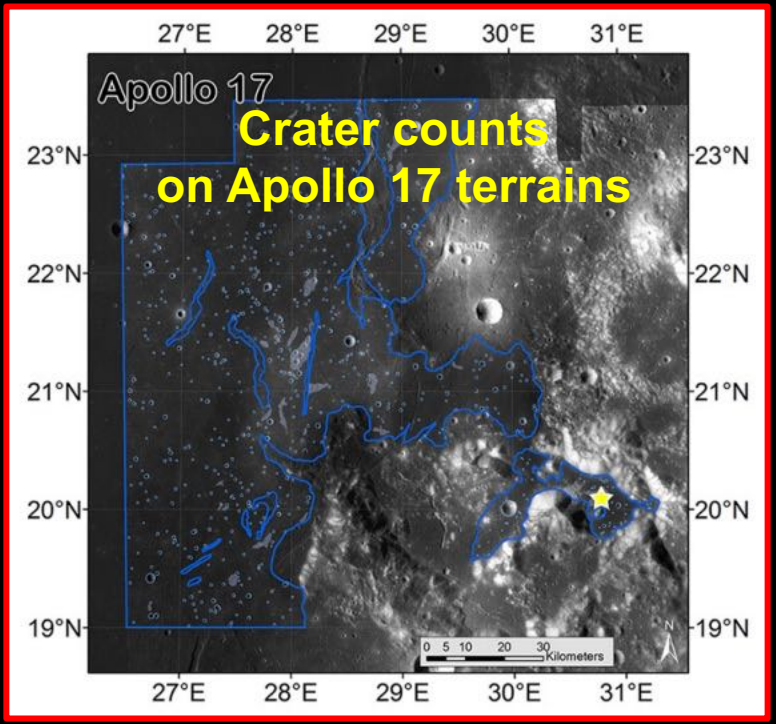
A Surge of Impacts 2 Billion Years Ago?

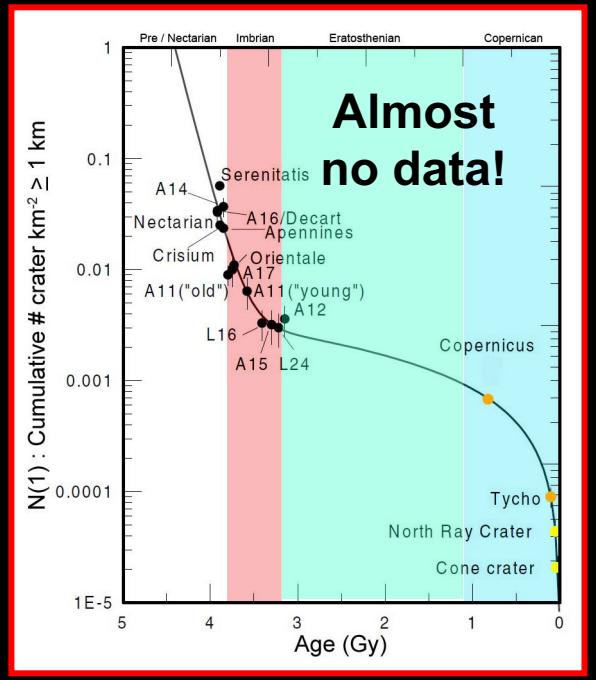
William Bottke (SwRI)
F. Scott Anderson (SwRI)

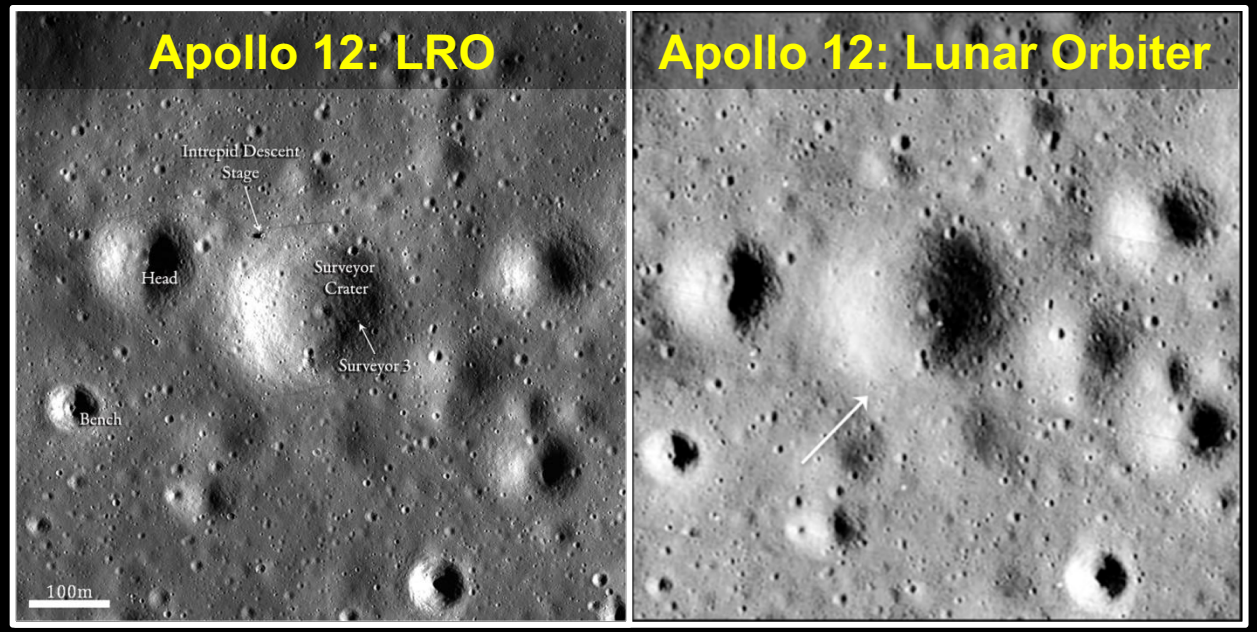
Lunar Chronology



- Lunar rocks yield landing site age.
- Crater counts yield “age-crater spatial density” function

Problem: Limited Data < 3 Ga

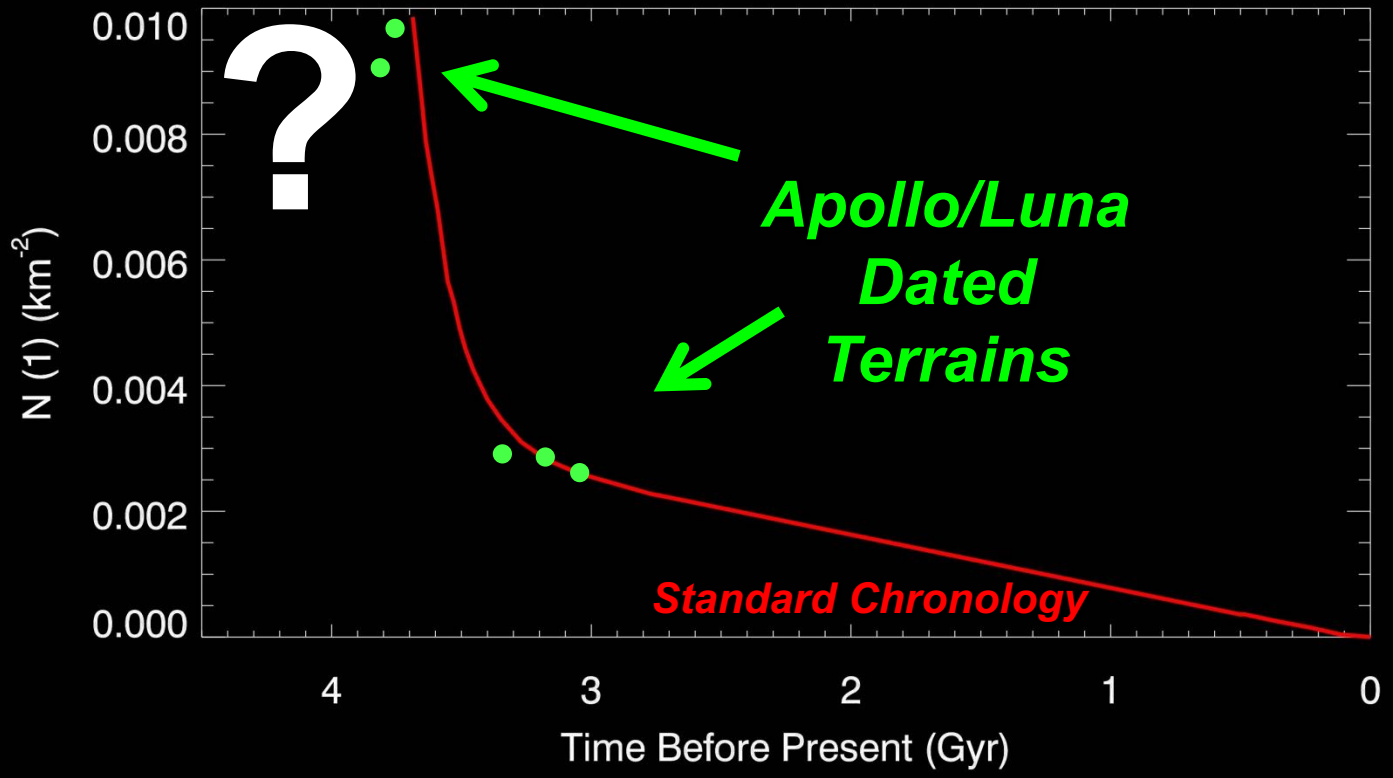




- Almost no dated terrains < 3.2 Ga!
- Crater counts often increase with new LRO images

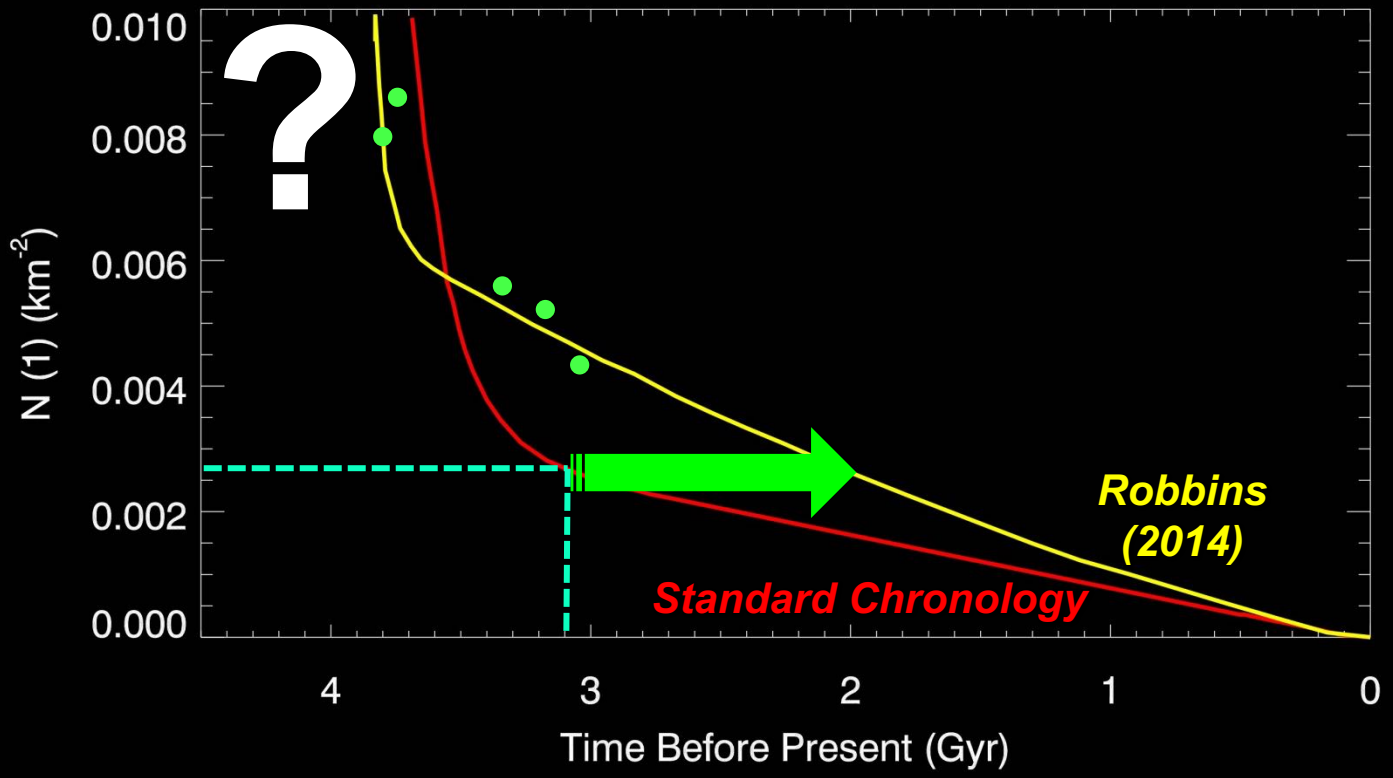
Sample references: Marchi et al. (2009); Robbins (2014)

Plausible Lunar Chronologies



Neukum et al. (2001); Marchi et al. (2009); Robbins (2014)

Plausible Lunar Chronologies



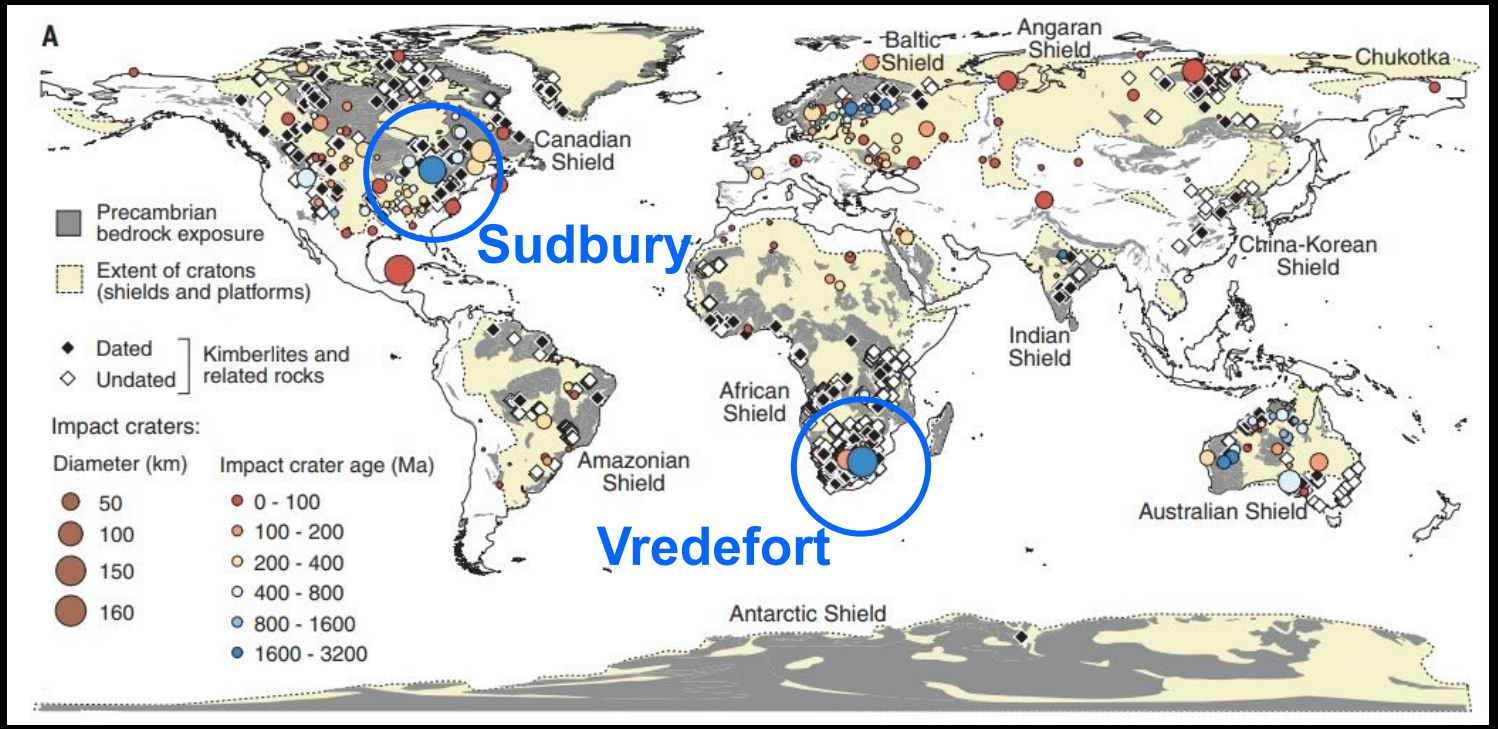
- **Max difference in chronologies is 1 Gyr: ~3 Ga becomes ~2 Ga!**

Neukum et al. (2001); Marchi et al. (2009); Robbins (2014)

-Bottke

New Chronology

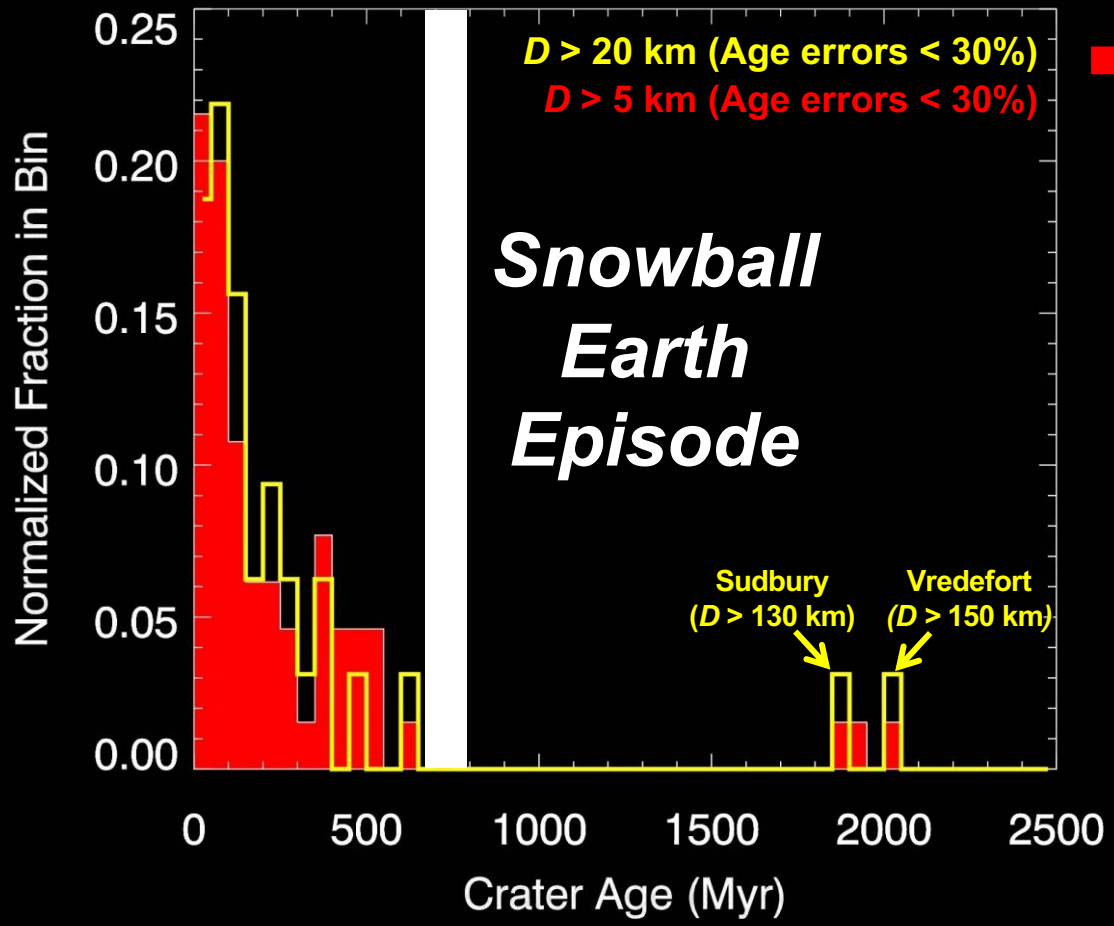
Terrestrial Craters



- Using Earth/Moon data, we found 10 ± 3% of Earth's surface is well searched for craters and fairly stable back to 650 Ma.
- Present-day area of continents goes back to 2 Ga.

Mazrouei et al. (2019)

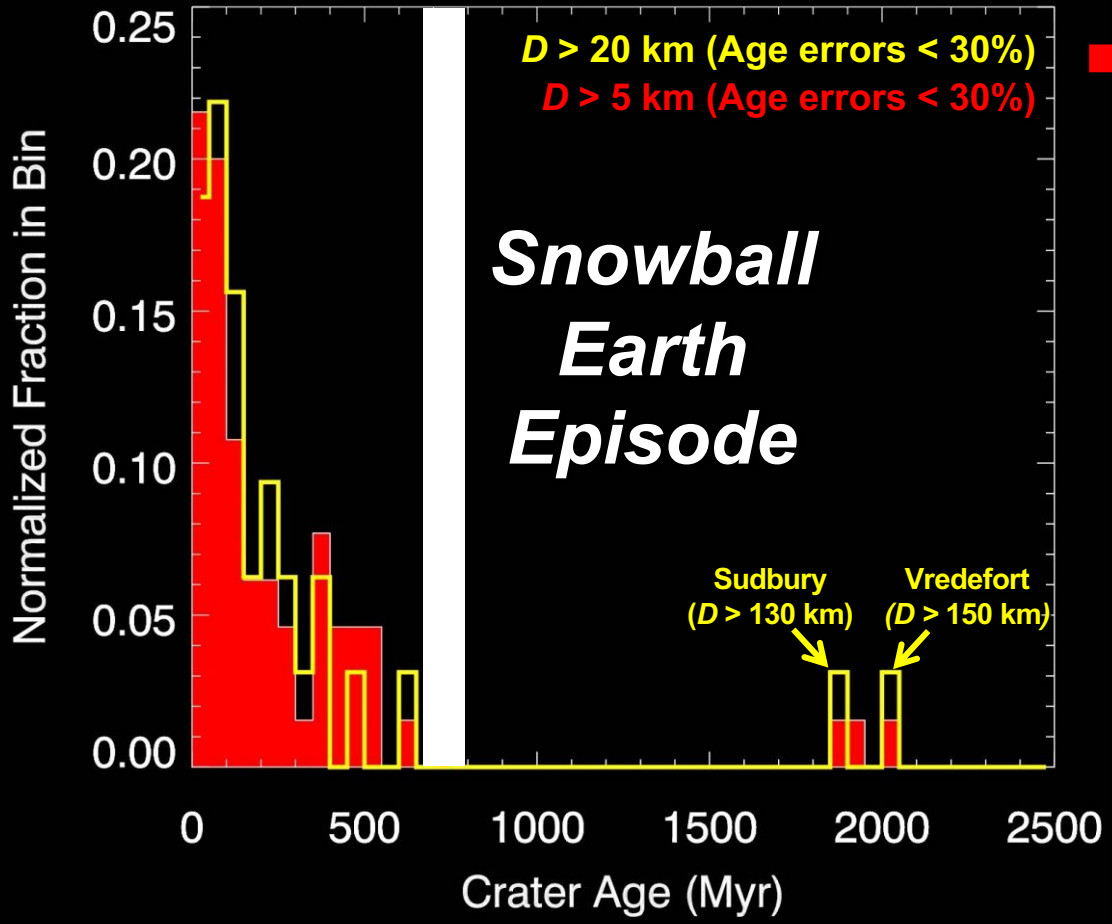
Why Do Sudbury/Vredefort Craters Exist?



- **Sudbury/Vredefort are *weird*!**
  - They formed near 2 Ga.
  - If only ~10% of Earth is stable, odds that two large impactors hit those terrains is ~1%!
  - Were there more big impacts?

Mazrouei et al. (2019); Keller et al. (2019)

Why Do Sudbury/Vredefort Craters Exist?

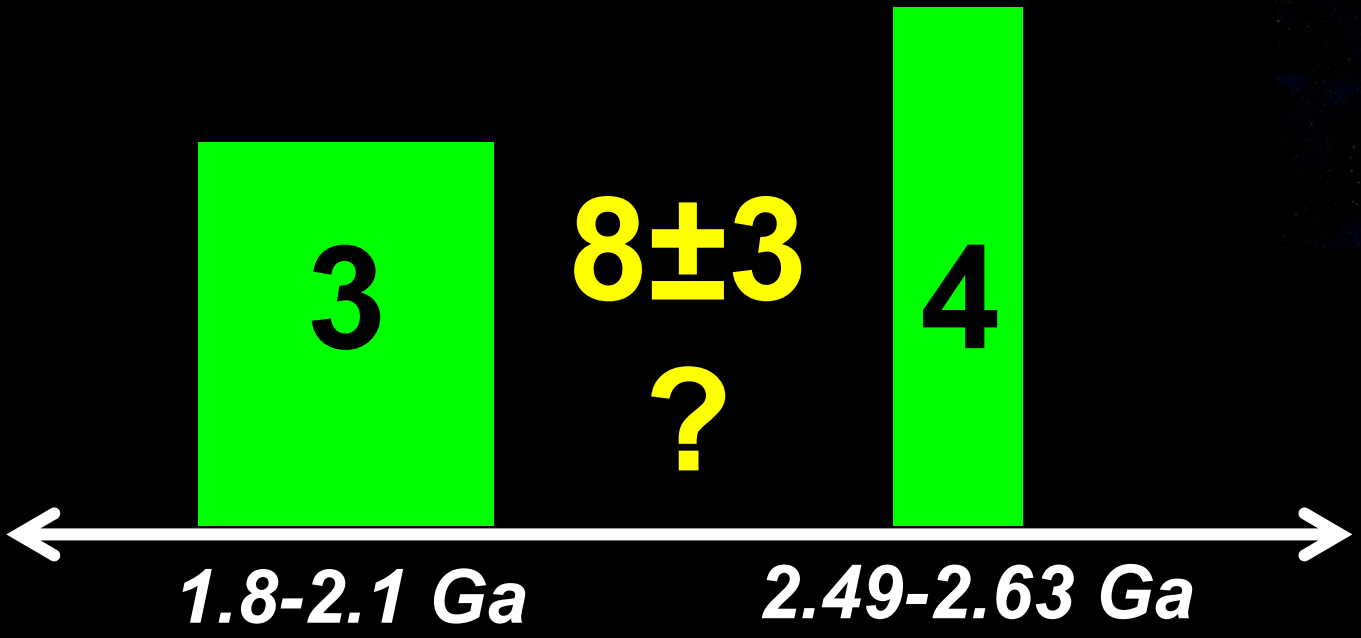


- **Sudbury/Vredefort are *weird*!**
  - They formed near 2 Ga.
  - If only ~10% of Earth is stable, odds that two large impactors hit those terrains is ~1%!
  - Were there more big impacts?

$$\frac{2 \pm 1\ impacts}{0.10 \pm 0.03} = 20 \pm 15\ impacts!$$

Mazrouei et al. (2019); Keller et al. (2019)

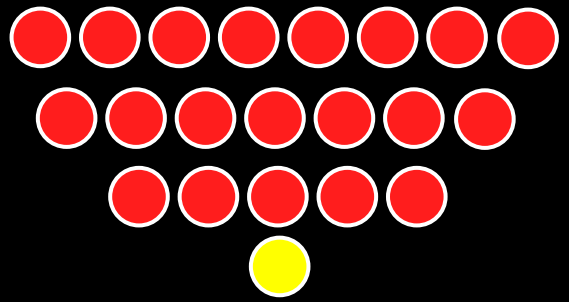
Impact Spherule Beds: 1.8-2.1 and 2.5-2.6 Ga



- Impact spherule bed tells us K-T-sized impact took place.
- Did 15 ± 4 K-T-sized impacts take place between 1.8-2.6 Ga?

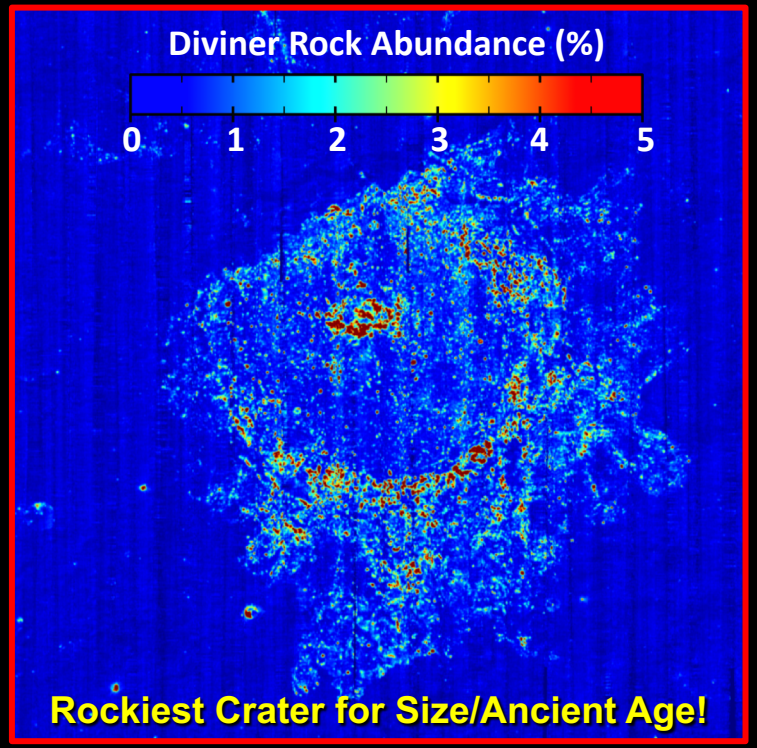
Bottke et al. (2012); Mougel et al. (2017)

Impact Ratio Between Earth and Moon



- For every 20 things that hit the Earth, one hits the Moon.
- *Prediction: ~2 Ga K-T sized crater should exist on Moon!*

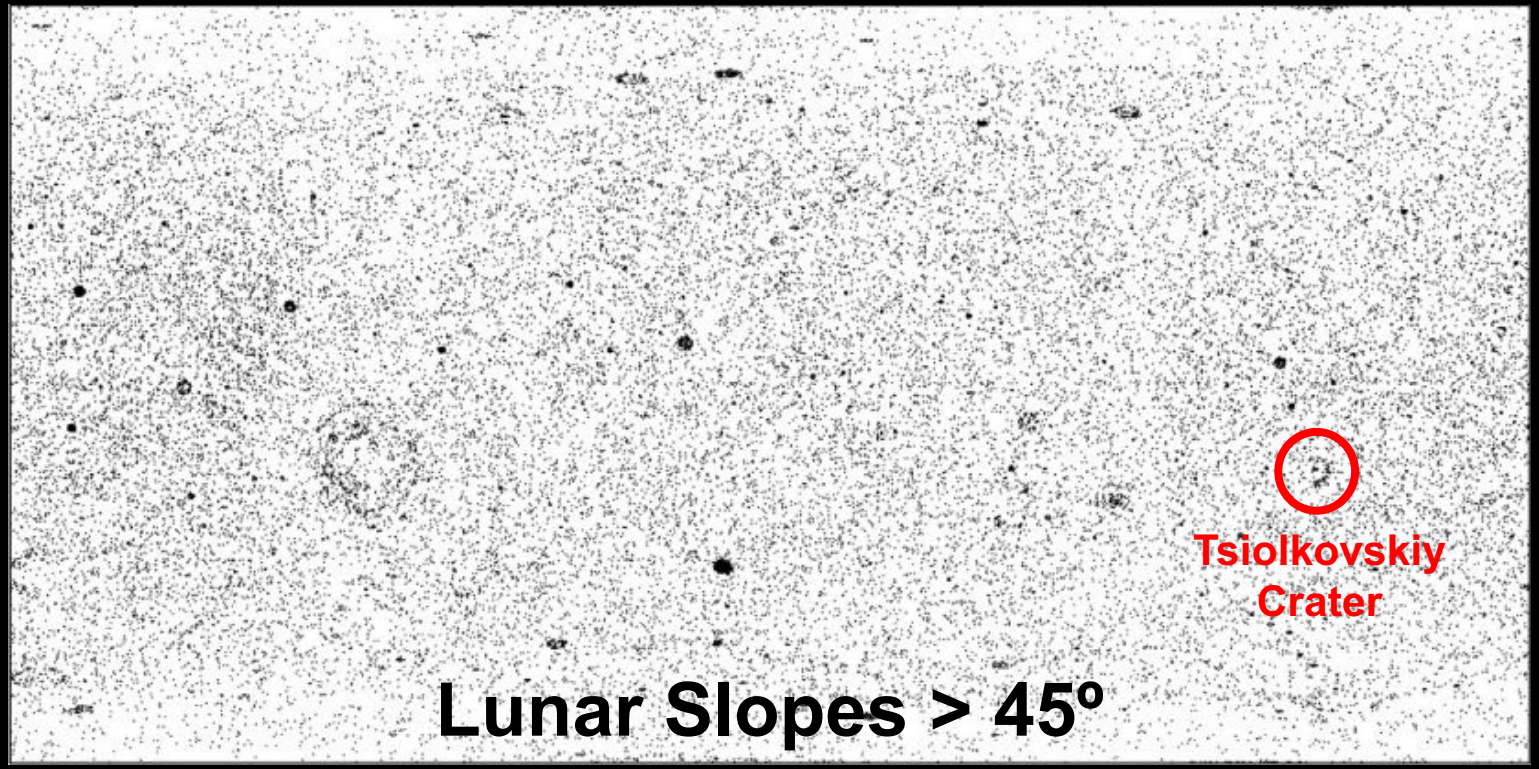
Young K-T Sized Event on the Moon?



- Tsiolkovskiy is the largest youngest crater on Moon.
- It is ~3.2 Ga in standard chronology, but super rocky! How? Why?

Greenhagan et al. (2016)

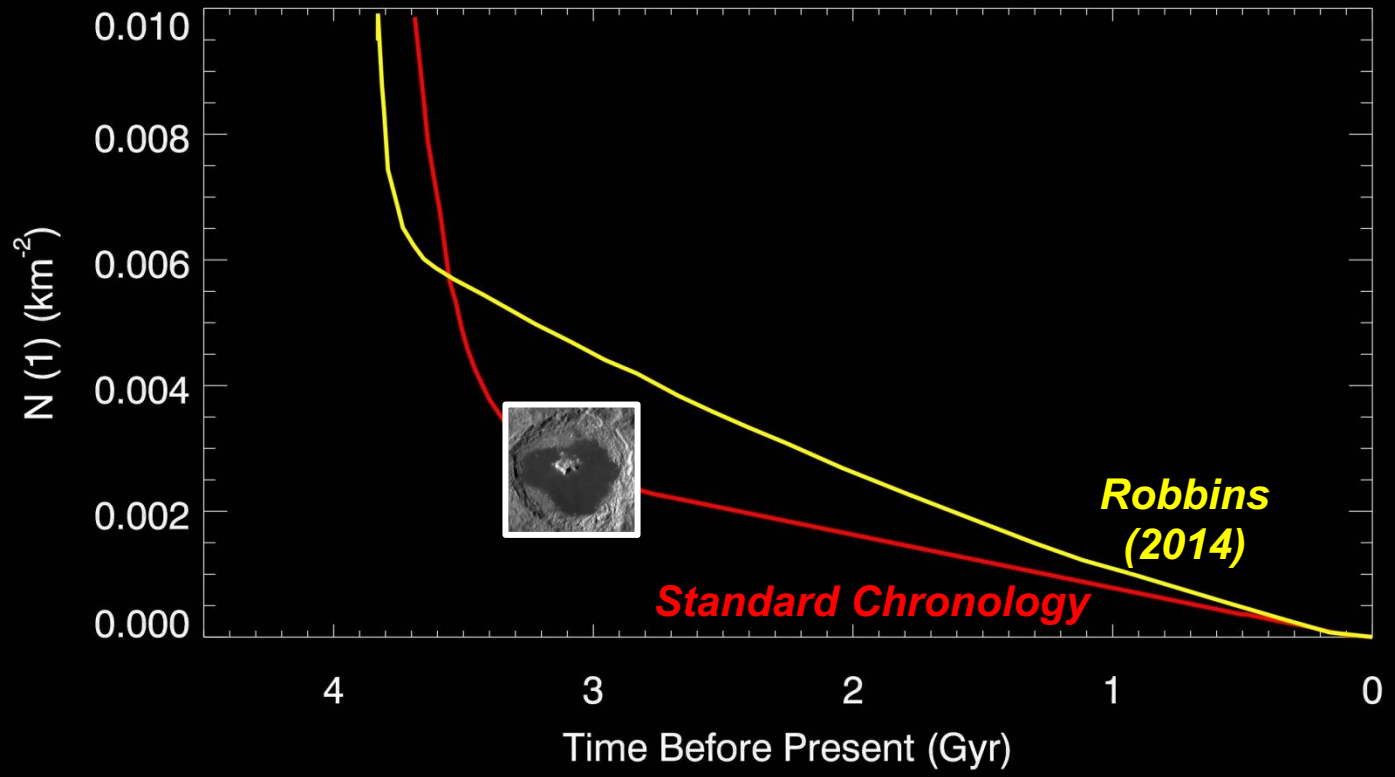
Young K-T Sized Event on the Moon?



- Tsiolkovskiy walls/central peak have many sites with slopes > 45º
- *Slopes indicate near Copernican/Eratosthenian in age!*

Kreslavsky and Head (2016)

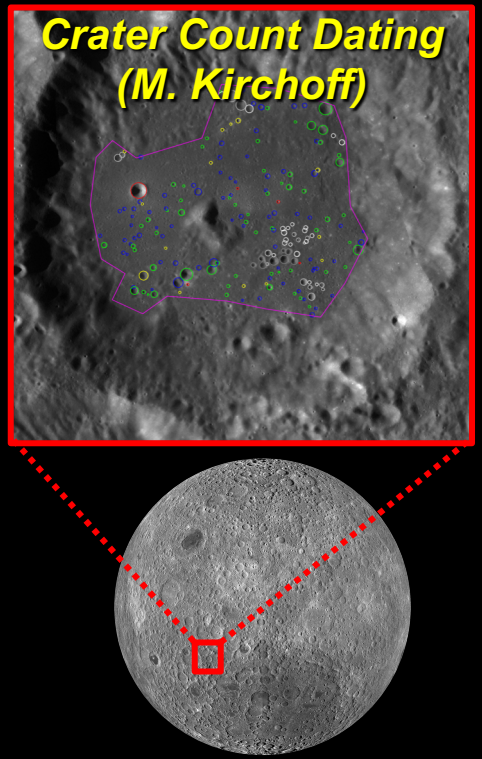
In New Chronology, Tsiolkovskiy is 2 Ga

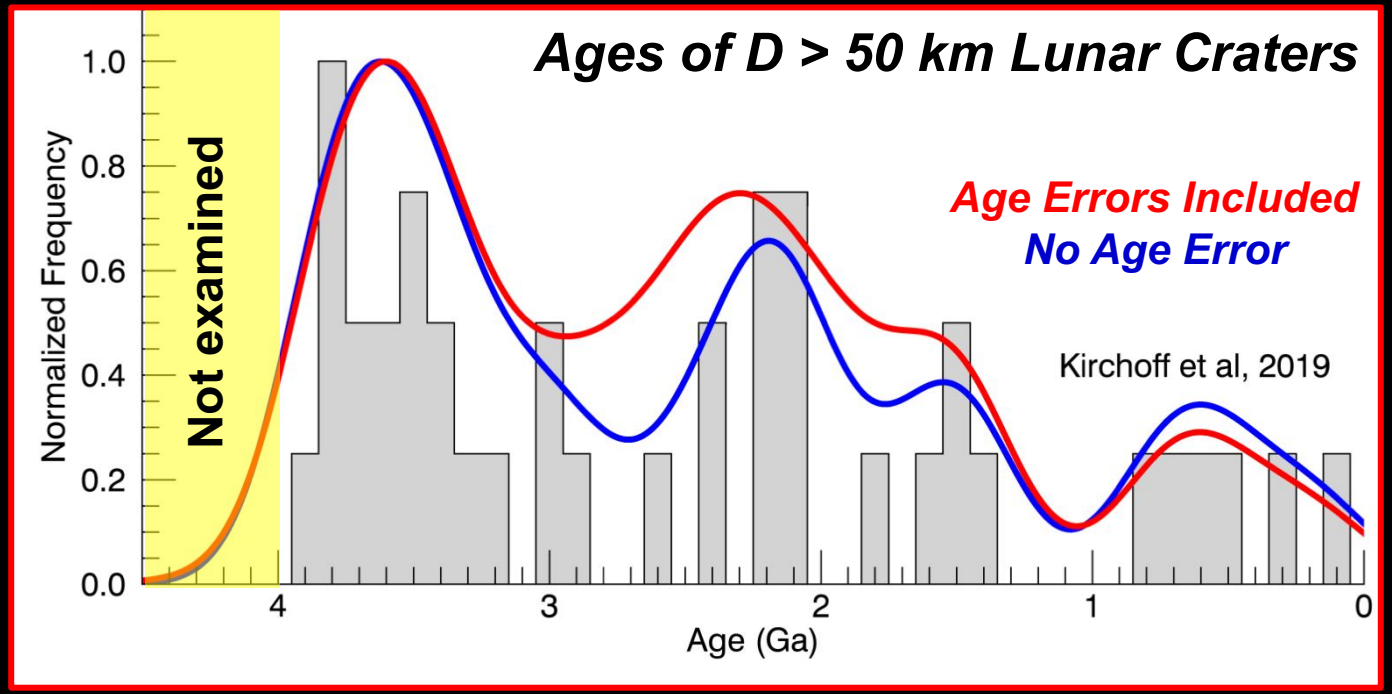


- **Revised age for Tsiolkovskiy is 2.0-2.3 Ga. Many things start to make sense on Earth/Moon.**

Neukum et al. (2001); Marchi et al. (2009); Robbins (2014)

Asteroid Shower ~2-2.5 Ga on Moon?

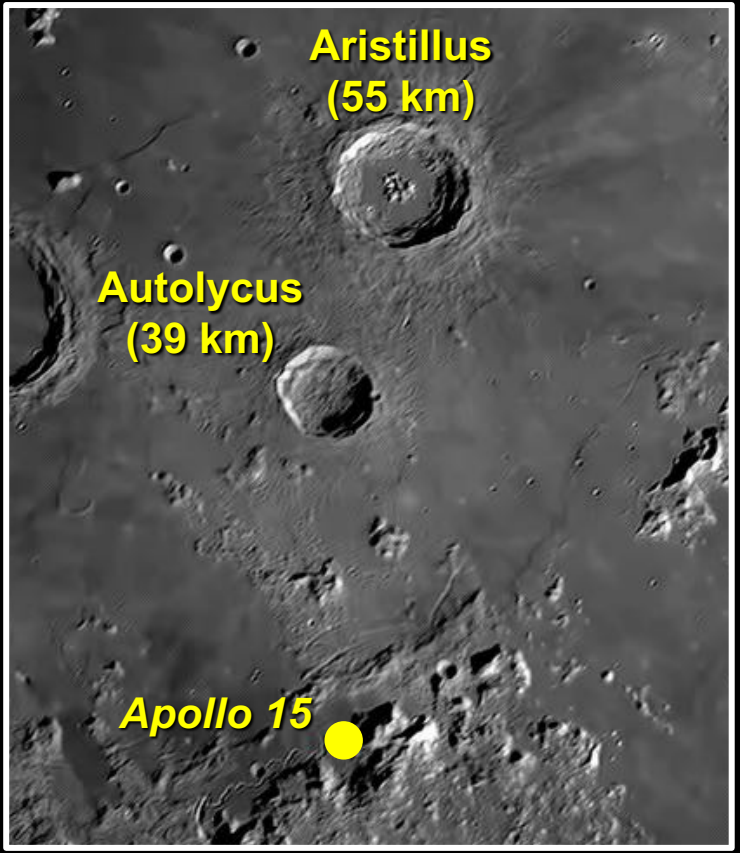




- Ages of *D* > 50 km craters yield possible ~2.0-2.5 Ga "impact shower"!

Kirchoff et al. (2019)

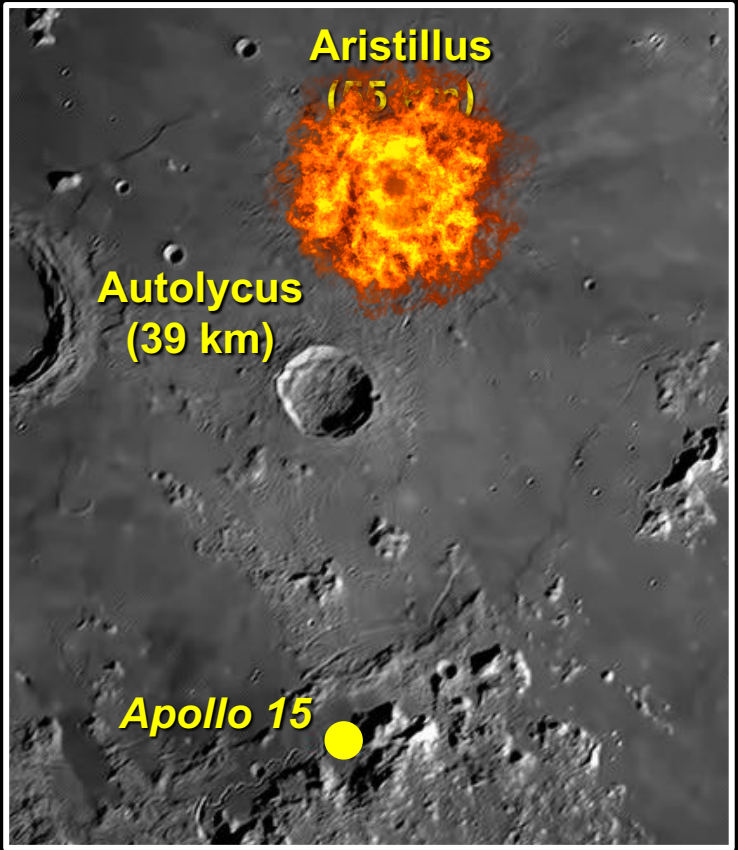
Aristillus, Autolycus, and Apollo 15



- Apollo 15 zircons reset at 1.41 ± 0.06 Ga and 1.94 ± 0.10 Ga by hot ejecta.
- Likely source Aristillus and Autolycus

Ryder et al. (1991); Grange et al. (2013)

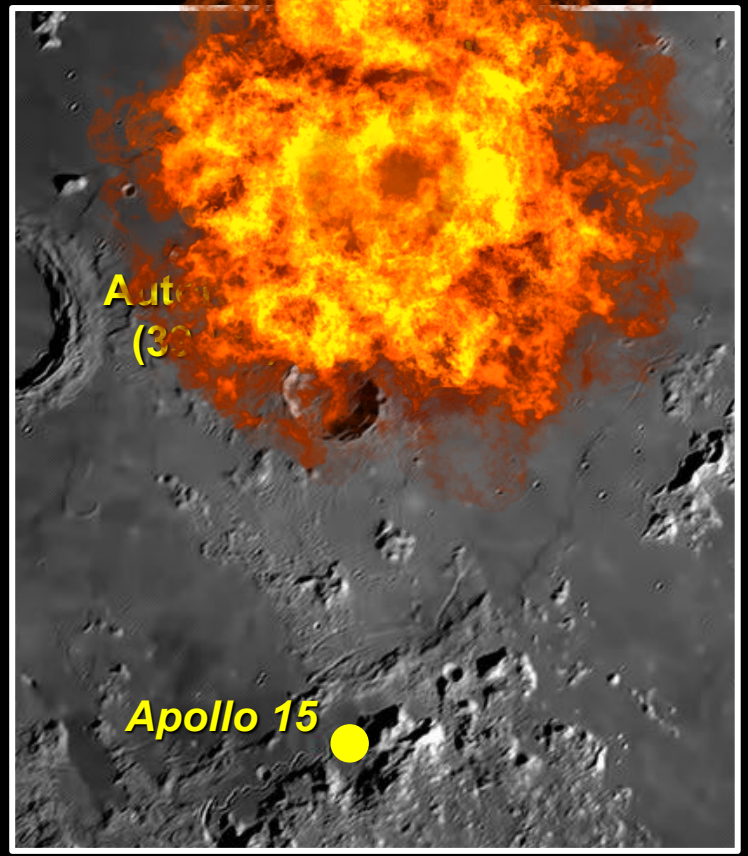
Aristillus, Autolycus, and Apollo 15



- Apollo 15 zircons reset at 1.41 ± 0.06 Ga and 1.94 ± 0.10 Ga by hot ejecta.
- Likely source Aristillus and Autolycus

Ryder et al. (1991); Grange et al. (2013)

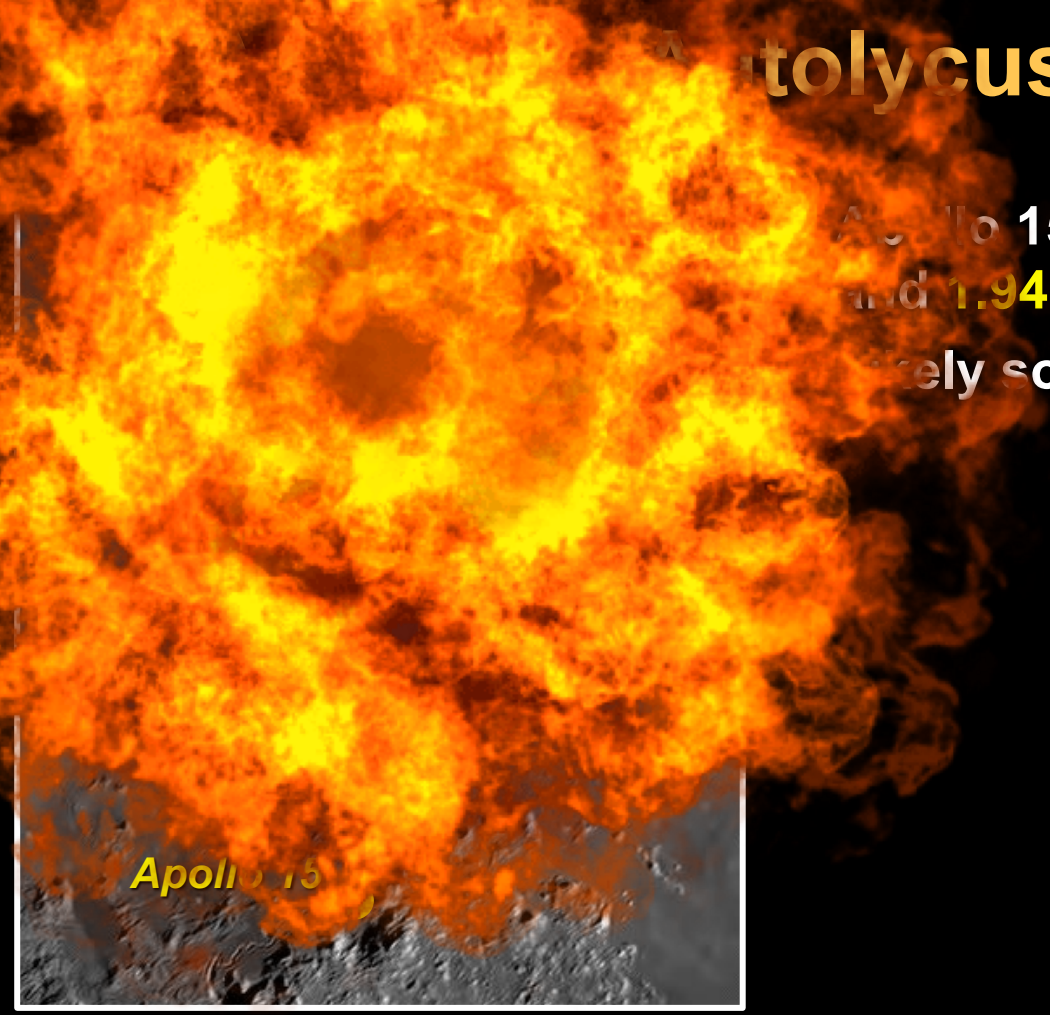
Aristillus, Autolycus, and Apollo 15



- Apollo 15 zircons reset at 1.41 ± 0.06 Ga and 1.94 ± 0.10 Ga by hot ejecta.
- Likely source Aristillus and Autolycus

Ryder et al. (1991); Grange et al. (2013)

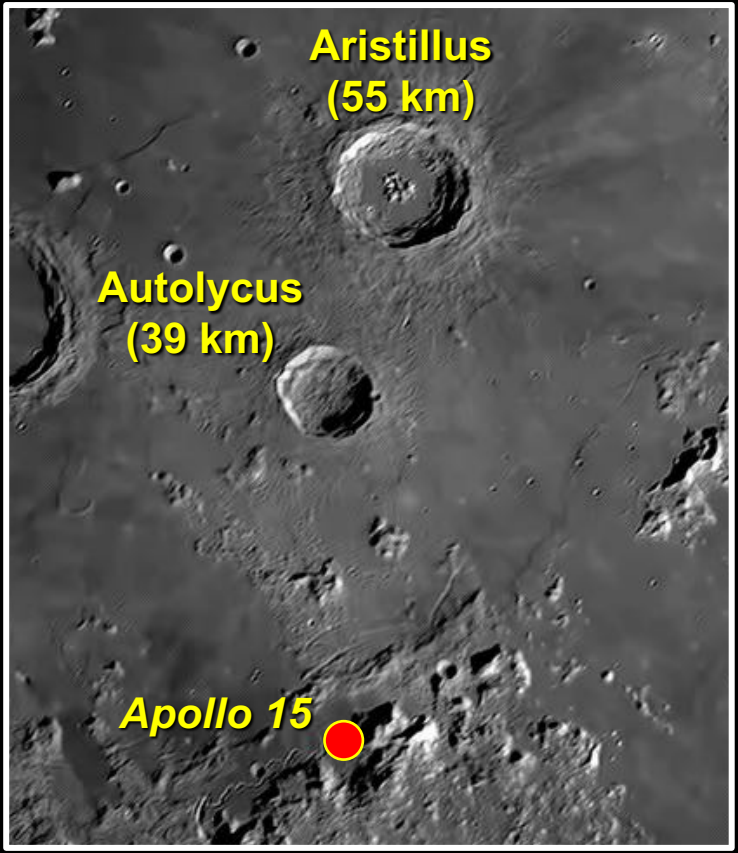
Autolycus, and Apollo 15



- Apollo 15 zircons reset at 1.41 ± 0.06 Ga and 1.94 ± 0.10 Ga by hot ejecta.
- Likely source Aristillus and Autolycus

Ryder et al. (1991); Grange et al. (2013)

Aristillus, Autolycus, and Apollo 15

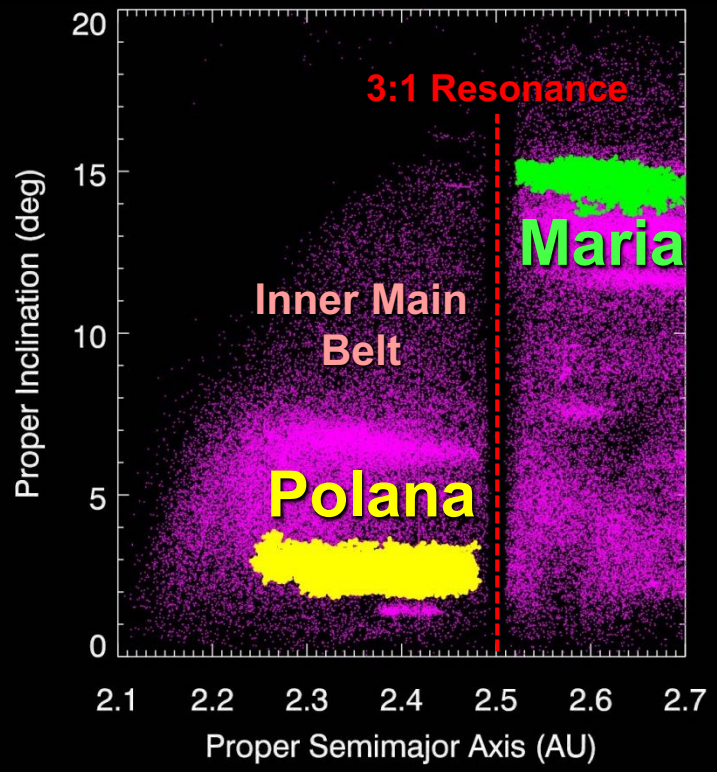


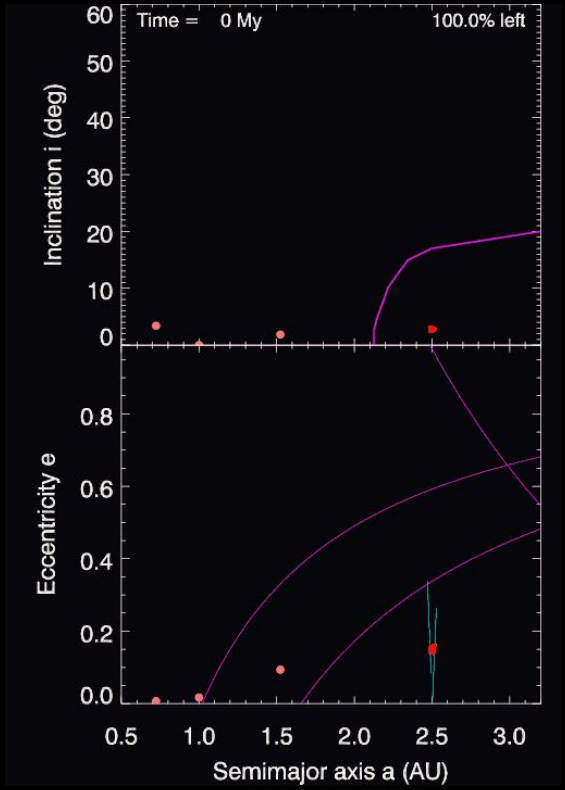
- **Aristillus**
  - Crater age of 1.6 ± 0.2 Ga overlaps 1.41 ± 0.06 Ga zircon age.
- **Autolycus**
  - Many secondaries from Aristillus!
  - Crater age of ~2.1 Ga close to 1.94 ± 0.10 Ga zircon age.

Using New Chronology, Crater Ages Match Zircon Ages!

Ryder et al. (1991); Grange et al. (2013); Hiesinger et al. (2016); Kirchoff et al. (2019)

Source: Polana/Maria Asteroid Families?





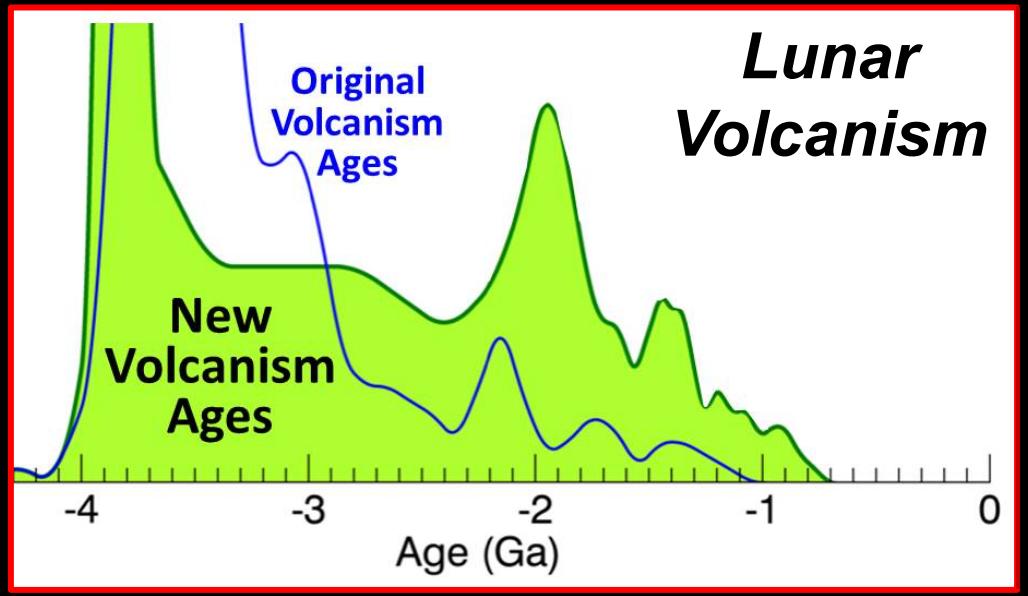
Family Members Injected into 3:1 Resonance

Driven into Near-Earth Space

- **Preliminary analysis: Polana and Maria families may have produced big asteroid shower ~2-2.5 Ga.**

Methods from Bottke et al. (2015)

Implications for Moon (and Earth)



Earth: 1.8-2.5 Ga:

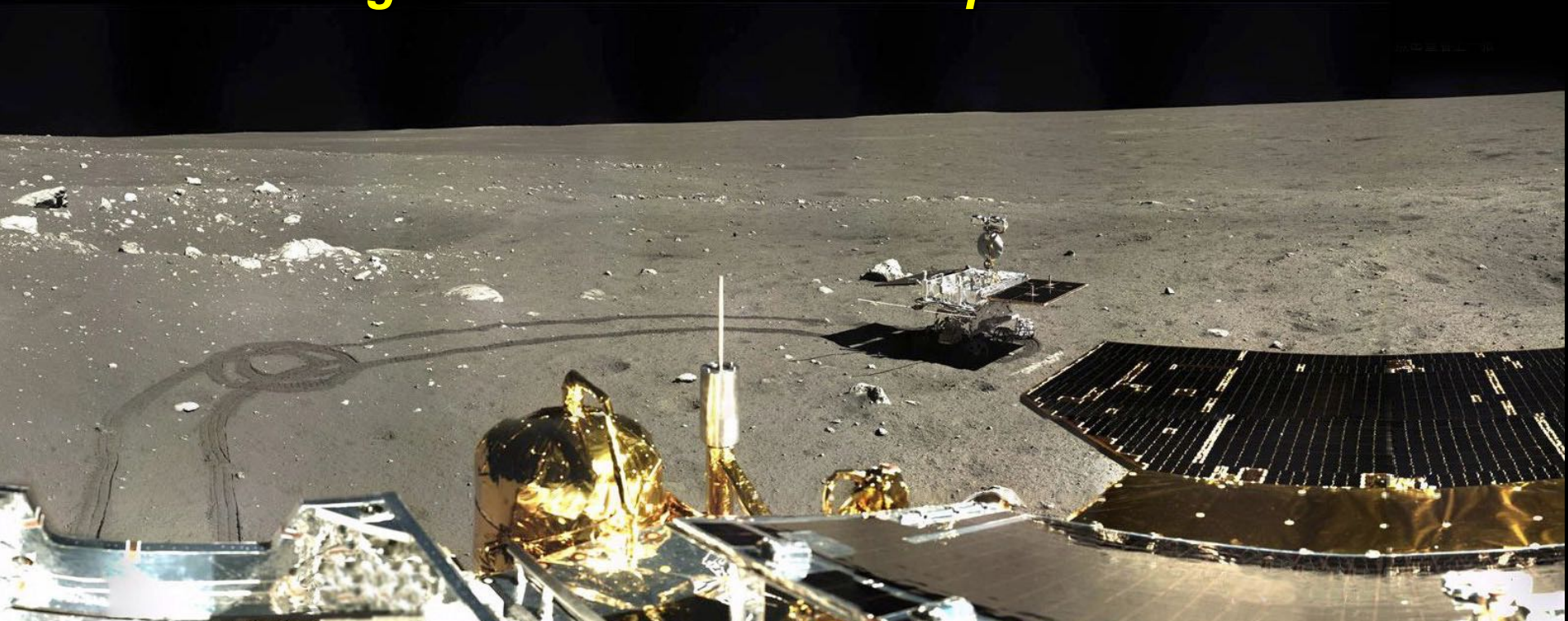
"Great Oxidation Event" (2.3 Ga)

Multiple Snowball Earth Events (2.1-2.3 Ga)

Huge Oxygen Swings (2-2.3 Ga)

- New chronology yields surge in young volcanism (~3 Ga to ~2 Ga).
- *Question: Could parts of Marius Hills, Aristarchus plateau be ~2 Ga?*
- ***Major changes on Earth 1.8-2.5 Ga. Impact related?***

Whitten and Head (2014); Lyons et al. (2014)

Dating Samples with Commercial Landers

- Landers may visit sites that are ~2-3 Ga.
- *In situ dating of lunar surfaces now plausible!*