Tidal-driven remelting of the Moon, 4.35Gy ago

A. Morbidelli (Collège de France)
F. Nimmo (UC, Santa Cruz)
T. Kleine (Max Planck Institute, Gottingen)

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THE HIGH-ECCENTRICITY LIBRATION OF THE HILDAS

S. FERRAZ-MELLO
Instituto Astronomico e Geofisico, Universidade de Sao Paulo, Sao Paulo, Brazil
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ABSTRACT

The analytical modeling of the planar motion of high-eccentricity asteroids near first-order resonances leads to three approximative laws: the law of structure relating the semimajor axis and the eccentricity at the libration centers, the law of periods giving the proper periods about the libration centers, and the law of the second forced mode giving the amplitude of the oscillation induced by the eccentricity of Jupiter. The law of structure shows the existence of a forbidden interval in the distribution of the mean semimajor axes at 0.763–0.773 (3.97–4.02 AU). However, the existence of asteroids whose osculating semimajor axis is in that interval is not excluded. The law of structure just prevents the asteroids from remaining there stationarily. This structural gap can be crossed and at any time some 15 of the presently known Hildas will be incursioning in it, some of them crossing it completely. The group appearance of the Hildas is due to the nonexistence of apocentric librators or inner circulators among them. In the case of the resonance 2:1, both groups exist, one on each side of the forbidden interval.

Article

Tidally driven remelting around 4.35 billion years ago indicates the Moon is old

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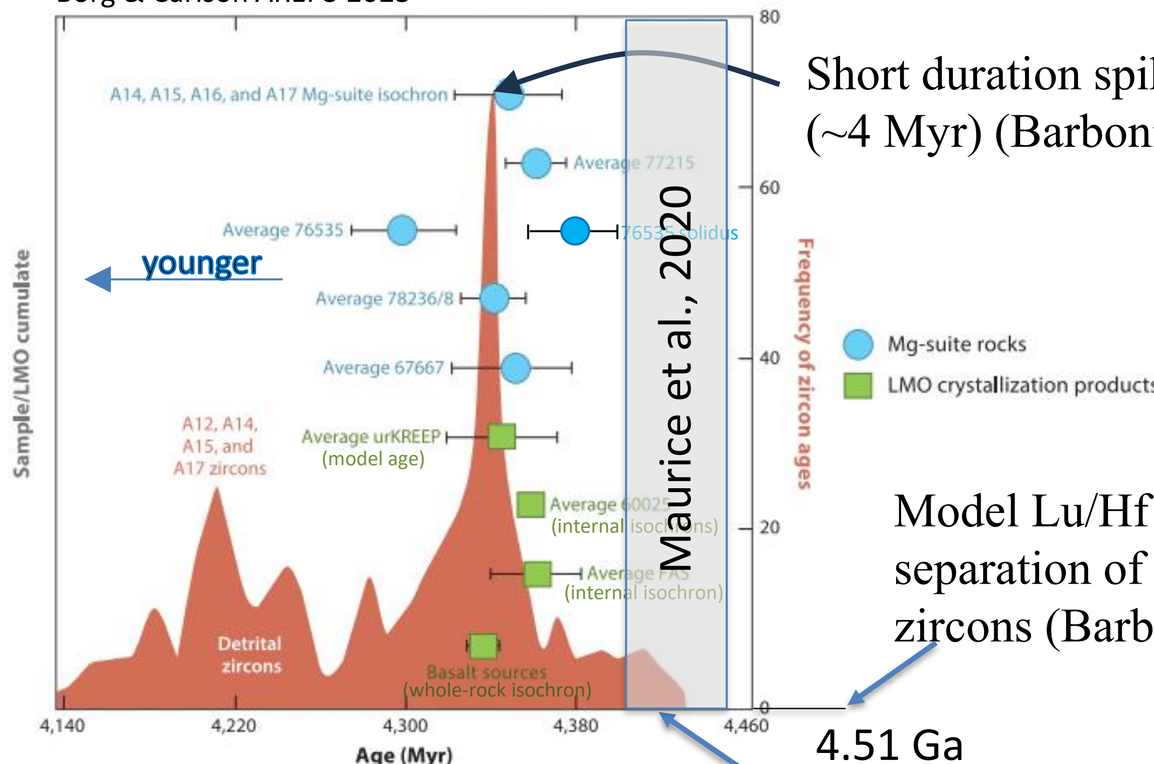
Francis Nimmo[1]✉, Thorsten Kleine[2] & Alessandro Morbidelli[3,4]

The last giant impact on Earth is thought to have formed the Moon[1]. The timing of this event can be determined by dating the different rocks assumed to have crystallized from the lunar magma ocean (LMO). This has led to a wide range of estimates for the age of the Moon between 4.35 and 4.51 billion years ago (Ga), depending on whether ages for lunar whole-rock samples[2–4] or individual zircon grains[5–7] are used. Here

The Moon has a cluster of ages around 4.36 Ga

Borg & Carlson *AREPS* 2023



Short duration spike (~4 Myr) (Barboni et al. 2024)

Model Lu/Hf age of separation of parent melt of zircons (Barboni et al., 2017)

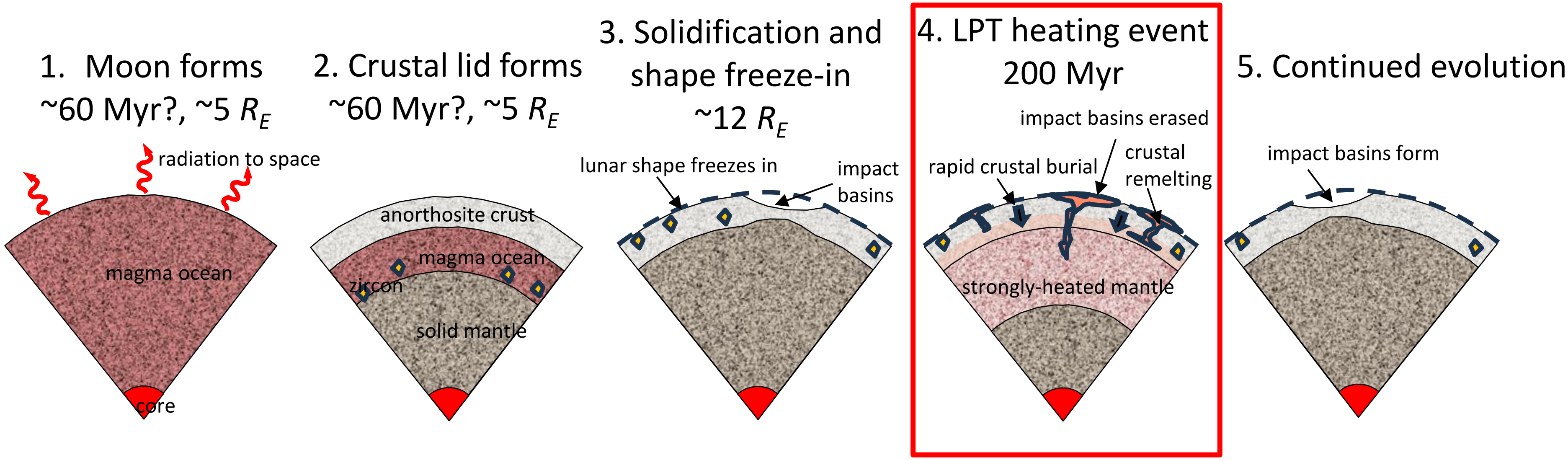
4.51 Ga

A handful of ancient zircons (>4.4 Ga) U-Pb ages

4.35Gy: HSE retention age (Morbidelli et al., 2018)

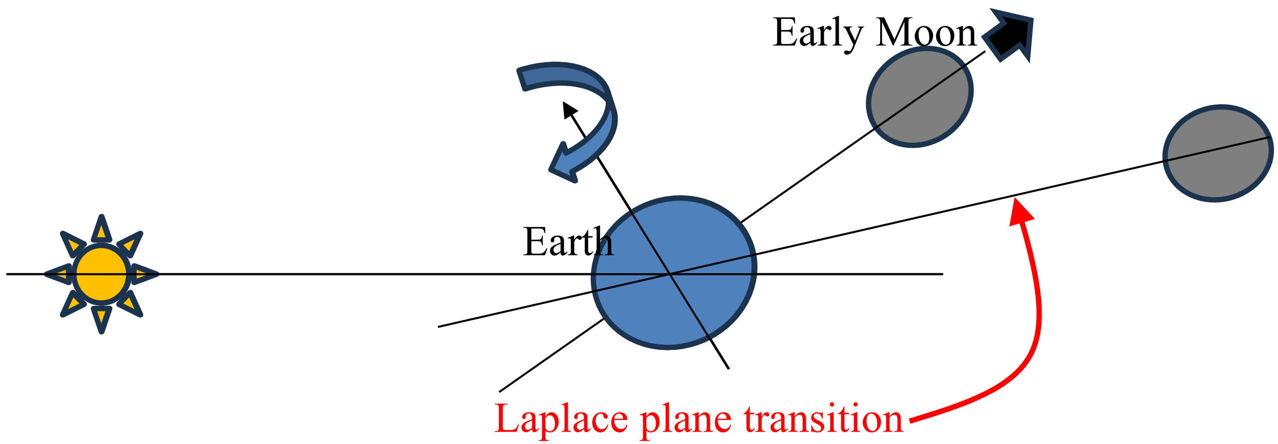
4.35Gy: crater/basin retention age (Nesvorny et al. , 2023)

Hypothetical scenario



“Laplace Plane Transition”
at 4.36 Ga (~19 R_E)

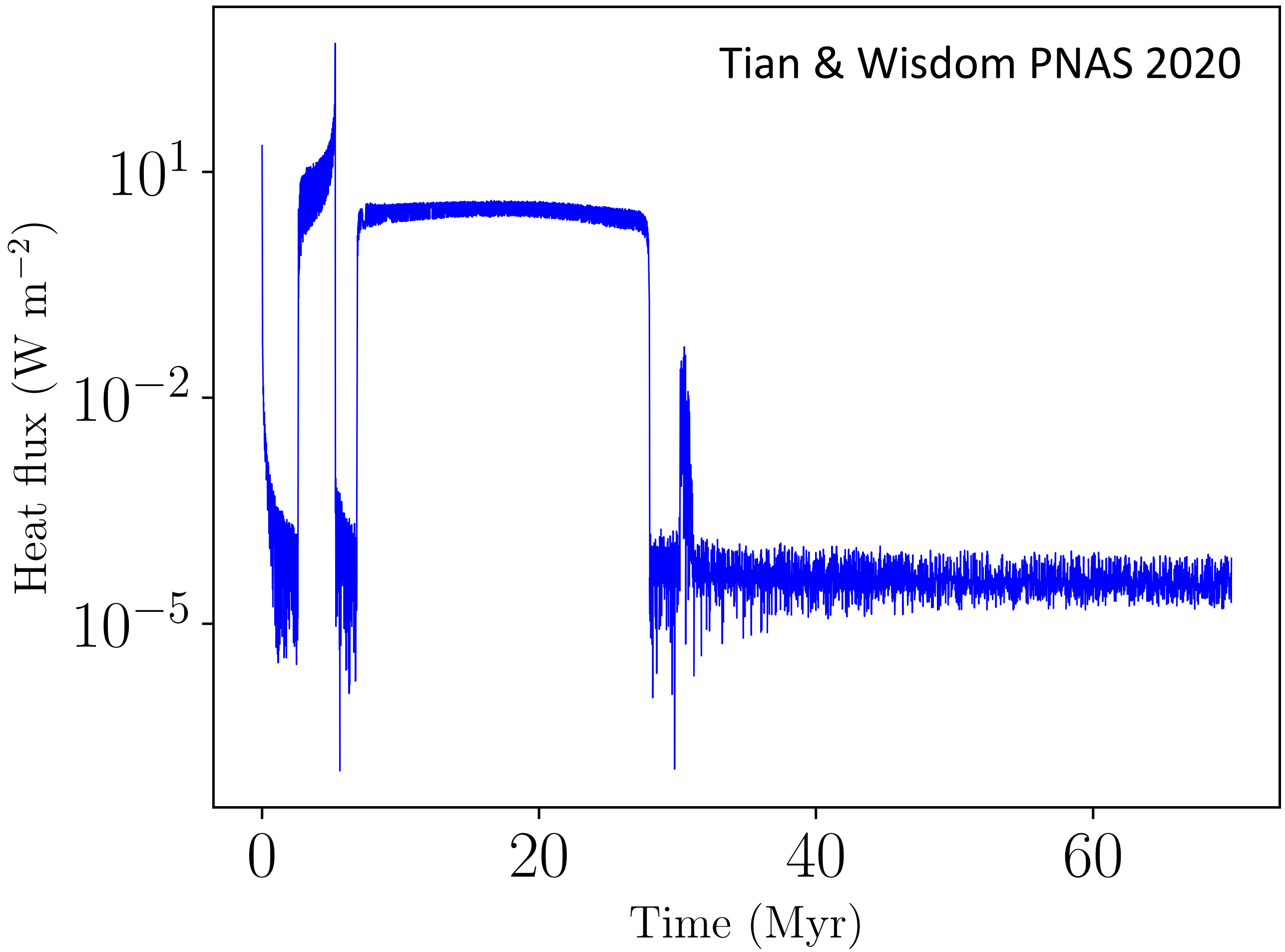
Tidal heating and the Laplace Plane Transition



(Occurs at ~19 R_E, lasts for a few to a few tens of million years)

"Tidal heating in the Moon reaches **10^{14}–10^{15} W** (3-30 Wm^{-2}). . . the lunar crust would contain the signal of major thermal events that occurred tens of millions of years after lunar accretion; thus, the **Laplace plane transition should be considered when interpreting the geochronology of lunar samples**." (Cuk et al. 2016)

Numerical model of LPT



See also Cuk et al. PSJ 2021

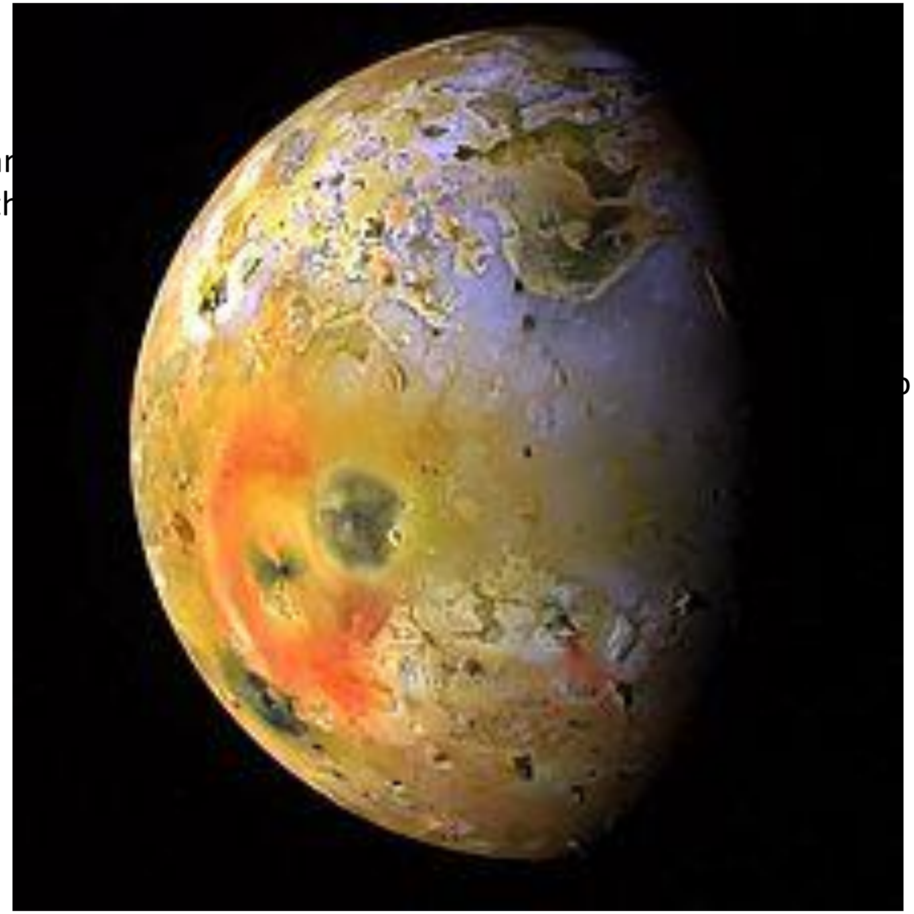
Massive tidal heating on the Moon?

- Tidal heating during the LPT: 3-30 Wm^{-2}!
  - Io generates 2 Wm^{-2}

buoyar
anorth

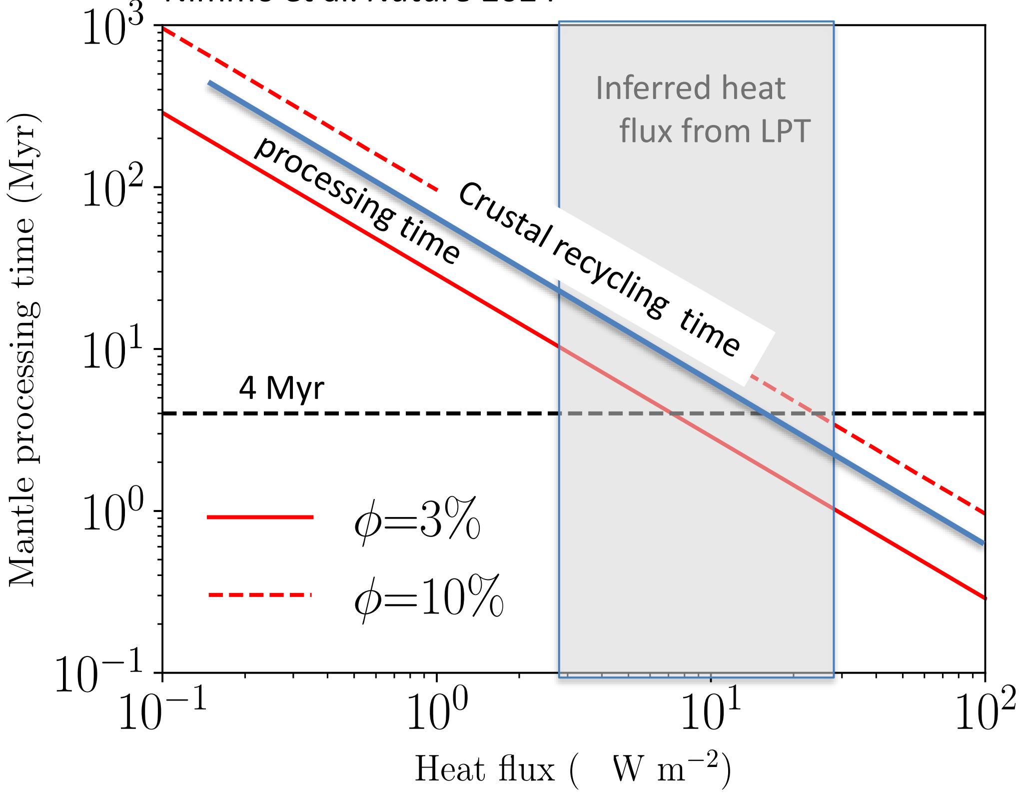
intrusion

on



Rapid mantle processing

Nimmo et al. *Nature* 2024



Entire mantle can get fluxed through melting region a few times

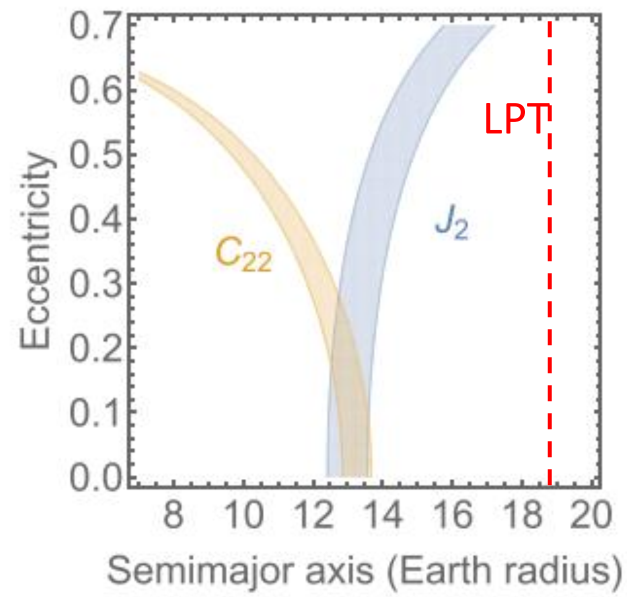
Cf. Borg et al. 2019 "The Sm-Nd isotopic equilibrium observed in the lunar sample suite collected over several thousand kilometers distance and derived from several hundred kilometers depths requires **a very large portion of the Moon to have been molten around 4.34 Ga**"

Shape of the Moon

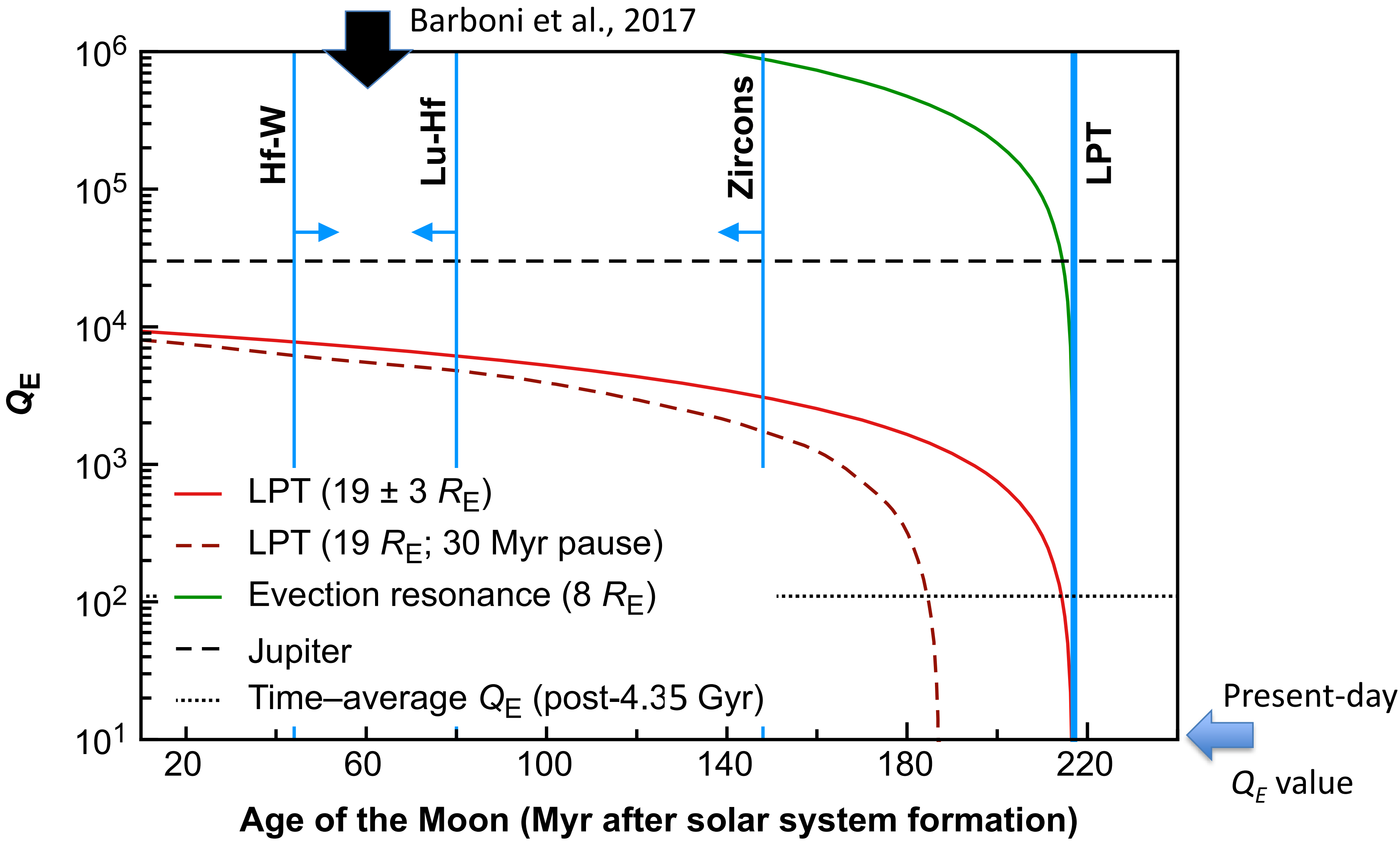
- Moon froze in its shape *before* the LPT

- But the "heat-pipe" process can retain a rigid lid 10s km thick (Io's crust is **40-60 km** thick), which preserves the shape

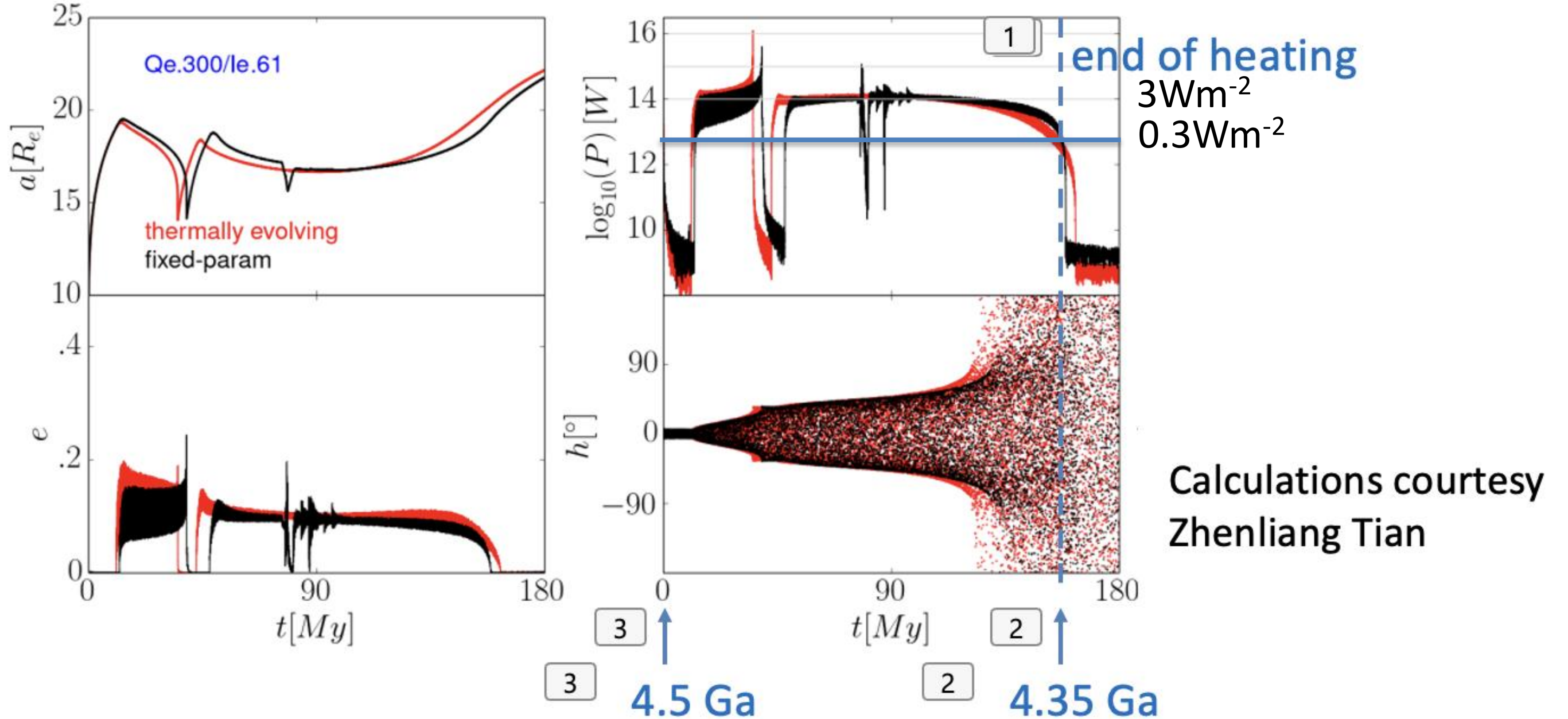
Matsuyama et al. 2021



Problem: could the LPT be reached so late?

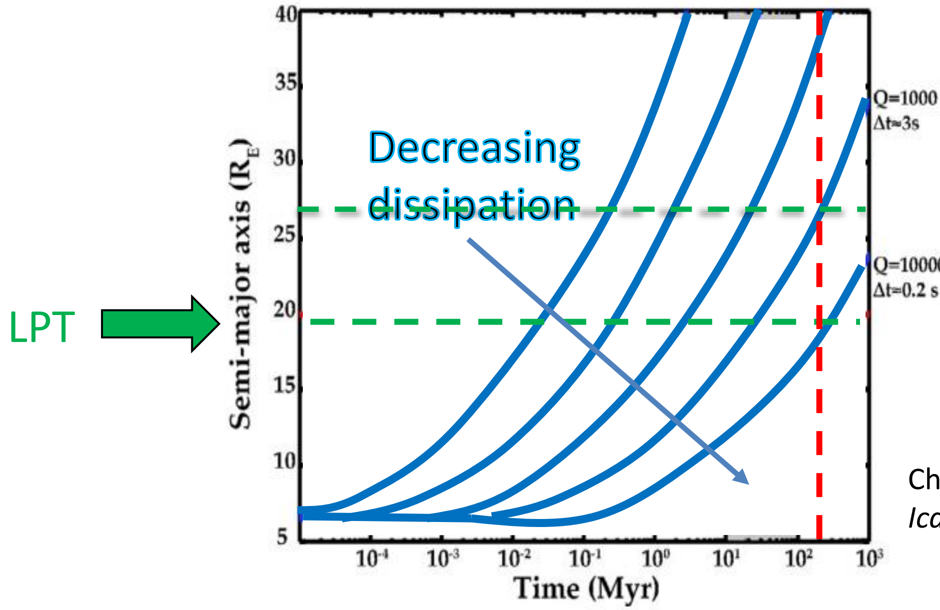


A first solution: protracted LPT phase



- A Q_{Earth}~300 gives a Moon of about the right age
- This is about the present-day Q of the *solid* Earth

A second solution: displacement of the LPT distance by the presence of a second satellite



Chen & Nimmo
Icarus 2016

$$r_L = \left(2J_2 \frac{M_E}{M_S} R_E^2 a_E^3\right)^{1/5}$$ (Cuk et al., 2016)

$r_L = 19R_E$ implies $J_2 = 0.03$
$r_L = 26R_E$ implies $J_2 = 0.15$

Mass and radius of satellite

Given: $$J_2 = \frac{1}{2}\frac{m}{M}\left(\frac{r}{R}\right)^2$$

Mass and radius of Earth

Eq. J_2 for a satellite around Earth

$J_2 = 0.15$ for:

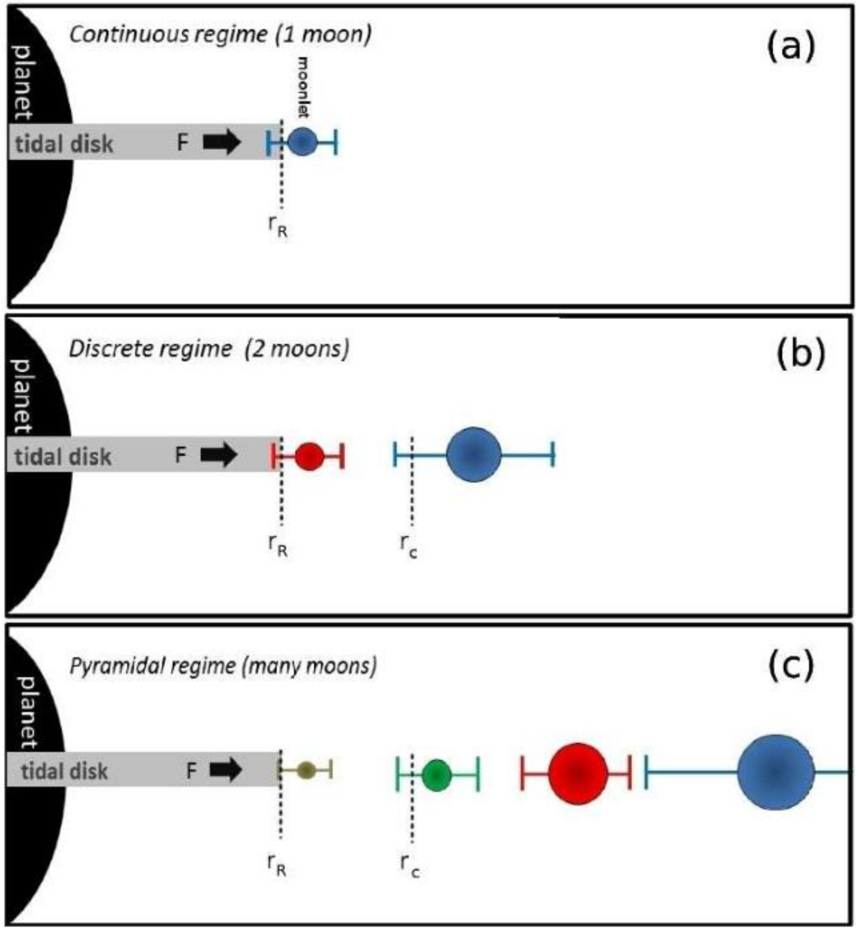
- A satellite of ½ Moon mass at 7 R_E
- A satellite of 0.1 Moon mass in 2/1 resonance with the Moon @26 R_E

Multiple Moon formation in context

- A satellite of ½ Moon mass at 7 R_E
- A satellite of 0.1 Moon mass in 2/1 resonance with the Moon @26 R_E

The LPT transition, increasing the eccentricity of the Moon, would lead to the collision of the two bodies

This can trigger global melting of the upper part of the Moon, possibly even more consistent with the data.



Crida and Charnoz, Science, 2012

Conclusions

- The Laplace Plane Transition at ~4.36 Ga could have **reset** most lunar chronometers
- The Moon probably formed at ~4.5 Ga

- Prediction – far-side sites should also show a preponderance of ~4.36 Gyr ages (*global* event)

- Future Work
  - Making a LPT transition at ~150My after lunar fomration consistent with a reasonable Q_E