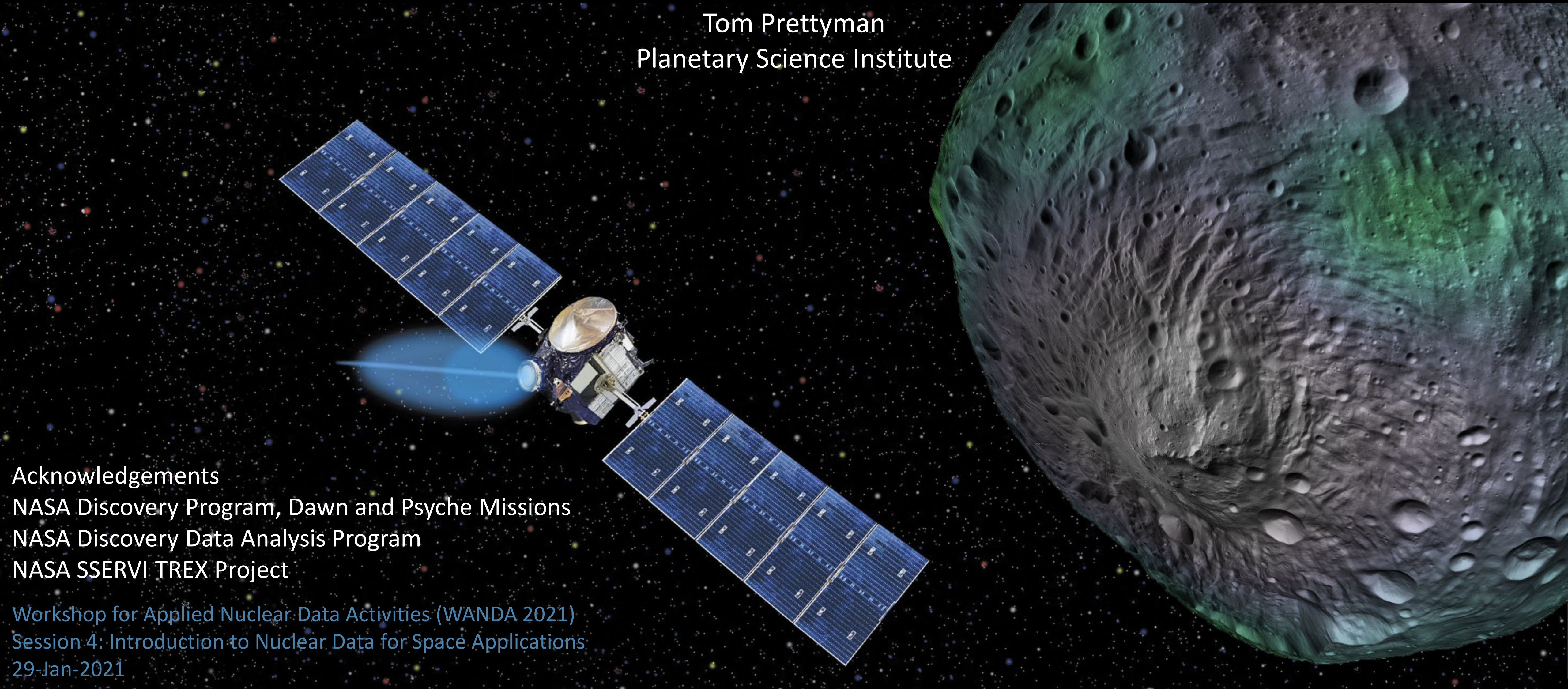
Planetary Nuclear Spectroscopy

Application Description and Data Needs



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Acknowledgements
NASA Discovery Program, Dawn and Psyche Missions
NASA Discovery Data Analysis Program
NASA SSERVI TREX Project

Workshop for Applied Nuclear Data Activities (WANDA 2021)
Session 4: Introduction to Nuclear Data for Space Applications
29-Jan-2021

Source: Passive interrogation

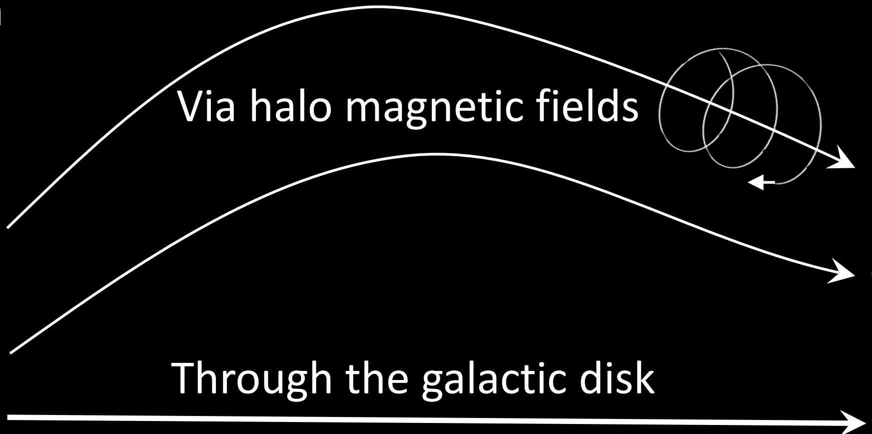
Natural particle accelerators and radioelements

https://apod.nasa.gov/apod/ap150705.html

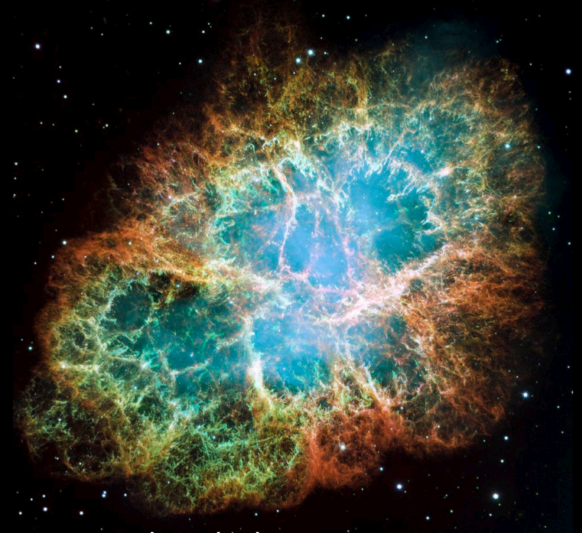
Modulation:

- Diffusion
- Convection
- Adiabatic deceleration

Propagation



Galactic cosmic ray production

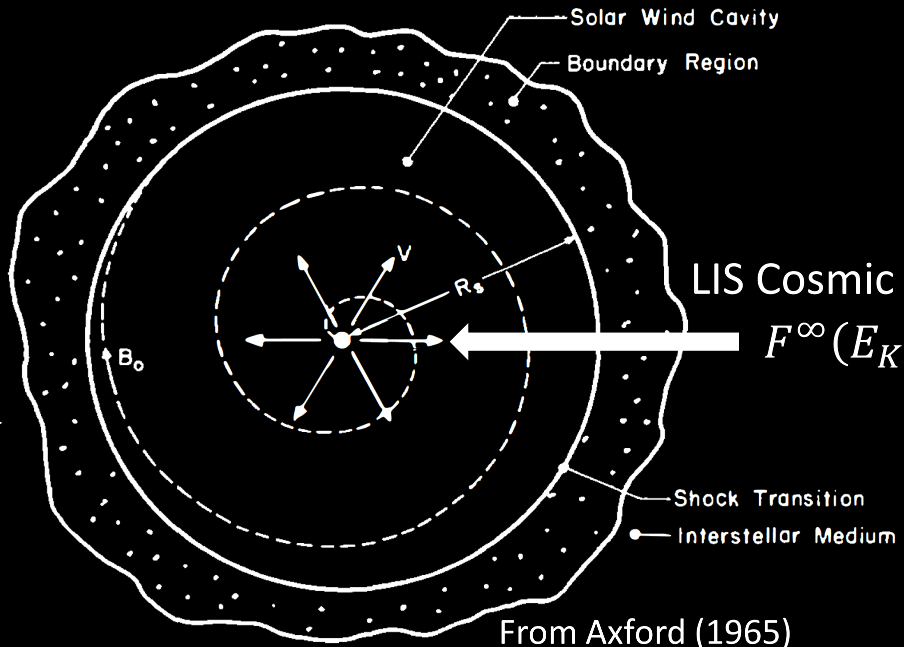


e.g., Crab nebula NASA/ESA/Hubble

- Fermi acceleration of ions (H to U) at shock fronts – shell type supernovae

- Relativistic jets of particles from active galactic nuclei

- Energy loss by ionization
- Spallation (secondary nuclei)
- Escape
- Radioactive decay



LIS Cosmic ray flux $F^{\infty}(E_K)$

From Axford (1965)

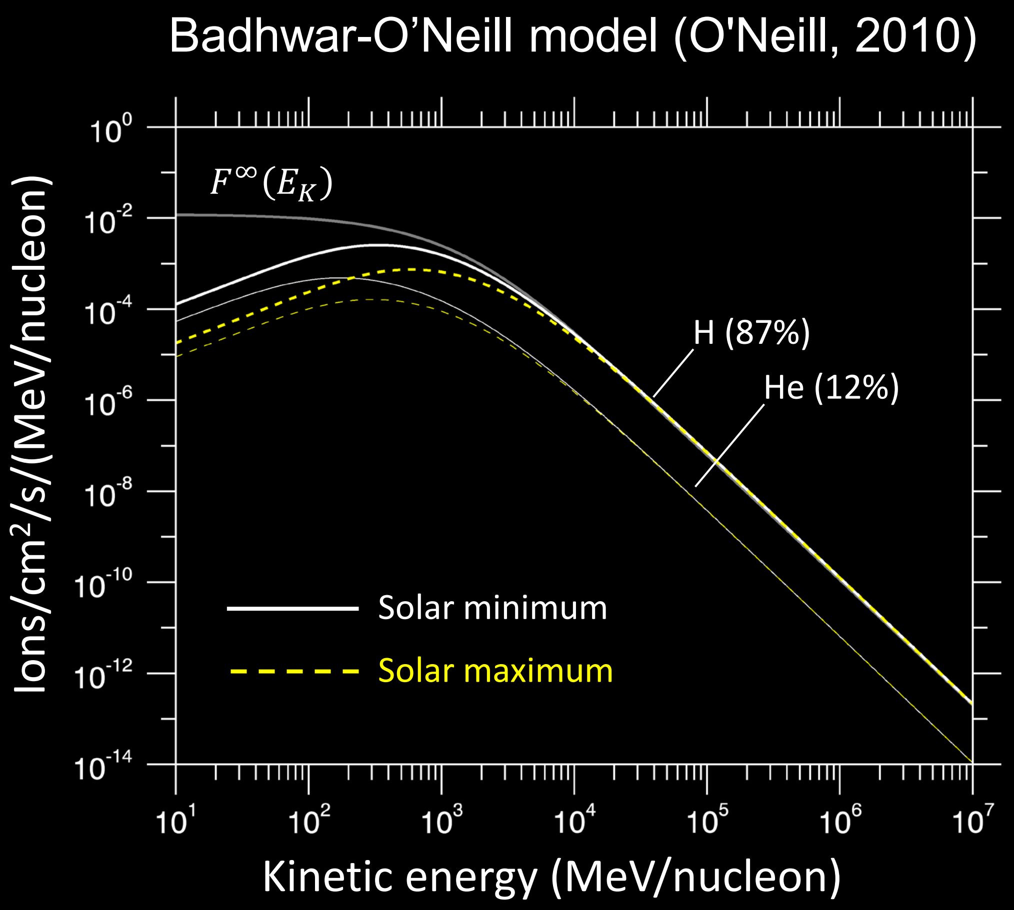
Force-field approximation to convection diffusion model:

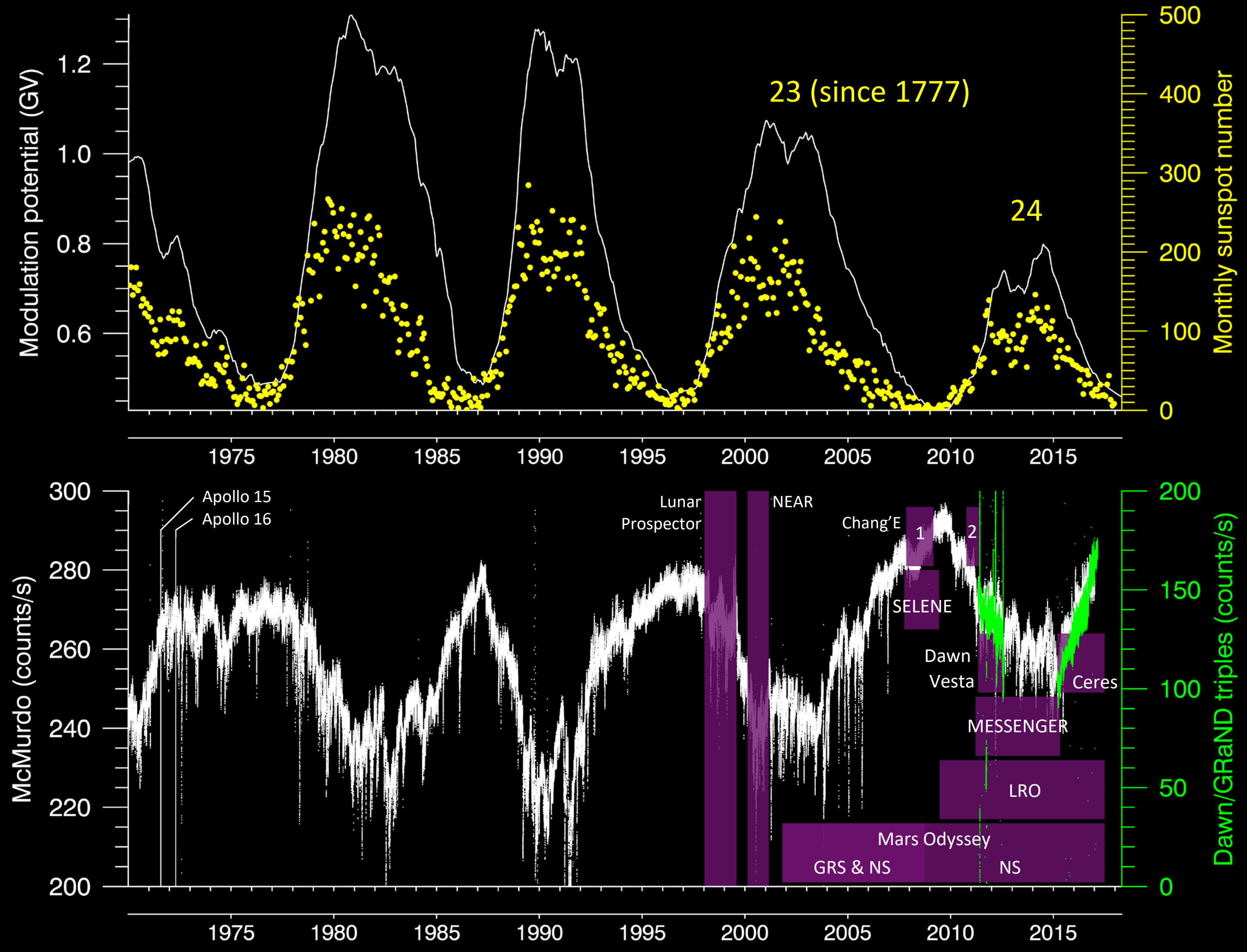
$$F\left(E_K\right) = F^{\infty}\left(E_K + \Phi z/A\right)\frac{E^2 - M^2}{\left(E + \Phi z/A\right)^2 - M^2}$$

After Simpson (1983)

Source: Passive interrogation

Natural particle accelerators and radioelements

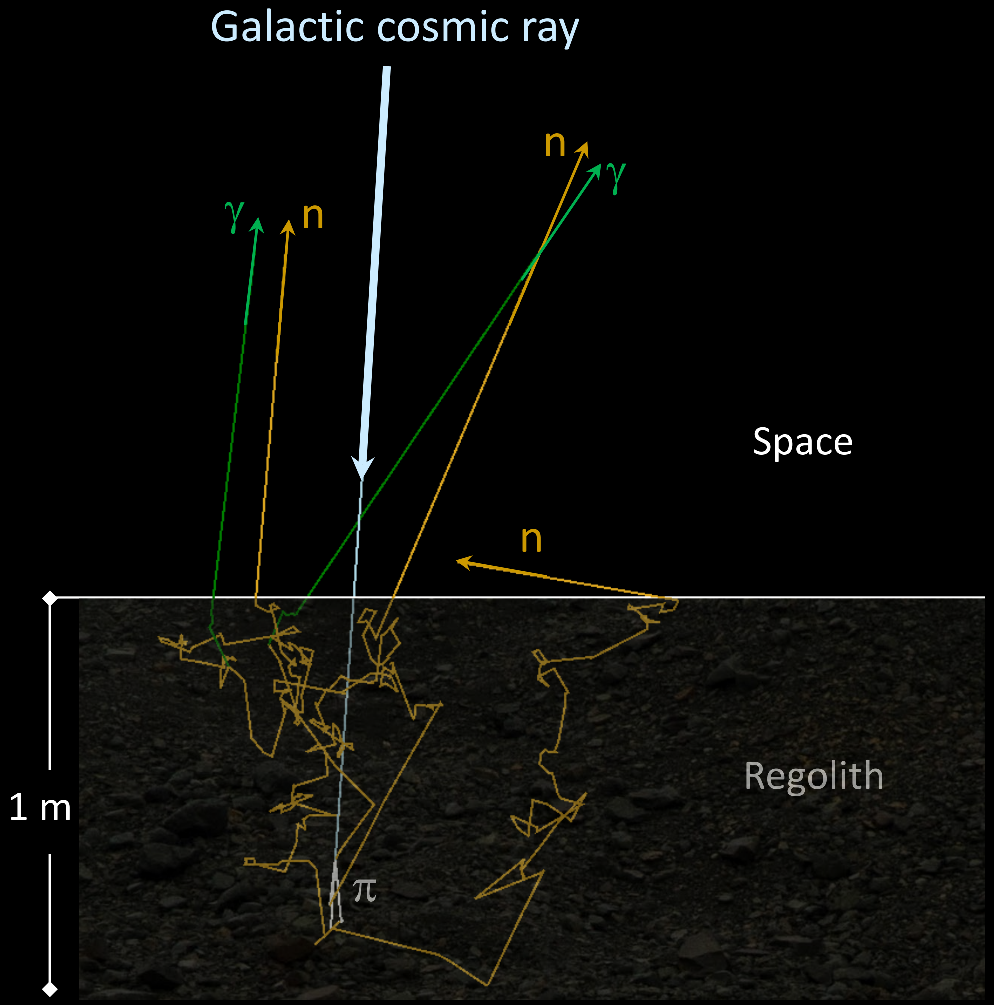




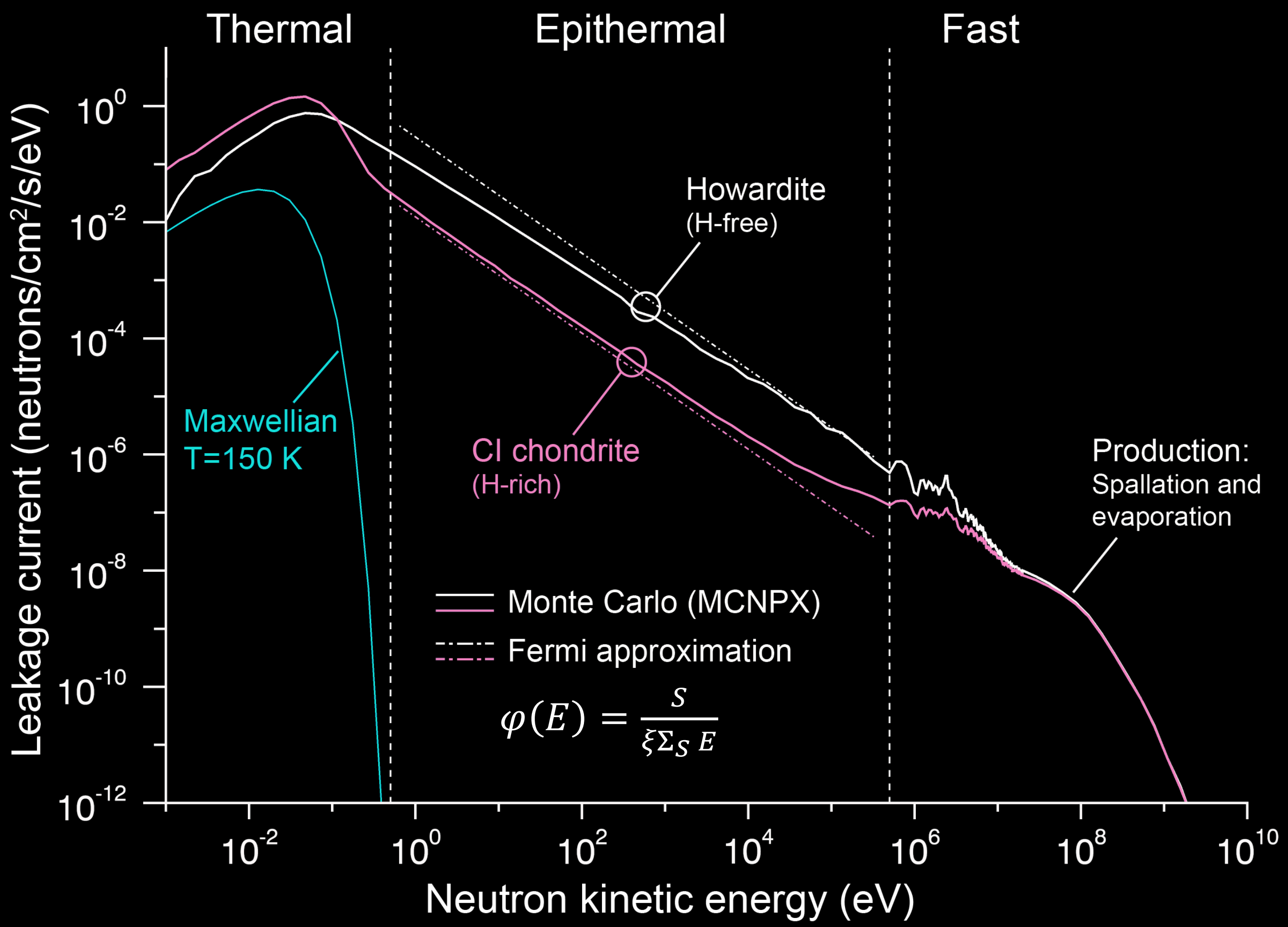
Introductory materials from Prettyman et al. (2019a), DOI: 10.1017/9781316888872

Information content

Beam stop for the cosmic accelerator (solid surfaces exposed to space)



Only the tracks of particles that escaped are shown



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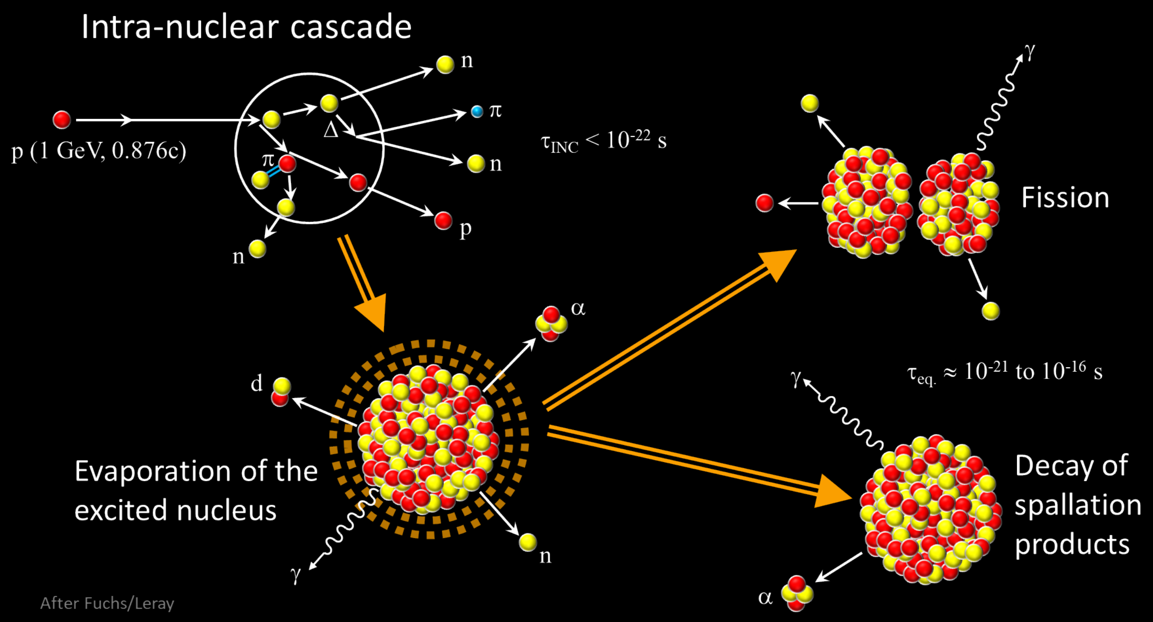
Information content

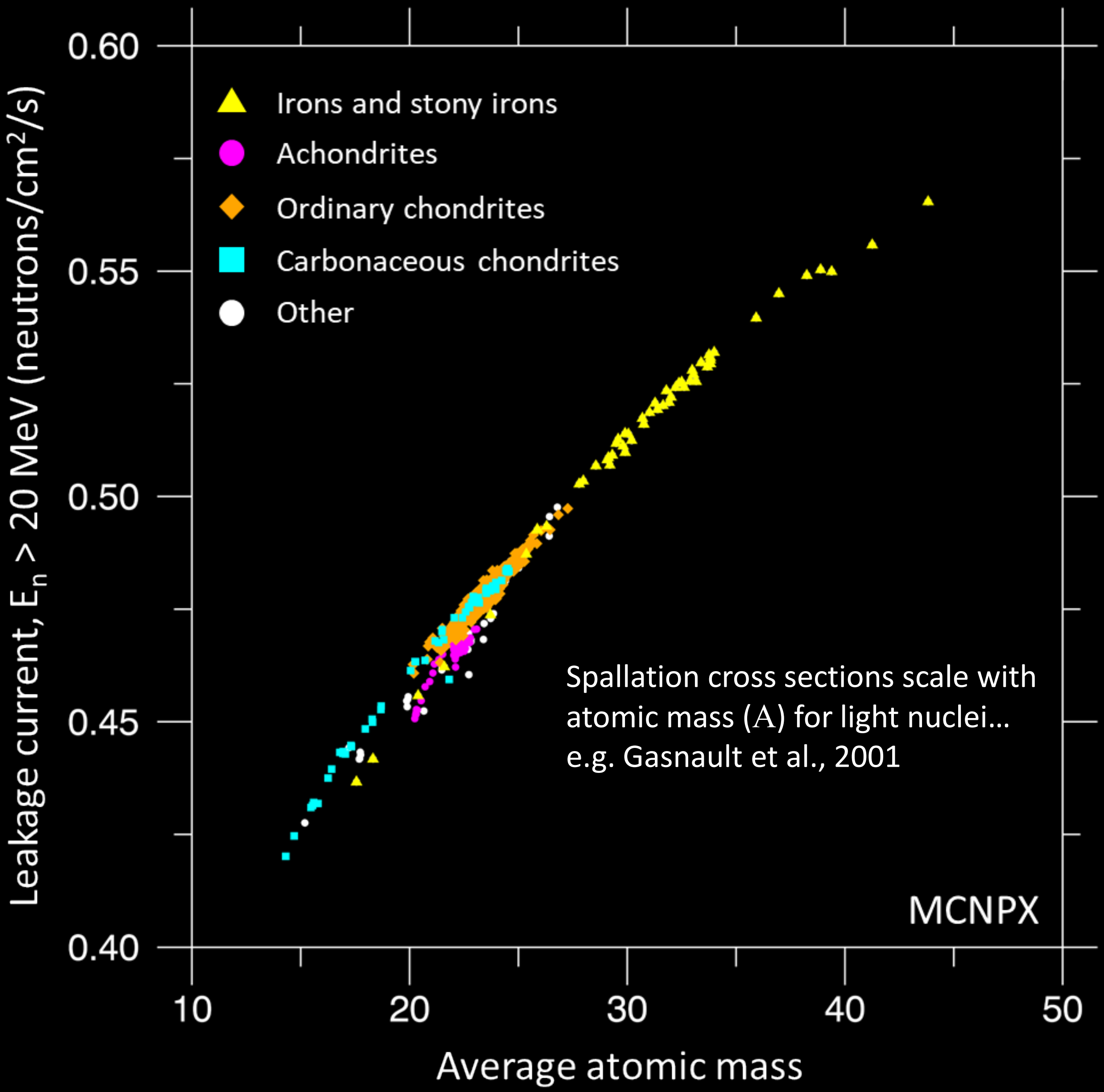
Secondary particle production by neutrons



Spallation is a complex process – Model parameters used in simulations are determined experimentally.

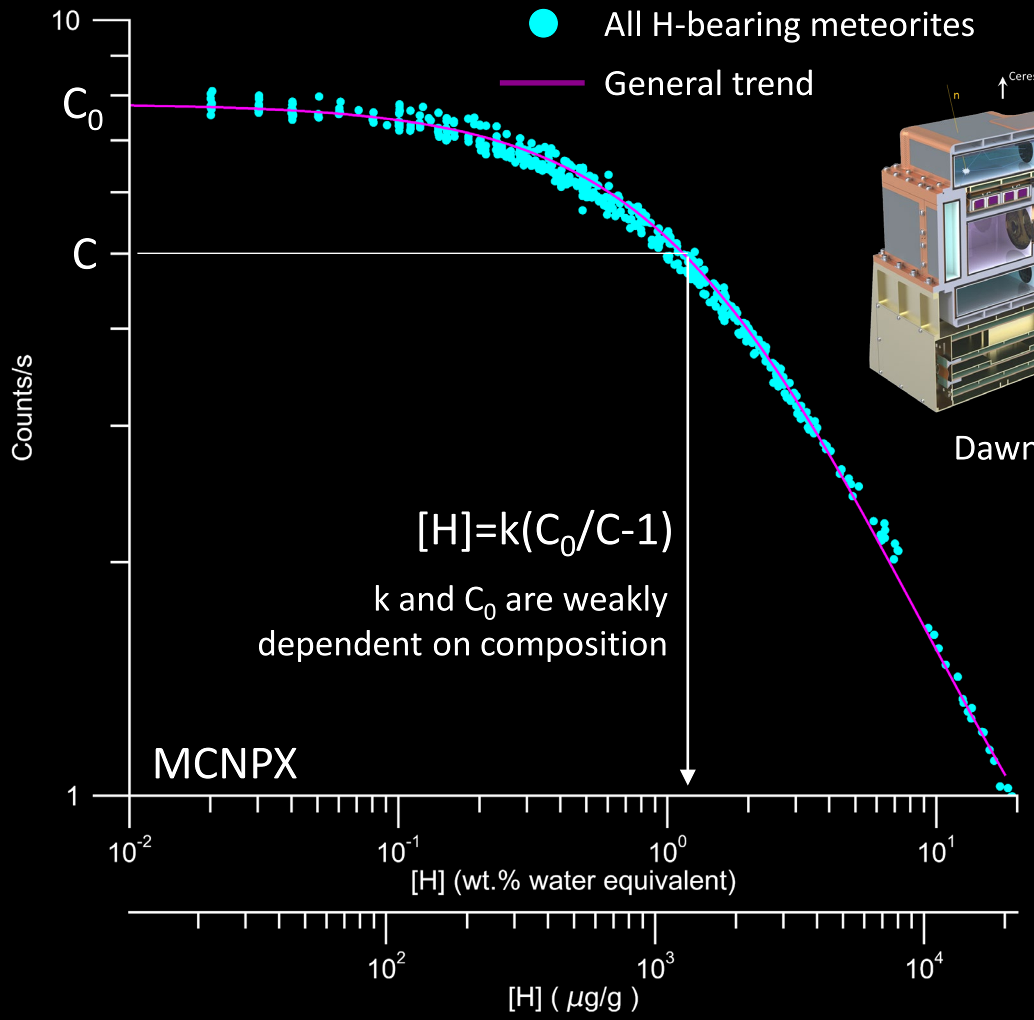
Uncertainties in neutron production in thick-target "GCR" experiments reported by Ratliff et al. 2018.

Quantitative analyses generally require "ground truth"

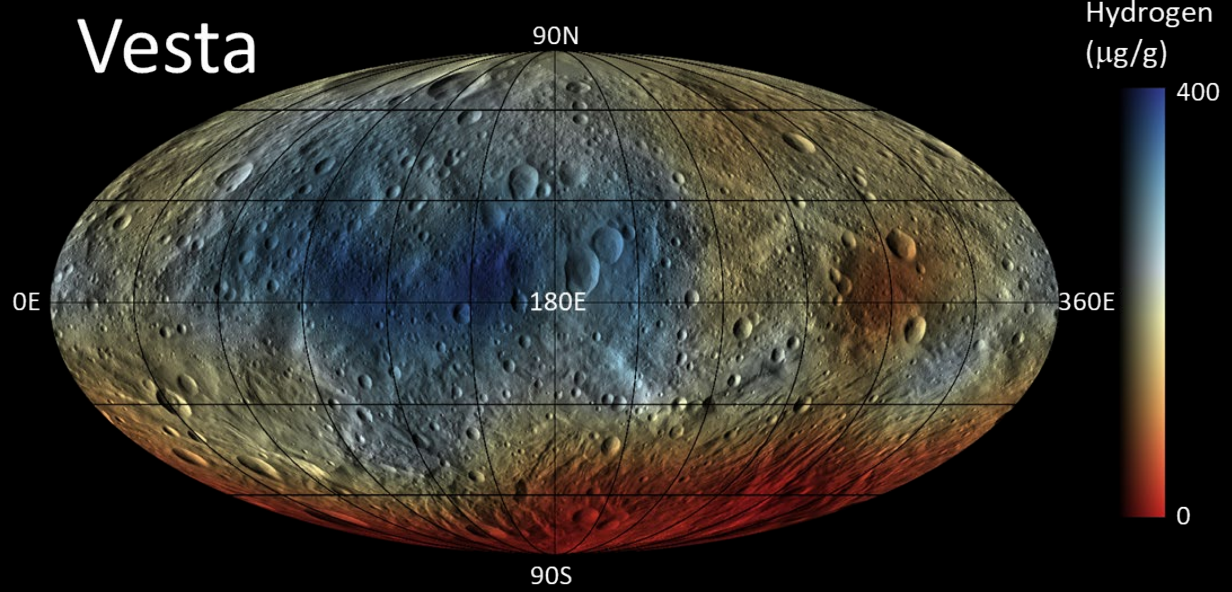


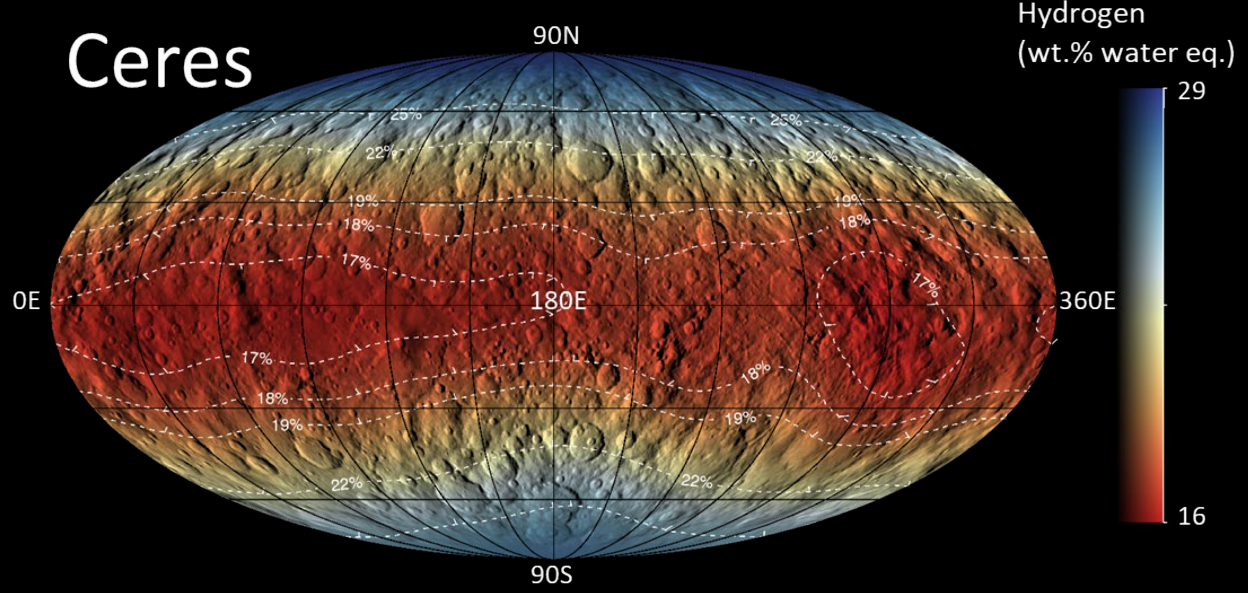
Information content

Moderated (epithermal) neutrons



Dawn/GRaND



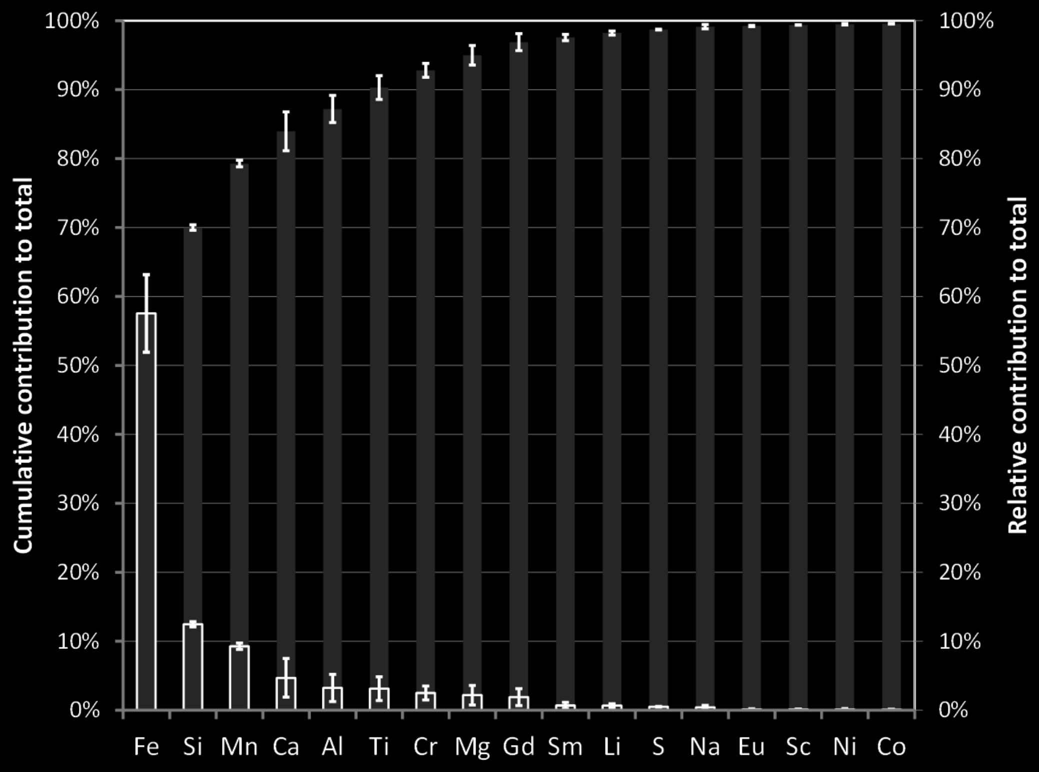


Prettyman et al. (2011, 2012, 2017, 2019b)

Information content

Low energy neutrons are sensitive to absorption

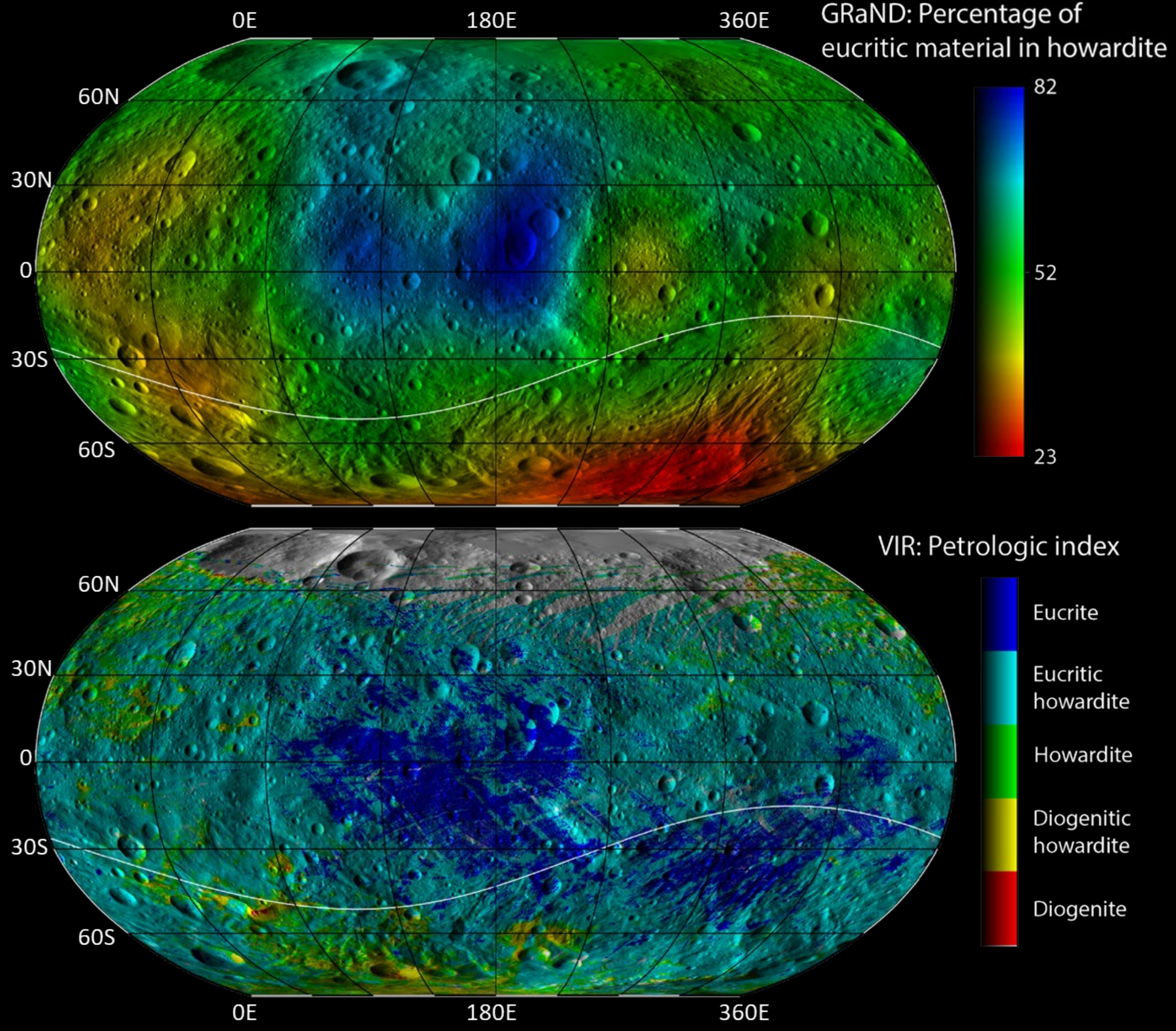
Elemental contributions to absorption
for selected howardite meteorites



$$\Sigma_A = \sum_{i=0}^{n-1} \left(N_0 \frac{\sigma_i}{A_i} \right) w_i$$

Asteroid 4 Vesta – Dawn mission

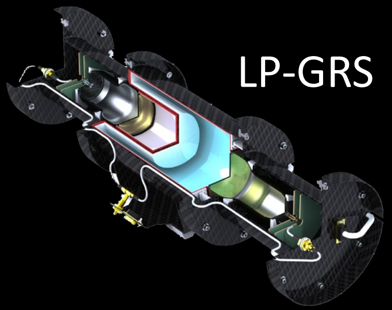
Neutron absorption map (top) compared to VIS-NIR petrology (rock type, bottom)



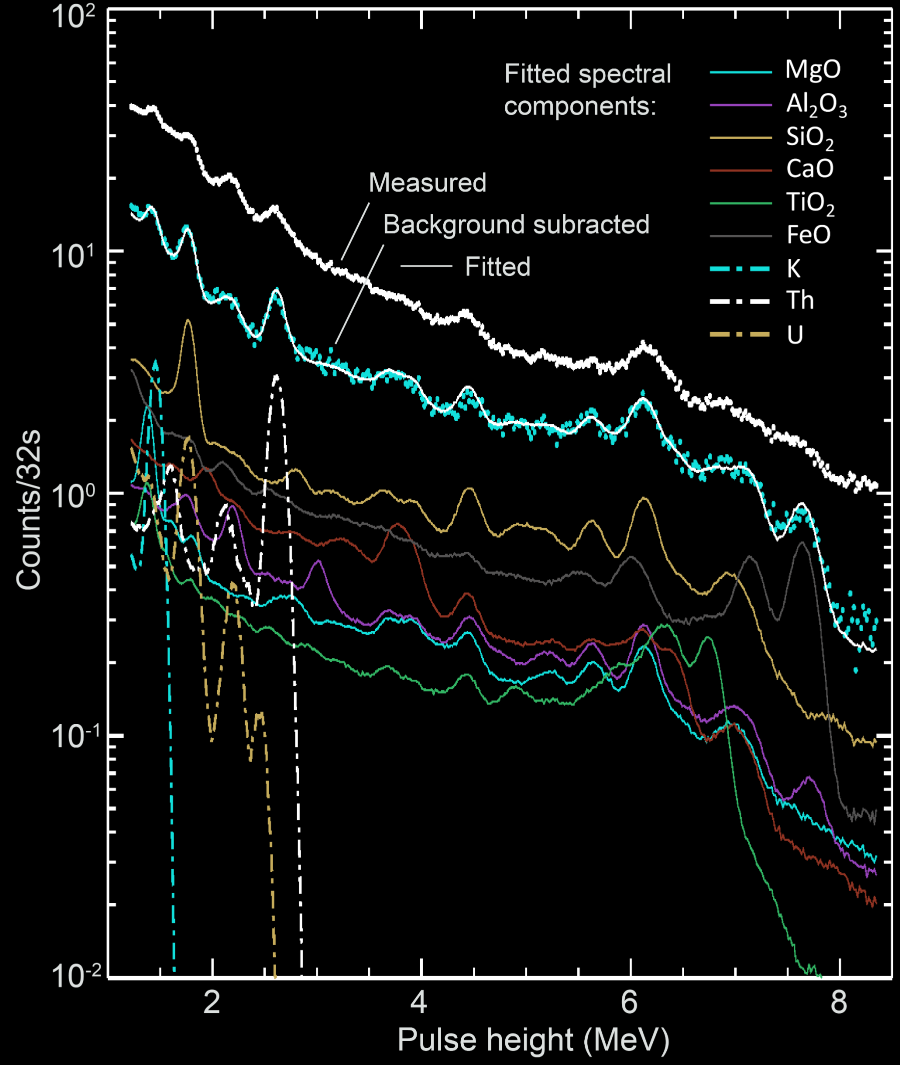
McSween et al. (2014); Ammannito et al. (2013); Prettyman et al. (2013)

Information content

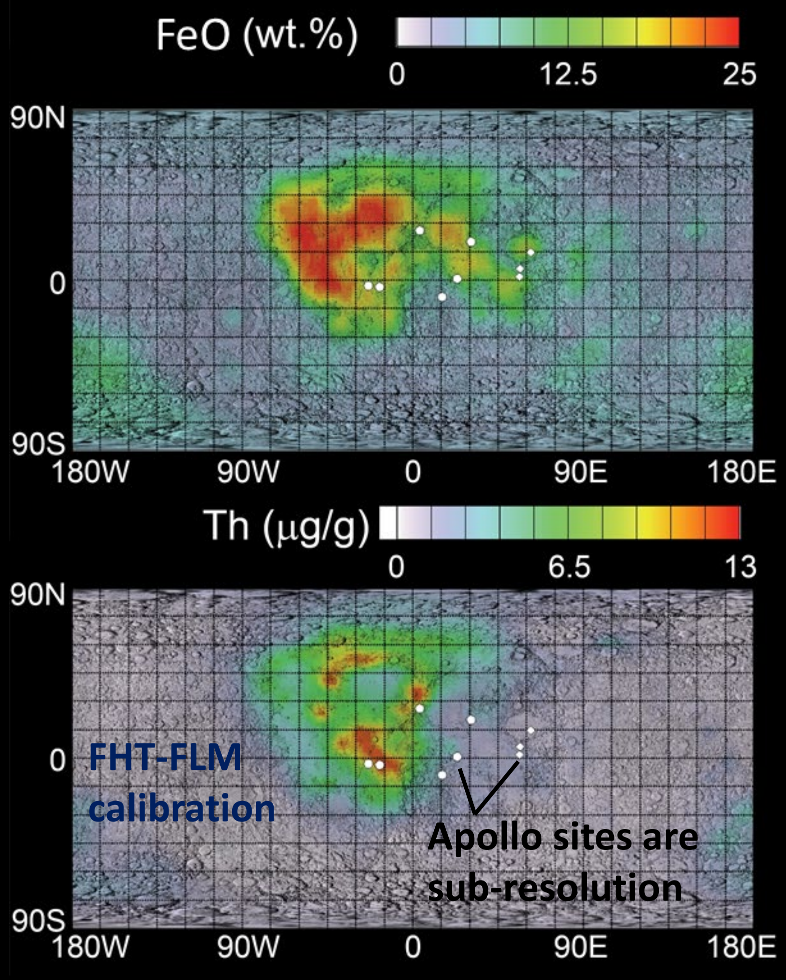
Specific elements via gamma-ray spectroscopy (with help from neutrons)



Spectral unmixing – Lunar Prospector

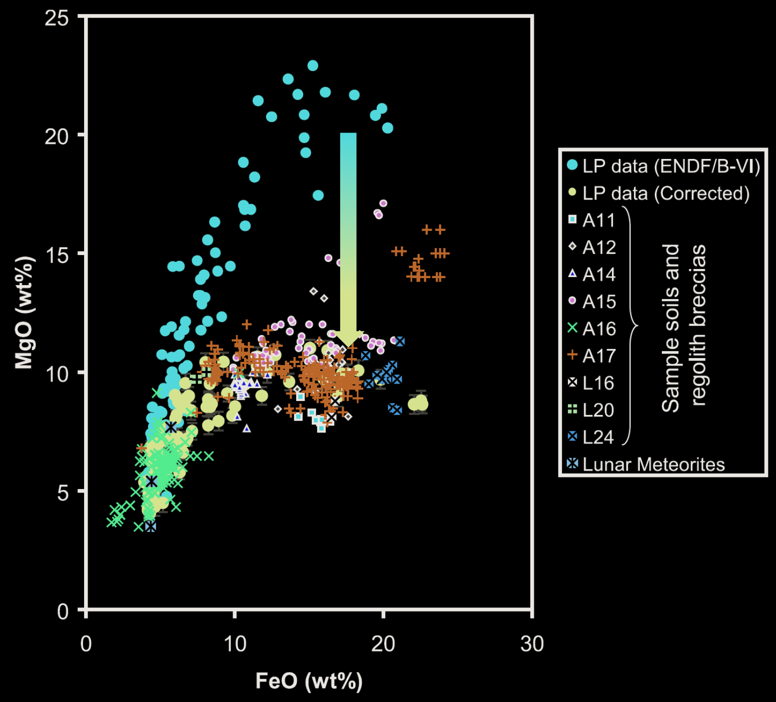


Lunar elemental maps



ENDF/B-VI - Mg library spectrum required correction

- 1368.6 keV gamma-ray primarily from ^{24}Mg(n,n′γ) represented as a broad peak



Peak analyses - Lawrence et al. (2000, 2002); Spectral unmixing - Prettyman et al. (2006)

LP-GRS artwork: S. Storms, LANL document LA-UR 10-05410

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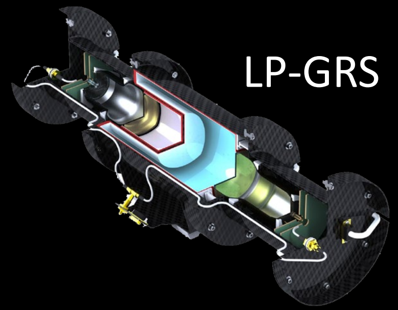

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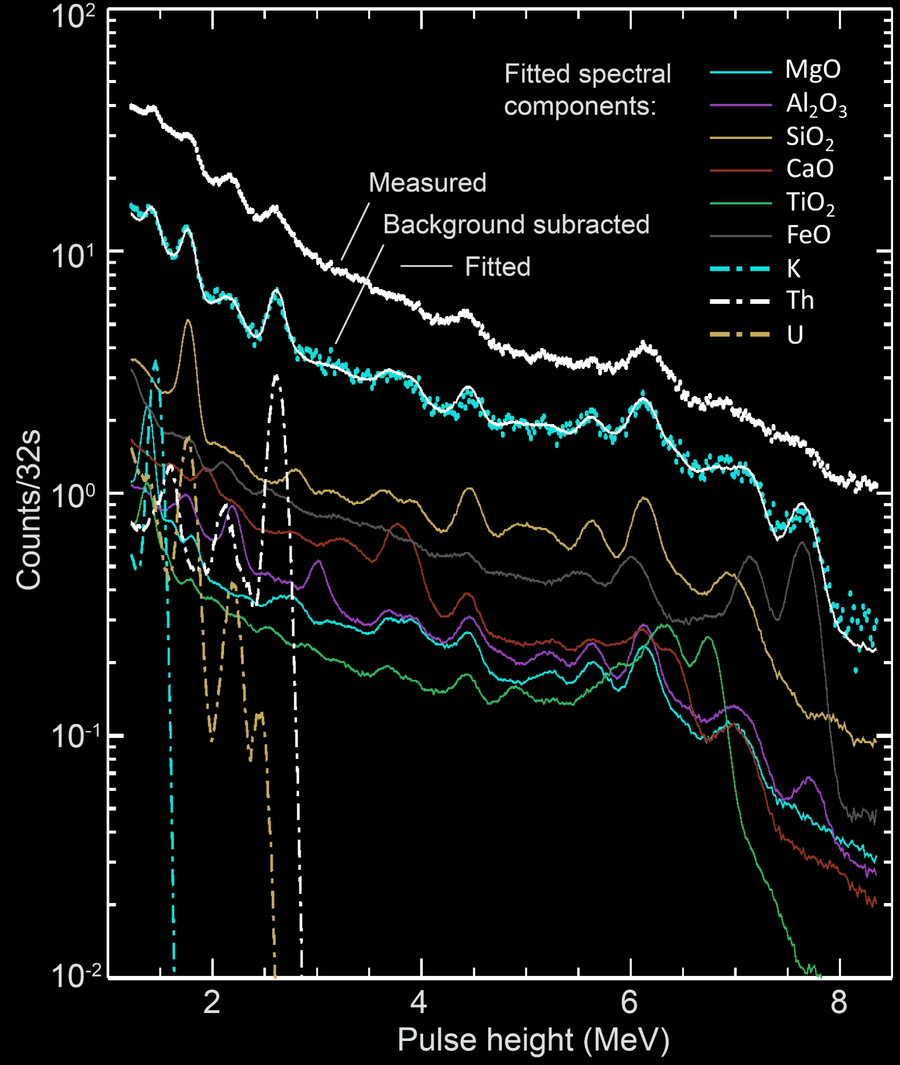

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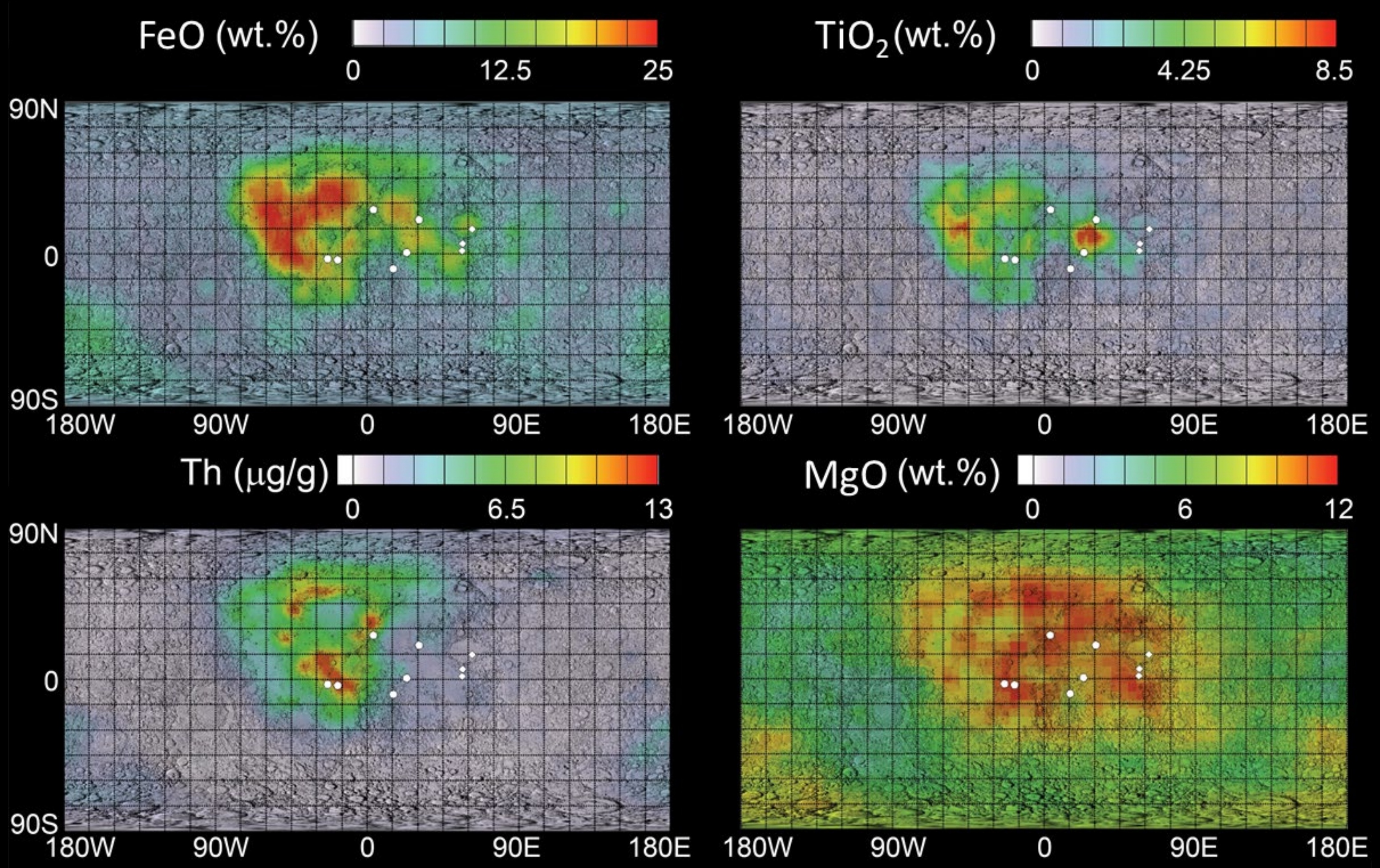

Peak analyses - Lawrence et al. (2000, 2002); Spectral unmixing - Prettyman et al. (2006)

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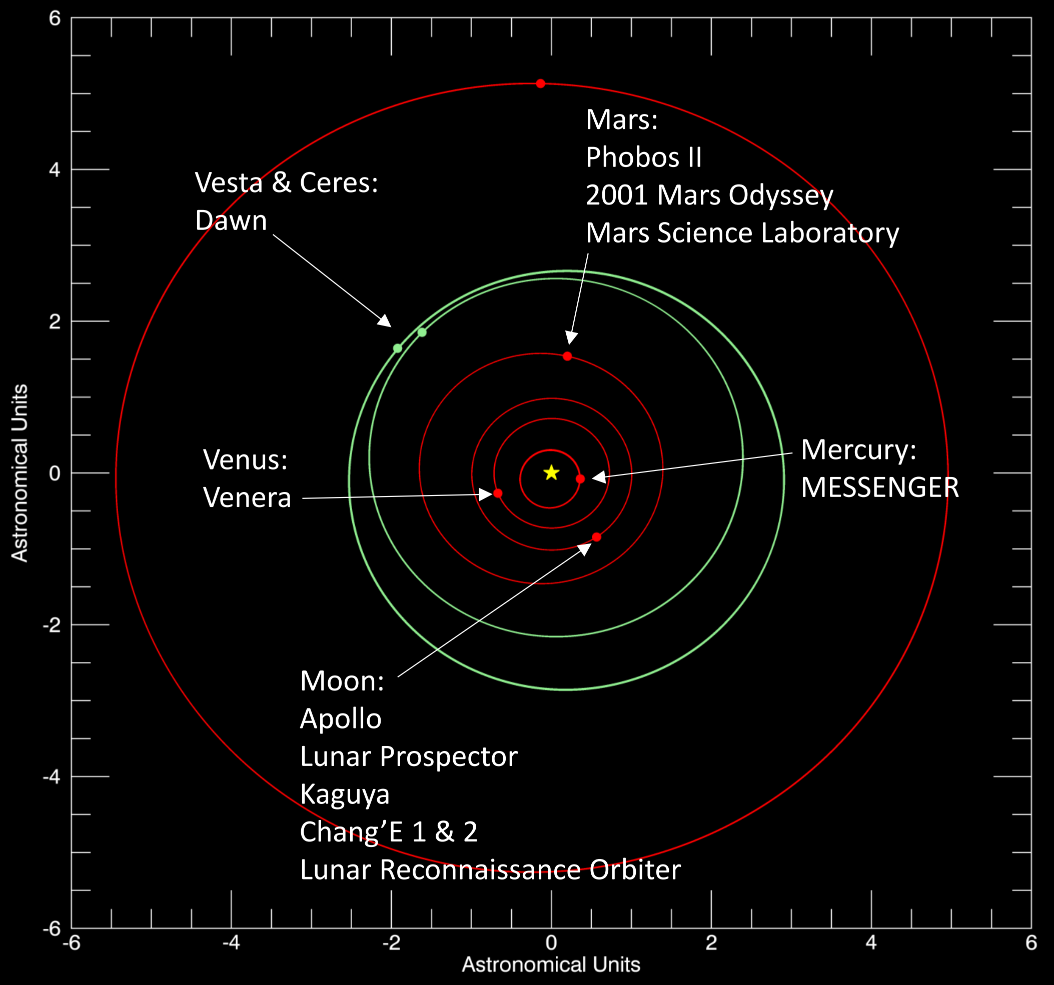
Instruments/Missions

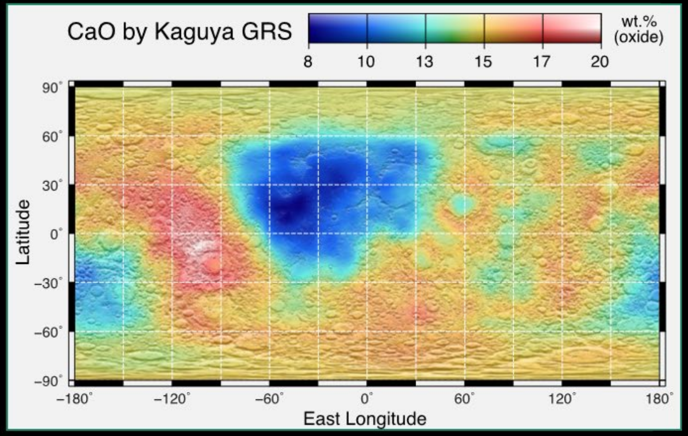
Many instruments flown, starting with Apollo



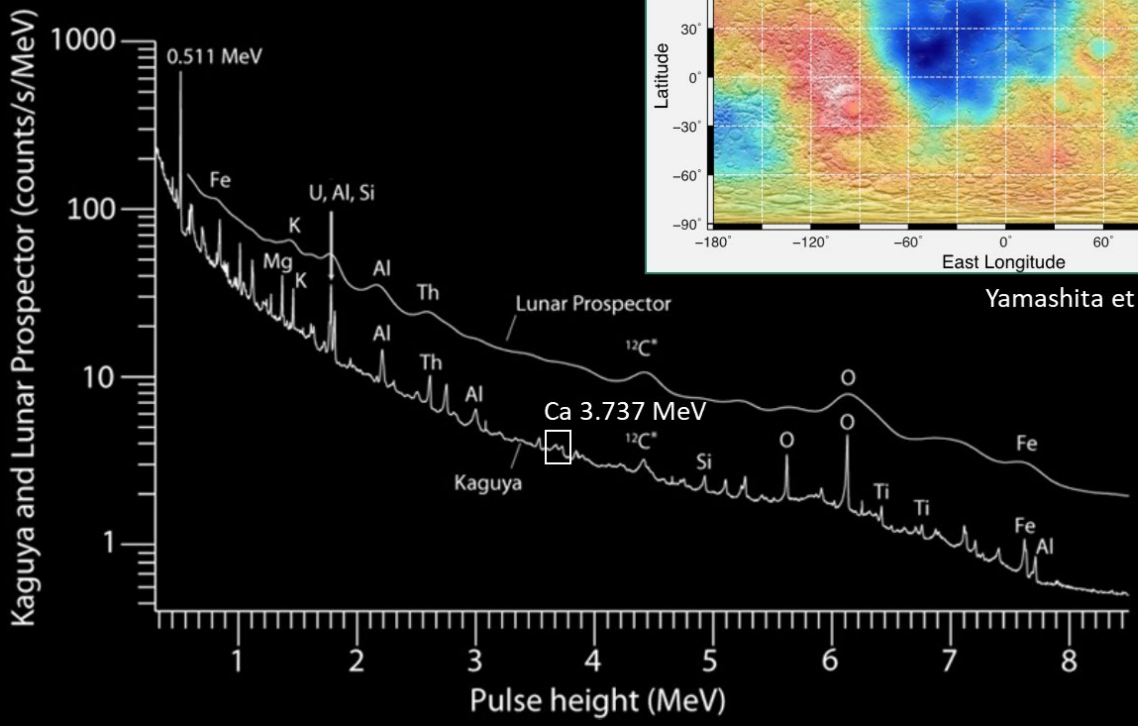
Features:

- Scintillators, semiconductors and gas proportional counters
- Compact, rugged, low-power configurations required
- Many, but not all, GRS instruments include cosmic ray veto
- Both boom and body mounted configurations demonstrated

HPGe improves analyses of lunar calcium



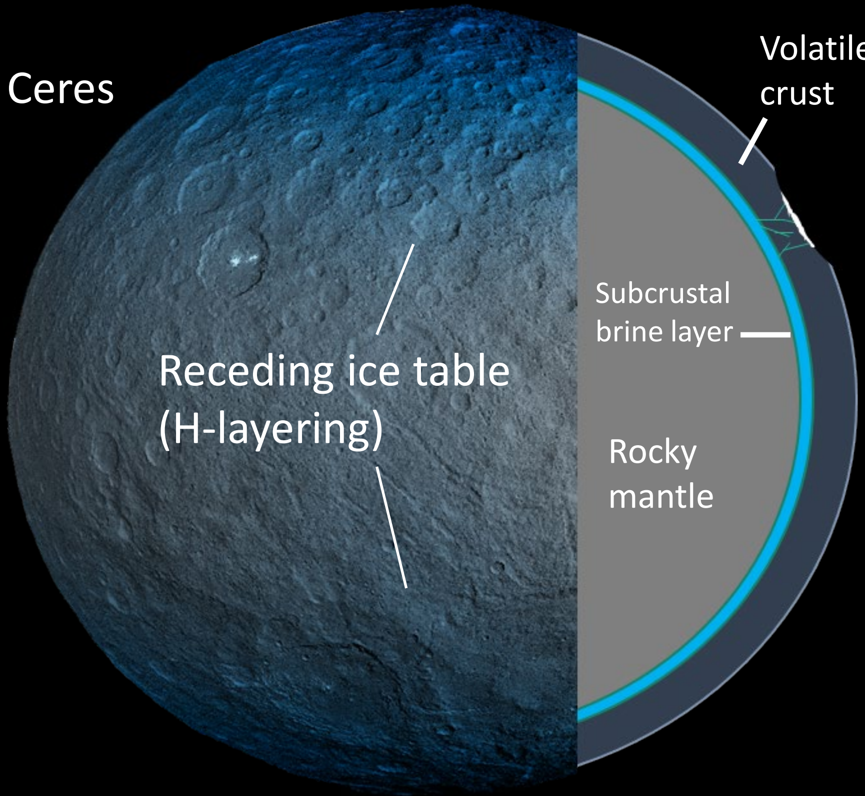
Yamashita et al., EPSL (2012)



Characterization of instrument response may require modeling of correlated reaction signatures for elements found in sensors, structure, and spacecraft.

Regolith materials

Igneous versus aqueous geochemistry

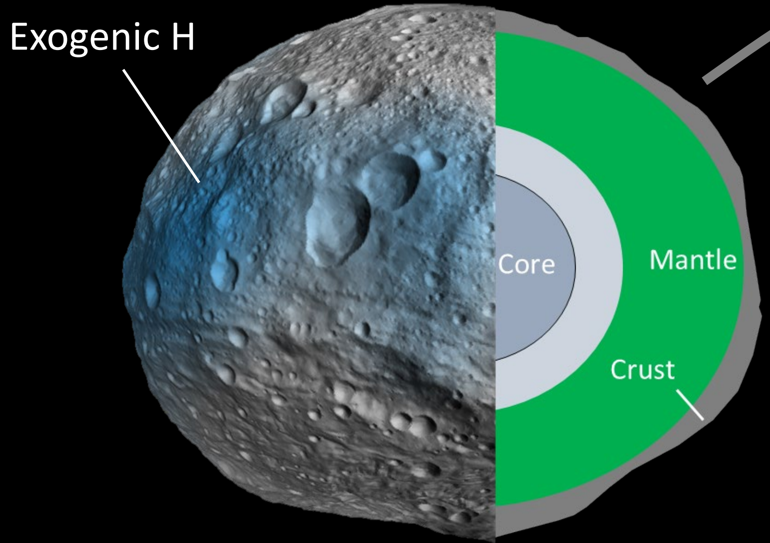


Aqueous alteration/differentiation

Salts (carbonates + halides)
- H, C, N, O, Na, Mg, Si, Cl, K, Ca

Aqueously altered rock (phyllosilicates and opaques)
- H, C, N, O, Na, Mg, Al, Si, P, S, K, Ca, Mn, Fe, Ni

Water ice and organic matter
- H, C, N, O

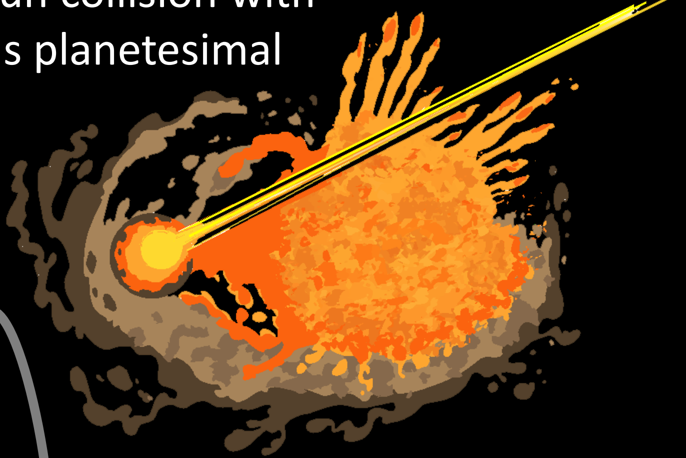


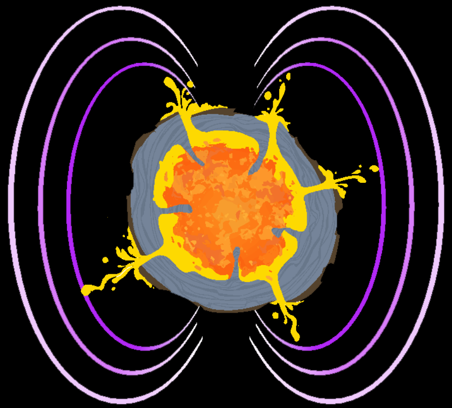
Igneous differentiation

Anhydrous silicate minerals (basalts + plutonic rocks)
- Li, O, Na, Mg, Al, Si, S, Ca, Ti, Mn, Fe, Co, Ni, Sc, REE (Sm, Eu, Gd)

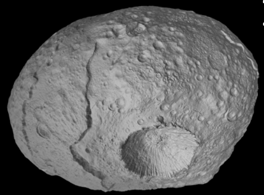
Variations in isotopic abundances generally ignored but might be important in some situations.

Hit & run collision with igneous planetesimal





16 Psyche?



Fe-Ni metal with light alloying elements
- H, C, O, Si, P, S, K, Fe, Ni

Psyche artwork courtesy ASU-led NASA Psyche mission

Summary of nuclear data issues

- Planetary nuclear spectroscopy is model based:
  - Models relate surface geology (chemistry, physical layering) to observations
  - Requires accurate nuclear data libraries and models of high-energy interactions (up to many GeV/nucleon)
  - Predictive capability is desired, $\sim$ 20% accuracy achievable for many relevant signatures/materials per lunar observations
  - “Ground truth” is required to achieve higher accuracy, i.e.,
    - Use of known geochemical trends or regional compositions for the target body (FHT-FLM $\rightarrow$ Moon)
    - Comparison of data acquired for different targets and observing conditions (Mars $\rightarrow$ Vesta)
    - Selection of model parameters vs. calibration

- Experimental validation of models
  - Apollo Lunar Neutron Probe Experiment (e.g., McKinney et al, 2006)
  - Accelerator and high-altitude balloon experiments with representative thick targets
  - Model-experiment discrepancies for neutron production by light ions in thick, low-Z targets (e.g., Ratliff et al., 2018)
  - Connections to space radiation shielding community

- General comments
  - Discrete gamma-ray lines by isotope needed for all elements of interest (see previous chart)
  - Analog Monte Carlo modeling of correlated signatures may be of interest for interpretation of in situ measurements and calculations of instrument response