Solar Coronal Events with Extended Hard X-ray and Gamma-ray Emission

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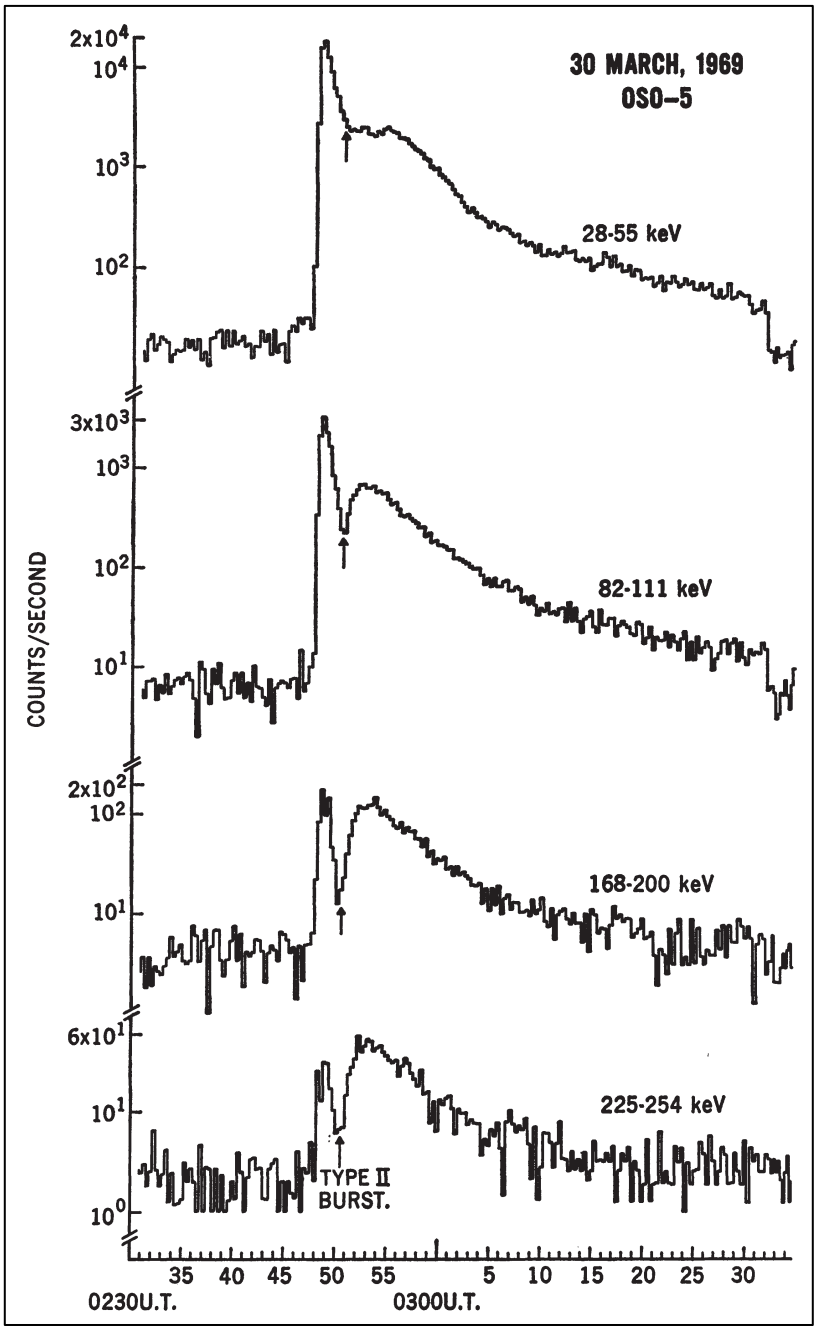
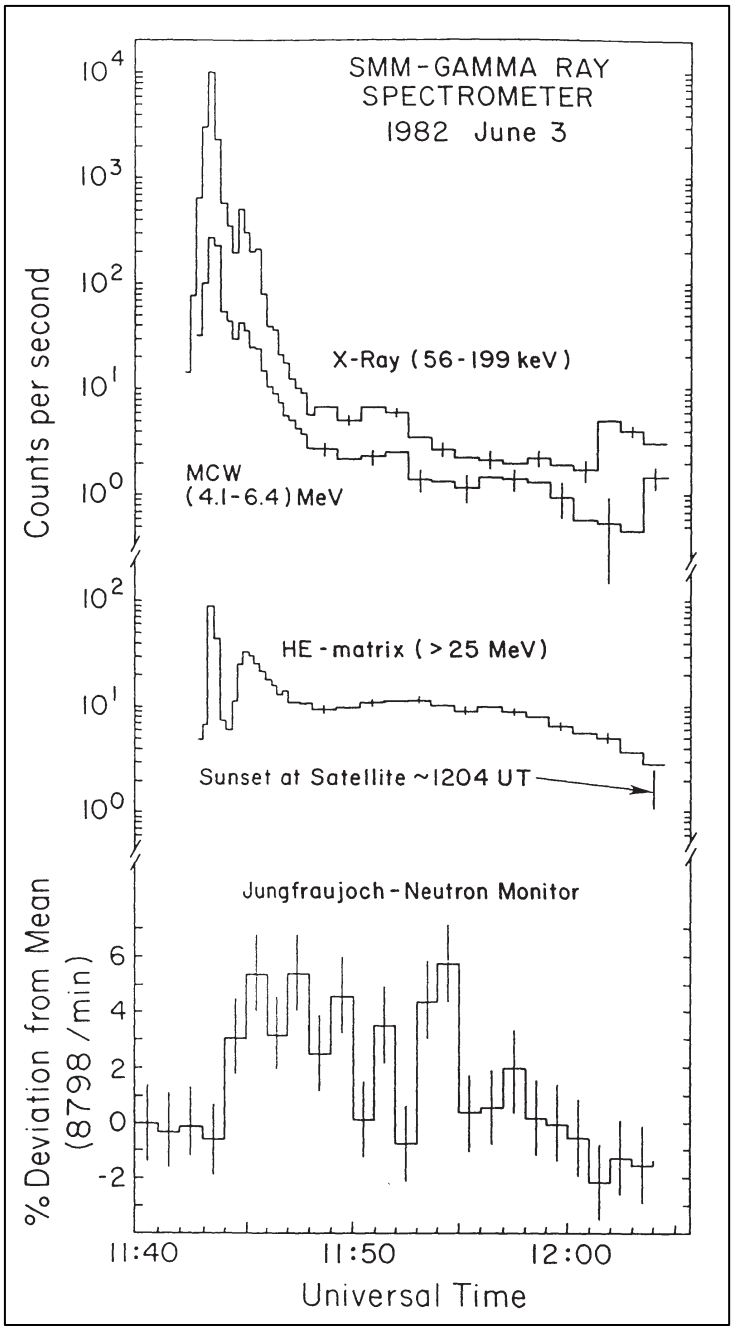
[*]With thanks to our ISSI team (MacKinnon, Vainio; see http://www.issibern.ch/teams/elucompofsolflare/

Mid-coronal Disturbances associated with CME flares

- Coronal HXR events, SOL1969-03-30 (Frost & Dennis, 1971; Enome et al. 1971)
- “Sustained” 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
28-55 keV
82-111 keV
168-200 keV
225-254 keV
TYPE II
BURST.
COUNTS/SECOND
0230U.T.
0300U.T.


SMM-GAMMA RAY
SPECTROMETER
1982 June 3
X-Ray (56-199 keV)
MCW
(4.1-6.4) MeV
HE-matrix (>25 MeV)
Sunset at Satellite ~1204 UT
Jungfraujoch-Neutron Monitor
Counts per second
% Deviation from Mean
(8798/min)
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:

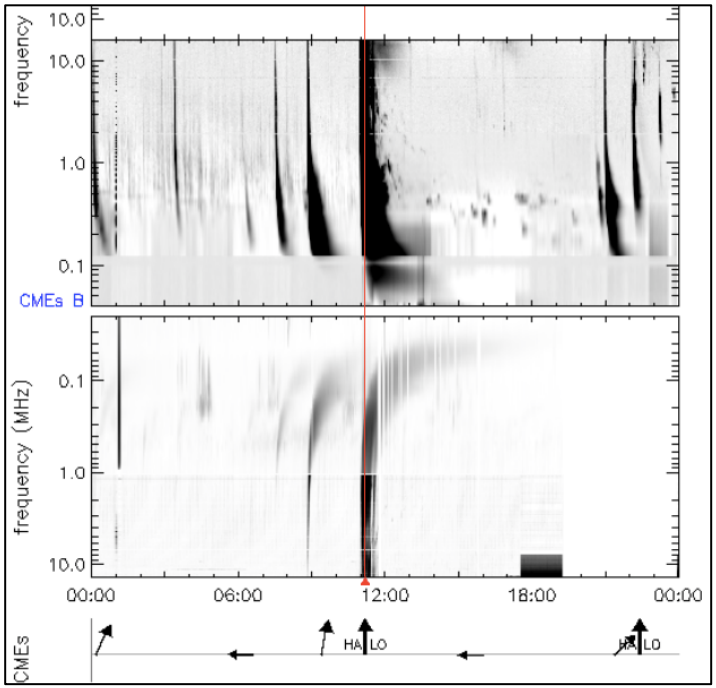
- What *are* these things? (Can't see them in AIA!)
- How can the GeV particles be related to the SEPs?

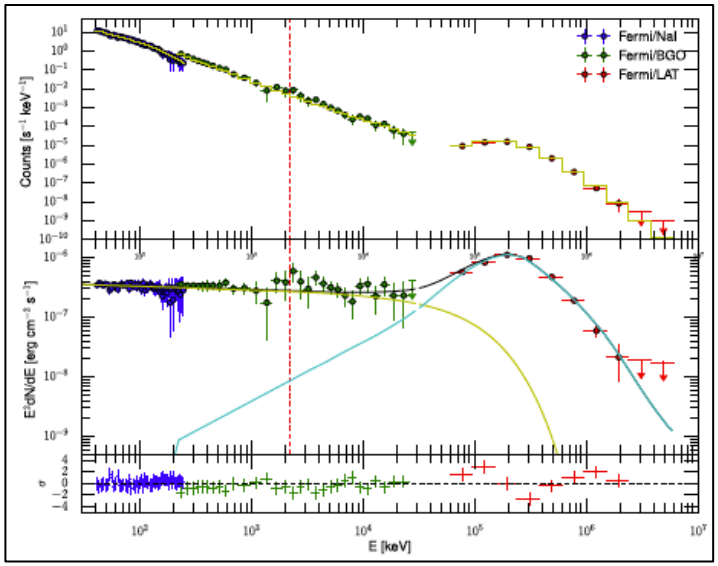
Frost-Dennis Events

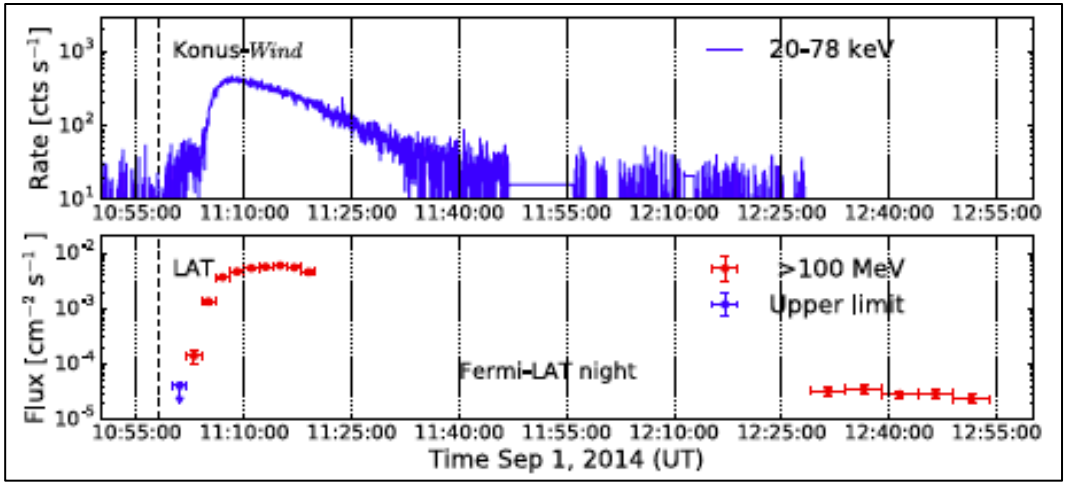
Event/GOES estimate	Microwaves	Hard X-rays
Pre-Fermi/LAT		
SOL1969-03-30T02:47 (???)	Yes	Yes
SOL1971-12-14T02:40 (???)	Yes	Yes
SOL1972-07-22T03:40 (???)	Yes	Yes
Fermi/LAT and STEREO		
SOL2013-10-11T07:01 (M4.9)	Yes	Yes
SOL2014-01-06T07:40 (X3.5)	Yes	Poor
SOL2014-09-01T11:00 (X2.1)	Yes	Yes

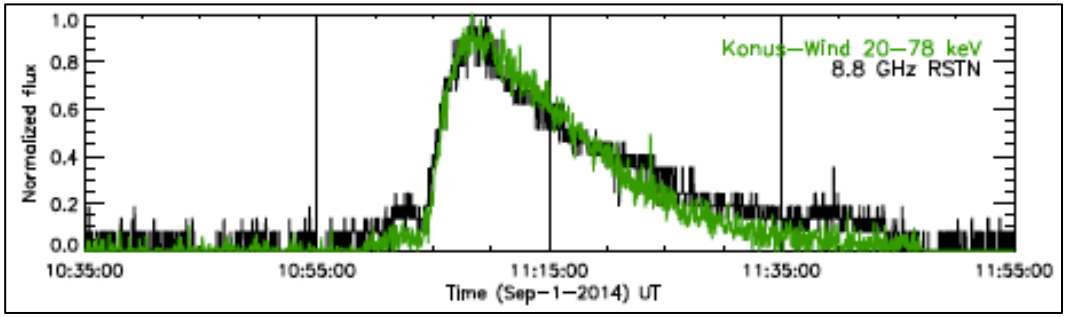
- Early (pre-Fermi) history: Cliver et al. 1986
- Fermi-era occulted events: Pesce-Rollins et al. ICRC 2015
  Share et al. preprint 2017

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.

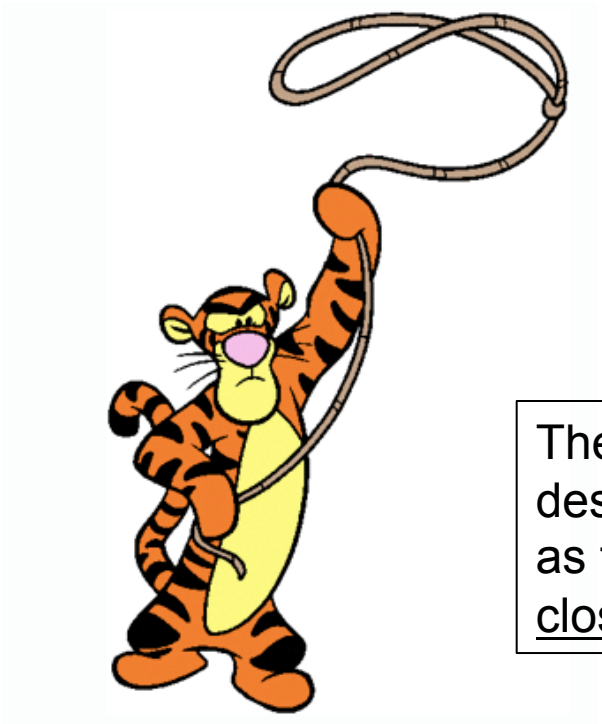
  - On closed fields, e.g. at 3 $R_\odot$, the loss cone is negligible (of order 10^{-3} sr), so the 1st adiabatic invariant strongly prevents precipitation.

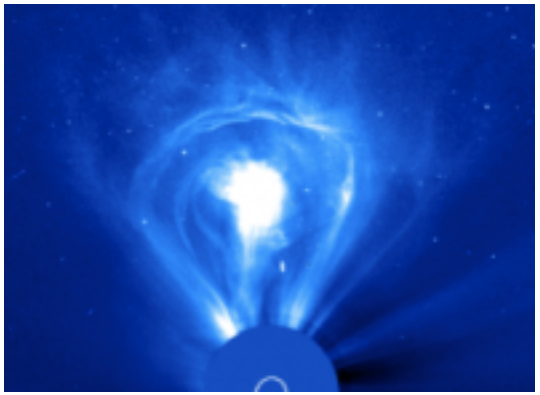
- These considerations do not readily fit the observations, interpreted as large fluxes of relativistic SEPs near the source active region on SGRE time scales

The Kelvin Force

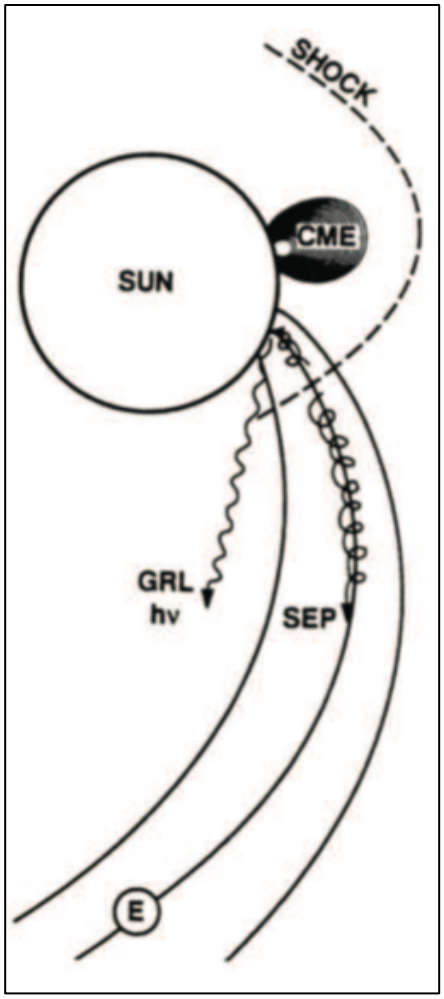
- L. Kocharov et al. (1996) quote: “…the effect of focusing of energetic particles is always essential as compared with scattering, no matter how small the value of the mean free path…”
- The Parker equation for cosmic-ray transport incorporates the focusing term, which must not be neglected
- K. Shibasaki, in preparation 2017: this “Kelvin force” is not commonly incorporated in MHD

The “Lasso” model

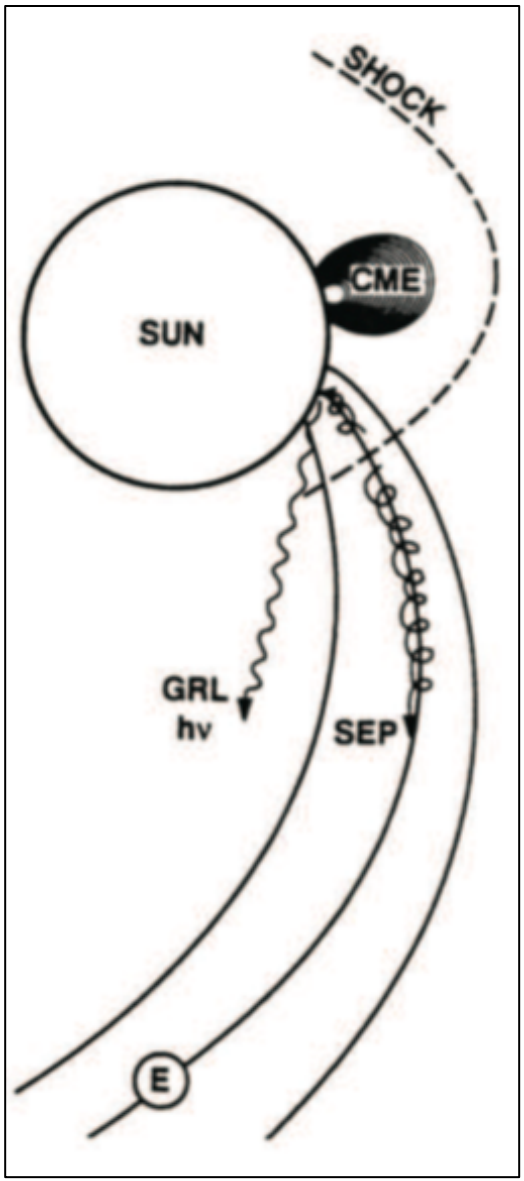




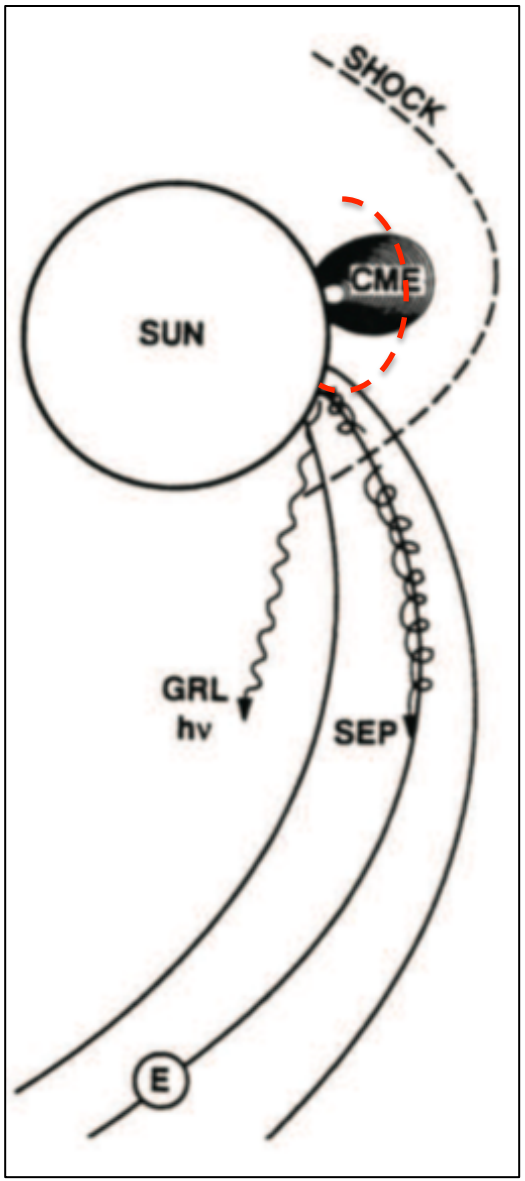
The Lasso model just describes the LDGRF protons as those SEPS corralled by closed coronal field.



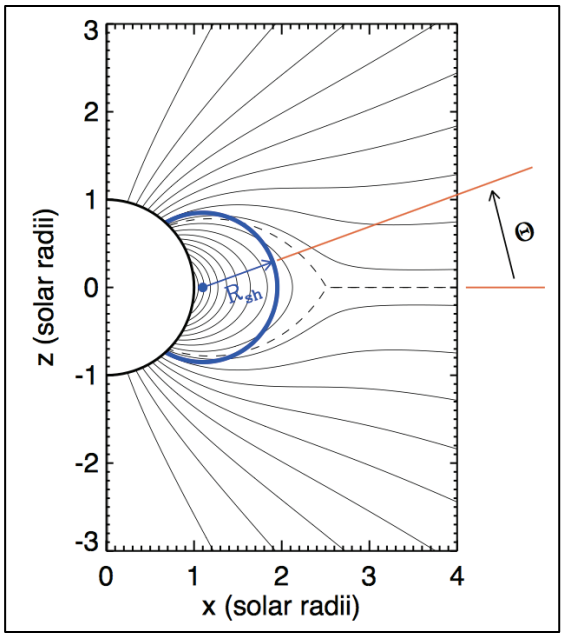
Cliver et al. (1993)



Cliver et al. (1993)



The Lasso tweak

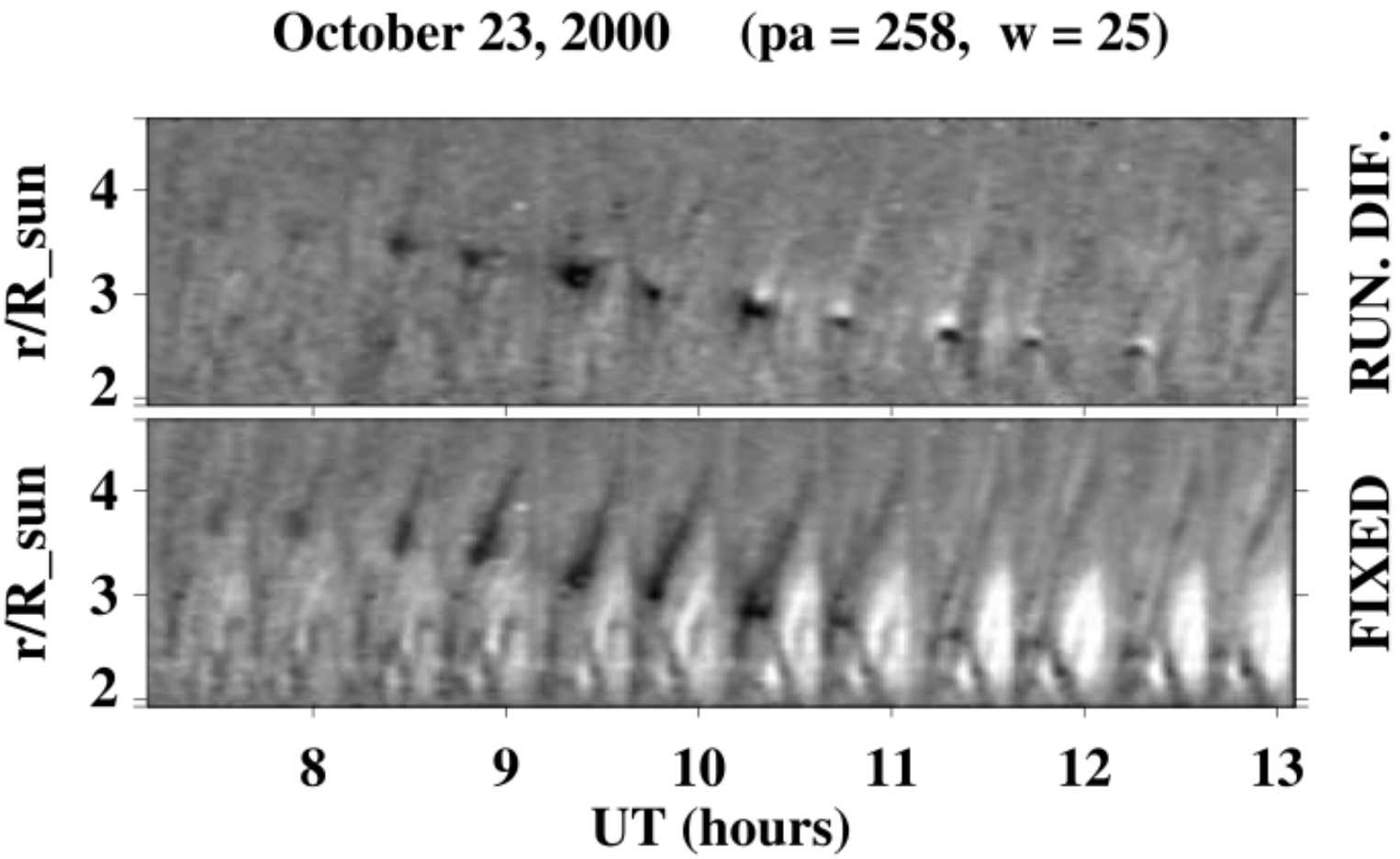


Kong et al. 2017

The Lasso model

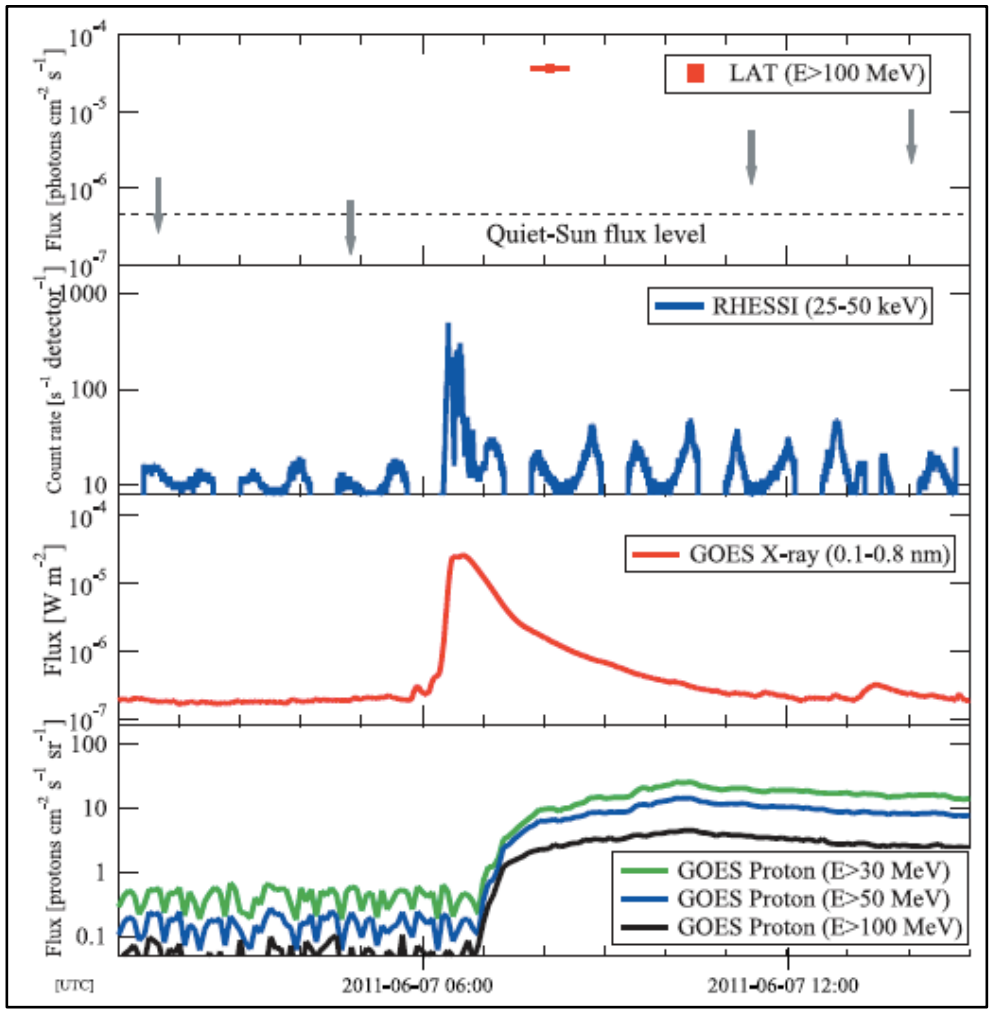
- Shock acceleration takes place in large closed-field structures (“loops”) ✓
- These then retract, leading to further (betatron and Fermi) acceleration ✓
- The restructuring gives better loss-cone access, leading to the observed radiations ?

Large-scale coronal loop retractions

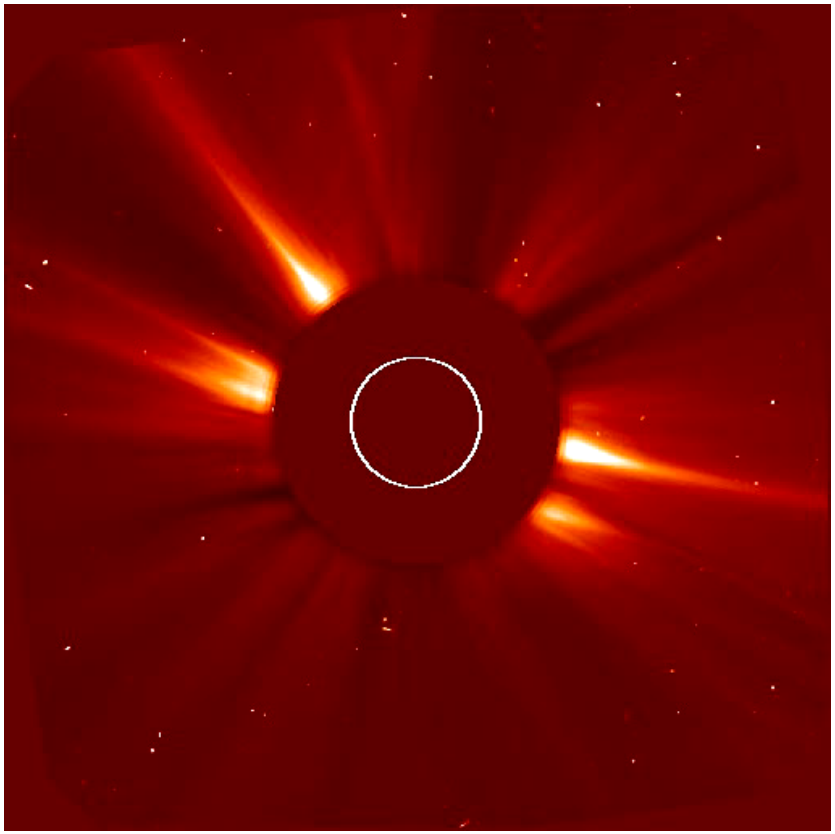


Sheeley et al. 2004

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)

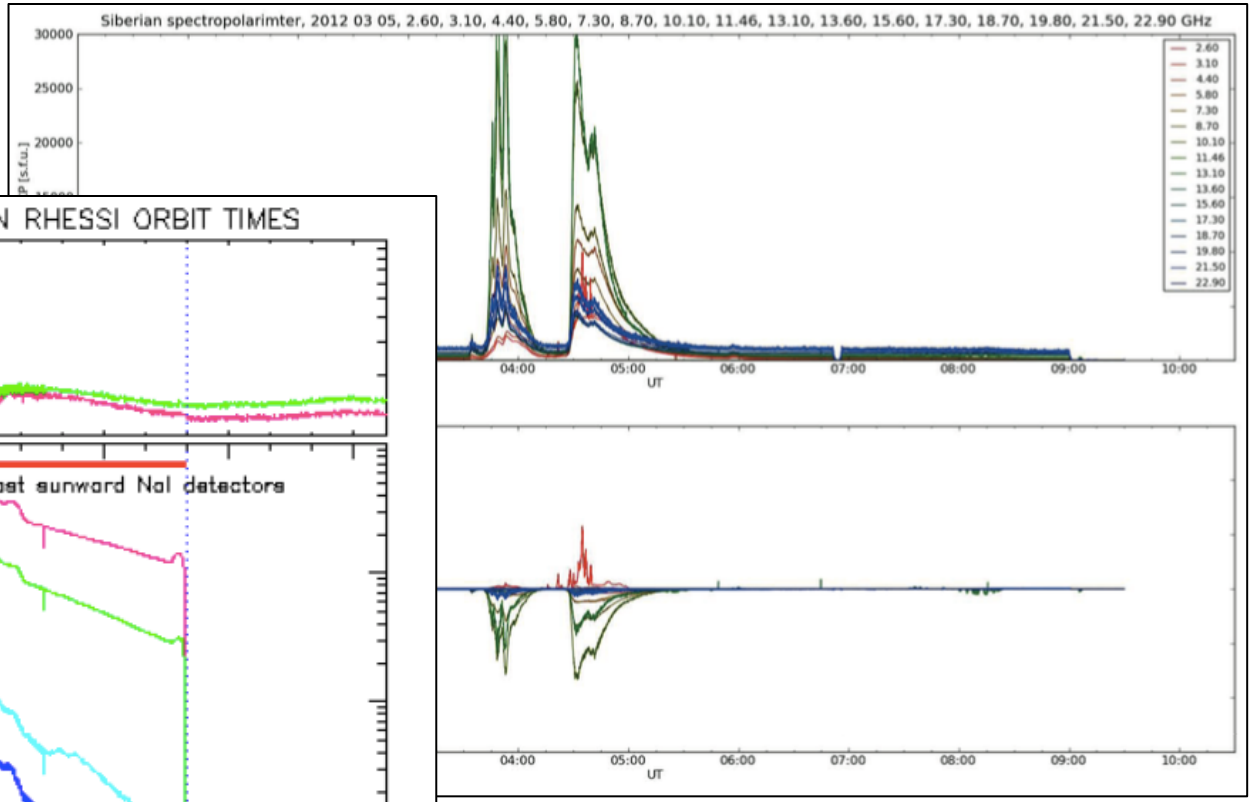
  - There is an interesting competition between betatron acceleration (v_{perp}) and Fermi acceleration ($v_{parallel}$)

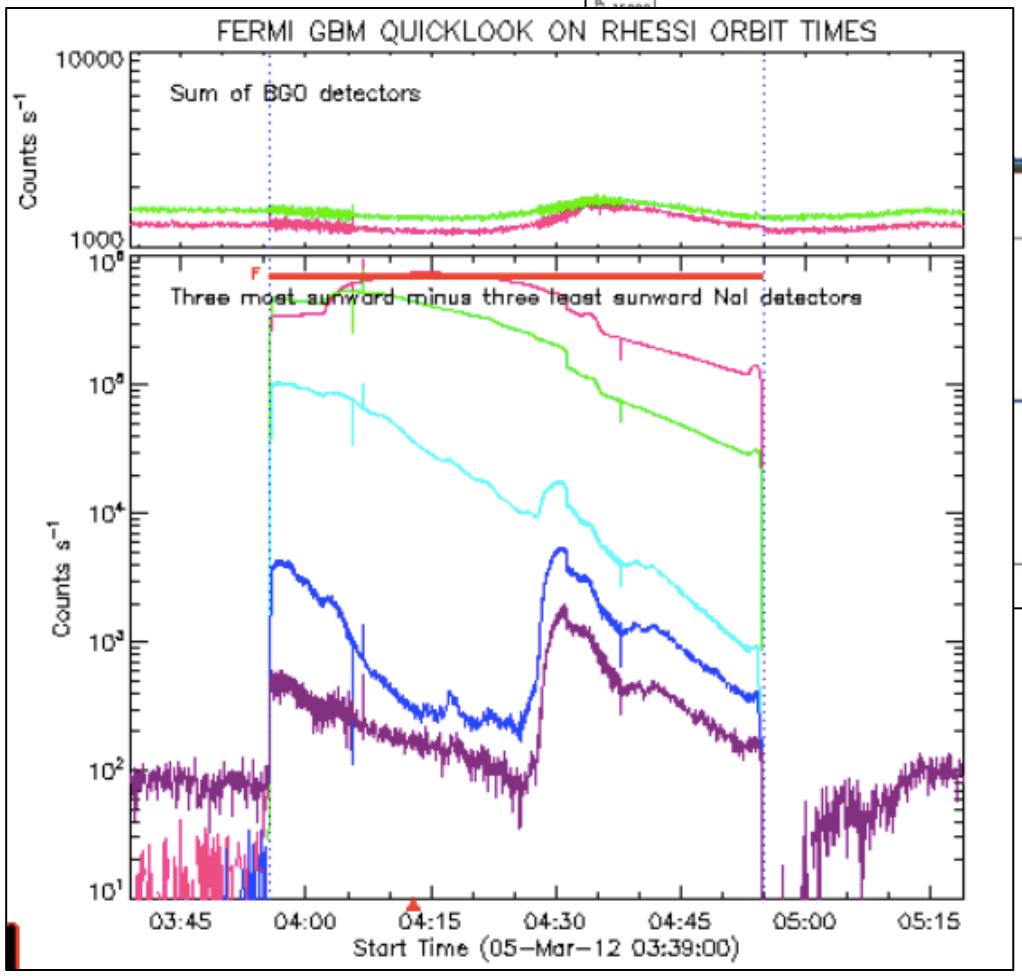
  - Many other factors might intrude (MHD geometry, scattering, turbulence, non-thermal pressure)

- 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)