JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

Lunar Volatile Reservoirs

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@mommascientist

The Moon is a Cornerstone for the history of the solar system

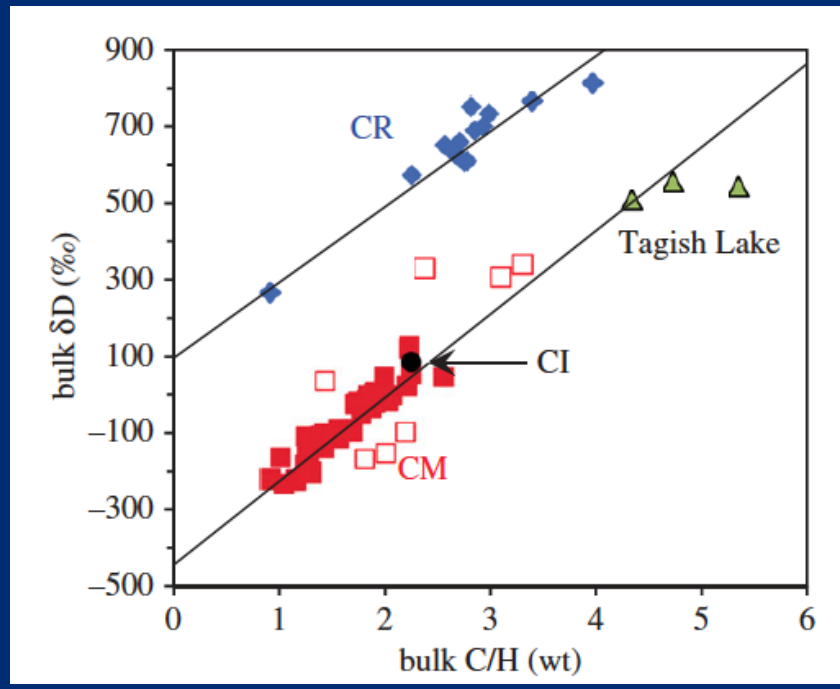
- Impact history for the Earth-Moon system, the terrestrial planets, and the solar system as a whole
- Terrestrial planet formation
- Terrestrial planet interior evolution
- Formation, evolution and loss of an atmosphere
- Contemporary processes
- History of volatile delivery to the Earth-Moon system

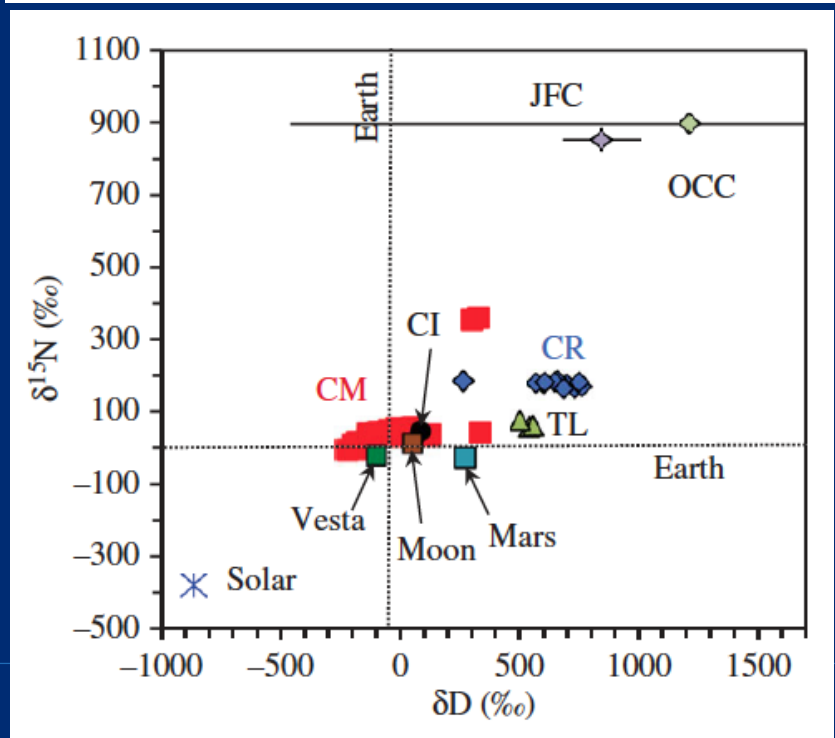
As we begin to explore and make use of volatile reservoirs on the Moon, it is essential to recognize their scientific value and fully characterize their composition.

The Science Value of Lunar Volatile Reservoirs

- Composition is important for understanding the source of Lunar (and terrestrial) volatiles.
- Important in situ measurements
  - Bulk elemental composition – CHON + Noble Gases
  - Isotopic composition – D/H $^{14}N/^{15}N$ $^{12}C/^{13}C$ + Noble Gas Isotopes
- Volatiles stored at the poles will have varying composition with depth depending on time of delivery

The sources of volatiles for polar cold traps serve as a cornerstone for the delivery of volatiles to the Earth.





Figs. 1 & 4 from Alexander (2017) *The Origin of Inner Solar System Water*

There is a Volatile Cycle on the Moon

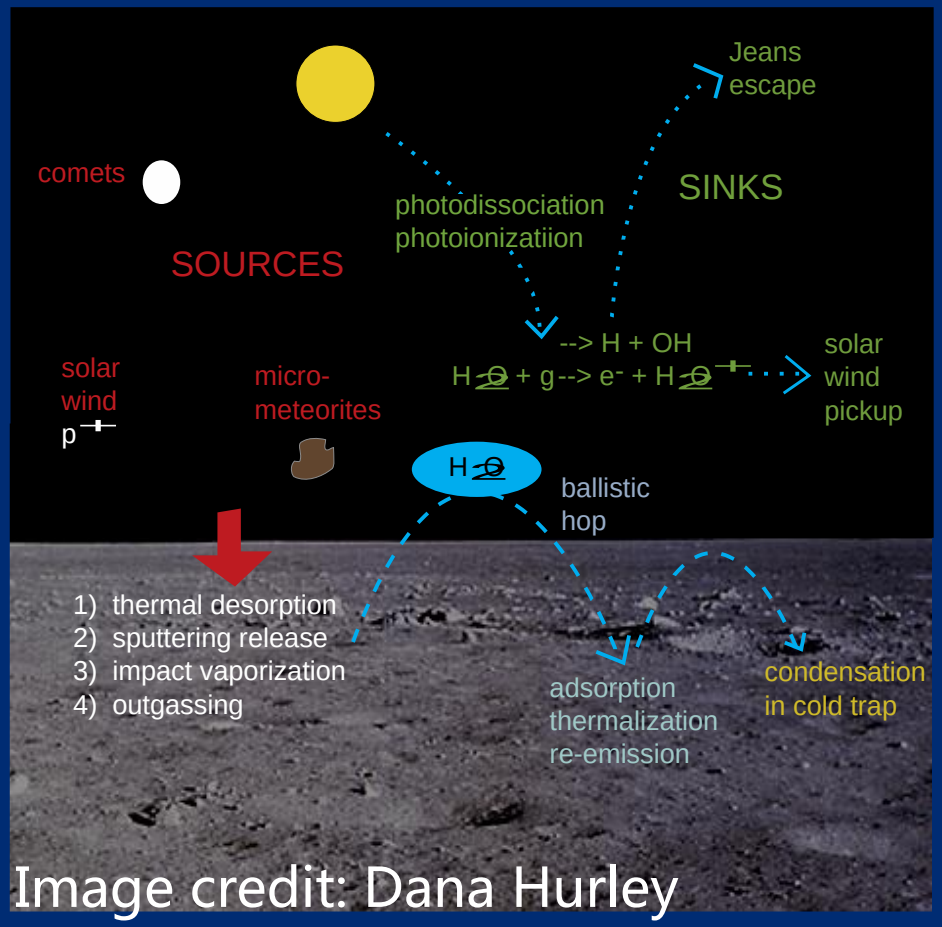
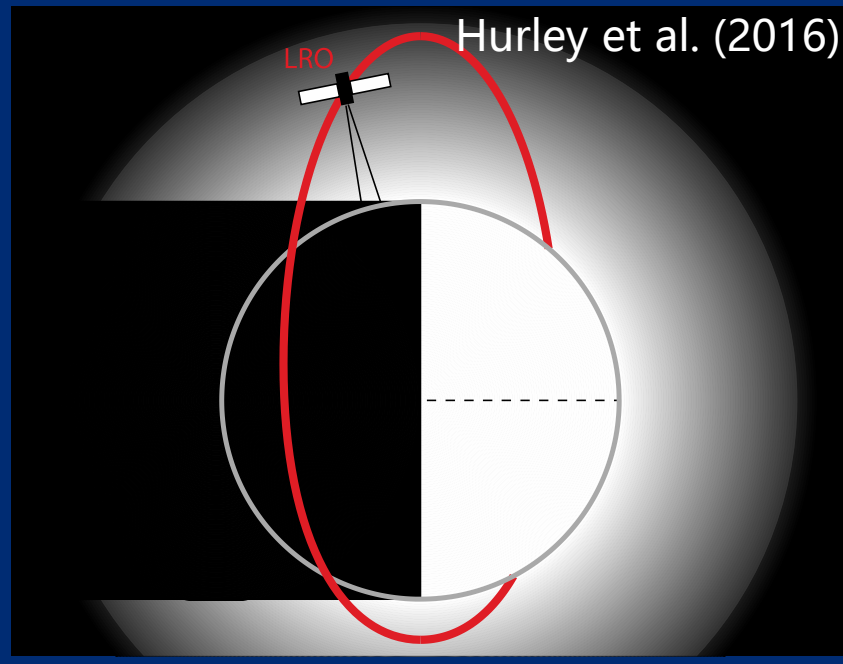
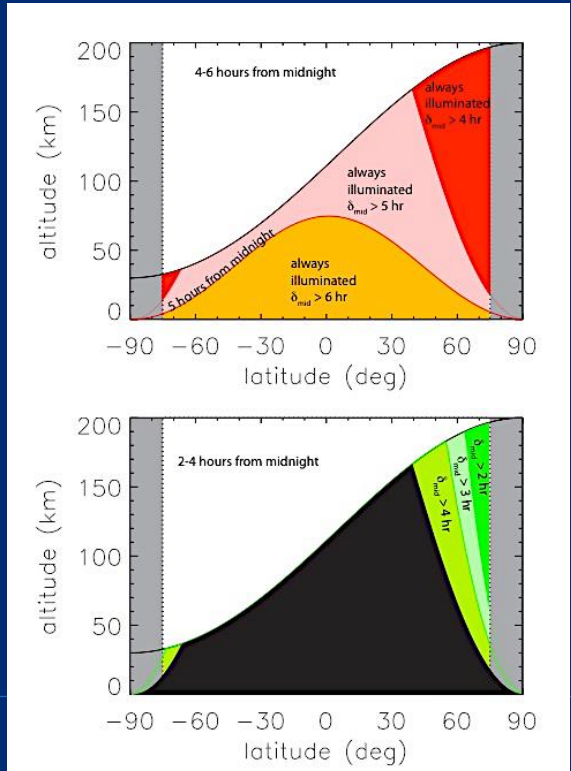


Image credit: Dana Hurley



Hurley et al. (2016)

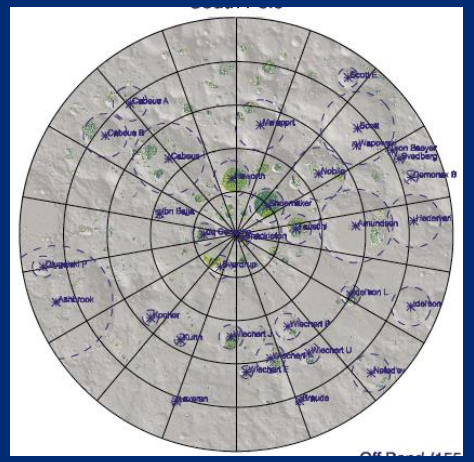
- Sources:
  - Solar wind
  - Comets
  - Meteorites/micrometeorites
  - Volcanic outgassing
- Processing:
  - Photochemistry
  - Surface interactions (chemistry, condensation and adsorption)
  - Transport in exosphere
  - Subsurface Transport
- Sinks:
  - Temporarily on the surface
  - Long-term in cold traps



Studying composition of volatile reservoirs will tell us about their sources and processing.

Probing Spatial Volatile Distribution: LRO Perspectives

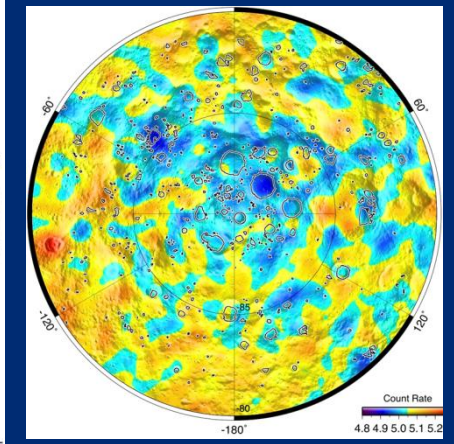
The NASA Lunar Reconnaissance Orbiter (LRO) has been gathering data at the Moon for nearly 10 years and, in that time, has revolutionized our understanding of lunar volatiles.



LAMP

- 1 to 2% water frost in the PSRs
- Diurnal variation on the dayside

Gladstone et al. 2012
Hendrix et al. 2012, 2019



LEND

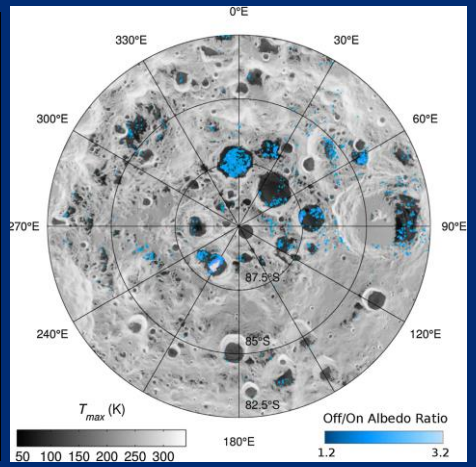
- Depressed epithermal neutron flux
- Upper latitudes
- Upper 1 m of regolith

Mitrofanov et al. 2010

LOLA

- 3 to 14% water depending on porosity/reflectivity assumptions

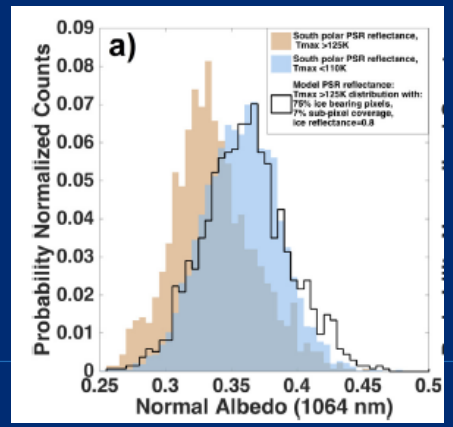
Lucey et al. 2014



LAMP/DIVINER

- 0.1 to 1% water
- Upper latitudes
- Low sun angle
- Top mm's of regolith

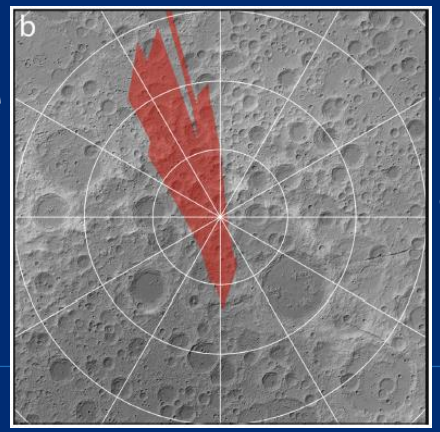
Hayne et al. 2015



LOLA/DIVINER

- Albedo/temperature correlation
- Consistent with water ice

Fisher et al. 2017

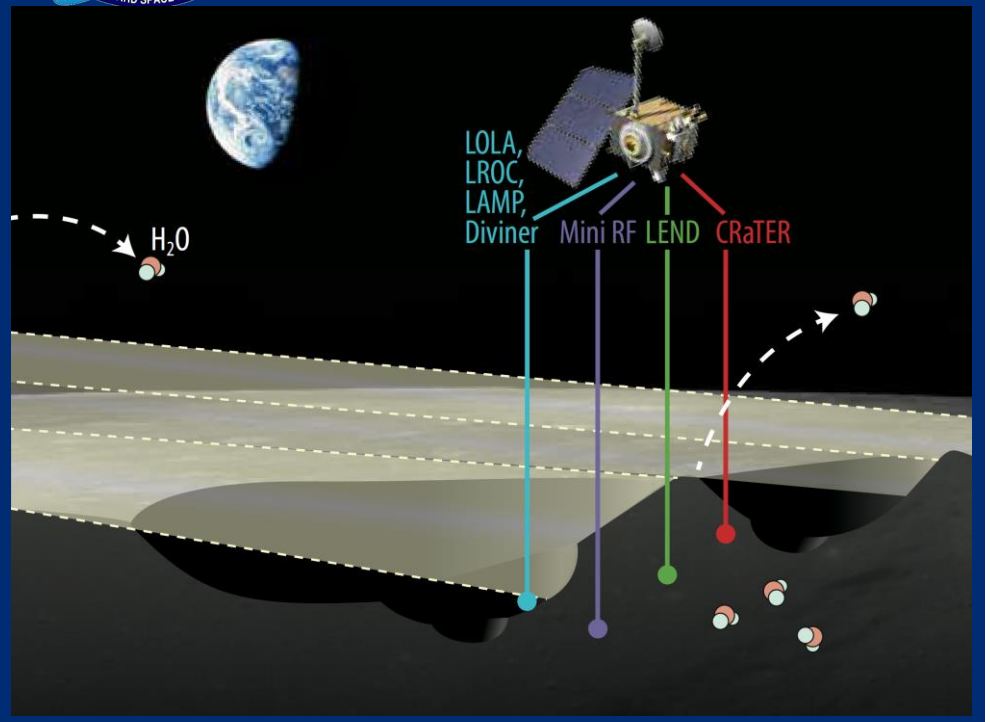


Mini-RF/Arecibo

- Cabeus observations
- Evidence for near-surface water ice

Patterson et al. 2017

Probing Volatile Distribution with Depth: Near Surface



- LRO-LAMP sees top few microns
- M^3 sees surface frost down to a few grains of regolith
- LOLA depth between these two

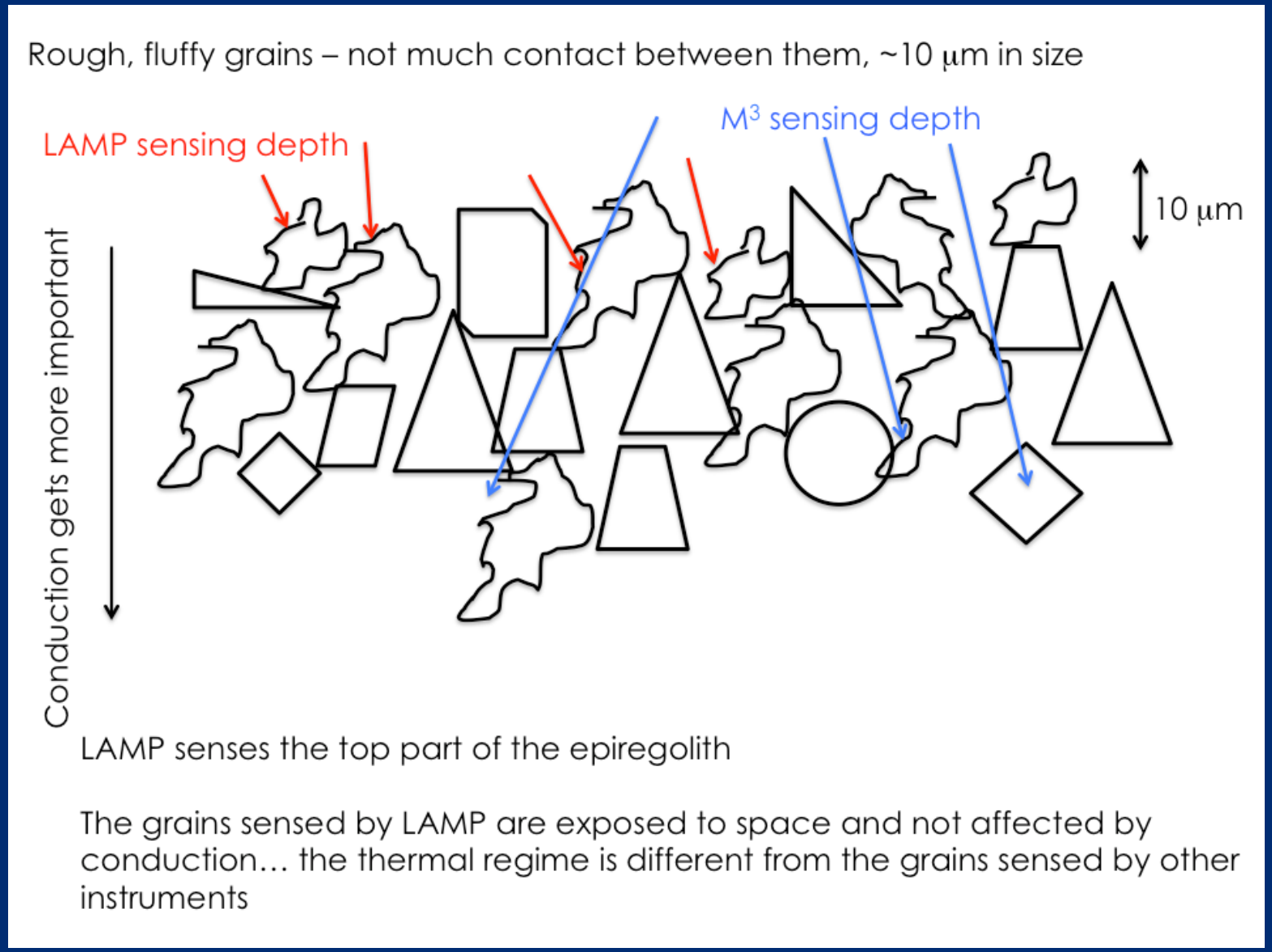
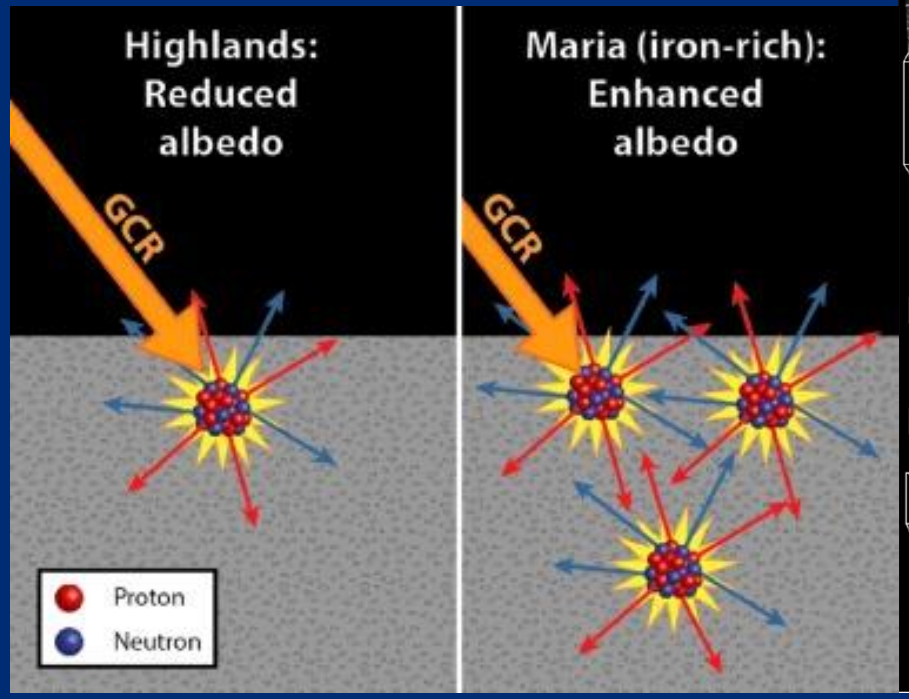
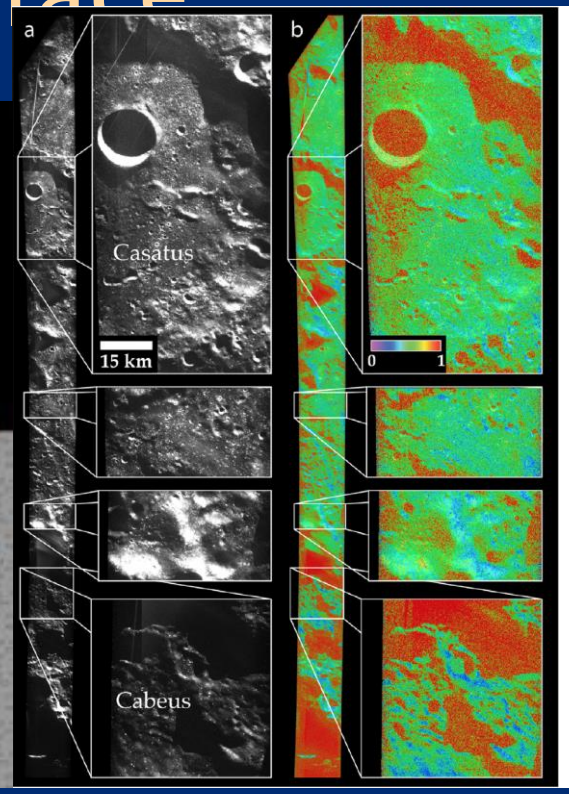
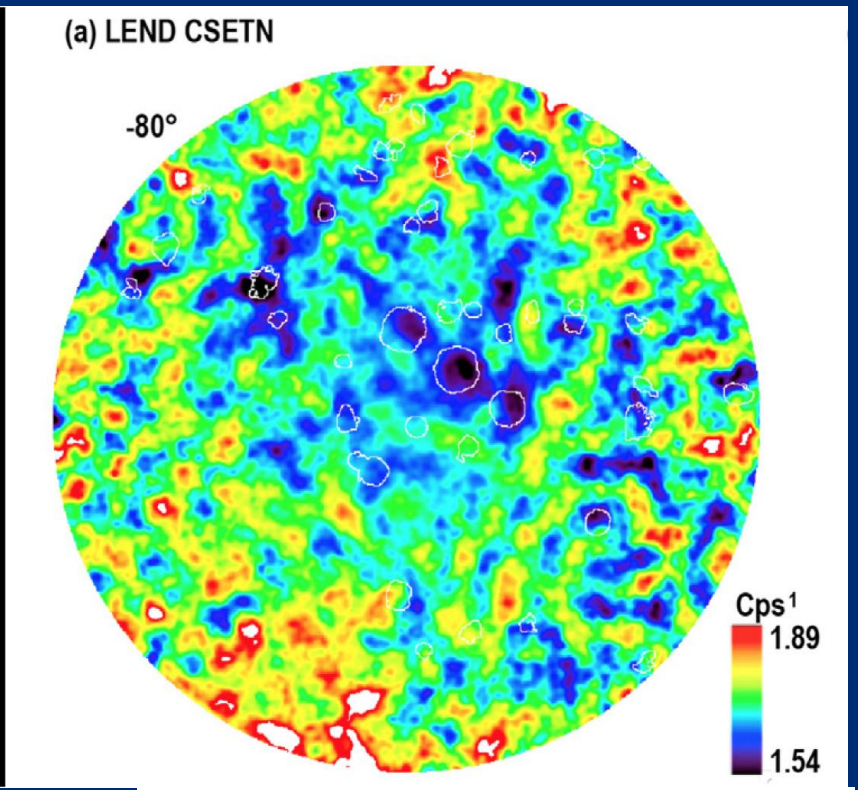


Image credit: Amanda Hendrix

Probing Volatile Distribution with Depth: Below the Surface





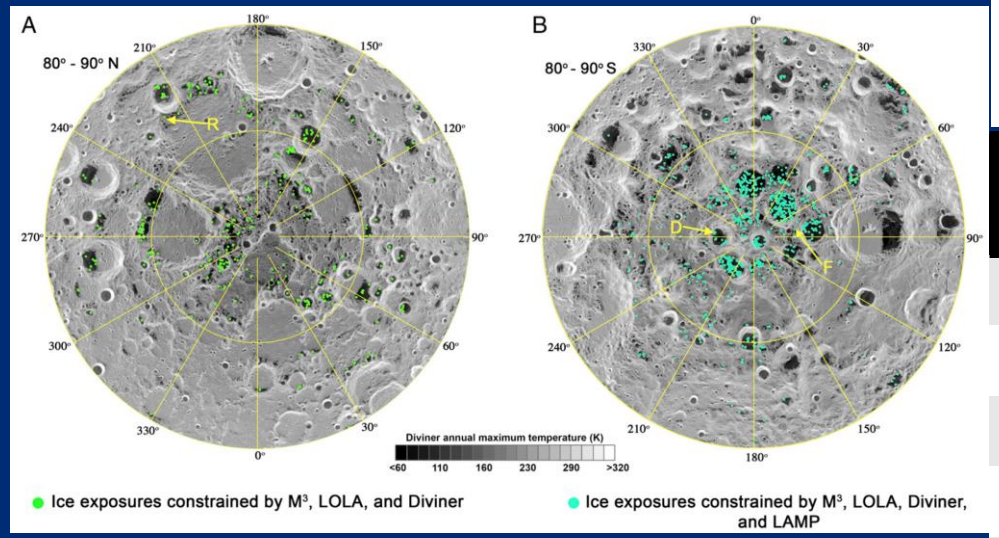


Schwadron et al. 2016 (left)
Patterson et al. 2017 (center)
Sanin et al. 2017 (right)

- LEND and CRaTER probe the top meter
- Mini-RF can probe up to several meters
- Spatial variability at the surface is different from spatial variability at depth

Probing Spatial Volatile Distribution: Other Investigations

- Surface frost observed by the Moon Mineralogical Mapper (M^3) on Chandrayaan-1 (next talk)
- LCROSS saw more than just water
- Conclusions:
  - Spatial variation is heterogenous
  - Composition is complex *and very interesting*



Li et al. 2018 (left)
Gladstone et al. 2010 (below)

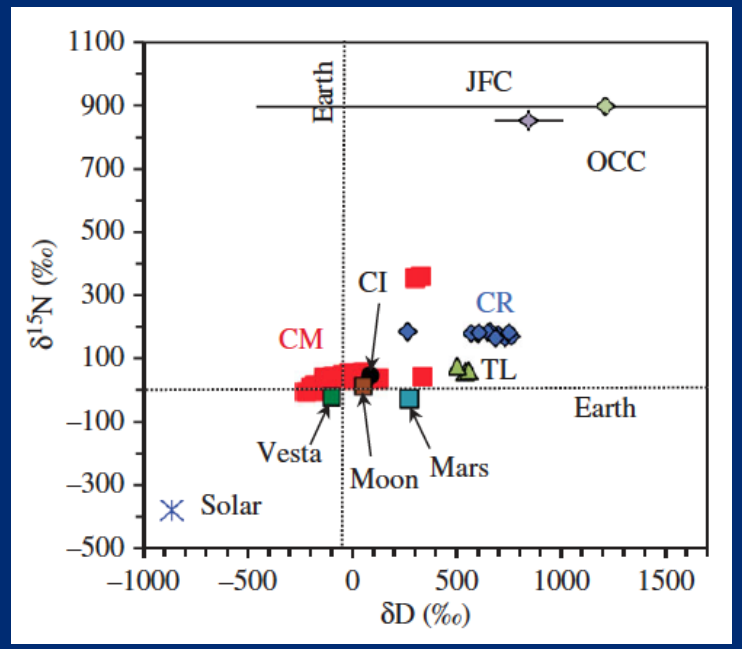
Species	Observed (kg)	Mass released (kg)
H_2	1.33	117±16
CO	0.70	41±3
Ca	0.16	16±1
Mg	0.04	3.8±0.3
Hg	0.12	12.4±0.8

Compound	Molecules cm^{-2}	% Relative to $H_2O(g)$*
H_2O	5.1(1.4)E19	100.00%
H_2S	8.5(0.9)E18	16.75%
NH_3	3.1(1.5)E18	6.03%
SO_2	1.6(0.4)E18	3.19%
C_2H_4	1.6(1.7)E18	3.12%
CO_2	1.1(1.0)E18	2.17%
CH_3OH	7.8(42)E17	1.55%
CH_4	3.3(3.0)E17	0.65%
OH	1.7(0.4)E16	0.03%

*Abundance as described in text for fit in Fig. 3C.

Colaprete et al., 2010

Include Volatile Experts in the Process

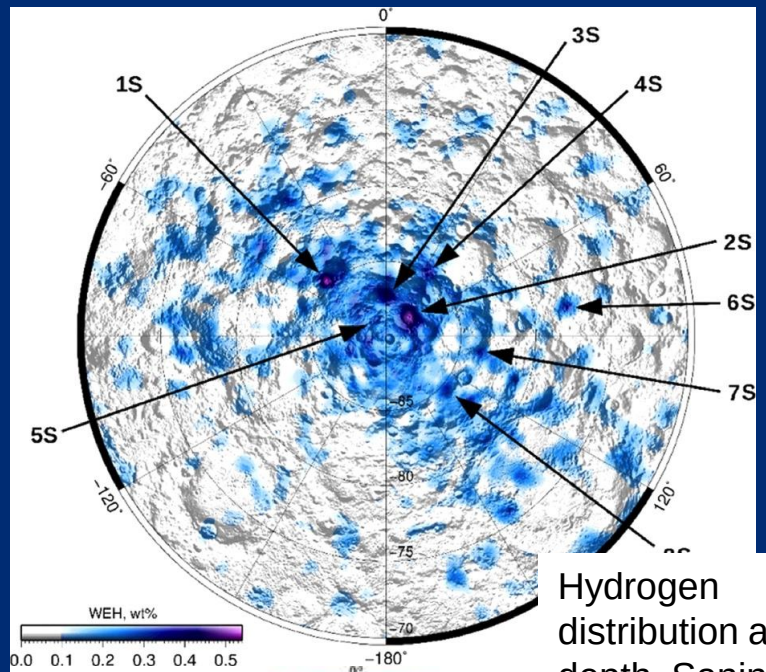


Remember: composition is important for understanding the source of Lunar (and terrestrial) volatiles.

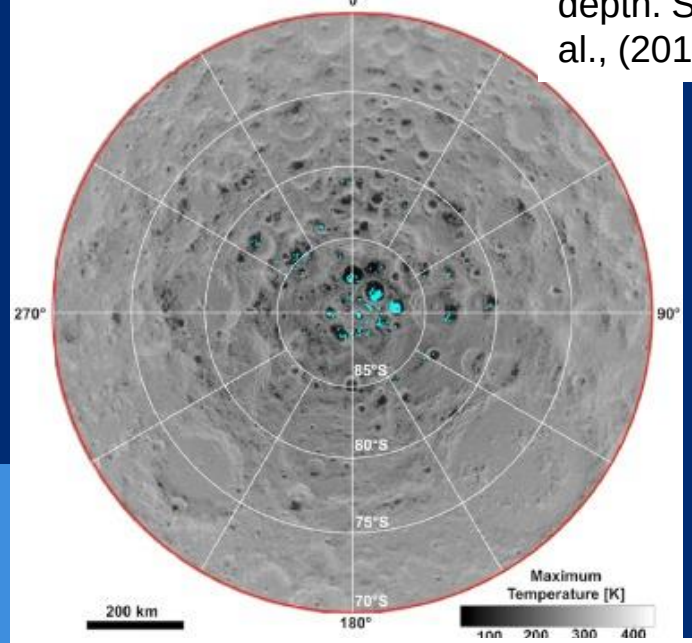
Fig. 1 from Alexander (2017) *The Origin of Inner Solar System Water*

- Volatile experts can help with
  - Identifying the best locations
  - Determining volatile stability with depth
- However, volatiles experts only get one chance to measure detailed composition of these non-renewable reservoirs

If the volatile science and ISRU communities work closely together we can use these reservoirs to learn about the history of volatiles throughout the solar system



Hydrogen distribution at depth. Sanin et al., (2017)



Map of the surface locations brighter than "cold" pixel mean. Fisher et al., (2017)

Summary and Discussion

- The Moon can serve as a cornerstone for volatil delivery to Earth
- Preparing for ISRU: Take advantage of LRO
  - Global observations of volatile transport
  - Targeted observations in the "ring of fire", namely Cabaeus ar Amundsen
- When you land: Characterize, Characterize, Characterize
  - We only get one chance to study these reservoirs
- Important in situ measurements
  - Bulk elemental composition – CHON + Noble Gases
  - Isotopic composition – D/H $^{14}N/^{15}N$ $^{12}C/^{13}C$ + Noble Gas Isotopes
- Volatiles stored at the poles will have varying composition with depth depending on time of delivery

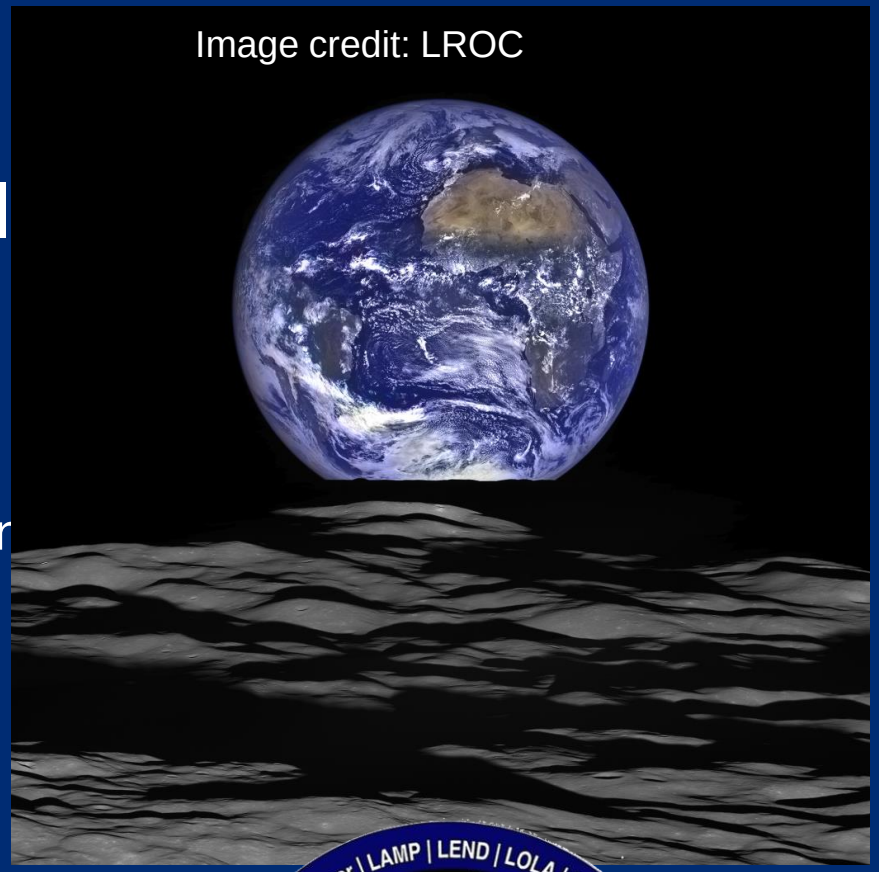


Image credit: LROC

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