The saw-tooth profile of the lunar bombardment: a new vision of the LHB

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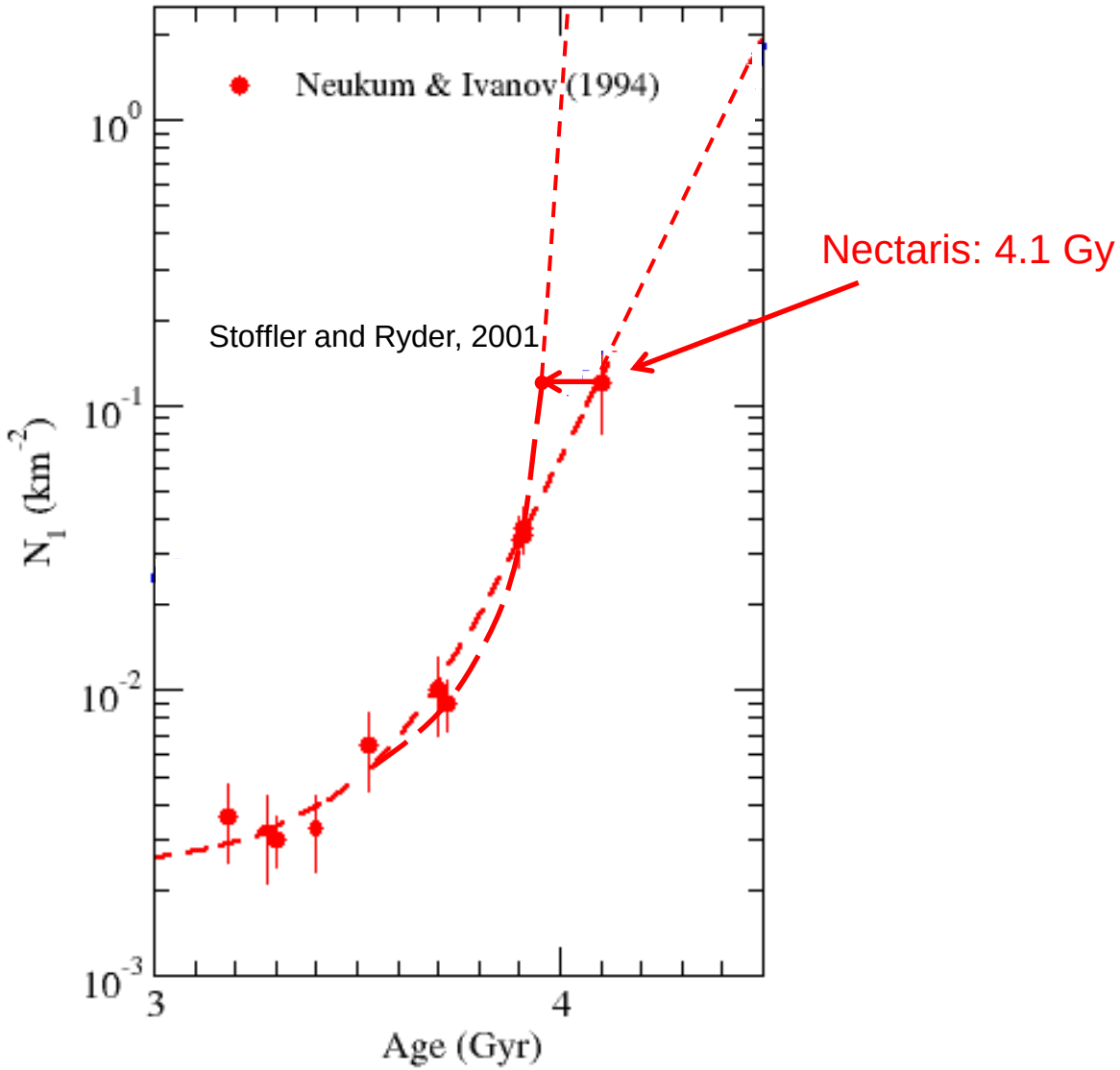
THE CONTROVERSY OF THE LUNAR BOMBARDMENT



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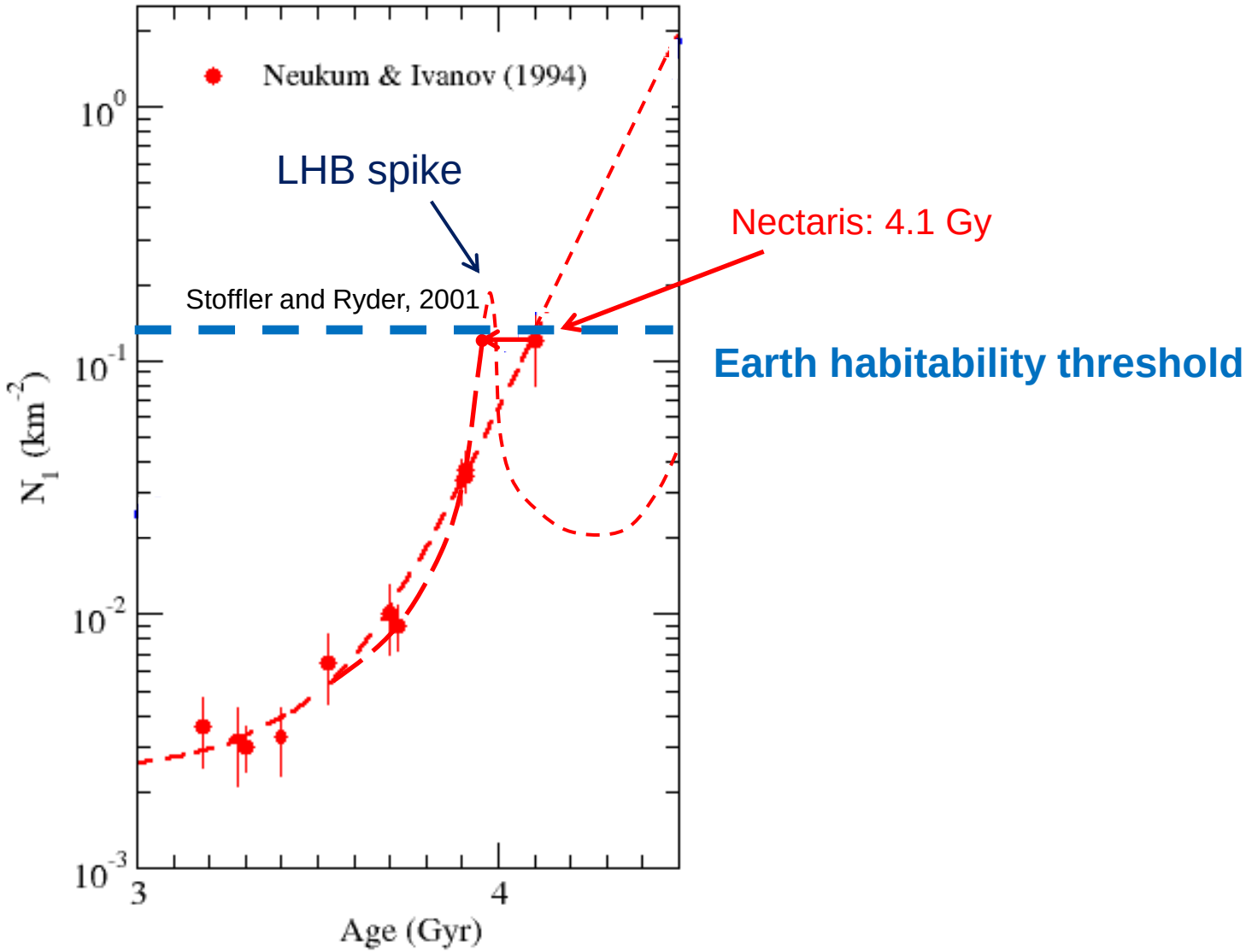


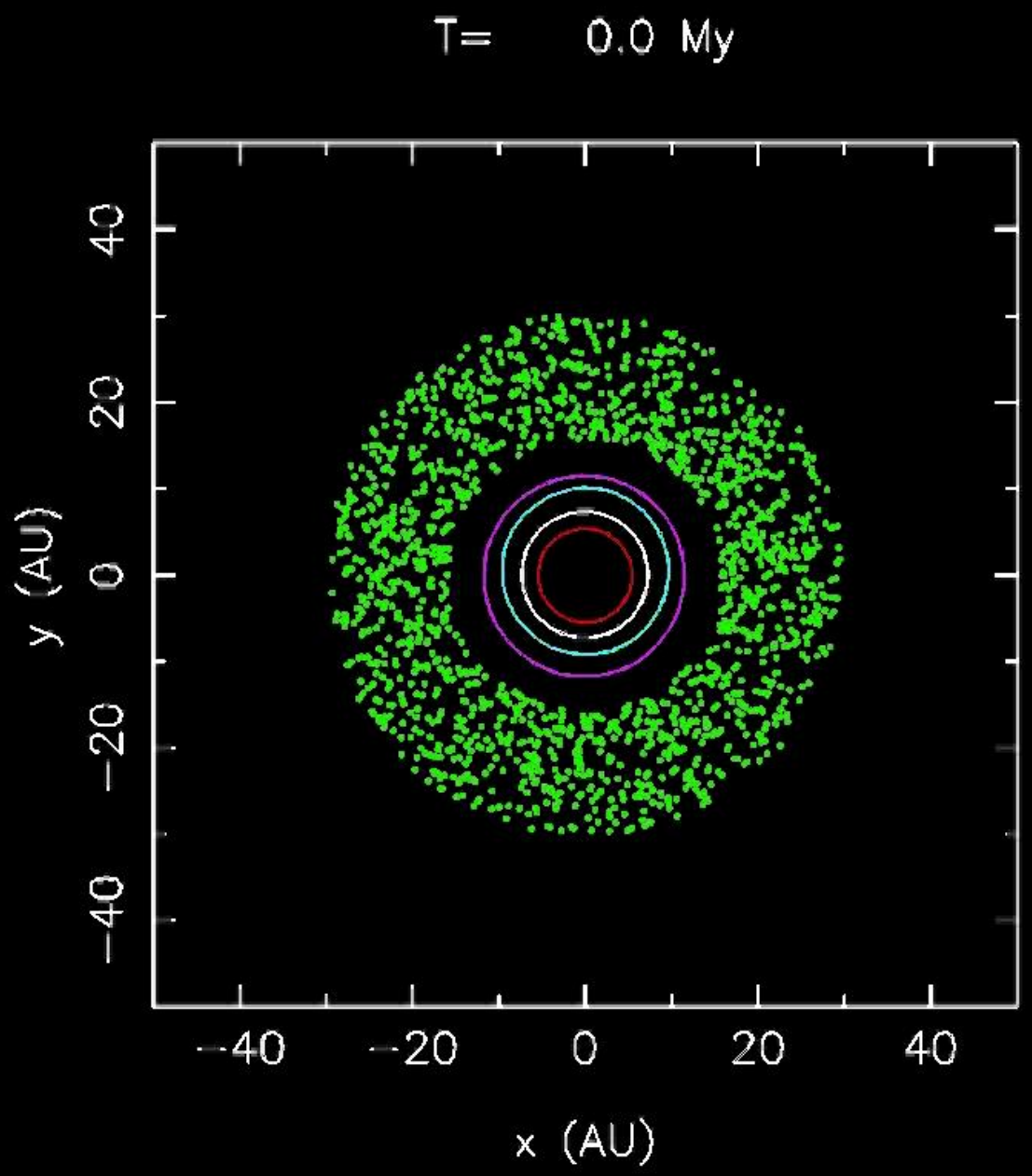
A spike or not a spike?

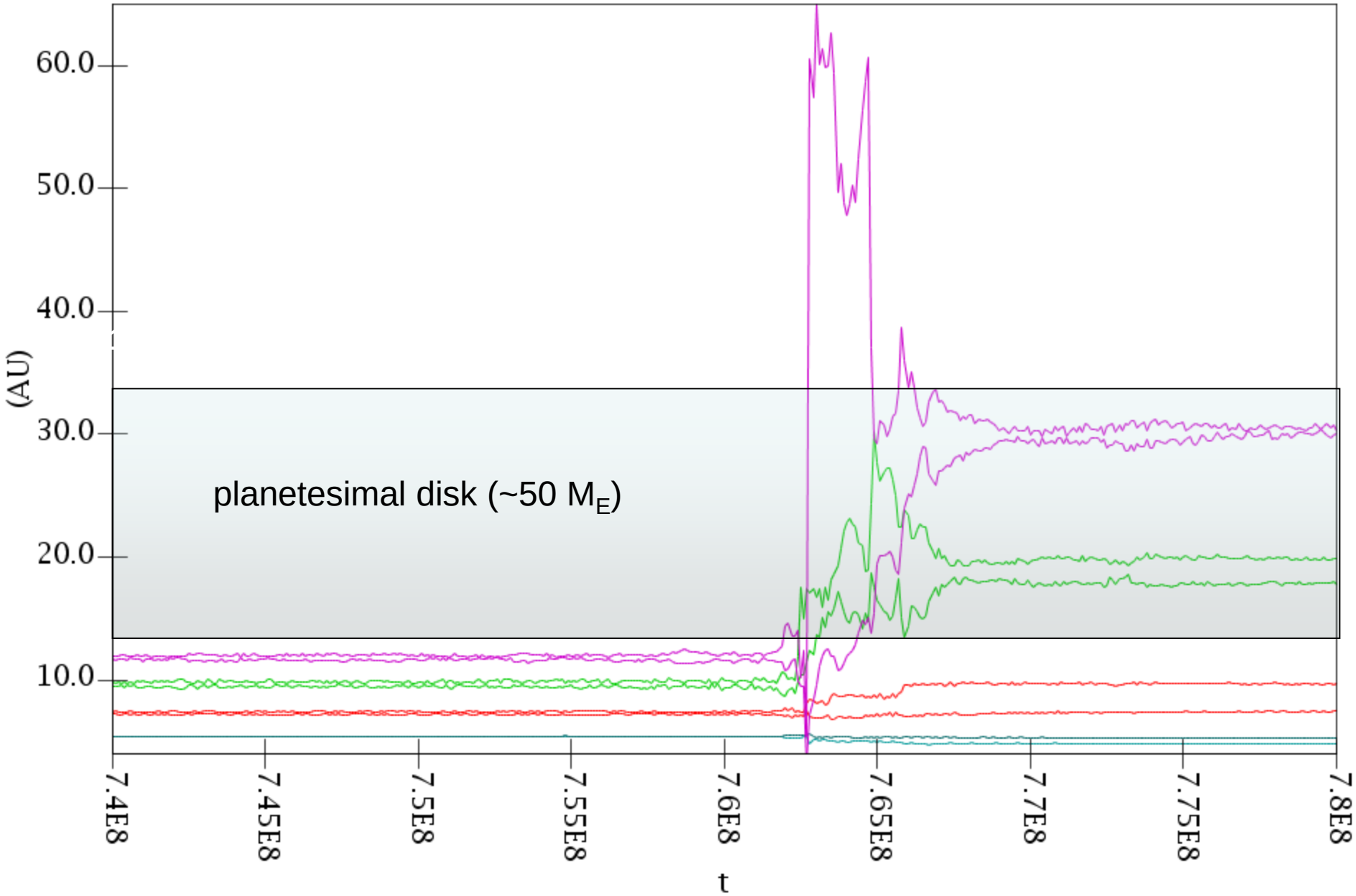
If there was an impact spike, then the solar system must have undergone a dynamical instability at the time of the spike (needed to destabilize a reservoir of planetesimals that had been stable up to that time)

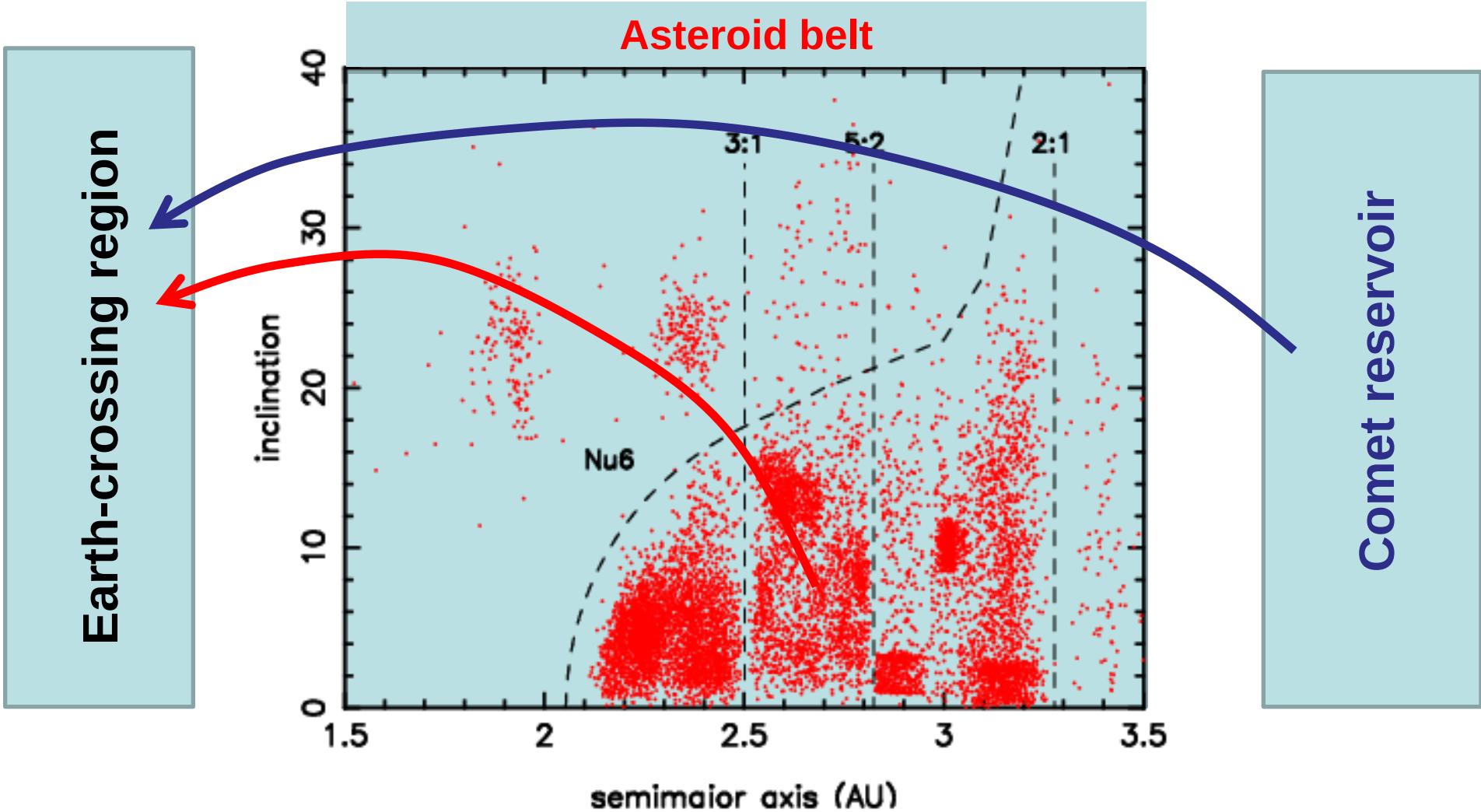
We know that giant planet instabilities are common (early or late) to explain the large eccentricities of giant extra-solar planets.

Also, we need a dynamical instability among the giant planets of the Solar System, because their current orbits do not correspond to those that these planets should have had at the dispersal of the disk of gas (resonant, quasi-circular, near coplanar).

THE NICE MODEL




60.0
50.0
40.0
30.0
20.0
10.0
(AU)
planetesimal disk (~50 M_E)
7.4E8
7.45E8
7.5E8
7.55E8
7.6E8
7.65E8
7.7E8
7.75E8
7.8E8
t

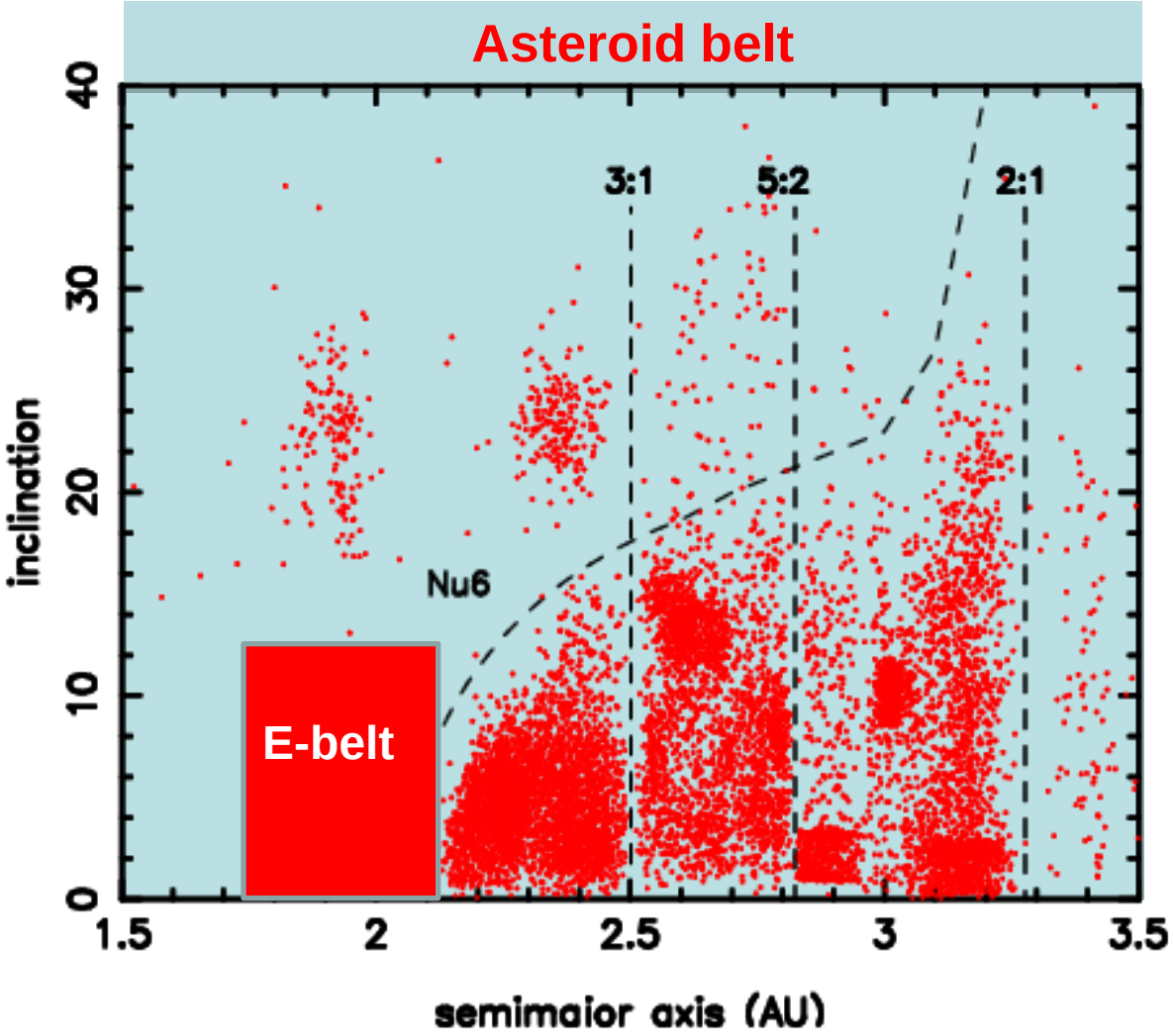


Probably not a dominant population of projectiles, particularly when accounting for physical disintegration when comets penetrate into the inner Solar System

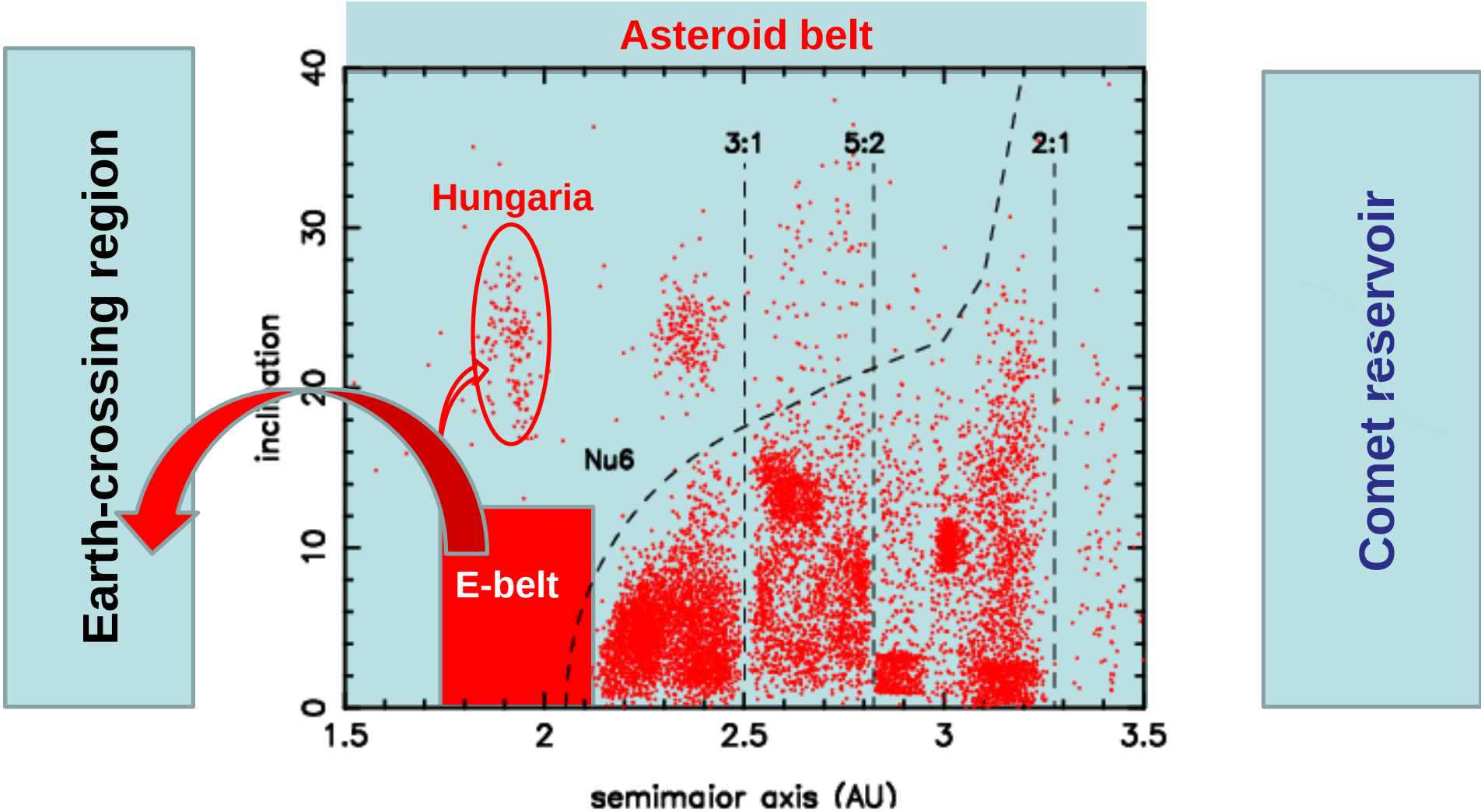
Account only for ~ 2-3 basins on the Moon (Morbidelli et al. (2010))

WHAT ELSE?

Earth-crossing region



Comet reservoir



Calibration of the E-belt population using:
(i) Hungaria population
(ii) main belt population density.

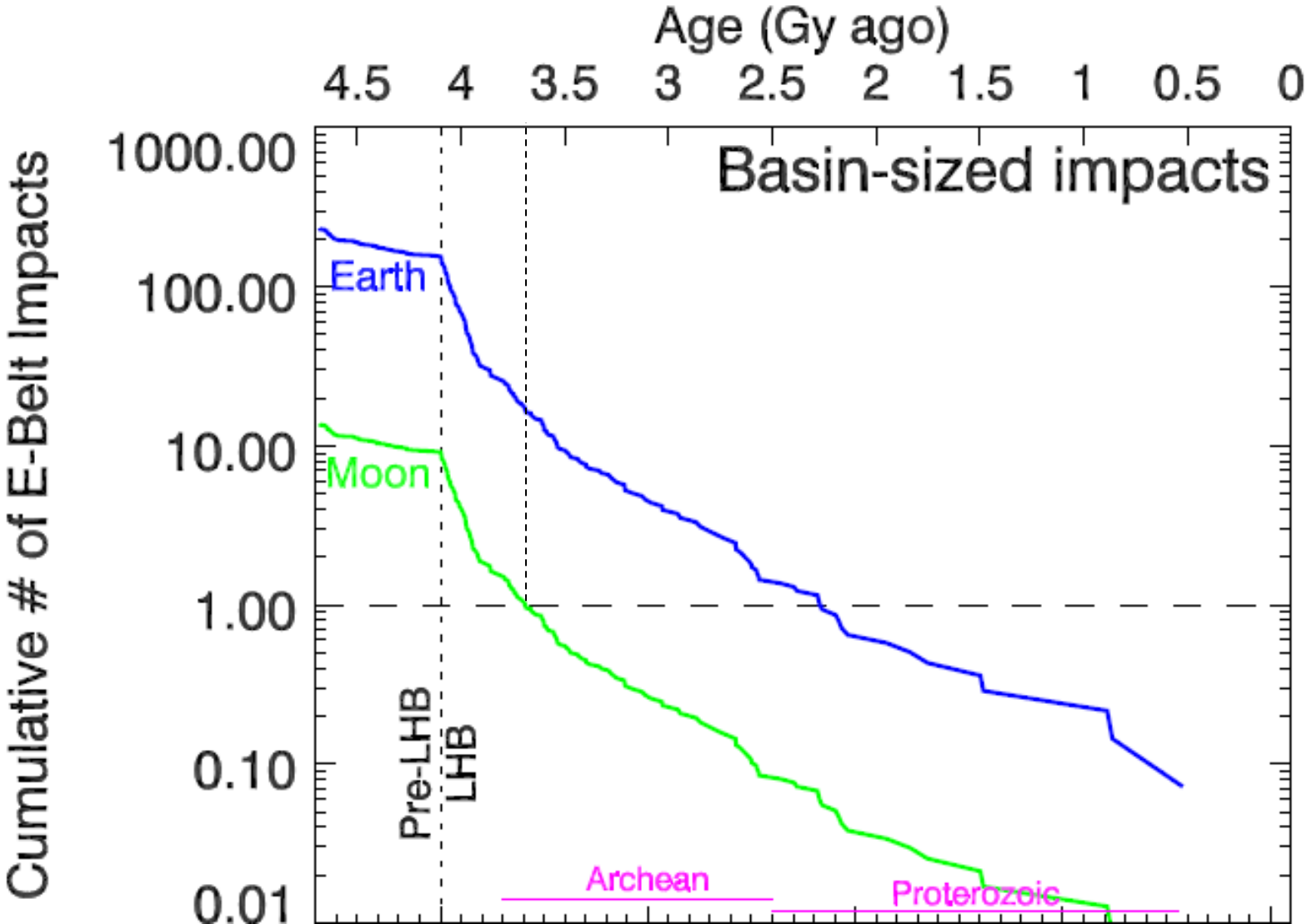
Give consistent results!

Bottke et al., 2012

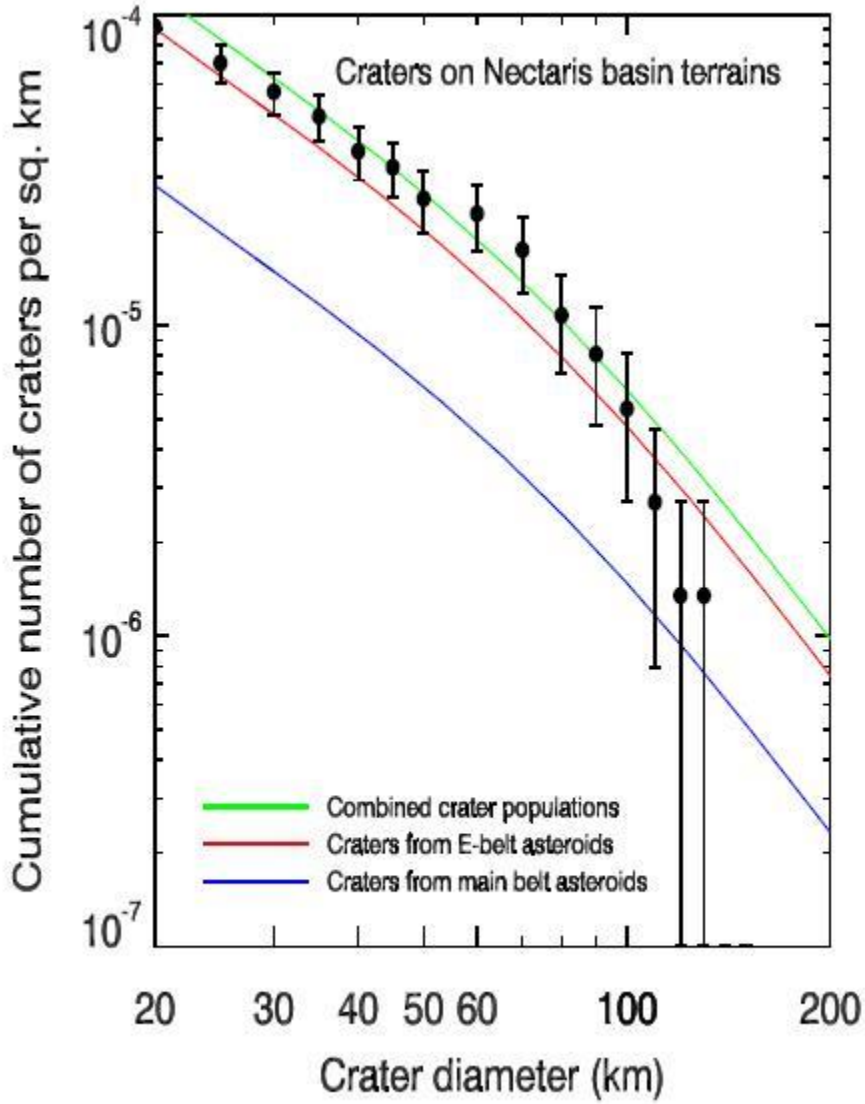
The E-belt could have produced ~10 basins on the Moon

Calibration of the time of the E-belt destabilization using the age of the last basin (Bottke et al., 2012)

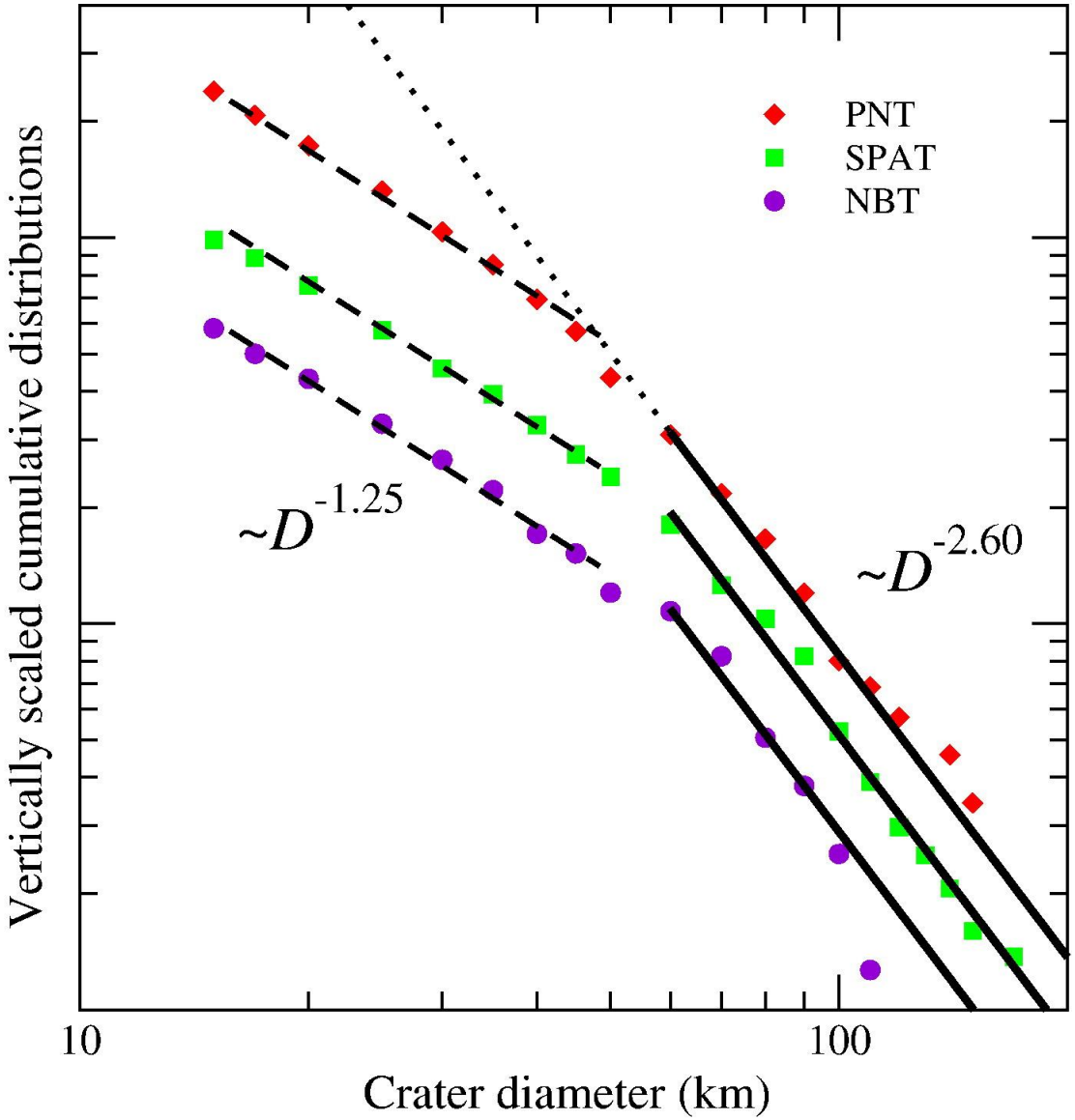
The first LHB basin (Nectaris?) occurred 4.1 Gy ago



Reasons to think that Nectaris was the ~first basin of the LHB:
1) The E-belt model predicts a density of craters on the first basin that agrees with crater counts on Nectaris (Marchi et al., 2012)



Reasons to think that Nectaris was the ~first basin of the LHB:
2) Nectaris carries the signature of a velocity change of the impactors (Marchi et al., 2012)



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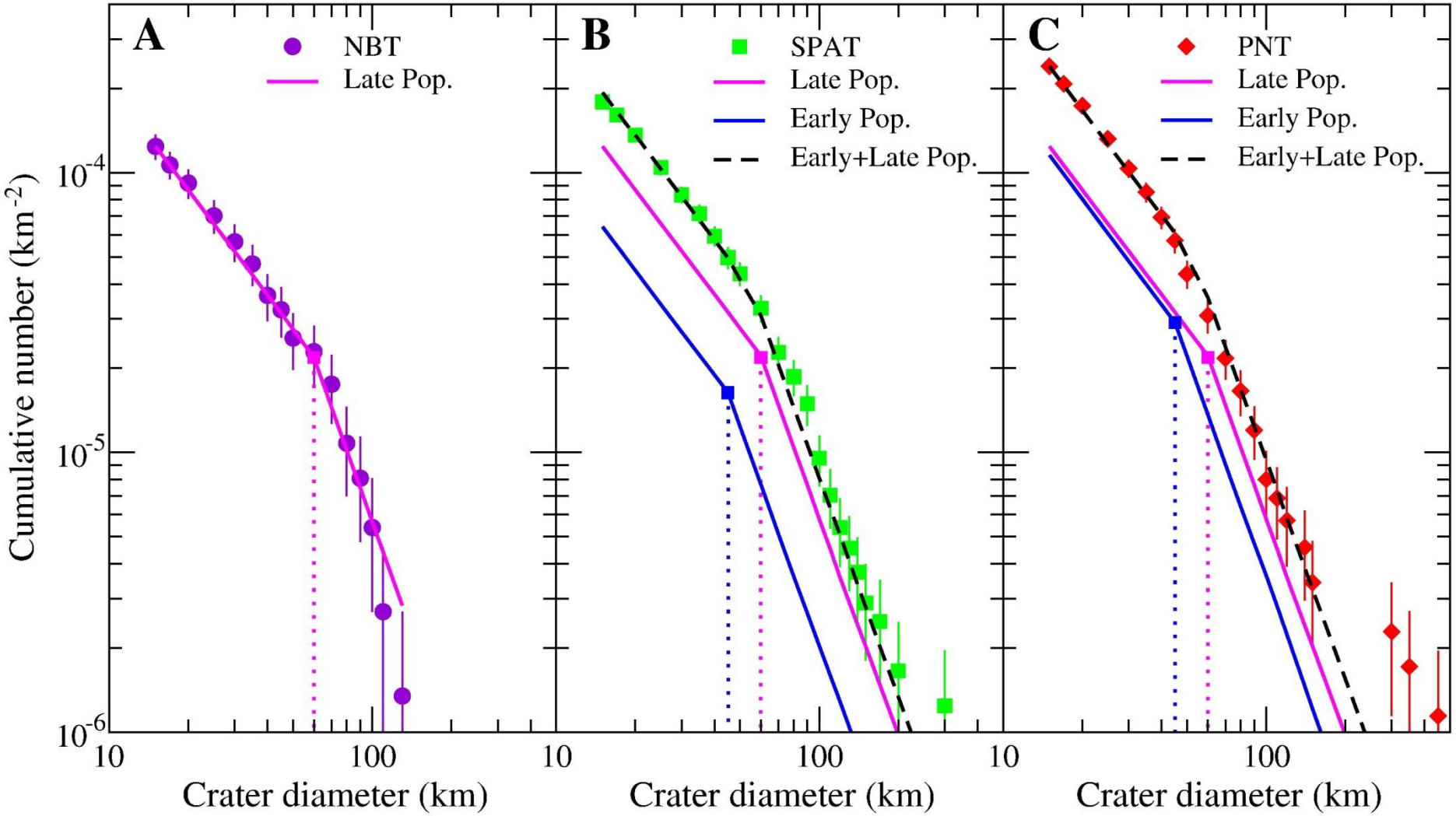


If Nectaris was the first basin formed by the E-belt, then it should have formed around 4.1 Gy ago

Neukum-Ivanov chronology assumes that Nectaris formed 4.1 Gy ago (from Maurer et al., 1978)

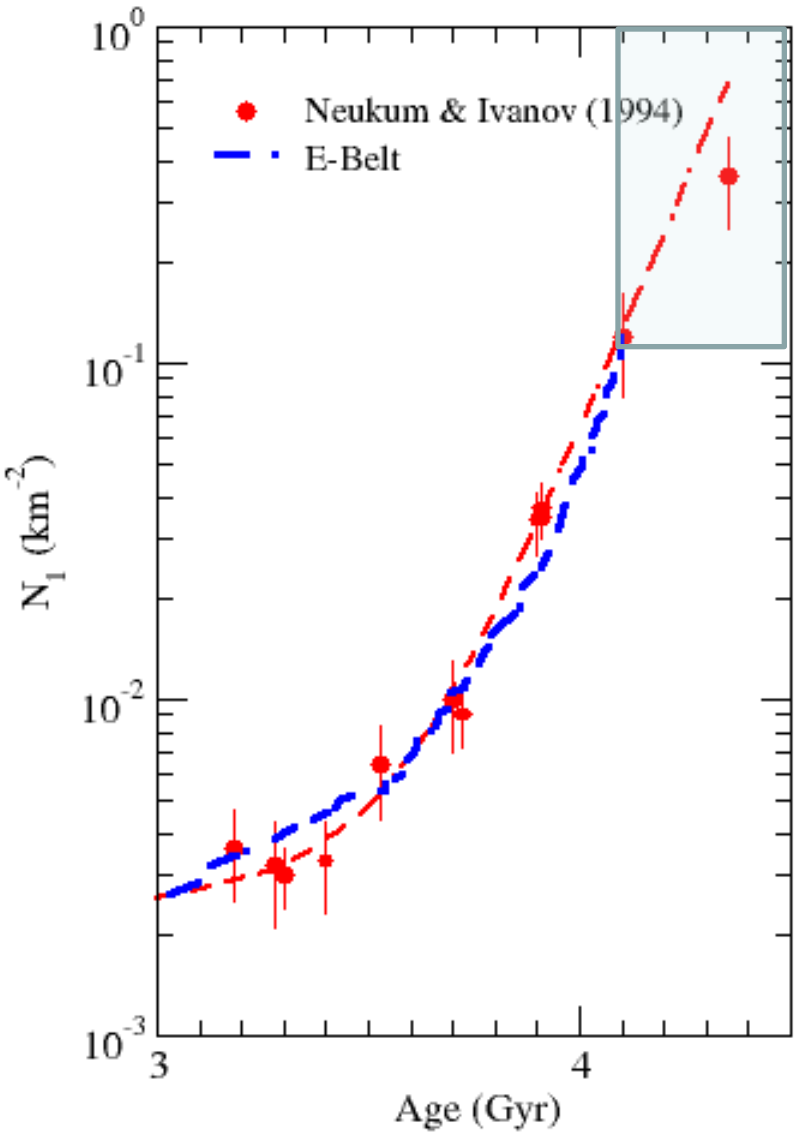
THE E-BELT MODEL SUPPORTS THE AGE OF NECTARIS ASSUMED IN NEUKUM-IVANOV CHRONOLOGY

The E-belt model and Neukum-Ivanov curve have to match on Nectaris datapoint at ~4.1Gy

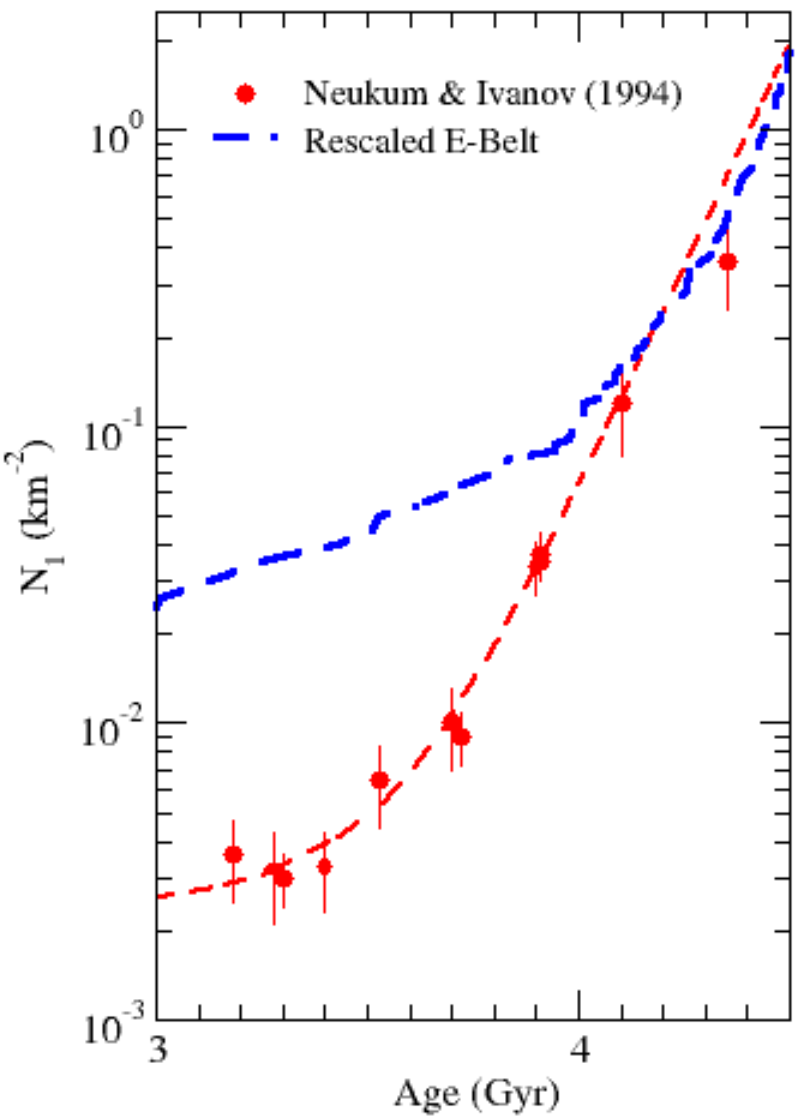
Unexpectedly, the E-belt model predicts a decay of the bombardment rate that matches the Neukum-Ivanov curve all over the 3-4 Gy period

Are Neukum-Ivanov right?
No LHB after all?

We think that the extrapolation of the exponential decay for t>4.1 Gy is not correct



I: We never found a population that matches the exponential decay over ~ 1 Gy. See also Bottke et al. 2007 for a general argument.



II: Siderophile elements argument:

The total amount of HSEs on the moon (mantle + crust) requires that the Moon accreted some 1.7×10^{19} kg of chondritic material (Day et al., 2010)

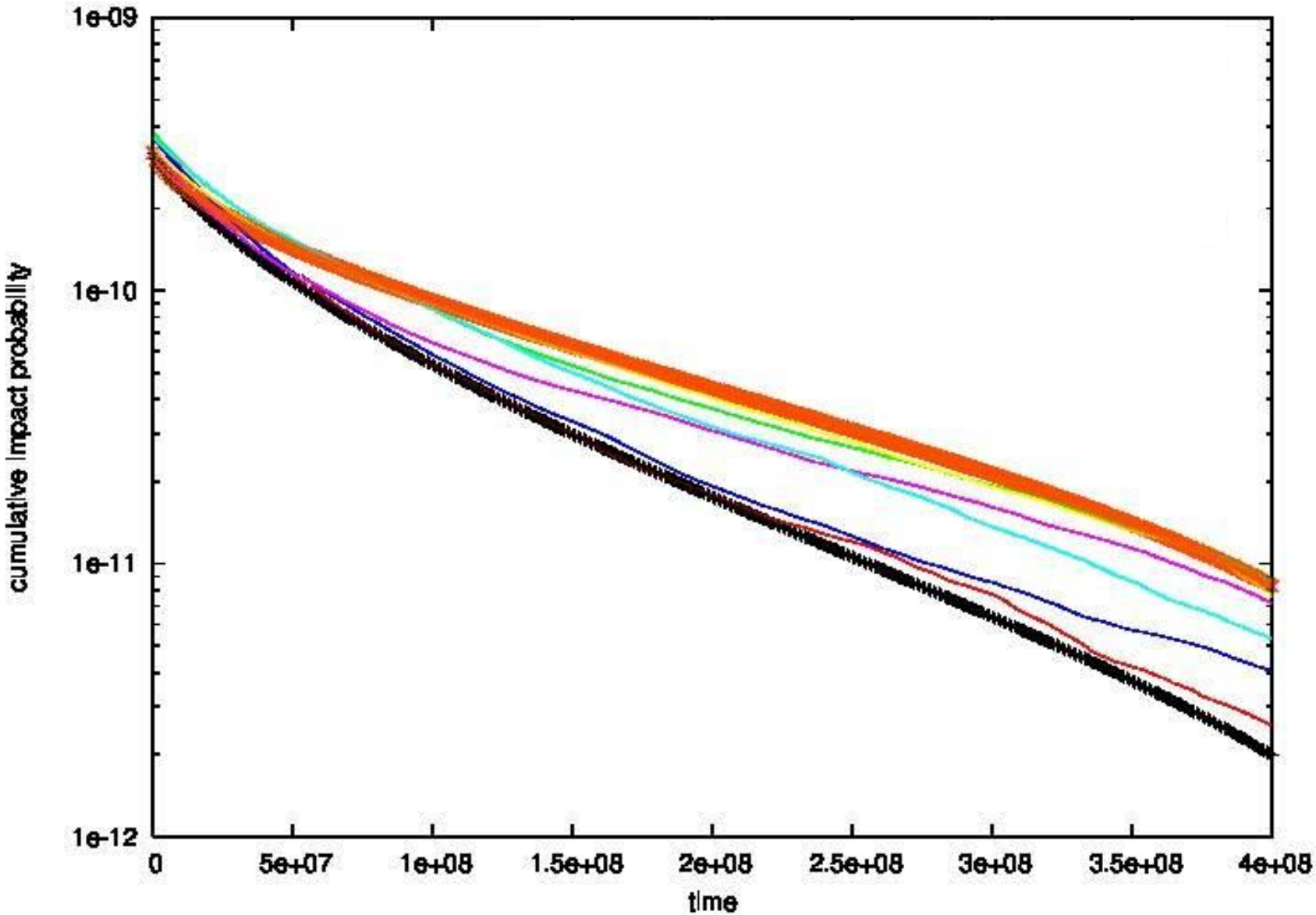
The extrapolation of the 3.7-4.1 bombardment rate back to 4.5Gy would imply that the Moon accreted ~ 10^{20} kg (~5x too much)

The only possibility is that the bombardment rate in the 4.5-4.1Gy and 3.6-4.1 Gy periods are due to two different populations, with different impact rates and temporal decays.

For the 3.6-4.1Gy period it is the E-belt population (with some contribution from the MB)

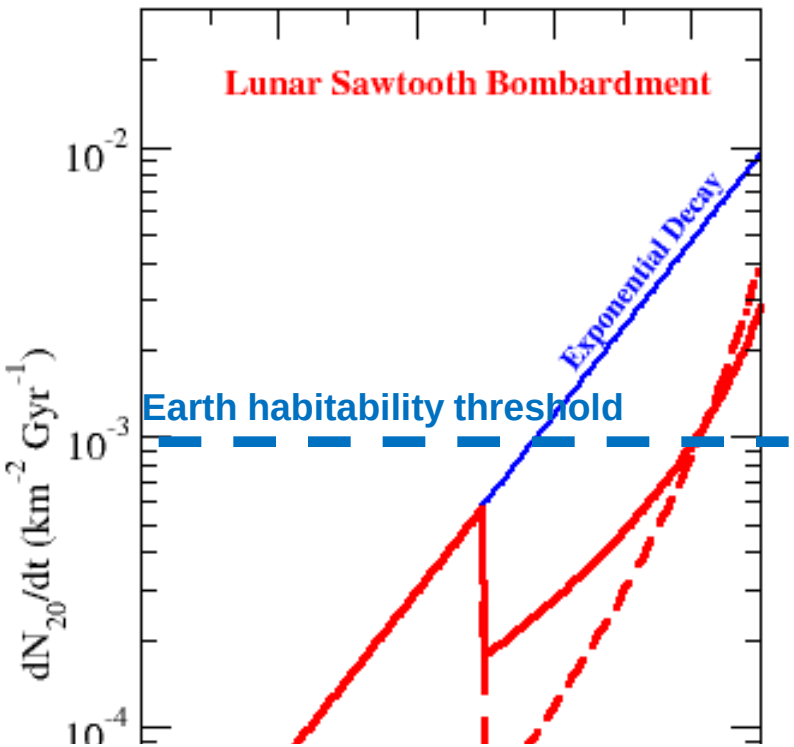
For the 4.1-4.5 Gy period it is the population of planetesimals in the terrestrial planet region, left-over from the planet accretion process.

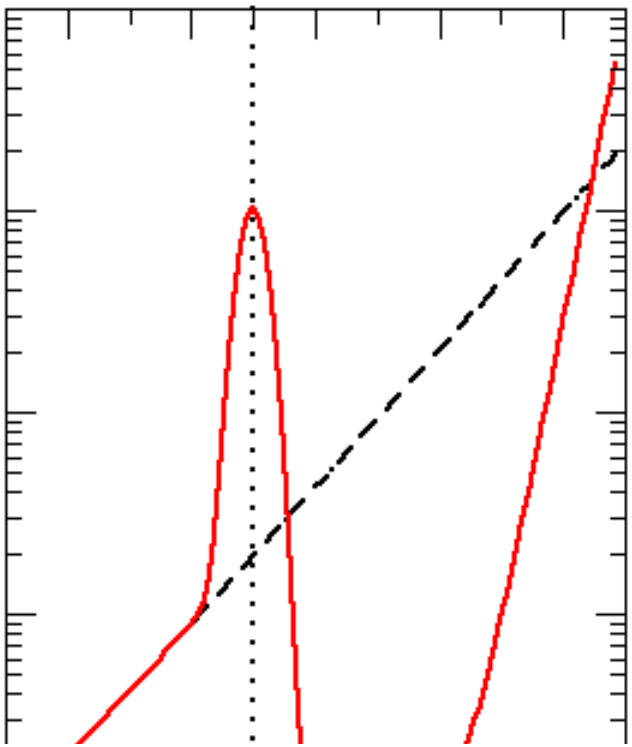
To characterize the latter we turn to the best-to-date simulations of terrestrial planet accretion (Walsh et al., 2011)



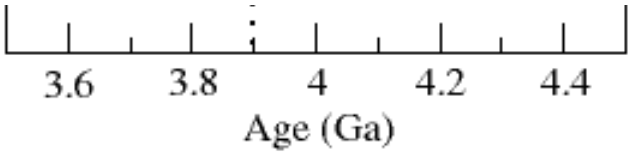
DIFFERENTIAL VIEW

OLD VIEW OF LHB SPIKE





EARTH PROBABILY HABITABLE SINCE 4.4 GY AGO



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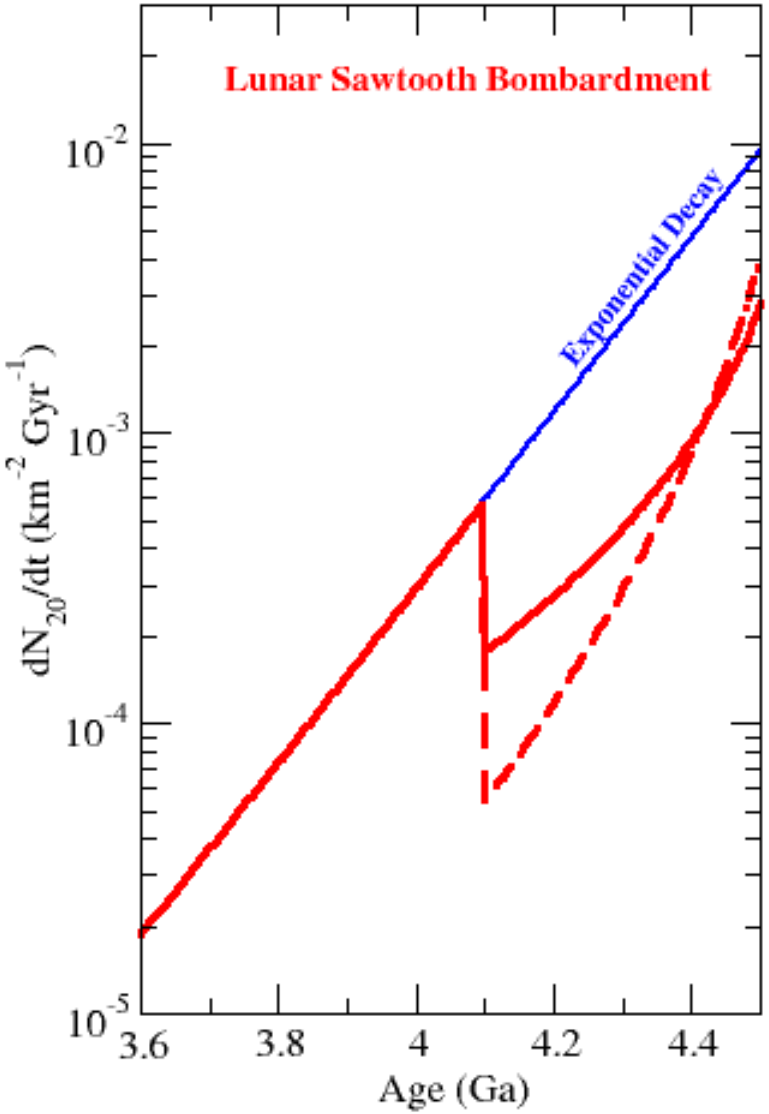
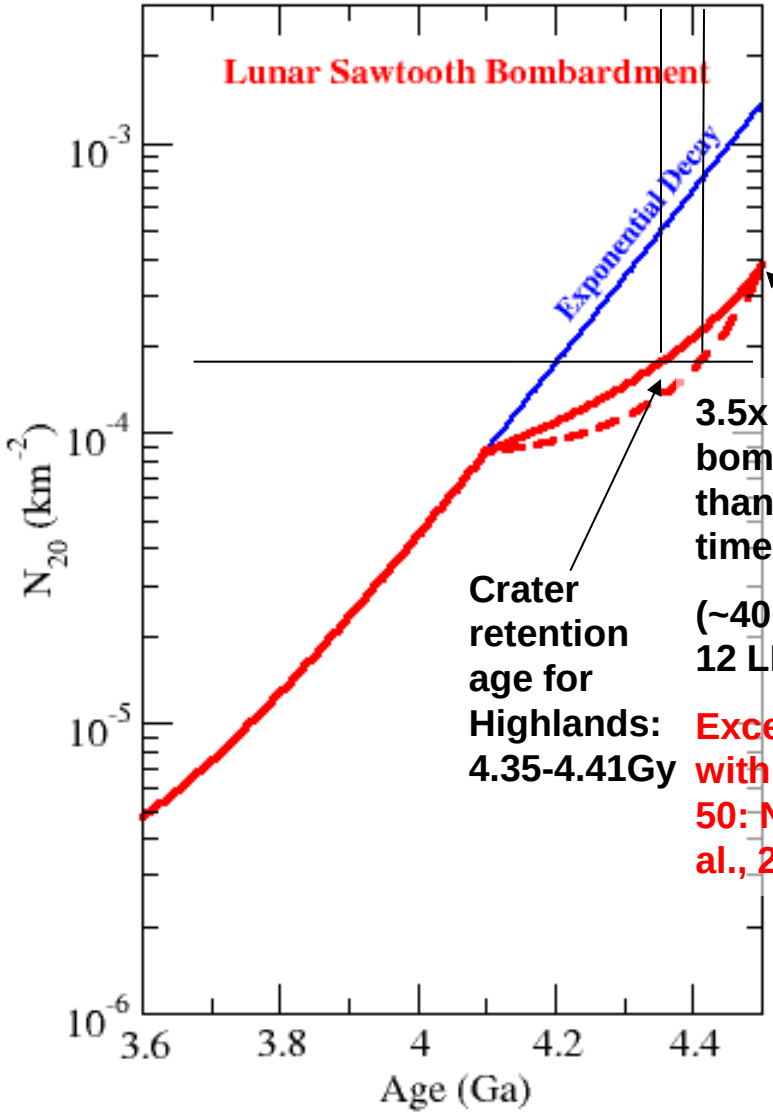


CUMULATIVE VIEW



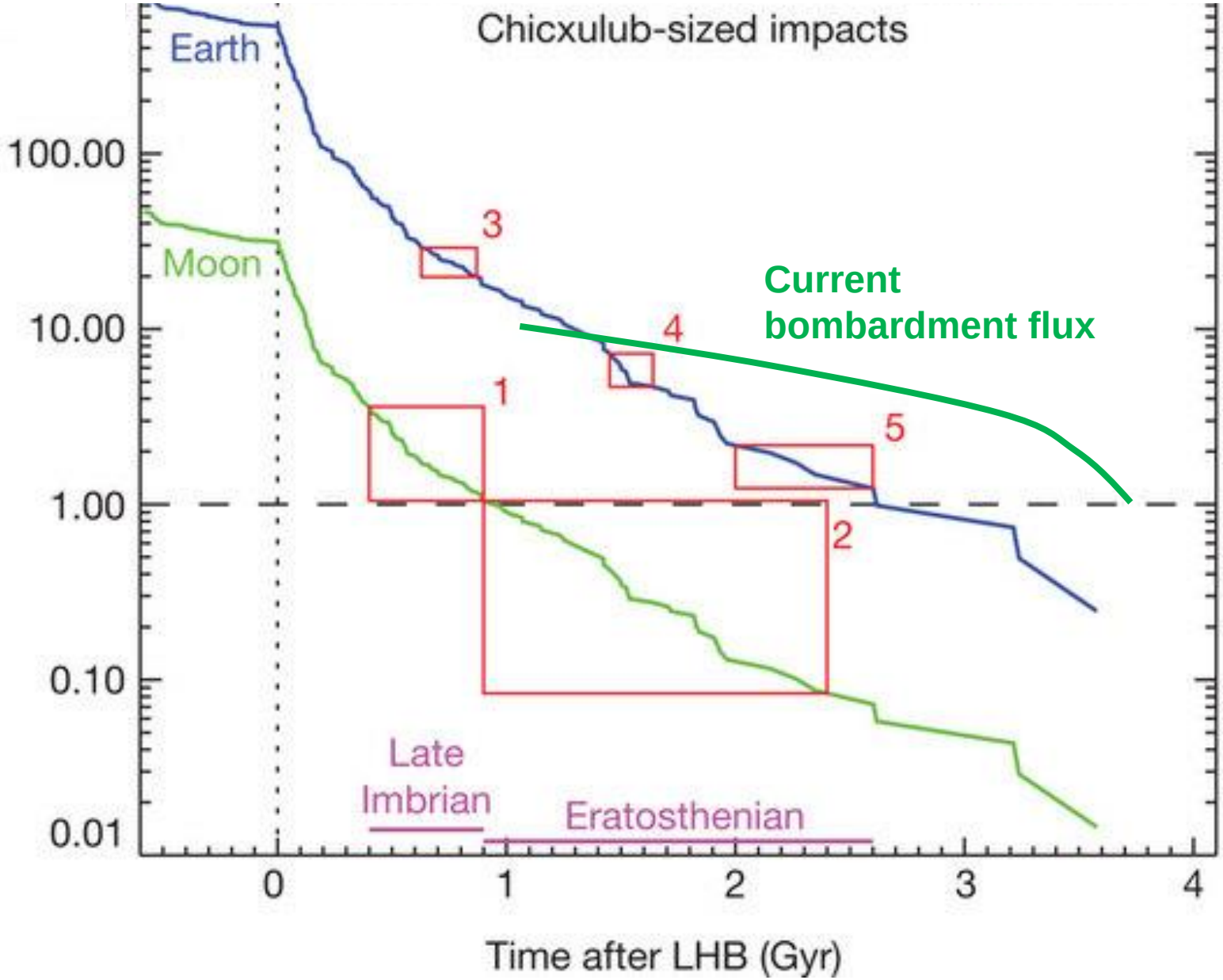
160 basins

3.5x more bombardment than since LHB-time

(~40 basins total, 12 LHB)

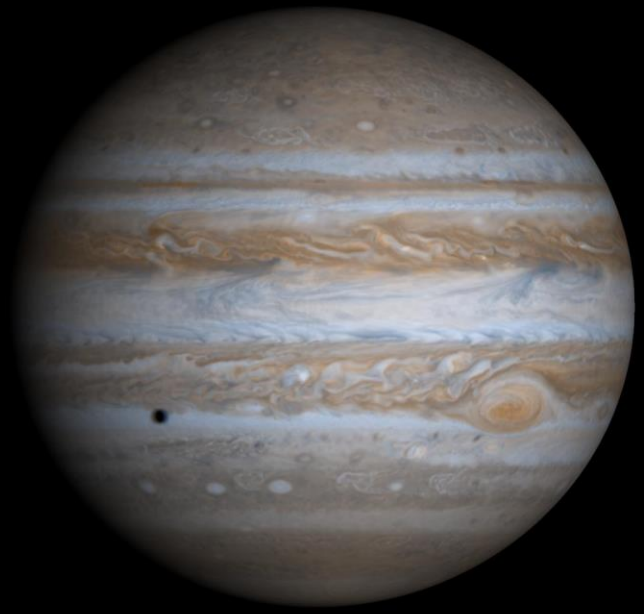
Crater retention age for Highlands: 4.35-4.41Gy

Excellent match with GRAIL (38-50: Neumann et al., 2013)


Chicxulub-sized impacts
Earth
Moon
100.00
10.00
1.00
0.10
0.01
0
1
2
3
4
Time after LHB (Gyr)
1
2
3
4
5
Current
bombardment flux
Late
Imbrian
Eratosthenian

CONCLUSIONS

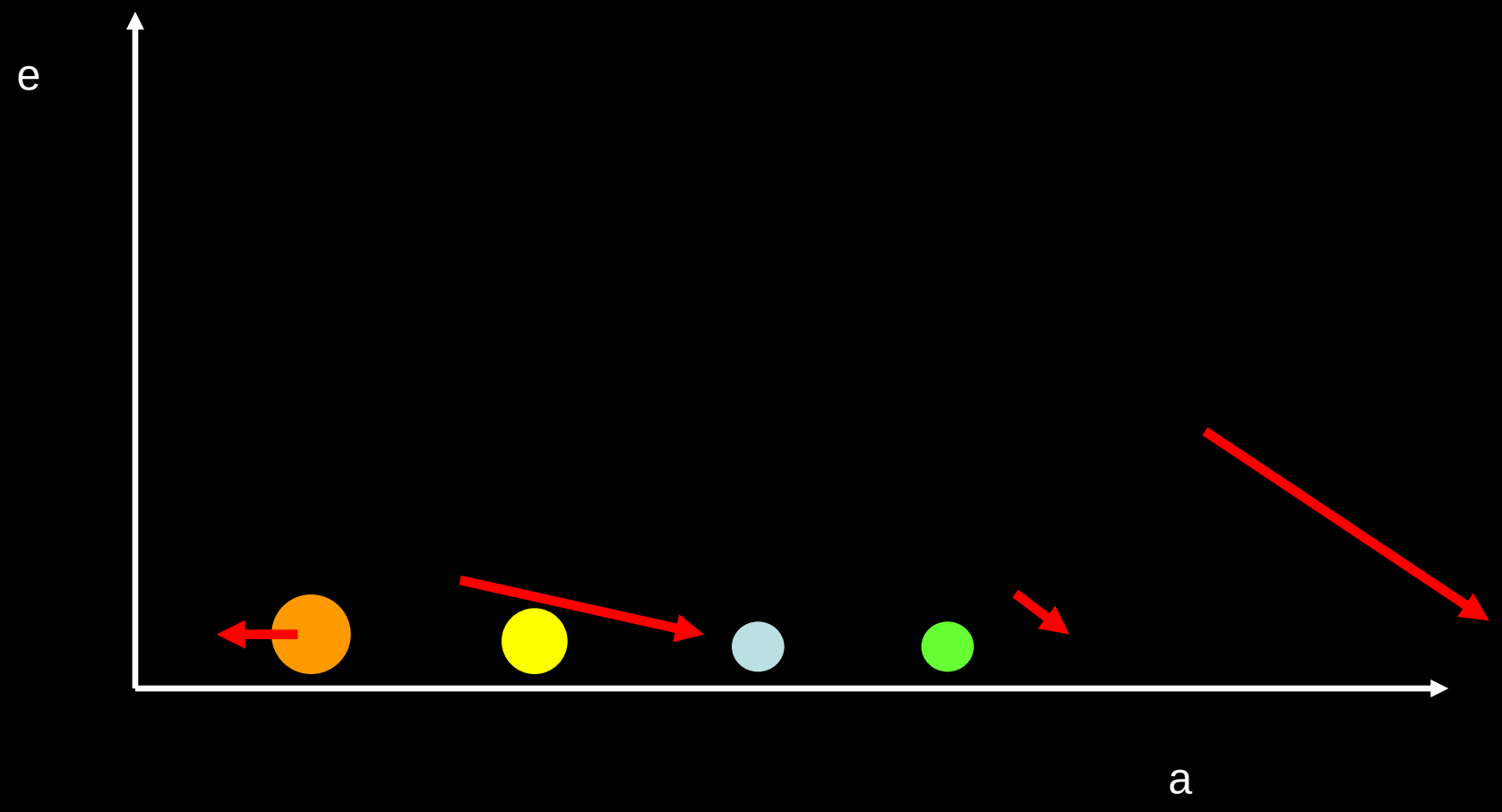
- The Nice model give the template to understand the existence of an impact "spike" in the bombardment history of the Moon
- A priori we cannot say when this spike happened nor its magnitude.
- The model needs to be calibrated
  - Giant planet dynamics is calibrated by analyzing constraints from the asteroid and terrestrial planet orbits
  - The current asteroid belt population then sets the magnitude of the LHB
  - The age of Imbrium (the best known of all basin ages!) sets the chronology
- Once calibrated, we obtain the SawTooth profile of the lunar bombardment
- Really a new view of the LHB, intermediate between the no-cataclysm view of Neukum and the extreme view of Ryder (speculated in a few papers by Hartmann)



Constraining the giant planets evolution after the trigger of their instability

Two possible evolutions from instability:

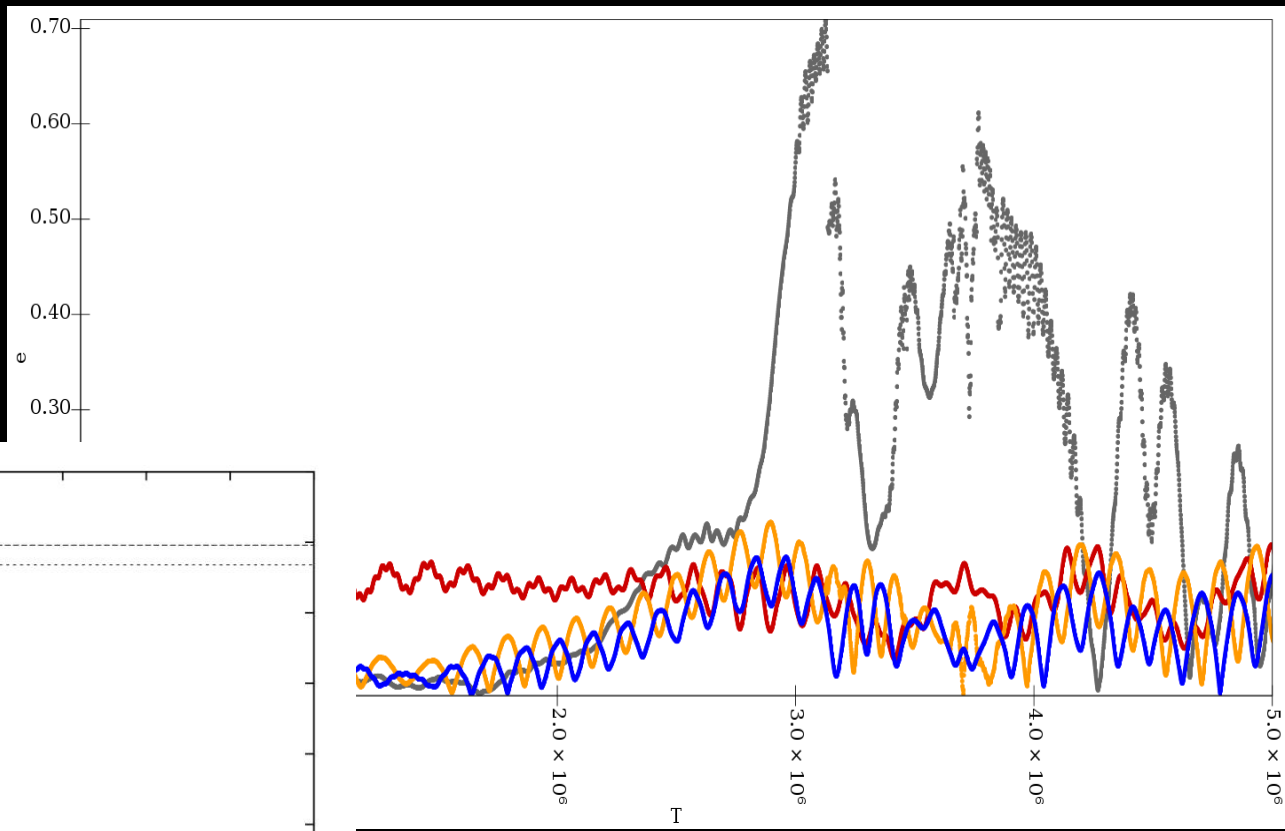
I) The divergent evolution of Jupiter and Saturn is dominated by planetesimal-driven migration

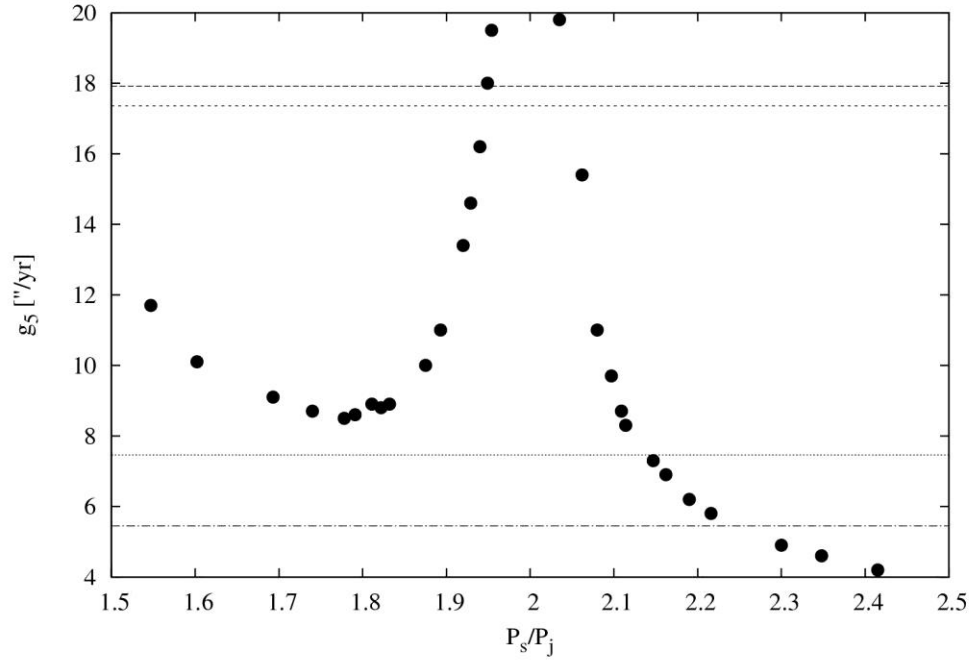


Typical timescale for Jupiter-Saturn separation: 10My

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

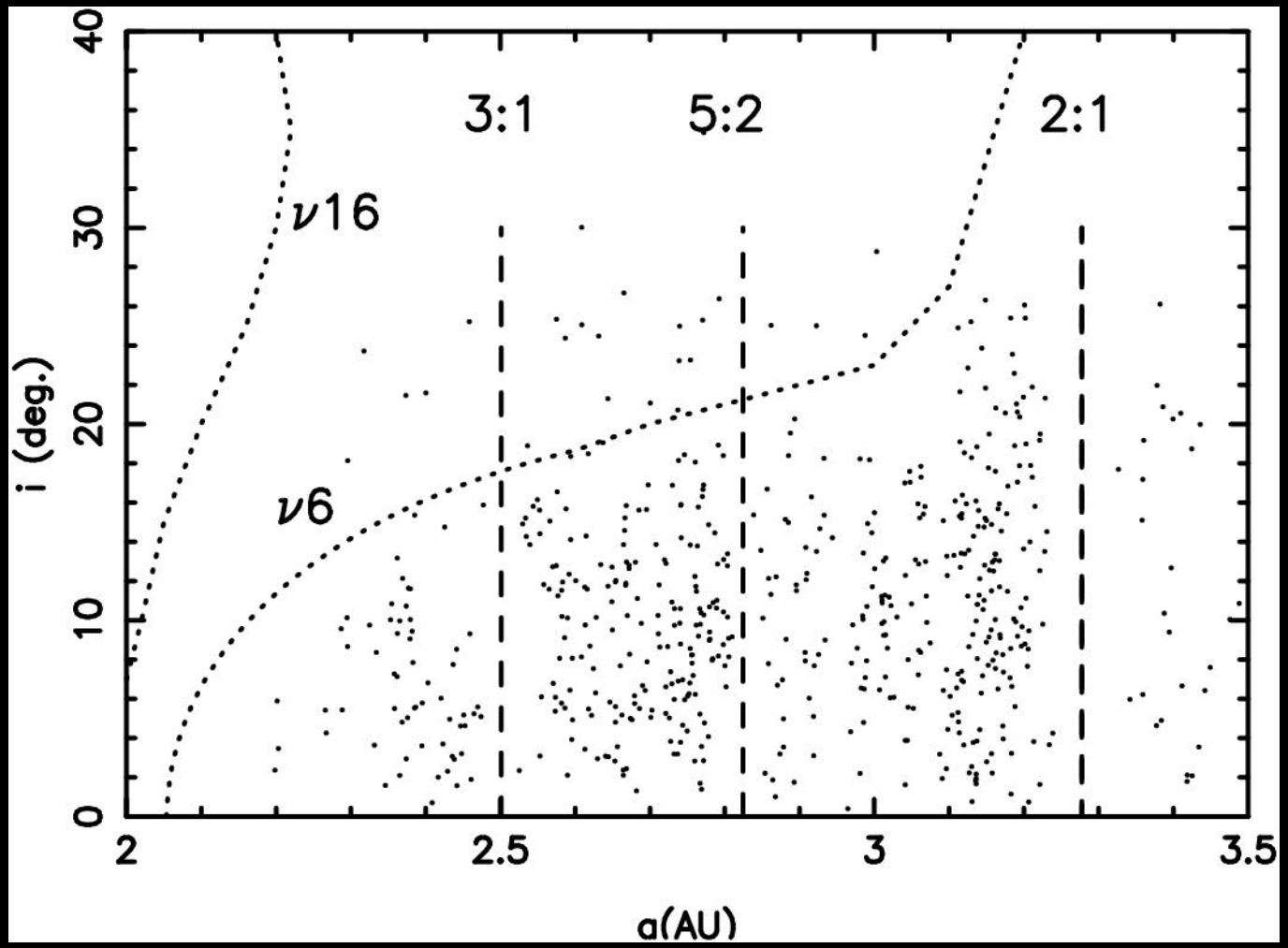




Brasser et al., 2009

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:

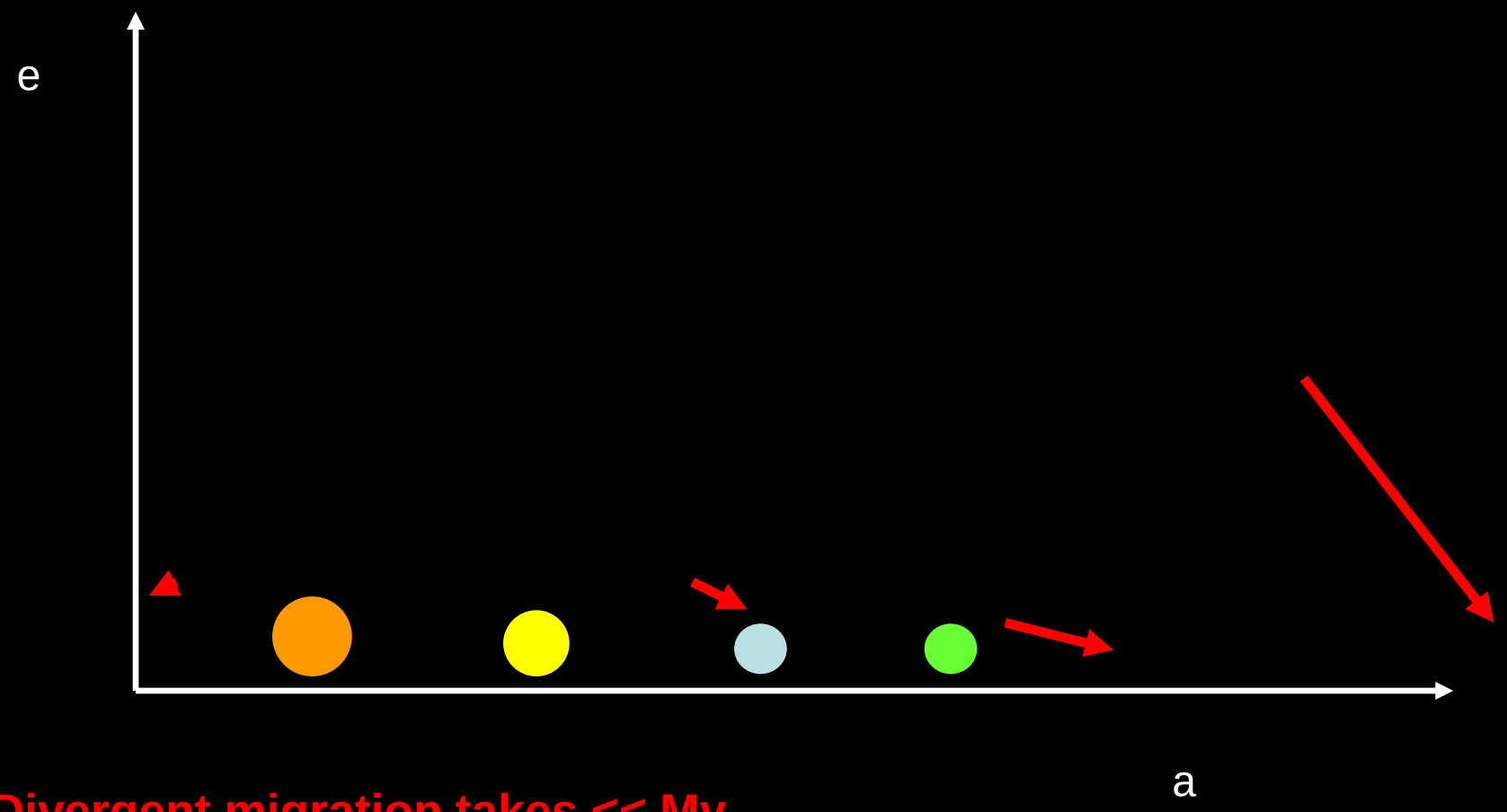
ii) Gives the asteroid belt a really weird orbital distribution



real

Two possible evolutions from instability:

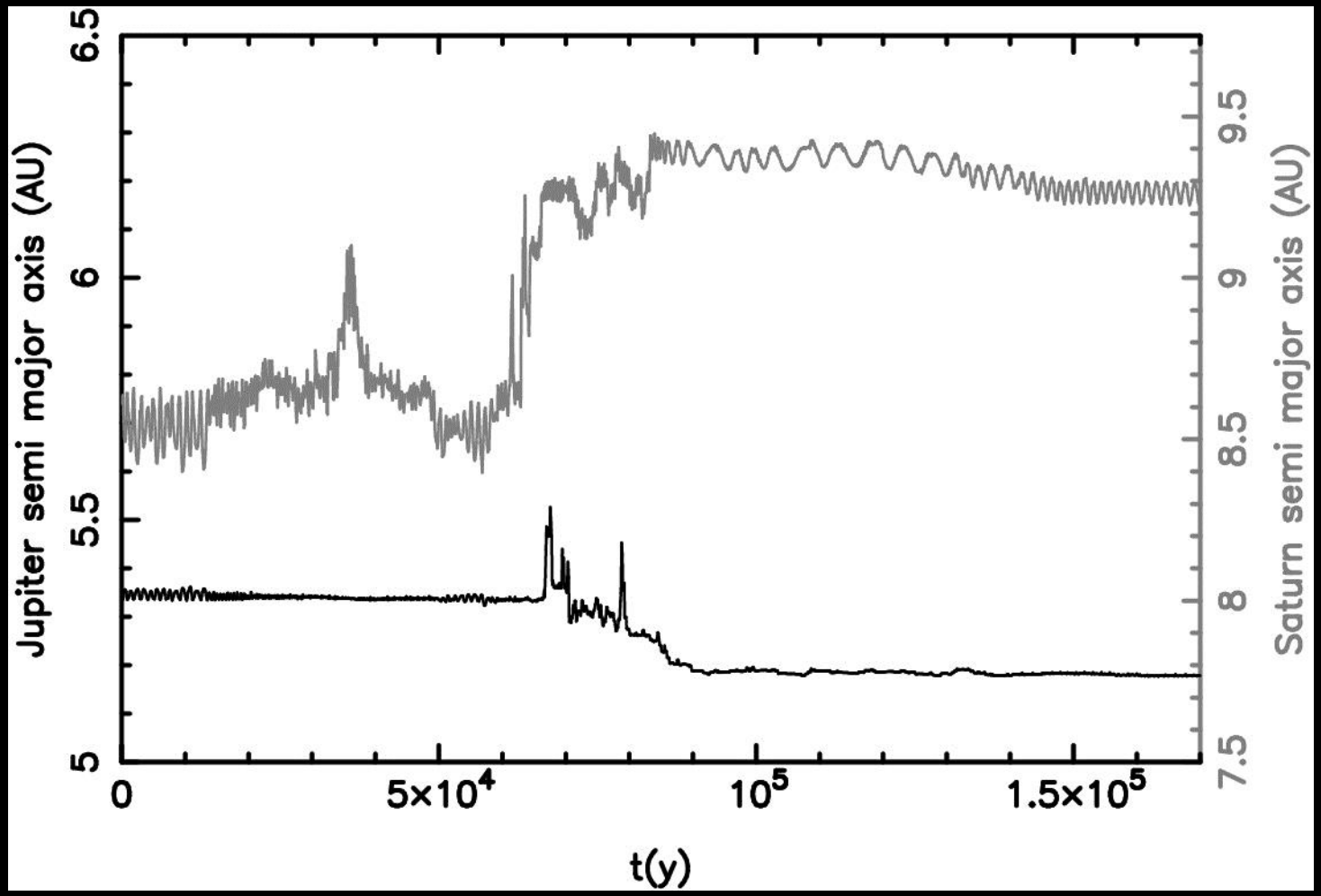
II) The divergent evolution of Jupiter and Saturn is dominated by encounters with Uranus or Neptune



Divergent migration takes << My

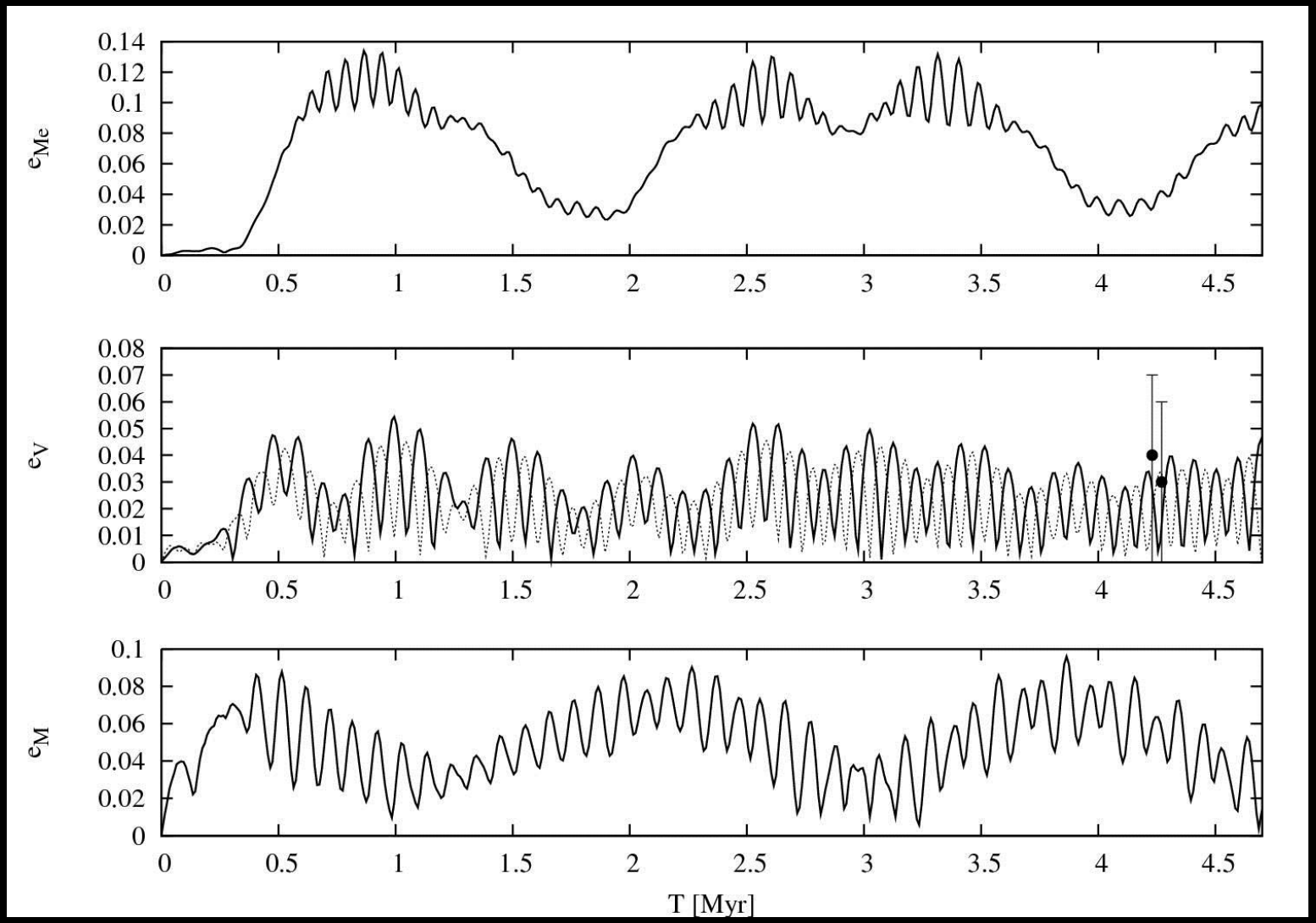
This kind of evolution occurs in ~10% of the successful runs in Nice 2005 and > 50% of those of Nice II

Example of Jumping-Jupiter evolution

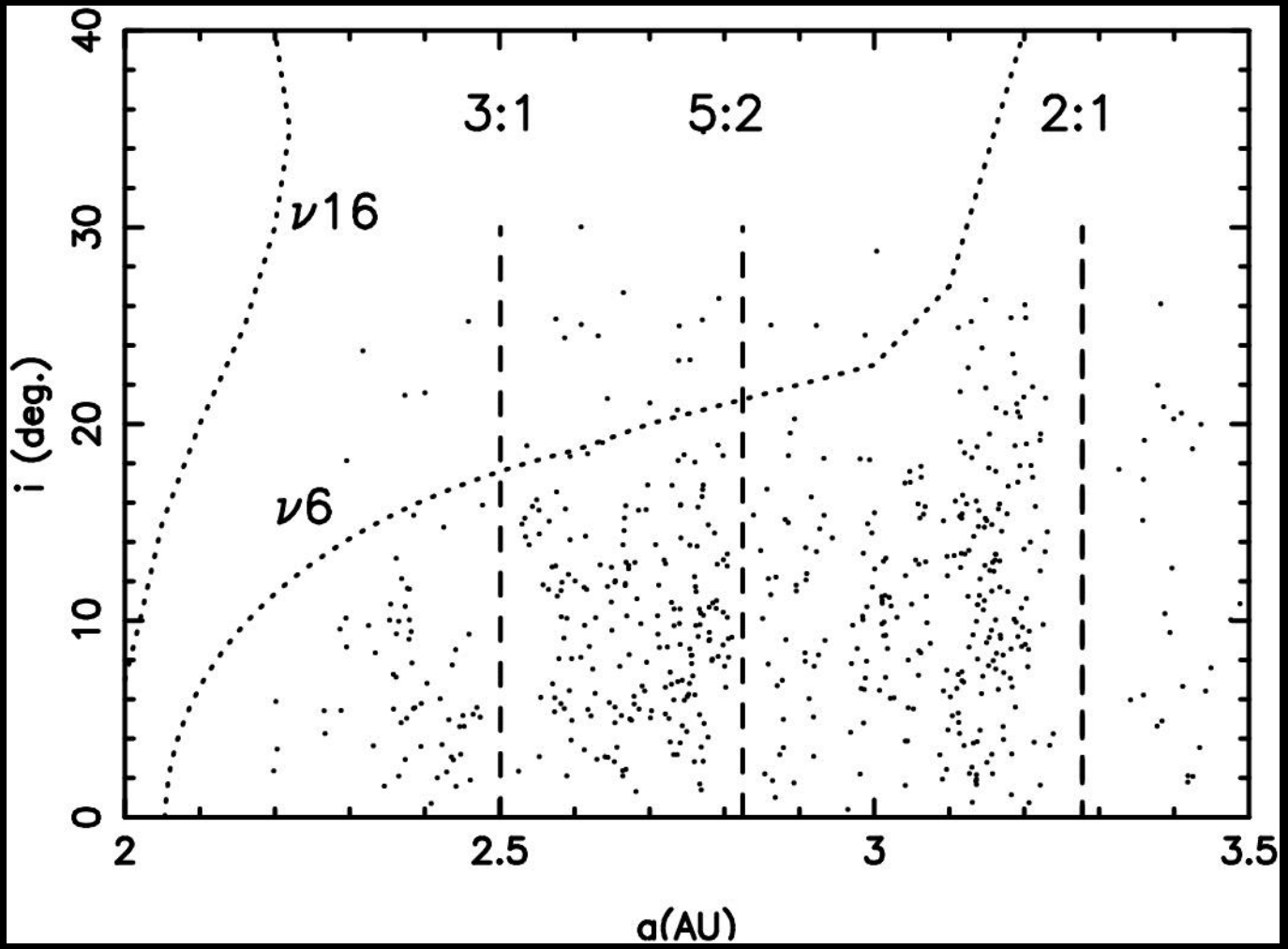


Nesvorny et al. (2007) argued that Jupiter-Uranus encounters did occur, otherwise only Saturn, Uranus and Neptune (NOT Jupiter) should have irregular satellites

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



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