

Parallel Session #5: Volatile Behavior, Reservoirs, and Resources on Airless Bodies

- **Behavior and reservoirs:**

- Gordon Chin: “Probing Planetary Bodies for the Structure of Subsurface Volatiles”
- Matt Siegler: “Temperature Spectroscopy: Application of Laser Reflectance of the Poles of the Moon and Mercury”
- Tim McClanahan: “Evidence for a Diurnal Cycling of Surface Hydration Towards the Moon’s Mid-Latitudes”
- David Smith: “Lunar South Pole Gravity and the Search for Water”
- Karl Hibbits: “Characterizing Water on Airless Bodies from Vacuum UV and IR Measurements”

- **Resources**

- Ted Roush: “Monitoring Volatiles While Drilling into Frozen Lunar Simulant”
- James Carpenter: “Prospecting on Luna-27”

Small-scale Cold Traps on Airless Planetary Bodies

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regions and for low solar angles (Figure 5). The experiments of Pettit and Nicholson measure surfaces that are strongly illuminated. However, heat conduction is important in studying the nighttime cooling of a lunar crater and will be discussed in a subsequent paper.

A second problem concerns the flux that will be conducted laterally across the surface of the crater because of lateral temperature gradients. This flux will smooth the temperature variations across the surface, creating a uniform temperature distribution in very small craters. Since the temperature distribution is established by the radiation balance at the surface, the effect of the conducted flux will be important only when it becomes of the order of the incident solar flux. To estimate the maximum temperature gradient that can exist on the surface, we need only know the thermal conductivity. Probable thermal conductivities for the moon vary from 3×10^{-6} for a pumice of 35% porosity to 6×10^{-5} for an open cell structure of 88% porosity [Glaser and Wechsler, 1965]. Taking an average value of 10^{-5} and a solar constant of 0.033 (cal/cm²/sec), we obtain the following maximum temperature gradient:

$$\partial T / \partial x = f_s / k = 3300^\circ \text{K/cm} \quad (2)$$

This value implies that a temperature difference of 100°K can exist in a crater as small as 1 mm in diameter. Thus, owing to the very low thermal conductivity of the lunar surface, the temperature gradients can be extremely large and still not disturb the radiation balance at the surface. As a consequence we will assume for our model that the temperature distribution in a lunar crater is completely determined by radiation.

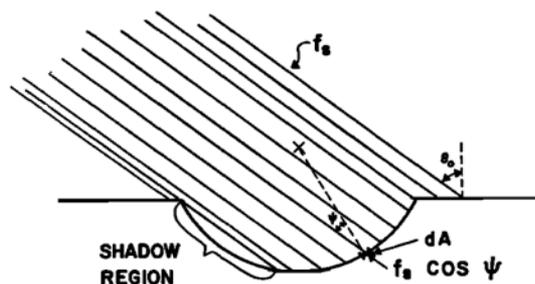


Fig. 3. Solar flux incident on a spherical crater.

emitted from the surface as thermal radiation. Because of the shape of the crater, certain regions will be in shadow for part of the day and hence receive no direct insolation. It is clear that each point in the crater receives a different illumination as a function of time. Therefore, the calculation of the temperature history of a point in the crater must take into account the effects of shadowing and local incidence angle.

In setting up the problem, the radiation interchange within the crater must be studied in detail. There are two processes that will be considered. Both processes involve the absorption of radiation from other parts of the crater. The most important effect is that some of the infrared radiation emitted by an element of area in the crater is intercepted by the rest of the crater. Thus, the flux absorbed at a point has a term that is a function of the amount of infrared radiation being emitted by all other points in the crater in addition to the direct solar flux term. A smaller effect is produced by the multiple reflection of the solar radiation within the crater. This optical reflection is, however, very quickly absorbed because of the low visual albedo (0.1). It is sufficiently ac-

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the temperature distribution is not uniform, the radiation balance at the surface of the crater will be affected. The conducted flux will be of the order of the solar flux. To estimate the maximum temperature gradient that can exist in a crater, we only know the thermal conductivities of lunar rocks: 3×10^{-6} for a pumice and 6×10^{-5} for an open-pore material [Glaser and others, 1961]. Using an average value of 10^{-5} cal/cm²/sec, the maximum temperature

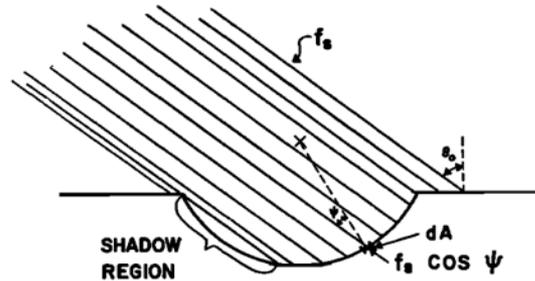


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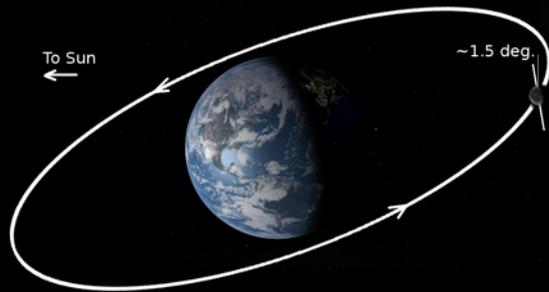
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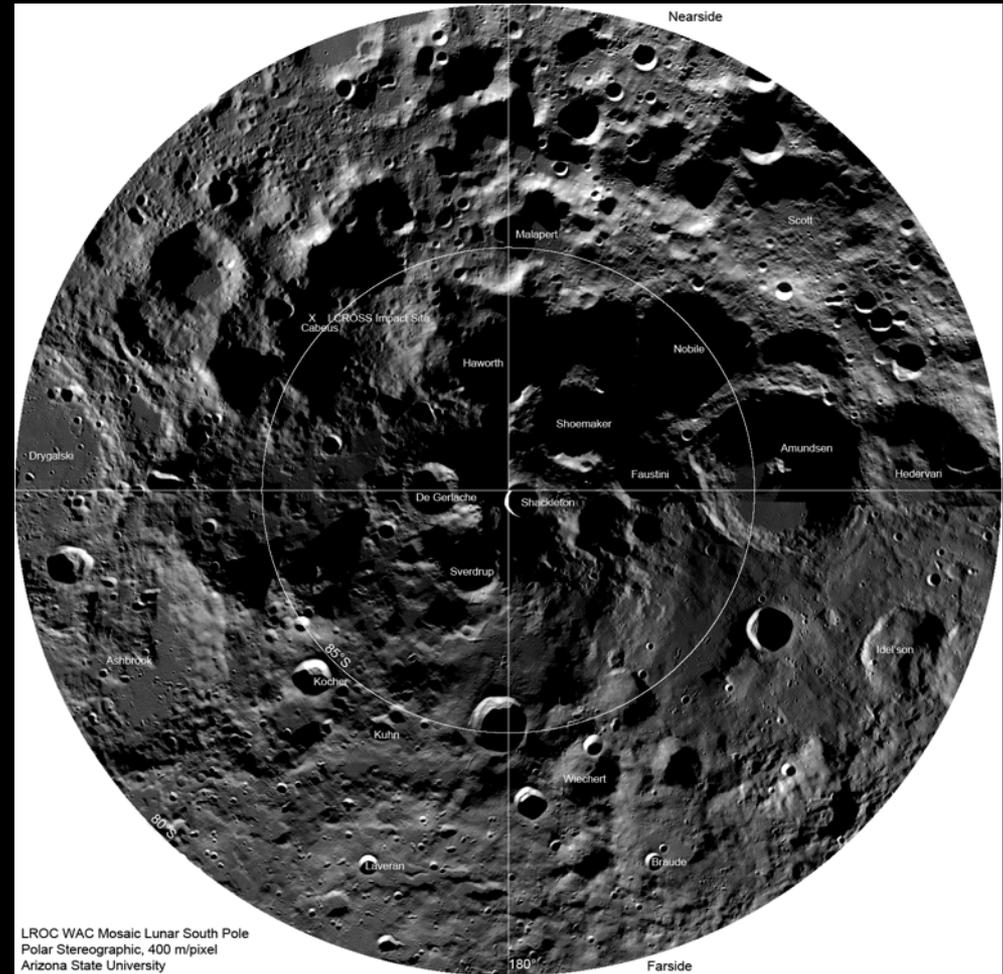


23 cm

Perennial Shadows on Low-Obliquity Bodies

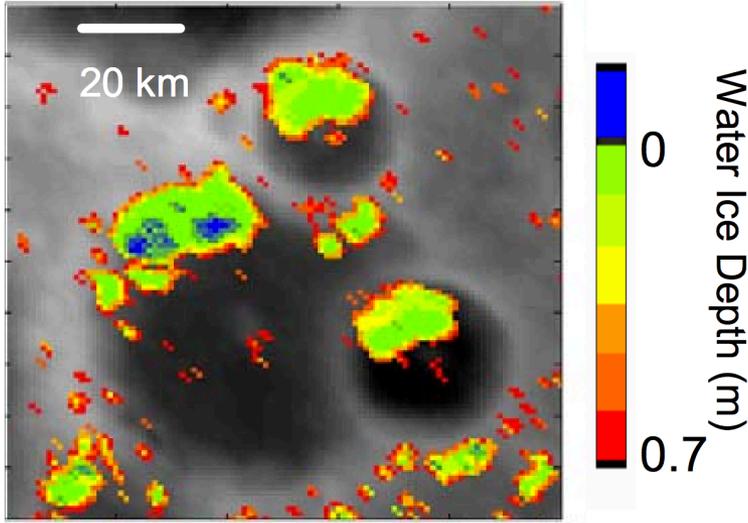


- Any planetary body with a (stable) low obliquity can have perennially shadowed regions
- Examples: Moon, Mercury, Ceres, Ganymede, Europa, etc.
- Cold traps mapped on the Moon are typically > 0.1 - 1 km in size

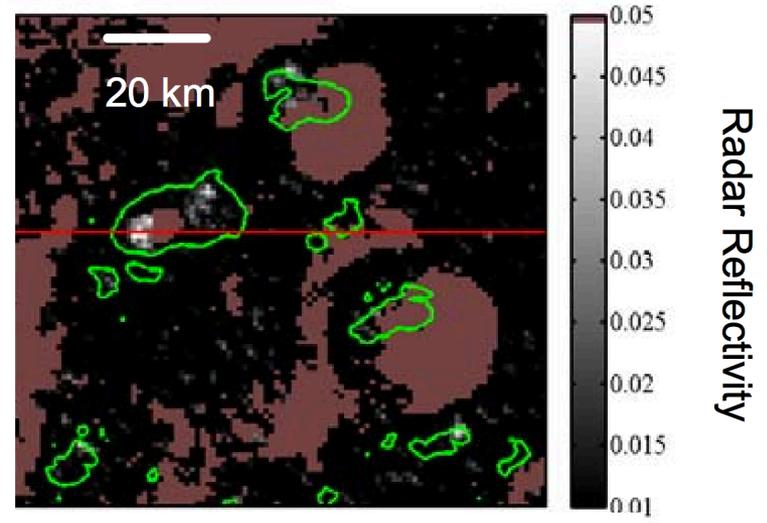


Mercury

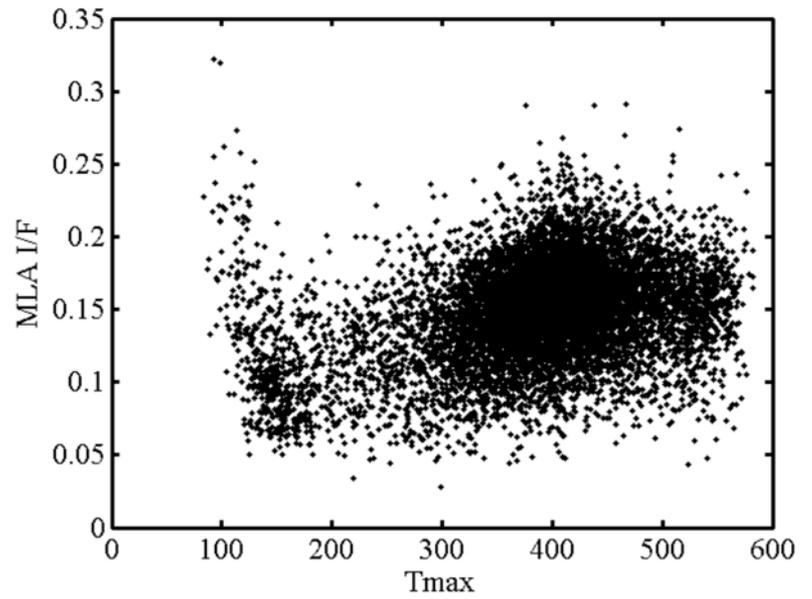
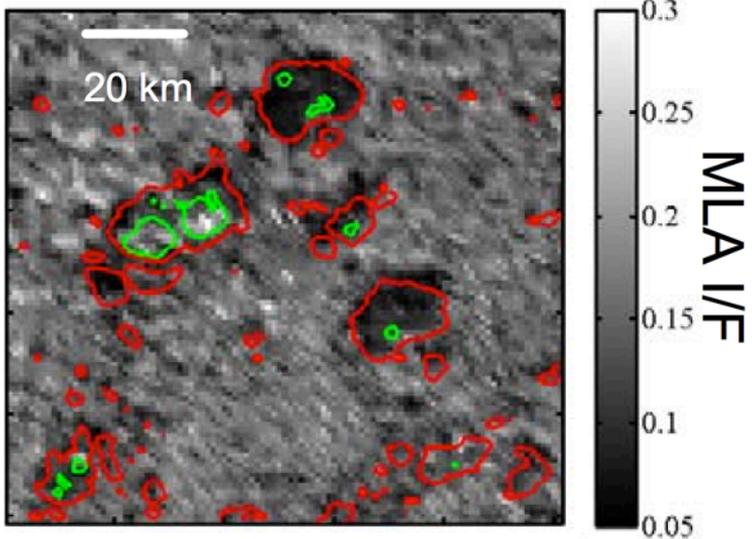
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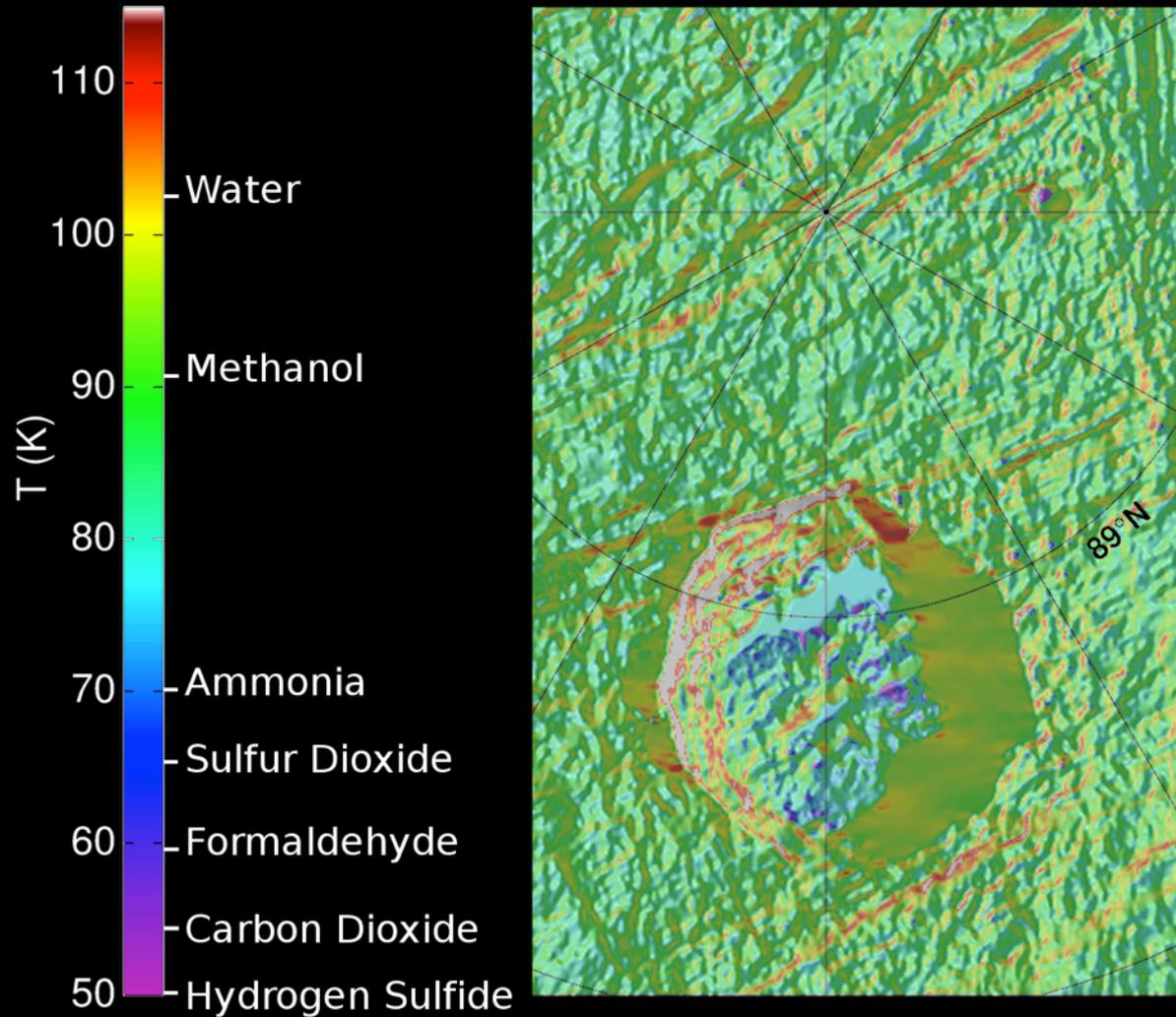
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Ganymede

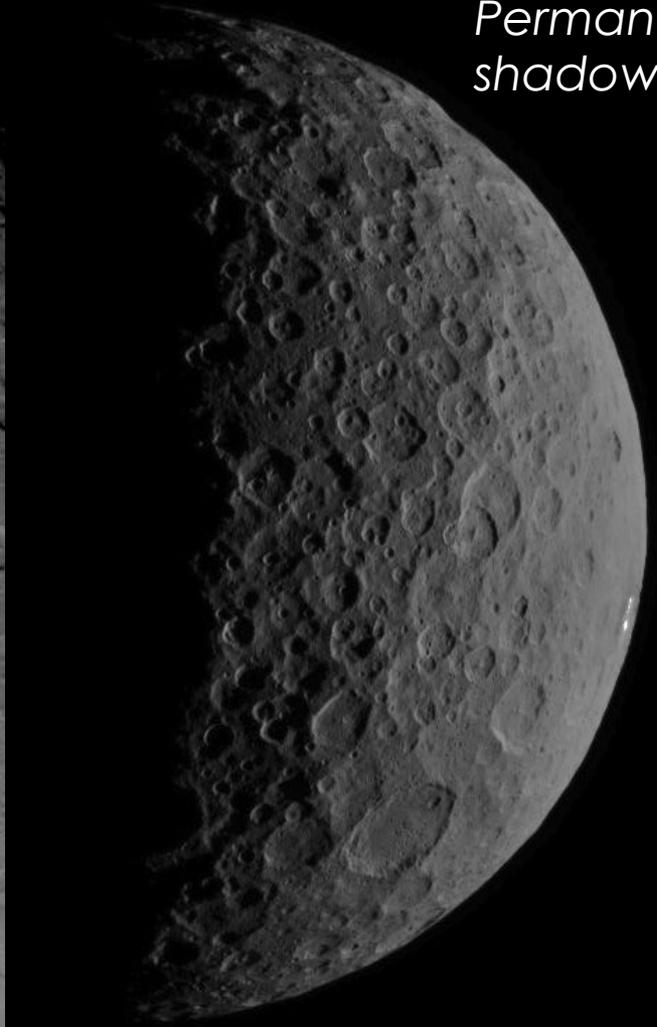


Ceres

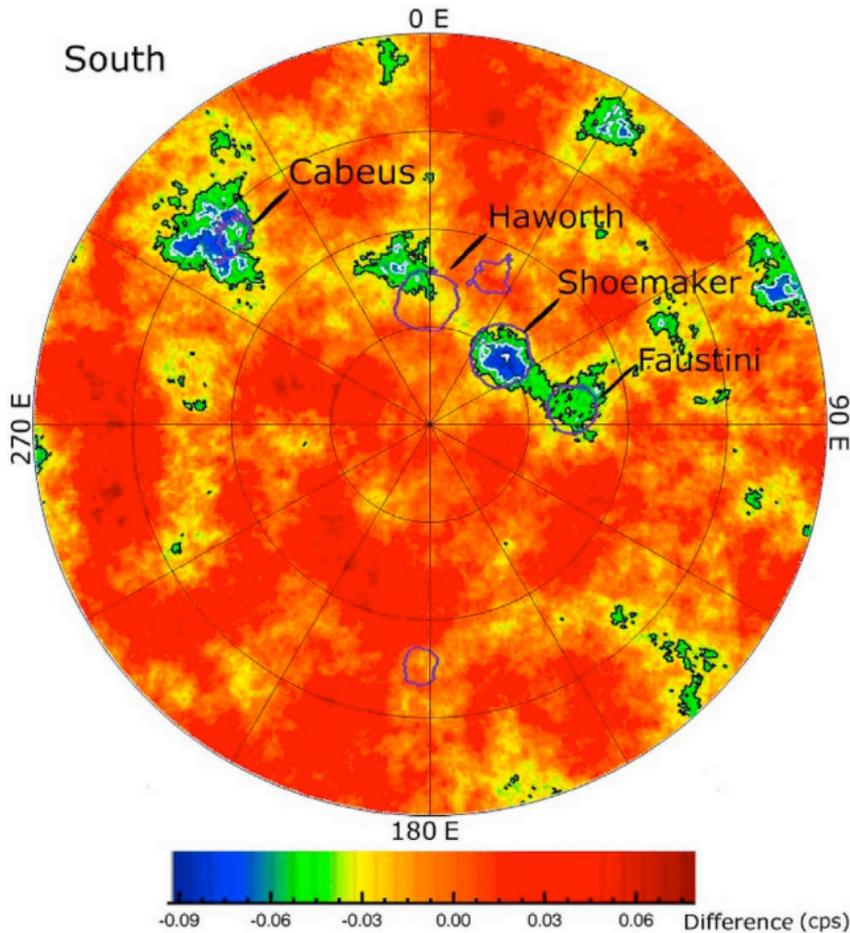
"Bright spots"



Permanent shadows

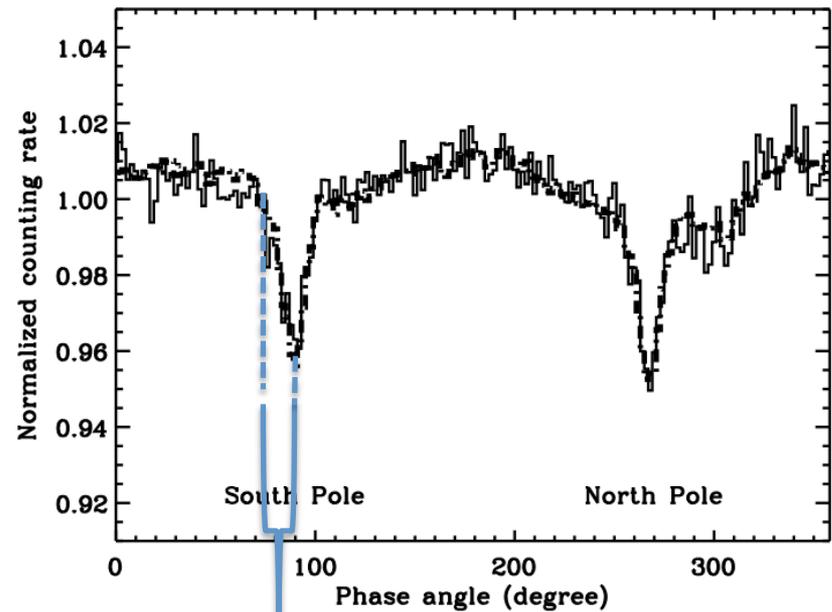


Lunar Neutron Data



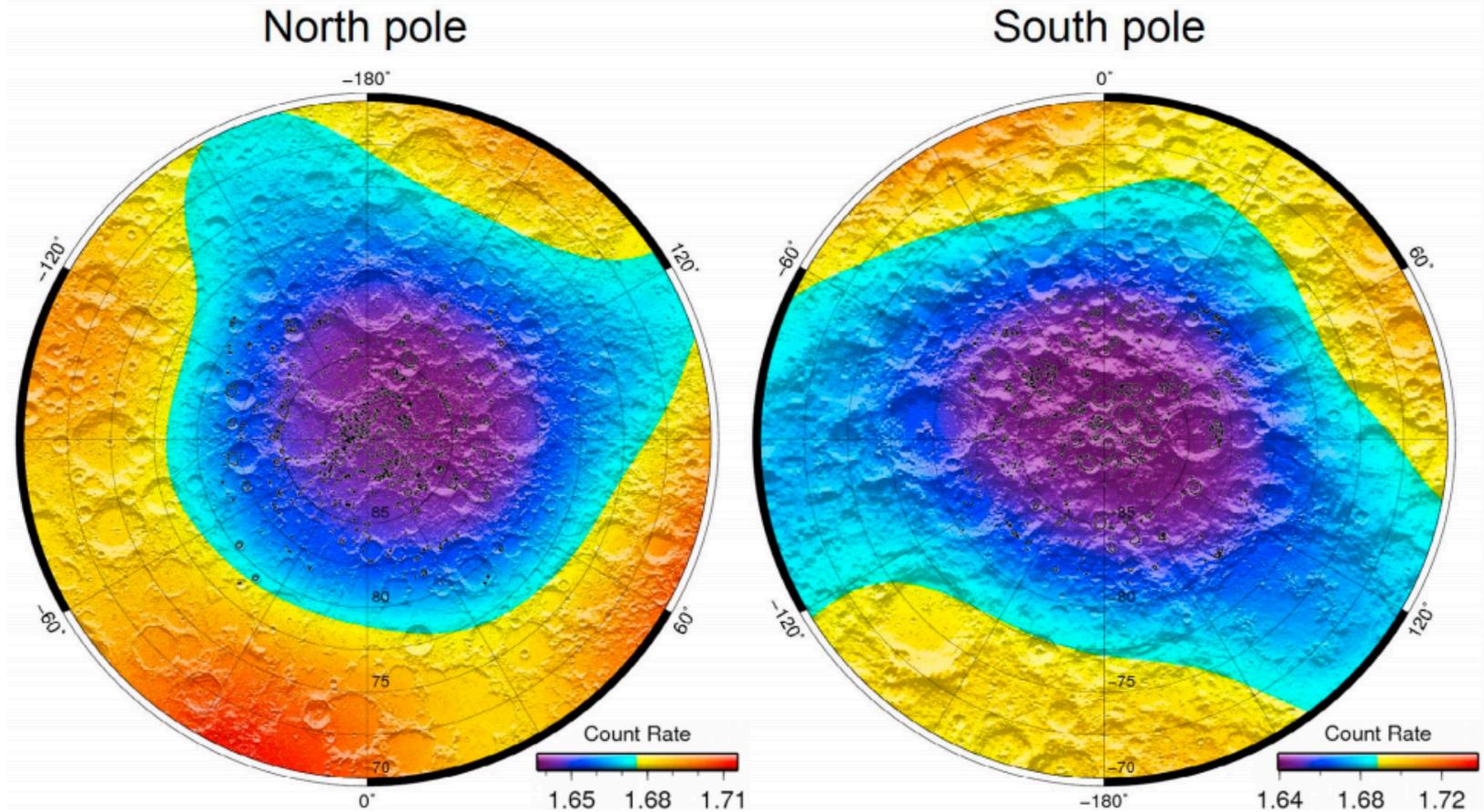
LEND epithermal neutron counts, minus background (Boynton et al., JGR, 2011)

LEND global mean epithermal neutron count rates (Litvak et al., 2011):

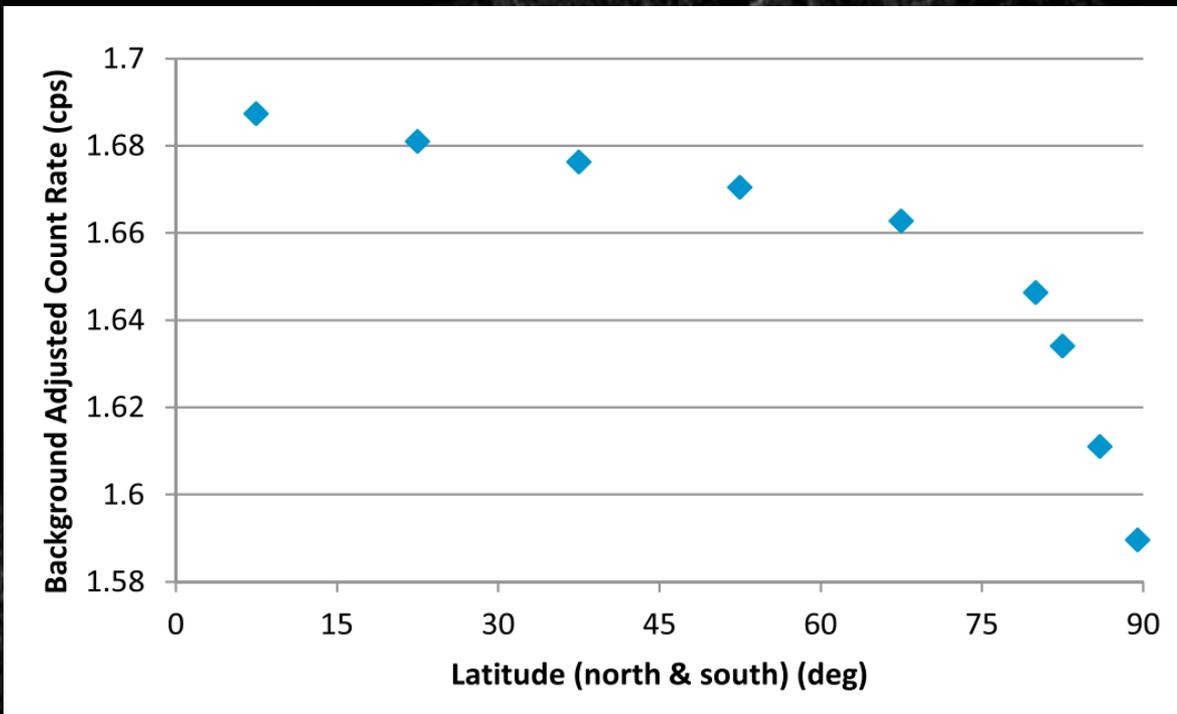


We are interested in this region. Is it all explained by the large PSRs?

Smoothed Background Hydrogen Map (LEND)



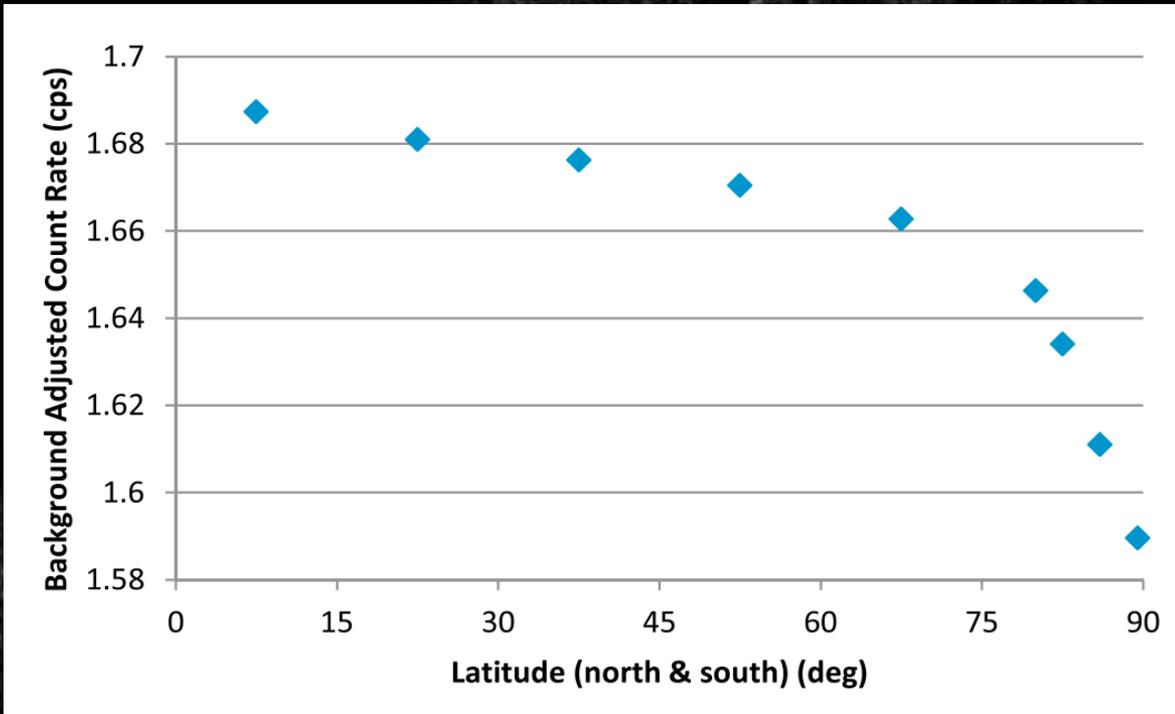
Mitrofanov et al., JGR, 2011



Epithermal neutron count rate ($\sim 1/\text{water}$) from LEND (Boynton et al., 2012)

Three possible explanations:

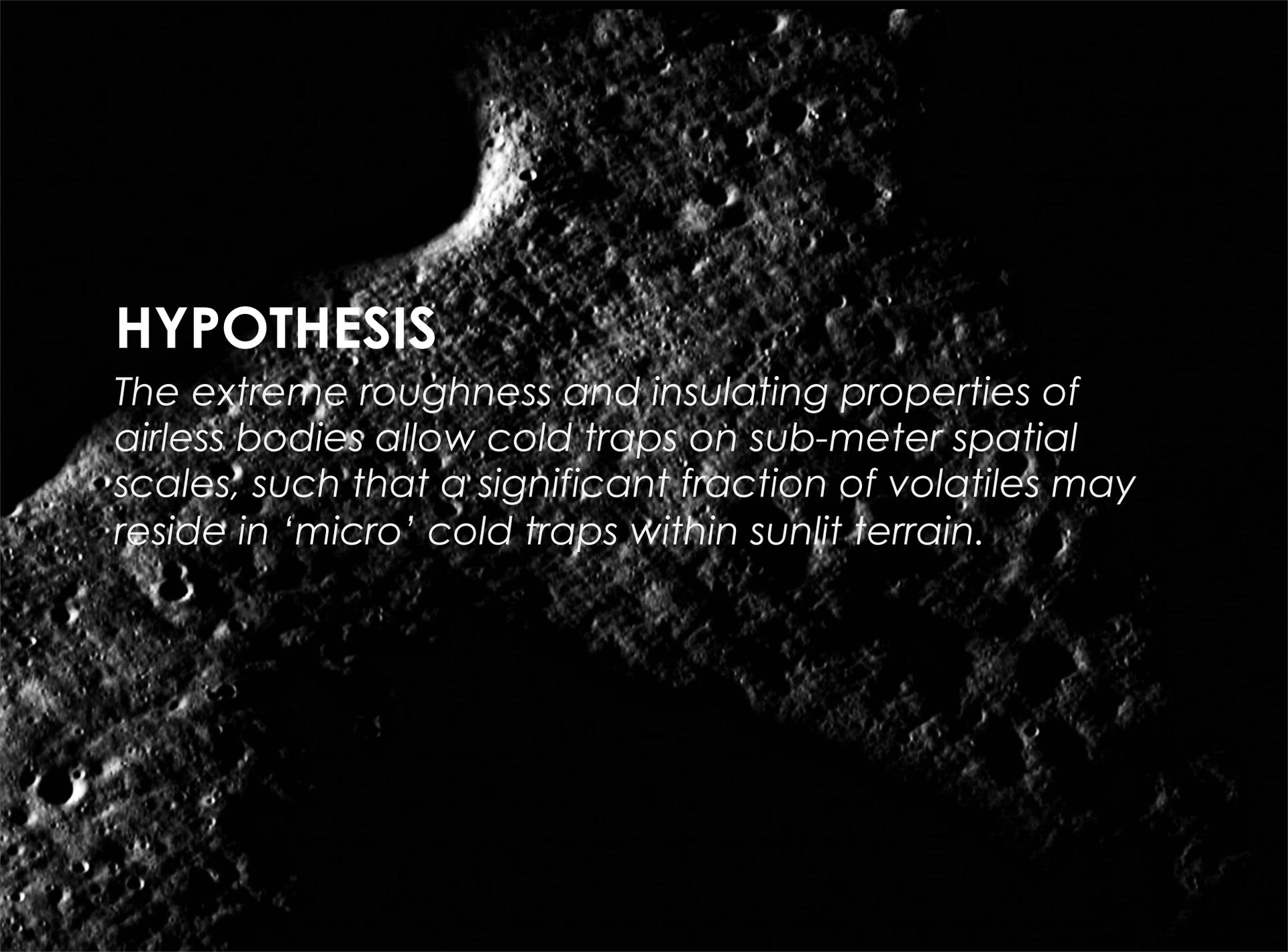
- Adsorbed $\text{H}_2\text{O}/\text{OH}$
- Subsurface ice
- Ice in unresolved small-scale cold traps



Epithermal neutron count rate ($\sim 1/\text{water}$) from LEND (Boynton et al., 2012)

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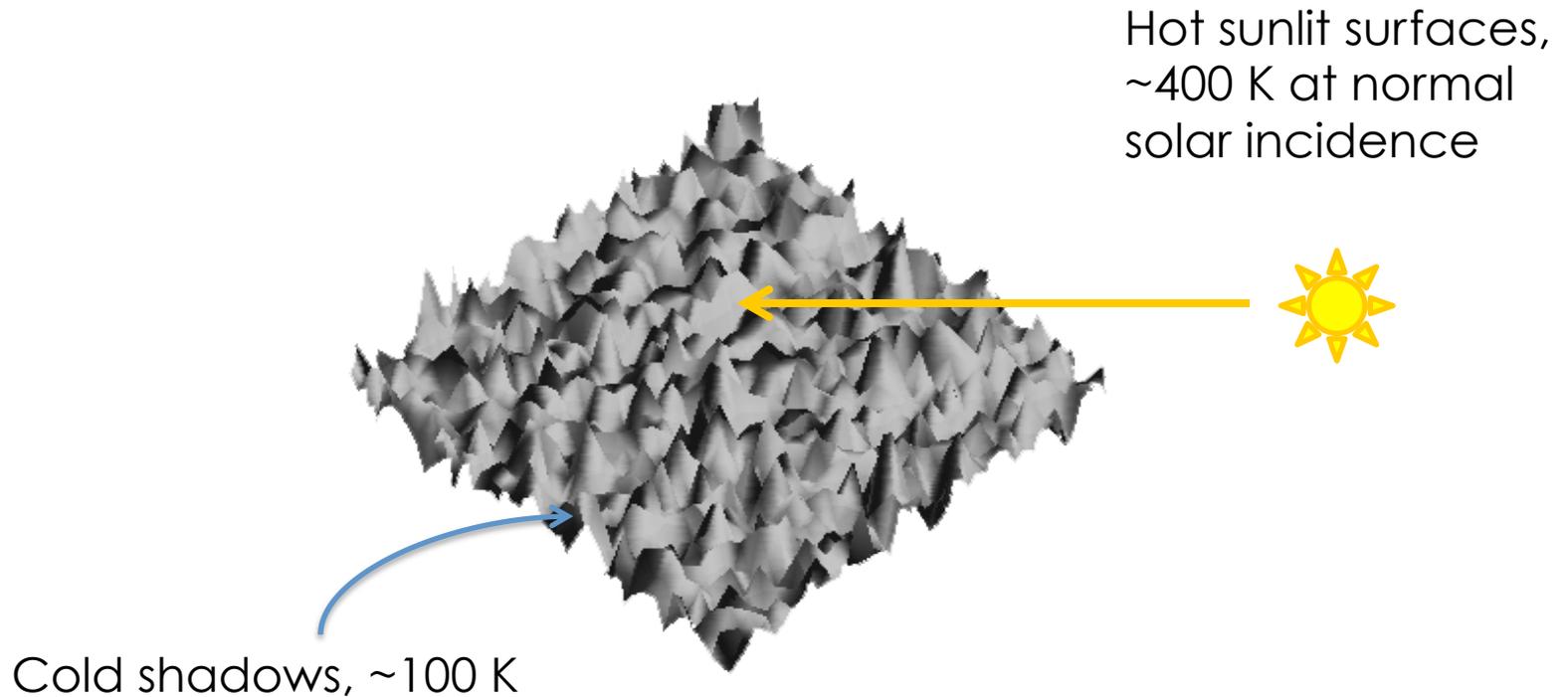
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HYPOTHESIS

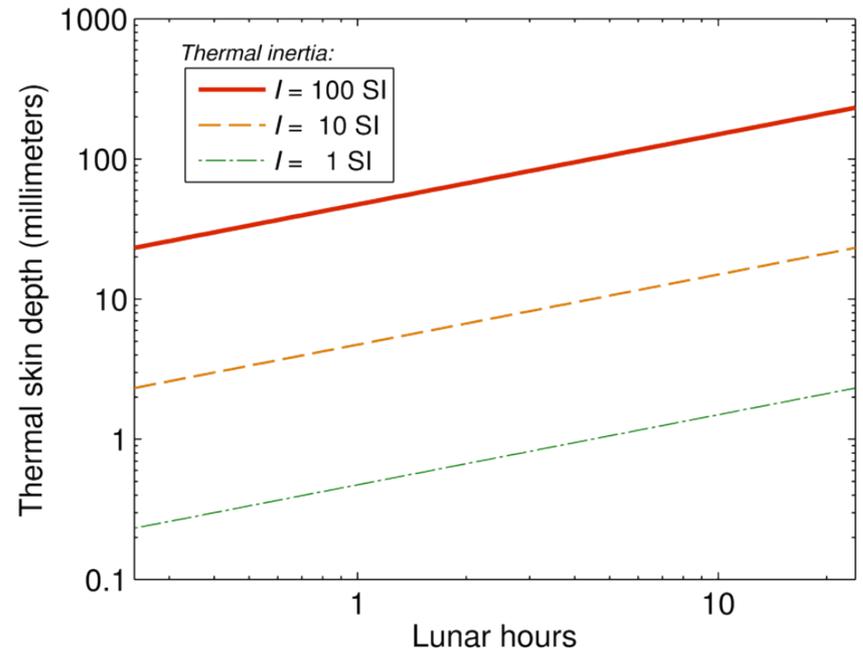
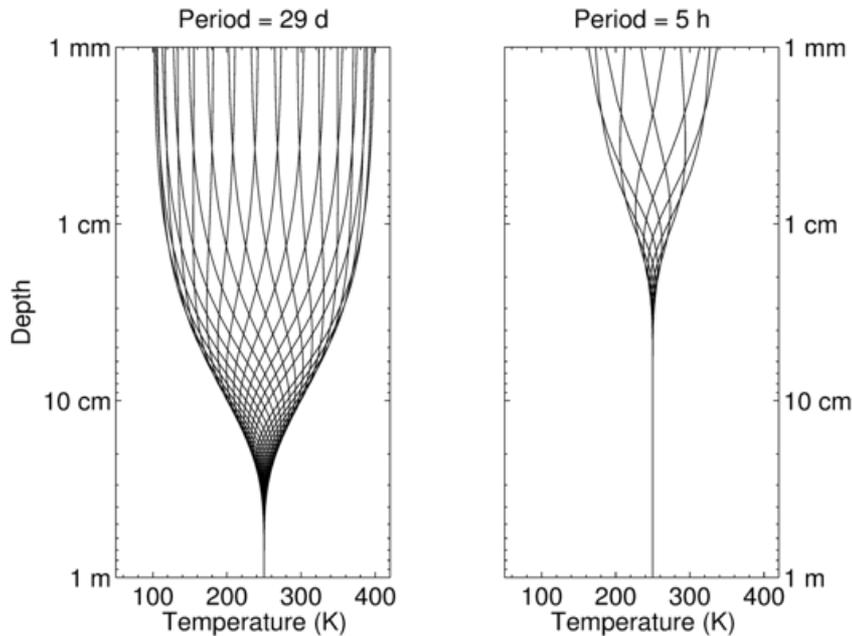
The extreme roughness and insulating properties of airless bodies allow cold traps on sub-meter spatial scales, such that a significant fraction of volatiles may reside in 'micro' cold traps within sunlit terrain.

Temperatures in Shadow and Sunlight



Thermal Isolation

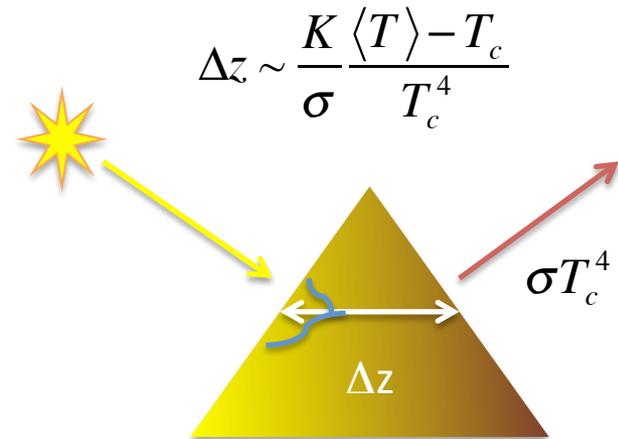
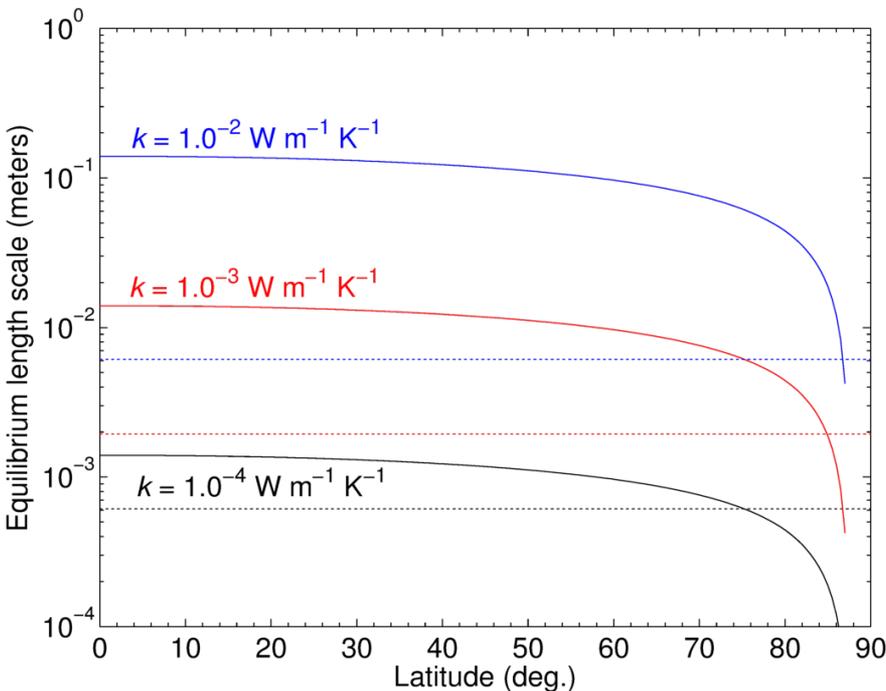
$$z_s \sim \sqrt{kt}$$



Diviner eclipse observations: TI \sim 10 SI within upper few millimeters (Hayne *et al.*, 2012)

Conduction Length Scale

Balance thermal emission from cold trap with mean annual temperature on nearby illuminated surface.

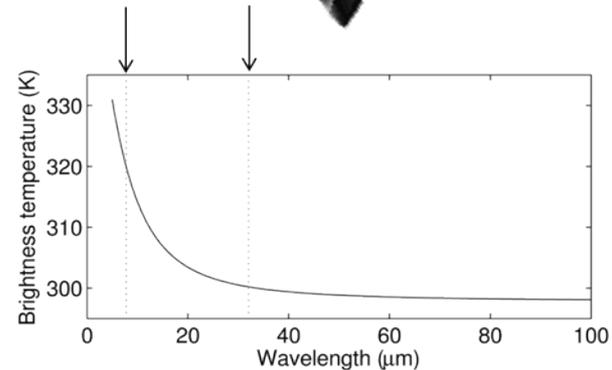
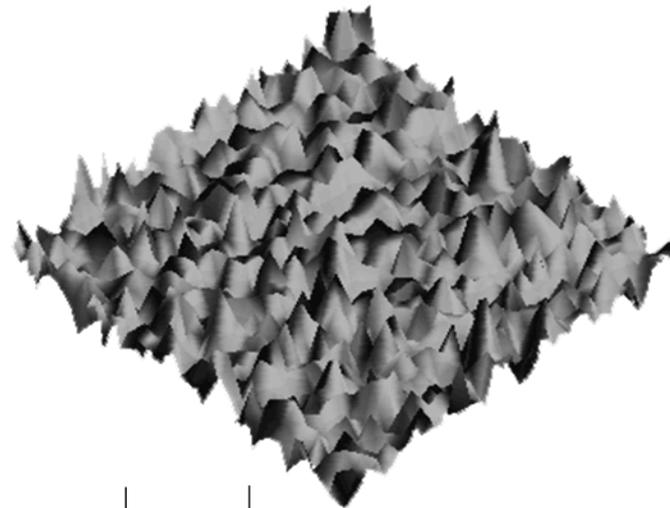
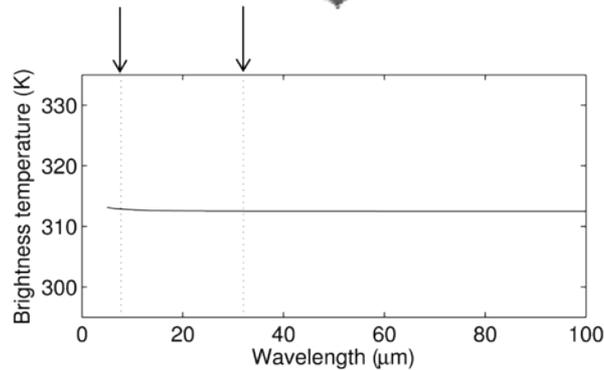
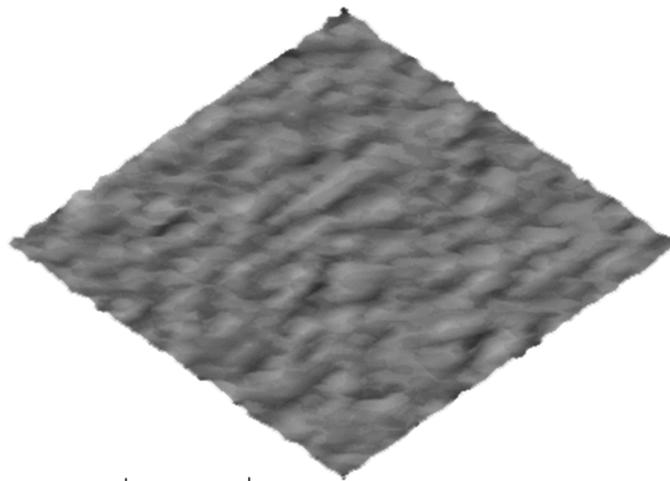


$$\Delta z \sim \frac{K \langle T \rangle - T_c}{\sigma T_c^4}$$

Dashed lines = diurnal thermal skin depth

→ Minimum cold trap size on the Moon is $< 10 \text{ cm}$, probably $\sim 1 \text{ cm}$

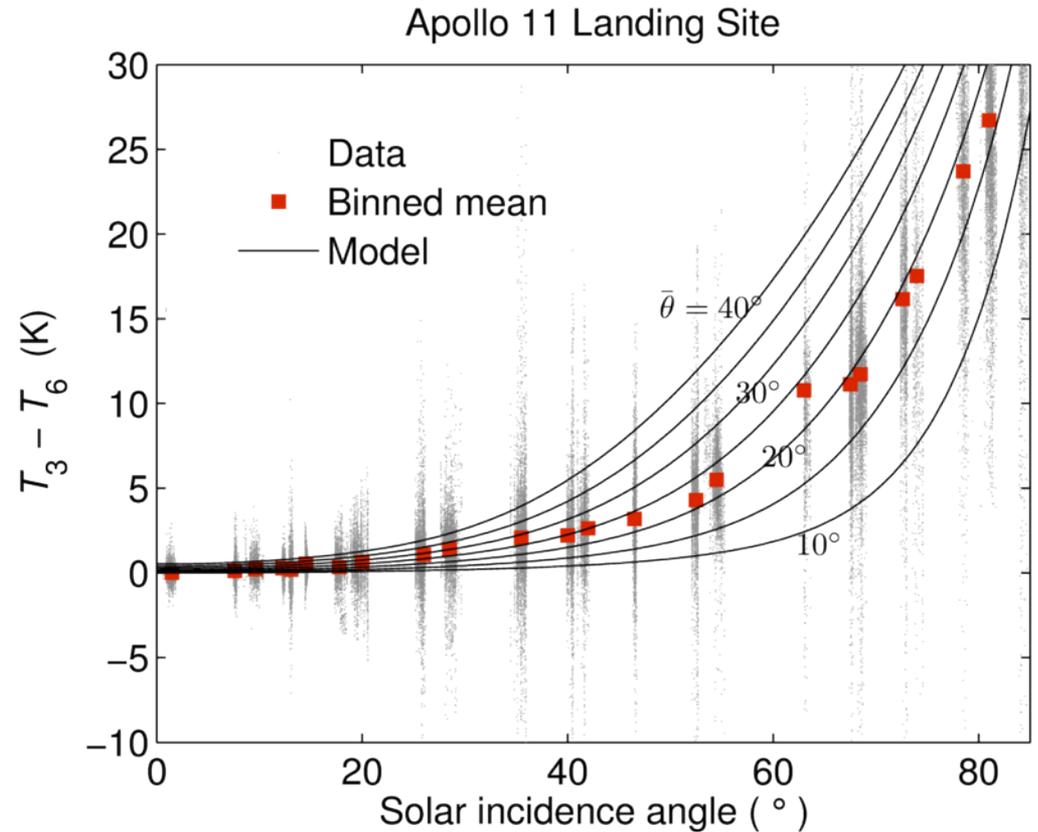
Measuring Surface Roughness via IR Emission



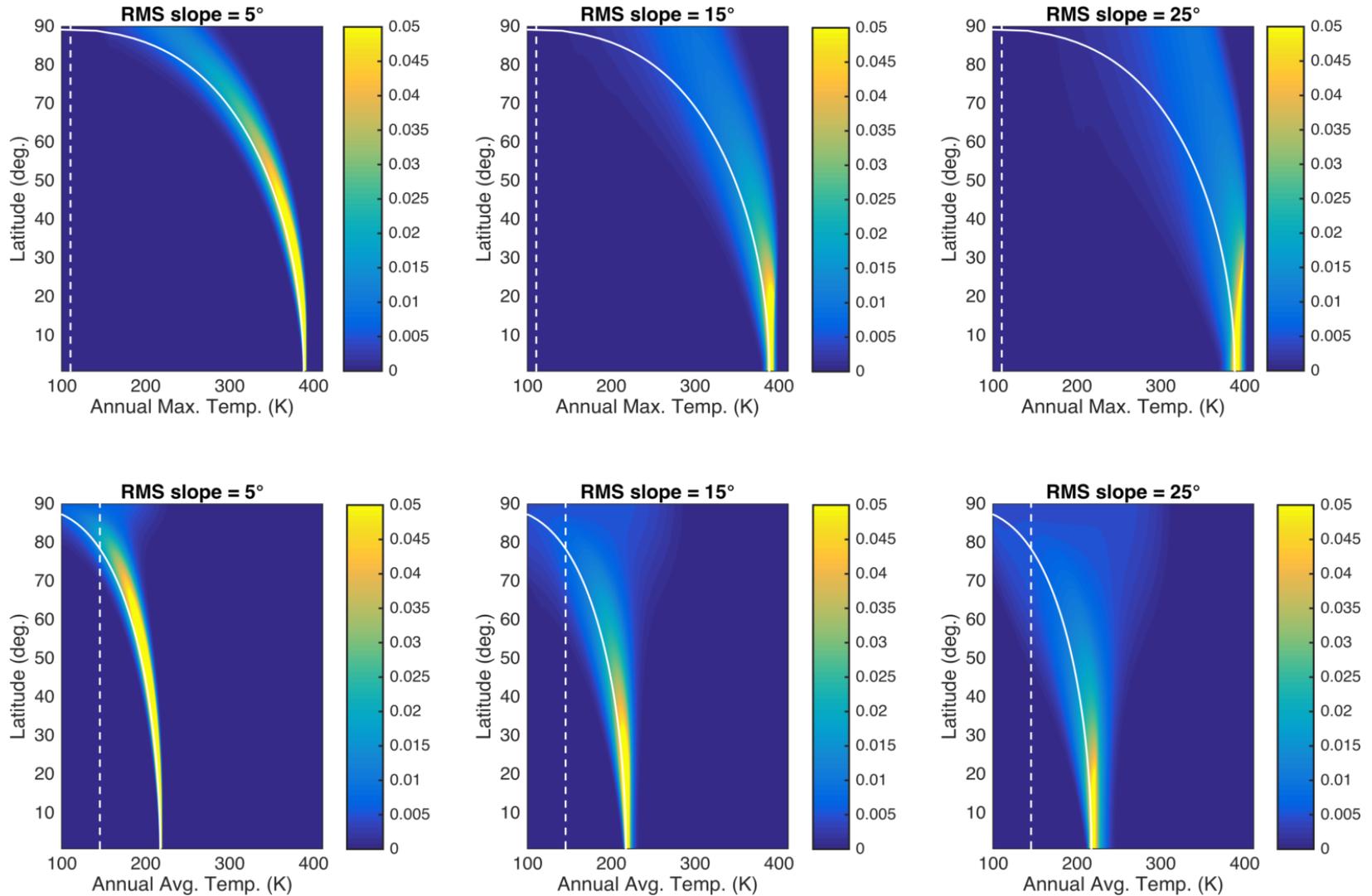
Emission at shorter wavelengths dominated by warmer facets (two Diviner channels indicated by arrows)

Surface Roughness from Diviner: Apollo 11 Landing Site

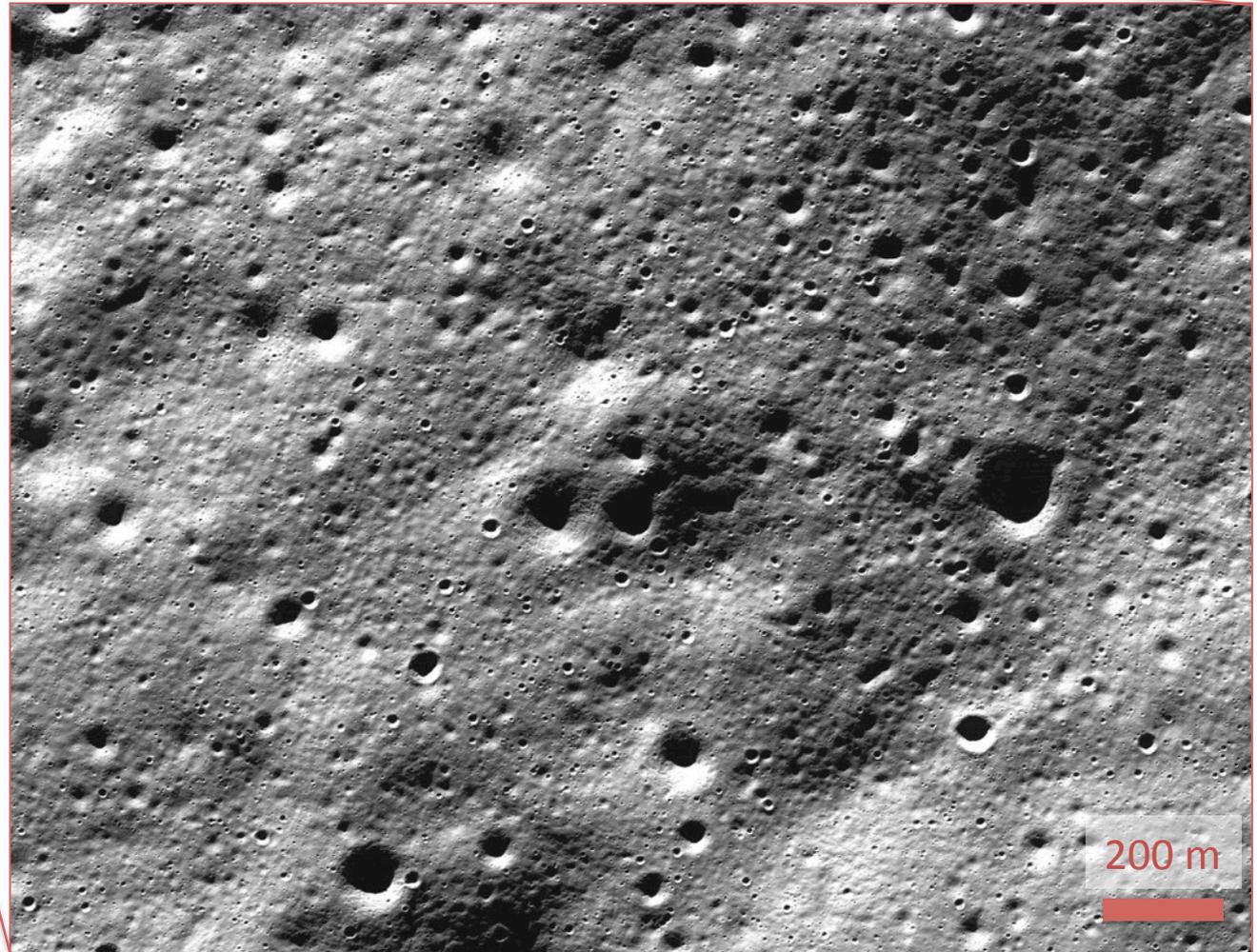
- Diviner data constrain roughness at scales < 250 m
- Best-fit RMS slope $\sim 20^\circ\text{--}30^\circ$
- This is fairly typical of both maria and highlands terrain



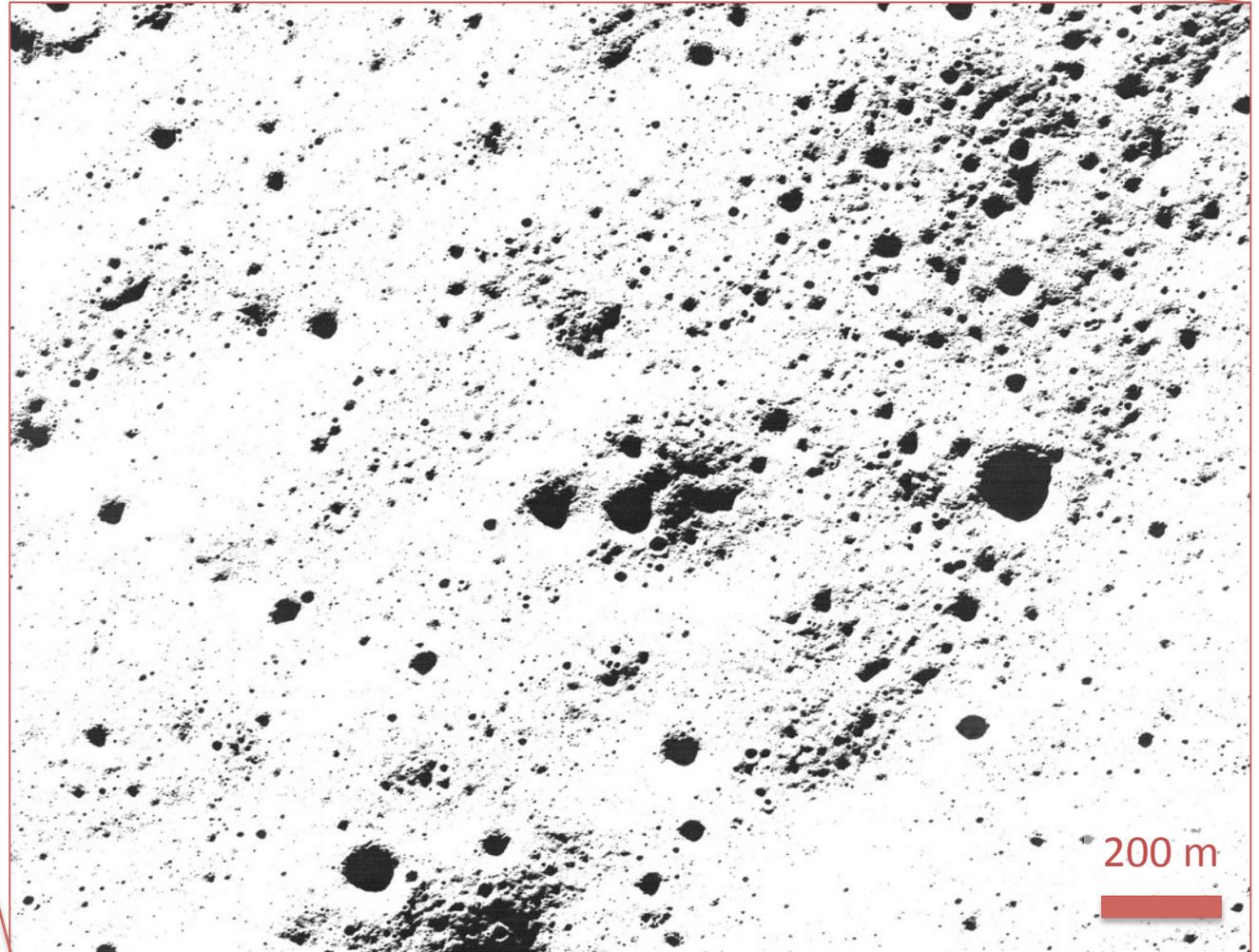
Rough Surface Temperatures



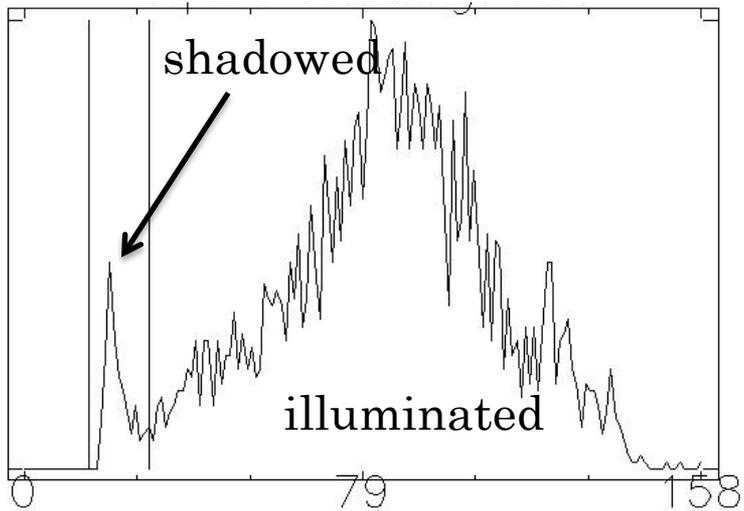
Shadows in LROC Images



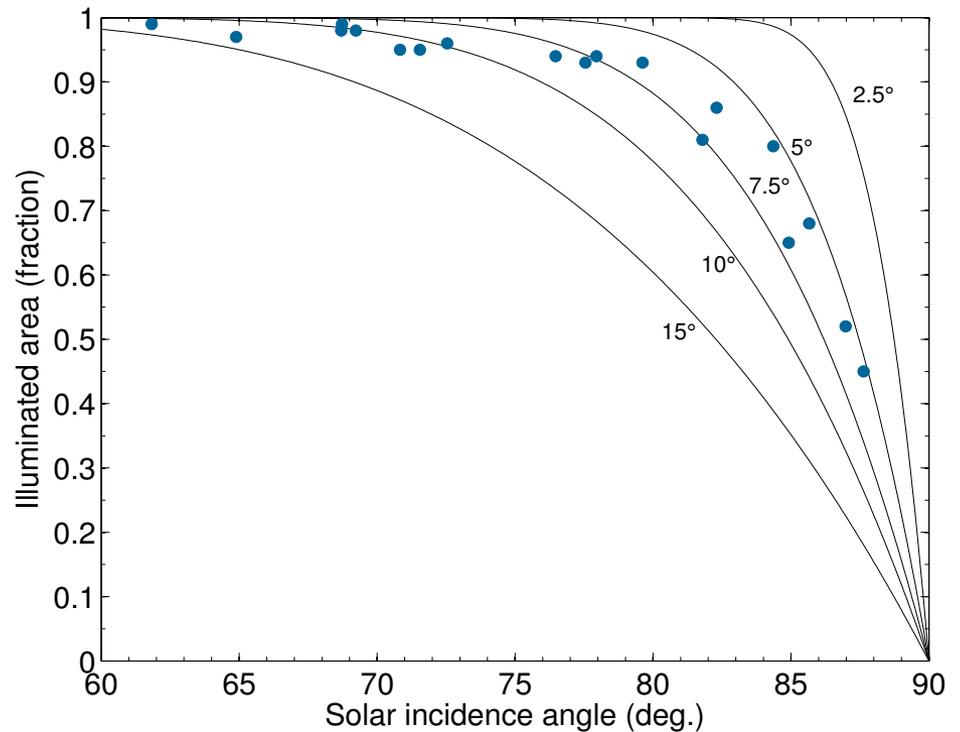
Shadows in LROC Images



Shadow Fraction: Model vs. Data



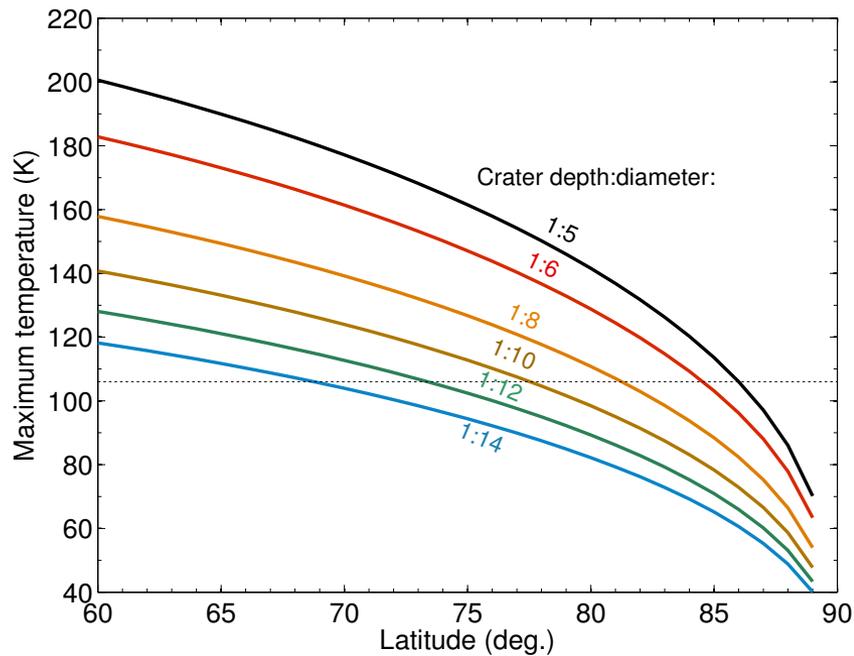
LROC NAC image brightness histogram



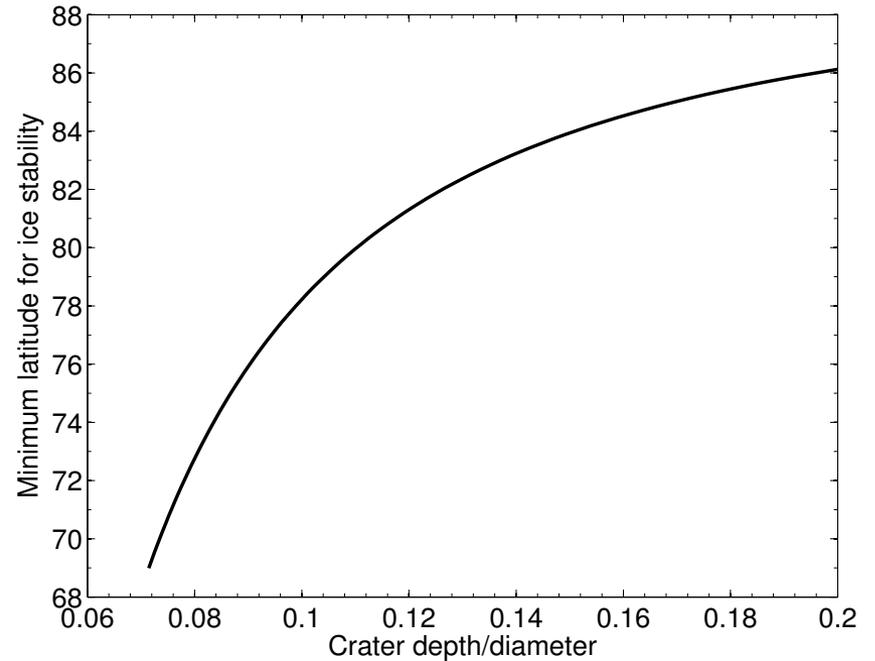
~5-10° RMS slope compares well with results of Rosenberg et al. (2011) using 17-m baseline LOLA data

Temperatures in Perennially Shadowed Craters

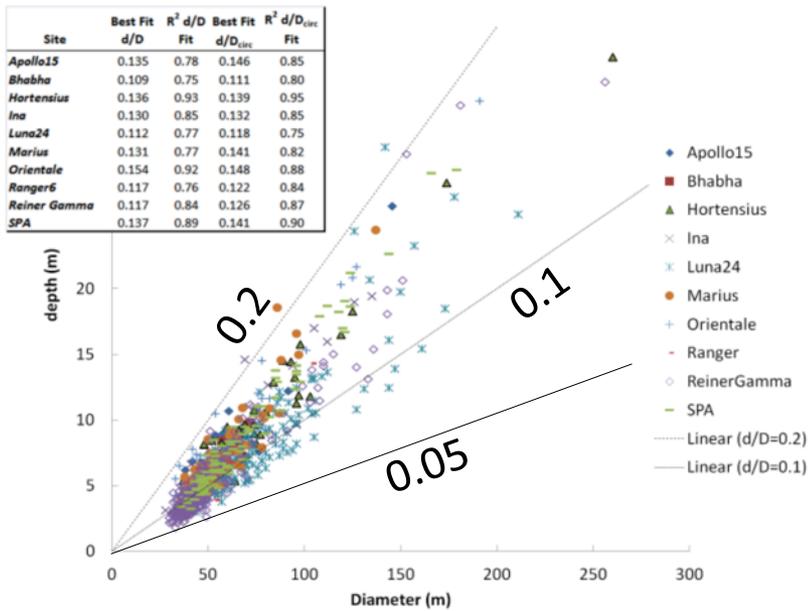
Maximum temperature in shadowed portion of crater



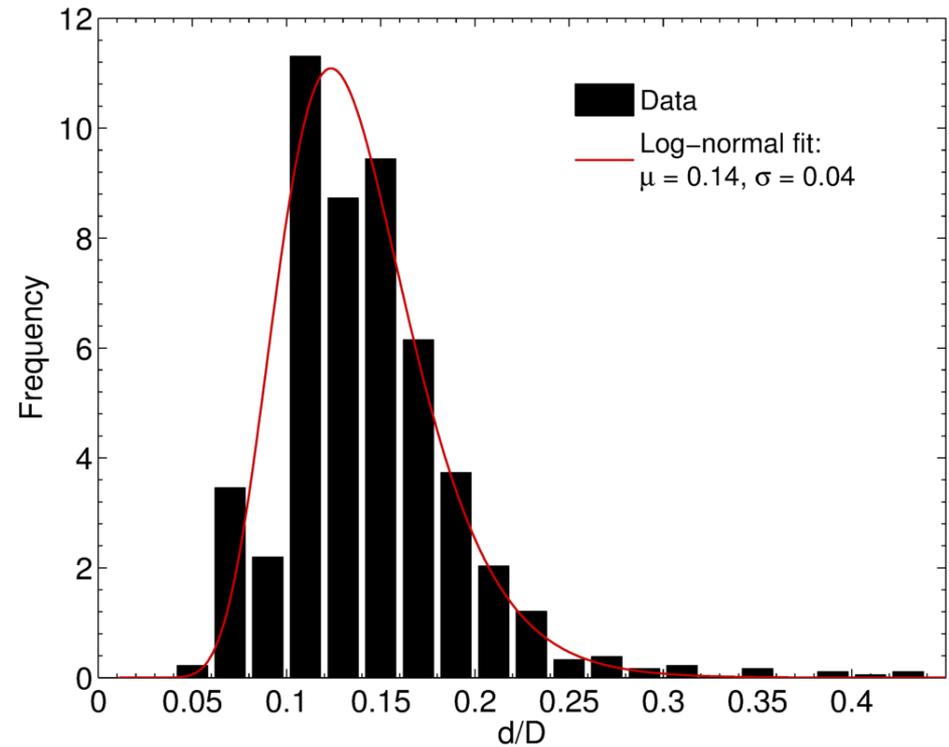
Lowermost latitude where ice is stable in the shadowed regions



Depth-diameter Ratios of Very Small Craters

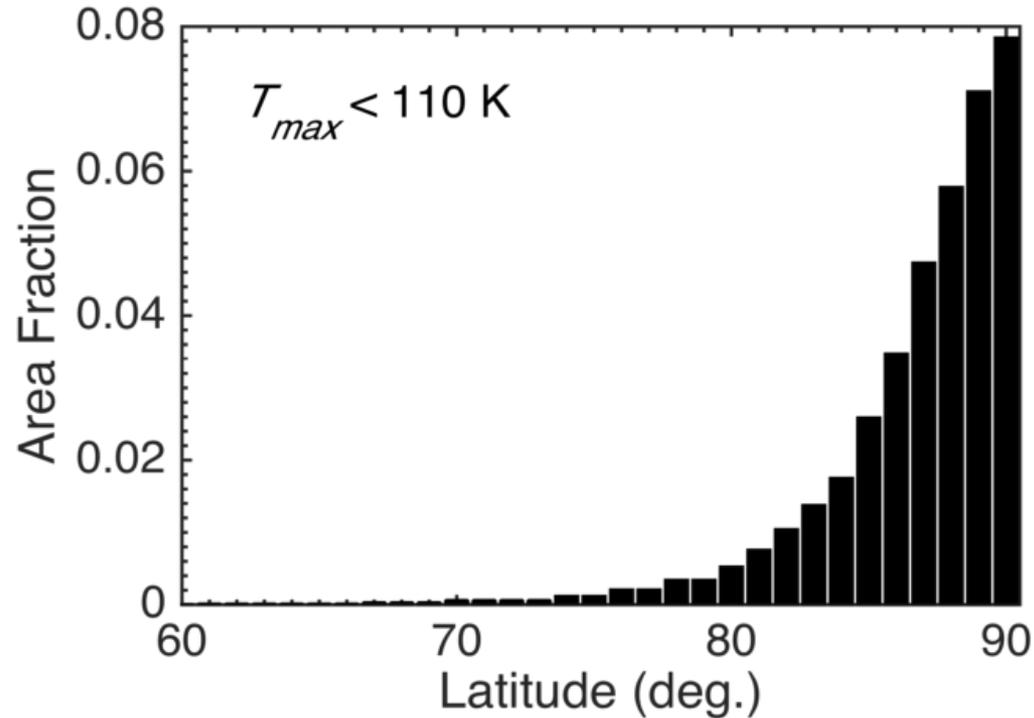


Stopar et al., 2012



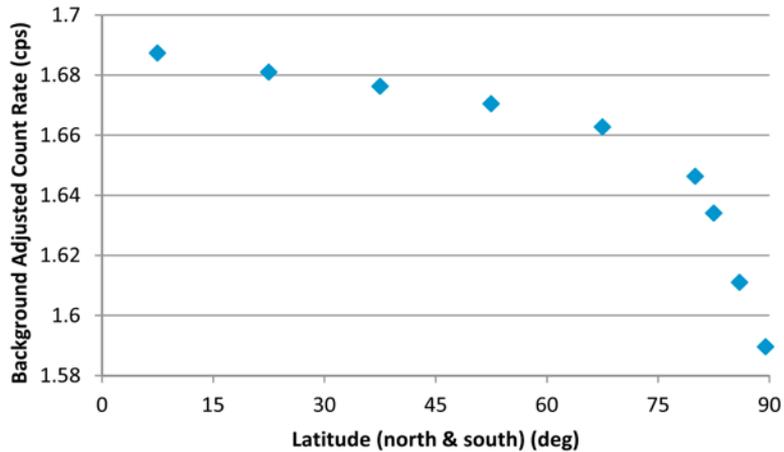
LROC data courtesy of Prasun Mahanti

Thermally Stable Area

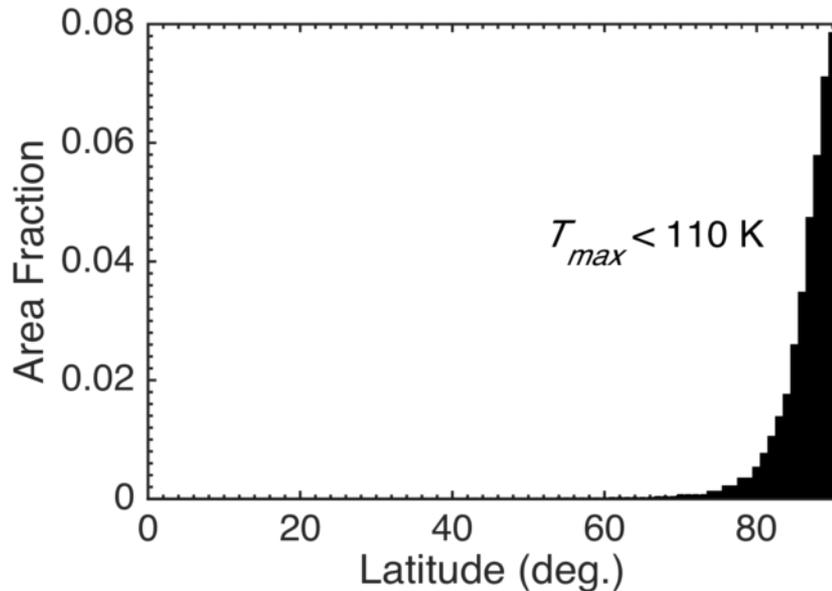


- Total area $\sim 10^5 \text{ km}^2$
- Comparable to area of larger mapped cold traps (Mazarico et al., 2011; Paige et al., 2010)

Comparison with Neutrons



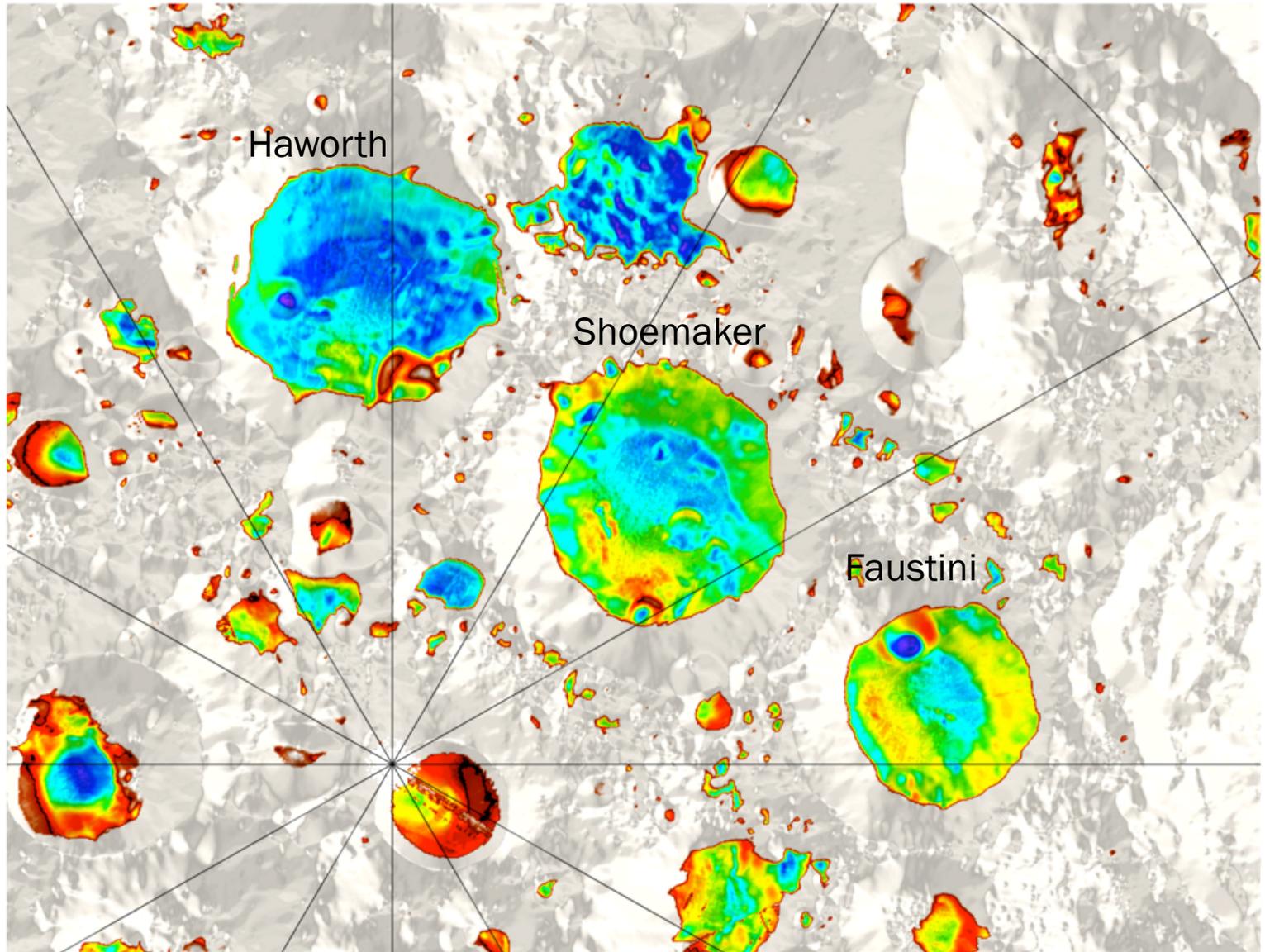
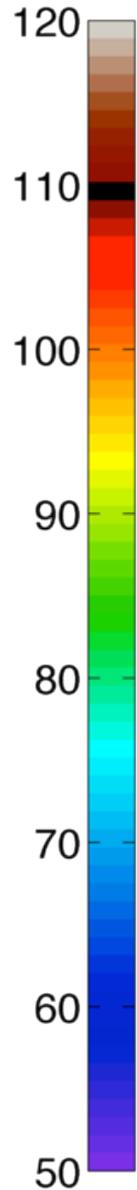
LEND background neutron suppression (Boynton et al., 2012)



Fractional surface area with temperatures conducive to stable surface water ice

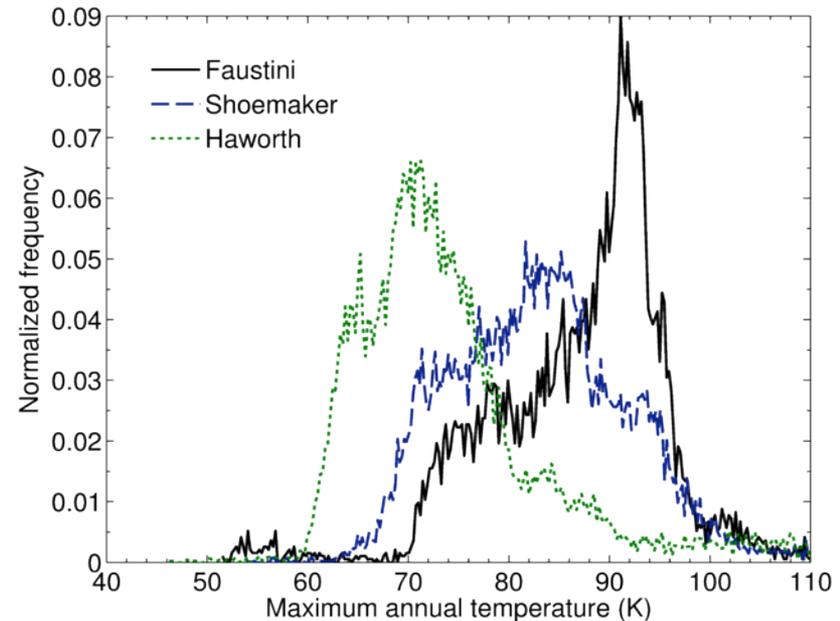
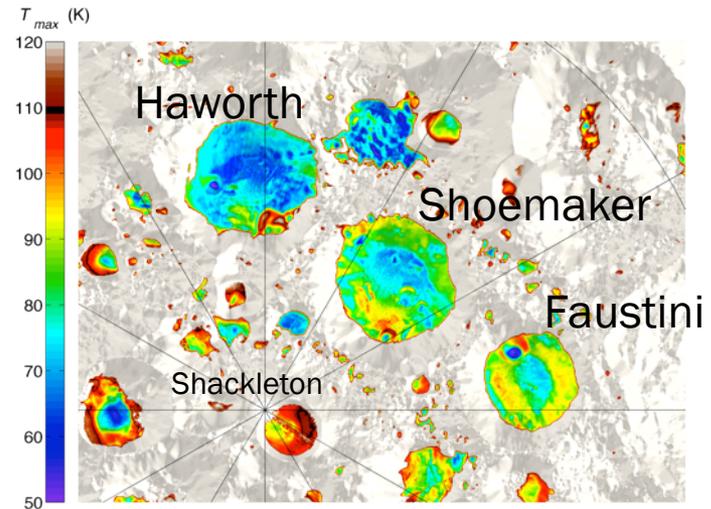
“Three Amigos”

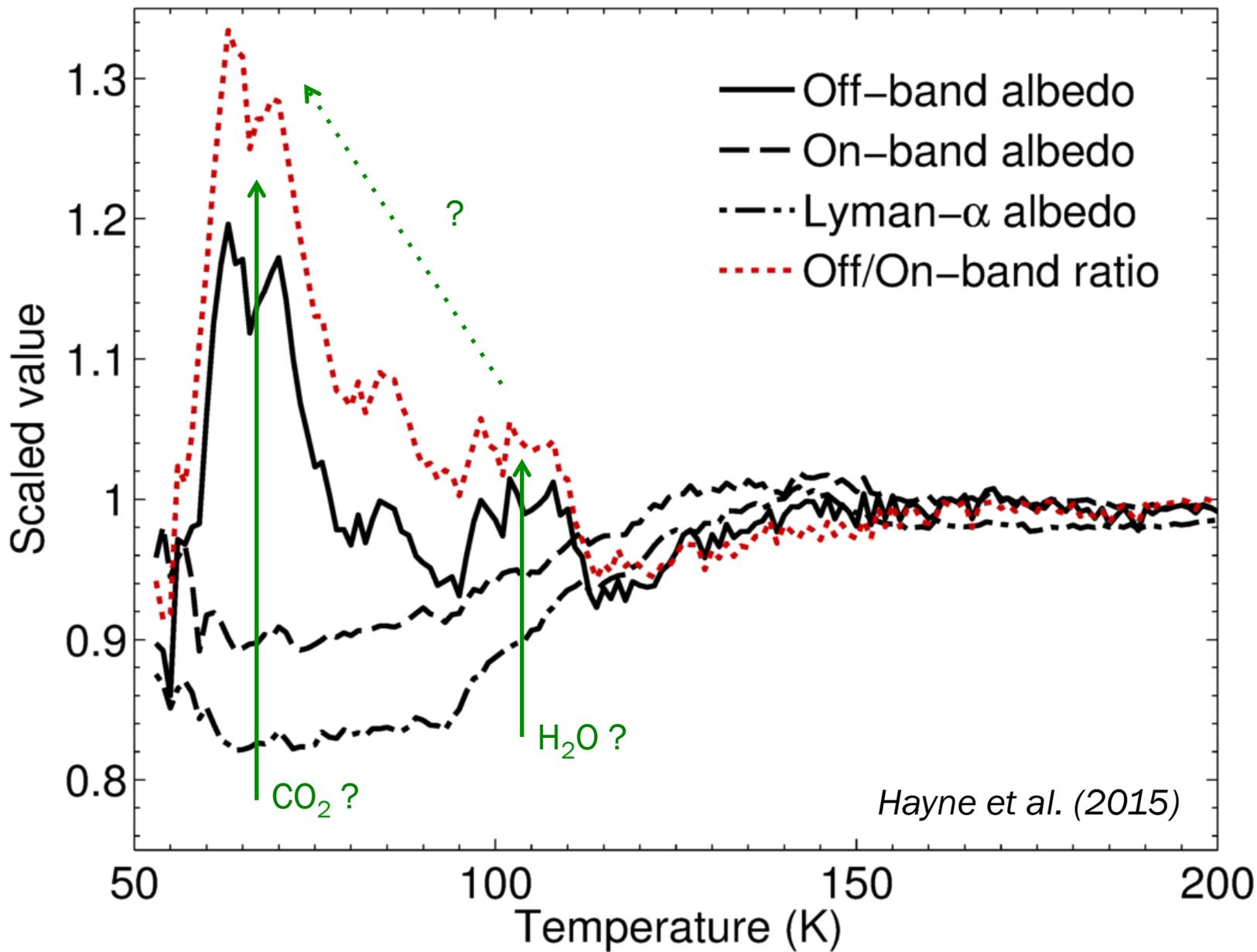
T_{max} (K)



“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 \gg Faustini $>$ Shoemaker





Conclusions

How small, and how prevalent are small-scale cold traps?

- Smallest cold traps are < 10 cm, probably ~ 1 cm at high latitudes, based on Diviner data
- Diviner thermal emission spectra consistent with RMS surface slopes ~ 20 - 30° , at scales < 250 m

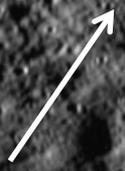
What are the distribution and importance of small cold traps for trapping ice?

- Temperature calculations predict a steep pole-ward increase in ice stability within little cold traps, consistent with neutron data
- Comparable surface area ($\sim 10^5$ km²) expected for micro cold traps compared to those resolvable on the ~ 250 m scale
- Future work should investigate transport, losses, burial and retention of volatiles in small cold traps

Why land here...



...when you can land here?



BACKUP

Cold Trapping at the Surface

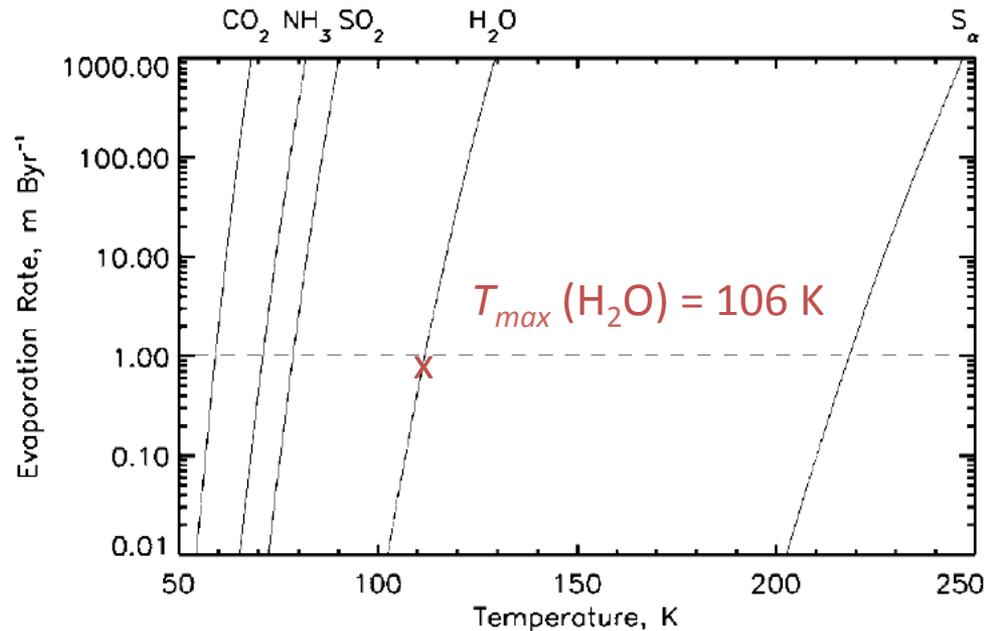


FIG. 1. Evaporation rates into a vacuum as functions of temperature for CO₂, NH₃, SO₂, cubic H₂O, and S_α (solid orthorhombic sulfur) ices. Vapor pressure data were taken from the *CRC Handbook of Chemistry and Physics* (Lide 1993), Bryson *et al.* (1974), and Moses and Nash (1991). The calculation of evaporation rates follows Watson *et al.* (1961). The dashed line marks the rate at which one meter of ice would survive for 1 billion years. The curves cross this line at 59, 71, 78, 112, and 218 K.

Ice Sublimation and Lag Formation

- Ice table moves downward as ice sublimates and diffuses through desiccated regolith layer
- Quasi-steady state can result if sources balance sinks, or if sublimation slow (~ 145 K; Schorghofer, 2008)
- Depth of ice table depends on insolation, regolith composition and porosity, impact gardening, etc.

