National Aeronautics and
Space Administration

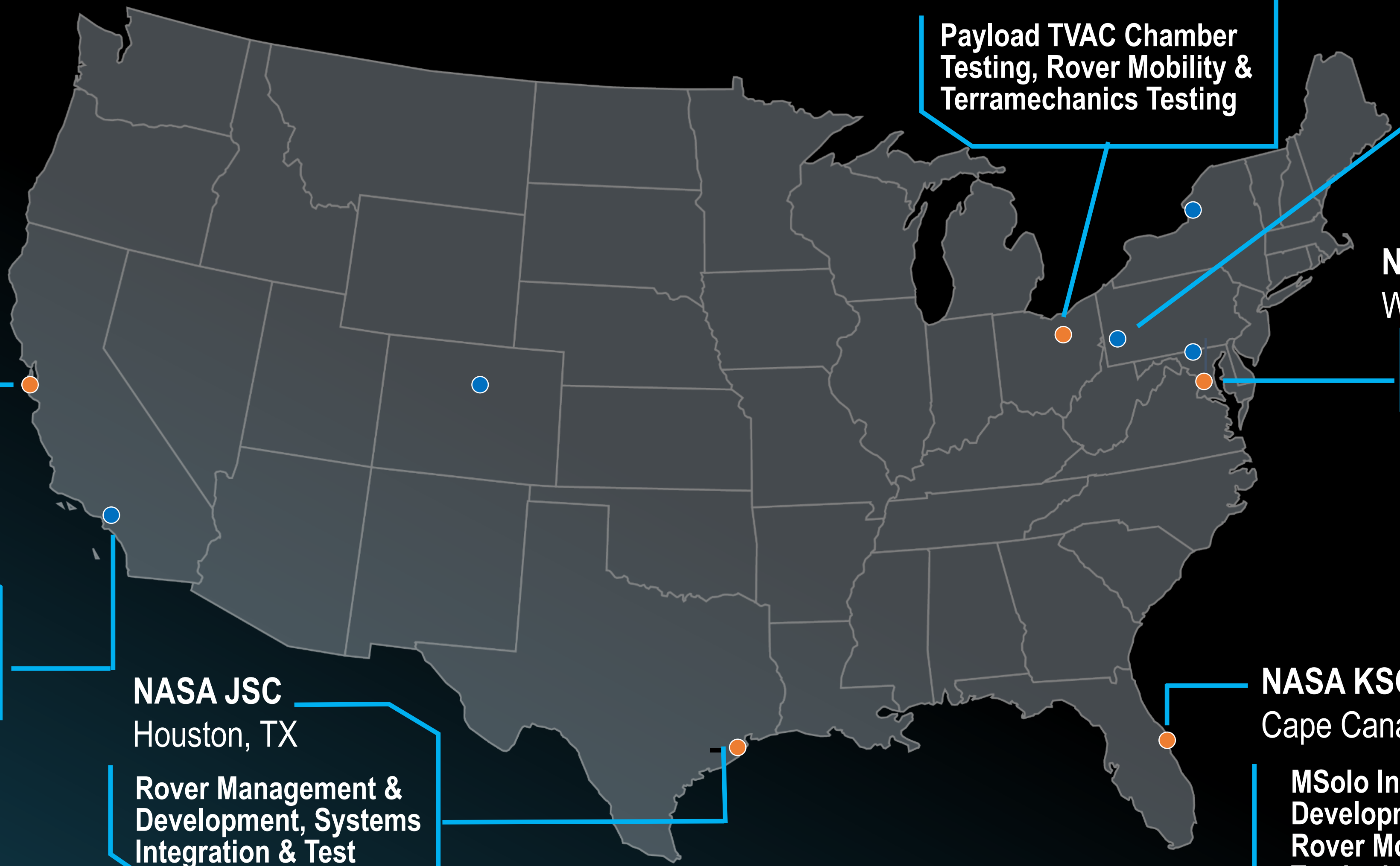
VIPER

Resource Mapping on Another Celestial Body

Kimberly Ennico Smith
VIPER deputy project scientist

June 7, 2022

VIPER Team Map



NASA ARC
Silicon Valley, CA

Mission Management, Science Management, NSS & NIRVSS Instruments, Rover Software & Mission Operations

Honeybee Robotics
Altadena, CA

Payload Drill Development

NASA JSC
Houston, TX

Rover Management & Development, Systems Integration & Test

NASA GRC
Cleveland, OH

Payload TVAC Chamber Testing, Rover Mobility & Terramechanics Testing

Astrobotic
Pittsburgh, PA

Commercial Lunar Payload Services (CLPS)

NASA HQ
Washington, DC

SMD/PSD Management

NASA KSC
Cape Canaveral, FL

MSolo Instrument Development, Rover Mobility Testbeds

● **Payload Partners:** Honeybee Robotics [TRIDENT] (CA), Blue Sun [software tools] (CO), Brimrose [prospecting payload sensor] (MD), Inficon [payload instrument sensor] (NY)

Not that long ago… not so far away….

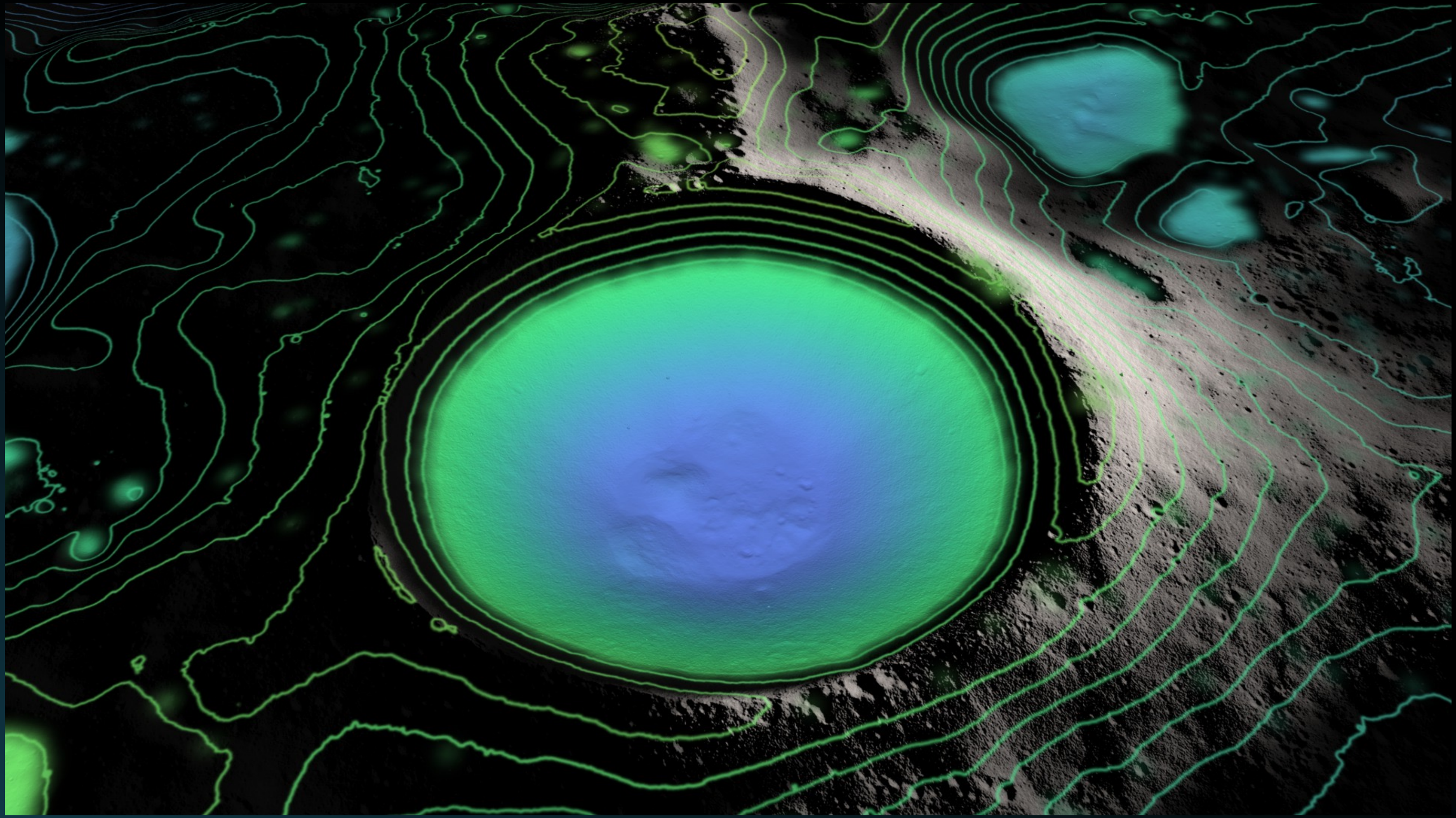
The Moon was a very different place to how we understand it today…

Studied from the Earth, in-situ and with samples returned to Earth.

The “general” thinking was:

- Surface was relative constant
- Thin exosphere of Argon, Sodium and Potassium
- Bone dry
  (~100 ppm of water in soils)

Permanently Shadowed Regions on the Moon



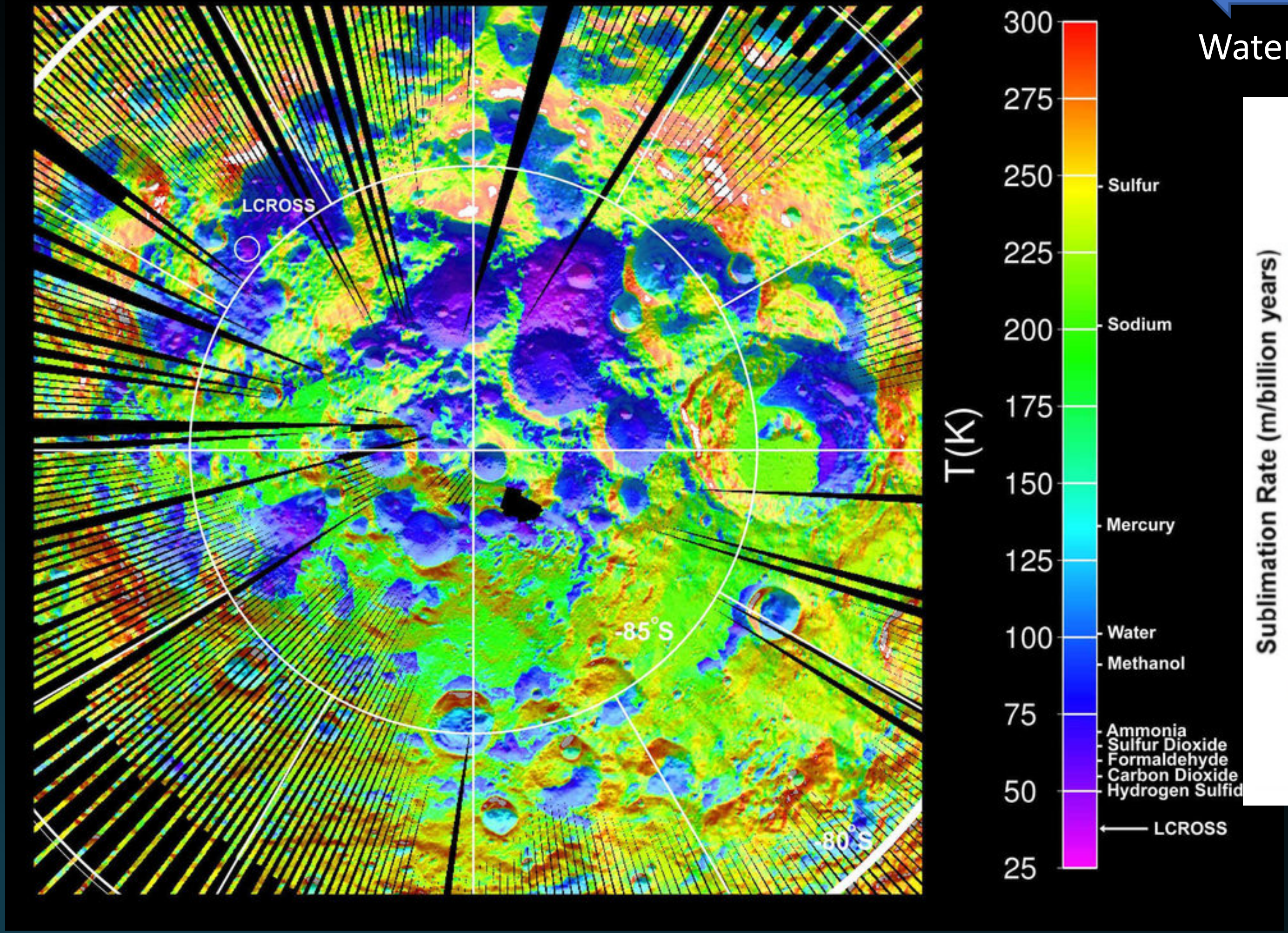
https://svs.gsfc.nasa.gov/4043

- Low obliquity
- At high latitudes, topography creates permanently shadowed regions (PSR)
- $>10^4$ km^2 area
- Exist on size scales ranging from sub-cm (micro) to 10 km
- Leading to Cold Traps 10-20 cm and larger (per Hayne et al. 2020)

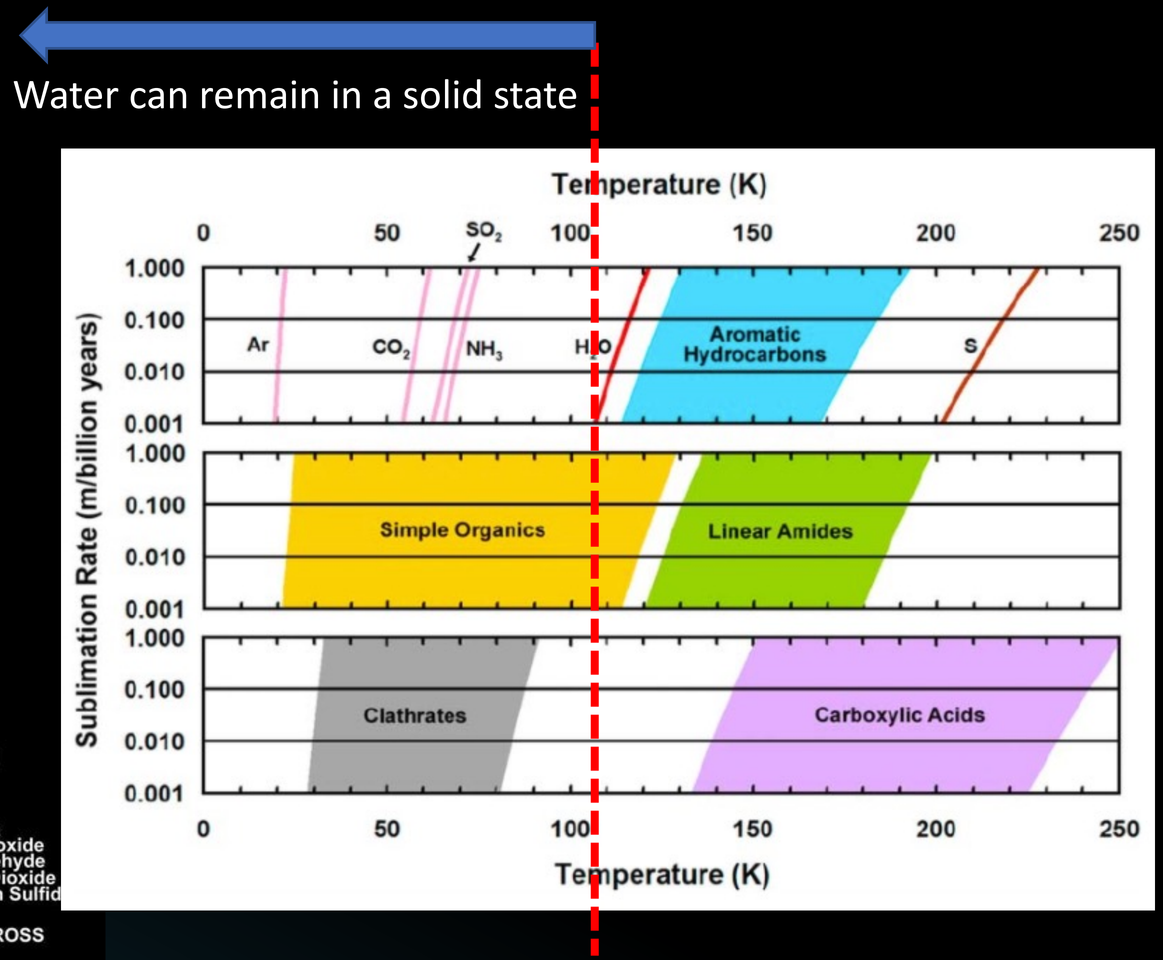
Near the pole, Sun against topography casts long shadows

PSR Temperature and Volatile Stability

Lunar South Pole



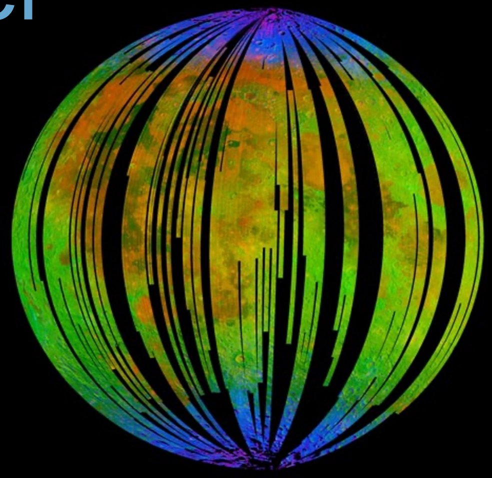
Paige et al. 2010



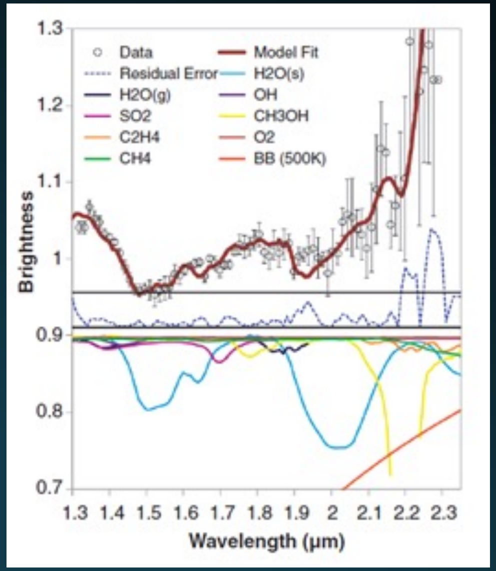
Zhang & Paige 2009

Towards Understanding Lunar Water

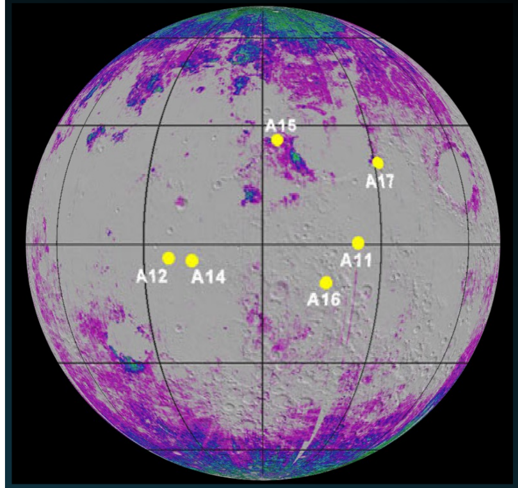
- Moon now known to host all three forms of Solar System water: endogenic, sequestered external and in-situ.
- Do not yet understand the concentration, evolution and interrelated dynamics of these varied sources of water.
- Surface measurements across critical scales are necessary to characterize the spatial distribution and state of the water.



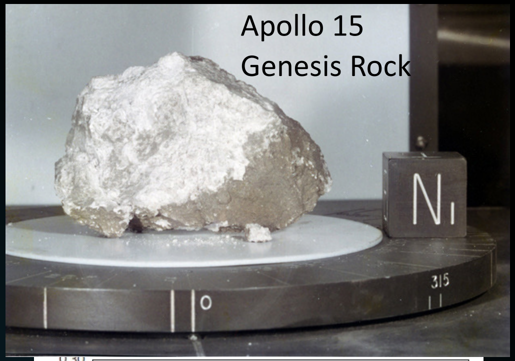
Pieters et al. 2009

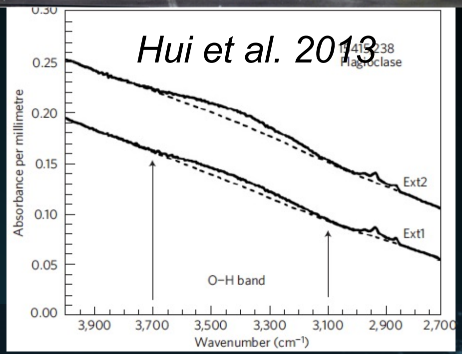


Colaprete et al. 2010

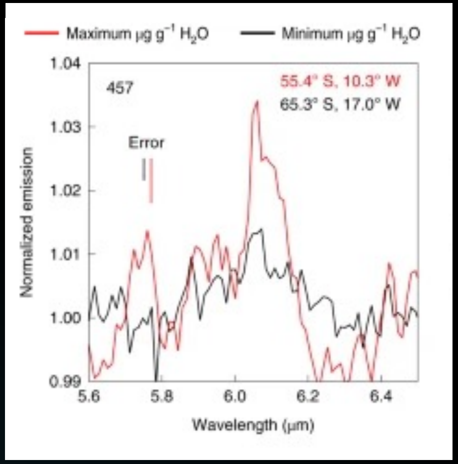


Li and Milliken 2017

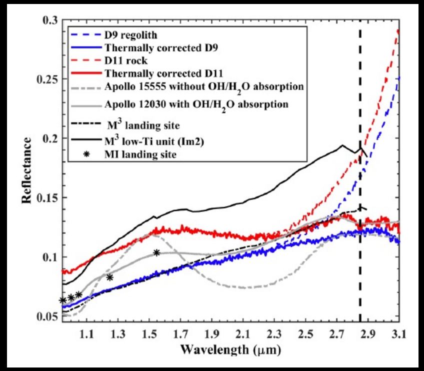




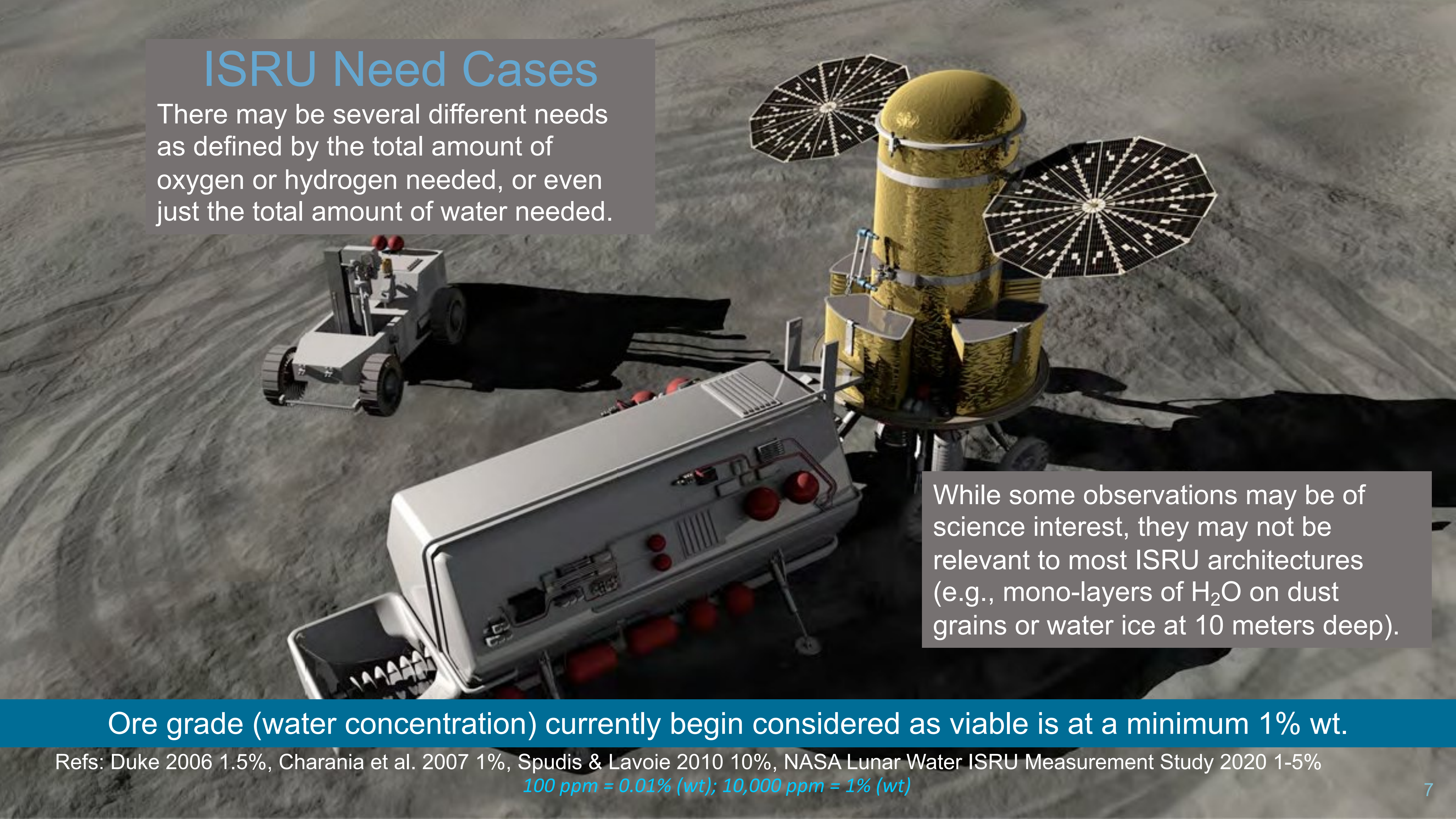
Hui et al. 2013



Honniball et al. 2020



Lin et al. 2022



ISRU Need Cases

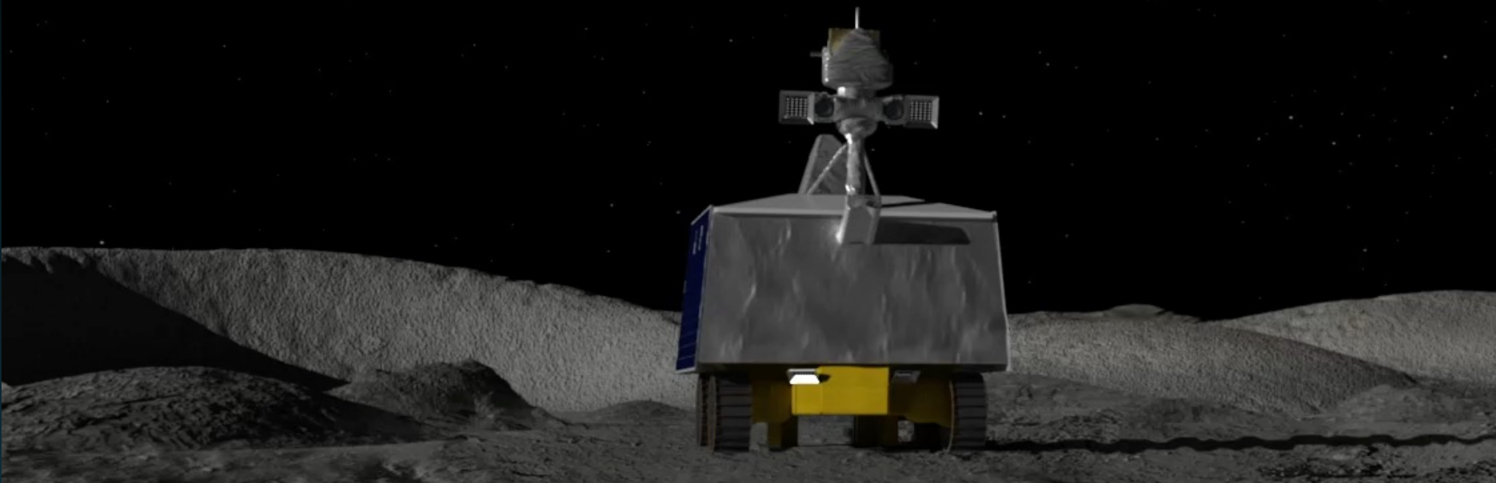
There may be several different needs as defined by the total amount of oxygen or hydrogen needed, or even just the total amount of water needed.

While some observations may be of science interest, they may not be relevant to most ISRU architectures (e.g., mono-layers of H_2O on dust grains or water ice at 10 meters deep).

Ore grade (water concentration) currently begin considered as viable is at a minimum 1% wt.

Refs: Duke 2006 1.5%, Charania et al. 2007 1%, Spudis & Lavoie 2010 10%, NASA Lunar Water ISRU Measurement Study 2020 1-5%

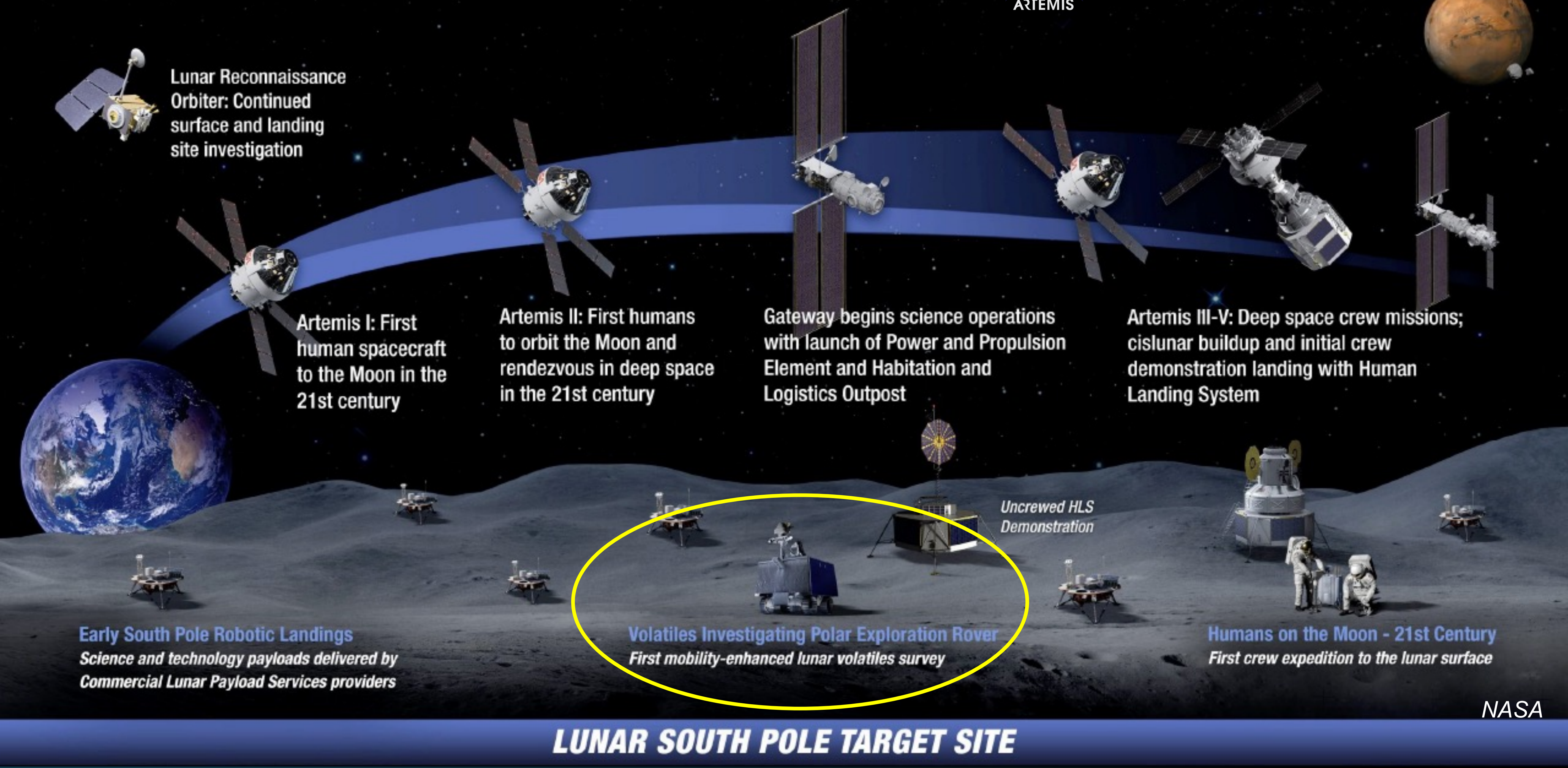
100 ppm = 0.01% (wt); 10,000 ppm = 1% (wt)



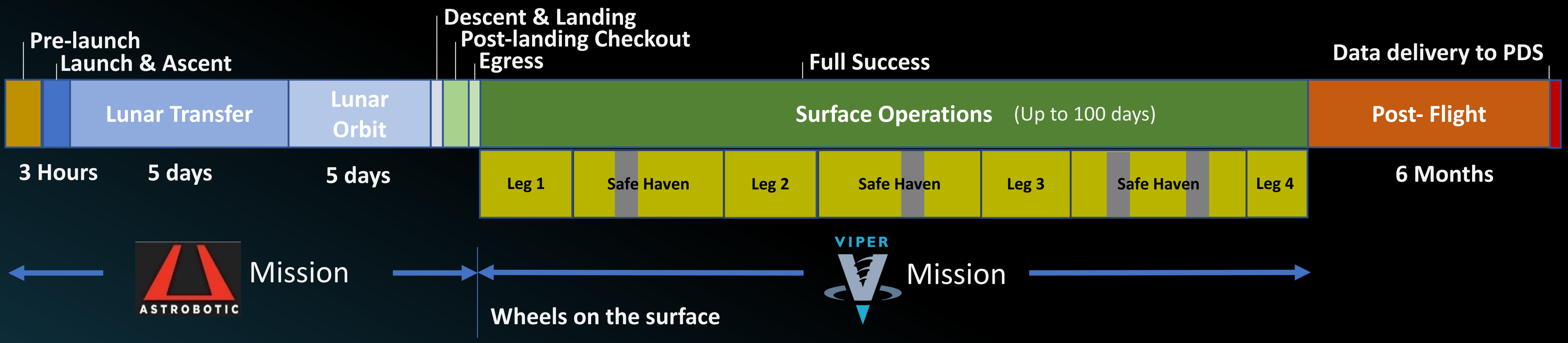
- Characterize the distribution and physical state of lunar polar water and other volatiles in lunar cold traps and regolith.
- Provide the data necessary for NASA to evaluate the potential return of In-Situ Resource Utilization (ISRU) from the lunar polar regions.

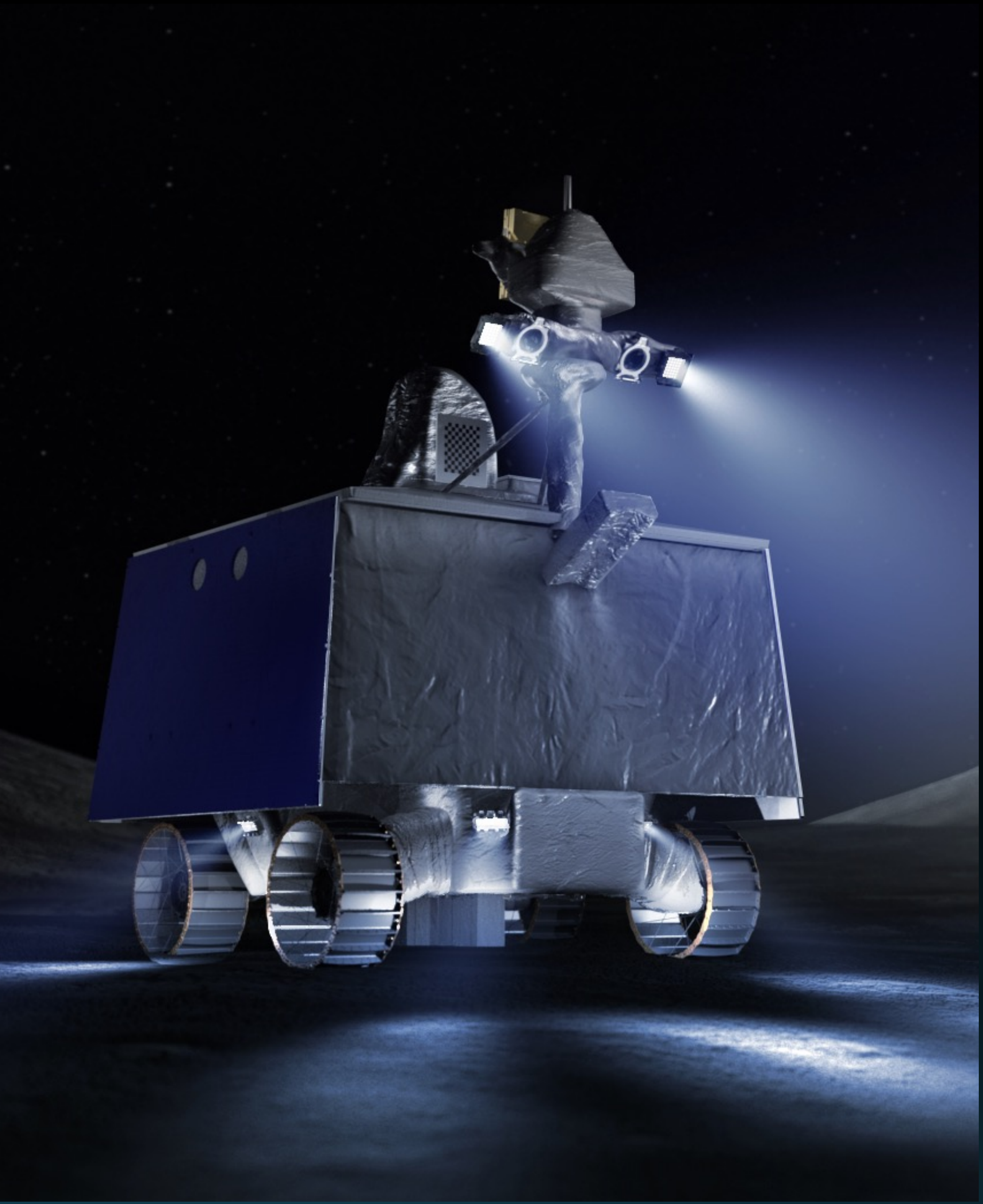
The next great leap in understanding lunar water is mapping these volatiles at the human scale.

Artemis: Landing Humans On the Moon



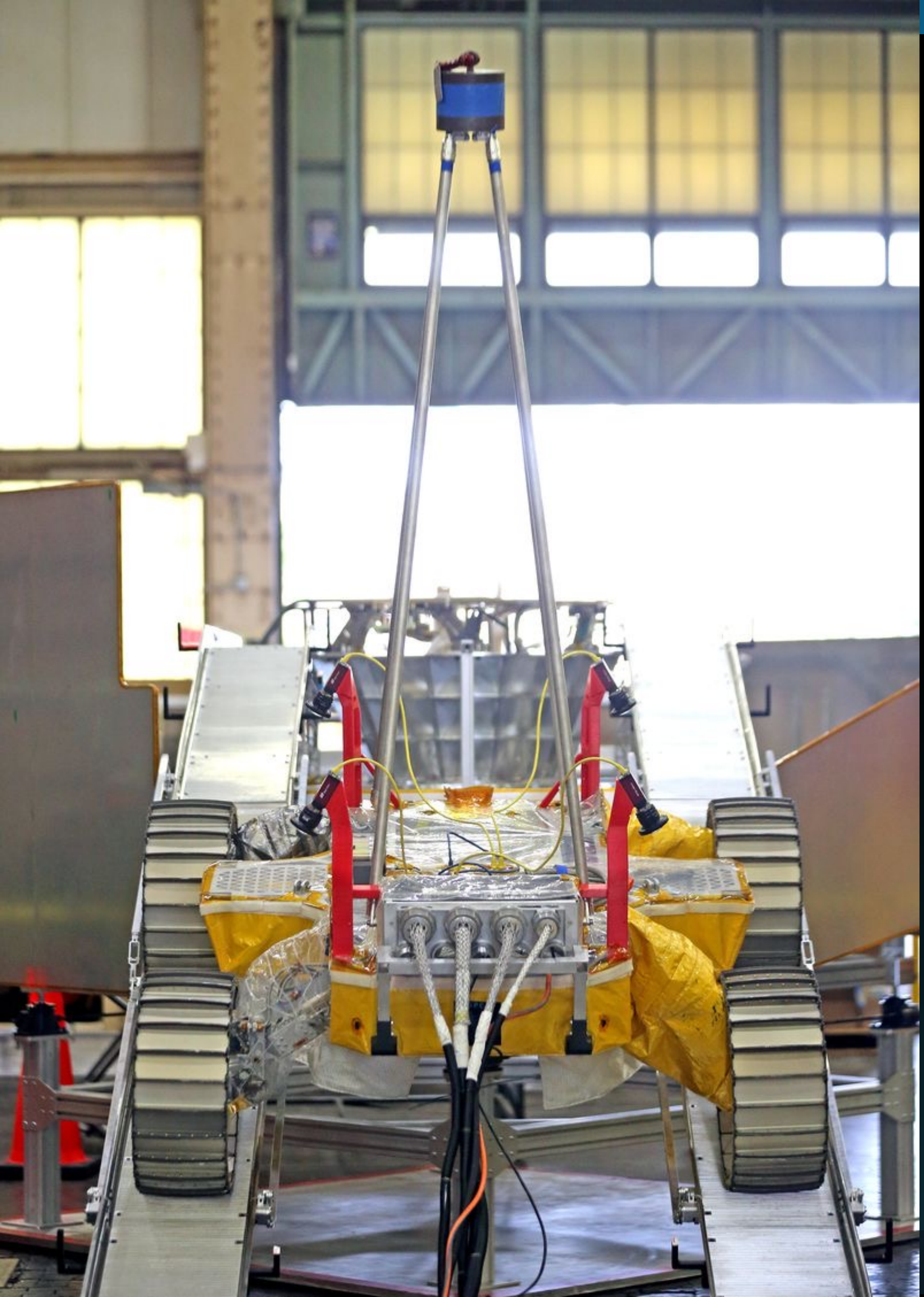
VIPER Mission Phases





VIPER Rover

- **Rolling Mass:** ~430kg
- **Power:** ~450W (corner-facing) or 320W per array
- **Communications:** X-band
  - Downlink: 256kbps ; Uplink: 2kbps
  - 6-15 s round-trip latency
- **Dimensions:** 1.7m x 1.7m x 2.5m
- **Wheel Diameter:** 0.5m
- **Steering:** Explicit steer; adjustable suspension
- **Top Speed:** 20cm/s (0.5MPH)
- **Prospecting Speed:** 10cm/s (0.25MPH)
- **Waypoint Driving:** 4.5m command distance
- **Camera Look-ahead:** stereo to 8m
- **Obstacles / Slopes:** 20cm / 15deg
- **Expected Cold Environment:** ~40K



Egress Testing – June 2, 2022

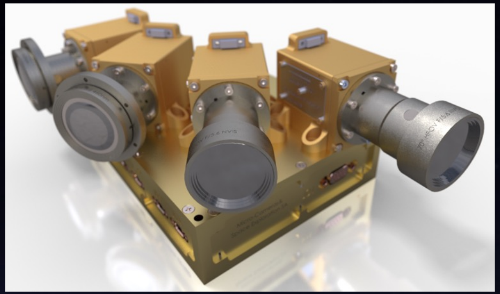
At NASA Glenn Research Center

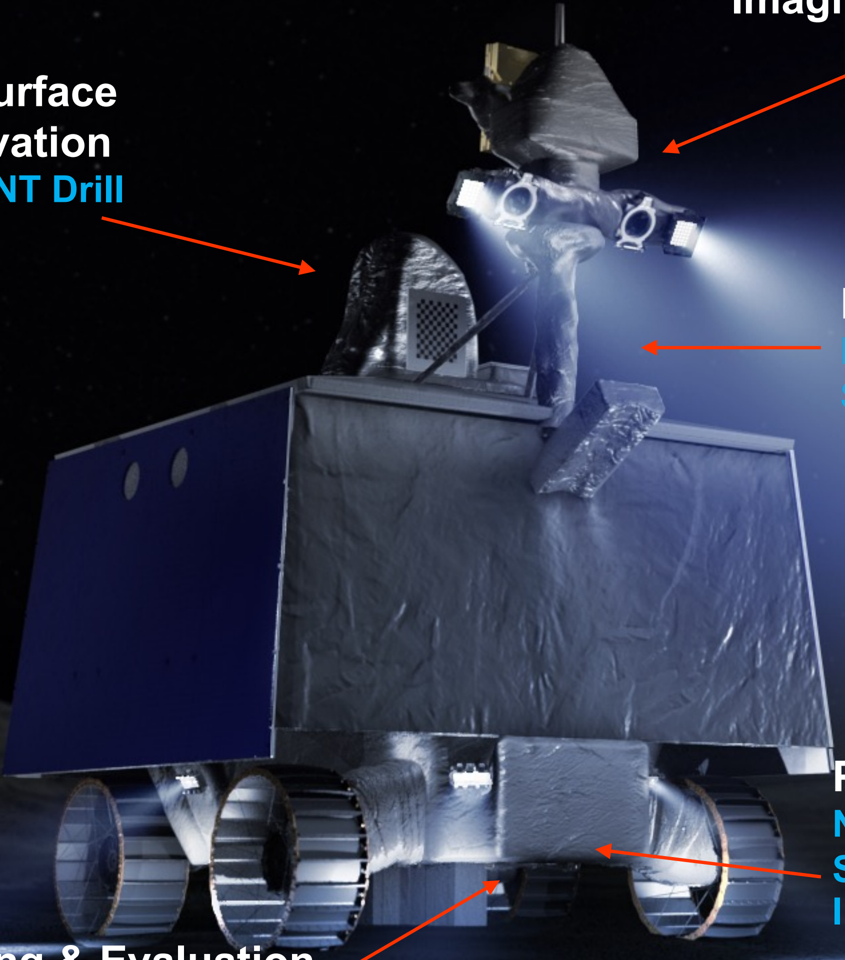
Joshua Gunter, cleveland.com

Science Instruments

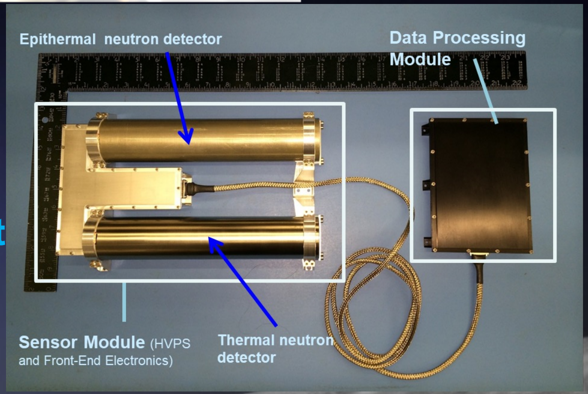
Subsurface excavation
TRIDENT Drill

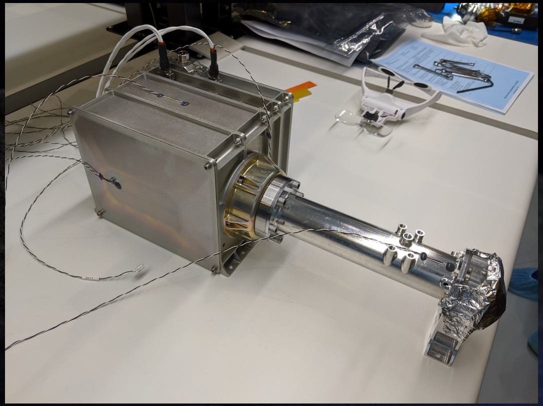
Imaging Science
VIS





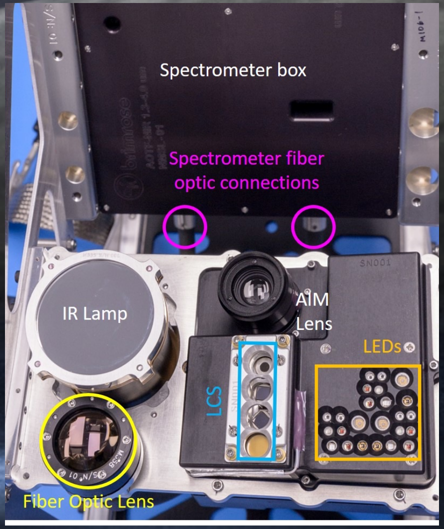
Prospecting
Neutron Spectrometer System (NSS) Instrument





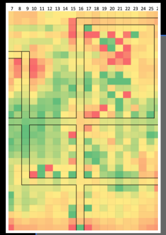
Prospecting & Evaluation
Mass Spectrometer Observing Lunar Operations (MSolo) Instrument

Prospecting & Evaluation
Near Infrared Volatiles Spectrometer System (NIRVSS) Instrument

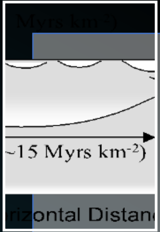


VIPER Key Science Measurements

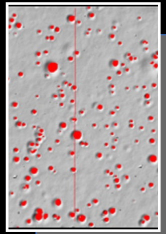
Sensitivity



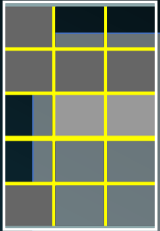
Coverage Density



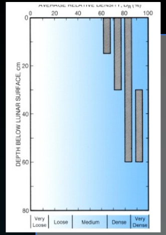
Length Scales



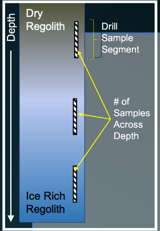
Area Coverage



Variability



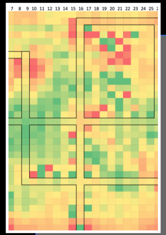
Vertical Coverage



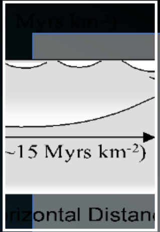
Vertical Sampling

VIPER Key Science Measurements

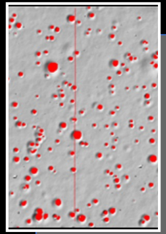
concentrations as low as 0.5% wt



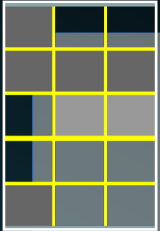
sample >10-15% per target area



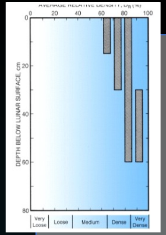
across scales from 10s to 100s of meters



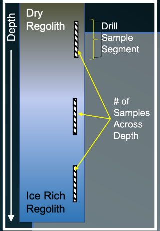
>3800 m^2 per ISR type



measure at scales of <5 meters and as large as 1000m, ISRs separated by 100 m



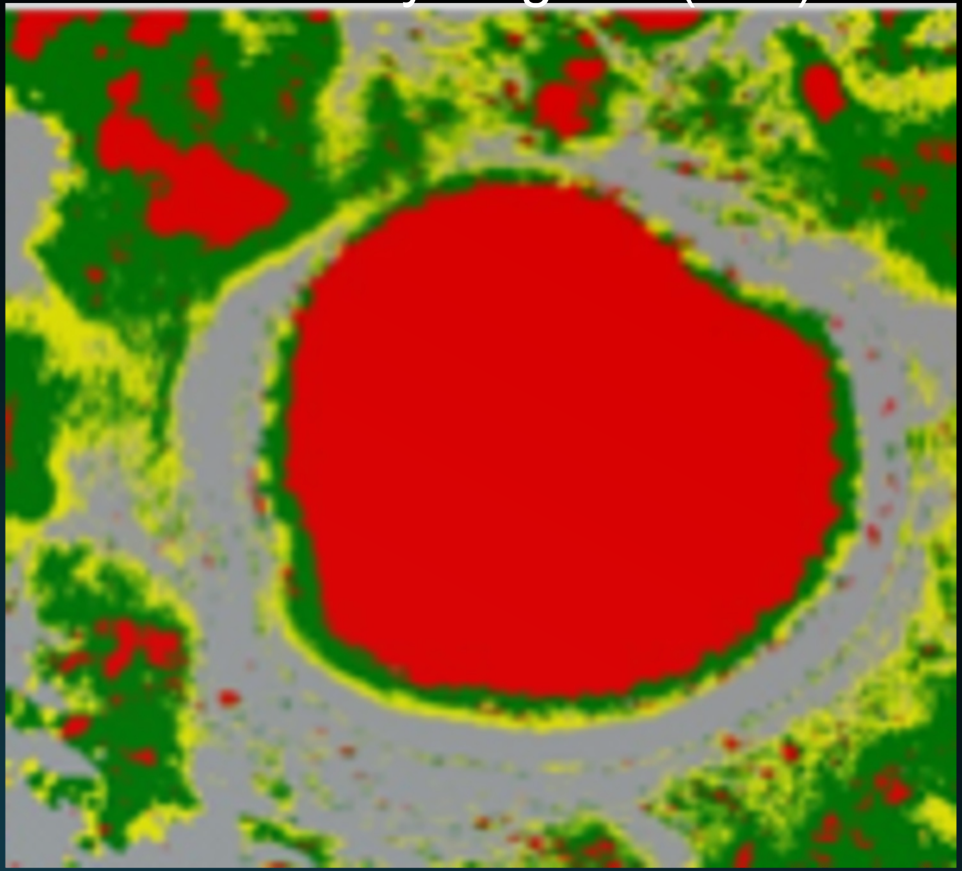
1 m drill depth



8-10 cm bite size, >5 samples along 0-80 cm depth

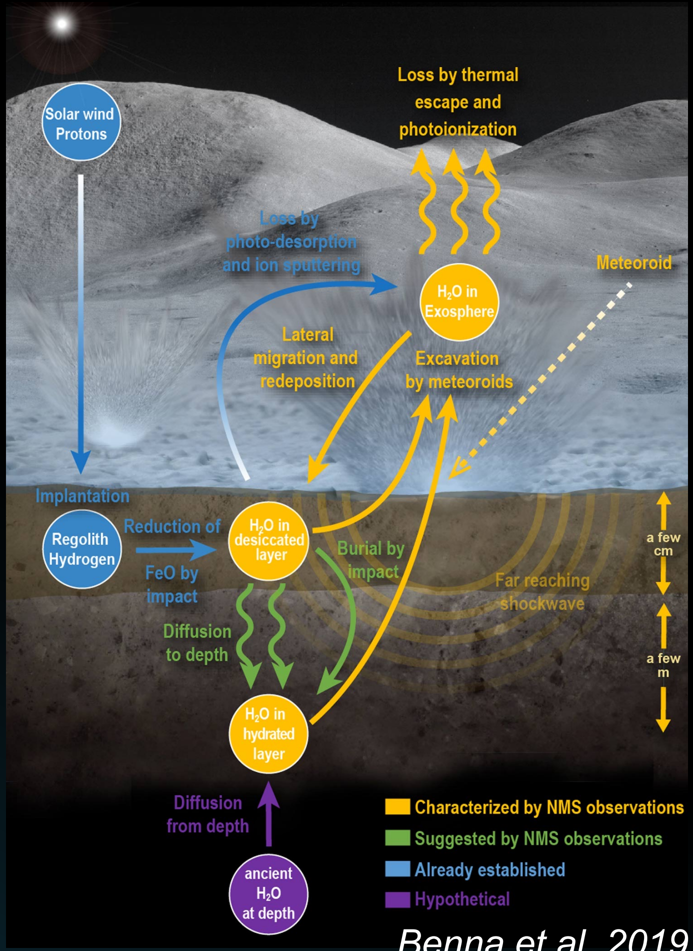
Mapping Approach: Thermal Proxy Model Concept

Ice Stability Regions (ISR)



after Siegler & Paige 2017, Siegler et al. 2018

■ Surface ■ Shallow ■ Deep ■ Dry



Benna et al. 2019

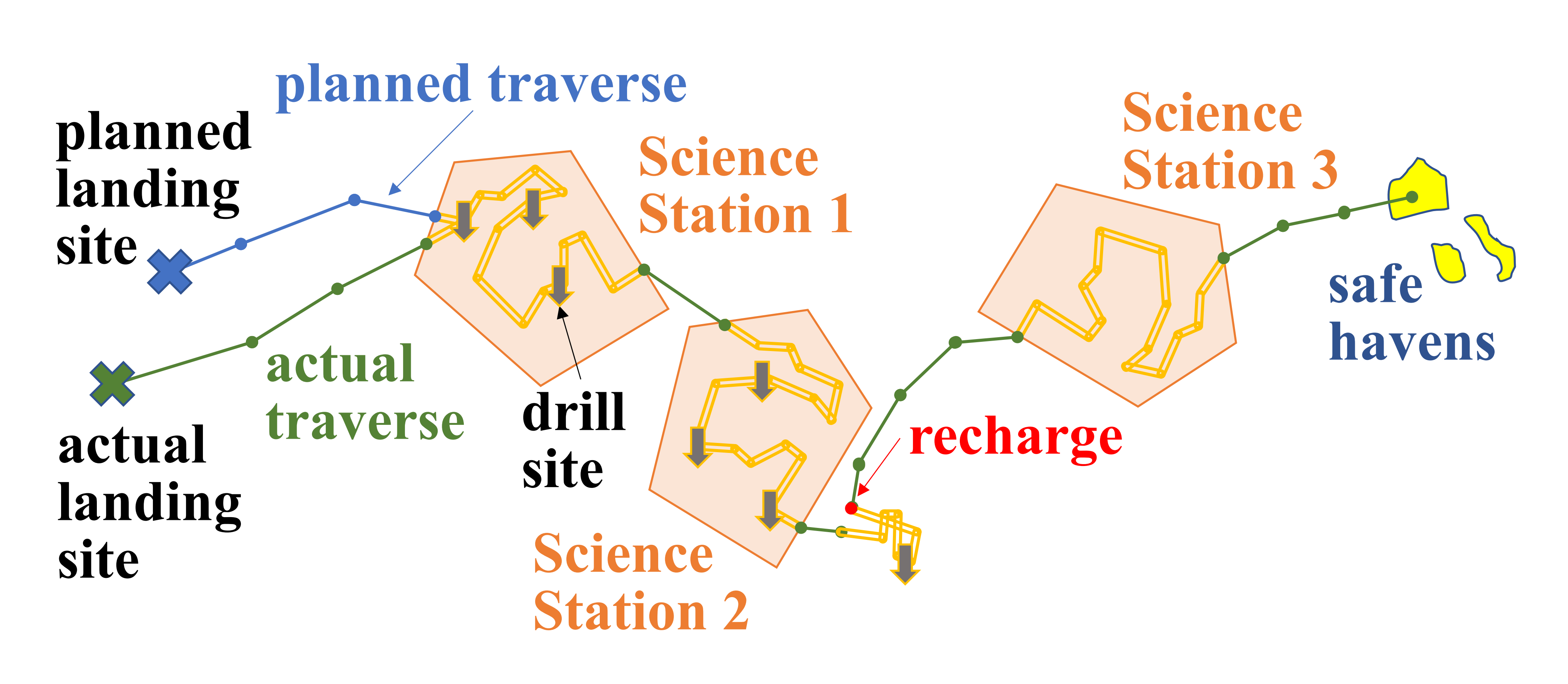
Surface - Ice expected stable at surface

Shallow - Ice expected stable 0-50 cm of surface

Deep - Ice expected stable 50-100 cm of surface

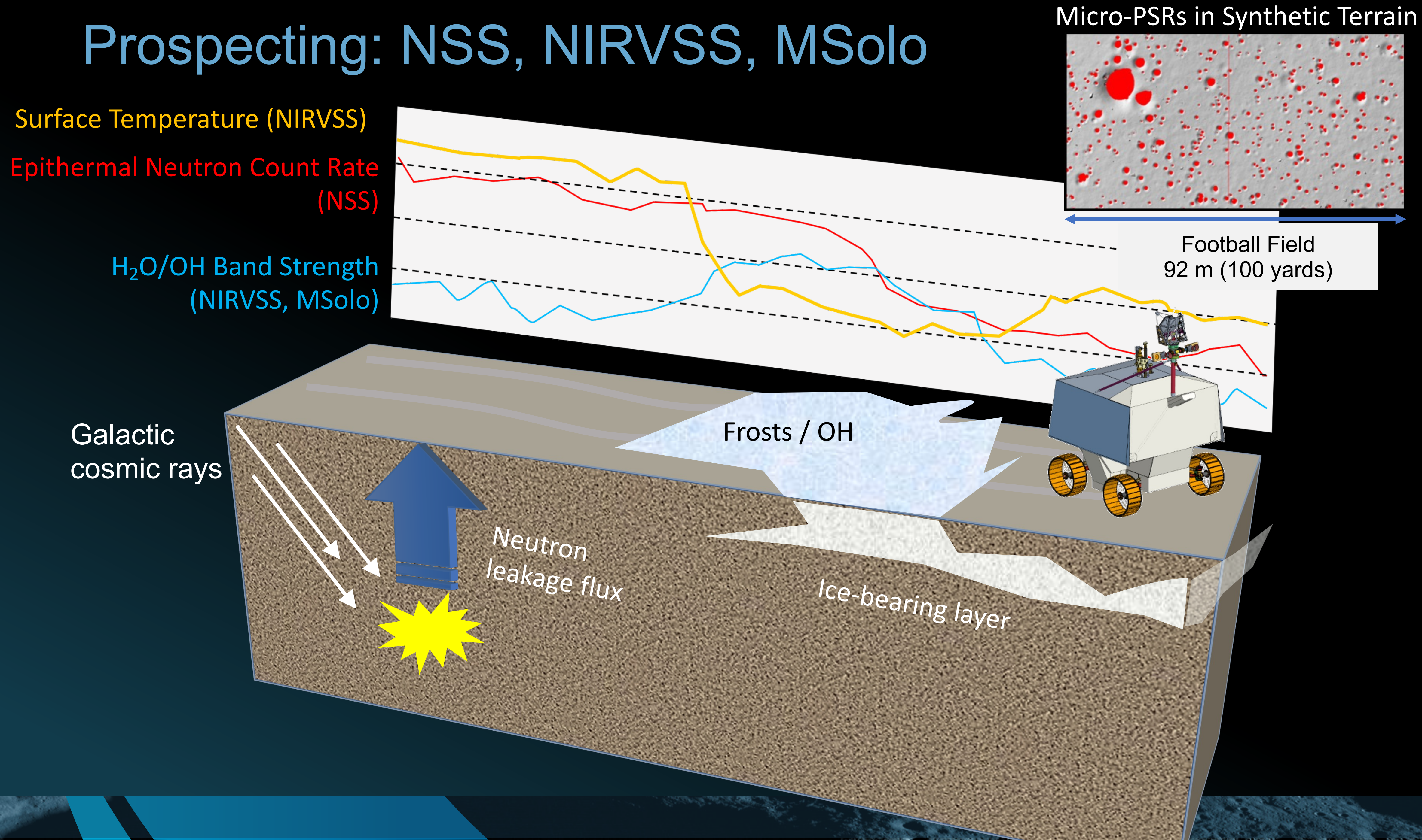
Dry – Ice not expected to be stable in 0-100 cm (“too warm”) or ice could be much deeper than 100 cm (VIPER’s drill limit)

Mapping via Science Station Activities

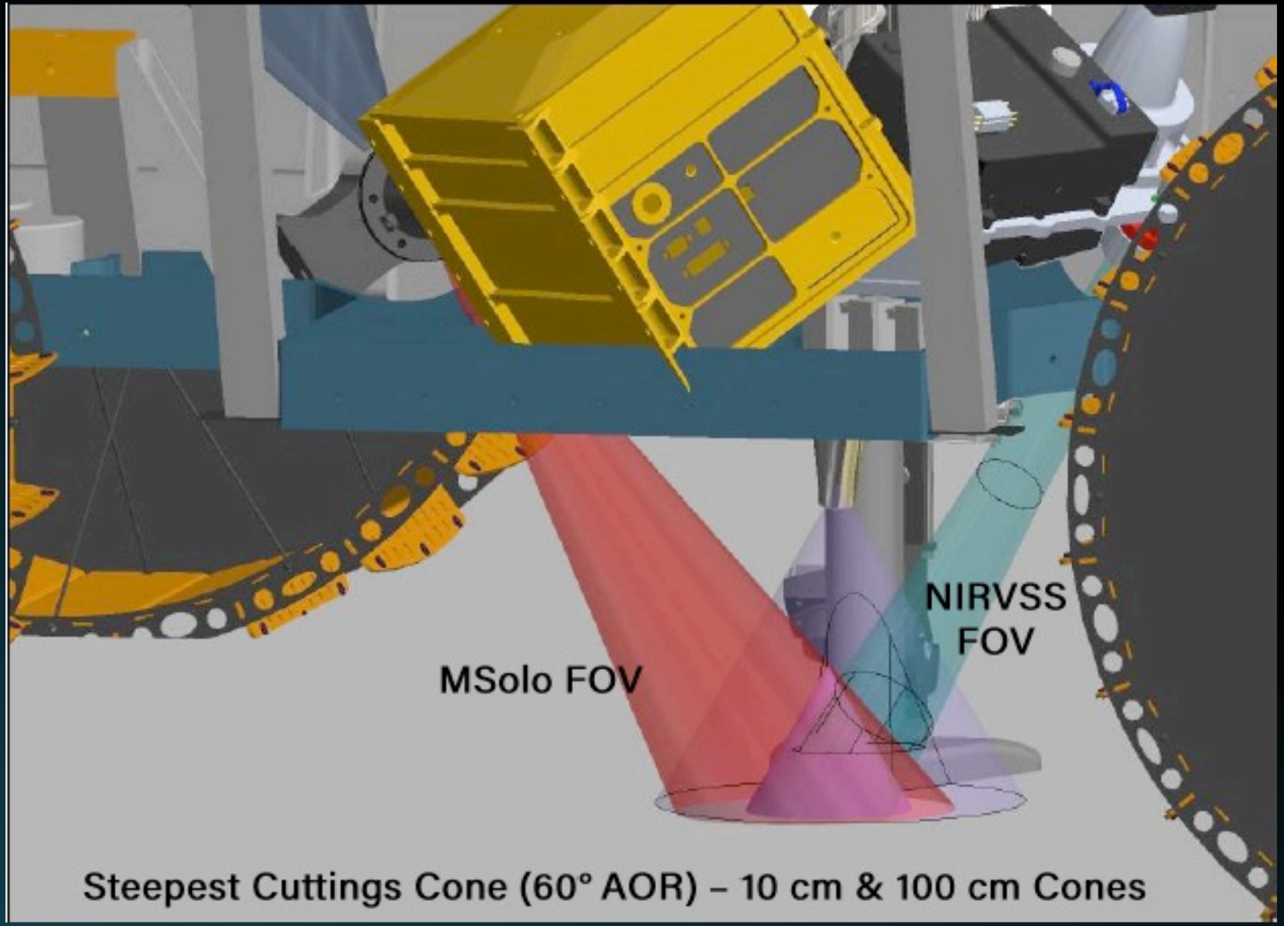


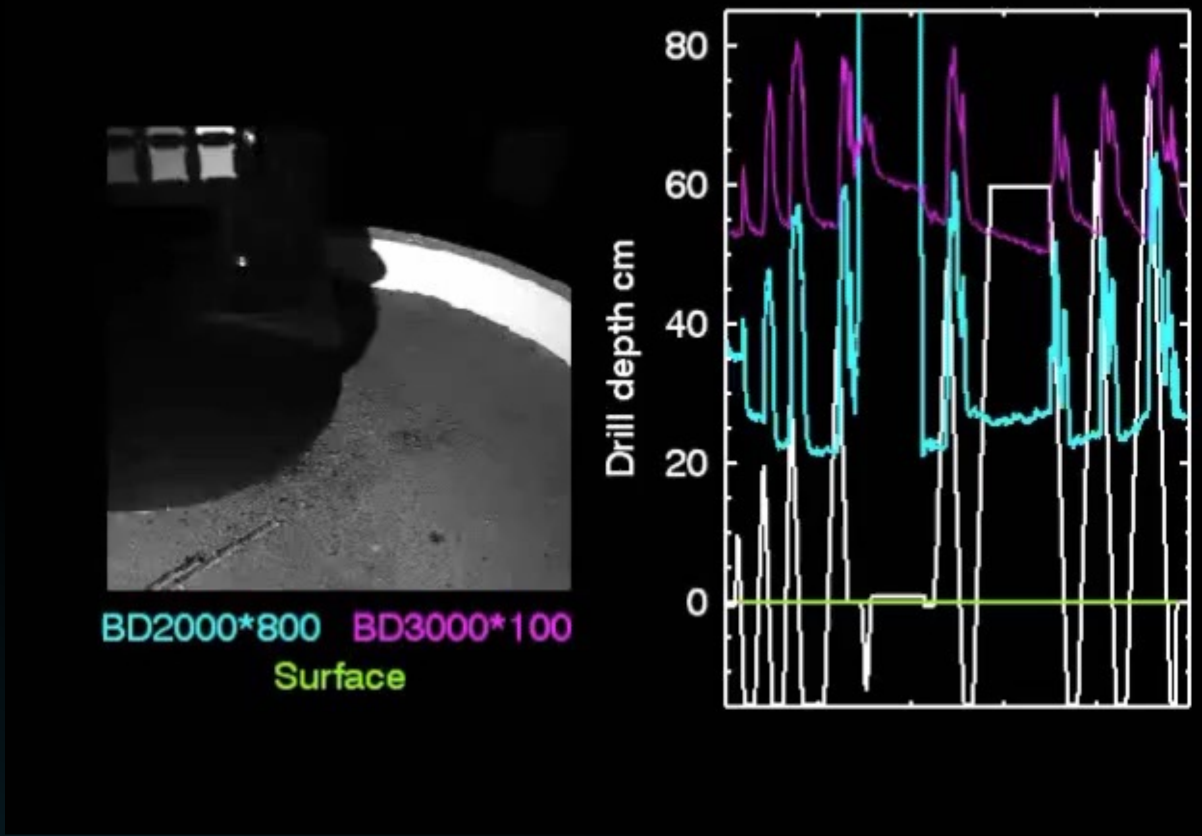
- Requires sufficient areal coverage (10-15% of a 3800 m^2 area of dominant ISR type)
- Drill three times, with at least one subsurface temperature measurement
- Separate measurements on scales from 5-1000 m. Minimum: Visit all 4 ISR types, repeat 2.

Prospecting: NSS, NIRVSS, MSolo



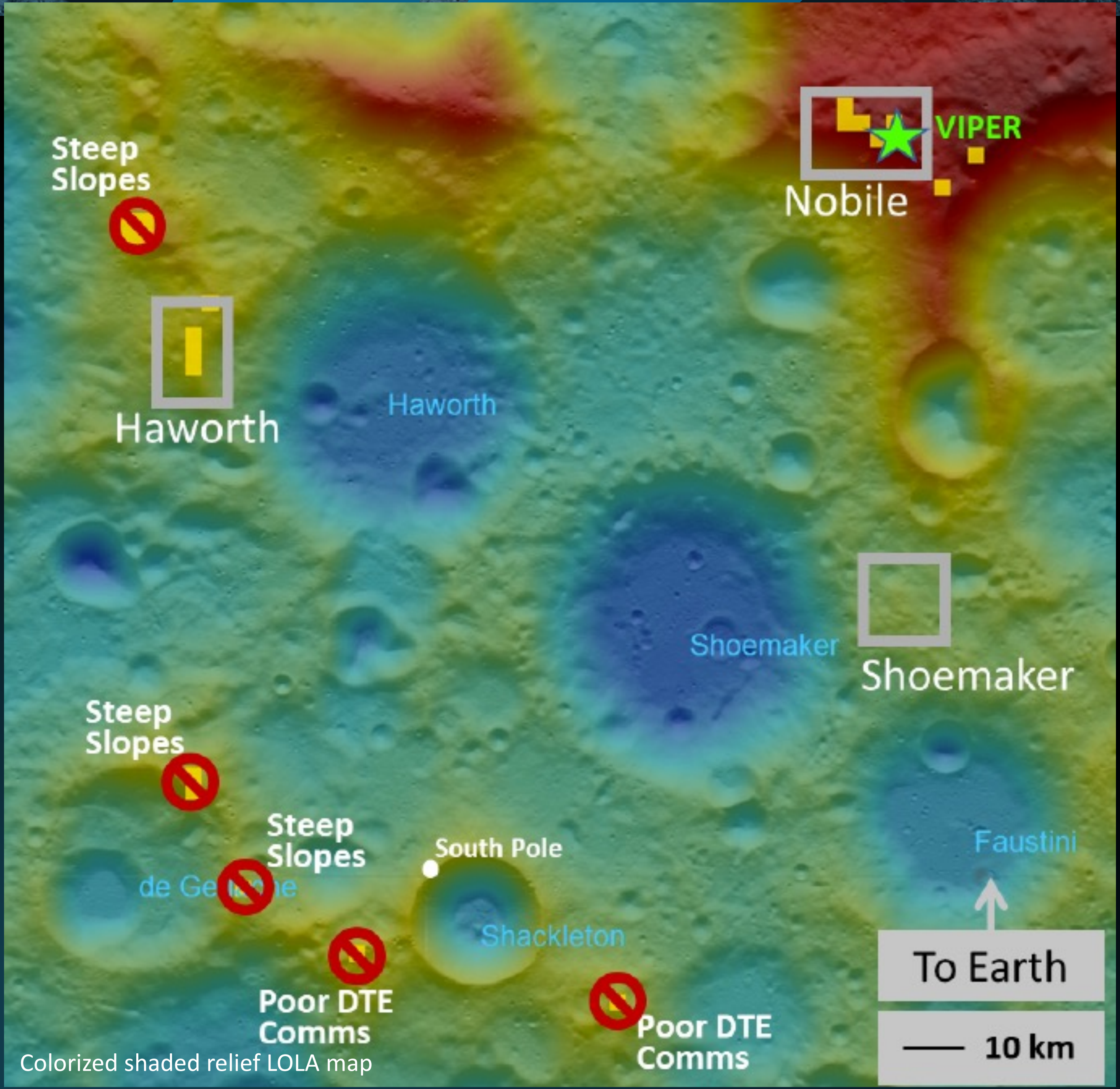
Subsurface Sampling: TRIDENT, NIRVSS, MSolo





Vacuum testing at Glenn – TRIDENT+NIRVSS
(not shown: data from TRIDENT+MSolo)

Landing Site Selection



Beyer et al. 2022

Nobile, Haworth and Shoemaker sites (grey boxes)

Safe haven (yellow squares)

- Location to park rover while Earth is below horizon
- <50 hours of continuous darkness

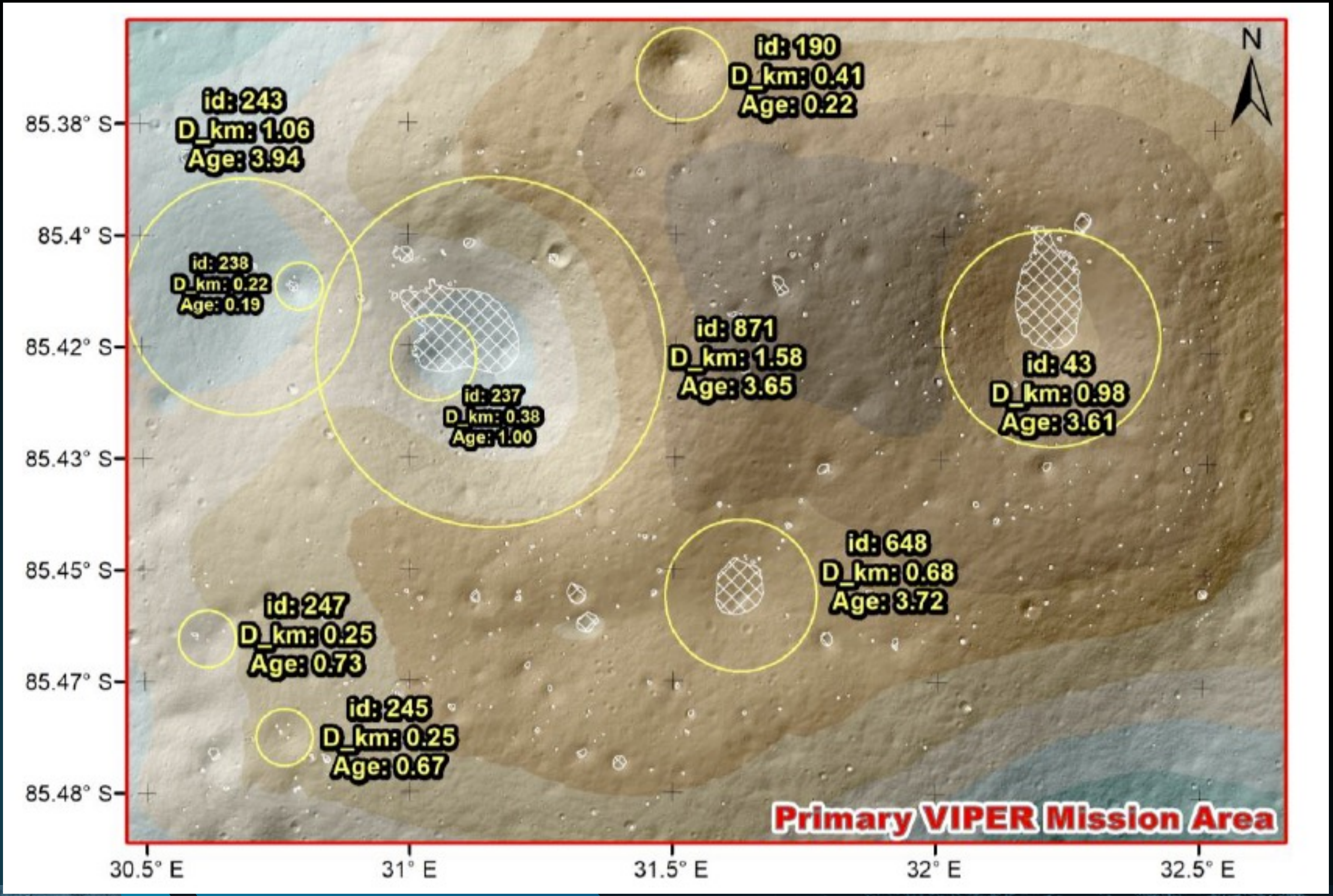
Finding working traverses requires finding safe havens close to permanent shadow

While all of these work for lighting, some did not work due to

- Steep slopes
- Distance to PSRs
- Poor direct-to-earth comms

- Nobile chosen – offered longest mission (> 2 months)

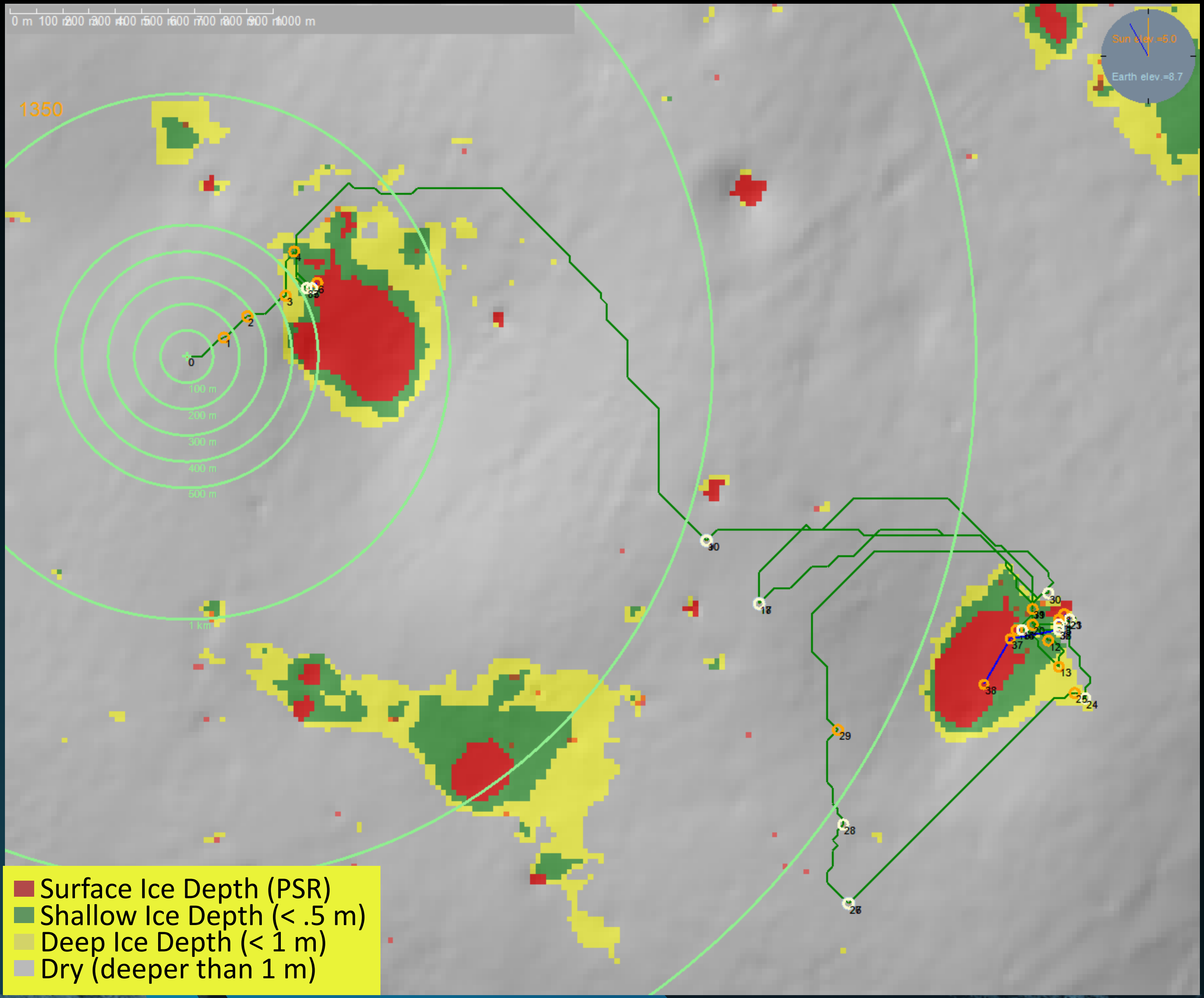
VIPER Mission Area



- 5 km x 5 km centered at 31.6218 E, 85.42088 S
- Hosts craters ranging from 100 Mya to >3 Gya
- Role that the age of PSRs plays in controlling the presence or absence of polar volatiles is of substantial interest for discerning volatile history

Fassett et al. 2022

Nobile Example Traverse*



Duration	91 days
Length	13.25 km
PSRs	2 (4 entries)
Shallow	6
Deep	3
Dry	2

1st lunar day: 1 dry, 1 deep, 1 shallow, 1 PSR

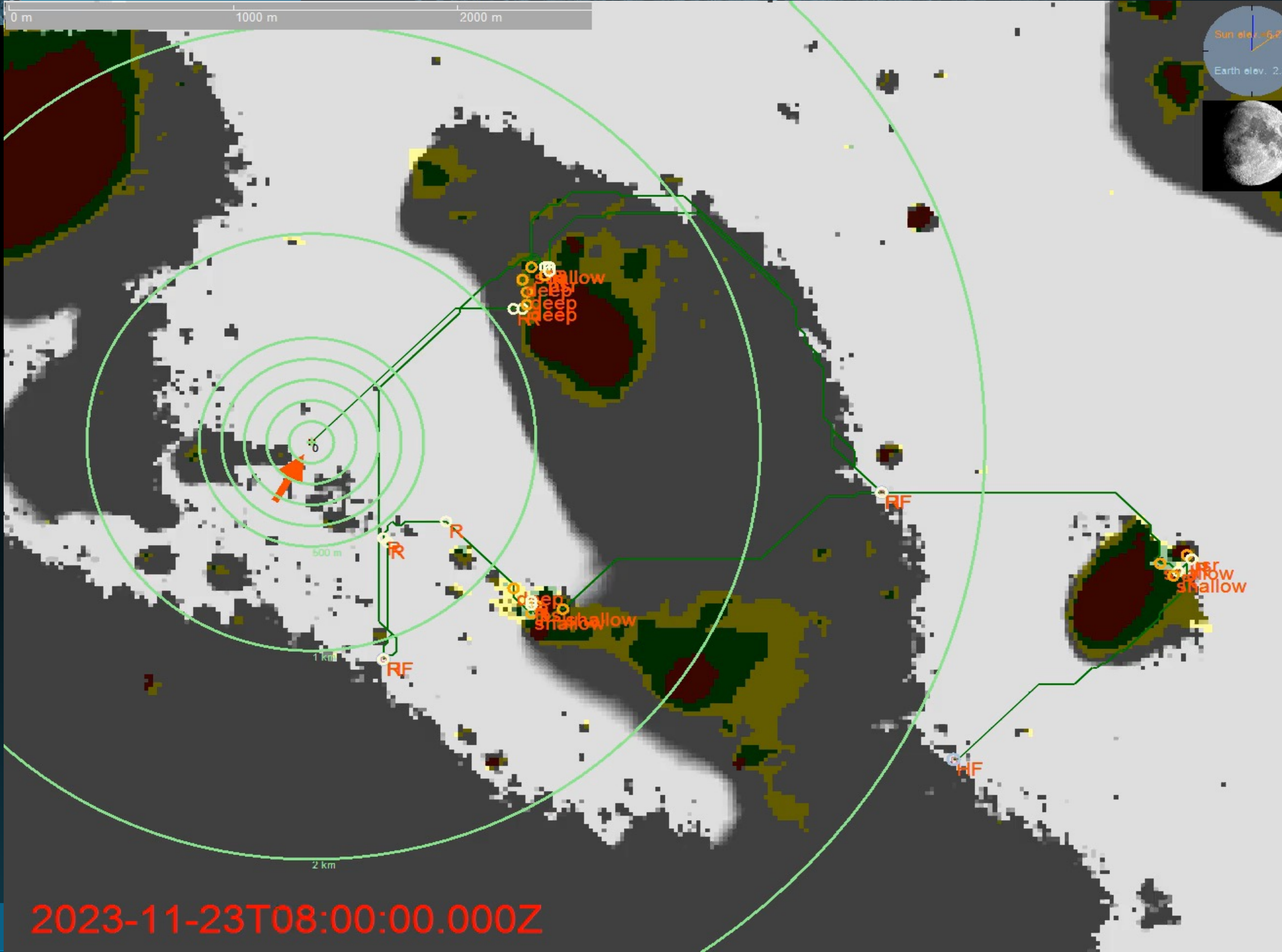
Full mission success on mission day 36, day 7 of second lunar day

Total number of drill sites = 35
Total mapped ISR area (m^2):
PSR = 765
Shallow = 2295
Deep = 1241
Dry = 765

*Not the final traverse. There are several iterations being investigated.

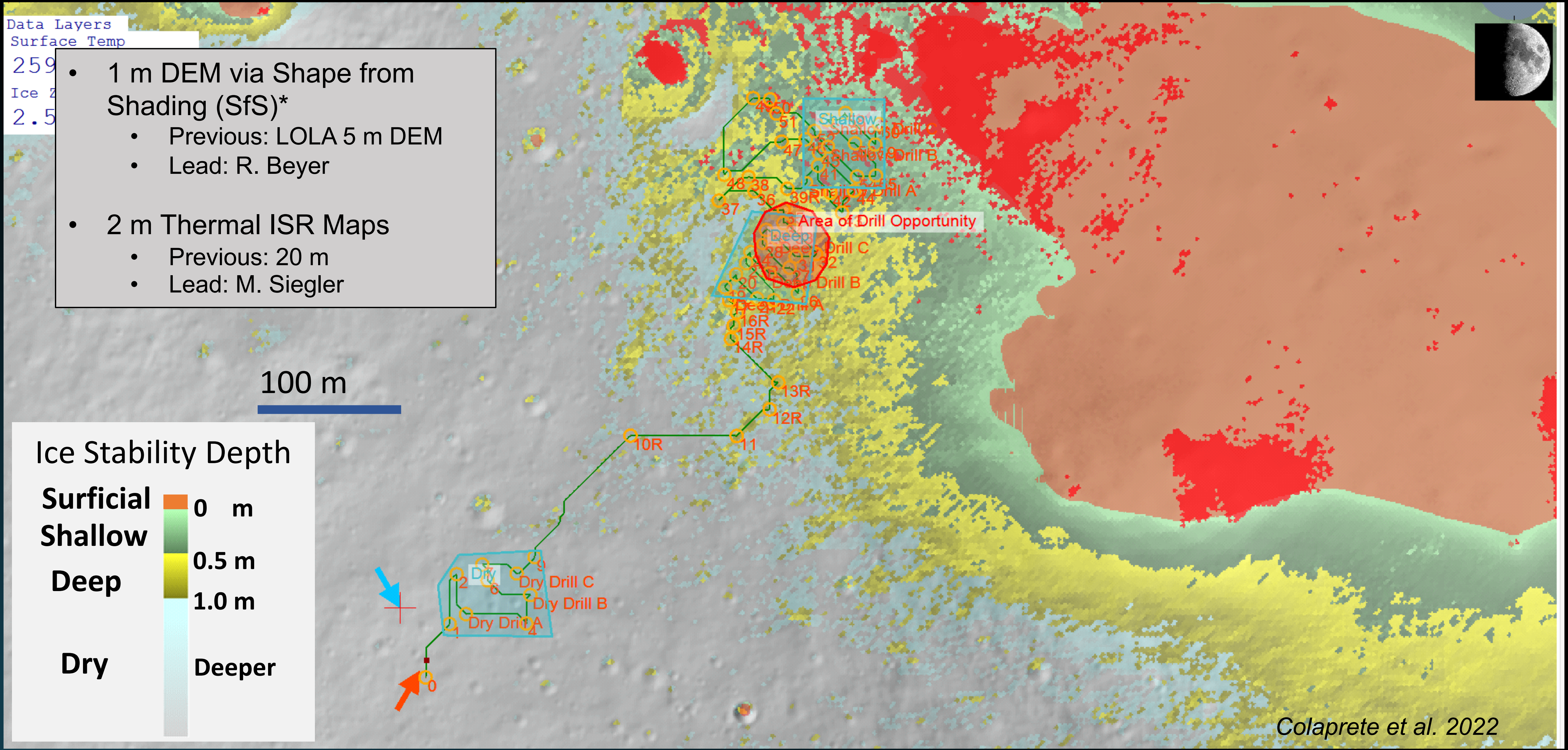
Lighting Constraints

- Avoid being in shadow > 50 hrs
- Always have Earth in line of sight when driving
- Visit all four ISR types



Surface Ice Depth (PSR)
Shallow Ice Depth (< .5 m)
Deep Ice Depth (< 1 m)
Dry (deeper than 1 m)

High resolution planning products



- 1 m DEM via Shape from Shading (SfS)*
  - Previous: LOLA 5 m DEM
  - Lead: R. Beyer
- 2 m Thermal ISR Maps
  - Previous: 20 m
  - Lead: M. Siegler

*Check out 1m DEM SfS for Haworth (PDS Annex): https://astrogeology.usgs.gov/search/map/Moon/Topography/photoclinometry/Lunar_LROnac_Haworth_sfs-dem_1m_v3

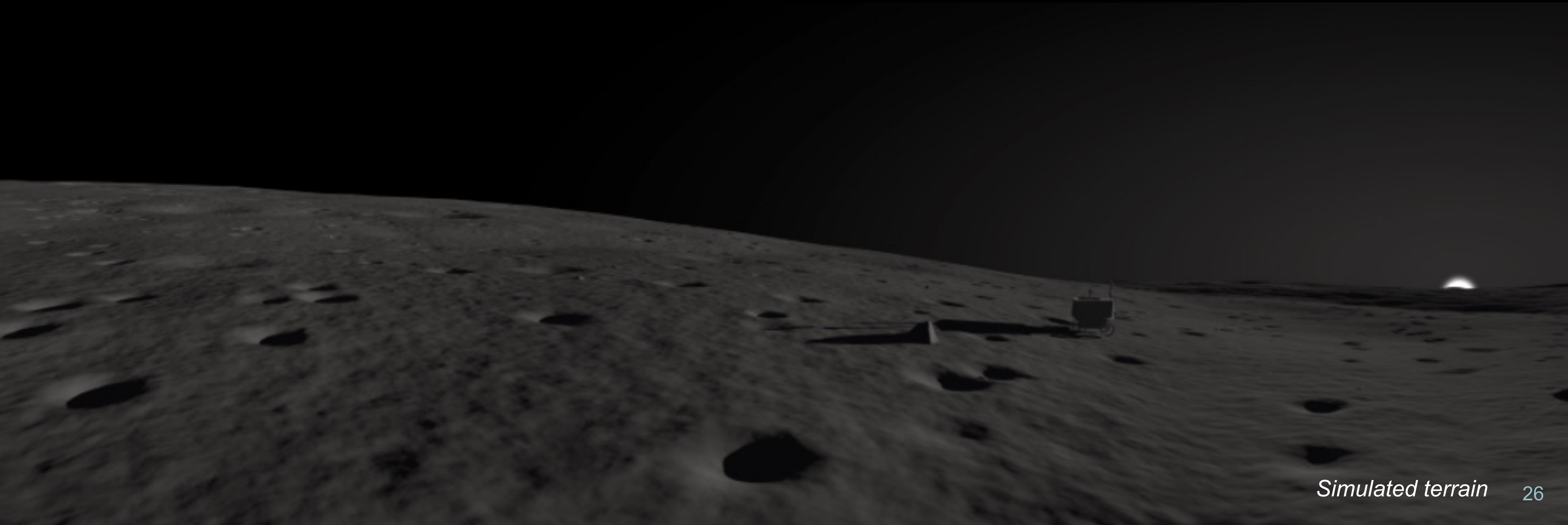
Moon Water

https://www.nasa.gov/viper

- The past decade of observations have built a fascinating and complicated story about lunar water.
- From "frosts" to buried ice blocks, there appears to be water everywhere, but its nature and distribution is very uncertain.
- The next steps in exploration require surface assets, including surface mobility.
- VIPER is that mission to conduct exploration science, modeled after terrestrial resource exploration processes and techniques.
- Knowing where the water is half the story. If we have an understanding of "how it got there" and "why it is *still* there" we can much better predict where the highest concentrations might be.

Simulated terrain

https://www.nasa.gov/viper

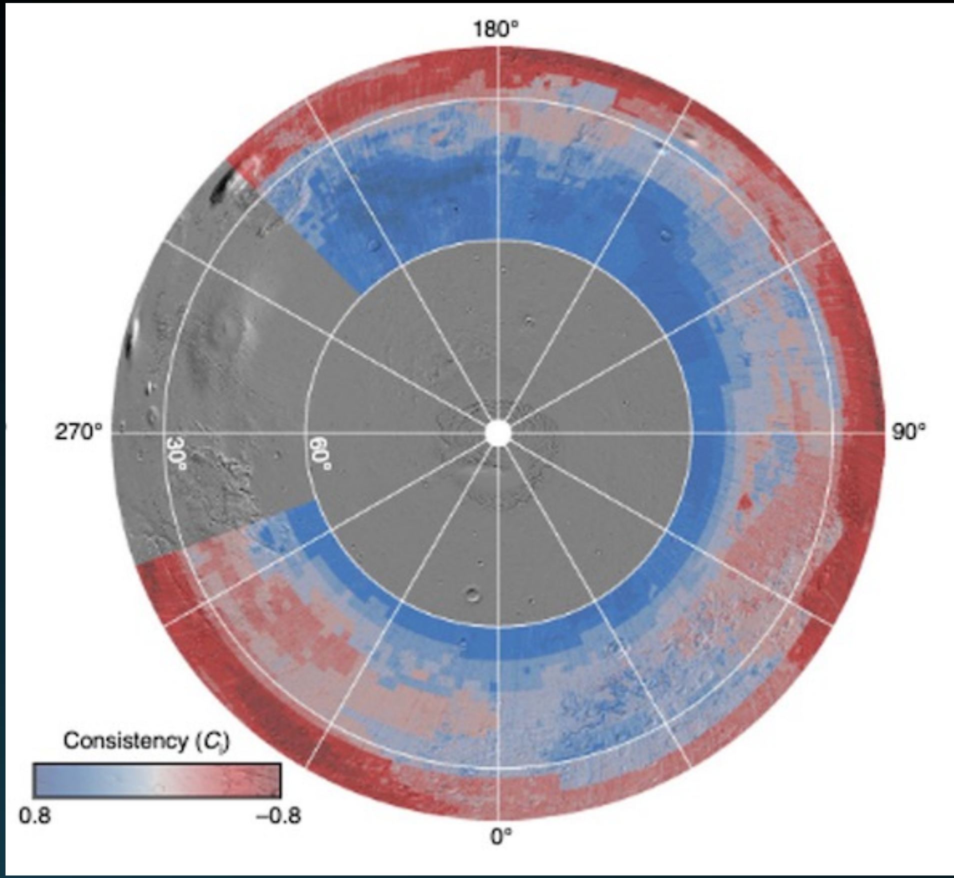


Simulated terrain

Backup

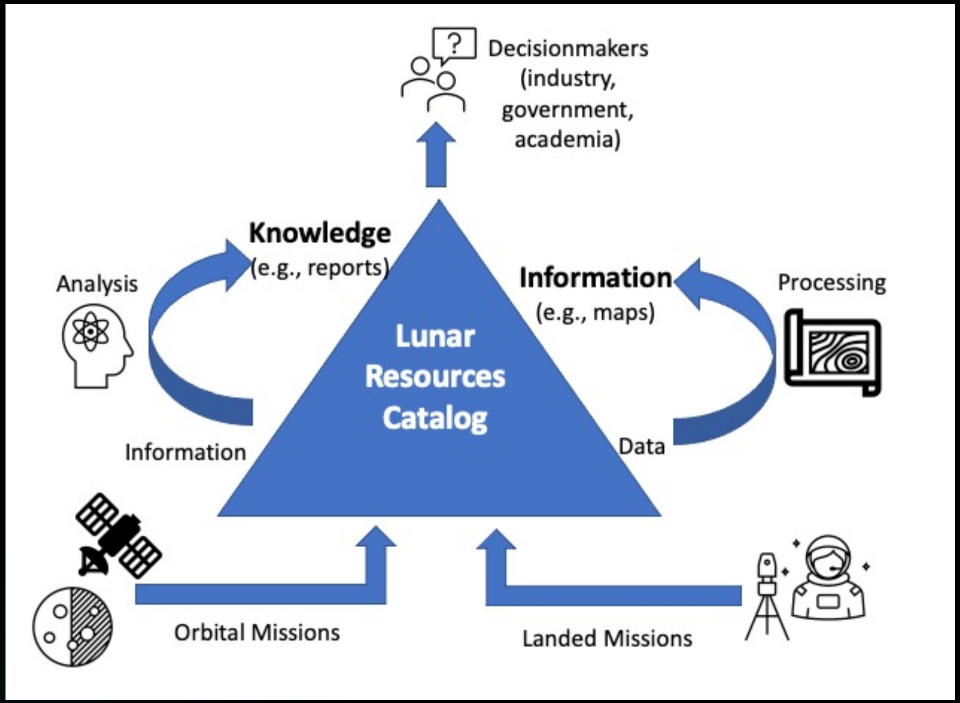
Towards a Catalog Focused on Lunar Resources

Work has begun on establishing an ISRU measurement plan (i.e., what data is needed) and the identification of Lunar Critical Data Products. How to *integrate* these data into the broader Planetary Data Ecosystem? VIPER dataset is one part.



Subsurface Water Ice Mapping (SWIM)

Morgan, G.A. et al. 2021



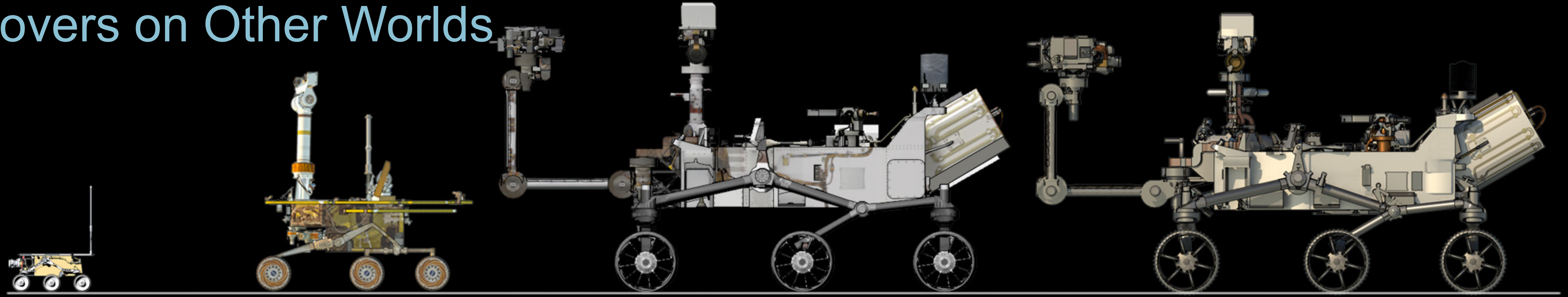
LRC is an information and knowledge management construct for the community.

Ennico-Smith, K., Keszthelyi, *L. et al. 2022*

VIPER Timeline

- 2019: Formulation through Reqs Lockdown
- 2020: Preliminary Design
- 2021: Critical Design
- 2022: System Integration & Test
- 2023: Launch (Nov 2023)
- 2024: Mission concludes (Mar 2024)

Rovers on Other Worlds



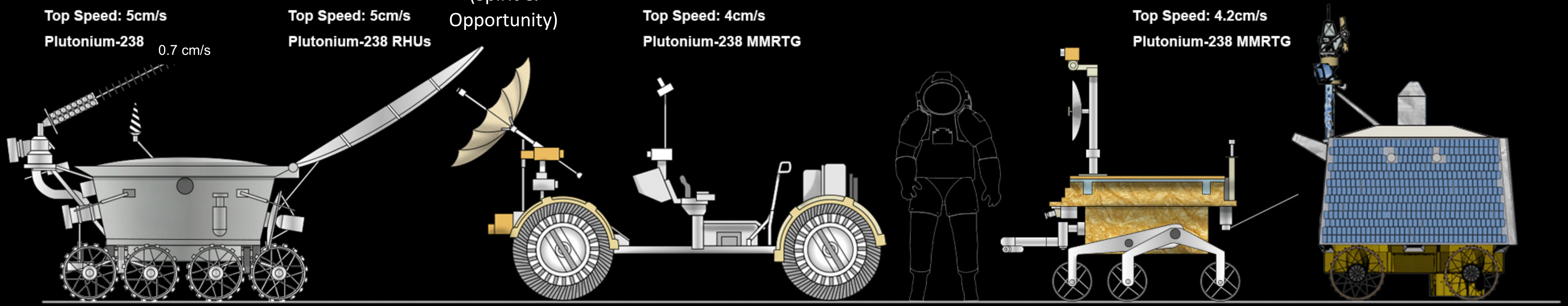
Sojourner
0.6m x 0.5m x 0.3m
11kg
Top Speed: 5cm/s
Plutonium-238

0.7 cm/s

Mars Exploration Rover (Spirit & Opportunity)
1.6m x 2.3m x 1.5m
180kg
Top Speed: 5cm/s
Plutonium-238 RHUs

Mars Science Laboratory (Curiosity)
3.0m x 2.8m x 2.1m
900kg
Top Speed: 4cm/s
Plutonium-238 MMRTG

Mars 2020 Rover (Perseverance)
3.0m x 2.7m x 2.2m
1025kg
Top Speed: 4.2cm/s
Plutonium-238 MMRTG



Lunokhod 1 & 2
2.3m x 1.6m x 1.5m
840kg
Top Speed: 55cm/s
Polonium-210 heat source

Lunar Roving Vehicle
3.1m x 1.6m x 1.5m
210kg
Top Speed: 500cm/s
2 silver-zinc 36 volt batteries

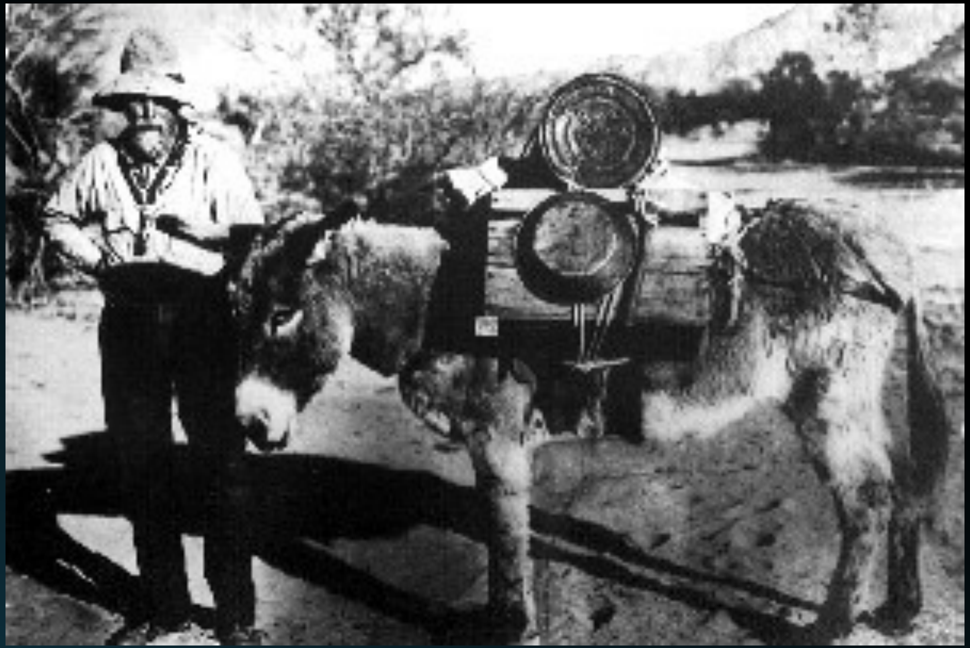
1 meter

Yutu 1 & 2
1.5m x 1.1m x 1.1m
140kg
Top Speed: 5cm/s
Plutonium-238 RHUs

VIPER (2023)
1.5m x 1.5m x 2.0m
430kg
Top Speed: 20cm/s
Electric heaters only

Resource Exploration: An Applied Science

Luck



Applied Science: Resource Map

Low Potential

- Low Certainty
- High Certainty

Medium Potential

- Low Certainty
- High Certainty

High Potential

- Low Certainty
- High Certainty

Unknown

An ultimate outcome of resource exploration is the development of a Mineral Model, or for the Moon, a Water Resource Model.

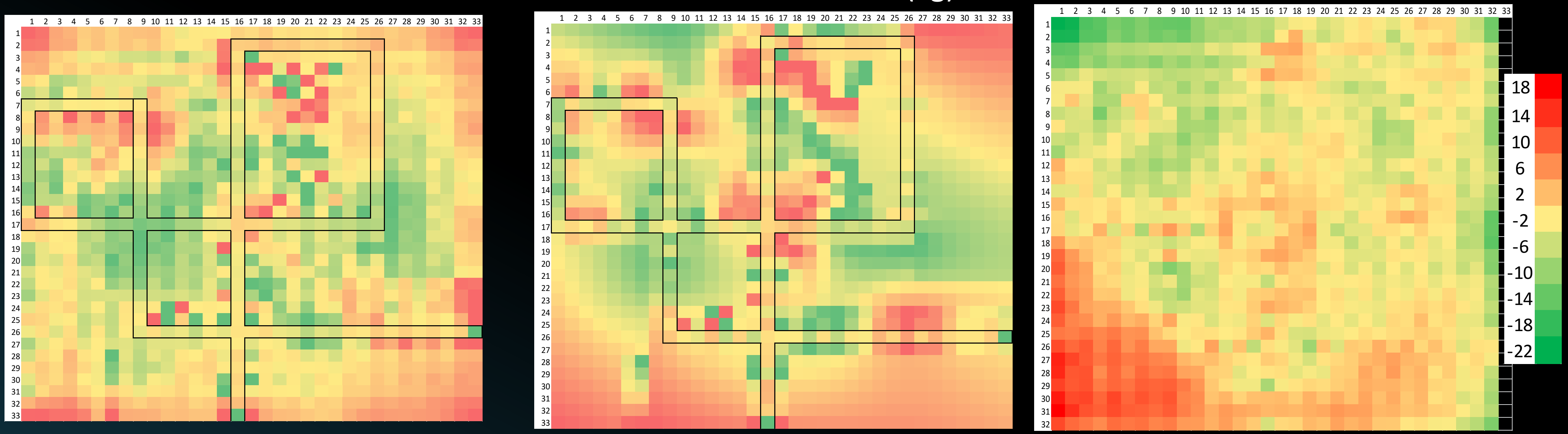
Map – Test Theories – Build Model

How Much Sampling is Needed?

Actual Water Mass (kg)

Predicted Water Mass (kg)

Difference

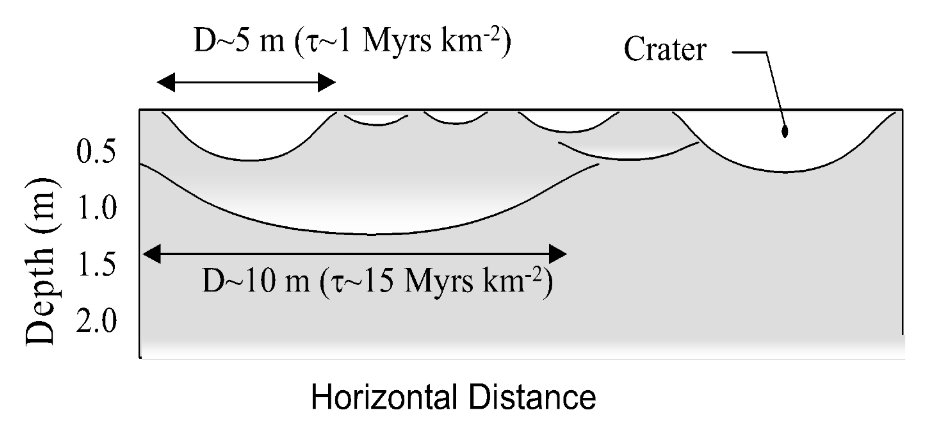


Simulations with random water concentrations and distributions (lateral and vertical) and “predicted” neutron observations (with uncertainties) along an arbitrary traverse. **You cannot sample everywhere.** Error is a strong function of the number of unique sites sampled (the traverse path). Can use a continuously monitoring spectrometer to meet sampling requirements.

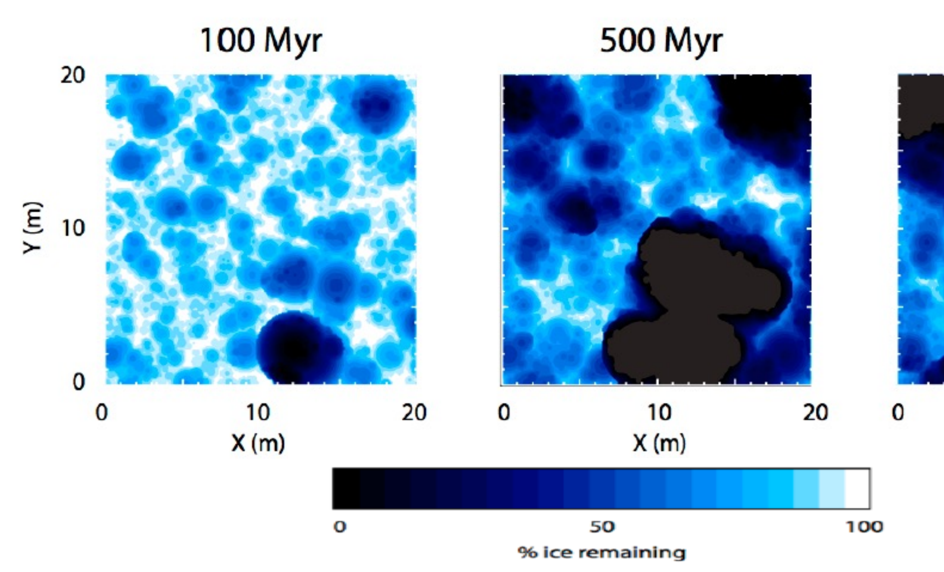
Characterize total water in area with uncertainty of <50% must sample with density of >10-15%

Factors that Control Distribution: Crater Mixing

- Dominant process affecting top meter of regolith is small impact cratering
- Distance between 10 m wide craters (~1 m deep) is ~50 -150 m
- Prediction: top meter is likely to be "patchy" at scales of 10's-100's of meters



Craters mix the top meters of regolith via excavation and burial

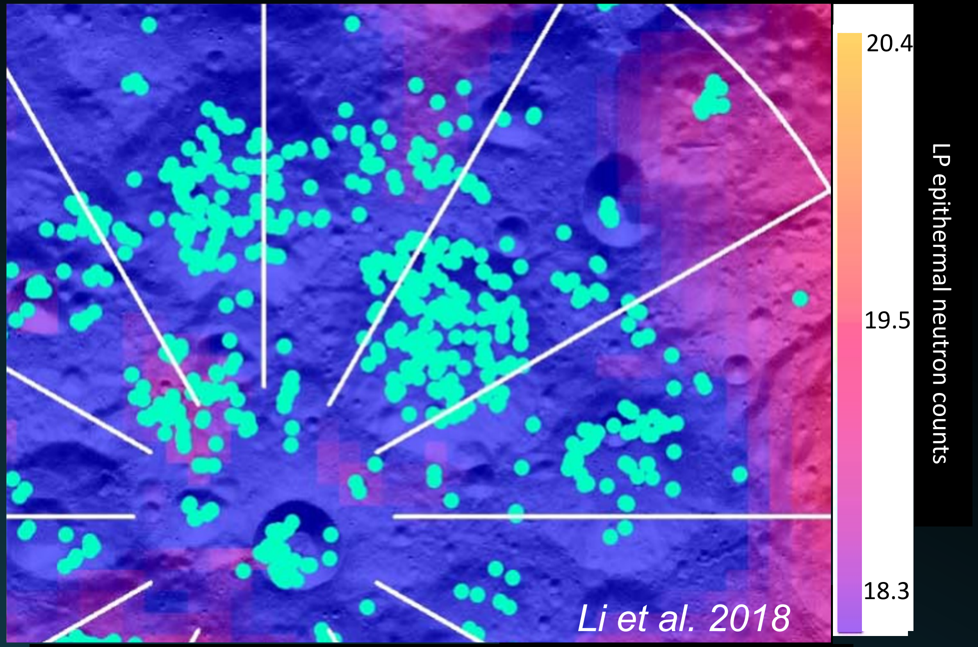


Hurley et al. 2013

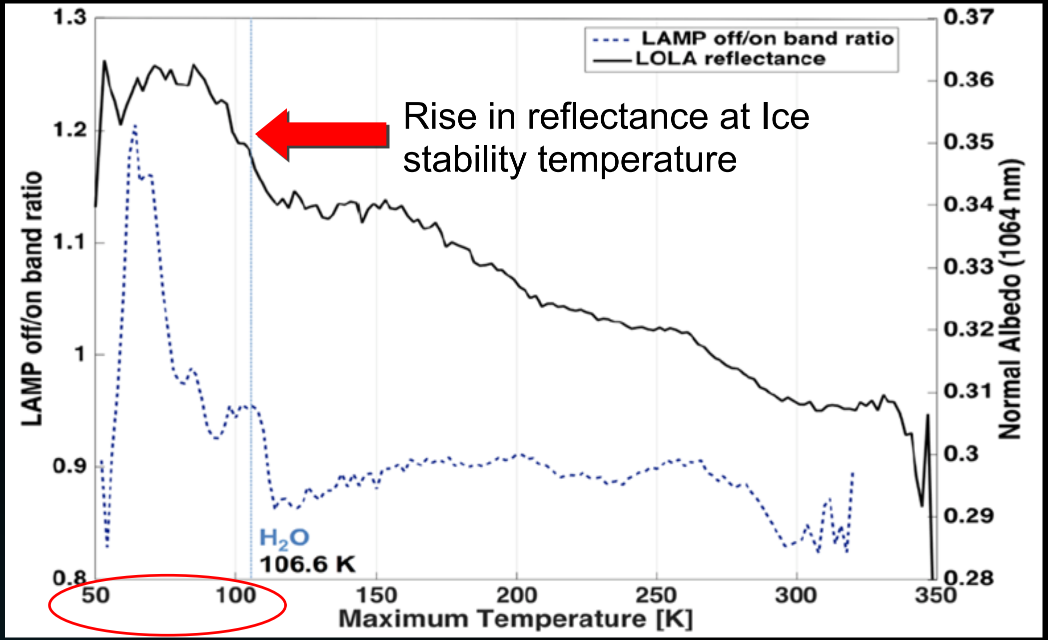
Need to map water ice at scales at or below physical scale of 10 meter diameter craters

Factors that Control Distribution: Temperature Control

- Temperature appears to be a necessary requirement, but not the only determinant of volatile presence.
- Temperature variations largely determined by topography and significant down to scales of <5 meters.



Ice exposures constrained by M3, LOLA, Diviner, LAMP

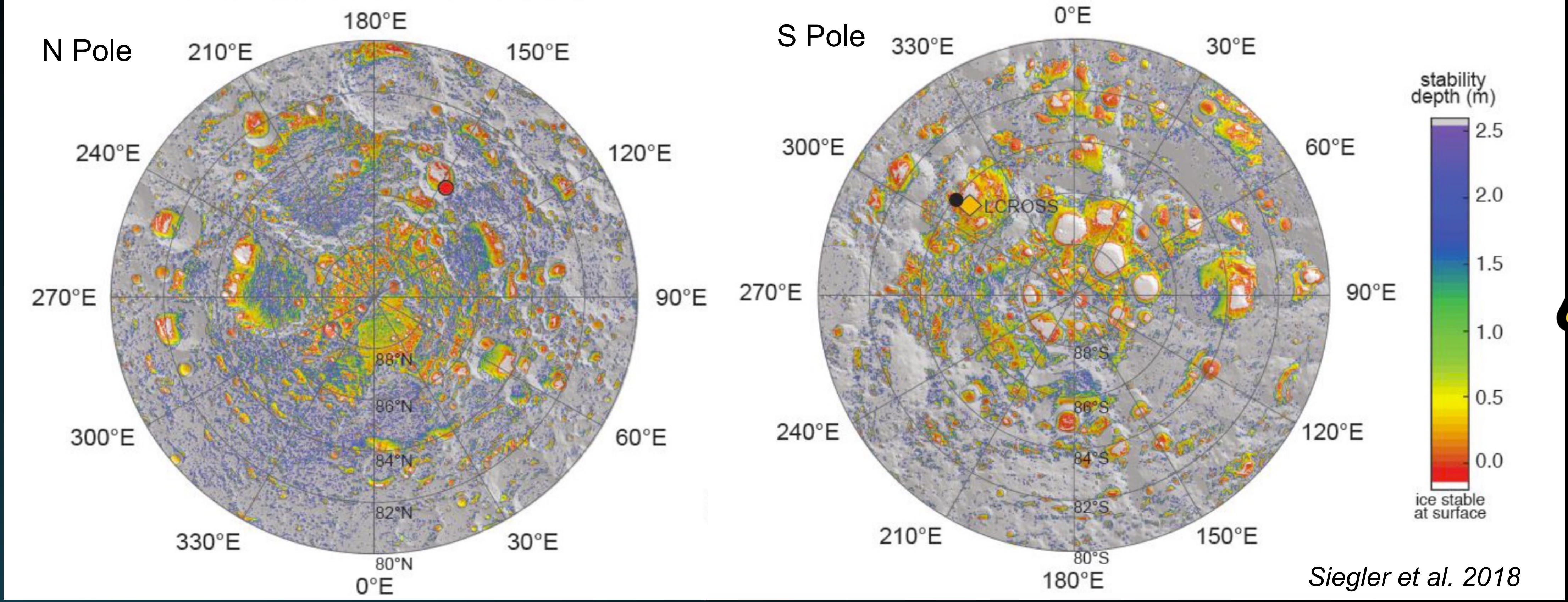


Fischer et al. 2017

Need to map water ice at scales at or below physical scale of 10 meter diameter craters

Factors that Control Distribution: Ice Stability Depth

- Depth at which the rate of ice sublimation would be less than 1 mm/Ga

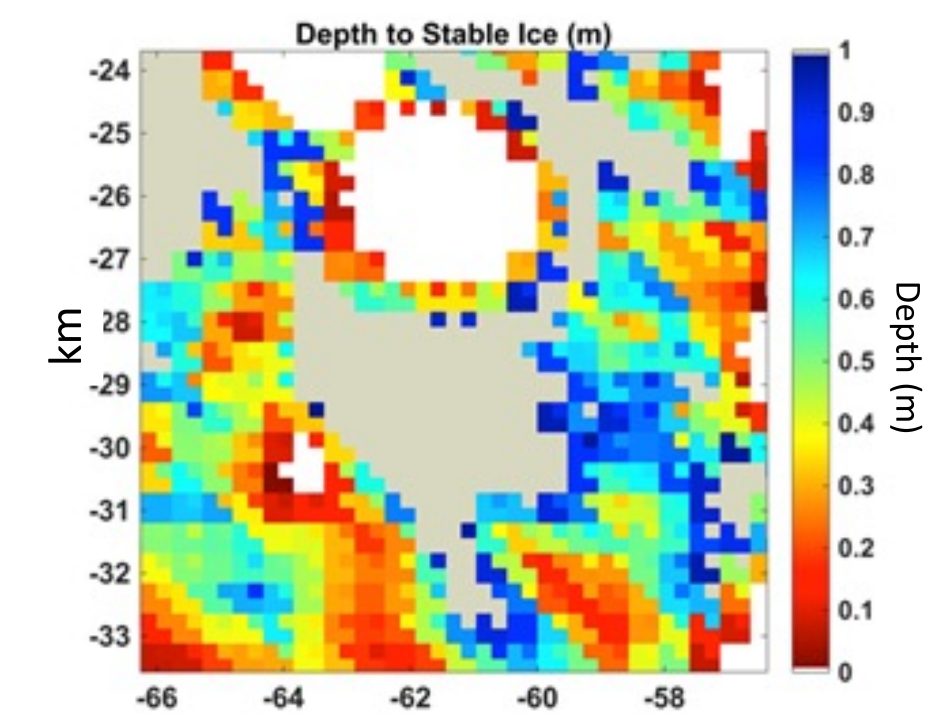


Using temperatures from the surface to 1 meter deep as primary surface proxy

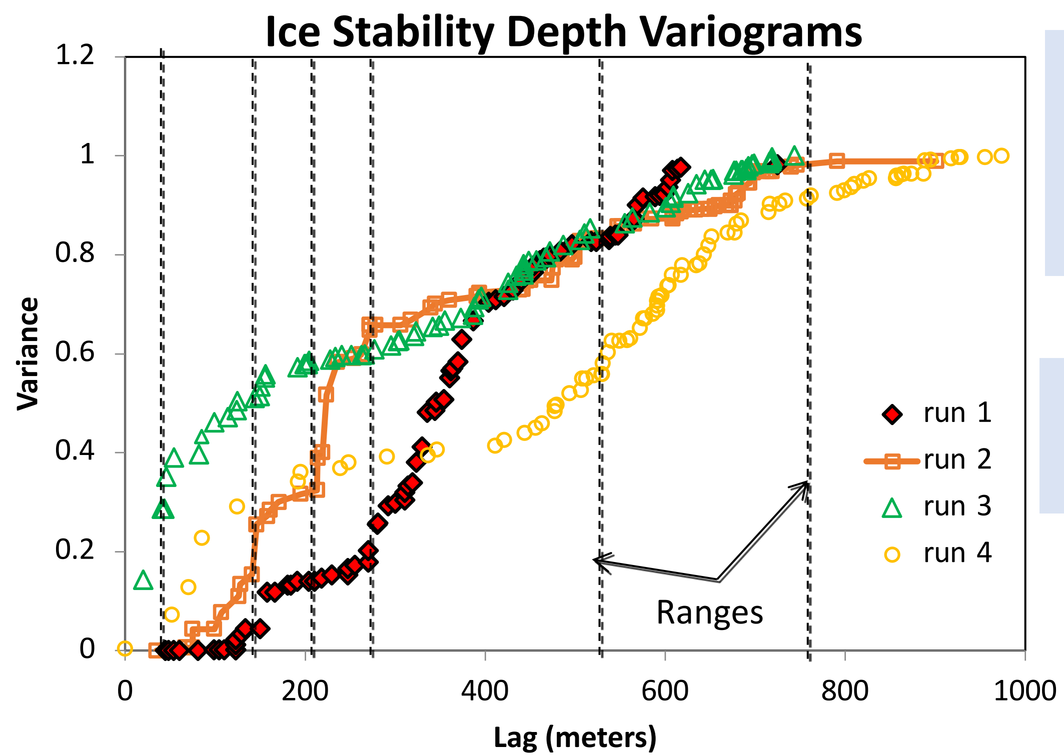
Lateral Scales

- We can use this "depth to water ice stability" to see at what spatial scales does the depth prediction vary.

Tool: Description of the spatial continuity of the data



Siegler & Paige 2017



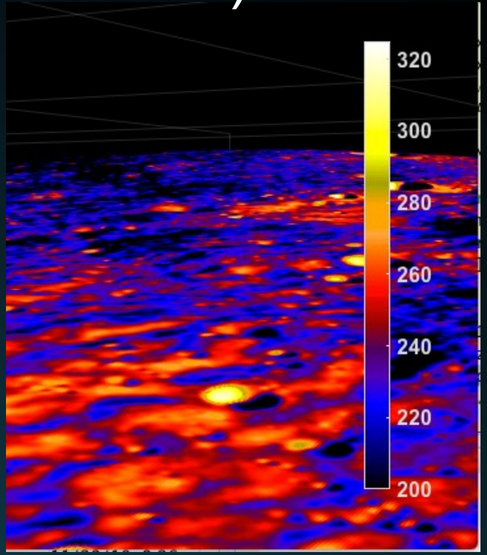
Variability will flatten out if they are no longer related to each other.

Inflections indicate correlation

Need to sample across scales from 10s to 100s of meters

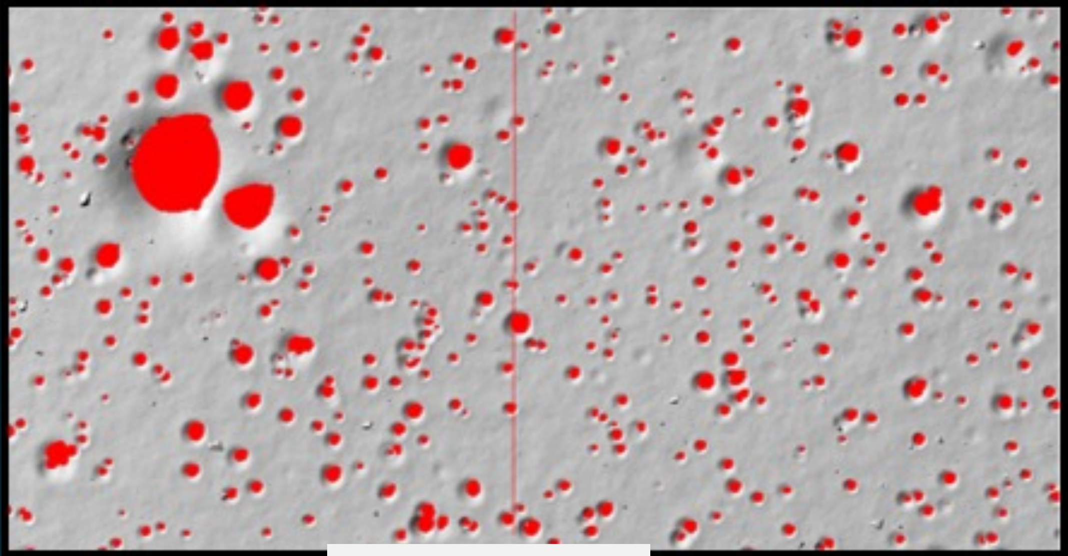
How Large an Area to Characterize?

- There will be significant temperature variation on the surface
- Any one region will have small scale temperature variations
- Small-scale permanently shadowed regions may be prevalent (Hayne et al. 2020)

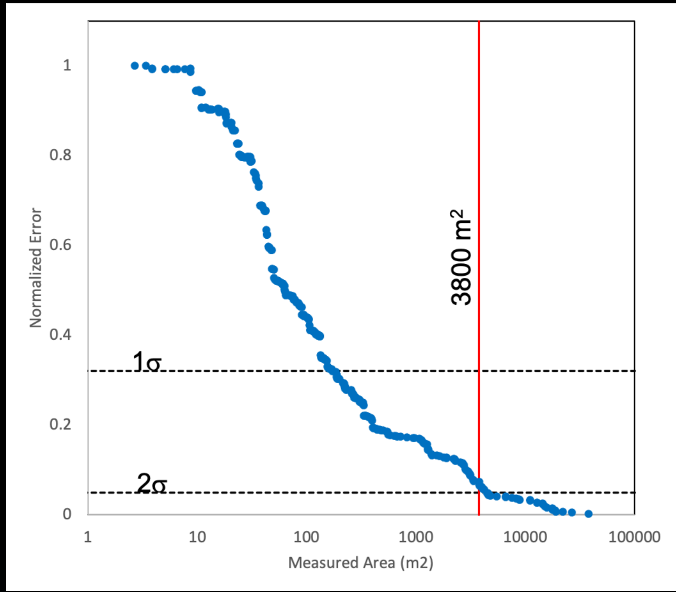


Surface Temperature, Kelvin

Micro-PSRs in Synthetic Terrain



Football Field
92 m (100 yards)



Analysis of error in ISR dominant type as a function of sample area

Must measure across an area of at least 3800 m^2 to ensure adequate sampling of the dominant thermal environment

Vertical Scales: How Deep?

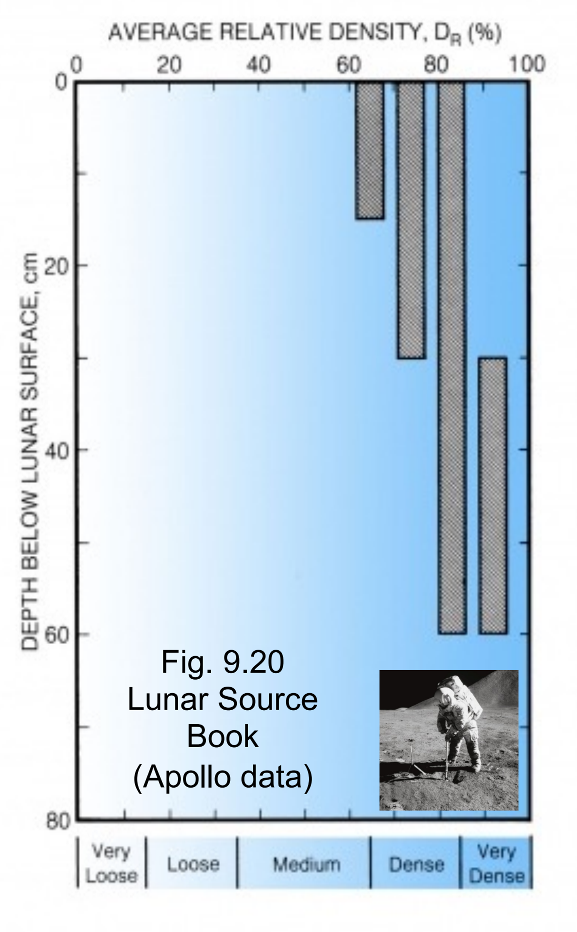
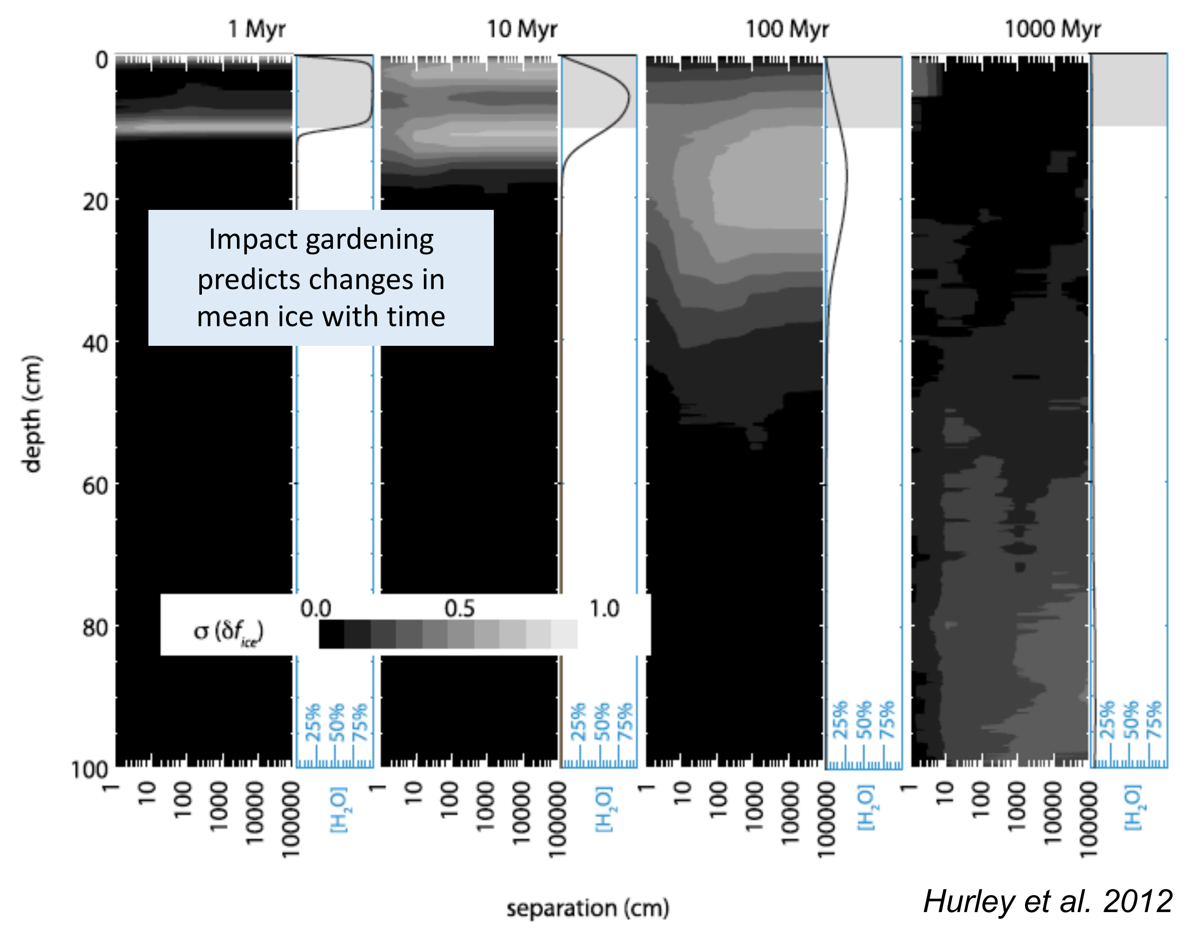


Fig. 9.20
Lunar Source
Book
(Apollo data)

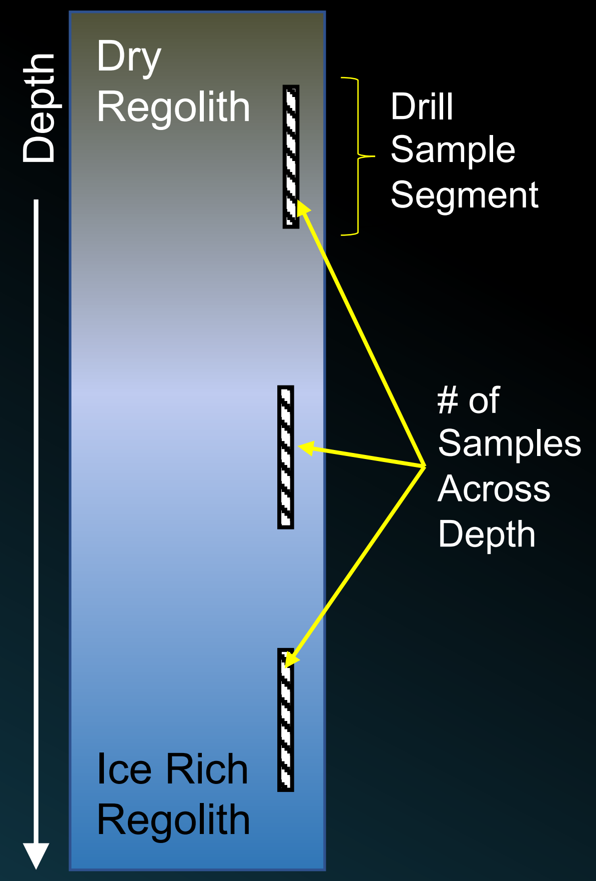
- Lunar soil becomes very dense very fast
- Desiccated regolith at depths down to ~30 cm
- Our current ability to sense hydrated materials at depth is limited



Hurley et al. 2012

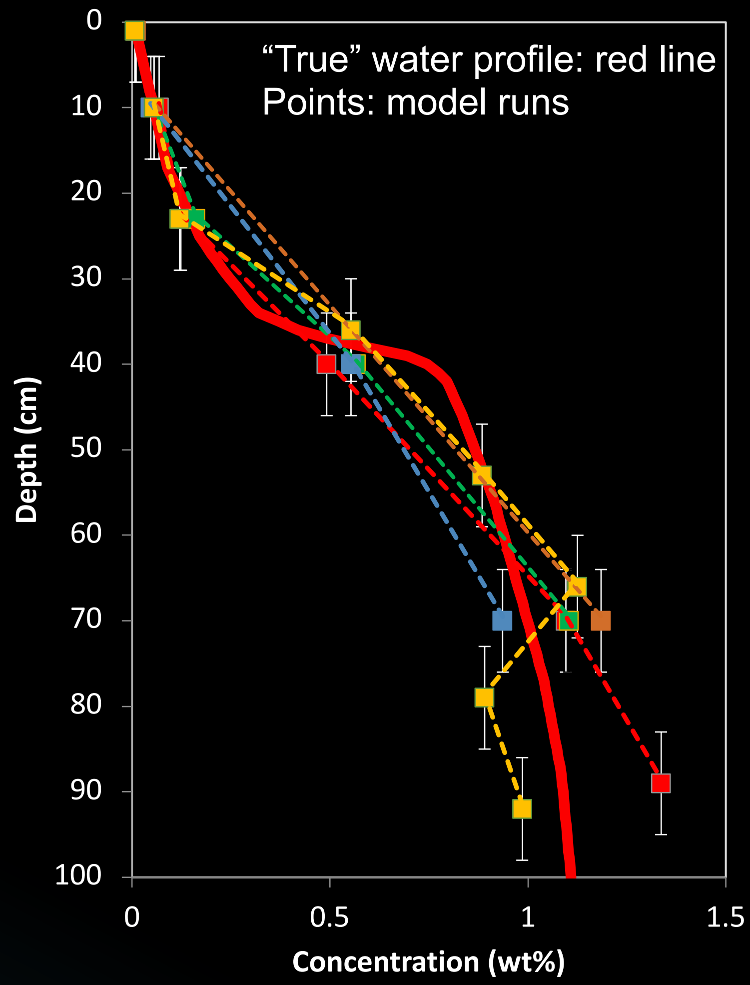
Must sample down to 1 meter

Vertical Sampling: How Fine?



Hypothetical scenario increasing water with depth

- Greatest changes in vertical mixing are expected to be between 20-50 cm depth.
- Need to resolve gradients in ice vertical distribution to inform neutron measurements.
- Need enough sampling to resolve variations in regolith density and water distribution.



Sample length of >8cm plus at least 5 samples per 80cm results in <10% integrated column uncertainty