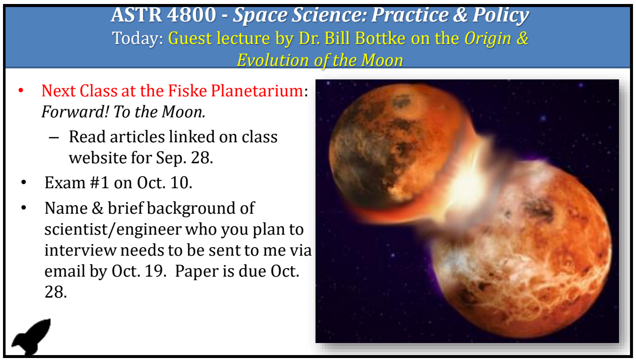
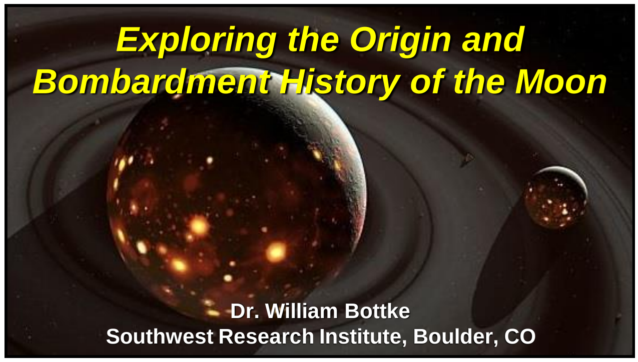
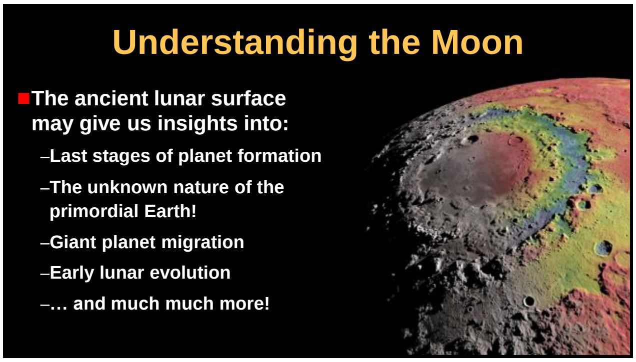

ASTR 4800 - Space Science: Practice & Policy
Today: Guest lecture by Dr. Bill Bottke on the Origin & Evolution of the Moon
• Next Class at the Fiske Planetarium: Forward! To the Moon.
– Read articles linked on class website for Sep. 28.
• Exam #1 on Oct. 10.
• Name & brief background of scientist/engineer who you plan to interview needs to be sent to me via email by Oct. 19. Paper is due Oct. 28.

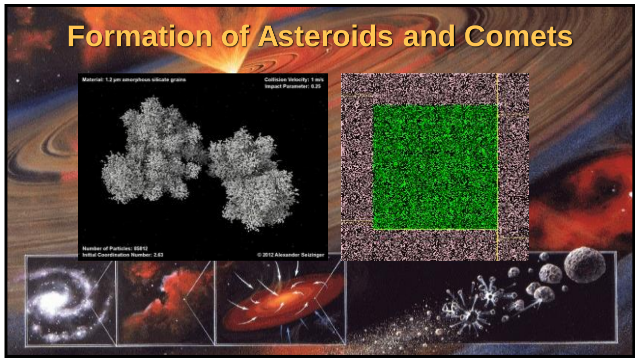
1


Exploring the Origin and Bombardment History of the Moon
Dr. William Bottke
Southwest Research Institute, Boulder, CO

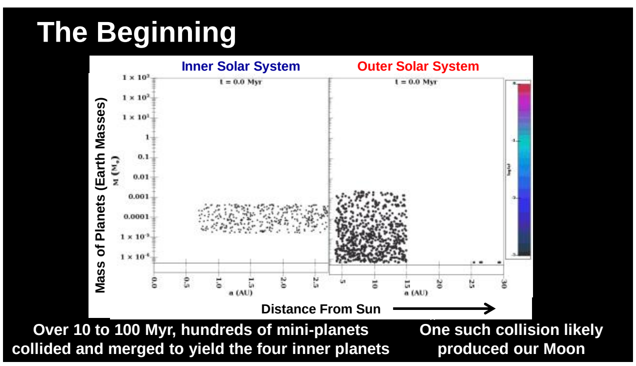
2


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

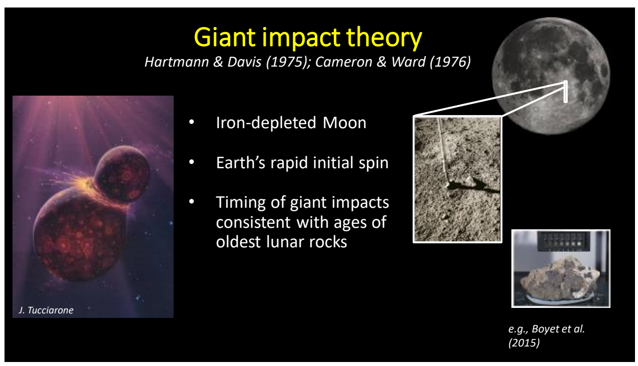
3


Formation of Asteroids and Comets

4


The Beginning
Inner Solar System
Outer Solar System
Mass of Planets (Earth Masses)
Distance From Sun
Over 10 to 100 Myr, hundreds of mini-planets collided and merged to yield the four inner planets
One such collision likely produced our Moon

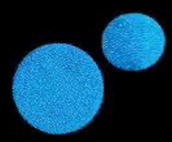
5


Giant impact theory
Hartmann & Davis (1975); Cameron & Ward (1976)
• Iron-depleted Moon
• Earth's rapid initial spin
• Timing of giant impacts consistent with ages of oldest lunar rocks
J. Tucciarone
e.g., Boyet et al. (2015)

6

Canonical impact by Mars-sized "Theia"

Canup & Asphaug (2001); Canup (2004, 2008)



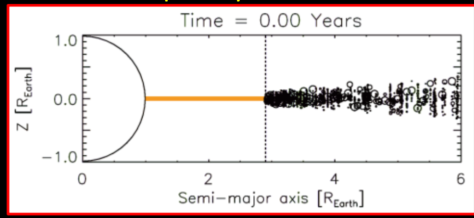
- ✓ Earth and Moon masses
- ✓ Lunar iron depletion
- ✓ Earth-Moon angular momentum
- ✓ Similar impacts predicted for ~ 20% of Earth-analogs

e.g. Jacobsen & Morbidelli (2014), Kaib & Cowen (2014)

Data from Canup (2004); rendering by American Museum of Natural History

7

Canonical impact by Mars-sized "Theia"

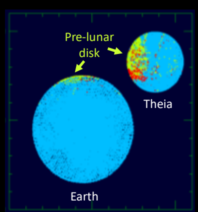


- **The Moon could form in as short as a few years or as long as 1,000 years.**
- **Moon formed ~50-70 Myr after the first solids (4.5 Ga)**

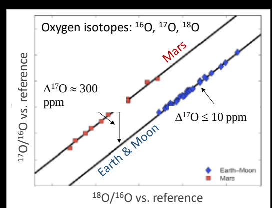
Touboul et al. (2009); Cuk & Stewart (2012); Canup (2012); Salmon and Canup (2013); Bottke et al. (2015)

8

Isotopic "crisis" for impact theory



In most collisions, Moon originates primarily from Theia



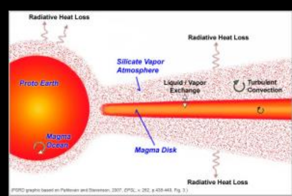
If Theia was Mars-like → Earth-Moon differences. Instead, Earth-Moon are isotopically identical.

9

Equilibration?

Pahlevan & Stevenson (2007)

Mixing between disk and Earth vapor equilibrates their isotopic compositions before Moon forms

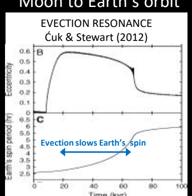


- Would equalize Earth-Moon across many elements, including W
- BUT: Efficiency remains unclear. Might expect Earth-Moon differences in refractory elements. But no difference for Ti & only small difference in Ca *(Zhang et al. 2012; Schiller et al. 2018)*

10

High-angular momentum impact?

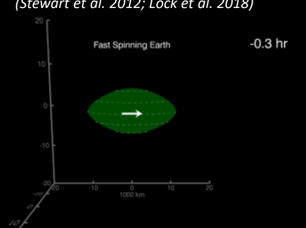
Solar interactions can transfer AM from Earth-Moon to Earth's orbit



Ćuk & Stewart (2012); Wisdom & Tian (2015); Ćuk et al. (2016); Ward et al. (2019)

Second example: Moon from mostly-Earth

(Stewart et al. 2012; Lock et al. 2018)

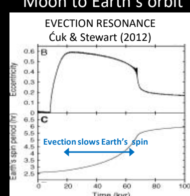


BUT: Needed impact and/or AM-change could be improbable. W match still difficult.

11

High-angular momentum impact?

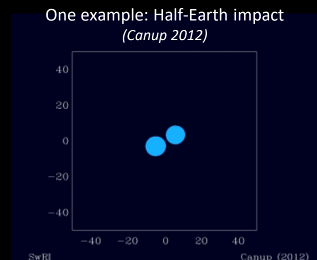
Solar interactions can transfer AM from Earth-Moon to Earth's orbit



Ćuk & Stewart (2012); Wisdom & Tian (2015); Ćuk et al. (2016); Ward et al. (2019)

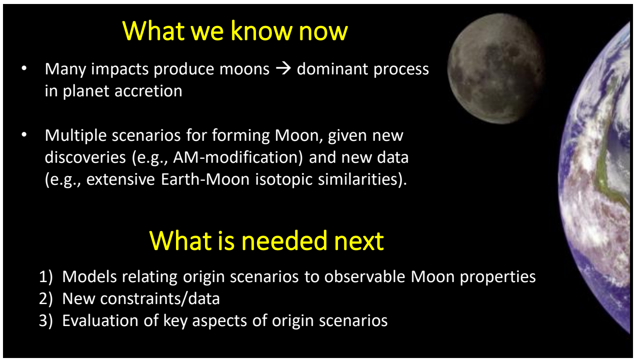
One example: Half-Earth impact

(Canup 2012)



BUT: Needed impact and/or AM-change could be improbable. W match still difficult.

12



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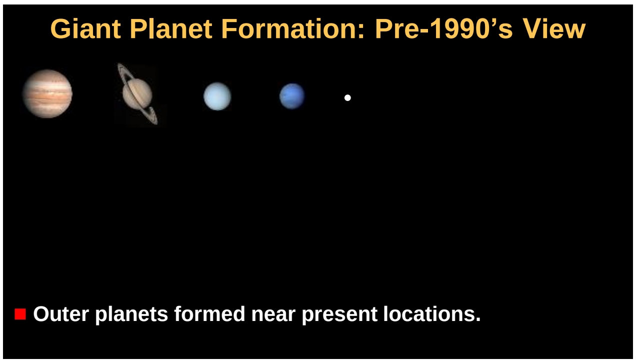

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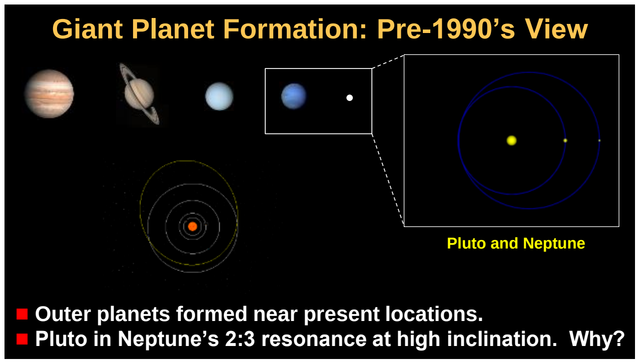

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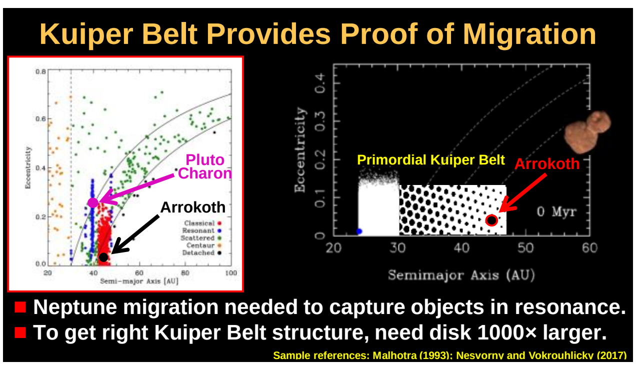

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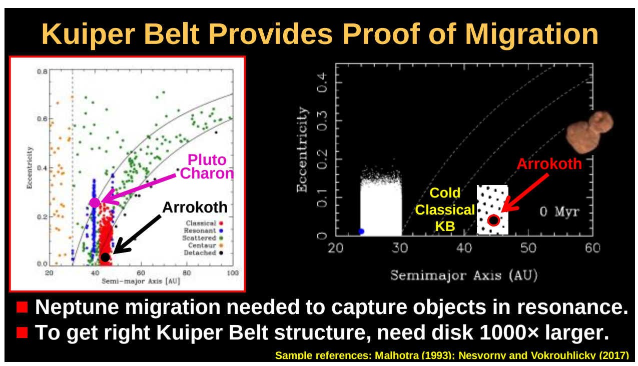

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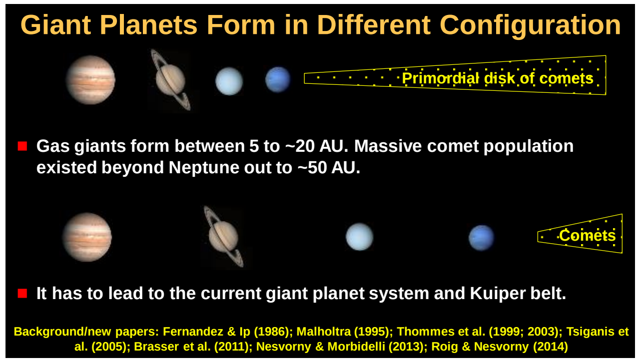

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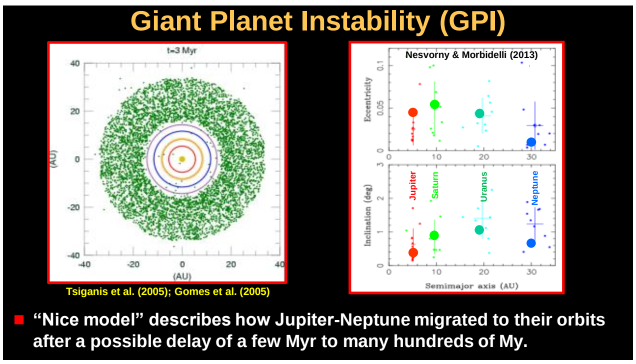

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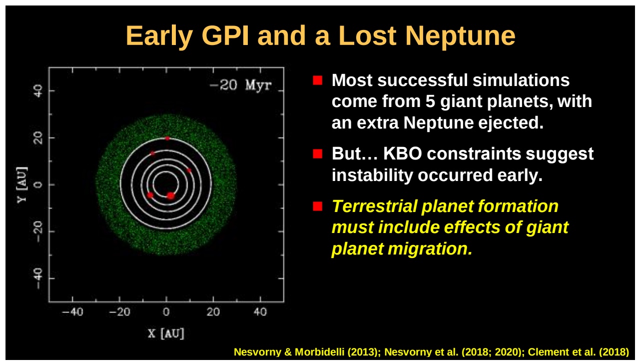

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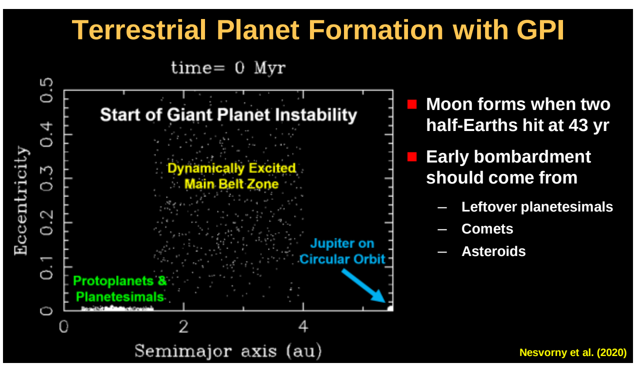

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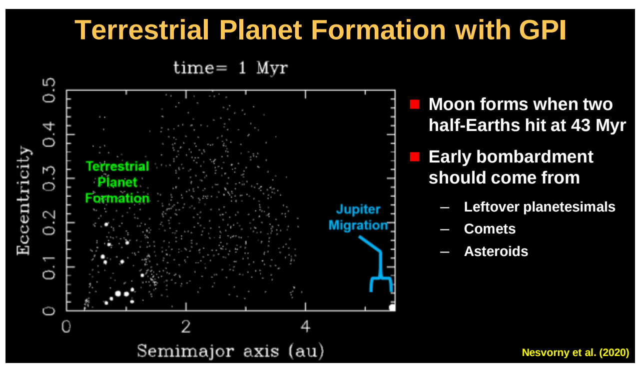

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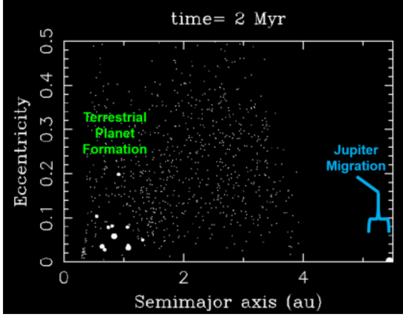
Terrestrial Planet Formation with GPI

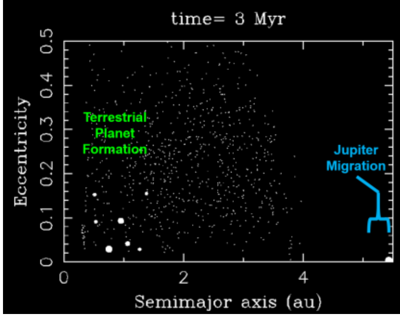


- Moon forms when two half-Earths hit at 43 Myr
- Early bombardment should come from
  - Leftover planetesimals
  - Comets
  - Asteroids

Nesvorny et al. (2020)

25

Terrestrial Planet Formation with GPI



- Moon forms when two half-Earths hit at 43 Myr
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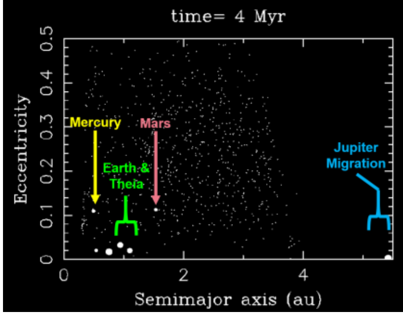
26

Terrestrial Planet Formation with GPI



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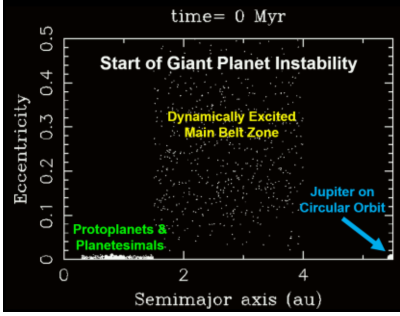
27

Terrestrial Planet Formation with GPI



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Nesvorny et al. (2020)

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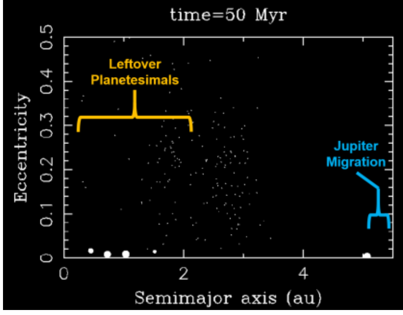
Terrestrial Planet Formation with GPI



- Moon forms when two half-Earths hit at 43 Myr
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Nesvorny et al. (2020)

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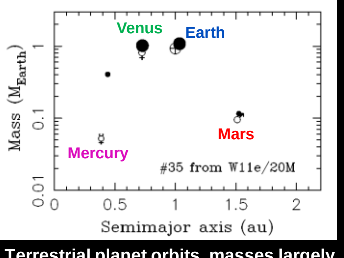
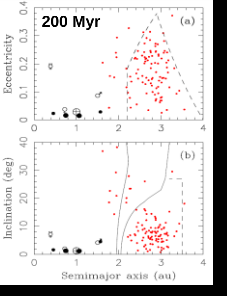
Best Run (So Far)





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

Nesvorny et al. (2020)

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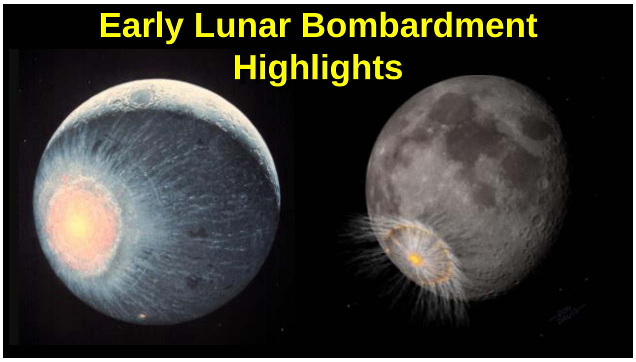

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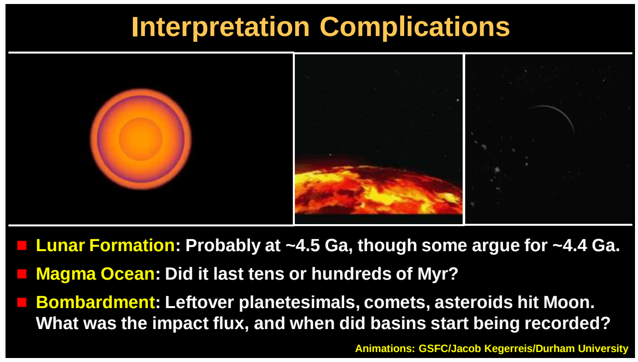

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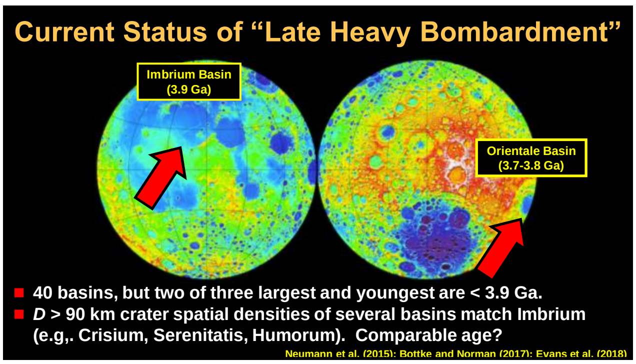

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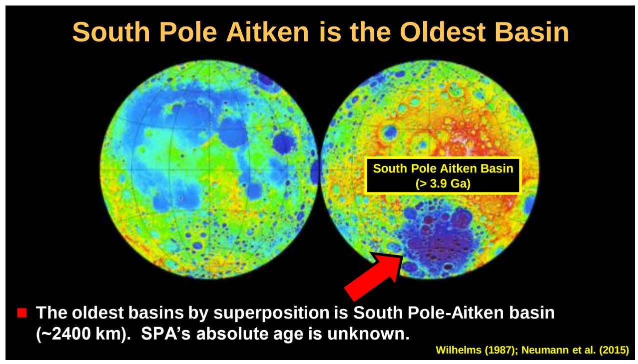

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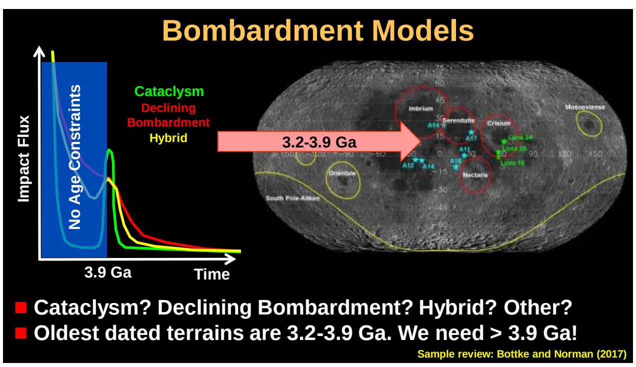

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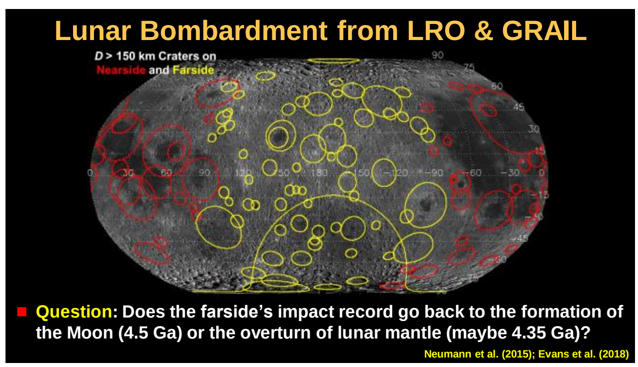

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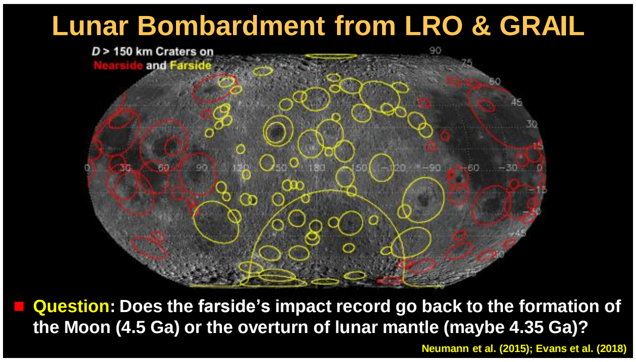

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SPA is geologically and geochemically diverse.

There is no single location on the Moon that can definitively and conclusively answer all of the priority SPA science questions—necessitating a sample return campaign.

Endurance is a sample return campaign in one mission

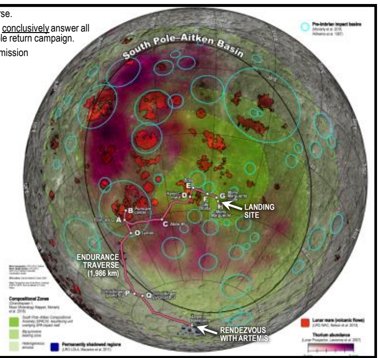
Endurance Science Objectives (as defined in the Decadal Survey, 22-16)	Sample Site Requirements (as defined in the Endurance concept study report)
Determine the age of the largest and oldest impact basin on the Moon, South Pole-Aitken (SPA) to anchor the earliest impact history of the Solar System.	≥1 sample* from the SPA impact melt sheet, as exposed by craters excavating through the SPA compositional anomaly.
Determine when post-SPA farside basins formed to test the giant planet migration and terminal cataclysm hypotheses, and to better constrain the inner solar system impact chronology used to date the surfaces of other planetary bodies.	≥1 sample* from the impact melt sheet and/or peak ring of a farside, pre-Imbrian, farside impact basin.
Determine the age and mineralogical and geochemical composition of deep and crustal materials exposed in SPA to understand the bulk composition of the Moon, its primordial differentiation and geologic evolution, and the significance of chronologic measurements completed on nearside samples for timing lunar solidification.	≥1 sample* from a Thorium hot-spot (>3 ppm) on the lunar farside.
Determine the age and nature of volcanic features and compositional anomalies on the lunar farside to characterize the thermochemical evolution of terrestrial worlds and constrain the origin of the Moon's nearside-farside asymmetry.	≥2 samples* from different farside volcanic deposits, including mare basalts, pyroclastics, or other volcanic units.
Determine the geologic diversity of the SPA terrane to provide geologic context for returned samples, ground truth for orbital measurements, and characterize the surface processes that shape planetary bodies.	≥1 sample* from each of the three major geochemical terrains within SPA: (1) SPACA, (2) Pyroxene Bearing Zone, (3) Heterogeneous Annulus.

Threshold Requirement: 6 samples*

Baseline Requirement: 12 samples*

1 sample* is defined as ≥200

NASA pre-decisional — for planning and discussion purposes only — page 40



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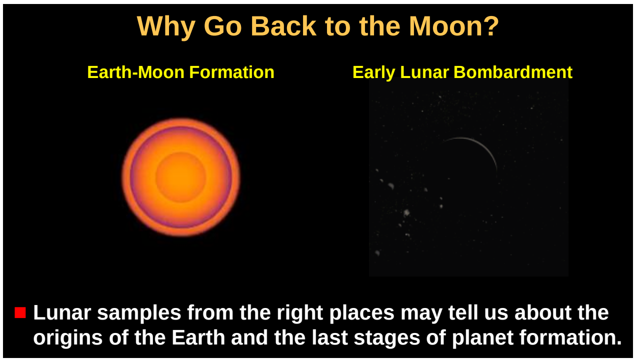

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Backup Slides

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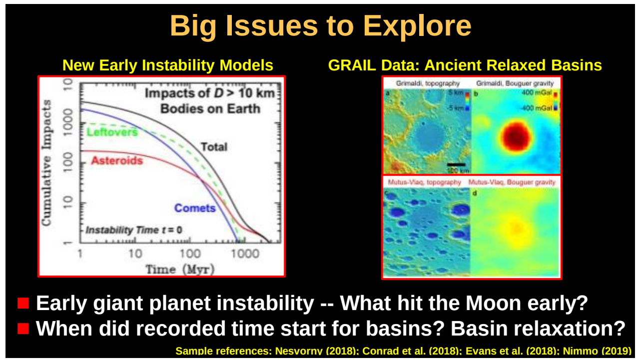

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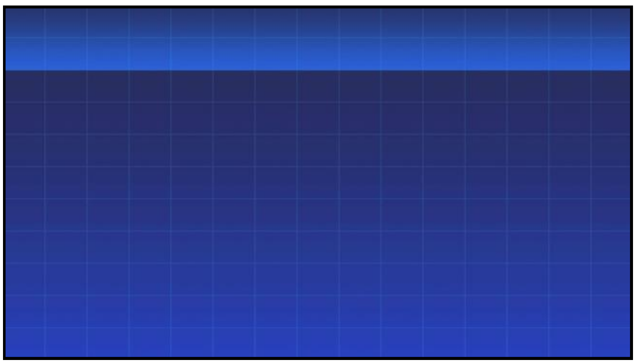

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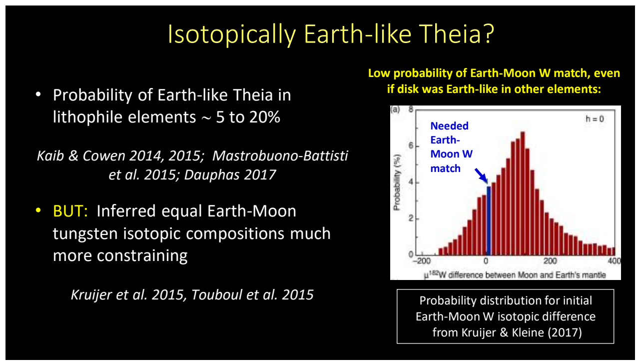

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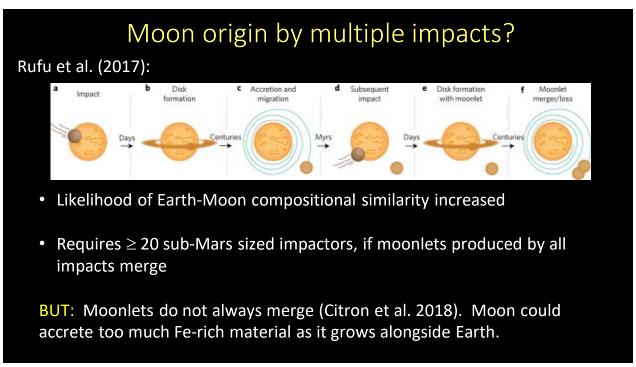

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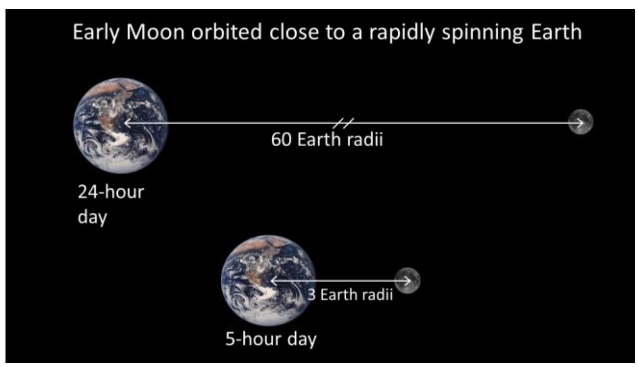

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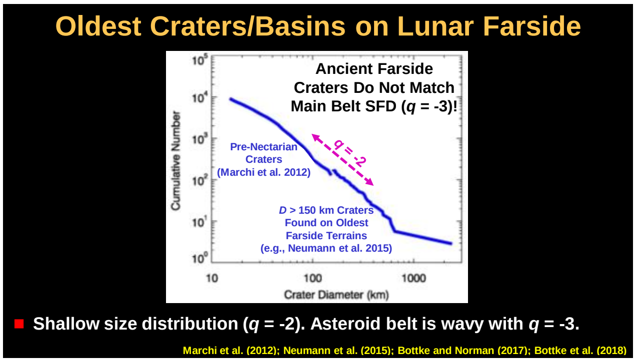
Oldest Craters/Basins on Lunar Farside
Ancient Farside Craters Do Not Match Main Belt SFD (q = -3)!
Pre-Nectarian Craters (Marchi et al. 2012)
q = -2
D > 150 km Craters Found on Oldest Farside Terrains (e.g., Neumann et al. 2015)
Cumulative Number
Crater Diameter (km)
Shallow size distribution (q = -2). Asteroid belt is wavy with q = -3.
Marchi et al. (2012); Neumann et al. (2015); Bottke and Norman (2017); Bottke et al. (2018)

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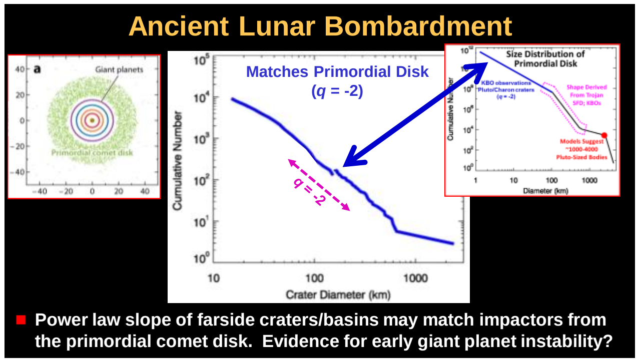
Ancient Lunar Bombardment
Giant planets
Primordial comet disk
Matches Primordial Disk (q = -2)
q = -2
Cumulative Number
Crater Diameter (km)
Size Distribution of Primordial Disk
Models Suggest ~1000-4000 Pluto-Sized Bodies
Diameter (km)
Power law slope of farside craters/basins may match impactors from the primordial comet disk. Evidence for early giant planet instability?

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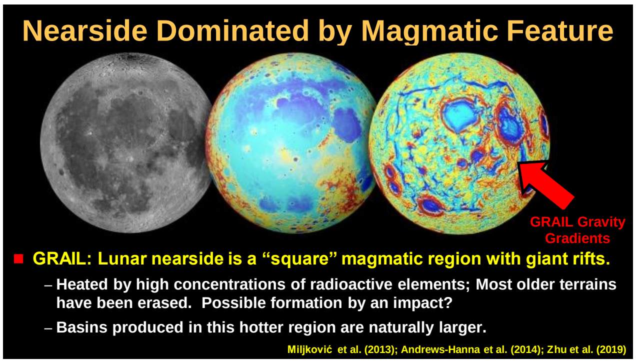
Nearside Dominated by Magmatic Feature
GRAIL Gravity Gradients
GRAIL: Lunar nearside is a "square" magmatic region with giant rifts.
– Heated by high concentrations of radioactive elements; Most older terrains have been erased. Possible formation by an impact?
– Basins produced in this hotter region are naturally larger.
Miljković et al. (2013); Andrews-Hanna et al. (2014); Zhu et al. (2019)

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