Reconciling Asteroid Collision Ages With the Late Heavy Bombardment

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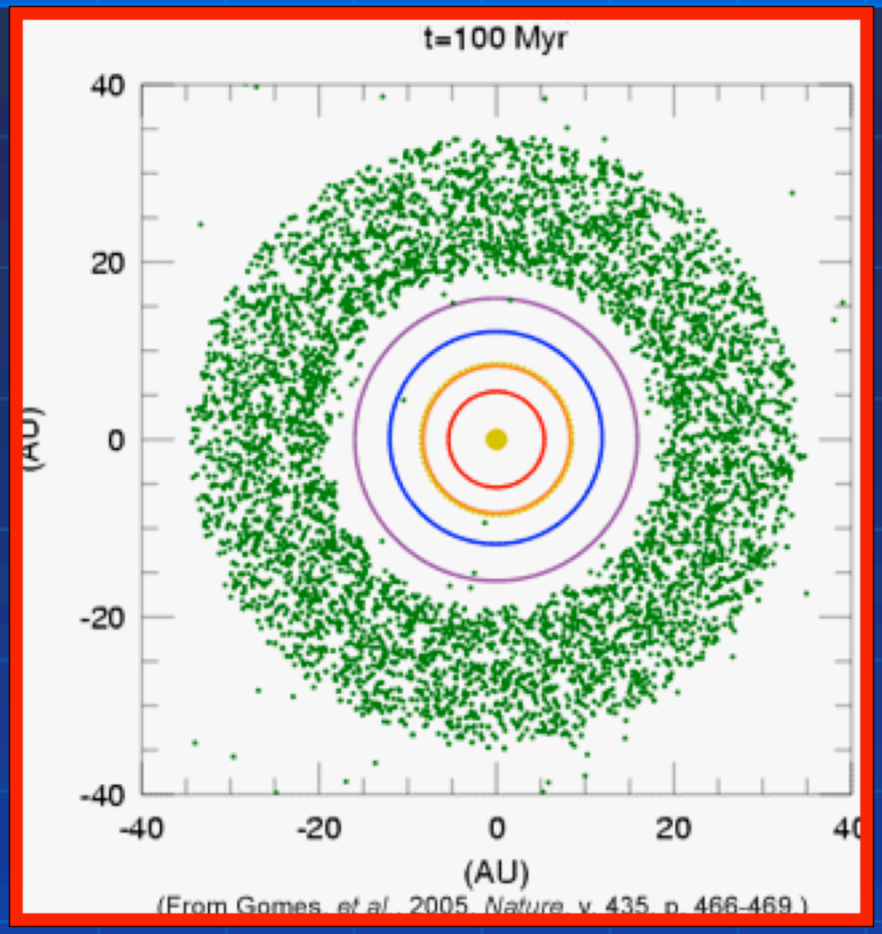
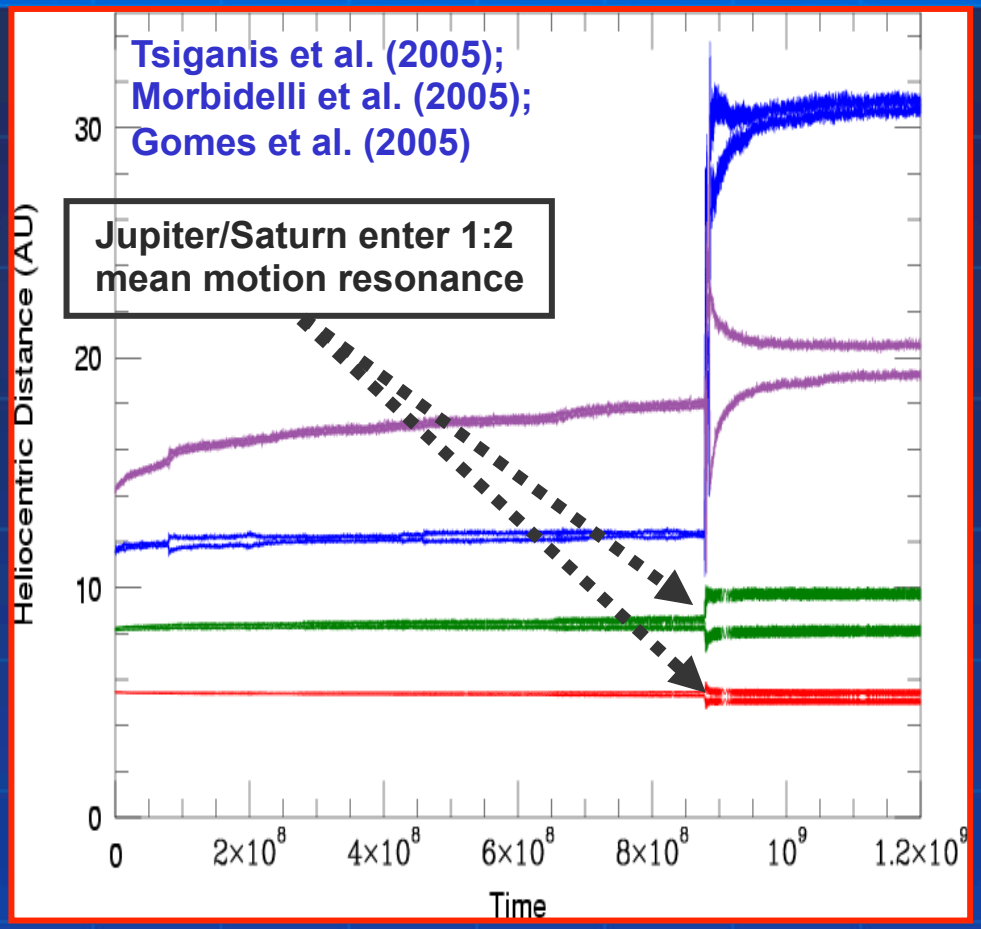
Prologue:
The Late Heavy Bombardment
“In only 90 seconds…”
Artwork from Dan Durda and LPI/CLSE

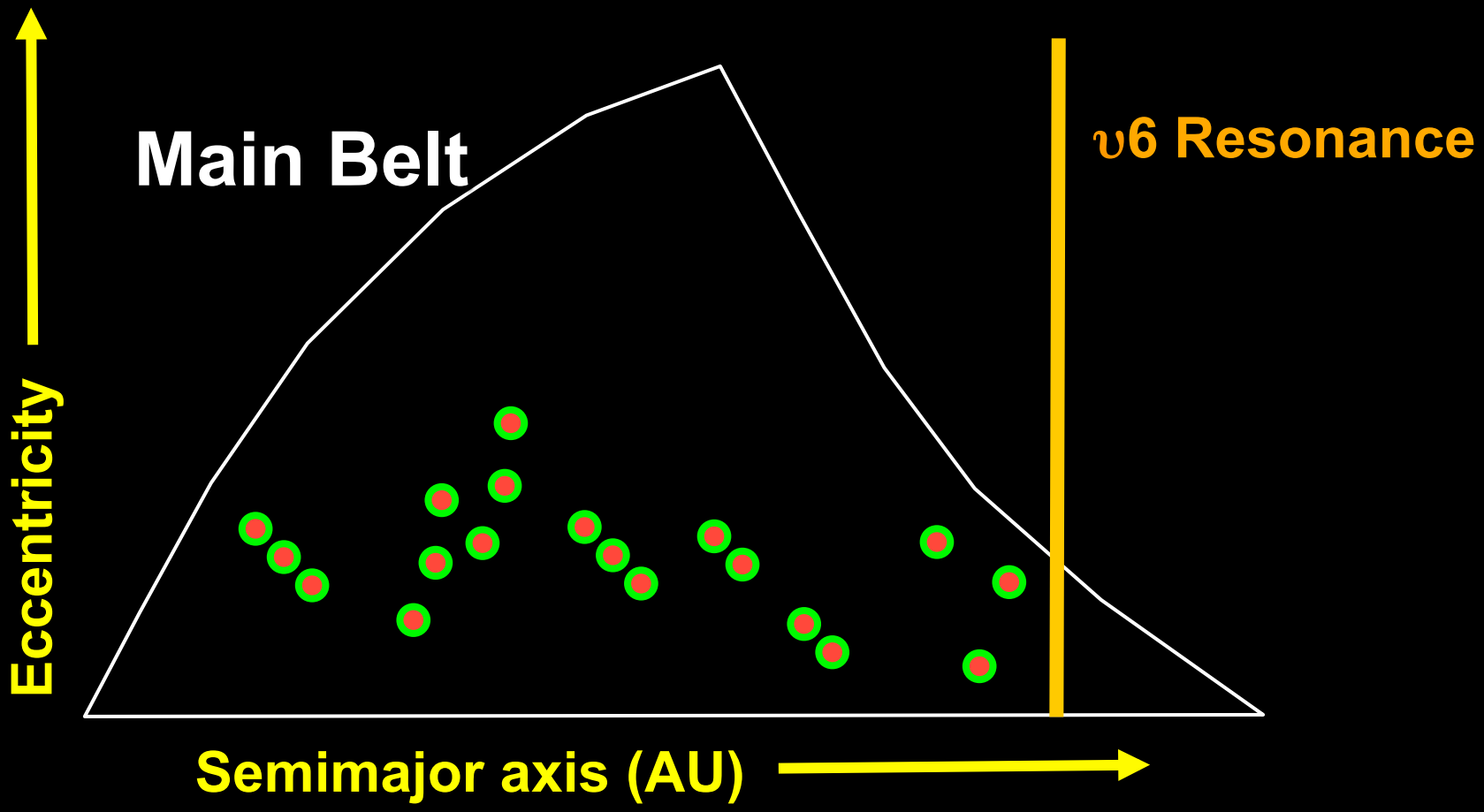
The Nice Model and the LHB





- The Nice model describes how Jupiter-Neptune migrated to their current orbits after a delay of many hundreds of My.

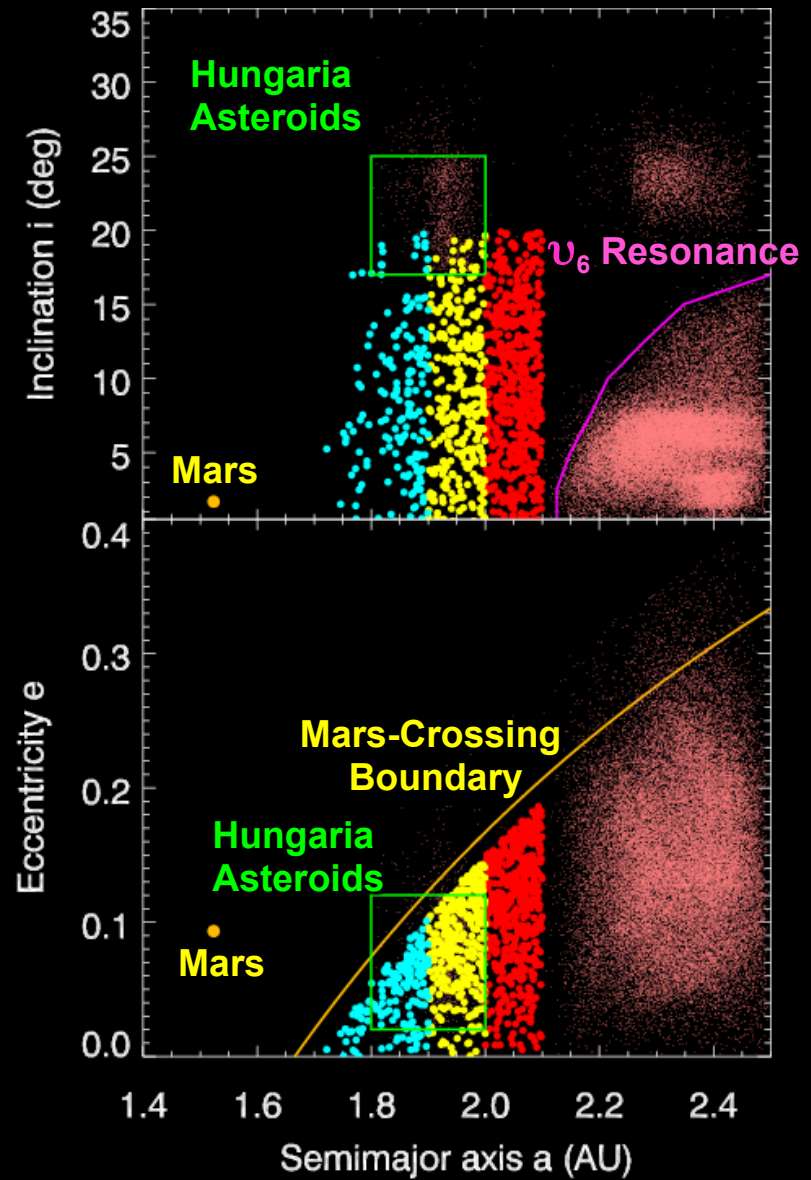
Effects of Sweeping υ6 Resonance



- Main belt > 4 times more massive for hundreds of My.
- Many asteroids pushed onto deep planet-crossing orbits.

Levison et al. (2001); Gomes et al. (2005); Minton and Malhotra (2009); Morbidelli et al. (2010)

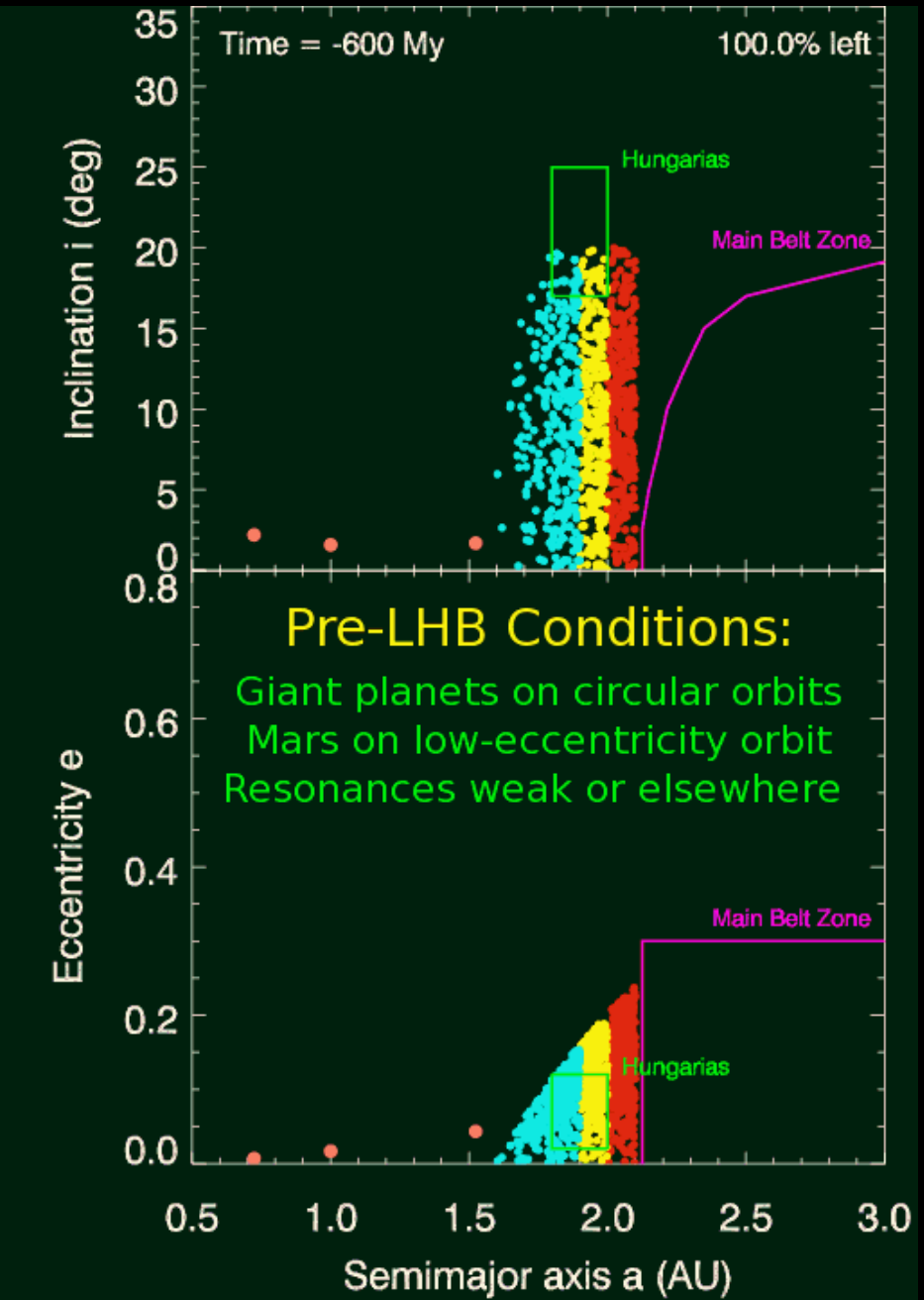
An Extension to the Asteroid Belt (E-Belt)



- Test bodies placed between Mars and the main belt.
- How affected by Nice model?
  - Giant planets on circular orbits for hundreds of My.
  - Then…late giant planet migration!

Bottke et al. (2012), Nature.

What is “Nice” About the E-Belt



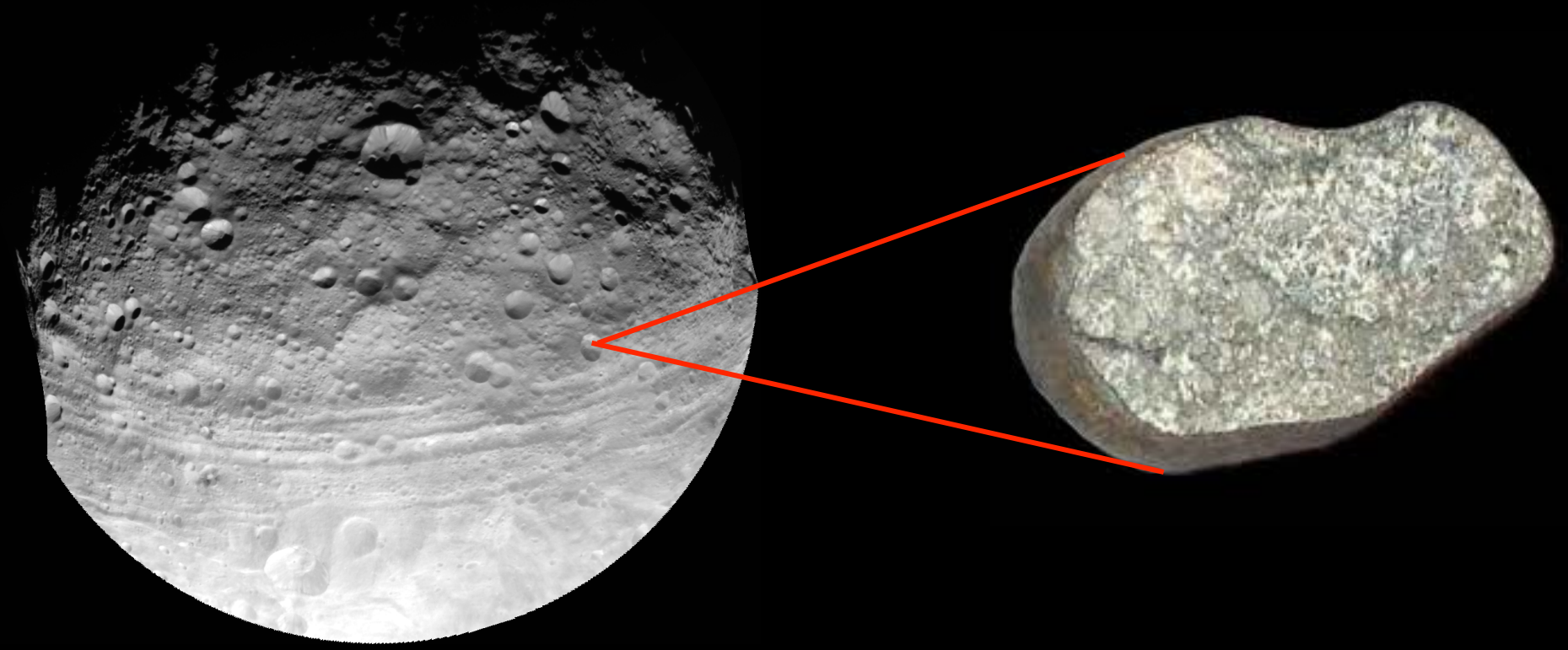
Objects ~10 × more likely to hit Moon than main belt asteroids!
(More bang for the buck!)

Many young lunar basins may come from this population.
(Long decay!)

Great impact profiles!
Matches constraints from Earth & Moon

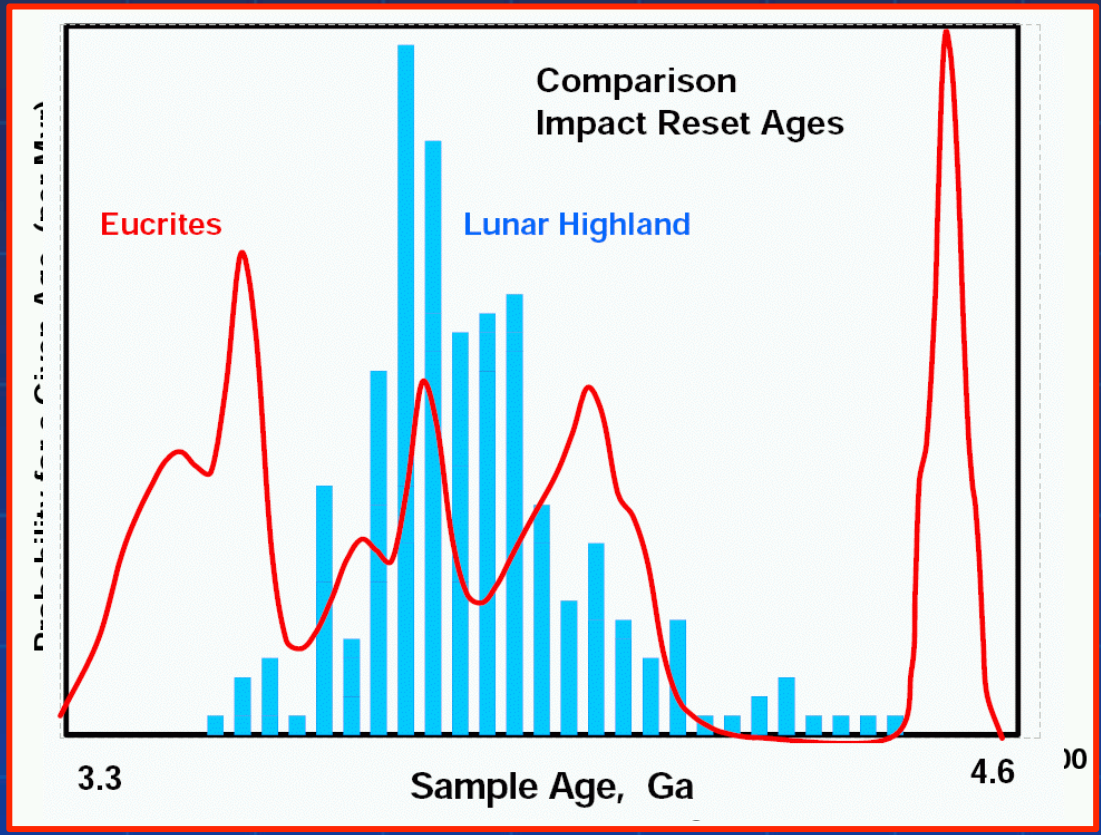
Bottke et al. (2012), Nature.

How Did the Late Heavy Bombardment Affect (4) Vesta and the HEDs?



- We turn to the HEDs, which can tell us the history of Vesta and perhaps that of the main asteroid belt itself.

Ar-Ar Shock Degassing Ages for Eucrites

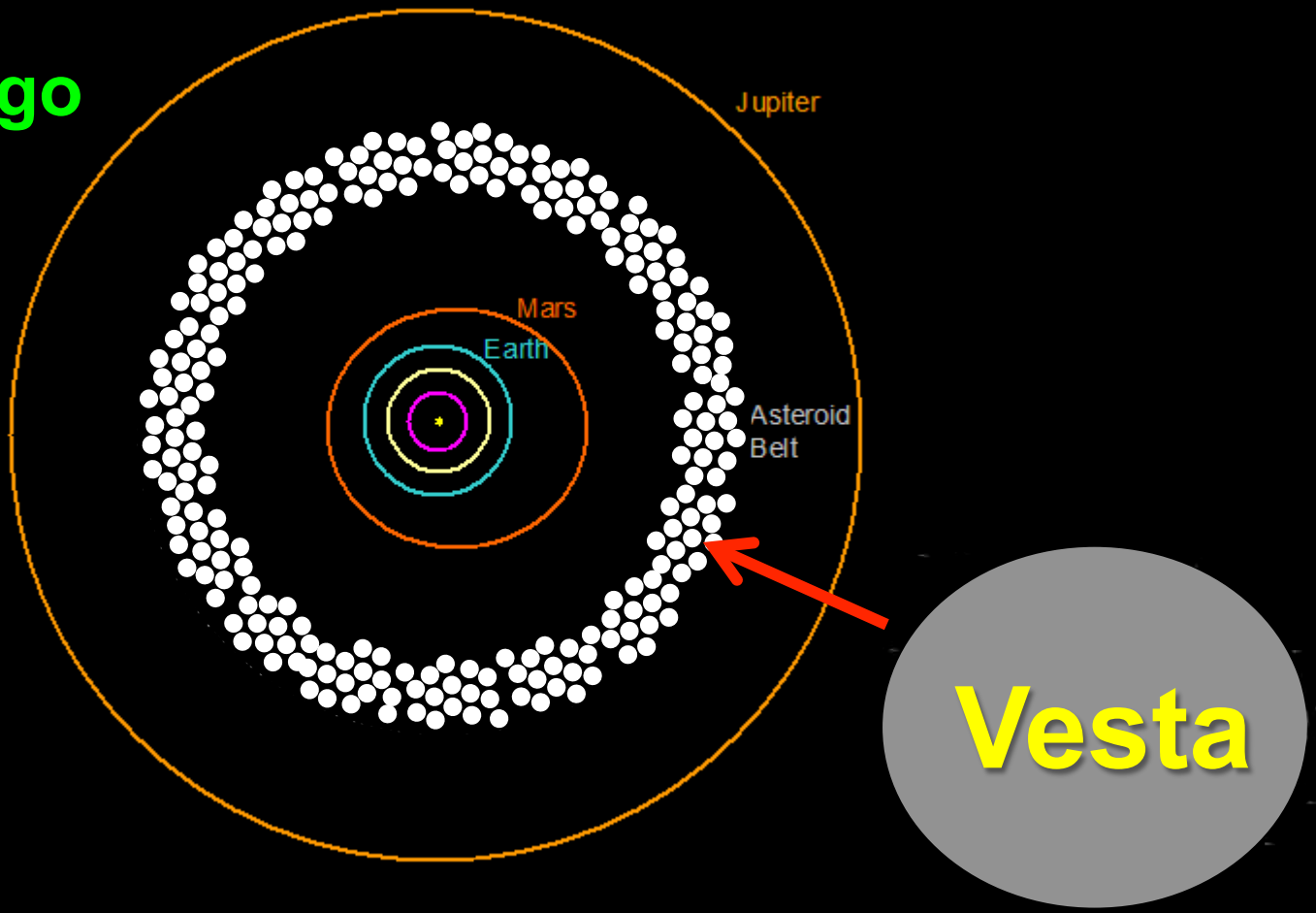


- ^{39}Ar-^{40}Ar chronometer can be reset by moderate heating.
  - Few events between 4.1-4.4 Ga, though many between 3.5-4.1 Ga.

Bogard (1995; 2011); Bogard and Garrison (2003); Cohen et al. (2007)

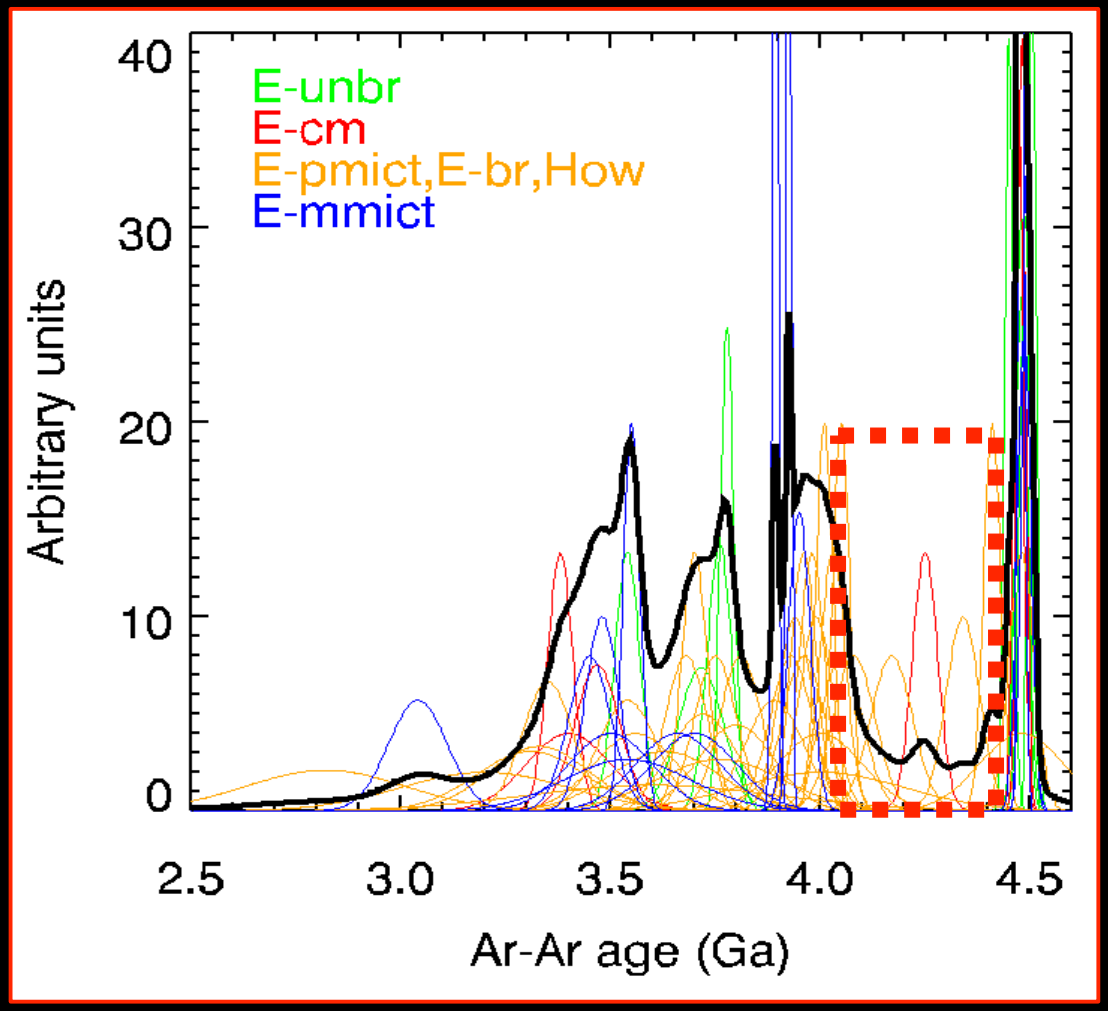
Problem #1:

4.1-4.5 Gy Ago



- **The Nice model predicts main belt massive until ~4.1 Ga. Vesta should have been beaten up!**

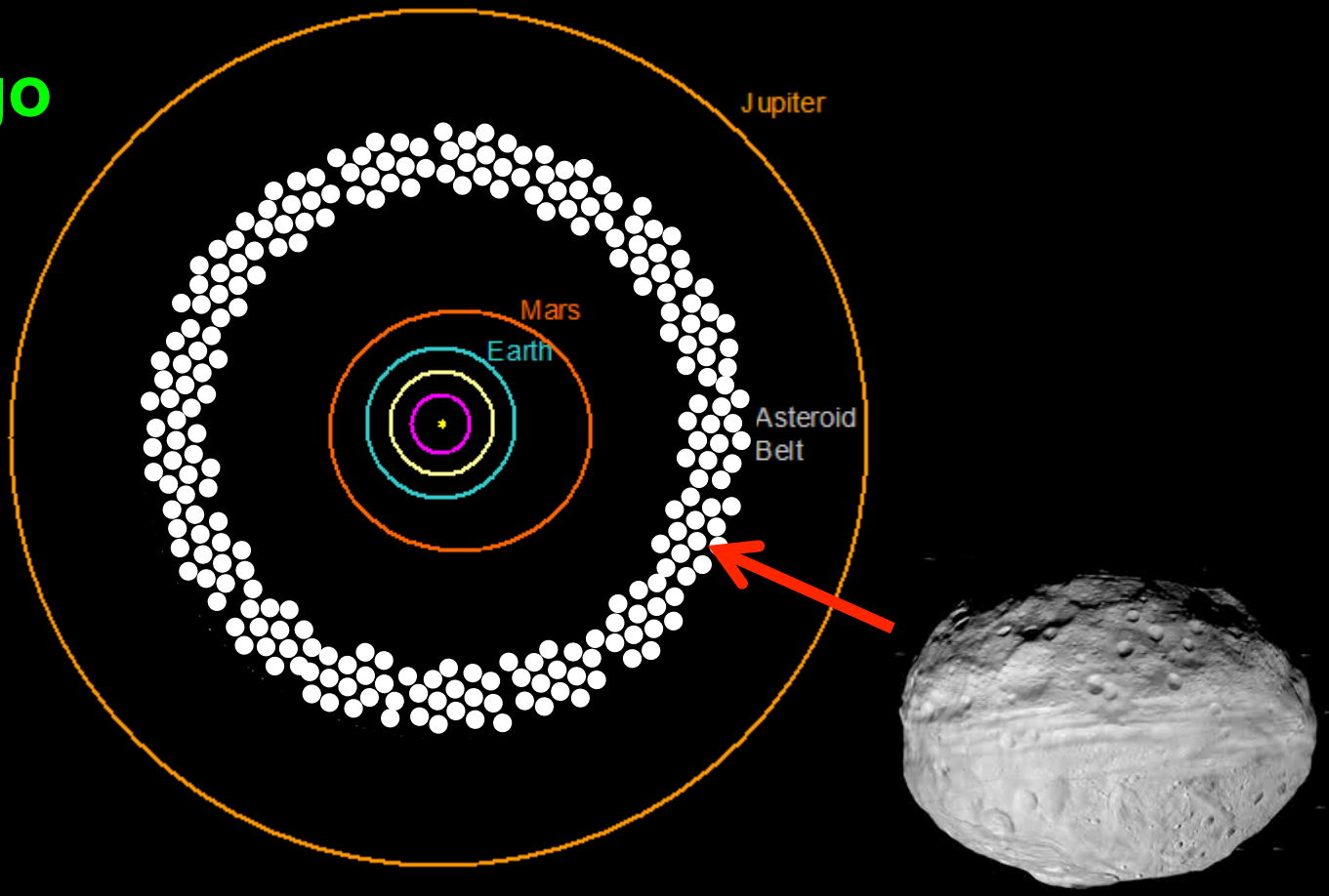
Problem #1:



- The Nice model predicts main belt massive until ~4.1 Ga. Vesta should have been beaten up!
- Why do we see a "gap" in Ar-Ar from 4.1-4.4 Ga?

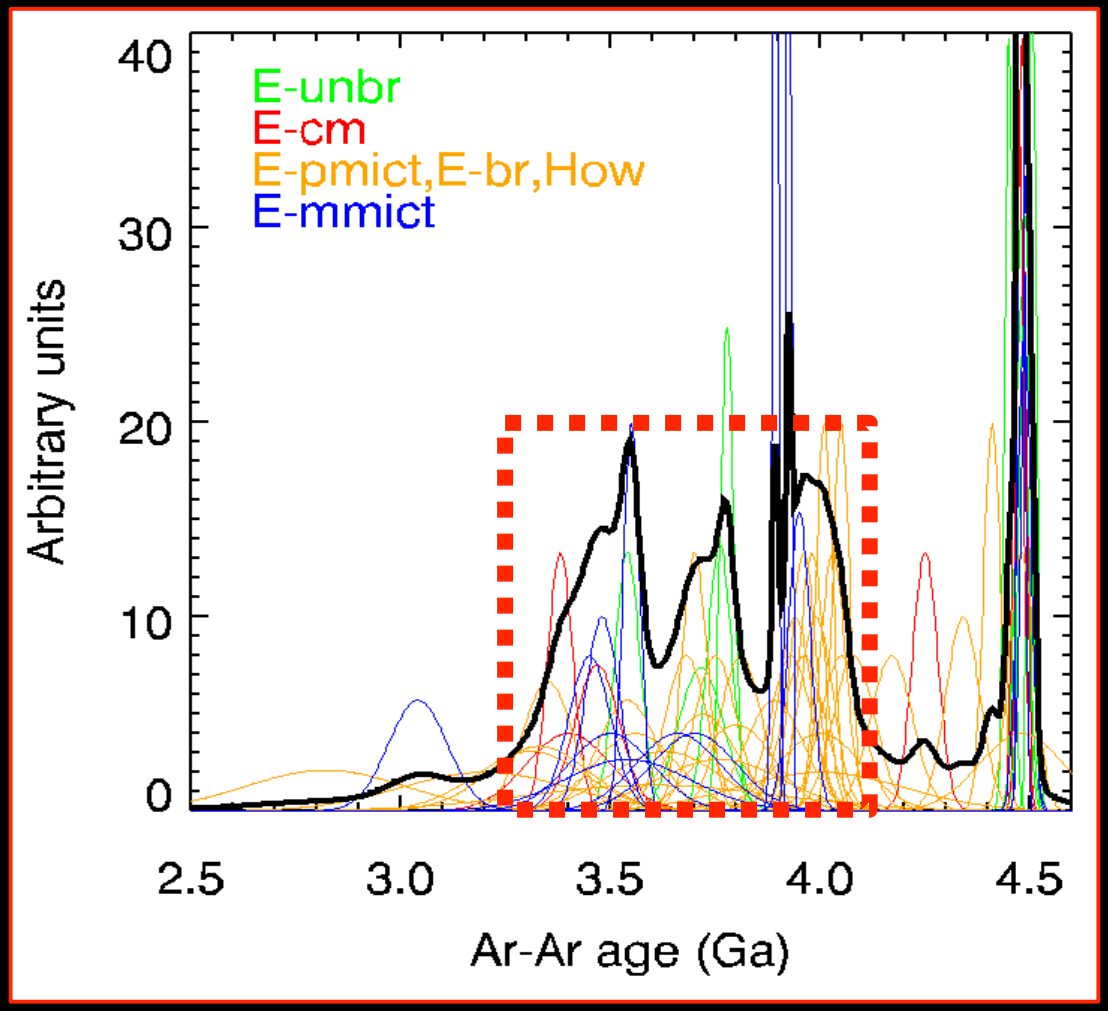
Problem #2:

< 4.1 Gy Ago



- **To explain lunar basins, main belt loses much of its mass ~4.1-4.2 Ga. This eliminates many potential impactors!**

Problem #2:



- To explain lunar basins, main belt loses much of its mass ~4.1-4.2 Ga. This eliminates many potential impactors!
- Why do we see so many Ar-Ar ages between 3.5-4.1 Ga?

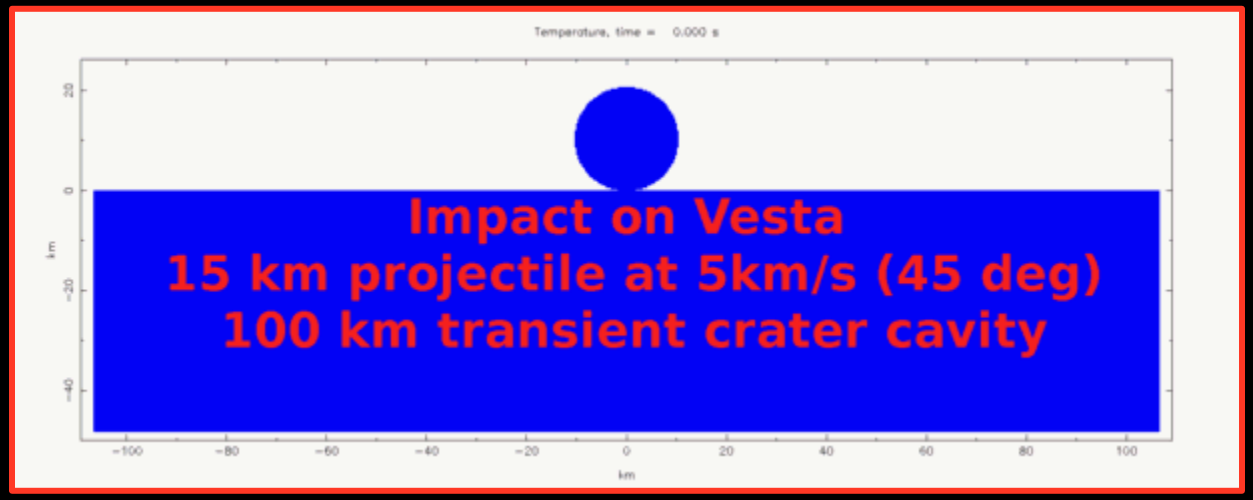
How Do We Make Ar-Ar Reset Ages?

- Ar-Ar reset ages are likely produced by crater formation.
- 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 on Vesta?

Impact Simulations on Vesta

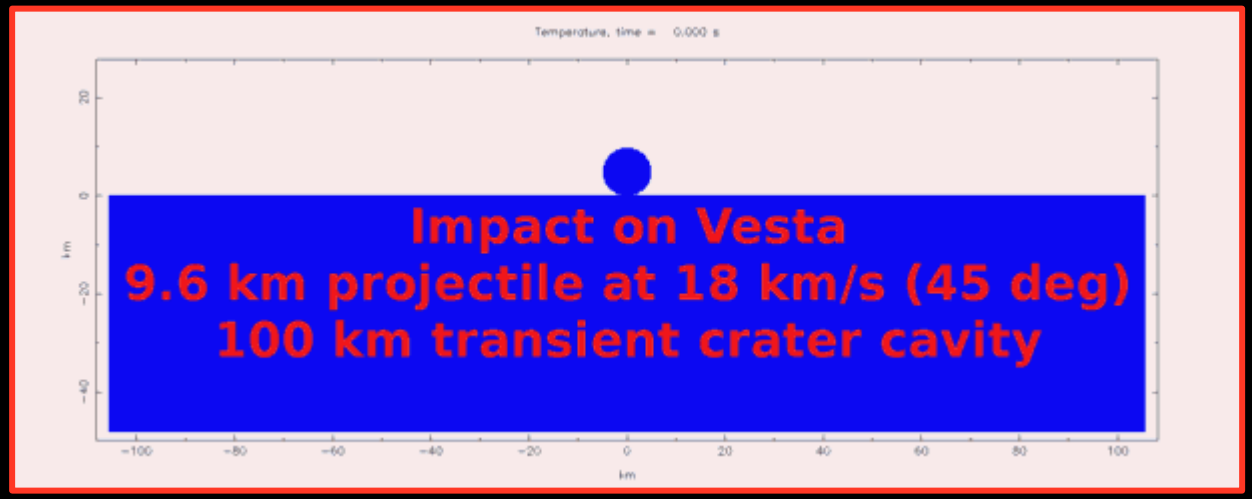
Big Projectile

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

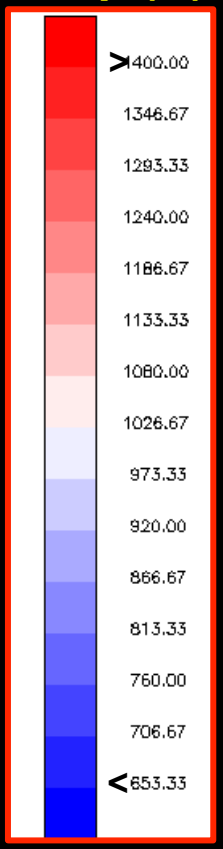


Small Projectile

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



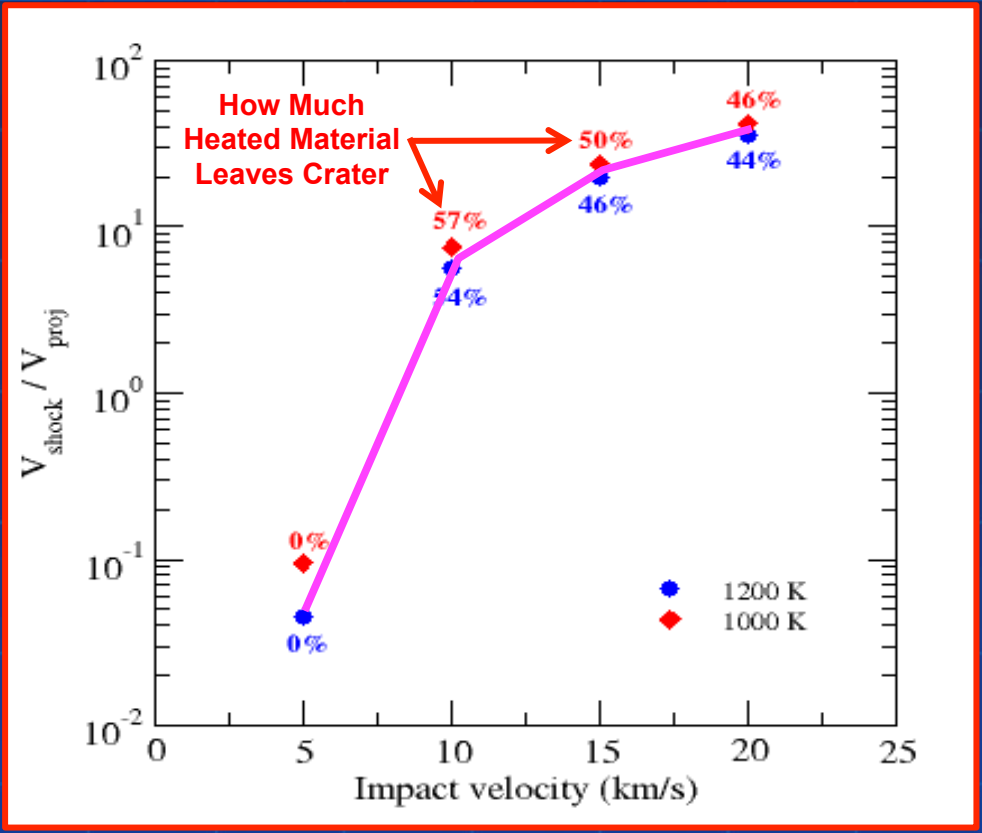
Temp (K)

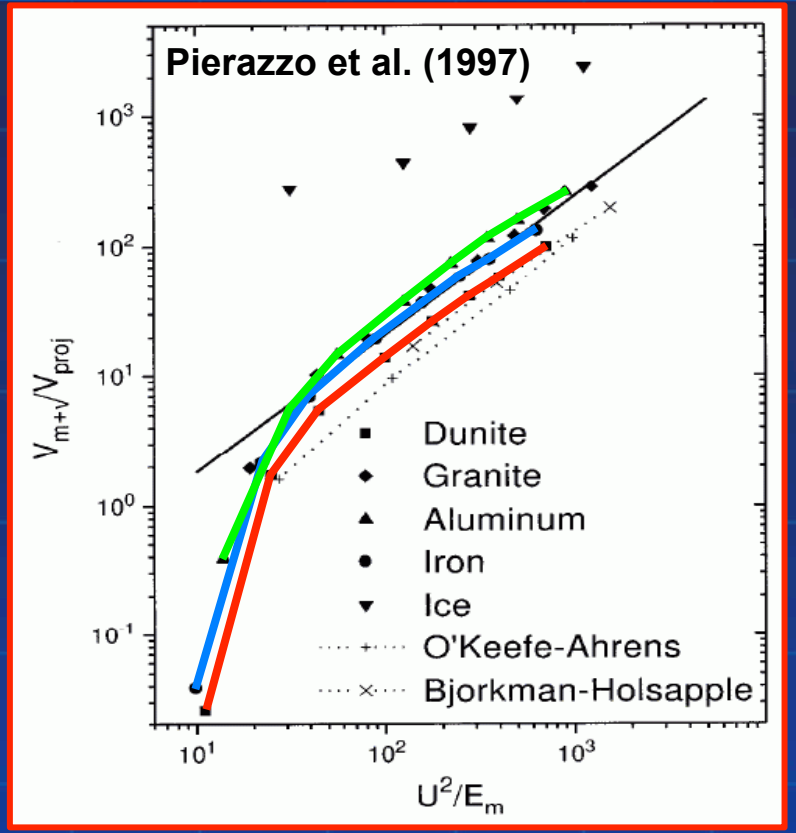


- **High velocity impacts produce higher temperatures and heat a larger volume of material.**

Simulations from Kai Wunnemann

Impact Heating Trends

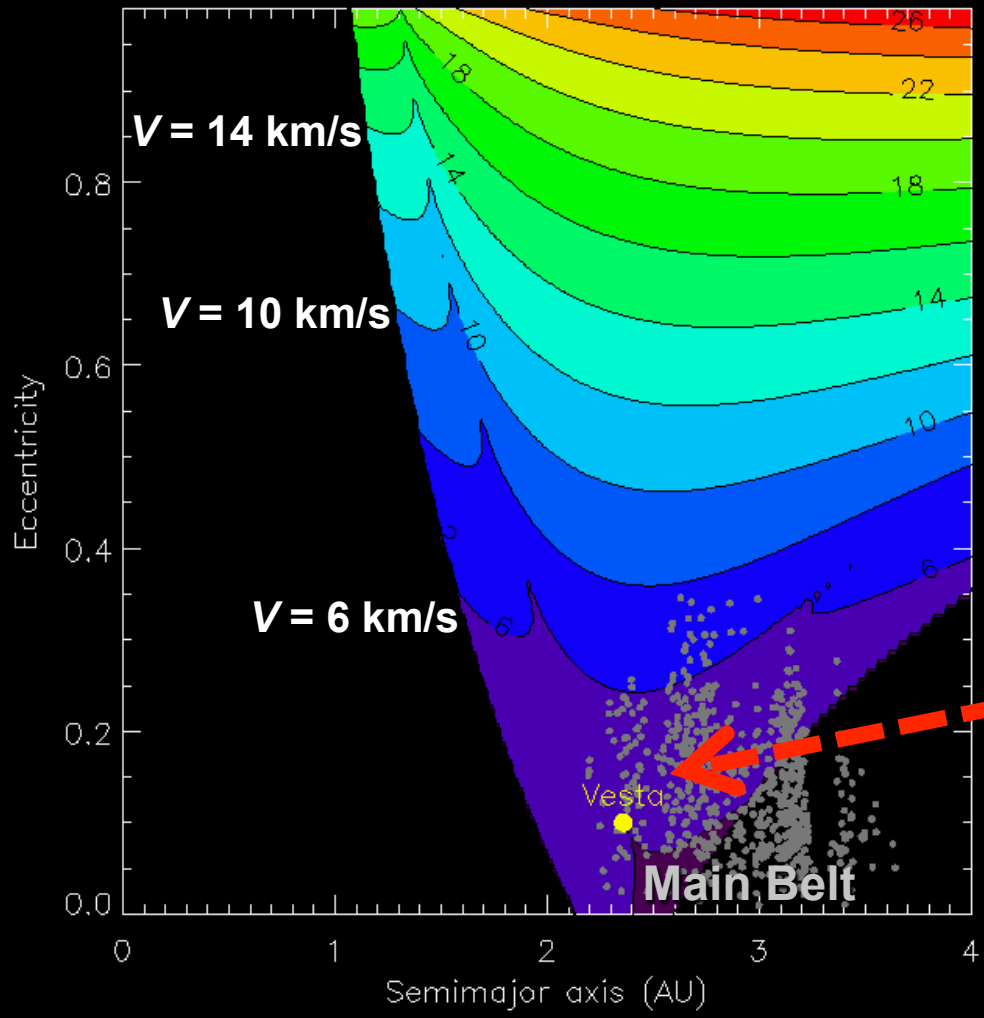


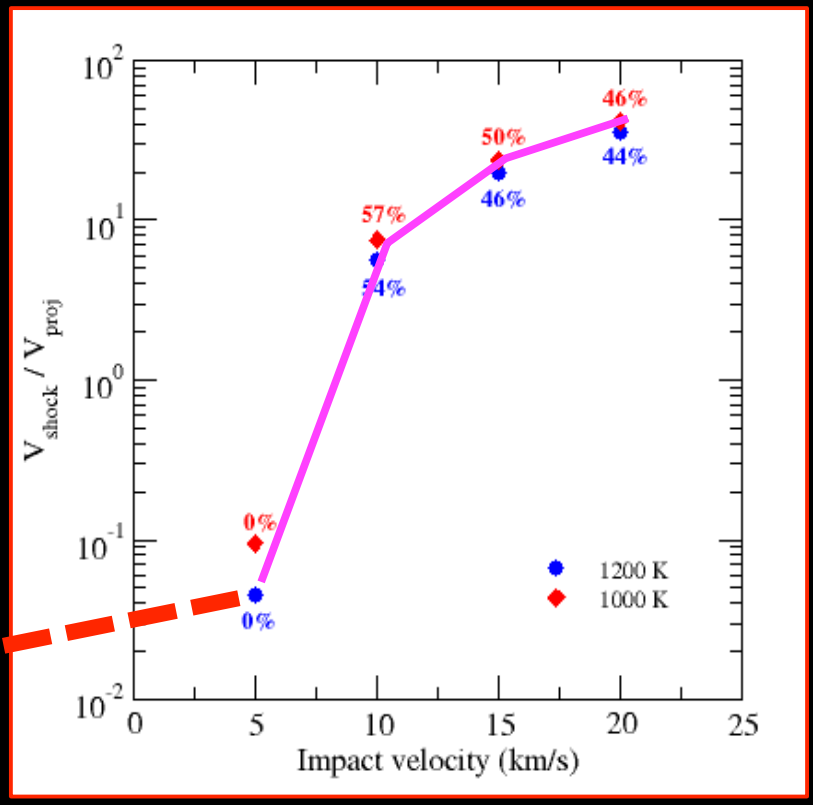


- **V < 5 km/s**: Relatively little heating takes place.
- **V > 10 km/s**: Volume of heated material increases!
- **V > 15 km/s**: Heated material scales with impact energy.

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

Impact Velocities on Vesta

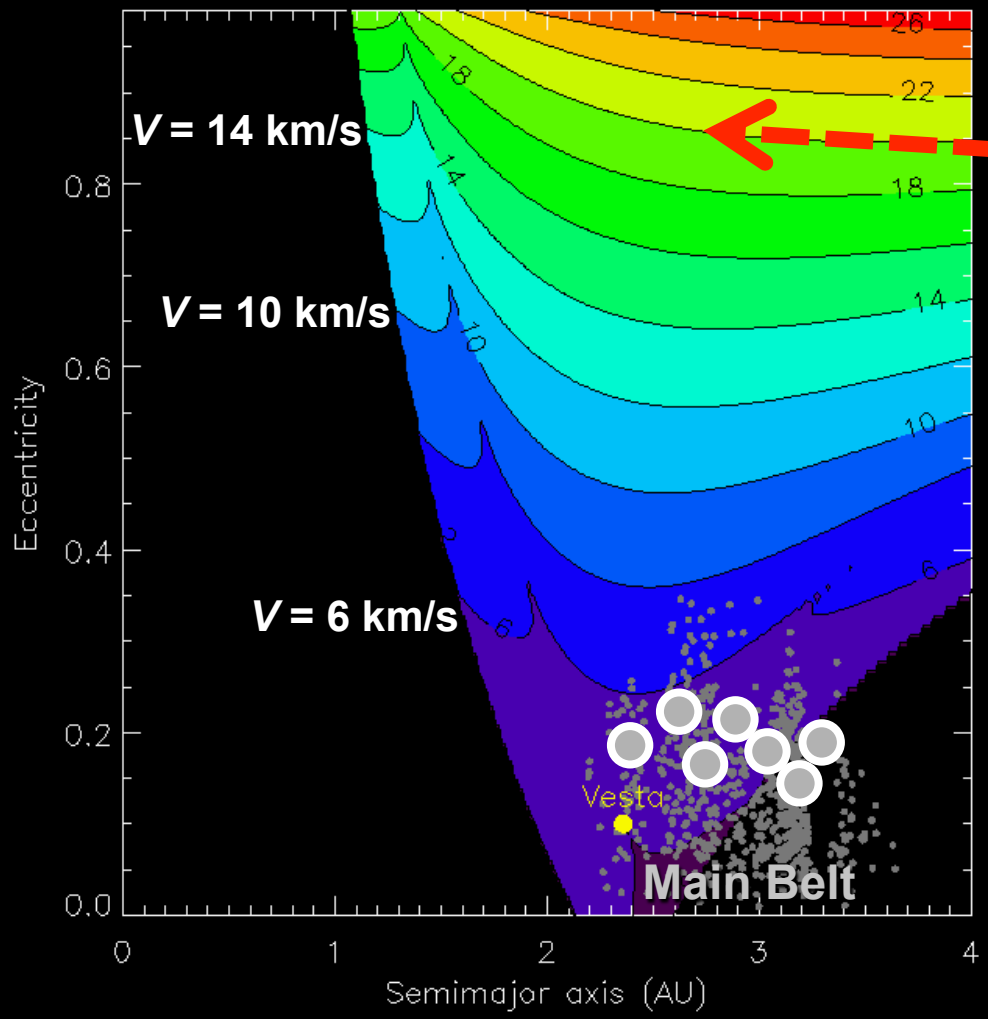


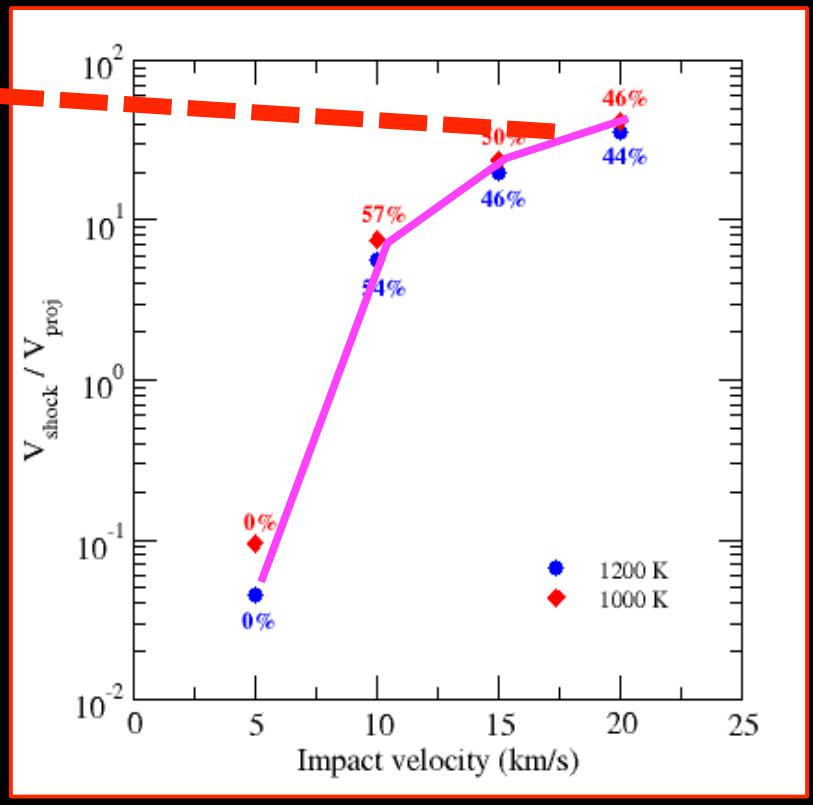


- Most main belt asteroids strike Vesta at $V < 6$ km/s.
- These events produce relatively little heating.

Bottke et al. (1994)

Impact Velocities on Vesta

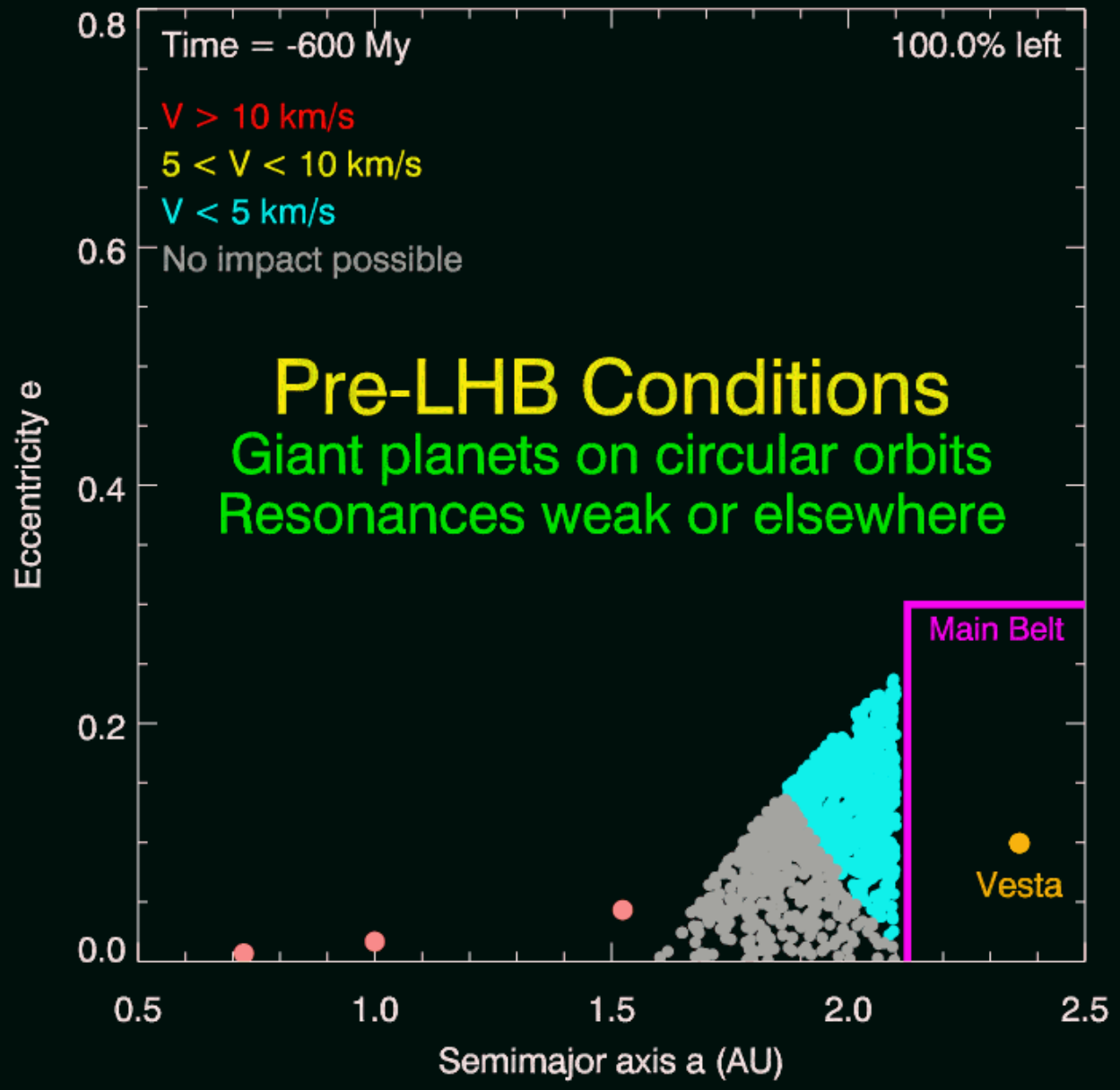


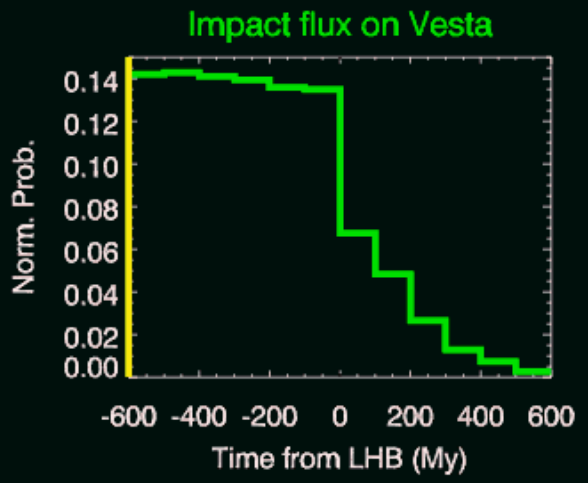


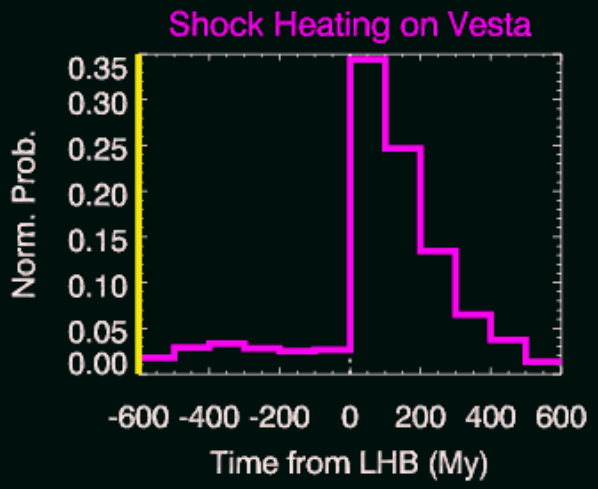
- High *V* comes from high *e* orbits, which can still hit Vesta!
- These impacts may produce ~1000 times more heating!

Bottke et al. (1994)

The LHB and Impact Heating on Vesta

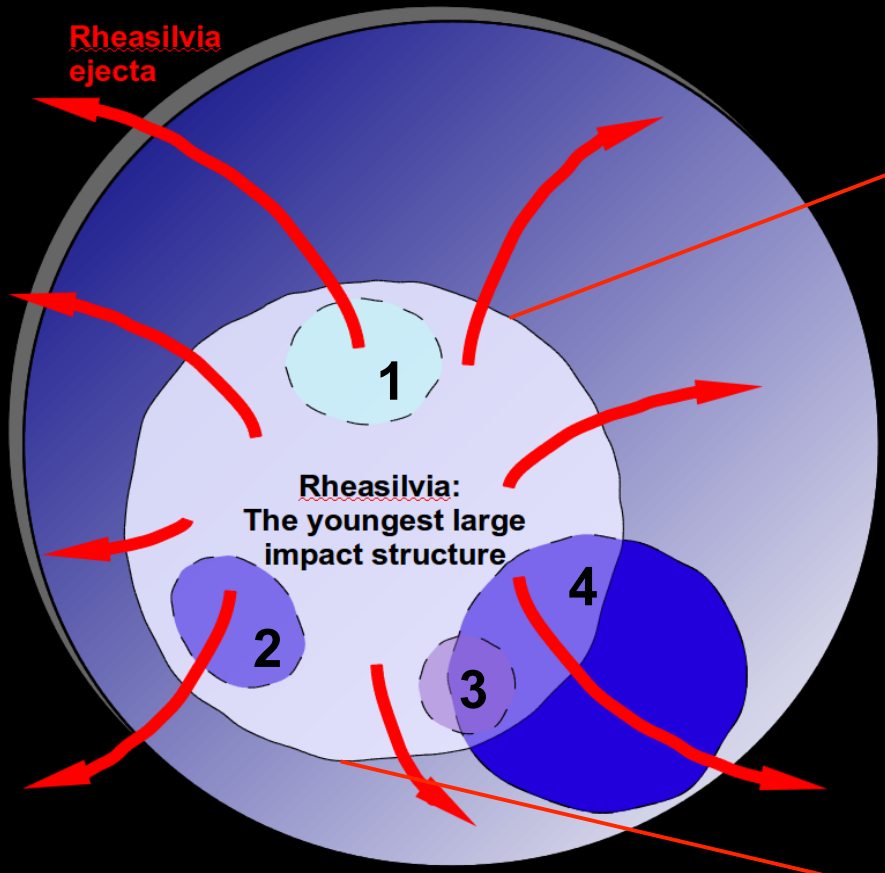


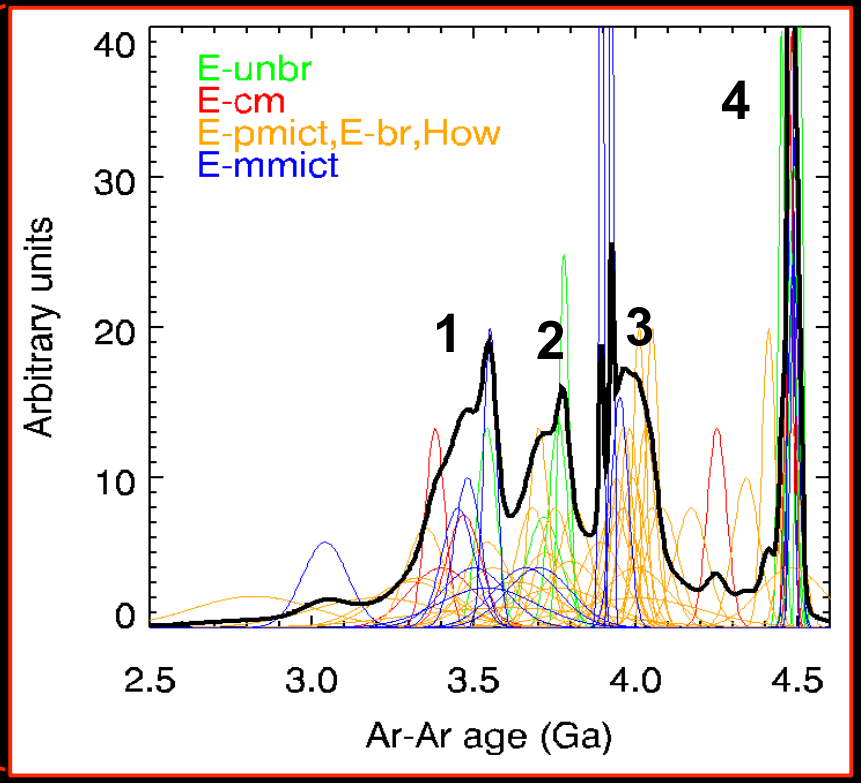




Vesta's Impact History

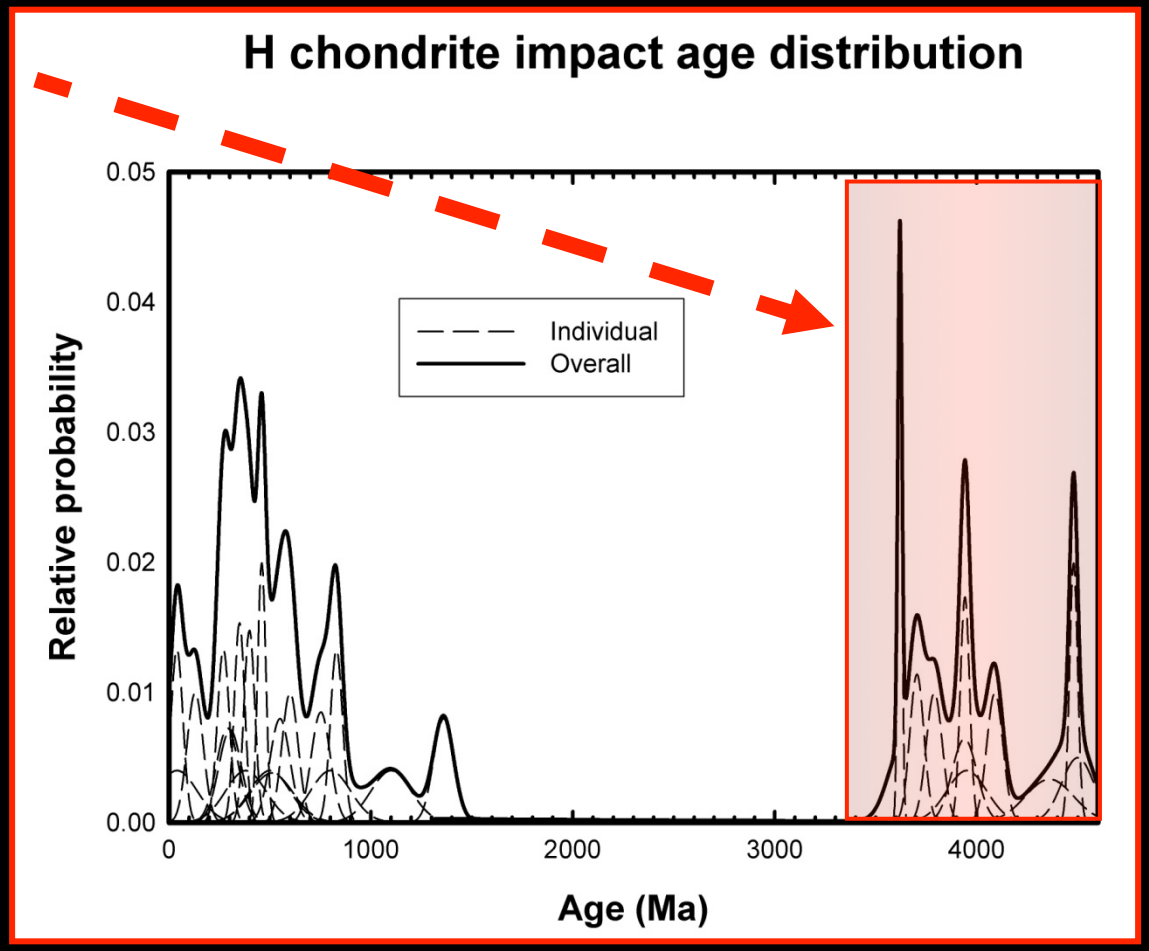
- **Material with LHB ages:**
  - Ejected by Rheasilvia ~1 Ga.
  - Now sitting in Vesta family.





Ar-Ar Ages Mark the Start of the LHB!

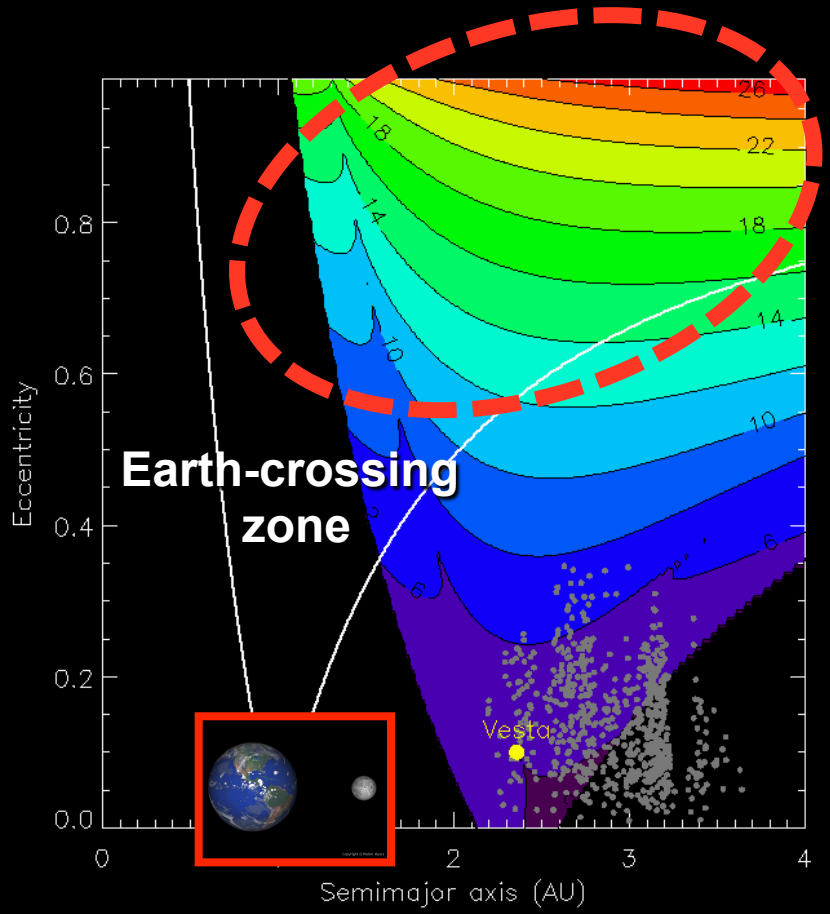
Impact History on H Chondrite Parent Body

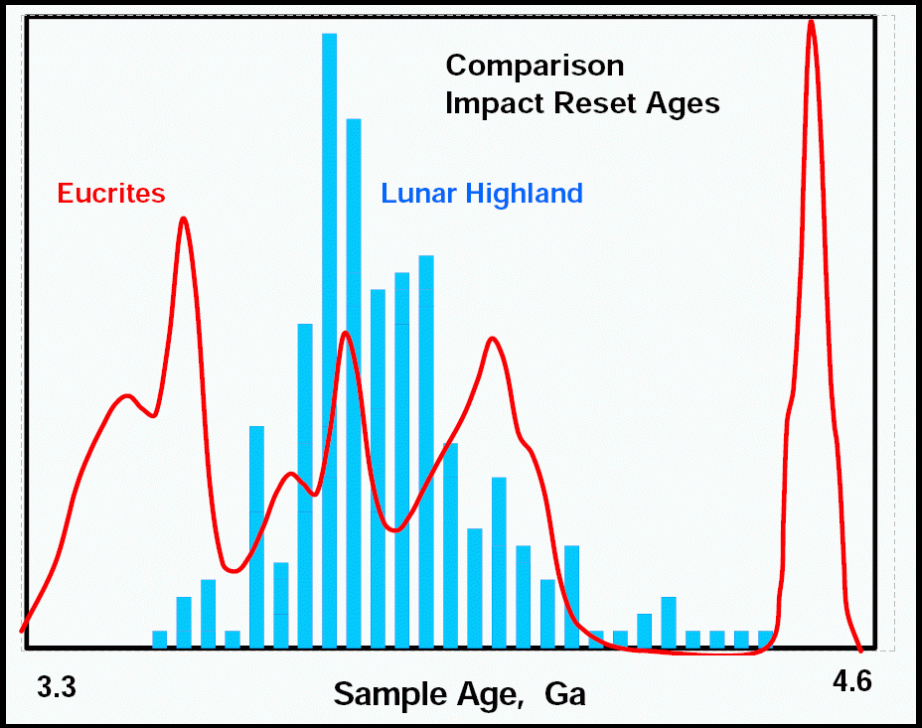


Similar Ar-Ar Trends in H Chondrites!

Swindle et al. (2009; 2012)

Similar Ar-Ar Ages on Vesta and Moon?





- The same population makes Ar-Ar reset ages on Vesta, the H chondrite parent body, and the Moon.

Bogard (1995; 2011); Bogard and Garrison (2003); Cohen et al. (2007)

Conclusions

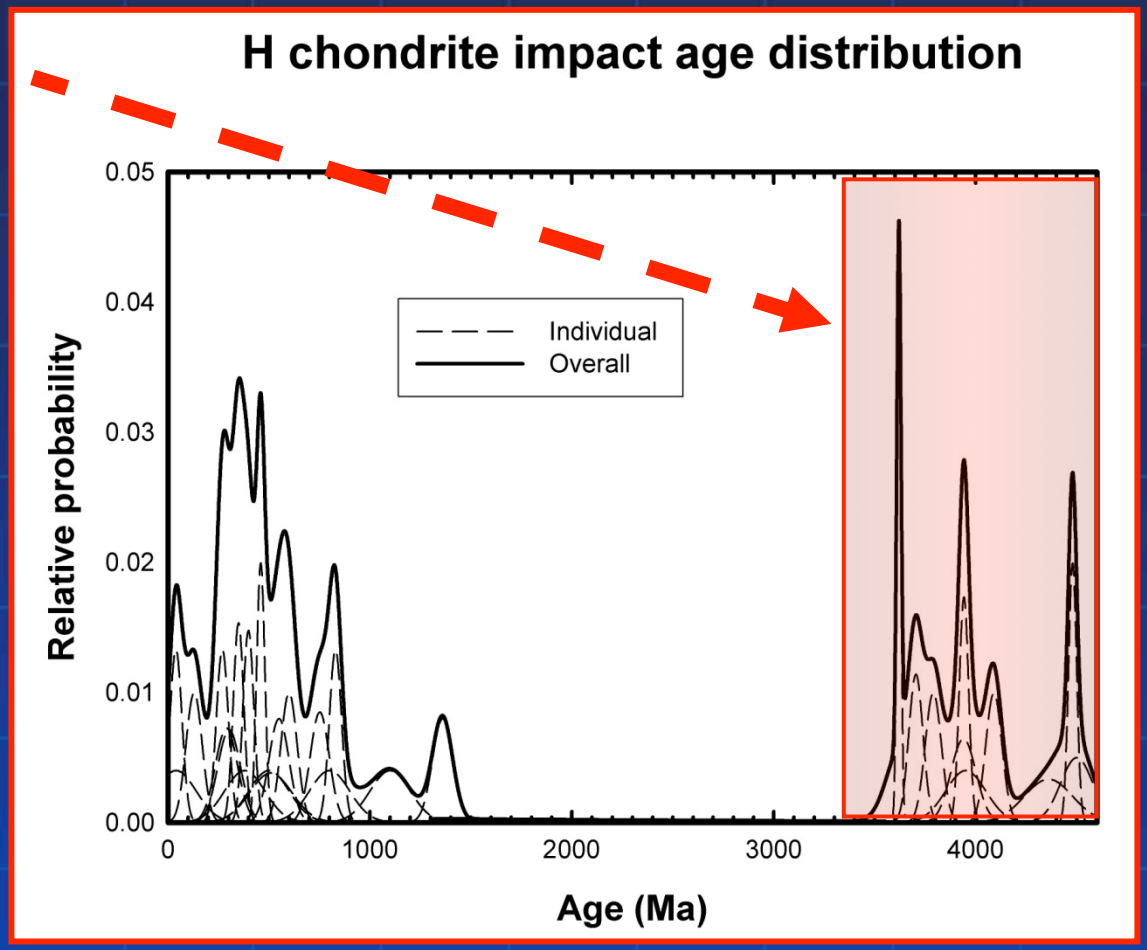
- ^{39}Ar-^{40}Ar ages describe the history of main belt and the Late Heavy Bombardment!
  - **4.1-4.4 Ga "gap":** Few asteroids pushed onto eccentric orbits.
  - **3.5-4.1 Ga "spikes":** High velocity impacts from asteroids ejected from main belt by late giant planet migration.

Conclusions

- The main belt's history can be told with Ar-Ar ages:
  - **4.1-4.4 Ga "gap":** Few asteroids pushed onto eccentric orbits.
  - **3.5-4.1 Ga "spikes":** Asteroids ejected by late giant planet migration.
- Most impact heating comes from high *V* impacts, which require highly eccentric and/or inclined orbits.
- The ~1 Ga Rheasilvia event placed LHB-heated material in the Vesta family, where it eventually reach the Earth.

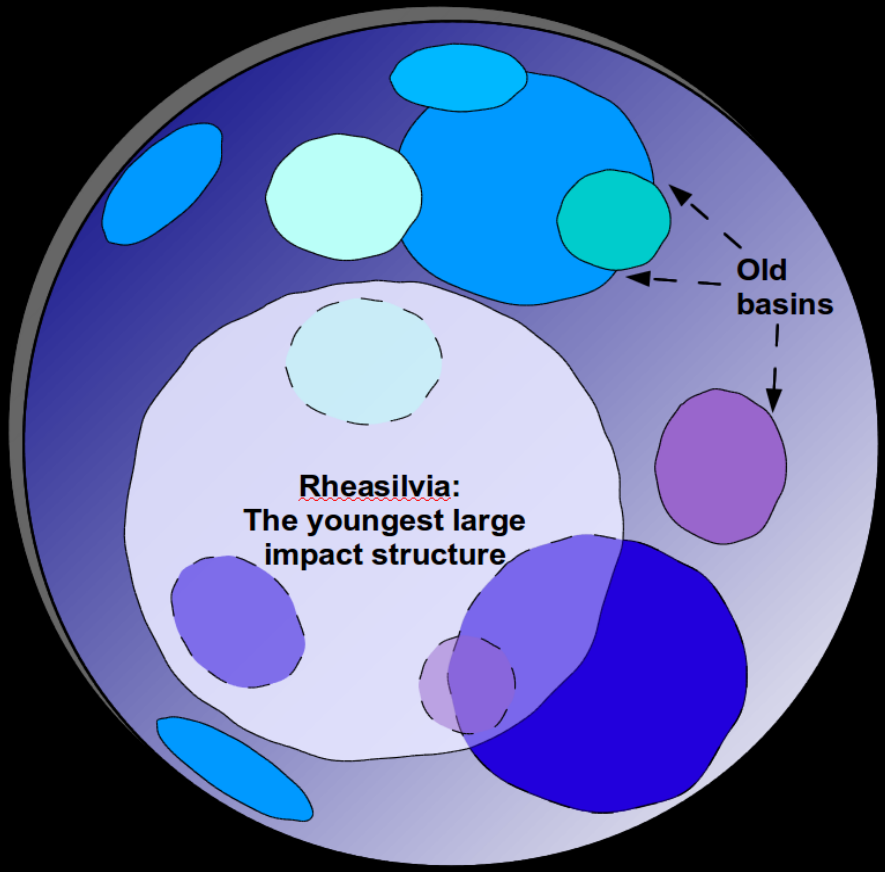
H Chondrites: Similar History to Vesta?

- Many 3.5-4.1 Ga ages.
- Few 4.1-4.4 Ga.
- Very similar to eucrite signatures.



Ages of impact-reworked (melted or shocked) H chondrites. Swindle et al. (2008)

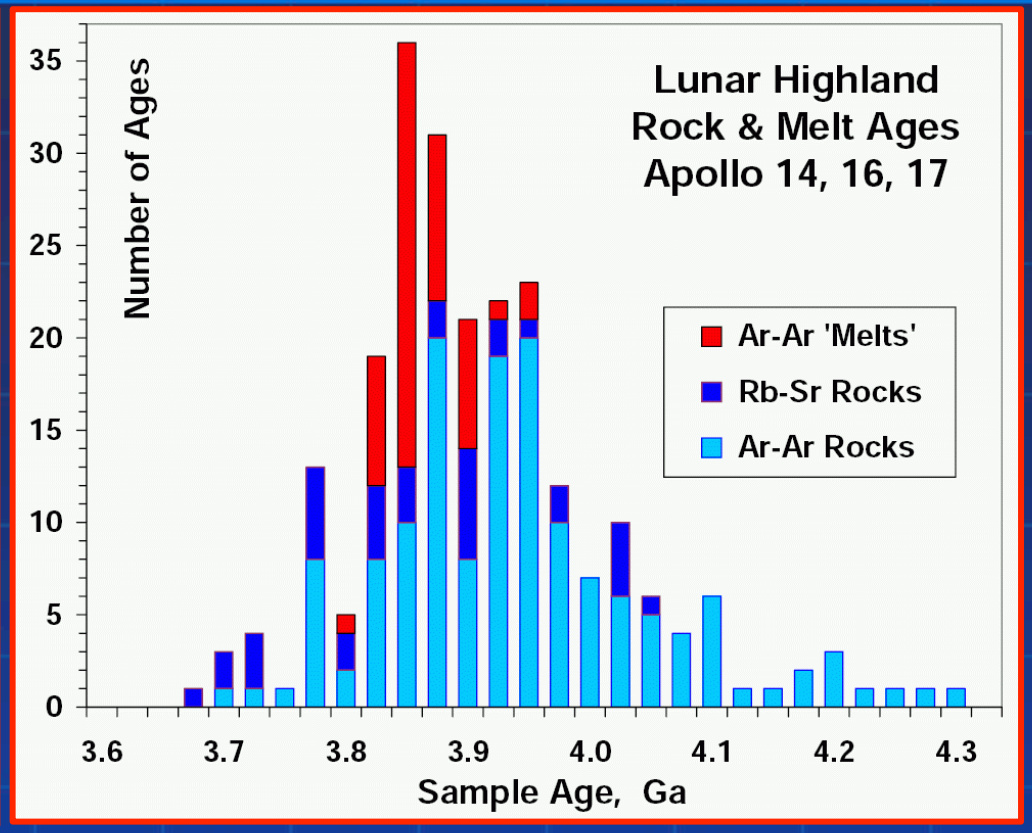
Ar-Ar Ages and Vesta's Cratering



- **Early:** Most craters made at low *V.* Little heating.
- **LHB:** Some craters form at high V. Heating!
- **1 Ga:** Rheasilvia formed.

Rocks Tell a Story

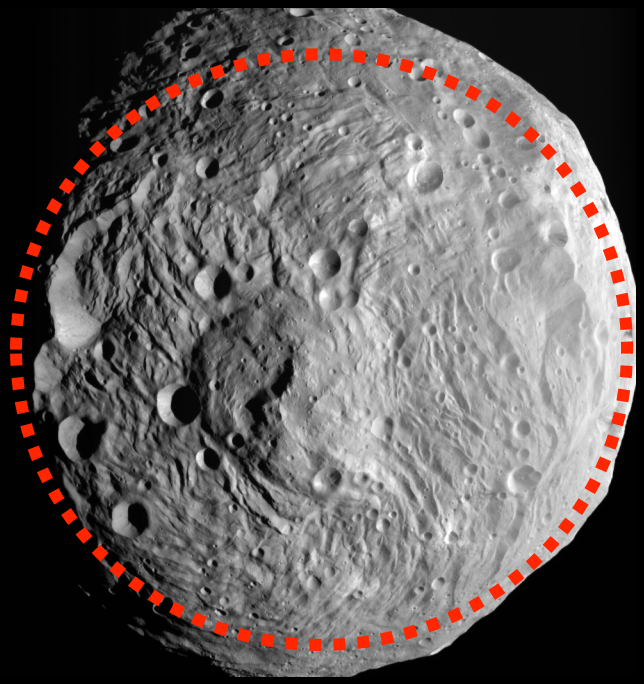
“Nice” Problems with the LHB: Moon



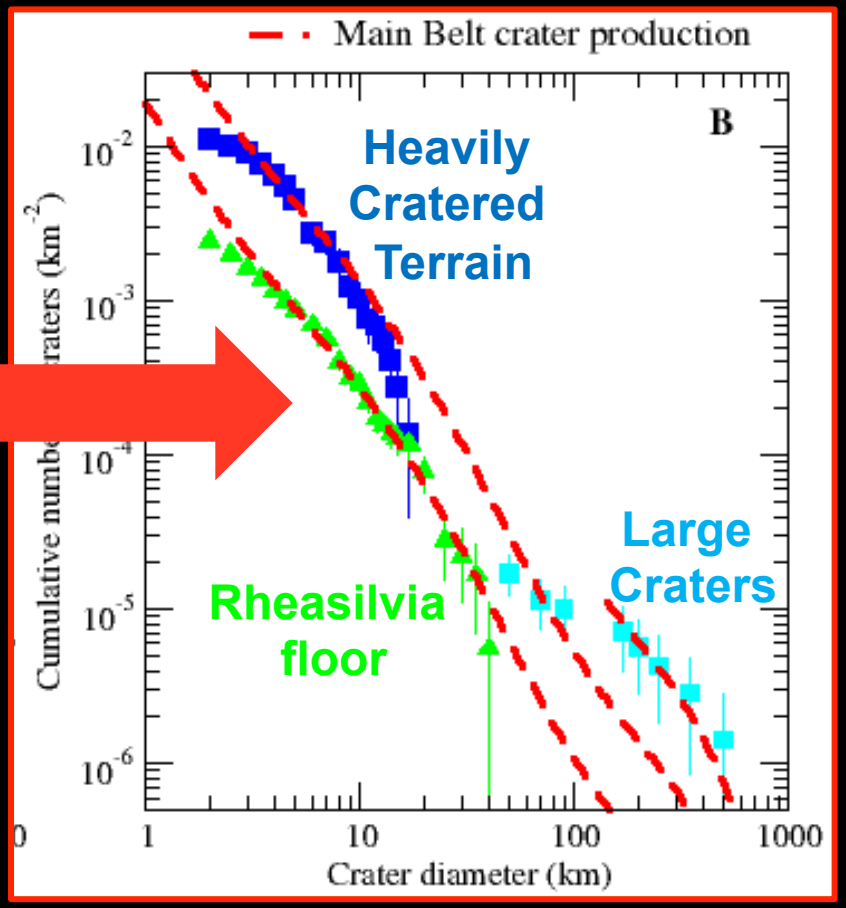
- Apollo astronauts returned rocks melted or shocked by impacts with age range of 3.7 to ~4.1 Ga.
- Impact melts cluster near 3.8-4.0 Ga.

Bogard (2006); Norman et al. (2010)

Problem #3:

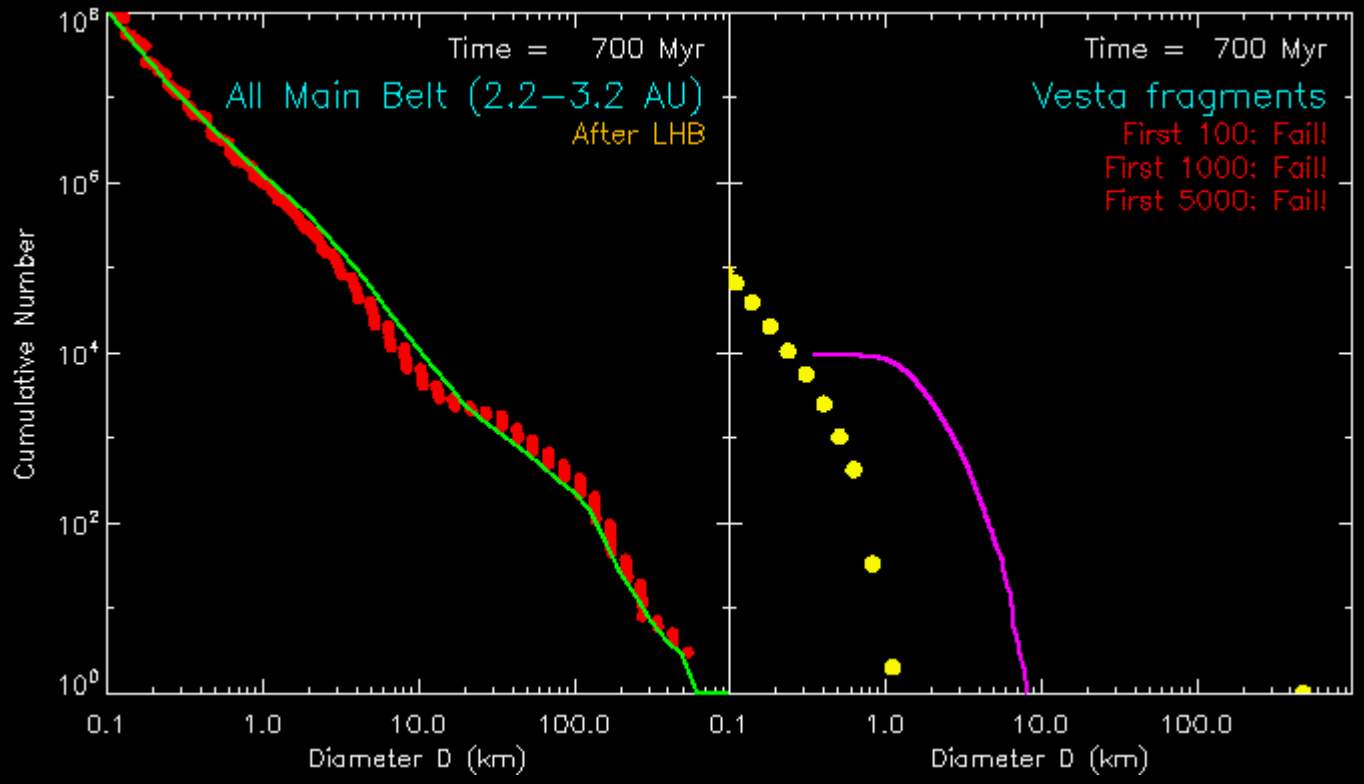


Rheasilvia Basin



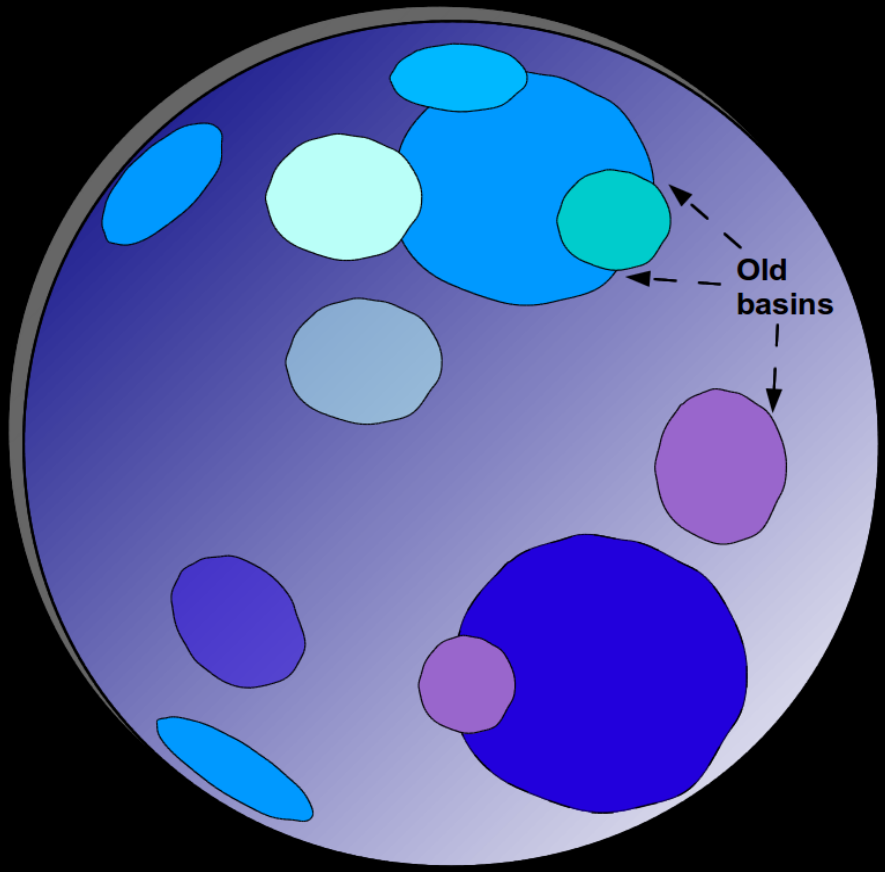
- Rheasilvia's crater density suggests it may be ~1 Gy old.
- If true, why is this mammoth event not seen in Ar-Ar?

Support for Rheasilvia's Young Age



- Collisions should quickly grind Vesta's size distribution to shallower slope, which is not observed.
- Over hundreds of runs, we predict 60% chance of < 500 My, and 80% chance of < 1000 My.

Vesta's Impact History



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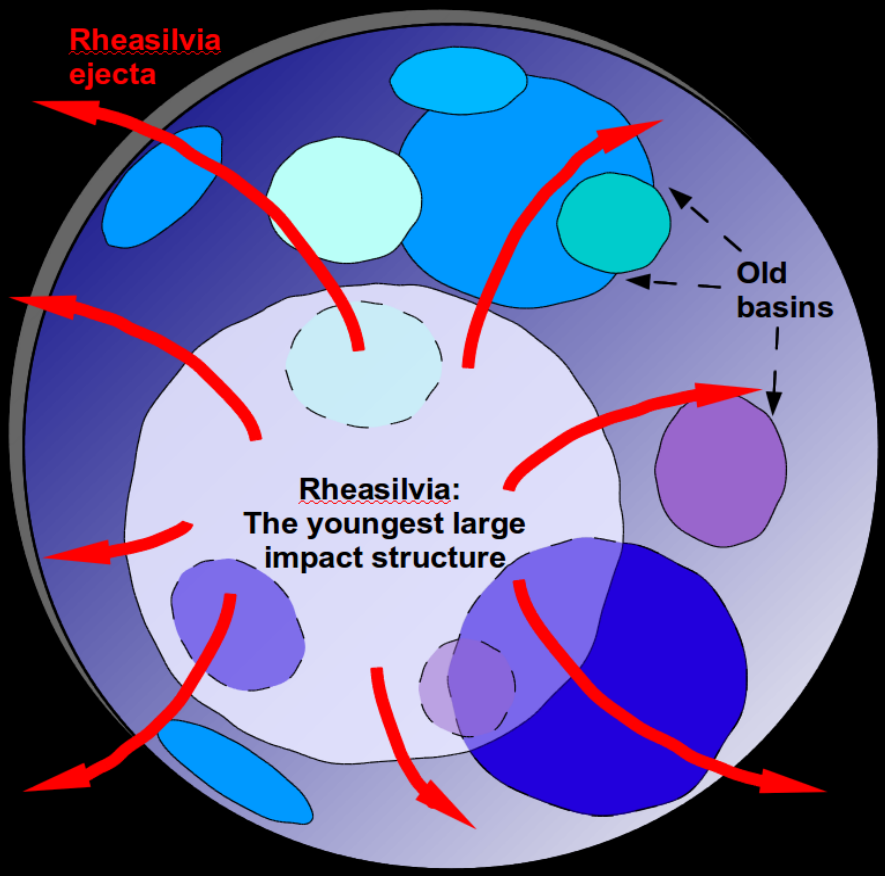

- **Early:** Most craters made at low *V.* Little heating.
- **LHB:** Some craters form at high V. Heating!
- **1 Ga:** Rheasilvia formed.
  - Vesta family formed.
  - Material from LHB-era craters is placed in family.
  - This material dominates current flux of HEDs.