SOUTH POLE HYDROGEN DISTRIBUTION FOR PRESENT LUNAR CONDITIONS: IMPLICATIONS FOR PAST IMPACTS. R. C. Elphic[1], D. A. Paige[2], M. A. Siegler[2], A. R. Vasavada[3], V. R. Eke[4], L. F. A. Teodoro[5], and D. J. Lawrence[6], [1]Planetary Systems Branch, NASA Ames Research Center, MS 245-3, Moffett Field, CA, 94035-1000, [2]Earth and Space Sciences Dept, University of California, Los Angeles, CA 90024, [3]Jet Propulsion Laboratory, Pasadena, CA, USA. [4]Institute for Computational Cosmology, Physics Department, Durham University, Science Laboratories, South Road, Durham DH1 3LE, UK, [5]ELORET Corp., Planetary Systems Branch, Space Sciences and Astrobiology Division, MS 245-3, NASA Ames Research Center, Moffett Field, CA 94035-1000, [6]Johns Hopkins University Applied Physics Laboratory, MP3-E104, 11100 Johns Hopkins Road, Laurel, MD 20723.

Introduction: It has been known since the Lunar Prospector mission that the poles of the Moon evidently harbor enhanced concentrations of hydrogen [1,2]. The physical and chemical form of the hydrogen has been much debated. Using imagery from Clementine it was possible to roughly estimate permanently-shadowed regions (PSRs), and to perform image reconstructions of the Lunar Prospector epithermal neutron flux maps [3,4]. The hydrogen concentrations resulting from these reconstructions were consistent with a few weight percent water ice in selected locations.

With the LCROSS impact, we now know that hydrogen in the form of ice does exist in lunar polar cold traps [5]. Armed with this information, and new data from LRO/Diviner, we can examine whether the present-day distribution of hydrogen in the form of water ice is consistent with a past large impact that delivered a large mass of volatiles to the lunar surface. These volatiles, mixed with solid impact ejecta, would then be lost from locations having high mean temperatures but would otherwise remain trapped in locations with sufficiently low mean annual temperatures [6]. The time scales for loss would depend on the location-dependent temperatures as well as impact history.

New Measurements: New results from Chandrayaan and NASA's Lunar Reconnaissance Orbiter are clarifying our picture of conditions at the lunar poles. Data from the Diviner Lunar Radiometer Experiment indicate extensive areas of very low temperatures (<100K) in the south polar region, and these areas are not limited to locations of strictly permanent shadow [7]. Such cold terrain has subsurface temperatures low enough to keep shallow buried ice stable for 1 Ga or longer [7]. Moreover, Chandrayaan M^3 spectral reflectance observations [8] have suggested the possible presence of H_2O and OH at mid-latitudes. Both of these results indicate that the confinement of potentially high hydrogen concentrations to permanent shadow is overly restrictive. The Lunar Prospector epithermal data can now be used to fit a model that includes these three possible hydrogen repositories.

Modeling: Figure 1 shows a model for the mean annual regolith temperature at 75 cm depth (T_{75}). Permanently-shadowed regions comprise a subset of the more areally extensive terrains that have annualized subsurface temperatures low enough to permit stable water ice. For that reason, reconstructions are likely to have lower average hydrogen abundance than in the PSR-only reconstructions. In effect, the same amount
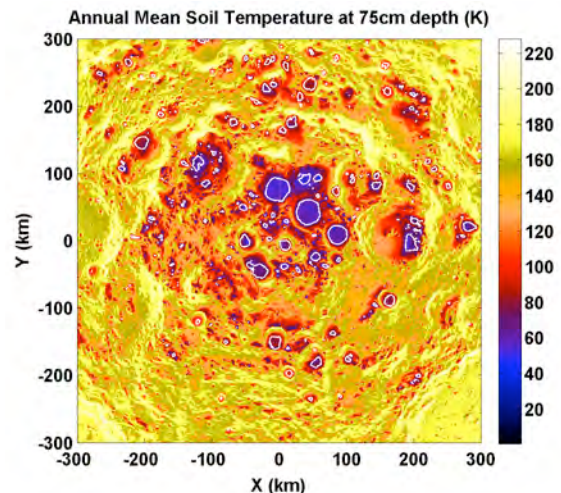

Fig, 1. Model mean annual temperature at 75 cm depth for the lunar south pole. Note that areas with subsurface temperatures below 110K (red through blue) are far more extensive than areas in strict permanent shadow (white outlines).

amount of hydrogen is placed into a larger area, resulting in lower average abundances.

This is illustrated in Figure 2, which shows two Pixons reconstructions for the Cabeus area. The upper panel shows the best-fit water-equivalent hydrogen (WEH) distribution assuming that concentrations higher than about 0.25 wt% are confined to permanent shadow. The lower panel shows the best-fit WEH distribution when ice is permitted in areas with subsurface temperatures below 110K. The WEH abundance at the LCROSS impact site is ~1wt% for the PSR-decoupled reconstruction, but ~0.3 wt% for the T_{75}<110K reconstruction.
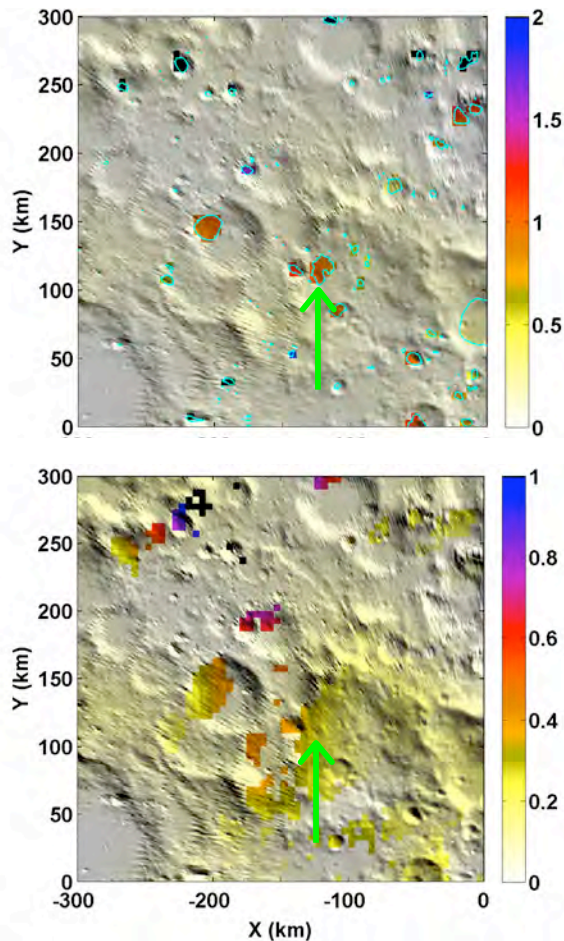
Fig. 2. Stereographic projections of water-equivalent hydrogen (WEH). (Upper) Decoupled Pixons reconstruction assuming WEH abundances > 0.25 wt% are confined to areas of permanent shadow. (Lower) Reconstruction assuming that WEH > 0.25 wt% are confined to areas with $T_{75}<110K$. Note differences in color bar scales. LCROSS impact site shown by green arrows.

We can compare present-day WEH distribution with what might be expected to remain following a large impact in the past. This calculation is based on work done on the sublimation of cold-trapped water ice in lunar regolith [9,10]. Figure 3 shows the sublimation rate of water ice versus temperature the vacuum lunar conditions from [10]. This strong temperature dependence will result in major loss (or downward retreat) of ice from areas with temperatures above about 130K. (This does not include the gardening and reworking processes described by Crider and Vondrak [11]). We present results of such ice evolution using LRO/Diviner-constrained surface and sub-surface temperatures, and compare with the Lunar Prospector results.

References: [1] Feldman, W.C., et al. (1998) *Science*

281:1496–1500. [2] Feldman, W.C. et al. (2000) *J. Geophys. Res.* 105:4175–4196. [3] Elphic R. C. et al. (2007) *Geophys. Res. Lett.,* 34, L13204, doi:10.1029/2007GL029954. [4] Eke, V. R. et al. (2009) *Icarus, 200,* 12-18, ISSN 0019-1035, doi: 10.1016/j.icarus.2008.10.013. [5] http://www.nasa.gov/mission_pages/LCROSS/main/prelim_water_results.html [6] Vasavada, A. R., et al. (1999), *Icarus*, *141*, 179 – 193. [7] Paige, D. A. et al. (2009) http://www.diviner.ucla.edu/blog/?p=123. [8] Pieters, C. M., et al. (2009), *Science 326*, 568 [9] Andreas, E. (2006) doi:10.1016/ j.icarus.2006.08.024. [10] Schorghofer, N., and G. J. Taylor (2007), *J. Geophys. Res.*, 112, E02010, doi:10.1029/2006JE002779. [11] Crider D. H. and Vondrak R. R. (2003) *JGR 108*, 5079.
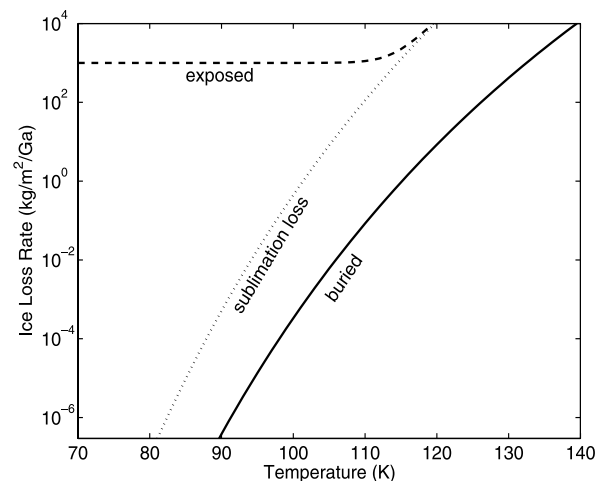

Fig. 3. Ice sublimation rates versus temperature, from [10].

Polar Volatile History:
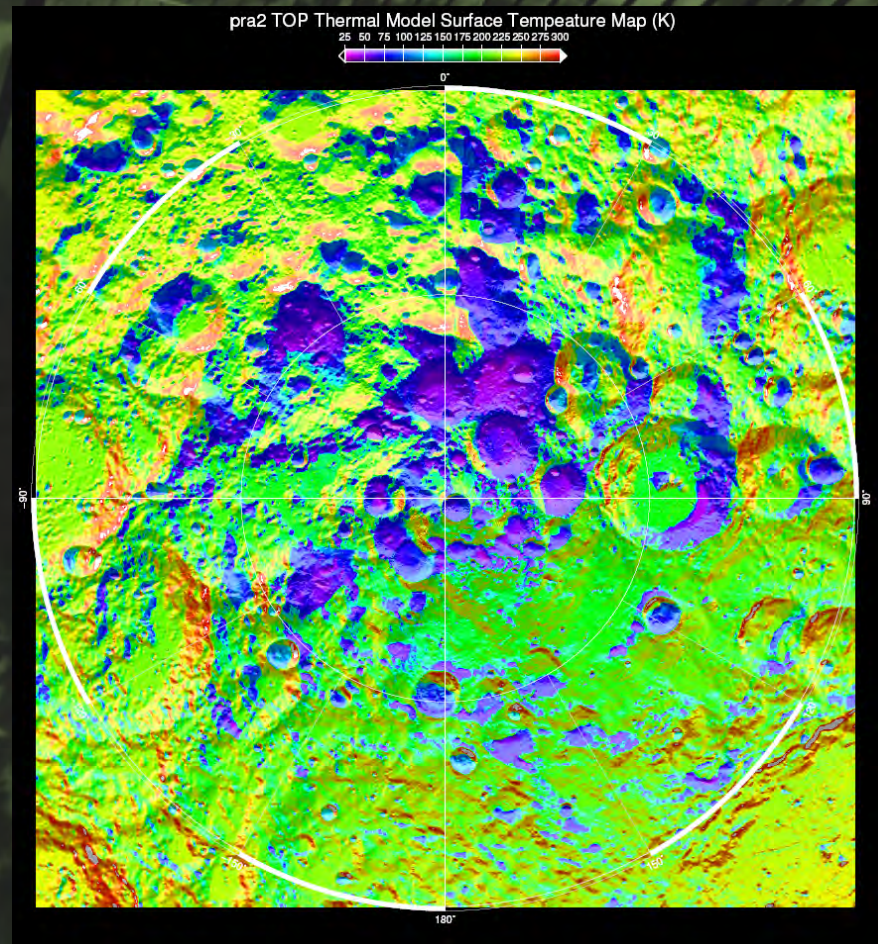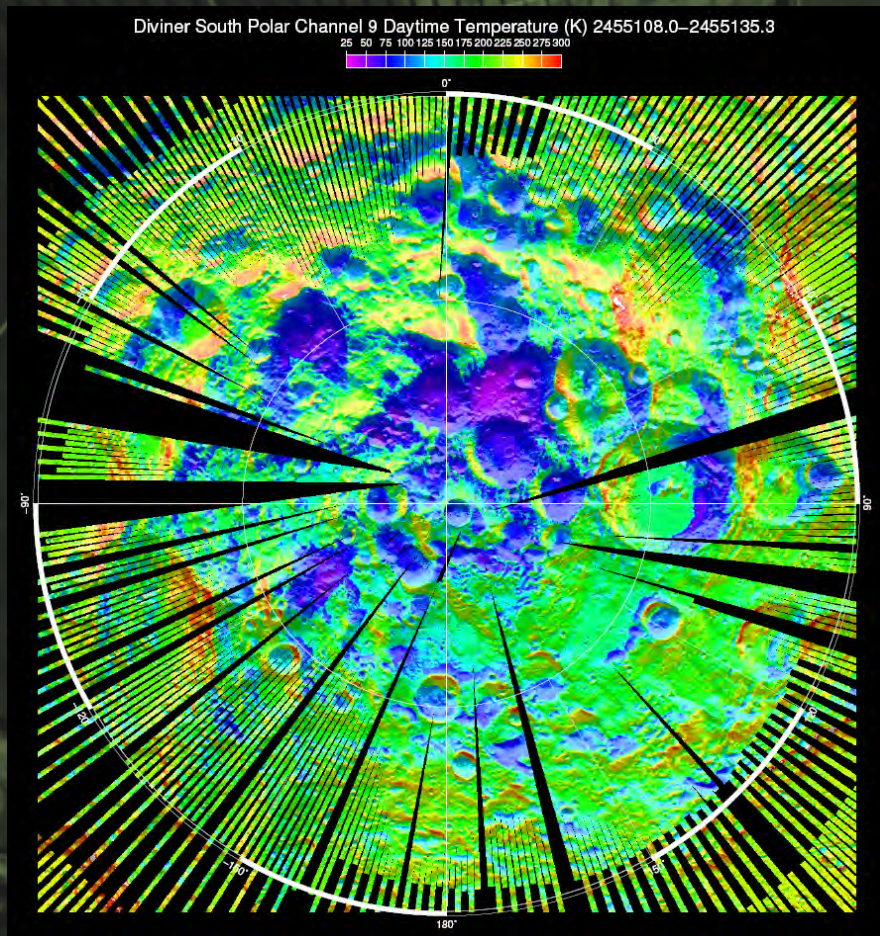# Diviner Results and Modeling

R. C. Elphic, D. A. Paige, M. A. Siegler, A. R. Vasavada, V. R. Eke, L. F. A. Teodoro, and D. J. Lawrence

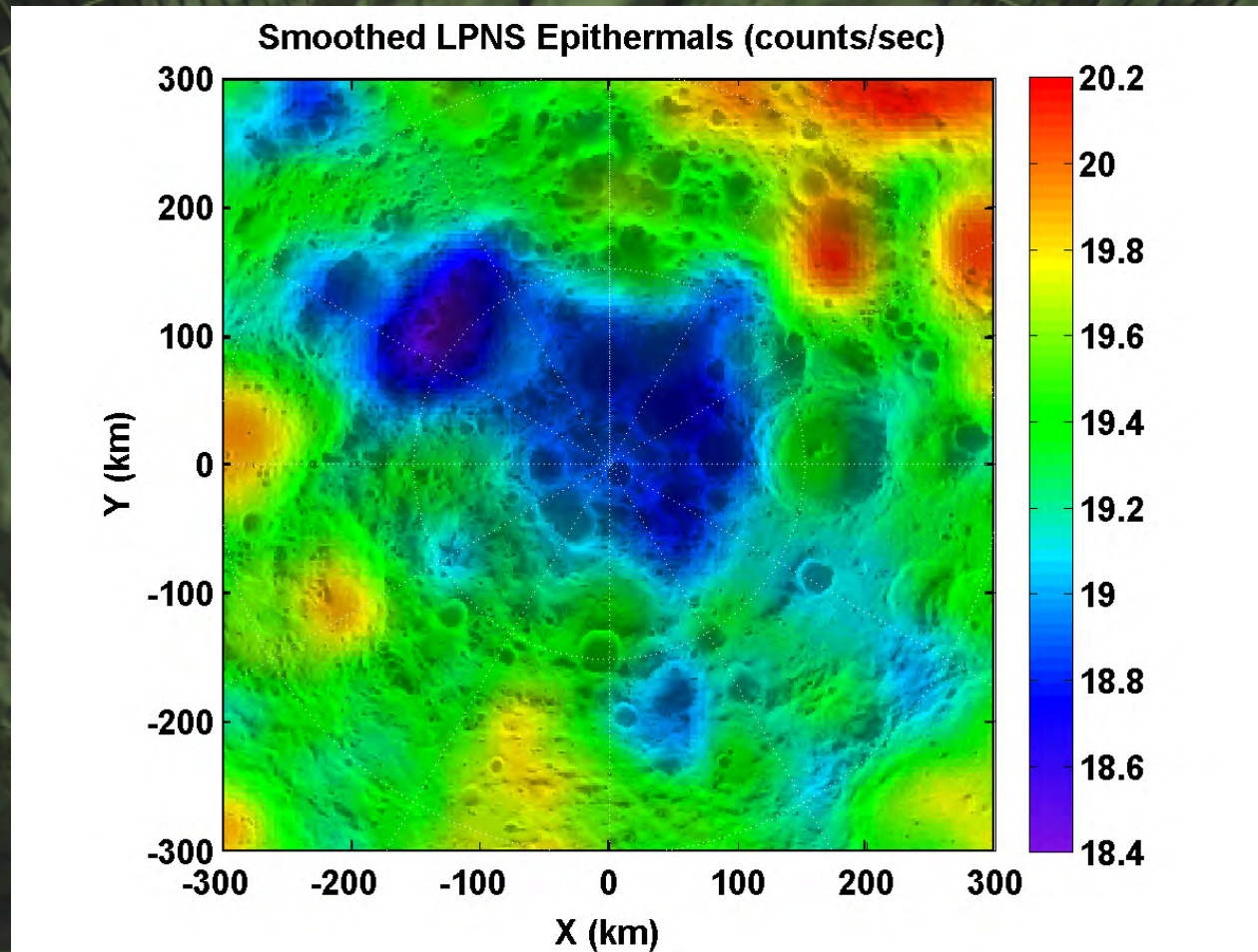With thanks to Norbert Schorghofer

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LRO Diviner Surface Temperatures

Diviner South Polar Channel 9 Daytime Temperature (K) 2455108.0–2455135.3

pra2 TOP Thermal Model Surface Tempeature Map (K)

"TOP" thermal model,
Vasavada et al. (1999)

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Is Lunar Polar "Ice" a Relic of a Single Large Event?

Smoothed LPNS Epithermals (counts/sec)

H$_2$O Residence Time vs. T
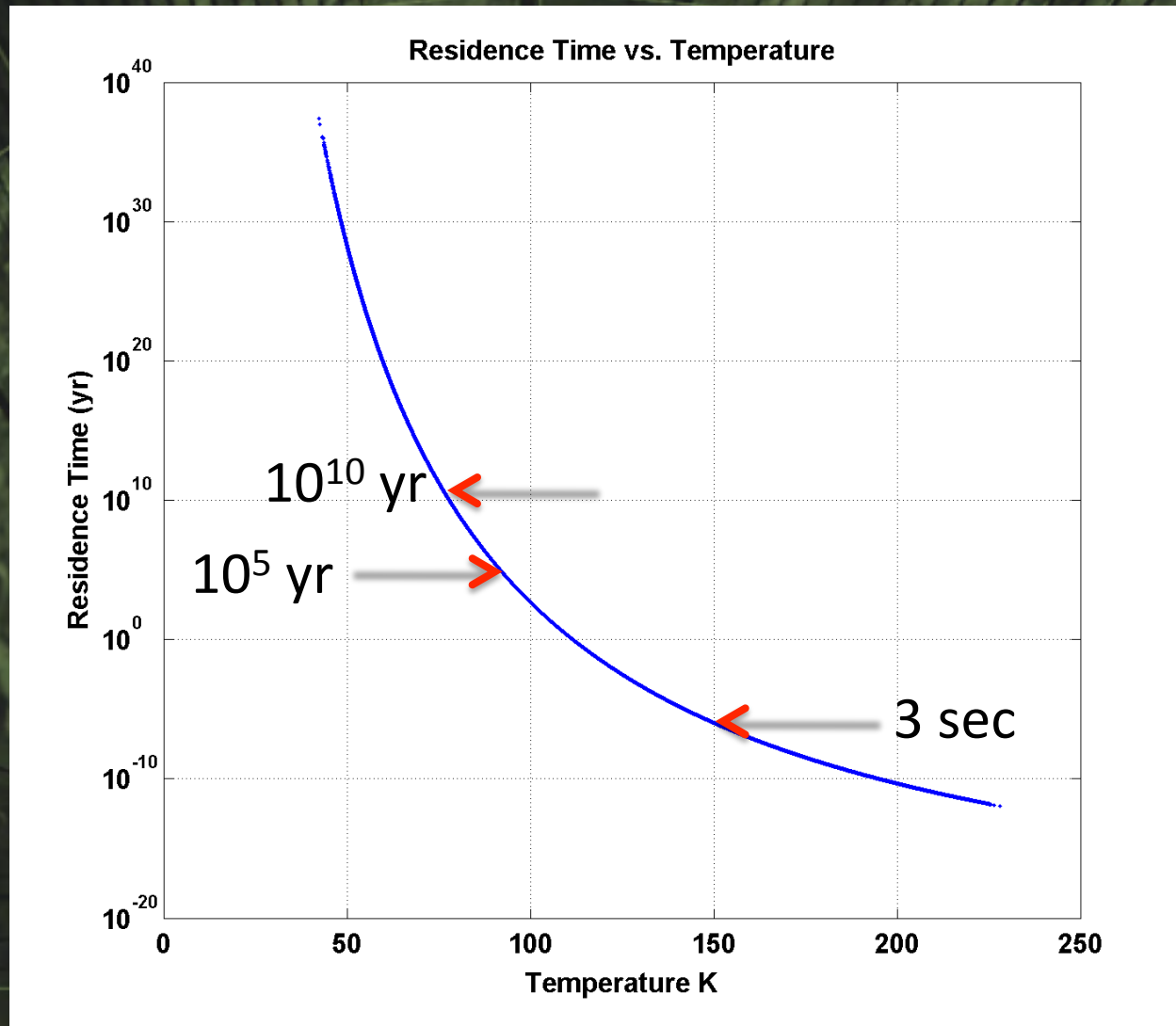
Model Subsurface Temperature

75 cm Depth

Annual Mean Soil Temperature at 75cm depth (K)
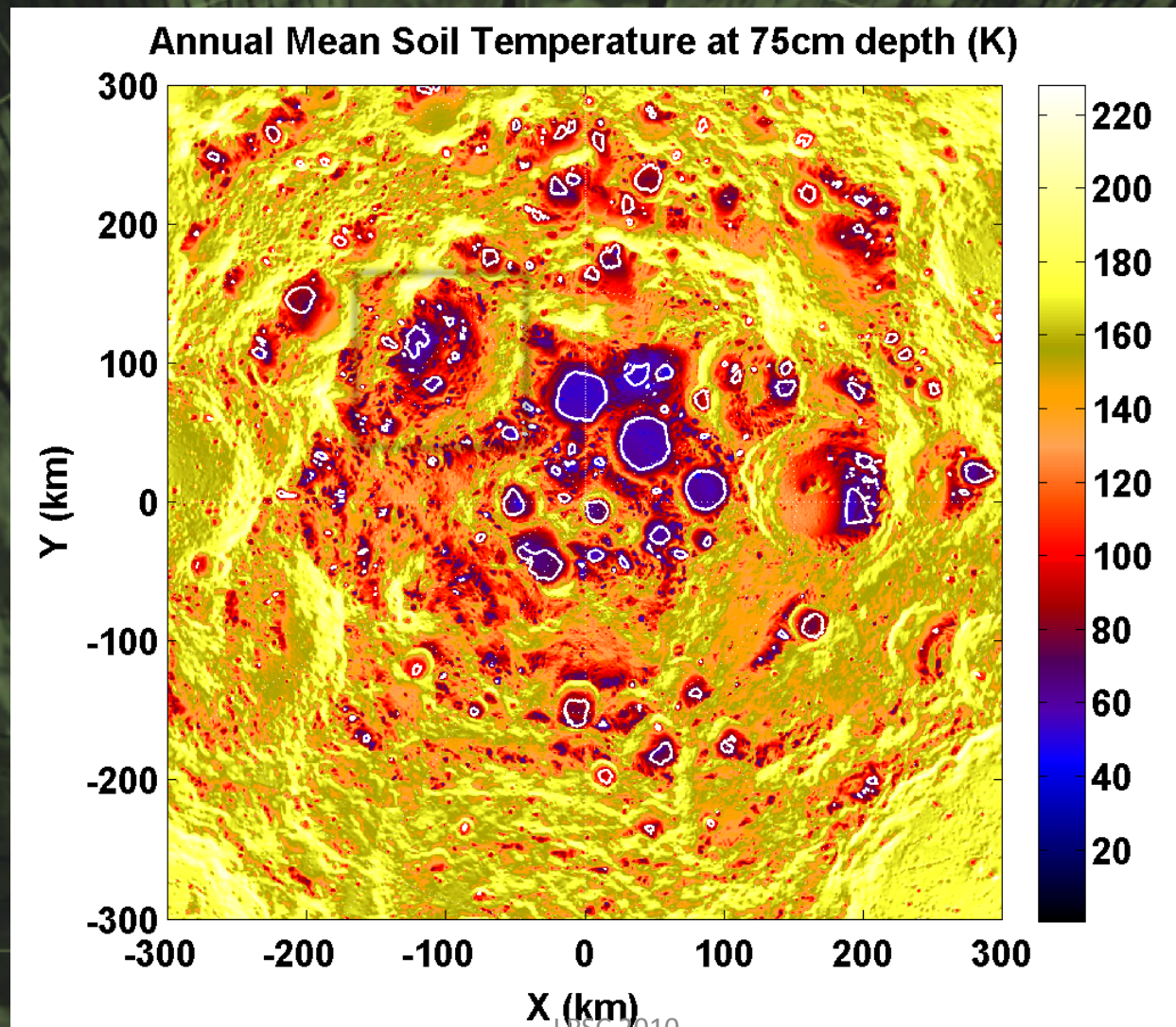
1-D Diffusion Problem
(after Schorghofer and Taylor, 2007)

- ! $\delta\rho/\delta t = D\,\delta^2\rho/\delta z^2$

- ! ρ = H_2O mass density, ρ/ρ_o is initially 1 wt%

- ! D is the diffusion coefficient, $= \ell^2/2\tau_{res}$

- ! τ_{res} is the molecular residence time

- ! ℓ is the pore size, ~75 μm

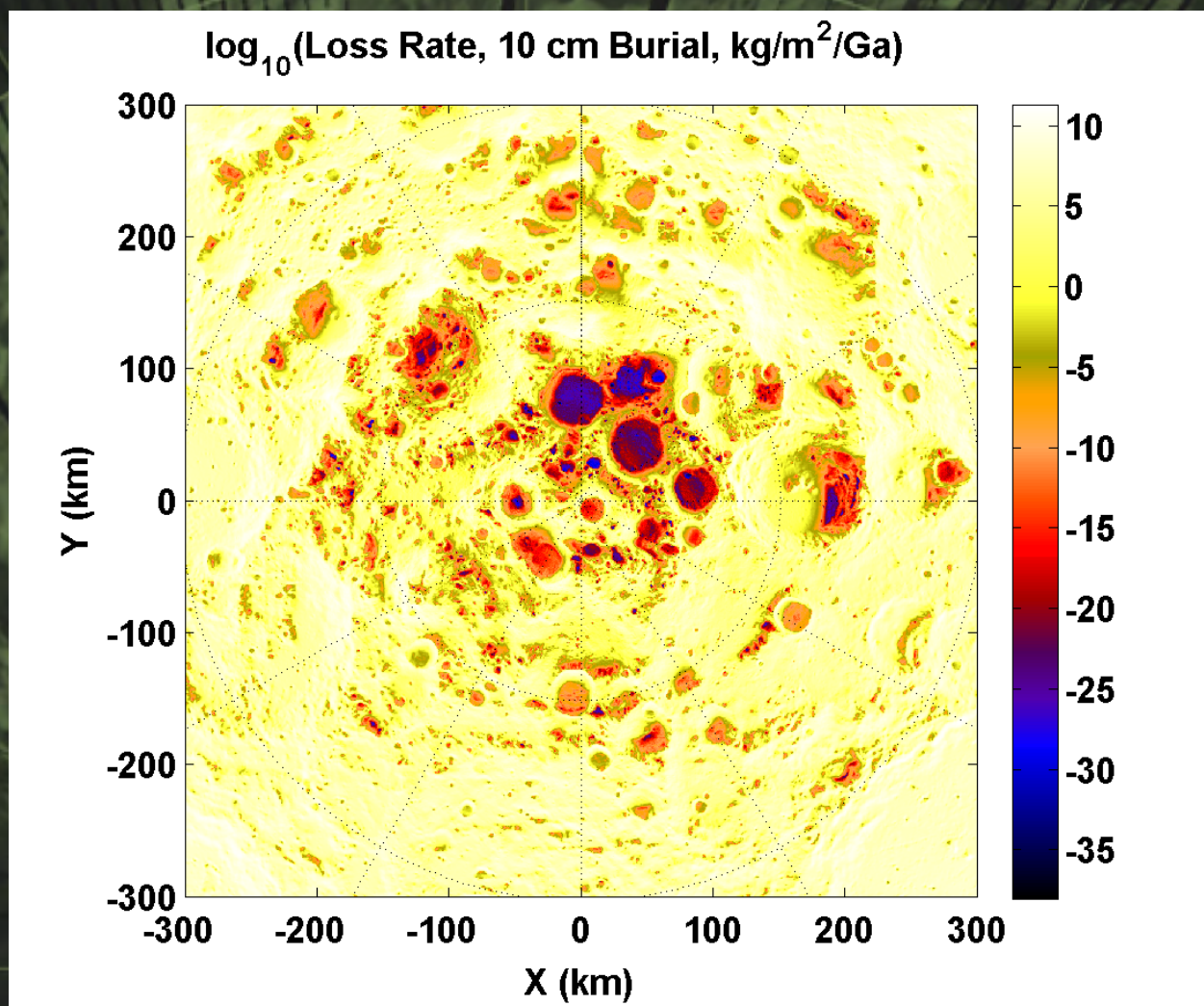- ! Gardening: 1 meter burial/10^9 yr

Gardening/Burial
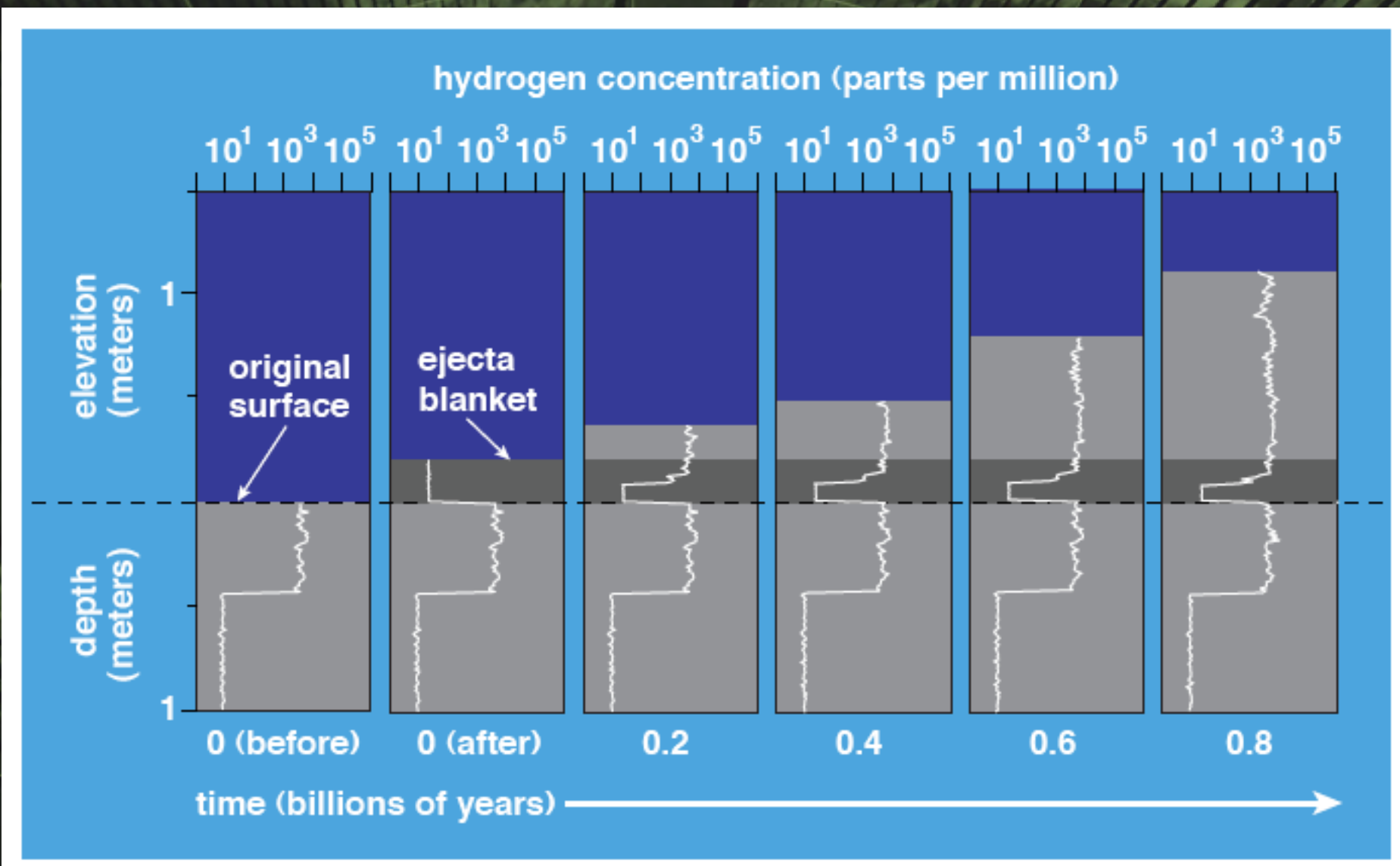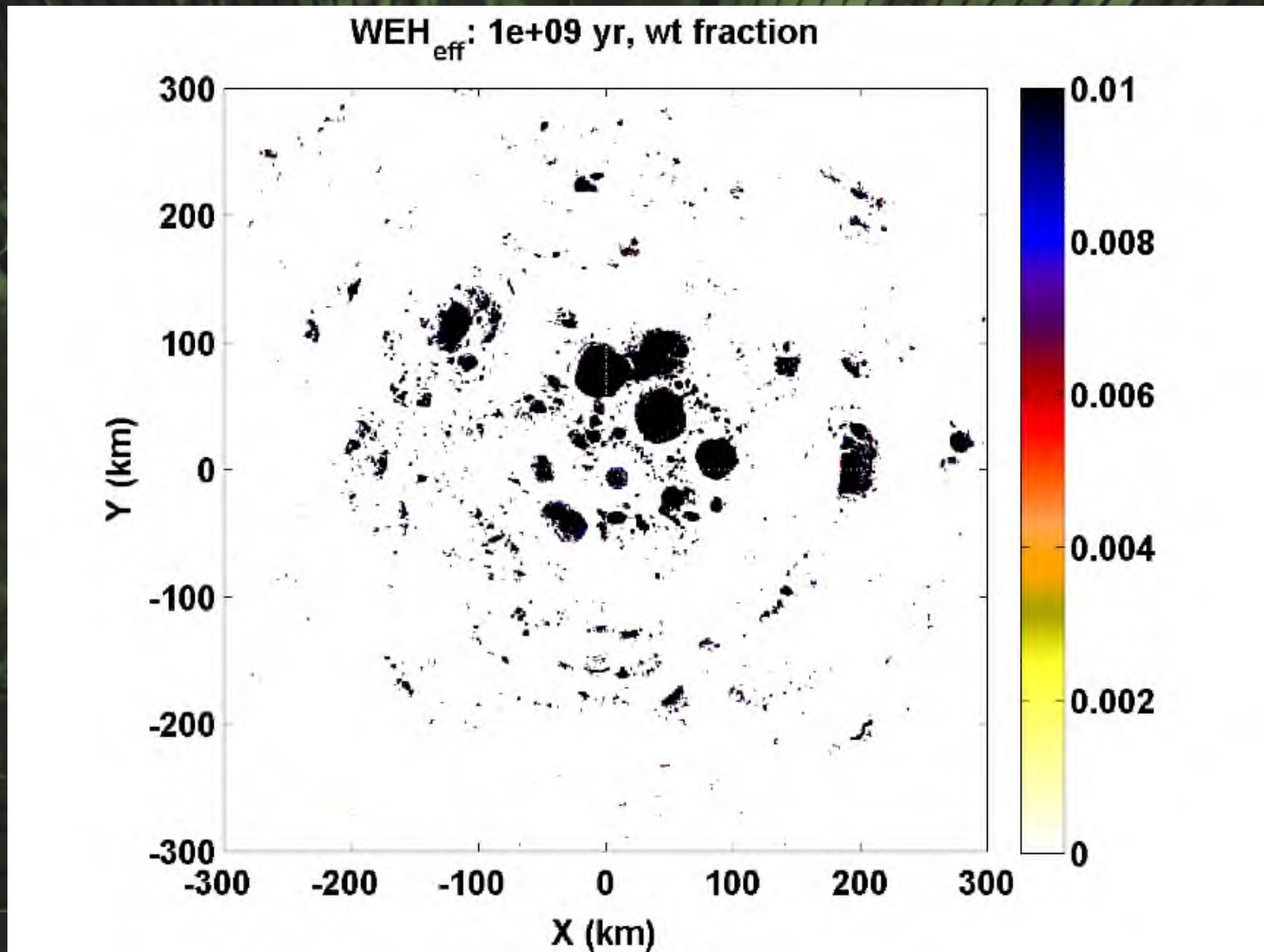
"Global" Layer of 1-meter thick, ice-bearing stuff

Diffusion history for 110K

D from Schorghofer & Taylor, 2007
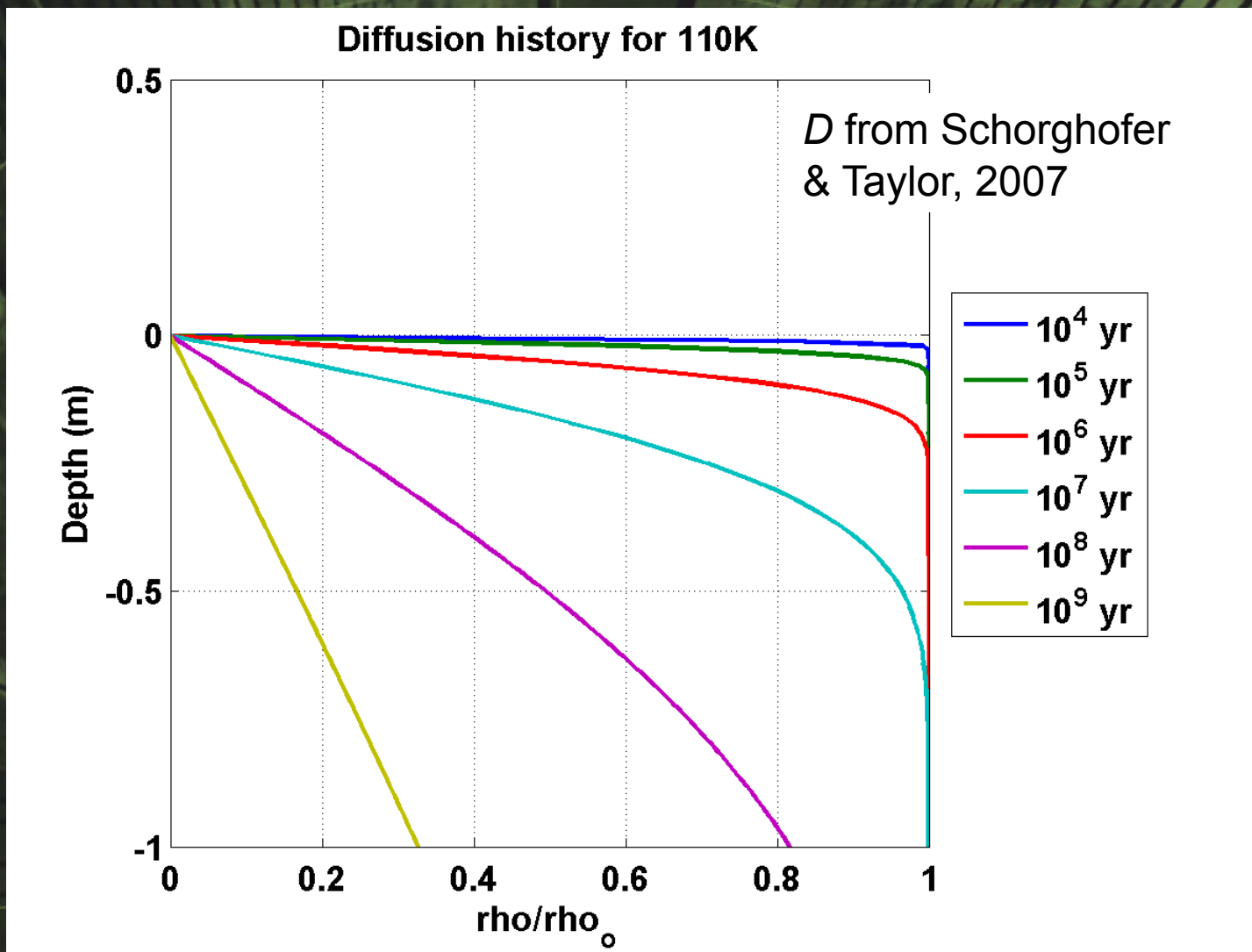
"Global" Layer of 1-meter thick, ice-rich stuff

$\log_{10}$(Loss Rate, 10 cm Burial, kg/m^2/Ga)

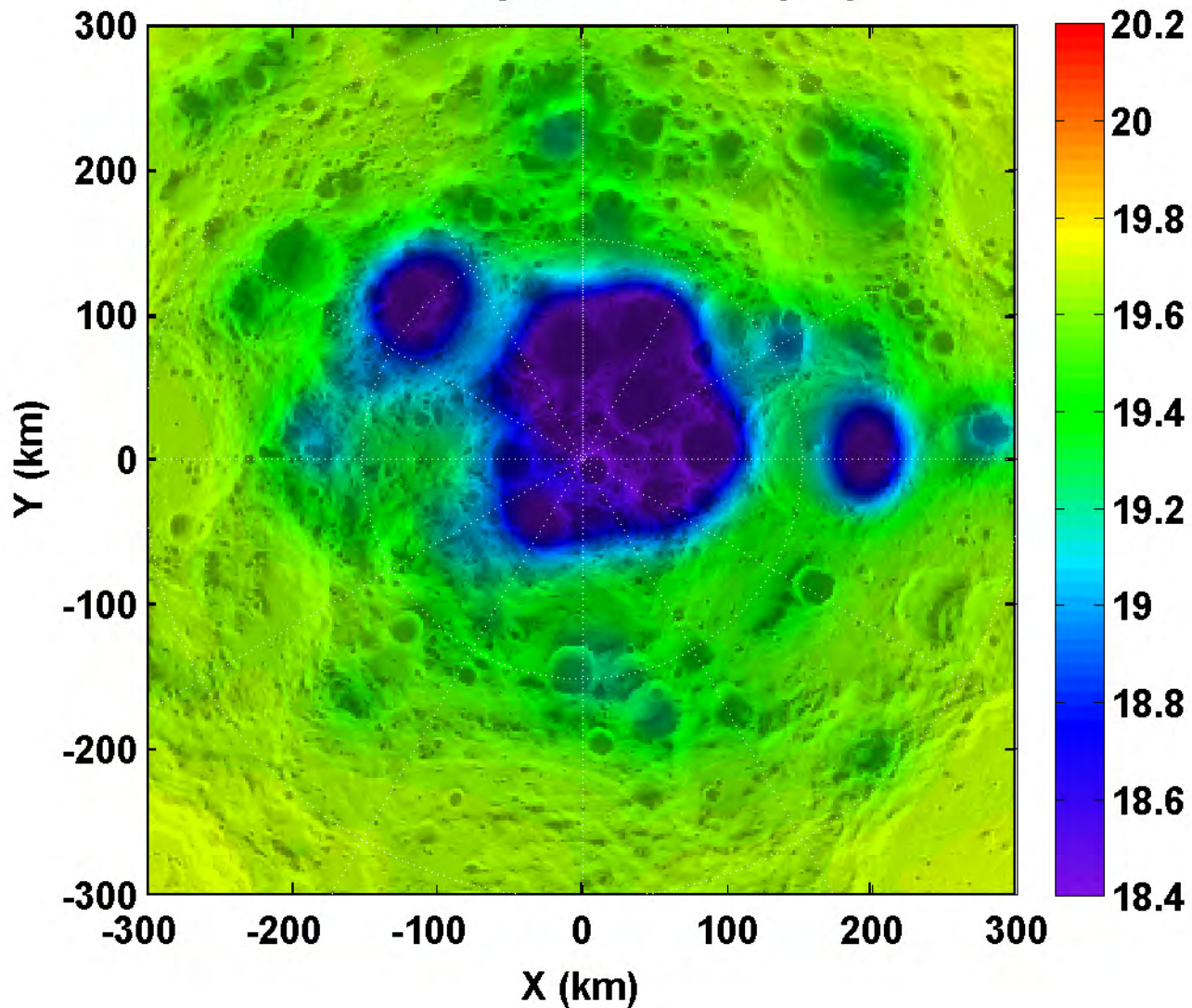# Mean WEH Fraction in Top 1 meter

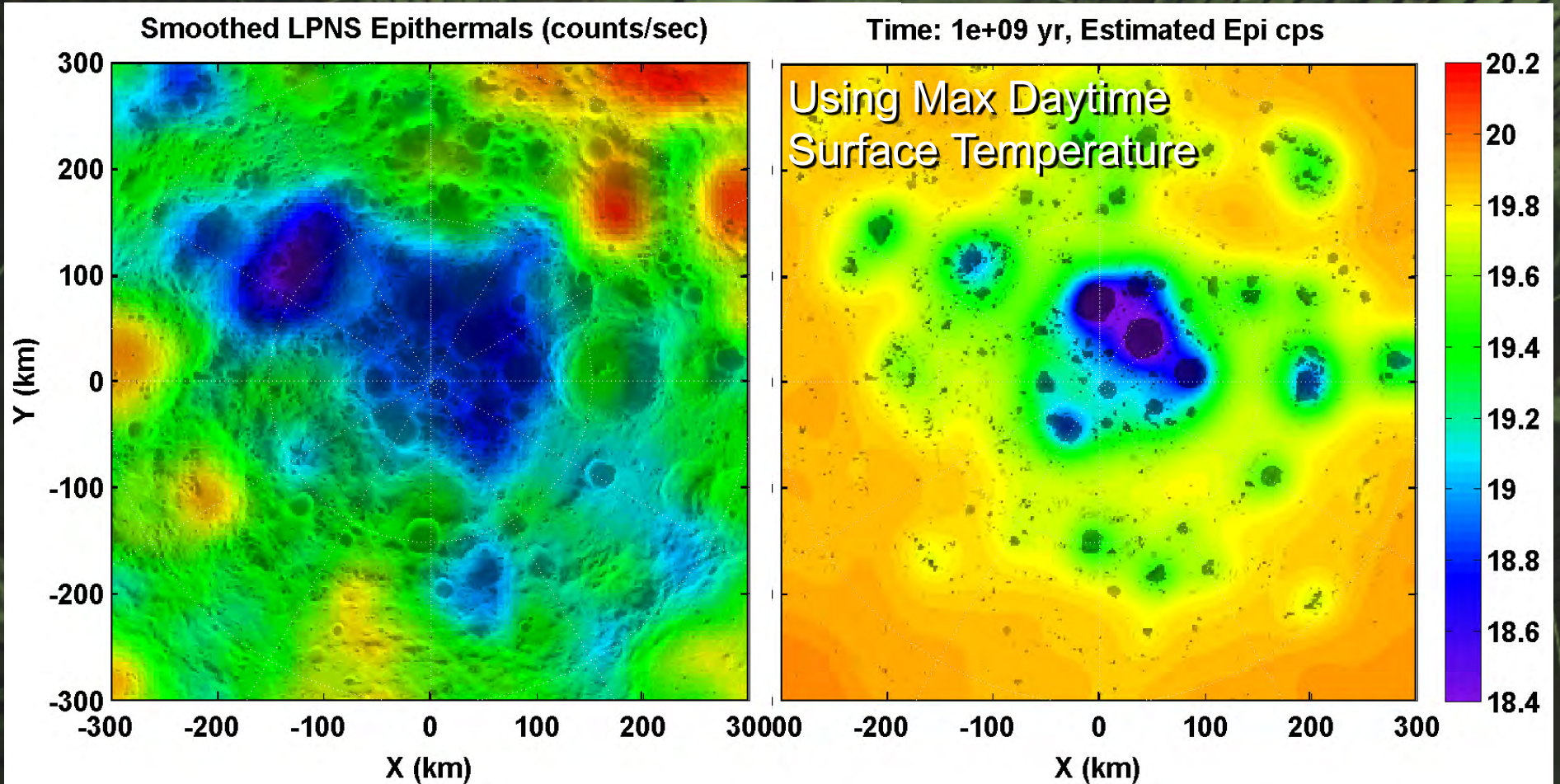

WEH$_{eff}$: 1e+09 yr, wt fraction

Time: 1e+09 yr, Estimated Epi cps
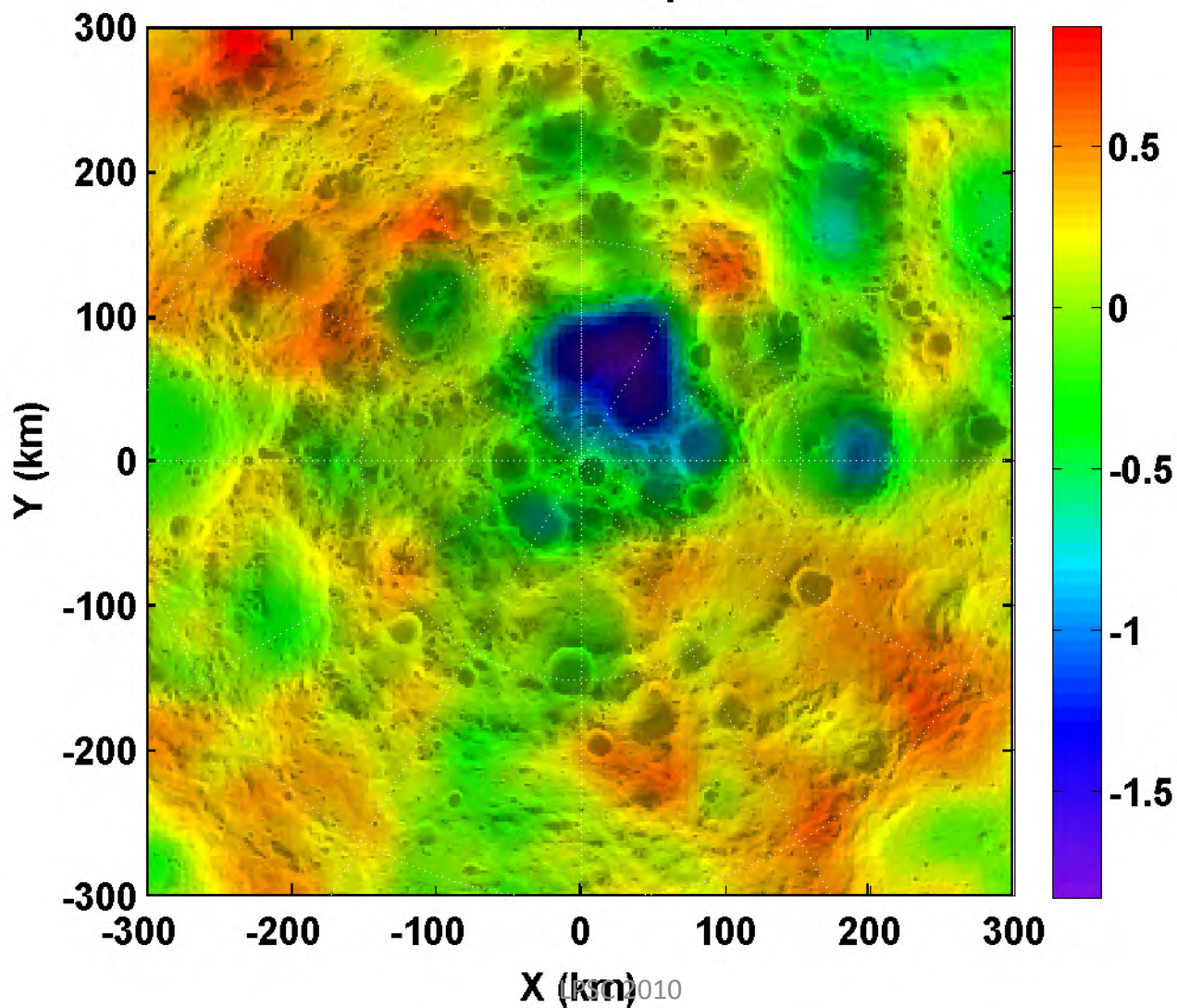
Modeled Epis vs. Observed

Model – LPNS

Model - LPNS Epi flux

Preliminary Results:
Relict Ice

- • Modeled epithermal flux spatially different from that of LPNS.

- • Predicts deep lows:
  - – Cabeus (which is seen)
  - – Faustini/Shoemaker/Haworth area (not seen)

- • Reconfirms what we found with Pixon reconstructions:
  - – Some large cold traps do NOT have high WEH.
  - – Localized sources?