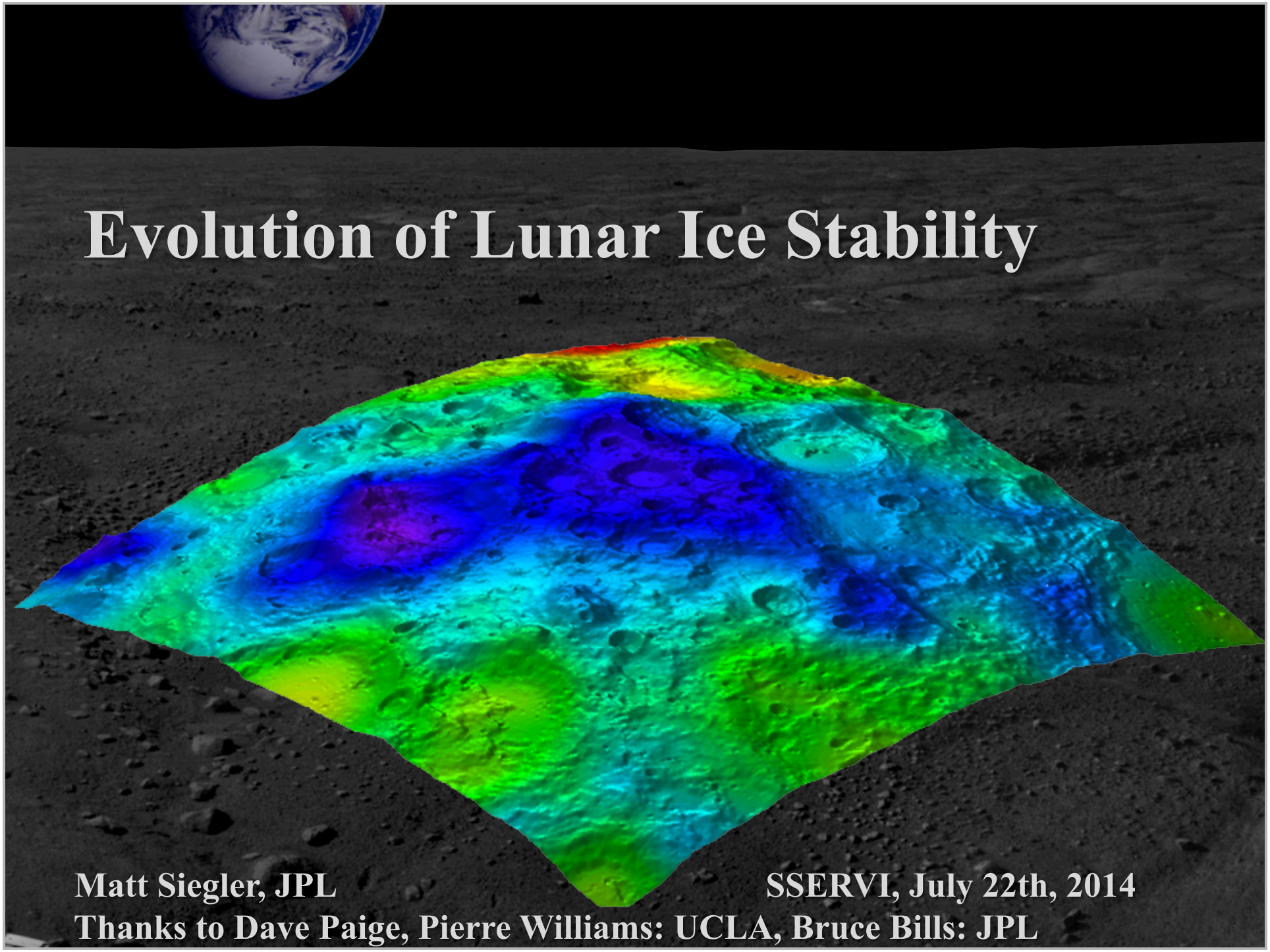
# Evolution of Lunar Ice Stability



Matt Siegler, JPL

SSERVI, July 22th, 2014

Thanks to Dave Paige, Pierre Williams: UCLA, Bruce Bills: JPL

# The Big Picture

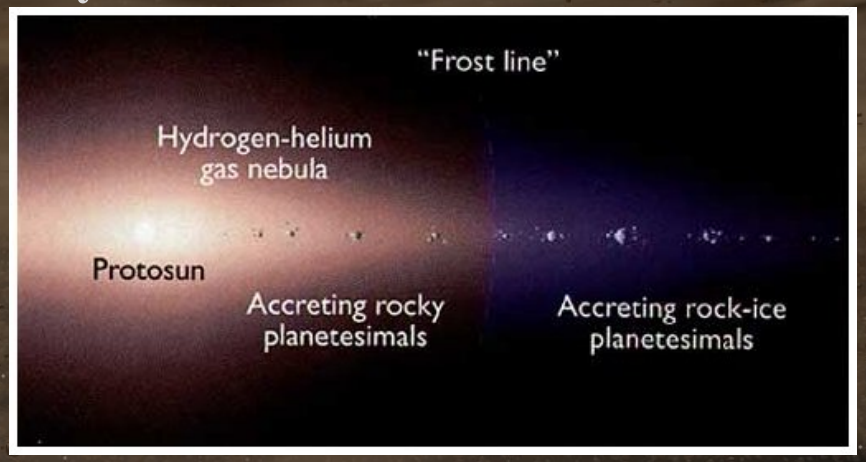
**PLANETARY SCIENCE DECADAL SURVEY (pg. 3-6)**

**"Major questions remain regarding how and when water and other volatiles were delivered to Earth.**

**What fraction of Earth's volatile inventory was delivered directly by planetesimals during accretion and later outgassed to the surface during differentiation and subsequent volcanism?**

**What fraction was acquired as a late veneer from impact of comets and volatile-rich asteroids during the late heavy bombardment?**

**Clues to address these questions could remain locked in chemical signatures at the surfaces and in atmospheres of Earth's neighbors."**

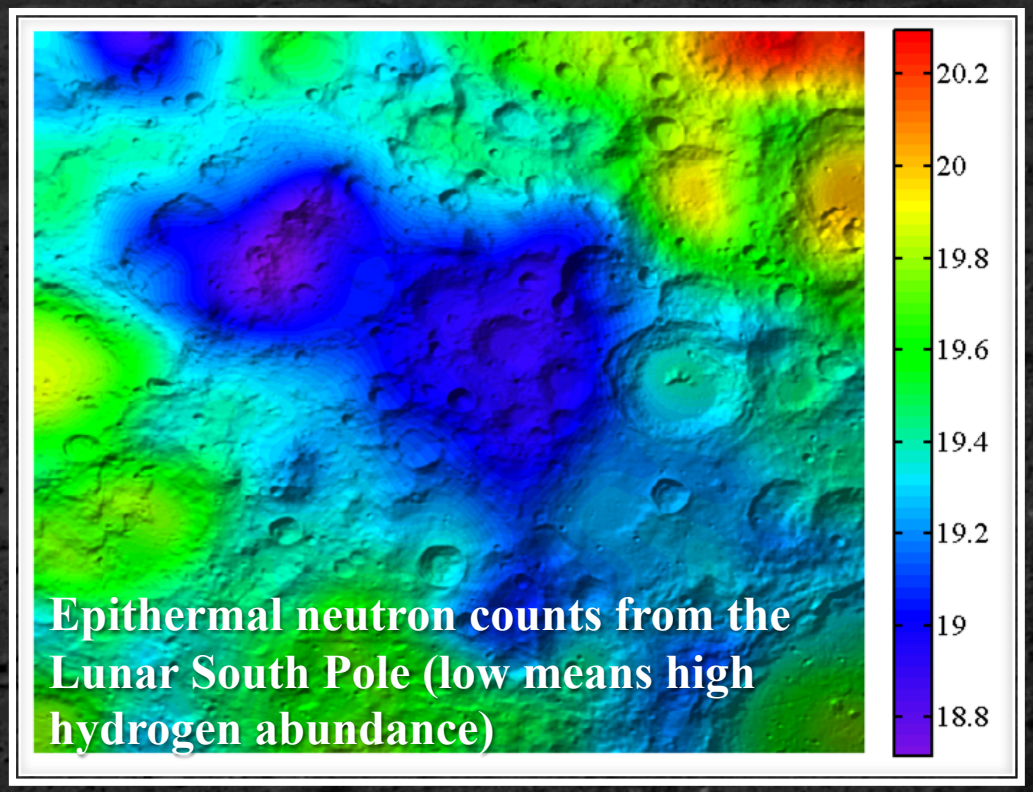


This begs two big questions:

<u>How</u> and <u>When</u> did volatiles come to the inner solar system?

<u>How</u>: Comet? Asteroid? Volcanic? Solar Wind? Interstellar medium?

<u>When</u>: Original? Late Heavy Bombardment? Recently?




Epithermal neutron counts from the Lunar South Pole (low means high hydrogen abundance)

after Elphic *et al.* , 2010

# Outline

1) Overview of the tools I use

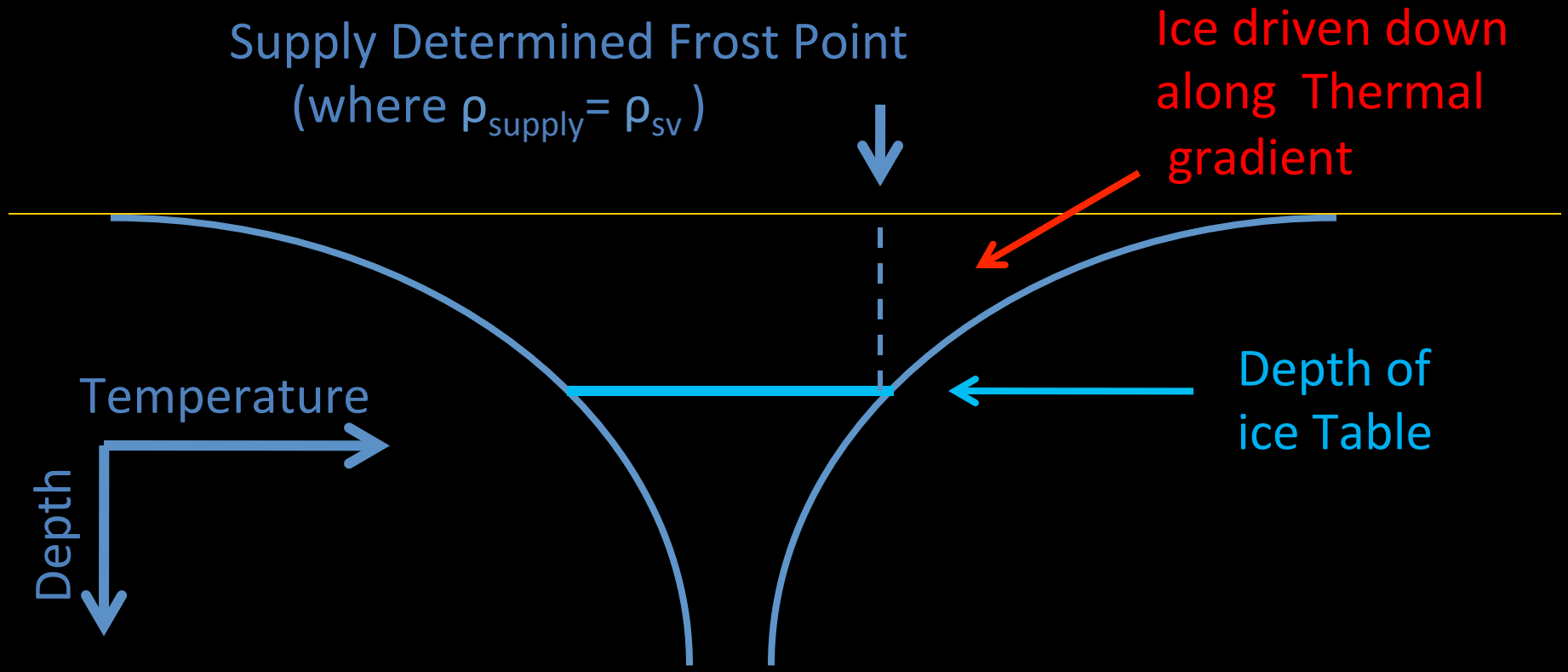
2) History of discovery of polar ices on the inner planets

3) The modern era of spacecraft measurements of the Moon and Mercury

4) Lunar Obliquity and ice deposition on the Moon

## 1) How do I look at Polar Ices?

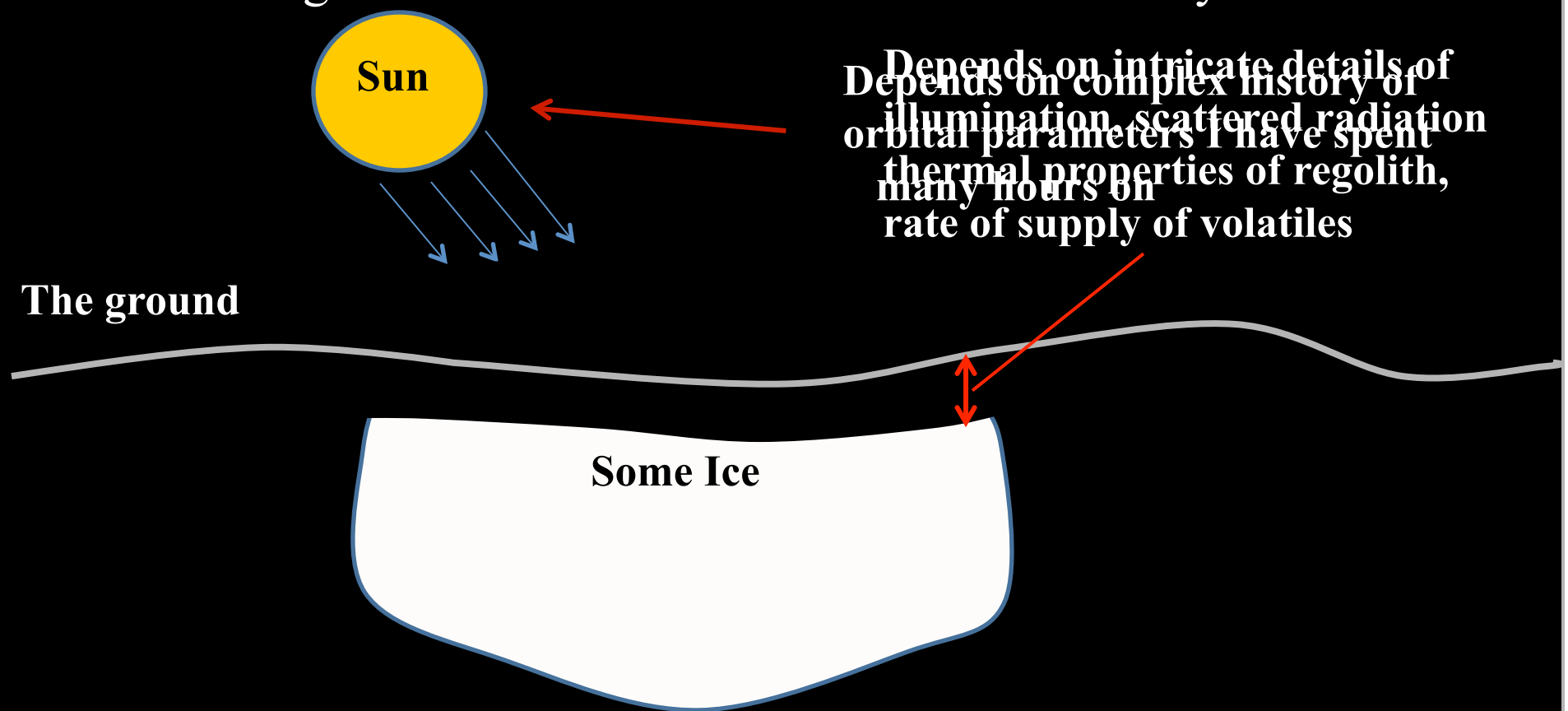
**…and built models determining at what depth ice would be stable in such a regolith…**



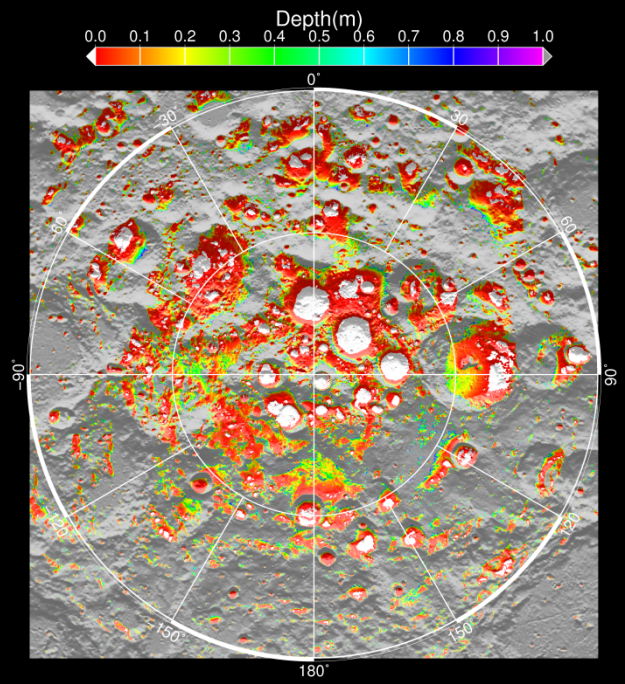
# 1) How do I look at Polar Ices?

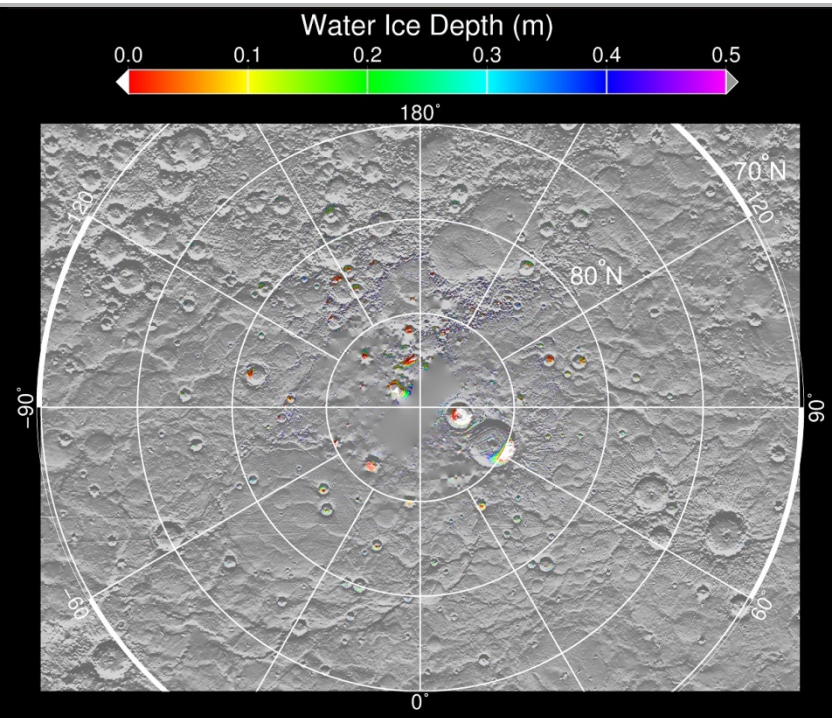
**"M-body" simulations:**

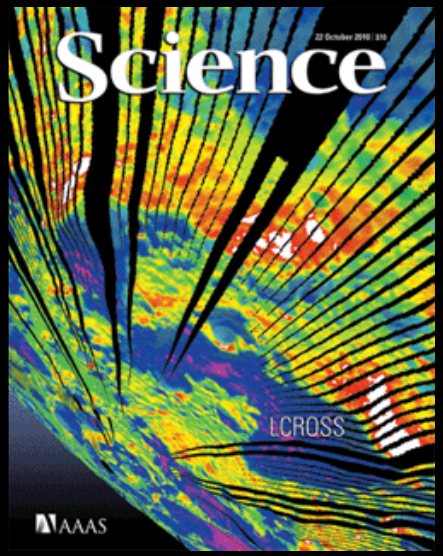
Modeling volatile behavior on Moon/Mars/Mercury



1)




2010: The Moon

## Diviner Lunar Radiometer Observations of Cold Traps in the Moon's South Polar Region

David A. Paige,[1] Matthew A. Siegler,[1] Jo Ann Zhang,[1] Paul O. Hayne,[1] Emily J. Foote,[1] Kristen A. Bennett,[1] Ashwin R. Vasavada,[2] Benjamin T. Greenhagen,[2] John T. Schofield,[2] Daniel J. McCleese,[2] Marc C. Foote,[2] Eric DeJong,[2] Bruce G. Bills,[2] Wayne Hartford,[2] Bruce C. Murray,[3] Carlton C. Allen,[4] Kelly Snook,[5] Laurence A. Soderblom,[6] Simon Calcutt,[7] Fredric W. Taylor,[7] Neil E. Bowles,[7] Joshua L. Bandfield,[8] Richard Elphic,[9] Rebecca Ghent,[10] Timothy D. Glotch,[11] Michael B. Wyatt,[12] Paul G. Lucey[13]

## Thermal Stability of Volatiles in the North Polar Region of Mercury

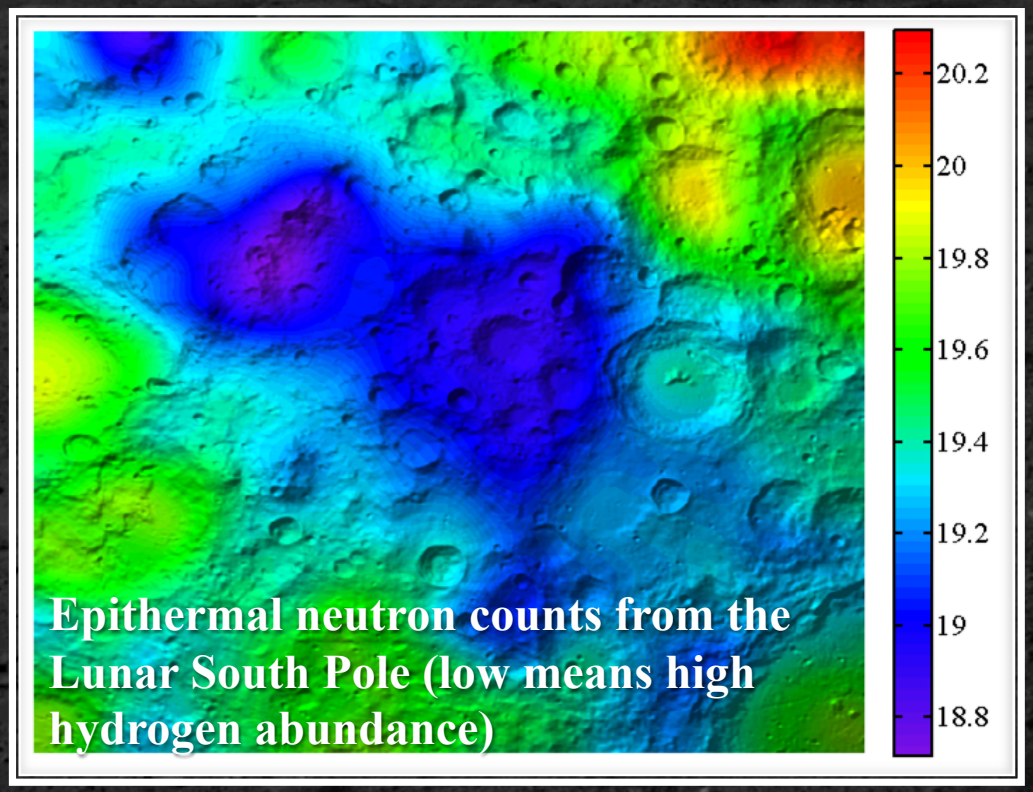
David A. Paige,[1] Matthew A. Siegler,[1,2] John K. Harmon,[3] Gregory A. Neumann,[4] Erwan M. Mazarico,[5] David E. Smith,[5] Maria T. Zuber,[5] Ellen Harju,[1] Mona L. Delitsky,[6] Sean C. Solomon[7,8]

2013: Mercury

# 3) What did spacecraft have to say?

The 1999 Lunar Prospector mission brought along the first planetary Neutron Spectrometer

This found clear evidence of small Hydrogen enhancement near the poles (especially the south)

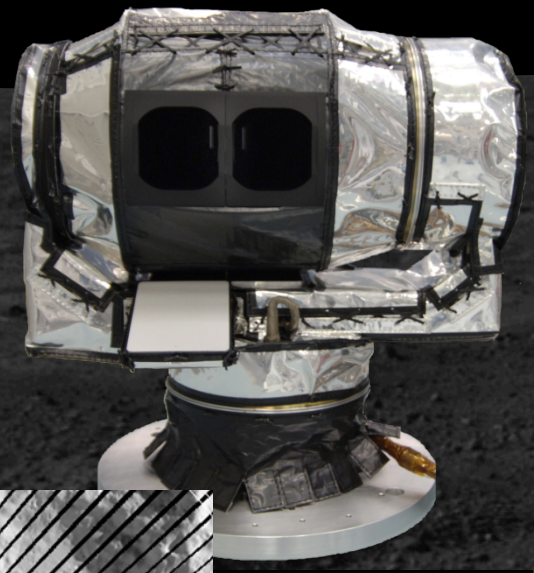



Epithermal neutron counts from the Lunar South Pole (low means high hydrogen abundance)

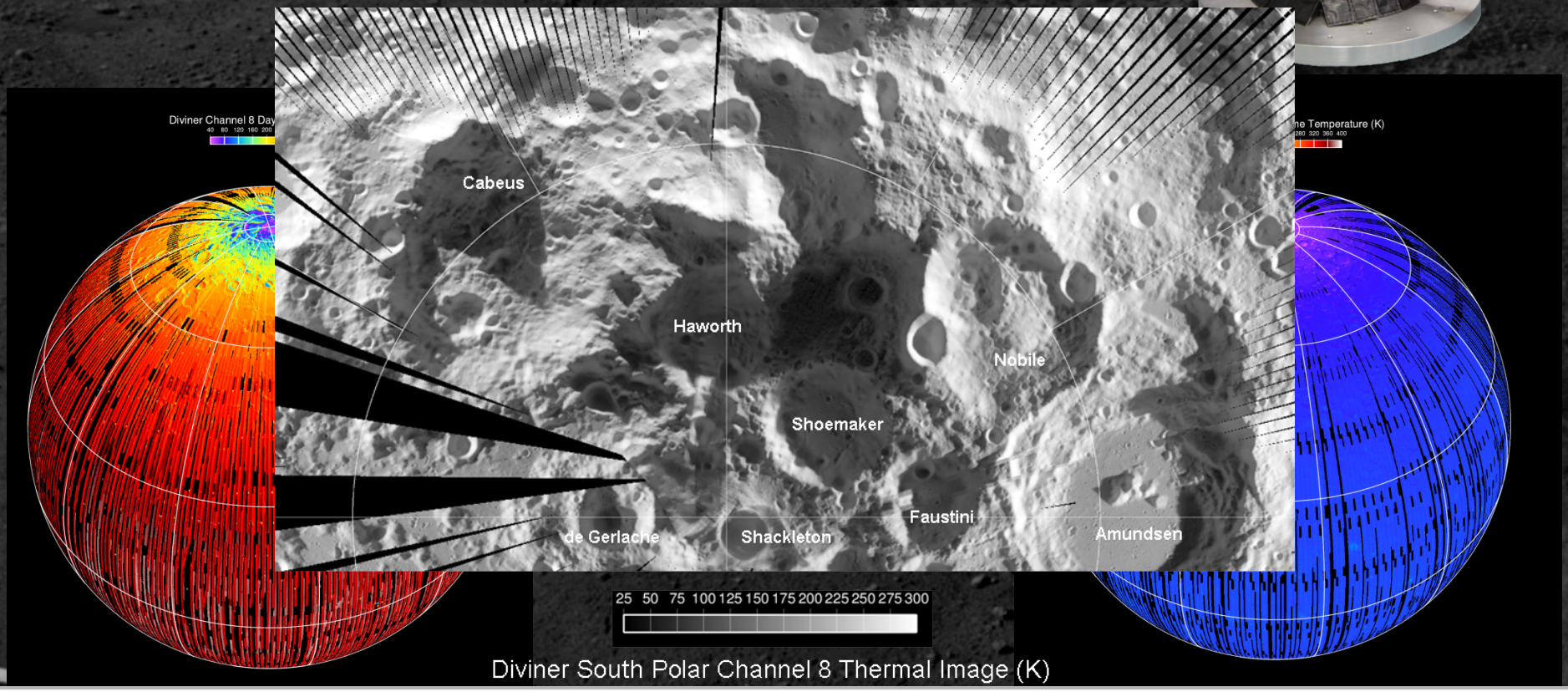
after Elphic *et al.* , 2010

## 3) What did spacecraft have to say?

# 2009 Lunar Reconnaissance Orbiter

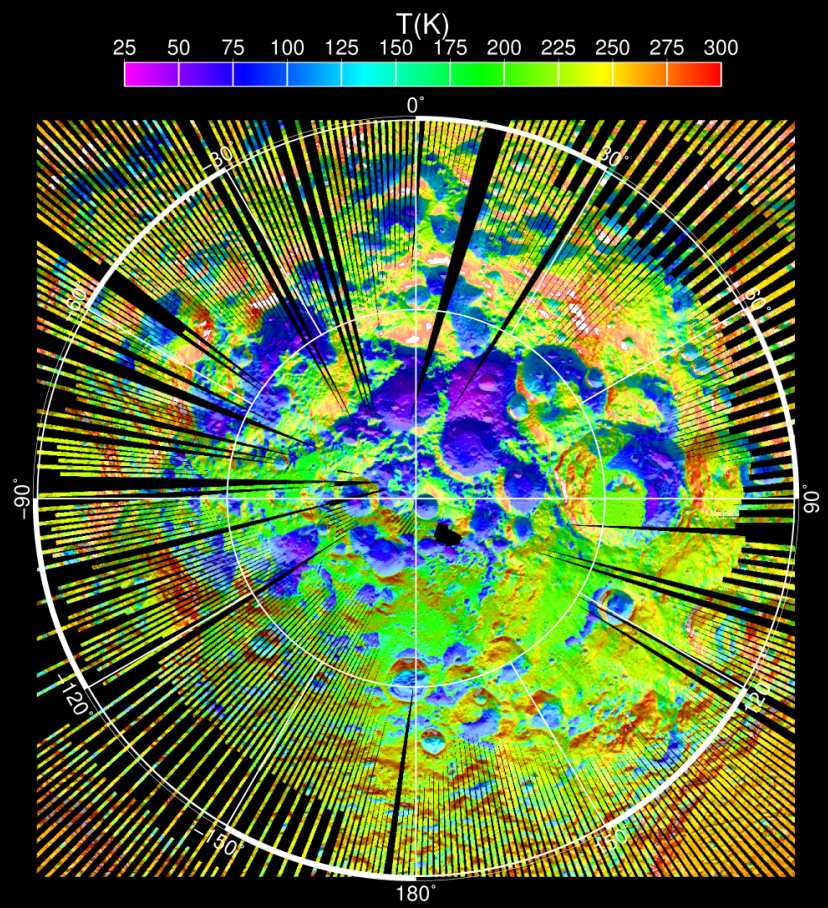


**I work on the Diviner Lunar Radiometer instrument, which measures 7 infrared bands And temperatures from about 20-400 K**

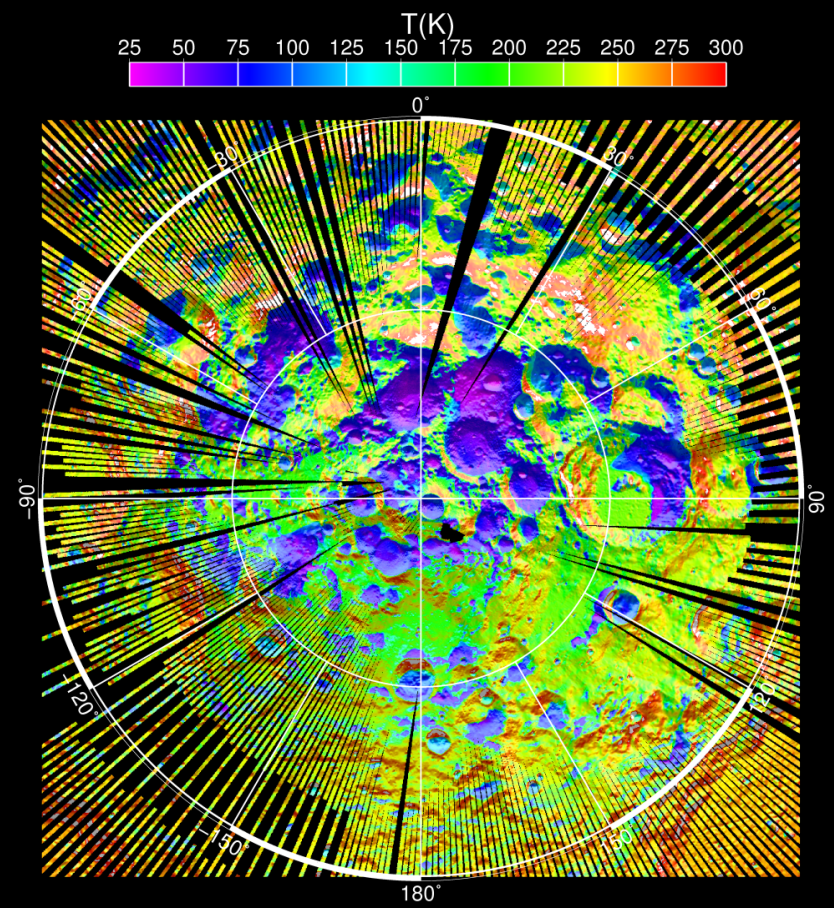


# 3) What did spacecraft have to say?

## Diviner Polar Temperatures and Models (Day)



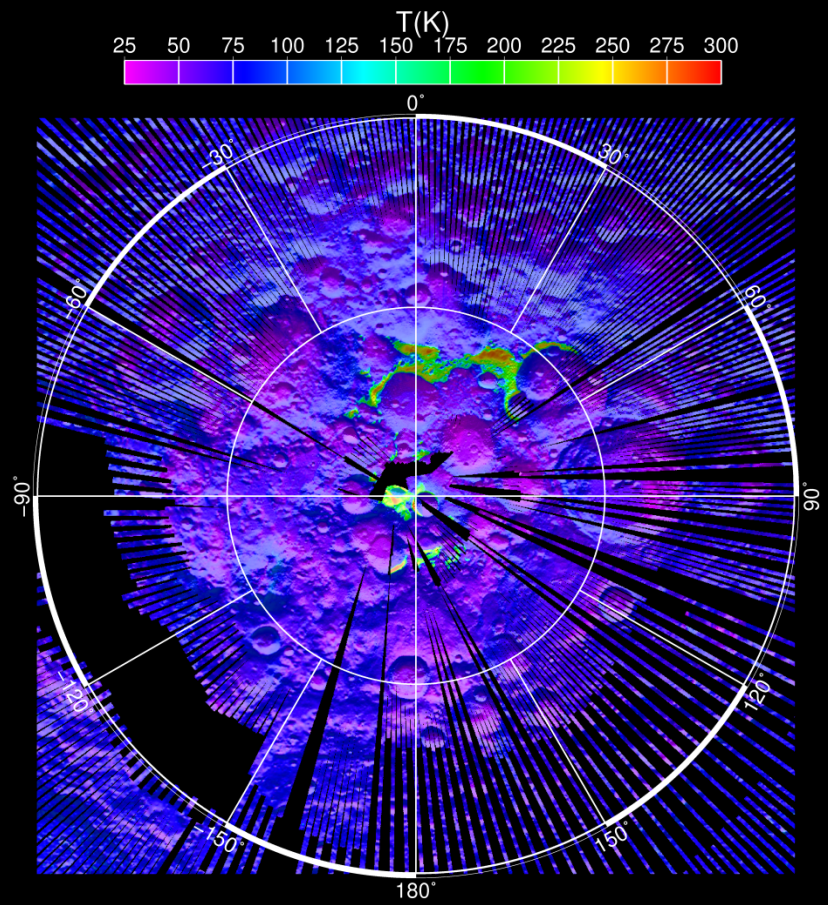

Data



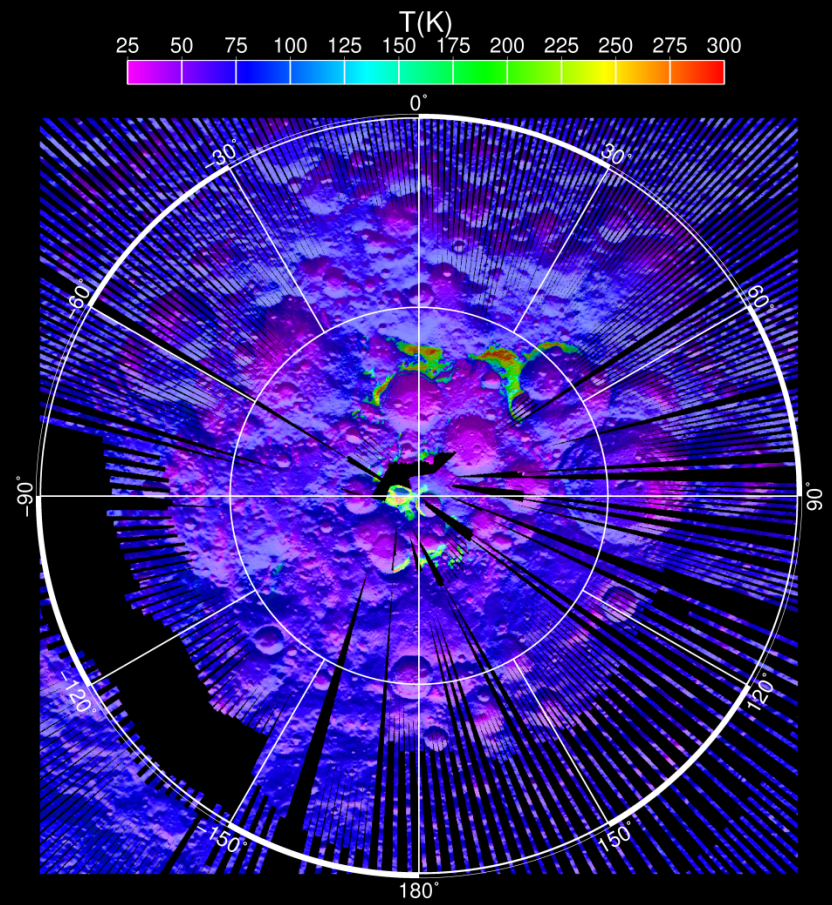

Model

# 3) What did spacecraft have to say?

## Diviner Polar Temperatures and Models (Night)



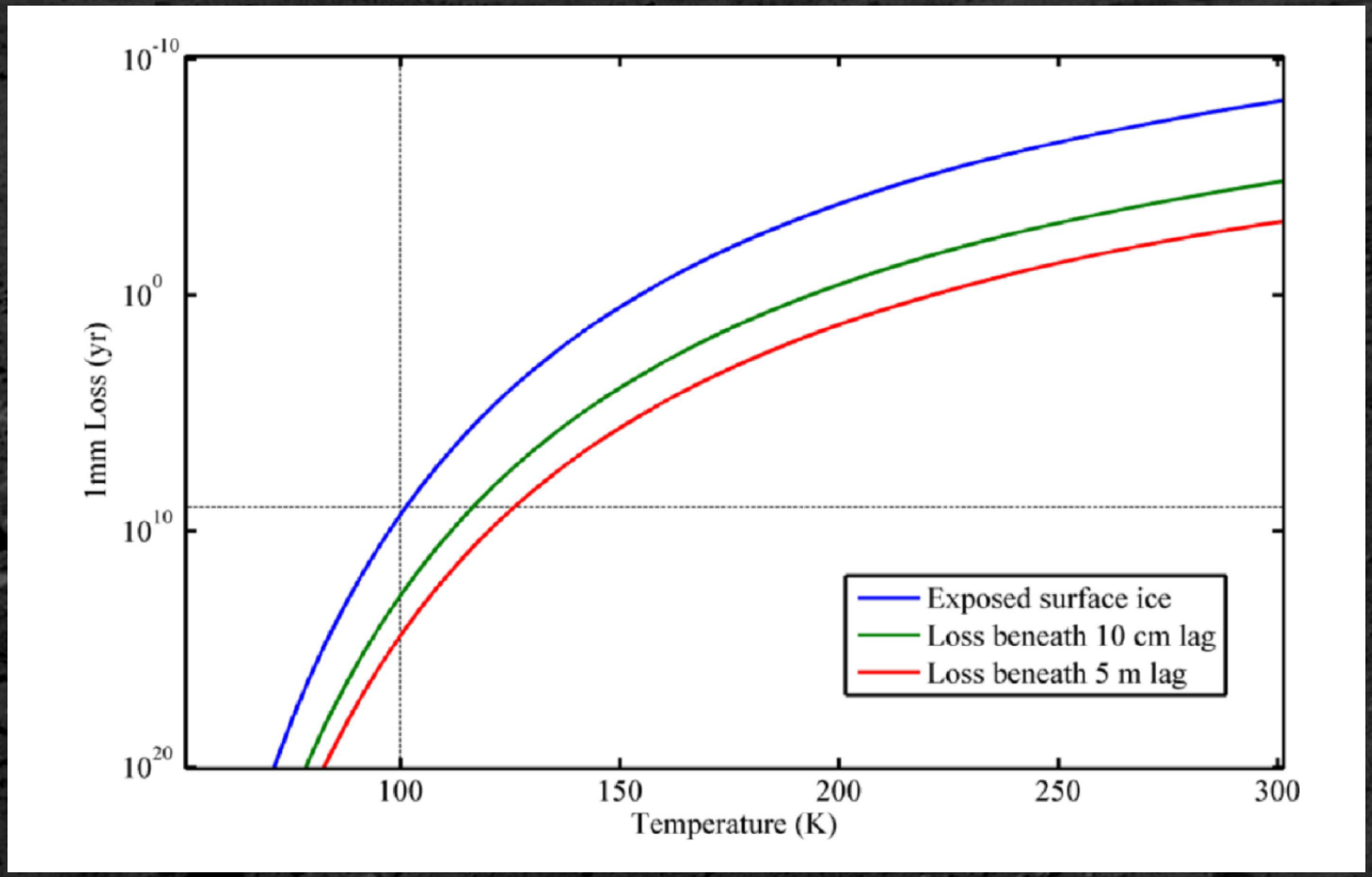

Data




Model

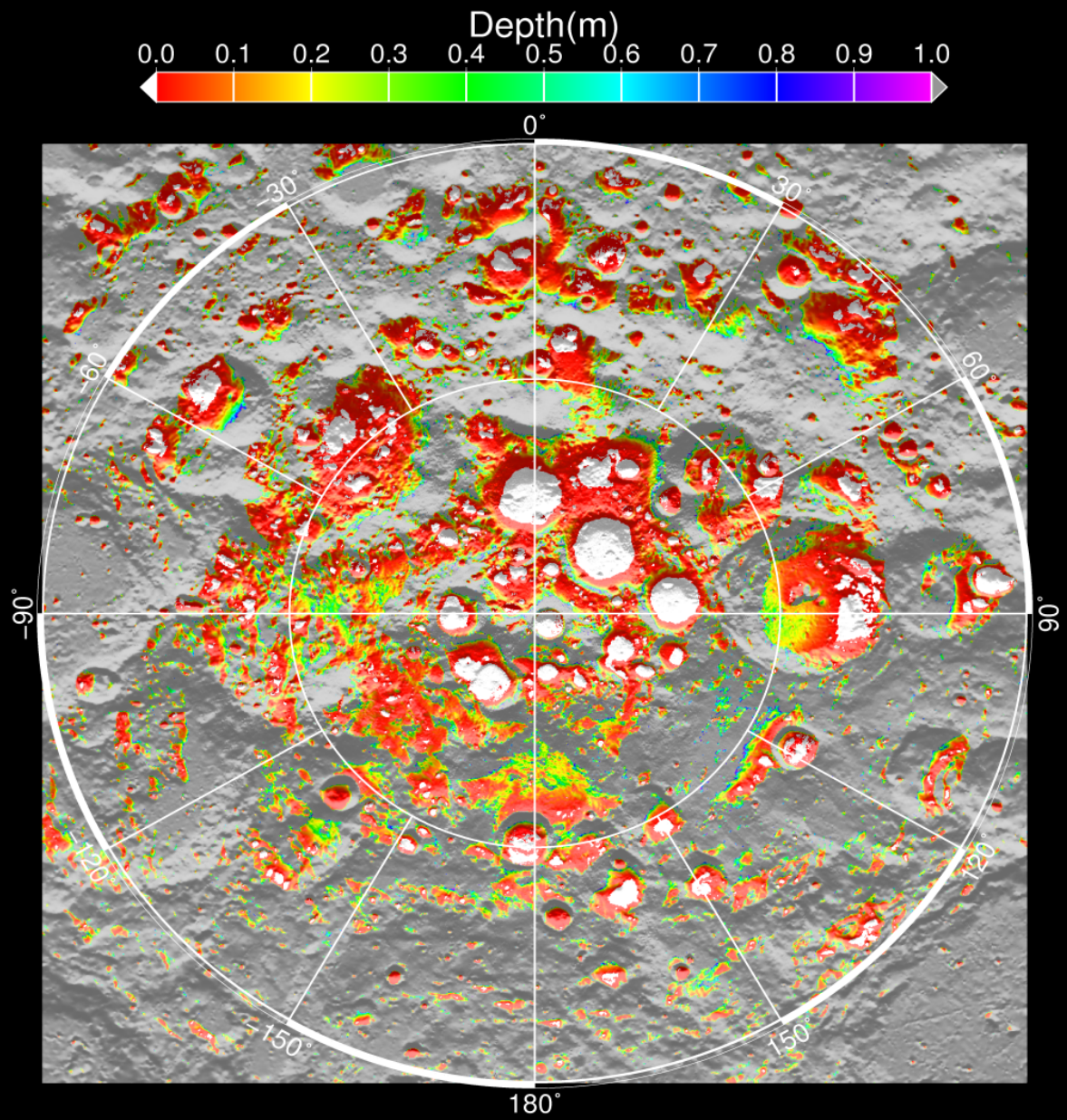
# 3) What did spacecraft have to say?

## What temperatures would we see water?




Paige and Zhang (2009)

# 3) What did spacecraft have to say?



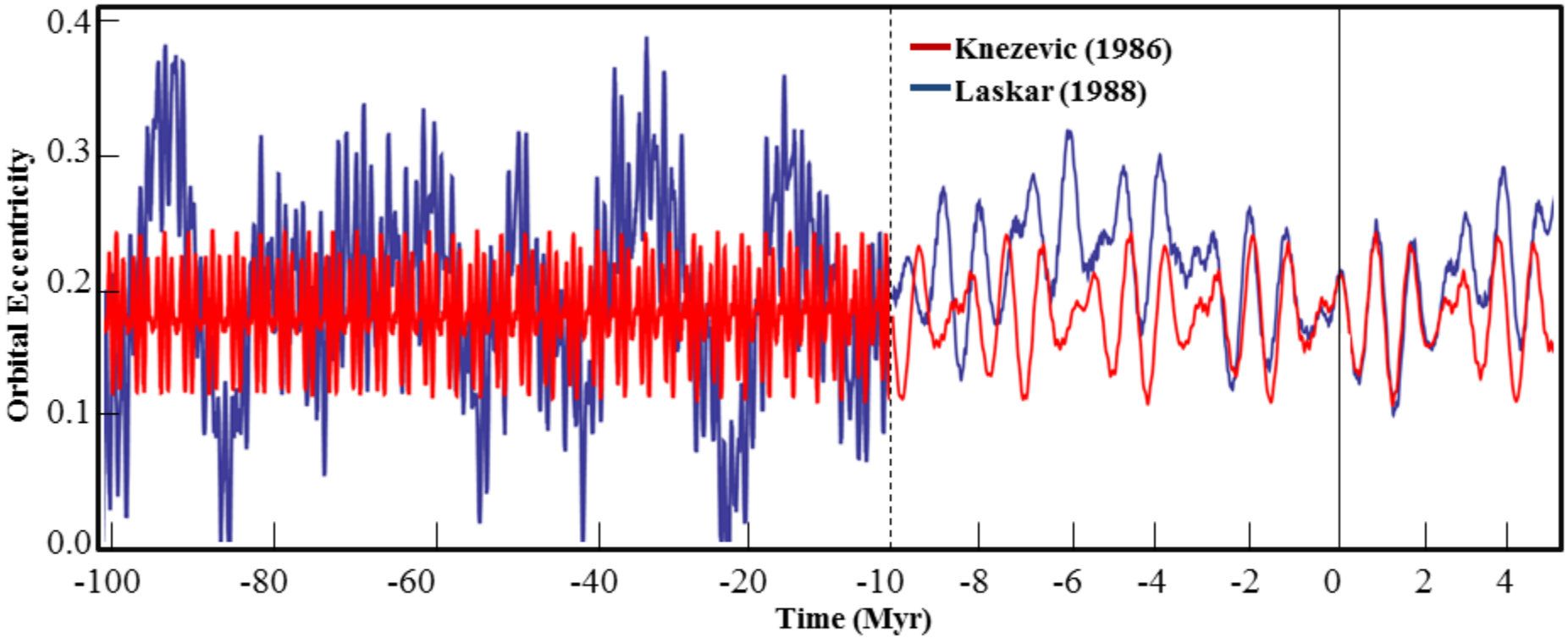
## My Conjecture:

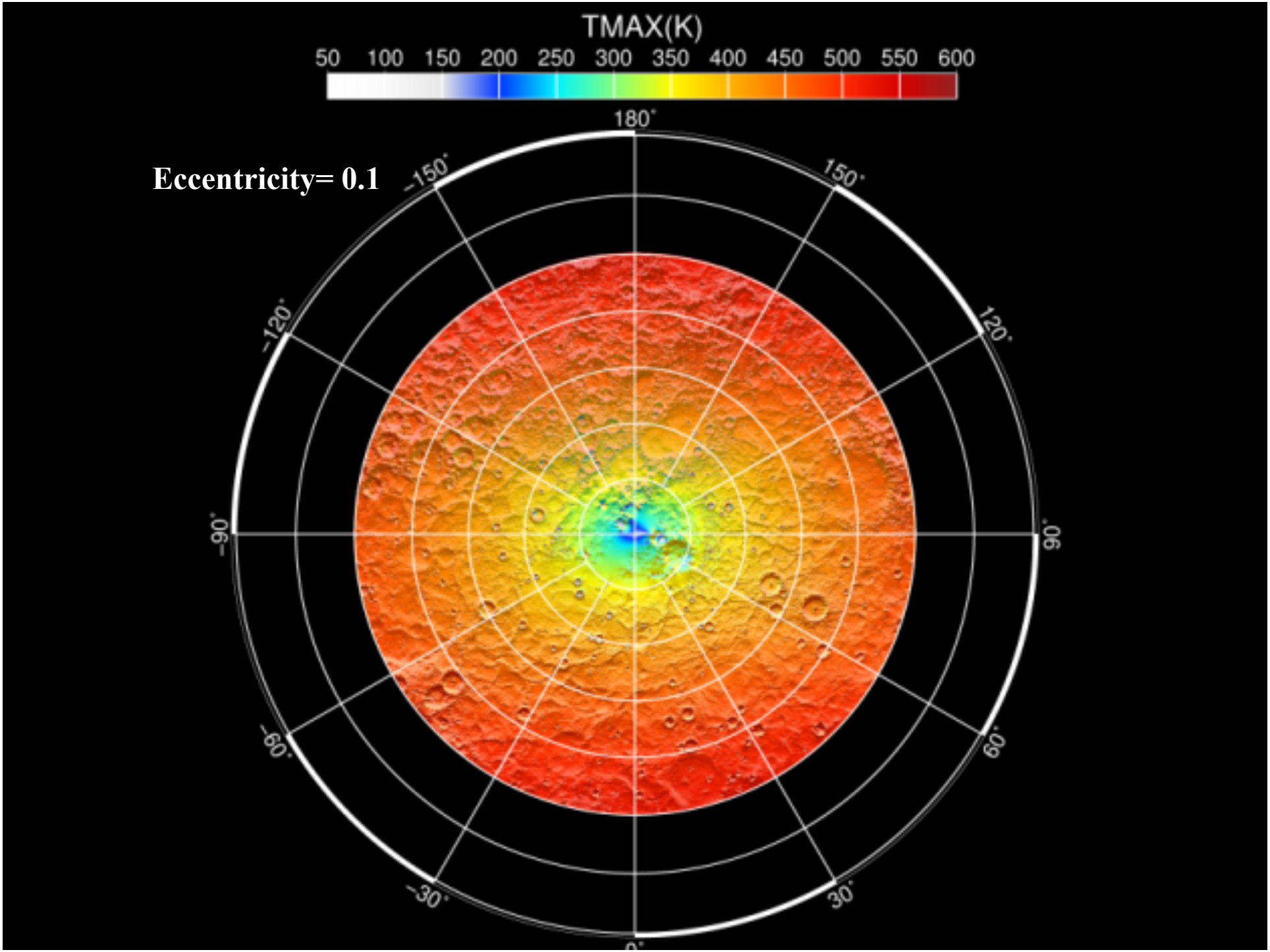
**Orbital histories of airless bodies combined with thermal/volatile stability models provide us a "paleoclimate" record for the inner solar system.**

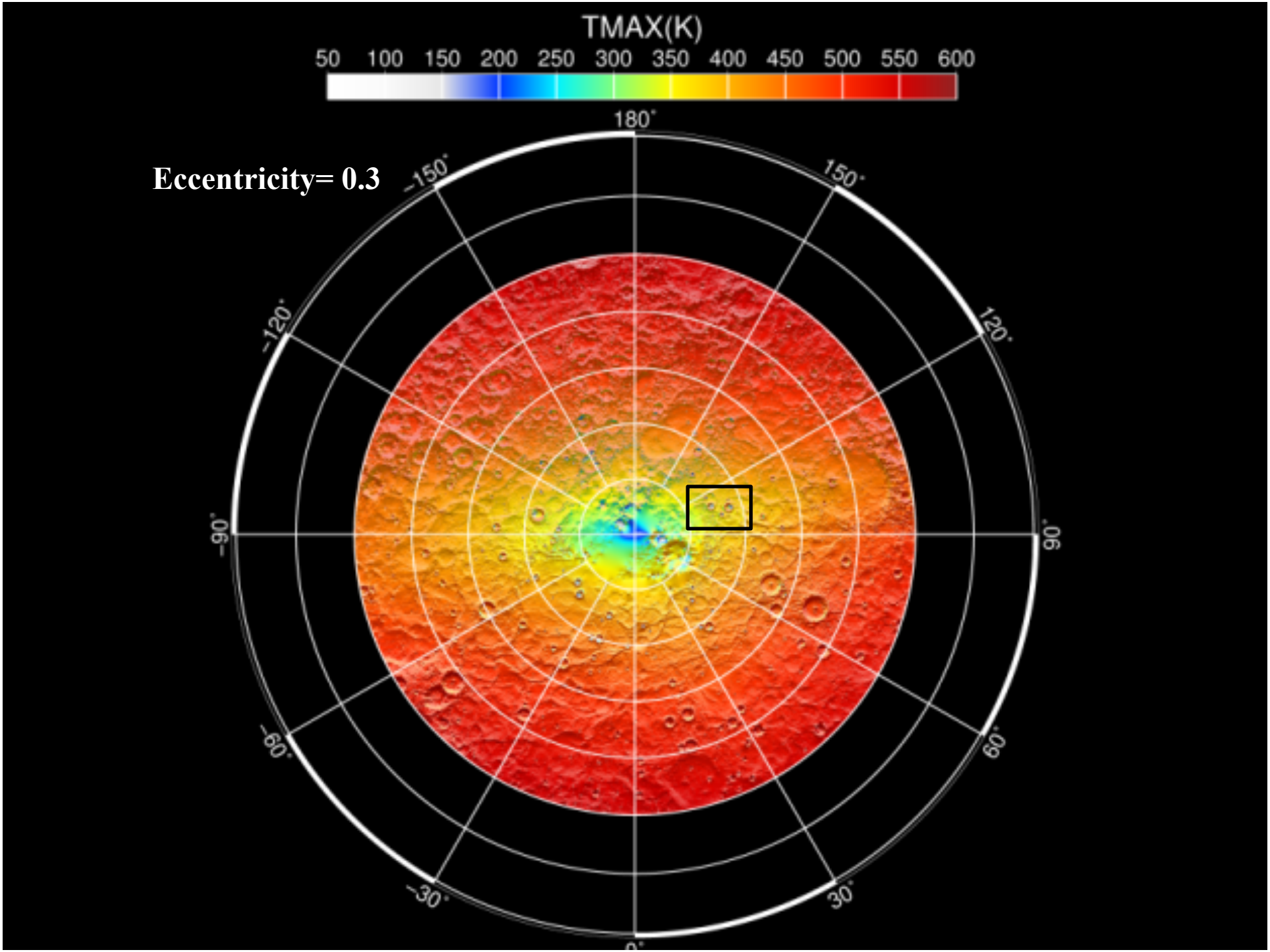
**The polar cold traps of the Moon and Mercury record different parts of the history of delivery of volatiles to this inner solar system**

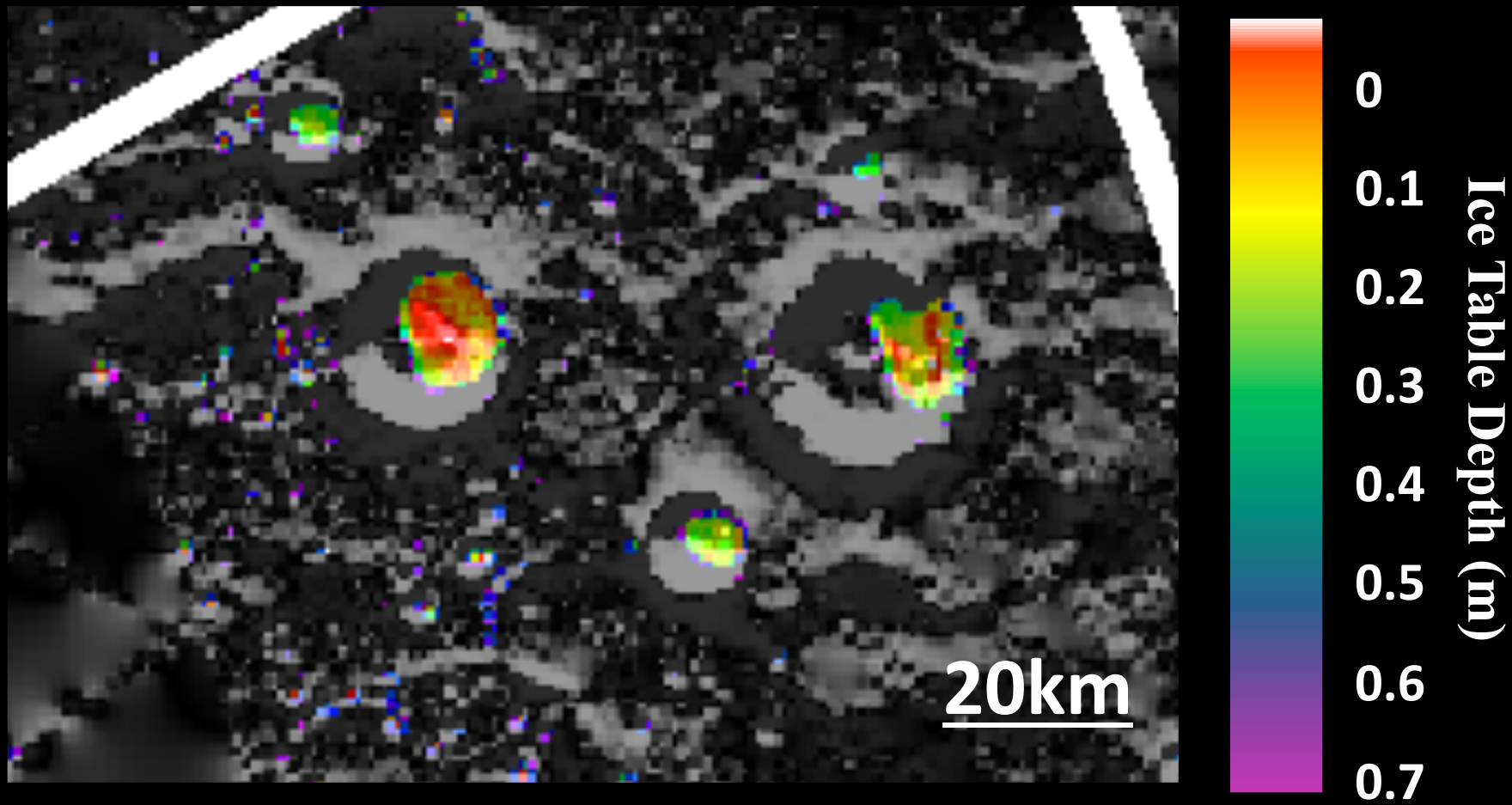
# 4) Remaining Mysteries

## Mercury:
## The largest variation was its eccentricity

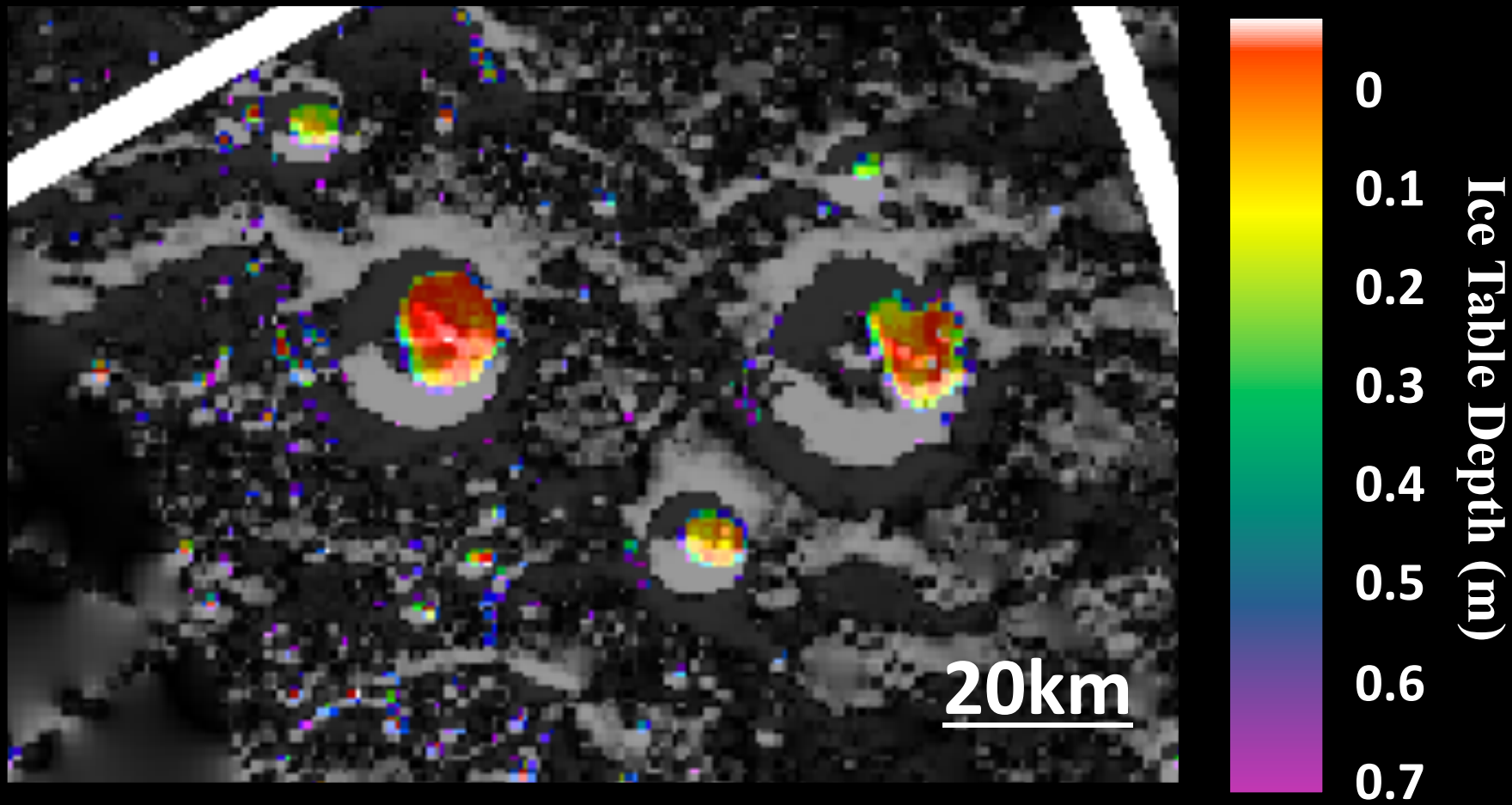



TMAX(K)
50 100 150 200 250 300 350 400 450 500 550 600
Eccentricity= 0.1
180°
-150°
150°
-120°
120°
-90°
90°
-60°
60°
-30°
30°
0°


TMAX(K)
50 100 150 200 250 300 350 400 450 500 550 600
Eccentricity= 0.3
180°
-150°
150°
-120°
120°
-90°
90°
-60°
60°
-30°
30°
0°




**Eccentricity= 0.1**




**Eccentricity= 0.3**

## 4) Remaining Mysteries

# The Moon is in a Cassini State

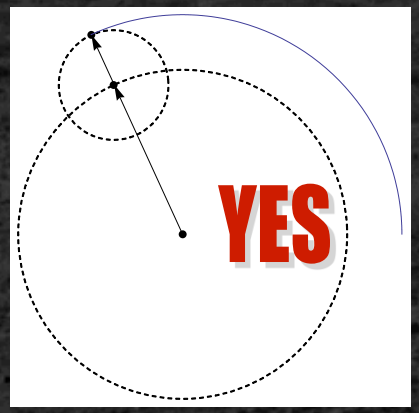
For a fully damped spin pole angular rates must match (Due to dissipation within Moon)

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

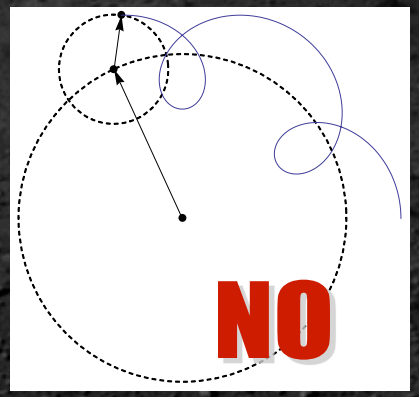
Depends on lunar semimajor axis

Depends on lunar moments of inertia and obliquity

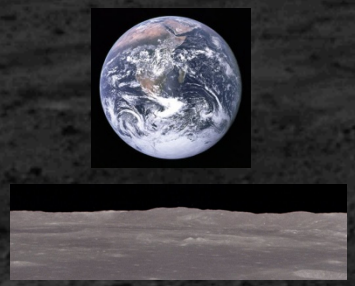
Damped Spin Pole



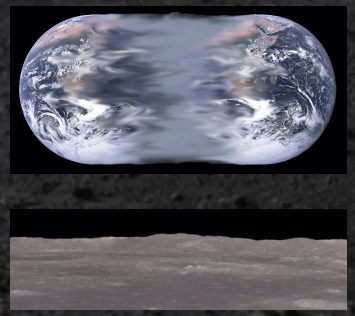

Undamped Spin Pole




Stationary Earth



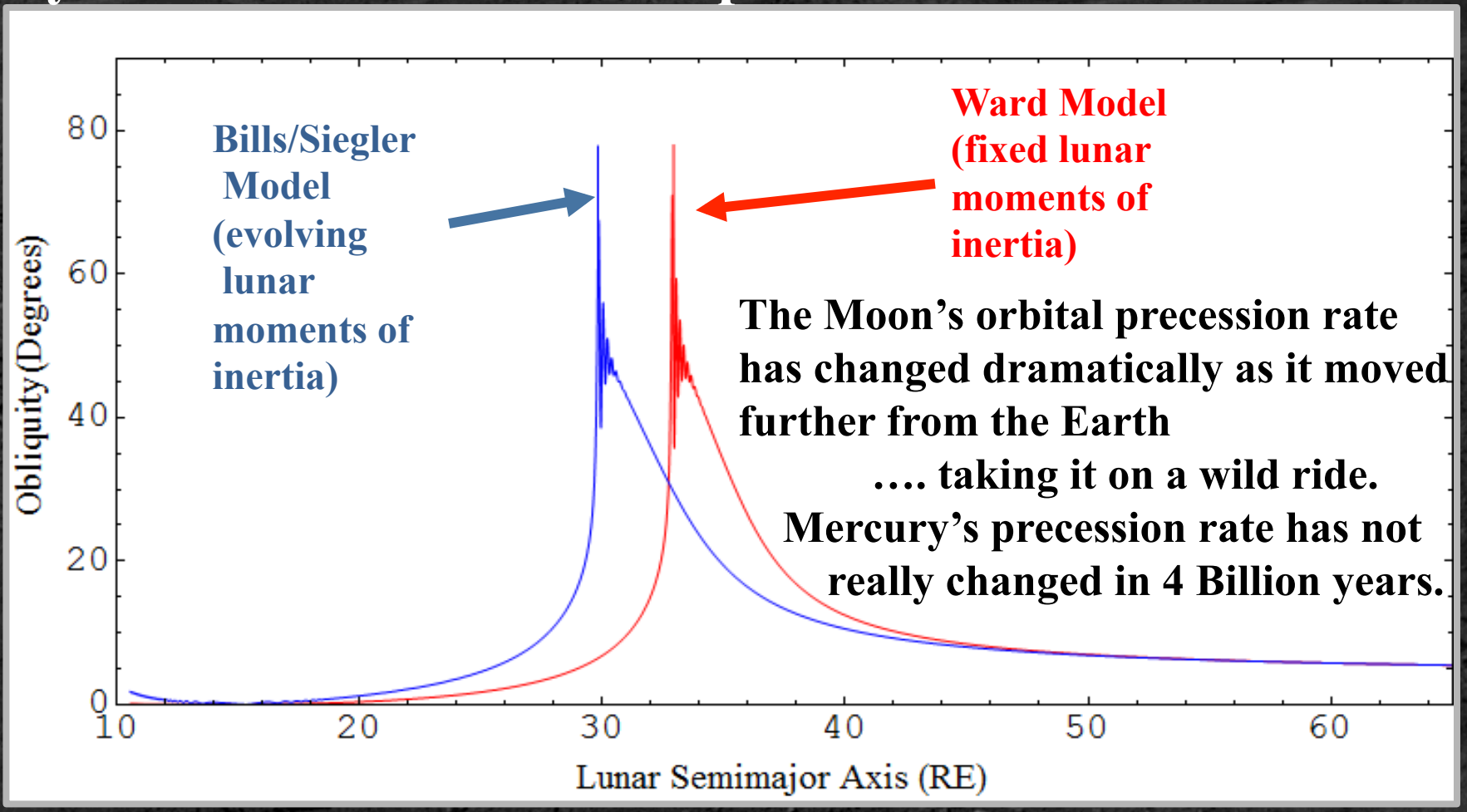
"Precessing" Earth



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

## 4) Remaining Mysteries

**What that means in practical terms is that their obliquity (their tilt with respect to their orbit plane) is controlled by the rate of their orbital precession**




**The Moon's orbital precession rate has changed dramatically as it moved further from the Earth**

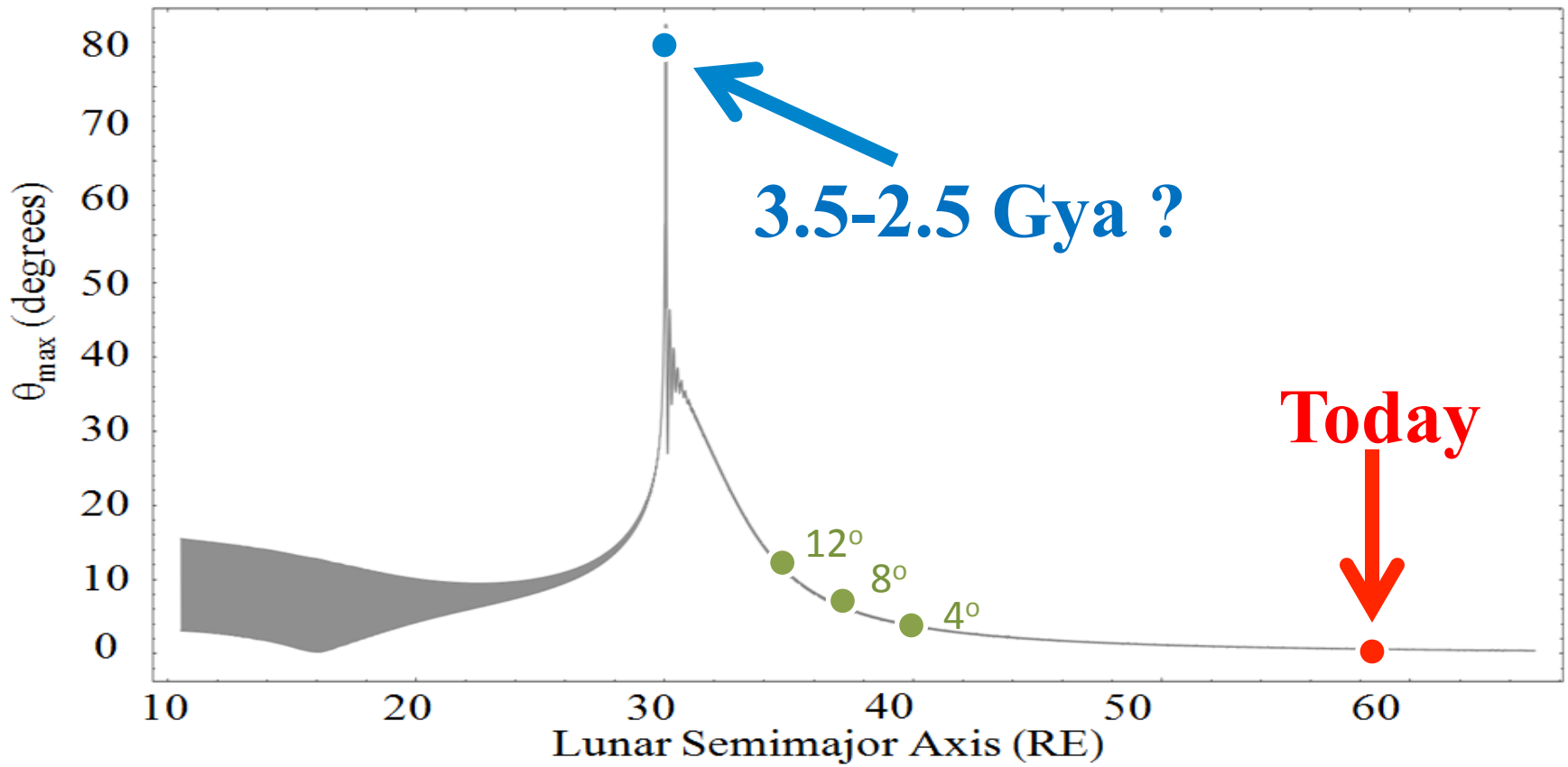
**…. taking it on a wild ride.**

**Mercury's precession rate has not really changed in 4 Billion years.**

## 4) Remaining Mysteries

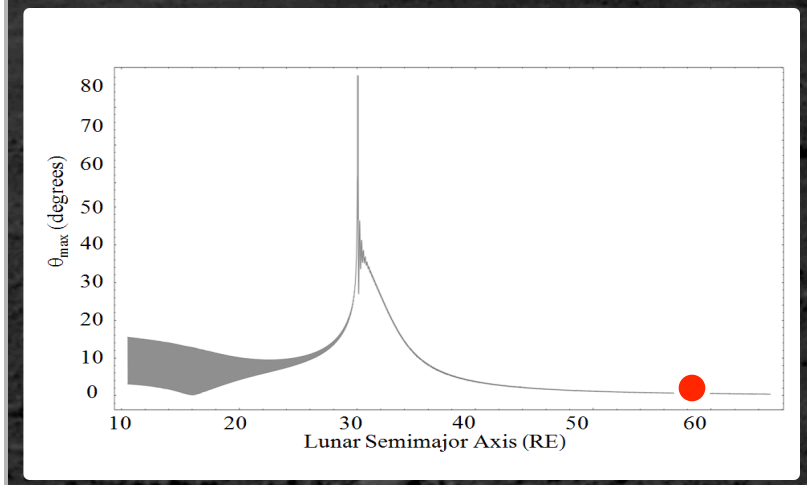
**Combined with early orbital inclination variations**

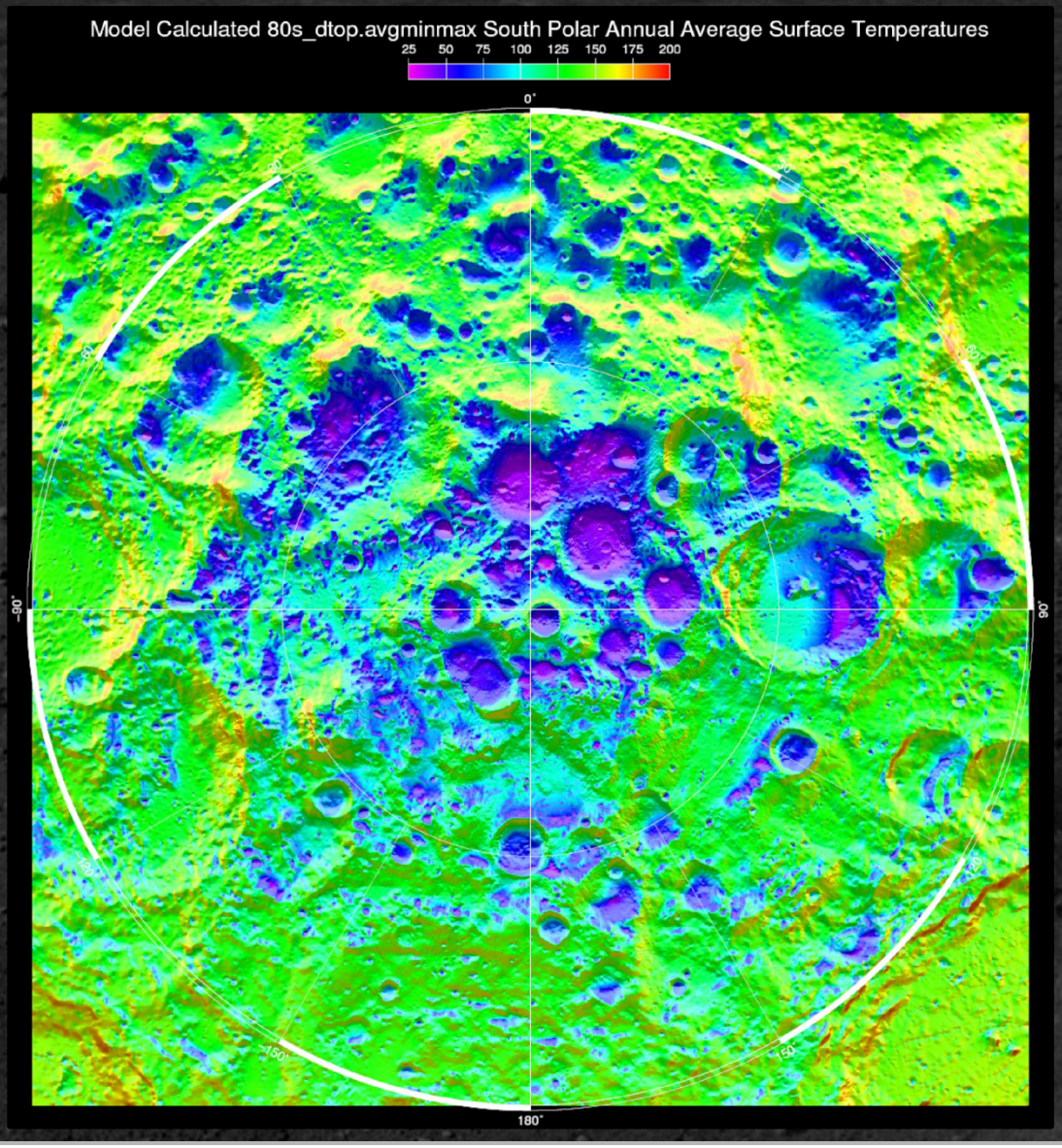
**This gave the Moon a very unique illumination history**



# 4) Remaining Mysteries

## When? Age should also be recorded in location

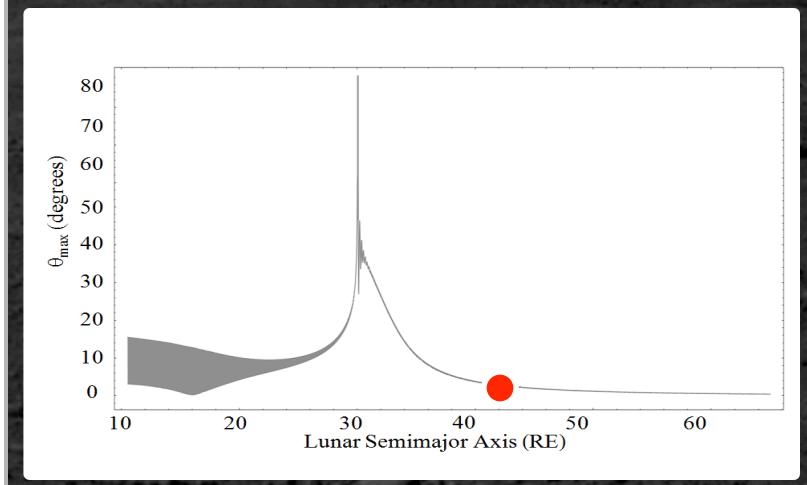


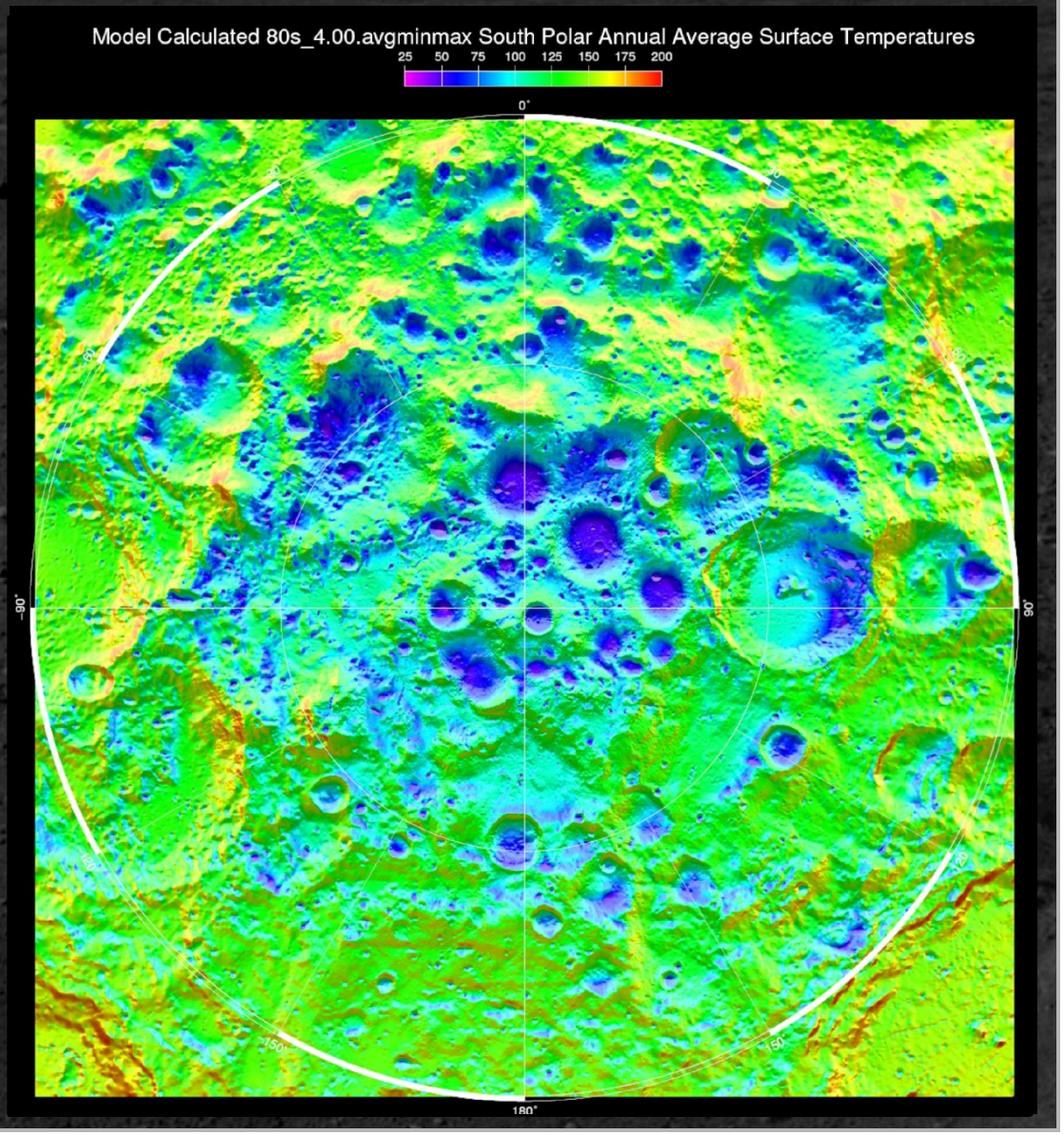




**Model Calculated Annual Average Temperature**
**Θ=1.54°**

# 4) Remaining Mysteries

## When? Age should also be recorded in location

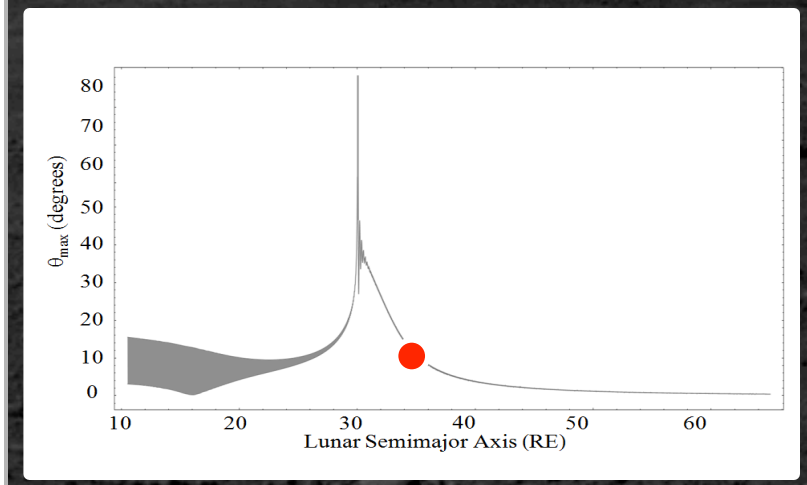


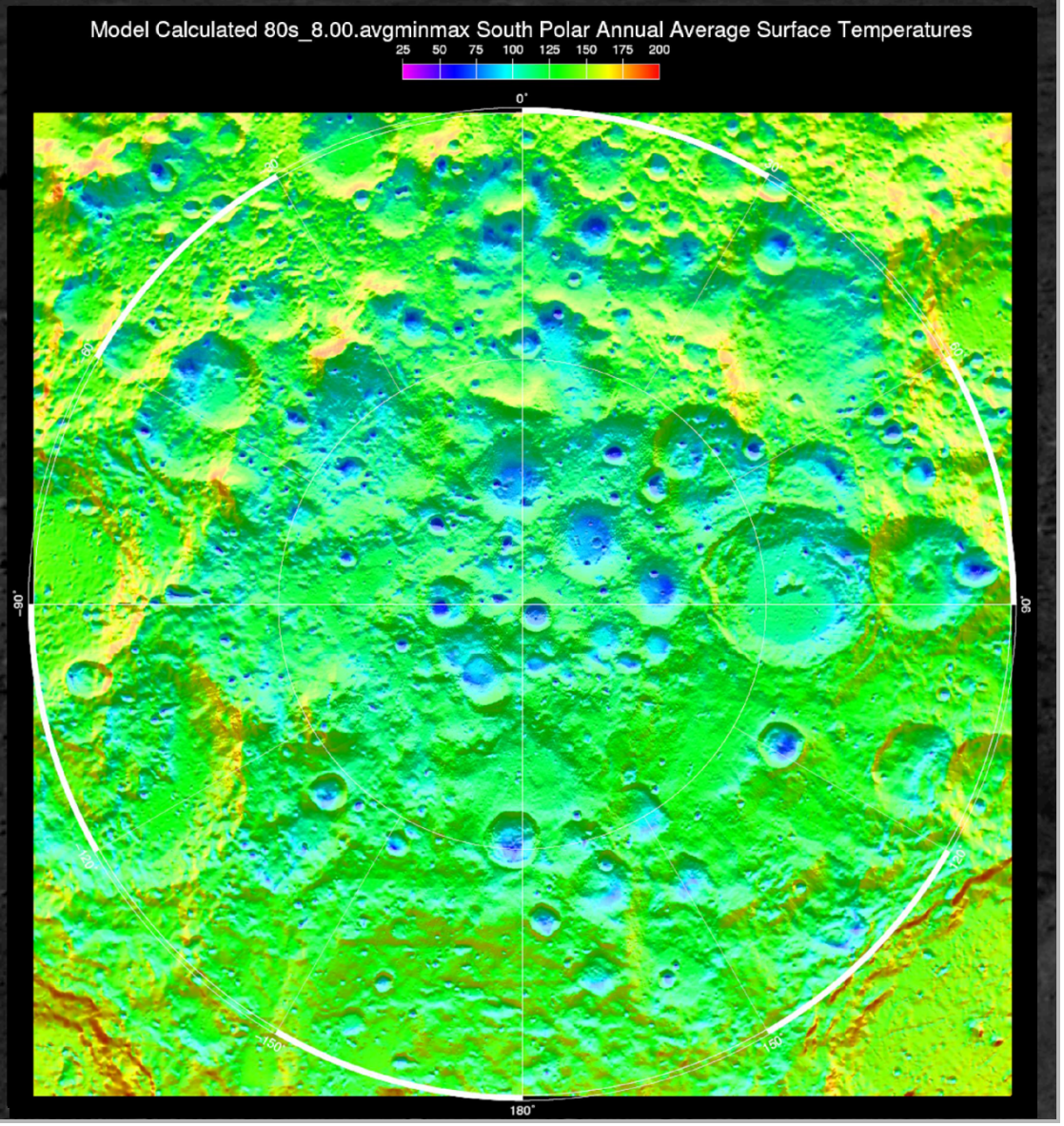




**Model Calculated Annual Average Temperature**
**Θ=4°**

# 4) Remaining Mysteries

## When? Age should also be recorded in location

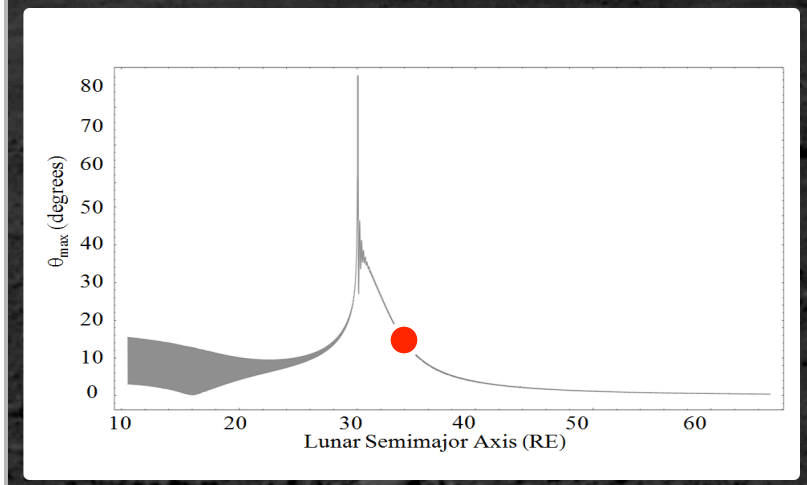


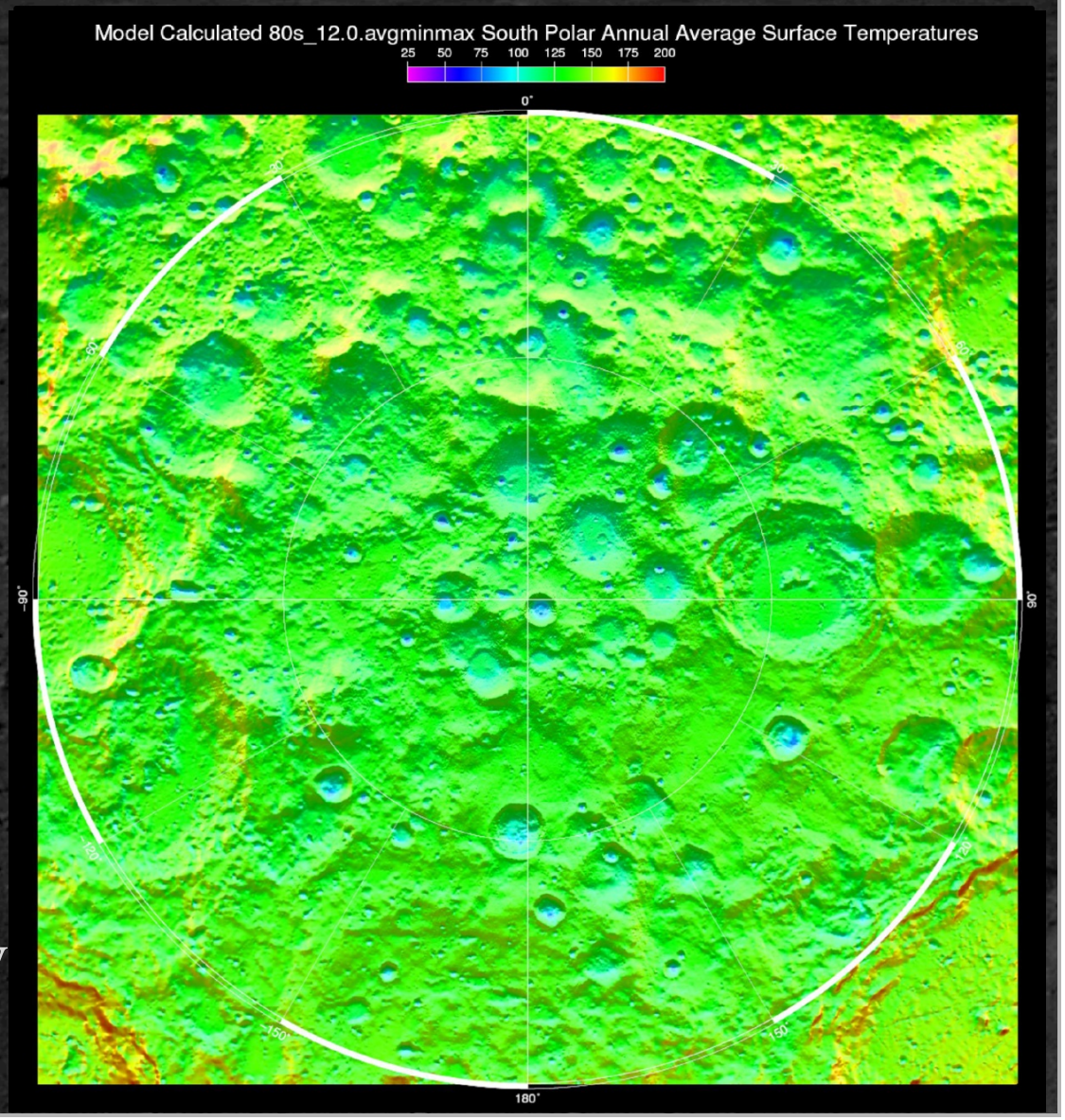




**Model Calculated Annual Average Temperature**
**Θ=8°**

# 4) Remaining Mysteries

## When? Age should also be recorded in location

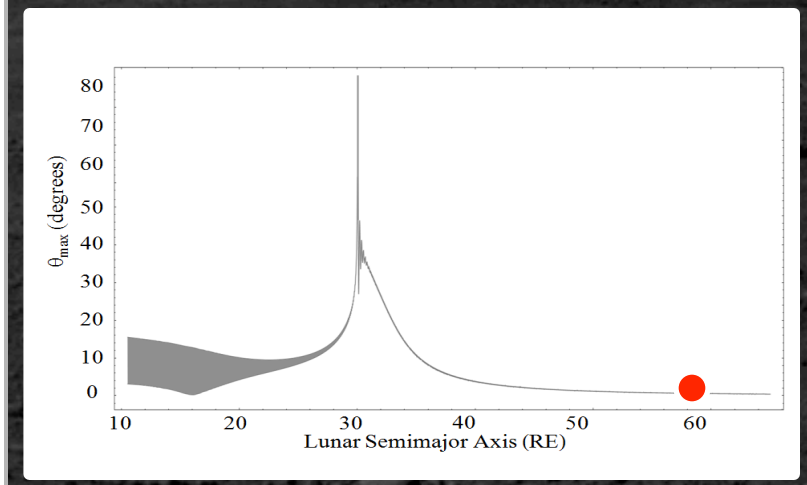


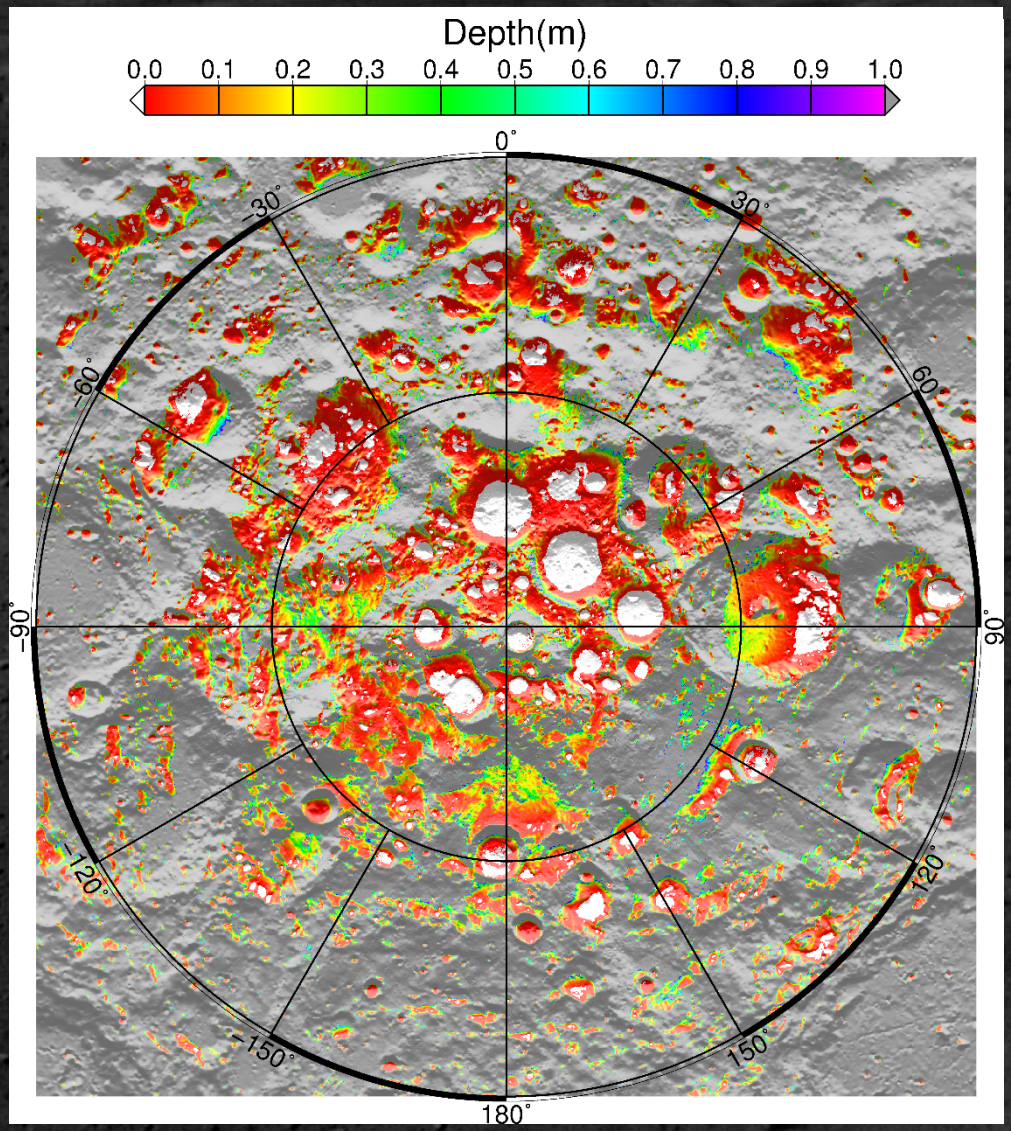




**Model Calculated Annual Average Temperature**
**Θ=12°**
**(Cold traps effectively did not exist)**

# 4) Remaining Mysteries

## When? Age should also be recorded in location

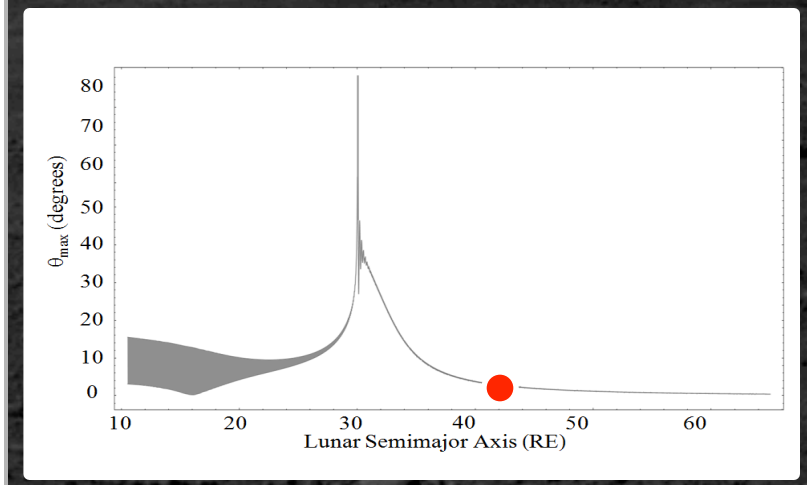


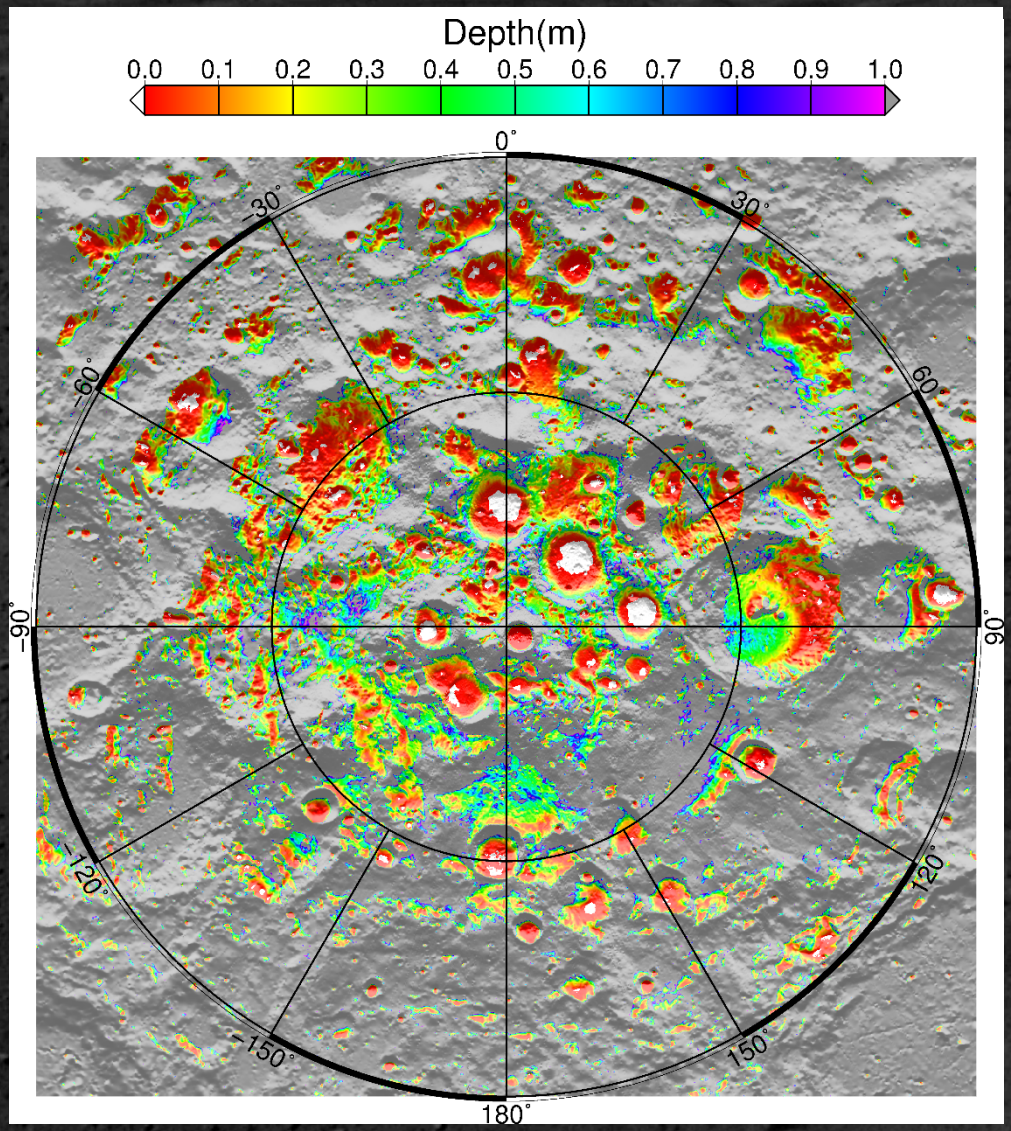




**Model Calculated Annual Average Temperature**
**Θ=1.54°**

# 4) Remaining Mysteries

## When? Age should also be recorded in location

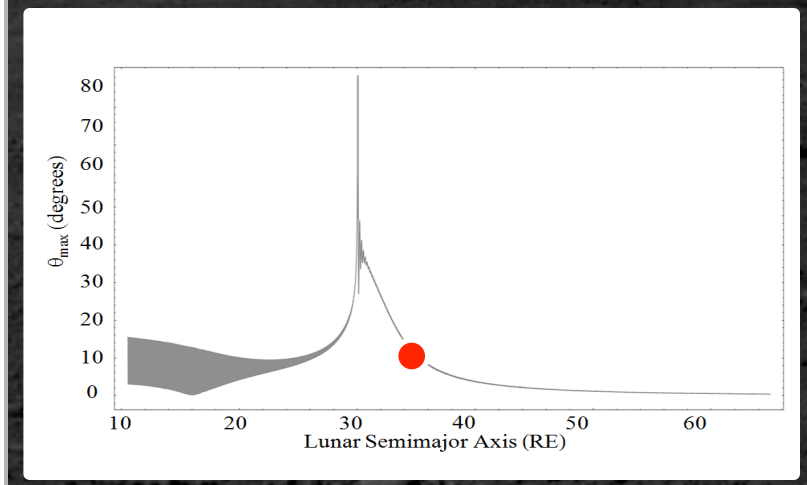


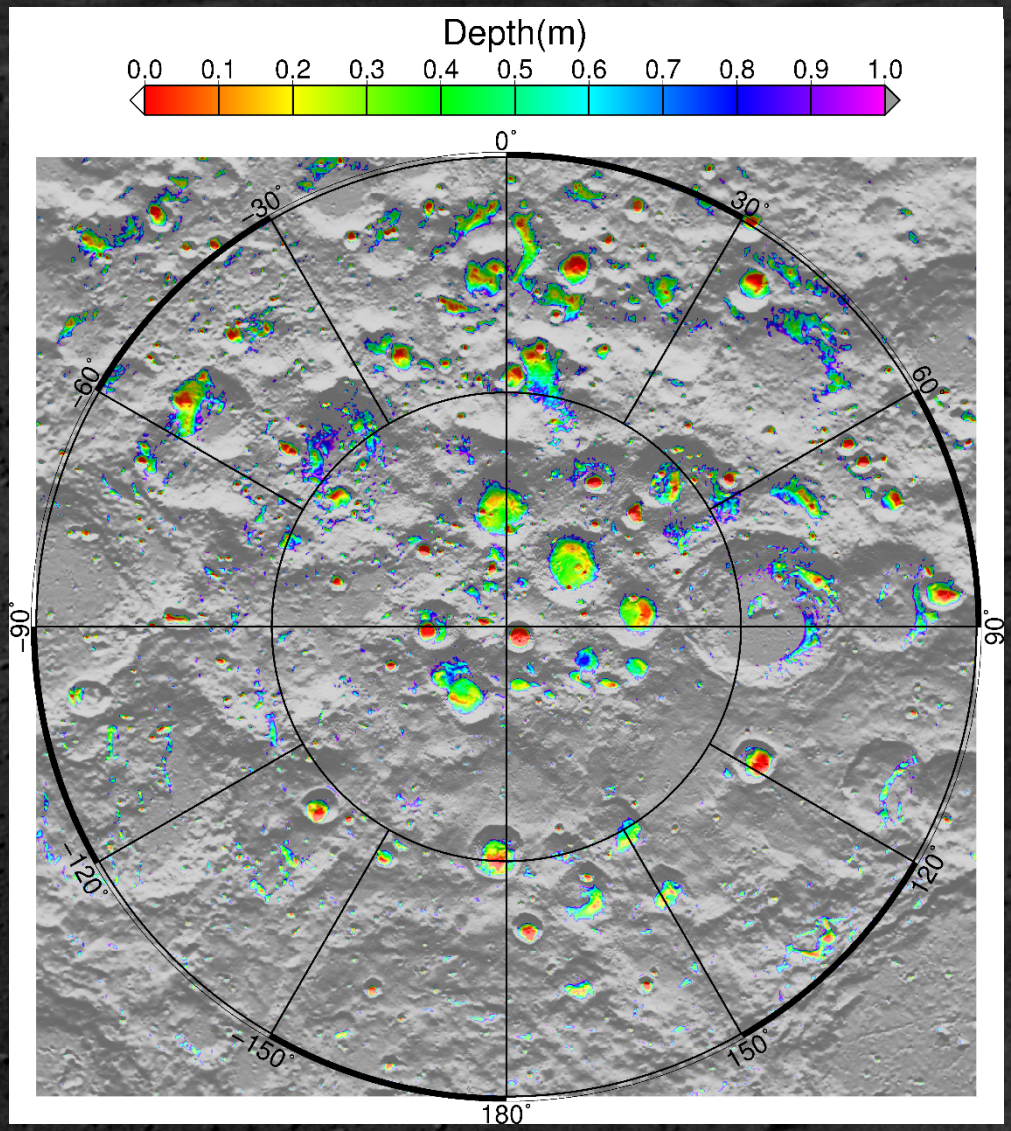




**Model Calculated Annual Average Temperature**
**Θ=4°**

# 4) Remaining Mysteries

## When? Age should also be recorded in location

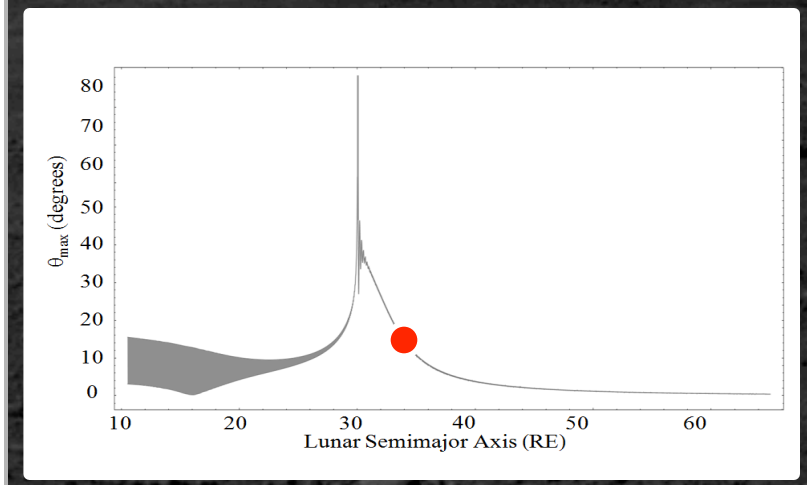


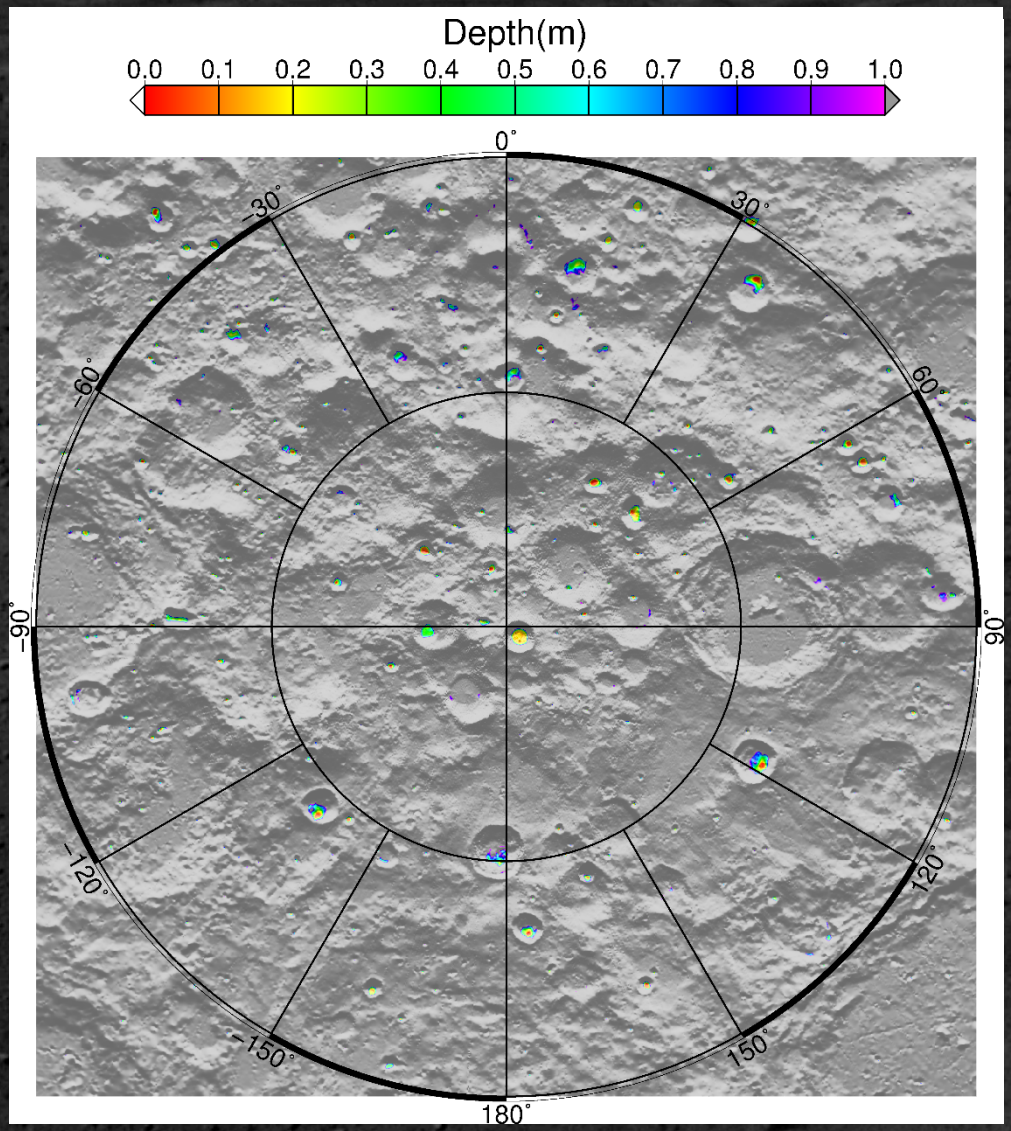




**Model Calculated Annual Average Temperature**
**Θ=8°**

# 4) Remaining Mysteries

## When? Age should also be recorded in location



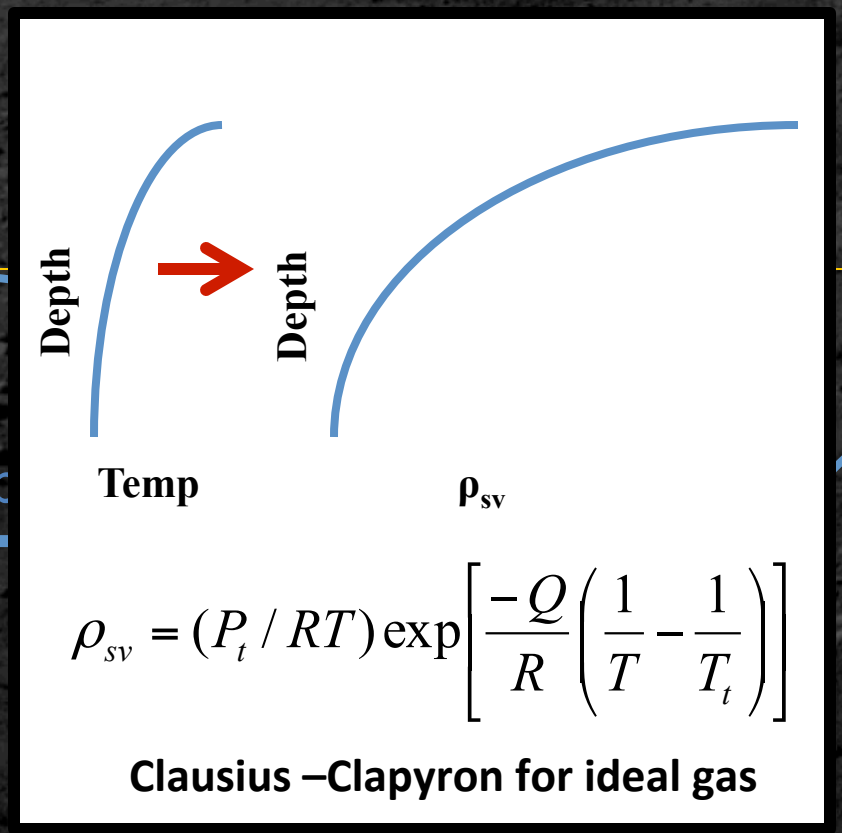




**Model Calculated Annual Average Temperature**
**Θ=12°**

# 4) Remaining Mysteries

## Simple Rules of Ice migration/retention:

1) Ice will migrate along thermal gradient when mobile
2) Ice will deposit where the soil is below the frost point




$$\rho_{sv} = (P_t / RT)\exp\left[\frac{-Q}{R}\left(\frac{1}{T} - \frac{1}{T_t}\right)\right]$$

**Clausius –Clapyron for ideal gas**

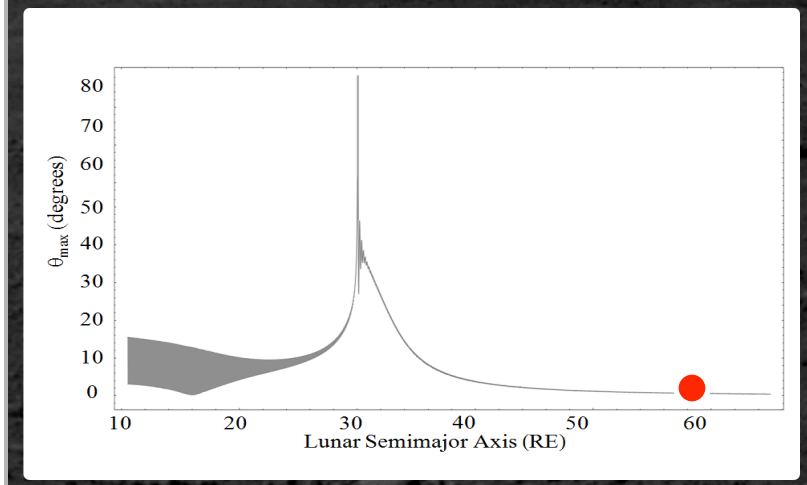
Ice driven down along Thermal gradient

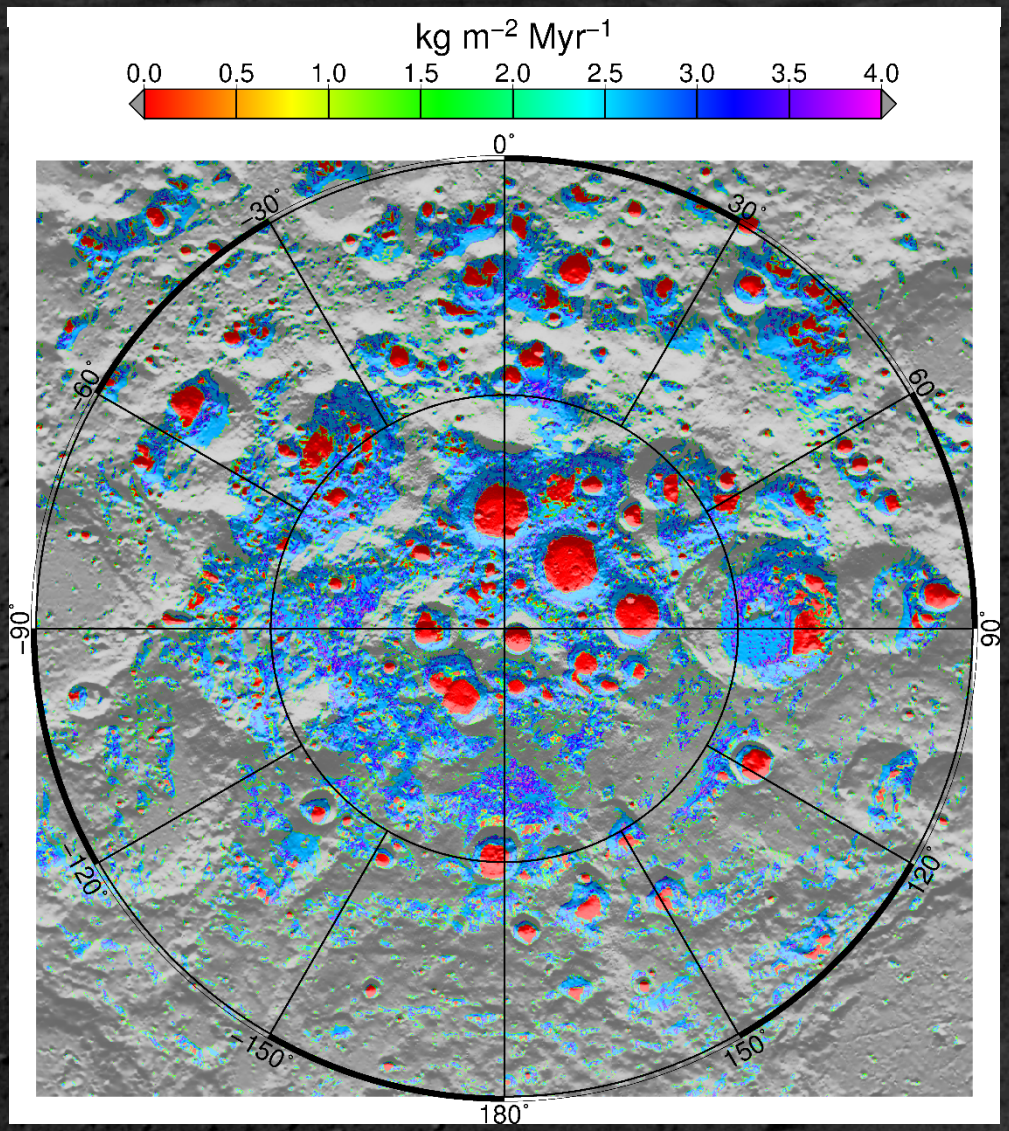
Temp

Depth

# 4) Remaining Mysteries

## When? Age should also be recorded in location

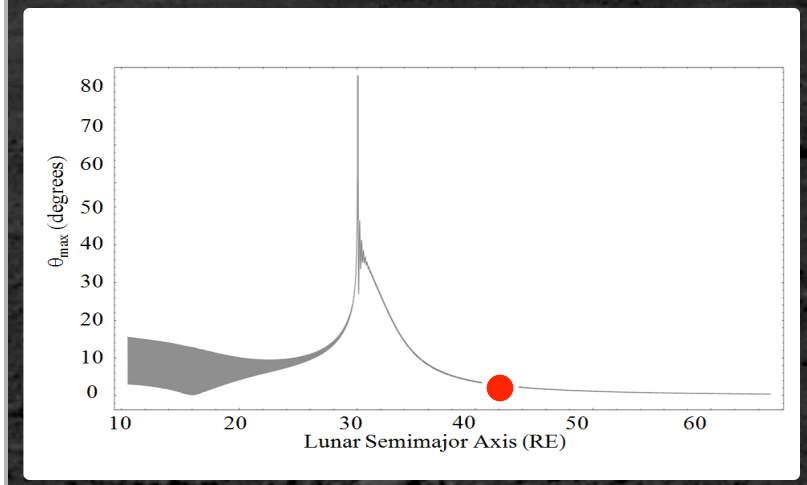


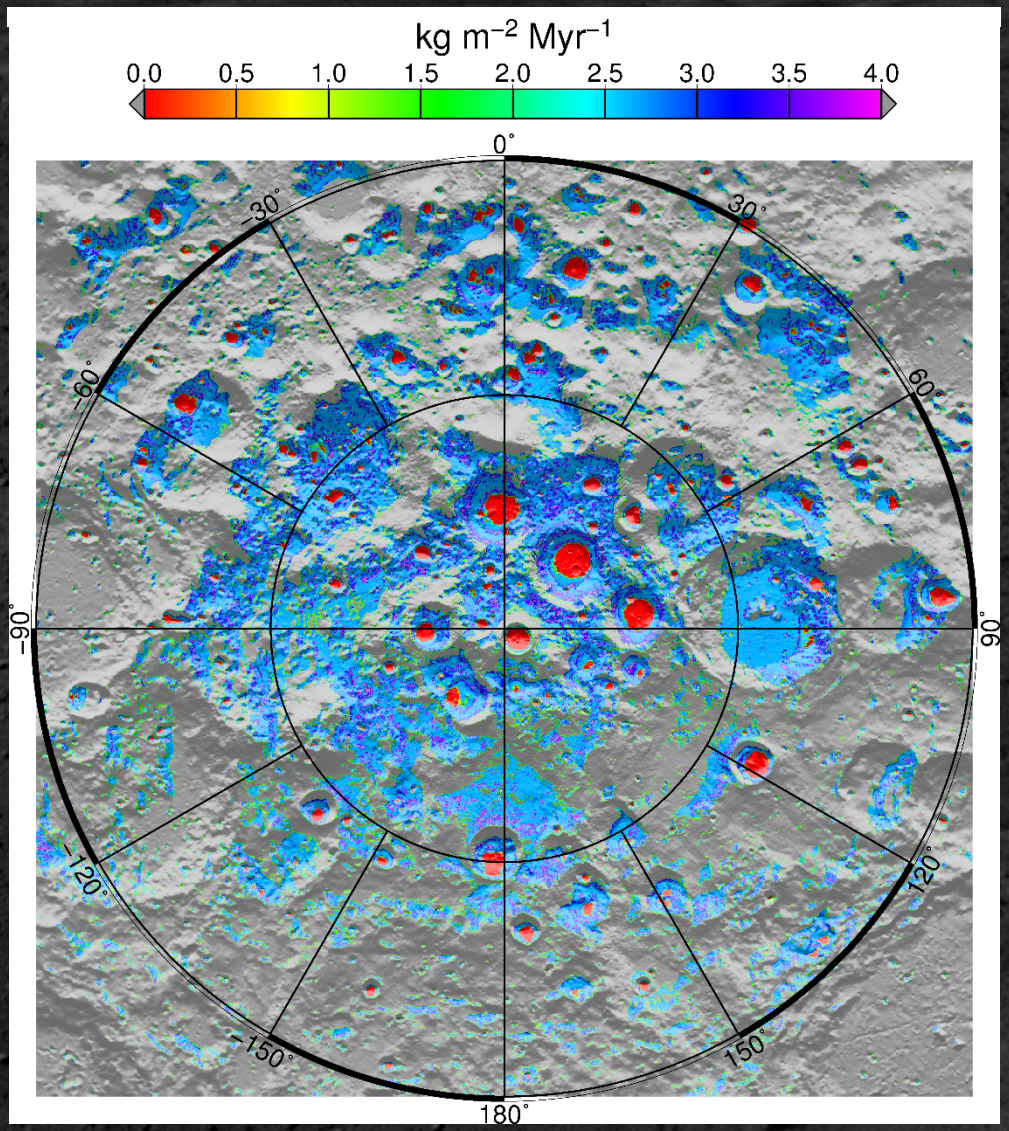




**Model Calculated Annual Average Temperature**
**Θ=1.54°**

# 4) Remaining Mysteries

## When? Age should also be recorded in location



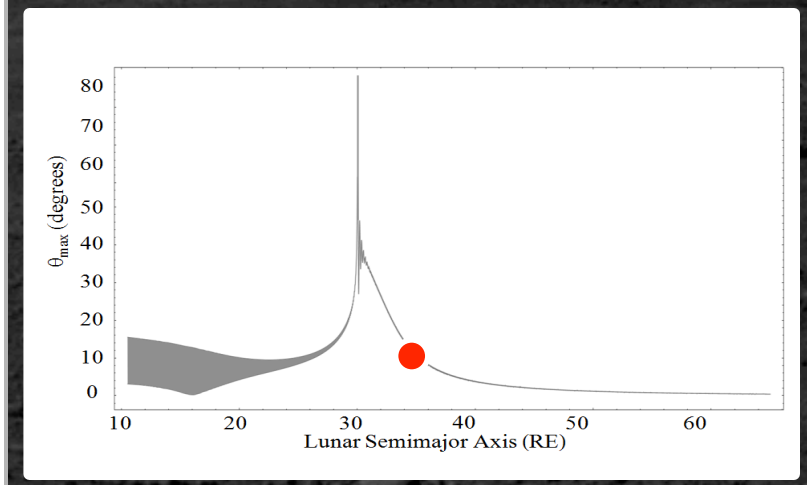



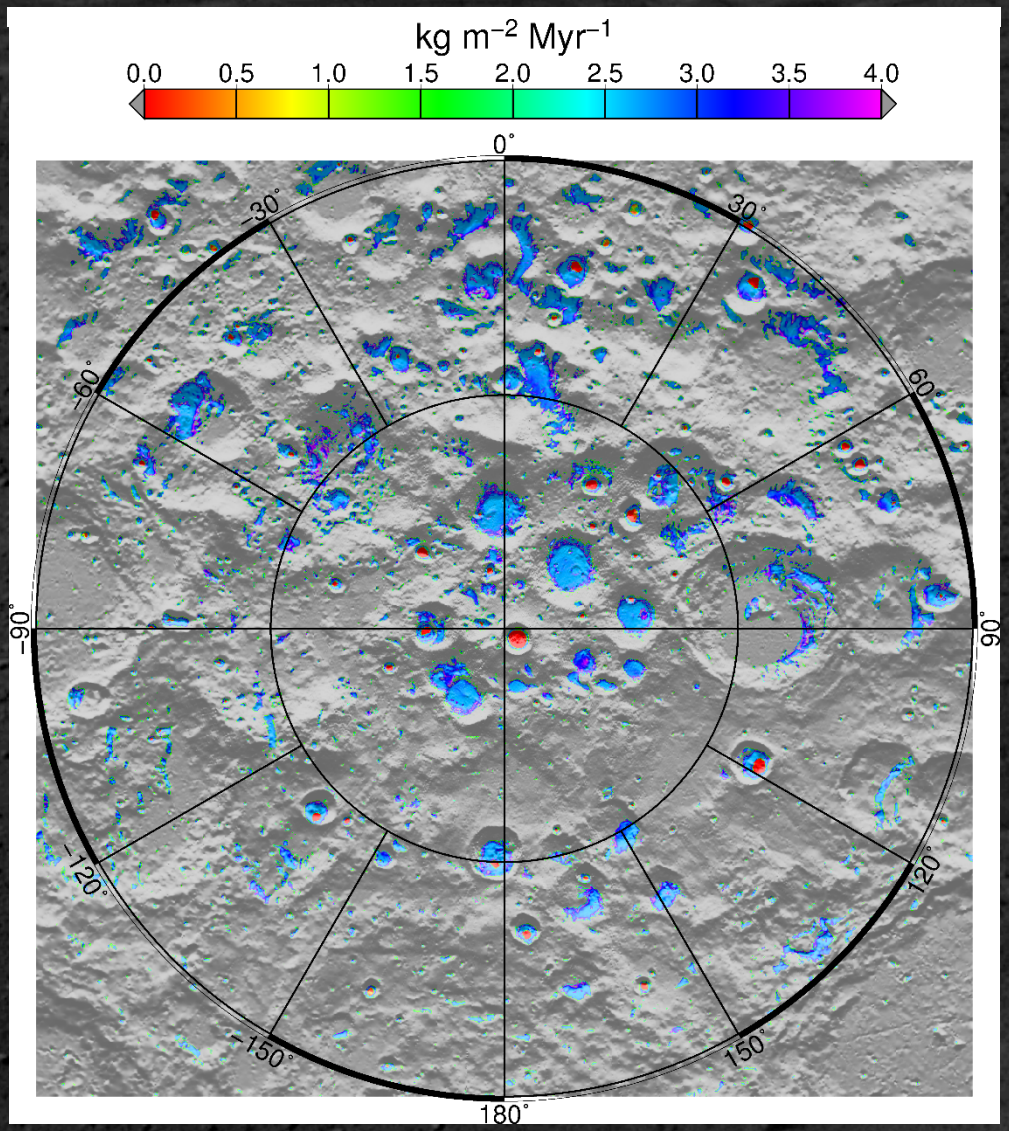

**Model Calculated Annual Average Temperature**

**Θ=4°**

# 4) Remaining Mysteries

## When? Age should also be recorded in location

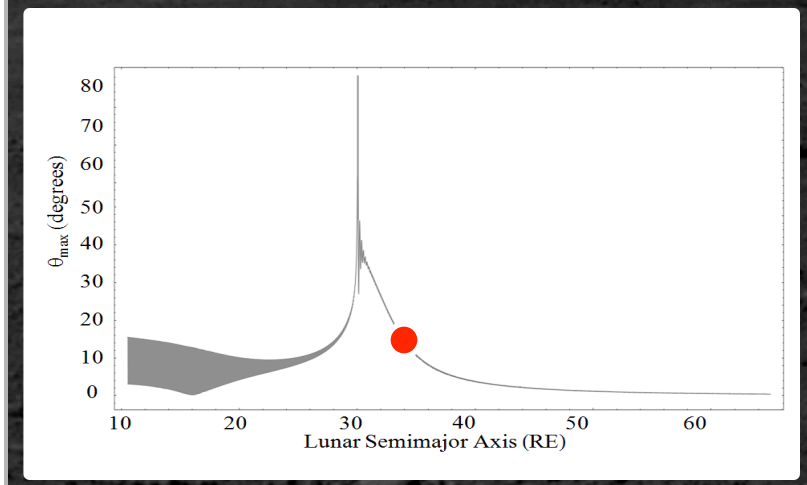


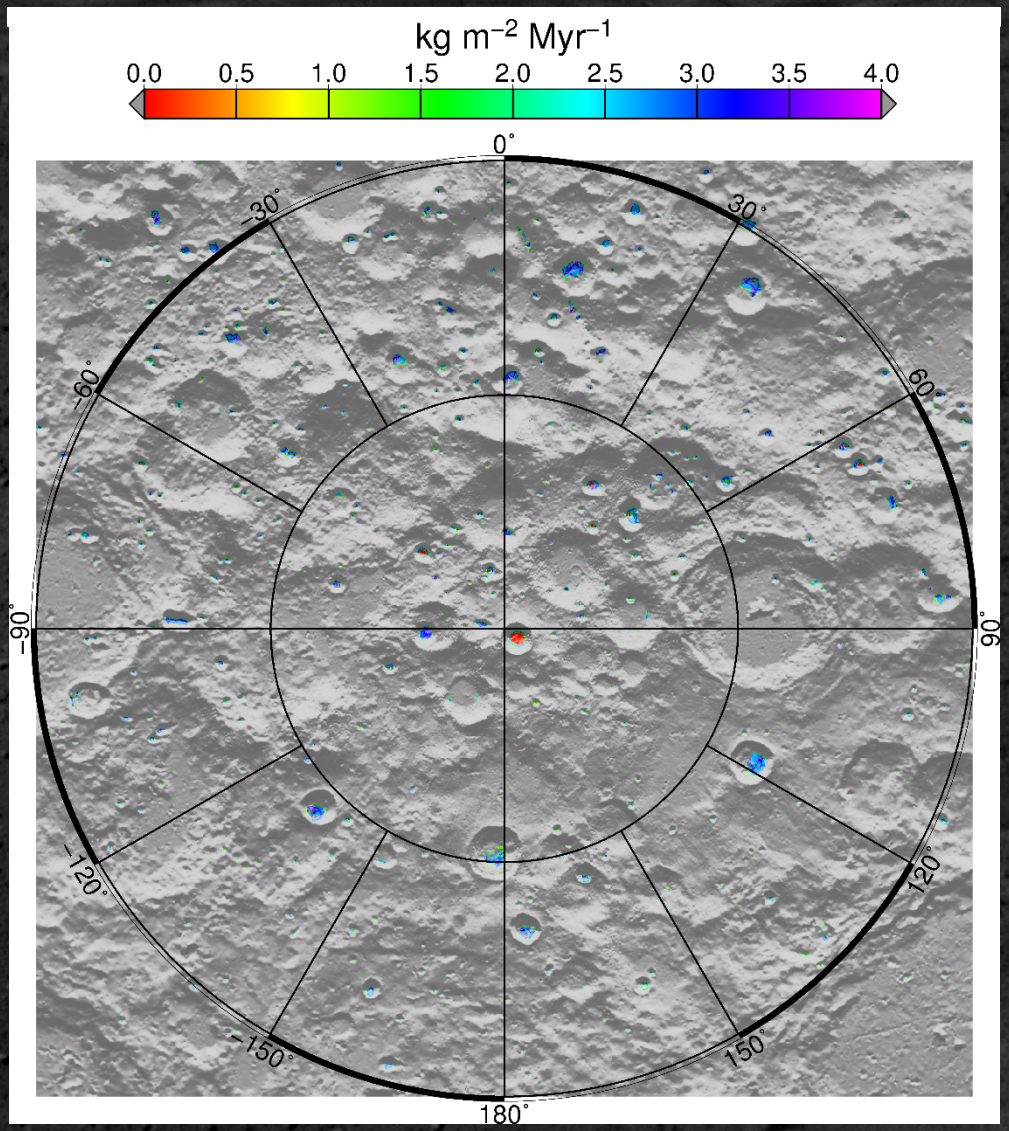




**Model Calculated Annual Average Temperature**
**Θ=8°**

# 4) Remaining Mysteries

## When? Age should also be recorded in location

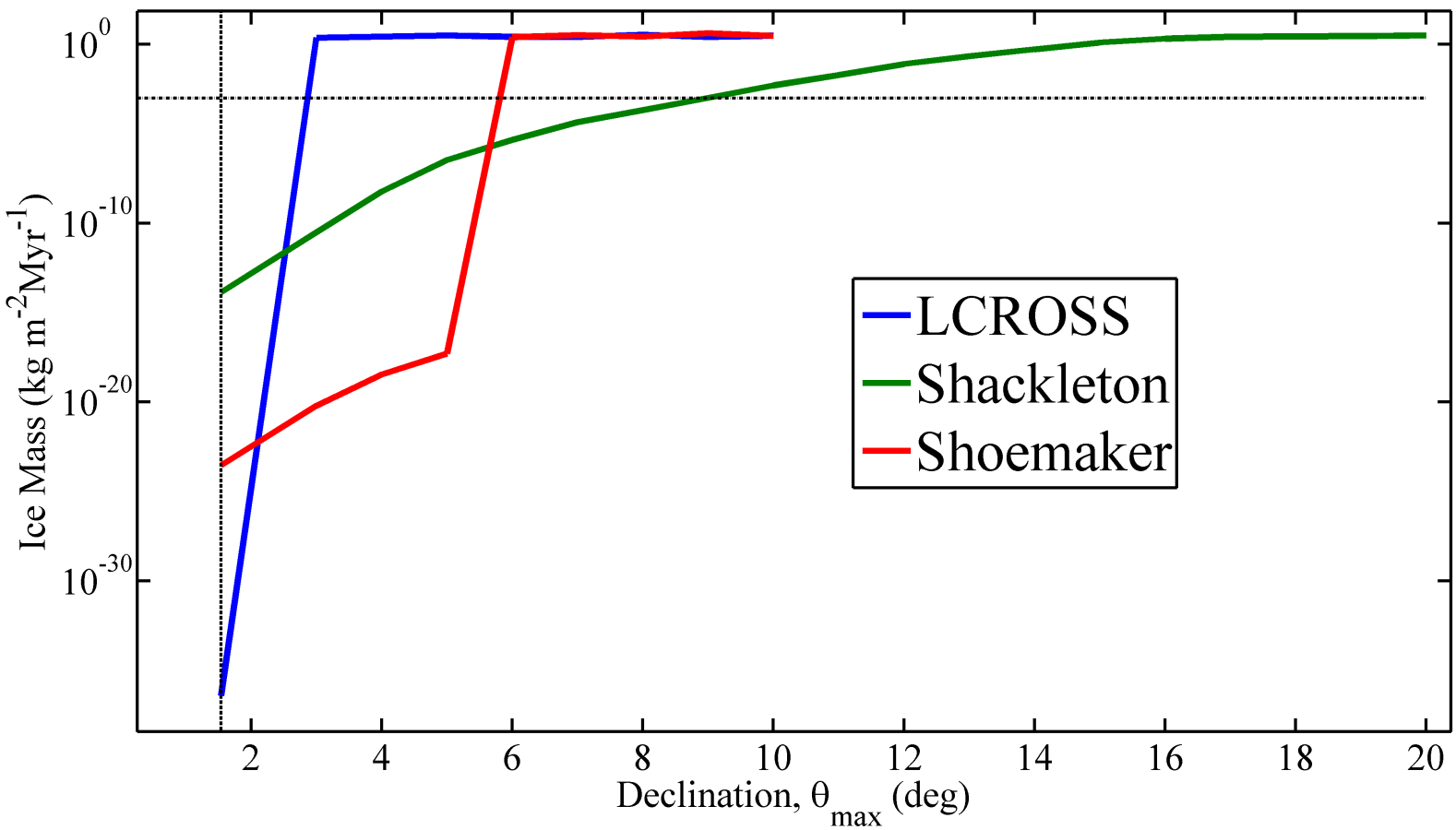


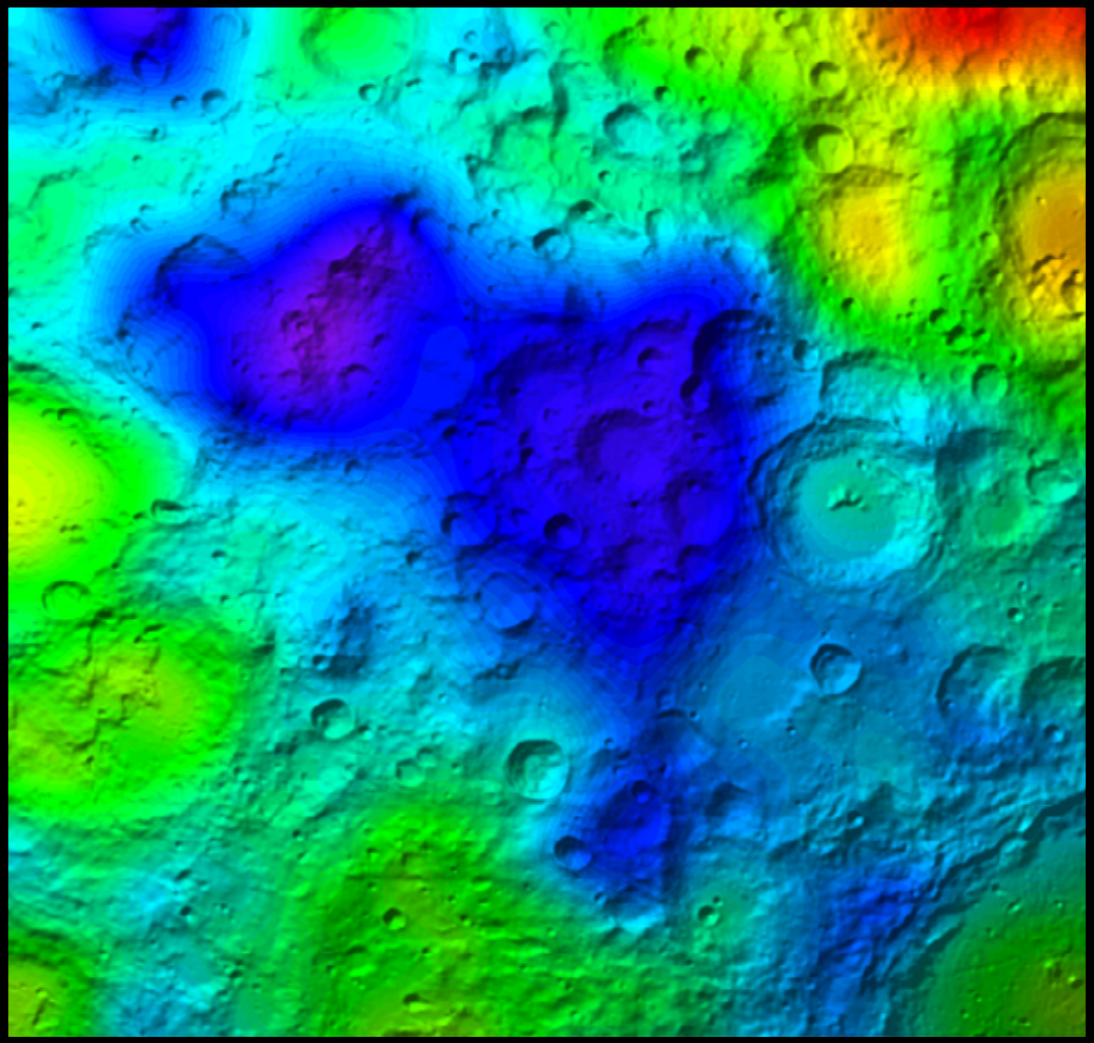

**Model Calculated Annual Average Temperature**
**Θ=12°**

# 4) Remaining Mysteries

## When? Age should also be recorded in location



# 4) Remaining Mysteries



# Overall conclusions

- Differing temperature histories record different segments of the history of volatile delivery to the inner solar system

- We don't yet understand why the Moon and Mercury have such different volatile reservoirs … but there differences may hold the key to understanding their source

- Thermal modeling is critical for our understanding of these volatile reservoirs

# Questions?