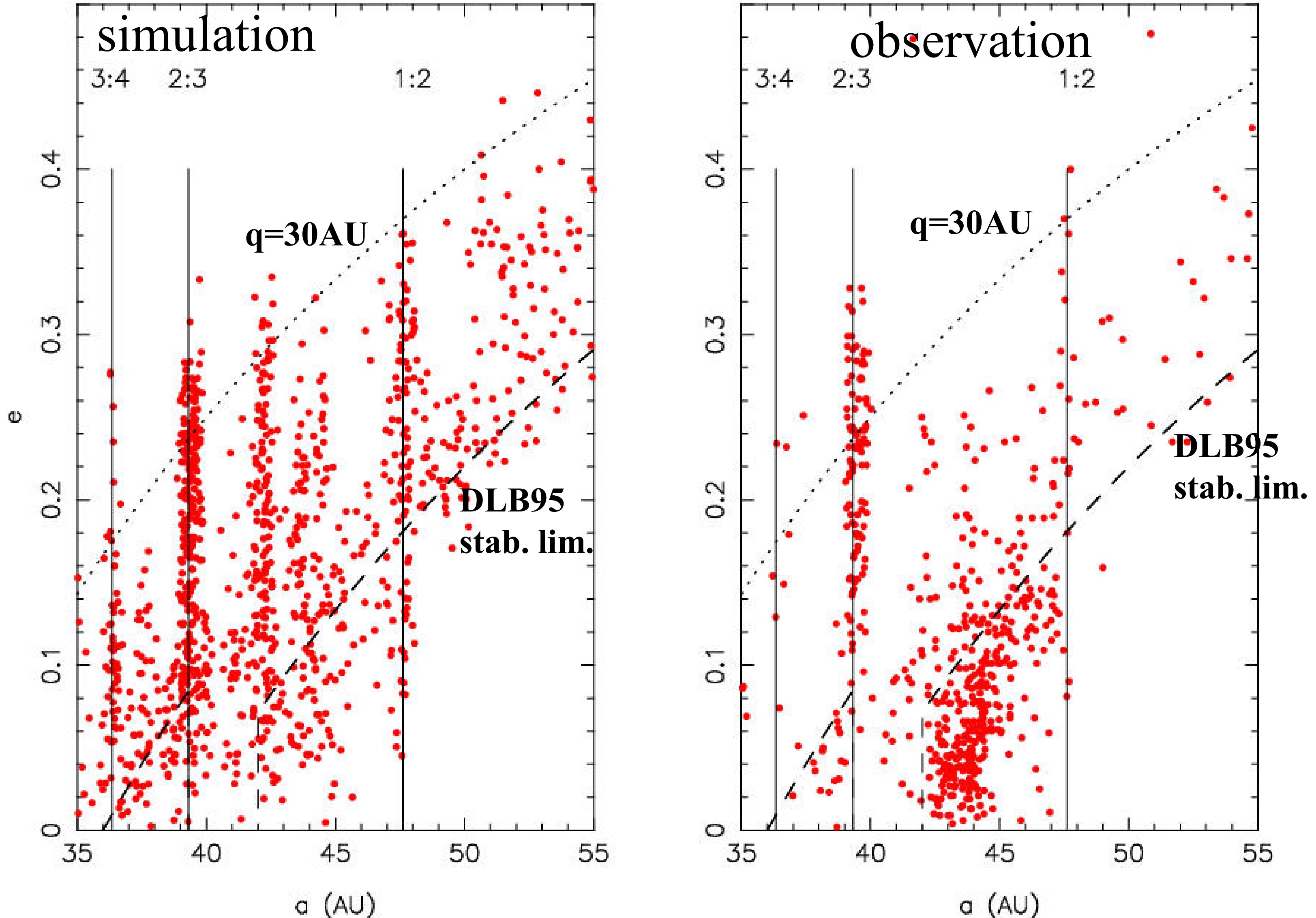
During the outward migration of Neptune, planetesimals are pushed into the Kuiper Belt region, upto 48 AU, the 2:1 MMR with Neptune.

**$e_{neptune}$=0.2, fixed**



# KUIPER BELT ORIGIN

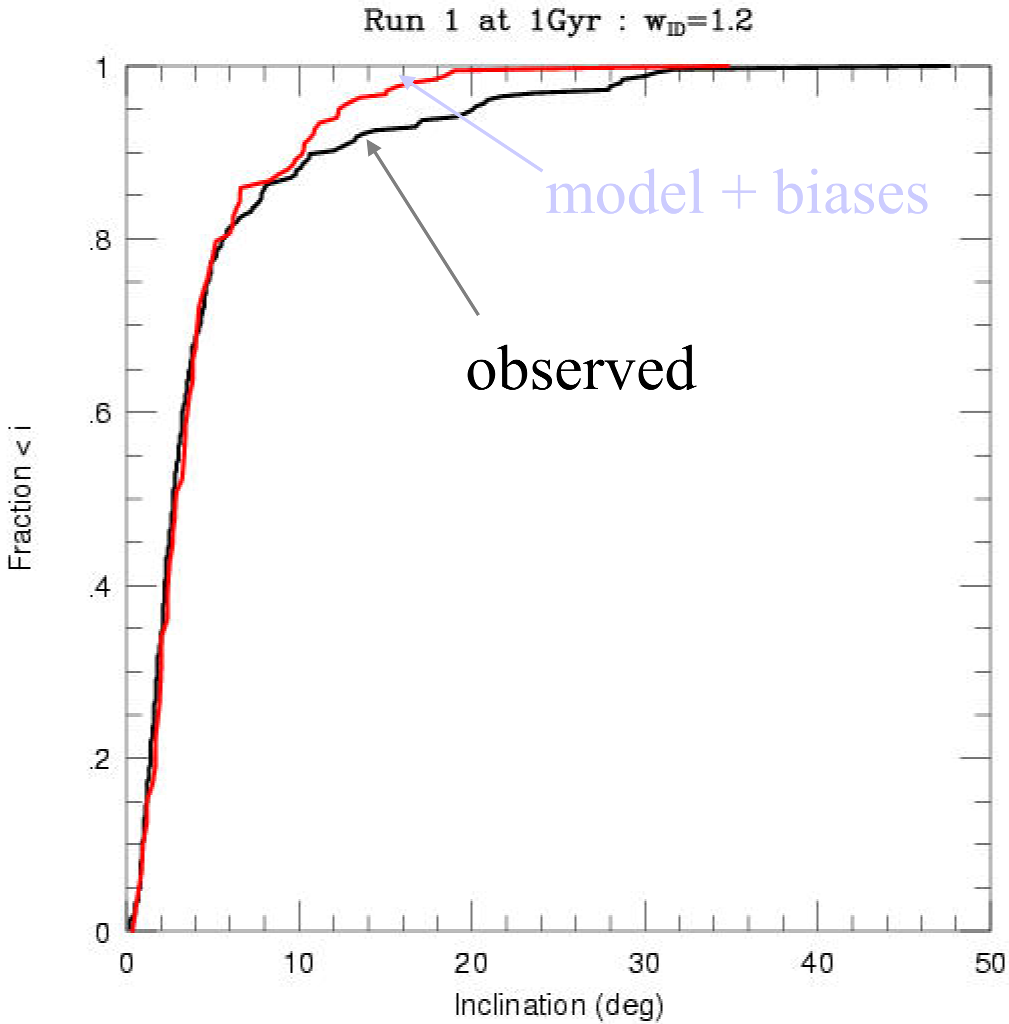
The distribution in the (a,e) plane is quite well reproduced
(Levison et al. 2010?).



# KUIPER BELT ORIGIN

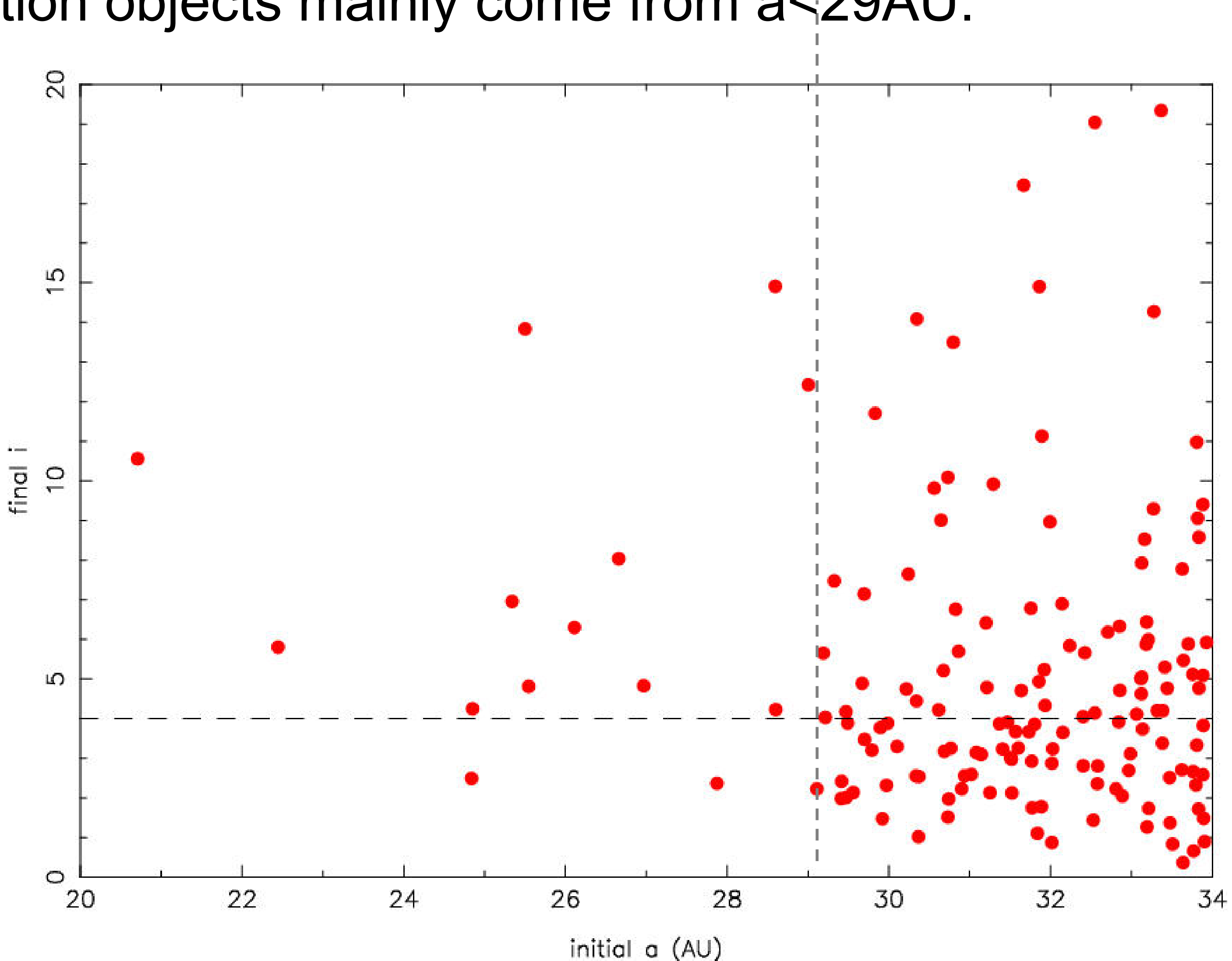
Distribution in i also correctly repropduces.

KS test says distributions match at 50% confidence level



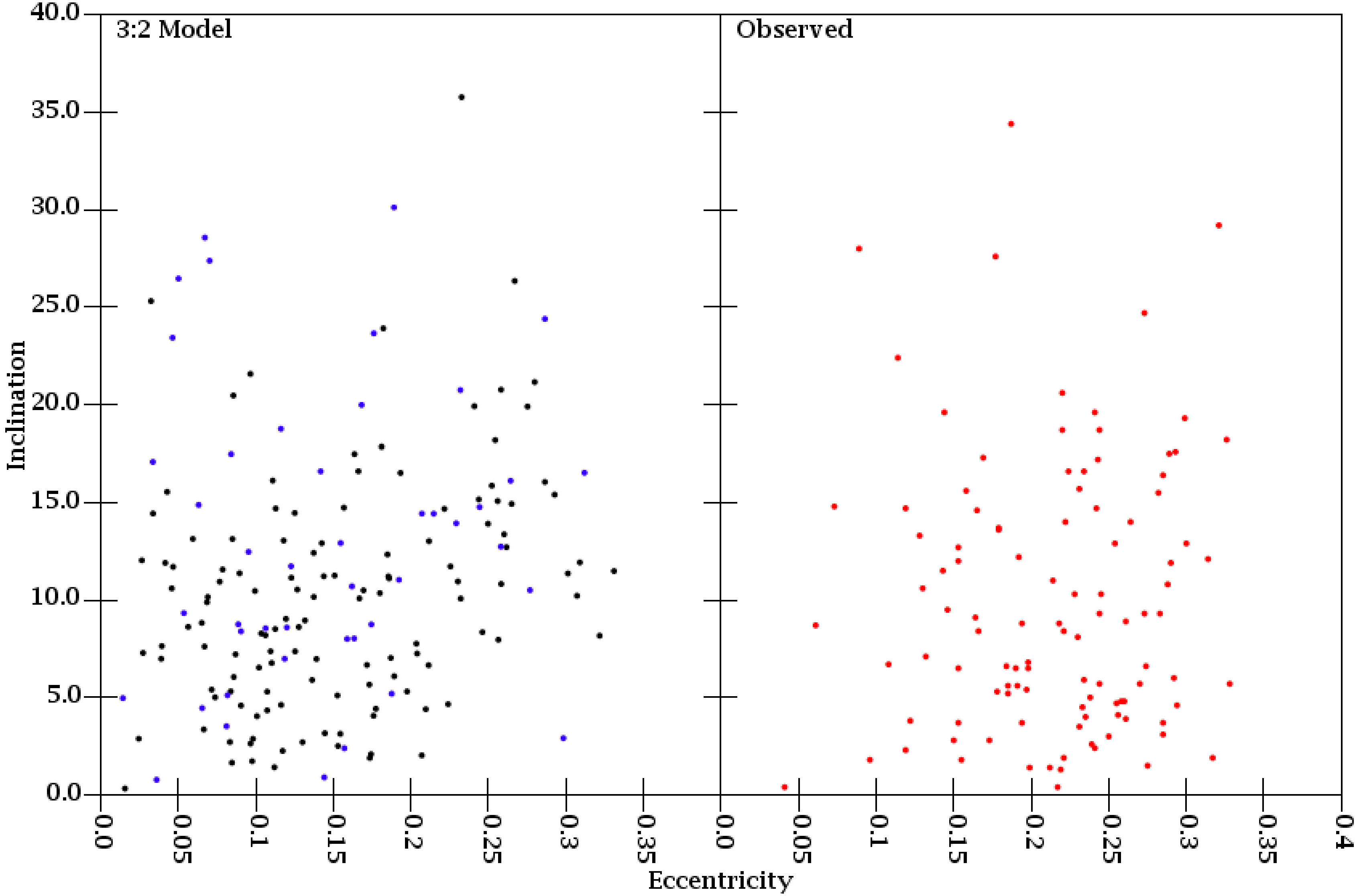
# KUIPER BELT ORIGIN

Possible explanation of the different physical properties of the « cold » K.B. (i<4°), and the objects at higher inclinations : low inclination objects mainly come from a<29AU.



# KUIPER BELT ORIGIN

Reproduction of the orbital distribution inside the resonances ex: here the 3:2 (with Pluto) .



# 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

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