# Space Energetic Particles and Space Weather from the Lunar Surface


SOUTHWEST RESEARCH INSTITUTE®

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# Outline

- Solar Energetic Particles
  - Introduction
  - Energy Spectrum
  - Longitudinal dependences and Composition
- Lunar Radiation Environment
  - Solar Wind and Magnetosphere
  - SEP at lunar orbit
  - Galactic Cosmic Ray
  - Radiation dosage at the Moon

# Two-Class of Solar Energetic Particle (SEP)

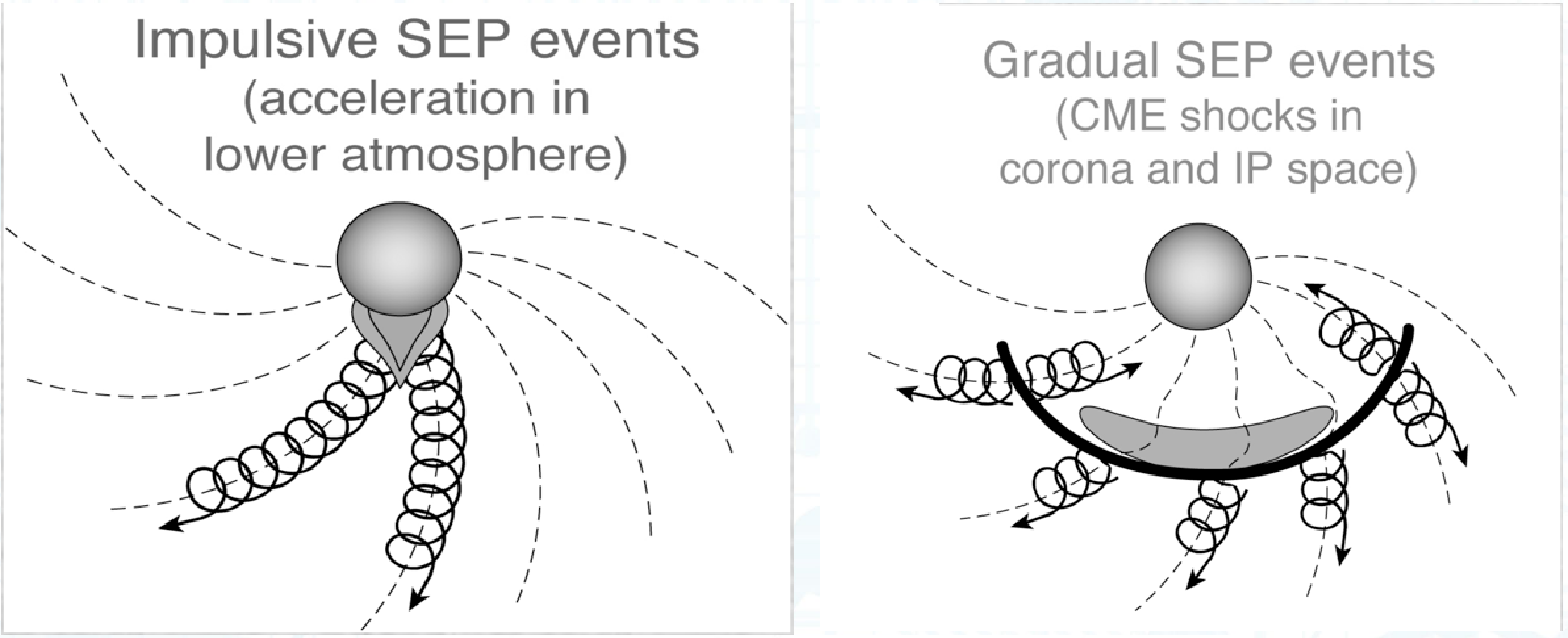


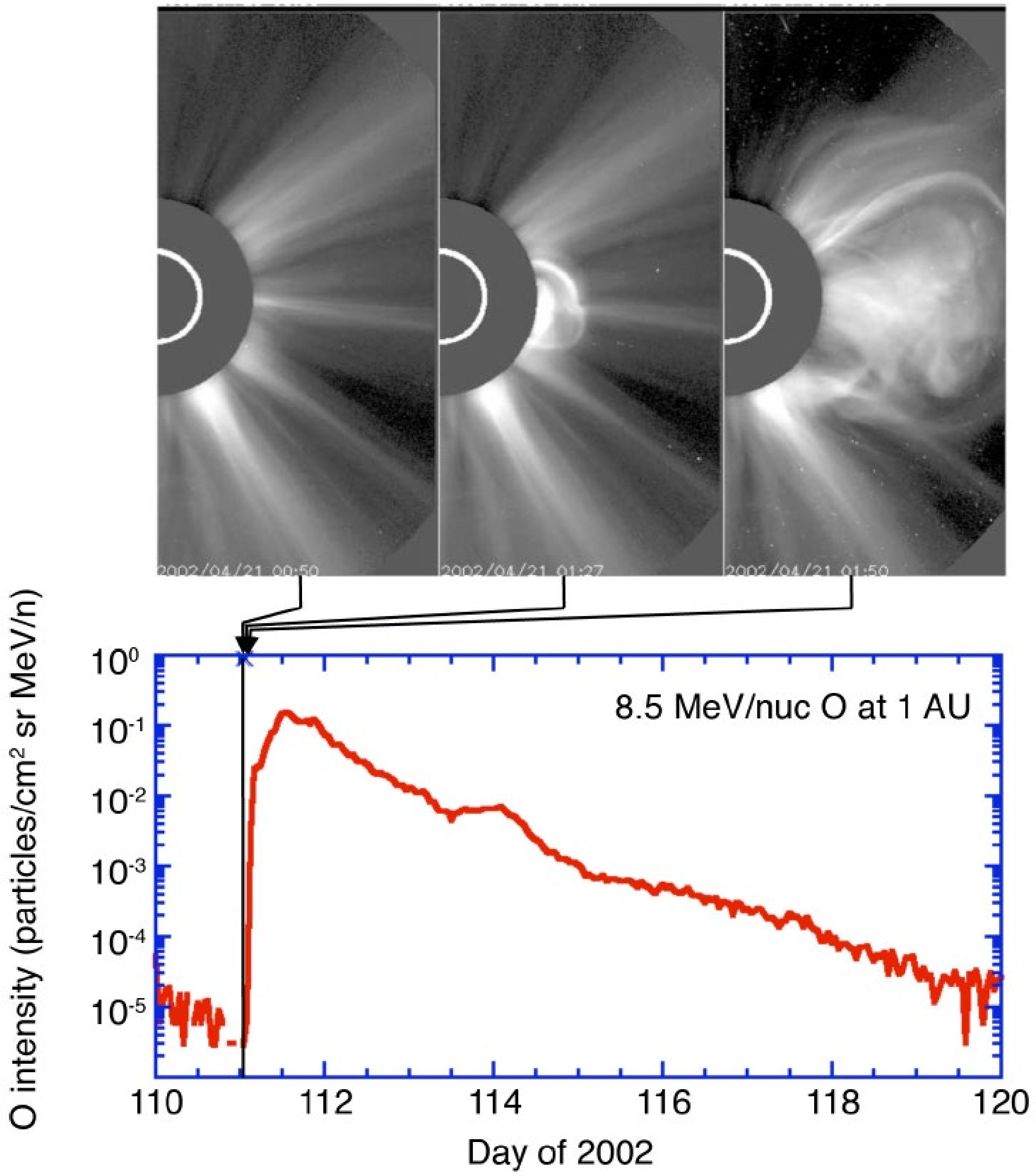

TABLE 1. PROPERTIES OF IMPULSIVE AND GRADUAL EVENTS (45)

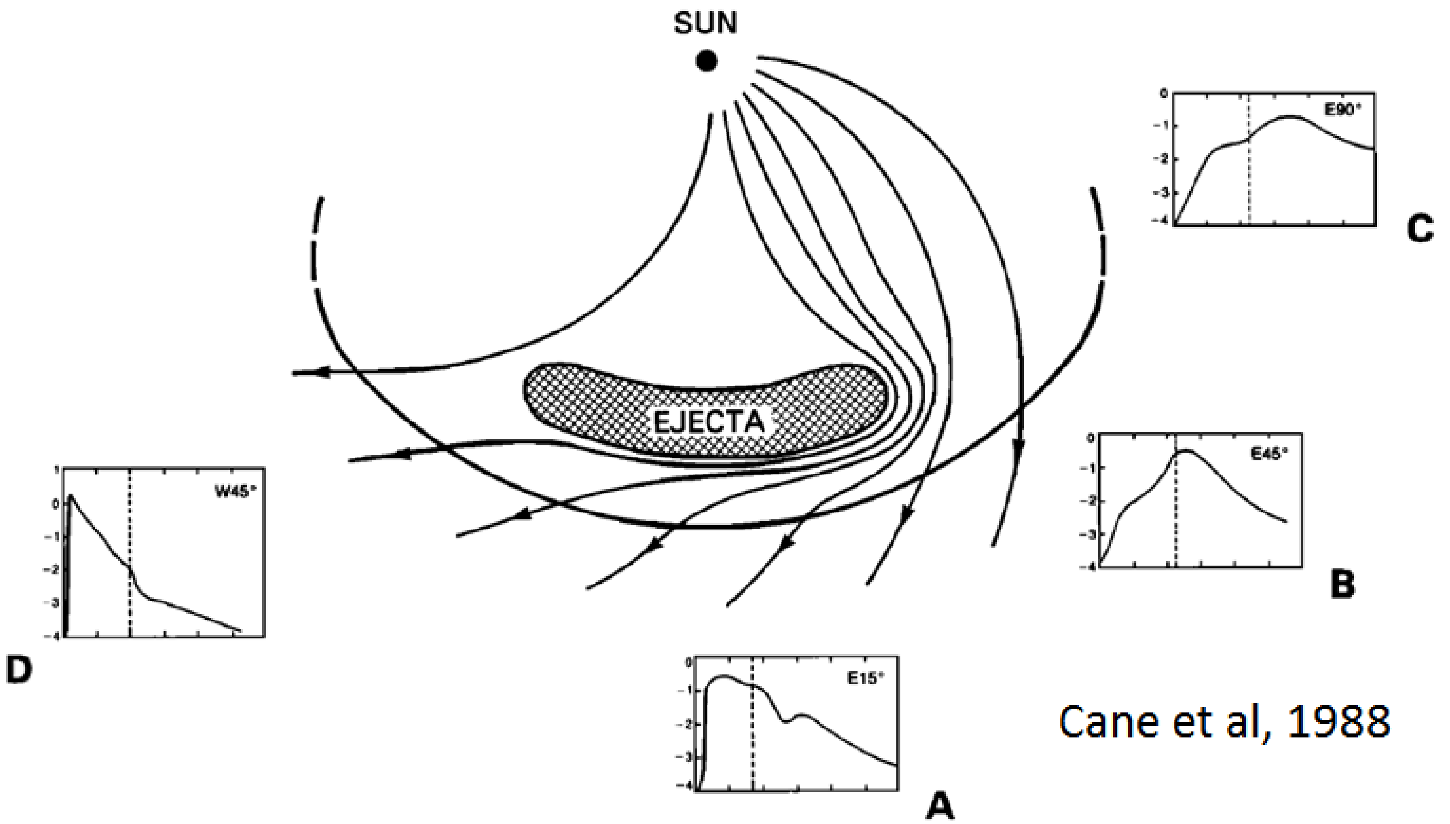
| | IMPULSIVE | GRADUAL |
|---|---|---|
| PARTICLES: | ELECTRON-RICH | PROTON-RICH |
| $^3He/^4He$ | ~1 | ~0.0005 |
| Fe/O | ~1 | ~0.1 |
| H/He | ~10 | ~100 |
| $Q_{Fe}$ | ~20 | ~14 |
| DURATION | HOURS | DAYS |
| LONGITUDE CONE | <30° | ~180° |
| RADIO TYPE | III, V(II) | II, IV |
| X-RAYS | IMPULSIVE | GRADUAL |
| CORONAGRAPH | --- | CME |
| SOLAR WIND | --- | IP SHOCK |
| EVENTS/YEAR | ~1000 | ~10 |

- Wild *et al.* (1963)
- Lin (1970)
- Pallavacini *et al.* (1974)
- Kahler *et al.* (1978)
- Mason *et al.* (1984; 1986)
- Cane *et al.* (1986; 1988; 1991)
- Reames 1988; 1995; 1999)

*Reames, Rev. Geophys., 1995*

# *Acceleration associated with CME-driven Shock*



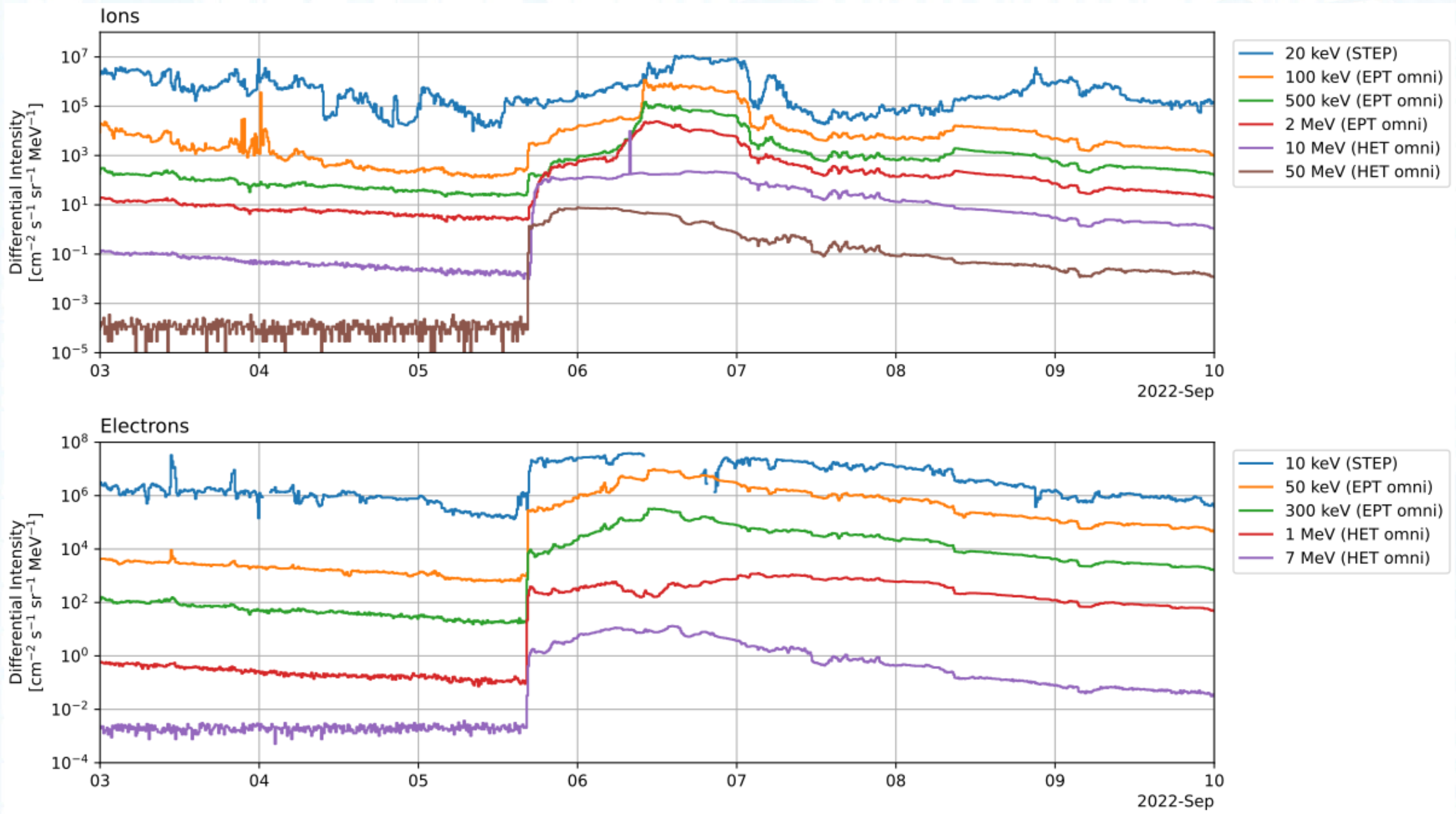



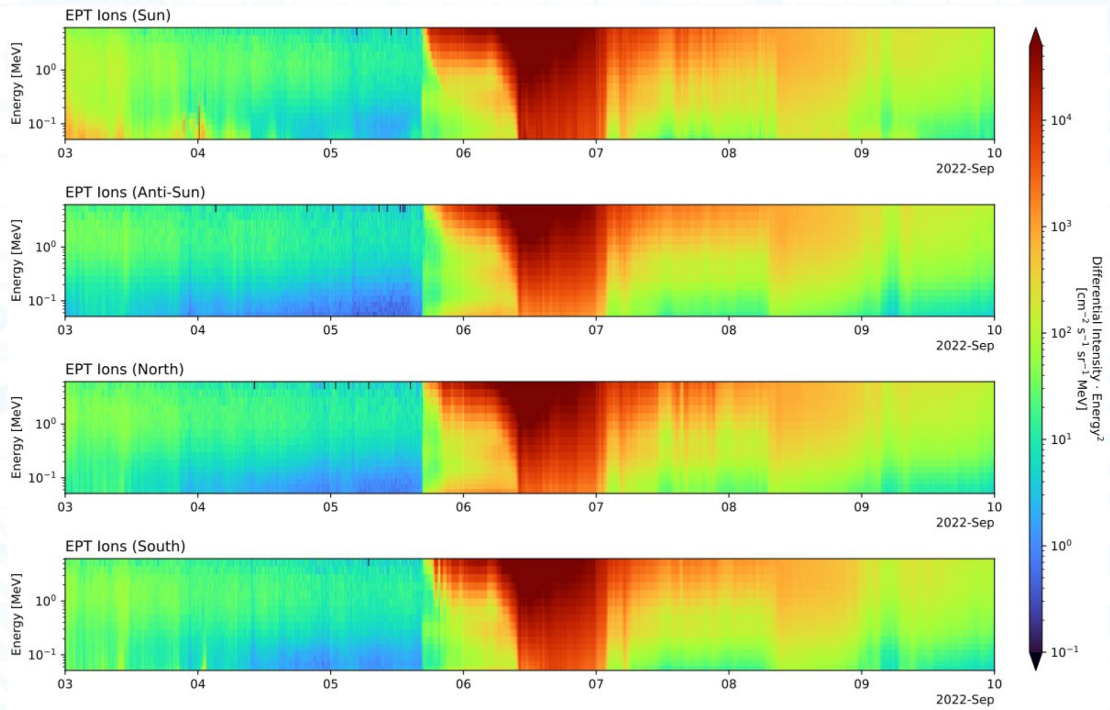

Cane et al, 1988

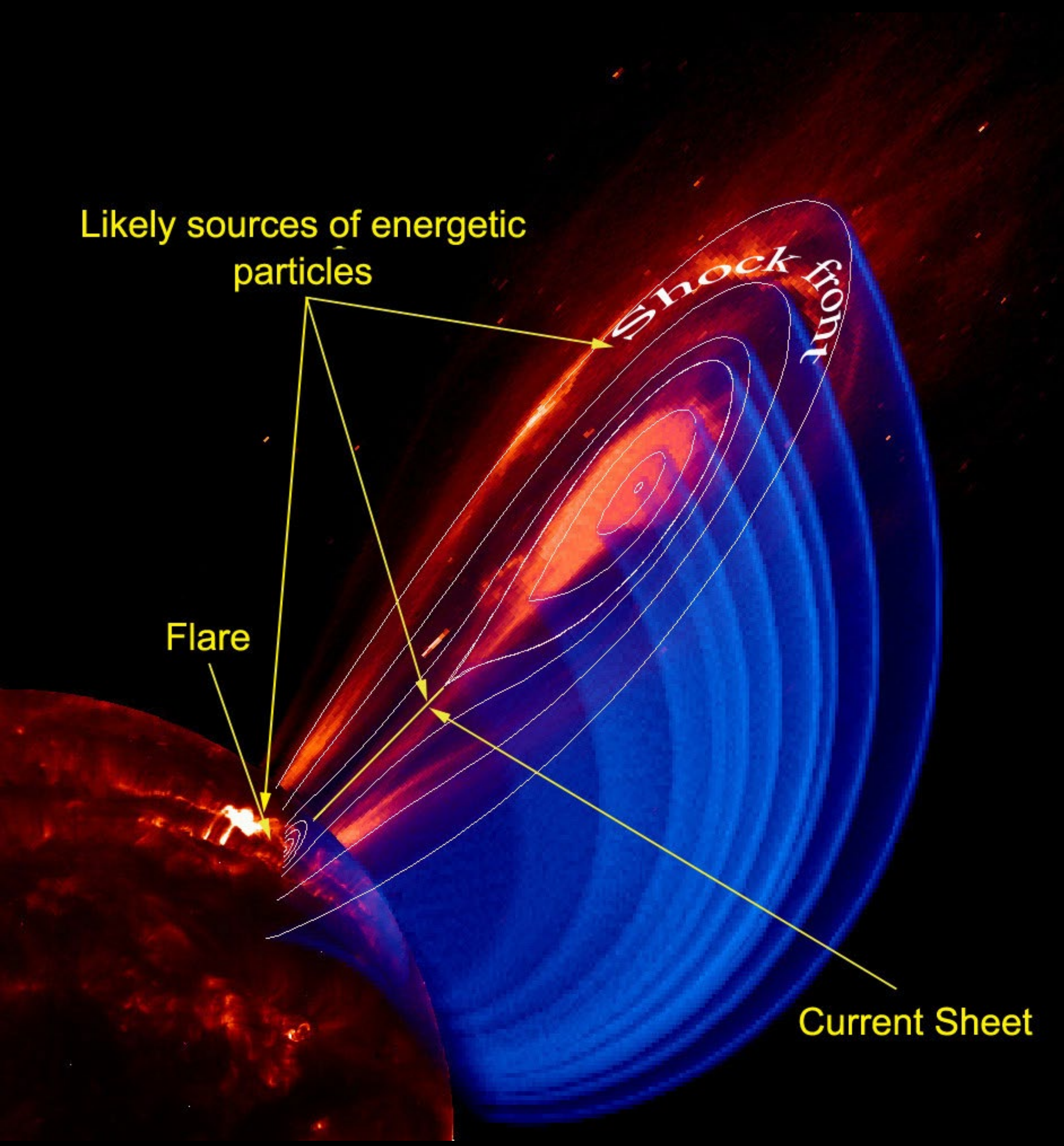
- CME-driven shock associated
- Proton rich
- Coronal like abundances
- Last for days
- Gradual X-ray

# Large SEP Anisotropy

2022 September 05

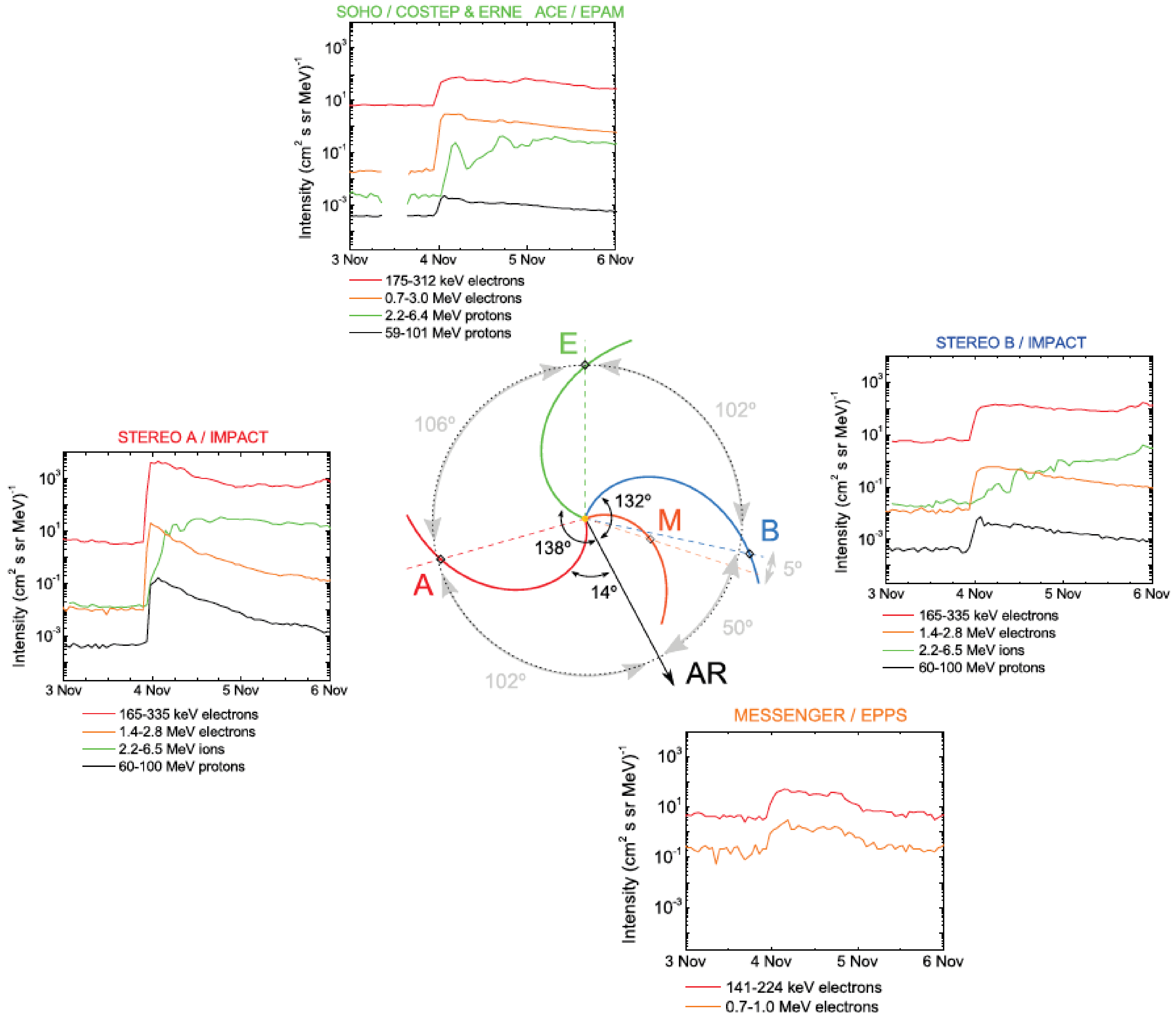




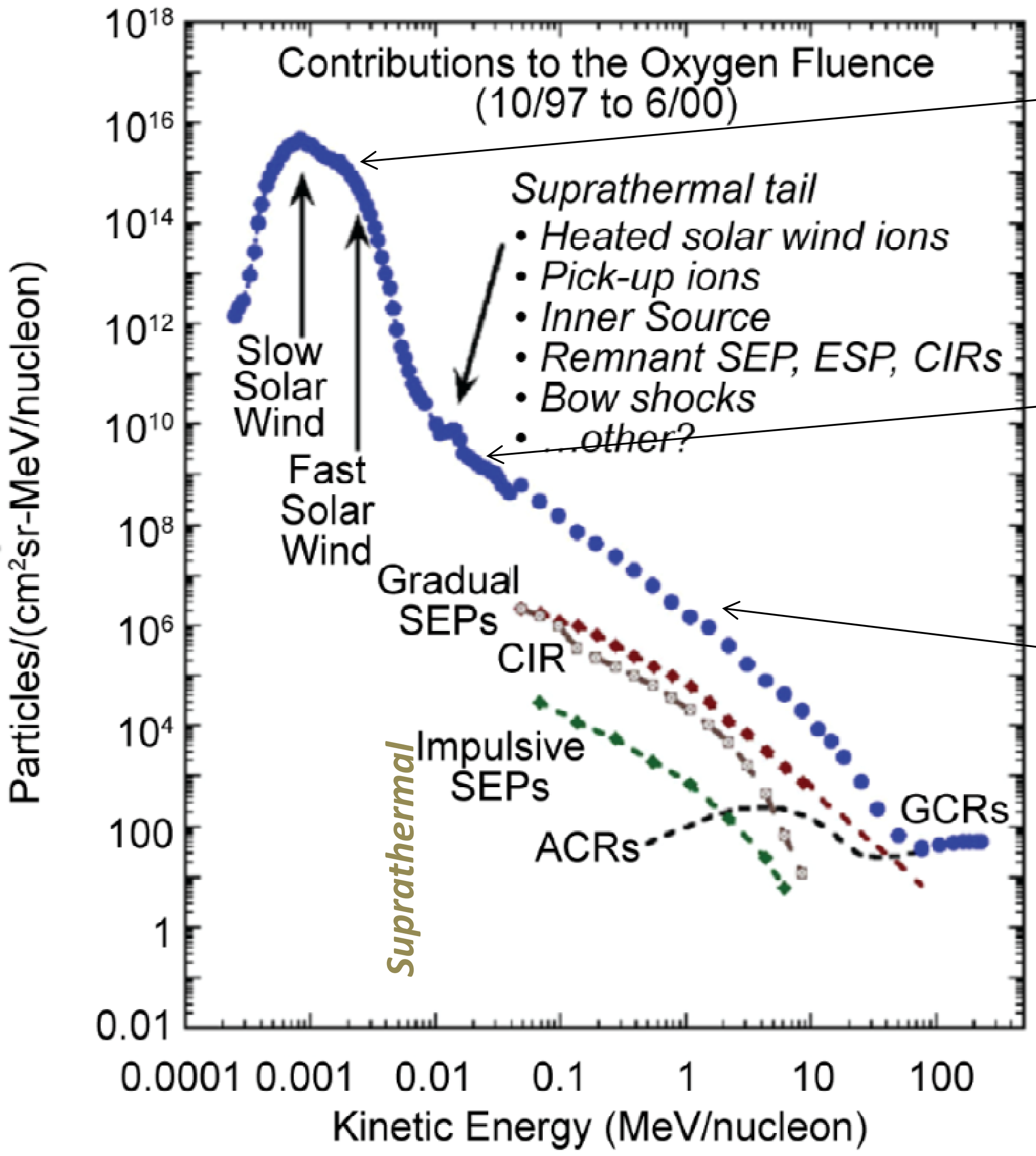
Likely sources of energetic particles
Shock front
Flare
Current Sheet

# Longitudinal Extend of SEP




Gómez-Haerreo et al., ApJ, 2005

# *Interplanetary Energy Spectrum*




***Bulk plasma*** (~keV)

- Typically measure by solar wind instrument

***Suprathermal*** (~10s keV)

- Gap between two measurement technique

***Energetic particle*** (~100s keV)

- Typically measure by particle instrument
- Highly variable
- Can extend up to 100s MeV

Mewaldt *et al.*, 2001

# Energy Spectral Break

THE ASTROPHYSICAL JOURNAL, 816:68 (18pp), 2016 January 10

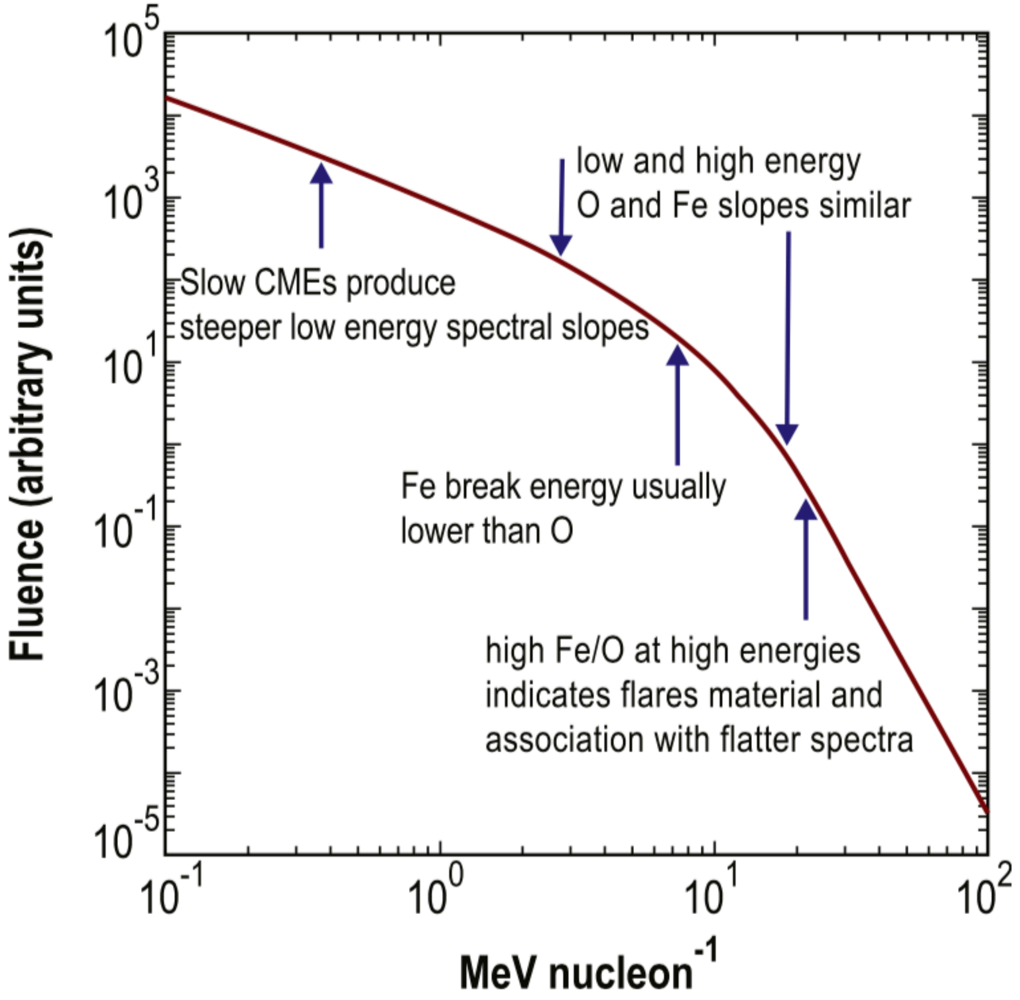
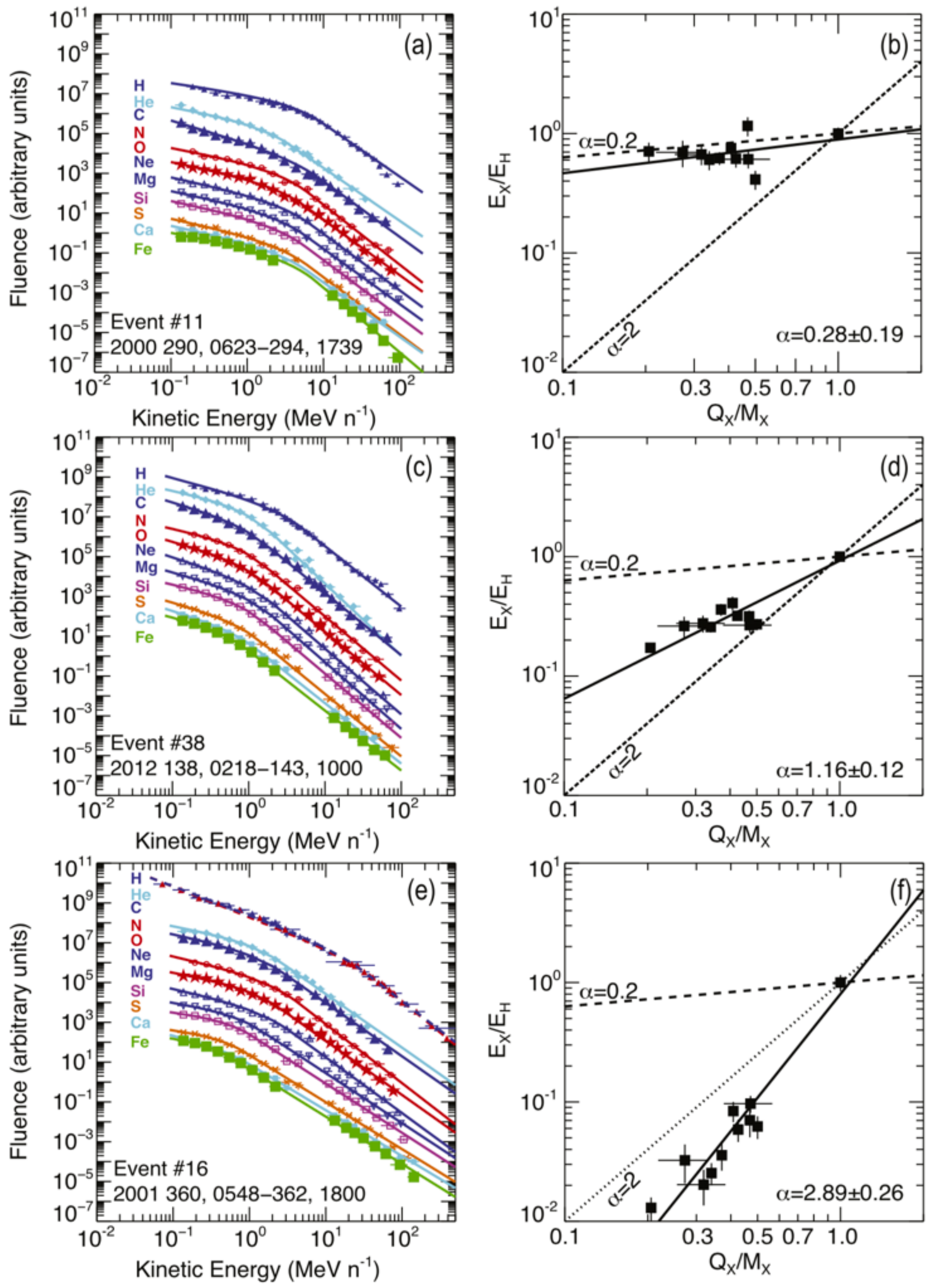


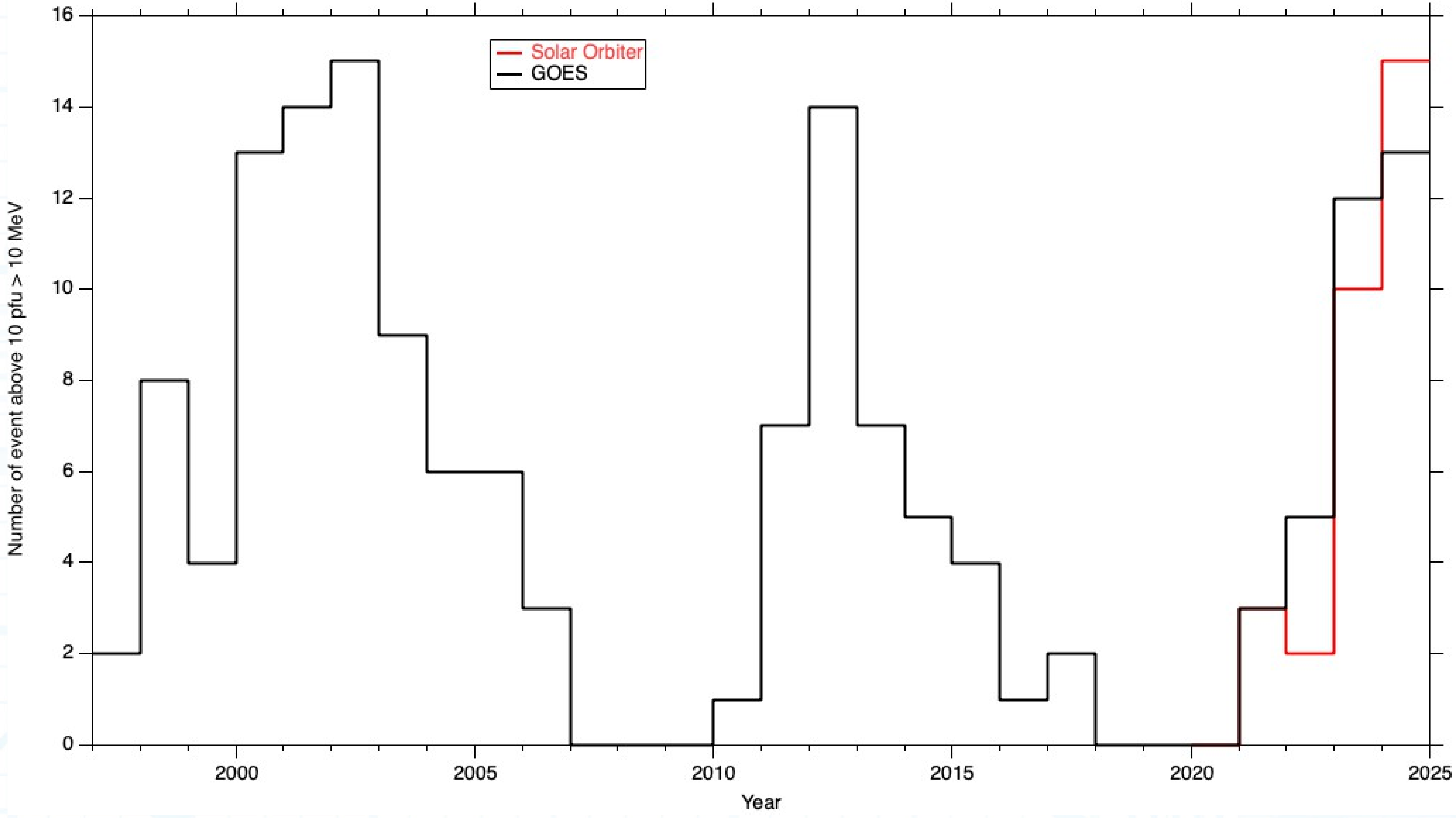

**Figure 14.** Arbitrary O spectrum summarizing our key results in terms of the SEP Band-parameters and their relationships with CME speeds and Fe/O ratios. (For further discussion see Section 5.)

*Desai et al. ApJ, 2016*

THE ASTROPHYSICAL JOURNAL, 828:106 (19pp), 2016 September 10 DESAI ET AL.



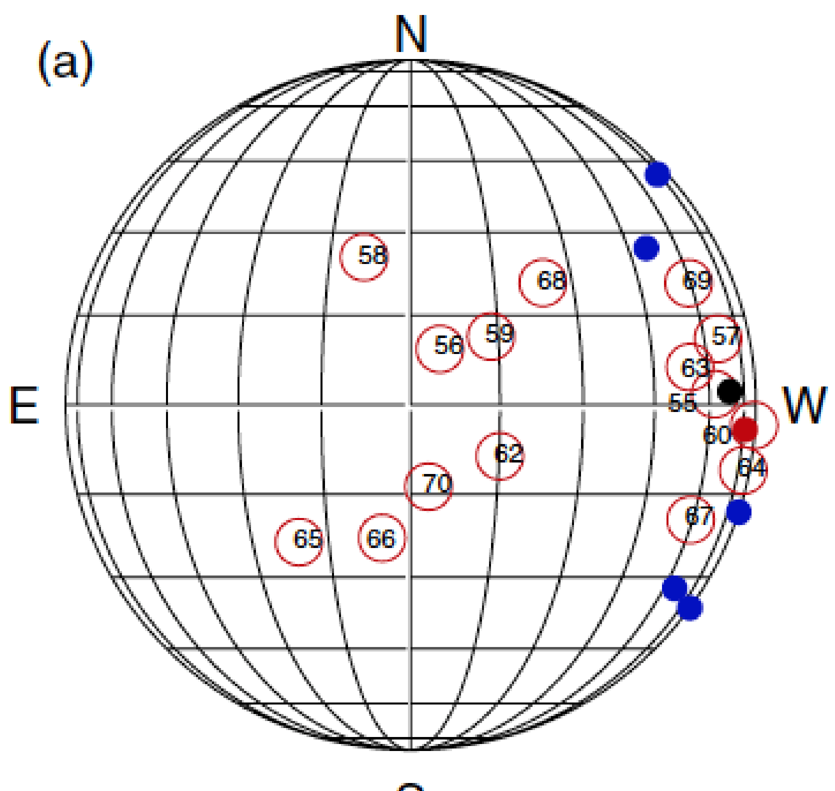
# SEP Activities for Solar Cycle 25



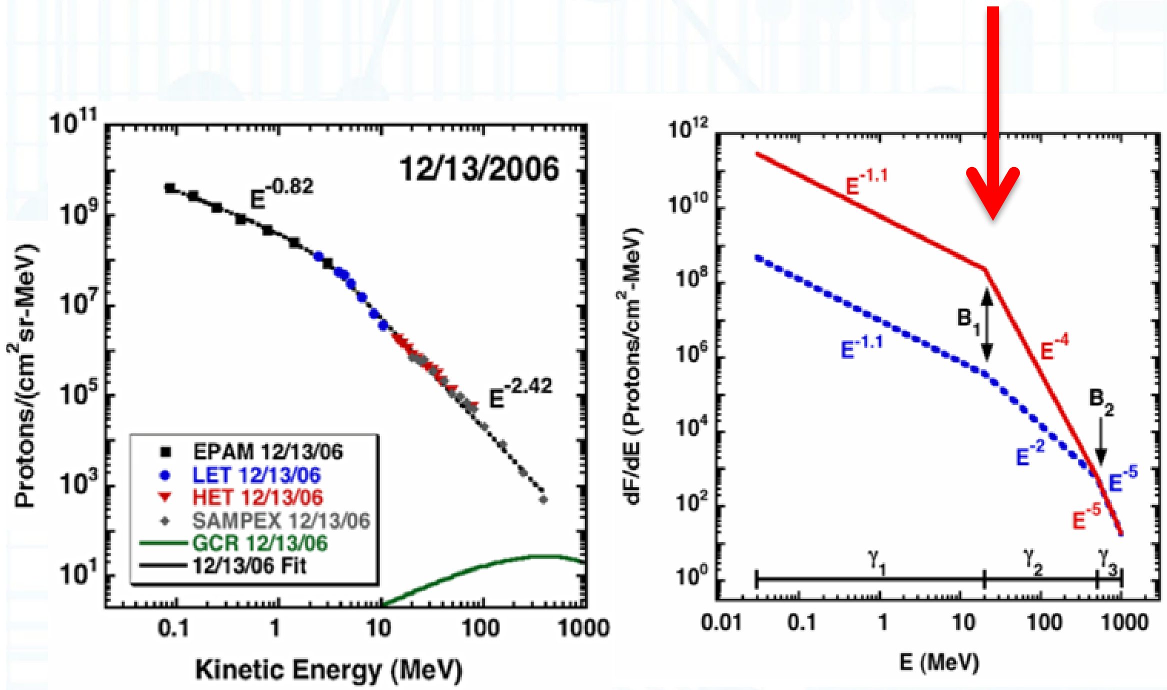

- Solar Cycle #25 was just as intense in SEP activities as in Cycle #23
- Number of > 10pfu @ 10 MeV comparable with Cycle #23

*Ho et al., 2025*

# Ground-Level Events During Solar Cycle 23 and 24




*Gopalswamy et al., ApJL, 2013*




*Mewaldt et al., Space Sci Rev, 2012*

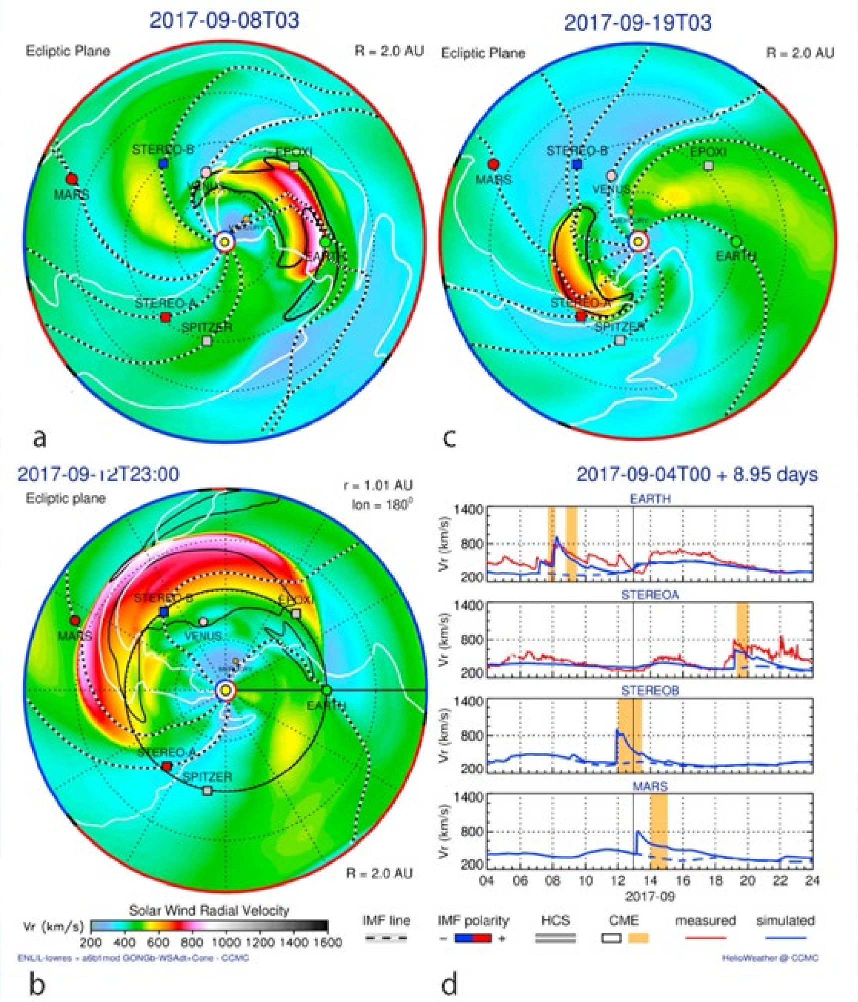
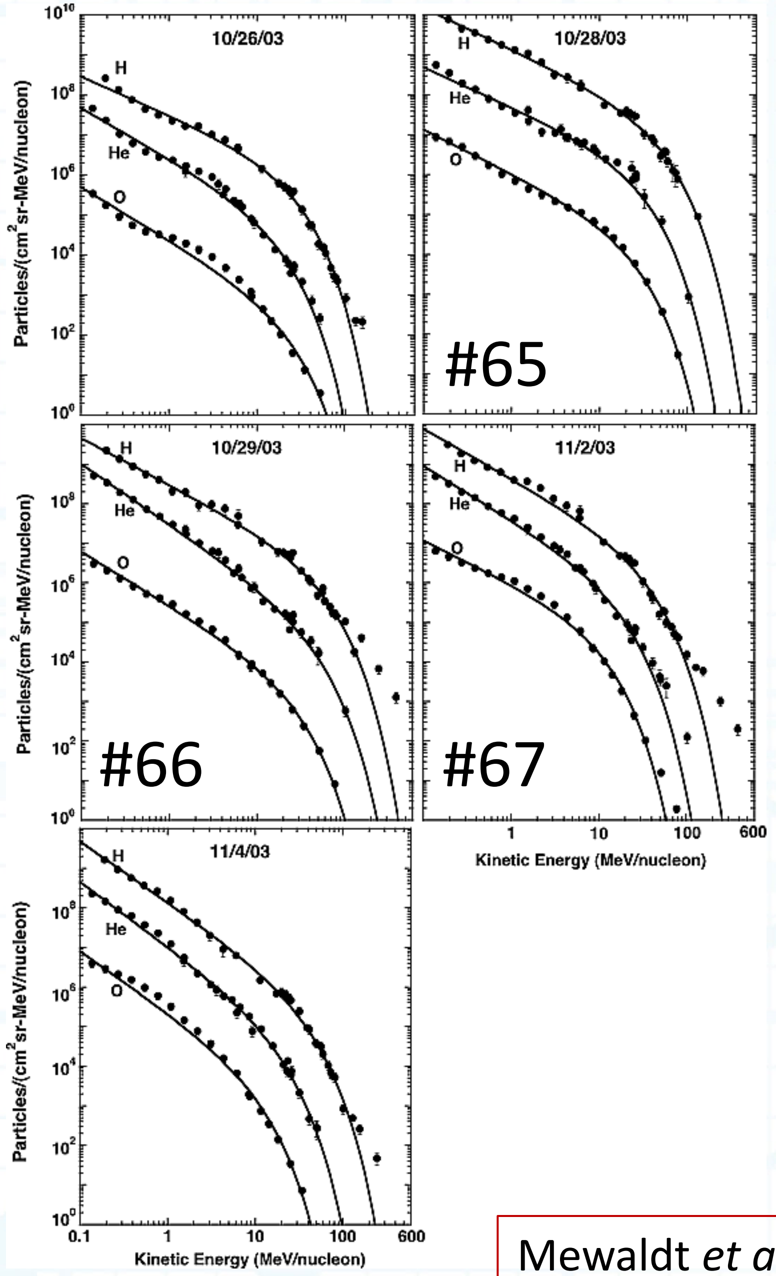



**Figure 4.** Same as Figure 3 but for 4–24 September 2017. CME = coronal mass ejection; HCS = heliospheric current sheet; IMF = interplanetary magnetic field.

*Luhmann et al., Space Weather, 2018*

- 16 (all) GLEs of solar cycle 23 and 2 GLEs of solar cycle 24
- Associated with fast (>2,000 km/s CME)
- Western and central meridian
- double power law (Band) gave best fit results
- critical importance of high energy slope:  3.18 for GLEs, 4.34 for large events that did not produce GLE

# Energy Spectra and Composition




Mewaldt *et al., JGR*, 2005

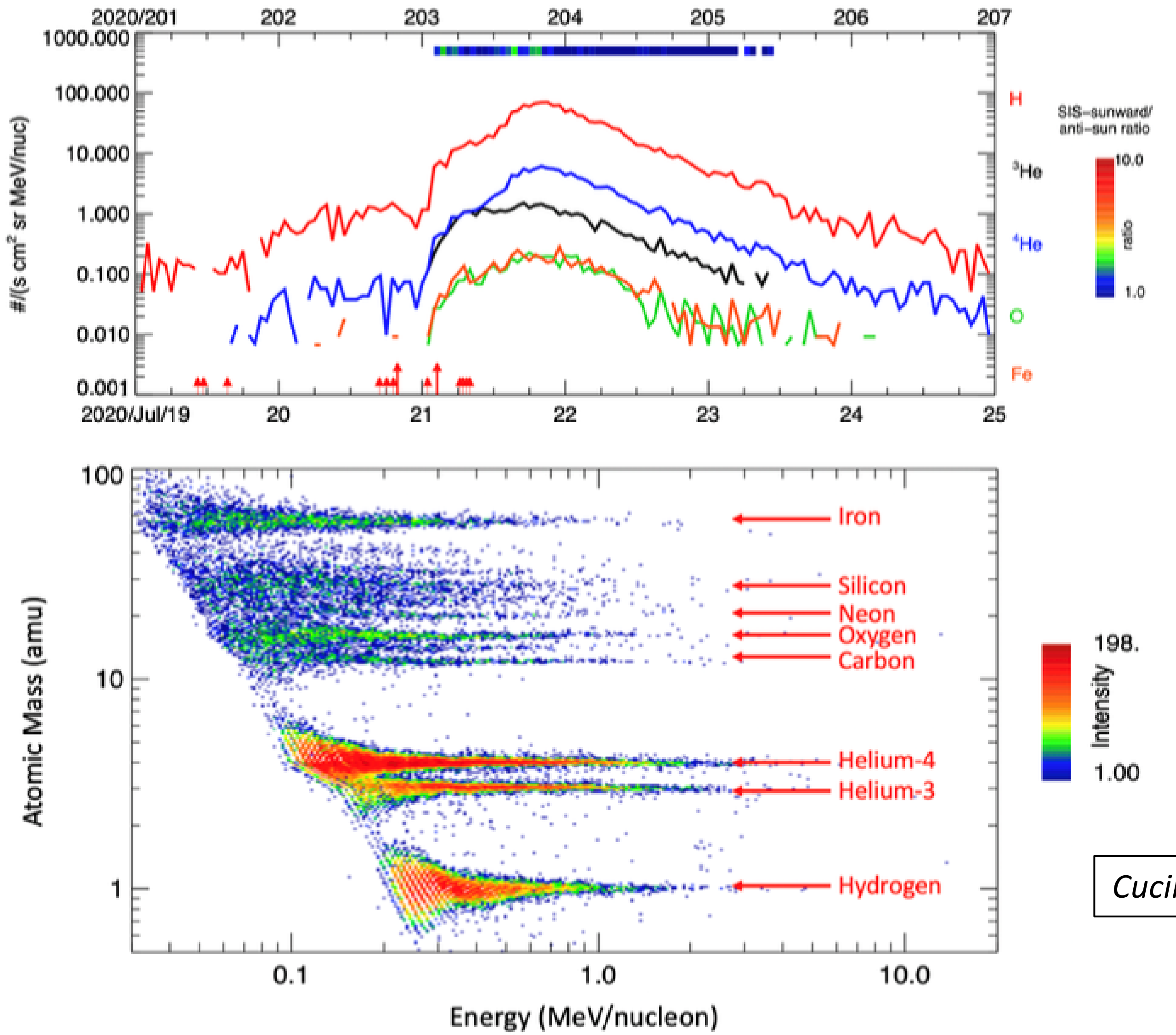
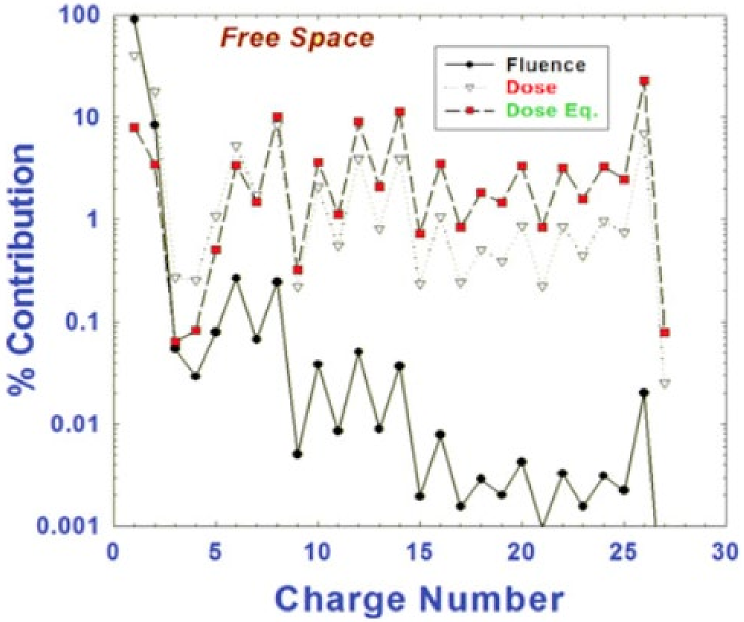


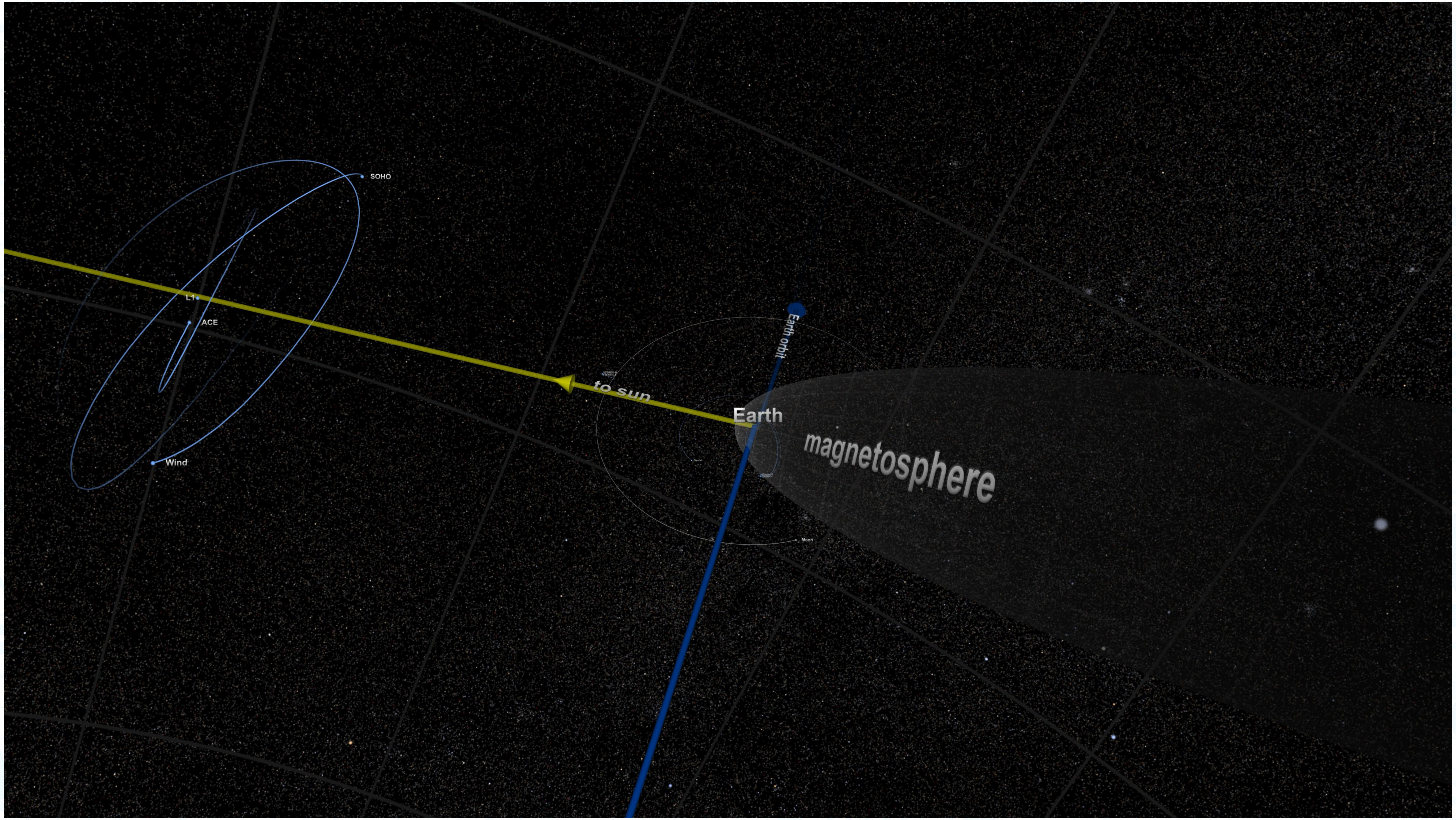

Fig. A.1 *Top:* particle intensities for 21-Jul-2020 event; *red arrows* mark times of type III bursts seen on STEREO; *bottom:* mass spectrogram.

*Mason et al., A&A, 2020*




*Cucinotta et al., Encyclopedia of Lunar Science, 2023*

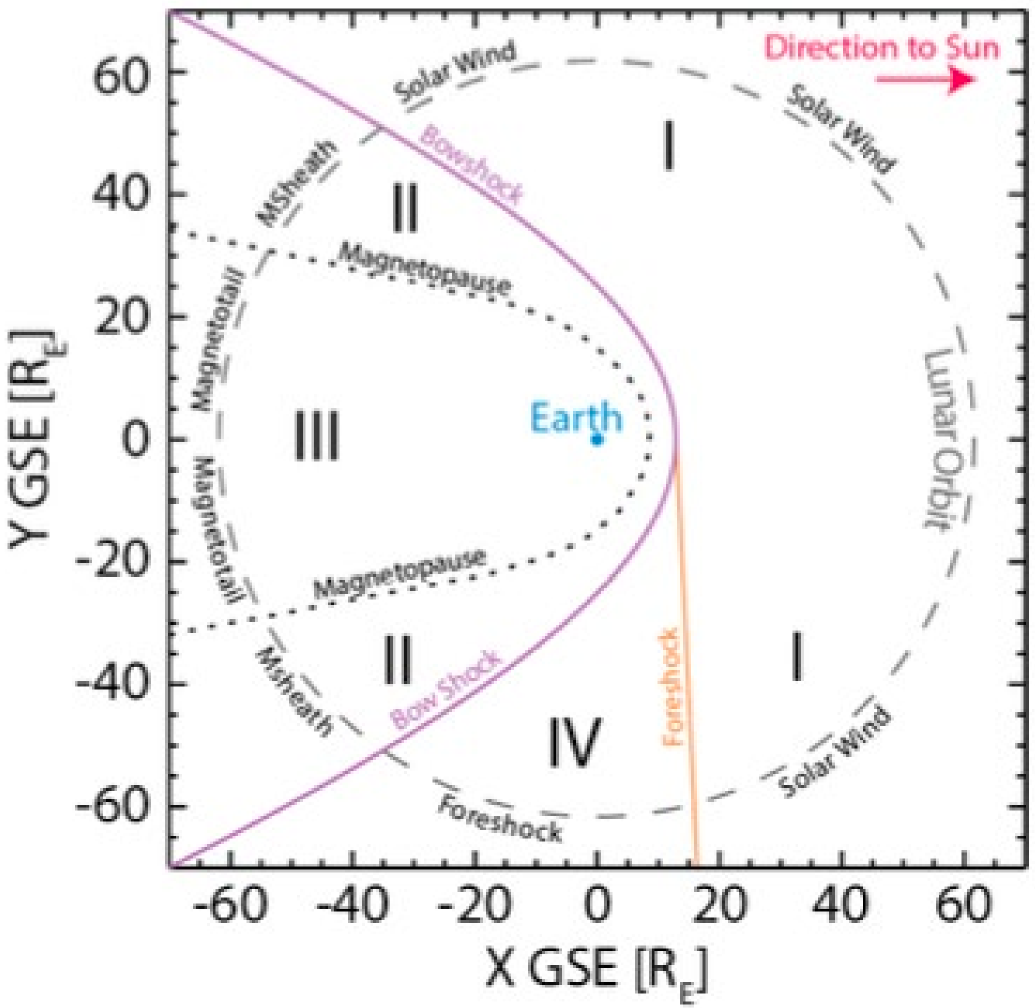
# Lunar Orbit

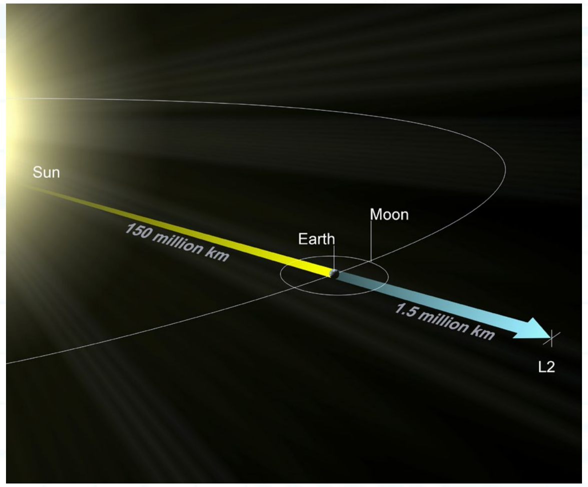


SOHO
L1
ACE
Wind
to sun
Earth orbit
Earth
magnetosphere
Moon

# Heliophysics Science at Lunar Orbit

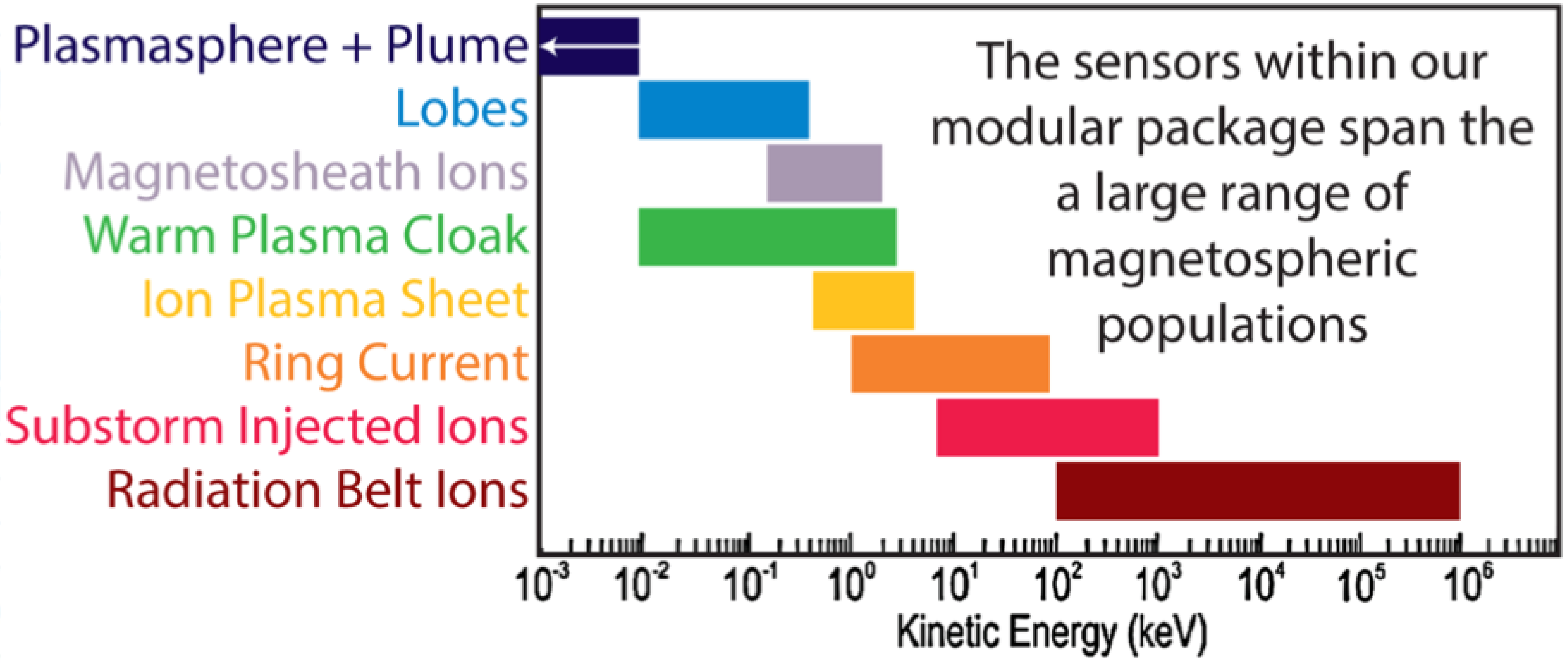
- Ideal location for long-term space weather observations from outside Earth's boundaries and simultaneously providing in-situ observations in the magnetotail and magnetosheath
- Measure the solar wind and its propagation at near-Earth vicinity
  - Large scale solar wind structures propagation (e.g. interplanetary shock; CME, CIR)
- Characterize the cis-lunar plasma and particle environment:
  - Solar wind-lunar interaction (e.g. neutral and ion)
  - Magnetosphere-lunar interaction (e.g. plasma)
  - In –situ radiation monitor (crew safety) with spectrum, dose and species information
- Remote sensing of the Earth's magnetosphere via energetic neutral imager
- And more…



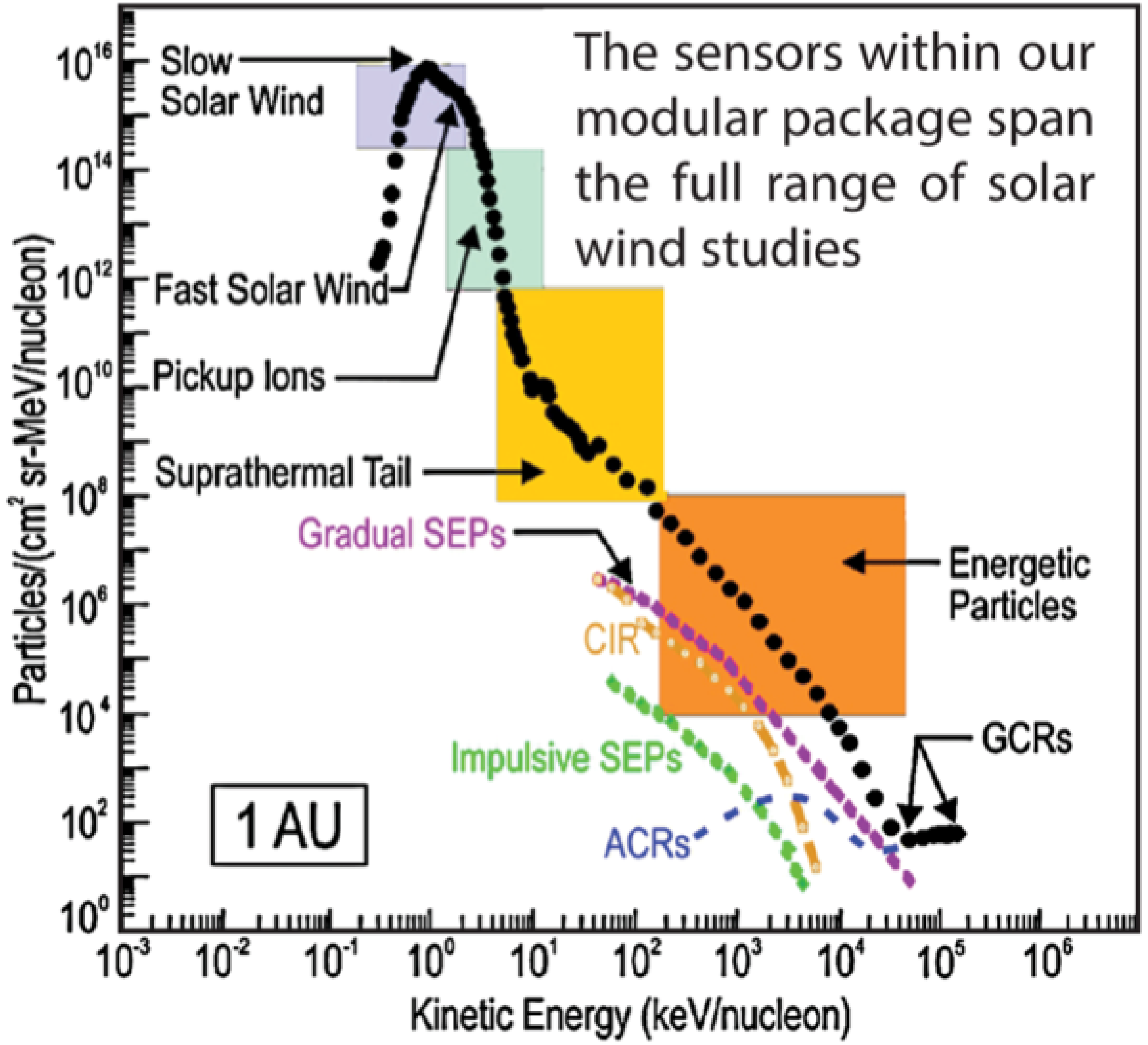



# Lunar Orbit Particle Environment

Magnetosphere

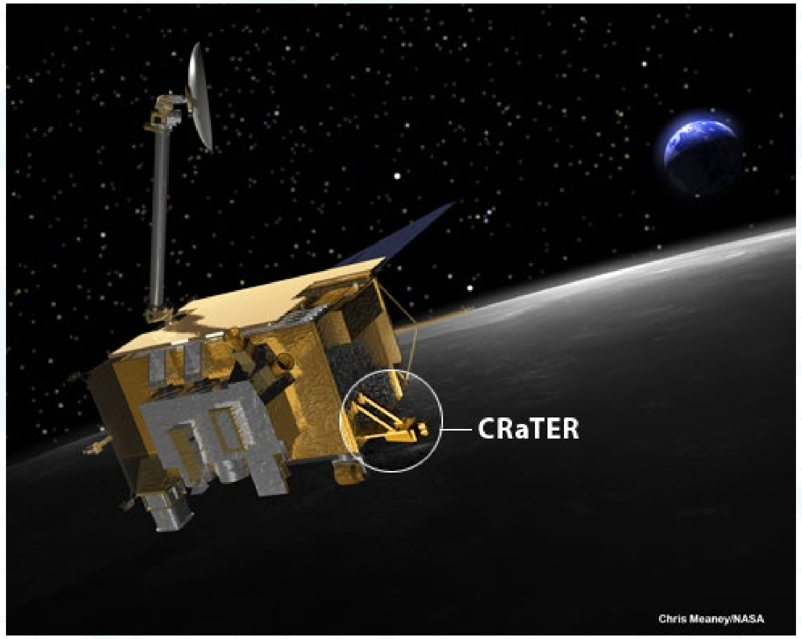


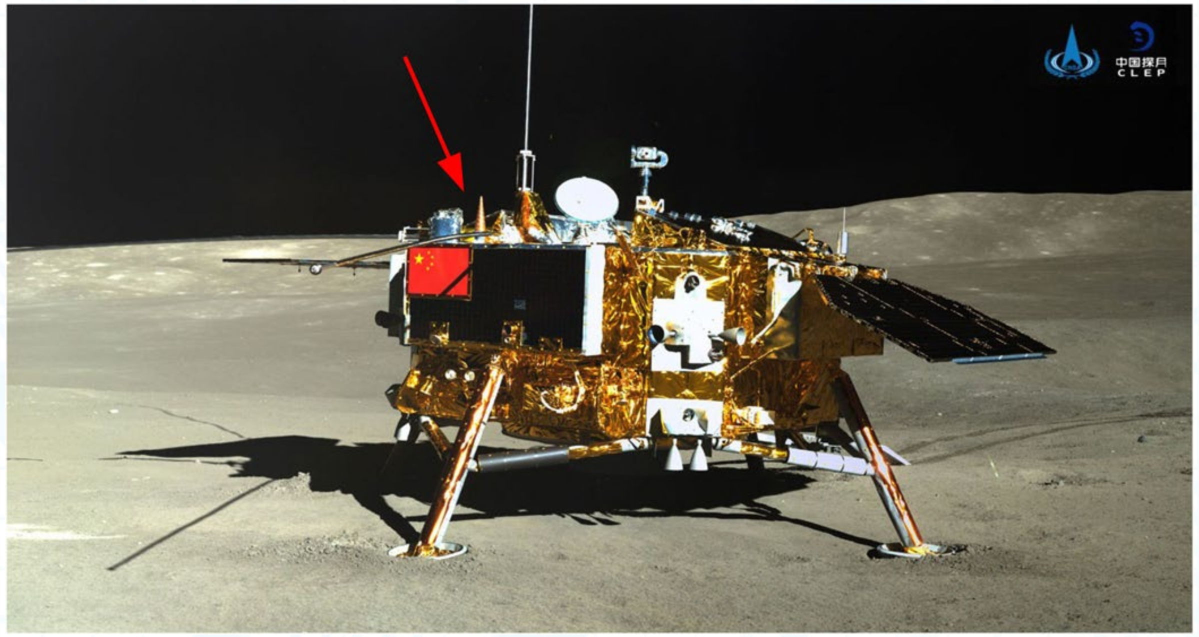

Solar Wind



# Recent Particle Instrumentation @ Moon

- Lunar reconnaissance orbiter (2009 - )
  - Cosmic Ray Telescope for the Effects of Radiation CraTER
- Chang'E-4 (2019 - )
  - Lunar Lander Neutrons and Dosimetry experiment (LND)



# GOES and LRO/CRaTER Comparison

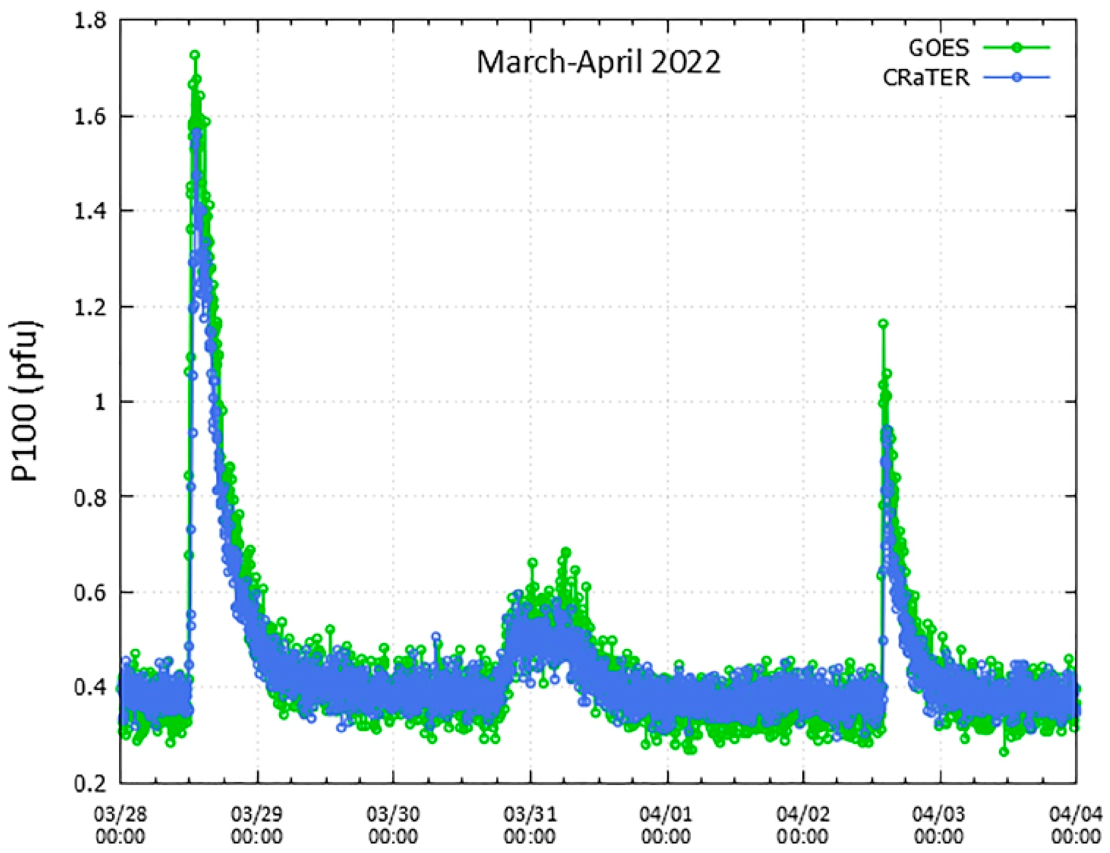



**Figure 5.** P100 fluxes for the late March and early April ESPEs in 2022. In between the two events in which the GOES-17 P100 flux exceeded 1 pfu, a smaller event occurred and was observed by both instruments. In GOES-16 data (not shown), the peak value of P100 was, like CRaTER P100, <1 pfu for the April 2 ESPE; had it been the primary measurement, the event would not have met our criterion for inclusion in this study.

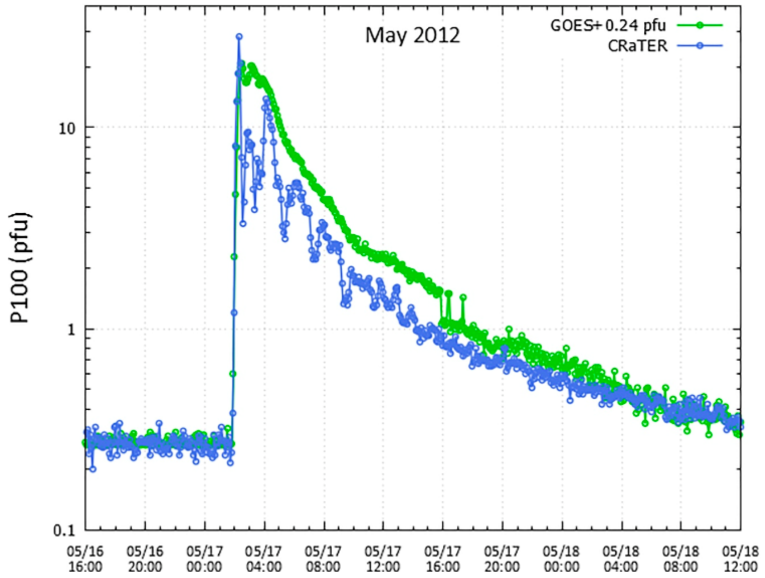
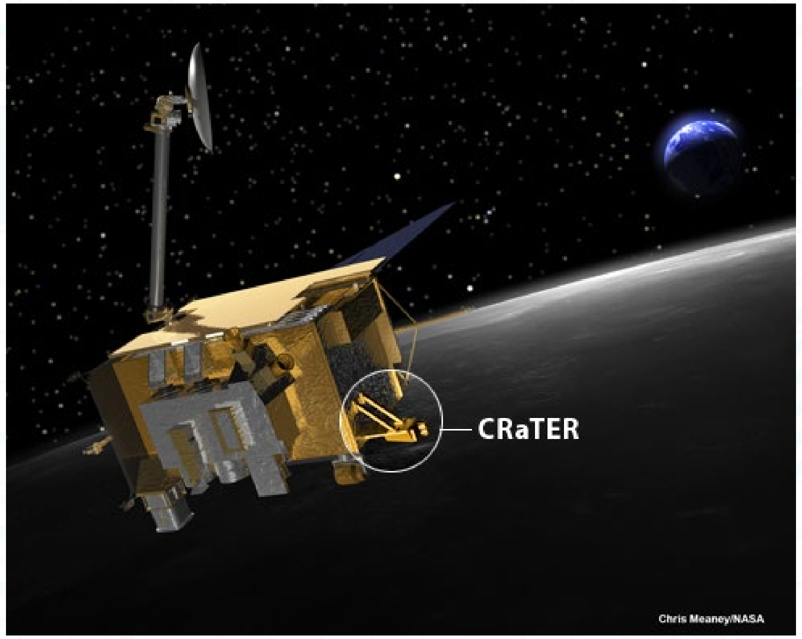



**Figure 8.** GOES-13 and CRaTER P100 fluxes for the May 2012 GLE.



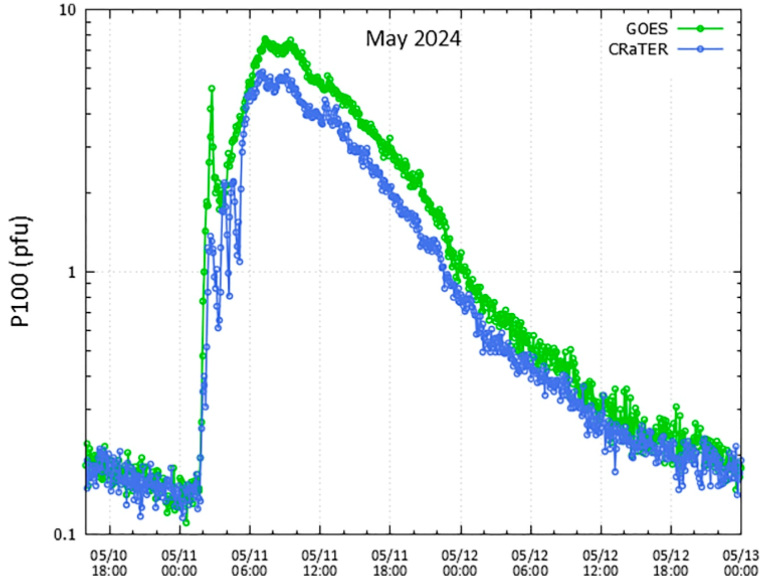




**Figure 6.** GOES-18 and CRaTER P100 fluxes for the May 2024 ESPE.

*Zeitlin et al. Space Weather 2025*

# ARTEMIS

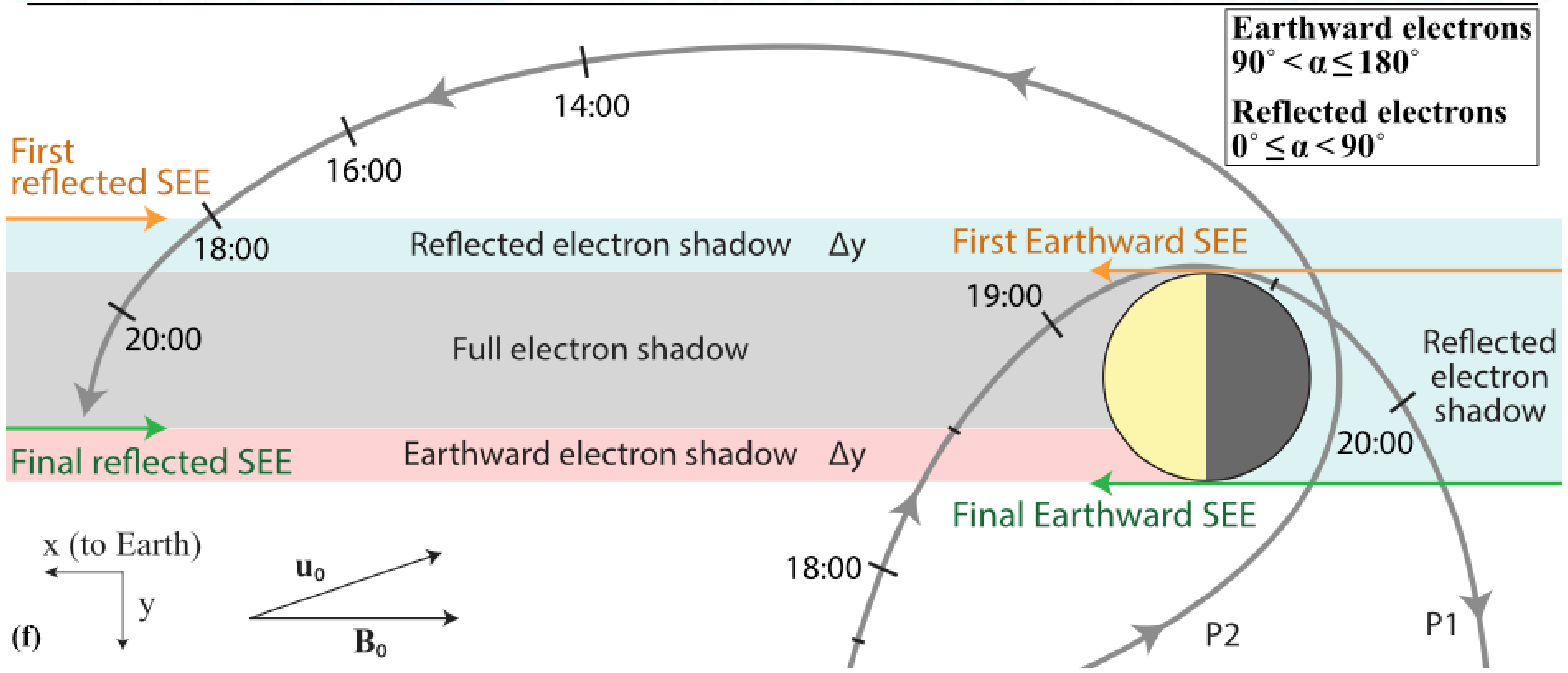
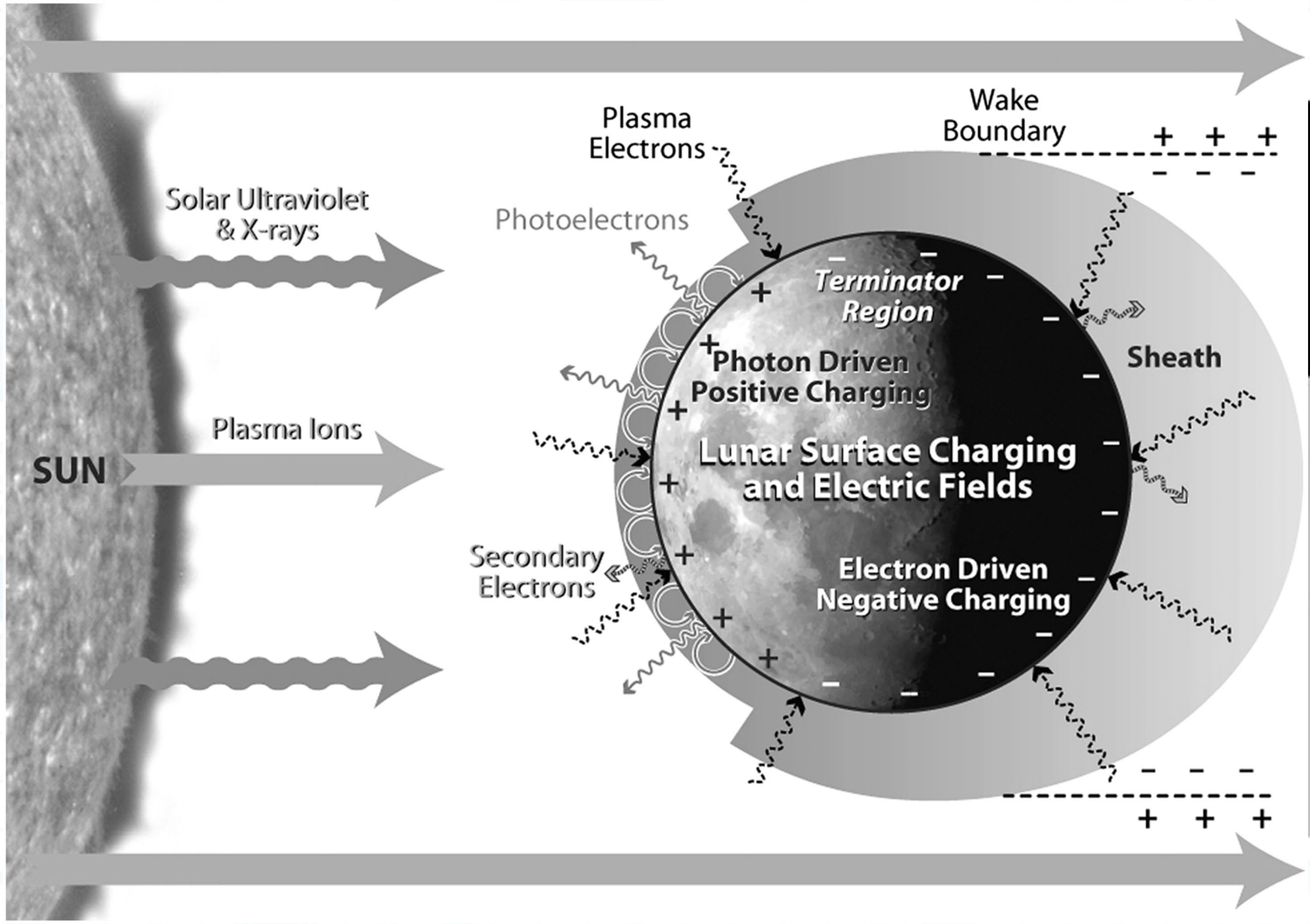



**Figure 2.** ARTEMIS solar energetic electron (SEE) observations on 31 July 2023 within Earth's southern magnetotail lobe. Black bars along the bottom of (e) show times where the probes were magnetically connected to the lunar surface, while magenta bars in (a) and (b) indicate regions depleted of SEEs. The P1 data gap at high energies corresponds to closest approach, where the Solid State Telescope attenuator was activated. Panel (f) displays a schematic explaining the SEE drop-outs, projected onto the Geocentric Solar Ecliptic $x$-$y$ plane and viewed from above the Moon's North pole. Colored regions correspond to SEE shadows, for (blue) reflected electrons, (red) Earthward electrons, and (gray) all electrons, and $\Delta y$ indicates the electron's displacement in the $-y$-direction caused by magnetotail convection.

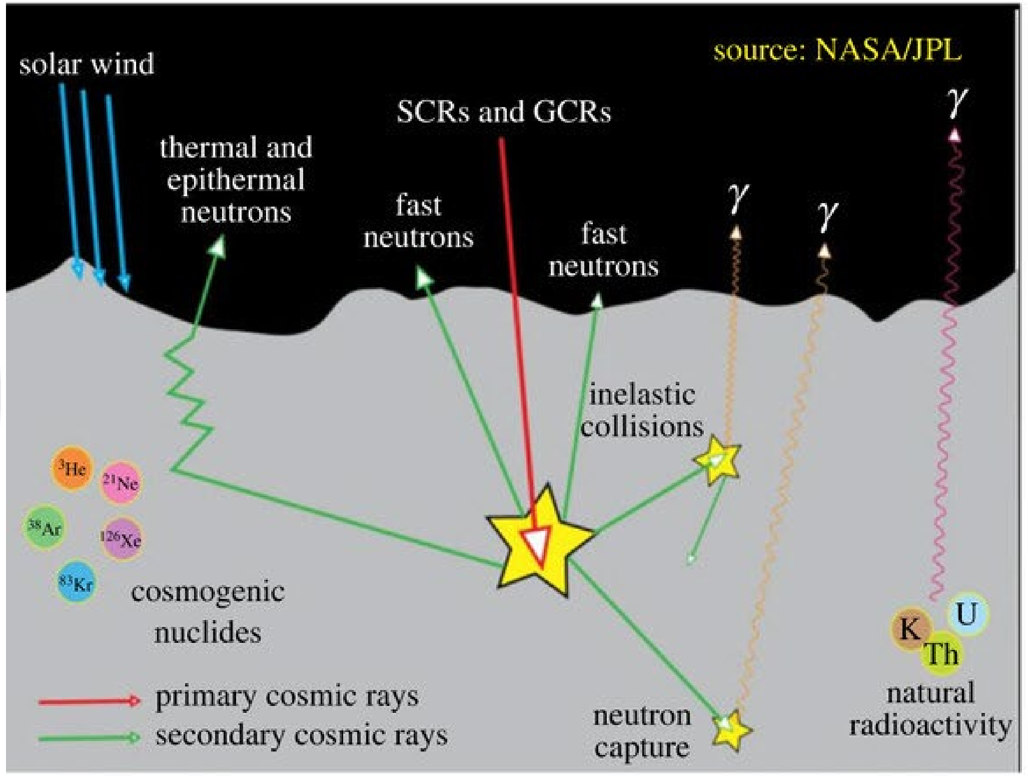
- High-energy electron flux near the Moon is unchanged during intense solar energetic electron events compared to measurements taken far upstream of Earth.
- However, the precipitation of these particles onto the lunar surface is non-uniform. Since these electrons gain access to the magnetosphere from down-tail of the Moon, they preferentially bombard the lunar far-side surface.
- future activities on the lunar surface, there exist regions across the lunar near-side where the relative flux of these electrons is reduced relative to the upstream value when the Moon is within the magnetotail

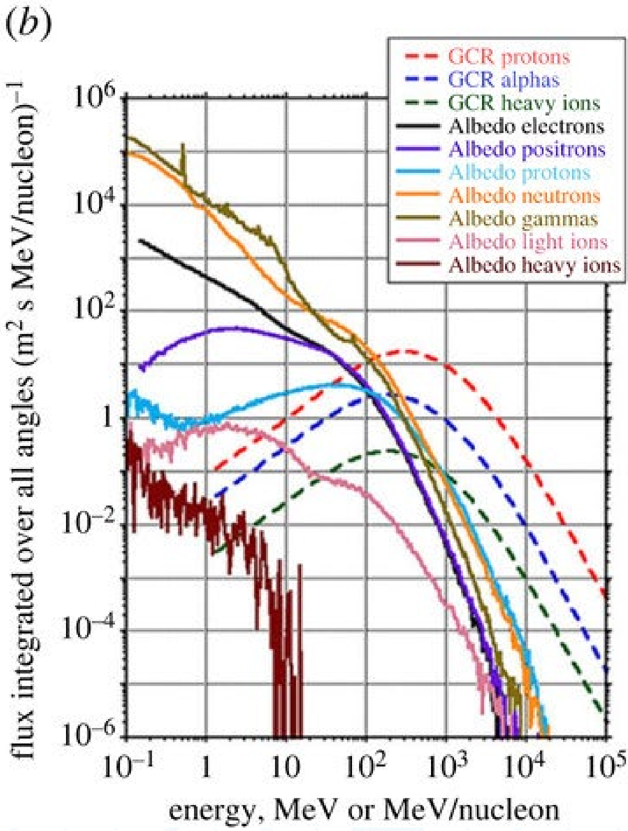
*Liuzzo et al. GRL, 2024*

# Secondary Processes on Lunar Surface




Stubbs et al., Plan. Planetary and Space Science, 2014




Dandours and Roussos, Phil. Trans. R. Soc. A 382, 2024

# Lunar Vertex

Lunar swirls and the co-located regions of magnetized crustal rocks: Two longstanding lunar mysteries.

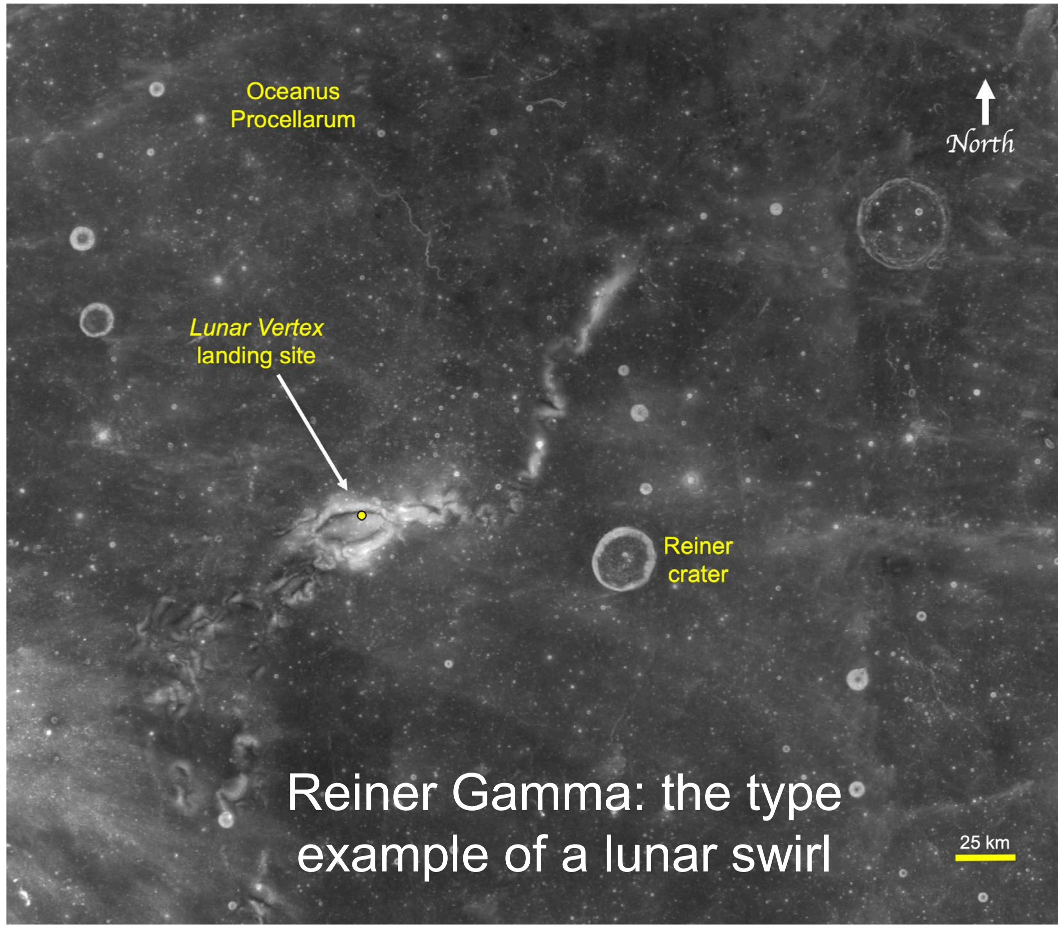
## Science Goals

1. Investigate the origin of lunar magnetic anomalies.
2. Investigate the origin of lunar swirls.
3. Determine the structure of the mini-magnetosphere that forms over the Reiner Gamma magnetic anomaly.

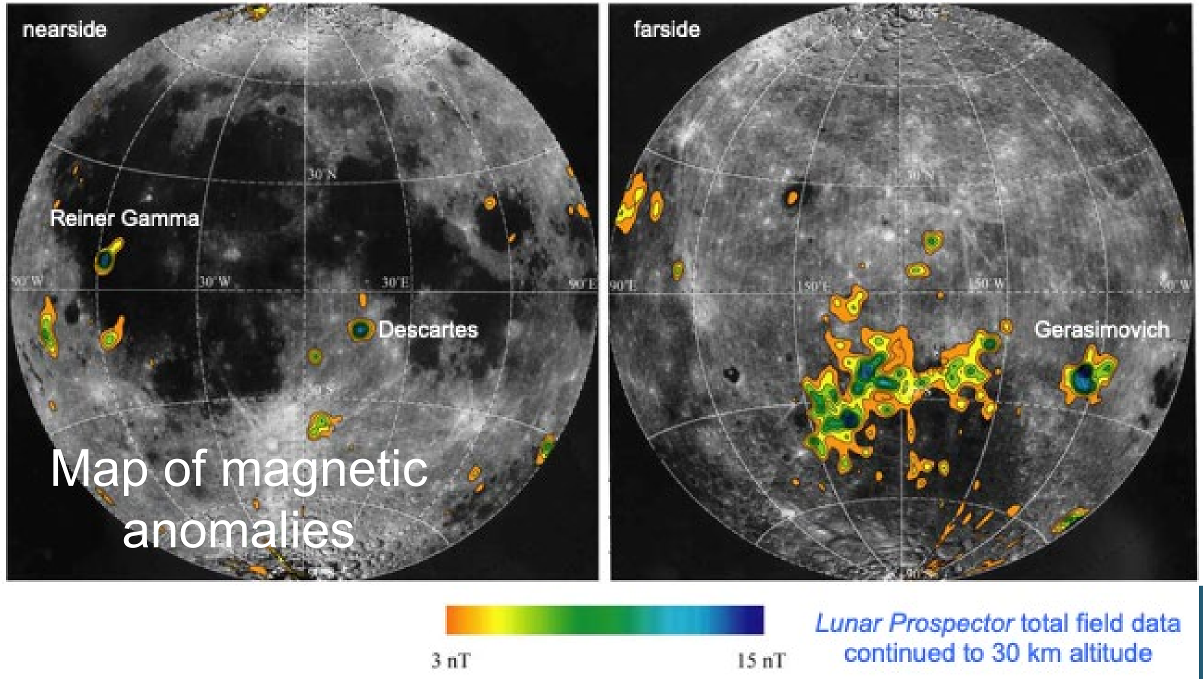
## Science Summary

- *Lunar Vertex*, the first PRISM investigation, will explore the unique environment of a lunar magnetic anomaly.

- *Lunar Vertex* will address key questions in major sub-disciplines of planetary science including geophysics, space plasma physics, and planetary geology. It will provide important information on the origin of lunar magnetic anomalies, the interactions of the solar wind with magnetized crust, the origin of lunar swirls, and the processes of space-weathering of silicate regolith.



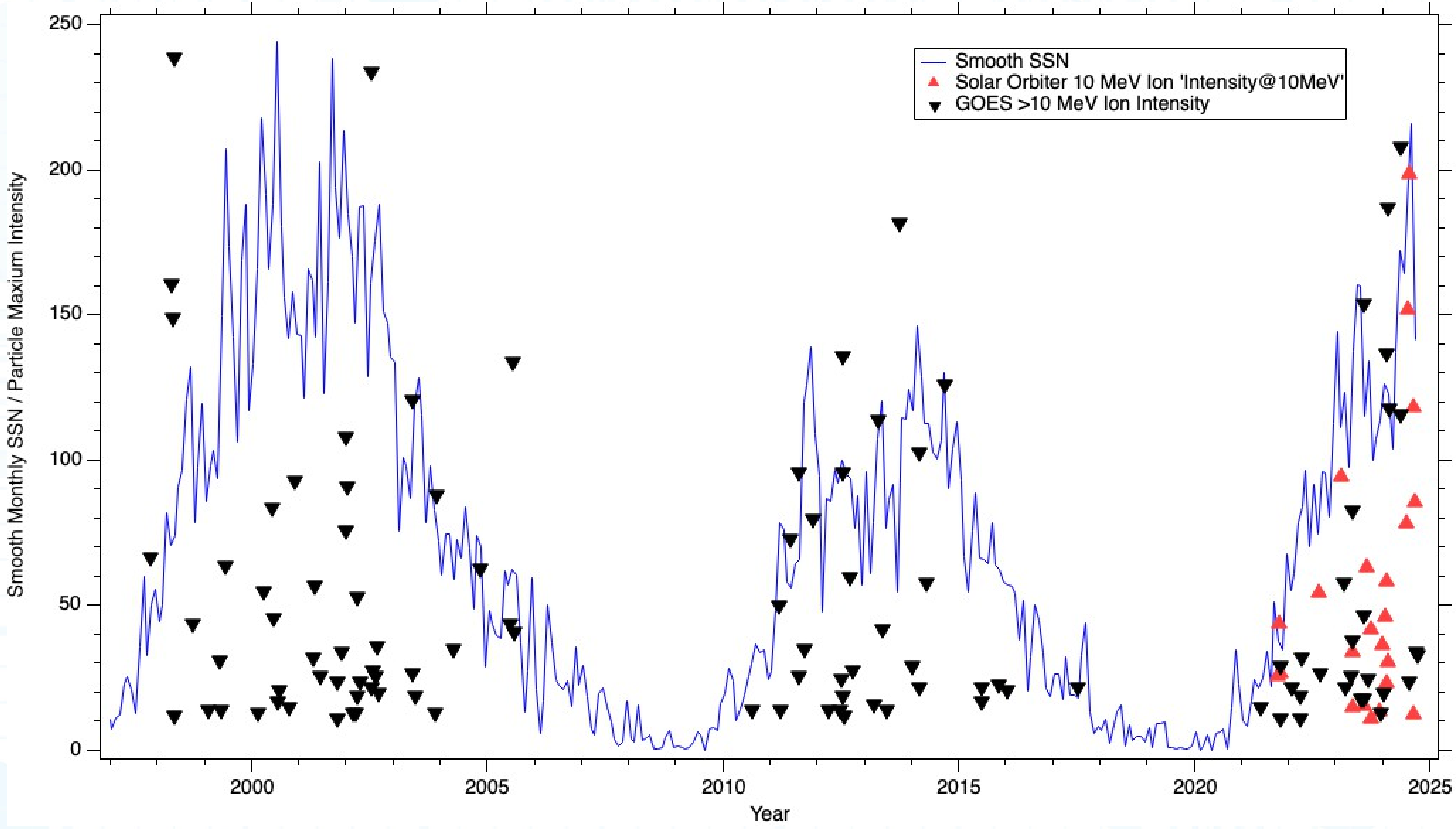
Reiner Gamma: the type example of a lunar swirl



Map of magnetic anomalies

*Lunar Prospector* total field data continued to 30 km altitude

# Solar Orbiter SEP Events




- The highest intensity events were in 2024
- July 27, 2024
- Sep 5, 2024
- Oct 9, 2024

*Ho et al., 2025*

# Radiation Dosage on the Moon

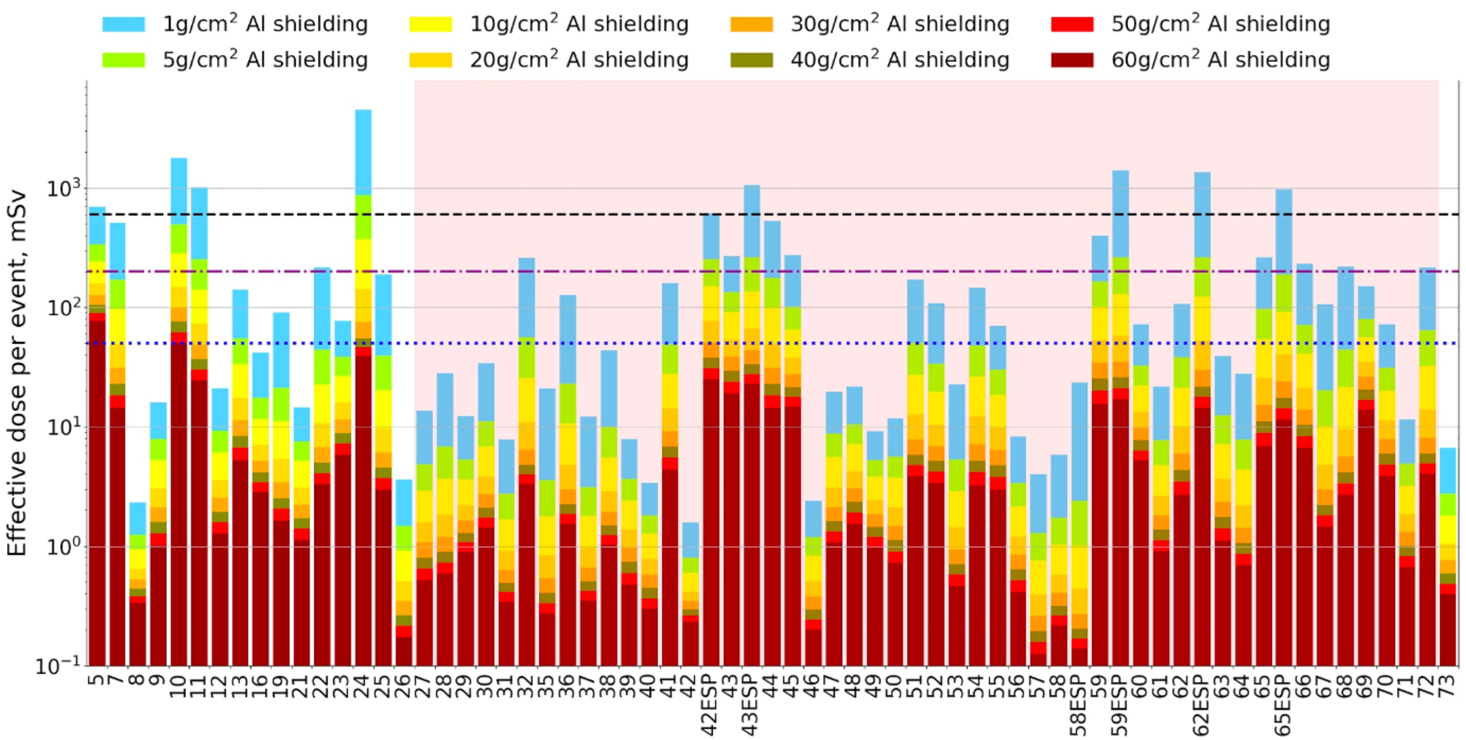



**Figure 5.** The effective dose of each GLE event with different aluminum shielding on the lunar surface. The GLE database starts from 1956 until 2021. Bars wi different colors show the results of different aluminum shielding. The career limit (600 mSv) and 2 annual limits (200 and 50 mSv) are marked by black dashed, pur dashed dotted and blue dotted lines, respectively. The red shaded area marks the GLE events that occurred between 1974 and 2,020 of the SEPEM database.

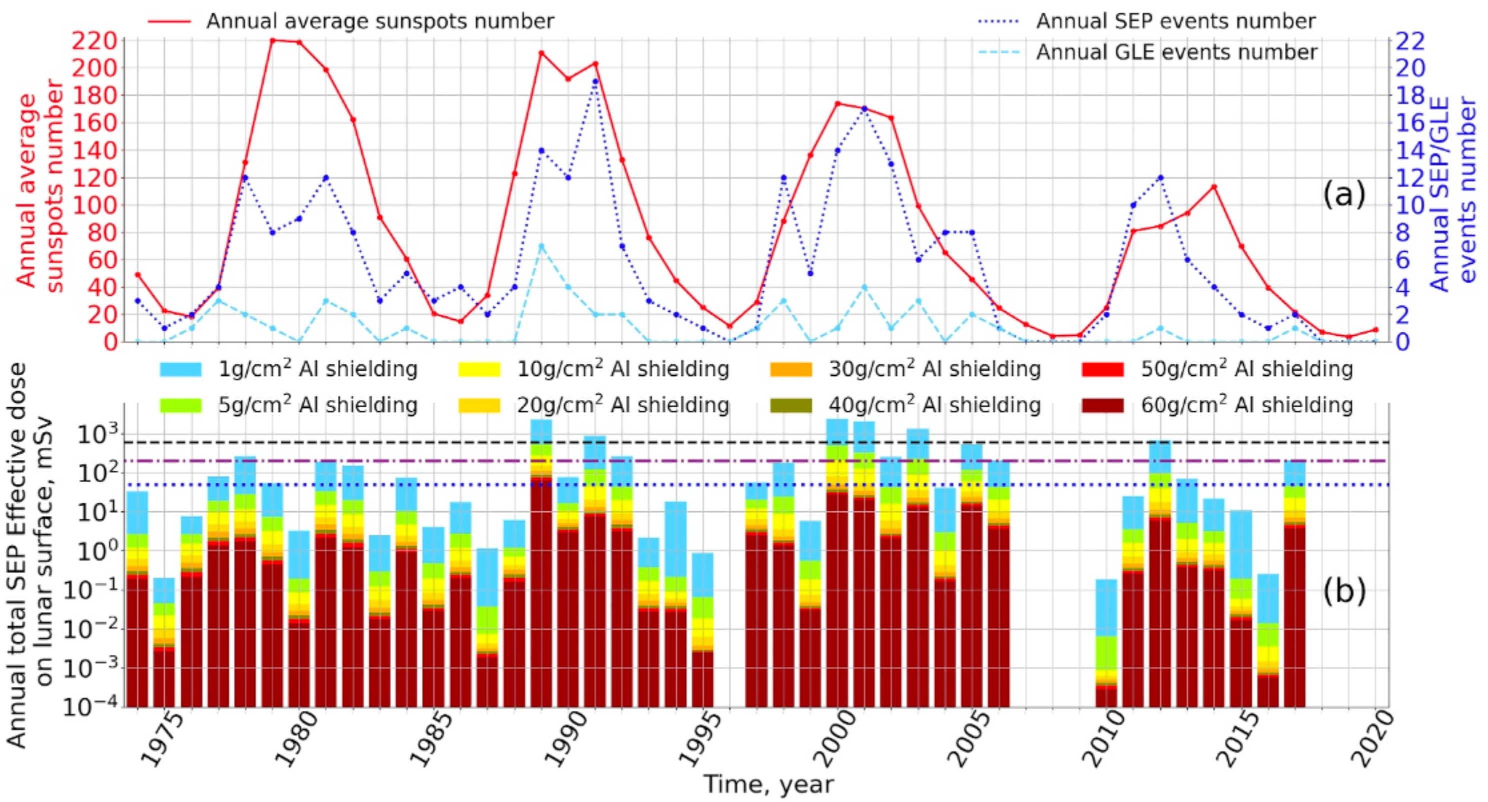



**Figure 3.** (a) The yearly averaged sunspots number (red, left *y*-axis) and the yearly SEP/GLE event number (blue and azure, right *y*-axis). (b) The total effective dose of SEP events per year on the lunar surface. Differently colored columns mark different aluminum shielding conditions. The career limit (600 mSv) and 2 annual limits (200 and 50 mSv) are marked by black dashed, purple dashed dotted and blue dotted lines, respectively.

*Liu et al. Space Weather 2024*

# Chang’E 4 LND

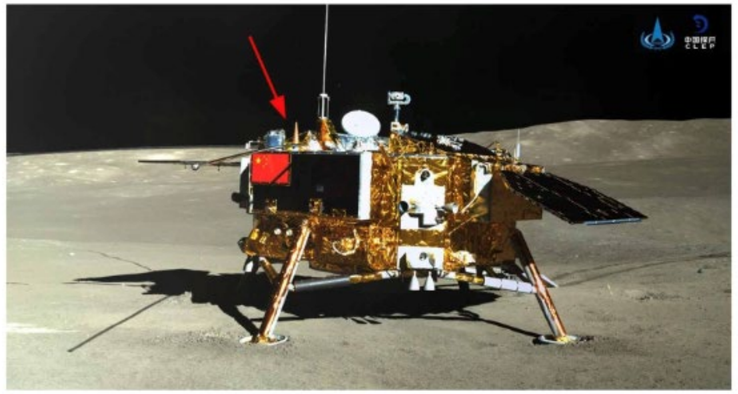


**Fig. 1. View of the Chang’E 4 lander with the location of the LND sensor head indicated by the red arrow.** LND is mounted in the Chang’E 4 payload compartment; the lid at the tip of the red arrow is closed at night to protect LND from the cold lunar night. Photo credit: Chinese National Space Agency (CNSA) and National Astronomical Observatories of China (NAOC).

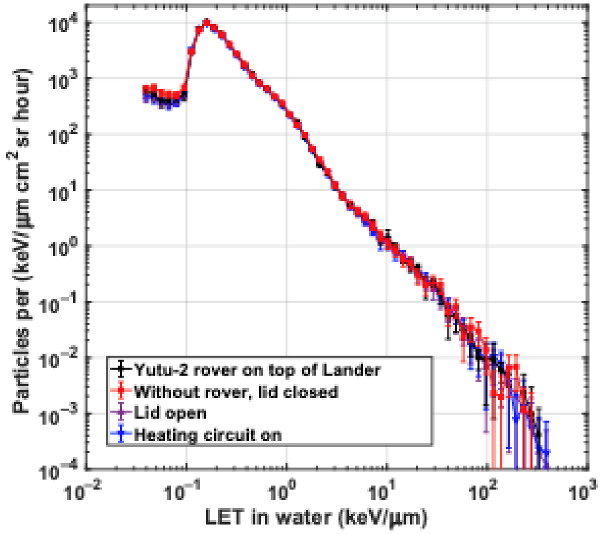
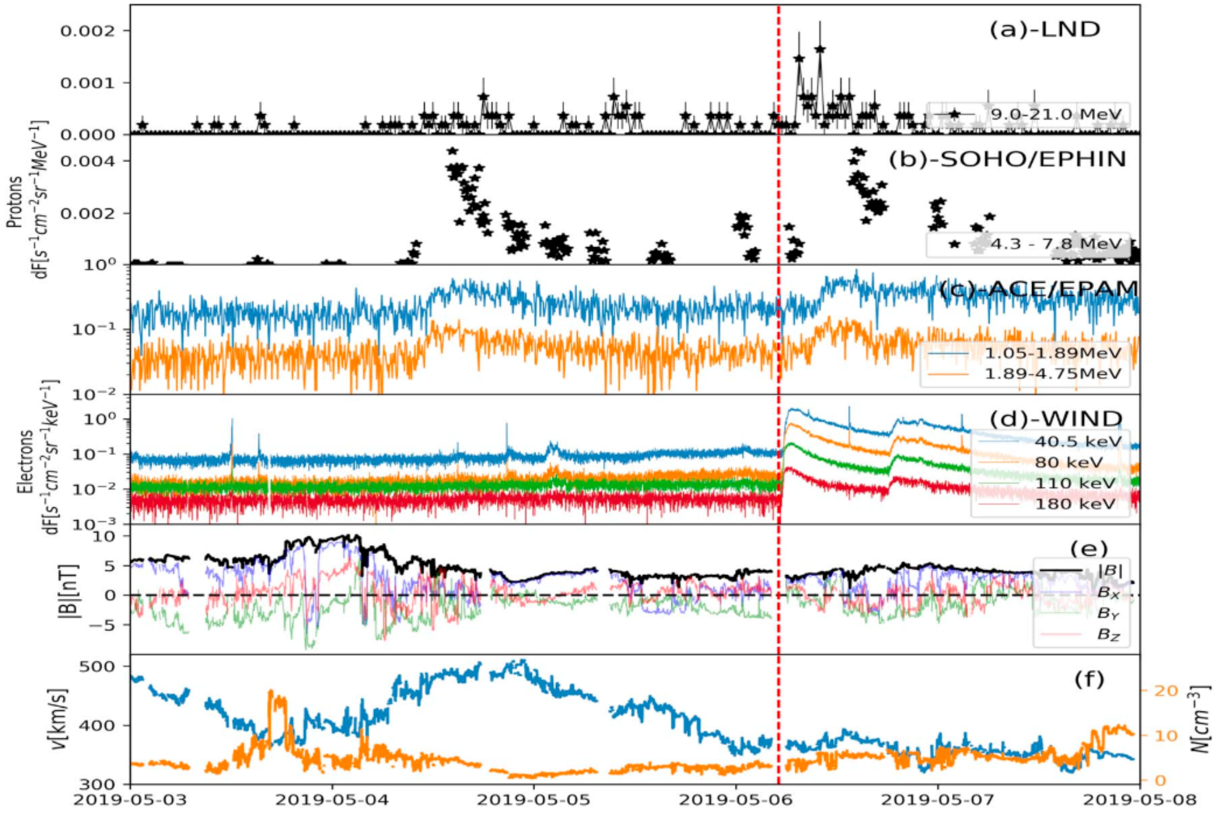
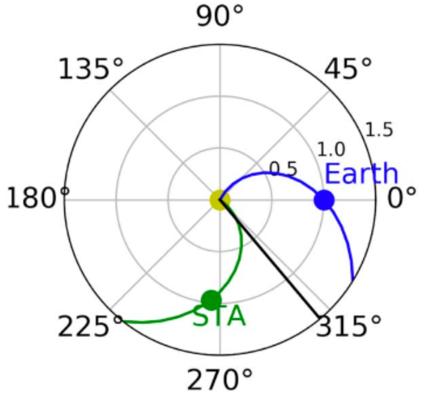


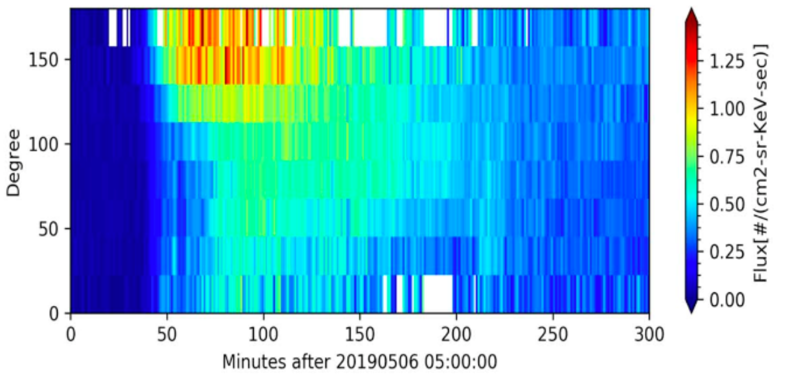

**Fig. 4. Linear Energy Transfer (LET) spectra (converted to LET in water) measured during four different time periods show only small variations.** The data shown as black circles were acquired before lander and rover separation; data shown in red after the rover left the lander but with the lid still closed; data in purple: normal operation of LND with the lid open; data in blue: with the Chang’E 4 heater circuit activated toward the end of the lunar day.

*Zhang et al. Sci. Adv., 2020*

The Astrophysical Journal Letters, 902:L30 (8pp), 2020 October 20 Xu et al.



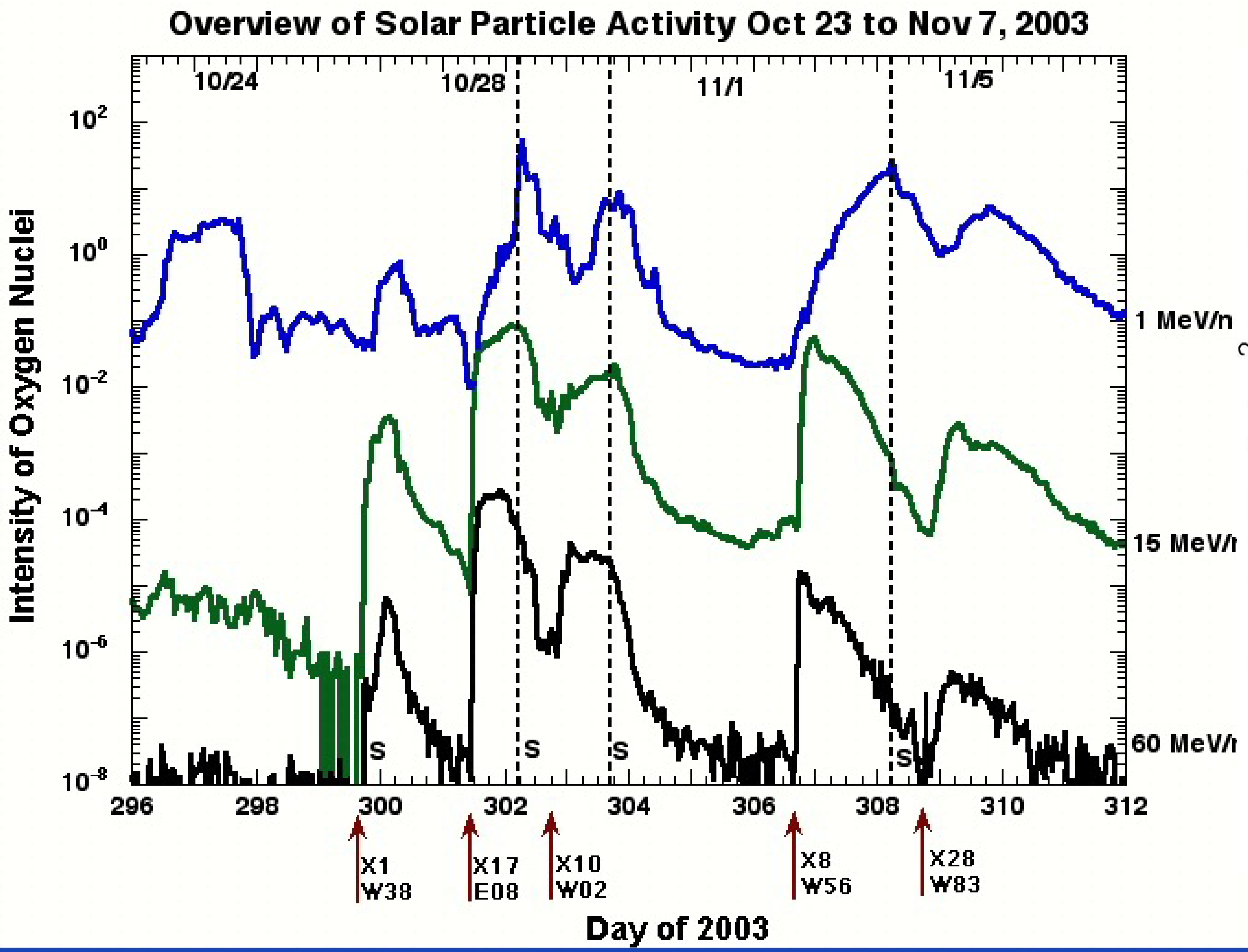

*Xu et al. ApJ, 2020*

# Summary

- SEP is highly relevant in the near-Earth system
- High-energy particle have access in the Earth's magnetosphere
  - Isotropic distribution
  - Minor difference due to geometry
- SEP has direct access to lunar surface due to the absence of a global magnetic field and atomsphere
  - Space weathering
  - Pose a direct task to lunar exploration and surface infrastructure

THE END

# Energetic particles events are associated with shocks both at 1 AU and at the Sun




Mewaldt et al., JGR, 2005