Update on the Prospects for Finding Ice on the Moon

Norbert Schörghofer

Planetary Science Institute, Arizona / Hawaii

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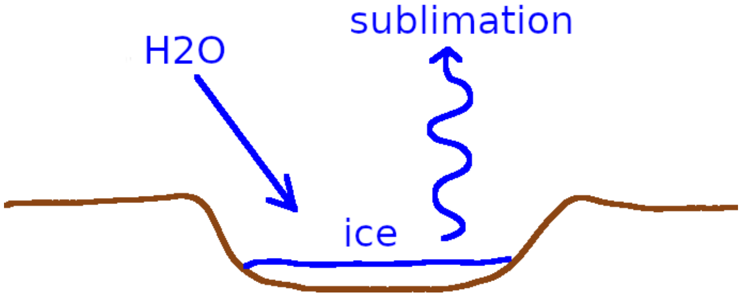
ShadowCam sees no surface ice



ShadowCam (on KPLO, 2022–) is designed to image shadowed regions, based on scattered sunlight

← Combination of LROC and ShadowCam image of Shackleton Crater
Image Credit: NASA/KARI/ASU
(Robinson et al. 2024)

Evidence for Buried Ice

1. Neutron spectroscopy *(Feldman et al. 1998)* measured hydrogen excess in both polar regions (LPNS 1998–1999 & LEND 2009–now)
2. LCROSS *(Colaprete et al. 2010)* identified H_2O in impact plume

Neutron observations have long suggested suggest burial!

- *Feldman et al. (1998, 2000)* “These data are consistent with deposits of hydrogen in the form of water ice that are covered by as much as 40 cm of desiccated regolith within permanently shadowed craters ...”
- *Lawrence et al. (2006)* “likely buried by 10±5cm of dry lunar soil”
- confirmed by LEND; *Mitrofanov et al. (2010)*

A Lesson from Asteroid Ceres

Extreme contrast between surface and subsurface ice abundance.

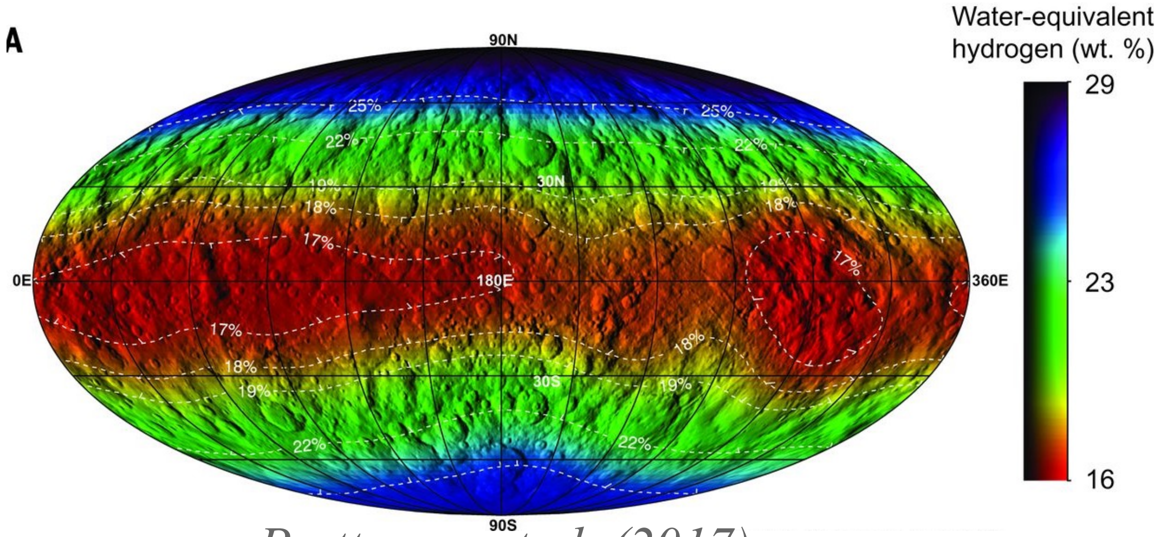
Surface, optical spectroscopy

Oxo Crater	6.8 km^2
-	<3.3 km^2
Messor Crater	1.4 km^2
Juling Crater	3.2-6 km^2
all other	< 2.4 km^2

~11-20 km^2 with H_2O;

Combe et al. (2019)

Subsurface, nuclear spectroscopy



Prettyman et al. (2017)

H_2O essentially globally (radius 470 km)

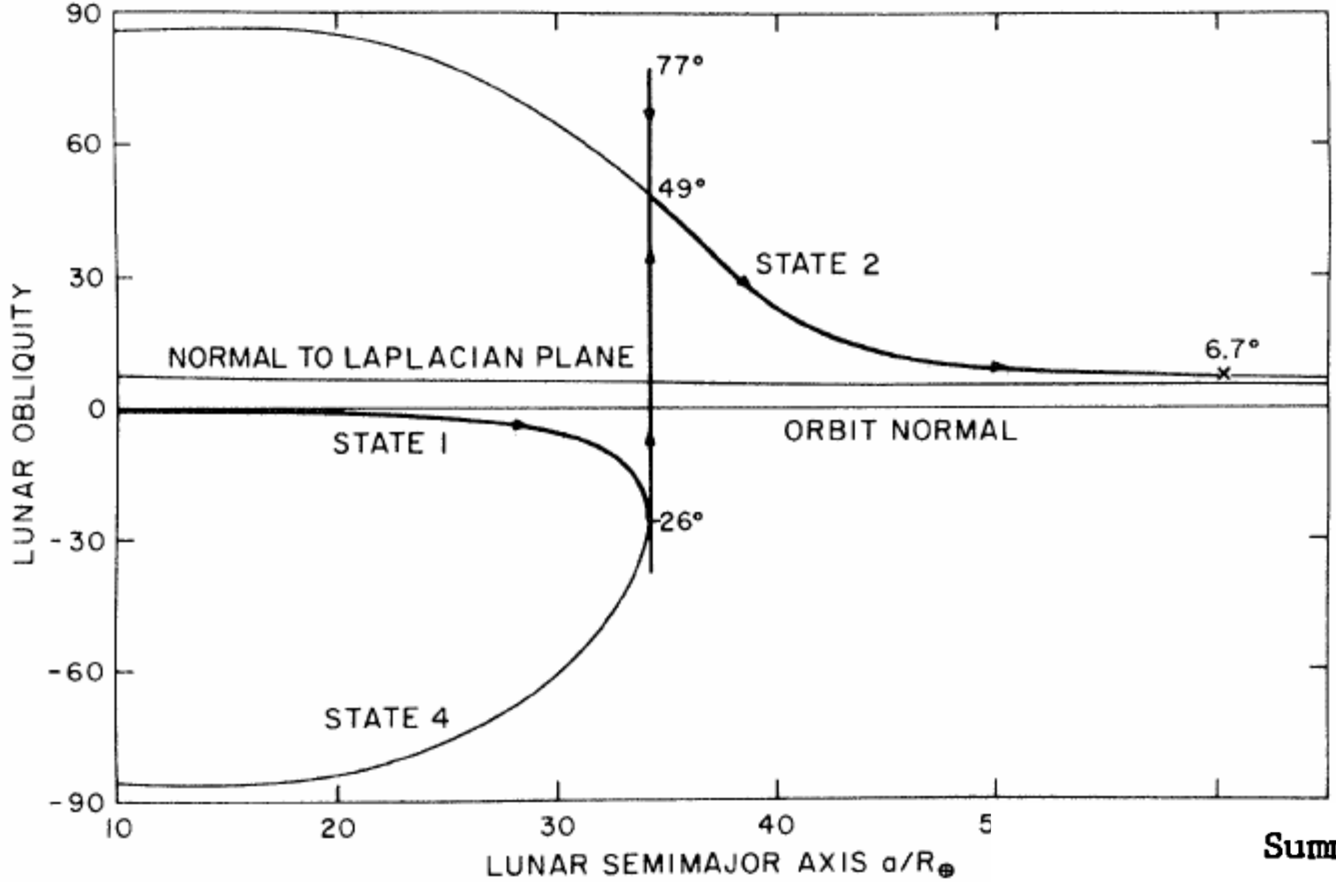
Ratio of area with H_2O detected by nuclear versus optical spectroscopy: 10^5

99.999% of near-surface is not exposed on the surface!

Conclusion I: Water ice is the Subsurface

- Strong observational evidence for near-surface ice, from neutron spectroscopy (LPNS & LEND) and LCROSS.
- Surface is devolatilized (ShadowCam), perhaps due to space weathering *(Farrell et al. 2019)*. To assess the presence of water ice, **it is necessary to probe the subsurface**. Measurements on the optical surface can never definitively exclude the presence of ice, not even at shallow depths.
- Probing to shallow depths <~20 cm may suffice.

Past Orientation of Lunar Spin Axis; Cassini State Transition



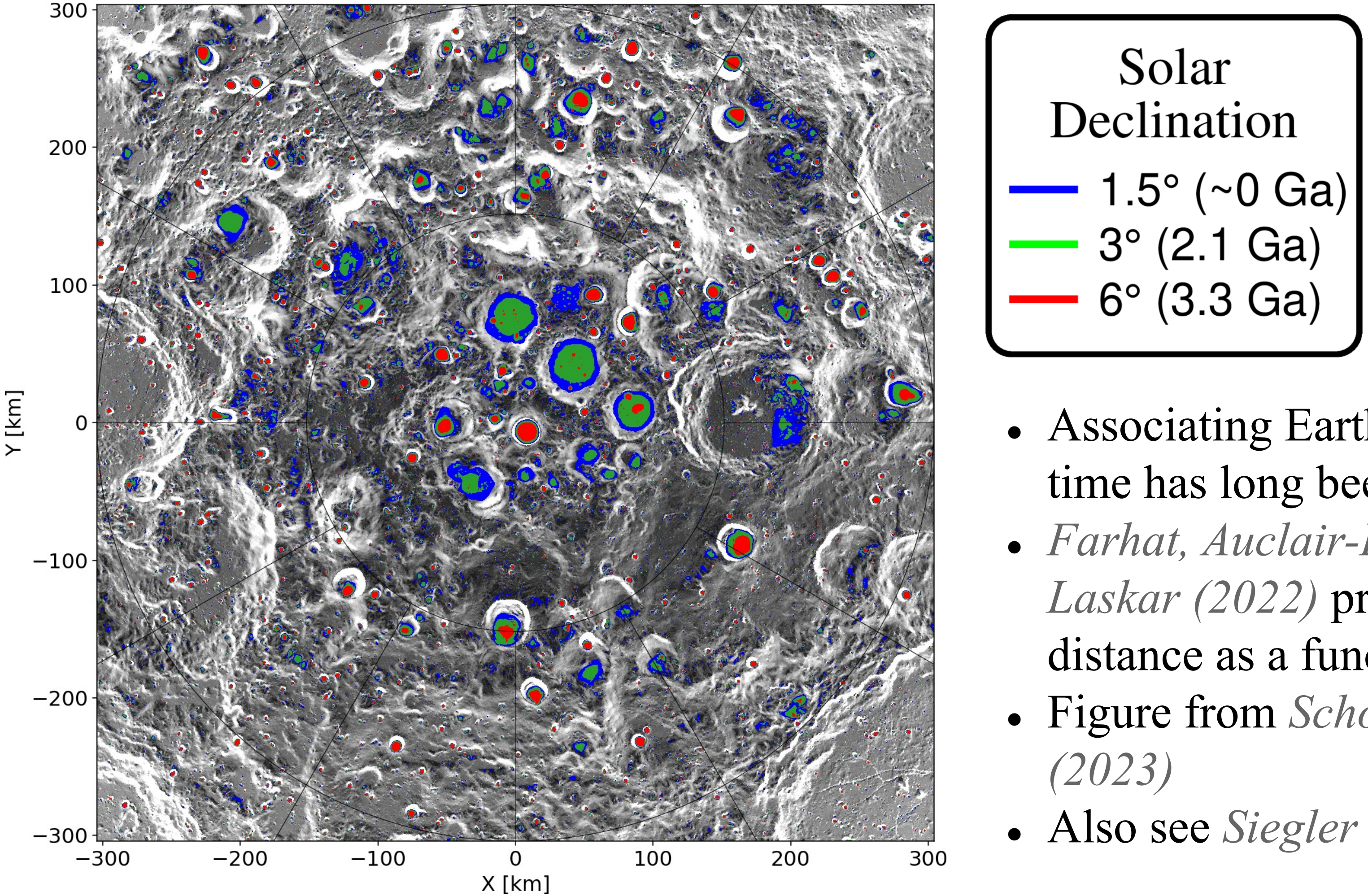
← ***Ward**, Science* ***(1975)***

Arnold**, JGR* ***(1979) →

Summary and Conclusions

In essential respects the conclusions of Watson, Murray and Brown [1961] have been confirmed, though the analysis is in some ways quite different. The cold traps seem to have been in place for $\sim 2 \times 10^9$ years. The WMB trans-

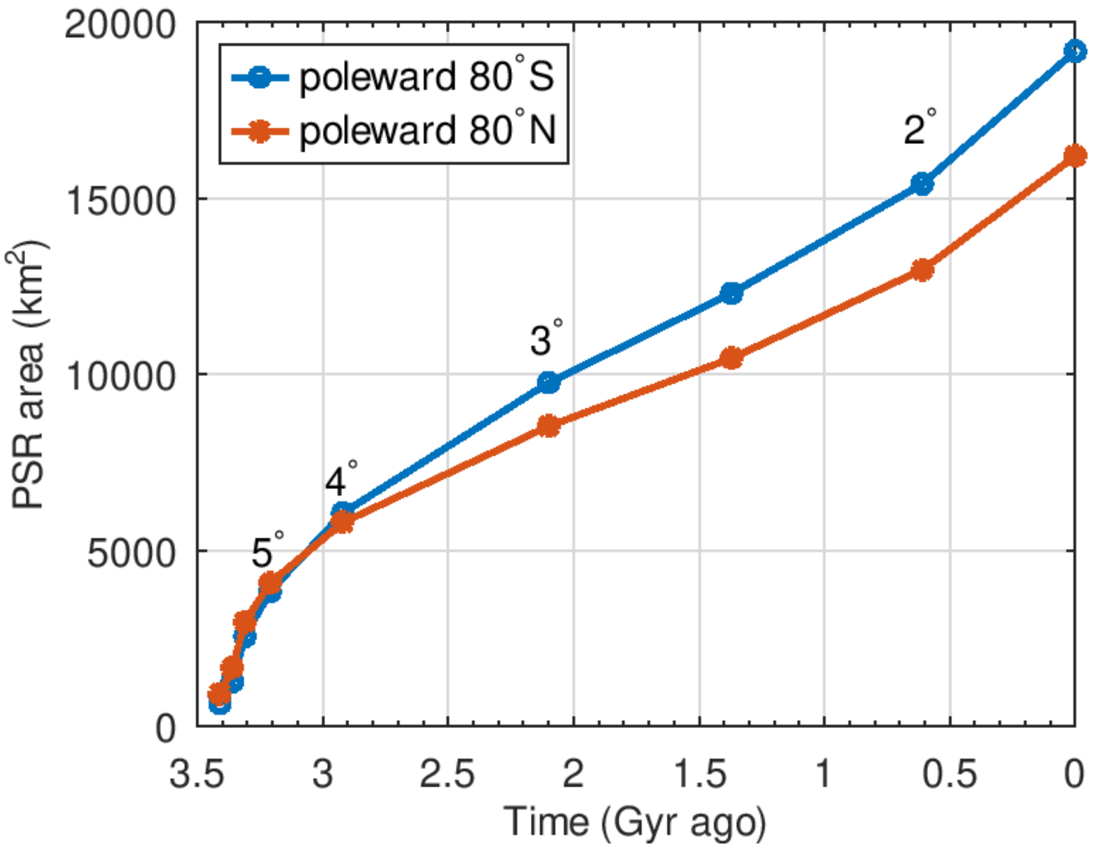
Past PSRs in South Polar Region



- Associating Earth-Moon distance with time has long been a challenge
- *Farhat, Auclair-Desrotour, Boué, Laskar (2022)* provide Earth-Moon distance as a function of time
- Figure from *Schorghofer & Rufu (2023)*
- Also see *Siegler et al. (2015)*

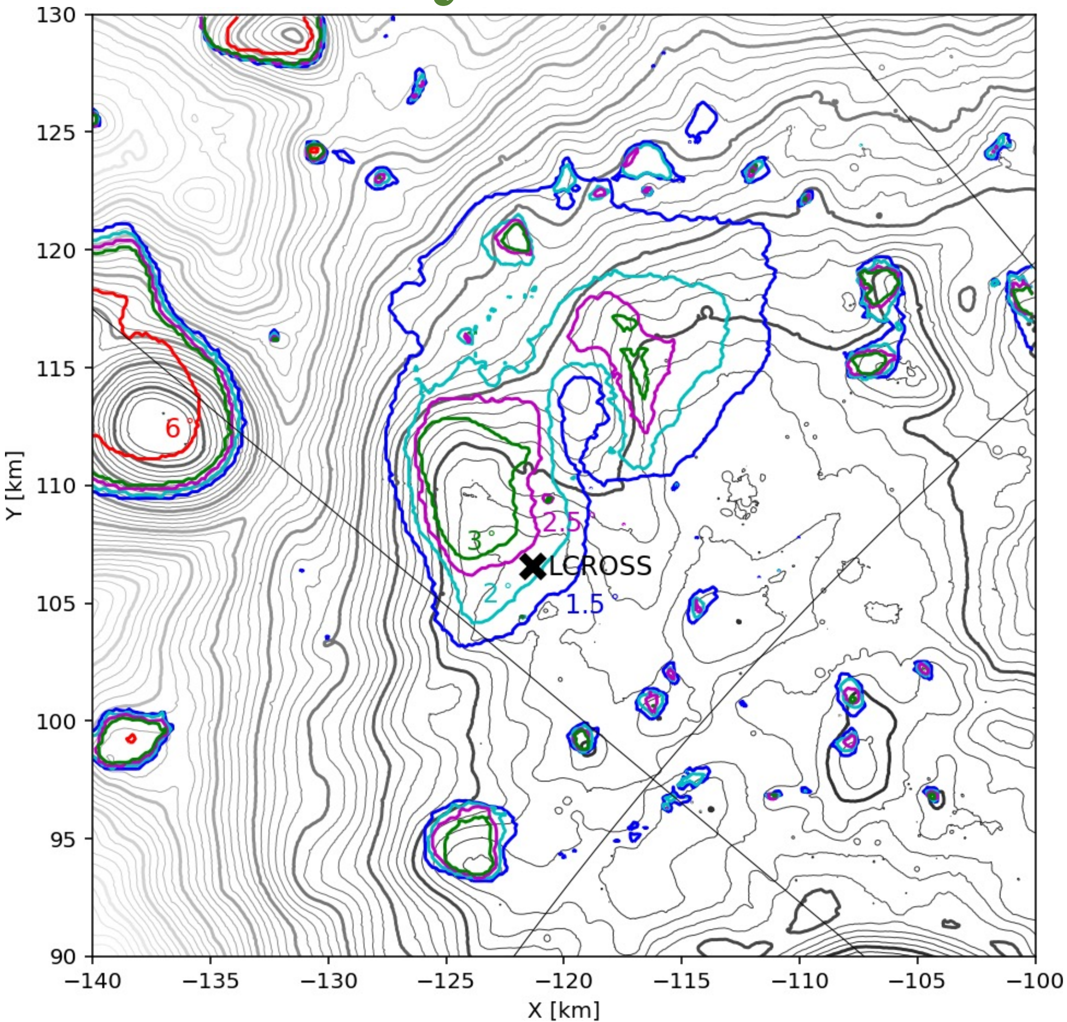
PSR area poleward of 80°

assumes current topography (LOLA 240 m/pixel)



- The older the PSR, the more ice it should contain
- PSR area was half as large 2.2 Ga ago
- PSR area is negligible beyond 3.4 Ga
- **Average age of PSRs is 1.8 Ga**
- Note: Cold traps are smaller and younger than PSRs

History of PSR at Cabeus (LCROSS)



- based on 40m/pixel LOLA topography
- LCROSS impact cite became a PSR at a solar declination below 2.2°.
- Volatiles detected *(Colaprete et al. 2010)* must have accumulated in the last ~0.9 Ga.
- Also supported by morphology *(Fassett et al., LPSC, 2024)*

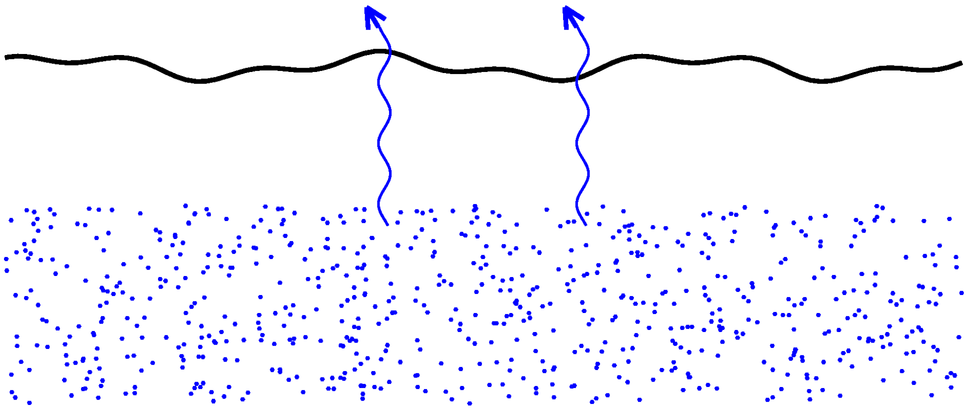
Conclusion II: Highest concentrations of ice are expected in old (large) cold traps

- Highest column-abundance of water ice are expected in the oldest cold traps. (Ironically, no mission seems to go there, because of the technical challenges for landing on an unilluminated surface and operating at cold temperatures)

- All cold traps older than 1 Gyr should have ≥~6% ice (as at the LCROSS impact site). (H_2O delivery is expected to be approximately uniform over the polar regions, whether cold-trapped from a temporary atmosphere or a water exosphere.)

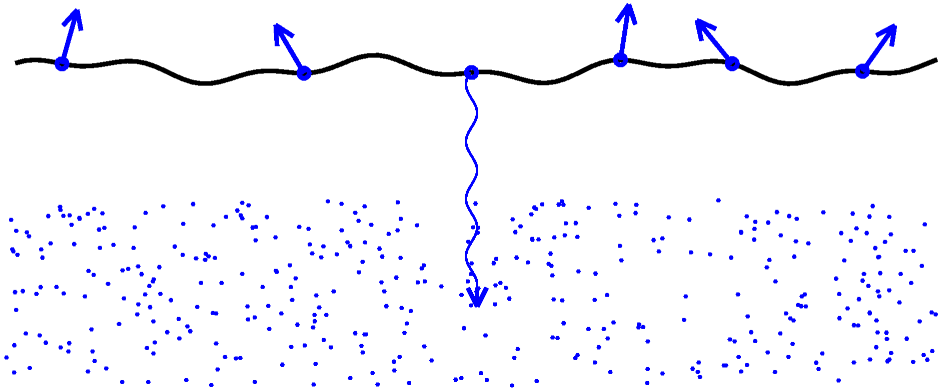
Ice Outside of Cold Traps:
2 Ice Storage Processes

Relic Buried Ice



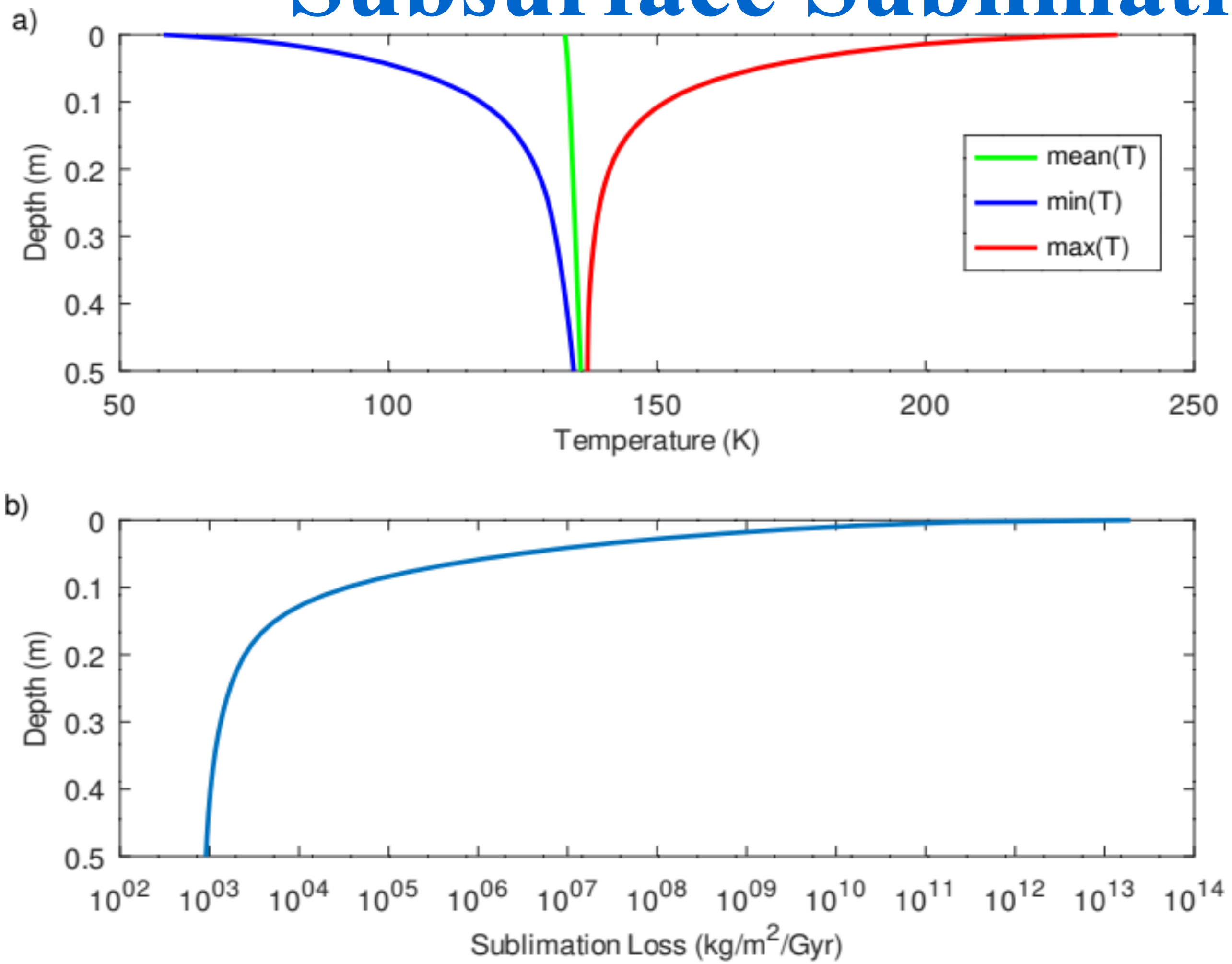
- reduced sublimation loss
- requires rapid burial (rare)
- T(subsurface) < 140 K

Vapor Pumping & Subsurface Cold-Trapping



- requires continuous delivery
- low yield
- T(subsurface) < 110 K

Buried Relic Ice: Subsurface Sublimation Rates



Shallow depths suffice to protect ice

Figure from *Schorghofer & Williams (2020)*

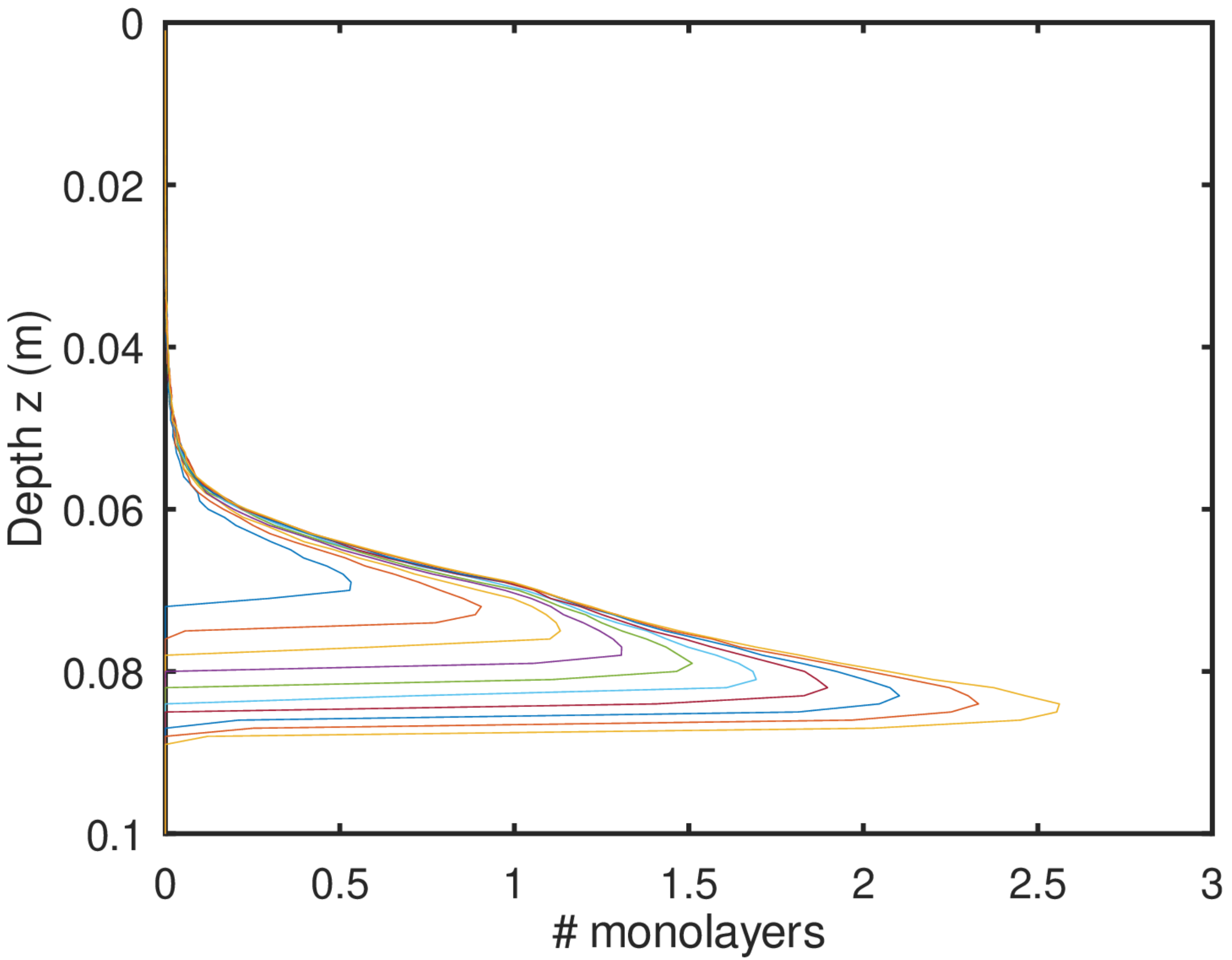
Ice Sequestration by Vapor Pumping

Top ~5cm remain desiccated

An estimated 0.1% of supplied H_2O is sequestered (which could be 1wt%)

would explain burial observed by neutron spectrometers; *Lawrence et al. (2006)* "likely buried by 10±5cm of dry lunar soil"

Schorghofer, ApJL (2022)



Conclusion III: Ice may be found outside of cold traps at shallow depths

1) Relic buried ice: even thin (centimeters) overlying layer provides substantial protection against sublimation; requires quick burial, and therefore many locations need to be probed

2) Subsurface cold traps (supplied by “vapor pumping”): requires quasi-continuous water delivery, but could be verified at single location; expected within the top 5-15 cm (more than the thermal skin depth)

Summary:
Prospects for Finding Ice on the Moon

I. Ice present in the subsurface of cold traps (measurements on the optical surface can never rule out presence of subsurface ice)

II. Old (i.e., large) cold traps are expected to have the highest column abundance of water ice, but these destinations are technically challenging. All cold traps older than 1 Gyr should have at least 6% ice.

III. Ice may be present outside of cold traps at shallow depths as a) relic buried ice (possibly at shallow depths) or b) due to sub-surface cold trapping (within ~10 cm). The former is sporadic; the latter could be determined with a single borehole.