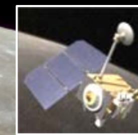
New (and evolving) Views of the Moon's Volatiles from the Lunar Reconnaissance Orbiter

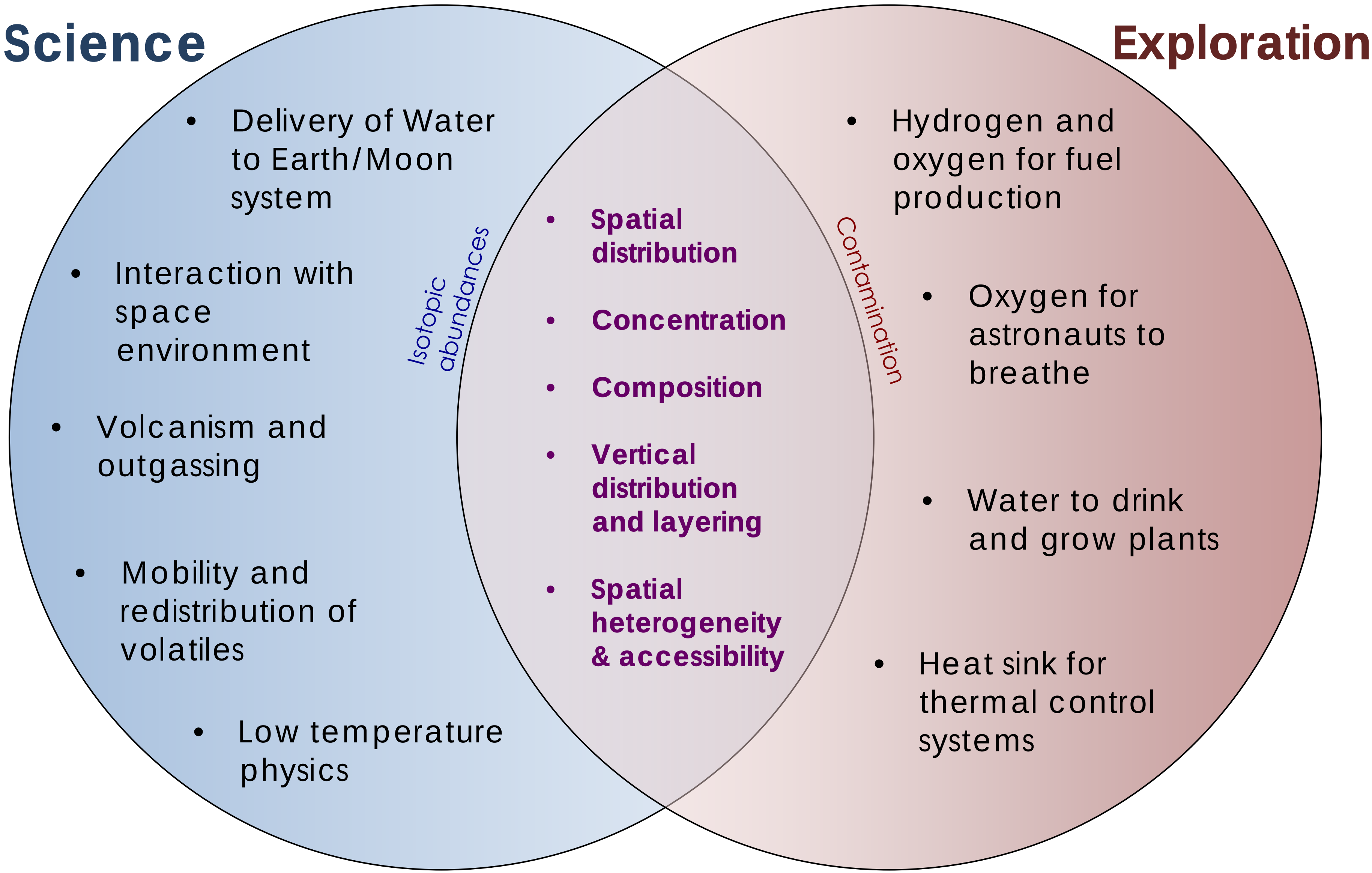


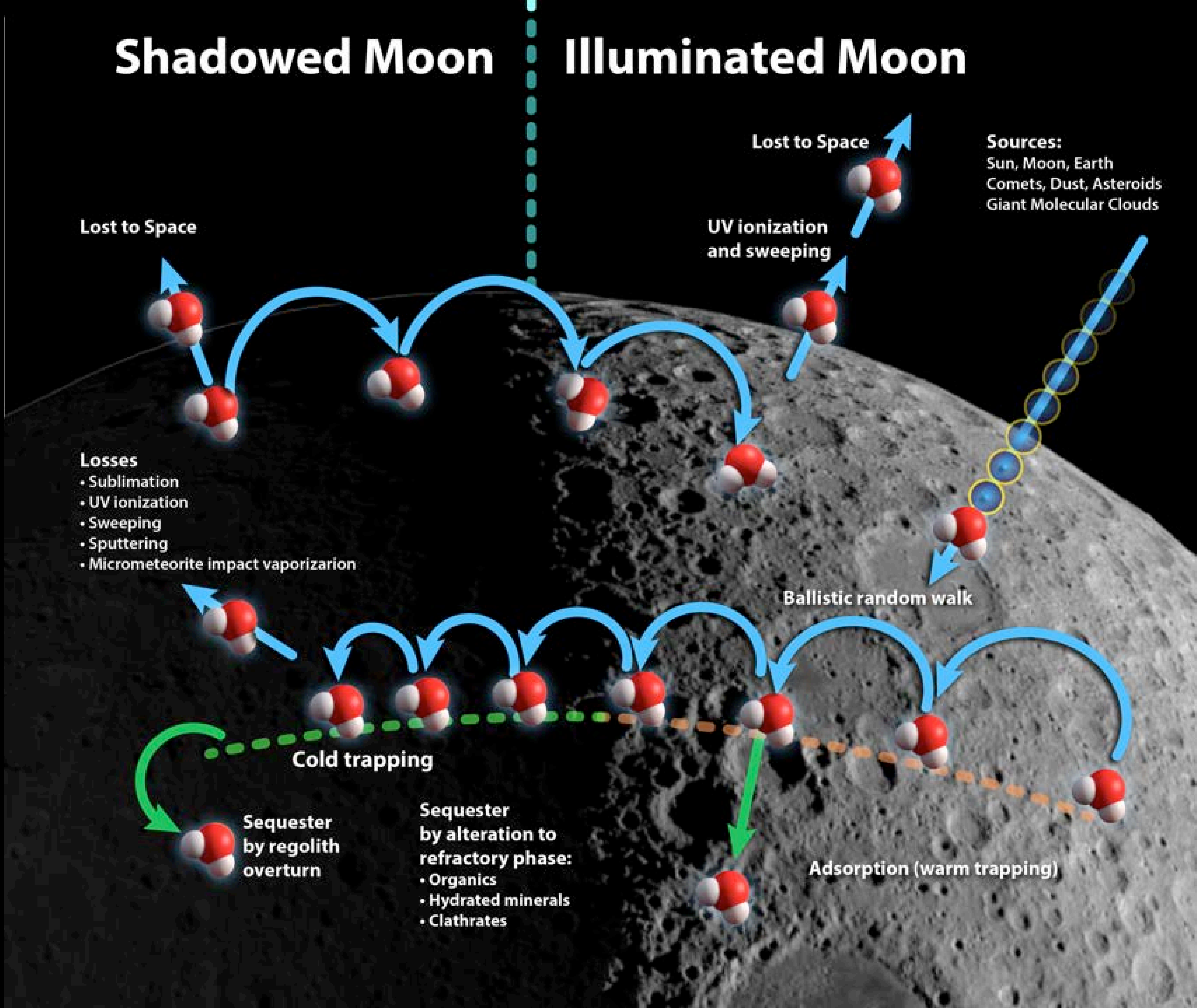
Paul Hayne[1] and the Lunar Reconnaissance Orbiter Science Team

[1]Jet Propulsion Laboratory, Caltech

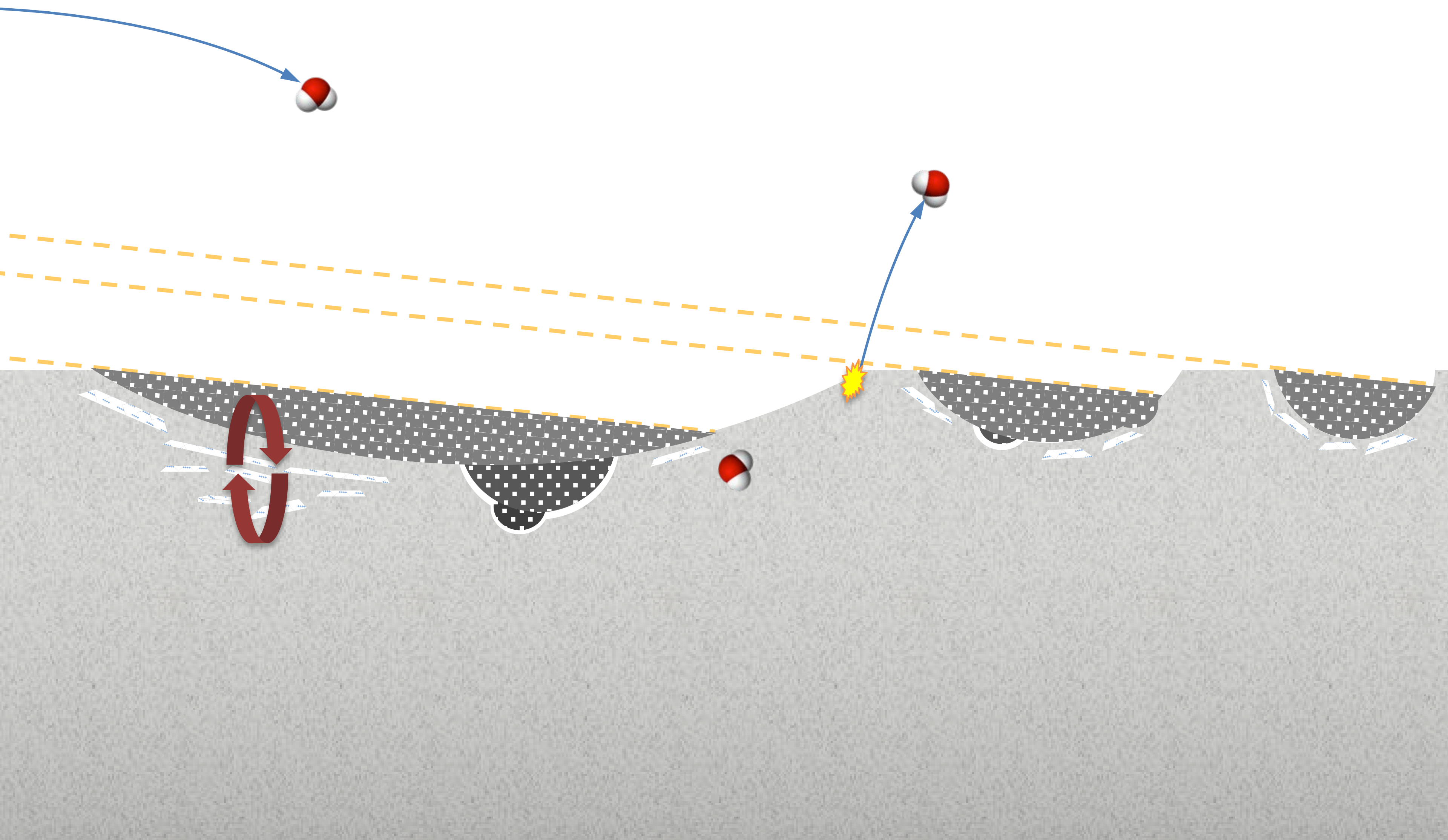
Lunar Exploration Analysis Group – Annual Meeting – Oct 2015

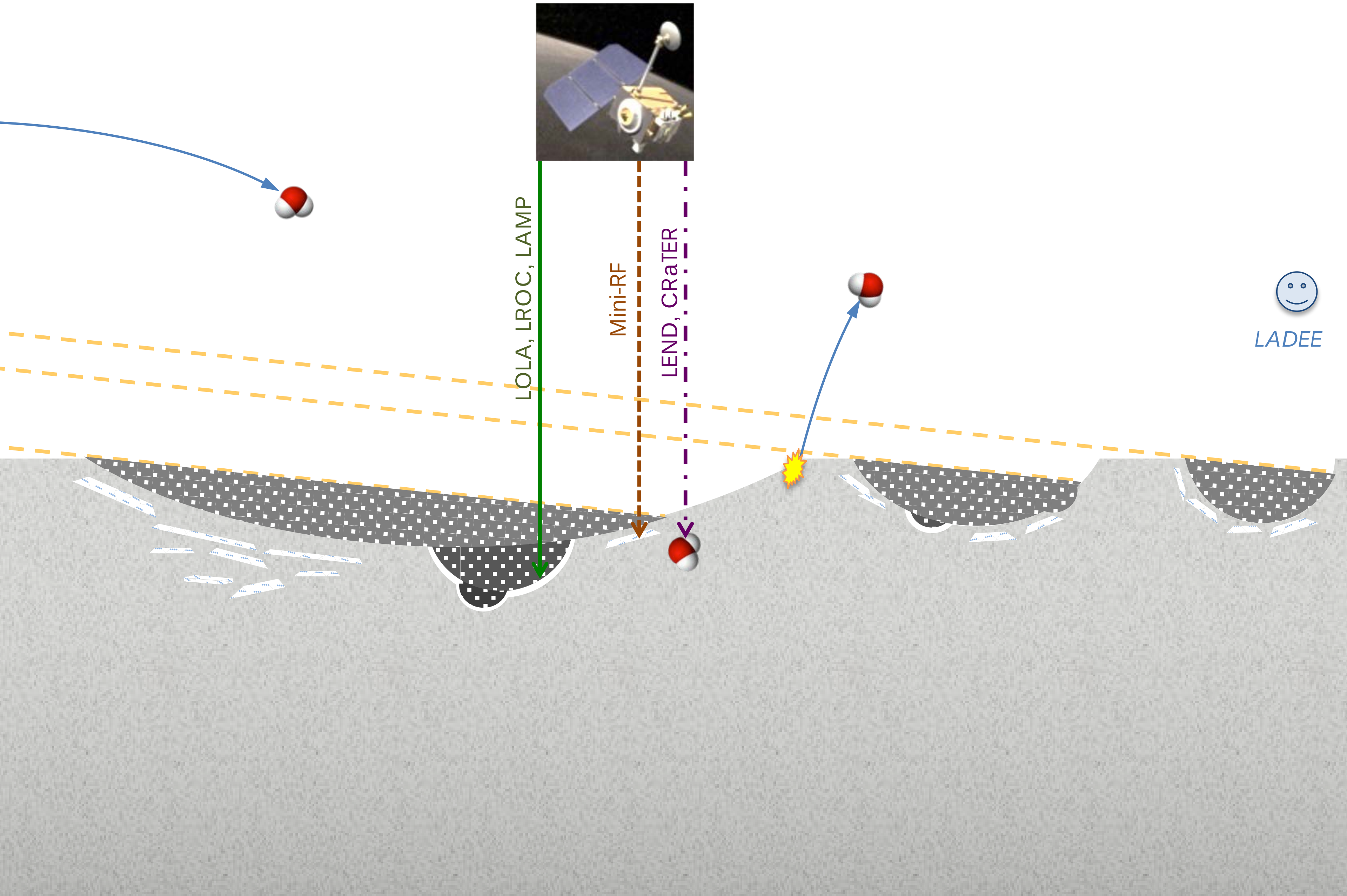
Lunar Volatiles





Shadowed Moon
Illuminated Moon
Lost to Space
Sources:
Sun, Moon, Earth
Comets, Dust, Asteroids
Giant Molecular Clouds
Lost to Space
UV ionization
and sweeping
Losses
• Sublimation
• UV ionization
• Sweeping
• Sputtering
• Micrometeorite impact vaporizarion
Ballistic random walk
Cold trapping
Sequester
by regolith
overturn
Sequester
by alteration to
refractory phase:
• Organics
• Hydrated minerals
• Clathrates
Adsorption (warm trapping)




LOLA, LROC, LAMP
Mini-RF
LEND, CRaTER
LADEE

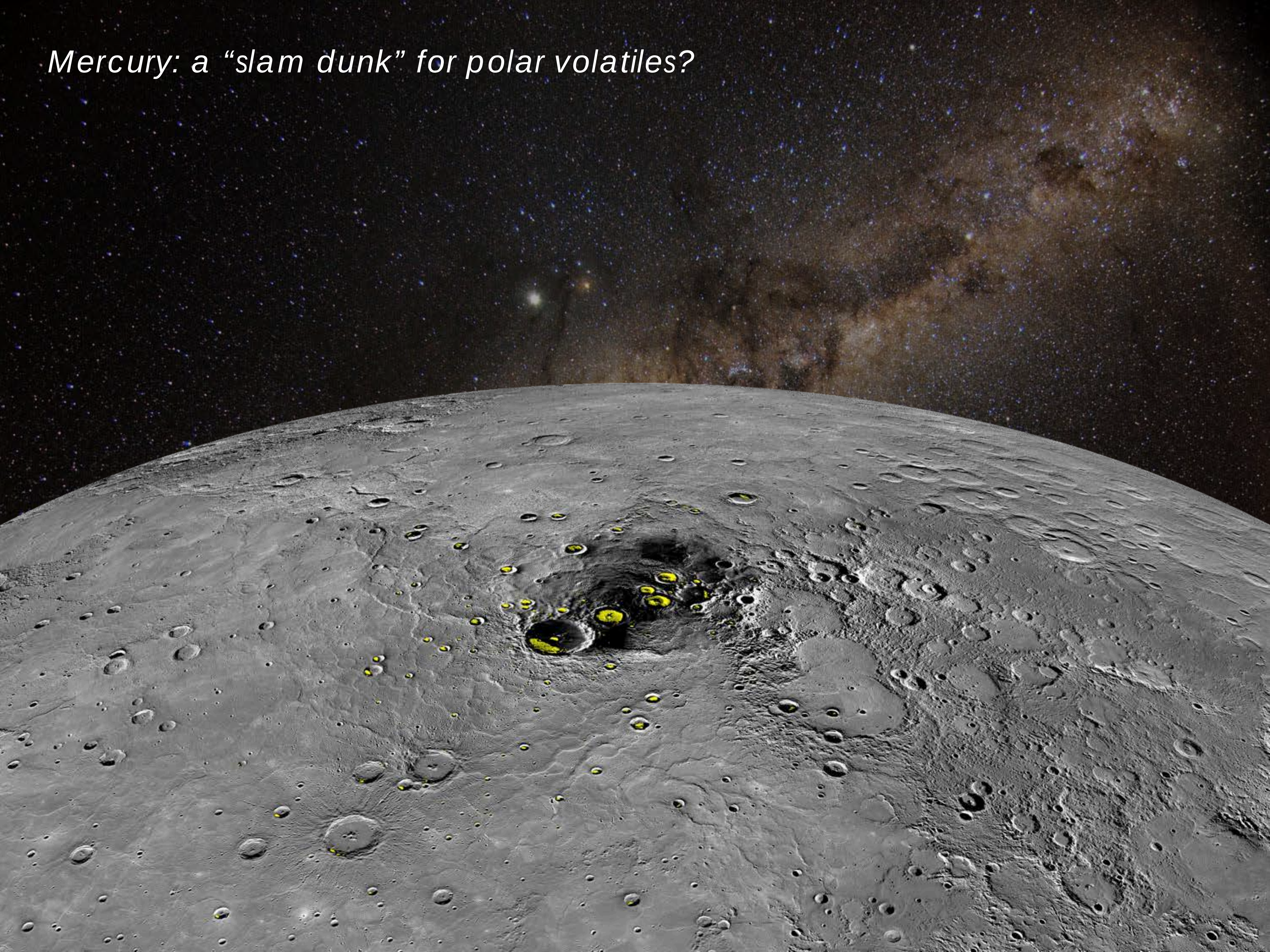
Technique	Result	Sensitivity	Depth	Resolution	Reference
Earth-based radar	Non-detection	>10-cm ice blocks	~1 m	125 m	*Stacy et al.* [1997]
Orbital mono-static radar	Disputed detection	>10-cm ice blocks	~1 m	75 m	*Spudis et al.* [2013]
Orbital bi-static radar	Disputed detection (Clementine); improved data pending (LRO)	>10-cm ice blocks	~1 m	75 m	*Patterson et al.* [2014]
Neutron spectroscopy	Detection of [H] = 1700 ± 900 ppm (~1% H_2O) average >70° latitude	H atoms at greater than ~100 ppm	~1 m	~50 km	*Feldman et al.* [2000, 2001]
Neutron spectroscopy	Detection of [H]; specific PSRs with ~200 – 4500 ppm (0.1% - 4% H_2O)	H atoms greater than ~100 ppm	~1 m	~10-50 km	*Mitrofanov et al.* [2012]
Infrared spectroscopy of impact plume	Detection of 5.6 ± 2.9% H_2O, at single point (84.7°S, 310.6°E)	H_2O ice and vapor at greater than ~1wt%	~3 m	30-m crater	*Colaprete et al.* [2010]
Ultraviolet spectroscopy	Possible detection in the PSRs; detection of H_2O (and diurnal variations) at low latitudes	H_2O with abundance greater than ~0.5wt%	~1 µm	240 m	*Gladstone et al.* [2012], *Hendrix et al.* [2012]
Infrared solar reflectance spectroscopy	Detection of 10 – 100 ppm OH and H_2O on mineral surfaces under direct solar illumination	H_2O and OH with abundance greater than ~10 ppm	~10 µm	140 m	*McCord et al.* [2011]
Analysis of lunar samples	Detection of ~0 – 1wt% H_2O in igneous melt inclusions	Various	Surface	-	*Boyce et al.* [2010], *Liu et al.* [2012]

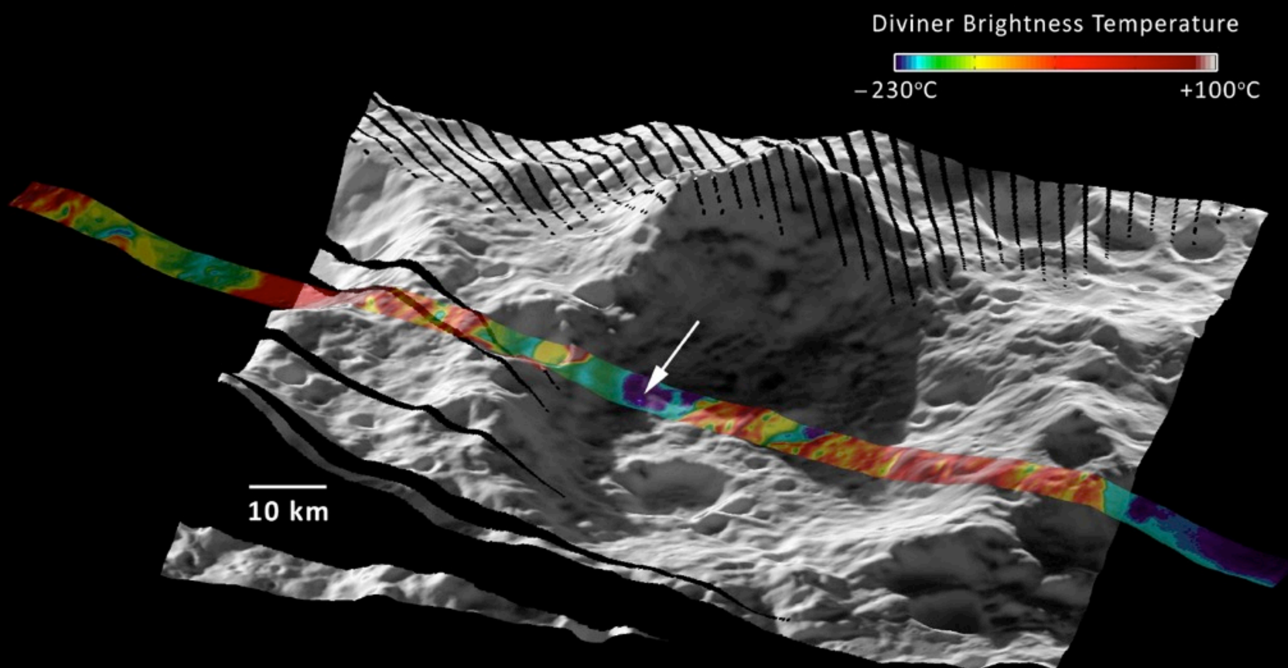
Hayne et al. (2014), *Keck Institute for Space Studies Report*

Distribution and concentration of ice is variable:

- **Vertically**
  - ✧ Vapor diffusion
  - ✧ Burial
  - ✧ Outgassing/sputtering/photolysis
- **Laterally**
  - ✧ Molecular hops
  - ✧ Water-rich impactors
  - ✧ Thermal environments

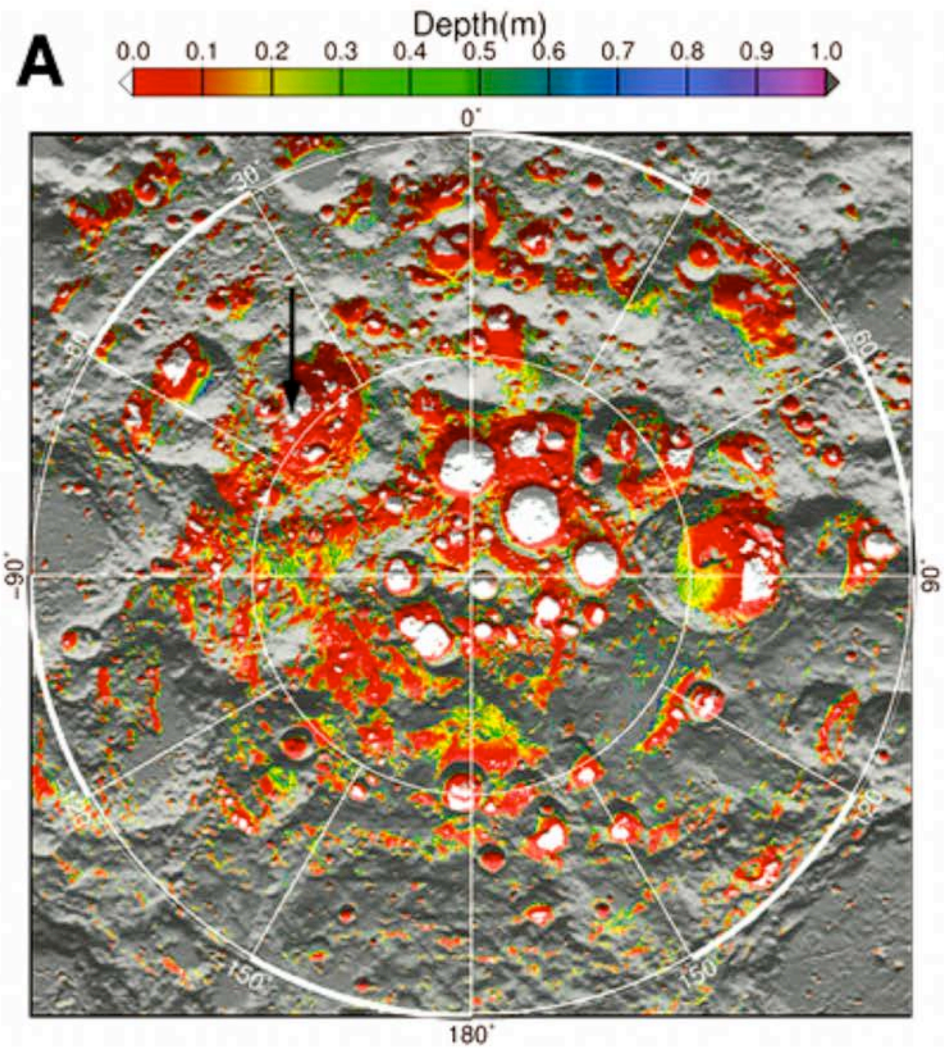
Mercury: a “slam dunk” for polar volatiles?



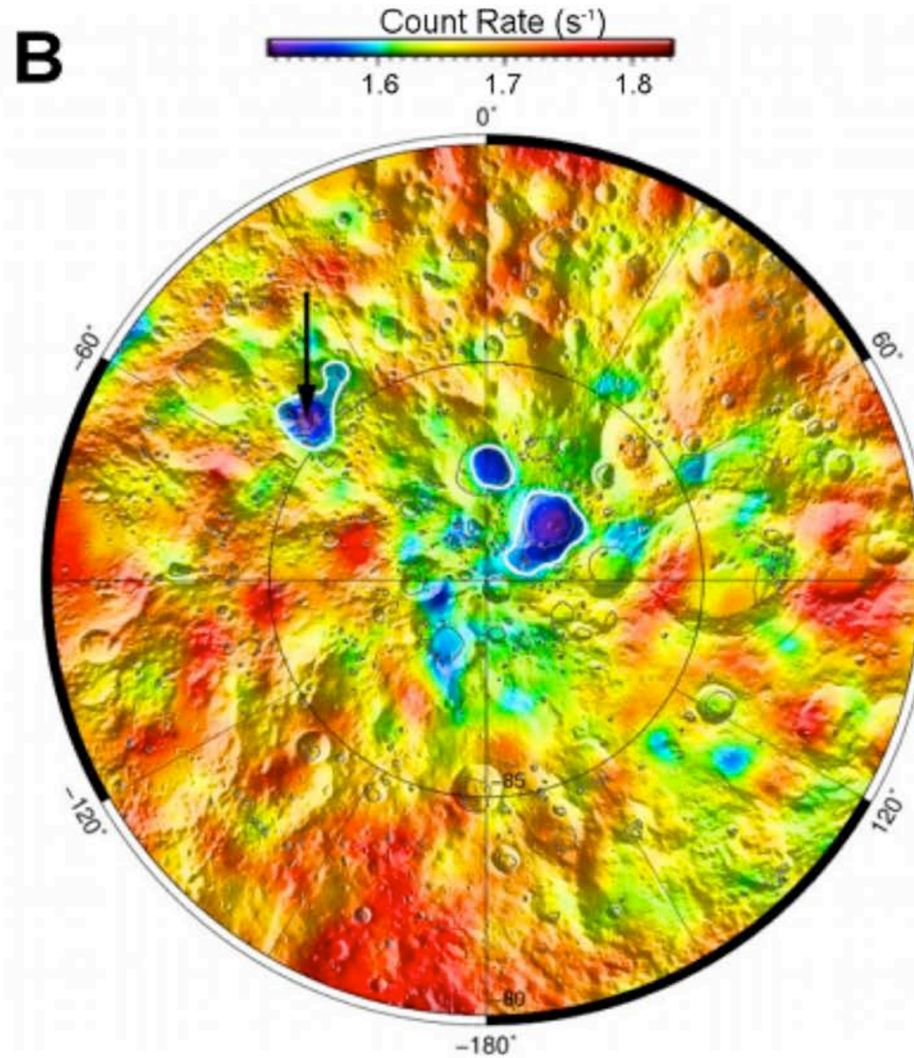


Diviner Brightness Temperature
−230°C
+100°C
10 km

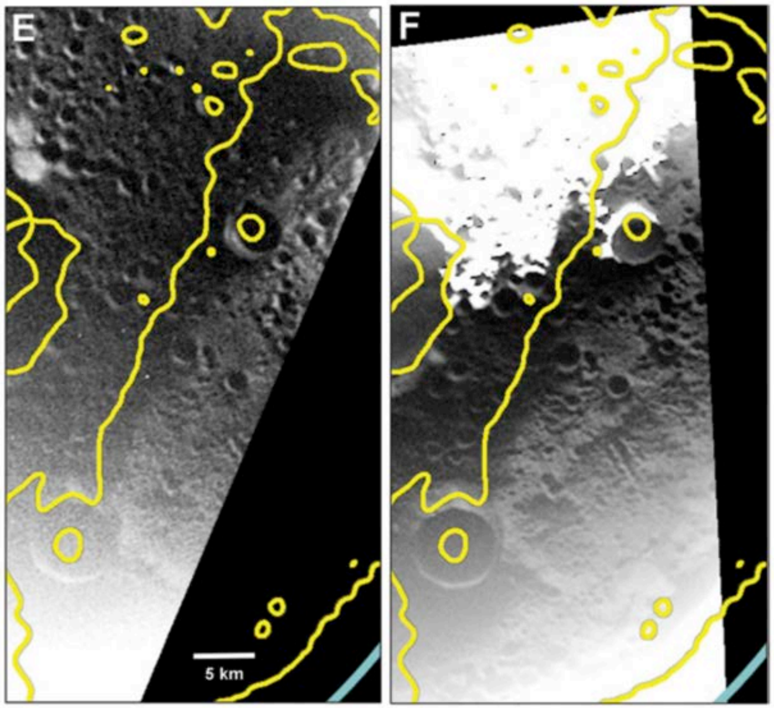
Diviner Ice Stability Map



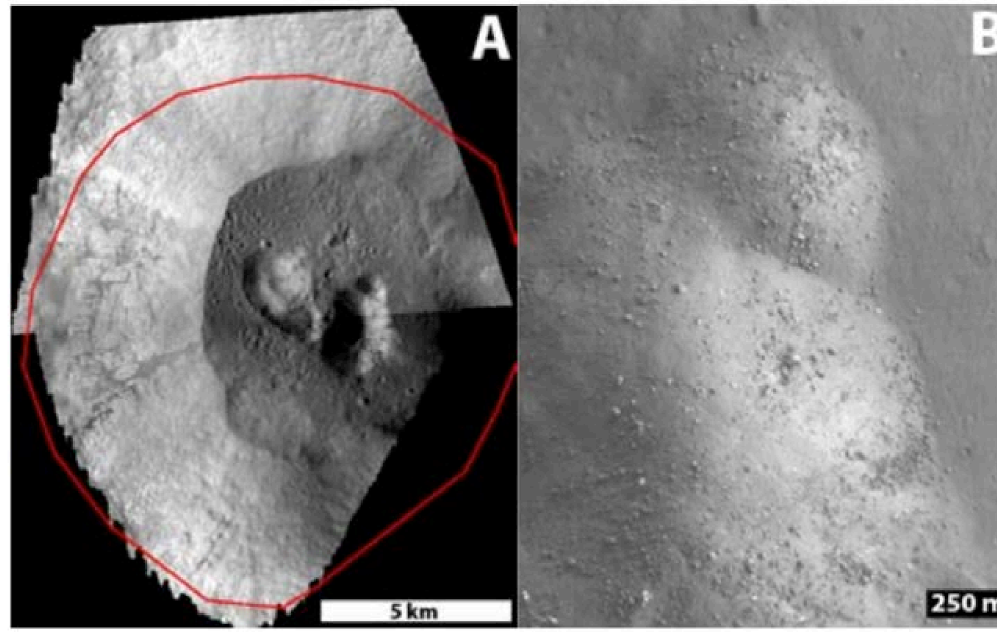
LEND Hydrogen Map



LROC

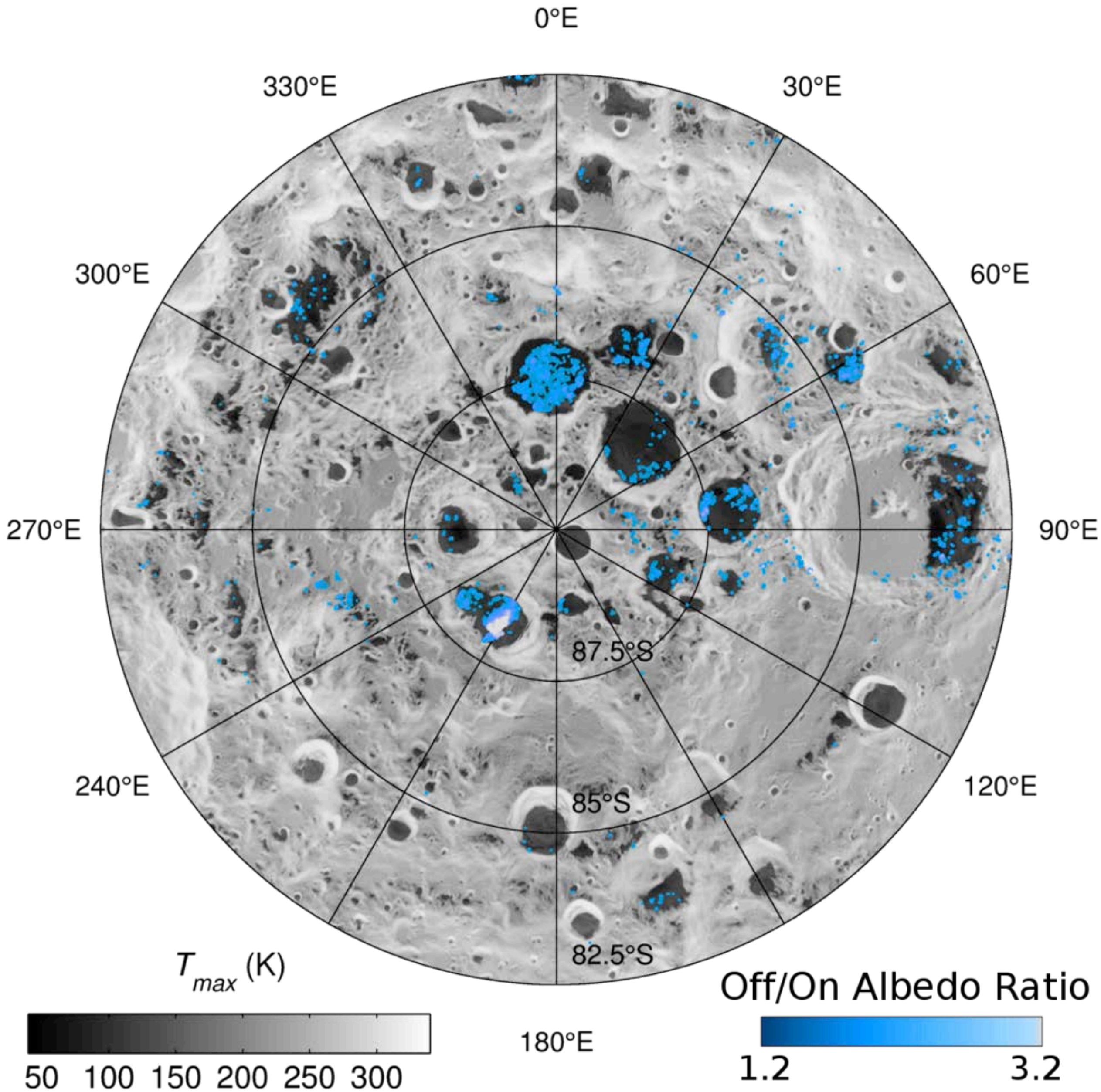


Mercury: well-defined ice boundary follows PSR (Chabot *et al.*, 2014)



Moon: no obvious albedo anomaly in PSR (Koeber et al., 2014)

LAMP Ice Index and Diviner Temperatures



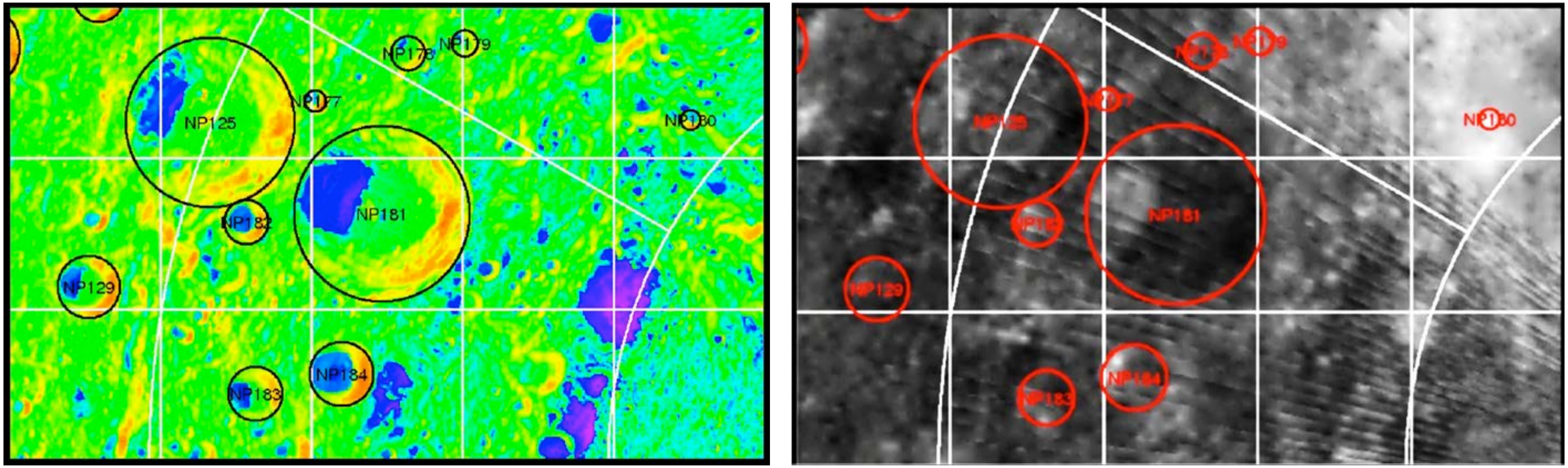
H_2O ice:

- ~1 – 10 wt%
- Patchy, heterogeneous distribution
- Supply rates ~ destruction/ burial rates

Some evidence for CO_2 ice

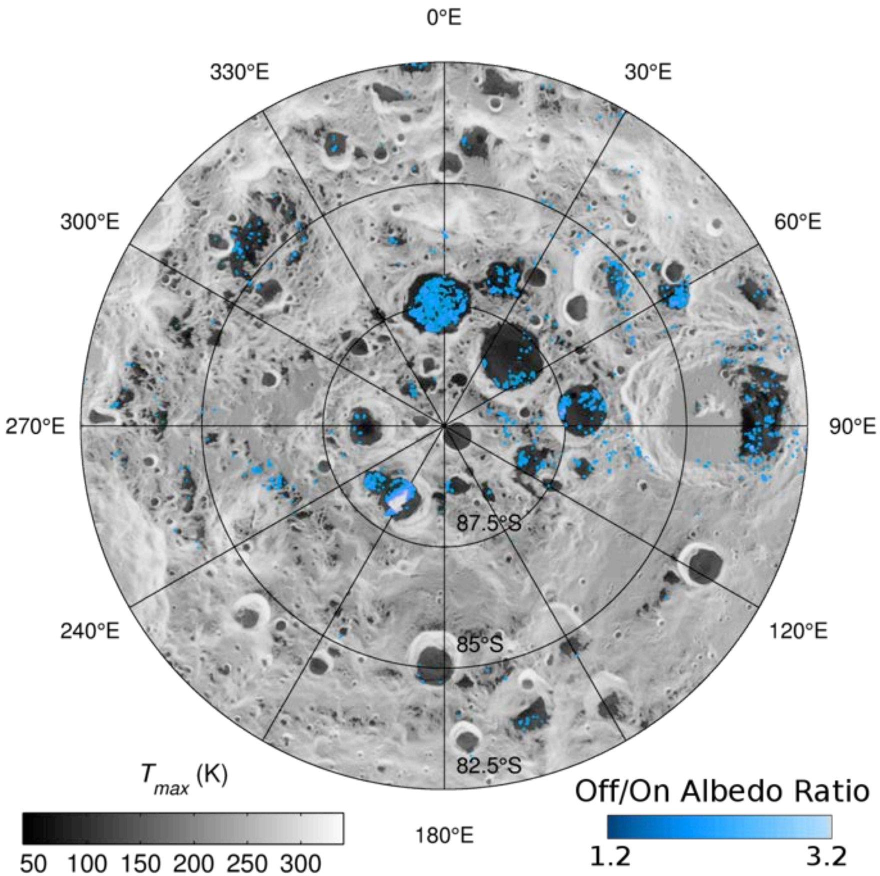
Hayne et al. (2015)

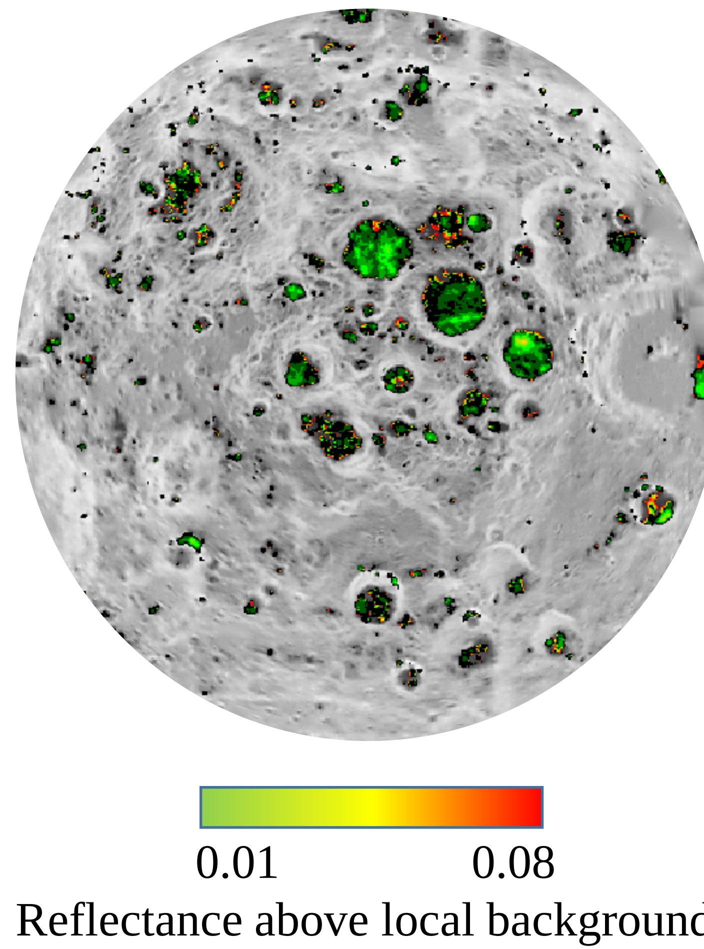
Diviner-LOLA Comparison



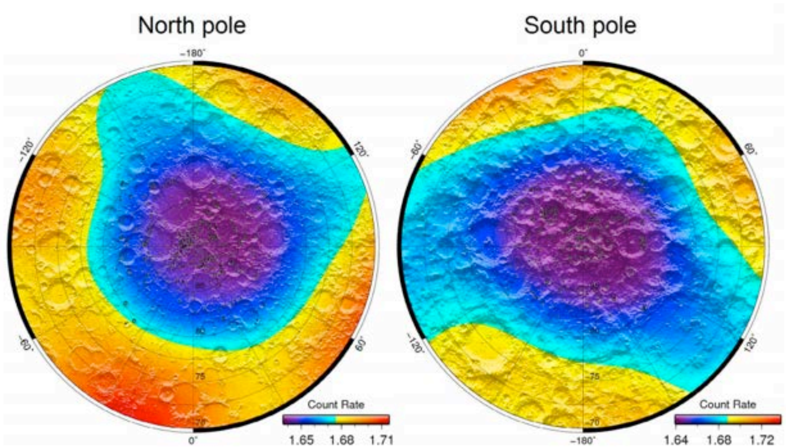
Diviner temperatures show well-defined cold traps, where LOLA often sees high-albedo deposits, consistent with surface frost
(D. Paige, Diviner PI)

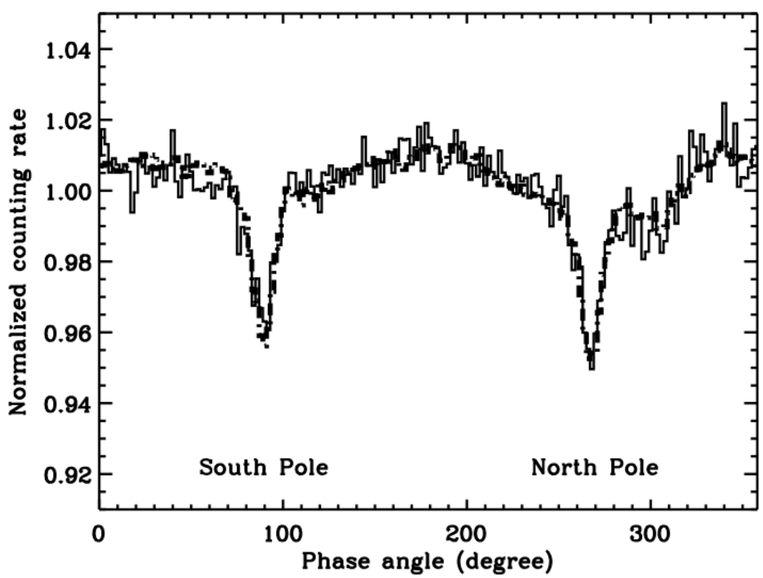
Diviner, LAMP and LOLA Comparison

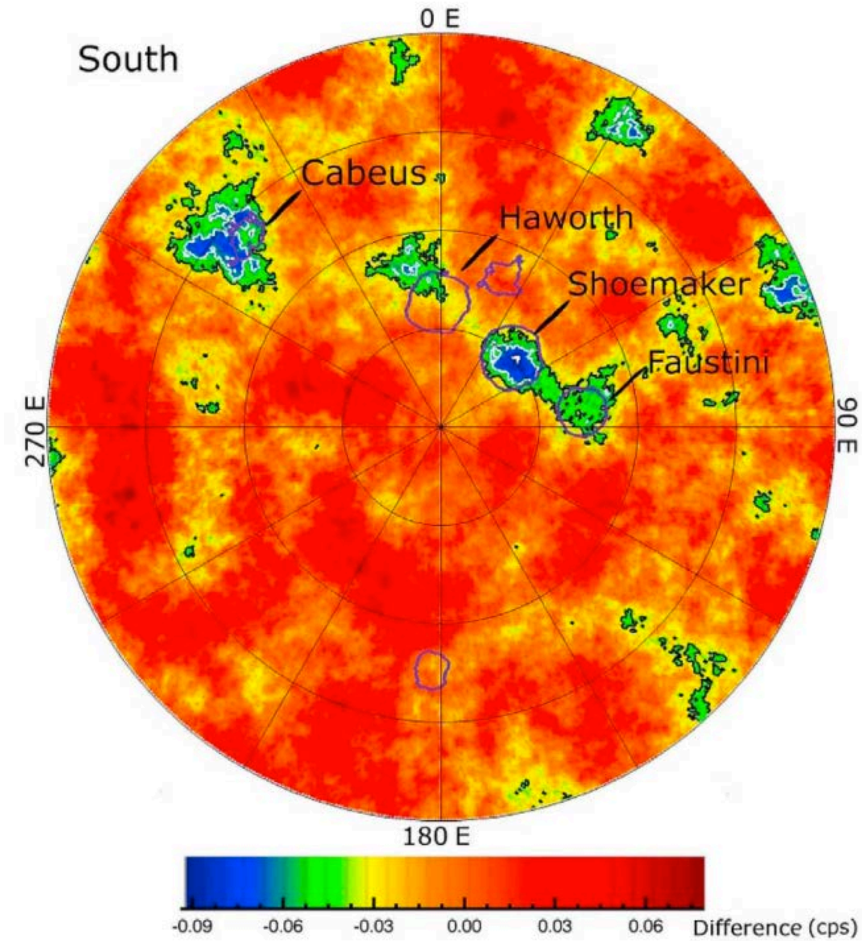




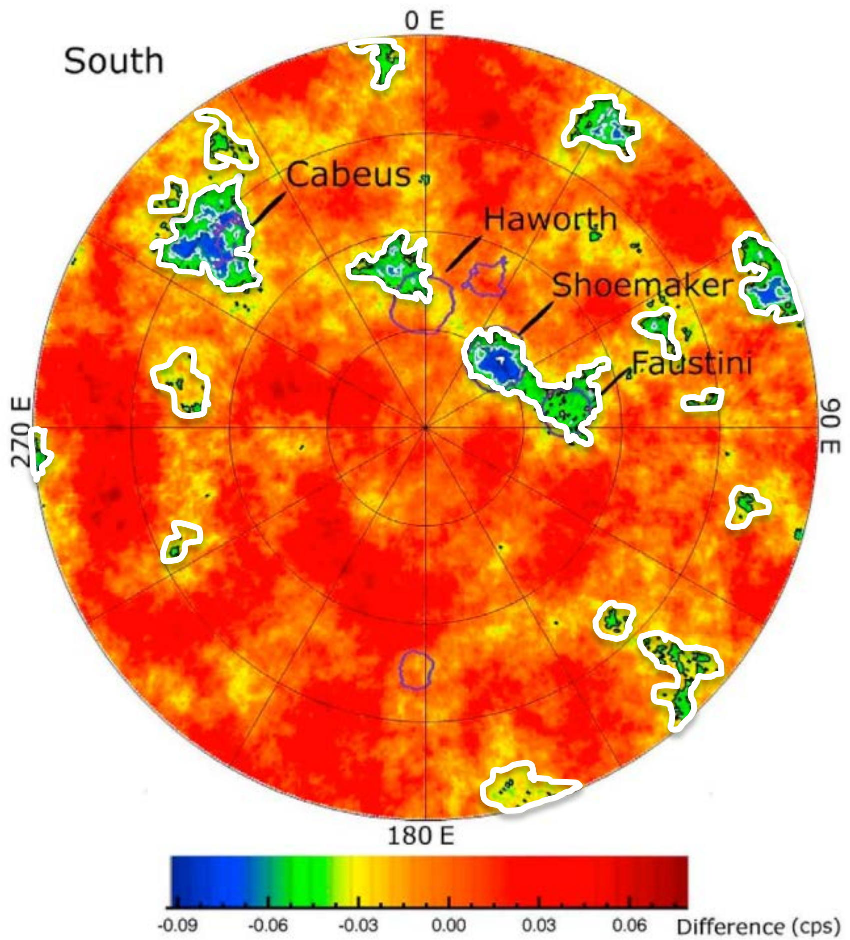
LEND

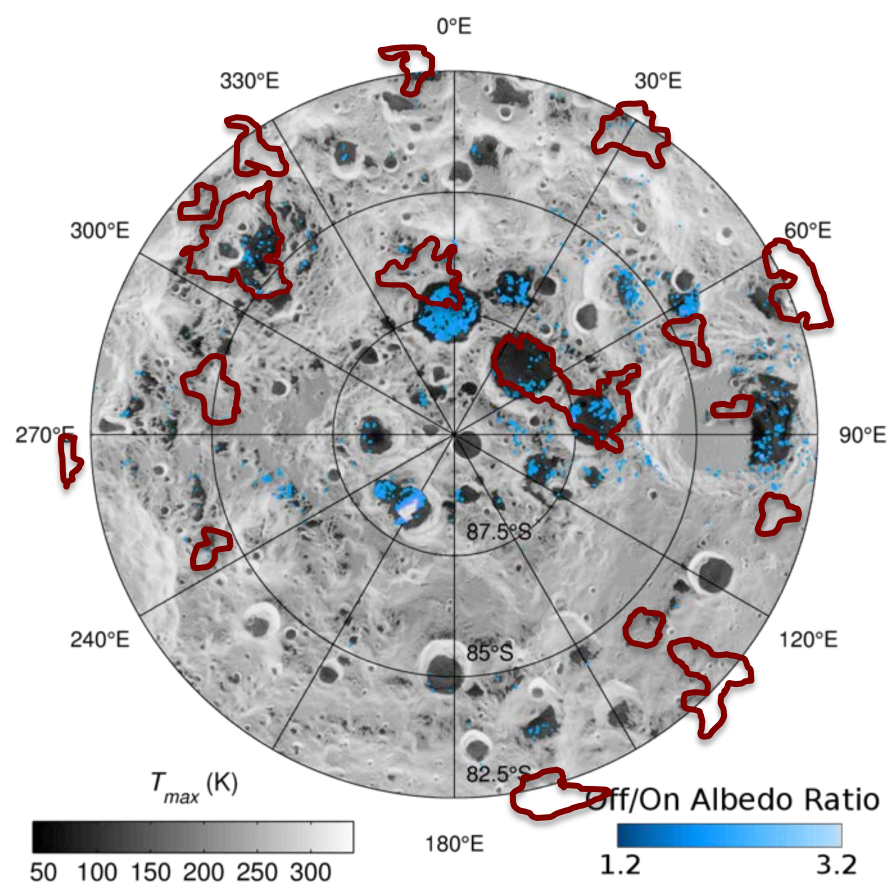

North pole
South pole
Count Rate
1.65 1.68 1.71
Count Rate
1.64 1.68 1.72


Normalized counting rate
1.04
1.02
1.00
0.98
0.96
0.94
0.92
South Pole
North Pole
0
100
200
300
Phase angle (degree)

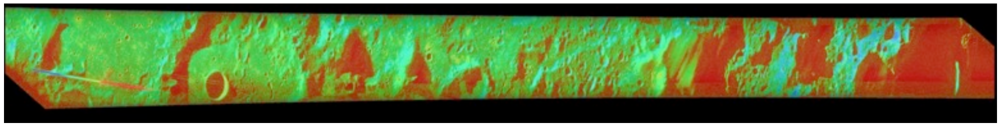

South
0 E
90 E
180 E
270 E
Cabeus
Haworth
Shoemaker
Faustini
-0.09 -0.06 -0.03 0.00 0.03 0.06
Difference (cps)

Diviner-LEND-LAMP Comparison



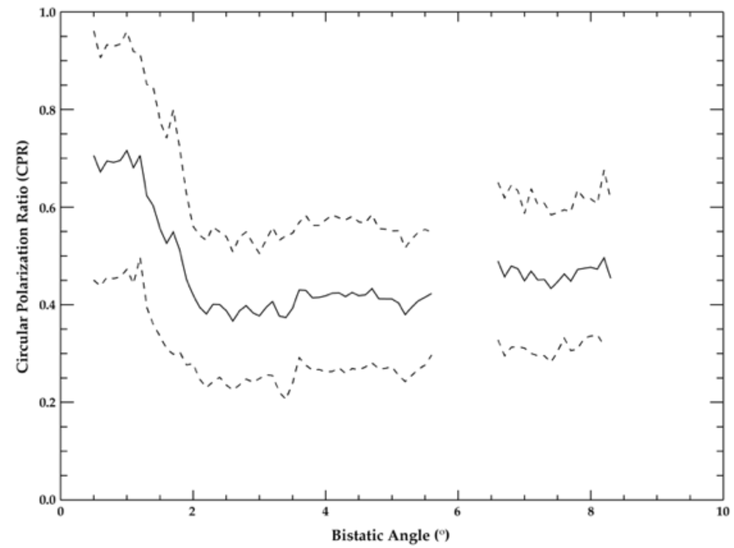


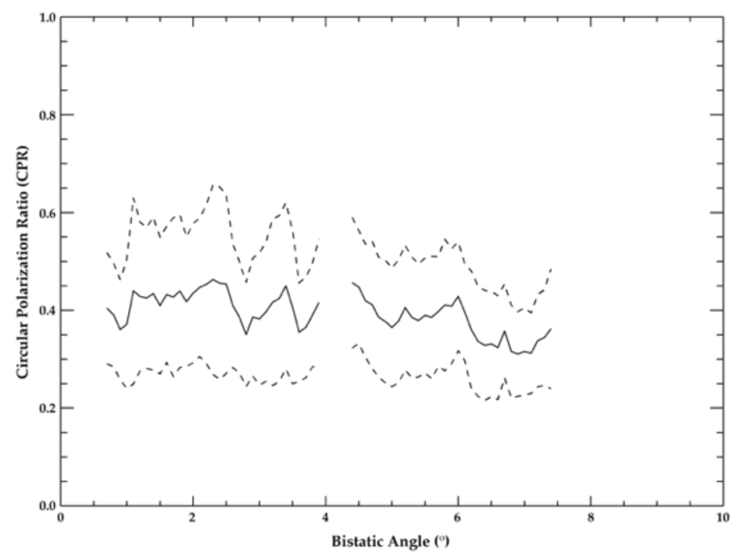
Mini-RF



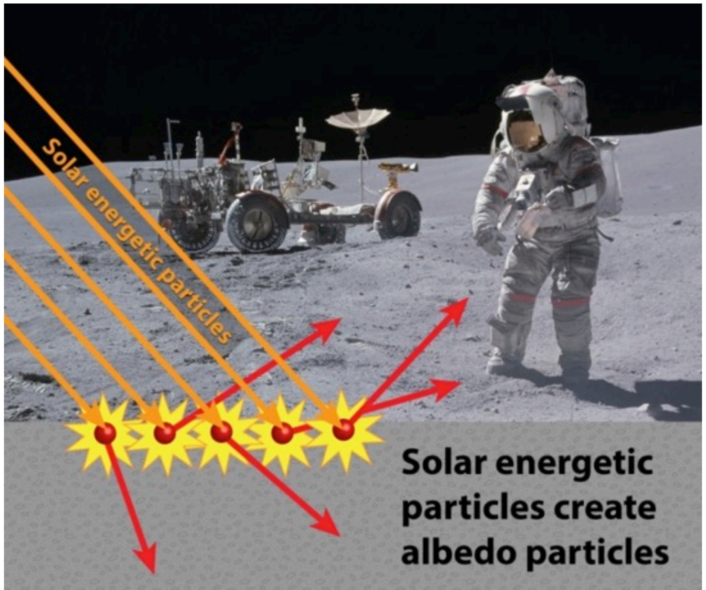
- Mini-RF monostatic observations do not show consistent evidence of widespread H_2O ice in PSRs

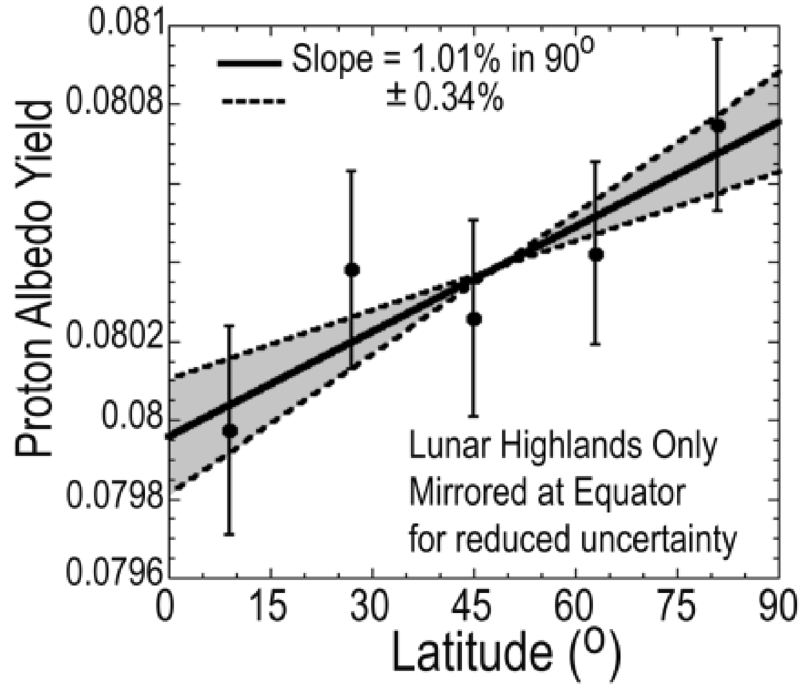
- New bi-static observations show phase behavior consistent with cm-scale ice layers (Patterson *et al.*, in prep)

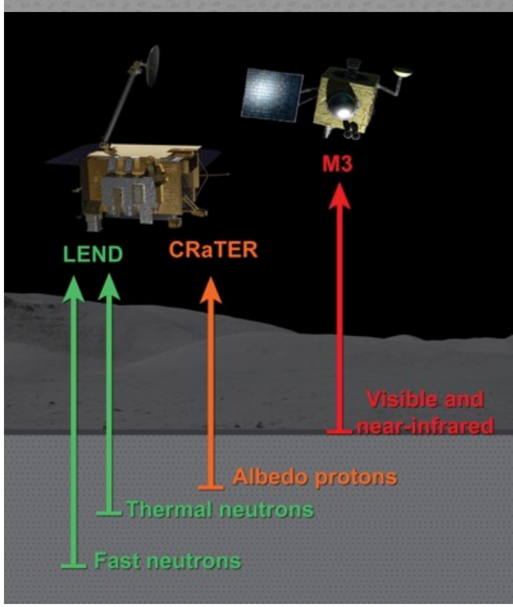




CRaTER



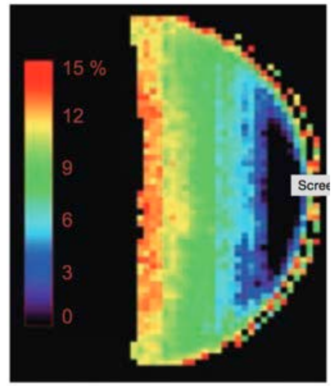




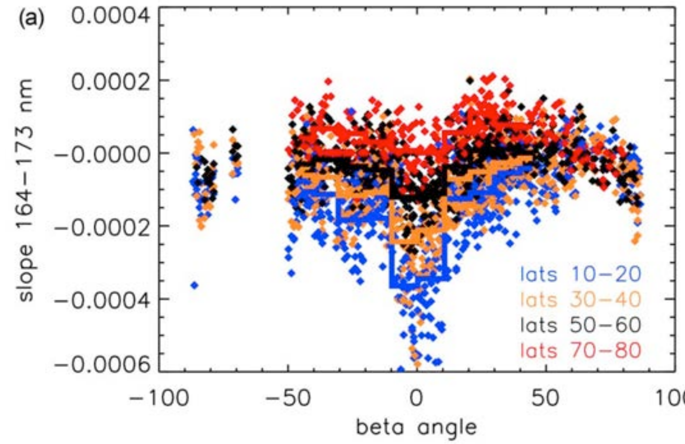
- Latitude trend in proton albedo suggests a 1-10 cm layer of hydrated regolith that is more prevalent near the poles [*Schwadron et al.*, submitted]

Mobility of Volatiles on the Moon

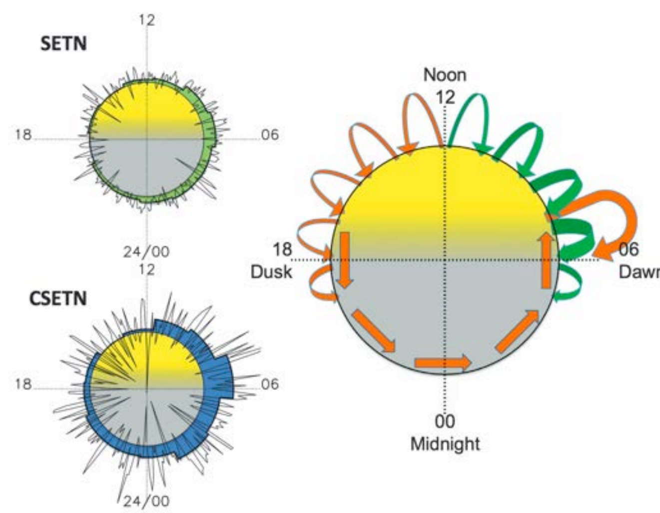
- Some evidence of diurnal variations in hydration: M^3, LAMP, LEND
- Mobility = source for cold traps
- Must be checked for consistency across datasets, and exospheric measurements



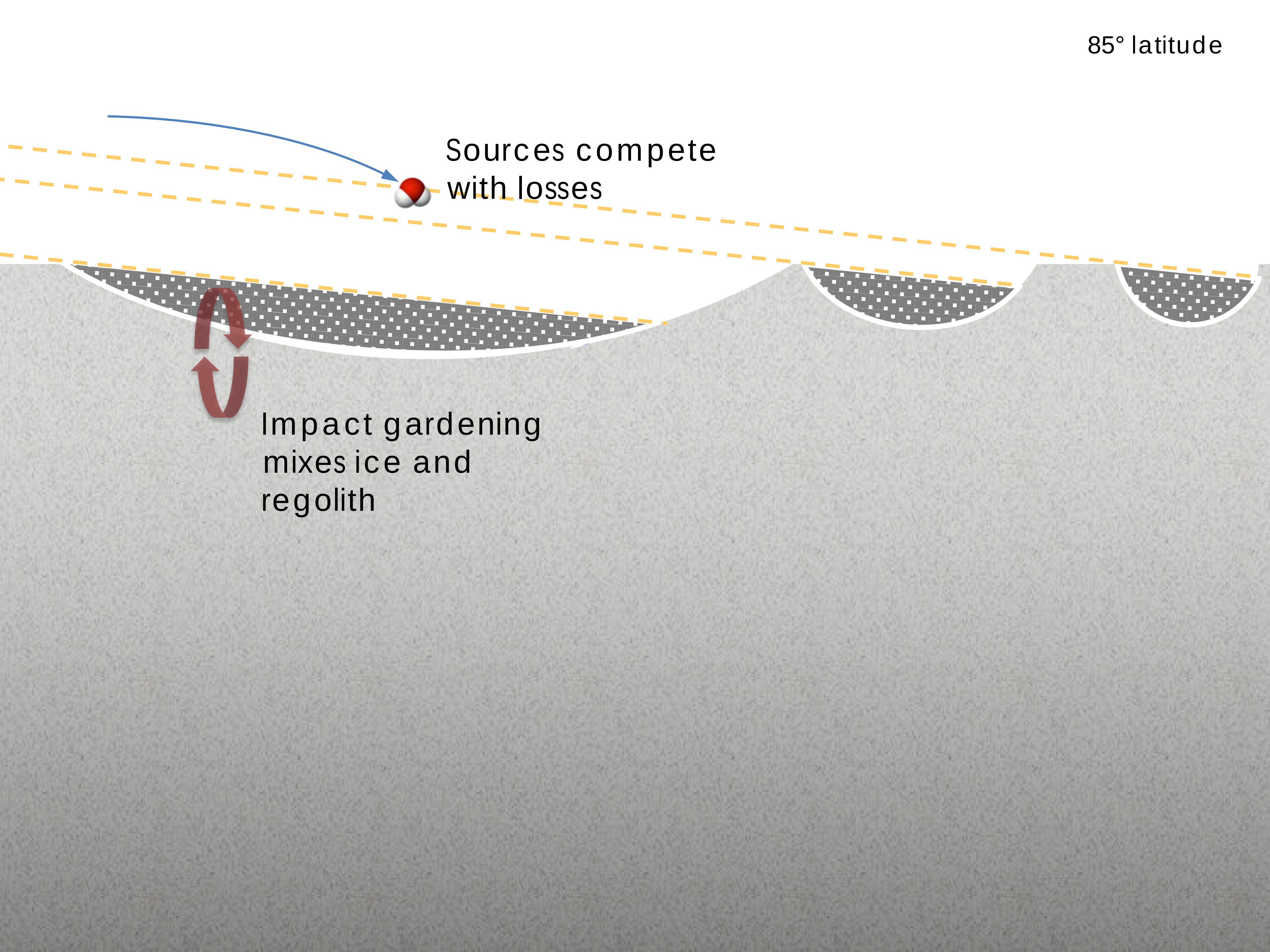
Sunshine et al. (2009)

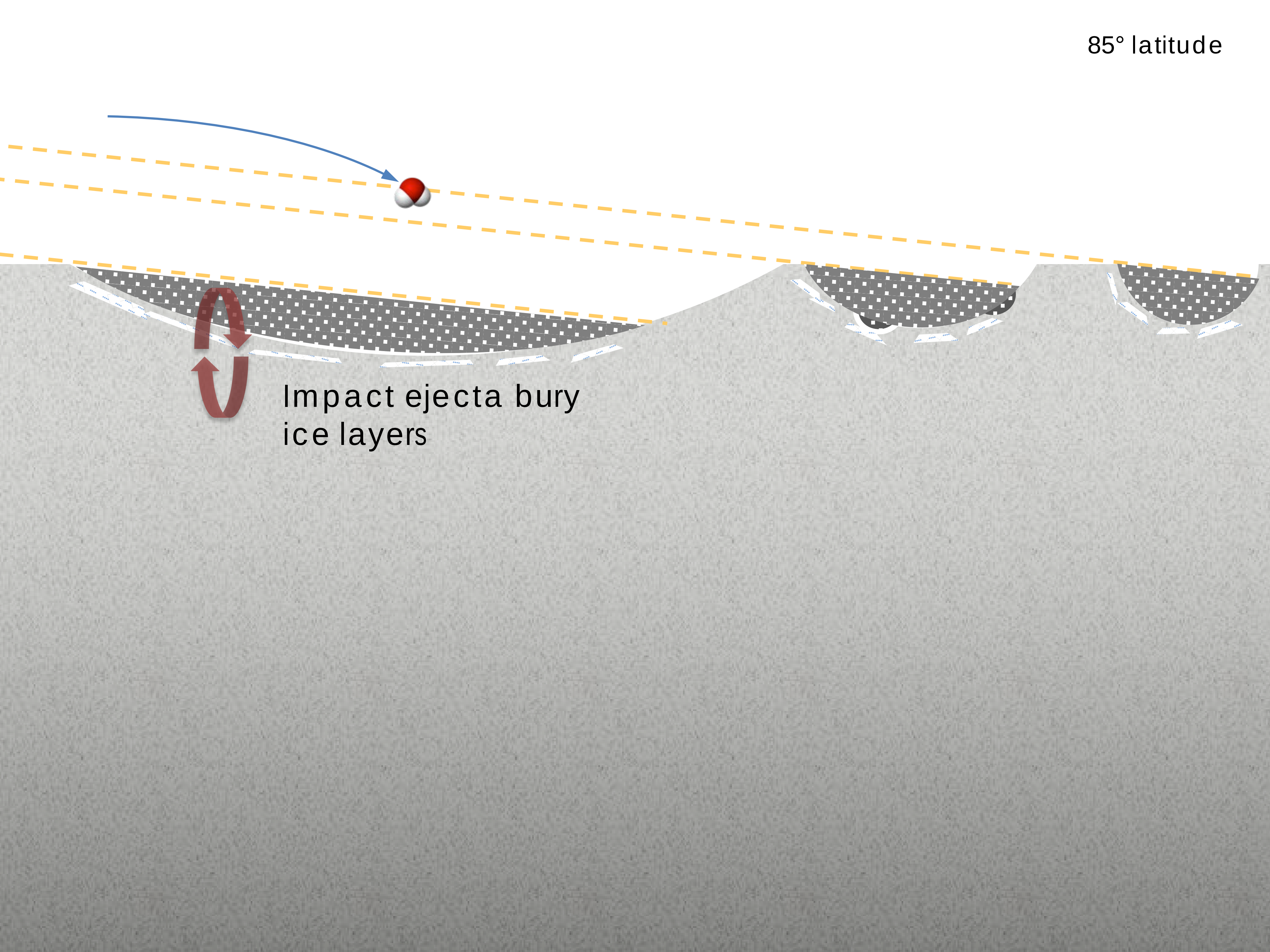


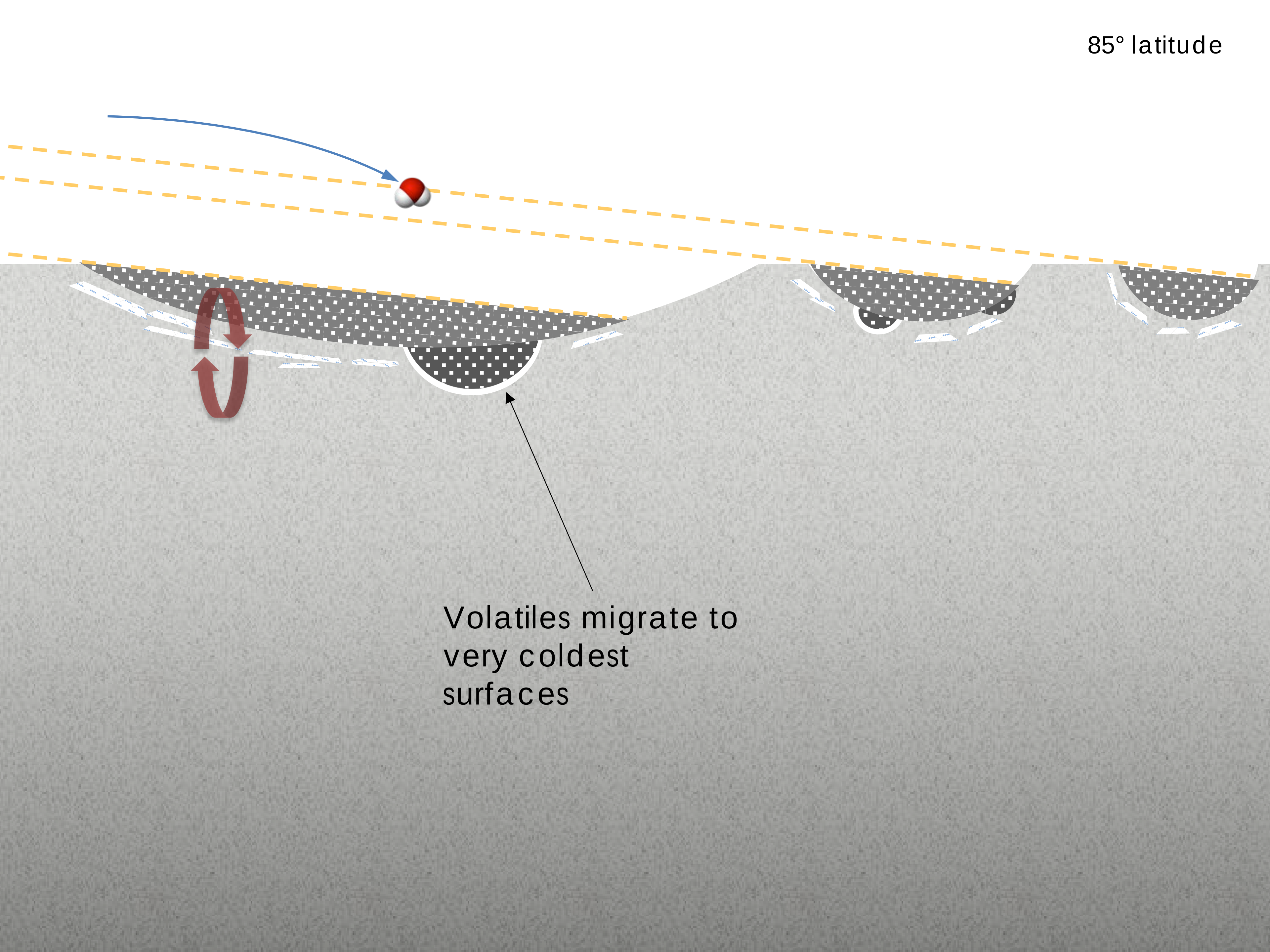
Hendrix et al. (2012)

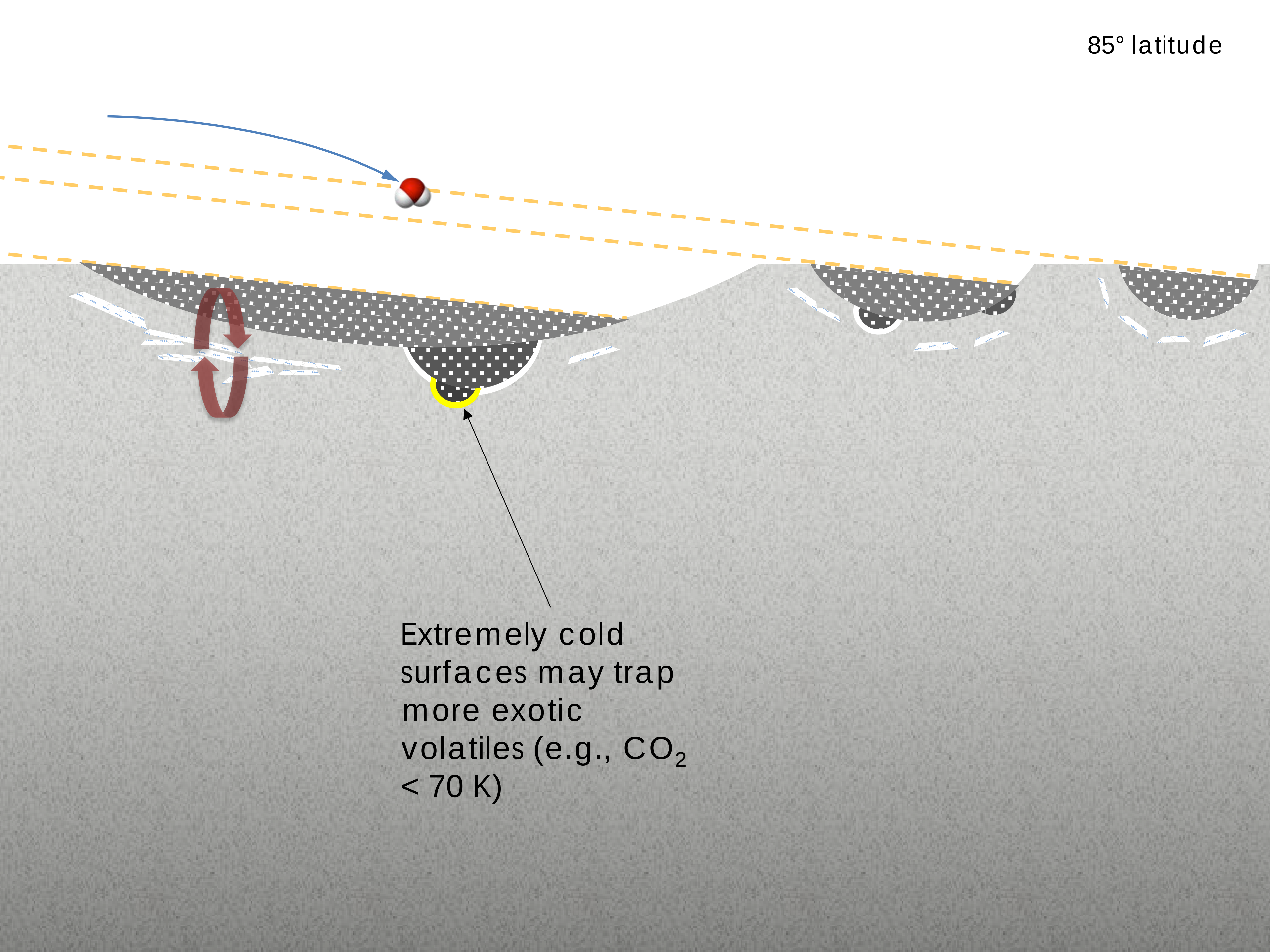


Livengood et al. (2015)


85° latitude
Sources compete with losses
Impact gardening mixes ice and regolith


85° latitude
Impact ejecta bury
ice layers


85° latitude
Volatiles migrate to very coldest surfaces


85° latitude
Extremely cold surfaces may trap more exotic volatiles (e.g., CO_2 < 70 K)

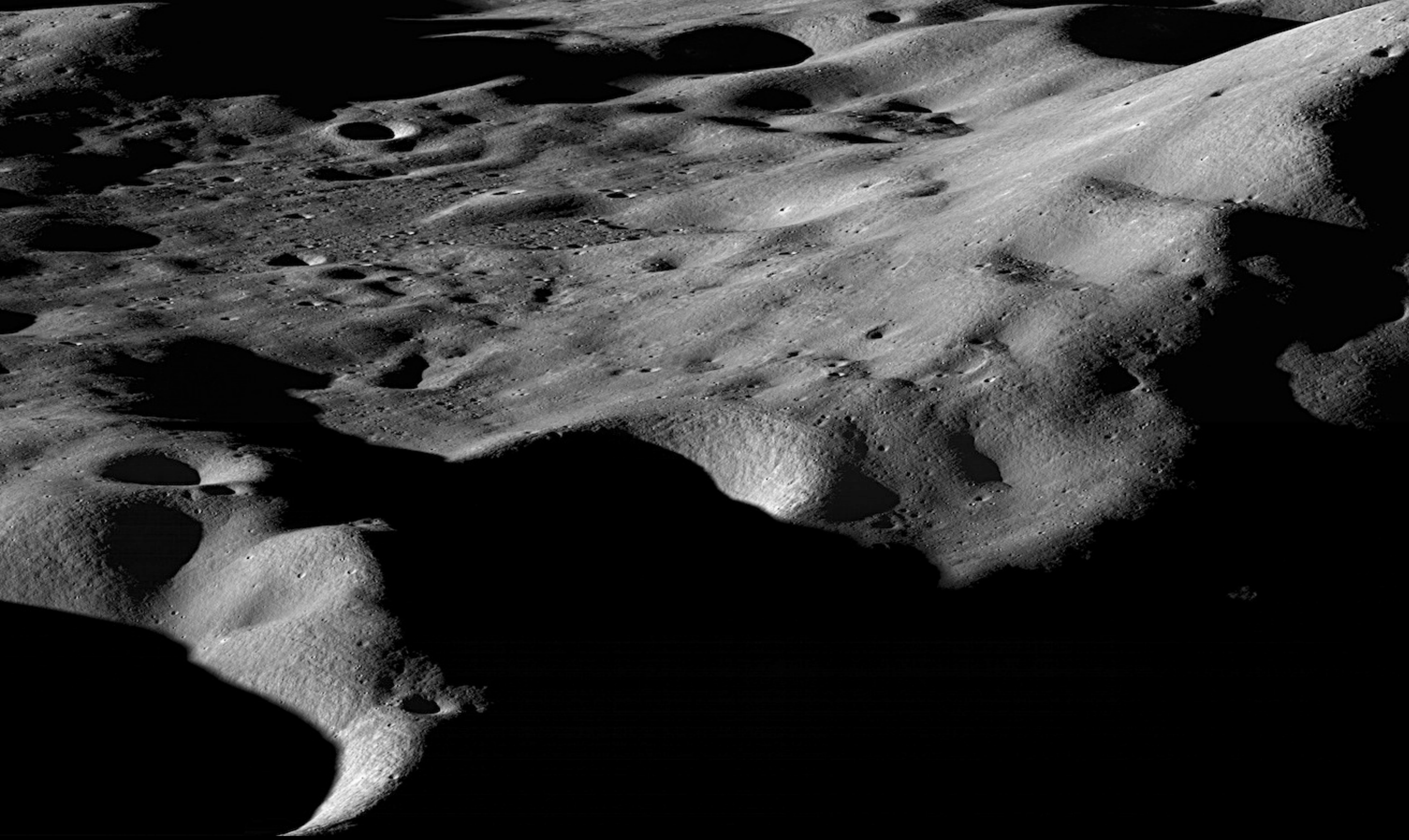
Preliminary LRO Volatiles Results and Future Measurements

- What we think we understand:
  - UV, visible, and near-IR reflectance data consistent with small quantities (~1%) of H_2O ice intimately mixed and/or patchy at small scales in the PSRs
  - Near-IR and neutron data consistent with very small quantities (up to ~100 ppm) outside the PSRs and at lower latitudes

- What we don’t understand fully:
  - High concentrations of H in regions of thermal instability
  - Diurnal variations with magnitude large enough to fill cold traps with ice

Preliminary LRO Volatiles Results and Future Measurements

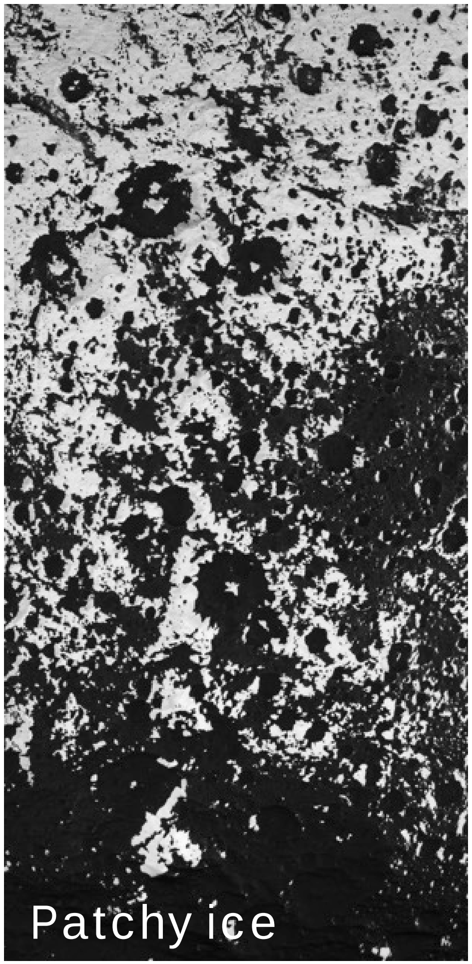
- **Exciting new measurements to watch out for in the next LRO Extended Mission:**
  - Mini-RF bi-static observations could reveal locations of "blocky" subsurface ice
  - CRaTER albedo proton measurements could confirm presence of hydrated upper cm layer in polar regions → highly complementary to LEND and LPNS data
  - New mode of LAMP observations with up to ~10x signal-to-noise for measuring dayside and nightside hydration → tests diurnal variation hypothesis
  - Evidence for polar wander in the epithermal neutron data? (Siegler et al., submitted)

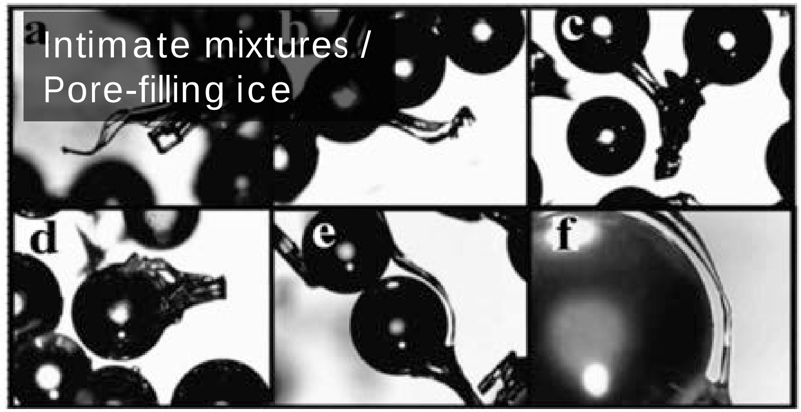


Acknowledgement: This work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

Backup slides

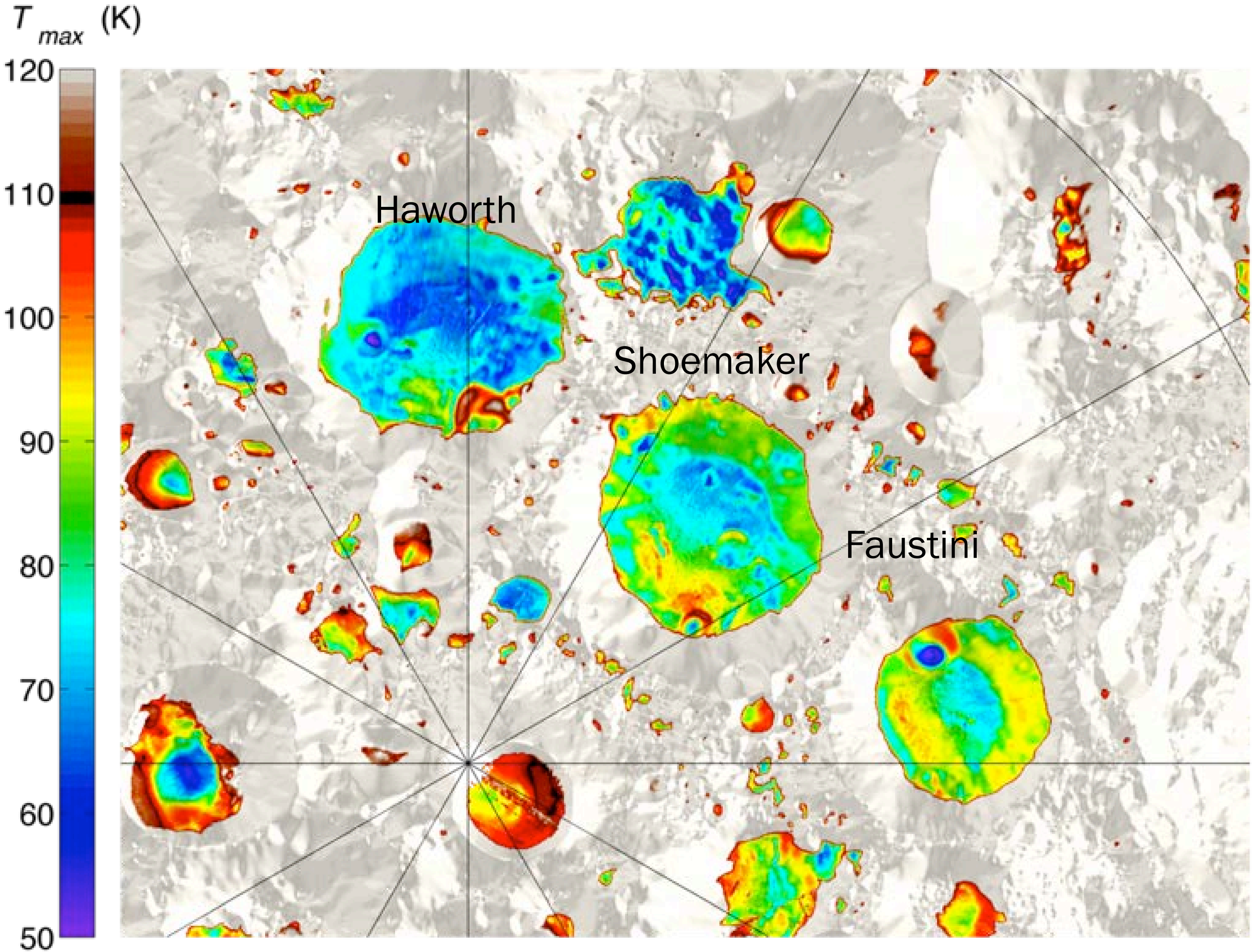
What kind of ice?





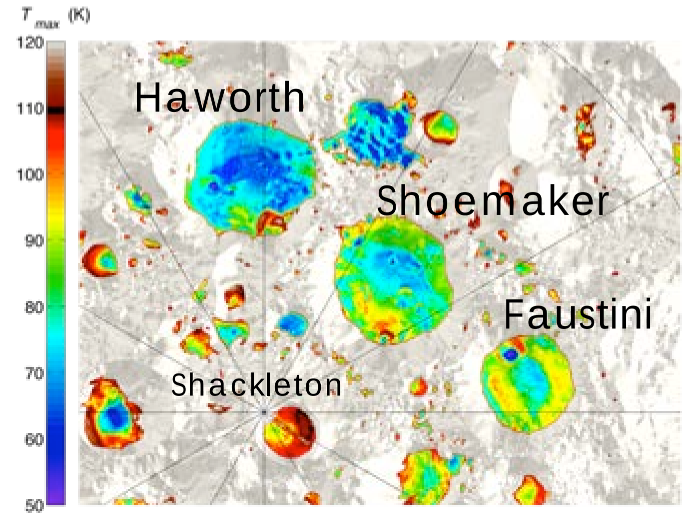
Siegler et al. (2012)

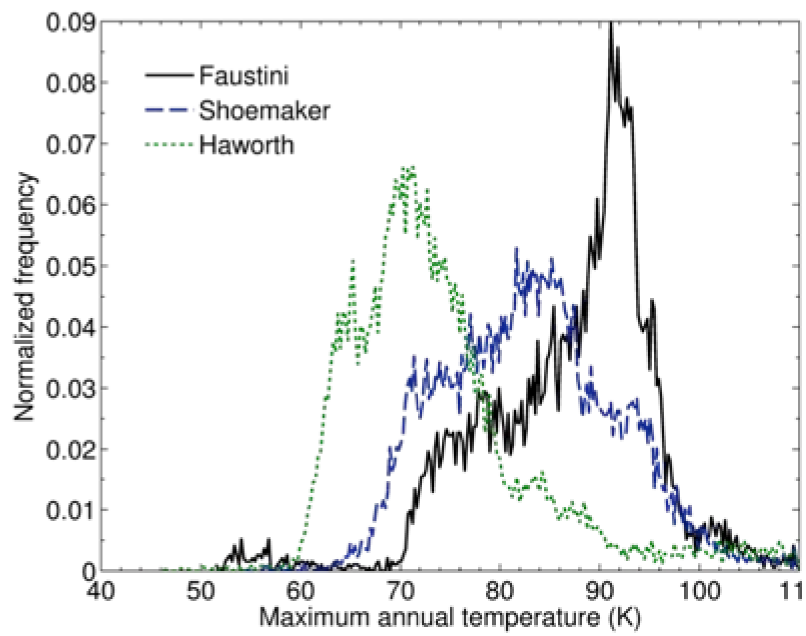
“The Three Amigos”



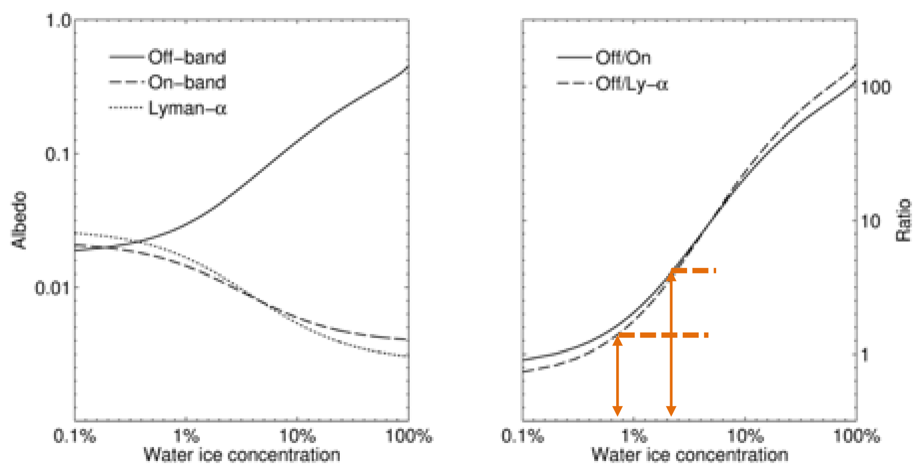
“The Three Amigos”

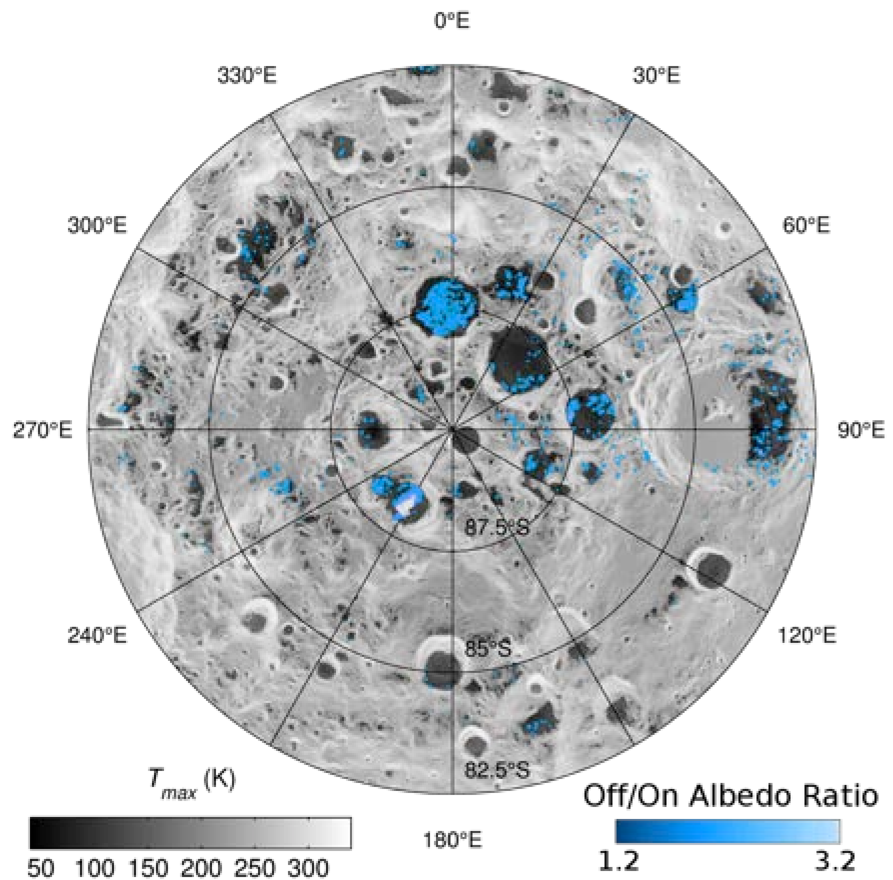
- Each crater actually has quite a different average and range of thermal environments
- Haworth is by far the coldest on average
- Faustini has the greatest diversity, with both < 80 K and even some > 100 K regions
- Trend in LAMP in increasing apparent ice content: Haworth >> Faustini > Shoemaker



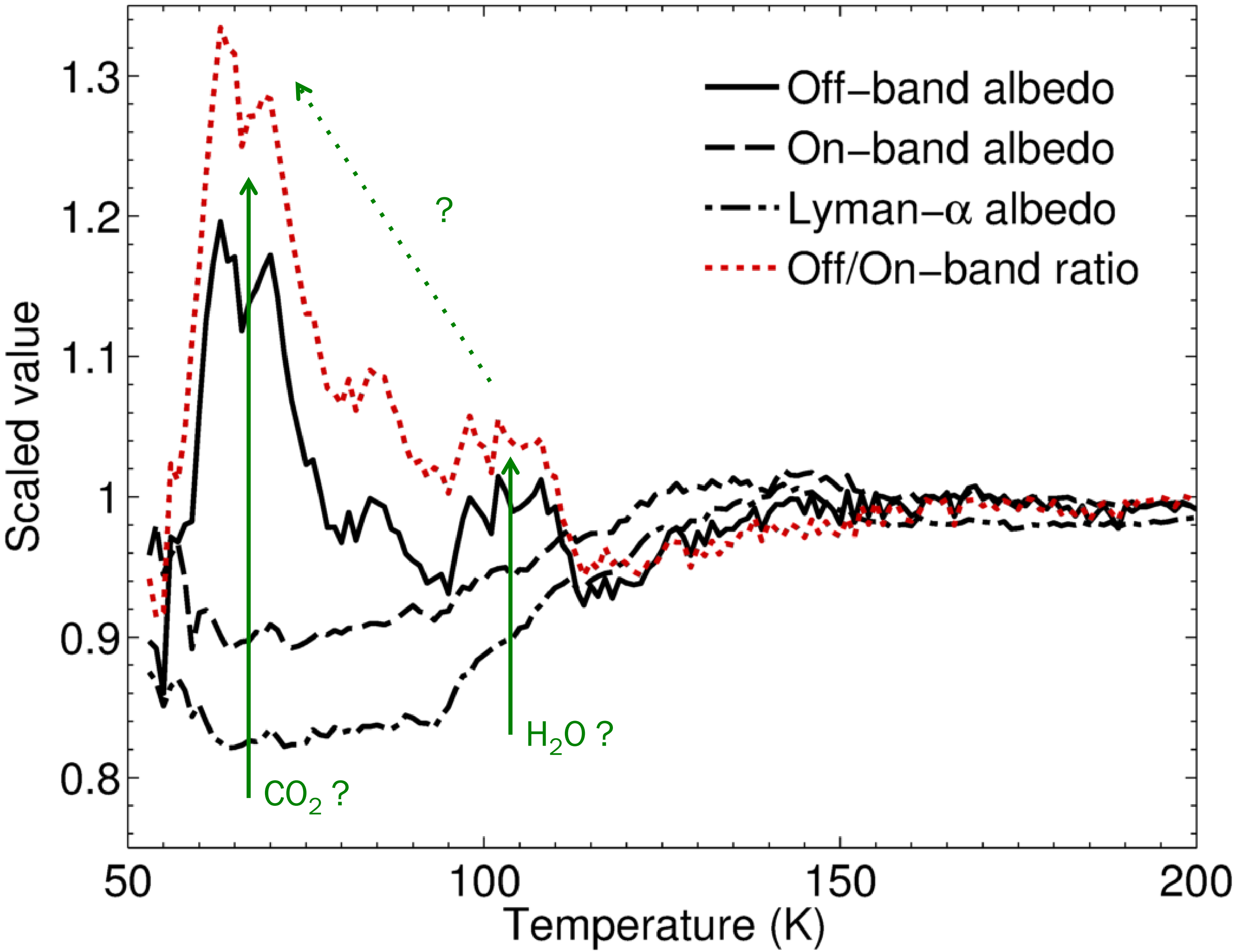


How Much Ice?





- Intimate mixture model: data consistent with ~1–2% water ice by volume
- Area mixing model: up to ~10% water ice by area



Off−band albedo
On−band albedo
Lyman−α albedo
Off/On−band ratio
Scaled value
Temperature (K)
1.3
1.2
1.1
1
0.9
0.8
50
100
150
200
?
H_2O ?
CO_2 ?