Nordita Winter School 2017

The Solar System's Early dynamical history :

GRAND TACK & NICE MODEL

UNIVERSITÉ CÔTE D'AZUR

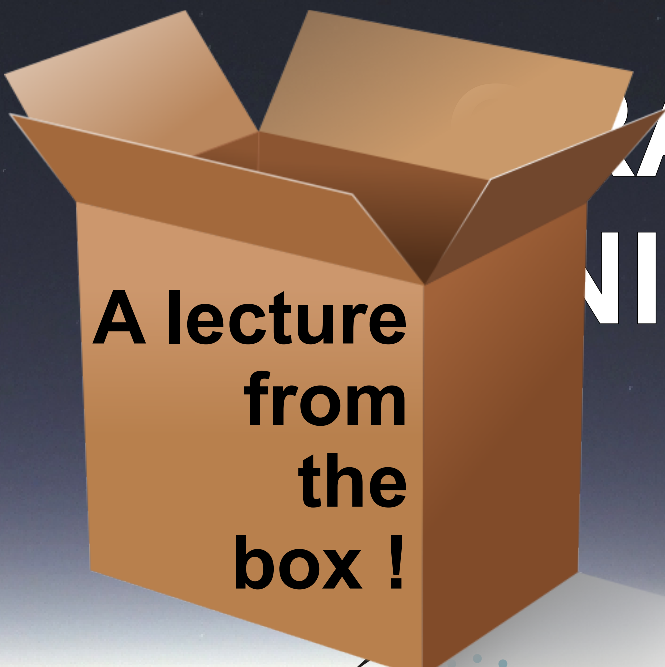
Observatoire de la CÔTE d'AZUR

Aurélien CRIDA

Nordita Winter School 2017

The Solar System's Early dynamical history :

RAND TACK &
NICE MODEL



UNIVERSITÉ CÔTE D'AZUR

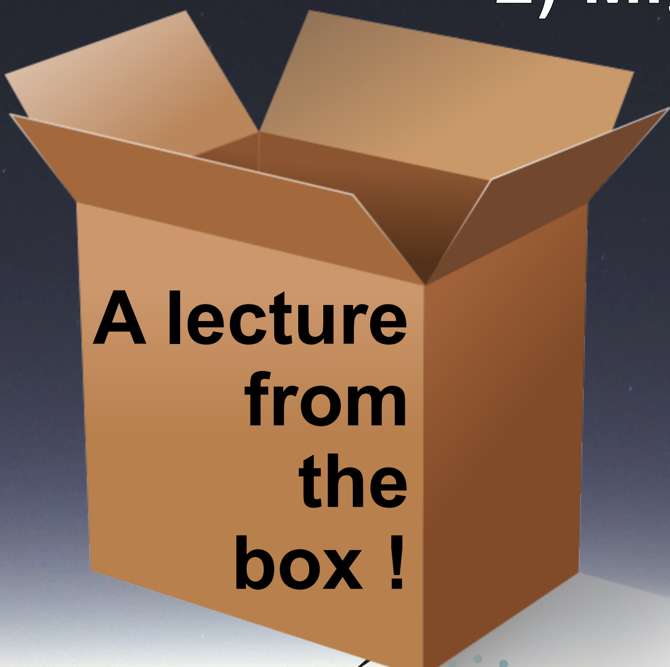
Observatoire de la CÔTE d'AZUR

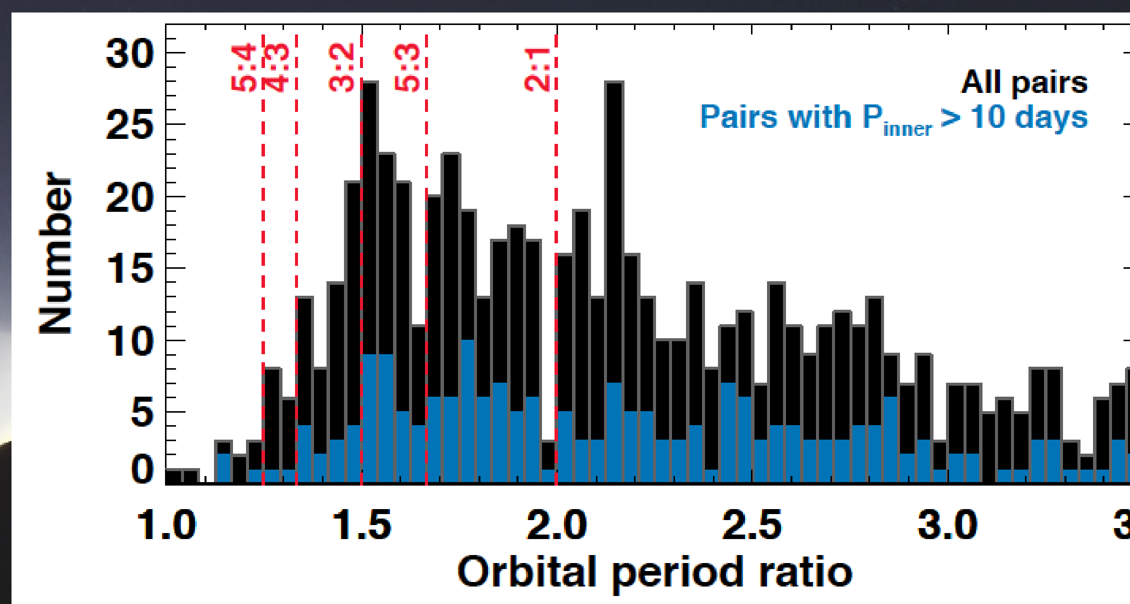
Aurélien CRIDA

Nordita Winter School 2017

Facts irritating for the box :

1) The most common planets are SENs
2) Migration plays a little role
3) Common close in exoplanets
4) Titus-Bode laws



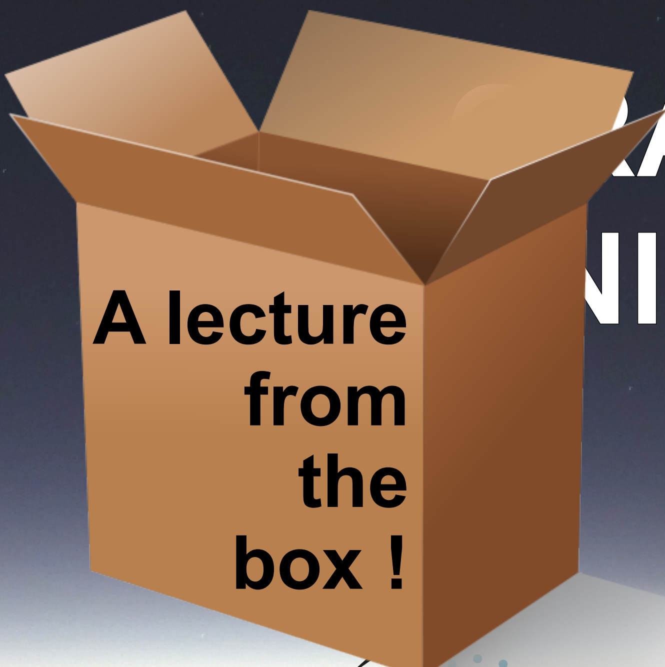


UNIVERSITÉ CÔTE D'AZUR

Nordita Winter School 2017

The Solar System's Early dynamical history :

RAND TACK & NICE MODEL



UNIVERSITÉ CÔTE D'AZUR

Observatoire de la CÔTE d'AZUR

Aurélien CRIDA

Nordita Winter School 2017

a) The GRAND TACK

Jupiter & Saturn's migration

in the gas disk

UNIVERSITÉ CÔTE D'AZUR

Observatoire de la CÔTE d'AZUR

Aurélien CRIDA

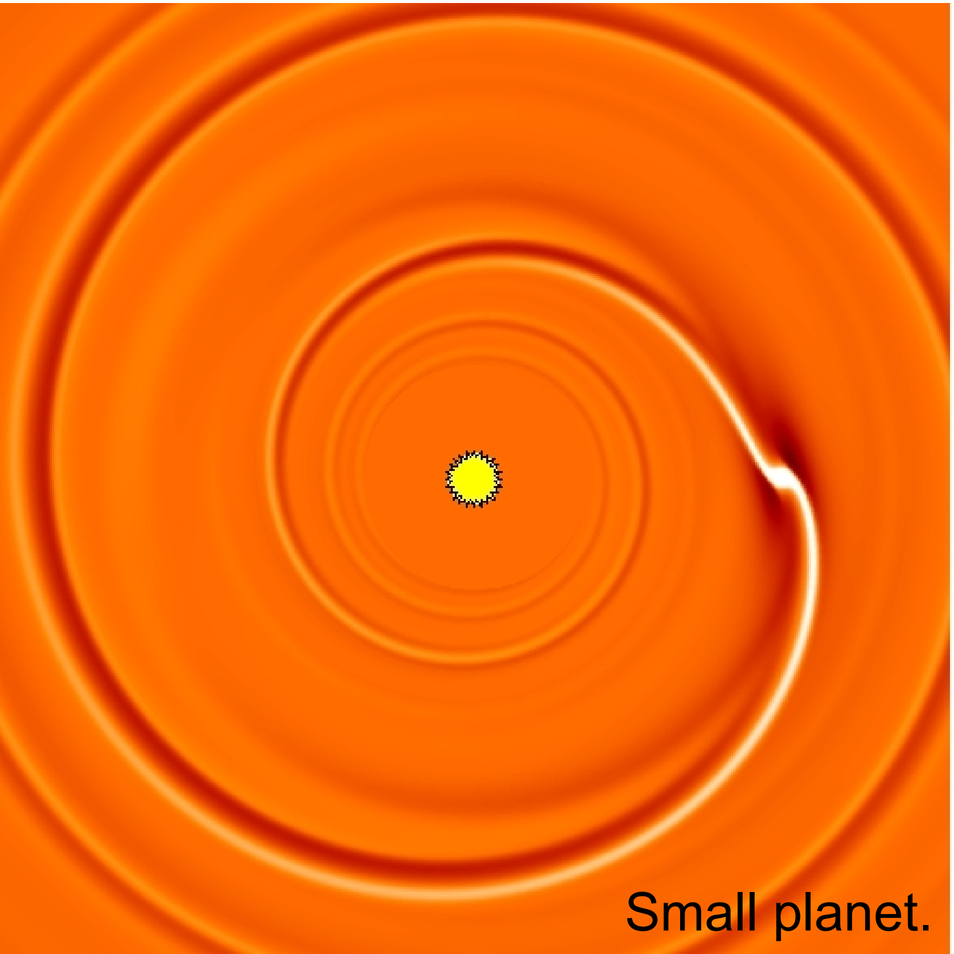
MIGRATION SUMMARY

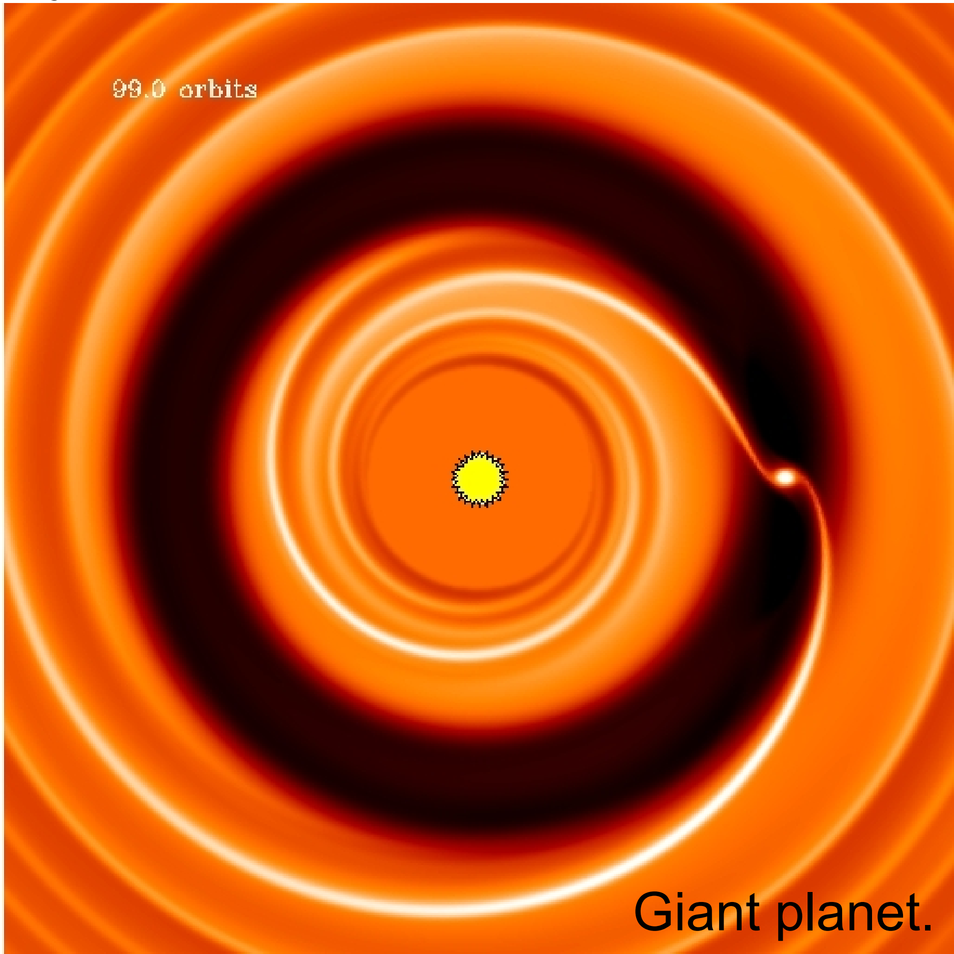
Planet – disk interactions => wake

→ 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

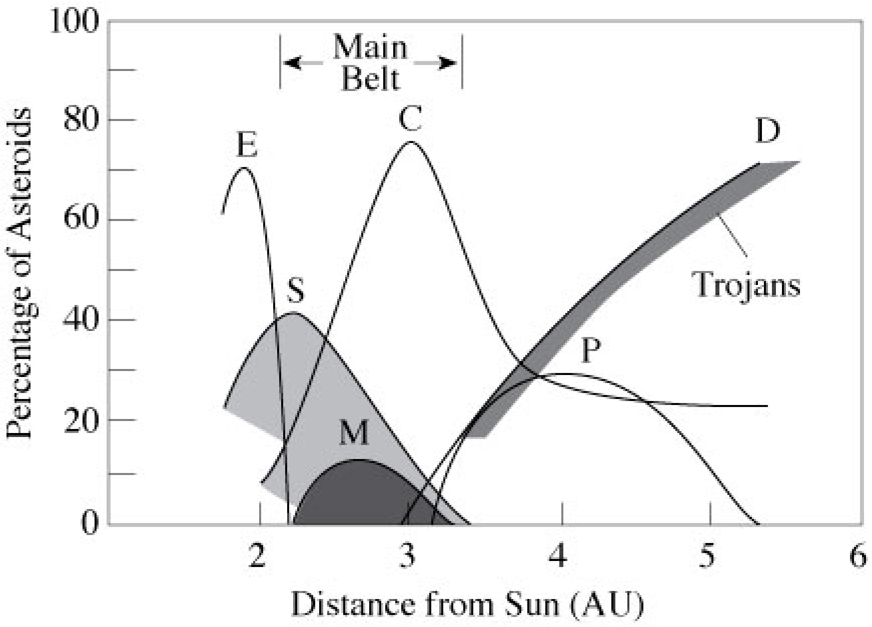
→ type I migration of small mass planets

→ 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* .

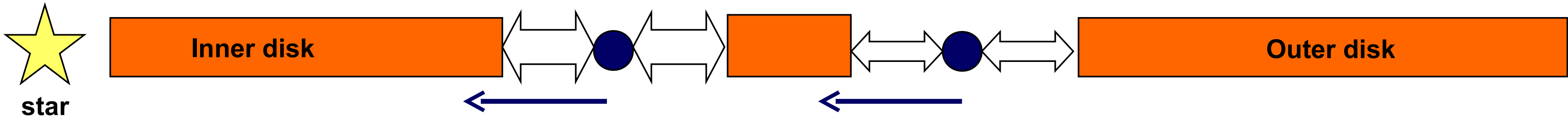


« The properties of the Main Asteroid Belt, between Jupiter and Mars, in particular its quite tight zoning of taxonomic types, show that Jupiter never orbited in this region. »

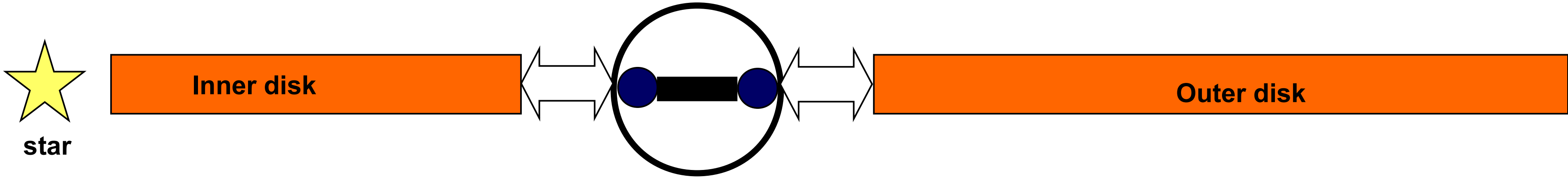
(A. Crida's PhD manuscript, 2006, under the supervision of A. Morbidelli)

MIGRATION in RESONANCE

Two planets in their own gaps migrate in parallel.



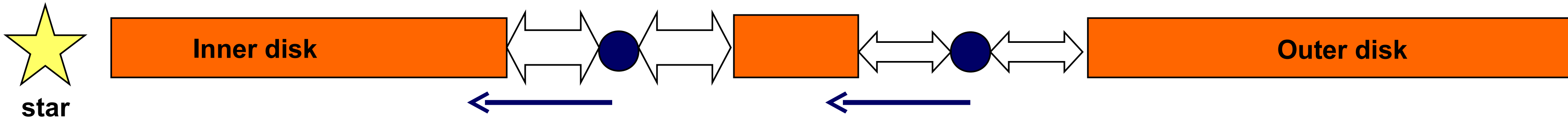
Two planets in a same gap approach each other → résonance.



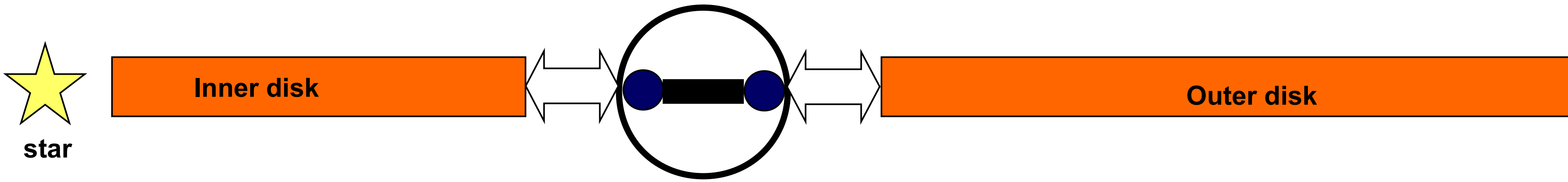
The pair of planet behaves like 1 object in type II migration.

MIGRATION in RESONANCE

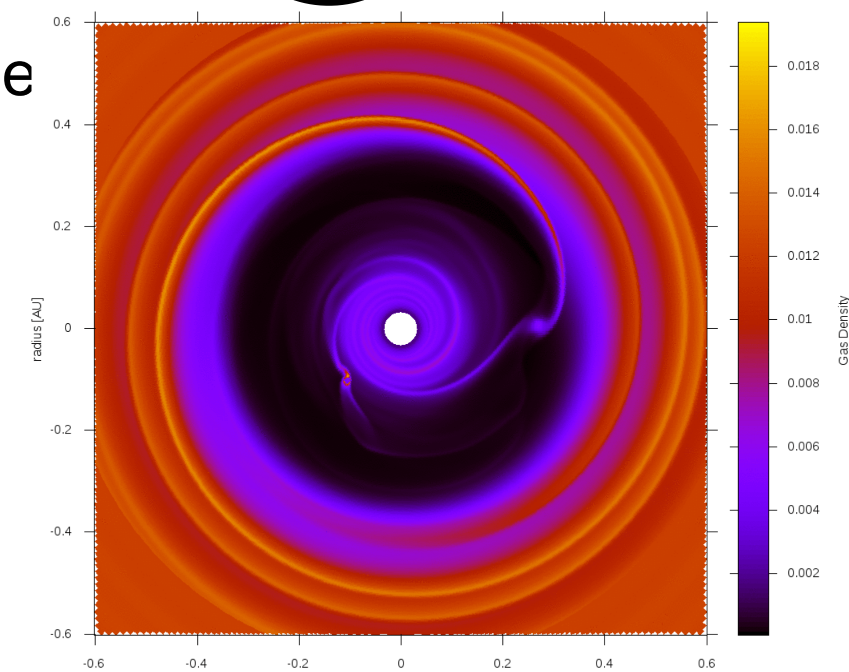
Two planets in their own gaps migrate in parallel.



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

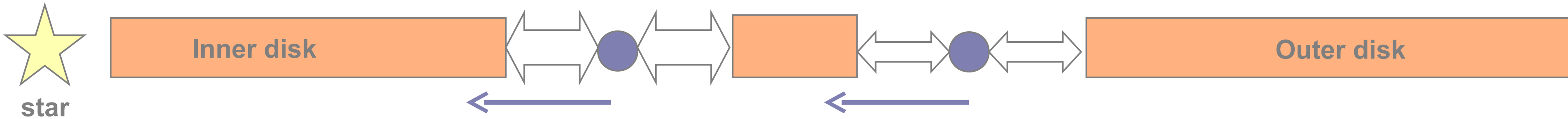


The pair of plane … e II migration.

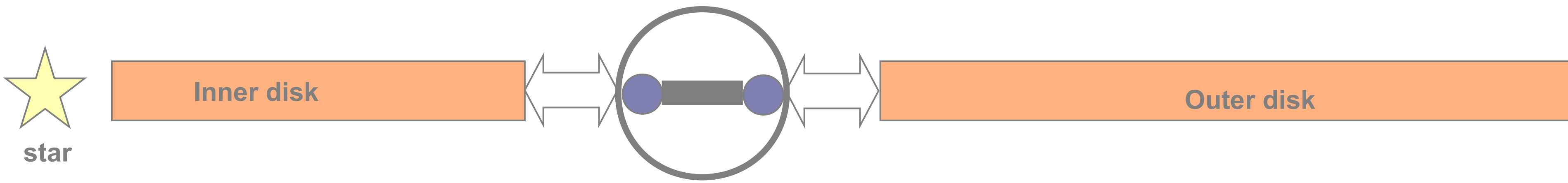


MIGRATION in RESONANCE

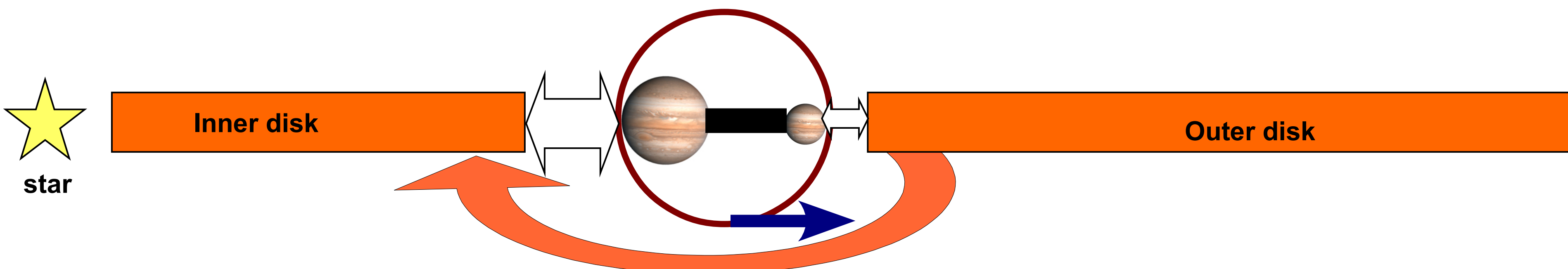
Two planets in their own gaps migrate in parallel.



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



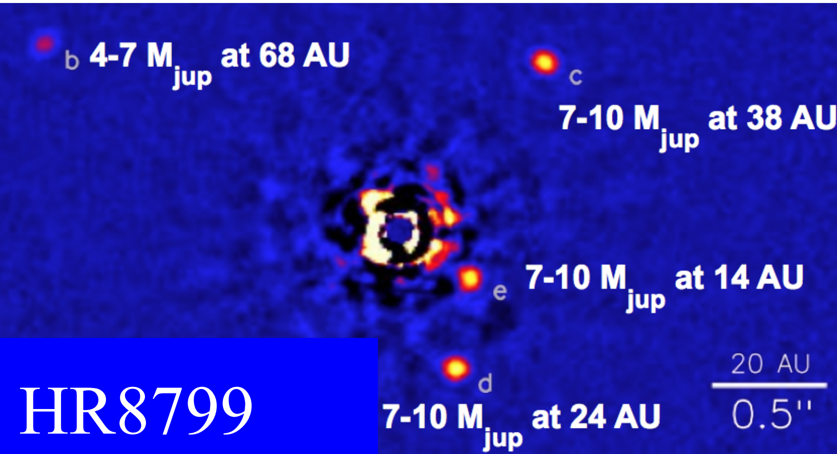
The pair of planet behaves like 1 object in type II migration.

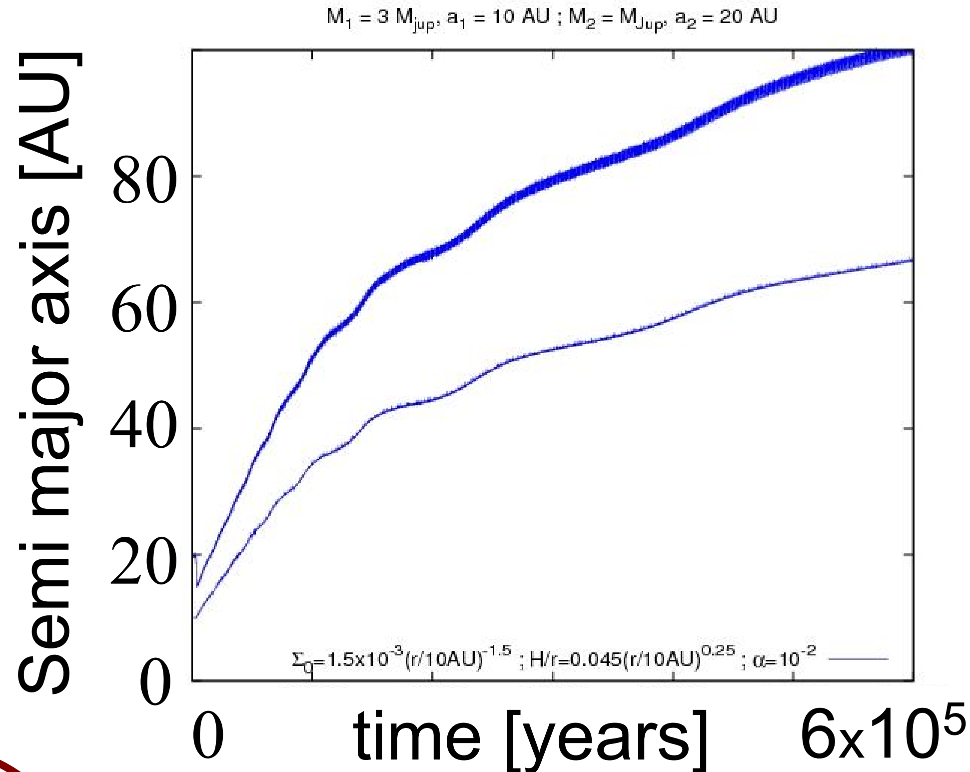


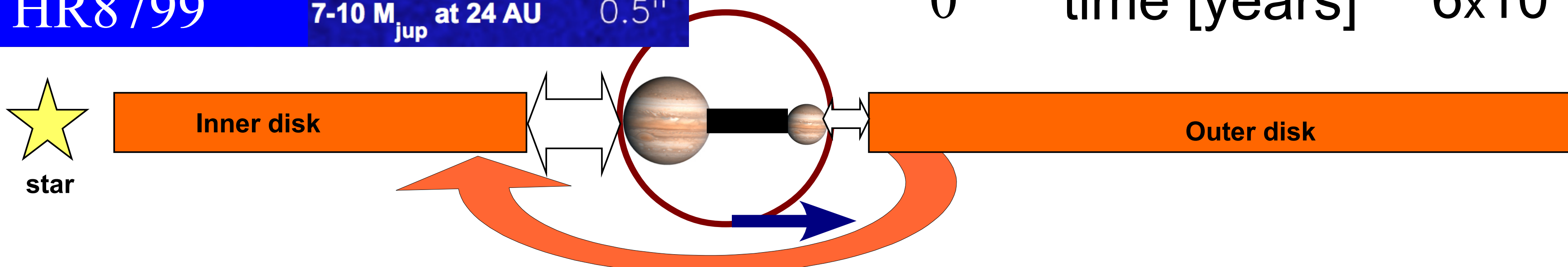
$M_2<M_1$ => smaller negative torque from outer disk than positive torque from inner disc (Masset & Snellgrove 2001).
The pair goes outwards, even if the disc goes inwards.

OUTWARD MIGRATION in RESONANCE

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





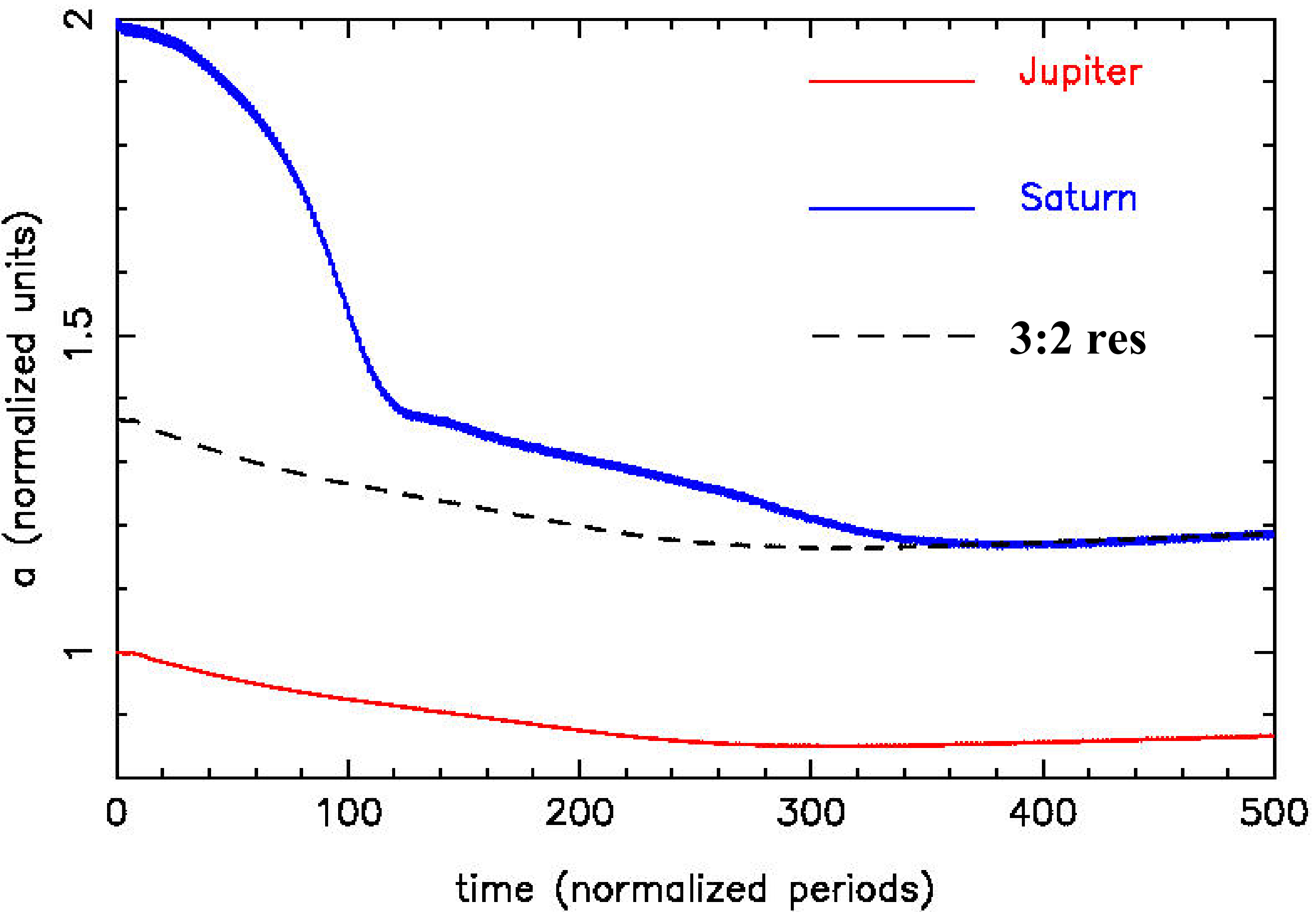


$M_2 < M_1$ => smaller negative torque from outer disk than positive torque from inner disc (Masset & Snellgrove 2001).
The pair goes outwards, even if the disc goes inwards.

JUPITER AND SATURN

How to prevent Jupiter from becoming « hot » ?

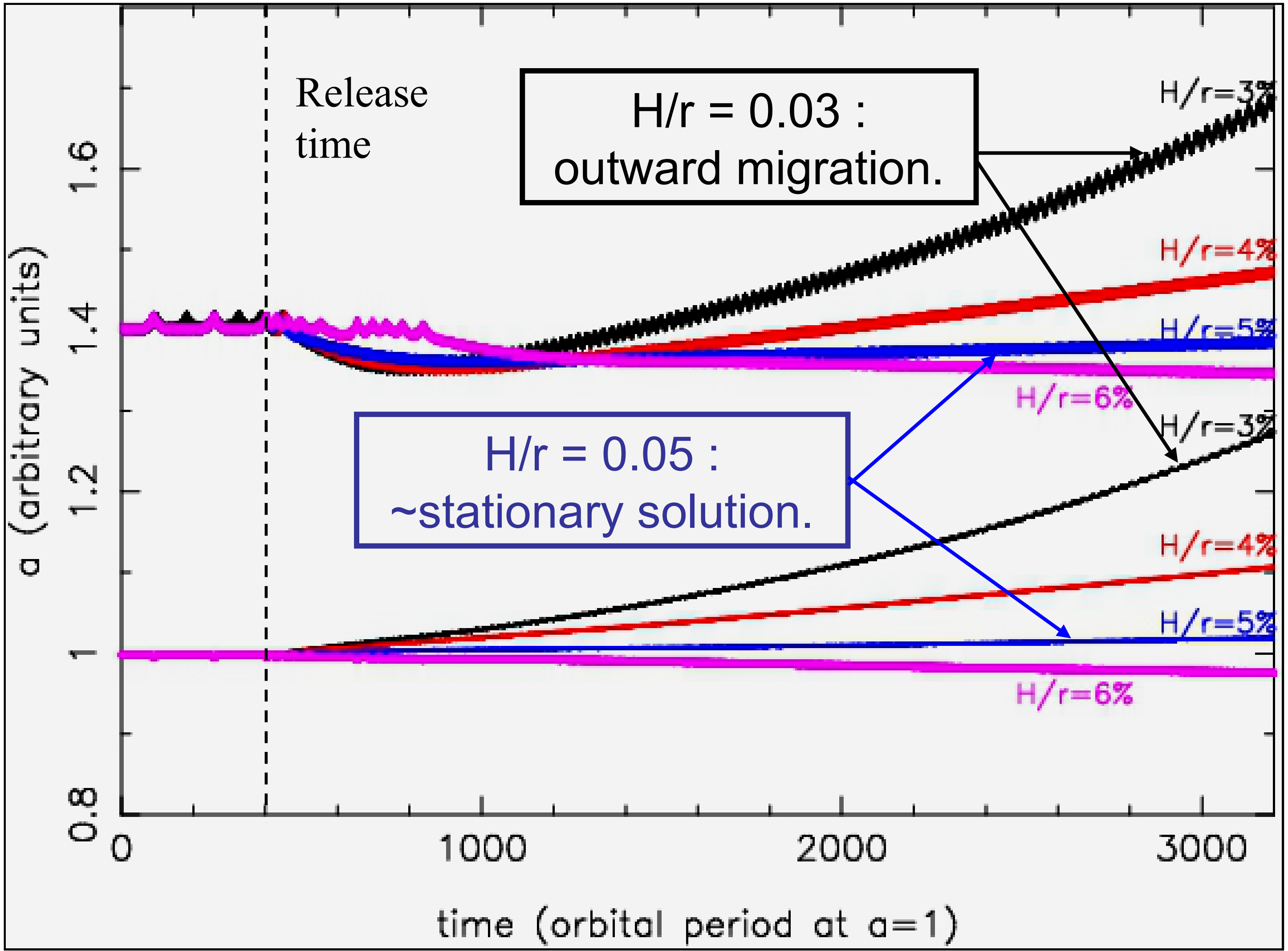
M_{Saturn} =~ $M_{Jupiter}$ / 3 => they can decouple from the disk !



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 !!!

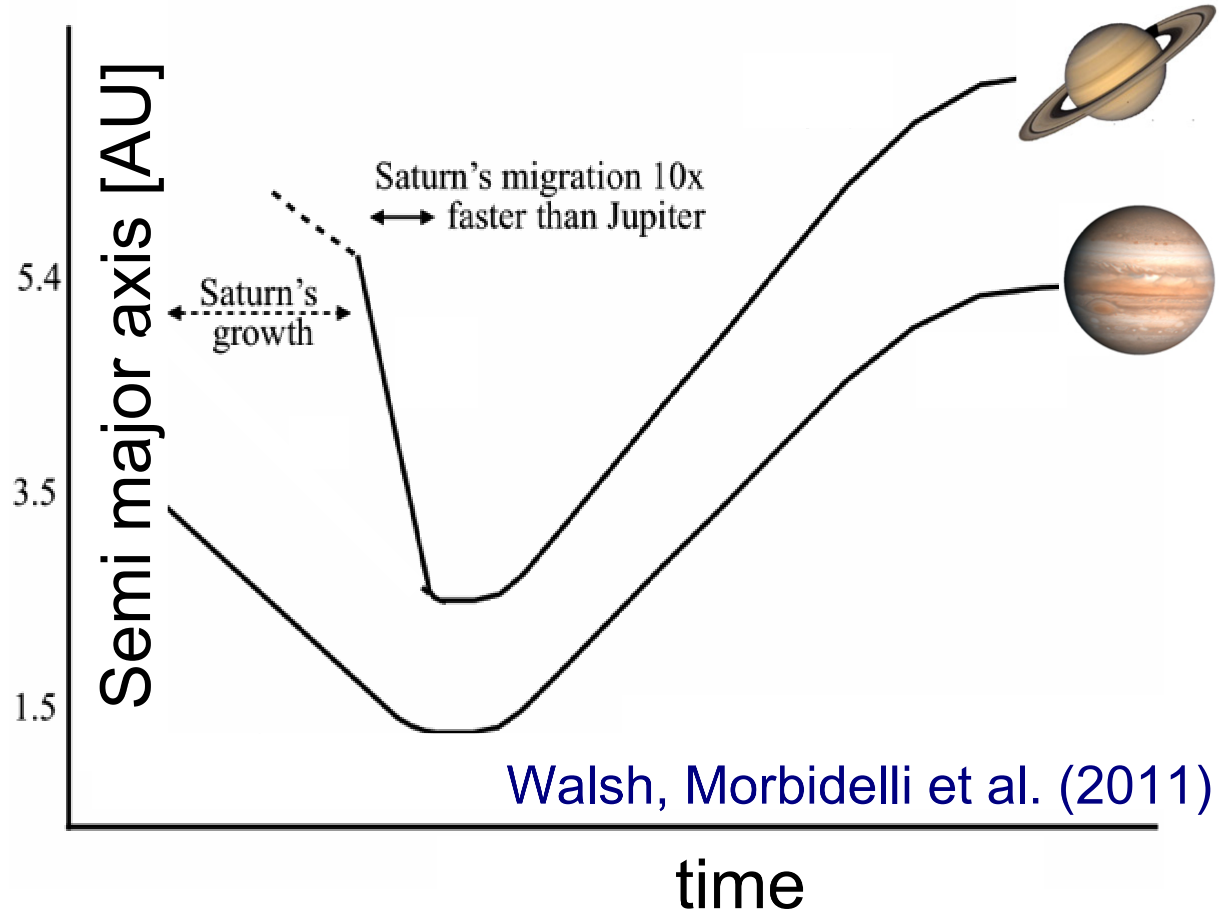
Jupiter & Saturn didn't migrate, I saved the Solar System.

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).

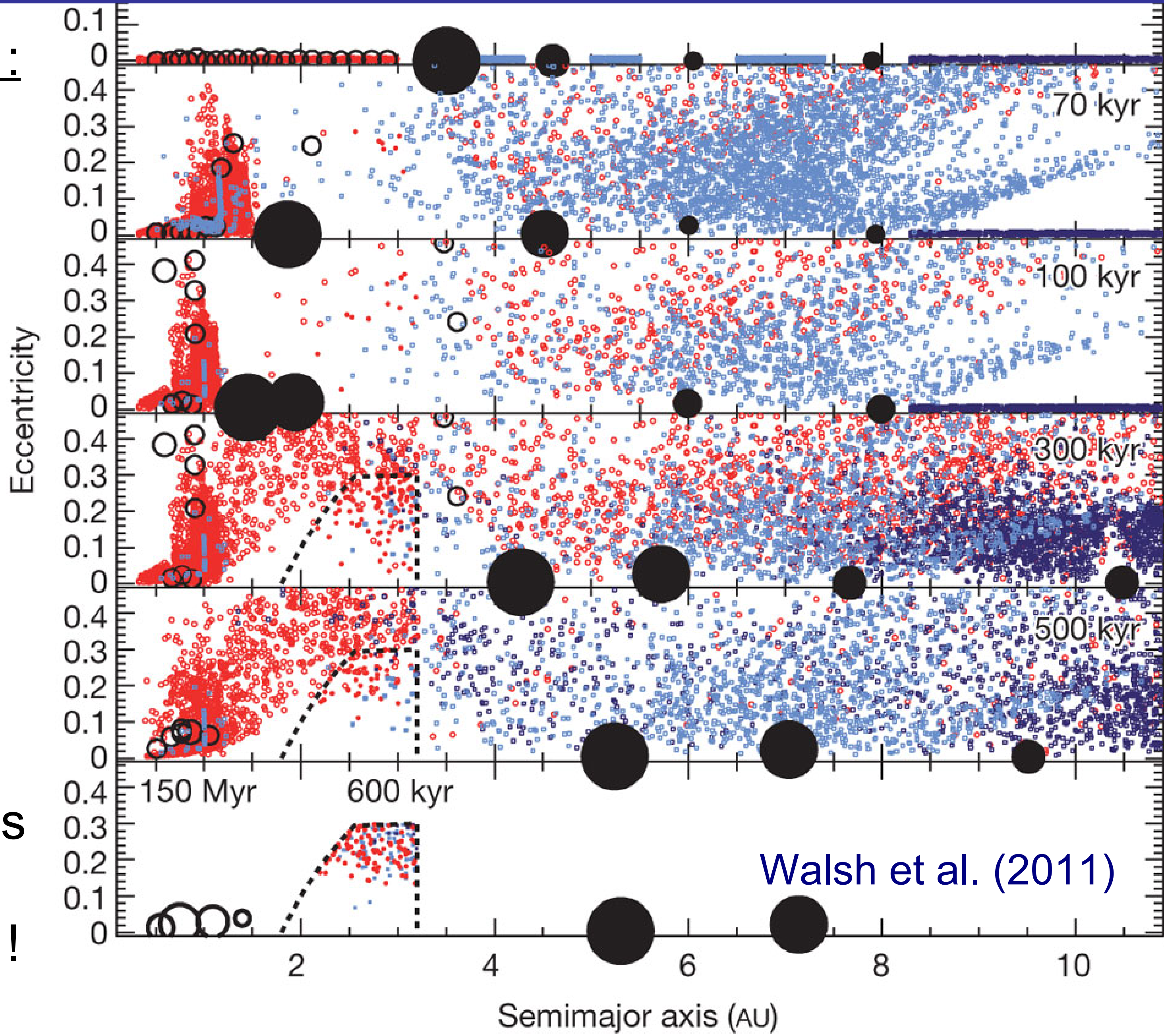


GRAND TACK SCENARIO

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 !



GRAND TACK AND TERRESTRIAL PLANETS

Movies GT1-3 for planetesimals.

→ reproduction of the Main Asteroid Belt

Movies GT4-6 for terrestrial planets.

→ production of the truncation at 1 AU.

PARAMETERS & CONSTRAINTS

Walsh et al. (2011) :

- assumed an equal mass in embryos and planetesimals.

- tested two possible embryo masses (0.025 and 0.05 ME)

Jacobson et al. (2014) tested many more possible initial conditions, in the frame of the Grand Tack model (truncated disk at 1 AU).

Influence on our constraints ?

- Masses (1 Earth, small mass of Mars)
- Formation of the Moon
- Accretion times
- Orbits (AMD, 4 planets well spaced)

1) Masses : original work

Walsh et al. (2011) :

- assumed an equal mass in embryos and planetesimals.

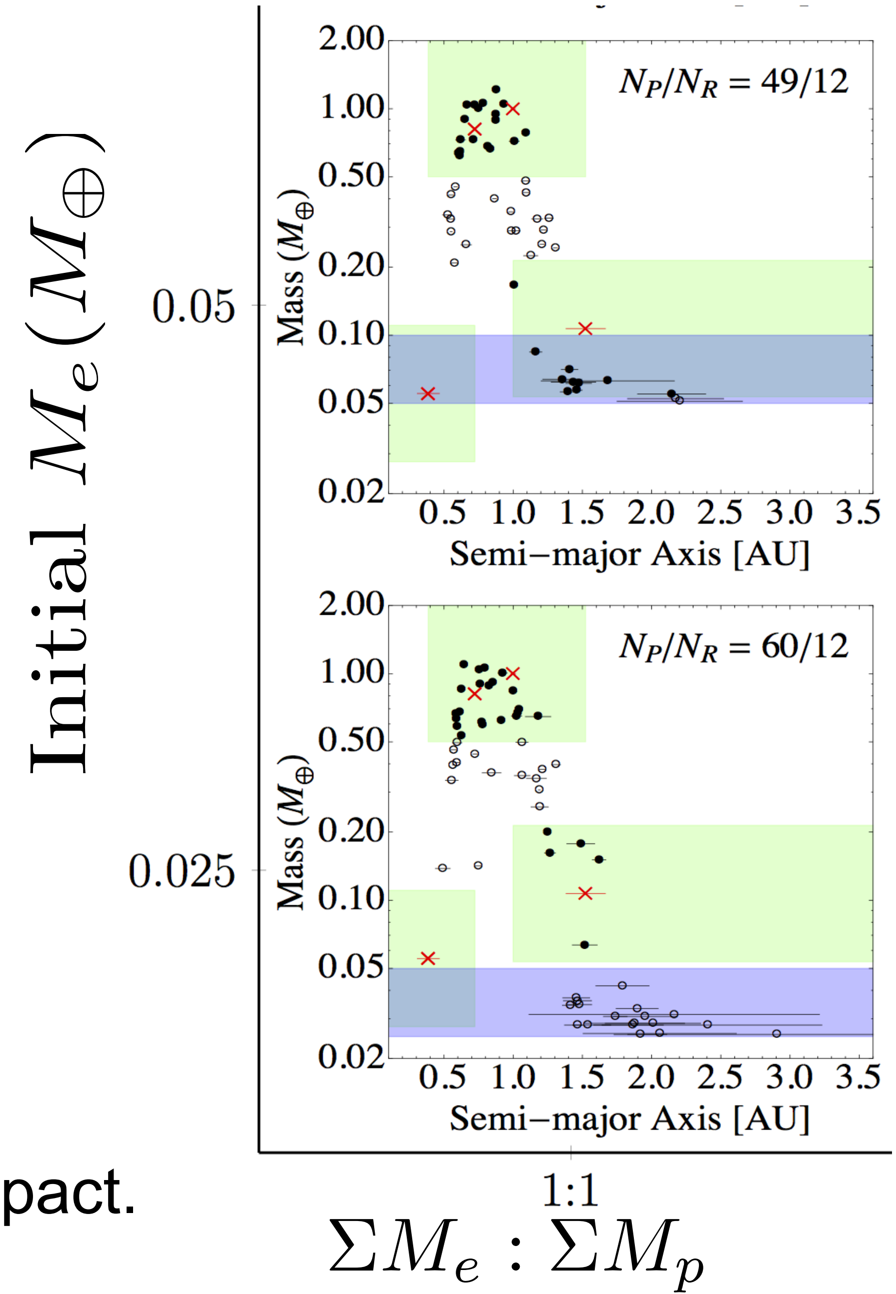
- tested two possible embryo masses (0.025 and 0.05 ME)

<u>Figure:</u>
Black points: from simulations,
+ data from O'Brien et al. (2013).

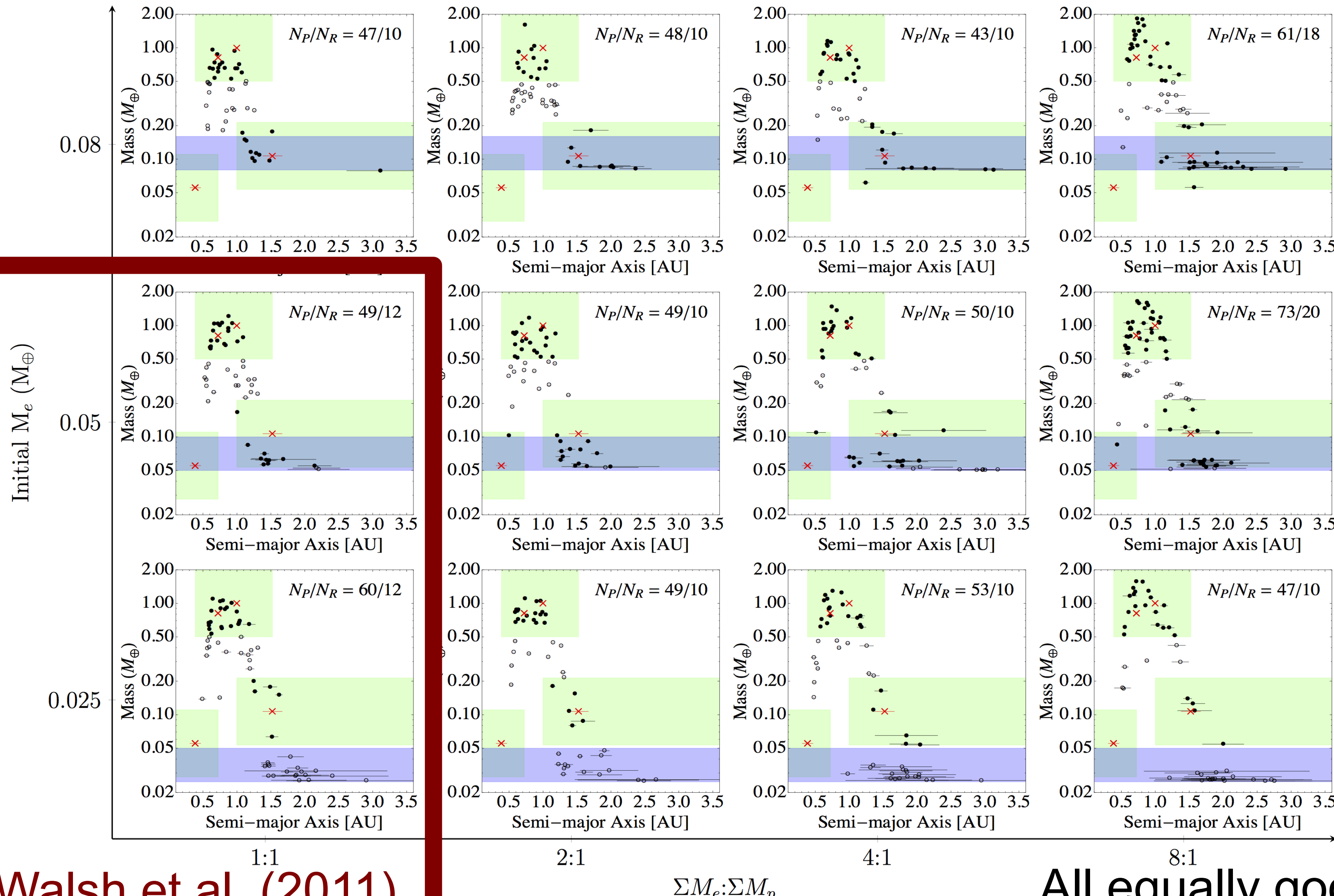
Red crosses: Terrestrial planets.

Green: analog regions.

Blue: single embryos, no giant impact.



1) Masses : EXPAND PARAMETER SPACE



Walsh et al. (2011)

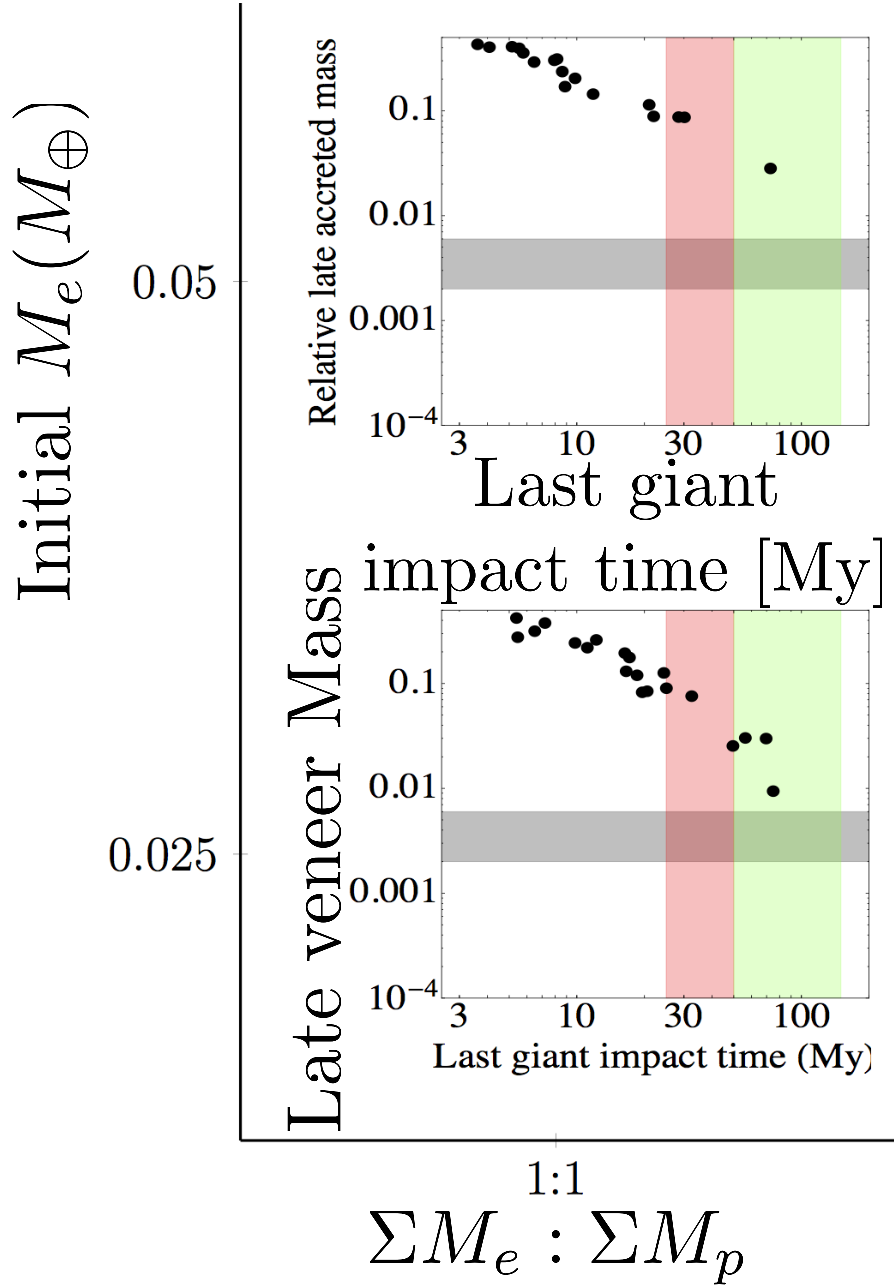
All equally good.

2) Timing of the last (moon-forming) giant impact

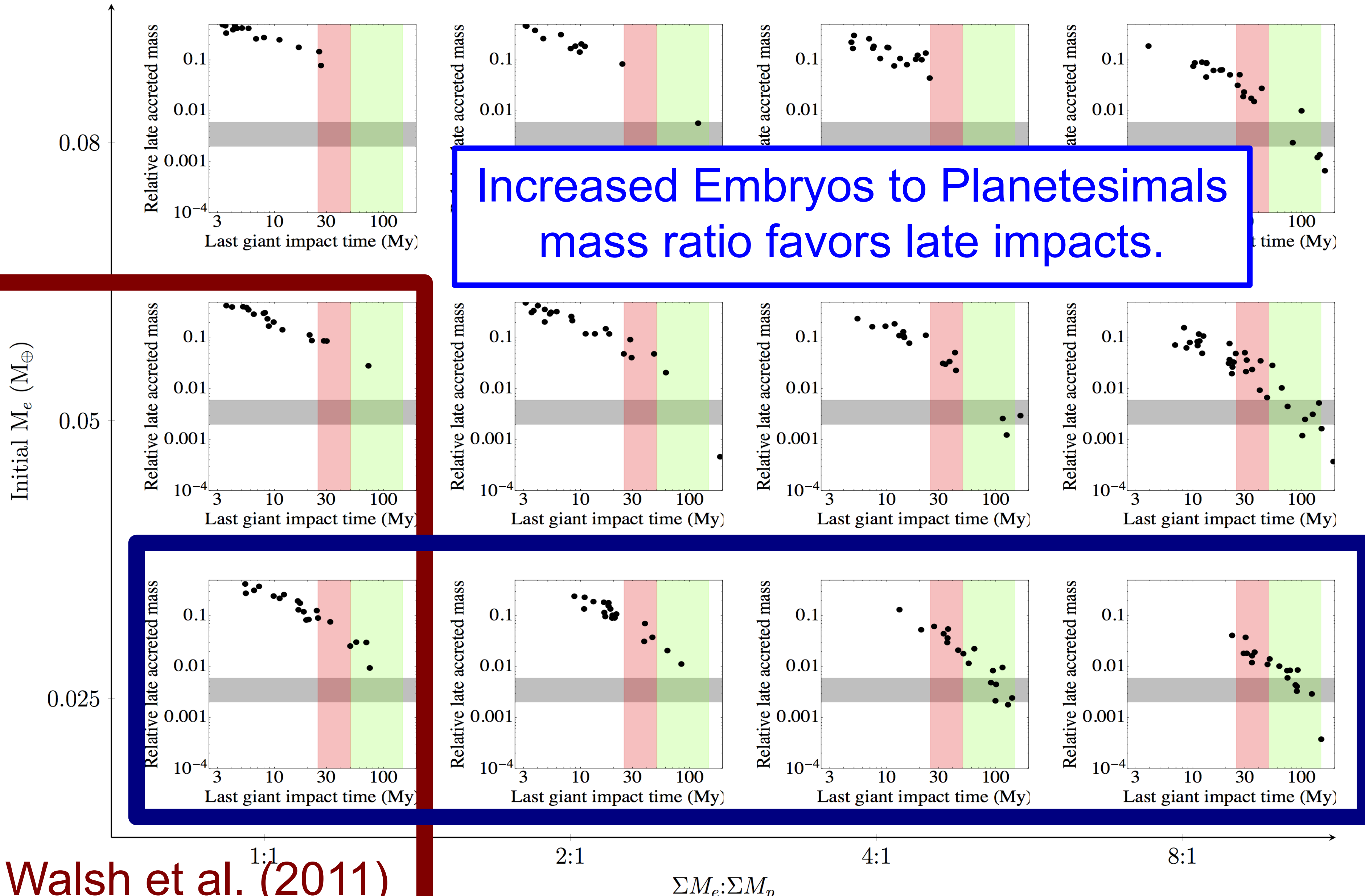
Walsh et al. (2011)
found a preference for early (~30 Myrs) last giant impacts.

Red band: early impact.

Green band: Late impact
(ex: Touboul et al. 2007)



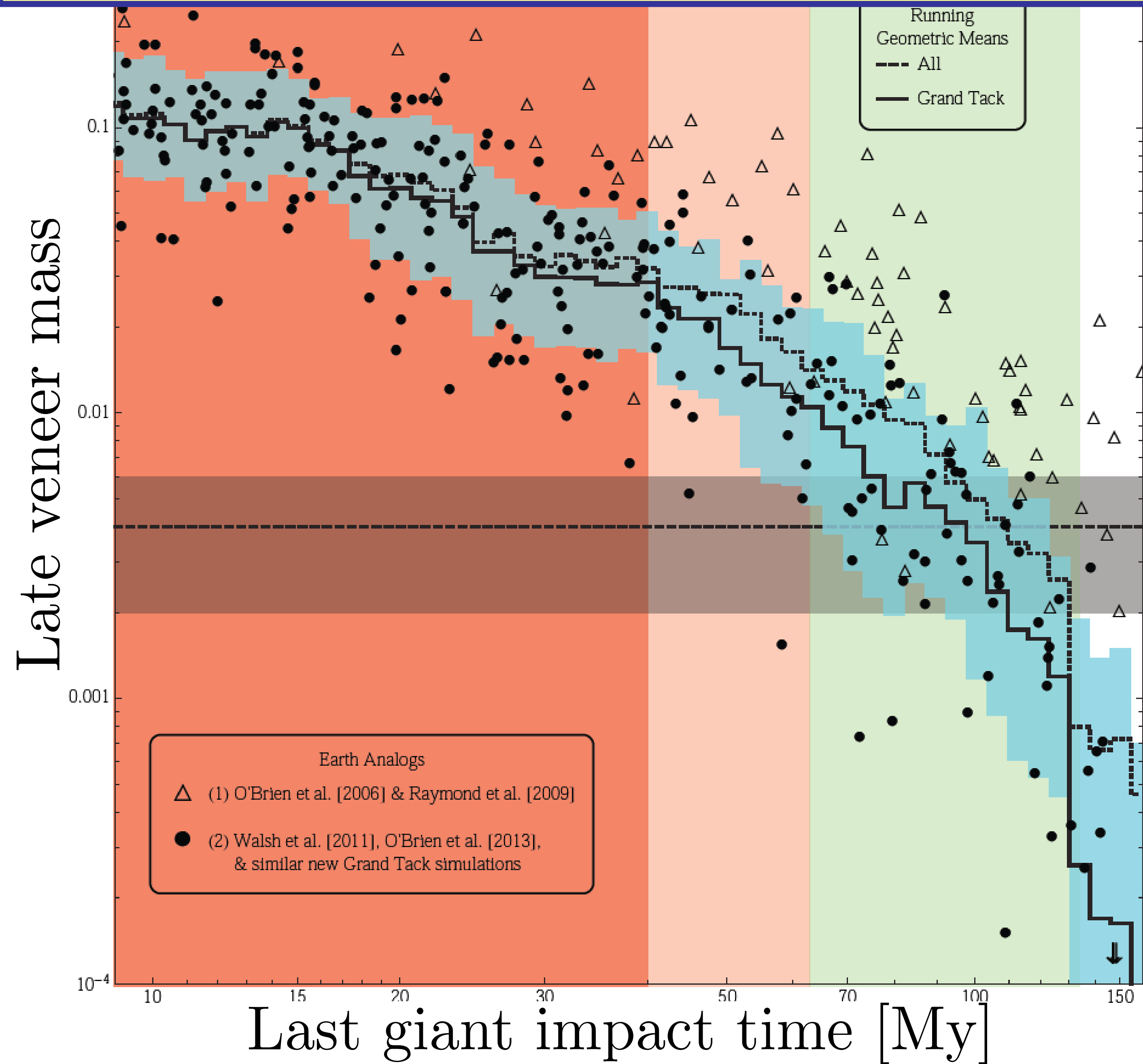
2) Timing of the last (moon-forming) giant impact



Increased Embryos to Planetesimals mass ratio favors late impacts.

Walsh et al. (2011)

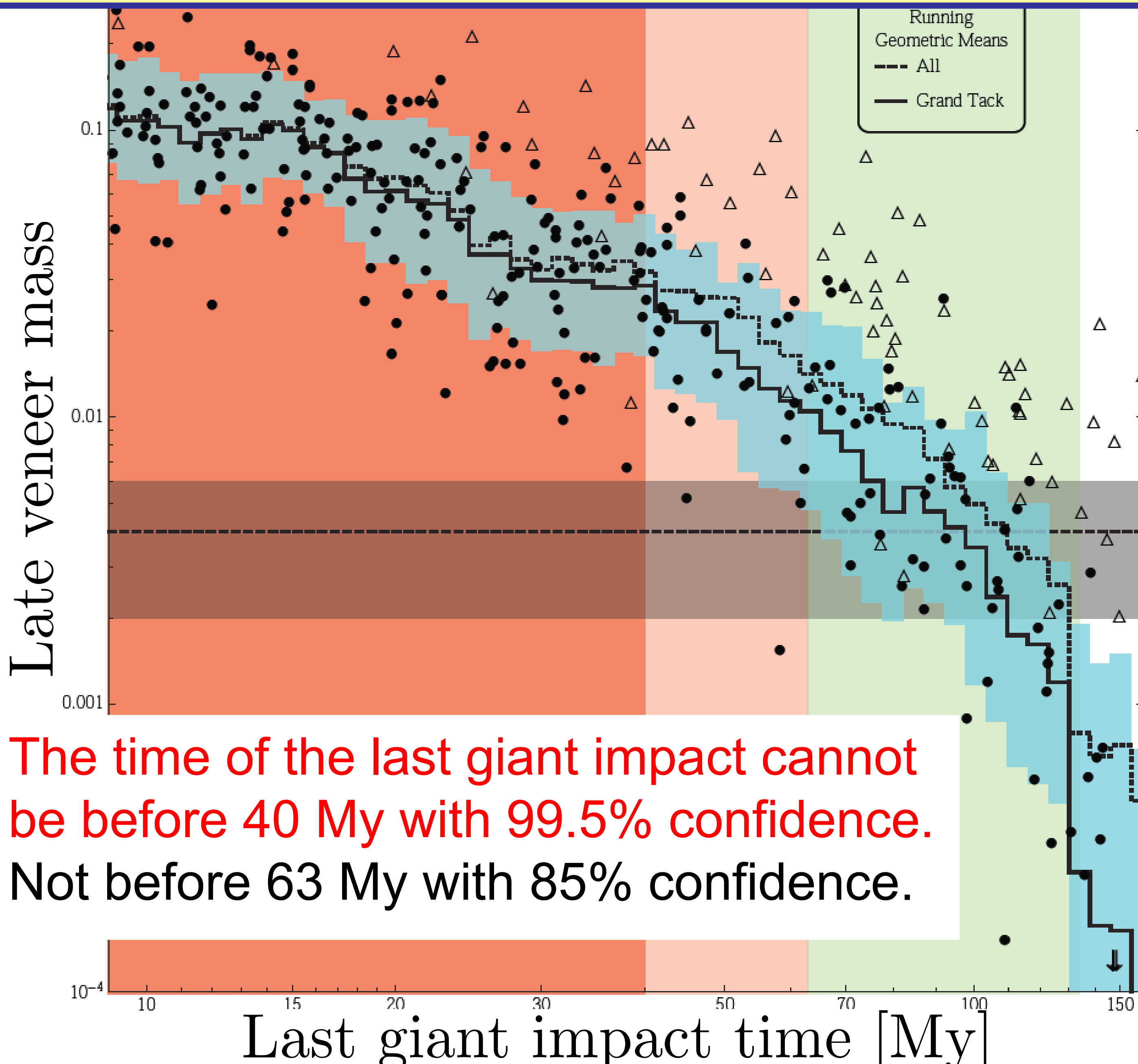
2) Timing of the last (moon-forming) giant impact



Jacobson et al. (2014):

Correlation between the time of the last giant impact and the amount of Late Veneer accreted after the formation of the Moon.

2) Timing of the last (moon-forming) giant impact



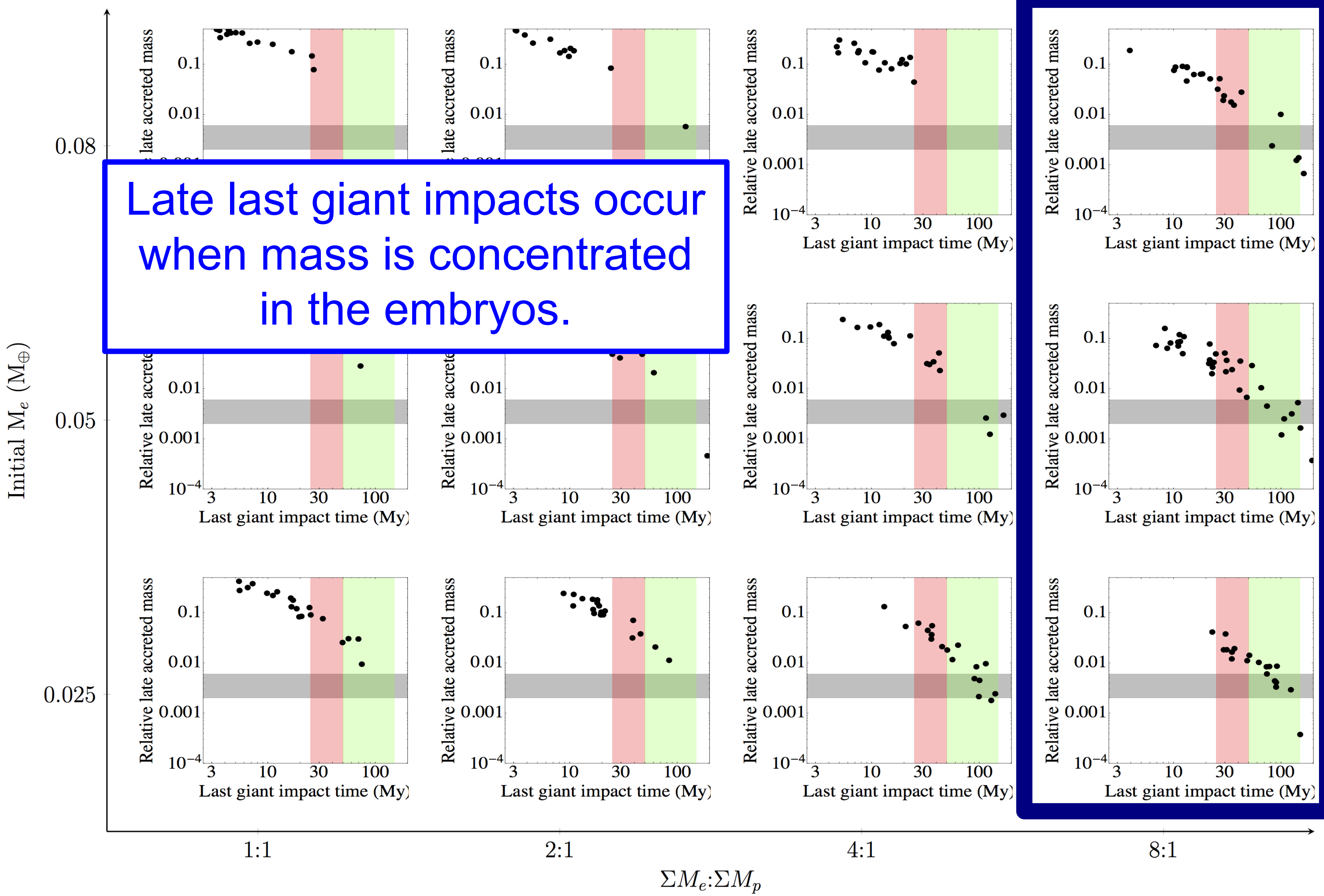
The mass of the late veneer is independently estimated by the abundances of highly siderophile elements: 4×10^{-3} M_{Earth} (grey band).

The time of the last giant impact cannot be before 40 My with 99.5% confidence.

Not before 63 My with 85% confidence.

This correlation dates the Moon forming impact to **95^{+37}_{-32} Myr** after t_0 of the Solar System.

Constrain back the initial conditions



Late last giant impacts occur when mass is concentrated in the embryos.

Constrain back the initial conditions

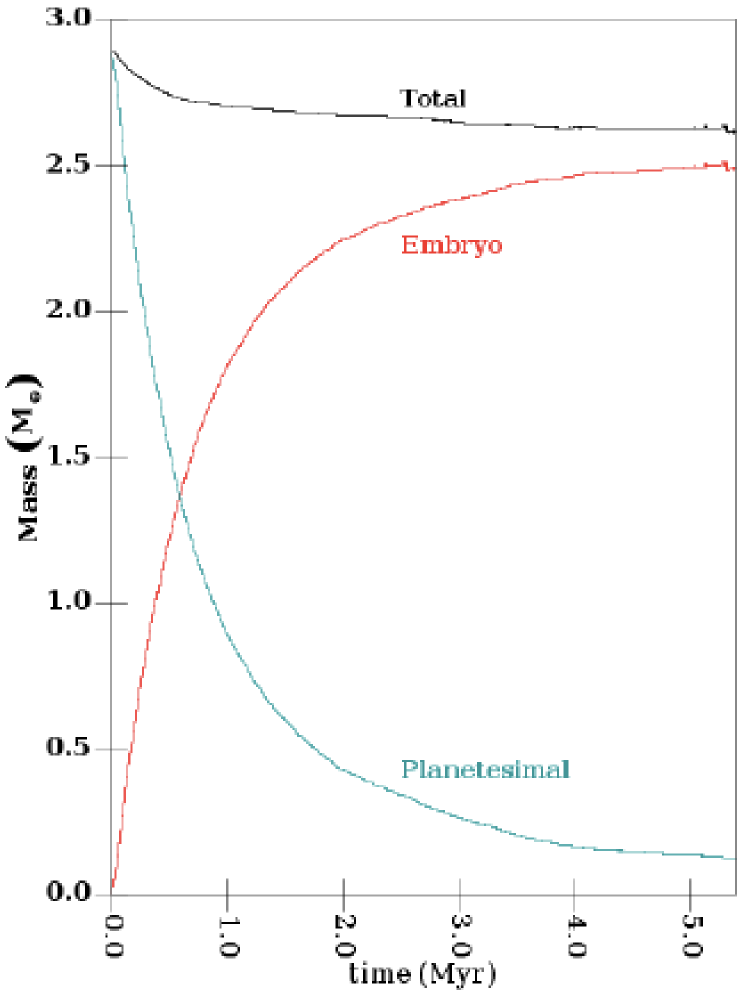
Why would mass be concentrated in the embryo population?

Collisional grinding

- Planetesimal-planetesimal collisions are erosive

Pebble formation

- Planetesimals might be rather rare
- Most planetesimals turn into embryos



Levison (2012)

3) Age of Mars

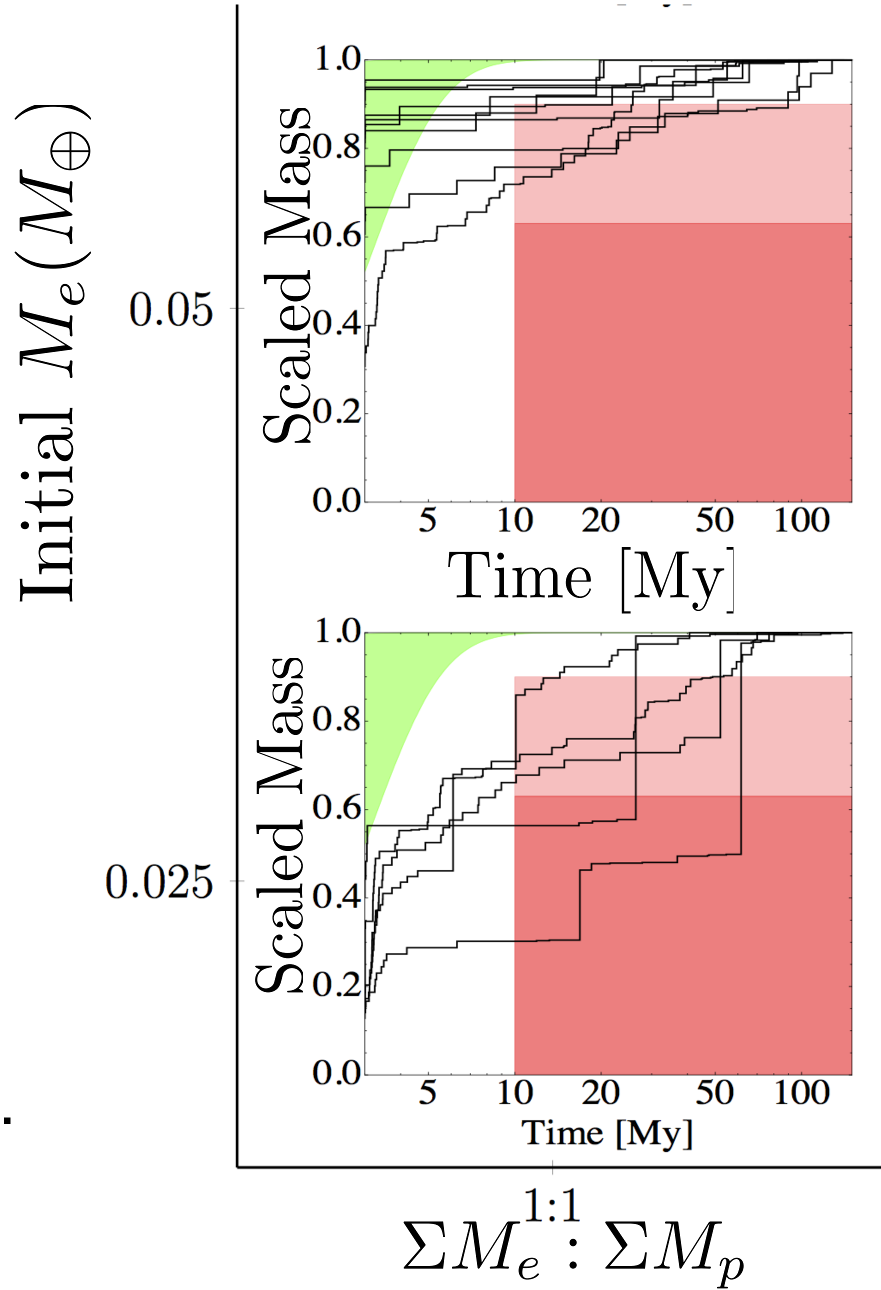
Can we break embryo mass degeneracy?

Mars forms quickly: few Myrs. (Nimmo & Dauphas 2007 ; Dauphas & Pourmand 2011).

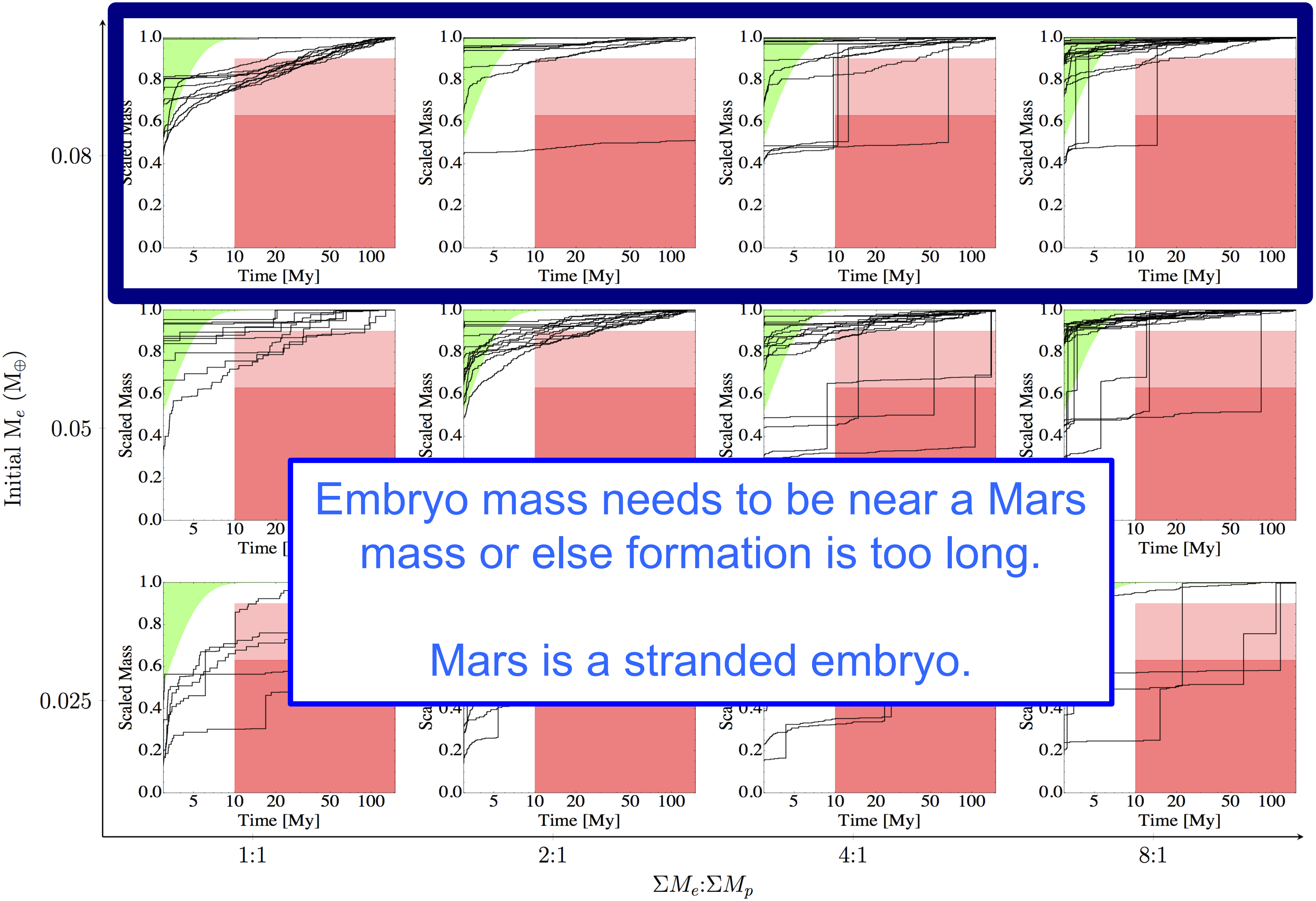
Remember start of Grand Tack scenario is not the same as time of first solids.

<u>Figure:</u>
time evolution of Mars' mass.

Green: compatible with constraints.
Red: forbidden zone.



3) Age of Mars



Embryo mass needs to be near a Mars mass or else formation is too long.

Mars is a stranded embryo.

GRAND TACK & TERRESTRIAL PLANETS

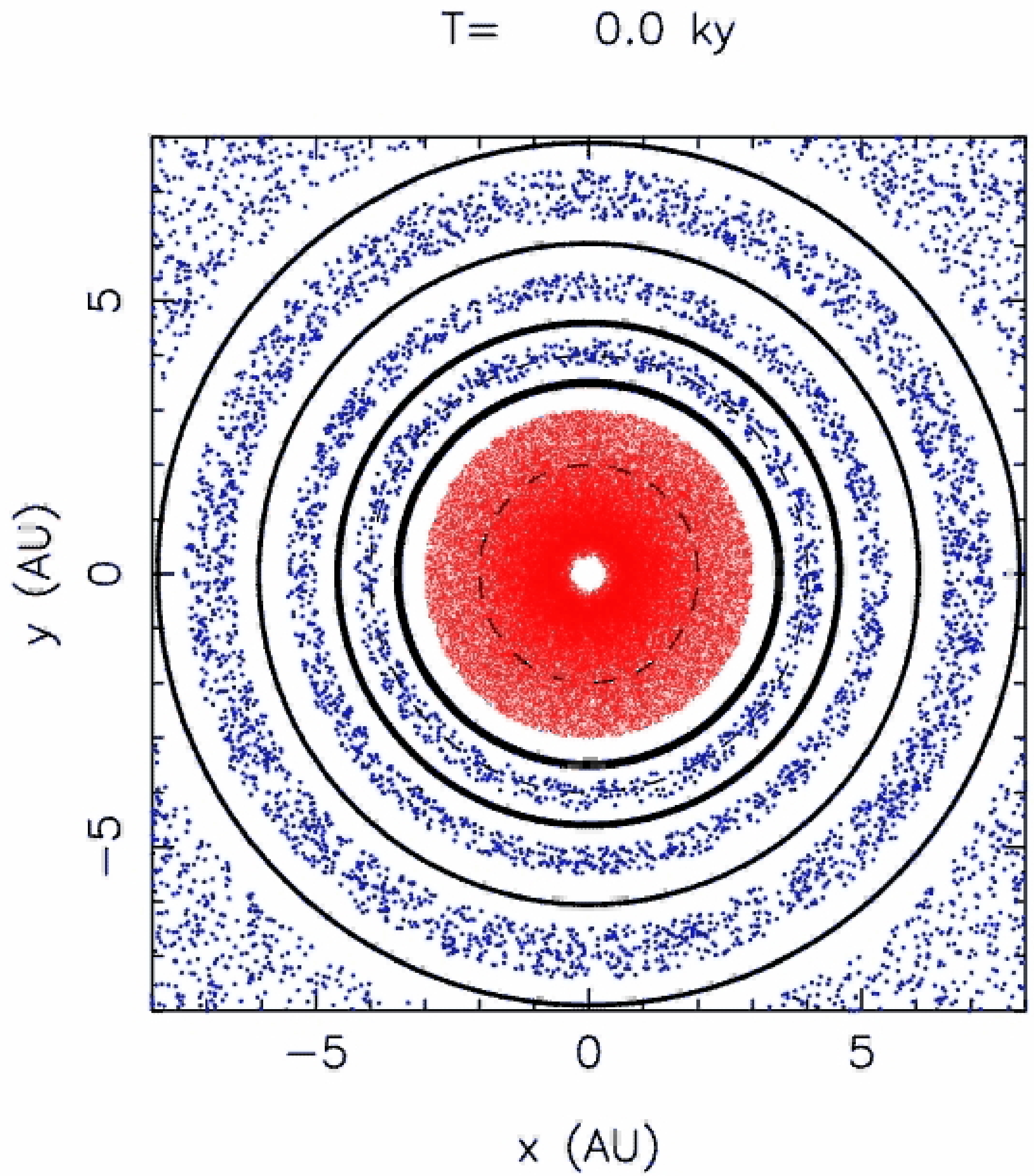
All isotopic chronometers exclude that the Moon formed earlier than 40 Myrs after CAI. It could be 40 to 100 Myrs.

There is a correlation between the time of the last giant impact and the late veneer mass.
This correlation dates the Moon forming impact to 95^{+37}_{-32} Myr after the formation of solids in the Solar System.
The time of the last giant impact cannot be before 40 Myr with 99.5% confidence in this scenario.

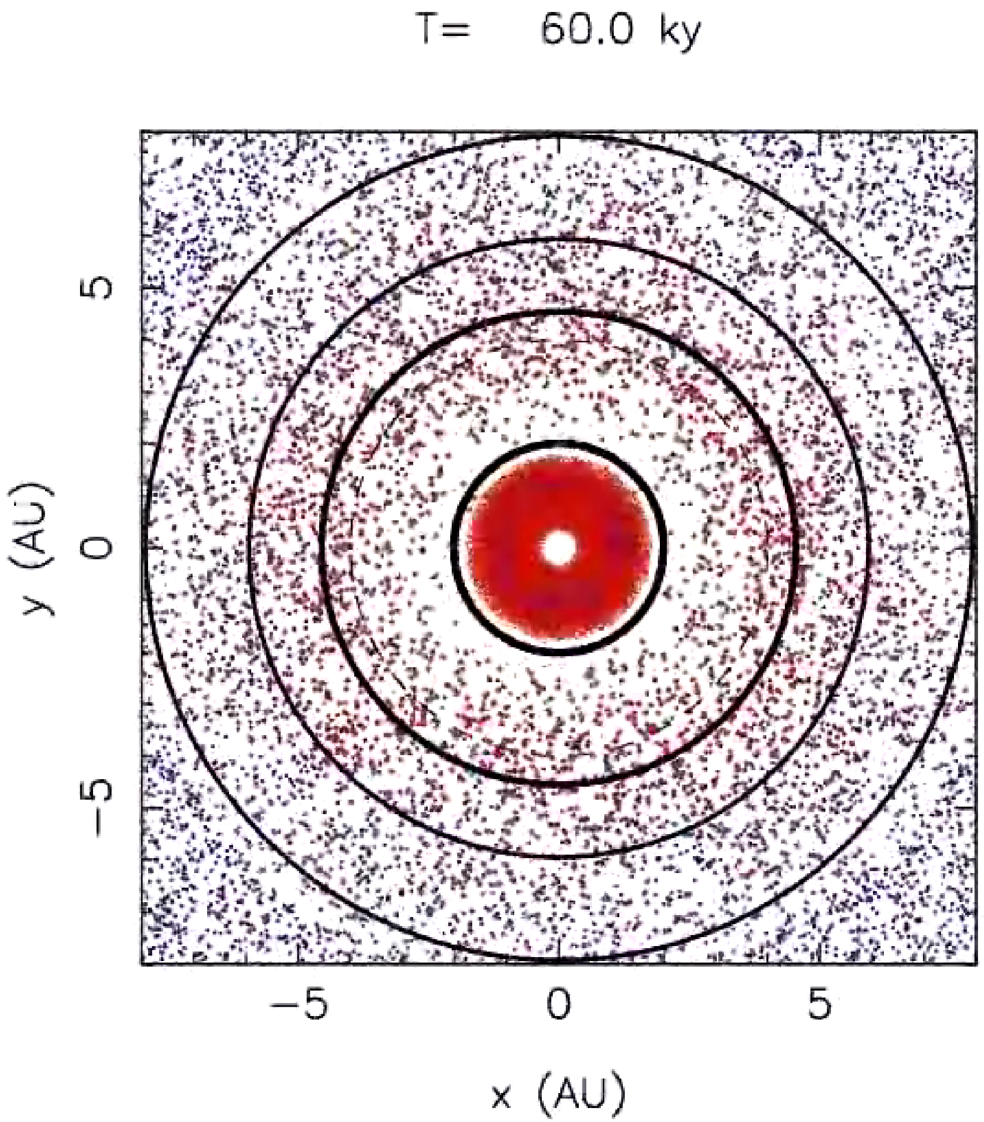
Late last Giant Impacts occur when mass is concentrated in the embryo population, likely due to pebble growth or collisional grinding.

In order to form Mars in time,
then Mars must be a stranded embryo.

MIGRATION IN THE SOLAR SYSTEM



MIGRATION IN THE SOLAR SYSTEM



(GRAND TACK AND) ICE GIANTS

Whether Jupiter tacks or not, it stopped at ~5 AU. With Saturn just behind.

Movie planets_1_158_JS_tIN_e :

Giant impacts among core.

Explanation for Uranus and Neptune's tilt (and rings?) + formation of 2-3 ice giants.

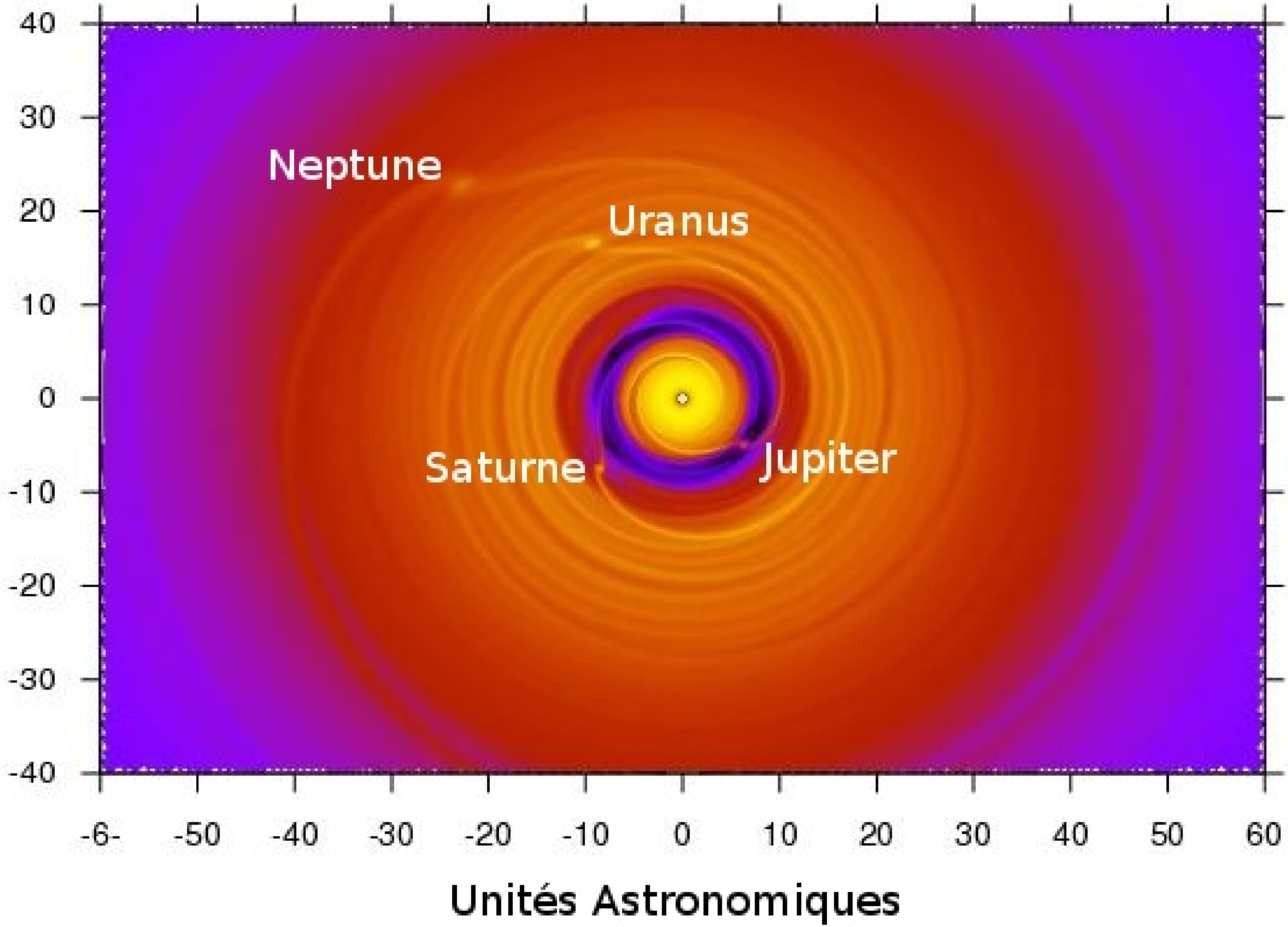
(GRAND TACK AND) PLANET 9

Whether Jupiter tacks or not, it stopped at ~5 AU. With Saturn just behind.

Movie planets_10_3_JS_tIN_e :

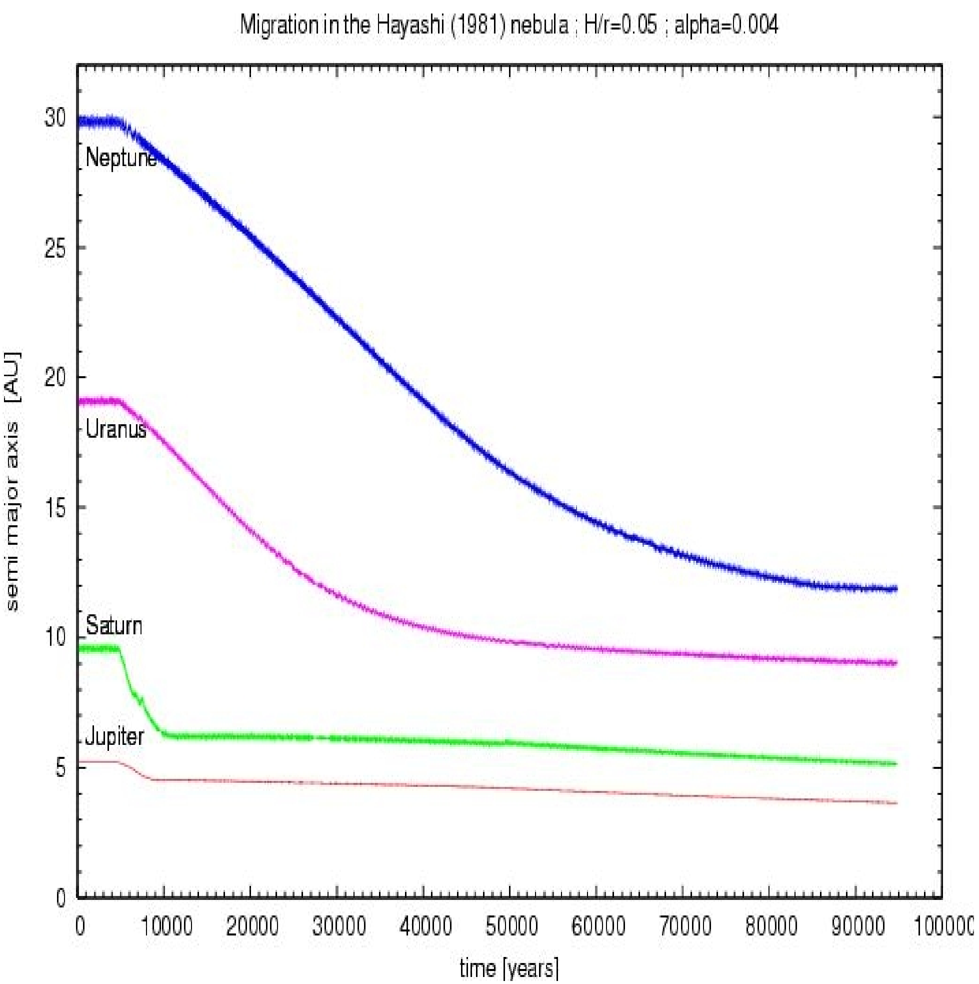
Inside the potential of the stellar cluster in which the Solar System formed, a scattered ice giant **can** be torqued to a large perihelion → decouple from J & S → end on an orbit similar to Planet 9's.

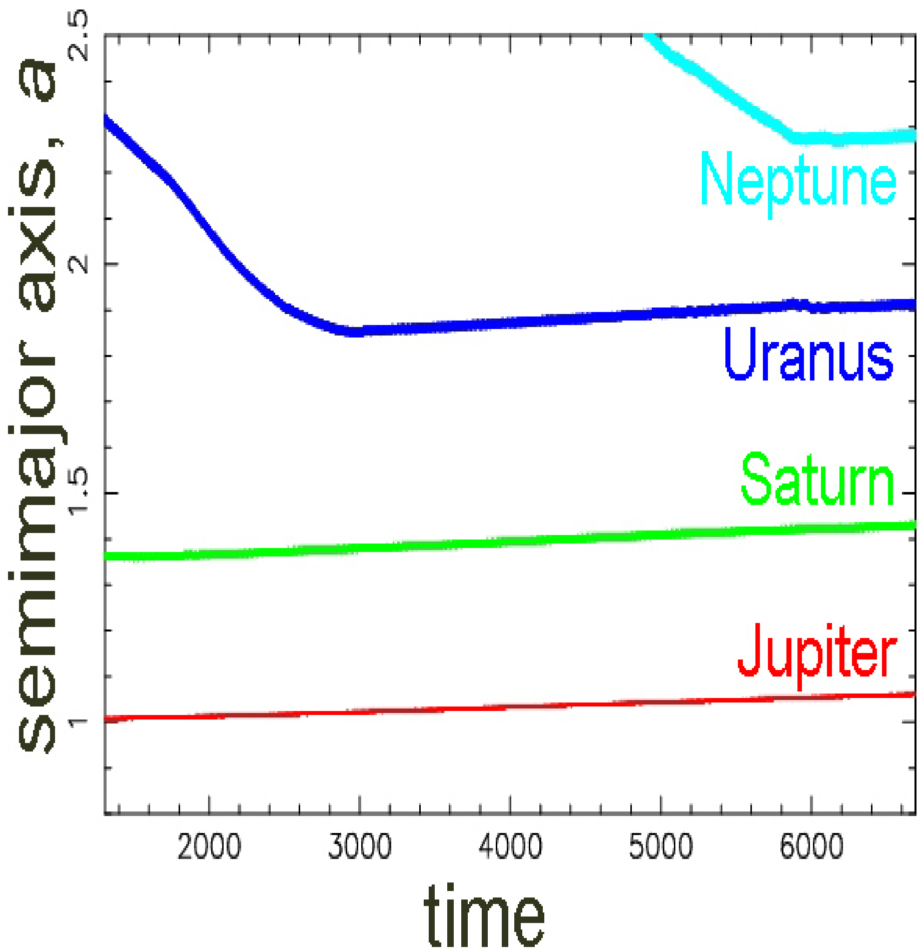
MIGRATION IN THE SOLAR SYSTEM



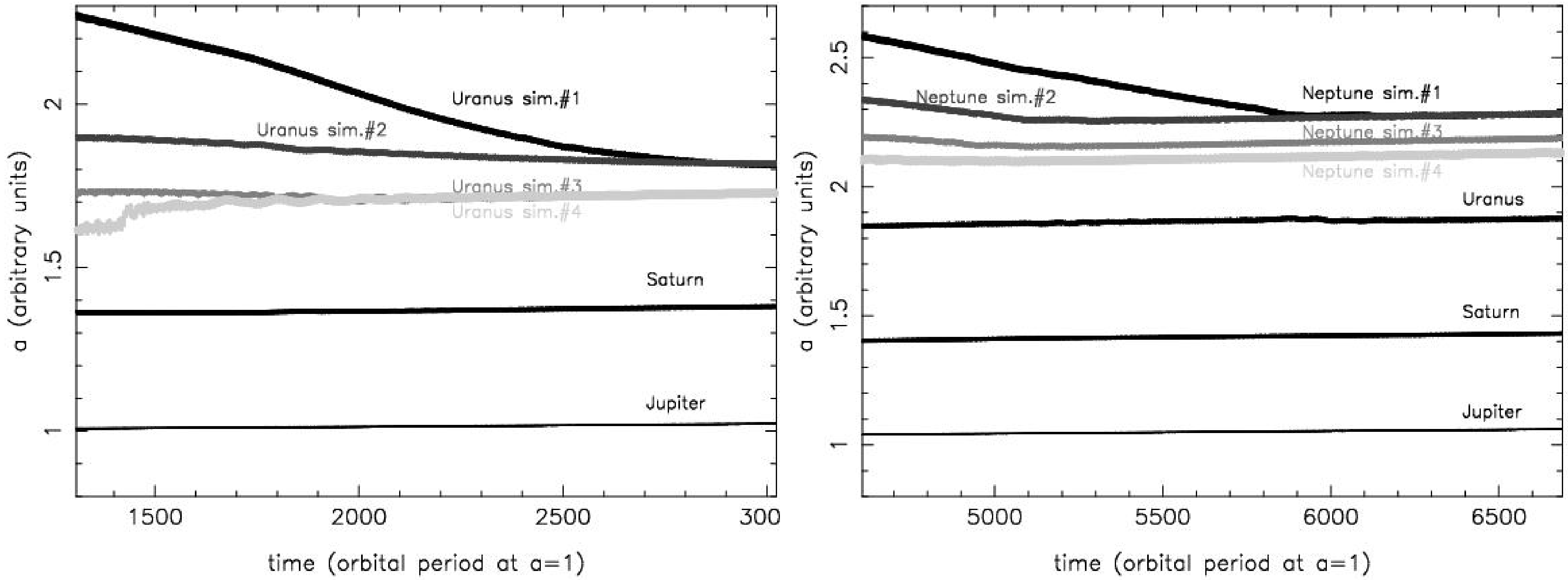
MIGRATION IN THE SOLAR SYSTEM

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





MIGRATION IN THE SOLAR SYSTEM



<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)

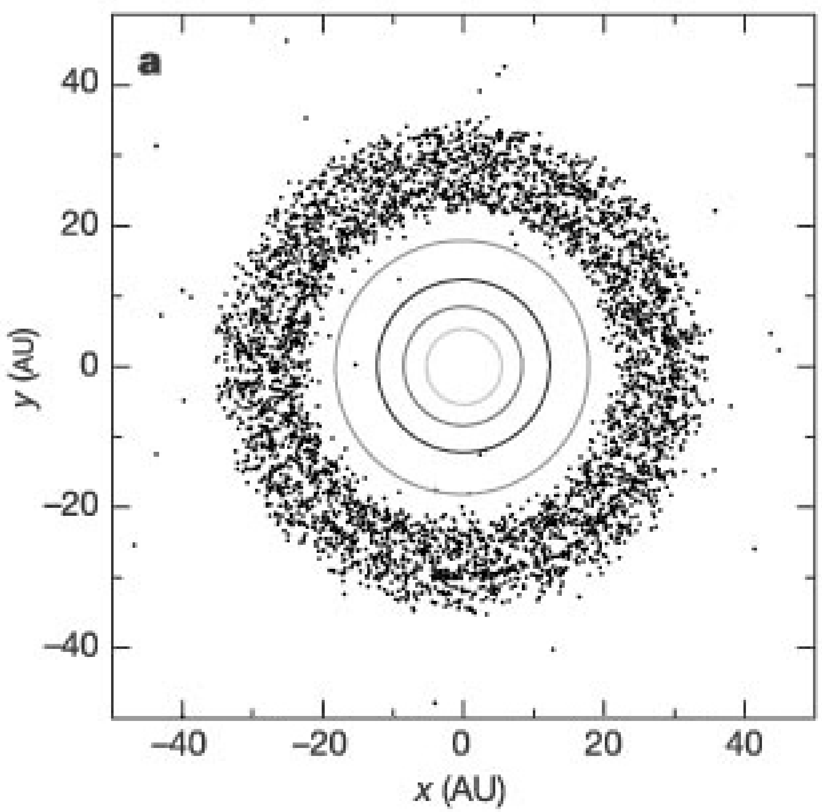
4 unstable in a few Myrs, 2 stable for more than 100 Myrs.

(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 ?



b) The NICE MODEL

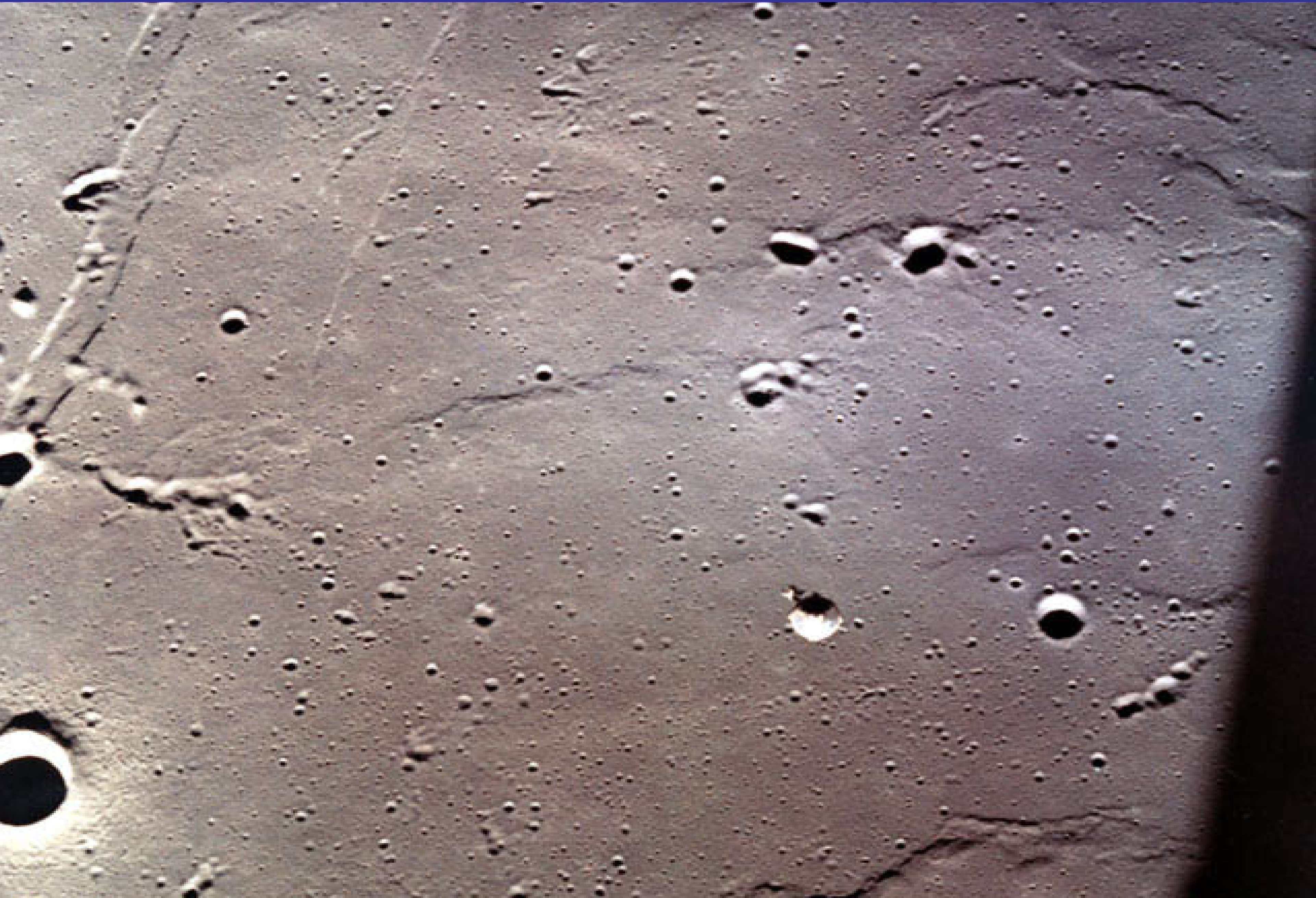
global instability in the giant planets' architecture

after dispersal of the gas disk

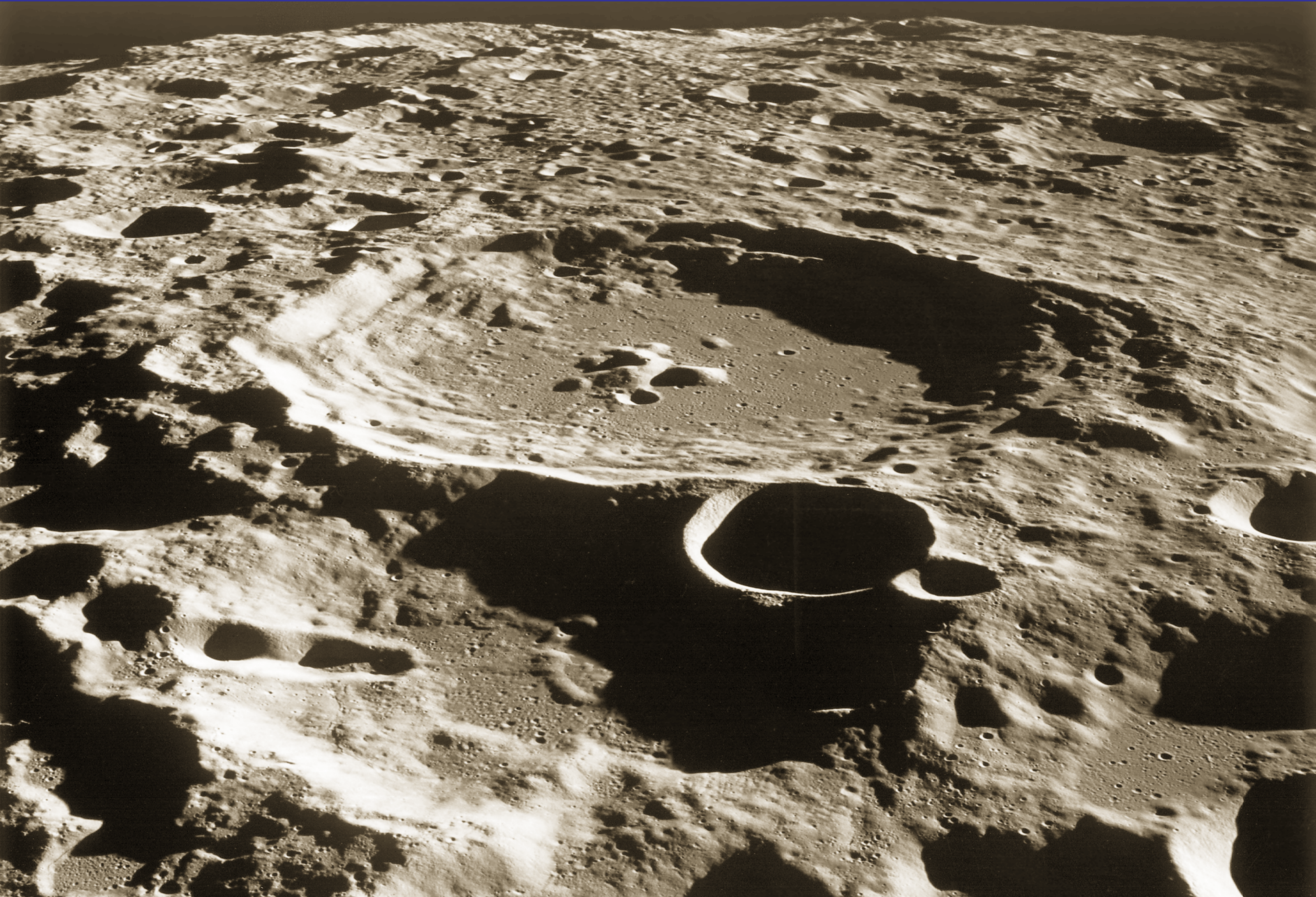
So, the giant planets didn't form where they are now ?!
That was thinking outside of the box !
But does it bring anything ? Does it solve problems ?
Does it work better than the previous assumption ?

A LATE HEAVY BOMBARDMENT ?

A LATE HEAVY BOMBARDMENT ?



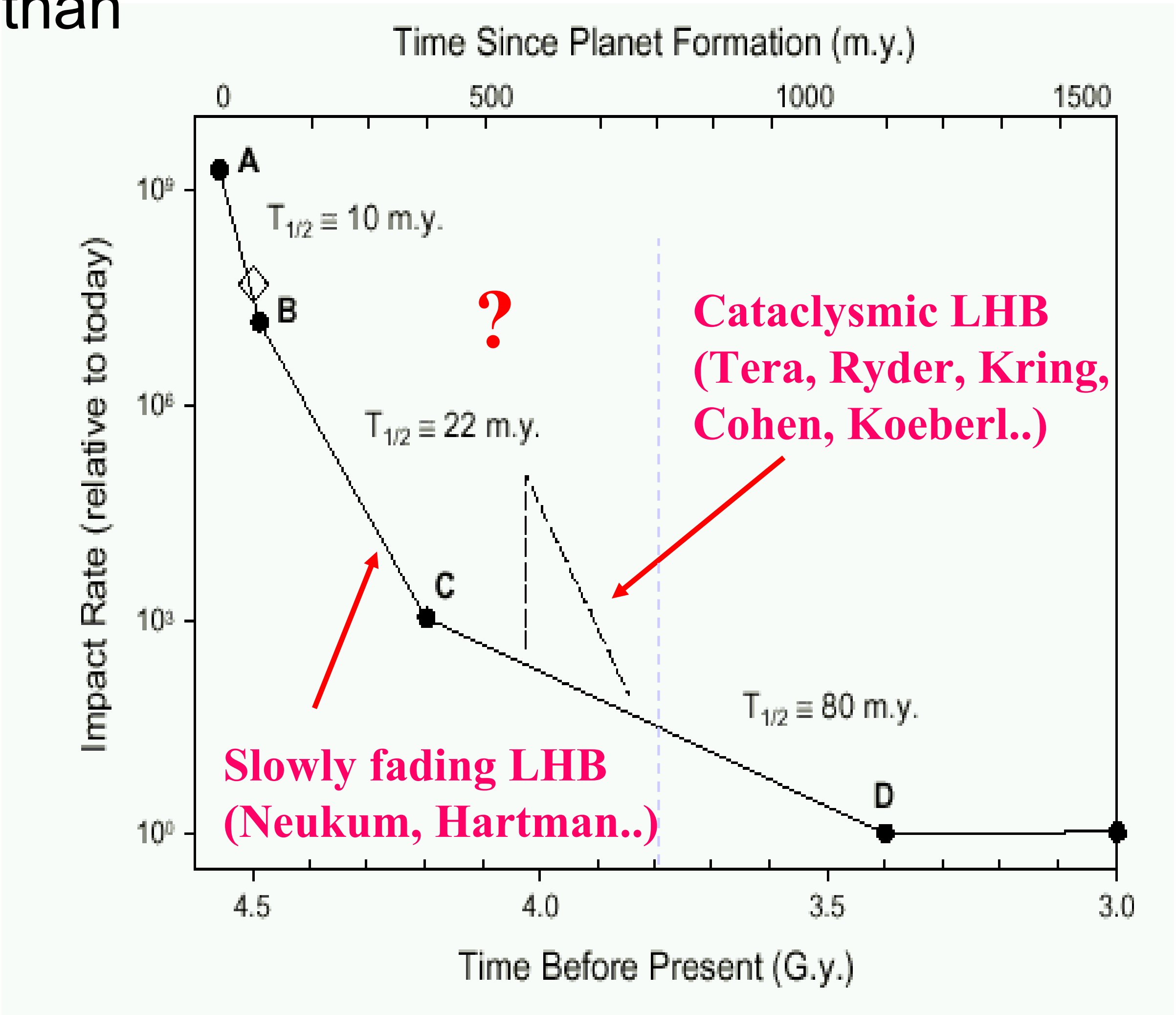
A LATE HEAVY BOMBARDMENT ?



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 ?

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"

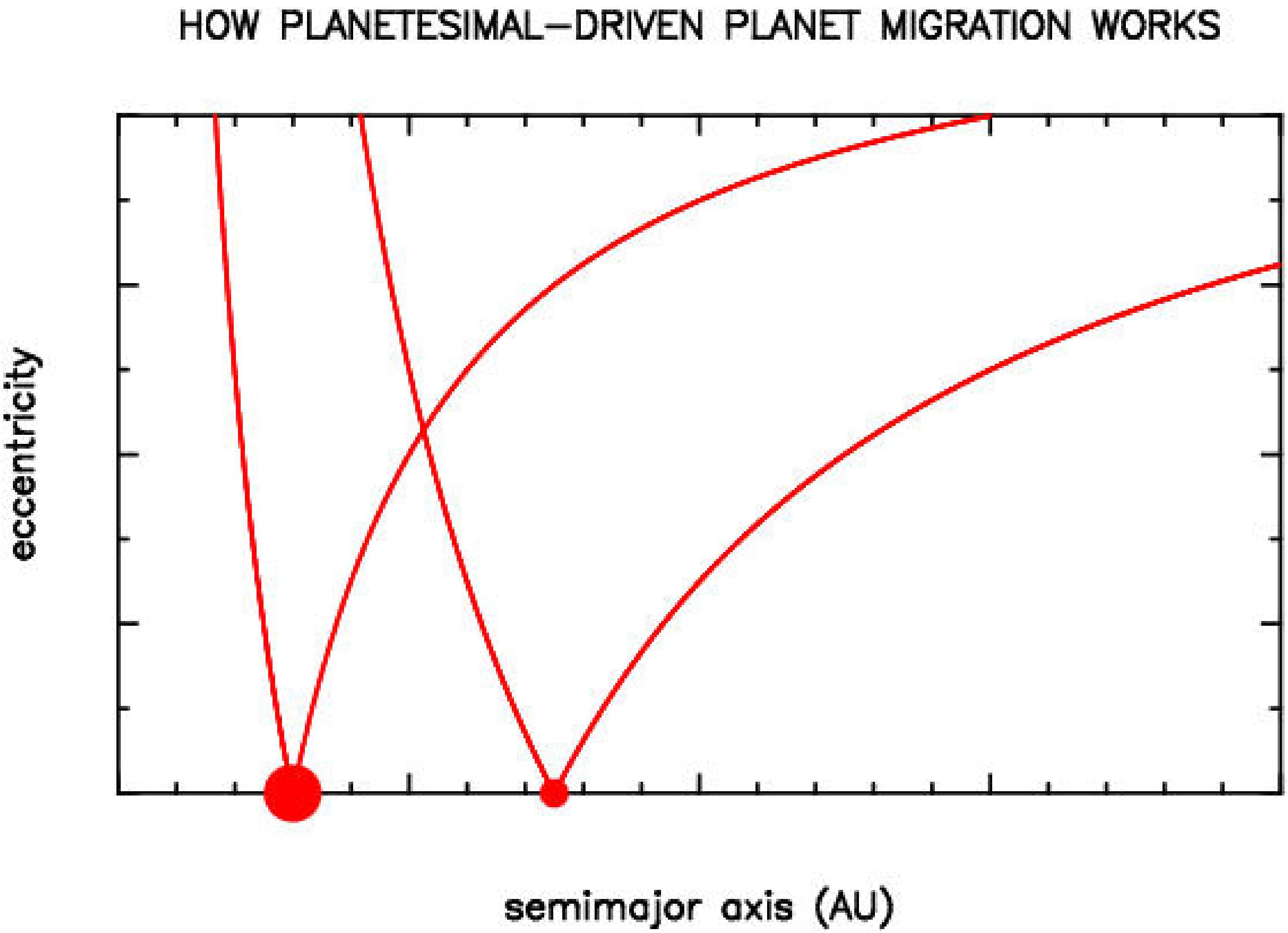
A LATE HEAVY BOMBARDMENT ?

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

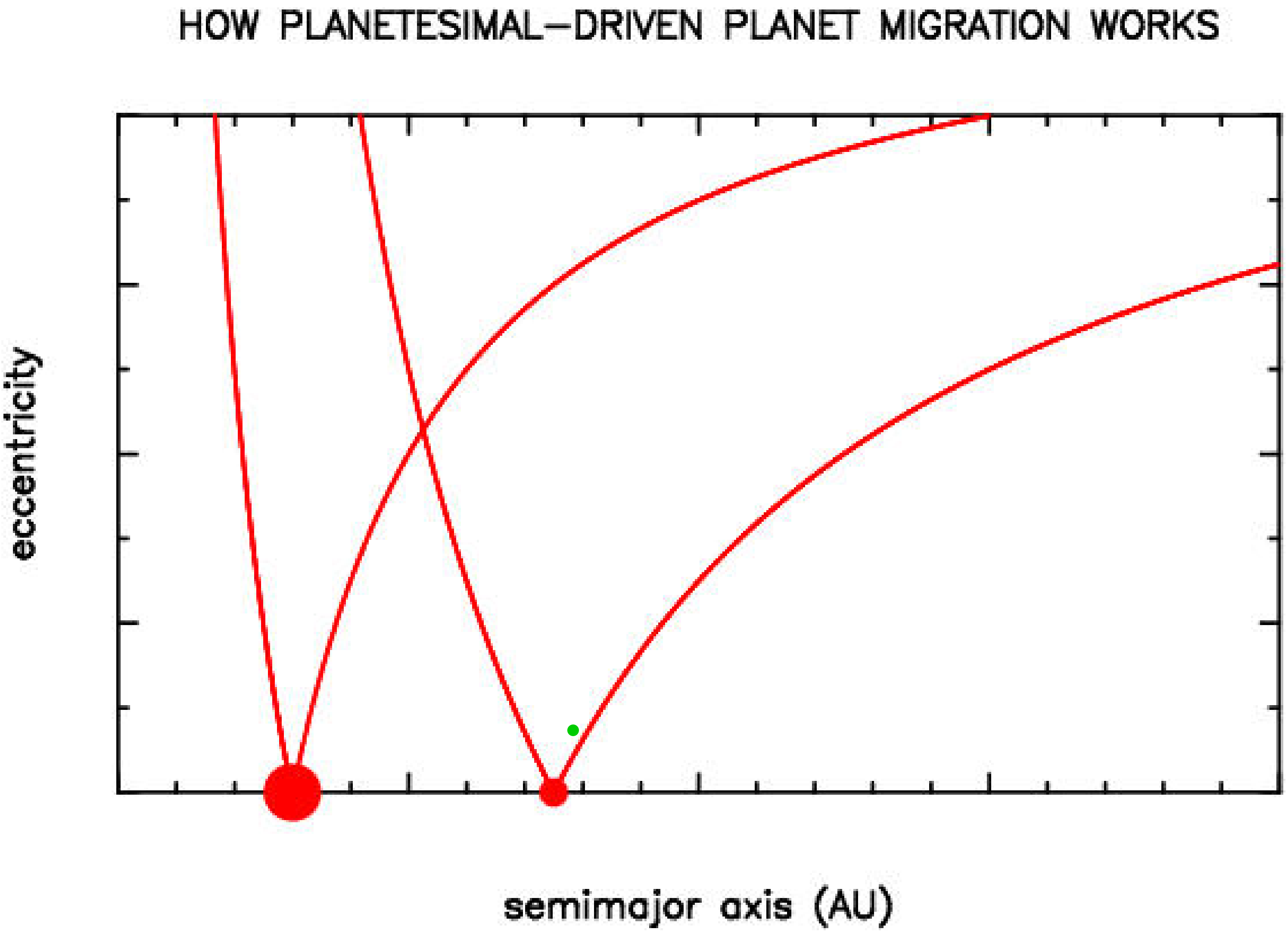
This is only possible if there is a change in the orbital structure of the giant planets.

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

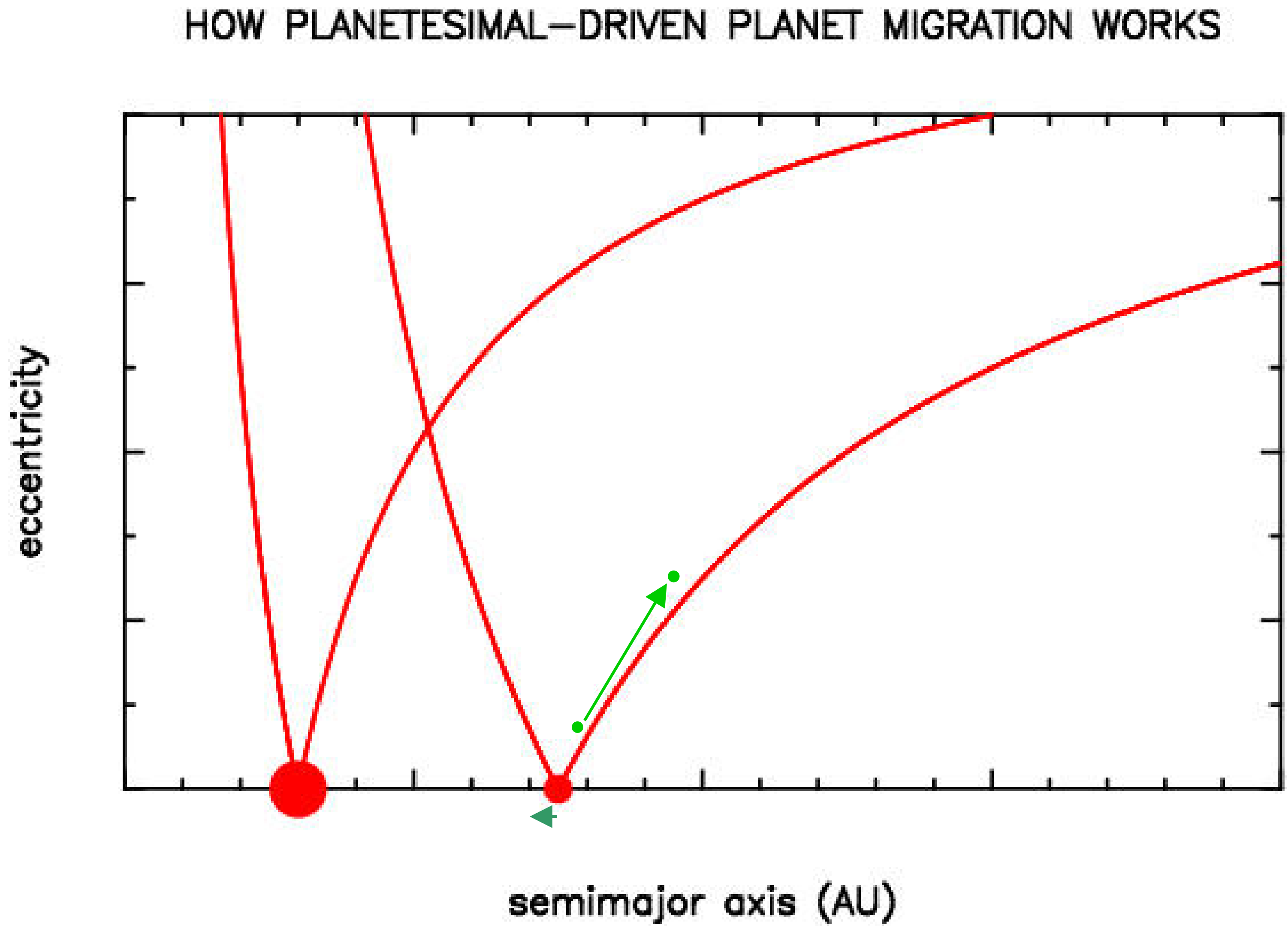
PLANETESIMALS DRIVEN MIGRATION



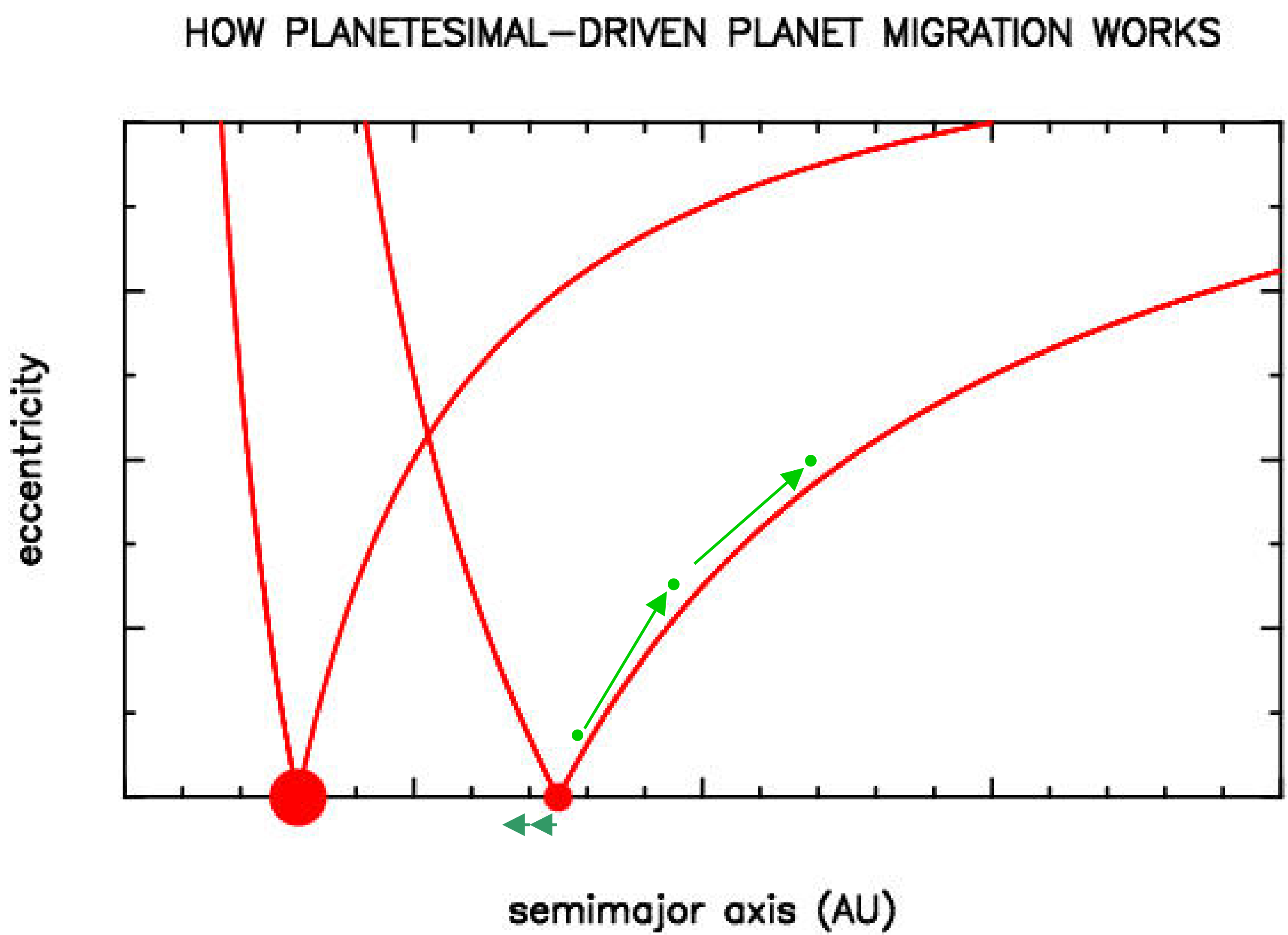
PLANETESIMALS DRIVEN MIGRATION



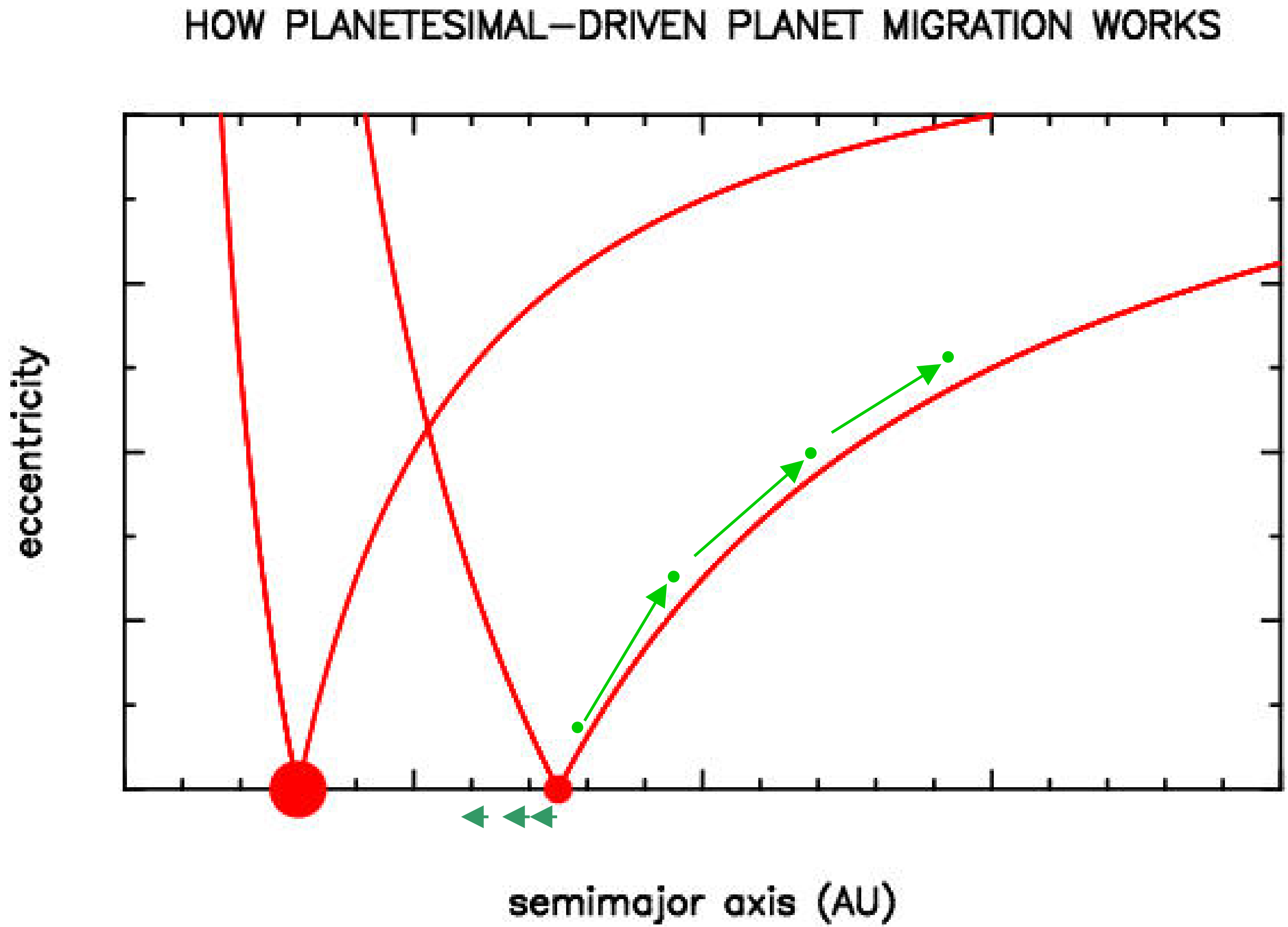
PLANETESIMALS DRIVEN MIGRATION



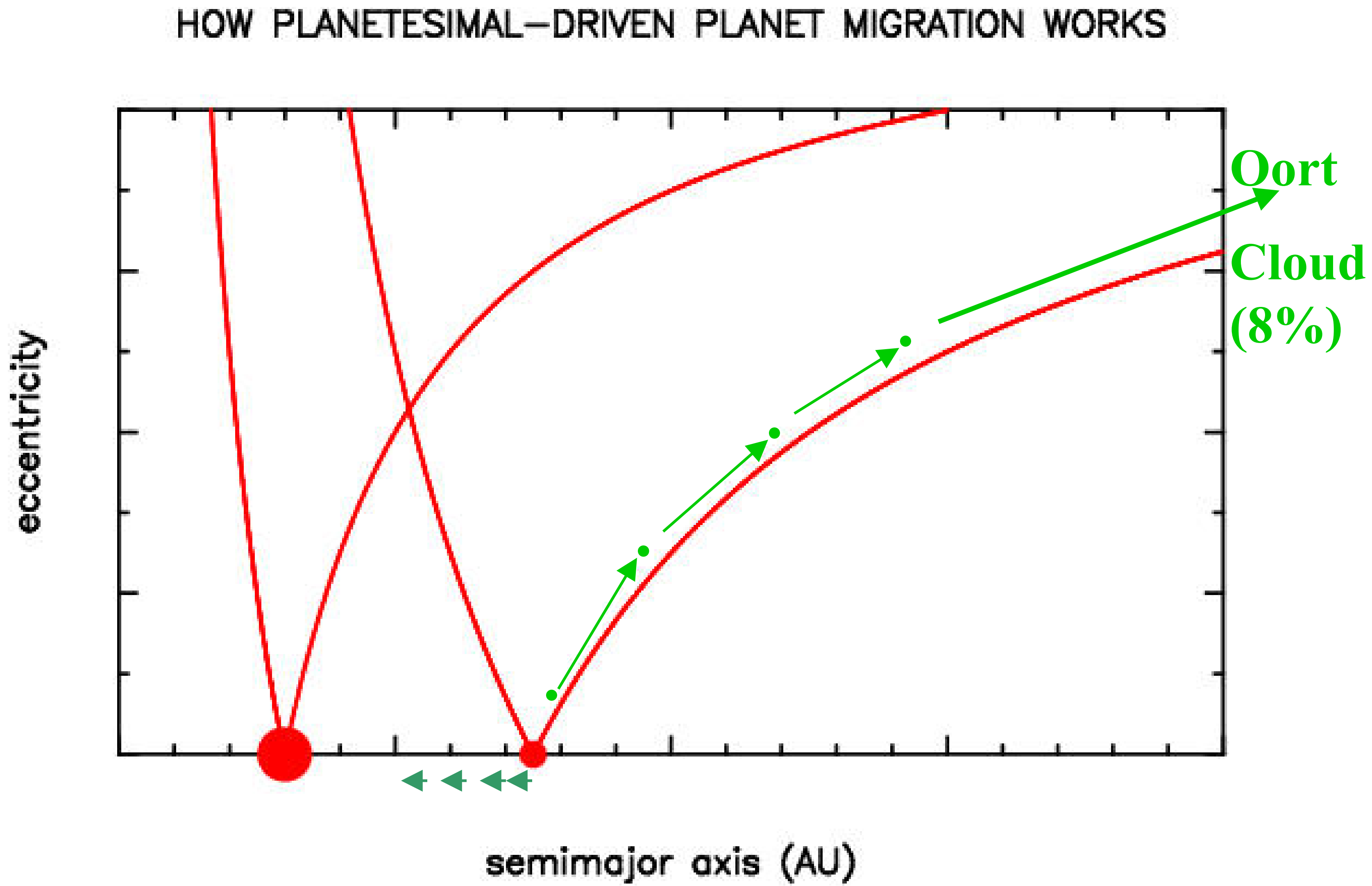
PLANETESIMALS DRIVEN MIGRATION



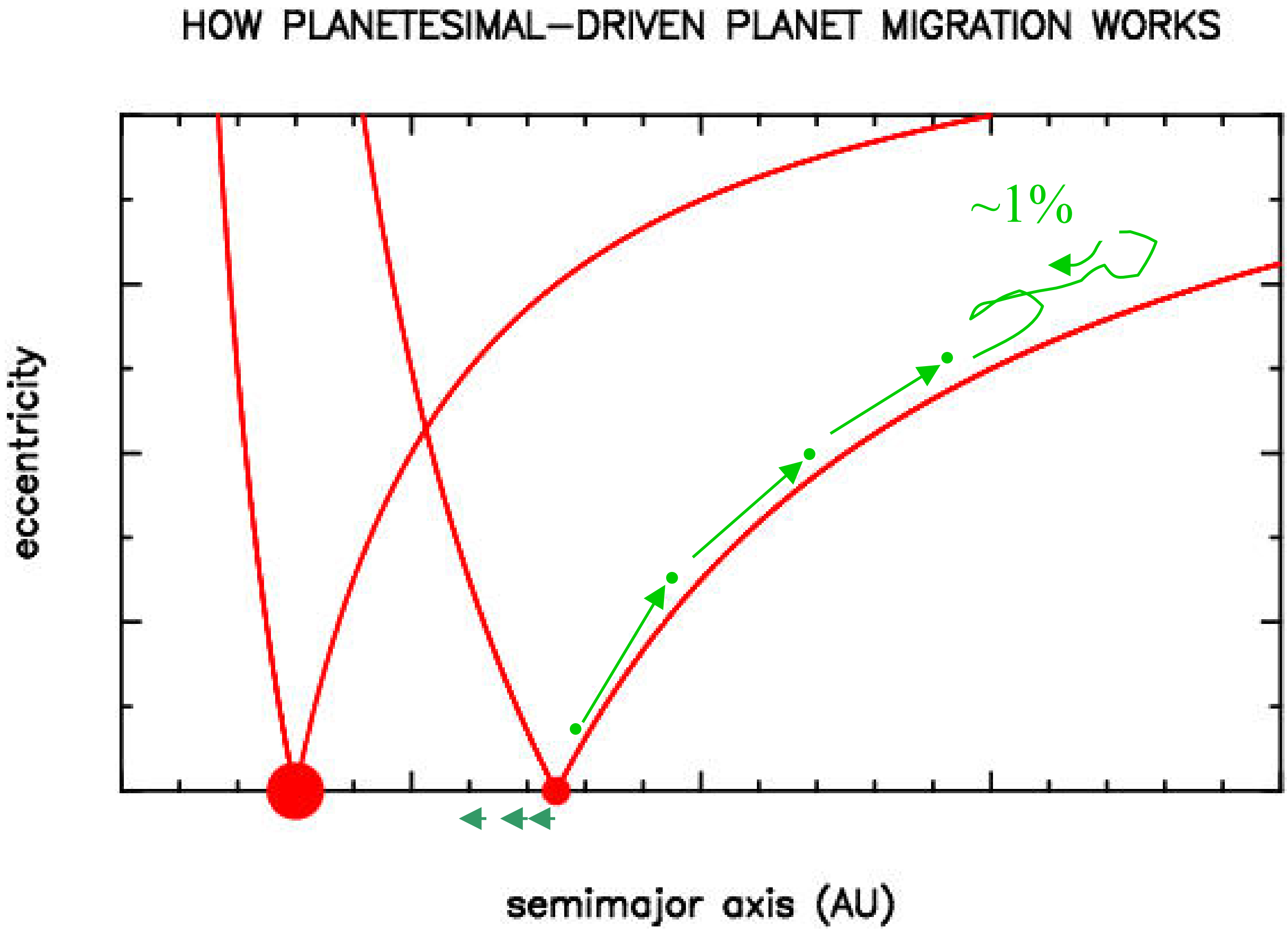
PLANETESIMALS DRIVEN MIGRATION



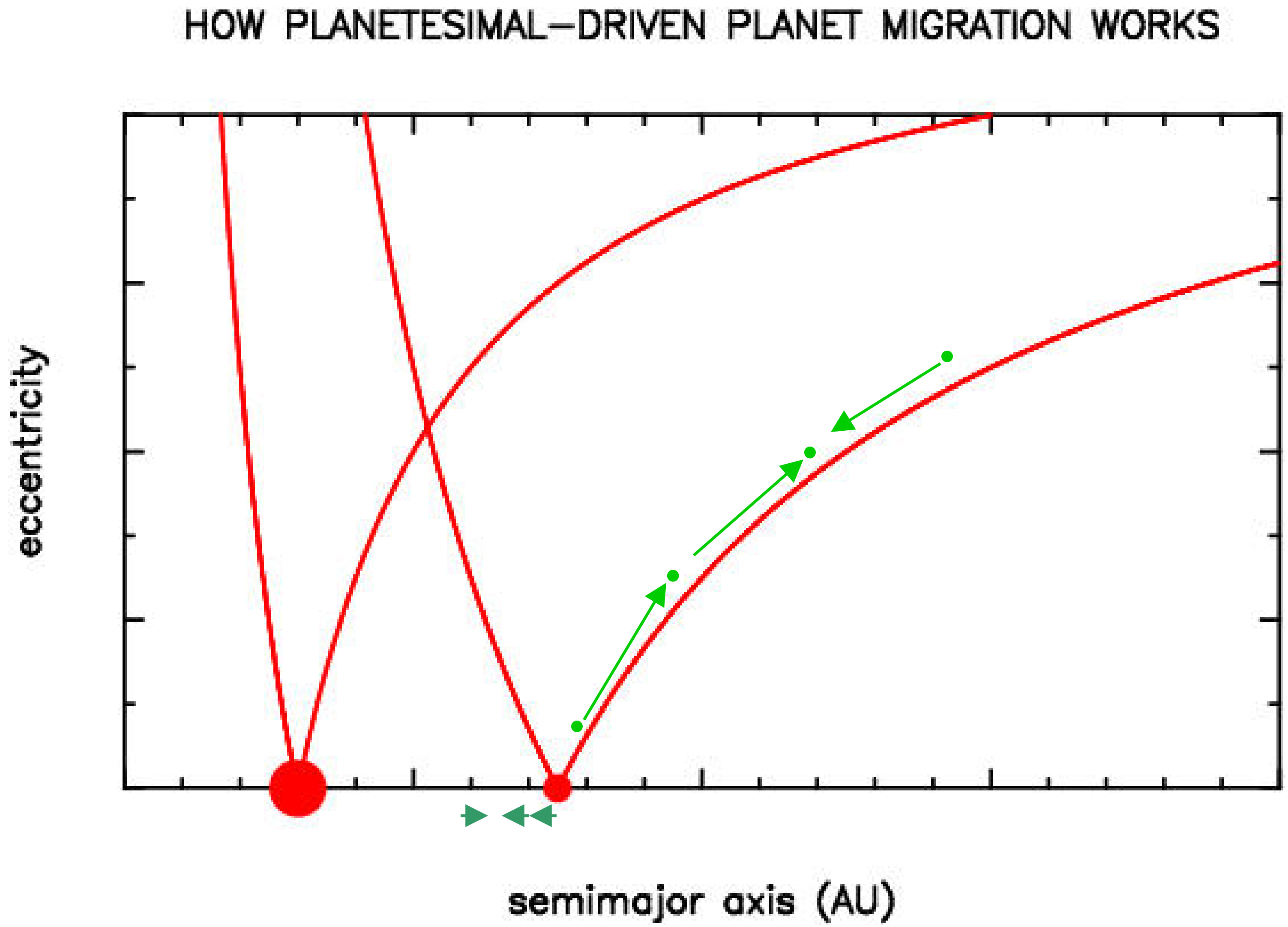
PLANETESIMALS DRIVEN MIGRATION



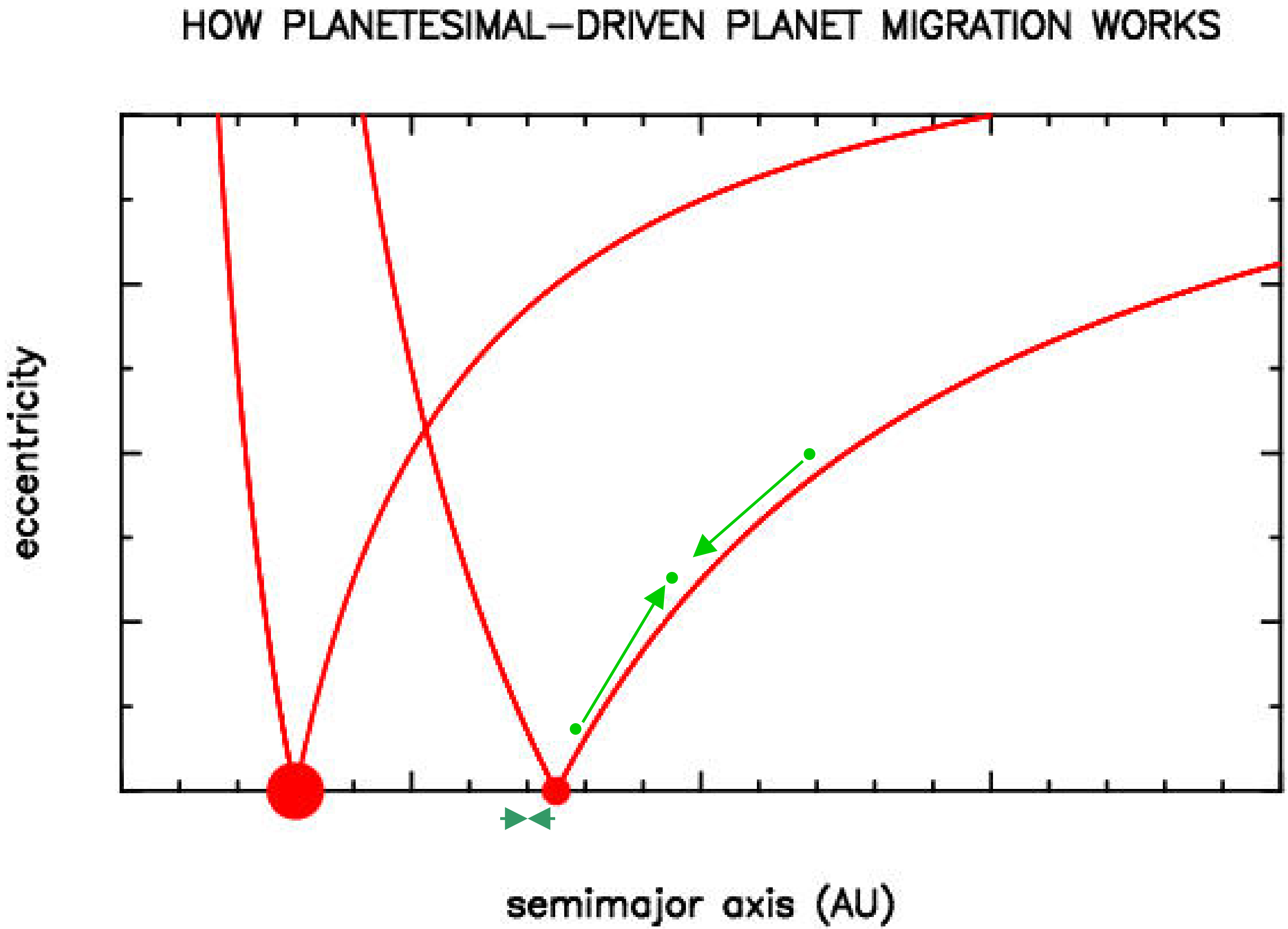
PLANETESIMALS DRIVEN MIGRATION



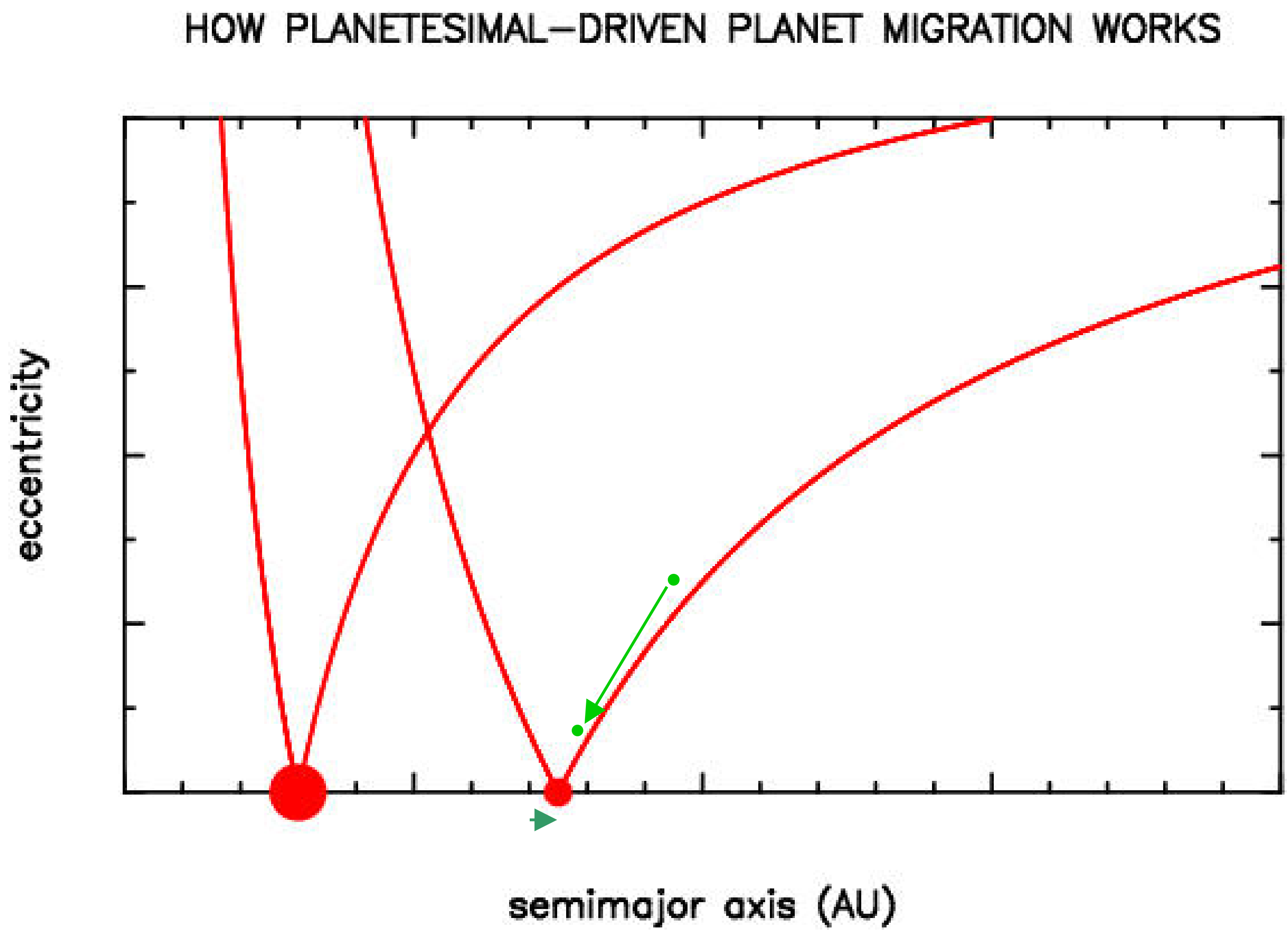
PLANETESIMALS DRIVEN MIGRATION



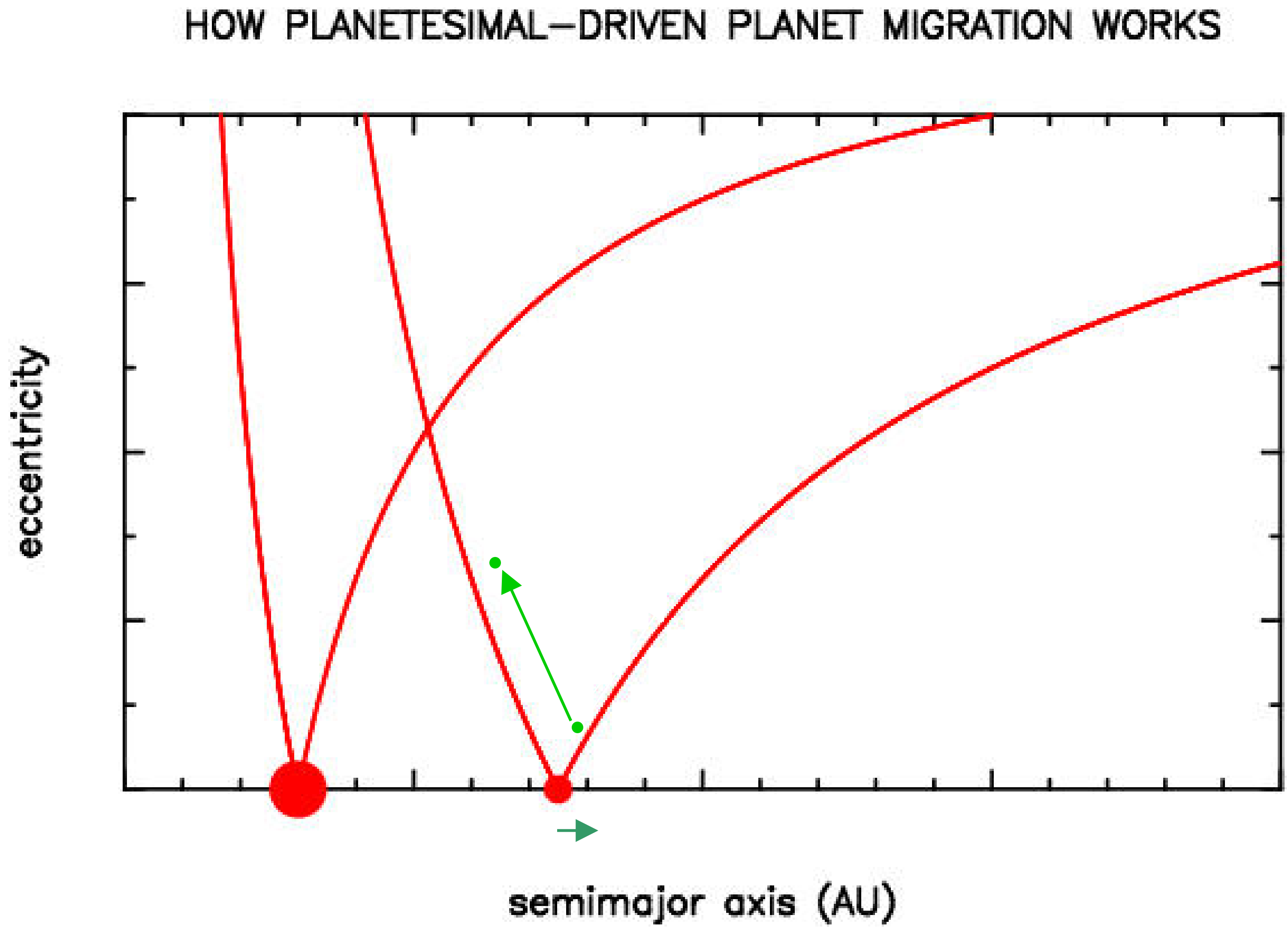
PLANETESIMALS DRIVEN MIGRATION



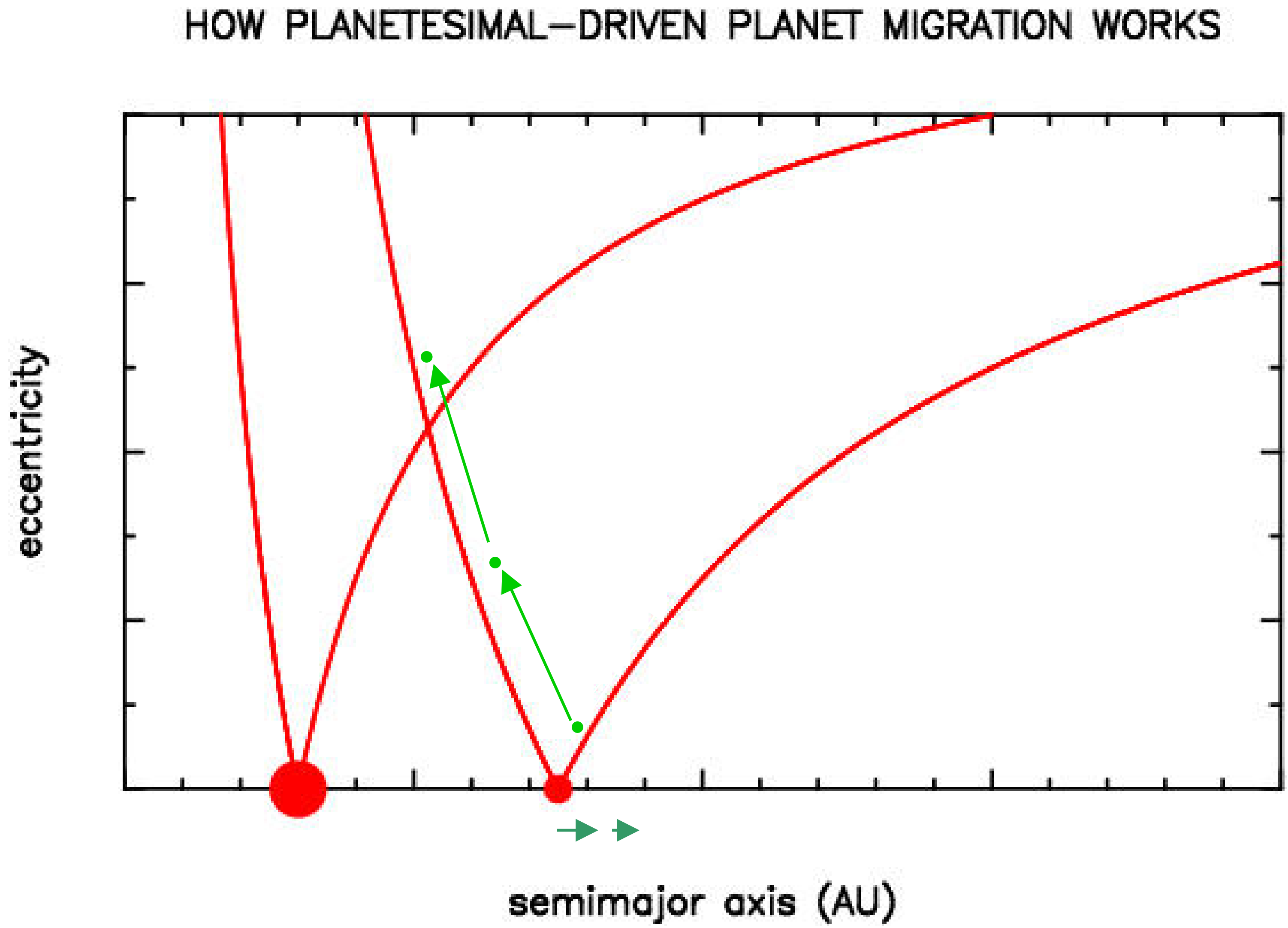
PLANETESIMALS DRIVEN MIGRATION



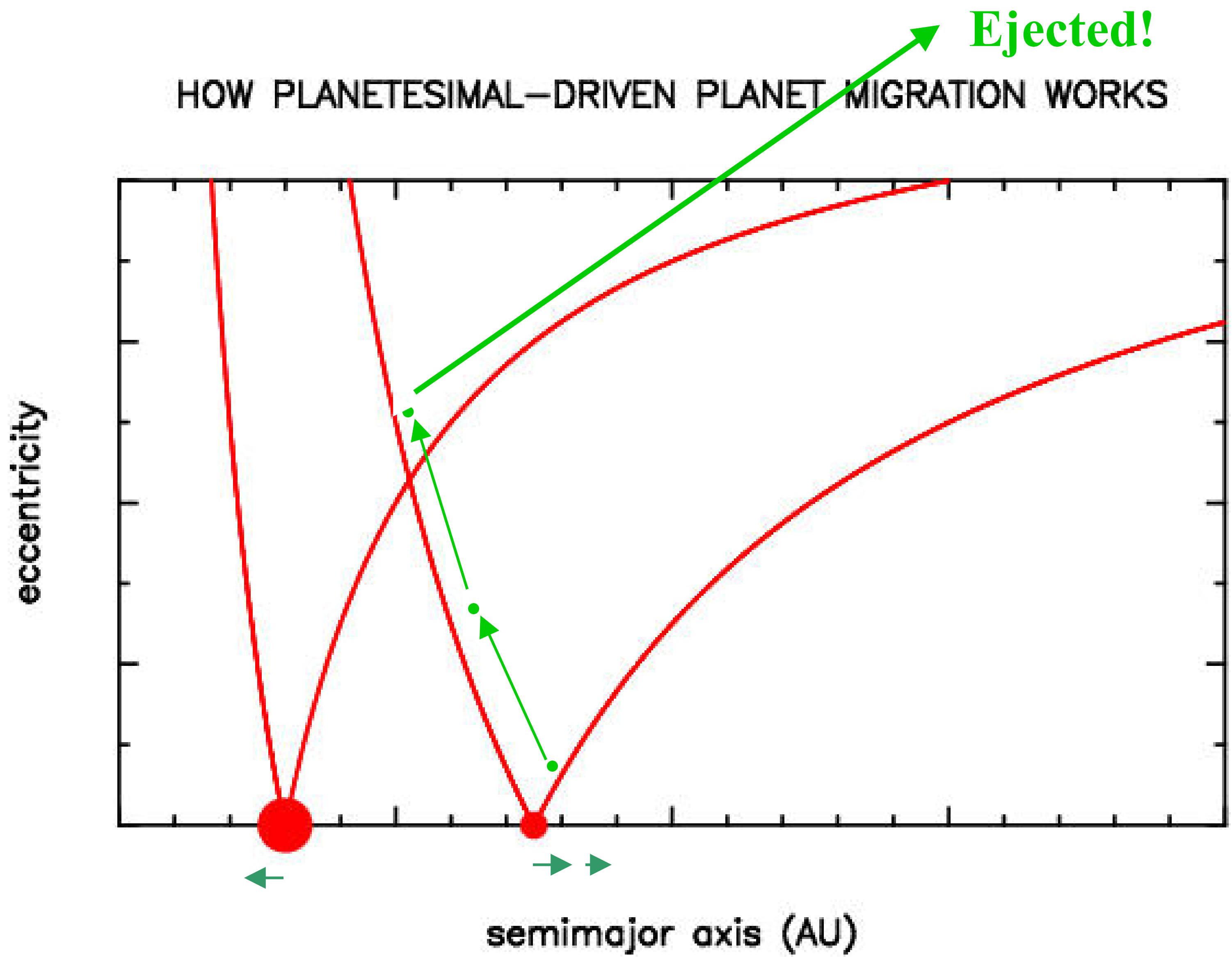
PLANETESIMALS DRIVEN MIGRATION



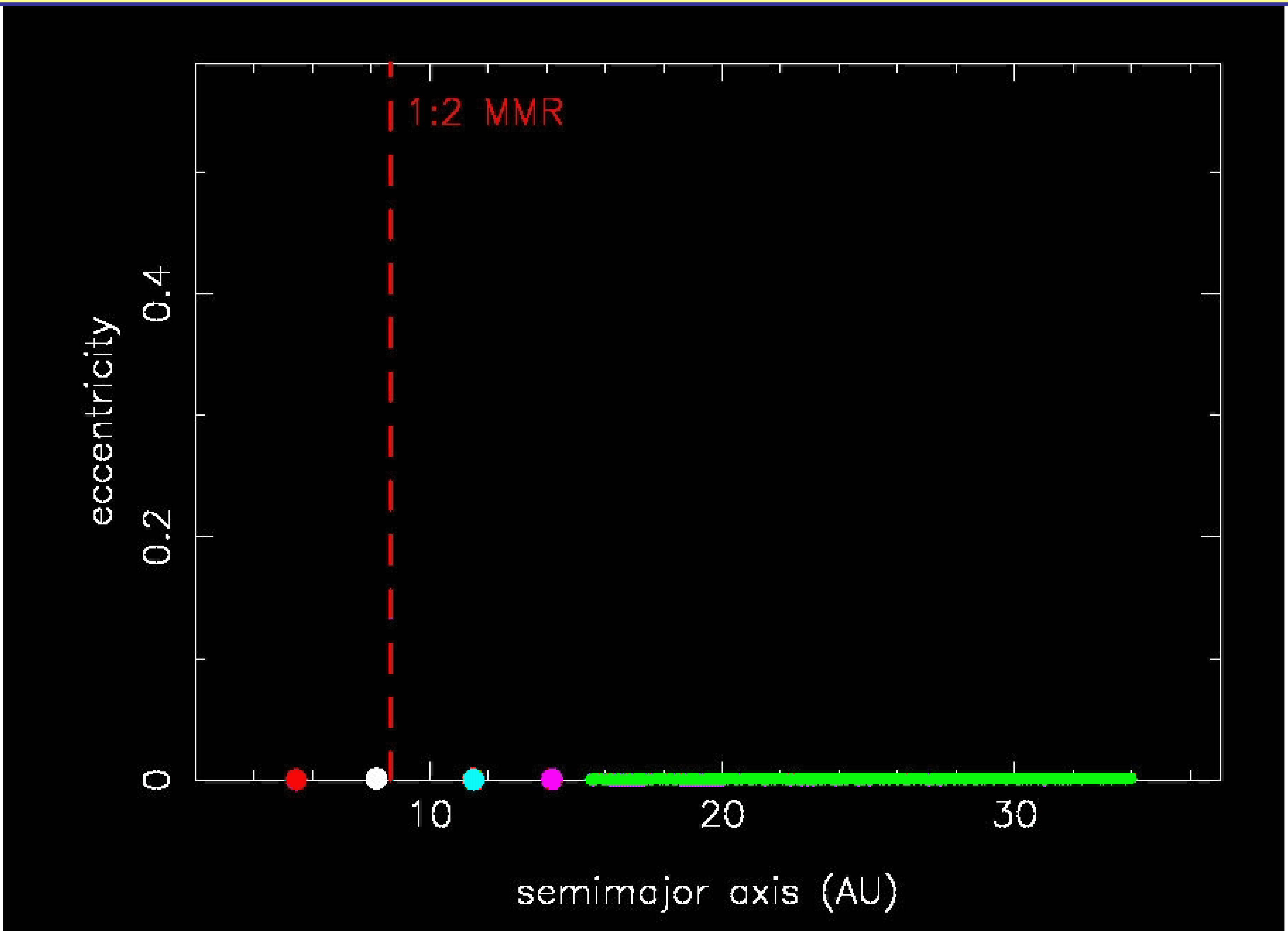
PLANETESIMALS DRIVEN MIGRATION

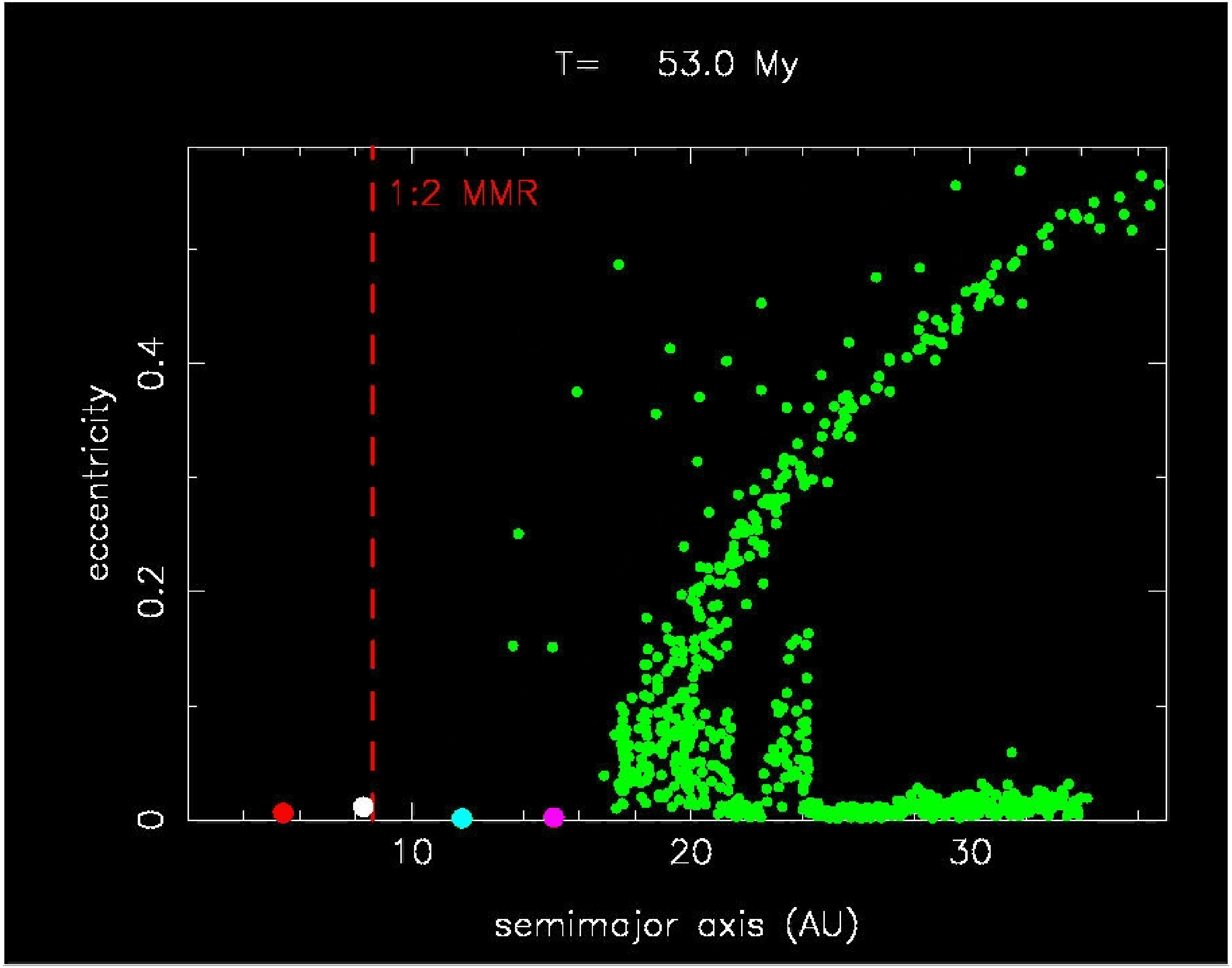


PLANETESIMALS DRIVEN MIGRATION



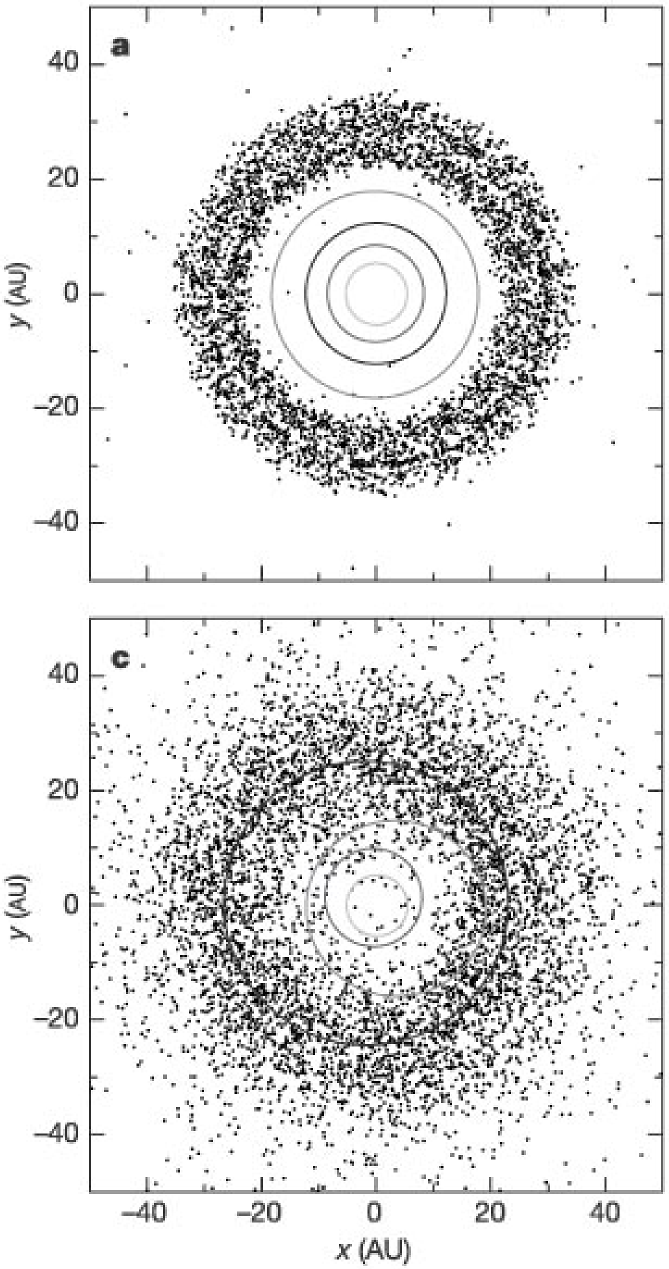
The NICE MODEL





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

The NICE MODEL



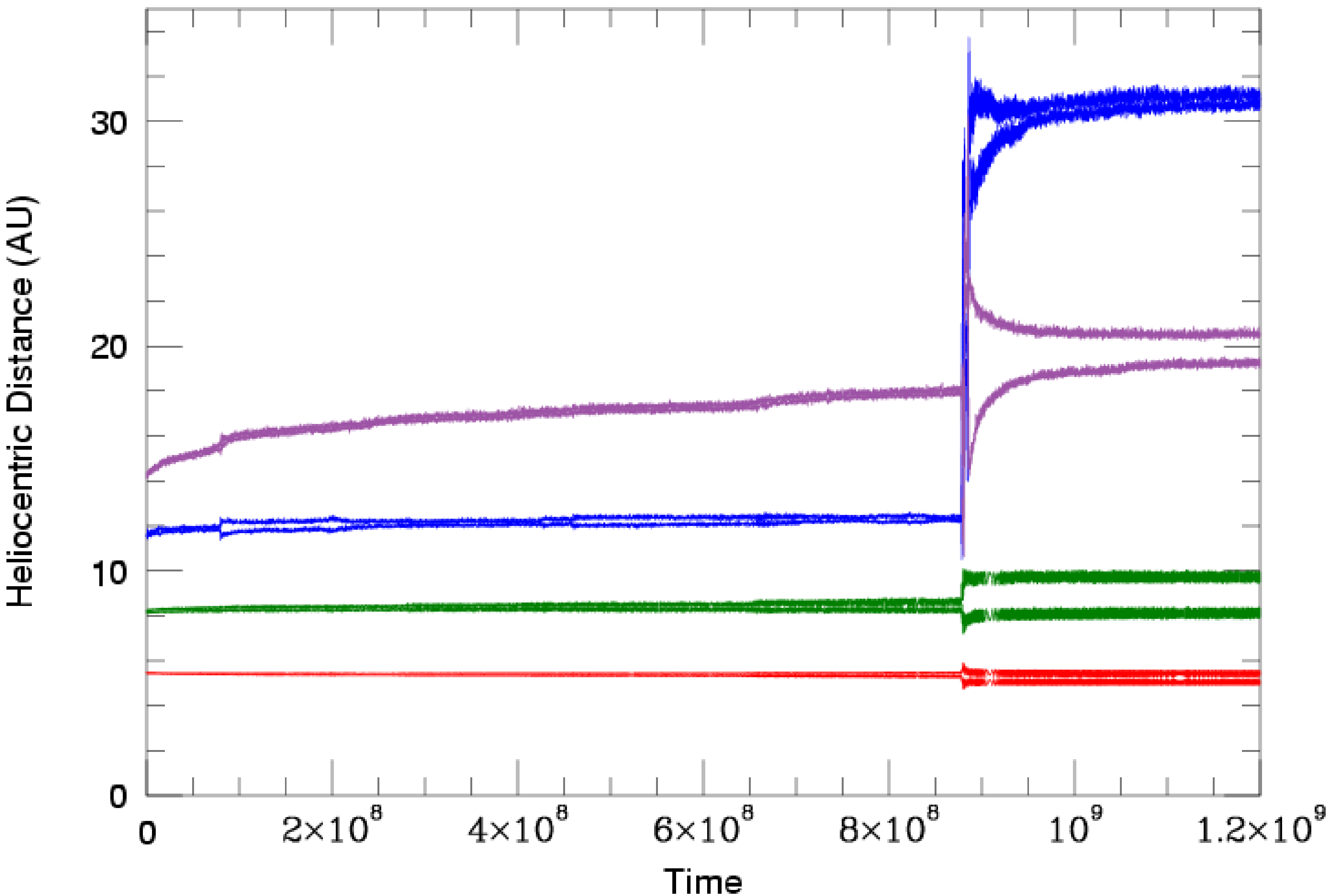
First, slow migration. Jupiter inwards, Saturn, Uranus & Neptune outwards.

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



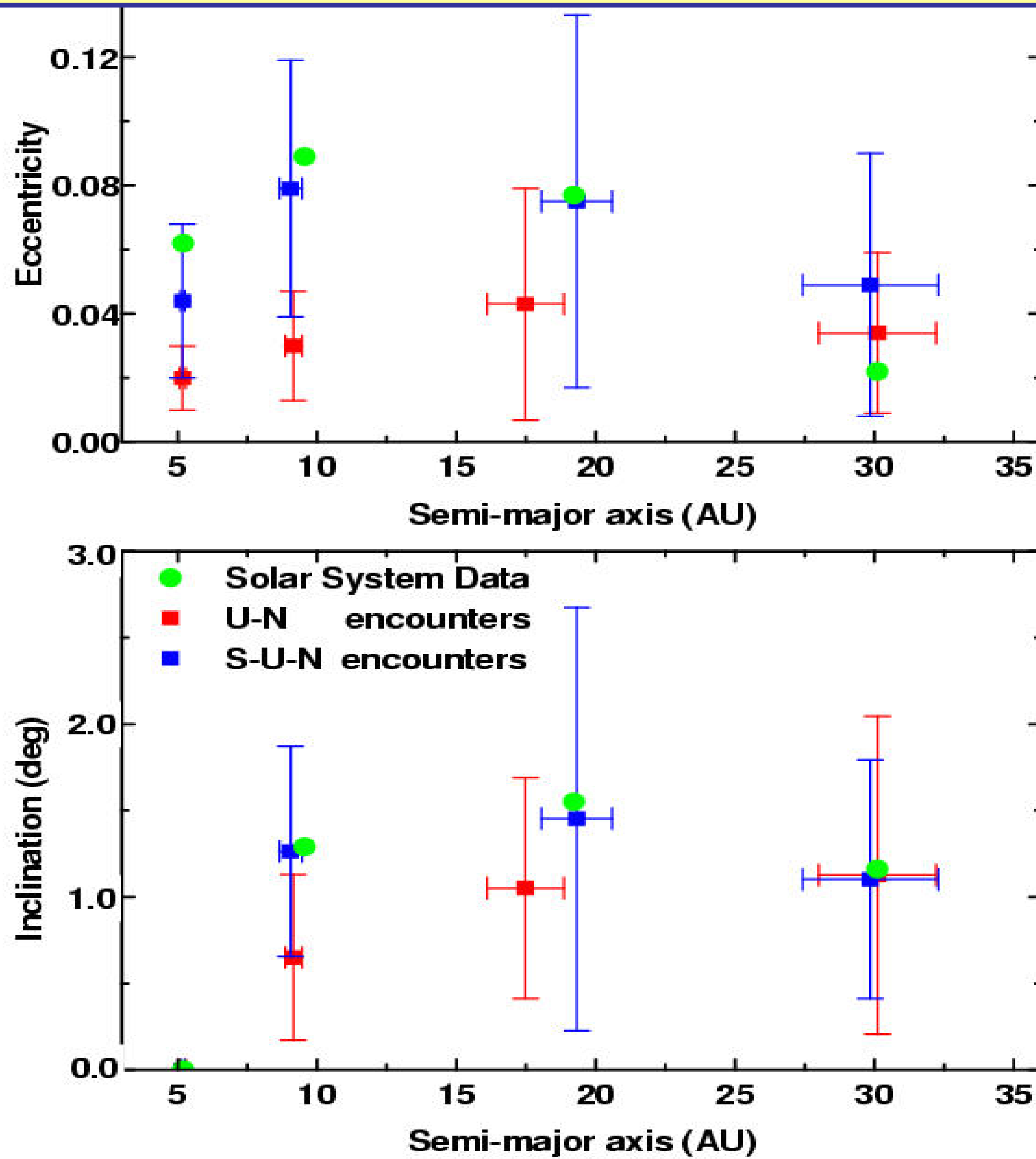
K. Tsiganis, R. Gomes, A. Morbidelli, H.F. Levison 2005. *Nature, 435, 459*

The NICE MODEL

Two strengths:

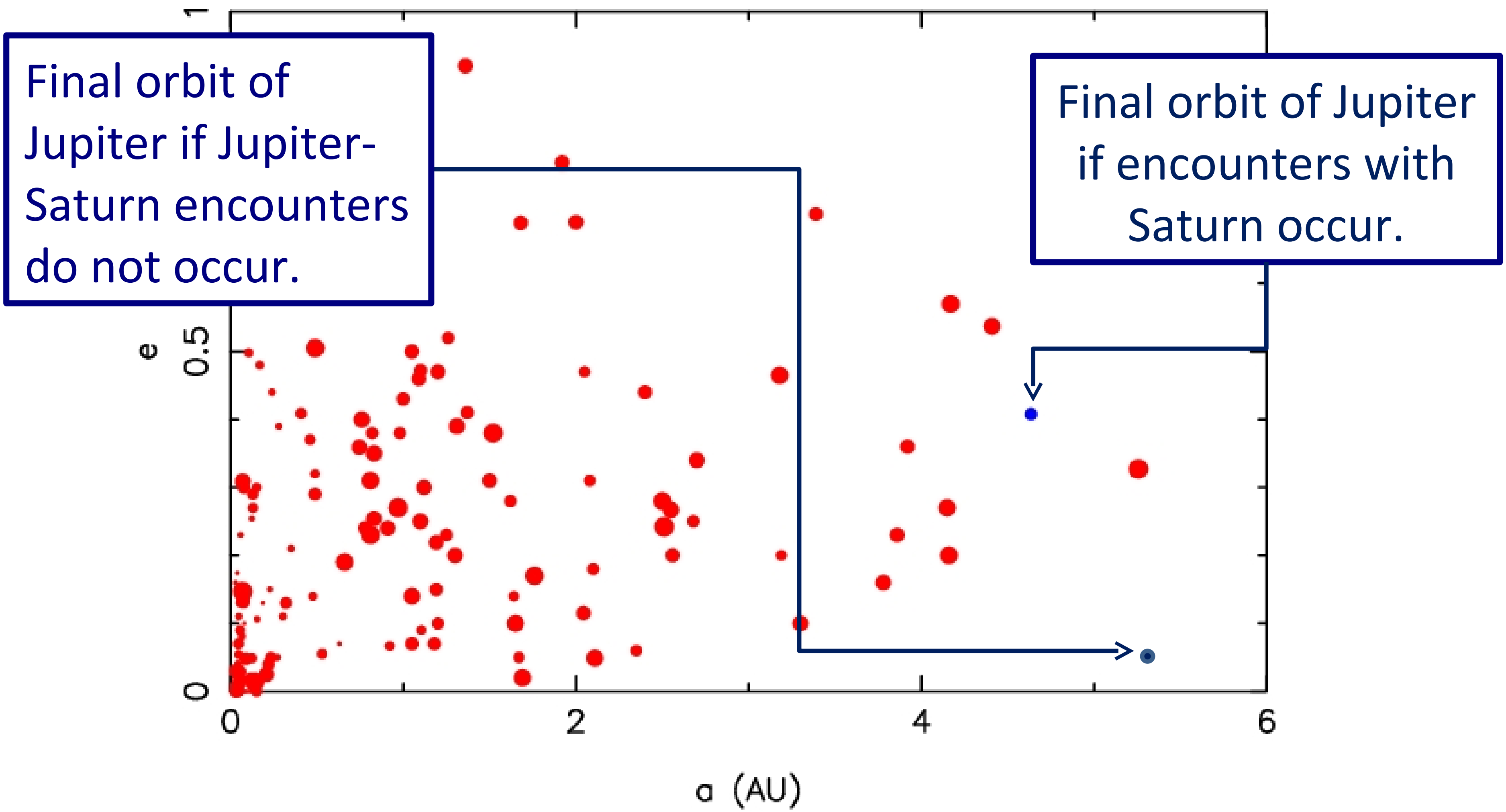
I: Explanation of the present orbits of the giant planets (semi-major axes, eccentricities, and inclinations) starting from <u>circular</u> orbits.

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



The NICE MODEL

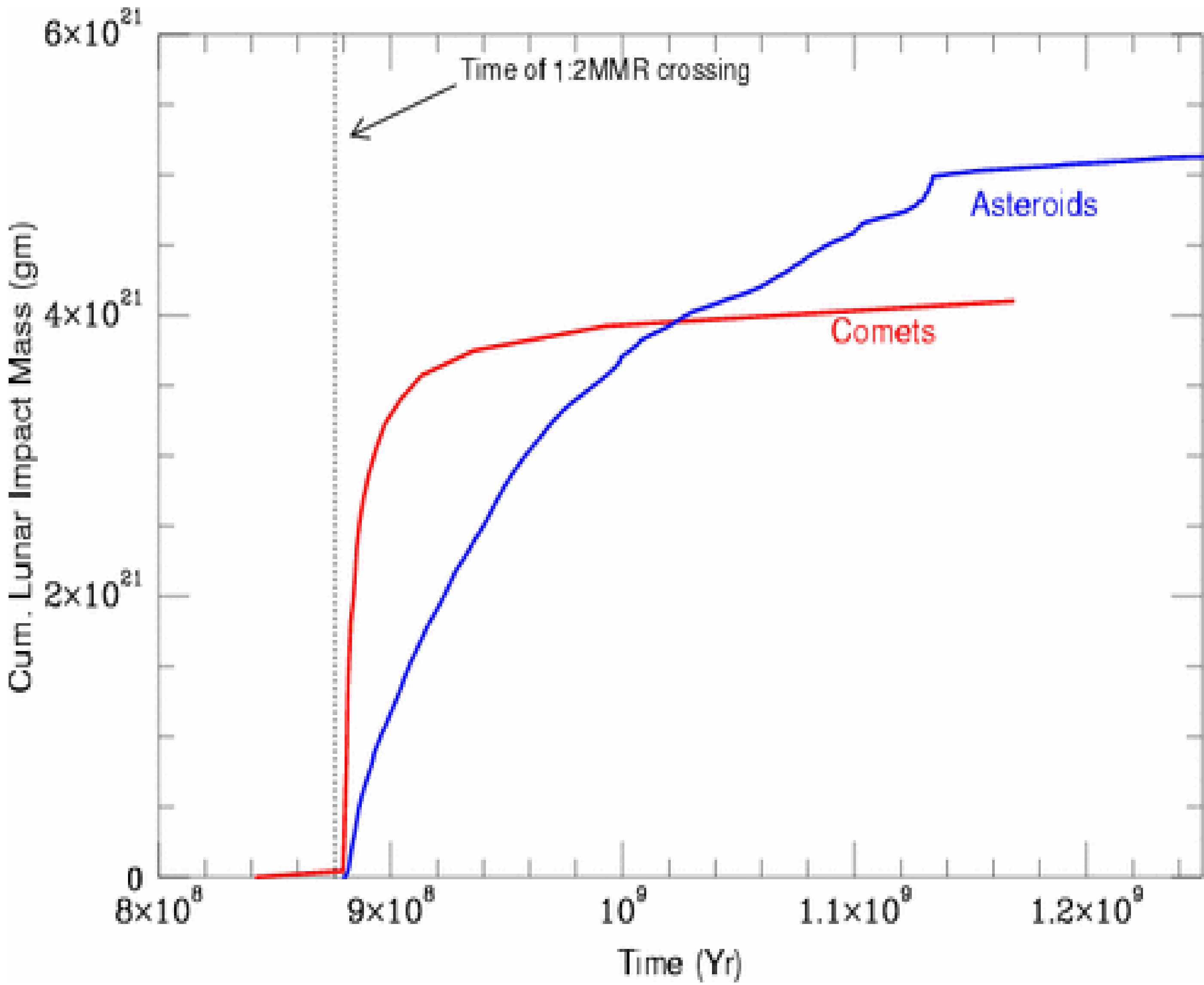
The instability was mild, because J & S are not very massive, and didn't have a close encounter.



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 !

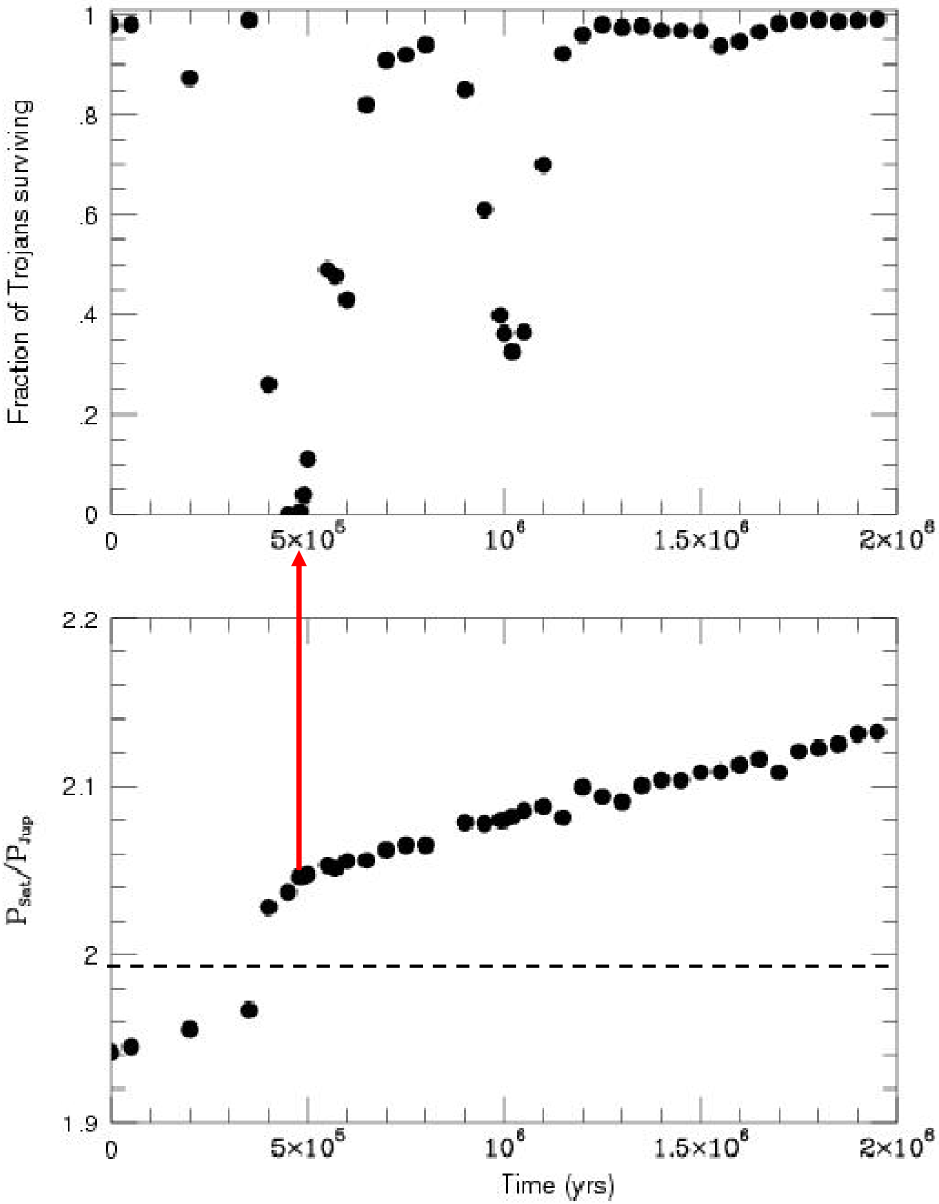
1) Jupiter's trojans

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...

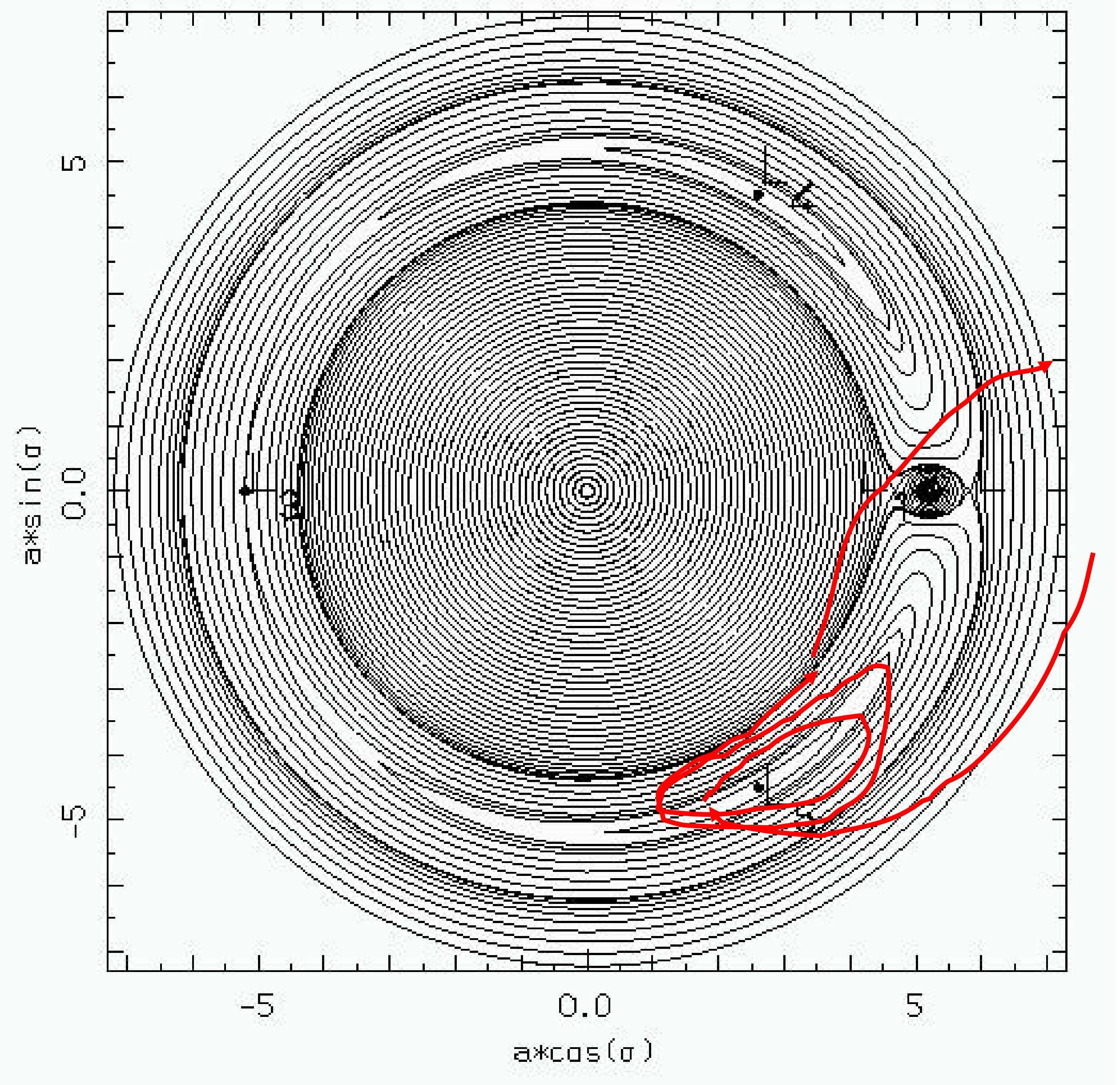
Problem !

JUPITER's TROJANS

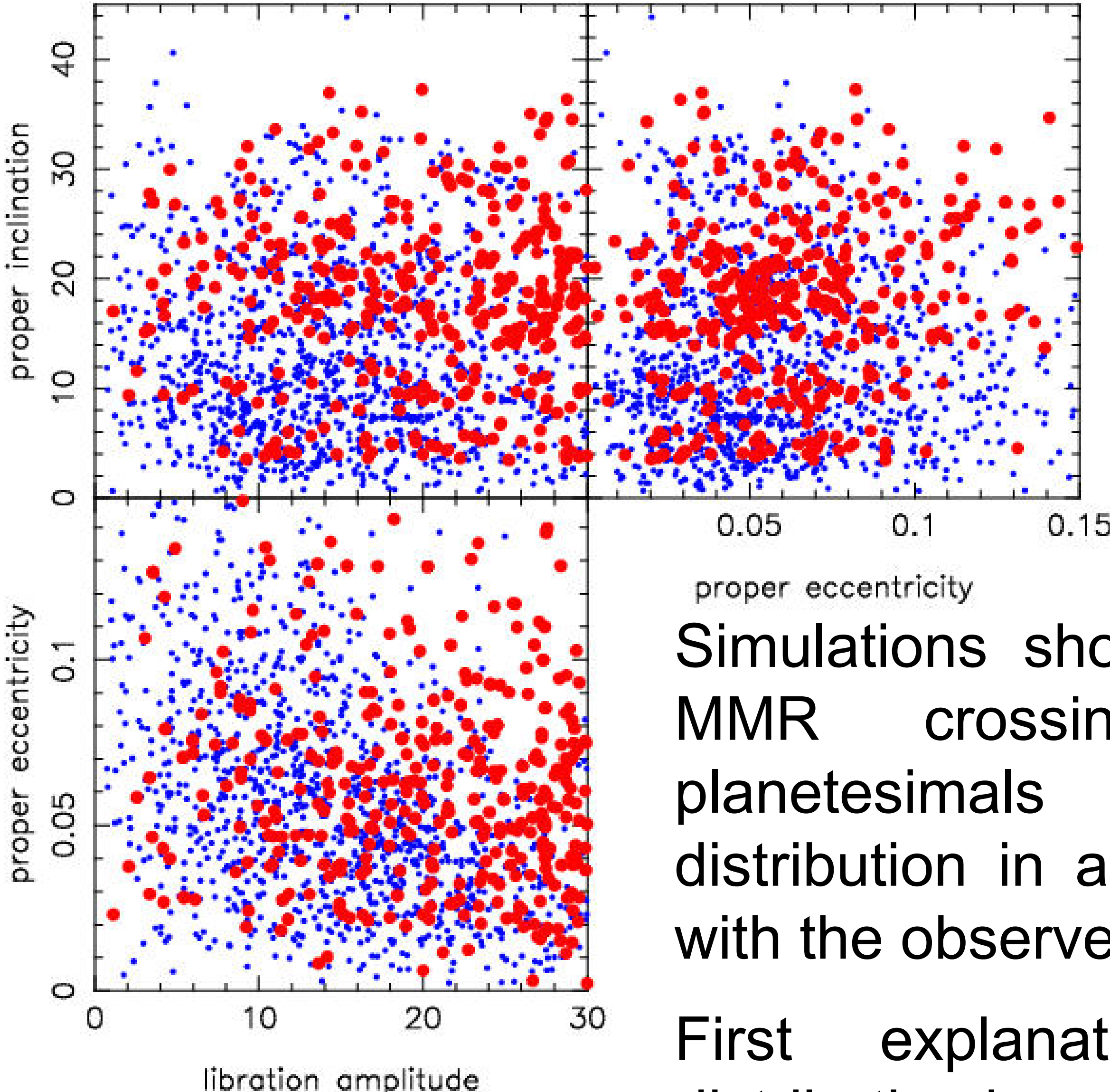
Solution :

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.

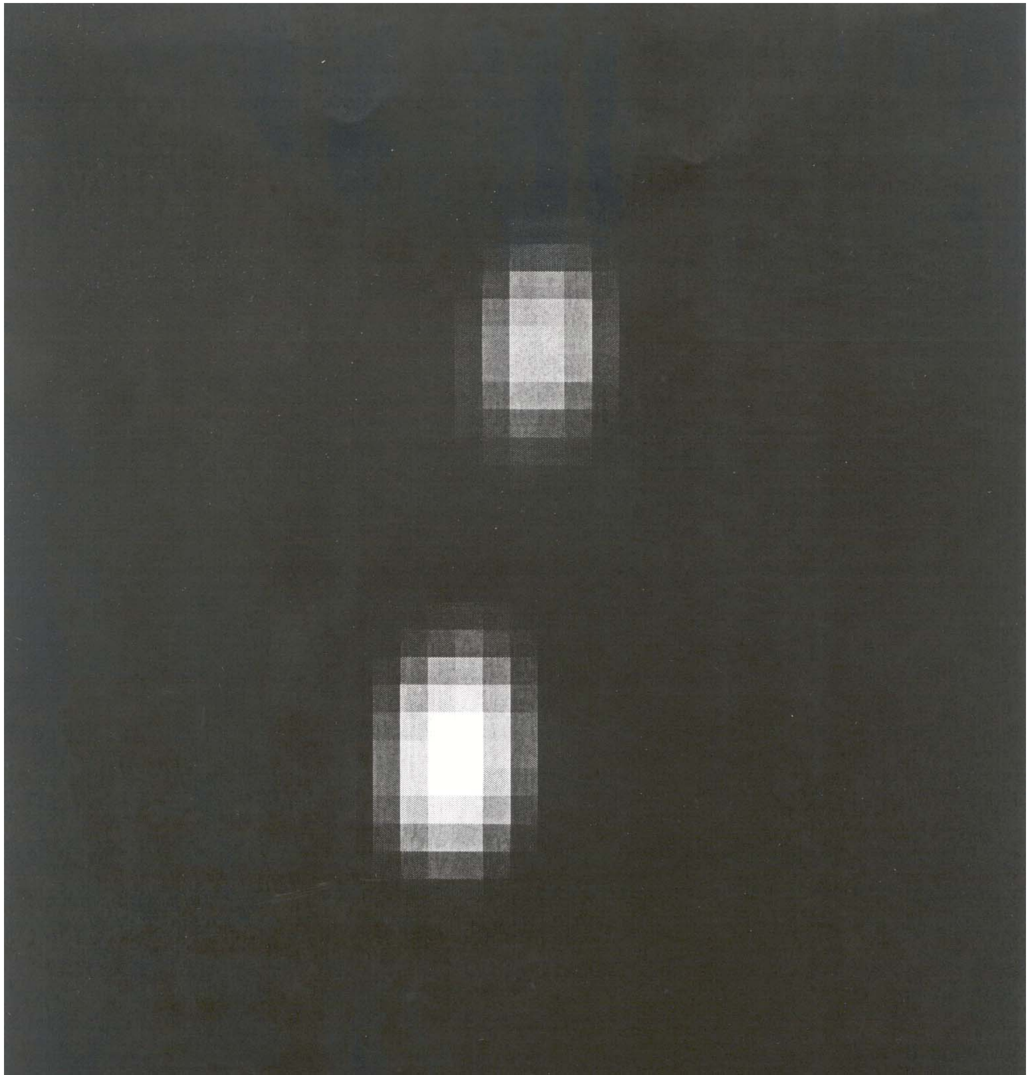
First explanation for the broad distribution in e and i of the trojans.

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

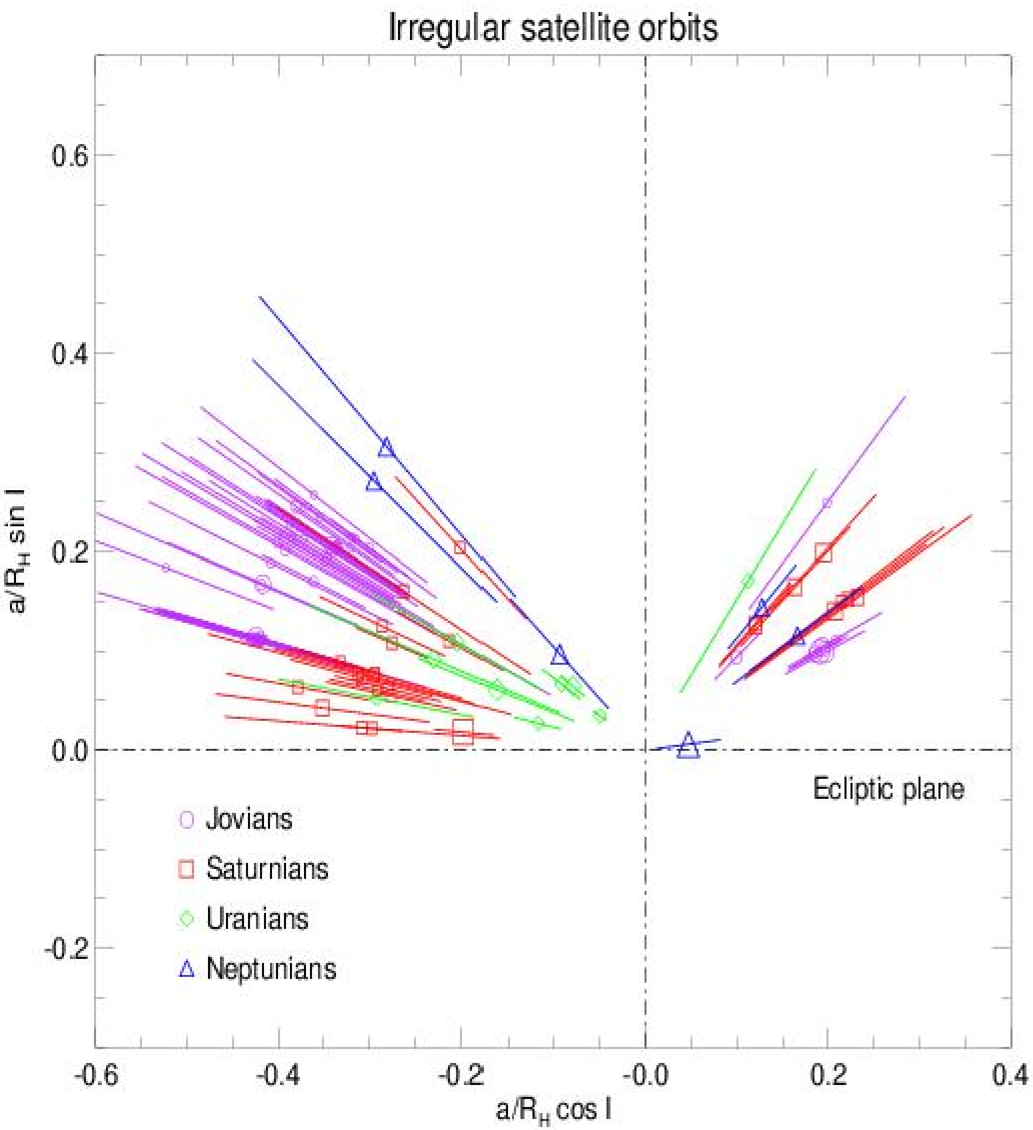
JUPITER's TROJANS

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...

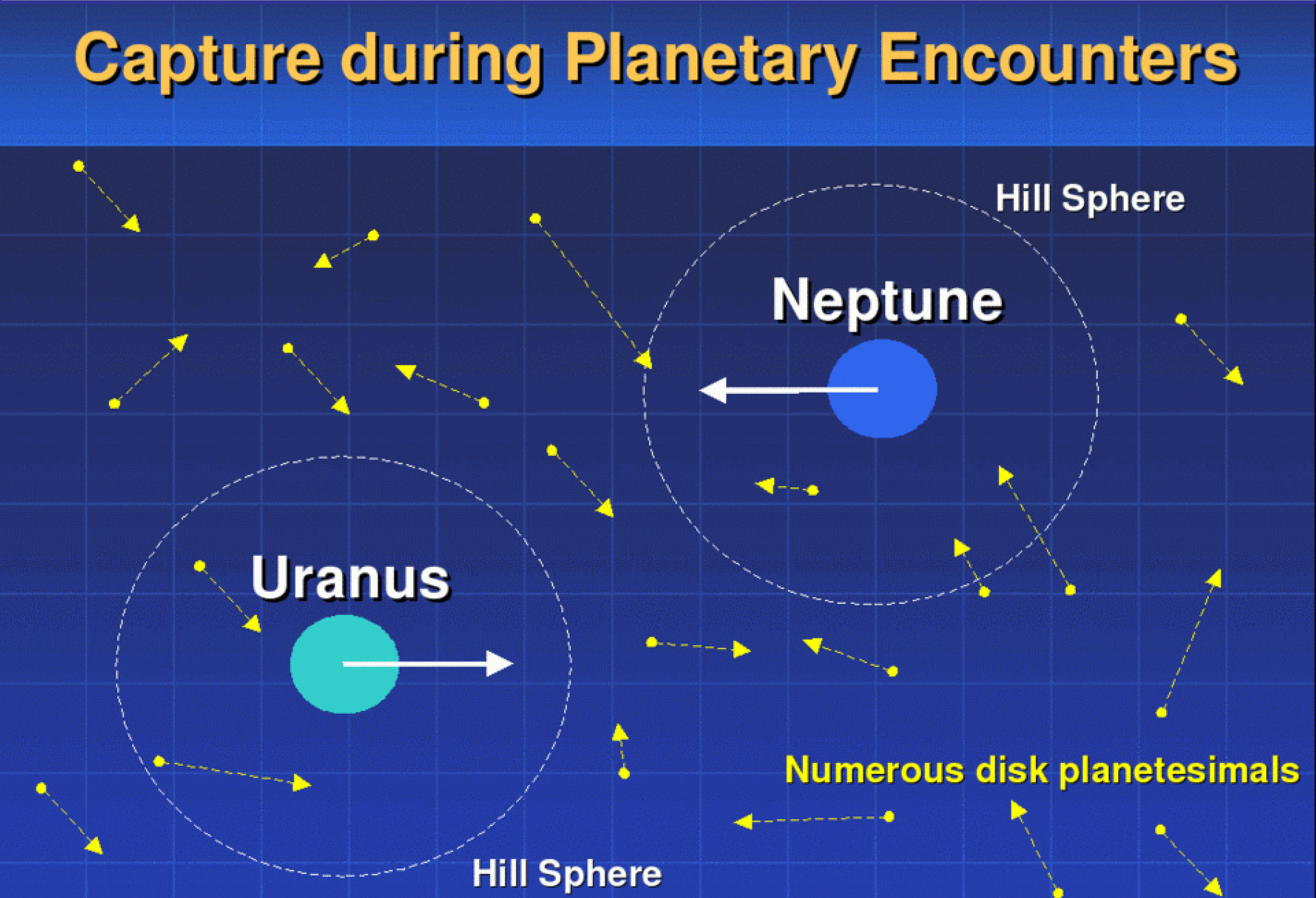
(Marchis et al., 2005)



IRREGULAR SATELLITES

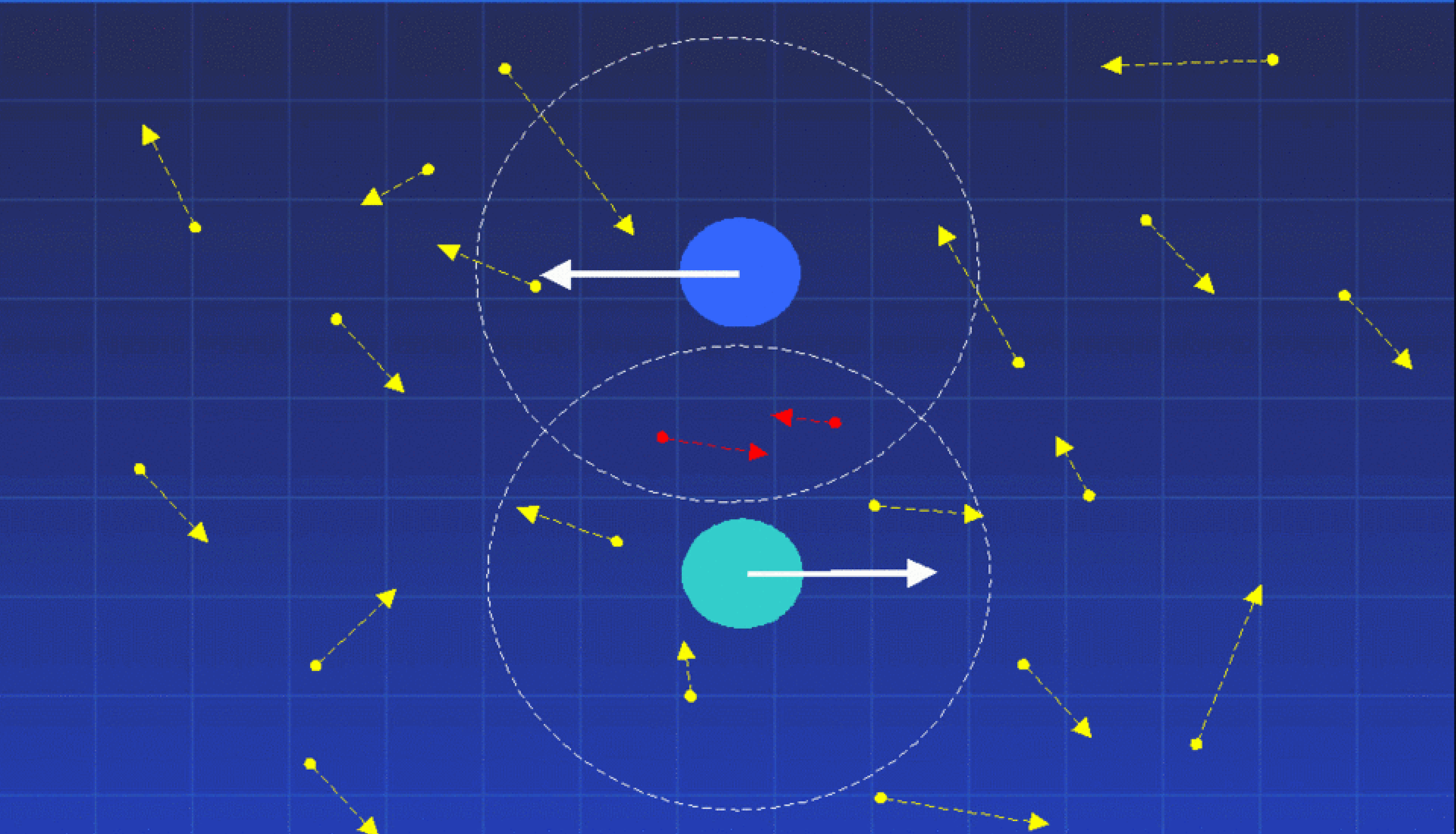


IRREGULAR SATELLITES



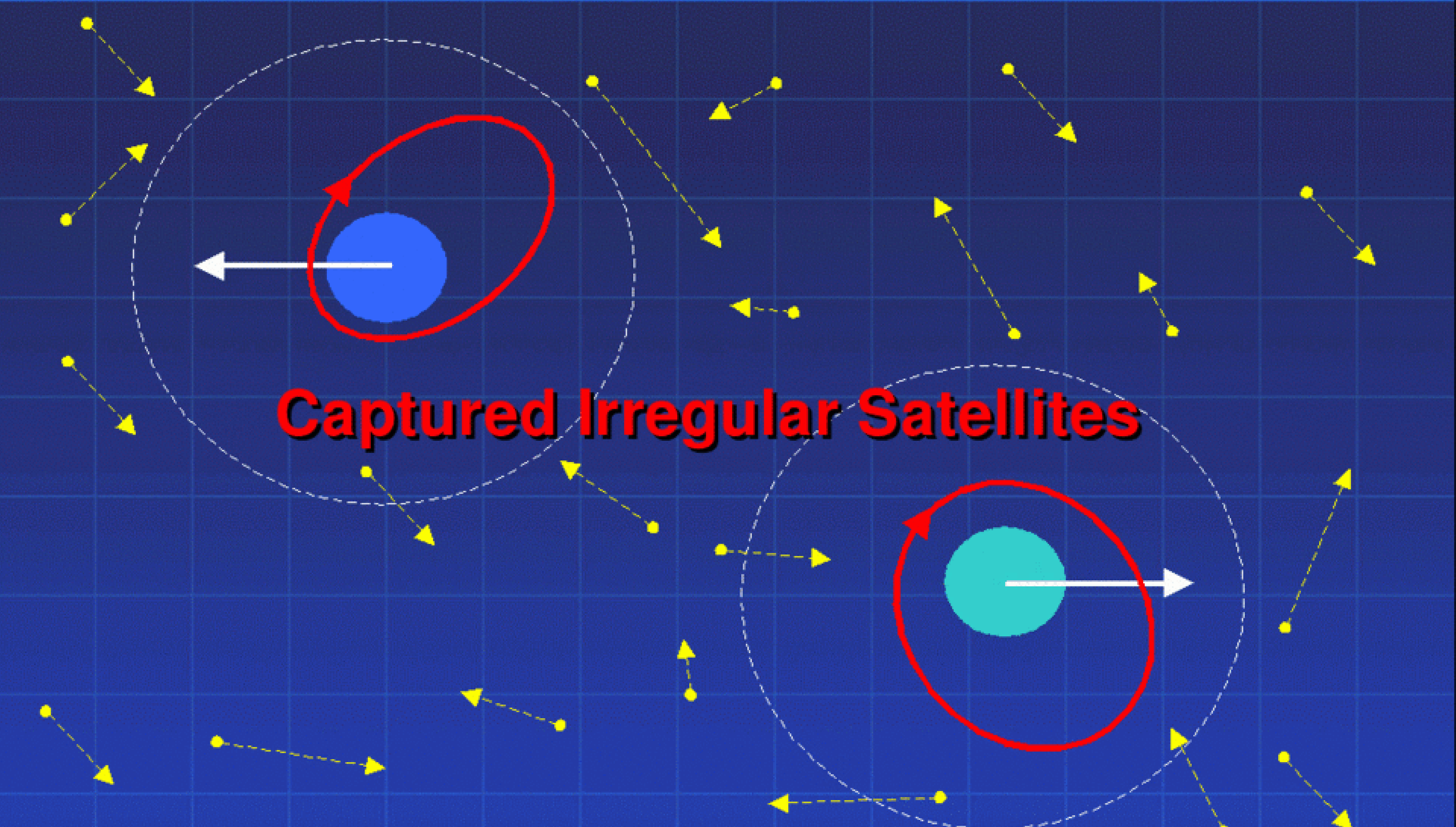
IRREGULAR SATELLITES

Capture during Planetary Encounters

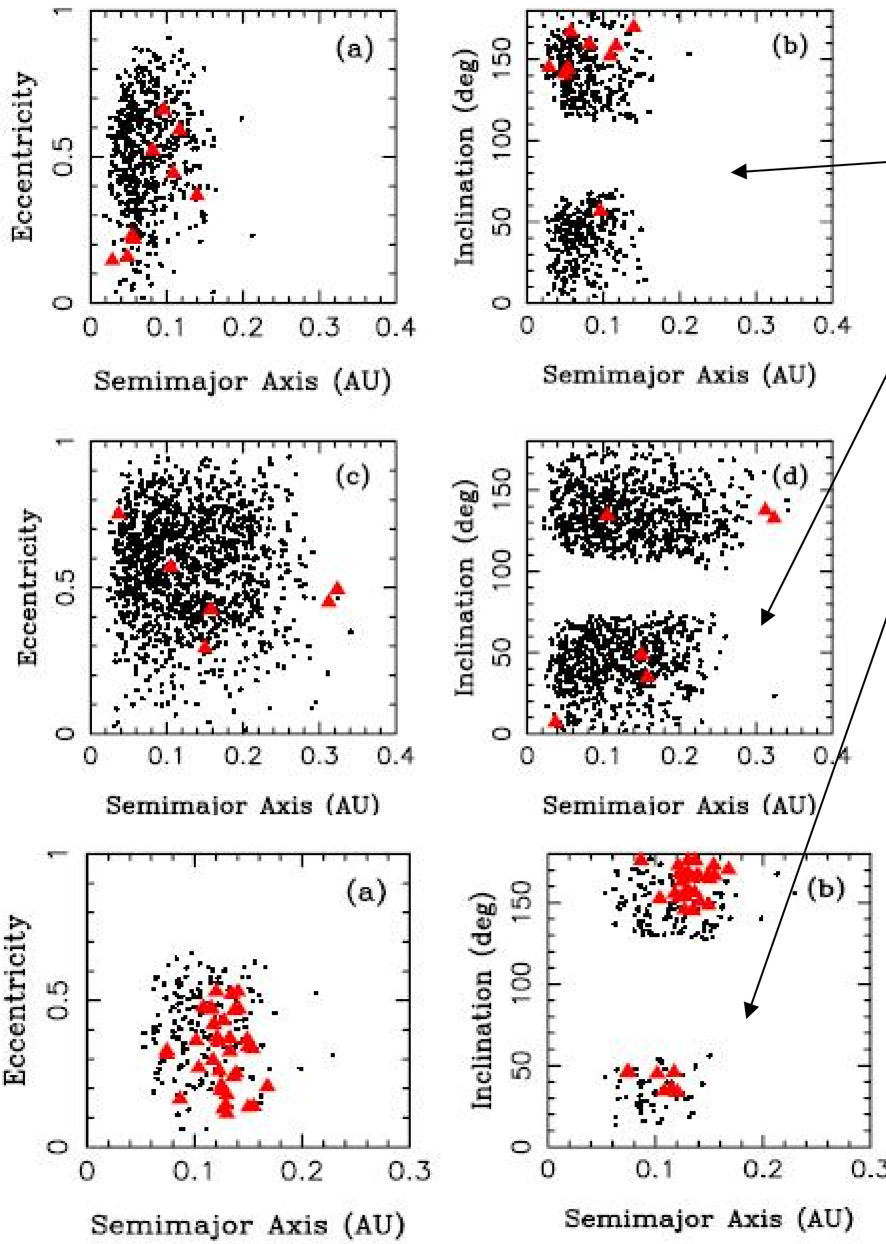


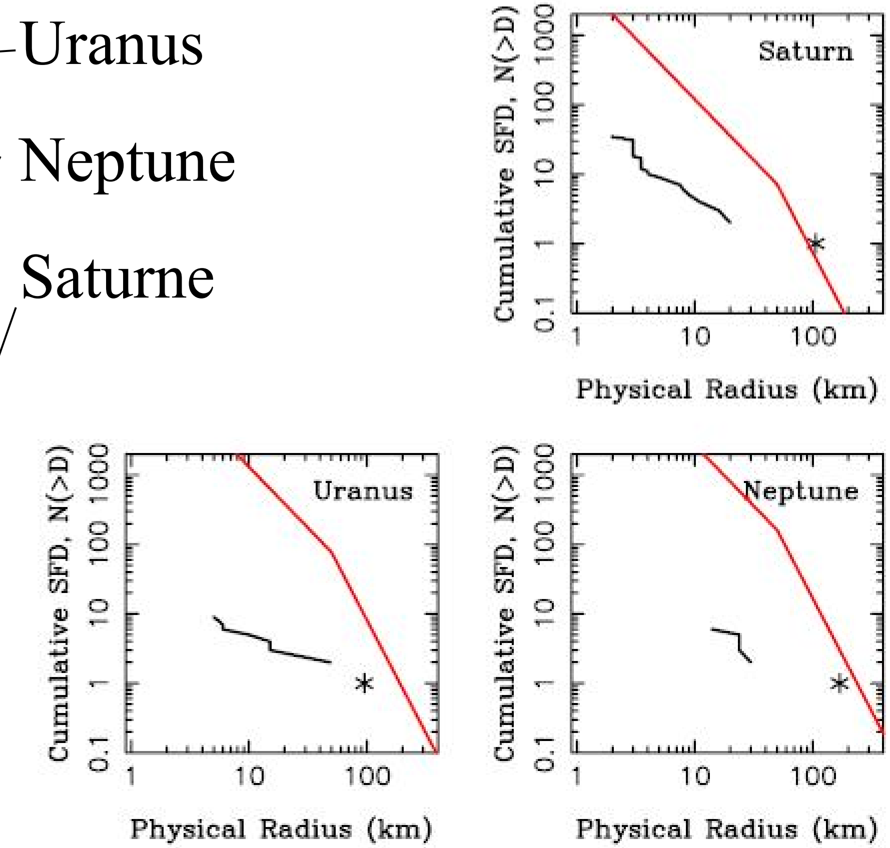
IRREGULAR SATELLITES

Capture during Planetary Encounters



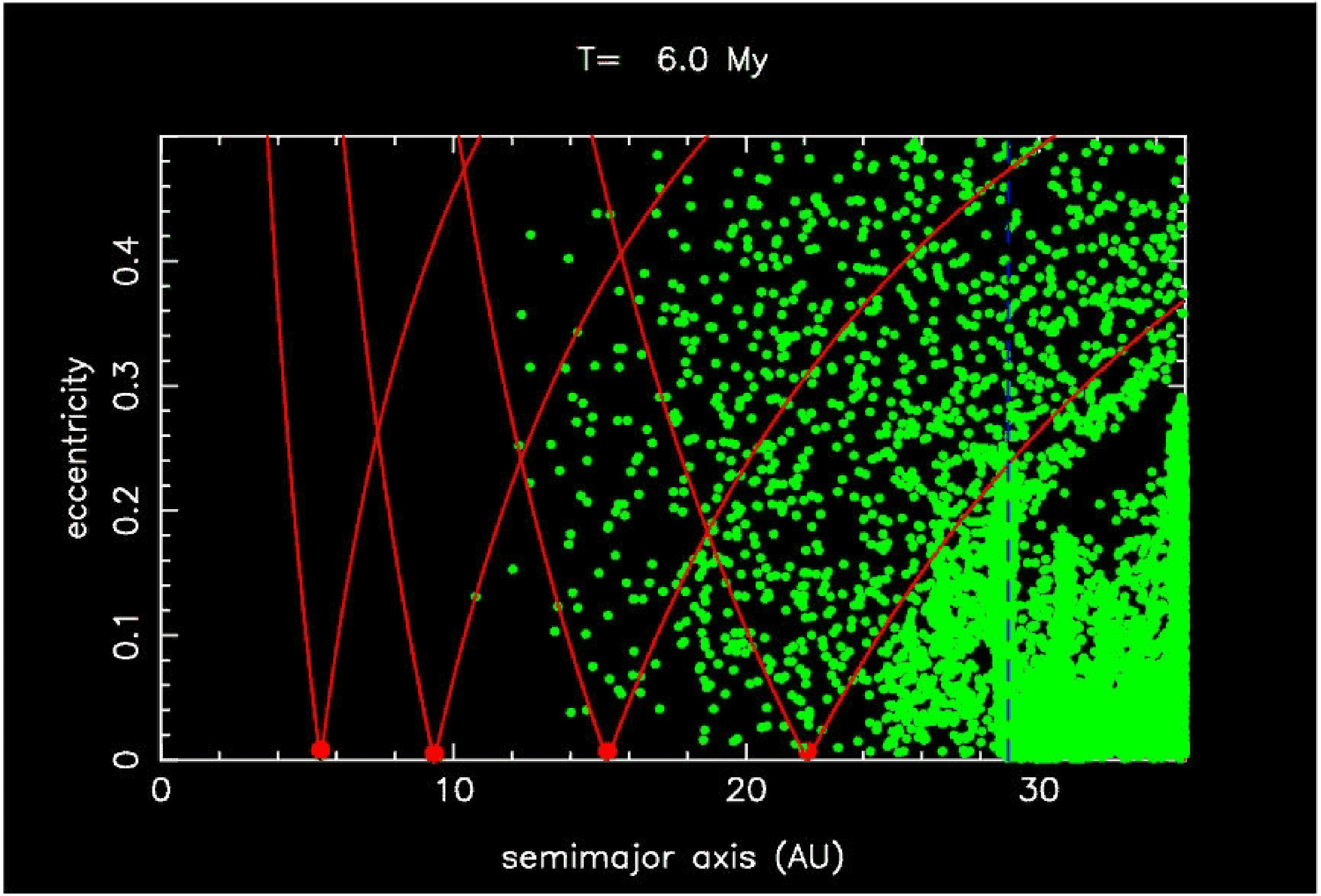
IRREGULAR SATELLITES





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

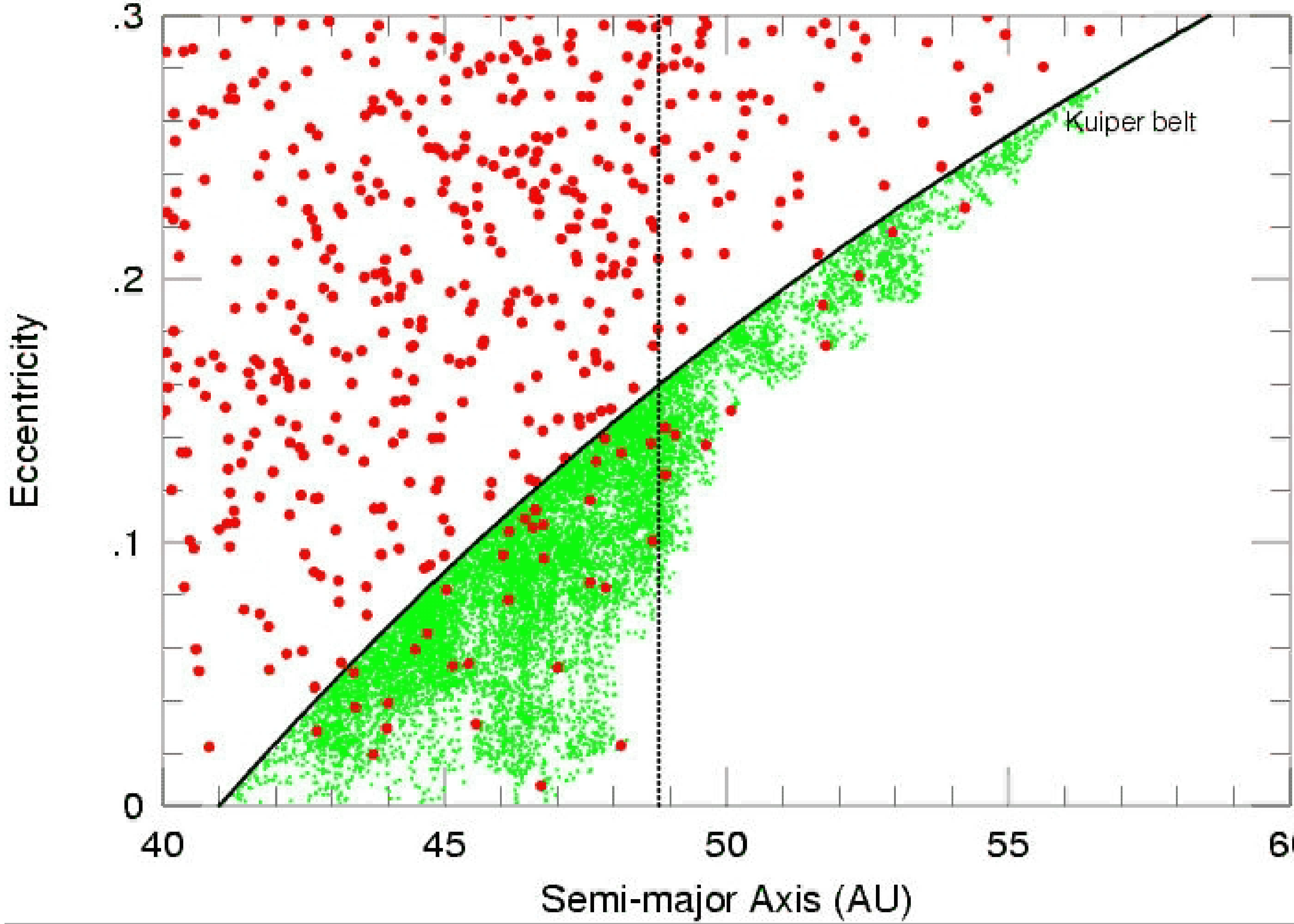
KUIPER BELT ORIGIN



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

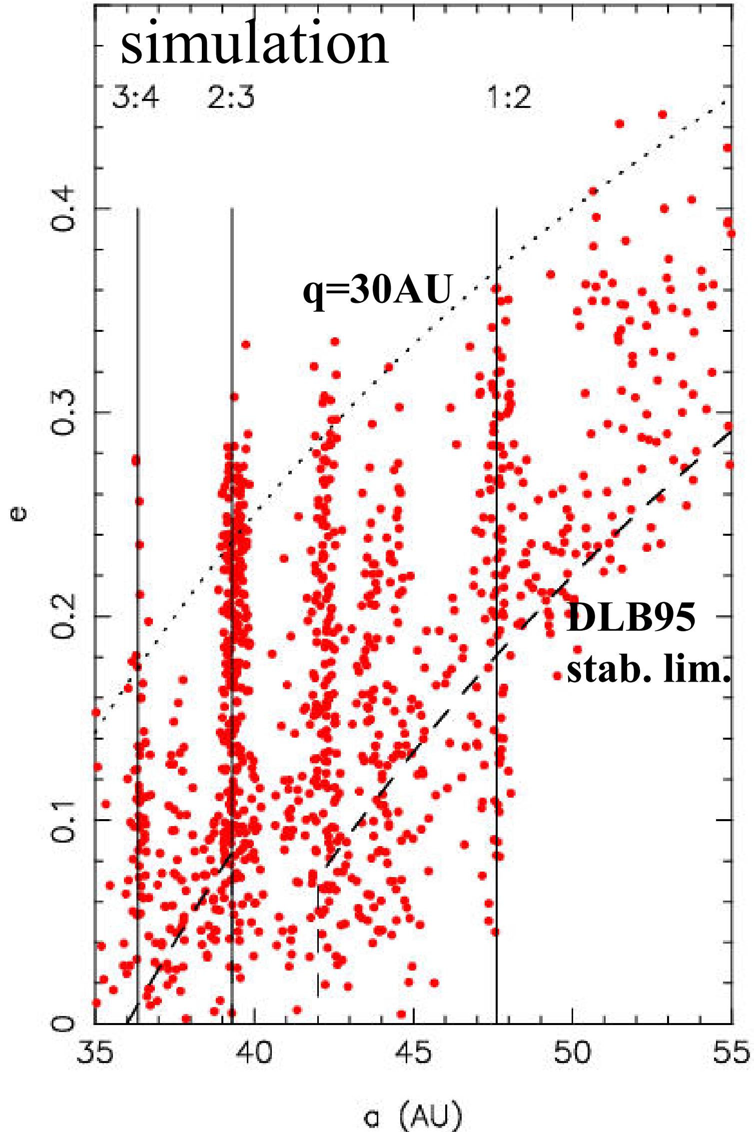
In total, ~30 objects out of simulated 30,000 are captured in the classical belt. Given that the initial mass of the planetesimal disk is ~35 Earth masses in the Nice model, we account for about 0.03-0.05 Earth masses in the Kuiper belt.

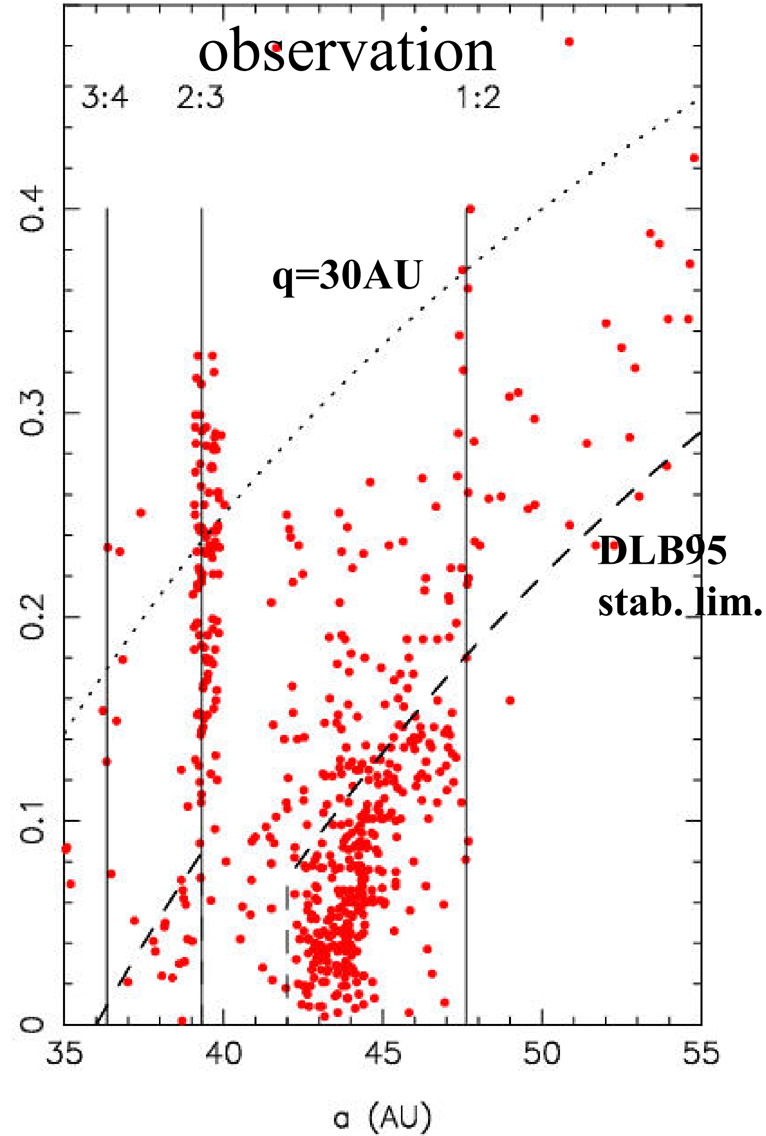
About right, provided that collisional erosion was not important. This implies that the size distribution was similar to the current one, but scaled `up' by a factor ~ 1,000.

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?).



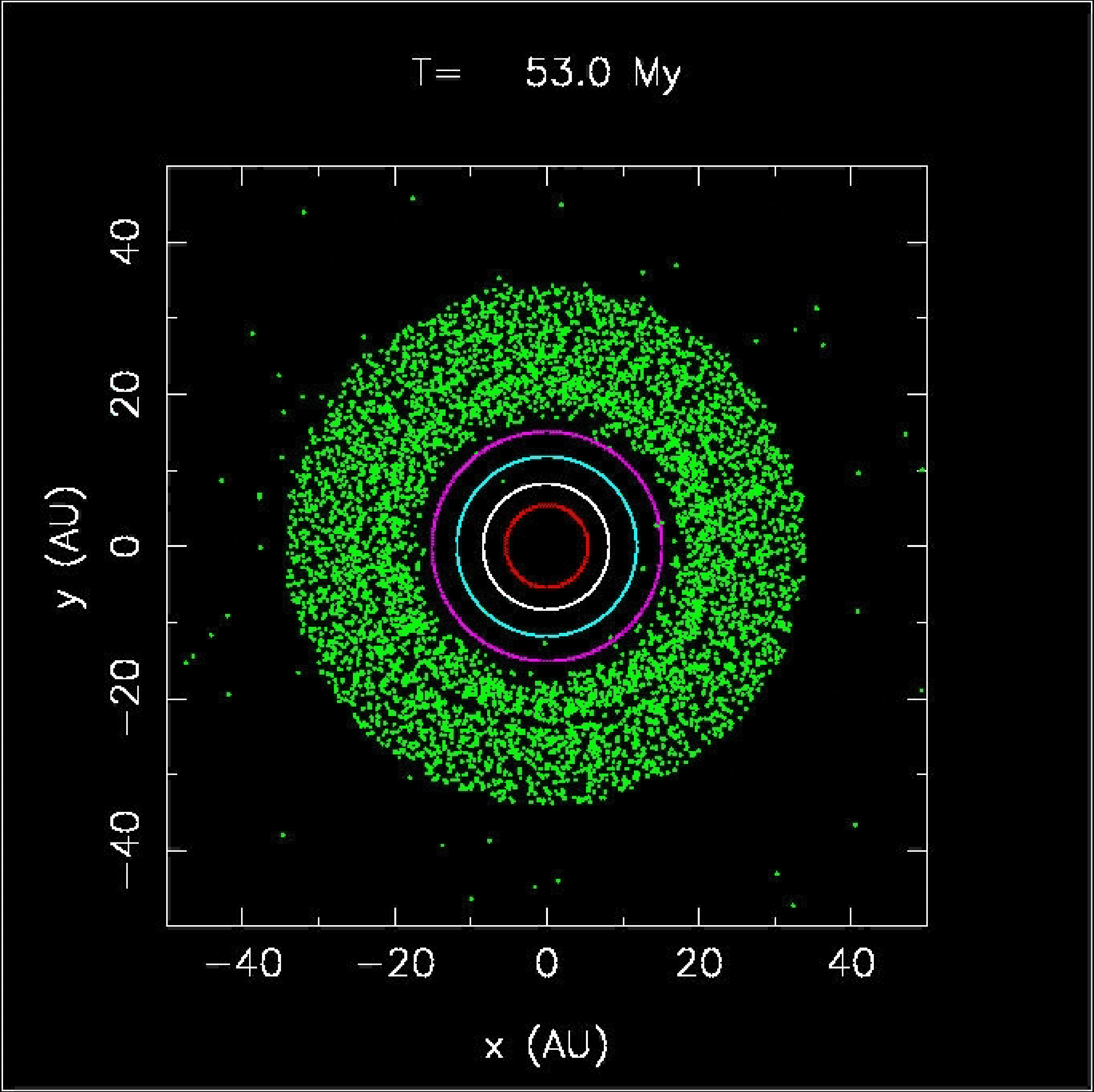


KUIPER BELT ORIGIN

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)
−40
−20
0
20
40
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...

UNIVERSITÉ CÔTE D'AZUR

Observatoire de la CÔTE d'AZUR

Aurélien CRIDA

How (a)typical is our solar system ?

Giant planets are the key :

The formation of SENs beyond the snowline should be generic…

…as well as their migration into the inner system.

IF the innermost SEN becomes a gas giant planet it can offer a dynamical barrier against the migration of the other SENs into the inner disk.

In most extrasolar systems, gas giant planets migrated down to ~ 1-2 AU

In our system, the mass ratio between Saturn and Jupiter promoted outward migration (distant giant planets). This kept our SENs (U & N) in the outer solar system, thus protecting the “terrestrial planet region”.

This allowed the Earth to form…..

Chemical properties (e.g. water abundance) are also set by the presence of giant planets governing the radial motion of icy particles.

How (a)typical is our solar system ?

The Three Chances of our Solar System:

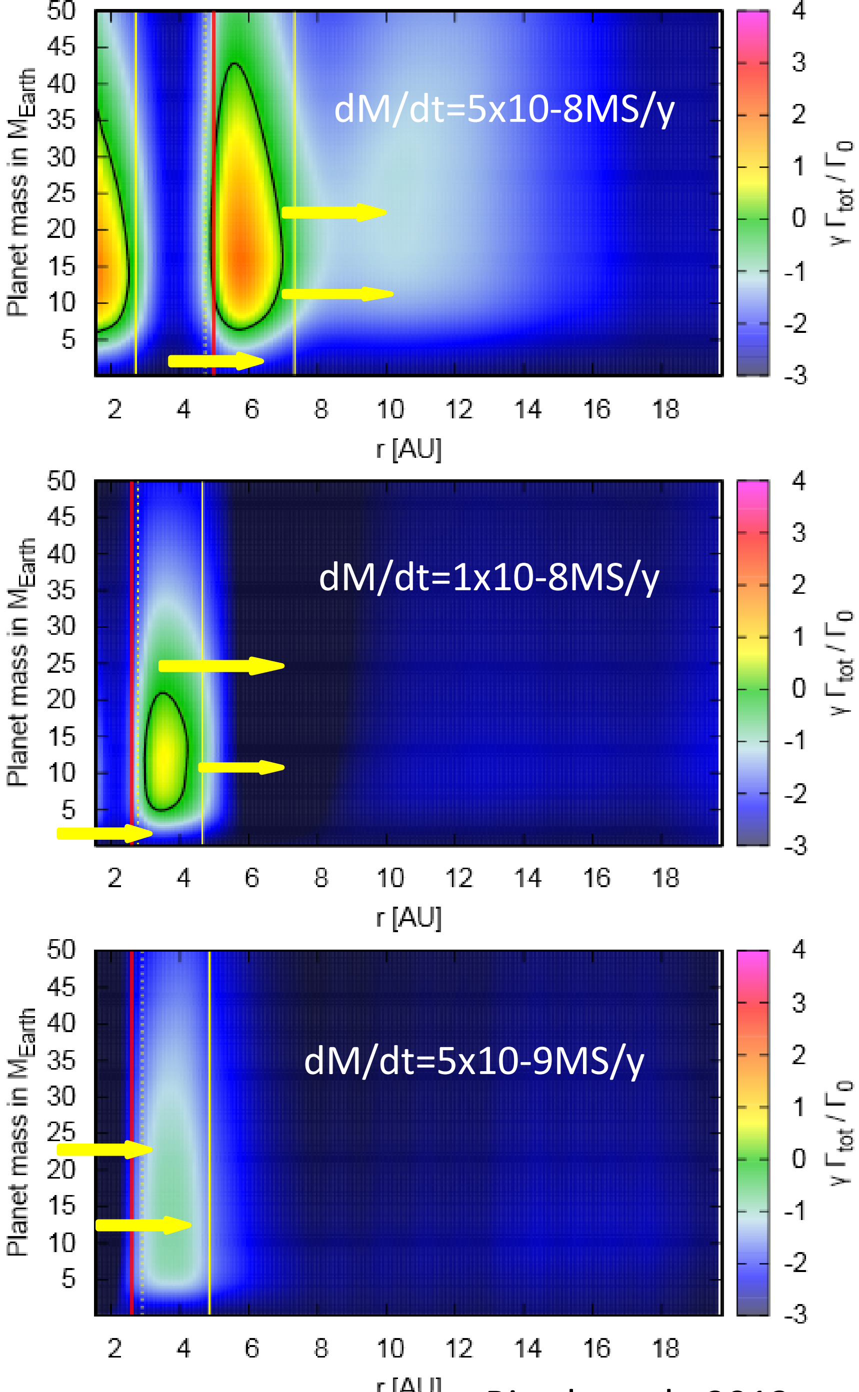
1) The innermost core became a giant planet.

2) The mass ratio between Jupiter and Saturn prevented these planets to come too close to 1 AU.

3) The giant planet instability was mild because Jupiter and Saturn avoided mutual encounters.

The Solar System should be atypical.

The standard framework of planet formation offers possibilities for a wide variety of planetary systems.



Bitsch et al., 2013

Outward migration regions work only for a limited mass-range of SENs and disappear as the disk evolves to a smaller accretion rate

All SENs should migrate from the outer disk to the inner disk, eventually.