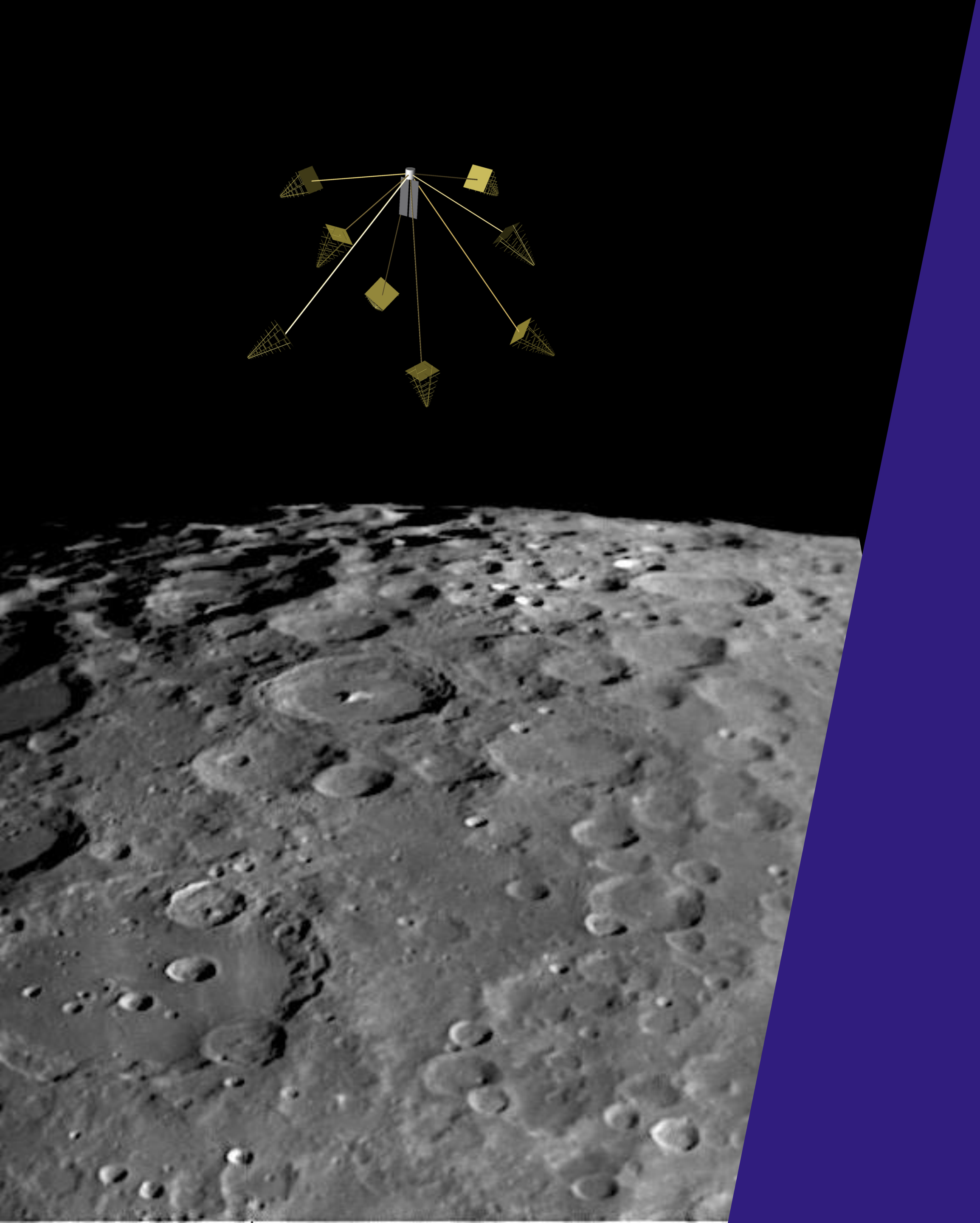

Lunar Subsurface Ice Detection with Cosmic-Ray Showers

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On behalf of the CoRaLS collaboration

ARENA June 12, 2024

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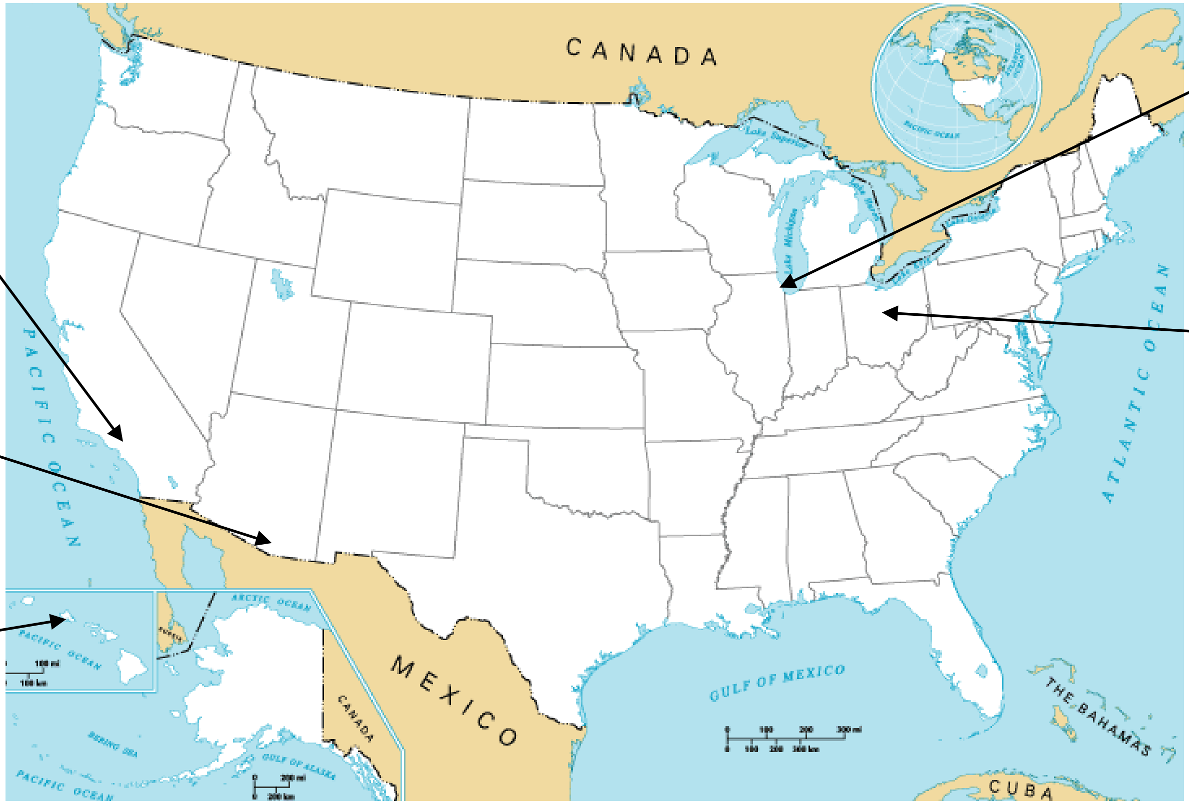

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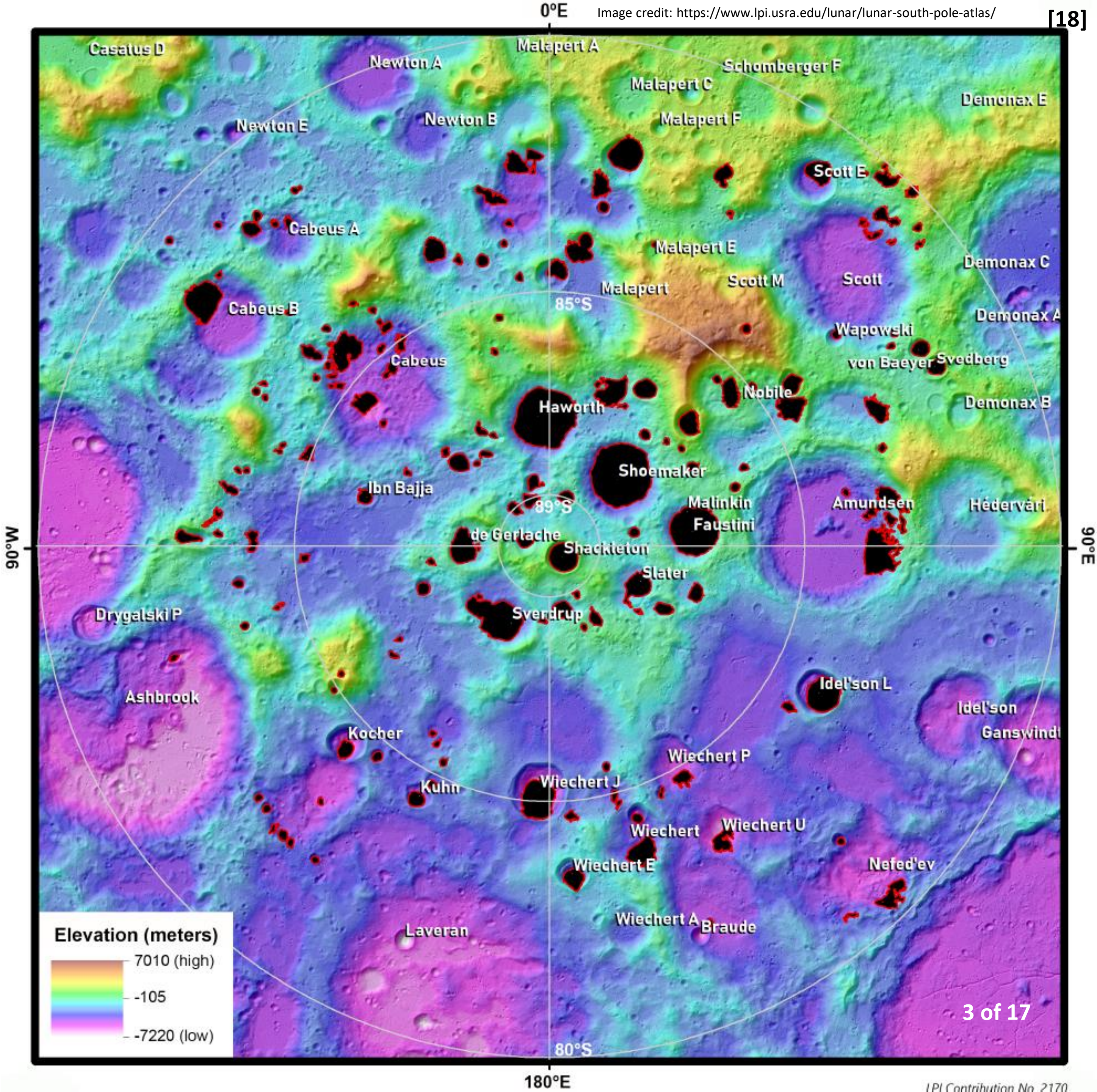
The Search for Ice

- (1994) Ice-detected in Mercury's Permanently Shadowed Regions (PSRs)
- (2009) LCROSS mission detected ~8% by weight of water in Cabeus crater ejecta plume
  - Excavated ~6m
- (2016) LEND onboard LRO maps hydration of top meter in the PSRs

Image credit: https://www.lpi.usra.edu/lunar/lunar-south-pole-atlas/ [18]



LPI Contribution No. 2170

Predictions

- Cannon et al. (2020)
  - Monte Carlo modeling of polar ice deposits
    - Deposited via hydrated asteroids and volcanic outgassing
    - Ejecta emplaced by age-dated large craters
    - Estimates for ice loss
    - Impact gardening
- There may be large near-pure ice deposits within these craters

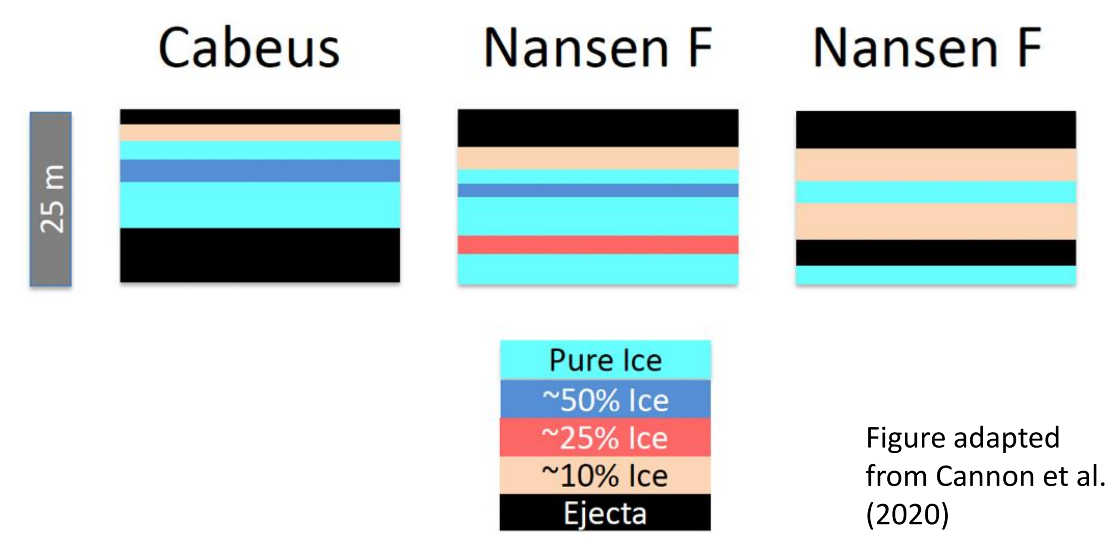


Figure adapted from Cannon et al. (2020)

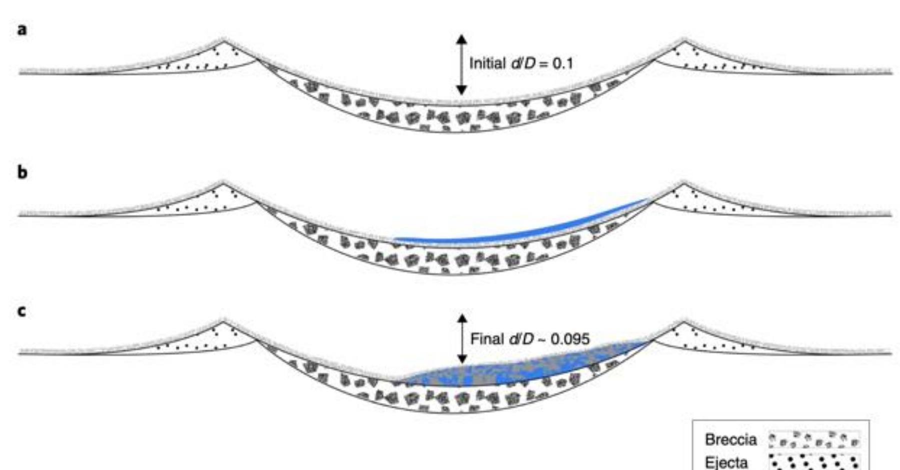


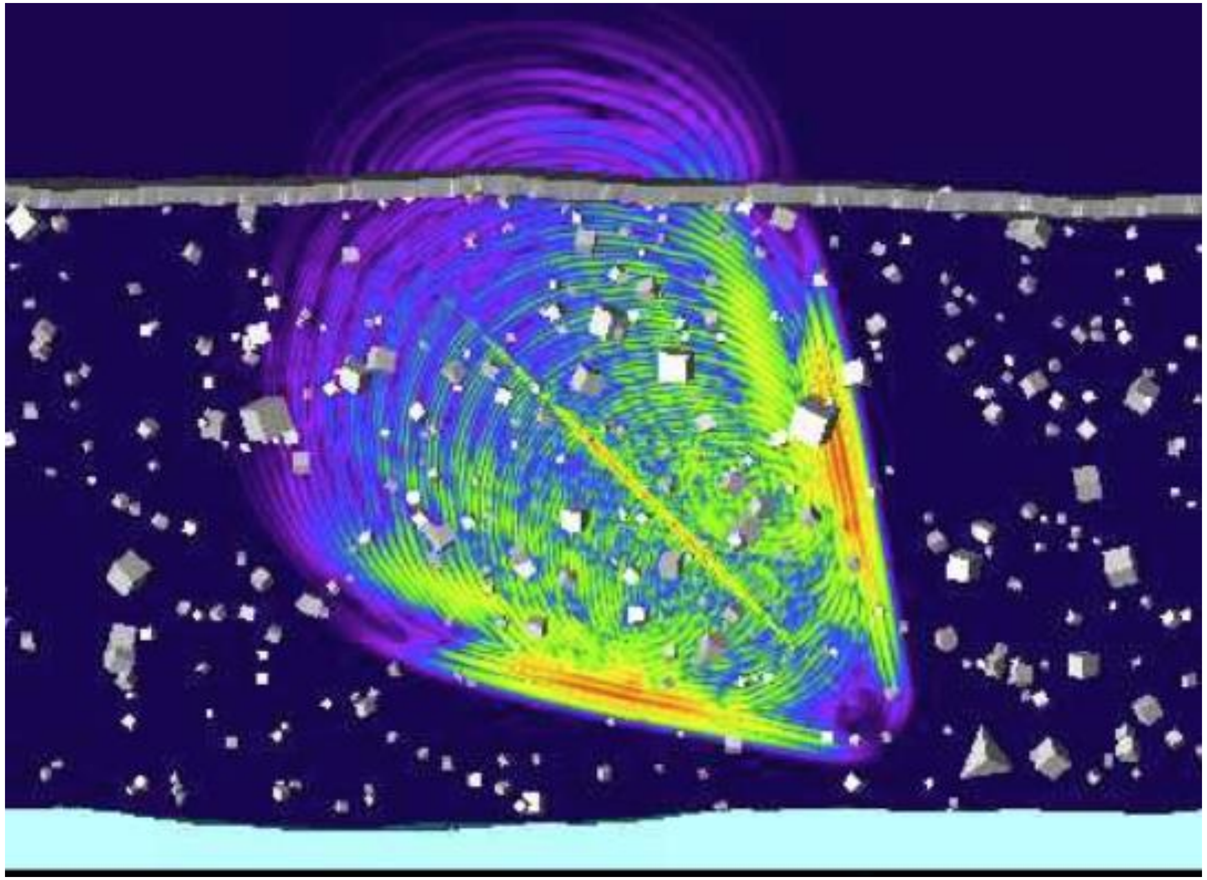
Figure source: Rubanenko et al. (2019)

Remote Sensing Detection Techniques

- **Active Radar**
  - Roughness and volume scattering greatly reduce sensitivity
  - Required high power transmitter

- **Ground Penetrating Radar**
  - Viewing area is on order square meter
  - Cannot easily be moved to gather statistics over a larger area

Initiate radar signals below the surface *all over* the moon



Cosmic-Ray Detection

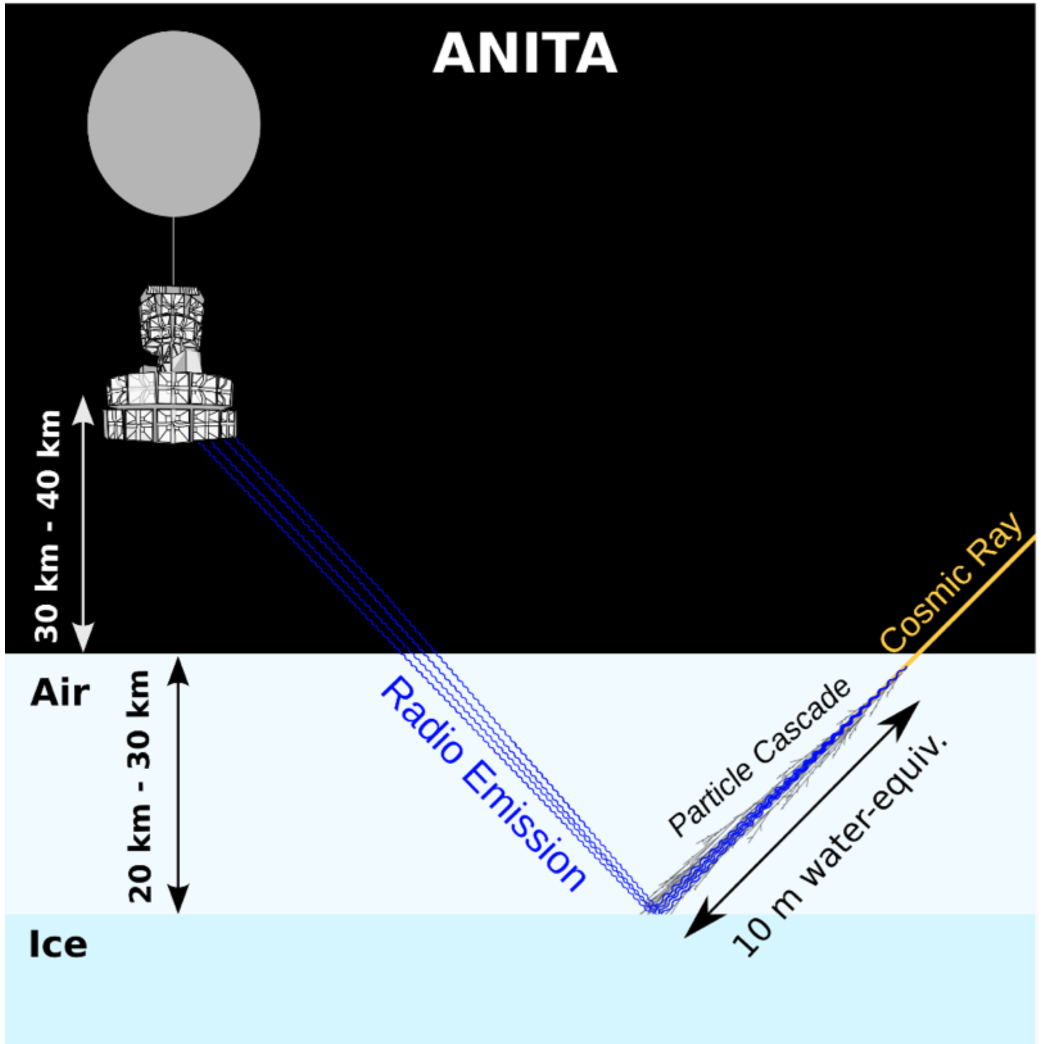
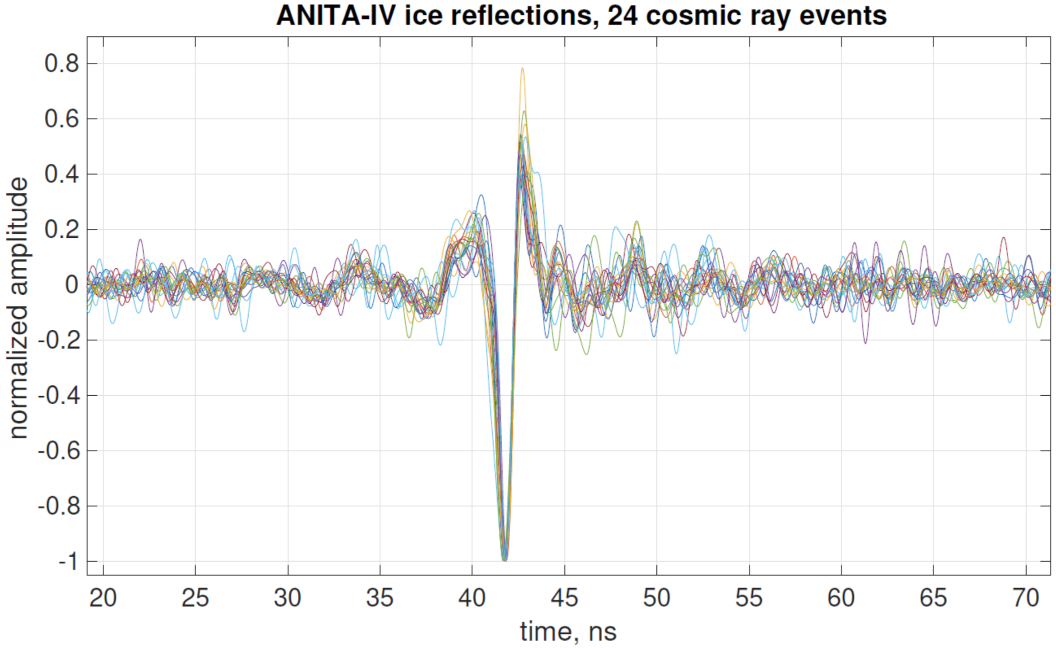


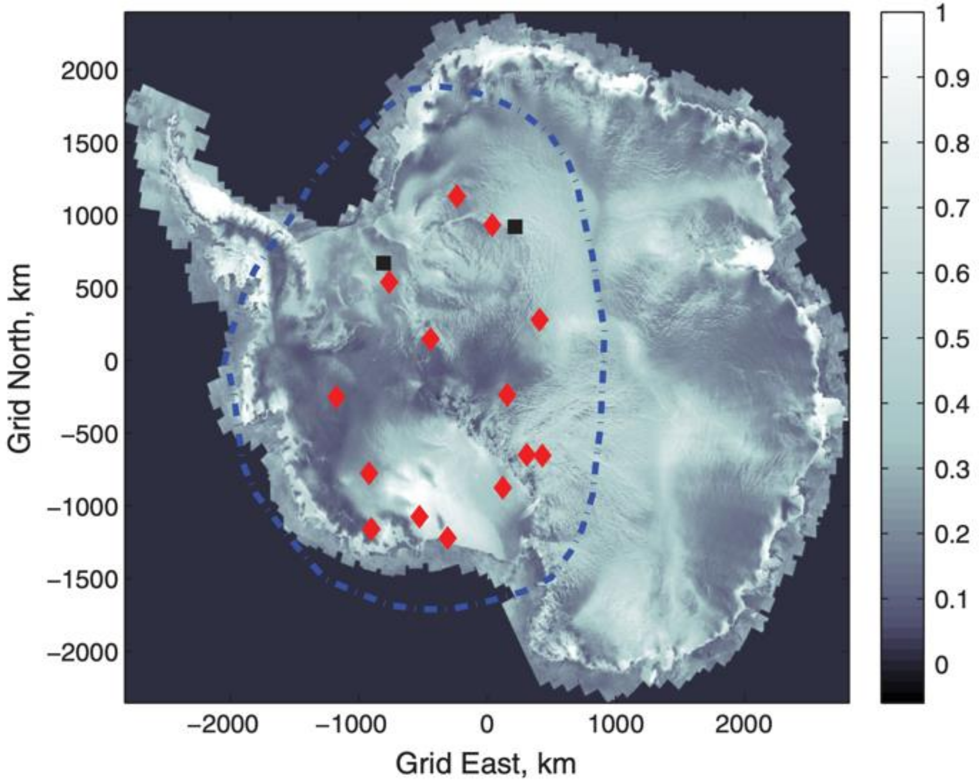
Image credit: Remy Prechelt

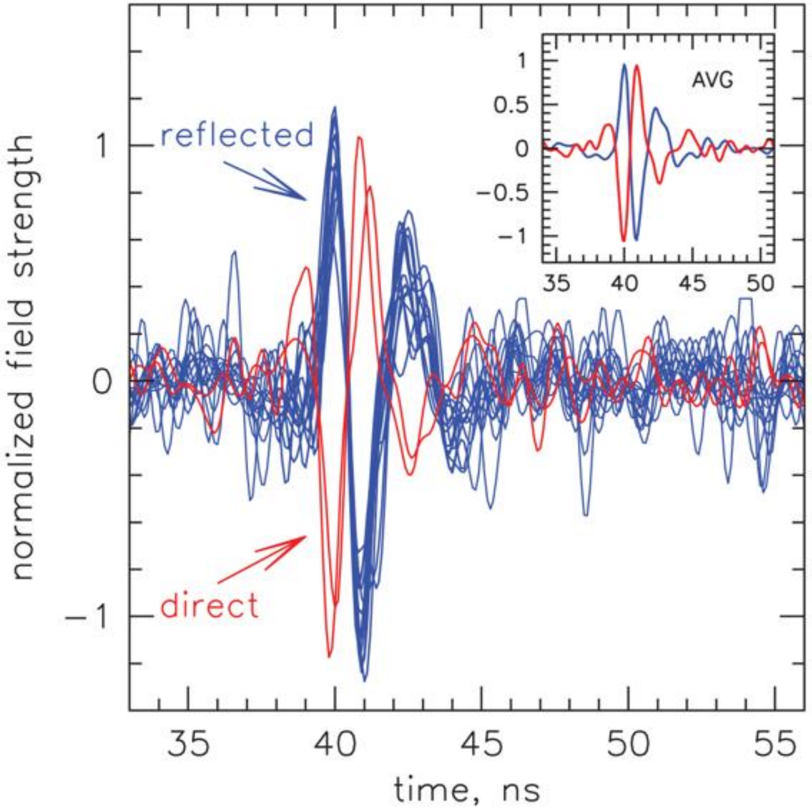
- CR induces an Extensive Air Shower (EAS)
- Radio pulse emitted by EAS can be detected by Antenna
- **Reflected CRs can be distinguished from direct by signal polarity**



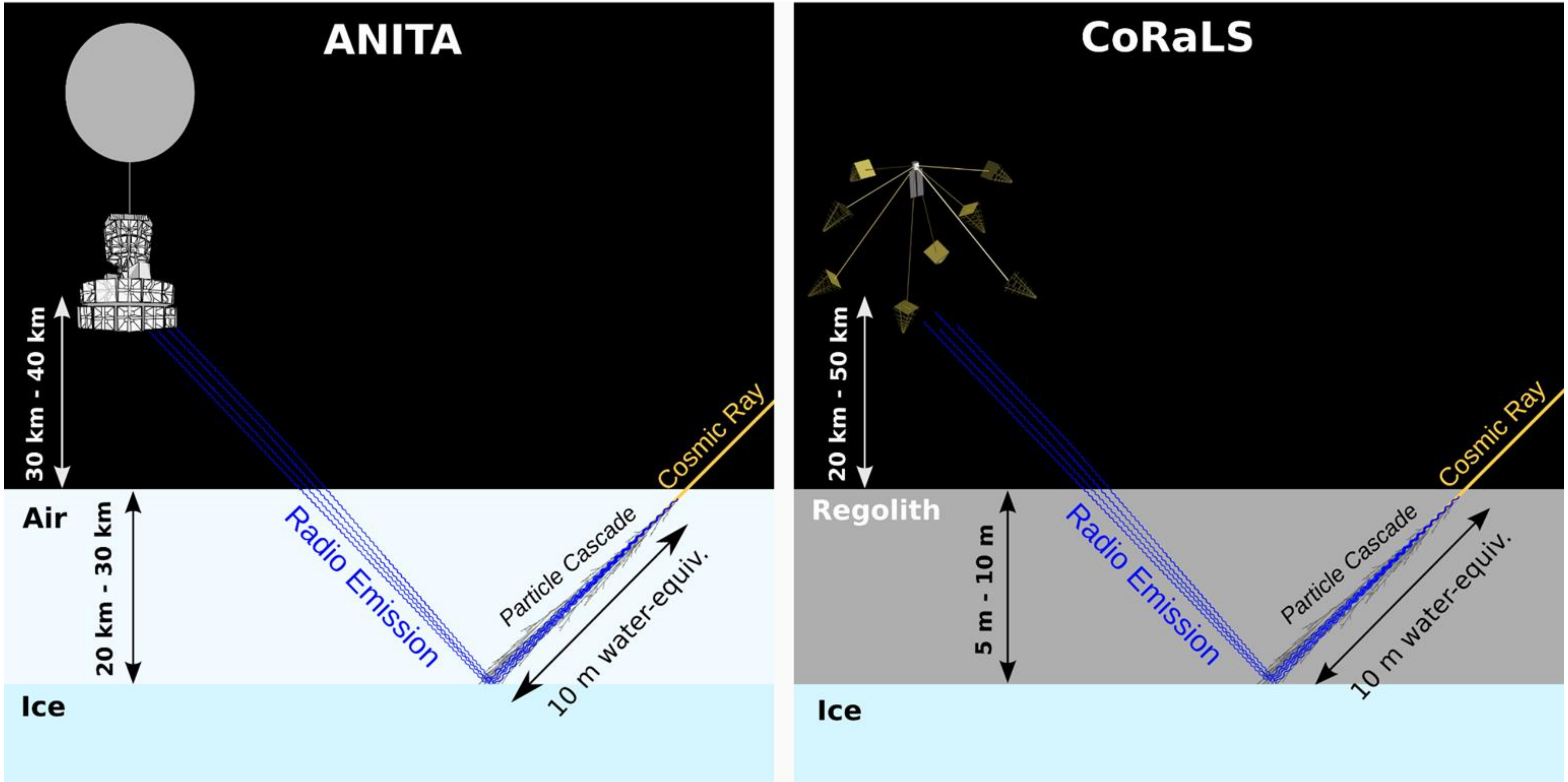
ANITA Cosmic-Ray Directionality

- Cosmic-Rays seen by ANITA could reliably be identified as reflected and direct
- Their directionality could be determined





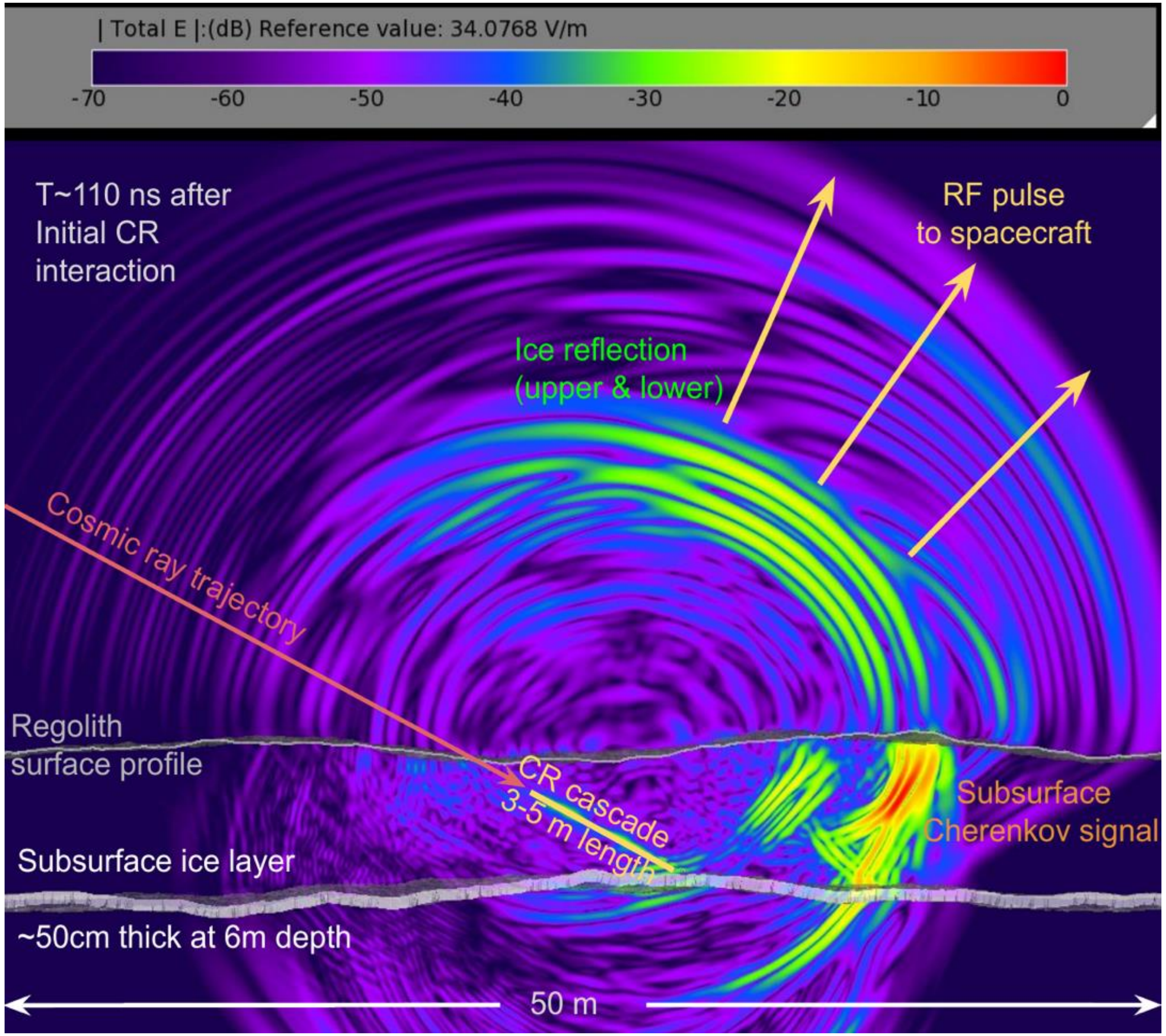
Hoover et al. PRL 105 (2010) 151101

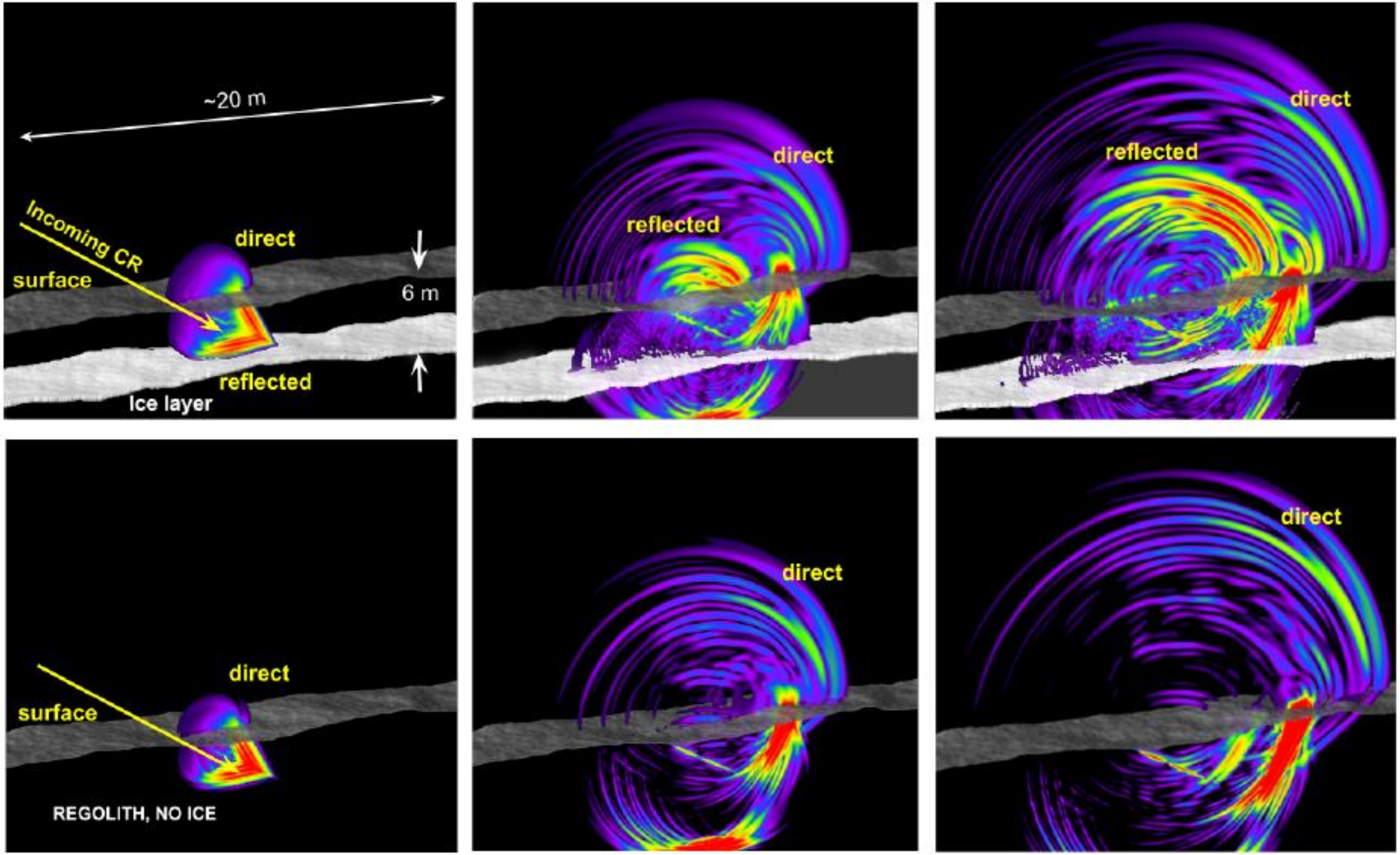


Analogously, 5 m – 10 m of regolith has roughly the same water equivalent of material as 20 km – 30 km of air

Cosmic Ray Lunar Sounder (CoRaLS)

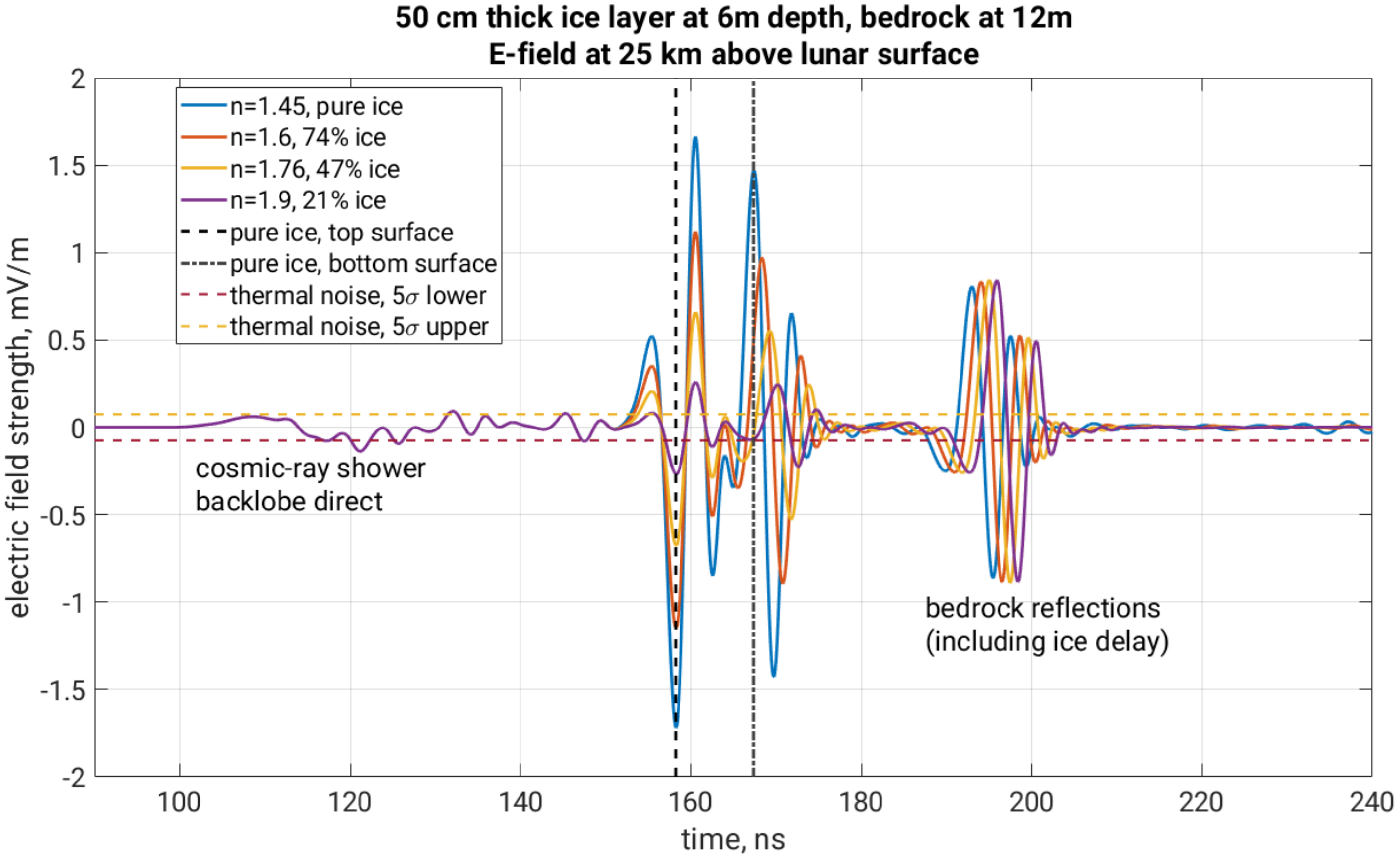
- CR showers initiated in regolith
- Detection of Askaryan effect emission
- Ice reflections possess polarity opposite of bedrock reflections




~20 m
Incoming CR
direct
surface
6 m
reflected
Ice layer
direct
reflected
direct
reflected
direct
surface
REGOLITH, NO ICE
direct
direct

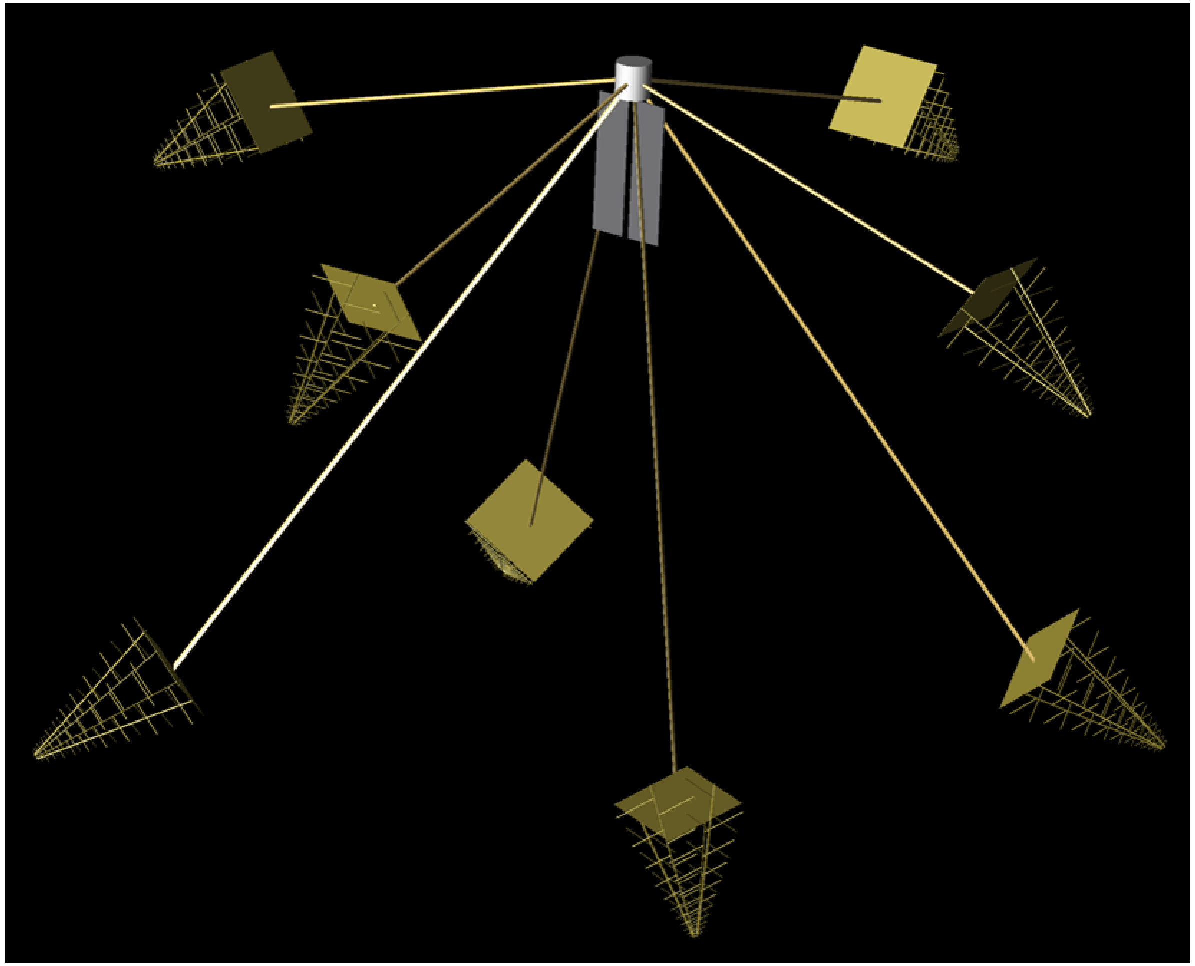
Simulated Results

- Ice presence gives a strong reflection
- Time delay in reflections provide data on ice thickness
- Absence of ice you can still expect to receive an impulsive signal from bedrock reflections



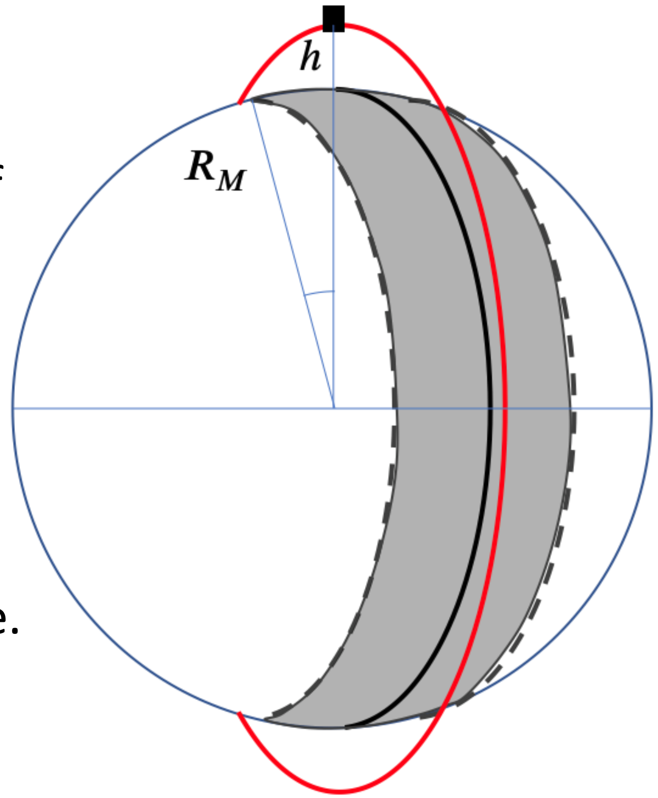
Instrument Concept

- Sensitivity to observables achieved with an ANITA-like array of wideband antennas
- Parameters
  - Cover the area covered by PSRs
  - Array of dual-polarized antennas
    - 150 – 800 MHz with ≥ 9dBi of gain
  - Trigger threshold SNR ≥ 4
  - Pointing resolution ≤ 1°
- Current design has 8 antennas
  - This can easily be scaled to more antennas to meet science goals



Events

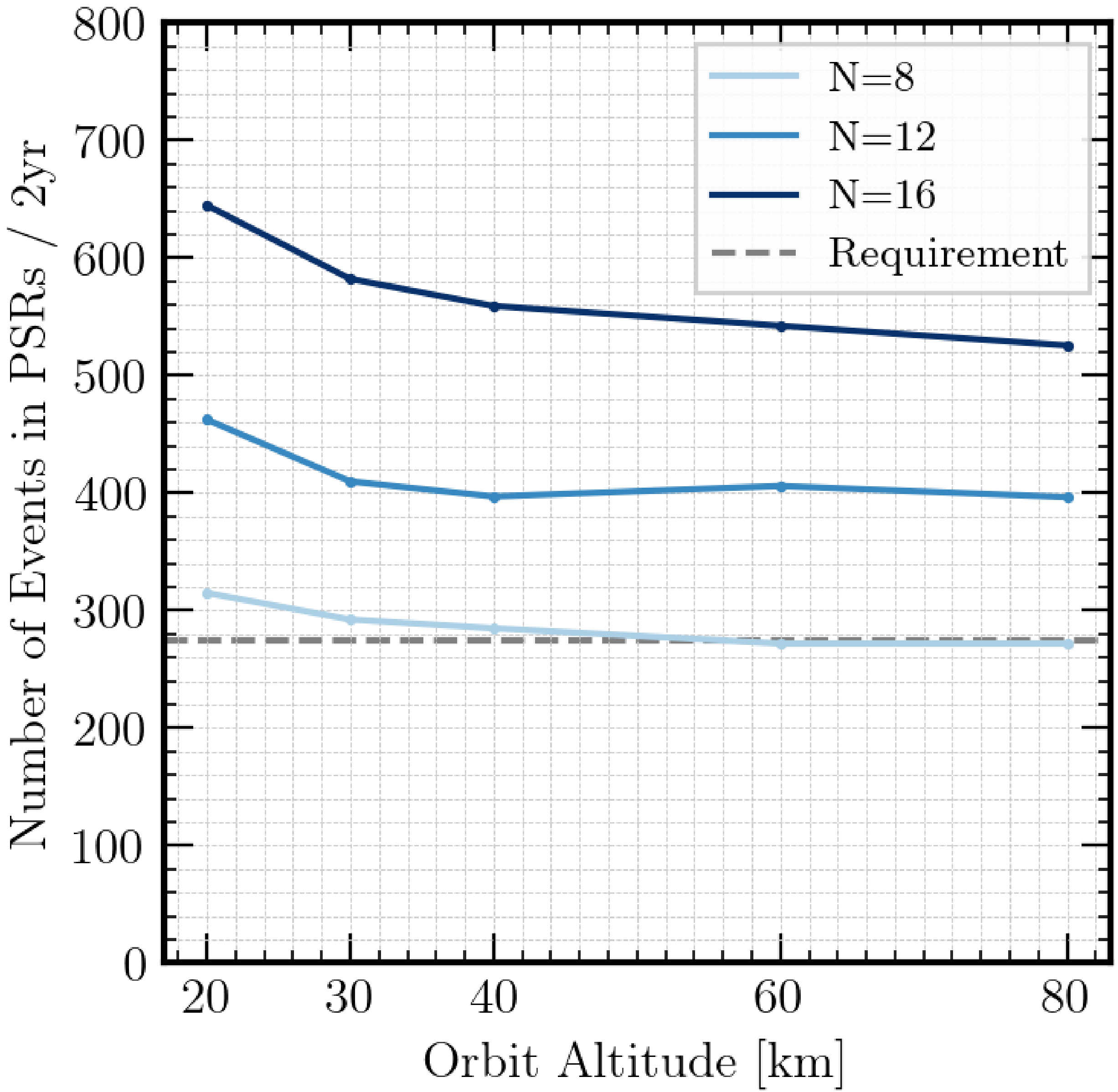
- Entire lunar surface is being impacted by cosmic rays - only the fraction of cosmic rays that impact in PSRs are "science events".
- Total area of PSRs is 28,921 km^2 distributed within 10 deg of each pole.
- Cosmic ray impacts outside of PSRs can be used for background estimation.
- CoRaLS should also detect ≥ 100,000 cosmic ray impacts in the lunar mare.



Orbit Altitude	Orbital Area	PSR Fraction	Events in PSRs / 2 yr
20 km	5.7×10^6 km^2	5.0×10^{-3}	300 - 650
30 km	7.0×10^6 km^2	4.2×10^{-3}	300 - 600
50 km	8.9×10^6 km^2	3.2×10^{-3}	275 - 550

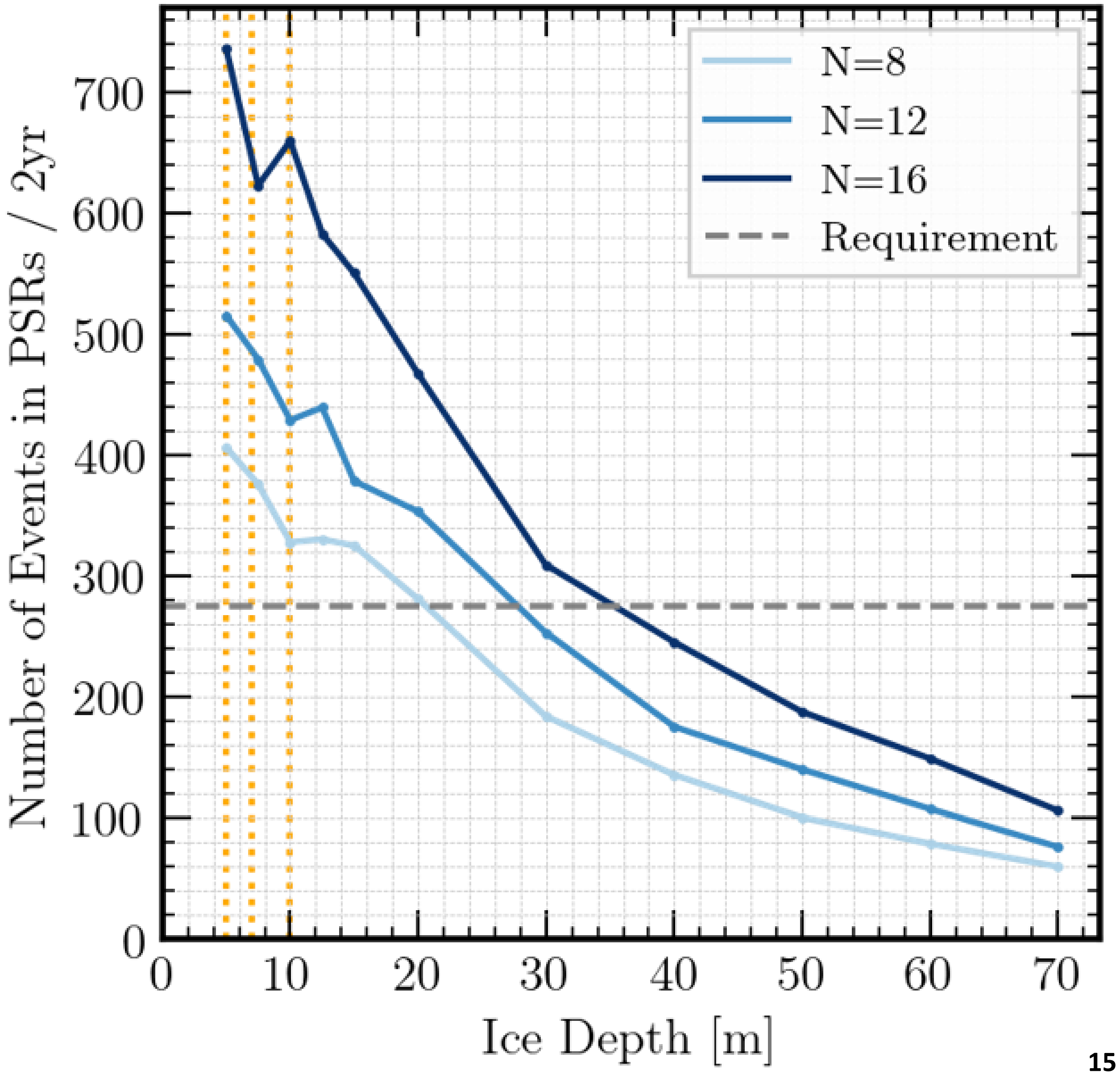
Altitude Sensitivity

- Down to ~20 km the number of PSR events increase
- Setting a baseline of ~300 PSR events, requirement can be met with 8 antennas
- Using 12 antennas increases PSR event rate by ≥45%



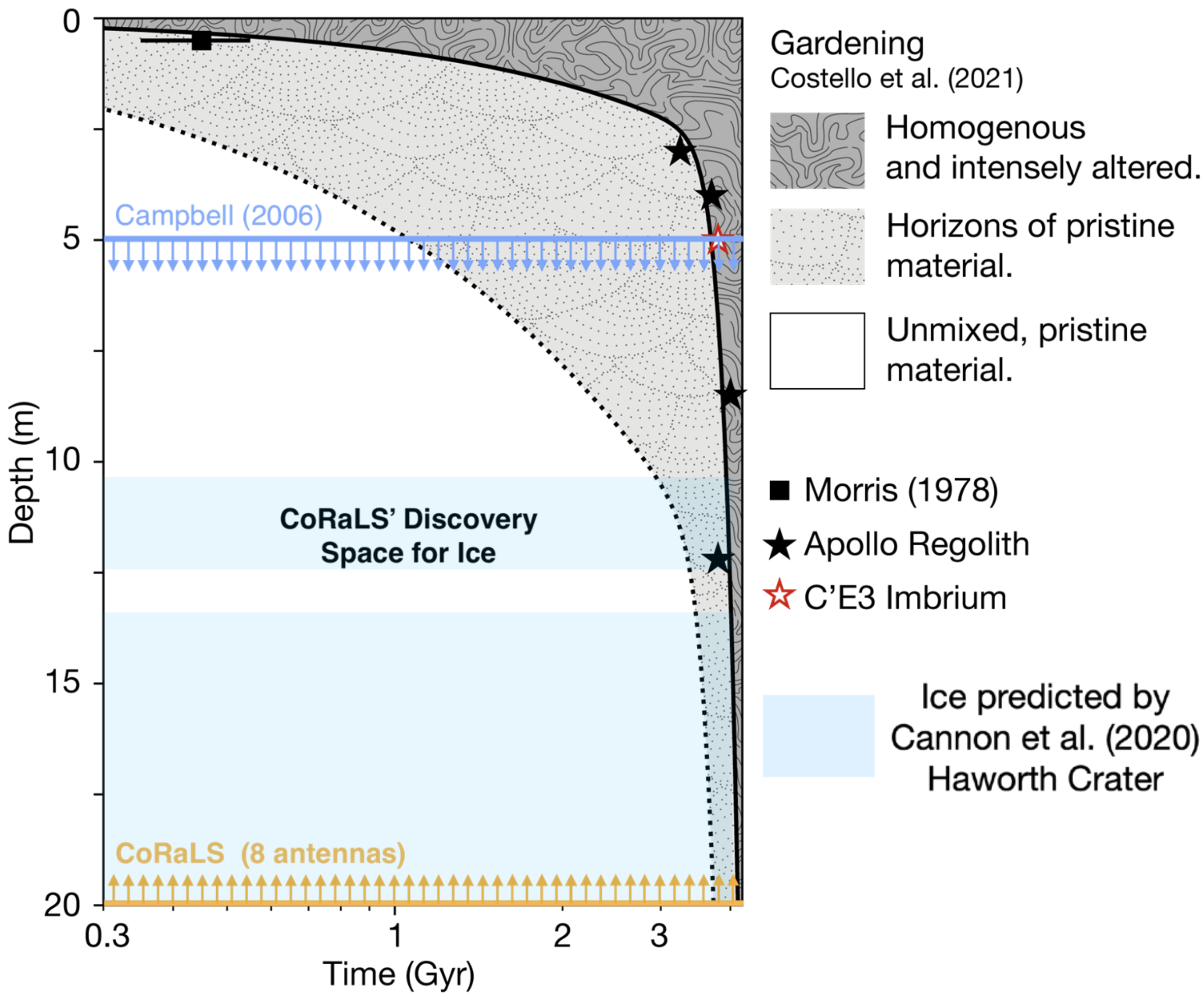
Expected PSR Event Rates

- Using Current Design
  - 8 antennas, ~9 dBi of gain
    - 150 – 800 MHz band coverage
  - Orbit at ~20 km
  - Assuming Mercury-like ice
    - Expect ≳300 PSR events to depths of 20 m
  - Depth of ice correlates to age of ice deposition



Conclusions

- Regolith models predict large near-pure ice deposits deep below the surface
- Previous missions didn't have probing depth necessary to reach ice layers
- Remote sensing techniques offered inconclusive results
- Building off the Cosmic-Ray detection techniques in ANITA, CoRaLS offers a novel approach for studying subsurface lunar structure
- With an 8-antenna design with a 2-year orbital mission would see enough cosmic ray events in the PSRs to help determine ice abundance

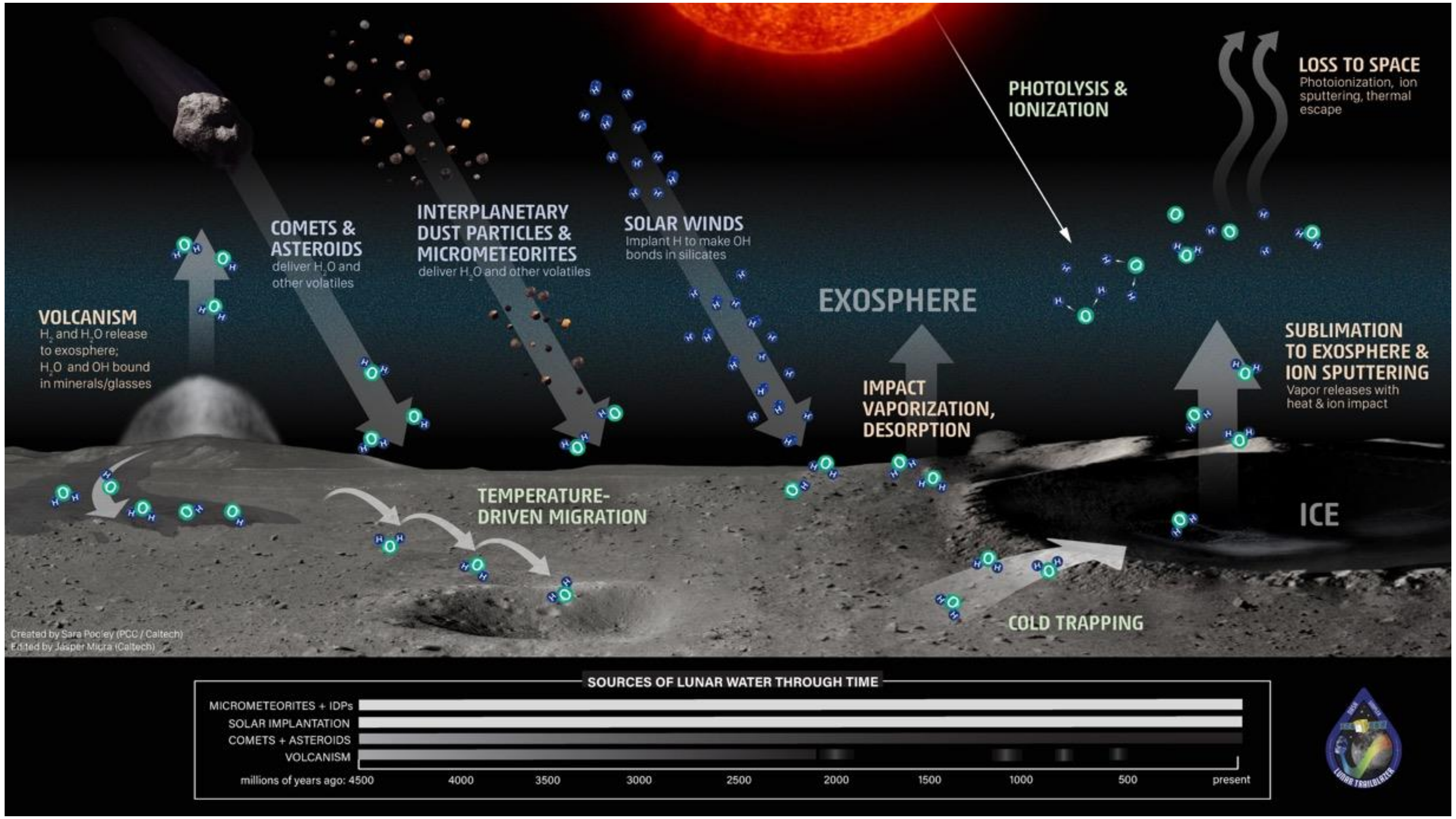


THANK YOU

<u>Motivation:</u> The water cycle on airless bodies

- Favored mechanism: <u>sudden & voluminous deposition of water ice.</u>
  - Impact gardening prevents low-rate accumulation over time.
    - Prompt & voluminous sources exponentially more durable against gardening.
    - Gardening <u>more efficient on the Moon</u> than on Mercury.
  - Sources: water-rich asteroids or large-scale volcanic outgassing.

- The Moon <u>could have relic (< 1 Gyr) ice deposits</u>.
  - Current radar data does not penetrate <u>below the first meter</u>.
  - <u>Buried ice</u>, if it exists, may be between 1 – 10 m depth.

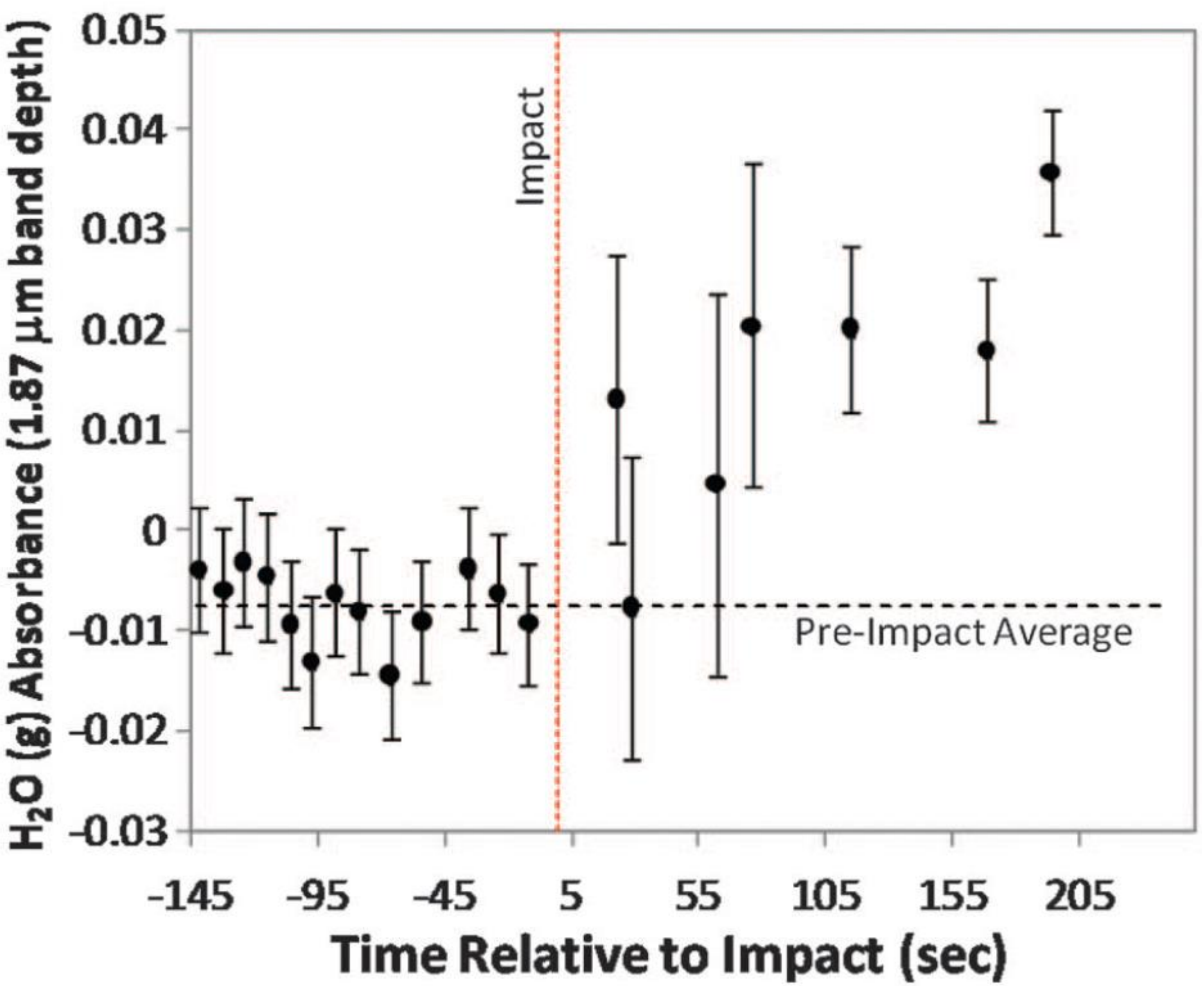


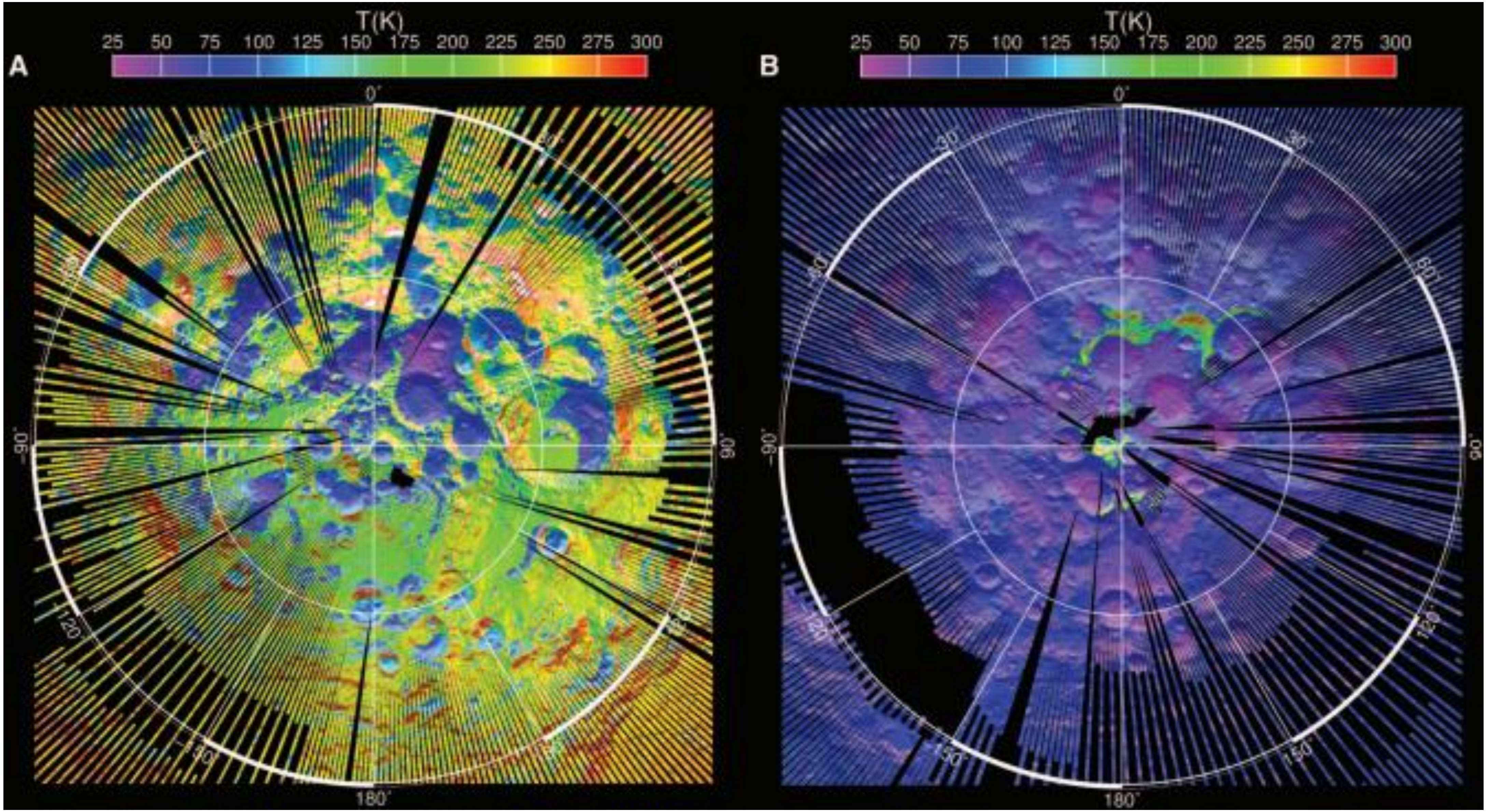
https://trailblazer.caltech.edu/news/lunarWaterCycle.html

References: Costello et al. 2020, JGR:Planets, 125(3), e2019JE006172; Needham & Kring 2017, EPSL, 478, 175-178; Cannon et al. 2020, GRL, 47(21), e2020GL088920;

LCROSS

- Centaur rocket detaches from LRO with LCROSS instrument
- Rocket impacted the Cabeus crater ejecting debris
- Used Near-infrared absorbance to measure water in ejecta plume
- Measured ~155± 12kg water vapor/ice
  - About 5.6±2.6% by mass





Paige, D. et al. (2010). Diviner Lunar Radiometer Observations
of Cold Traps in the Moon’s South Polar Region

Hydration Map from Neutron Detection