Evidence of Dynamic Hydrogen, Hydroxyl, and Water at the Moon

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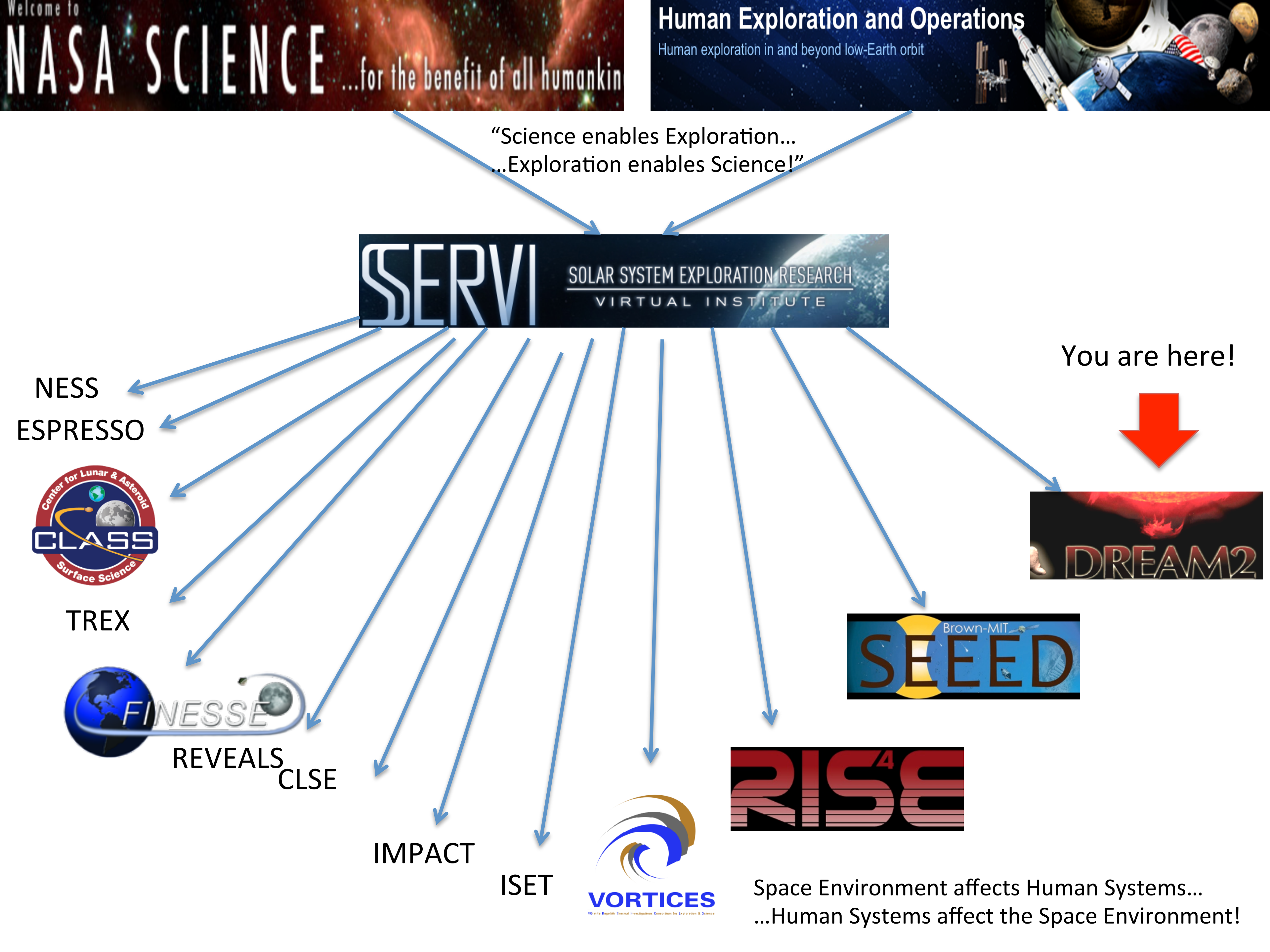
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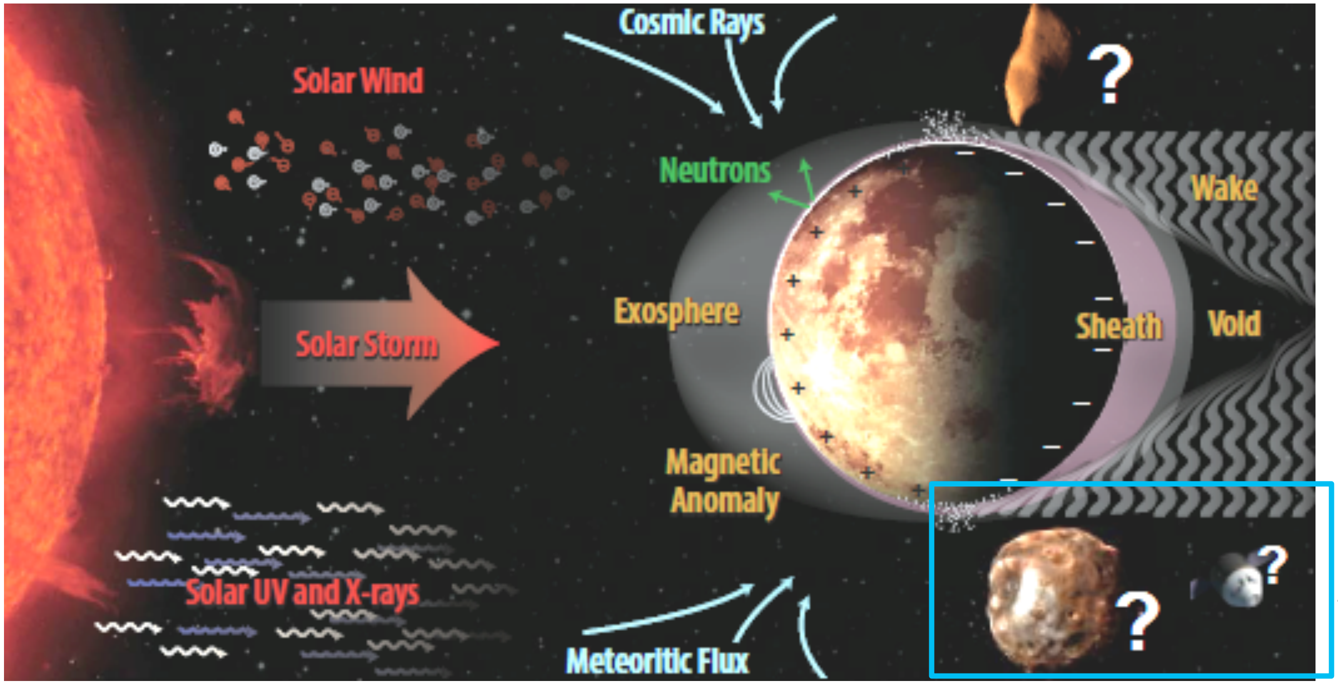
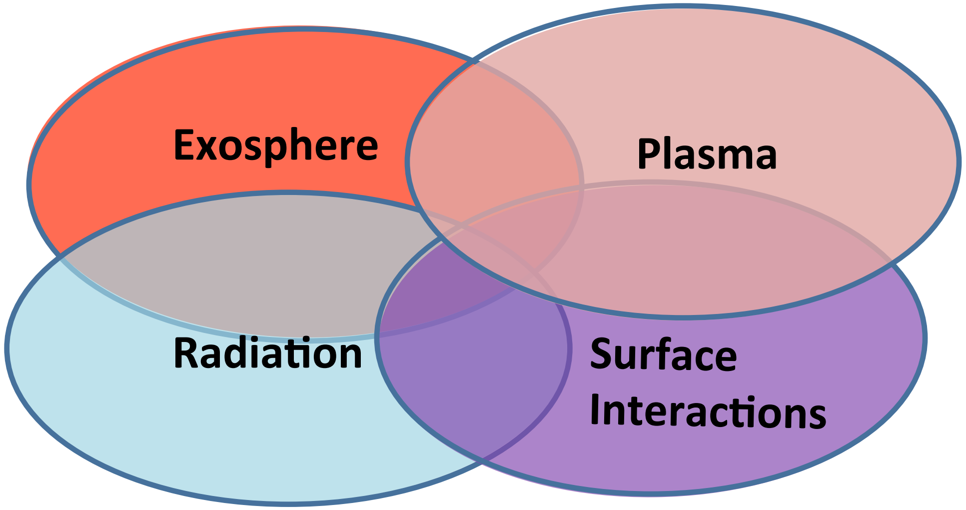
You are here!
Space Environment affects Human Systems...
...Human Systems affect the Space Environment!



body-body interactions

- Theory, modeling, data center emphasizing the space environment- airless body connection
- "How does the highly-variable environmental energy at an airless body affect volatiles, plasma, new chemistry, and surface micro-structure?"
- Emphasize the dynamics and extreme events – solar storms and human interaction
- Provide support to missions like LADEE, LRO, Resource Prospector
- ~30 investigators from 14 partnering institutions, GSFC PI.

Dynamic Response of Environments at Asteroids, Moon, and moons of Mars (DREAM2)



Fundamental Themes
- -Exospheres
- -Plasmas
- -Particle Radiation
- -Surface Interactions

Applied Themes:
- -Extreme Events
- -Applications to missions and HEO

"How does the highly-variable environmental energy at an airless body affect volatiles, plasma, new chemistry, and surface micro-structure?"

Focus on common processes at all target bodies

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Vital Stats

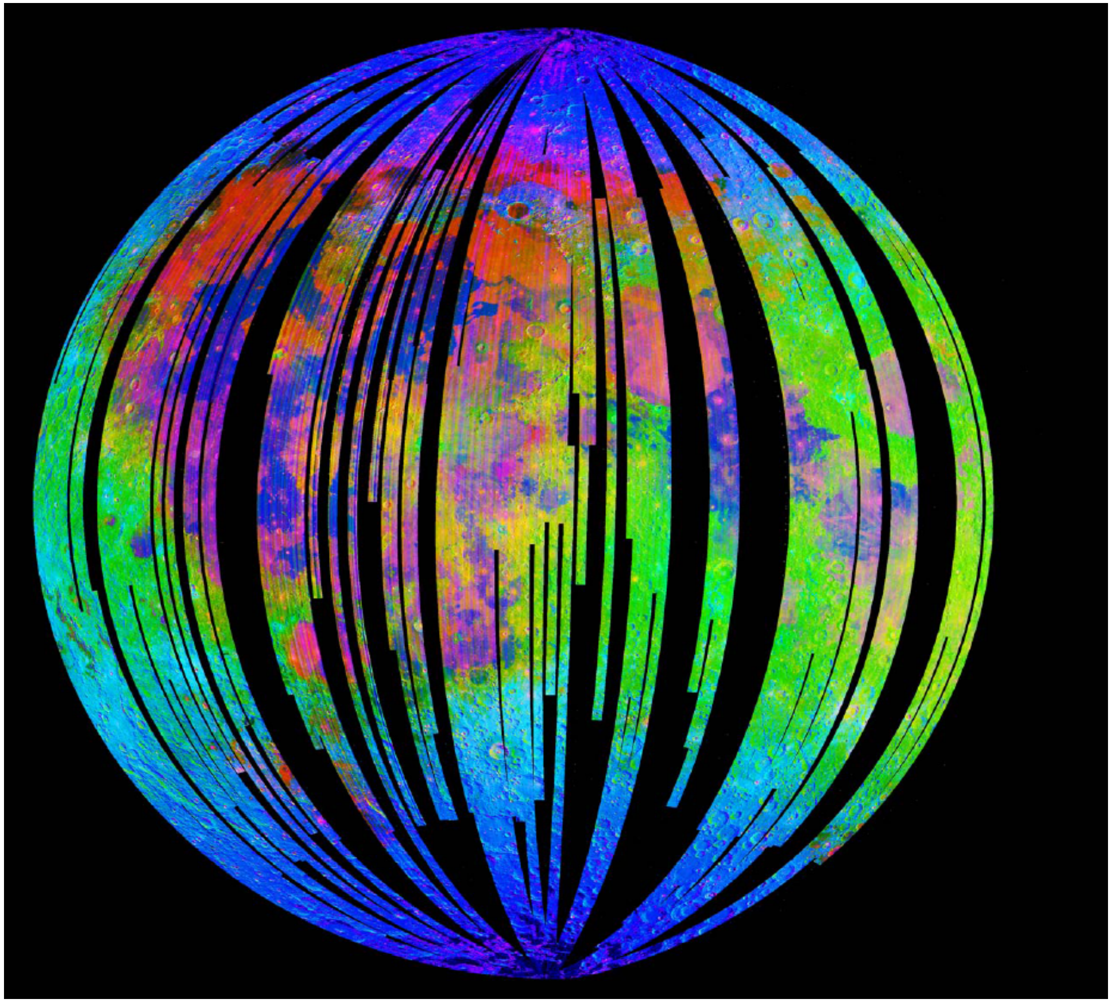
- **Team members:** 31 Investigators, 3 Education and Comm reps, 14 partner institutions
- **DREAM2 Tools:** >20 models, >10 data sets, 4 laboratories
- **Current Science Papers (as of 5/31):** 94 total; 88 in press or published
- **E/PO:** DREAM2-Howard Univ Intern Program & DREAM2Explore teacher workshops (Lora B., Andrea J., and P. Misra, HU)
- **Activities:** In any given year, > 30 tasks ongoing. See our annual report

  https://ssed.gsfc.nasa.gov/dream/docs/DREAM2.annualreport.PY4.pdf

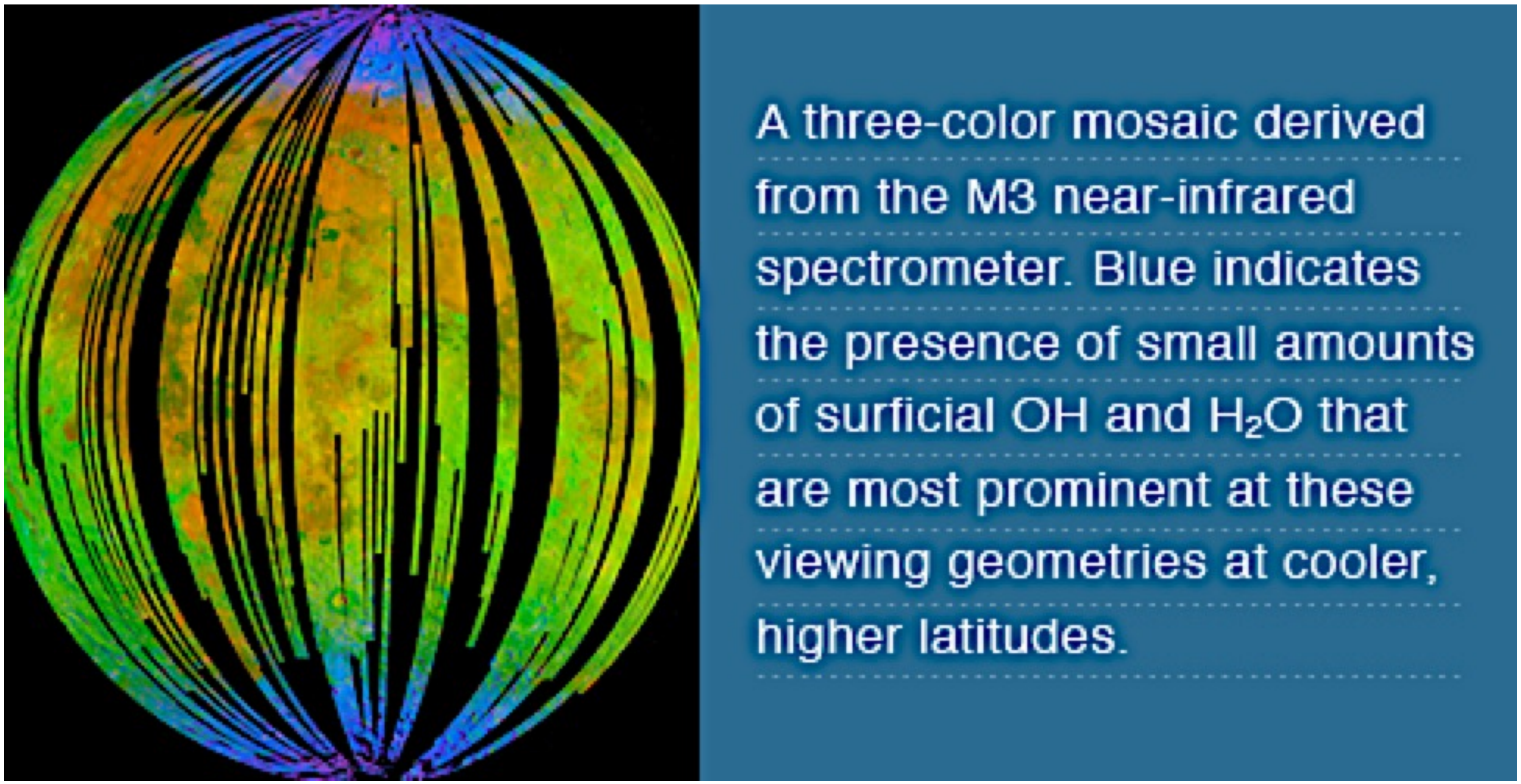
When you think of the Moon….not very dynamic!

Like black and white image…has an 'old' look to it ….before color

Clark et al, 2010

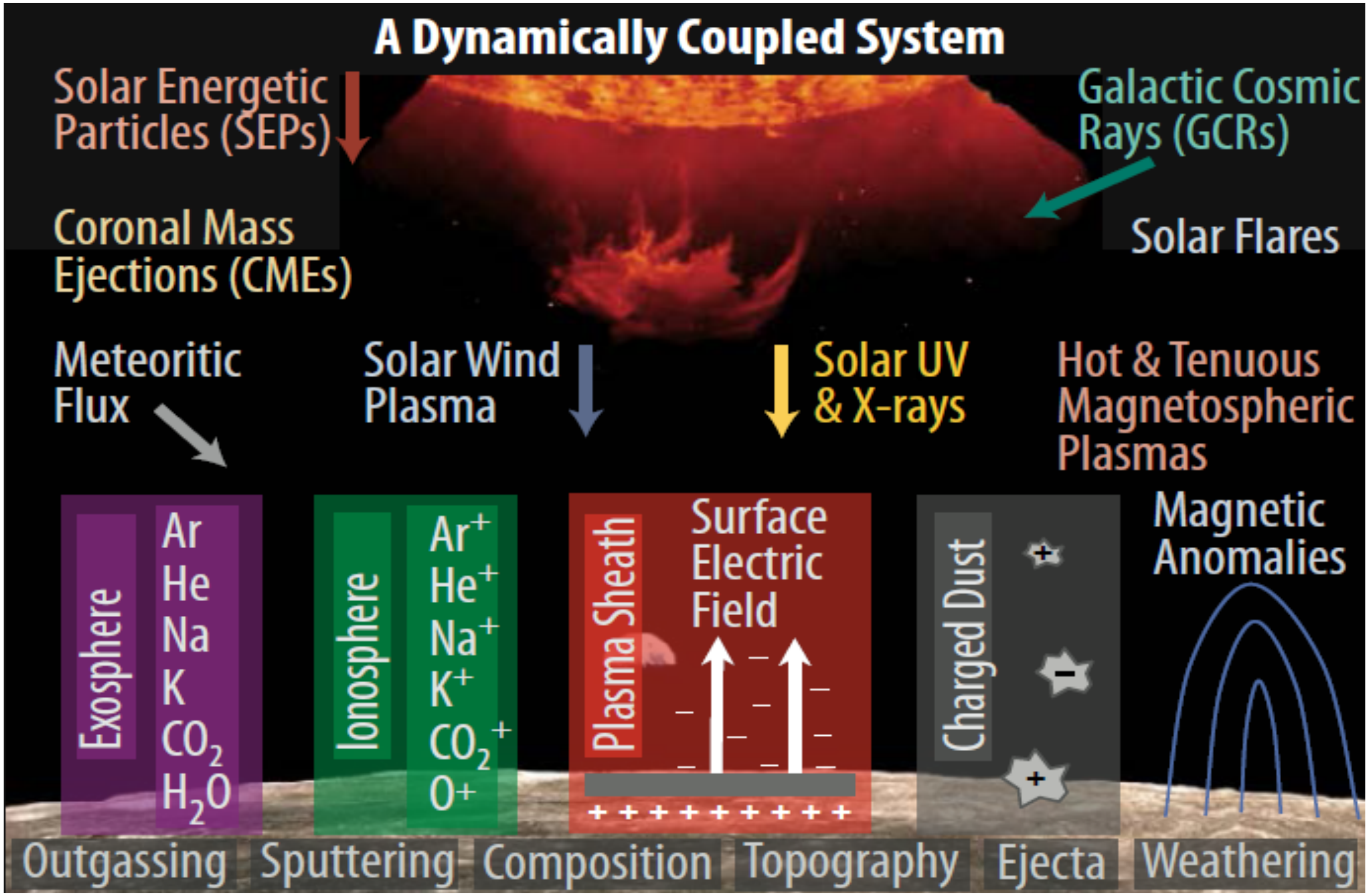


Is this a little more interesting?



At the microscopic level, the Moon is very active and dynamic!

Environmental energy and matter incident at surface: Drives a response



Exosphere = Collisionless atmosphere   Moon does have an 'atmosphere' at ~$10^5/cm^3$

Prior to 2009…Moon was considered dry, 'anhydrous'

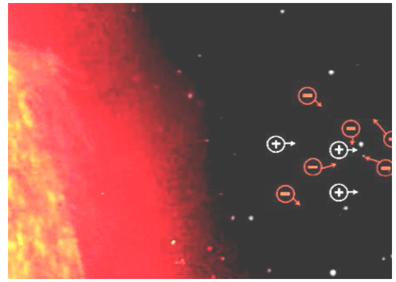
Whereas now, we even speak in terms of a water cycle

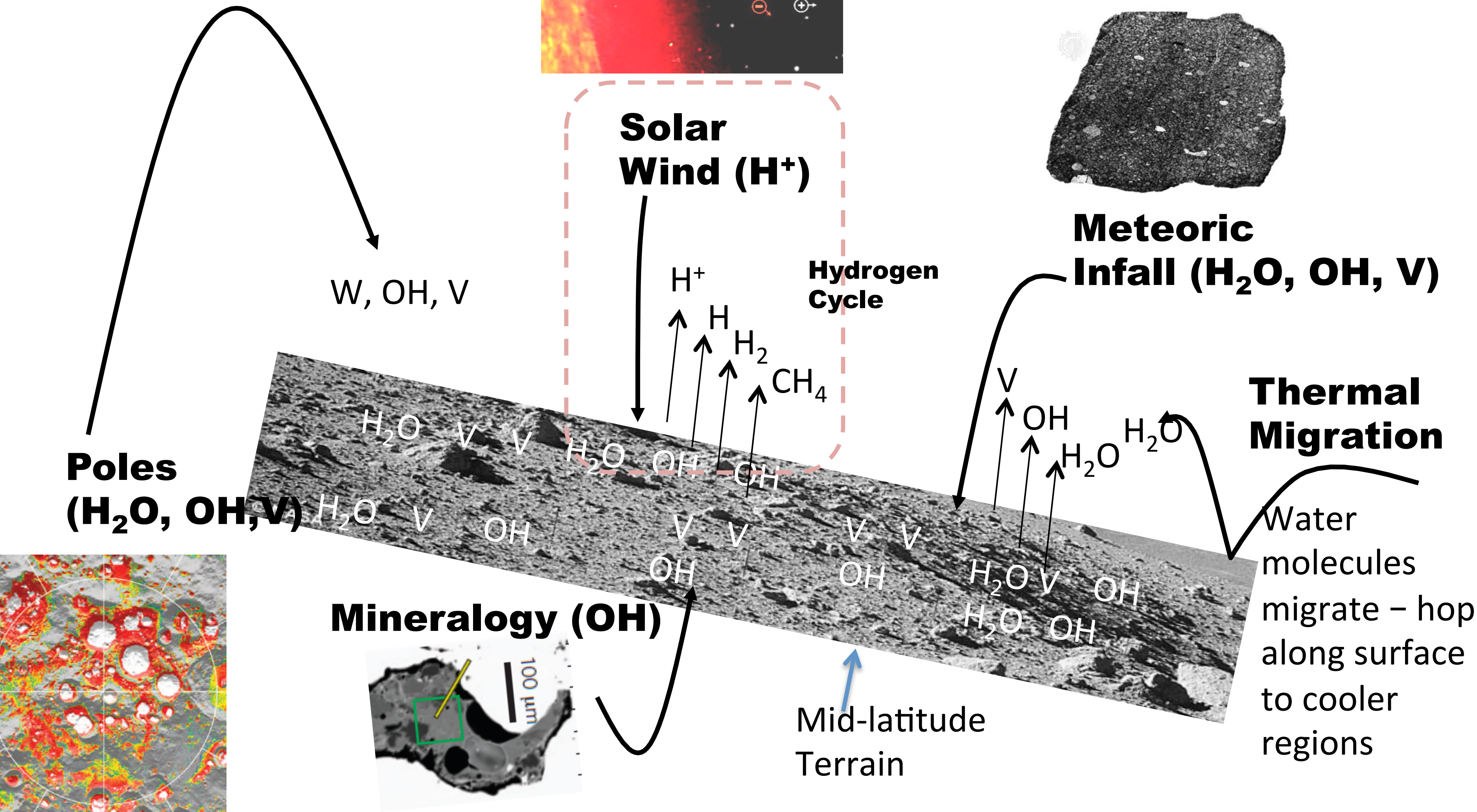
So…what happened? How did the view change?

3 revolutions: in the lab, in remote sensing, and in an active lunar experiment that changed our view

Lunar Hydrogen/OH/Water: A Dynamic System

$$\partial W/\partial t + \nabla \bullet (W\mathbf{v}) = S_{SW} + S_{infall} + S_{poles} - L_{desorp} - L_{photodiss} - L_{sputter} - L_{impactvapor}$$





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Source #1 Polar Source of Water

- Permanently shadowed craters at the lunar poles –bigger area in the south pole
- Very cold: < 40K (thanks to LRO/Diviner)
- Trap water and other volatile species (LRO senses these)

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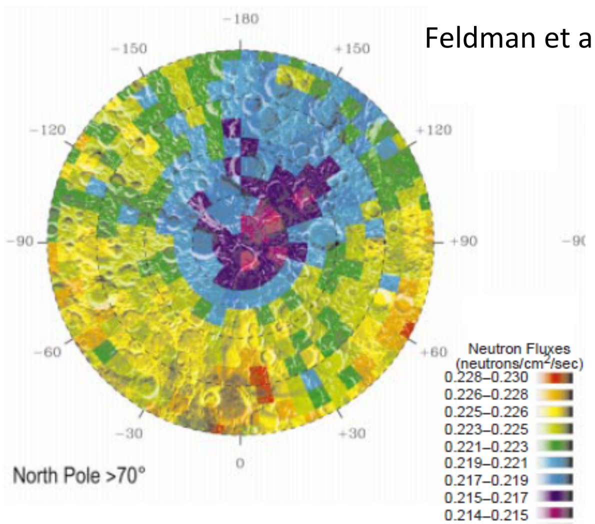
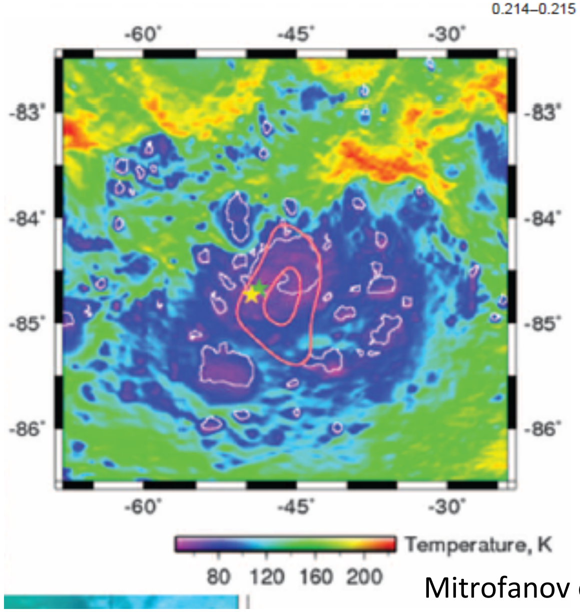
Water in Lunar Polar Cold Traps

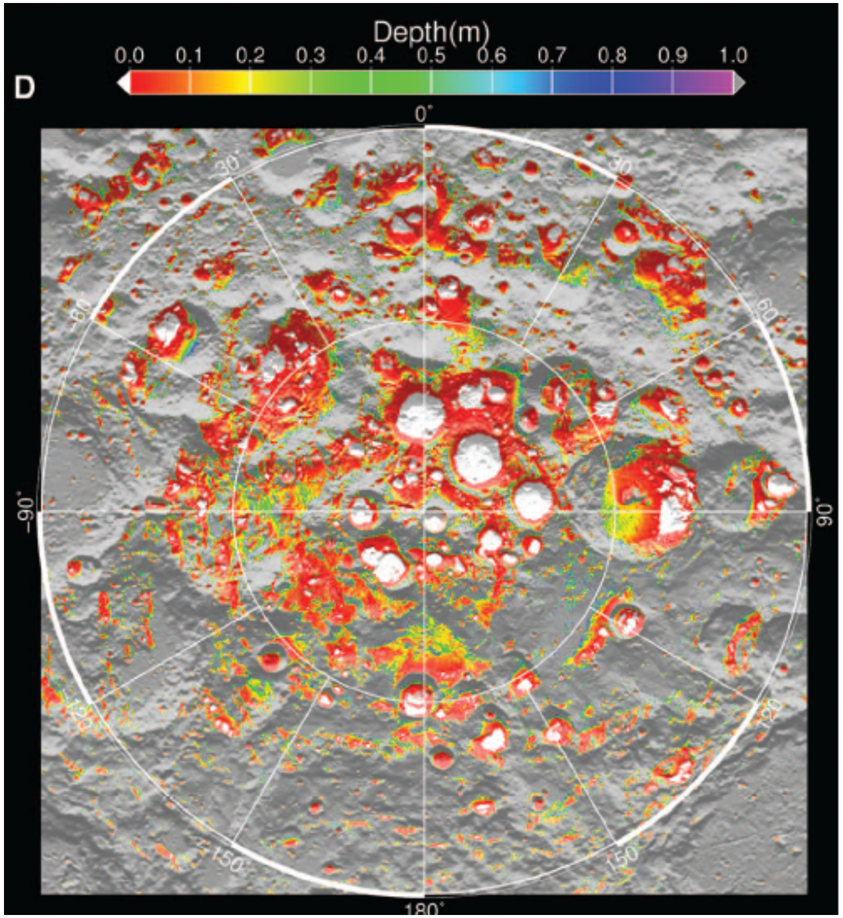


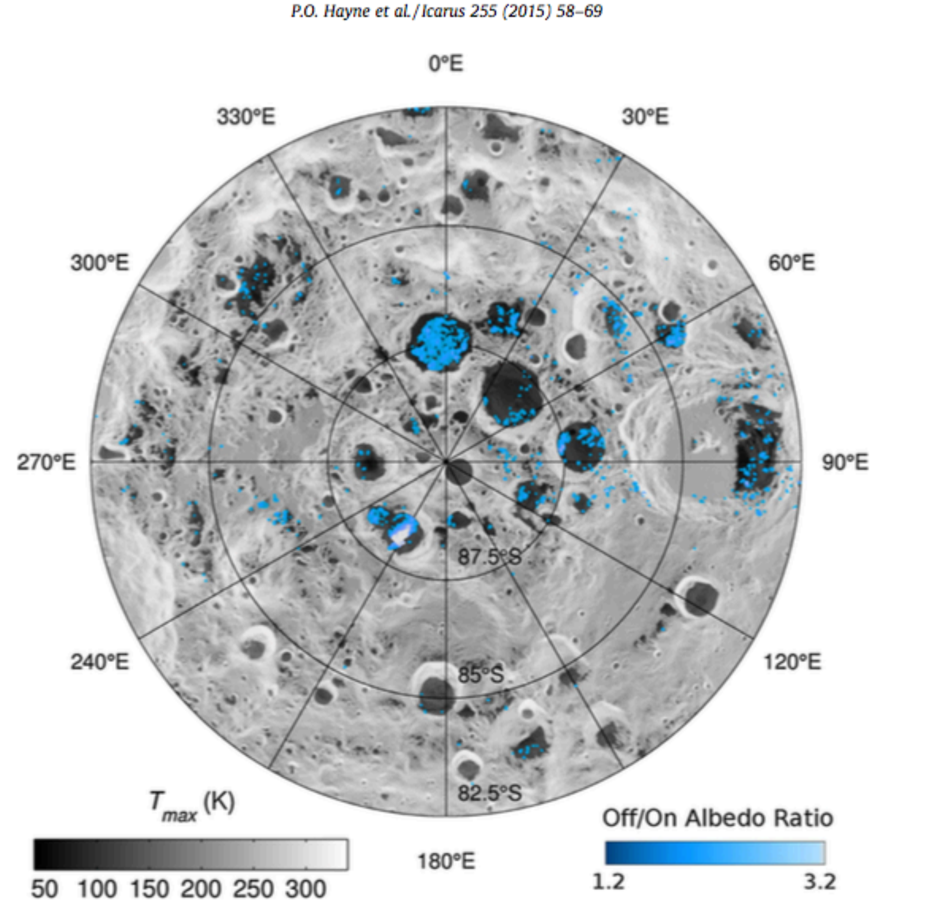
Feldman et al., 1998



Mitrofanov et al., 2010

- Suspected poles trap water since early 1960s [Watson et al., 1961, 1963]
- Lunar Prospector Neutron Spectrometer: epithermal neutron reduction indication of H-bearing minerals (Feldman et al., 1998)
- Statistically significant reduction in lunar polar regions
- LRO/LEND (Mitrofanov et al., 2010) **Neutron Suppressed Regions**
  - Statistically significant NSRs in Cabeus and Shoemaker
  - H content at 300- 500 ppm
- Presence of water validated (and then some) via LCROSS





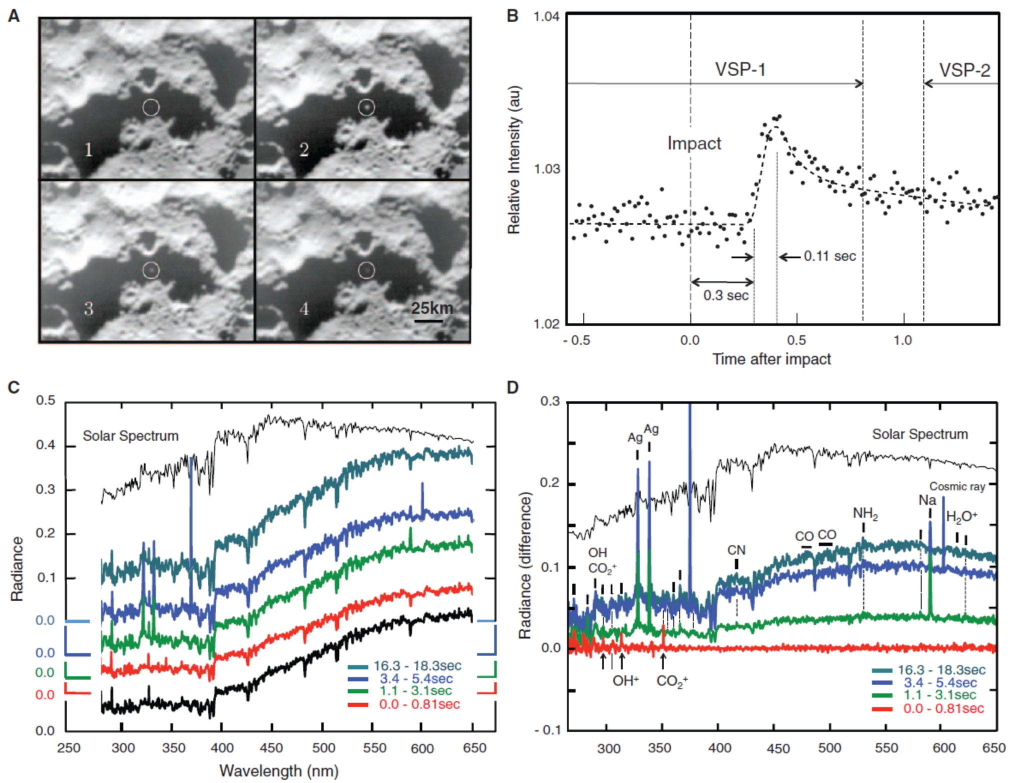
Water Thermal Stability Model
Paige et al 2010
White areas= water stable at surface
Orange areas= water stable in first 10 cm

FUV signature of water
Haynes et al., 2015
Dark = cold polar croater
Blue= ratio of high and low wavelength bands

Two forms of water in the poles:

- Deeper H (water) reservoir observed by Neutron spectrometers considered water
  - At least a meter deep, with a dry layer ~10 cm overtop [Feldman et al., 2000]
- A Frost-like layer in the top 100 microns
  - 1-5% water ice/regolith mix
  - Don’t know how deep and relationship to the reservoir
  - Observed by LRO UV and lidar

Revolution #1: LCROSS 2009 Impact



- Revealed water ice and vapor in plume at about ~ 5%wt

-Plume rich in other species

-In fact, more water than LP and LEND would suggest…but also impact deeper than neutron sensing

Schultz et al 2010

<u>Science 2010 set:</u>

Colaprete et al

Schultz et al

Gladstone et al

Haynes et al

Paige et al

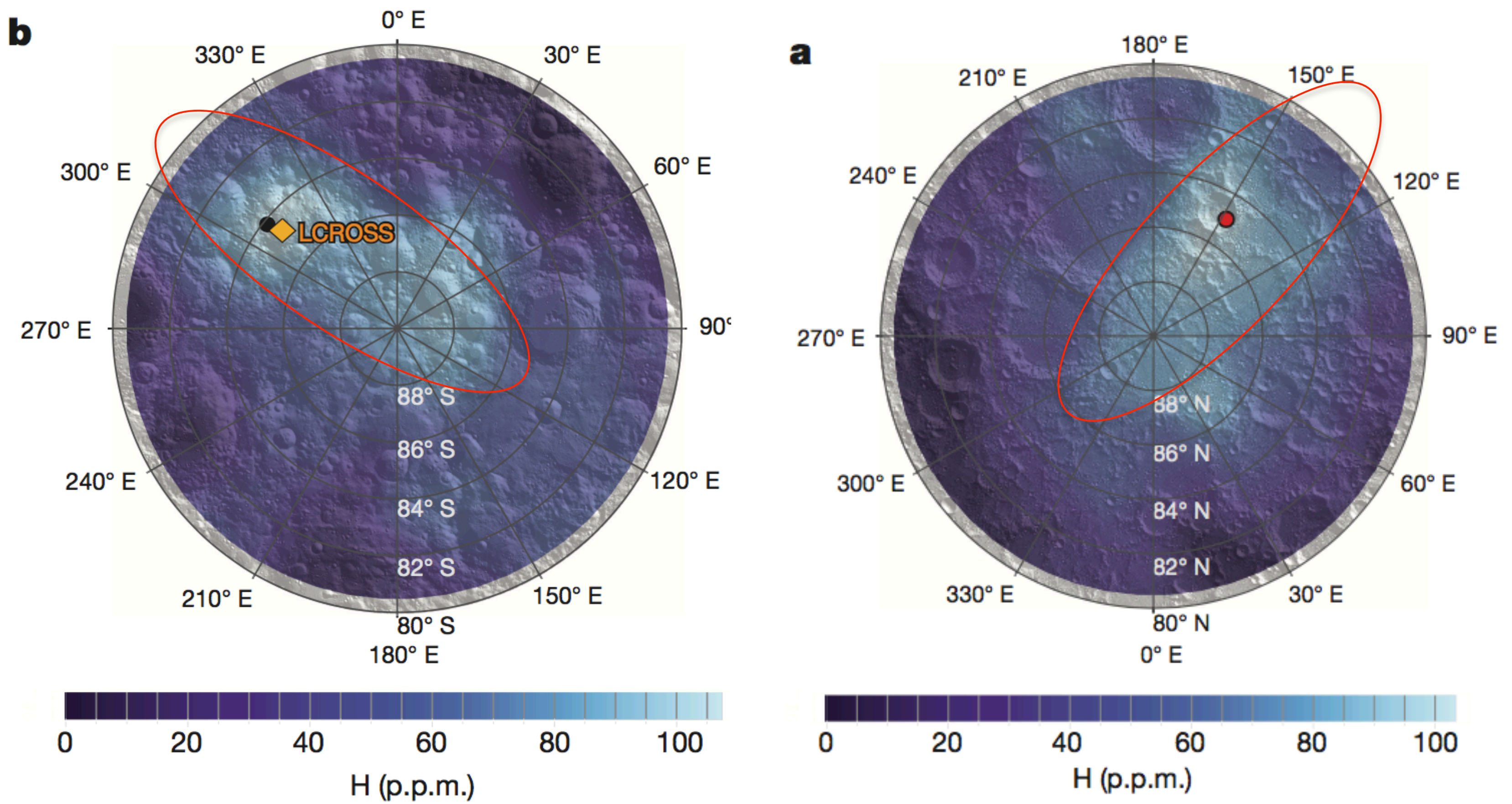
Kerr review

Table 1. Summary of the total water vapor and ice and ejecta dust in the NIR instrument FOV. Values shown are the average value across the averaging period, and errors are 1 SD.

	Water mass (kg)			
Time (s)	Gas	Ice	Dust mass (kg)	Total water %
0–23	82.4 ± 25	58.5 ± 8.2	3148 ± 787	4.5 ± 1.4
23–30	24.5 ± 8.1	131 ± 8.3	2434 ± 609	6.4 ± 1.7
123–180	52.5 ± 2.6	15.8 ± 2.2	942.5 ± 236	7.2 ± 1.9
Average	53 ± 15	68 ± 10	2175 ± 544	5.6 ± 2.9

Colaprete et al. 2010

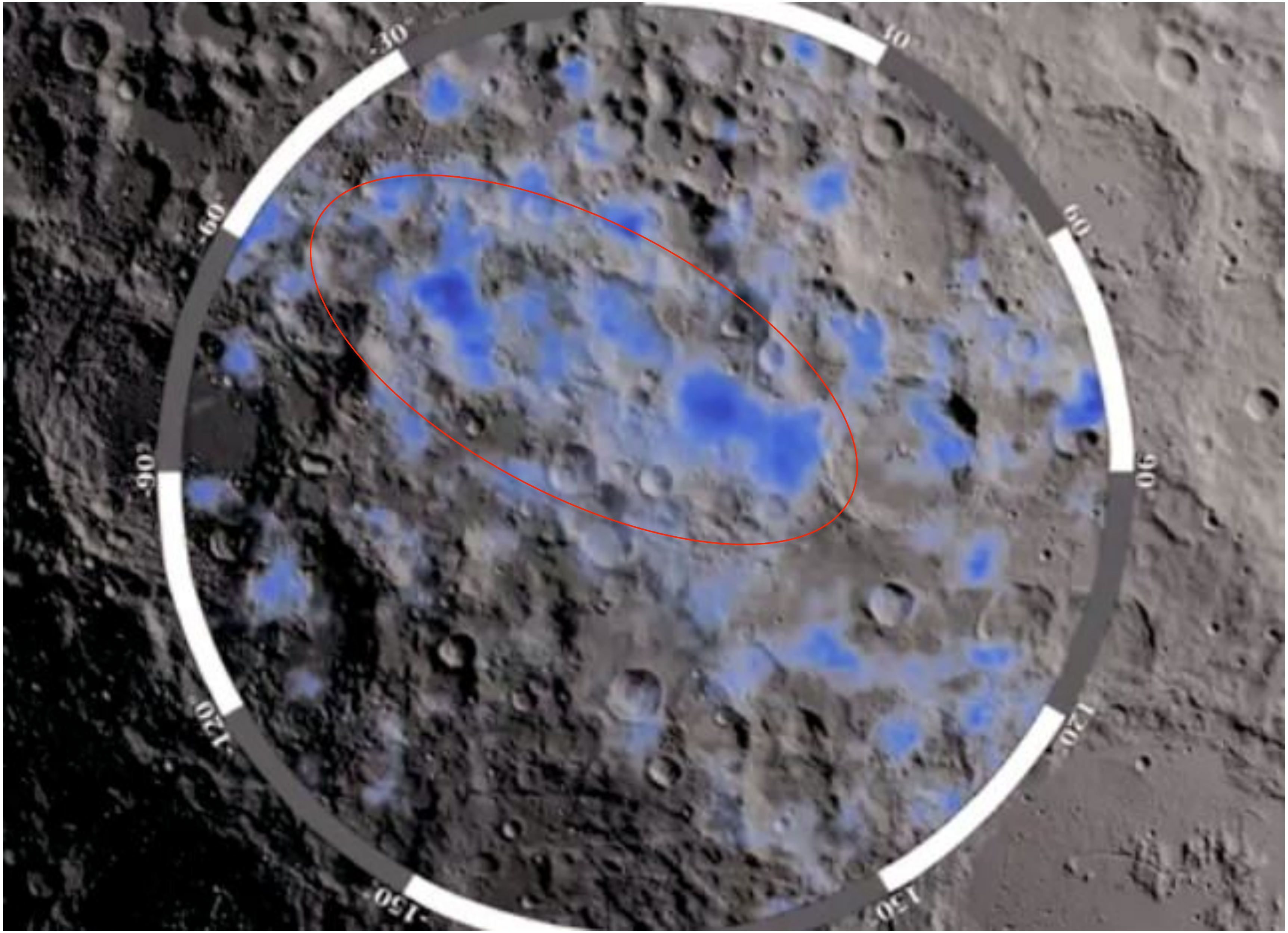
Distribution of Deeper H Reservoir



South North

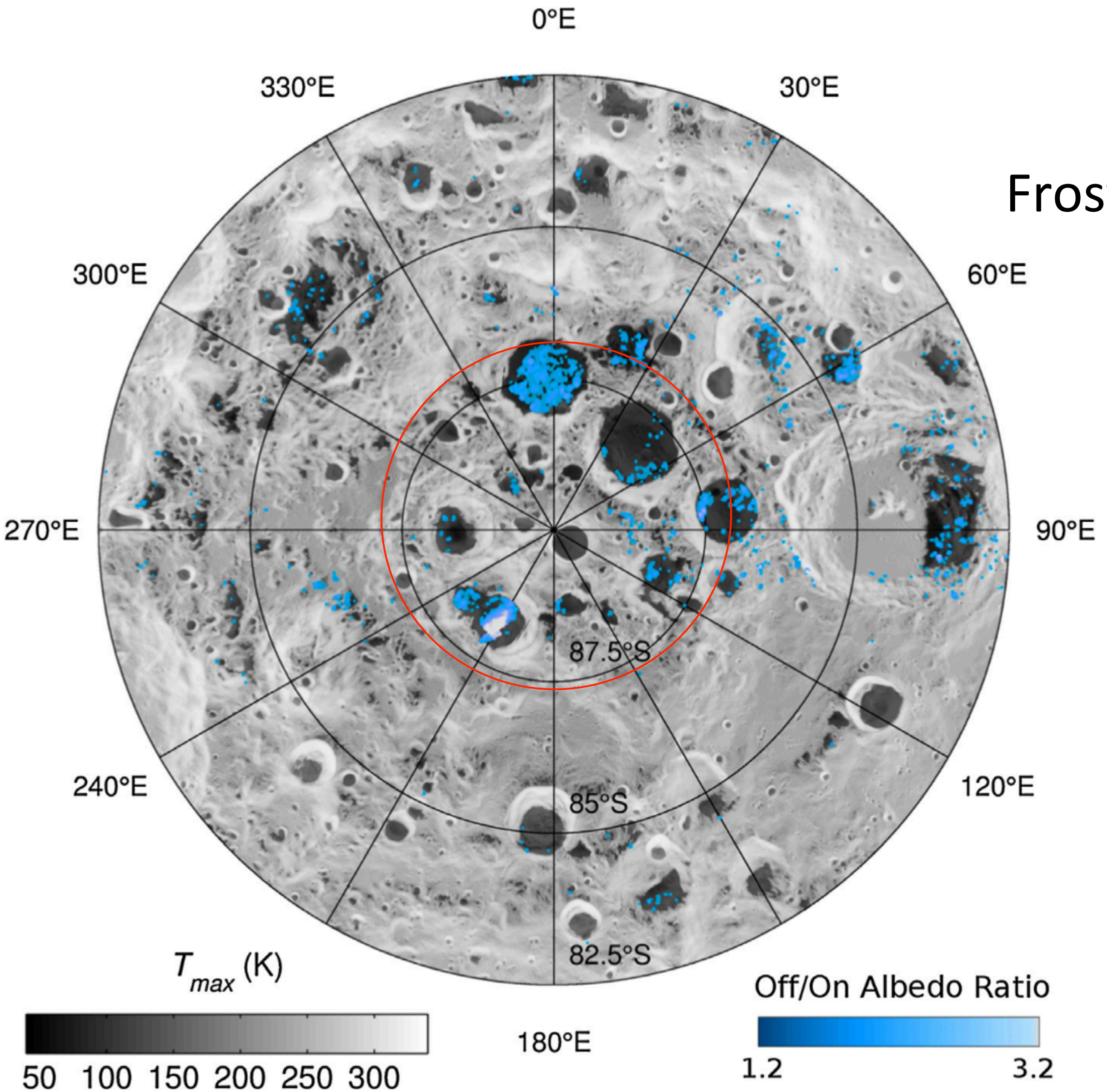
Siegler et al., 2016 – LP Neutron Spectrometer shows distribution of deeper H concentrations, Near-antipodal distribution, not a modern source

A Cabeus shift



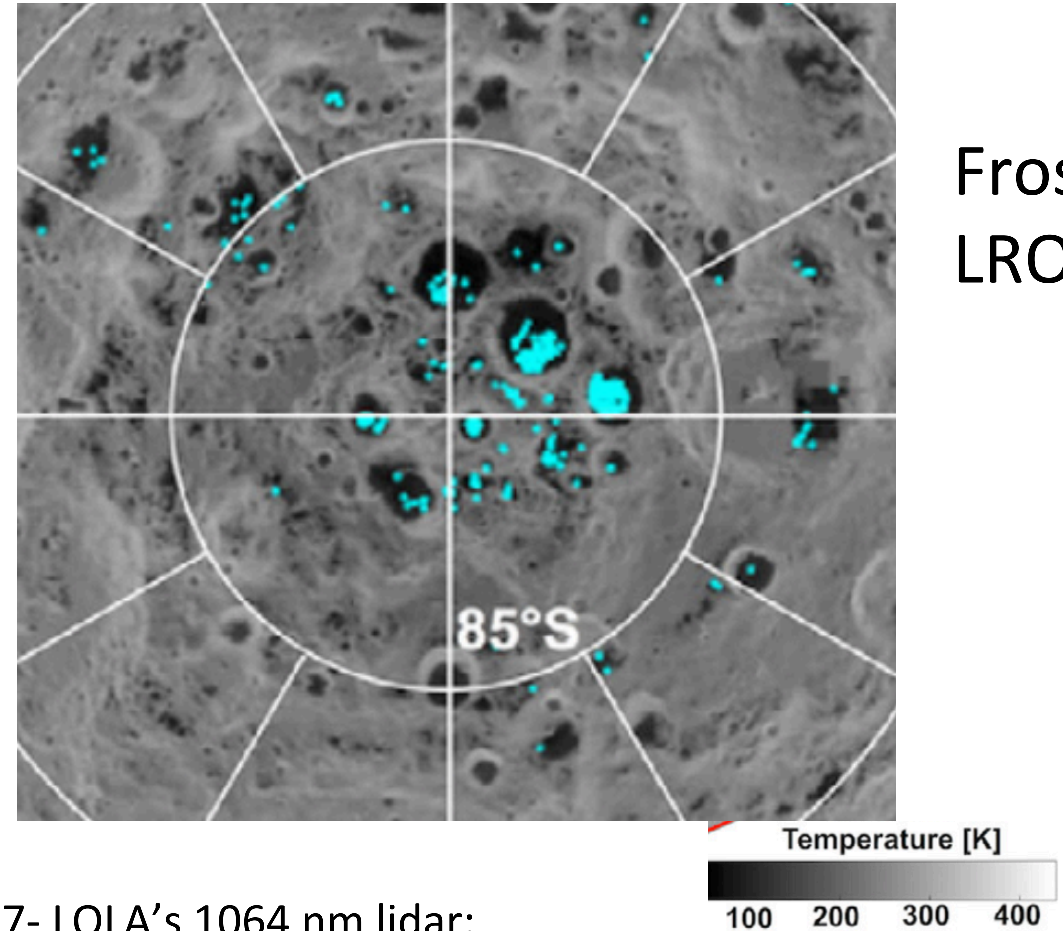
LEND Map − 2012 press release of neutron data also shows the Cabeus shift

Frost in the UV



Hayne et al 2015- Locations of surface water frost in the UV.
Cabeus shift not obvious

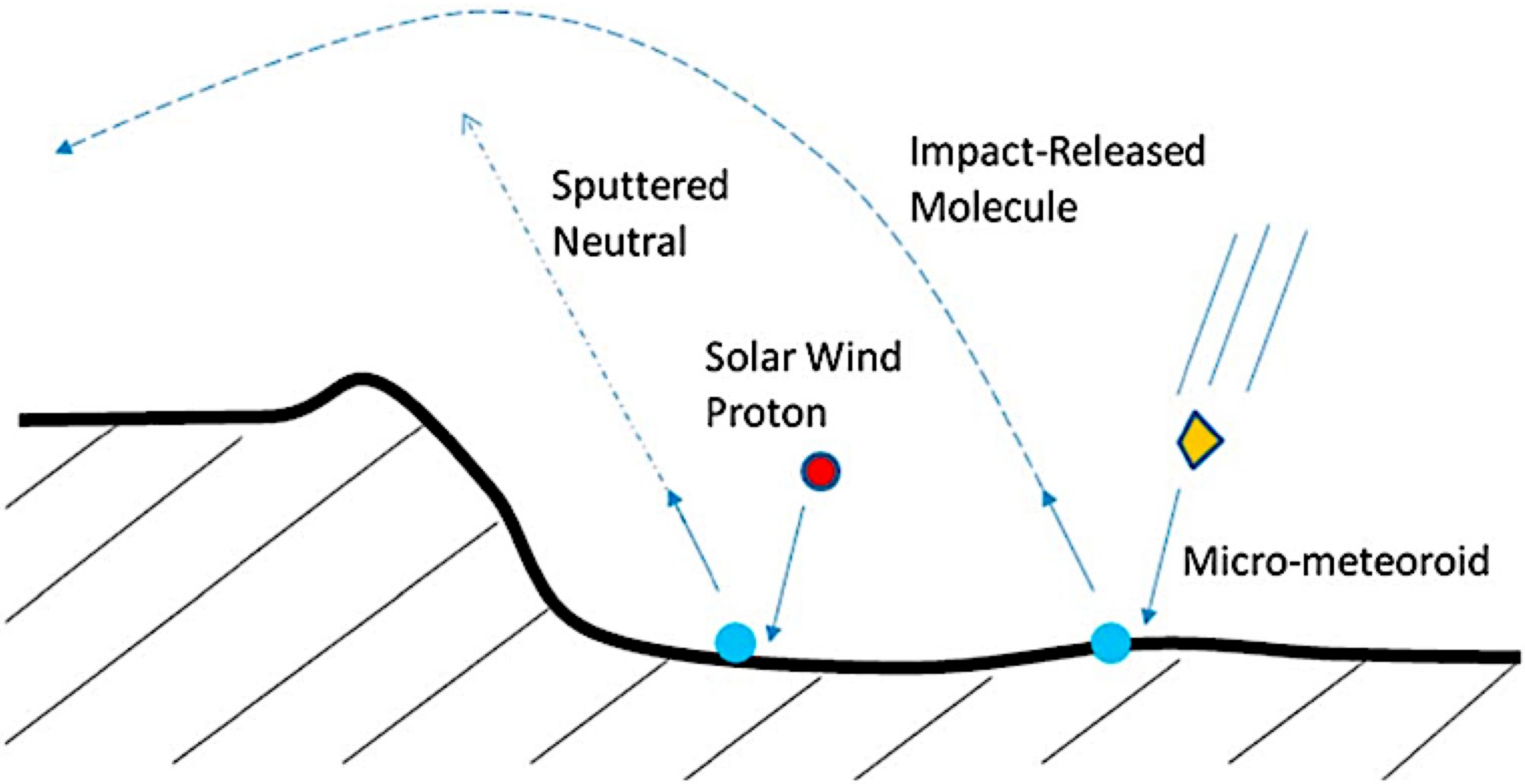
Frost in the LRO IR LIDAR



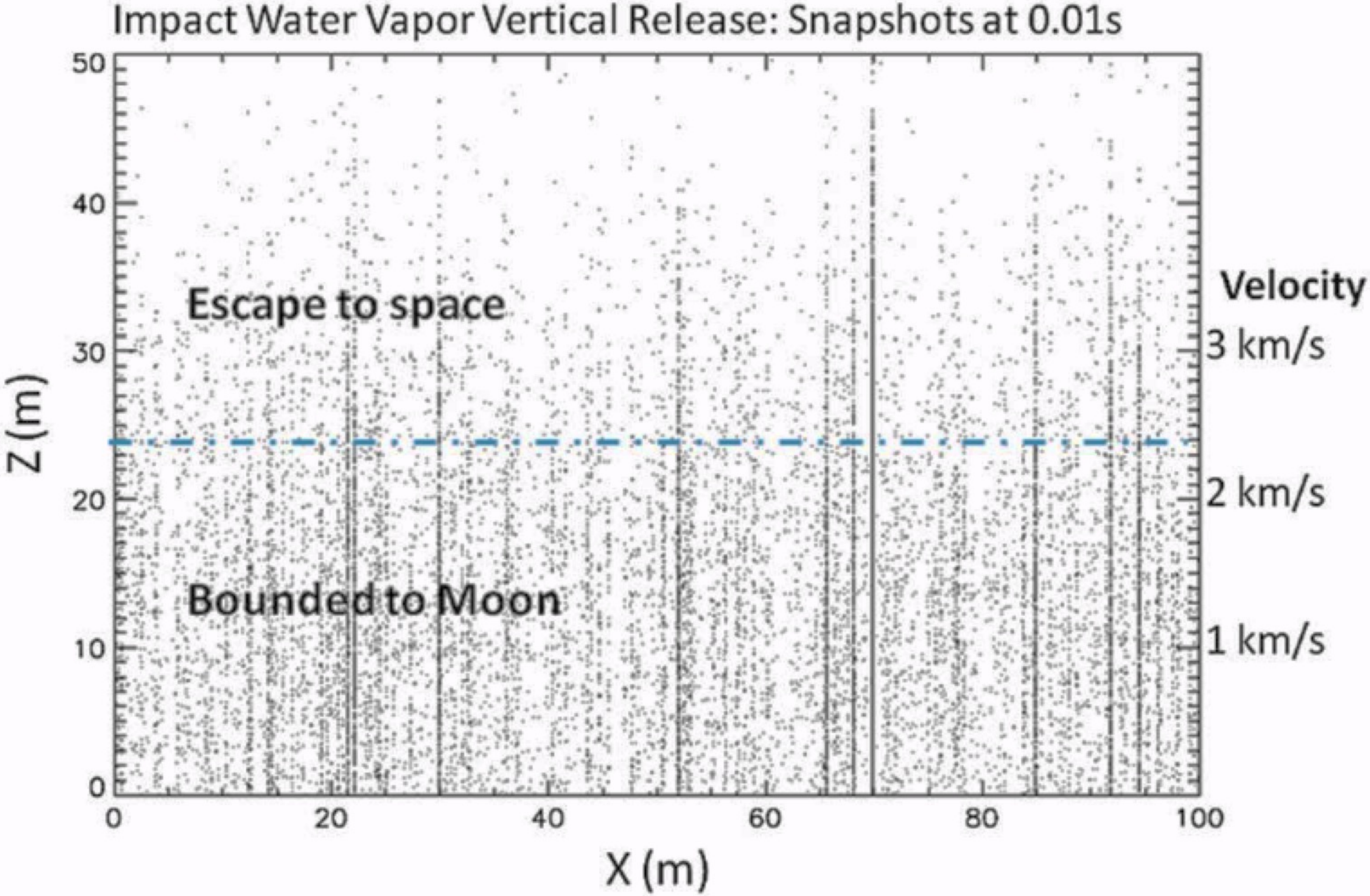
Fisher et al 2017- LOLA's 1064 nm lidar;
Anomalously bright pixels possibly from water surface frost
Also no Cabaeus shift

Suggests that the Frost and Deep H Reservoir are not entirely connected ….could affect how we prospect for water as a resource. Frost could be a 'red herring' to ID the resource.

Environmental Losses to Polar Water Frost



Frost is Exposed to the Space Environment: Its Dynamic!
DREAM2 modeling work here



Farrell et al., 2015

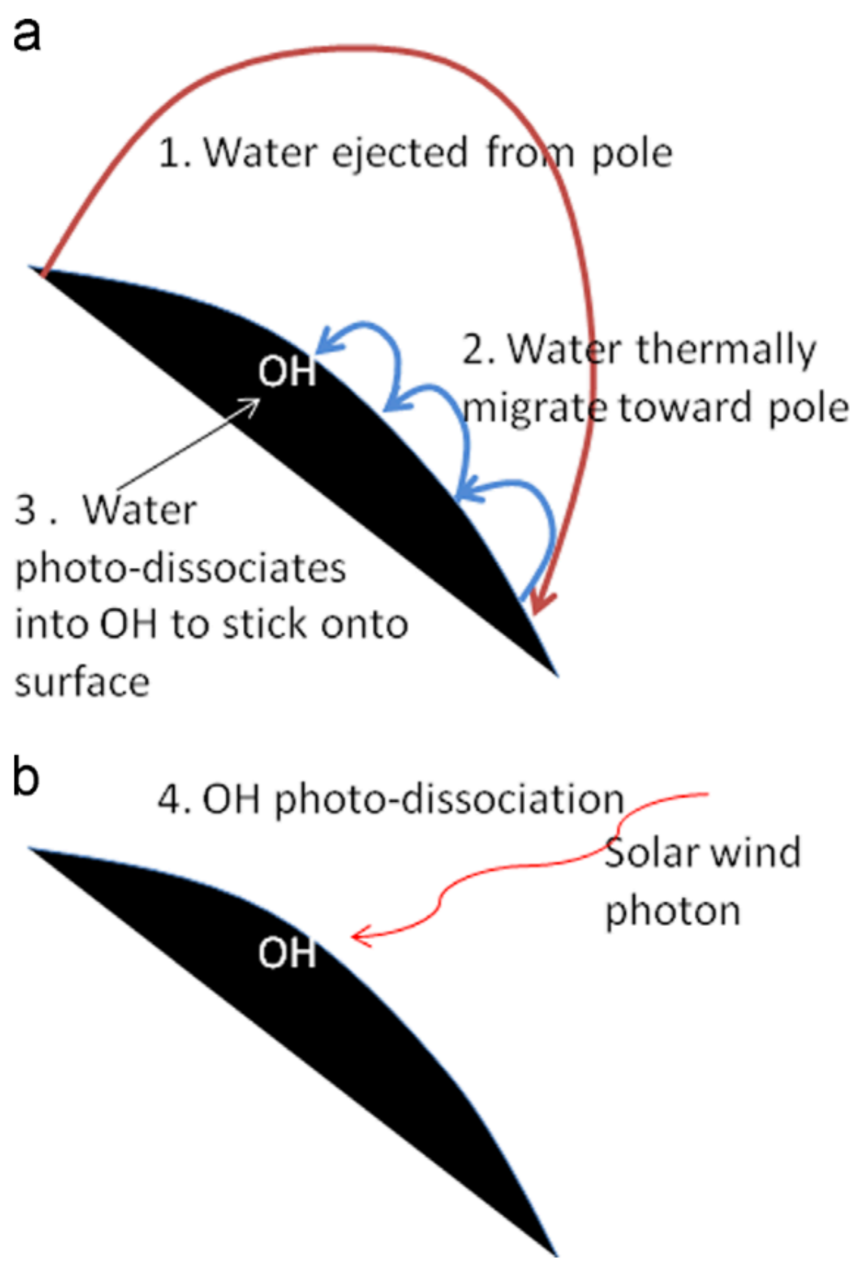


Fig. 1. An illustration of the process in creating the OH and water veneer.

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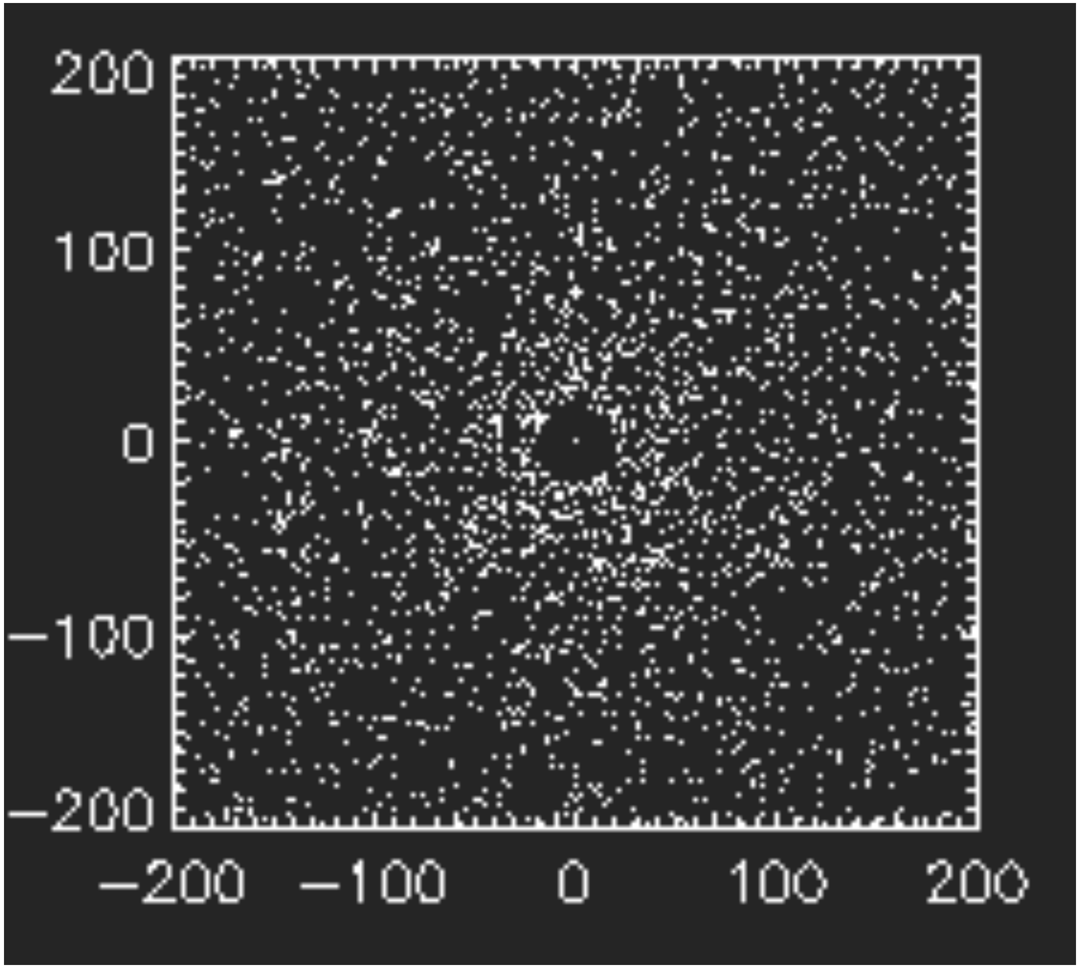
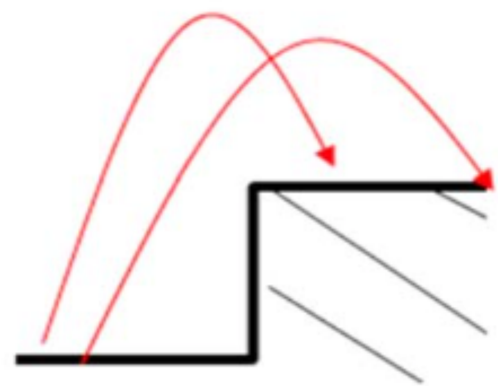


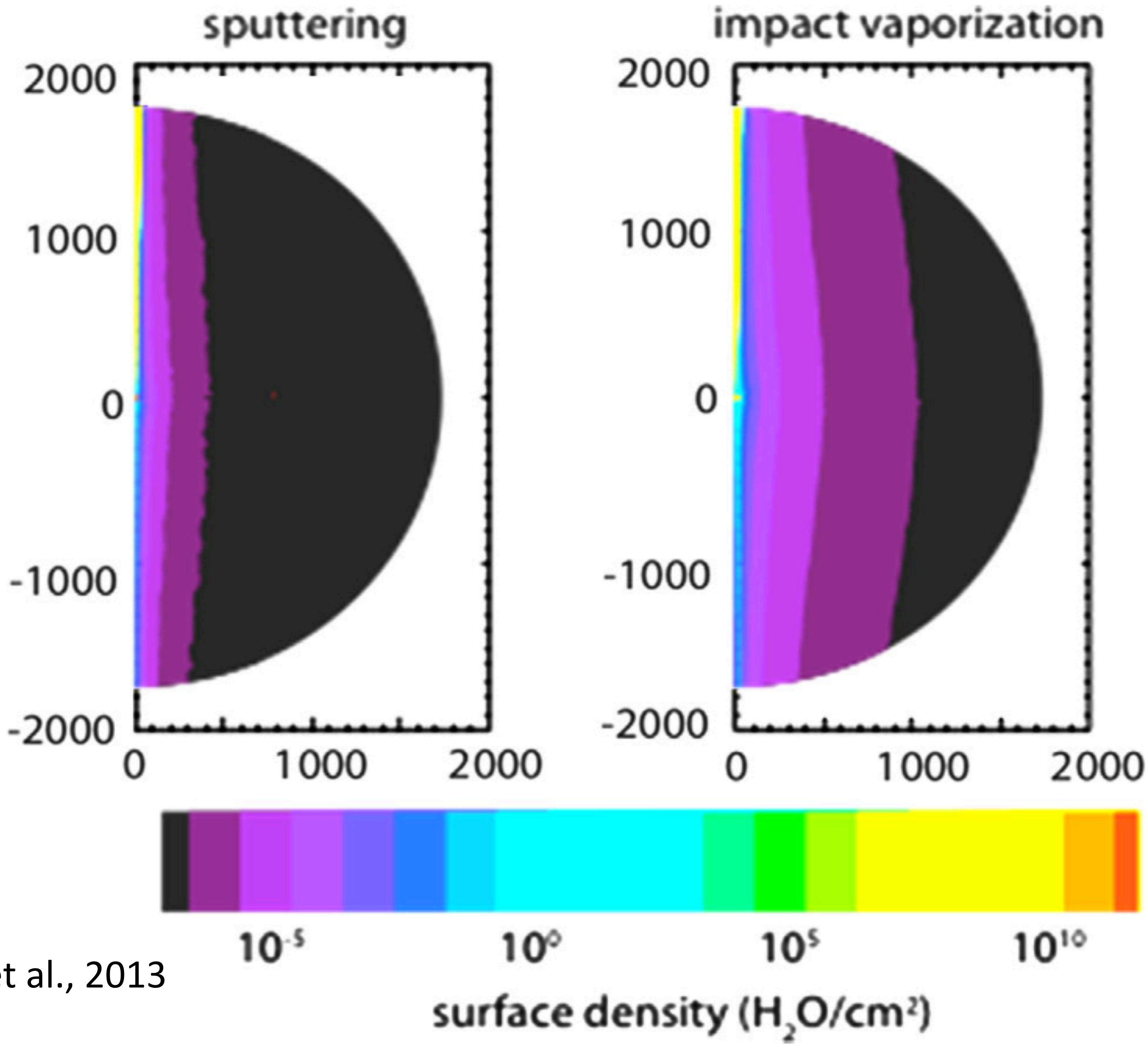
Farrell et al, 2015

Model 20 km by 20 km polar crater

Water 'spilled' over crater by meteor impacts and plasma sputtering

1% water ice/regolith (soil) mixture on crater floor

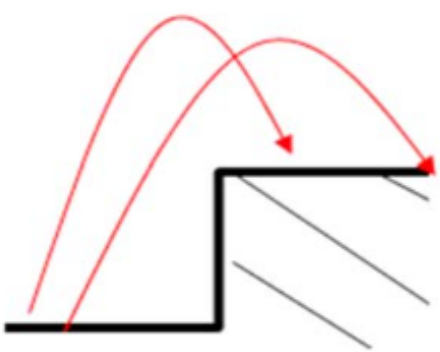




Farrell et al., 2013

Possible Dynamic Equilibrium of the Water Frost in PSRs

2. A second implication involves the observation of the 1–2% water frost detected in some of the polar craters by the LRO/LAMP instrument [*Gladstone et al.*, 2012]. Specifically, if that frost layer is in dynamic equilibrium ($dn_W/dt = 0 = \text{Sources} - \text{Losses}$) then there has to be some unidentified source of the water frost replenishing the surface at ~10^{7-8} waters/m^2 s in order to replace the impact-vaporized and sputtered water loss of comparable value. It suggests that these lunar polar crater surfaces are dynamic, and the source of the frost is modern and ongoing. *Zimmerman et al.* [2013] reached a similar conclusion when examining plasma sputtering as the primary loss process.



Farrell et al., 2015

$dn_w/dt = S - L \sim 0$

If we know loss rate at ~10^8 waters/m^2-s, then some source has to be active to compensate

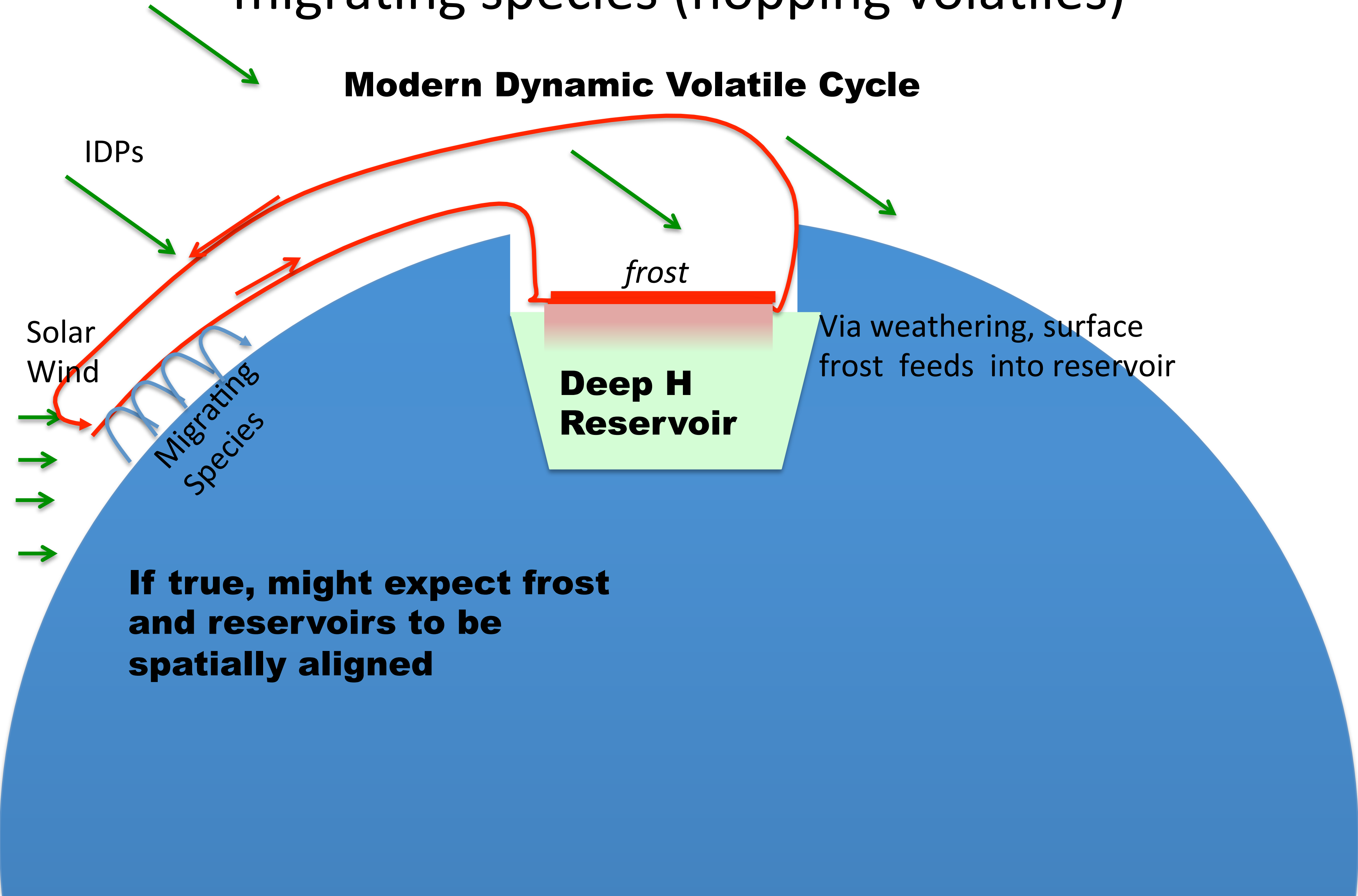
Key Questions Regarding Polar Water

- Where did the deep water detected by the neutron spectrometers come from? Past comet? Is Seigler's idea of polar wander in the H distribution correct?
- How deep is this H layer? Is it really water or some other H species?
- Is the polar frost −thin veneer − connected to the deep H reservoir? If not connected do they have different sources?
- Could some TBD process at mid-latitudes create water to have that water deposit in the cold traps? (Does water flow into PSRs?)
- Does polar water contribute to the OH signature at mid-latitudes? (Does water flow out of PSRs to infall at mid-latitudes)?
- How dynamic is the frost deposit on the PSR floor? (really re-stating the two questions above)
- How global is the water cycle?

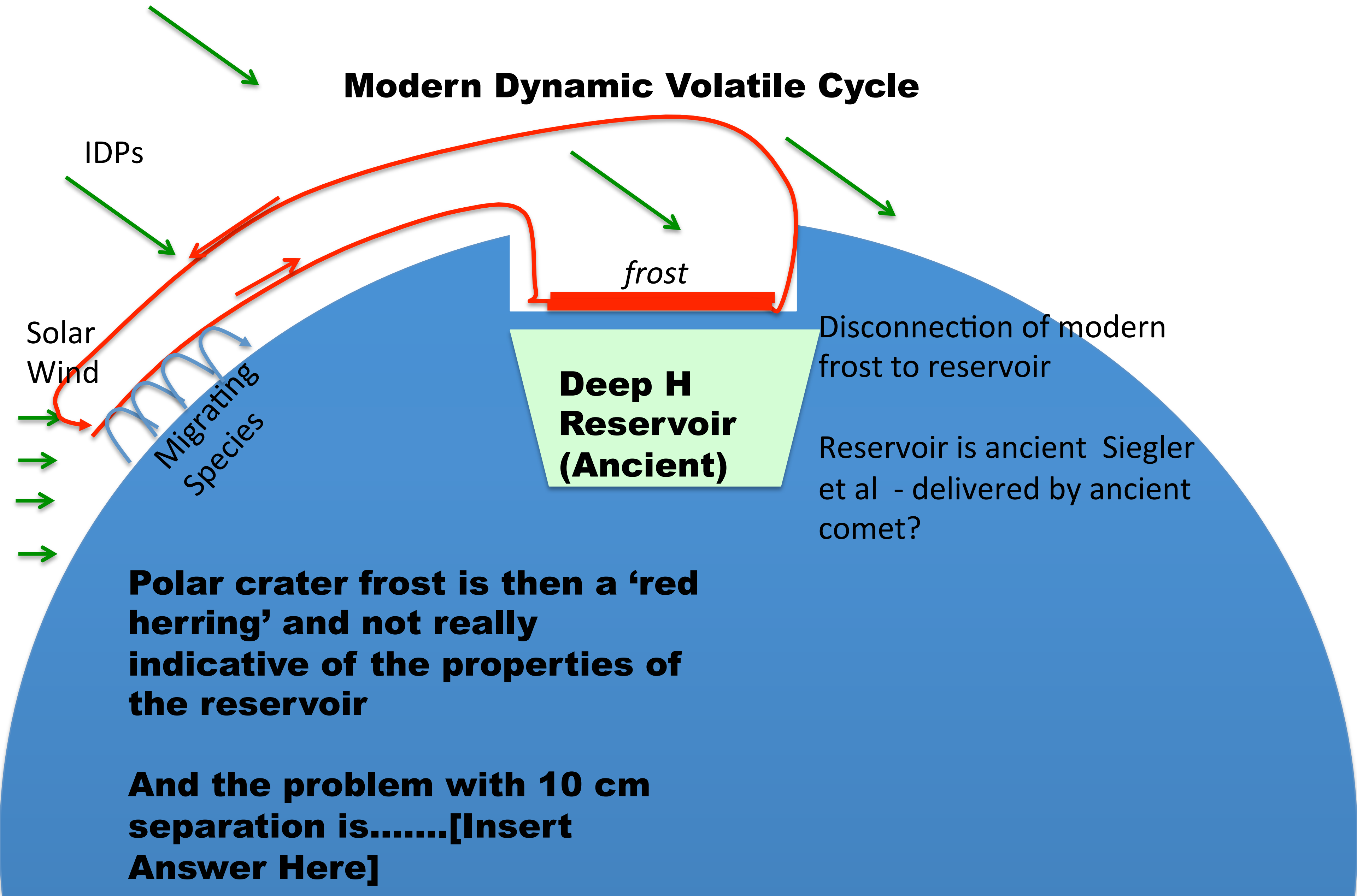
Need to get into polar craters/permanently shadowed to figure all this out

But also need the big picture…

Strong Cycle-Reservoir Connection featuring migrating species (hopping volatiles)



Alternate view: Cycle-Reservoir Quasi-disconnected



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Let's take a moment here…

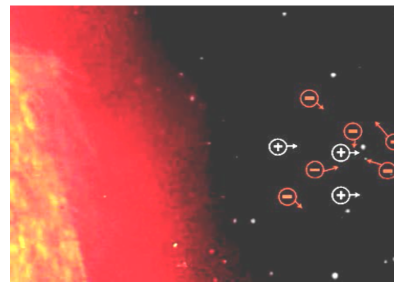
…we are now talking about a possible water cycle at the Moon.

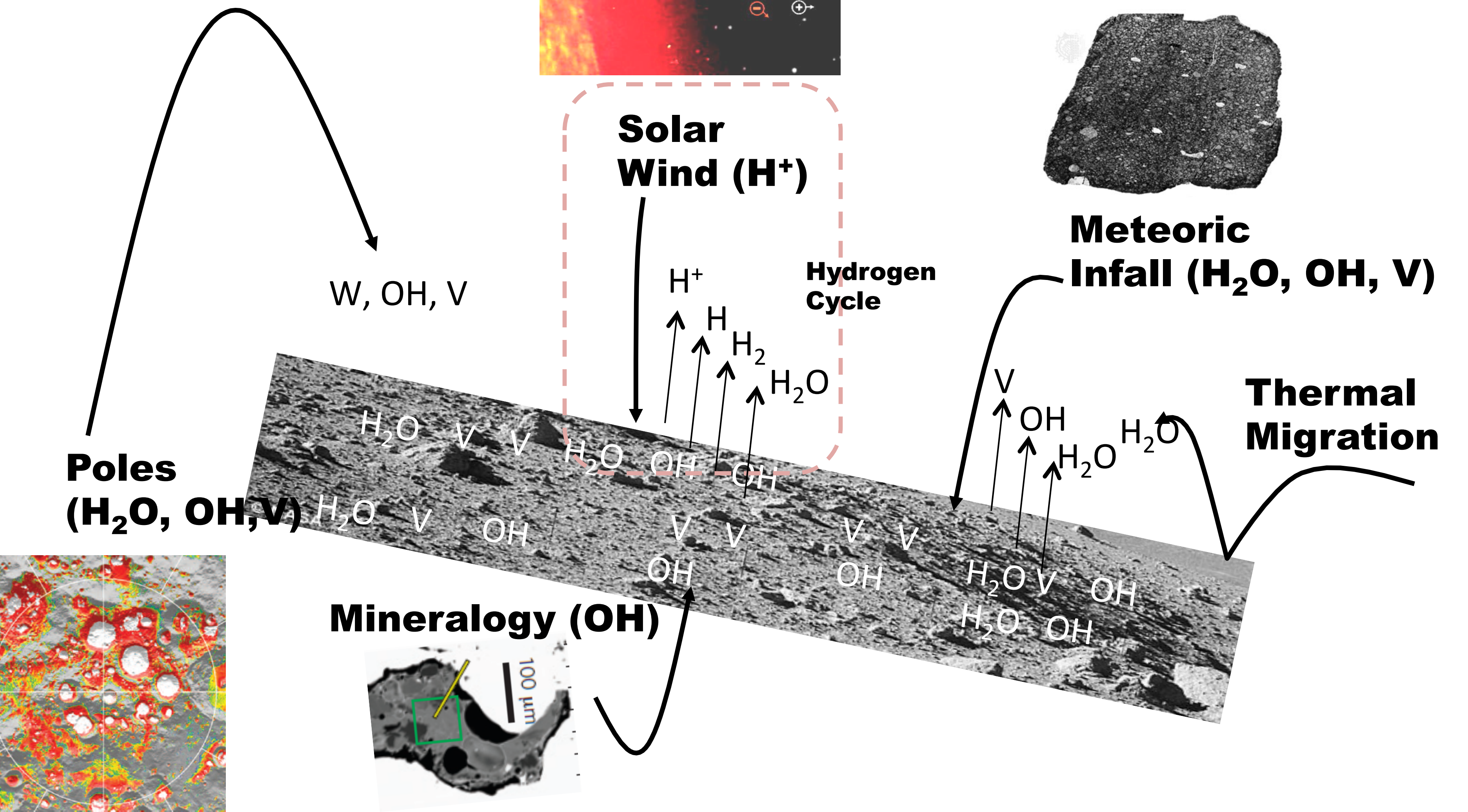
That scientist are actively pursuing an understanding about a modern volatile flow into and out of a cold trap regions where a reservoir of water exists….on the Moon.

And we now think this is could happening at Mercury and Ceres as well.

Lunar Hydrogen/OH/Water: A Dynamic System

$$\partial W/\partial t + \nabla \bullet (W\mathbf{v}) = S_{SW} + S_{infall} + S_{poles} - L_{desorp} - L_{photodiss} - L_{sputter} - L_{impactvapor}$$





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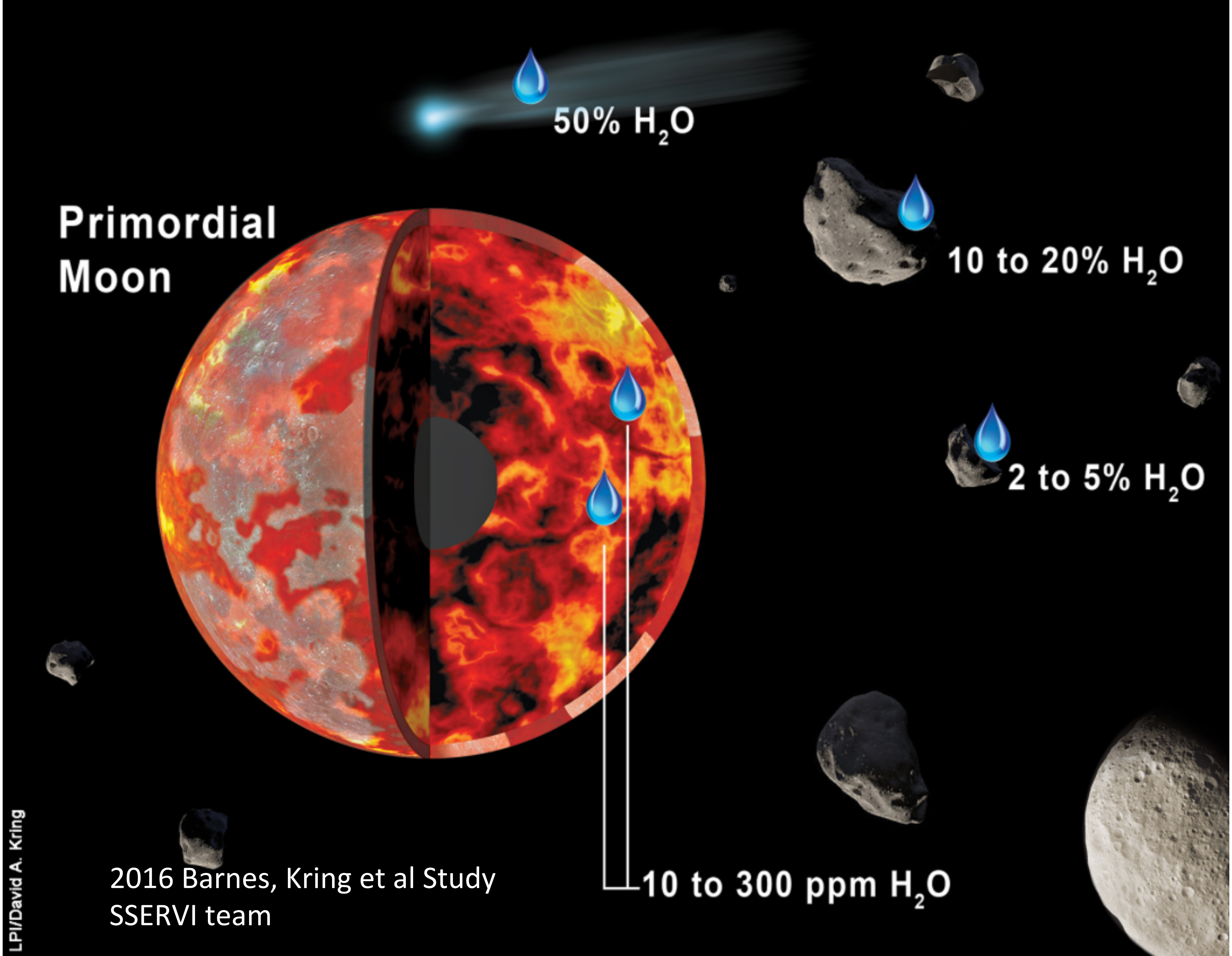
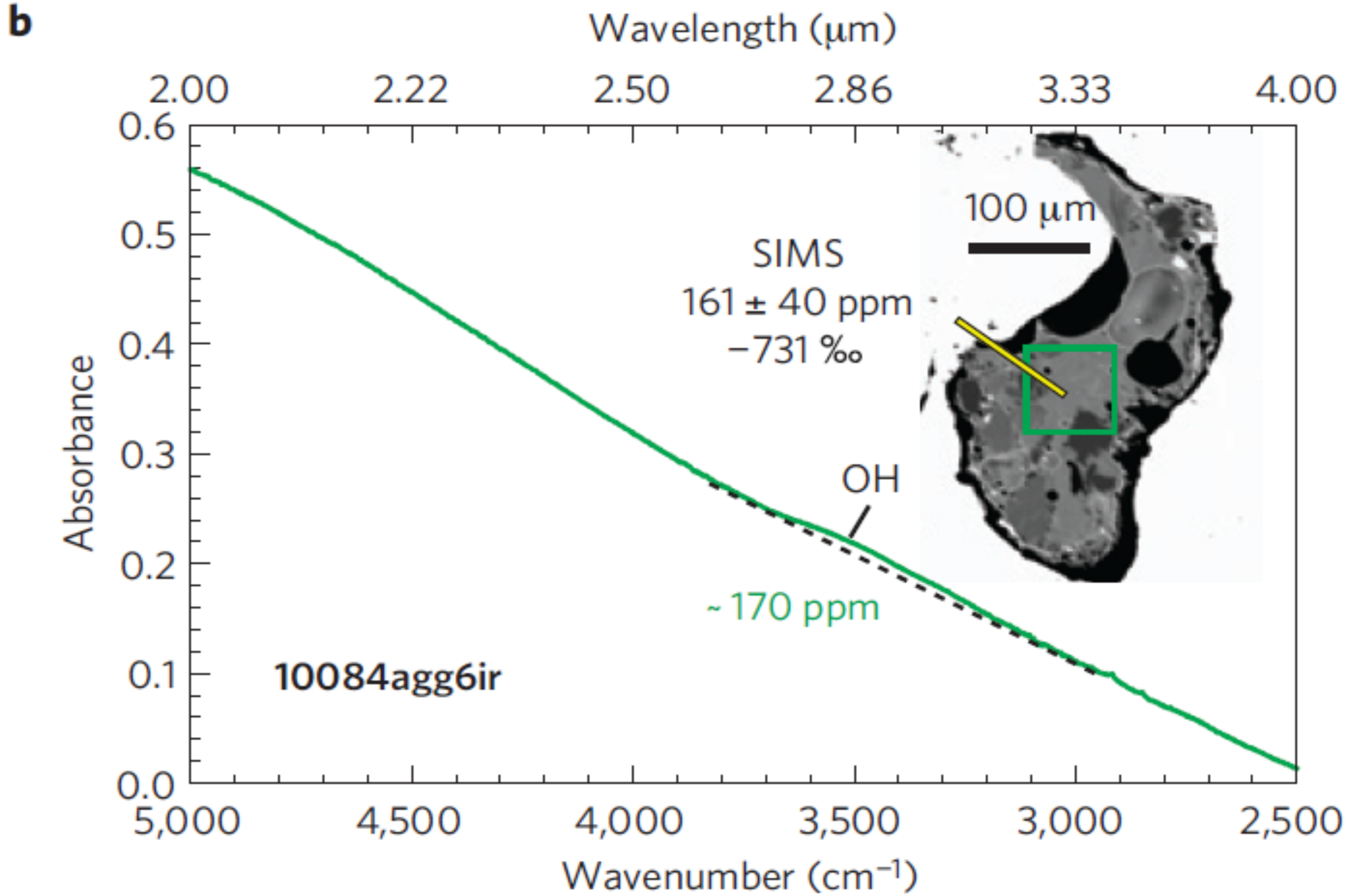
Source #2 Mineralogical Source of OH/ Water

Revolution #2 in the recent analysis of returned Apollo samples:

- Enhanced water levels preserved in Volcanic Glasses [Saal et al., 2008]
- Enhanced OH in apatite mineralogy from end of magmatic period [McCubbin et al., 2010]
- Enhanced levels of OH in agglutinates (solidified impact melts) [Liu et al., 2012]


50% H_2O
10 to 20% H_2O
Primordial Moon
2 to 5% H_2O
10 to 300 ppm H_2O
LPI/David A. Kring
2016 Barnes, Kring et al Study
SSERVI team

OH in Agglutinates (solidified impact melts)



D/H ratio
-H appears to originate from Solar wind

Liu et al., 2012 – 100's of ppm of OH in agglutinate (impact glass) material
space environment modification: Impact melting and solar wind implantation
Suggests the solar wind protons/hydrogen in the melting processes creates OH.

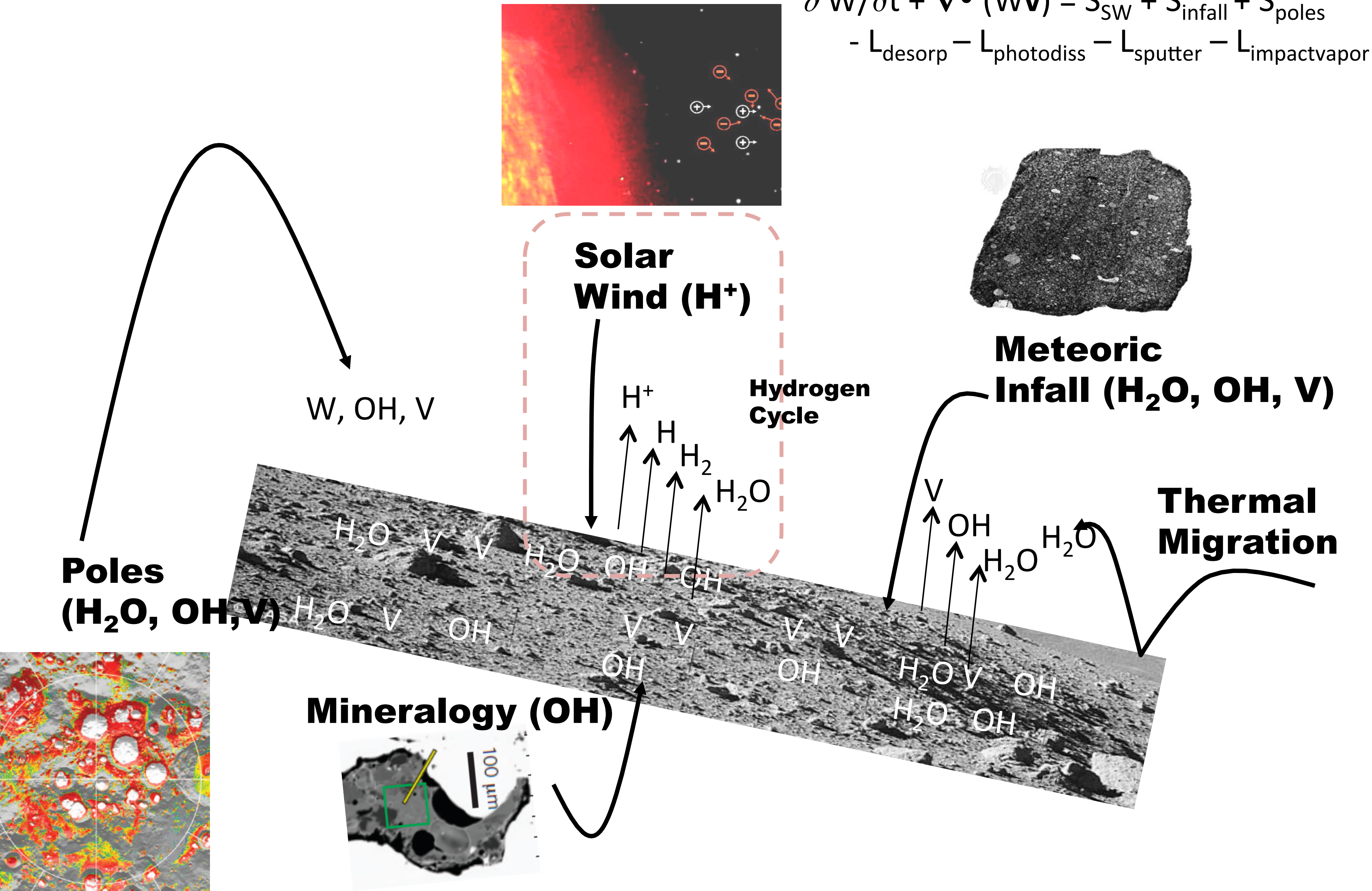
Key Questions regarding the Mineralogy Source of OH and Water

- What was the water content when the Moon was formed? Higher than originally thought?
- What delivered water to the Moon ?[Barnes study may have answered part of this!] So, what delivered water to the Earth?
- Is OH creation a part of the impact process that forms the agglutinates? How? What is the sequence of events?
- Is the OH creation process by impacts on-going today as micro-meteoroids impact the Moon?

Some of this OH and water is not mobile − not dynamic. The OH in agglutinates, however, may result from dynamics….associated with high speed meteor impacts.

Lunar Hydrogen/OH/Water: A Dynamic System

$$\partial W/\partial t + \nabla \bullet (W\mathbf{v}) = S_{SW} + S_{infall} + S_{poles} - L_{desorp} - L_{photodiss} - L_{sputter} - L_{impactvapor}$$



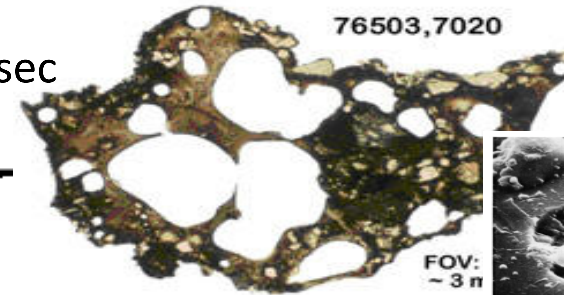
Source #3 Delivery via Meteoric Infall

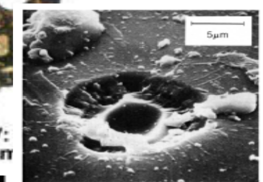
[This topic overlaps last topic since the agglutinate mineralogy sources traces back to infall of material]

- Moon constantly bombarded by particulates large and small
- ~ 10-40 km/s
- This infall delivers volatiles to the surface of the Moon
- Impact at ~4000K, prompt local loss but some volatiles remain
- Certain kinds of meteors can be water and hydrocarbon rich – outer main belt sources have tend higher content of volatiles (we know this because of the meteors that land on Earth…)

Impactors

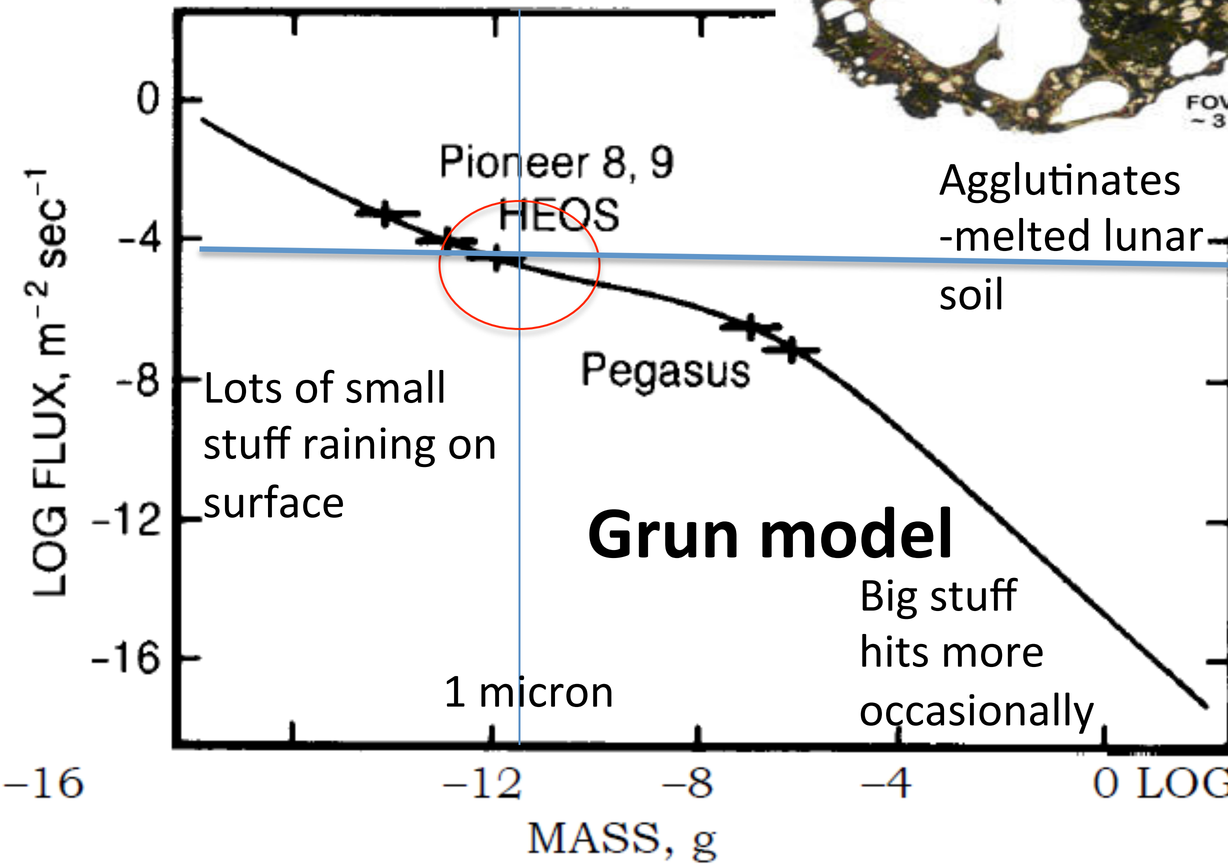
-Steady rain of micron-sized dust particles at 10's of km/sec
-Micron-sized particles called **micro-meteoroids**





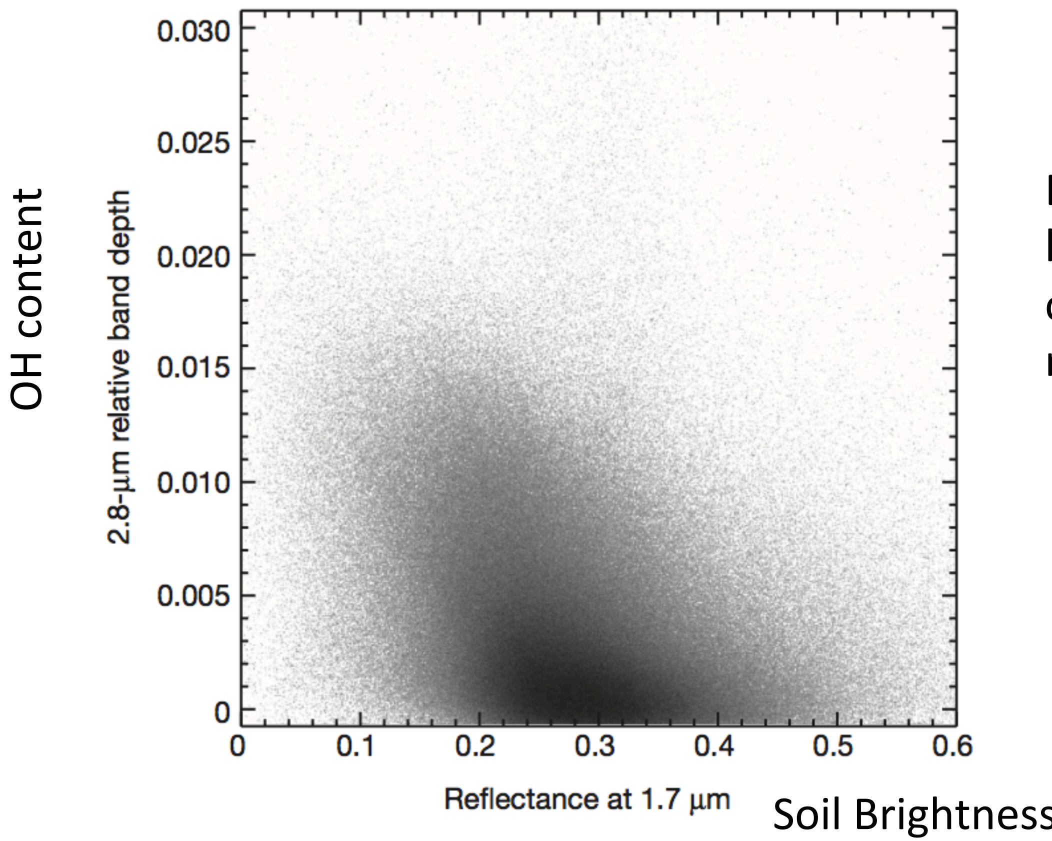
On Earth, most **meteors** burn up in atmosphere

On Moon, meteors impact the surface



-Expect a < 1 micron meteor strike in 1 square meter every 3 hours
-Expect a <1 micron meteor strike in 100-m x 100-m every second

Vesta: OH found in dark material from infall [McCord et al., 2012]

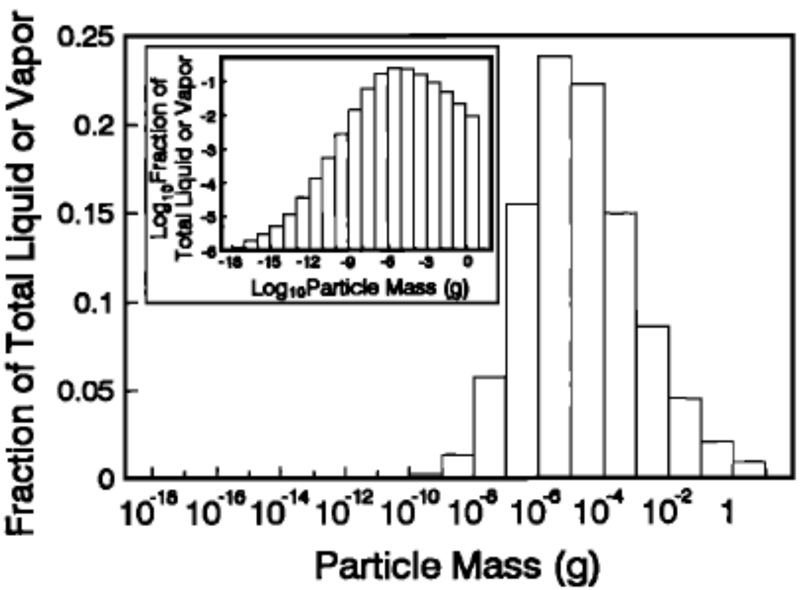


Dark= infall of hydrated carbonaceous material

Figure 5 | Correlation of OH spectral absorption with material reflectance. Two-dimensional scatter plot from global observations of Vesta by VIR show a diffuse anti-correlation of the OH-related 2.8-µm-absorption band depth[9,15] and Vesta's reflectance at 1.7 µm (Fig. 1). The OH signature is correlated with the dark material in Vesta's surface.

Micro-meteoroid Water Delivery at the Moon

Cintala, 1992 Micro-meteoroid model at the Moon



Morgan and Shemansky, 1991 Micro-meteoroid water source

shall assume that the abundance of water is 5% H_2O by mass (M. Zolensky, private communication, 1988). Thus, the meteoritic H_2O source amounts to

$$S_{H_2O} = 0.75 \times 10^{-17} \text{ g cm}^{-2}\text{s}^{-1} = 2.5 \times 10^{+5} \text{ molecules cm}^{-2}\text{s}^{-1} \quad (6)$$

~2.5 x 10^9 waters/m^2-s delivered by small meteoroids

‘Prompt loss following impact’

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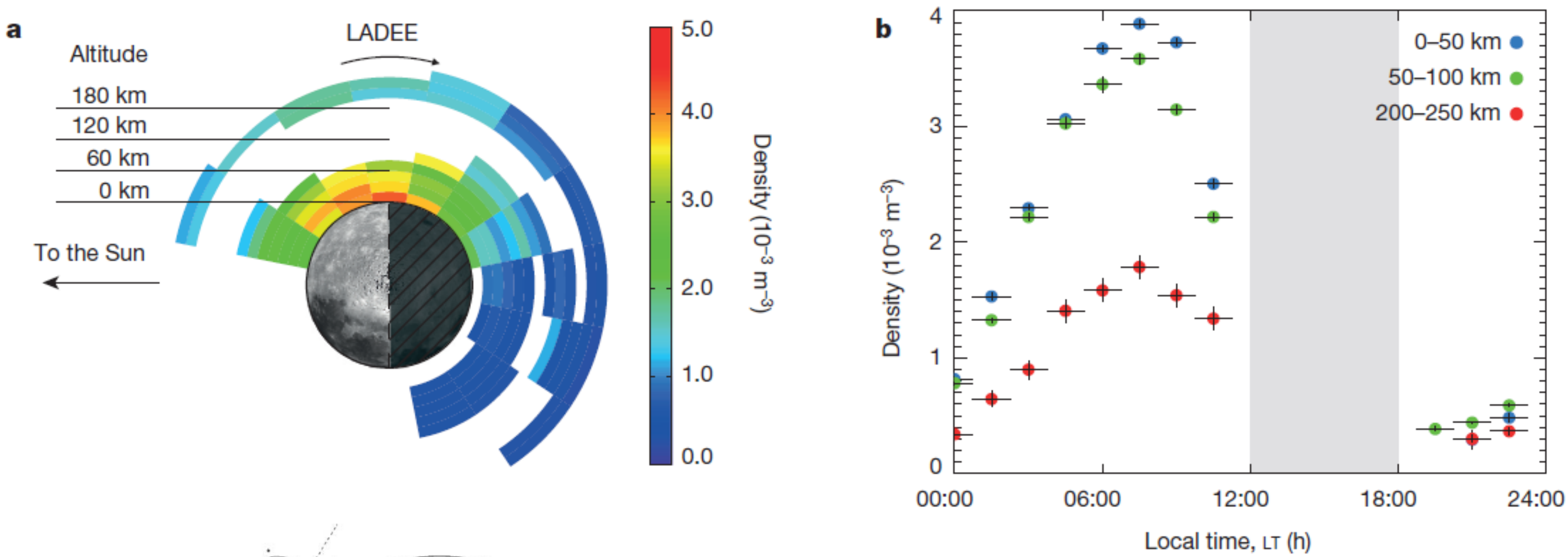
LADEE Dust Detection from Secondary Impact Ejecta [Horanyi et al., 2015]



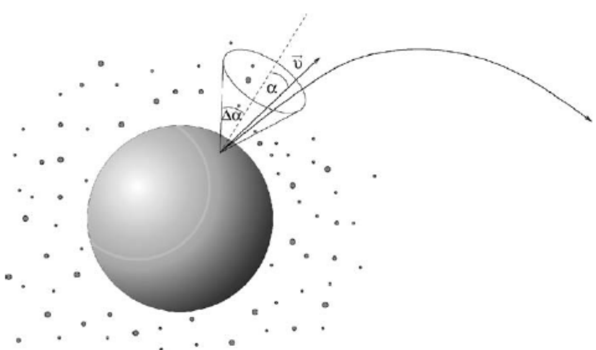


Fig. 1. Sketch of the impactor-ejecta model. An energetic projectile has hit

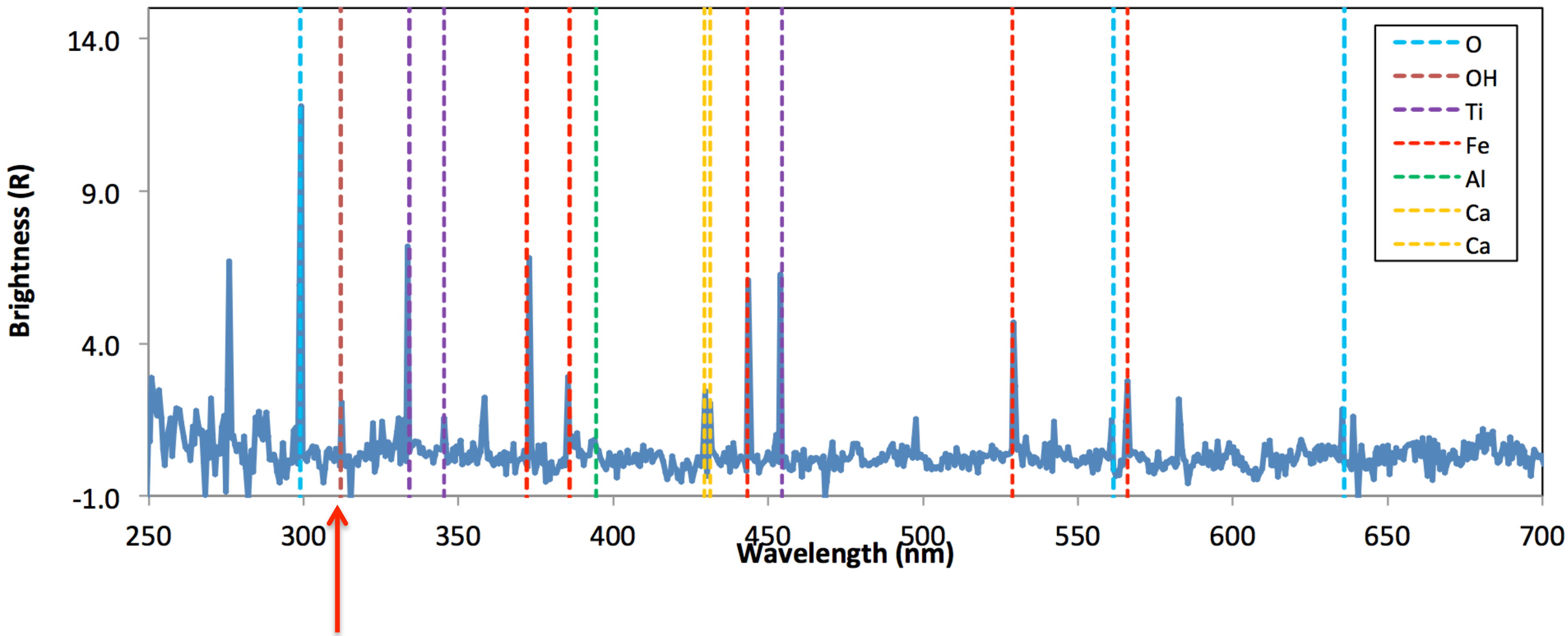
Spahn et al., 2006

LADEE – Lunar Atmosphere and Dust Environment Explorer

Colaprete et al., 2015, LADEE UVS

Initial comparison of Pre- and Post Geminids Dawn Limb Spectra

- Only spectra taken while the SC was in shadow (lunar umbra) and with a solar longitude (the position of the telescope filed-of-view grazing point) between 275-300 deg were used.
- For all measurements the dark current and instrument bias was corrected for, and "hot pixels", identified through a series of on orbit dark calibrations, were removed.
- >100 spectra were co-added to improve the signal-to-noise ratio.

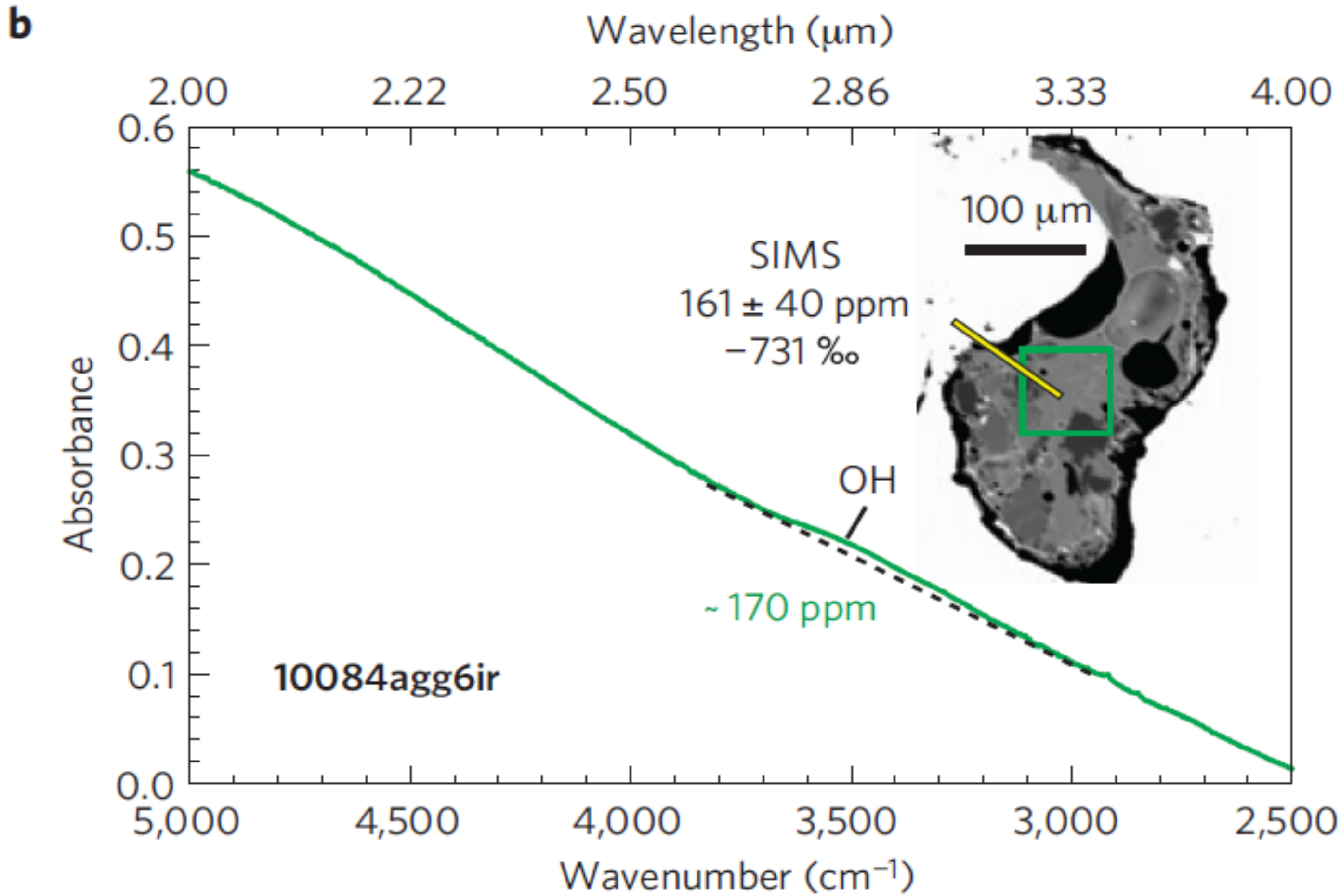


Colaprete et al., 2015; Exploration Science Forum – Observations from UVS on Lunar Atmosphere and Dust Environment Explorer (LADEE)

Is this OH already residing in surface and released by impacts?

Or is the OH exogenic (in meteoroid) and part of the prompt release & impact vaporization?

OH in Agglutinates (solidified impact melts)



D/H ratio
-H appears to originate from Solar wind

Liu et al., 2012 – 100's of ppm of OH in agglutinate (impact glass) material
space environment modification: Impact melting and solar wind implantation
Suggests the solar wind protons/hydrogen in the melting processes creates OH.

Gladstone's 2011 Provocative idea: Polar Crater Water Frost is Locally Generated by micro-meteroids

surfaces of PSRs than originally thought. At this reduced desorption rate the loss of water from IPM Ly α photolysis is comparable to the steady source of water due to micrometeoroids and the episodic source due to comets (i.e., 1.9×10^5 cm^{-2} s^{-1} and 3.4×10^5 cm^{-2} s^{-1}, respectively, from *Morgan and Shemansky* [1991, Table 3]). The fact that the sources and sinks of water are roughly equal may explain the observed heterogeneity in the FUV albedos of the PSRs, since it would make the retention of frost very dependent on local conditions and their history. Over the billion-year history of the PSRs some frost migration (vertically and horizontally) is expected. At the lowest PSR temperatures measured by Diviner, thermal diffusion is extremely slow [*Schorghofer and Taylor*, 2007]. However, in warmer PSRs, thermal cycling can increase diffusion rates considerably [*Siegler et al.*, 2011]. Thus, some heterogeneity may be caused by temperature differences. Even in the coldest regions, impact gardening is expected to substantially redistribute volatiles with depth [e.g., *Crider and Vondrak*, 2003].

Zimmerman et al., 2014
Hayne et al., 2015

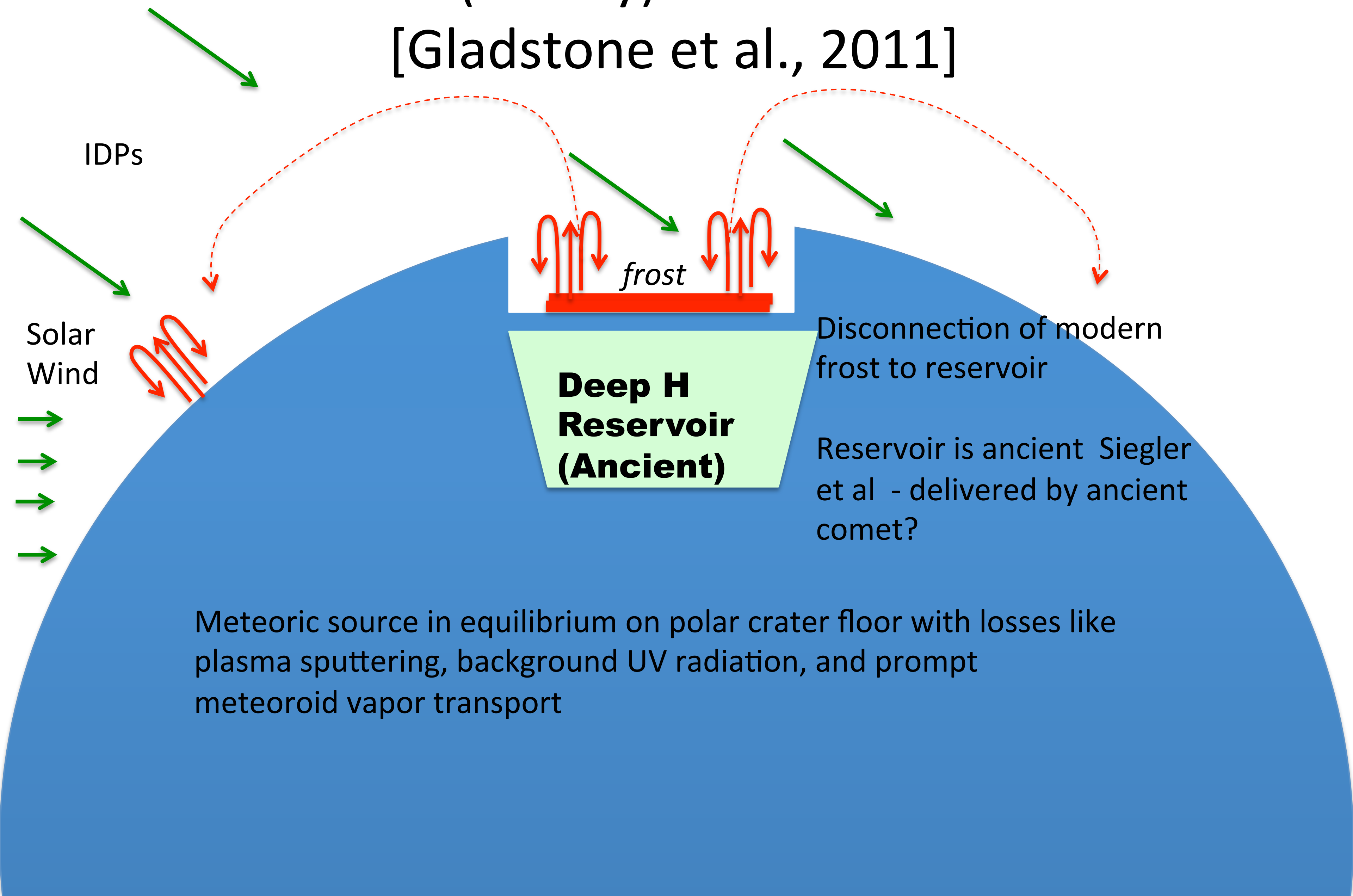
Source: Local delivery of volatiles into PSRs by meteoritic infall
-Prompt Vaporization
-Most of vapor cloud local

Loss: PSD via Lyman-α, prompt impact vaporization

In dynamic equilibrium - disequilibrium creates the heterogeneity in T and illumination, etc

Don't necessarily need a global migration system

No Cycle, Volatile Frost via Meteoroid Infall
A (mostly) local effect
[Gladstone et al., 2011]

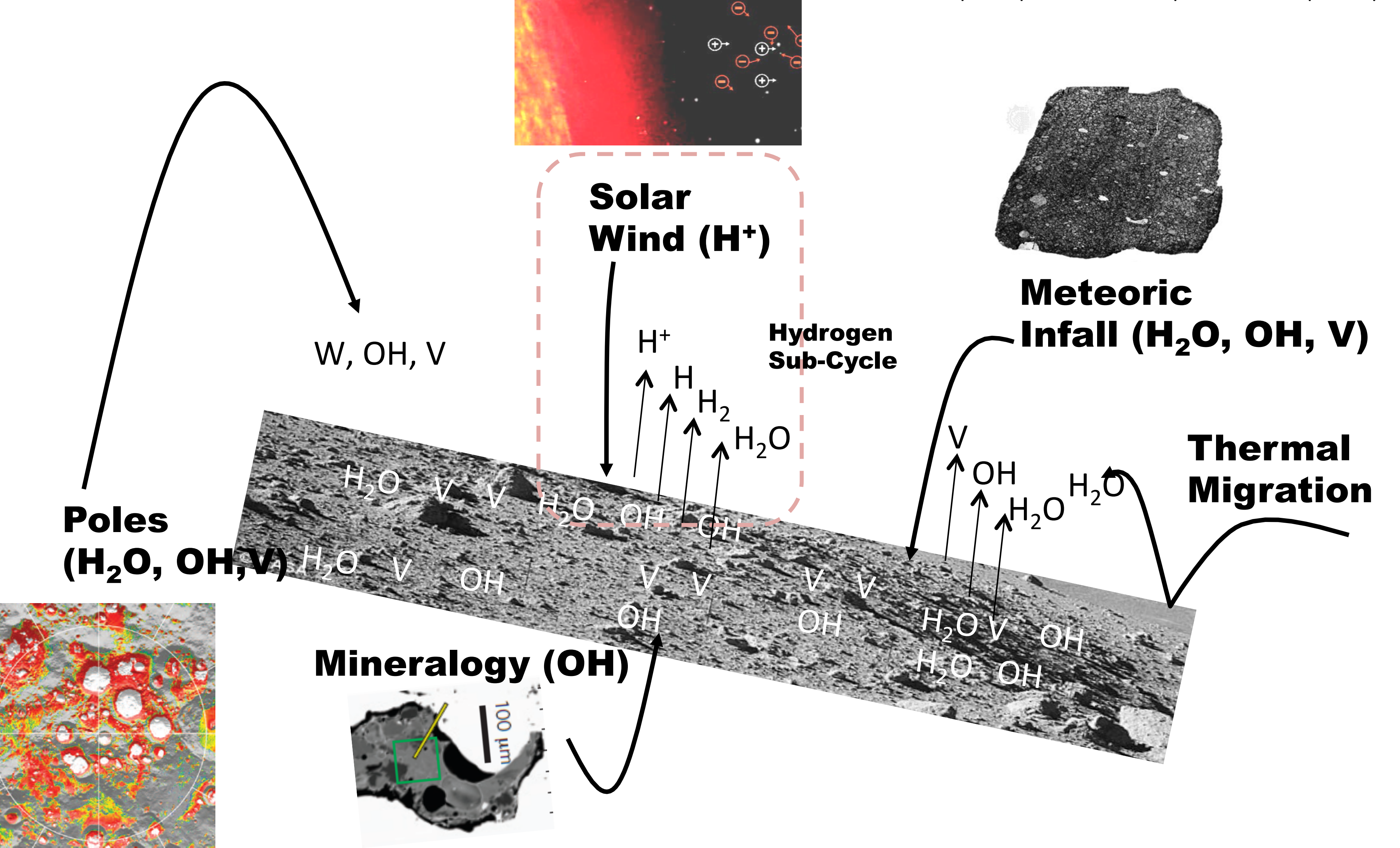


Key Questions for 'Infall' of Water/OH

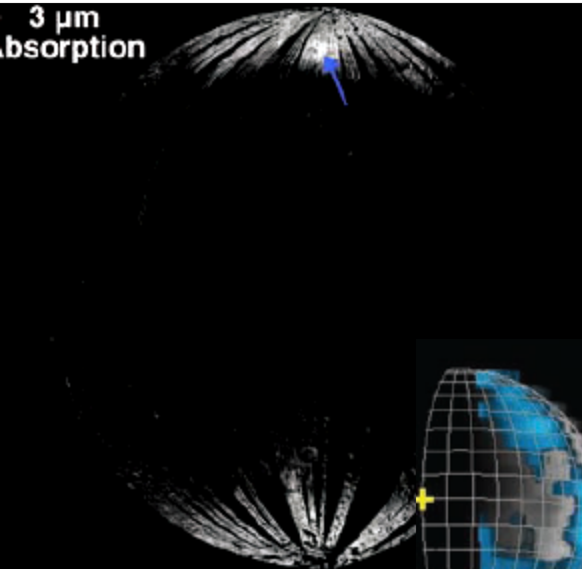
- Does the infall of micro-meteoroids continually deliver OH and water to the Moon like it does at Vesta?
- How is the agglutinate water and Geminids exospheric OH increase related? Are they complementary manifestations of the same impact-related process?
- Is the water frost at the poles simply a local impact process creating local coverage within the cold traps as per Gladstone et al., 2011? [

Lunar Hydrogen/OH/Water: A Dynamic System

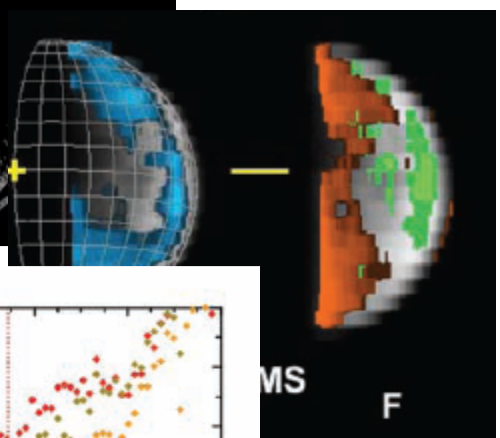
$$\partial W/\partial t + \nabla \bullet (W\mathbf{v}) = S_{SW} + S_{infall} + S_{poles} - L_{desorp} - L_{photodiss} - L_{sputter} - L_{impactvapor}$$



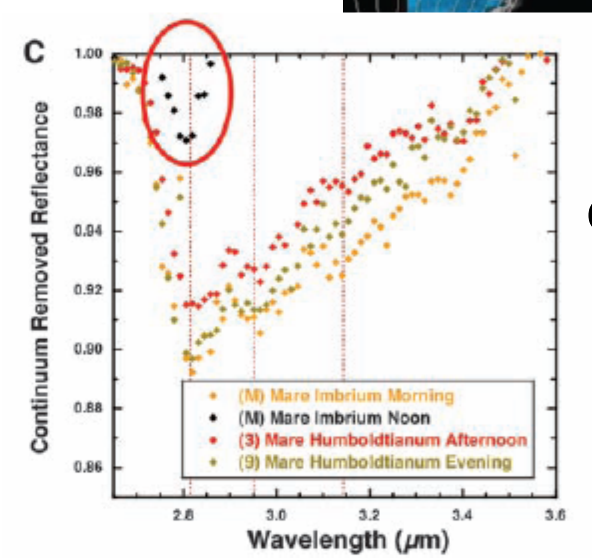
2009! – The Discovery of an OH Mid-Latitude Veneer (Revolution #3)



Pieters et al [2009]



Clark et al [2009



Sunshine et al [2009]

- Publication of Chandrayaan-1 M^3 [Pieters et al., 2009], Cassini VIMS [Clark et al. 2009], and EPOXI HRI-IR [Sunshine et al., 2009] IR observations of OH/ water content in near-surface of regolith
- Observe an IR absorption feature near 3 micron in reflectance spectra
- Vary with SZA (OH increase in cool regions)
- See similar signature at many S-class asteroids
- Dynamic!

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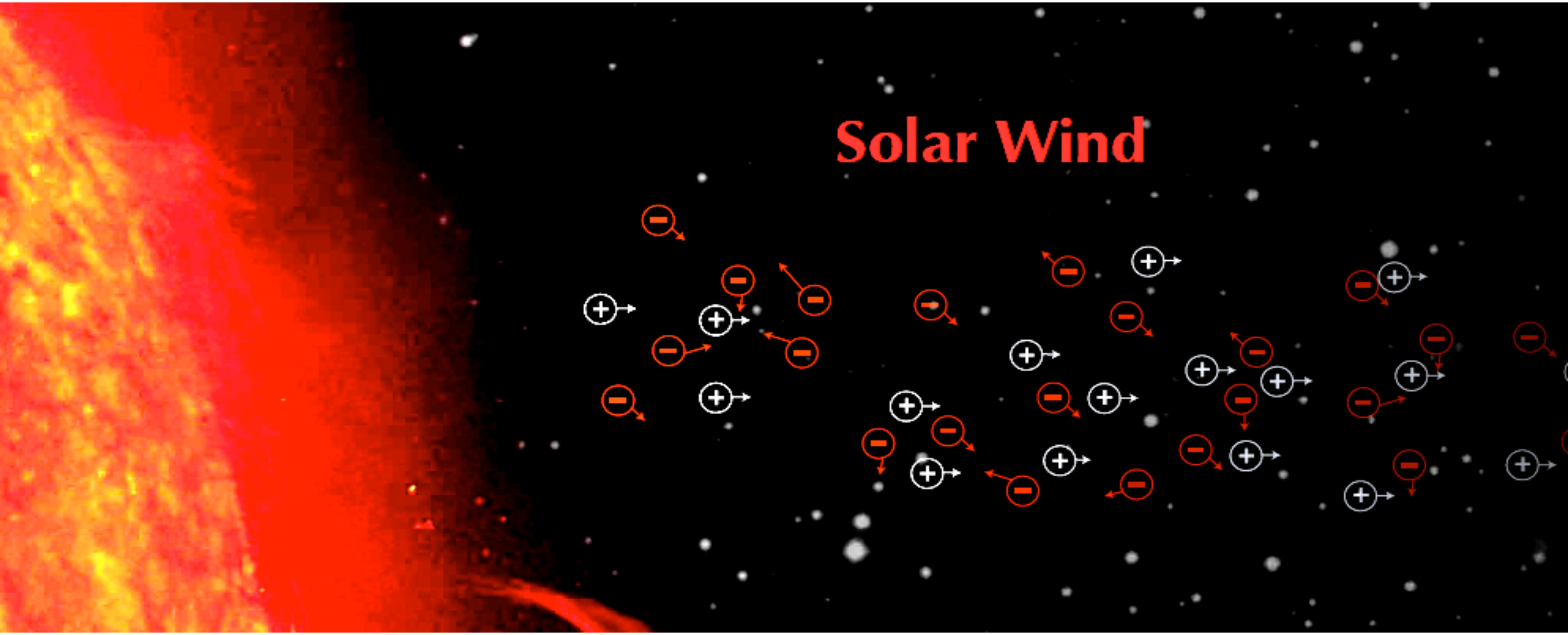
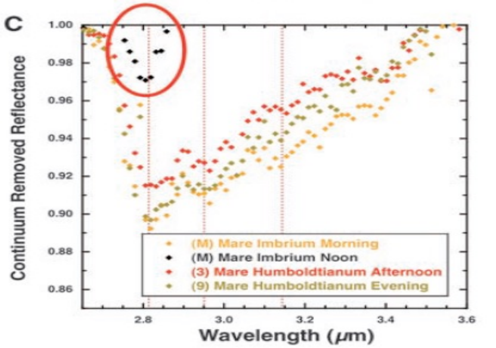
DREAM2

The Prime Suspect: Solar Wind

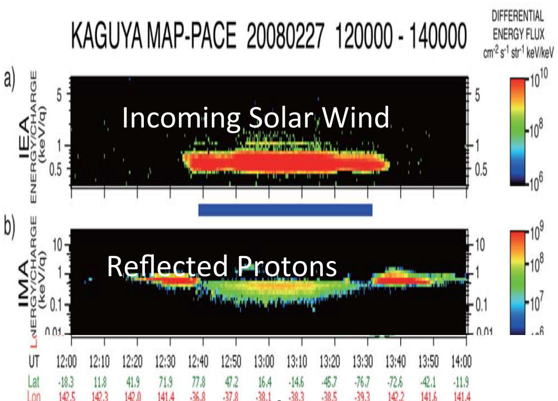


- Solar wind – tenuous ionized gas: Plasma is the 4th State of matter, most mass in universe, good example: our sun
- Protons and electrons at 5/cm^3 streaming at 400 km/sec, temperature near 100000K
- Airless body is a obstacle in this conductive plasma 'fluid' flow!
- 95% H^+ (few %: He^{++}, O^{+7}) incident at surface to implant, sputter, change crystal structure

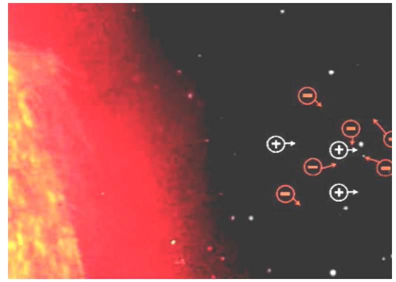
Dynamic Solar Wind Protons and Surface Conversion

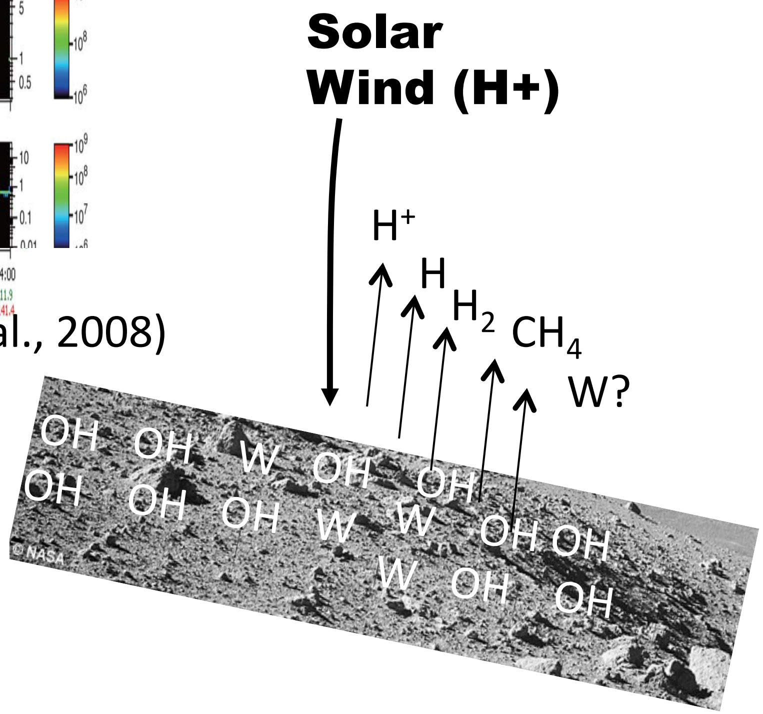


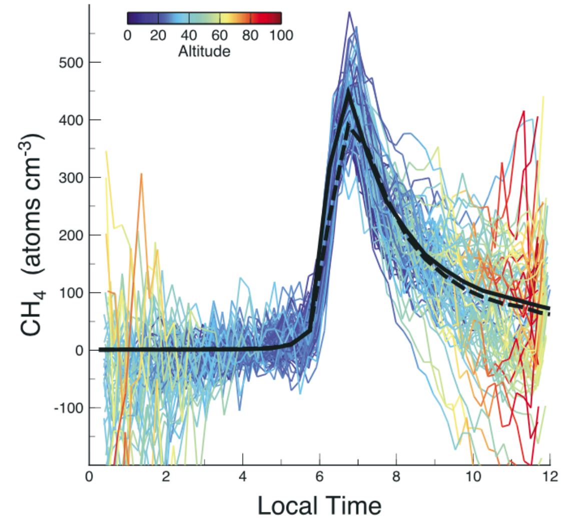
EPOXI OH (Sunshine et al., 2009)



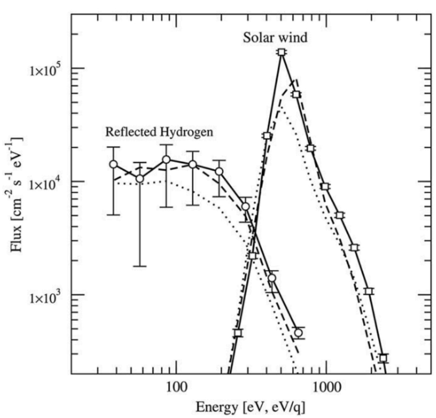
Kaguya H+ (Saito et al., 2008)



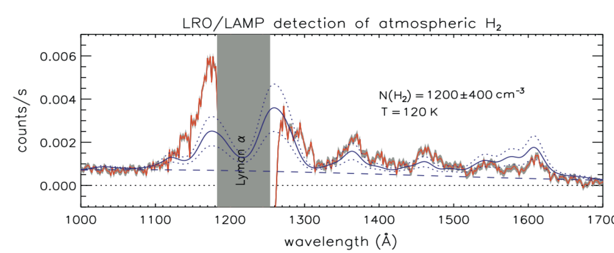




LADEE Methane (Hodges, 2016)

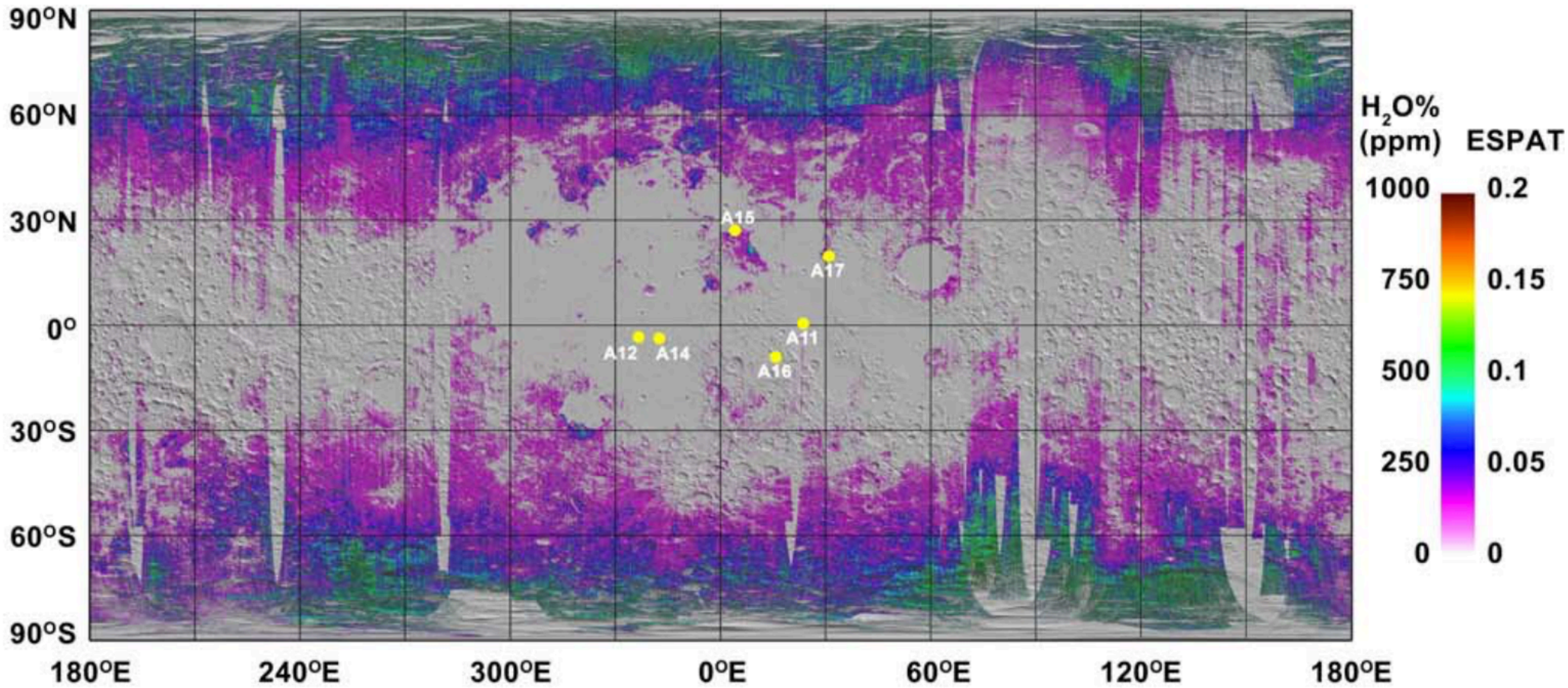


Chandrayaan-1 Fast H (Wieser et al., 2009)



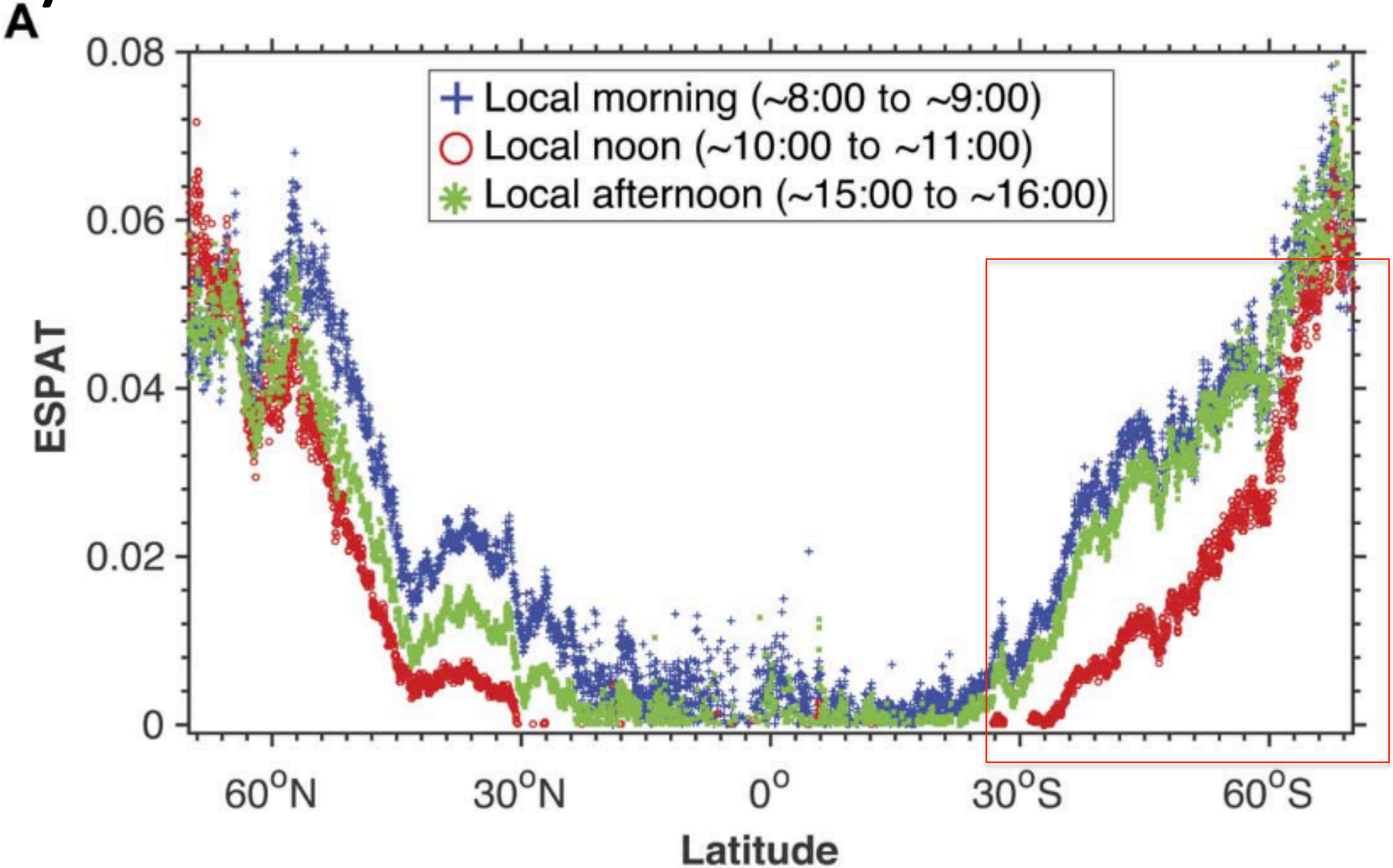
LAMP H_2 (Stern et al., 2013)

Map of 2.8 micron band depth feature



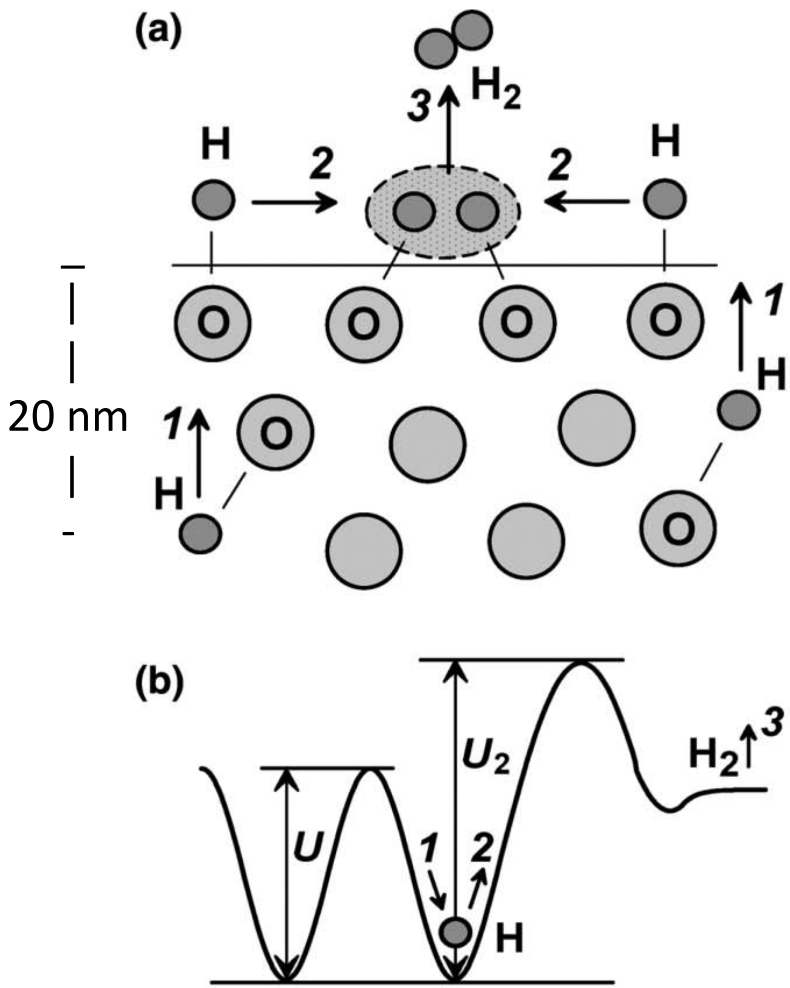
Li and Milliken 2017 − Map of surficial OH in the IR from M^3

Dynamic Diurnal Surface Variation of H



Li and Milliken, 2017 − Effective Single Particle Absorption Thickness, proportional to H content

What we think is happening in the soil?



Starukhina 2006

H Residency time:

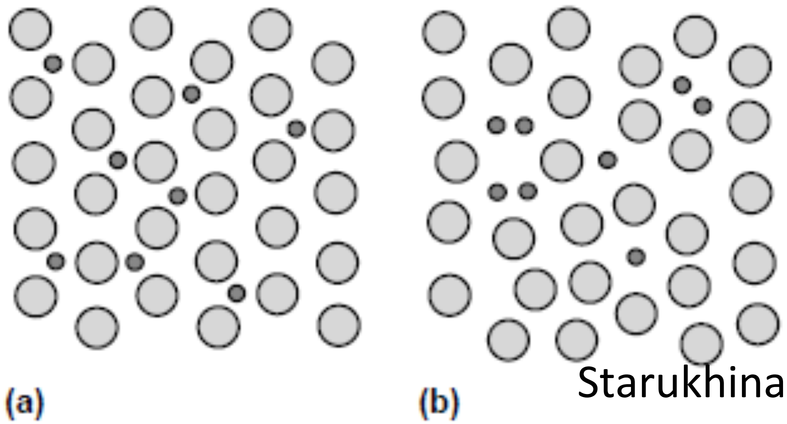
$\tau = \tau_o \exp(U/T)$

U is activation energy or 'trapping' energy

1-U is larger at vacancy sites, Thus H -residency time, τ, is longer

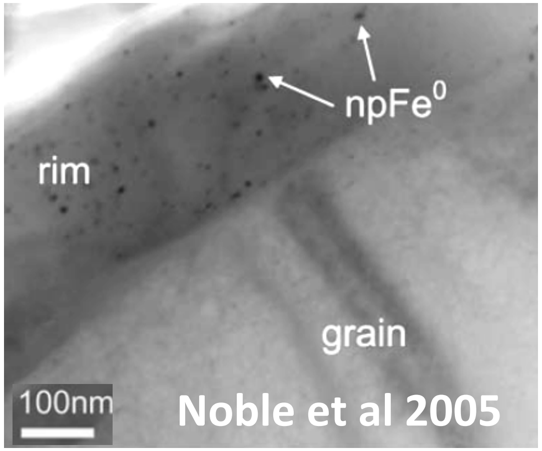
2-U is larger near radiation-damaged O atoms

Defect Properties and H Diffusion



Starukhina 2006

- Lunar surface is oxide-rich: SiO_2, TiO_2, FeO_2
- **Defects** important [Starukhina, 2006; Dyar et al., 2010]
- Damaged lattice can retain H longer (i.e., vacancy)
- Samples have rims: amorphous crystalline structure – so damaged that original crystal destroyed
- Oxygen chemistry can also 'delay' the migration of H



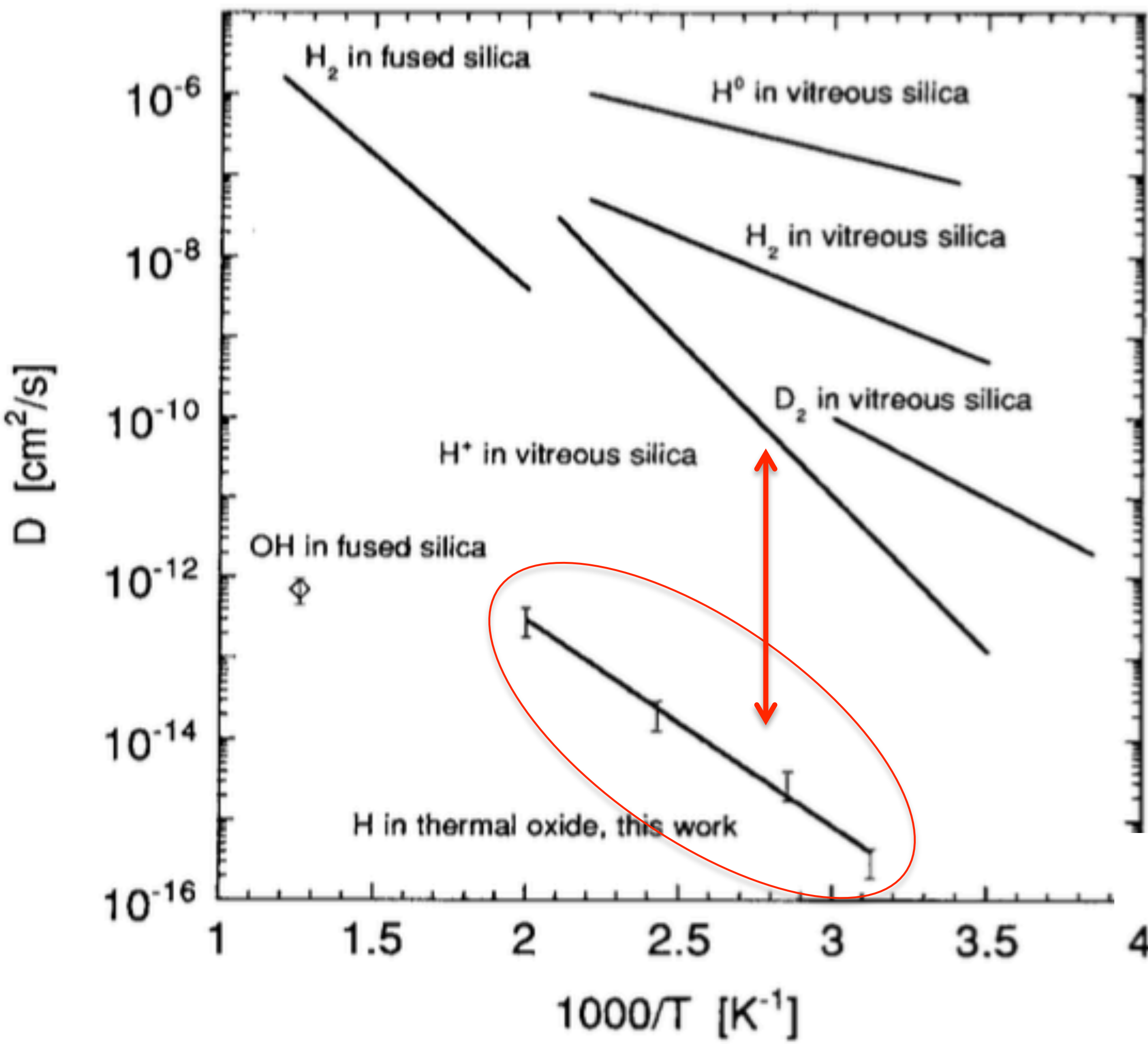
Noble et al 2005

Near-surface damage created via the space environment: impacts, radiation damage (tracks), solar wind plasma damage

Hydrogen implantation and diffusion in silicon and silicon dioxide

D. Fink[1], J. Krauser[1], D. Nagengast[1], T. Almeida Murphy[1], J. Erxmeier[1], L. Palmetshofer[2], D. Bräunig[1], A. Weidinger[1]

[1]Departments FD. AT, and FH of the Hann-Meitner-Institute Berlin, Glienicker Strasse 100, D-14109 Berlin, Germany
(Fax: + 49-30/8062-2293)
[2]Institute for Experimental Physics, J. Kepler University, A-4040 Linz, Austria



Irradiated Silica (Fink et al., 1995)

'Hindered H diffusion'

Irradiated O have a relatively stronger bond with passing H

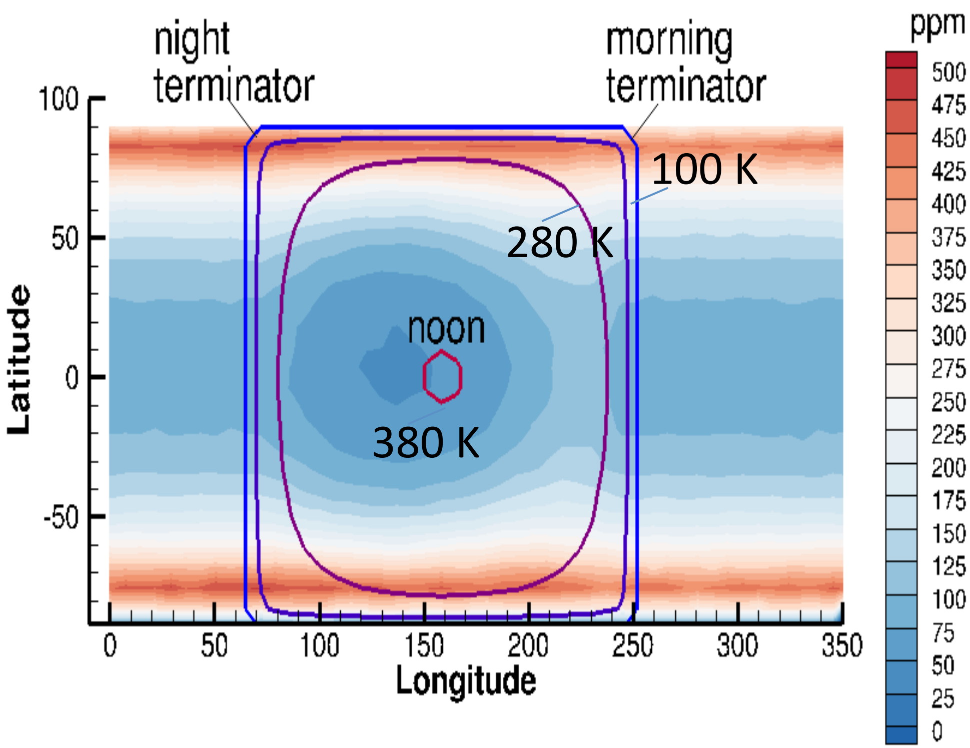
$D_o \sim 10^{-12}\ m^2/s$
$U_o = 0.52$ eV
$\Delta U = +/-0.15$ eV

Form 'meta-stable' O-H pairs

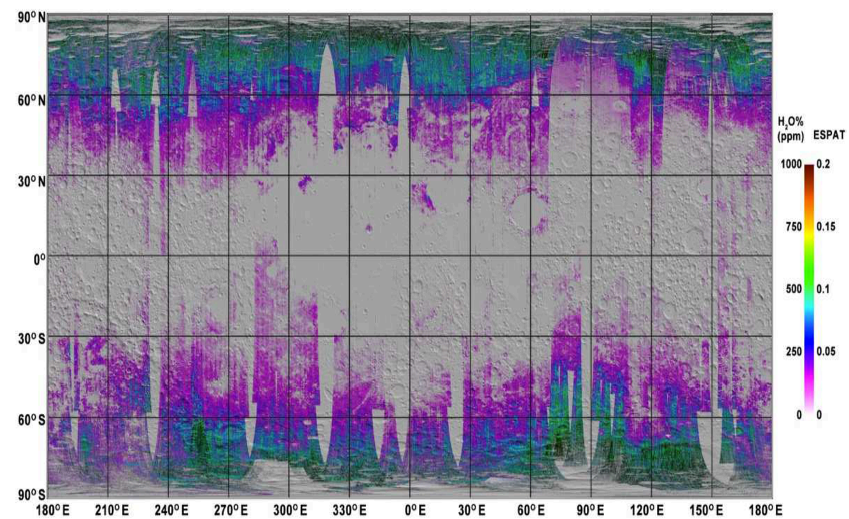
$$\frac{1}{2}H_2 + Si^{4+} + 2O^{2-} \Leftrightarrow OH^-Si^{3+} + O^{2-}.$$

Global OH Modeled of ‘Hindered’ H Diffusion

$f\,(U_0 = 0.5\text{ eV}, U_C = 0.1\text{ eV})$



Li and Milliken (2017) Global water map from M³



Simulation snapshot after ~ 18 lunations

Tucker et al. 2018 (DREAM2 team work]

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A Possible Solar Wind Implanted H to OH to Water 'Recipe'

- SW Implanted protons create damage
- Damage generally slows the outgassing hydrogen diffusion
  - Form meta-stable OH around broken O bonds

Once OH is in the surface:

- Micro-meteoroids can impact and make new chemistry – possibly water
- OH's themselves may merge to make new chemistry (possible water via recombinative desorption, Orlando team 2018)

Where does hydrogenation, hydroxylation, and hydration begin and end? The boundaries are amorphous…space environment 'smearing' the boundaries

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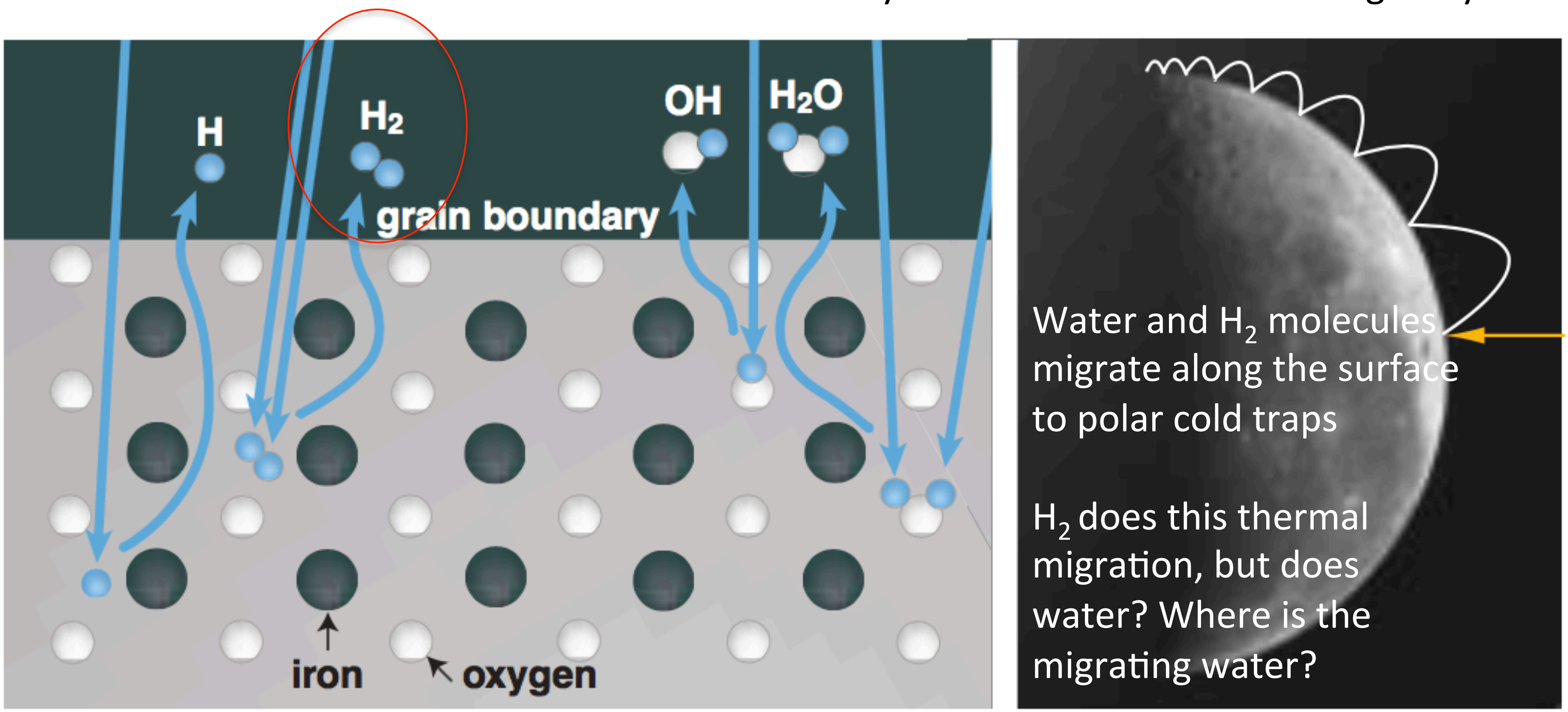
Key Questions for Solar Wind OH and water?

- What are the chemical pathways for implanted hydrogen in the surface? Are we missing any? [Where did methane come from?]
- What is the form of the OH in the surface? Meta-stable, lightly bonded O-H pairs or strong covalently bonded OH? [Where does hydrogenation end and hydroxylation begin?]
- Given the OH, can water be generated and released from the mid-latitude lunar surface – to 'hop' to the poles?
- What role do impactors play in chemically- changing the hydroxyl-rich regolith to water?
- Why has water/OH not been detected in the exosphere (region above the surface), except for impact events?

Lot of H_2…not a lot of OH and water detected (only during impacts)

H2 detected by LRO/LAMP
Water could be sensed by LADEE instruments .. not regularly seen



Vondrak and Crider, 2003

Where is the exospheric water?

- Mostly solar wind seems to convert to H_2 and energetic H….
- No water in the exosphere reported as yet for nominal periods
- However, LADEE team has reported water and OH in exosphere during impact events

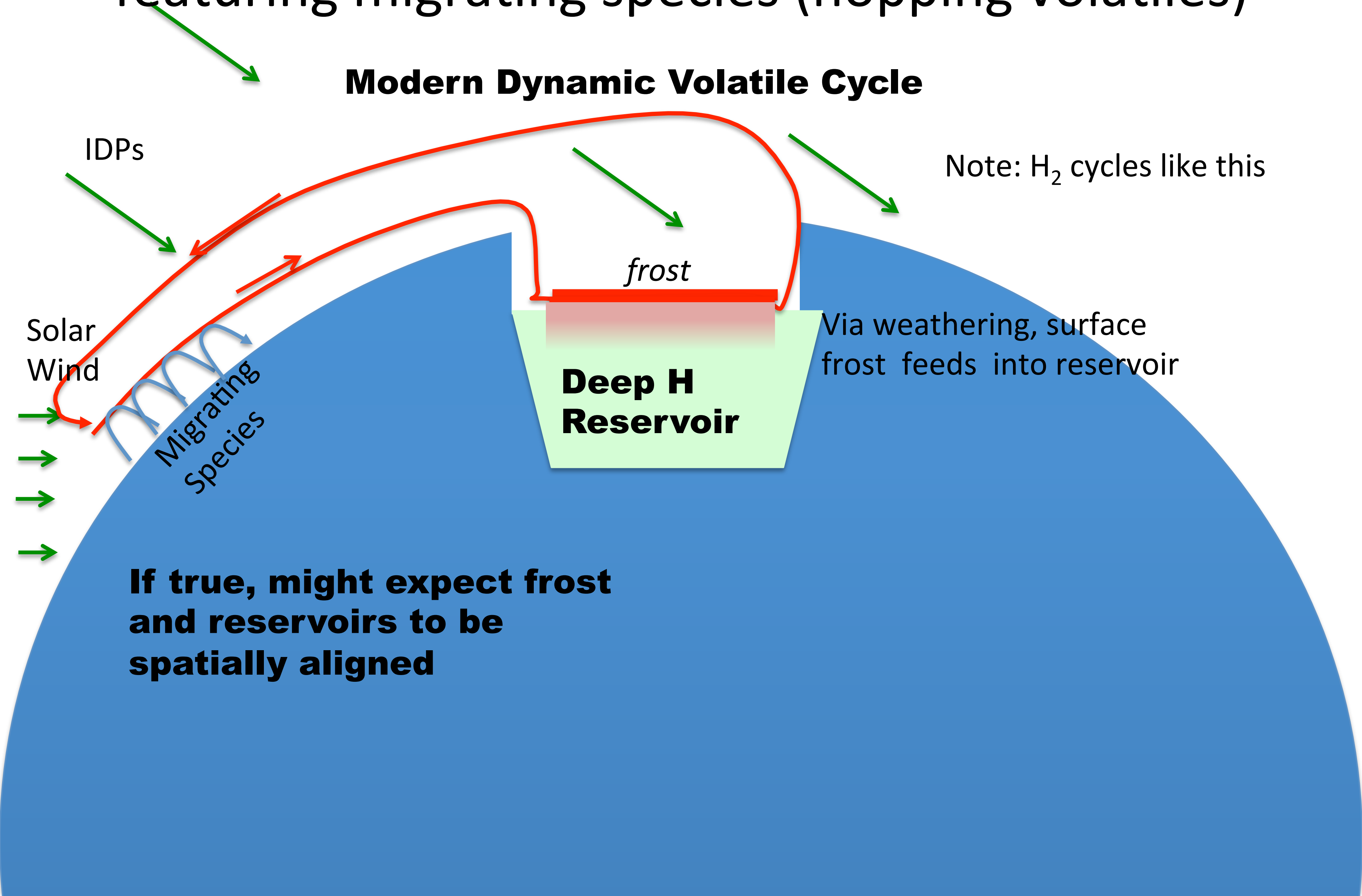
So where is the exospheric water at nominal times at mid-latitudes?

- Might be a low flux species in nominal periods.

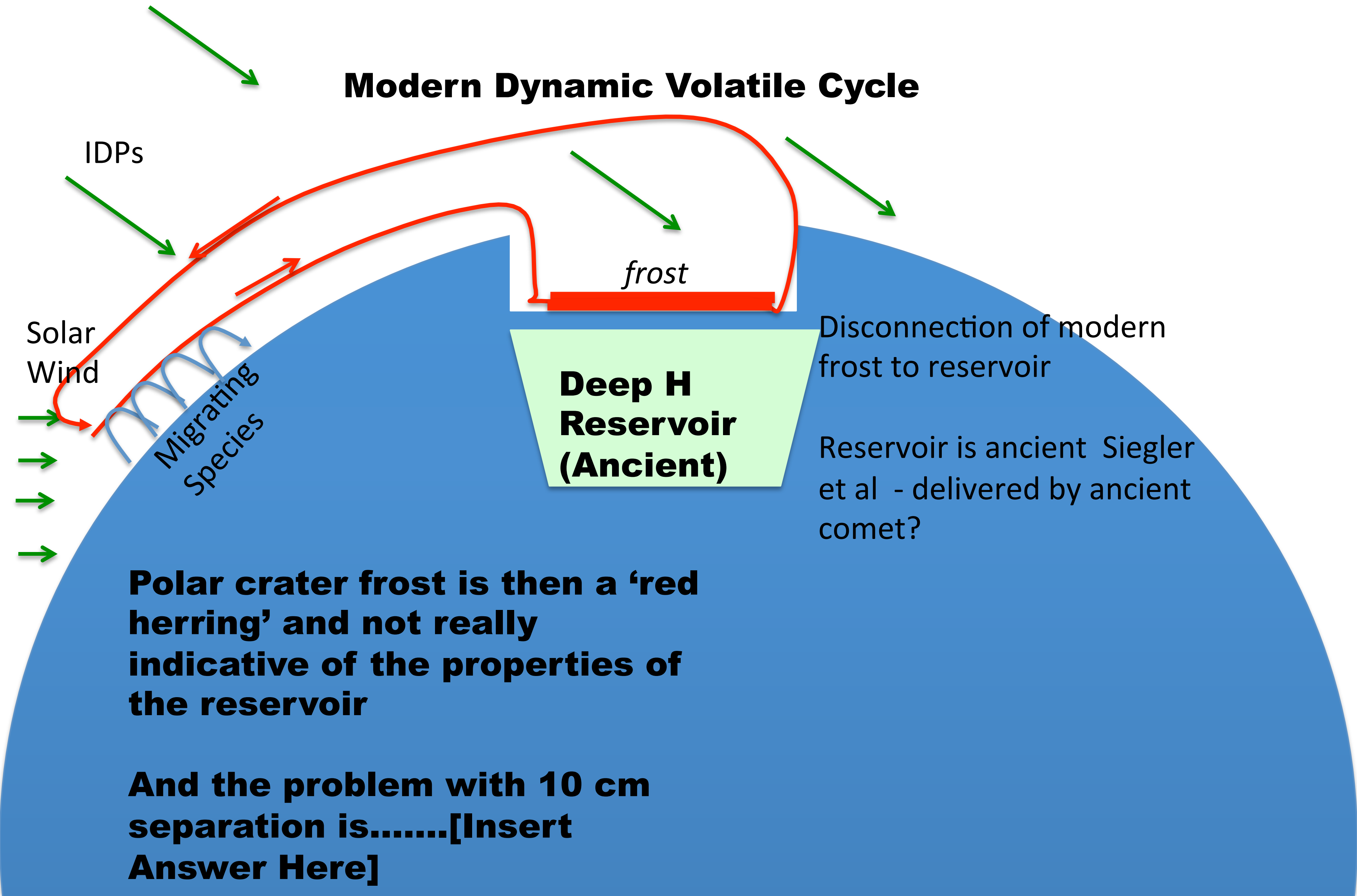
Conclusions

- For the modern Moon: Hydrogenation (H), hydroxylation (OH), and hydration (H_2O) connected and blended by the space environment.
  - 'see' incoming solar wind protons (dynamic),
  - 'see' incoming micro-meteoroid effects (dynamic),
  - 'see' the OH in the surface (dynamic),
  - 'see' the H_2 in the exosphere (dynamic),
  - 'see' water at the poles (revealed via dynamic LADEE event),
  - 'see' OH at mid-latitudes during meteor events (dynamic)
  - …..but don't 'see' not a lot of water at surface and exosphere at mid-latitudes − cannot yet establish flow out of poles or into poles.
- If exospheric water were as dominant as H_2, it would have detected…would have seen it
- Back to the big picture
  - 3 possible scenarios for the lunar H/OH/H_2O
  - Currently don't know which is correct

Scenario #1 – Strong Cycle-Reservoir Connection featuring migrating species (hopping volatiles)



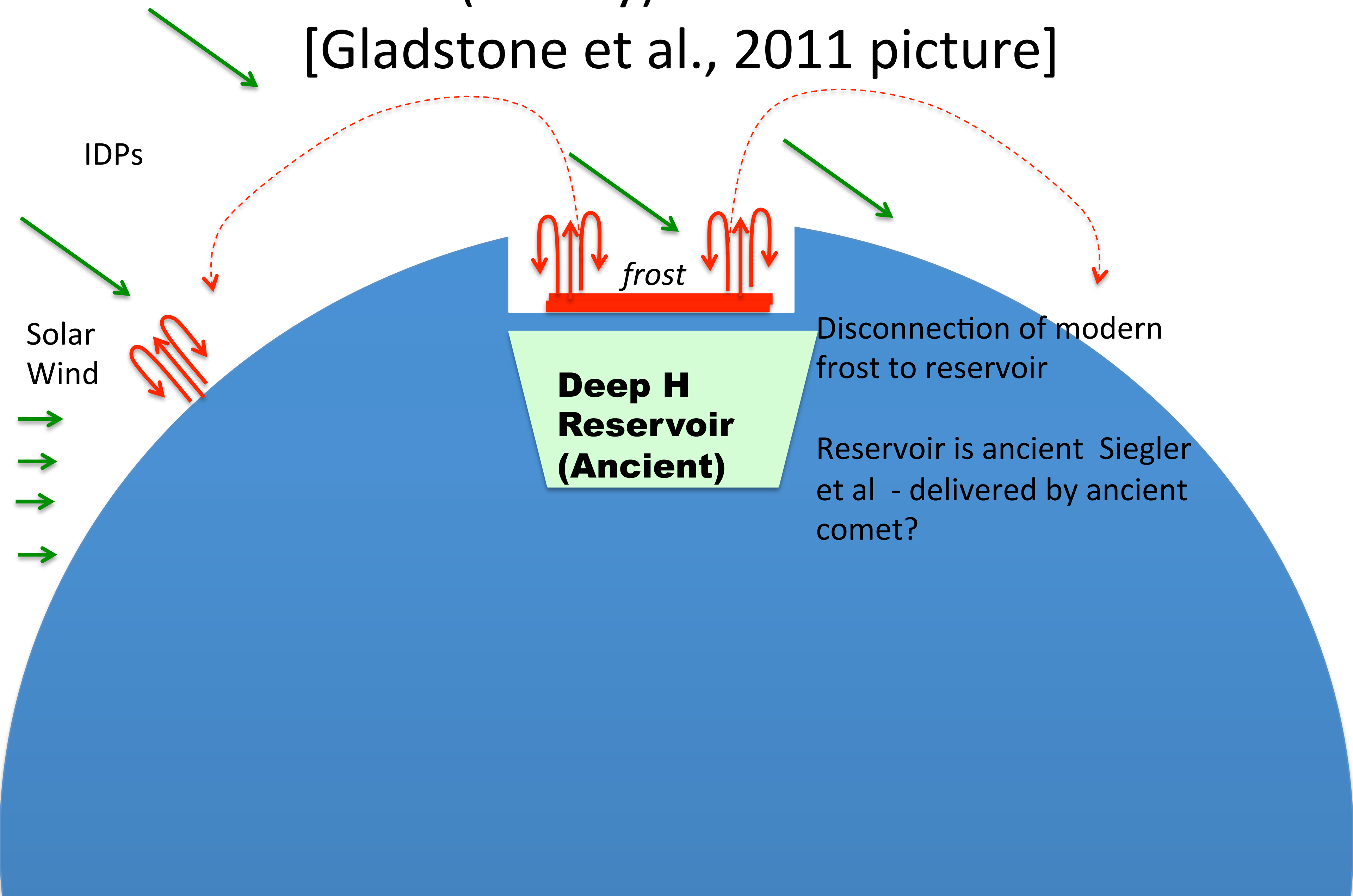
Scenario #2 – Cycle-Reservoir Quasi-disconnected



Scenario #3 – No Cycle, Volatile Frost via Meteor Infall

A (mostly) local effect

[Gladstone et al., 2011 picture]



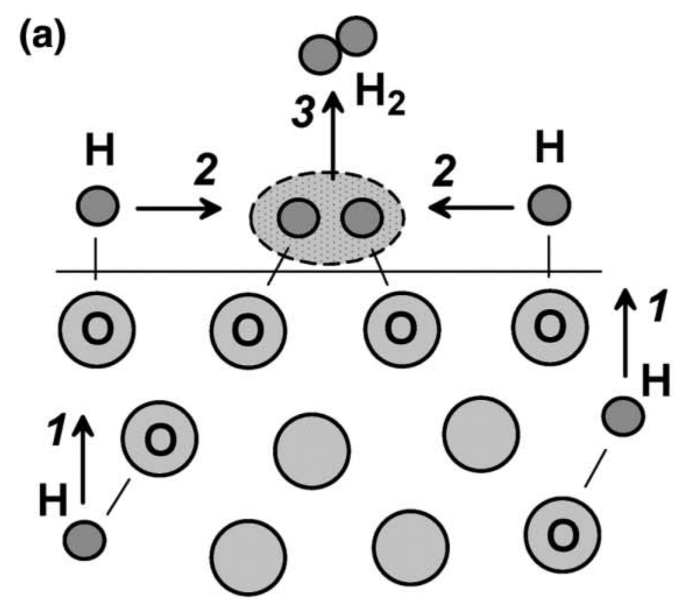
Backup/under construction

Table 2
Comparison of mass fluxes from various sources.

	Flux ($g\,cm^{-2}\,s^{-1}$)	Mass rate ($g\,s^{-1}$)	Expected source rate of H_2 ($g\,s^{-1}$)	Efficiency that would produce $1200\,cm^{-3}$ H_2	Upper limit using $9000\,cm^{-3}$ H_2
Micrometeoroid delivery	6.67e−16	58	<0.09	Insufficient source	Insufficient source
Solar wind delivery	3.34e−16	31.5	<28	7%	54%
Micrometeoroid liberation	1.77e−15	170	< 0.17	Insufficient source	Insufficient source

About 7-54% of incoming solar wind converted to H_2

Like predicted by Starukhina 2006



Conclusions

- Back to the big picture
- 3 possible scenarios for the lunar H/OH/H_2O
  - Currently don't know which is correct

- Cant get blood from a turnip but might get water from a (lunar) rock
  - Have to hold it up to the solar wind first
  - Might have to pelt it with particulates (4000K)
  - Or heat it to 600K

CRIDER AND VONDRAK: SOLAR WIND SOURCE OF LUNAR HYDROGEN

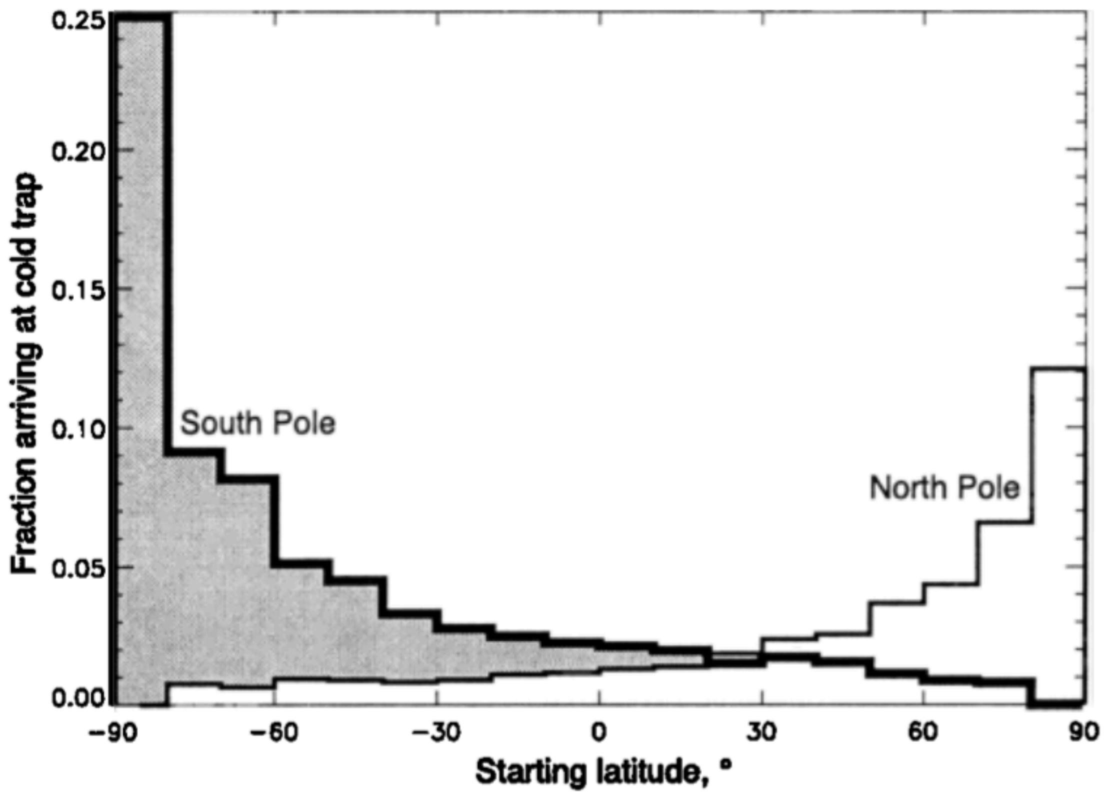
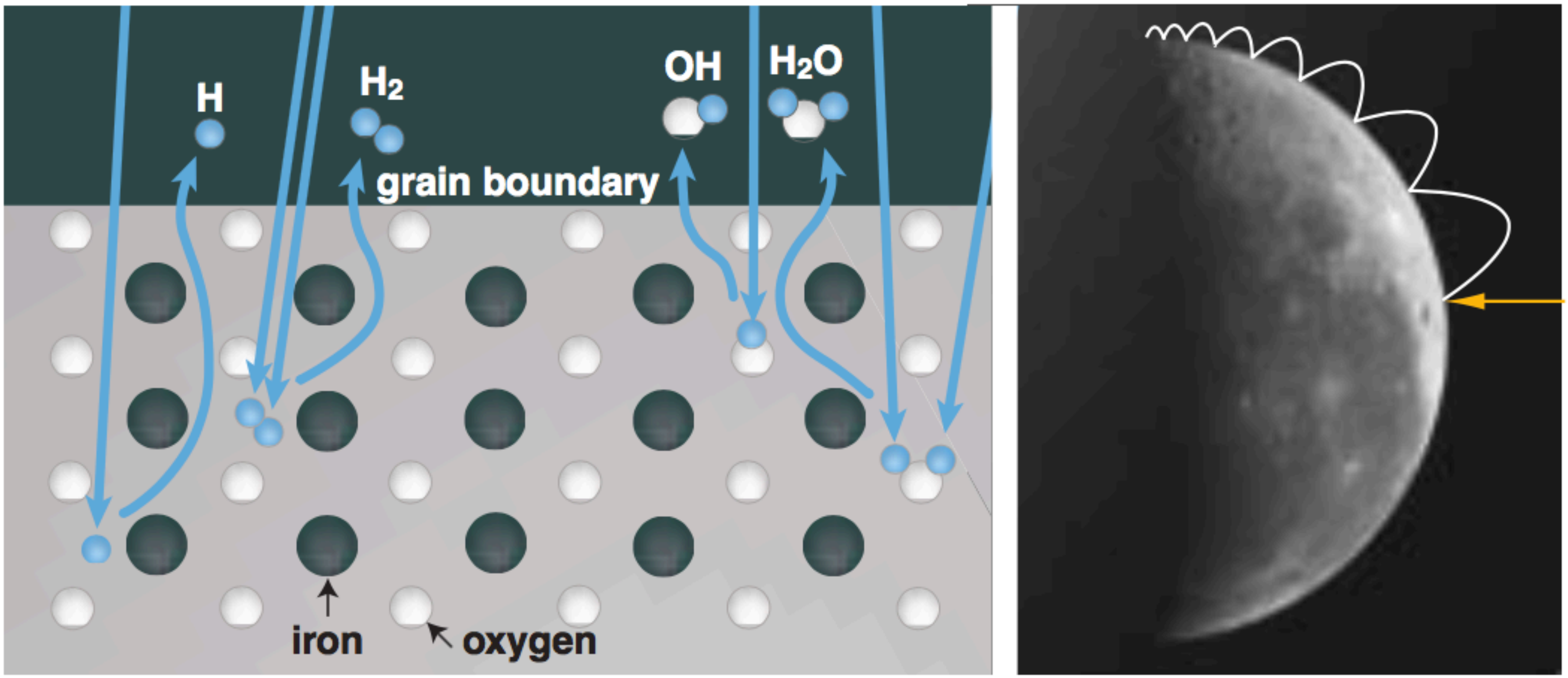
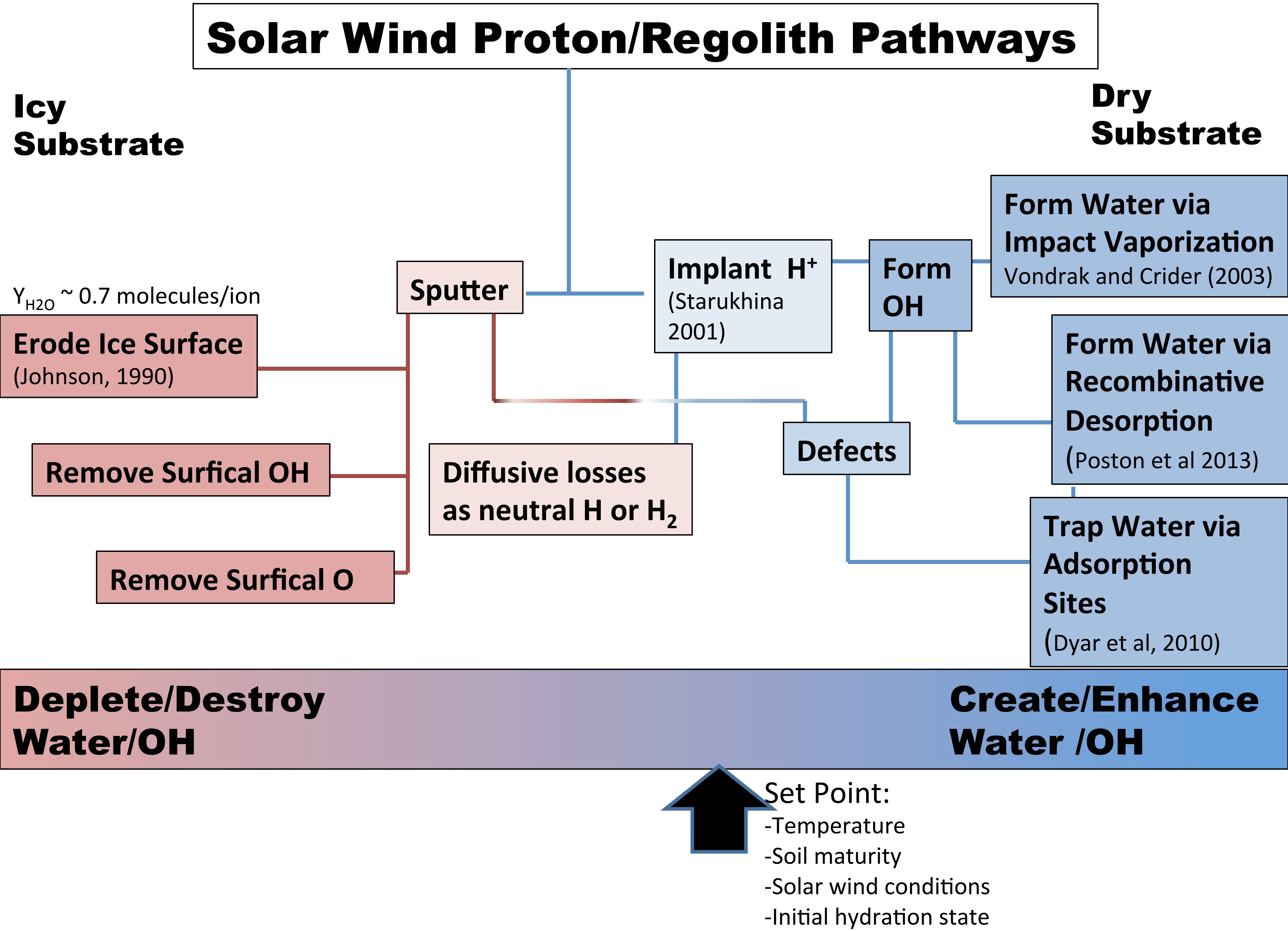


Figure 5. Histograms showing the fraction of particles reaching each pole by latitude bin. The number of particles for each bin in Figure 4 is divided by the total number of particles that began in that bin, yielding the percentage of that bin that arrives at each cold trap.

To date: Observe copious amounts of H_2 but not water in exosphere

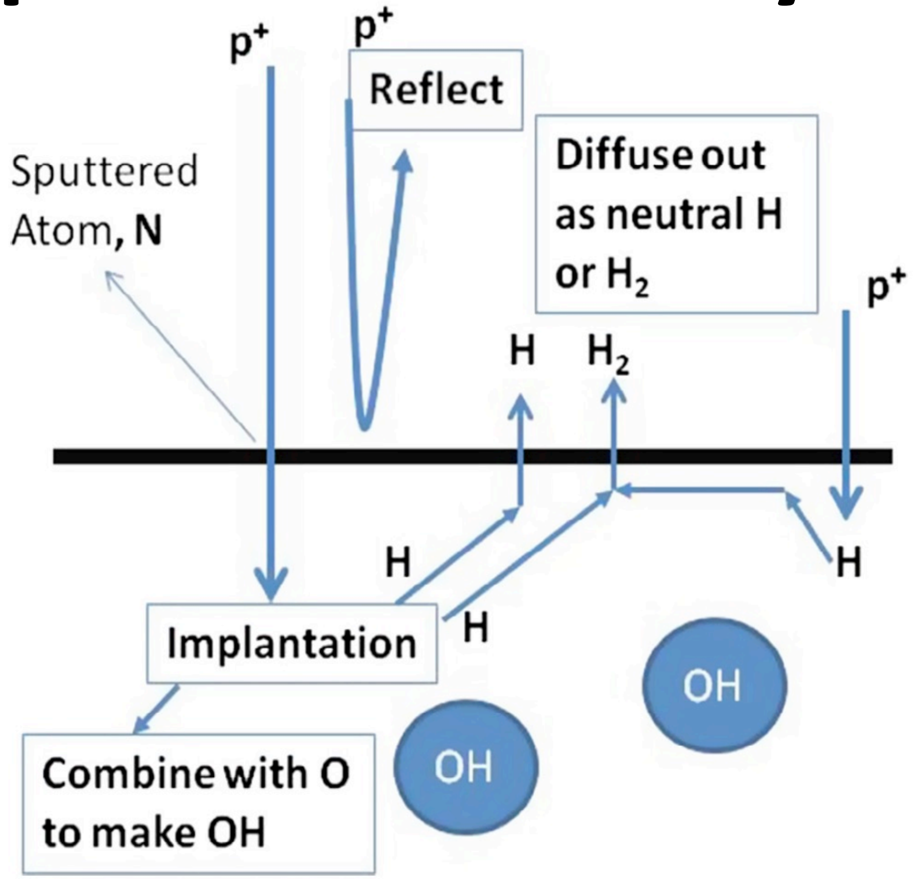


Vondrak and Crider, 2003



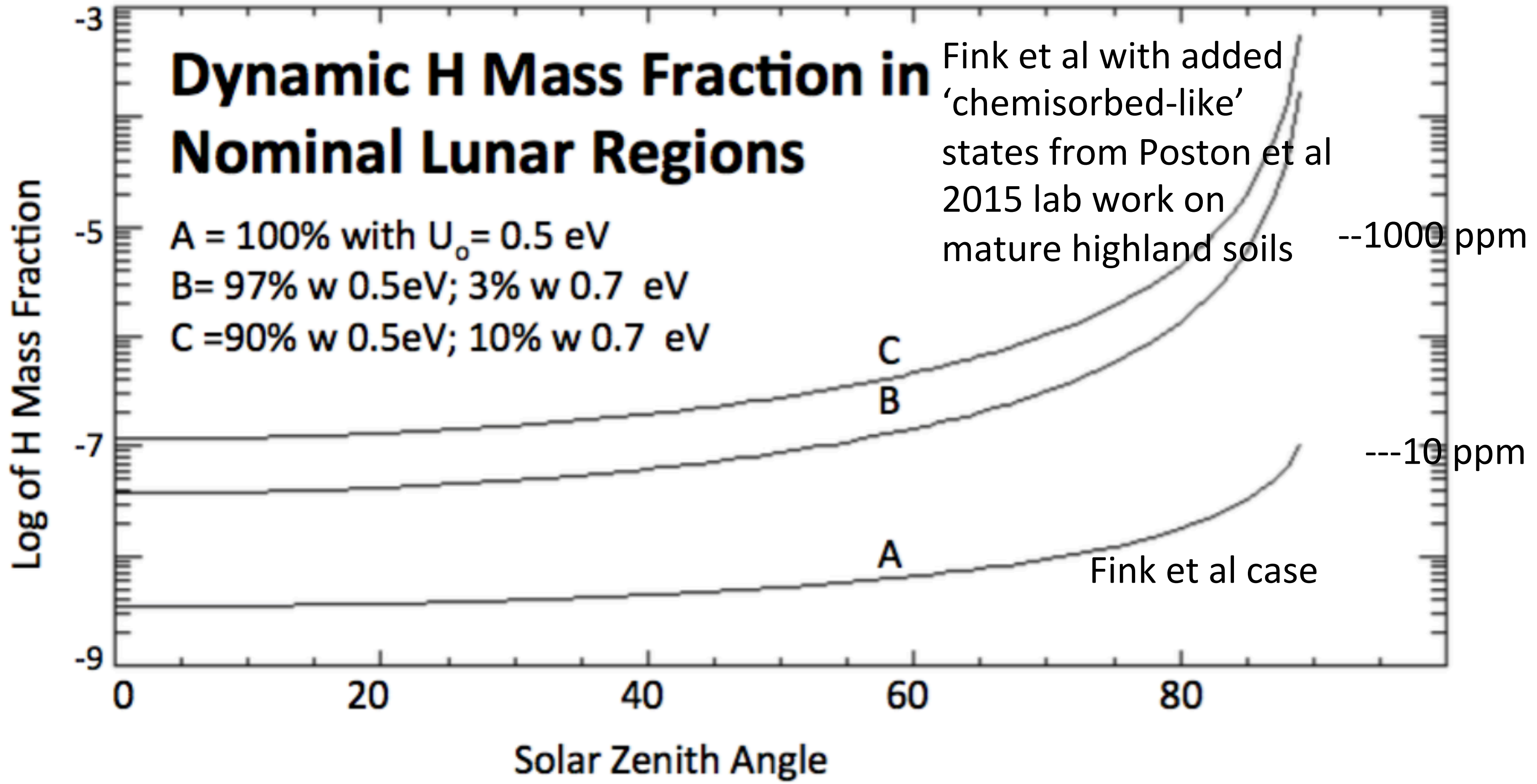
Solar Wind Proton/Regolith Pathways
Icy Substrate
Dry Substrate
Y_{H2O} ~ 0.7 molecules/ion
Sputter
Erode Ice Surface (Johnson, 1990)
Remove Surfical OH
Remove Surfical O
Diffusive losses as neutral H or H_2
Implant H^+ (Starukhina 2001)
Form OH
Defects
Form Water via Impact Vaporization Vondrak and Crider (2003)
Form Water via Recombinative Desorption (Poston et al 2013)
Trap Water via Adsorption Sites (Dyar et al, 2010)
Deplete/Destroy Water/OH
Create/Enhance Water /OH
Set Point:
-Temperature
-Soil maturity
-Solar wind conditions
-Initial hydration state

H Implantation in Dry Regolith



- Why do some H's stay trapped in the regolith and some allowed to leave?
- Is the Moon manufacturing OH via **loitering Hs**?
- **What role does the harsh space environment perform to form OH?**

Solar Wind-Implanted H Mass Fraction



Fink-like Diffusion Parameters

D_o ~ 10^{-12} m^2/s

U_o = 0.5 eV (and U_o = 0.7 eV)

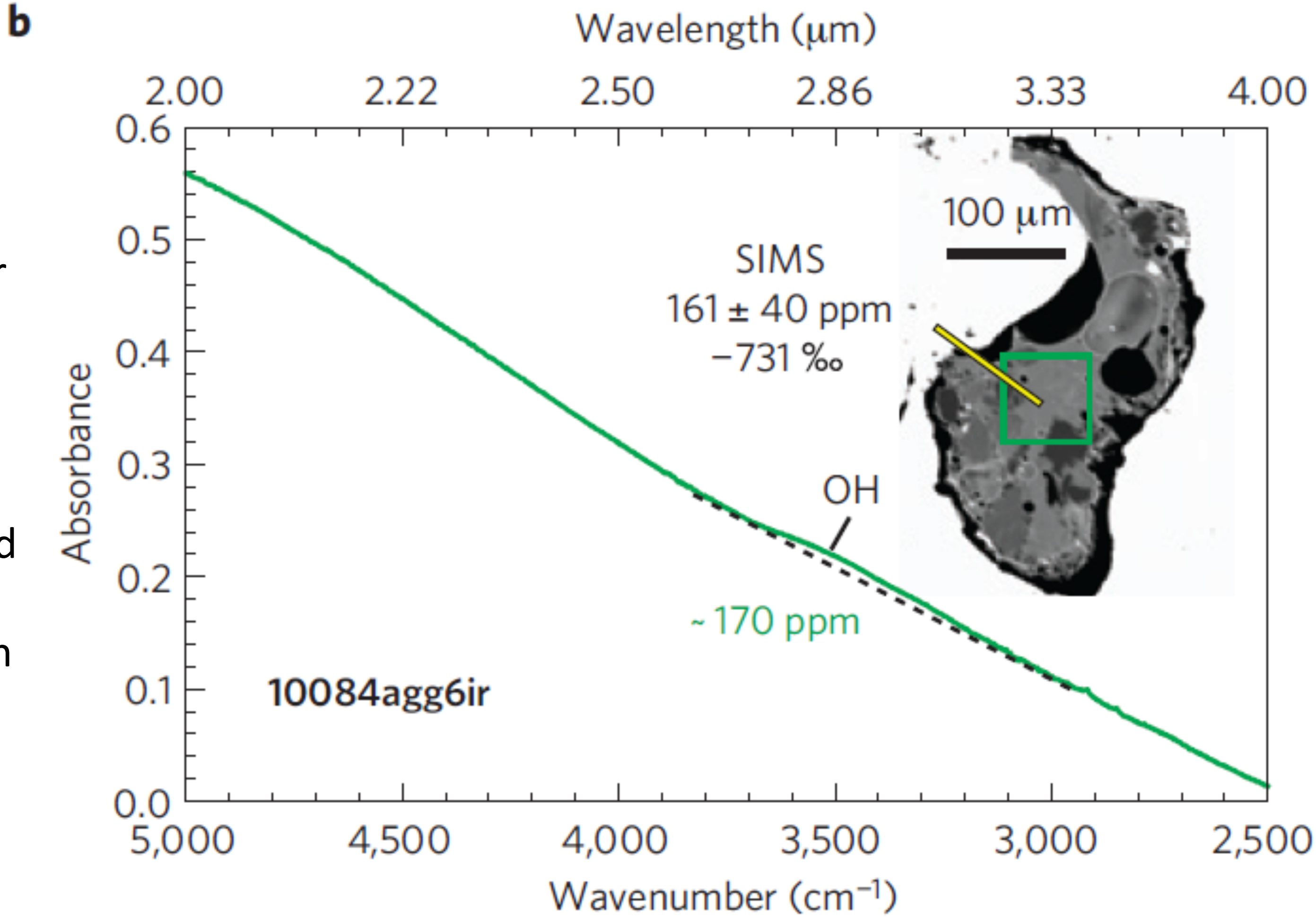
ΔU= 0.1 eV

T = 280 $\cos^{0.25}(Z)$ +100 (Crider and Vondrak, 2000)

Farrell et al., 2017

OH in Agglutinates (solidified impact melts)

Is the Impactor 'pre-treating' the soil for increased H retention ?



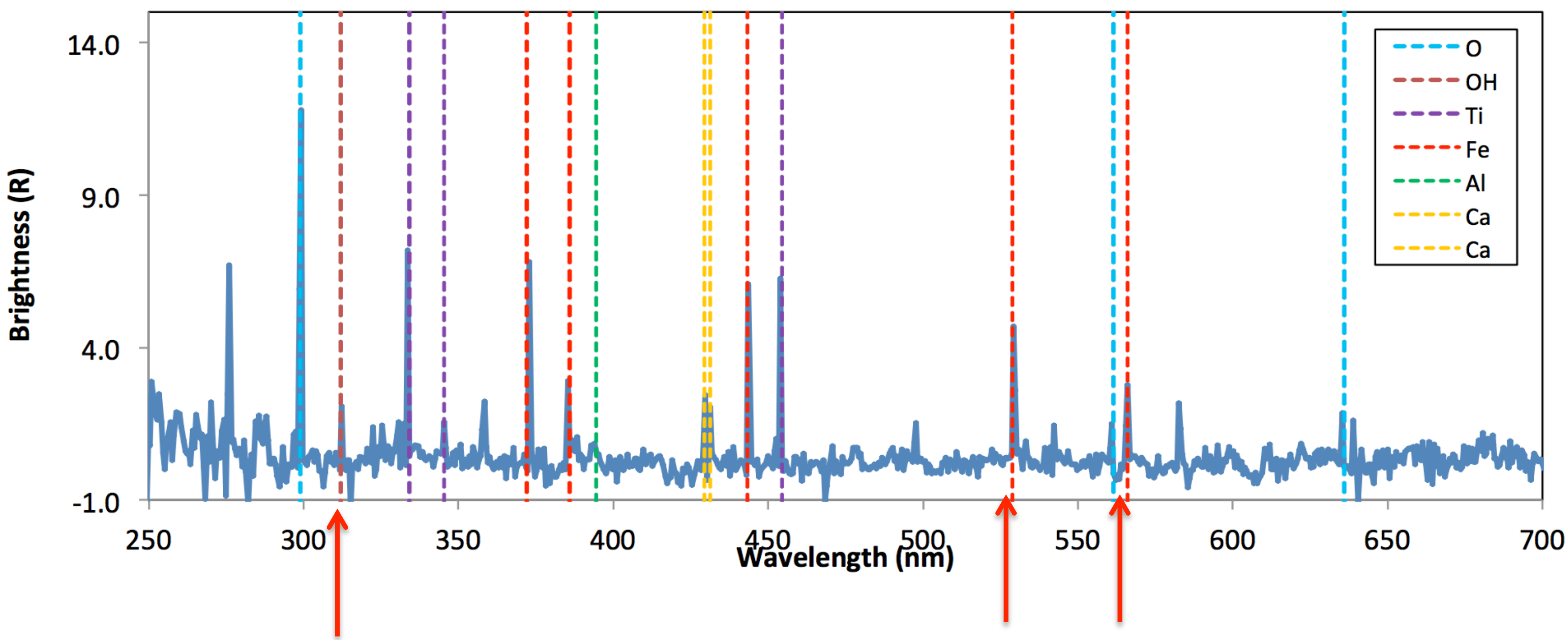
D/H ratio
-H appears to originate from Solar wind

Liu et al., 2012 – 100's of ppm of OH in agglutinate (impact glass) material

space environment modification: Impact melting and solar wind implantation

Initial comparison of Pre- and Post Geminids Dawn Limb Spectra

- Only spectra taken while the SC was in shadow (lunar umbra) and with a solar longitude (the position of the telescope filed-of-view grazing point) between 275-300 deg were used.
- For all measurements the dark current and instrument bias was corrected for, and “hot pixels”, identified through a series of on orbit dark calibrations, were removed.
- >100 spectra were co-added to improve the signal-to-noise ratio.



Colaprete et al., 2015; Exploration Science Forum – Observations from UVS on Lunar Atmosphere and Dust Environment Explorer (LADEE)

Is this OH endogenic (from SW implantations) and released by impacts?

Or is the OH exogenic (in meteoroid) and part of the prompt release & impact vaporization?

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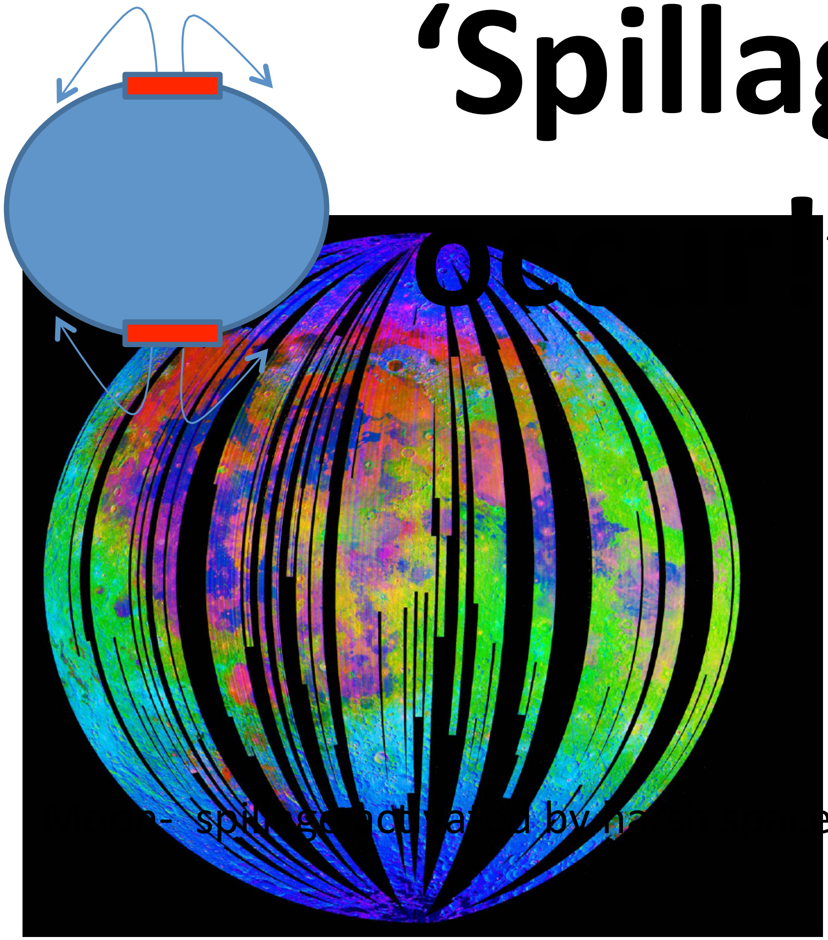
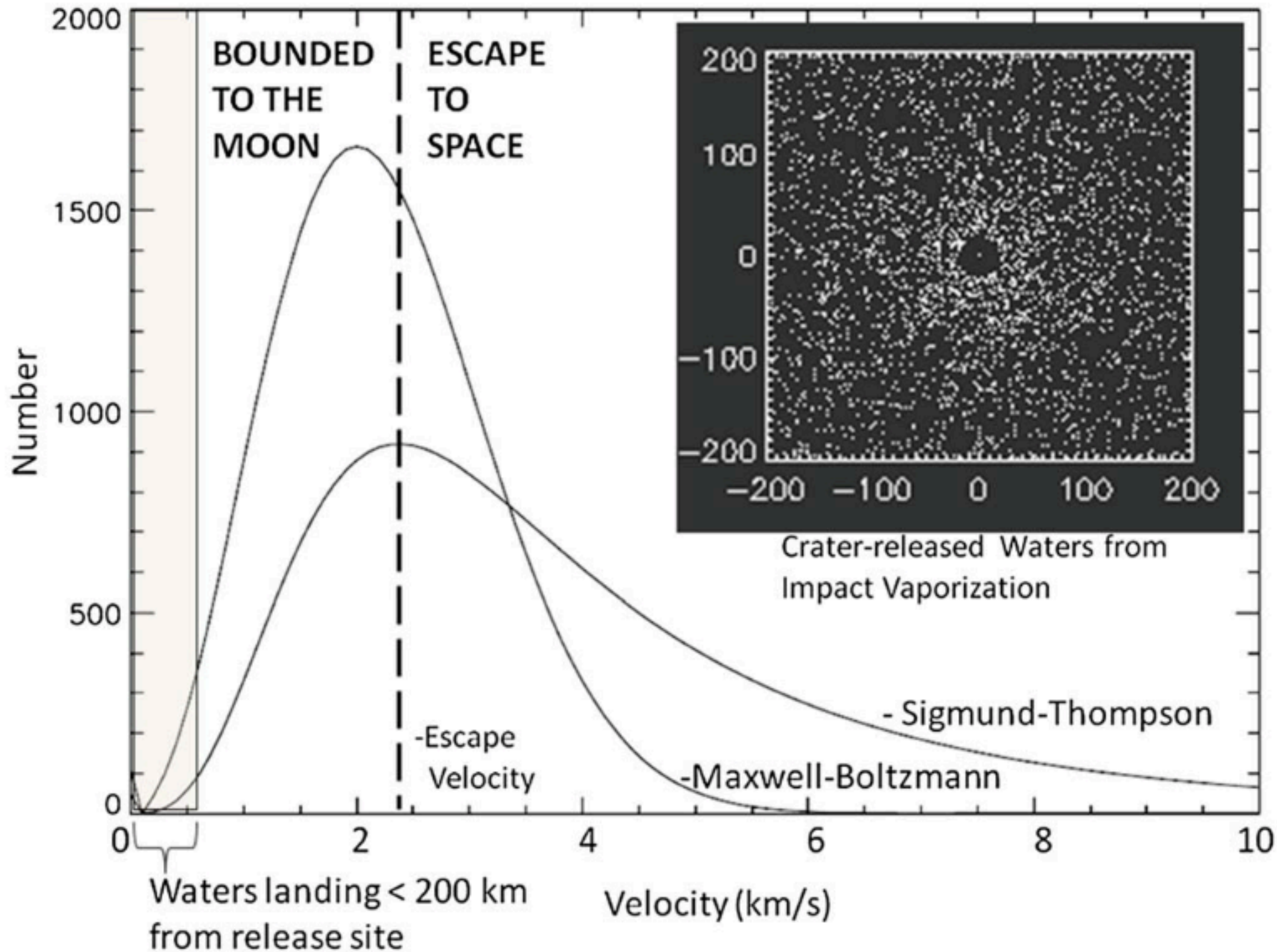
'Spillage may oc... d'



Clark et al, 2010
3 micron IR

... e environment?

-Part of OH Veneer signature: **'Redistribution'** or transport of polar crater volatiles to mid-latitudes


BOUNDED TO THE MOON
ESCAPE TO SPACE
Crater-released Waters from Impact Vaporization
- Sigmund-Thompson
-Escape Velocity
-Maxwell-Boltzmann
Number
Velocity (km/s)
Waters landing < 200 km from release site
2000
1500
1000
500
0
2
4
6
8
10
200
100
0
−100
−200
−200
−100
0
100
200

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DREAM2

Bullialdus Crater Central Peak

a

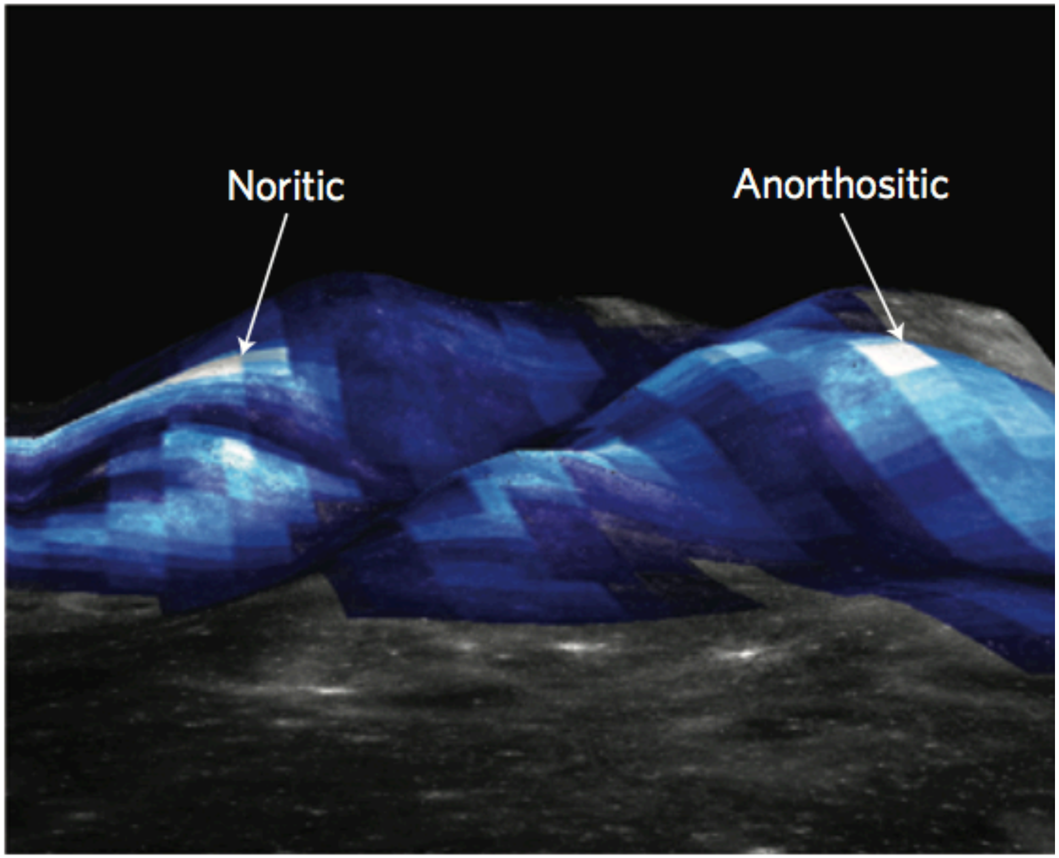
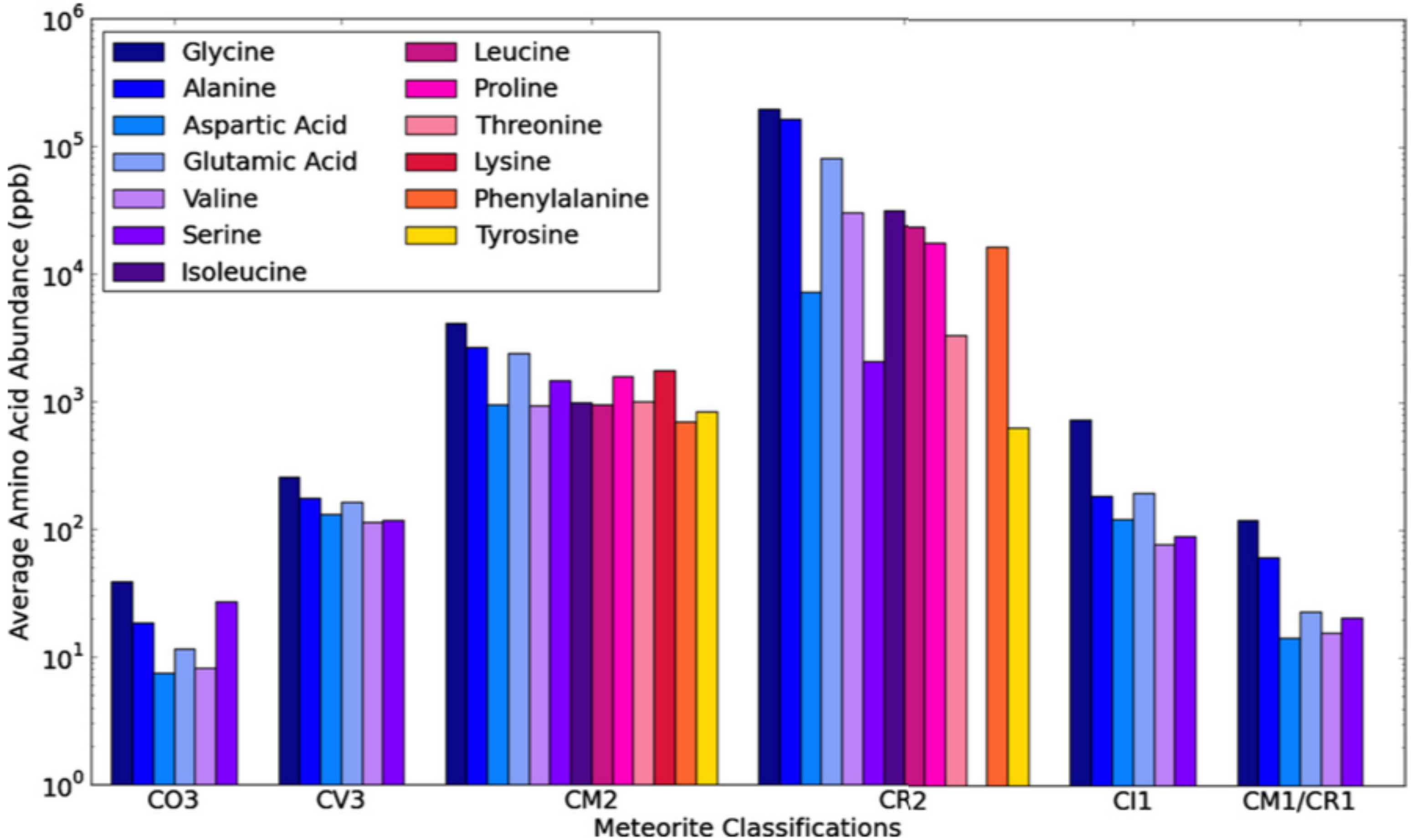


Figure 3 | Geology of Bullialdus Crater central peak. a, Pe

IR signature of OH in impact-excavated material

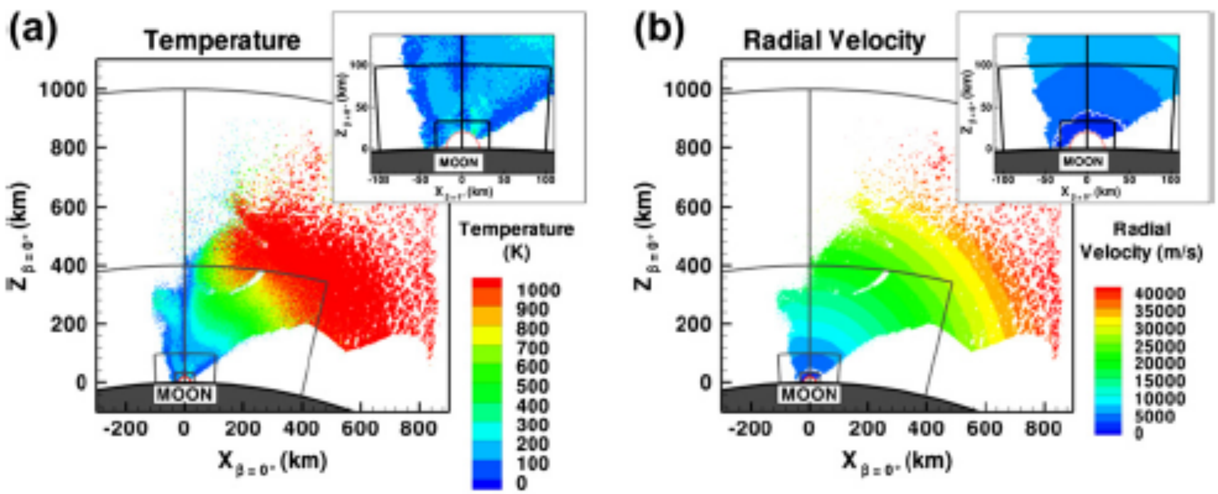
Hydroxyl bound to magmatic minerals

Klima et al.,2013

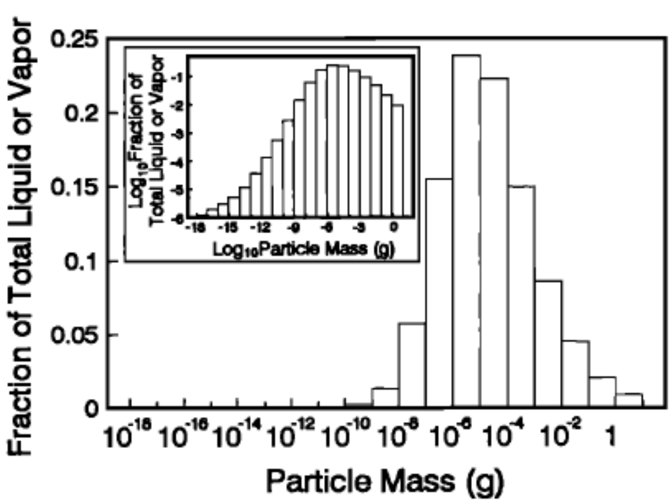


Glycine
Alanine
Aspartic Acid
Glutamic Acid
Valine
Serine
Isoleucine
Leucine
Proline
Threonine
Lysine
Phenylalanine
Tyrosine
Average Amino Acid Abundance (ppb)
10^6
10^5
10^4
10^3
10^2
10^1
10^0
CO3
CV3
CM2
CR2
CI1
CM1/CR1
Meteorite Classifications

Body Infall (large and small)



Stewart et al., 2012
Ong et al 2010



Cintala, 1992

Morgan and Shemansky, 1991

shall assume that the abundance of water is 5% H_2O by mass (M. Zolensky, private communication, 1988). Thus, the meteoritic H_2O source amounts to

$$\begin{aligned} S_{H_2O} &= 0.75 \times 10^{-17} \text{g cm}^{-2}\text{s}^{-1} \\ &= 2.5 \times 10^{+5} \text{ molecules cm}^{-2}\text{s}^{-1} \end{aligned} \quad (6)$$

‘Prompt loss following impact’

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