JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

# Lunar Volatiles and Solar System Science

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*Corresponding author, Johns Hopkins Applied Physics Laboratory. Co-author contributions and institutional affiliations are included in the white paper, available at: https://tinyurl.com/volatiles-wp. **It is a pleasure to acknowledge many other colleagues (not listed above) whose work informed this white paper.**

**Presentation to the Decadal Survey Panel on Mercury and the Moon**
**November 20th, 2020**

Background image: Oblique view of the illuminated rim of Shackleton crater, at the lunar South Pole [NASA/GSFC/Arizona State University].

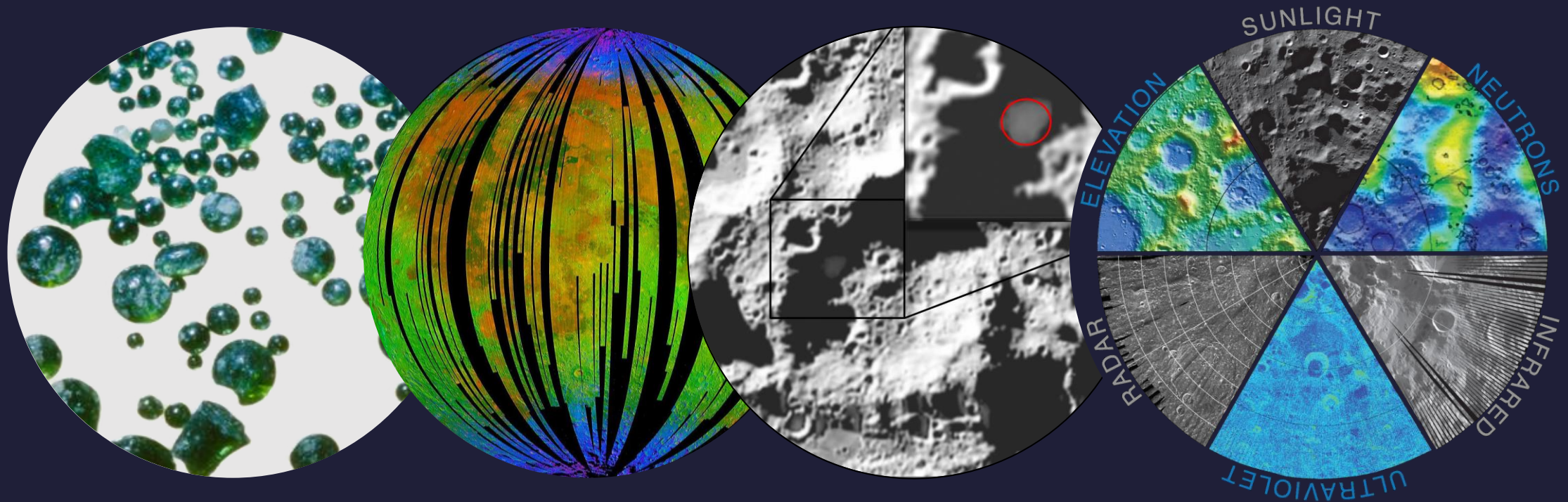
# The Molecule That Launched A Thousand Spacecraft

Water has played a key role in the history of the Earth-Moon system, and is central to some of the Big Questions of planetary science: where are we, how did we get here, and where do we go next?


The lunar volatile system consists of **water and other species** (from noble gases to alkali metals) and spans the **surface**, **interior** and **exosphere**.

# An Incomplete Revolution

This decade marked the beginning of a revolution in our understanding of the lunar volatile system...

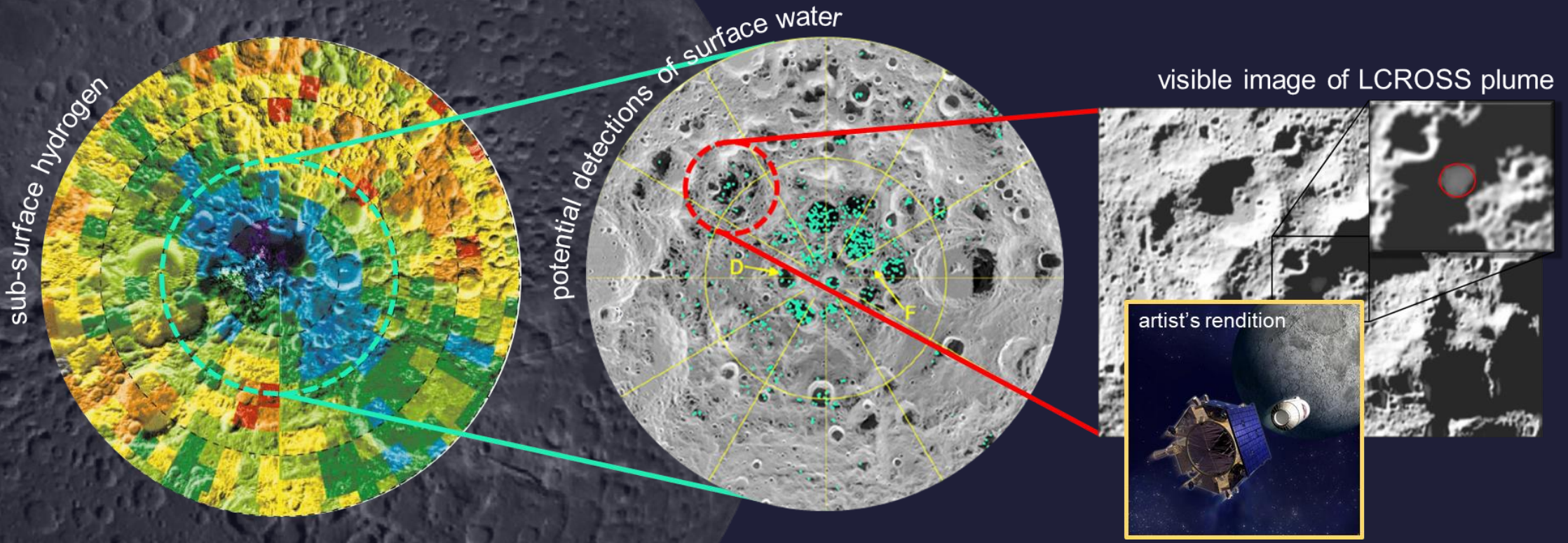



…yet many fundamental questions remain to be answered.

Left to right: Green glass beads (10-100 μm) from Apollo sample 15426 [NASA/JSC]; Moon Mineralogy Mapper color composite map of the lunar surface [ISRO/NASA/JPL-Caltech/Brown Univ./USGS]; visible camera image of the LCROSS plume [NASA]; LRO views of the lunar south polar region [NASA/GSFC].

# Science Questions for the Next Decade

- What is the composition (elemental and isotopic), concentration, distribution (lateral and vertical), and physical form of polar volatiles?



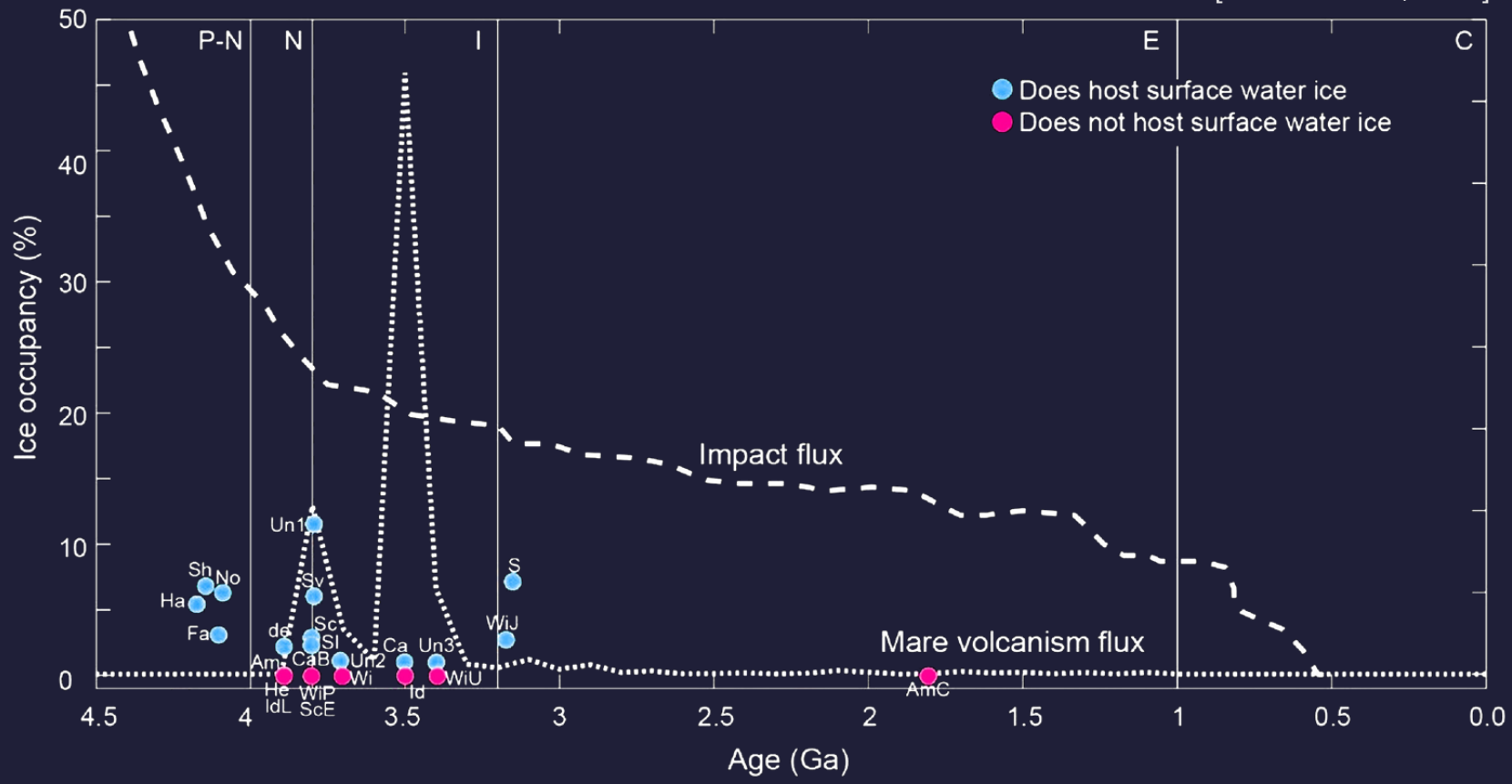

Left: Epithermal neutron flux [Feldman et al., 1998]. Center: Ice exposures constrained by M3, LOLA, Diviner, LAMP [Li et al., 2018]. Right: LCROSS [NASA].

# Science Questions for the Next Decade

- What are the relative contributions of impacts, volcanism and solar wind to the lunar polar volatile inventory, and how have these contributions varied over time?

  **Comparative planetology:** Why are the poles of Mercury so different from the Moon?

[Deutsch et al., 2020]




**Solar System Science**

The Moon's polar PSRs hold **a unique record** of the history of volatiles in the inner Solar System.

# Science Questions for the Next Decade

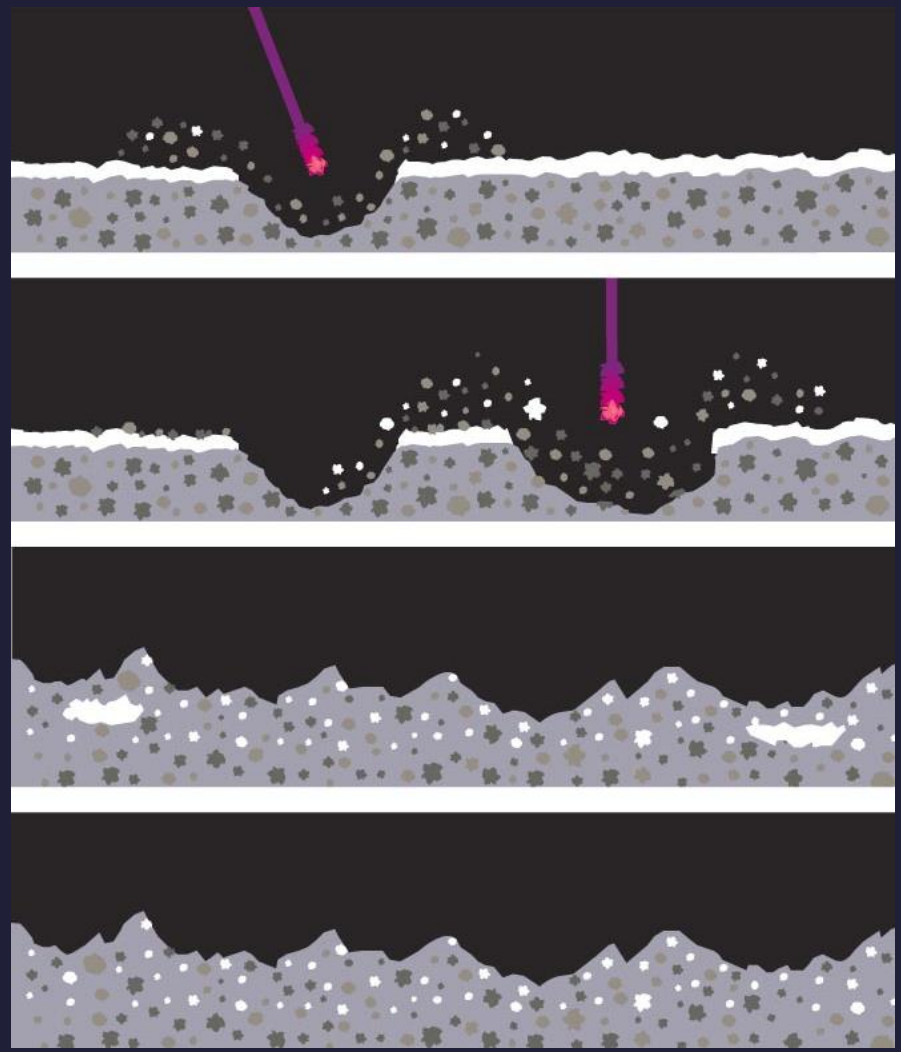
- What are the transport, retention, alteration, and loss processes that operate on volatiles in the lunar polar environment?

  Impact gardening, plasma sputtering, UV photolysis, slow sublimation, thermal diffusion, and chemistry (including synthesis of organics and alteration products) have all been hypothesized and/or modeled – but remain to be studied in situ.

**Solar System Science**

The lunar **polar microenvironment** is a natural laboratory in which to study abiotic/prebiotic chemistry and other surface processes under extreme conditions.

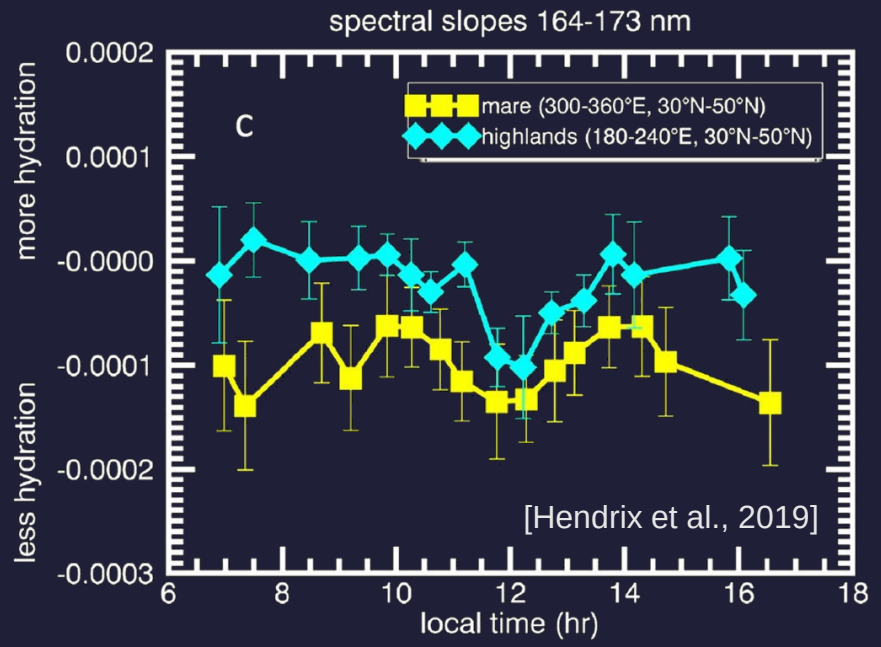
[Dana M. Hurley/JHU APL]

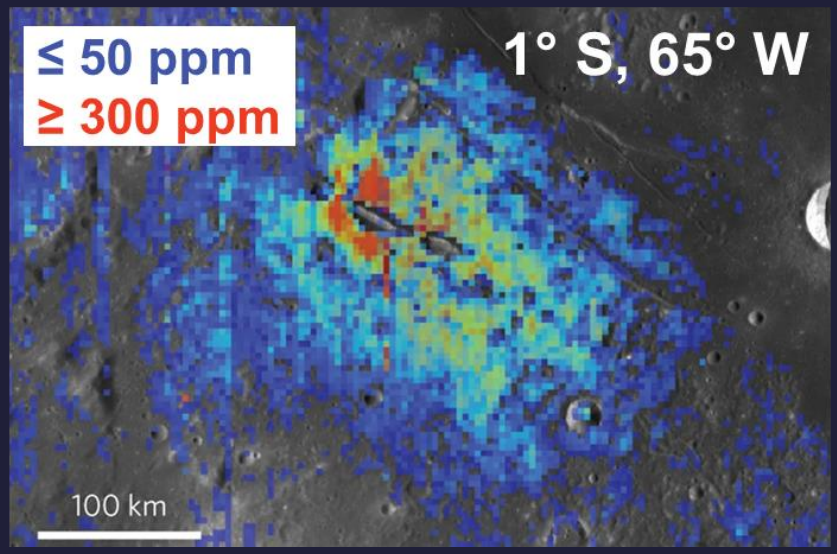


# Science Questions for the Next Decade

- What is the distribution and physical form of lunar surface volatiles beyond the poles?

  Including at pyroclastic deposits, crater peaks and swirls; at the surface and in the subsurface; with latitude and time of day.




[Milliken and Li, 2017]

**Solar System Science**

The **formation of volatiles** by solar wind bombardment may be an integral part of **space weathering** on all airless bodies.

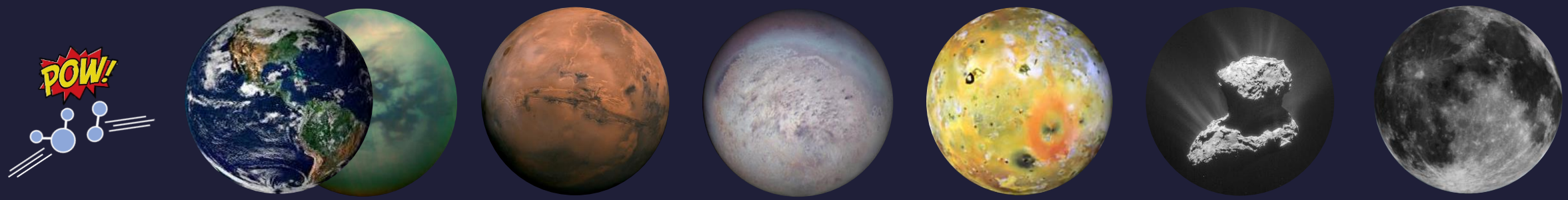
The volatile content of the lunar interior is closely linked to the **origin and early evolution** of the Earth-Moon system and inner Solar System.

Left: Variation of UV signature with time of day over mare and highland terrain [Hendrix et al., 2019]. Right: Hydration at a pyroclastic deposit [Milliken and Li, 2017].

# Science Questions for the Next Decade

- How does the contemporary lunar volatile cycle operate? **and**
- How has the lunar atmosphere changed over time, and how is this history preserved?

**time-varying sources, processes, sinks**




**Solar System Science**

The lunar exosphere is our closest example of the **most common class of atmosphere in the Solar System** – a surface bounded exosphere.

The evolution of the lunar atmosphere informs our understanding of **rarefied atmospheres** across the Solar System, including **how atmospheres arise, and then fade**.

Left to right: Earth, Titan, Mars, Triton, Io, Comet 67P, and the Moon.

# Science Questions for the Next Decade

- Is lunar water a viable resource for Solar System exploration?

  Rooted in answers to the preceding questions, but also more integrative, with scientific, technological and socioeconomic dimensions.

**Some related white papers:**

Space Resources Science (Gertsch)

Promoting the 'A' in SPACE: 'Arts' run the places STEM takes us (Grace)

Creating Spaces for Indigenous Voices within Planetary Science – Parts 1 and 2 (Kaluna, Kamai, Baybayan)

The Mutuality Between Science and Commercial Exploration of the Moon (Kramer et al.)


**Solar System Science**

How do we interact with the environments of other solar system worlds that we visit?

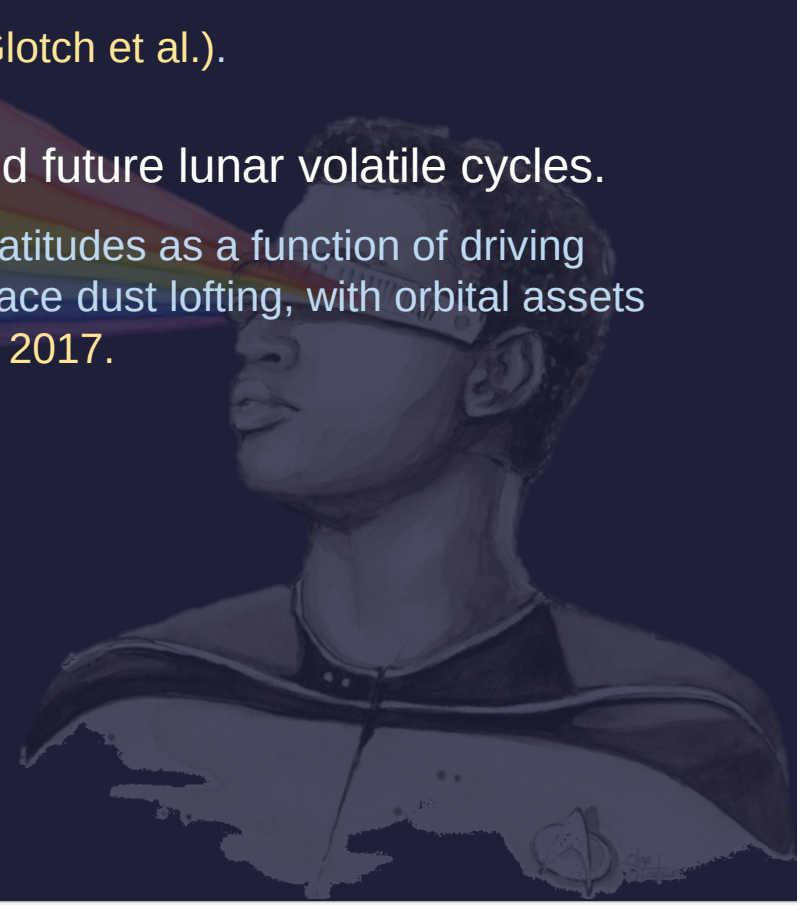
# What Does It Take To Address These Questions?

- Data can be acquired in a variety of ways, each with its strengths and limitations.
- Orbiters, landers and rovers ***of a range of mission classes*** can play critical roles.

  Other presentations today, and several other white papers including:
  Lunar Volatiles Orbiters (Lucey et al.), A Next Generation Lunar Orbiter Mission (Glotch et al.).

- Long-term, global observations are crucial to understanding past, present and future lunar volatile cycles.

  "Landed volatile-sensing stations could detect volatile transport from mid- to high-latitudes as a function of driving space environmental (solar storm, meteor stream) conditions, as well as near-surface dust lofting, with orbital assets serving to provide a global context." LEAG Advancing Science of the Moon report, 2017.



Background art: Olga Shvartsur

# What Does It Take To Address These Questions?

- Stable, long-term funding for a broad range of science and scientists is key.

  Data analysis, sample analysis, lab experiments, and theoretical/computational modeling have all played pivotal roles over the past decade.

- Virtual institutes (NLSI, SSERVI) and extended missions (LRO) have played a central role in driving volatiles science over the past decade.

  Value of Virtual Institutes & the Synergy of Science and Exploration (Schmidt et al.)
  Extended Missions in Planetary Science: Impacts to Science and the Workforce (Daubar et al.)

  Not only funding, but community-building (e.g. SSERVI focus groups, LunGradCon).

- Major breakthroughs have resulted from international partnerships.

  Several current and planned missions are planning volatiles-related science;
  reciprocal participating scientist programs and other avenues for engagement are important.

Background art: Olga Shvartsur