The Role of Extensive Air Showers in the Inner Heliosphere

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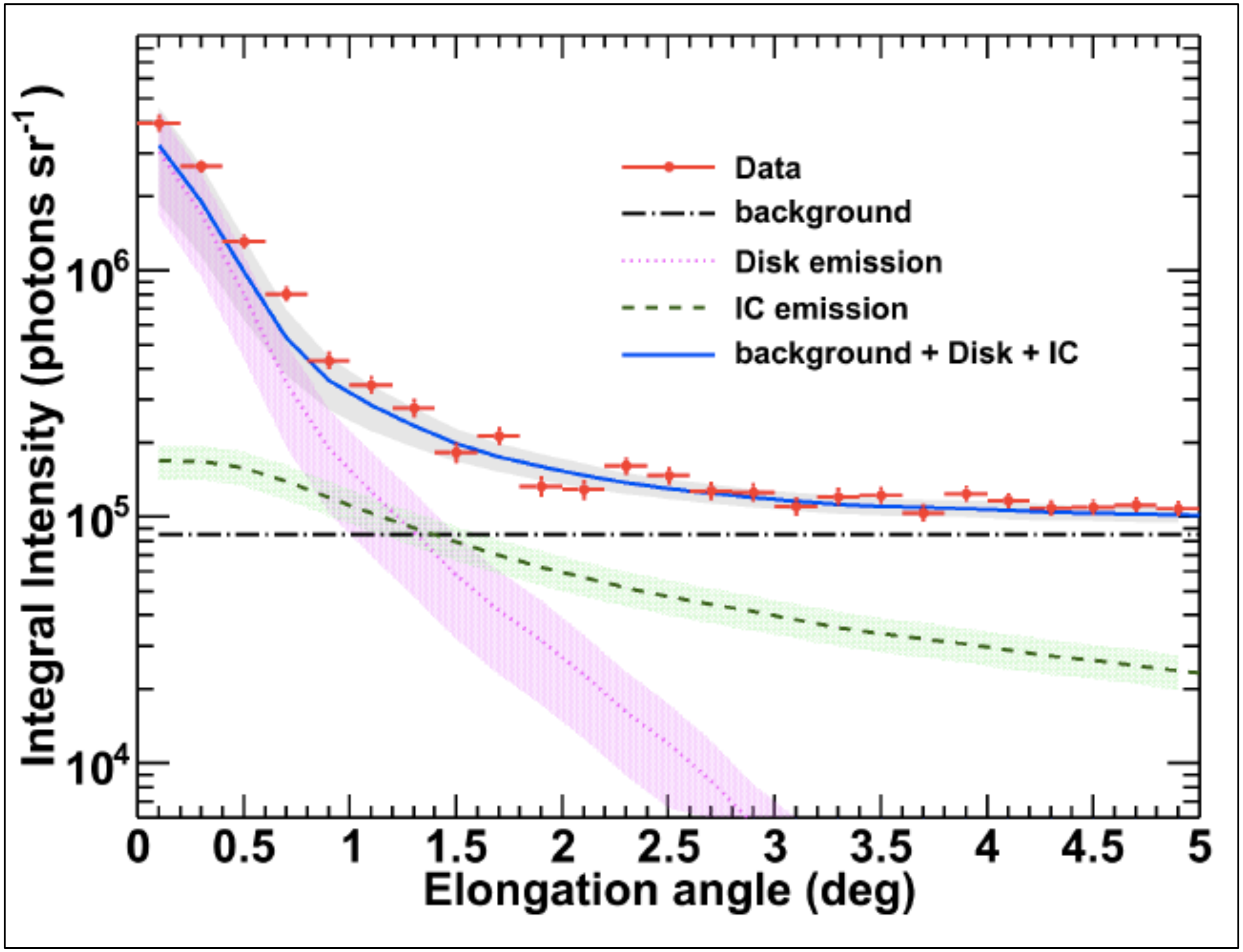
Fermi/LAT solar gamma rays



Abdo et al. 2011

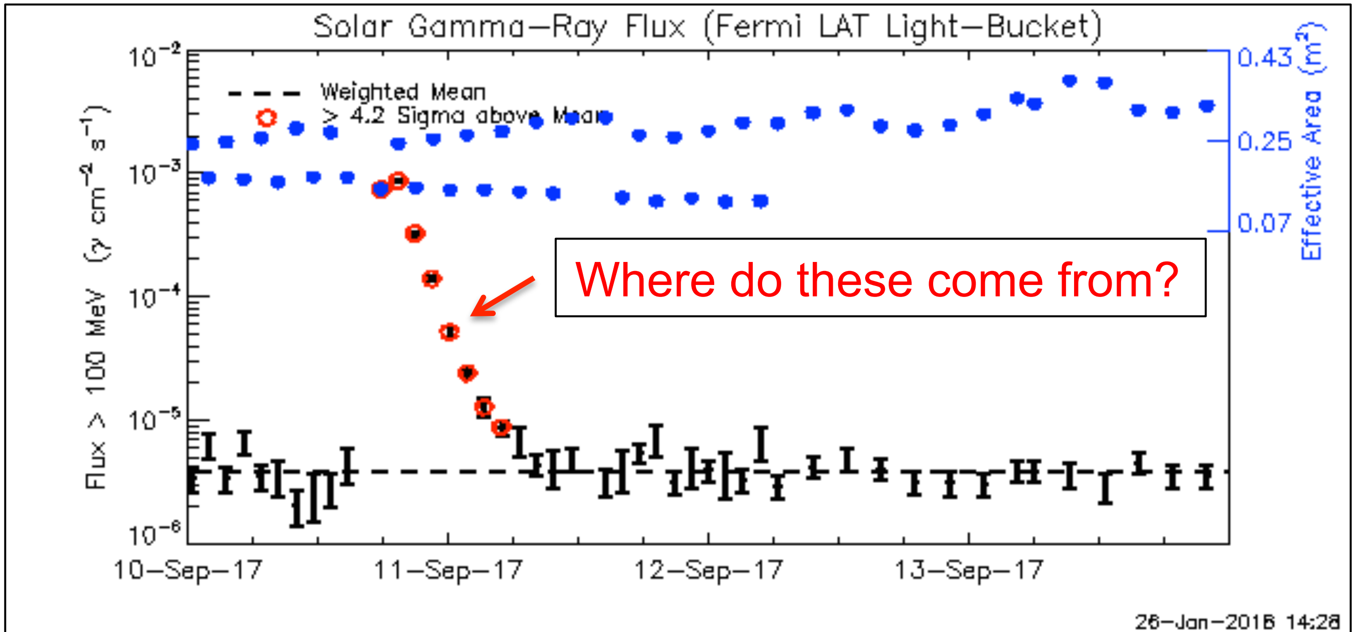
Fermi/LAT solar gamma rays

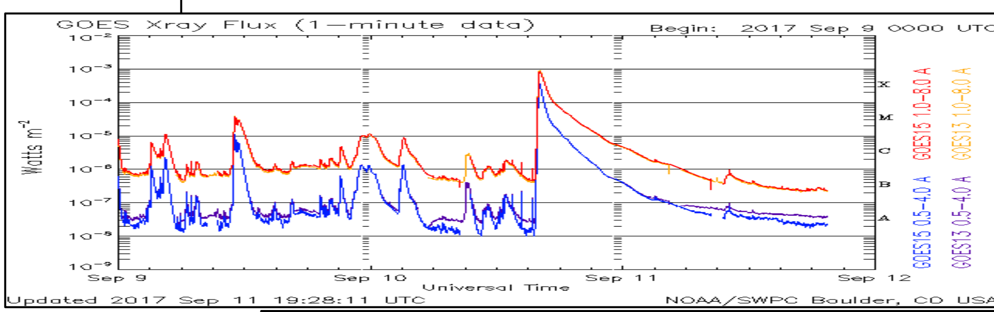
- Fermi/LAT detects multiple γ-ray sources from the quiet Sun above 500 MeV:

    - A “disk” component, likely to be cosmic-ray secondary radiation
    - A “halo” component due to Compton scattering of cosmic-ray electrons
    - Something else? Linden et al., arXiv1803.05436; Tang et al. arXiv180406846T

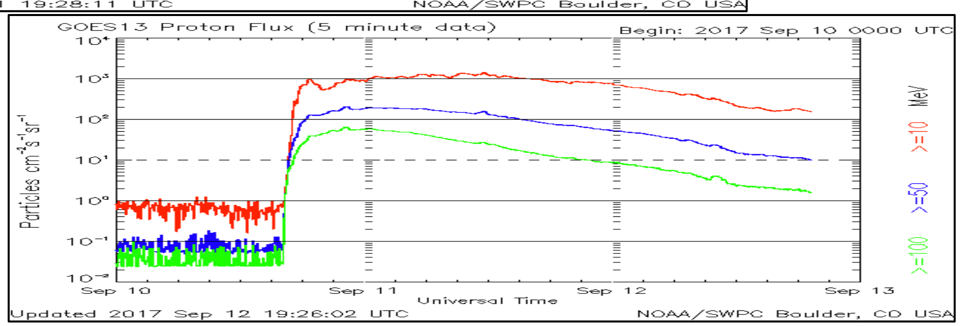
- Fermi/LAT detects flares.

Fermi/LAT flare, GLE No. 72



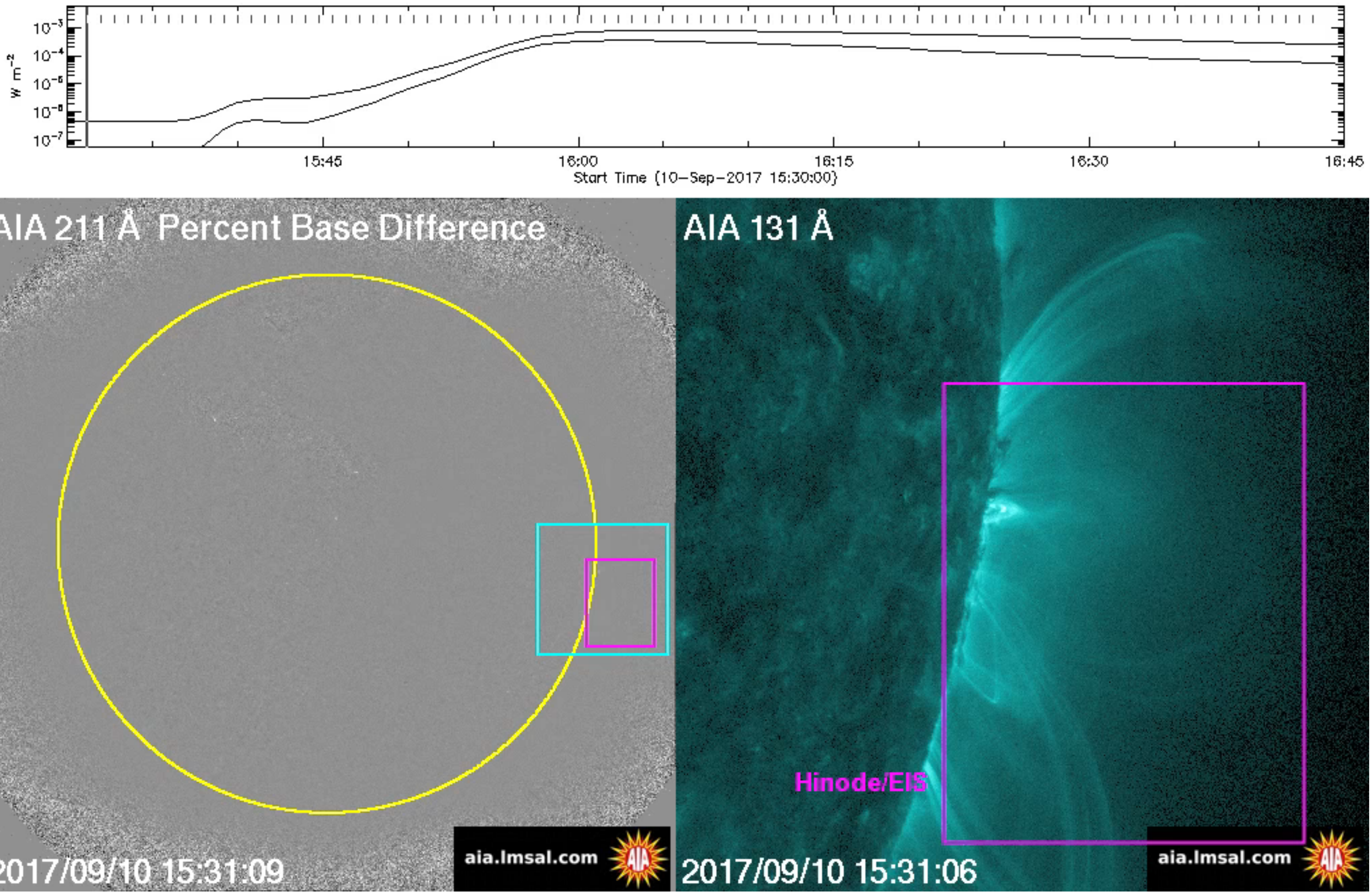


RHESSI Browser



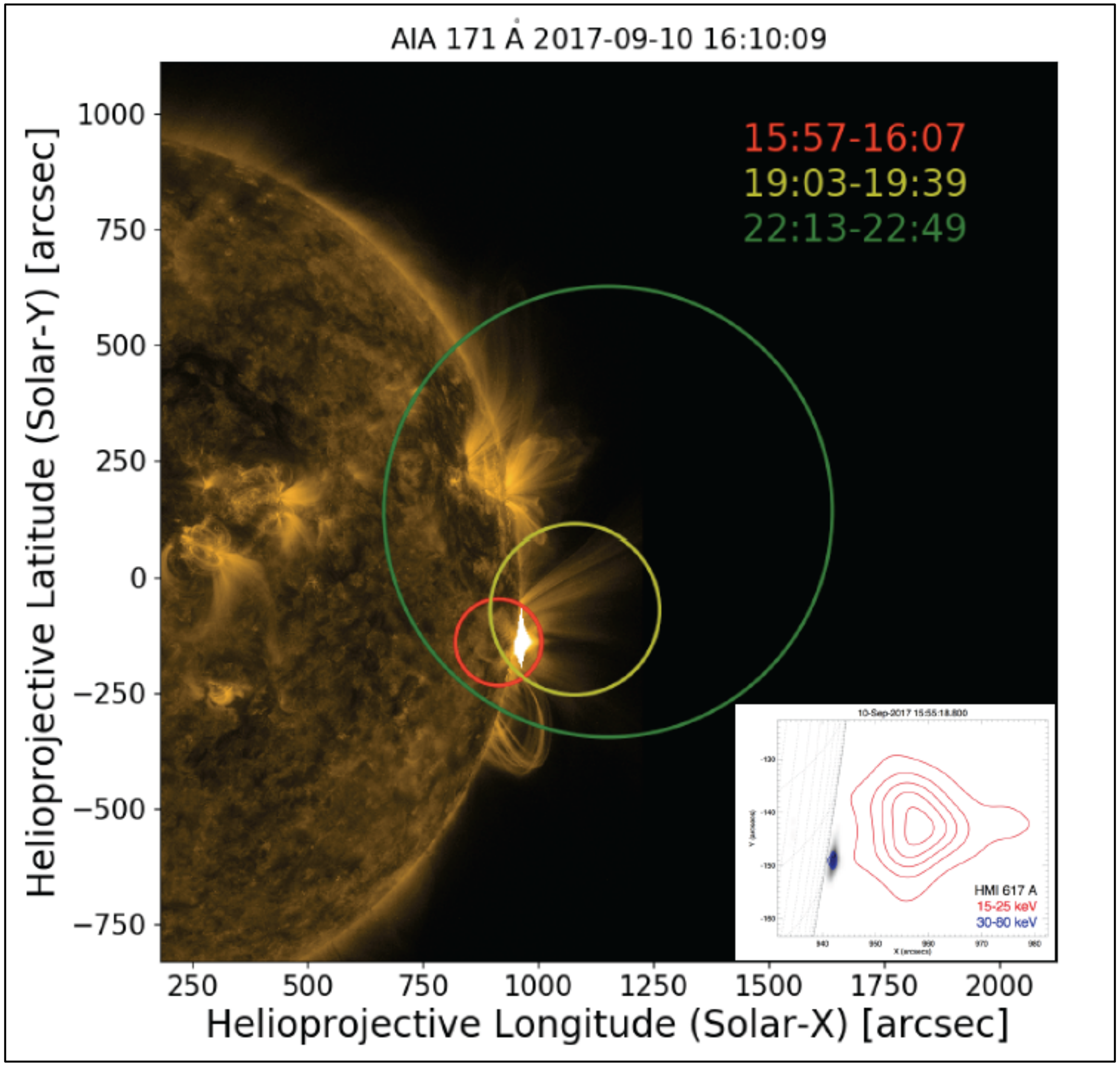
GOES SEPs

The Nitta movie of SOL2017-09-10



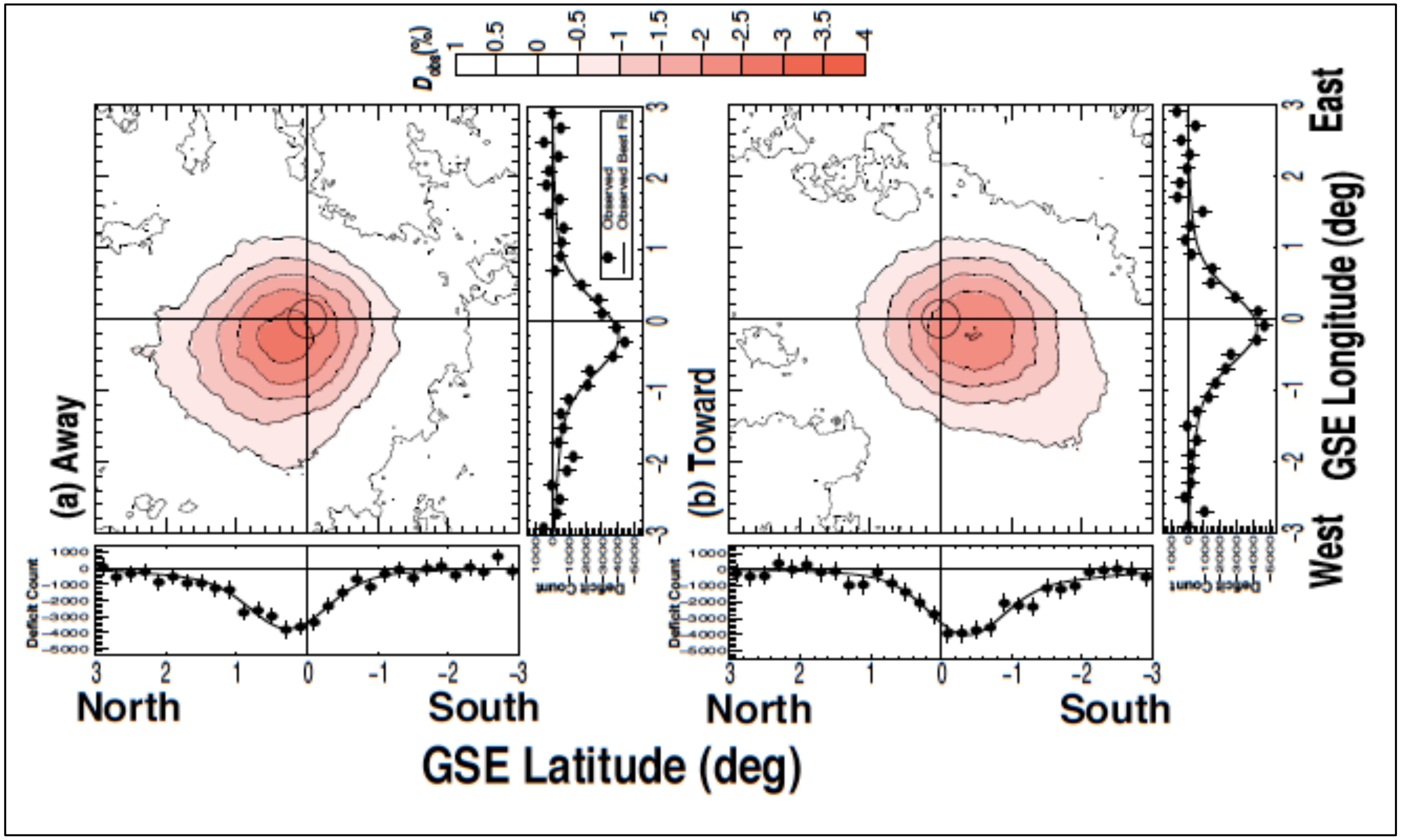
Somewhere, in this movie, there are 10^{12} gallons of protons at 10^6 kT.

Here they are!



Omodei et al. 2018

Cosmic-ray shadows



5-200 TeV

Amenomori et al. 2018

Cosmic-ray shadows

- These images are from the Tibet-III air-shower array, but improved resolution and throughput will be coming, e.g. from HAWC.
- The solar shadow is different from the lunar shadow: it varies with time, across the solar cycle, and it significantly reflects the magnetic “sector structure” of the solar wind.
- The detectability of the shadow encourages us to study the “limb shower” development from the cosmic-ray interactions: there should be a bright, thin annulus (e.g., Zhou et al. 2014).

FOM = radius x scale height x modulation / distance^2

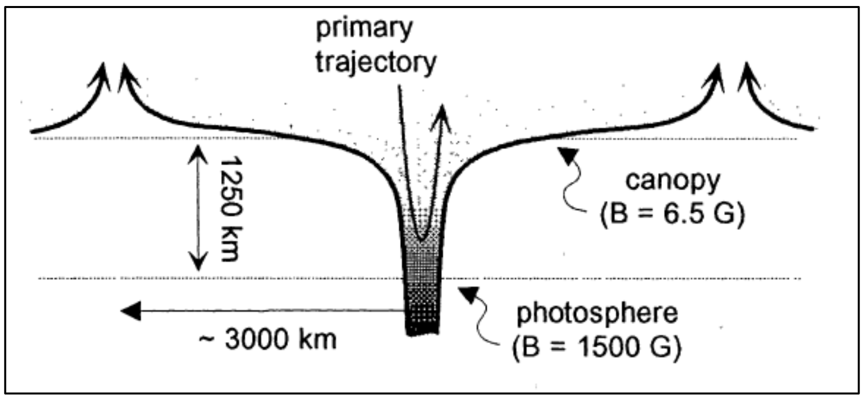
Sun	4
Venus	0.2
Jupiter	0.05

Gamma-rays from the quiet Sun

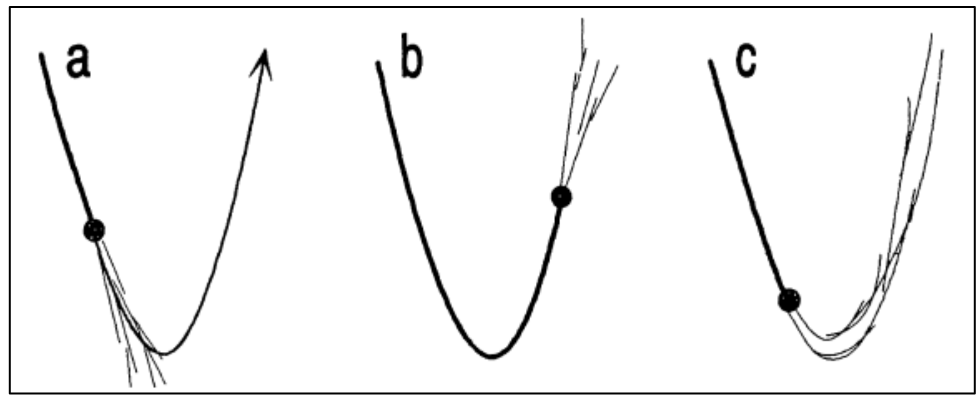
- Seckel et al. 1991, 1992:

  - Diffusive transport and then mirroring interactions (hence limb showers)

  - Monte Carlo estimations about 1/10 the LAT result



Mirroring in strong flux tubes

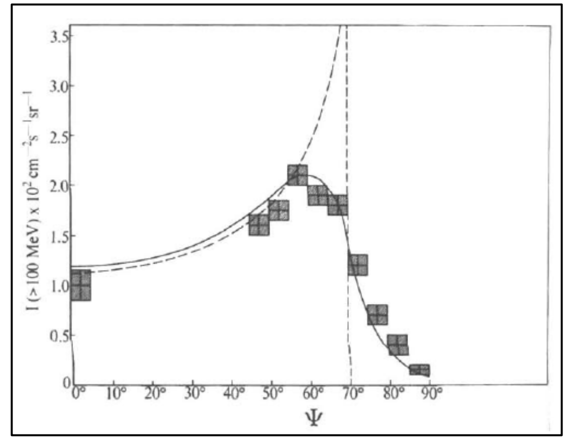


Shower generation at any point

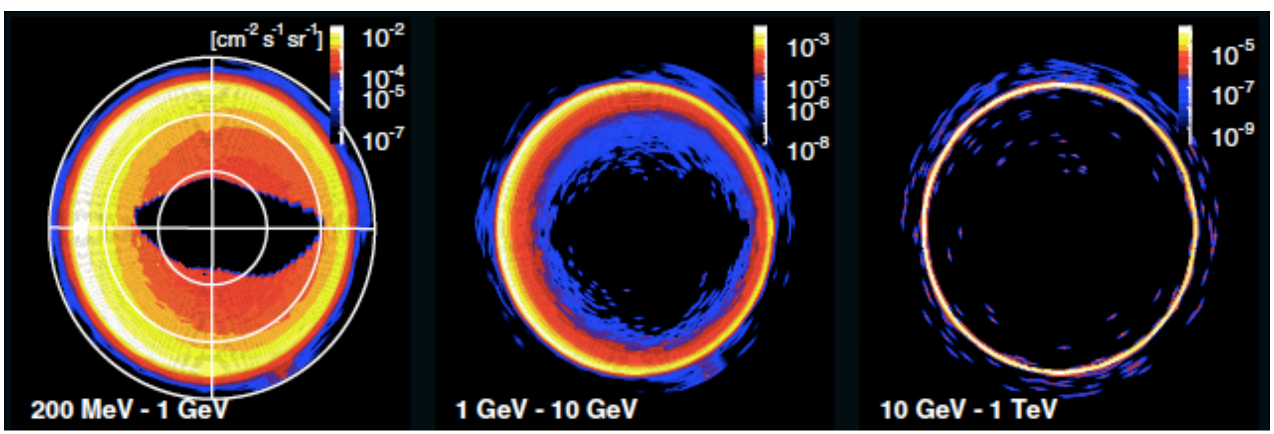
From the solar point of view, the Larmor motion sensitively probes the atmospheric model: Zweibel-Haber? Bifrost?

Literature

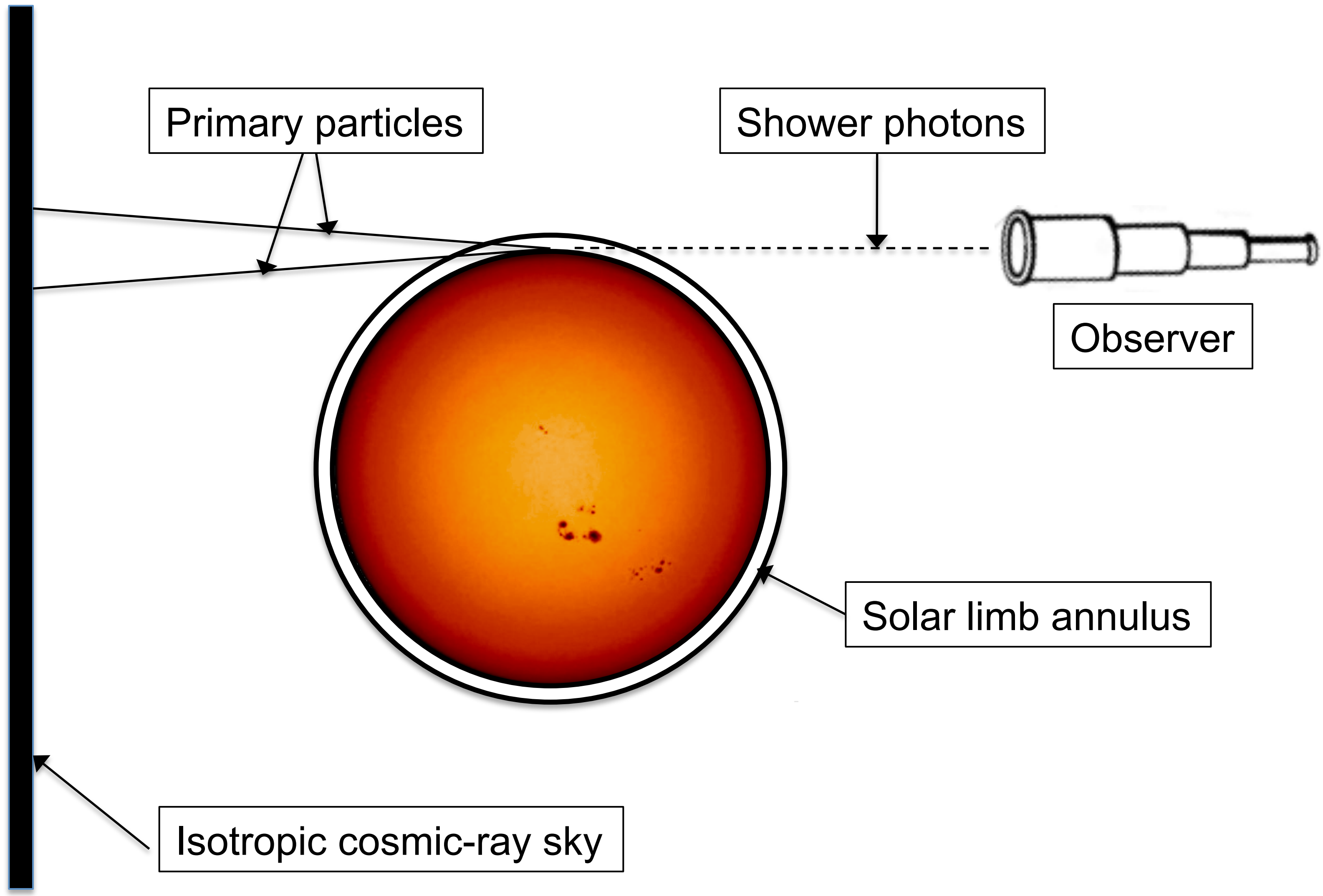
- Stecker (1974): theory shows extreme Earth limb brightening.



- Morris (1984): detailed Monte Carlo calculations for GRO/EGRET Earth observations.
- Abdo et al. (2009): Earth albedo from air showers.



Limb Shower Geometry



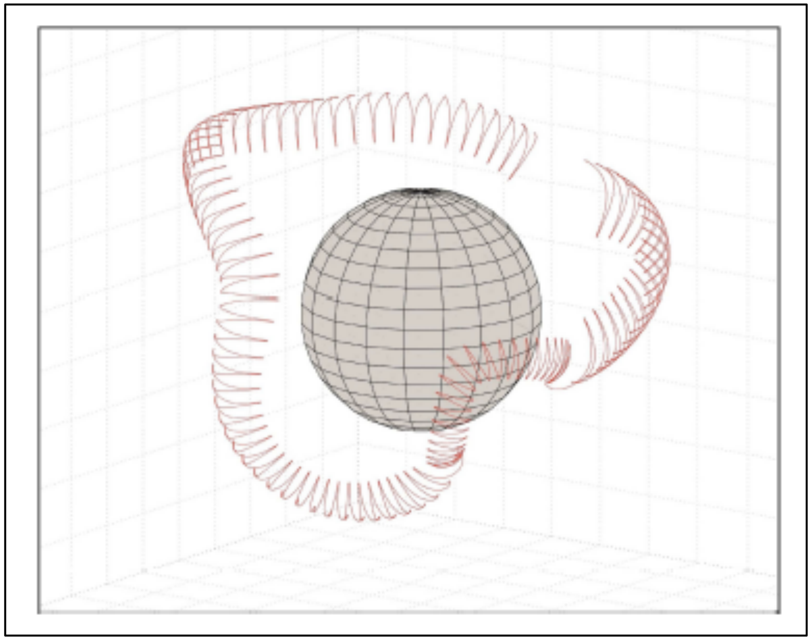
Limb Shower Implications

- First-generation secondary products will be directly detectable in the annulus region.
- Later-generation shower products will greatly amplify the resulting photon intensity from the annulus, but diminished from full shower development.
- The limb showers inject products into the corona.
  - Solar CRAND: hardly discussed.
  - Solar radiation belts: Hudson et al. 2009.
  - Exotic particles (Venus spews them into the heliosphere).

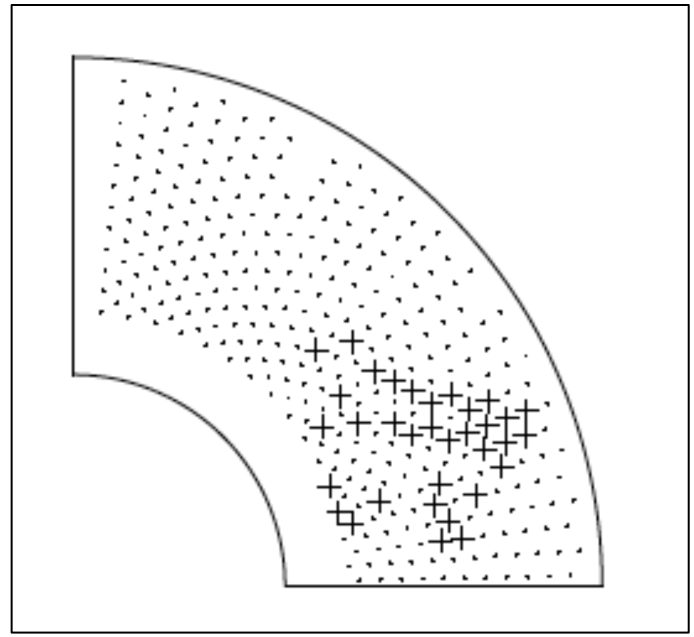
Conclusion

- Cosmic rays, solar or not, play a big role in the inner heliosphere.
- The "limb shower" mechanism may provide novel clues about solar structure and about particle propagation.

Solar radiation belts?



A single ^{83}Bi test particle has circumnavigated the Sun!



(R, θ) map of successful test particles

Hudson, McKinnon, DeRosa, & Frewen (2009) showed conservation of all three invariants for high-energy particles – a hint regarding the Størmer problem.

The Venus test case

- We want to study the Sun via the limb showers, but it is very model-dependent theoretically.
- Venus has a thick, hot, high-Z atmosphere (CO_2), and no intrinsic magnetic field.