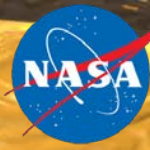


# Signatures of Volatiles in the CRaTER Proton Albedo



N. A. Schwadron, J. K. Wilson, M. D. Looper,  
A. P. Jordan, H. E. Spence, J. B. Blake, A. W. Case,  
Y. Iwata, J. C. Kasper, W. M. Farrell, D. J. Lawrence ,  
G. Livadiotis, J. Mazur, N. Petro, C. Pieters  
M. S. Robinson, S. Smith, L. W. Townsend, C. Zeitlin

# Select Recent Publications



## >50 Refereed Publications from the CRaTER team

6 refereed publications in 2014

11 refereed publications so far in 2015

## CRaTER Special Issue of *Space Weather* - 10 Articles on CRaTER Measurements and Implications

- Schwadron, N. A., S. Smith and H. E. Spence, The CRaTER Special Issue of Space Weather: Building the observational foundation to deduce biological effects of space radiation, *Space Weather*, 11, 47, doi:10.1002/20026, 2013
- Case, A.W., The Deep-space Galactic Cosmic Ray Lineal Energy Spectrum, 2013, *Space Weather*, doi:10.1002/swe.20051
- Looper, M.D. et al., The Radiation Environment Near the Lunar Surface: CRaTER Observations and Geant4 Simulations. *Space Weather*, Vol. 11, 142-152, doi:10.1002/swe.20034, 2013
- Joyce, C.J., et al., Validation of PREDICCS Using CRaTER/LRO Observations During Three Major Solar Events in 2012 using CRaTER and the EMMREM Model. *Space Weather*, Vol. 11, pp. 1-11, doi:10.1002/swe.20059, 2013
- Spence, H. E., et al., Relative contributions of galactic cosmic rays and lunar proton "albedo" to dose and dose rates near the Moon, *Space Weather*, 11, 643, 2013
- Porter, J. A., et al., Radiation environment at the Moon: Comparisons of transport code modeling and measurements from the CRaTER instrument, *Space Weather*, 12, 329, 2014
- Joyce, C. J., et al., Radiation modeling in the Earth and Mars atmospheres using LRO/CRaTER with the EMMREM Module, *Space Weather*, 12, 112, 2014
- Zeitlin, C.; et al. Measurements of Galactic Cosmic Ray Shielding with the CRaTER Instrument. *Space Weather*, Vol. 11, pp. 284-296, doi:10.1002/swe.20043, 2013
- Schwadron, N., Bancroft, C., Bloser, P., Legere, J., Ryan, J., Smith, S., Spence, H., Mazur, J., and Zeitlin, C., Dose spectra from energetic particles and neutrons, *Space Weather*, 11, 547, 2013
- Schwadron et al., Does the Worsening Galactic Cosmic Radiation Environment Preclude Future Manned Deep Space Exploration, *Space Weather*, 2014





# Select Recent Publications



## Articles on Charging of Regolith and Changing Space Environment

- Jordan, A. P., T. J. Stubbs, J. K. Wilson, N. A. Schwadron, H. E. Spence and C. J. Joyce, **Deep dielectric charging of regolith with the Moon's permanently shadowed regions**, *JGR Planets*, 119, doi:10.1002/2014JE004648.
- Jordan, A. P., T. J. Stubbs, J. K. Wilson, N. A. Schwadron, and H. E. Spence (2015), Dielectric breakdown weathering of the Moon's polar regolith, *J. Geophys. Res. Planets*, in press, doi: 10.1002/2014JE004710.
- Smith, C. W., McCracken, K. G., Schwadron, N. A., and Goelzer, M. L., The heliospheric magnetic flux, solar wind proton flux, and cosmic ray intensity during the coming solar minimum, *Space Weather*, 12, 499, 2014
- Jordan et al., The rate of dielectric breakdown weathering of lunar regolith in permanently shadowed regions, *LRO Special Issue of Icarus*, 2015
- Spence et al., Space Weathering throughout the solar system, in work, 2015

## Articles on Proton Albedo and Implications

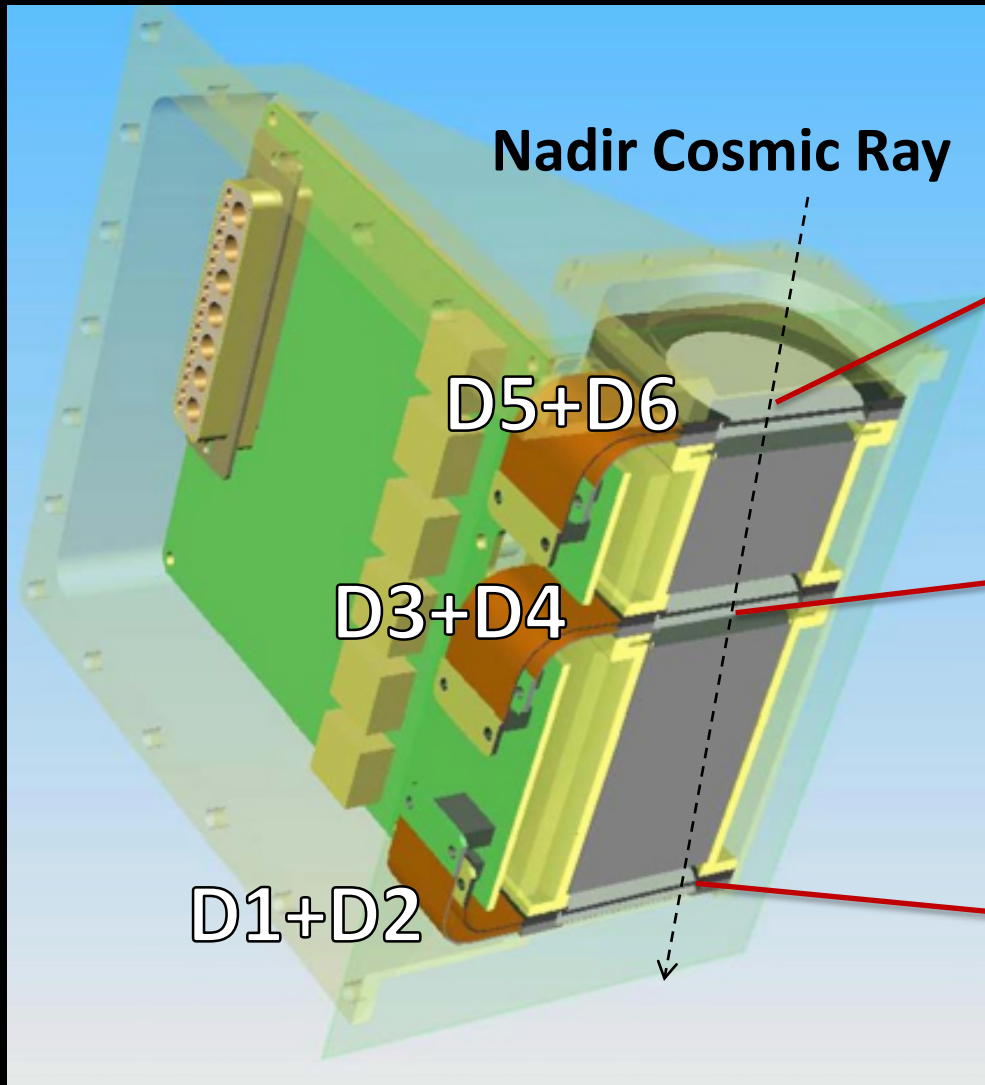
- Wilson, J., et al., **Localized Features in the Albedo Proton Map of the Moon**, *LRO Special Issue of Icarus*, 2015
- Schwadron et al., Signatures of Volatiles from Albedo Protons, *LRO Special Issue of Icarus*, 2015

## Articles with Impact for Human Exploration

- Joyce et al., Analysis of the potential radiation hazard of the 23 1 July 2012 SEP event observed by STEREO A using 2 the EMMREM model and LRO/CRaTER, *Space Weather, In Press*, 2015
- Mazur et al., Update On Radiation Dose From Galactic and Solar Protons at the Moon Using the LRO/CRaTER Microdosimeter, *Space Weather*, 2015
- Winslow et al., Interplanetary Coronal Mass Ejections from MESSENGER orbital observations at Mercury, *JGR*, in press 2015
- de Wet, W.C.; Townsend, L.W.; Xu, G.; and Smith, W.J.: The Standalone Package for Enhanced Estimation of Dose Distribution. Nuclear Technology, December 2015 (in press).



# Kinetic Energy and Linear Energy Transfer (LET): Primary Data & Key to Directionality



**High Kinetic Energy**

→ Low LET

**Lower Kinetic Energy**

→ Intermediate LET

**Even lower Kinetic Energy**

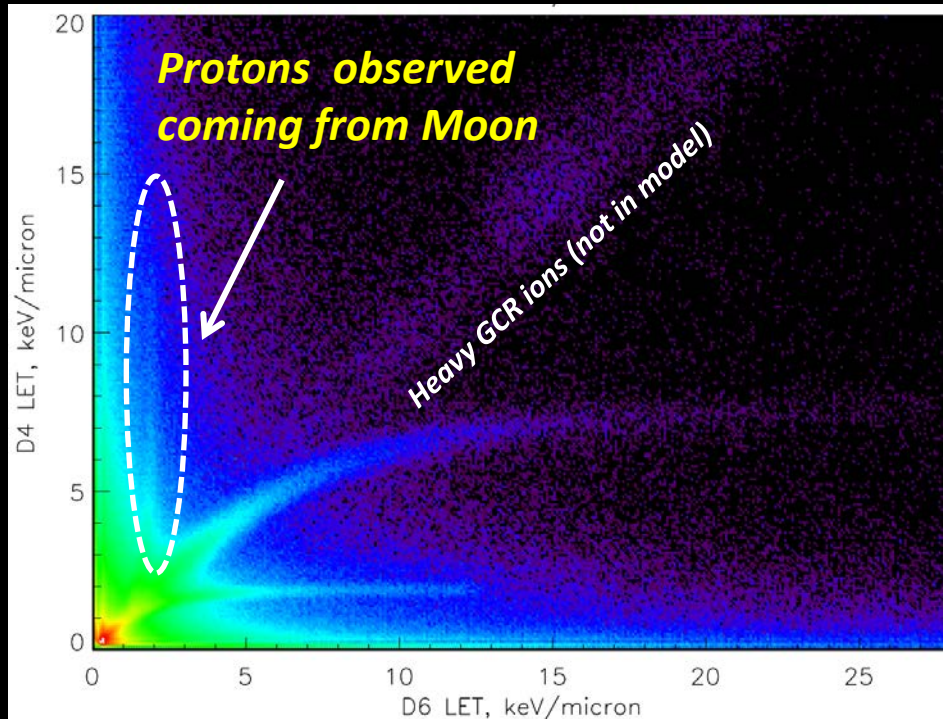
→ **High LET**



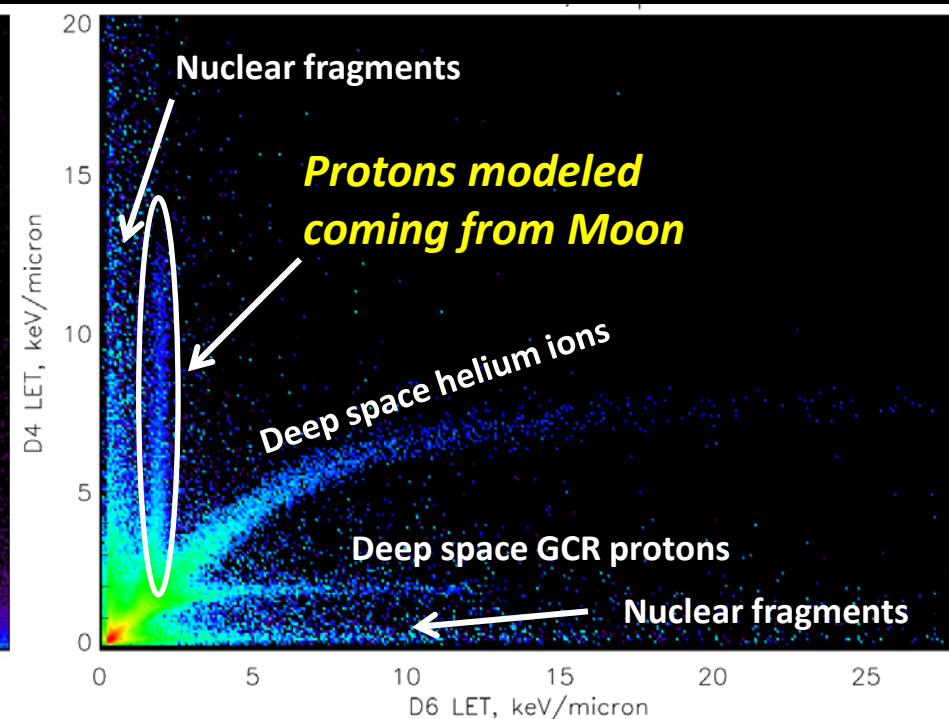
# Proton Albedo and Nuclear “Scruff”



*After Looper et al., 2013*



**4-Months of CRaTER Observations**



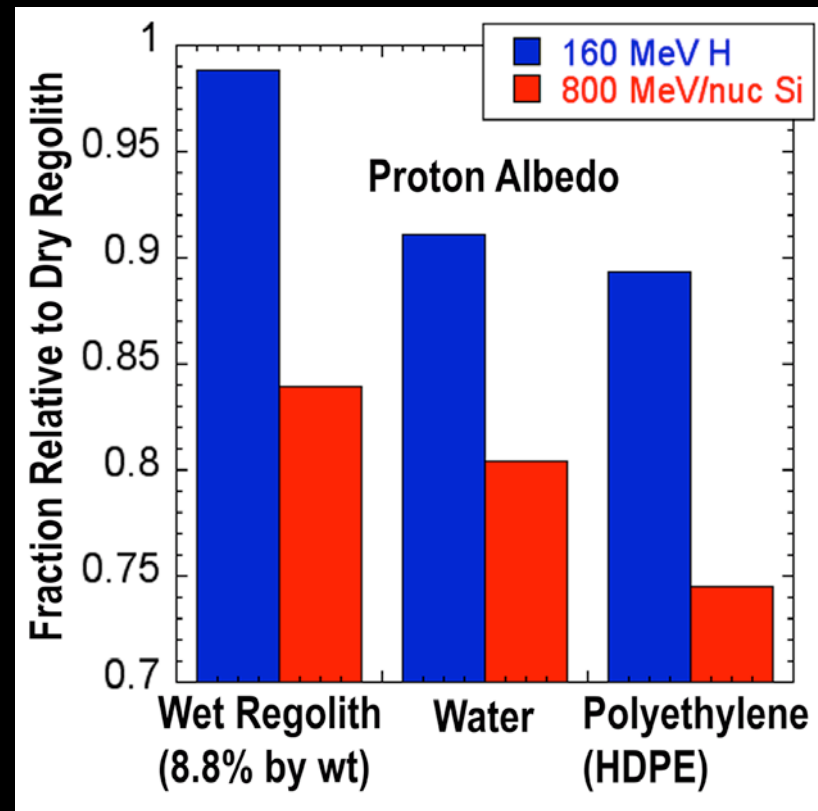
**CRaTER Model Response to GCR**

- CRaTER confirms existence of lunar proton albedo (adds to well-known neutron albedo) → created by nuclear evaporation process
- Upward-moving lunar protons (albedo) created from primary GCR slamming into the Moon
- Nuclear fragments (mostly pions, kaons, etc.) generated as GCR interacts with tissue-equivalent plastic within CRaTER – a major motivation for this experiment
- Heavy GCR ions (not included in model) seen clearly in observations out to Iron





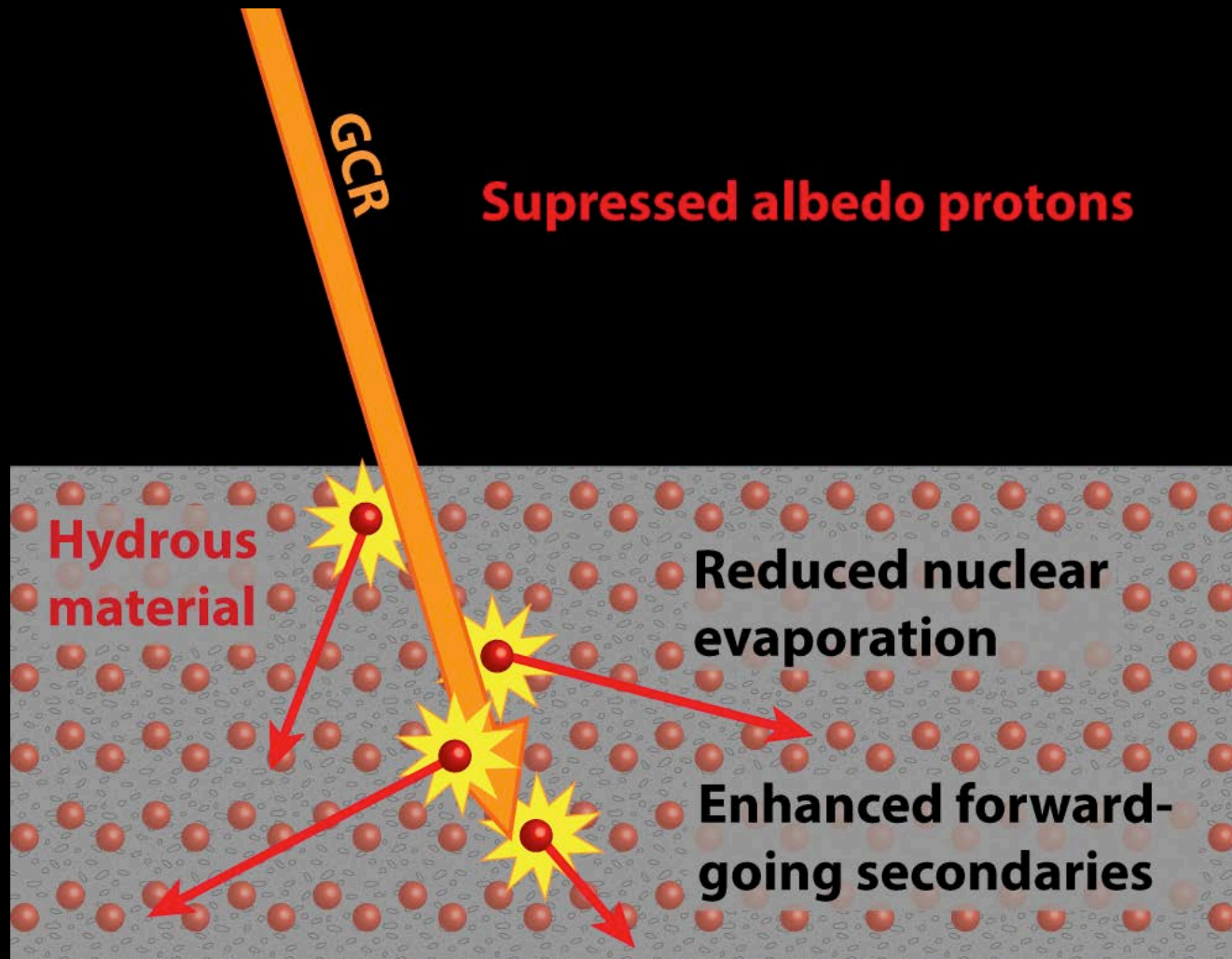
# Beam Measurements Show Deficit in Albedo from Wet Regolith



Schwadron et al., Icarus, 2015



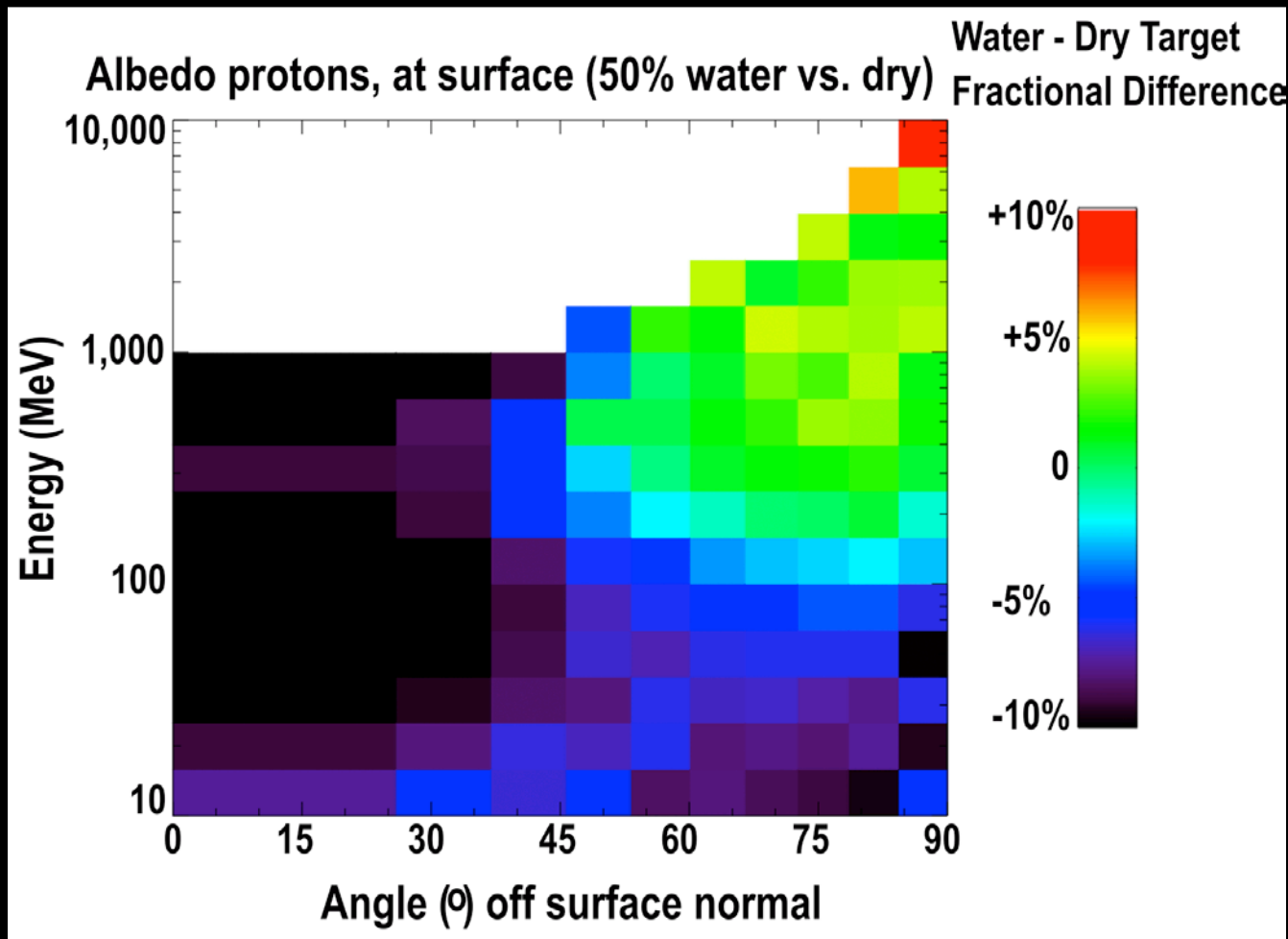
# Deficit Caused by Enhanced Forward Scattering



Schwadron et al., Icarus, 2015



# Deficit in Albedo Confirmed from Geant4 Simulations



Schwadron et al., Icarus, 2015

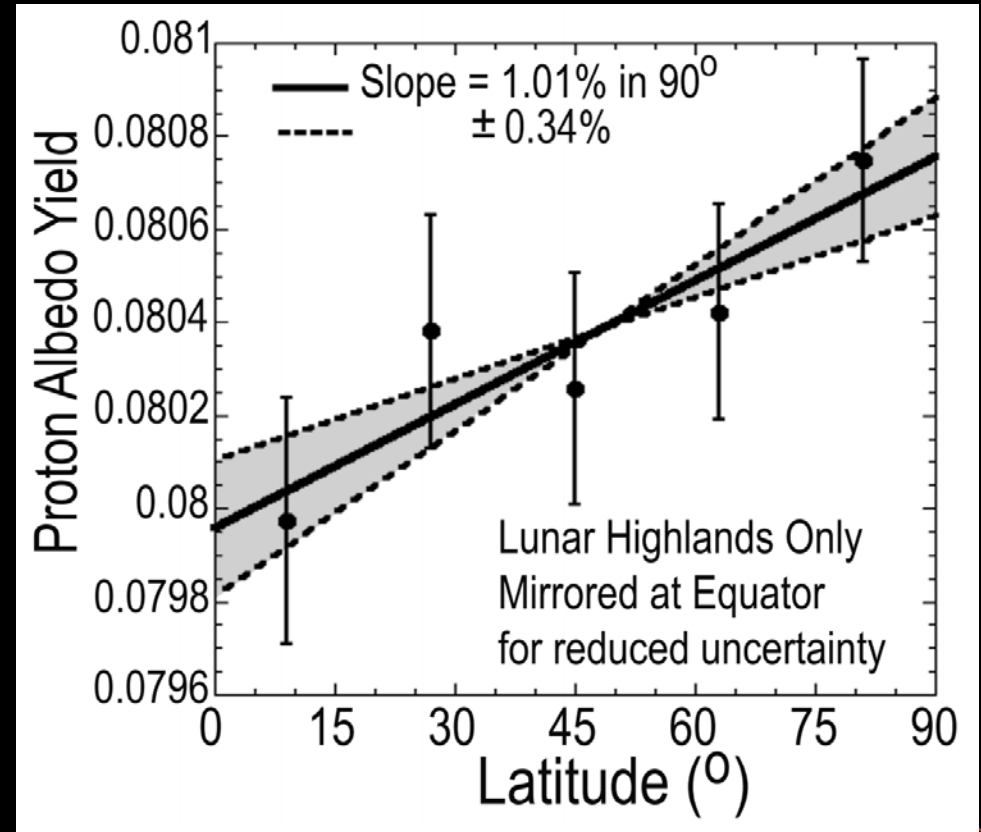
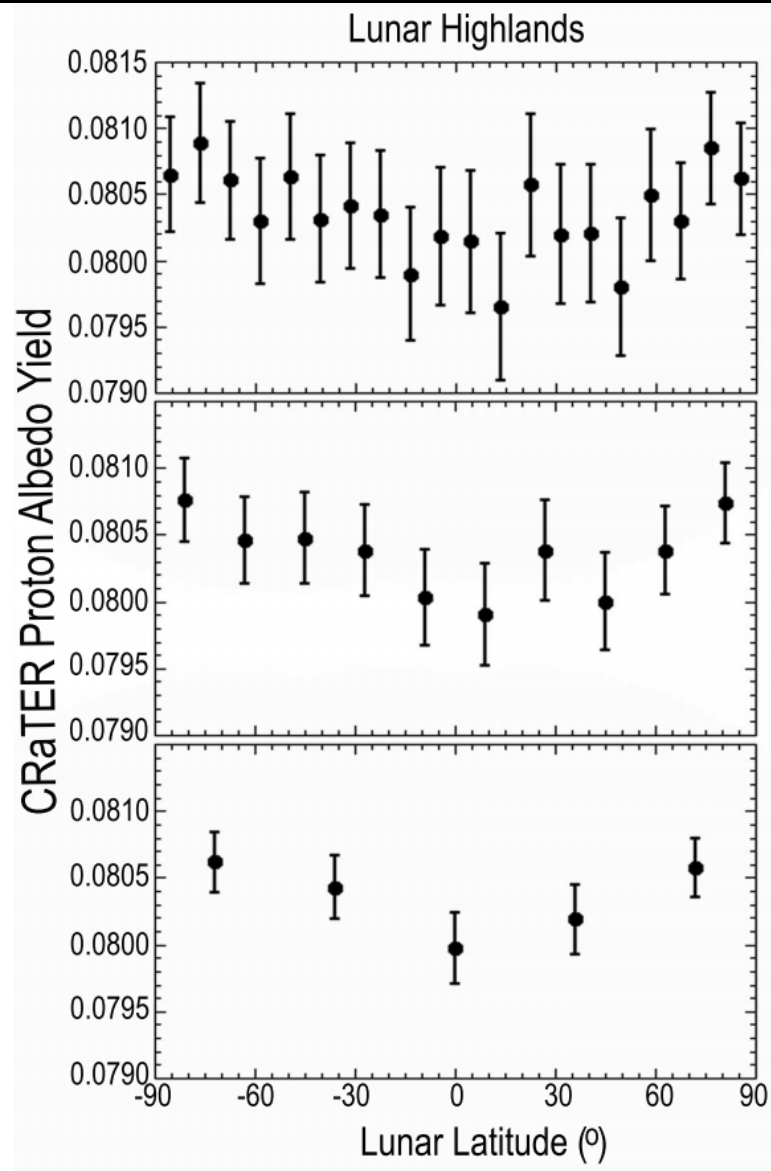




# Proton Albedo with Latitude in Highlands



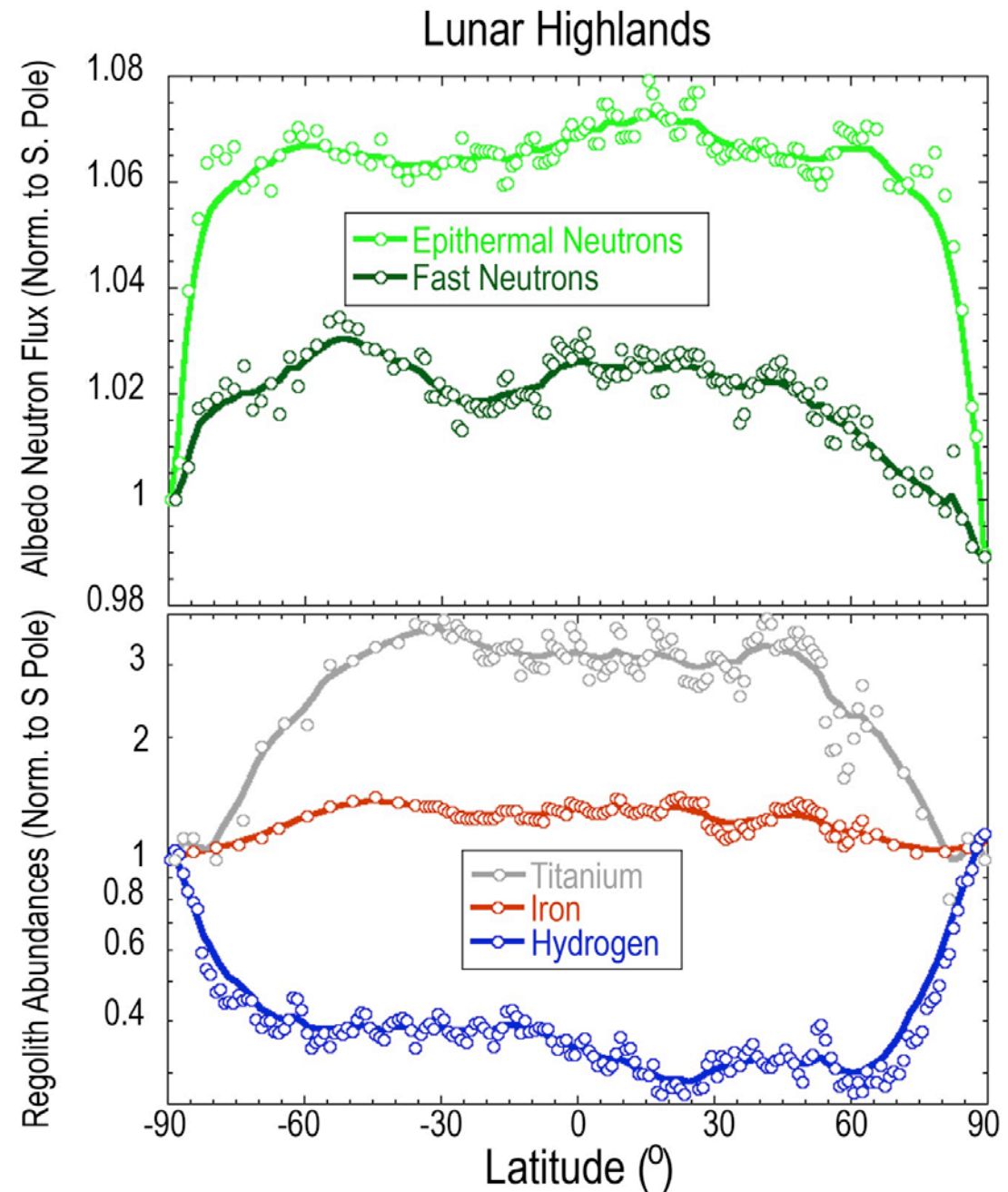
See Wilson et al. Poster – **LEAG, #2064**



Schwadron et al., Icarus, 2015

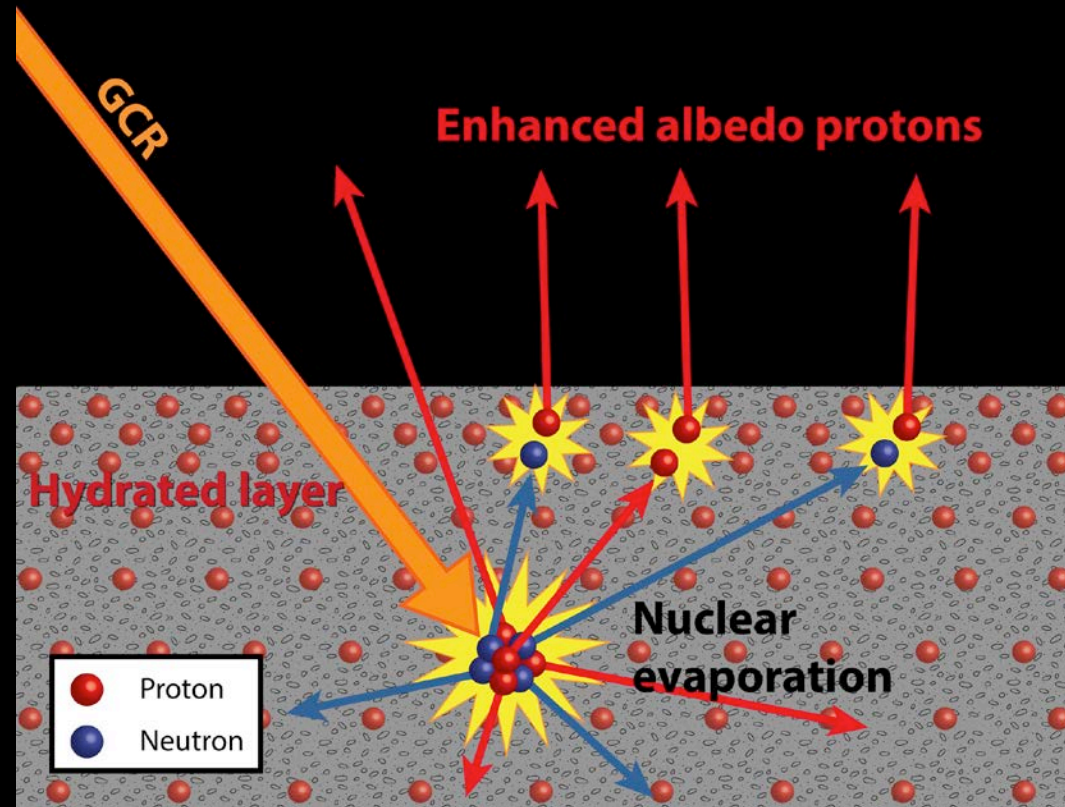
# No clear links to other observations

- *Positive Lat. Gradient* inconsistent with epithermal and fast neutrons
- Inconsistent with nuclear evaporation from heavies



# Idea: Production of Tertiary Protons

- Step 1: Production of collision products (lots of neutrons) through nuclear evaporation at depth
- Step 2: Knock-on collisions (p-n) create tertiary protons





# Hydrated Surface Layer - Properties



$$F'_p = F_p + F_n(dn_H\sigma_{np})$$

$F'_p$  Proton  
Flux from  
Top regolith

$F_p$  Proton  
Flux  
from  
depth

$F_n$  Neutron  
Flux  
from  
depth

$$\Delta \approx (dn_H\sigma_{np})F_n/F_p$$

Fractional Excess

$$dn_H \approx \Delta F_p / (F_n\sigma_{np})$$

Column density in upper layer

$$\Delta = 1.01 \pm 0.34\%$$

$\rightarrow d \sim 20 \text{ cm} \rightarrow \text{H } 200 \text{ ppm by weight}$   
 $\rightarrow d \sim 2 \text{ cm} \rightarrow \text{H } 2000 \text{ ppm by weight}$

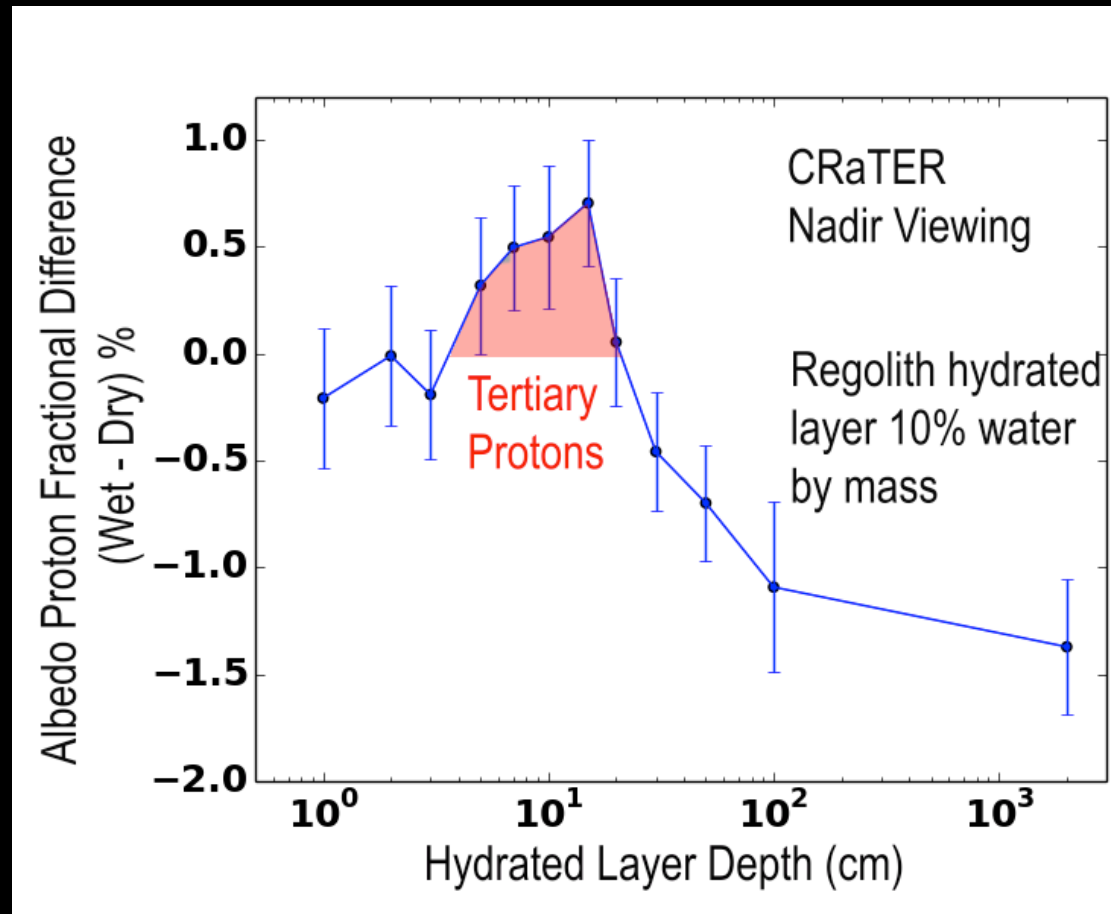
Modeled H in cold traps **200-4000 ppm**, Teodoro et al., GRL, 37, L12201, 2010



# Geant 4 Simulations – Proof of Concept



- Simulations include *only* GCR proton input
- Sets a *minimum* for tertiary proton production!

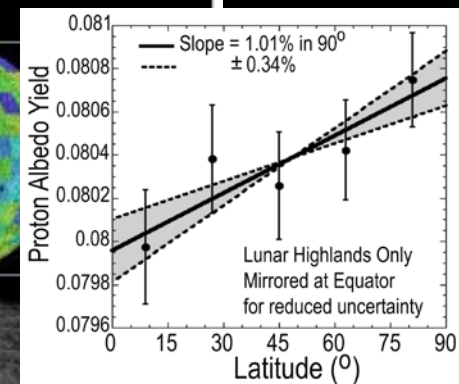
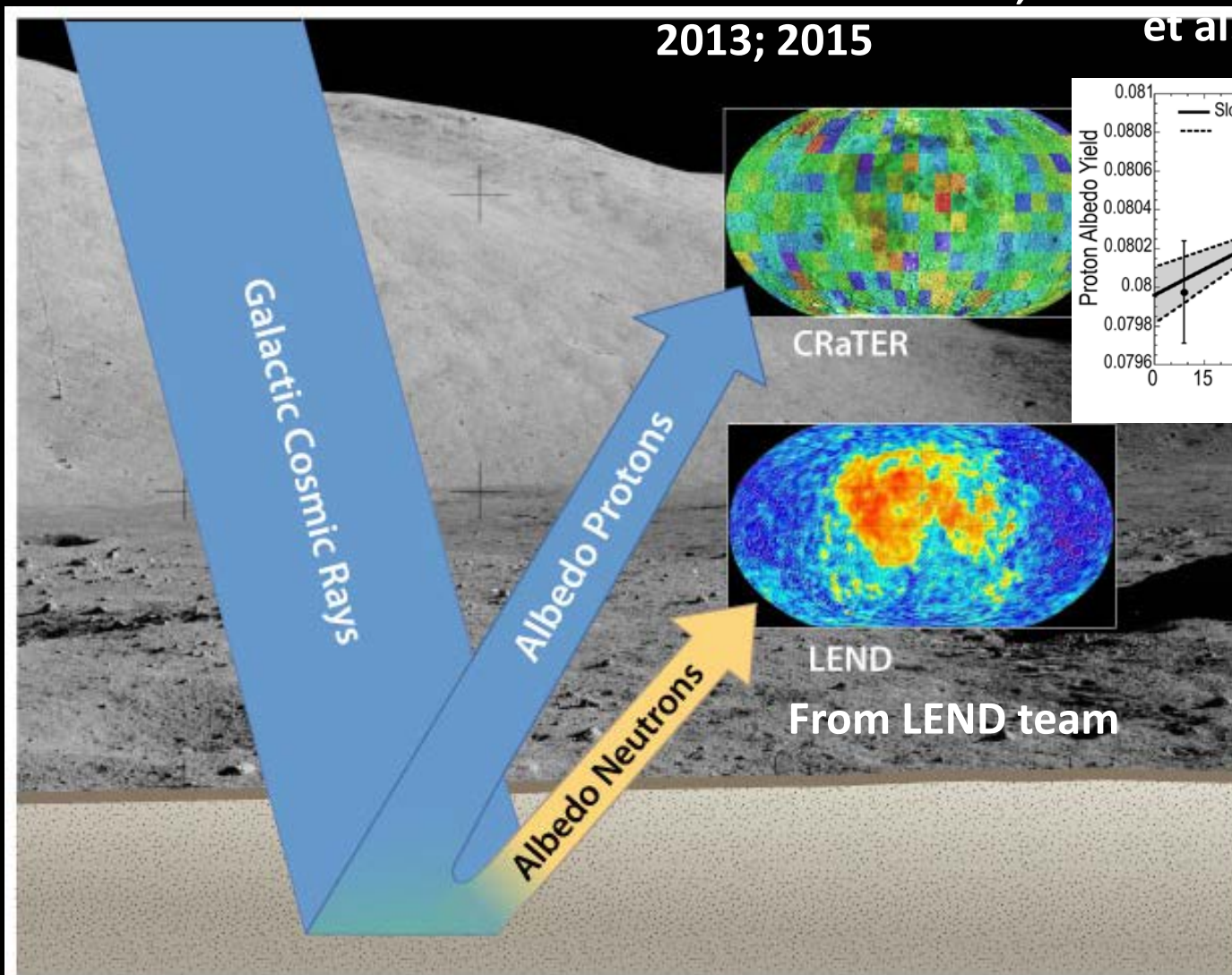


# Remote sensing of regolith from GCR- produced energetic particle albedo



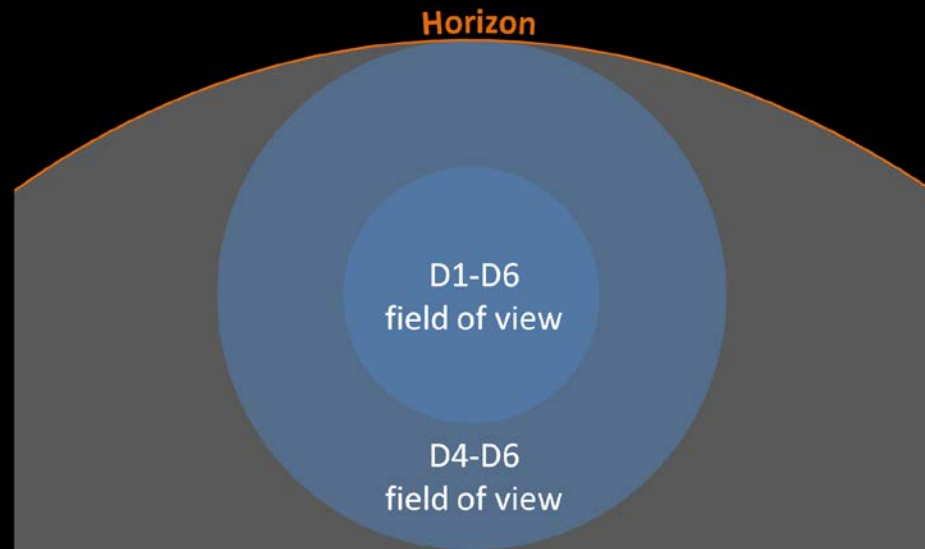
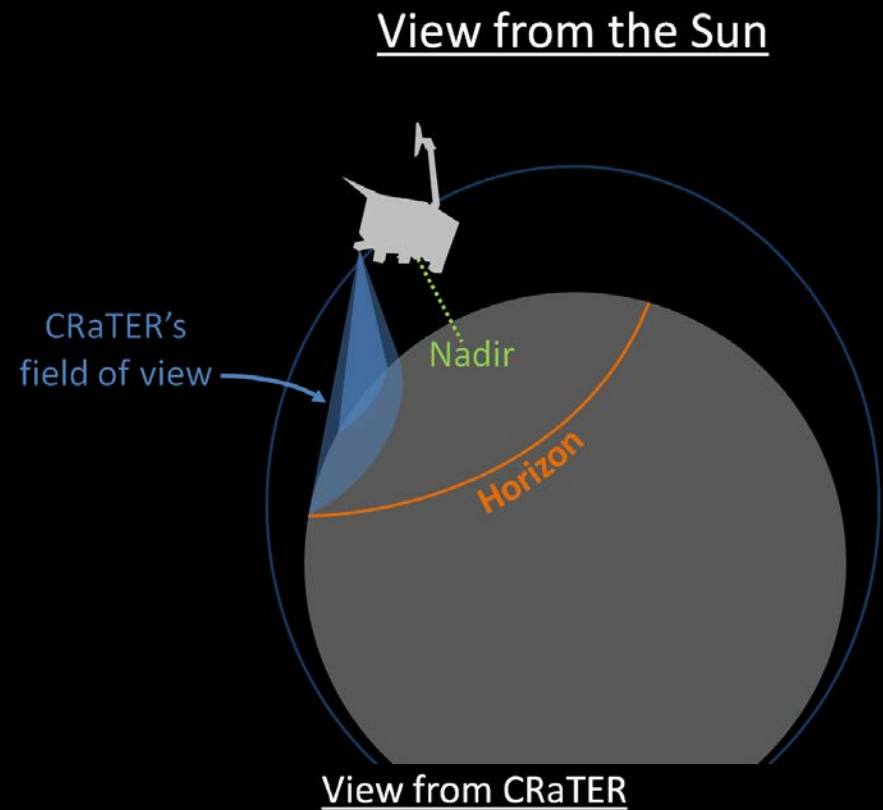
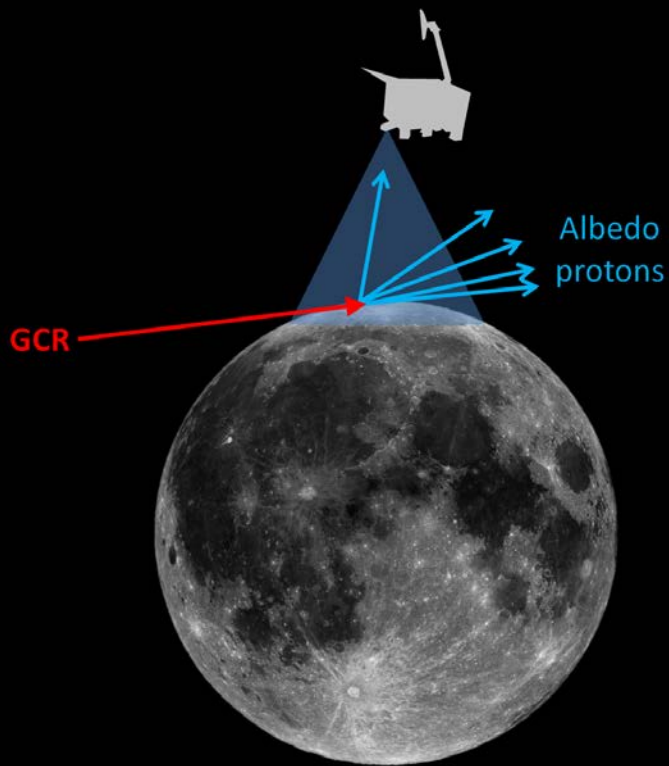
From Wilson et al.,  
2013; 2015

From Schwadron  
et al. 2015





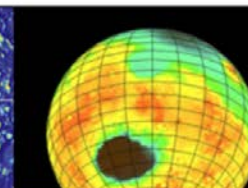
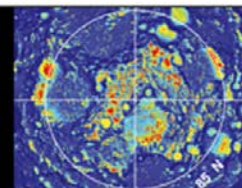
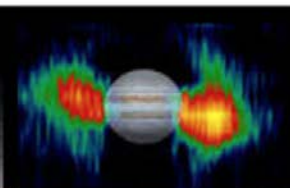
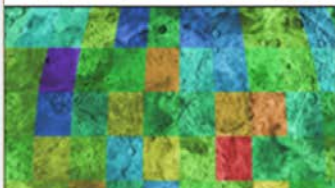
# CRaTER Slews Importance for Extended Missions





INTERNATIONAL  
SPACE  
SCIENCE  
INSTITUTE

## ISSI Research Team: Radiation Interactions at Planetary Bodies



Abstract and Team Proposal

Team Members

Schedule & Meetings

Project Publications & Reports

**The International Space Science Institute (ISSI)** is an Institute of Advanced Study, bringing together scientists from all over the world meet in a multi- and interdisciplinary setting to advance the understanding of results from space missions, ground based observations and laboratory experiments.

The international research teams are set up in response to an Annual Call by ISSI. Their goal is to carry out a research project leading to publications in scientific journals.



### Proposal Abstract

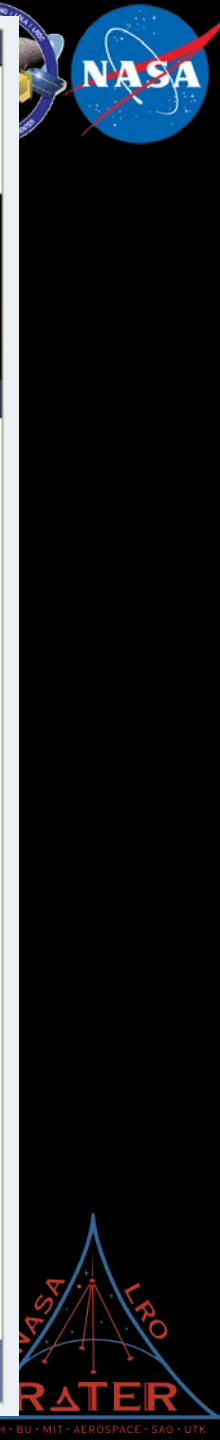
#### Radiation Interactions at Planetary Bodies

SINCE THE LAUNCH of the Lunar Reconnaissance Orbiter (LRO) in 2009, the Cosmic Ray Telescope for the Effects of Radiation (CRaTER) has directly measured the Lunar radiation environment and mapped albedo protons ( $\sim 100$  MeV) coming from the Moon. Particle radiation has widespread effects on the lunar regolith ranging from chemical alteration of lunar volatiles to the formation of subsurface electric fields with the potential to cause dielectric breakdown that could modify the regolith in permanently shaded craters. LRO/CRaTER's direct measurements are transforming our understanding of the lunar radiation environment and its effects on the moon.

Similarly, the Radiation Assessment Detector (RAD) has been measuring the energetic particle radiation environment on the surface of Mars since the landing of the Curiosity rover in August 2012. The Martian surface is protected by the atmosphere above; though only about 1% as thick as Earth's, its depth is sufficient to stop solar wind ions and the large majority of Solar Energetic Particles. RAD, like CRaTER, measures radiation dose, dose equivalent (related to human health risks), and particle spectra to enable rigorous tests of environment and transport models.

Recent measurements of galactic cosmic radiation and solar energetic particle radiation at other planetary objects (e.g., the moons of Mars) raise new fundamental questions about how radiation interacts at planetary bodies and what its long term impacts are.

This ISSI team will advance the study of radiation interactions.  
[Read more... \(proposal and abstract, pdf\)](#)



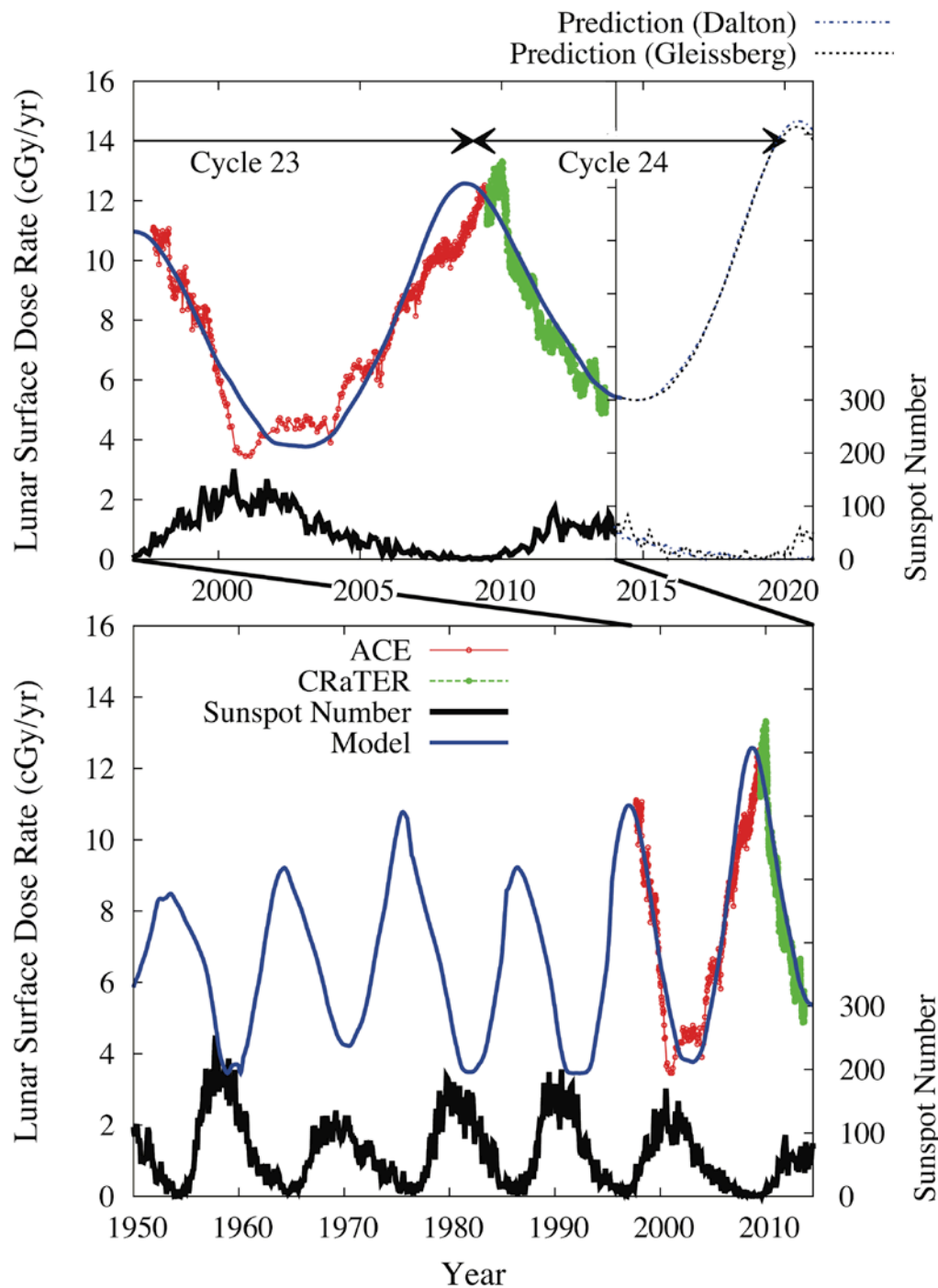


# Summary

- LRO/CRaTER team highly productive, more than 50 papers on Planetary and Exploration Topics!
  - Highlighted in New **ISSI Team on Radiation Interactions**
- Discovery of Positive Latitude Gradient in Albedo Protons
  - Implications for Tertiary Proton Production
  - Possibly Produced from **Upper 10 cm Hydrated Layer**
- New CRaTER Observing Slews Allow New Tests (e.g., Time-of-Day Tests) in **Next Phase of LRO!**

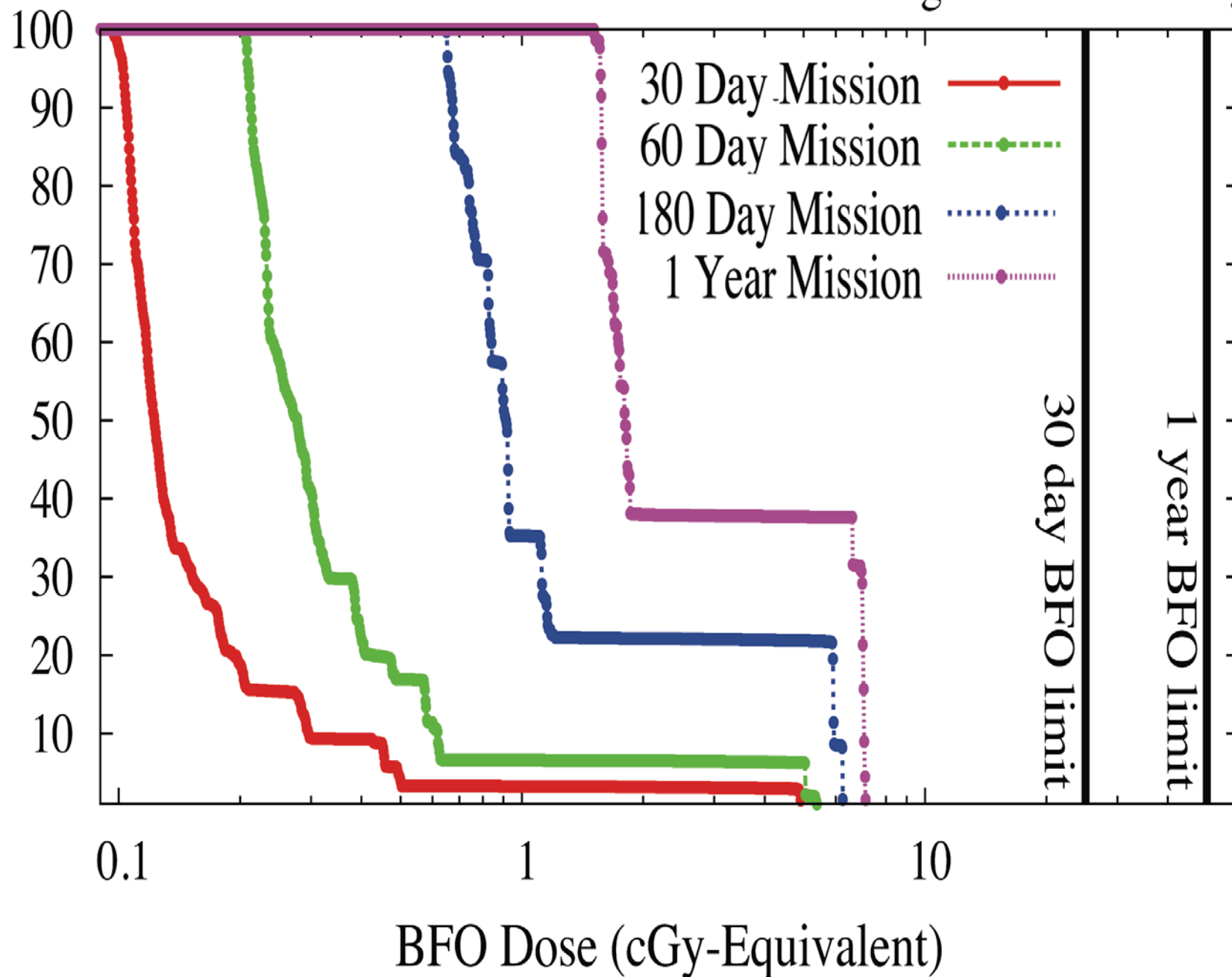






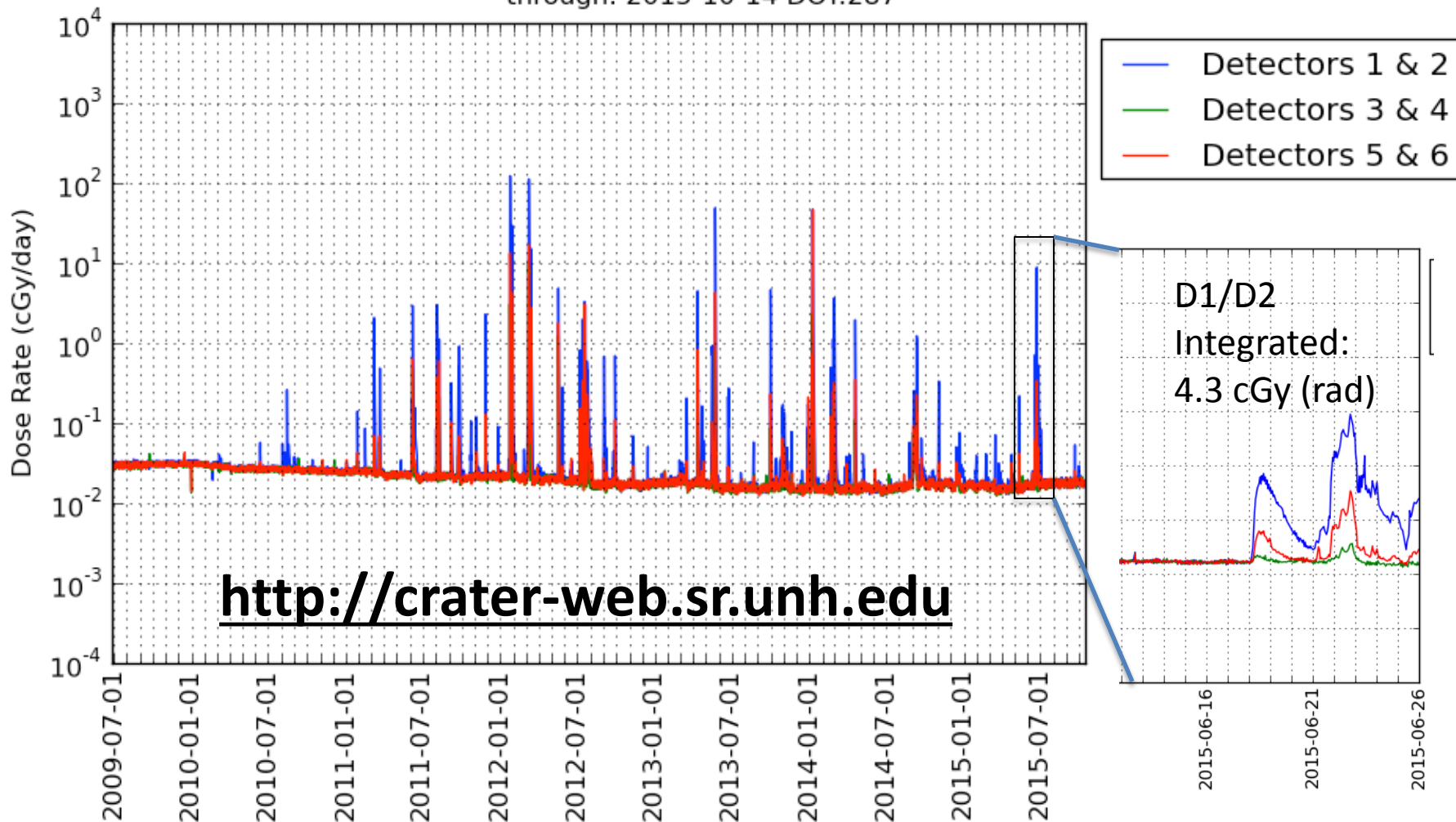
10 g/cm<sup>2</sup> Al shielding

Probability (%)



# Is Activity in Decline?!

CRaTER 2302 day combined detectors dose rate data  
from: 2009-06-26 DOY:177  
through: 2015-10-14 DOY:287





# Are there further surprises in store?

CRaTER 183 day combined detectors dose rate data  
 from: 2015-04-15 DOY:105  
 through: 2015-10-14 DOY:287

