Lunar Far-UV Albedos Reveal Surface Water Frost and Porosity in PSRs

Exosphere to Surface Volatile Connections

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& the LRO/LAMP Team
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NLSF 2012

Outline

- Exosphere Introduction
- LCROSS Plume Gas Results
- LAMP Helium Detection
- LAMP Horizon Glow Dust and Other Upper Limits
- Volatile Transport
- LAMP and its PSR Viewing Technique
- LAMP Porosity Diagnostic and Results
- LAMP Detections of Surface Water Frost in PSRs

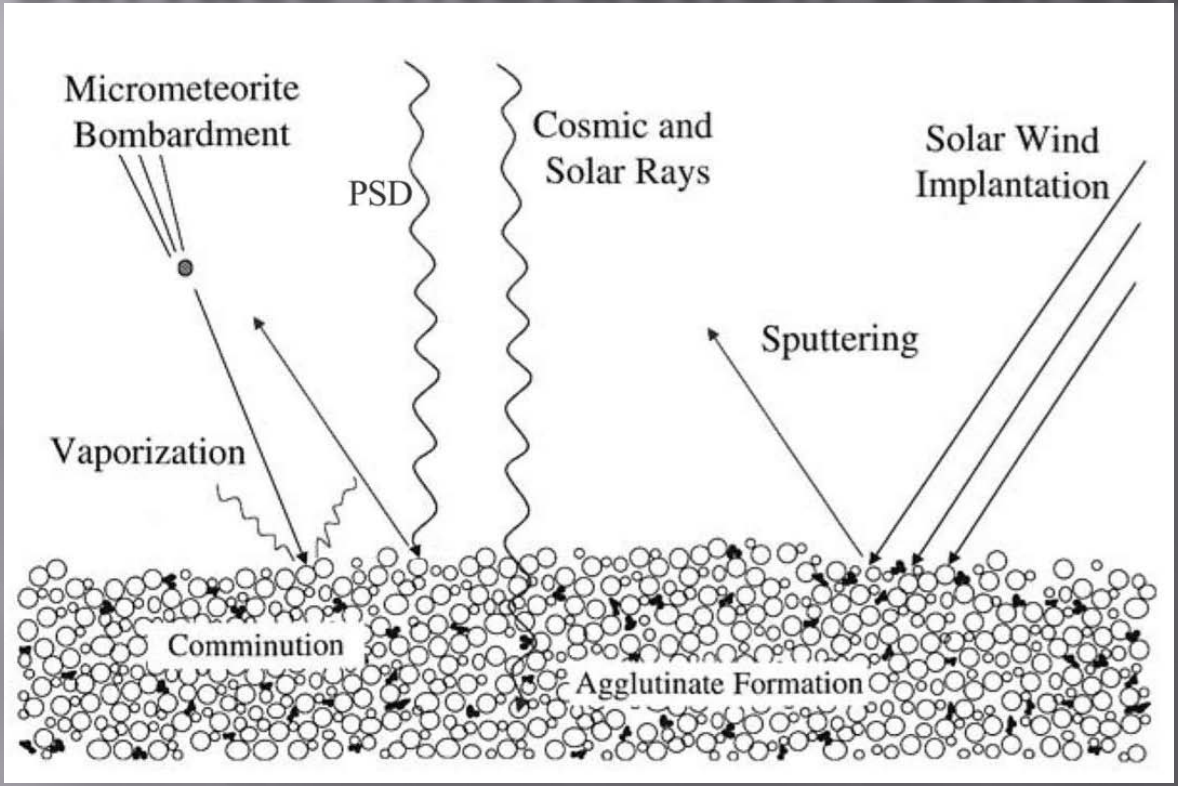
Lunar Exosphere and Volatiles

Exciting times for lunar exosphere and surface volatile studies!

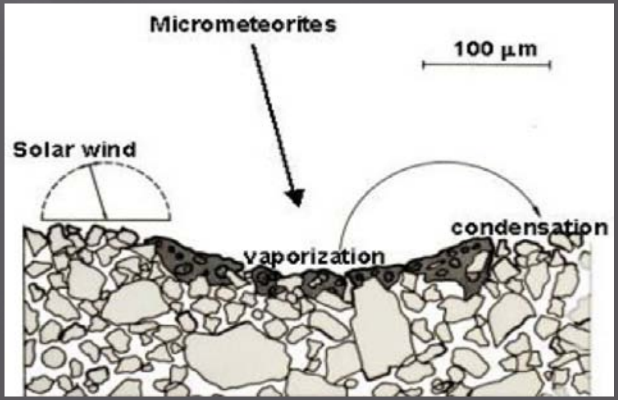
- Lunar Reconnaissance Orbiter
  - Sub-surface, surface, & PSR water signatures *(Boyton/LEND Wed., Siegler Wed., Bussey Thurs., Hendrix Thurs.; Hurley Thurs.; Hibbitts Thurs.)*
  - LCROSS plume gas and thermal response
  - Lunar helium exosphere *(Feldman today)*
  - Galactic cosmic ray interactions
- ARTEMIS
  - Plasma & Fields *(Halekas today, Sarantos today; Samad poster)*
- LADEE
  - Gas, Ions, & Dust *(Delory today, Horanyi Wed.)*

- Richness of International Mission Collaborations
- Ground-based observing *(Killen today; Morgan poster, Oliversen poster)*
- Earth-based observing - IBEX energetic neutral atoms, ROSAT X-ray *(Collier poster)*
- Laboratory studies *(Poston Thurs.)*
- NLSI focused research *(e.g., Farrell Thurs.)*
- Comparative Planetology – Mercury, Outer Planet Satellites, Small bodies, etc.

Lunar Exosphere – Surface Interaction Sources

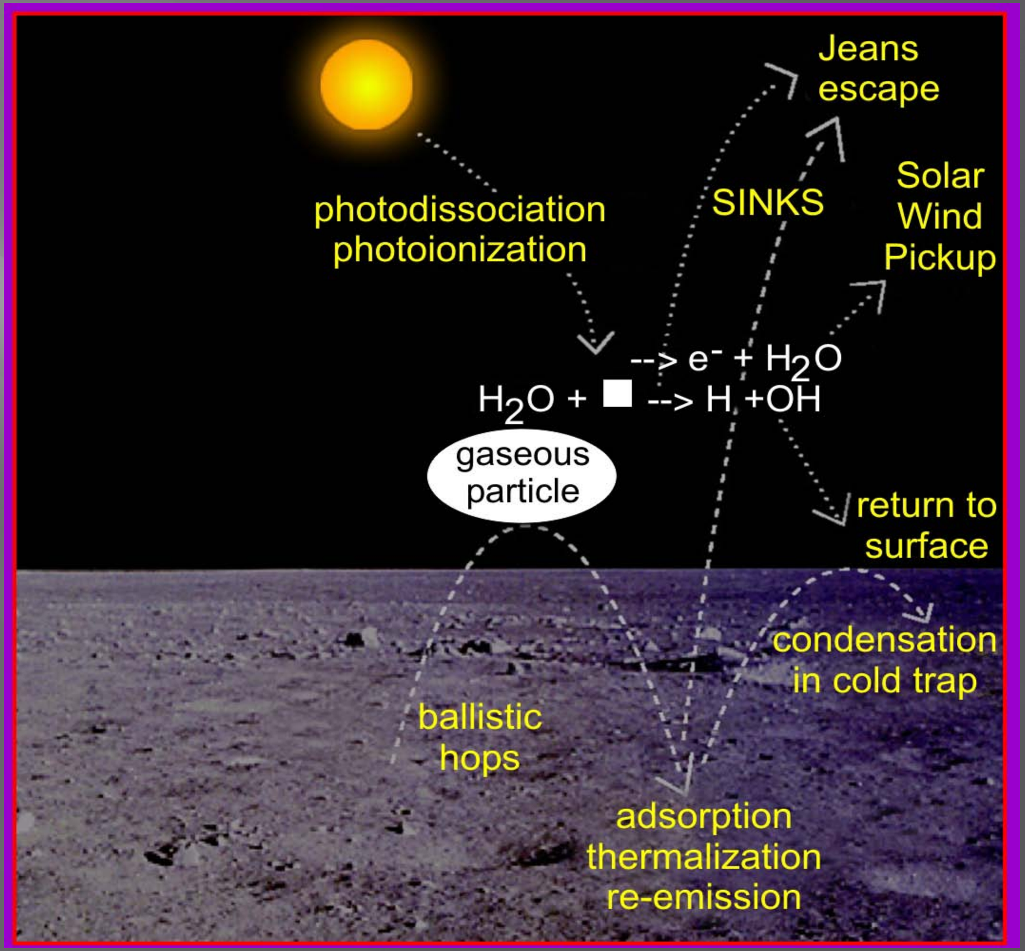


- Sources
  - Sputtering
  - Impact Vaporization
  - Photon Stimulated Desorption
  - Diffusion from Sub-surface
  - Other Assorted: Comets/impactors (e.g., LCROSS), landers, astronauts, etc.



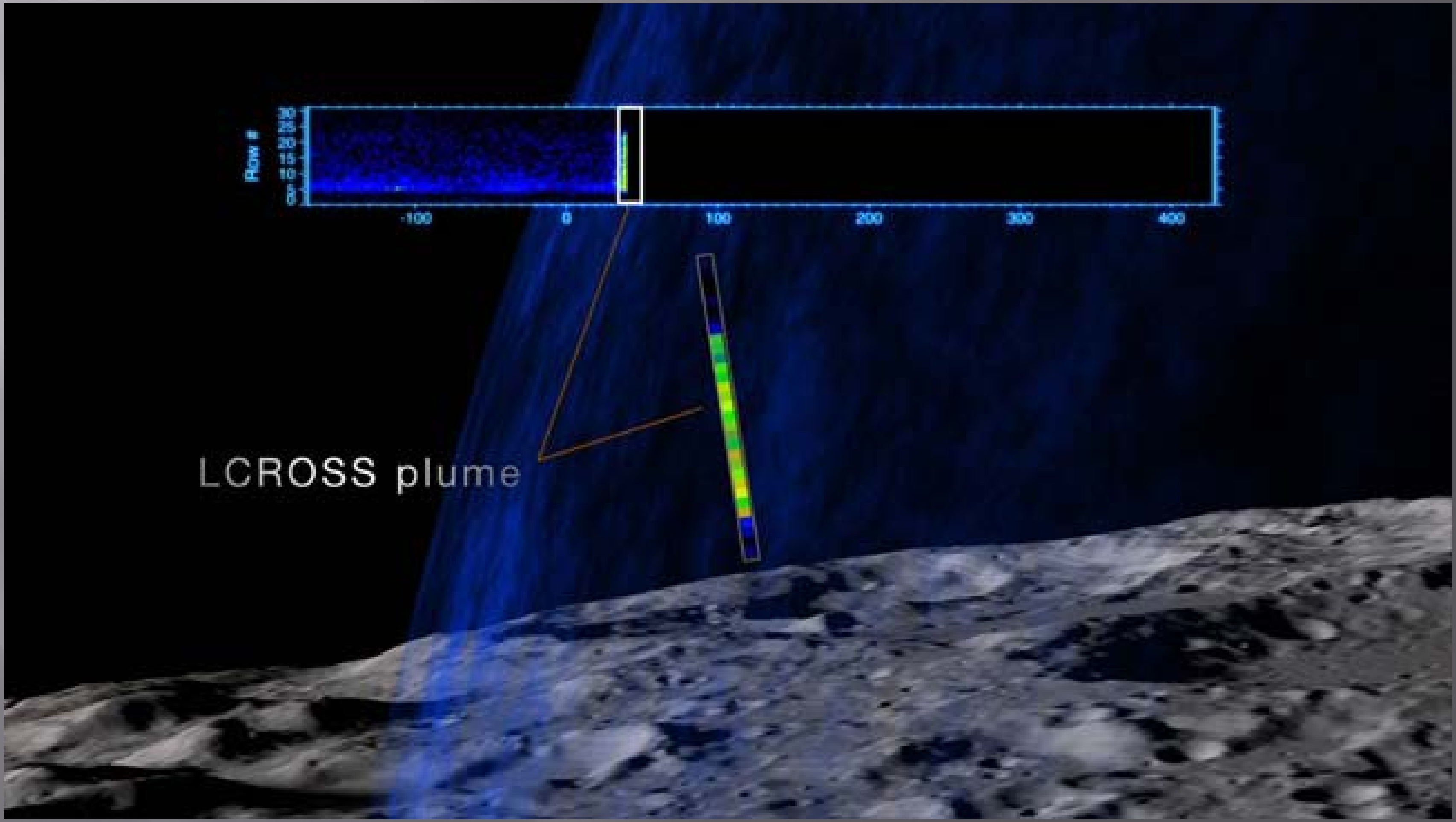
Lunar Exosphere – Variability & Distribution

- Solar wind, meteoritic, and internal outgassing sources inherently variable
- Surface temperature-based thermalization (diurnal, latitudinal, PSRs)
- Losses by photoionization, thermal escape, radiation pressure
- Lifetimes of exospheric particles balance source and loss timescales, ranging from hours to days



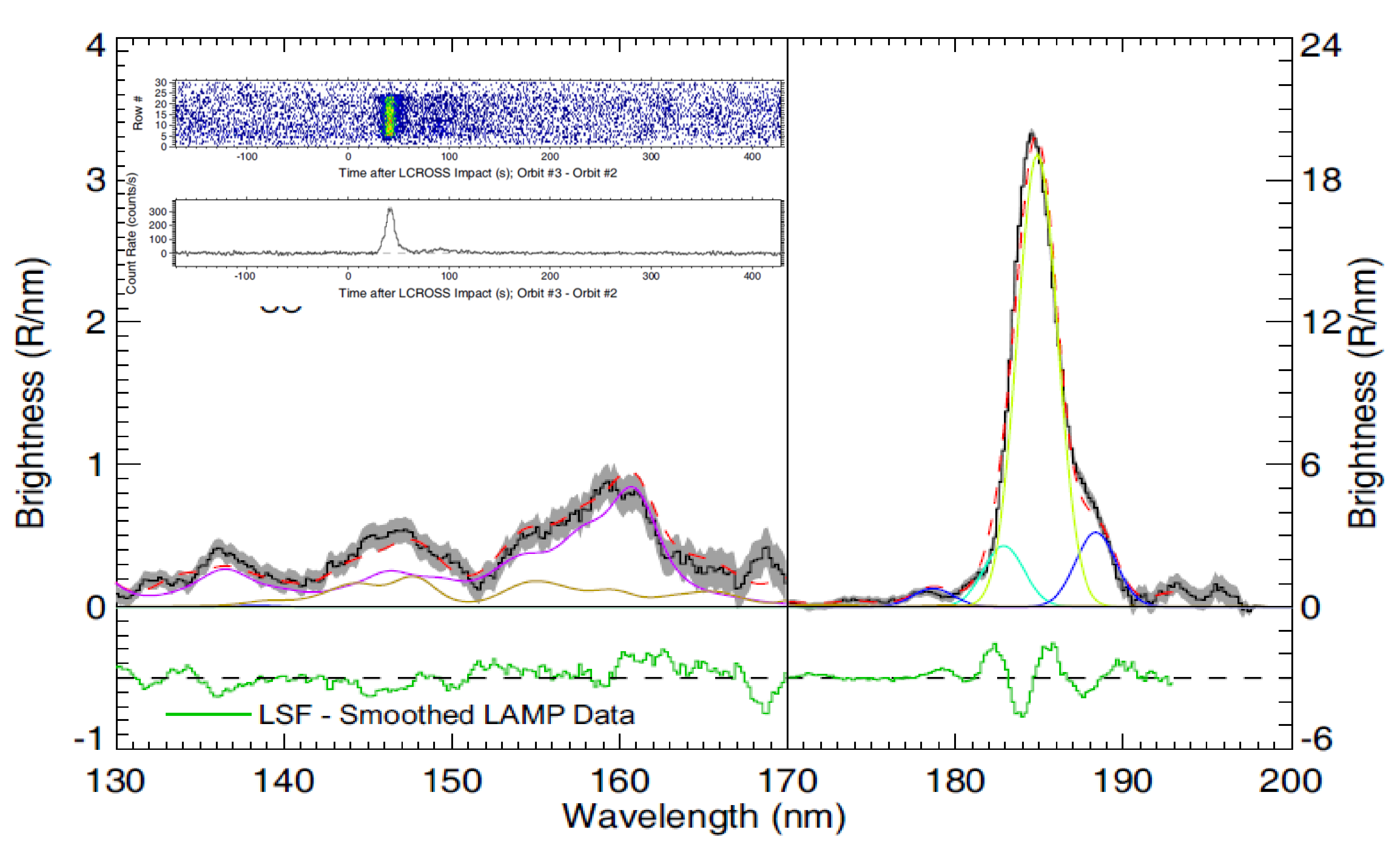
LAMP LCROSS Plume Data

- **LAMP's LCROSS light curves are a rich data set for constraining detailed plume models**



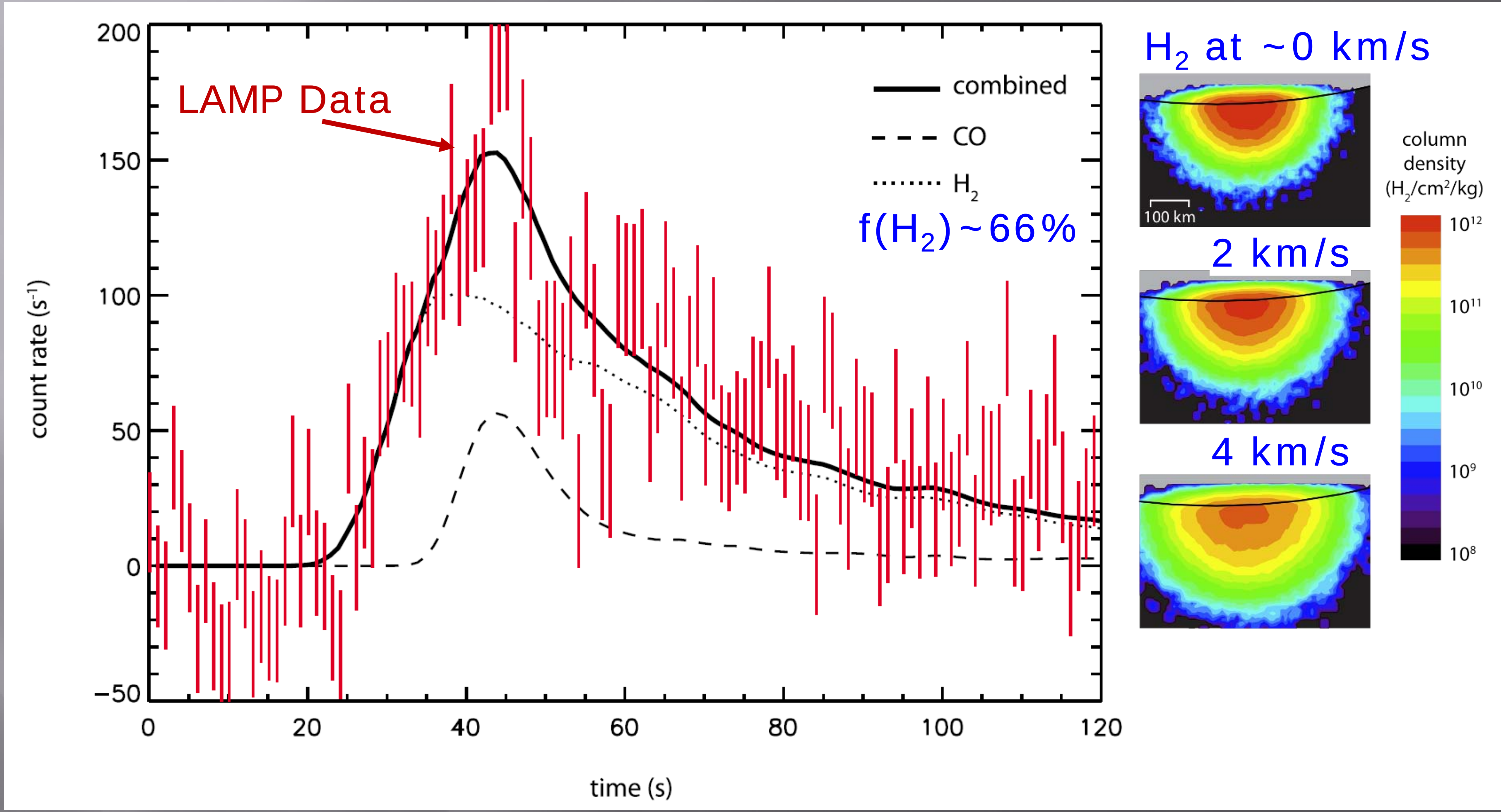
Detection of LCROSS Plume Atmosphere

- **LAMP Detected Five Gaseous Species**
  - H_2 & CO fluorescence emissions from 105-165 nm (T=1000 K)
  - Neutral atomic Hg at 185 nm w/ contributions from Ca and Mg



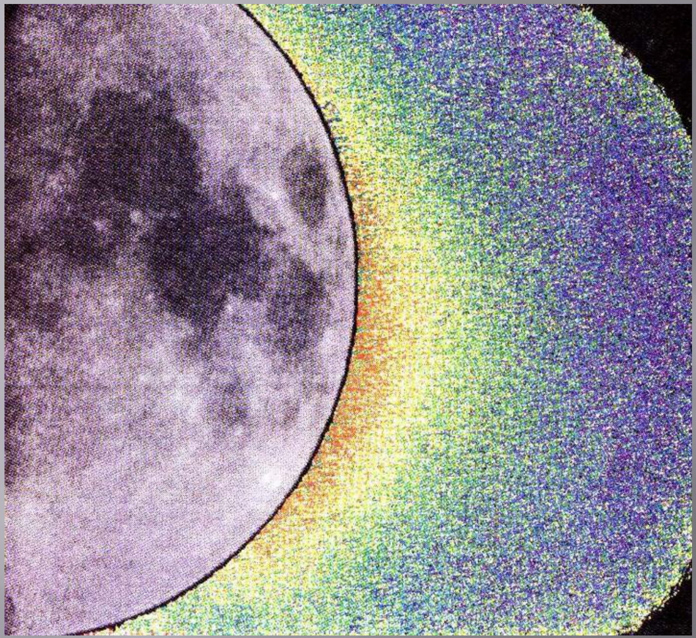
Useful Light Curves for Modeling

Hurley et al. *JGR* 2012 Simulated 130-170 nm Time Series



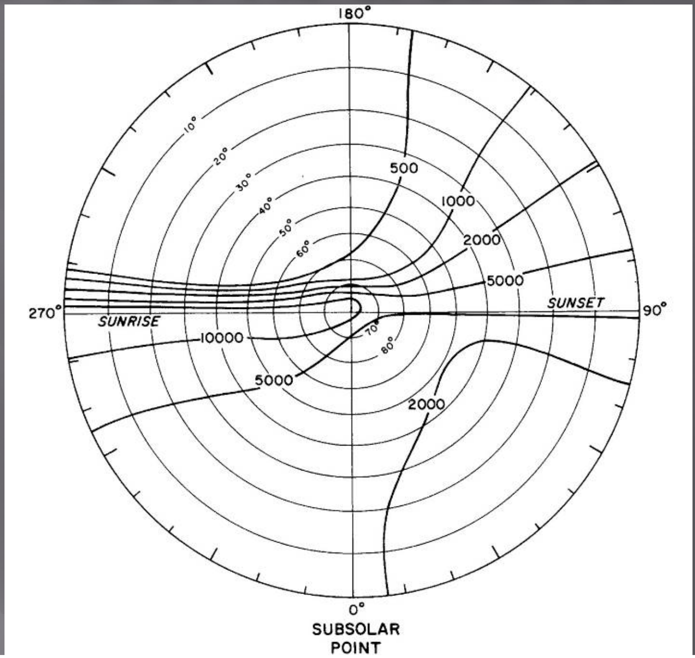
We've learned that water is just one of many interesting volatile species collecting in the PSRs - H_2 is surprisingly abundant

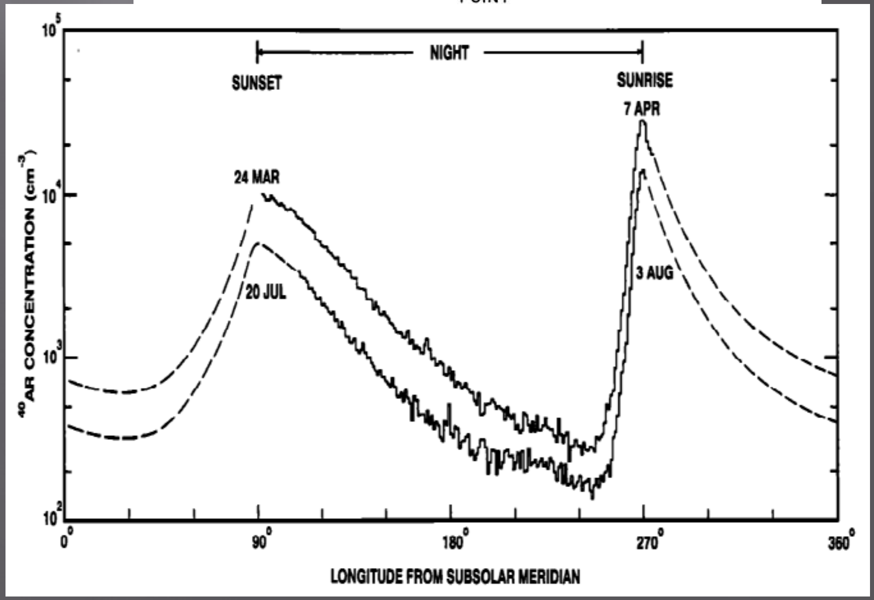
Lunar Exosphere Distribution



Sodium Corona Image: Potter et al., JGR, 1998, Viewed at 51° lunar phase

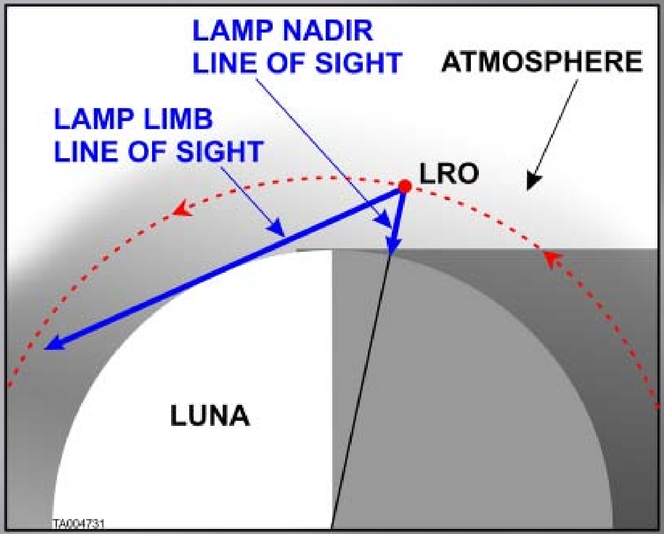
Argon distribution: Hodges et al., The Moon, 1975

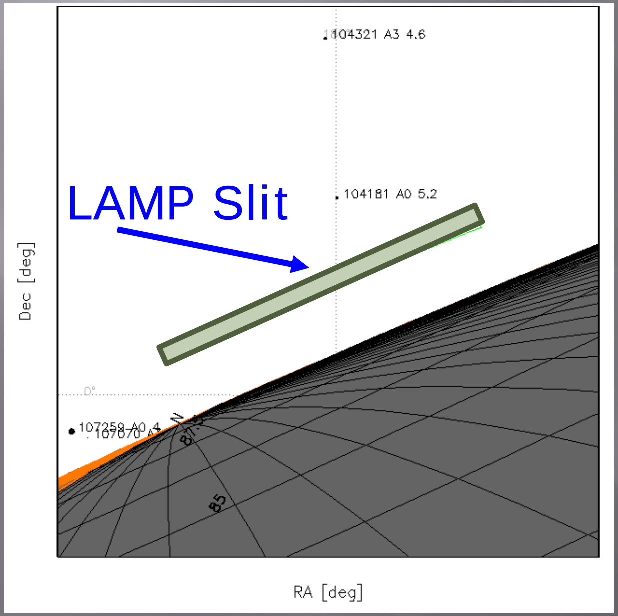




- Argon and other constituents may be concentrated near the dawn terminator and poles.
- Sodium and other constituents may be concentrated near the sub-solar point.
- Helium surface density enhanced on nightside by thermal accommodation.

LAMP Atmosphere Objectives

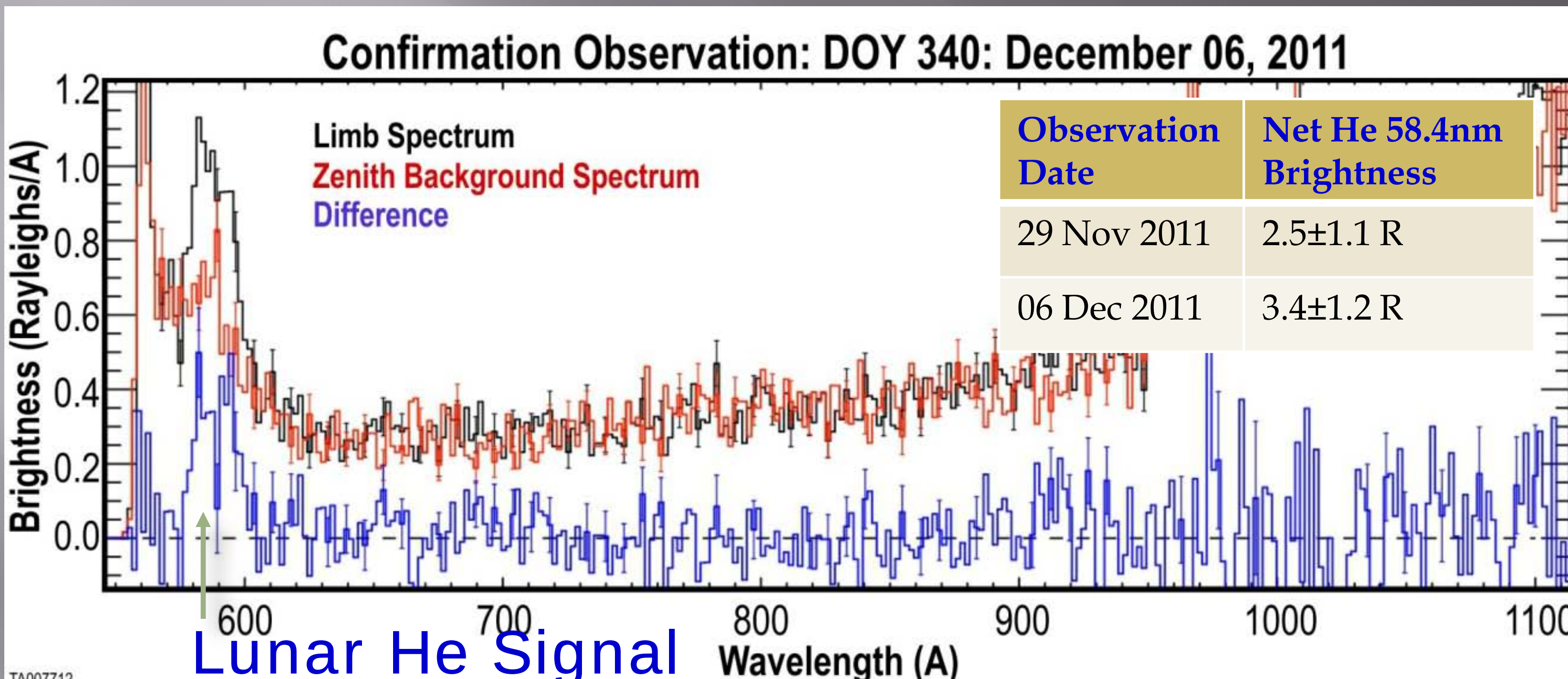




- Search for Ar and He in atmosphere
- Search for H and O signatures of sub-surface water outgassing near the lunar poles
- Search for signatures of carbon-bearing volatiles, e.g., CO
- Search for H_2 in lunar atmosphere to confirm that solar wind protons are converted to molecules in surface
- Search for ionospheric constituents, e.g., O^+ and C^+
- Search for localized outgassing near likely sites, e.g., Ina; will require targeted observations for detailed study
- Search for transient volatiles associated with meteor showers, magnetotail crossings
- Constrain exospheric dust column abundances through forward scattering horizon glow observations

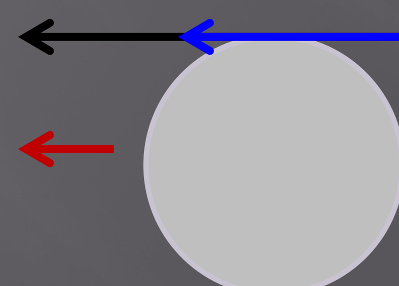
LAMP Helium Detection

- First remote detections, first since the Apollo LACE discovery of helium; Stern et al., *GRL*, 2012



Observation Date	Net He 58.4nm Brightness
29 Nov 2011	2.5±1.1 R
06 Dec 2011	3.4±1.2 R

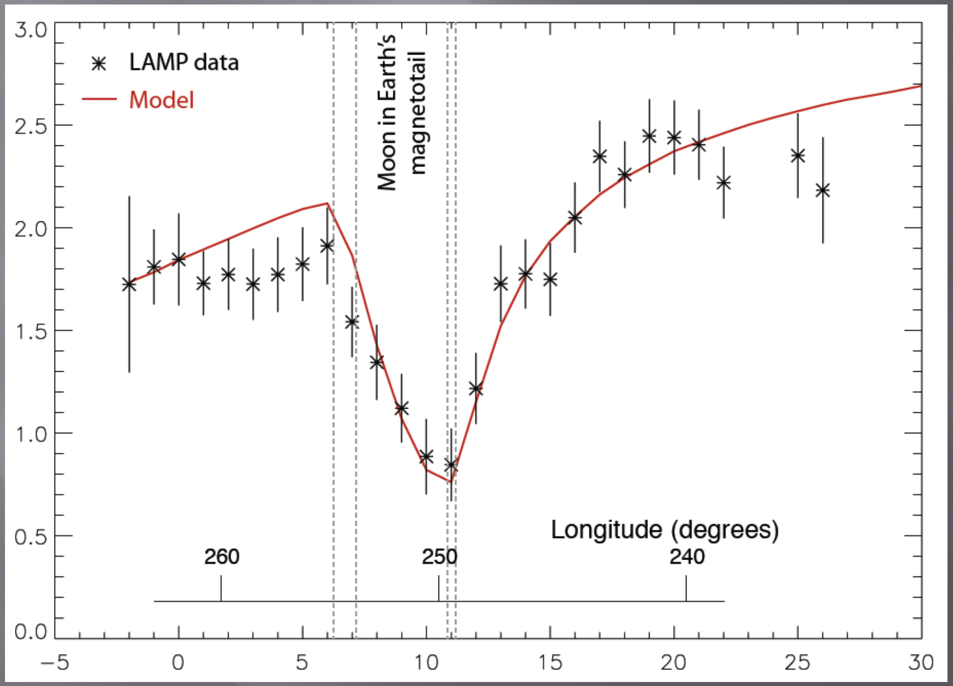
Dedicated LRO limb-pointings probed tangential columns across the poles (black) and sky background (red) when pointed zenith at equator. The near-moon He is their difference (blue).



Important Lunar Helium Variations Detected

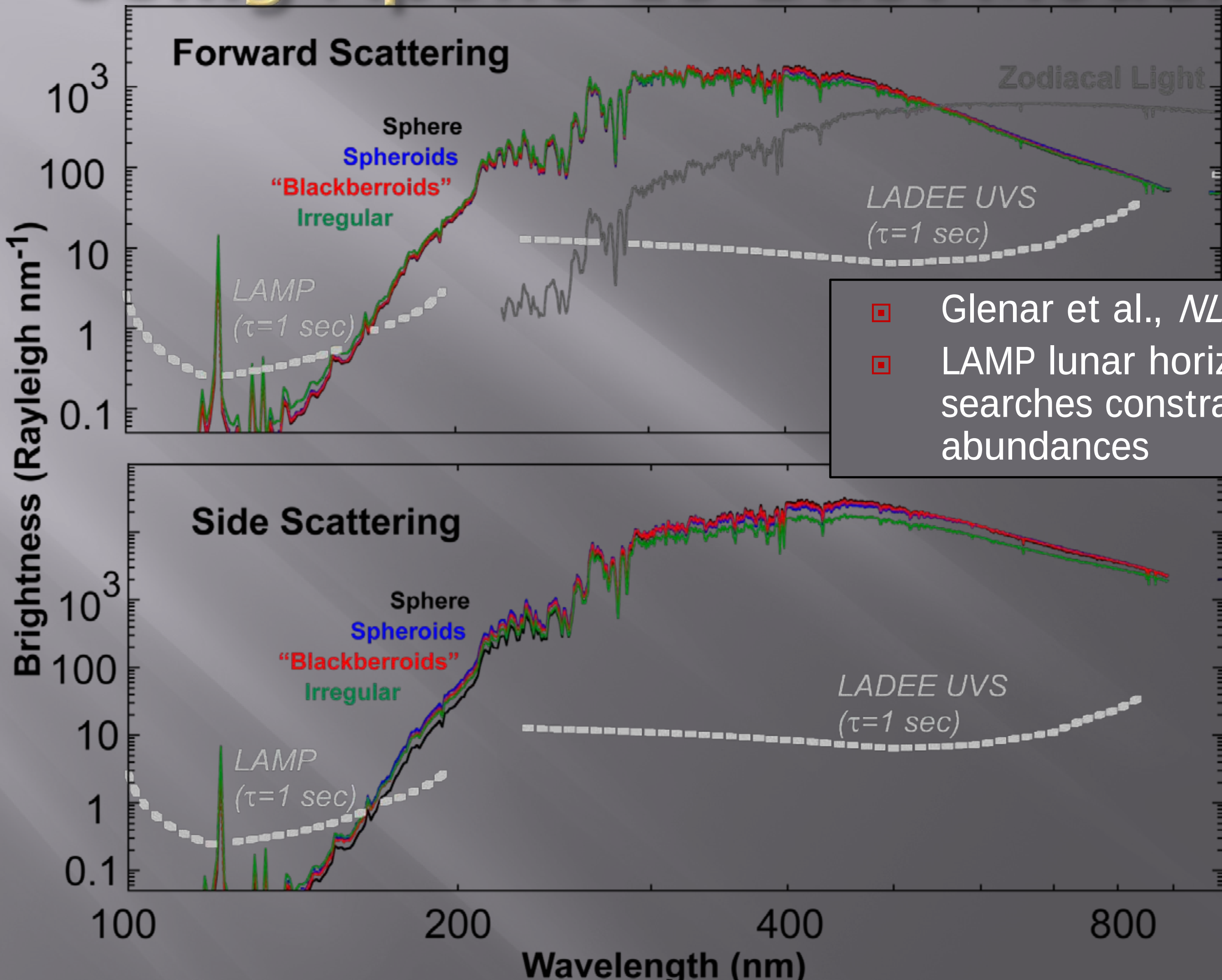
- Variations in lunar helium are now also observed with LAMP and show strong correlations with the solar wind, confirming long-standing theory.
  - A clear decrease is observed during passages into the Earth's magnetotail; Feldman et al., *submitted to Icarus*, 2012 (***and talk today at 4:00***).
  - Models show correlations with thermal release from the dayside surface (red points); Hurley et al. in prep.

Helium Surface Density ($\times 10^4$ cm^{-3})



Day of January 2012

Expected Limb Brightness Using Apollo 15 Dust Models



- Glenar et al., *NLSF*, 2011
- LAMP lunar horizon glow searches constrain dust abundances

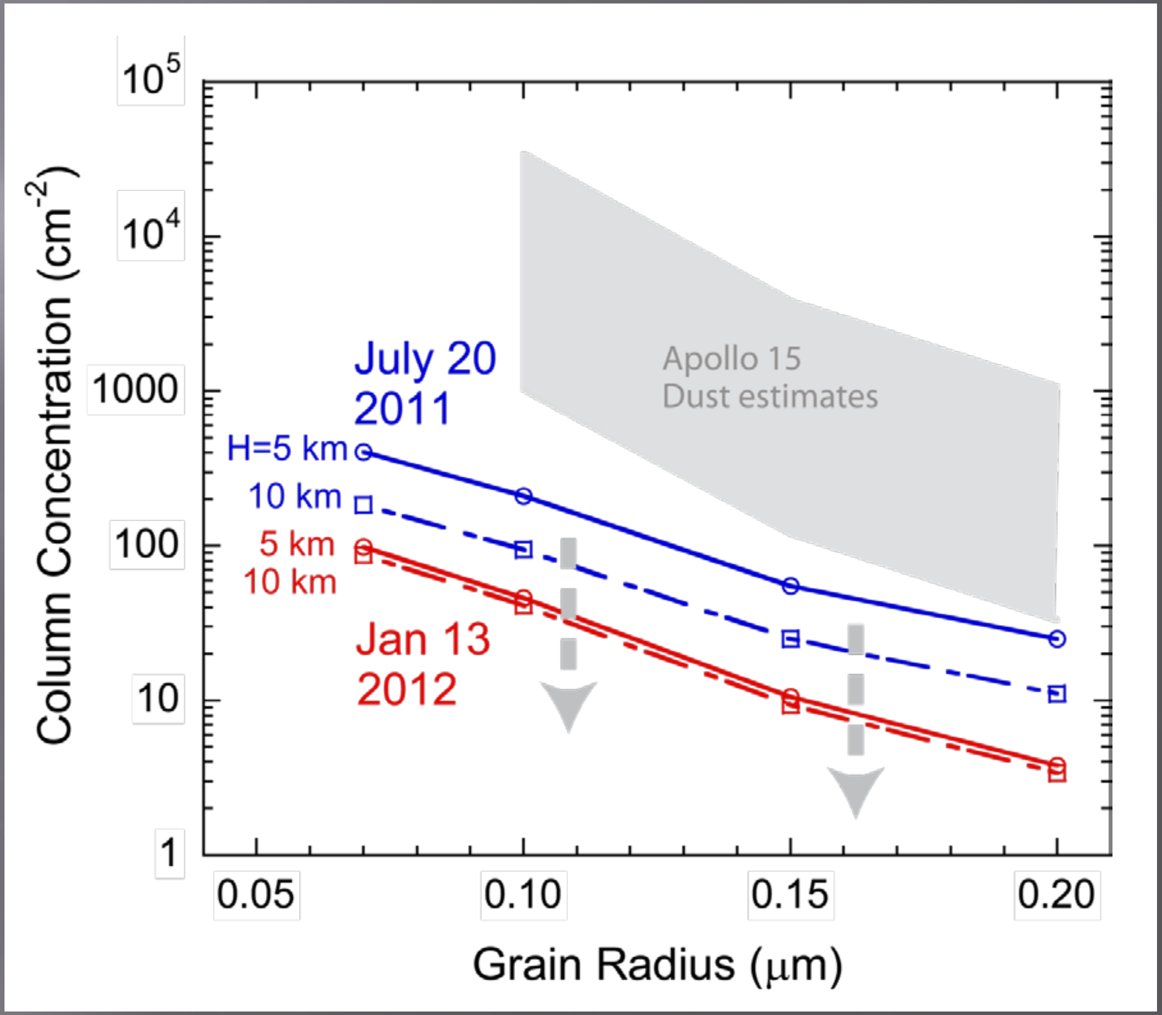
Exospheric Dust Upper Limits from Recent LAMP Measurements: July 20, 2011 and Jan 13, 2012

Assumptions:

- Consider 1D vertical dust models
- Mie scattering
- Apply LRO observing geometries, with 5 km tangent height
- Equate dust signal with LAMP noise-equivalent radiances:

  < 0.05 R Å^{-1}

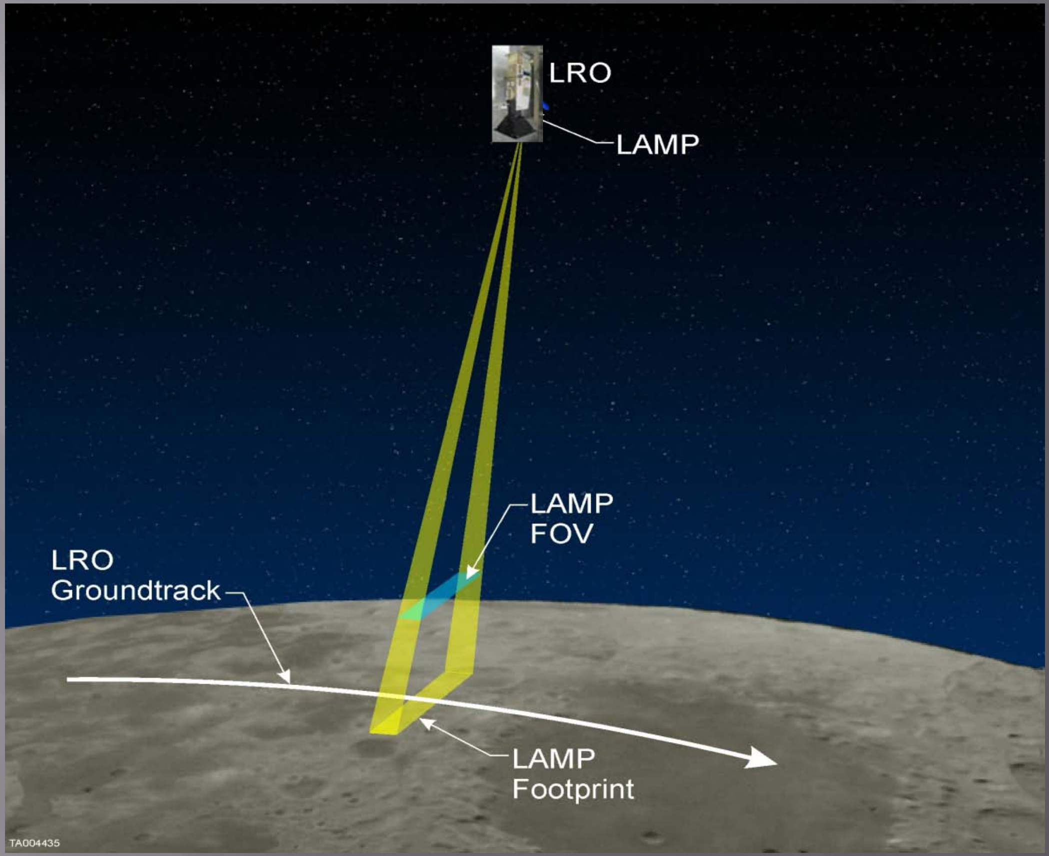
  < 0.08 R Å^{-1}



Exospheric Volatile Transport

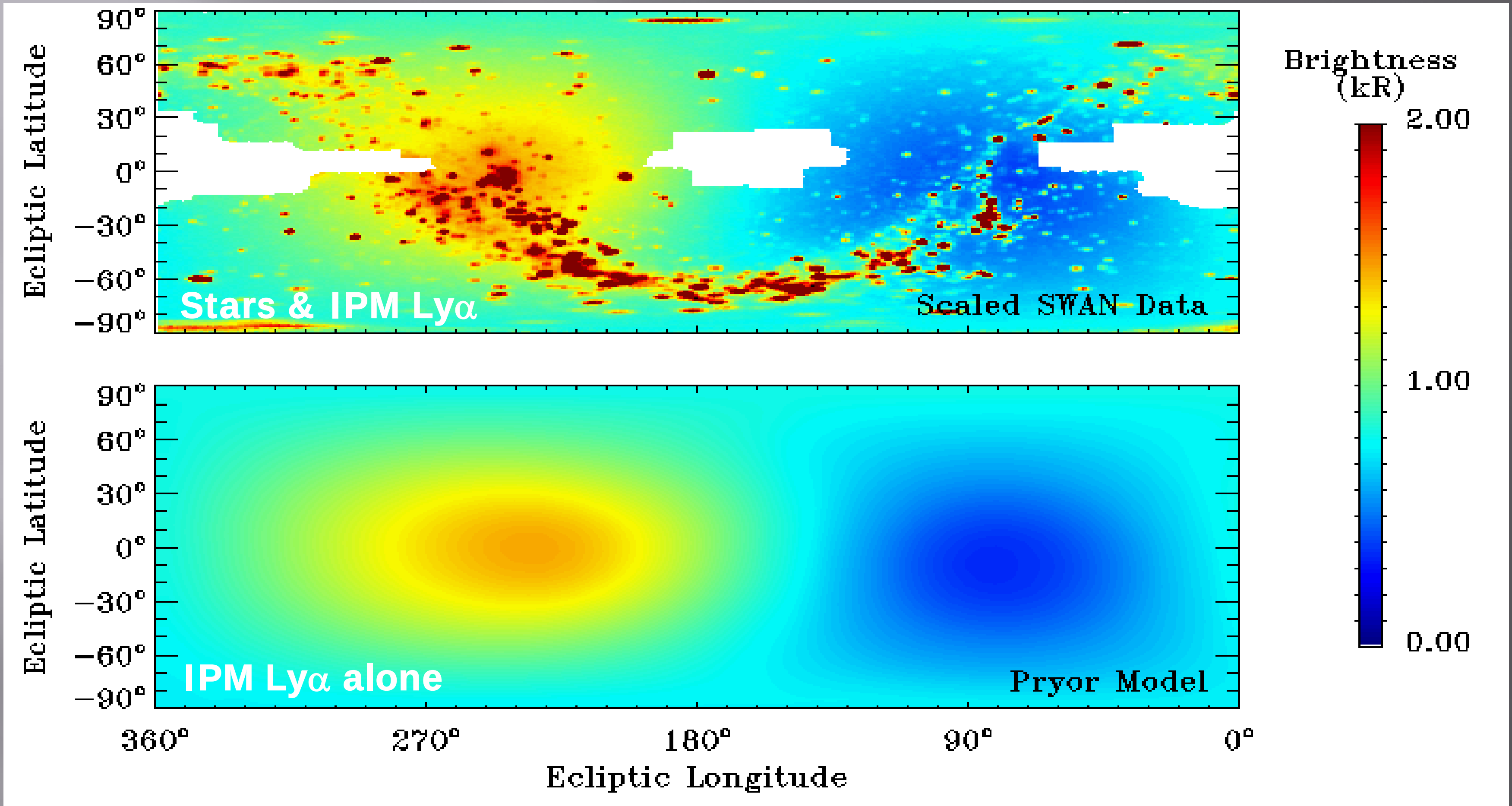
- LAMP is providing new upper limits for several gas species – the search continues
- Argon is a puzzle – LAMP should be sensitive to LACE measured densities, despite limited instrument sensitivity at 104.8 nm (more to come at DPS, AGU)
- H, H_2, H_2O gas constituents have diagnostic spectral features in the FUV
  - Neutral atomic H gas emissions would be faint (~0.5 R) and are difficult to separate from sky background Lyman-α (~500 R)
  - H_2 and H_2O gas are important lunar species, but are at low densities compared to relevant cross-sections for fluorescence or absorption – LAMP data is currently not constraining
  - Focus instead on FUV surface reflectance diagnostics for key water group volatiles

The LAMP Concept



- Use interplanetary medium (IPM) Lyα (along with UV starlight) as a source of illumination to look at the lunar nightside and permanently shadowed regions (PSRs)
- The IPM illumination is about the same both inside and outside of PSRs, so any observed differences must be due to chemistry (i.e., composition) or physics (i.e., soil structure)

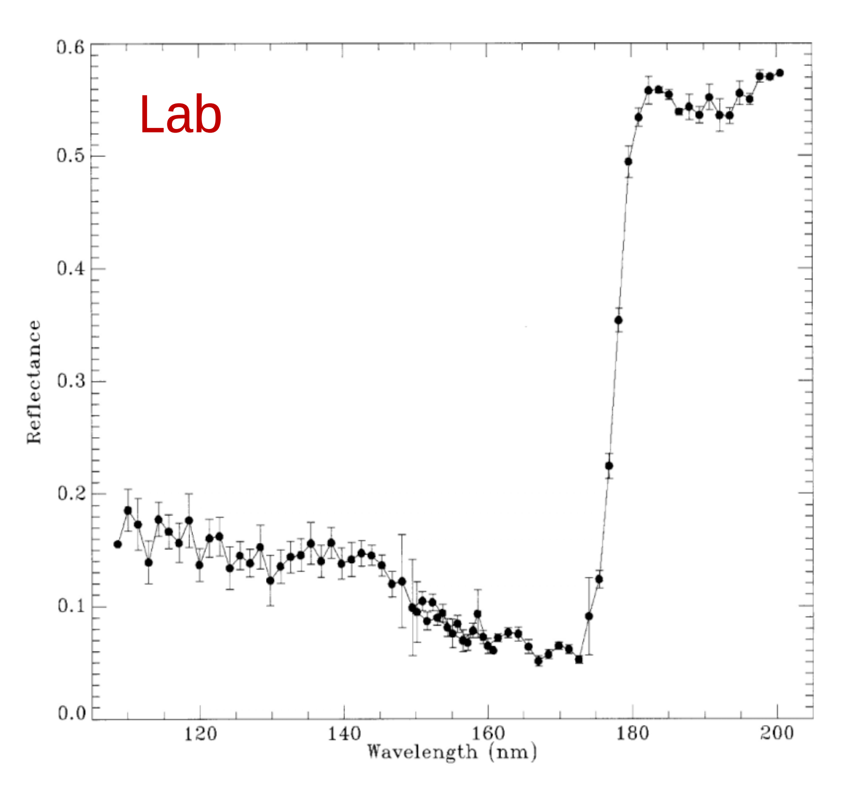
IPM Lyα Data & Model

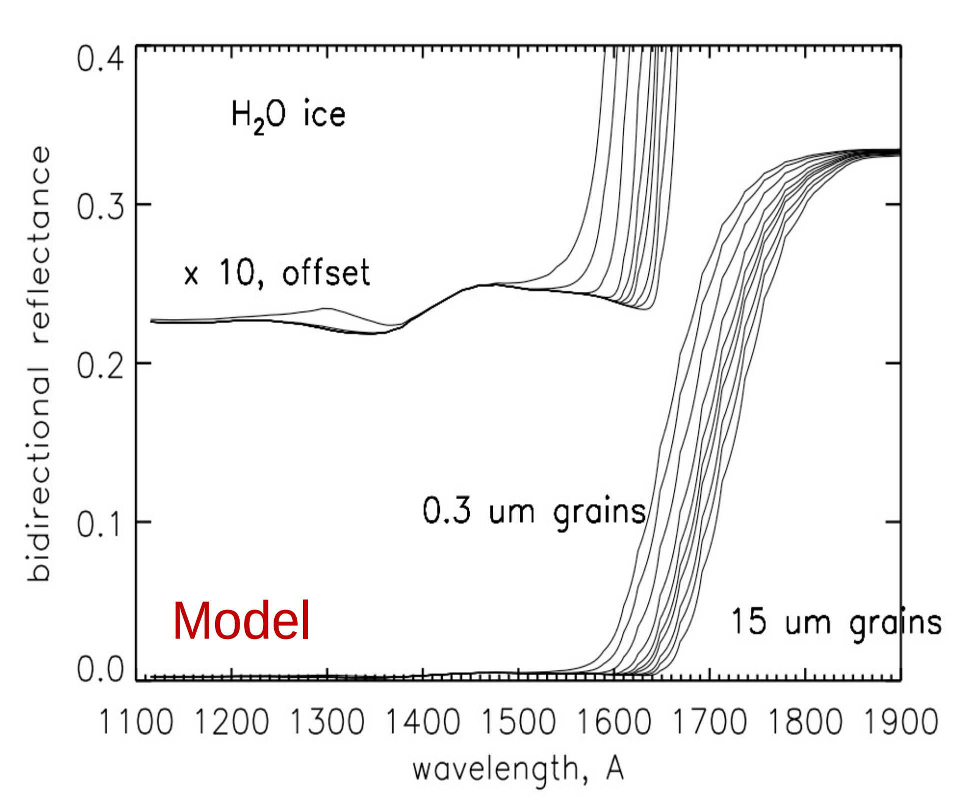


- At 121.6 nm, the night sky glows in Lyα light from H atoms passing through the solar system – the interplanetary medium (IPM)
- Compared to direct sunlight it would be like twilight on an overcast day
- Starlight is another (~20x fainter) illumination source we exploit

Water Ice Detection Technique

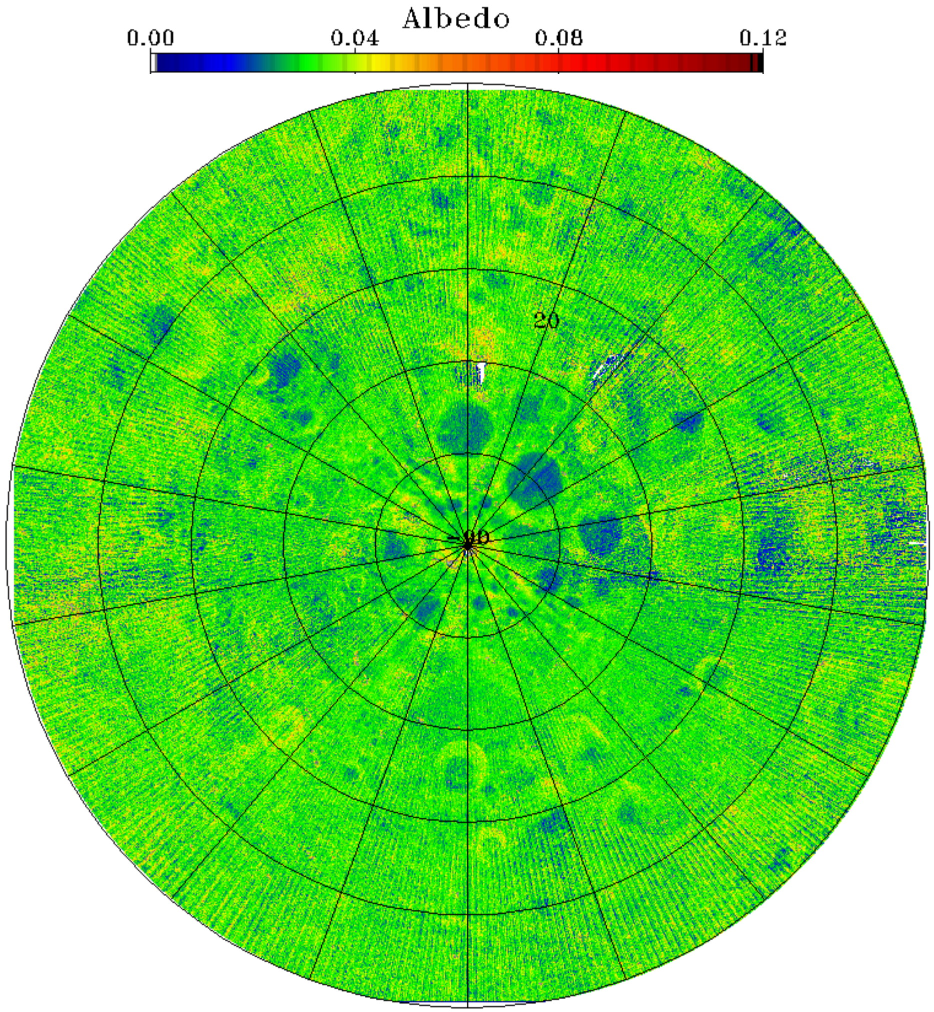
- Lab measured water frost reflectance shows a distinct broad UV absorption band or “cut off” in reflectivity at ~160-180 nm
- LAMP searches for this spectral signature of water ice in PSR albedo measurements covering 57-196 nm



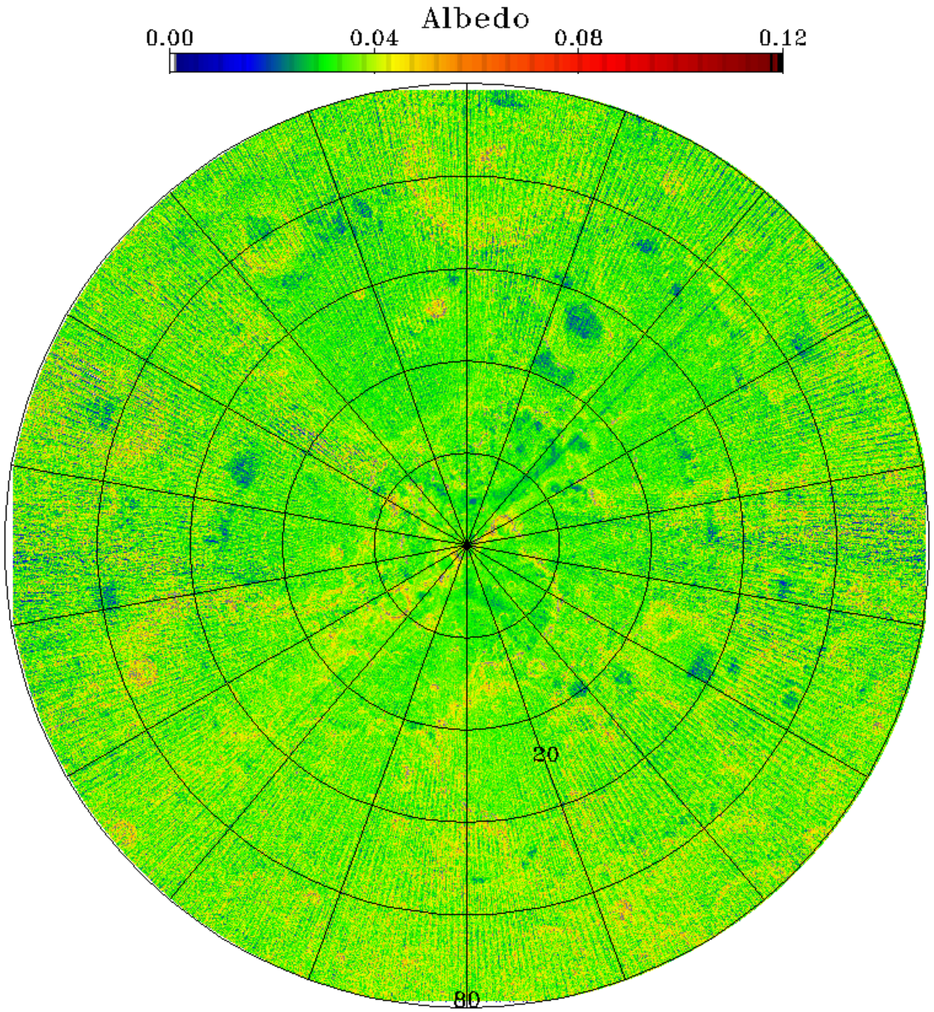


Cumulative Polar Nightside Lyman-α Albedo Maps

South Pole



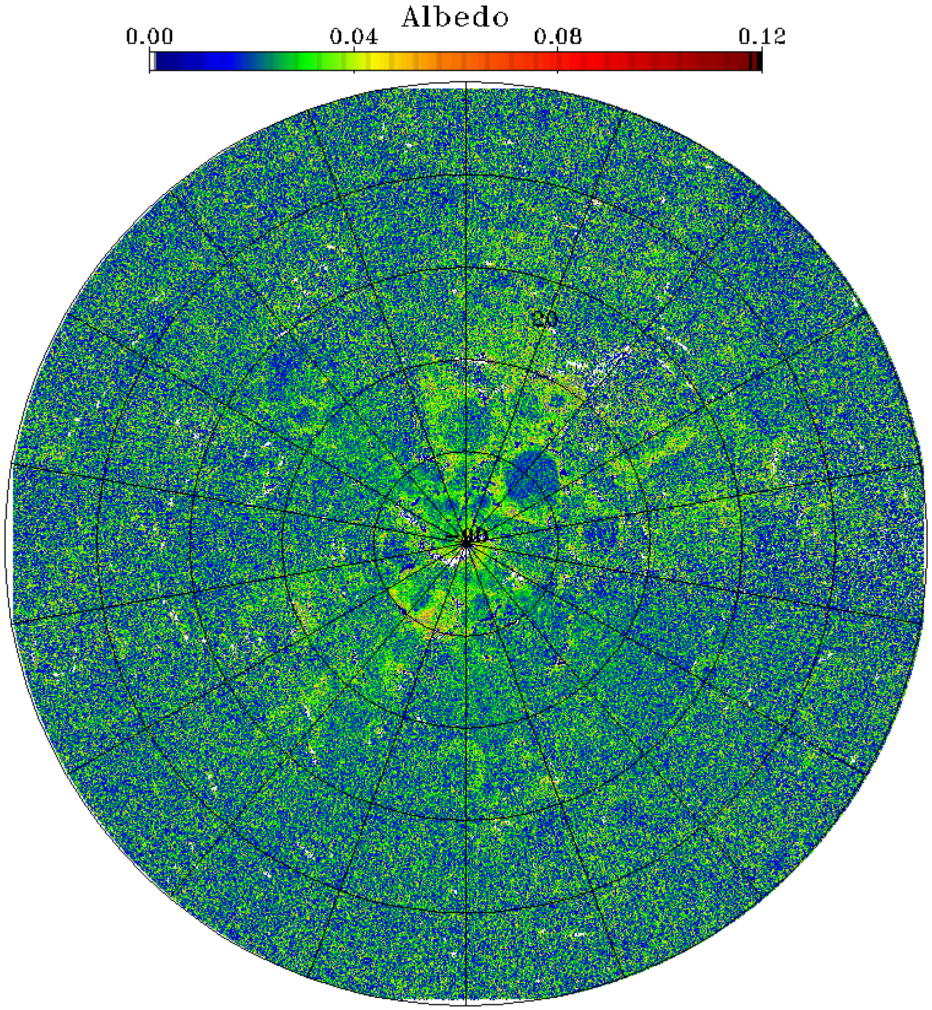
North Pole



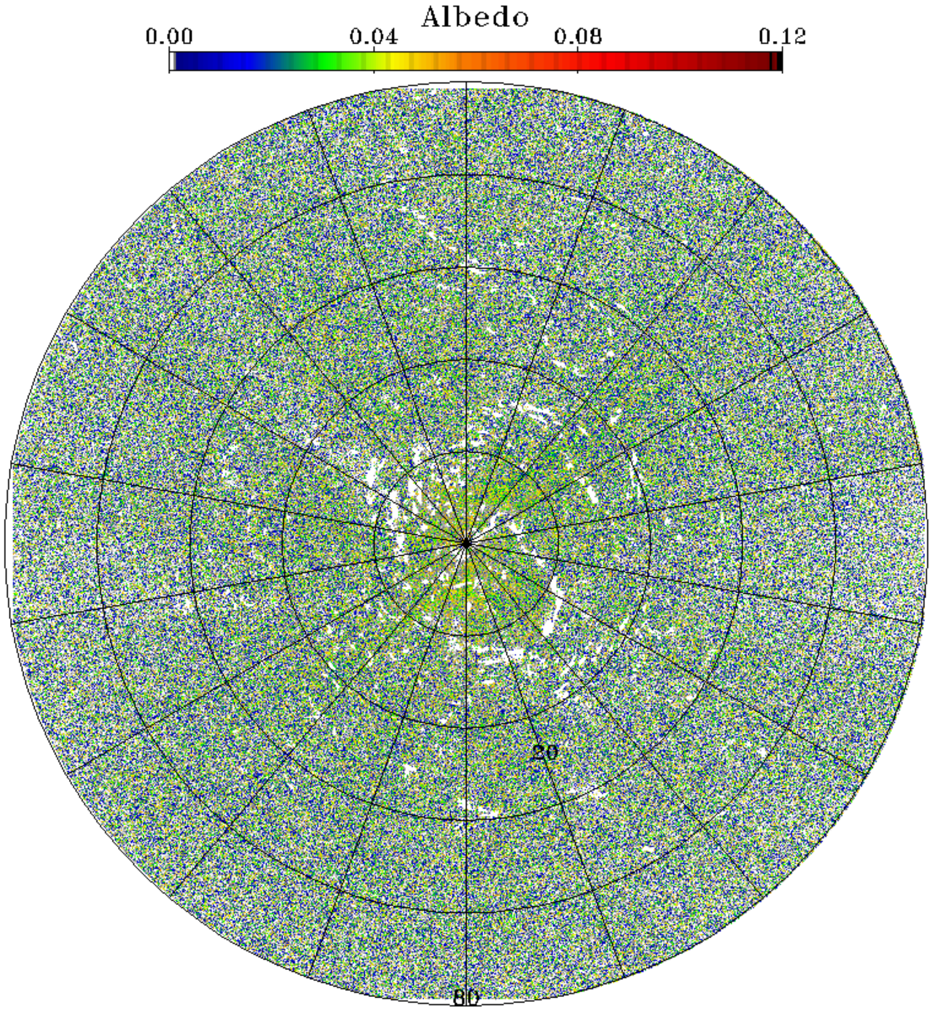
- PSRs have substantially darker FUV albedos than their surroundings

Cumulative Polar Nightside 130-190nm Albedo Maps

South Pole



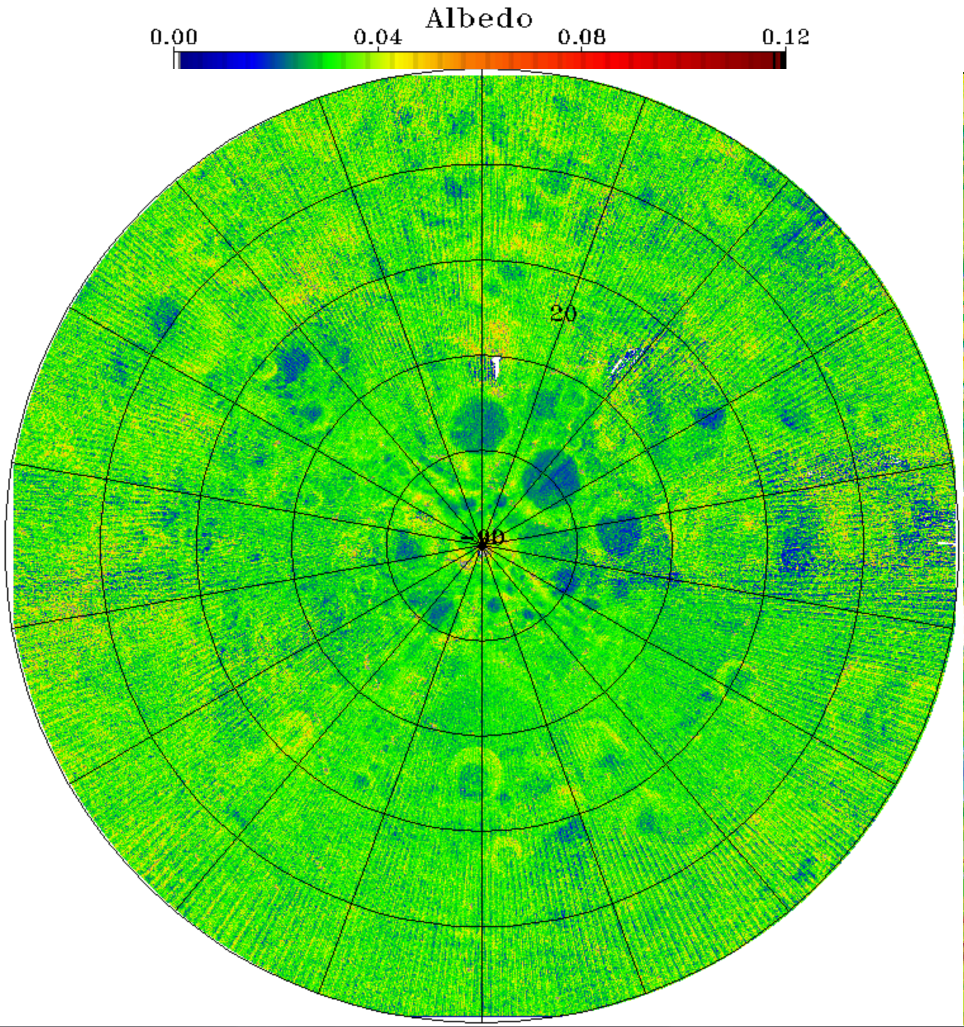
North Pole



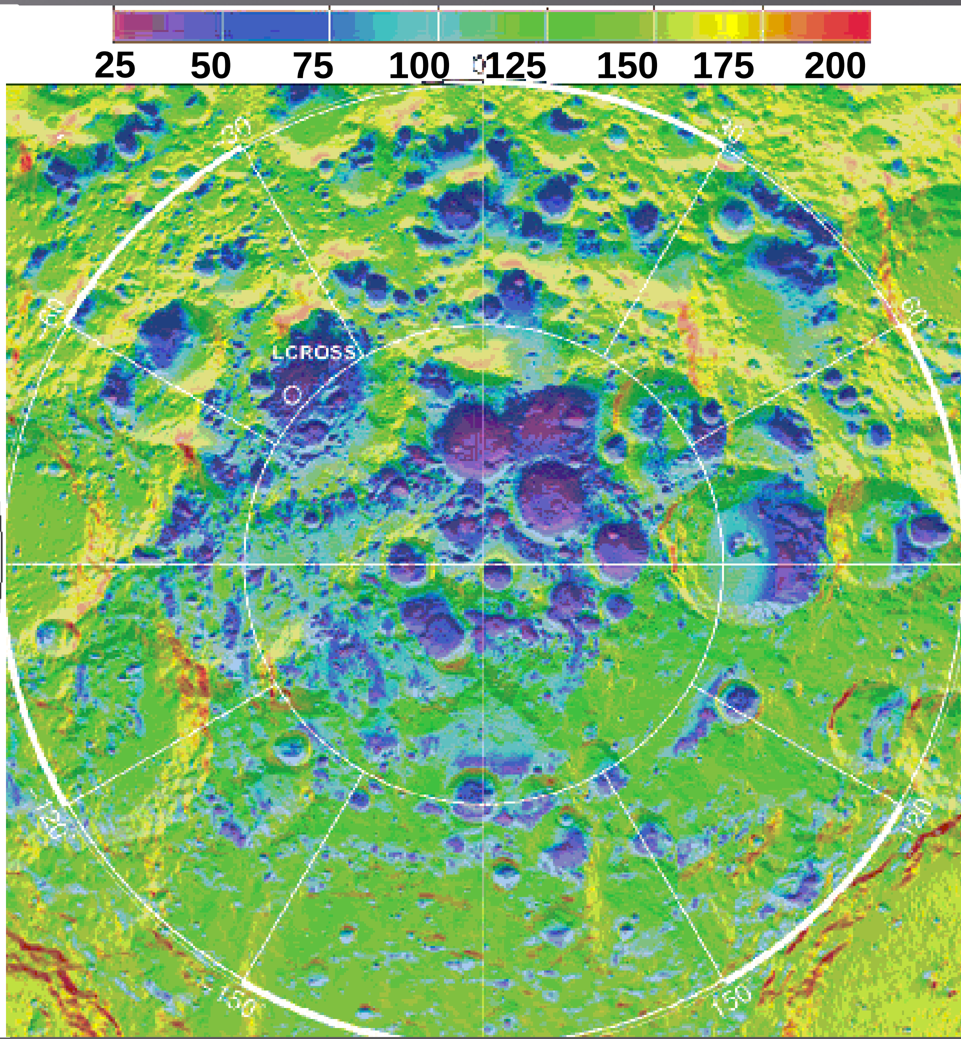
- Relatively noisy (starlight is a very faint source of illumination!)

LAMP Lyα Albedo vs. Diviner Temperature Model

LAMP South Pole



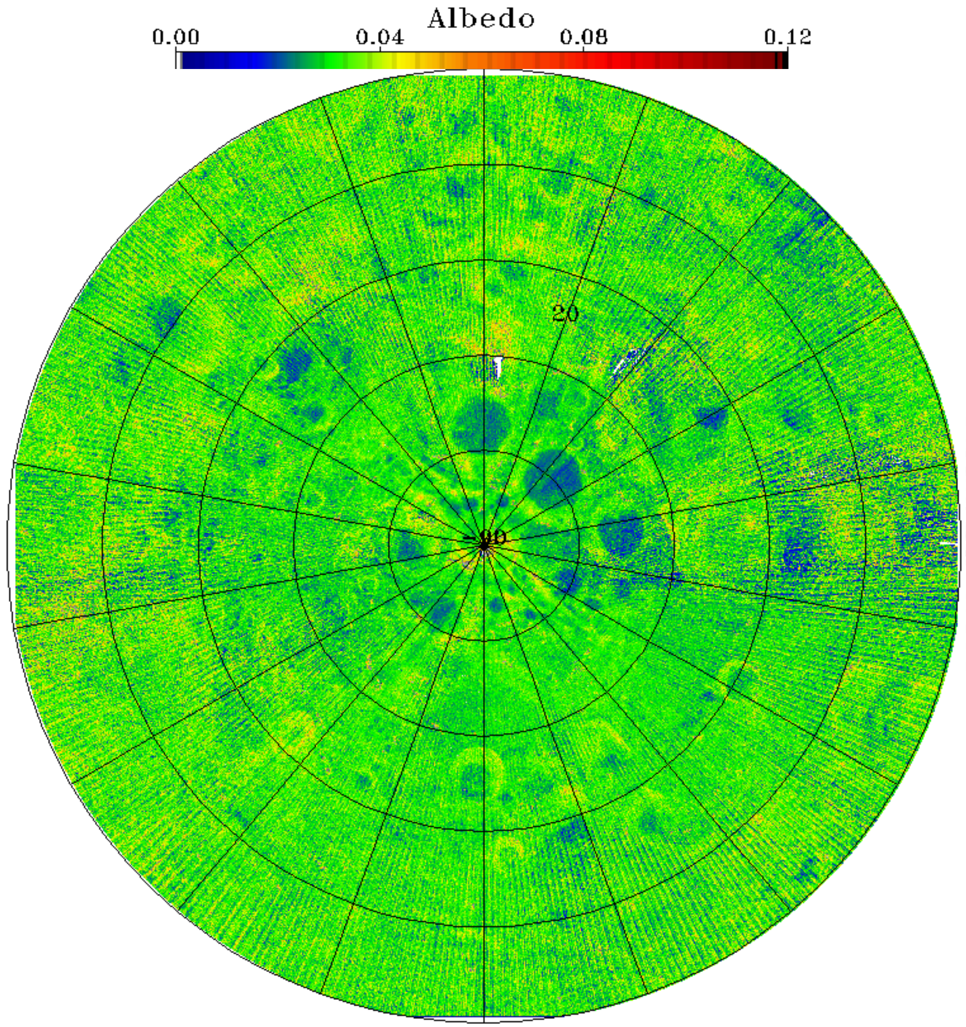
Diviner Model Annual Average T(K)



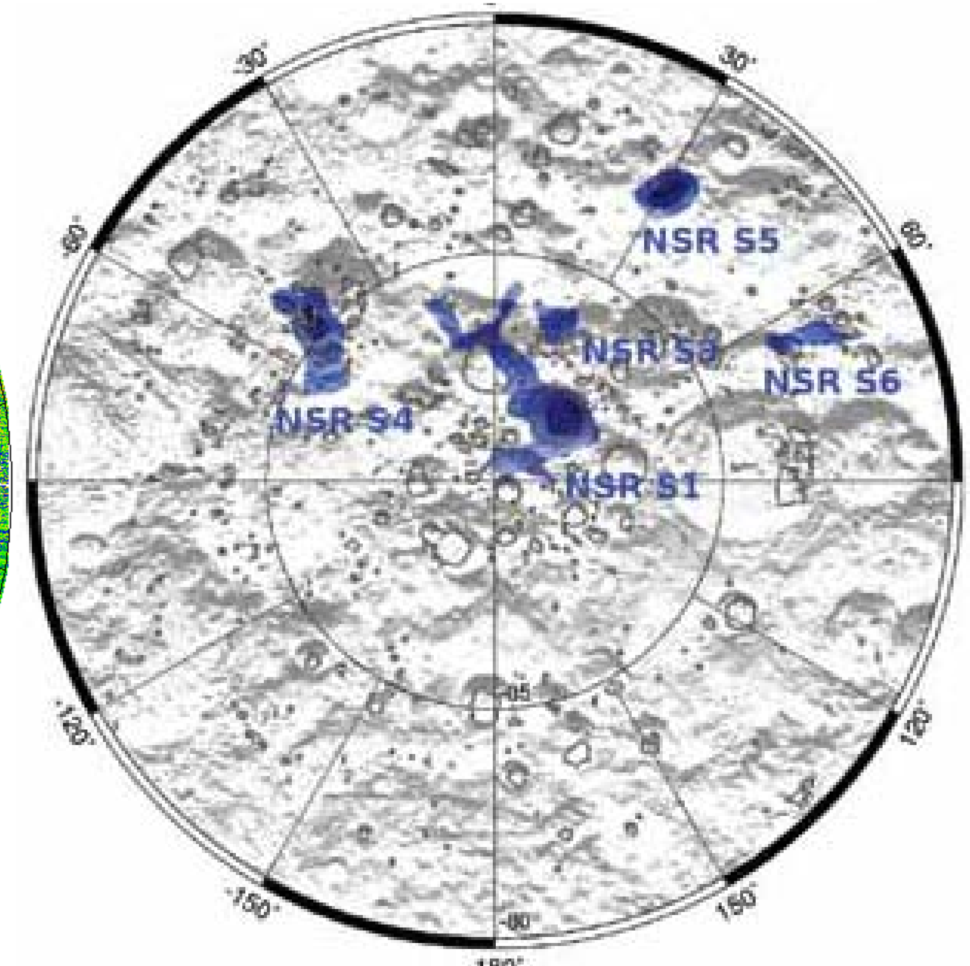
- Darker FUV albedos are well-correlated with colder temperatures

LAMP Lyα Albedo vs. LEND Epithermal Neutrons

LAMP South Pole

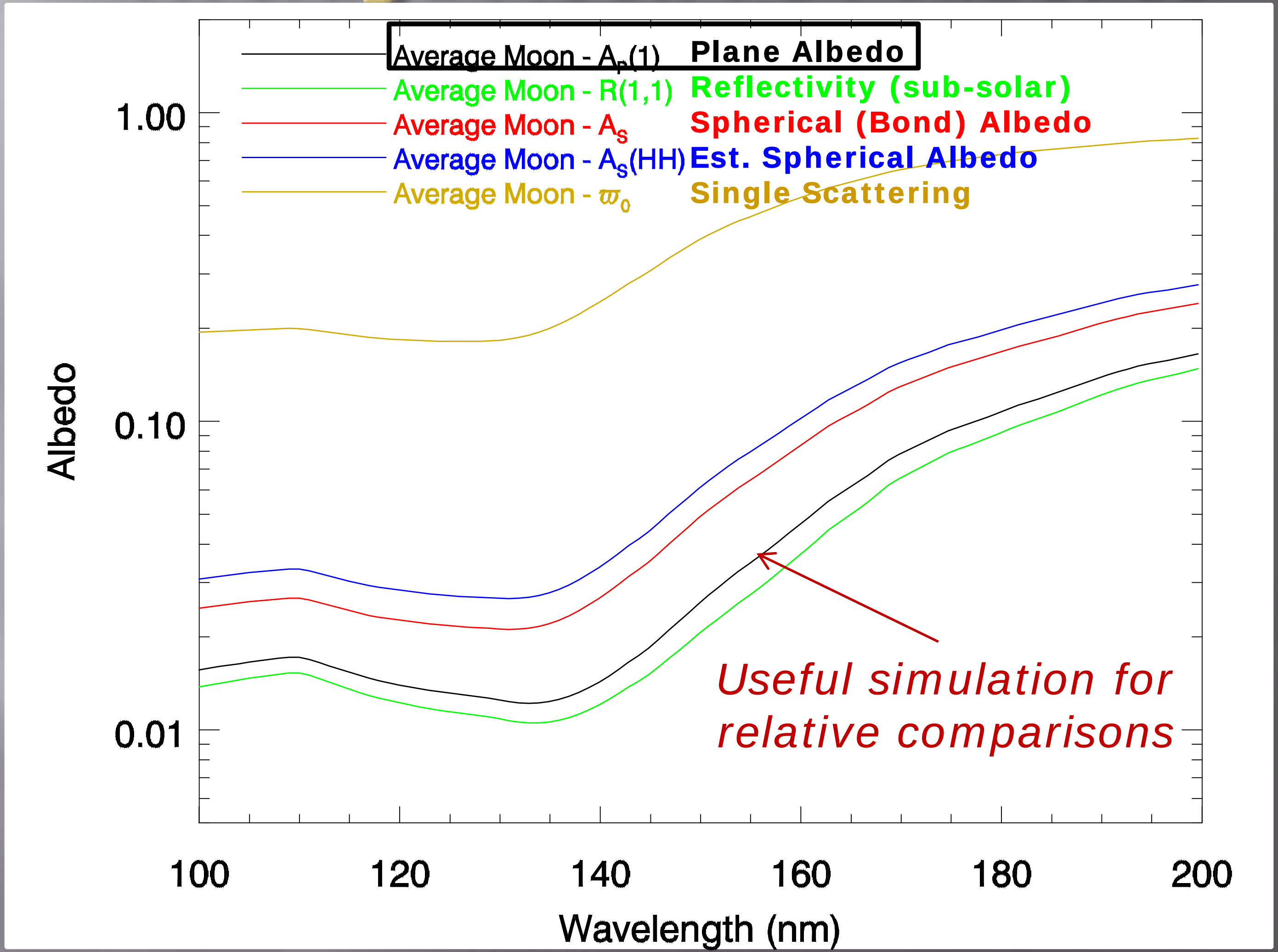


LEND South Pole Neutron Suppression



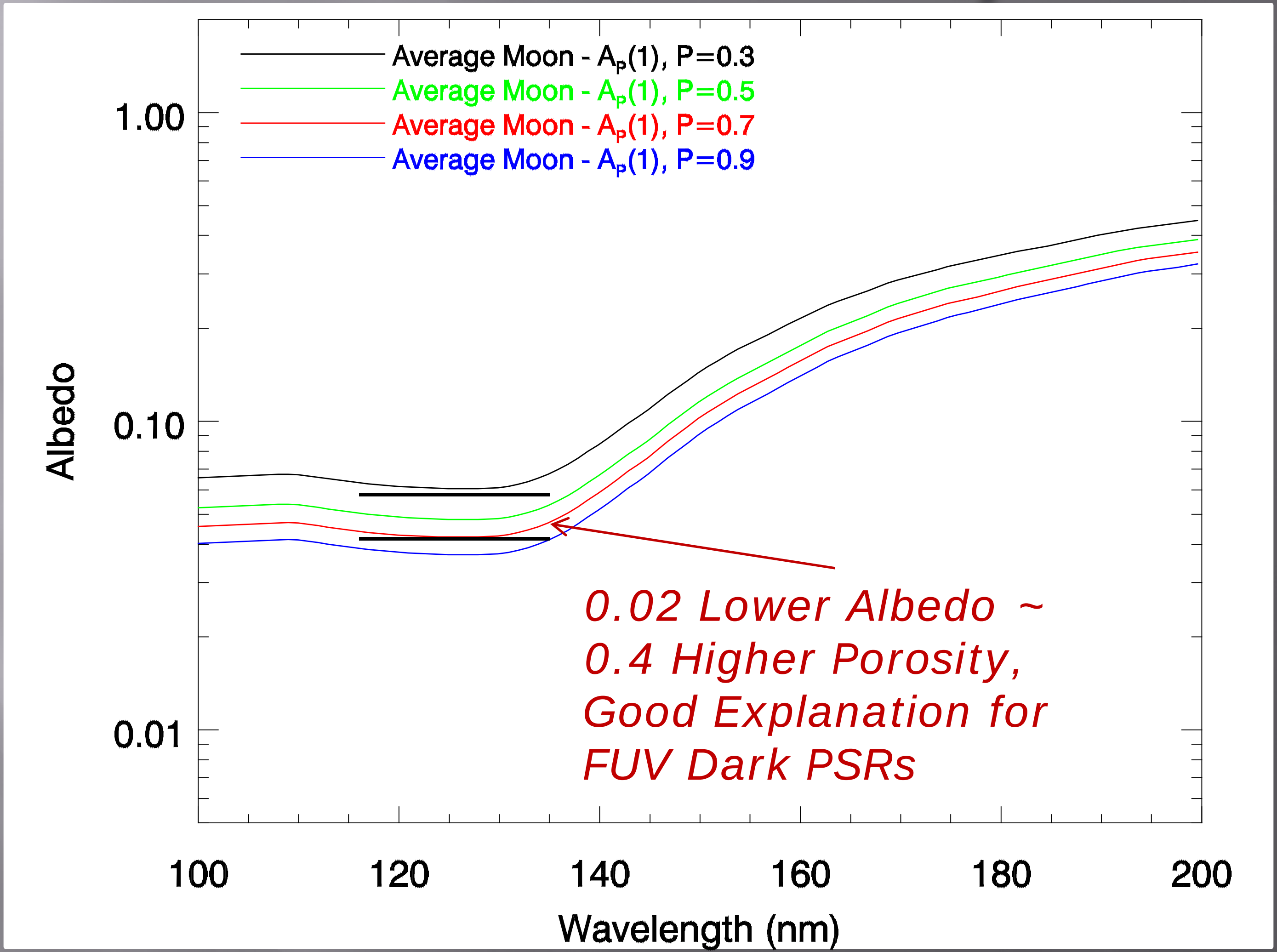
- FUV PSR albedos show some agreement with epithermal neutron suppression regions

Average Moon FUV Albedos



- Gladstone et al. 2012 calculated using the Shkuratov et al. (1999) average Moon optical constants and the Mishchenko et al. (1999) radiative transfer code
- Same particle size distribution as used by Goguen et al. 2011 to fit visible lunar photometry

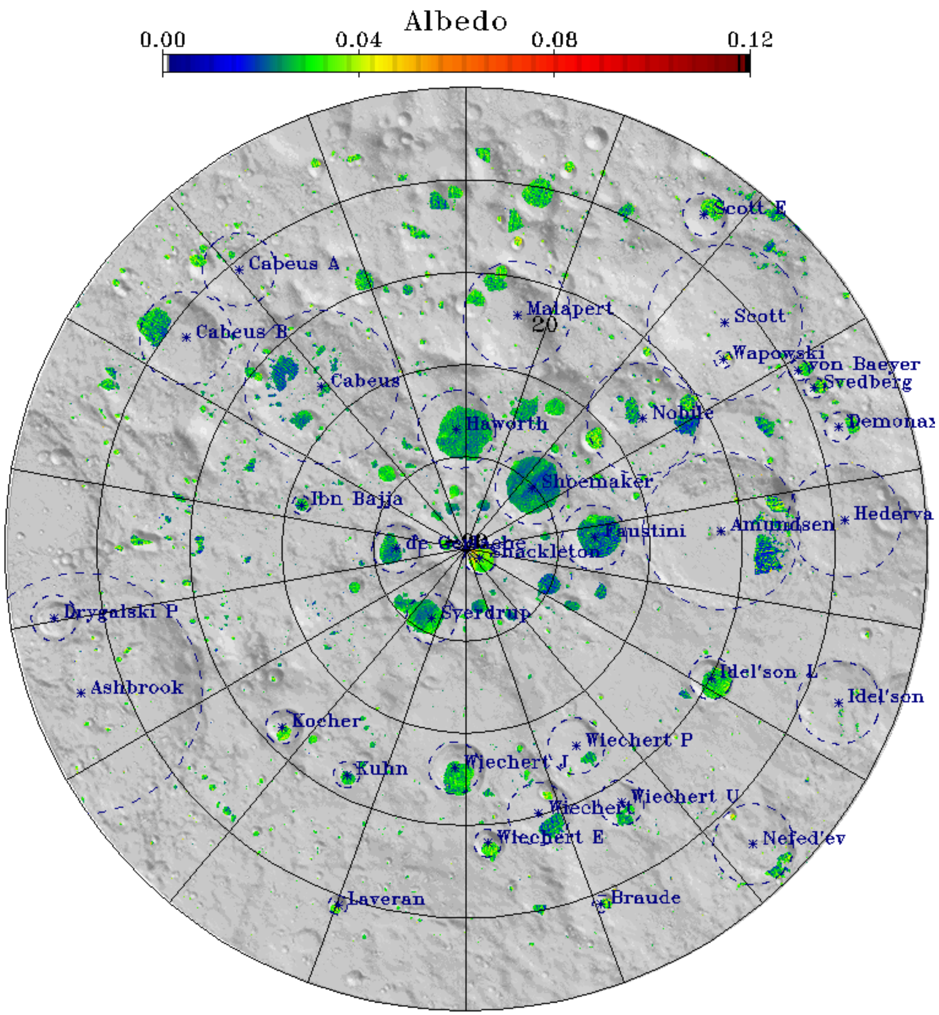
Effect of Porosity



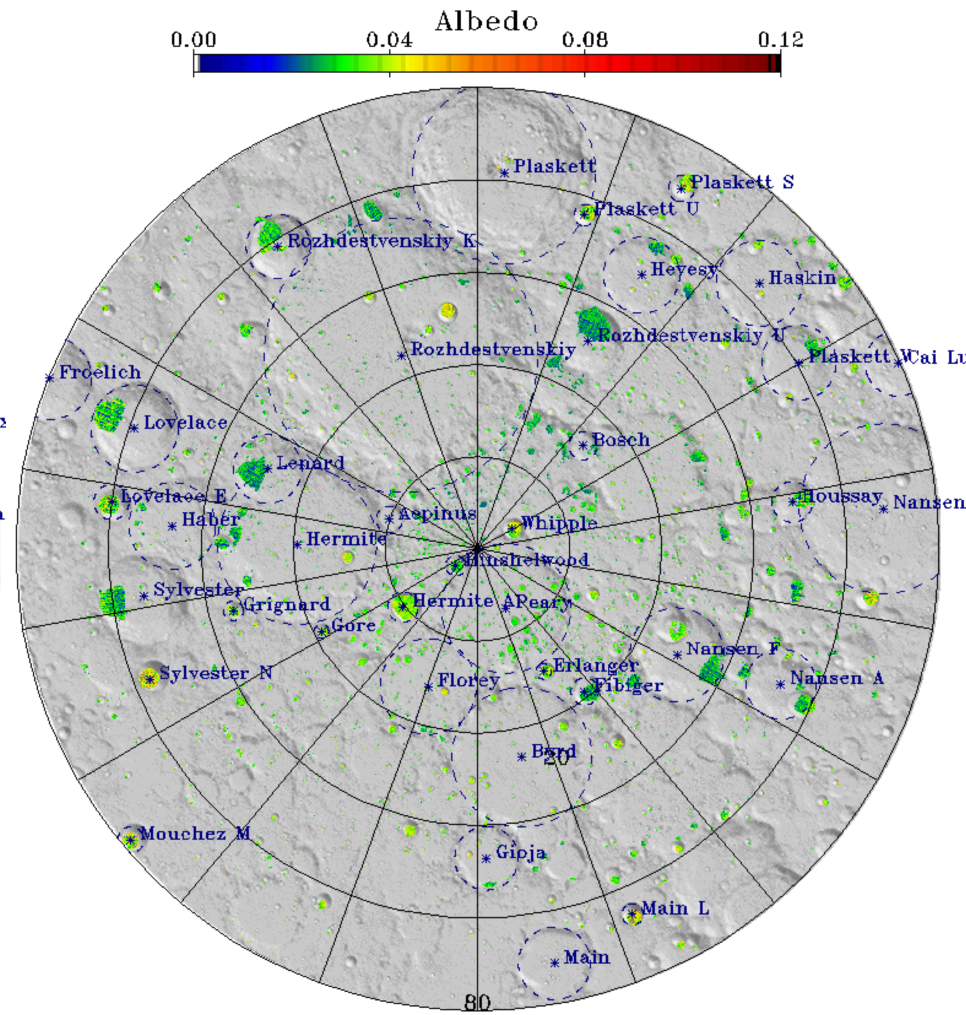
- Gladstone et al. 2012 calculated using the Shkuratov et al. (1999) average Moon optical constants and the Hapke (2008) approximation
- Same particle size distribution as used by Goguen et al. 2011 to fit visible lunar photometry

PSR-only Lyα Albedo Maps

South Pole

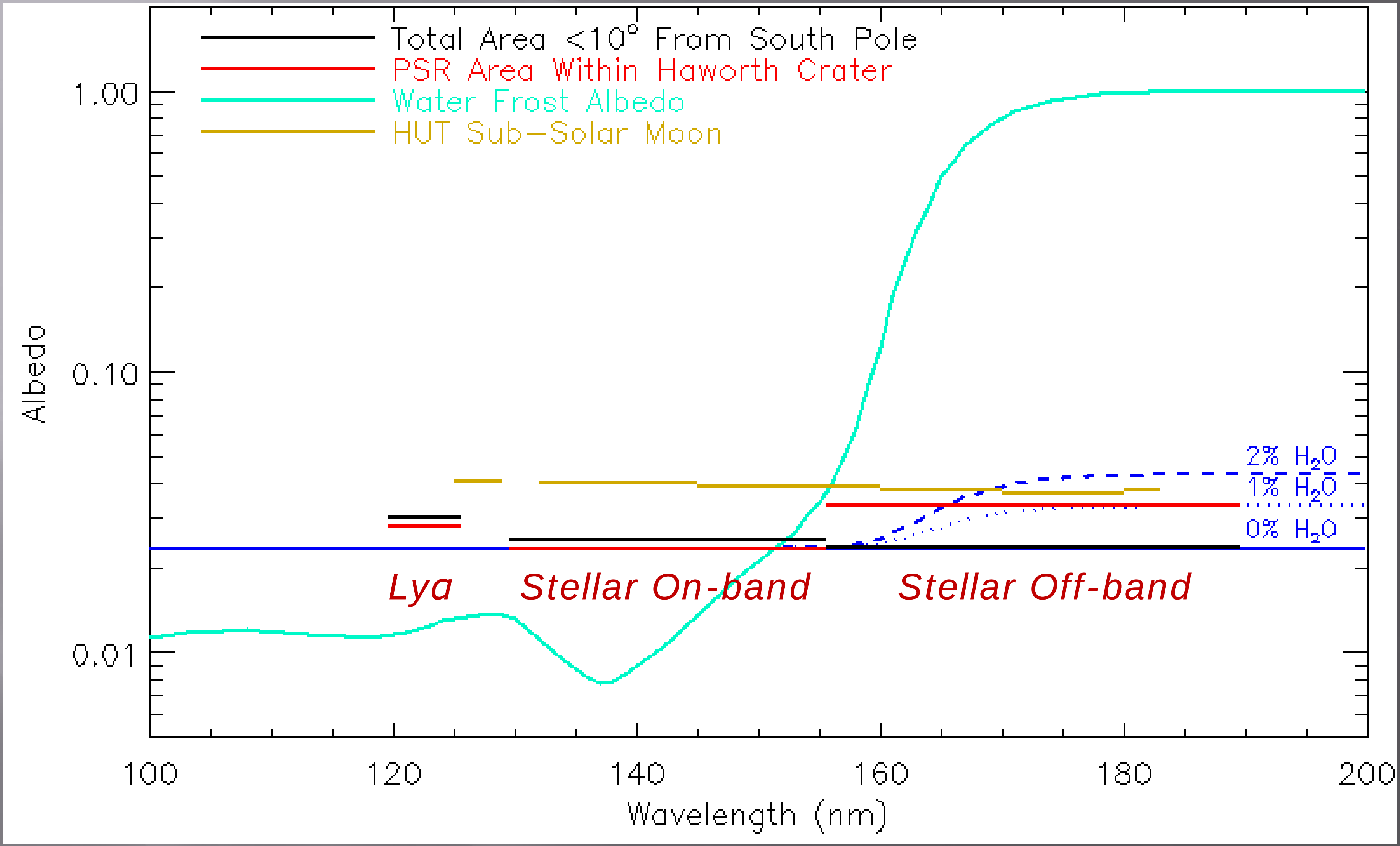


North Pole



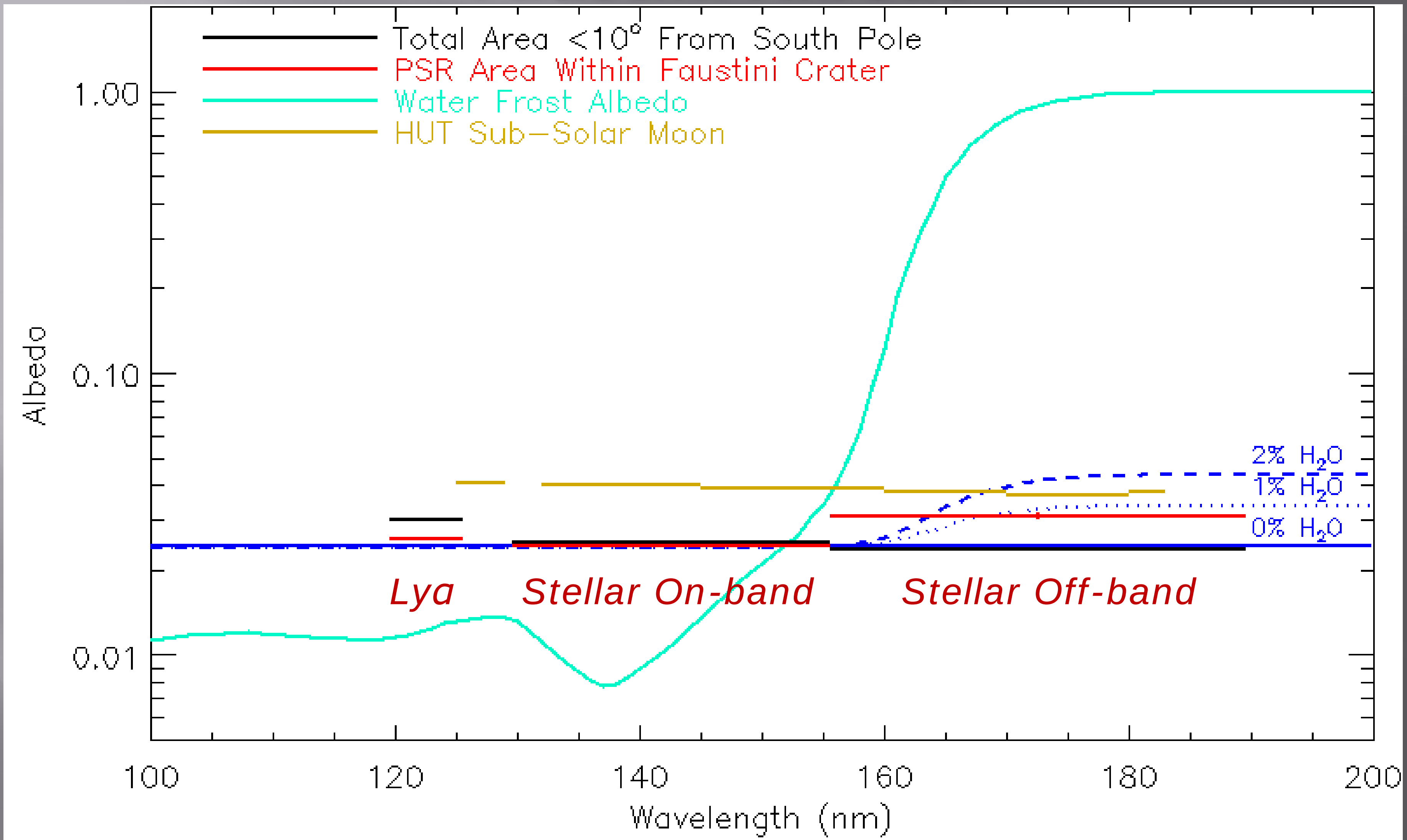
• PSRs are not all the same! (e.g., Shackleton is relatively bright)

Haworth Albedo



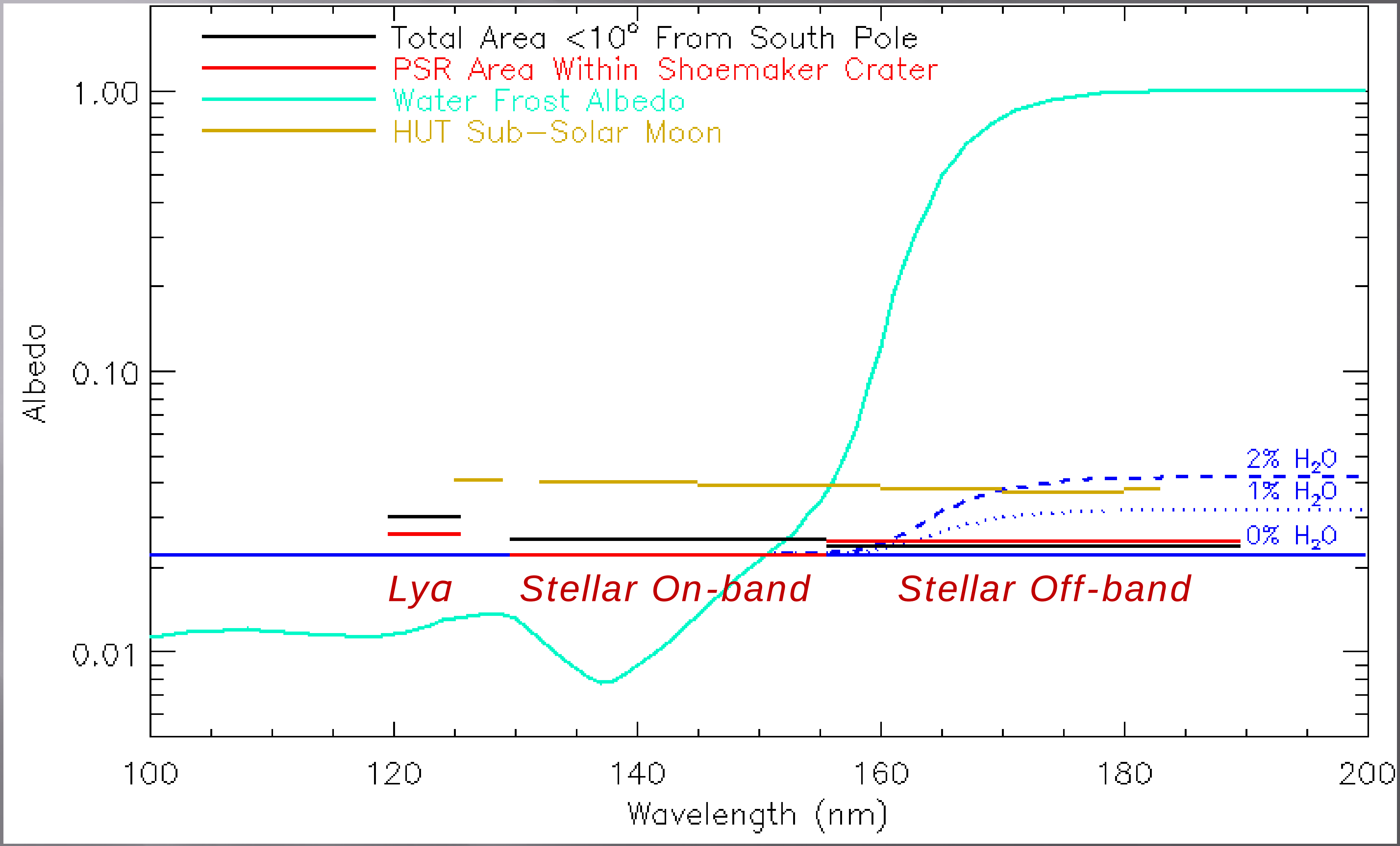
- PSR Lyα albedo generally lower than surroundings ⇒ higher porosity
- Substantial increase in PSR albedo at longer wavelengths is consistent with presence of volatiles. But is it H_2O? Possibly ~1% surface frost

Faustini Albedo



• Similar results for Faustini; lower Lyα albedo consistent with "fluffy" PSRs (P~0.7), higher albedo at longer FUV wavelengths consistent with ~1% surface frost

Shoemaker Albedo

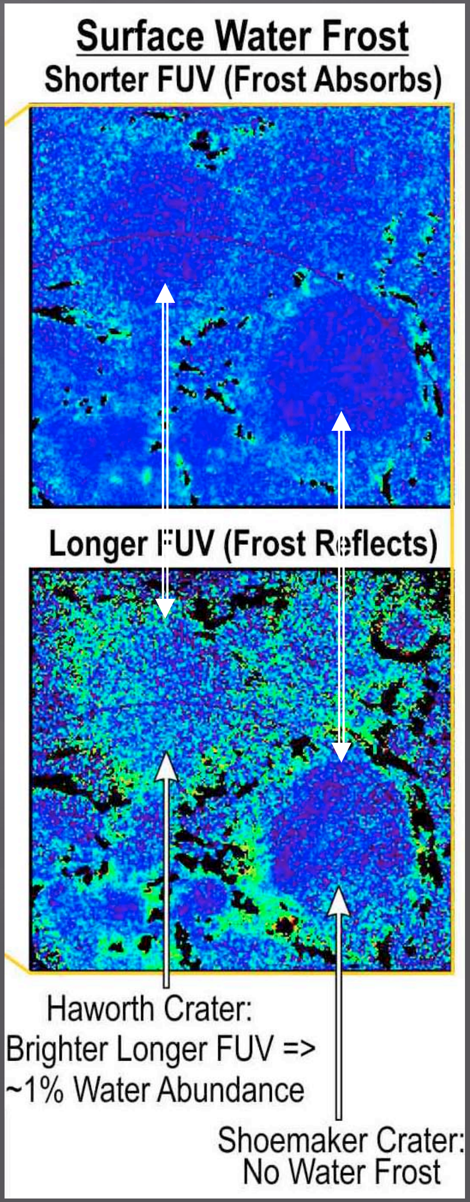


- In contrast, Shoemaker, although fluffy (i.e., low Lyα albedo), shows no large albedo increase at longer FUV wavelengths ⇒ no surface frost (at most ~0.3%, challenging to reconcile with LEND neutron result)

LRO/LAMP Evidence of Surface Water Frost in Lunar Polar Craters

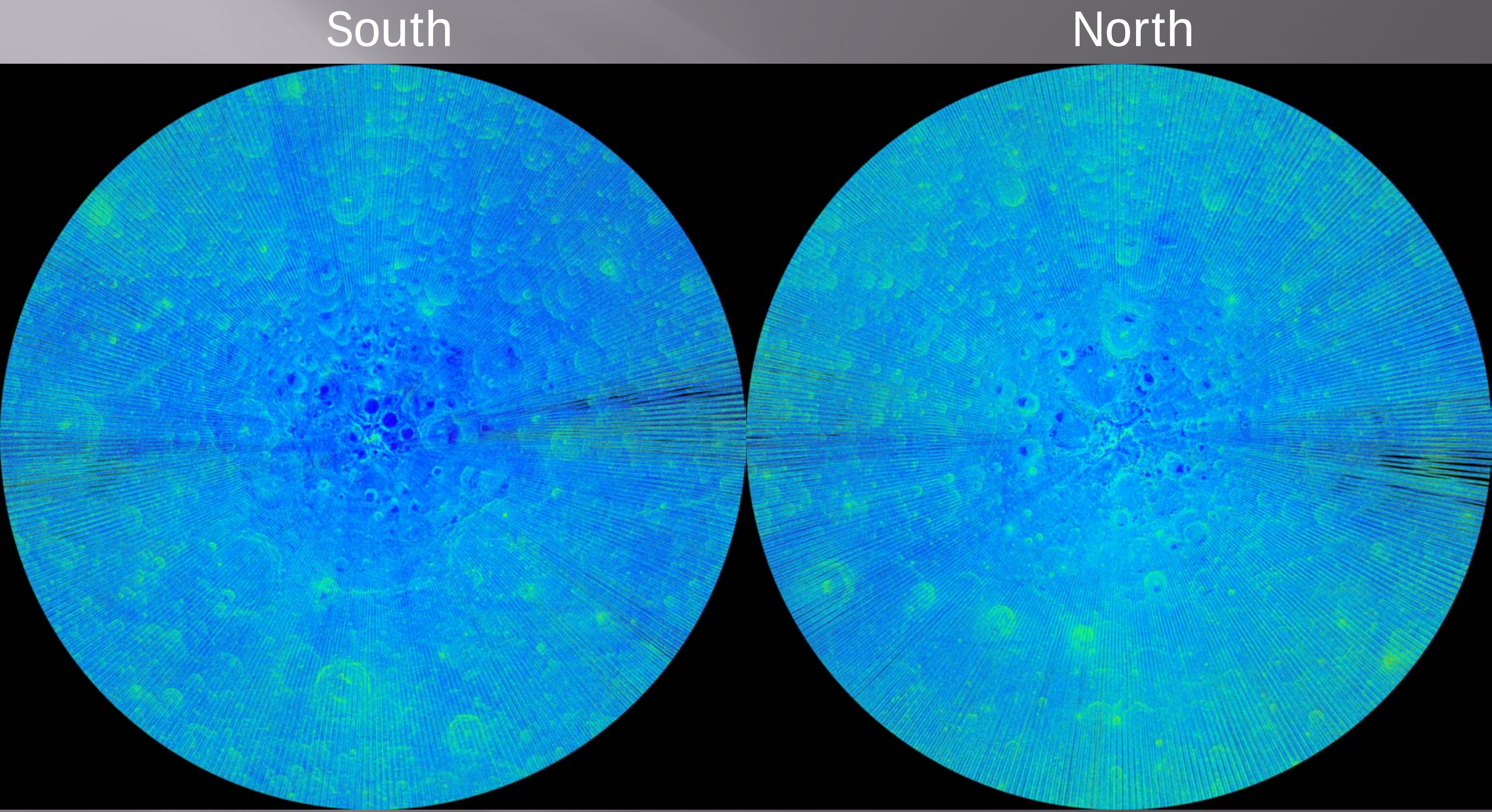
LAMP's nightside Lyman-α maps show lower albedos (dark blue), consistent with higher porosity surfaces.

Comparisons of star-illuminated surfaces at FUV wavelengths with a diagnostic water spectral signature (shortward and longward of 160 nm) indicate that PSRs such as Haworth crater (inset) are best explained by 1-2% abundances of water frost right at the surface.



LAMP provides the first indications of surface water frost in permanently shadowed polar craters

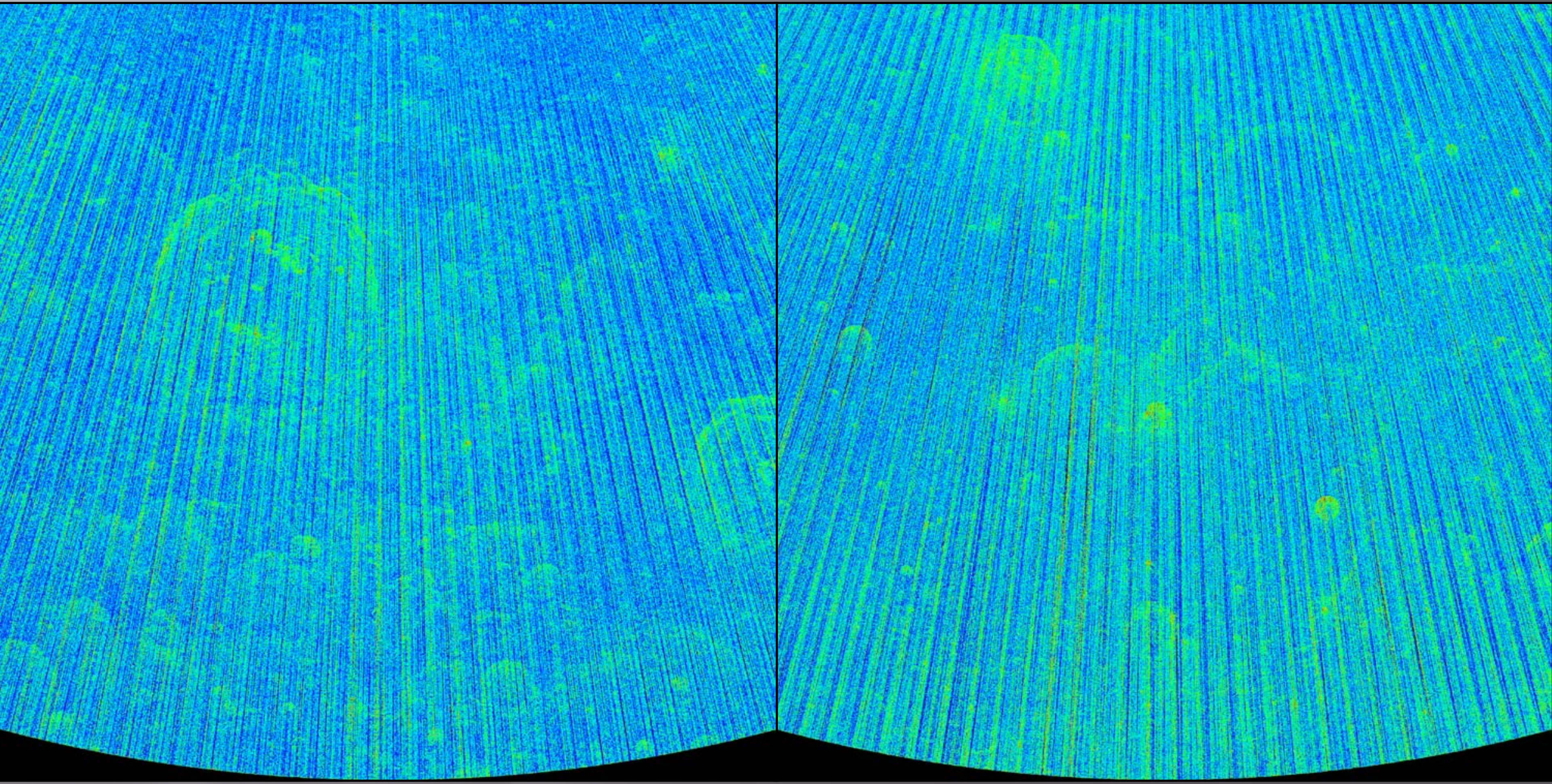
Lyman-alpha Albedos >60° Lat.



- Lyman-α nightside albedo maps of the poles at ~240 m × 240 m per pixel

Many Interesting FUV Features

South North



No sunlit features are found to have albedos as low as the PSRs

See also Hendrix talk Thurs.

Summary

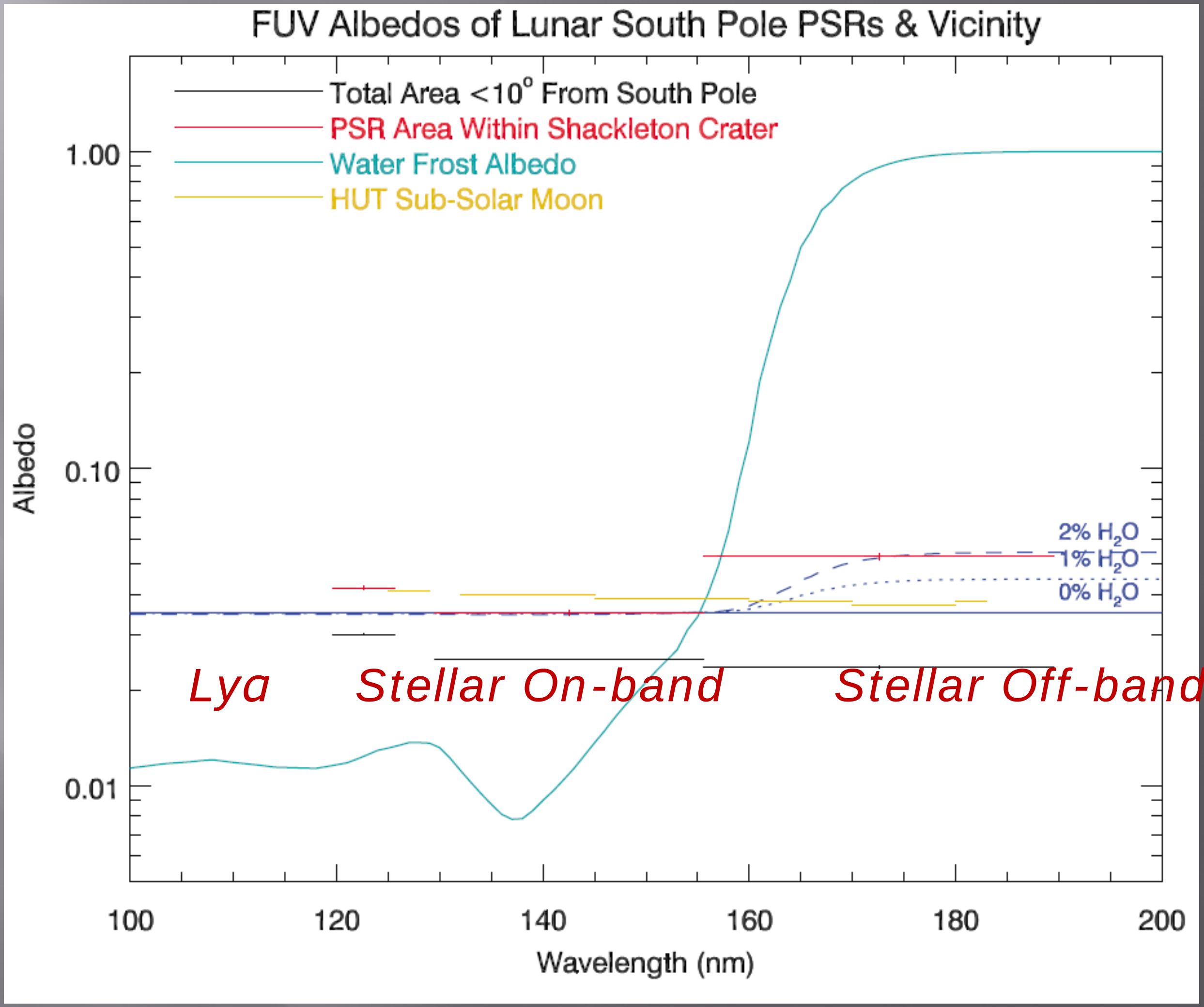
- LAMP is mapping out and searching for exposed water ice in permanently shadowed regions at the poles
- LAMP uses a spectral "fingerprint" for water ice that can identify exposed water ice on the surface
- LAMP-observed low Lyα albedos suggests high porosity or "fluffiness" (P~0.7) in most permanently shadowed regions (PSRs)
- LAMP-observed reddening at longer FUV wavelengths suggests 1-2% surface water frost in several PSRs
- LAMP detected a response to the LCROSS impact that we've identified as H_2 and CO molecular fluorescence emission and resonantly scattered Hg, Mg, and Ca neutral atom emission
- LAMP remotely senses the global helium exosphere and its variability
- LAMP continues to study how water and other volatiles are formed and are transported through the lunar atmosphere

LRO Extended Mission Plans – LAMP Volatiles Objectives

- LRO/LAMP plans to capitalize and expand upon these recent discoveries in the Extended Science Mission proposed through Sept. 2014.
- Need more FUV data at a variety of incident and emission angles to improve signal, spectral, and photometric quality and further develop LAMP's innovative nightside observing technique.
- Target UV-interesting regions and focus on key PSRs identified by LRO/LEND, and Mini-RF as potentially water rich.
- Global searches of FUV water signatures will continue *outside of PSRs*, following Hendrix et al., *submitted to JGR*, 2012 – a compliment to infrared water/hydroxyl measurements.

Backup

Shackleton Albedo



- Shackleton shows similar results as for Haworth and Faustini; lower Lyα albedo consistent with “fluffy” PSRs (P~0.7), higher albedo at longer FUV wavelengths consistent with ~2% surface frost