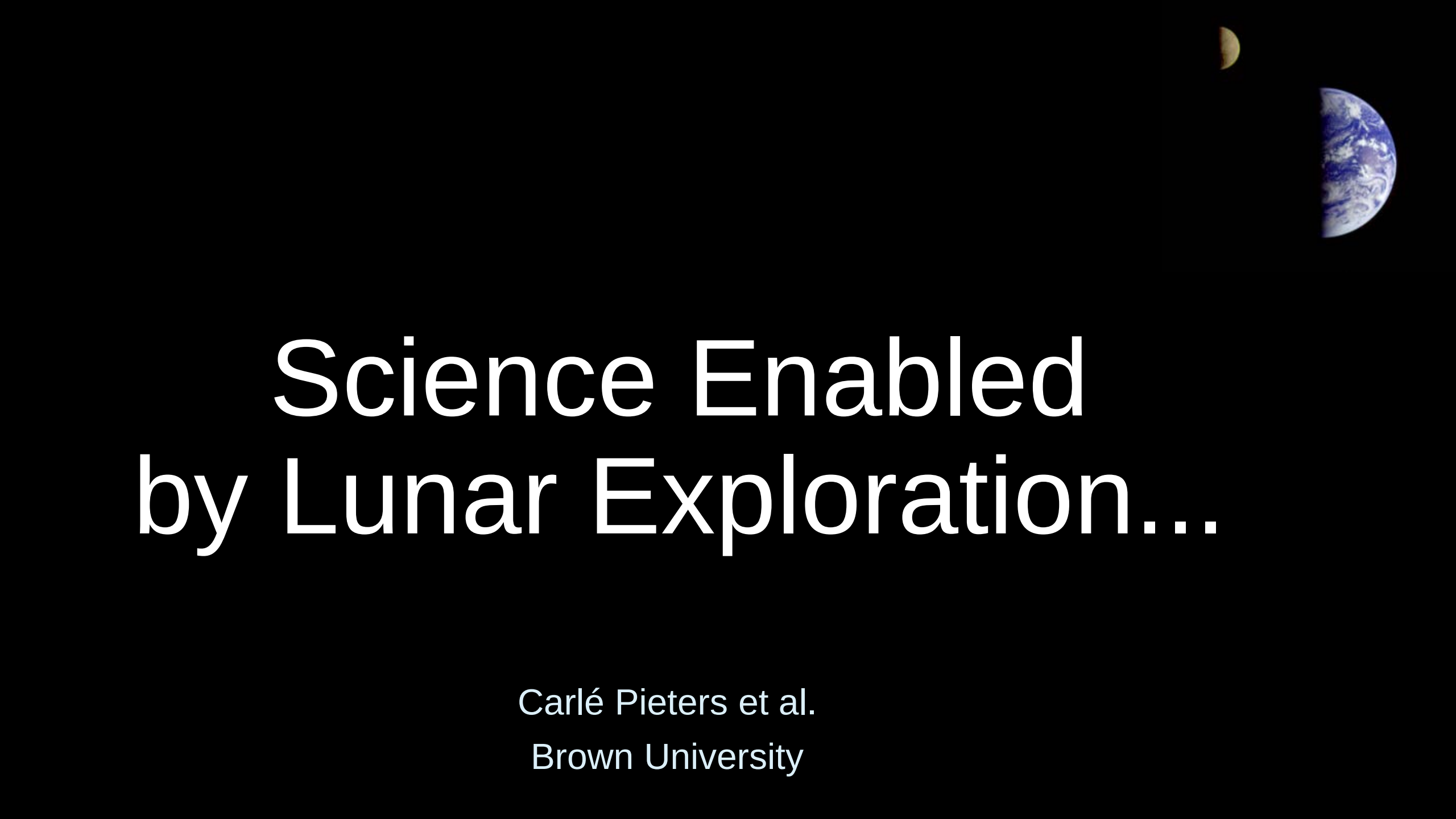


Science Enabled by Lunar Exploration...

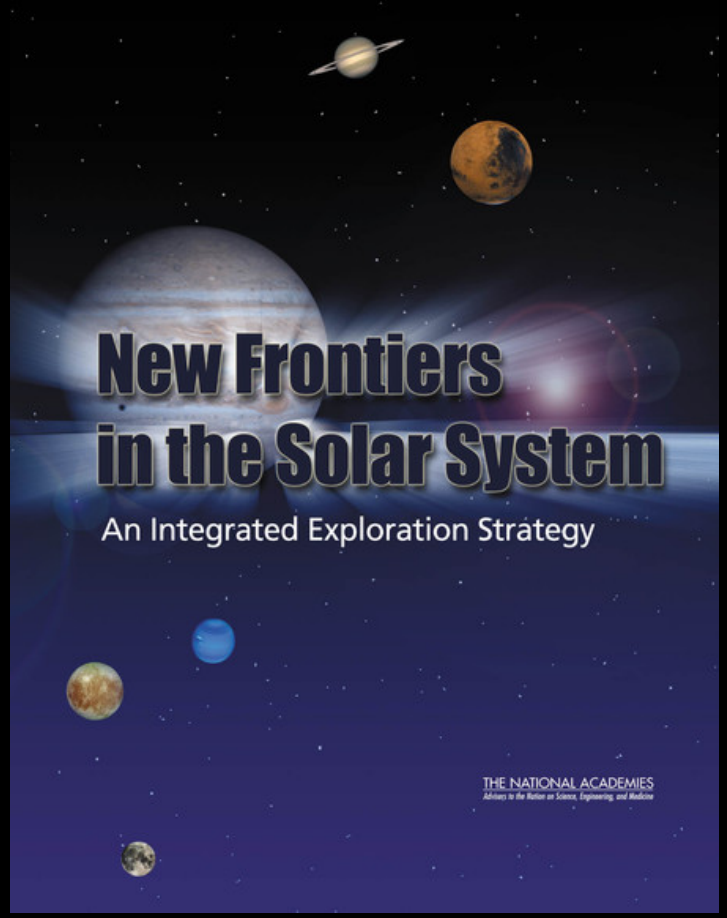
Carlé Pieters et al.

Brown University

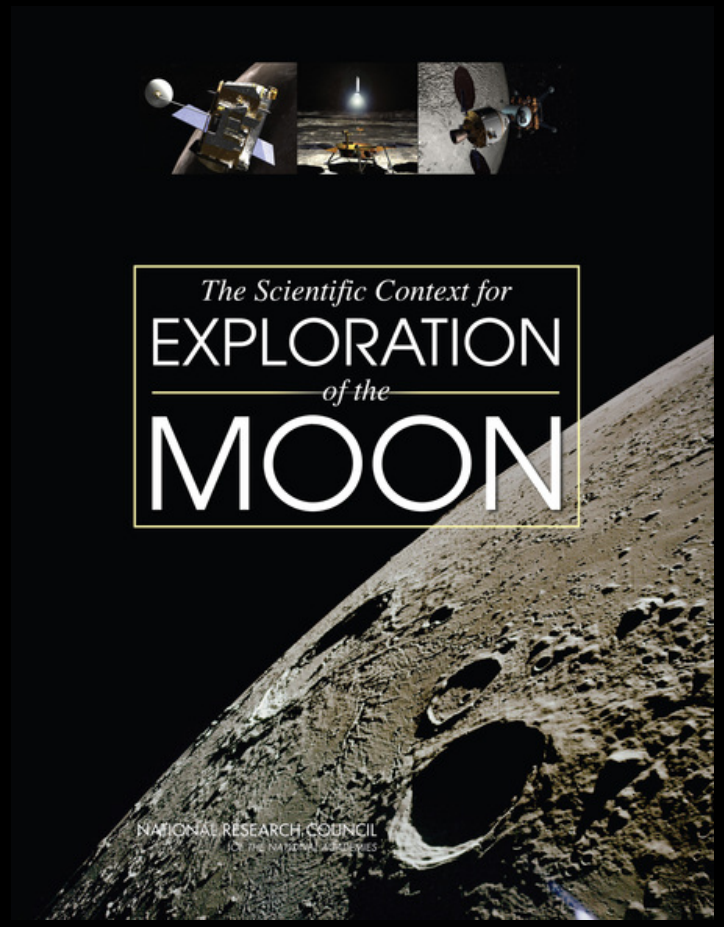
Which?
M – E - S/C
E – M - S/C

NRC Planetary Science Reports

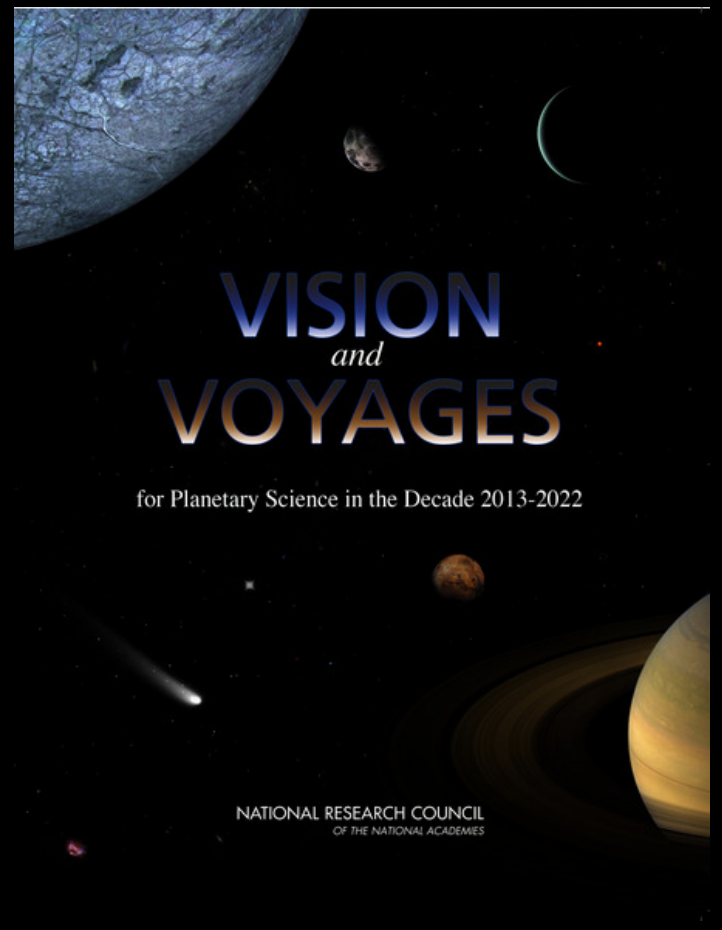
2003 Decadal



2007 SCEM



2011 Decadal



NRC Planetary Science Reports

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Prioritized New Frontiers *
Missions:

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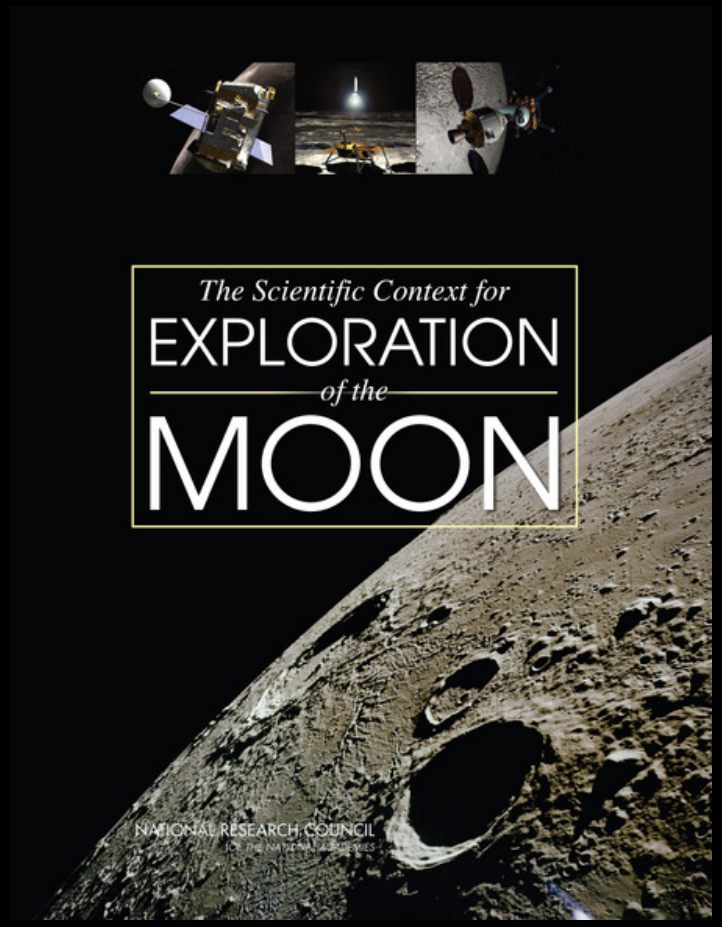
2007 SCEM
Discussed at 1 pm



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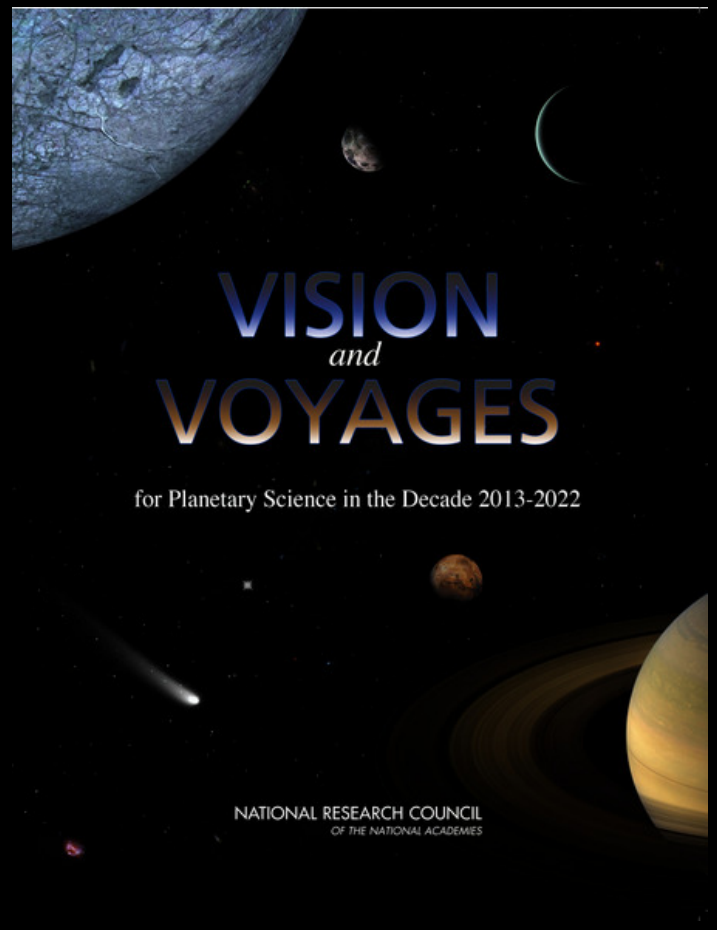

SCEM: Lunar science encompasses four overarching themes of solar system exploration.

2003 Decadal

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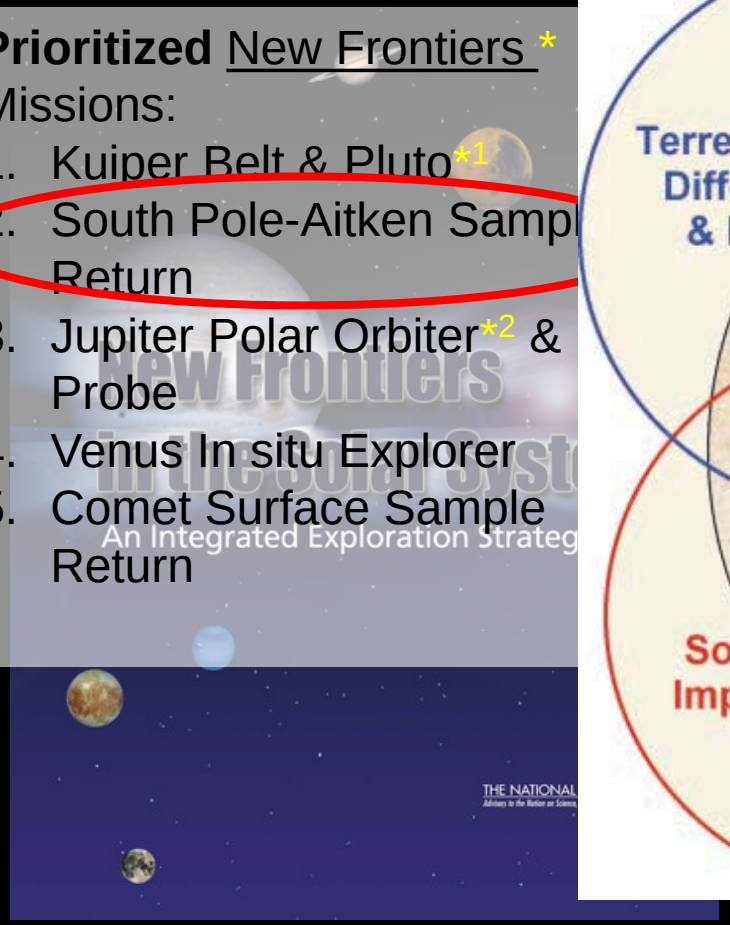

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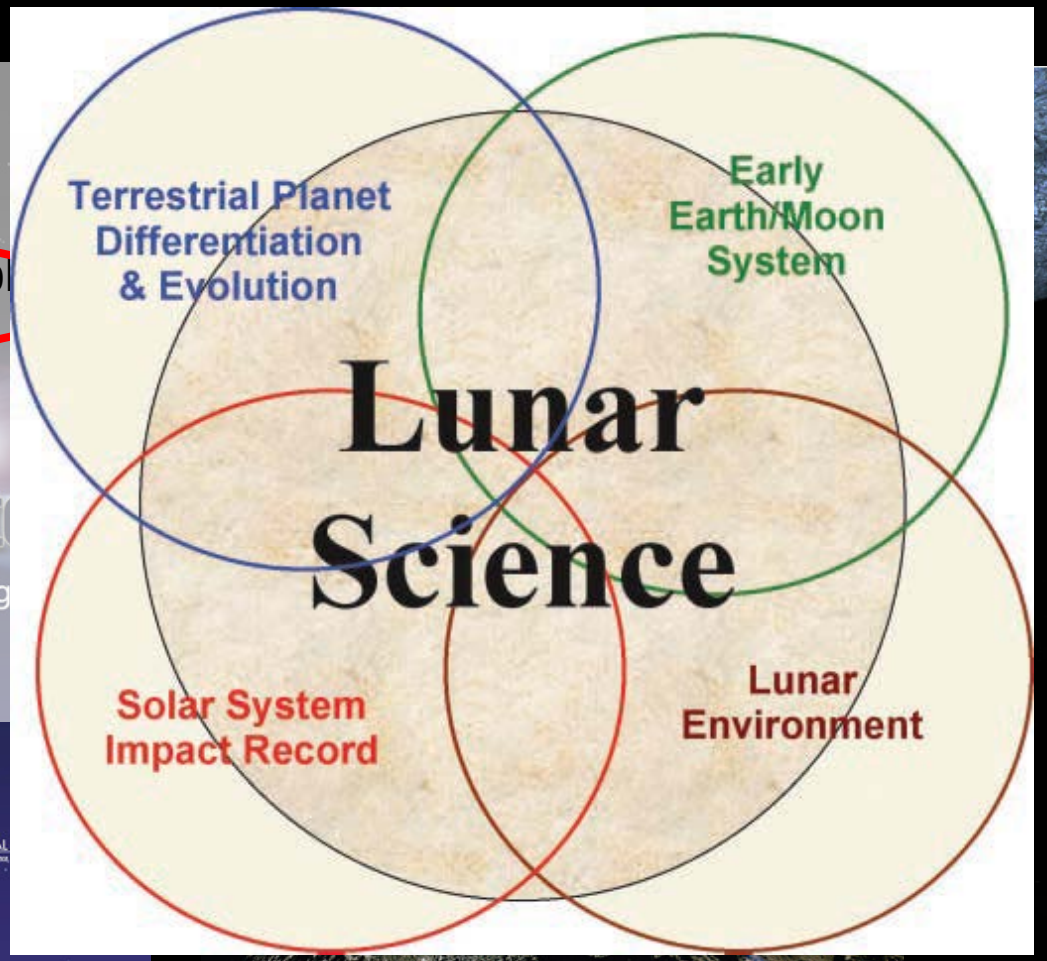

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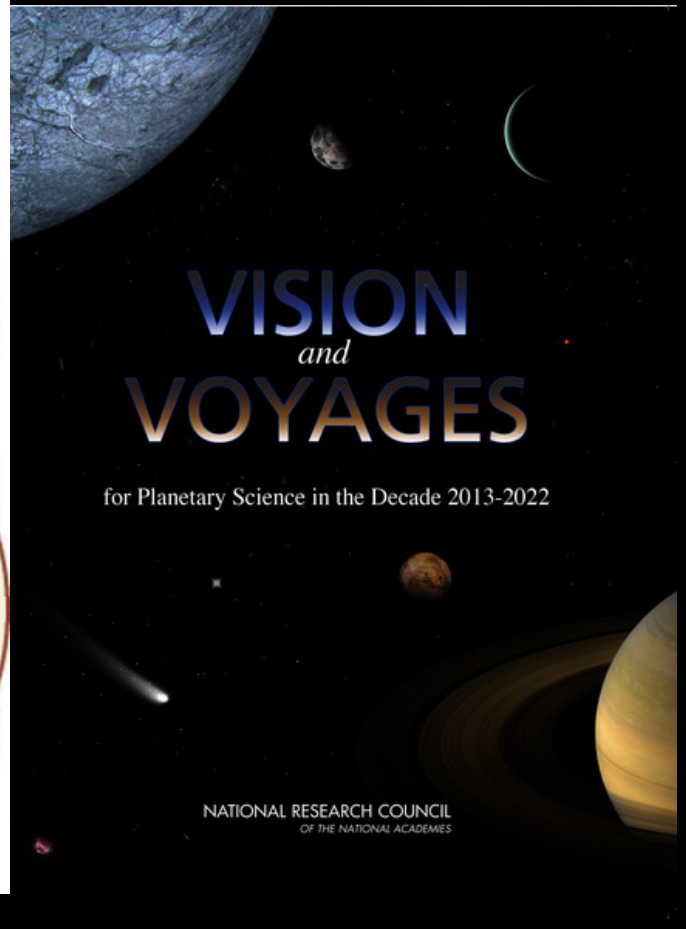

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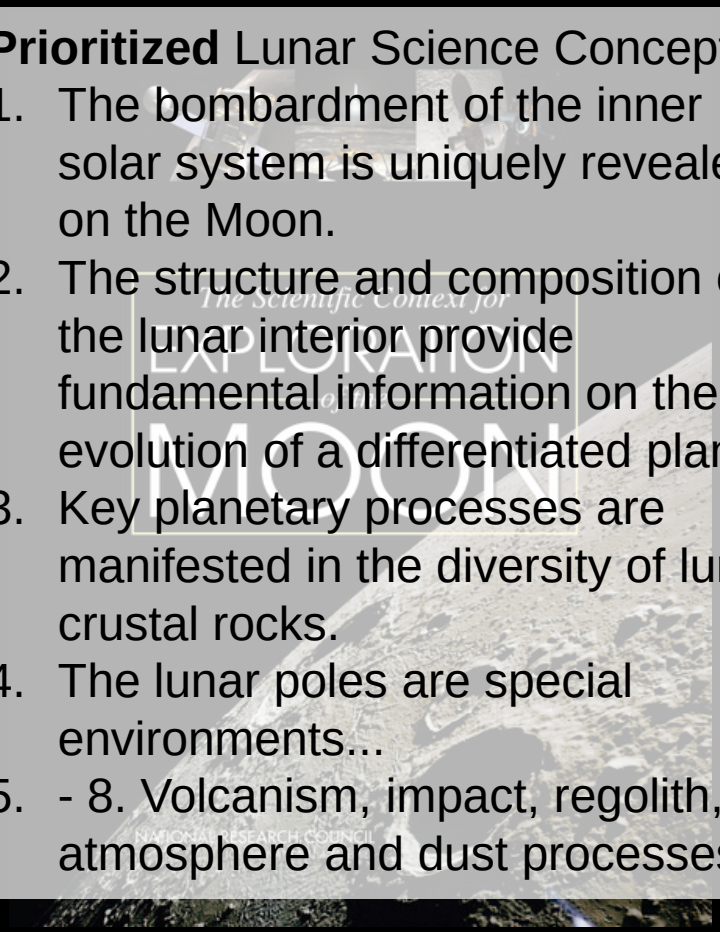
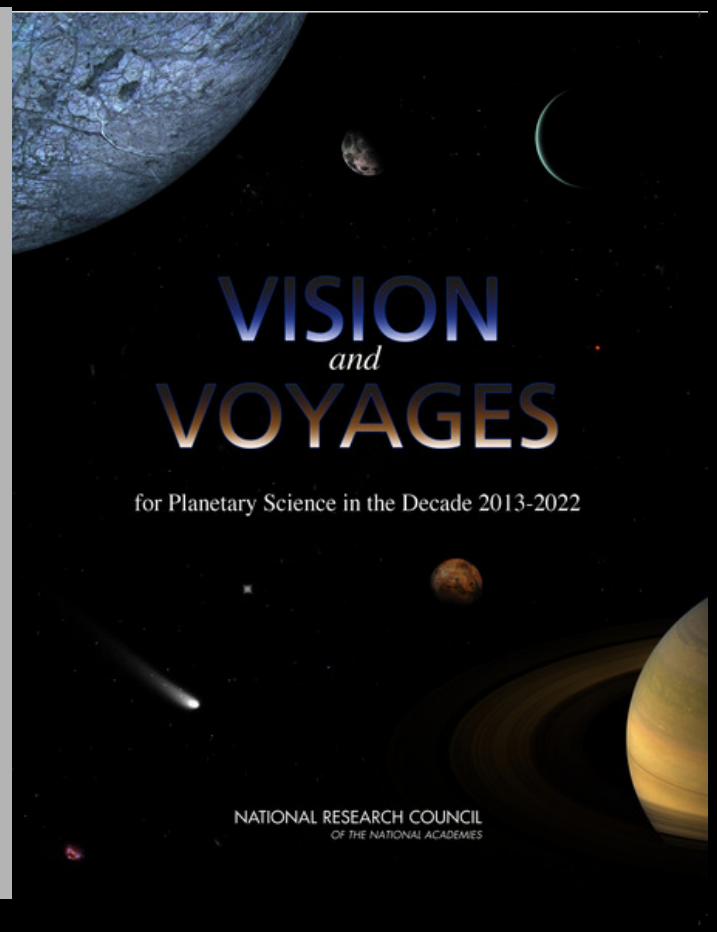
3. Key planetary processes are manifested in the diversity of lunar crustal rocks.
4. The lunar poles are special environments...
5. - 8. Volcanism, impact, regolith, atmosphere and dust processes....



2011 Decadal



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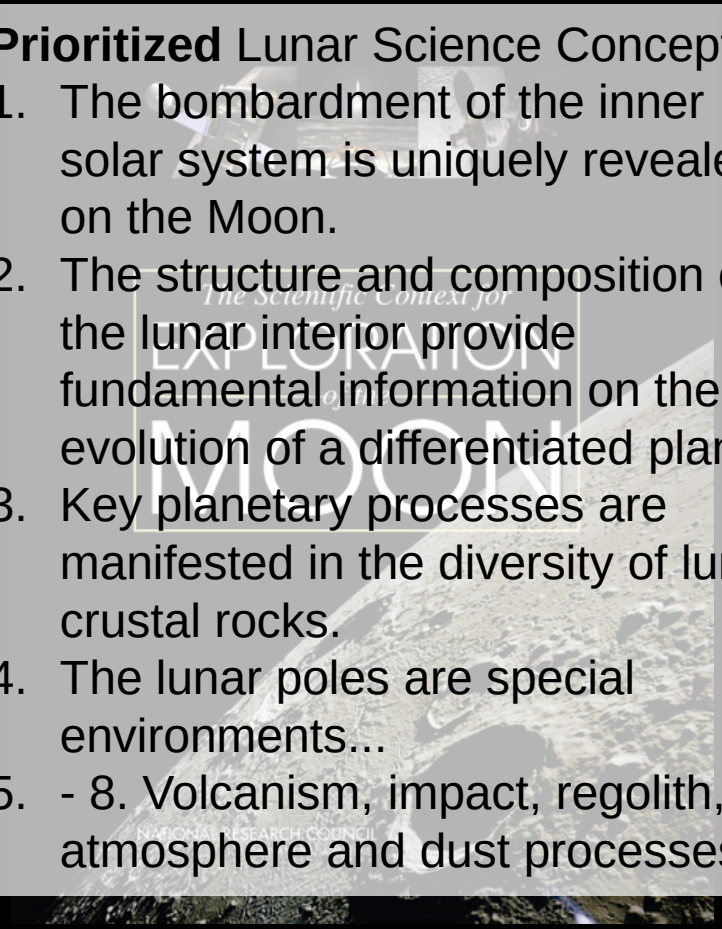


2011 Decadal

New Frontiers Missions (no priority):

New Frontiers 4 (in Phase A):

- Comet Surface SR*
- South Pole-Aitken SR
- Saturn Probe

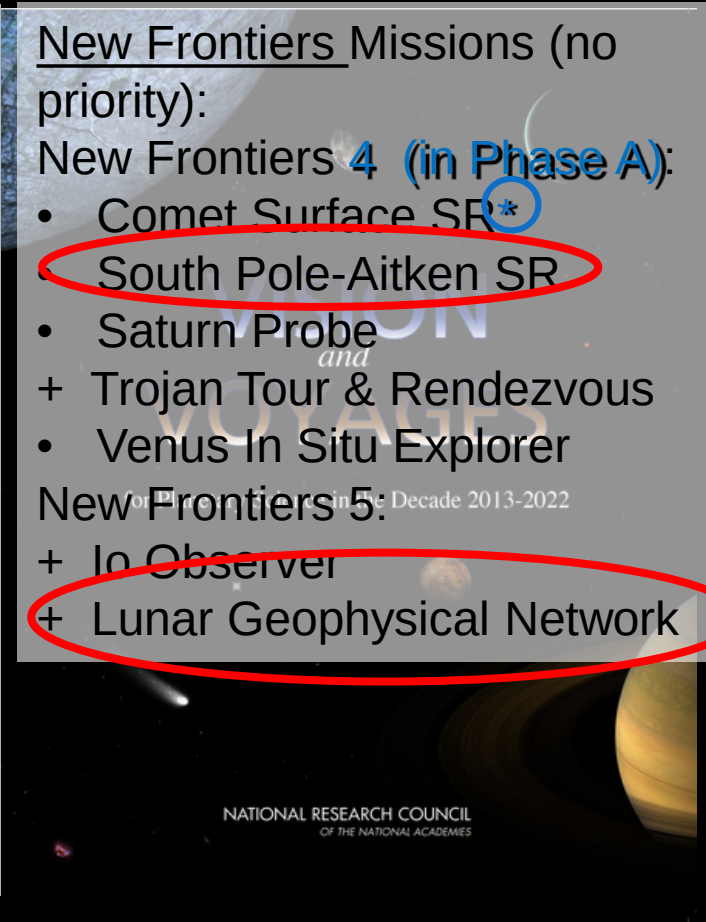
\+ Trojan Tour & Rendezvous

- Venus In Situ Explorer

New Frontiers 5:

\+ Io Observer

\+ Lunar Geophysical Network



NRC Planetary Science Reports

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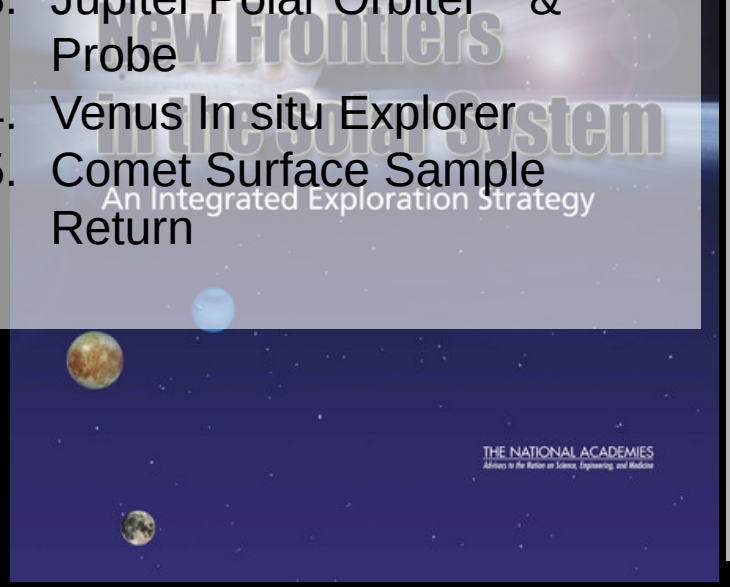

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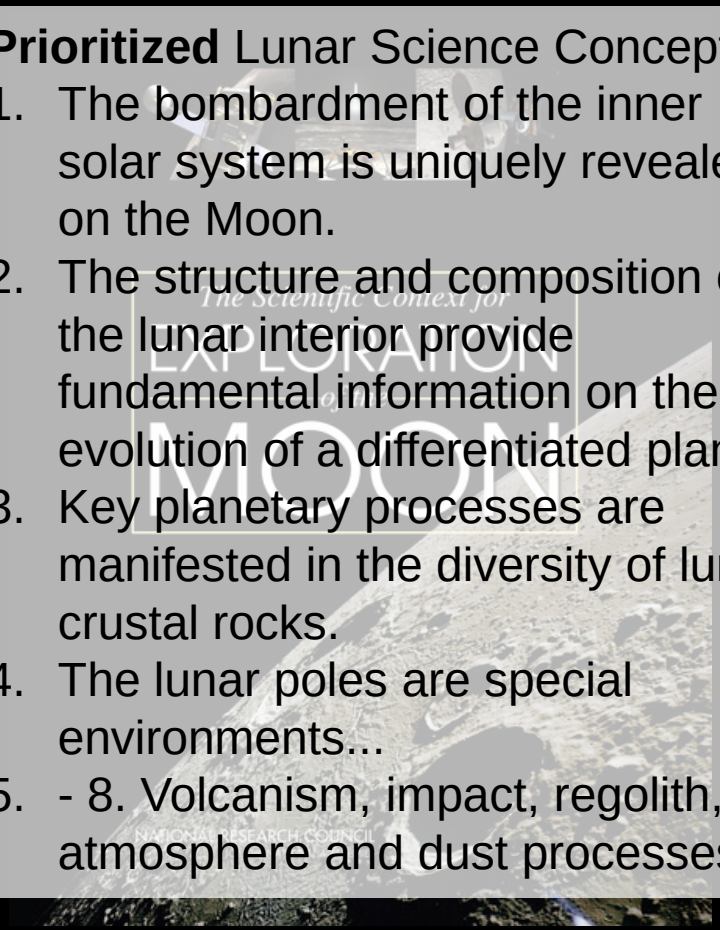

2011 Decadal

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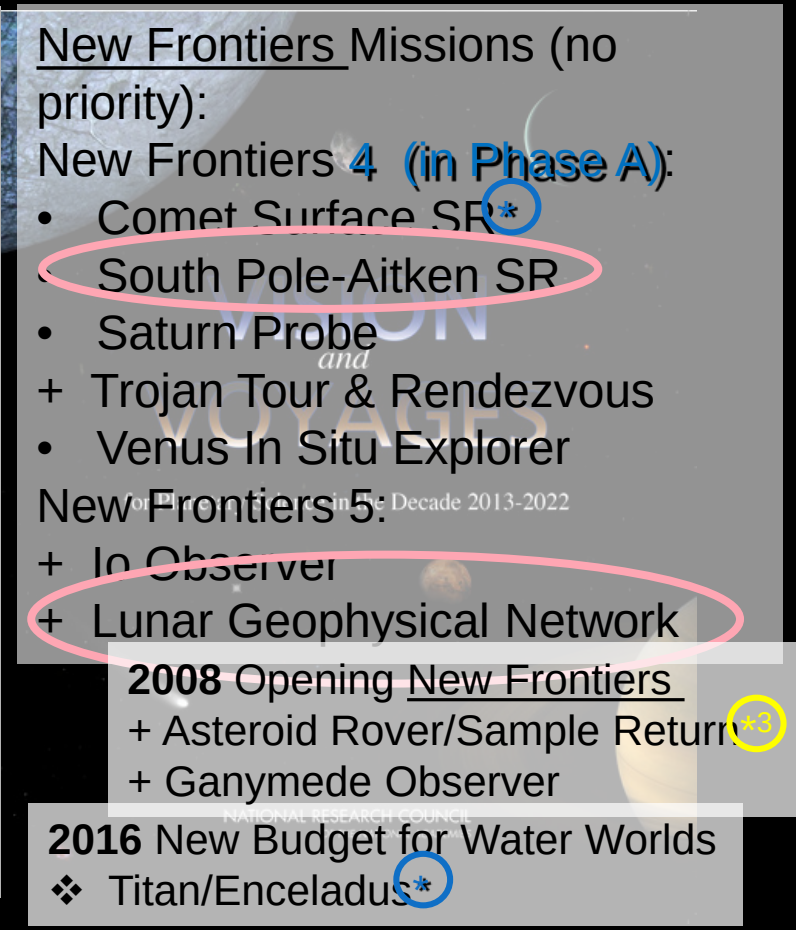
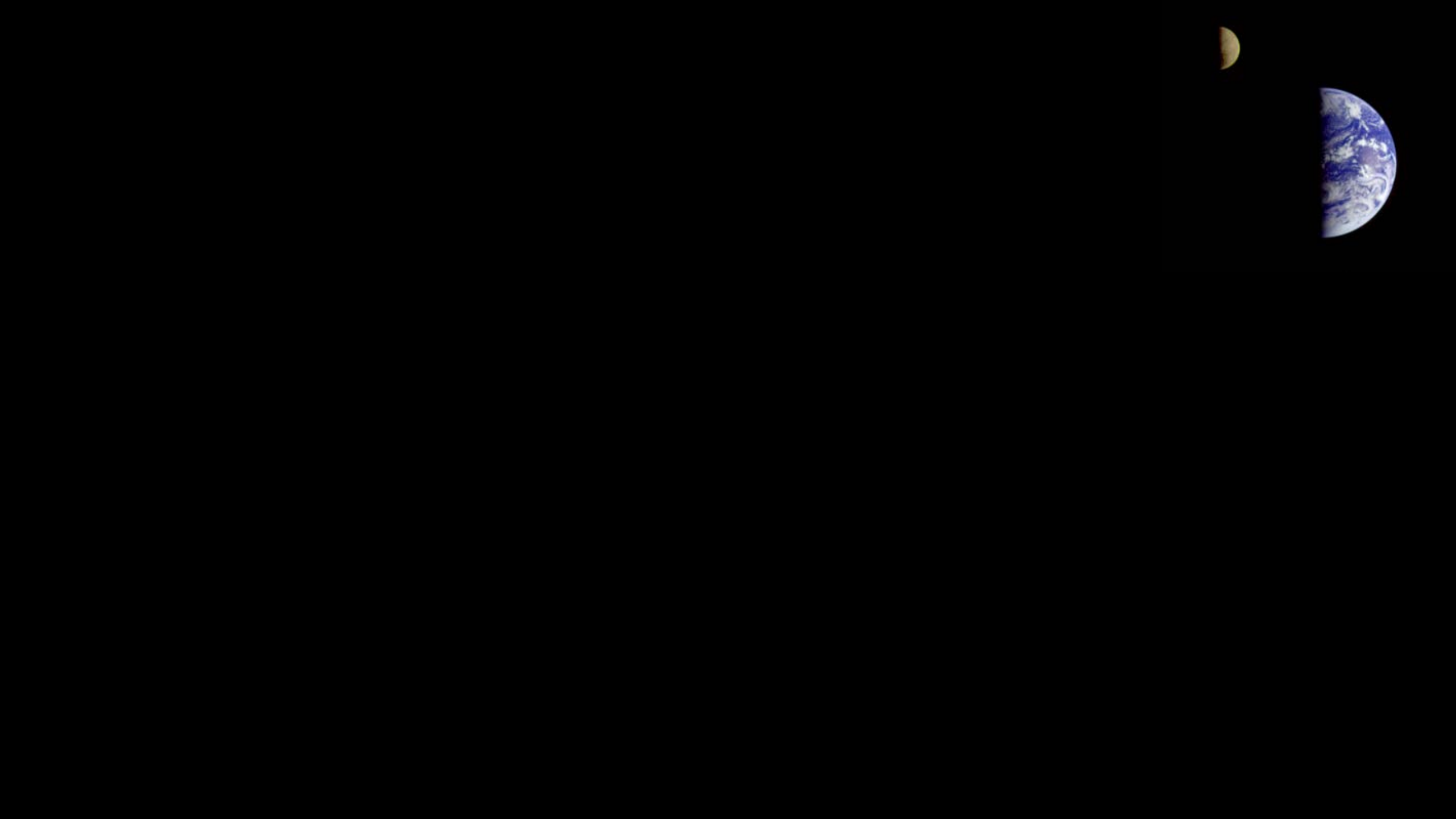


2008 Opening New Frontiers *3
\+ Asteroid Rover/Sample Return
\+ Ganymede Observer

2016 New Budget for Water Worlds
❖ Titan/Enceladus*



Q: What are some examples of ***Transformative*** Lunar Science?

... The most important opportunities and potentially greatest scientific payoffs from future space exploration associated with the Earth-Moon system....

Pursues science and exploration issues for potential NASA targets of the near future:

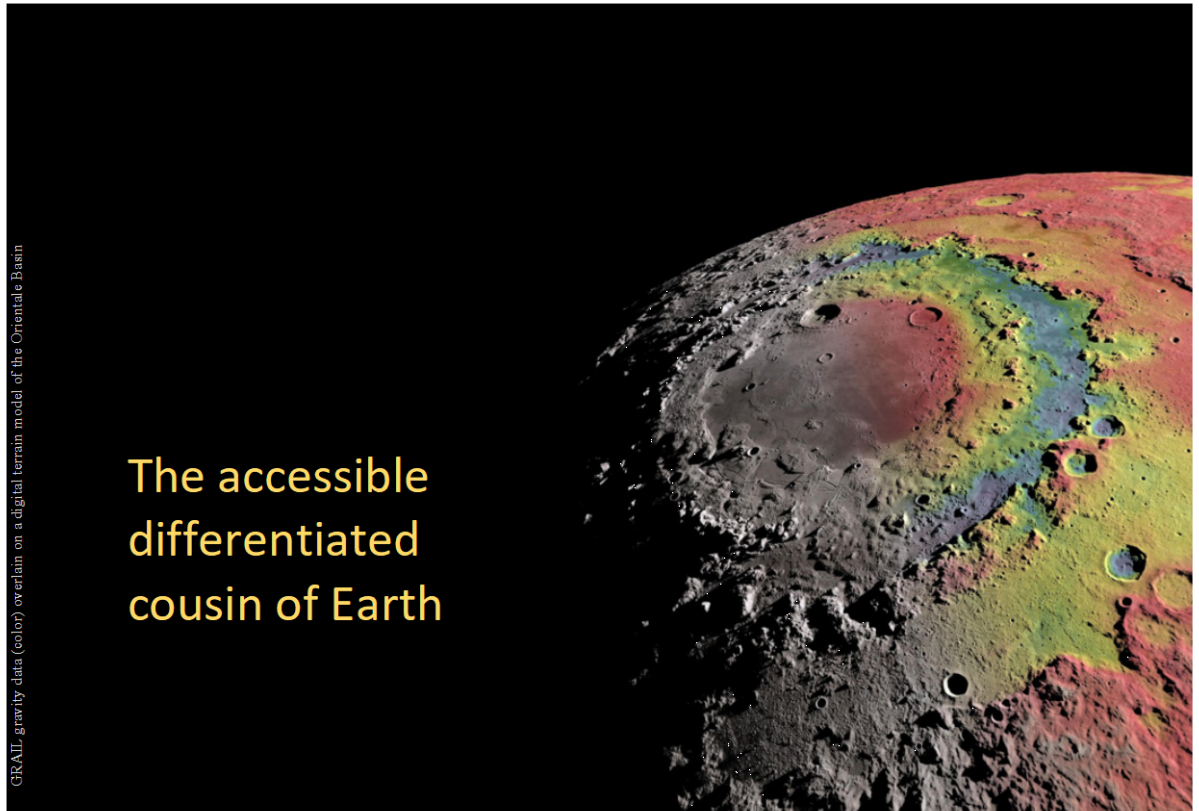
- The Moon
- Asteroids
- Phobos/Deimos

Transformative Lunar Science

Recommendations from scientists of the
Solar System Exploration
Research Virtual Institute (SSERVI)

Principal Contributors:
Dr. Carlé M. Pieters [Brown University]
Dr. Robin Canup [Southwest Research Institute]
Dr. David Kring [USRA Lunar and Planetary Institute]
Dr. James W. Head, III [Brown University]
Astronaut David R. Scott [Apollo 15 Commander]

Prepared: January 2018



The accessible differentiated cousin of Earth

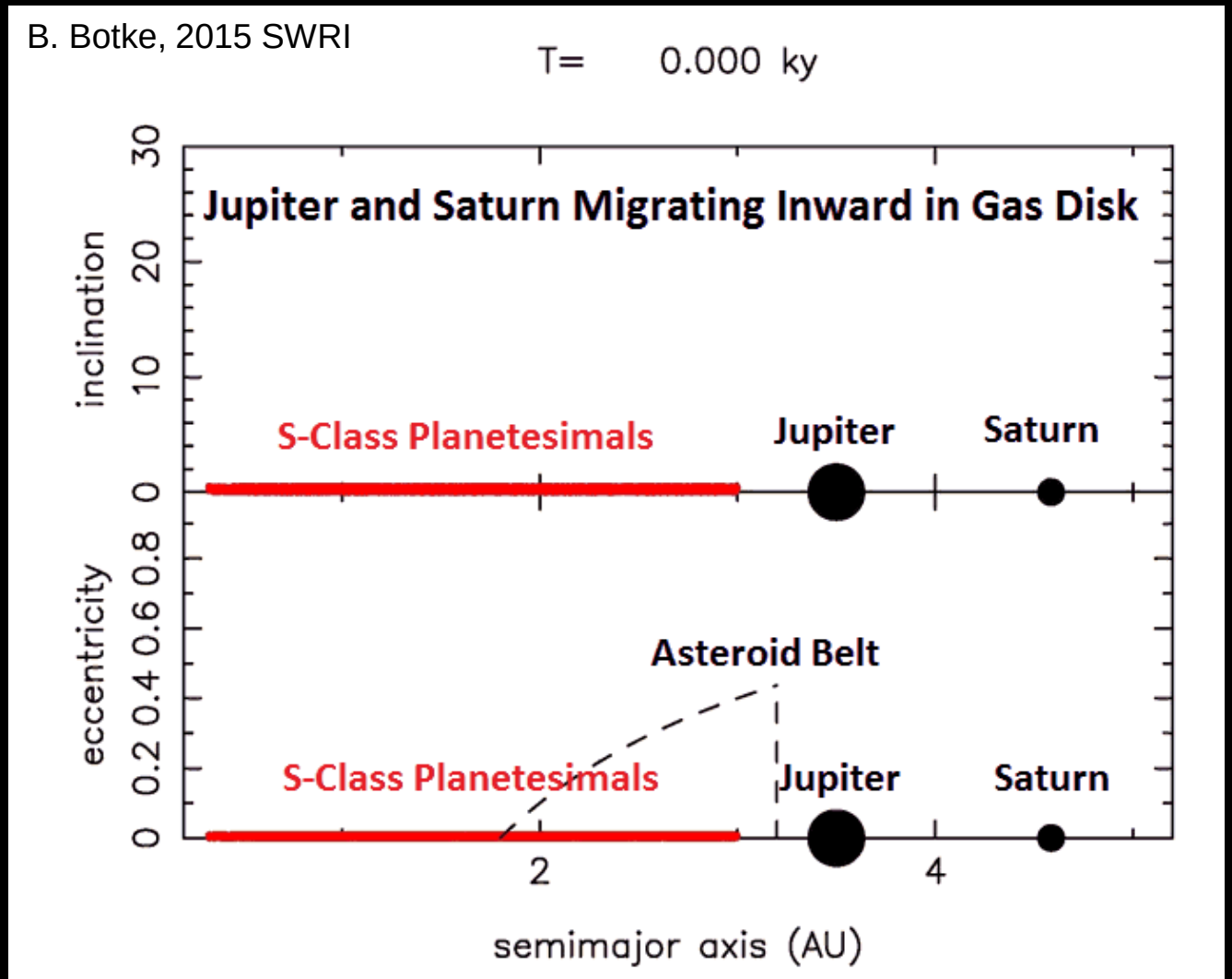
Available through the SSERVI website: https://sservi.nasa.gov/

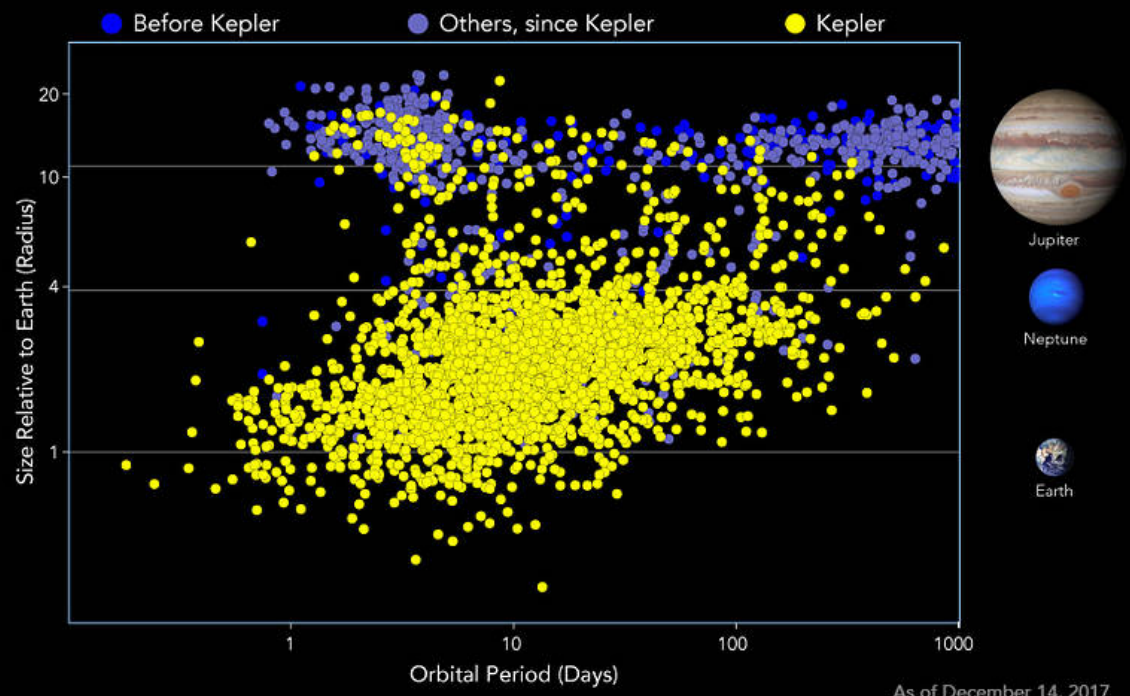
Contents:

- Game-changing Science Examples
- Moving Forward

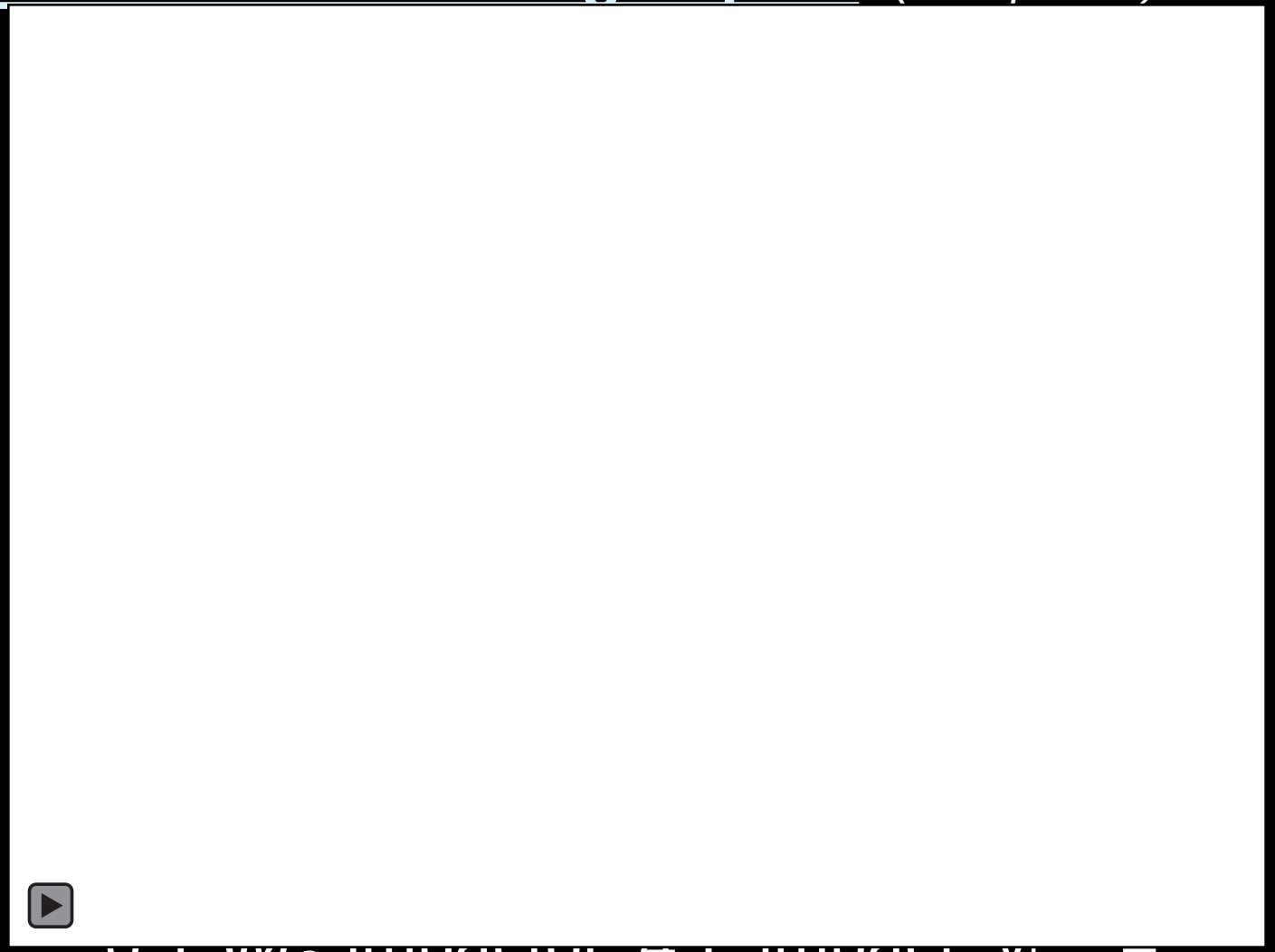
Early Giant Planet Formation, Migration.....

B. Botke, 2015 SWRI





Canonical lunar-forming impact: *(Canup 2004)*

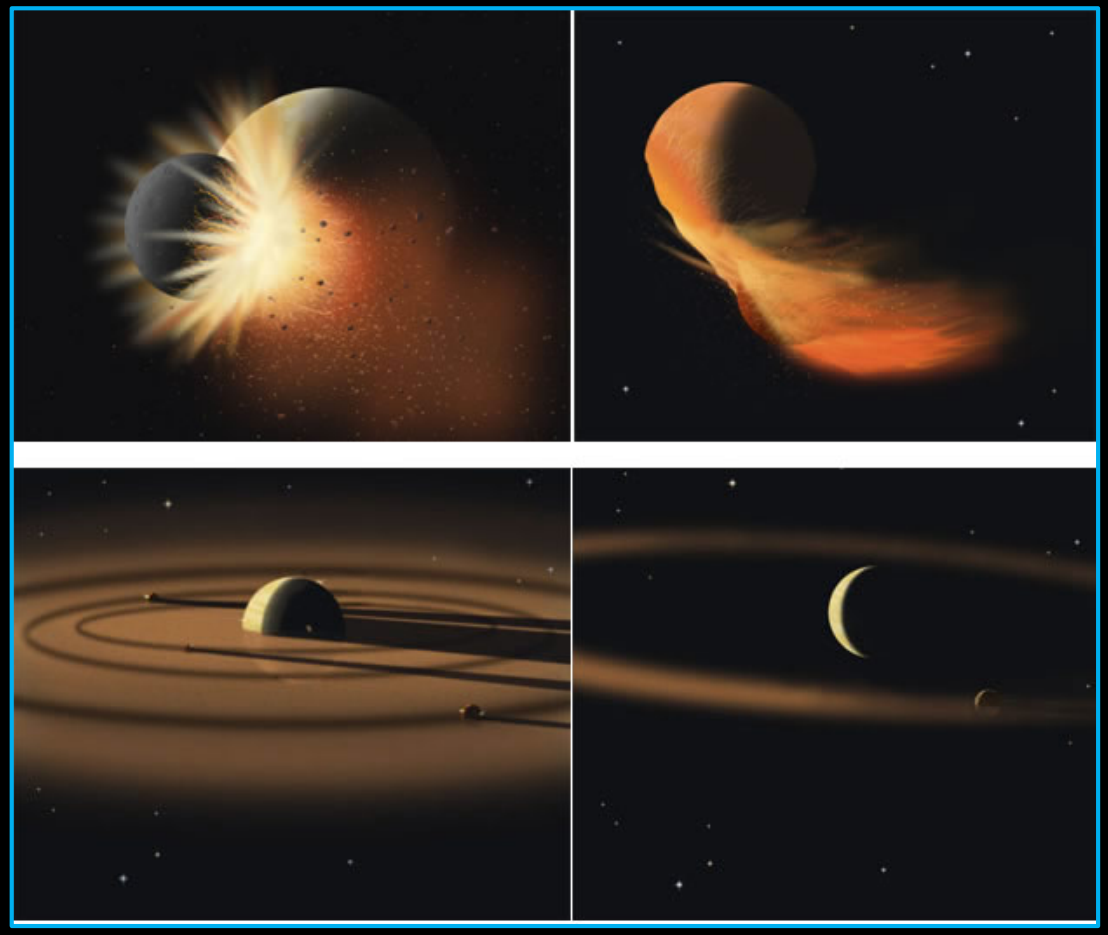


$0.13M_{\oplus}$ impactor, 45° impact, $v_{imp} = v_{esc}$

2000 K > 7000 K

The Moon holds the key to understanding the earliest evolution of our Solar System

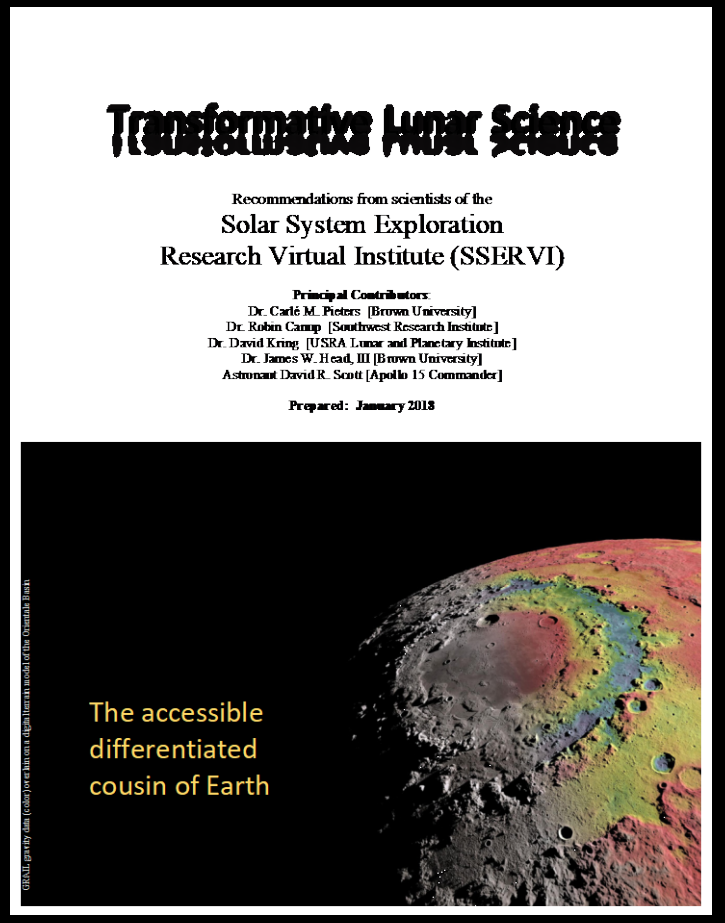
Giant Impacts & the Origin of the Earth-Moon System



- The early Solar System bombardment appears to be tied to a reorganization of the Solar System.
- What type of disk did the Earth-Moon forming impact produce; did the proto-Earth and proto-Moon chemically and isotopically equilibrate?
- During the first billion years, over 40 basins 300 to 2,500 km in diameter were produced on the Moon. The bombardment of Earth was inevitably even **more** severe.

Transformative Lunar Science

- Game-changing Science Examples
- Moving Forward



Examples of Transformative Lunar Science

a) Establish the period of giant planet migration and its effects in our Solar System.

b) Provide an absolute chronology for Solar System events.

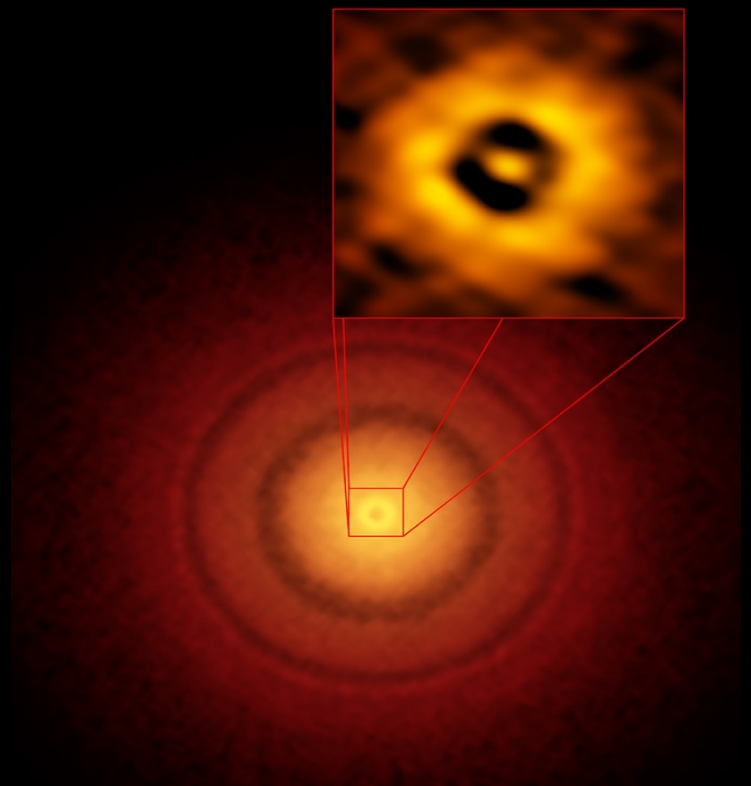
c) Use the accessible vantage from the lunar farside to view the universe.

d) Understand and utilize the special water cycle of the Moon and other airless bodies. [NEW]

e) Characterize the Moon's interior to reveal how this differentiated neighbor of Earth formed and evolved.

f) Evaluate the extended record of space weather and fundamental processes of plasma interactions with surfaces.

Establish the period of giant planet migration and its effects in our Solar System.



ALMA [2016] 870 μm data of TW Hya proto-planetary disk highlighting the evolving distribution of small particles around the young star. Centermost gap is at ~ 1 AU.

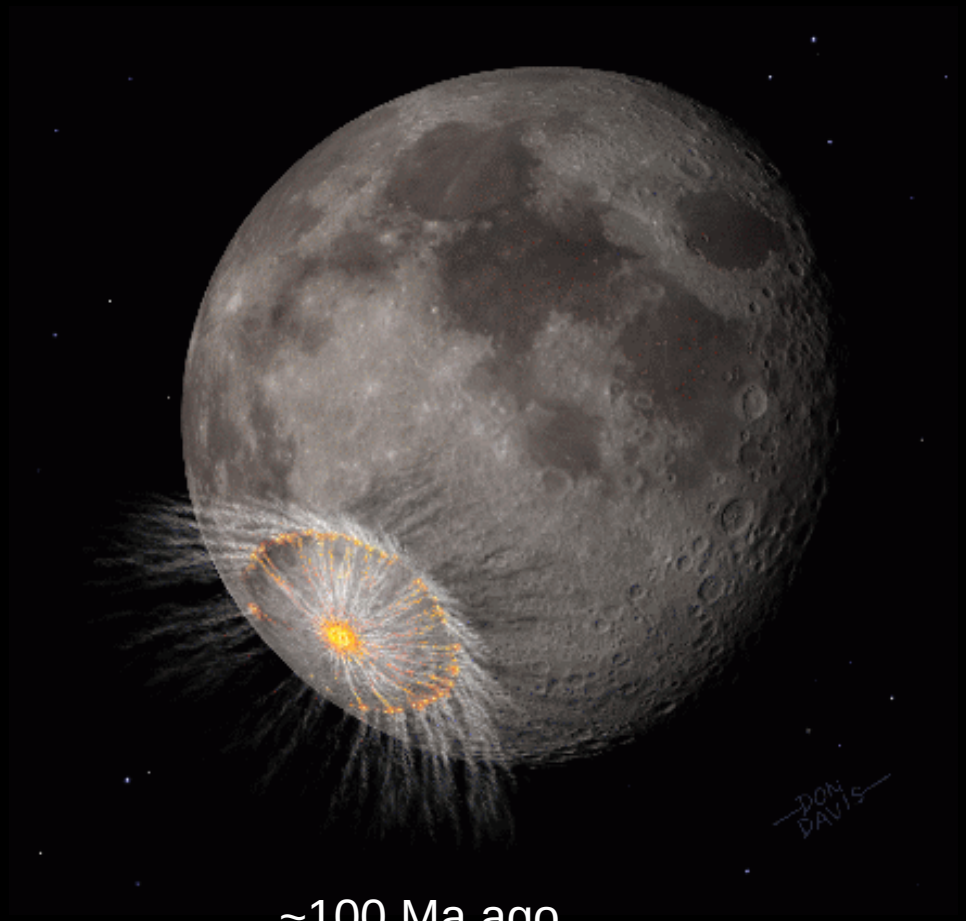
- Date the sequence and duration of basin forming events at 1 AU.
- Evaluate the effects on early internal structure.

Need:

➢ Targeted basin samples (melt and deposits) returned for detailed analysis.

➢ Probe the crust/mantle composition and interface for each (seismic net).

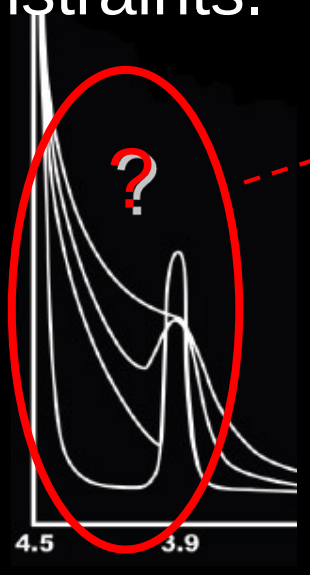
Provide an absolute chronology for Solar System events.

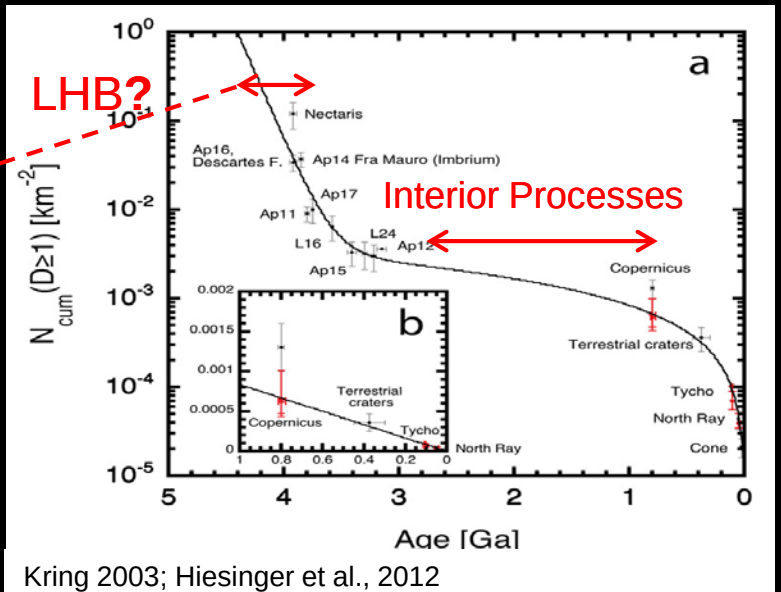


~100 Ma ago

- Airless bodies are continually bombarded by impacts.
- The number of craters accumulate with time.
- If the absolute age of several surfaces are known, CSFD* allow unvisited surfaces to be dated. *[corrected for planet location, gravity, etc.]

Need targeted **samples** to establish key age constraints.





Kring 2003; Hiesinger et al., 2012

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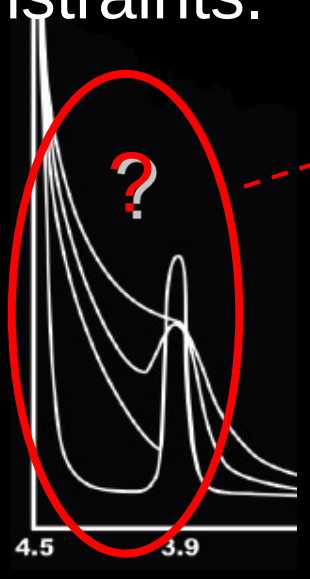

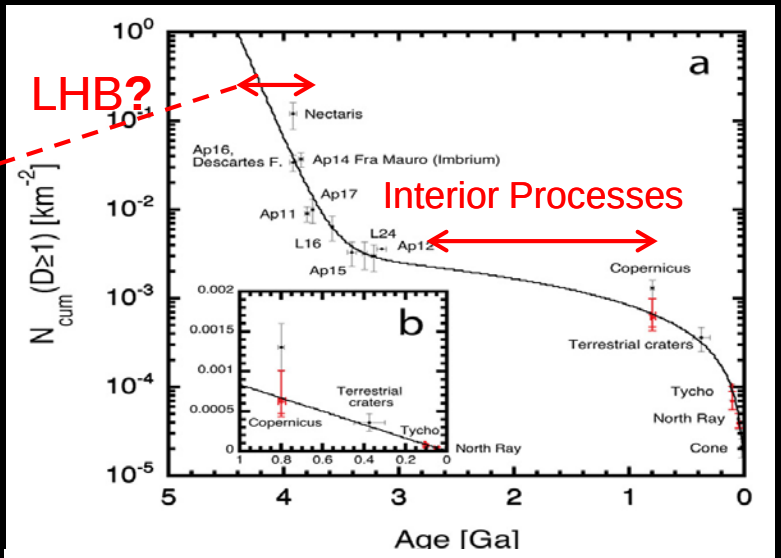

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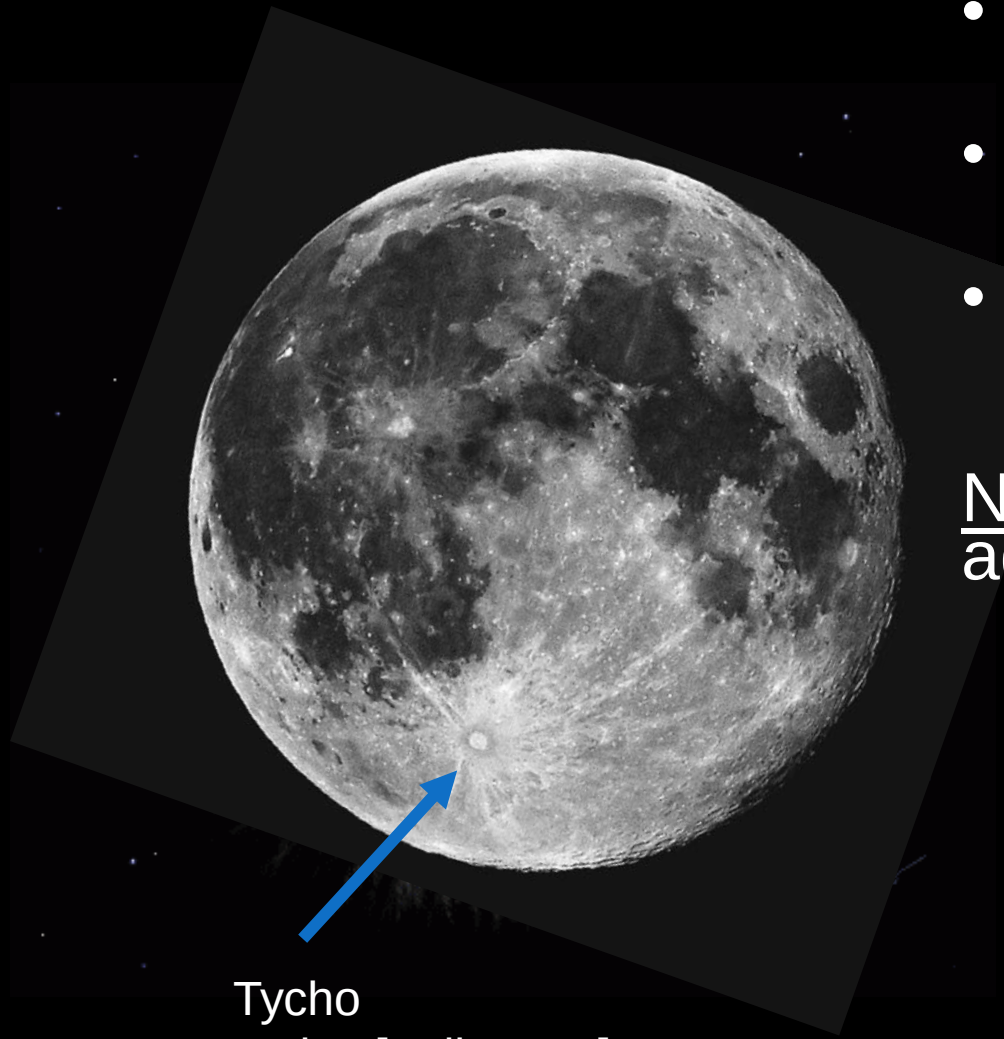

Tycho
Today [Full Moon]

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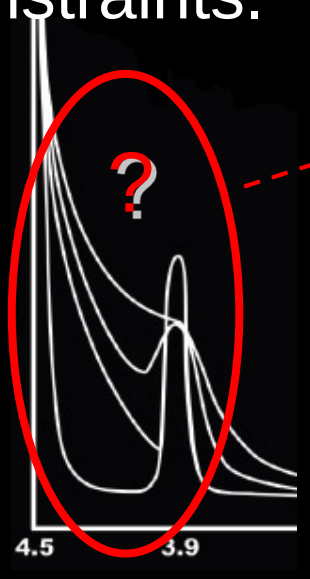
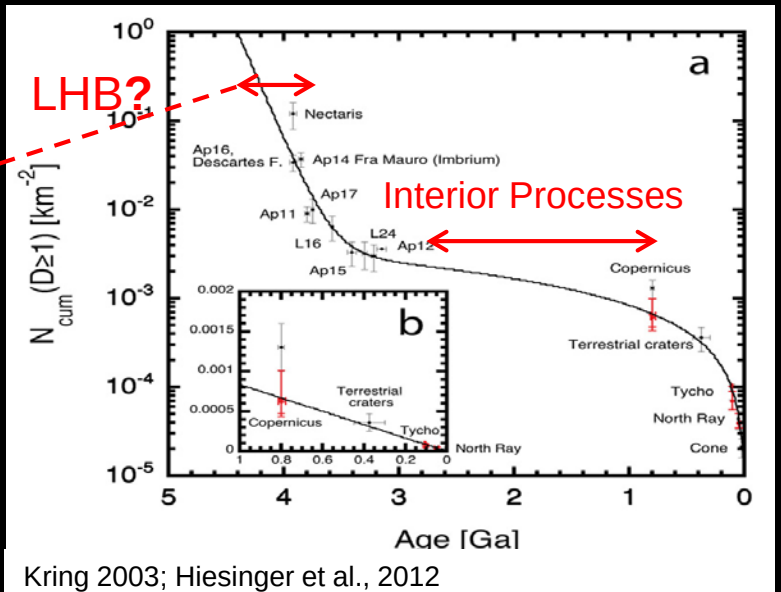
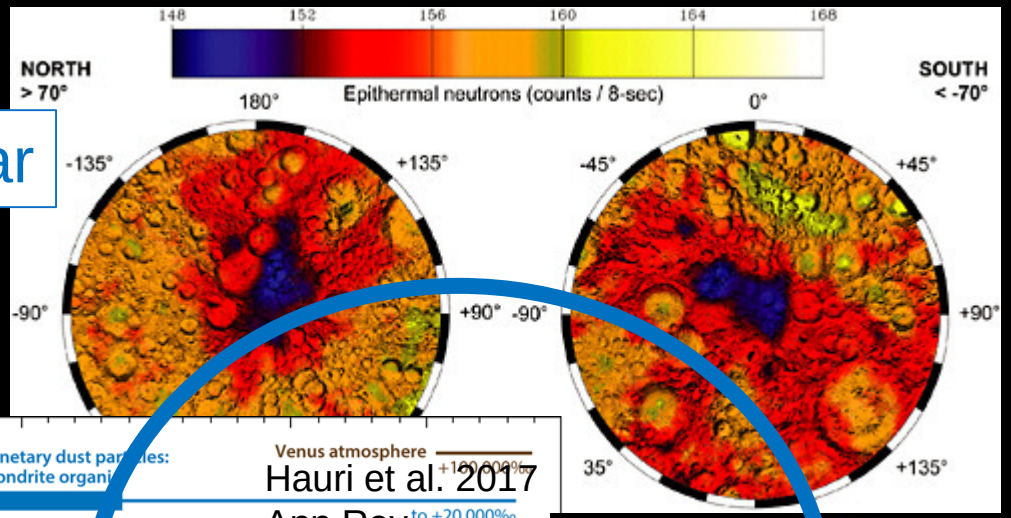


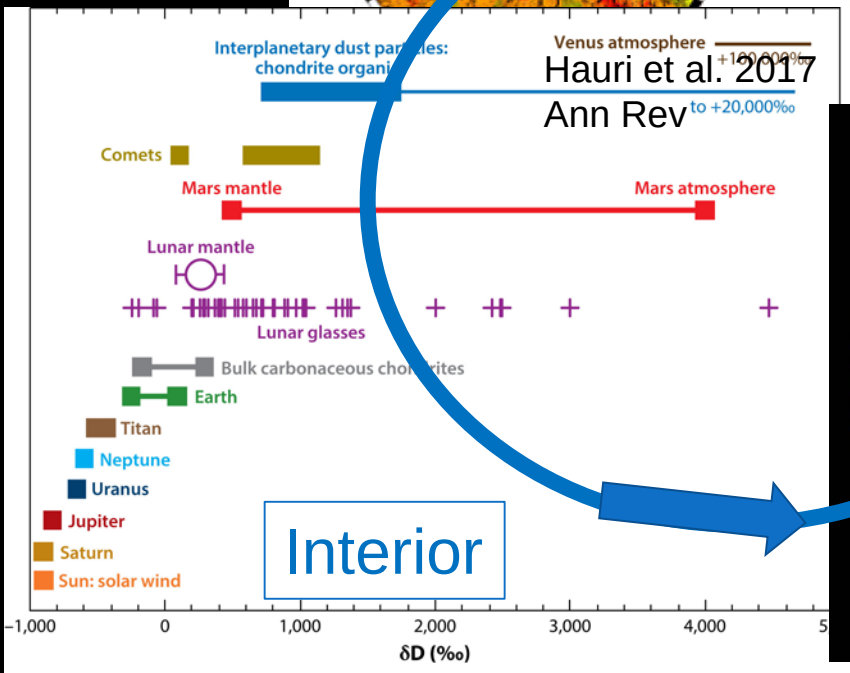


Kring 2003; Hiesinger et al., 2012

Understand and utilize the special water cycle of the Moon (and other airless bodies).

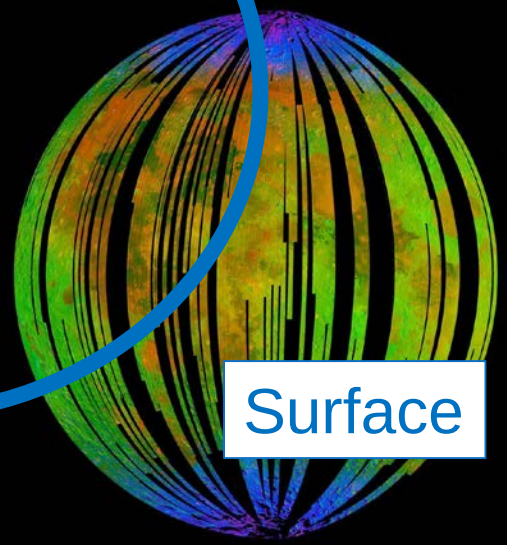


Polar



Hauri et al. 2017
Ann Rev

Interior



Surface

- NEW science issues (~10 yrs)
  Polar, Interior, Surface (SW) OH/H2O
- Tied to origin & evolution of water in the SS.

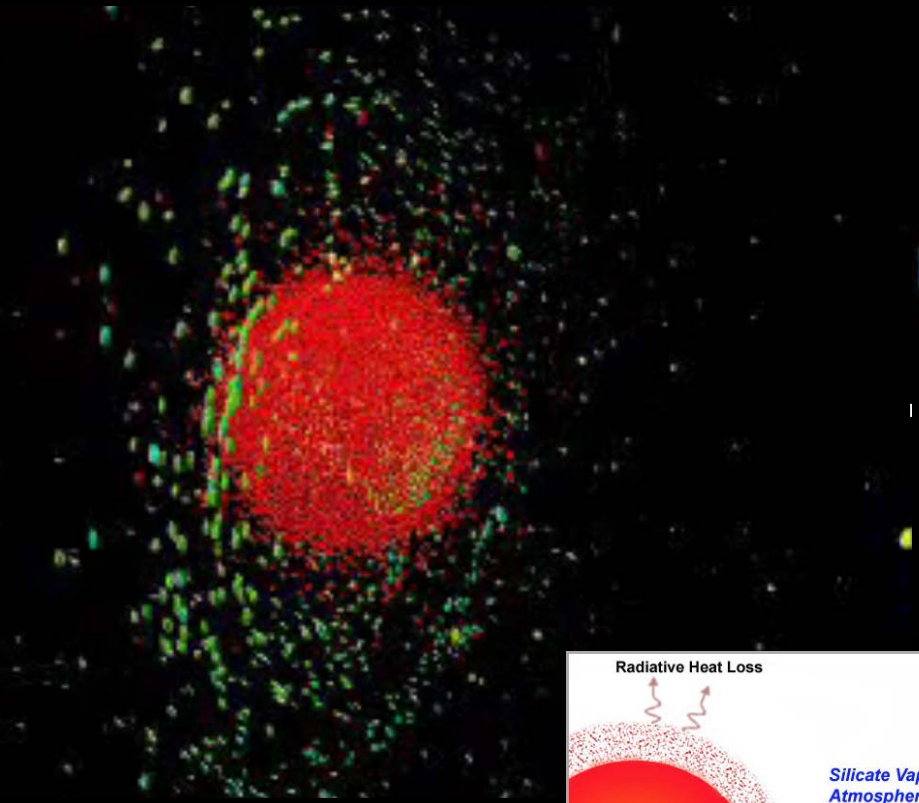
<u>Need</u>:

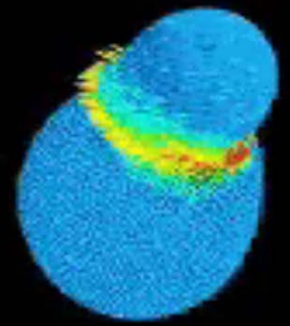
➢Orbital global & temporal documentation

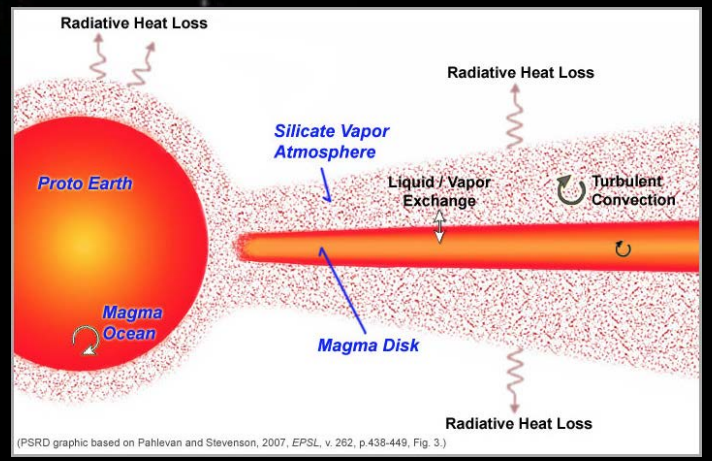
➢In-situ surface, depth, and temporal measurements

➢Samples

Characterize the Moon's interior to reveal how this differentiated cousin of Earth formed and evolved.



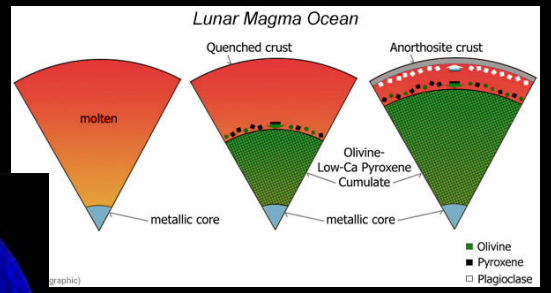




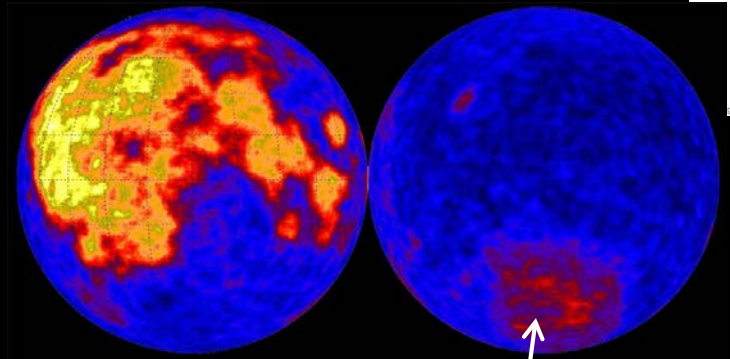
- Some form of early giant impact forming the Earth-Moon system is now generally accepted
- ...but details are hotly debated.

- Constraints on this later part of terrestrial accretion are essential and can best be obtained from the Moon.

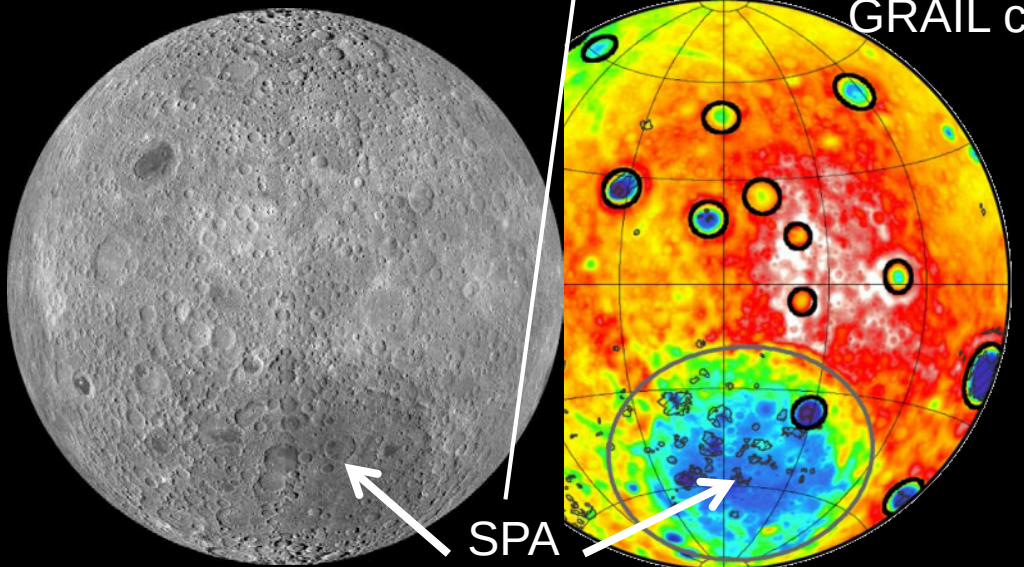
Characterize the Moon's interior to reveal how this differentiated cousin of Earth formed and evolved.



LP Nearside – Farside FeO



Farside
LRO mosaic
GRAIL crustal thickness



- Formation of the crust & mantle occurred w/in a few 100 Myr, including 'mantle overturn'.
- Global scale variations are formed, but with no plate tectonics, major impacts are the principal probes to the interior.

<u>Need</u>

➢Global geophysical network

➢Samples excavated from interior

Evaluate the extended record of space weather and fundamental processes of plasma interactions with surfaces.

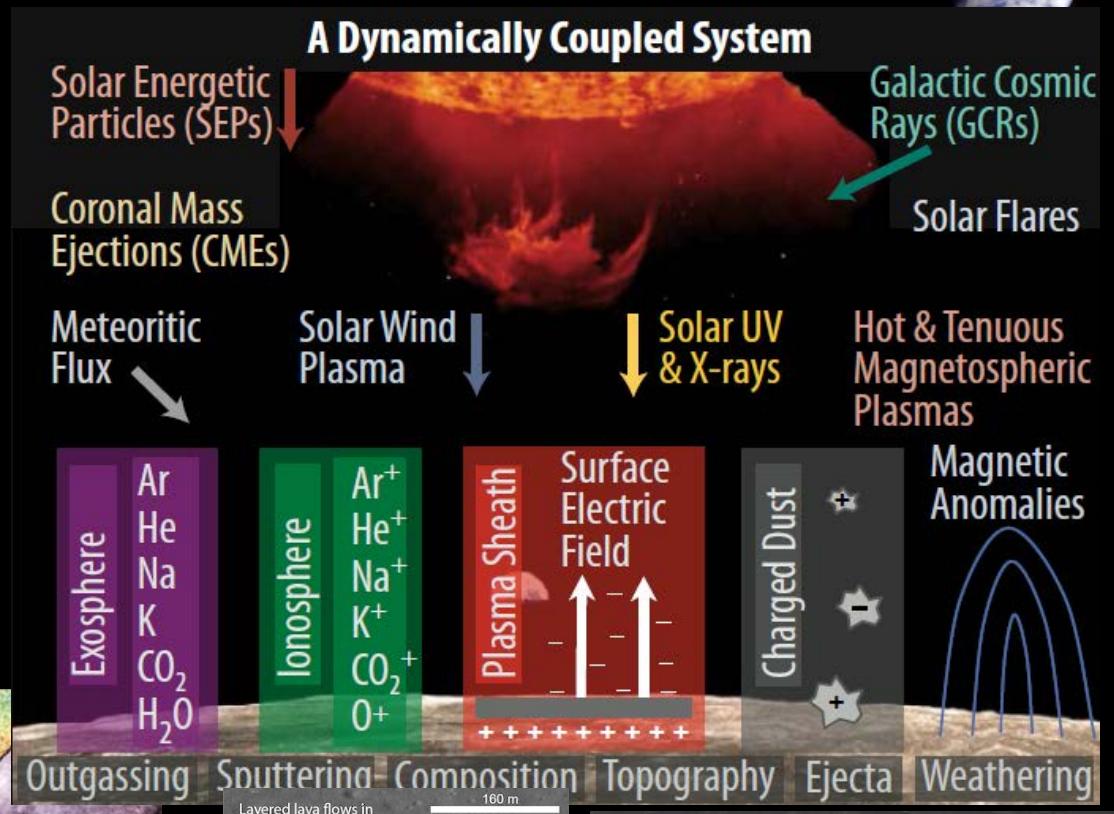
- Airless bodies are continuously exposed to and interact with the harsh space environment.
- The lunar regolith responds to diurnal cycles and also accumulates and records the history of the sun at 1 AU.

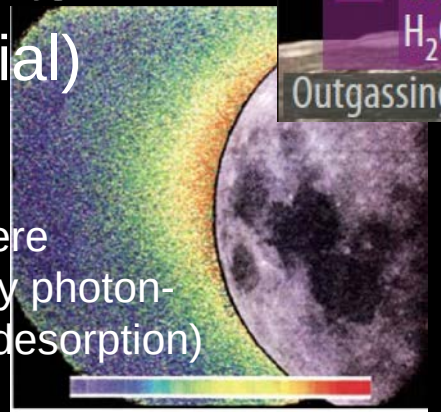
<u>Need</u> plasma and particle experiments:

➢Orbital (low-res temporal and spatial)

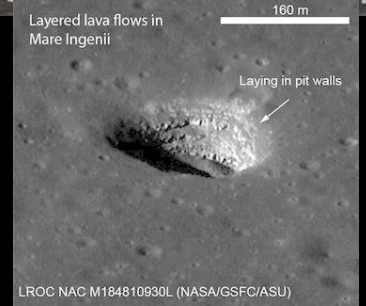
➢In situ (temporal details)

➢Rover (spatial details)





Na exosphere (liberated by photon-stimulated desorption)



Reiner Gamma

Moving Forward [NASA Commitments]

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- Achieve Global leadership in lunar exploration (with international partners).
- Establish a solid lunar exploration infrastructure.
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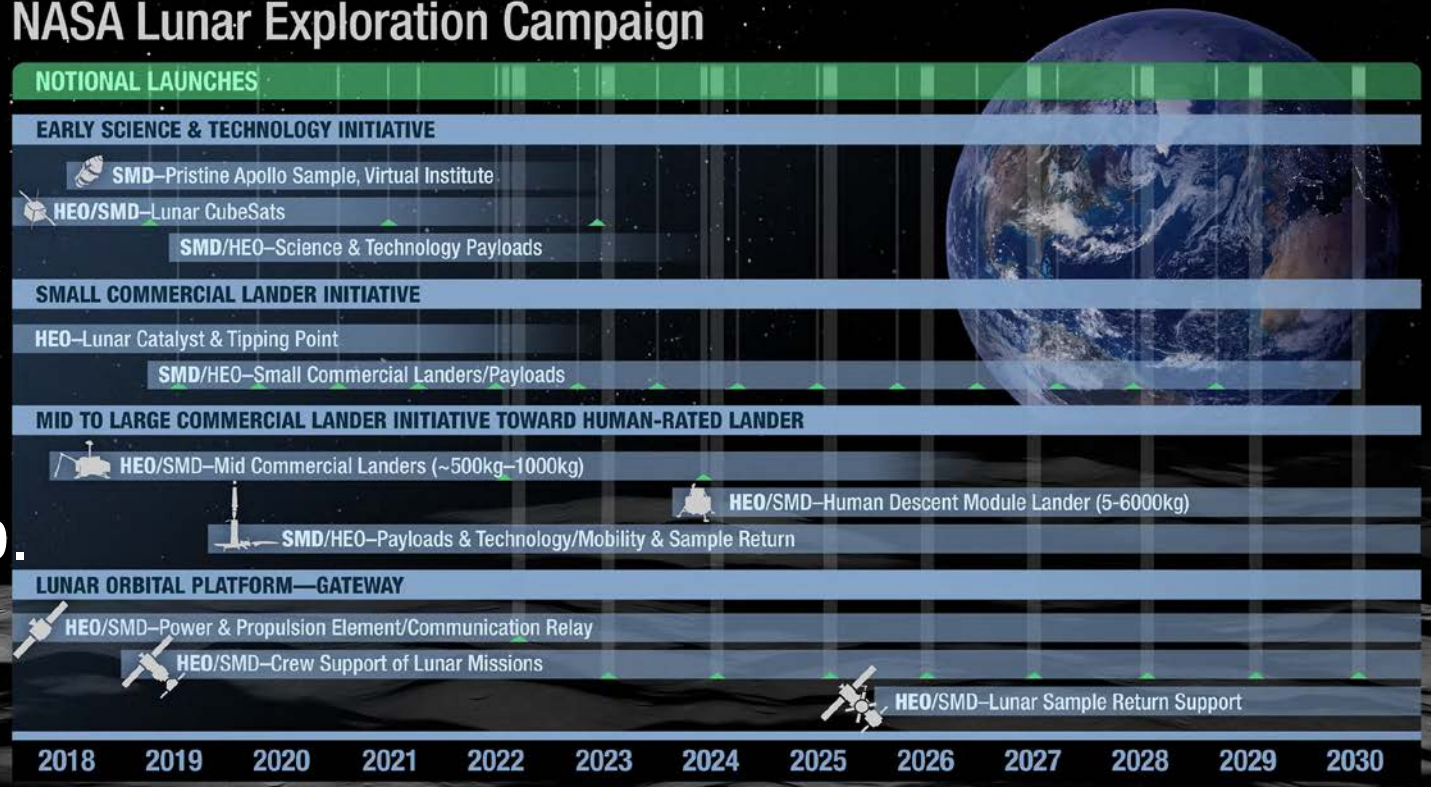

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Essential elements:

- Global access
- Modern communication and strong data downlink network [streaming video and virtual reality are expected]
- Known and reliable launch opportunities
- Long duration operations

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New era of planning and operations:

- Integrate Science and Engineering from the beginning. [See NRC 1993-1997 CHEX reports & Section 7 of SCEM]
- Train engineers and astronauts on science goals; train scientists on engineering constraints.
- Iterate. Improve Design Reference Campaigns.

Moving Forward [NASA Commitments]

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HIGH interest and commitment

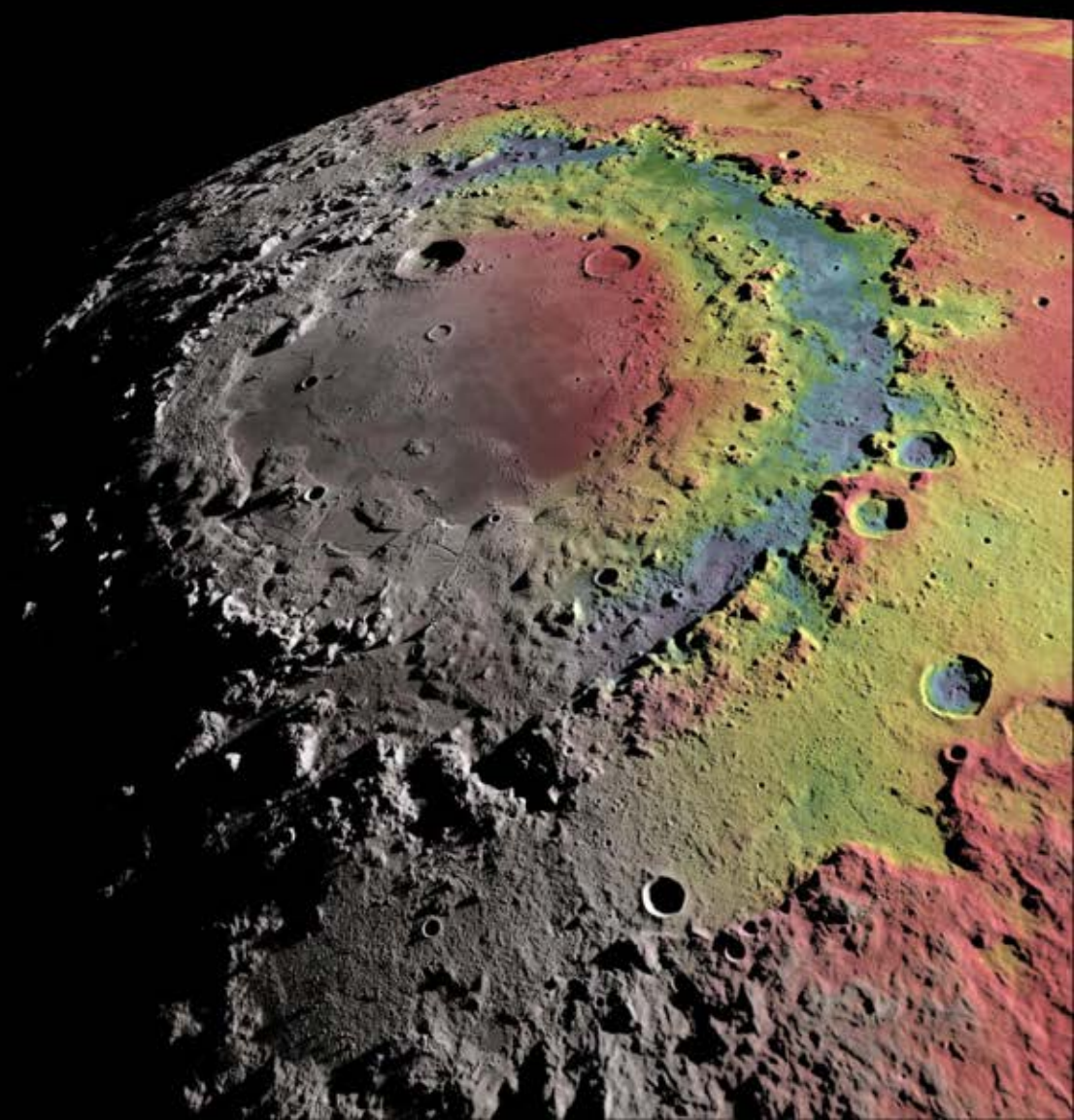
- Moon Express
- Astrobotic
- Team Hakuto
- Blue Origin
- Team Indus
- SpaceX
- Etc.

Moving Forward [NASA Commitments]

In summary,

A strong NASA-led International Lunar Exploration Program would not only demonstrate continued leadership of the U.S. and garner attendant pride and prestige, but would also develop the international and commercial partnerships that would help prepare and propel the next great exploration endeavors beyond the Earth-Moon system.

The accessible differentiated cousin of Earth



GRAIL gravity data (color) overlain on a digital terrain model of the Orientale Basin

Which?
M – E - S/C
E – M - S/C