The Great Archaean Bombardment (and the Late Heavy Bombardment)

Ramon Brasser

in collaboration with

Bill Bottke, David Vokrouhlicky, David Minton, David Nesvorny, Alessandro Morbidelli, Hal Levison and Bruce Simonson

Overview

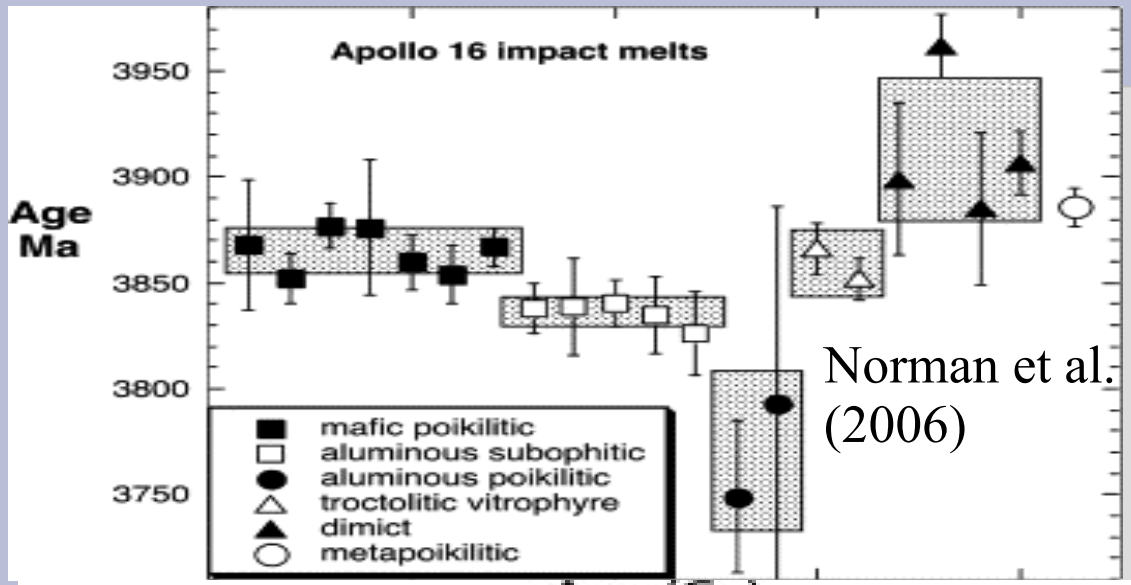
- Evidence for the Late Heavy Bombardment (LHB)
- Origin of the LHB and the Nice model
- Where are the comets?
- The E-belt hypothesis
- The Great Archaean Bombardment
- Conclusions

What is the Late Heavy Bombardment?

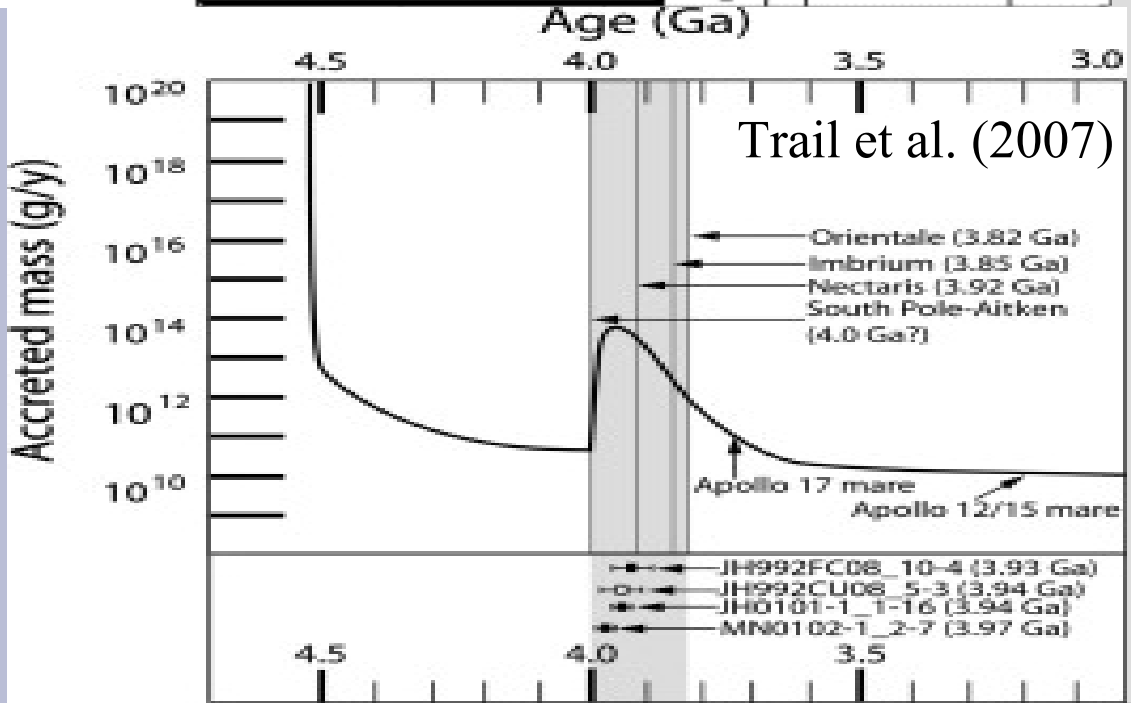
- The Late Heavy Bombardment (LHB) was a cataclysmic cratering event triggered 3.8 Gyr ago, ~600Myr after the formation of the terrestrial planets
- Global event: traces found on Mercury, Venus, Earth, Mars, Vesta…., possibly on giant planets satellites
- LHB had 20.000 times the current cratering rate: 1 km object impacting the Earth every 20 years!
- Duration: 50-150 Myr

It suggests that a reservoir of small bodies, which remained stable for ~600 Myr, suddenly became unstable. How could this have happened? Some evidence of the LHB first.

Some evidence for the LHB

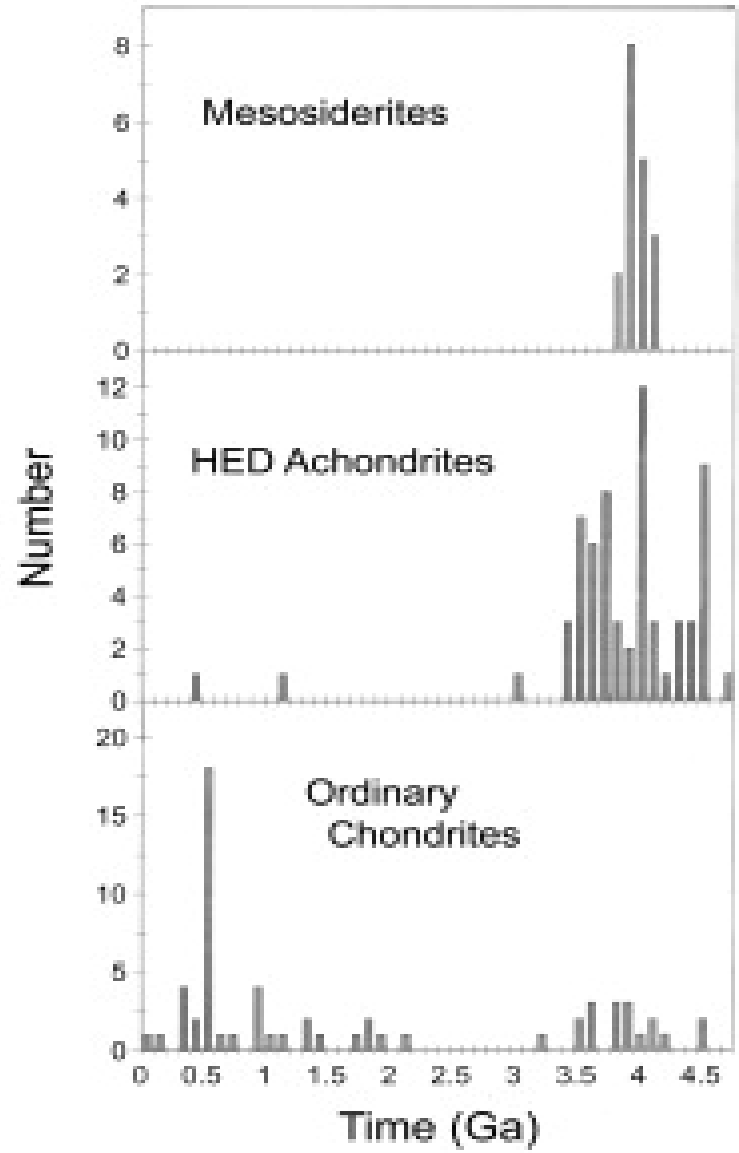


Norman et al. (2006)



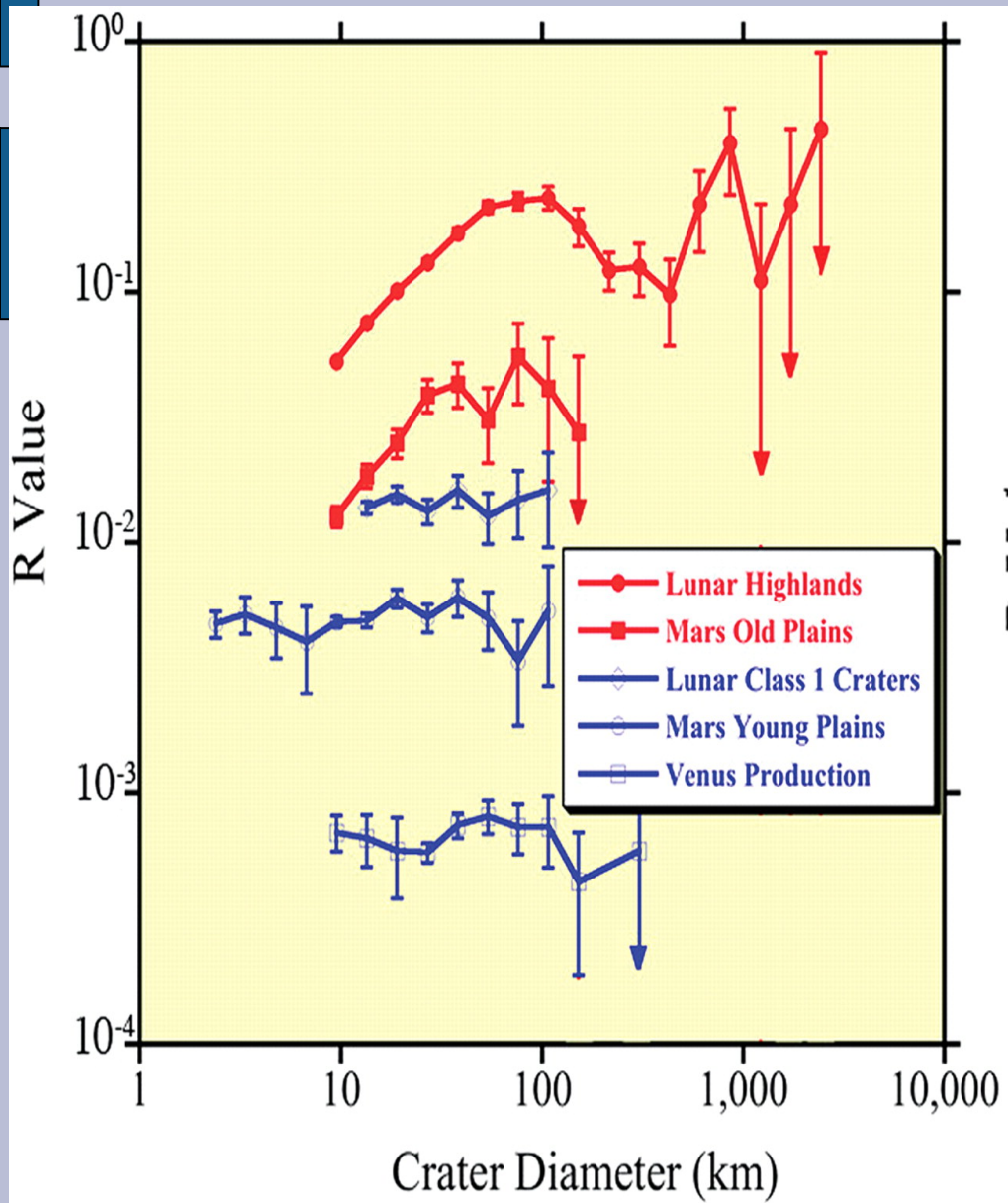
Trail et al. (2007)

Kring & Cohen (2002)

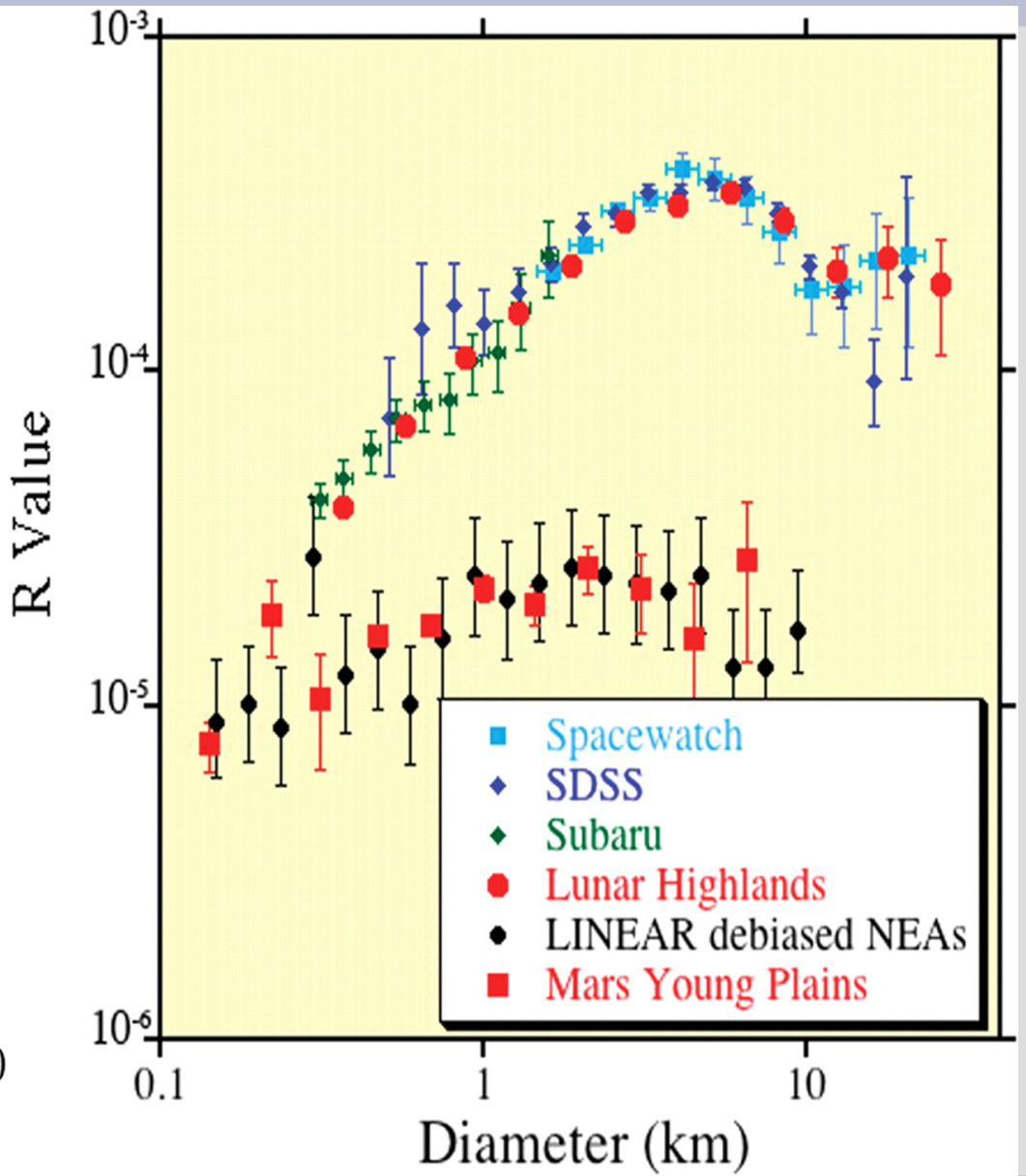


Some evidence for the LHB II

Strom et al. (2005)

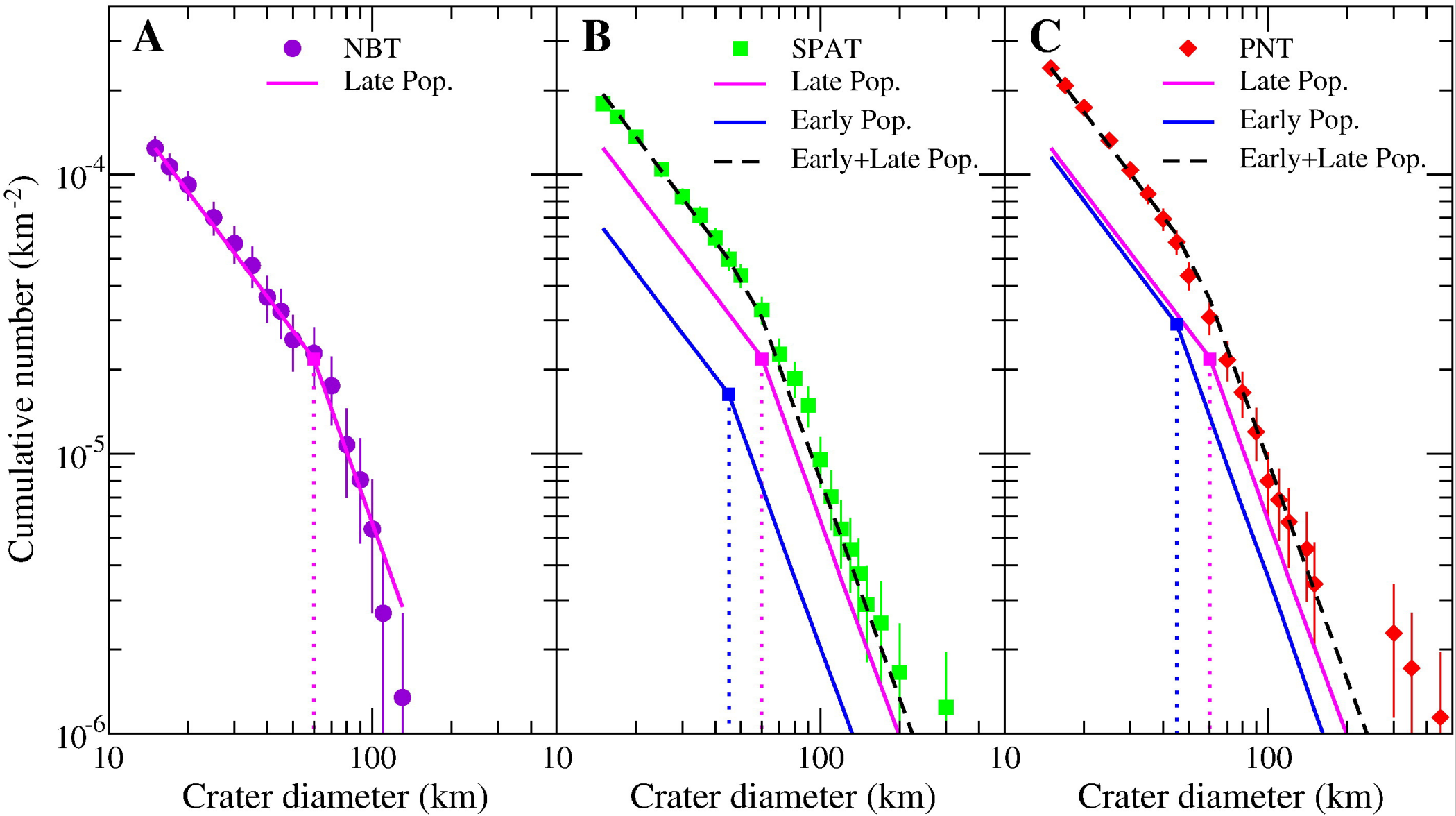


Strom et al. (2005)

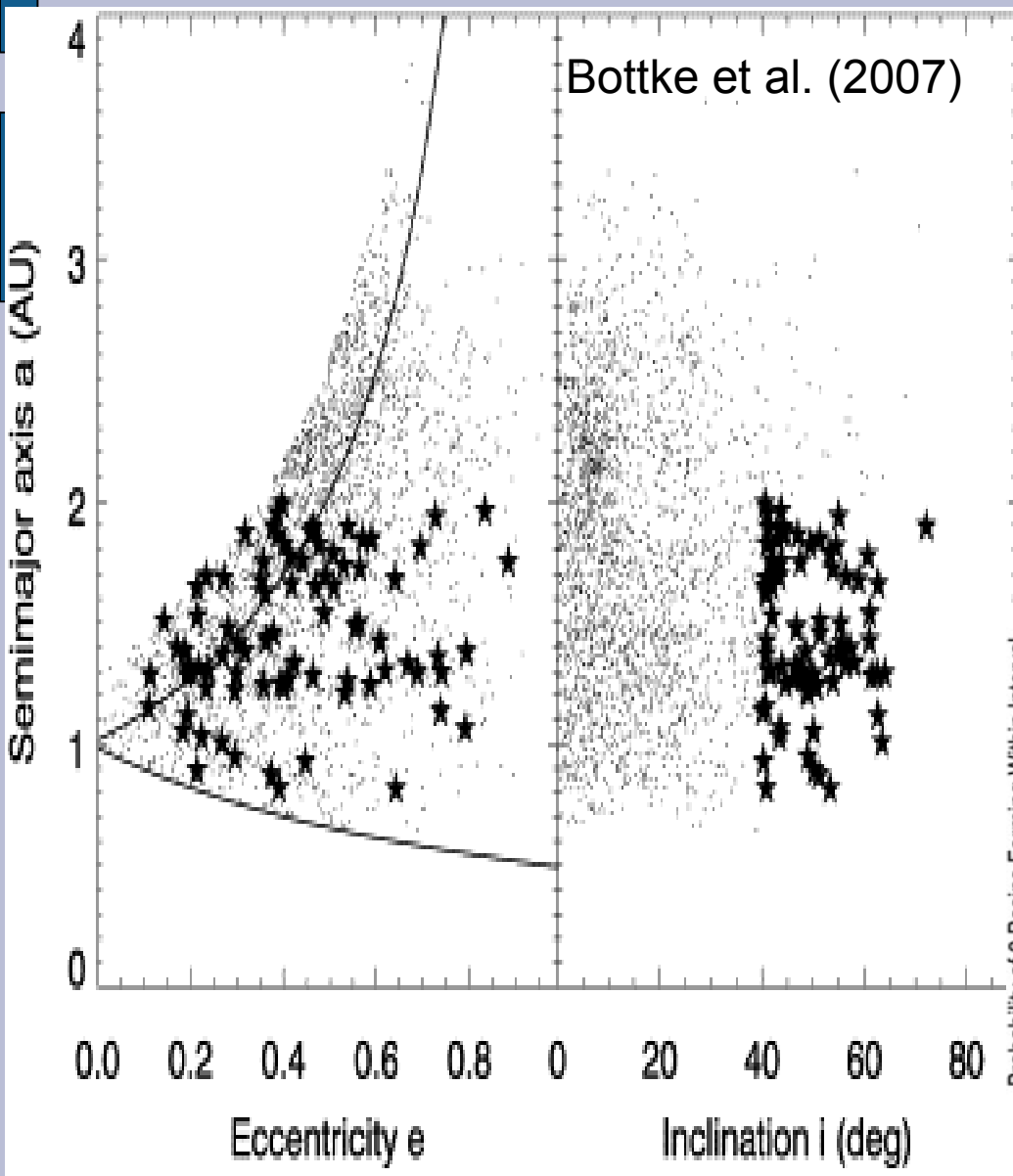


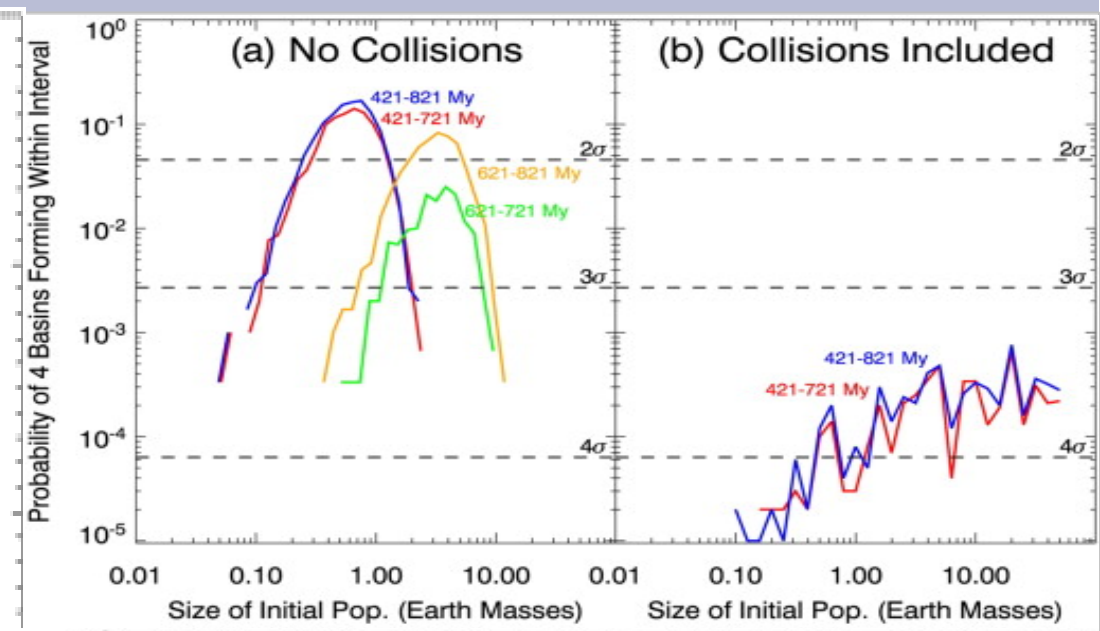
Some evidence for the LHB III

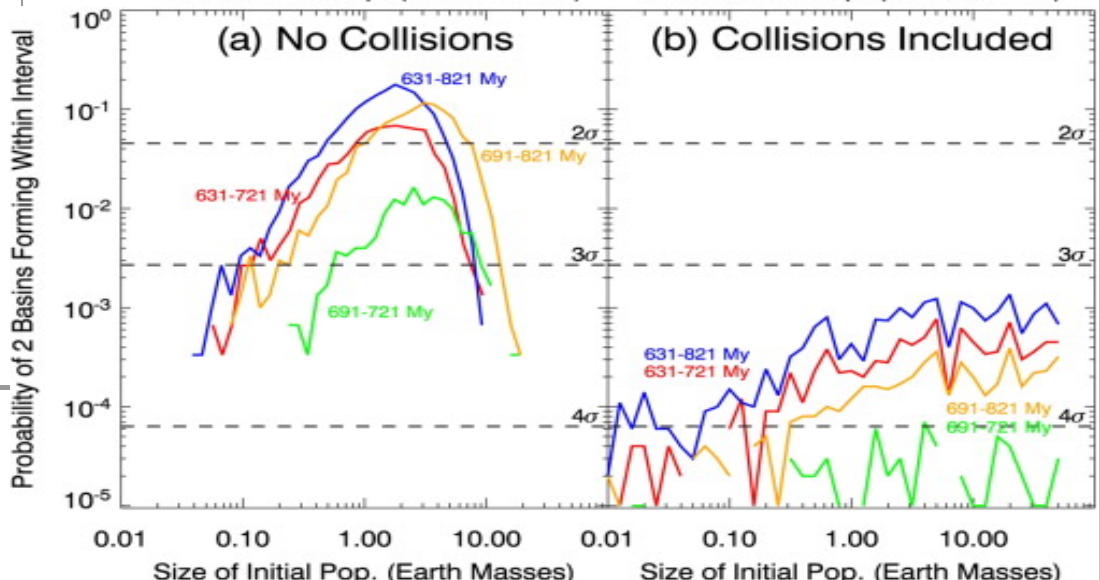
Marchi et al. (2011)



Evidence for the LHB IV







Evidence for the LHB V

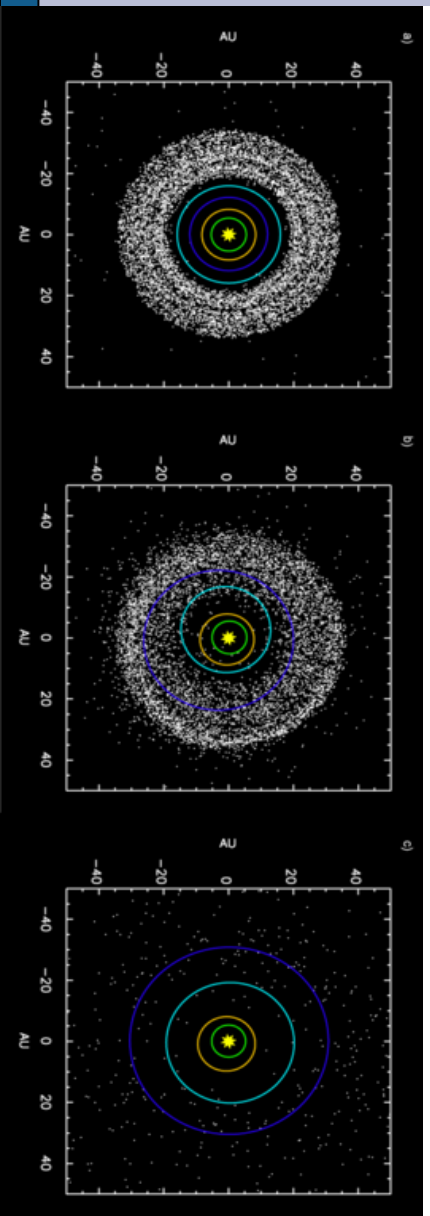
Strom et al (2005): LHB was the last major event that sculpted the Solar System. It was a global event that involved the whole solar system.

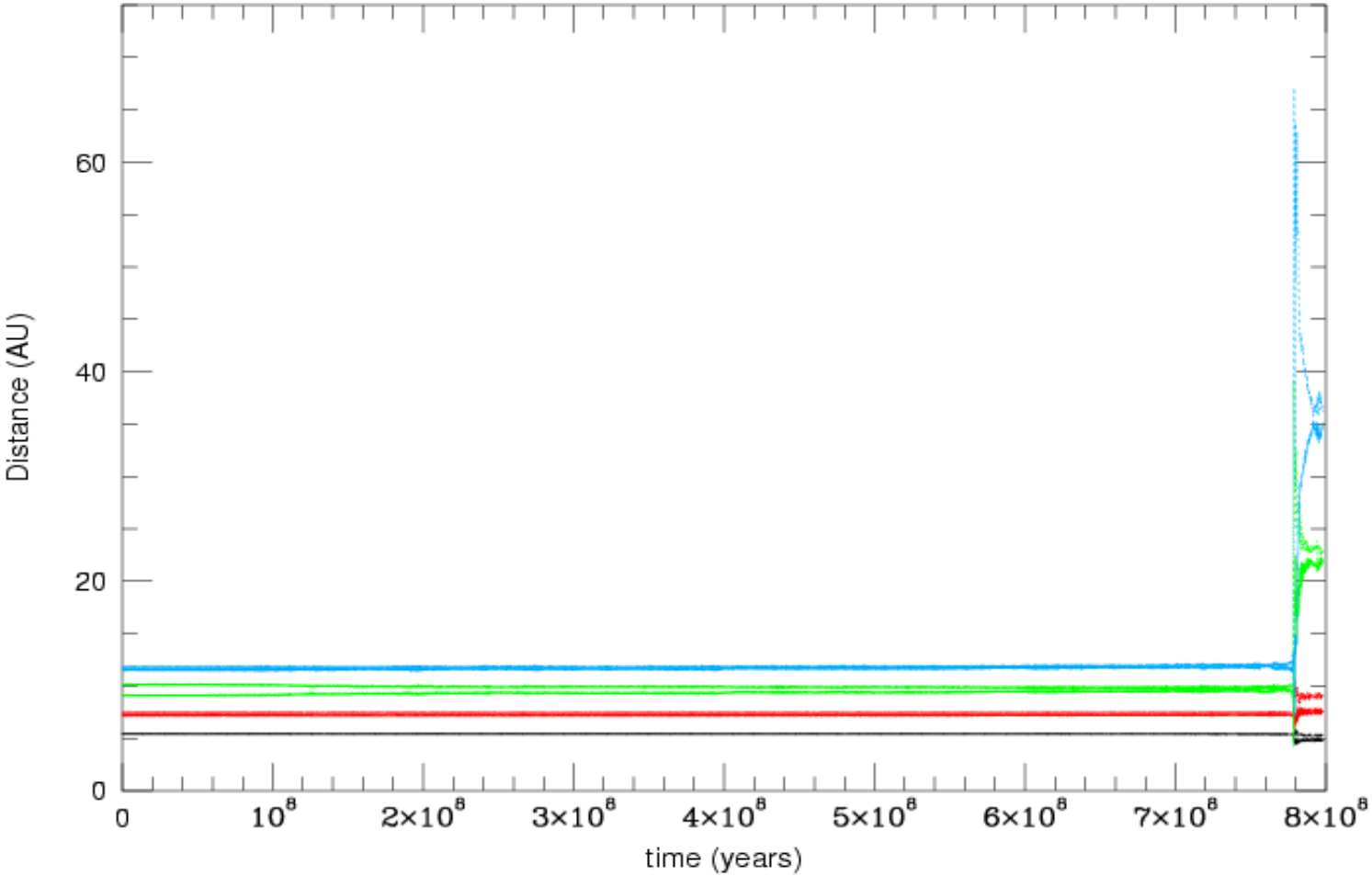
LHB impactors are asteroidal.

What was the most likely cause?

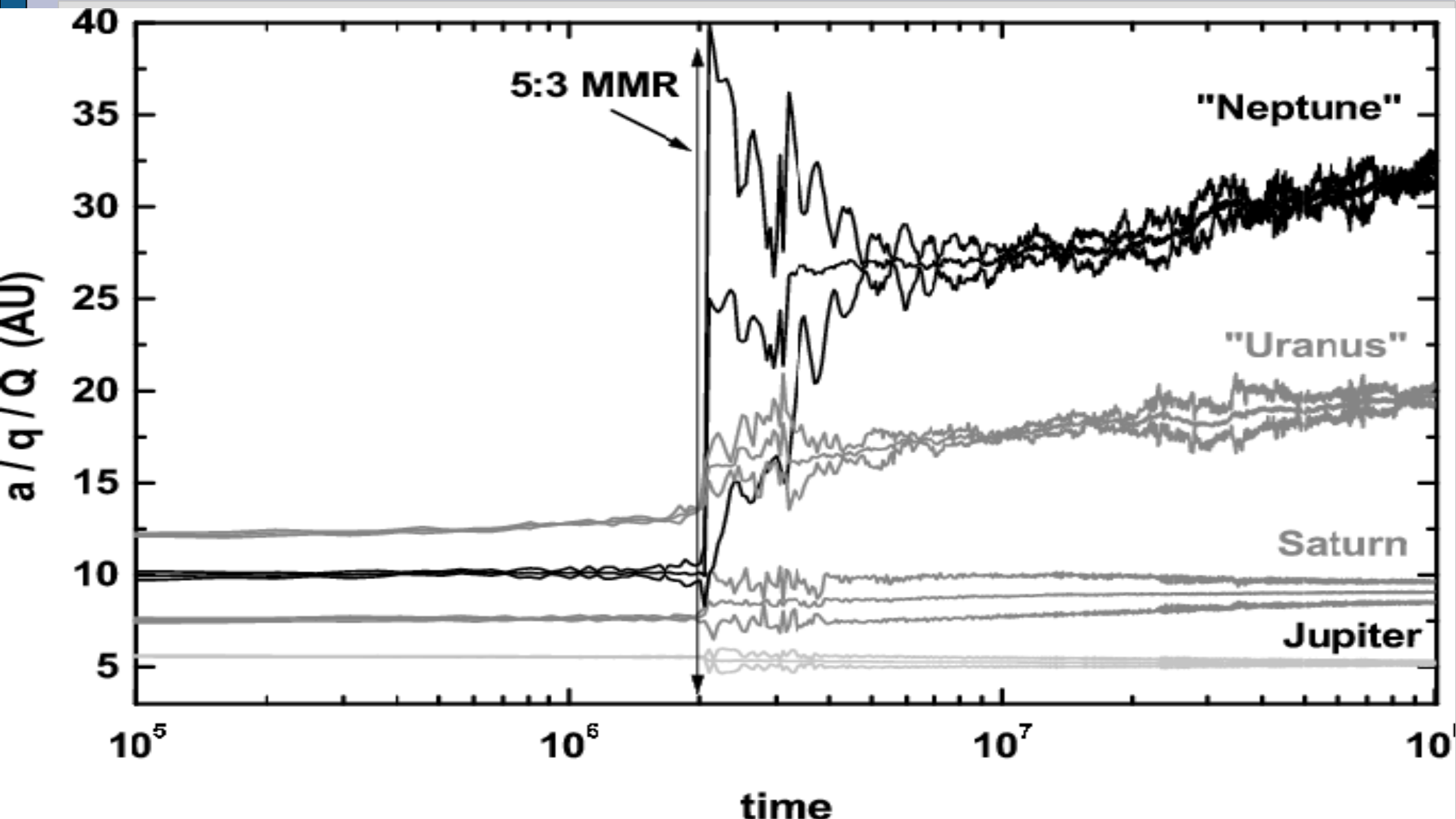
Giant planet scattering and migration.

The Nice model of giant planet instability

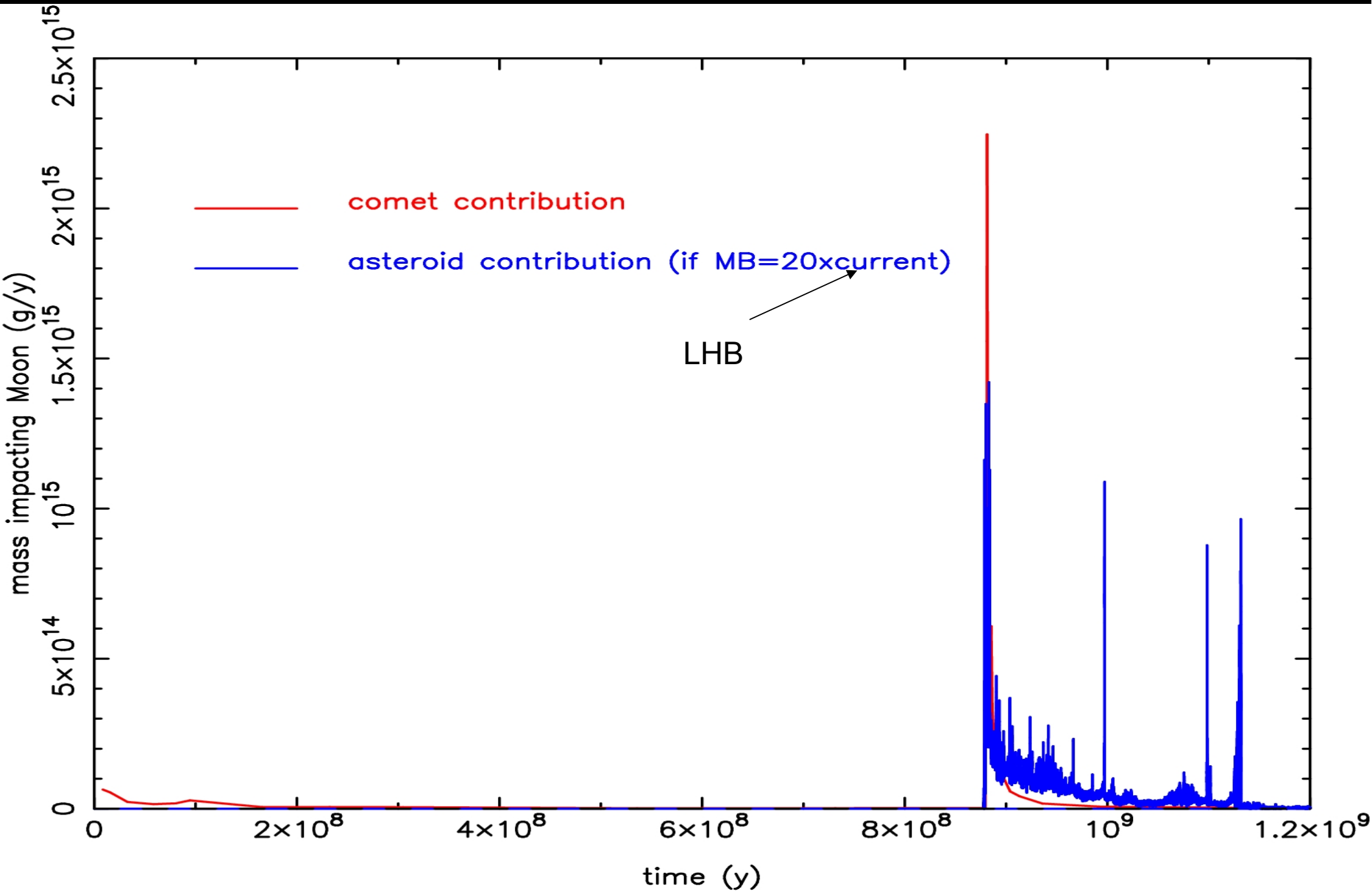




The Nice model II

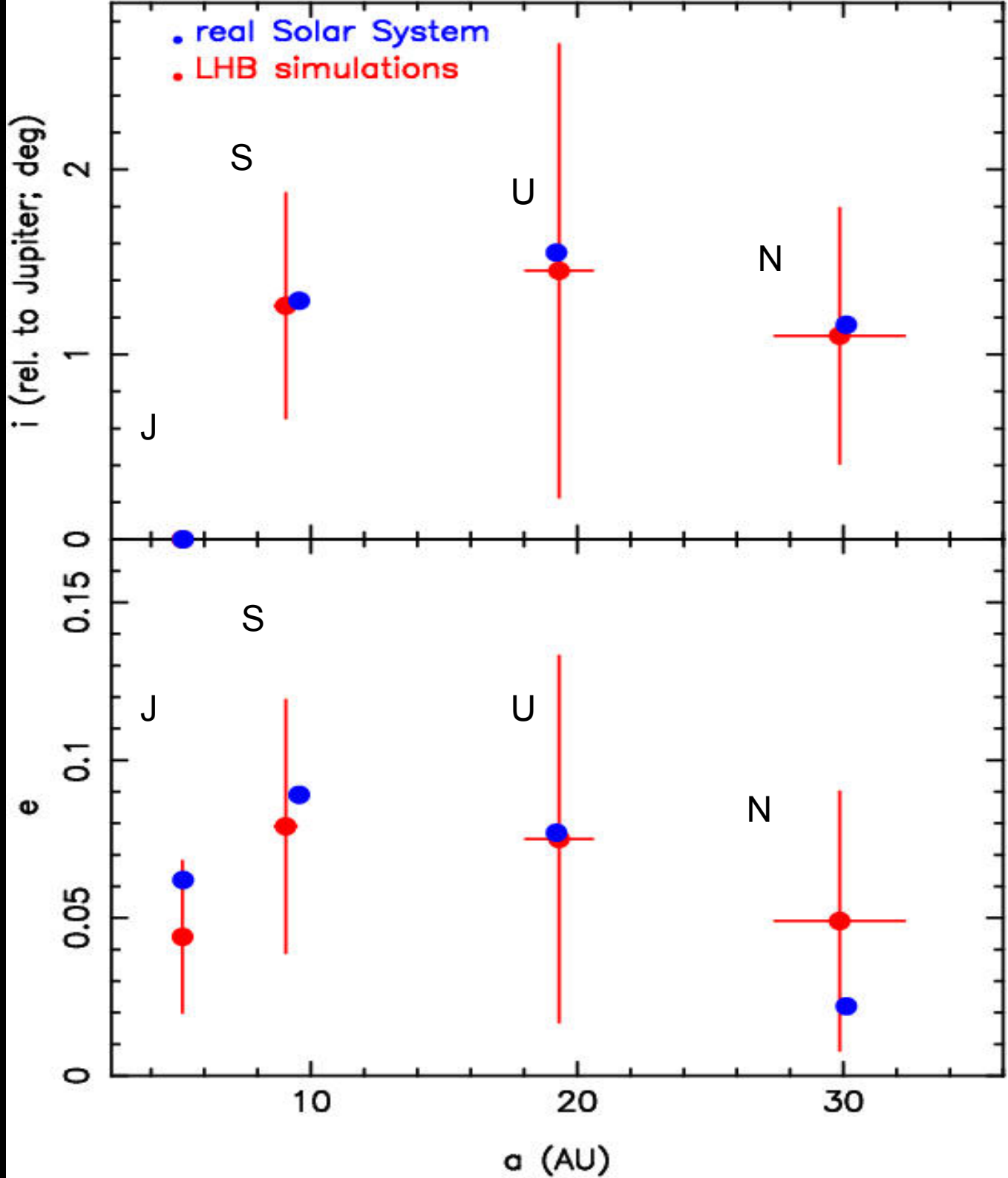


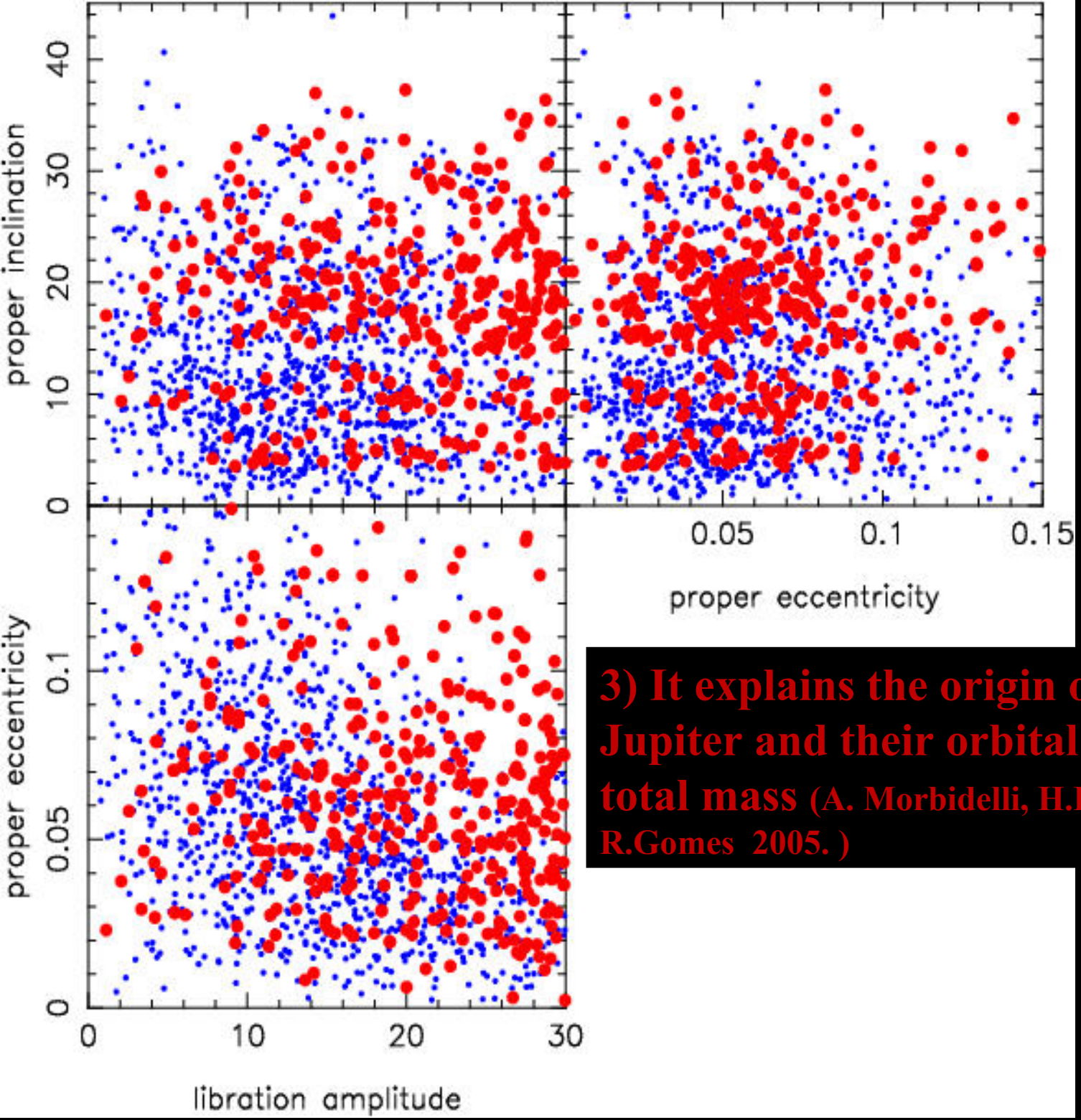
1) It explains the `spike' in the bombardment rate, with good magnitude and duration Gomes, Levison, Tsiganis et Morbidelli, 2005.



2) It explains the current orbits of the giant planets (separation, eccentricities, inclinations) from initially compact, quasi-circular and co-planar orbits

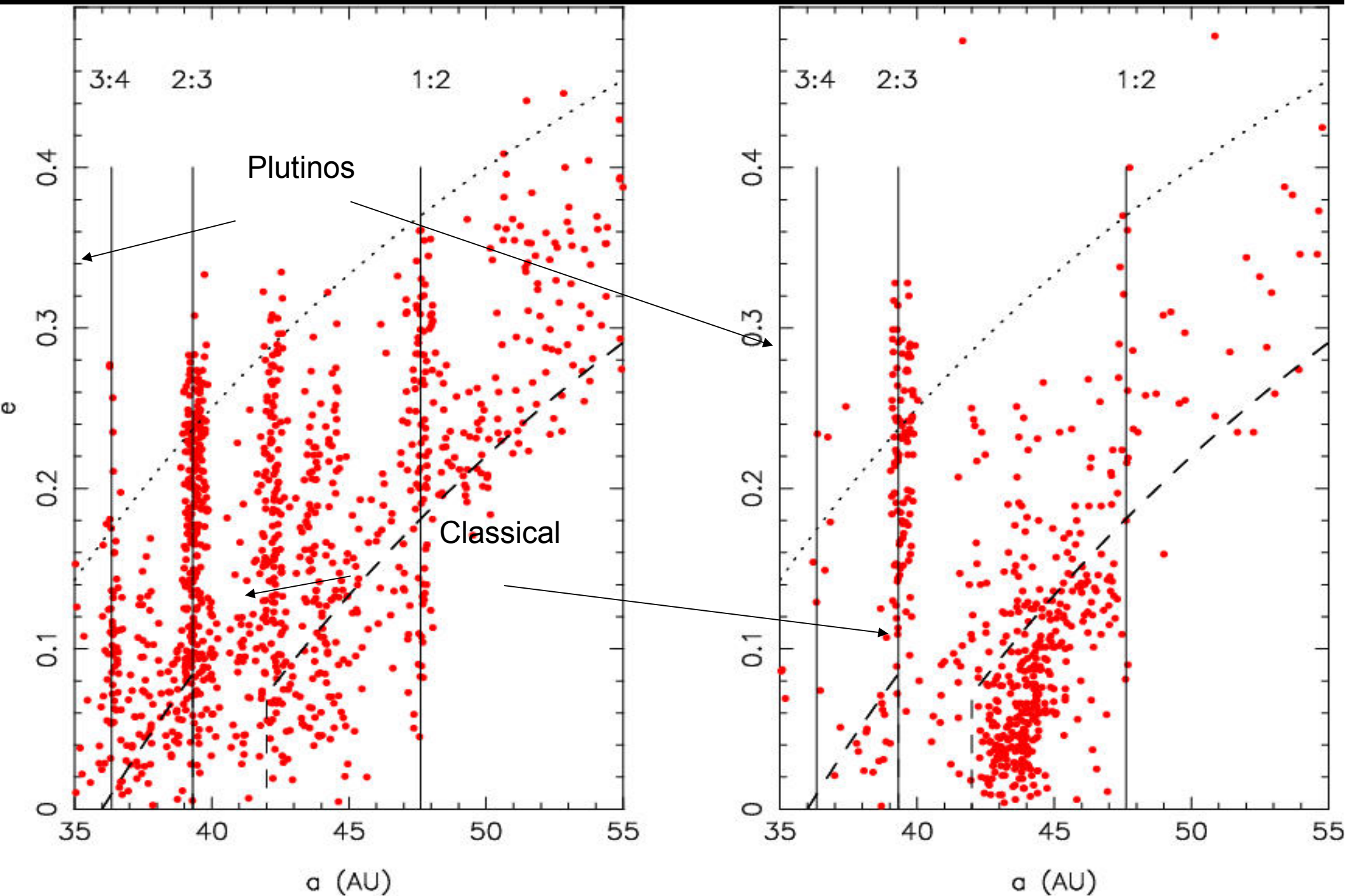
K. Tsiganis, R. Gomes, A. Morbidelli, H.F. Levison 2005.



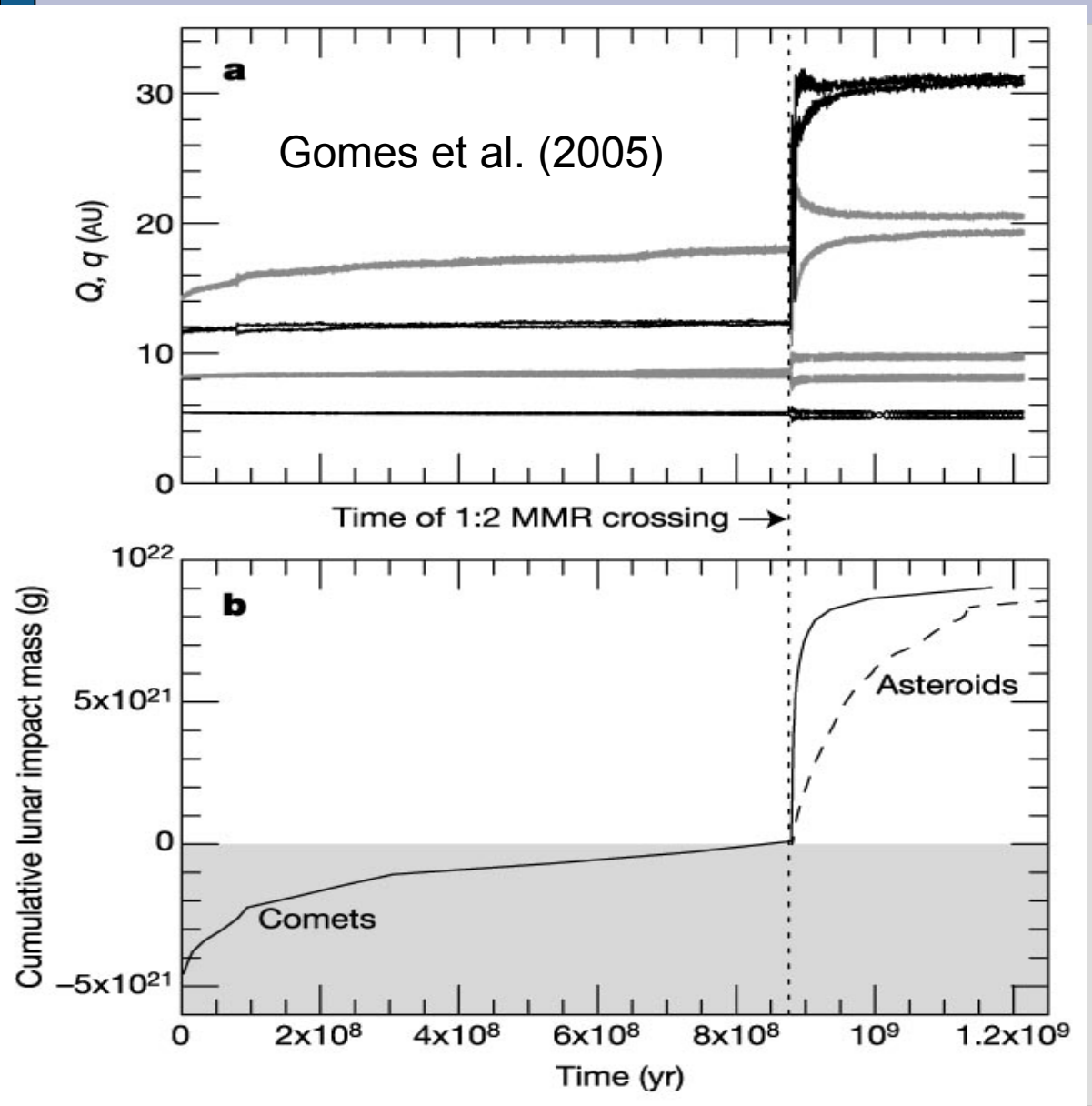


3) It explains the origin of the Trojans of Jupiter and their orbital distribution and total mass (A. Morbidelli, H.Levison, K.Tsiganis, R.Gomes 2005.)

4) It mostly explains the existence, the structure and the small mass of the Kuiper belt (Levison, Morbidelli, Vanlaerhoven, Gomes & Tsiganis 2008)



Demography of impactors

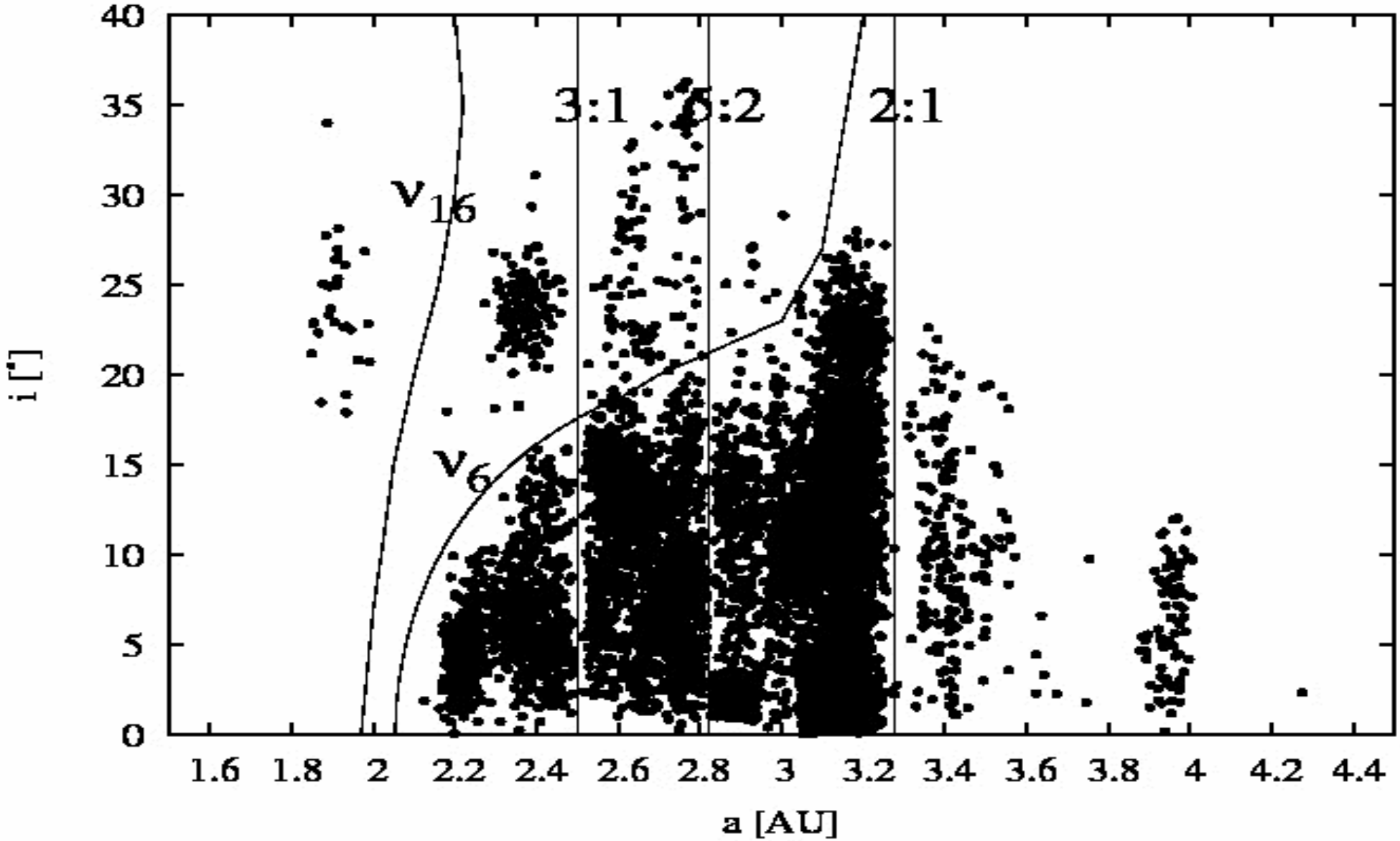


The Nice model predicts the far majority of the impactors on the Moon to be cometary in nature.

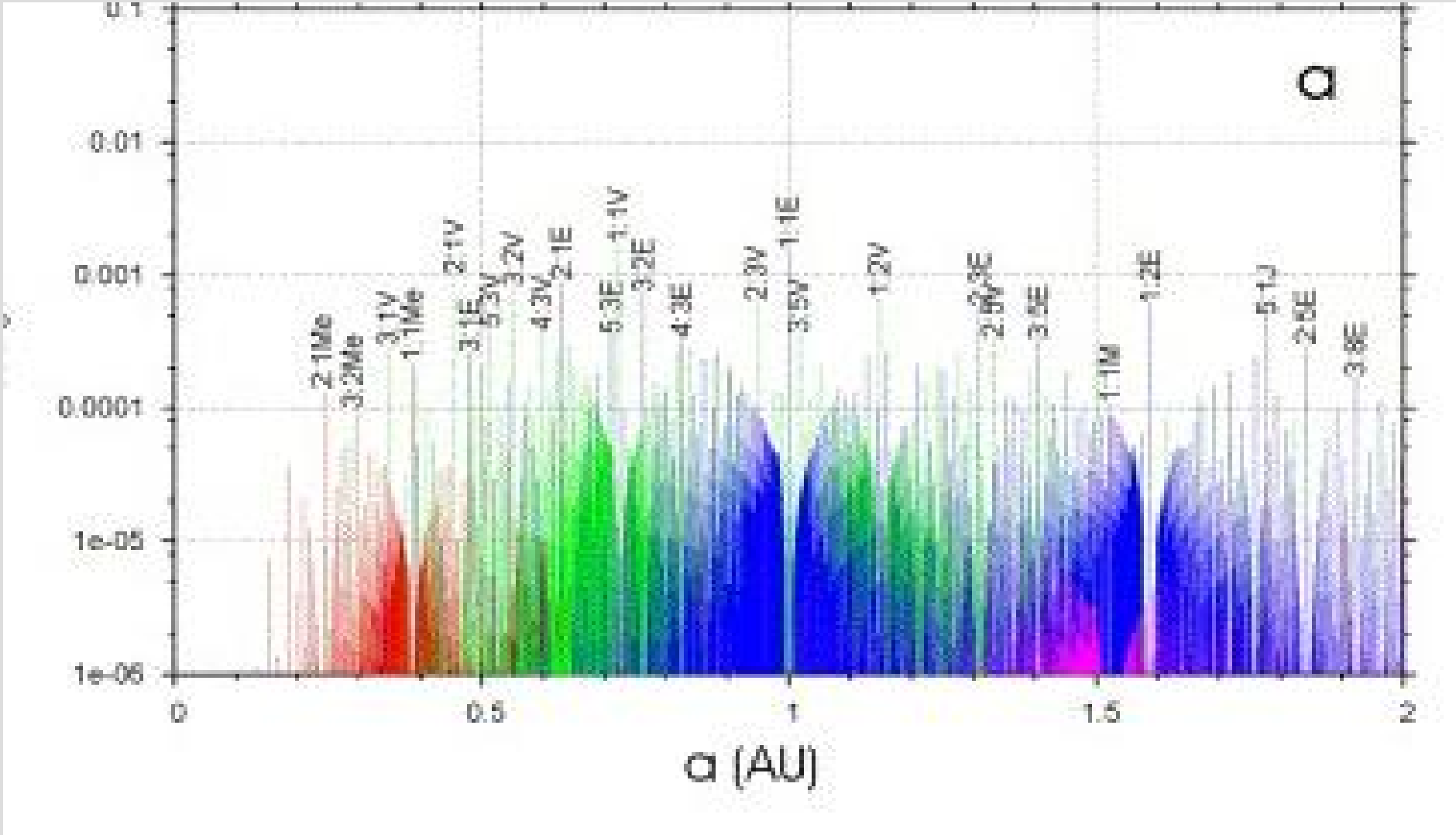
Yet there is little to no evidence for cometary impacts to have occurred (Bottke et al., 2012). Most impacts are asteroidal.

We need a new source: The now-empty E-belt asteroid belt.

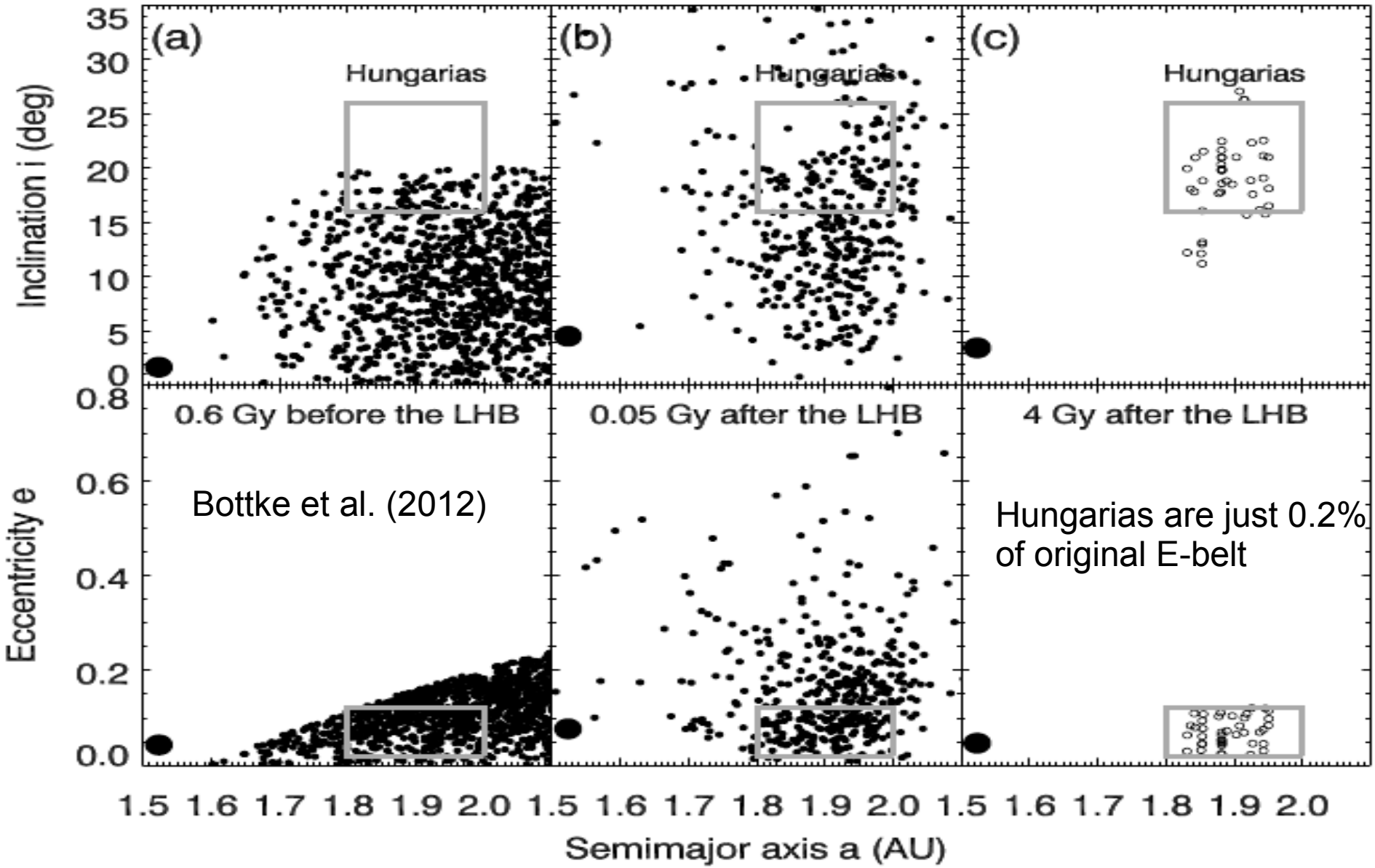
Orbital distribution of the asteroid belt



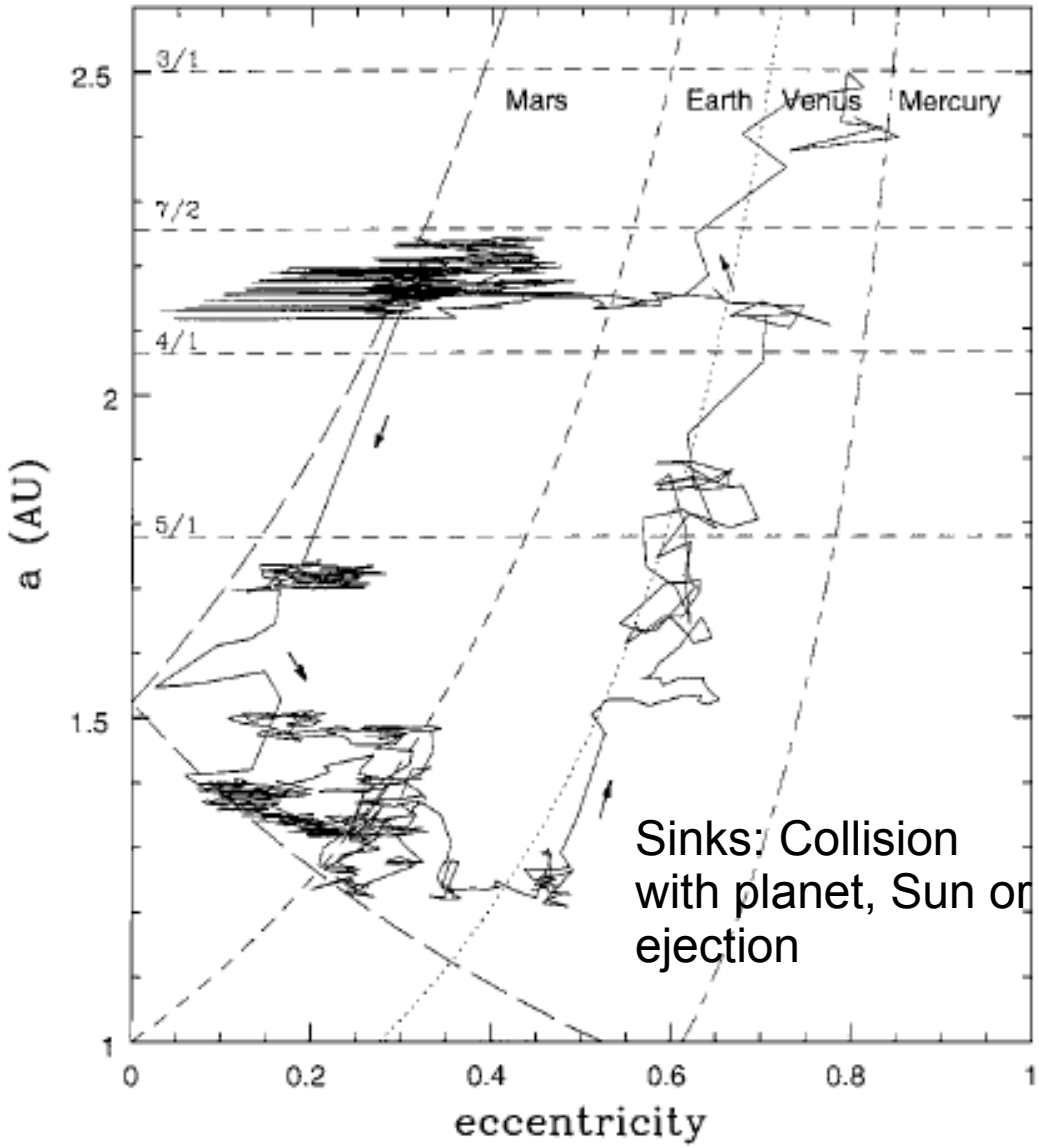
Instability of the E-belt

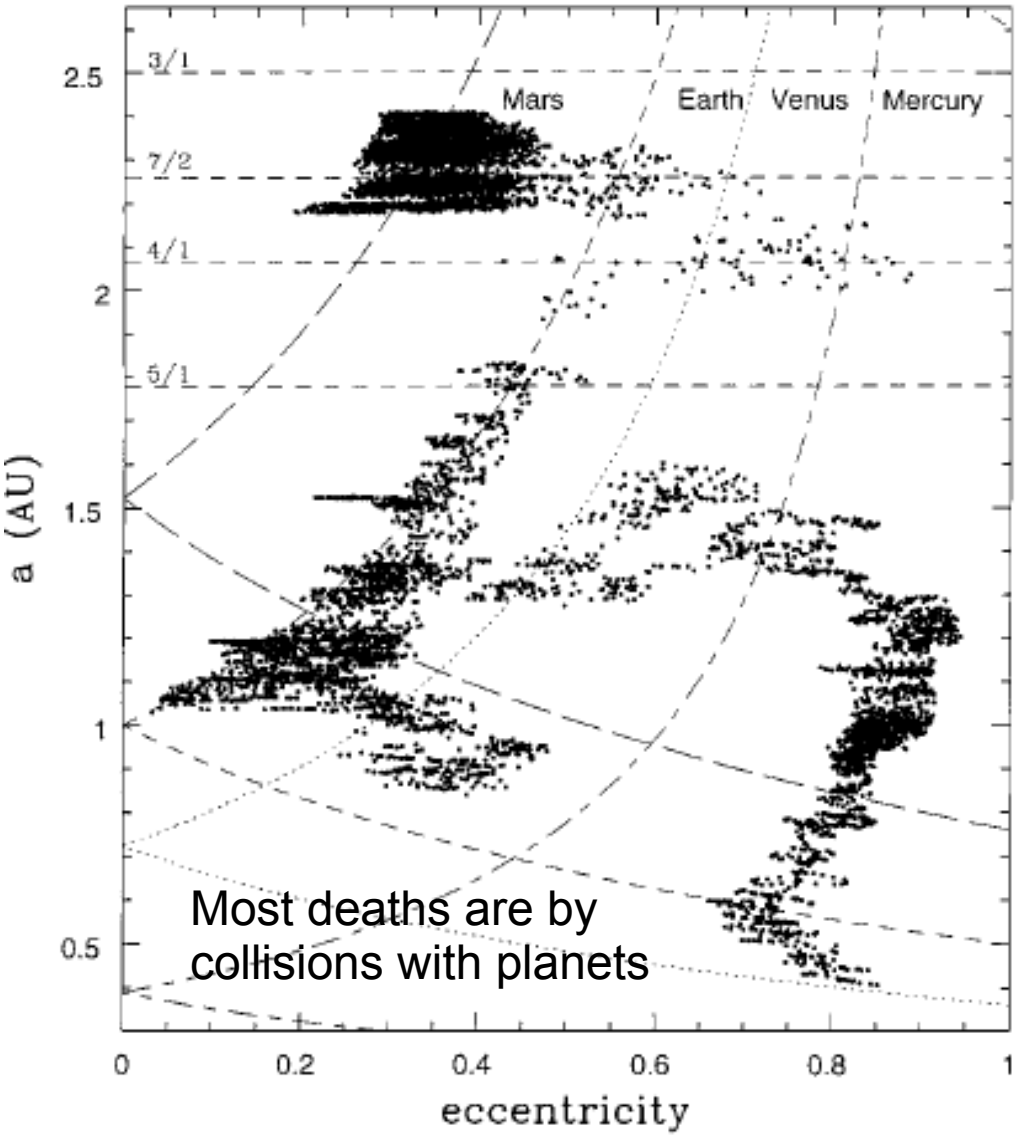


The Great Archaean Bombardment



Dynamical evolution of NEAs





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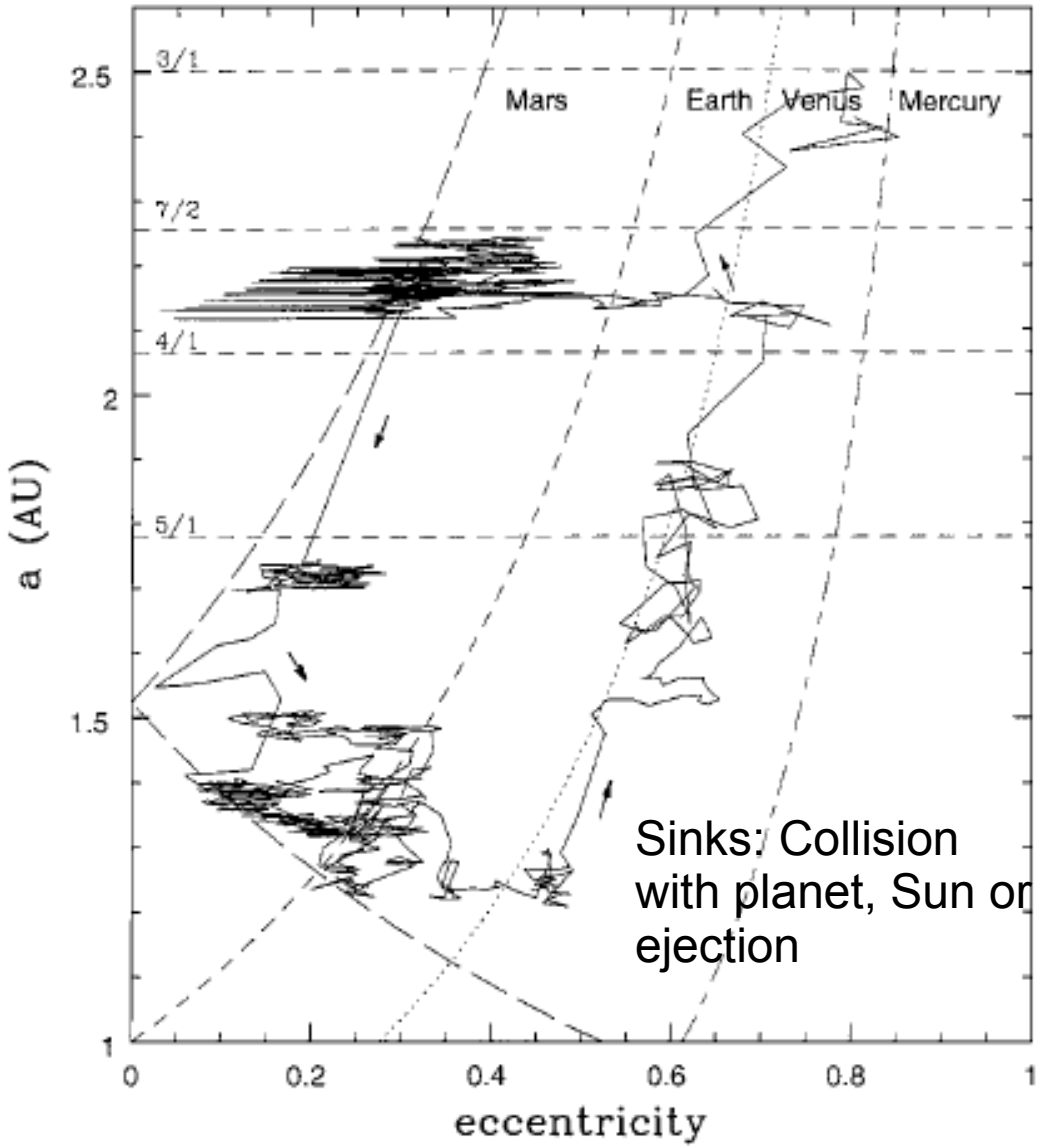
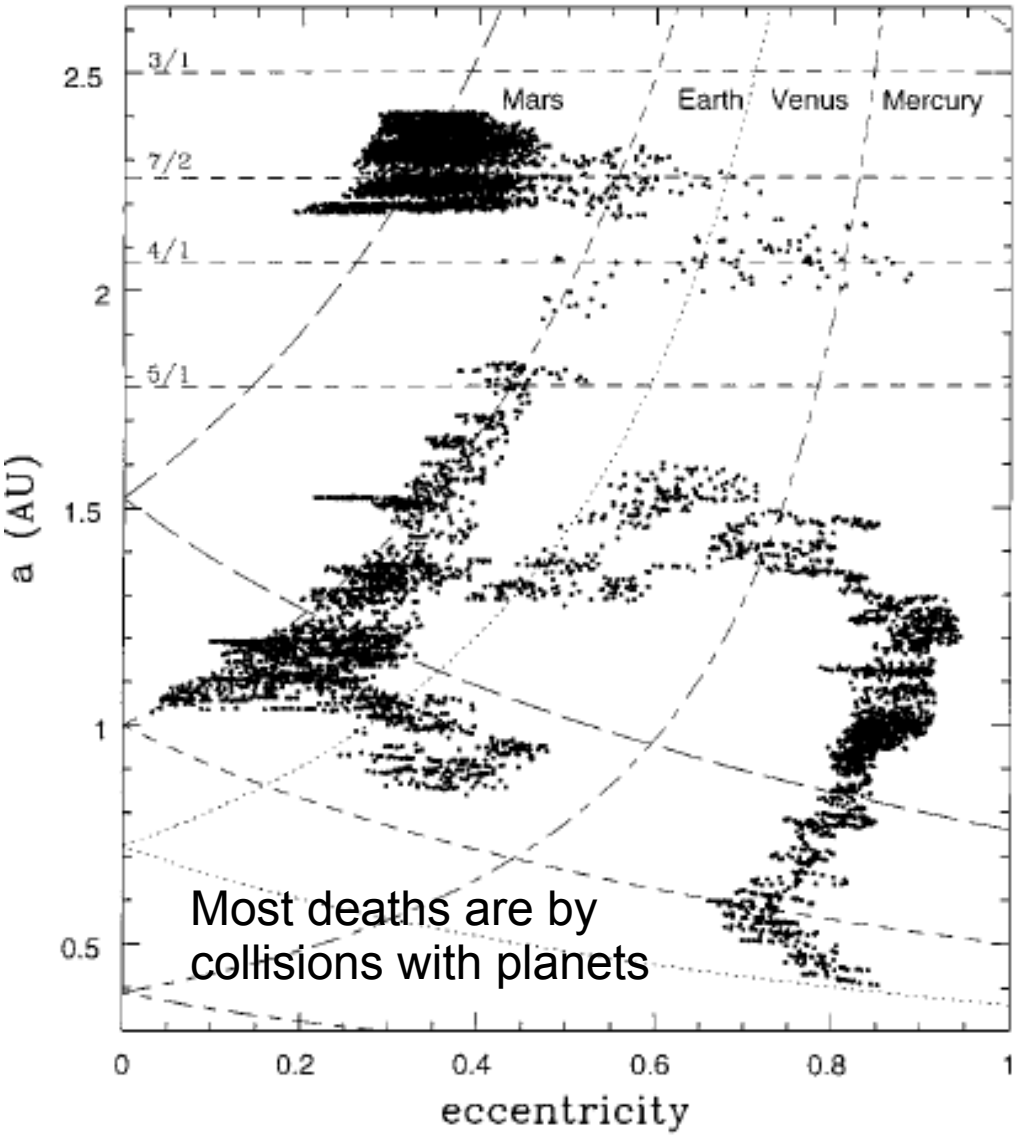
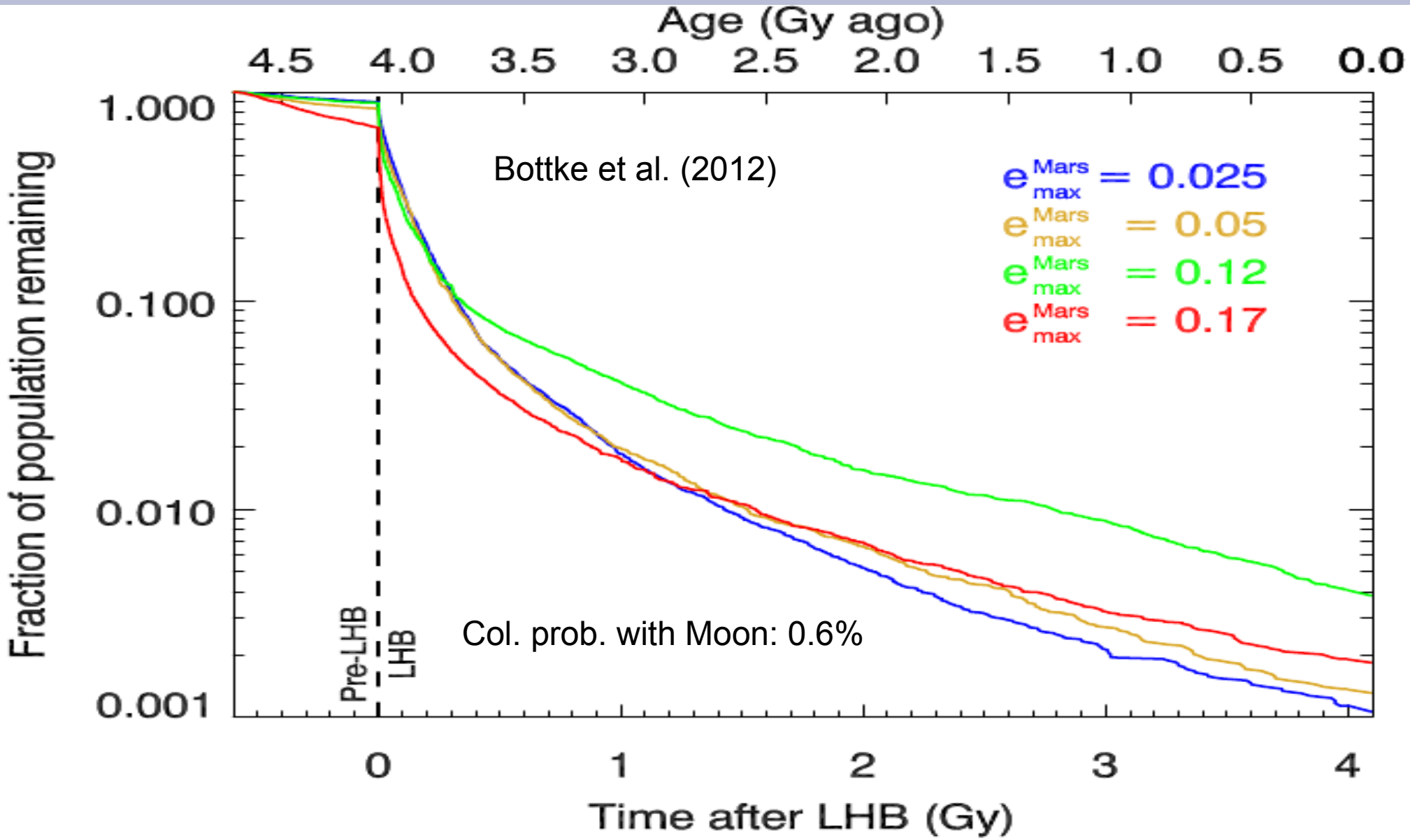
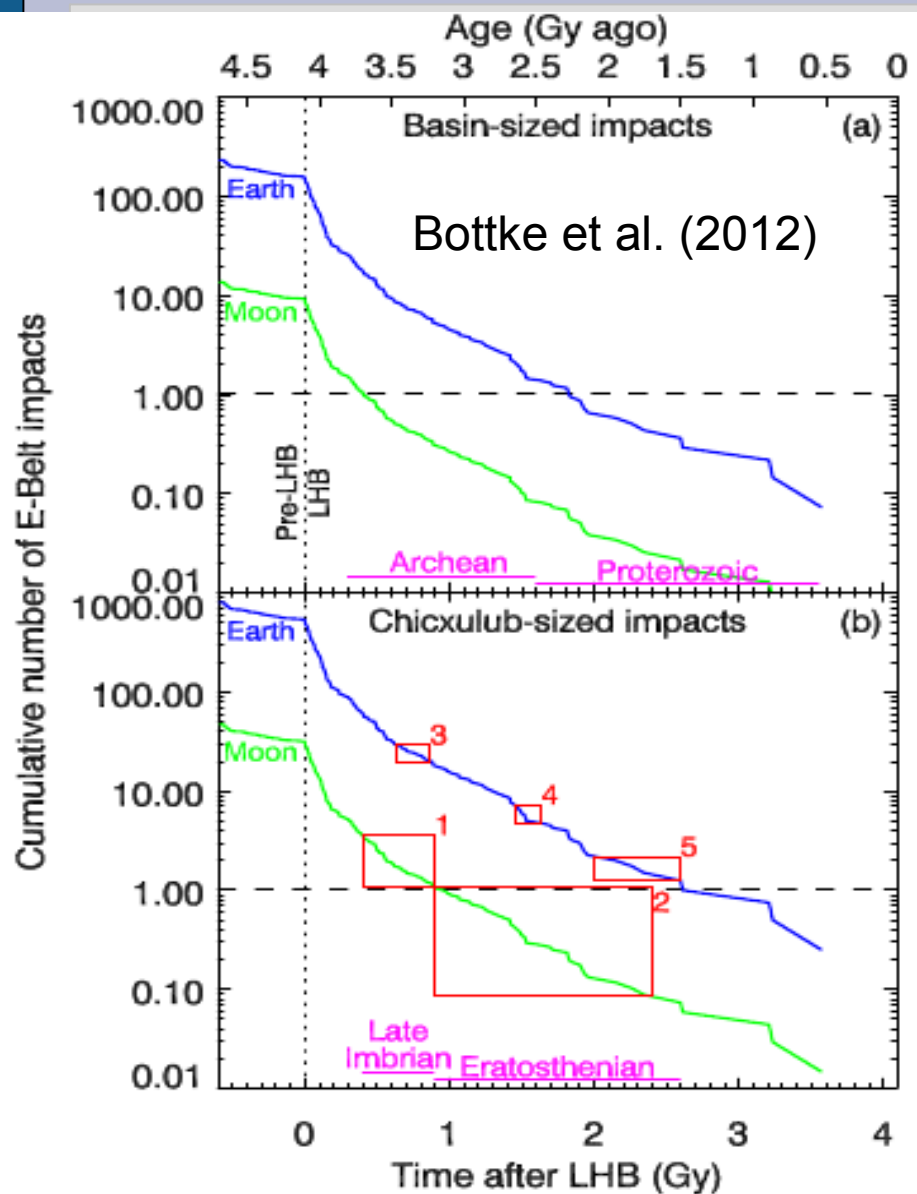




The Great Archaean Bombardment II



The Great Archaean Bombardment III



The E-belt model produces approximately 10-12 basins (craters with D>300 km) on the Moon, in accordance with previous estimates. It also produces approximately 100 to 200 on the Earth.

The LHB ceases to affect the Moon after about 300 Myr but it lasts for a total of 1.5 Gyr on the Earth! Thus the LHB's last gasp on Earth occurred just 2.5 Gyr ago!!

The number of Chicxulub-sized craters – the one that wiped out the dinosaurs – is of the order of 80 on the Moon and close to 1000 on the Earth. Impacts of this size continued until about 1 Gyr ago on the Earth.

Nectaris basin (age 4.1 Ga) may have coincided with the onset of the LHB, and not Imbrium or Orientale (ages ~ 3.9 Ga and 3.75 Ga).

Impact velocities of projectiles with Moon before and during LHB

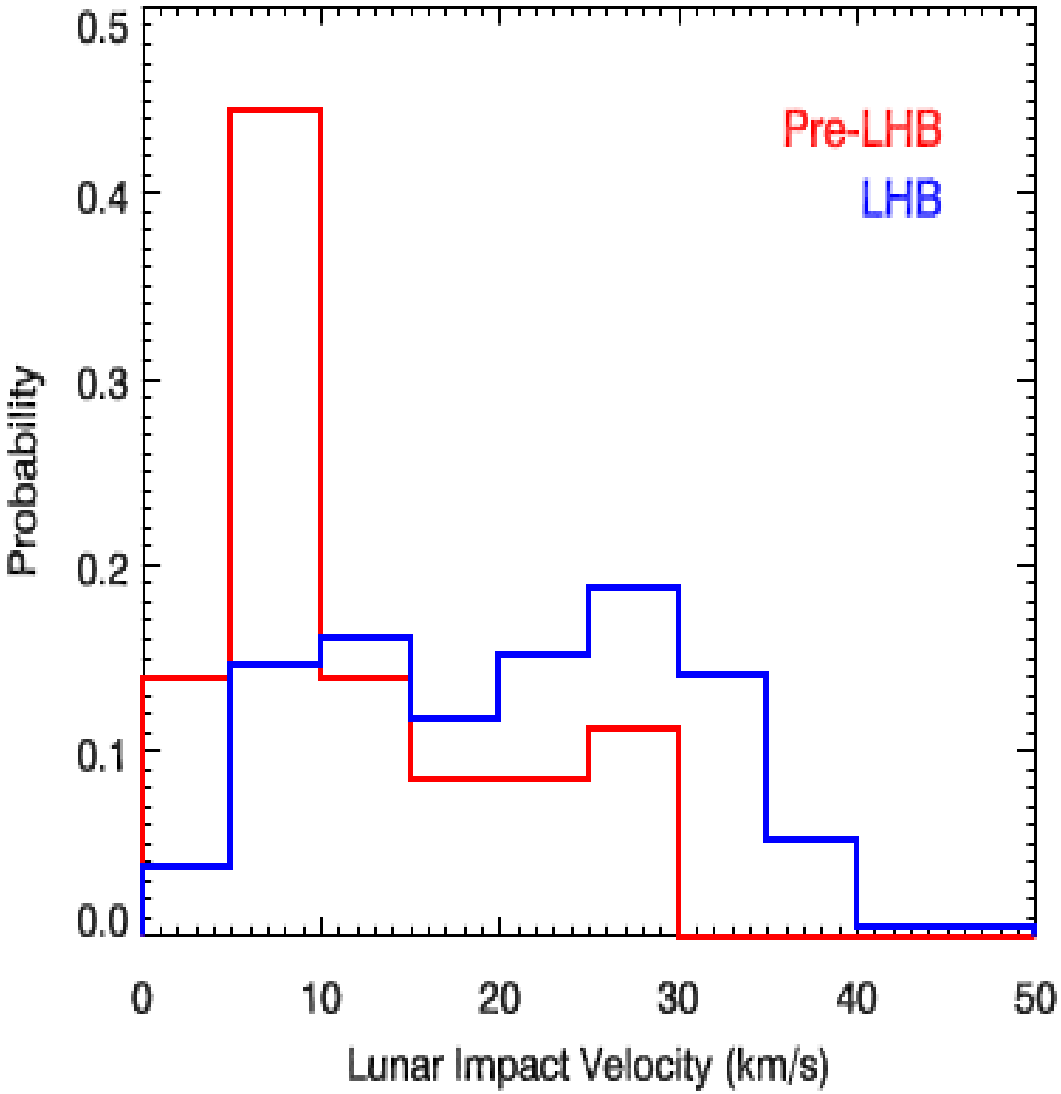


Figure S 1: The impact velocity distribution of E-belt asteroids on the Moon. They were calculated from the orbital parameters of the test bodies that struck in the Earth in the combined $e_{\mathrm{max}}^{\mathrm{Mars}}$ = 0.025, 0.05, 0.12, and 0.17 runs. No significant changes were seen between the runs. The velocity distribution for the pre-LHB-era was based on 36 impact events, while the LHB-era was based on 213 events. The mean and median velocities at in the Pre-LHB were V = 11.9 ± 8.1 and 8.6 km s^{-1}, while those for the LHB were V = 20.7 ± 9.8 and 20.9 km s^{-1}.

Total lunar cratering

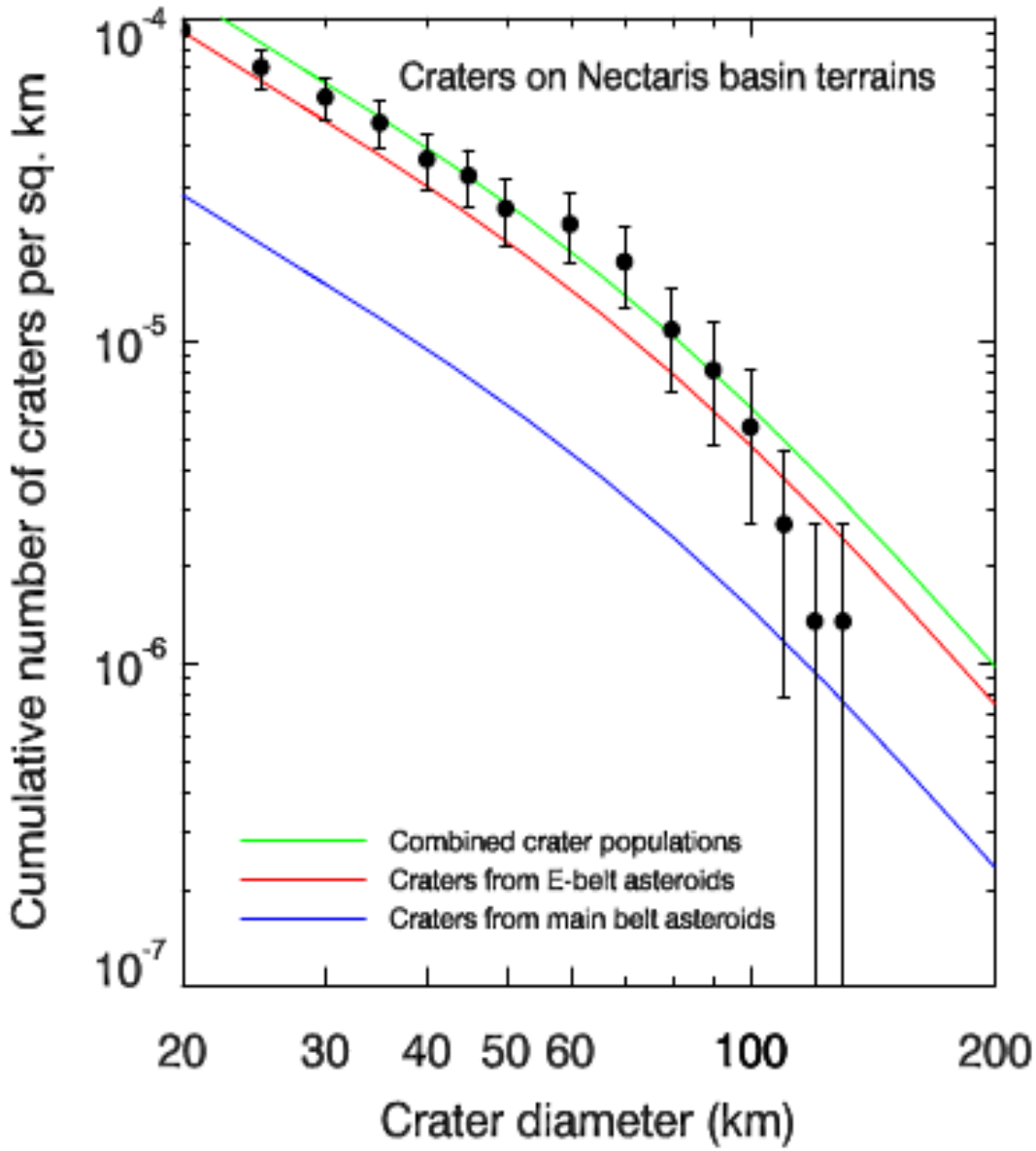


Figure S 2: A comparison between observed and model craters formed on terrains affected by Nectaris basin, which may have formed close to the start of the LHB. The black points represent craters counted using Lunar Orbiter Laser Altimeter data (see [26] for details). The model craters come from the E-belt (red curve) and main belt (blue curve). The green curve shows both populations combined together.

Further support for the E-belt model

Other advantages of the E-belt model:

a) The inferred mass of the E-belt is compatible with the currently-known density distribution of the asteroid belt → No need to invoke a ridiculously heavy belt or skewed density distribution.

b) The E-belt favours a low-eccentricty pre-LHB Mars, consistent with terrestrial planet formation simulations and planet migration simulations.

Conclusions

The LHB was an intense cratering of the terrestrial planets and the Moon that occurred between 3.8 and 4.1 Gyr ago.

The most likely trigger for the onset of the LHB was a dynamical instability in the outer solar system which made the giant planets scatter each other.

The eccentric giant planets and the appearance of secular resonances at 2 AU destabilised the E-belt, which is now empty.

This population was sent to the inner solar system and bombarded the terrestrial planets.

The number of basins that formed on the Moon during this epoch are consistent with observations without invoking an unusually massive E-belt or strange density profile of the asteroid belt.

The LHB lasted on Earth for about 1.5 Gyr and only ended early during the Proterozoic aeon, lasting all through the Archaean.