Rethinking Solar System Bombardment: New Views on the Timing and Delivery of Lunar Impactors

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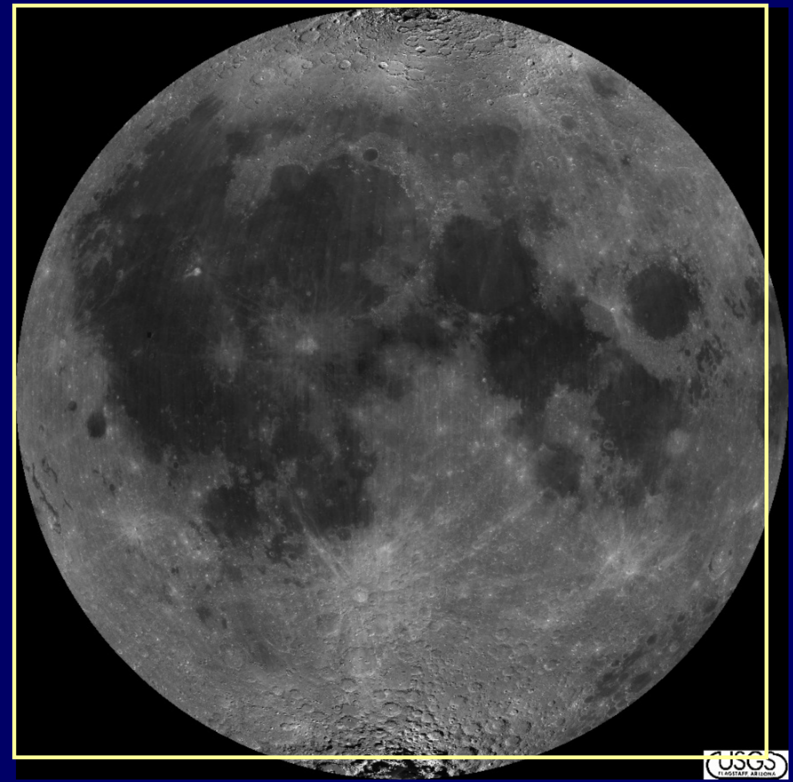
WHERE DISCOVERIES BEGIN

Why the Moon?

Samples and surface are (mostly) undisturbed by “geo”logical processes



Craters can be counted

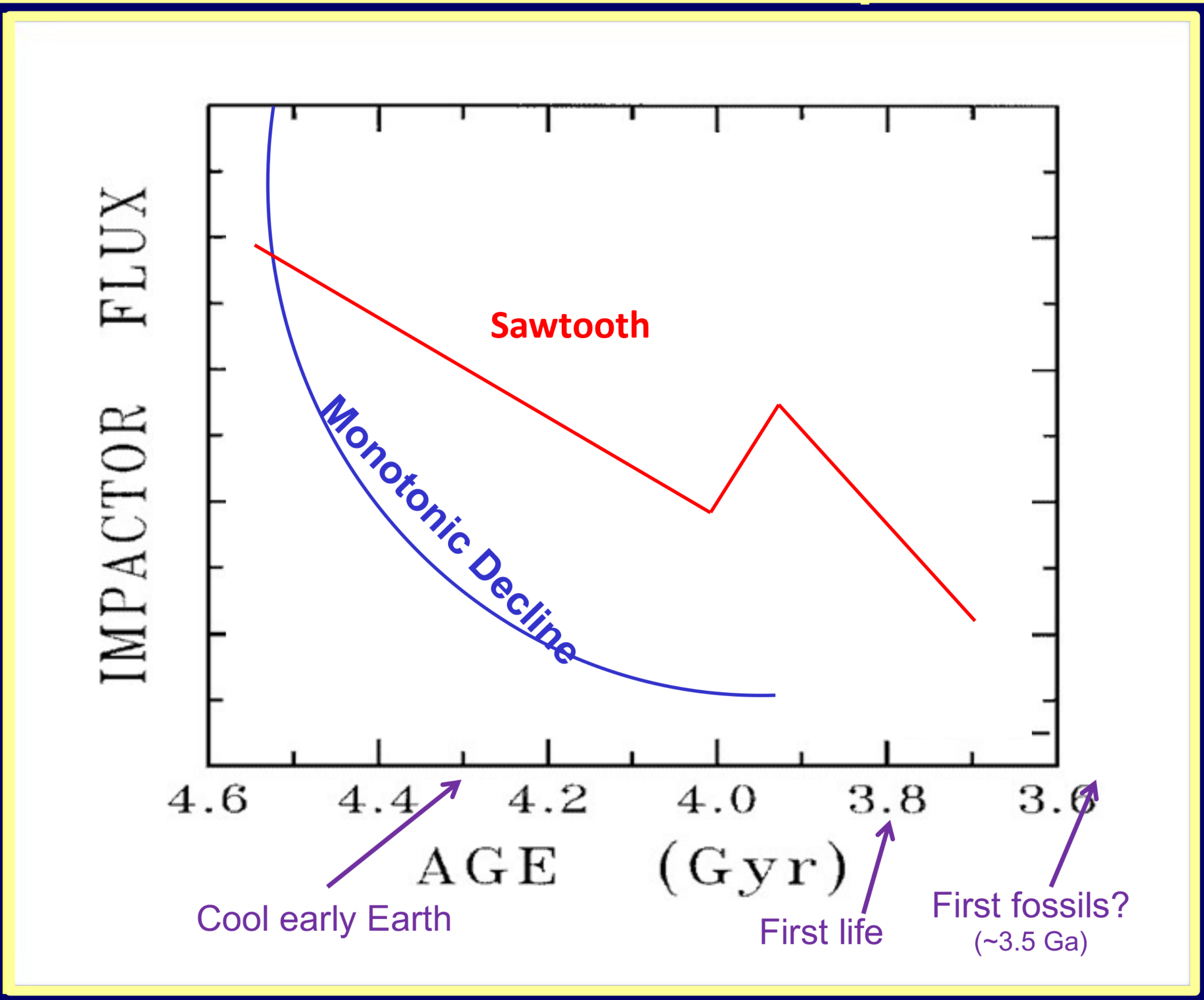
Samples can be dated

$\rightarrow$ ^{40}Ar/^{39}Ar, U-Th-Pb

$\rightarrow$ ^{87}Rb/^{87}Sr, ^{147}Sm/^{143}Nd

Lunar cratering rate anchors the impact chronology for the entire (inner) Solar System

What is the Lunar Impact Flux?



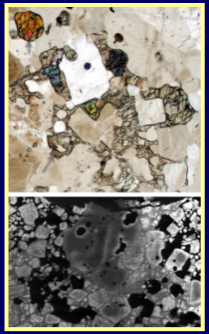
Modified from Zellner (PhD thesis); Hartmann (1965, 1966, 2000); Tera *et al.* (1974); Morbidelli *et al.* (2012)

The Impact Flux

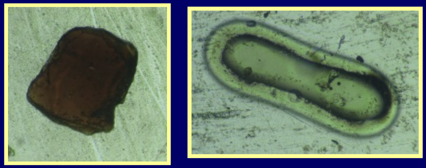
Ways to interpret the time-varying impact flux:

Samples:

- crystalline melts in Apollo samples
- crystalline melt clasts in meteorites
- zircons
- lunar impact glasses



10s μm



~200 μm

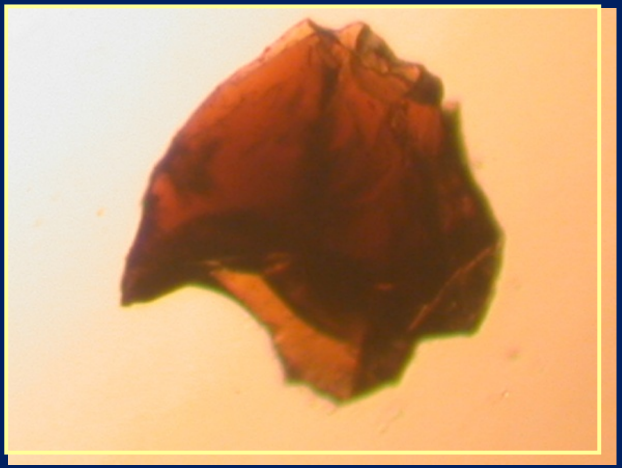
Other:

- crater counting and stratigraphy

Lunar Glasses

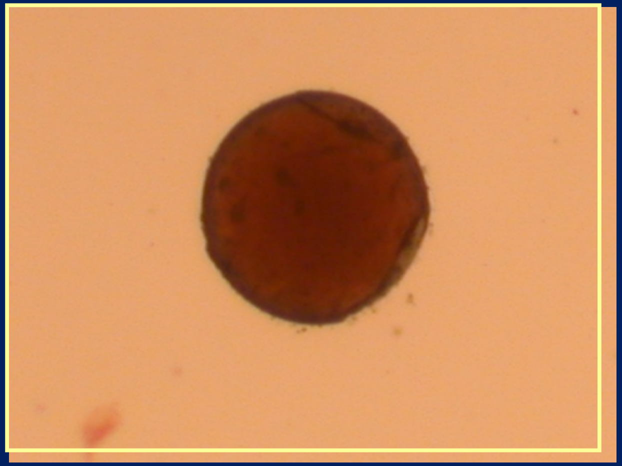
Glasses are formed when regolith is melted during a high-temperature event

→where, when, how often impacts and volcanism occurred



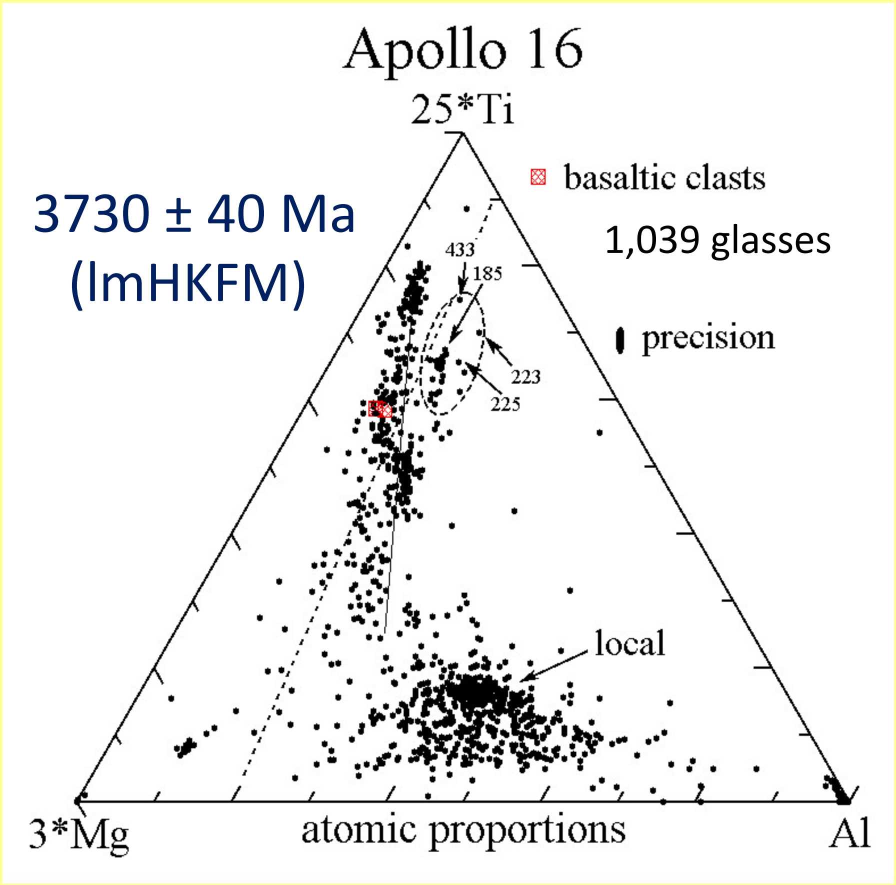
415 µm x 375 µm

Glasses are small, "clean", numerous, and optically homogeneous

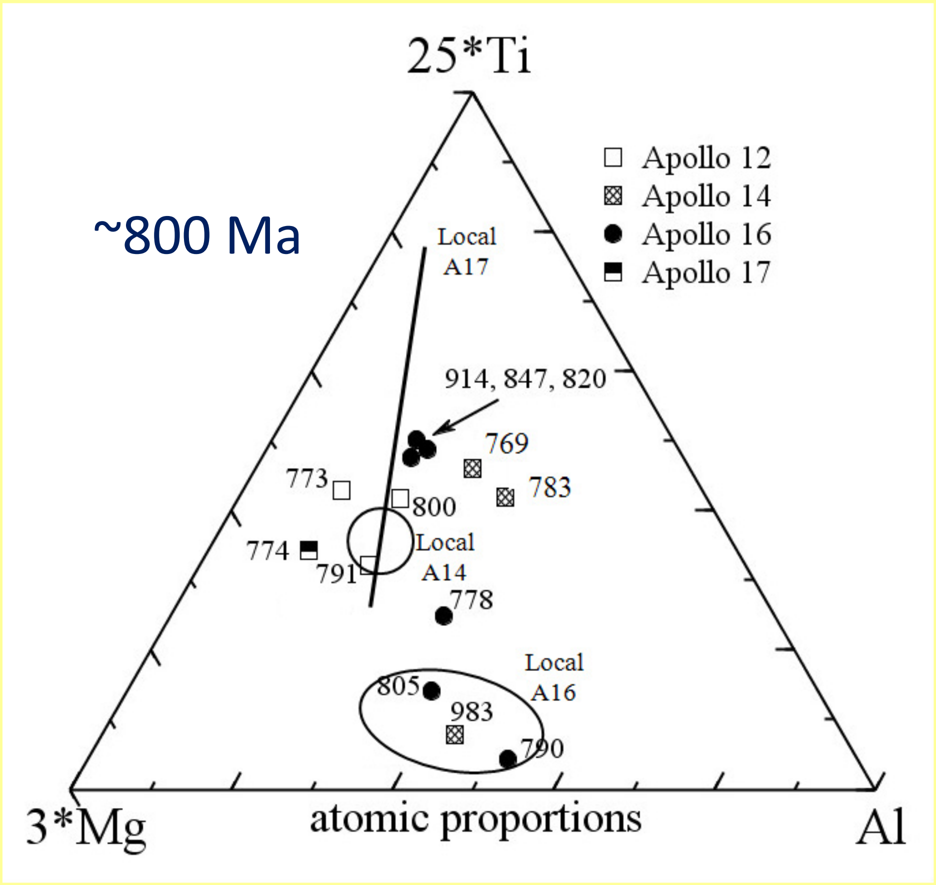


240 µm

Impact Glasses:
Composition, Age, and Shape



Delano *et al*. (2007): 1 large distant impact produces 4 glass shards w/ same age



Zellner *et al.* (2009): 9 glass shards and spheres from 3 landing sites indicate 7 impacts w/ same age

**** Useful tools to extract info about impact flux ****

The "Lunar Cataclysm"

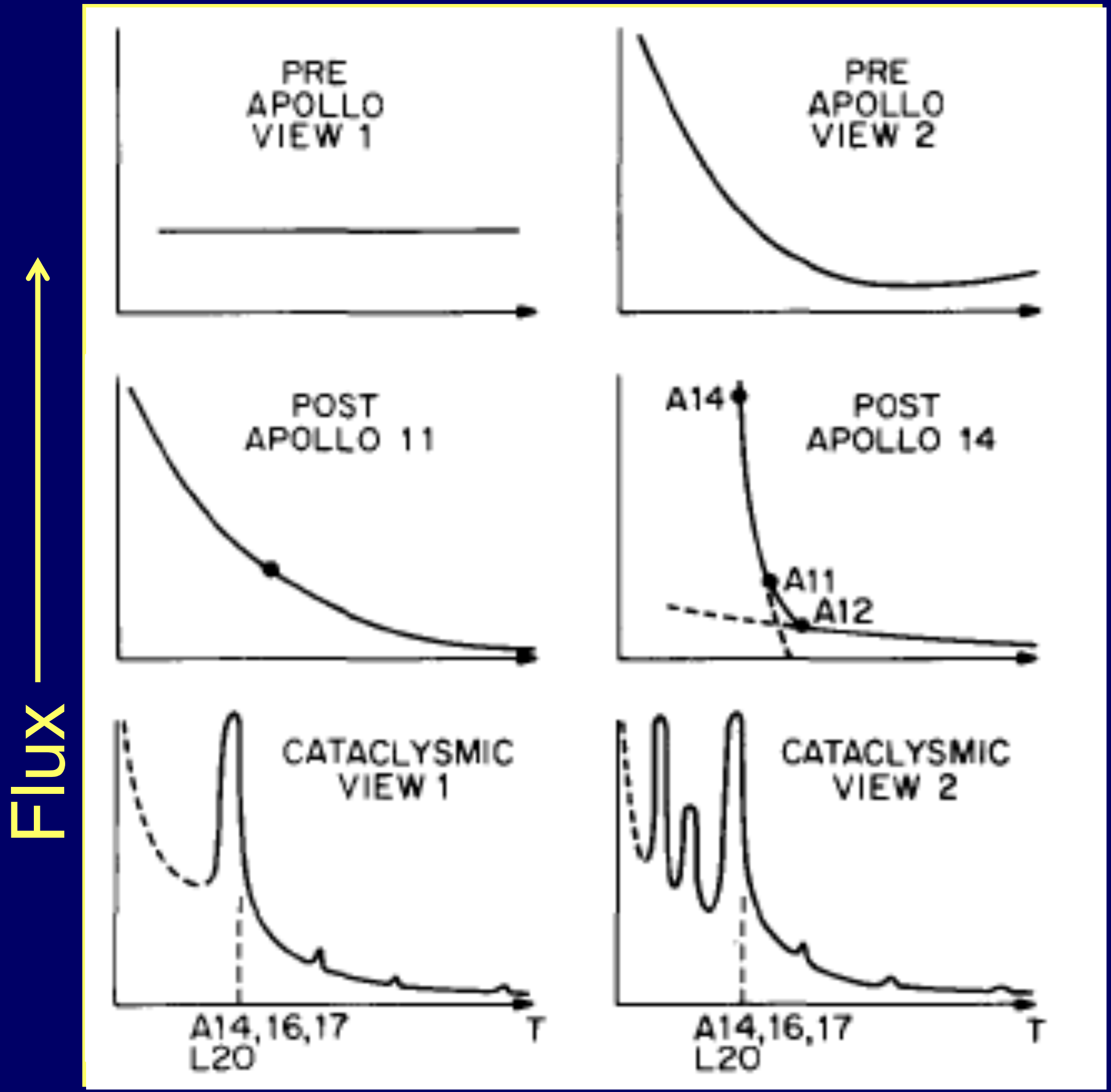
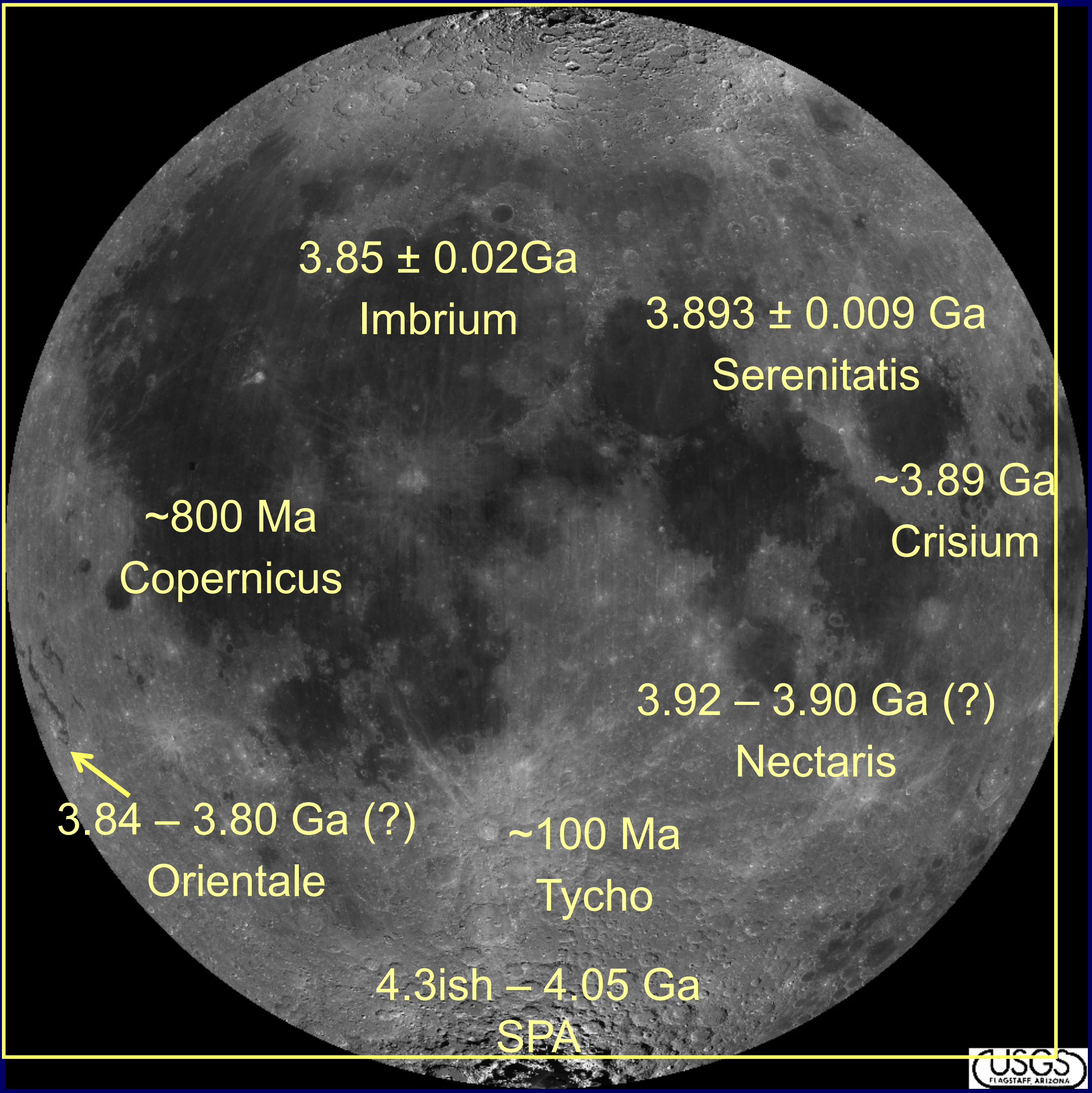


Figure 6 in Tera *et al.* 1974

Lunar cratering rates from

U-Pb ages of 18 Apollo and Luna rock samples



The "Cataclysm"

U-Pb ages

Stratigraphy

Crater counting

A15, A17 breccia

$^{40}Ar/^{39}Ar$ ages

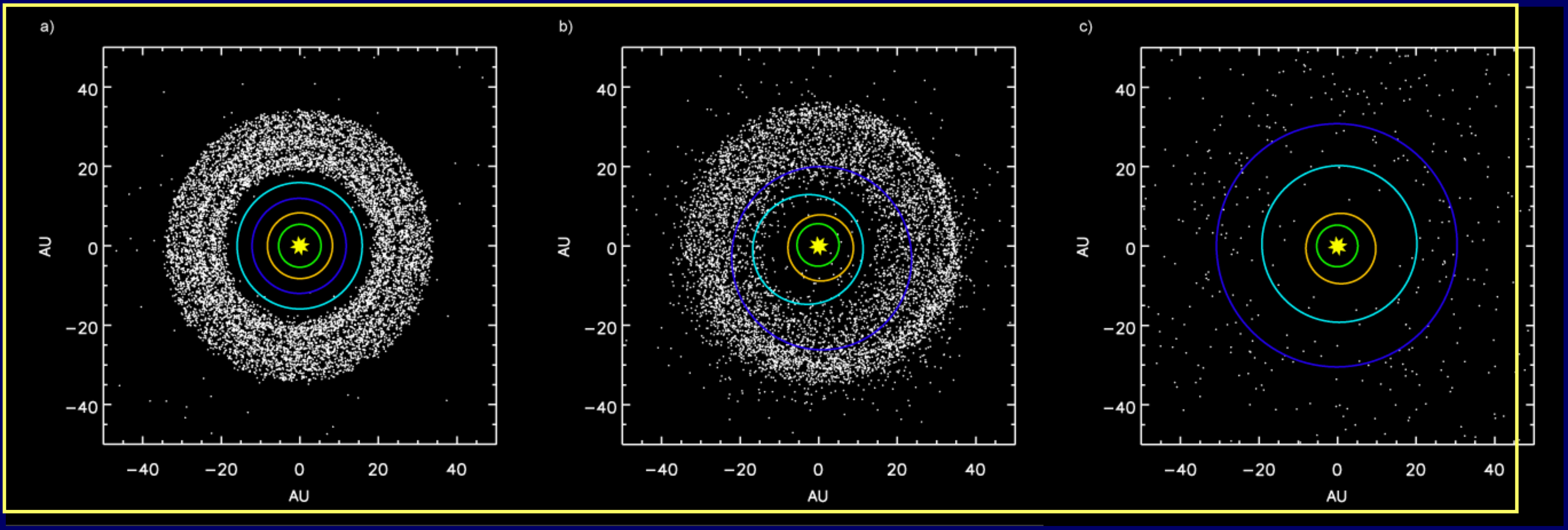
(Dalyrymple & Ryder, 1993, 1996)

Wilhelms (1987), Hartmann (2000), Ryder *et al*. (2000), Koeberl (2006)

Describing the Impact Mechanism

Nice Model:

Gomes *et al.* (2005); Tsiganis *et al.* (2005); Morbidelli *et al.* (2005)



Early configuration, before Jupiter and Saturn reach a 2:1 resonance (JSNU)

Objects scatter into the inner Solar System after the orbital shift of Neptune (dark blue) and Uranus (lt. blue)

Current-ish Solar System, after ejection of objects by planets (JSUN)

Changing Views: New Data

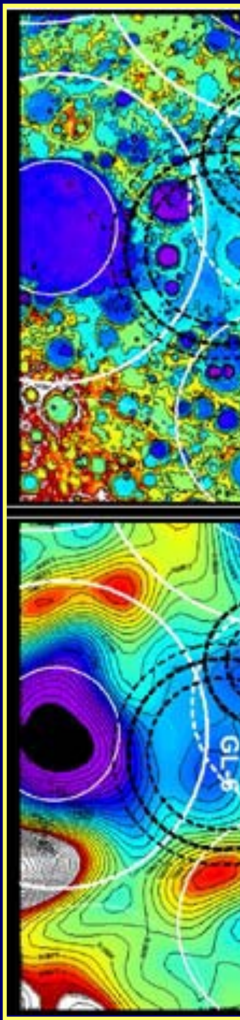
Orbital Data

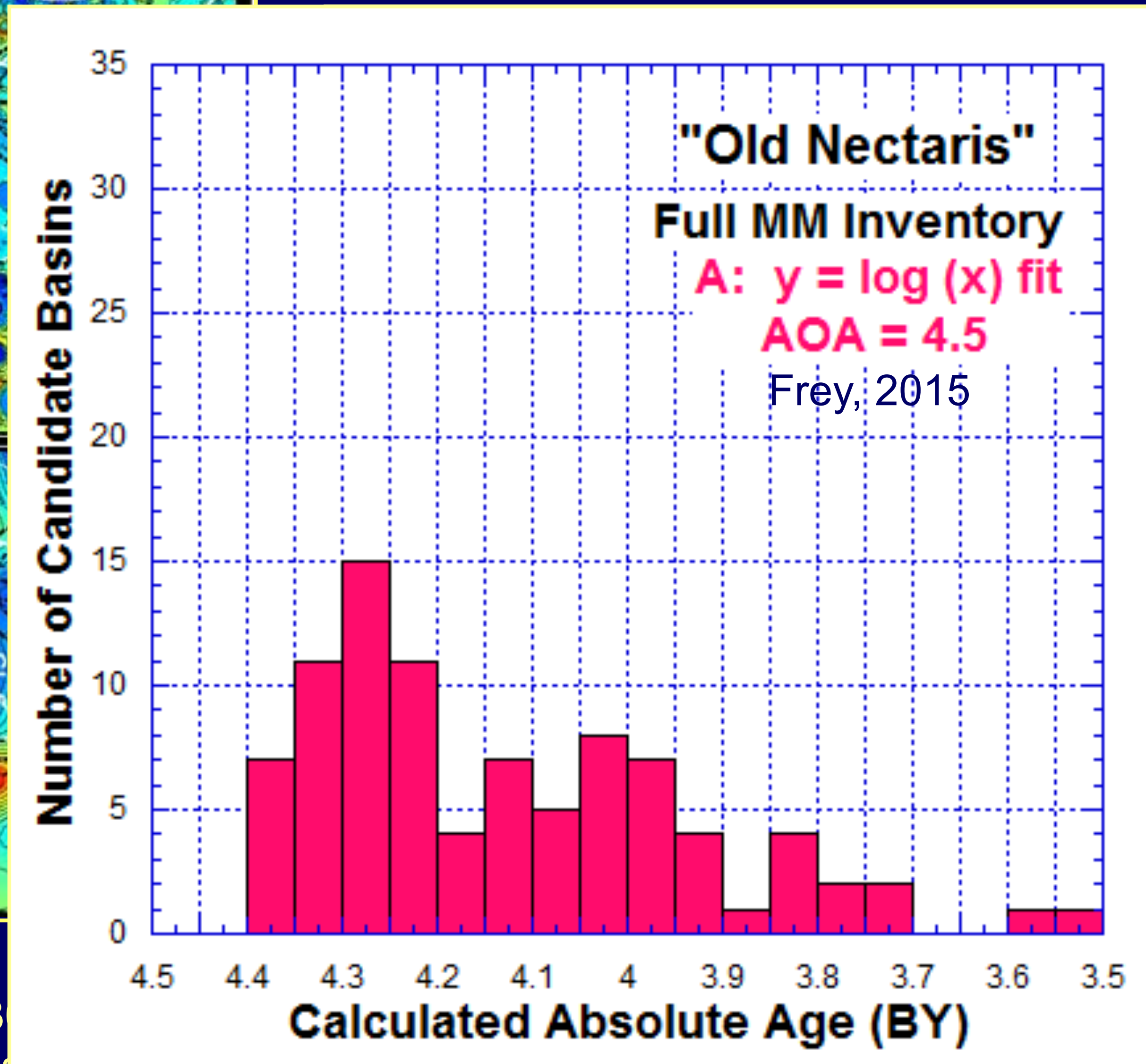
LRO: LOLA
LROC

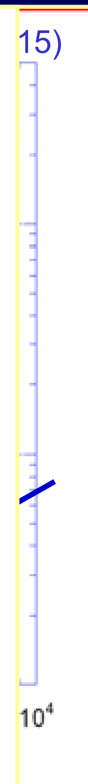
Sample Data

New Interpretations
More Data
More Sophisticated Analytical Techniques

What’s New? LOLA Data







CSFD curve

diameters
ater studies
ly impacts
et al. (2012)

>100 >3
(LOLA data, crustal thickness maps)

What's New? Isotope re-Calibrations

Recal'd $^{39}Ar/^{40}Ar$ standards and U-Pb analyses: similar ages in samples with similar compositions from multiple different Apollo landing sites

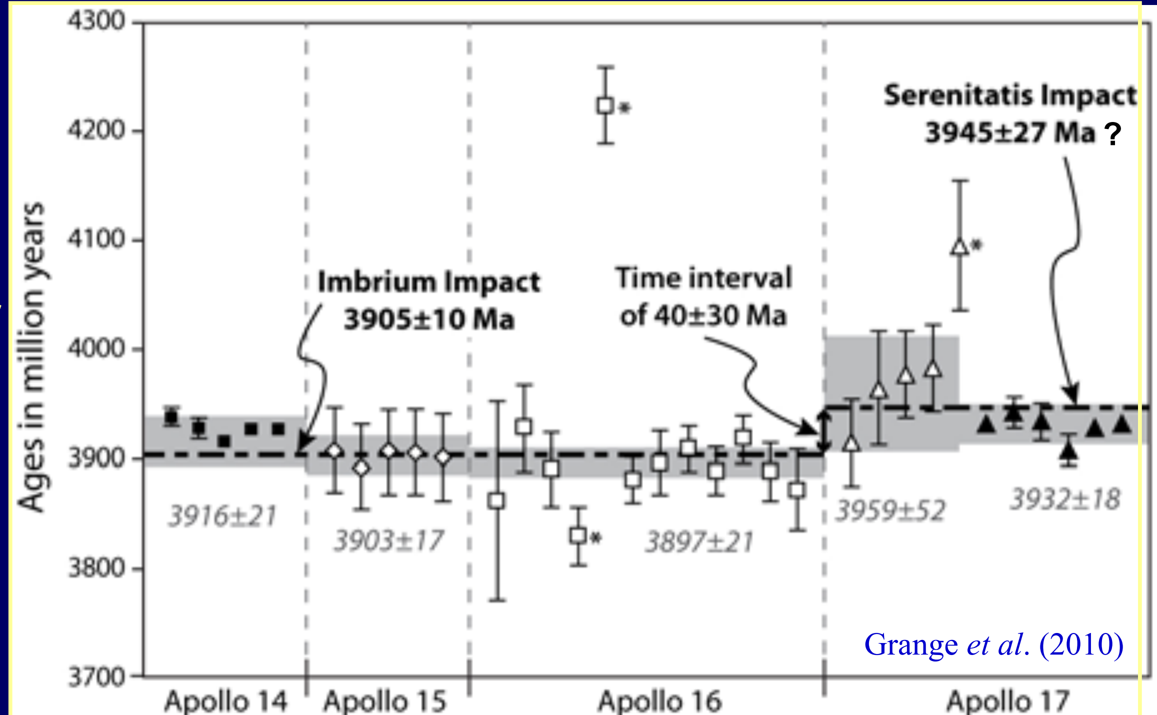


Figure 1: Filled symbols=U-Pb ages. Open symbols=Ar-Ar ages. The grey bands represent the mean ages and their errors for each landing sites and correspond to the italicized numeric values given in the figure. The symbols marked with an asterisk are excluded from the average calculation.

Result: Many were derived from Imbrium (~3.9 Ga) and represent one event

(Other samples may represent basin-forming events *or* smaller local impacts.)

Liu *et al.* (2012)
Merle *et al*. (2014)
Mercer *et al.* (2015)

What's New? Updated (but still uncertain) Ages

(based on new calibrations and superpositioning of ejecta blankets from orbital data)

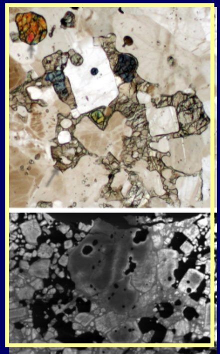
Crater	**Age (today)**	**Age (before)**
SPA	4.2 Ga (?)	4.3ish – 4.05 Ga
Serenitatis	>4.1 – 3.87 Ga	3.893 ± 0.009 Ga
Nectaris	4.1 Ga (?)	3.92 – 3.90 Ga (?)
Crisium	~3.9 Ga (?)	~3.89 Ga
Imbrium	3.77-3.90 Ga+	3.85 ± 0.02 Ga

+ Imbrium's age is based on Apollo 14 and Apollo 15 samples, whose geologic provenance is not well-established

Norman (2008); Grange *et al.* (2010); Spudis *et al.* (2011)

New: Old Lunar Sample Ages

Apollo 16 impact breccia U-Pb age: large event at 4.22 ± 0.01Ga



10s μm

Norman et al. (2016)
Norman and Nemchin (2014)

Apollo 16 melt ^{40}Ar–^{39}Ar ages: 4.21 ± 0.05 Ga and 4.29 ± 0.04 Ga

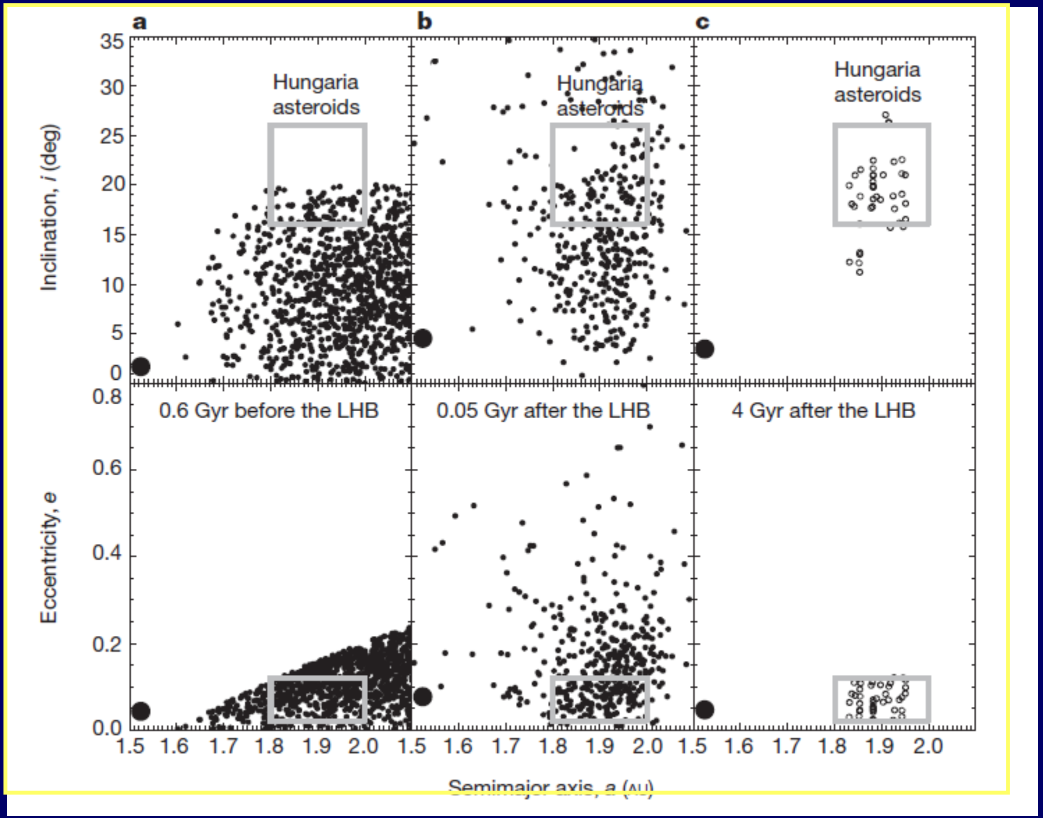
Fernandes *et al*. (2013)

Lunar zircon heating events with U–Pb ages: 4.3 ± 0.01, 4.2 ± 0.01, and 3.9 ± 0.01 Ga

Hopkins and Mojzsis (2015)

What's New? Dynamical Models

Existence of Hungaria Asteroids explained via E-Belt (1.7- 2.1 AU) that was destabilized by late giant planet migration



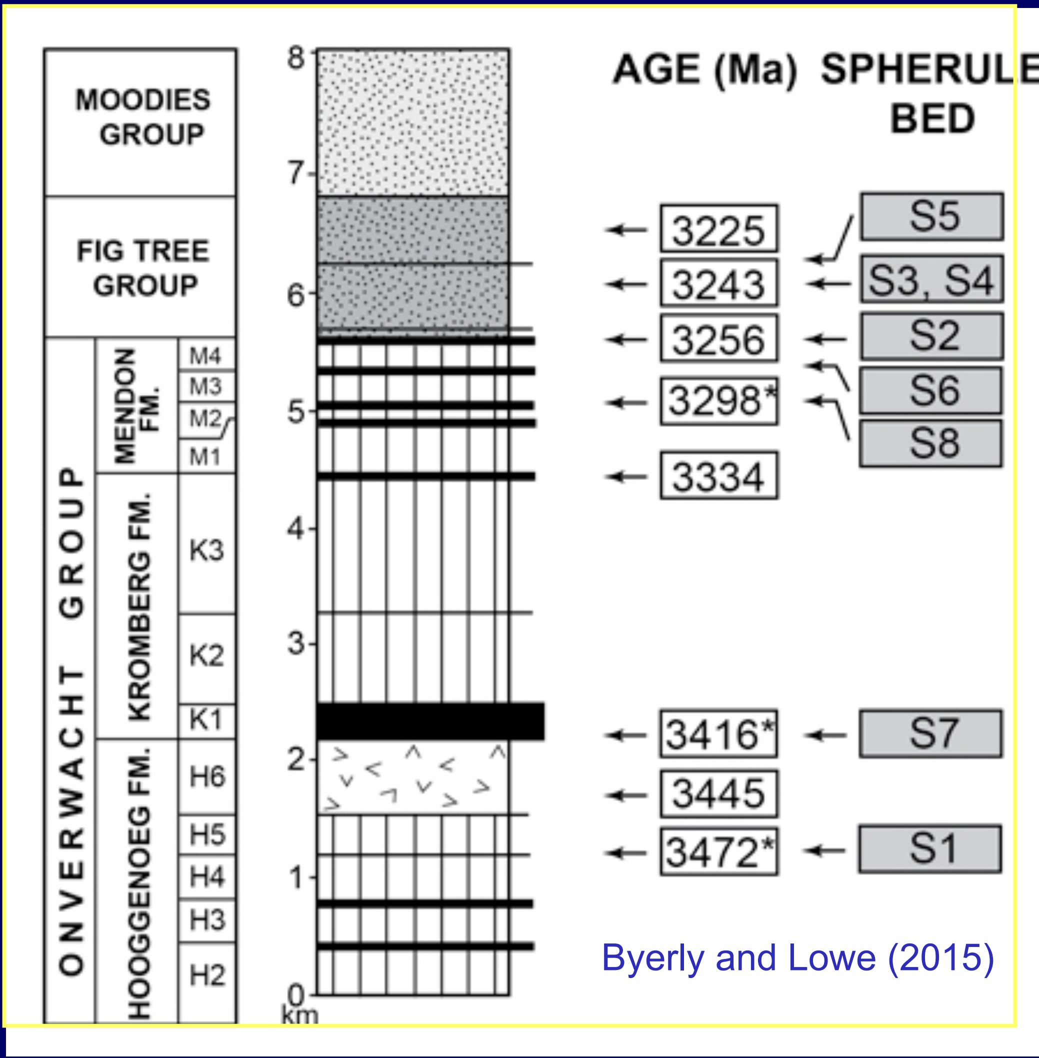
Result:

1. LHB started at
   ~4.1 Ga (age of Nectaris?)
2. LHB not very high

3. No "cataclysm"
   @ ~3.9 Ga

Figure 1 from Bottke *et al*. (2012)

New: Terrestrial Archean Impacts



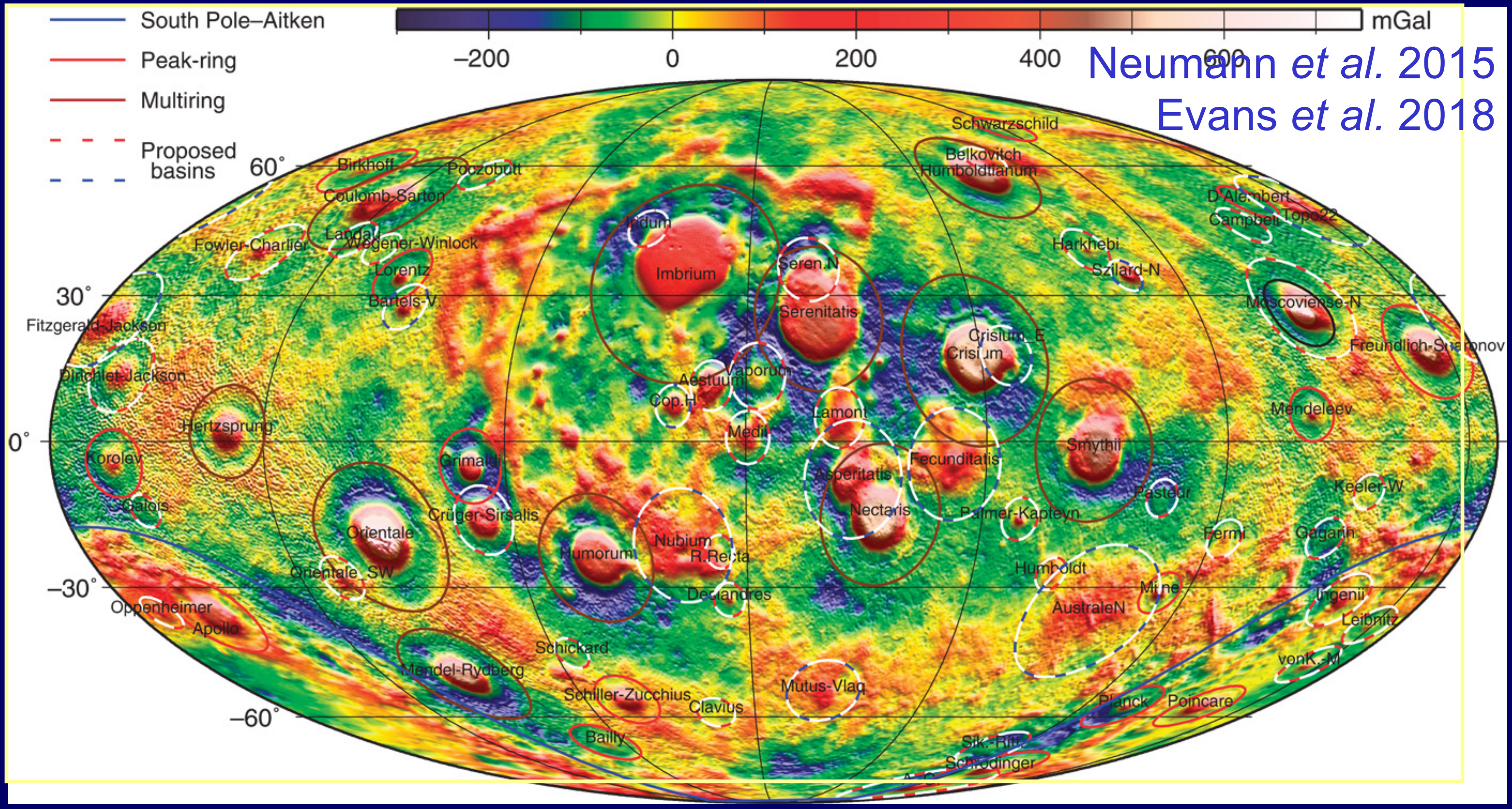
Barberton (SA):

Multiple impact spherule layers from large distal impacts between 3.5 and 3.2 Ga

(Byerly and Lowe, 2010;
Lowe *et al*. 2014;
Byerly and Lowe, 2015)

Result: LHB lasted longer than we thought

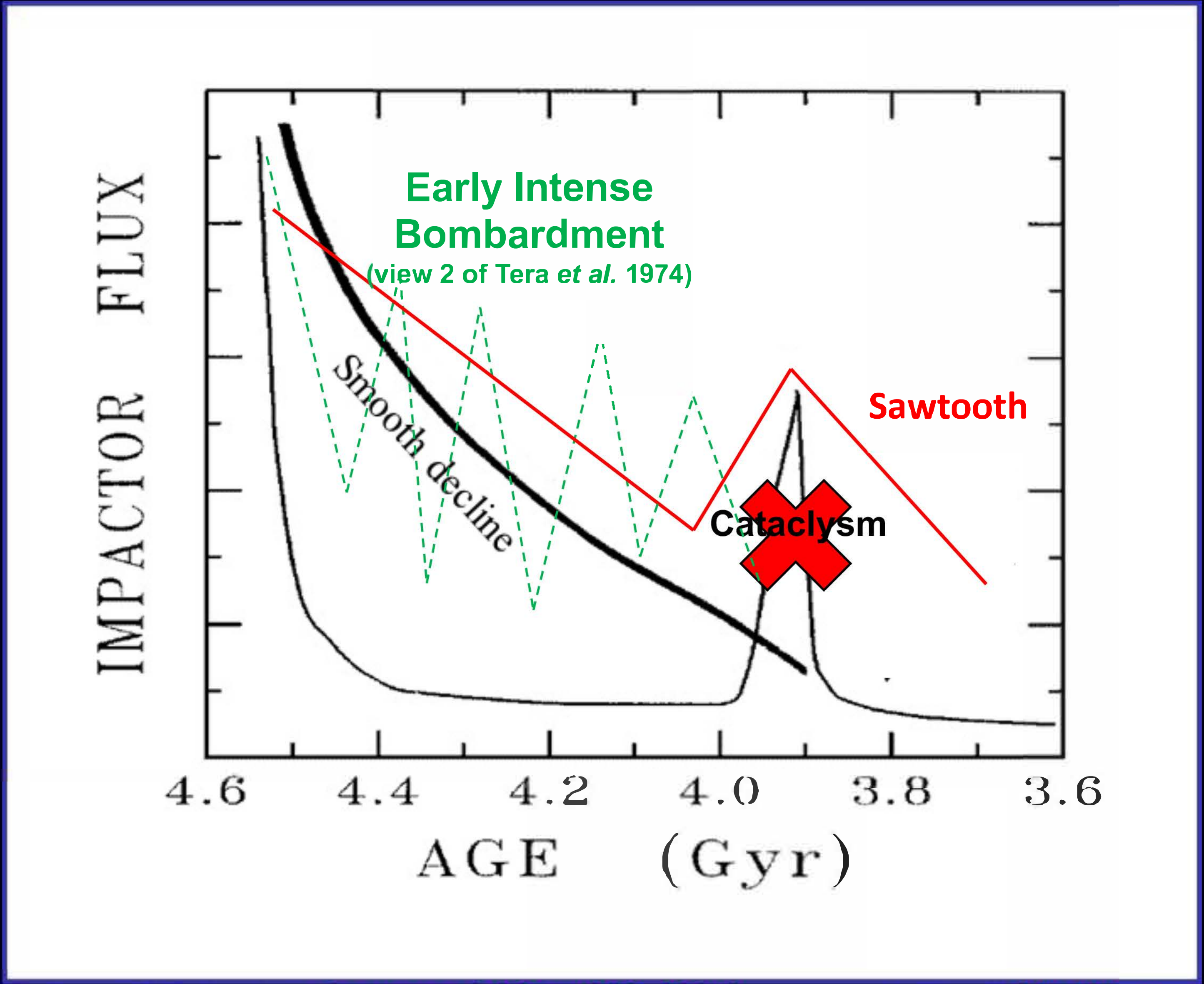
What's New? GRAIL Data



Multiple new basins w/ >300 km diameters
6 known basins with D >200 km larger than previously measured

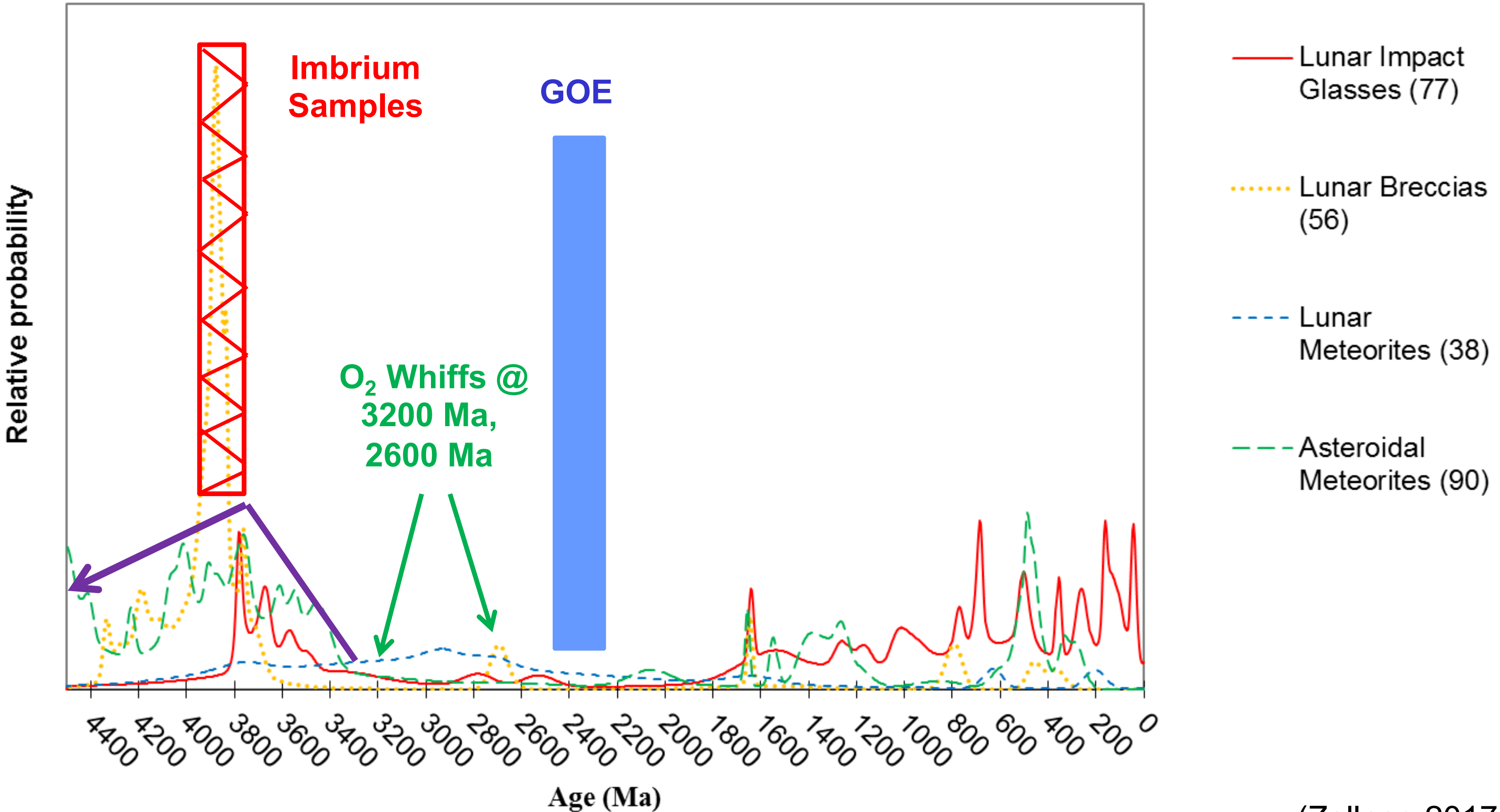
Result: Impact flux needs to be recalibrated: # impactors capable of forming basins (≥90 km) decreased substantially thru Nectarian and Imbrian periods

What *is* the Early Impact Rate?



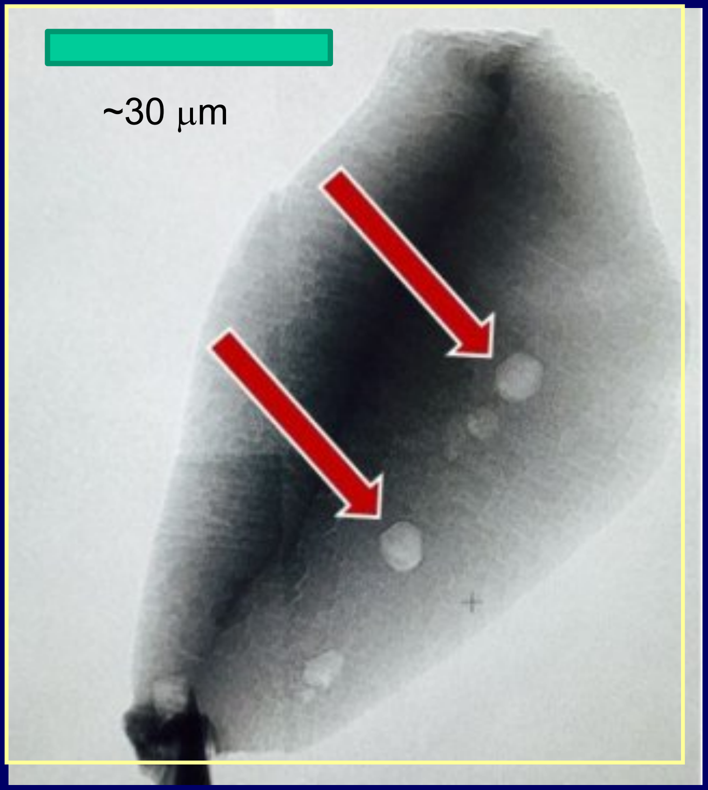
Modified from Zellner (PhD thesis); Hartmann (1965, 1966, 2000); Tera *et al.* (1974); Morbidelli *et al.* (2012)

Impact Ages of all Samples



(Zellner, 2017)

Old Biogenic Carbon in Zircon



Bell *et al.* (2015)

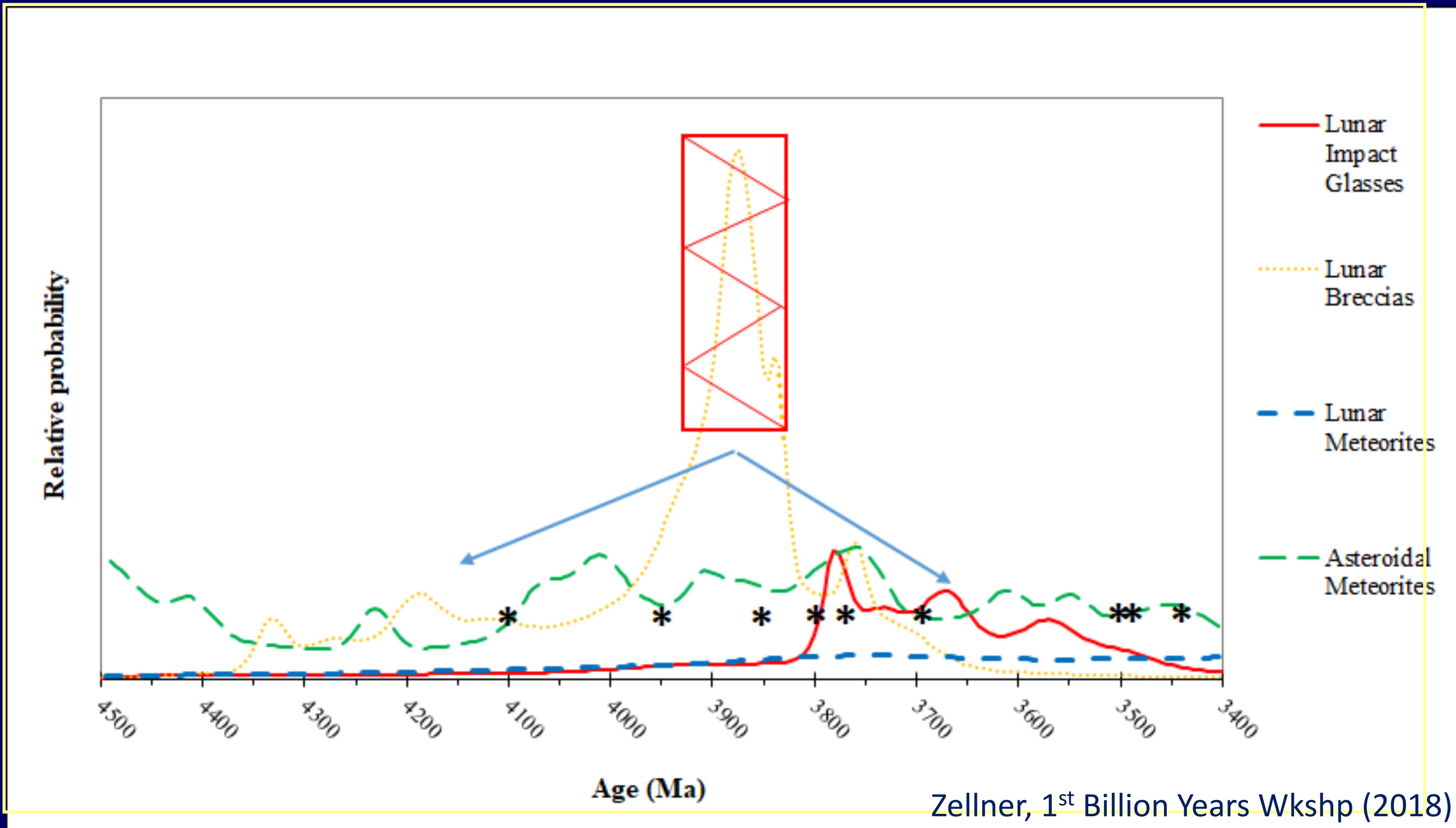
10,000 Jack Hills zircons

1 with age >4.0-Ga and containing graphite as a primary inclusion
→ zircon was crack-free

$\delta^{13}C_{PDB} = -24 \pm 5‰$ consistent with a biogenic origin

Evidence that a terrestrial biosphere had emerged by 4.1 Ga?

The 1st Billion Years



* = biological events on Earth, in the context of impact flux

Back to the Moon!

Lots of interest in the Moon:
China, India, Japan, ESA, US

Volatiles, Water
Other Resources?

Locales for settlement?
Active Interior?

Much more to explore…

Apollo 14 (3.6 km)
Garry *et al*., 2012, LPSC

Transformative Science

- Advances in technology & instrumentation
- Orbital data, sample data, and models: holistic view of Moon's history, incl. impacts, H_2O
- Expt's designed to test observational evidence: results support delivery & production of complex molecules

Cross-disciplinary efforts make more progress than disciplinary efforts in isolation.

MoonRise

Focus on SP-A, presumed to be the oldest basin on the Moon

Return 1 kg samples:

- Lunar deep crust (mantle?)
- Lunar impact chronology
- Moon’s thermal evolution

Humans Back to the Moon!

Samples

- Science
- Extraction/Use

Bases

- Settlements
- Exploration
- Science (e.g., Astro)

Acknowledgements

NSF Astronomy and Astrophysics Program
NASA SSW Program
NASA Astrobiology Institute
NASA LASER Program

UNIVERSITY AT ALBANY
State University of New York

ALBION COLLEGE

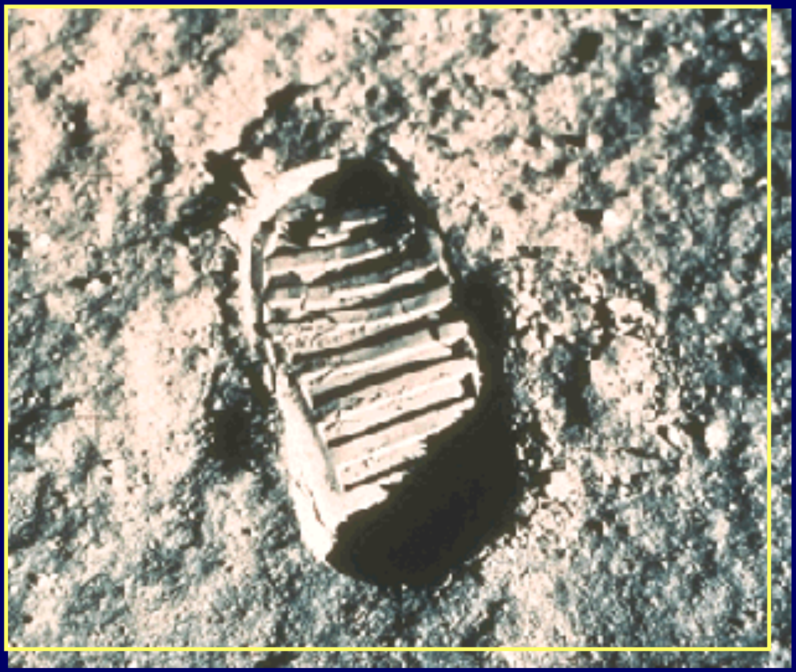
National Science Foundation
WHERE DISCOVERIES BEGIN

The New York Center for ASTROBIOLOGY
A MEMBER OF THE NASA ASTROBIOLOGY INSTITUTE

NASA

Lunar Regolith Samples

Apollo 11 footprint in lunar regolith



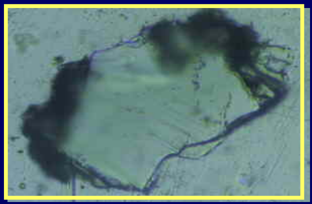
Billions of years impacts have pulverized the surface into a fine powder called *regolith*

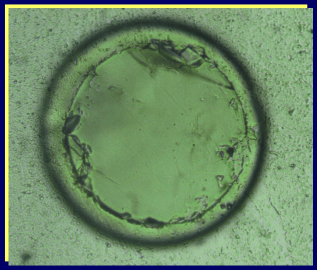
Regolith looks and feels like sticky brown talcum powder

Lunar Glass Samples

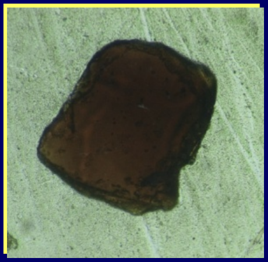
Glasses are formed when regolith is melted during a high-temperature event

Where, when, how often impacts, volcanism occurred

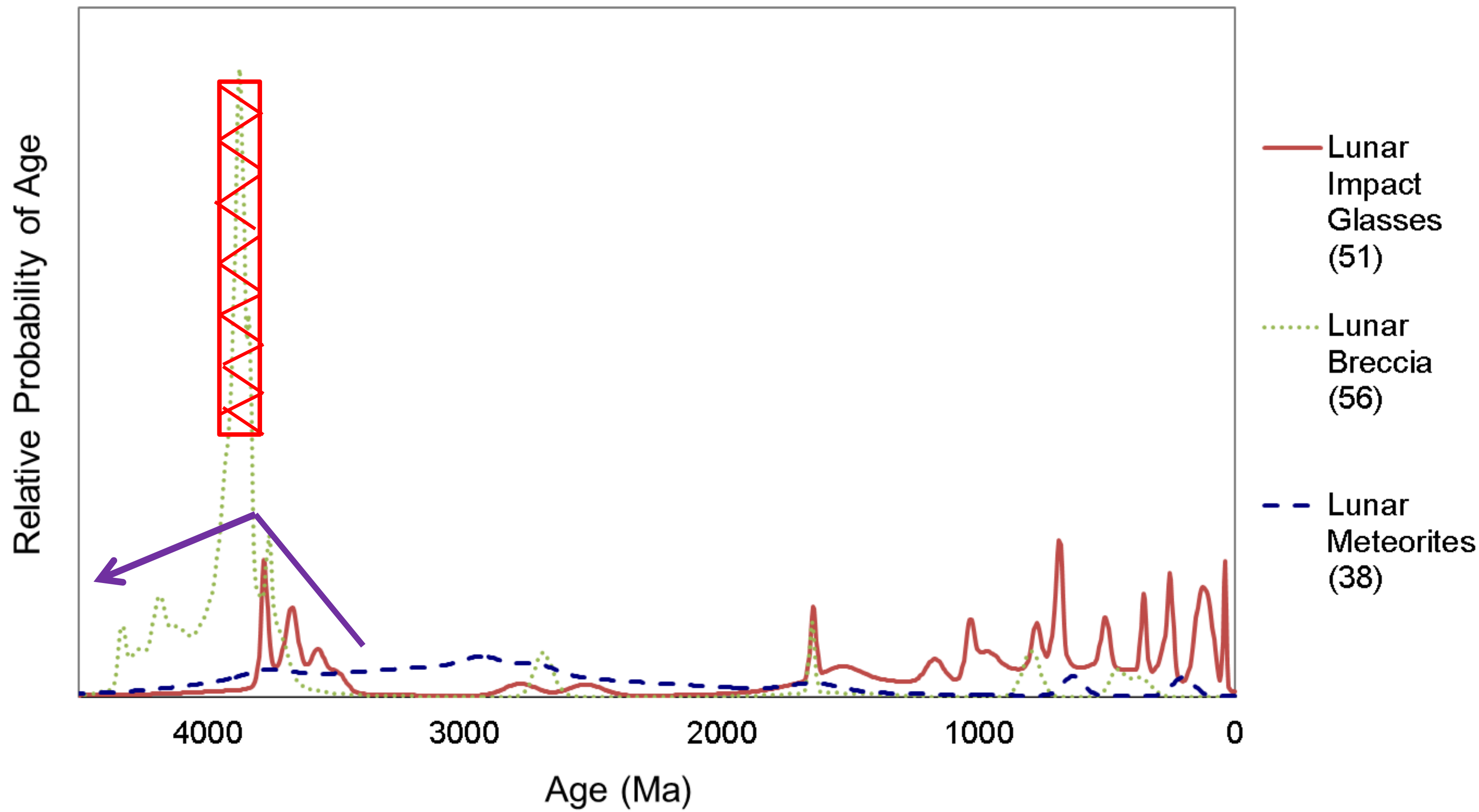




Glasses are small, numerous, and homogeneous.

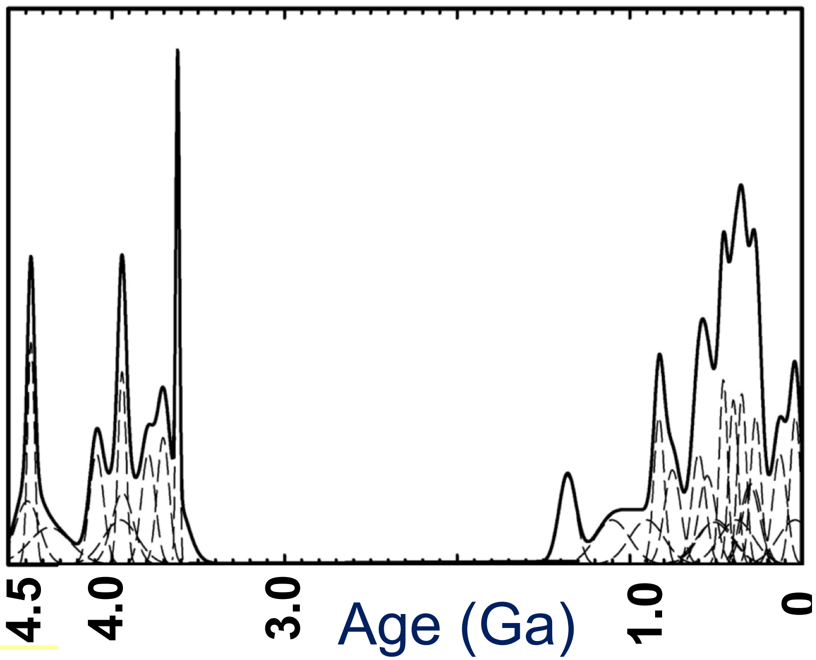


Age Distribution of Lunar Samples

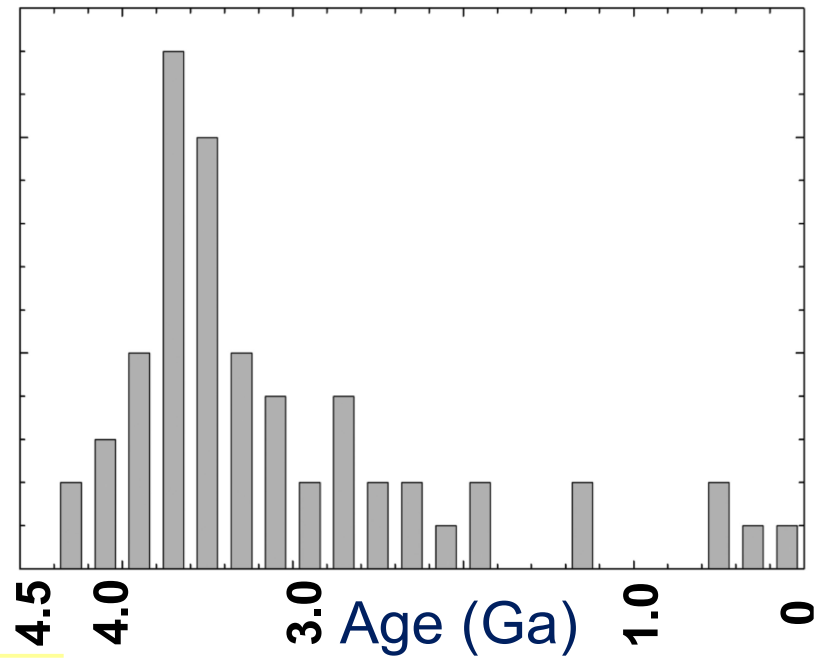


Impact Ages of H Chondrites

$^{40}Ar/^{39}Ar$ ages from Swindle *et al.* (2009)



U, Th-He ages from Wasson and Wang (1991)



Impact Ages of HED Meteorites

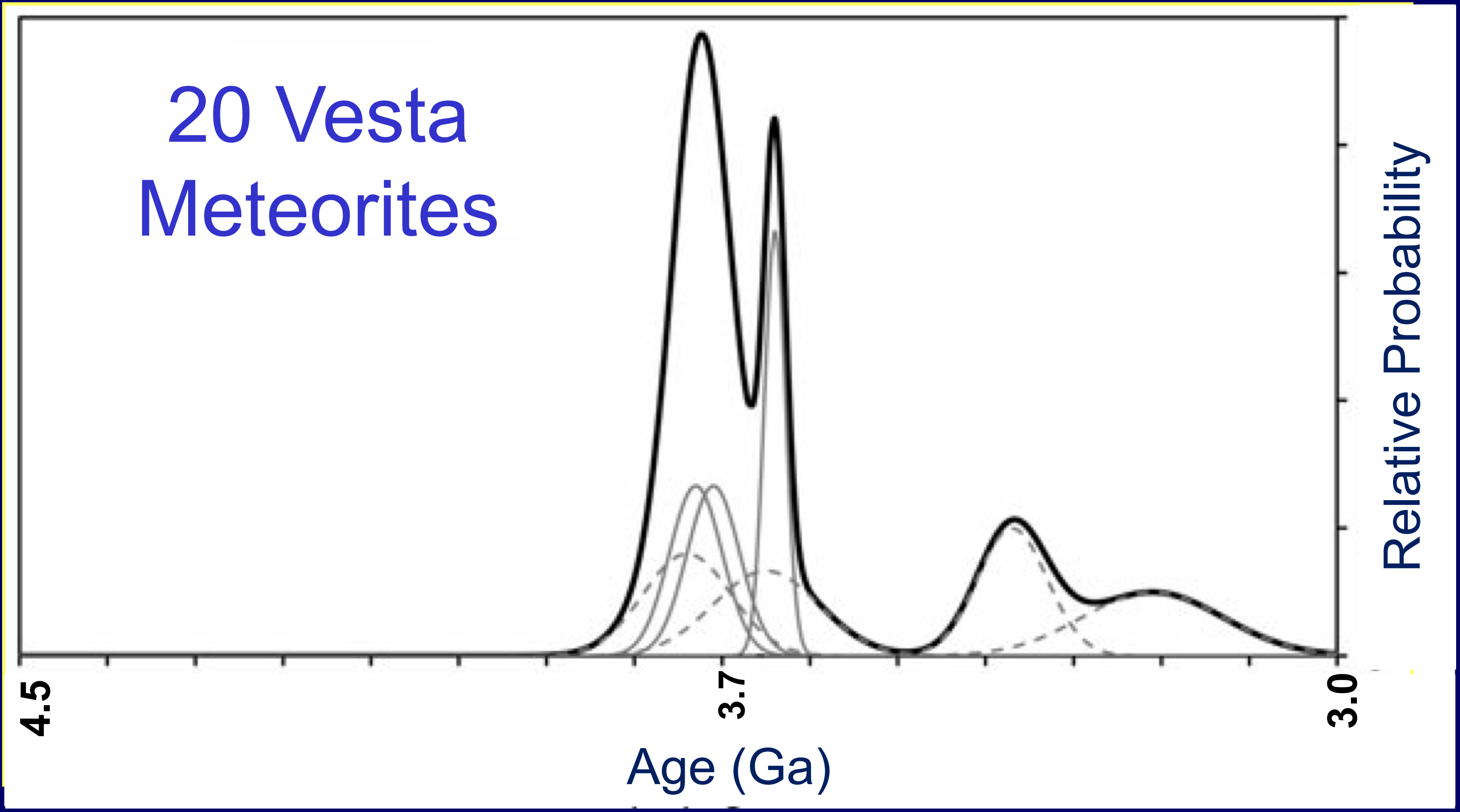
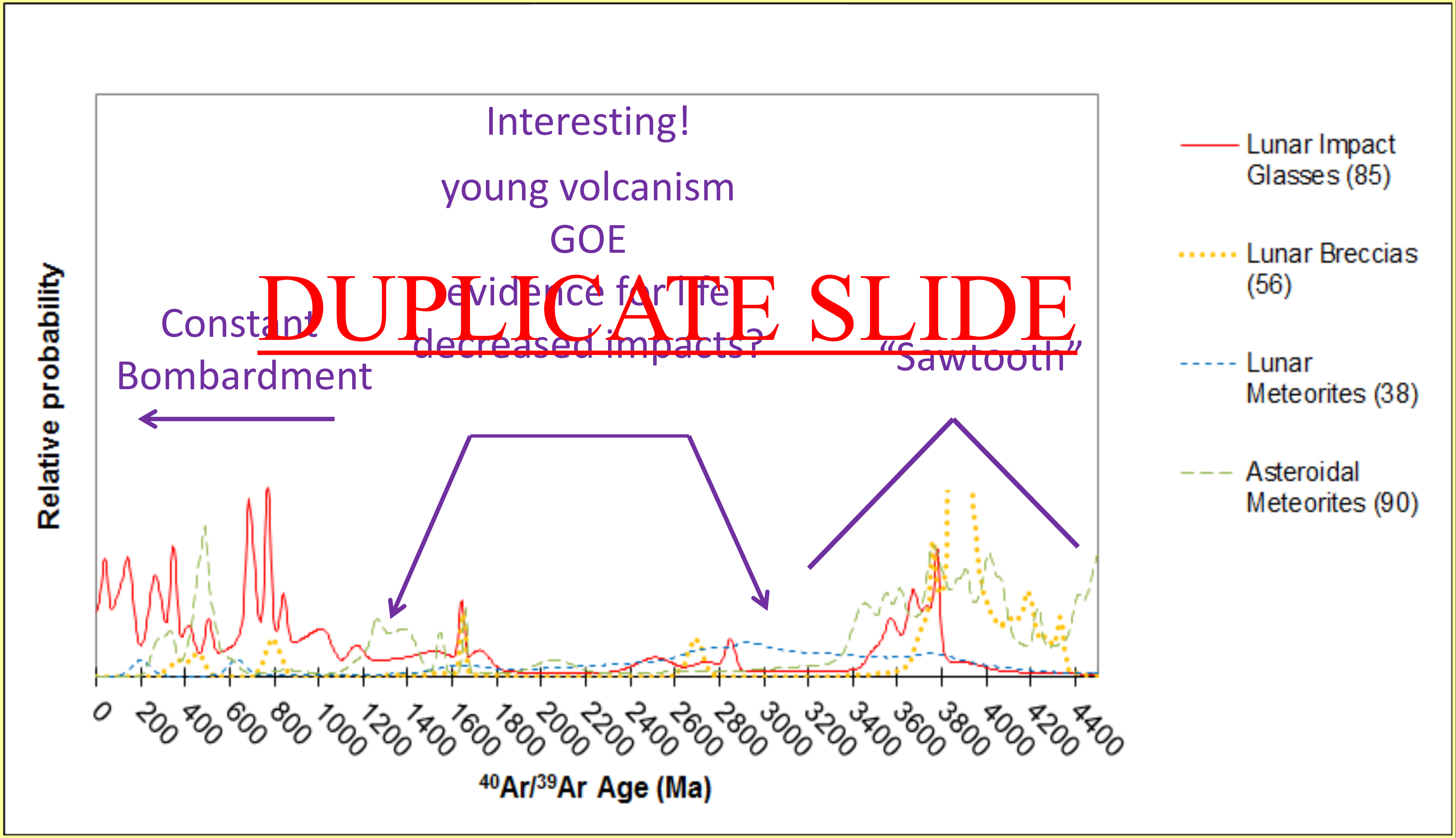


Figure 9 in Cohen 2013

In Total: Impact Sample Ages



Modified from Zellner, *OLEB,* 2017

Summary: Lunar Impact Rate

Lunar Samples are being re-analyzed

- Lunar ages re-calibrated, rocks re-analyzed
- Few lunar impact glasses with ages ≥ 3.9 Ga
  - Limited by available K?
  - Limited by number of impact events?

Glass spheres turn into shards over time

Duration and nature early lunar impact flux still uncertain