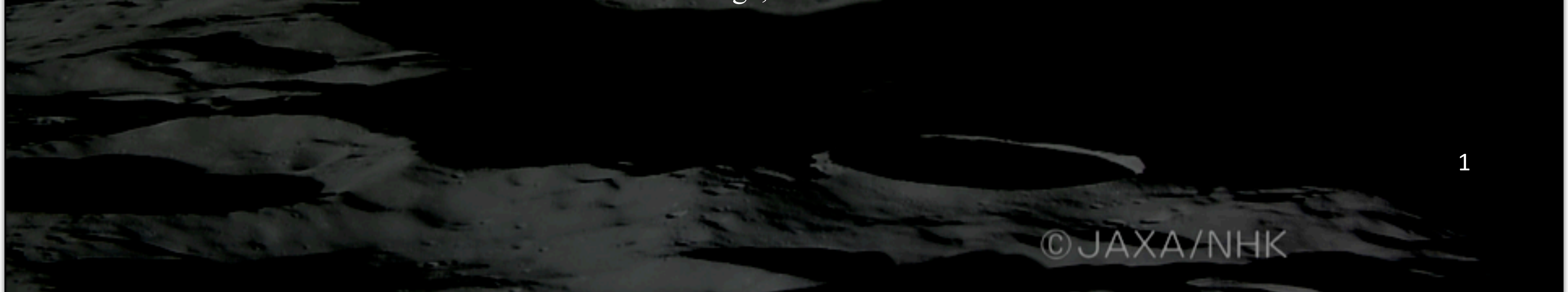
The Thermal Evolution of Lunar Volatiles

Matthew A. Siegler

NLSI Lunar Grad Con 2010

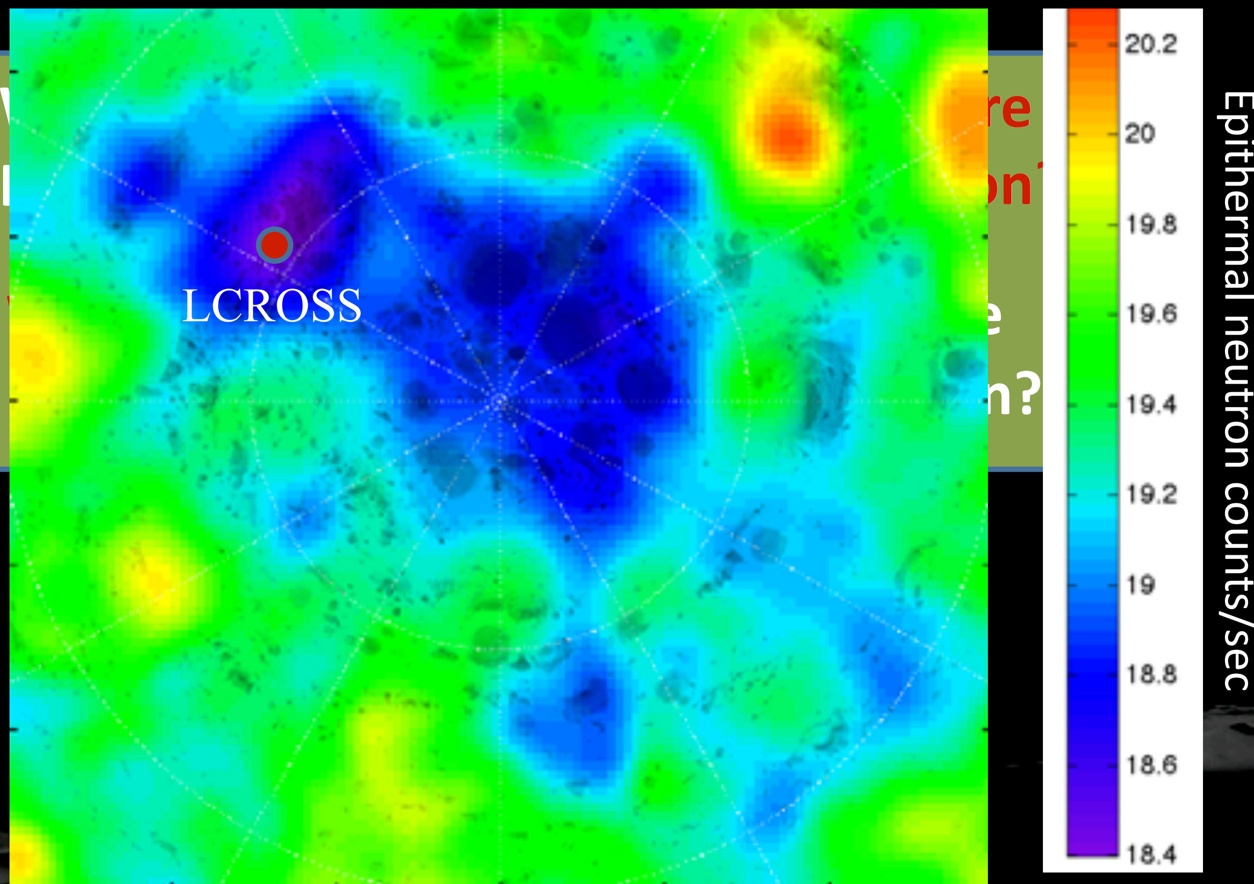
A production in association with:
David Paige, Bruce Bills



These two can be summed up by asking: “What’s so special about Cabeus?”

Is there something special about its location and past?

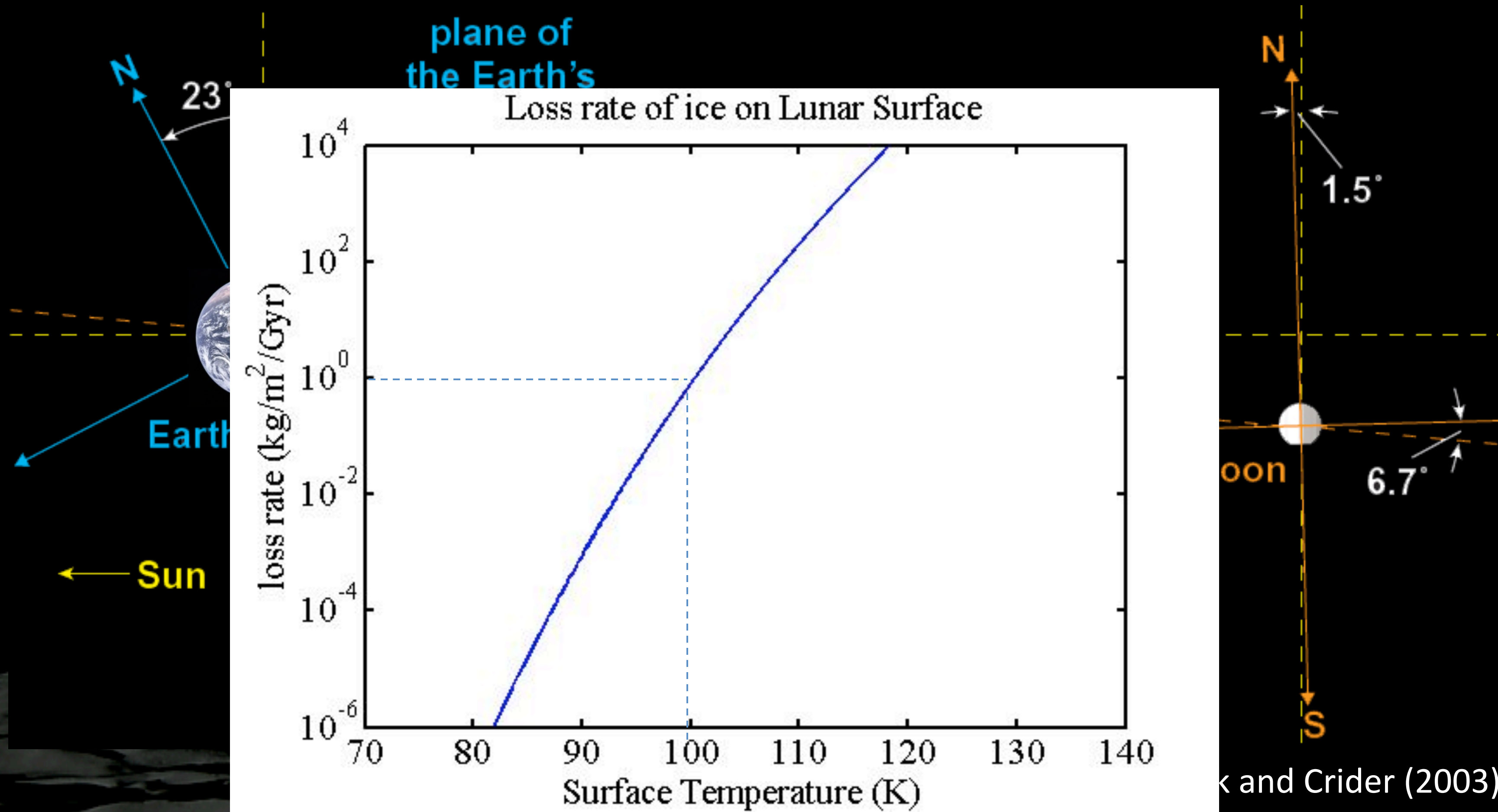
Big Questions



Motivation: Why would there be ice on the Moon?

(Watson, Murray, Brown, 1966)

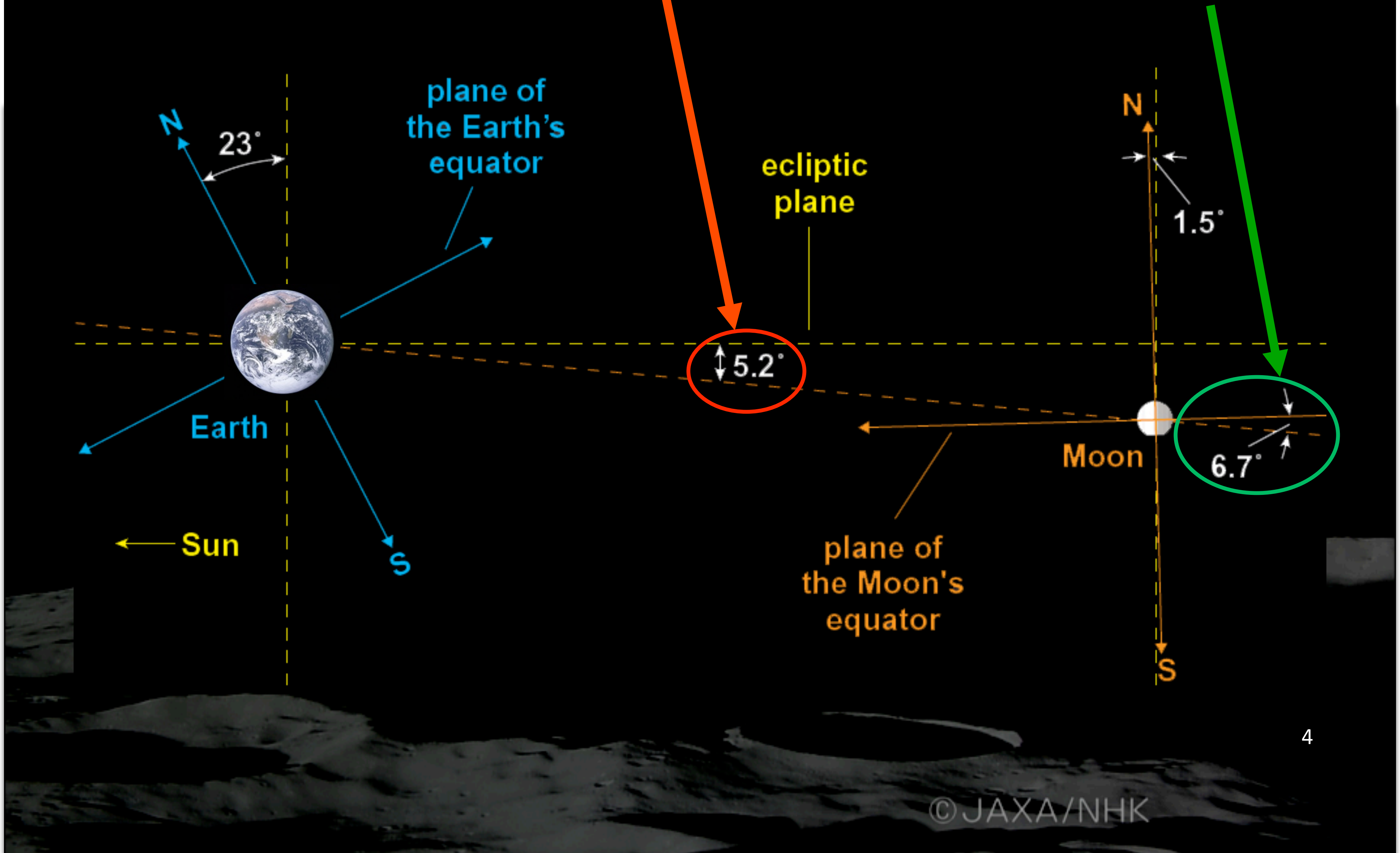
Temperature is the primary control of ice presence



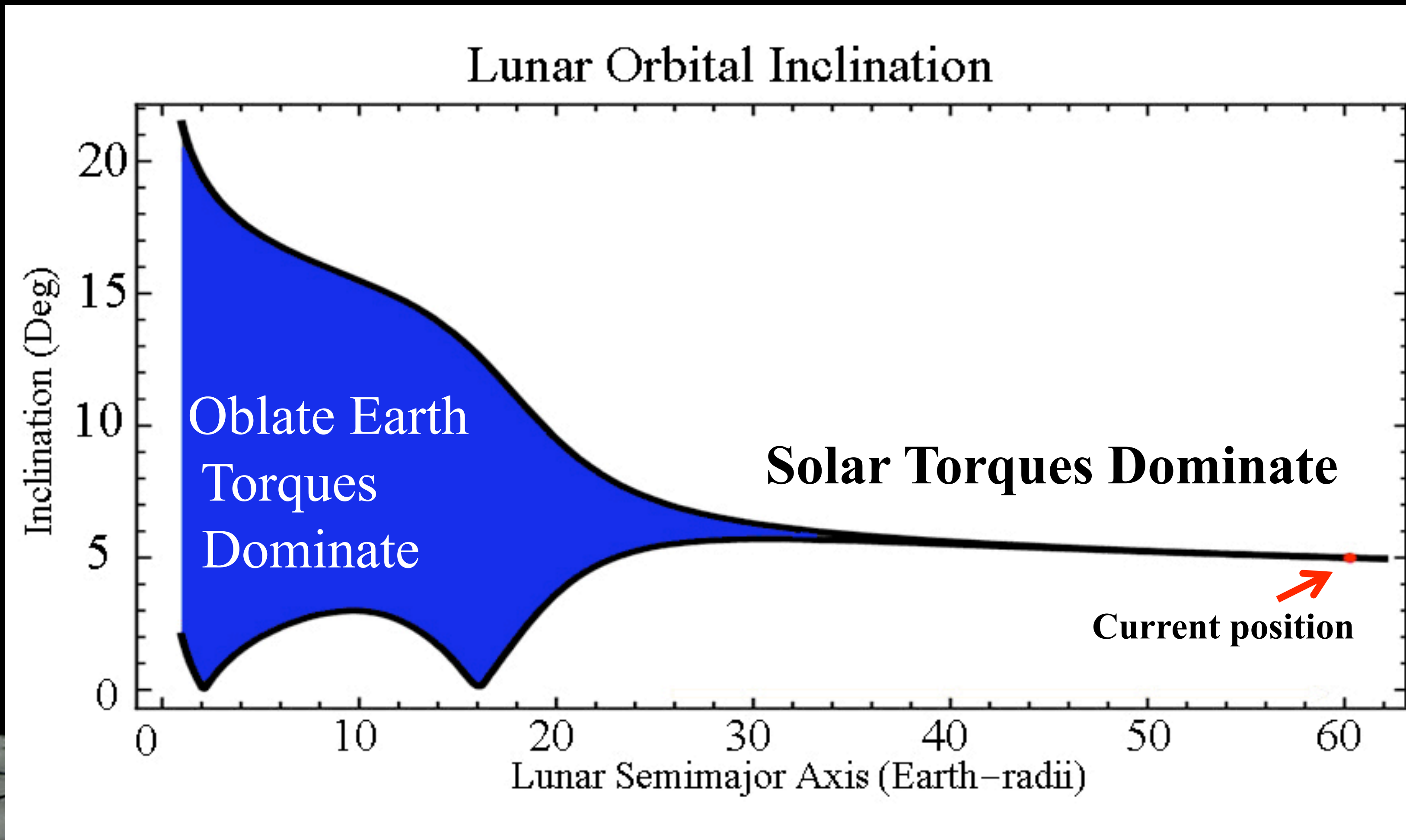
and Crider (2003)

Orbital Modeling: What controls the temperature

Important angles: **Inclination** **Obliquity**

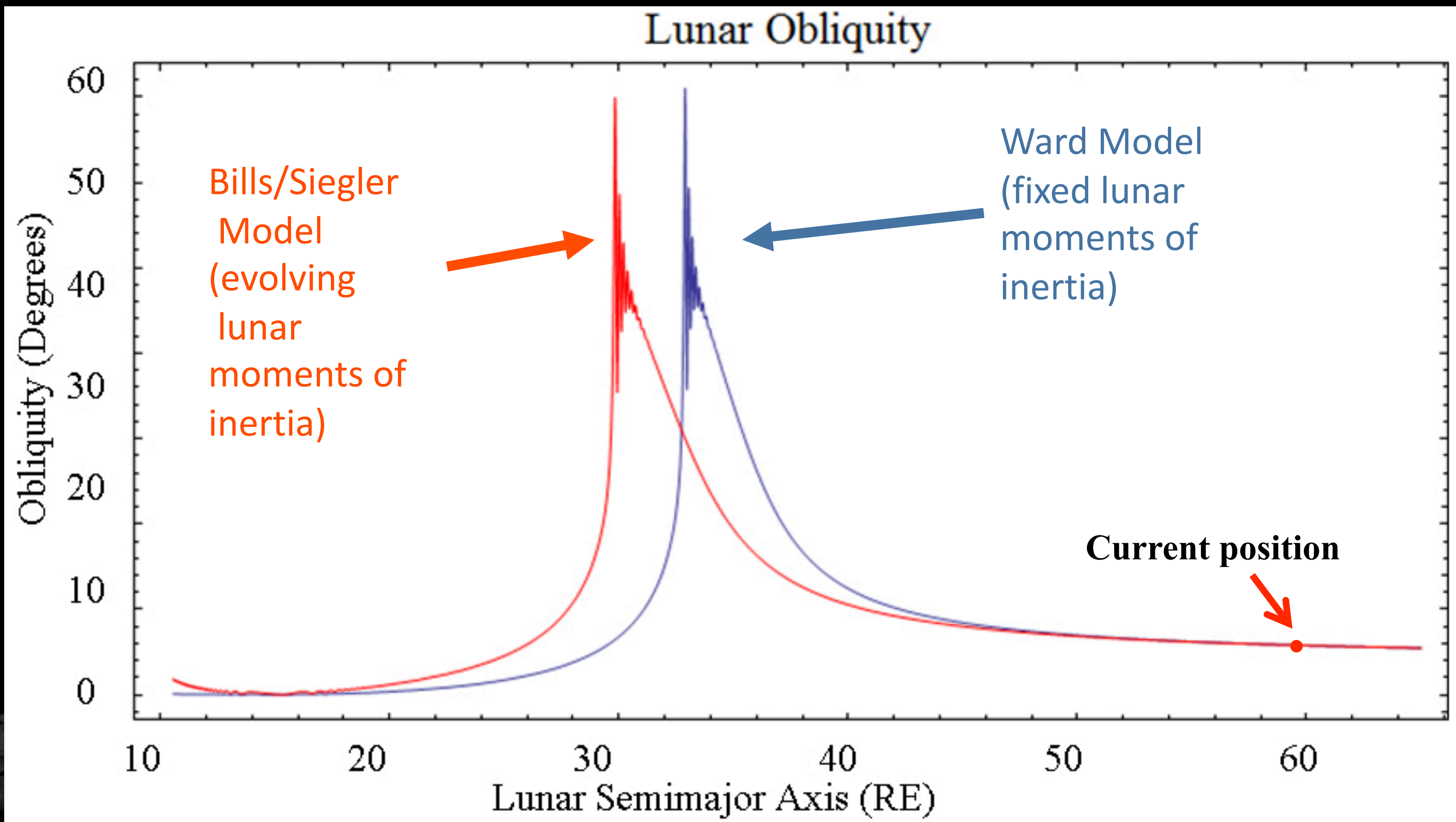


Orbital Modeling: Inclination



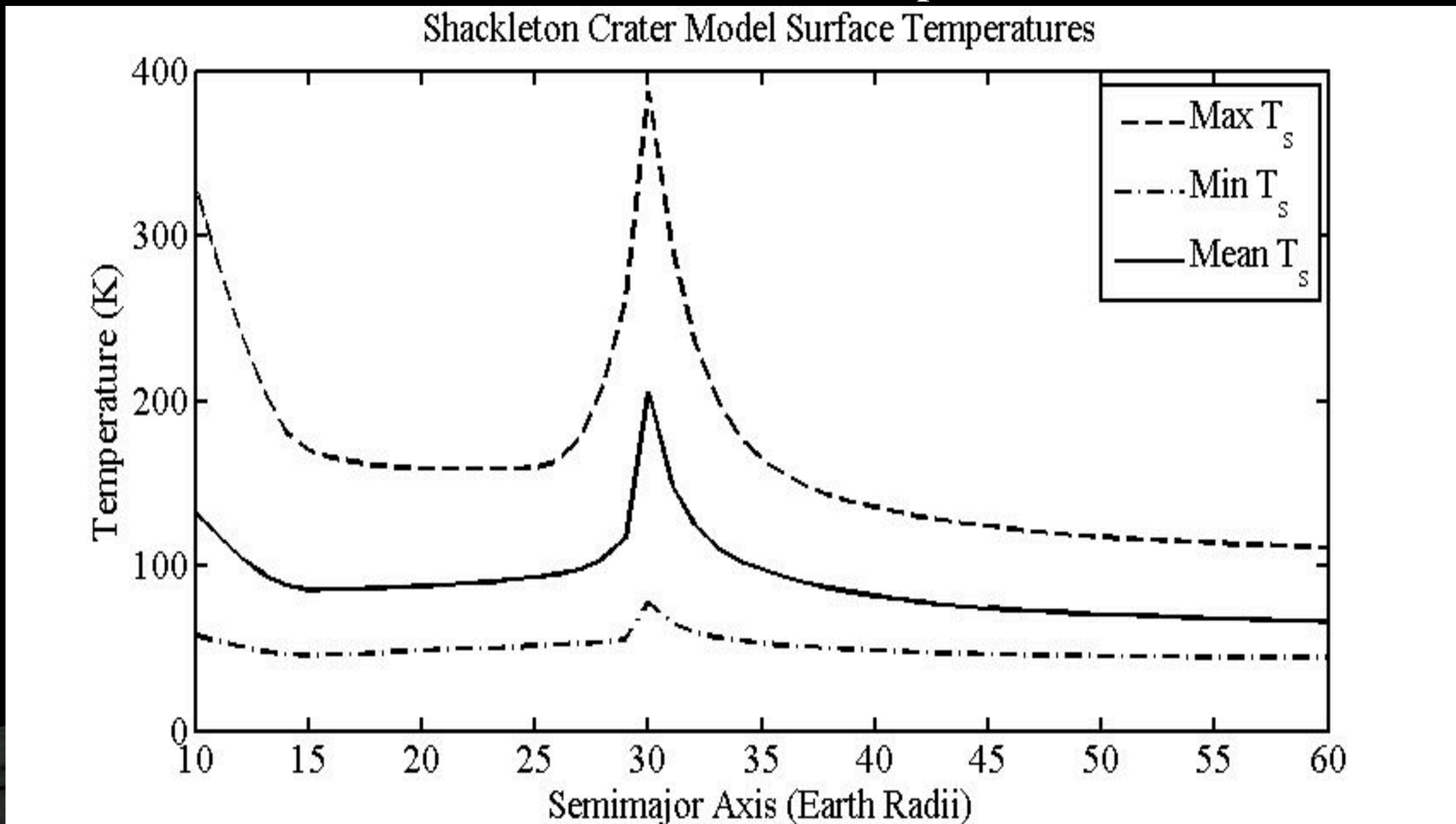
Orbital Modeling: Obliquity

Obliquity history will vary with different moments of inertia



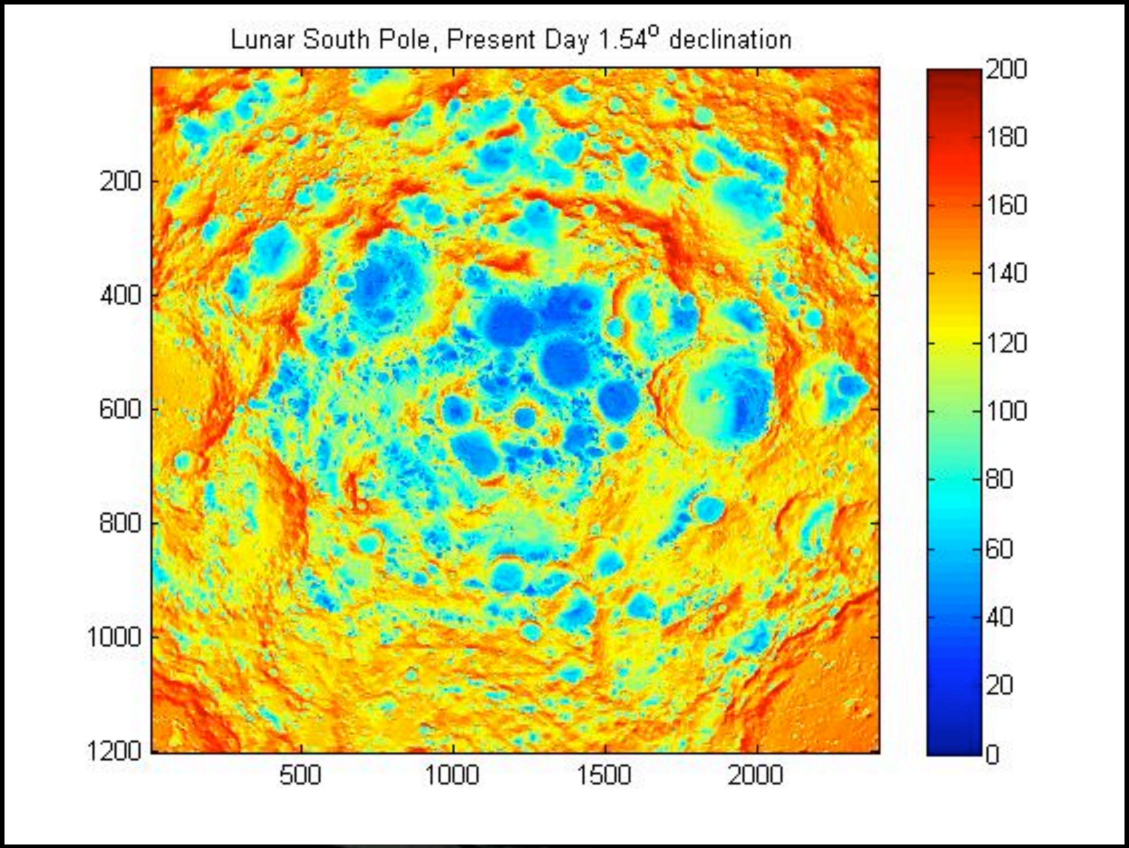
Orbital Modeling: Declination, "Sun angle"

Solar "Declination" determines maximum amplitude of seasonal variation



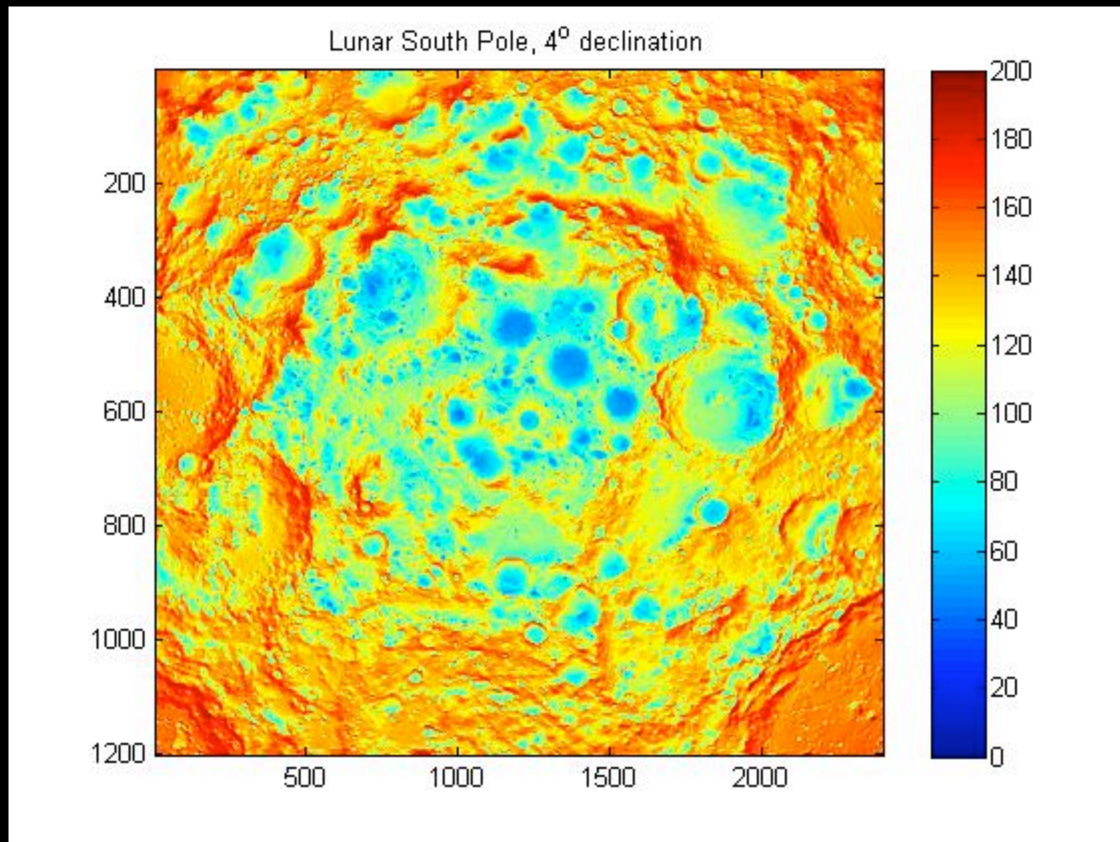
Applications: Thermal History

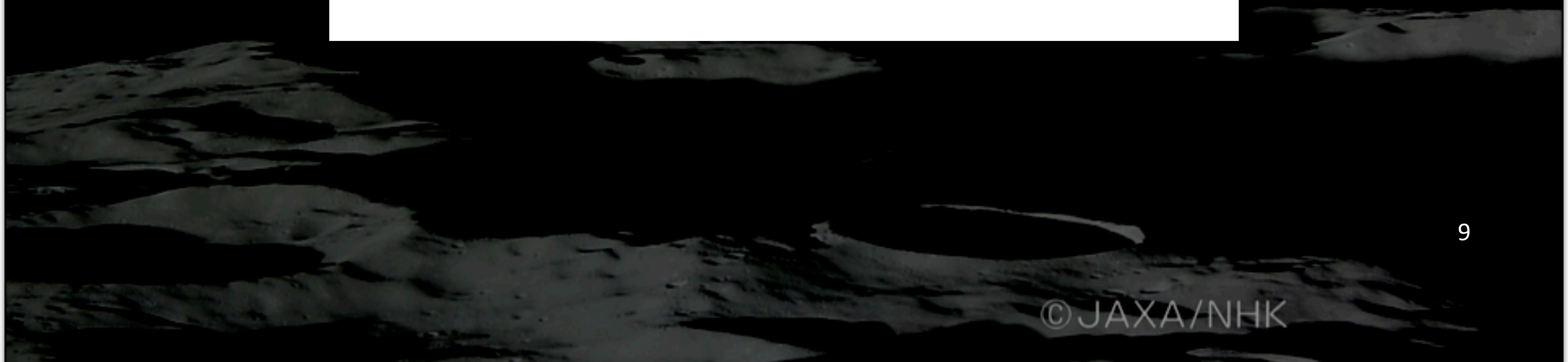
When was there Ice on the Moon?



Applications: Thermal History

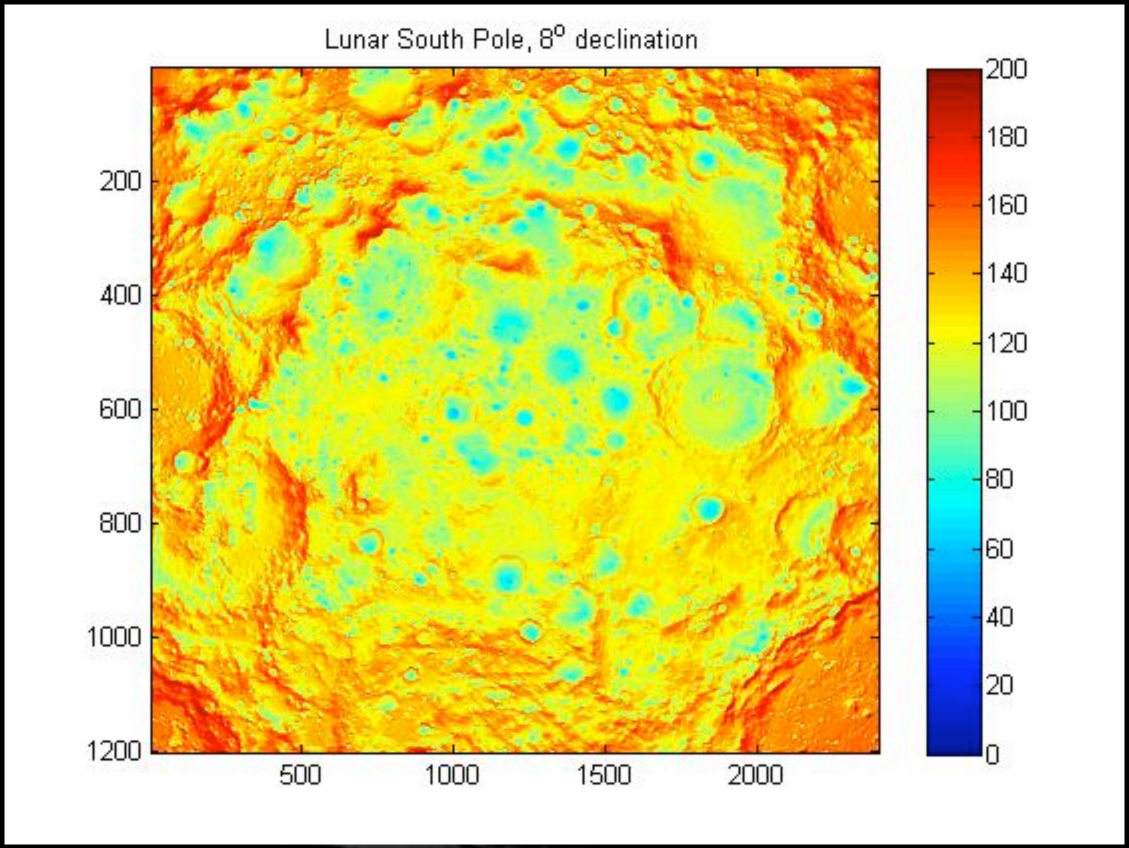
When was there Ice on the Moon?





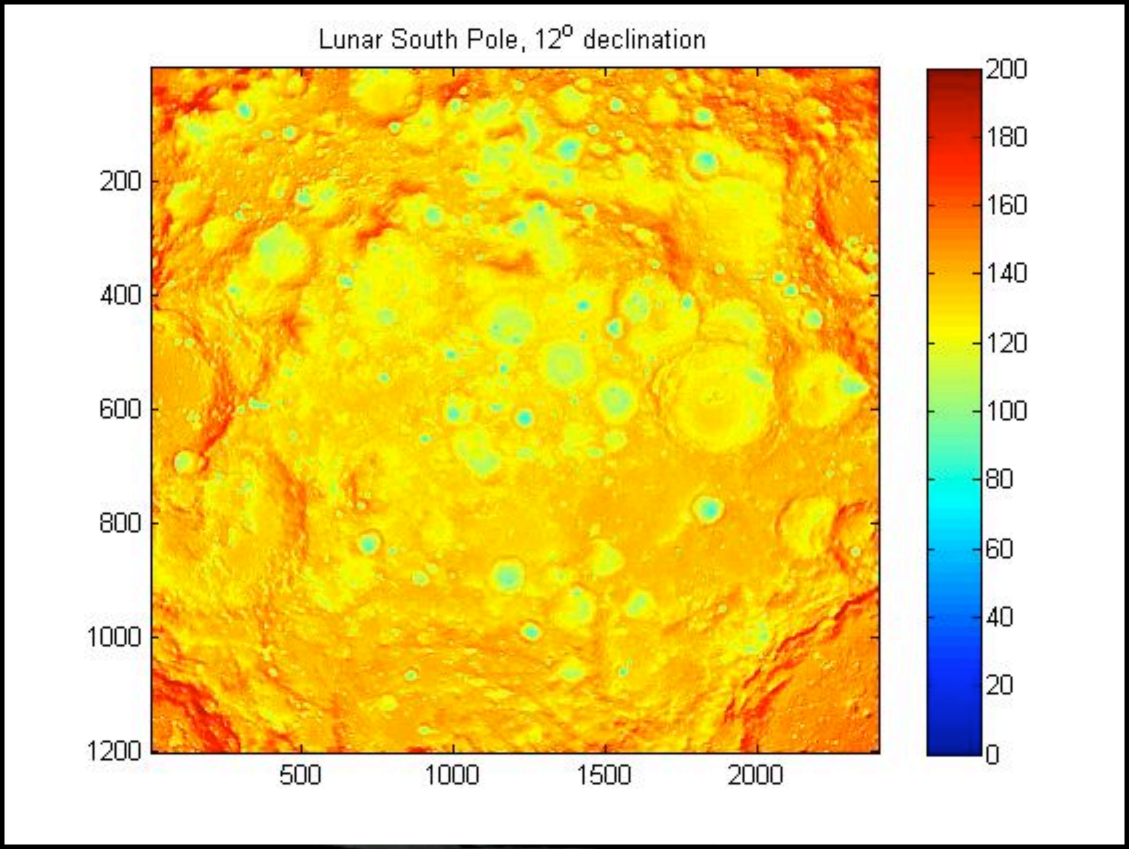
Applications: Thermal History

When was there Ice on the Moon?



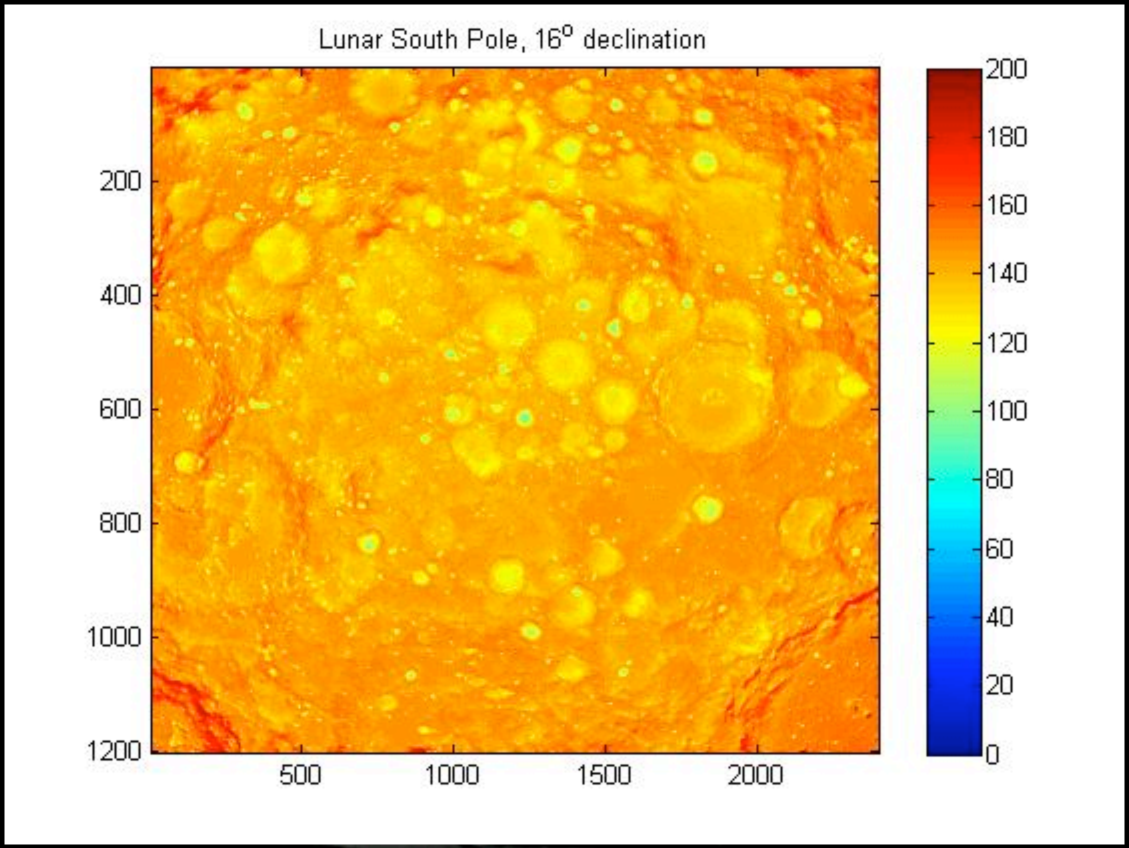
Applications: Thermal History

When was there Ice on the Moon?



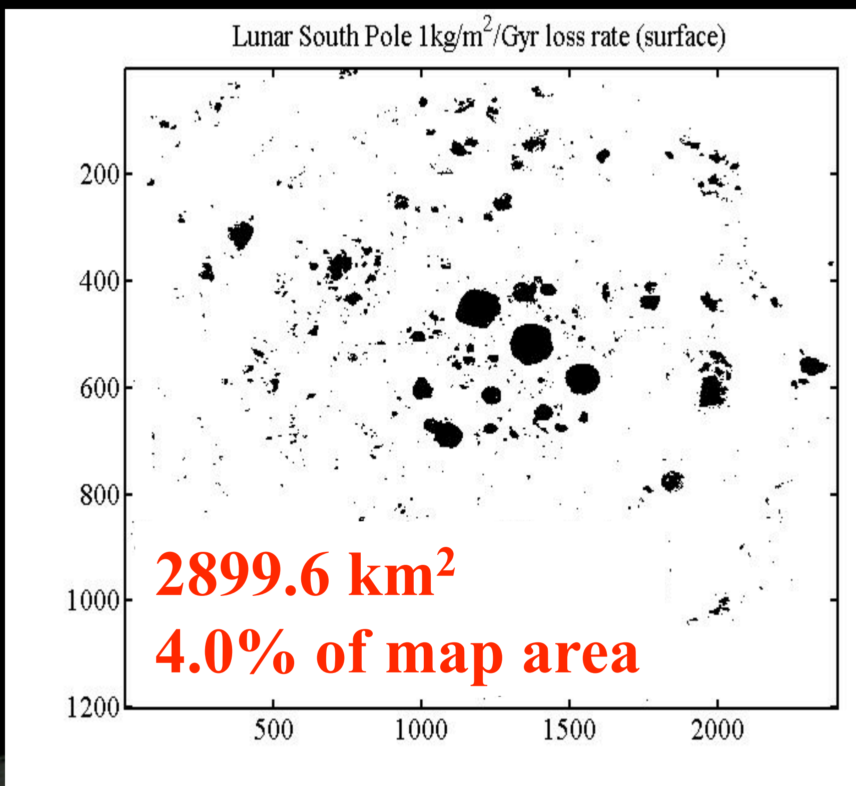
Applications: Thermal History

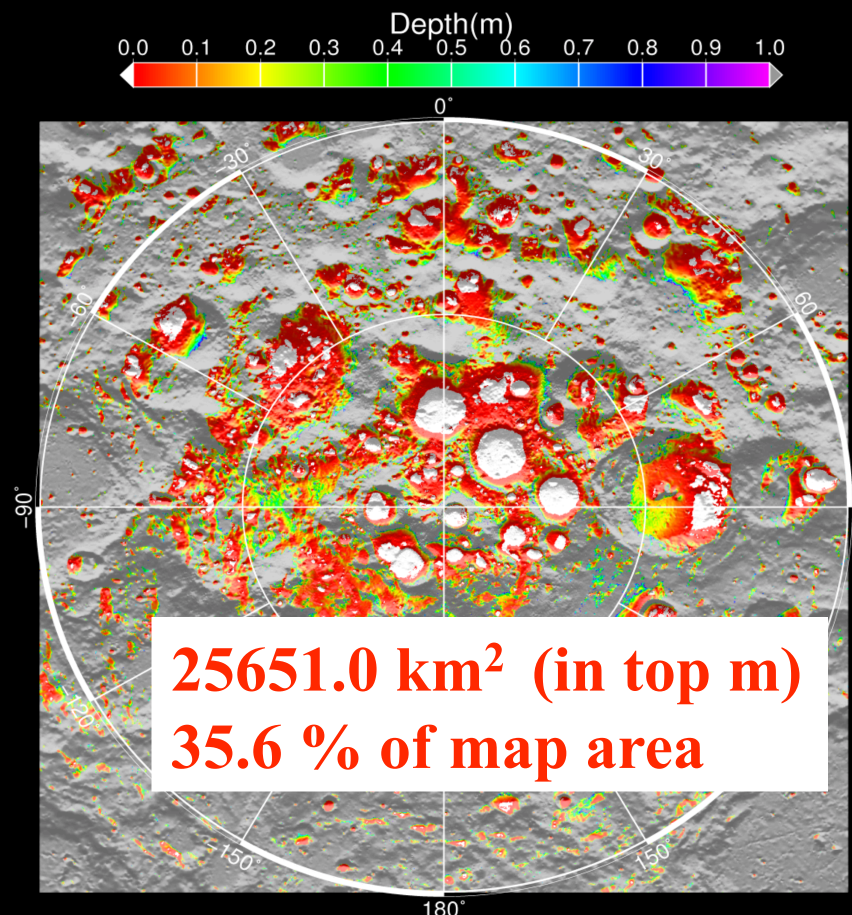
When was there Ice on the Moon?



Stability modeling: Identifying "lunar permafrost"

In the simplest case, one can look at diffusive barriers to ice loss, which will greatly increase ice stability



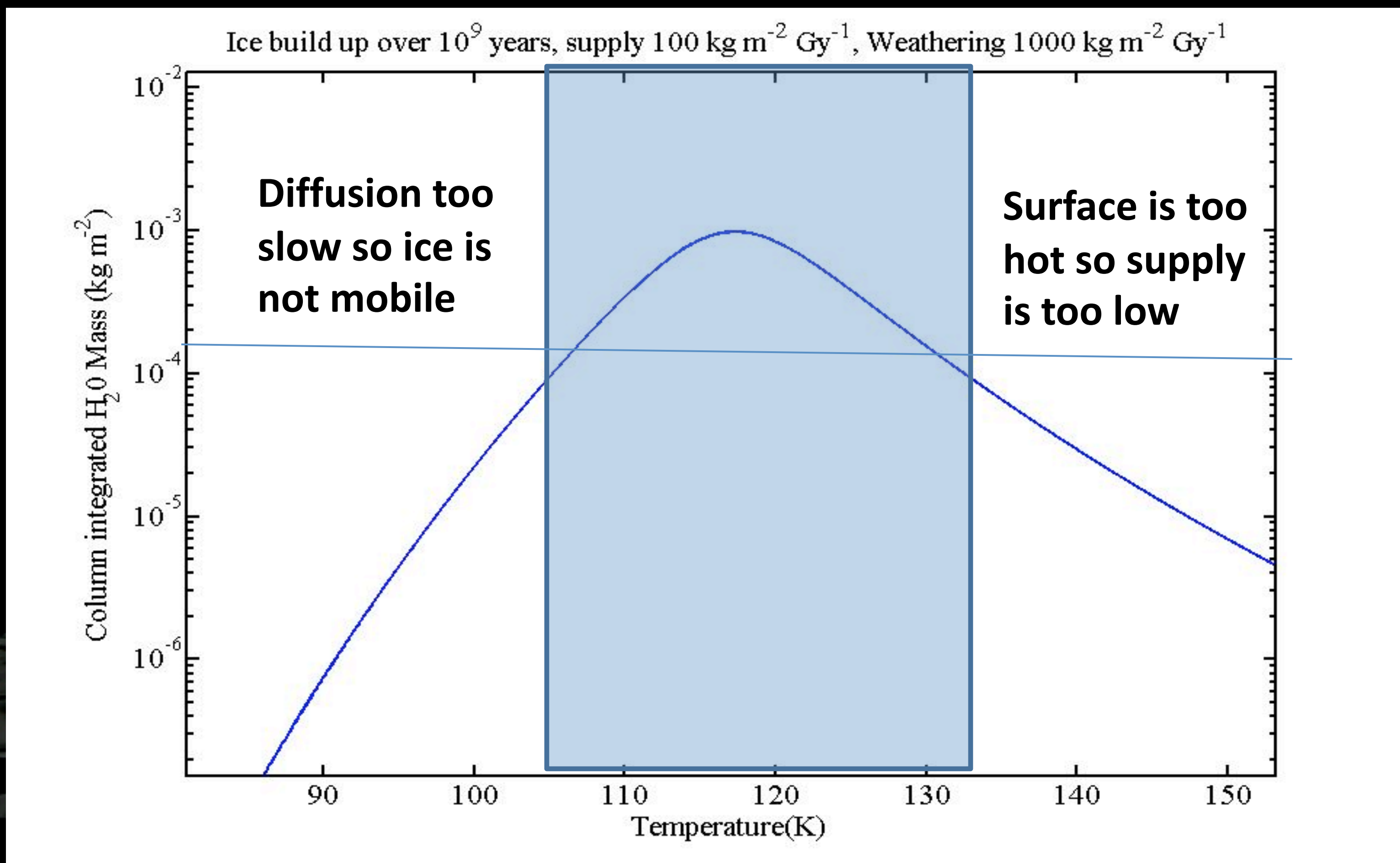


Which greatly changes the definition of "cold trap"
Margot (1999) shadowed area estimate 5100 km^2
(Note: Some shadows > 100K)

Diffusion Modeling: quantifying "lunar permafrost"

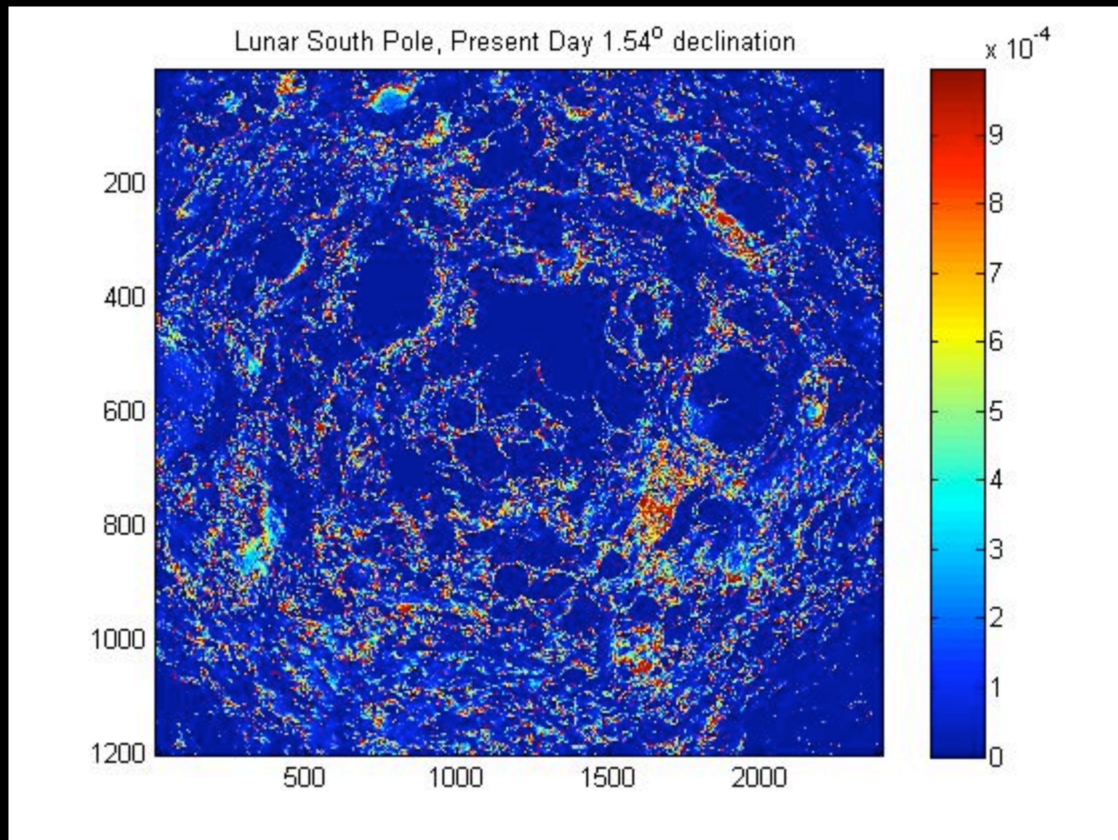
For a given surface supply and loss rate, one can look at how much ice might build up in the regolith at a give temperature

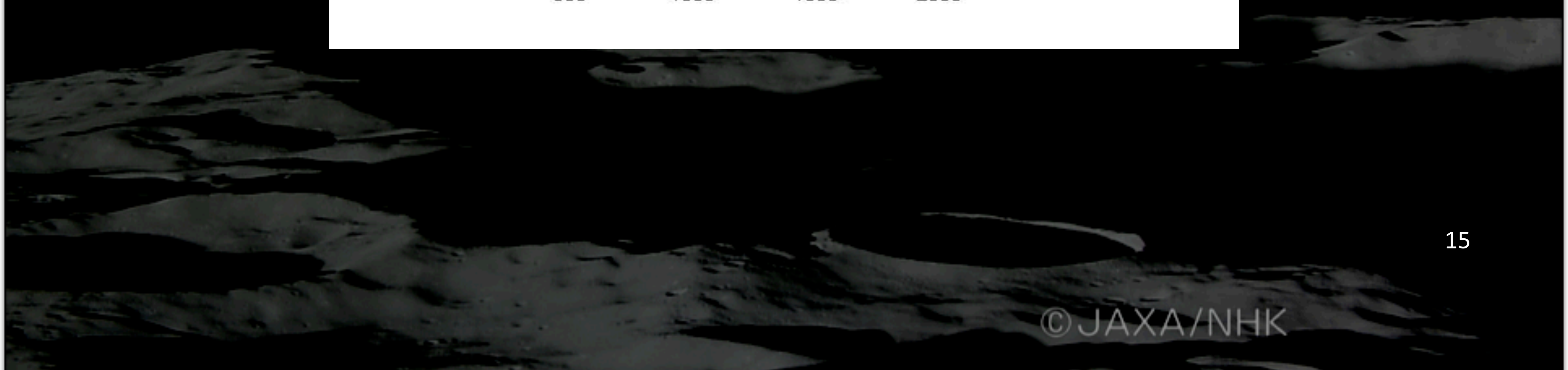
In this example, surface weathering exceeds supply, so now surface ice would form (Schorghofer and Taylor, 2007).



Applications: Mobility History

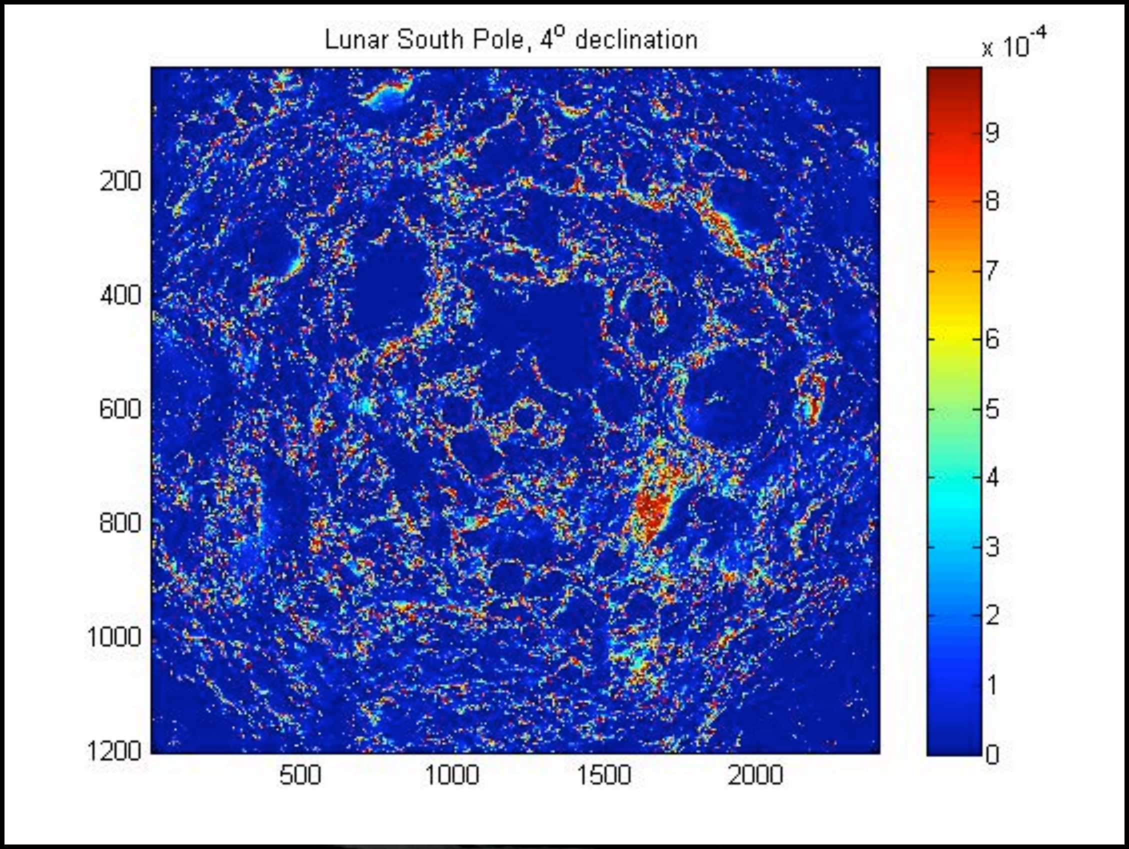
When and Where was there Ice on the Moon?





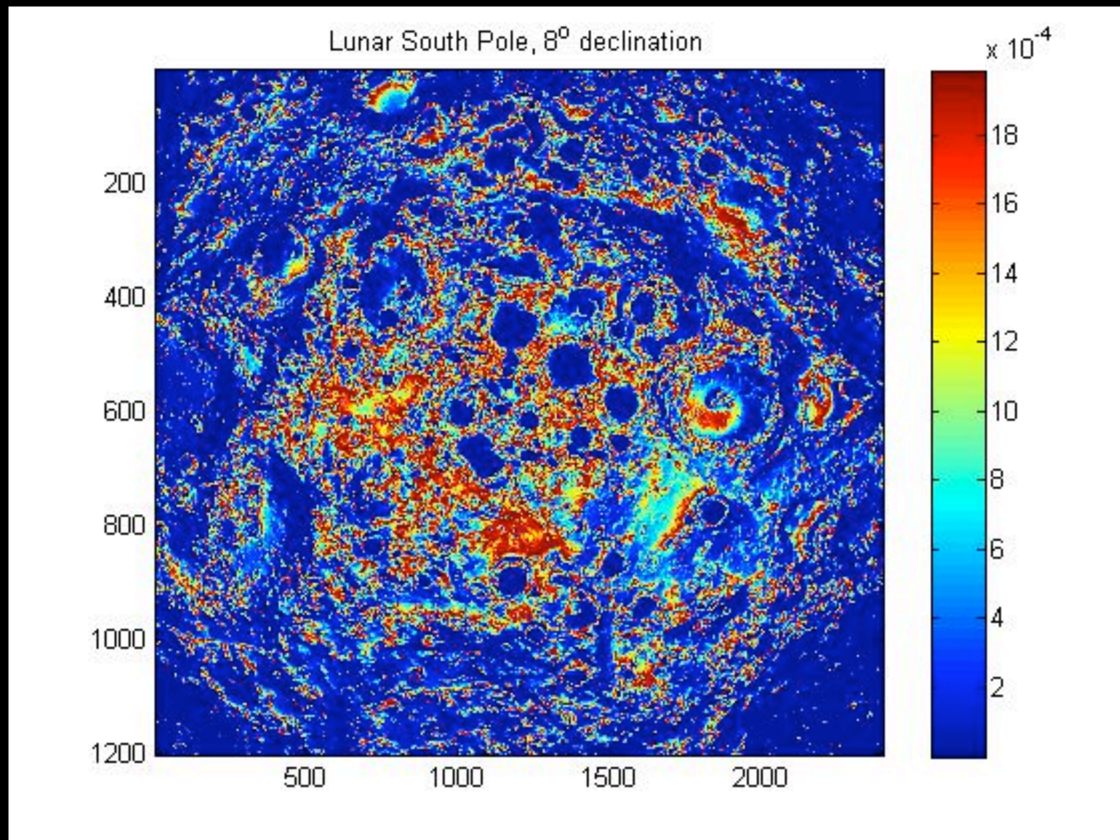
Applications: Mobility History

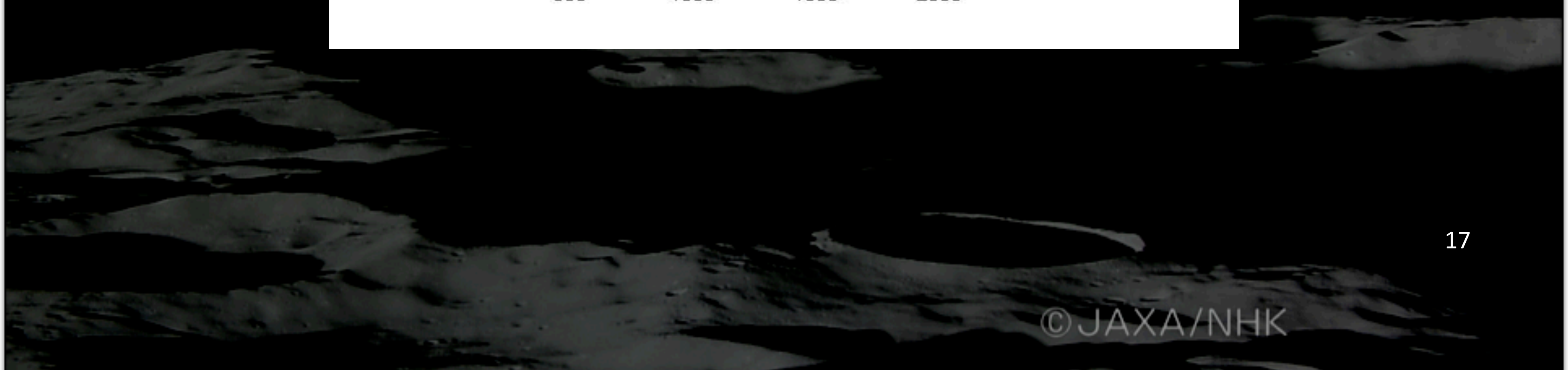
When and Where was there Ice on the Moon?



Applications: Mobility History

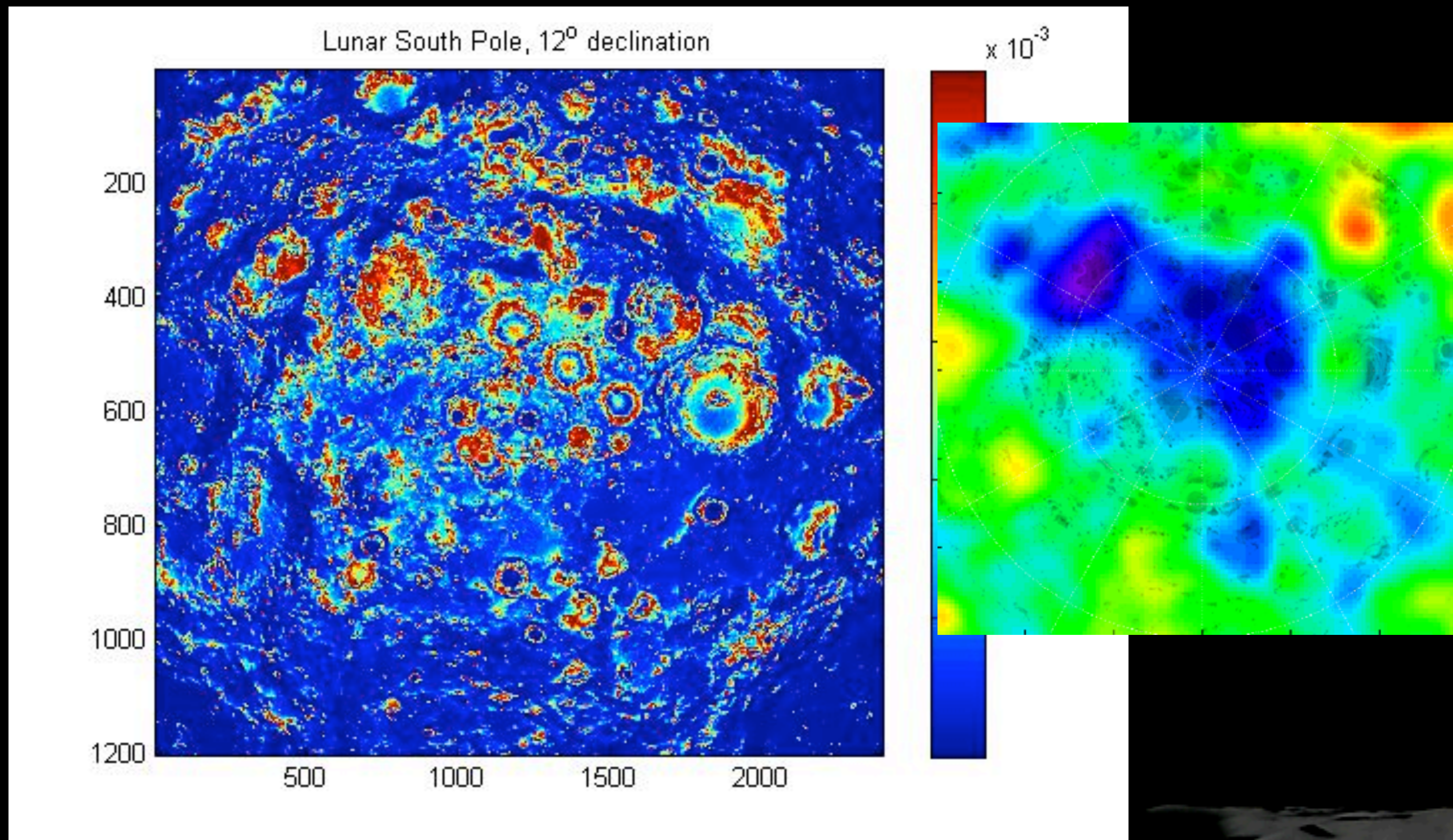
When and Where was there Ice on the Moon?

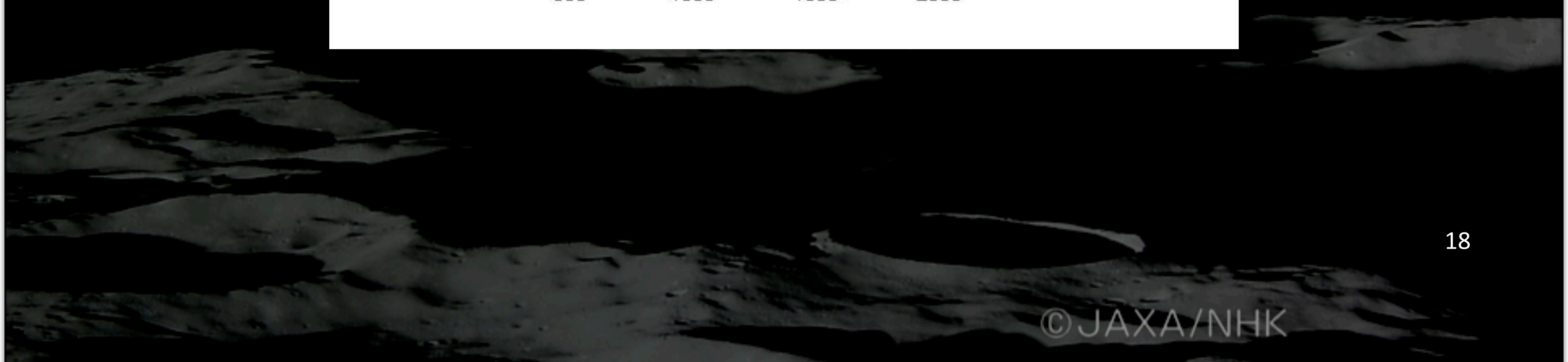




Applications: Mobility History

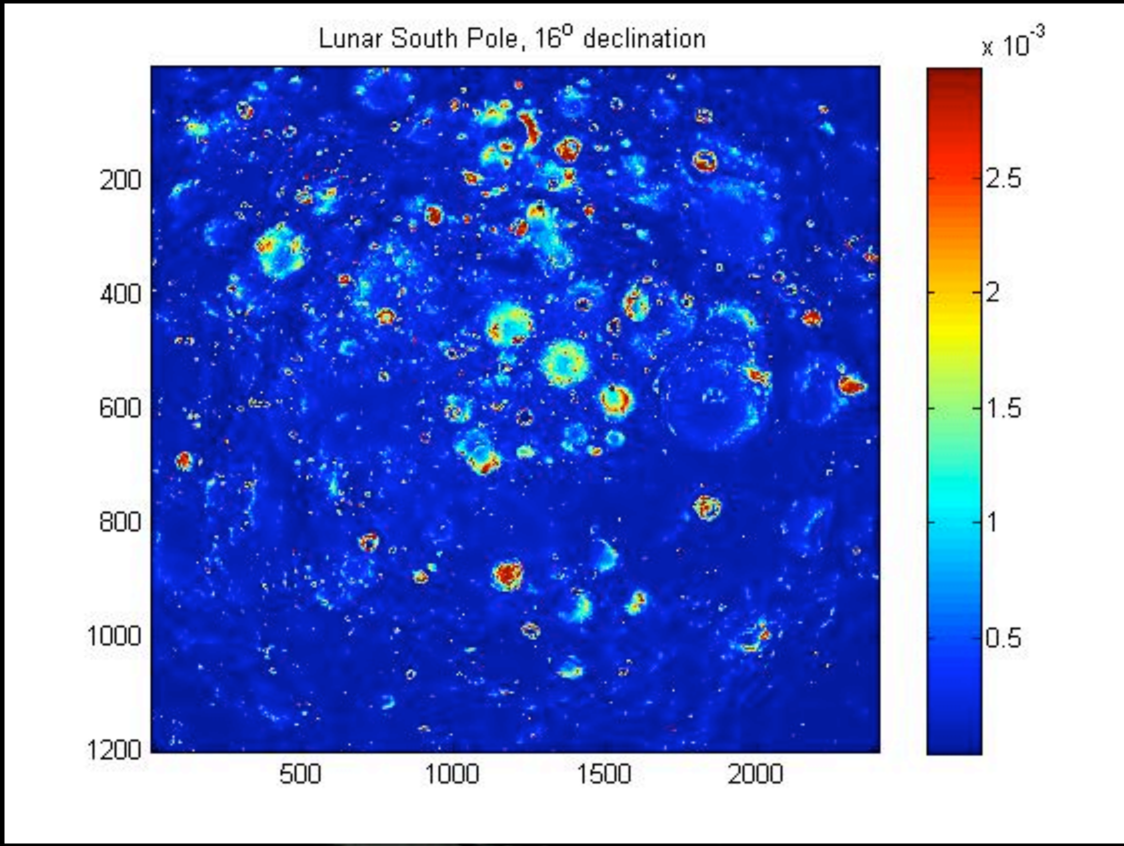
When and Where was there Ice on the Moon?





Applications: Mobility History

When and Where was there Ice on the Moon?

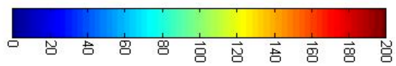


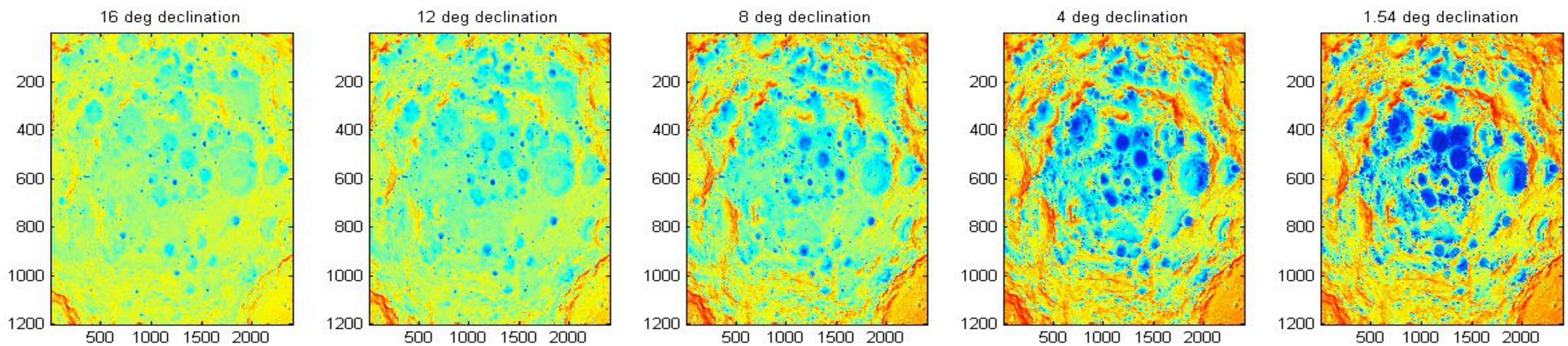
Diffusion Modeling: Applications

History of post-Cassini thermal depositional environments

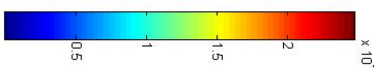
When and Where was there Ice on the Moon?

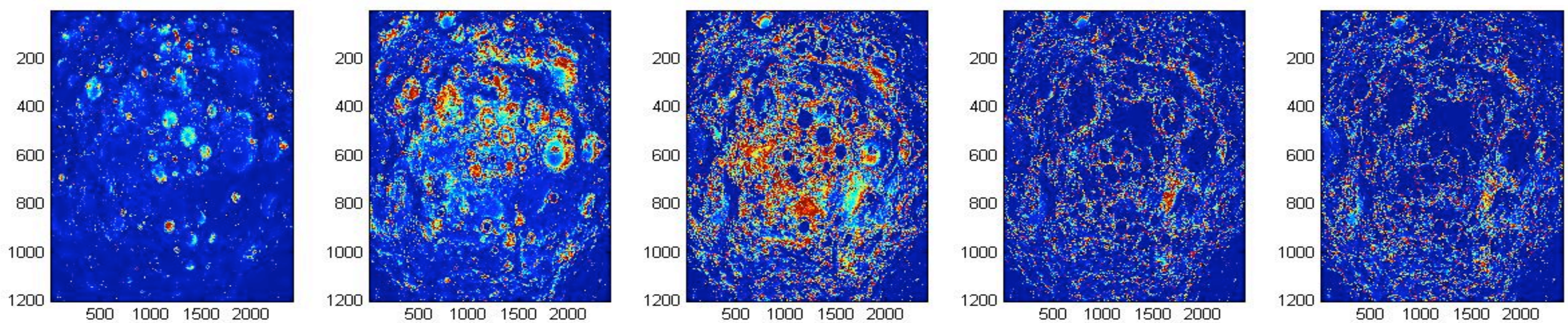
Temperature (0-200 K color stretch)

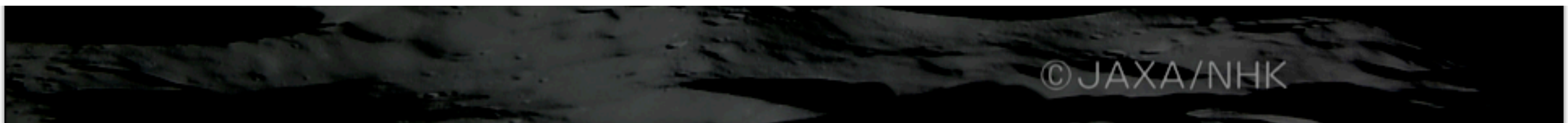




Column integrated ice mass in 10^8 years ($0\text{-}10^{-3}$ kg m^{-2} color stretch)





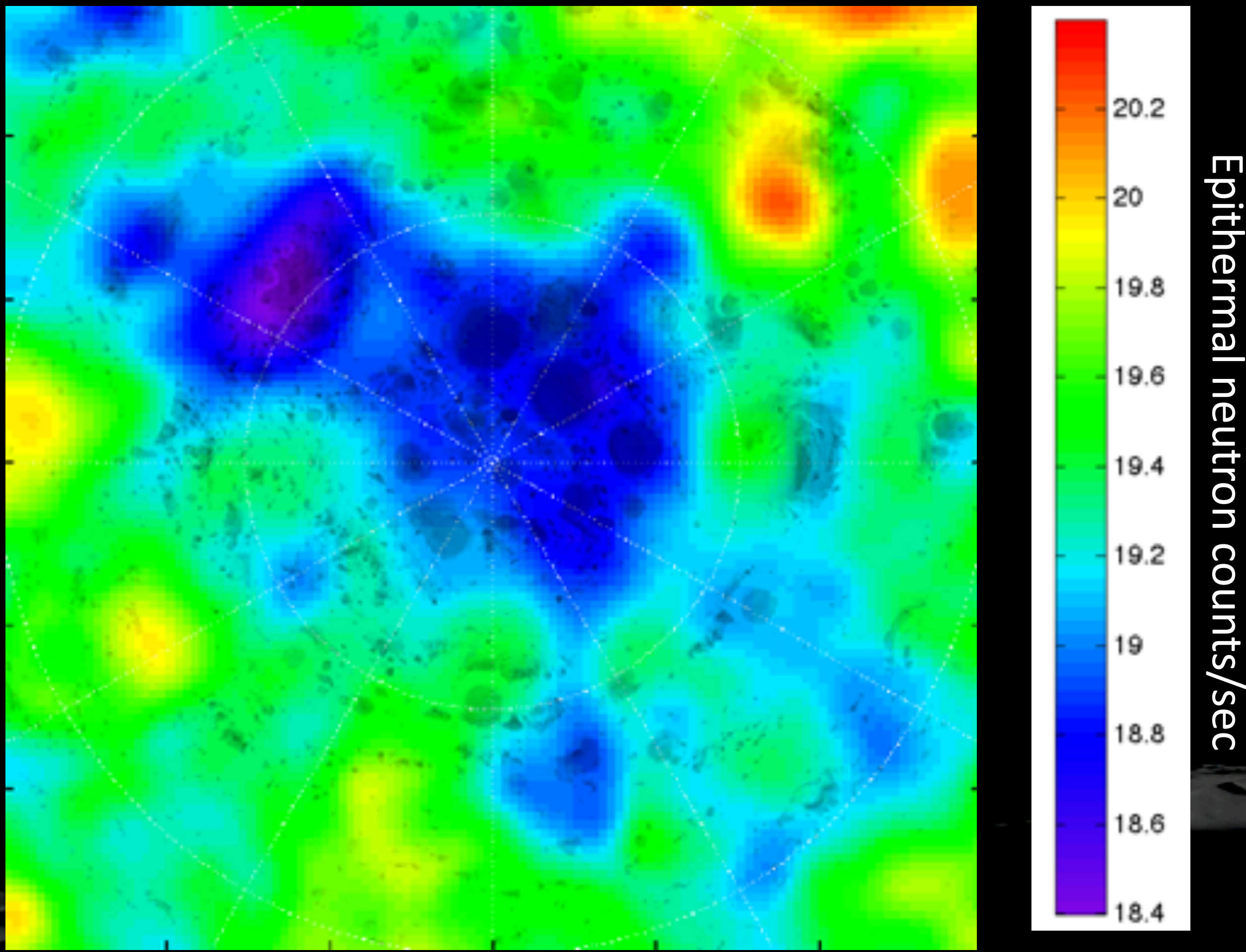


Diffusion Modeling: Applications

When, Where, and How much Ice is on the Moon?

Constraining model parameters based on LPNS data

One can then adjust <u>supply</u> axis, surface <u>weathering</u> rate, and <u>gradening</u> processes, as a function of semimajor for a given recession rate

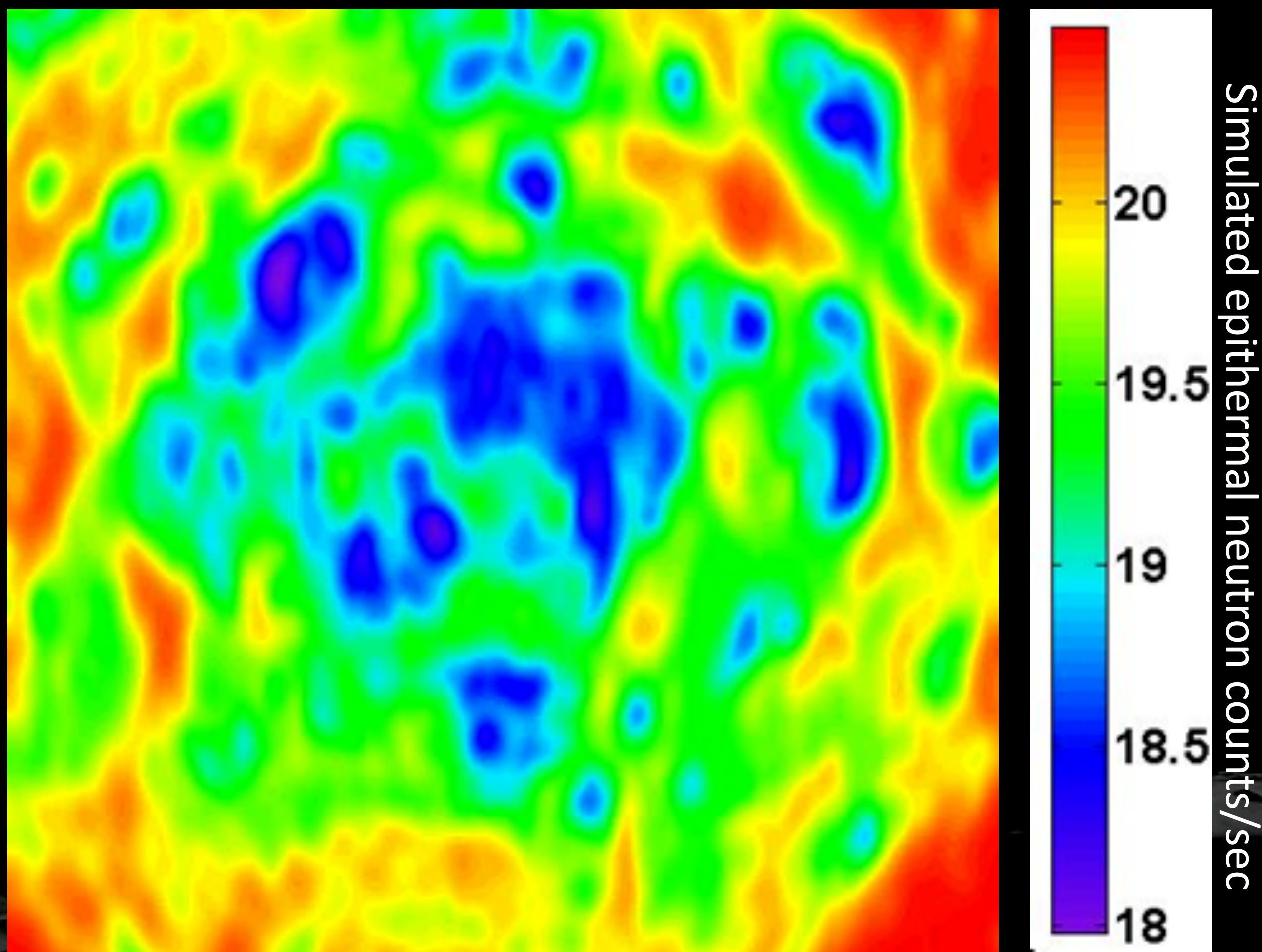


Work in progress: Comparing to LPNS

When, Where, and How much Ice is on the Moon?

Constraining model parameters based on LPNS data

Example model where supply was 3x greater at 30RE than current (assumed 100 kg/m^2/Gyr), weathering 7.5x current supply (no surface deposit), no gardening, recession 3x faster at 30RE



Conclusions

- Thermal picture is crucial for understanding ice on the Moon, past and present

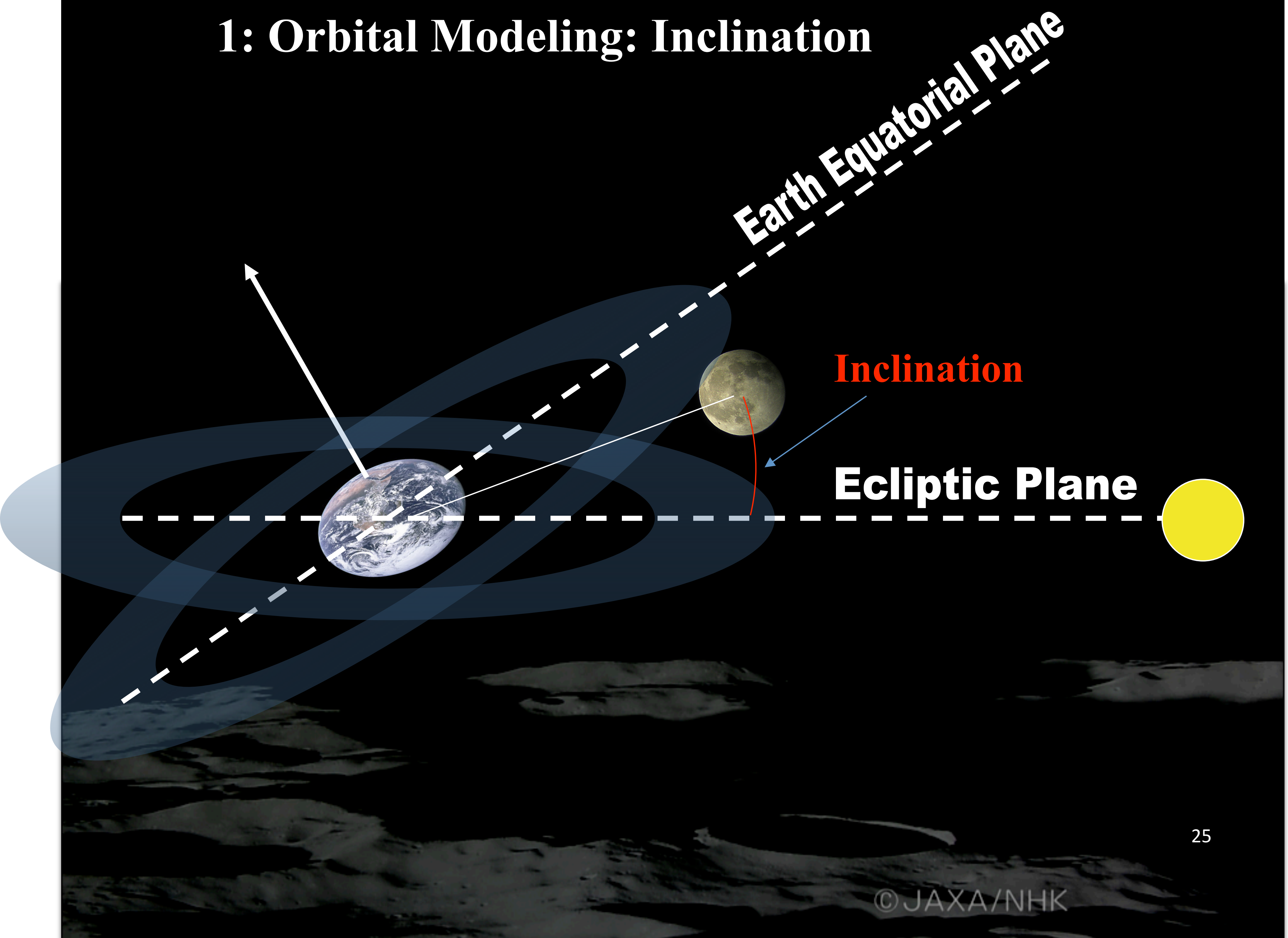
- Cold traps are presently much more complex than the community has included and evolve over time

- Very simple models show promise to answer big questions of When, Where, How, and Why ice might be on the Moon

- More detailed modeling justified

End

1: Orbital Modeling: Inclination



1: Orbital Modeling: Obliquity

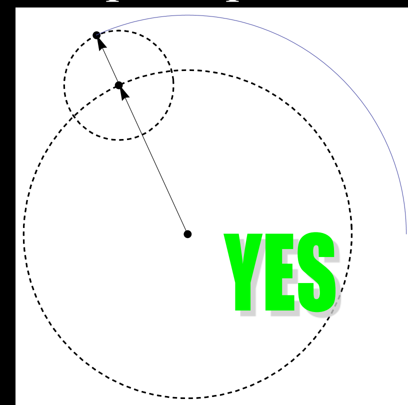
For a fully damped spin pole
(Due to dissipation within Moon)

$$\frac{dn}{dt} = \frac{ds}{dt}$$

Depends on lunar semimajor axis

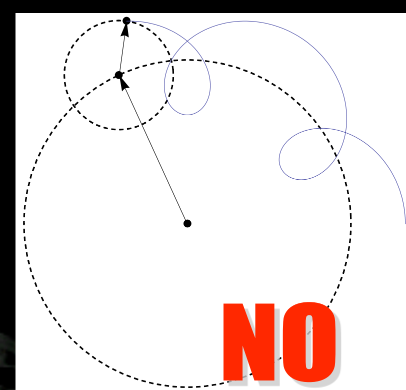
Depends on lunar moments of inertia and obliquity

Damped Spin Pole

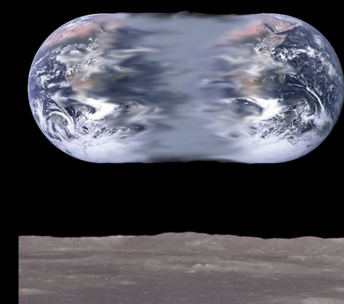


Stationary Earth

Undamped Spin Pole

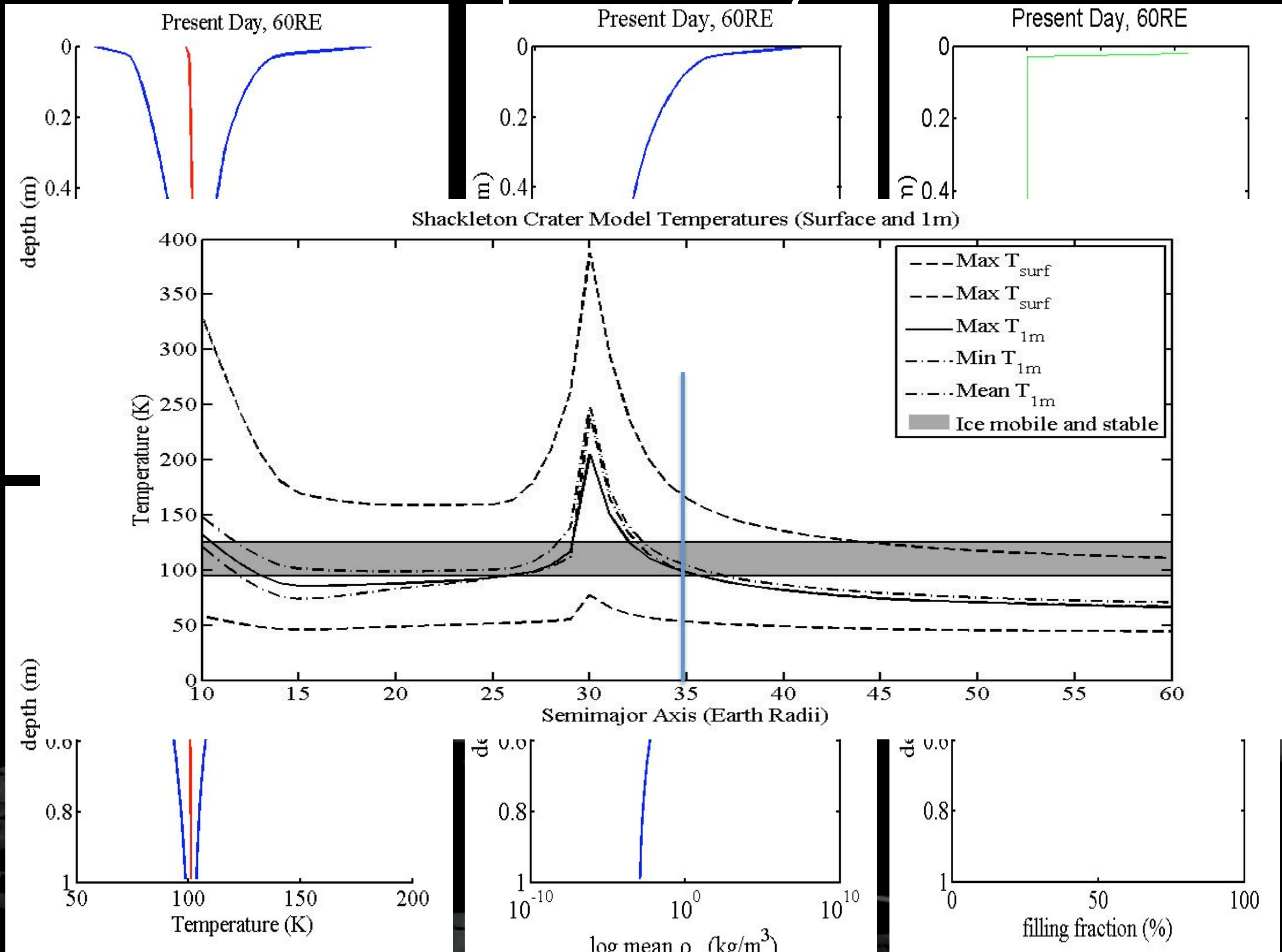


"Precessing" Earth

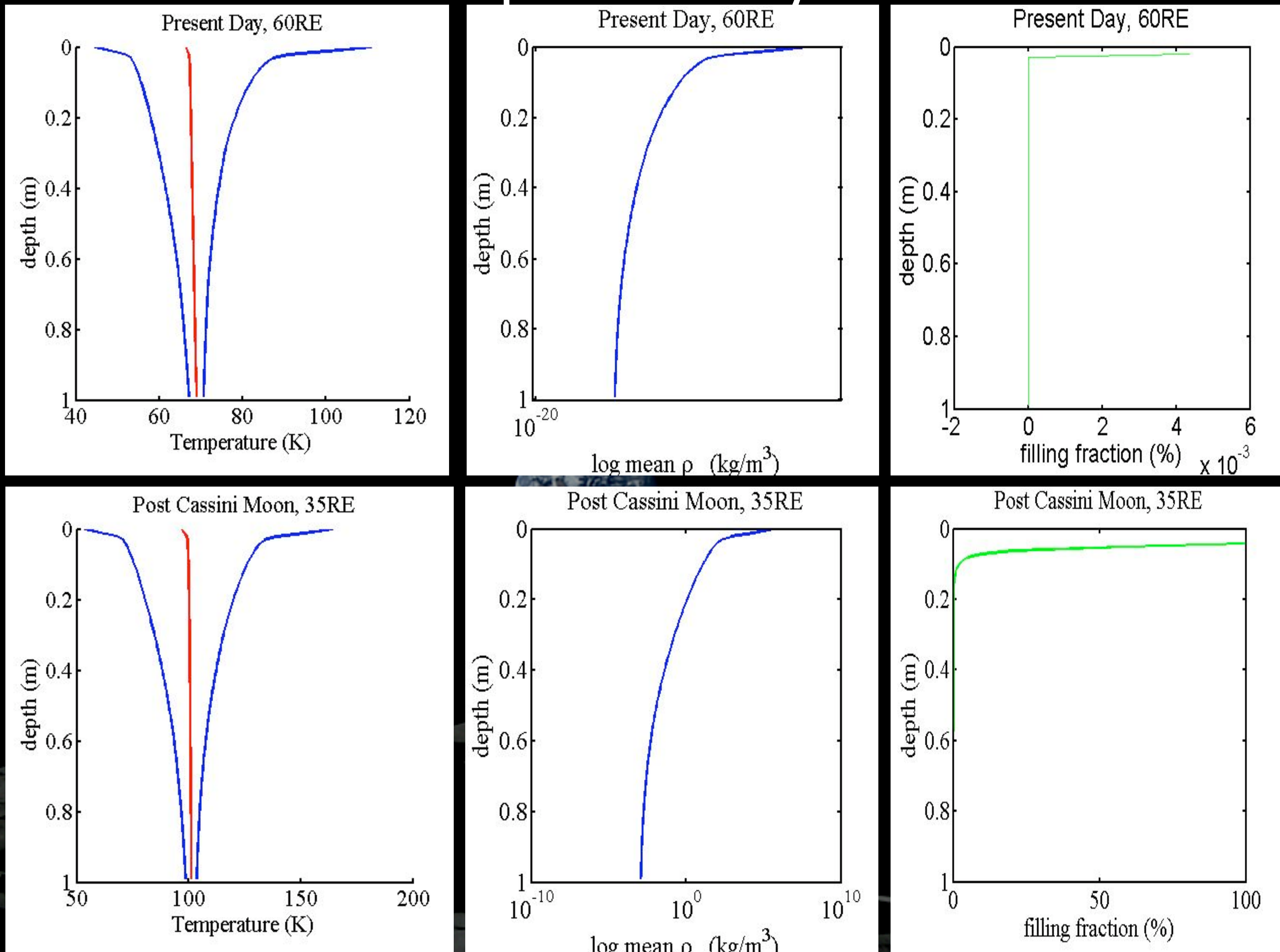


So dissipation will drive obliquity to change in predictable way for given shape

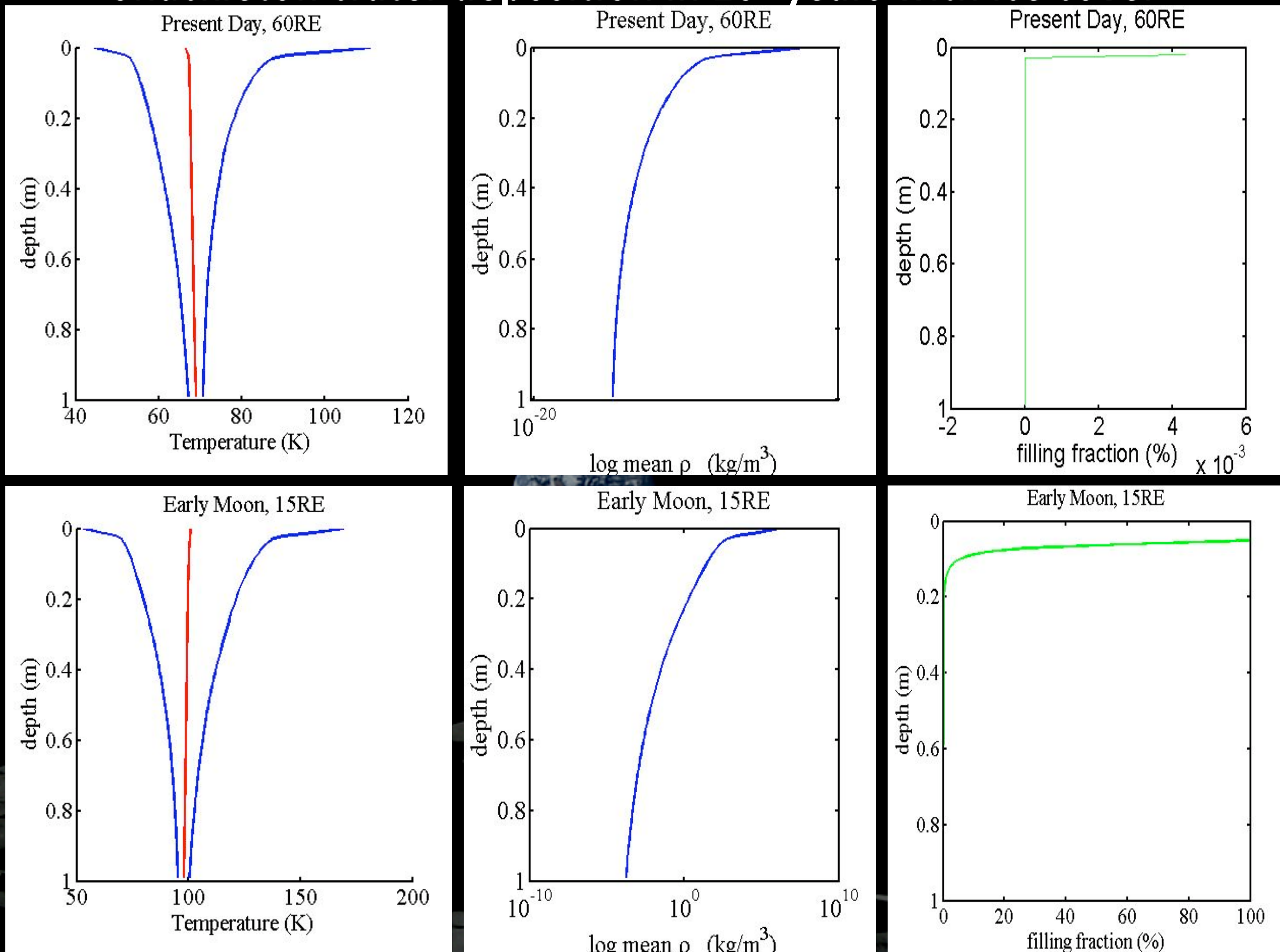
Shackleton crater deposition in 10^8 years with ice cover

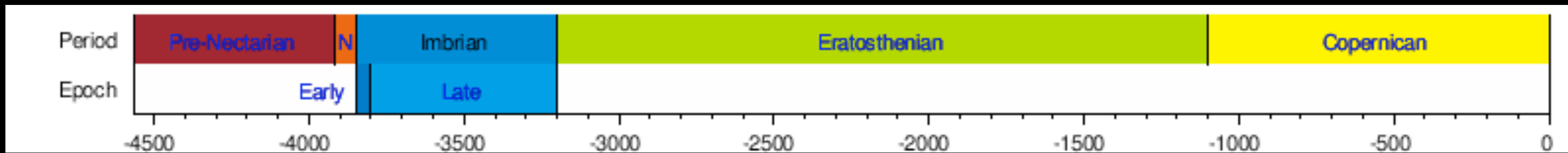


Shackleton crater deposition in 10^8 years with ice cover

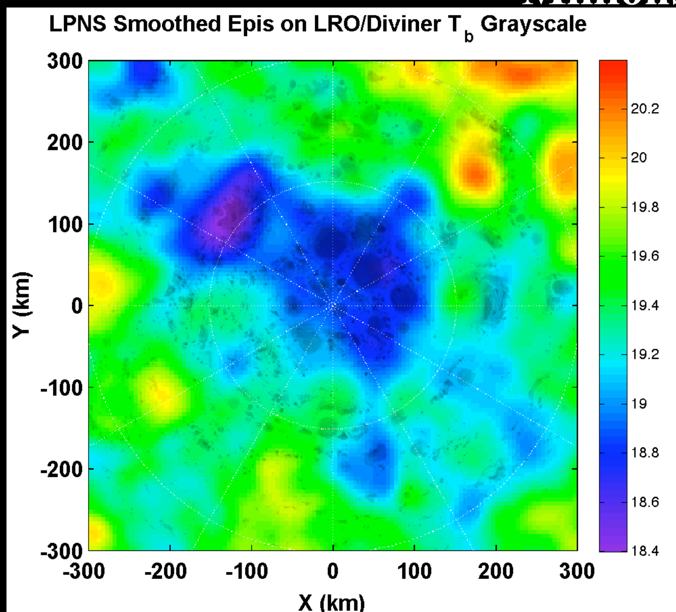


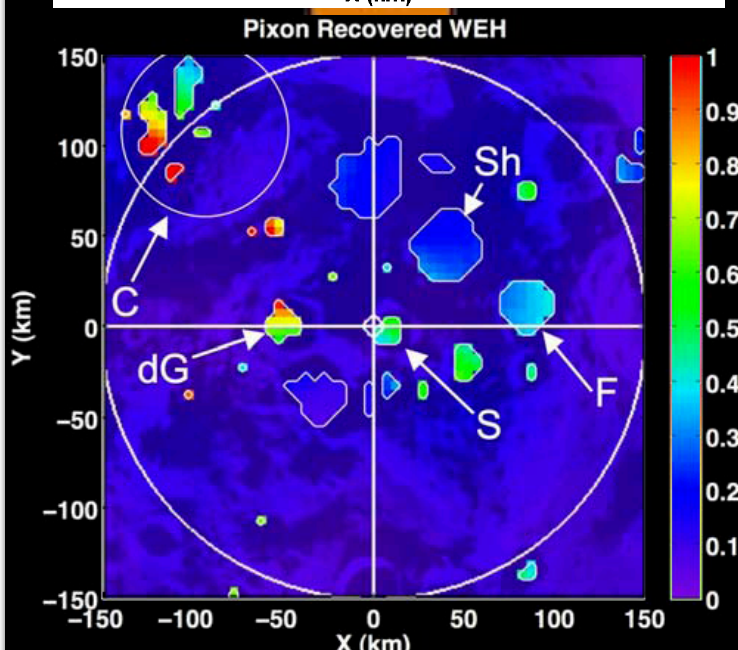
Shackleton crater deposition in 10^8 years with ice cover





Millions of years before present

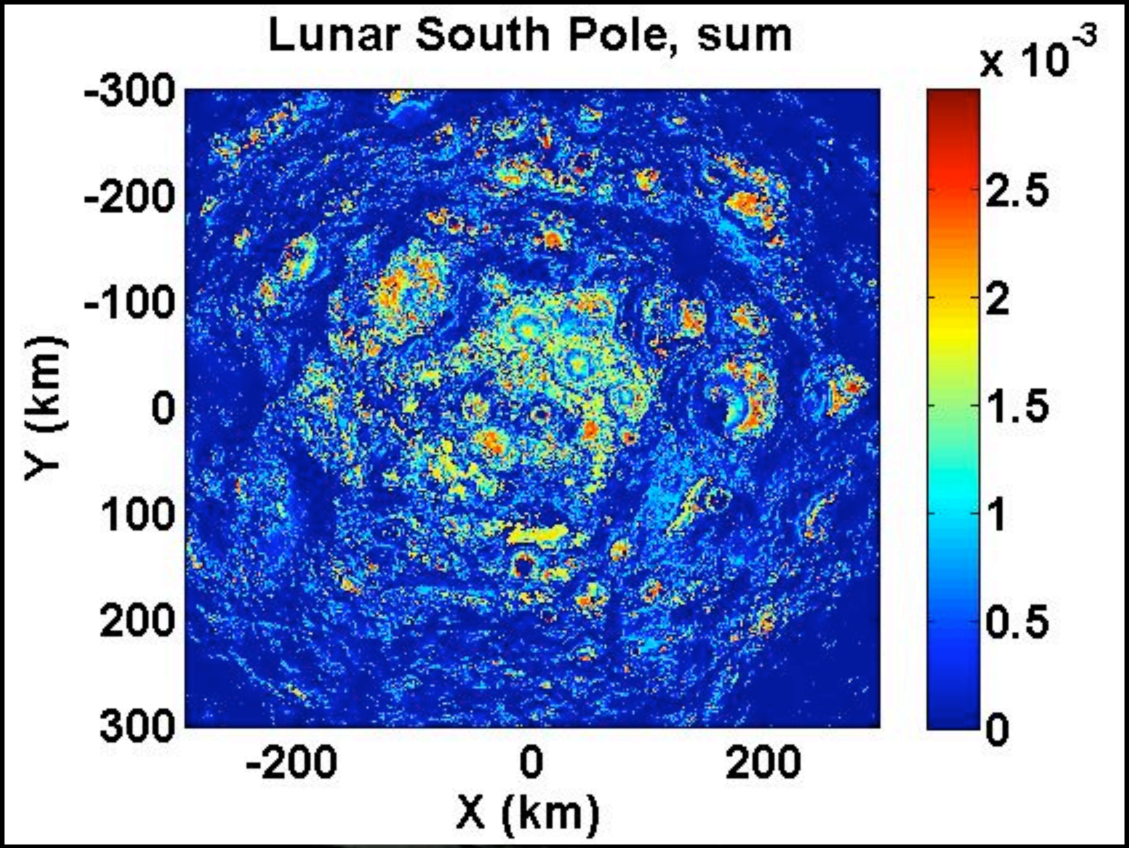


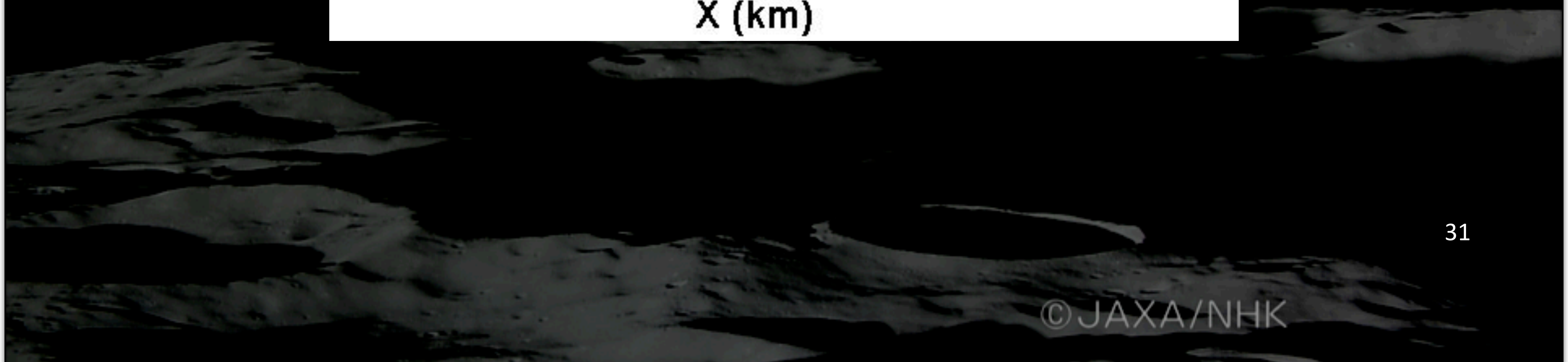


ges, yellow being youngest (Copernican),
sthenian), Imbrian (blue)
ec-tarian and pre-Nectarian)

Applications: Net ice deposition

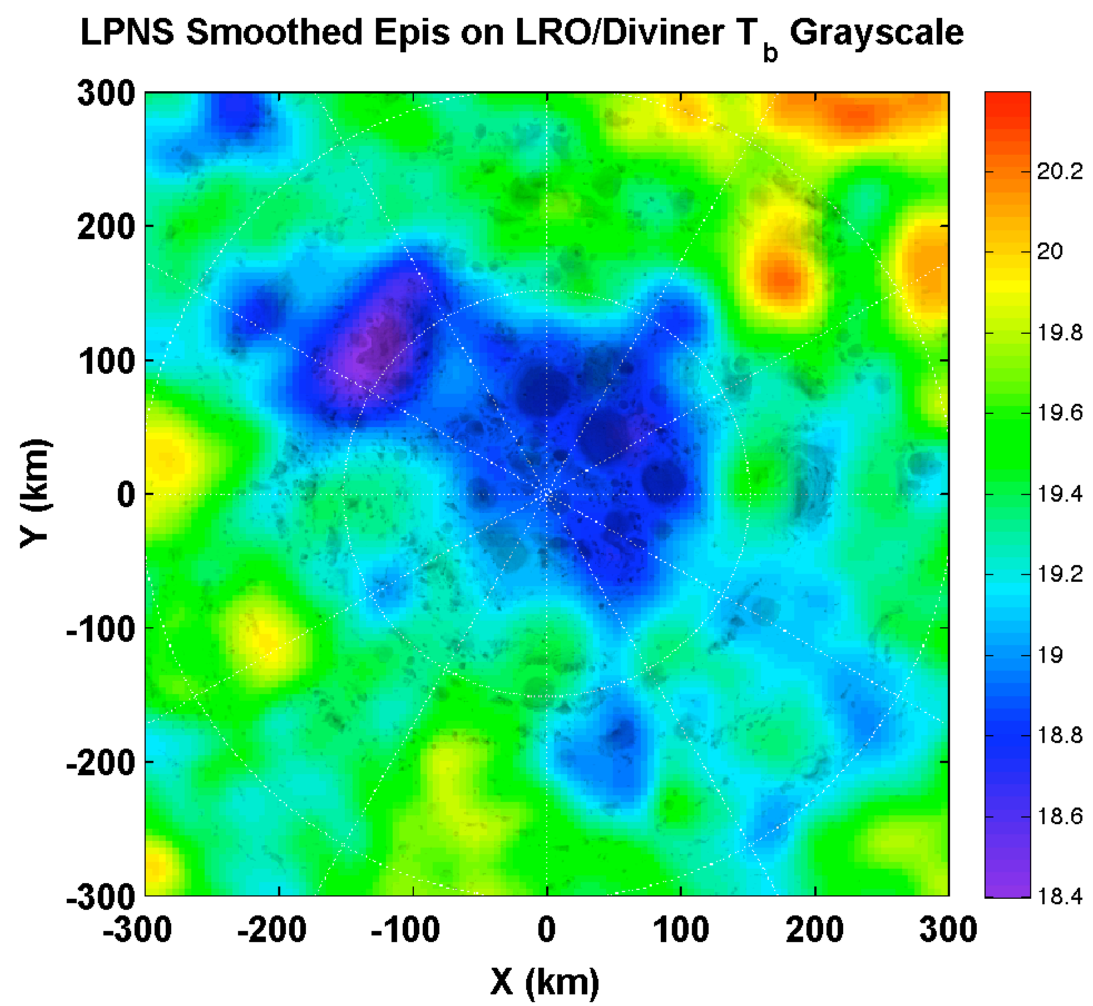
How much Ice is on the Moon?





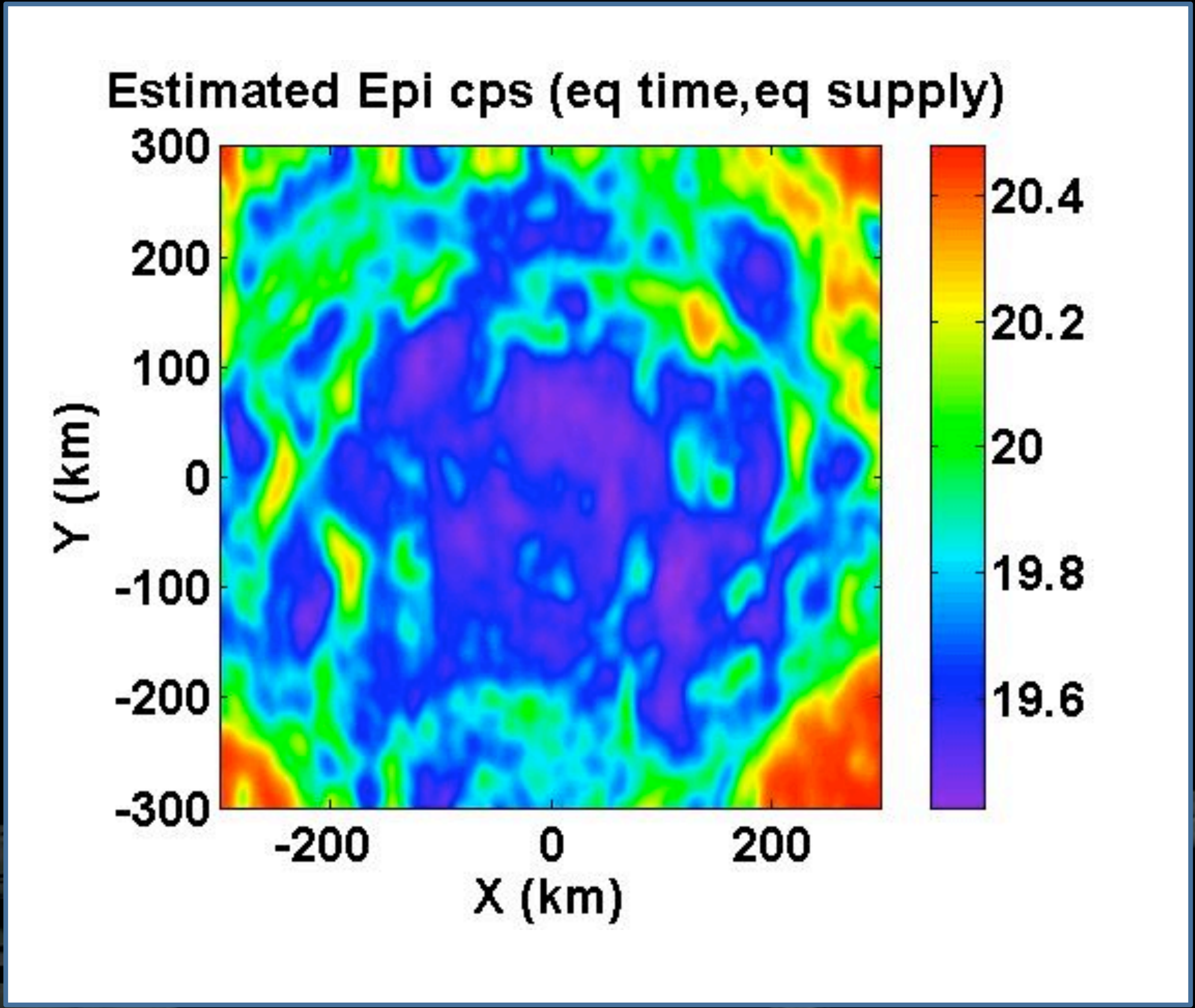
Applications: Neutron Distribution

How much Ice is on the Moon?



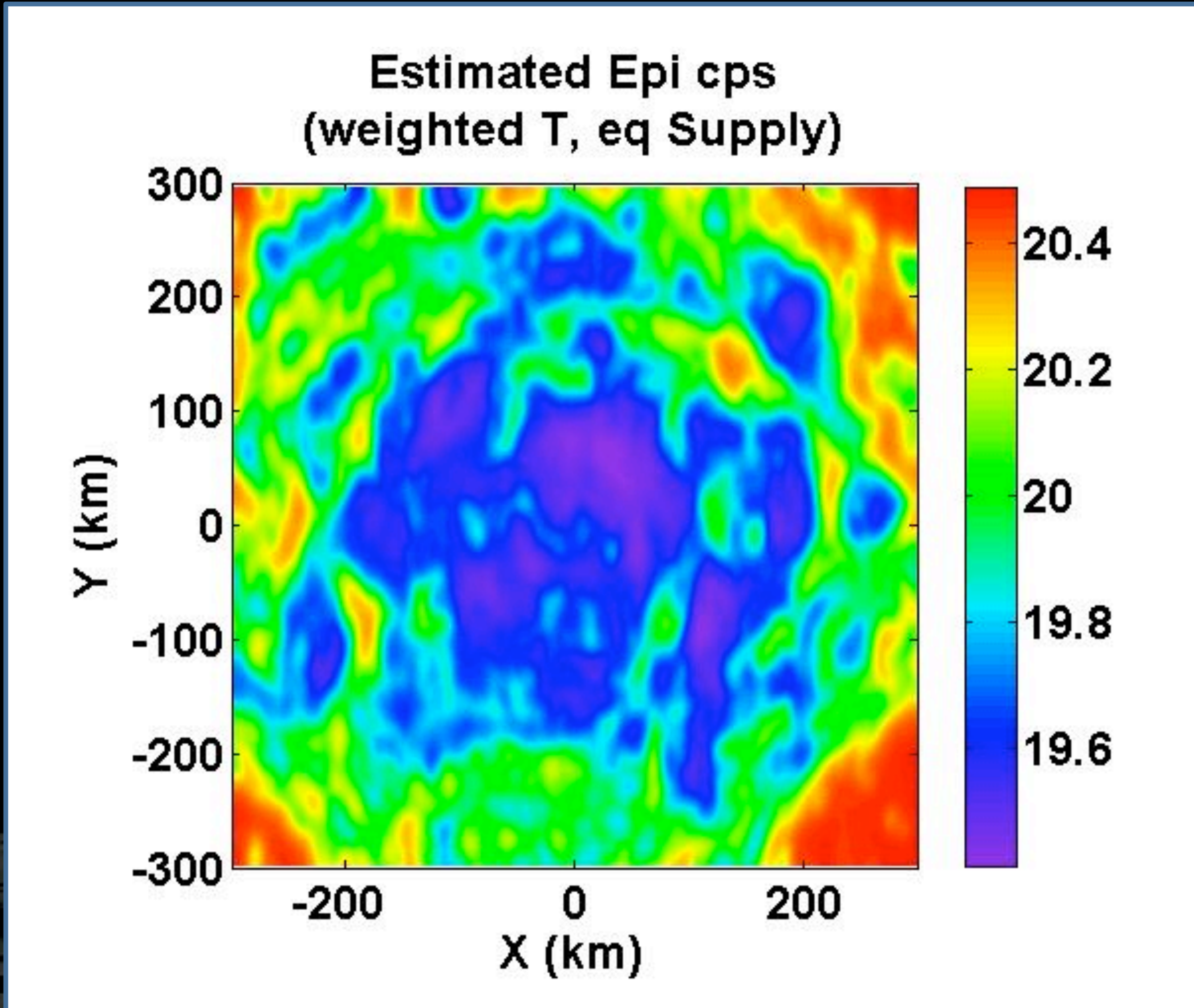
Applications: Neutron Distribution

How much Ice is on the Moon?



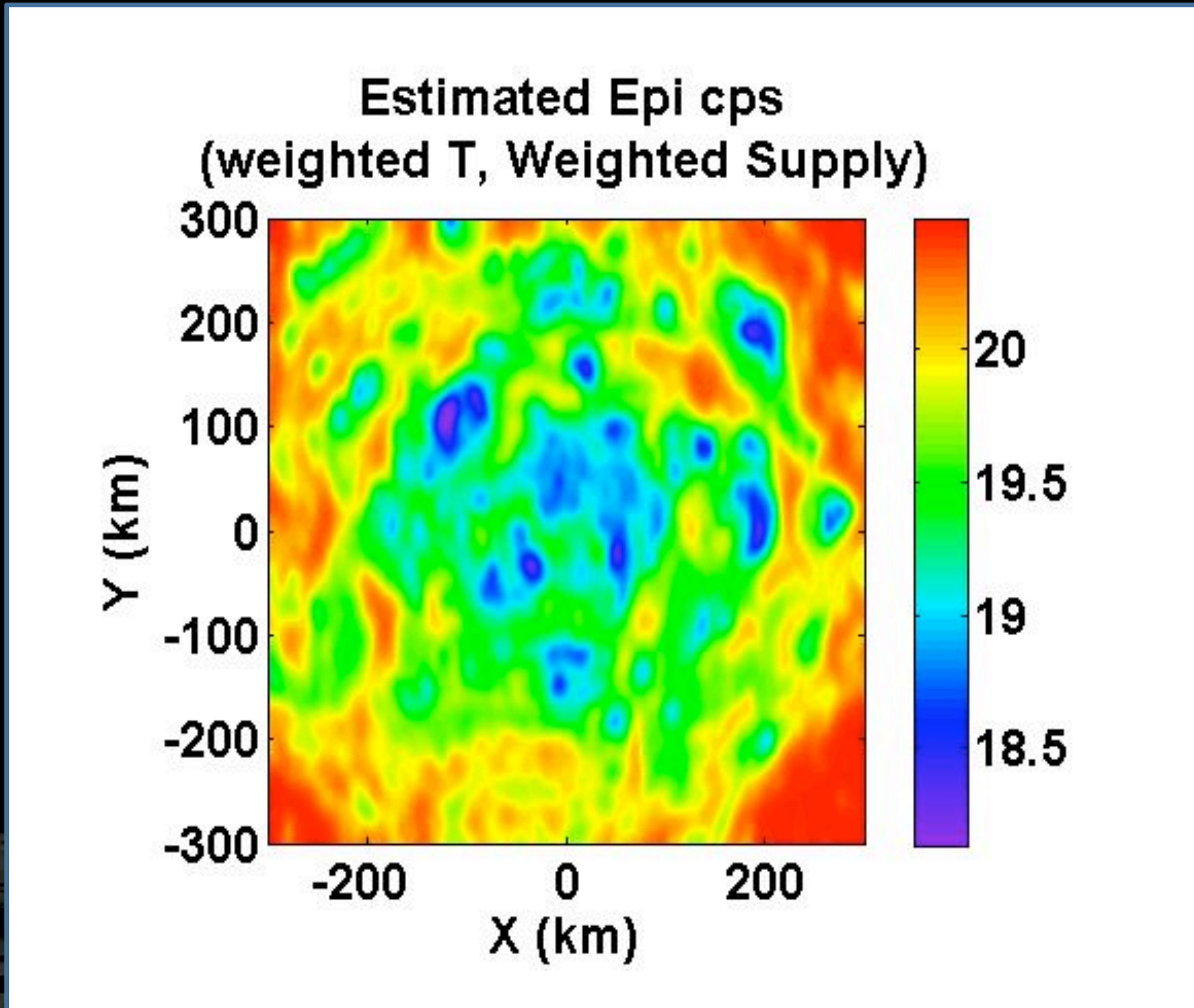
Applications: Neutron Distribution

How much Ice is on the Moon?



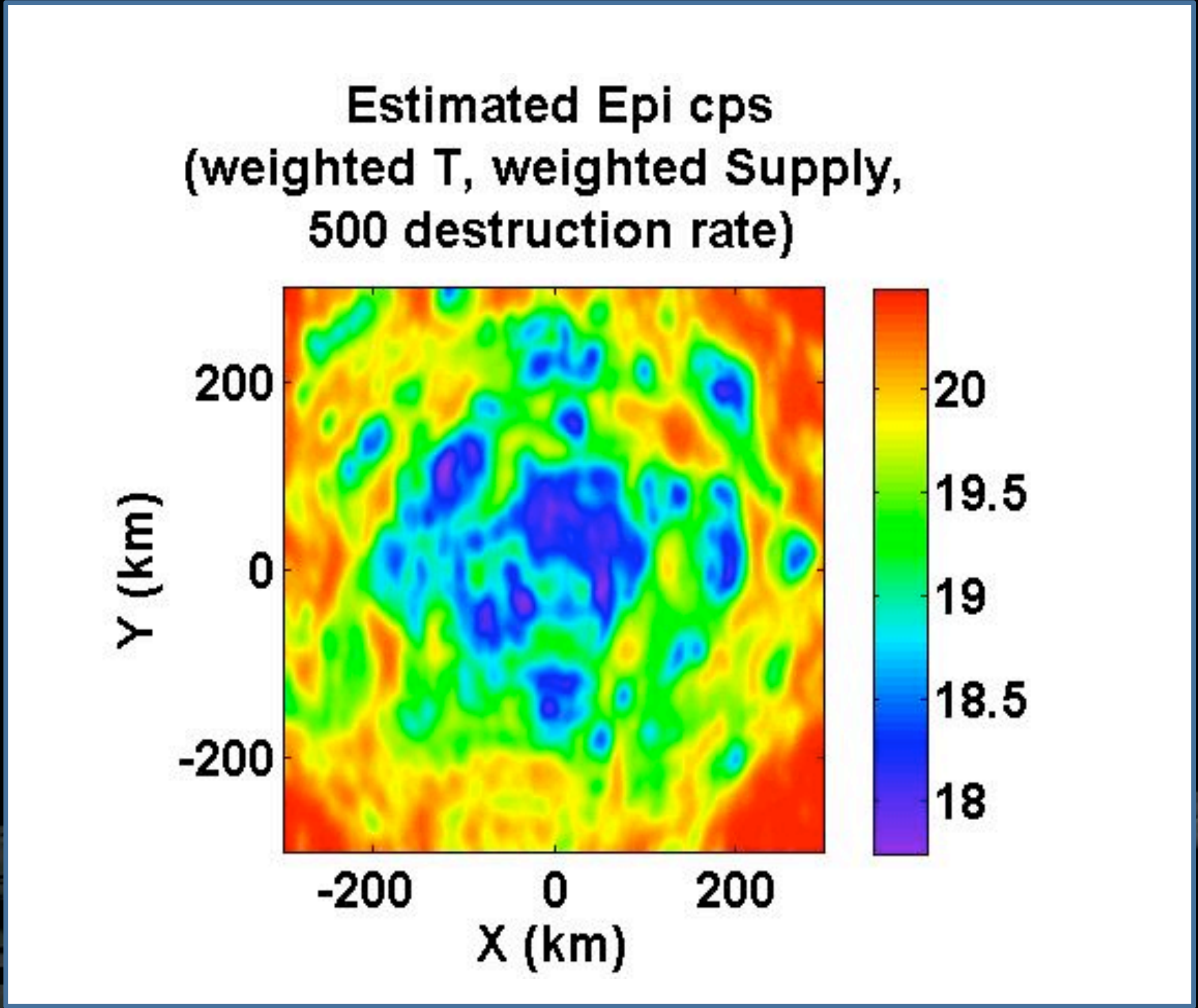
Applications: Neutron Distribution

How much Ice is on the Moon?



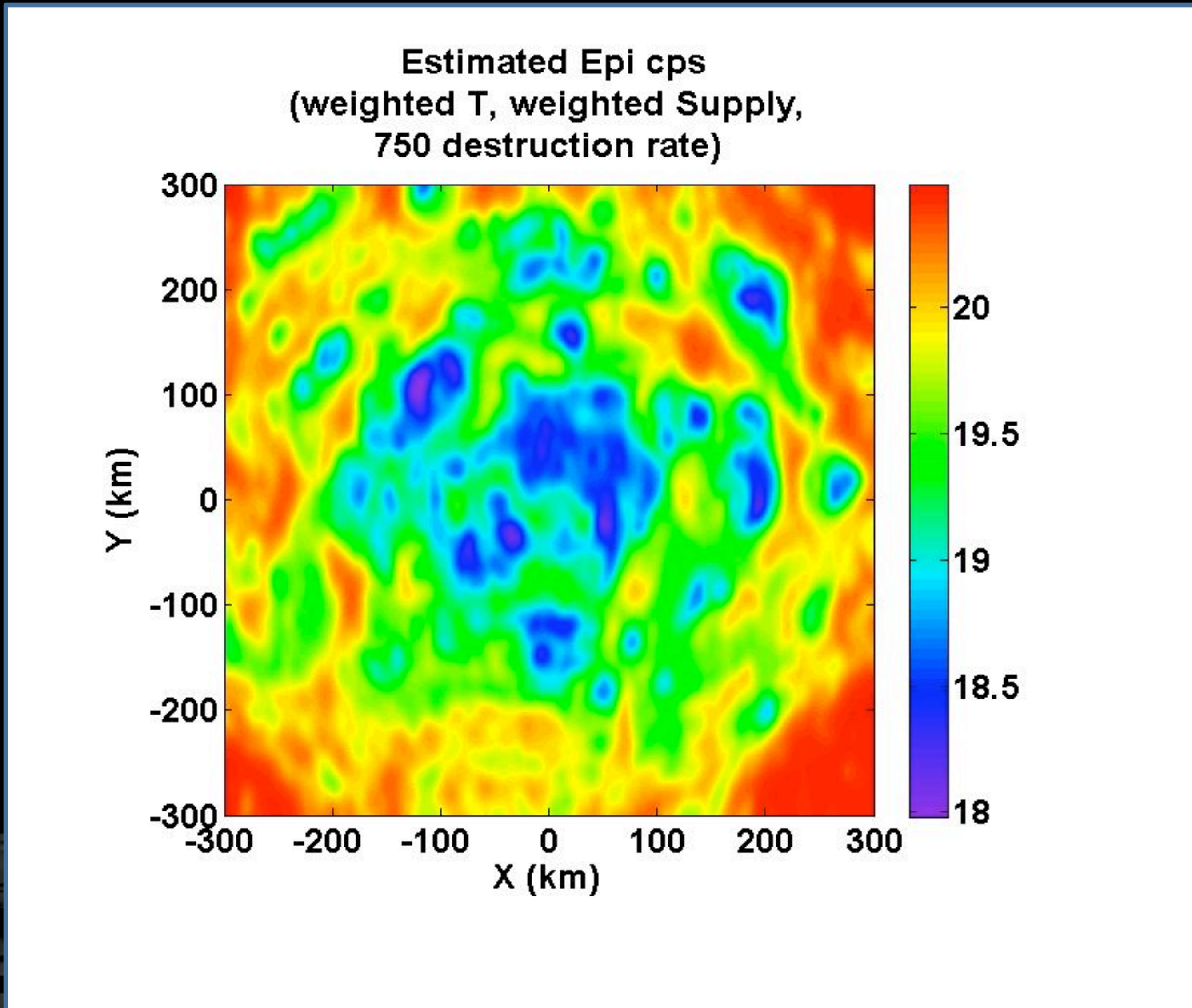
Applications: Neutron Distribution

How much Ice is on the Moon?



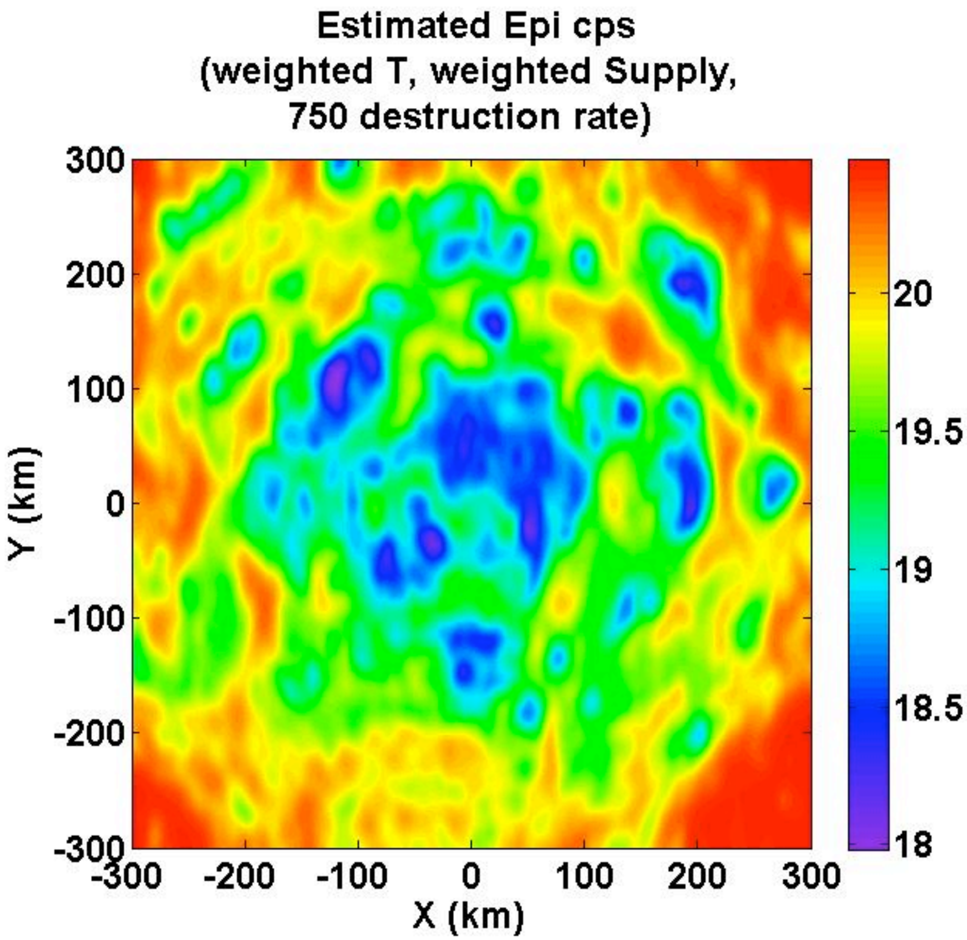
Applications: Neutron Distribution

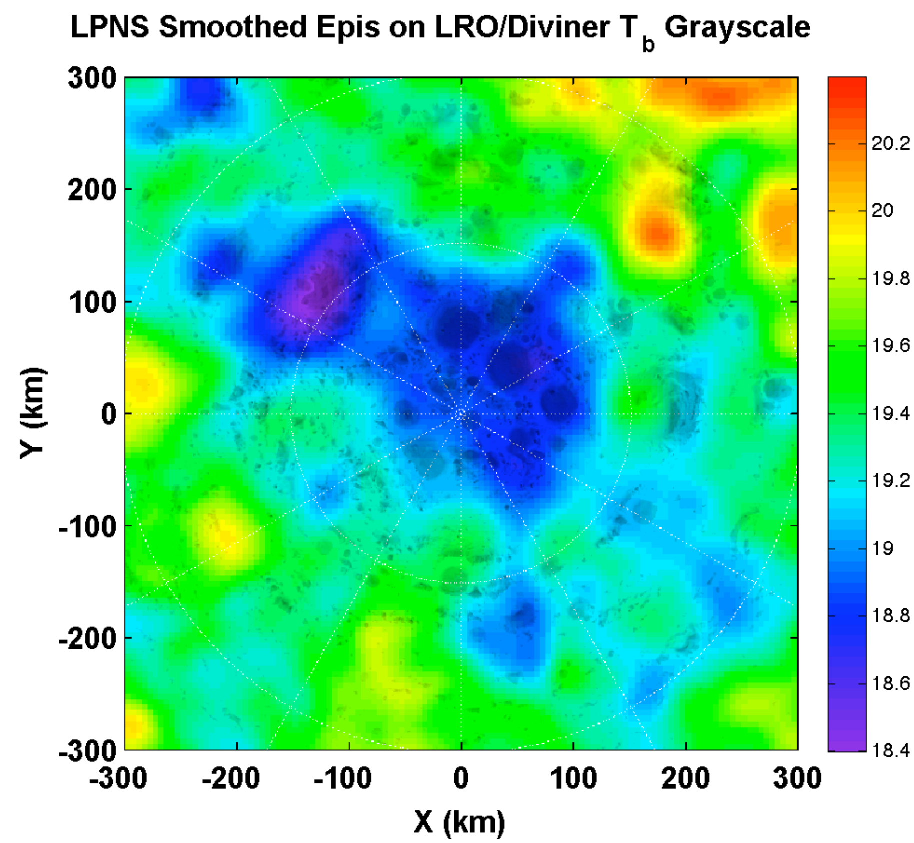
How much Ice is on the Moon?

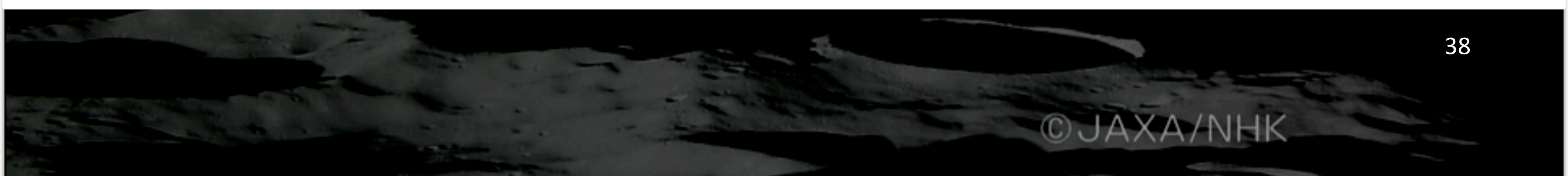


Applications: Neutron Distribution

How much Ice is on the Moon?

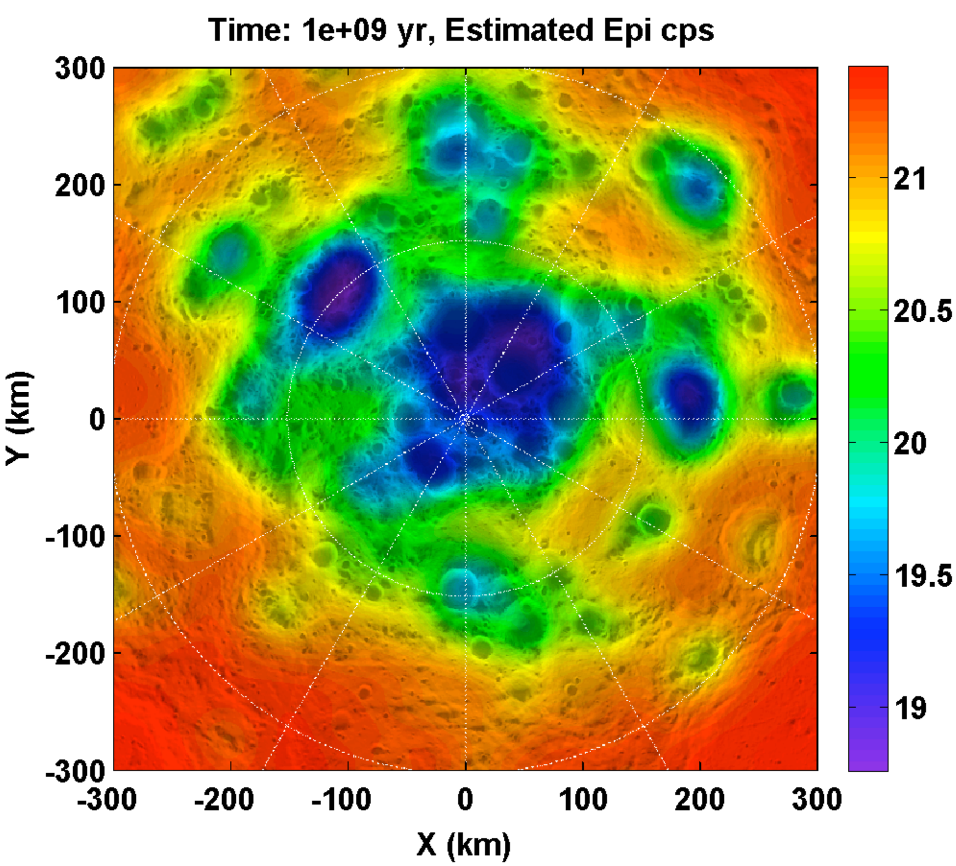


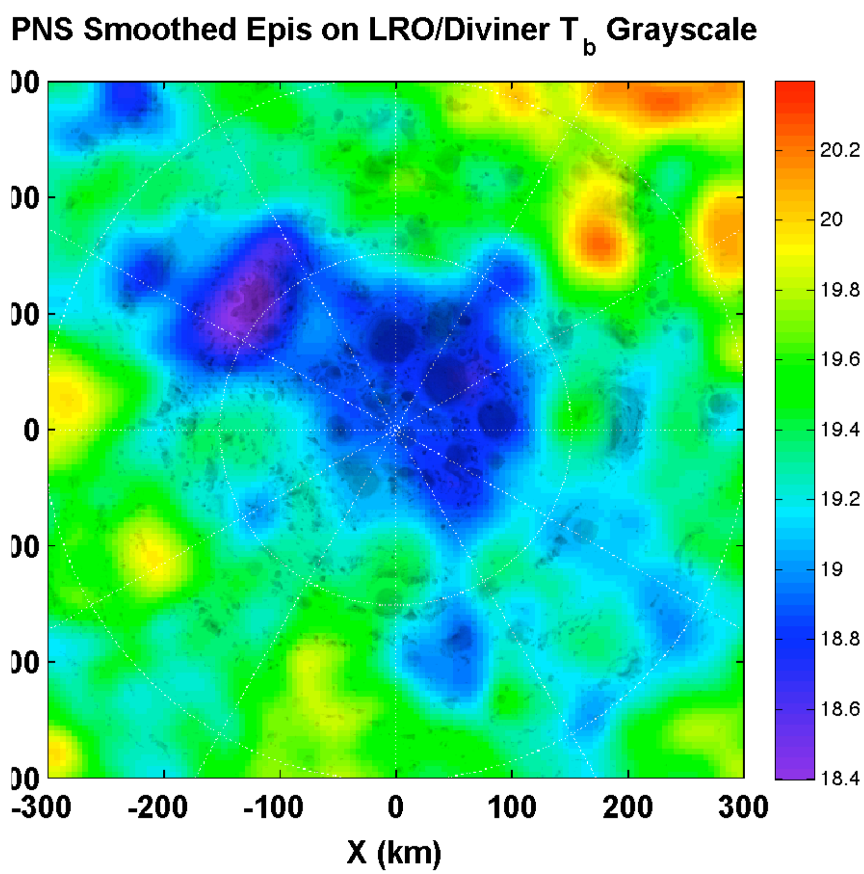




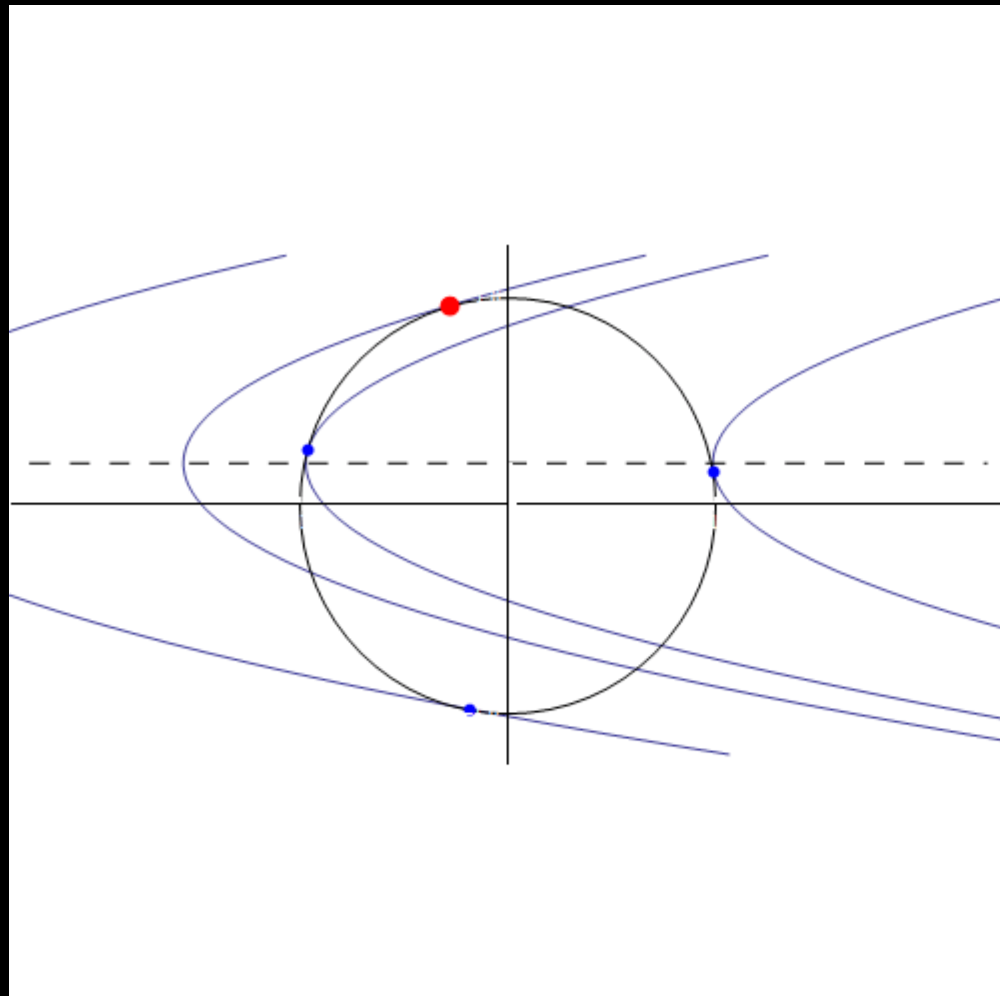
Modeled Epis vs. Observed

For current Moon with burial (Elphic 2010)

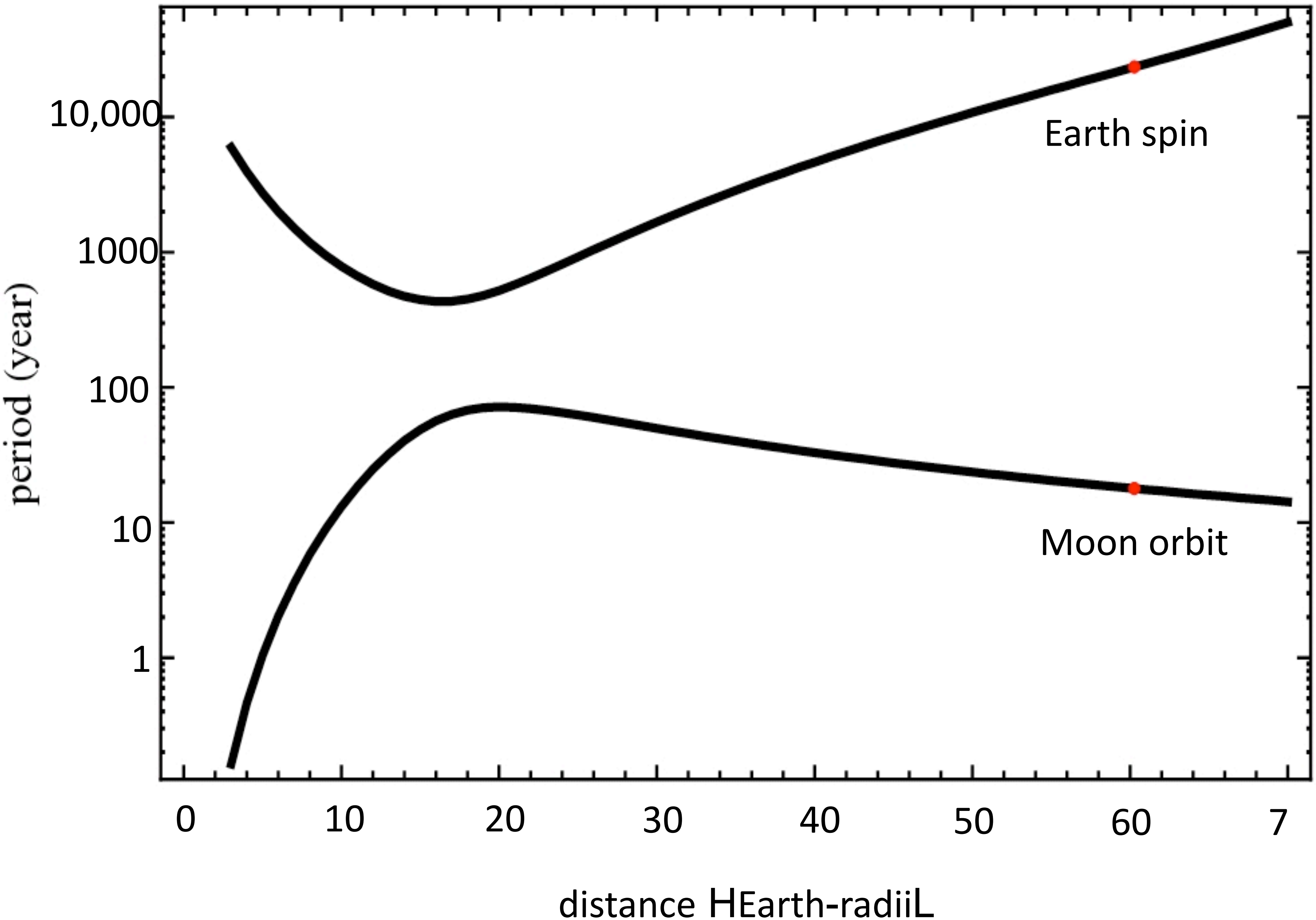


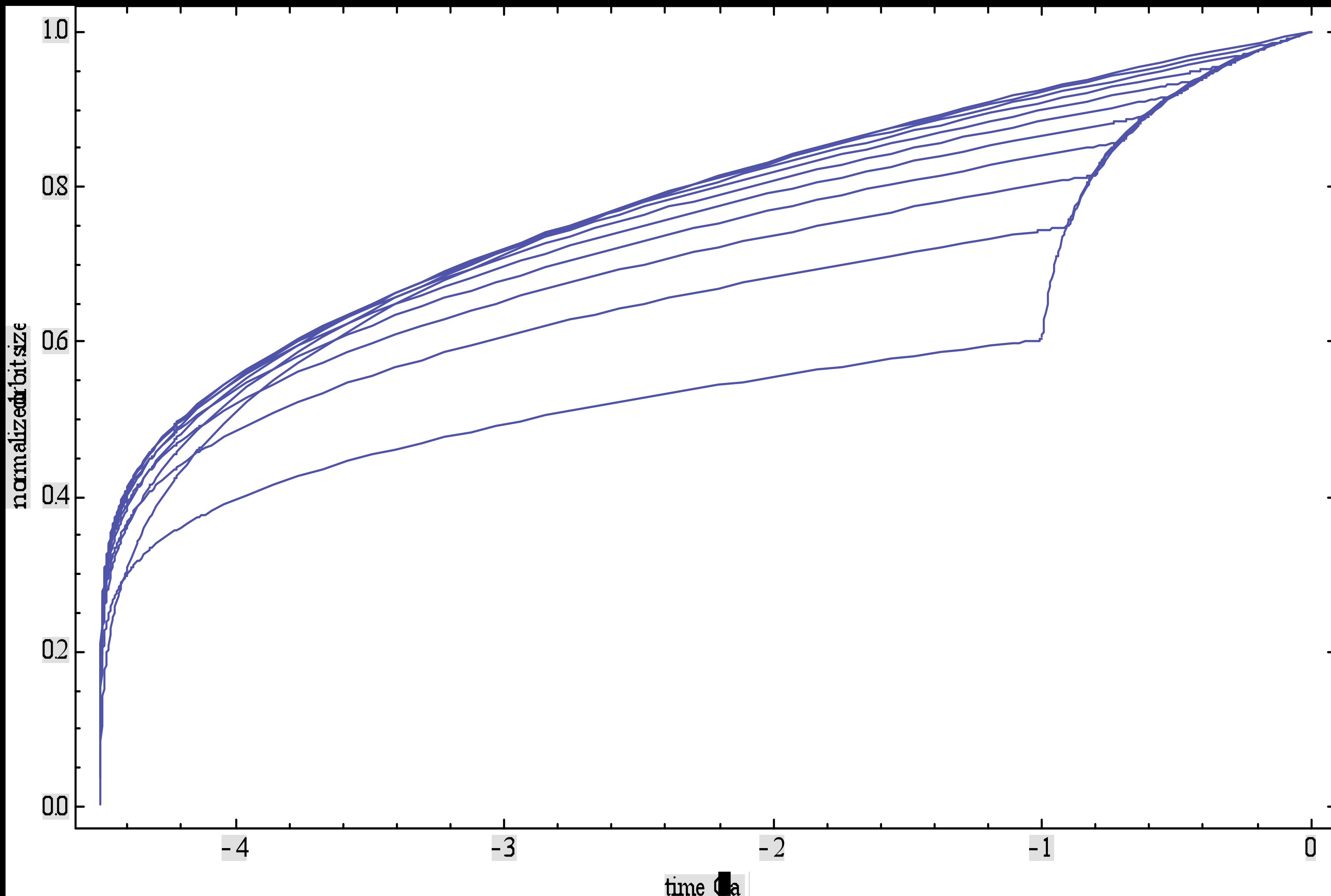


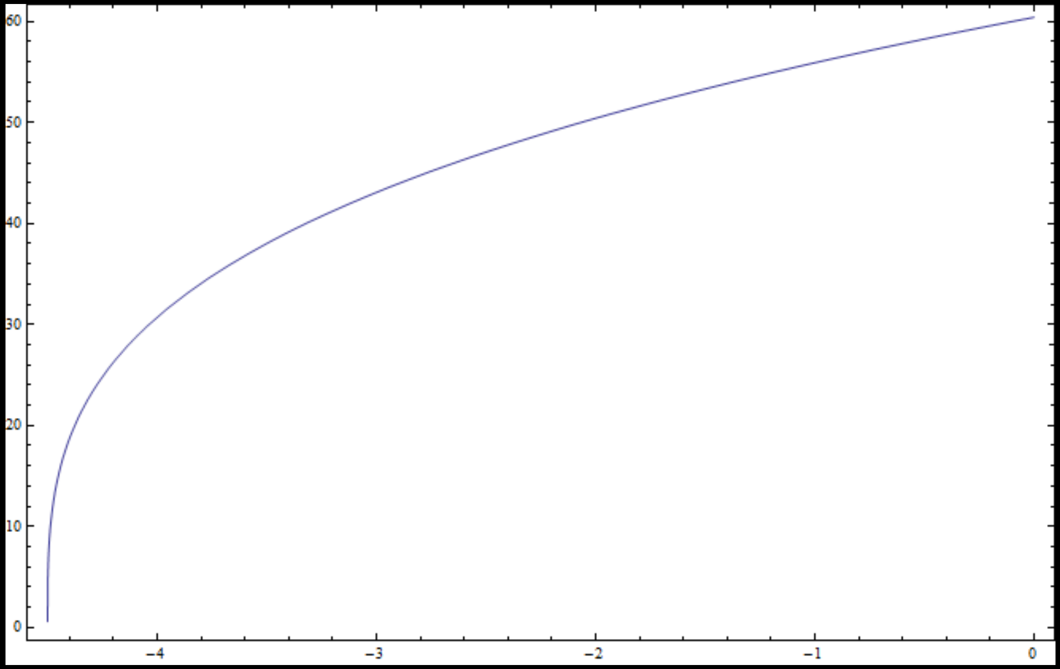
1: Orbital Modeling: Obliquity



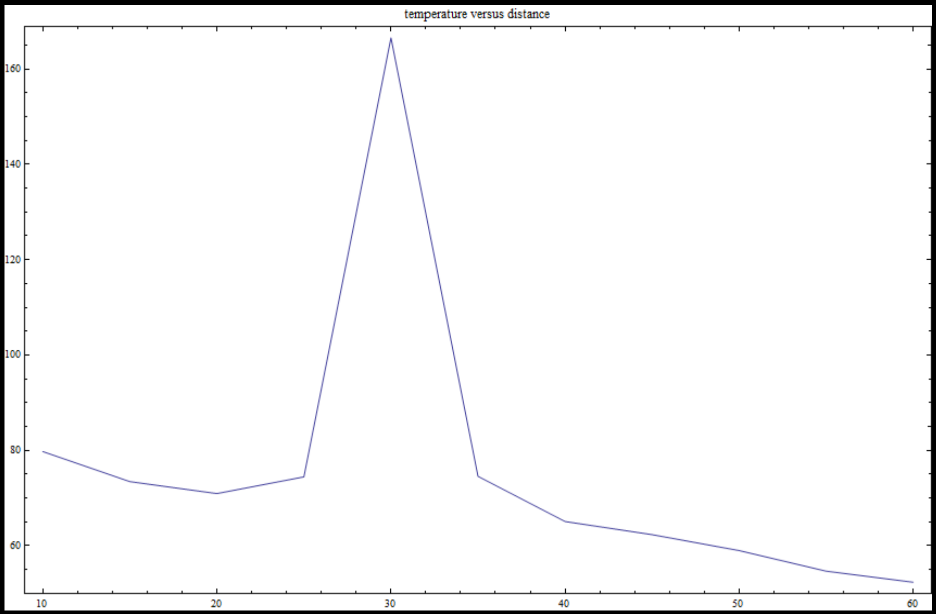
precession periods



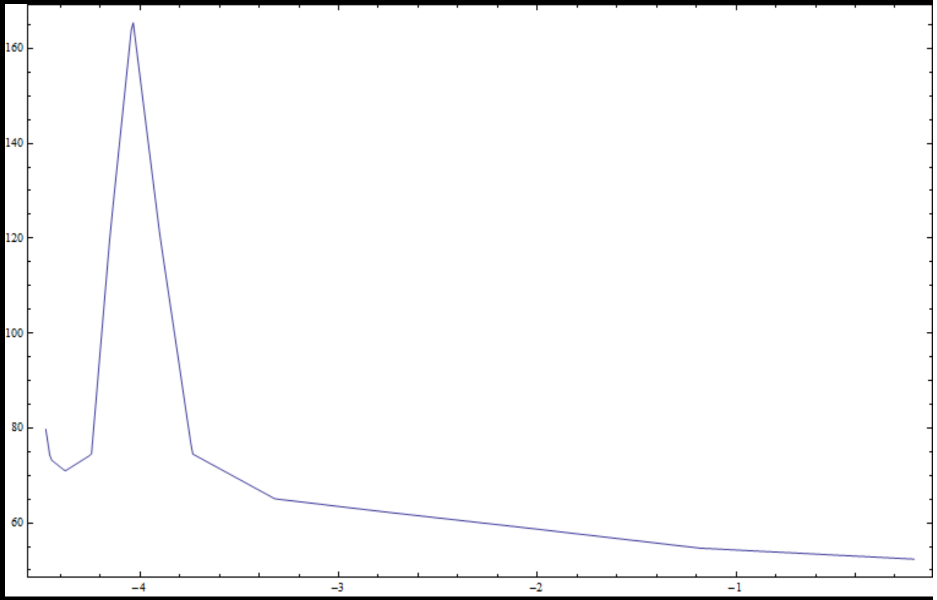

1.0
0.8
0.6
0.4
0.2
0.0
normalized orbit size
-4
-3
-2
-1
0
time Ga



60
50
40
30
20
10
0
−4
−3
−2
−1
0

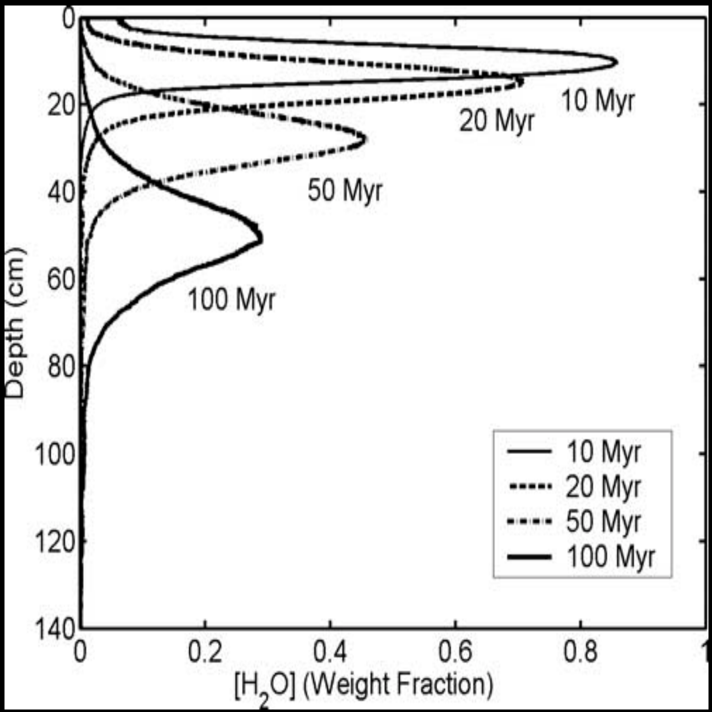


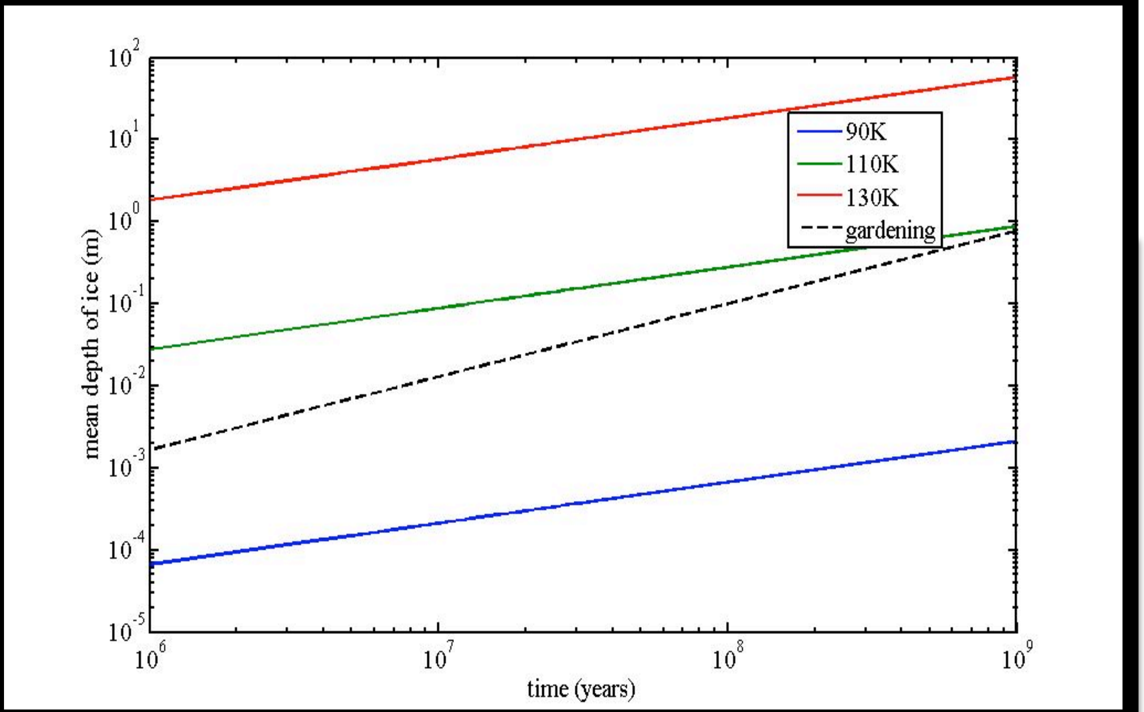
temperature versus distance
160
140
120
100
80
60
10
20
30
40
50
60



160
140
120
100
80
60
−4
−3
−2
−1

6: Diffusion Modeling





1: Orbital Modeling: Obliquity

$$Torque = \tau = r \times F = r \times m \nabla V$$

$$\tau = r \times \frac{Gm}{2r^3}\left(3A(\hat{r}\cdot\hat{i}) + 3B(\hat{r}\cdot\hat{j}) + 3C(\hat{r}\cdot\hat{k})\right)$$

$$V \approx -\frac{Gm}{r} - \frac{G[Tr(I) - 3J]}{2r^3}$$

$$J = \hat{r}\cdot I \cdot \hat{r}$$

$$I = \begin{bmatrix} A & 0 & 0 \\ 0 & B & 0 \\ 0 & 0 & C \end{bmatrix}$$

MacCullagh's Potential

Assuming A=B (oblate spheroid)

$$\tau = \frac{3Gm}{2r^3}(C - A)\left(\hat{r}\cdot\hat{k}\right)\left(\hat{r}\times\hat{k}\right)$$

Subscripts: m = Moon
o = Moon's orbit
s = Sun
e = Earth

Spin pole precesses about orbit pole...

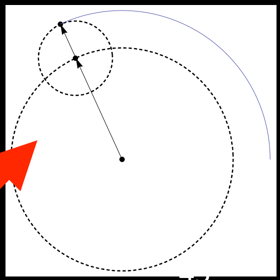
$$\frac{ds}{dt} = \frac{\tau_m}{C_m\omega_m} = \frac{3}{2}\frac{n_e^2}{C_m\omega_m}(C_m - A_m)(\hat{n}\cdot\hat{s})(\hat{n}\times\hat{s}) - \gamma(\hat{n} - \hat{s}(\hat{n}\cdot\hat{s}))$$

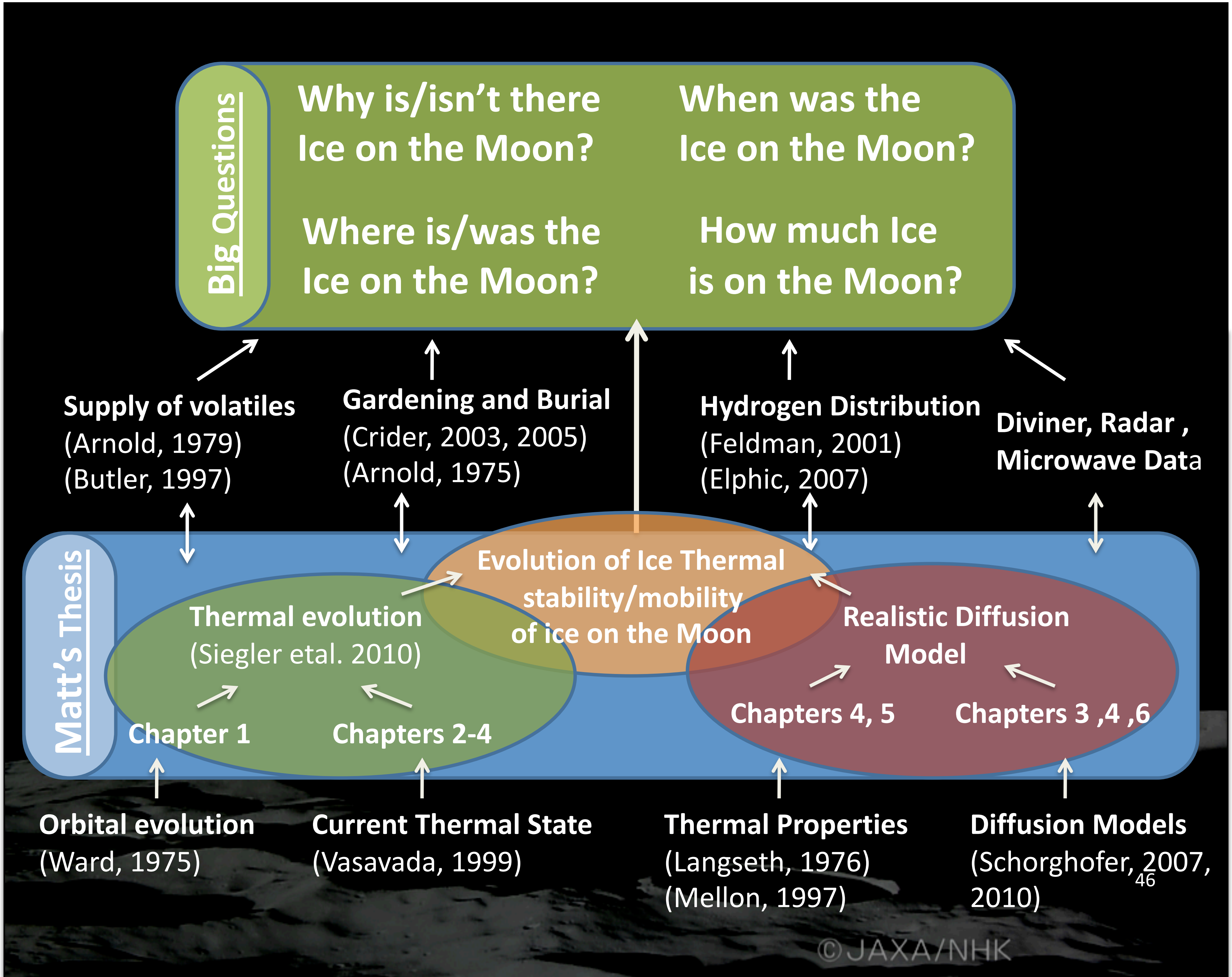
$$n_x = \sqrt{\frac{Gm_x}{r_{xy}^3}}$$

...and damps towards it

$$\frac{dn}{dt} = \frac{\tau_o}{C_o\omega_o} = \frac{3}{2}\frac{n_s^2}{C_o\omega_o}(C_o - A_o)(\hat{k}\cdot\hat{n})(\hat{k}\times\hat{n})$$

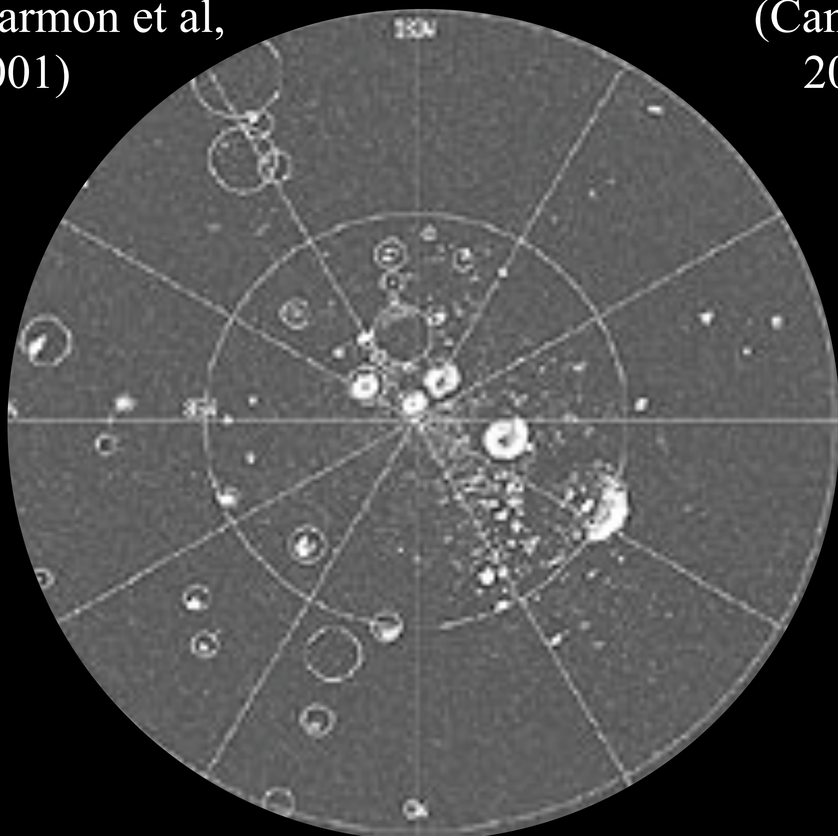
For a Cassini State, projections of $\frac{ds}{dt}$ and $\frac{dn}{dt}$ onto ecliptic plane are equal.



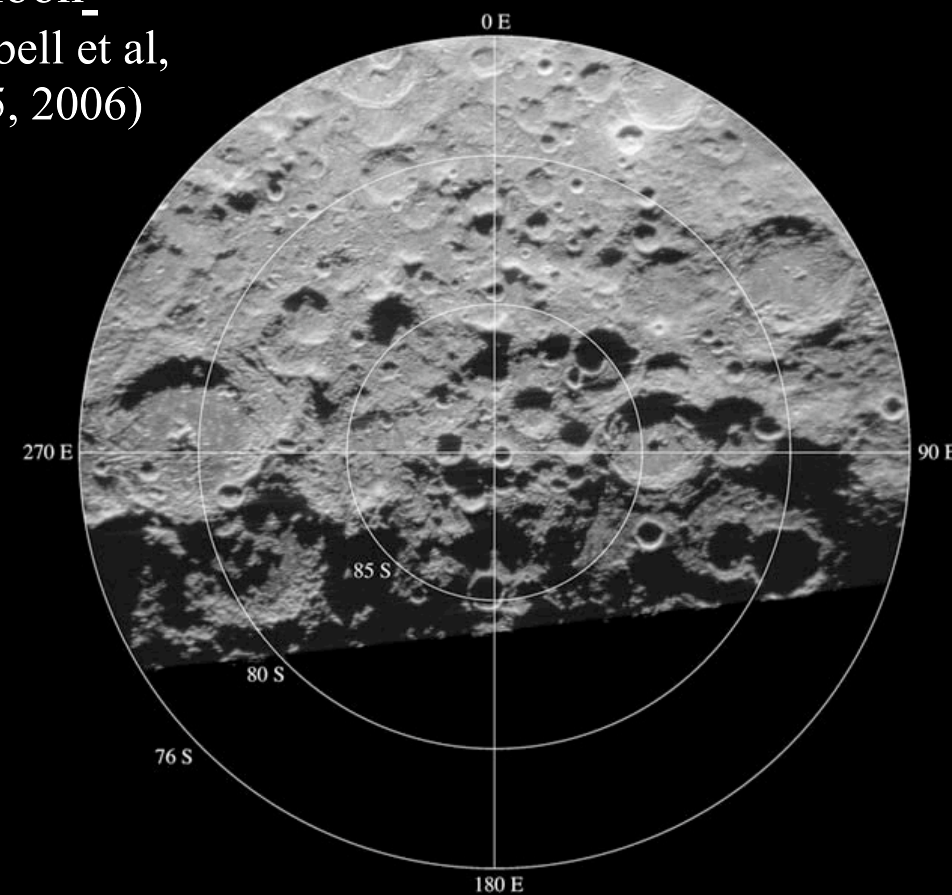

Big Questions
Why is/isn't there Ice on the Moon?
When was the Ice on the Moon?
Where is/was the Ice on the Moon?
How much Ice is on the Moon?
Supply of volatiles (Arnold, 1979) (Butler, 1997)
Gardening and Burial (Crider, 2003, 2005) (Arnold, 1975)
Hydrogen Distribution (Feldman, 2001) (Elphic, 2007)
Diviner, Radar , Microwave Data
Matt's Thesis
Evolution of Ice Thermal stability/mobility of ice on the Moon
Thermal evolution (Siegler etal. 2010)
Chapter 1
Chapters 2-4
Realistic Diffusion Model
Chapters 4, 5
Chapters 3 ,4 ,6
Orbital evolution (Ward, 1975)
Current Thermal State (Vasavada, 1999)
Thermal Properties (Langseth, 1976) (Mellon, 1997)
Diffusion Models (Schorghofer, 2007, 2010)
©JAXA/NHK

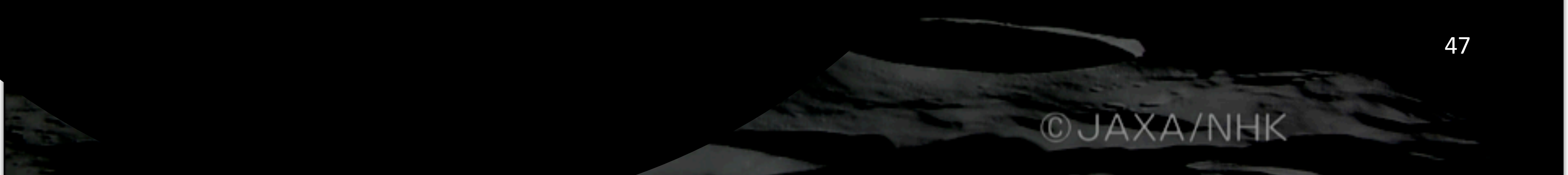
Motivation: Ice on Mercury, why not the Moon?

Mercury
(Harmon et al,
2001)



The Moon
(Campbell et al,
2005, 2006)





6: Diffusion Modeling

One can also look at ice mobility, supply to surface, and surface destruction

Equilibrium Surface Areal Density

$$\sigma_0(t=\infty) = \frac{s}{\frac{1}{2\tau} + \frac{\delta}{\theta}}$$

Surface Supply Rate

Surface Distruction Rate

Integrated Mass with depth

$$m = \int_0^\infty dz\, \rho(z,t) = \mu \frac{\sigma_0(\infty)}{\ell} \sqrt{\frac{4Dt}{\pi}}$$