Examining the Connection between Solar Energetic Particles and Long-Duration Gamma-ray Flares

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On behalf of the PAMELA Collaboration

Introduction : Long Duration Gamma-ray Flares

* LDGRFs (Ryan 2000)
  >50 MeV γ-ray emission often with durations > several hrs).

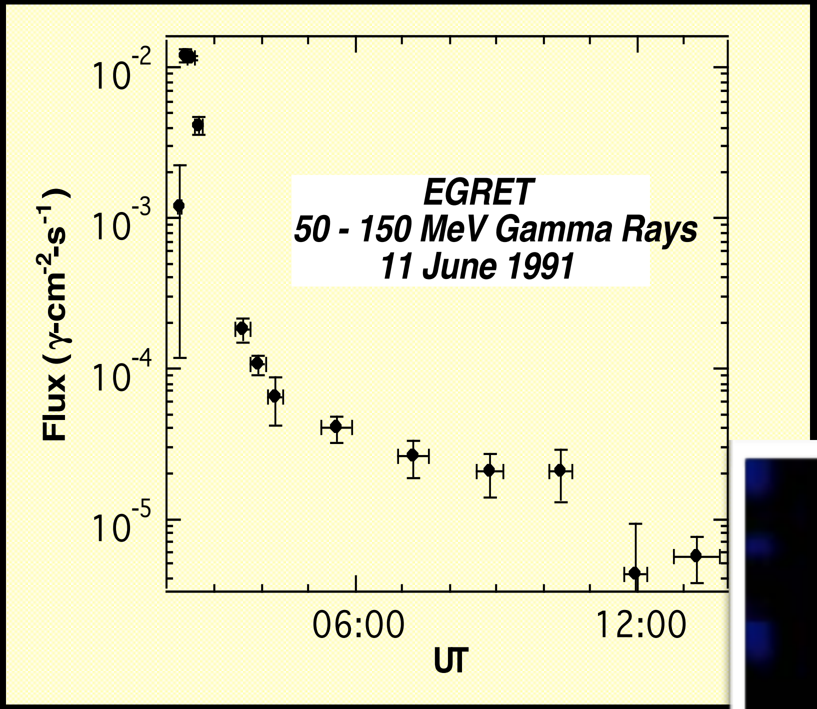
* Detection of dozens of LDGRFs with SMM and CGRO, some with LDGRF (see reviews of Chupp & Ryan 2009, Vilmer et al. 2011).

* Spectrum often > 1 GeV

* Delays many minutes after HXR and μ-wave

* Continues while other emission has ceased

* Associated with CMEs, Type II & III radio emission, & SEPs



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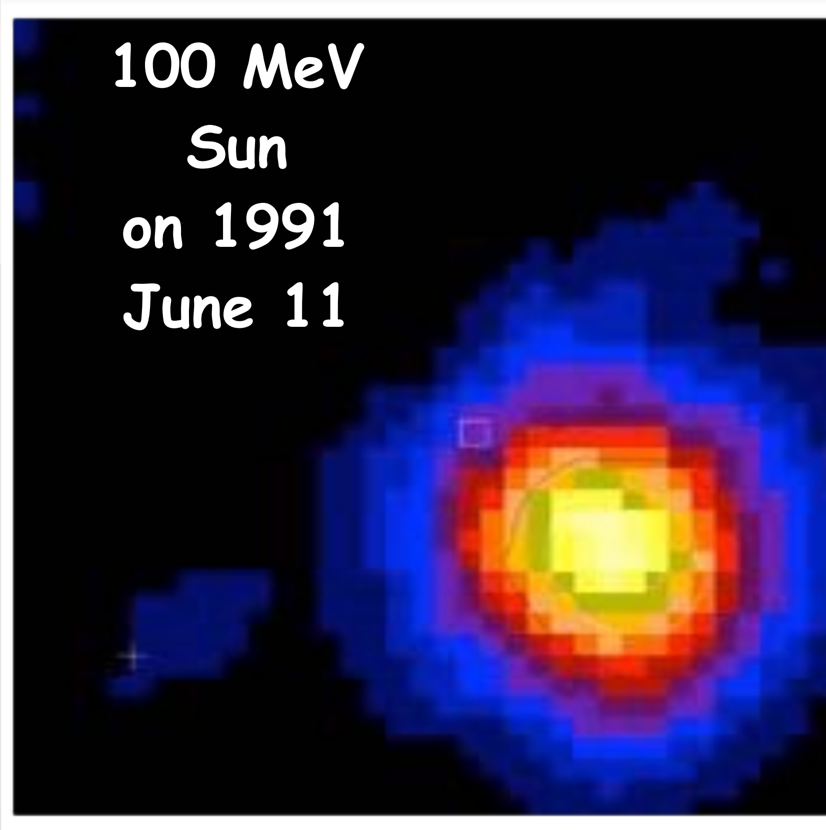


8 hour exposure starting 90 minutes after the flare

The origin is still unknown & the challenge to theory is to explain the extreme energies & long durations !

γ-ray Production

High-energy gamma-ray emission (>100 MeV) is thought to originate primarily from the decay of pions, produced by protons (and alphas) above ~300 MeV (above ~200 MeV).

$$\left.\begin{array}{l} p + {}^{4}He \rightarrow X + \pi^{\pm} \\ p + p \rightarrow X + \pi^{\pm} \end{array}\right\} \rightarrow \text{Bremsstrahlung and annihilation radiation}$$

or π^0

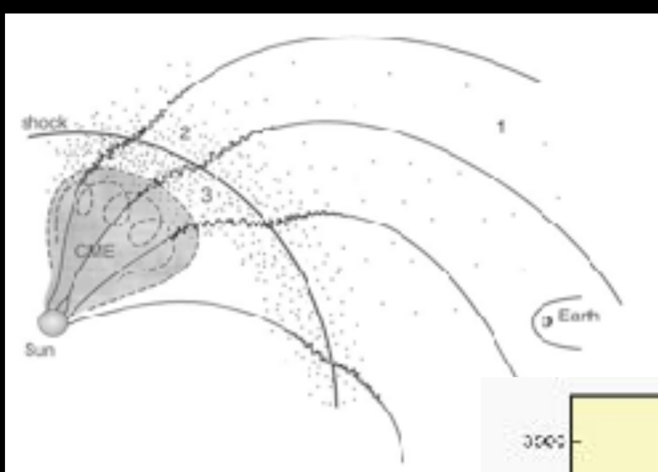
Doppler Broadened 69 MeV γ

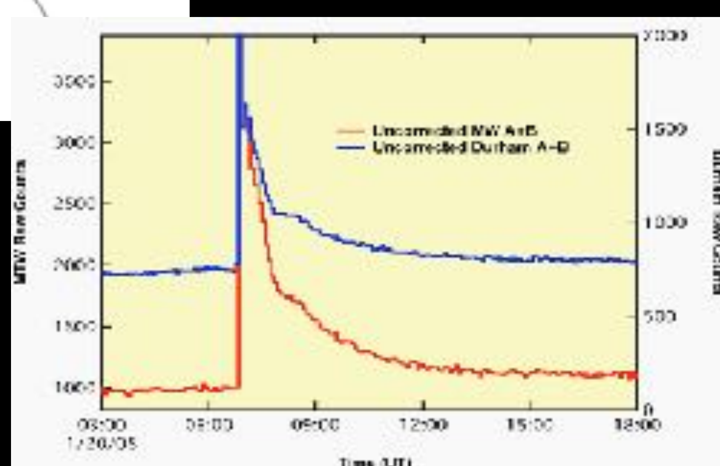
Two Competing Scenarios

CME back-precipitation Scenario

— Attributed to CME-shock-accelerated protons that make their way back to the photosphere (local).

[Cliver et al. 1993; Kocharov et al. 2015]

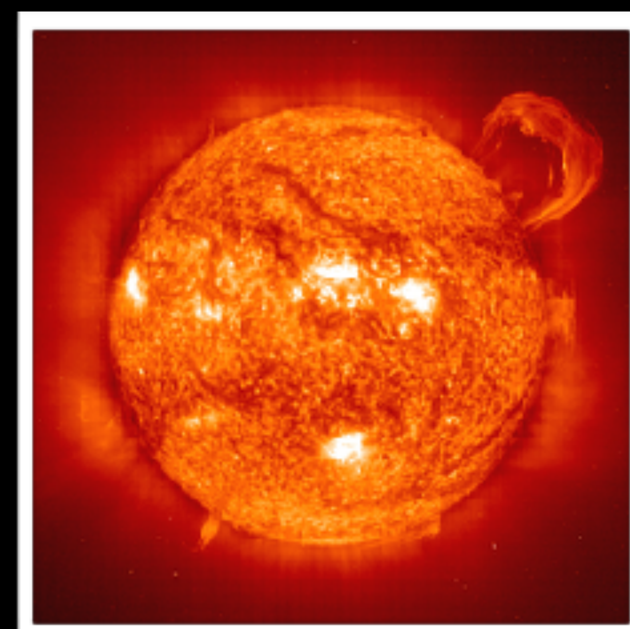


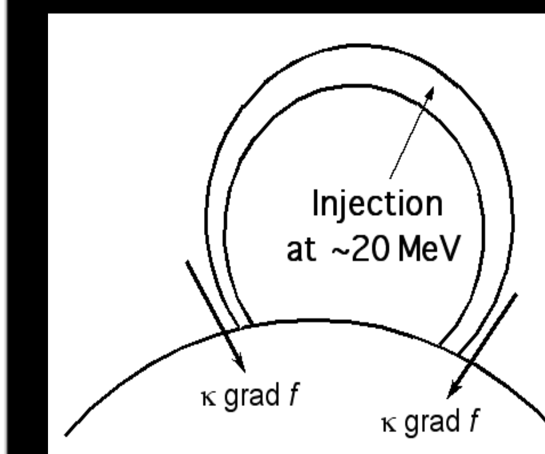


Trapping & continuously accelerated in Large Coronal Loops

Consider injection & acceleration of particles along large coronal loops (precipitating in the photosphere) where pitch-angle scattering from magnetic turbulence may serve to further accelerate the particles (remote).

[Chupp & Ryan 2009; Ryan & Lee 1991; Mandzhadivze & Ramaty 1992]





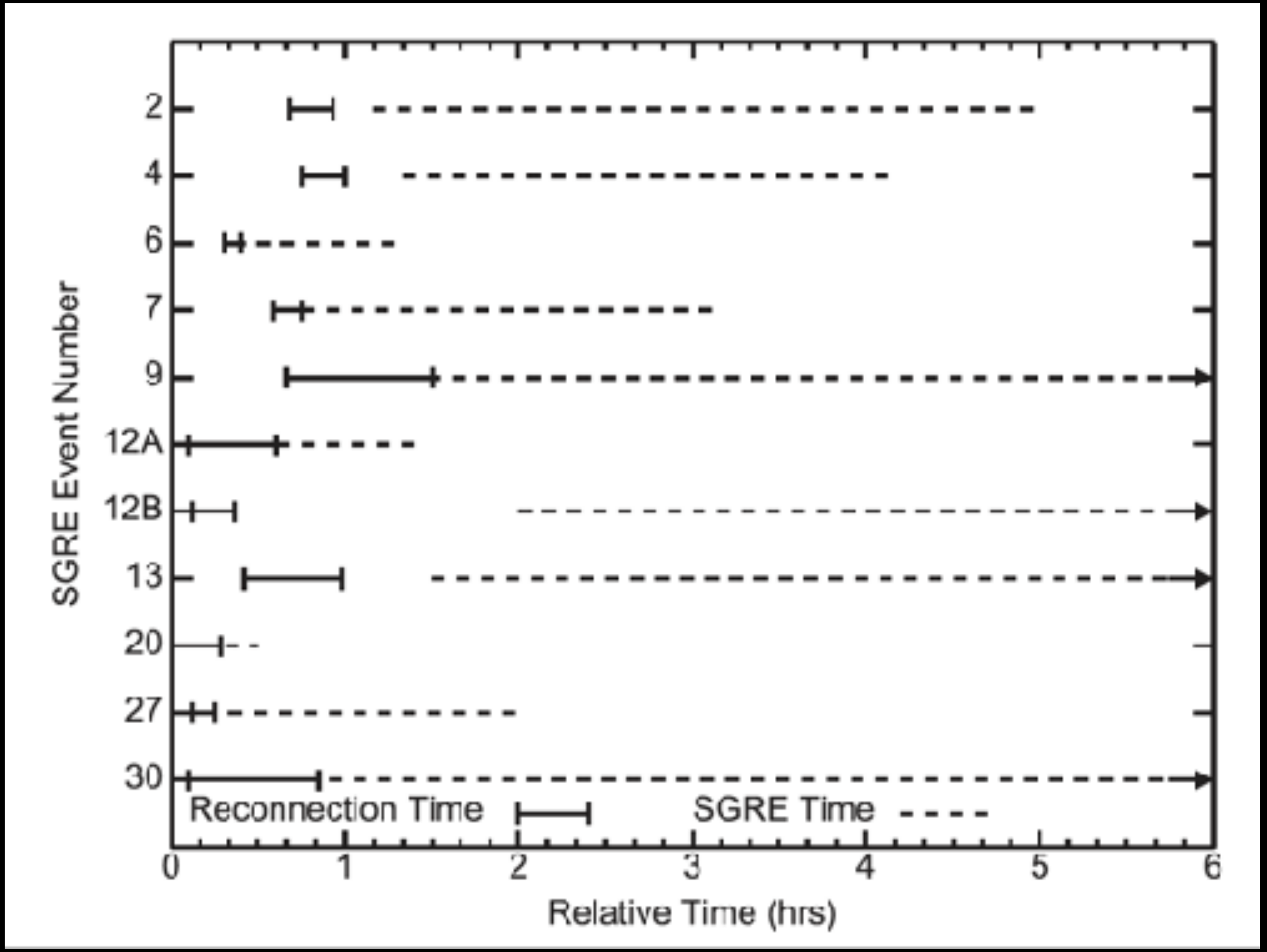
Protons obey spatial and momentum diffusion (second order Fermi)

$$\frac{\partial f}{\partial t} = \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D \frac{\partial f}{\partial p}\right) + \frac{\partial}{\partial x}\left(\kappa \frac{\partial f}{\partial x}\right) + Q$$

⇒ both models have supporting observations

Other Scenarios

Particle acceleration in reconnection electric fields in AR flare loops formed behind the CME (Ryan 2000). Although recently Kahler et al. (2018) showed that the AR magnetic arcade formation is terminated well before the extended periods of LDGRFs. Also this model does not account for spatially extended emission associated with behind-the-limb events.



Kahler et al. 2018

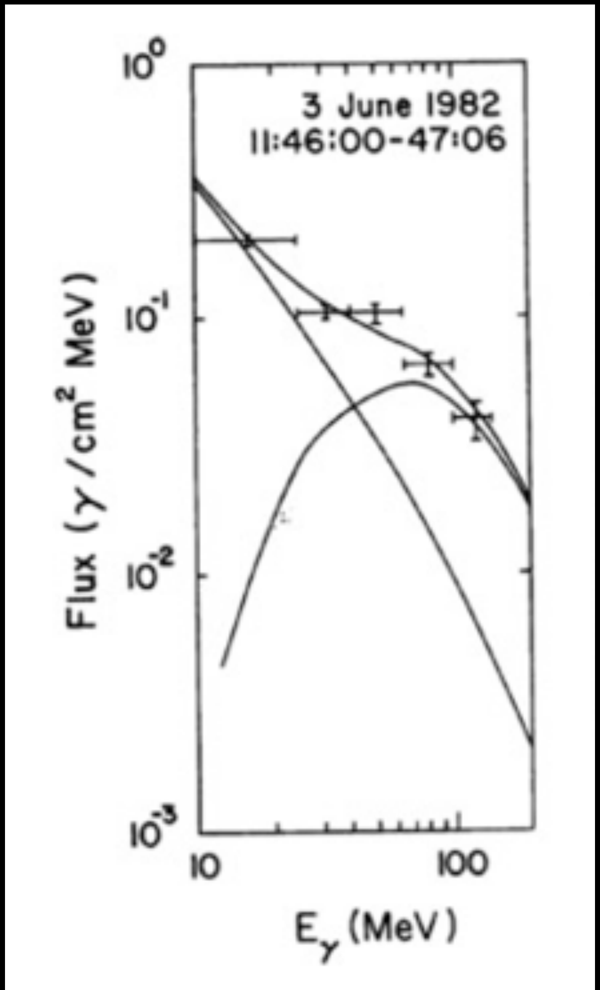
Hudson (2018) proposed a "lasso" model in which acceleration occurs along open and closed magnetic field lines through a protracted loop structure (maybe out to several Rs that transports particles to the chromosphere/photosphere as it retracts (e.g., post CME inward flows). See hints of such an inflow w/ the 2014 Sept. 1 behind-the-limb event.

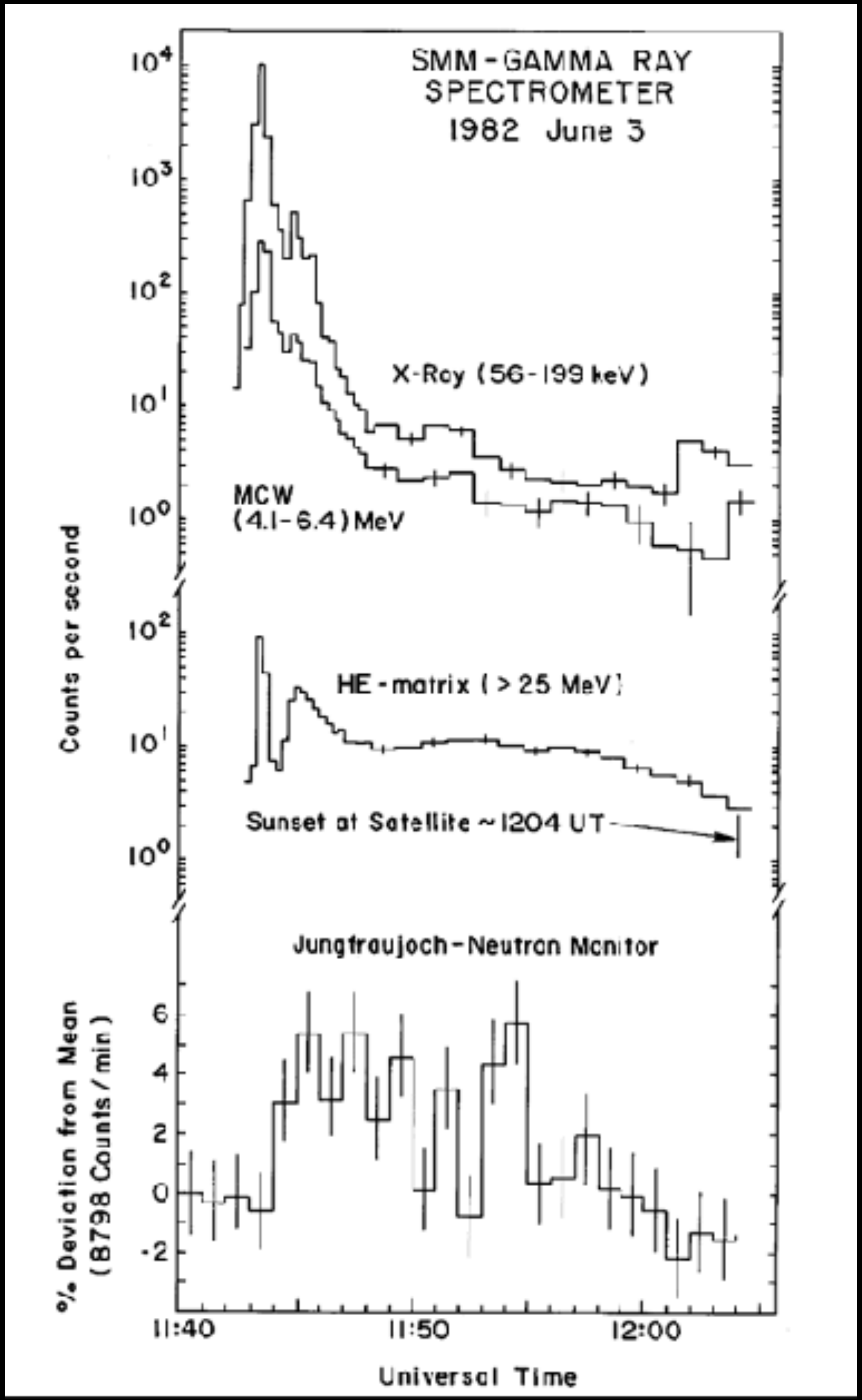
Historical Perspective of Long Duration Gamma-ray Flares

- First observed on 1982 June 3 with the Solar Maximum Mission satellite (0.3-100 MeV) associated with X8.0 class flare (Chupp et al. 1987).

- *Impulsive flare lasted ~1 min followed by an extended phase lasting ~15 min with a harder energy spectrum suggestive of pion decay.*

- This event was associated with fast CME and type II radio emission suggesting connection with the acceleration of SEPs (Ramaty et al. 1987).



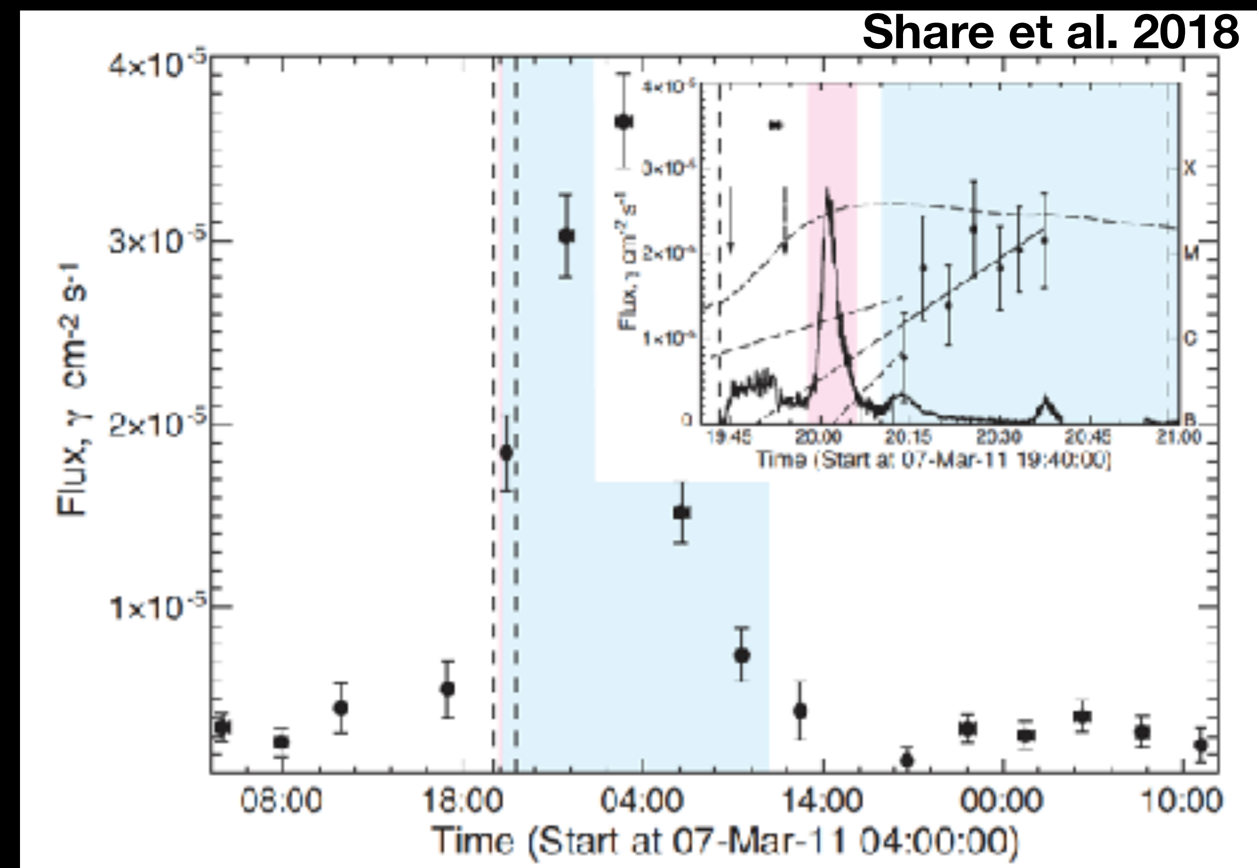


Fermi/LAT Observations of Long Duration Gamma-ray Flares

New opportunities to investigate LDGRFs with Fermi/LAT : Dozens of LDRGFs (or SGRE) observed from 2008 to 2016 (Share et al. 2017; Ackermann et al. 2014).

Already a number of important constraints to add to a growing picture:

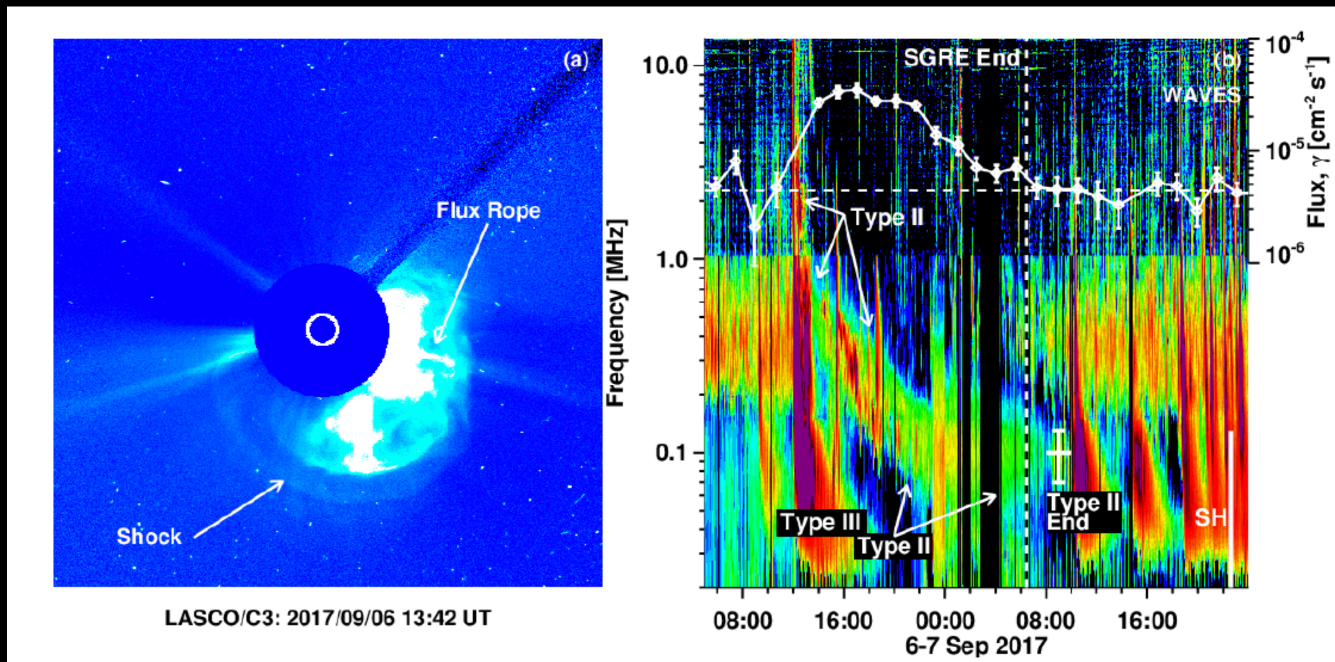
- **spectra consistent with the production from the decay of neutral and charged pions**
- **temporally distinct from impulsive phase, with smooth exponential decay**
- **highly correlated with impulsive HXR**
- **More (x10) fluence in delayed than impulsive phase**
- **somewhat spatially extended emission**
- **strong association with CMEs, Type II & III radio emission and SEPs**

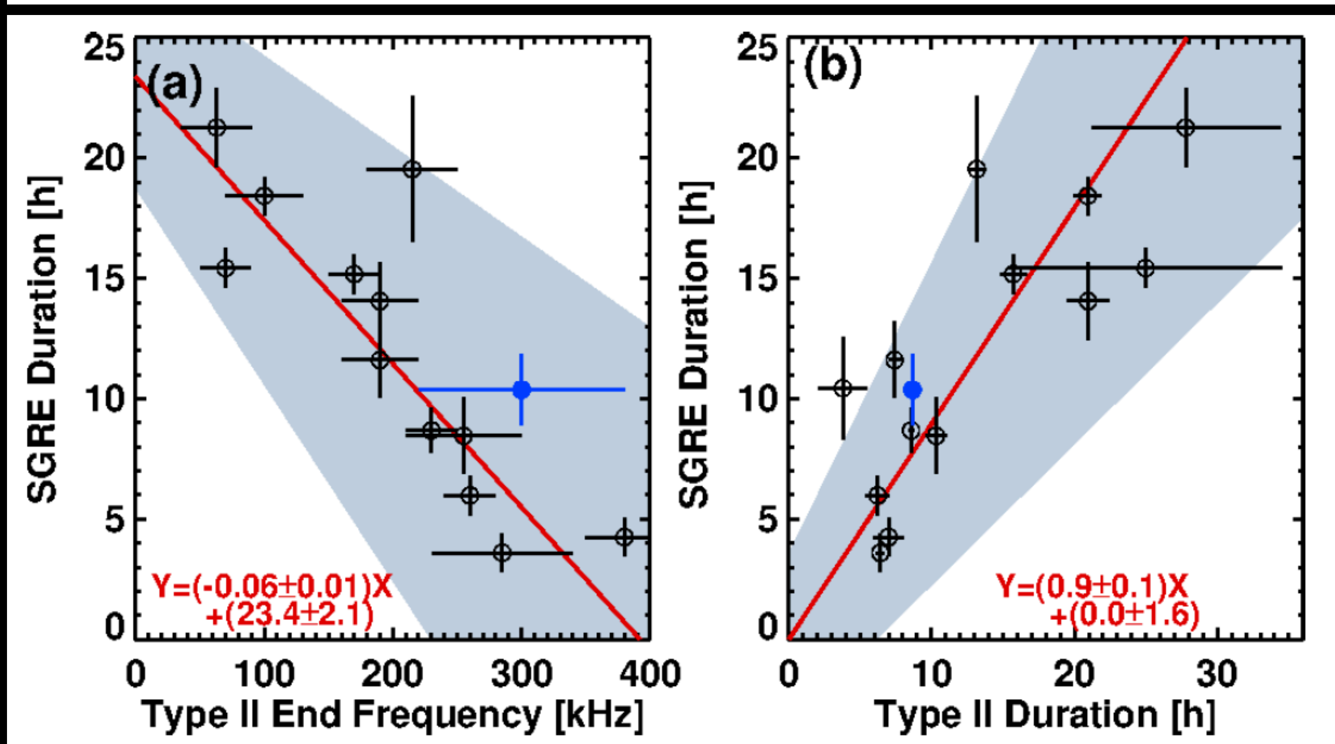


Time history of > 100 MeV gamma-ray flux from Fermi/LAT. Inset compares with GBM 100-300 keV & dashed curve is soft x-rays

⇒ Share et al. favor the CME shock scenario. Agrees with comprehensive study of correlations between LDGRF emission, CMEs, and Flare properties by Winter et al. 2018.

Type II Radio Burst





Gopalswamy et al. (2018) found that LDGRF emission & Type II bursts are highly correlated:

* **The end frequency has an inverse linear relation with the duration of the LDGRF emission (suggesting that IP shocks remain strong over larger distances from the Sun).**

* **The duration of Type II bursts and LDGRF emission have a linear relationship, suggesting the same shock is responsible for the acceleration of both electrons and protons.**

=> Supports the CME shock-driven scenario

Modeling Particle transport in the CME shock Scenario

* *Models of particle transport, assuming a radial magnetic field from the shock to the Sun, suggests only ~1% of particles will precipitate back to the Sun, particularly due to reflections from the mirror force (Kocharov et al. 2015; Klein et al. 2018; Hudson 2018).*

* *However, recently Afanasiev et al. (2018) modeled two energetic SEP events (2012 Jan 23 and May 17) by combining a coronal shock model with DownStream Propagating (DSP) model including diffusive downstream particle transport. This is arguably a more realistic particle transport model utilizing a Monte Carlo calculation of scattering in a turbulent field (that includes advection and adiabatic deceleration). This model appears to results in ample production of interacting protons at the Sun.*

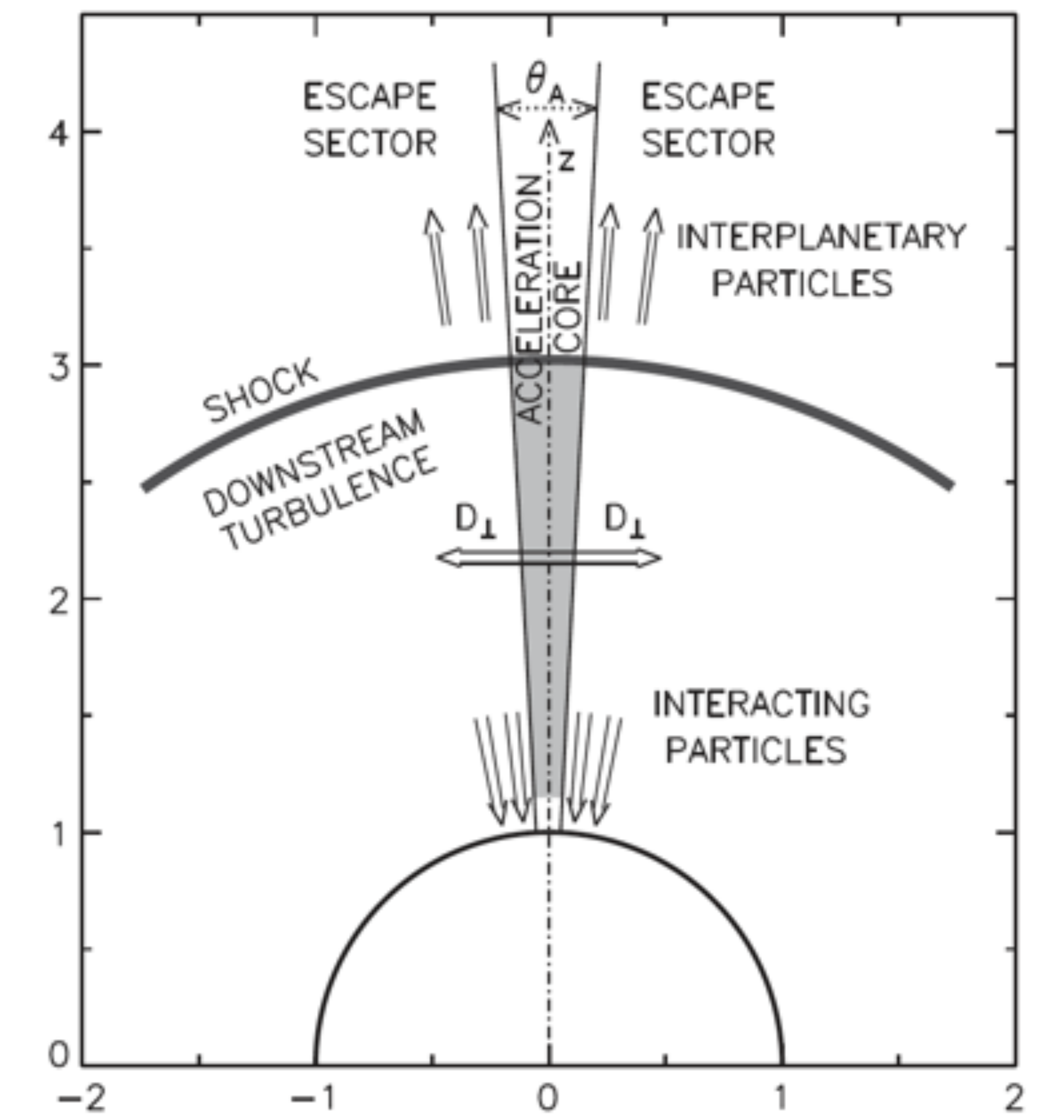
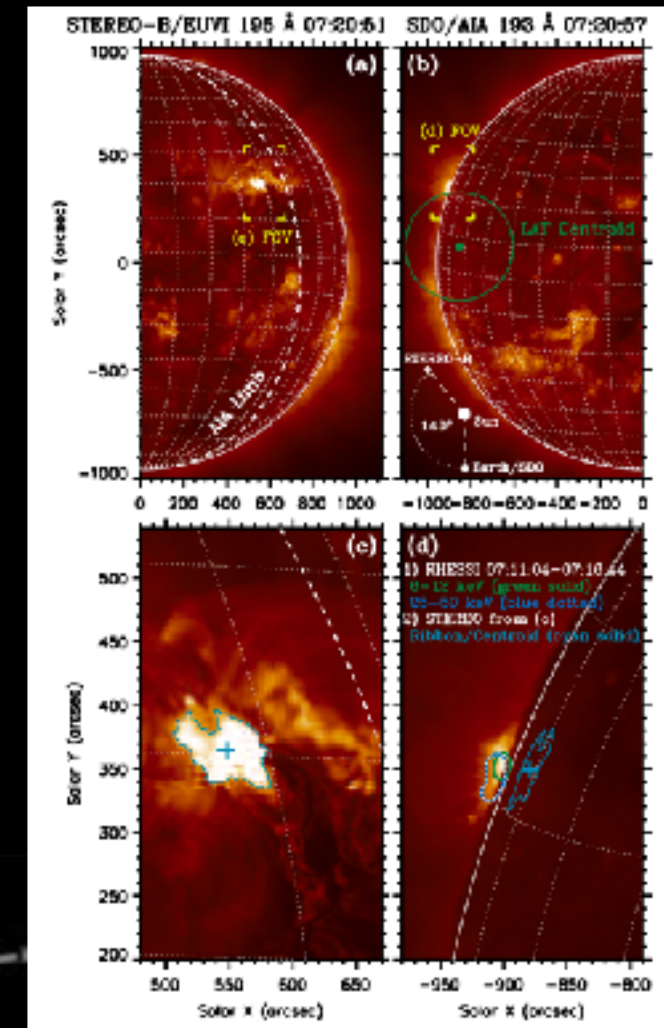


Figure 2. Particle acceleration and transport model. The region of stochastic re-acceleration of the shock-accelerated particles is shaded. The vertical extent of this region depends on the total number of resonant protons.

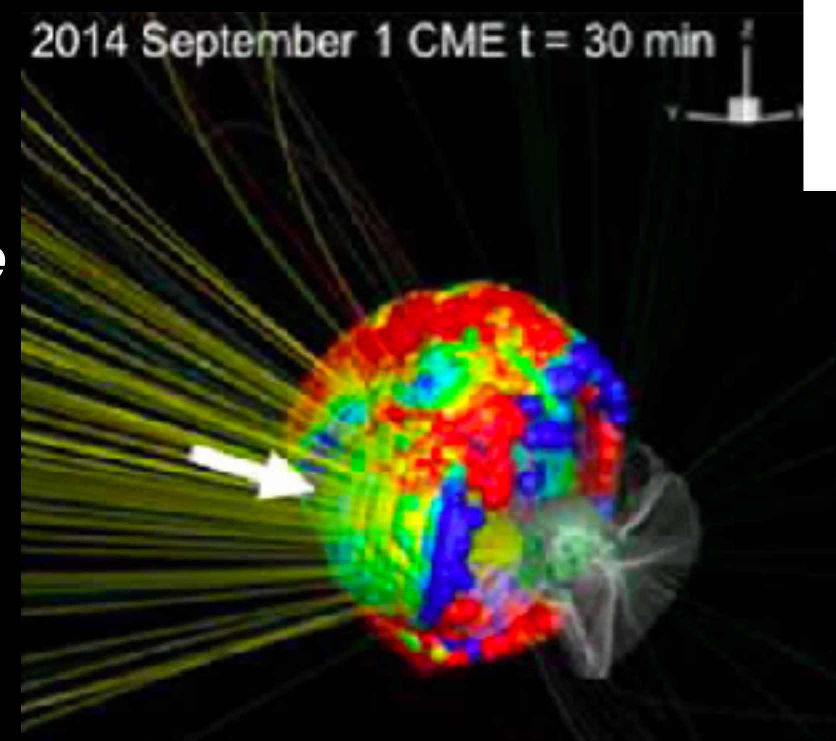
Insight from *Behind-the-Limb* LDGRFs



Possible to Explore connectivity with Behind-the-limb events

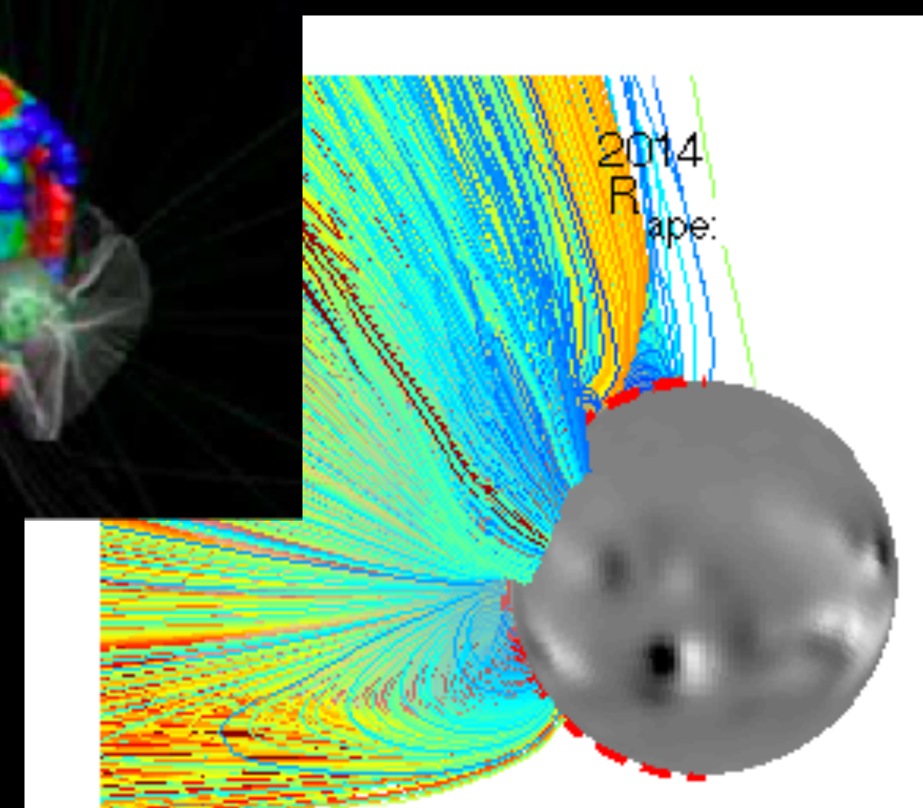
* *First behind-the-limb LDGRF was 1989 September 29 with a large spatial extent of ~ 30^o (SMM, Vestrand & Forrest 1993). Also largest SEP event since 1956 with protons up to ~20 GeV*

* Fermi/LAT also observed three LDGRFs associated with behind-the-limb sources, 2013 Oct. 11, 2014 Jan 6, and 2014 Sept 1 (Pesce-Rollins et al. 2015; Ackermann et al. 2017)



* *From these events, it appears that magnetic connectivity is maintained between the shock and solar surface enabling particle precipitation (Plotnikov et al. 2017)*

* *Furthermore, it appears that the reconstructed shock fronts become magnetically connected to visible solar surface just before onset of >100 MeV γ-ray emission while a drop off in intensity is observed as the shock transitioned to quasi-parallel shock geometry (Jin et al. 2018).*

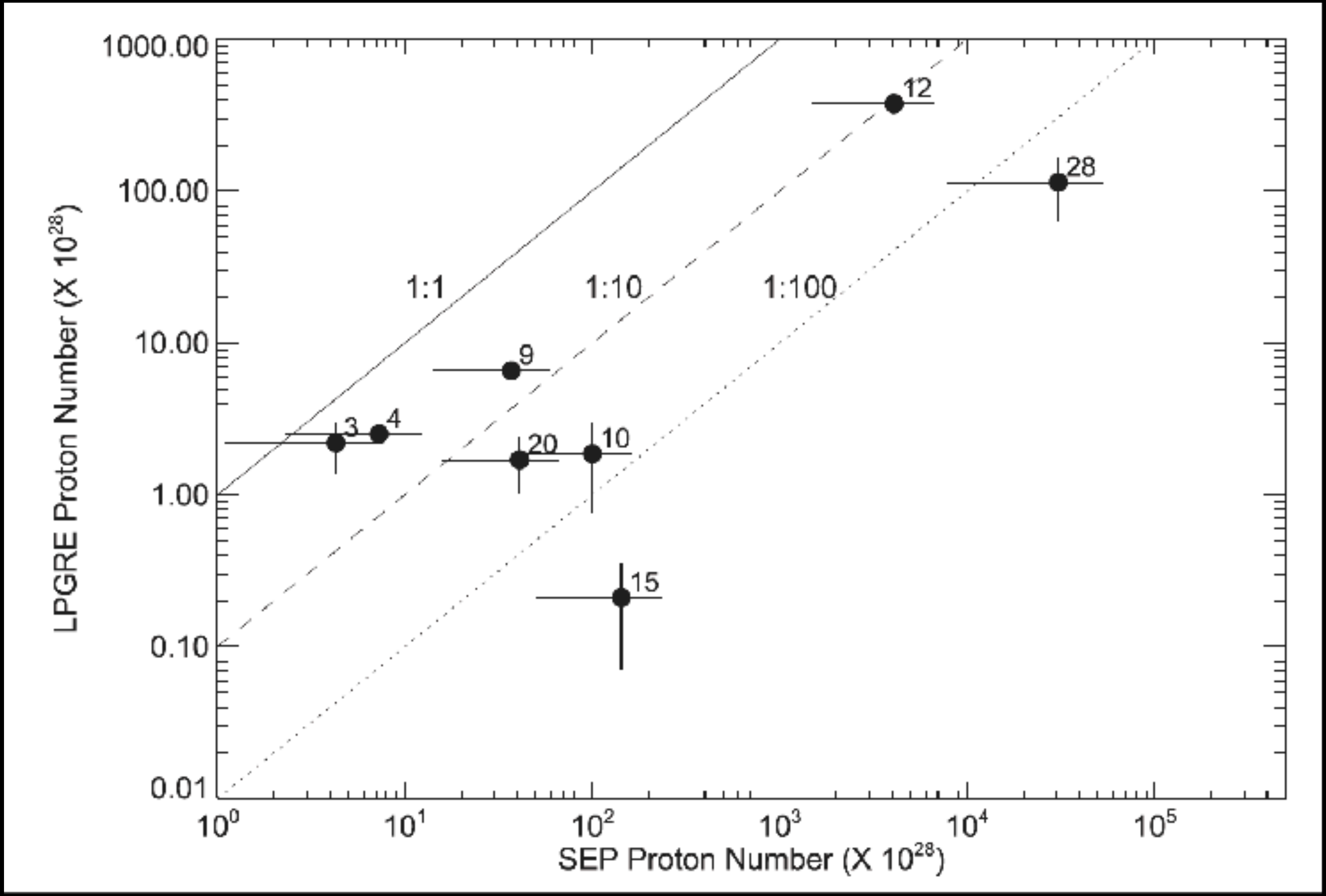


Plotnikov et al. 2017
Jin et al. 2018

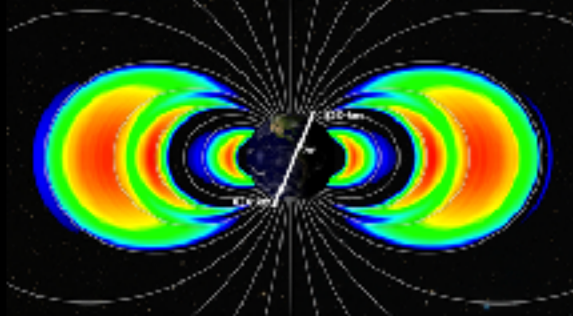
G. A. de Nolfo

Further Constraining LDGRF Origin Scenarios

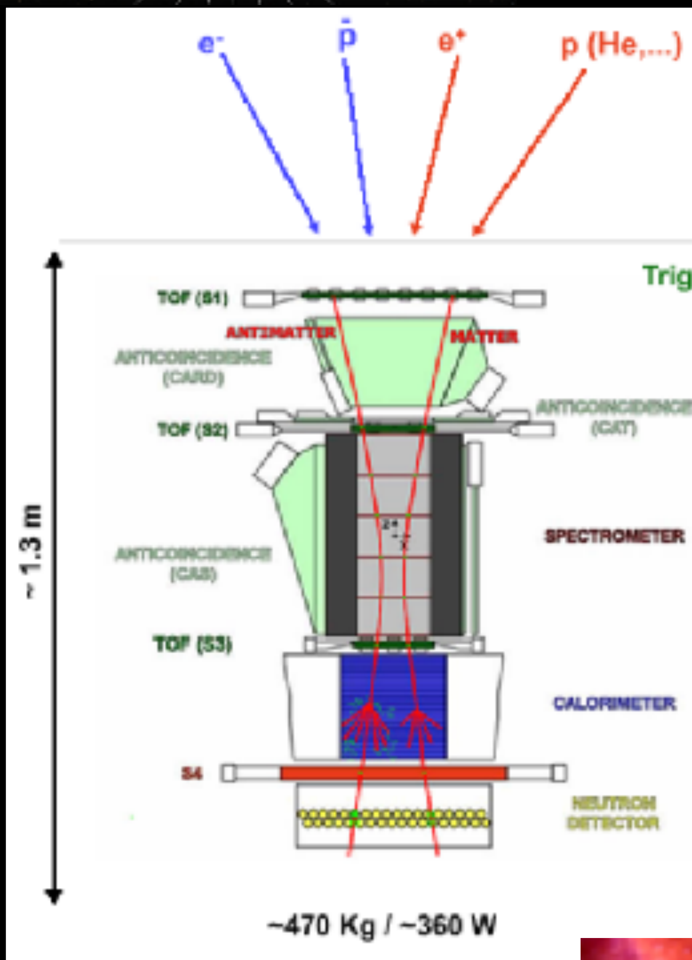
⇒ Key is a direct comparison between SEPs and the number of precipitating particles at the Sun.



** The Number of precipitating protons varied between .1 to 50% (Share et al. 2018)*

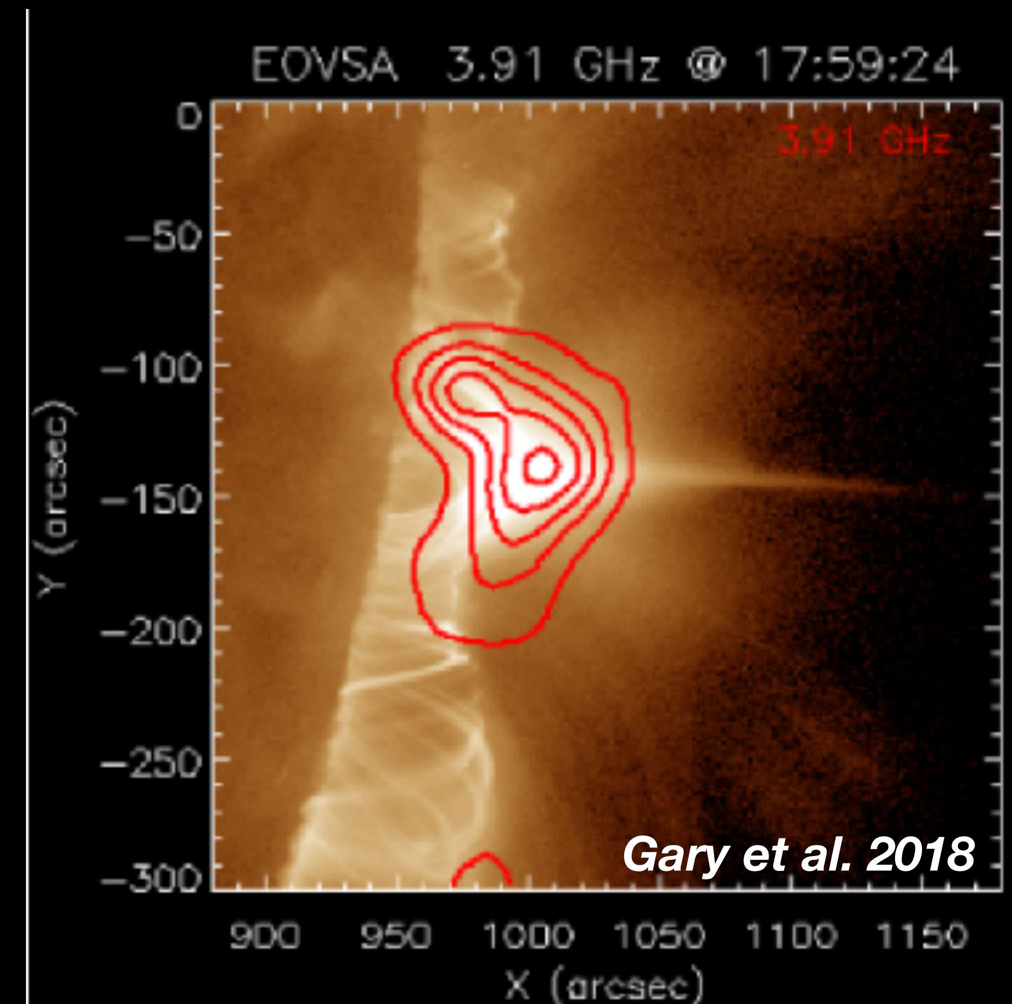


Astrophysics Heliophysics



Payload for Matter-Antimatter Exploration and Light Nuclei Astrophysics (PAMELA)

Magnetic spectrometer with silicon tracking system, a ToF, and EC to measure CRs from several tens of MeV up to several hundreds GeV. Also detect SEPs (see Bruno et al. 2018)



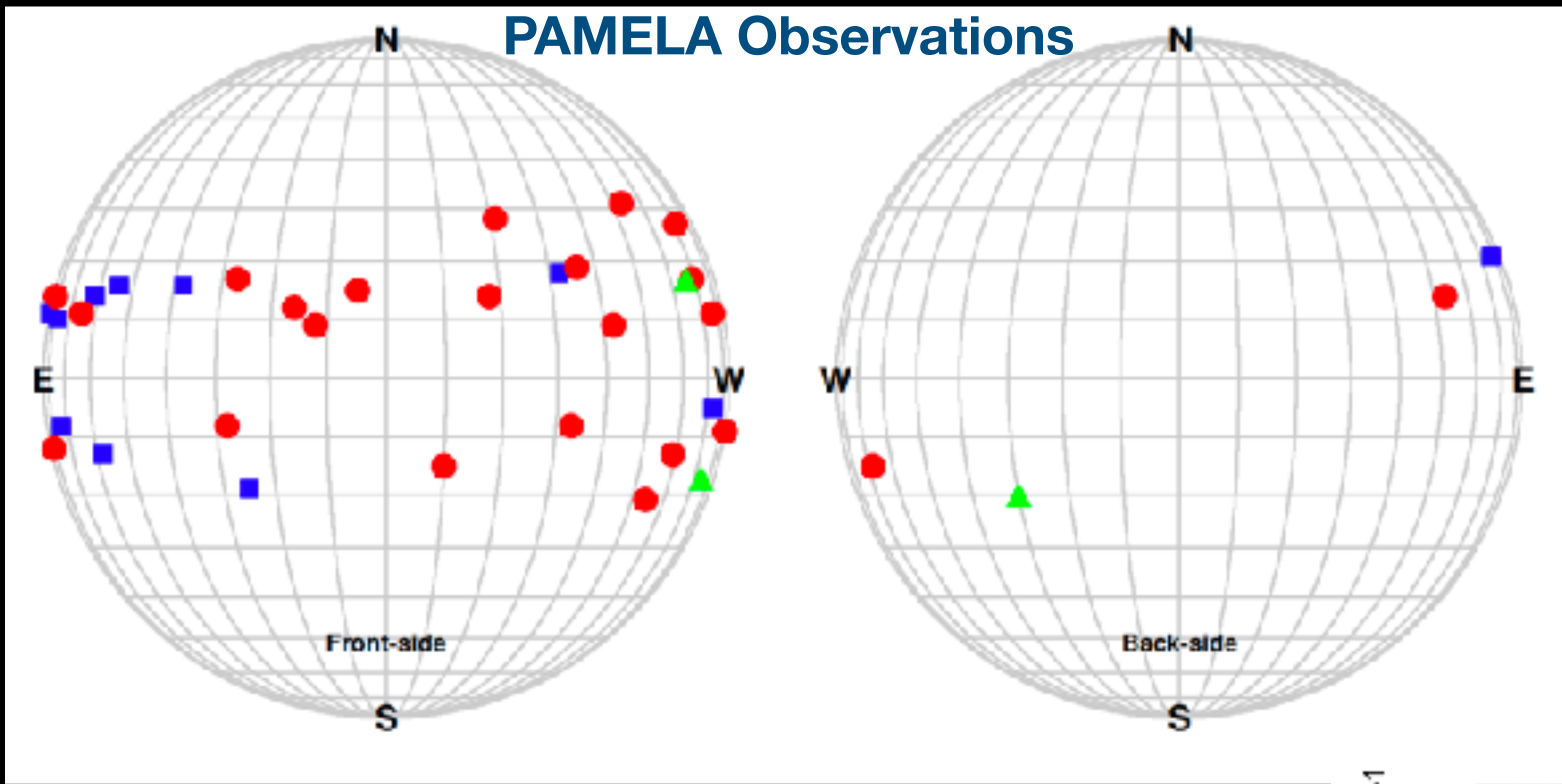
***Fermi*/LAT**

pair-conversion telescope with sensitivity to γ-rays between 20 MeV and 300 GeV & duty cycle for solar events of ~20%

Ions producing the LDGRFs are in the SAME energy range as that observed by PAMELA!

Possible to address the question of the origin of LDGRFs with PAMELA, STEREO, and Fermi/LAT for the first time!

⇒ Gain some insight into origin of LDGRFs by comparing with SEPs measured by PAMELA (either the populations are related or result from distinct processes)



Fermi/LAT (>100 MeV) and PAMELA (>500 MeV)

Red : Fermi & PAMELA

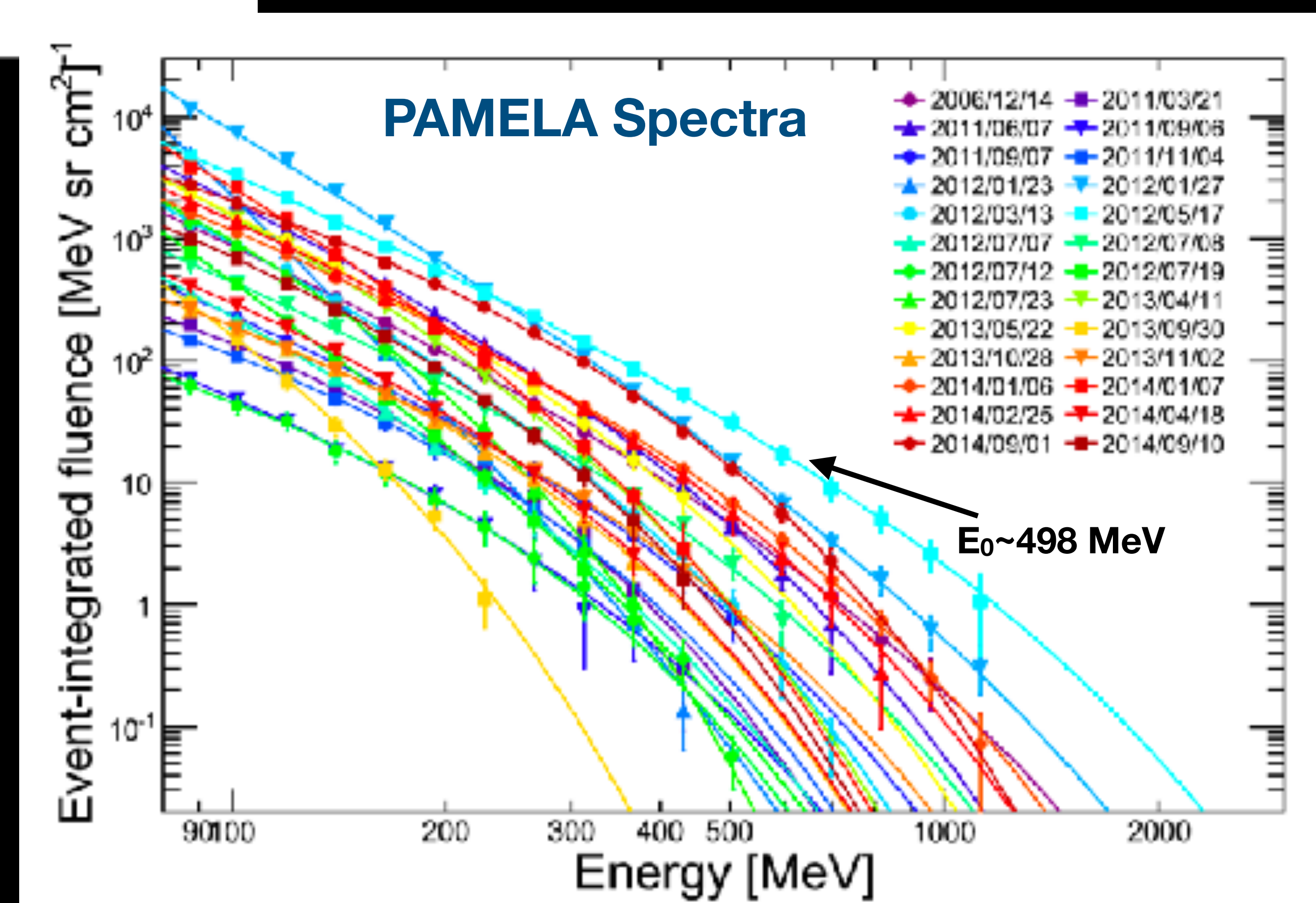
Blue : Fermi/LAT only (preponderance of eastern events)

Green PAMELA only (backside events and poor LAT coverage)

In summary, 14 out of the 25 SEP events observed by PAMELA were associated with LDGRFs by Fermi/LAT

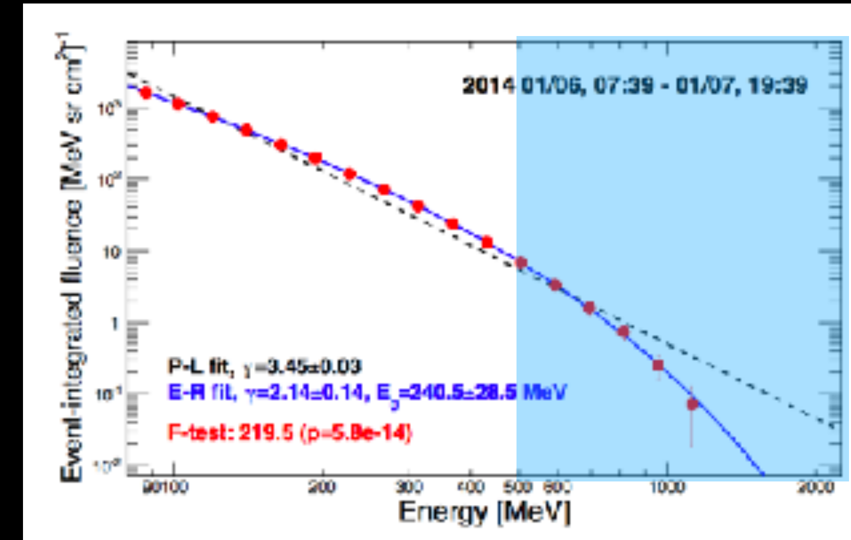
Fluxes are consistent w/ the Ellison & Ramaty (1985) functional form consisting of a power-law with exponential cutoff

$$\Phi_{sep}(E) = A \times (E/E_s)^{-\gamma} \times e^{-E/E_0},$$



* PAMELA measured spectra for 26 SEP events (see: *Bruno, A. et al. (2018), ApJ 862:97 also, Bruno et al. ICRC 2019)*
** 14 SEP events were associated with LDGRF emission (see de Nolfo et al. 2019)*

Approach: Compare Total Proton Numbers at the Sun and in Space



1. Compute >500 MeV fluencies based of ER fits, accounting for spectral roll-overs

(1)

$$N_{SEP} = \overline{N}_{cross}^{-1} \int_{4\pi} d\Omega \int_S dS\,(\boldsymbol{J} \cdot \boldsymbol{n})$$
$$= \overline{N}_{cross}^{-1} \int_{4\pi} d\Omega \int_S dS\, cos(\theta)\, J(\Omega, S),$$

dΩ = dφdϑsin(ϑ) is the solid angle element of the particle velocity direction at a point centered on the sphere and J is the event-integrated intensity

2. Compute number of protons assuming particle spatial distributions that is characterized by a periodic Gaussian (G(δ)) & integrate over a heliocentric spherical surface, S, at 1 AU.

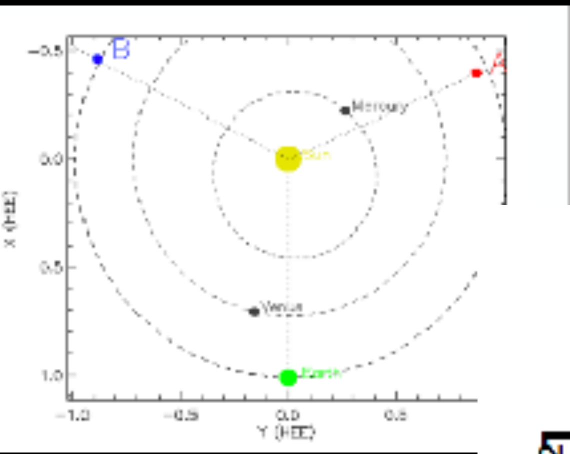
(2)

$$N_{SEP} = 2\pi\, \overline{N}_{cross}^{-1}\, J_{max} \int_S dS\, G(\delta)$$
$$= 2\pi\, \overline{N}_{cross}^{-1}\, J_E\, S_J\, C_{spa};$$

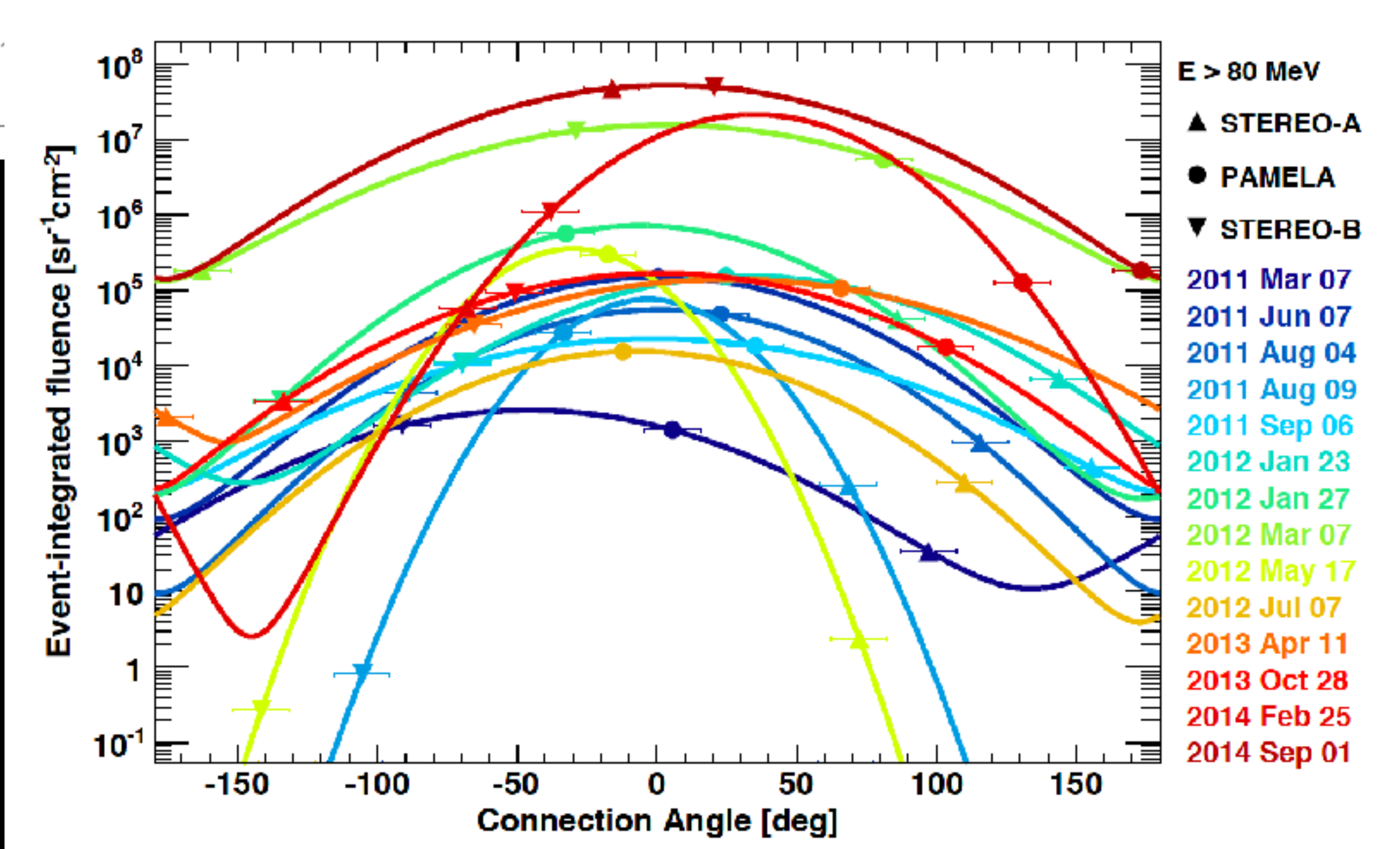
J_E is the > 500 MeV event-event-integrated intensity observed by PAMELA
S_J is the spherical area weighted by the particle spatial distribution
δ is the great-circle distance wrt the peak of the SEP partial distribution

Need to account for two important corrections:

1. C_{spa} accounts for PAMELA's observations not being made on interplanetary magnetic field lines that connect with the peak of the particle distribution (corrections both in longitude and latitude),
2. N_{cross} takes into account multiple measurements of the same particles (beam vs. isotropic)

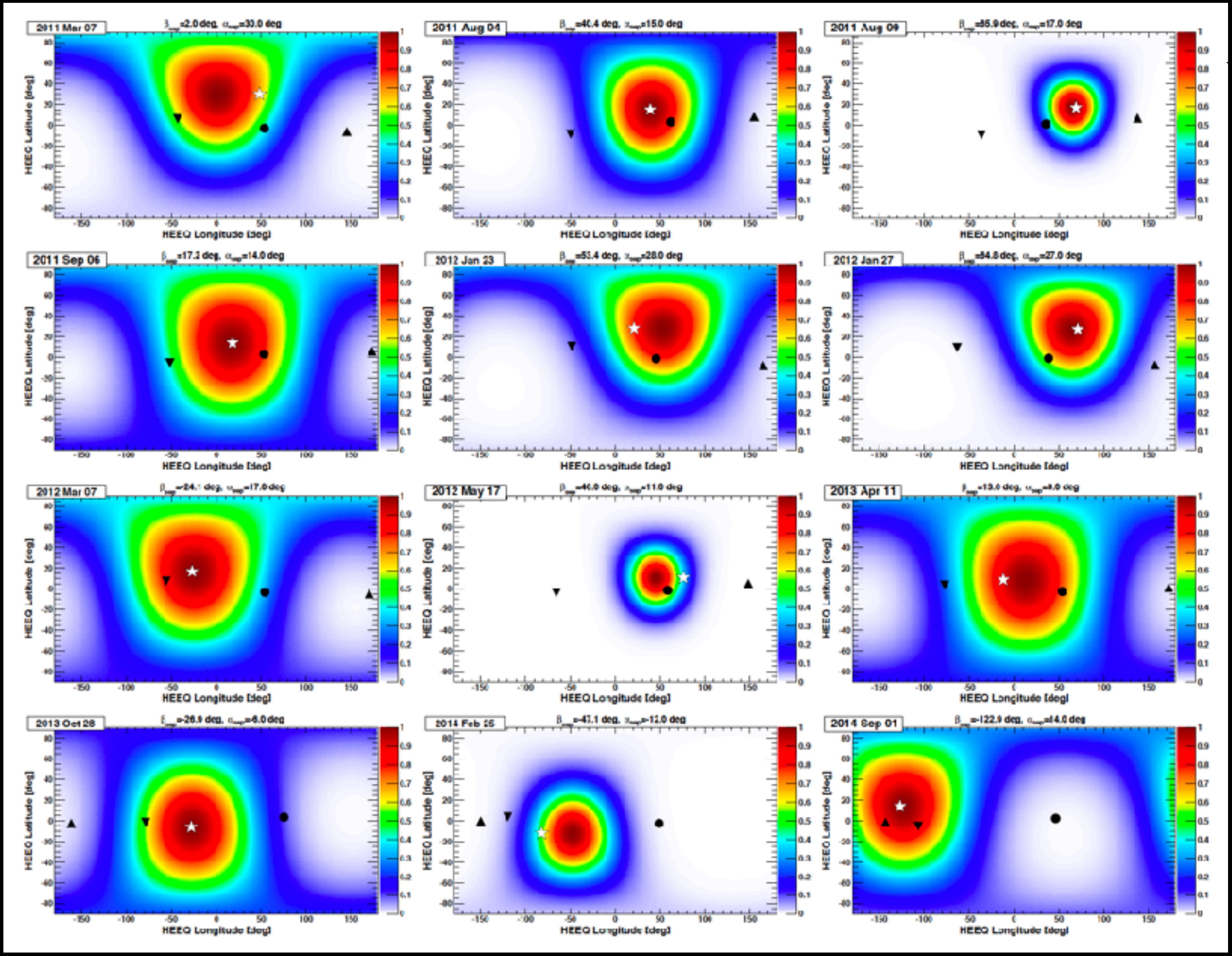


Periodic Gaussian Fits at > 80 MeV Fluences



Longitudinal extent of SEP events determined from the fits of the event-integrated intensities (>80 MeV) measured by PAMELA and STEREO A/B as a function of connection angle between the S/C magnetic footpoint at 30 R_s & the location of the parent flare.

SEP spatial distribution in HEEQ coordinates based on event-integrated fluences > 80 MeV

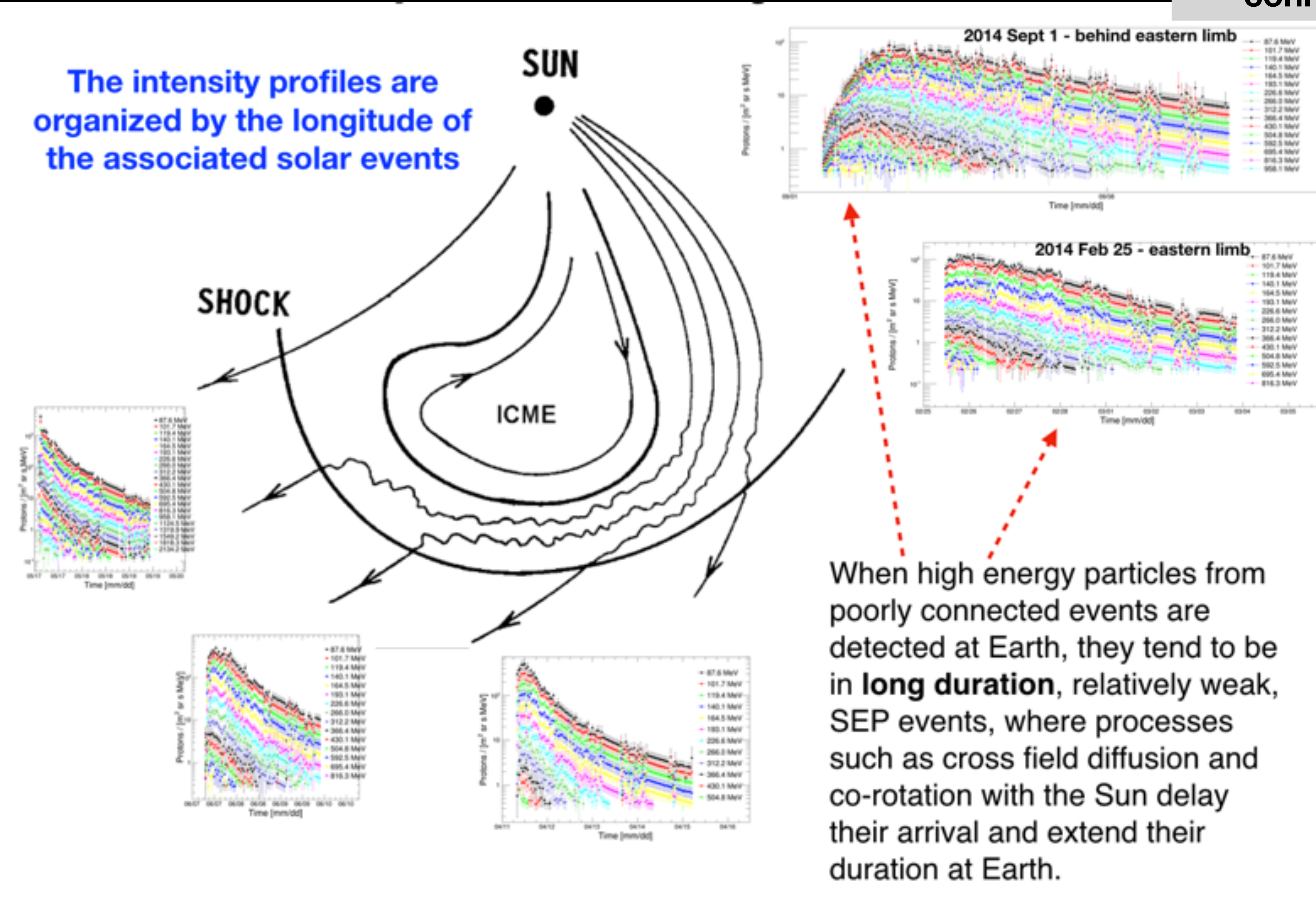


★ flare location

footpoints
● PAMELA
▲ STEREO

SEP Transport

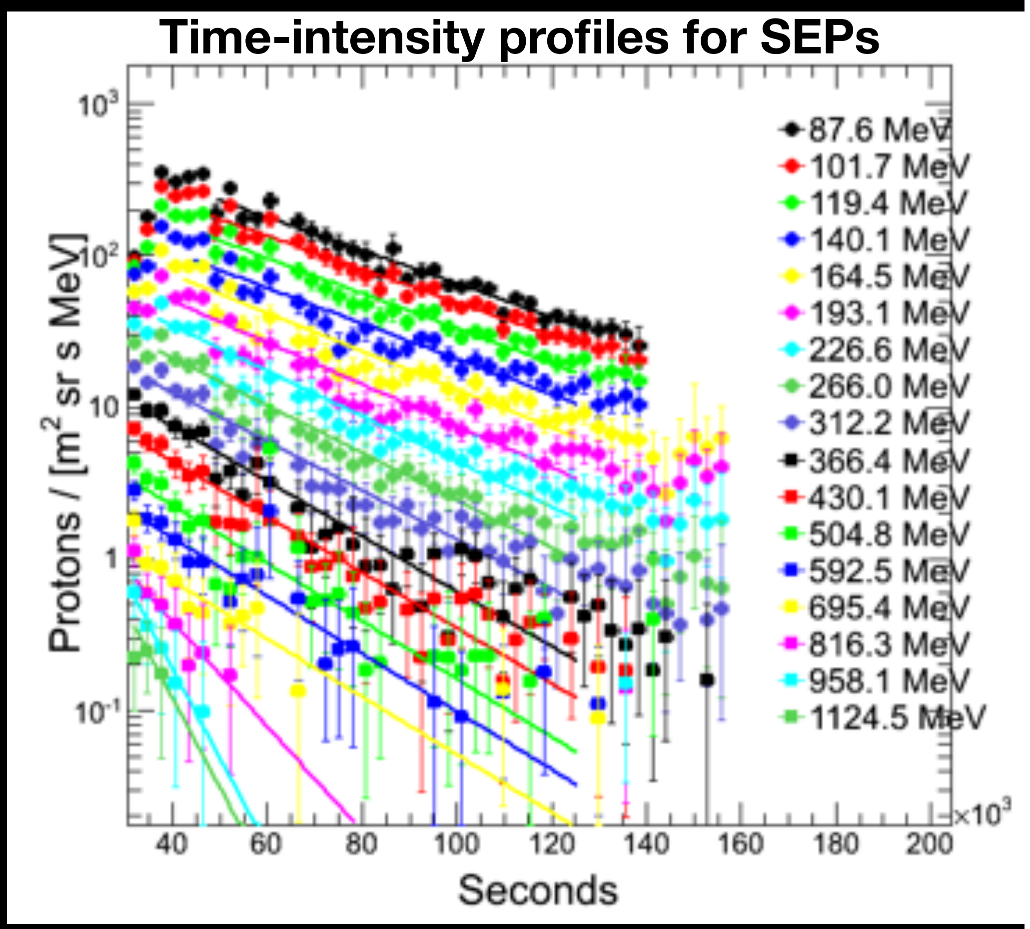
Longer time profiles for events that are not well connected

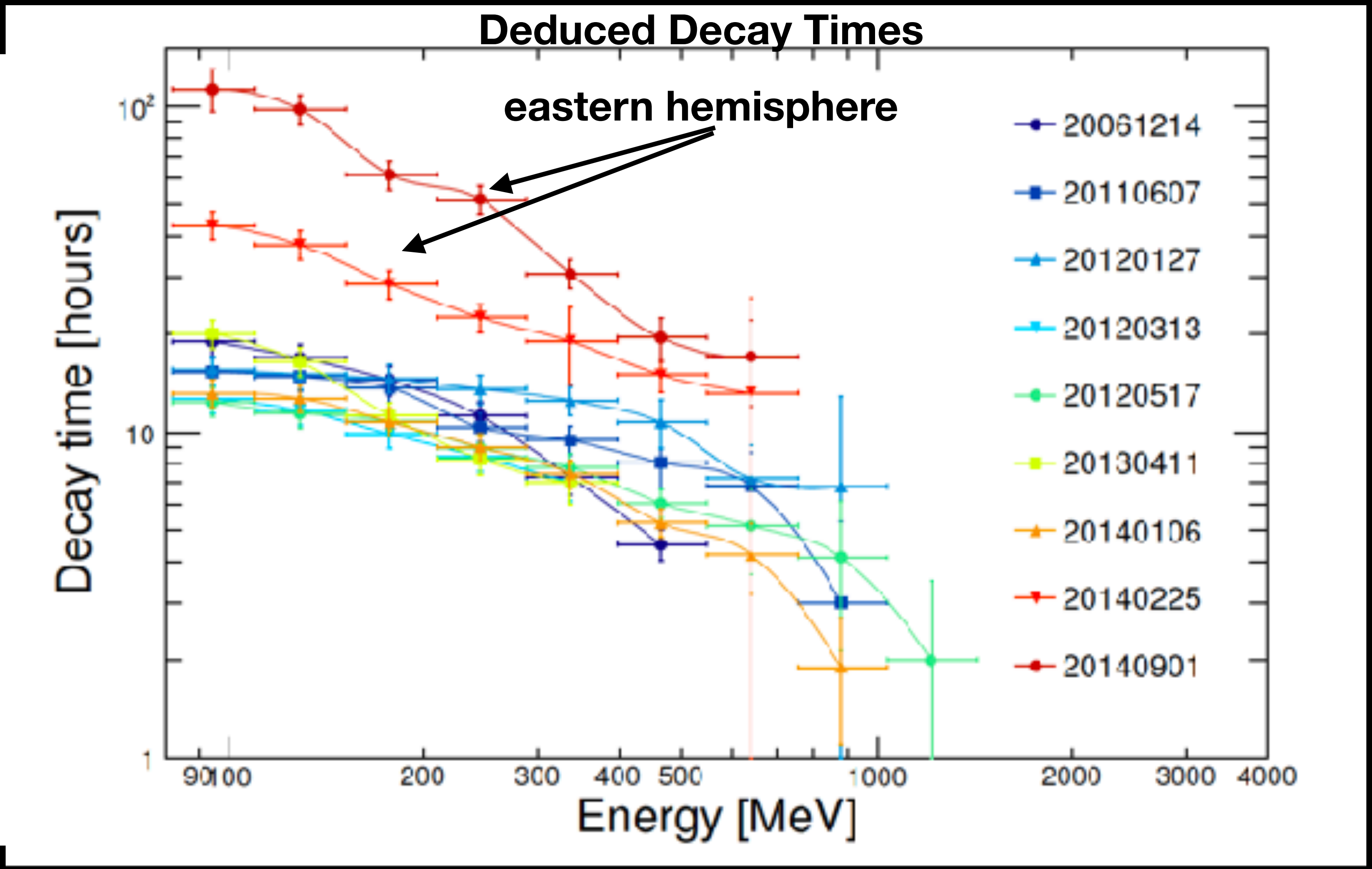


When high energy particles from poorly connected events are detected at Earth, they tend to be in **long duration**, relatively weak, SEP events, where processes such as cross field diffusion and co-rotation with the Sun delay their arrival and extend their duration at Earth.

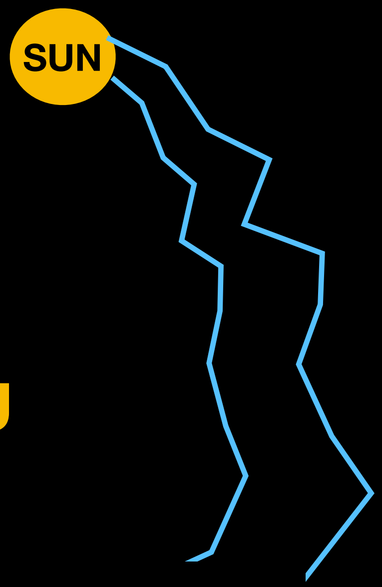
PAMELA Observations also help to constrain transport

* SEP transport is governed by both large scale magnetic topology & scattering from small scale magnetic turbulence
* The amount of scattering affects the SEP intensity and anisotropy distributions





Such trends are extremely helpful in constraining amount of scattering for SEPs



Modeling SEP Transport & Multiple Crossings

⇒ Depending on the amount of scattering, SEPs may cross 1 AU several times and this multiple scattering needs to be taken into account

—> Can determine N_{cross} through simulations of particle propagation under a variety of scattering conditions

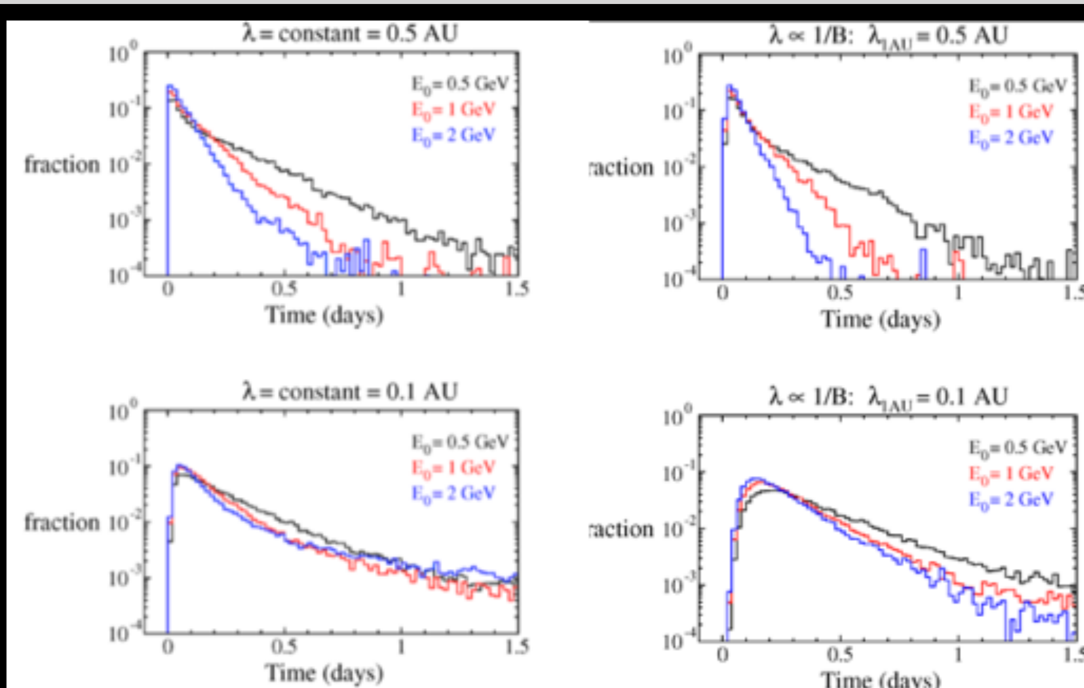
Consider 2 test particle models

1) Simulation by Chollet et al. 2010
2) Simulation by Battarbee et al. 2018

Both assume impulsive injection of mono-energetic isotropic particles at 0.1 AU, following the particles for 10 days, and both include magnetic focusing & scattering off of an unspecified plasma turbulence field.

Modeling SEP Transport

For the Chollet et al. 2010 model, we assume two forms for the turbulence 1) uniform or 2) proportional to the gyro-cyclotron radius (Chollet et al. 2010)



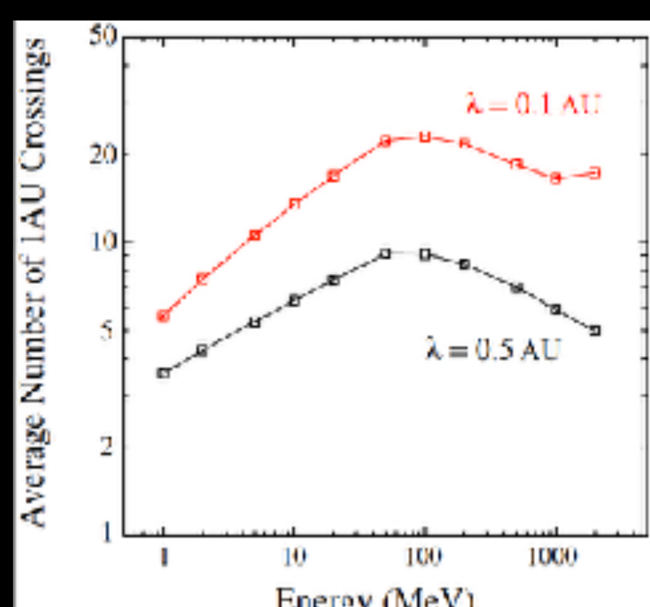
⇒ short λ

results in longer decay times

Predictions for the time-dependent development and decay of the intensity at 1 AU

The degree of scattering is adjusted to increase or decrease the anisotropy and associate decay time

*assumed flat HCS and A^+



Battarbee et al. 2018 model includes the effects of different configurations of the Heliospheric Current Sheet (HCS) and solar magnetic polarity.

*assumed λ = const

These calculations show that N_{cross} varies for :

1) different configurations of the HCS (none, flat, or wavy).
2) magnetic polarity , A+ / A-

⇒ Large differences in N_{cross} for different polarities is due to particle drift along the HCS (e.g., A+ helps protons outward from the inner heliosphere faster

N_{cross} for flat HCS, A^+ is consistent with results of Chollet et al. simulations for similar conditions.

Full simulation of 2012 May 17 is consistent with PAMELA for λ=0.3 AU (*Dalla et al., in prep*)

Computation of Total Proton Numbers

$$N_{SEP} = 2\pi\, \overline{N}_{cross}^{-1}\, J_{max} \int_S dS\, G(\delta)$$
$$= 2\pi\, \overline{N}_{cross}^{-1}\, J_E\, S_J\, C_{spa;}$$

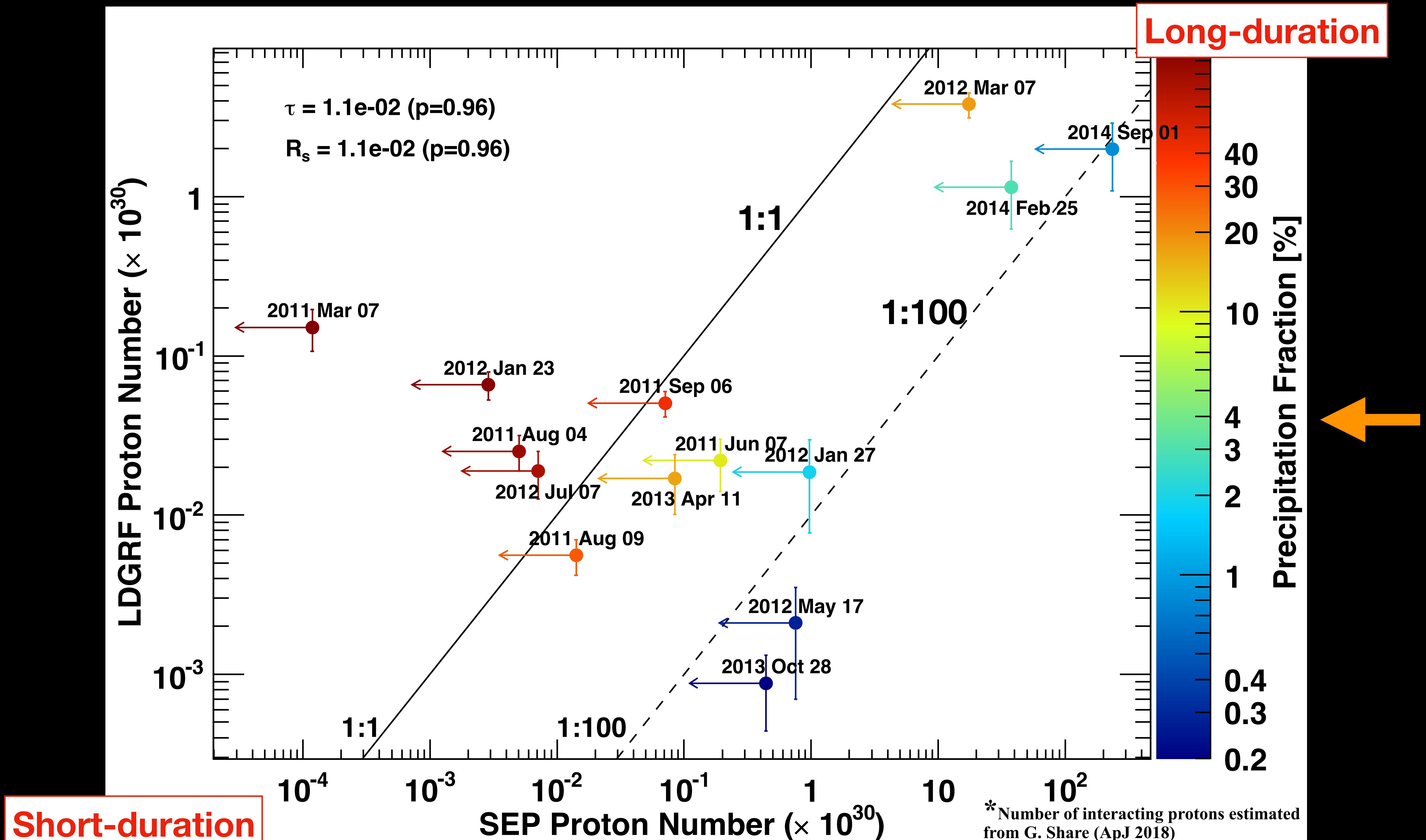
Compute number of protons assuming an isotropic flux & integrate over spherical surface at 1 AU.

Important Assumptions :

1. **Use > 80 MeV proton distributions to define longitudinal extent**
2. **Assume the same angular distribution for latitudinal dependence**
3. **Assume λ_o~ 0.5 AU & wavy HCS ⇒ Np ~ 8-11**

⇒ Compute upper limits for N_p

Comparing > 500 MeV N_p in space and at the Sun

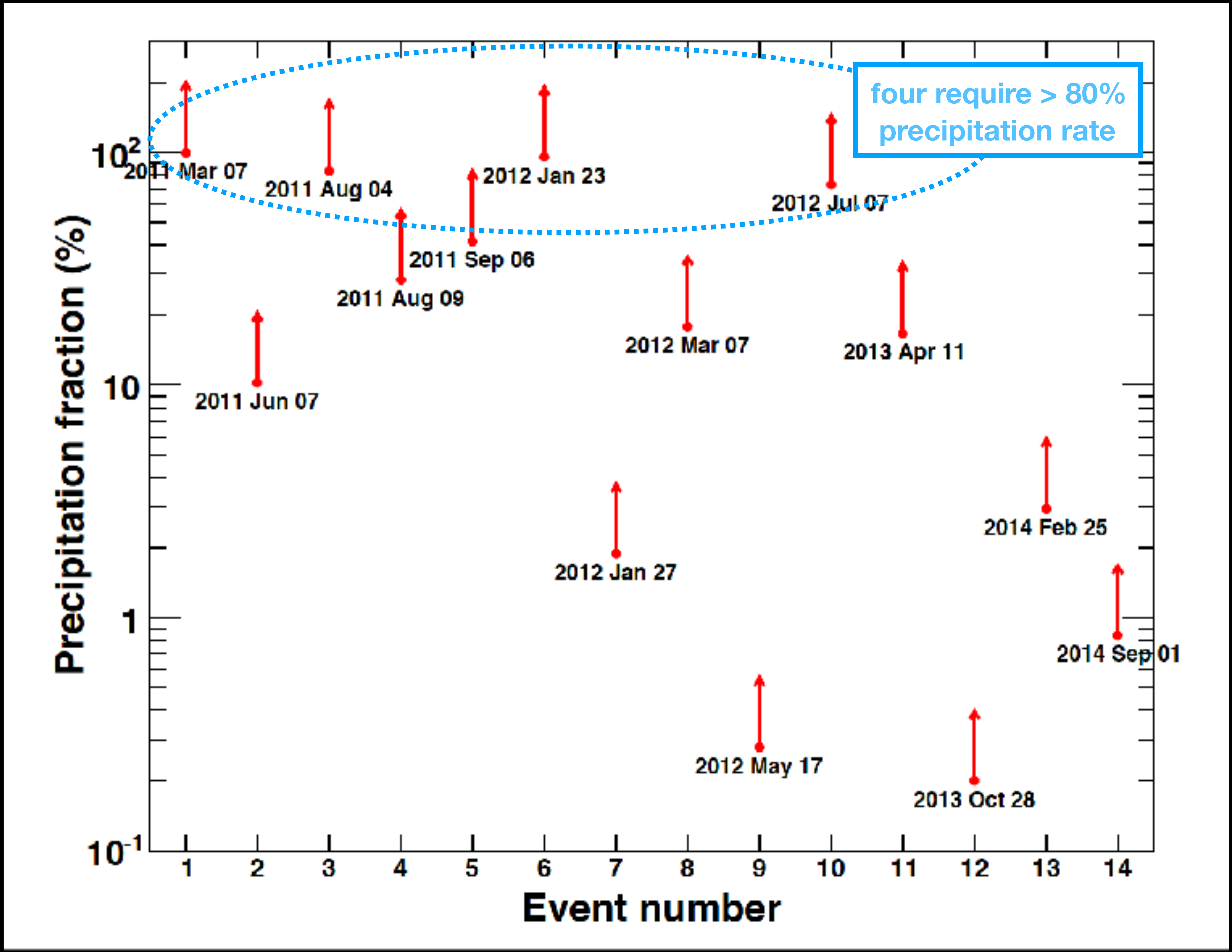


*No correlation (low values of the Kendall's τ and Spearman rank correlation coeffs).

*N_{SEP}/N_{LDGRF} ratio spans > 5 decades of magnitude from 7.8×10^{-4} to $\sim 5.0 \times 10^{2}$

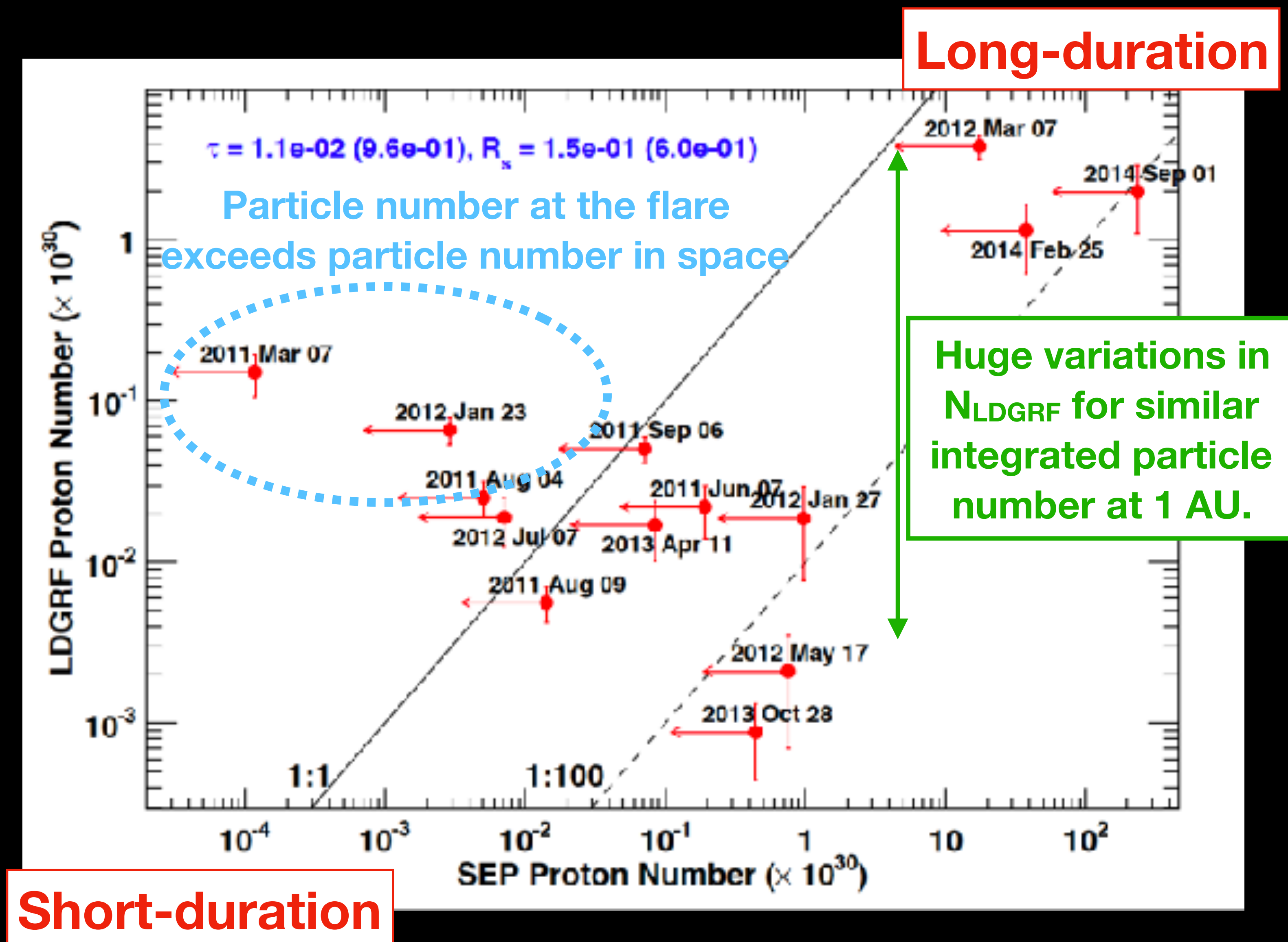
*Constraints by looking at the total number of protons (those that escape + those that produce LDGRFs) needed to precipitate to produce LDGRFs .

Precipitation Rate : $N_{LDGFR}/(N_{LDGRF}+N_{SEP})$



Total number of protons (those that escape as SEPs plus those that produce LDGRFs) that would have to precipitate to account for the LDGRF emission.

Does Back Precipitation from CME-driven Shocks Work?



— Huge variations could be the result of sporadic & unpredictable magnetic connectivity, although such widely varying connectivity isn't supported by the smoothly decaying LDGRF emission from Fermi/LAT

— Large N_{LDGRF} number with nearly 80% precipitation would imply :

1) an enormous loss channel for the shock
2) high shock formation heights, resulting in a weakening shock, adding to the challenge of accelerating particles to high-energy.

— Additionally challenges:
2012 Oct 23 & 2012 Nov 27 exhibit LDGRF emission but have no CMEs (and likewise examples of fast, full-halo CMEs with no > 100 MeV γ-ray emission)

Alternate Scenario: Trapping in Large Coronal Loops

Particle acceleration (via second-order *Fermi* mechanism) & trapping within extended coronal loops, & ions diffuse to the denser chromosphere to radiate (Ryan & Lee 1991).

1) Impulsive phase ions are injected into a large magnetic structure (length L) containing plasma and MHD turbulence such that the scattering path length, $\lambda \ll L$.
2) Particles diffuse to the ends of the loops and precipitate in the dense chromosphere/photosphere, but they are also accelerated by second-order Fermi process to higher energies.
3) spatial diffusion in the loop with loss at the boundaries is given by the characteristic spatial diffusion time scale $\tau_d = L^2/\pi^2\kappa$, where L is the loop length and κ is the spatial diffusion coefficient (note $\kappa = \lambda v/3$).
4) the acceleration time scale is given by $\tau_{acc} = 9\ \kappa/V_A^2$ and is inversely proportional to the spatial diffusion coefficient (the greater κ, less momentum diffusion).
6) $\tau_d * \tau_{acc} = 9L^2/\pi^2 V_A^2$ (product is constant and independent of κ)
5) L and κ are determined by fits to the photometry and further constrained by observations where possible

Qualitatively worked to explain the 1982 June 3 LDGRF with $L \sim 10^5$ km and $\lambda \sim 110$ to 450 km

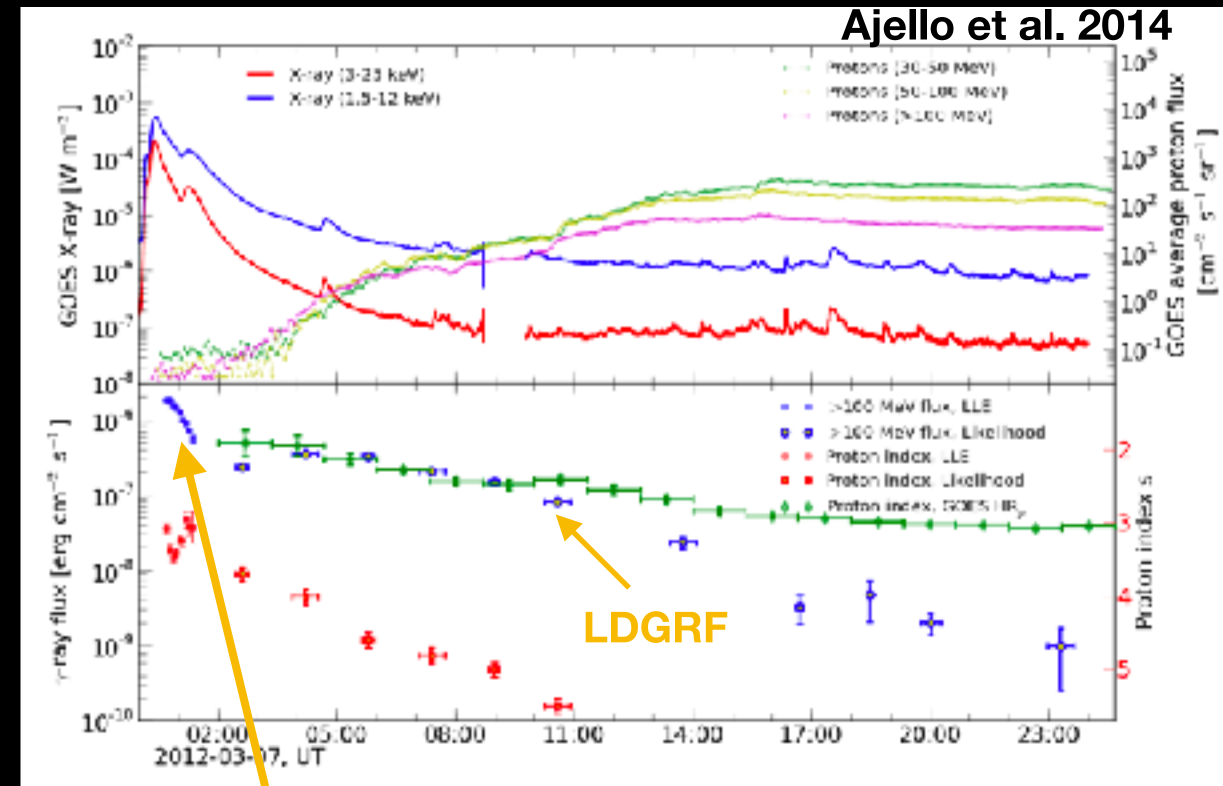
Fermi/LAT Observations of 2012 March 7

* *One notable event is the 2012 March 7 lasted 20 hours (see Ajello et al. 2014). It was associated with X5.4 and X1.3 class flares from AR 11429 N16E29 one hr apart (peak 00:24 UT & peak 01:14 UT) & fast CMEs (2700 and 1800 km/s) and SEPs.*

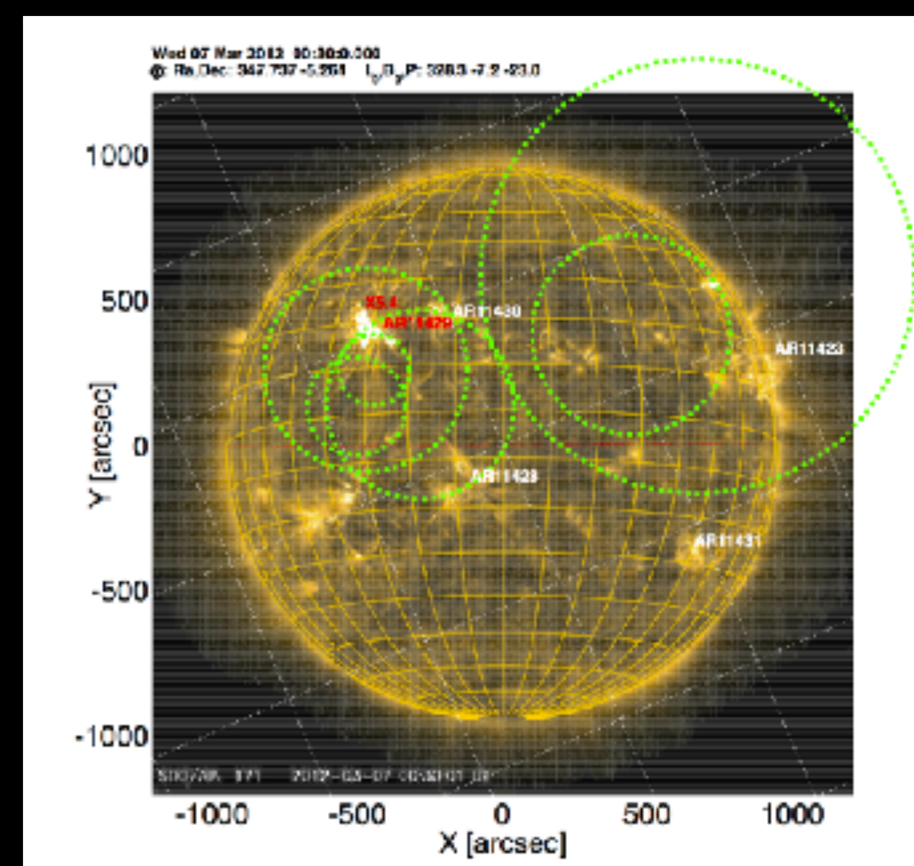
* *First X5 flare/CME responsible for SEPs (Kouloumvakos et al. 2016; Ding et al. 2016; Richardson et al. 2014).*

* *Here, the spectrum softened with time*

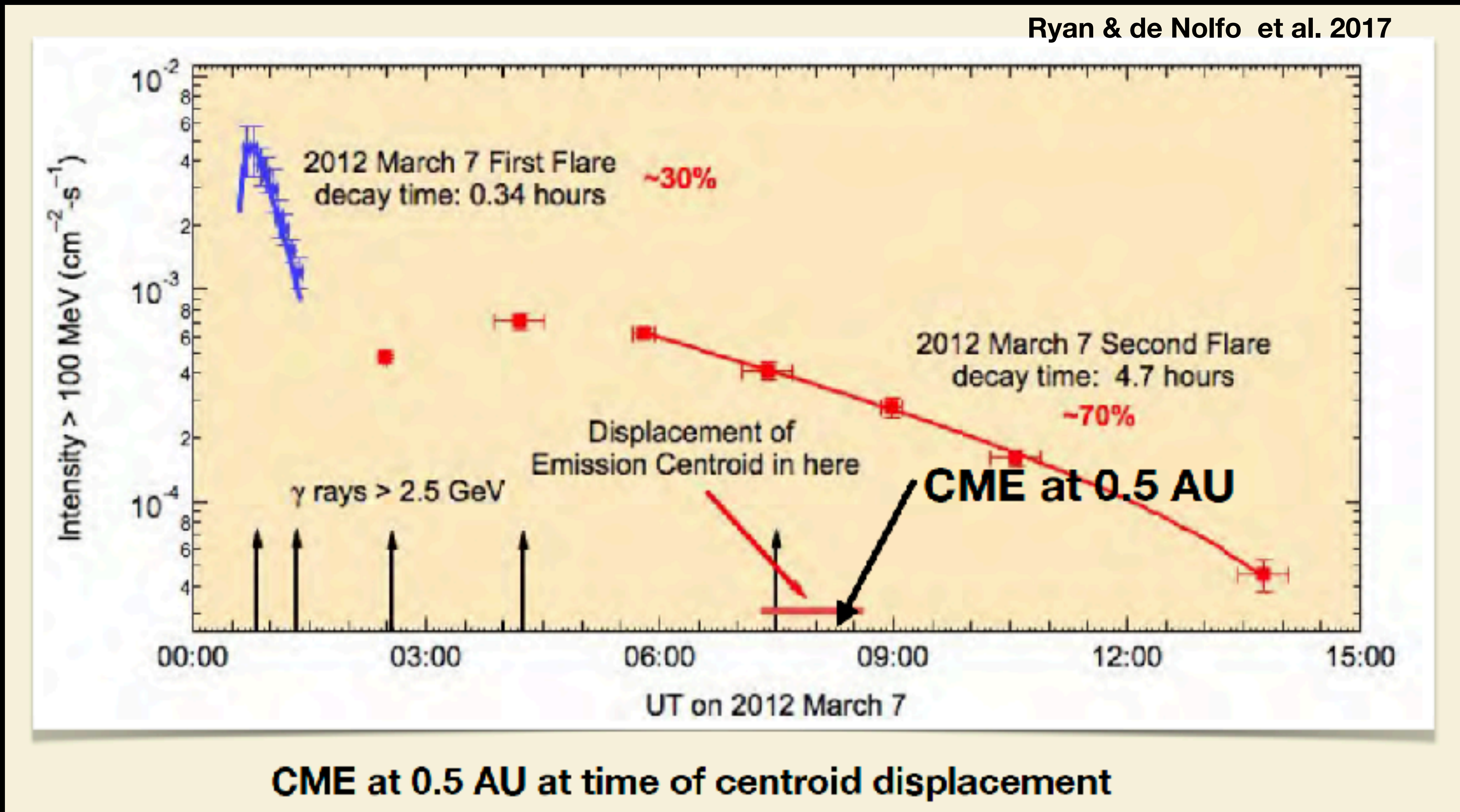
* *The centroid of the emission was consistent with the flare locations to within 10º and some evidence that the source of the emission moved westward over several hours (first vs. second flare?).*



originally thought to be impulsive phase



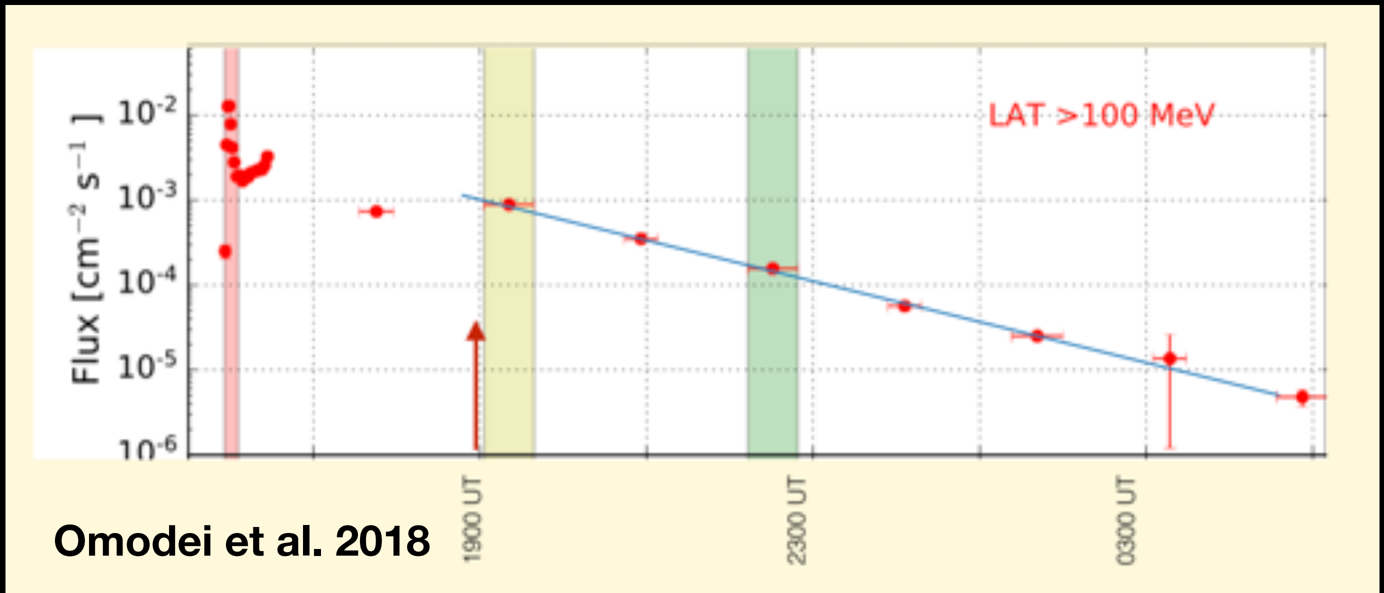
Continuous Acceleration Model for 2012 March 7



- ***First flare produced LDGRF with L ~ 1 Rs***
- ***Second flare L ~ 3 Rs (recall CME is quite far from Sun, and no IP contribution)***
- ***Other combinations of spatial diffusion coefficient and loop lengths are possible, but it is clear that large coronal structures (>10^5 km) are necessary for acceleration beyond the pion-productions threshold.***

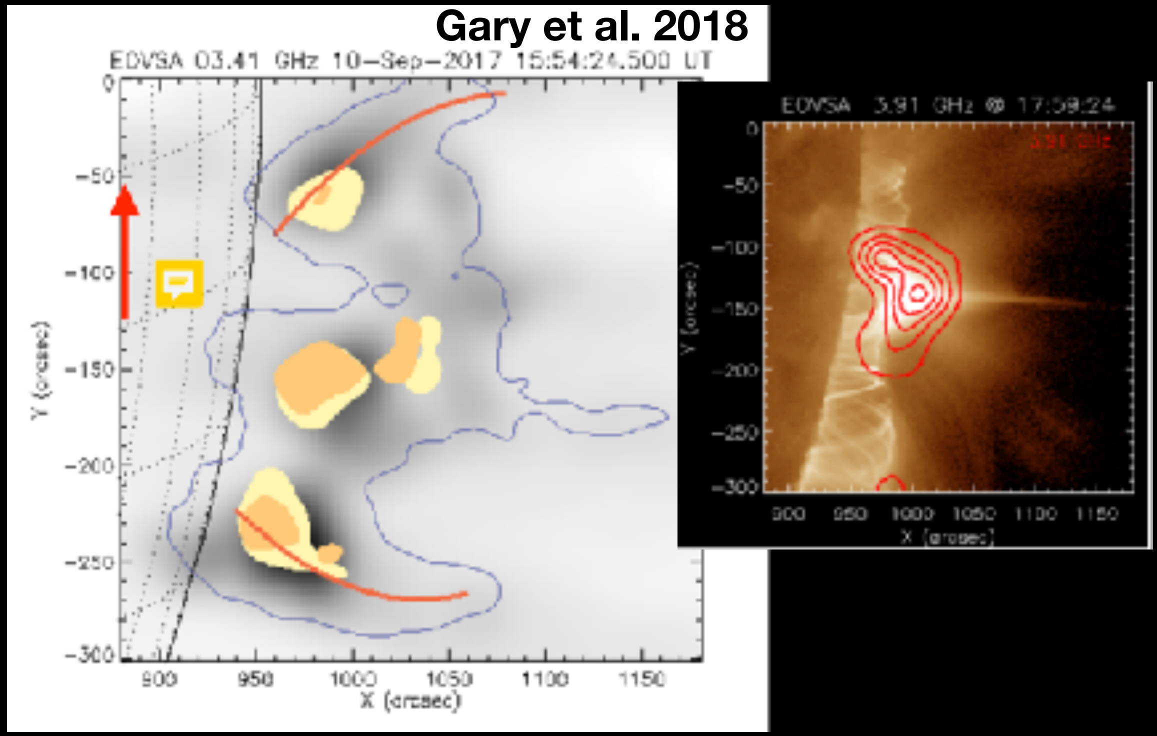
LDGRF Emission from 2017 Sept 10

2017 September 10 : Major LDGRF Hi-E Flare & Ground Level Enhancement



Fit (blue) is smooth exponential decay after 1900 UT, 3 hrs after CME liftoff, J ~ exp[-(t/6500 s)] +/-20%
Parent proton spectrum softens from -4.3 to -6.0

Event Integrated Image at 3.4 Ghz from the Expanded Owens Valley Solar Array (EOVSA)

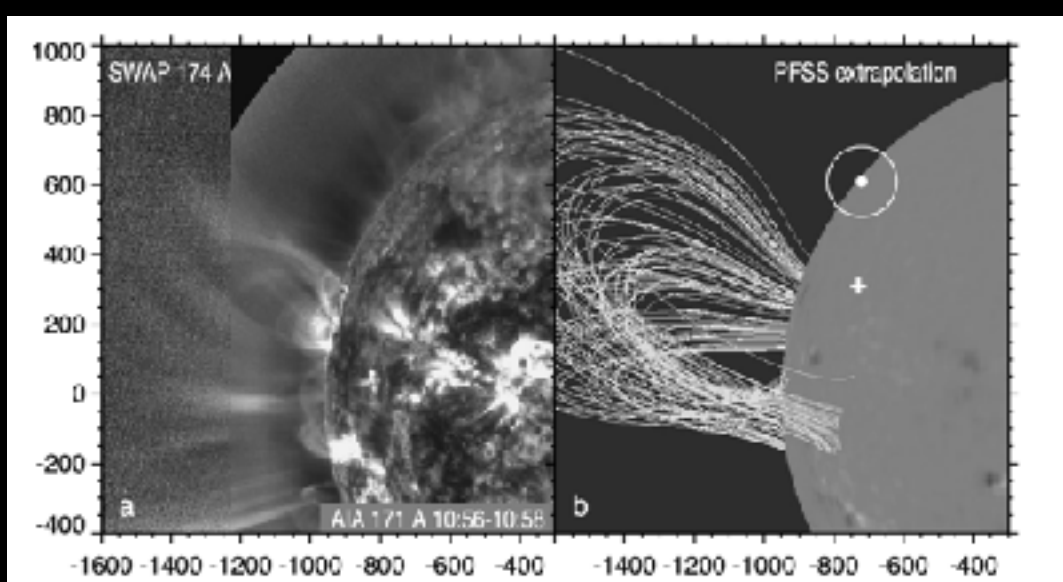


1) reveals complete inner region associated with the lower half of a reconnection event (beneath CME)
2) reveals footpoints of a larger loop with height of 0.4 Rs and L ~ 1.4Rs

Continuous Acceleration Model for 2017 Sept 10

- A roughly 6500-s decay and L~1.4 Rs ($\tau_x \sim L^2/\pi^2\kappa$) ⇒ λ (=3κ/v) of 200 km (✓)
- 200 km from λ implies a $k^{-5/3}$ integrated wave intensity of 0.7 ergs-cm^{-3} (Lee 1983)
- 1 G B field at loop top ⇒ δB/B of 10 (x) at top and 0.4 at base (✓)
- Acceleration time τ_a(=9κ/V_A^2) requires only V_A ~ 140 km-s^{-1} (✓)

Grechnev al. 2018

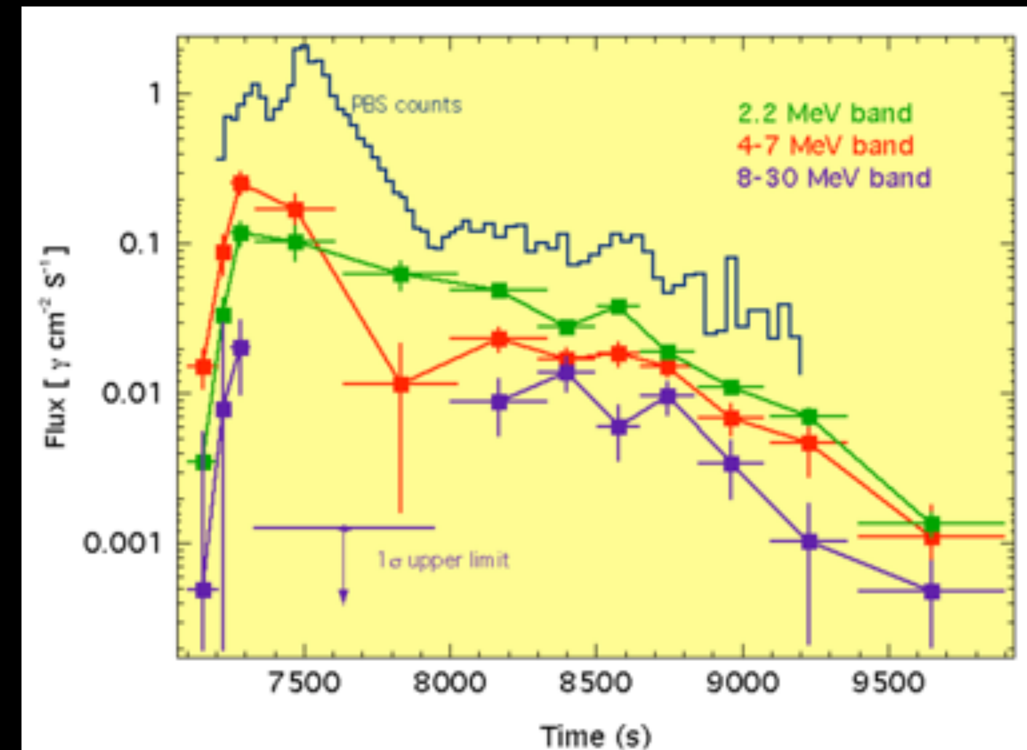


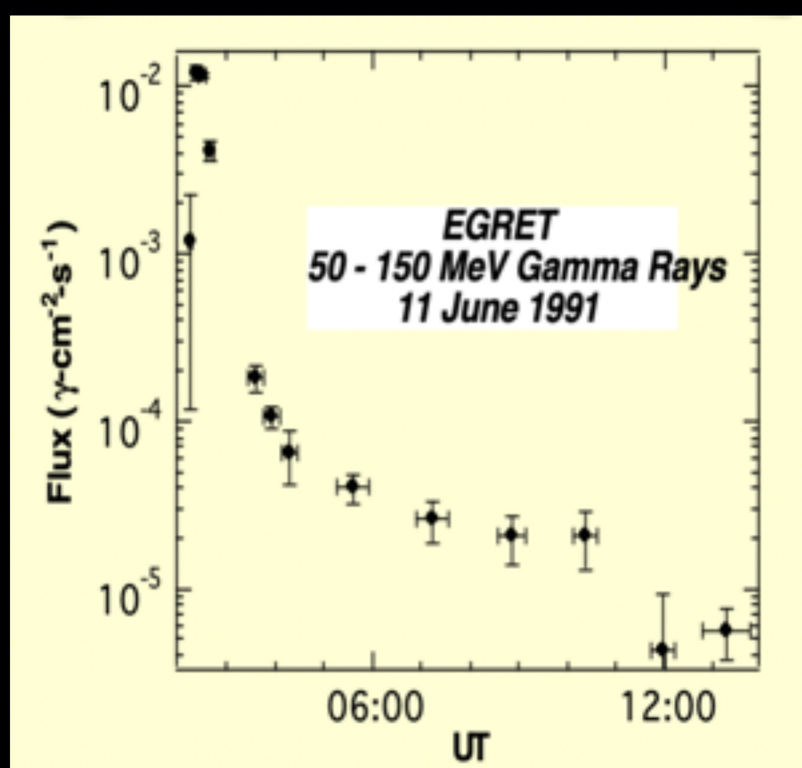
Grechnev et al. (2019) provided evidence through radio observations (NRH) that the behind-the-limb flare of 2014 Sep 1 involved two distinct quasi-static loops of different sizes with emission consistent with prolonged confinement (and perhaps reaccelerating)

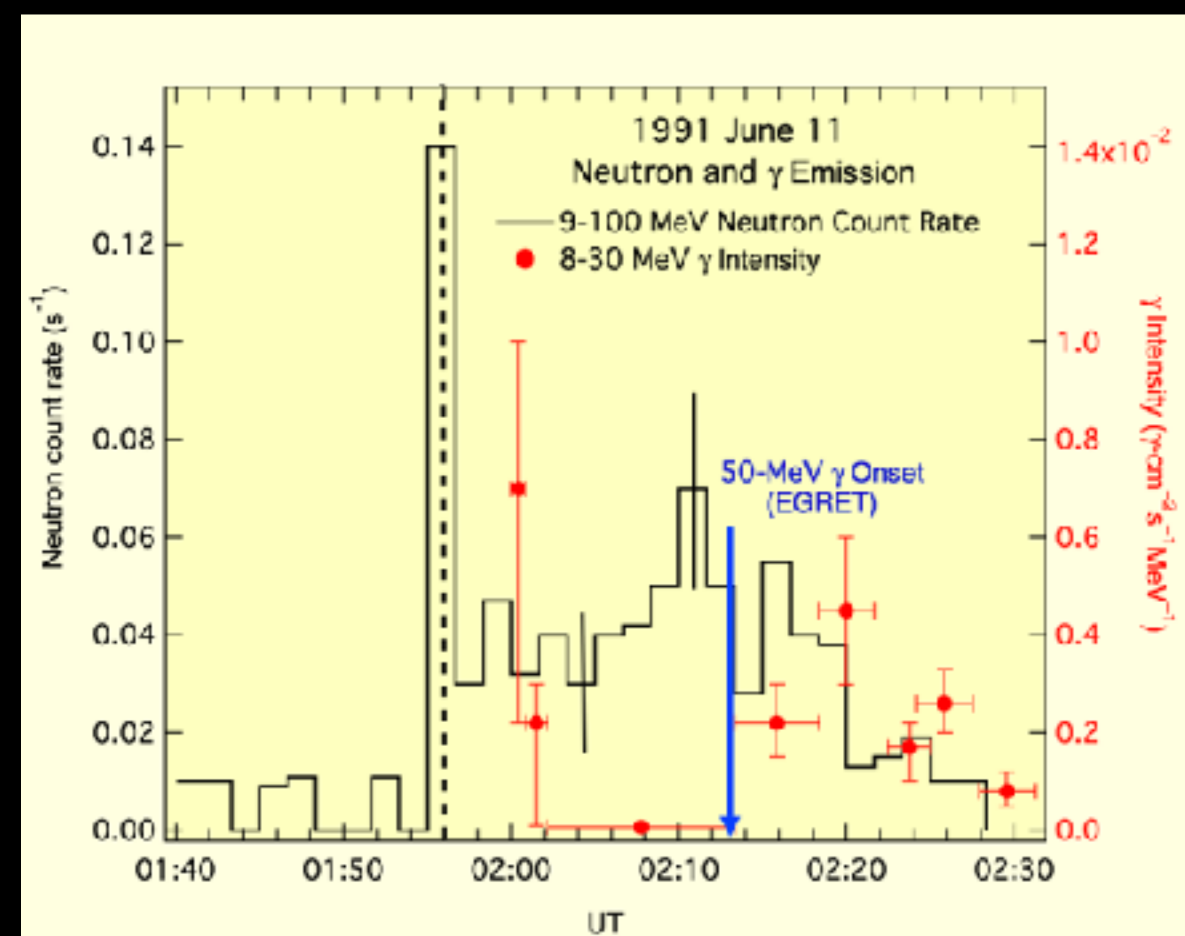
However, Omodei et al. 2018 found localization consistent with flare over 6 hrs and inferred from the temporal variation 3 phases the last of which is consistent with LDGRF emission originating in a CME-driven shock wave.

Evidence for continuous, progressive acceleration ?

Compton Gamma-Ray Observatory







Possible Complications

1) Simplified model: include non-uniformity of the magnetic field
2) Energy loss mechanisms (collisions, gradient drifts)
3) Currently spatial diffusion coefficient κ is independent of energy and position, making the momentum diffusion ~p^2
4) Need to investigate loop dimensions and relation to CME (and stability of loop during the eruptive process)
5) Maintaining appropriate level of turbulence in large loop to accelerate ions to >300 MeV over many hours, investigate possibility of self-generated waves produced by the low-energy protons that resonate with higher energy protons, producing a non-Kolmogorov spectrum, similar to that computed by Lee (1982).
6) include a momentum-dependent diffusion coefficient that will produce a varying power law spectral index.

Remaining Challenges

Problems with Remote Acceleration

- Smooth decay of gamma-rays and how does this relate to the path the particles take back to the Sun?
- Wildly discrepant numbers of particles estimated in space and at Sun.
- Some events require ~100% of IP particles to precipitate back to Sun.
- "Flare" spectrum significantly harder than IP spectrum.

Problems with Local Production

- Maintaining wave field for hours.
- Large loops quite common, but difficult to visualize.
  - ✓ Little glowing gas (SXR).
- With no indicators of loop size, difficult to estimate κ from *L*.

Summary & Conclusions

Long Duration Gamma-ray Flares are one of the most energetic processes at the Sun and pose significant challenges for modeling given the high energies and prolonged emission.

Based on recent comparisons with PAMELA covering the energy range of interest for studying LDGRFs (above pion production threshold of ~ 300 MeV), we conclude:

1) N_{SEP} is not correlated with N_{LDGRF}

⇒ Observe large variations (ratio spans 5 orders in magnitude)

2) Precipitation rates place challenging constraints on CME shocks as the source of LDGRFs

⇒ An alternate explanation for LDGRF emission is coronal trapping/

acceleration which decouples the SEPs from the interacting protons and where the effects of diffusion are consistent with smooth, exponentially decaying γ-ray light curves. Recent observations support the existence of large, persistent coronal loops and modeling efforts are promising.

Back ups