# Evolution of Giant Impact Ejecta

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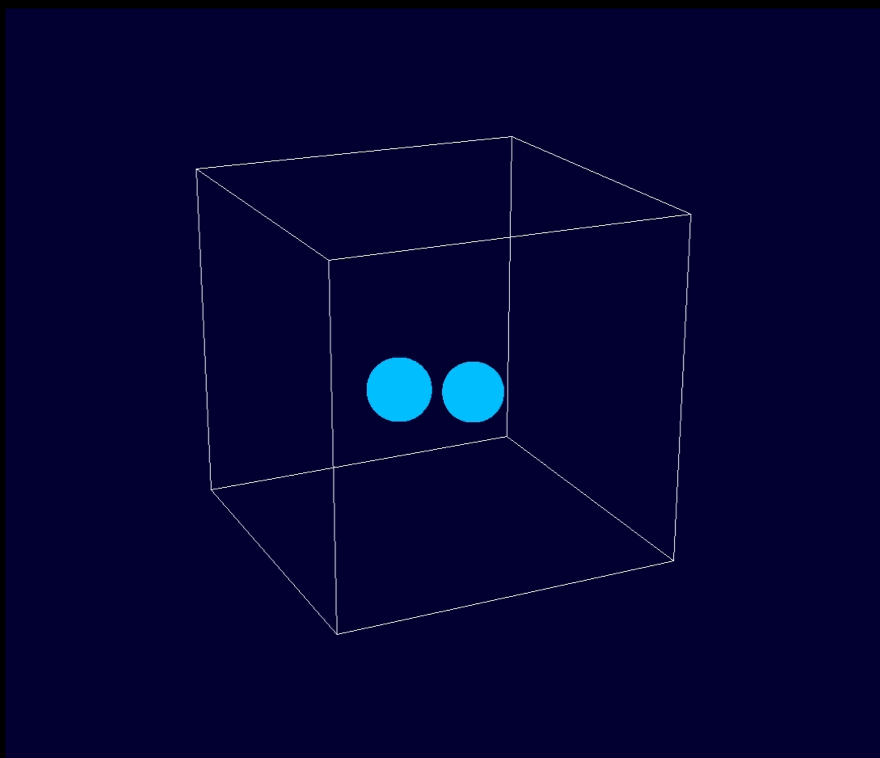
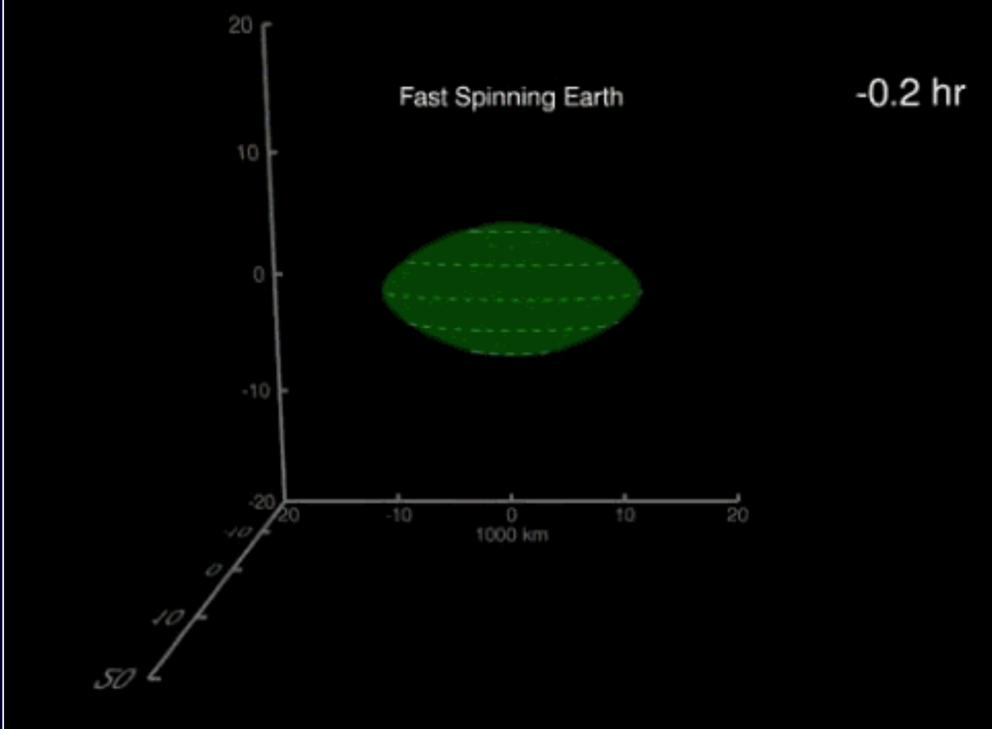
# *Moon-Forming Impact:*
# *Likely the Largest Youngest Collision in Terrestrial Planet Region*






## *Only ~0.5% of Earth mass added to Earth afterwards (HSE abundances: Ir, Pt, Au)*

**Bottke et al. (2010); Canup (2008; 2012); Cuk and Stewart (2012)**

# What Happens to Giant Impact Ejecta?

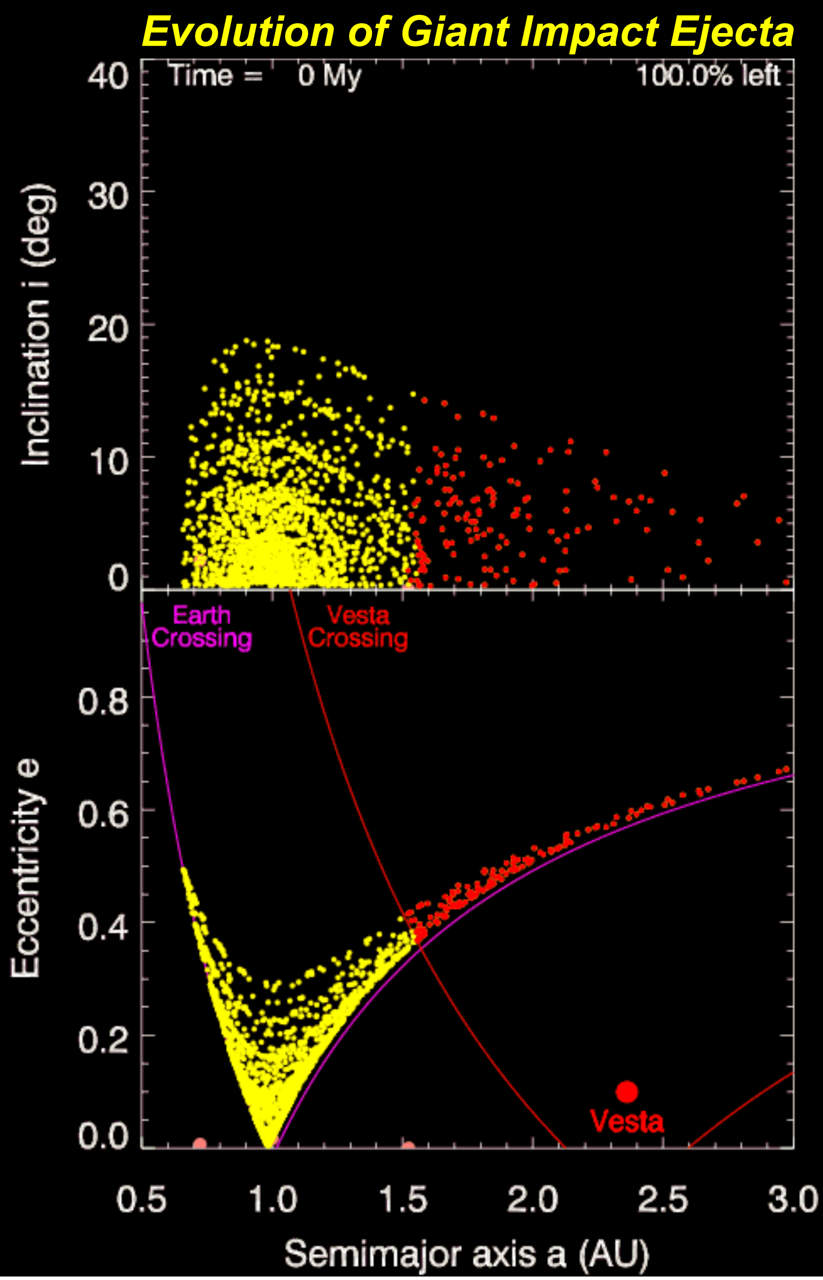
- **Giant impact ejects 1-2% Earth masses out of Earth-Moon system (~20-40 main belt masses).**
- **These bodies were input into inner solar system during endgame of planet formation!**
- ***Did GI ejecta leave behind signatures?***

**Canup (2012); Jackson and Wyatt (2012)**

# Question: Did Giant Impact Debris Leave Their Mark on Asteroids (and Meteorites)?

**Answer: Yes…if you know what to look for!**

# Ejecta Evolution From Giant Impact




- Consider giant impact debris ejected from Earth-Moon system.
- Encounters and resonances spread it around!
- Some ejecta reaches orbits where it can hit asteroids (e.g., Flora, Vesta).
- *Key point: Ejecta will hit asteroids at very high velocities (> 10 km/s)!*

See also Jackson and Wyatt (2012)

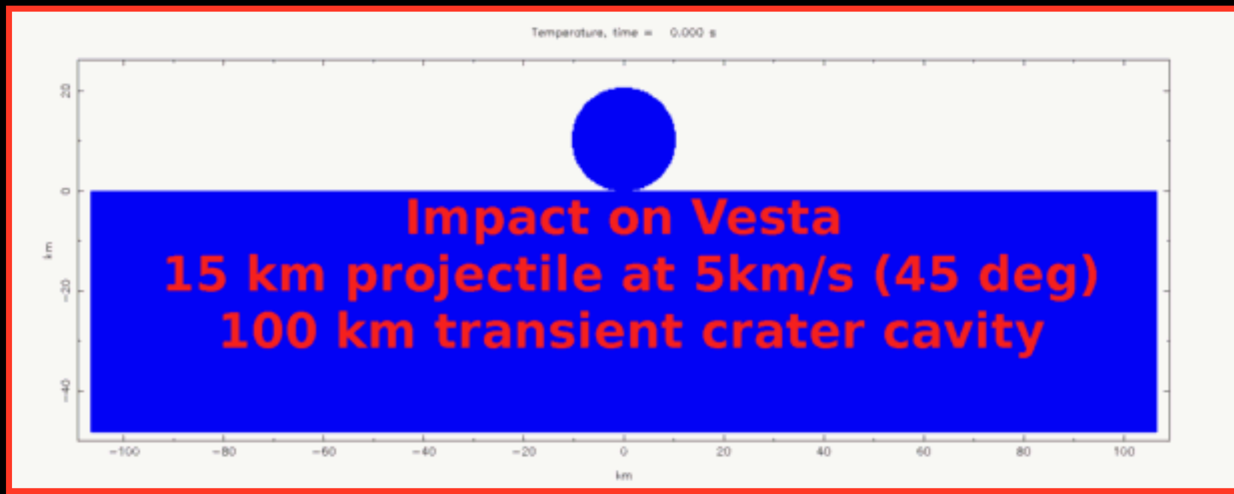
# Links to $^{40}$Ar-$^{39}$Ar Shock Reset Ages?

- Many $^{40}$Ar-$^{39}$Ar reset ages are made by crater formation on parent body. These heated rocks ejected by later event.
- Crater debris must be hot enough long enough to strongly heat material in the breccia lens or ejecta blanket.
- What kind of impacts can do this to asteroids?

# Impact Simulations on Vesta

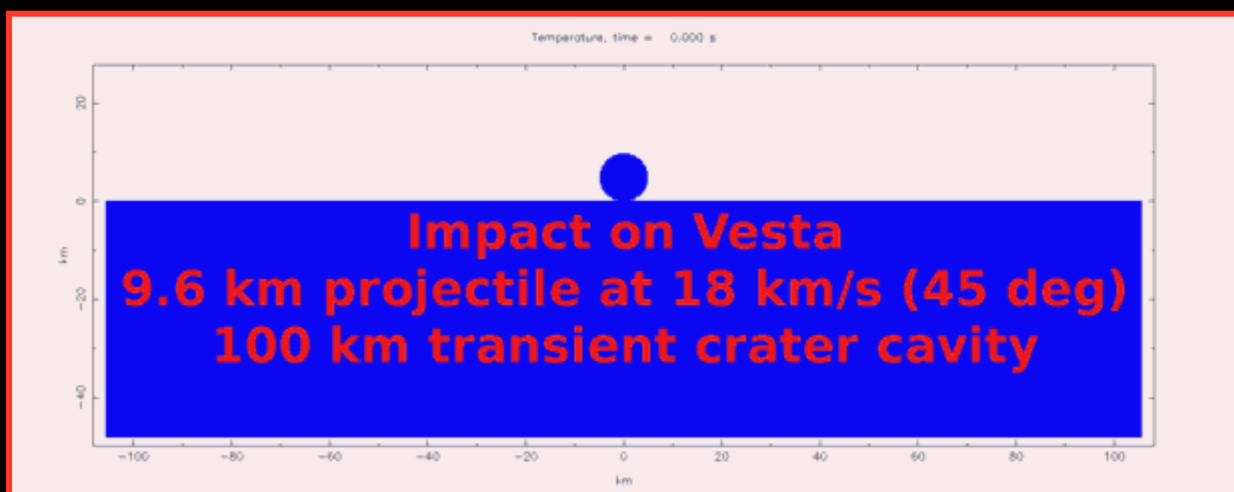
**Big Projectile**

***V* = 5 km/s**

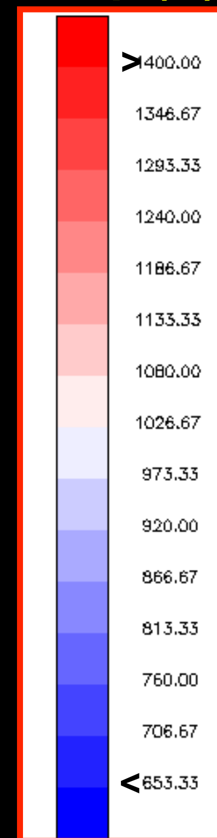



**Small Projectile**

***V* = 18 km/s**



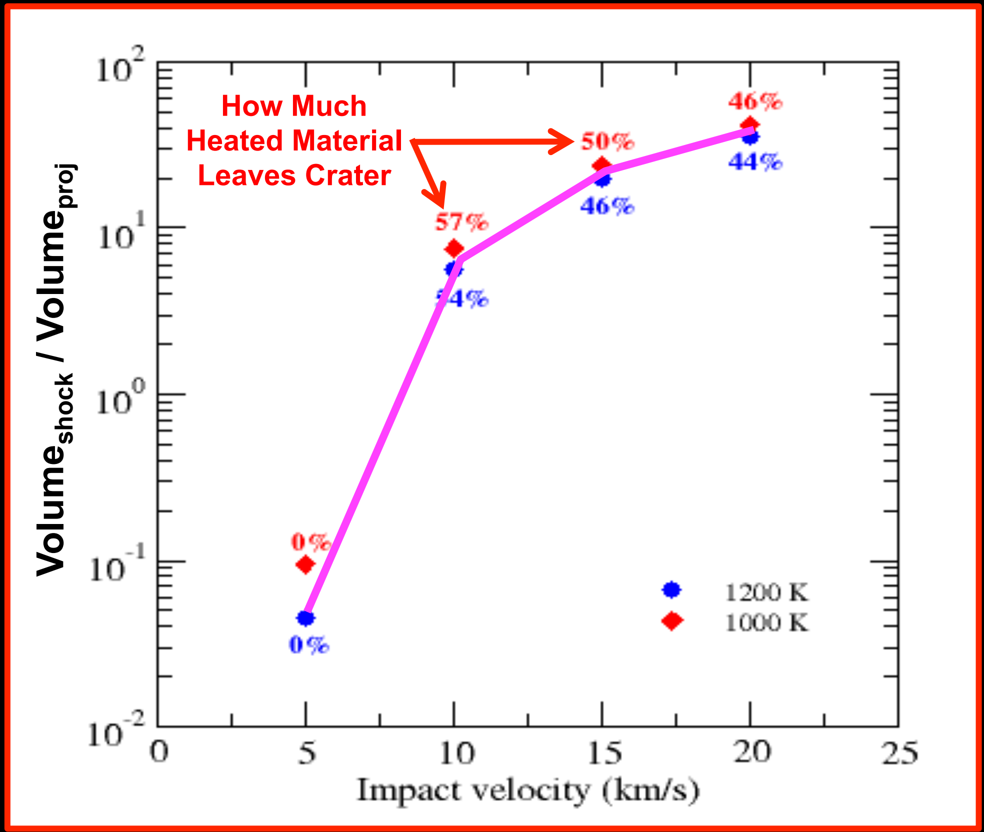

**Temp (K)**




- **High velocity impacts produce higher temperatures and heat a larger volume of material.**

**Simulations from Kai Wunnemann**

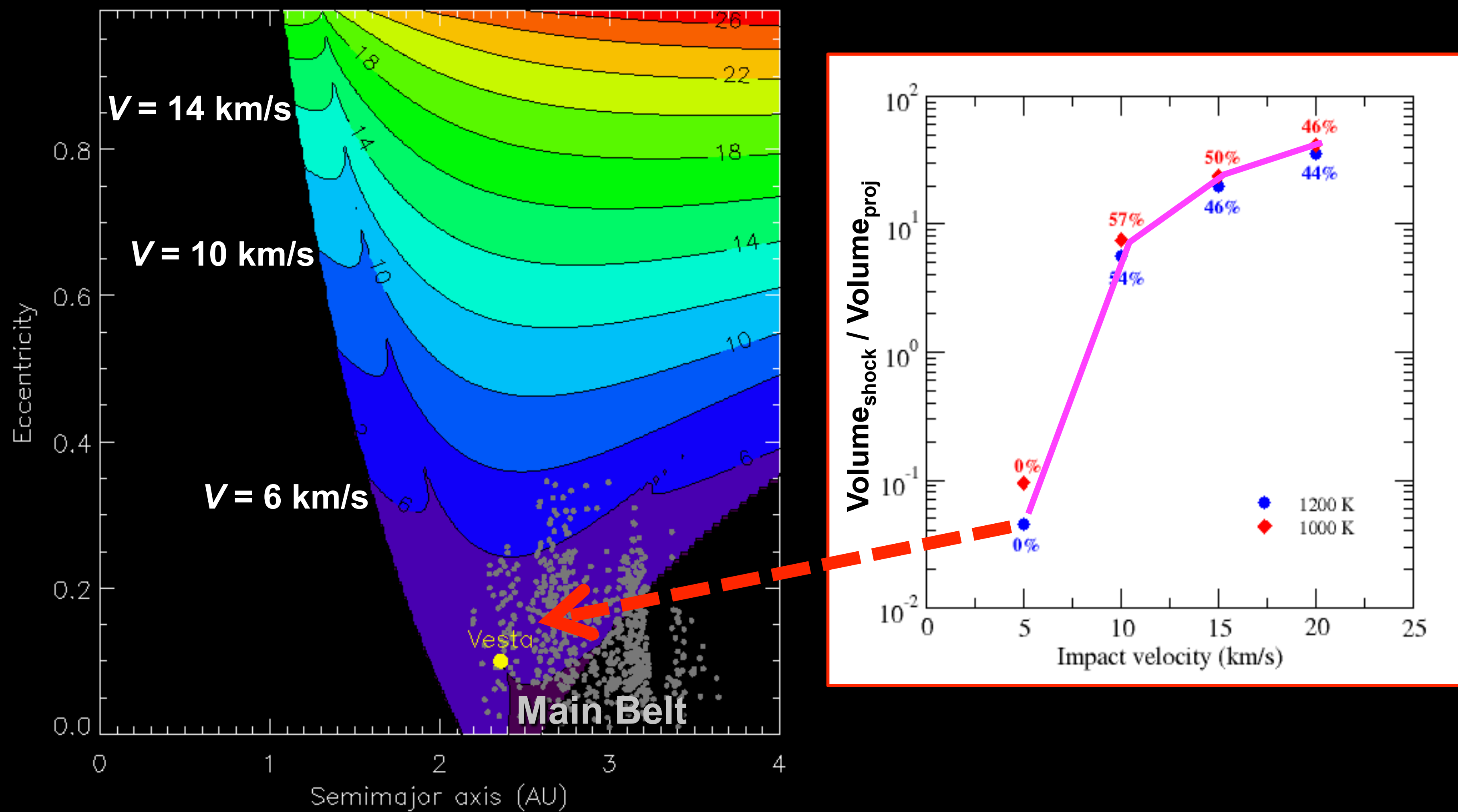
# Impact Heating Trends




- **V < 5 km/s**: Relatively little heating takes place.
- **V > 10 km/s**: Volume of heated material increases!
- **V > 15 km/s**: Heated material scales with impact energy.

Pierazzo et al. (1997); Wunnemann et al. (2008); Barr and Citron (2011)

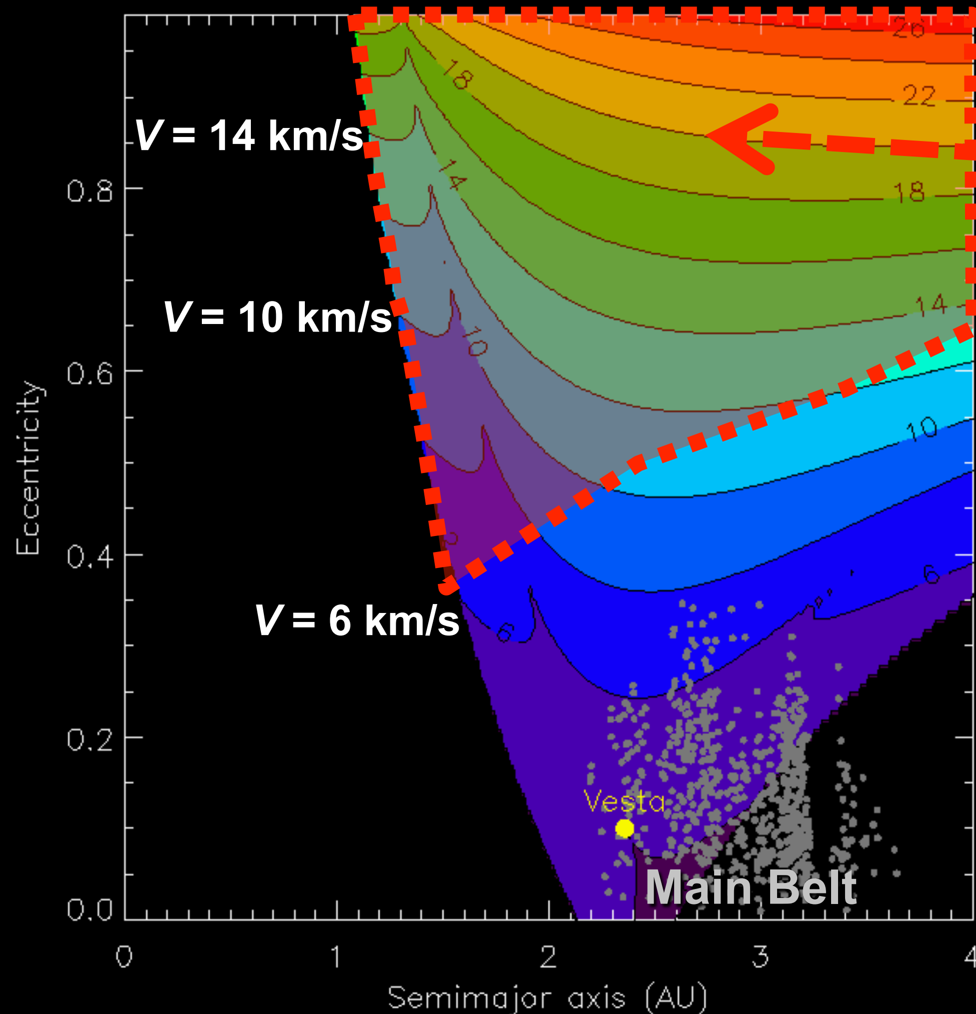
# Impact Velocities on Vesta

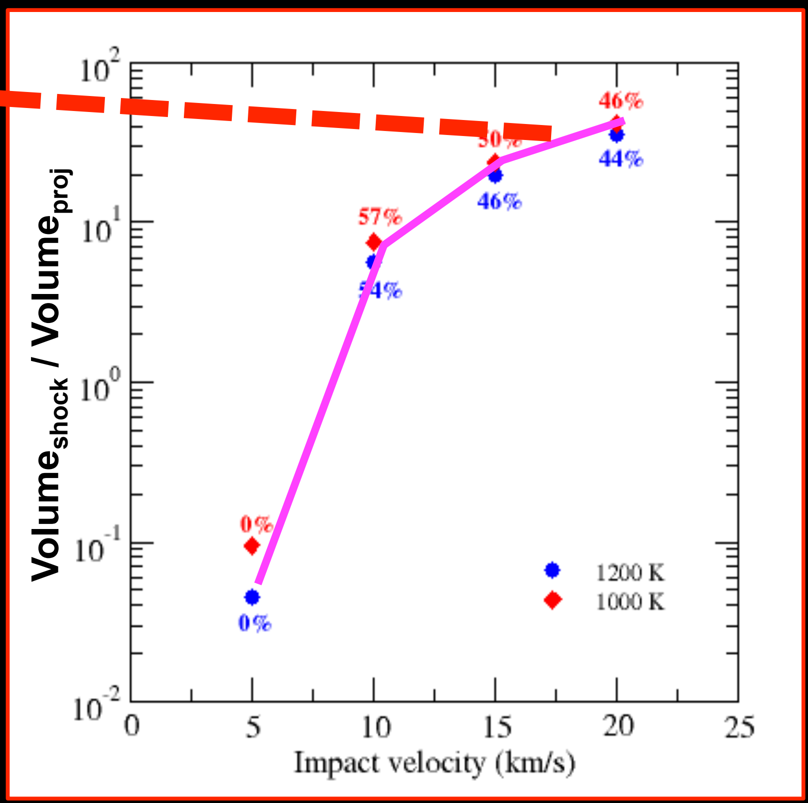



- Most main belt asteroids strike Vesta at *V* < 6 km/s.
- These events produce relatively little heating.

Bottke et al. (1994); Marchi, Bottke et al. (2013)

# Impact Velocities on Vesta

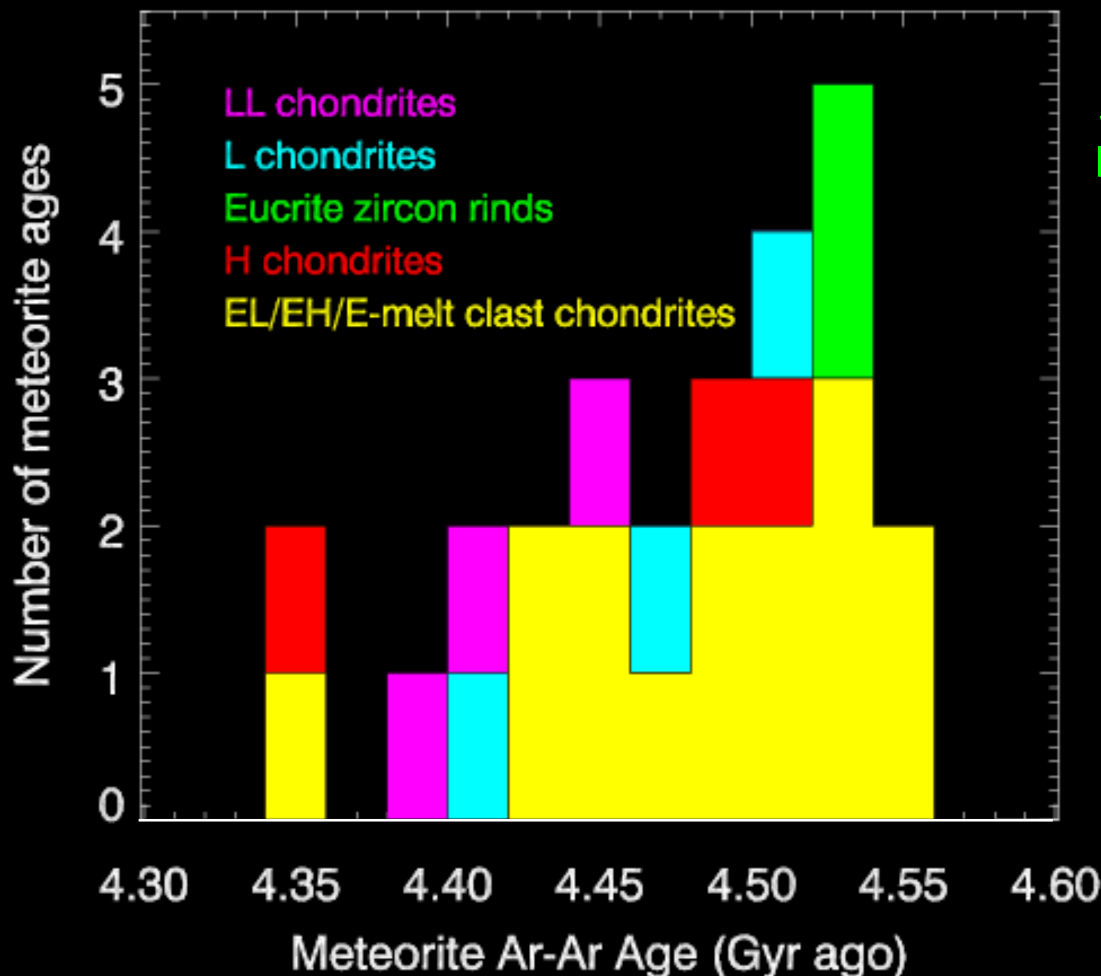



- High *V* comes from high *e* orbits, which can still hit Vesta!
- These impacts may produce ~1000 times more heating!

Bottke et al. (1994); Marchi, Bottke et al. (2013)

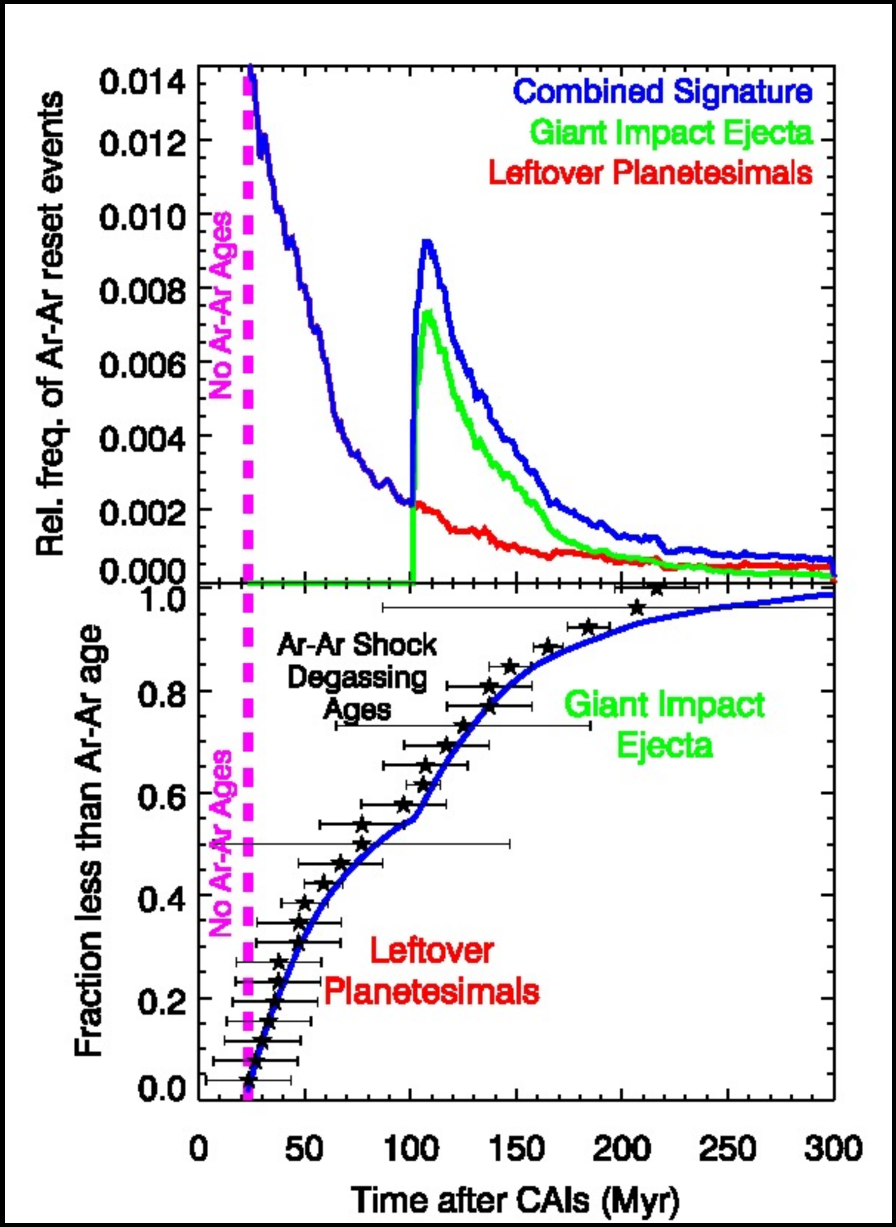
# Ar-Ar Shock Ages From Stony Meteorites




Bogard (2011)
Swindle et al. (2013)
Hopkins et al. (2014)

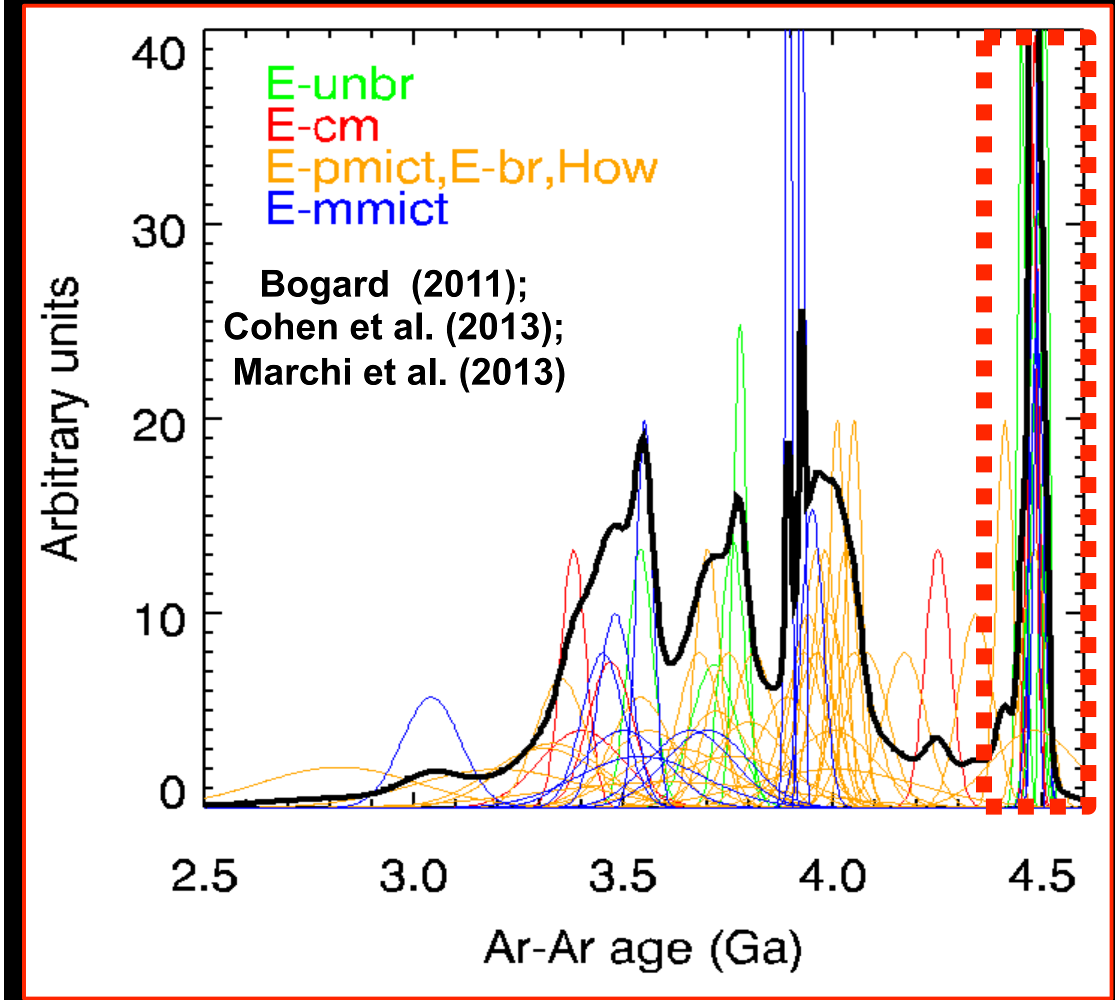
- **A collection of Ar-Ar shock degassing ages from eucrites and chondrites produced by impact heating.**

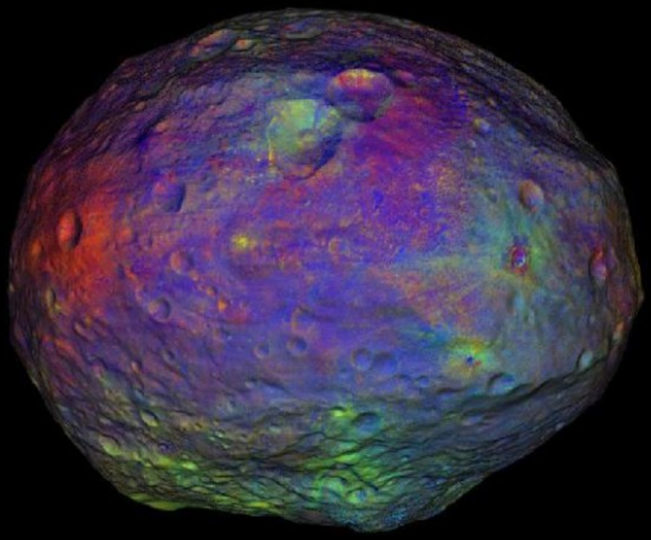
# Results for Shocked Stony Meteorites




- Leftover planetesimals and GI ejecta hit asteroids and make Ar-Ar reset ages.
- Excellent fits between model and data!
- Predict giant impact at 105 ± 25 My after CAIs

# Impacts on Vesta at Same Time

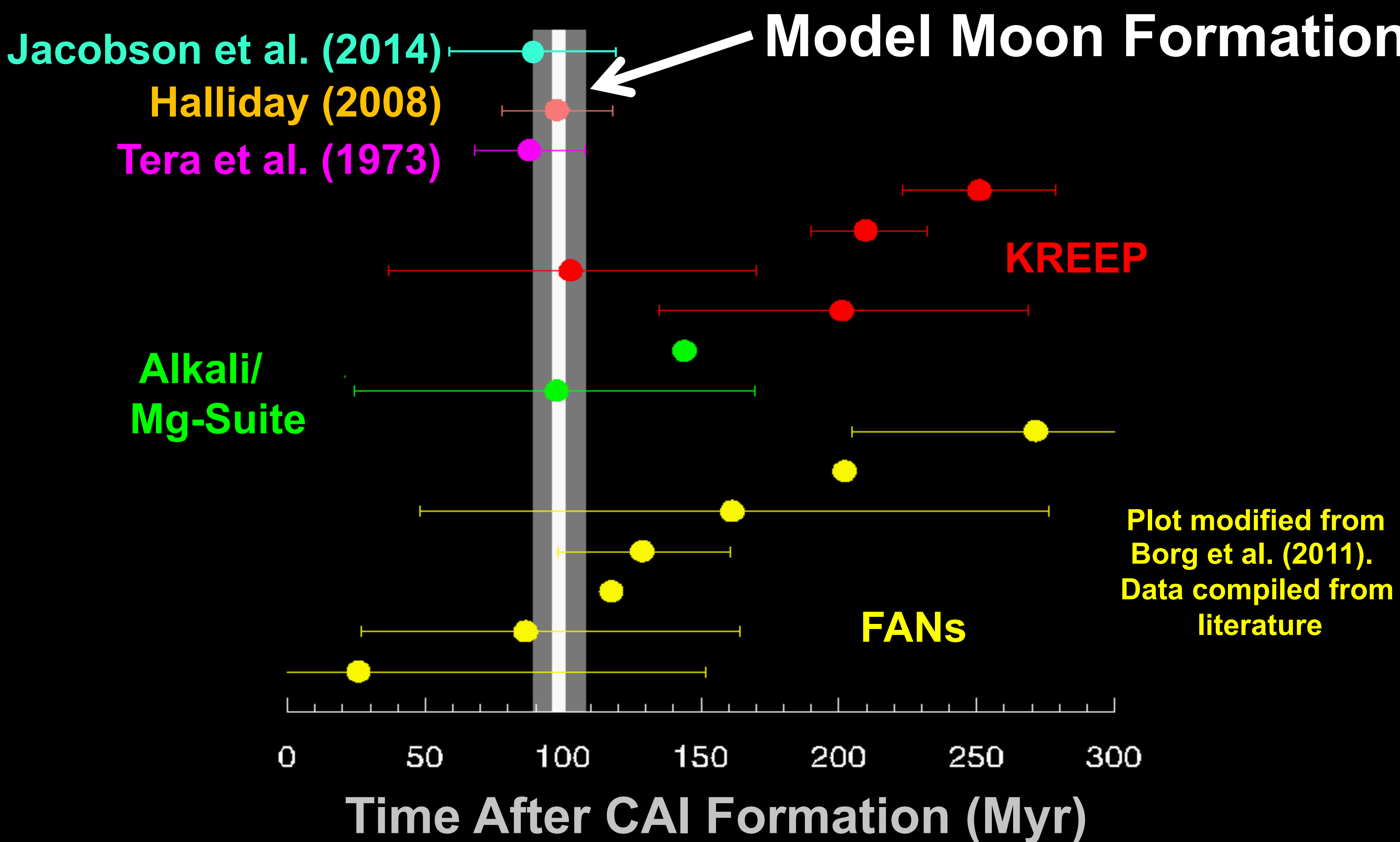


(4) Vesta, with colors set to mineral compositions

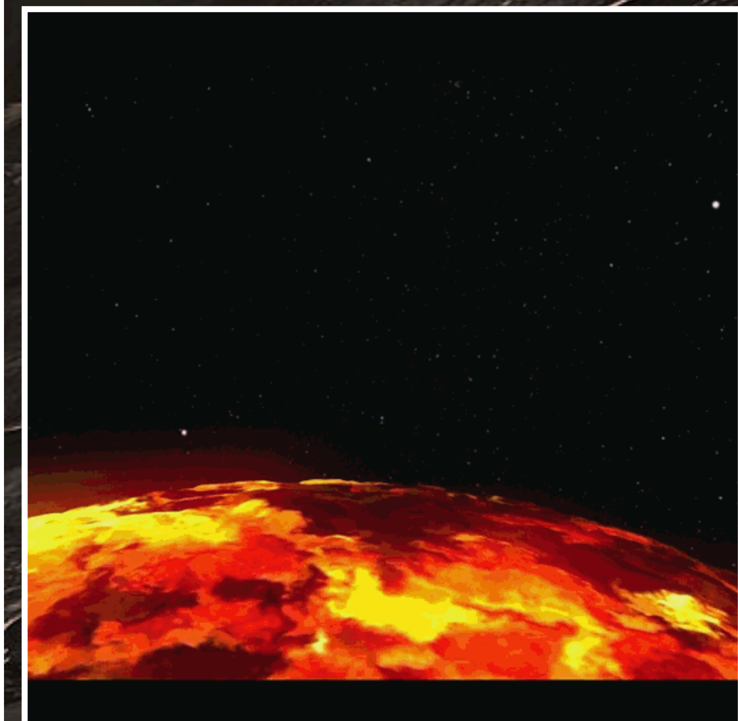
- *__Unshocked__* eucrites show Ar-Ar age spike at ~4.48 Ga. Hot material excavated by impact that quickly cooled.
- Our model makes several *D* > 10 km craters at this age!

# Comparison with Oldest Lunar Ages




- Our Moon formation age agrees with the oldest known ages of lunar rocks and many model predictions.

# What About GI Ejecta and the Moon?



Conductive Lid on Magma Ocean

What Bombardment Happened Here?

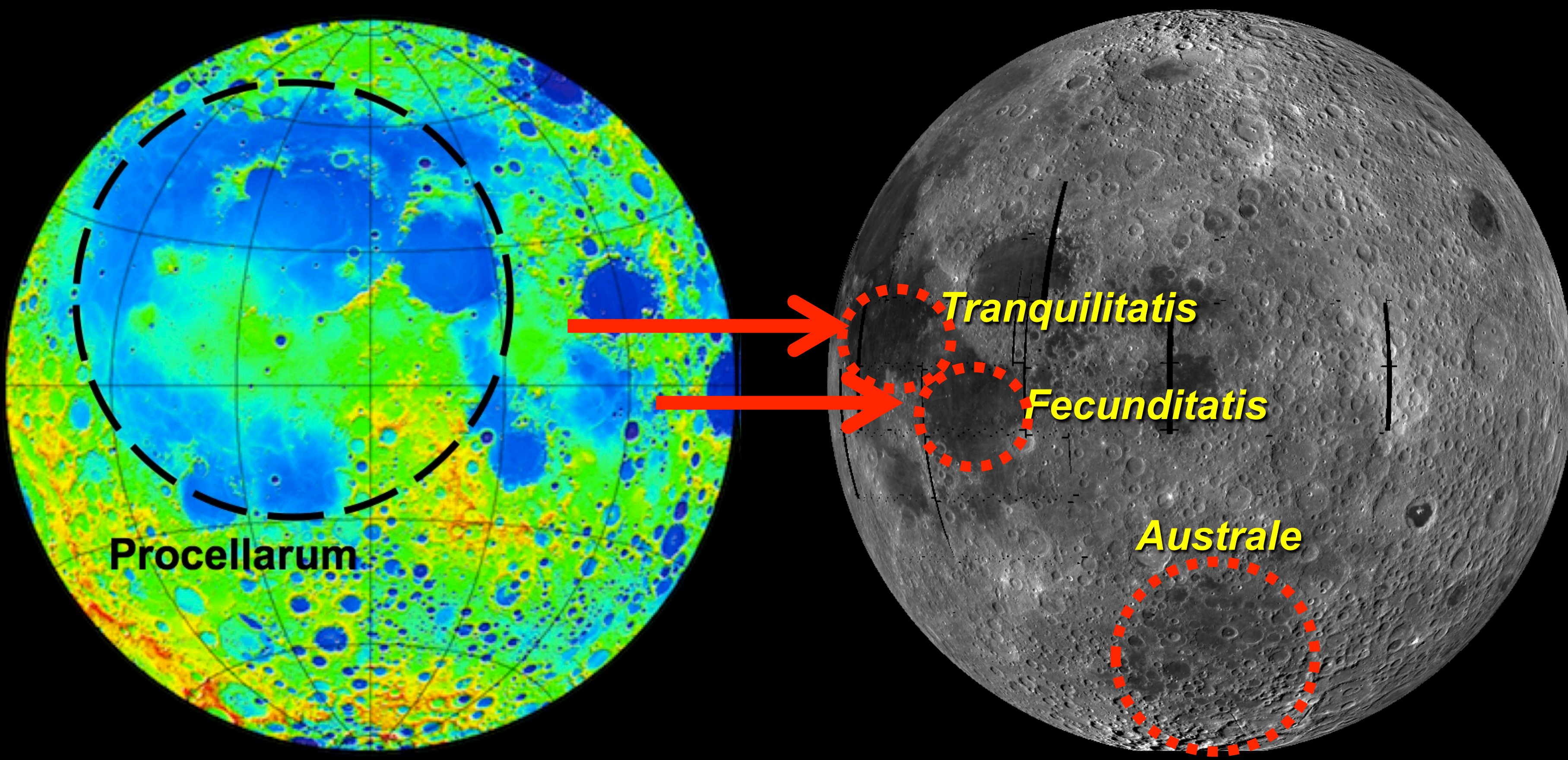
~4.1 to 4.48 Ga?

Late Heavy Bombardment

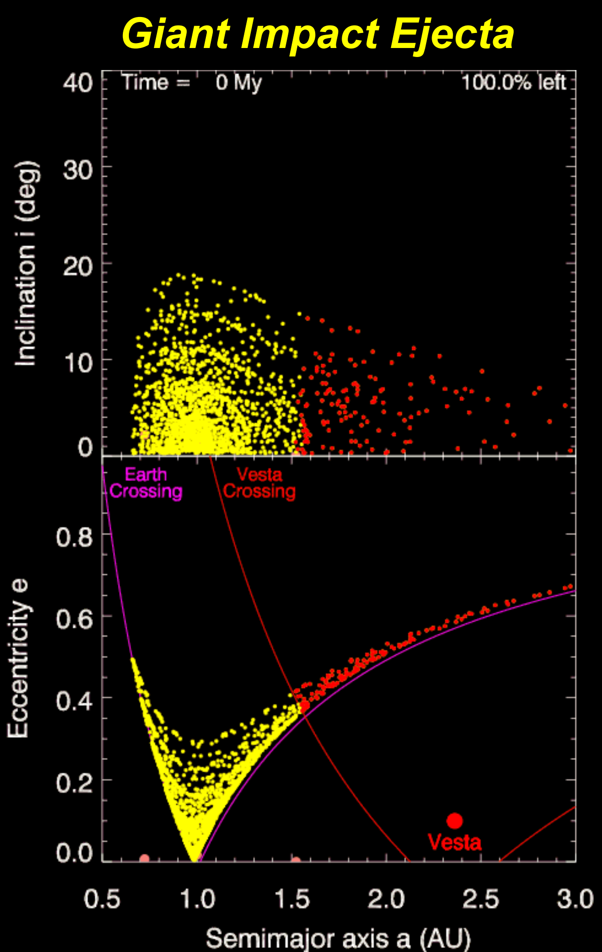
- ***Prediction*: *D* ~ 1 km bodies from giant impact dominate leftover planetesimals after the GI.**
- ***Implication*: GI ejecta must also affect the Moon**

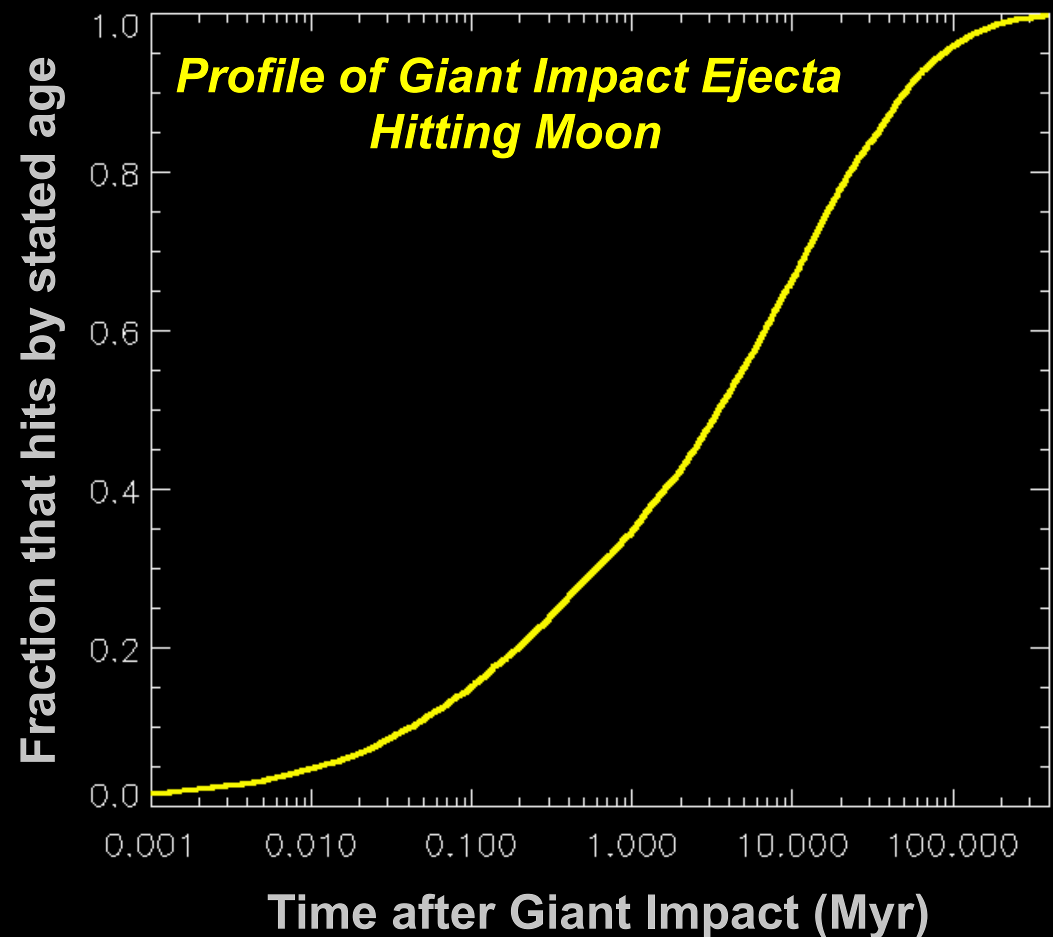
# Early Lunar Bombardment Issues

- Early lunar impacts were $V \sim 10$ km/s (Marchi et al. 2012).
- Several early "basins" from Wilhelms (1987) show little topographic or gravity signatures from GRAIL data?
  - Procellarum, Tranquillitatis, Fecunditatis, Australe



# Giant Impact Ejecta Evolution



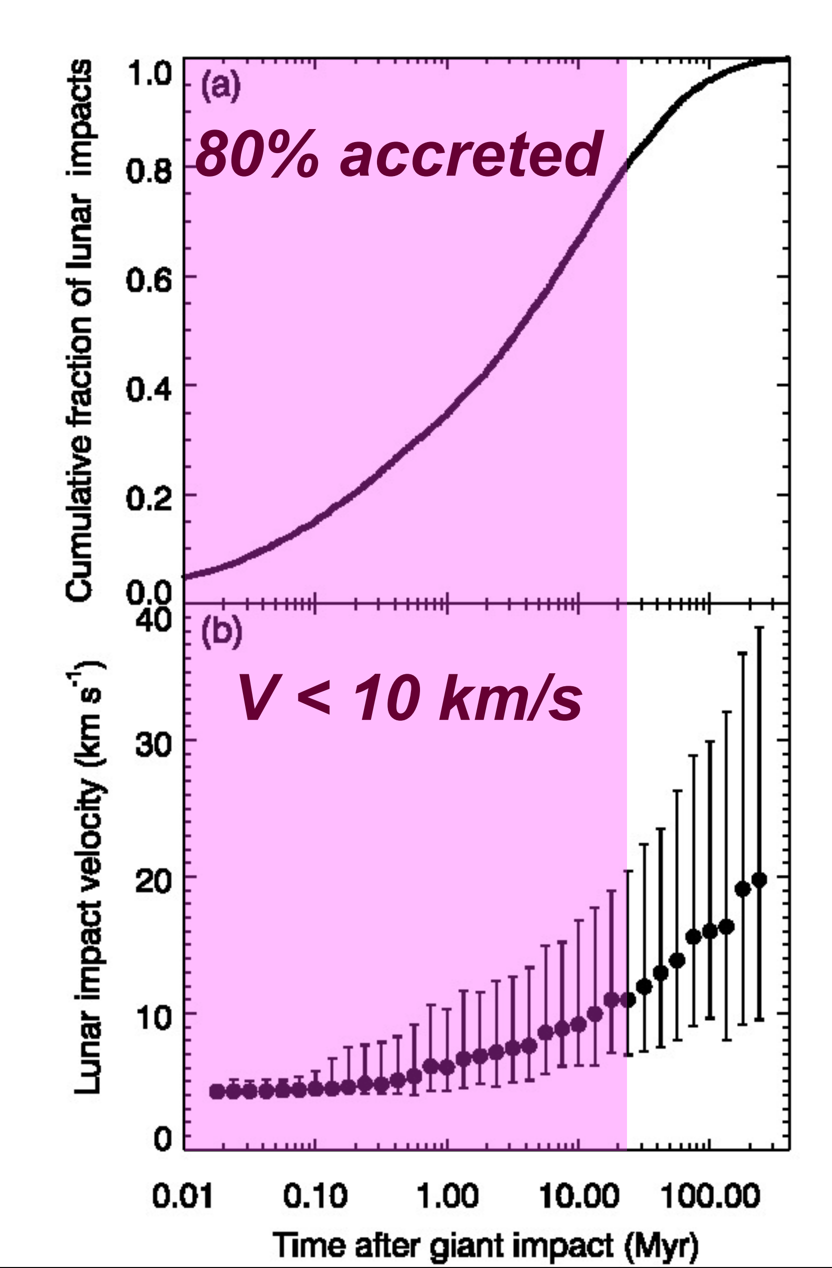




- Assuming no collisional evolution, ~1% of GI test bodies strike the Moon between 0.001-300 My after the GI.

Calculation uses: Bandermann and Singer (1973); Garrick-Bethel et al. (2011); Chen and Nimmo (2014)

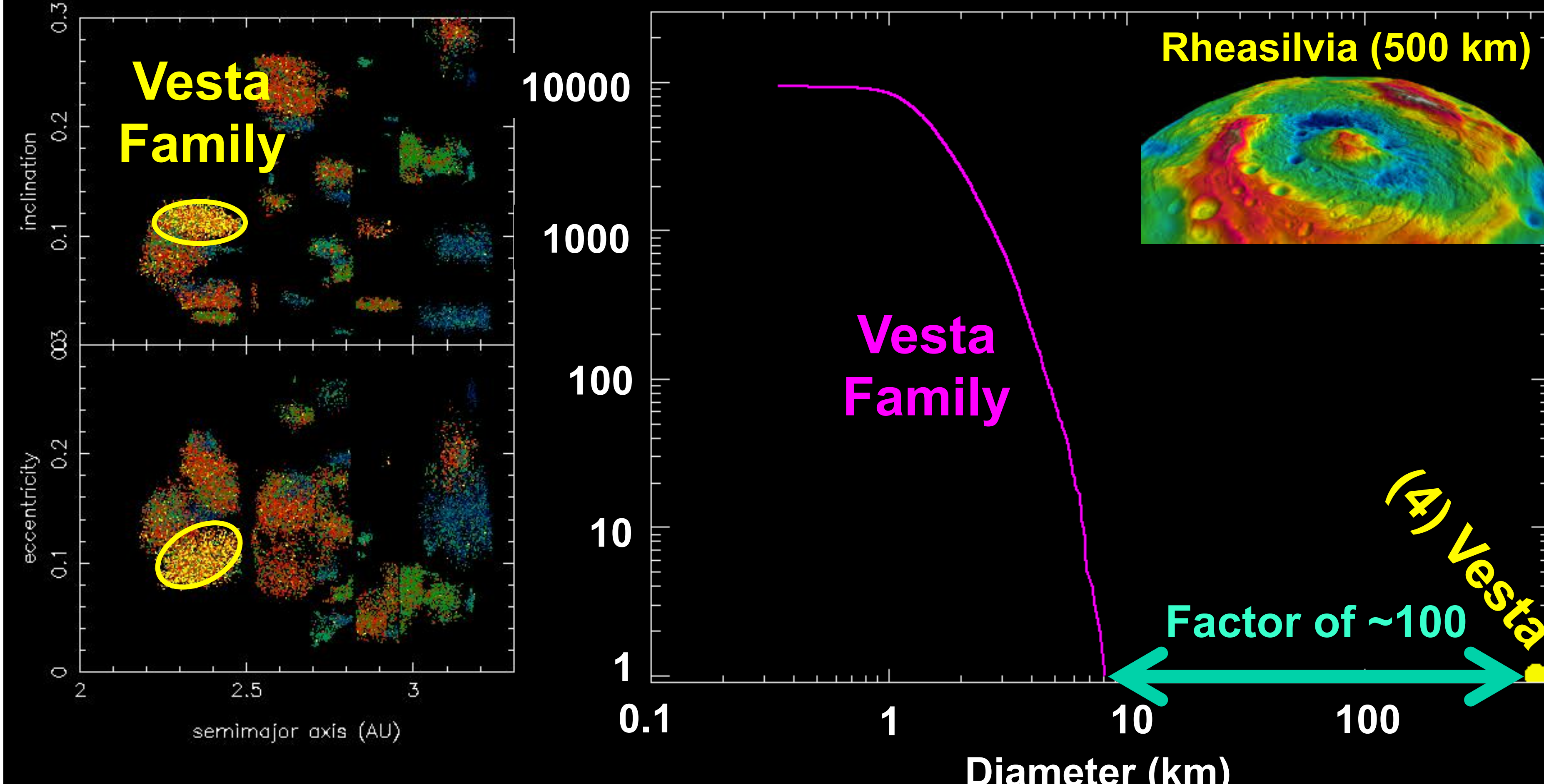
# Giant Impact Ejecta Evolution

- **Test body evolution:**
  - 80% of GI test bodies strike Moon at V < 10 km/s before ~20 My.
- **Scenario passes first test!**

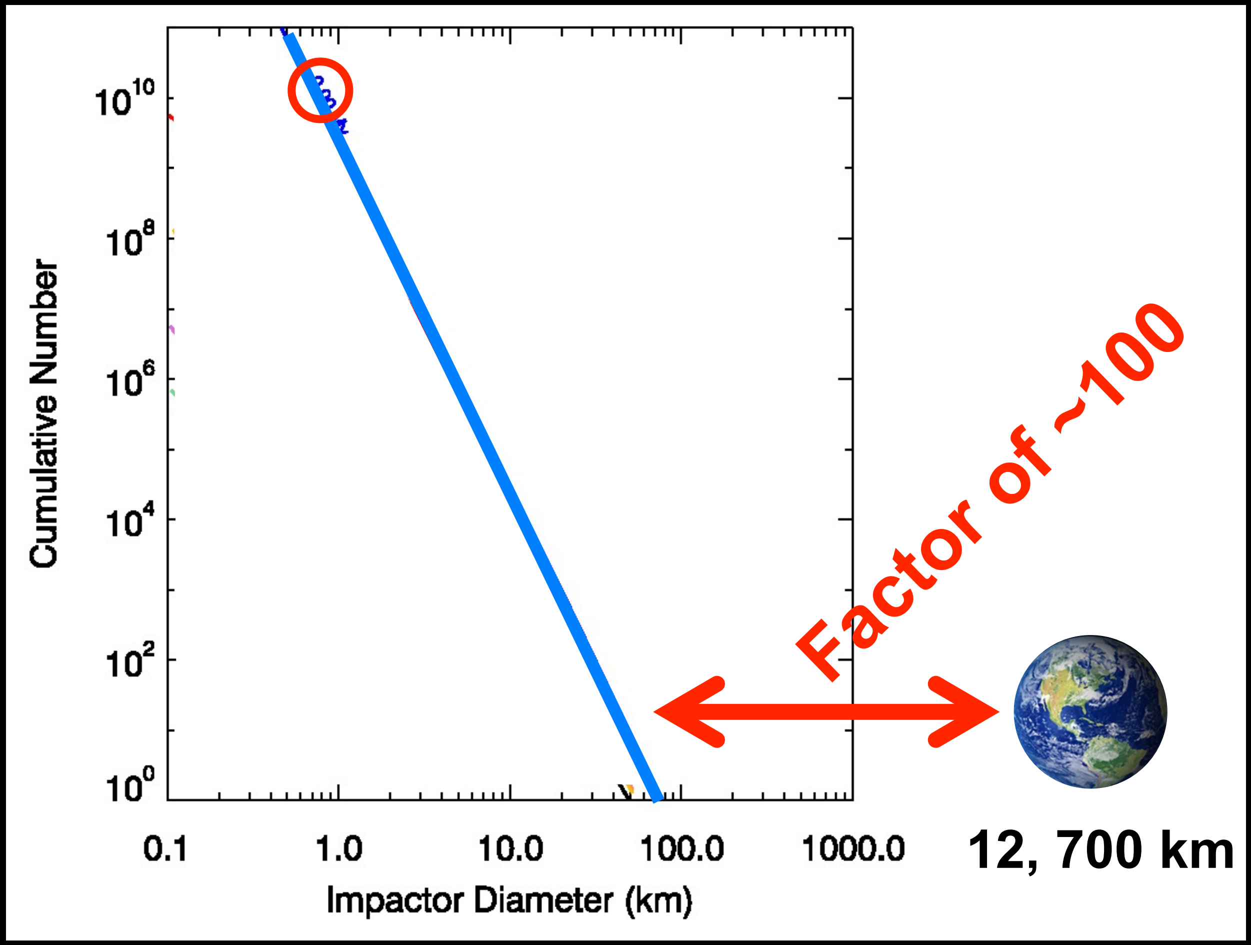


# Choosing a Size Distribution for GI Ejecta

- Not much known. Insights gleaned from asteroid collision models and the "Vesta family" created by Rheasilvia basin.

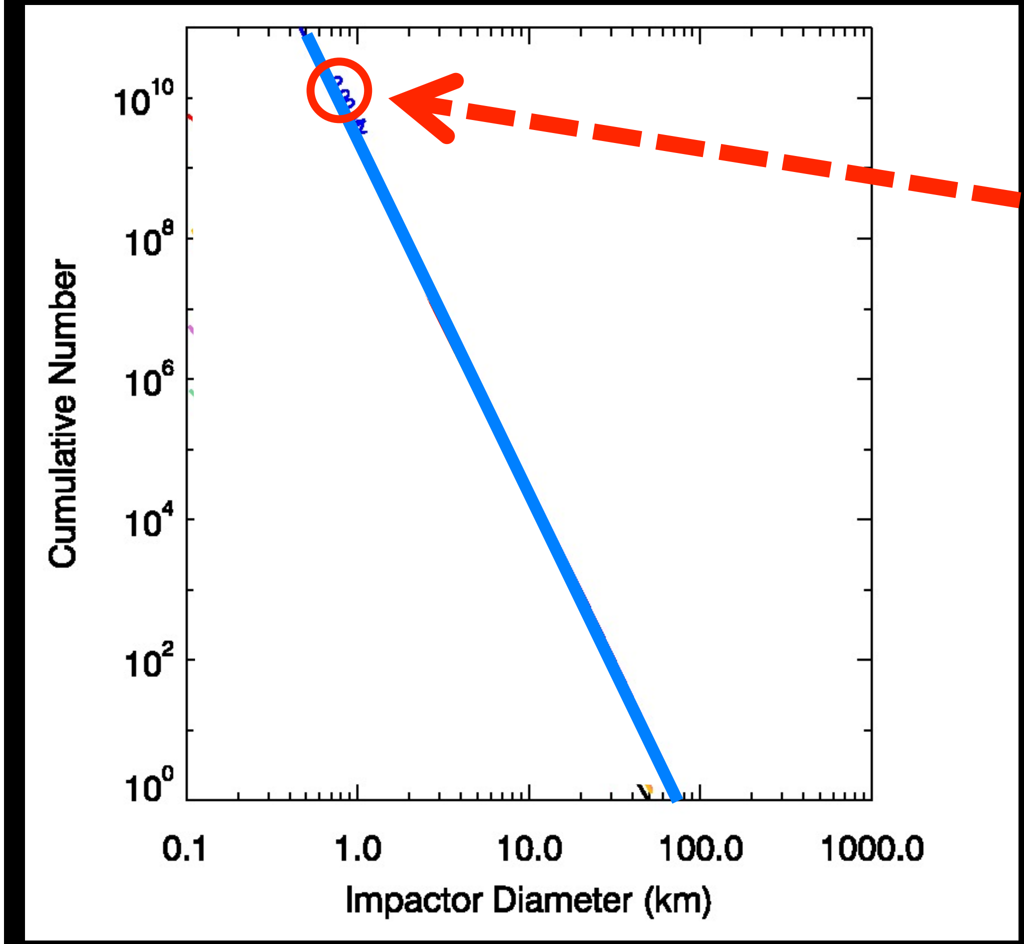


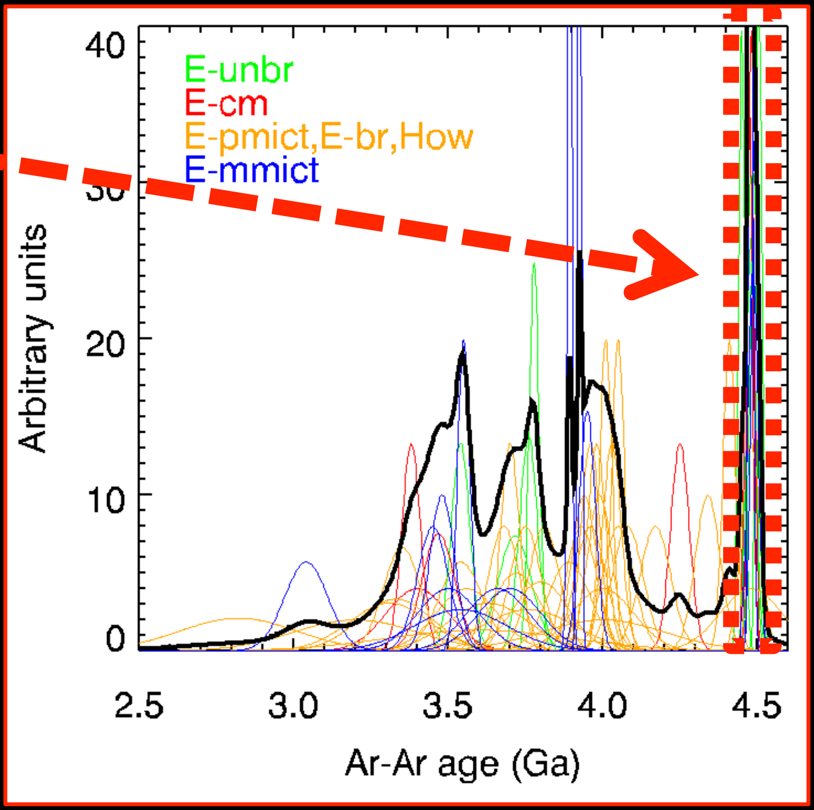
# Possible GI Ejecta Size Distribution




- We assume GI ejecta size distribution has simple shape.
- By mass balance, 1-2% Earth masses becomes $\sim 10^{10}$ $D$ > 1 km bodies.

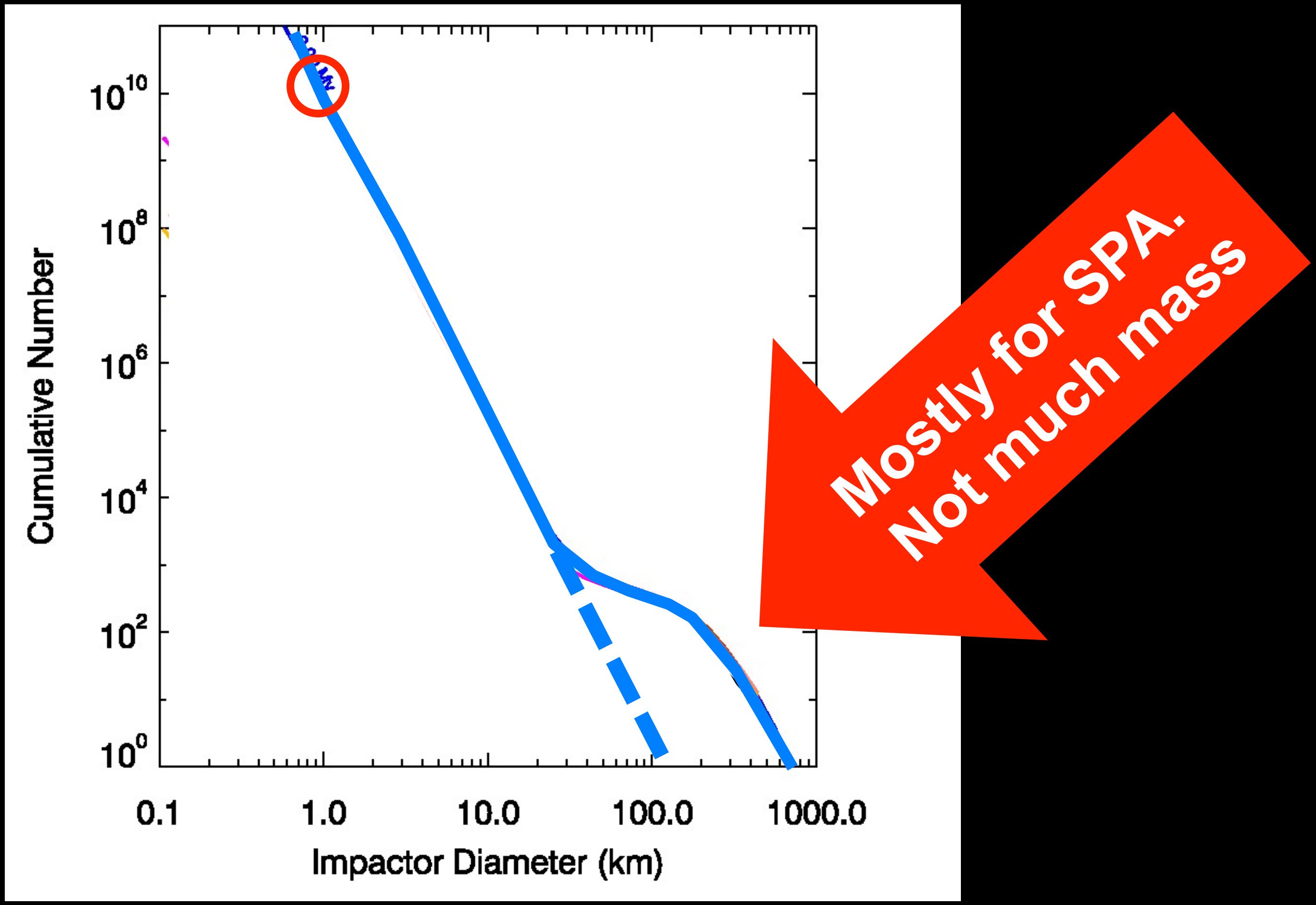
# Possible GI Ejecta Size Distribution



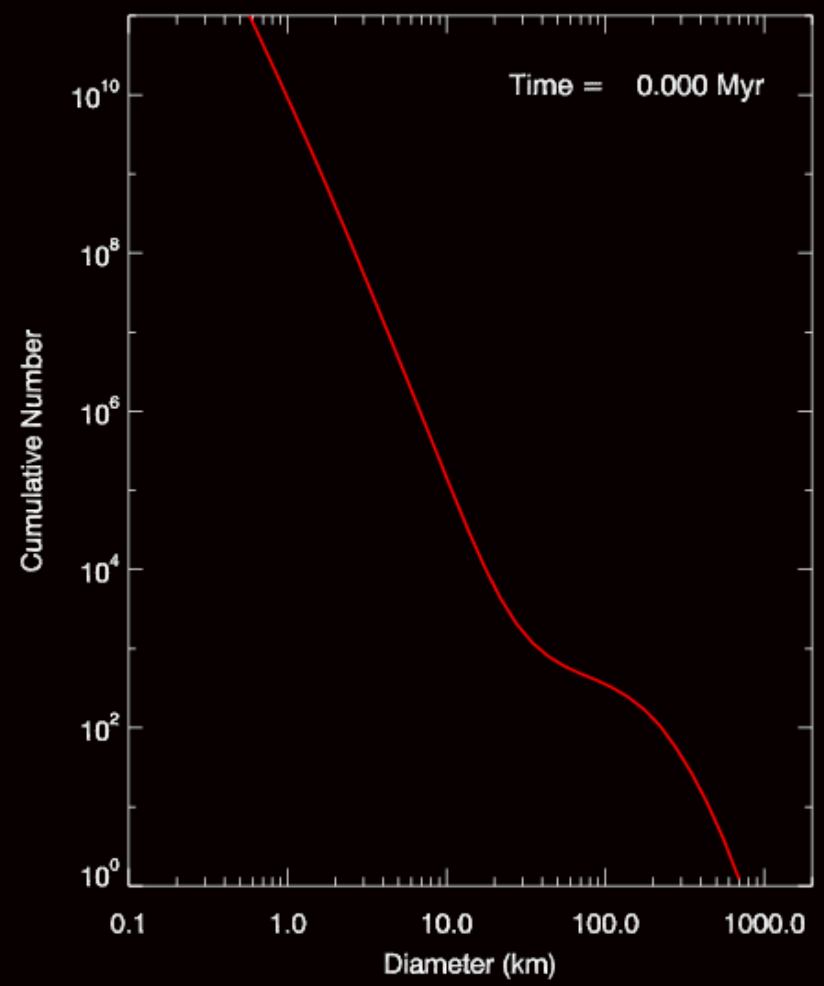

***~$10^{10}$ D > 1 km projectiles will create many Vesta craters. They can "dig up" warm eucrites at ~4.48 Ga!***

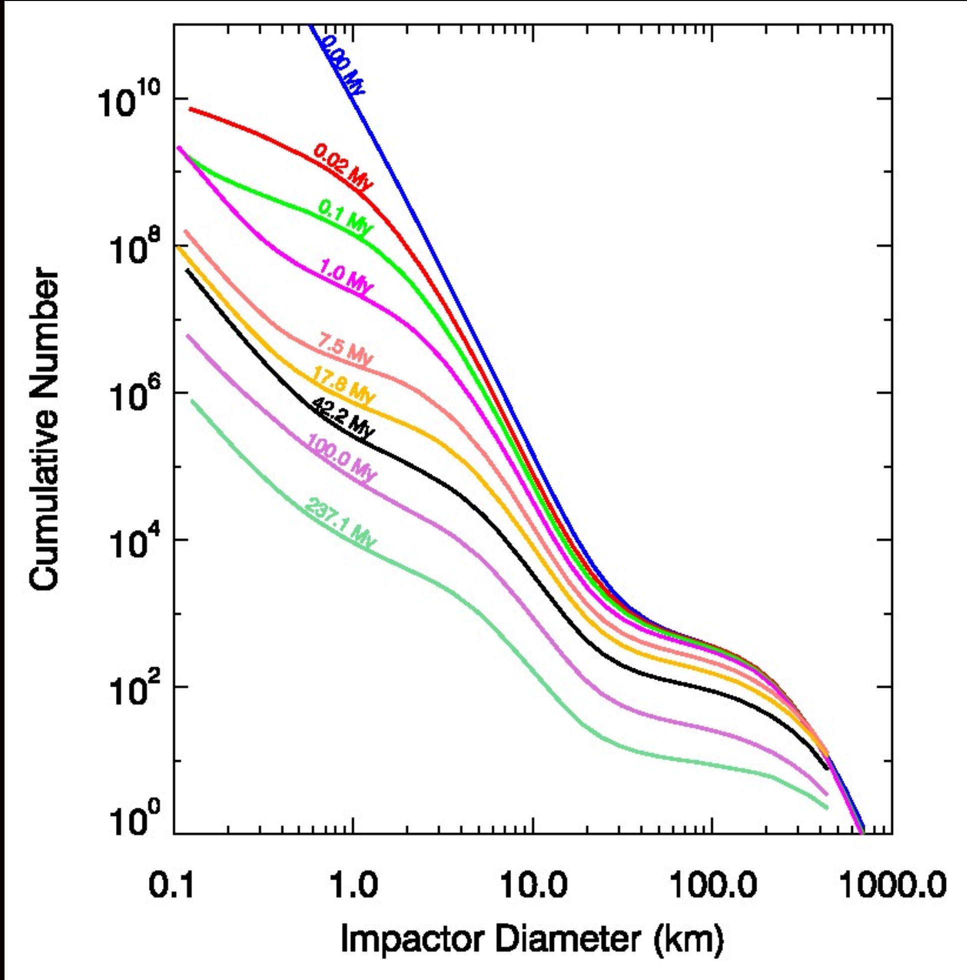
# Possible GI Ejecta Size Distribution




***Few big bodies needed to make early lunar basins!***
***Moon has ~1-2 SPA basins and ~25 pre-Nectarian basins.***

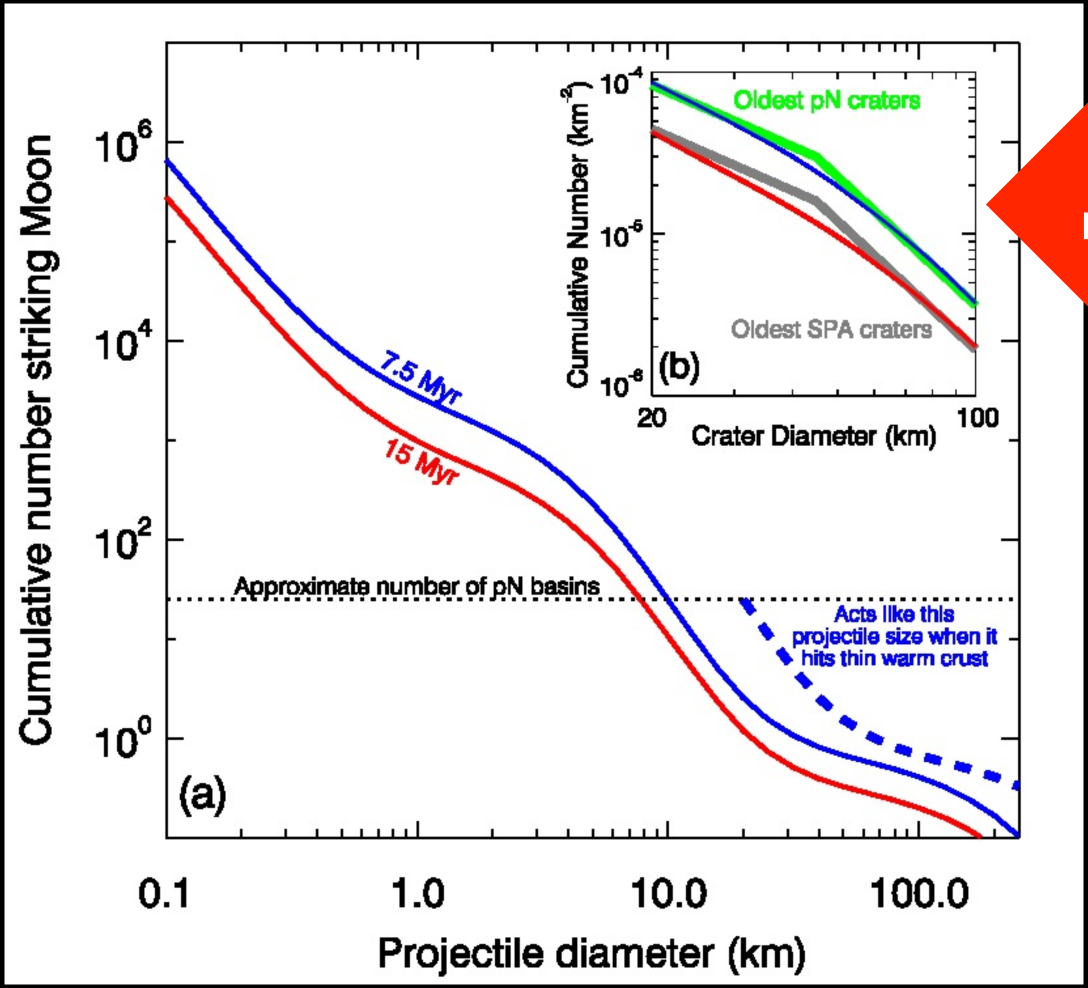
# Collisonal Evolution of GI Ejecta




- GI ejecta loses factor of ~100 in mass in < few My.
- The wave-like shape is diagnostic of collisional evolution.

# Impacts on the Early Moon

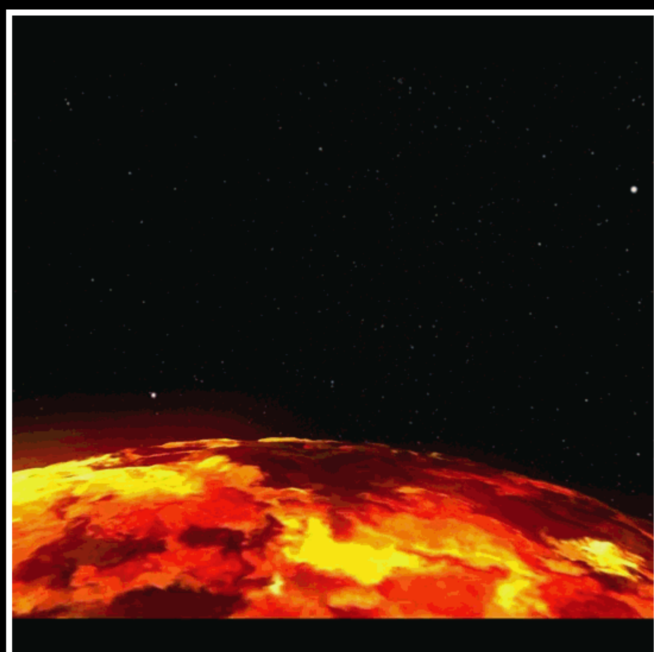


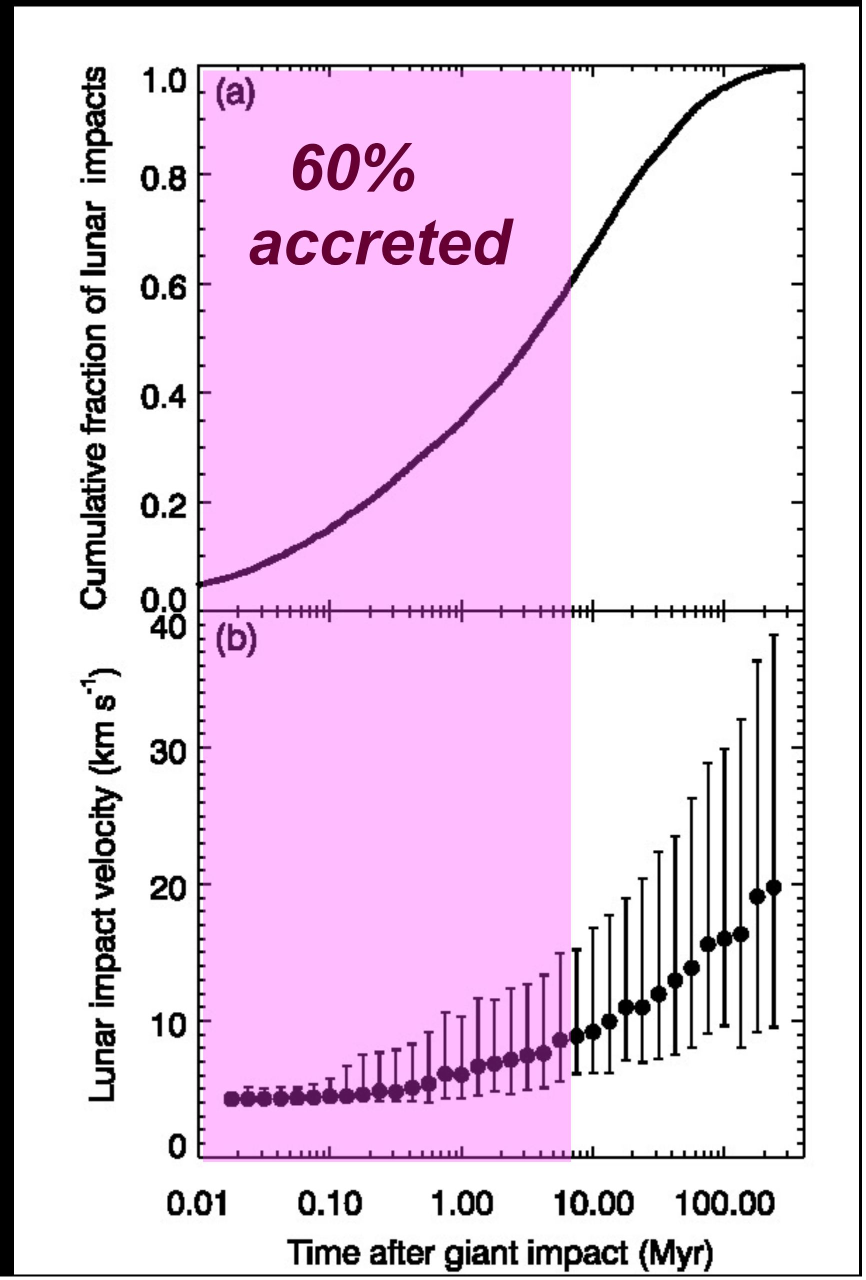


- Wavy size distribution and low V reproduce ancient craters on oldest Pre-Nectarian terrains and SPA basin.
- Oldest cratered terrains form ~8 My after giant impact.

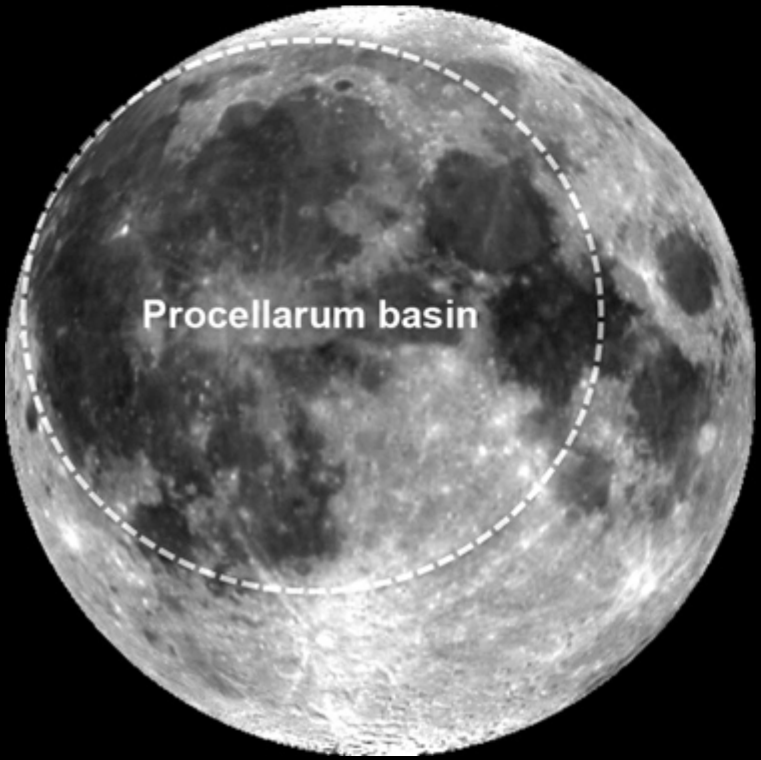
# Ejection Evolution from Giant Impact

- 60% of GI ejecta hits Moon prior to oldest Pre-Nectarian cratered terrains.
- Early impactors hitting thin, warm, mushy crust overlying magma ocean.





# Palimpsest-Like Early Basins?



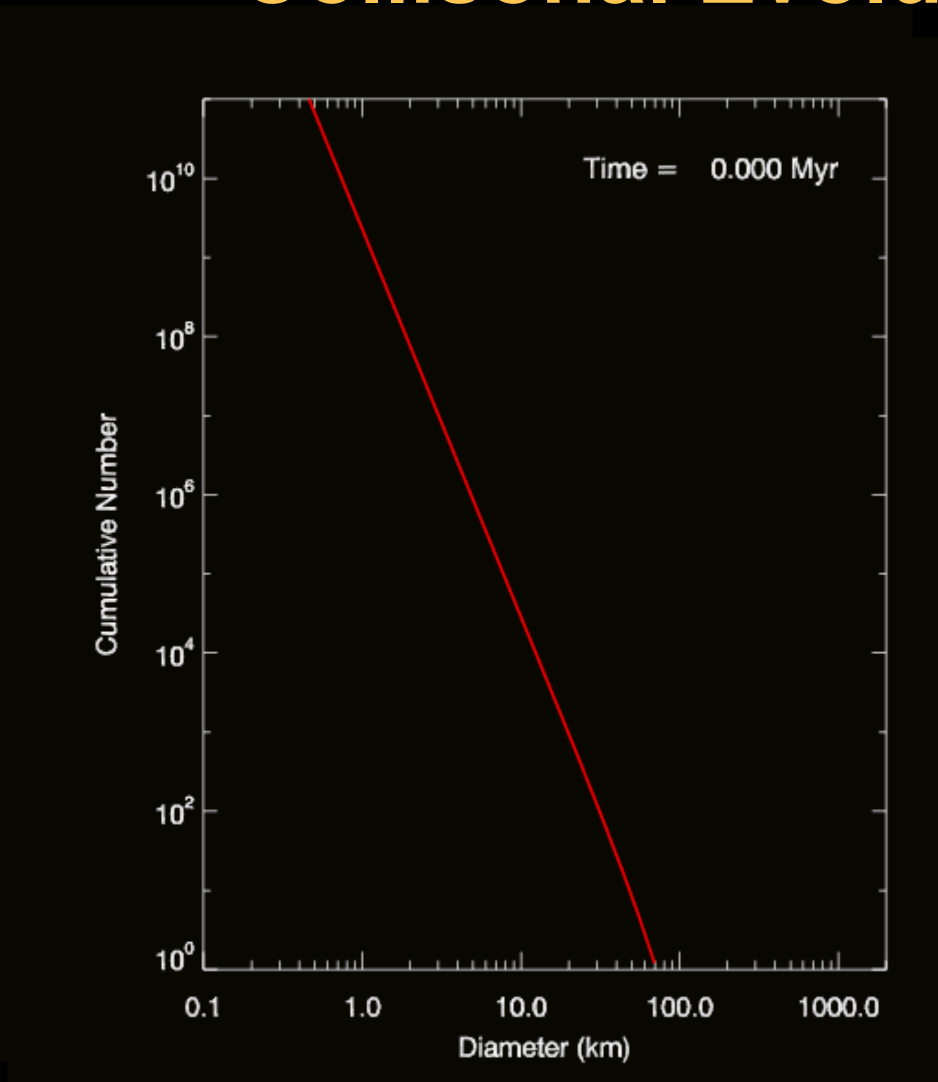


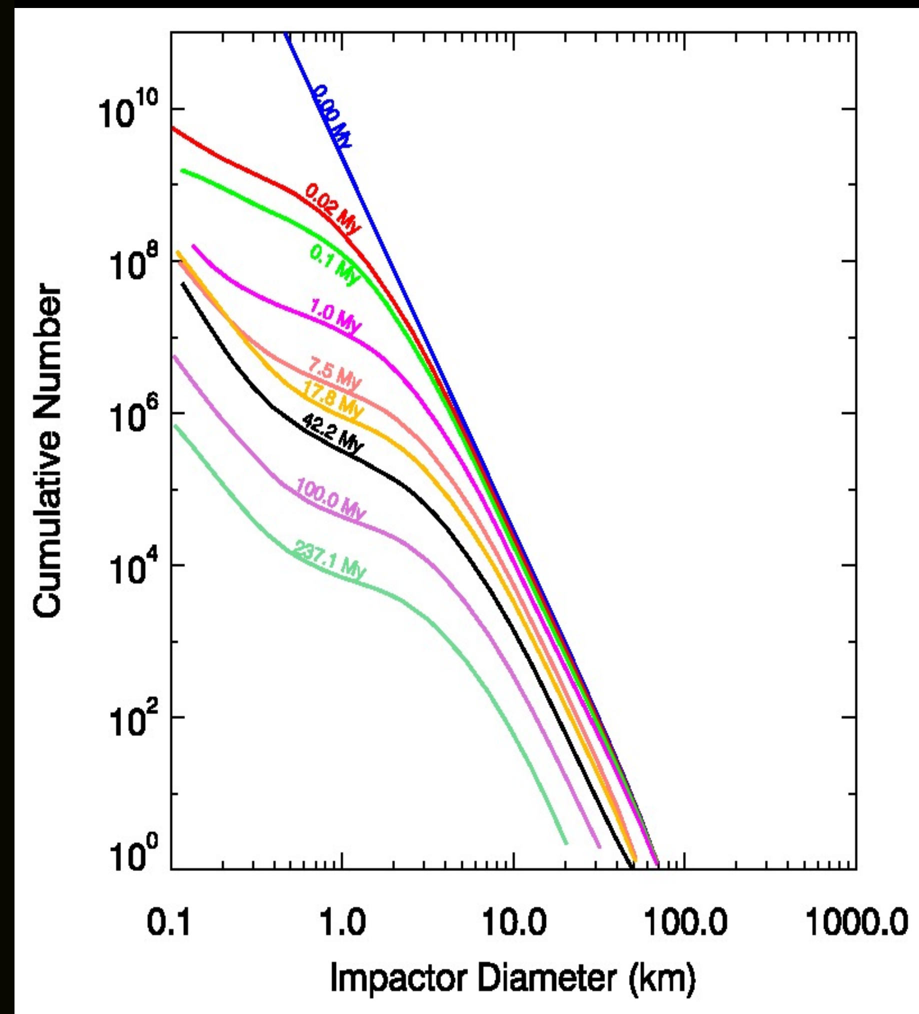
- Procellarum, Australe, and Tranquillitatis-like features:
  - If they formed shortly after giant impact, they might form palimpsest-like basins like those seen on Callisto.
  - Missing topographic and gravity signatures in GRAIL data might be explained in this manner.

# Conclusions

- GI ejecta made many Ar-Ar ages in asteroidal meteorites. They predict GI took place ~100 My after CAIs.
- GI ejecta hitting Moon may explain Pre-Nectarian impacts.
  - Oldest cratered terrain on Moon ~8 My after GI.
  - Big impacts < 8 My may make basin-like palimpsests.
- This model still <u>requires</u> a "Late Heavy Bombardment" to explain Nectarian and younger basins/craters.

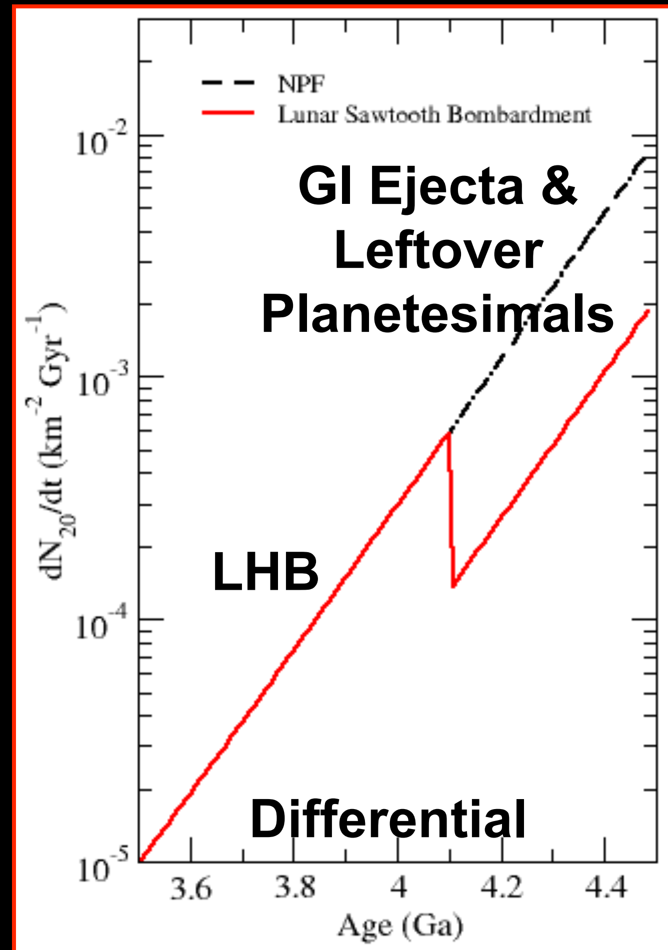
# Collisonal Evolution of GI Ejecta



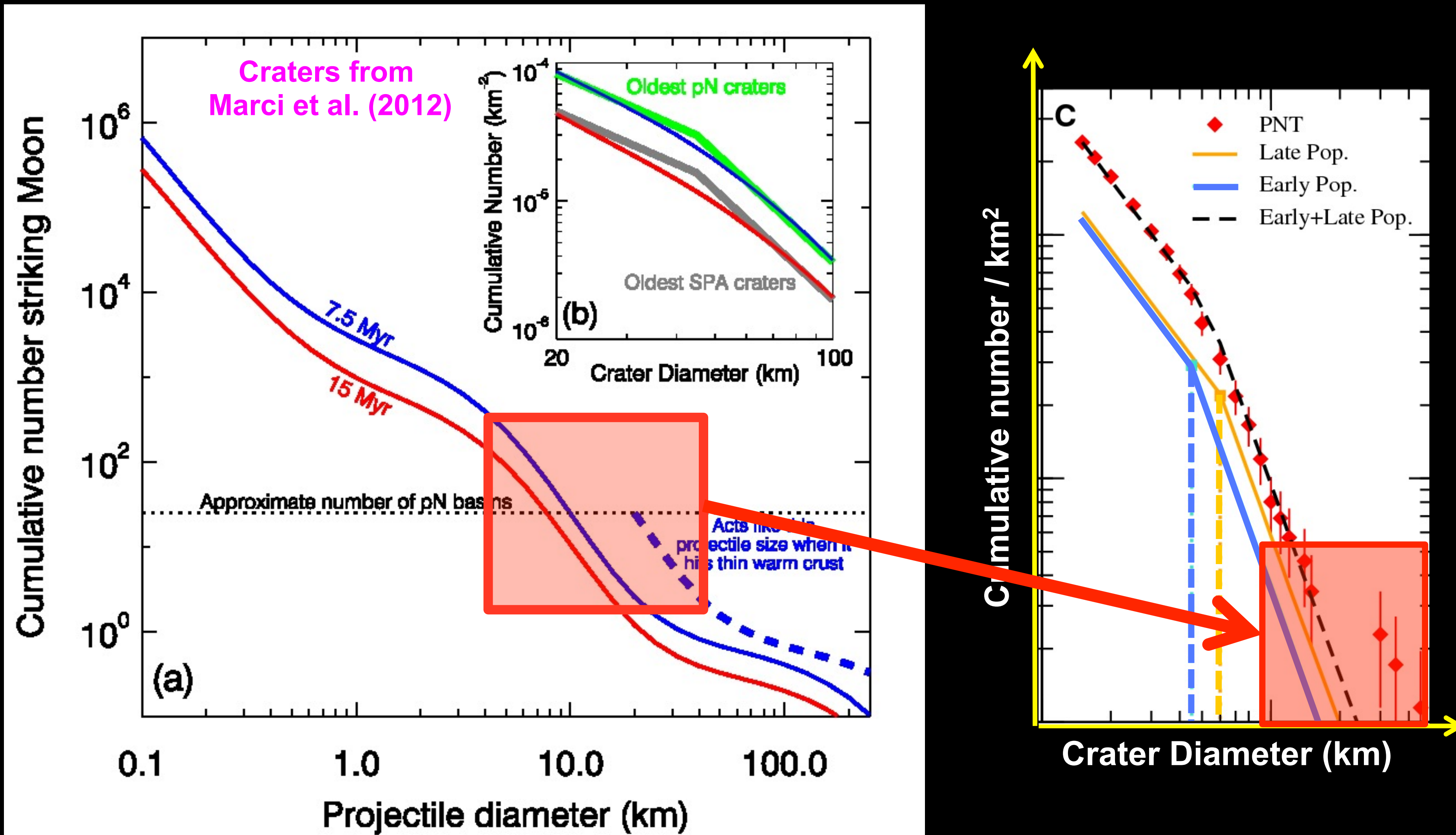

- GI ejecta loses factor of ~100 in mass in < few My.
- The wave-like shape is diagnostic of collisional evolution.

# Needed: A Late Heavy Bombardment



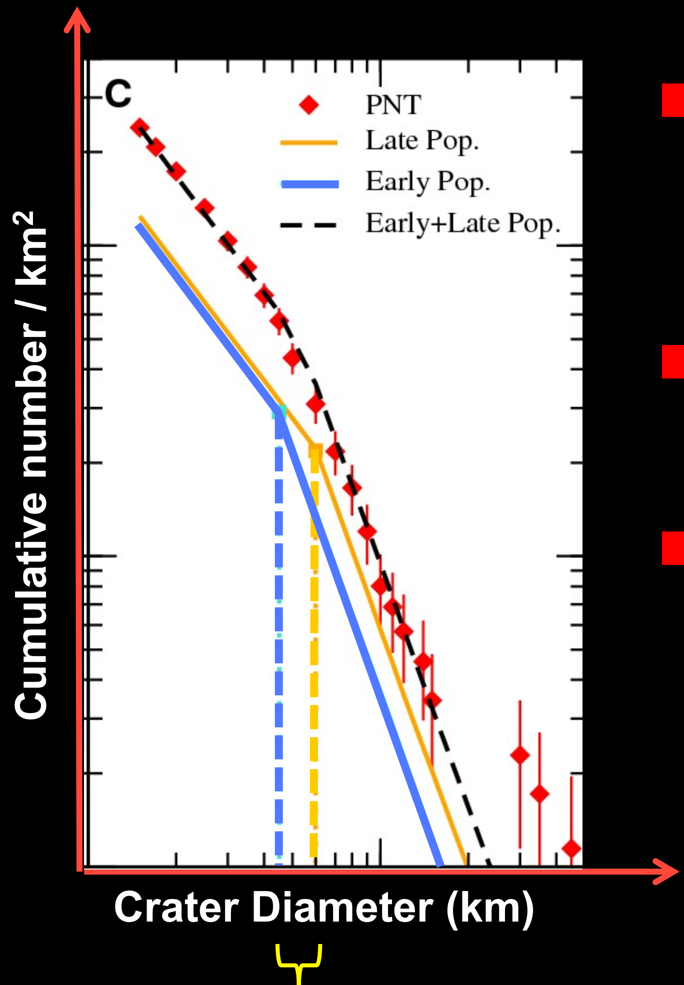

- GI ejecta has wrong impact profile and lacks sufficient mass to explain Nectarian-era and younger basins.
- We still need the Late Heavy Bombardment (< 4.1 Ga)!

# Impacts on the Early Moon




- Impacts into hot mushy crust may allow us to reproduce Pre-Nectarian basin populations

# Question #1: Early Impact Velocities

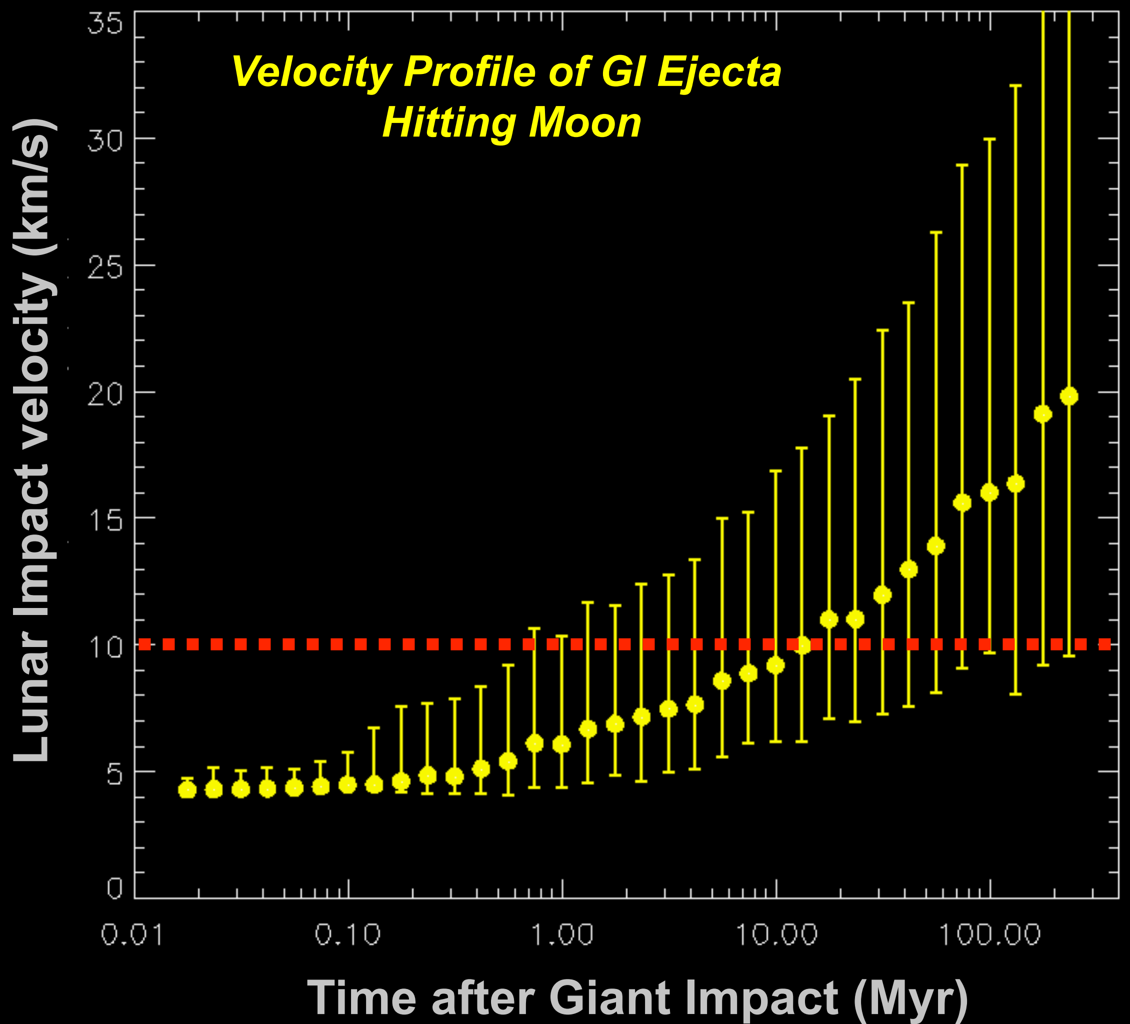



- Craters on ancient terrains suggest impact velocities ***doubled*** from early bombardment to late bombardment.
- Velocities for the "late" population predicted to be $V \sim$ 20 km/s.
- ***This suggests early craters formed at velocities V ~ 10 km/s.***
  - ***Hard to get with leftover planetesimals!***

$$V_{Late} / V_{Early} \sim (60 \text{ km}/45 \text{ km})^{(1/0.44)} \sim 2$$

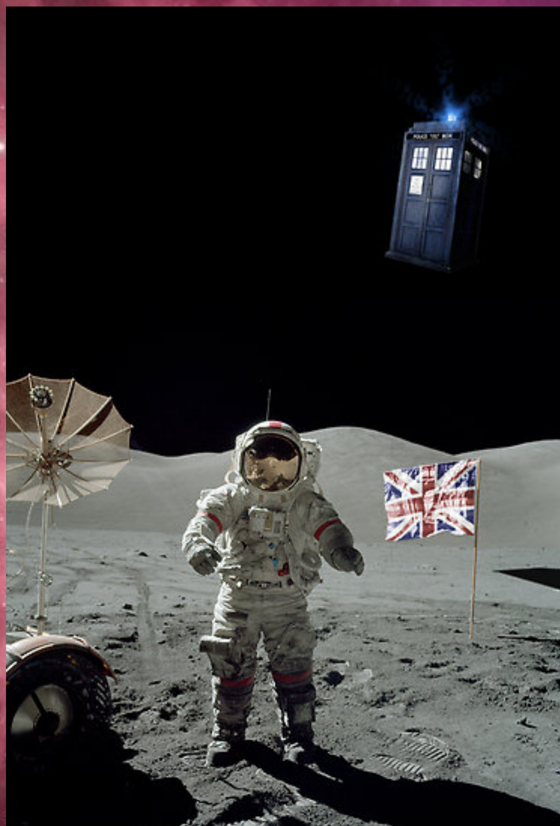
Marchi, Bottke et al. (2013)

# Giant Impact Ejecta Evolution




- Lunar impact velocities V < 10 km/s for ~20 My after GI.

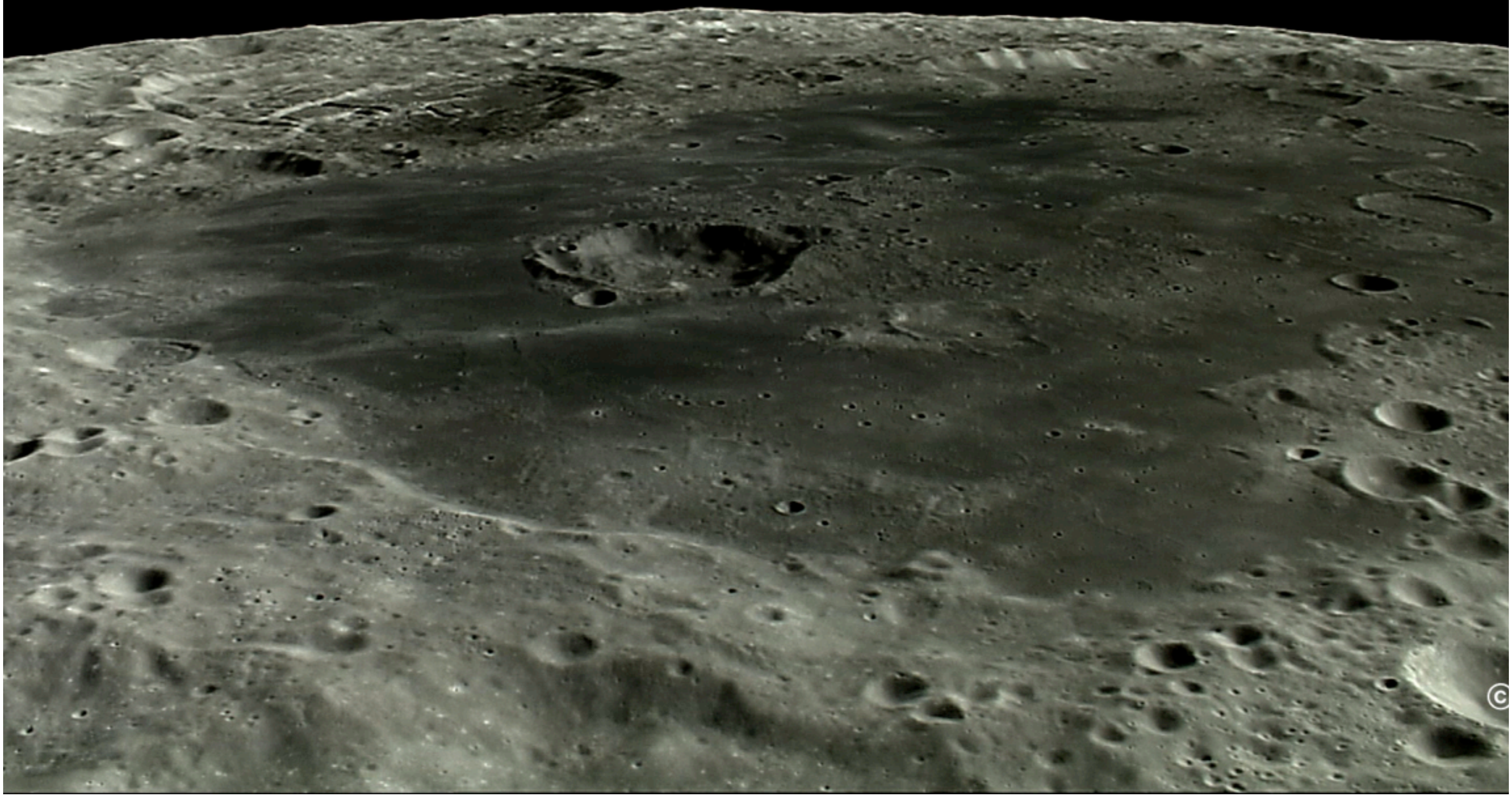
# Words From a Great Philosopher…




**"Never ignore a coincidence…"**

**"… unless you're busy, in which case, always ignore a coincidence".**

# Part 1:
# Using Meteorites to Find the Age of the Moon-Forming Event



# Part 2:
# Giant Impact Ejecta and the Earliest Bombardment of the Moon