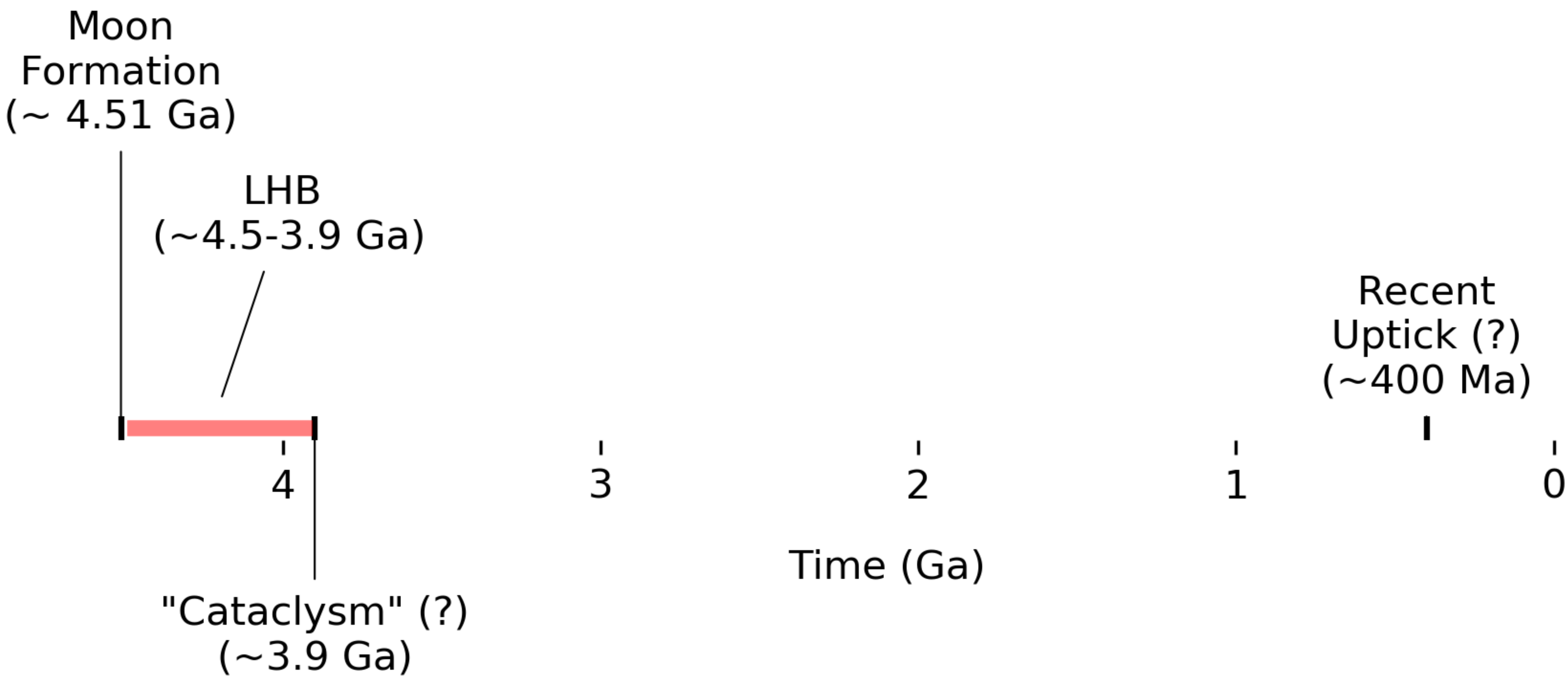
The Moon: New Views on Formation and Impact History

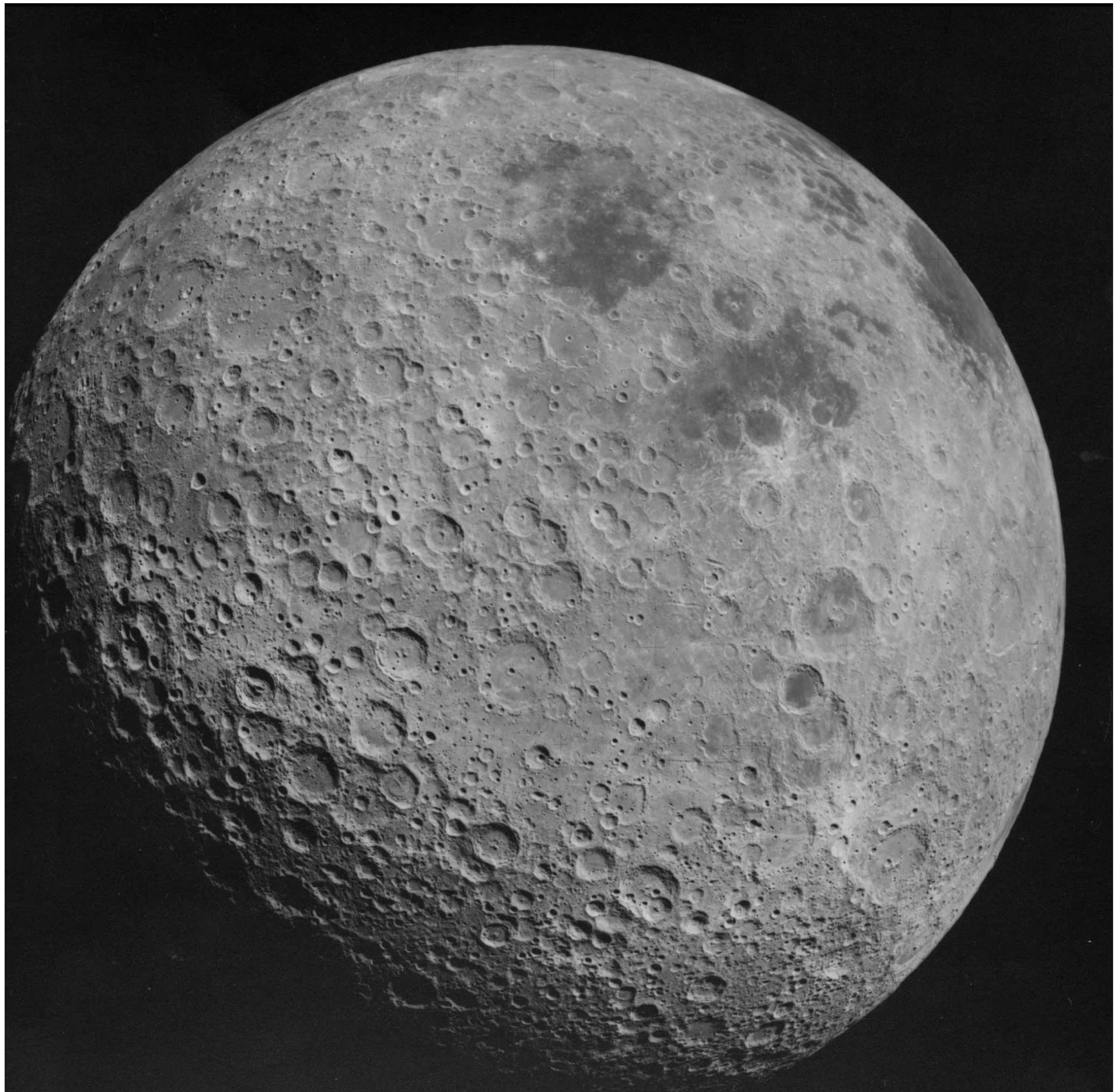
Pham Nguyen
Michigan State University
and
Albion College

Outline


Moon
Formation
(~ 4.51 Ga)
LHB
(~4.5-3.9 Ga)
Recent
Uptick (?)
(~400 Ma)
4
3
2
1
0
Time (Ga)
"Cataclysm" (?)
(~3.9 Ga)

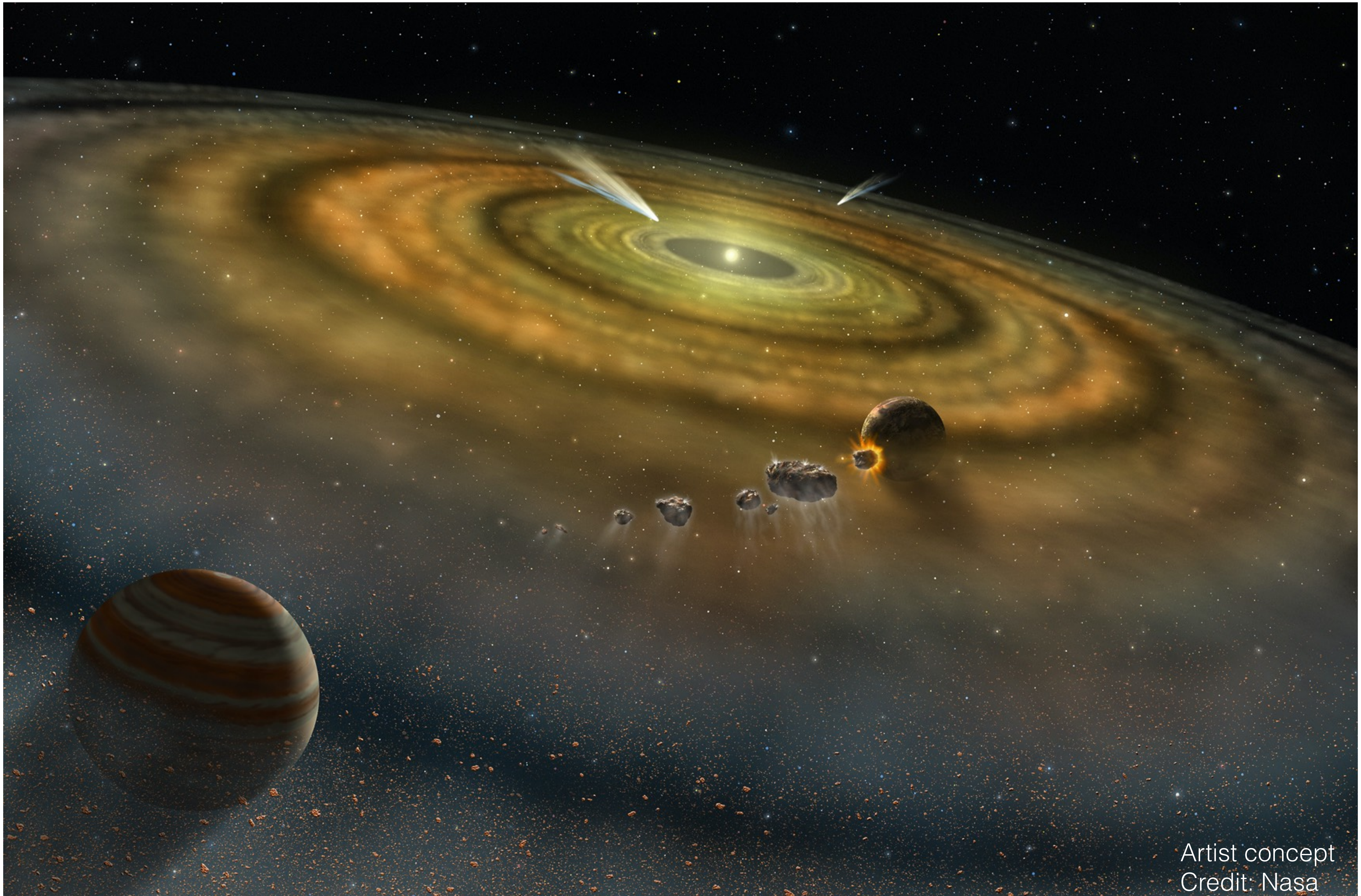
Why Study the Moon?

It has a well preserved impact history



Far side of the Moon taken
during Apollo 16
Credit: NASA

Informs dynamical models of the solar system



How do we Study the Moon?

Lunar Samples

Apollo Missions

~382 Kg

Apollo 16 sample 60025

Credit NASA/Johnson Space Center photograph

S72-42187

Luna Program

~0.326 Kg

20 cm portion of Luna 20 core sample

Credit NASA/Johnson Space Center photograph

S73-17207

Lunar Samples (Cont.)

Meteorites (~150 found)

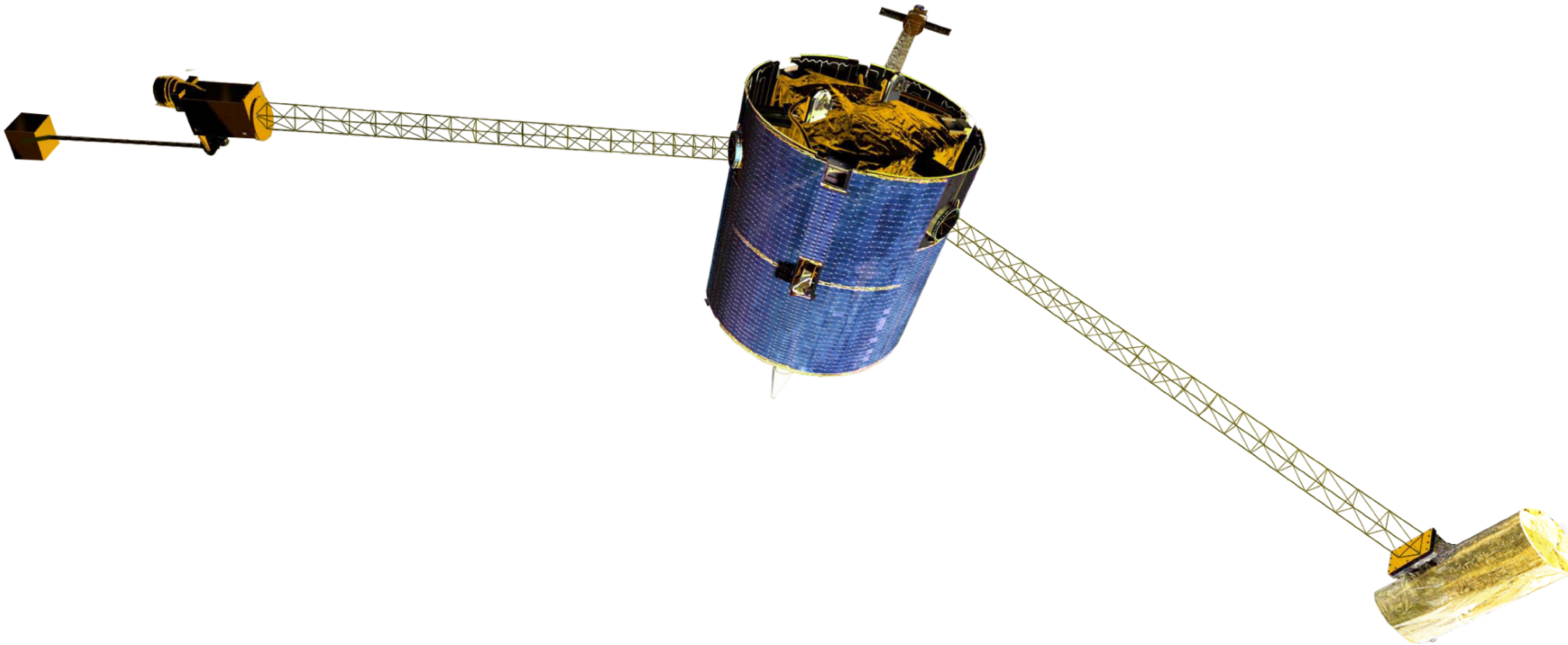
MAC 88105 a 663 gram sample found in Antarctica

Credit: NASA photo S89-38379

Lunar Orbiters

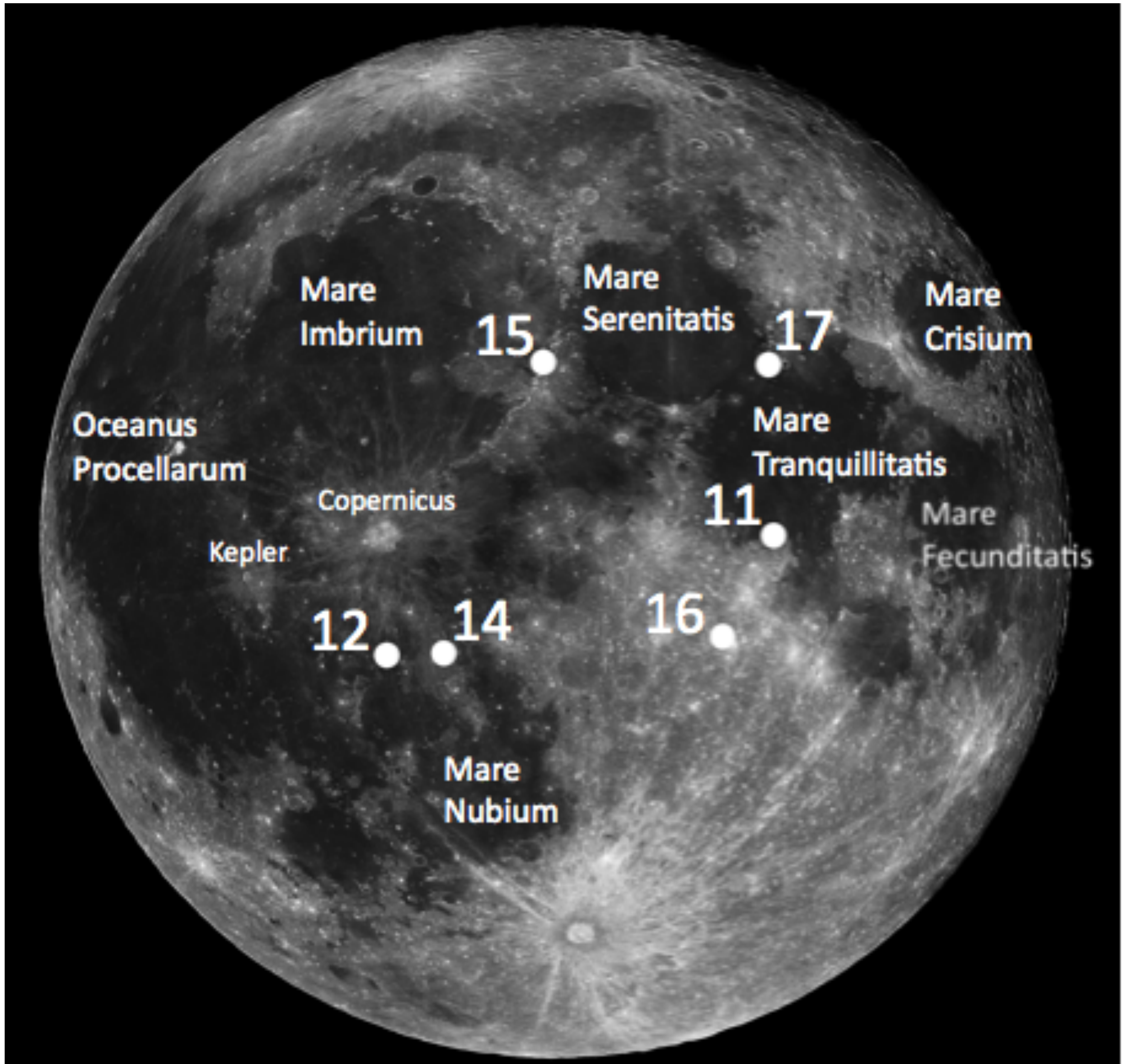
Many lunar orbiter missions including:

- Lunar Prospector (1998-1999)
- Lunar Reconnaissance Orbiter (2009-Present)
- Gravity Recovery and Interior Laboratory (2011-2012)



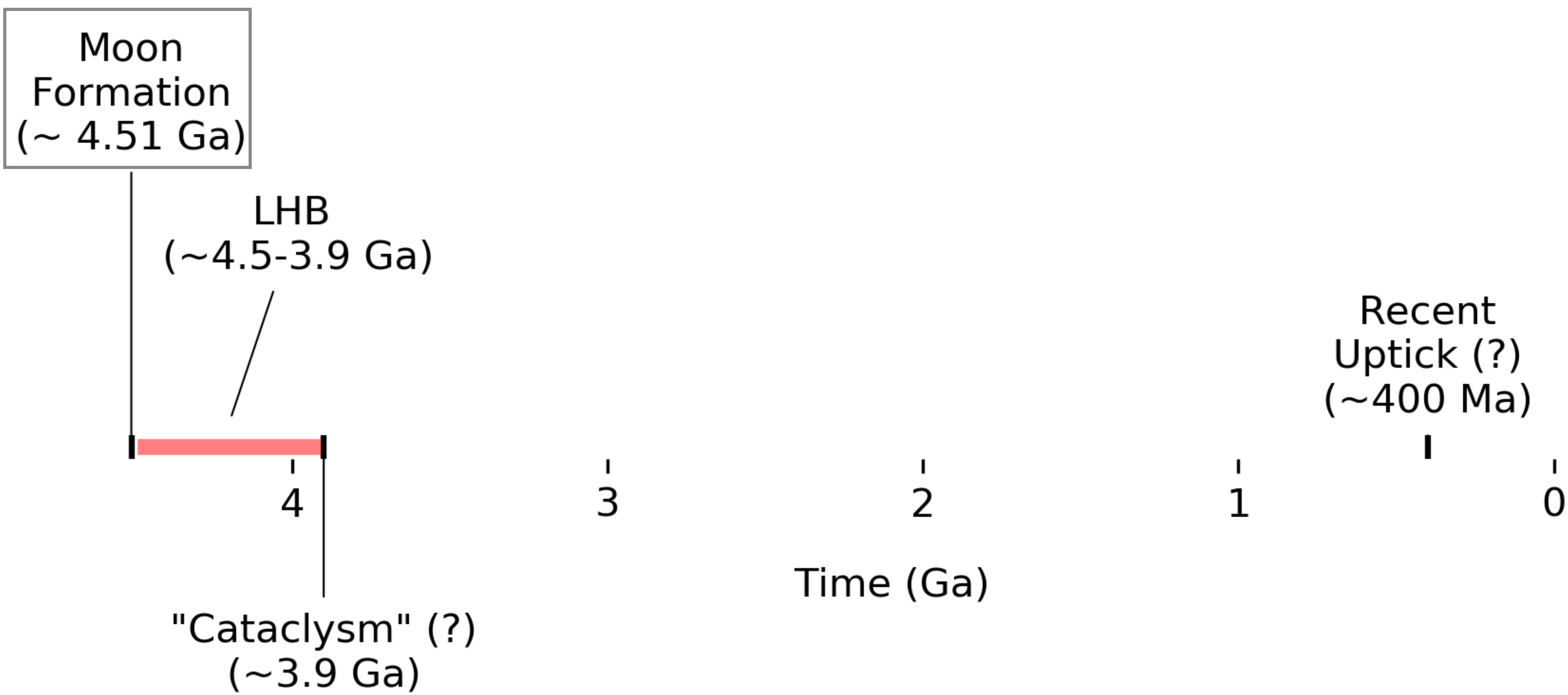
So….what is the Moon like?

Surface Features of the Moon



Credit: Dustin Scriven

Outline



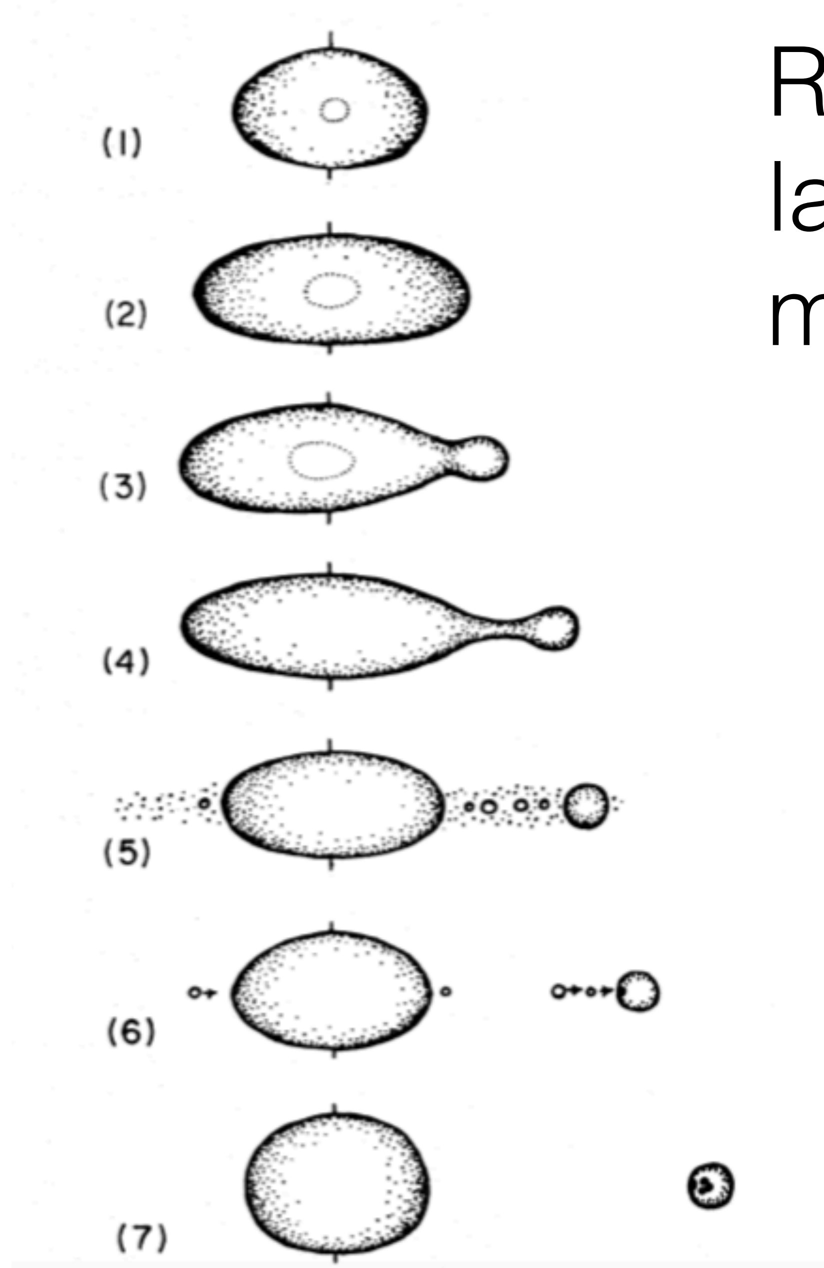
Moon Formation (~ 4.51 Ga)
LHB (~4.5-3.9 Ga)
Recent Uptick (?) (~400 Ma)
4
3
2
1
0
Time (Ga)
"Cataclysm" (?) (~3.9 Ga)

To Make a Moon

What aspects of the Moon need to be explained?

- Angular momentum
- Composition (lack of volatiles)
- Small (iron) core

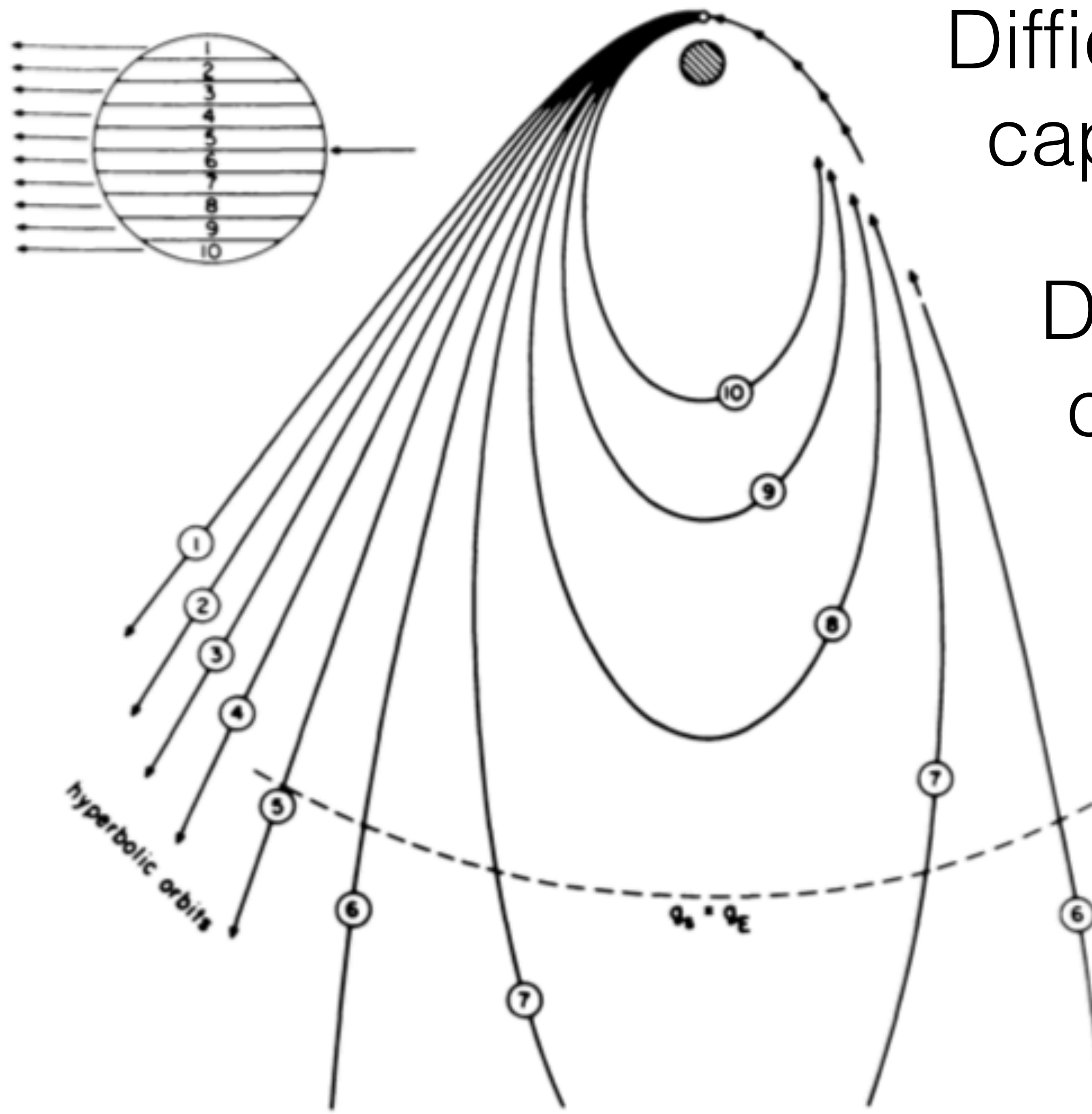
Fission



Requires very large angular momentum

Wise. D. U. 1966

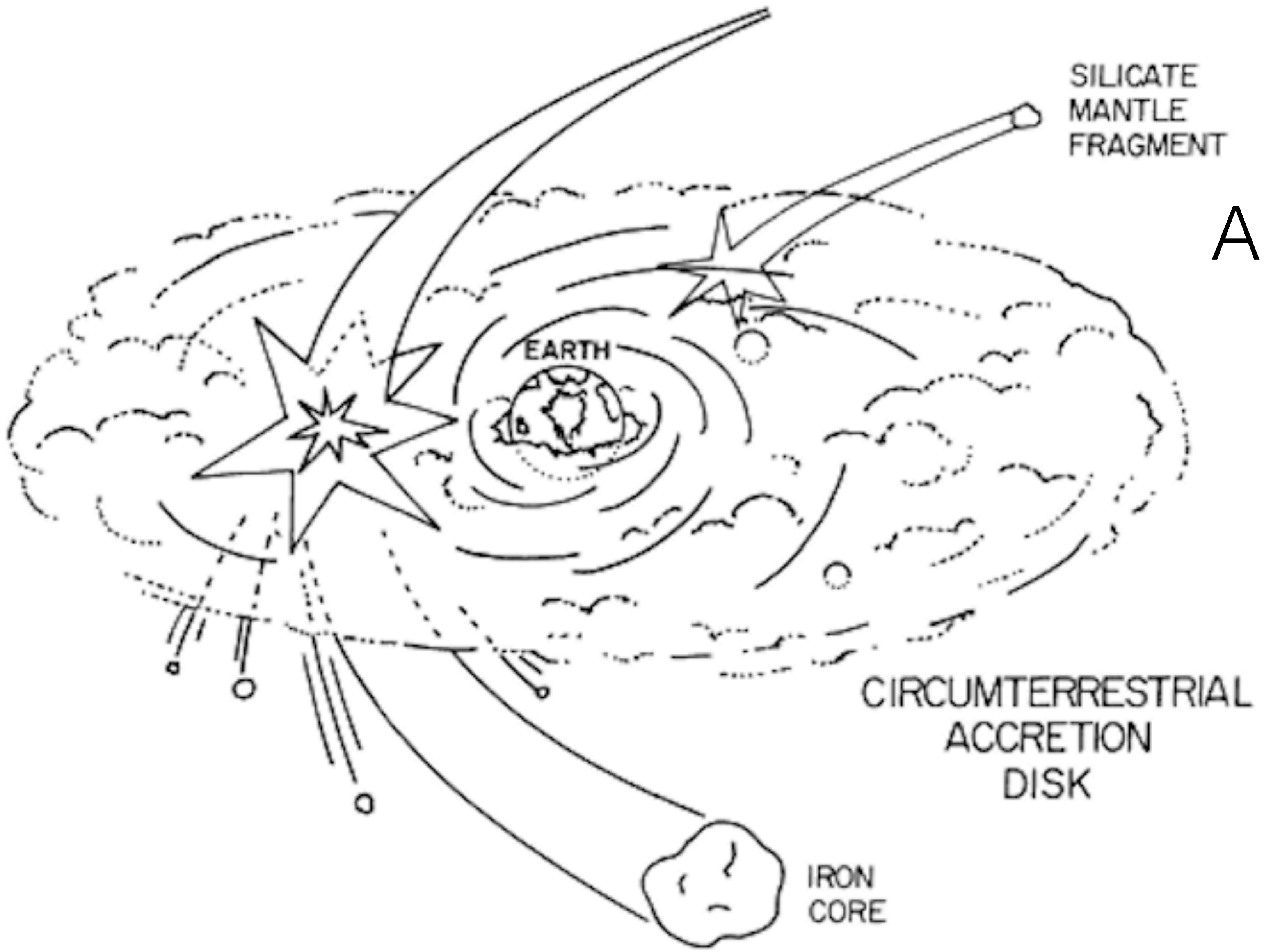
Capture



Difficult to capture

Doesn't explain compositional similarities

Binary Accretion

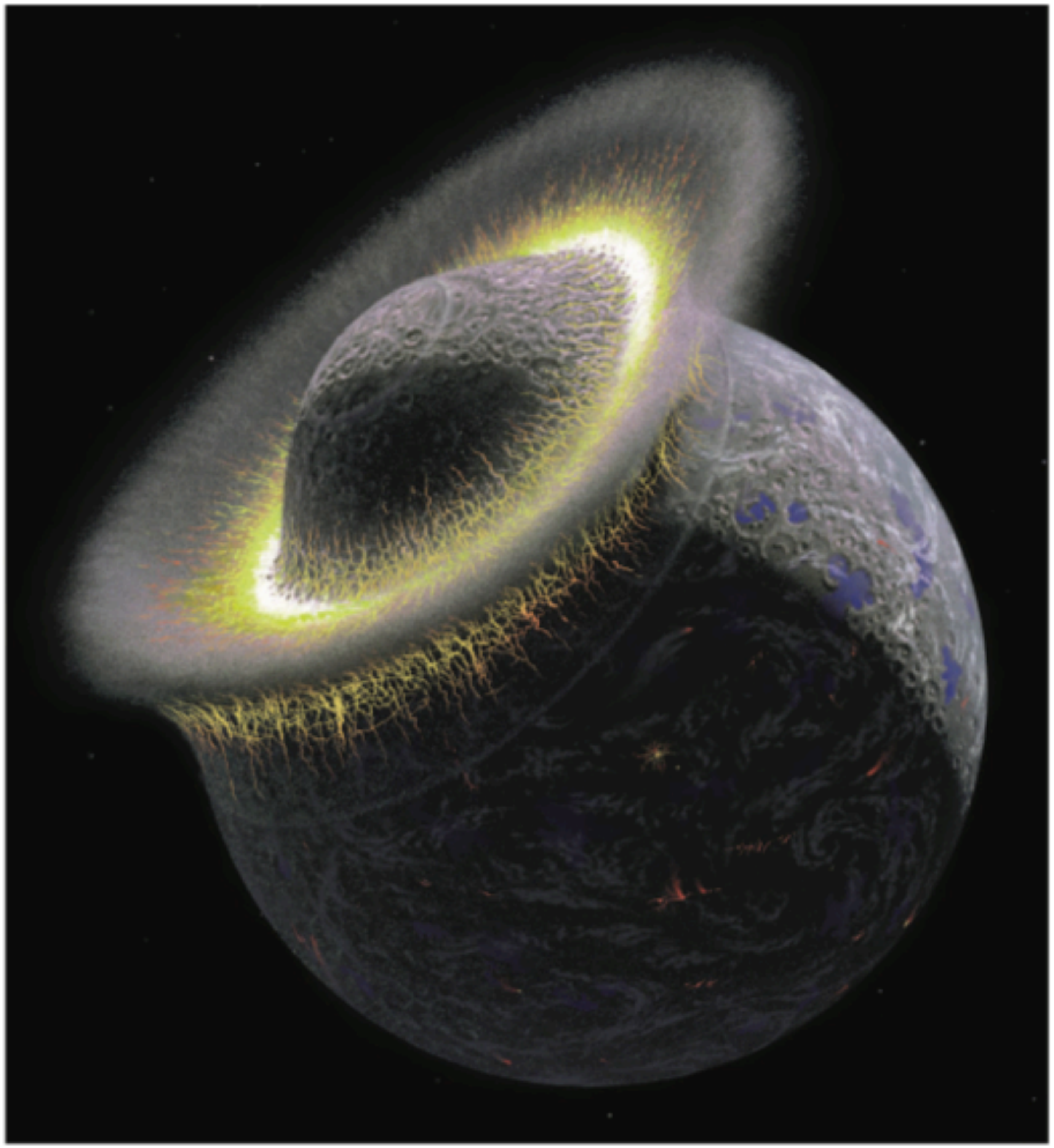


Doesn't explain small core

Angular momentum issues

Weidenschilling et al. 1986

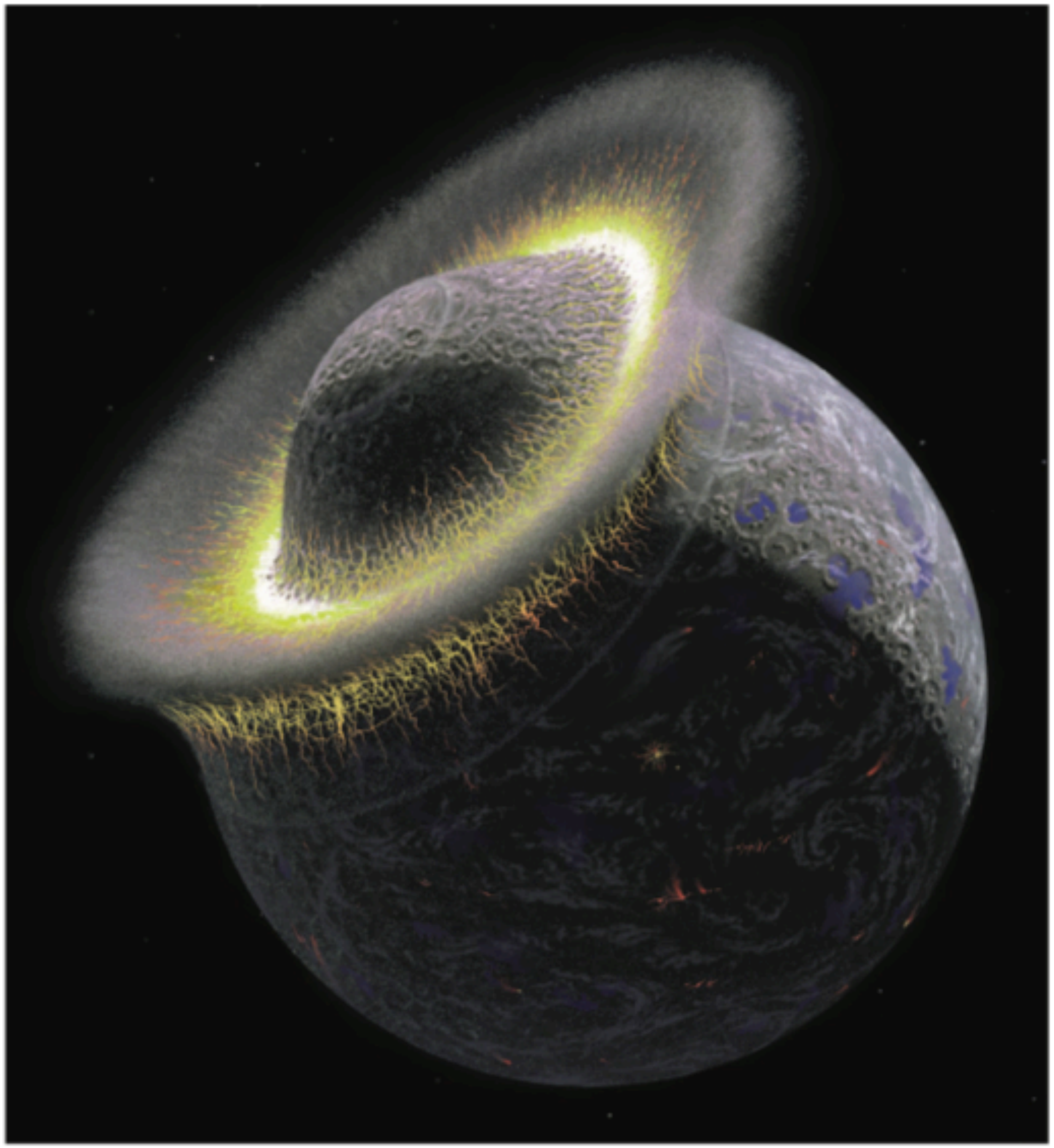
Giant Impact



General Model:

- Mars sized impactor ('Theia')
- Angled impact
- Moon accretes from debris disk

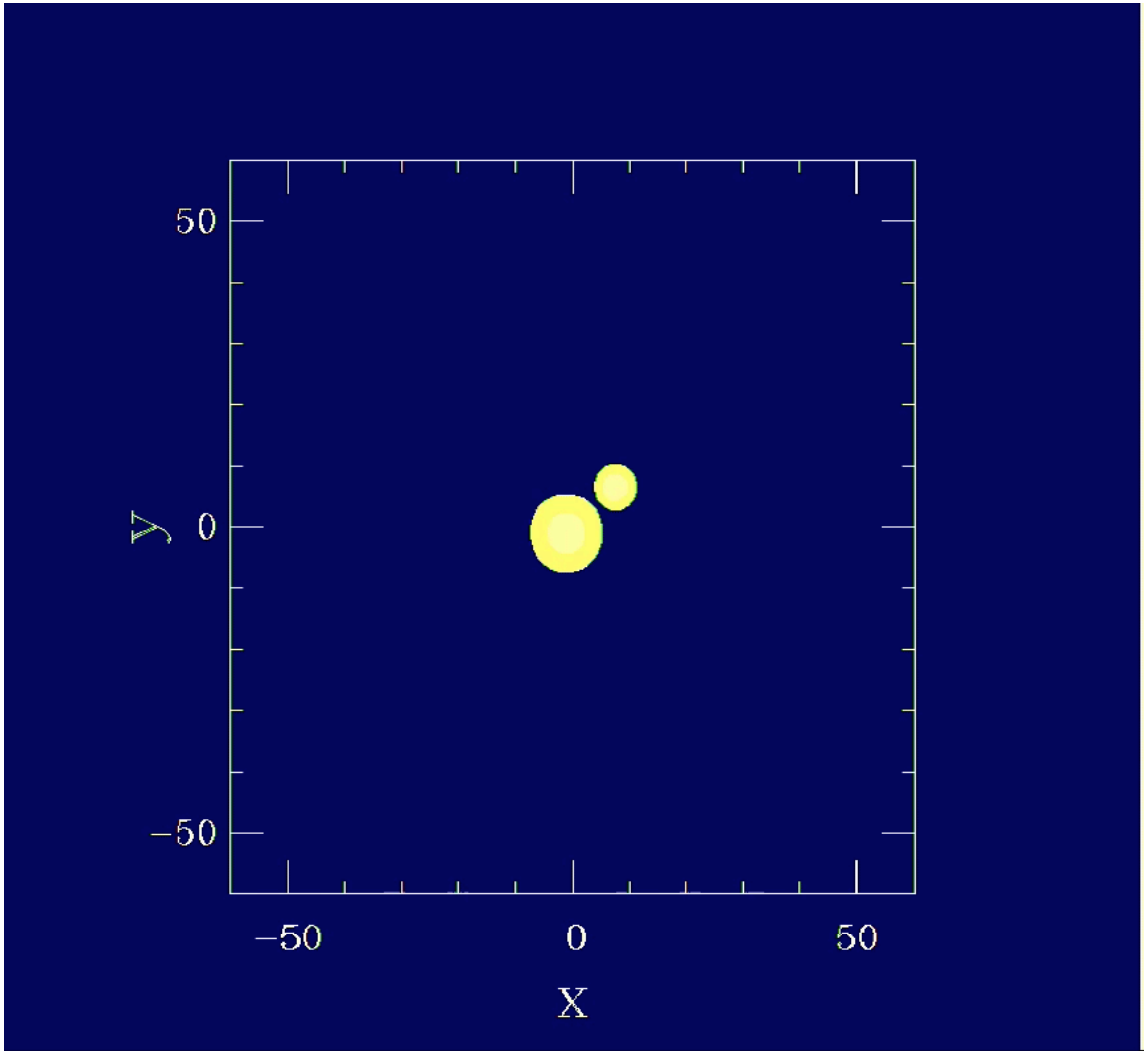
Giant Impact



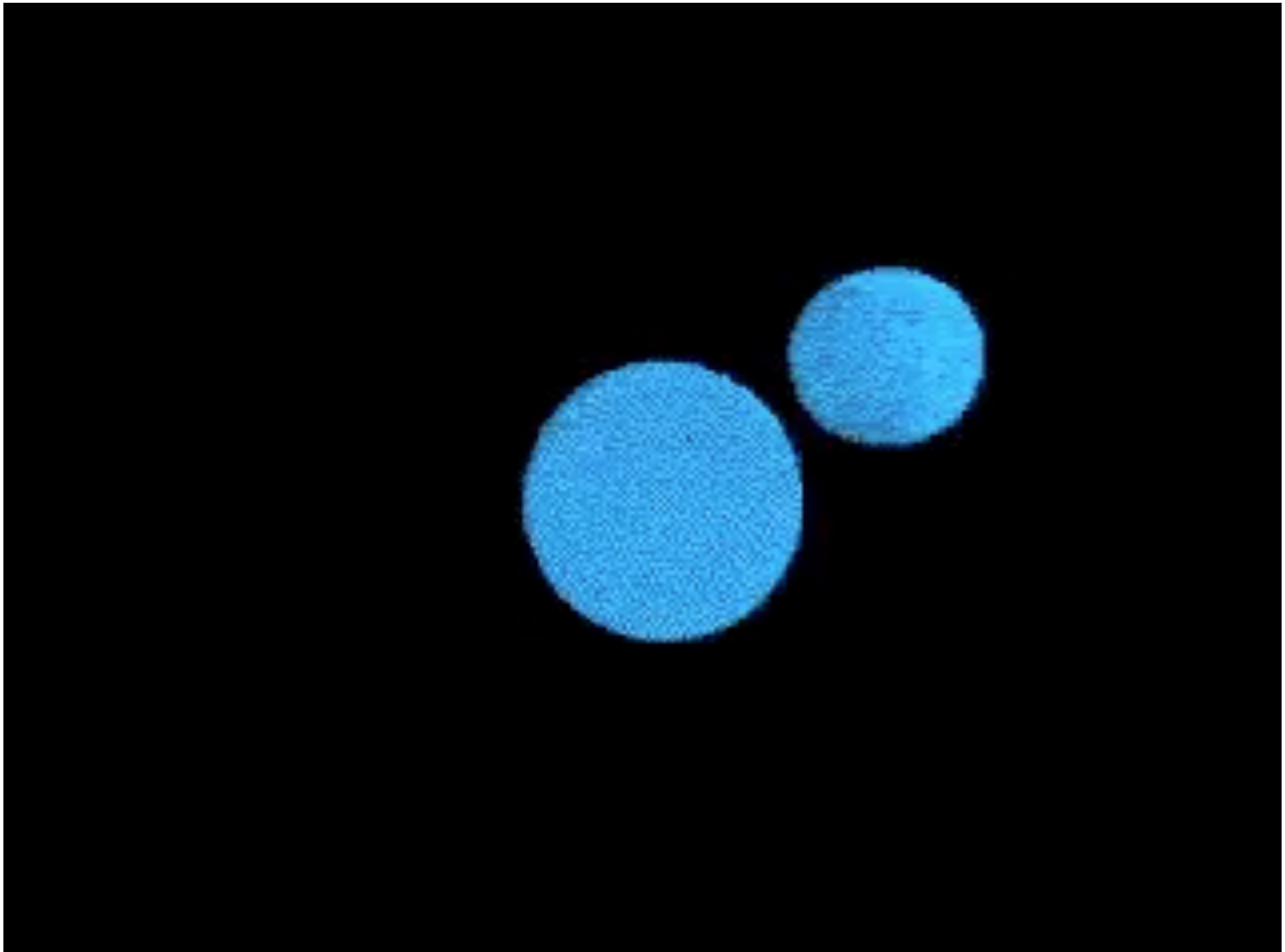
Features:

- Angular moment
- Depleted iron core
- Common in early solar system

Impact Simulation

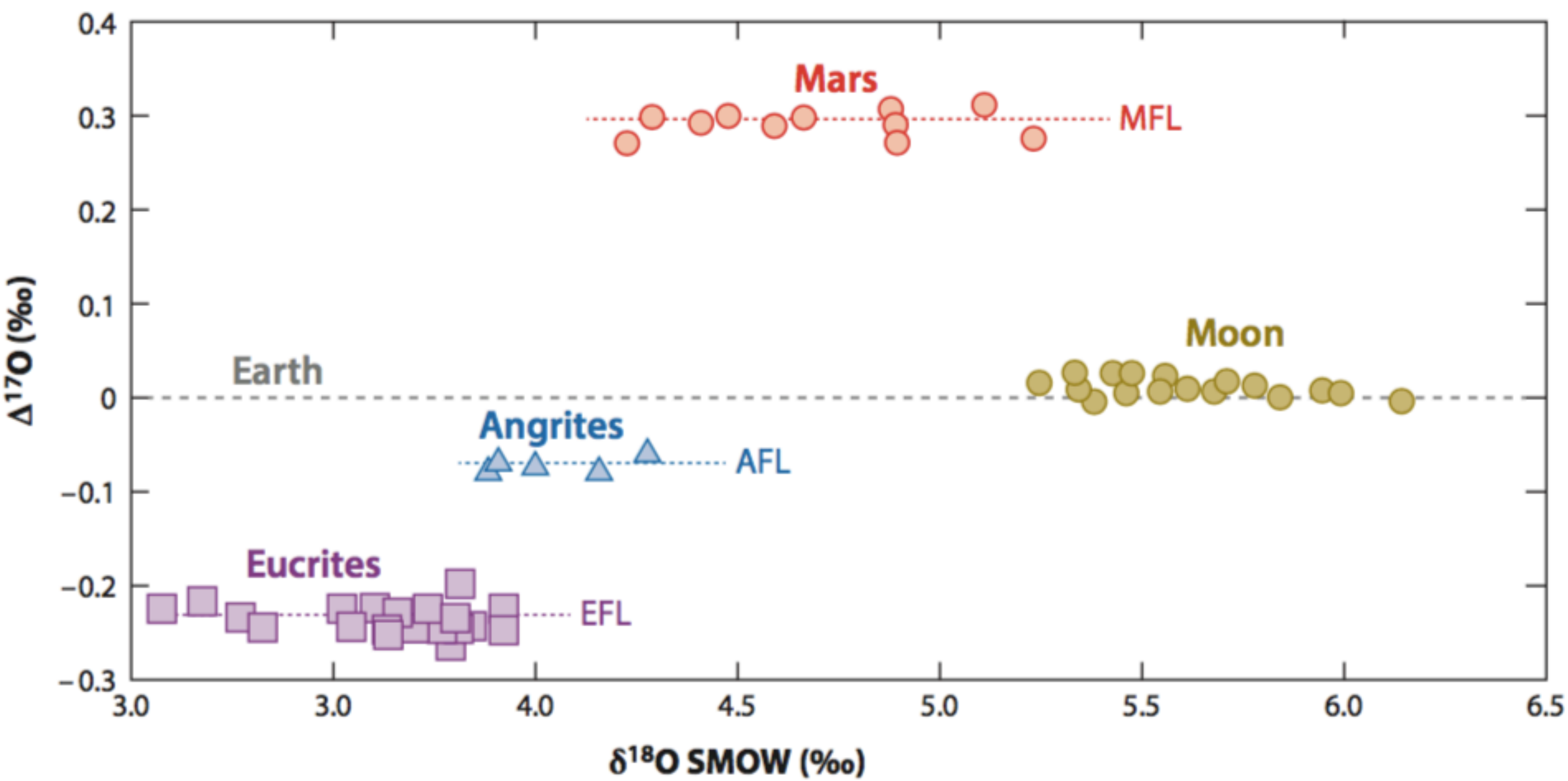


Impact Simulation (Cont.)



Geochemistry Challenge

The Moon is TOO similar to Earth!

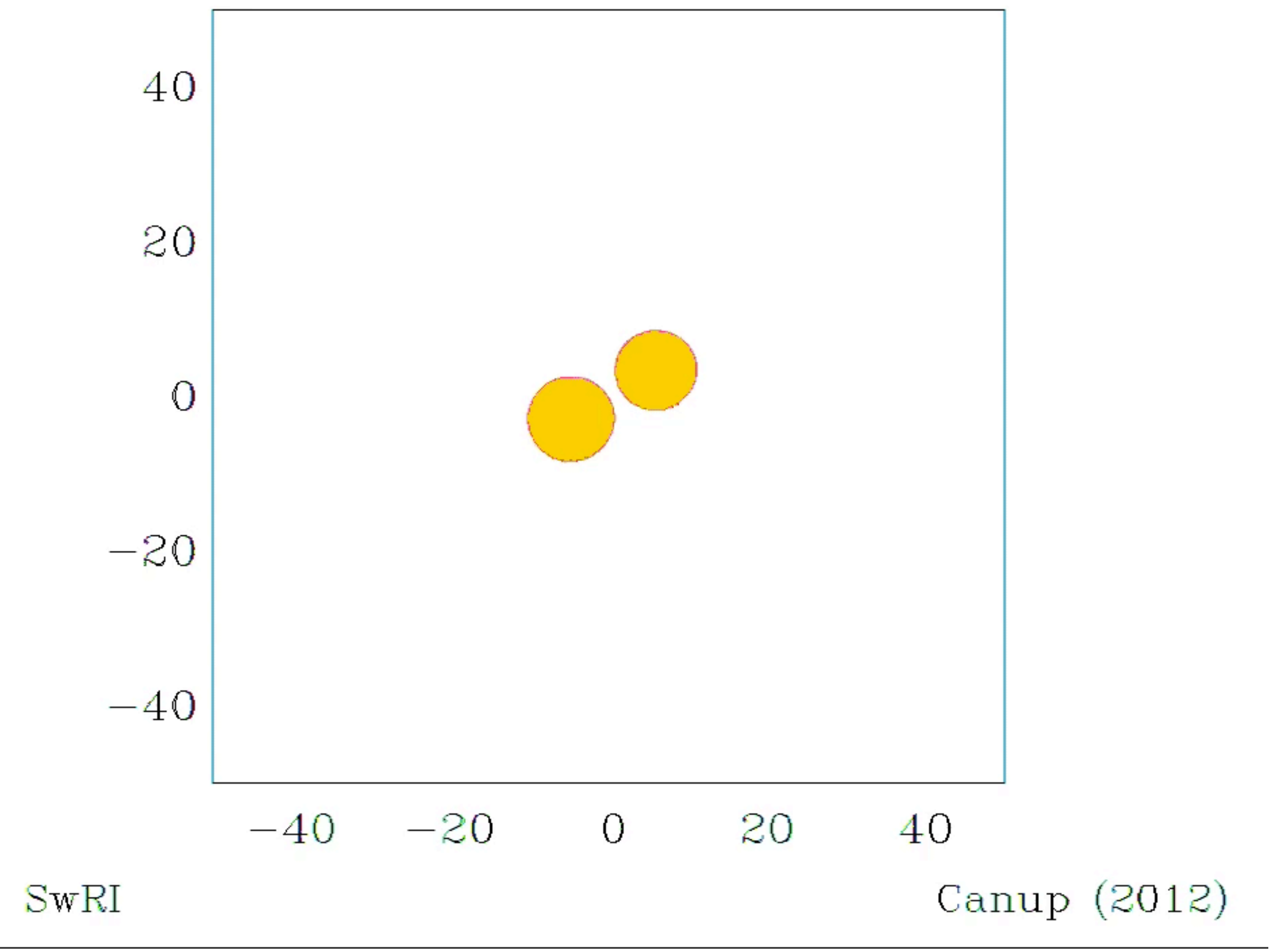


Asphaug 2014

Also similar in Ti, W, K, O…

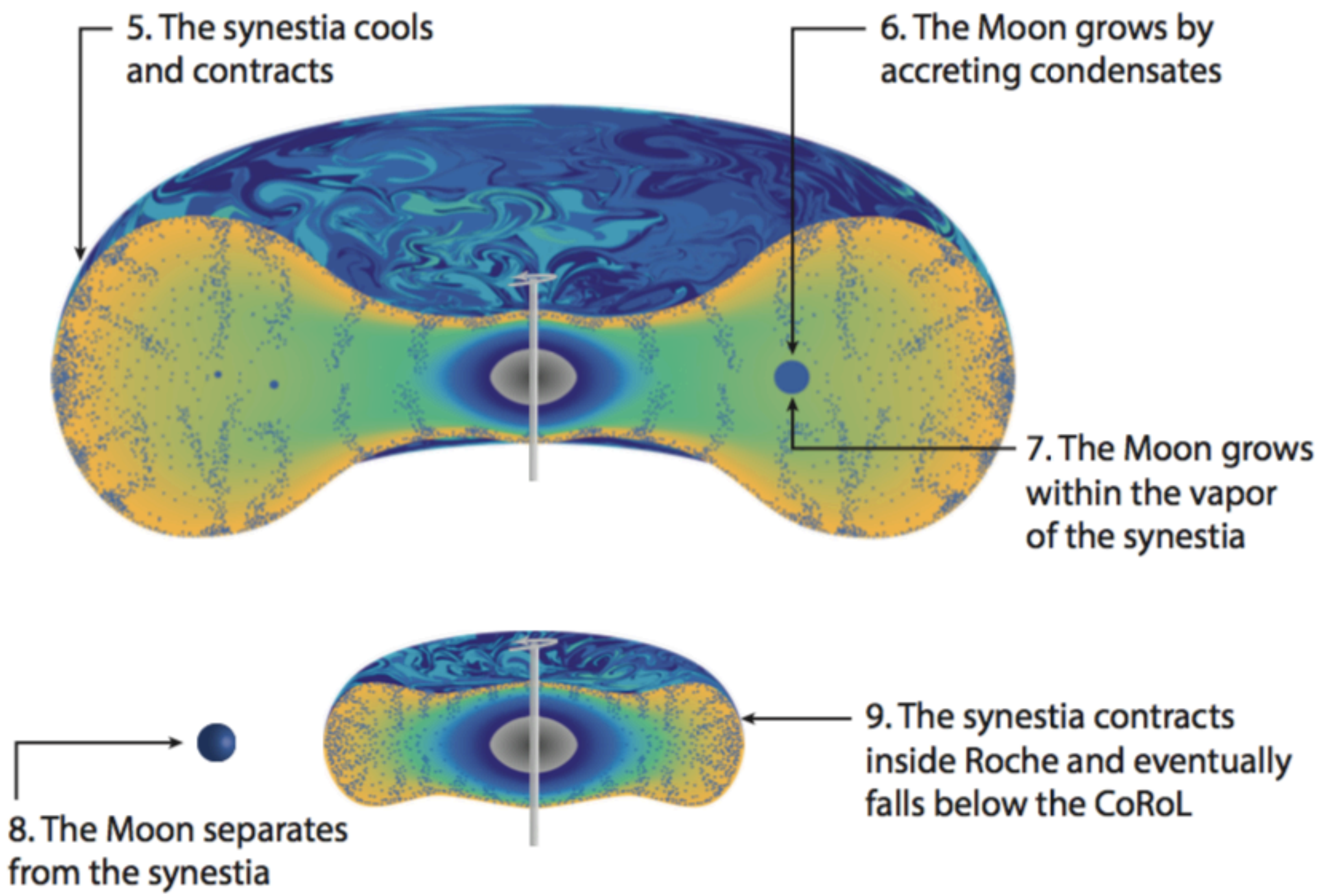
Alternative Impact Models

Two objects with equal masses



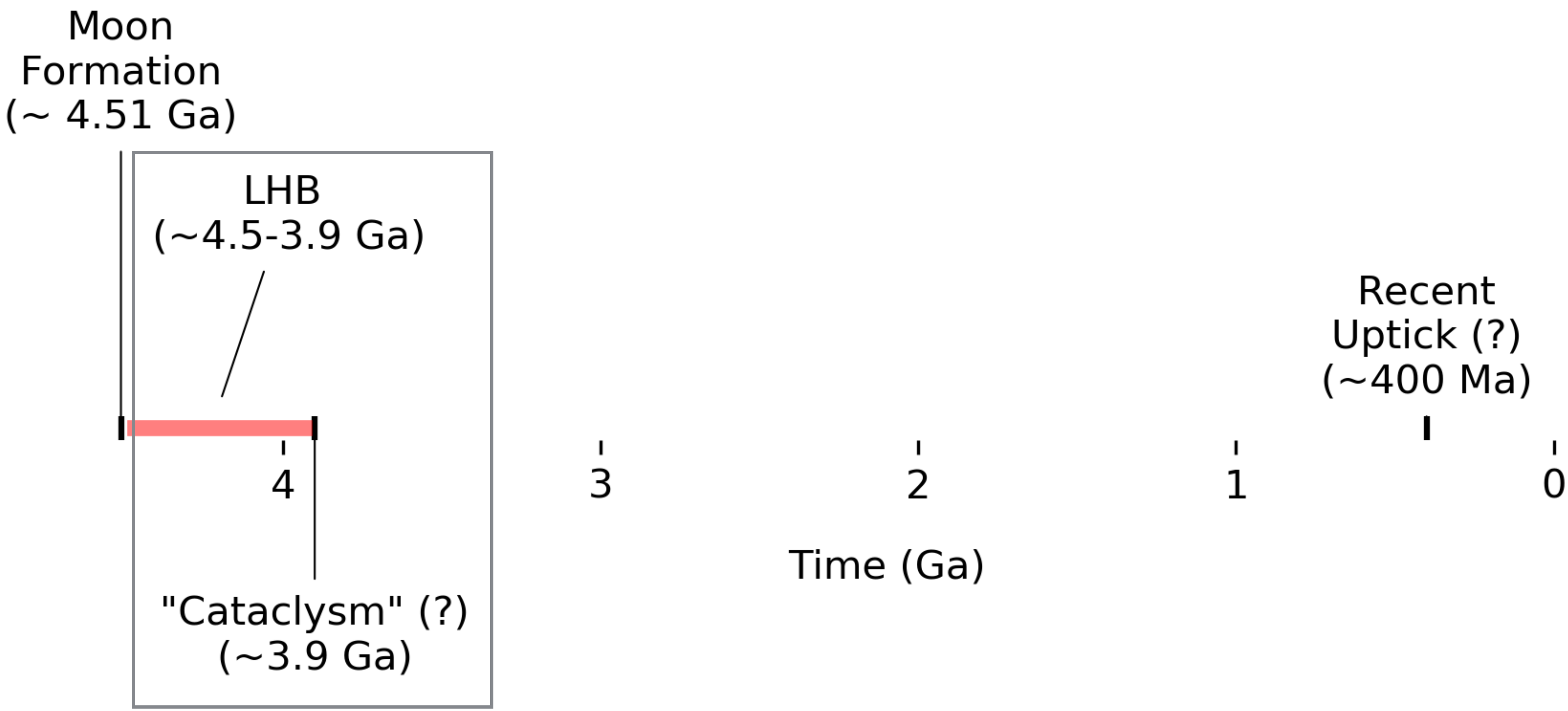
Alternative Impact Models (Cont.)

Donut shaped cloud of debris ('synestia')



Lock et al. 2018

Outline

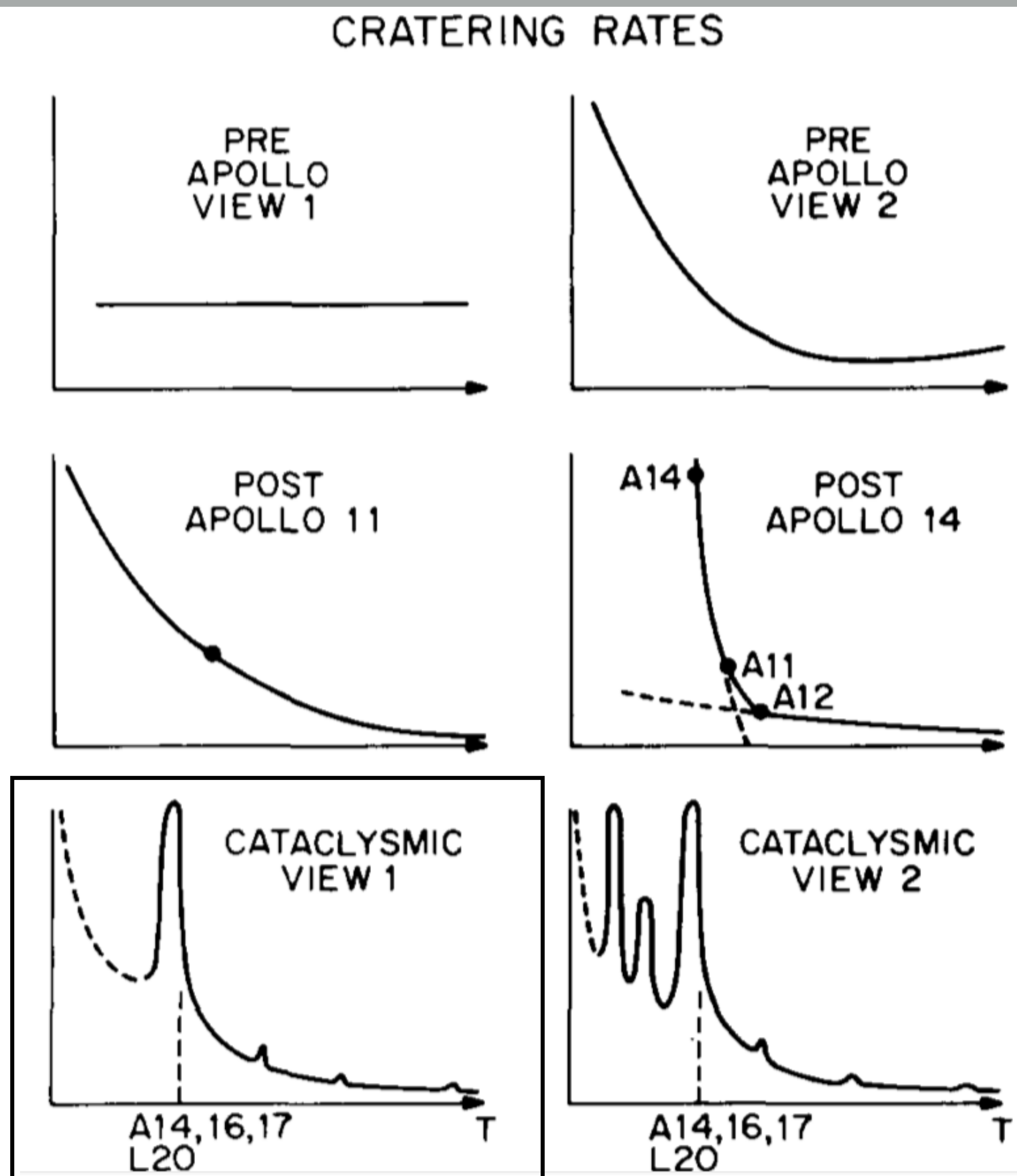

Moon Formation (~ 4.51 Ga)
LHB (~4.5-3.9 Ga)
Recent Uptick (?) (~400 Ma)
4
3
2
1
0
Time (Ga)
"Cataclysm" (?) (~3.9 Ga)

The Late Heavy Bombardment

First ~600 million years of solar system

Credit: NASA's Goddard Space Flight Center Conceptual Image Lab

Models of Impact Flux and the 'Terminal Cataclysm'

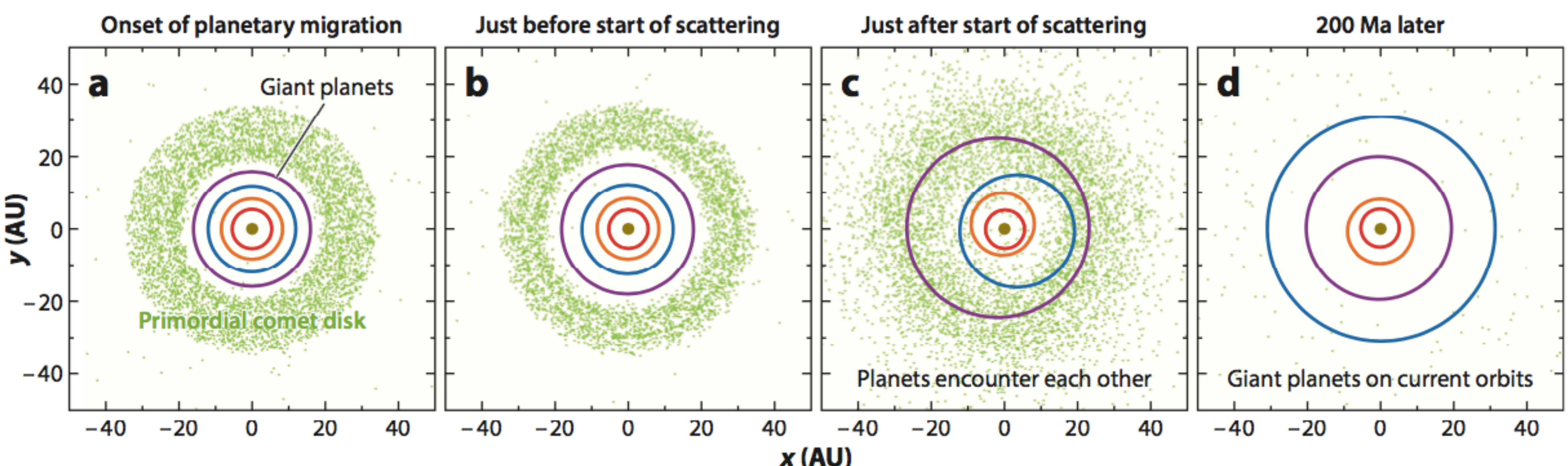


Prevailing view from 1990s

Tera et al.1974

The Nice Model

How do we explain a late impact flux increase?

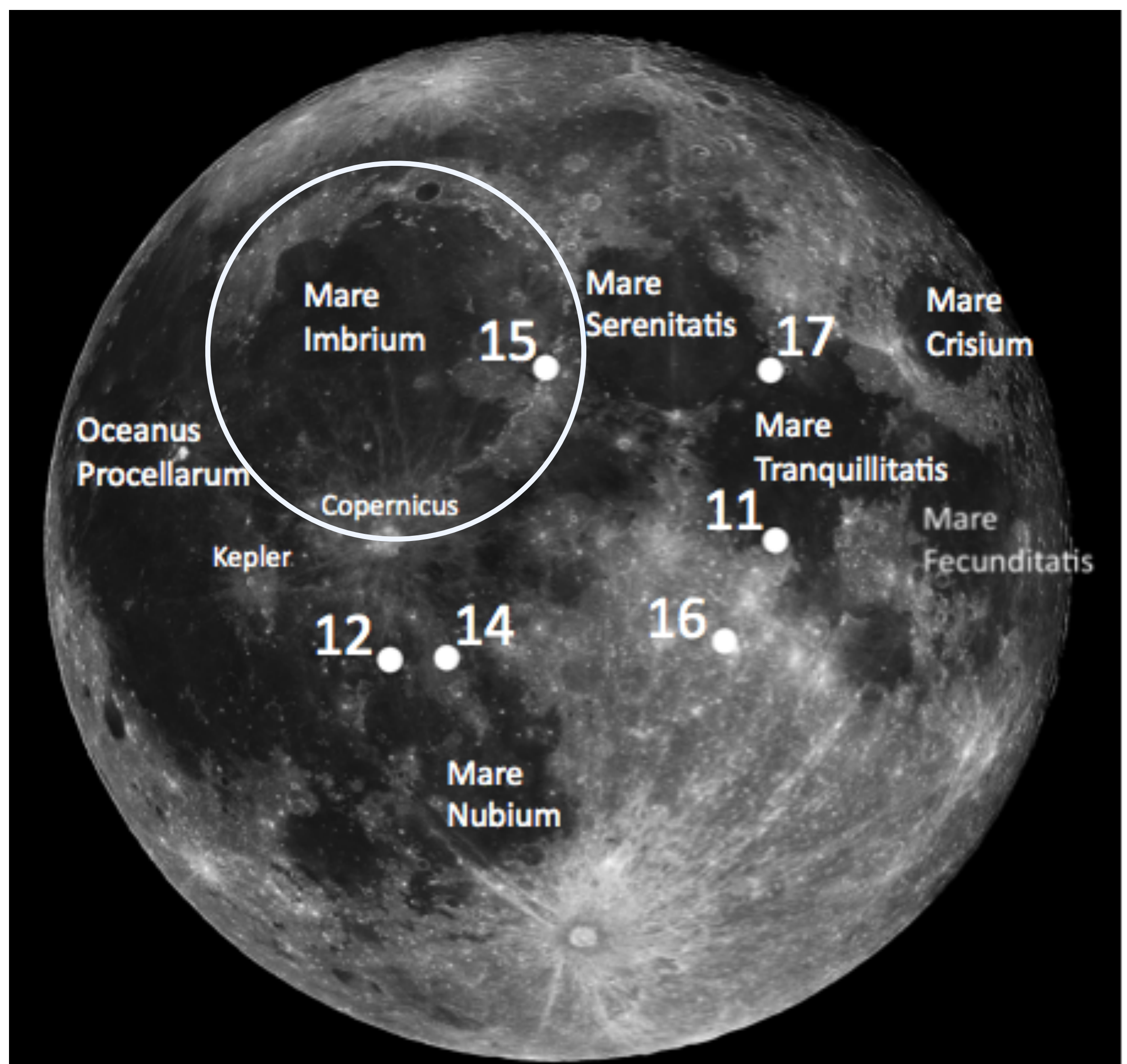


Bottke and Norman 2017

Many modifications e.g. ‘Jumping Jupiter model’

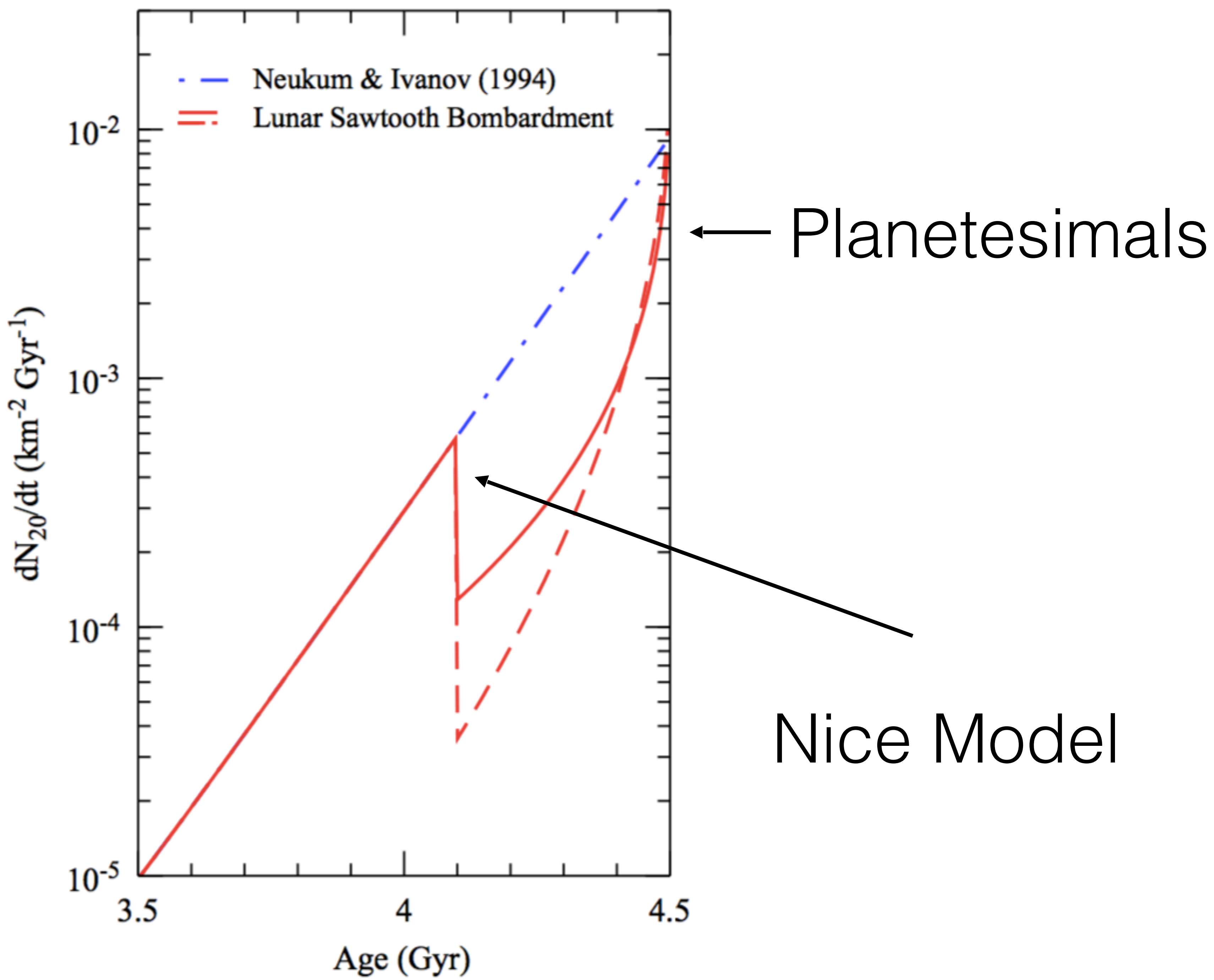
Did a Terminal Cataclysm Happen?

- Material > 3.9 billion years old
- Contamination from Imbrium
- Orbital data reveals more impact craters

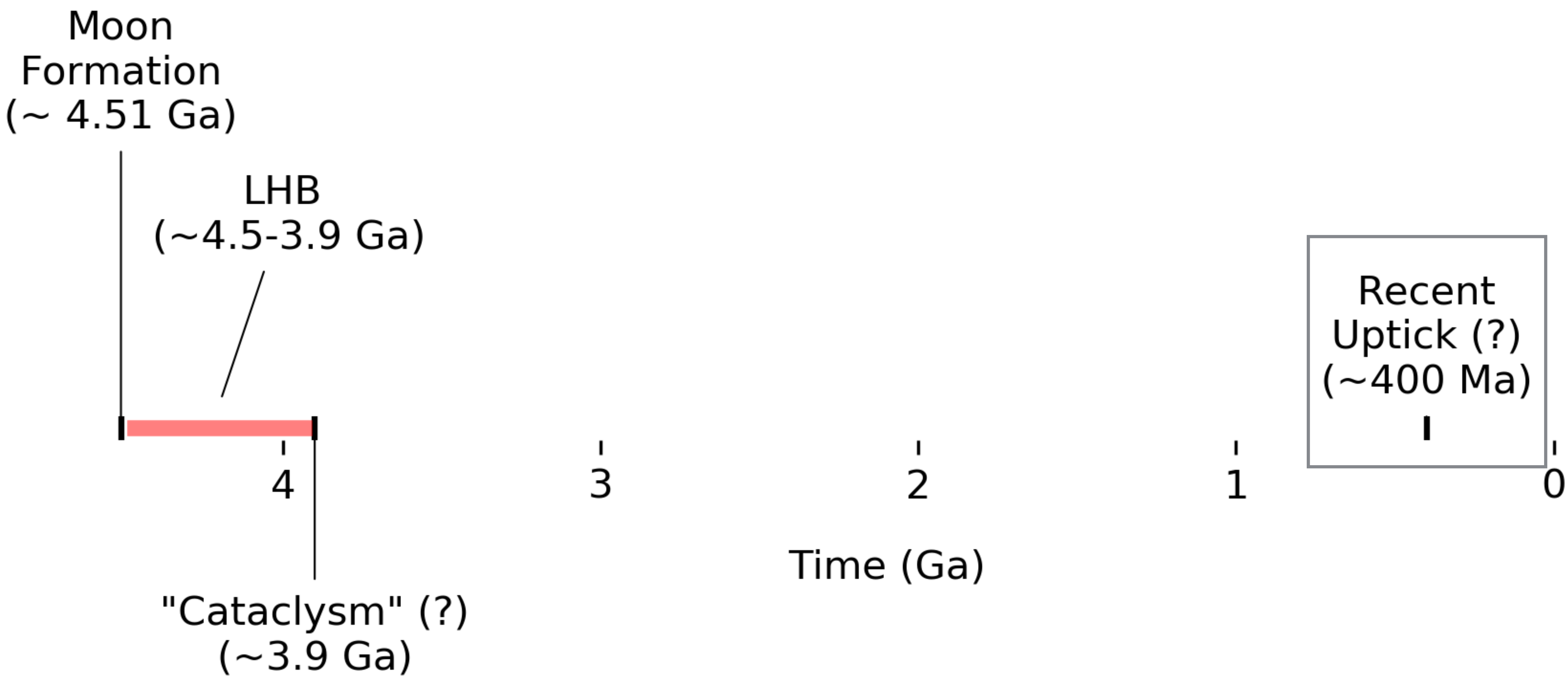


Sawtooth Model

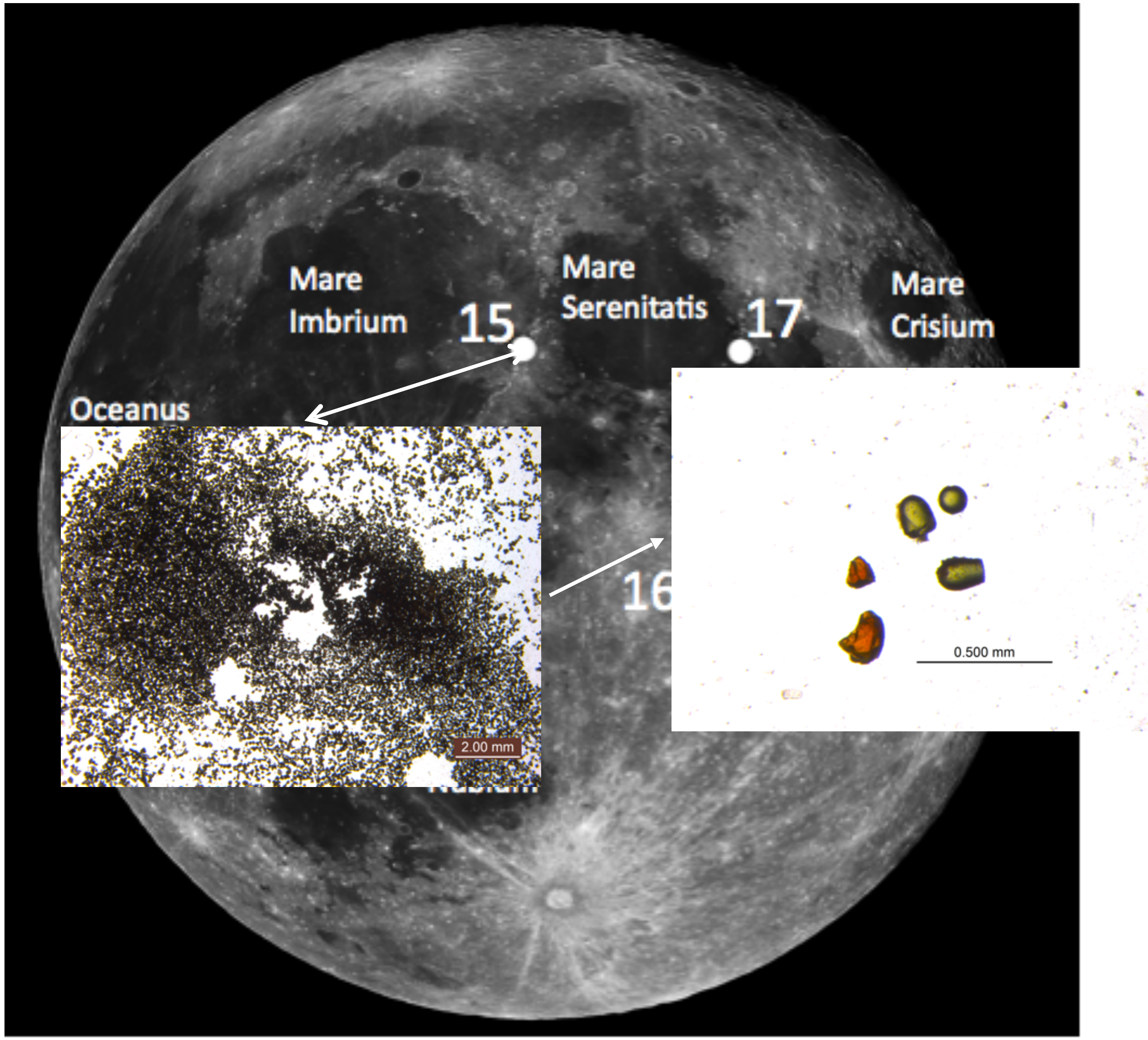
Modest increase starting ~4.2 - 4.1 Ga



Outline


Moon Formation (~ 4.51 Ga)
LHB (~4.5-3.9 Ga)
Recent Uptick (?) (~400 Ma)
4
3
2
1
0
Time (Ga)
"Cataclysm" (?) (~3.9 Ga)

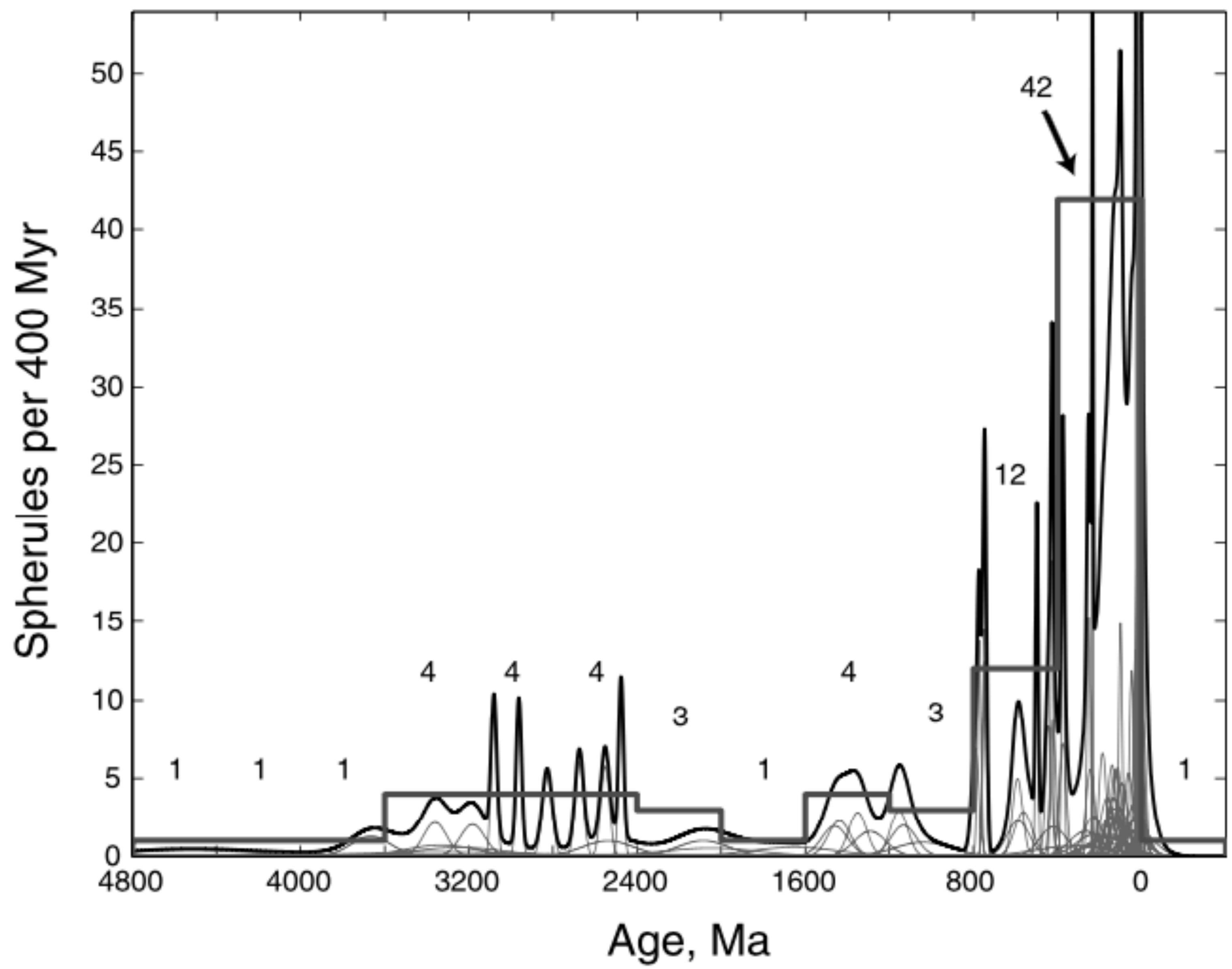
Lunar Impact Glasses



Credit: Dustin Scriven

Research Project

Investigate claimed increase in flux over last 0.4 Gy



Levine et al. 2005

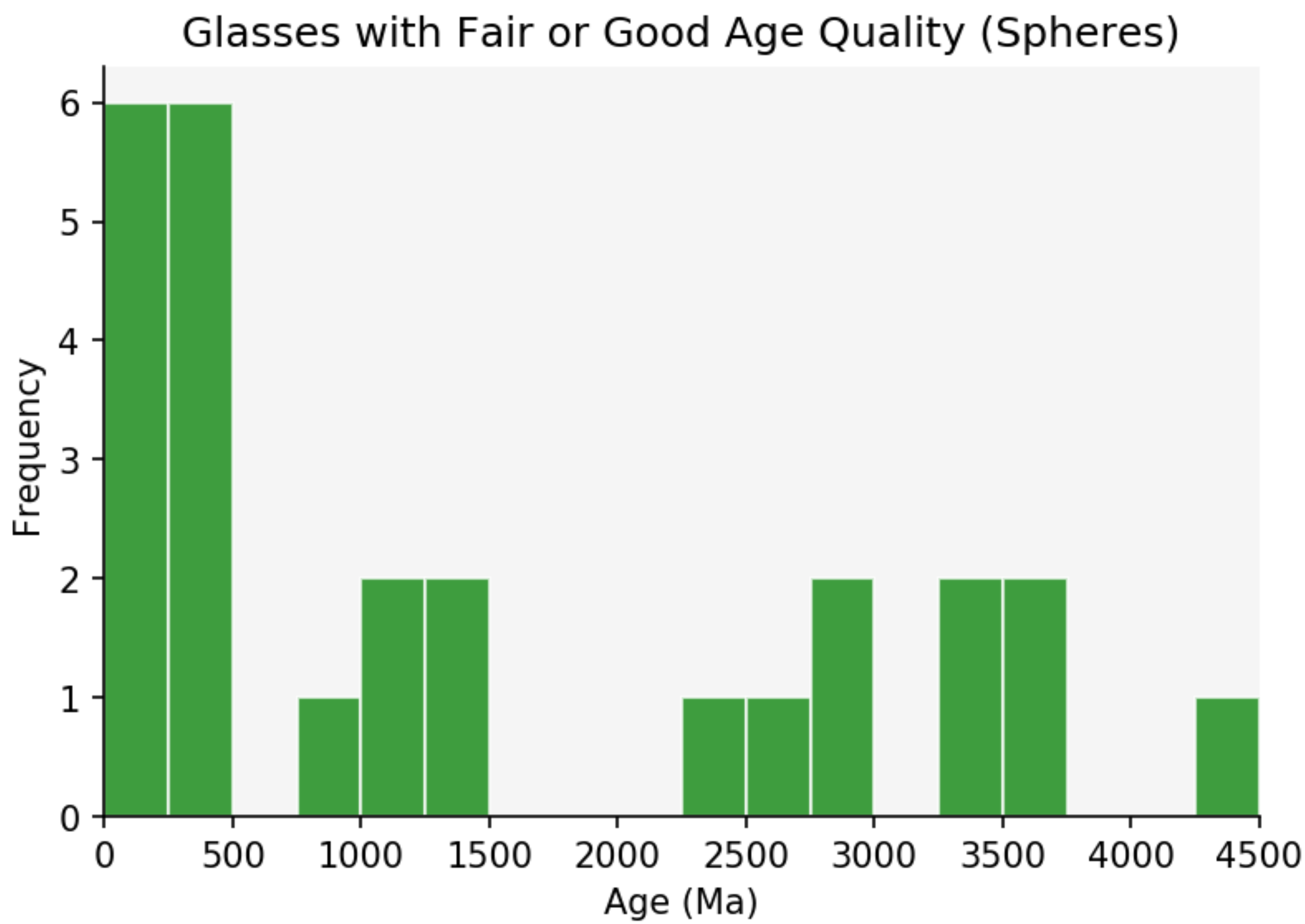
Impact Glasses

Characteristics:

- Age ($^{40}Ar/^{39}Ar$ dating)
- Composition (MgO, TiO_2, etc.)
- Shape (shards vs spheres)

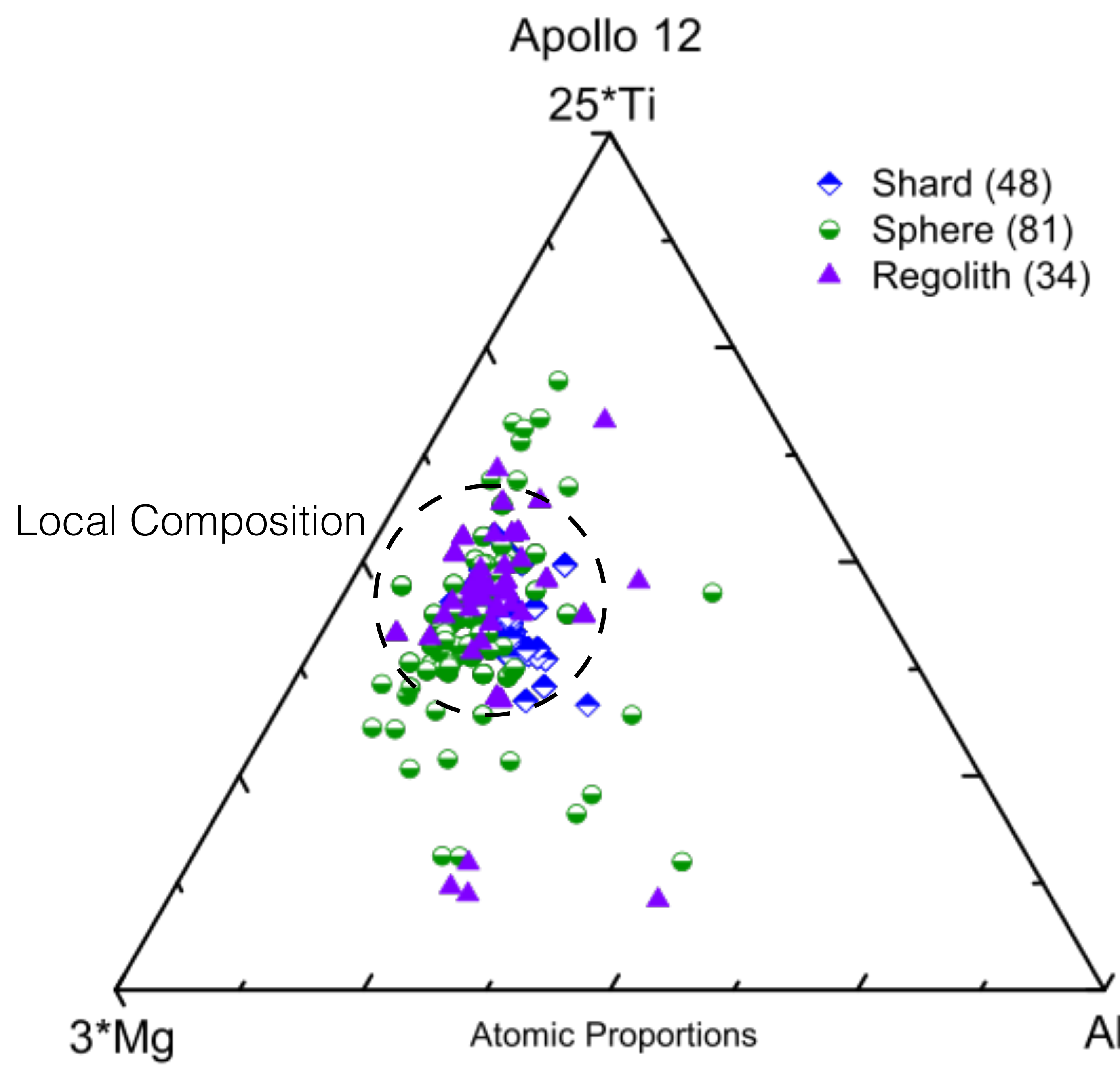
Key question: Are spheres bias to young ages?

Age Trends



Glasses with Fair or Good Age Quality (Spheres)
Frequency
0
1
2
3
4
5
6
0
500
1000
1500
2000
2500
3000
3500
4000
4500
Age (Ma)

Compositional Trends



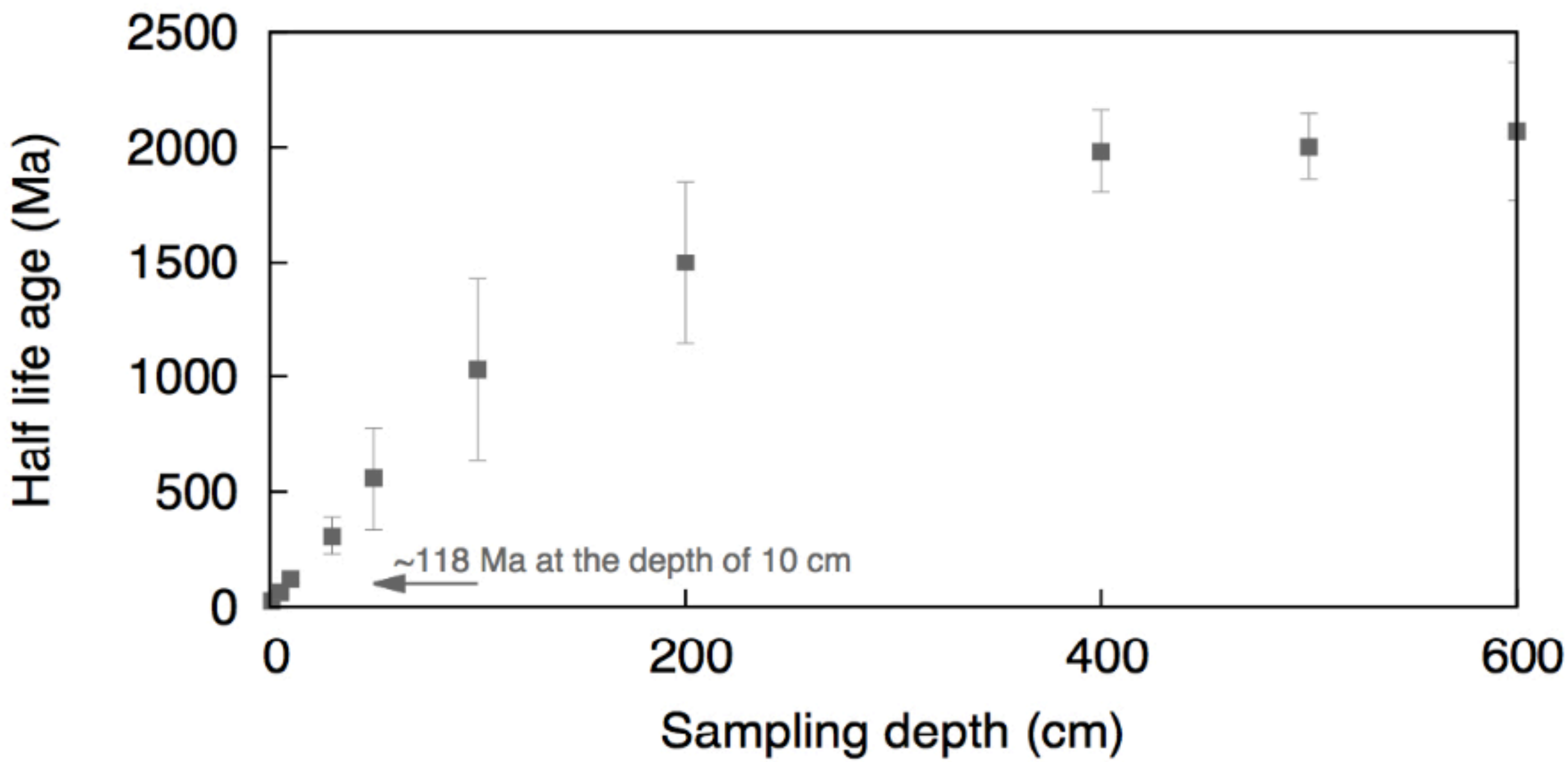
Korotev et al. (2011), Levine et al. (2005), Meyer et al. (1971), and Wentworth et al. (1994)

Hypothesis

Over time, Impact events destroy older spheres

Regolith Dynamics Models

Simulations can model impact events and populations of impact glasses



Conclusion

Apparent increase in impact flux is the result of sampling bias

Summary

- Moon formed from an impact event
- ‘Terminal Cataclysm’ falling out of favor
- No recent increase in impact flux

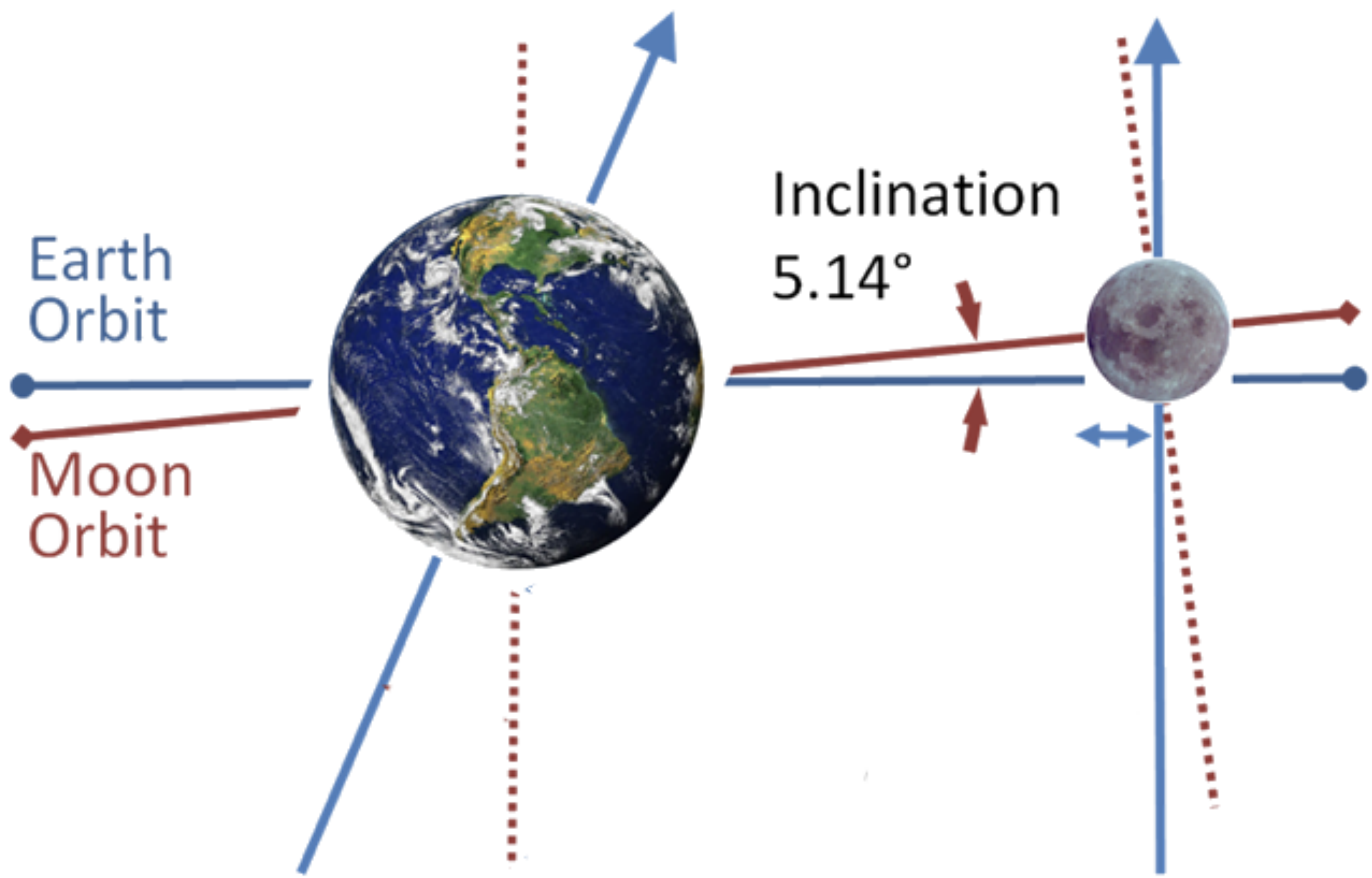
Acknowledgements

- Dr. Zellner
- Albion College
- NSF Astronomy and Astrophysics grant

Thank you!

Problems

Moon's orbital inclination

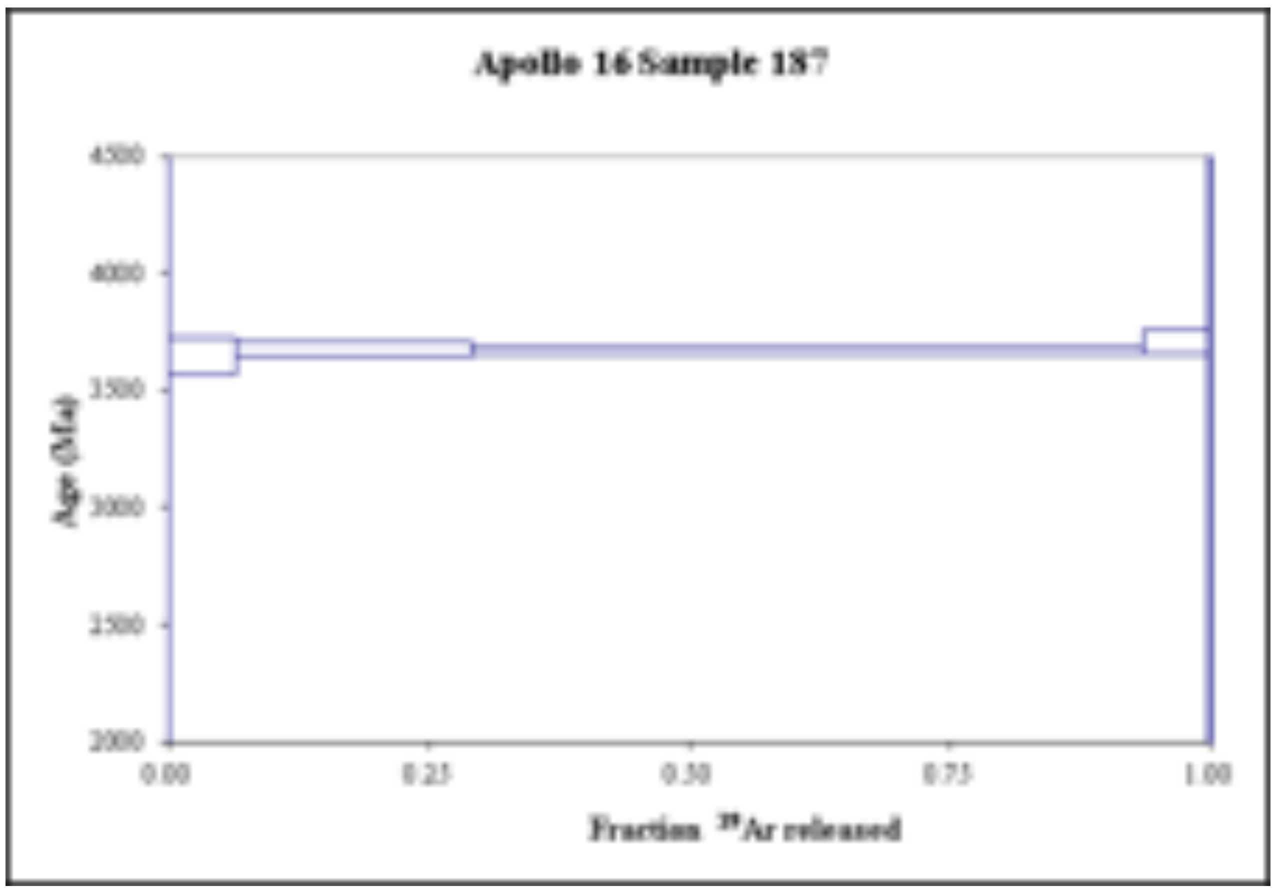


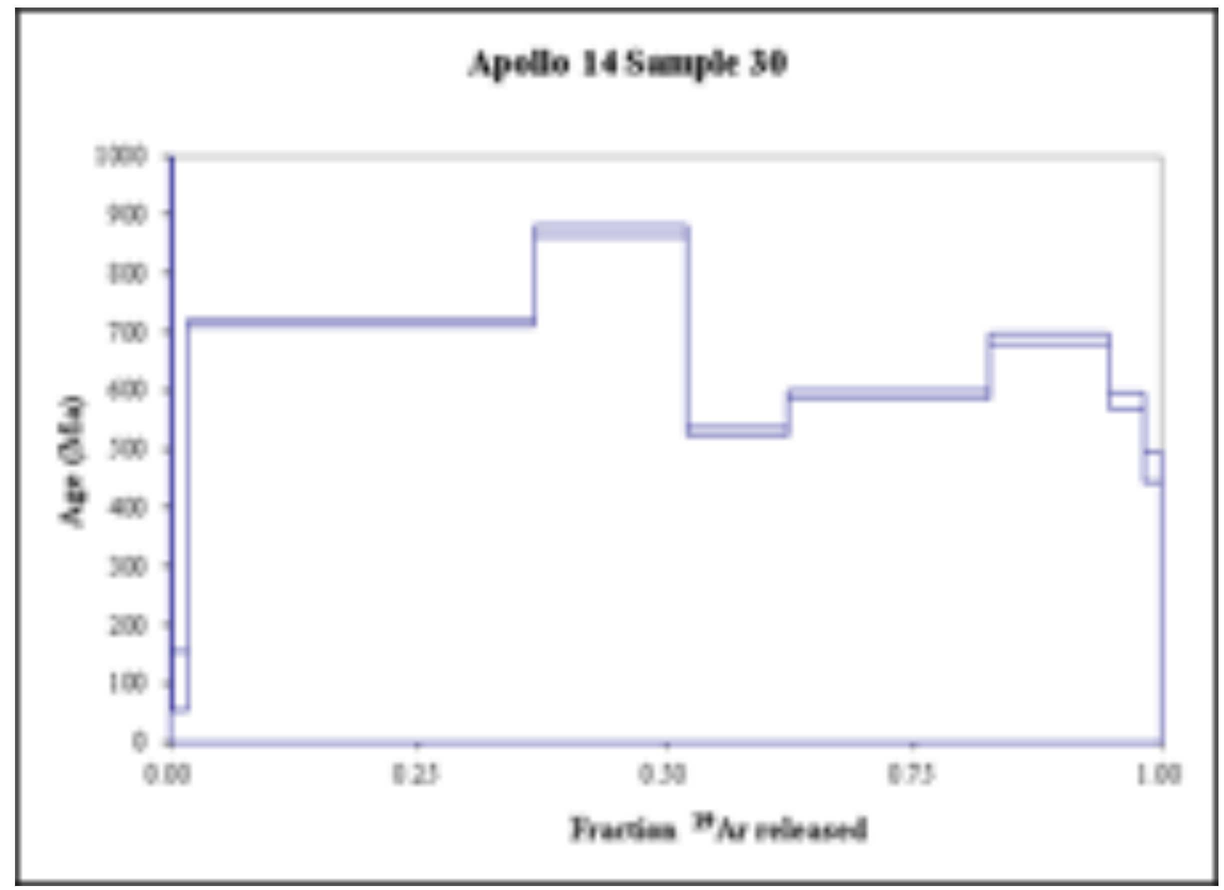
Solutions

Gravitational interaction with planetesimals

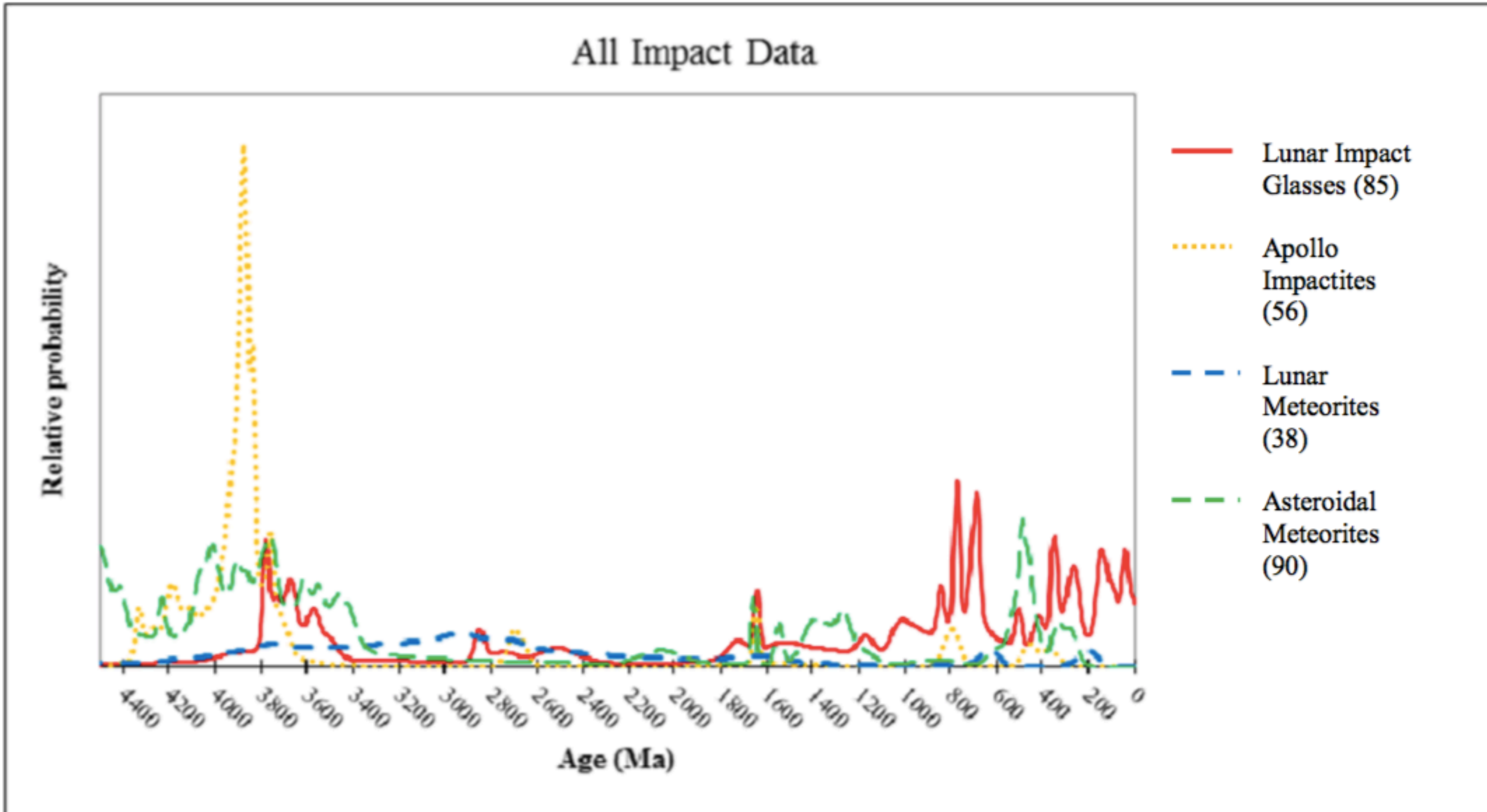
Tidal evolution from the Sun

Argon Dating





Timeline



Zellner 2017

Basin Ages

Crater	Age (Ga) (1974–2006)	Age (Ga) (2009-present)
South Pole - Aitken	4.05 – ~4.3	4.0–4.4 (?)
Serenitatis	3.893 ± 0.009	3.83–4.1+
Nectaris	3.89–3.92	3.92–4.2 (?)
Crisium	3.85–3.93	~3.9 (?)
Imbrium	3.85 ± 0.02	3.72–3.93
Orientale	3.77–3.83	3.72–3.93

Zellner 2017