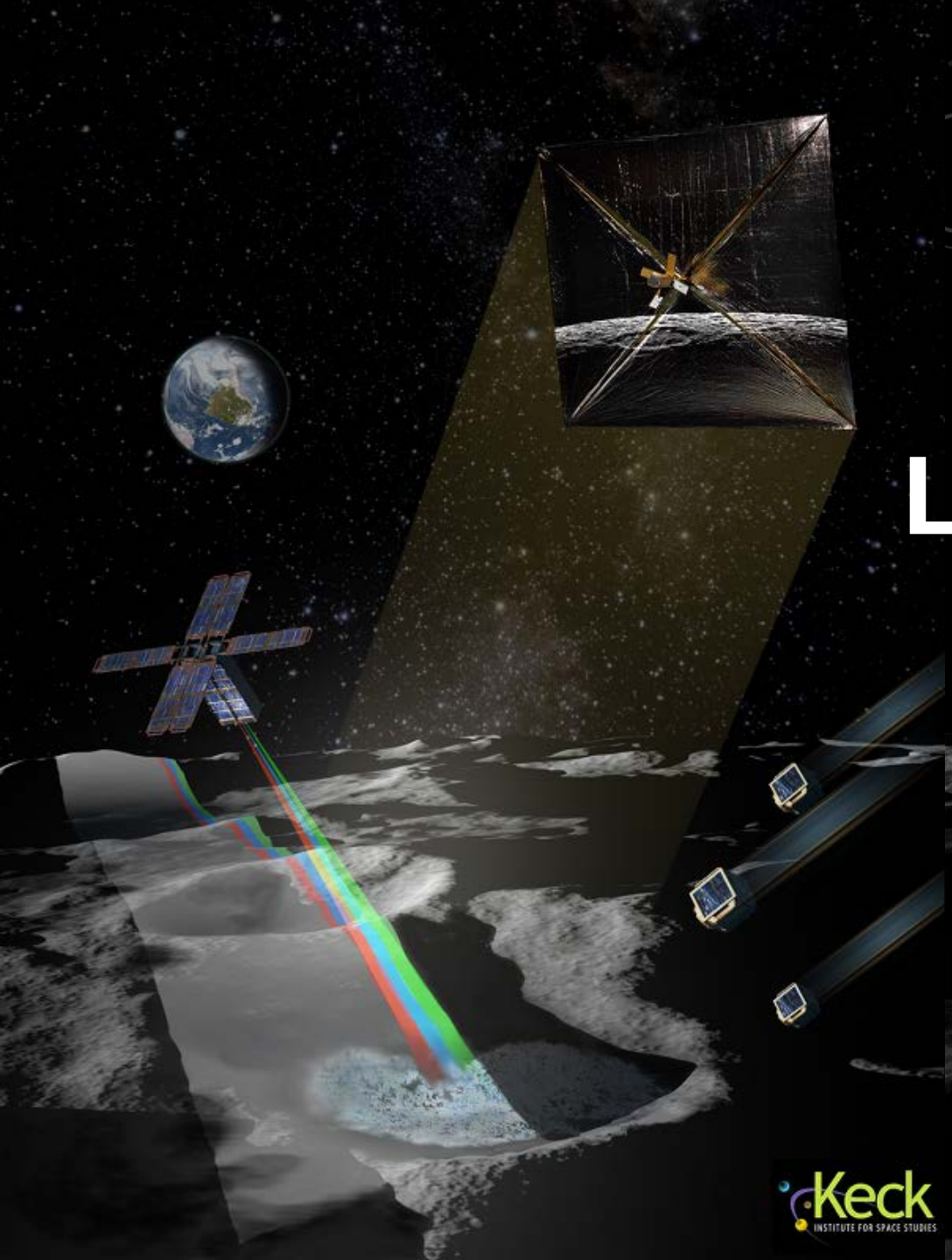


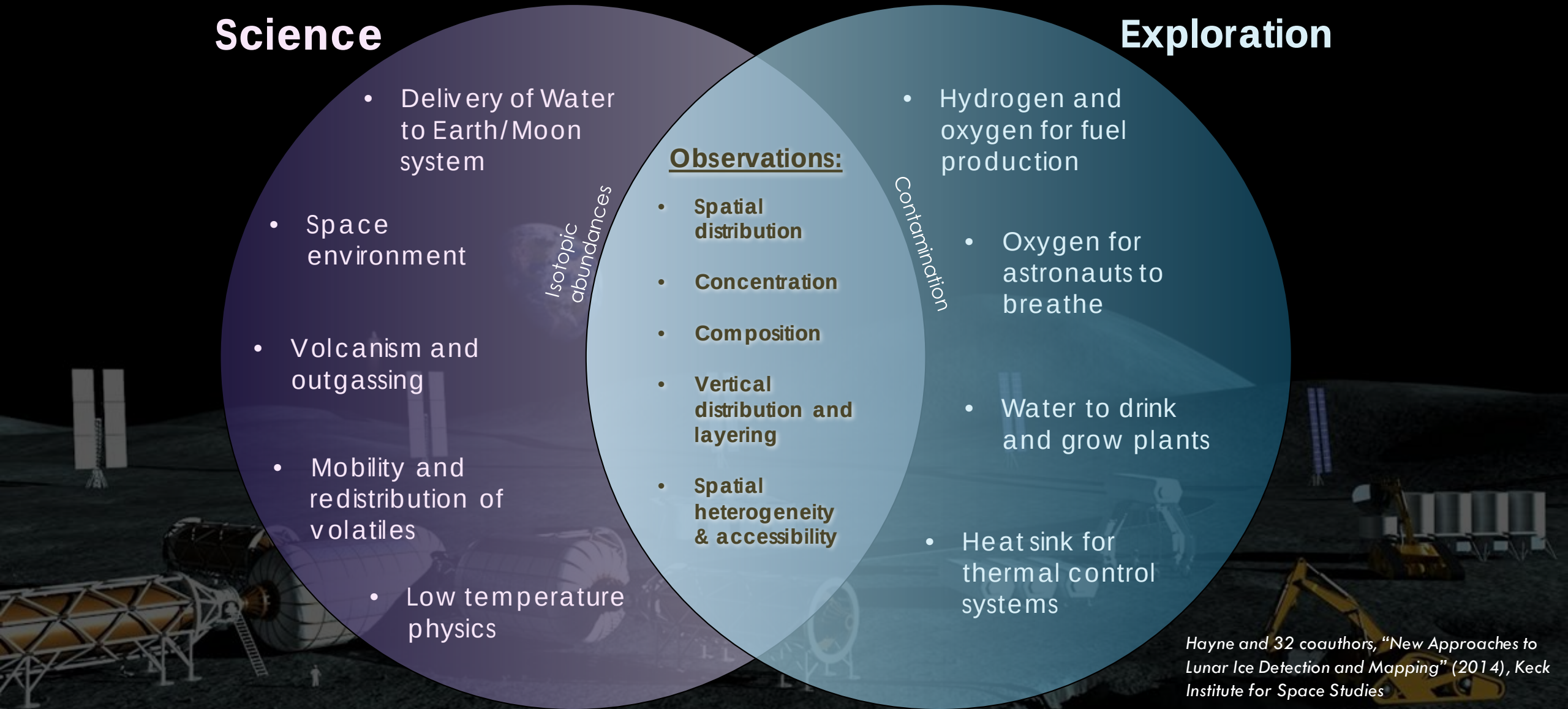
New Approaches to Lunar Ice Detection and Mapping

Paul Hayne, David A. Paige, Andrew P. Ingersoll, Oded Aharonson, Shane Byrne, Barbara Cohen, Anthony Colaprete, Christopher S. Edwards, Emily J. Foote, Benjamin T. Greenhagen, Amanda Hendrix, Brendan Hermalyn, Mihaly Horanyi, Yang Liu, Paul G. Lucey, Benjamin K. Malphrus, Thomas B. McCord, Michael J. Poston, Gerald B. Sanders, Norbert Schörghofer, Matthew M. Siegler, Robert L. Staehle, Wayne Zimmerman, and the participants of the study sponsored by the

Keck Institute for Space Studies

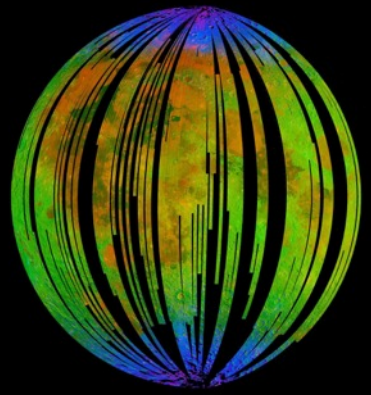
A white paper submitted to Decadal Survey on Planetary Science and Astrobiology
Mercury and the Moon Panel – November 19, 2020

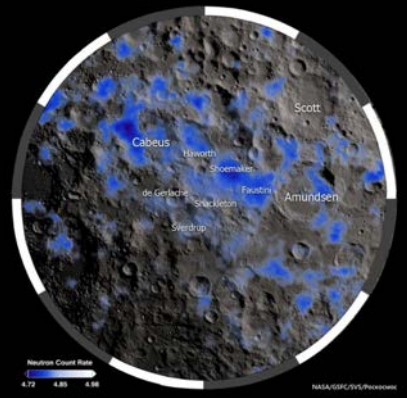
IMPORTANCE OF WATER ON THE MOON



Hayne and 32 coauthors, "New Approaches to Lunar Ice Detection and Mapping" (2014), Keck Institute for Space Studies

Motivation





1. Discoveries from the prior decade indicate the presence of water and other volatile ices at the lunar poles
   - Lunar Prospector (2001)
   - Chandrayaan/M^3 + DI + Cassini (2009)
   - LCROSS (2010)
   - Lunar Reconnaissance Orbiter (2010+)

Yet, **fundamental questions remain**

2. Technology developments, esp. in small-sats and rugged, miniaturized instruments, have enabled **new approaches** to ice detection and mapping

Study Group

32 experts from science and engineering fields
16 institutions, including 5 NASA centers

Workshop 1:

- Science Objectives
- Instrumentation
- Mission Classification

Workshop 2:

- Mission Concepts
- Tech Priorities

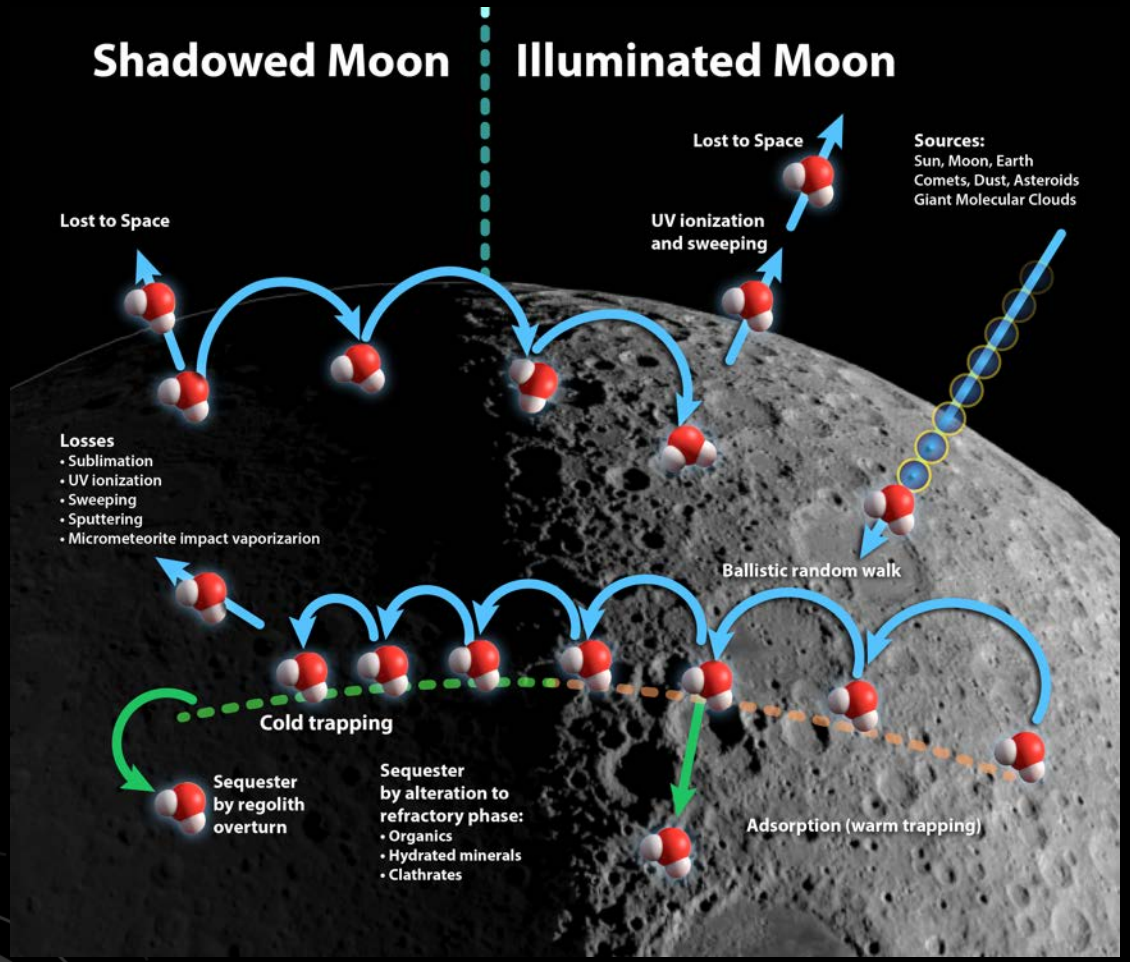
Driving Questions

1. What are the origins and evolution of water in the inner solar system?

2. Where are the operationally useful* deposits of water on the Moon?

*For ISRU *and* Science

Summarizing Current Understanding



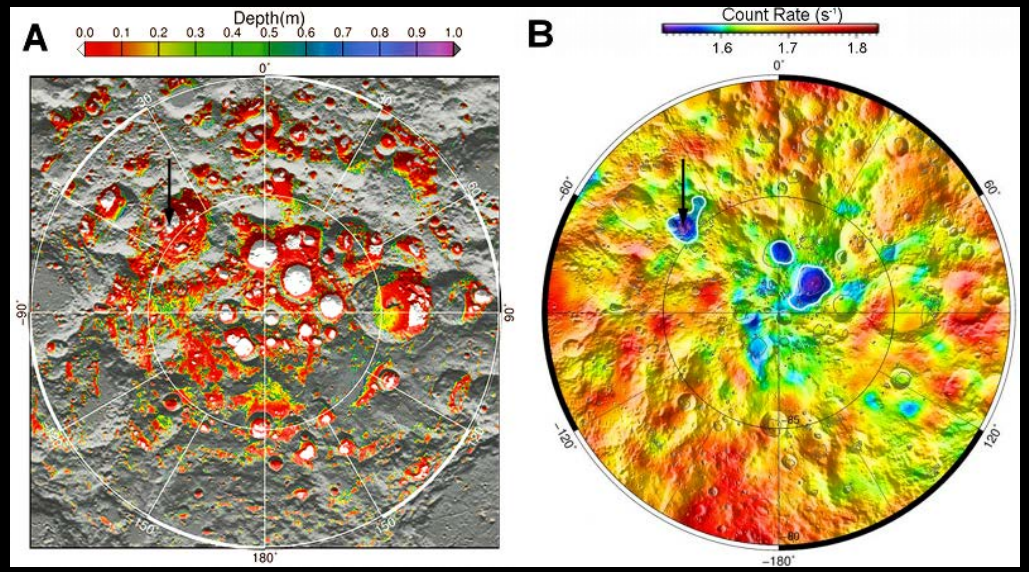
1. **There is ice at the lunar poles**, w/ abundances locally up to at least ~10%

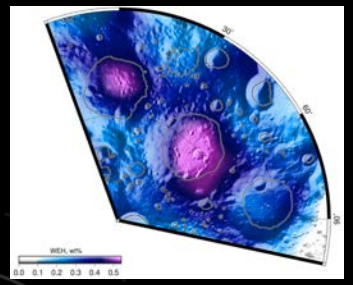
2. **Lunar polar volatiles are distributed heterogeneously**, even within the PSRs

3. **Temperatures in PSRs are among the coldest in the solar system**, capable of trapping range of comet-like volatiles

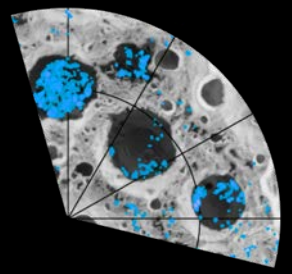
FINDING: The Moon's **water cycle** provides a natural laboratory for the study of processes occurring throughout the solar system

Outstanding Questions

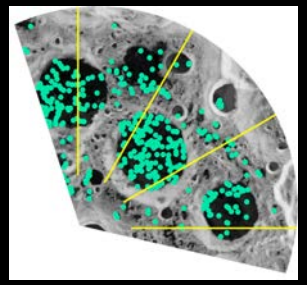




Water-equiv. [H]



UV detections



NIR detections

Inventory and distribution:

1. Is there molecular water in sunlit regions of the Moon, or only hydroxyl (OH)?
2. What is the geographic distribution of subsurface water, and its vertical extent?
3. What other volatiles are present besides water?

Abundance:

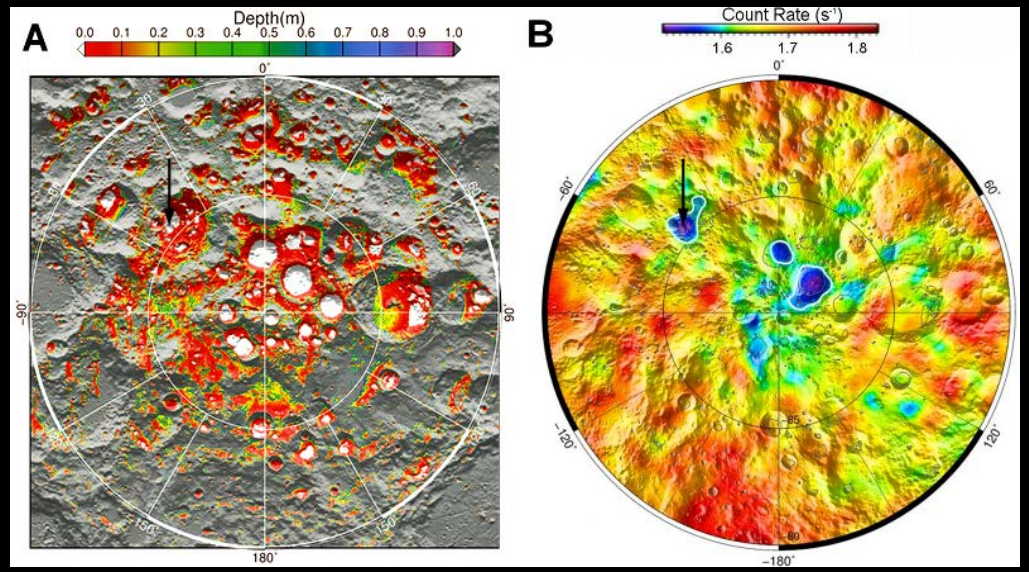
1. Is surface ice present in sufficient quantities for science and ISRU?
2. Do higher concentrations of ice exist at depth?

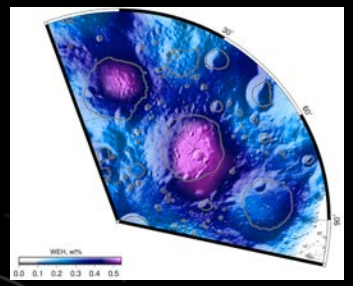
Form:

1. Are ice deposits concentrated in layers?
2. Does ice form coatings on grains or fill voids?
3. Does ice migrate vertically by thermal forcings?
4. Do water-rich impacts form discrete layers?

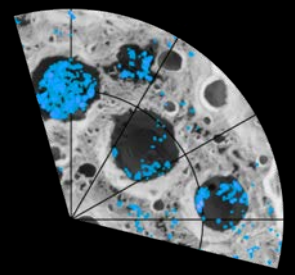
FINDING: Heterogeneity and disagreement among data and models suggest new approaches are needed

Outstanding Questions

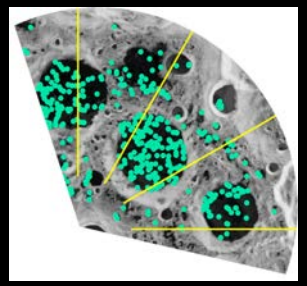




Water-equiv. [H]



UV detections



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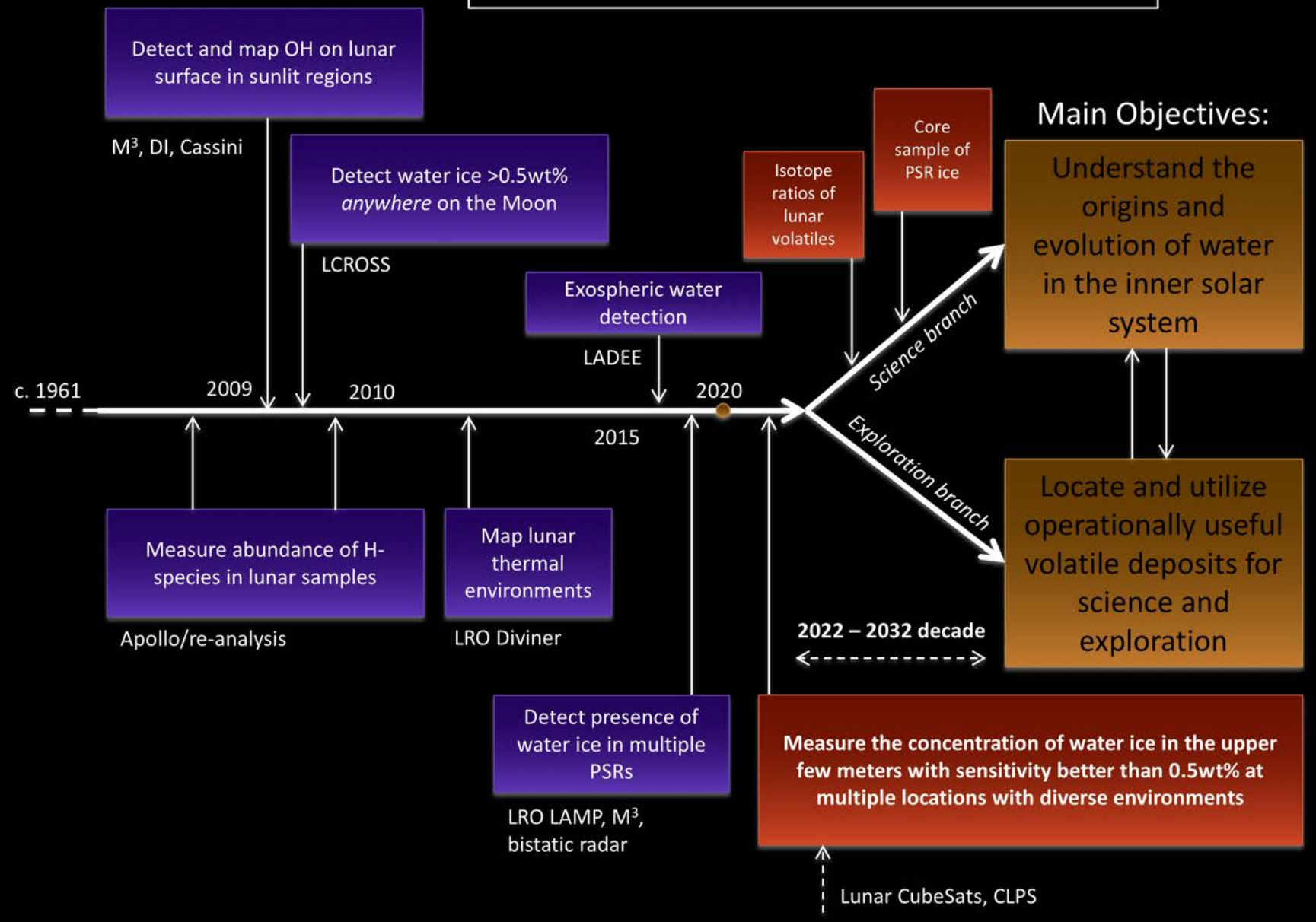
FINDING: Heterogeneity and disagreement among data and models suggest new approaches are needed

Key Measurements Needed

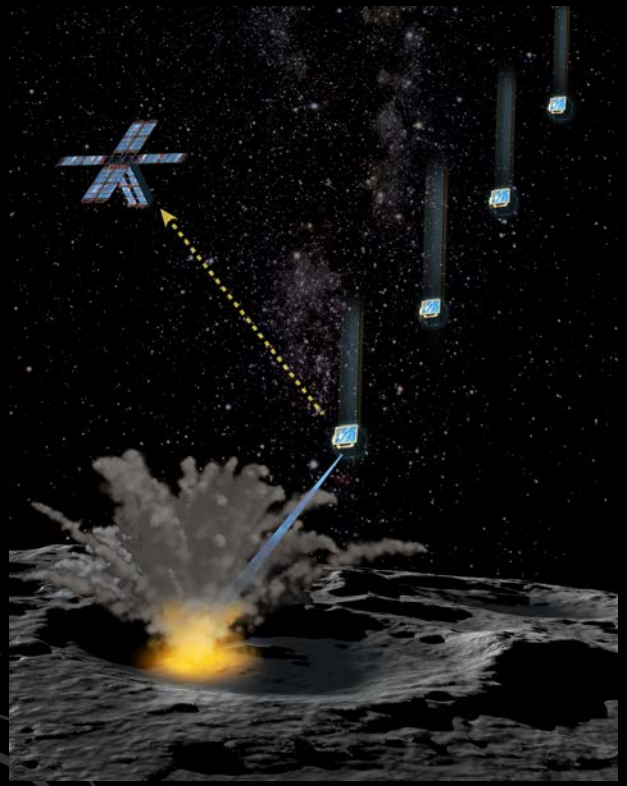
"Determine the **concentration** of water in the **upper few meters** with sensitivity better than **0.5 wt%** at **multiple locations** with diverse thermal environments"

Roadmap of Lunar Ice Investigation

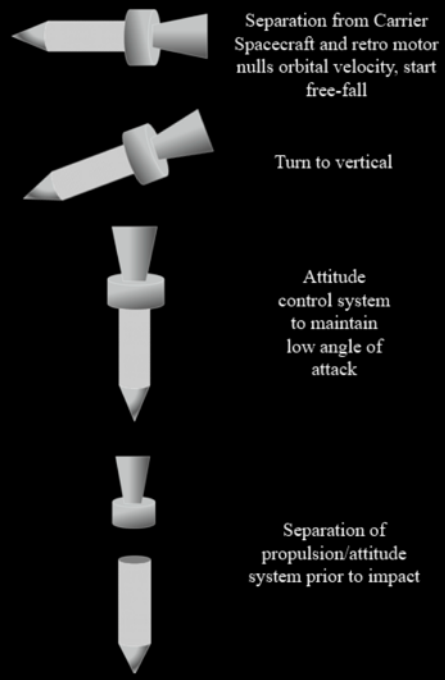


Some New Approaches

1. Multi-impactor plume sounding

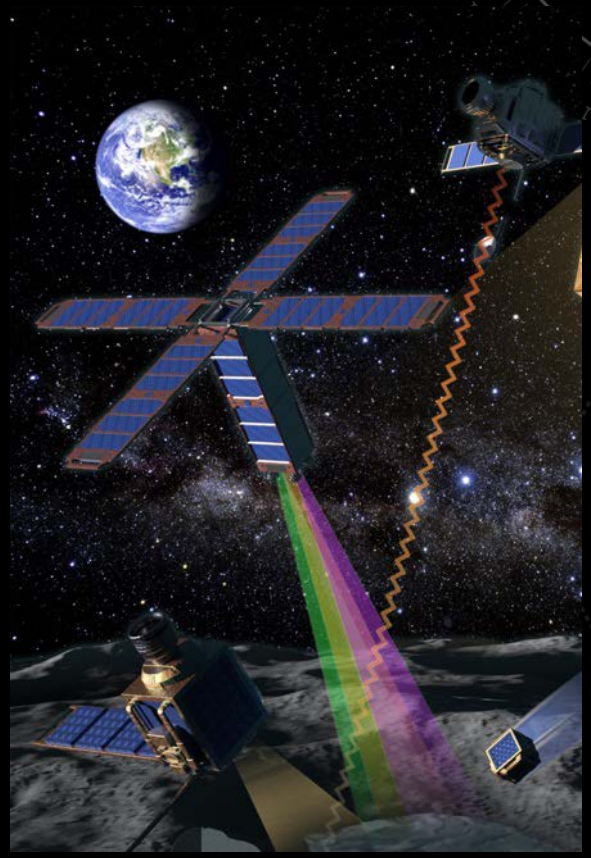


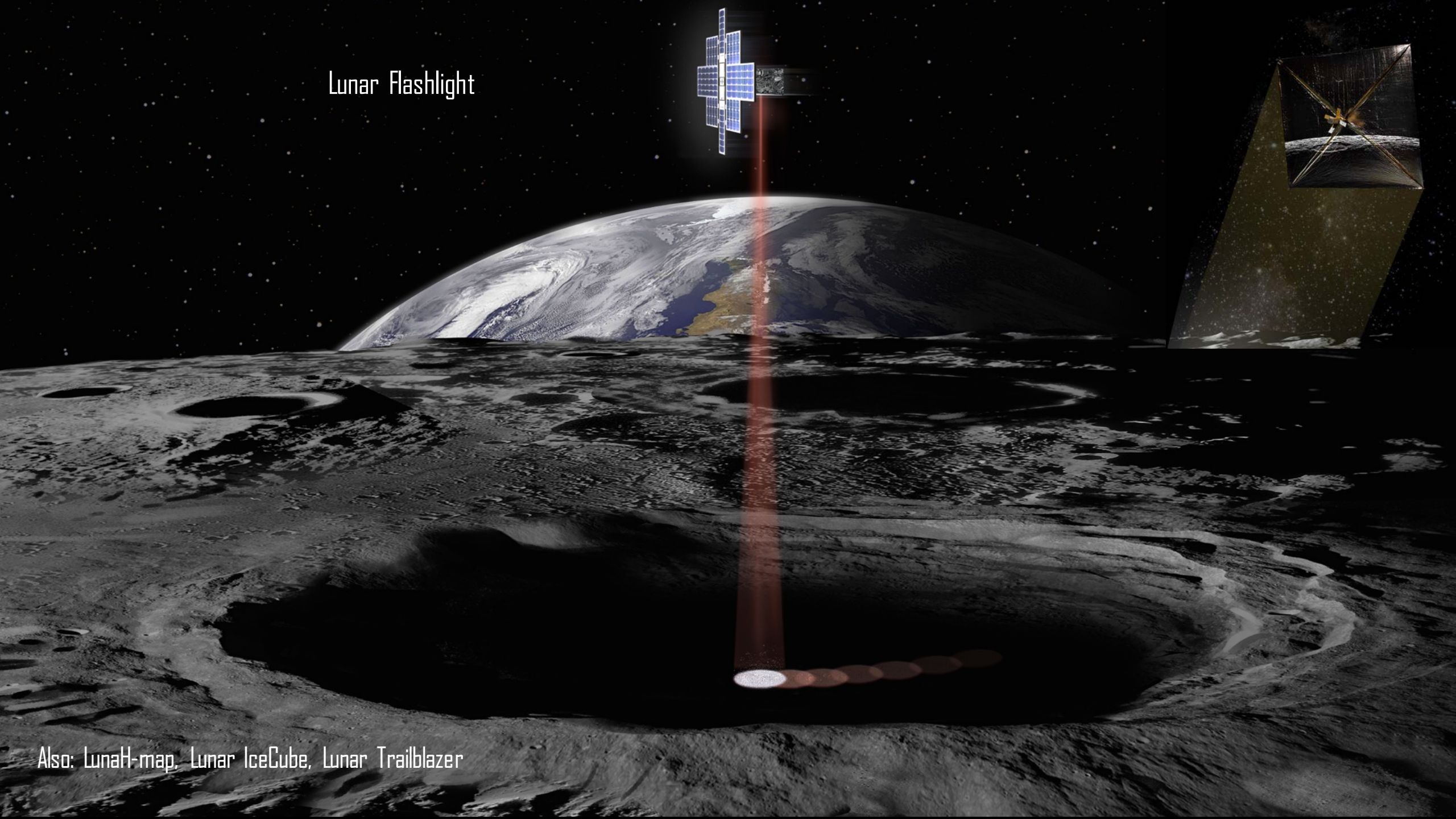
2. Multiple instrumented penetrator probes



See Decadal white paper by Paige et al. and publication by Ahrens et al. (2021, submitted)

3. Orbiter w/ active spectral reflectometry

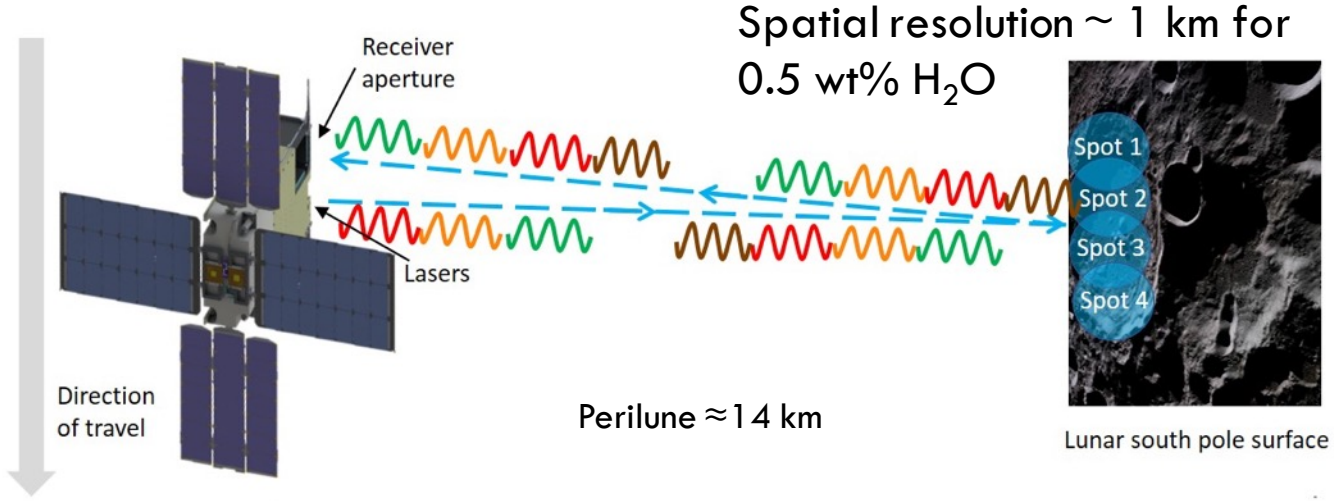



Lunar Flashlight
Also: LunaH-map, Lunar IceCube, Lunar Trailblazer

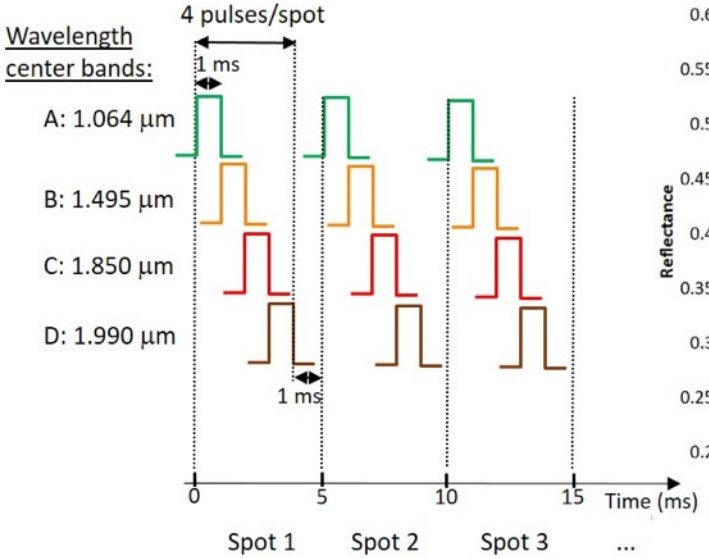
MEASUREMENT APPROACH

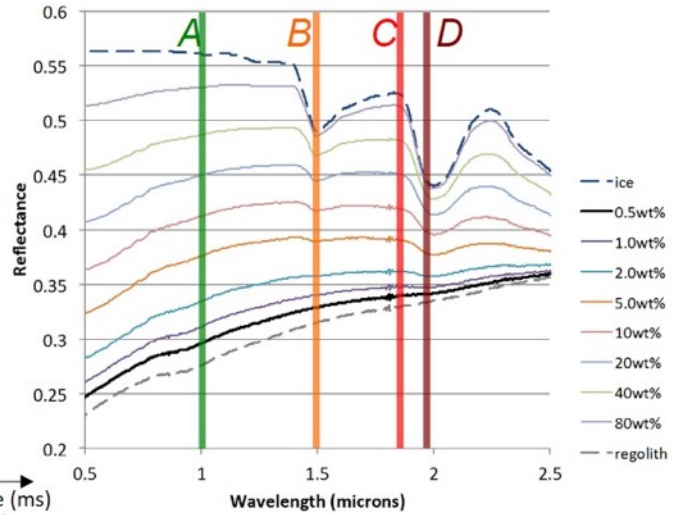
Spatial resolution ~ 1 km for 0.5 wt% H_2O

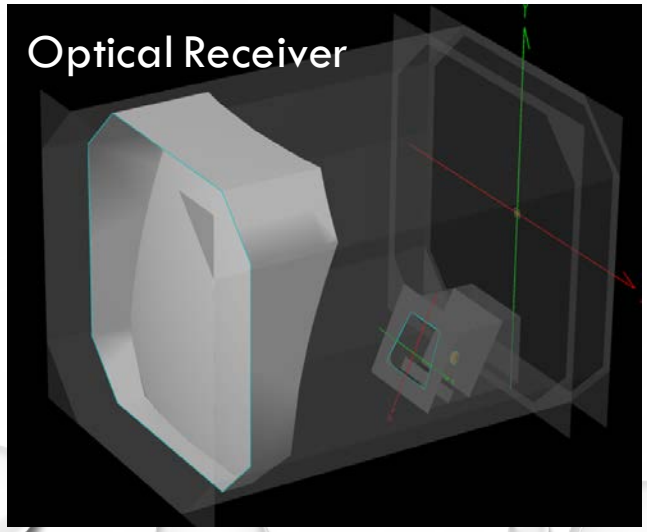
Laser Transmitter



Perilune ≈14 km

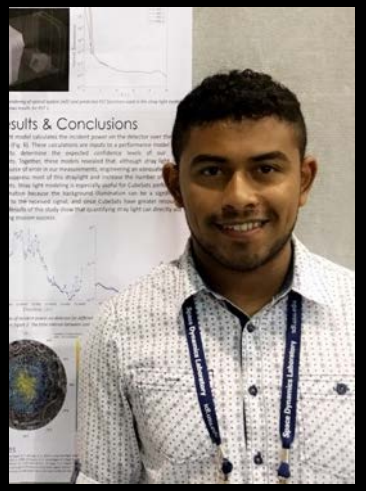






Vinckier et al. (2017, 2019)

Jose Martinez-Camacho (SMU)



LUNAR
FLASHLIGHT

Also: student involvement at Morehead State U.

Conclusion and Recommendation

- Although substantial progress has been made in the last decade to understand origins, distribution, and abundance of lunar ice, fundamental questions remain unanswered

- Making progress requires innovative approaches, focused on key measurements

- Small spacecraft and instrumentation with higher than average risk tolerance are suitable for advancing this goal

We recommend that NASA continue to support and invest in low-cost, innovative missions and instrument development with regular and appropriately funded opportunities through programs such as SIMPLEx and PRISM, and possibly through a more organized program.