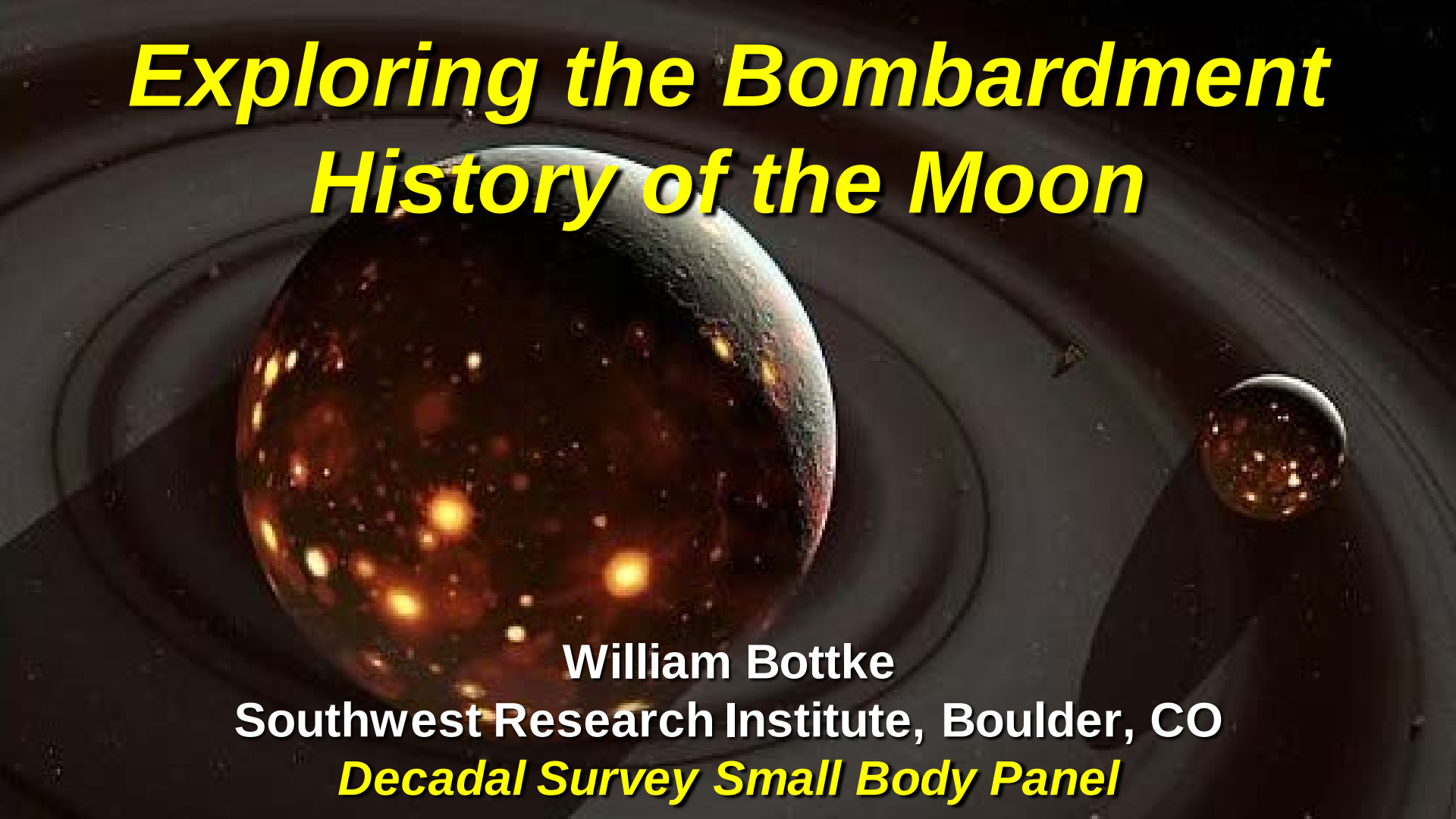




# ***Exploring the Bombardment History of the Moon***

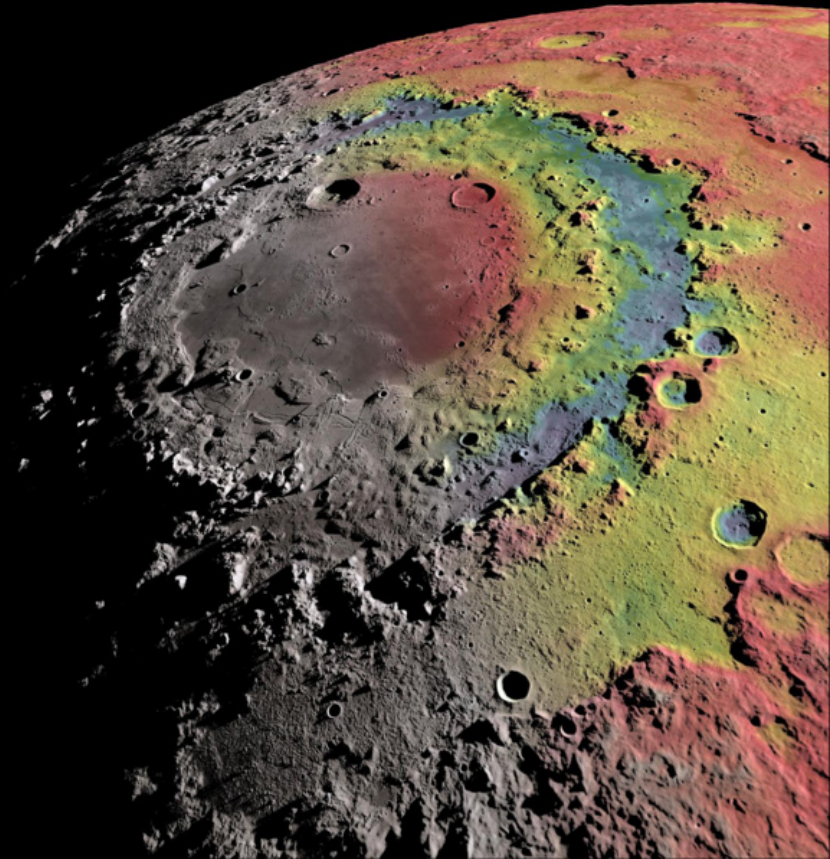
**William Bottke**

**Southwest Research Institute, Boulder, CO**

***Decadal Survey Small Body Panel***

# Understanding Lunar Bombardment: A Critical Decadal Survey Goal

- The ancient lunar surface may give us insights into:
  - Giant planet migration
  - Last stages of planet formation
  - The unknown nature of the primordial Earth!
  - Early lunar evolution
  - ... and much much more!



# **Context for Lunar Bombardment:** **A Brief History of Planet Formation** **and Giant Planet Migration**

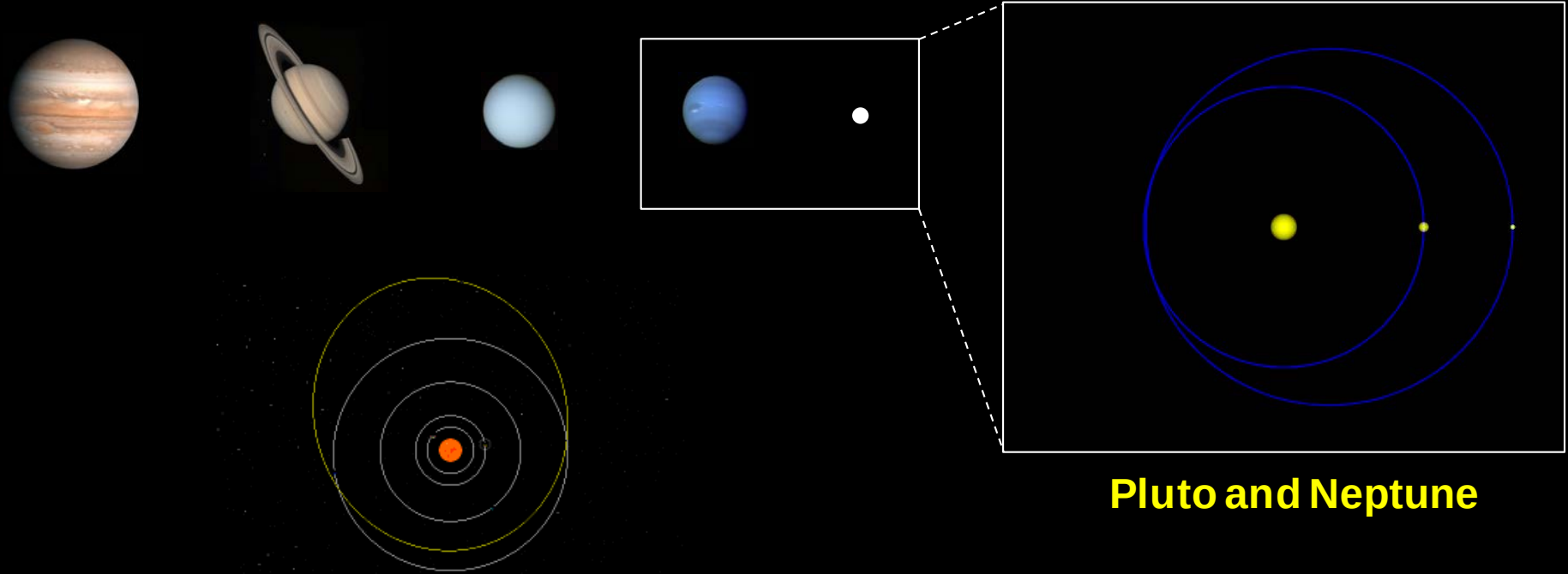


# Giant Planet Formation: Pre-1990's View



- Outer planets formed near present locations.

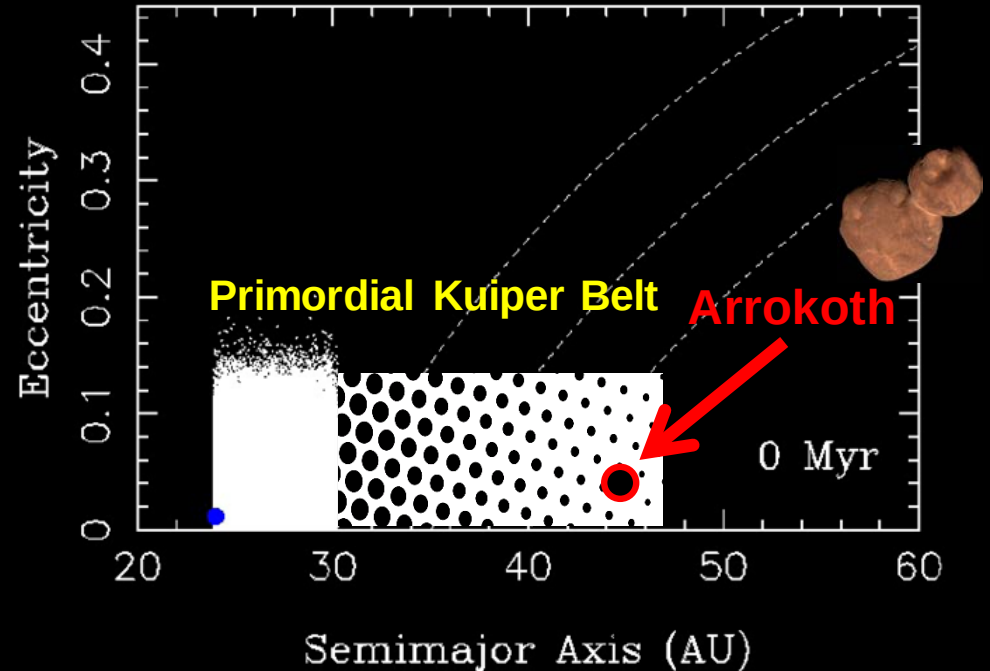
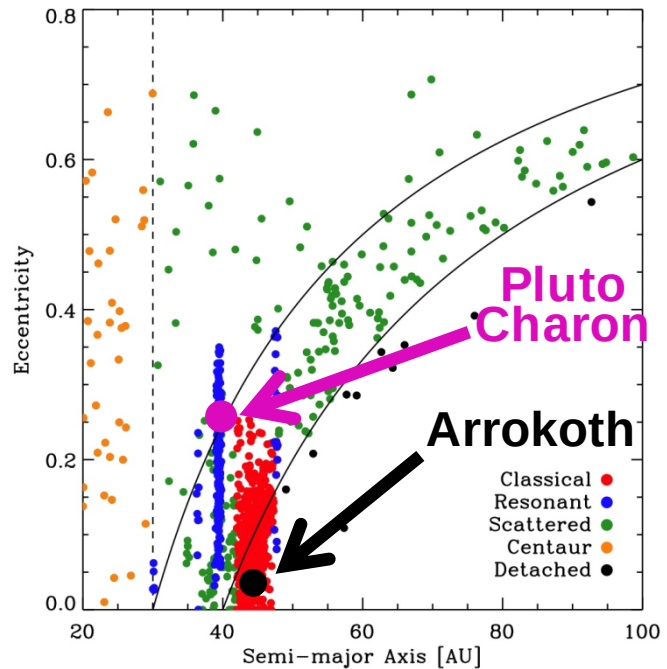
# Giant Planet Formation: Pre-1990's View



Pluto and Neptune

- Outer planets formed near present locations.
- Pluto in Neptune's 2:3 resonance at high inclination. Why?

# Kuiper Belt Provides Proof of Migration

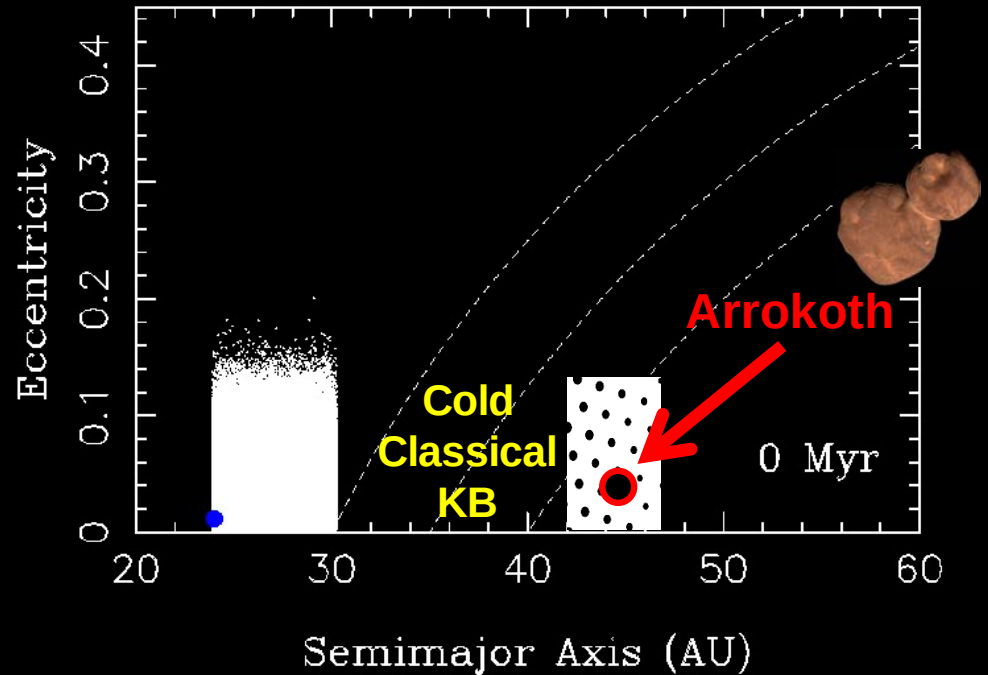
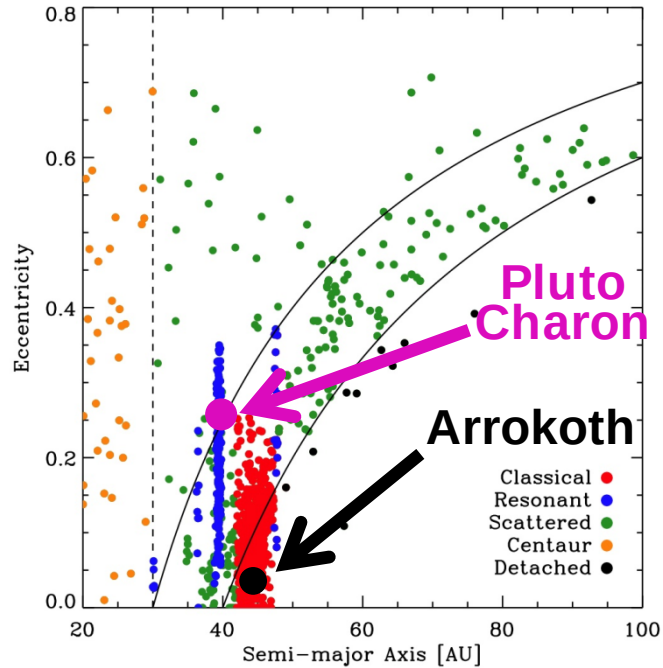


- Neptune migration needed to capture objects in resonance.
- To get right Kuiper Belt structure, need disk 1000× larger.

Sample references: Malhotra (1993); Nesvorny and Vokrouhlicky (2017)



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A dramatic space scene featuring a bright, glowing star in the upper right corner, casting a warm orange and yellow light across the scene. A comet with a long, bright tail streaks across the upper right. In the lower left, a large, dark, spherical planet is visible. The background is filled with numerous small, dark rocks or asteroids of various sizes, scattered throughout the space. The overall color palette is dominated by the warm tones of the star and the cool blues and purples of the distant space.

# **If: Neptune Migrated** **Then: Different Giant Planet Orbits**



# Giant Planets Form in Different Configuration



Primordial disk of comets

- Gas giants form between 5 to ~20 AU. Massive comet population existed beyond Neptune out to ~50 AU.

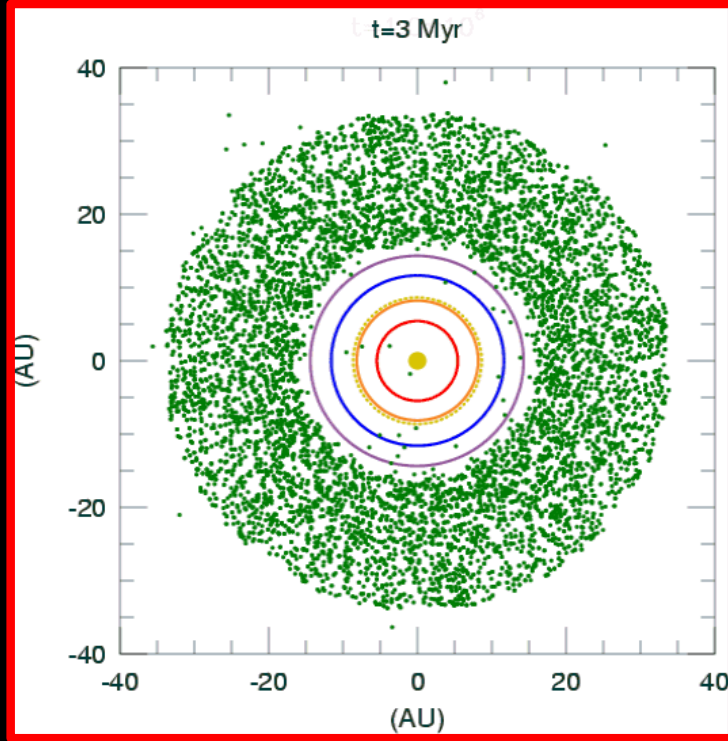


Comets

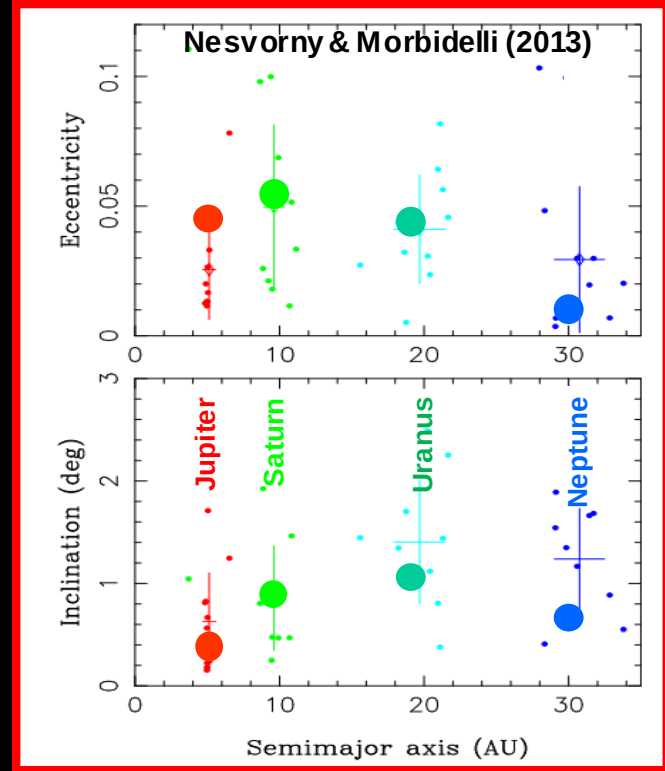
- It has to lead to the current giant planet system and Kuiper belt.

Background/newpapers: Fernandez & Ip (1986); Malholtra (1995); Thommes et al. (1999; 2003); Tsiganis et al. (2005); Brasser et al. (2011); Nesvorny & Morbidelli (2013); Roig & Nesvorny (2014)

# Giant Planet Instability (GPI)

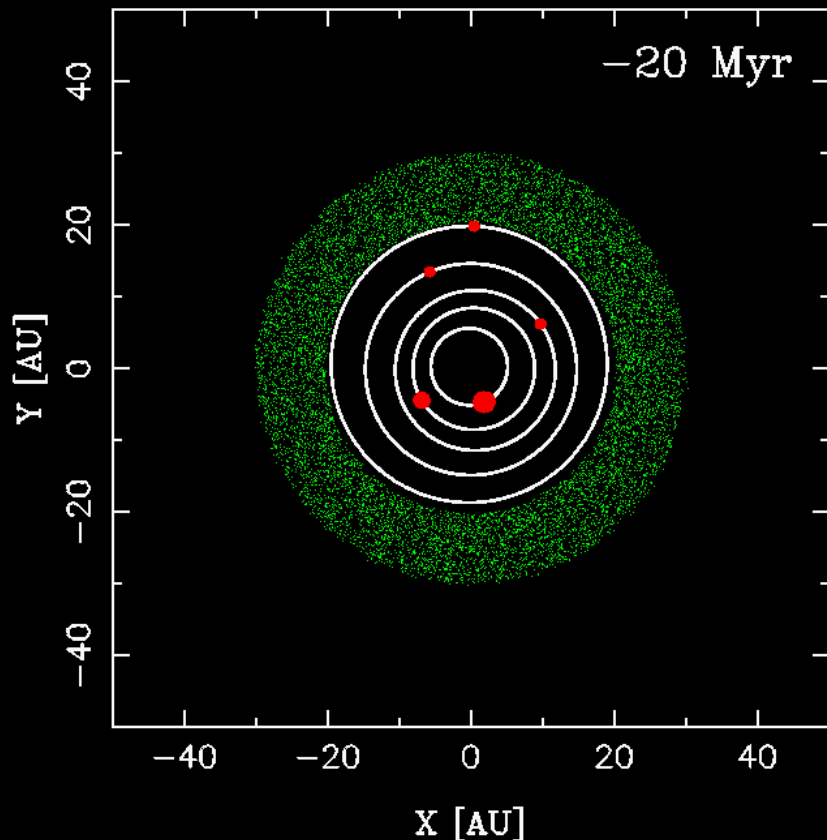


Tsiganis et al. (2005); Gomes et al. (2005)



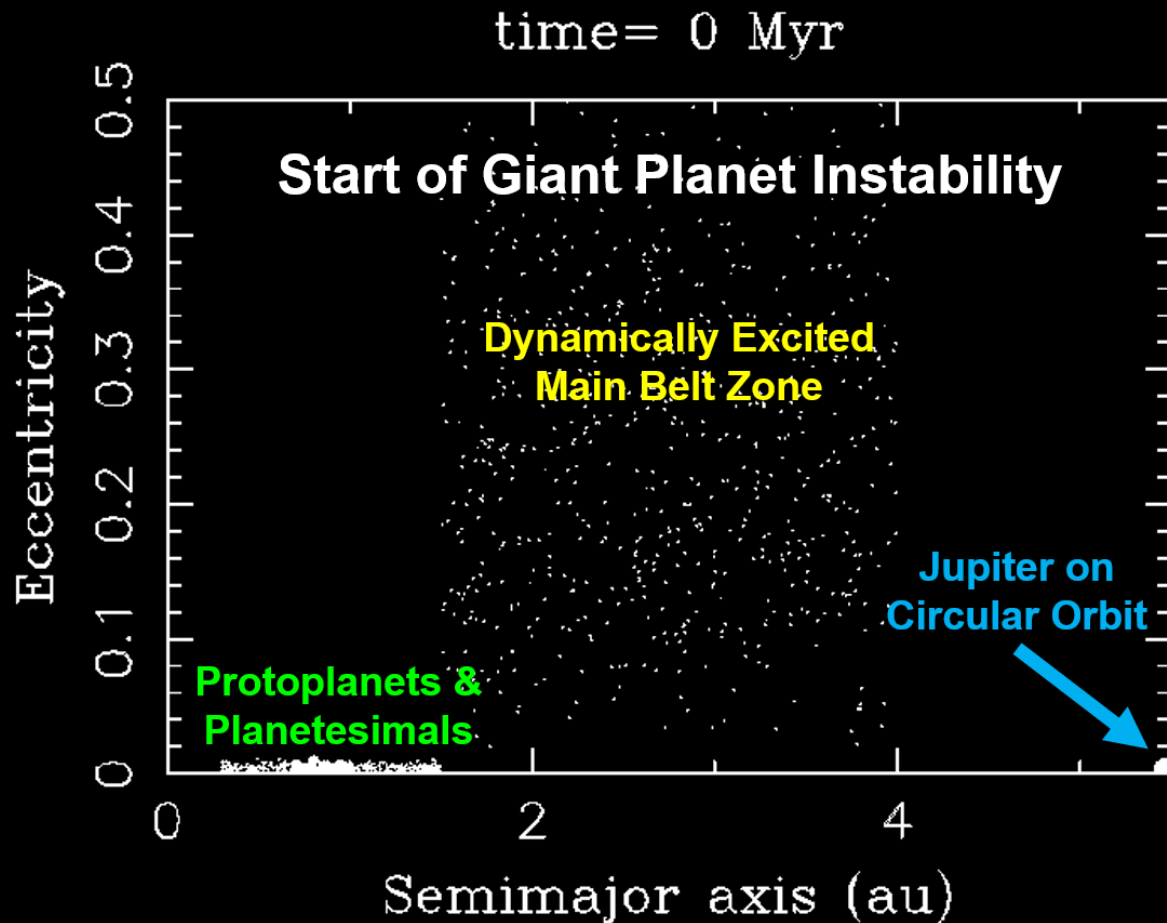
- “Nice model” describes how Jupiter-Neptune migrated to their orbits after a possible delay of a few Myr to many hundreds of My.

# Early GPI and a Lost Neptune



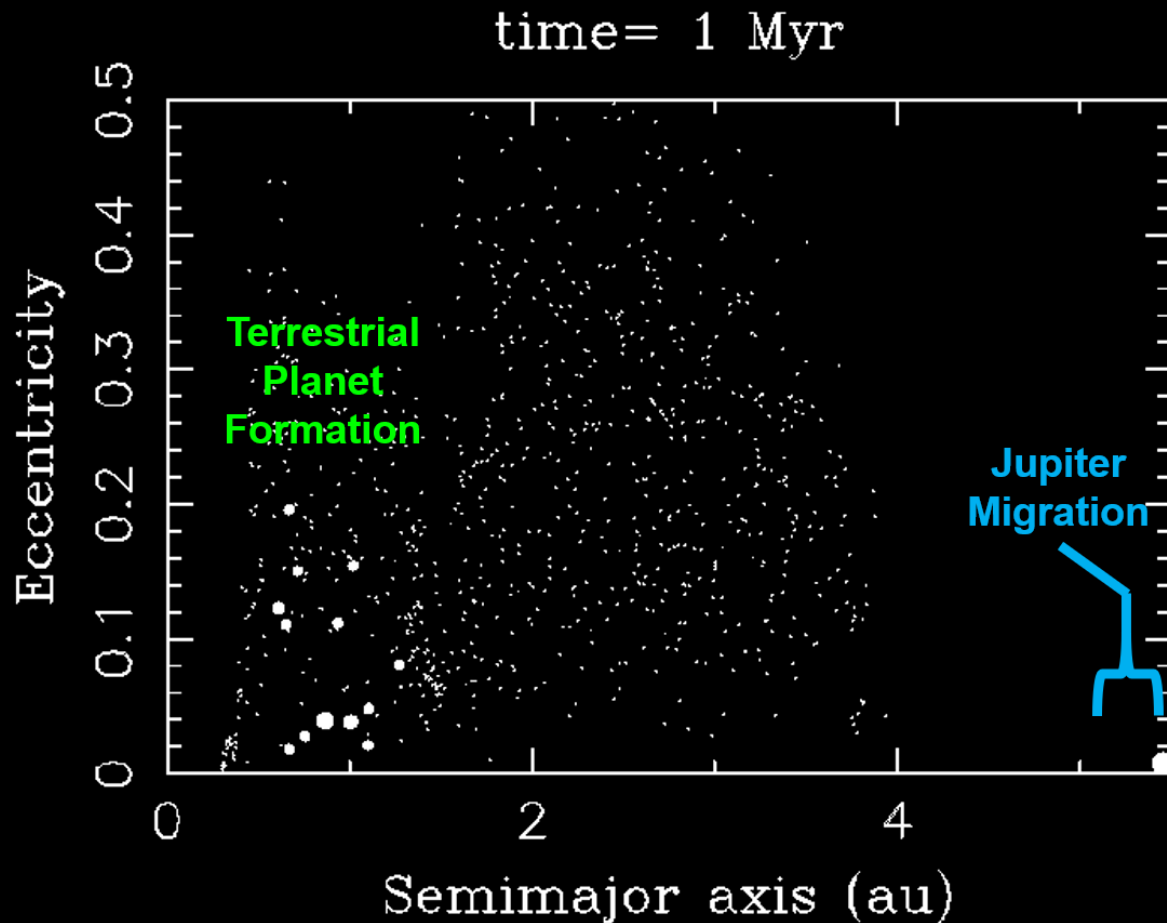
- Most successful simulations come from 5 giant planets, with an extra Neptune ejected.
- But... KBO constraints suggest instability occurred early.
- *Terrestrial planet formation must include effects of giant planet migration.*

# Terrestrial Planet Formation with GPI



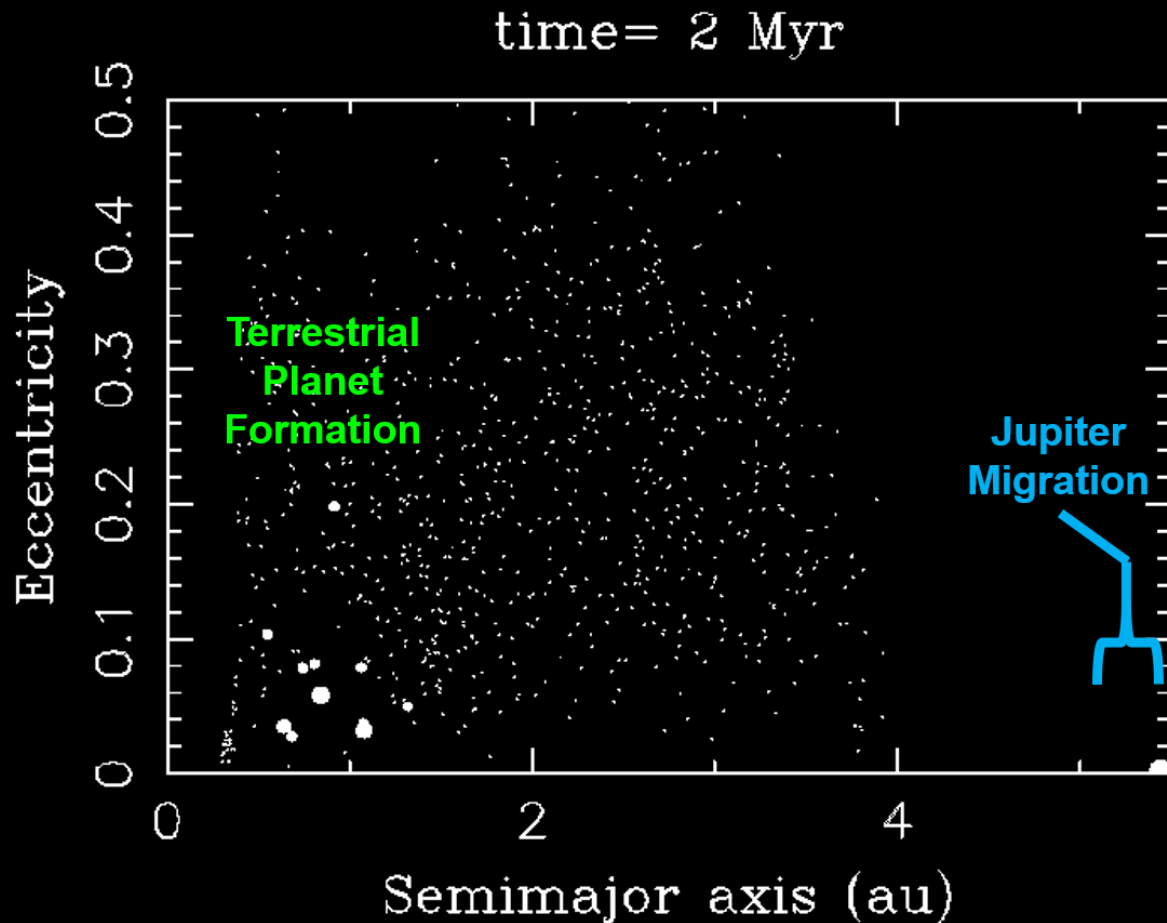
- Moon forms when two half-Earths hit at 43 yr
- Early bombardment should come from
  - Leftover planetesimals
  - Comets
  - Asteroids

# Terrestrial Planet Formation with GPI



- Moon forms when two half-Earths hit at 43 Myr
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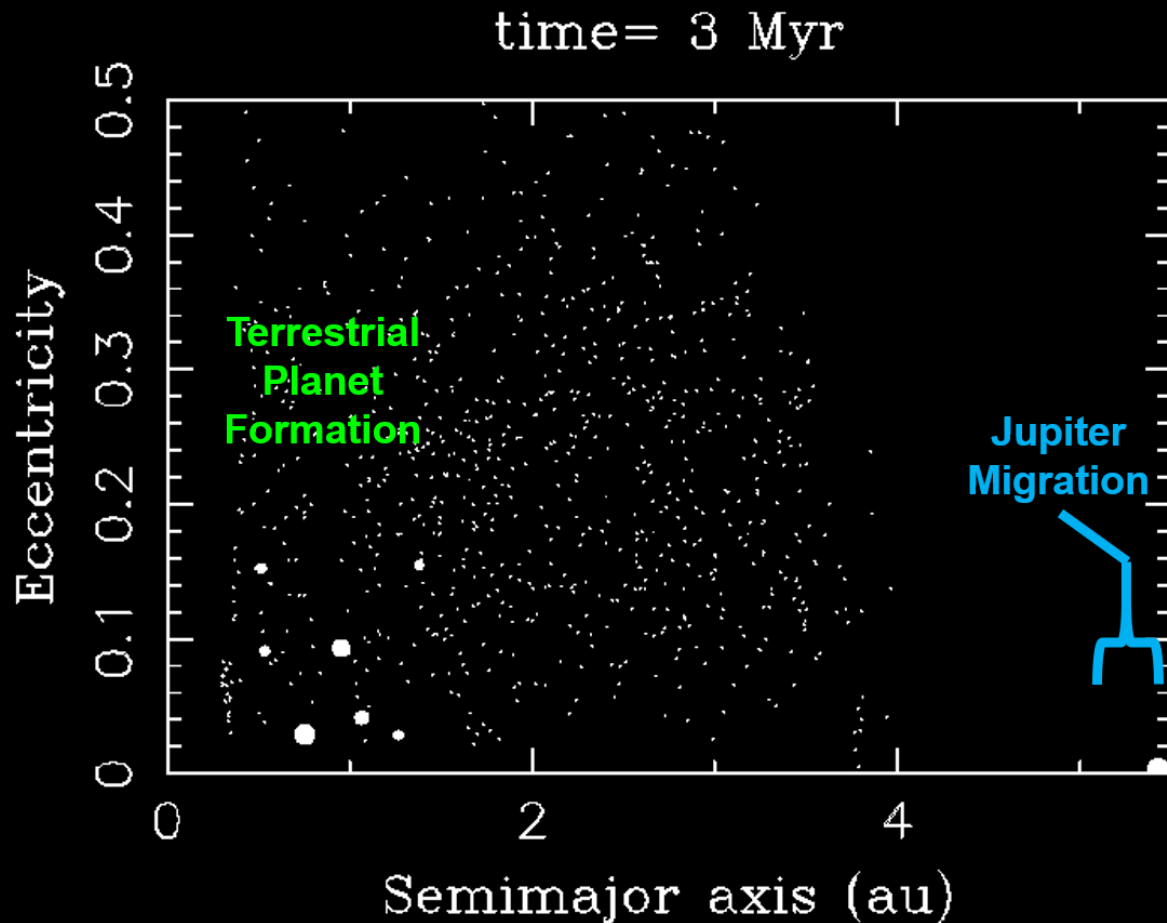
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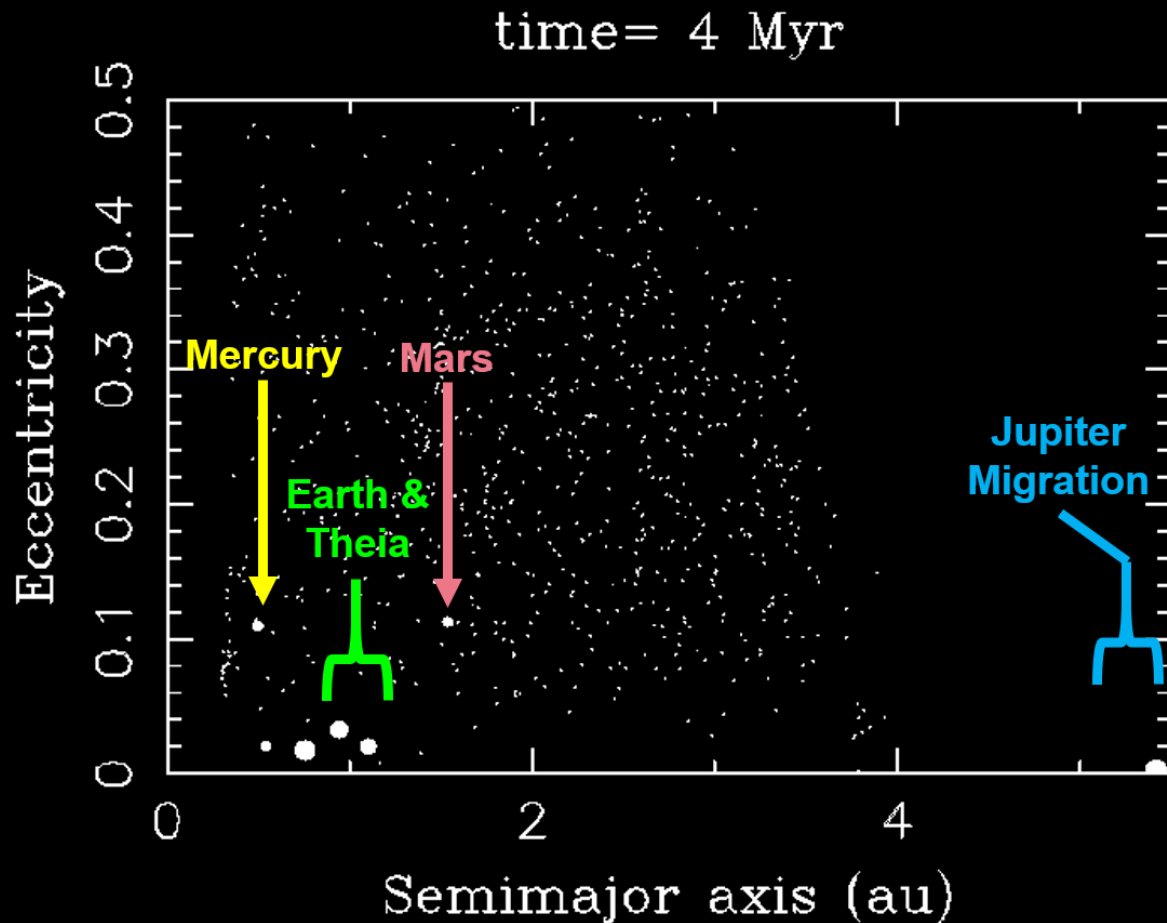


# Terrestrial Planet Formation with GPI



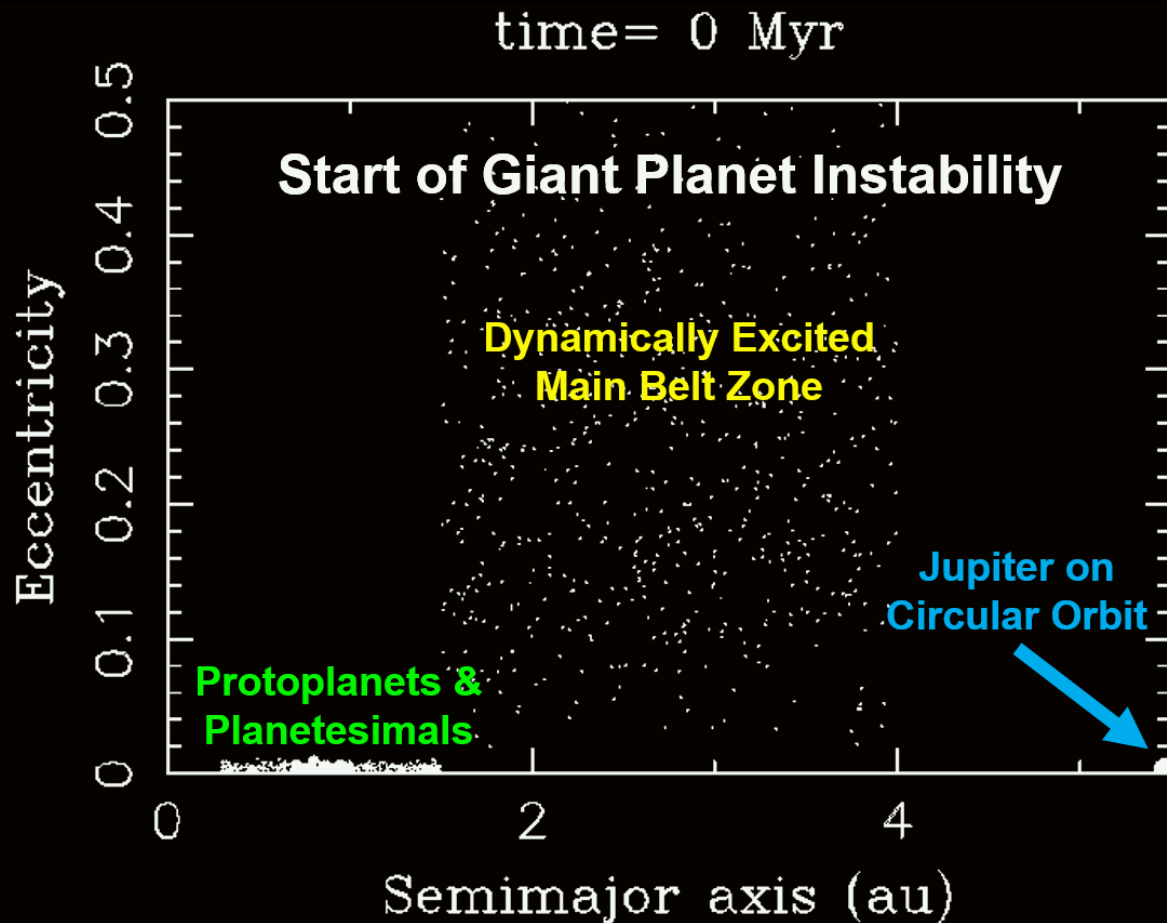
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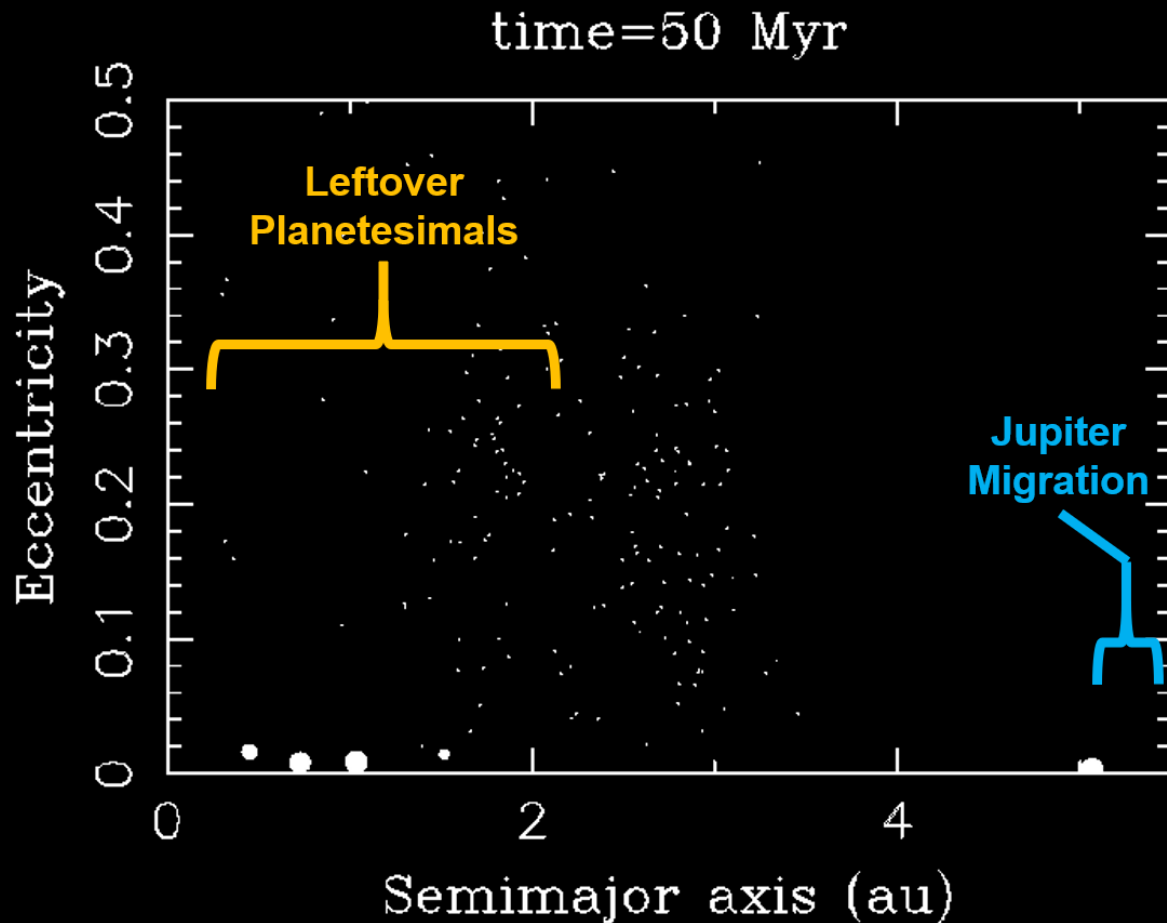
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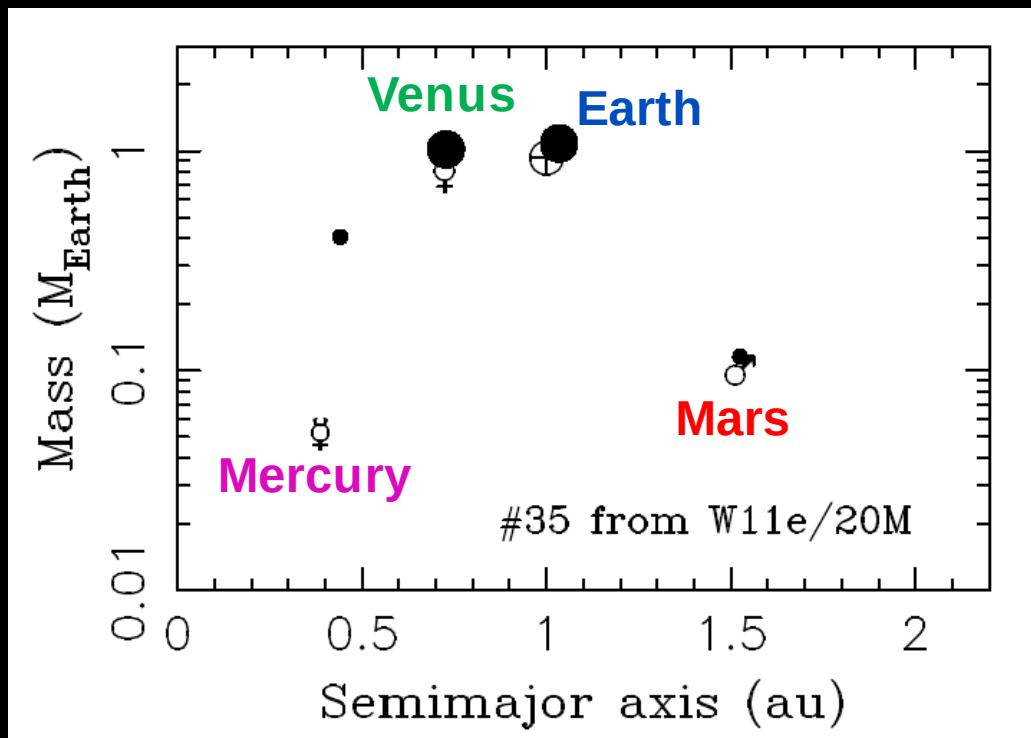
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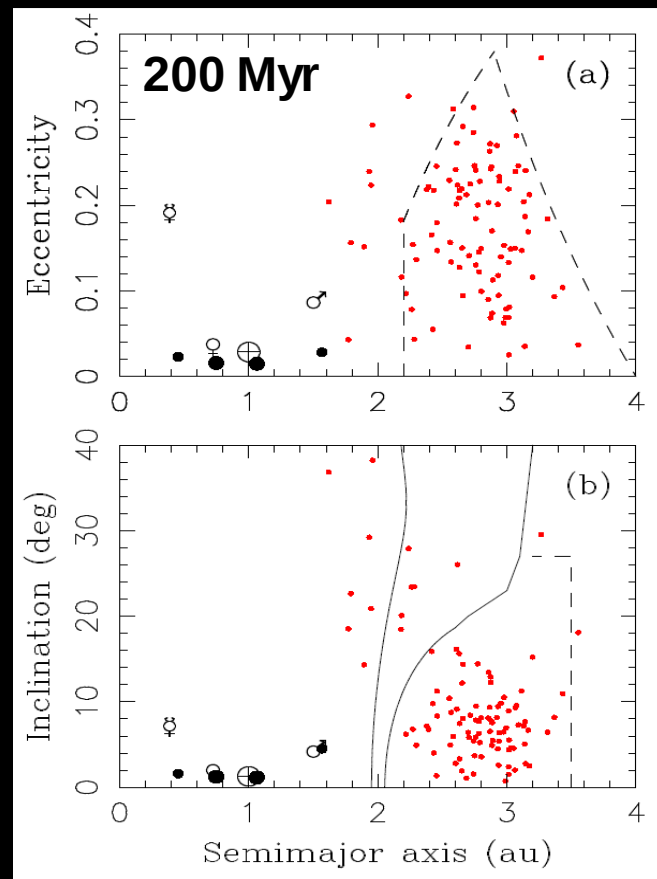


- Moon forms when two half-Earths hit at 43 Myr
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# Best Run (So Far)



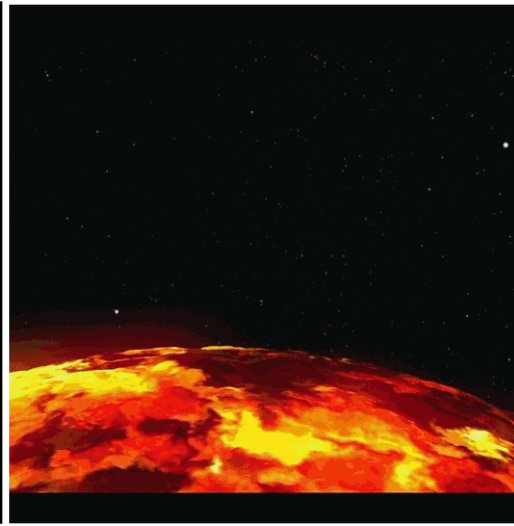
- Terrestrial planet orbits, masses largely reproduced (except for Mercury's mass)
- Bombardment next step...



# Early Lunar Bombardment Highlights

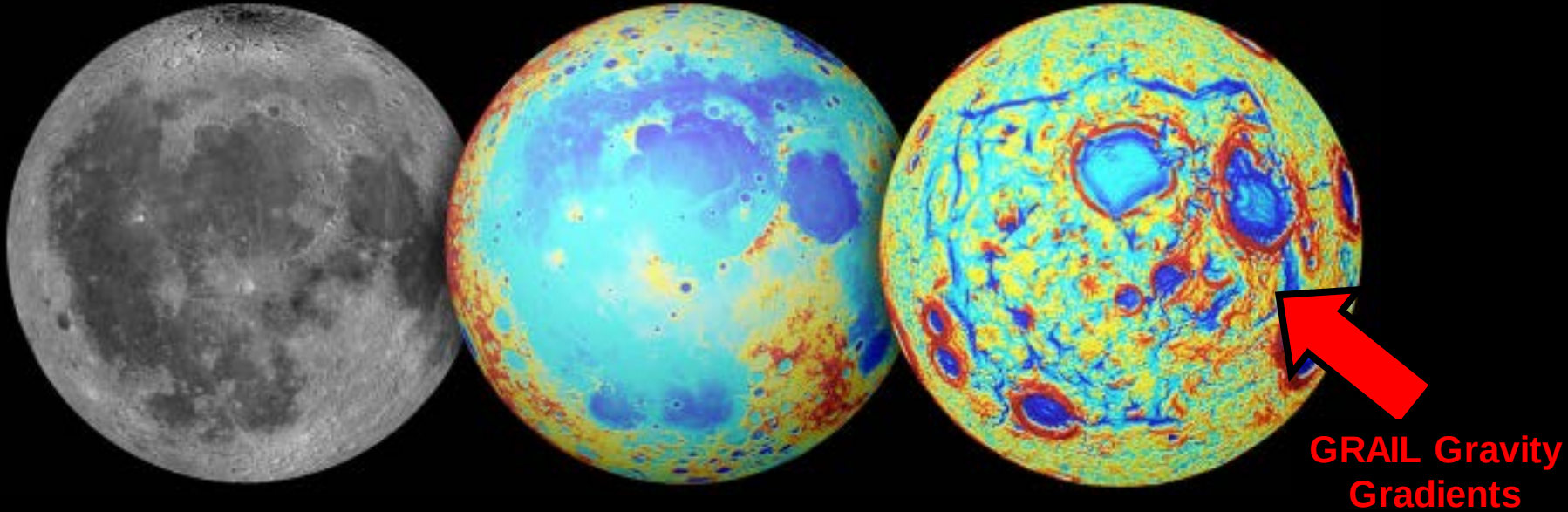


# Interpretation Complications



- **Lunar Formation:** Probably at  $\sim 4.5$  Ga, though some argue for  $\sim 4.4$  Ga.
- **Magma Ocean:** Did it last tens or hundreds of Myr?
- **Bombardment:** Leftover planetesimals, comets, asteroids hit Moon.  
What was the impact flux, and when did basins start being recorded?

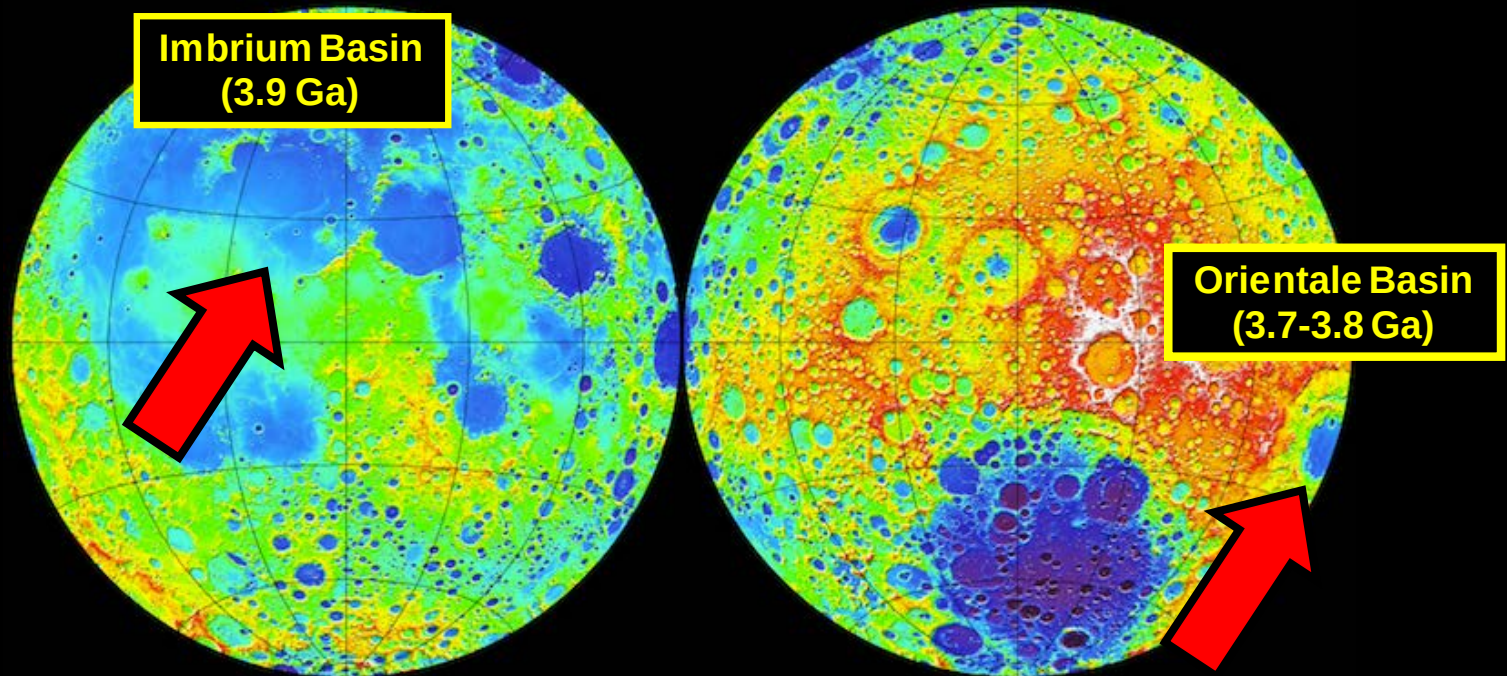
# Nearside Dominated by Magmatic Feature



- **GRAIL: Lunar nearside is a “square” magmatic region with giant rifts.**
  - Heated by high concentrations of radioactive elements; Most older terrains have been erased. Possible formation by an impact?
  - Basins produced in this hotter region are naturally larger.

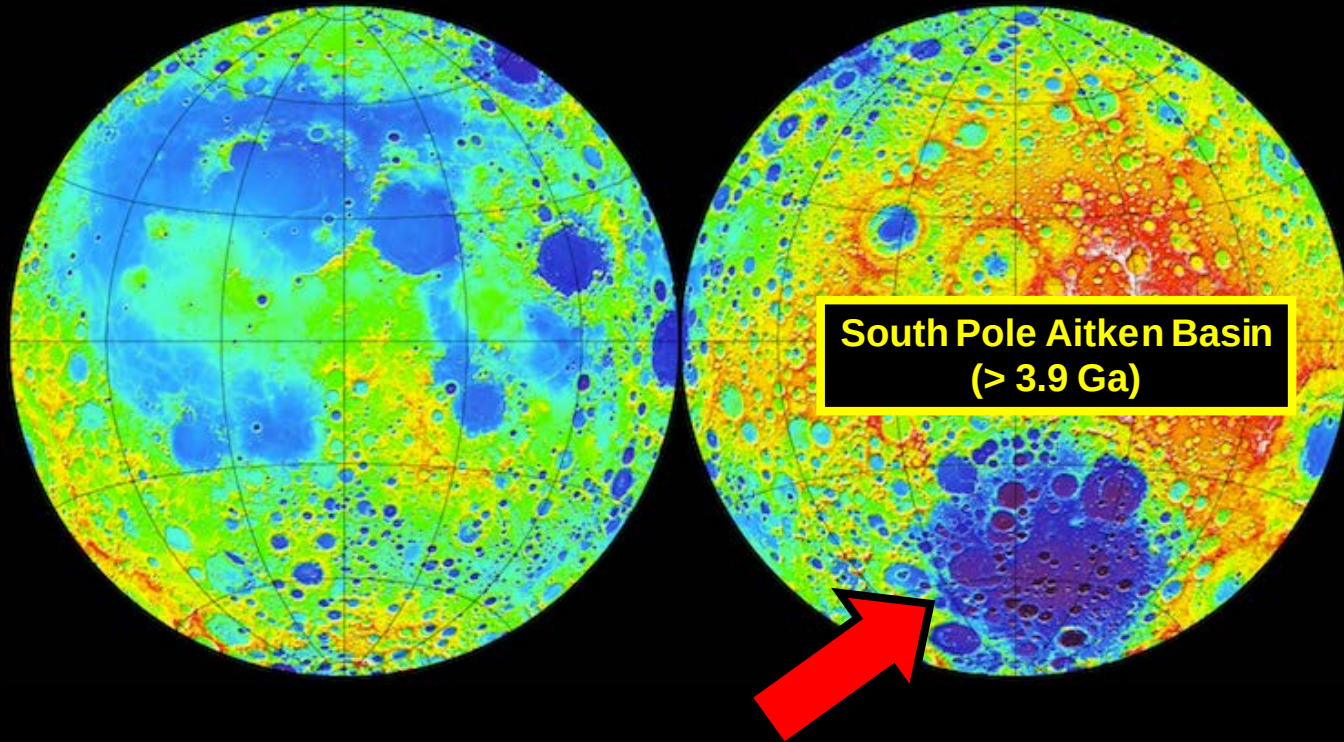


# Current Status of “Late Heavy Bombardment”



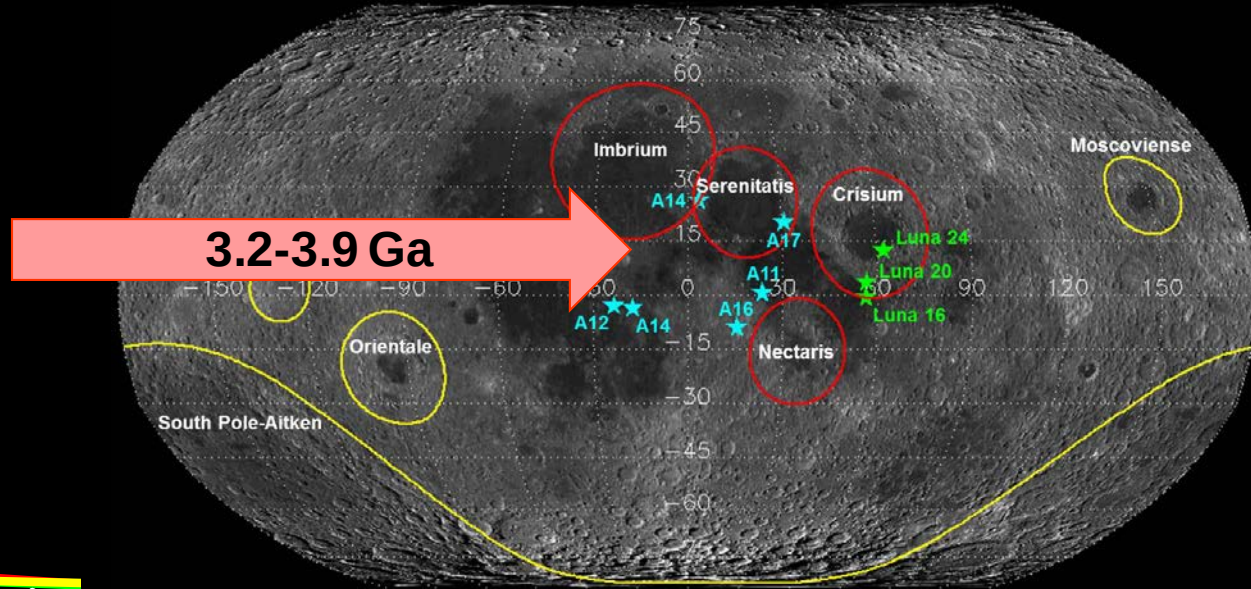
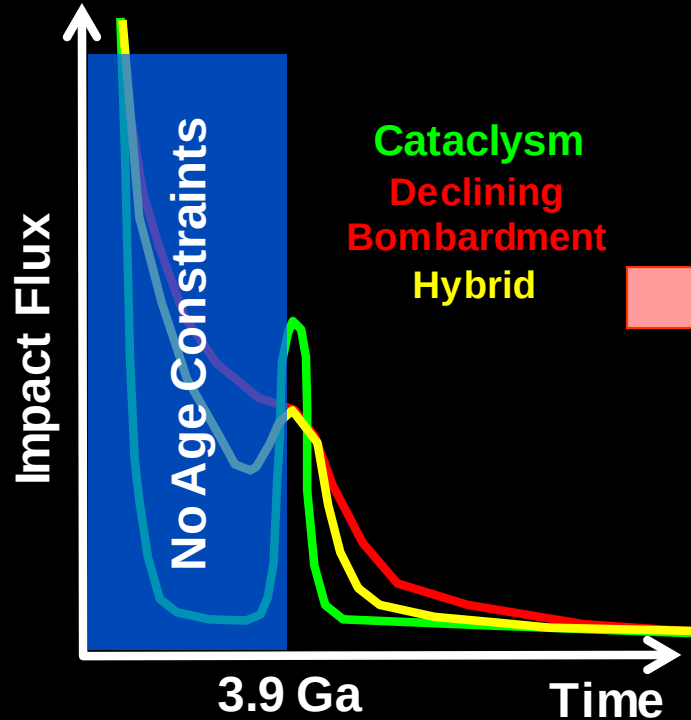
- 40 basins, but two of three largest and youngest are  $< 3.9$  Ga.
- $D > 90$  km crater spatial densities of several basins match Imbrium (e.g., Crisium, Serenitatis, Humor). Comparable age?

# South Pole Aitken is the Oldest Basin



- The oldest basins by superposition is South Pole-Aitken basin (~2400 km). SPA's absolute age is unknown.

# Bombardment Models

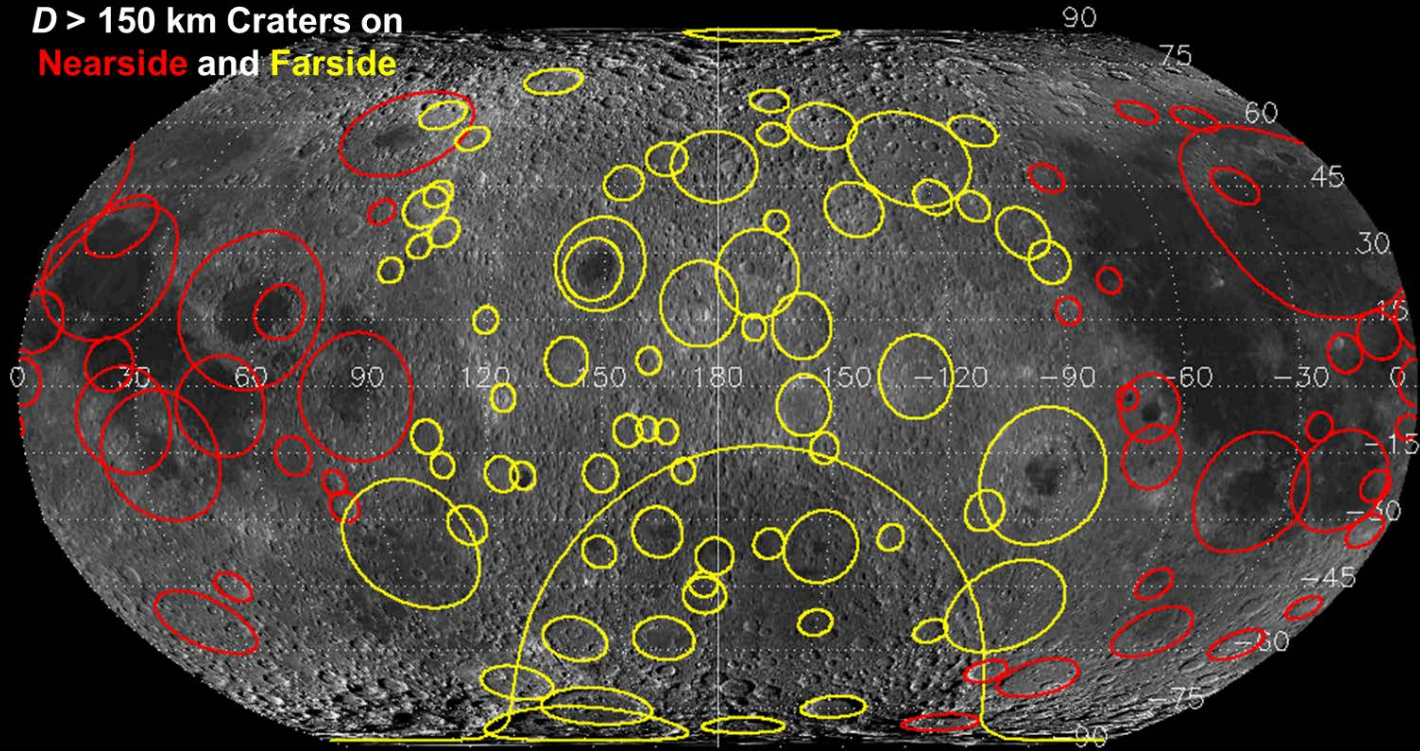


- Cataclysm? Declining Bombardment? Hybrid? Other?
- Oldest dated terrains are 3.2-3.9 Ga. We need  $> 3.9$  Ga!



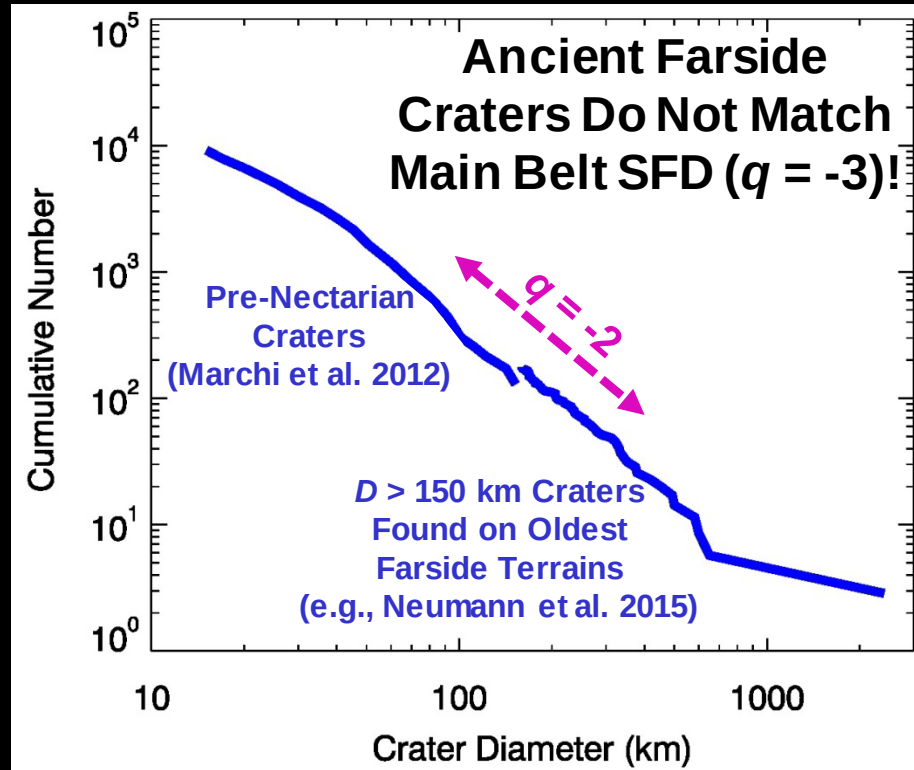
# Lunar Bombardment from LRO & GRAIL

$D > 150$  km Craters on  
Nearside and Farside



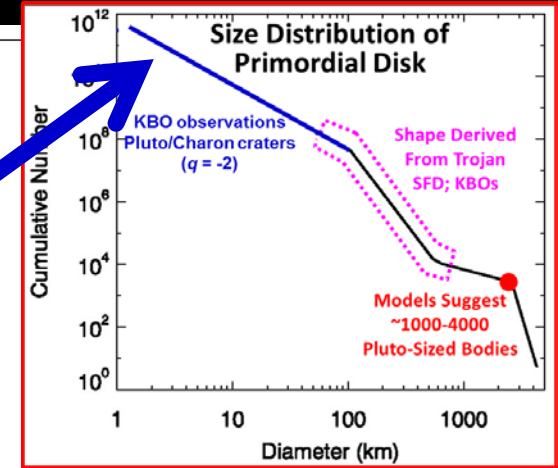
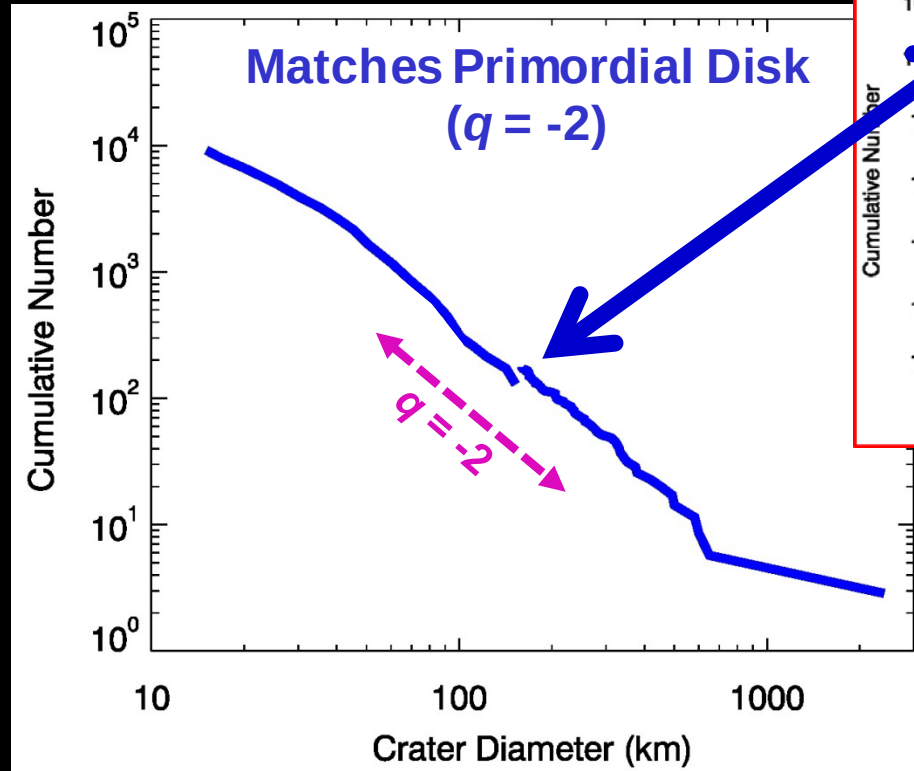
- **Question:** Does the farside's impact record go back to the formation of the Moon (4.5 Ga) or the overturn of lunar mantle (maybe 4.35 Ga)?

# Oldest Craters/Basins on Lunar Farside



- Shallow size distribution ( $q = -2$ ). Asteroid belt is wavy with  $q = -3$ .

# Ancient Lunar Bombardment



- Power law slope of farside craters/basins may match impactors from the primordial comet disk. Evidence for early giant planet instability?

# Lunar Bombardment Addresses Key Decadal Survey Science Questions

- The NRC's 2007 report, "*The Scientific Context for the Exploration of the Moon*" made understanding the Moon's bombardment history their top science goal.
- It was the top priority science concept of the 2018 LEAG report "*Advancing the Science of the Moon: Report of the Specific Action Team*"
- Applications to 2020 Decadal Survey science topics include:
  - **Origins**: Protoplanetary Disk Evolution, Accretion, Origin of Earth & Inner SS Bodies
  - **Processes**: Impacts and Dynamics, Solid Body Interior and Surface Evolution, Structure and Evolution of the Giant Planets
  - **Habitability & Life**: Origins of Terrestrial Life, Habitats

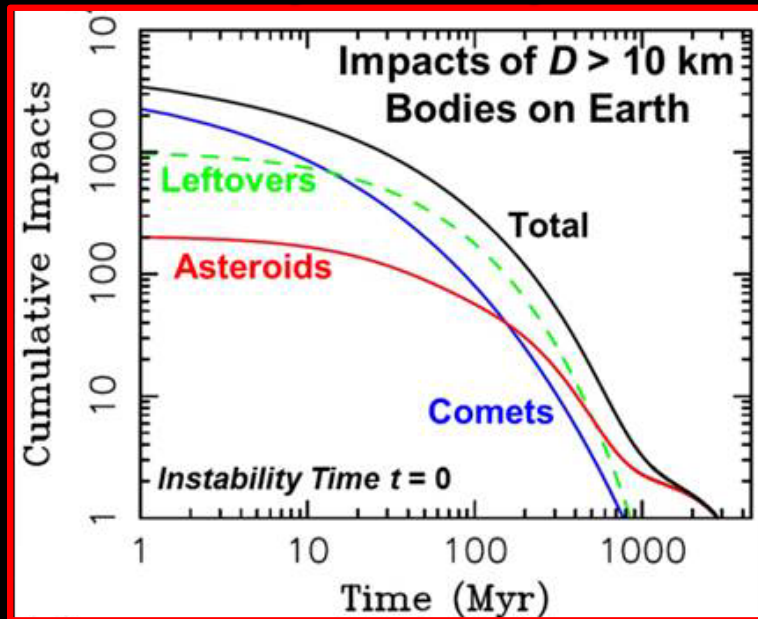




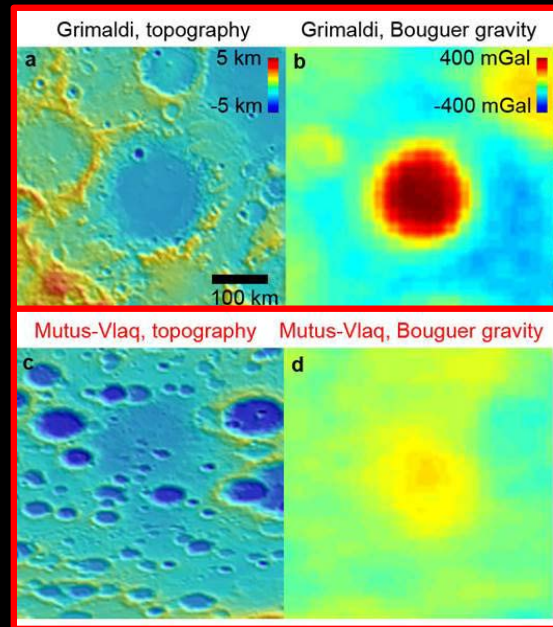
# Backup Slides

# Big Issues to Explore

## New Early Instability Models



## GRAIL Data: Ancient Relaxed Basins



- Early giant planet instability -- What hit the Moon early?
- When did recorded time start for basins? Basin relaxation?

Sample references: Nesvorný (2018); Conrad et al. (2018); Evans et al. (2018); Nimmo (2019)