Comparing Long-Duration Gamma-ray Flares and High-Energy Solar Energetic Particles

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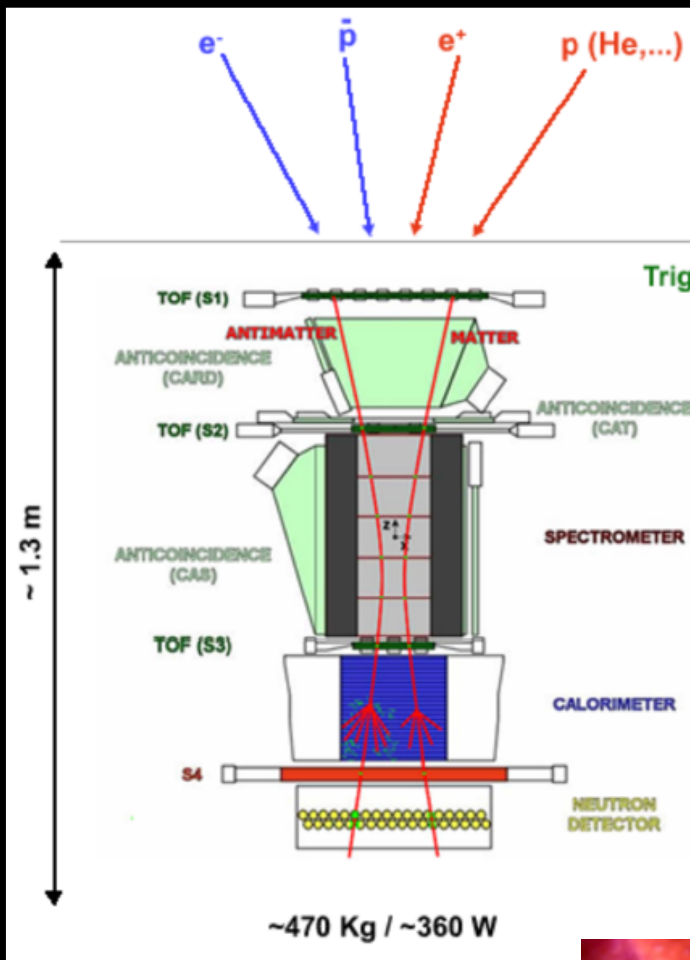
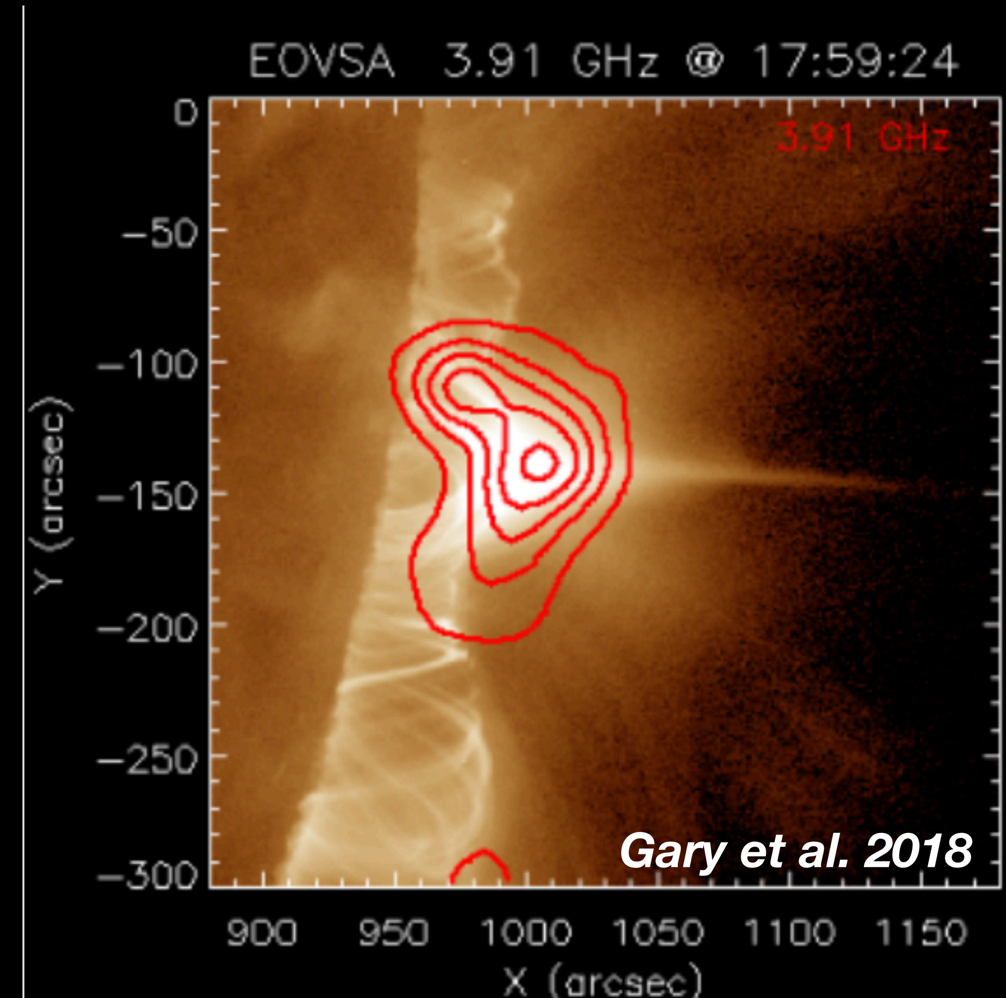
On behalf of the PAMELA Collaboration

Astrophysics Heliophysics



Payload for Matter-Antimatter Exploration and Light Nuclei Astrophysics (PAMELA)
Magnetic spectrometer with silicon tracking system, a ToF, and EC to measure GCRs from tens of MeV up to hundreds GeV
Also detect SEPs (see Bruno et al. 2018, this ICRC as well)



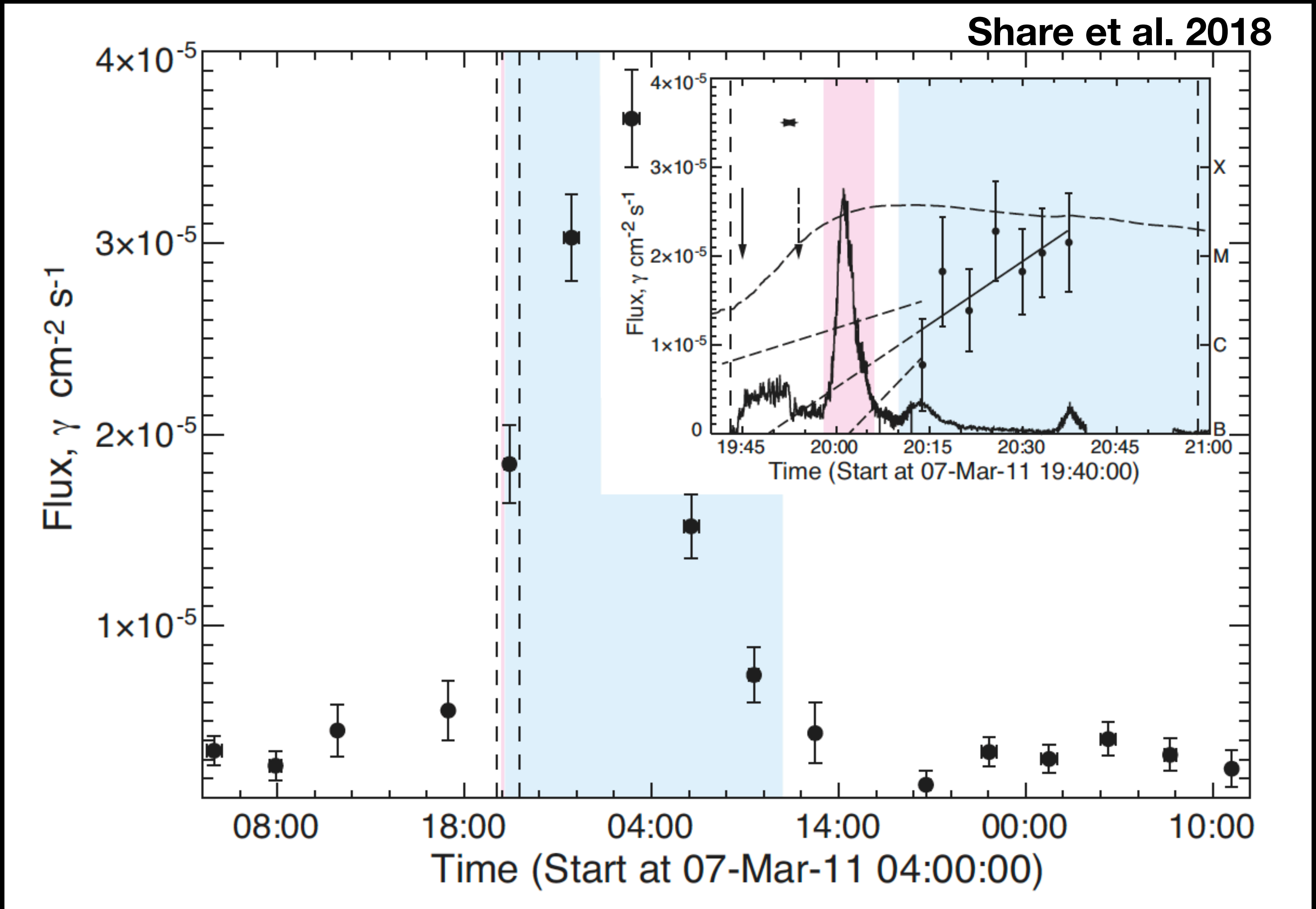
***Fermi*/LAT**
pair-conversion telescope with sensitivity to γ-rays between 20 MeV and 300 GeV & duty cycle for solar events of ~20%

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!

Introduction : Long Duration Gamma-ray Flares

* Delayed and prolonged > 50 MeV γ-ray emission well after the impulsive phase (durations up to 20 hrs!).
* Associated with > 100 keV X-ray emission, CMEs, Type II & III radio emission (see *G. Share et al. 2018*)
* More (x10) fluence in delayed phase than impulsive phase



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

* 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). See, for instance, *Ackermann et al. 2017*

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

Two Competing Theories

CME back-precipitation Scenario

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

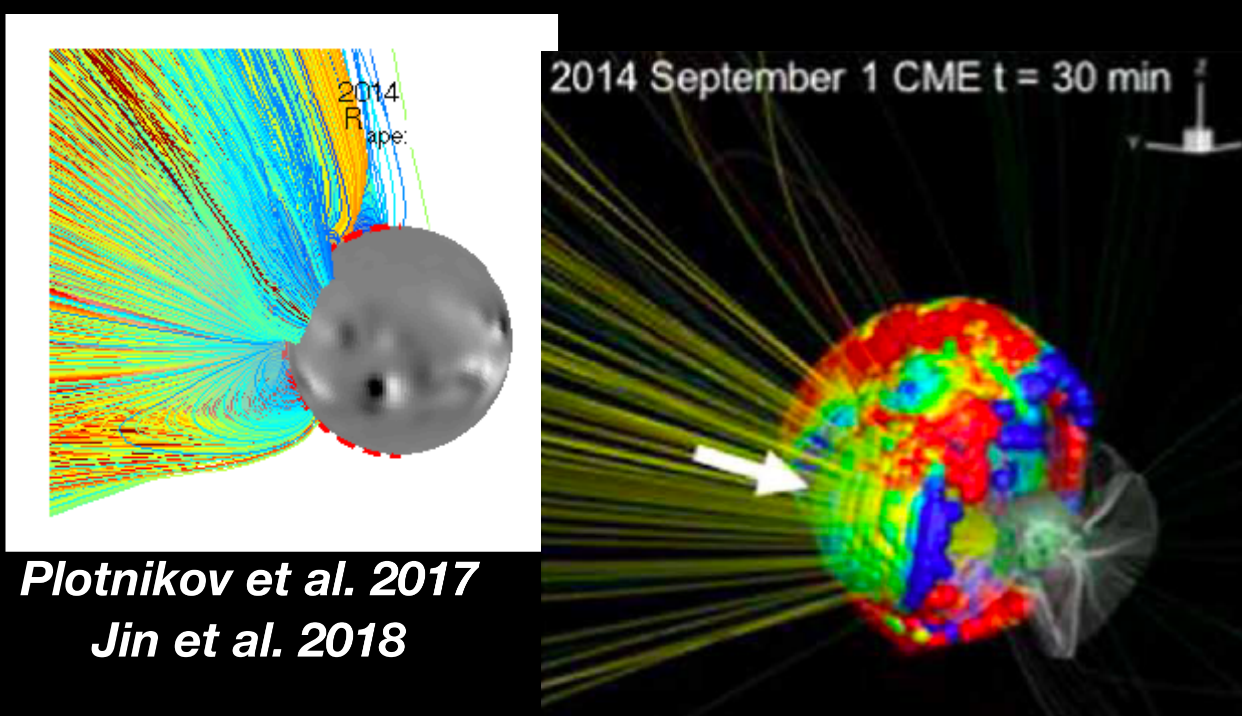
— Attributed to CME-shock-accelerated protons that make their way back to the photosphere.

— Show that the reconstructed shock fronts become magnetically connected to visible solar surface just before onset of > 100 MeV γ-ray emission

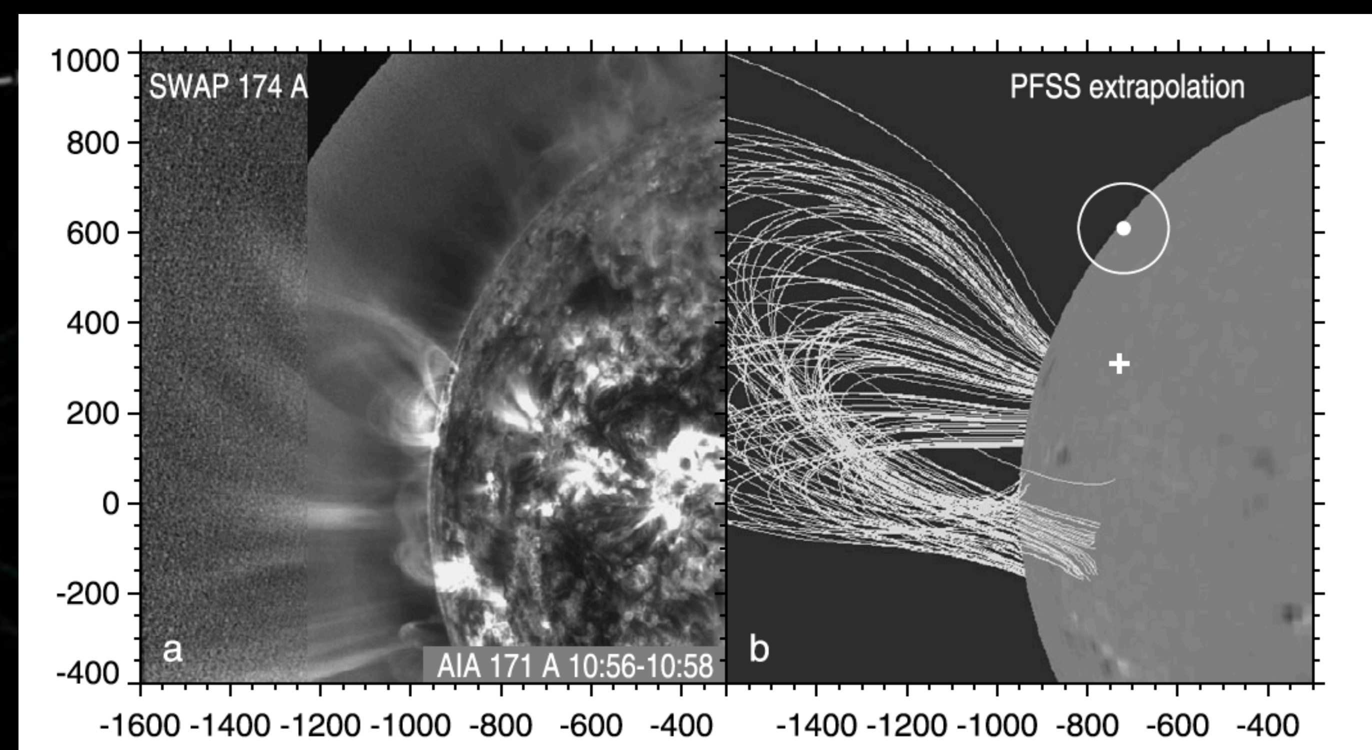
Trapping & Acceleration in Large Coronal Loops

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

Consider injection and 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.



Plotnikov et al. 2017
Jin et al. 2018



Grechnev et al. 2018, see also *Ryan et al. this ICRC*

Compelling correlations between LDGRFs, CME speed, and Type II radio emission *(Winter et al. 2018 ; Gopalswamy et al. 2018)*.

⇒ both models have supporting observations

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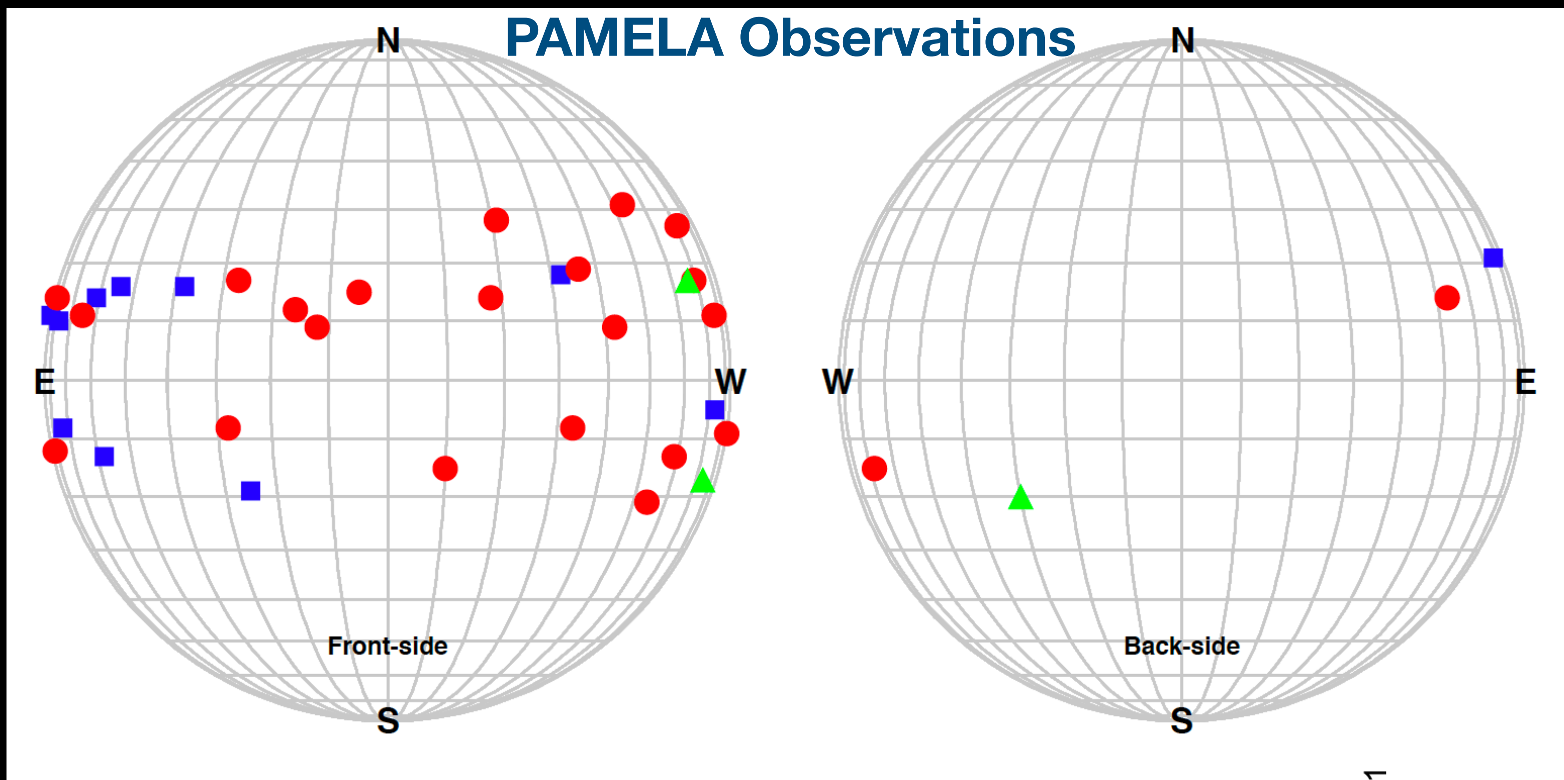
⇒ Gain some insight into origin of LDGRFs by comparing with SEPs measured by PAMELA (either the populations are related or result from distinct processes)



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)

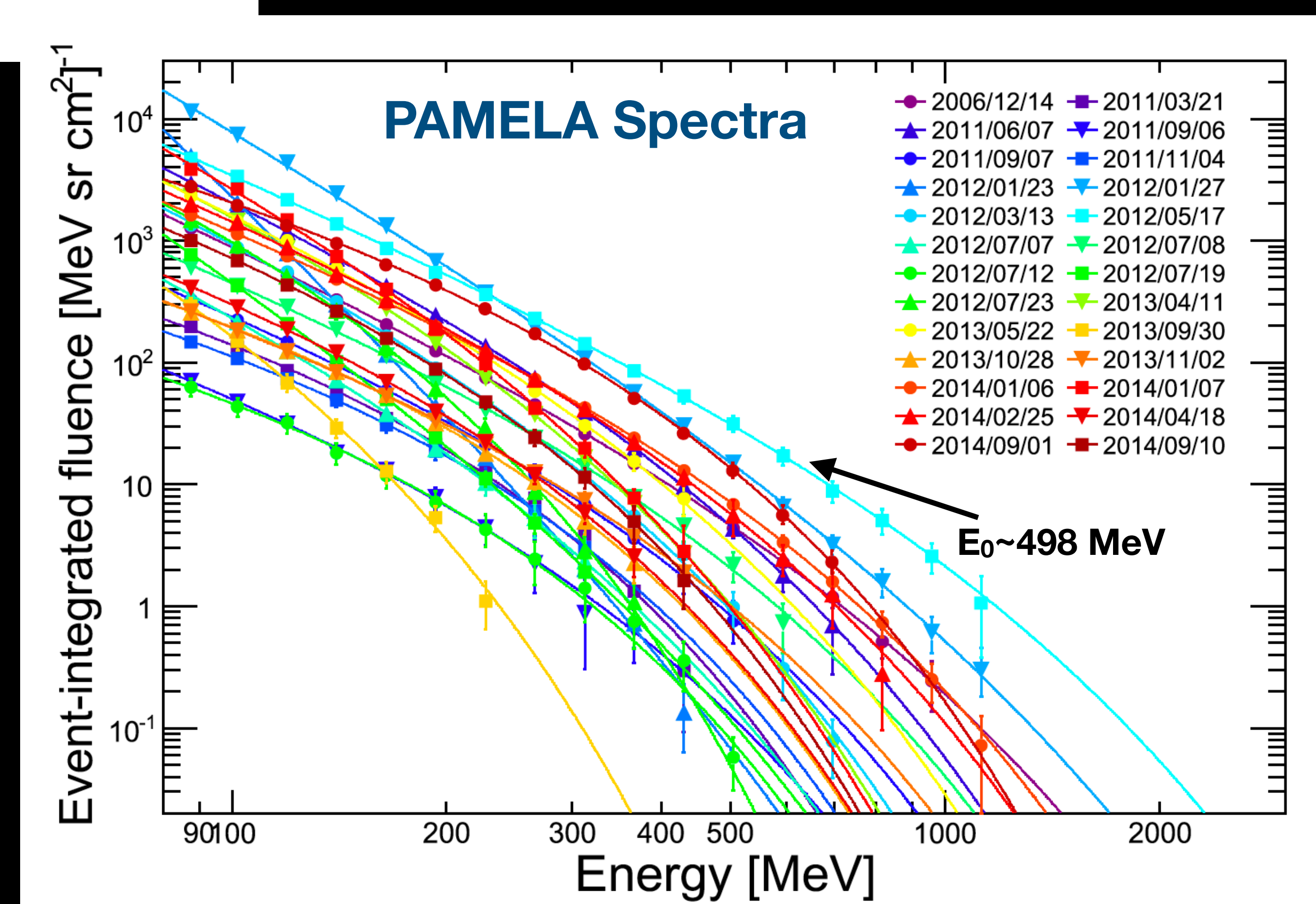
In summary, 18 out of the 25 SEP events observed by PAMELA were associated with LDGRFs by Fermi/LAT

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

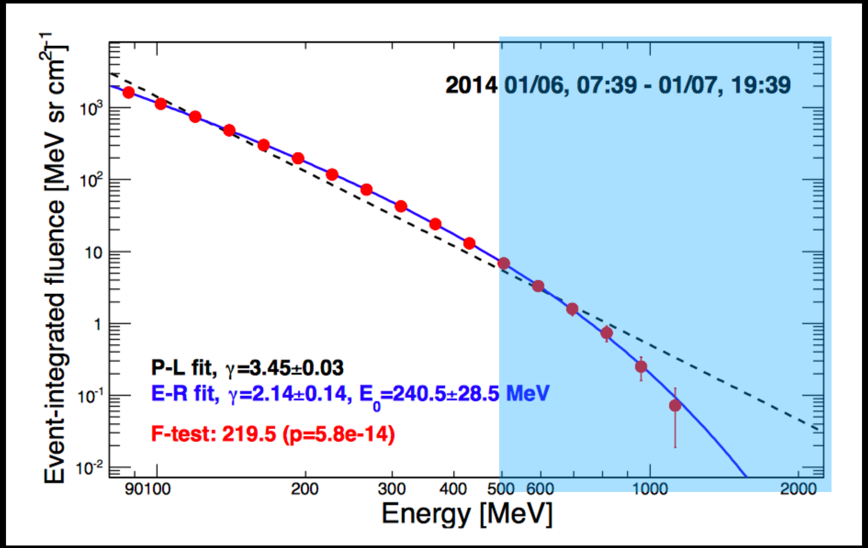
$$\Phi_{sep}(E) = A \times (E/E_s)^{-\gamma} \times e^{-E/E_0},$$

* PAMELA measured spectra for 26 SEP events (see: *Bruno, A. et al. (2018), ApJ 862:97 also, Bruno et al. this ICRC)*

** 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

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

$d\Omega = d\varphi d\vartheta \sin(\vartheta)$ is the solid angle element of the particle velocity direction at a point centered on the sphere and J is the event-integrated intensity

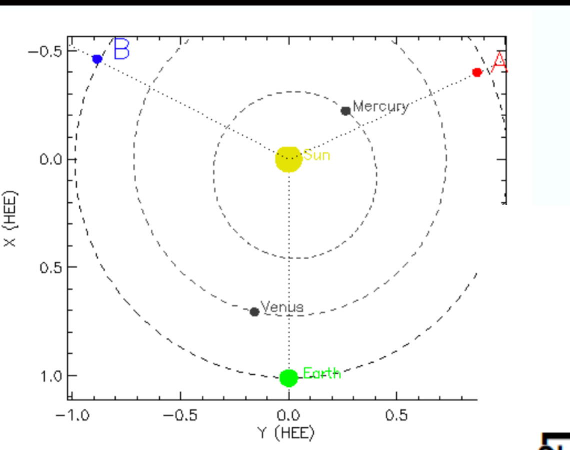
2. Compute number of protons assuming particle spatial distributions that is characterized by a periodic Gaussian (G(δ)) & integrate over a heliocentric spherical surface, S, at 1 AU.

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

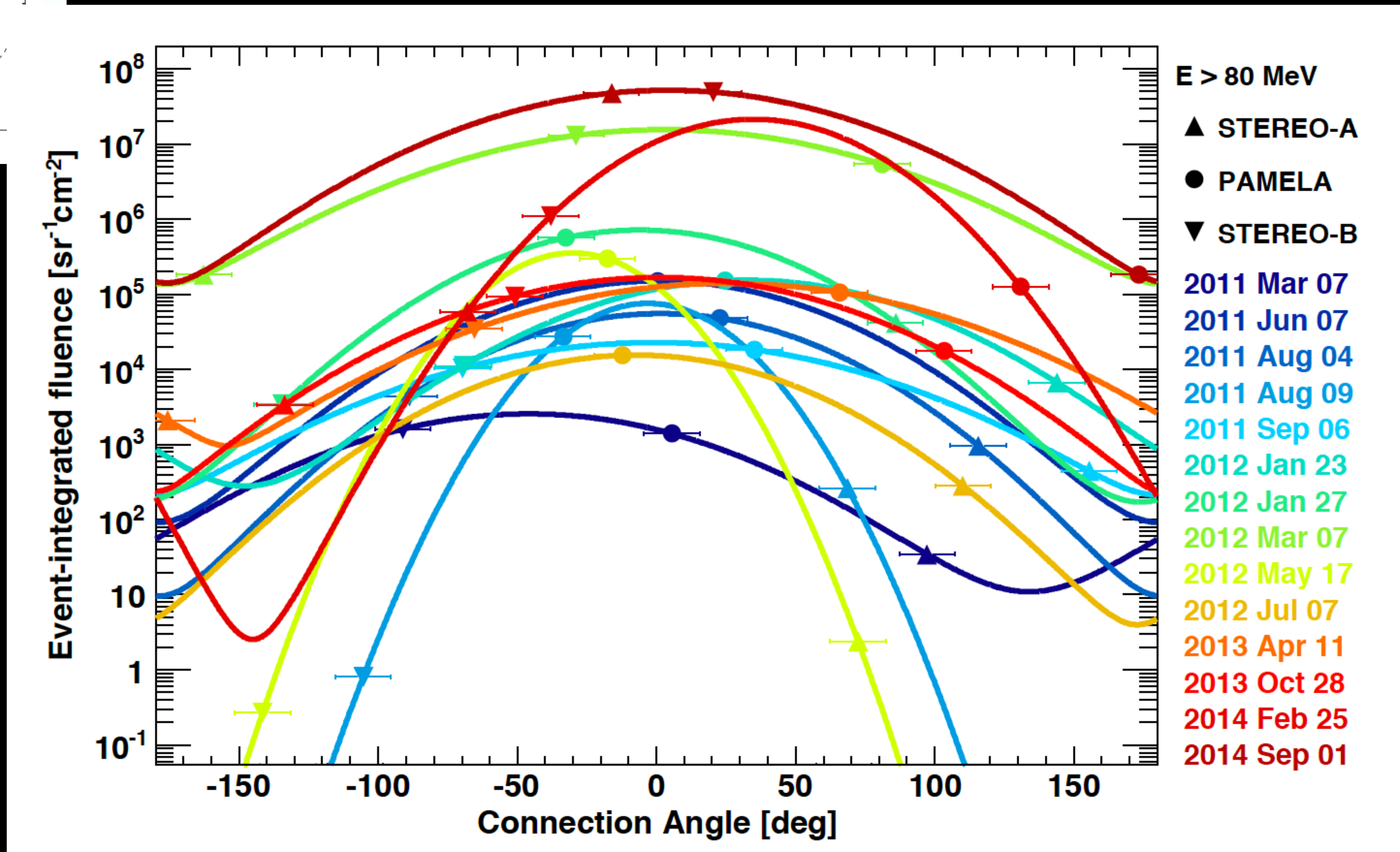
J_E is the > 500 MeV event-event-integrated intensity observed by PAMELA
S_J is the spherical area weighted by the particle spatial distribution
δ is the great-circle distance wrt the peak of the SEP partial distribution

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,
2. N_{cross} takes into account multiple measurements of the same particles (beam vs. isotropic)



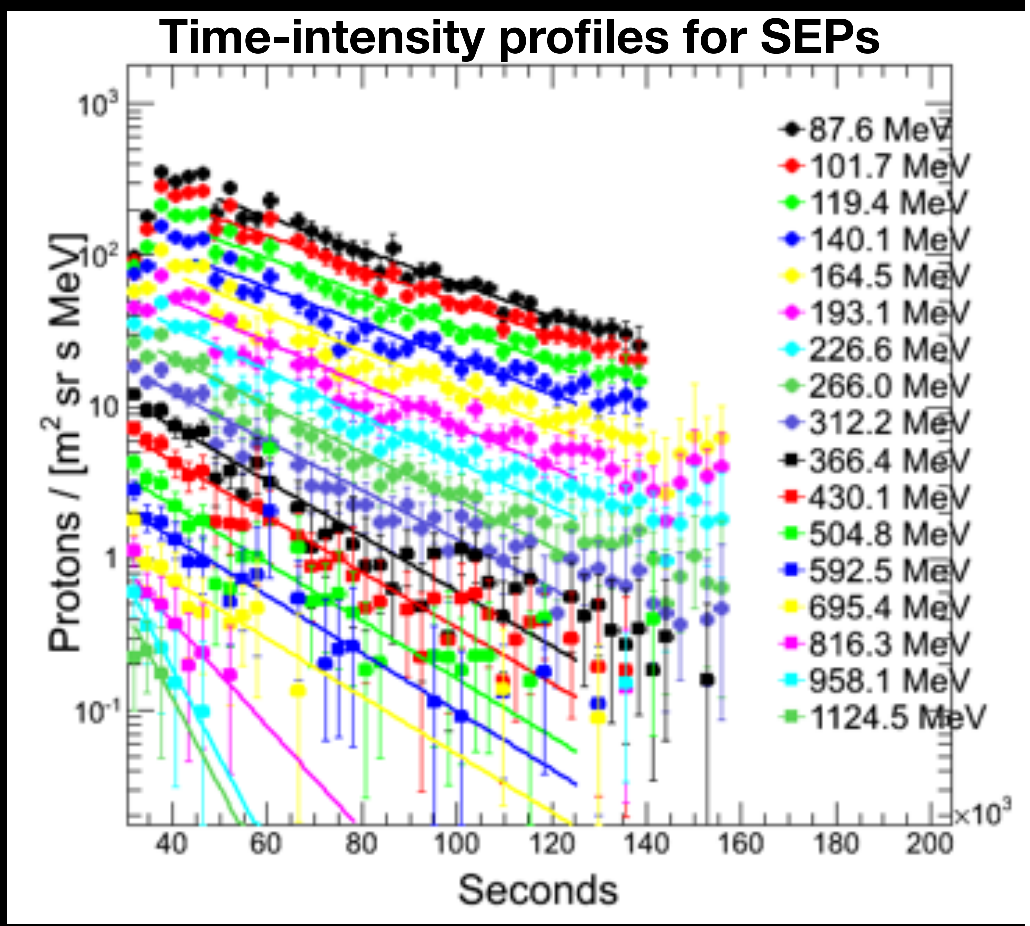
Periodic Gaussian Fits at > 80 MeV Fluences

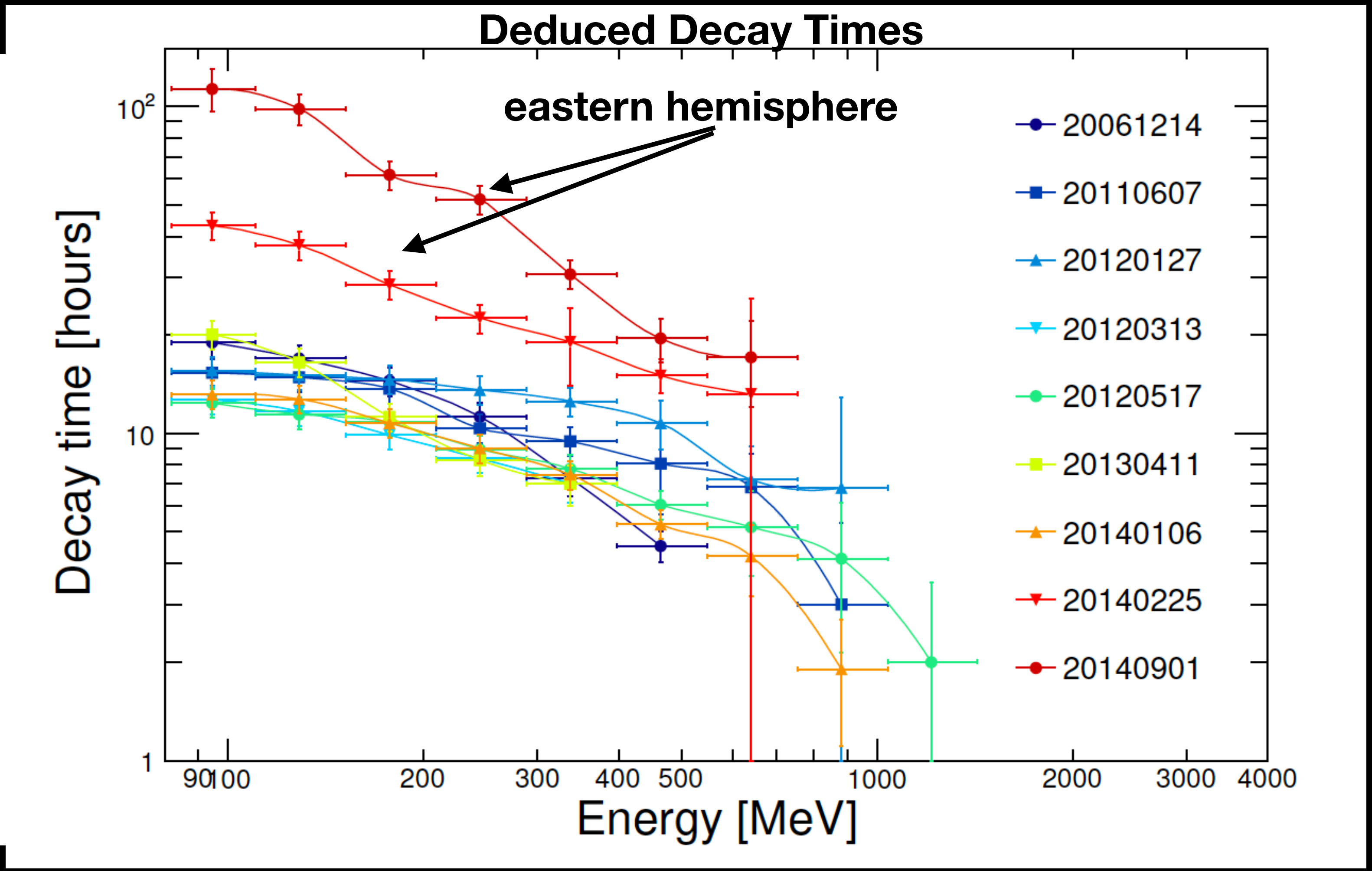


Longitudinal extent of SEP events determined from the fits of the event-integrated intensities (>80 MeV) measured by PAMELA and STEREO A/B as a function of connection angle between the S/C magnetic footpoint at 30 R_s & the location of the parent flare.

PAMELA Observations also help to constrain transport

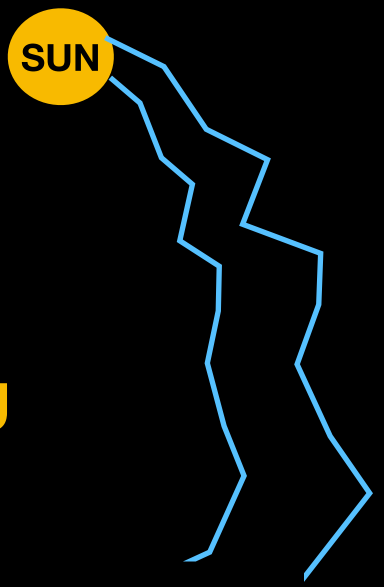
* SEP transport is governed by both large scale magnetic topology & scattering from small scale magnetic turbulence
* The amount of scattering affects the SEP intensity and anisotropy distributions





Such trends ae 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

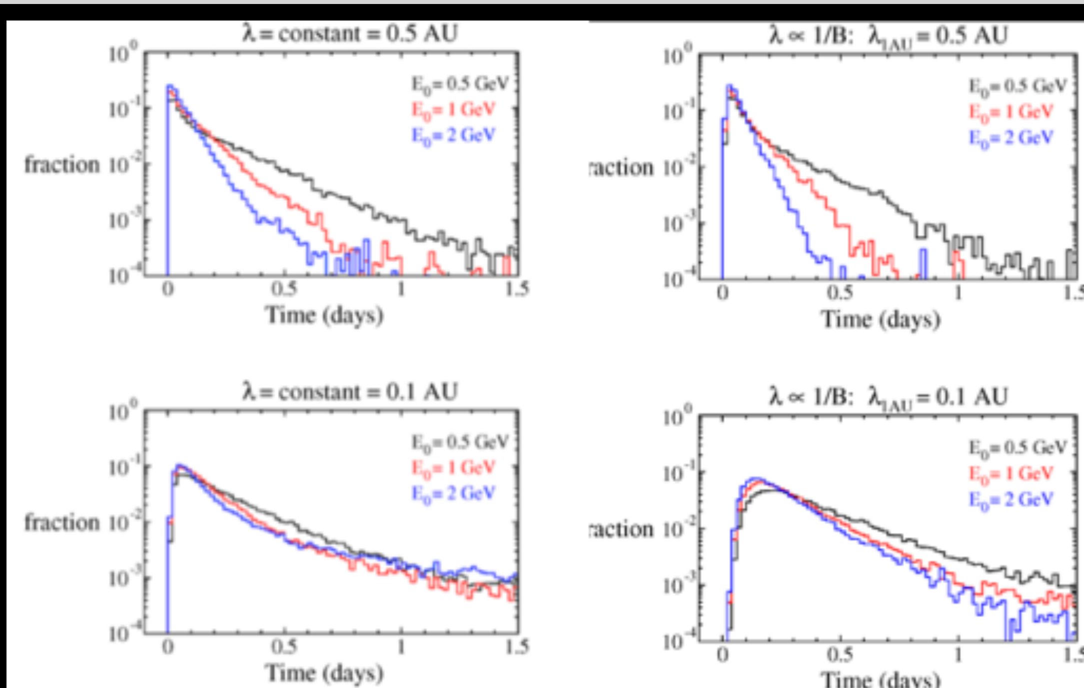
Consider 2 test particle models

1) Simulation by Chollet et al. 2010
2) Simulation by Barttarbee 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)



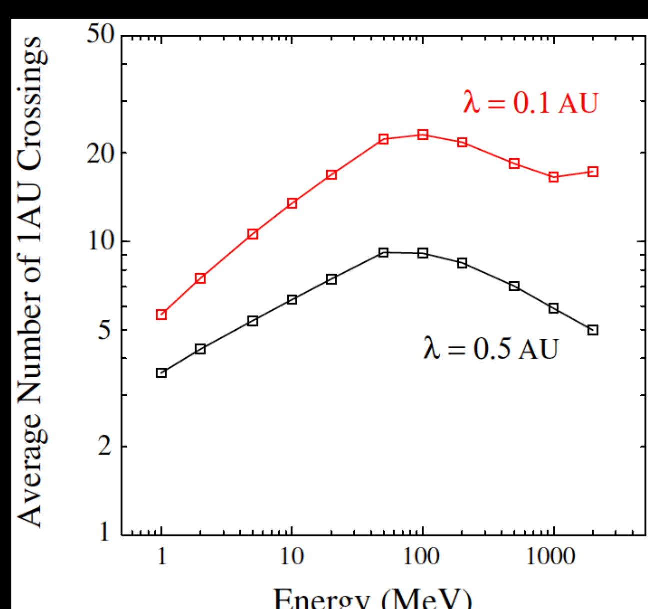
⇒ short λ

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

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

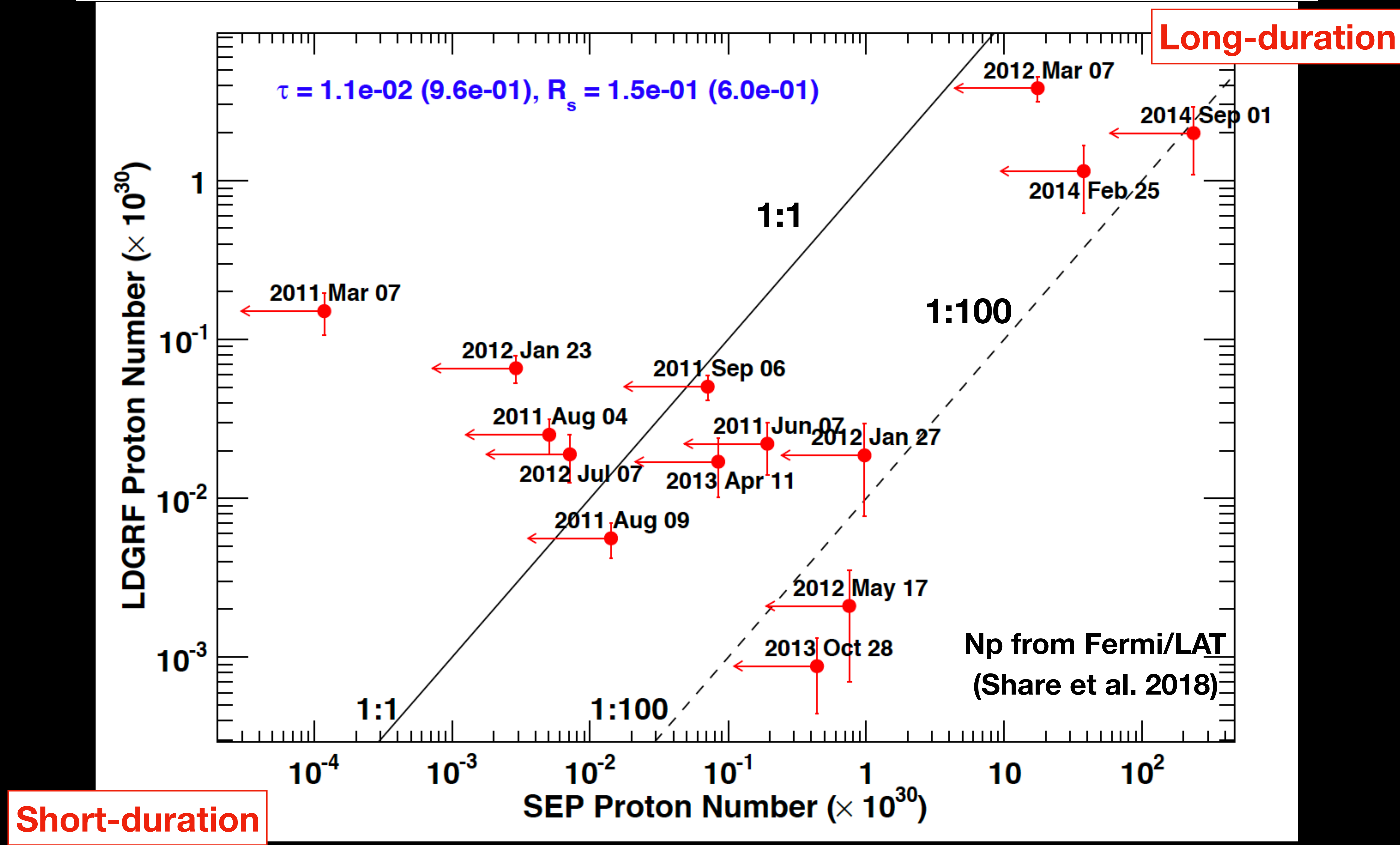
Compute number of protons assuming an isotropic flux & integrate over spherical surface at 1 AU.

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

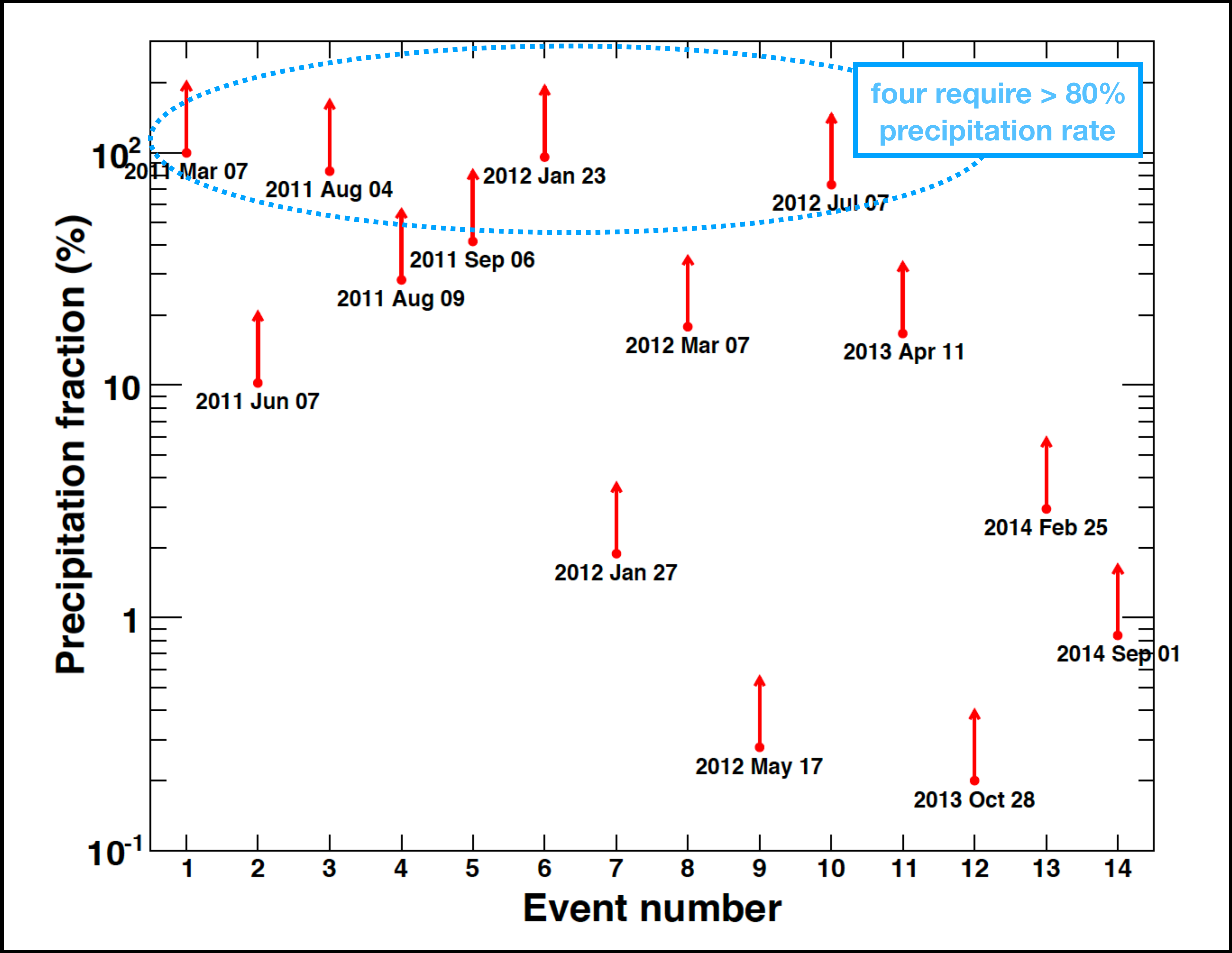
⇒ Compute upper limits for N_p

Comparing > 500 MeV N_p in space and at the Sun



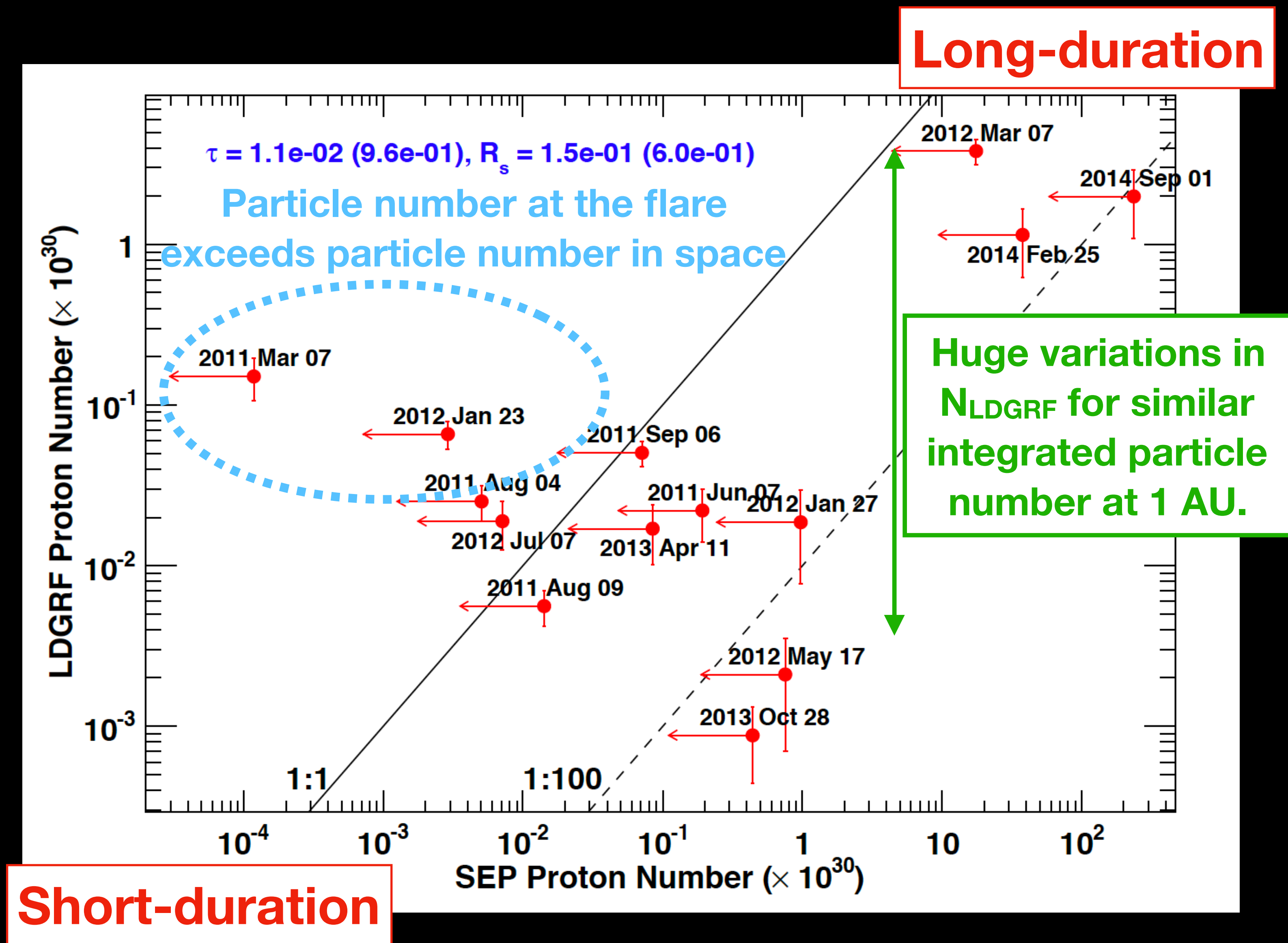
* No correlation (low values of the Kendall's τ and Spearman rank correlation coeffs).
* N_{SEP}/N_{LDGRF} ratio spans > 5 decades of magnitude from 7.8×10^{-4} to $\sim 5.0 \times 10^{2}$

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 :

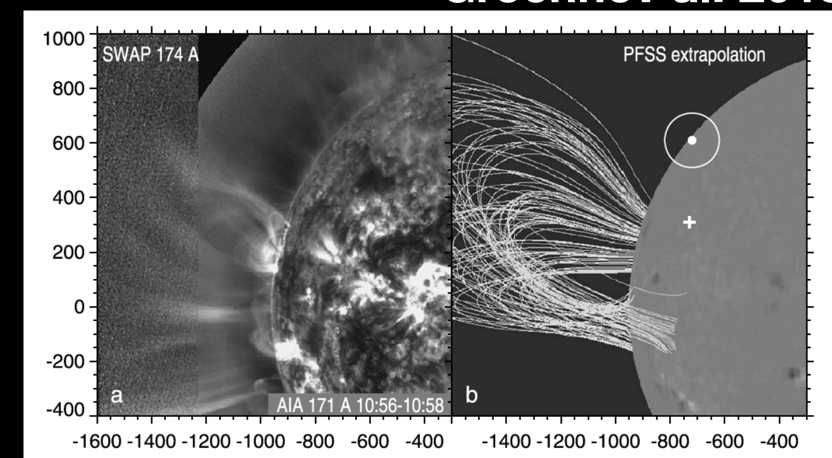
1) an enormous loss channel for the shock
2) high shock formation heights, resulting in a weakening shock, adding to the challenge of accelerating particles to high-energy.

— 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)

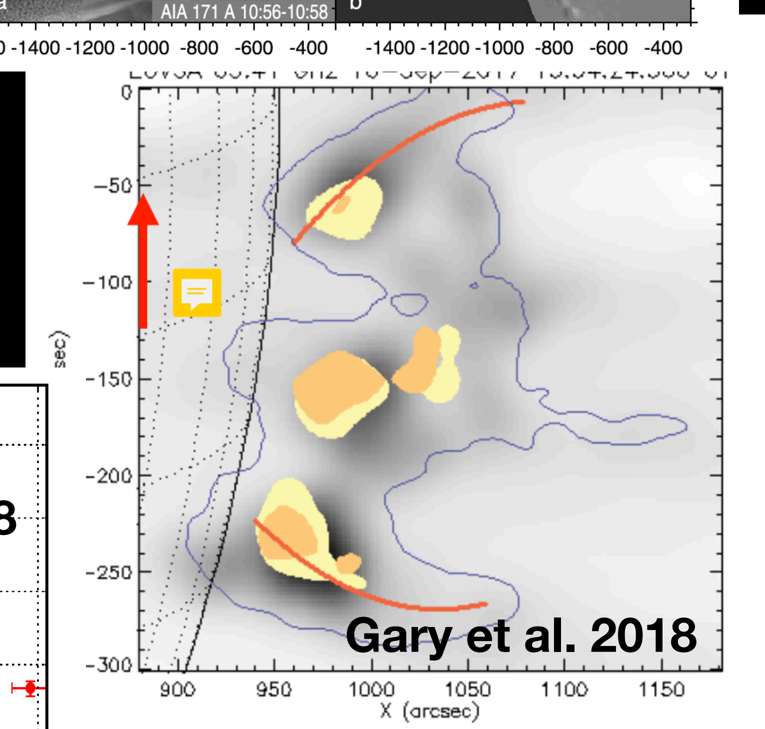
Alternate Scenario: Trapping in Large Coronal Loops

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

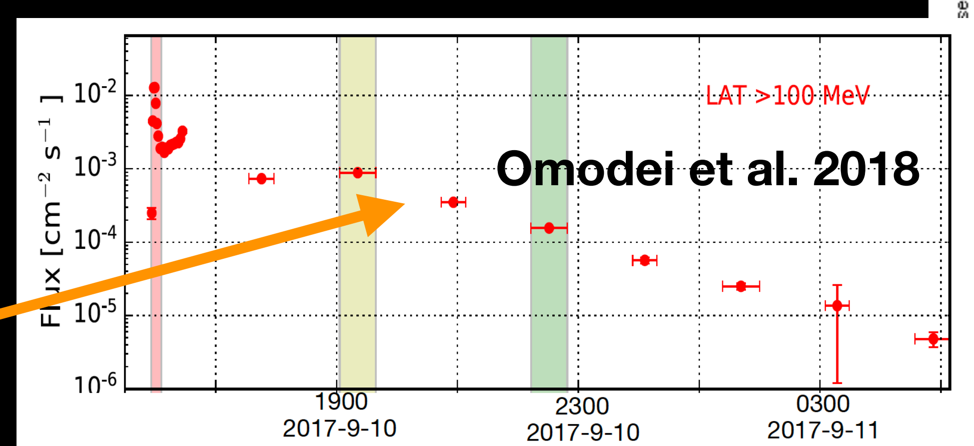
Grechnev al. 2018



1) **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)**



2) **Gary et al. (2018) used microwave (EOVSA) observations to show footpoints of a large coronal loop for the 2017 Sep 10 flare with circular length of 1.4 R_s & microwave emission persisting into the period of the > 100 MeV γ-ray emission.**



⇒ Smooth, robust exponential decay argues for coronal trap scenario, with spatial and momentum diffusion governing the precipitation (see Ryan et al. this ICRC)

What Have We Learned?

— Unique observations of PAMELA SEPs cover the energy range of interest for studying LDGRFs (above pion production threshold of ~ 300 MeV)

⇒ Observe spectral roll-overs important as well as properly accounting for the spatial distribution and transport (N_{cross})

— N_{SEP} is not correlated with N_{LDGRF}

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

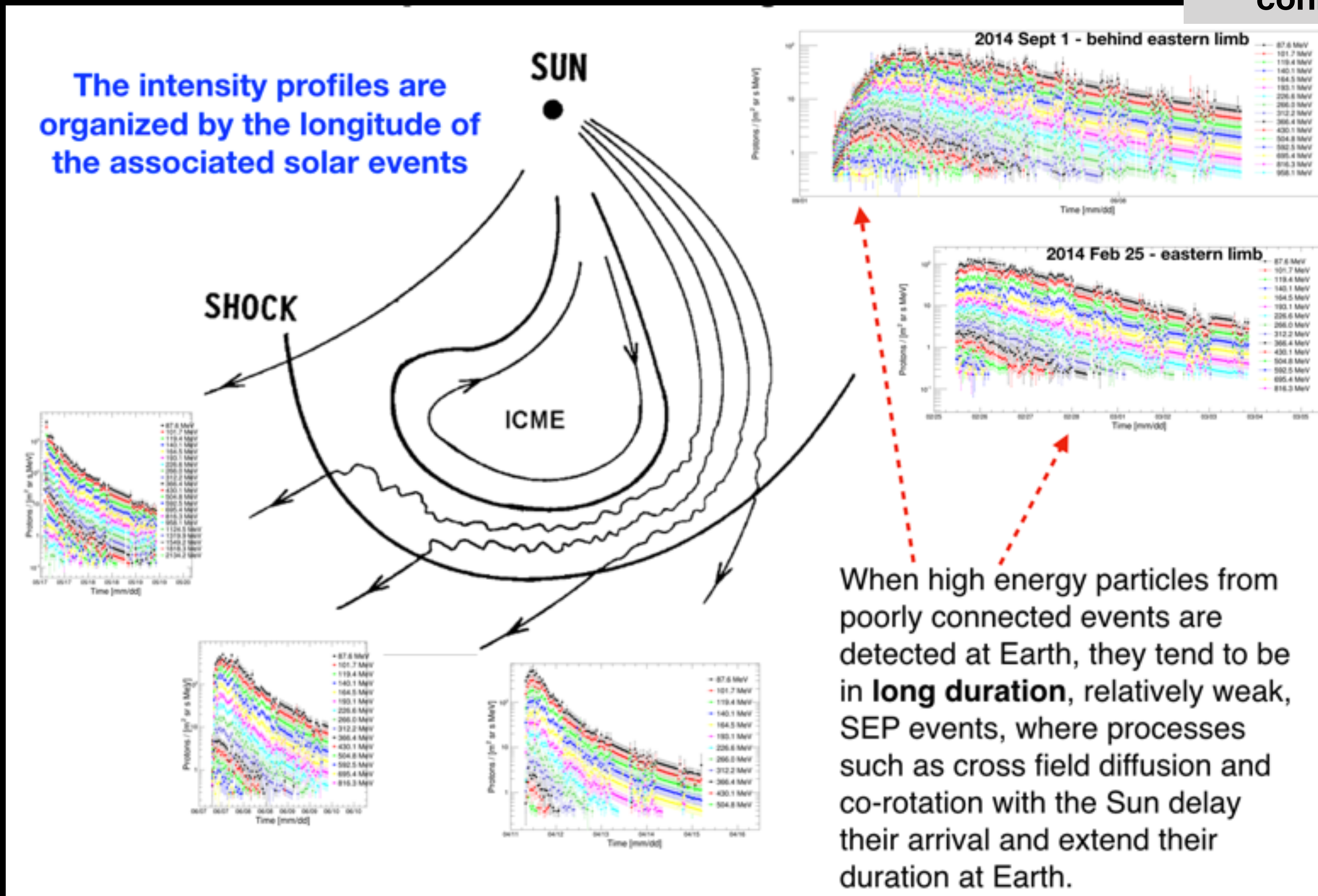
⇒ Precipitation rates place challenging constraints on CME shocks as the source of LDGRFs (see *de Nolfo et al. 2019*).

⇒ 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 (see *Ryan et al. this ICRC*).

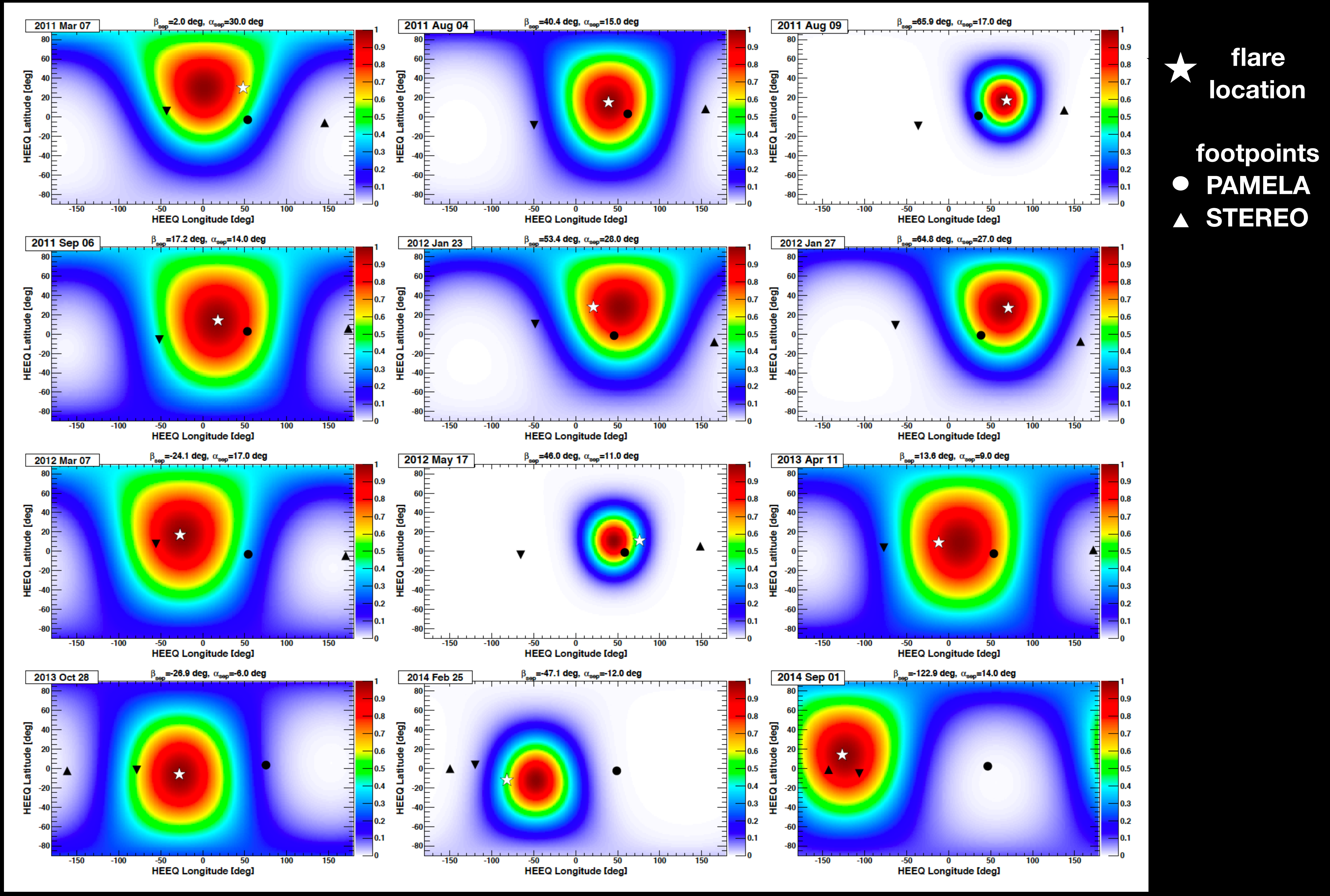
Back ups

SEP Transport

Longer time profiles for events that are not well connected



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

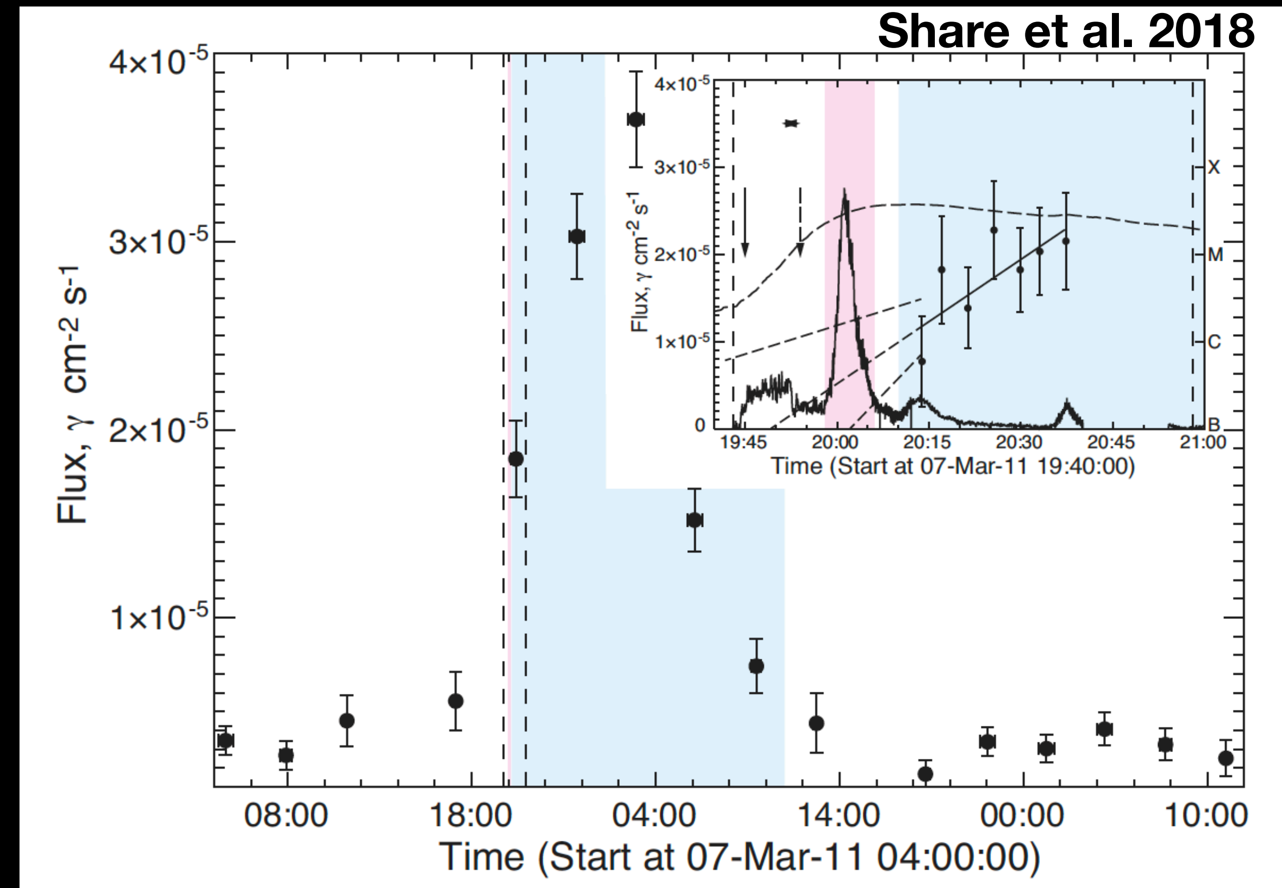


G. A. de Nolfo Heliocentric Earth Equatorial (HEEQ)coordinates ICRC 2019

Introduction : Long Duration Gamma-ray Flares

* Delayed and prolonged >50 MeV γ-ray emission well after the impulsive phase.

* High-energy gamma-ray emission (>100 MeV) is thought to originate primarily from the decay of pions, produced by protons (and alpha) particles above ~300 MeV (above ~200 MeV). See for instance Ackermann et al. 2017)



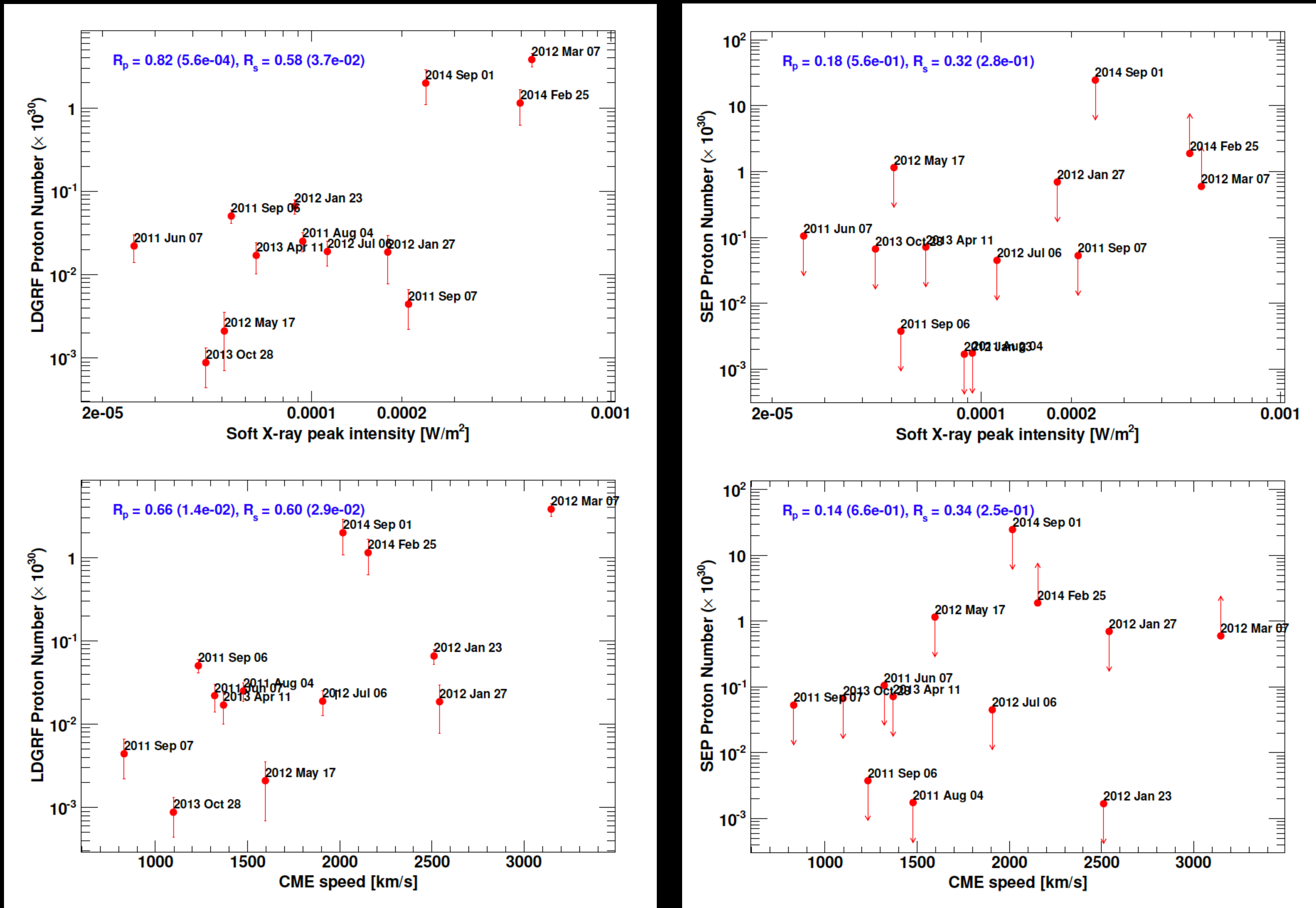
Time history of > 100 MeV gamma-ray flux from Fermi/LAT. Inset compares with GBM 100-300 keV & dashed curve is soft x-rays

Recent comprehensive work by Share et al. 2018 on "Late Phase Gamma-ray Emission"

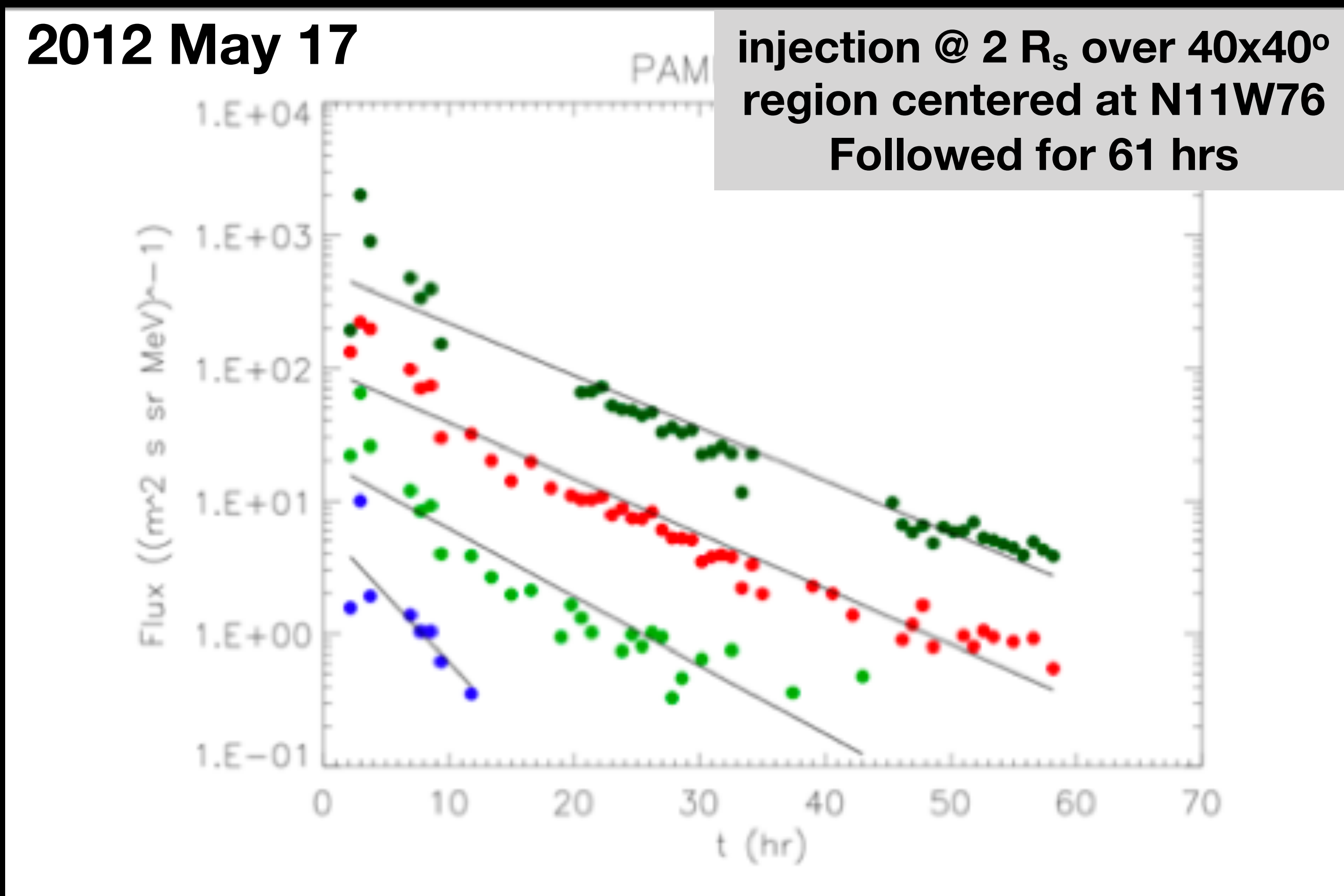
1. Delayed γ-ray emission is associated with impulsive > 100 keV x-ray emission
2. There are x10 more protons accelerated in delayed phase than impulsive
3. There is a delay from CME onset of a few minutes to ~6 hours
4. Most LPGREs were associated with CMEs, Type II & III radio emission
5. > 500 protons needed to produce LPGRE range from 0.1 to 50% the number of protons in SEPs

=> Use direct observations of high-energy spectra from PAMELA and improve statistics

Comparing N_p to CME, X-ray Flare Parameters



Battarbee et al. 2018 model simulation for GLE 2012 May 17



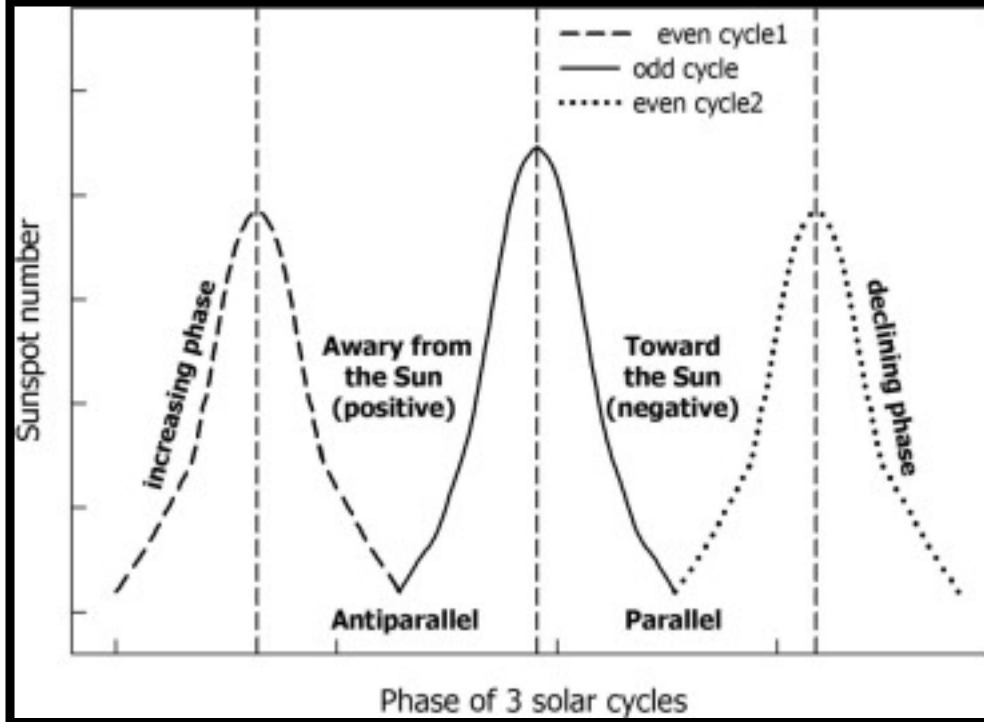
Full simulation of the 2012 May 17 event, with initial proton distribution given by a power law, shows good agreement with PAMELA intensity time profiles for the case where λ = 0.3 AU (Dalla et al., in preparation).

λ = const, crossings over entire 1 AU sphere are added together and averaged over the monoenergetic population considered.

We assume λ = 0.5 AU (and wavy HCS) conservatively in order to compute upper limits to the proton numbers in space from SEPs

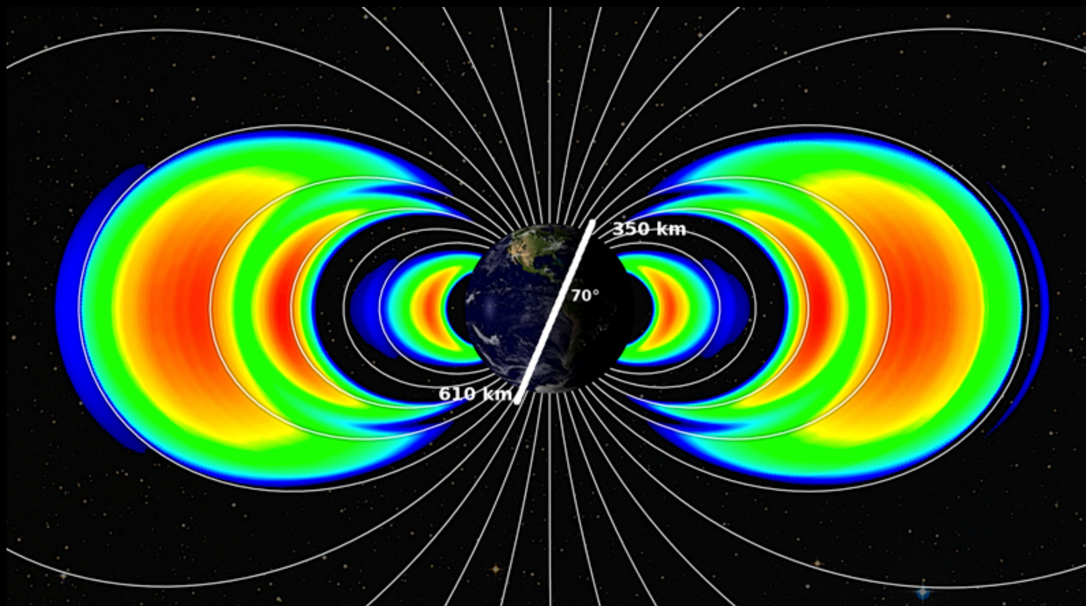
HCS Polarity Effects

Energy (MeV)	λ (AU)	HCS configuration	Polarity	$N_{crossings}$
1000	0.1	no HCS	+ve everywhere	31
1000	0.1	no HCS	-ve everywhere	28
1000	0.1	flat HCS	A^+	15
1000	0.1	flat HCS	A^-	28
1000	0.1	wavy HCS	A^+	17
1000	0.1	wavy HCS	A^-	29
500	0.1	flat HCS	A^+	19
500	0.1	flat HCS	A^-	29
500	0.5	flat HCS	A^+	8
500	0.5	flat HCS	A^-	11



The number of crossings depends on the solar polarity and varies for different configurations of the Heliospheric Current Sheet (HCS)

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



PAMELA: ~circular orbit (580 km altitude); 70° inclination

PAMELA is sensitive to the energy range (~80 MeV to several GeV) that corresponds to the interacting ions at the Sun that produce the LDGRFs!