Particle Radiation Environments and Their Effects at Exploration Destinations

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CRaTER
UNH - BU - MIT - AEROSPACE - SAO - UTK

SSERVI Exploration Science Forum
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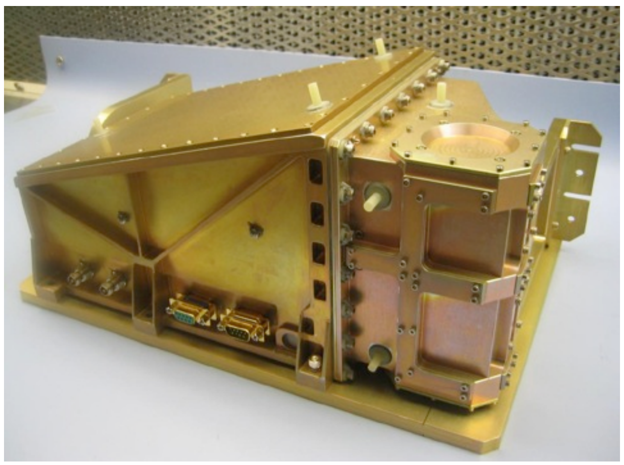
Credit: NASA

Overview

- Brief summary of what have we learned at the Moon from CRaTER – environment and effects
- Scaling the lunar particle radiation environment (GCR and SEP) to other exploration destinations
- Comparing other key parameters (temperature) of airless planetary bodies that control the effects of radiation
- Estimating relative importance of effects – still a work in progress, but ultimate goal of study…

Cosmic Ray Telescope for the Effects of Radiation (CRaTER) Investigation

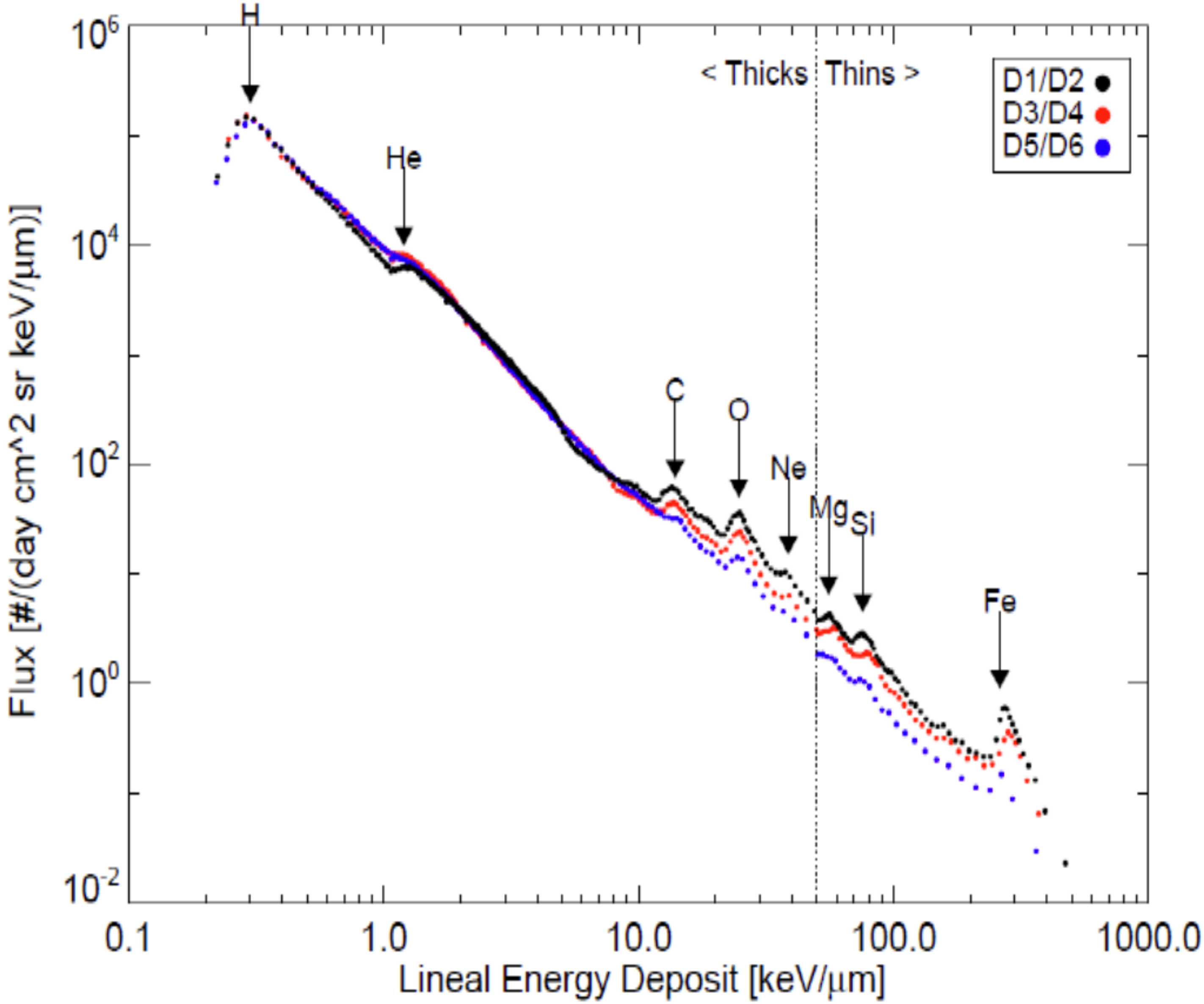
(Spence et al., Space Sci. Rev., 2010)



- **Launched in June 2009**
- **Nadir/Zenith viewing along "telescope" axis**
- **Designed to estimate Linear Energy Transfer of galactic cosmic rays and solar protons near the Moon**

LET Spectra & Shielding: Galactic Cosmic Rays

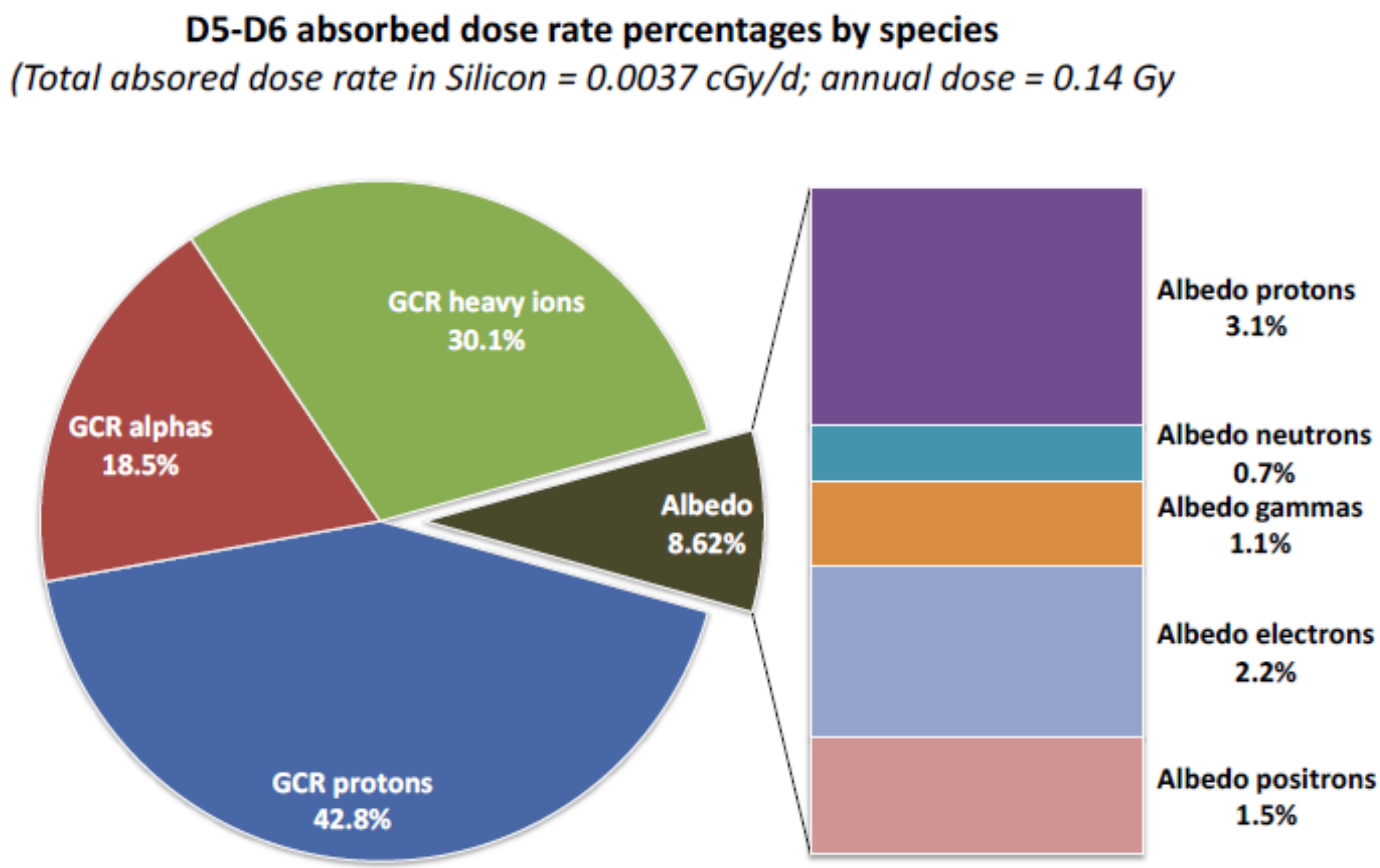
After Case et al., 2013; Zeitlin et al., 2013; and Porter et al., 2013



- CRaTER is providing high-resolution estimates of LET from GCR over the course of the mission
- Thin-thick pairs permit exploration of the LET spectrum from the low end, dominated by protons to the high end dominated by heavy ions
- Evolution of LET through the various sections of TEP are allowing us to explore and test theories of space radiation shielding

GCR Dose and Dose Rate Estimates

After Spence et al., 2013



- **Use validated GEANT4 model of CRaTER response to primary GCR and lunar secondaries to assess contributions by species**
- **Secondary albedo particles account for ~10% of absorbed dose rate**

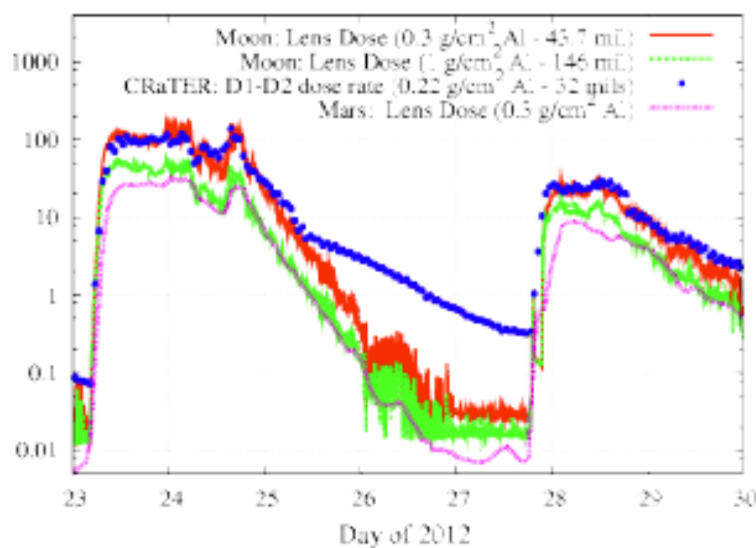
Solar Proton Model Prediction/Validation

After Schwadron et al., 2012

SEP Events During 2012: Indicators of Larger SEP Events in the New Cycle (24)

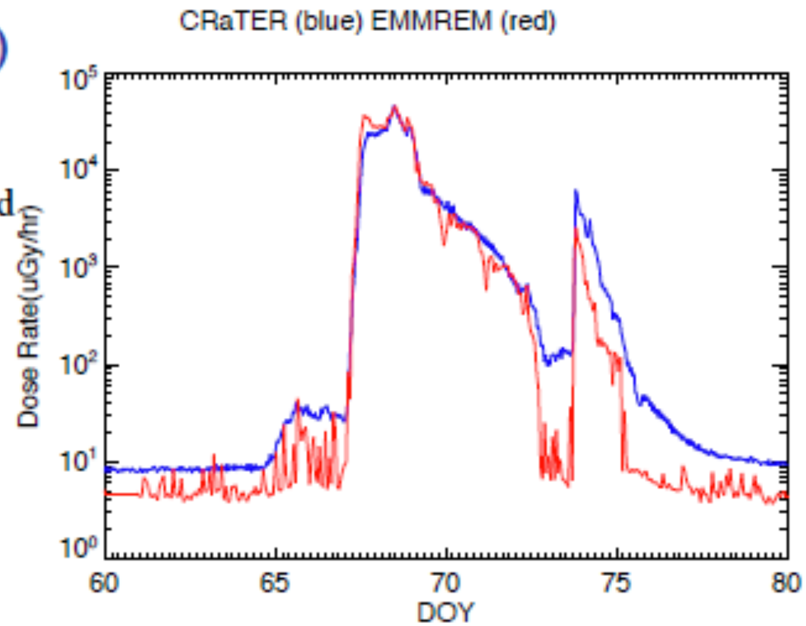
- Shown here are the major SEP events of 2012 and the comparisons between CRaTER observations (blue) and EMMREM/PREDICCs model predictions (red and green).
- Agreement reveals overall accuracy of models, while deviations likely reveal heavy ion contributions to dose observed by CRaTER

Jan. 23rd 2012 Event

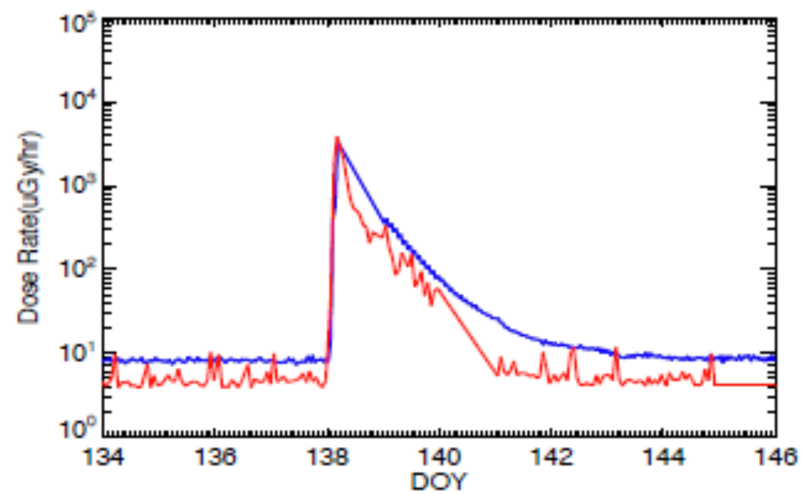


http://prediccs.sr.unh.edu

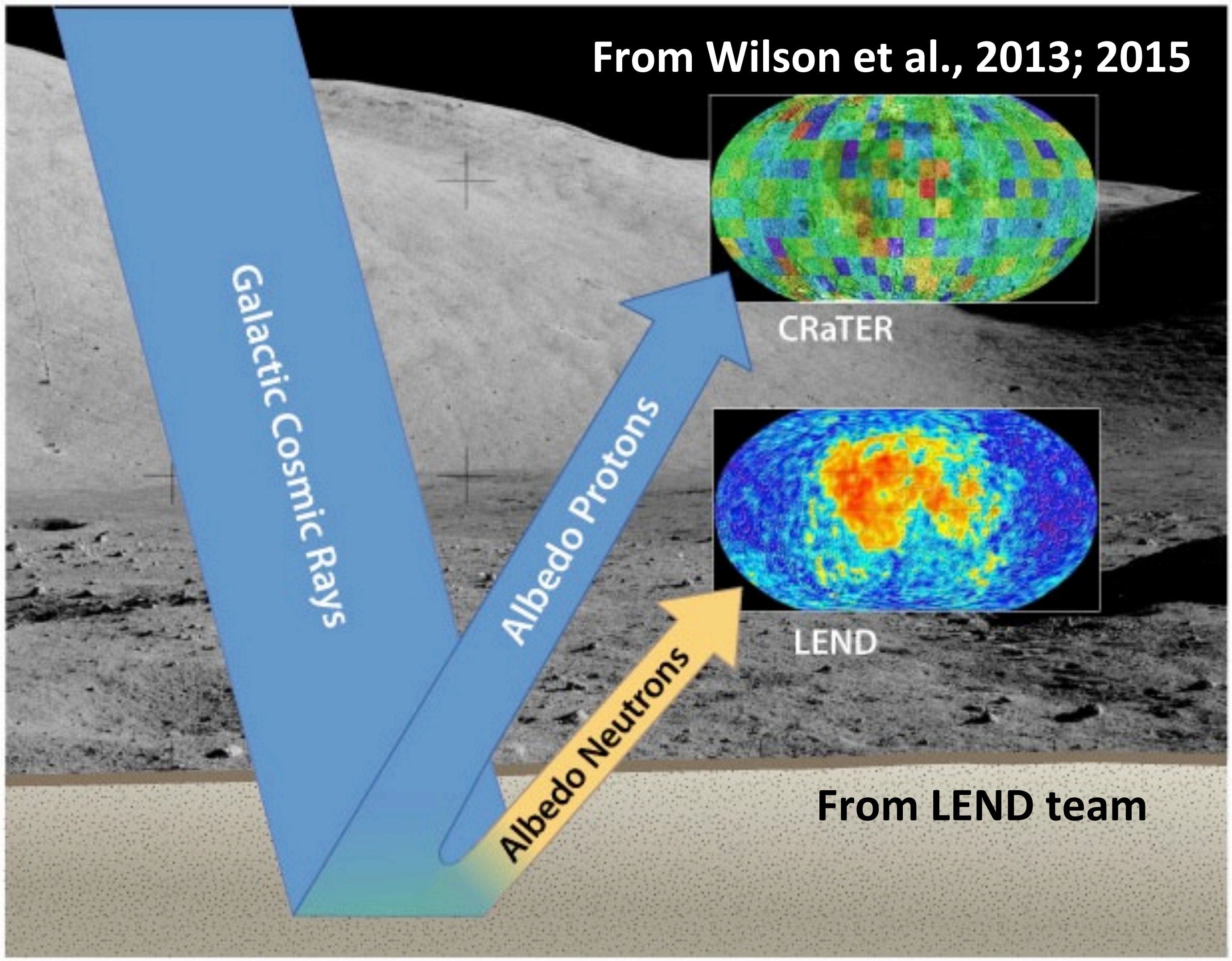
Mar 7, 2012 Event



May 16, 2012 Event



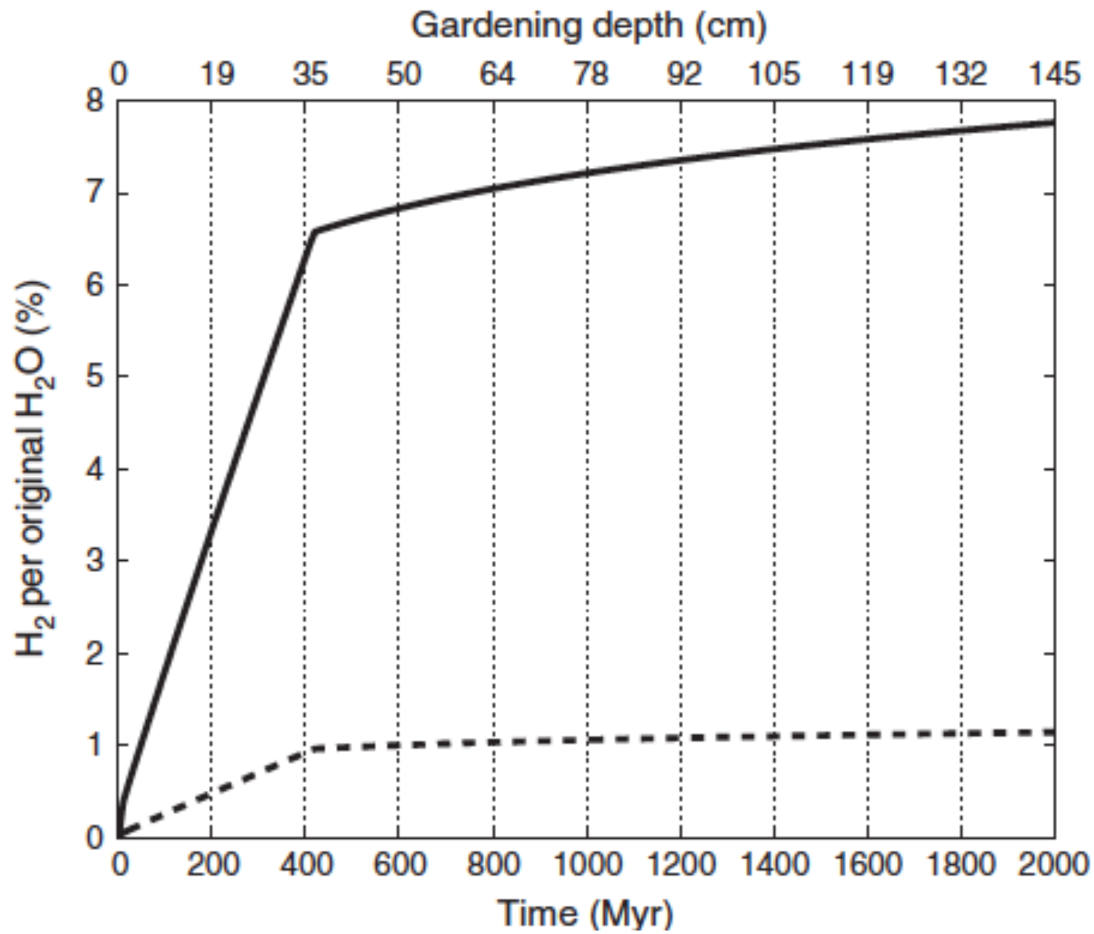
Remote sensing of regolith from GCR-produced energetic particle albedo



Chemical Weathering from GCR and SEP

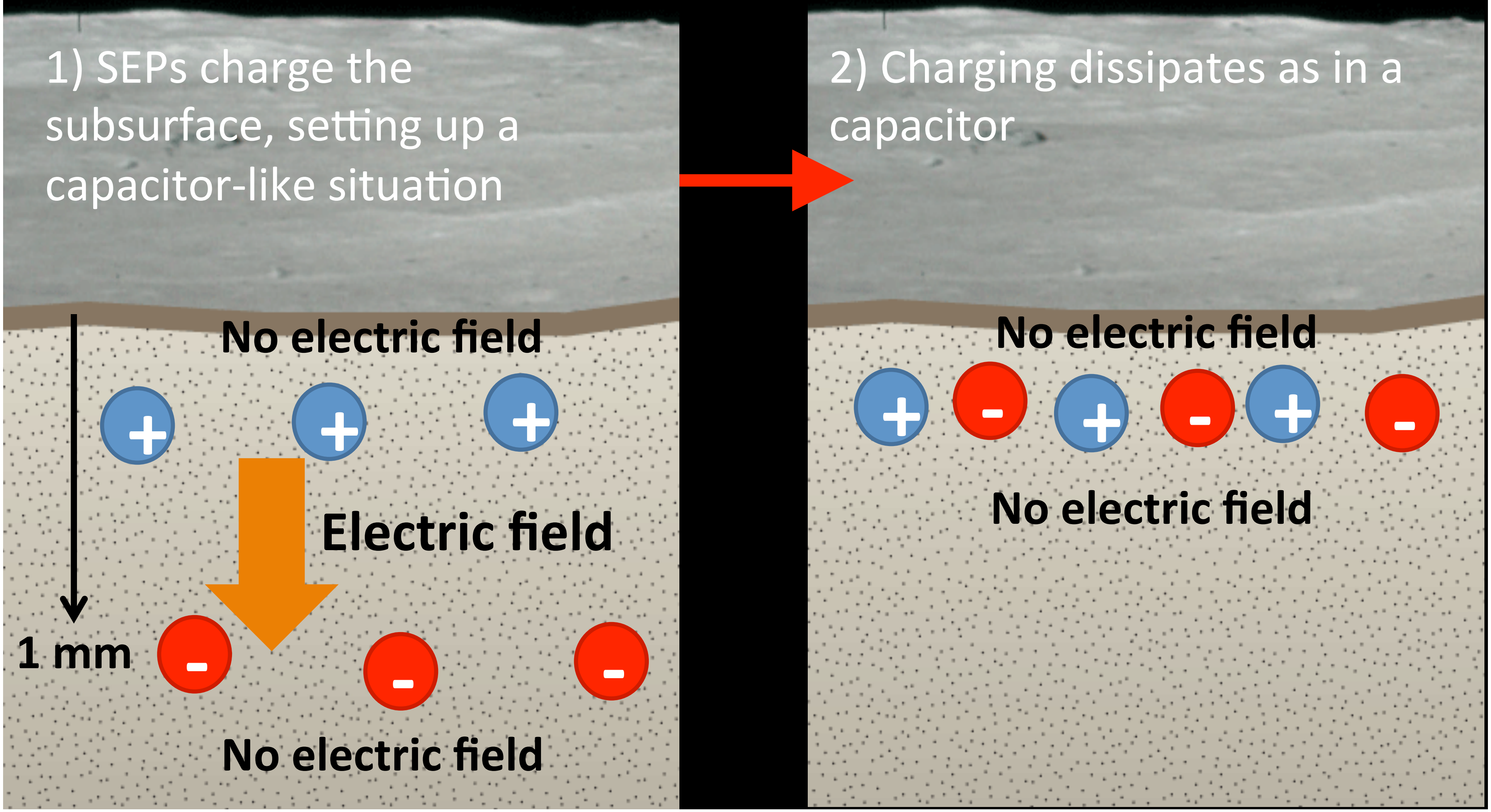
After Jordan et al., 2013

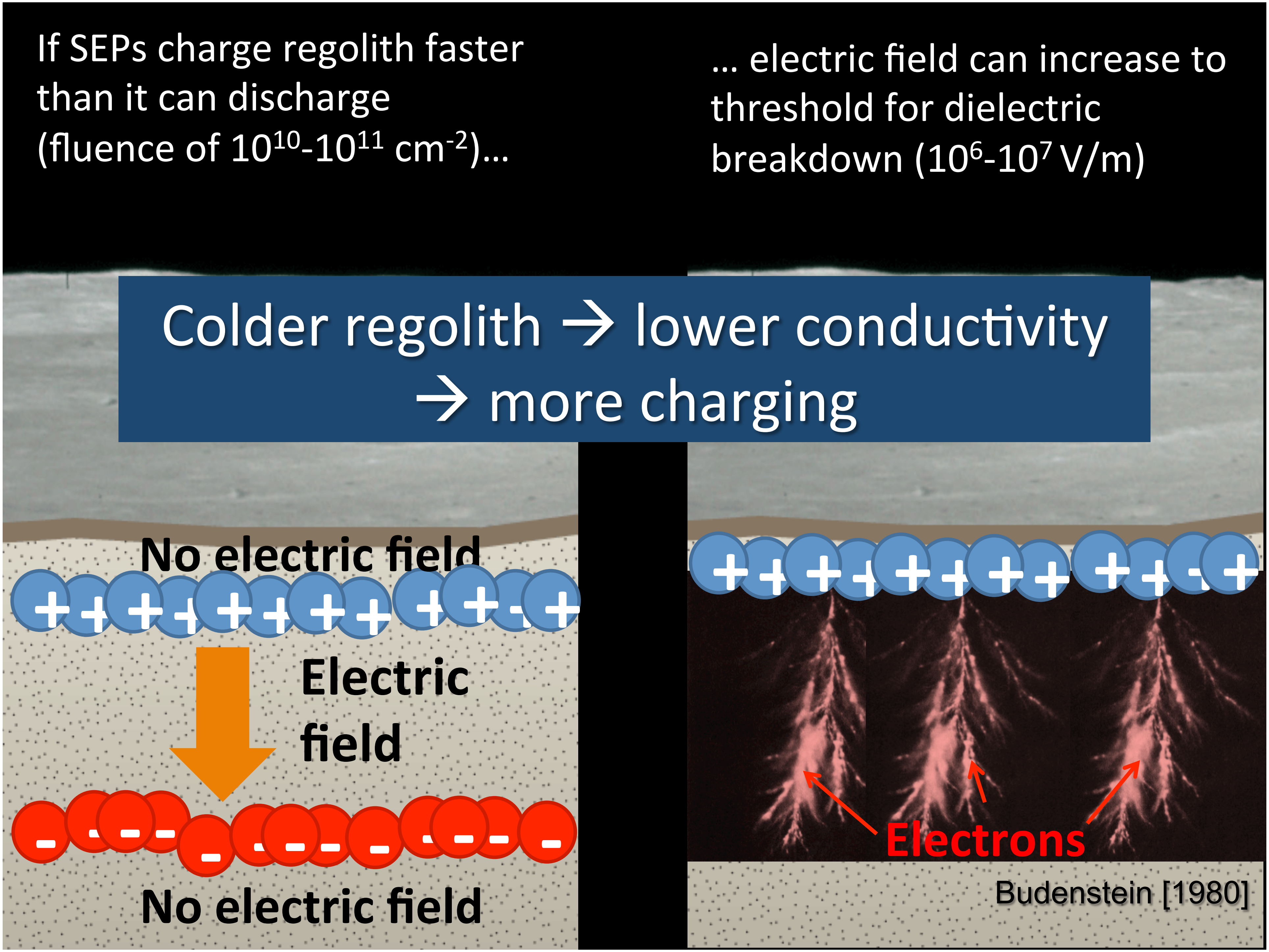
- GCRs and SEPs can penetrate the regolith in permanently shadowed regions and dissociate molecules in water ice and form H_2.
- We discover that GCRs and SEPs can convert perhaps all of the original water molecules into H_2 as observed by LCROSS and LRO's Lyman Alpha Mapping Project (LAMP) during the impact

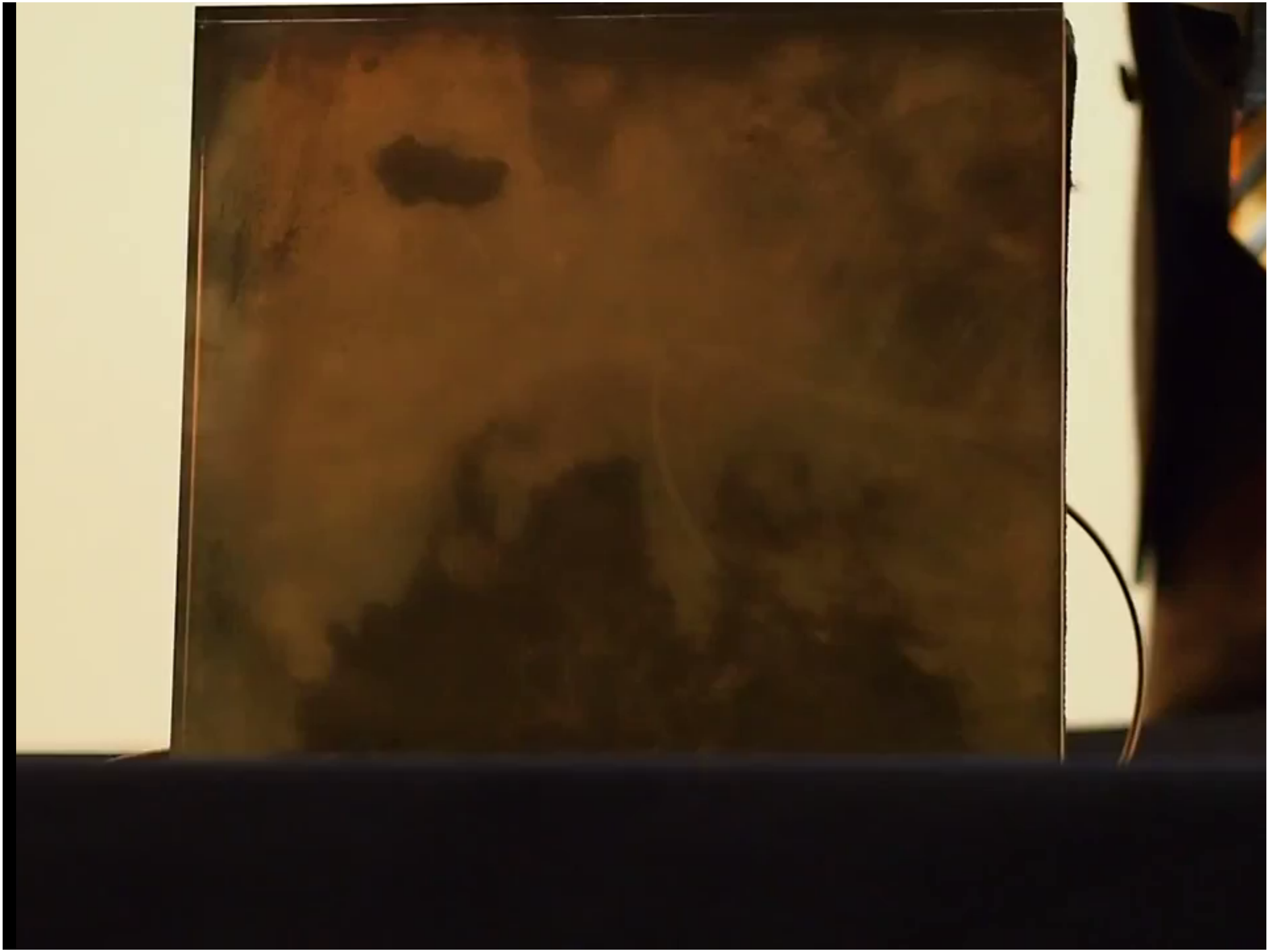


The percentage of H_2 molecules created by GCRs and SEPs with respect to the original number of water molecules as a function of gardening time (lower axis) and depth (upper axis). We assume that the GCR dose is applicable to 36 cm and the SEP dose to 0.18 cm.

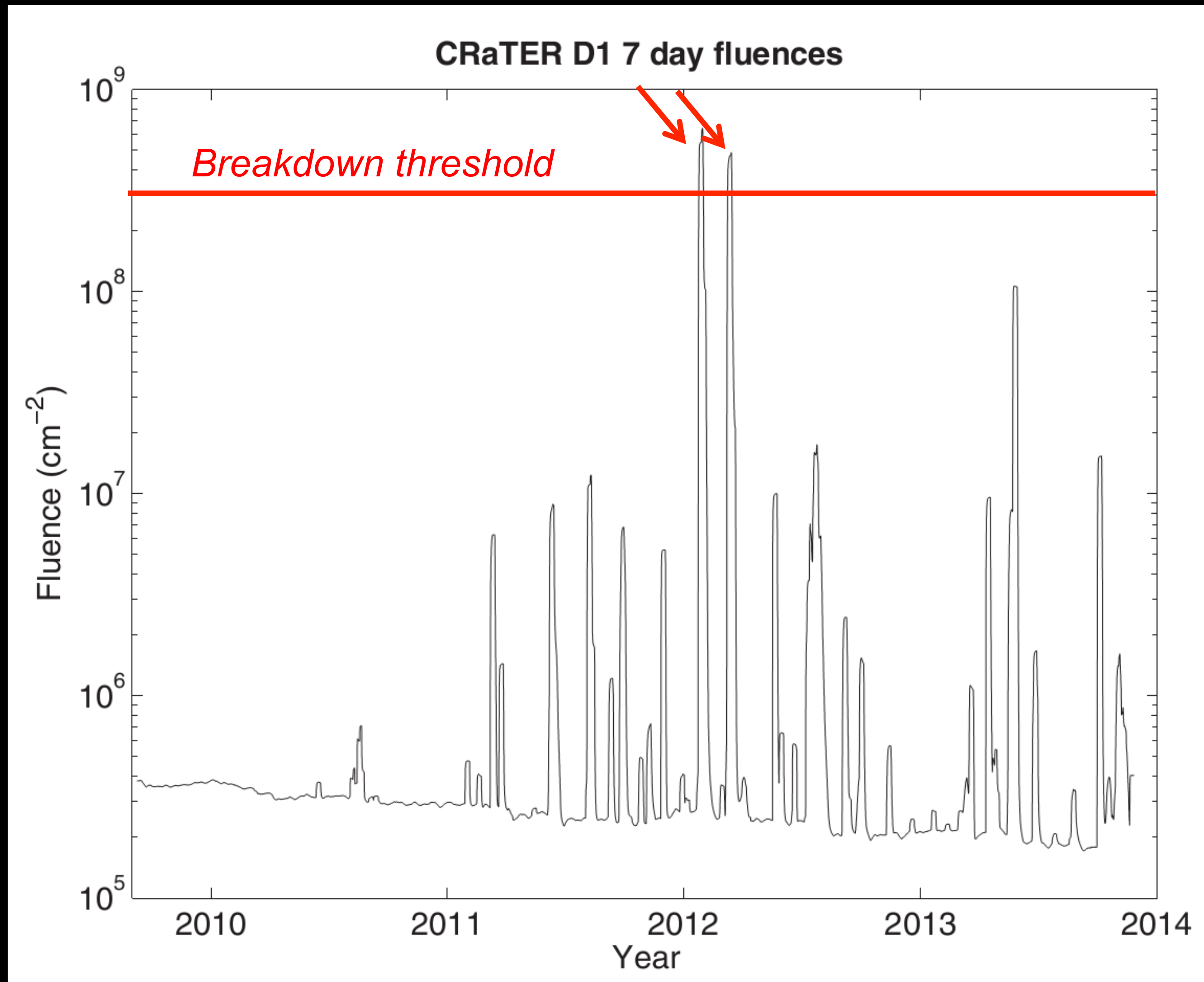
Solar Energetic Particles produce deep dielectric discharges




If SEPs charge regolith faster than it can discharge (fluence of 10^{10}-10^{11} cm^{-2})…
… electric field can increase to threshold for dielectric breakdown (10^6-10^7 V/m)
Colder regolith → lower conductivity → more charging
No electric field
Electric field
No electric field
Electrons
Budenstein [1980]



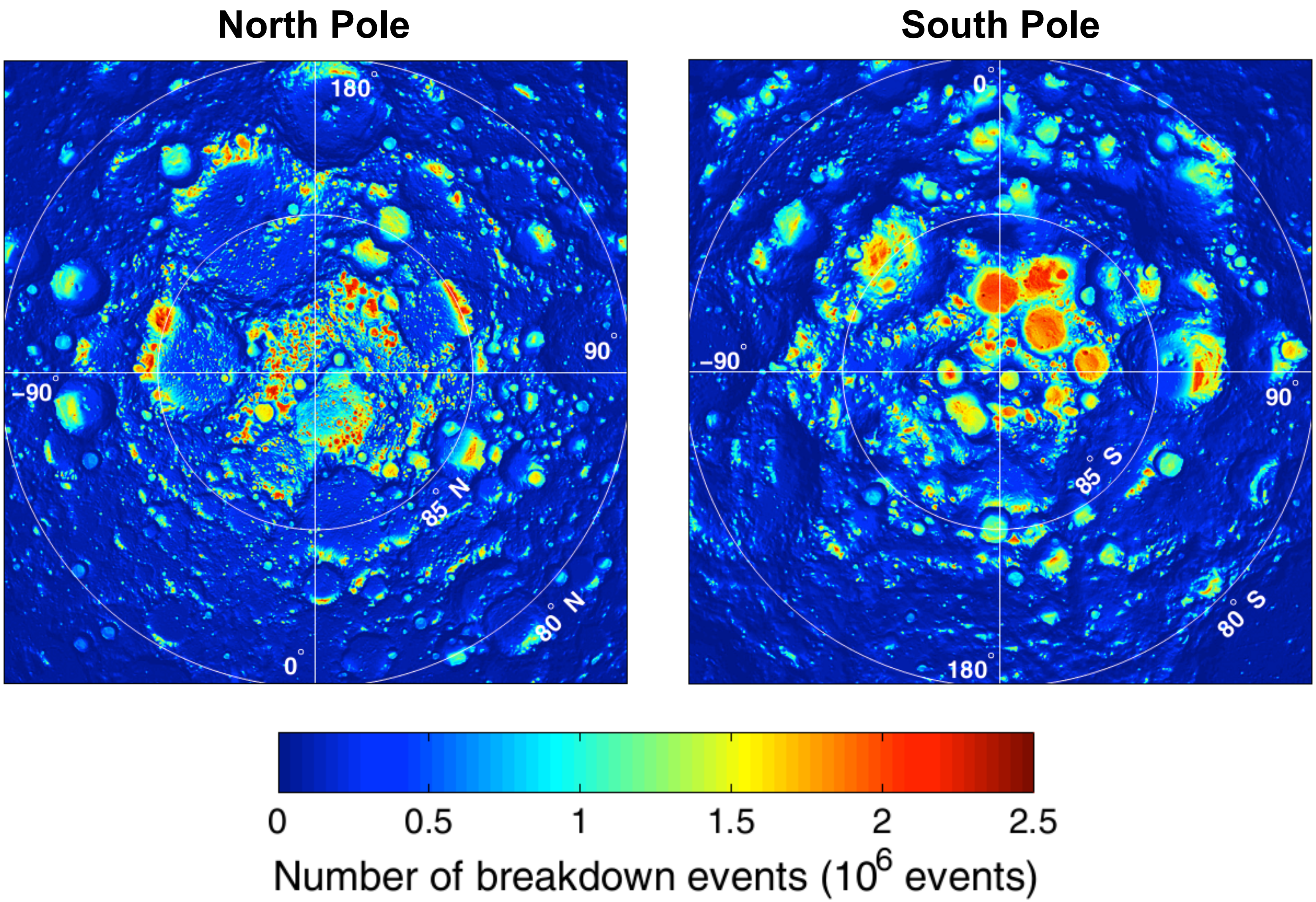
LRO/CRaTER data indicates two breakdown-causing SEP events occurred during mission.



(Jordan et al., 2015)

→ Up to 8% of PSR regolith grains in top 1 mm have received a breakdown channel during LRO's mission.

All gardened soil within PSRs has likely experienced ~10^6 SEP events capable of causing breakdown



(Jordan et al., 2015)

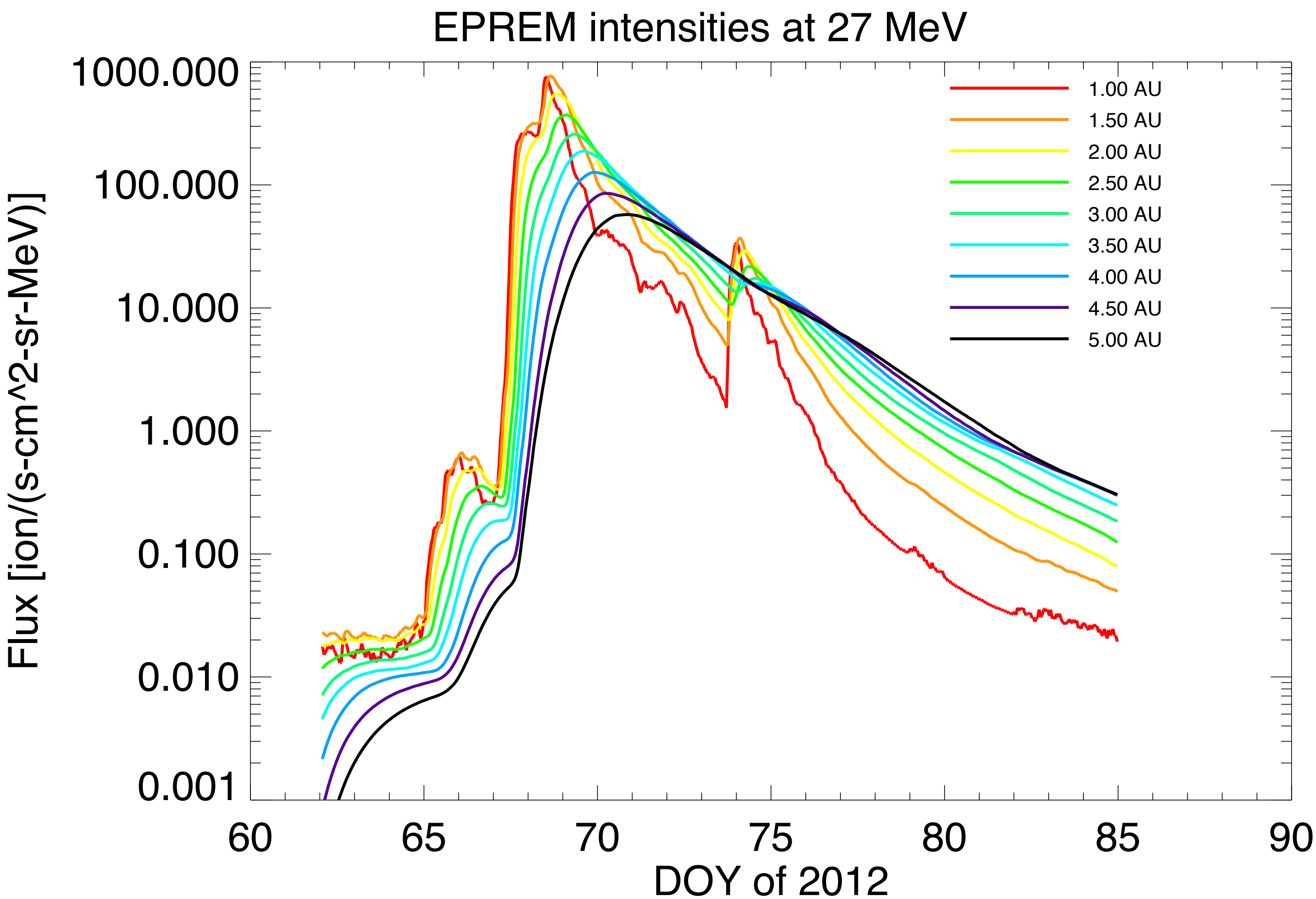
Scaling GCR Intensity

- Interplanetary magnetic field of solar origin poses obstacle for incoming GCR
- Establishes a radial gradient in GCR intensity: highest near edge of heliosphere, lowest near Sun (expected ratio of relevant particles is ~4 from Mercury to Pluto's orbit)
- GCR intensity varies over solar cycle by a factor of ~2 ever 11 years
- Relatively modest variation in environment between inner and outer solar system objects
- Similar (order-of-magnitude) production of GCR-derived albedos at Mercury, Moon, Phobos/Deimos, and Pluto – compositional differences would of course produce yields that are tracers of the different bulk regolith compositions

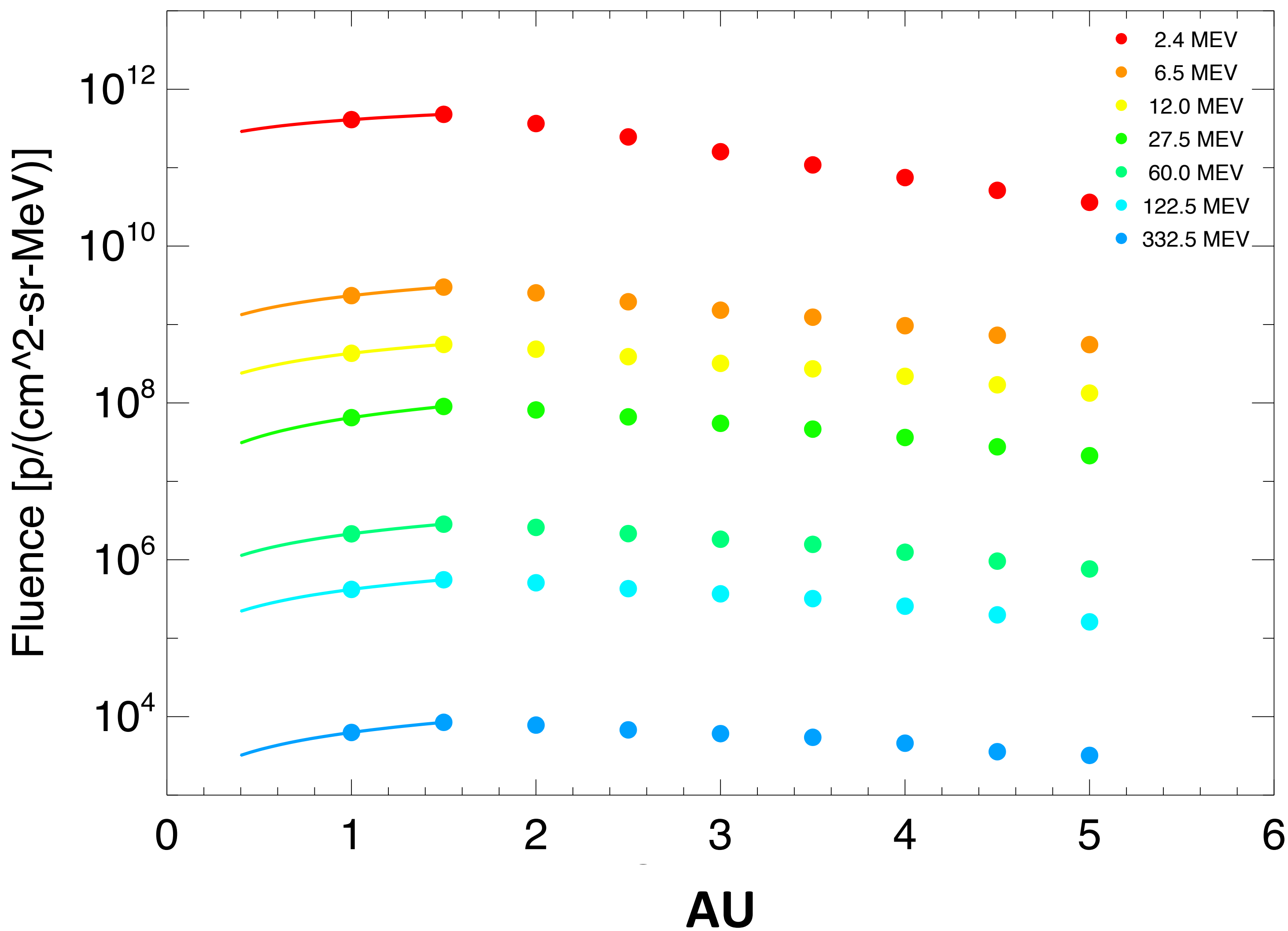
Scaling SEP Intensity

- Solar energetic particles (SEPs) generated near Sun during explosive release of magnetic energy (shocks associated with coronal mass ejections)
- SEPs propagate away from Sun, constrained by interplanetary magnetic fields, ultimately filling vast portions of the heliosphere
- Use EPREM model to estimate how SEP intensity varies as a function of distance from the Sun out to Jupiter, then scaled geometrically thereafter

SEP Flux vs. Time
(as a function of heliocentric distance)

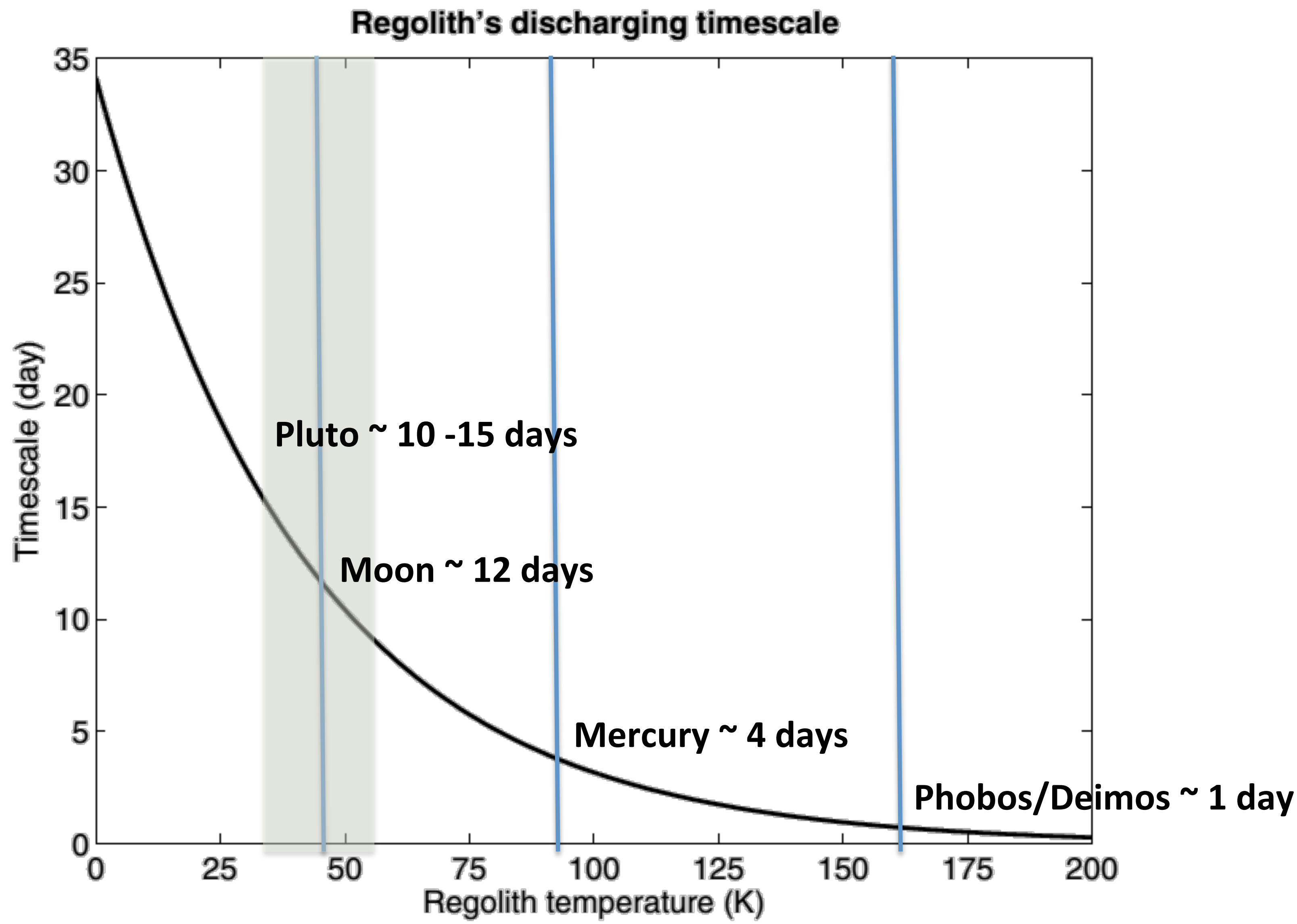


SEP Fluence vs. Heliocentric Distance (as a function of energy)

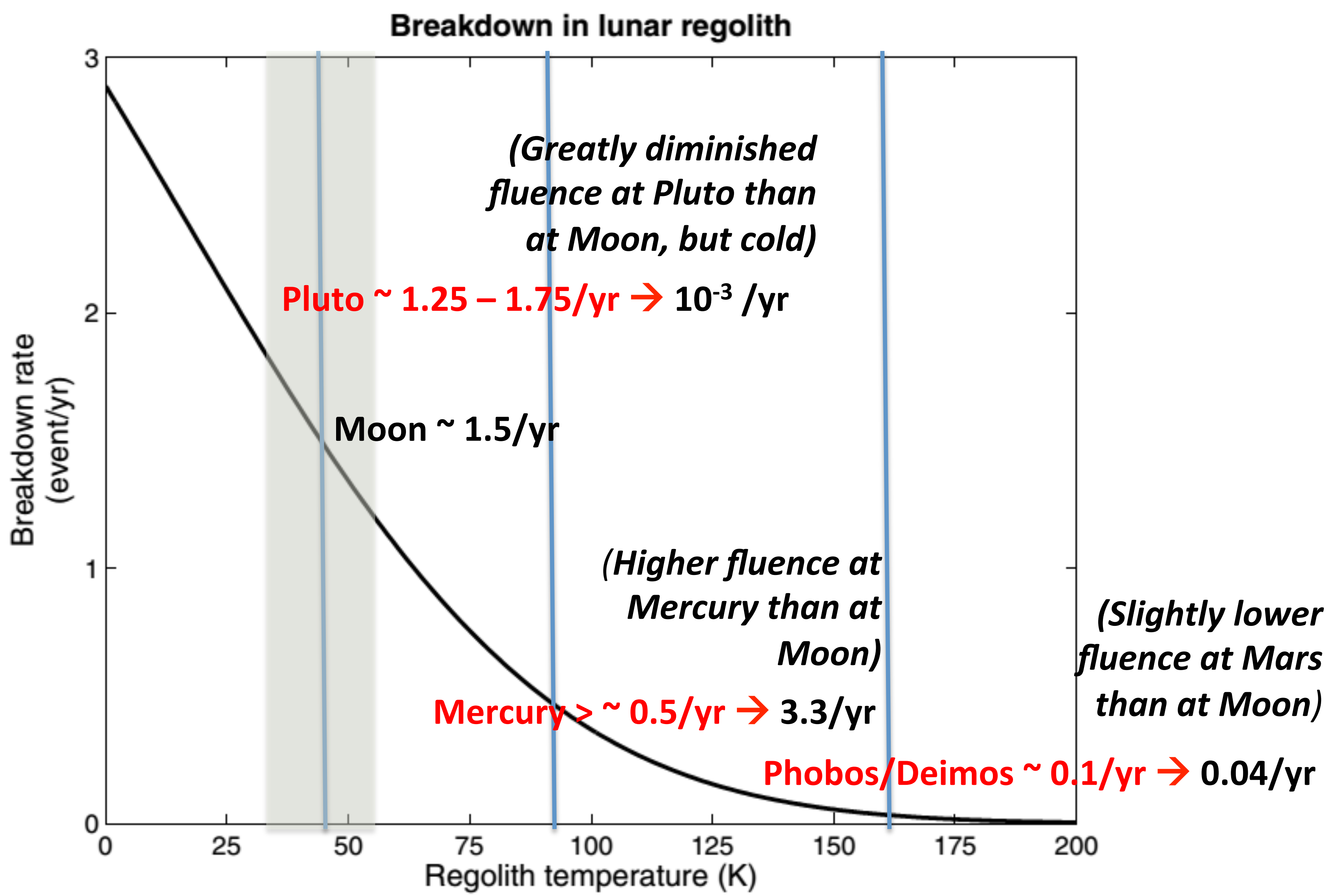


- Use this EPREM result to scale SEP fluences in inner solar system
- Beyond 5AU, use geometric scaling

Temperature Dependence of Regolith Electrostatic Breakdown Timescale



Temperature Dependence of Regolith Electrostatic Breakdown Rate

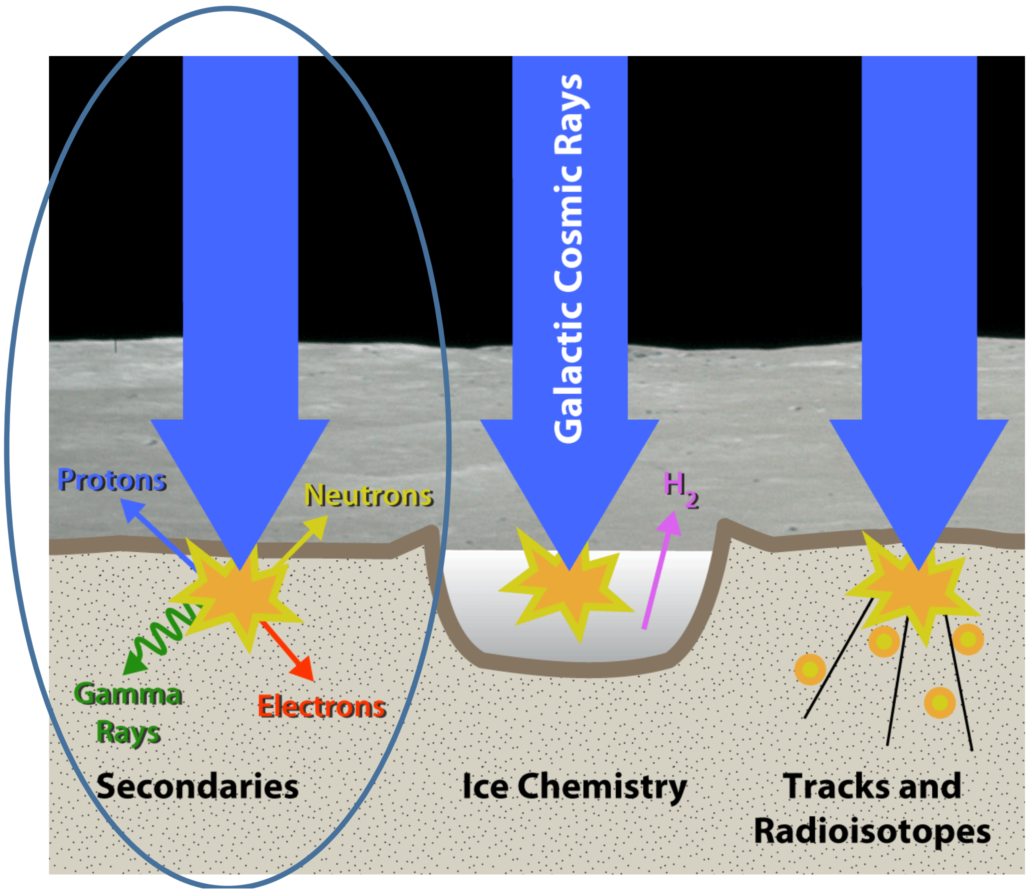


Summary

- Ionizing radiation throughout the heliosphere and at planets has both intrinsic science value ("truths") and exploration applications ("consequences")
  - Lunar Reconnaissance Orbiter discovering the roles that ionizing radiation plays in modifying planetary surfaces
    - **Solar particle events causing deep dielectric discharges may be as important as meteoritic weathering at Moon, particularly in PSRs**
    - **Same space weathering effects may also be important in PSRs at Mercury and at Phobos and Deimos**
    - **Less likely an important effect in outer solar system (i.e., Pluto, KBOs, etc.) as SEP fluence greatly diminished**
- Examples underscore how ionizing radiation studies, motivated initially by exploration, also provide insights on the scientific processes shaping solar system objects

Backup Slides

Consequences of Lunar Energetic Particle Albedo from LRO



NASA LRO CRaTER
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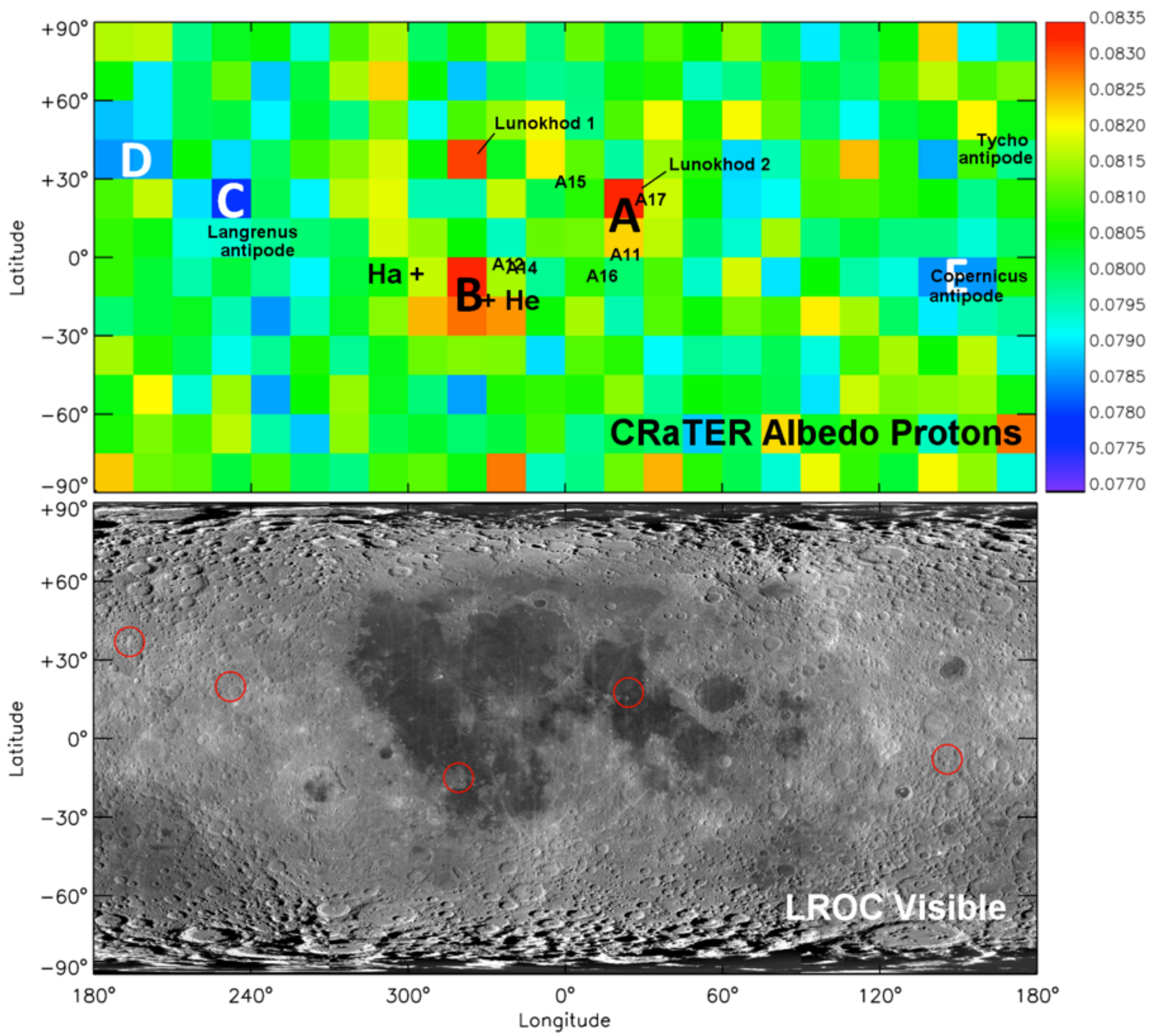
How the Moon looks through the lens of proton albedo from GCR source

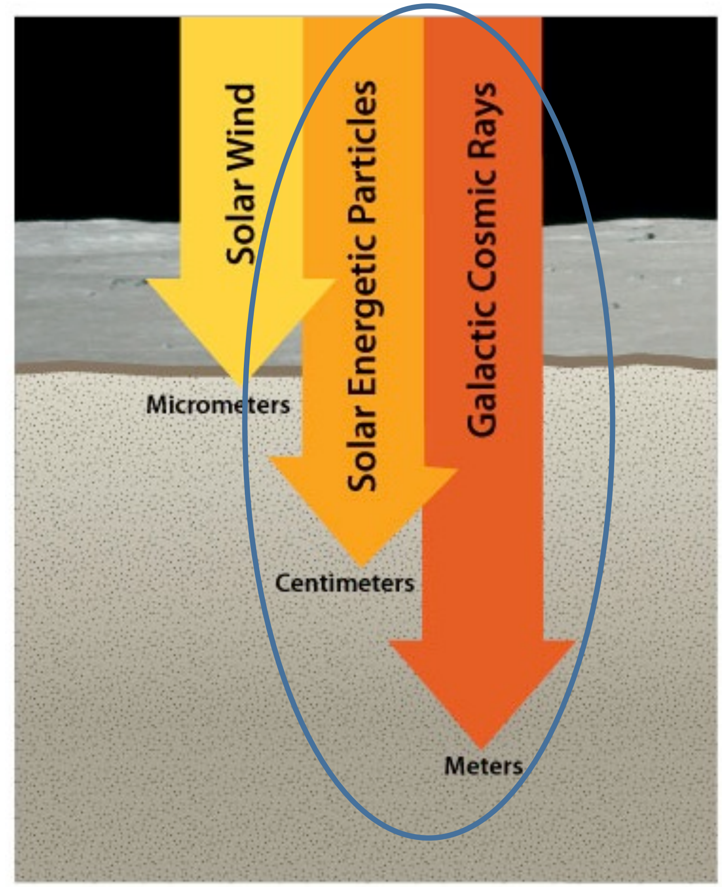


From Wilson et al., 2013; 2015

- Yield from mare statistically greater than from highlands (consistent with bulk elemental composition differences)
- High/low albedo spots still not well understood – statistics improving with time will help differentiate potential mechanisms

What do we mean by Energetic Particle Albedo?

- The term “albedo” borrowed loosely from optical physics
- Particle “albedo” refers to particles released from Moon owing to processes occurring within lunar regolith
- Specifically here, focus on albedo particles produced through <u>nuclear</u> reactions when solar energetic particles and galactic cosmic rays interact with material in outer layers of regolith – requires HIGH impact energies to get nuclear interactions
- Albedo particles are **energetic secondary** particles created and released after primary cosmic ray particles strike surface down to a few meters



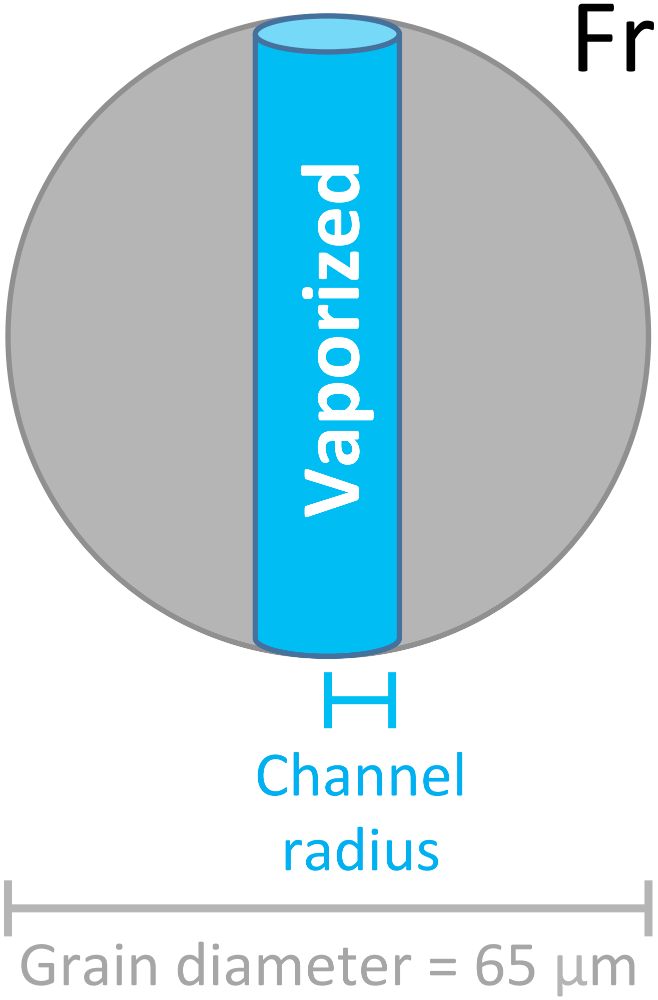
What can breakdown weathering do?

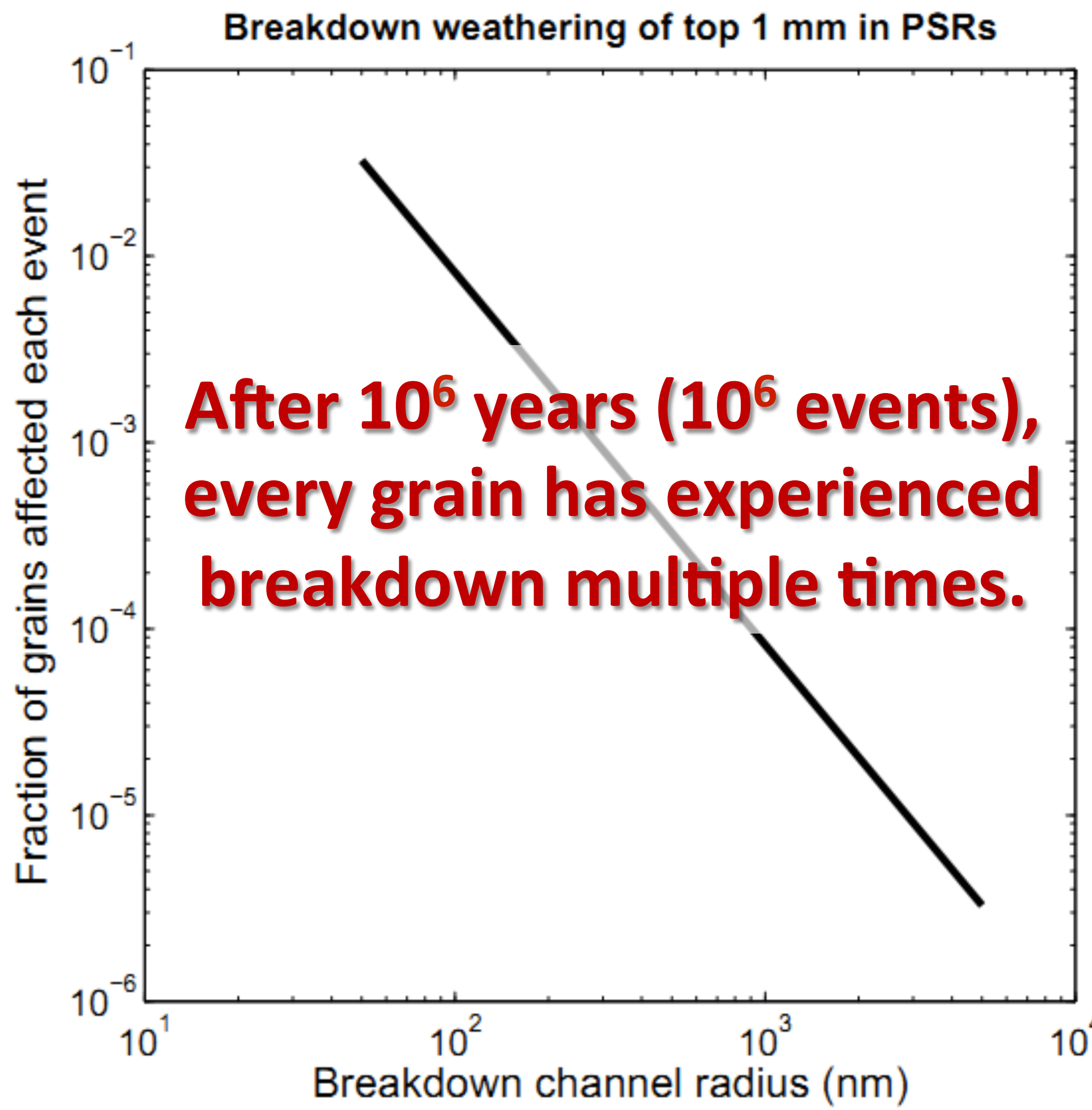
- E-field energy density due to large SEP event: $\mathbf{u_E \approx 880\ J\ m^{-3}}$ (assuming 10^7 V/m)
- Energy density needed to vaporize all regolith: $\mathbf{u_{reg} = \rho_{reg}\ c_p\ (T_{vapor} - T_{PSR}) = 7.3 \times 10^9\ J\ m^{-3}}$
- Fraction of top 1 mm vaporized each event: $\mathbf{u_E / u_{reg} = 1.2 \times 10^{-7}}$
- After 10^6 yr (10^6 events), percentage vaporized: **~12%**

How does breakdown weathering compare to meteorite weathering?

- **Meteorite weathering**
  - Energy flux:
    F_m = 12 J m^{-2} yr^{-1} (Grün et al., 1985)
  - Meteoritic vapor/melt production:
    P_m = 1.8 x 10^{-7} kg m^{-2} yr^{-1} (Cintala, 1992)
- **Breakdown weathering**
  - Breakdown energy flux:
    F_E ≈ 0.88 J m^{-2} yr^{-1}
  - Breakdown vapor/melt production:
    P_E ≈ 1.8 x 10^{-7} kg m^{-2} yr^{-1}

Fraction of grains affected by breakdown weathering

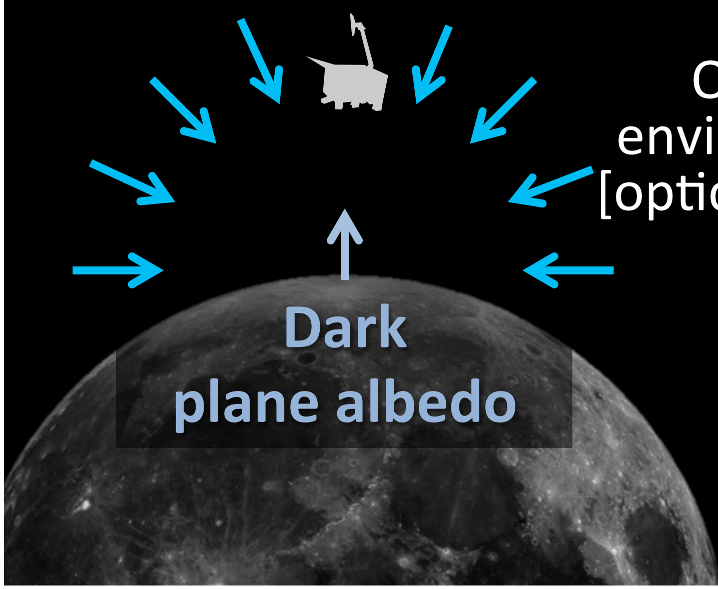




After 10^6 years (10^6 events), every grain has experienced breakdown multiple times.

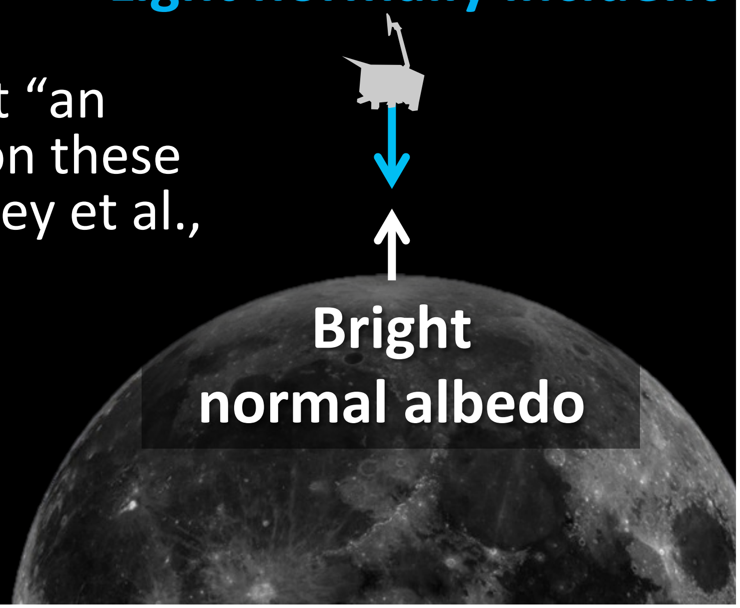
Instrument	Observation of PSR regolith
LCROSS	Increased porosity in Cabeus (Schultz et al., 2010)
LRO/LAMP	Darker plane albedo / increased porosity (Gladstone et al., 2012)
LRO/LOLA	Brighter normal albedo (Lucey et al., 2014)

LRO/LAMP:
Light incident from 2π sr



Observations suggest "an environmental control on these [optical] properties" (Lucey et al., 2014)

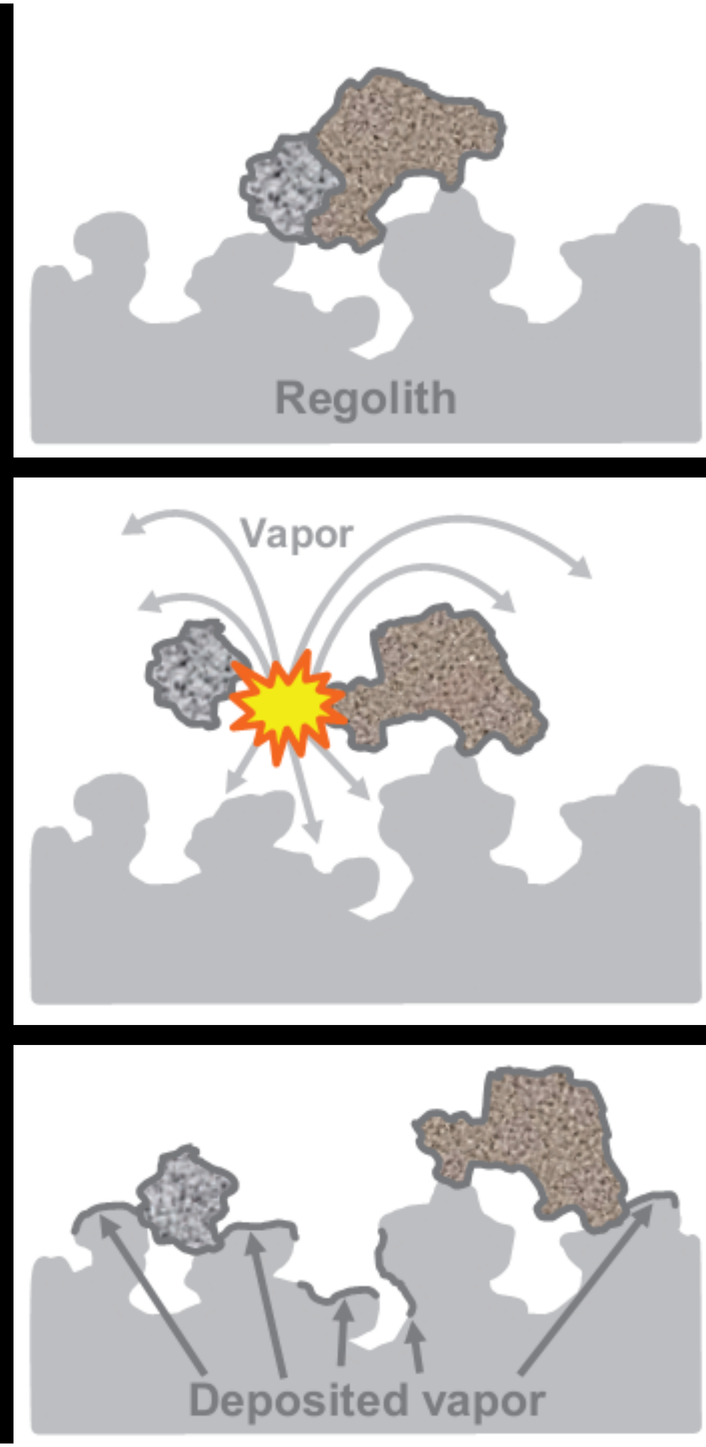
LRO/LOLA:
Light normally incident



Grain at regolith's surface

Breakdown vaporizes some of grain's material and splits grain

Deposited vapor increases nanophase iron, and regolith's porosity changes



Jordan et al. (2015)

Science summary #2 – Significant radiation impacts to lunar regolith

Breakdown weathering in PSRs

- may produce vapor/melt comparable to meteoritic weathering
- affects ~12% of gardened regolith
- may help explain PSR observations

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