Unrestricted Solar Energetic Particle Access to the Moon While Within the Terrestrial Magnetotail

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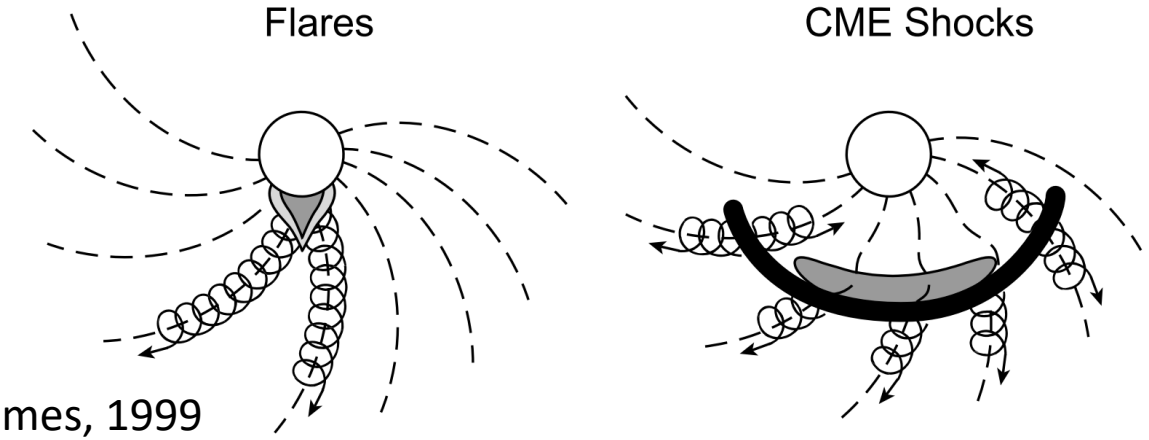
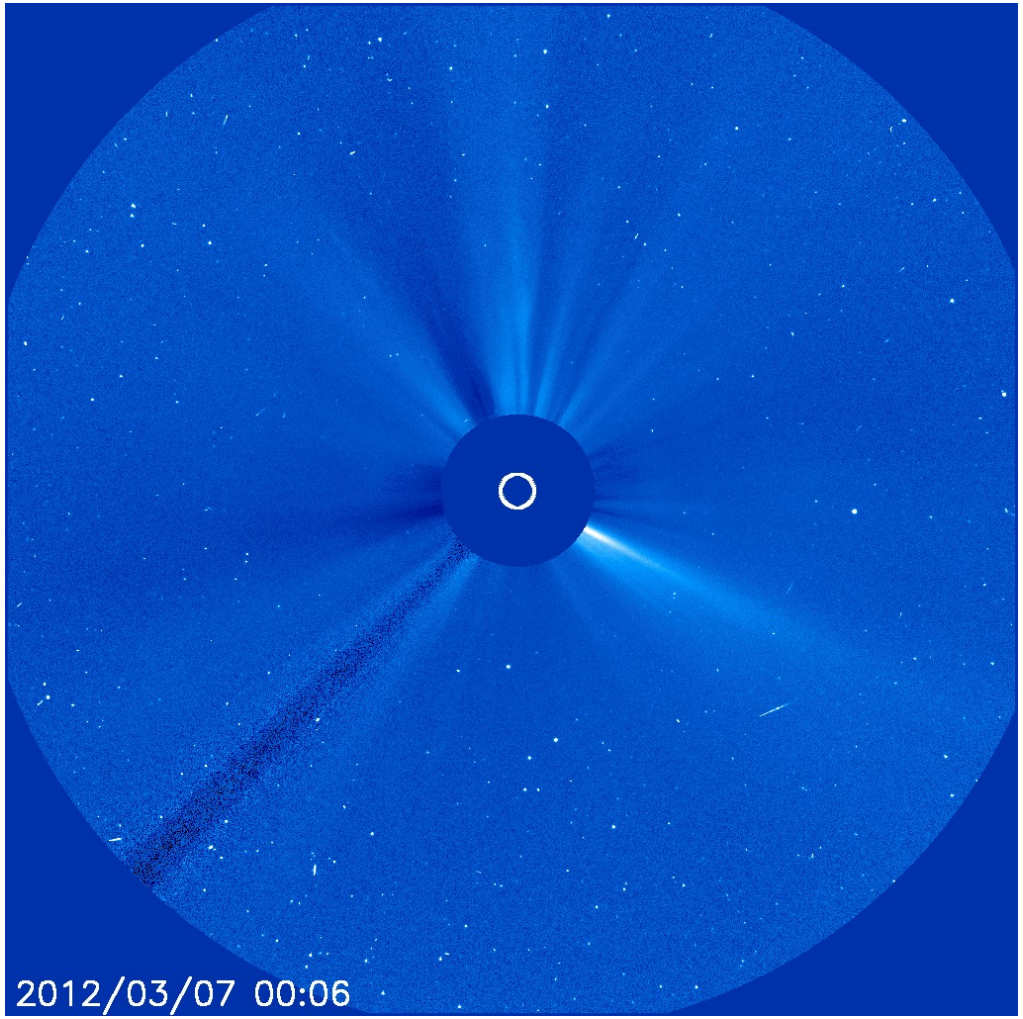
What are Solar Energetic Particles?

- High-energy (keV – MeV) particles
  - More energetic than solar wind
  - Less energetic than ACRs/GCRs
- Predominantly protons + electrons
- Mainly generated by two processes:
  - Solar flares: “Impulsive”
  - CME shock fronts: “Gradual”



Reames, 1999

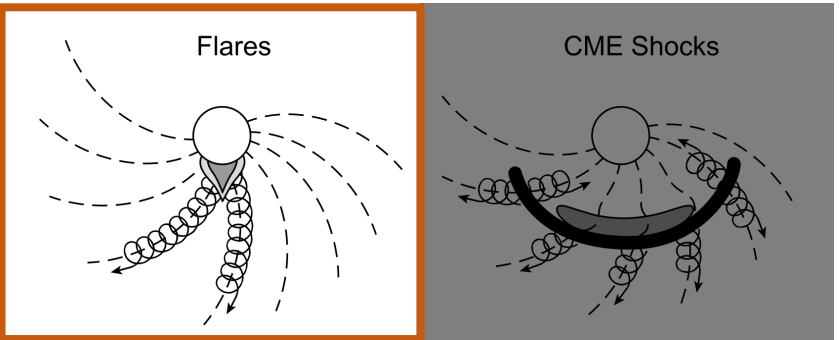


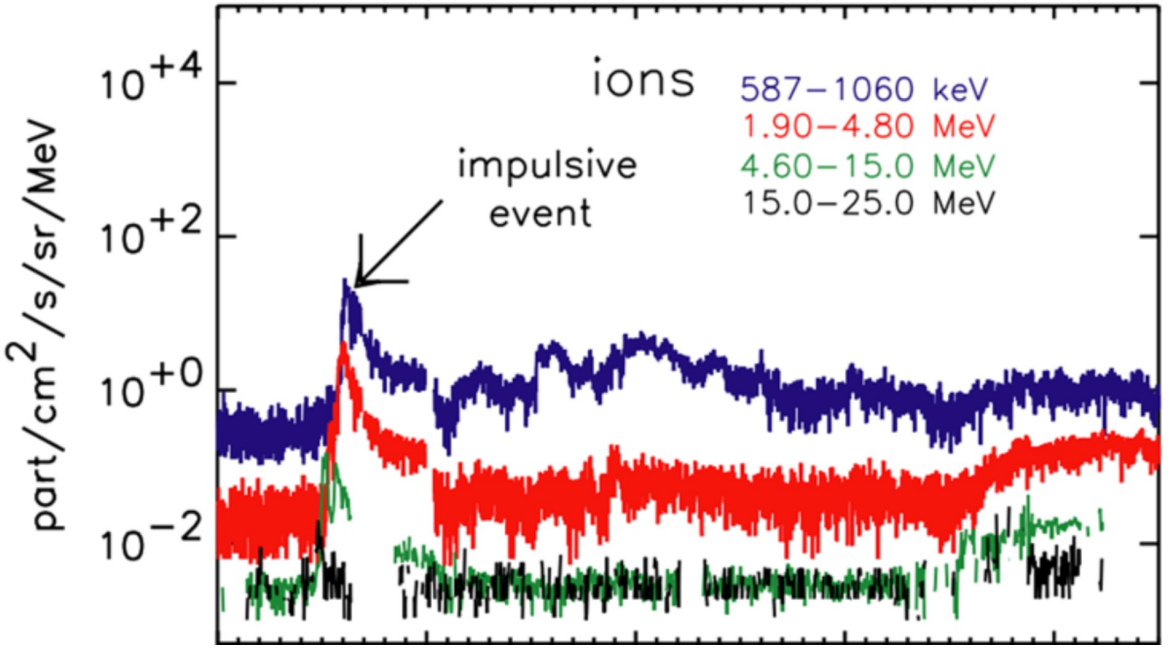
SOHO LASCO C3 Coronagraph
SEPs from X5.4 flare

What generates SEPs?

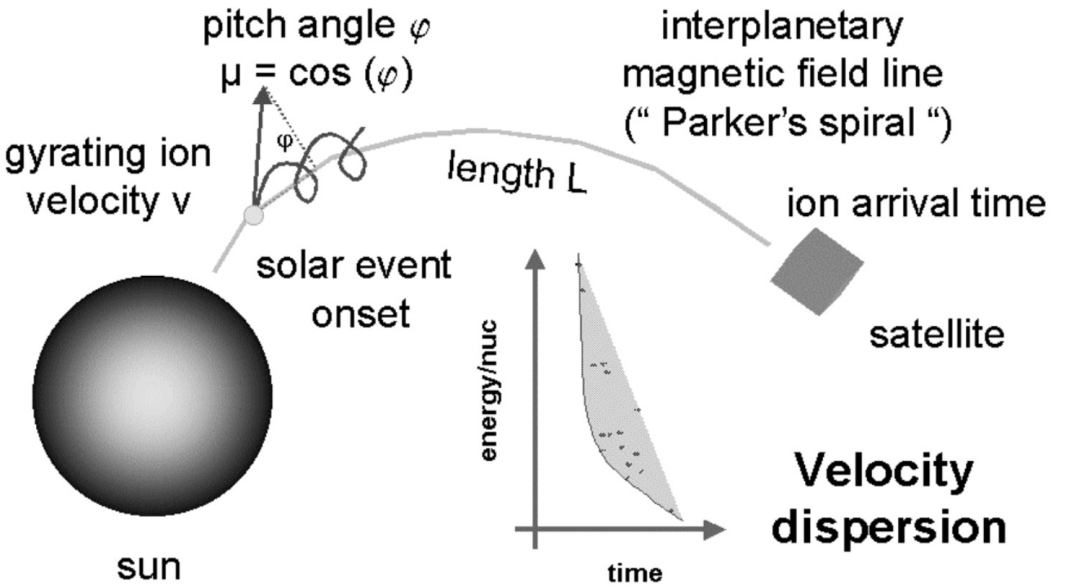
Impulsive events

- Flare-accelerated particles generated near the Sun (far from Earth)
- Magnetic connection to source region
- Dispersive velocities in SEP ions
  - Highest-energy ions arrive first
  - Lowest-energy ions arrive last
- Sudden onset in SEP electrons
- Small intensities, short periods (hours-long)





Oka et al., 2018

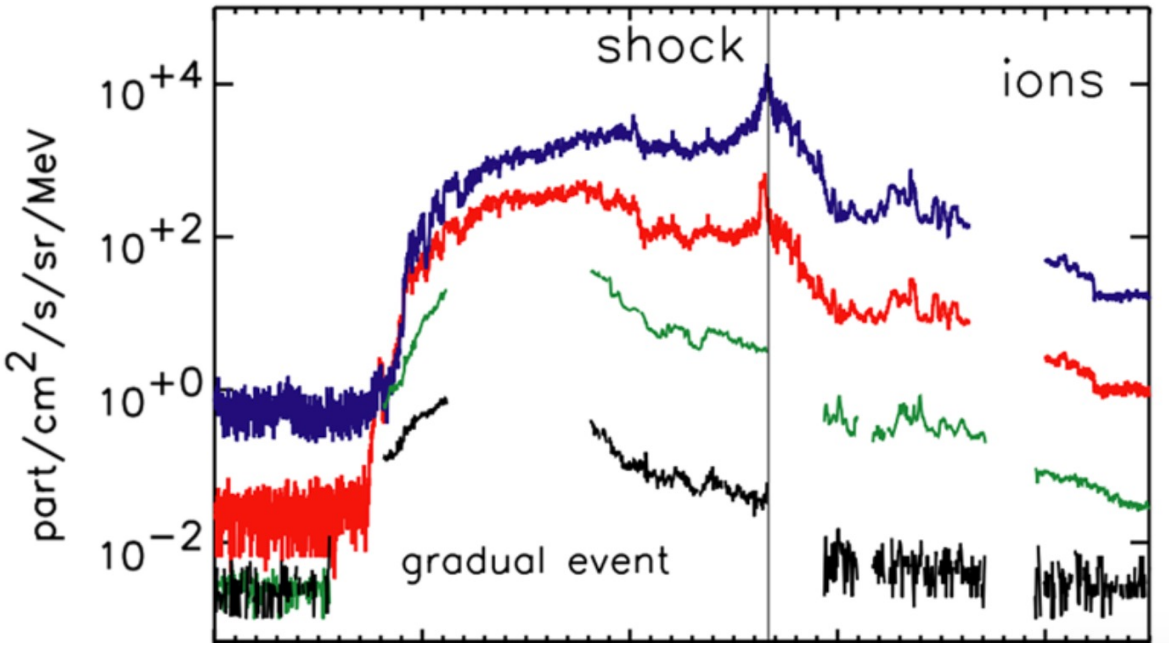


Hilchenbach et al., 2003

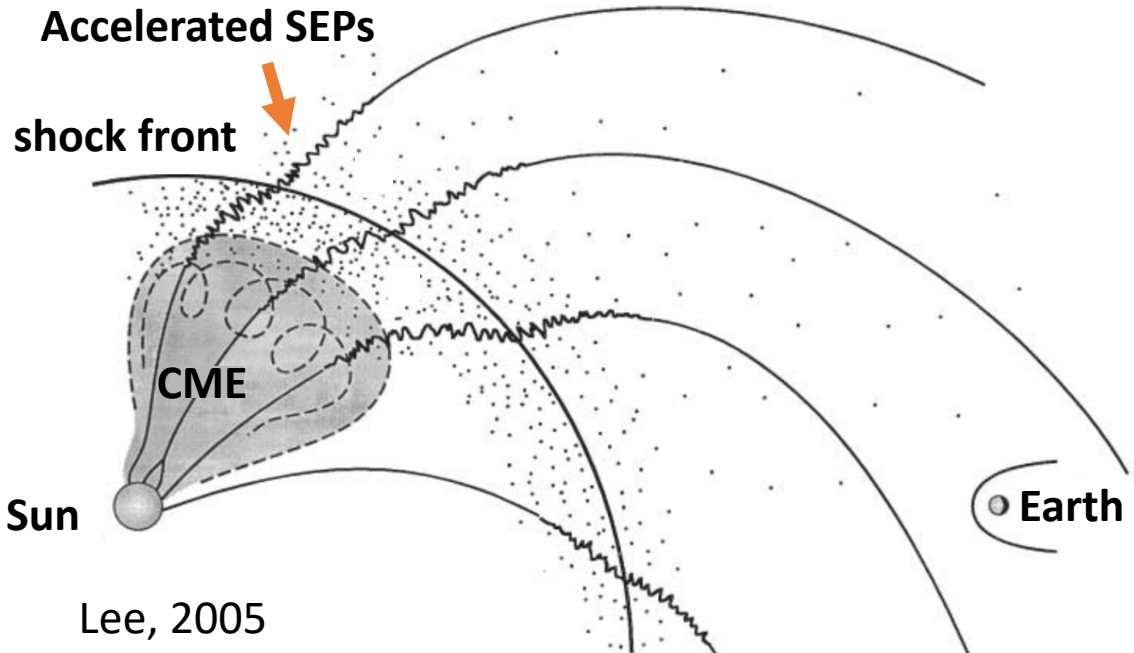
What generates SEPs?

Gradual events

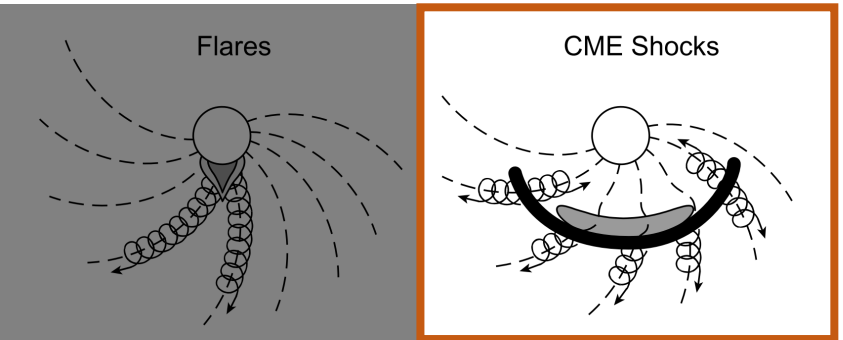
- CME expansion compresses the solar wind
- Particles energized and accelerated along the magnetic field
- Generated anywhere in space, along the CME shock front
- Locally generated: “Energetic Storm Particles”
- Large intensities, extended periods (days-long)



Oka et al., 2018

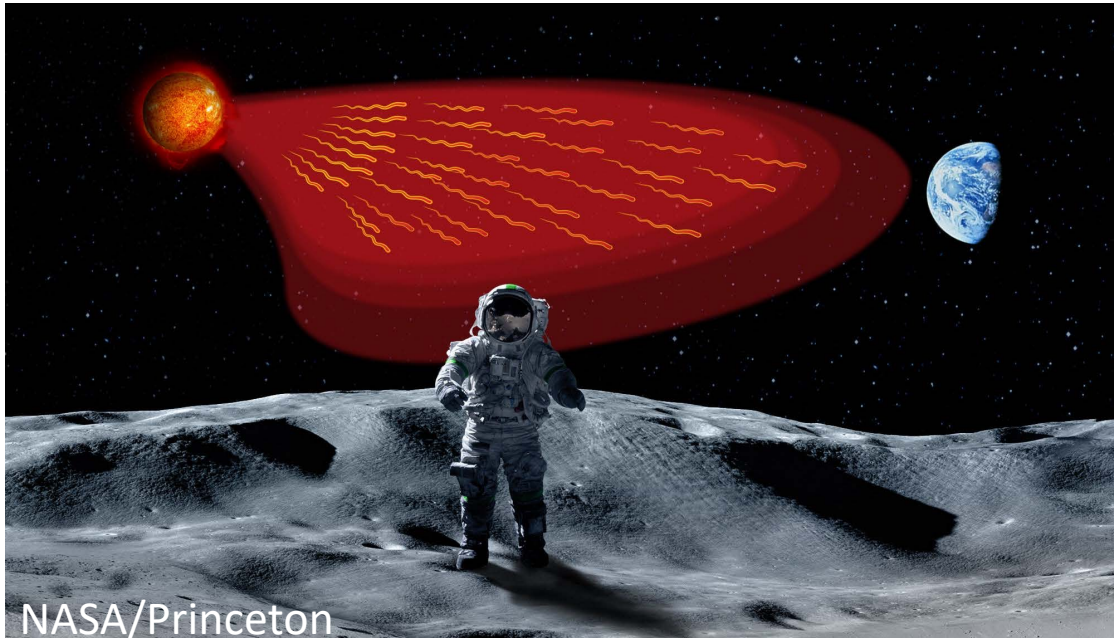


Lee, 2005



Why study SEPs at the Moon?

- Surface processing and weathering
  - Stimulate organic synthesis in polar volatiles
  - Deposit energy into the lunar surface
  - Charge the lunar surface to potentials of -4.5 keV
- Radiation hazard to astronauts
  - During EVA/spacewalks on the surface
  - Living on a base
  - Orbiting in Lunar Gateway

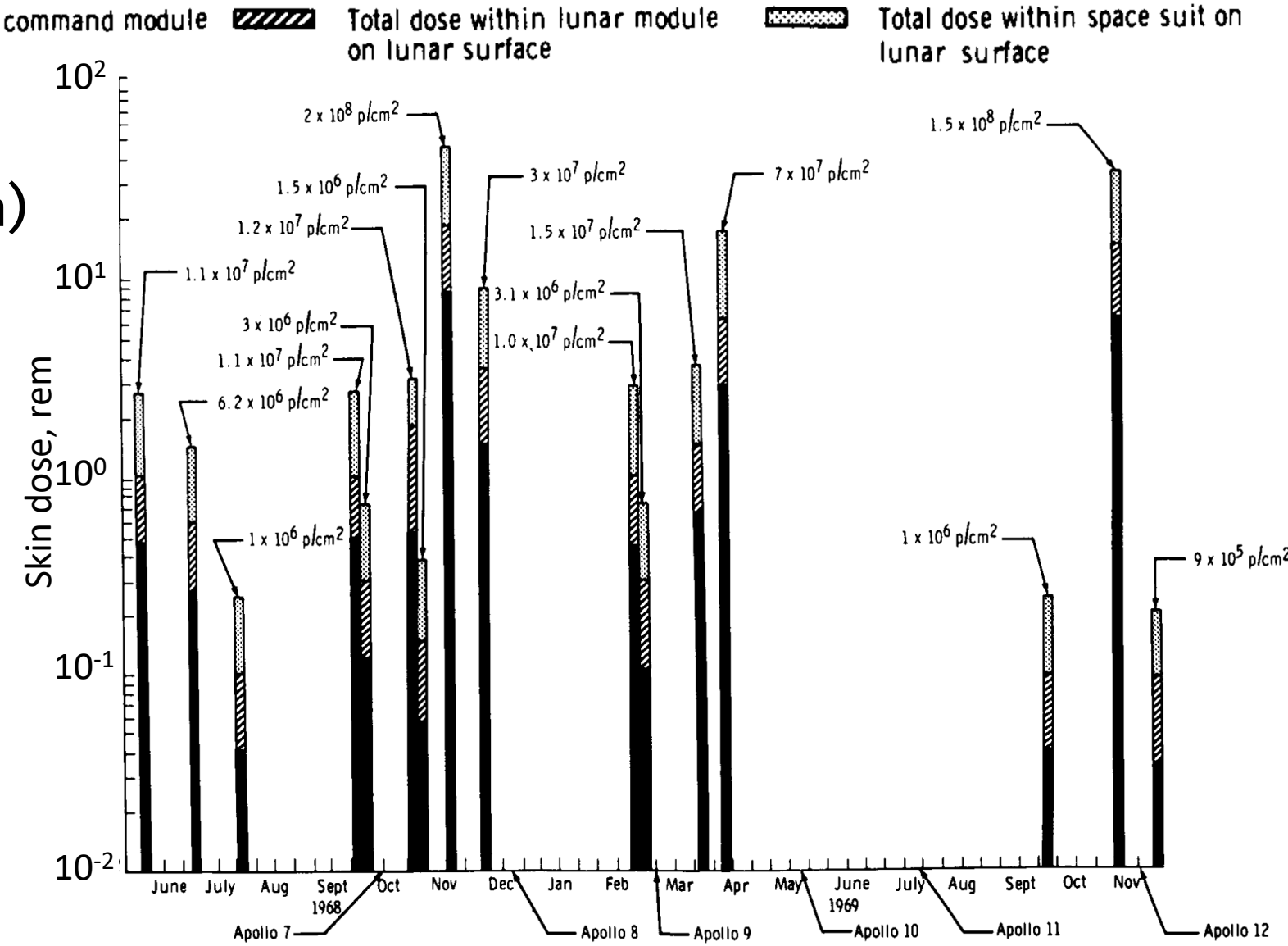

NASA/Princeton

Why study SEPs at the Moon?

Common radiation doses
(Roentgen equivalent man, rem)

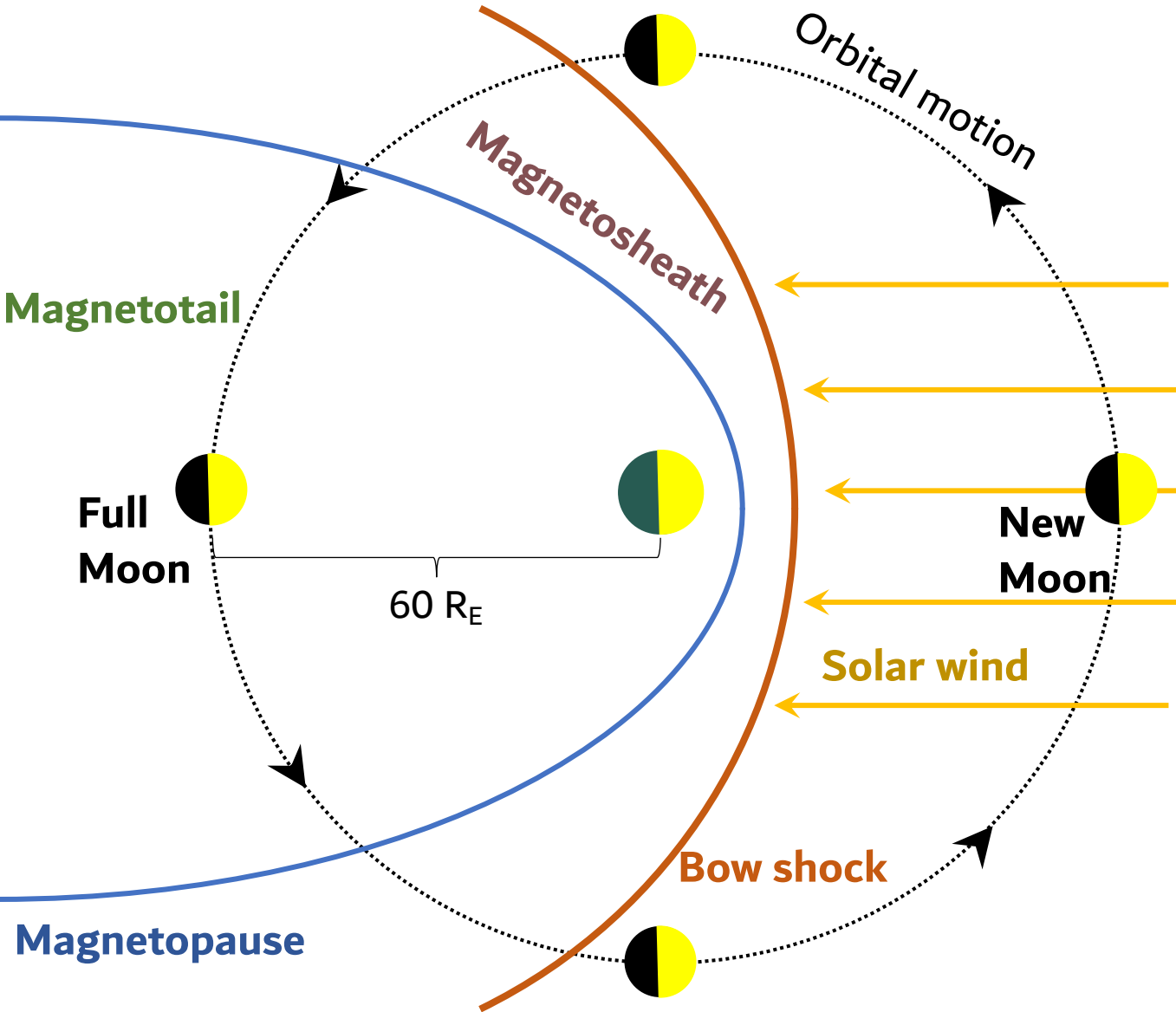
- Xray: 10^{-3} – 10^{-1}
- Flight: 10^{-3} /1000 miles
- Living in Denver: 10^{-2} /year
- Occupational limit: 5 /year

Lifetime astronaut limit is 37– 147 rem



English+ 1973: Apollo Experience Report

Lunar orbit through the magnetosphere



~75% of lunar orbit: solar wind

- SEPs above ~100 keV have nearly uniform access to the lunar surface

~25% of lunar orbit: magnetotail

- Models suggest the magnetosphere shields SEPs $\lesssim$ GeV (e.g., Winglee & Harnett 2007, Jordan+ 2022)
- But observations from LRO/CRaTER show signatures of ~10 MeV SEP ions (e.g., Case+ 2010)

Imperative to constrain SEP access to the Moon with upcoming lunar missions (Gateway, Artemis)

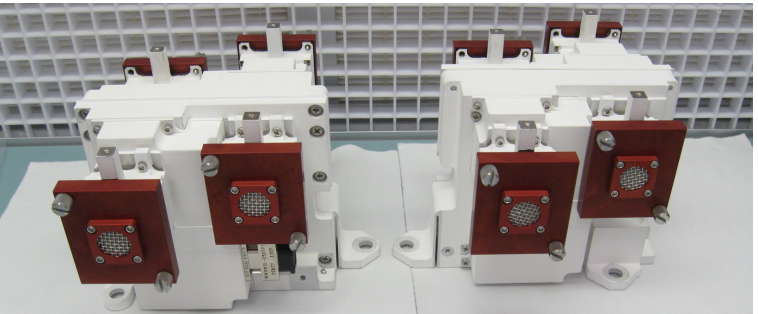
Can the magnetosphere block SEP access to the Moon?

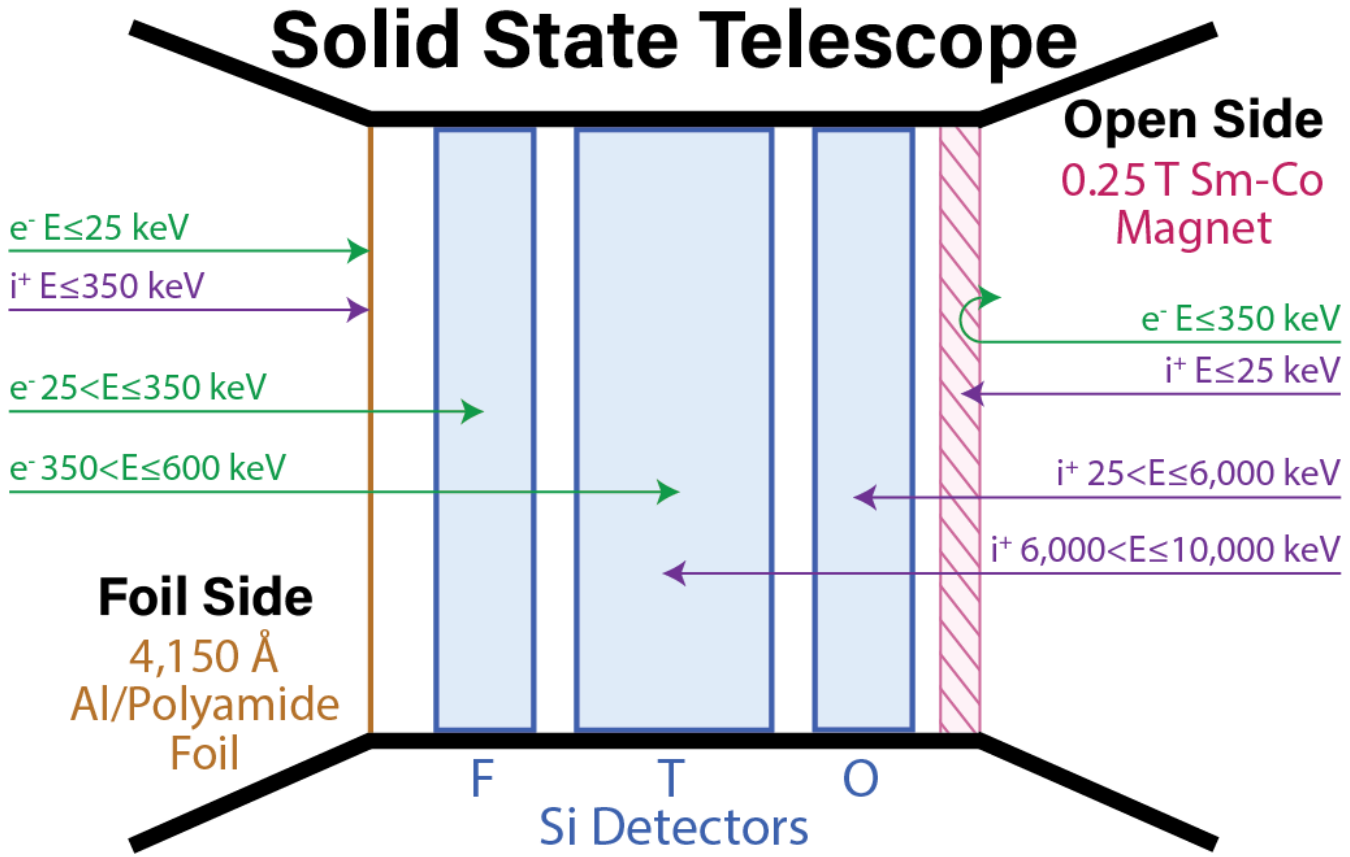
- Constrain SEP access to the terrestrial magnetotail
- Focus on two spacecraft missions
  - Wind
    - Upstream at Earth-Sun L1 point since 2004
    - Provides baseline information for the “ambient” SEP fluxes
  - THEMIS-ARTEMIS
    - Orbiting the Moon since 2011
    - Dual-probed mission with identical instrument suites

Solid State Telescopes: SEP detectors

Wind and ARTEMIS equipped with Solid State Telescopes

- Two-sided instrument:
  - Foil side → electrons > 25 keV
  - Open side → ions > 25 keV
- Common heritage between Wind and ARTEMIS SSTs
- This presentation focuses on **SEP ions** (open side)

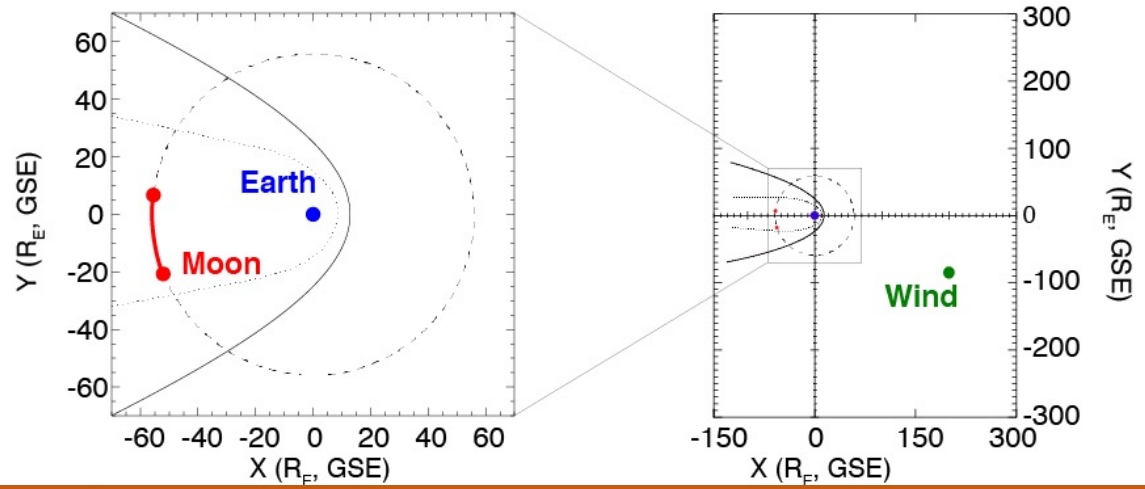


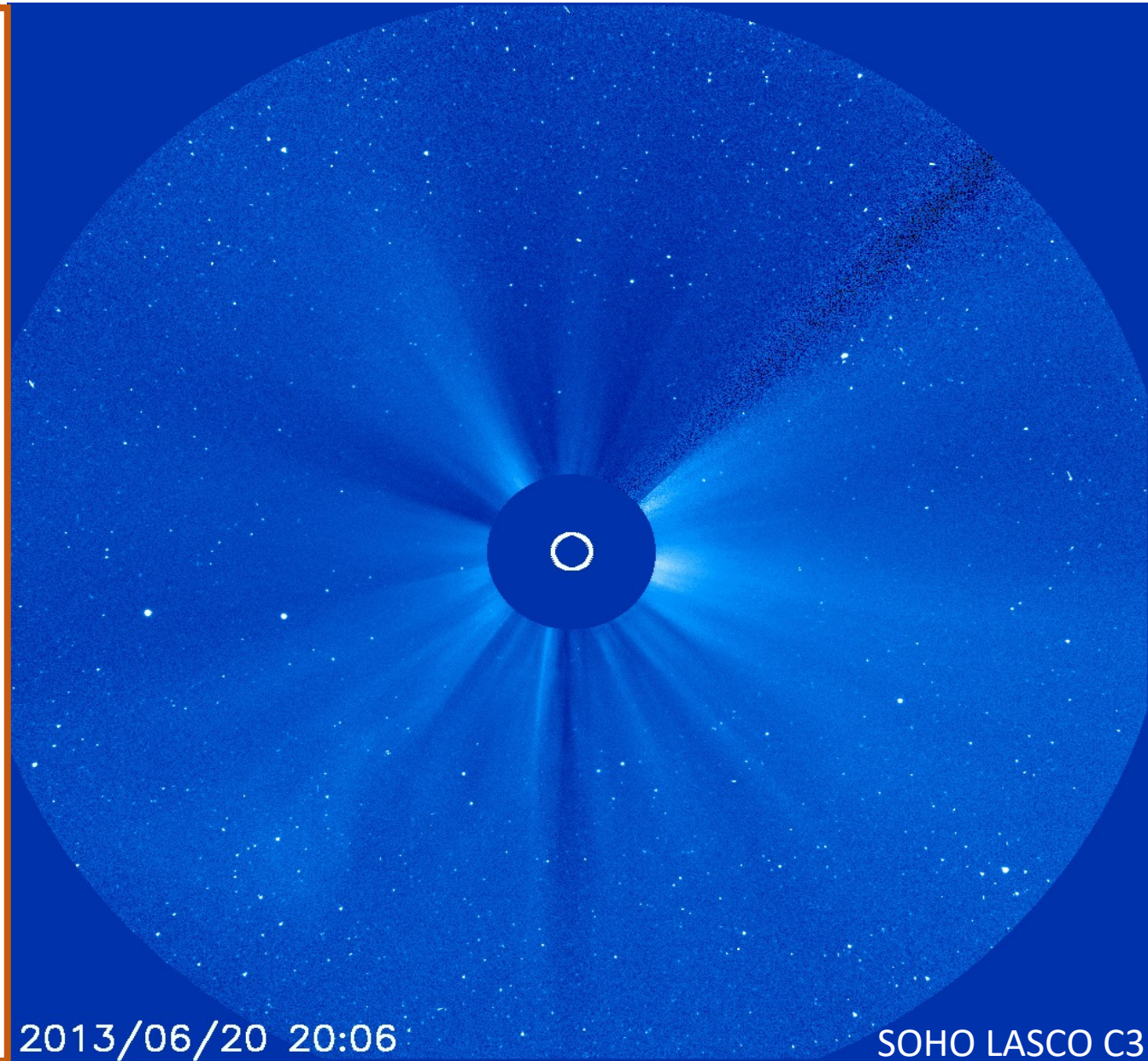


Two SEP events

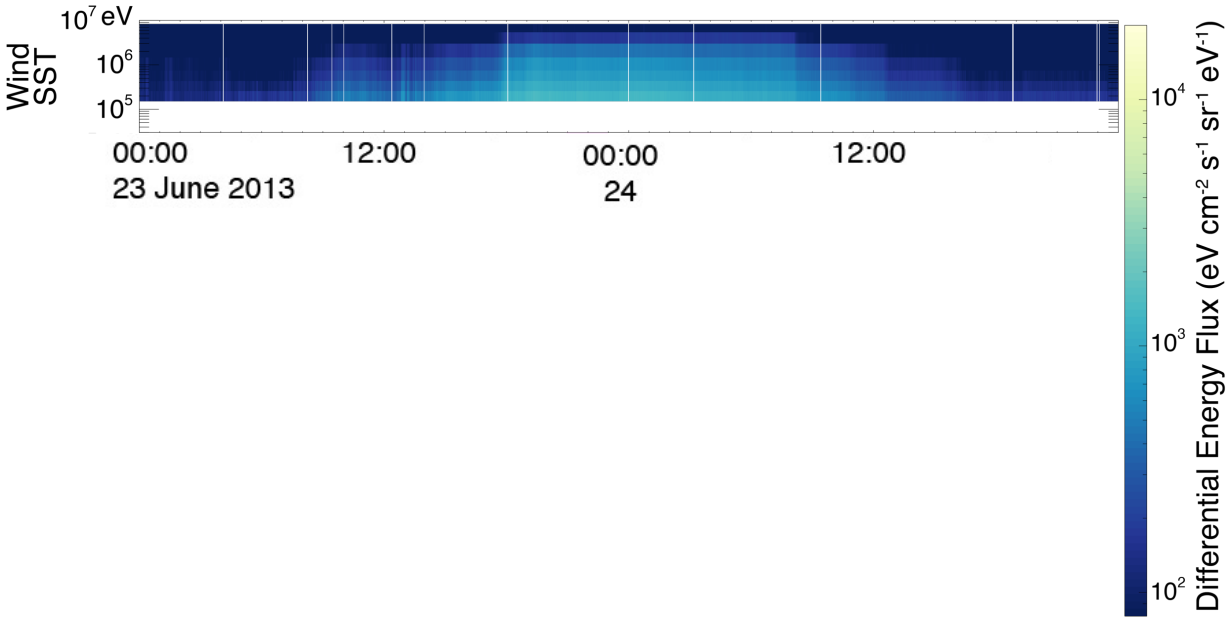
23 – 24 June 2013

- ICME-driven, multi-day long event
- Observed by multiple spacecraft throughout the solar system (MESSENGER, STEREOs, GOES)
- Moon in the tail, Wind upstream





23 – 24 June 2013 SEP event



Wind (200 R_E upstream)

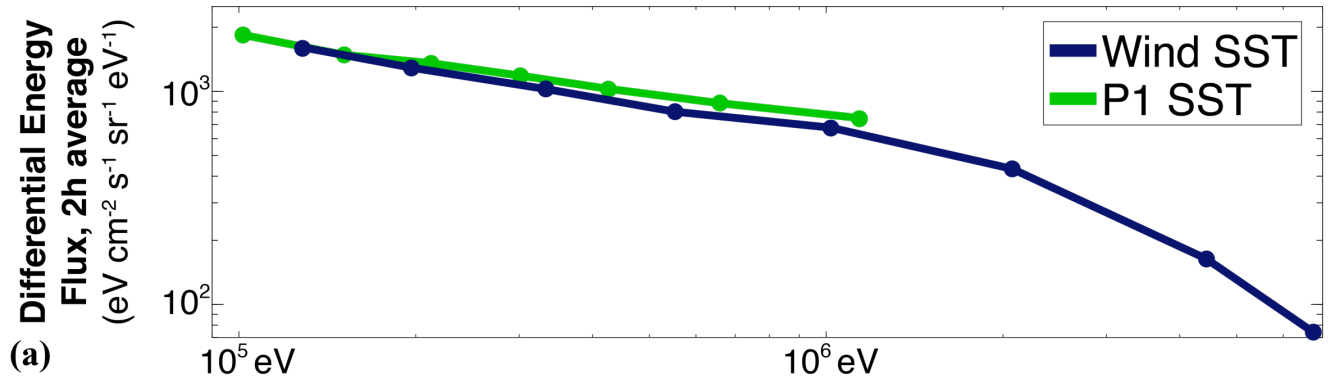
- 100 keV – 10 MeV ions enhanced
- "Gradual" SEP event: ICME-generated energetic storm particles

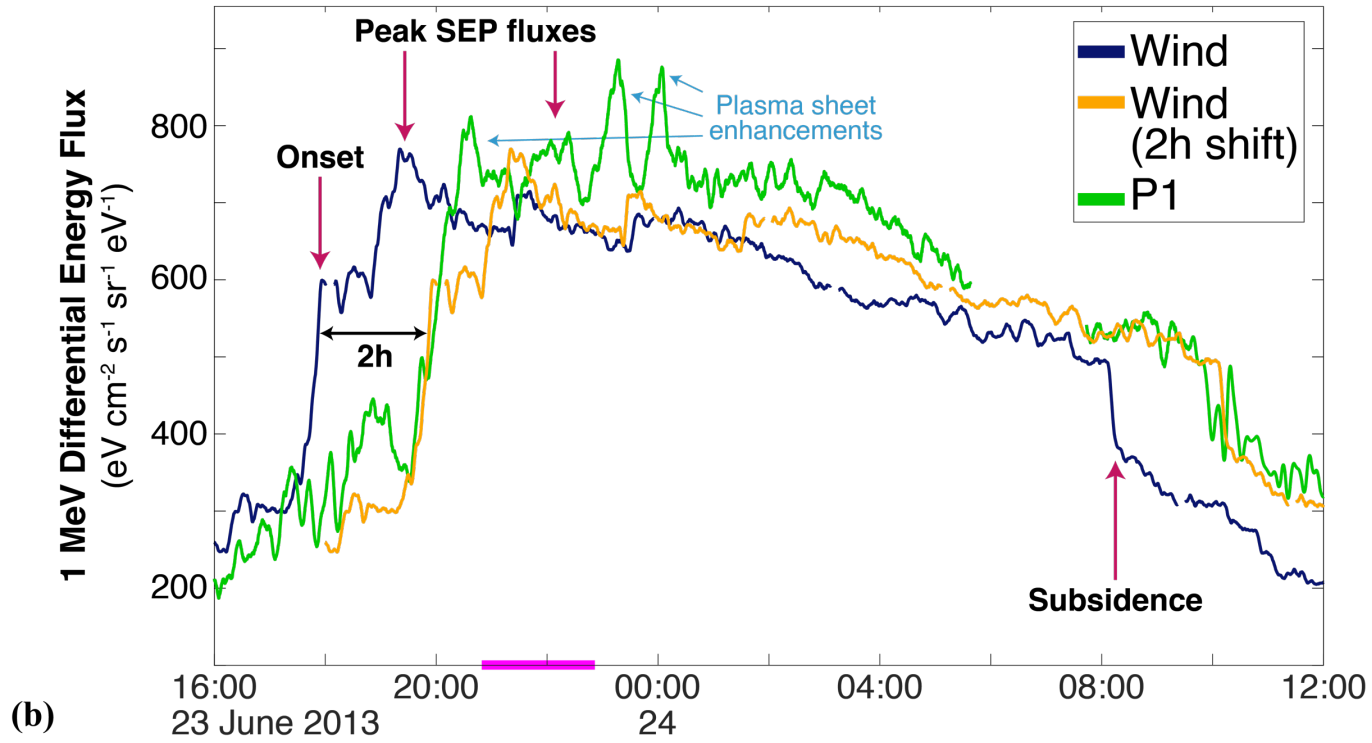
P1 & P2 (within magnetotail)

- Plasma sheet crossings visible (bursts down to 10 eV)
- Overlain with 100 keV – >1 MeV ion enhancement
- SEPs detected within N&S lobes *and* the plasma sheet

Liuzzo+, submitted

Wind and ARTEMIS comparison





Liuzzo+, submitted

Time-averaged fluxes

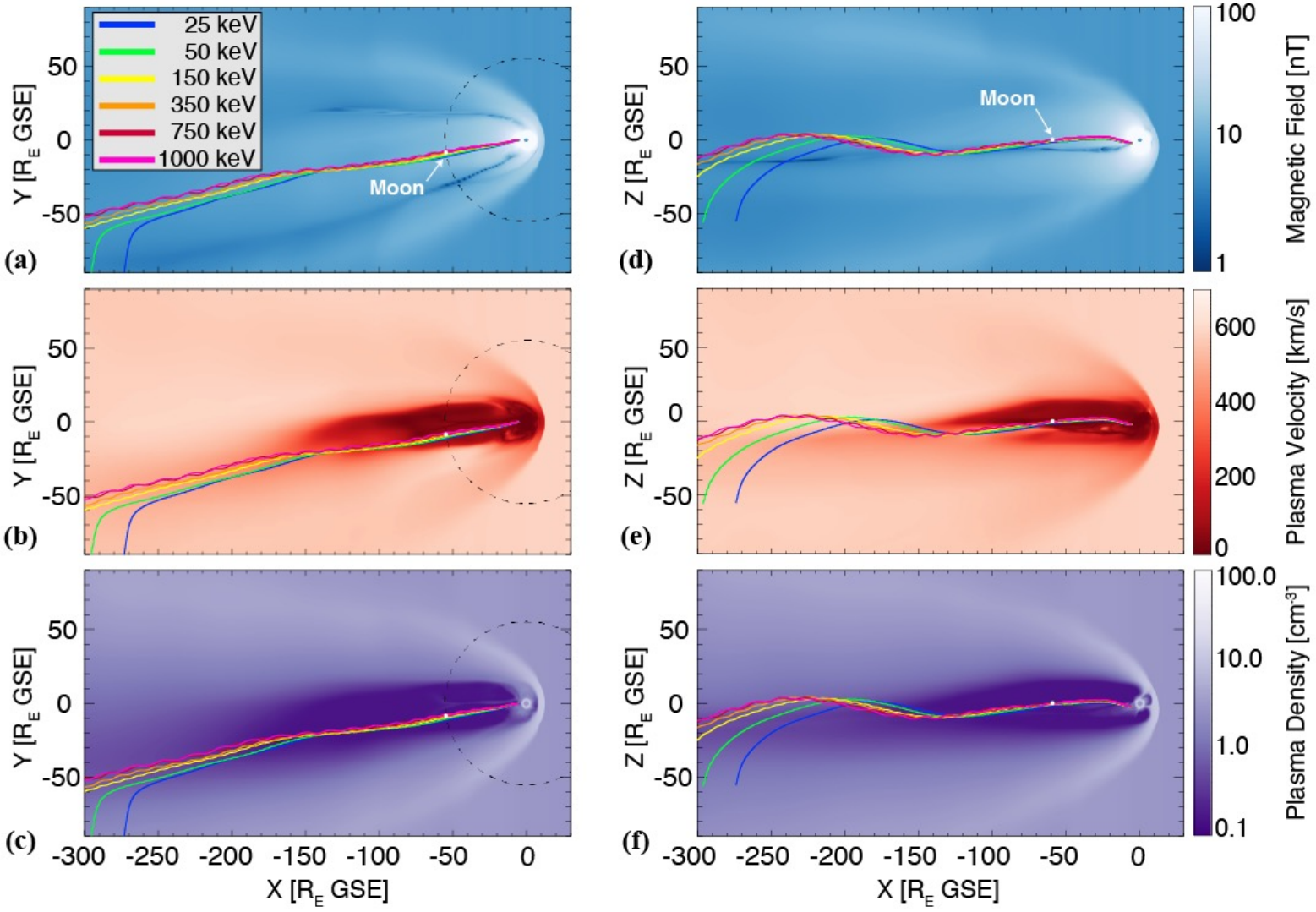
- Wind & ARTEMIS detected nearly identical spectral signature

1 MeV timeseries

- Wind timeseries shifted ~2h compared to ARTEMIS
  - ICME velocity ~800 km/s
  - ICME distance traveled ~900 R_E

→ 1 MeV SEPs entered the tail ~640 R_E downstream

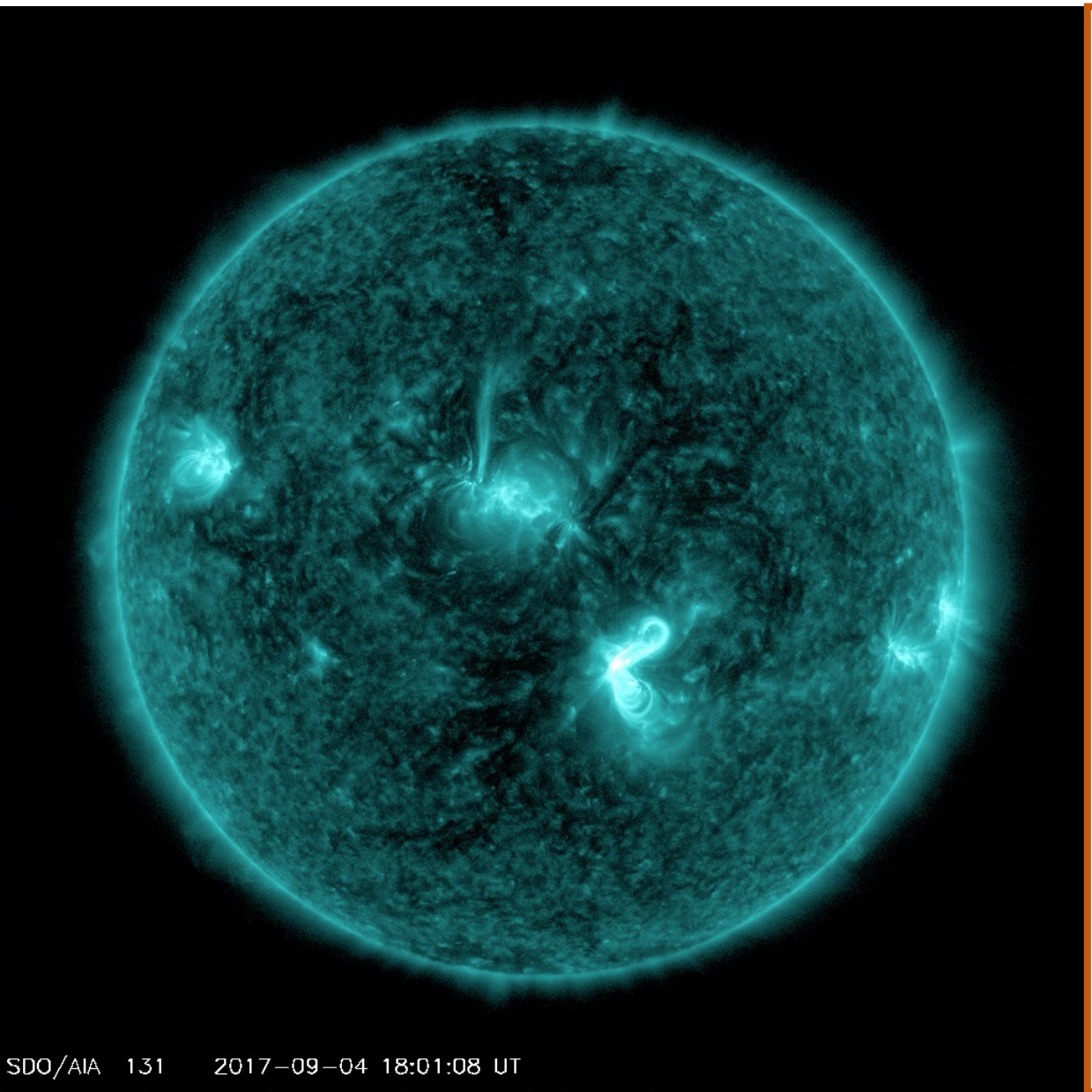
Where do SEPs gain access to the tail?



- OpenGGCM MHD model at CCMC
- SEPs enter the tail via magnetopause crossing
- 25 & 50 keV SEPs enter near x ≈ -300 R_E
- Higher-energy particles enter farther downstream
- SEP detection in both lobes and plasma sheet suggests global entry!

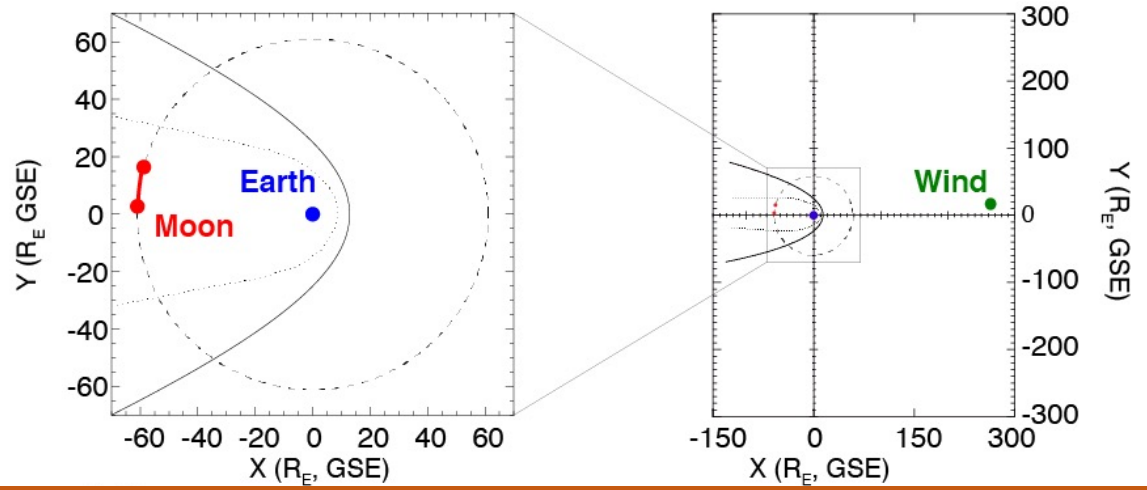
Liuzzo+, submitted

Two SEP events

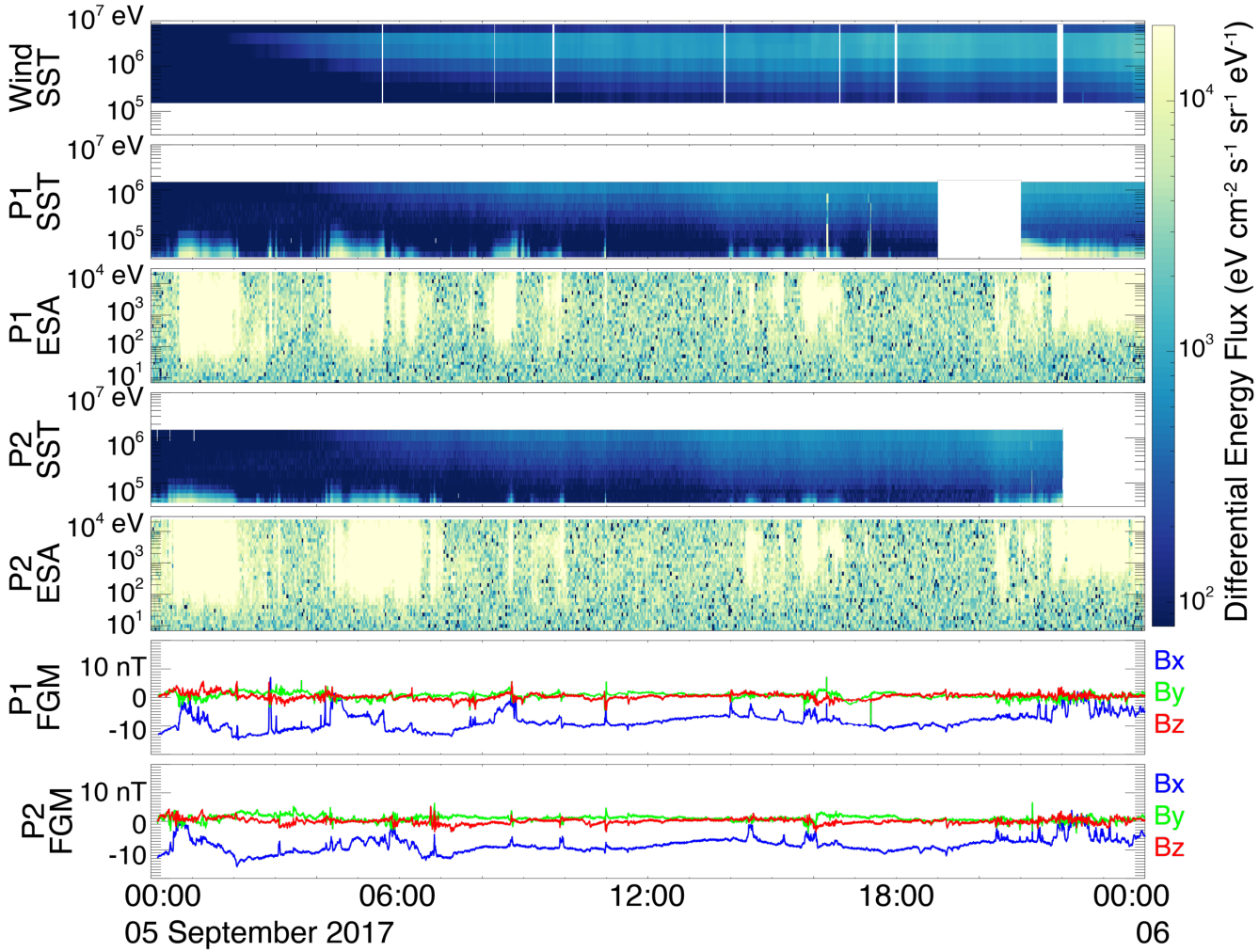


05 September 2017

- Flare-driven, day-long event
- Moon in the tail, Wind upstream



05 September 2017 SEP event



Wind (200 R_E upstream)

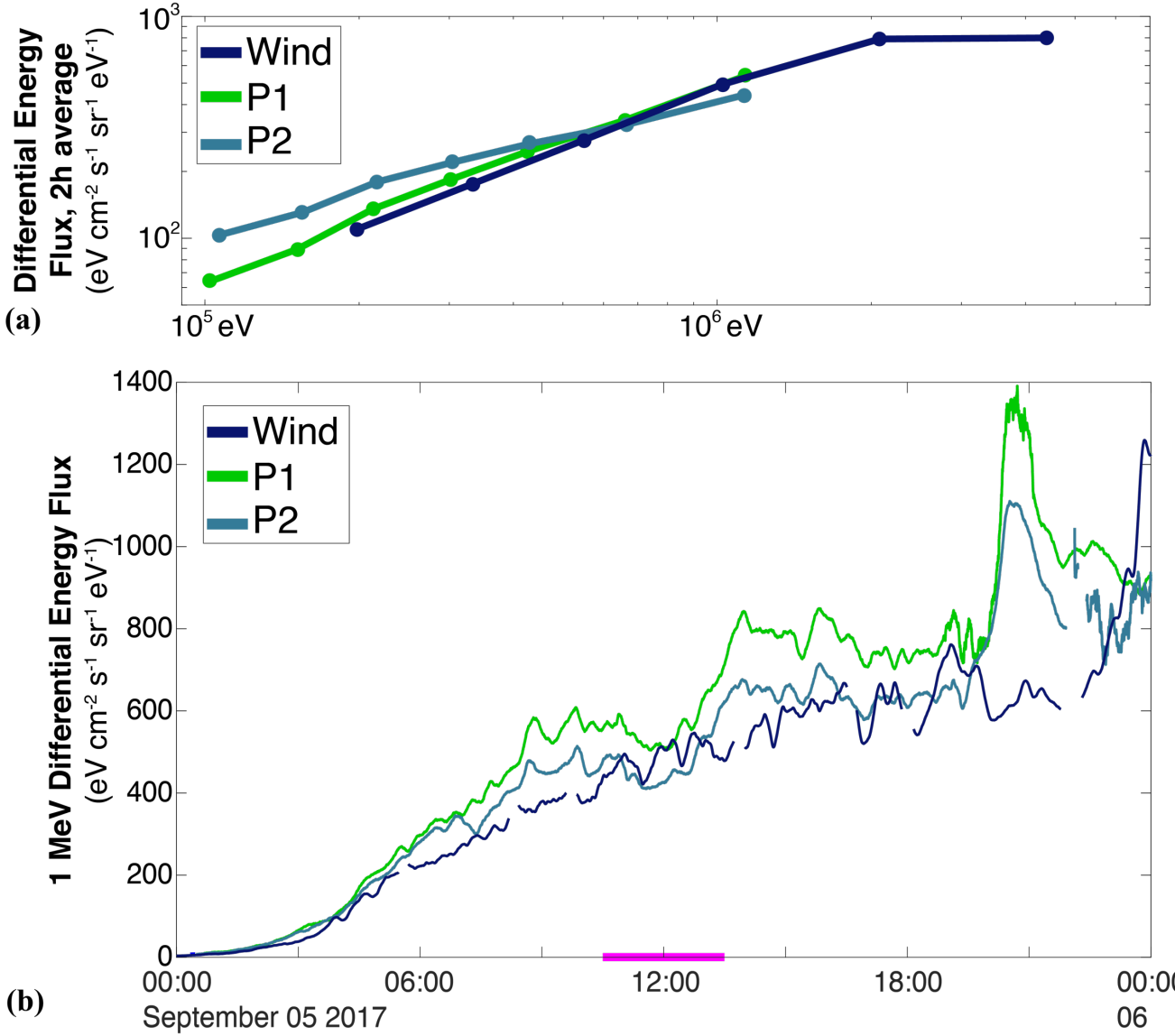
- 100 keV – 10 MeV ions enhanced
- "Impulsive" SEP event: flare-generated, dispersive ion velocity

P1 & P2 (within magnetotail)

- Probes within southern lobe
- Similar plasma sheet encounters
- SEPs >100 keV detected throughout the day

Liuzzo+, submitted

Wind and ARTEMIS comparison



Liuzzo+, submitted

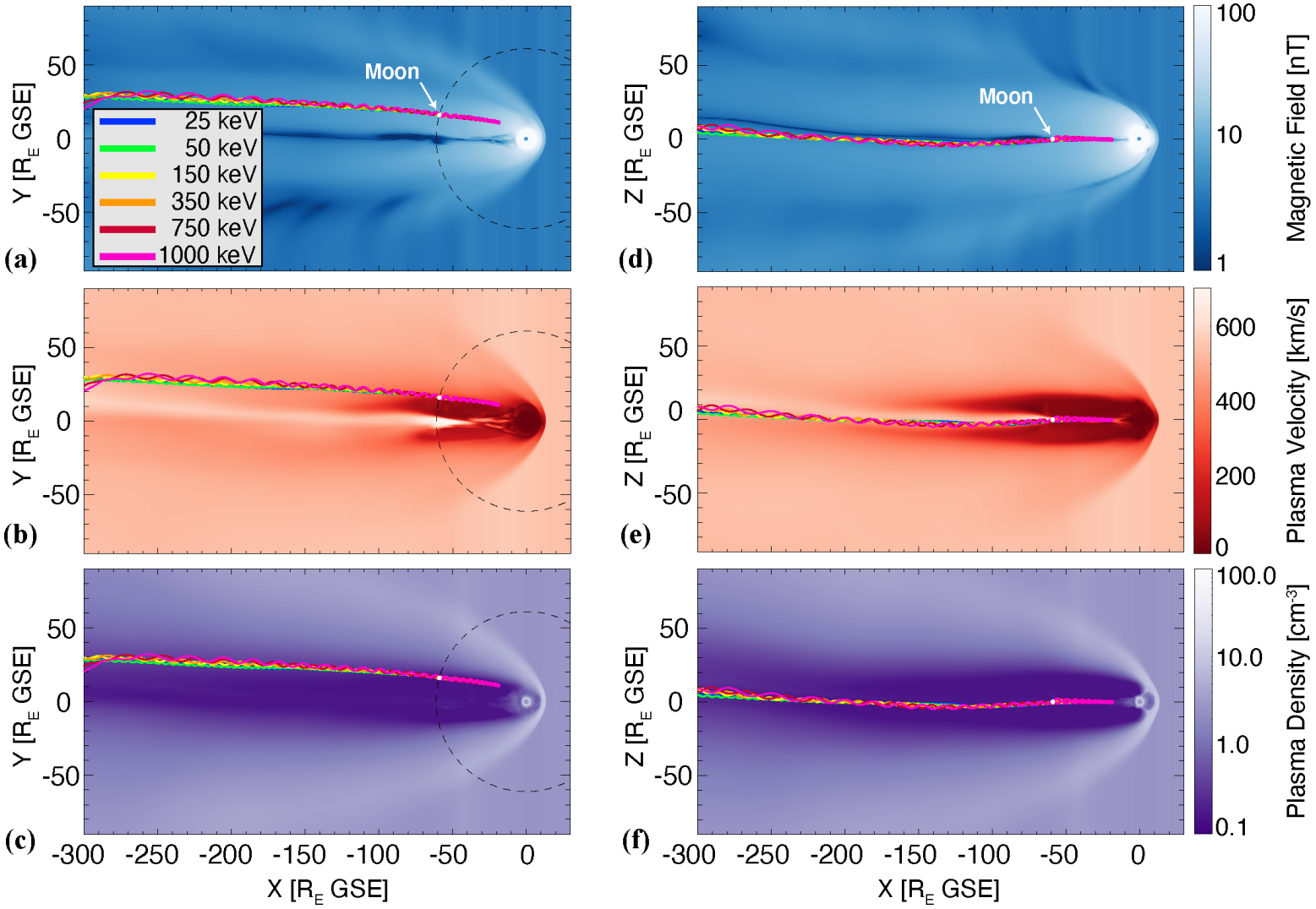
Time-averaged fluxes

- Wind & ARTEMIS detected similar spectral signatures

1 MeV timeseries

- Nearly no time-delay in arrival times to Wind and ARTEMIS
  - Flare-generated SEPs
  - Intermittent signatures of high-energy magnetospheric plasma sheet in P1, P2

Where do SEPs gain access to the tail?



- SEPs enter the tail far downstream (beyond OpenGGCM boundary)
- Difficult to constrain entry distance of these SEPs (>300 R_E downtail)

Liuzzo+, submitted

Conclusions

- Focused on two SEP events: one ICME-generated, one flare-generated
- Wind SEP observations far upstream are nearly identical to ARTEMIS within the terrestrial magnetotail
- SEPs have nearly **unrestricted access** the magnetotail
- SEPs enter the tail along field lines open on one end to the solar wind
- Implies the magnetotail may provide only ***limited shielding*** during future exploration of the lunar surface