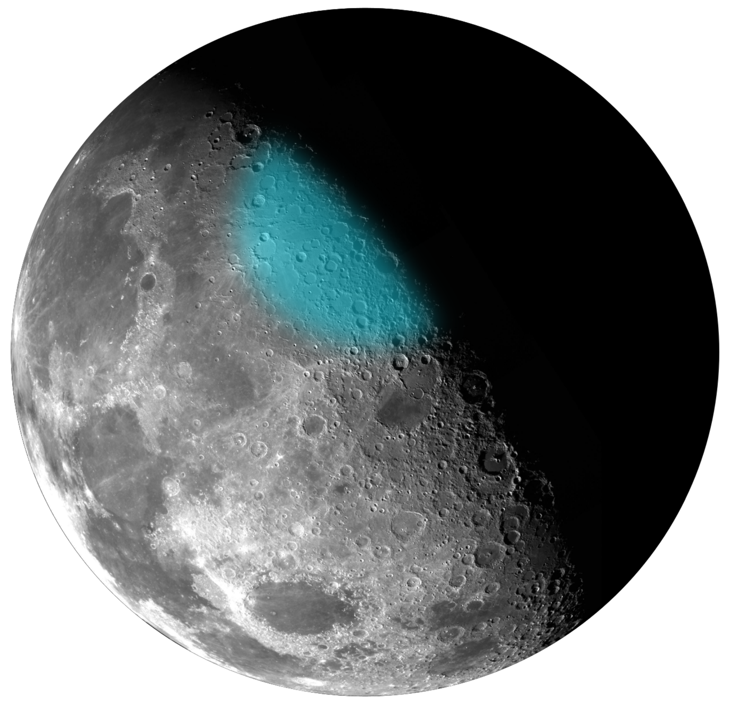

# Toward a history of the Moon's ice caps: Synthesizing surface and subsurface measurements


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**Summary**

(1) It is important to look at the large-scale distribution of the Moon's "ice caps"

(2) The history of the ice can be constrained by the offset of the ice caps from the poles

(3) Many datasets show an ice cap boundary at ~±70° latitude, so it seems possible to find any offsets in the ice caps (i.e., determine the ice's history) as a function of depth

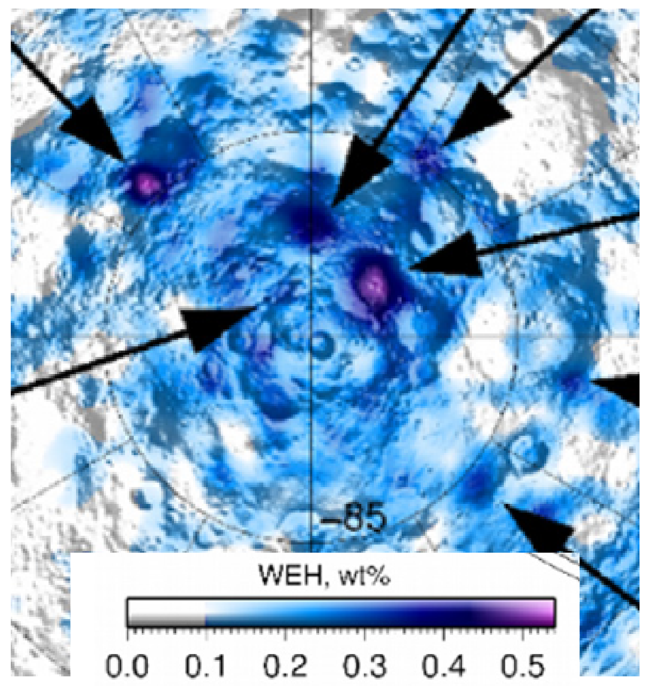

## 1

It has been difficult to determine the history and distribution of water ice in the Moon's polar regions:

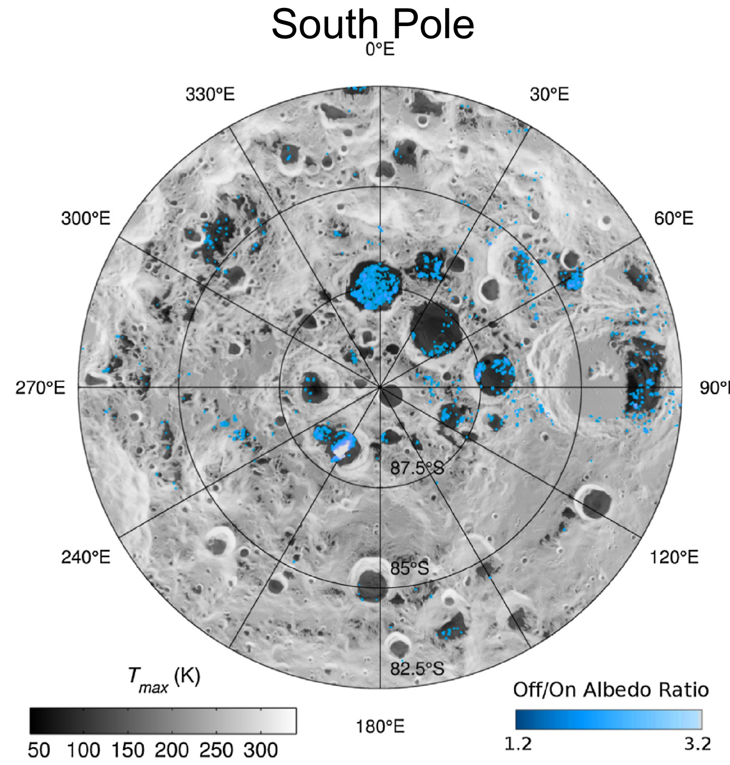
- Ice is heterogeneous on crater-scales
- Interpretations differ among datasets

(See two figures at right)

Some permanently shadowed regions (PSRs) seem to lack ice, others seem to have only surface ice, and others seem to have only buried ice.




Buried (~50 cm) water equivalent hydrogen (WEH) using neutron flux from LRO/LEND (Sanin et al., 2017)

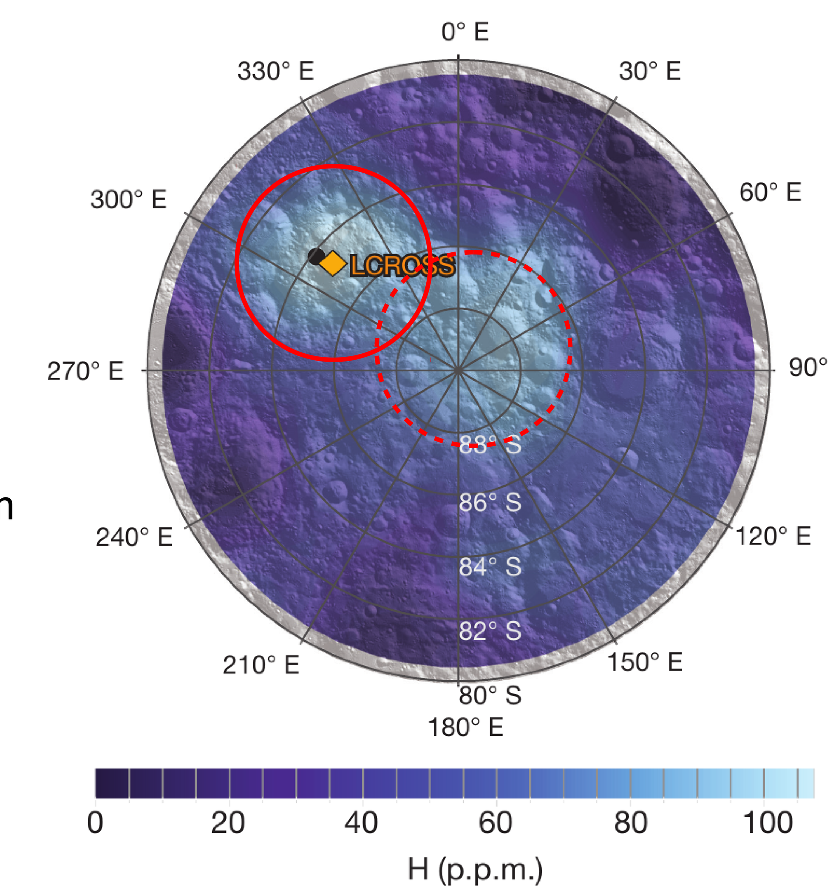


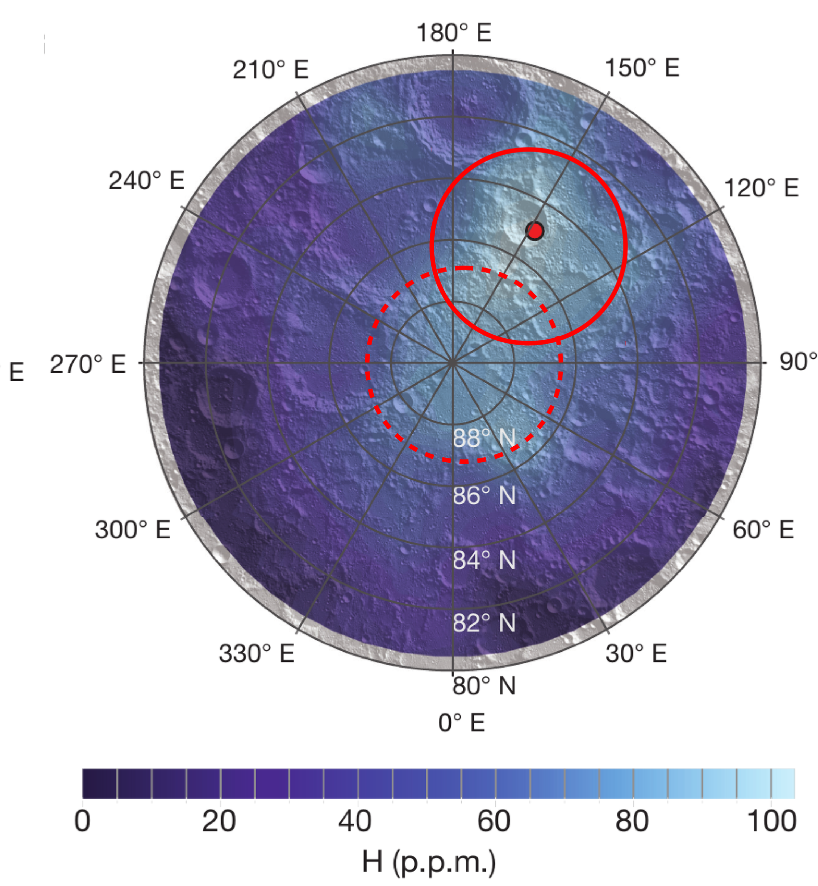

Surface ice using UV reflectance (off/on ratio > 1.2) from LRO/LAMP (Hayne et al., 2015)

Though these smaller scales are important, there is much to learn from large scales.

For example, Siegler et al. [2016] looked at neutron data and found that the maxima in hydrogen concentrations (black and red dots at right) were antipodal and offset from the current poles.

This implies that some ice was buried when the Moon had different spin axis (>3.5 Gyr ago).




Siegler et al. [2016] also found the data are best explained by an admixture of ancient (red solid circles) and recent (red dashed) ice.

Thus, the large-scale distribution of ice, i.e., the extent and location of the Moon's "ice caps," can help determine the history of that ice.

## 2

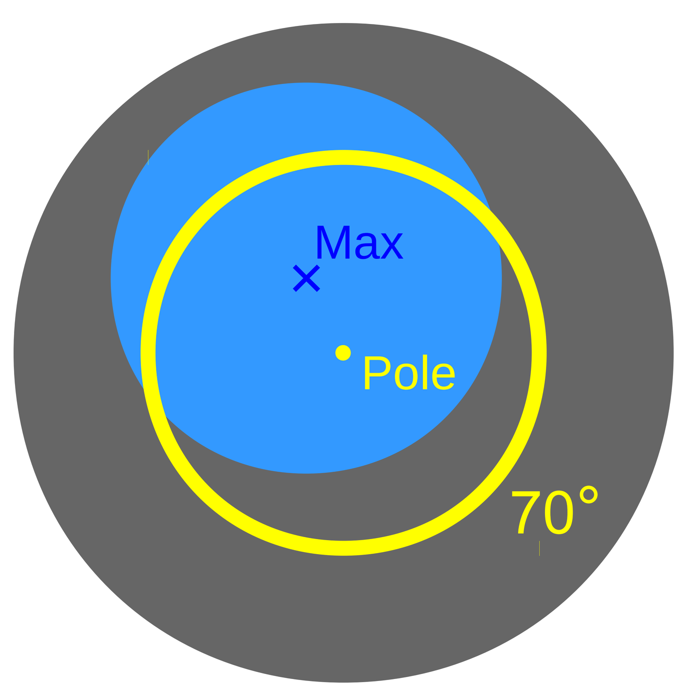
To interpret ice data, we develop a framework with two main components:

- Maximum concentration of ice ("x")
- Boundary of ice cap (blue region)

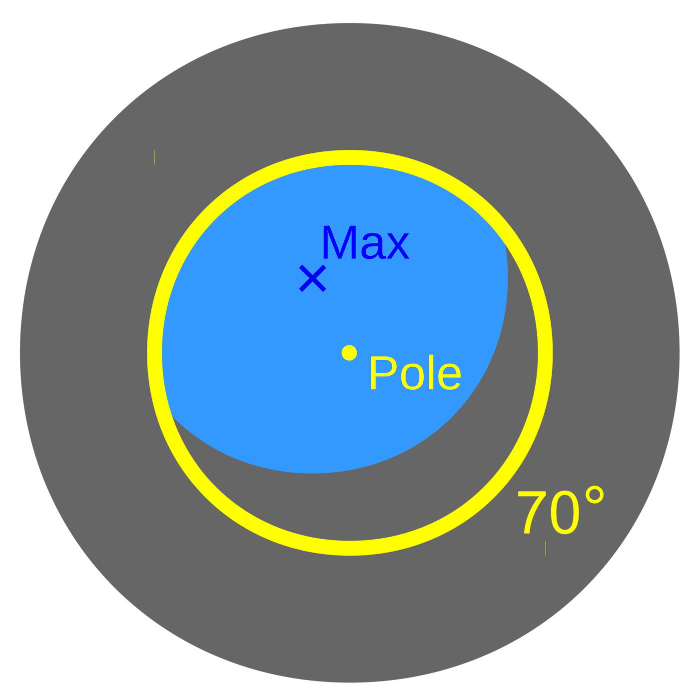
(Some possible hypothetical scenarios are shown at right)

These components can help constrain the processes that have affected the origin, loss, and/or migration of ice.

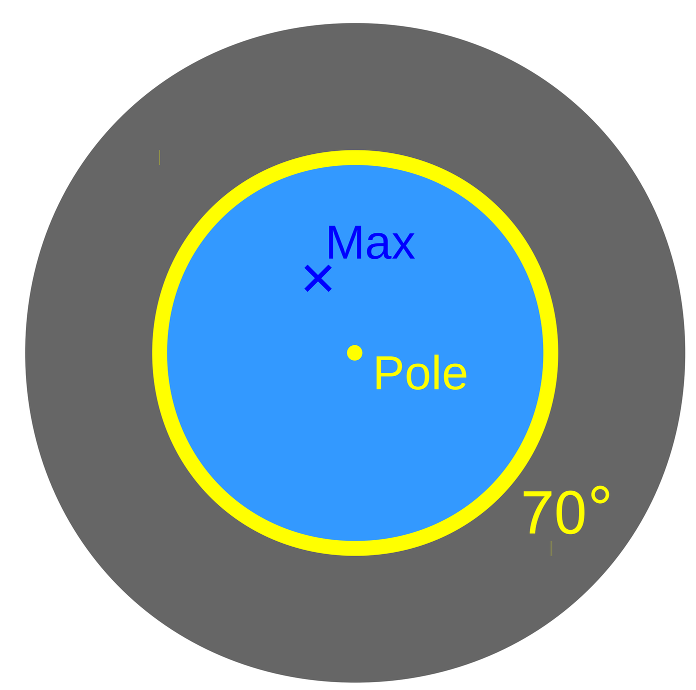
In the figures, 70° latitude is marked, because it is predicted to be the boundary of the "ice cap" [e.g., Watson et al., 1961; Arnold, 1979].



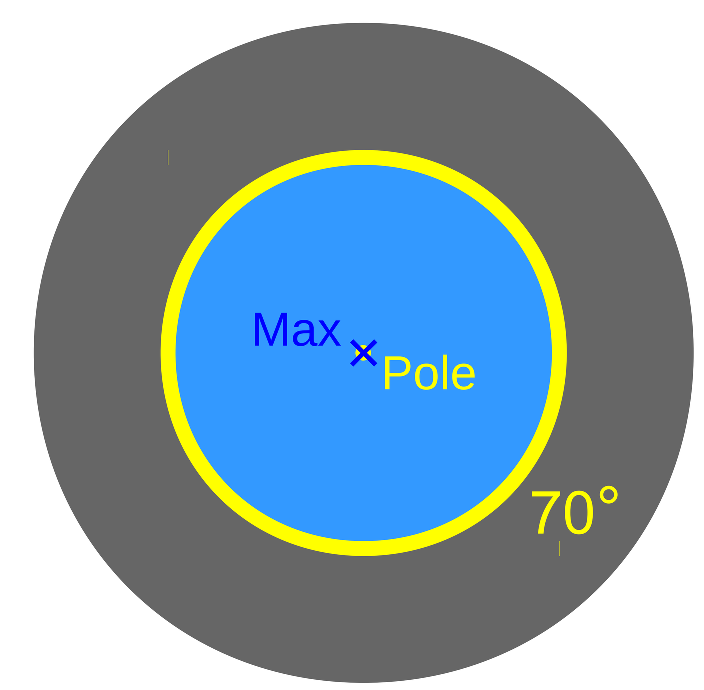

**Ancient deposit with...**
**NO** new ice added
**NO** old ice lost
Max: *at palaeopole*




**Ancient deposit**
**NO** new ice added
Some old ice **LOST**
Max: *at palaeopole*




**Ancient + recent deposits**
New ice **ADDED**
Some old ice **LOST**
Max: *at palaeopole*



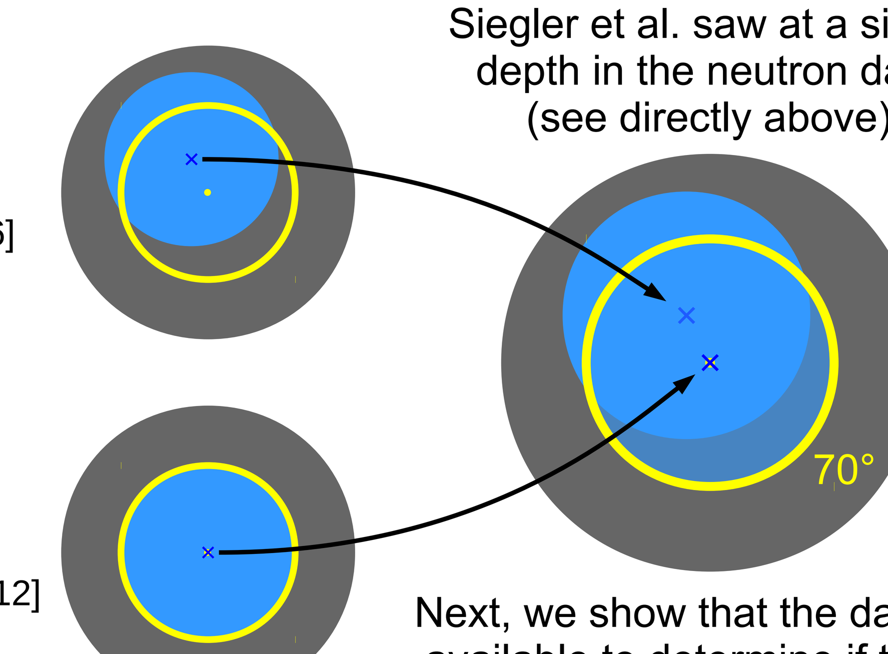

**Recent deposit**
Some/most of old ice **LOST**, if ever present
Max: *at current pole*

*Example:* A possible scenario shows the importance of identifying ice caps as a function of depth

Measurements would show a deep, offset "ice cap" and a surficial "ice cap" centered on the pole—similar to what Siegler et al. saw at a single depth in the neutron data (see directly above)

Assume ancient buried ice [e.g., Siegler et al., 2016]

Assume recent surface ice [e.g., Gladstone et al., 2012]

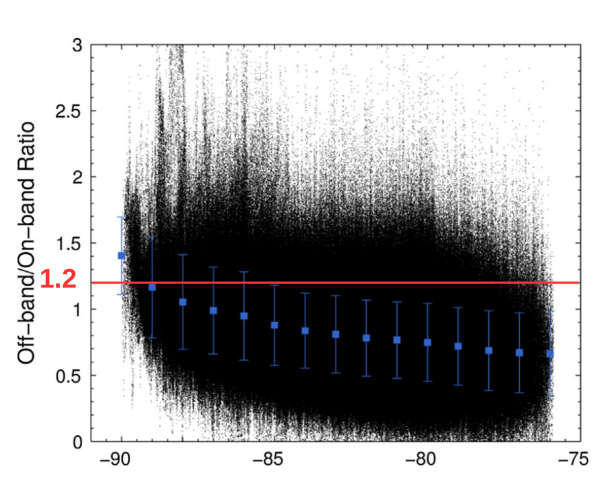


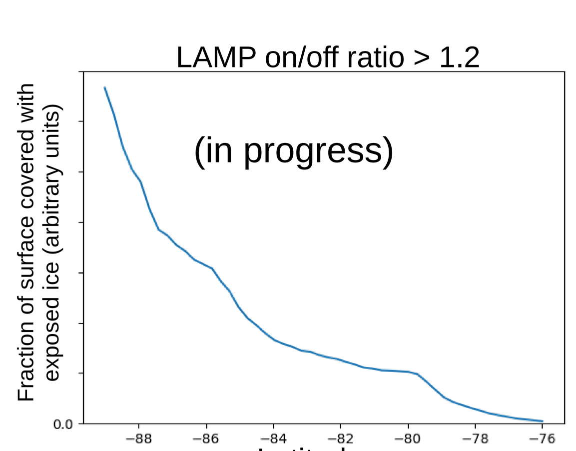

Next, we show that the data are available to determine if this or another scenario reflects reality.

## 3

**Surface:** LRO/LAMP (Hayne et al., 2015)

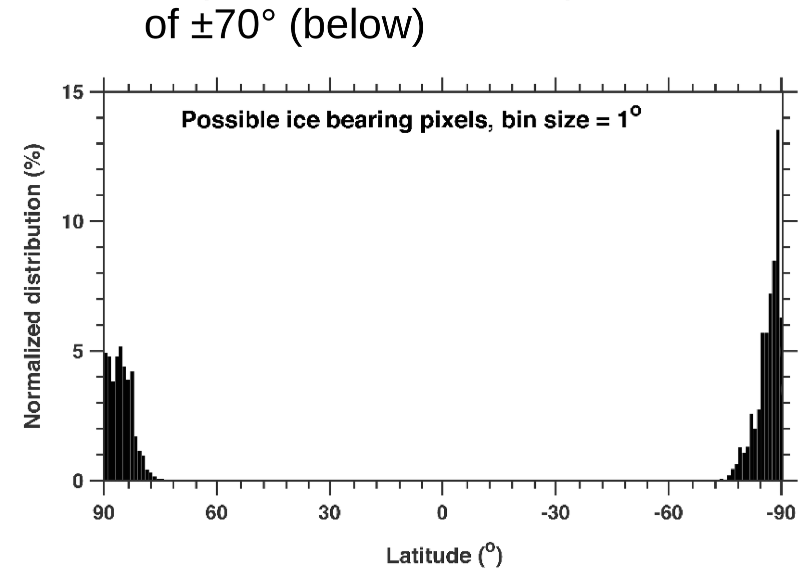
- Instrument measures UV surface reflectance
- At South Pole: "general pole-ward increase in the off-band/on-band albedo ratio, which appears independent of the larger PSRs" (top right)
- Off-band/on-band ratio > 1.2 is consistent with water ice (red line)
- Fraction of surface covered with ice goes to zero near -75° (bottom right)



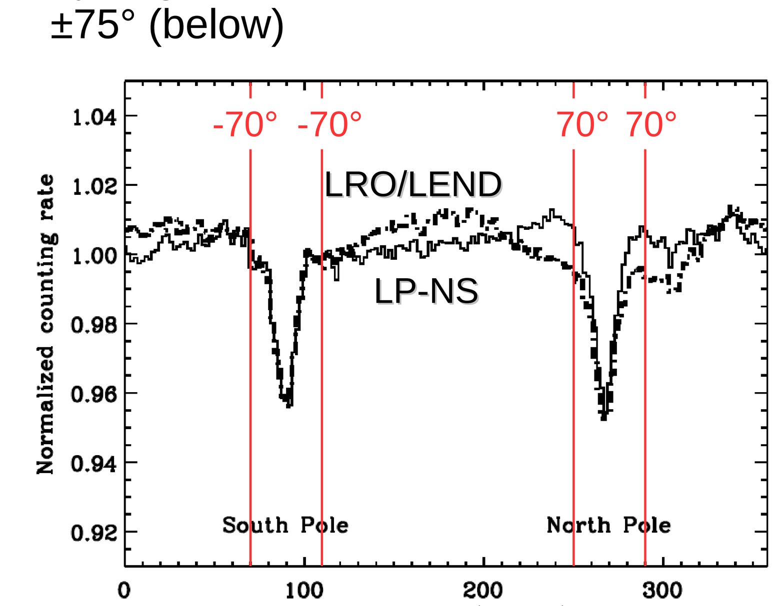

**Surface:** Chandrayaan-1/M3 (Li et al., 2017, under review)

- Instrument measures near-infrared surface reflectance
- Detects ice absorption features in PSRs via indirect lighting
- All positive results are poleward of ±70° (below)



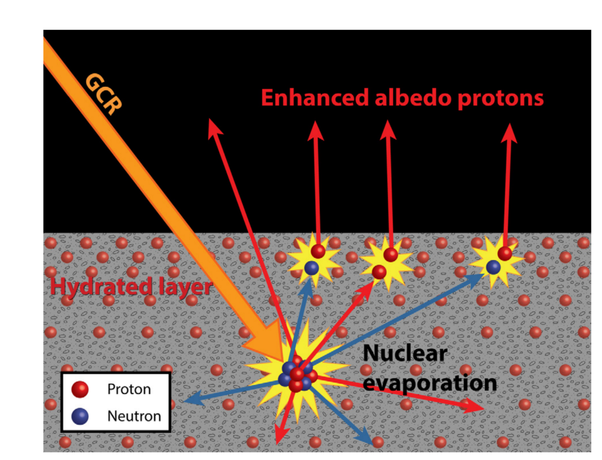

**~10-100 cm deep:** LP-NS & LRO/LEND (Feldman et al., 2011; Litvak et al., 2012; Boynton et al., 2012)

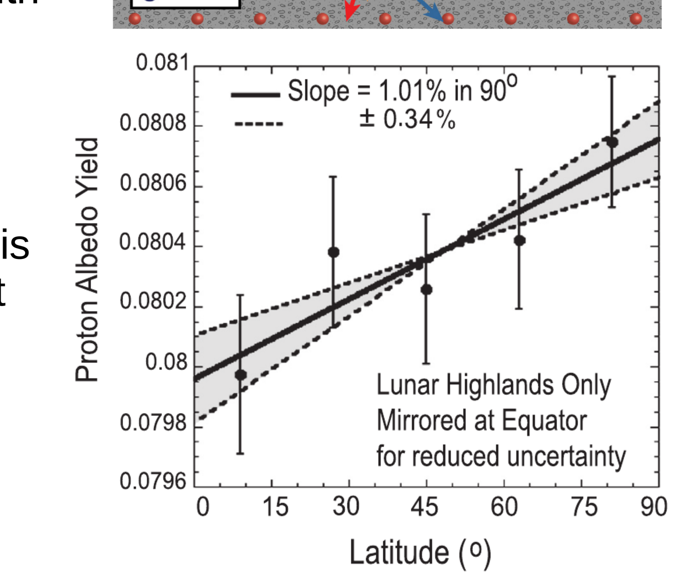
- Instruments measure neutron albedo
- Both poles contain large areas of hydrogen, with boundaries near ±70° or ±75° (below)




**~1-10 cm deep:** LRO/CRaTER (Schwadron et al., 2016)

- Instrument links surface and neutron data
- Instrument measures proton albedo (top right)
- Latitude trend is consistent with hydrogen increasing toward poles (bottom right)
- We are developing a new method to increase statistics; this may show whether there is a boundary at ±70° and if that boundary is symmetric with longitude




### Conclusions

On large scales, surface and subsurface data show "ice cap" boundaries near ±70°, as predicted by Watson et al. [1961] and Arnold [1979]

The location of the ice caps as a function of depth can constrain the history of the ice deposit(s): sources, losses, and age(s)

LRO/CRaTER provides a critical link between the deep (~10-100 cm) and surface measurements of water ice

*Open questions:* Which scenario(s) best describes the neutron data? Do the offset maxima [Siegler et al., 2016] change with depth? In other words, are the offsets different in the proton albedo and/or surface reflectance measurements?