Cosmic-ray Issues in the Inner Heliosphere

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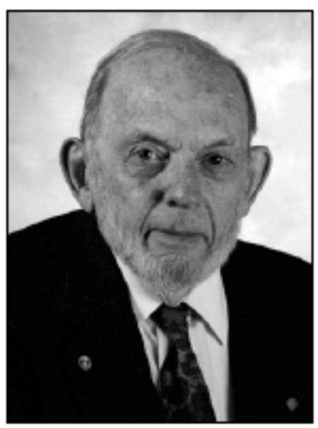
Academic Background

- Kinsey Anderson (PhD Minnesota 1955)
- John Winckler (PhD Princeton 1946)
- Rudolph Ladenburg (PhD Munich 1906)
- Wilhelm Conrad Röntgen (PhD Zurich 1869)
- August A.E.E. Kundt (PhD Berlin 1864)
- Heinrich Gustav Magnus (PhD Berlin 1827)
- Miscellaneous German chemists…

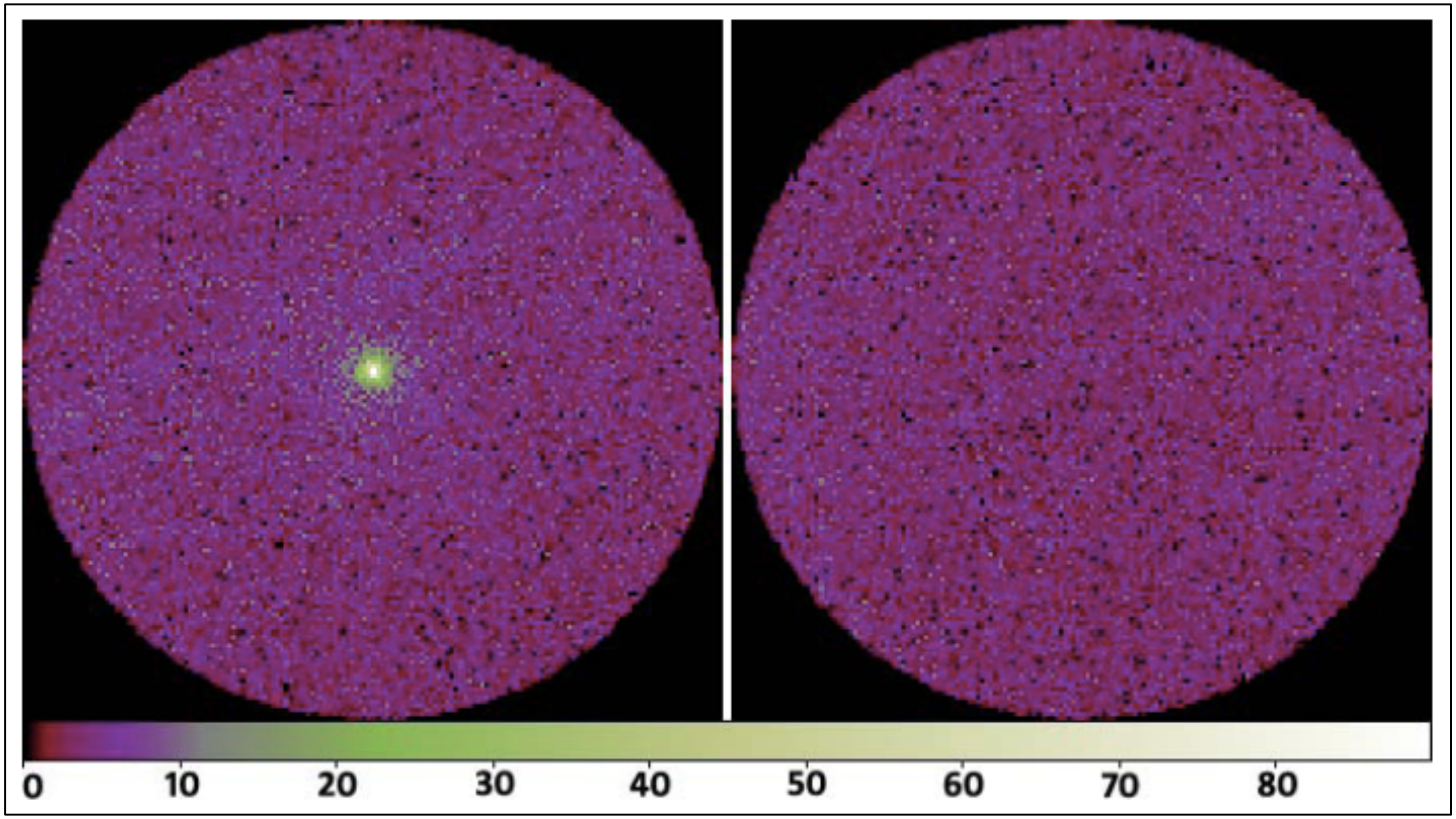


Cosmic rays at Minnesota

There were many contributions to cosmic-ray physics at the University of Minnesota following WWII: Freier, Kellogg, McDonald, Ney, Waddington, Winckler…

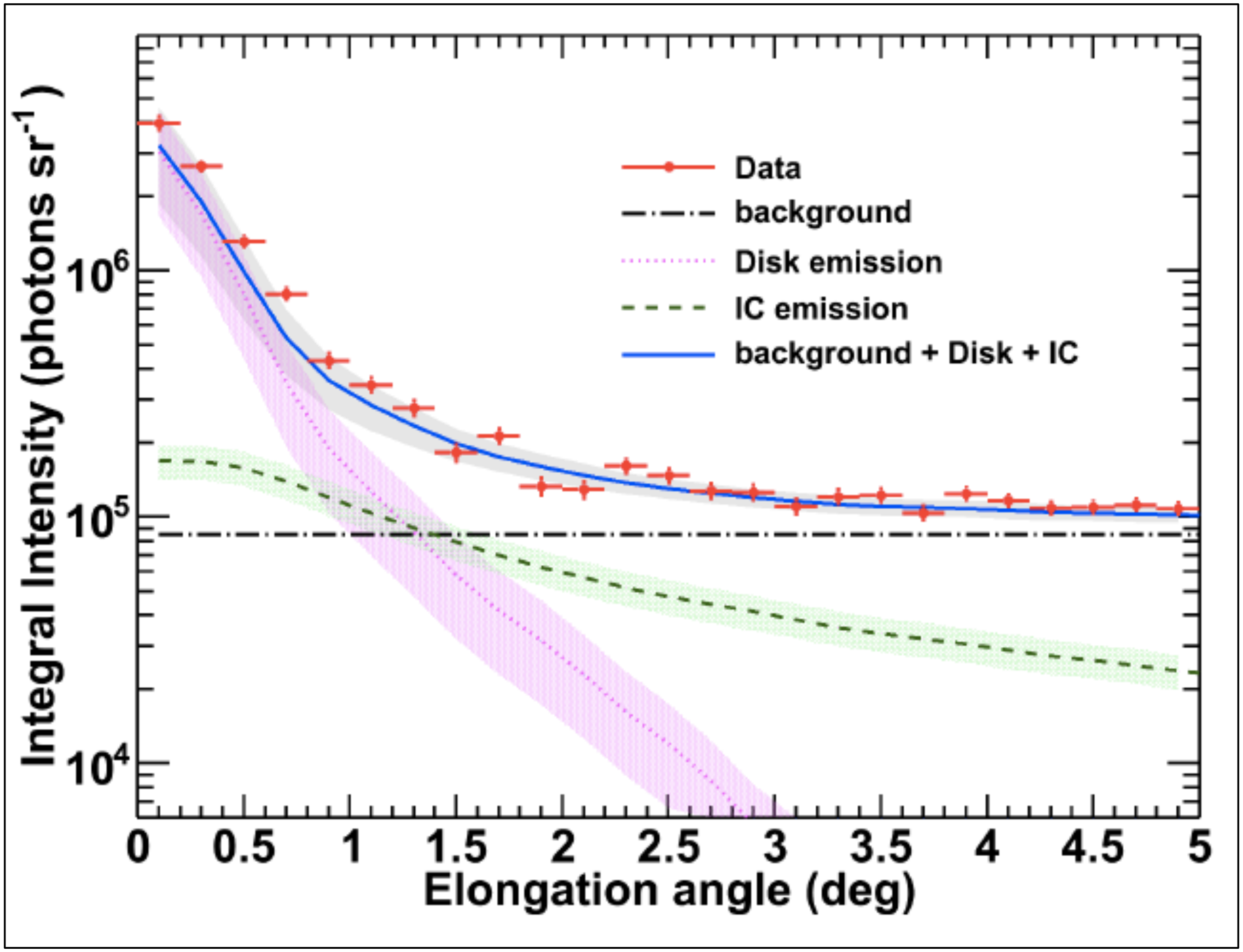
Especially interesting technical things were detector development and the use of high-altitude research balloons.

Fermi/LAT solar gamma rays



Abdo et al. 2011

Fermi/LAT solar gamma rays



Abdo et al. 2011

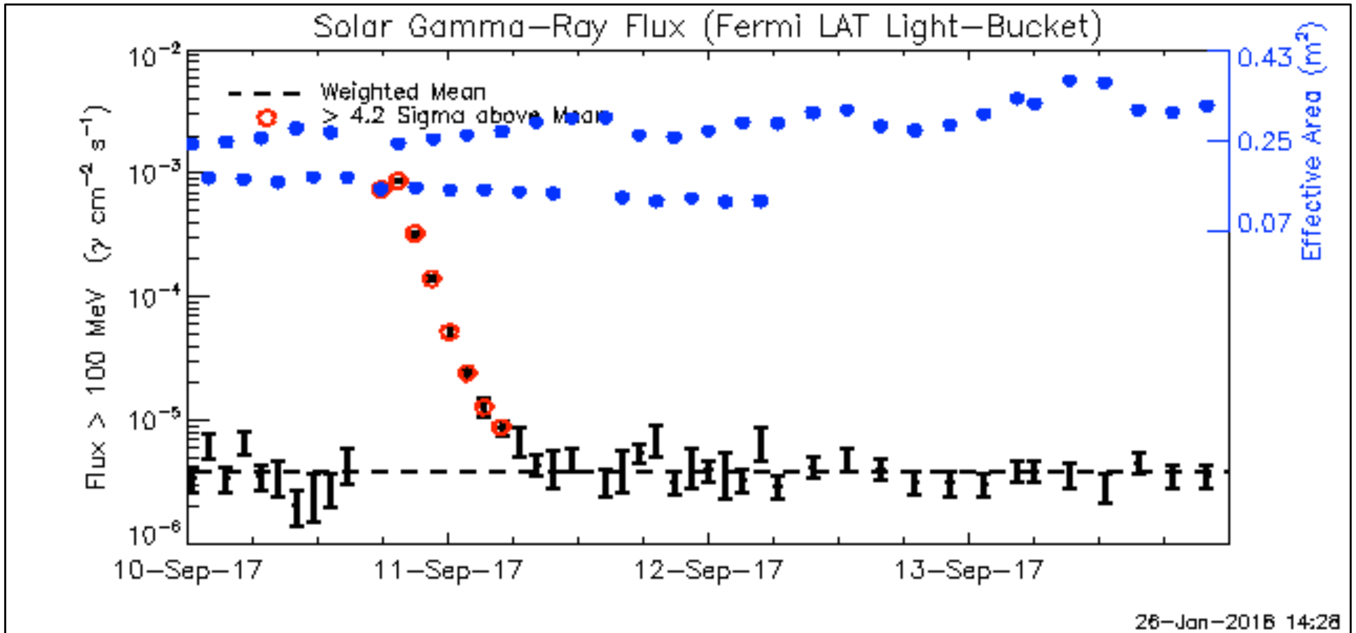
Fermi/LAT solar gamma rays

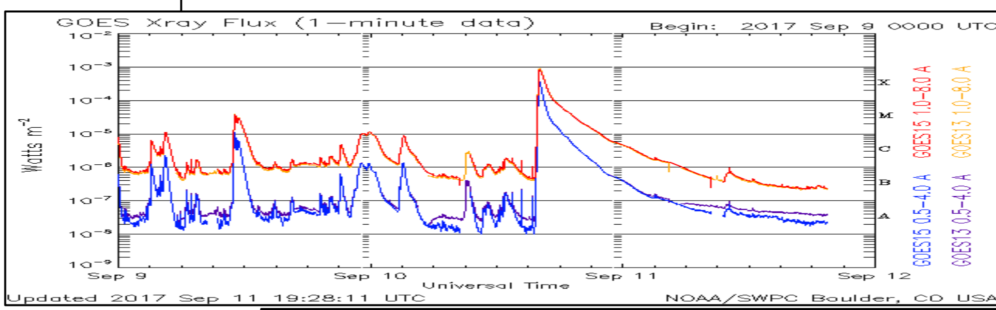
Fermi detects two γ-ray sources from the quiet Sun above 500 MeV:

- A "disk" component, likely to be cosmic-ray secondary radiation

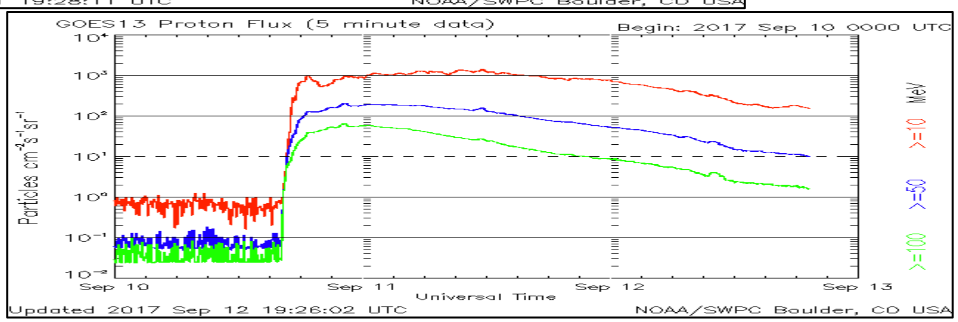
- A "halo" component due to Compton scattering of cosmic-ray electrons

Fermi/LAT flare, GLE No. 72



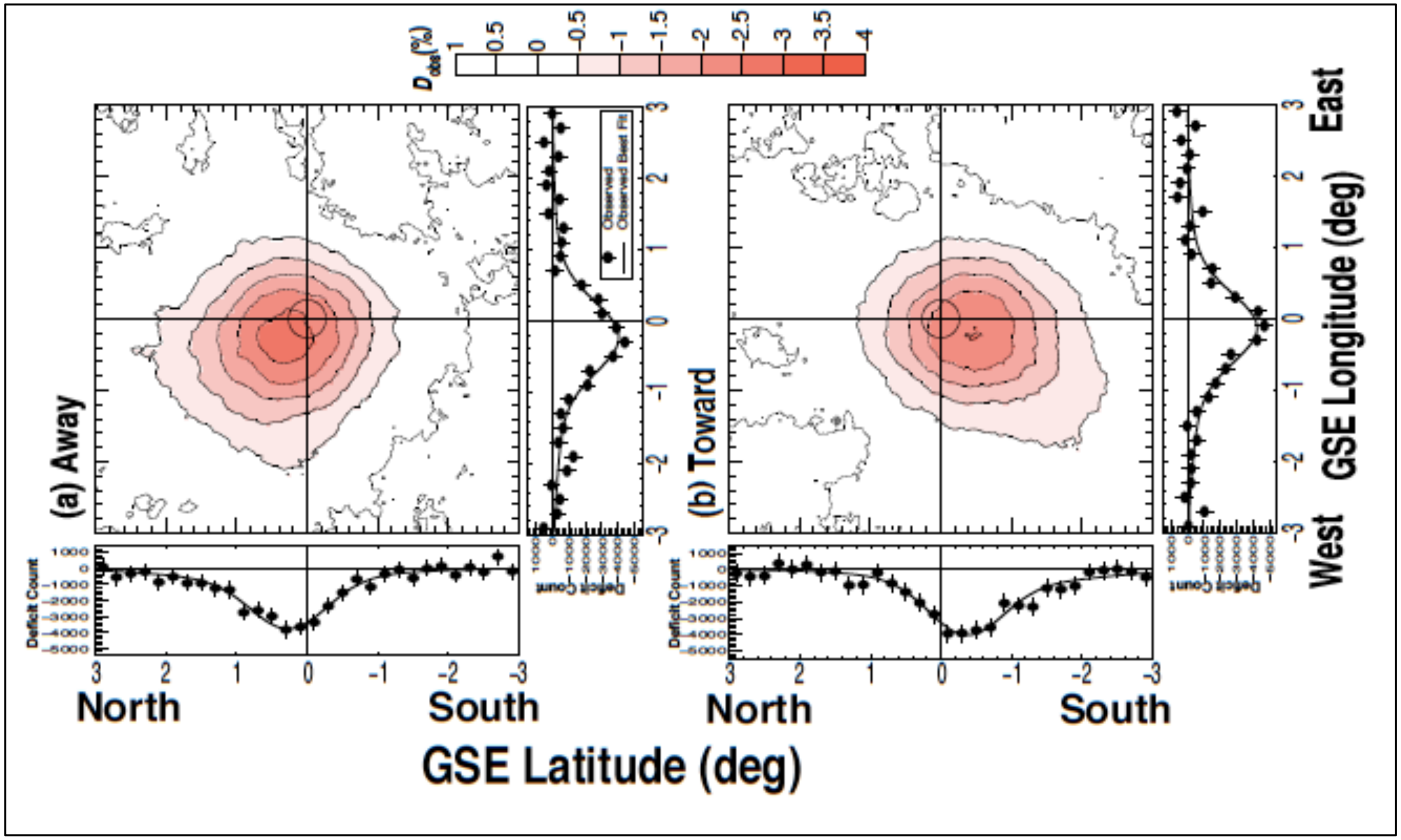


RHESSI Browser



GOES SEPs

Cosmic-ray shadows



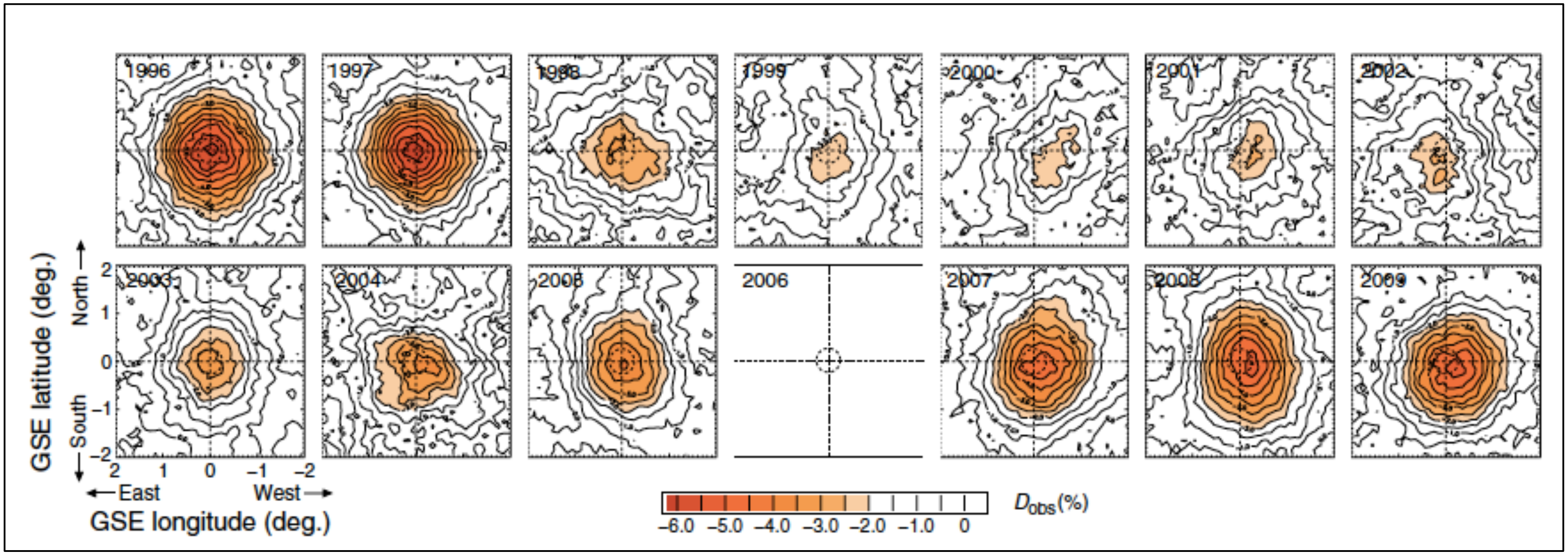
5-200 TeV

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 sector structure in the mean.

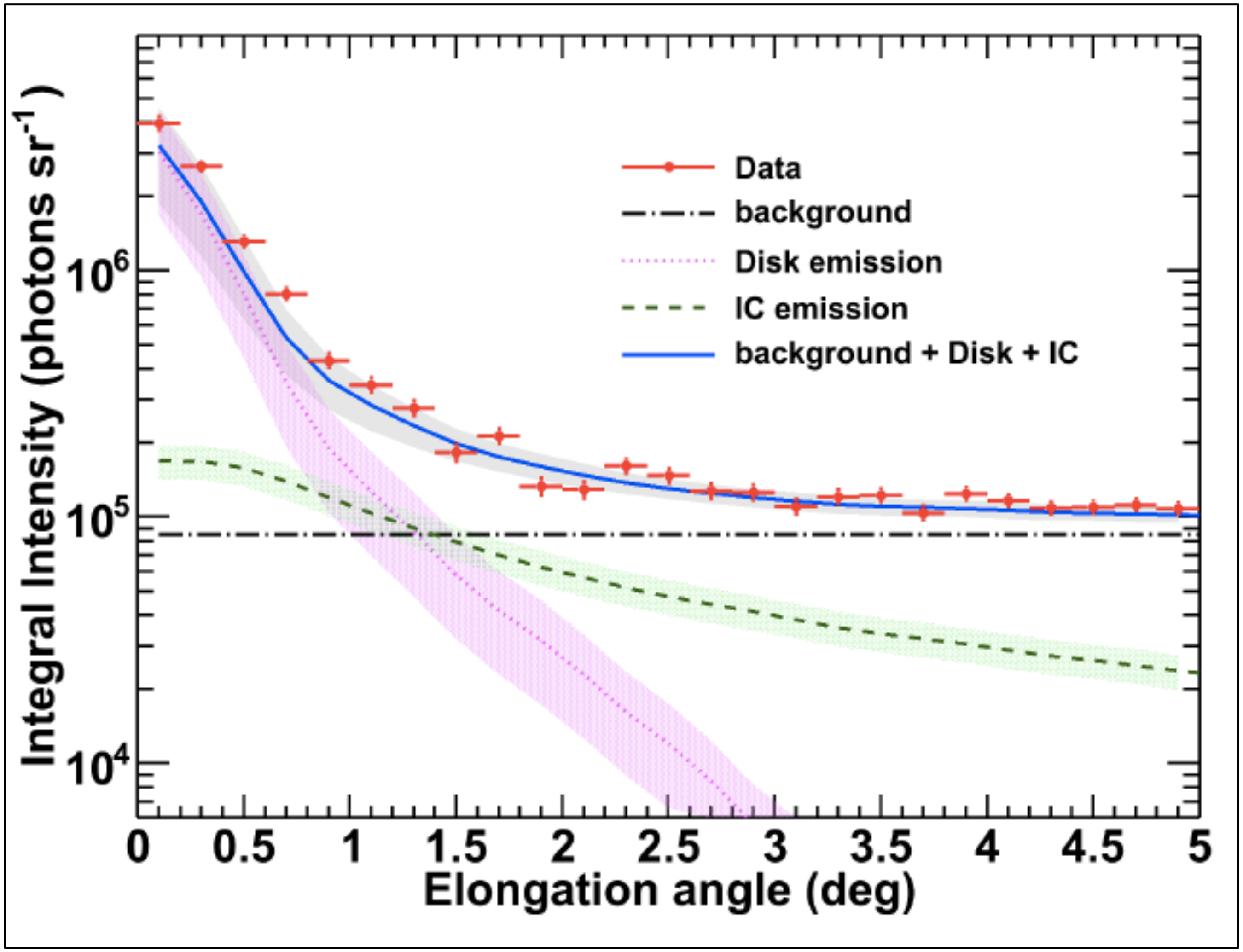
The shadow over the cycle



Amenomori et al. 2013

- Most of the refraction must be in closed fields – but why the sector dependence?

Fermi/LAT solar gamma rays



Abdo et al. 2011

How do we observe the coronal magnetic field at a few $R_\odot$?

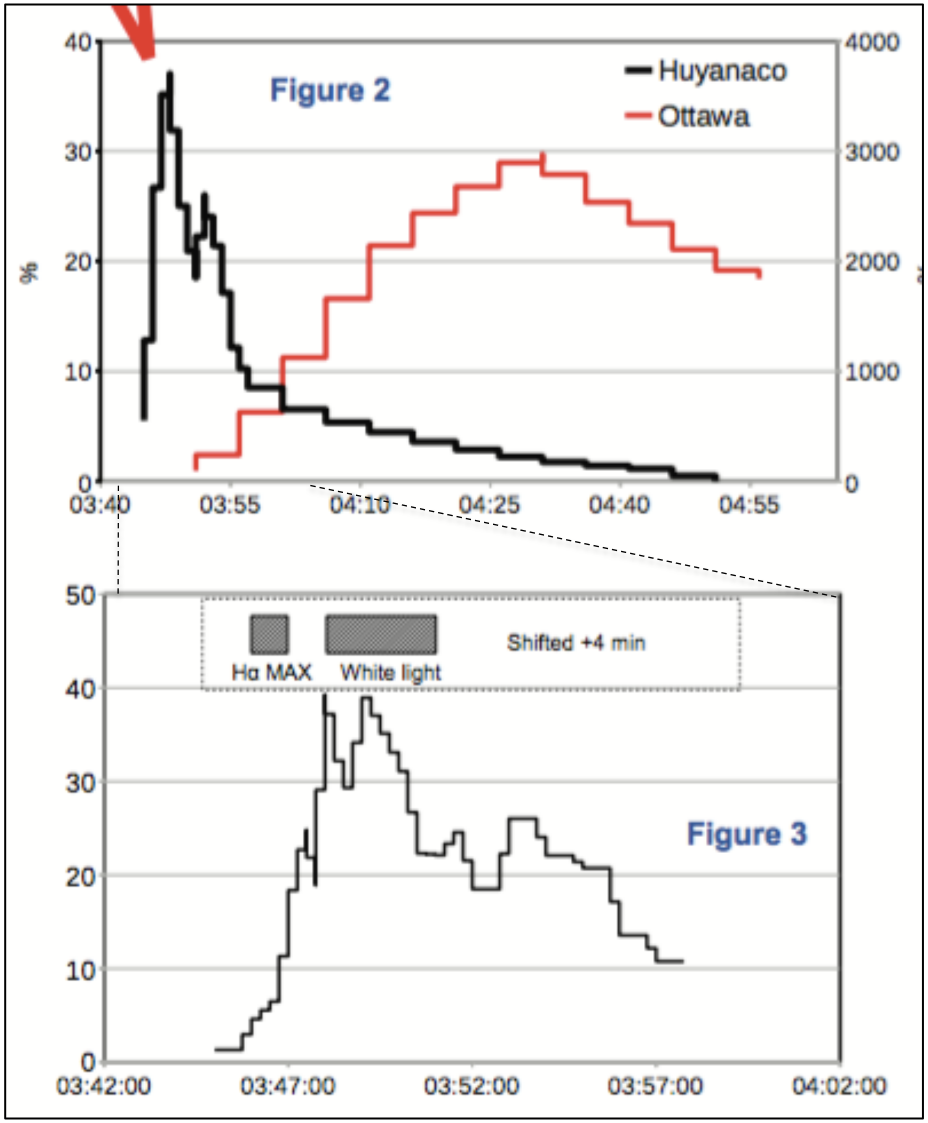
- Eclipse morphology
- Faraday rotation
- Cosmic-ray shadowing
  - mean model parameters
  - Forbush decreases

Other high-energy signatures

- Forbush decreases, remote Forbush decreases, SEPs propagation mysteries, ENAs and direct detection of energetic solar neutrons, solar radiation belts…
- Solar “multi-messenger astrophysics”

- *See RHESSI Nuggets No. 157, 258, 268, 280, 300 etc.*

Historical footnote on GLEs

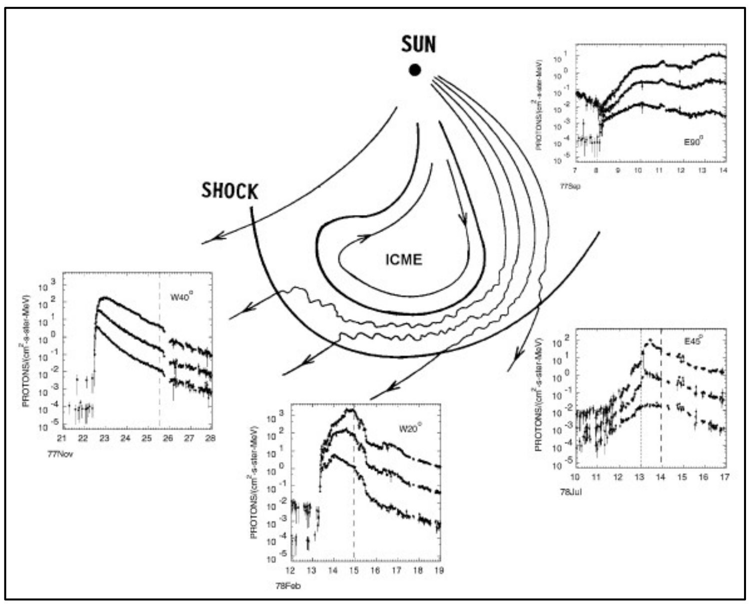


SEPs (~20 GeV) in GLE No. 5

These are original Forbush records from Huancayo on SOL1956-02-23, recovered from unpublished records found by Ken McCracken in 2016. They show 15-s time variability in 20 GeV solar cosmic rays.

Significance of relativistic ions

- At relativistic particle energies, the particles arrive as soon as photons do, plus the increment due to the magnetic connection.
- Forbush's observations show rapid variability, which must reflect small-scale structures in the source.
- The observed time scales do not seem consistent with shock acceleration, nor with diffusive transport

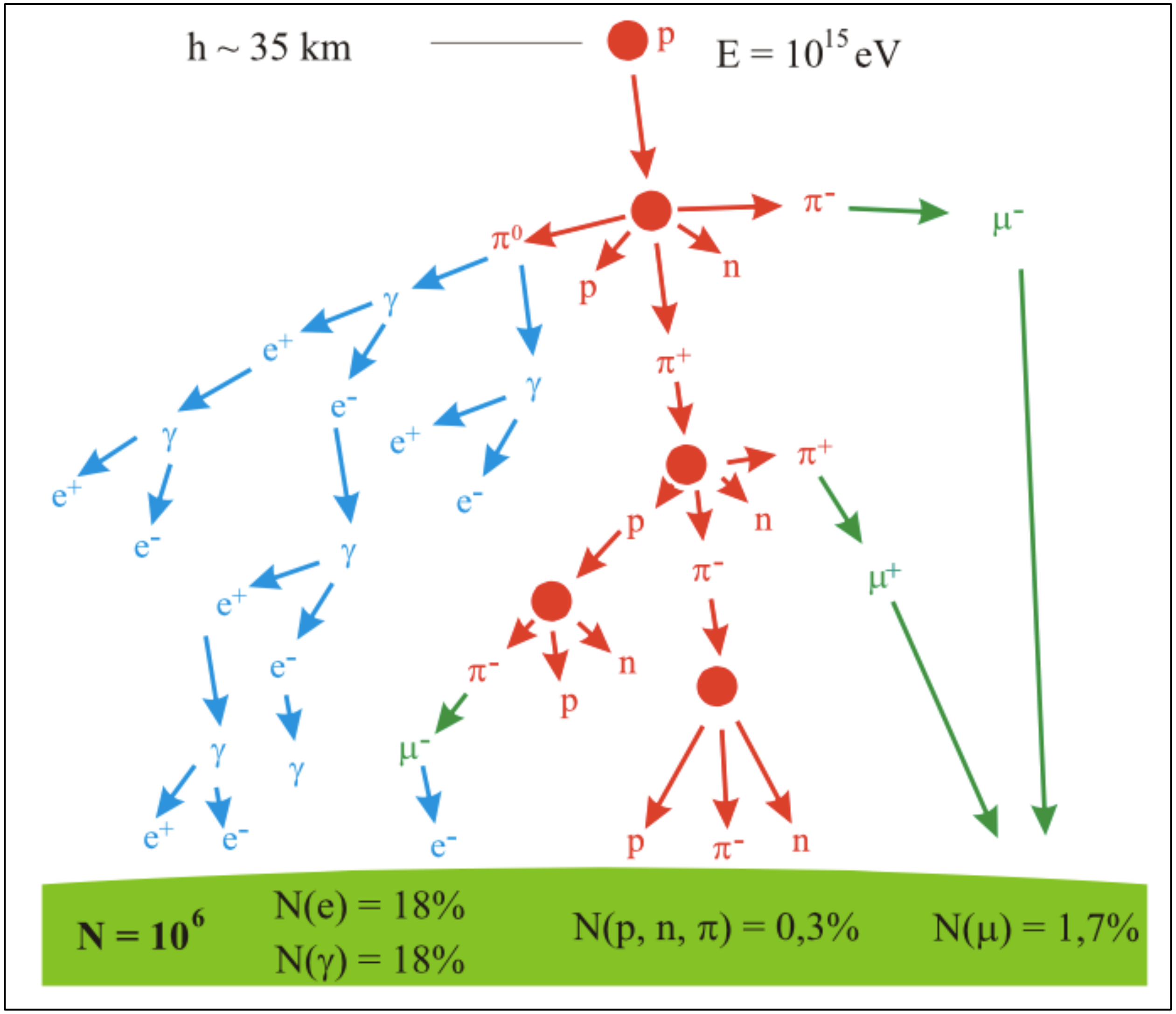


Cane et al., 1988

Limb showers

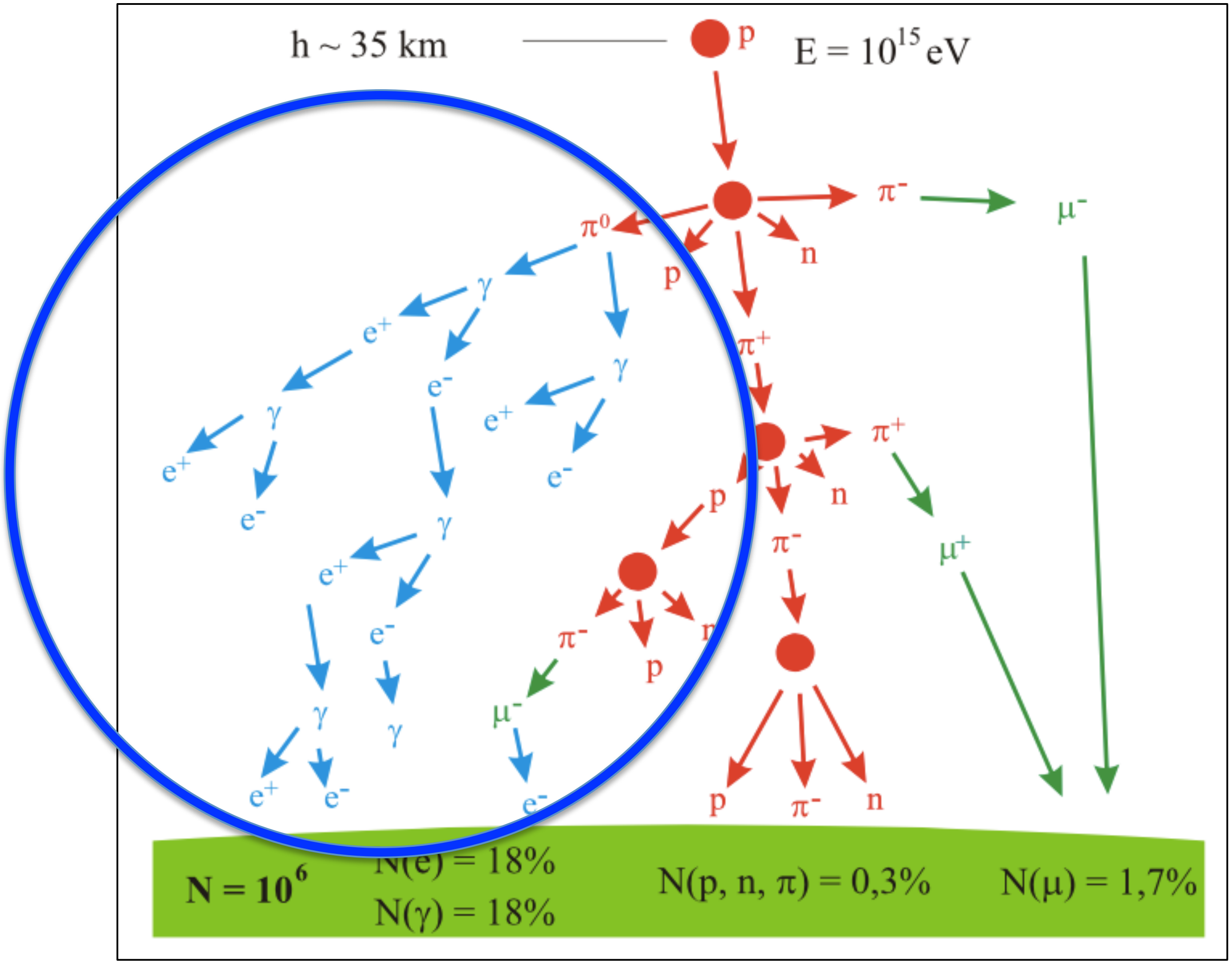
- The equivalent of extensive air showers will happen in other solar-system bodies, notably the Sun, Venus, and Jupiter.
- Escaping shower products will appear as an intense annulus slightly above the limb of the body.
- The γ-ray component is a pair/bremsstrahlung cascade, with a very hard spectrum.

Extensive air showers



Wikipedia

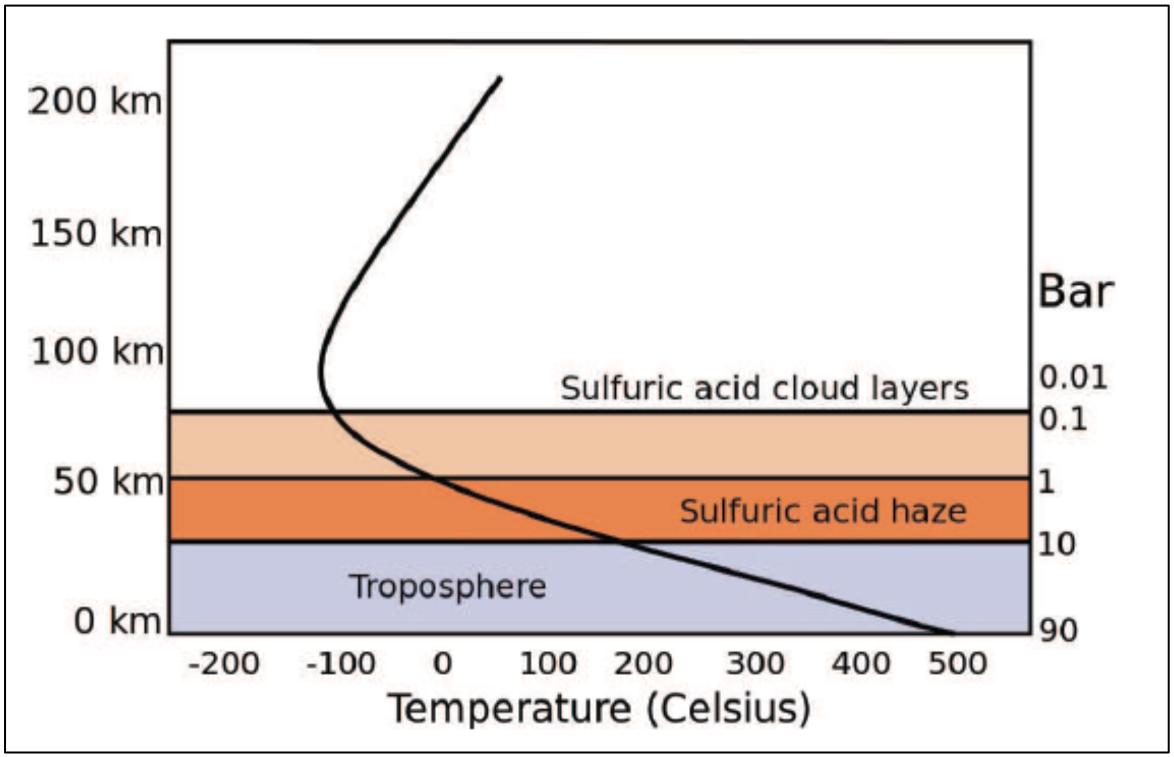
Extensive air showers



Wikipedia

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.



Solar-system bodies

We can estimate a geometrical figure of merit for cosmic-ray detection via limb showers via

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

Sun	4
Venus	0.2
Jupiter	0.05

Comments

- The limb shower idea is fairly new and not well-characterized yet.
- One should use GEANT4, for example, to handle the nuclear physics.
- Propagation (except for Venus) has major uncertainties, but that makes it very interesting.
- Radio detection (ALMA? JVLA?) might allow recording of individual shower events on Venus or Jupiter.

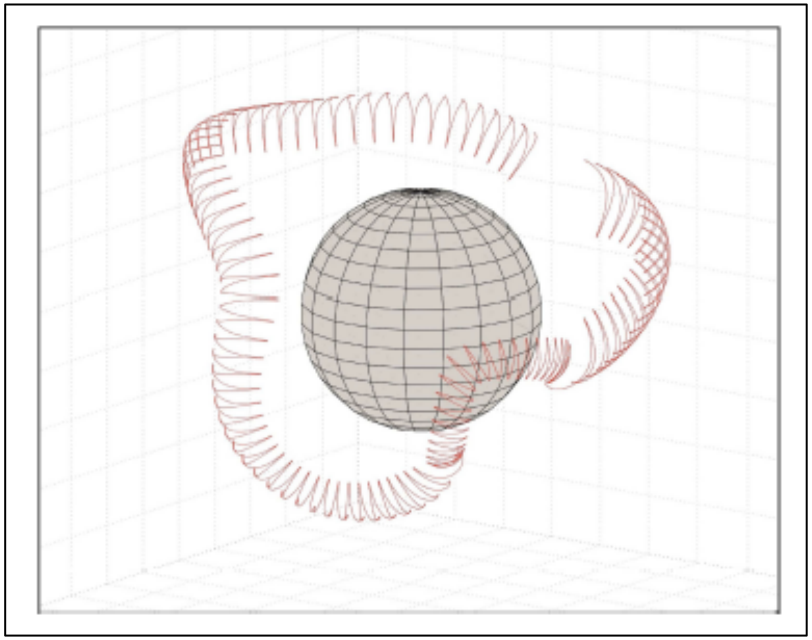
Conclusion

- High-energy radiations (hard X-rays, γ-rays, and other "messengers") play an important role in our understanding of heliospheric structure and of solar activity.
- We have new tools that may help to understand propagation in the inner heliosphere.
- The "limb shower" mechanism may provide essential clues.

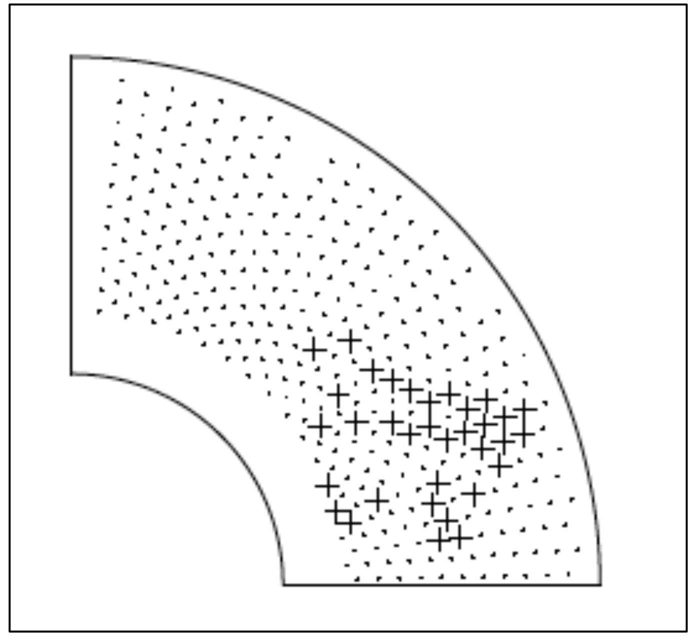
Addendum

- In case the bus has not left already, some comments about SEP behavior near the Sun… if there’s any interest…

Solar radiation belts?



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



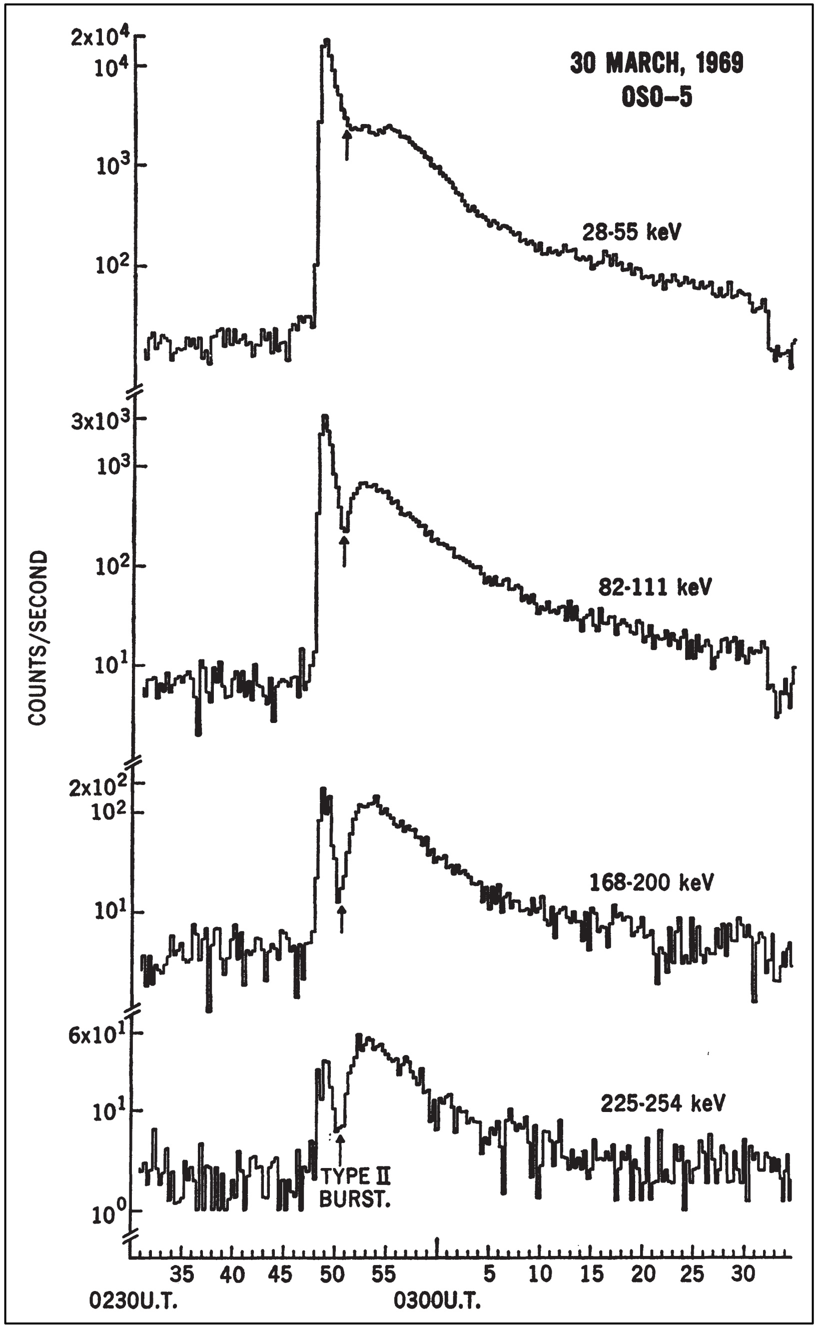
(R, θ) map of successful test particles

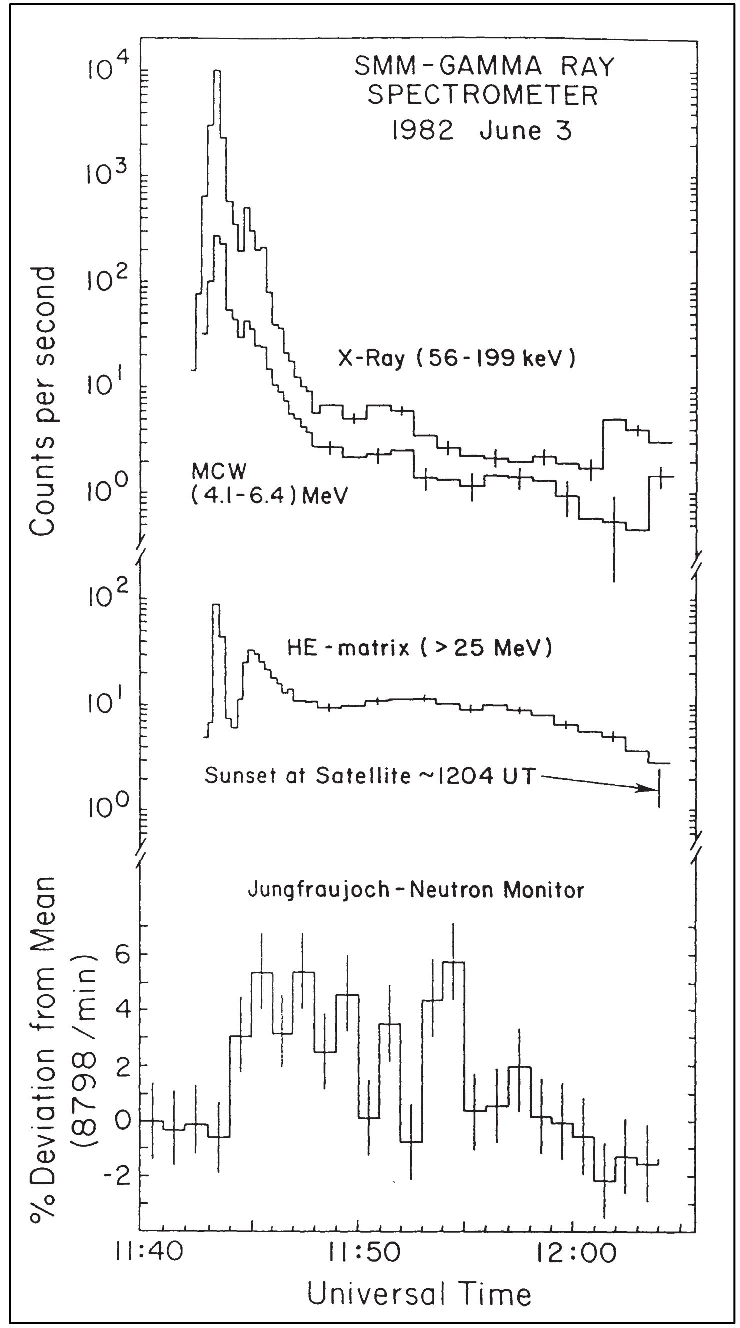
Hudson, McKenzie, DeRosa, & Frewen (2009) showed conservation of all three invariants for high-energy particles – a hint regarding the Størmer problem.

Mid-coronal Disturbances associated with CMEs/flares

- Coronal HXR events, SOL1969-03-30 (Frost & Dennis, 1971; Enome et al. 1971)
- Long-duration γ-ray events, SOL1982-06-03 (Forrest et al, 1985)
- Meter-wave Type II/IV bursts (e.g., Kundu 1965)

I think these phenomena belong together, and with novel plasma dynamics we may be able to explain them


30 MARCH, 1969
OSO-5
COUNTS/SECOND
2x10^4
10^4
10^3
10^2
28-55 keV
3x10^3
10^3
10^2
10^1
82-111 keV
2x10^2
10^2
10^1
168-200 keV
6x10^1
10^1
10^0
225-254 keV
TYPE II
BURST.
35 40 45 50 55 5 10 15 20 25 30
0230U.T.
0300U.T.


SMM-GAMMA RAY
SPECTROMETER
1982 June 3
Counts per second
X-Ray (56-199 keV)
MCW
(4.1-6.4) MeV
HE-matrix (>25 MeV)
Sunset at Satellite ~1204 UT
Jungfraujoch-Neutron Monitor
% Deviation from Mean
(8798/min)
6
4
2
0
-2
11:40
11:50
12:00
Universal Time

SOL1969-03-30 HXR

- Coronal origin (by occultation)
- Hard spectrum, $J_\nu \alpha (h\nu)^{-2}$
- Low peak microwave frequency
- Association with type II/IV burst
- Drifting cm-wave source
- SEPs

- Un-imageable scale (*RHESSI*)
- CME association

SOL1982-06-03 γ-ray

- Very high energies (GeV)
- Pion decay radiation
- Long duration, up to hours
- Association with type II/IV burst
- Neutrons
- SEPs

- Coronal origin (*Fermi*)
- CME association

Two big mysteries:

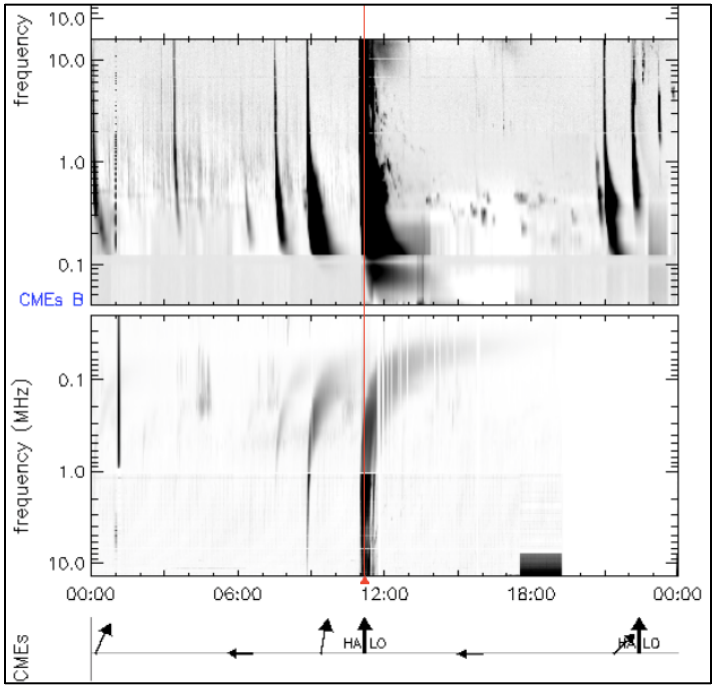
- What *are* these things? (Can't see them in AIA!)
- How can the GeV particles be related to the SEPs?

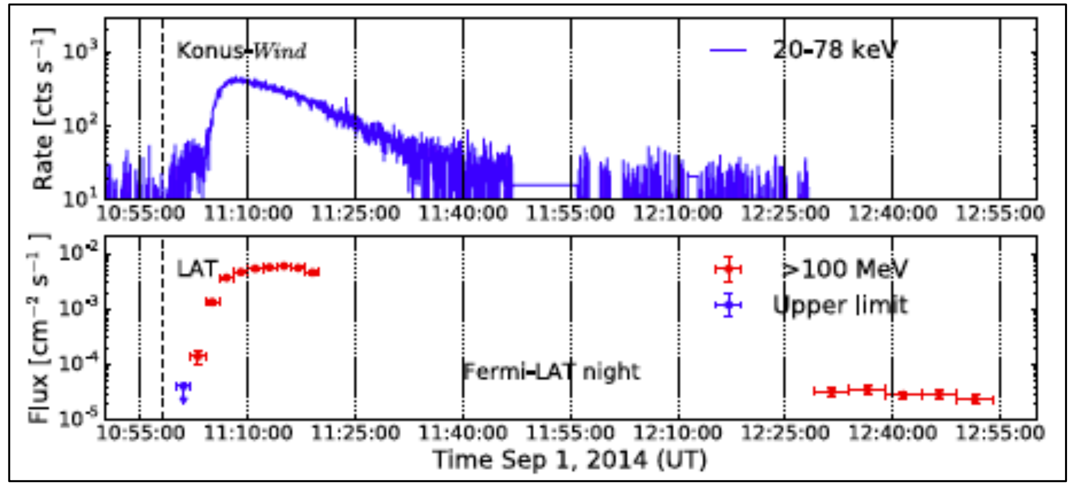
Frost-Dennis Events

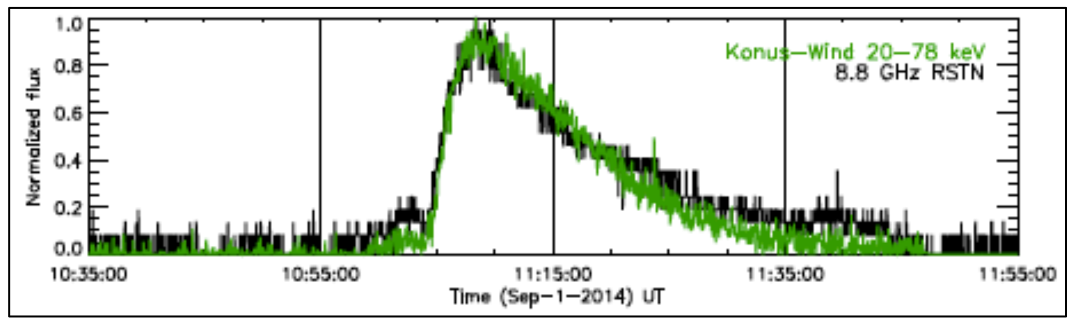
Event/GOES estimate	Microwaves	Hard X-rays
Pre-Fermi/LAT		
SOL1969-03-30T02:47 (???)	Yes	Yes
SOL1971-12-14T02:40 (???)	Yes	Yes
SOL1972-07-22T03:40 (???)	Yes	Yes
Fermi/LAT and STEREO		
SOL2013-10-11T07:01 (M4.9)	Yes	Yes
SOL2014-01-06T07:40 (X3.5)	Yes	Poor
SOL2014-09-01T11:00 (X2.1)	Yes	Yes

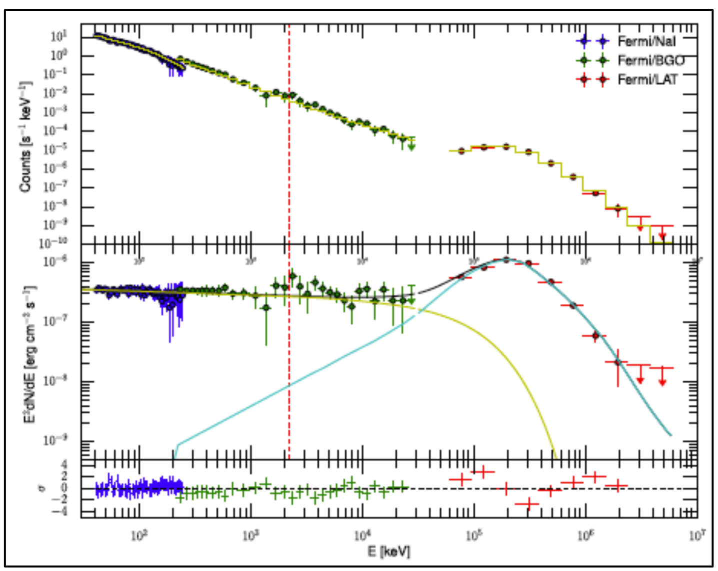
- Early (pre-Fermi) history: Cliver et al. 1986
- Fermi-era occulted events: Pesce-Rollins et al. ICRC 2015; Share et al. preprint 2017

SOL2014-09-01 (a recent archetype)









- Ackermann et al. 2017 overview paper
- N14E126 “X2.4”, Pesce-Rollins et al. 2015
- Height of sources > $R_\odot$
- CME, II, IV, pions, HXR, LDGRF..., exactly on prototype morphology

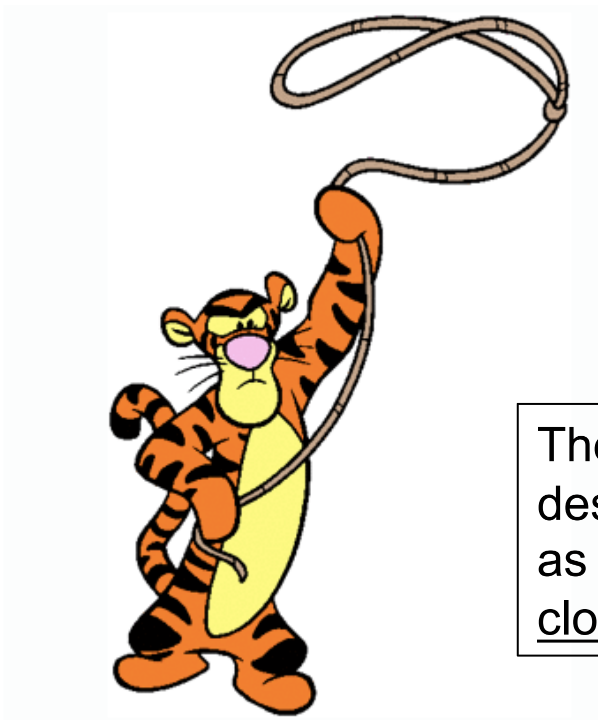
The loss-cone problem for SEPs

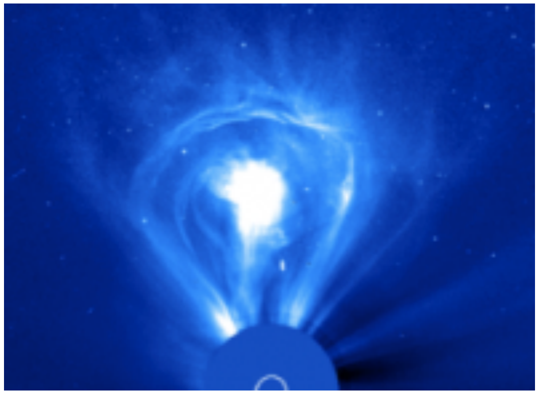
- The SEPs presumably come from CME-driven shock waves.

  - On open fields at 3 $R_\odot$, the particles would just go away and never interact to produce pions and γ-rays.

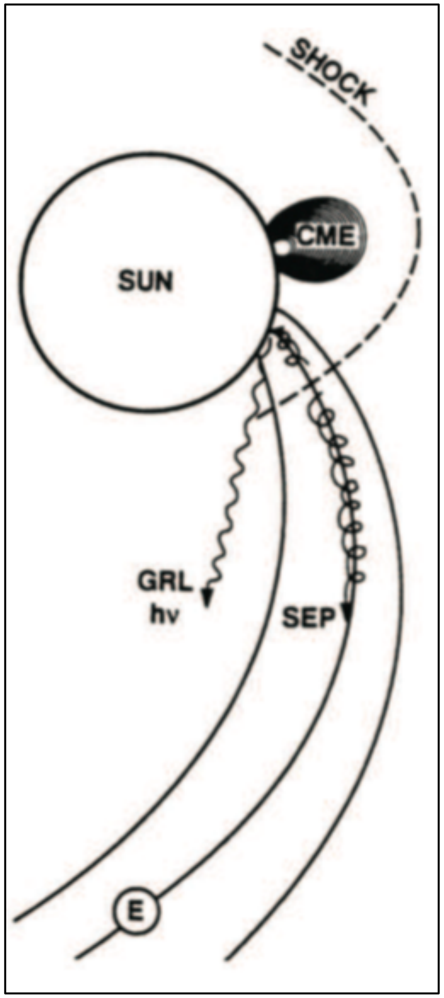
  - On closed fields, e.g. at 3 $R_\odot$, the loss cone is negligible (of order 10^{-3} sr), so the 1^{st} adiabatic invariant strongly prevents precipitation.
- These considerations do not readily fit the observations, interpreted as large fluxes of relativistic SEPs near the source active region on SGRE time scales

The “Lasso” model

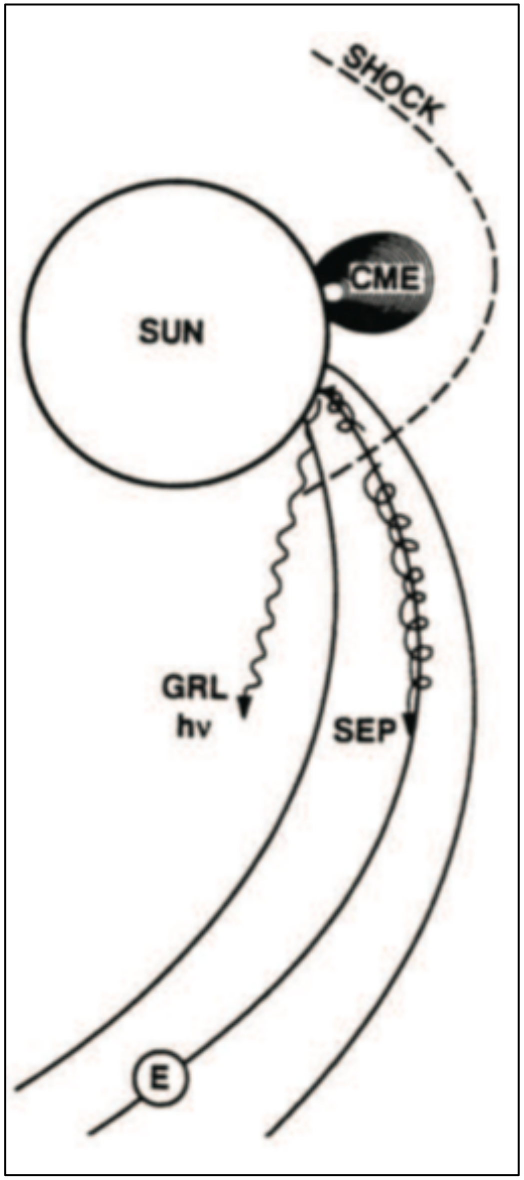




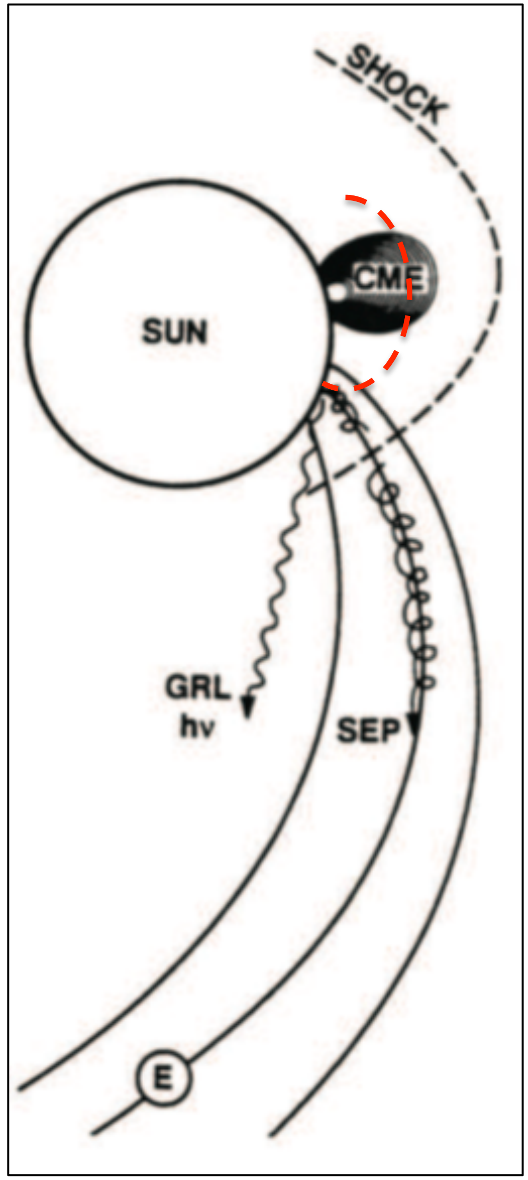
The Lasso model just describes the LDGRF protons as those SEPS corralled by <u>closed</u> coronal field.



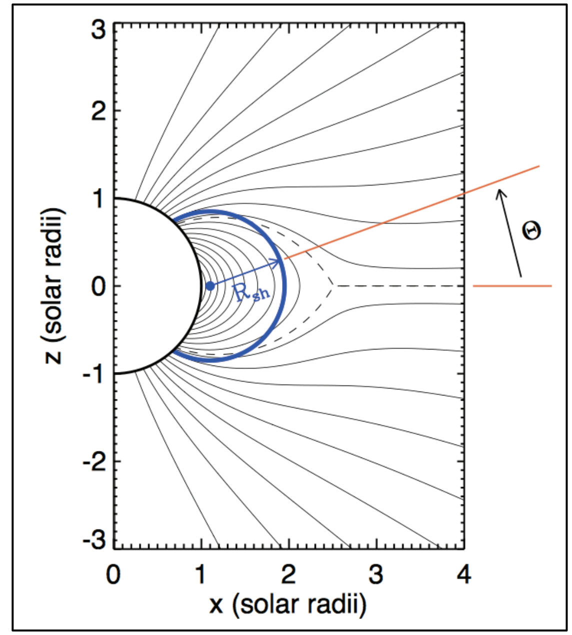
Cliver et al. (1993)



Cliver et al. (1993)



The Lasso tweak

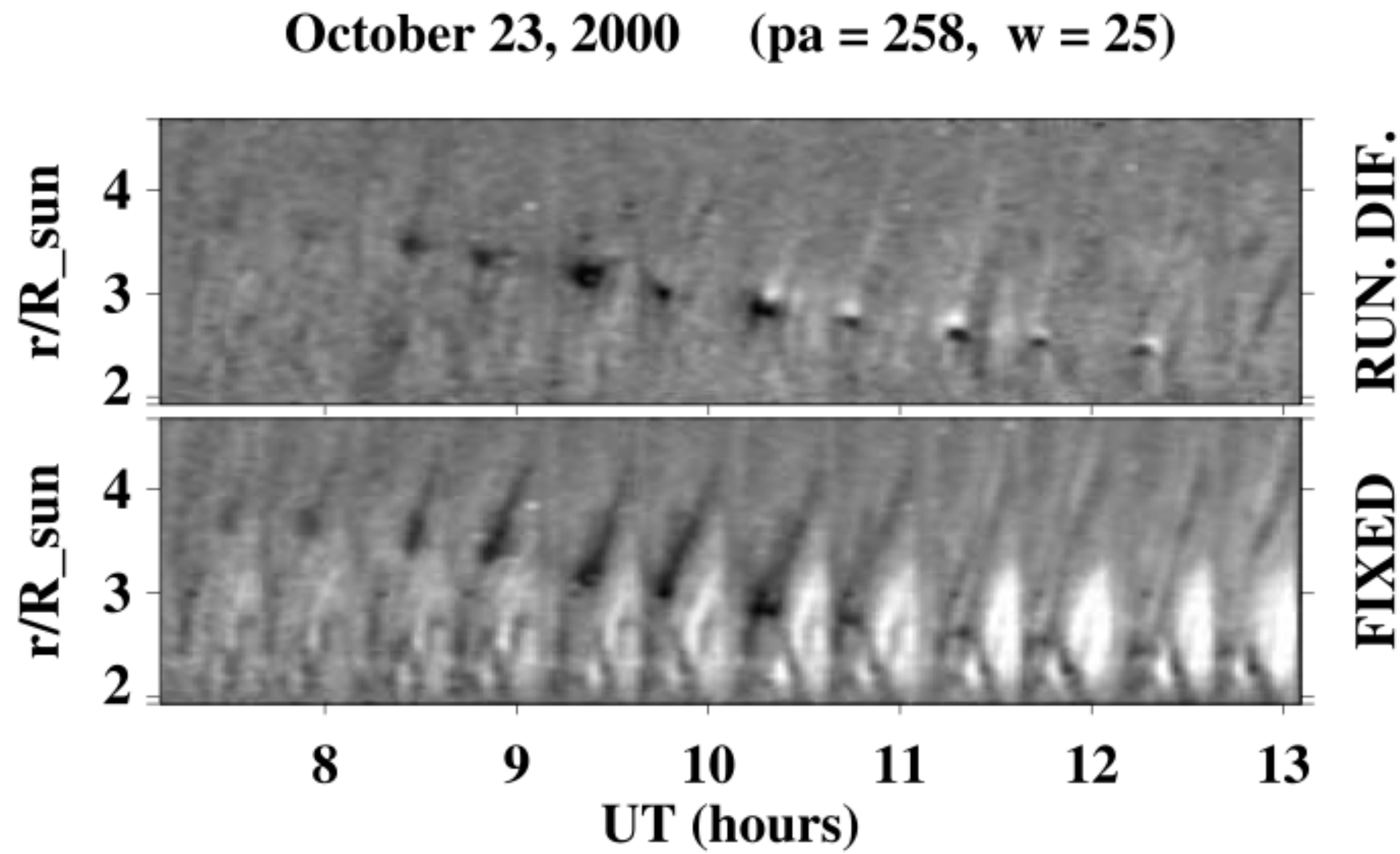


Kong et al. 2017

The Lasso model

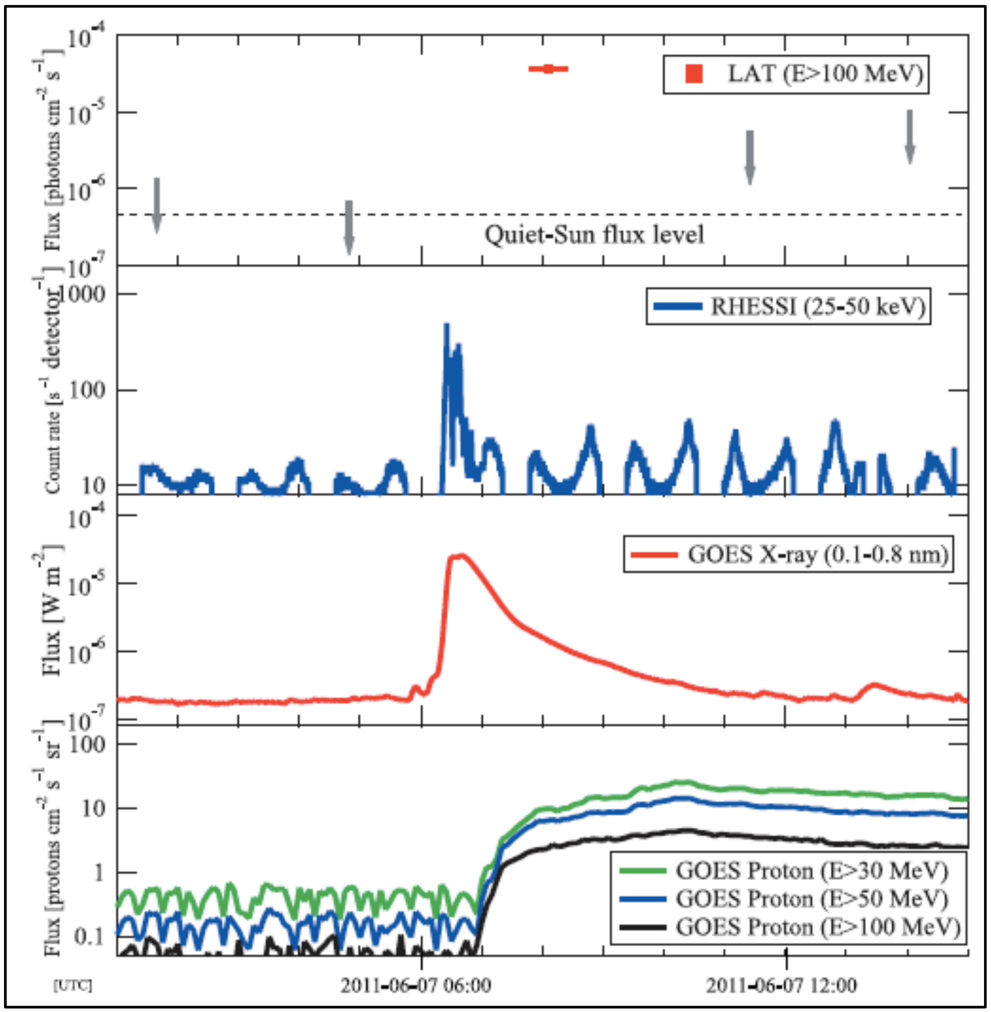
- Shock acceleration takes place in large closed-field structures (“loops”) ✓
- These then retract, leading to further (betatron and Fermi) acceleration ✓
- The restructuring gives better loss-cone access, leading to the observed radiations ?

Large-scale coronal loop retractions

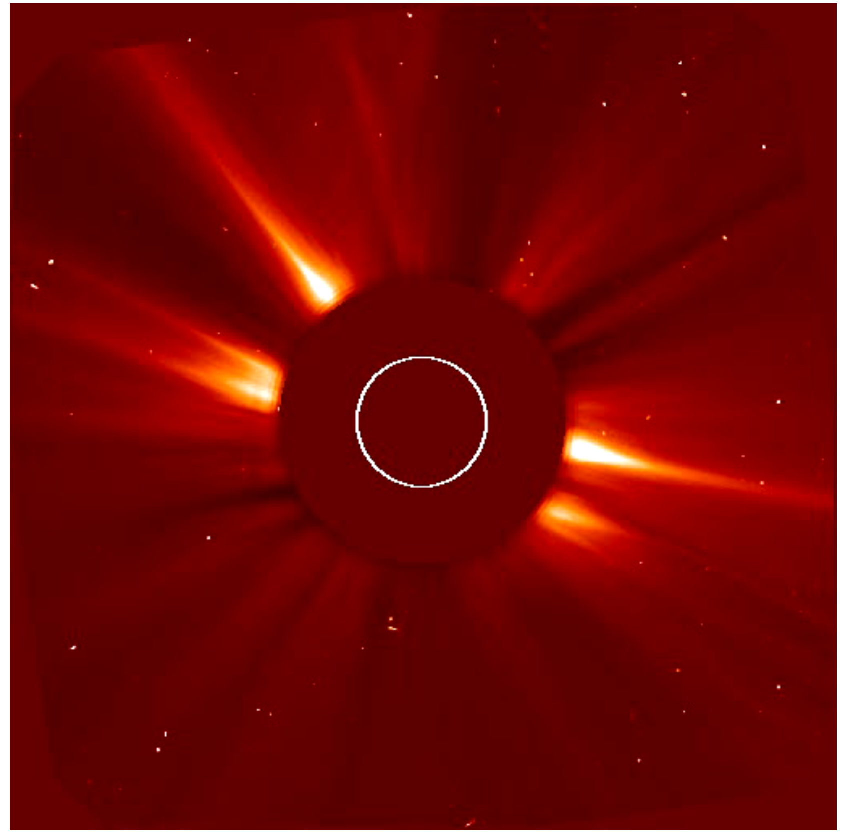


Sheeley et al. 2004

SOL2011-06-07 LDGRF



Ackermann et al. 2012



Note the image evidence for retracting fields following this LDGRF (SGRE)

Lasso model concerns I

- Is the CME/shock geometry realistic?
- Are the trapping time scales OK?
- How in the world do we relate the electron signatures to the ions?
- Are the Lasso model's "predictions" observable?

  - is a shock observed in a good geometry?

  - can we detect the retracting structures?

  - do we see consistent γ-ray centroid motions?

Lasso model concerns II

- Can we solve the loss-cone problem?

  - Extensive test-particle literature exists (Birn… Somov-Kosugi… Barta-Karlicky… *al. et* Neukirch)

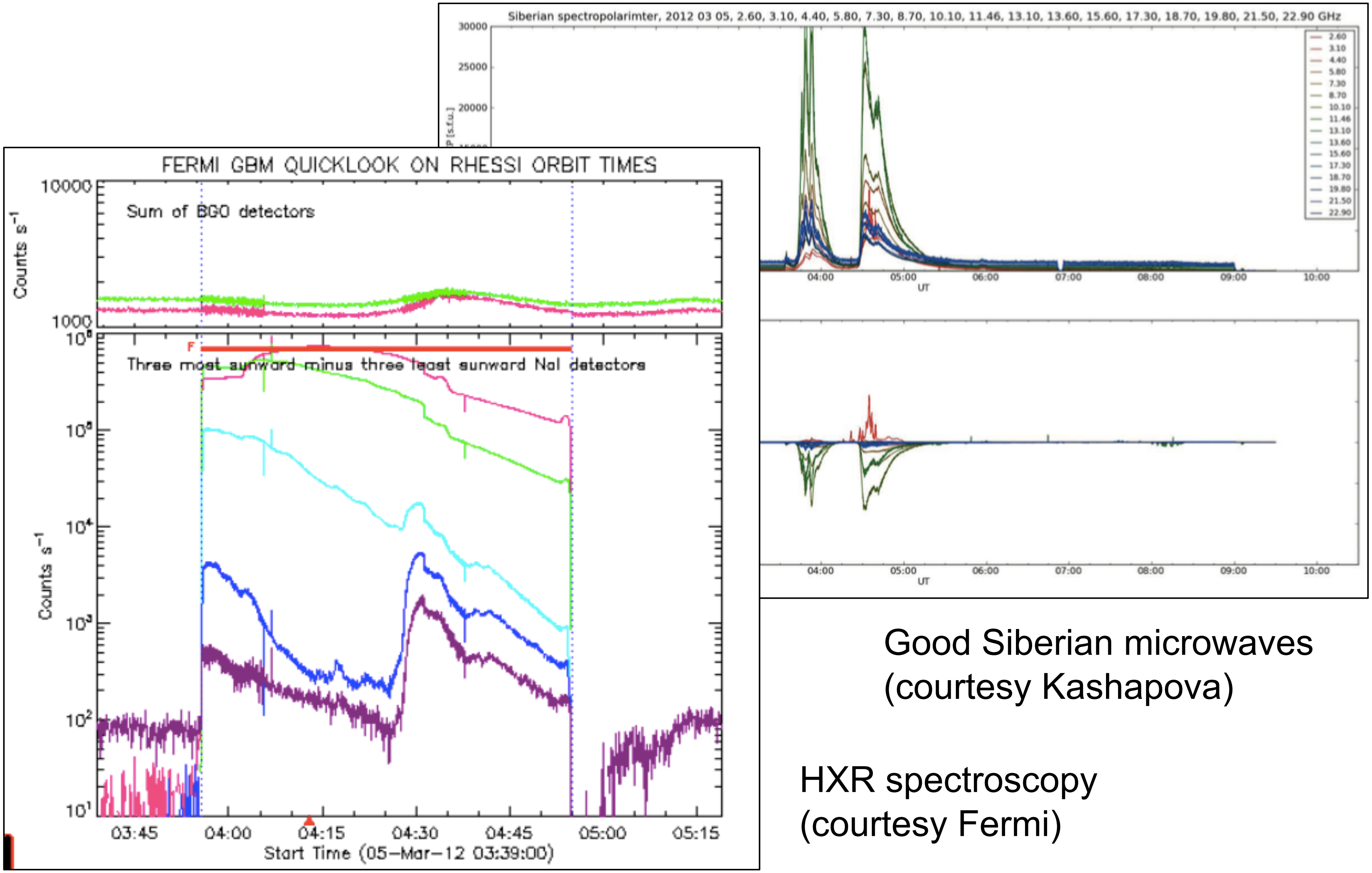
  - There is an interesting competition between betatron acceleration (v_{perp}) and Fermi acceleration ($v_{parallel}$)

  - Many other factors might intrude (MHD geometry, scattering, turbulence, non-thermal pressure)

- It seems possible that retraction can help with the loss-cone problem (Eradat Oskoui et al. 2014)

Microwaves and hard X-rays

SOL2012-03-05



Good Siberian microwaves (courtesy Kashapova)

HXR spectroscopy (courtesy Fermi)