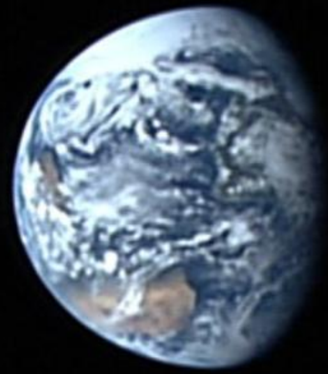


Origin and Bombardment History of the Moon

Dr. William Bottke

Southwest Research Institute, Boulder, CO
Center for Lunar Origin and Evolution (CLOE)

Why Should We Study the Moon?

"This is really cool"

"Been there, done that!"

- We have a "Big Picture" problem:
  - The public has almost no idea why we should go back to the Moon from a science perspective.
  - Most planetary scientists have the same problem!

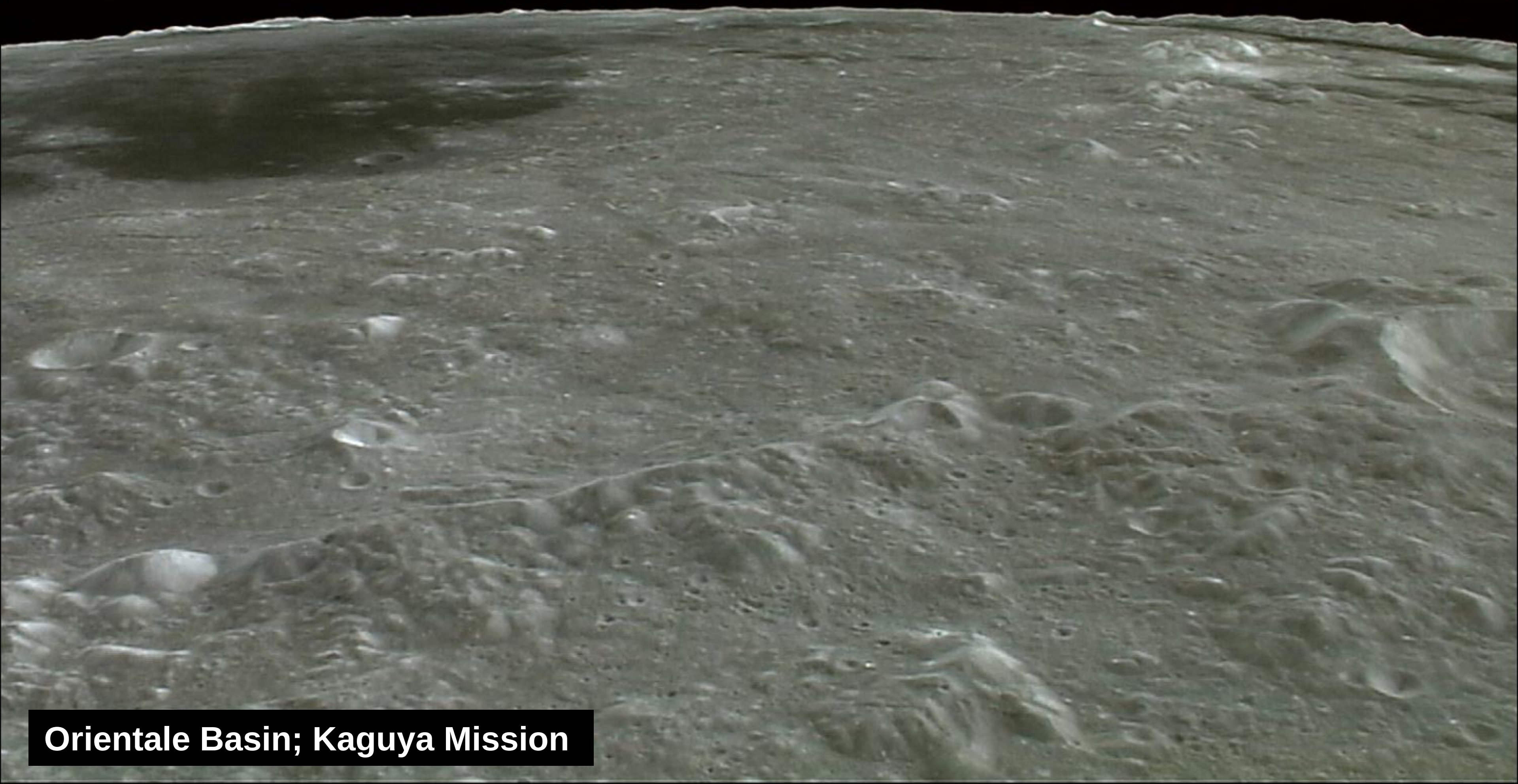
What Most People Do Not Consider

- The Moon itself is fascinating, but it is also a “Rosetta Stone” for telling us about:
  - The unknown nature of the primordial Earth!
  - The critical last stages of planet formation throughout the solar system!

Impact History of the Moon

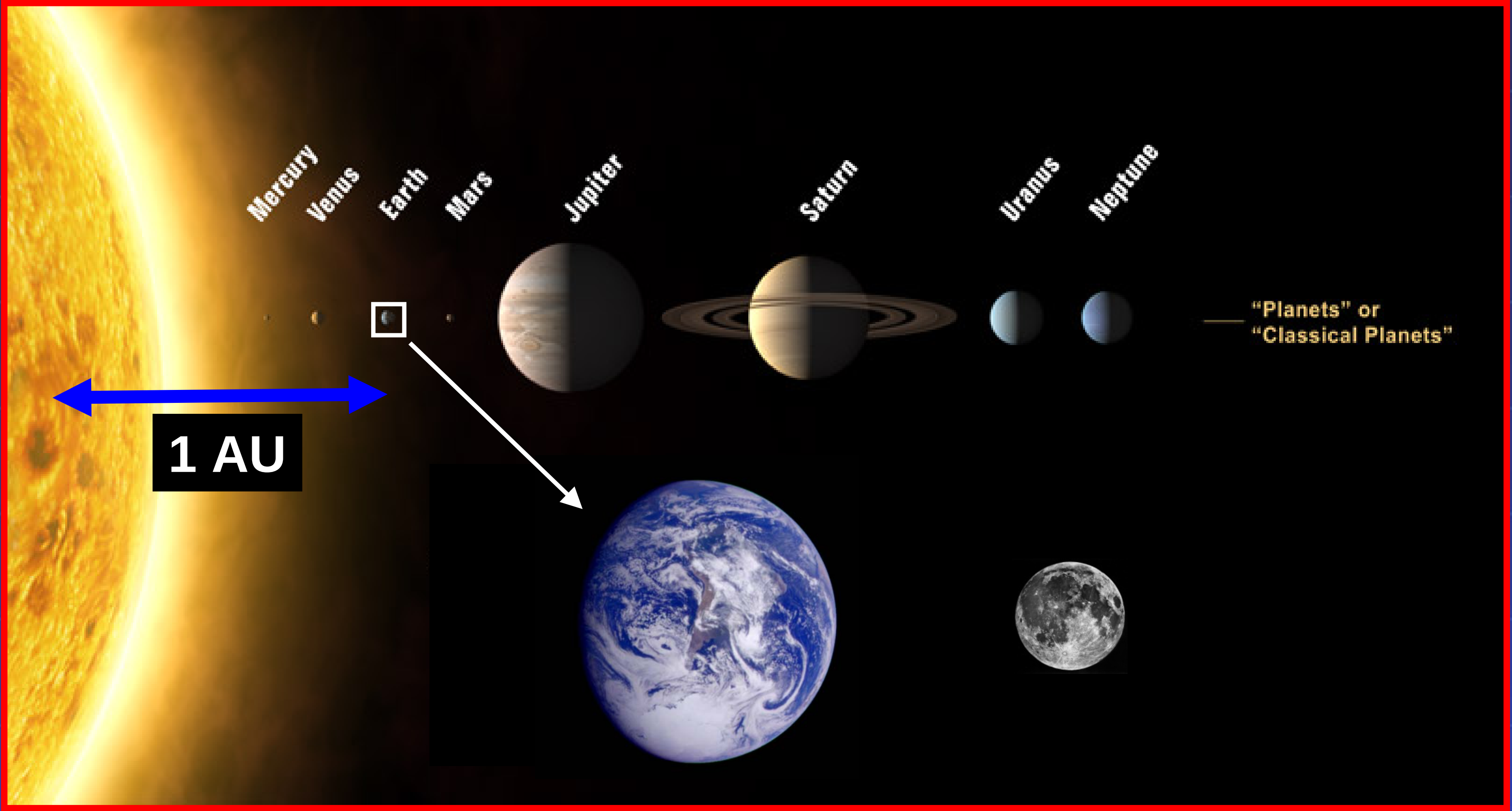
- The Moon has the most complete and clear impact history available of the last 4.5 billion years of Solar System evolution.

Part 1:
Formation of the Moon



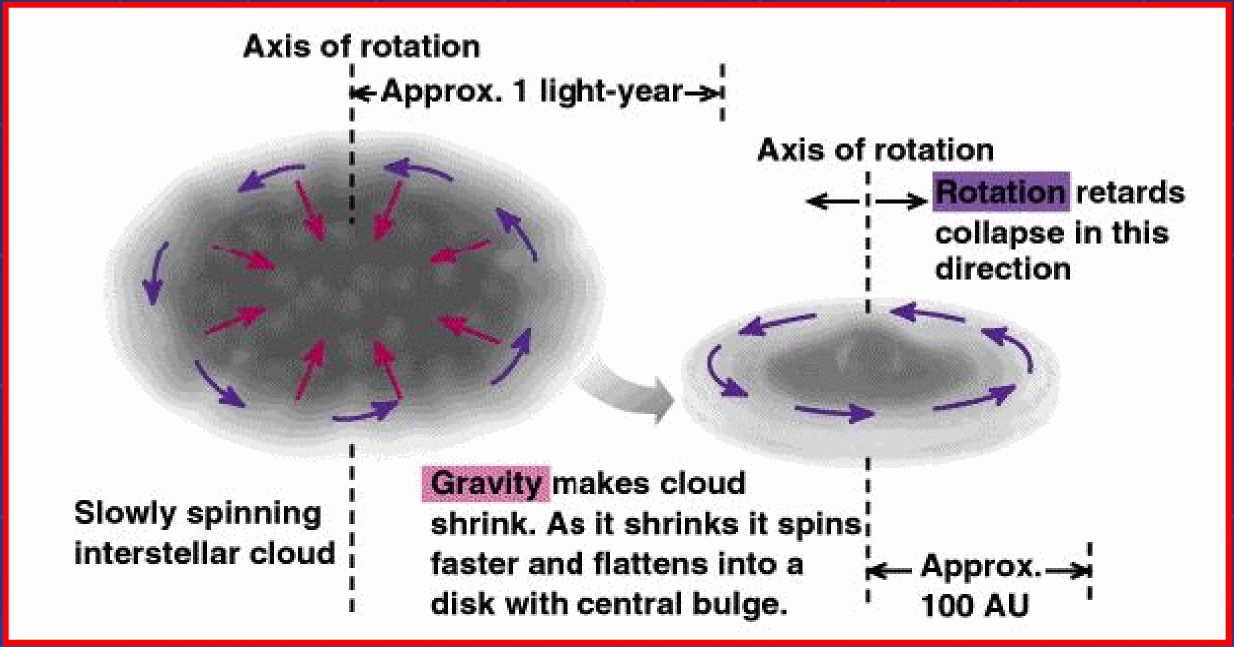
Orientale Basin; Kaguya Mission

The Known Solar System

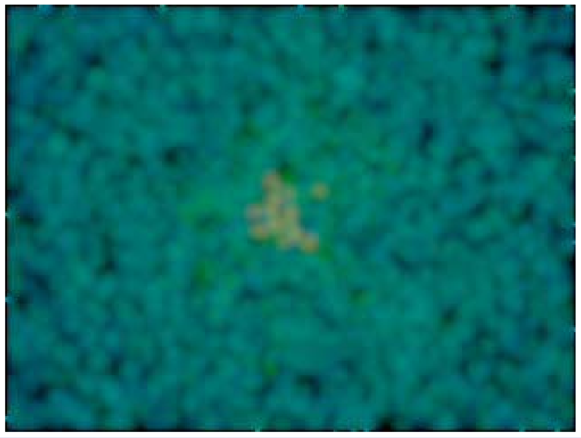


- The solar system did not always look this way!

Formation of Protoplanetary Disk

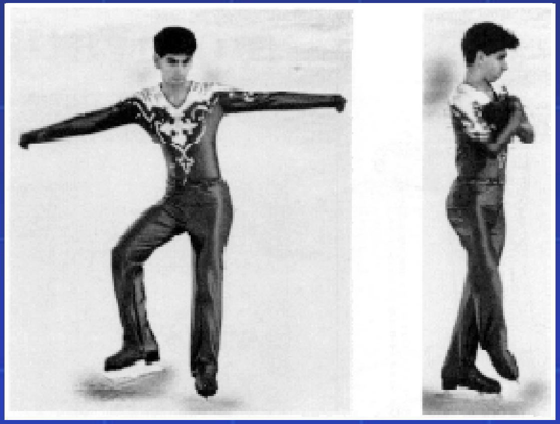


- Gravity causes cloud to flatten.
- Conservation of ang. momentum causes it to spin faster.

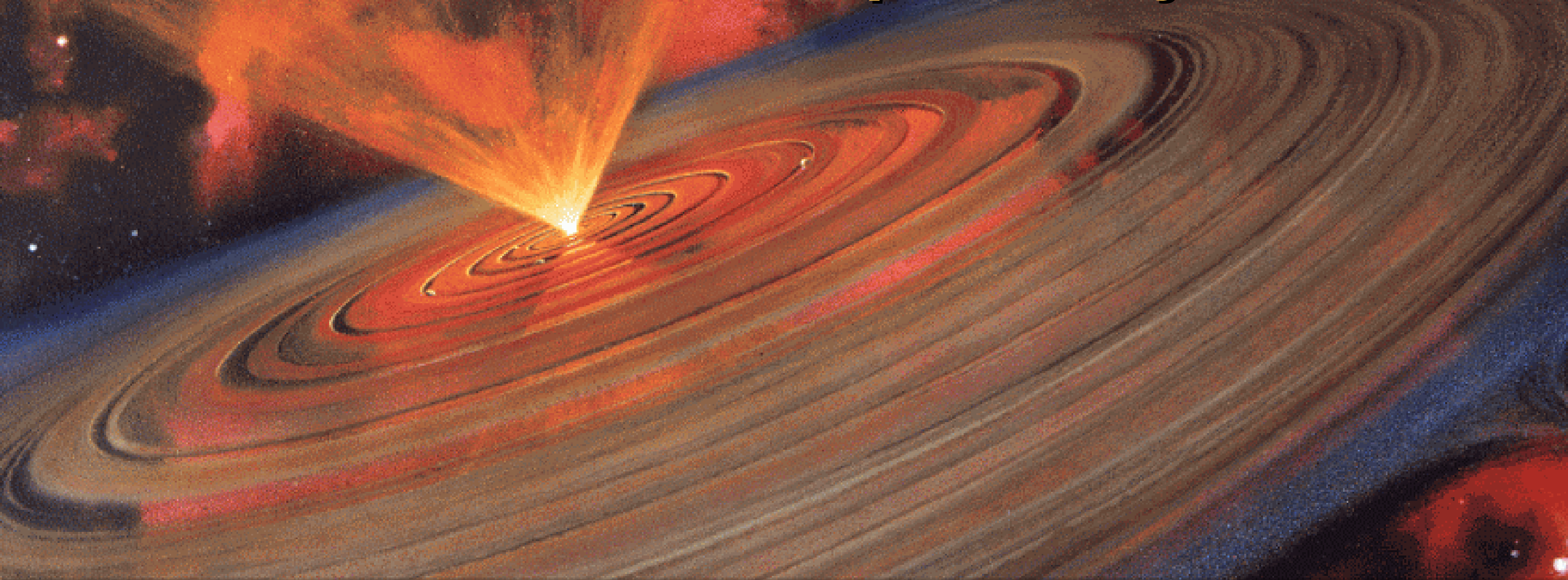


Top View

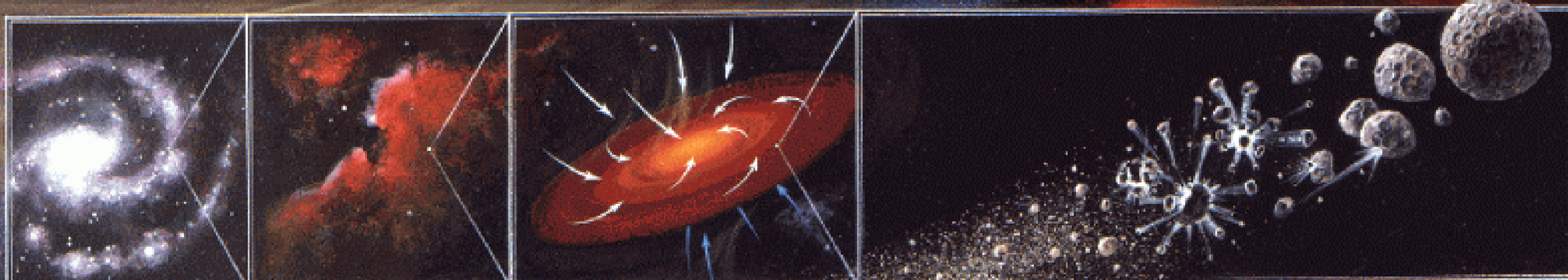
Side View



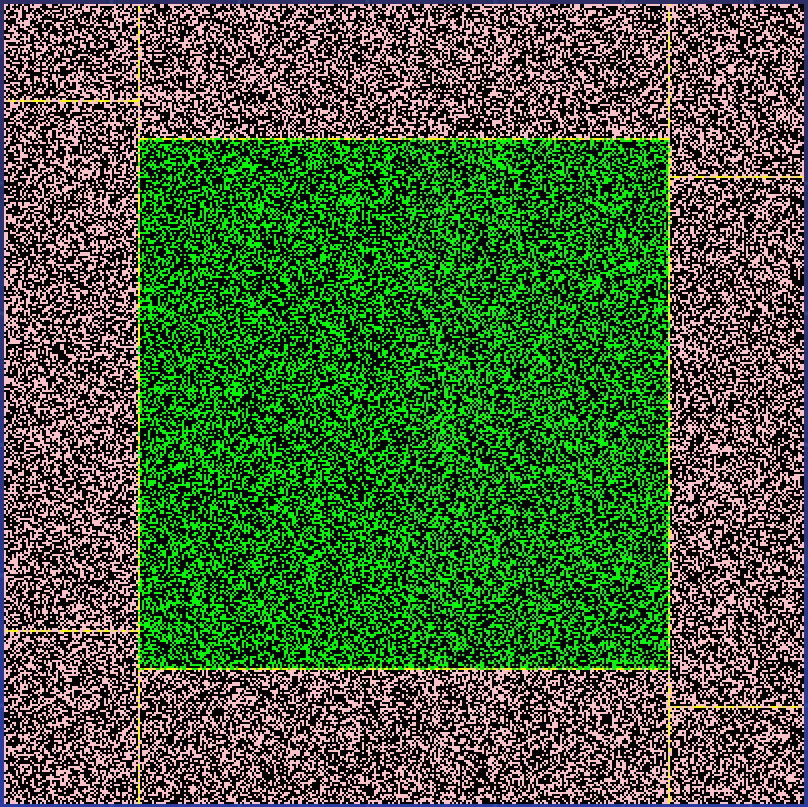
Formation of Protoplanetary Disk

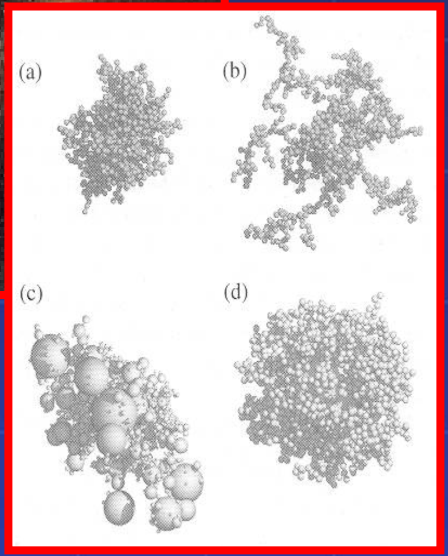


- Collapse of cloud produces newly formed Sun surrounded by an orbiting disk of gas and dust.



Growing Planets

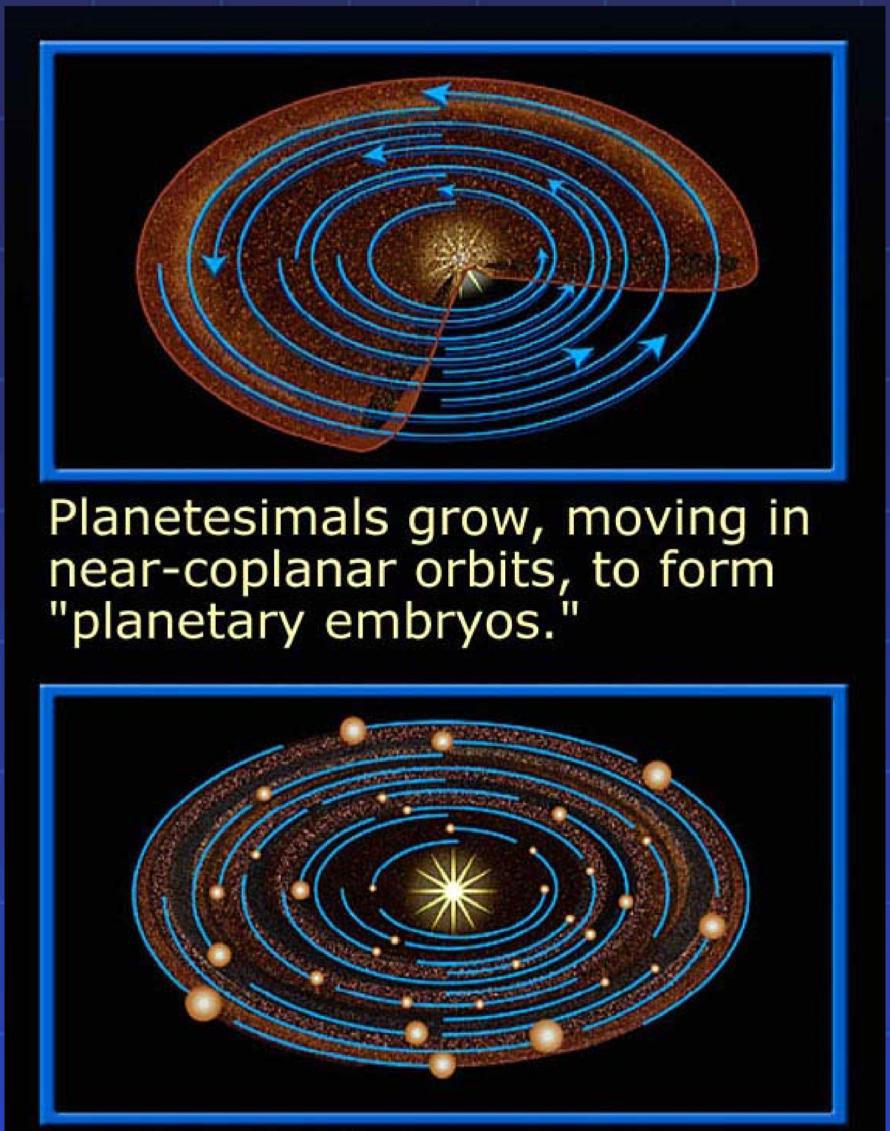


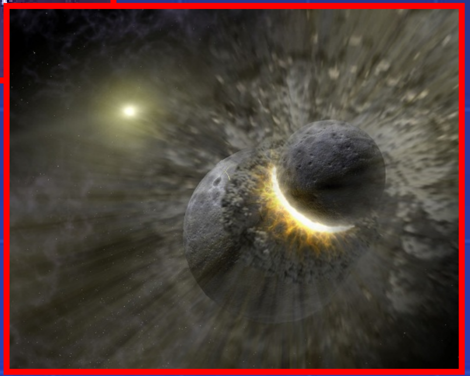


- Disk particles come together by gravity. Collisions make larger and larger objects by “accretion”.

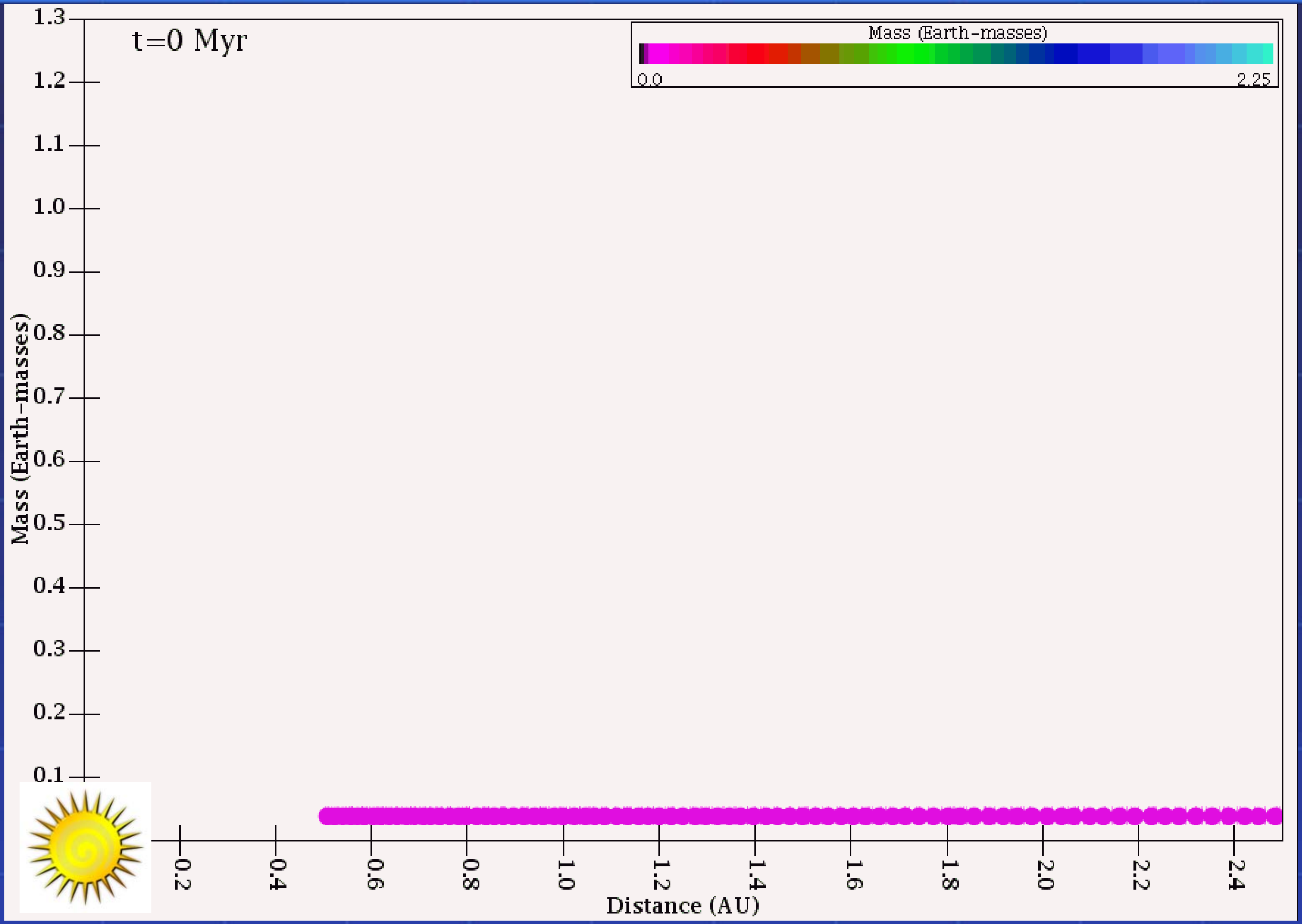
Animation from Tanga et al. (2003)

Collisions Make Large Bodies!



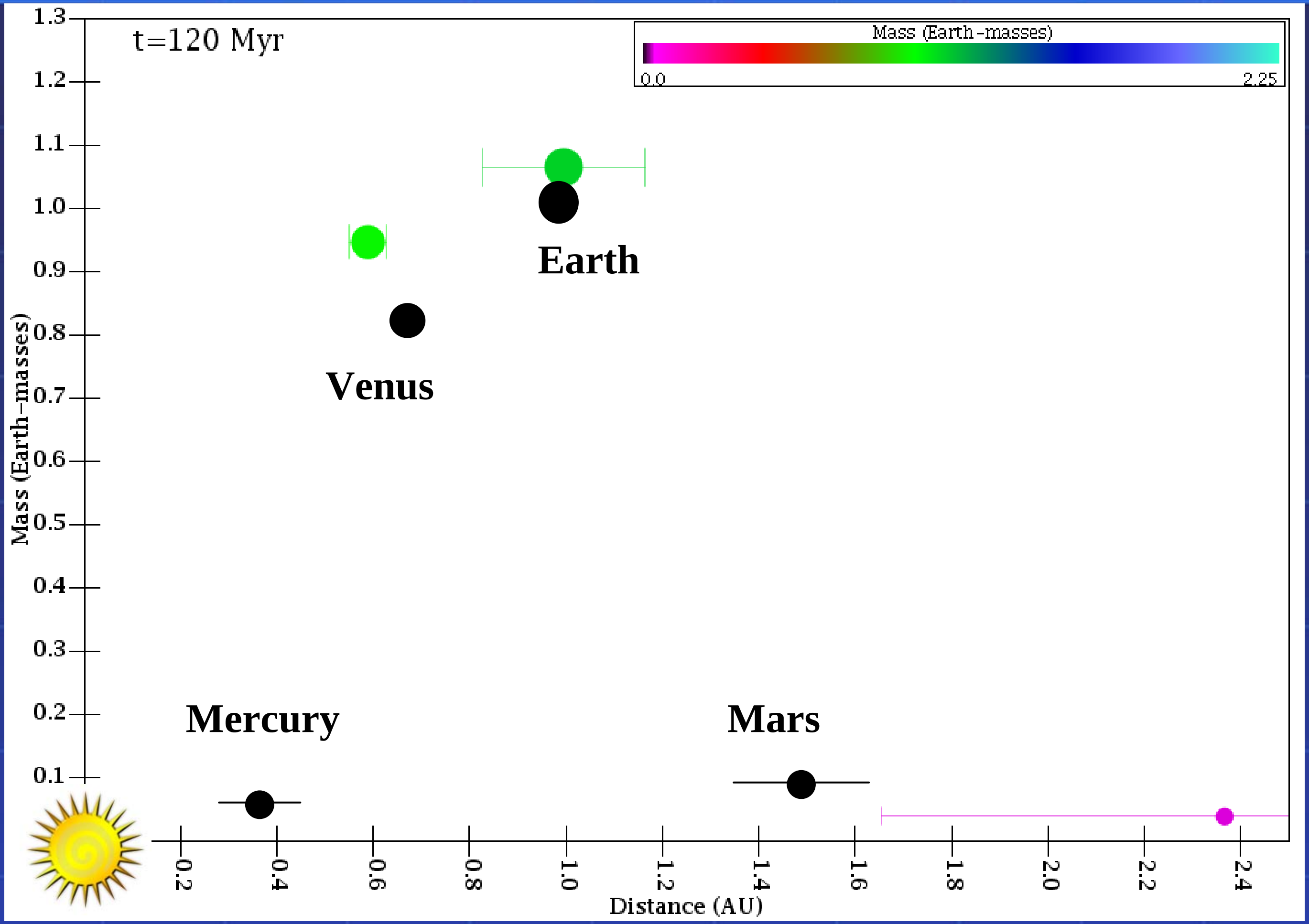


Simulated Planet Growth



- Starting with several hundred “mini-planets”, collisions cause bodies to merge and form big planets!

Simulated Planet Growth



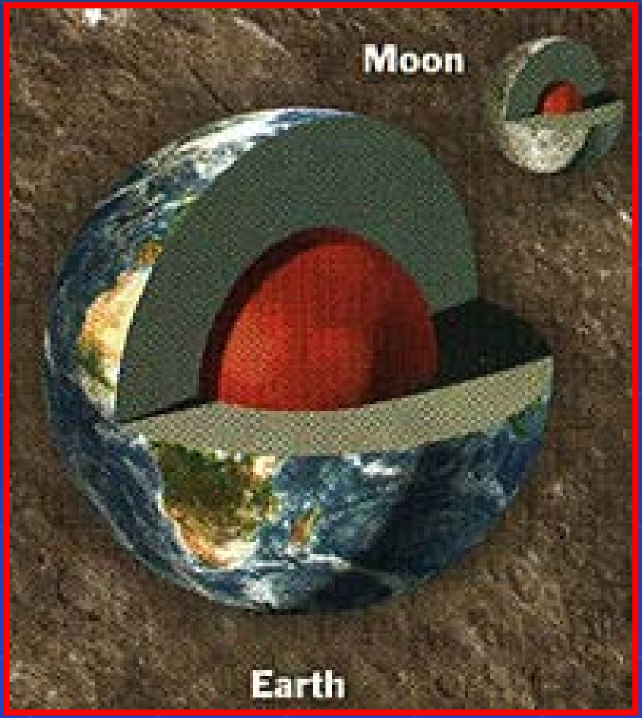
- In the end, we end up with model planets like our own.

Properties of the Moon

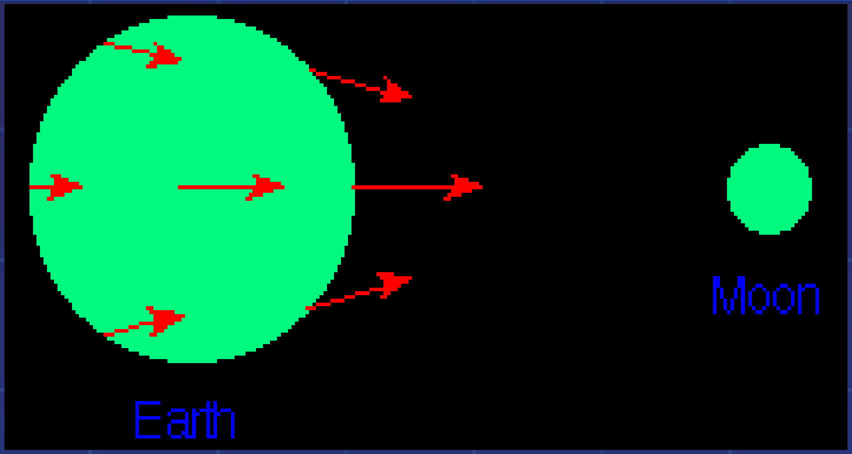
- Large, single Moon

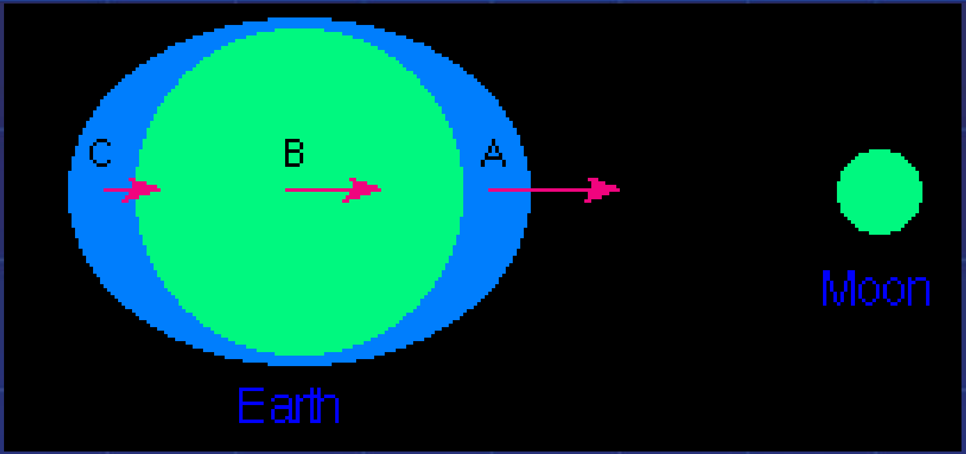
Properties of the Moon

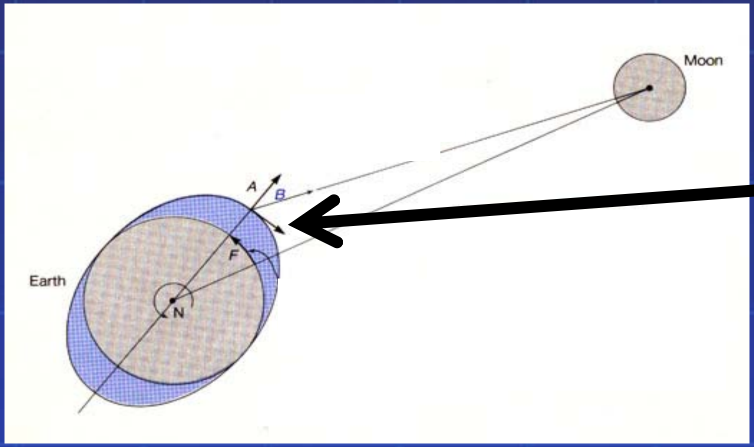
- Large, single Moon
- The Moon is depleted in iron.



Properties of the Moon







Lunar tide forms about 2º ahead of line between Earth-Moon centers

- The lunar orbit is expanding as it tidally interacts with Earth (2 cm per year).

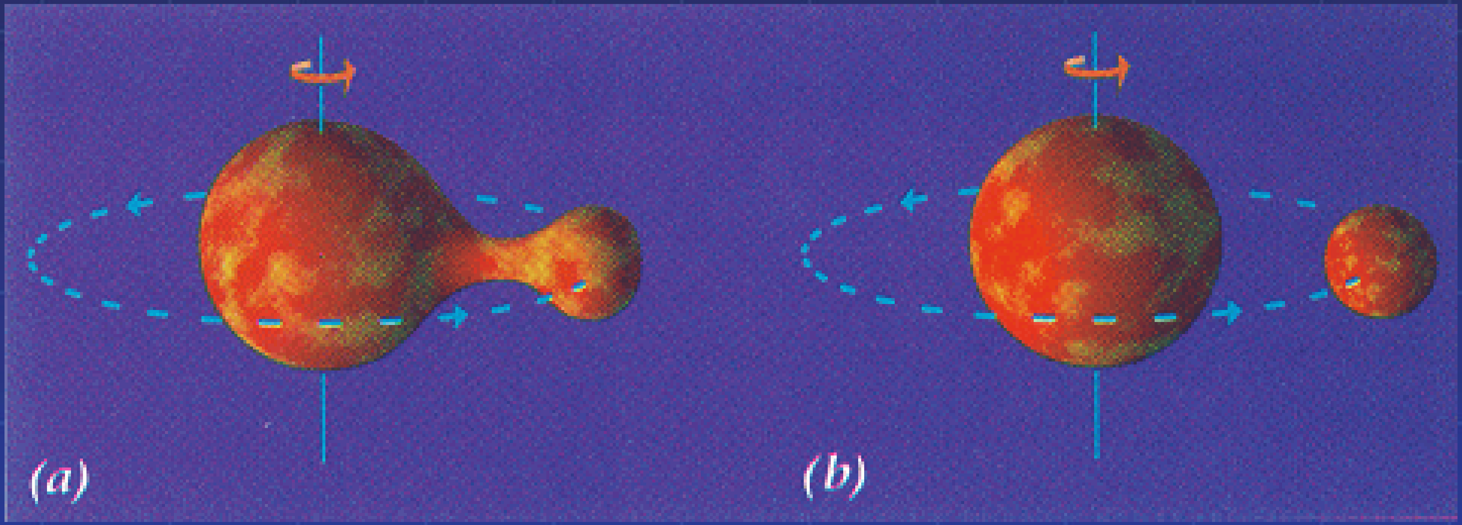
Properties of the Moon

Lunar orbit at 60 Earth radii and Earth's 24-hour day
→
5-hour Earth day when Moon formed near Earth 4.5 billion years ago

- Using conservation of momentum, we know the Moon formed near a rapidly-rotating Earth!

Lunar Formation Ideas:
1. Fission

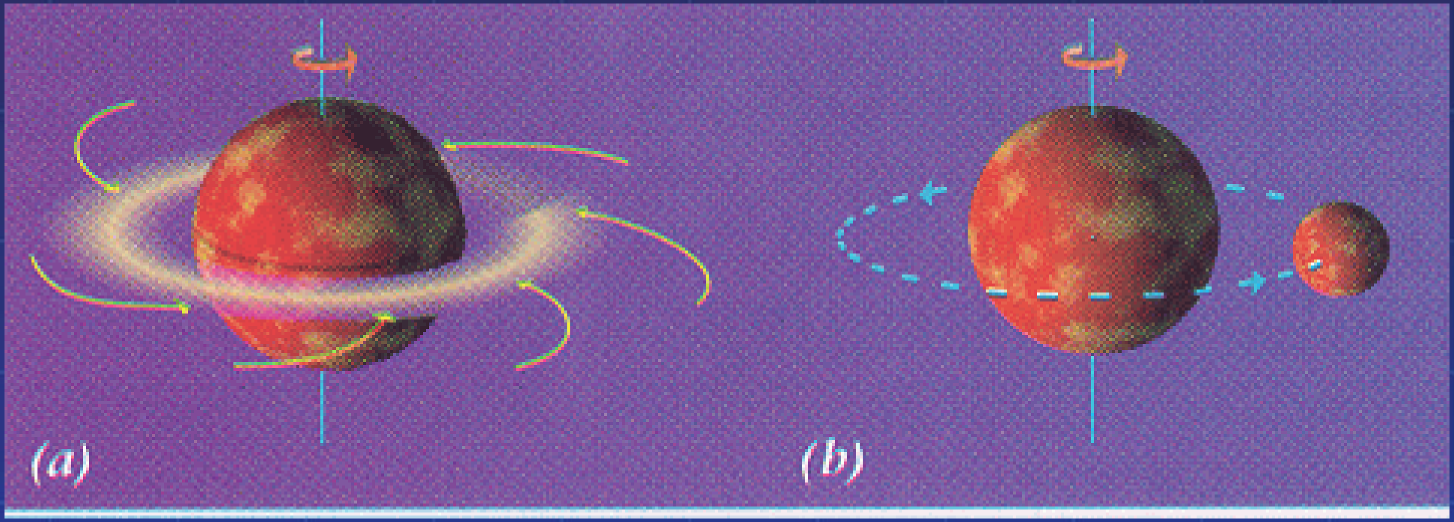
- Moon rapidly breaks off when rapidly spinning Earth becomes rotationally unstable.



  – **Pro:** Explains why Moon doesn't have much iron.
  – **Con:** Requires initial Earth day of 2.5 hours; models indicate only small objects are thrown off.

Lunar Formation Ideas:
2. Co-Formation

- Moon forms alongside Earth and grows with it.

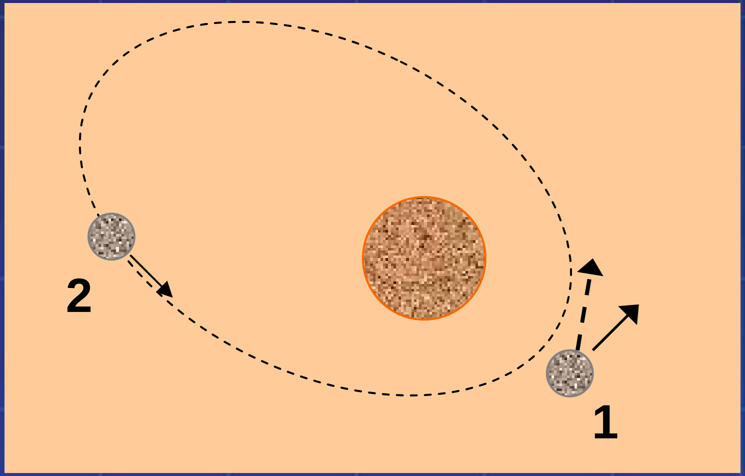


– **Pro:** We think some satellites of gas giants are formed this way.

– **Con:** Does not explain the Moon's lack of iron or the fast early rotation of the Earth.

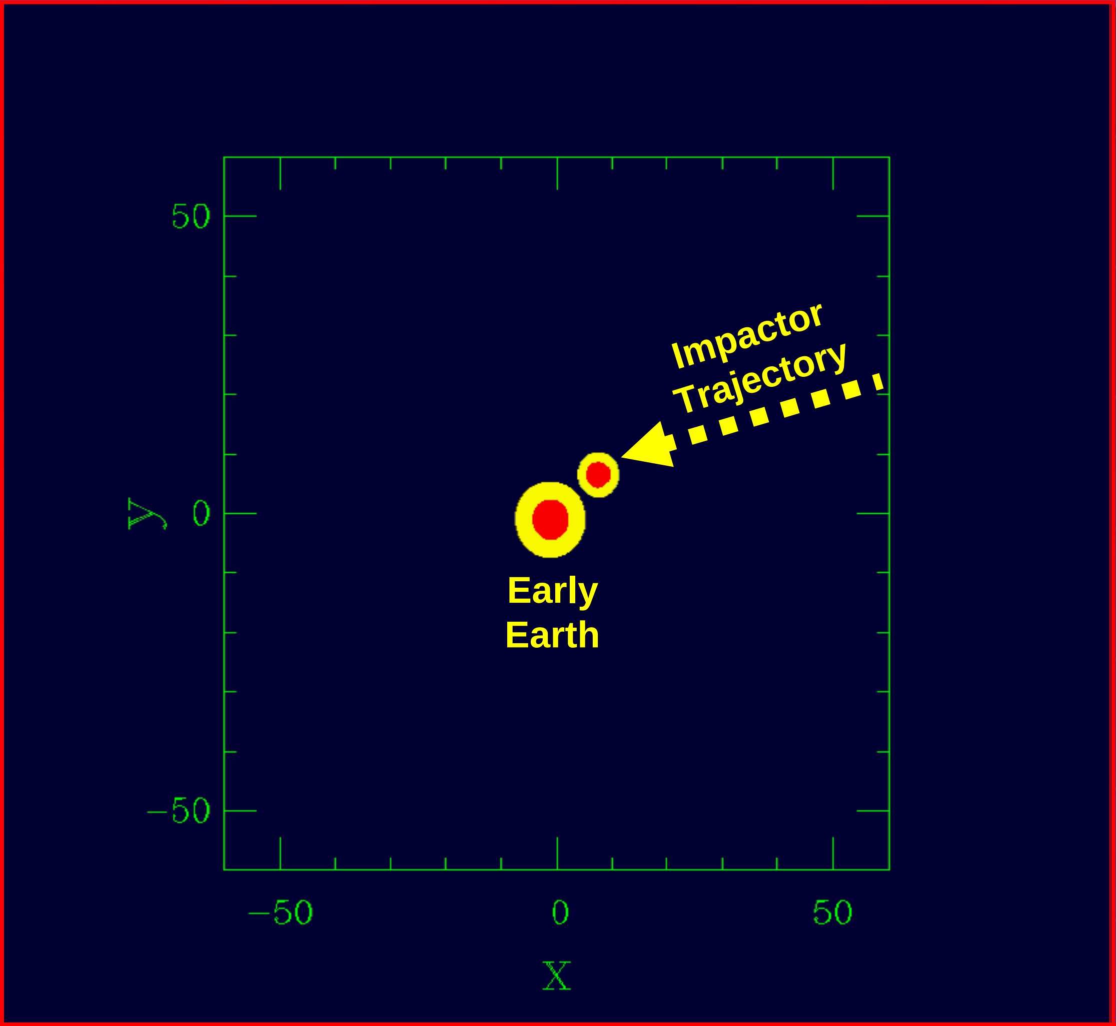
Lunar Formation Ideas:
3. Capture

- Moon forms independently and was captured into Earth orbit during a close fly-by.



  - **Pro:** Moon is similar in size to believed “mini-planets”
  - **Con:** Does not explain lack of lunar iron, or fast early Earth rotation. Very hard to do.

Giant Impact Model of Moon Formation

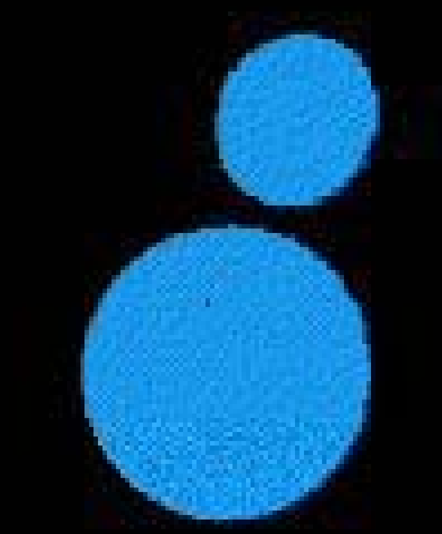


Iron core vs. stony mantle

Animation from Robin Canup

- Mars-sized body hits Earth and forms Moon from debris disk.
- This model explains:
  - Large Moon!
  - High Earth/Moon angular momentum.
  - Lack of iron in Moon.
  - Large impacts common!

Giant Impact Model of Moon Formation



Temperature

> 11,000°

10^4 → 11,000°

9100 → 10,000°

8200 → 9100°

7100 → 8200°

6200 → 7100°

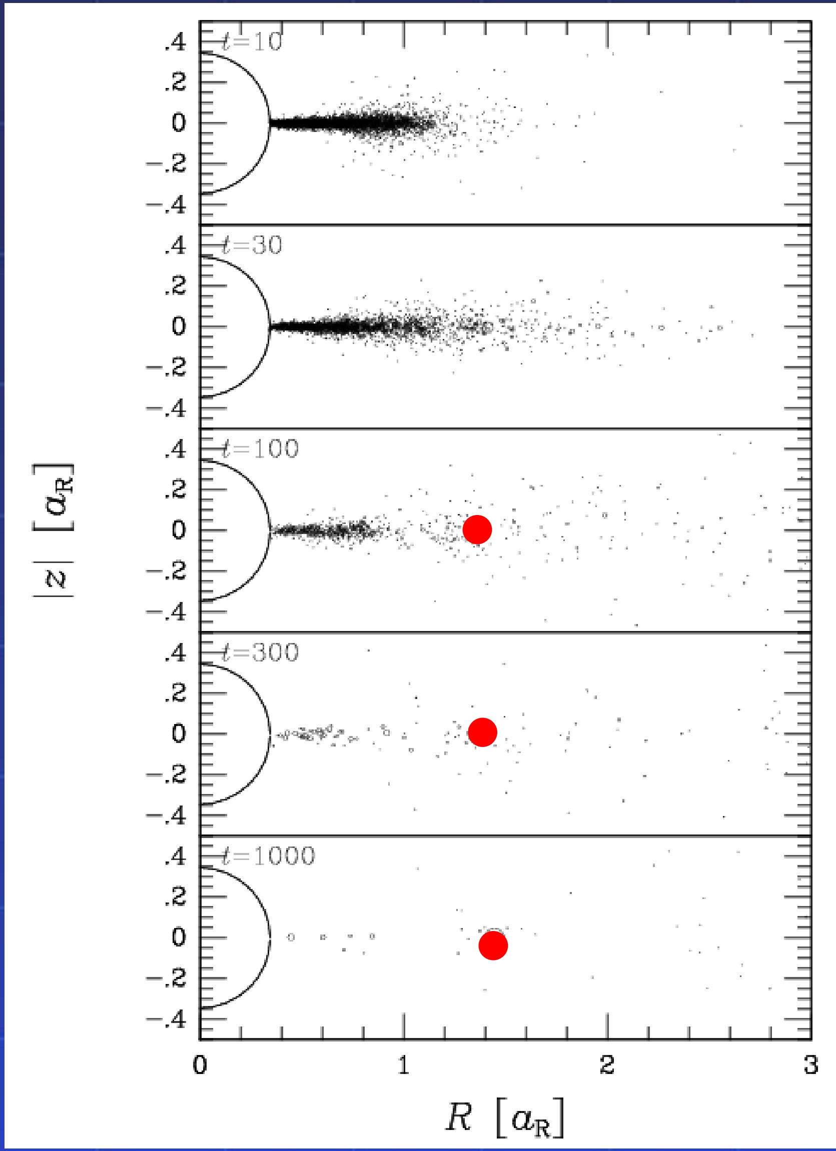
5100 → 6200°

4200 → 5100°

3100 → 4200°

Animation from Robin Canup

Lunar Accretion Simulations



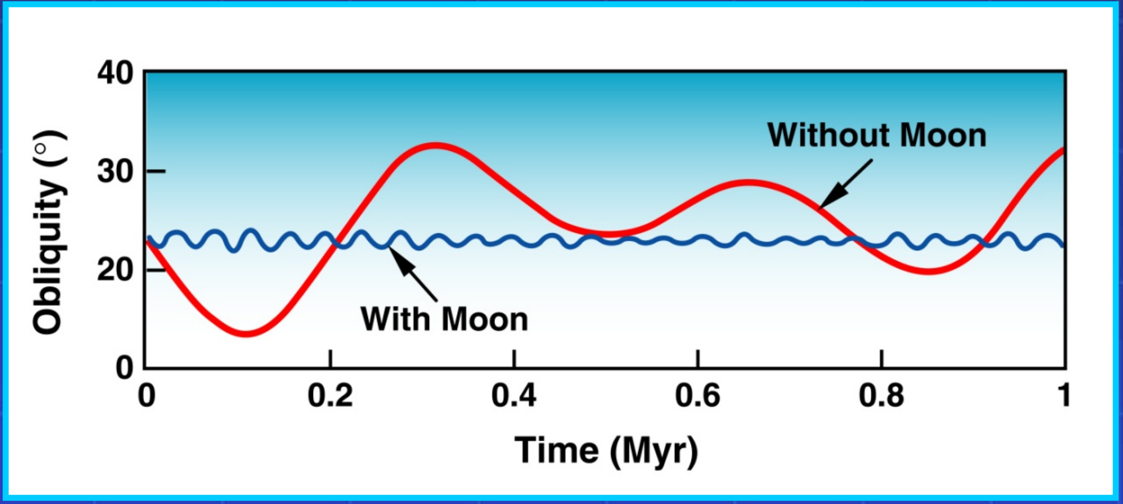
- Models allow us to track disk particles forming into Moon.
- The Moon could form in as short as a few years or as long as 10,000 years.

Some Implications

- Planet properties affected by final large impacts
  - Tilt of planet's axis (north pole), its rotation rate, whether it had a moon.
- Earth & Moon resulted from single chance event!
  - A collision between a Mars-size protoplanet and the newly formed Earth 4.5 billion years ago.

Effects of Our Moon

- 23.5º tilt of our planet's axis & seasons' properties were affected by final large impacts
- 24 hour day
- Primary ocean tides
- Moon helps minimize variation of Earth's tilt.



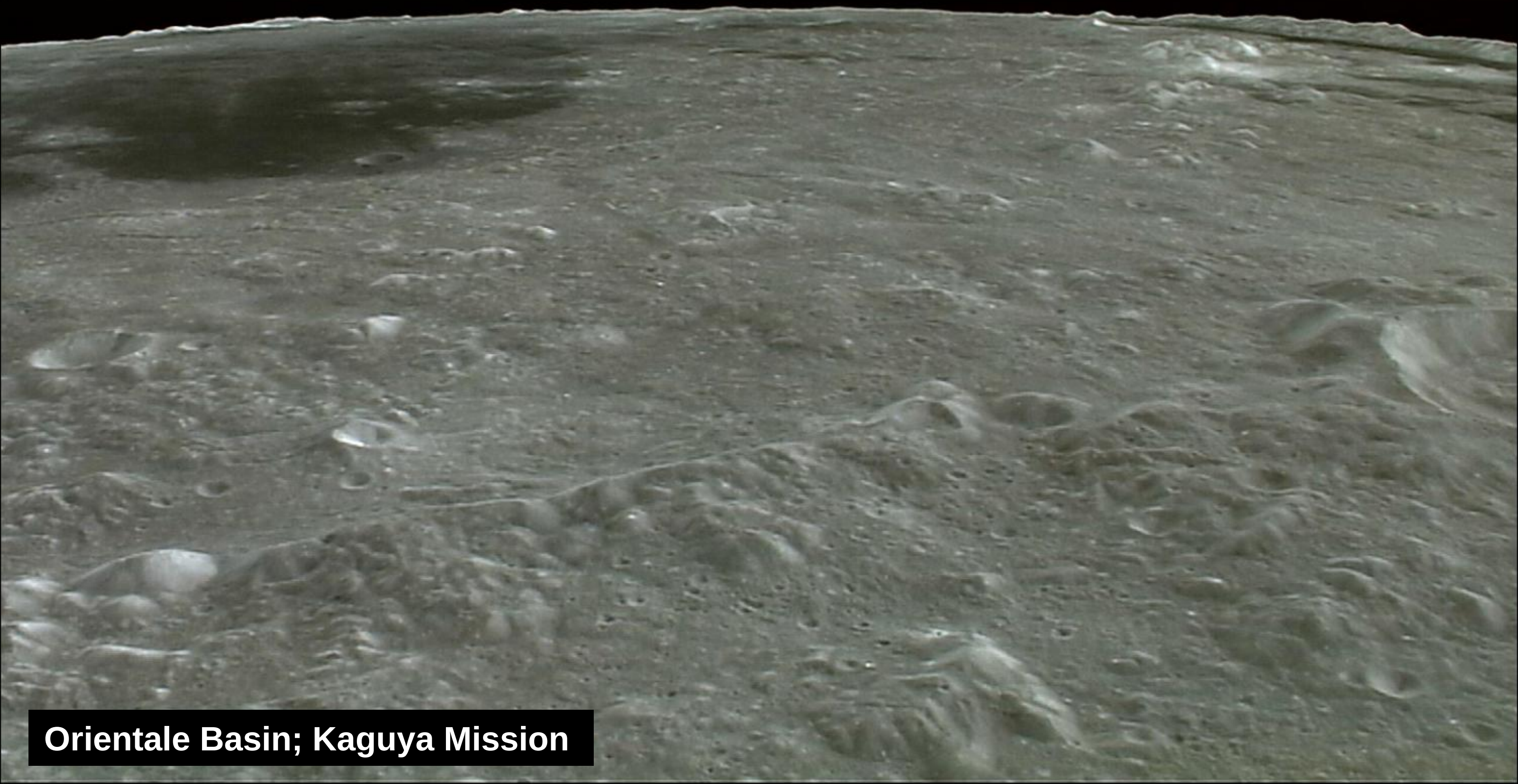
Starting Time for Lunar Impact History

- Best available age of the Moon-forming event and start-up of the magma ocean is ~60 (+90, –10) My after the formation of CAIs at 4.56 Ga.
- The oldest known sample of the lunar crust formed ~100 My after CAI formation (4.46 Ga).
- Hence, the starting time for the Moon's impact record (i.e., t = 0) is probably >100 My after CAI formation.

Norman et al. (2003); Touboul et al. (2007).

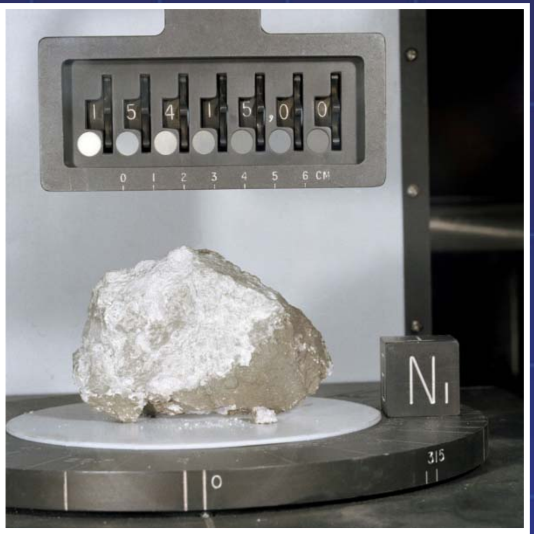
Part 2a:

What is the Lunar Late Heavy Bombardment?



Orientale Basin; Kaguya Mission

Rocks Tell a Story

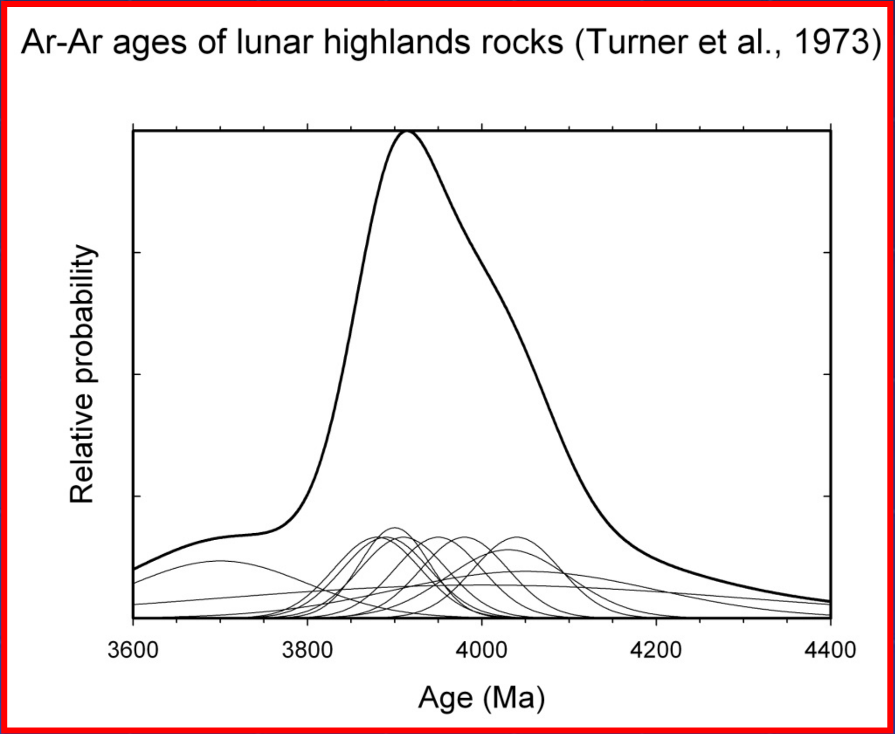


"A rock is the most efficient way to encode information about a planet."

– Bruce Banerdt (as paraphrased by Bob Grimm)

Apollo Insights: Ages of Lunar Samples

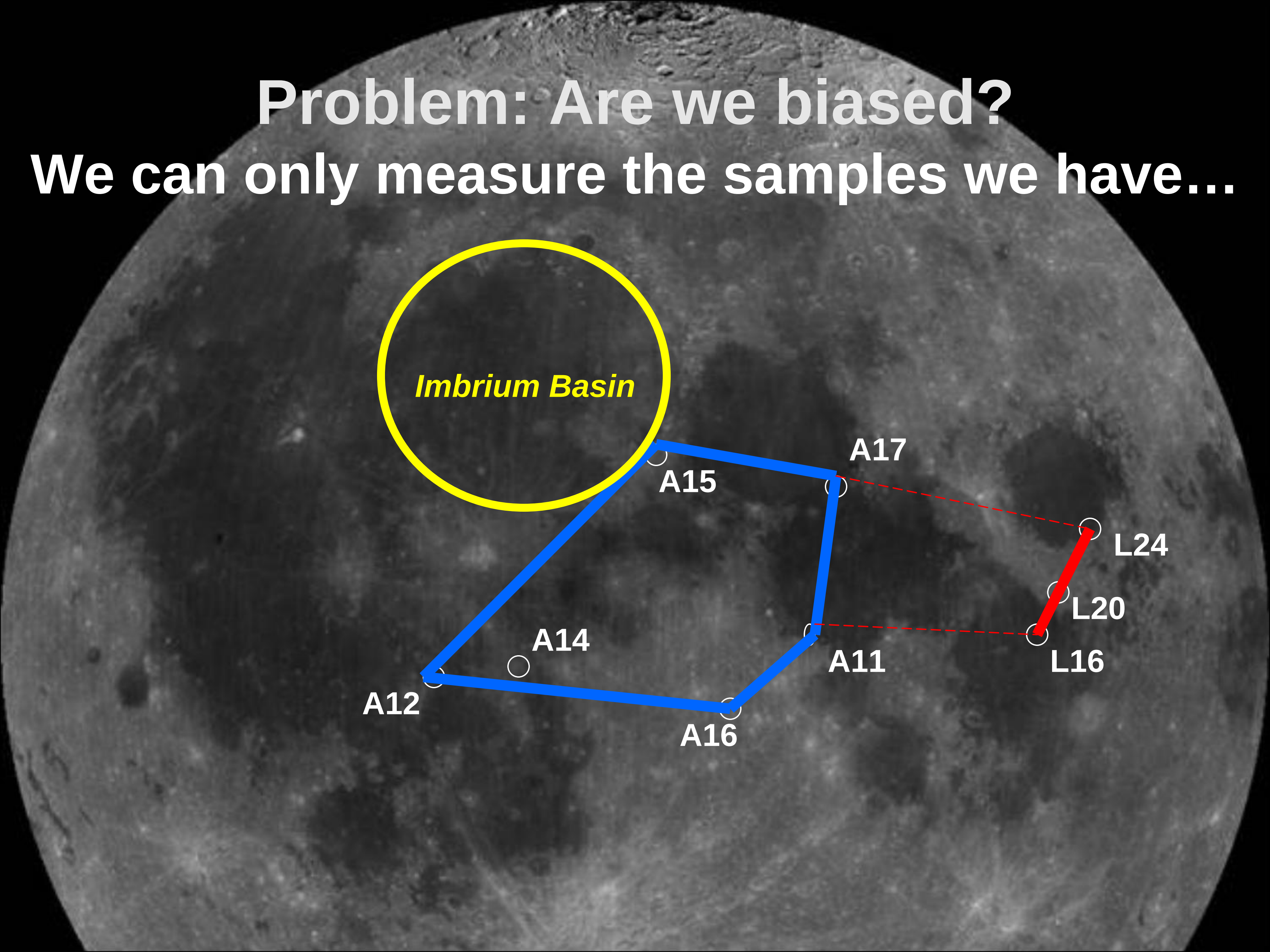
- Most ancient lunar rocks cluster near ~3.8-3.9 Ga.
  - Ar-Ar-based ages of basins cluster near 3.9 Ga.



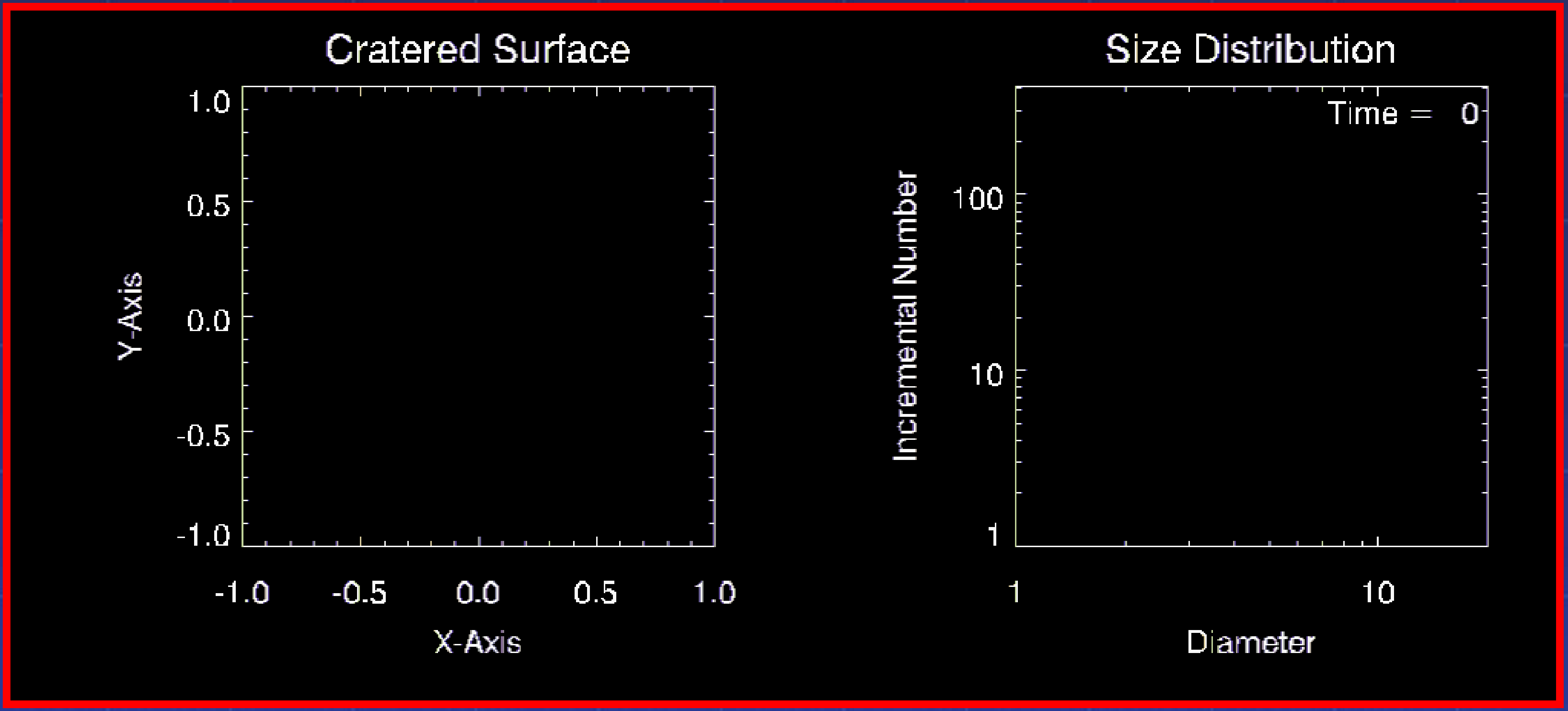
All available Ar-Ar ages of highlands rocks as of 1973. Gaussians along bottom (of equal area) represent individual samples. Dark line ("ideogram") is sum of those Gaussians. Data from Turner et al. (1973)

Problem: Are we biased?

We can only measure the samples we have…

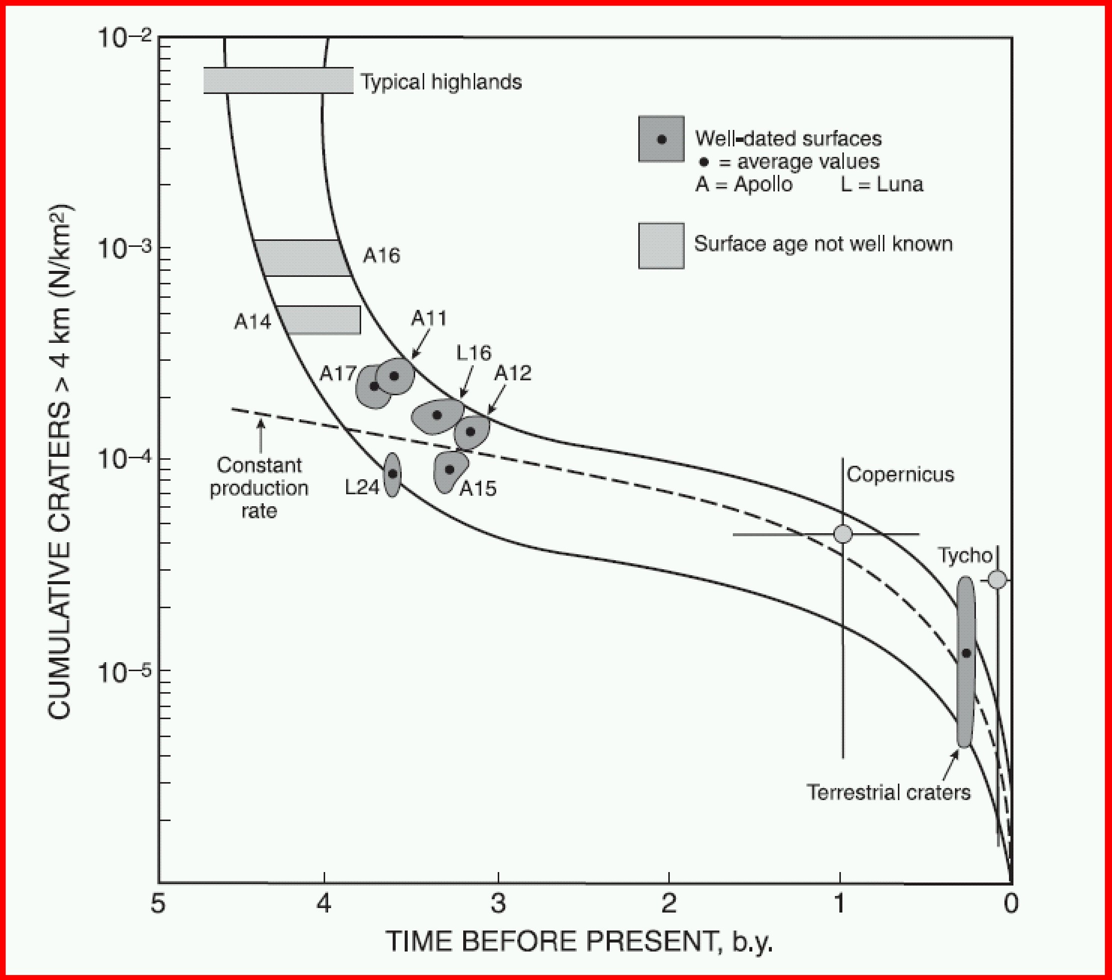


Planetary Chronology from Crater Counts



- Relative surface ages can be derived from crater counts.
- Absolute ages of various surfaces can be estimated if we understand the impact flux over time (and vice versa).

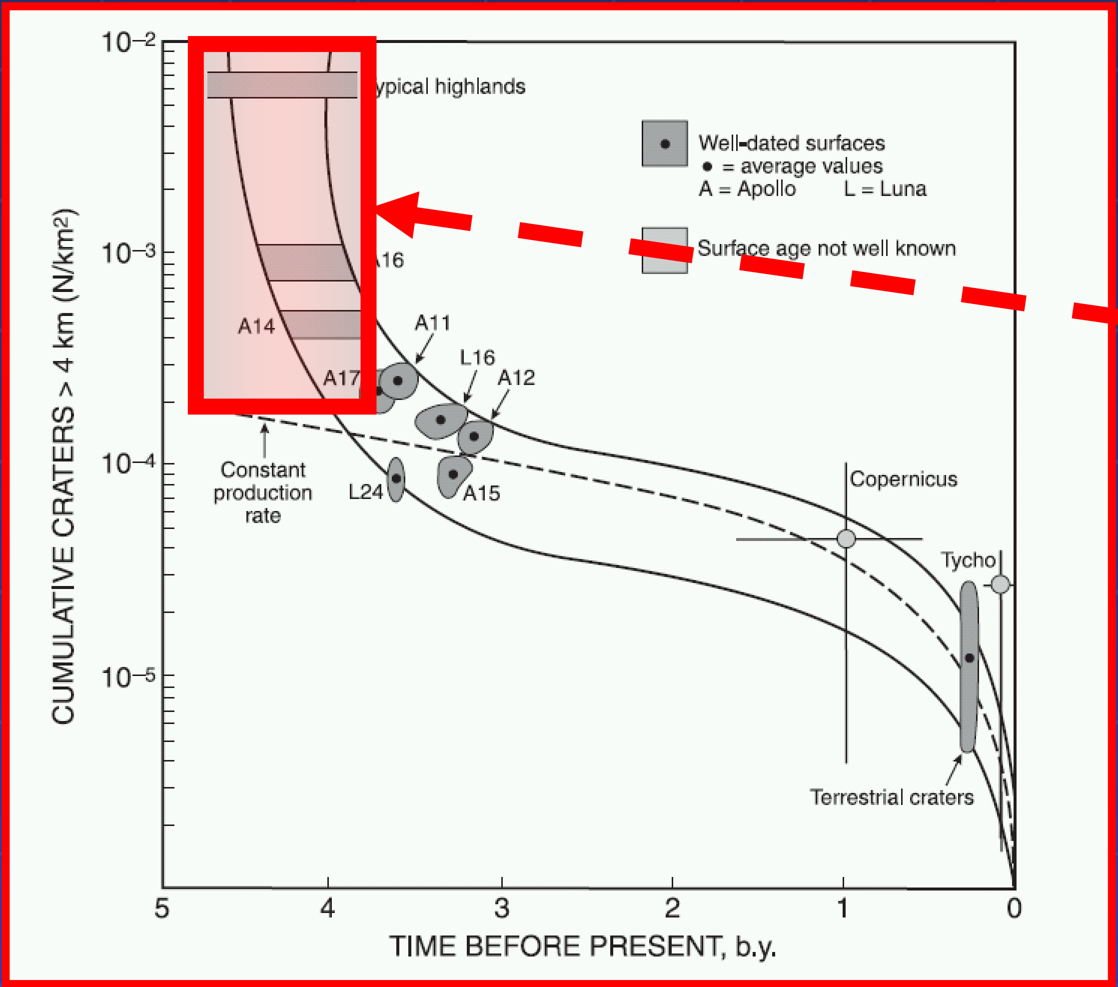
The Lunar Impact Rate



- Lunar impact rate has been variable with time.

Hartmann et al. (1981); Horz et al. (1991)

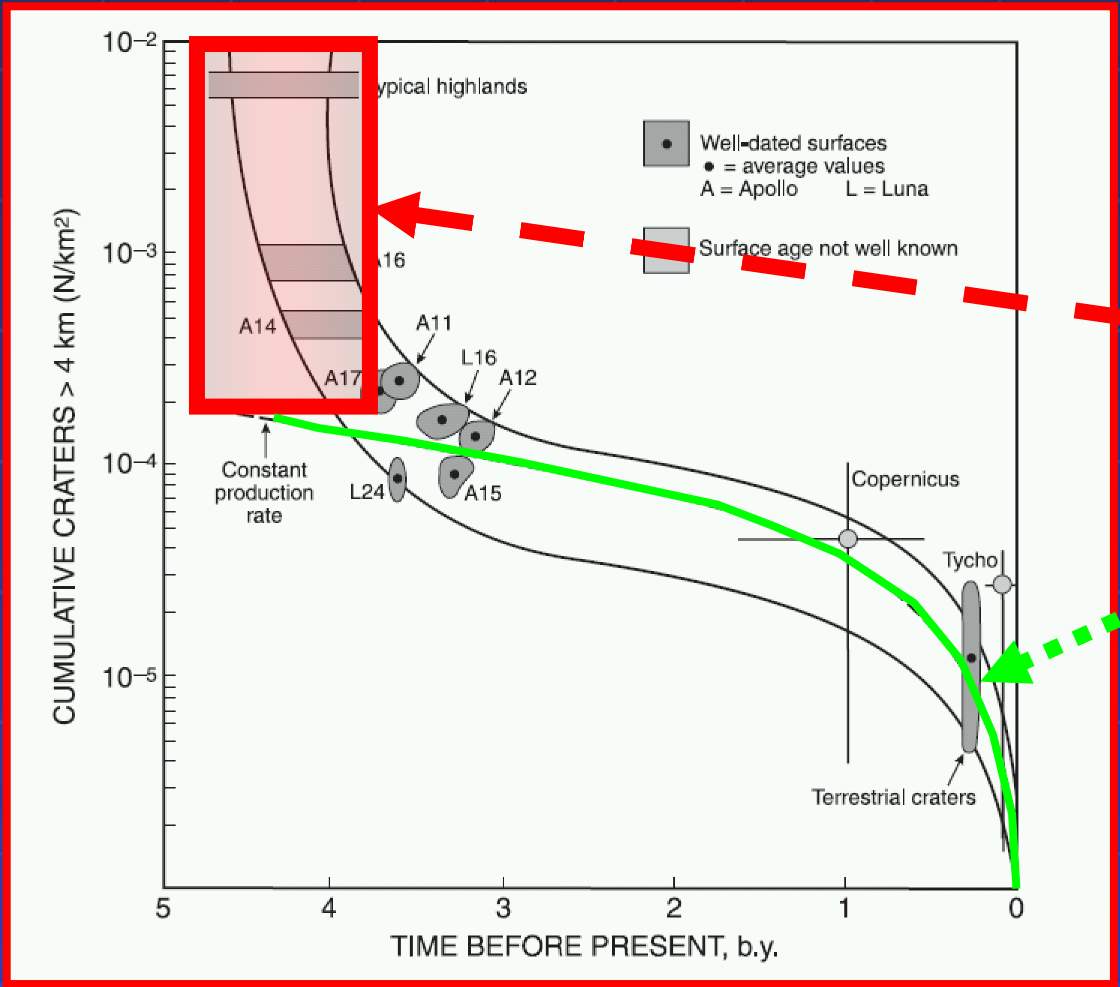
The Lunar Impact Rate



Hartmann et al. (1981); Horz et al. (1991)

- Lunar impact rate has been variable with time.
- Crater production rates >100 times higher >3.8 billion years ago.

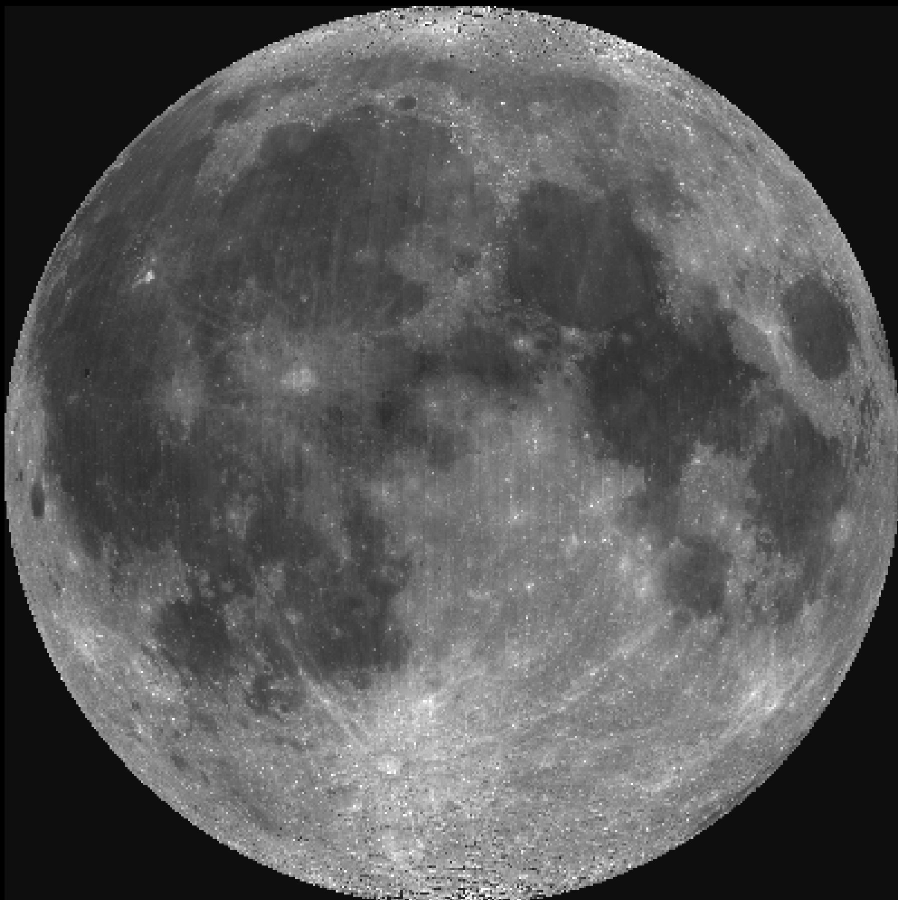
The Lunar Impact Rate



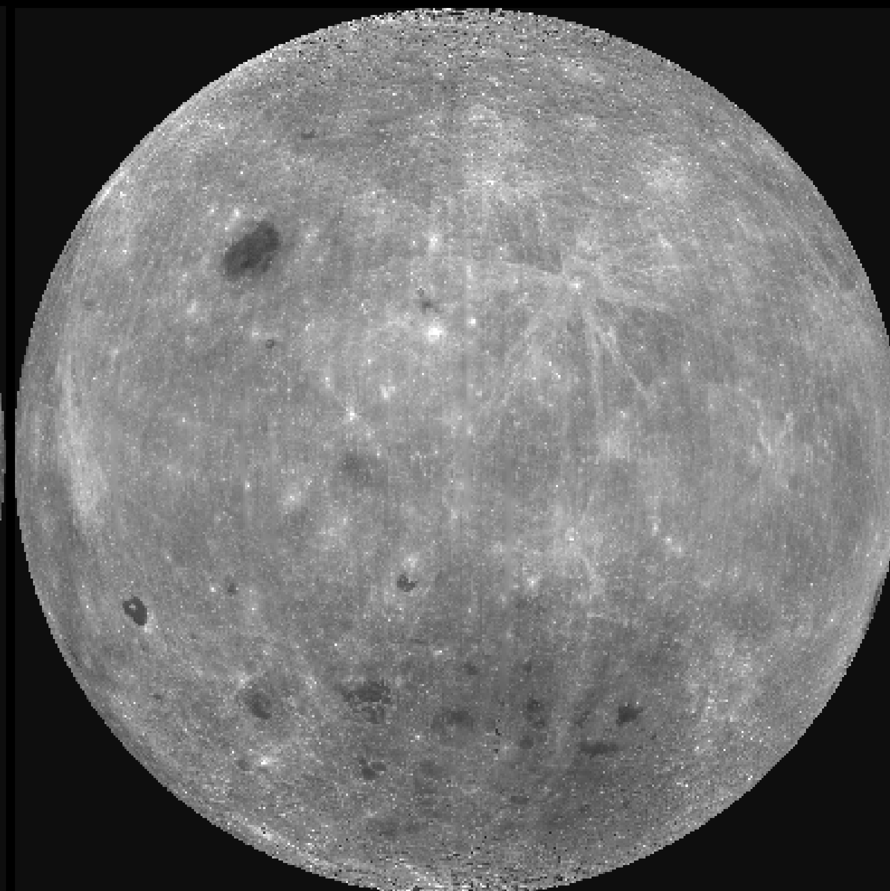
Hartmann et al. (1981); Horz et al. (1991)

- Lunar impact rate has been variable with time.
- Crater production rates >100 times higher >3.8 Gy ago.
- Relatively constant crater rate since ~3.2 Ga.

Lunar Basins



Near Side

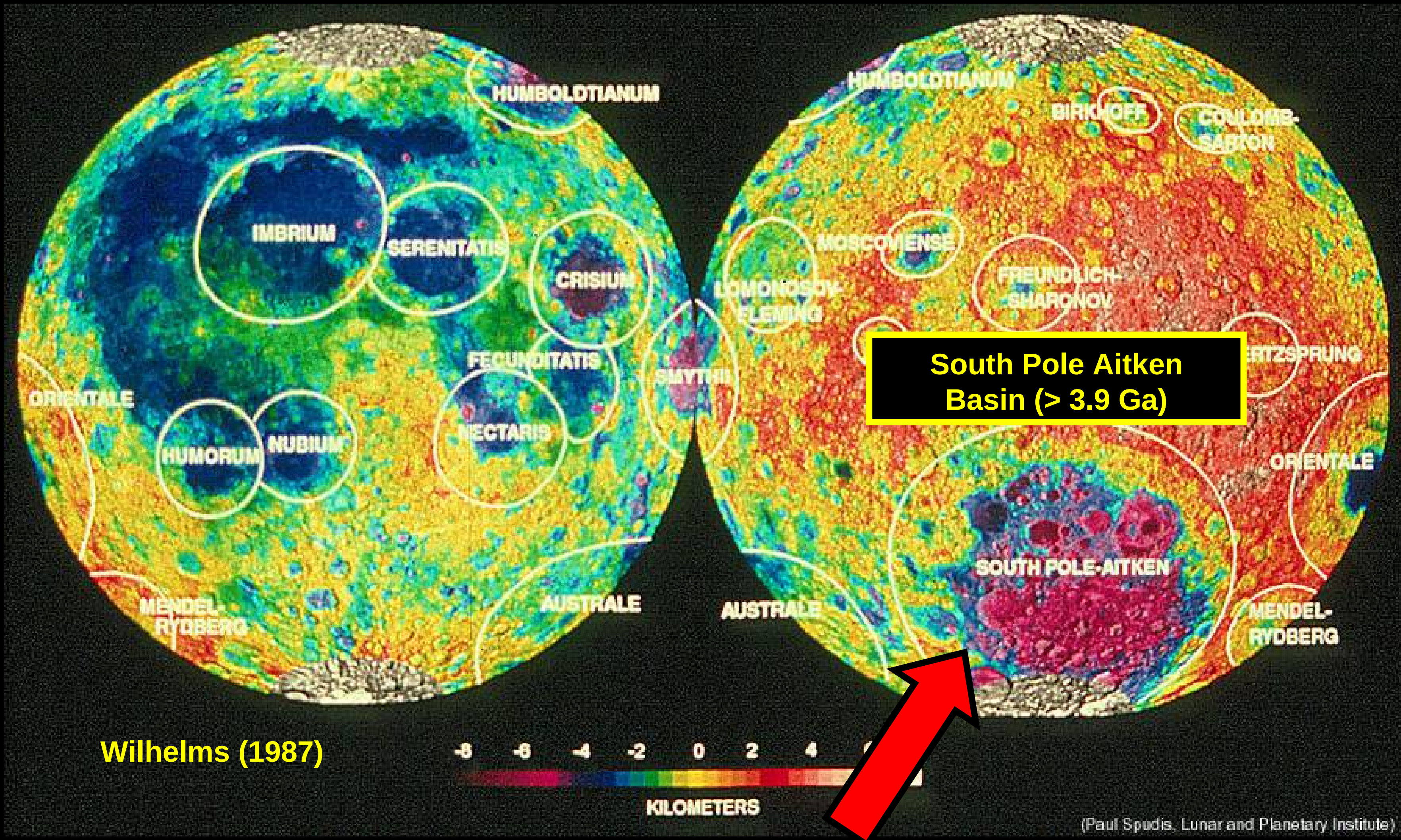


Far Side

- Estimates indicate that 45-90 lunar basins (*D* > 300 km) formed between 3.8 and ~4.5 billion years ago.

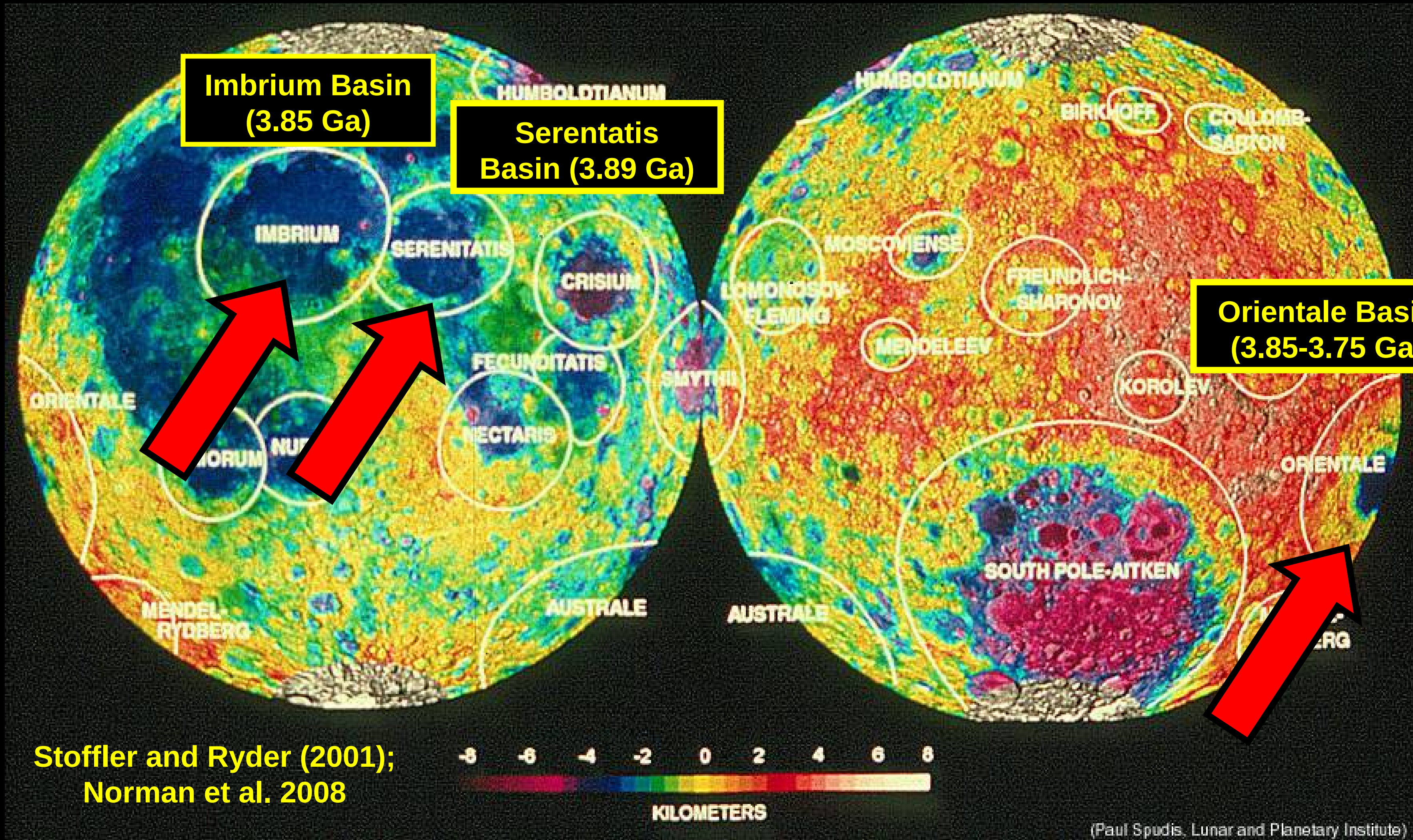
Wilhelms (1987); Frey et al. (2008)

Lunar Basins



- The oldest basin by superposition is South Pole Aitken basin (2500 km). SPA's absolute age is unknown.

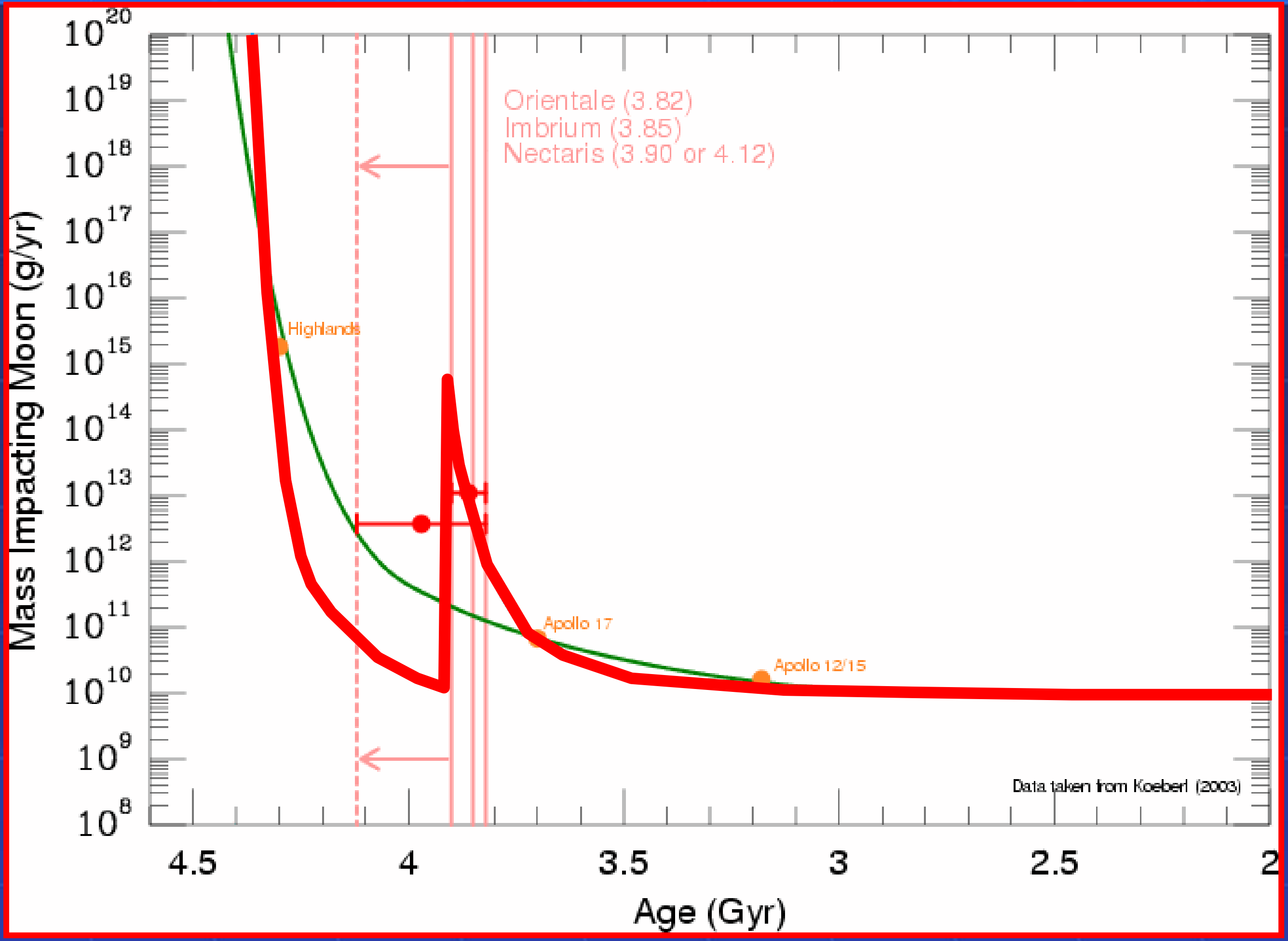
Lunar Basins With Accepted Ages



Stoffler and Ryder (2001); Norman et al. 2008

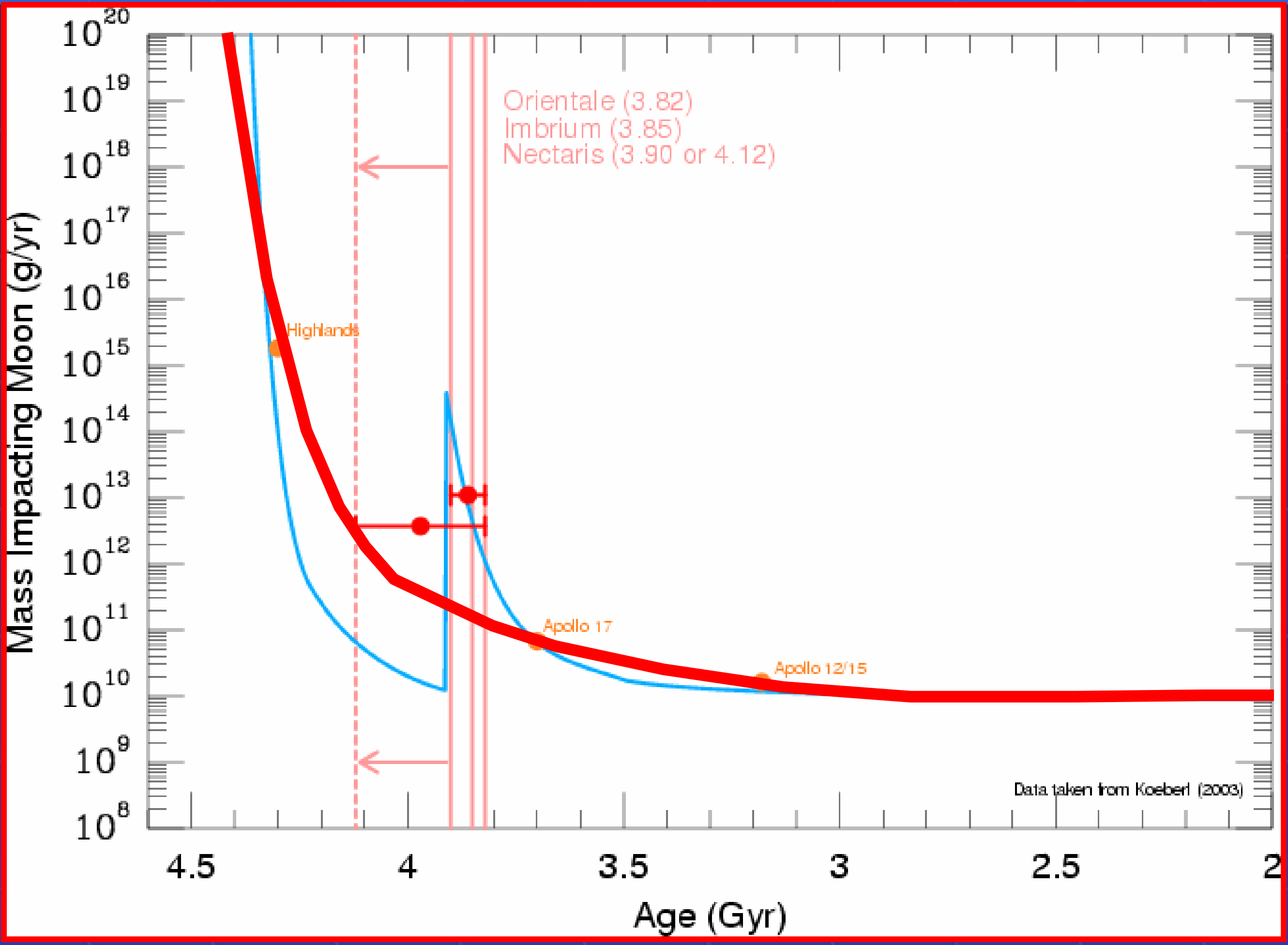
- Basins with accepted ages are 3.8-3.9 Ga: Serentatis (920 km), Imbrium (1160 km) and Orientale (930 km).

Lunar Late Heavy Bombardment



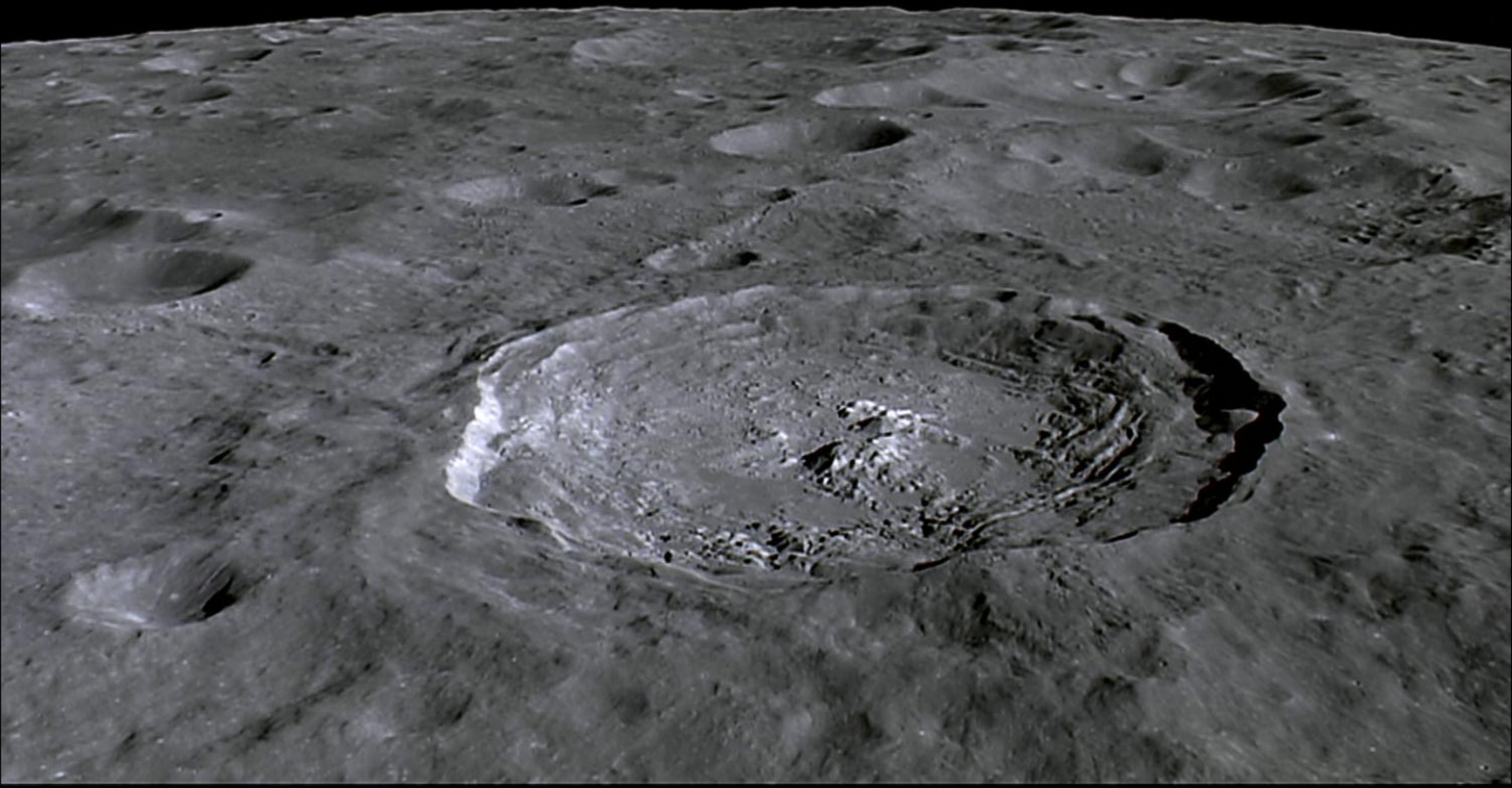
- Were most large basins produced by a spike of impactors near ~ 3.9 Ga, creating a **terminal cataclysm**?

Lunar Late Heavy Bombardment

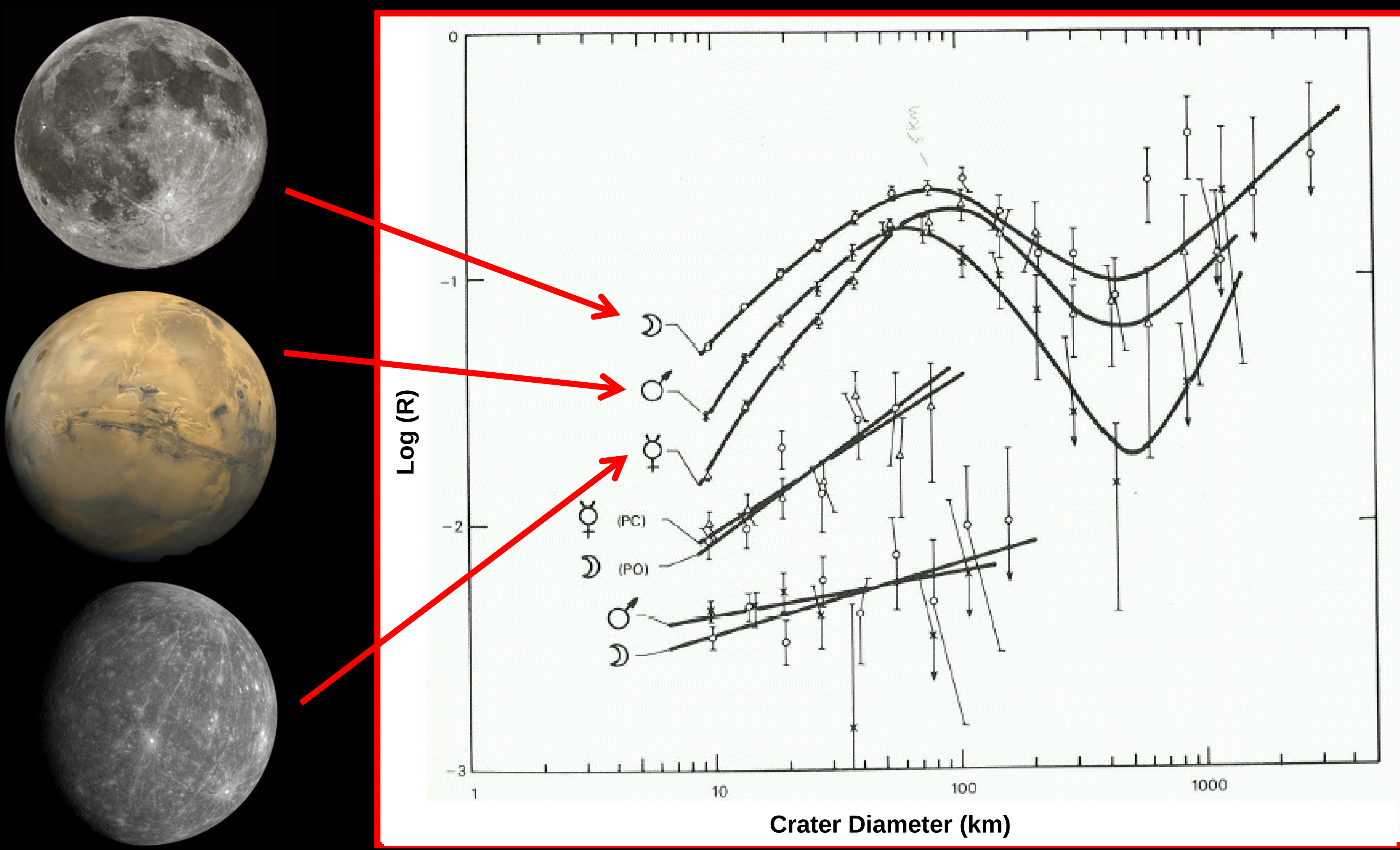


- Or were most produced by a **declining bombardment** of leftover planetesimals from terrestrial planet formation?

Part 2b:
Was The Bombardment “Local” or Solar System-Wide?



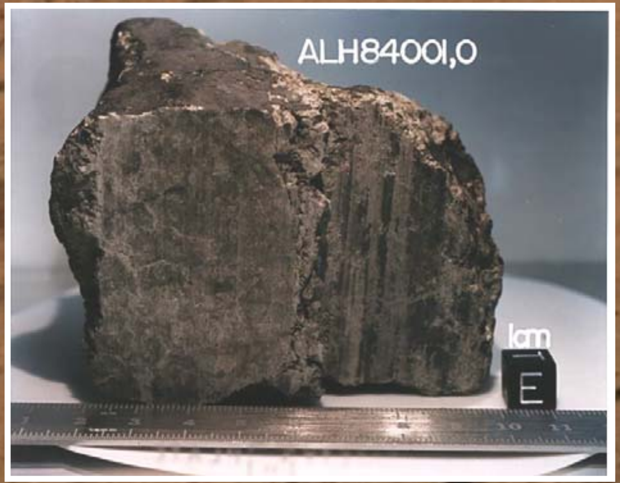
Similar Ancient Crater Populations on Moon, Mars, and Mercury



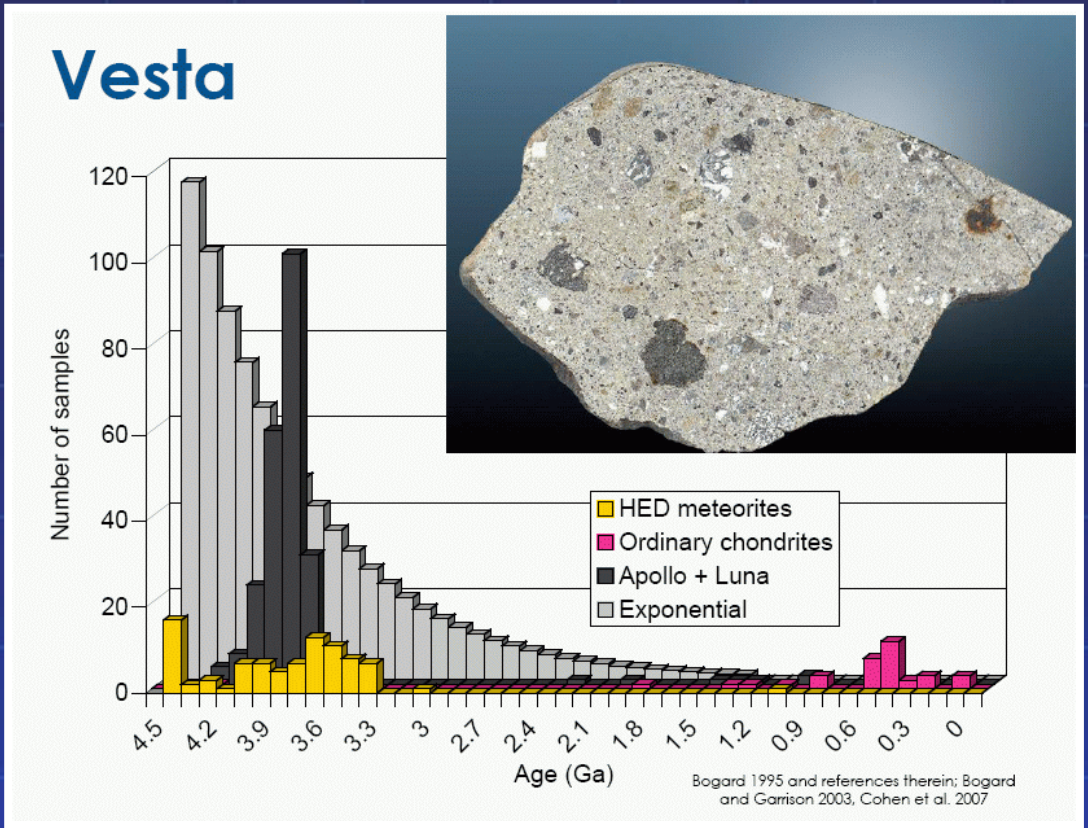
Strom et al. (1989; 2005); Frey et al. (I2008)

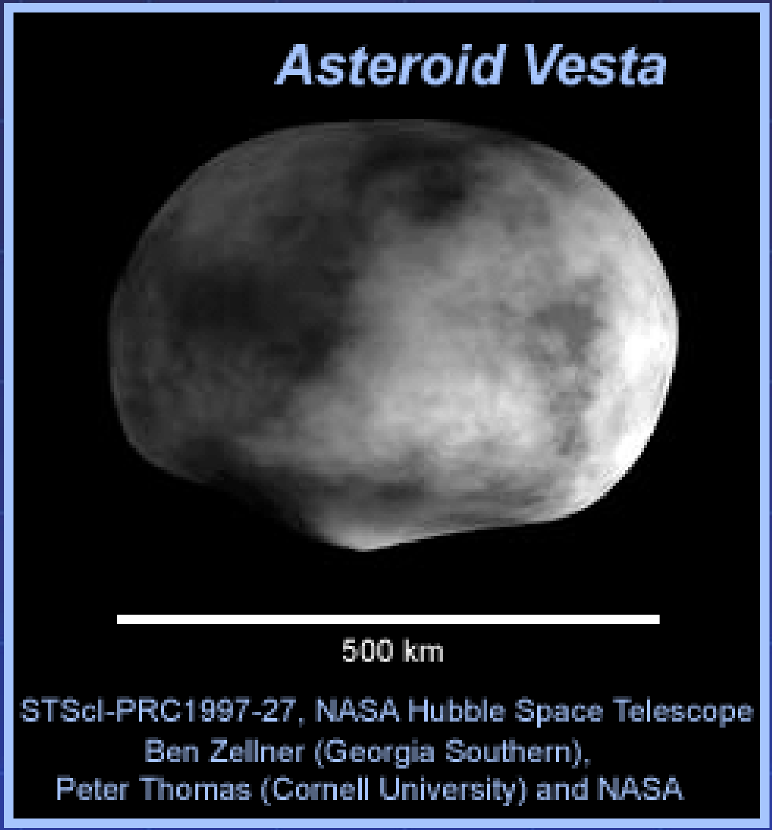
Mars Meteorites

- Only one meteorite old enough to have seen Cataclysm – ALH 84001
- Crystallization age ~4.5 Ga, reset by impact ~4.0 Ga
- Cataclysm age, but not a strong argument.



Asteroids and Meteorites: Vesta and the Eucrites



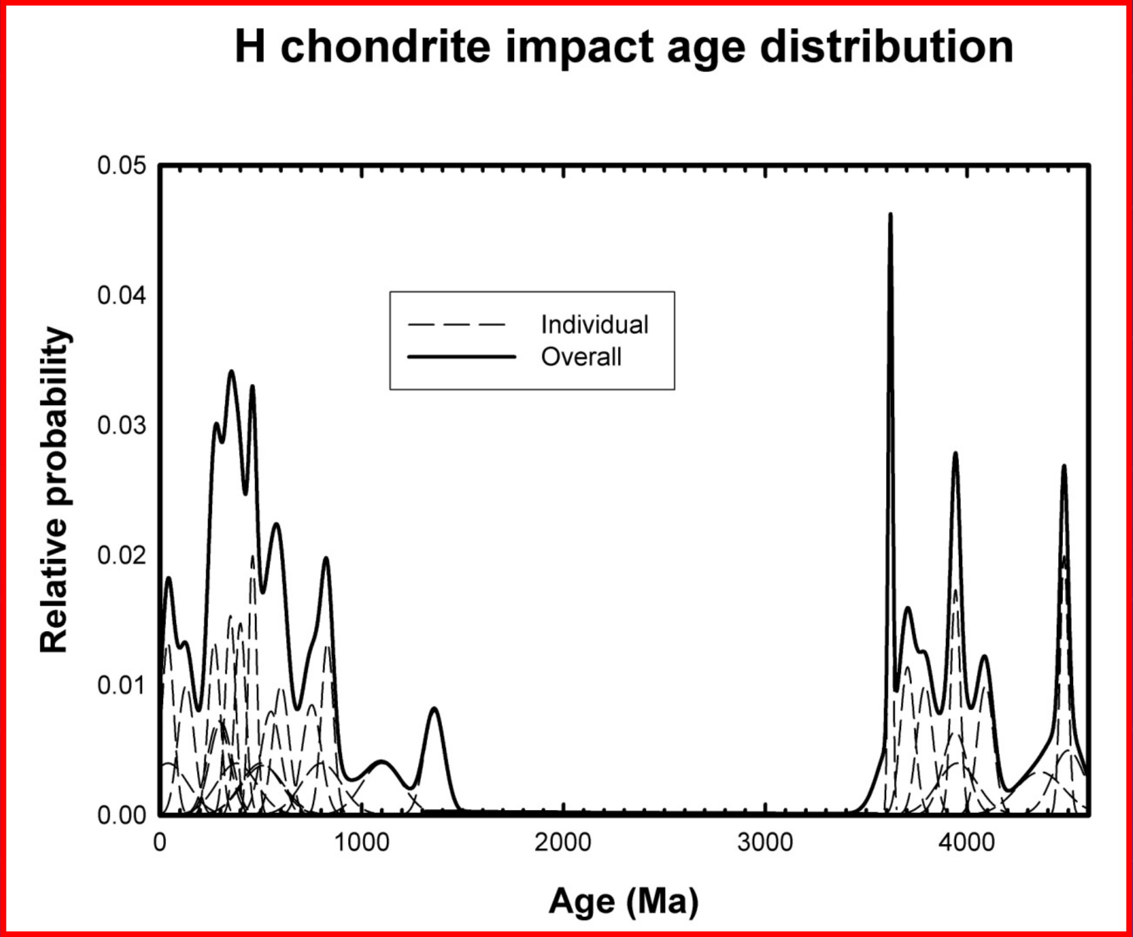


- **Many ages with 3.3-4.1 Ga, suggestive of lunar cataclysm.**
  - **The cataclysm cannot be local to Moon or from Imbrium alone!**
  - **Not a sharp spike. Few events between 4.1 and 4.5 Ga.**

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

Asteroids and Meteorites: H Chondrite Parent Body

- Many ages with 3.5-4.1 Ga, suggestive of cataclysm.
  - Two events at 4.5 Ga
  - Few with 4.1-.4.5 Ga.
- Not a spike. Very similar to eucrite signature.
- Some meteorites show related cataclysm ages (LLs, IIE irons, etc.)



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

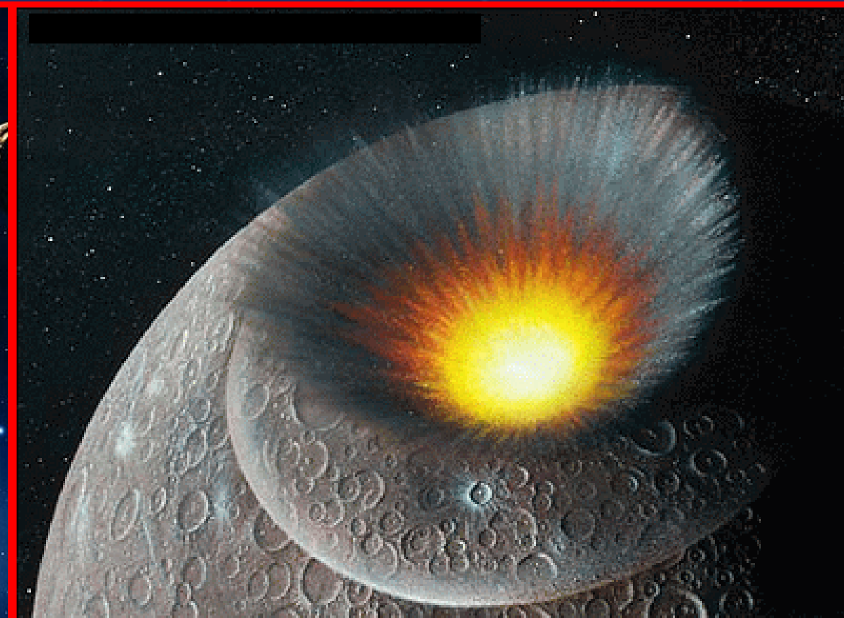
Summary of Data

- A solar-system-wide bombardment event was initiated ~3.9 Gy ago.
- Most of the evidence for a sharp impact spike comes from Apollo samples (near Imbrium), though hints of it remain elsewhere.
- The LHB signature in meteorites is not spiky! Instead, the LHB appears to be drawn out several hundreds of My.
  - There is a shock age "desert" between 4.1-4.5 Ga.
- Earlier lunar bombardments cannot be ruled out.

Part 3:
Lunar Bombardment Populations

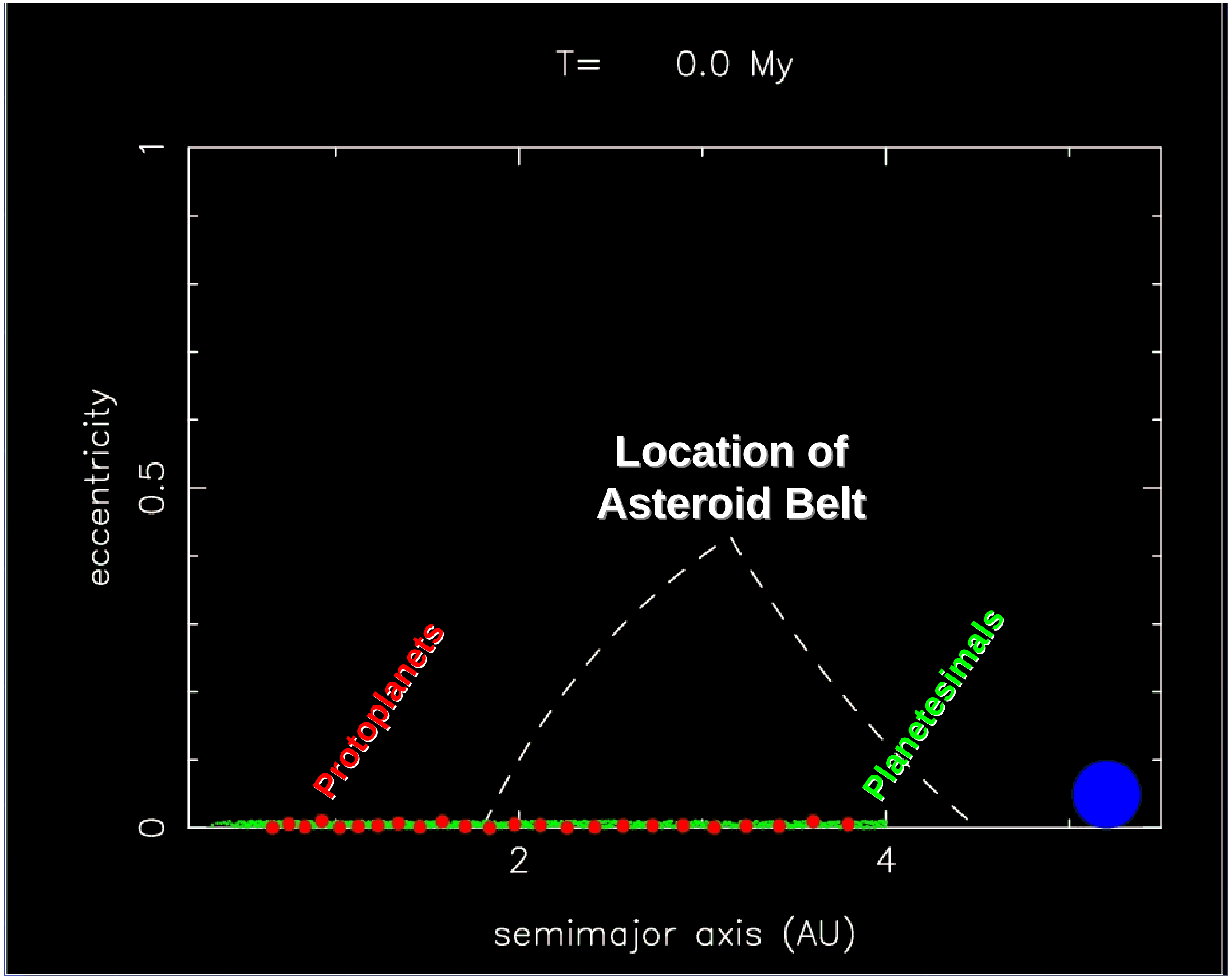
Mare Moscoviense; Kaguya Mission

Ancient Lunar Bombardment Populations



- The prime suspects for an early lunar bombardment are:
  - Leftover planetesimals in the terrestrial planet region.
  - Asteroid refugees from the main asteroid belt region.
  - Cometary refugees from the outer solar system's primordial disk.
- All of these populations collisionally/dynamically evolve; The lunar impact flux may change dramatically with time.

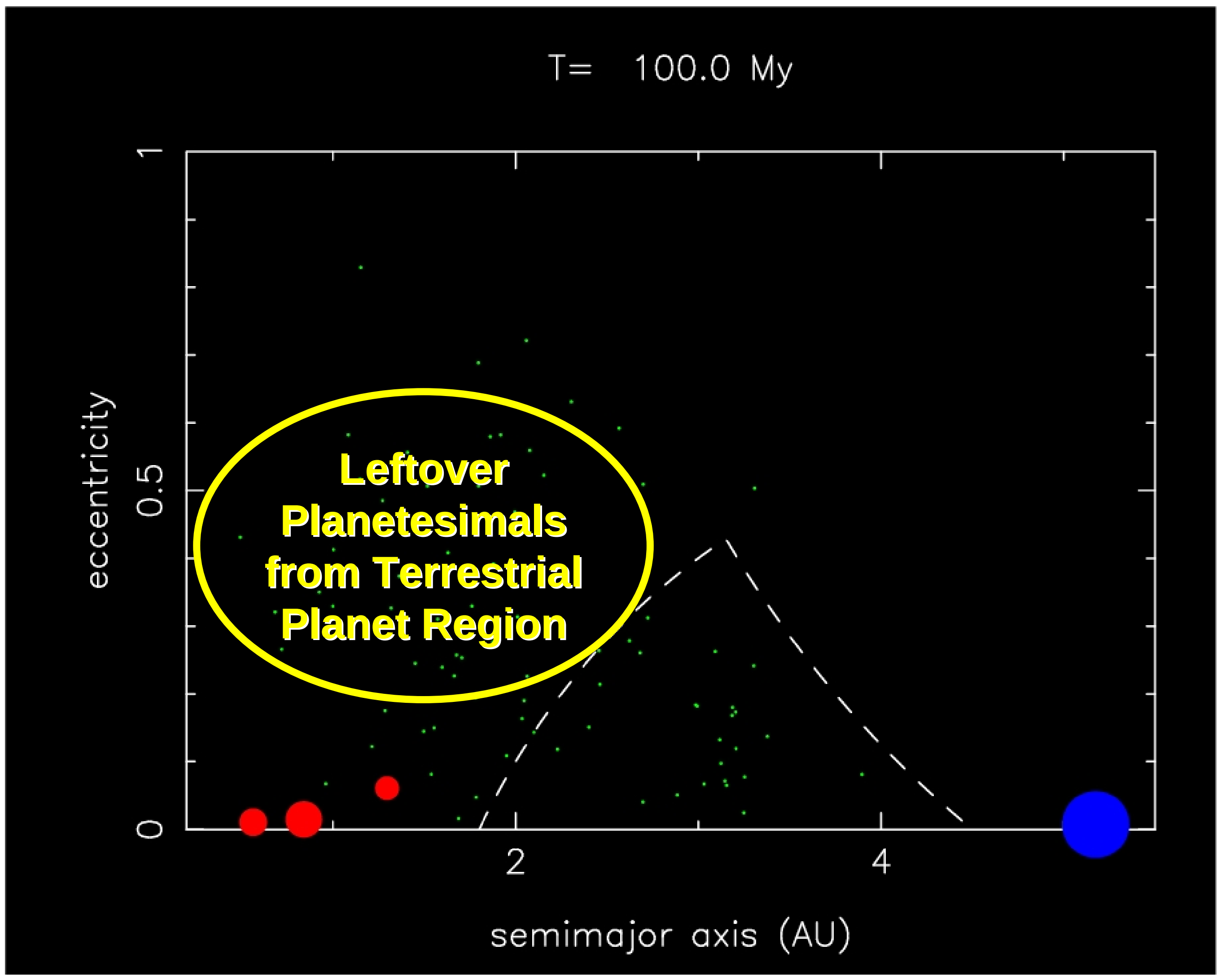
Planet Formation in the Inner Solar System



- Sea of bodies:
  - Moon to Mars-sized bodies
  - Smaller planetesimals.
- Collisions create planets!
- Some bodies reside at high eccentricities & inclinations.

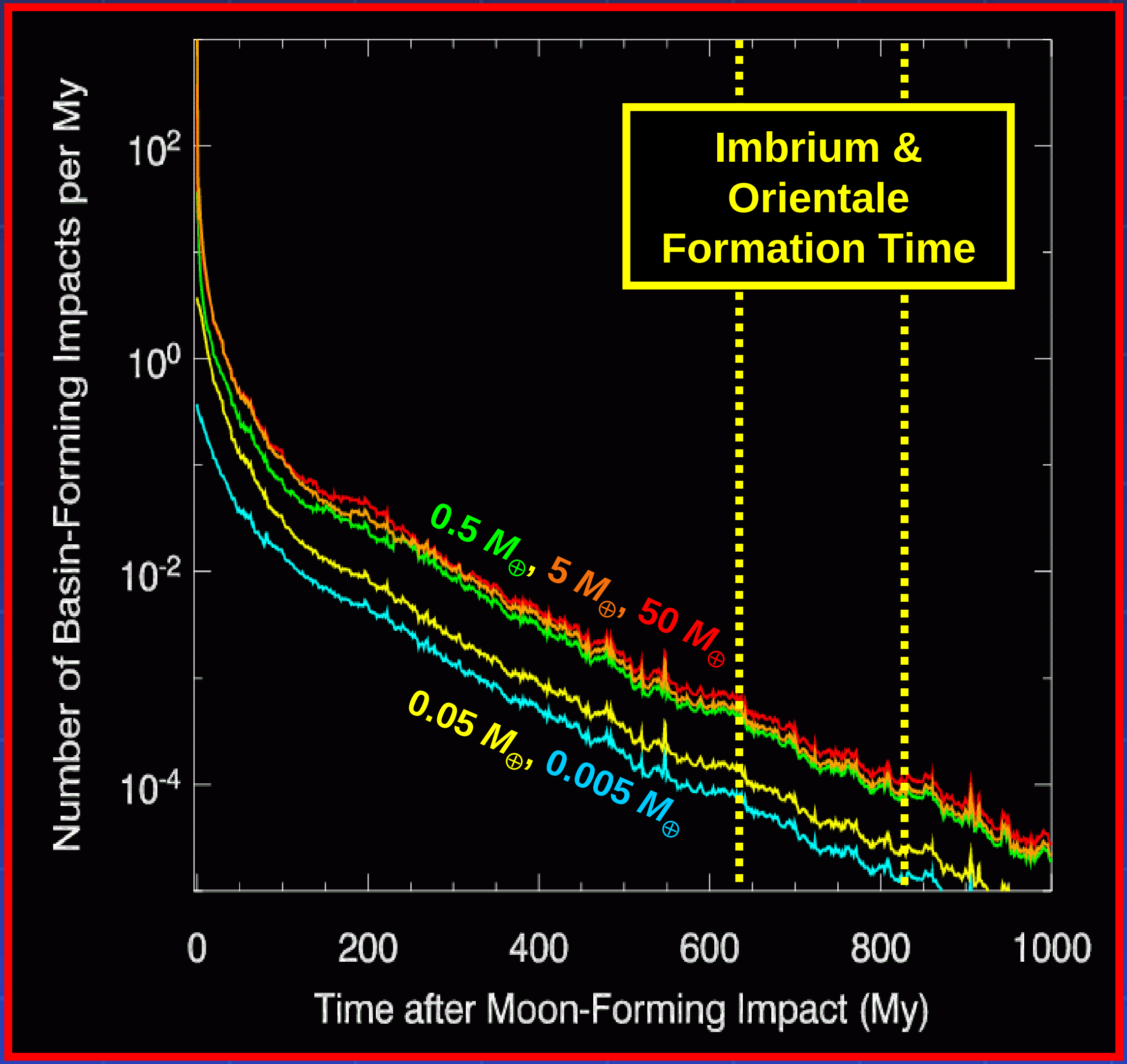
Sample references: O'Brien et al. (2006); Raymond et al. (2006)

Leftover Planetesimals from the Terrestrial Planet Region



Bottke et al. (2007)

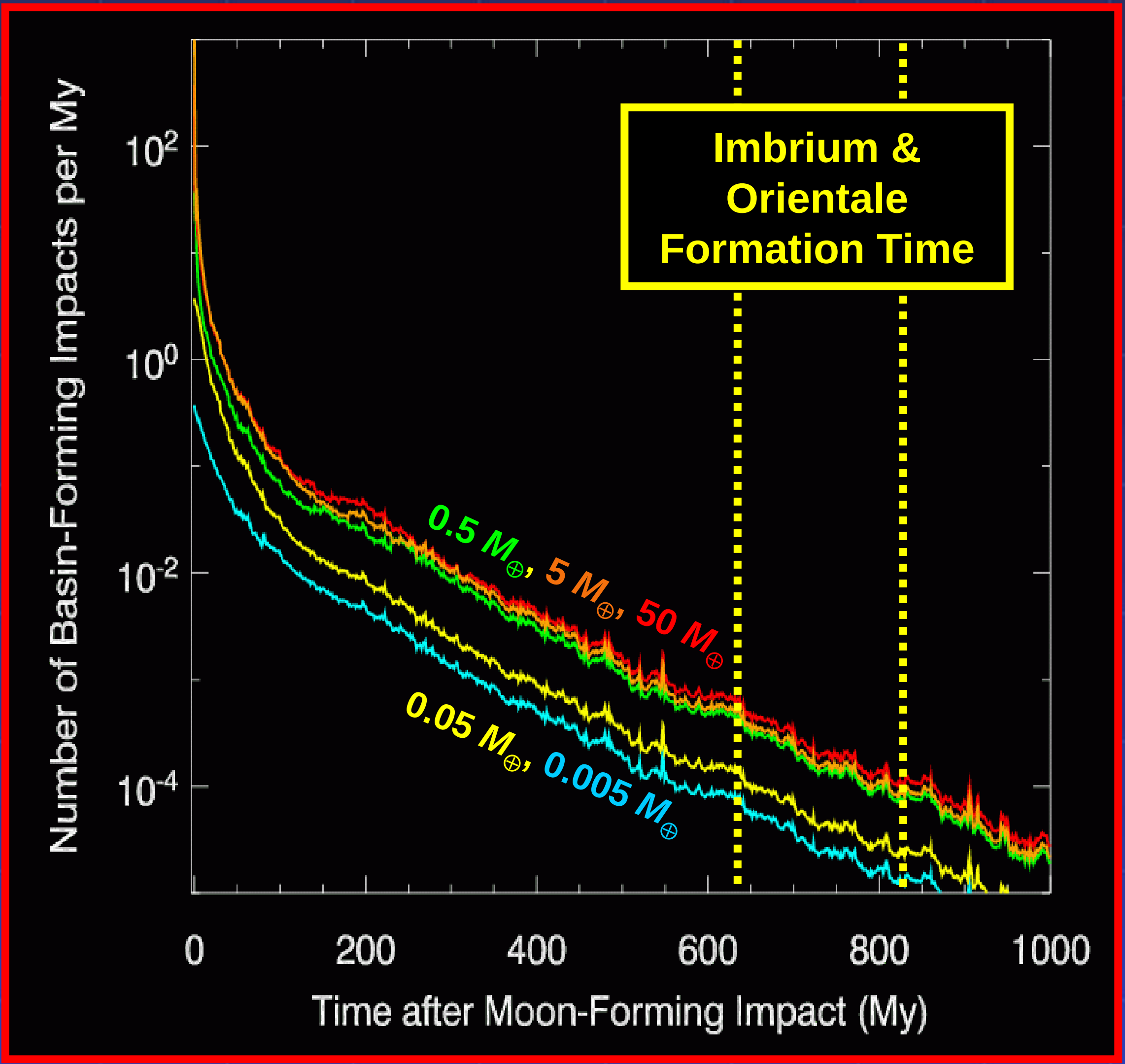
Lunar Impact Rate from Leftover Planetesimals



- **Model**
  - Dynamical evolution
  - Collisional evolution
  - Assumed population had a range of starting masses.
- **Goal:** Reproduce Imbrium and Orientale at their inferred ages.

Bottke et al. (2007)

Lunar Impact Rate from Leftover Planetesimals



- LHB population self-destructs!
- We find an impact rate of 10-4 basins / My × 200 My = 0.02 basins.
- We see 2 basins!

Bottke et al. (2007)

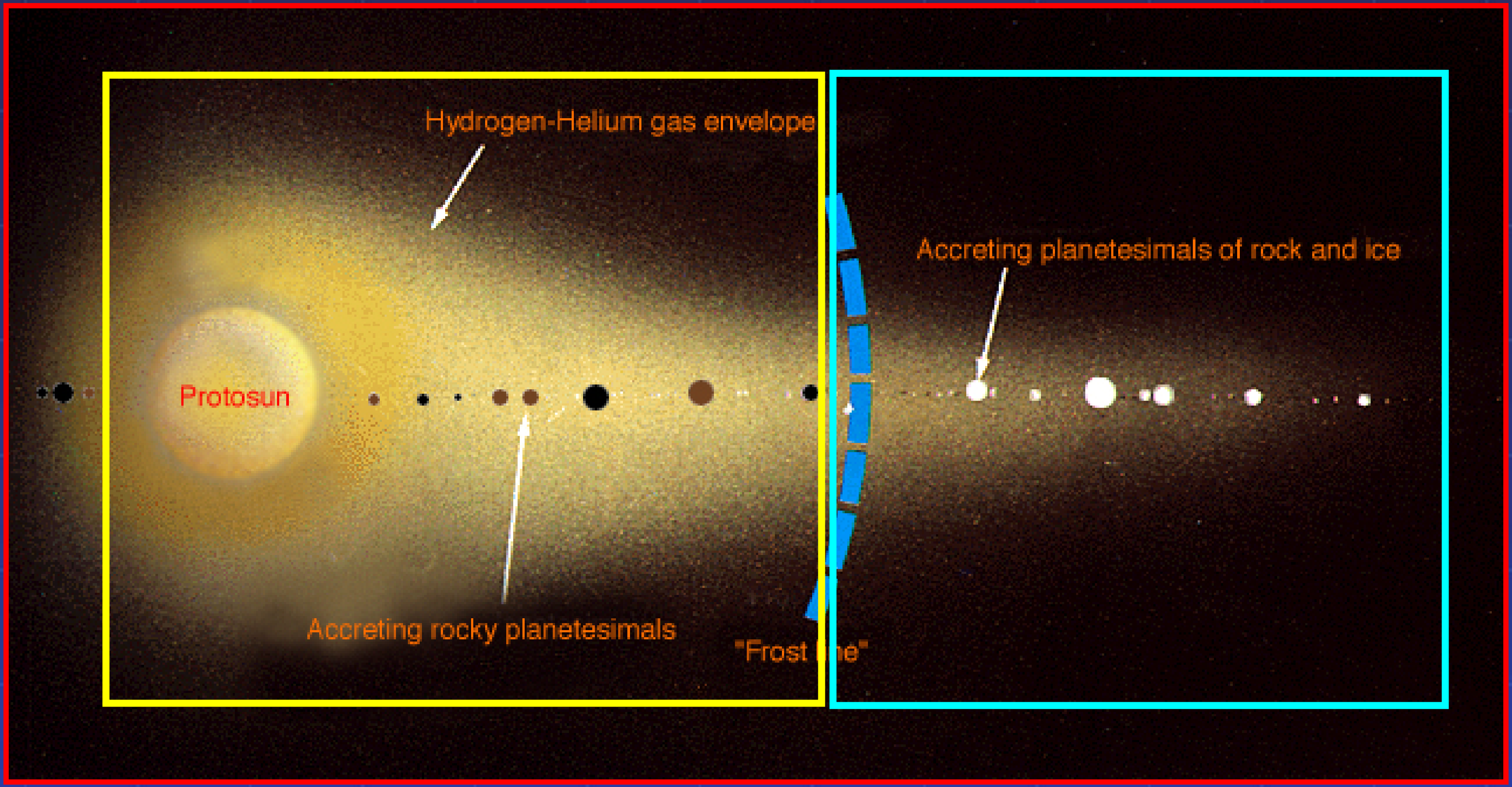
Model Conclusions (So Far…)

- The declining bombardment model cannot produce Imbrium and Orientale (as well as other young basins formed near 3.9 Ga).
- Existing lunar basin constraints may be more consistent with a terminal cataclysm.

The "Nice" Model of the Lunar Late Heavy Bombardment

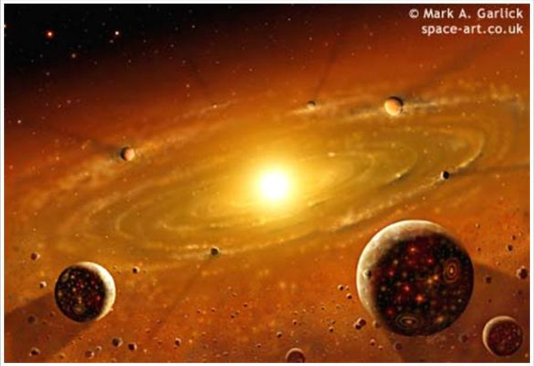
Much of this work is found in 3 *Nature* papers: Tsiganis et al. (2005); Morbidelli et al. (2005); Gomes et al. (2005)

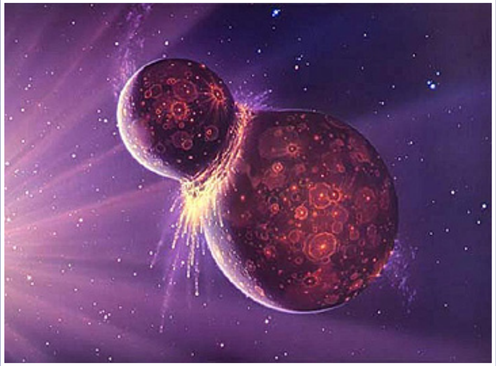
Planet Formation in the Outer Solar System



- Planet formation events in the outer solar system may have a critical effect on what happens to the Moon and other solar system bodies.

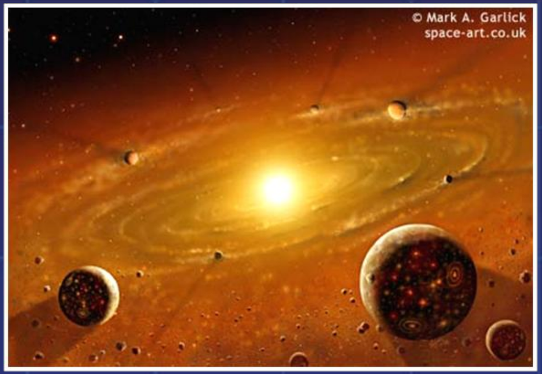
How Does One Create a "Terminal Cataclysm"?

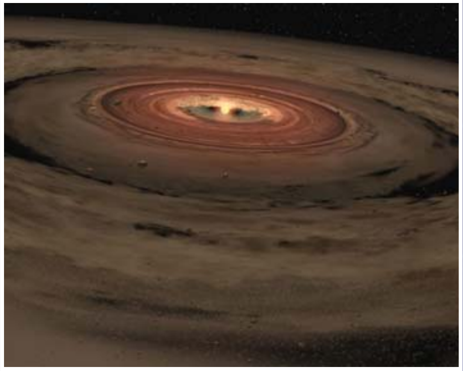


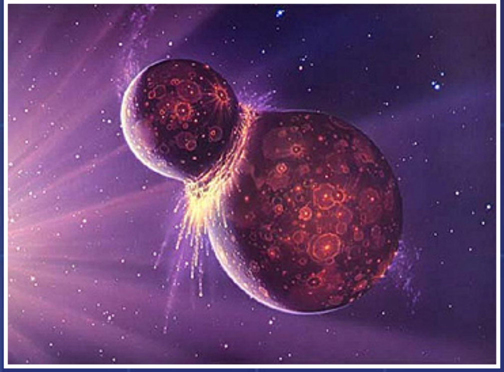


- If the declining bombardment model cannot work, many lunar basins formed in an impact spike ~3.9 Gy ago.
- To produce a system-wide cataclysm, we need to destabilize a large reservoir of asteroids and/or comets.
- The only known way to do this is modify the architecture of the solar system!

Related Planet Formation Problems?



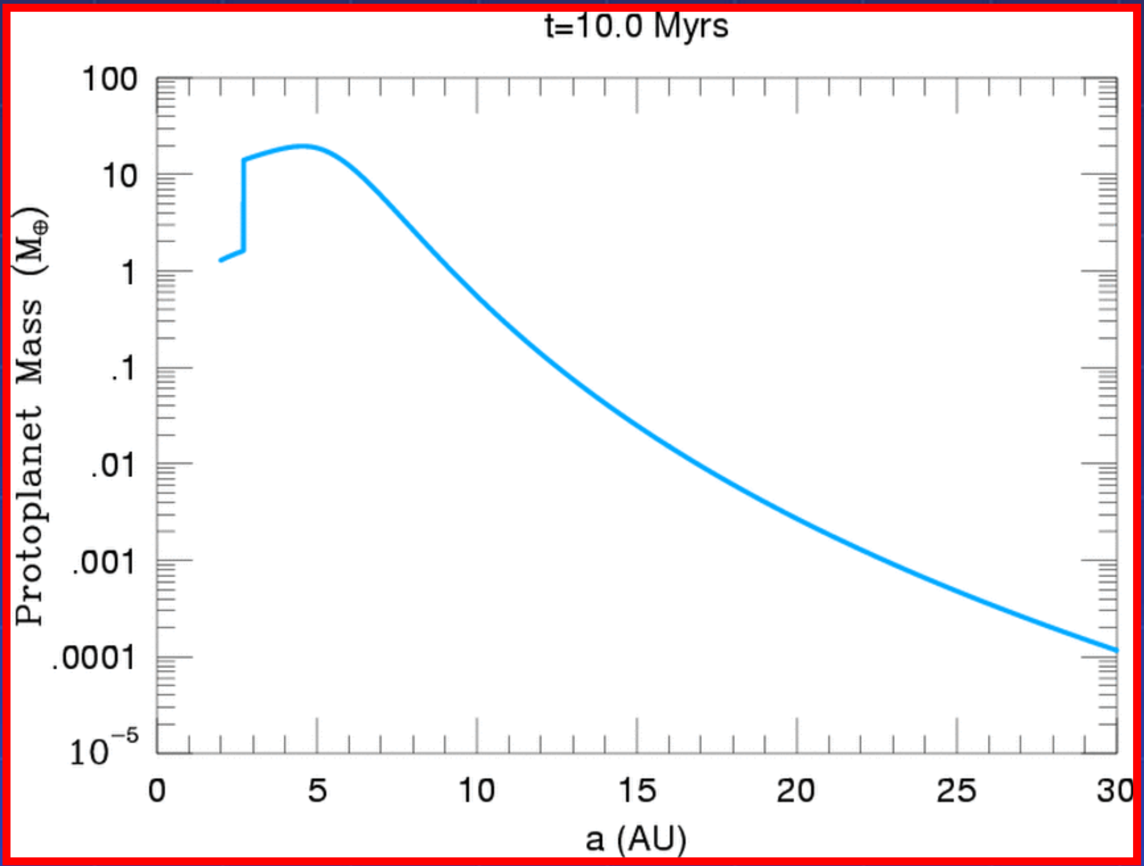




- **Problem 1:** Standard accretion models cannot make Uranus and Neptune in the age of the Solar System (if they formed near current locations).
- **Problem 2:** Jupiter and Saturn have non-trivial eccentricities and inclinations. Gas accretion should reduce these values to zero!
- **Problem 3:** Current Kuiper belt only contains ~0.1 Earth masses of material, too small to make Pluto et al.

Making the Jovian Planets

Formation of Planetary Embryos



Thommes et al. (1999)

- To speed up planet formation, assume Jovian planet cores formed closer to Sun!
- Objects then need to move to current locations.

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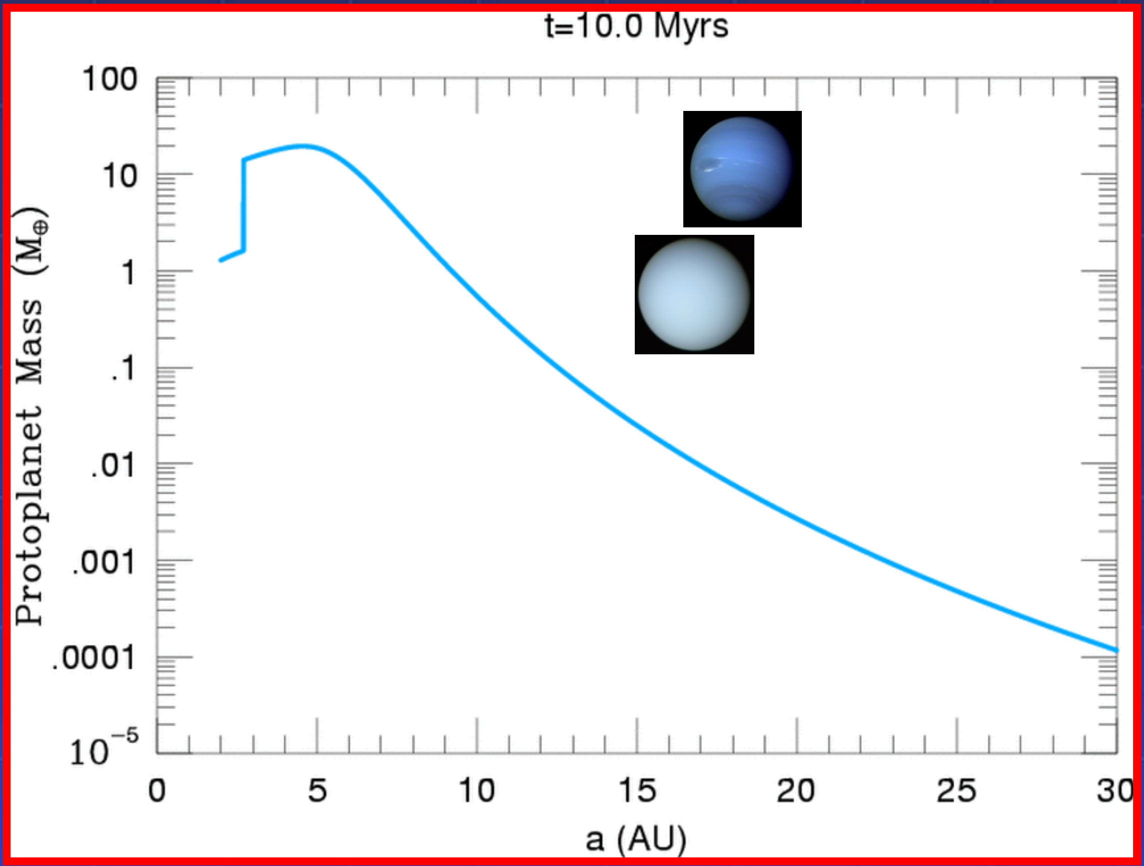

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New Solar System Formation Scenario

- **Old view.** **Gas giants/comets formed near present locations (5-30 AU) and reached current orbits ~4.5 Gy ago.**

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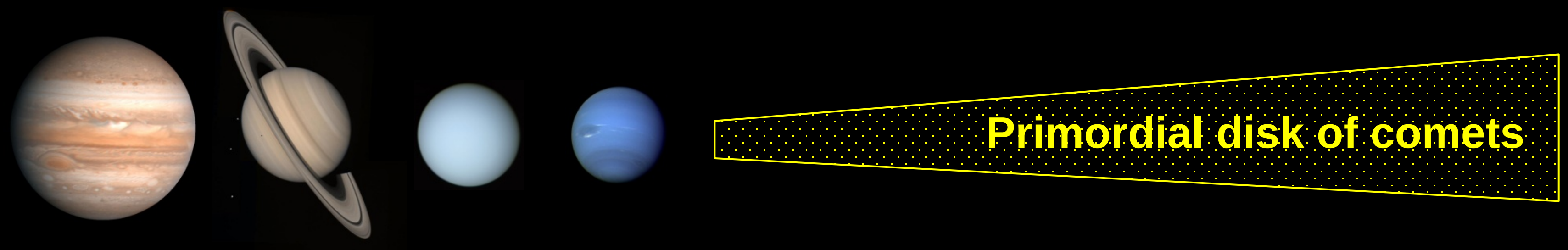

- **New view.** Gas giants formed in more compact formation between 5 to ~20 AU. Massive comet population existed out to ~30 AU. Fernandez and Ip (1986); Malholtra (1995); Thommes et al. (1999; 2003)

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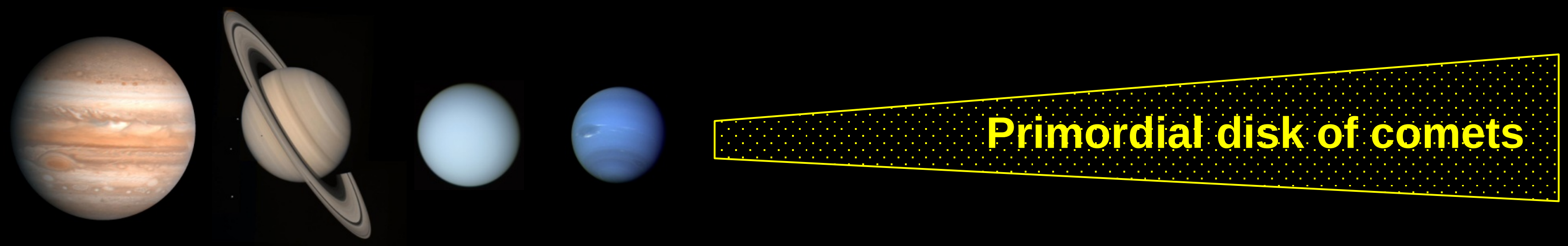

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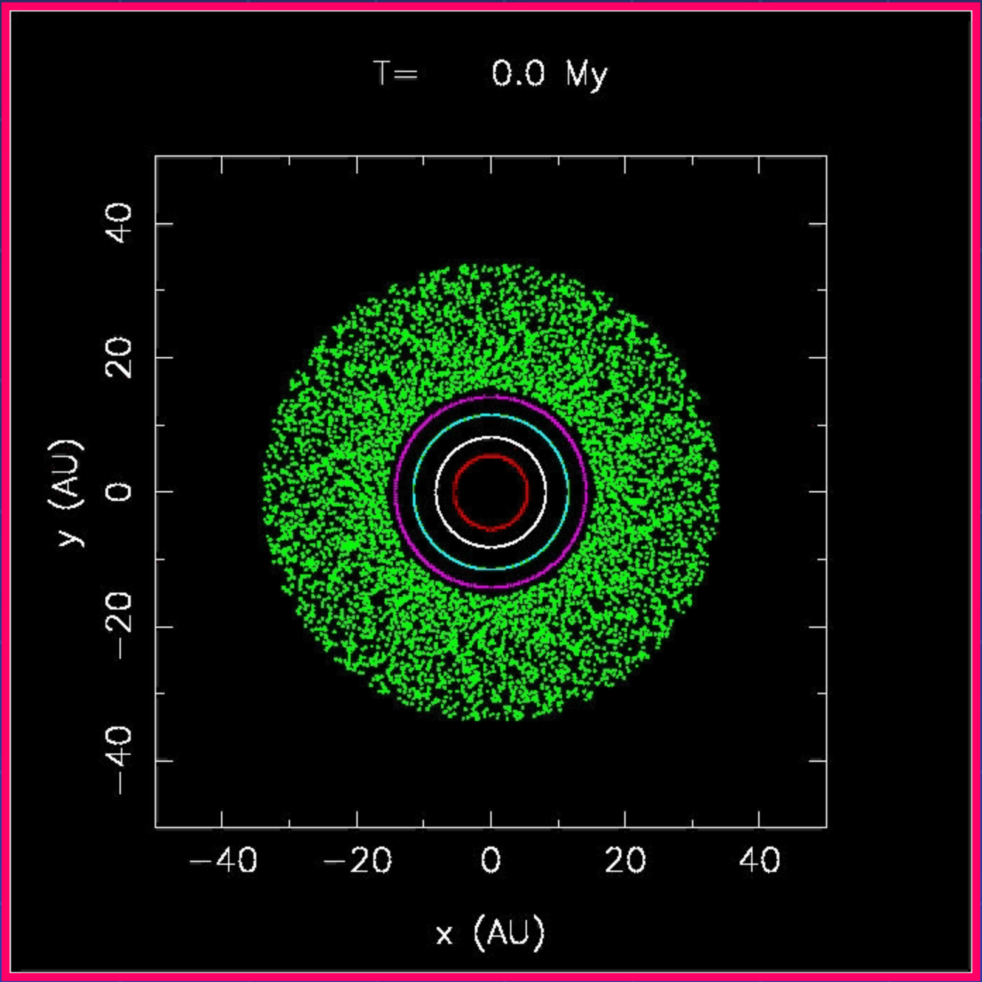
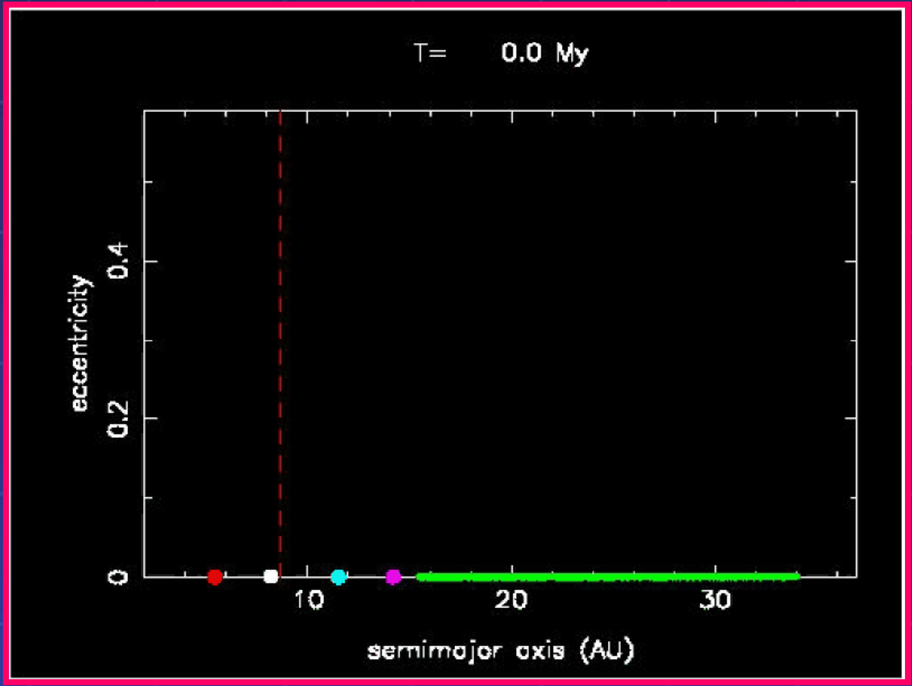
  - Best developed and most successful scenario of this is the Nice Model. Tsiganis et al. (2005)

Destabilizing the Outer Solar System

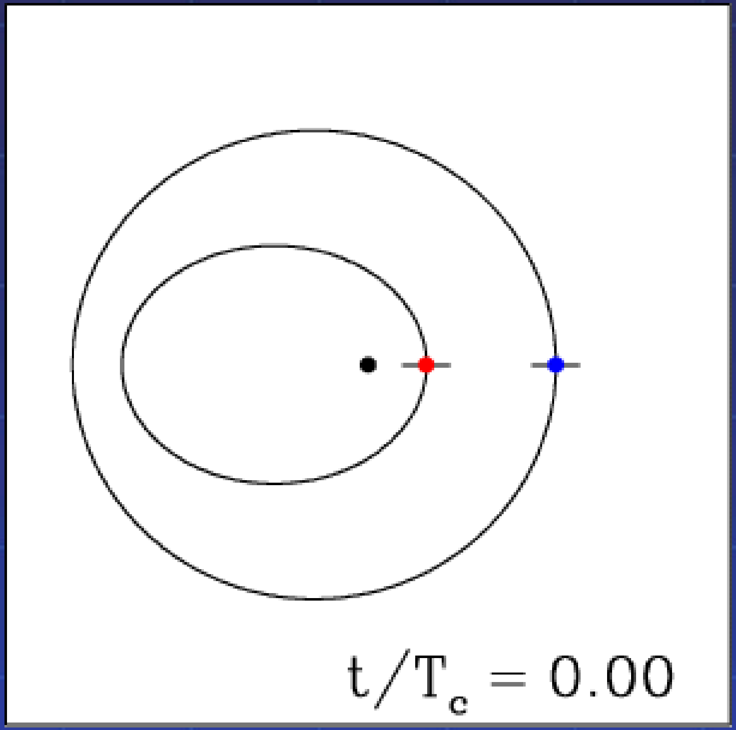


Tsiganis et al. (2005); Morbidelli et al. (2005); Gomes et al. (2005)



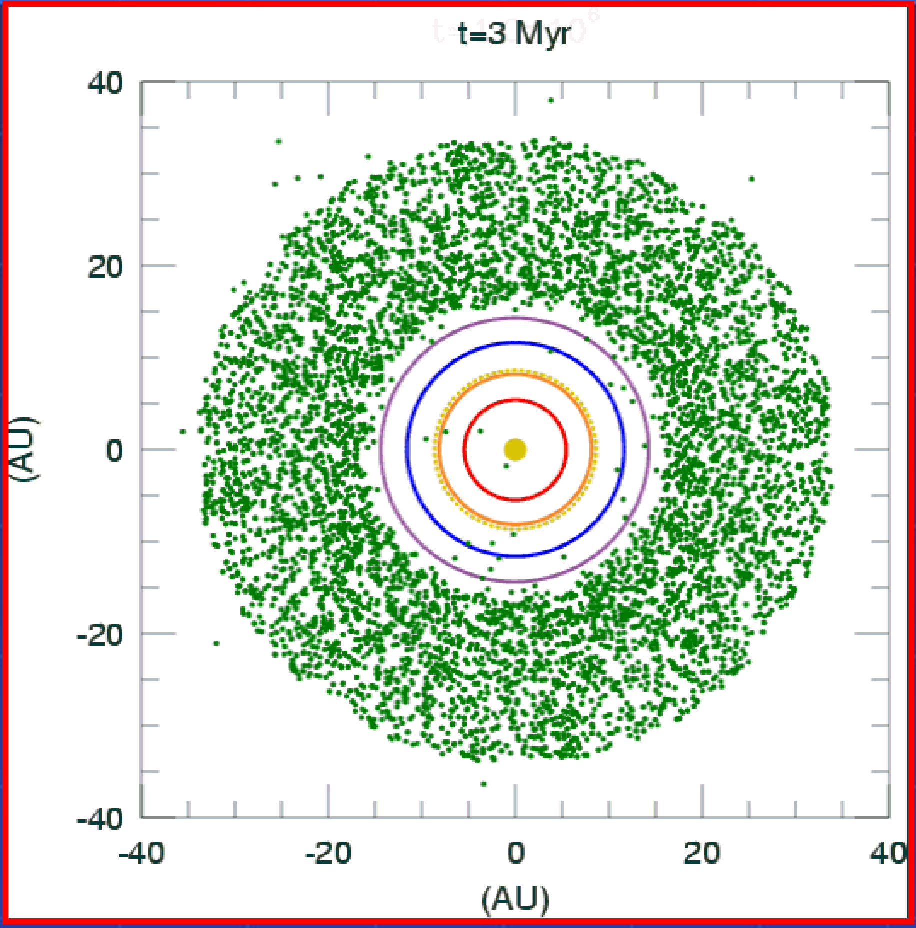
Watch what happens after 850 My!

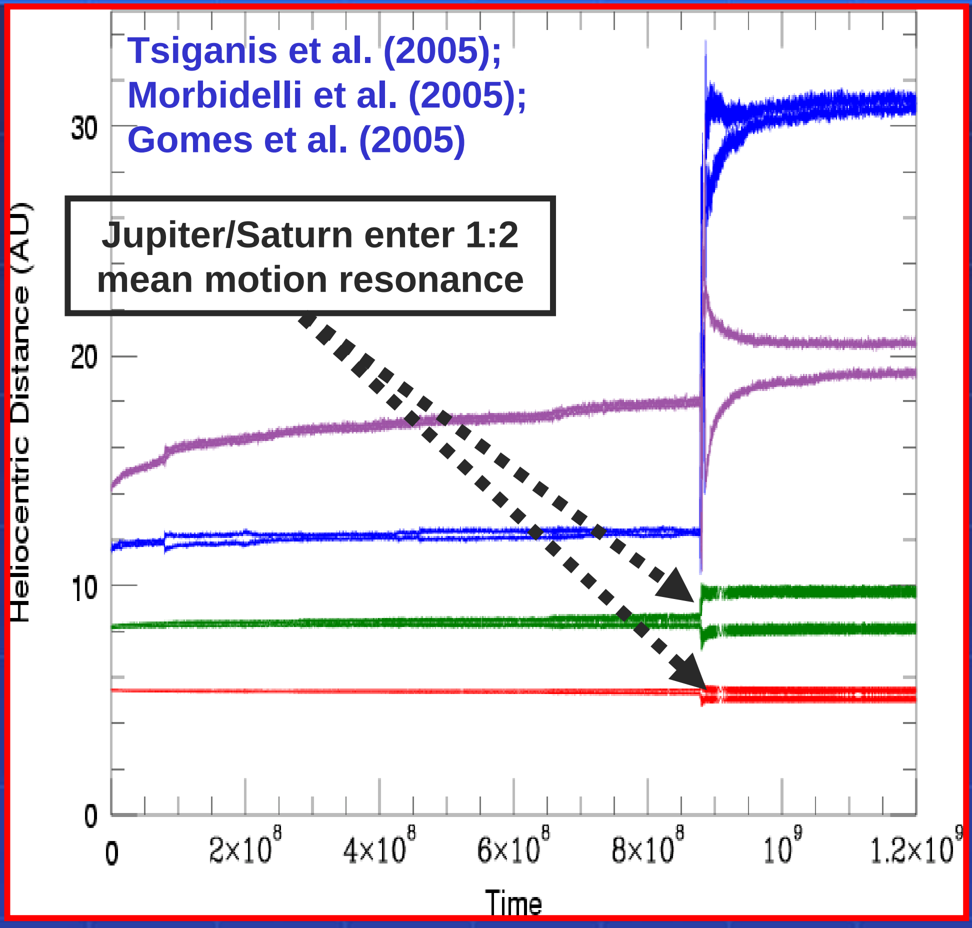
Mean Motion Resonances



- The ratio of the rate of motions of two bodies around the Sun (i.e., 1 / revolution period) is a simple fraction.
- This is an example of the 2:1 mean motion resonance

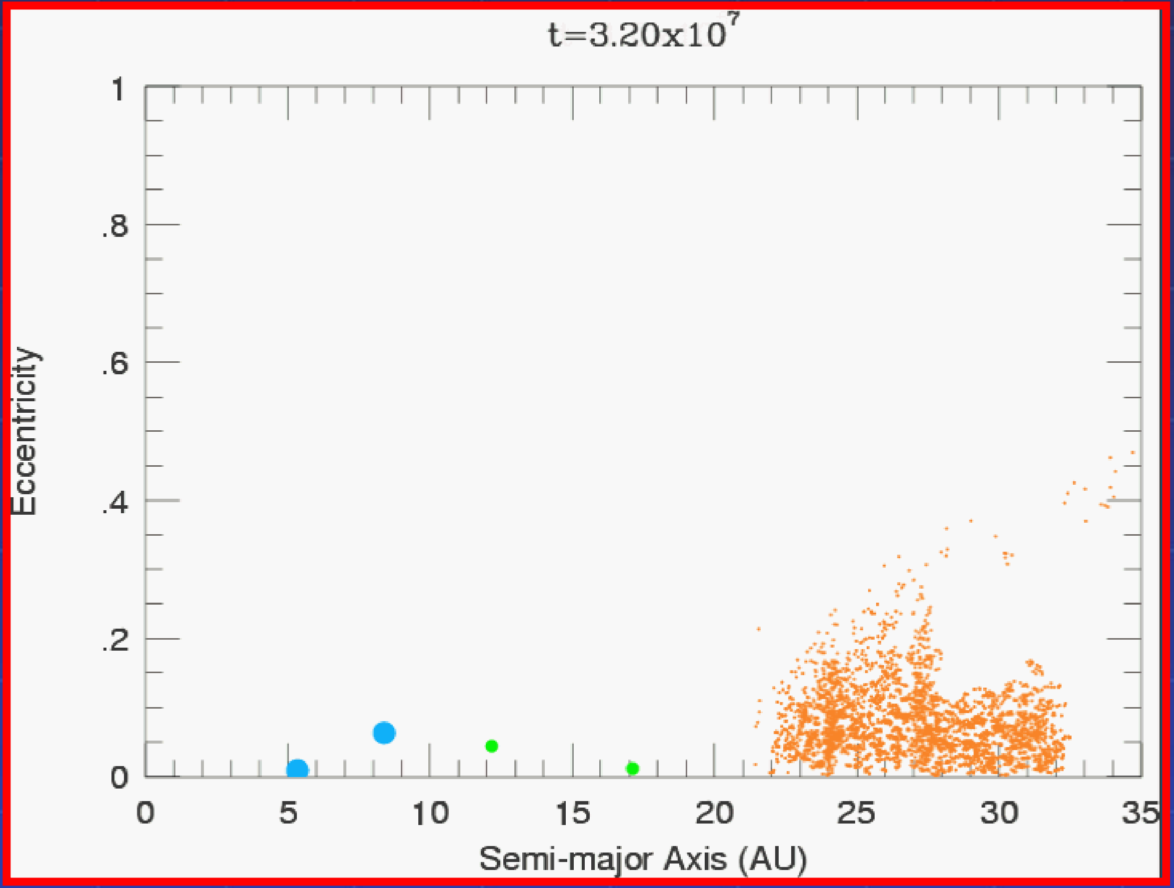
Slowly Depleting… and Then Destroying the Primordial Comet Disk





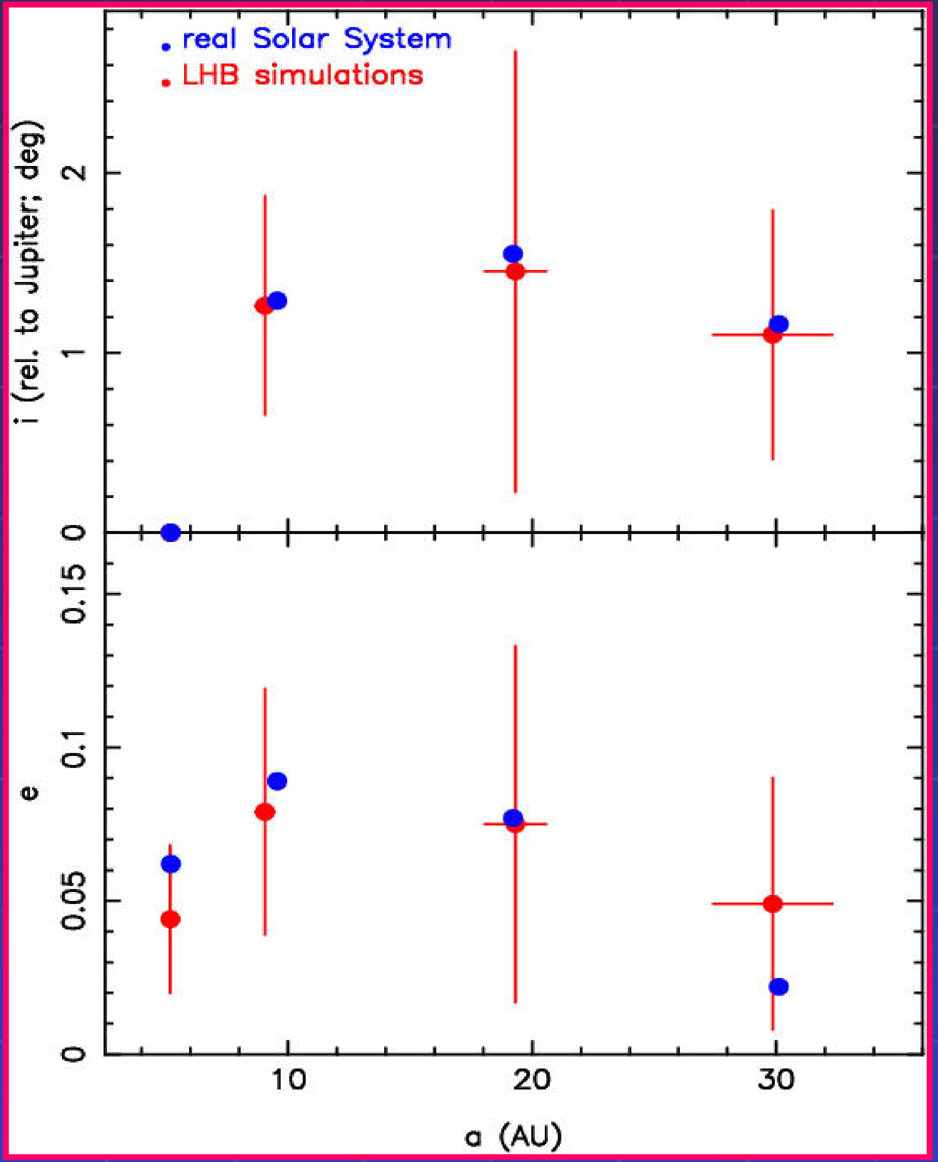
- Gravitational interactions with planetesimals cause migration. In this simulation, at 850 My, Jupiter/Saturn enter 1:2 MMR.
- This pushes Uranus and Neptune into comet disk.

Uranus and Neptune May Switch Positions



- A “close up” view of the instability.
- Uranus/Neptune:
  - Go unstable and scatter off Saturn.
  - Migrate through disk.
- Dynamical fraction causes orbits to “cool down”.

Orbits of Giant Planets

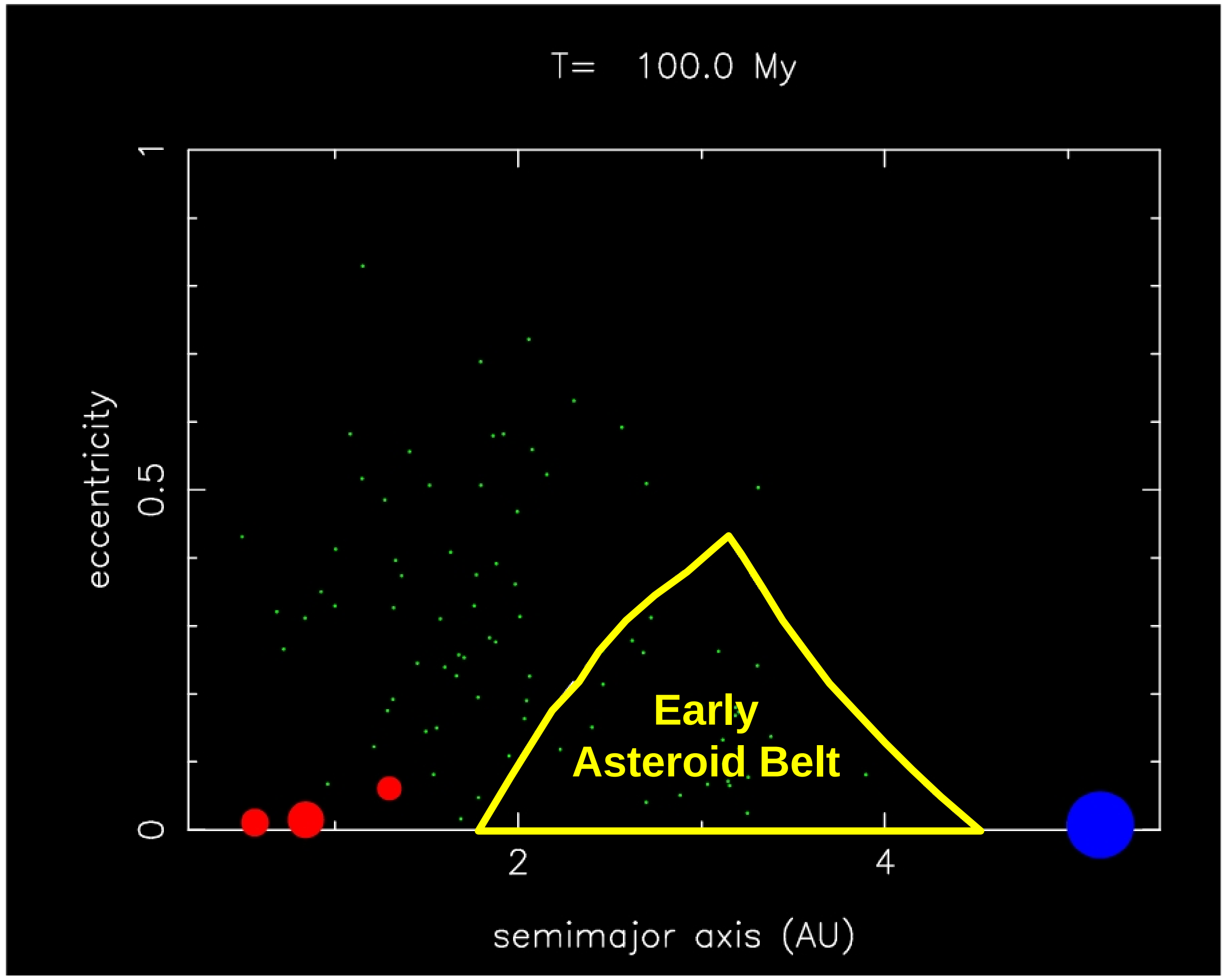


- Nice model reproduces orbital elements of giant planets.
- Model sensitive to one parameter: disk mass.
- A ~35 Earth mass disk produces long delay and orbits of planets.
- Condition: The disk must end at 30-35 AU (or Neptune would continue to migrate)

Other Applications

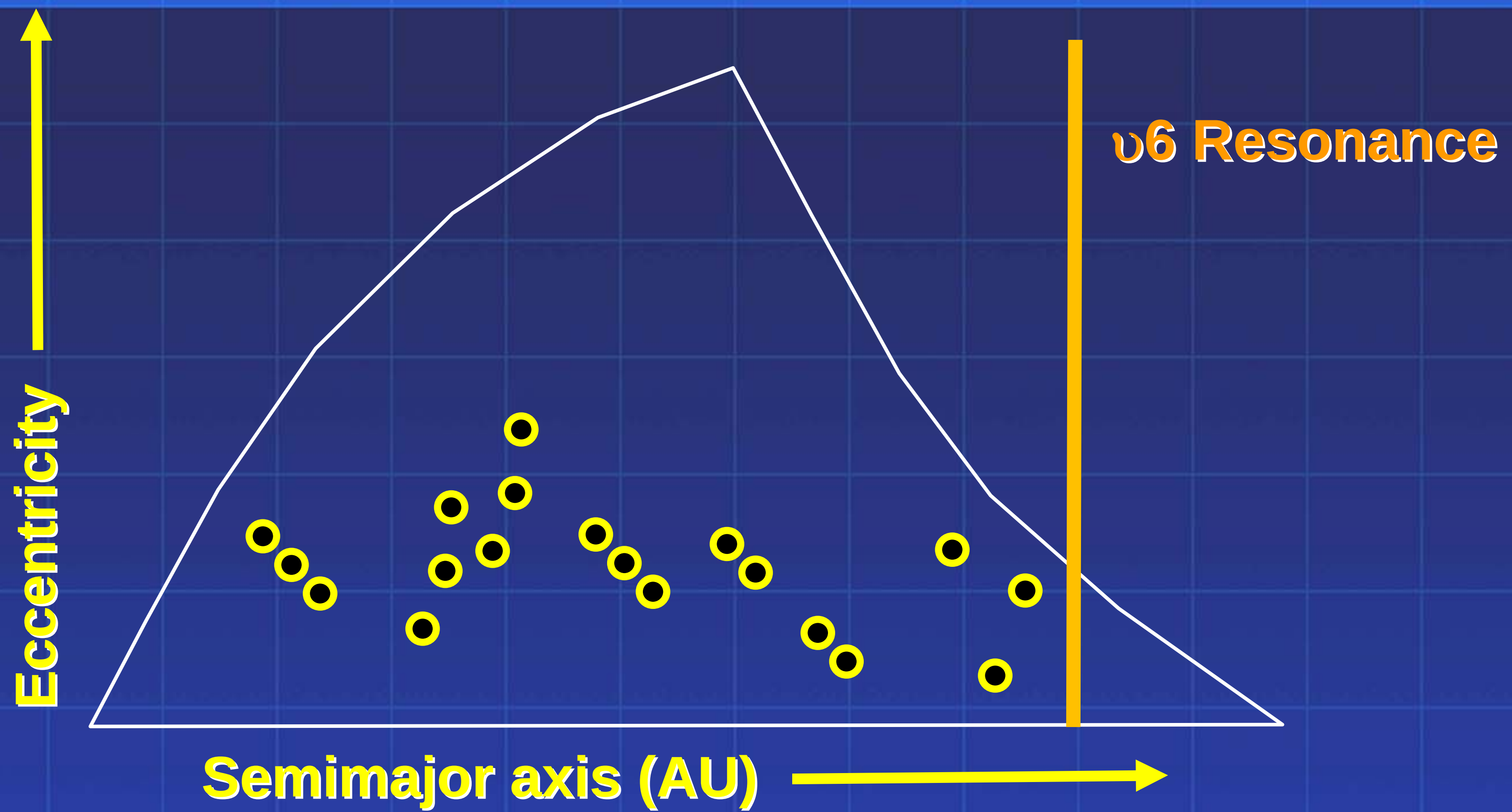
- So far, the Nice model can also explain:
  - The approximate mass and orbital distribution of the Trojan asteroids and Kuiper belt objects.
  - The surprising similarities in size distributions between these populations.
  - The presence of dormant comet-like objects in the outer main belt and Hilda populations.
  - All sorts of fun things related to the irregular satellites.

What Happens to the Asteroid Belt?



O'Brien et al. (2006)

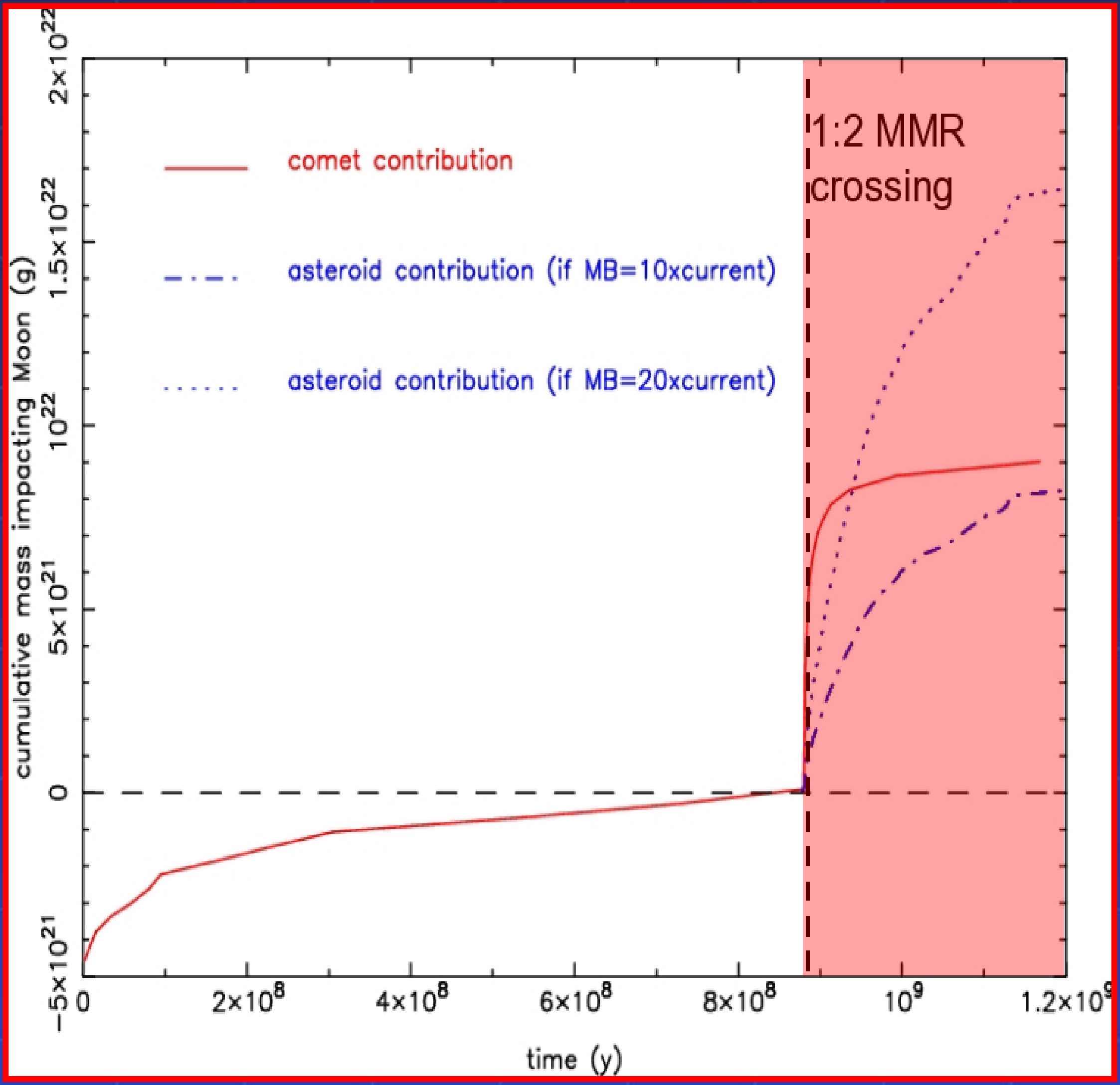
Effects of Sweeping υ6 Resonance



- Planet migration excites (e, i) of main belt asteroids.
- Approximately ~50-90% of existing main belt is ejected!

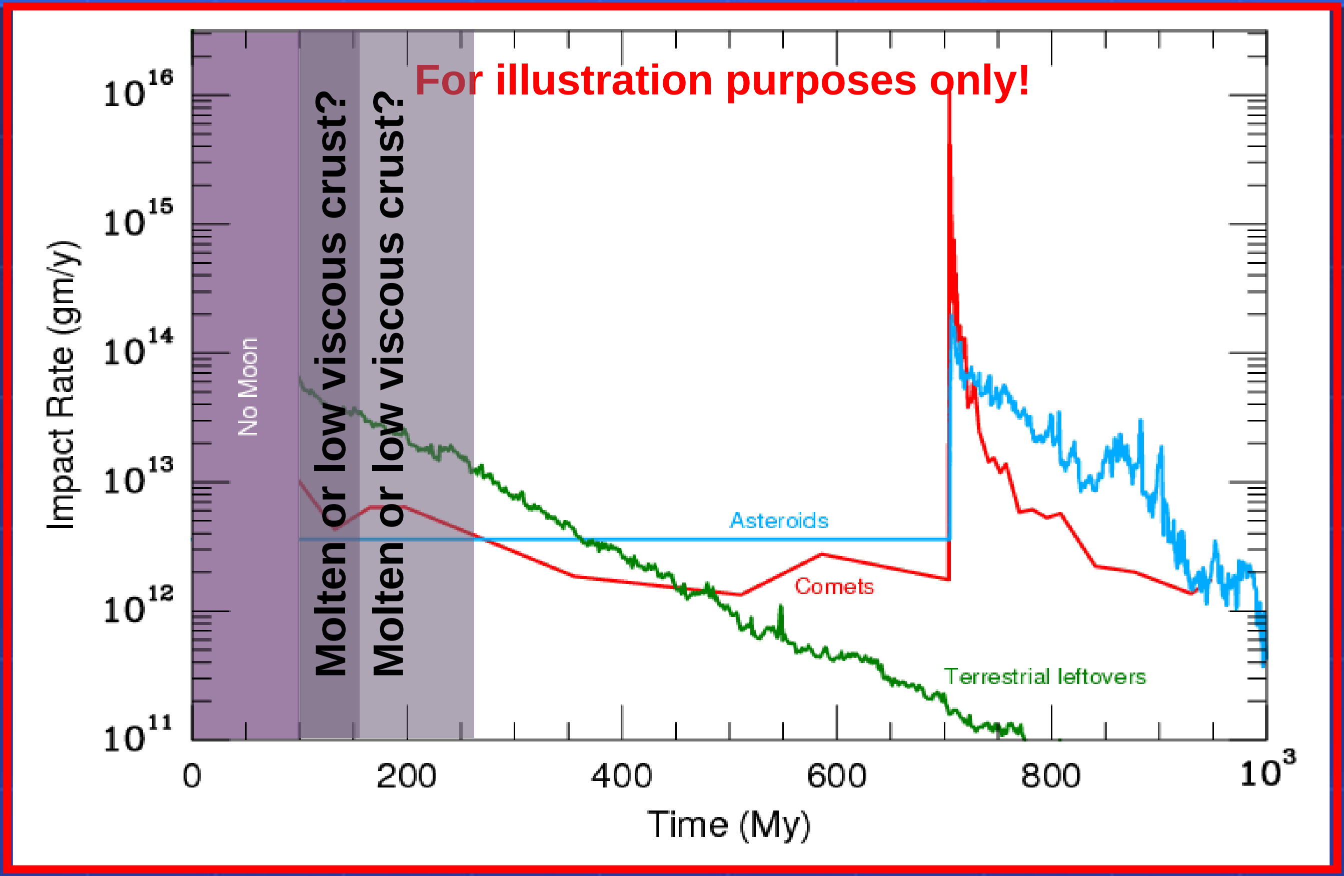
Levison et al. (2001); Gomes et al. (2005); Minton and Malhotra (2009)

The Terminal Cataclysm on the Moon



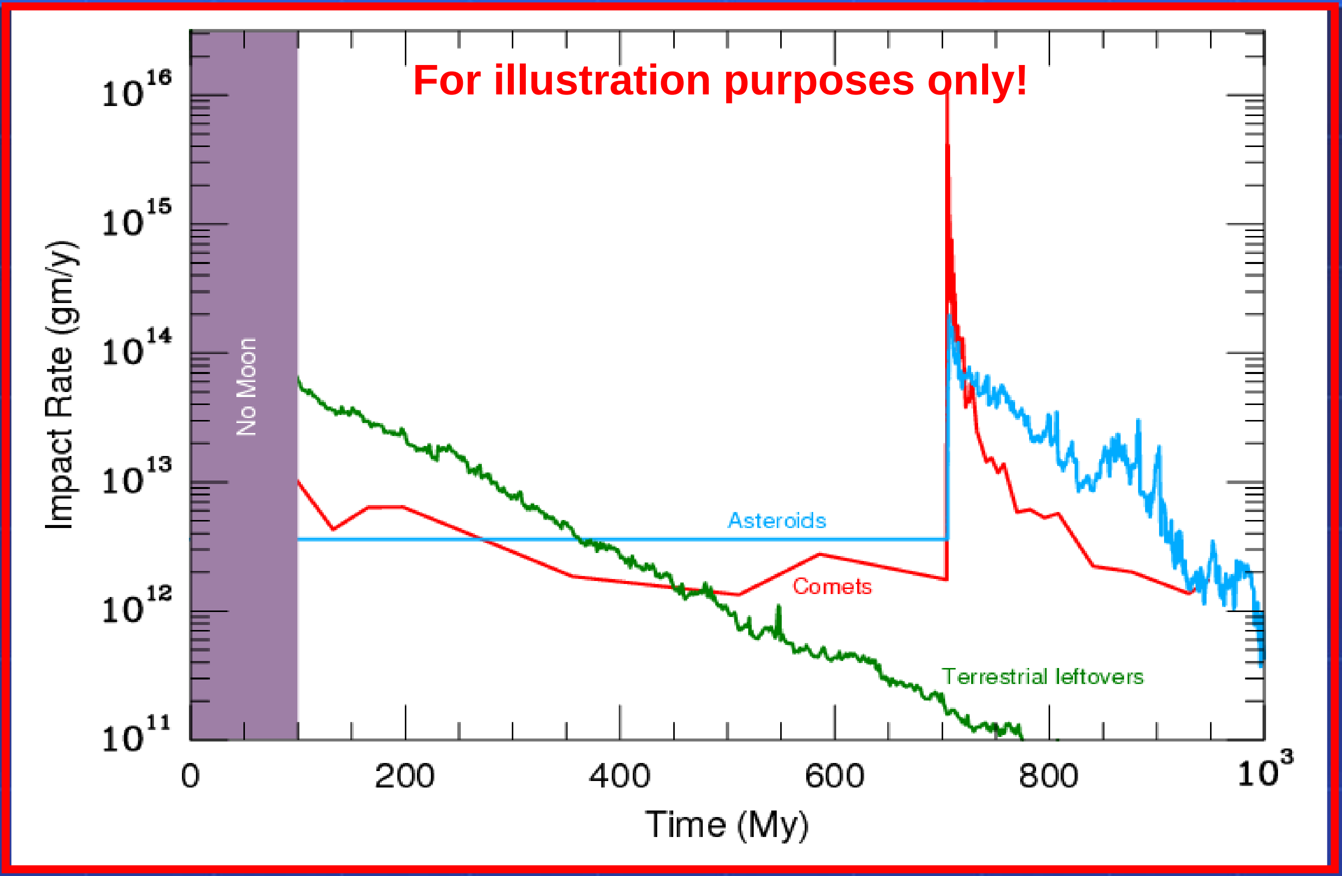
- Comets strike the Moon first; asteroids last.
- Secular resonances sweeping causes asteroid belt to lose ~90% of its pop.
- The Moon accretes 6×10^{21} g, consistent with mass flux estimates from basins.

The Early Lunar Impact Rate



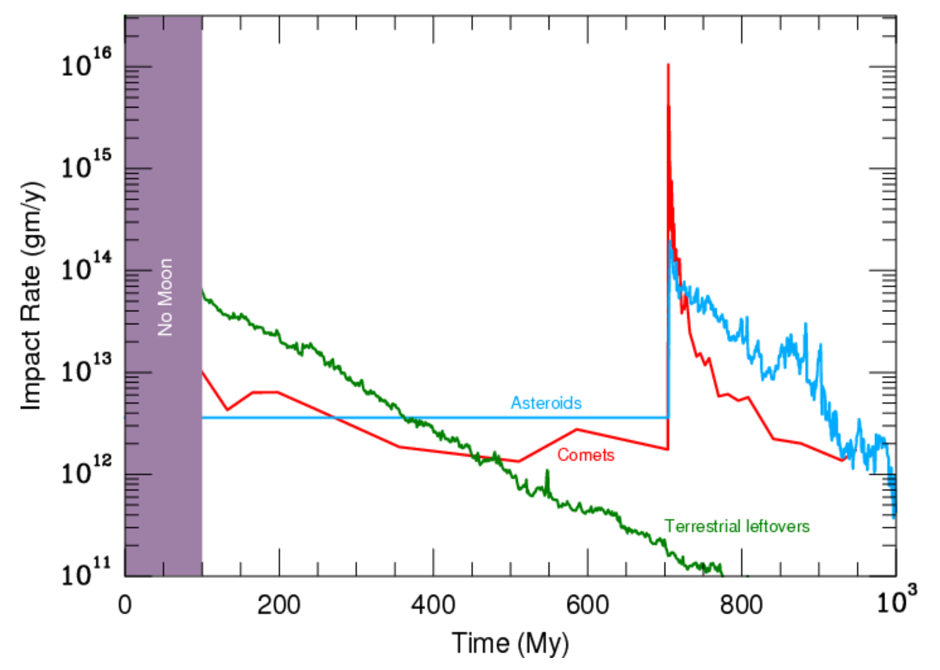
- Overall, we expect a roughly **bimodal distribution** of lunar basins (i.e., perhaps everybody wins…)
- **NOTE!** We really do not know these numbers very well yet.

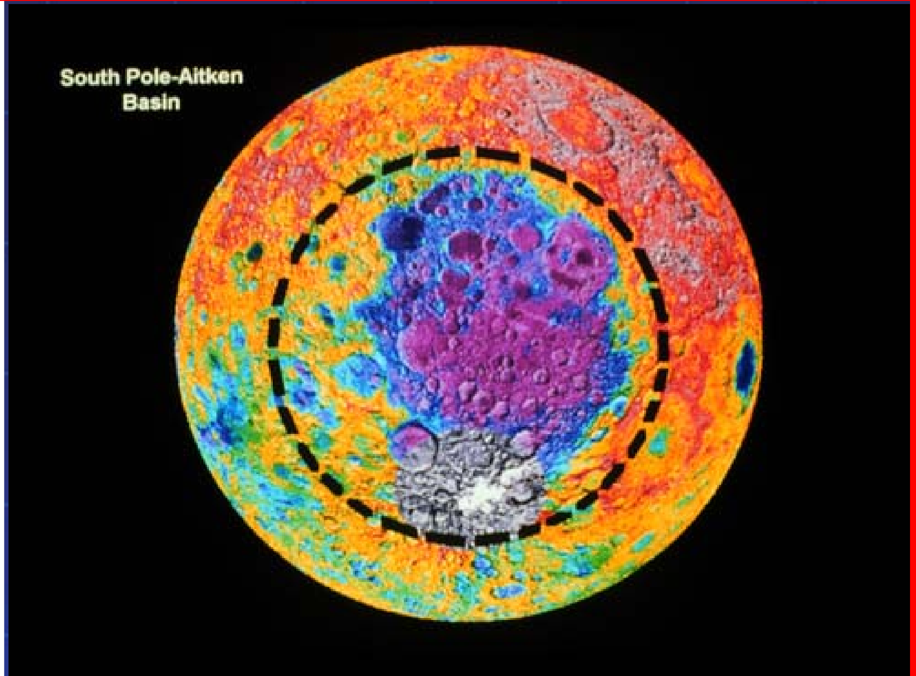
The Early Lunar Impact Rate



- Early basins probably come from leftover planetesimals.
- Very late basins probably come from comets/asteroids liberated by events started in the outer solar system.

Possible Interpretations for the Age of South Pole-Aitken Basin





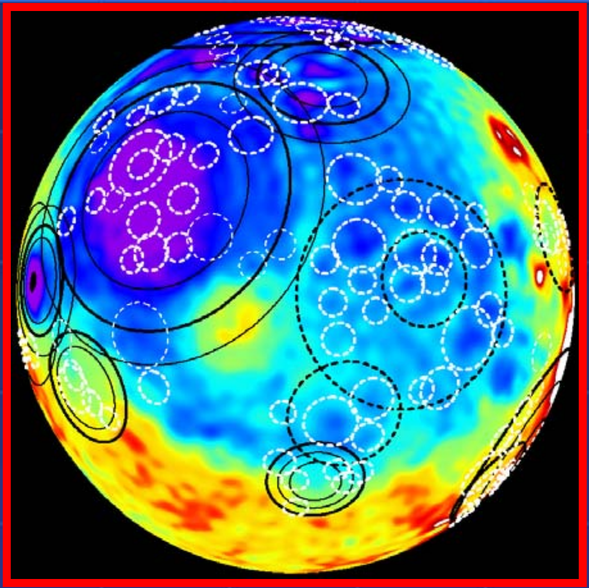
- 3.8-4.0 Ga: SPA likely formed during a terminal cataclysm.
- 4.2-4.4 Ga: Source of SPA is difficult to interpret (for now).
- 4.4-4.5 Ga: SPA likely a leftover planetesimal from terrestrial planet formation.

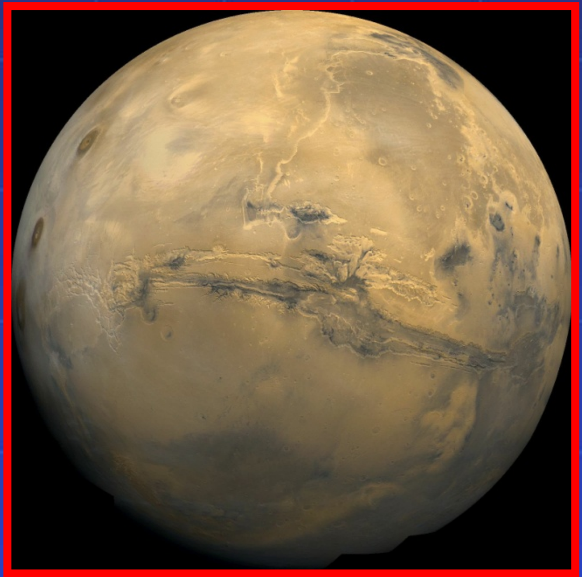
Why Go Back to the Moon?

- Lunar samples from the right places may tell us about the very last stages of planet formation!

Extra slides from this point on…

Implications for Mars





- Comet bombardment may have delivered water to Mars ~3.8 Ga
- Like the Moon, few Martian surfaces may older than ~3.8 Gy old!
  - Ancient surfaces may have been eliminated.
  - Rocks older than 3.8 Gy can exist and are not a surprise.
- The earliest Martian events (Early Noachian) may have took place over a much more compressed timescale than previously thought.

Conclusions

- **The Moon is the best and most assessable place in the solar system to investigate:**
  - The nature of the primordial Earth
  - The last stages of planet formation
  - The possible reorganization of the solar system ~3.9 Ga (that potentially affected all solar system bodies!)

Marius Hills; Kaguya Mission