Coronal Mass Ejections and Solar Gamma-ray Emission

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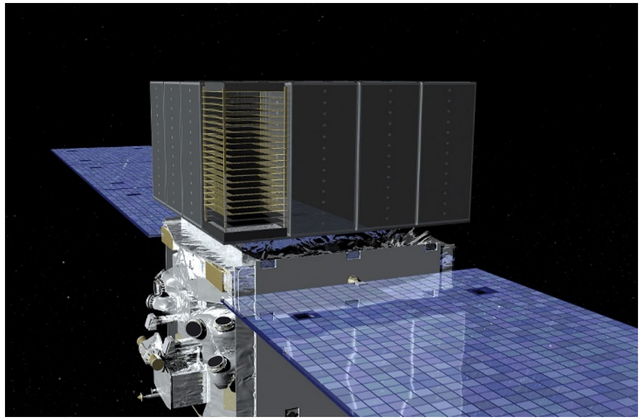
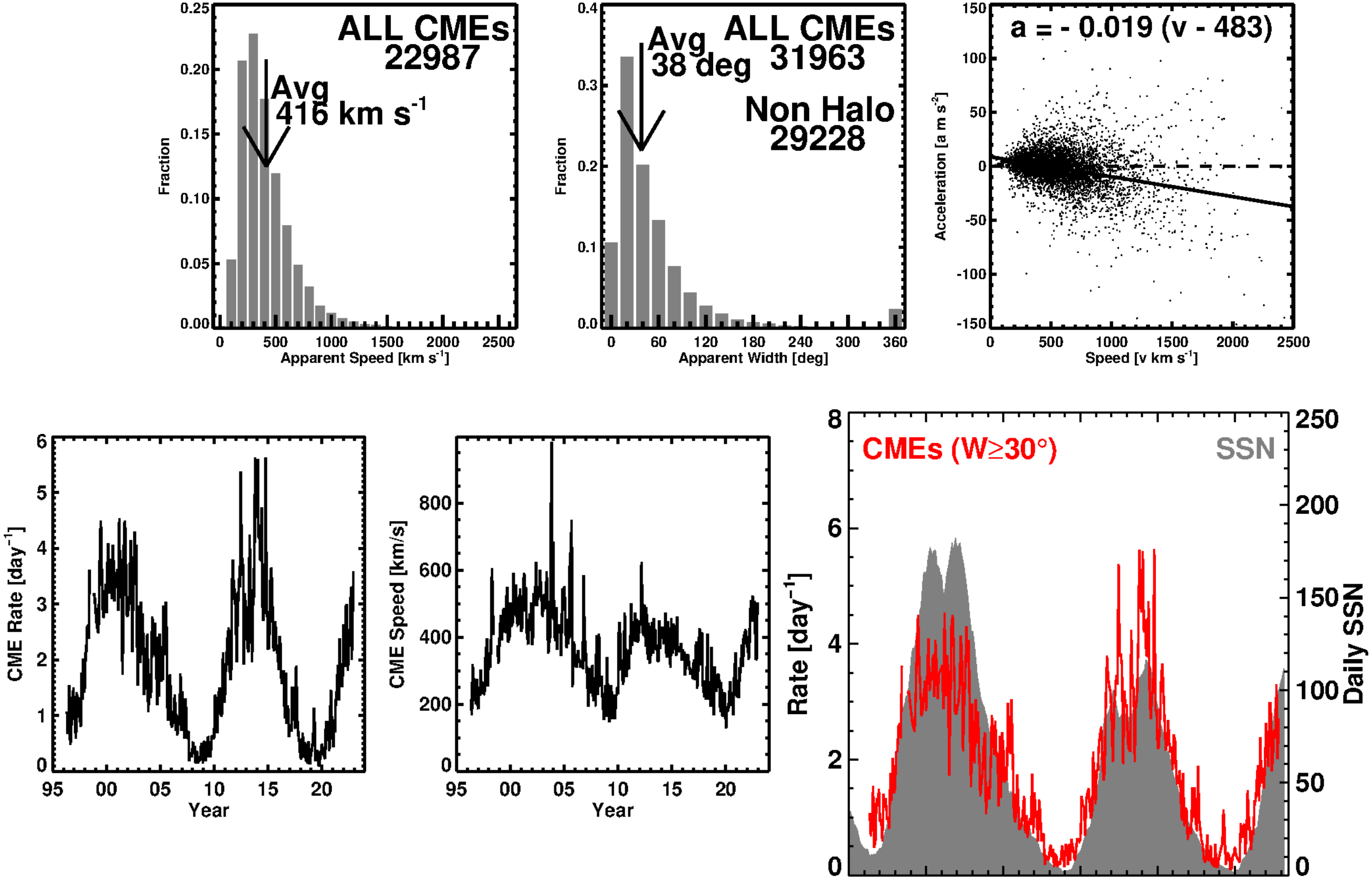
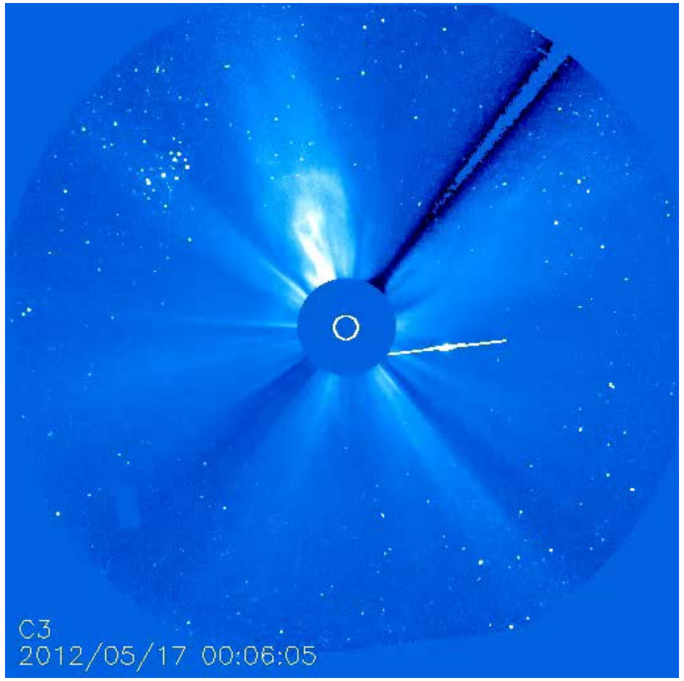
Fermi



Mid-Atlantic Senior Physicists Group Seminar
2023 April 19

Coronal Mass Ejections





ESA/NASA/SOHO

Speed: <100 km/s to >4000 km/s

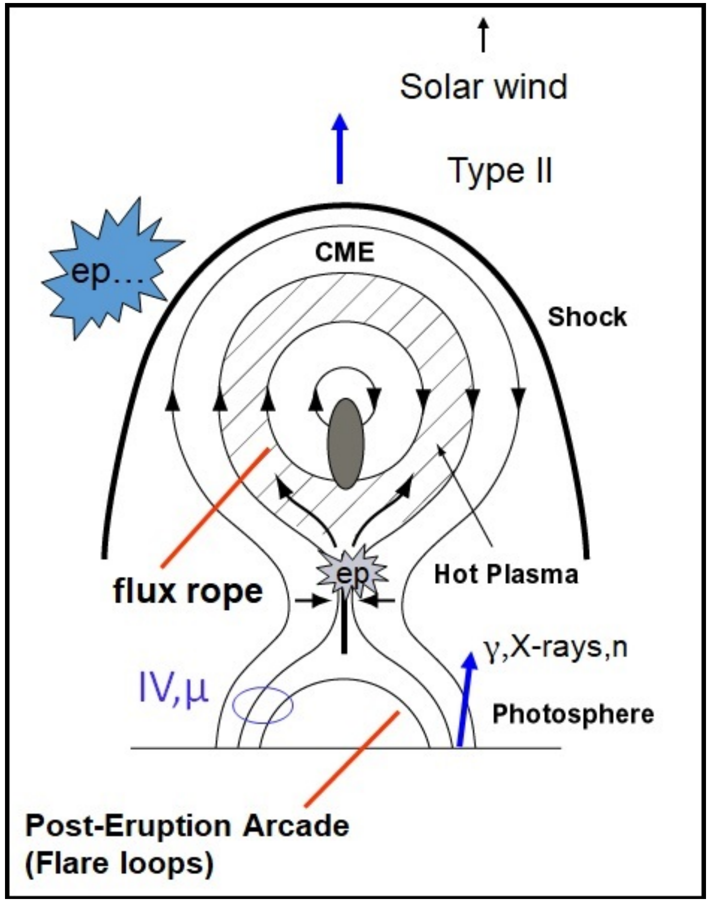
Mass ~ 10^{15} g

KE ~10^{30} erg

Coronal Mass Ejections: Associated Phenomena and Consequences

- Solar Flares
- Shocks
- Solar energetic particles
- Solar radio bursts

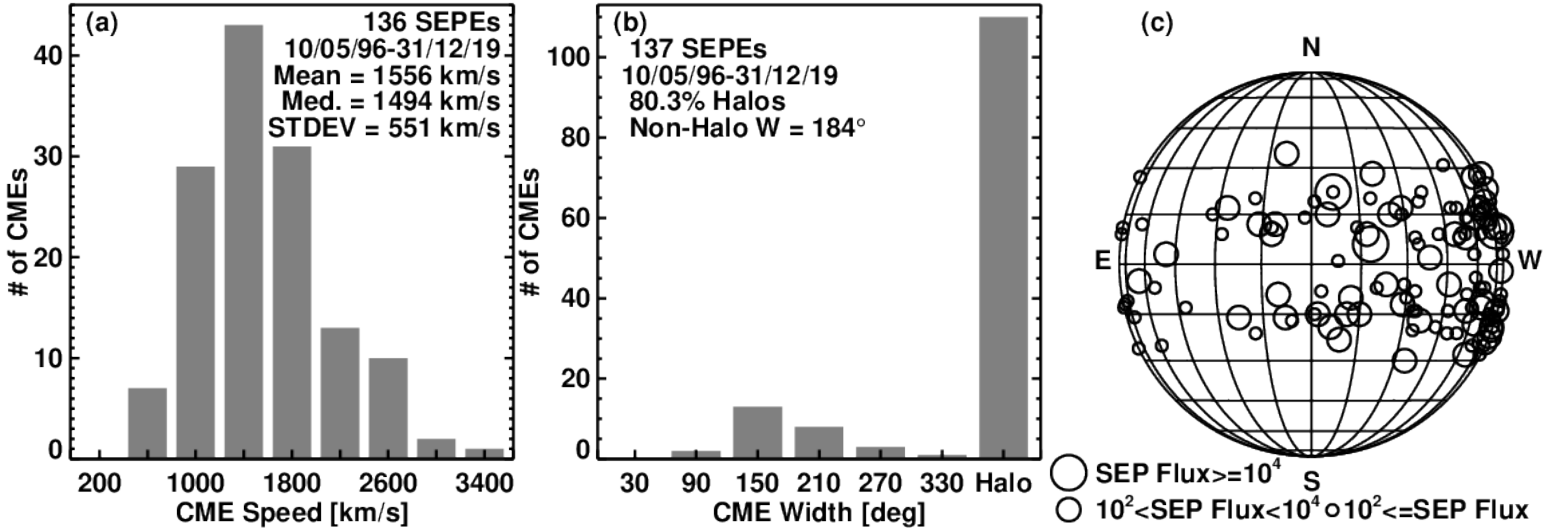
- Particle radiation hazard (SEU, dielectric discharge, astronauts, airplane passengers)
- Geomagnetic storms (Van Allen belt, GIC, ionospheric disturbances, atmospheric chemistry)



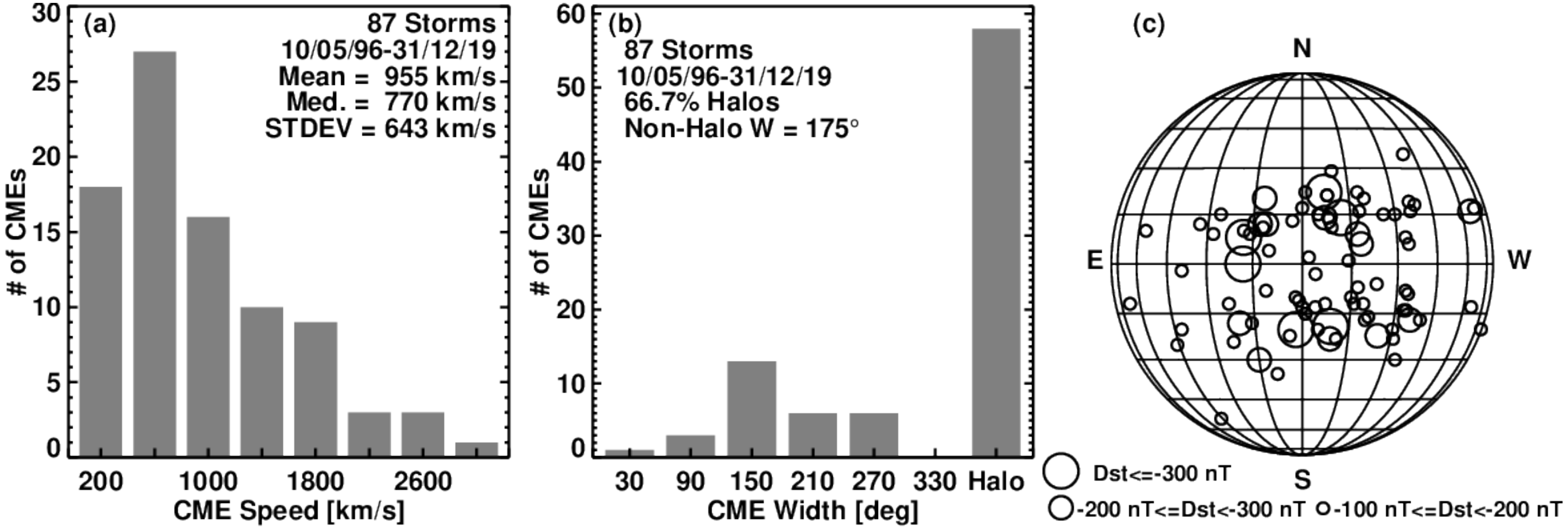
CMEs of Significant Consequences

Solar Gamma-rays

SEP CMEs

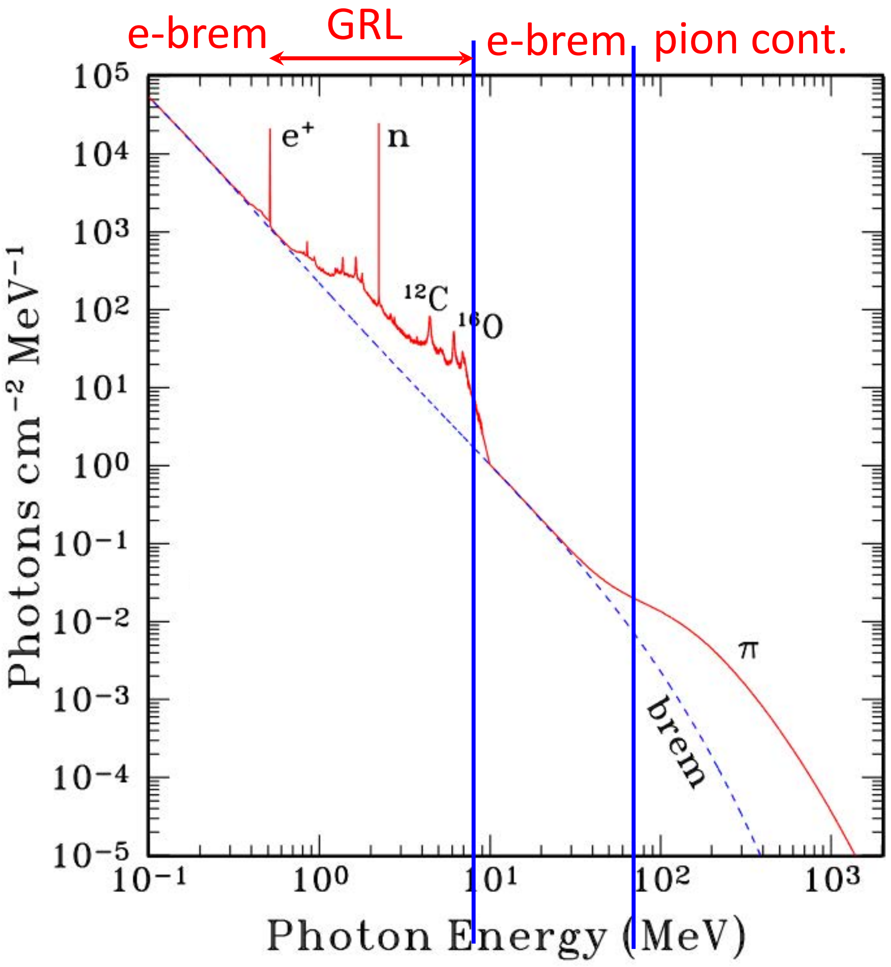


GM storm CMEs



Solar Gamma-rays

- Solar gamma rays were predicted by Morrison (1958) and observed by OSO-7 Gamma-ray Monitor (Chupp et al. 1973)
- Three types of gamma-ray emissions are known from solar eruptions:
- Gamma-ray line (GRL) emissions (from excited or newly formed nuclei), typically in the energy range 0.5-8 MeV (e.g., Forrest & Murphy, 1988)
- Bremsstrahlung Gamma rays from up to the energy of the electrons/positrons (directly accelerated electrons or charged pion-decay electrons/positrons, e.g., Rieger & Marschhauser, 1990)
- Pion-decay gamma rays: π^0 decay with a characteristic peak at 68 MeV (Forrest et al. 1985)



Ramaty & Mandzhavidze 1998

Sustained Gamma-ray Emission (SGRE

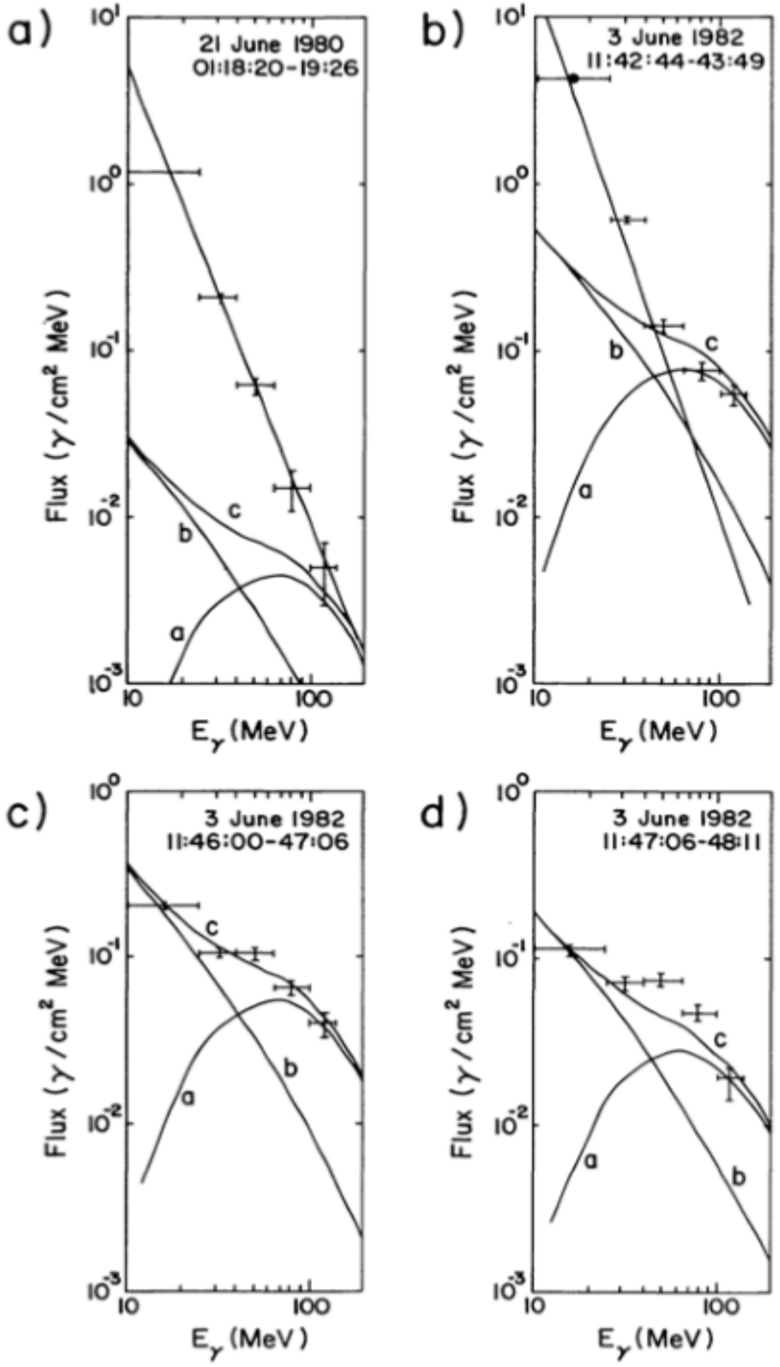
Forrest et al. (1985): SMM/GRS high-energy spectra

- The 1980 June 21: mostly bremsstrahlung gamma-rays
- The 1982 June 3 event: mostly bremsstrahlung in the impulsive phase with some pion emission; only pion emission after the impulsive phase
- In the 1982 June 3 event, >300 MeV protons were present
- Suspected that the required high energy protons may be similar to the ones observed in SEP events, different from those in the impulsive phase

Two possibilities:

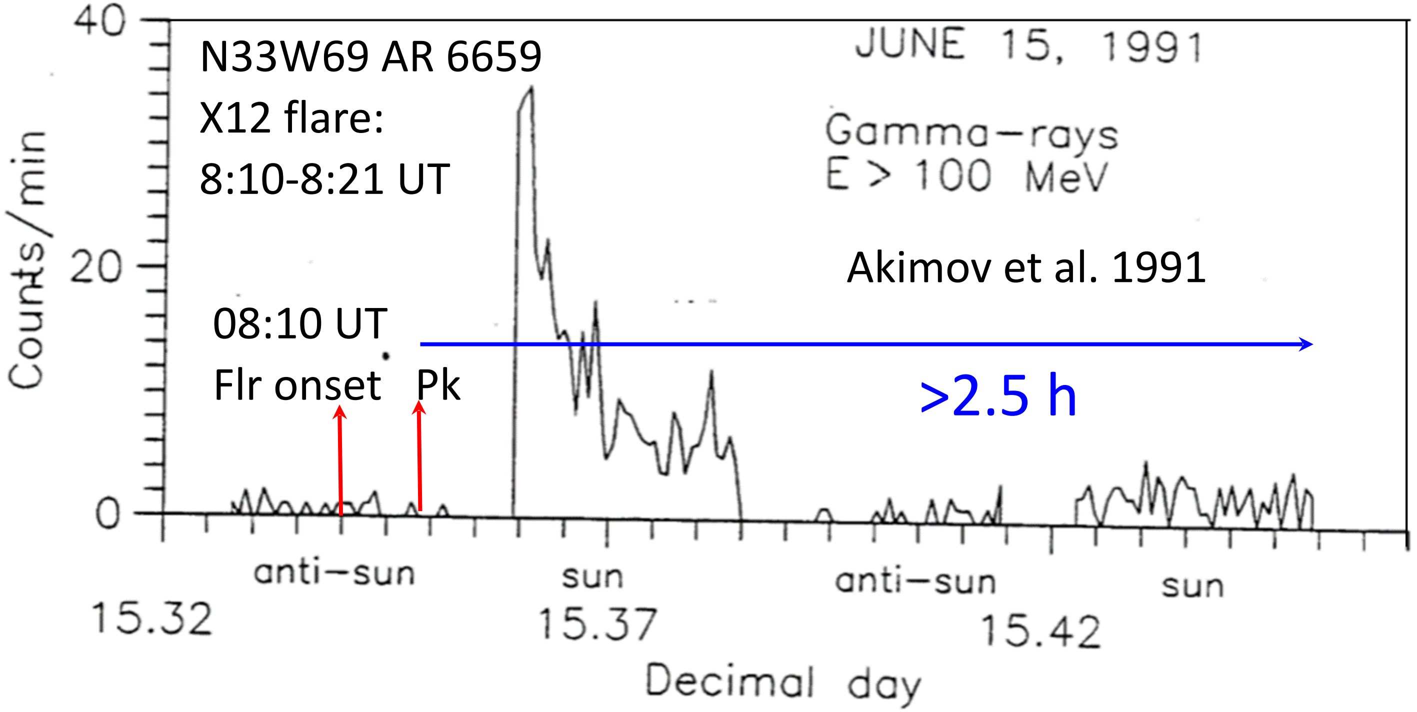
- Sunward diffusion of shock particles (Murphy et al., 1987; Ramaty et al. 1987)
- The flare particles linger in loops; get reaccelerated (Ryan & Lee 1991)

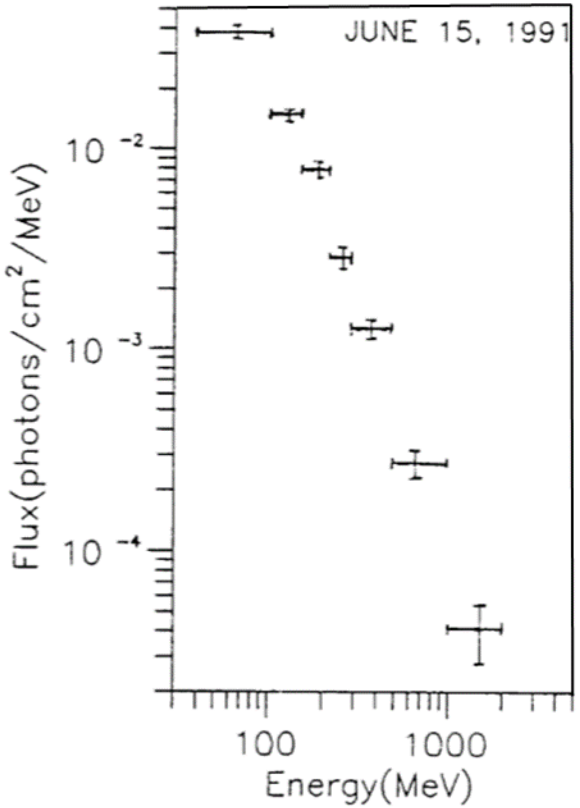
*aka LDGRF (long duration gamma-ray flare – Ryan 2000), LPGRE (late phase gamma-ray emission – Share et al. 2018)



SGRE with Duration >2 h from GAMMA-1

Akimov et al. 1991

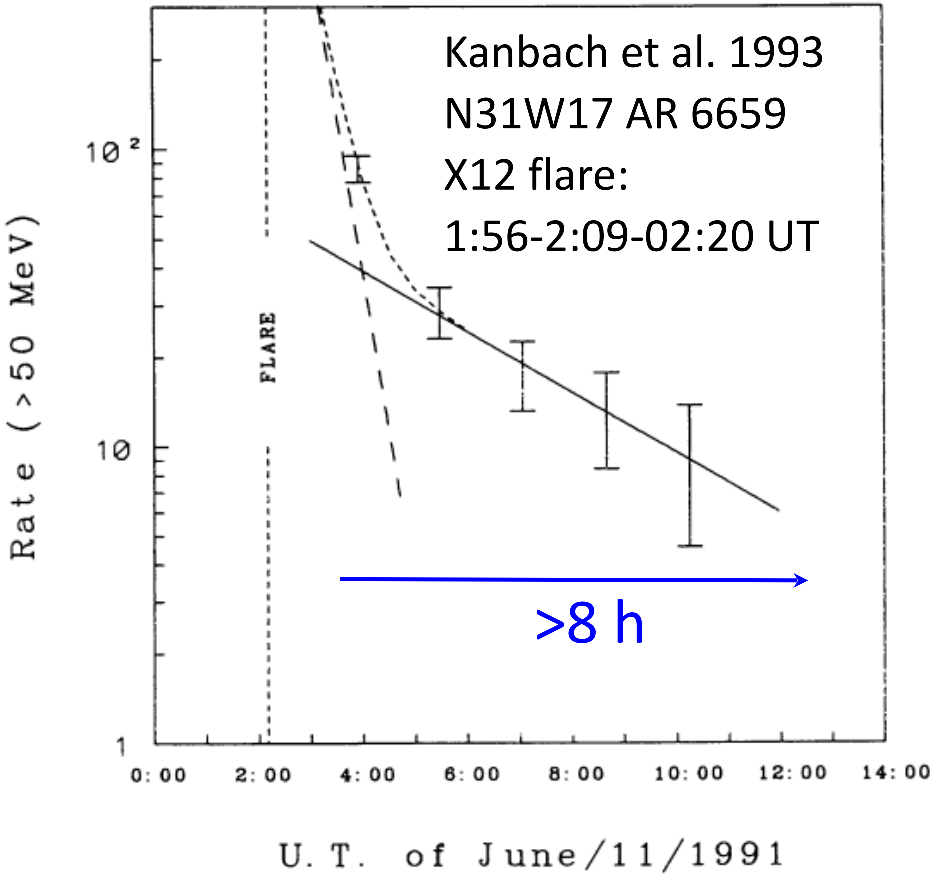




- First extended-duration gamma ray event
- Gamma rays detected at energies >1 GeV (SMM up to a few 100 MeV)
- Spectrum consistent with shock particles
- Metric type II burst observed (evidence for shock)

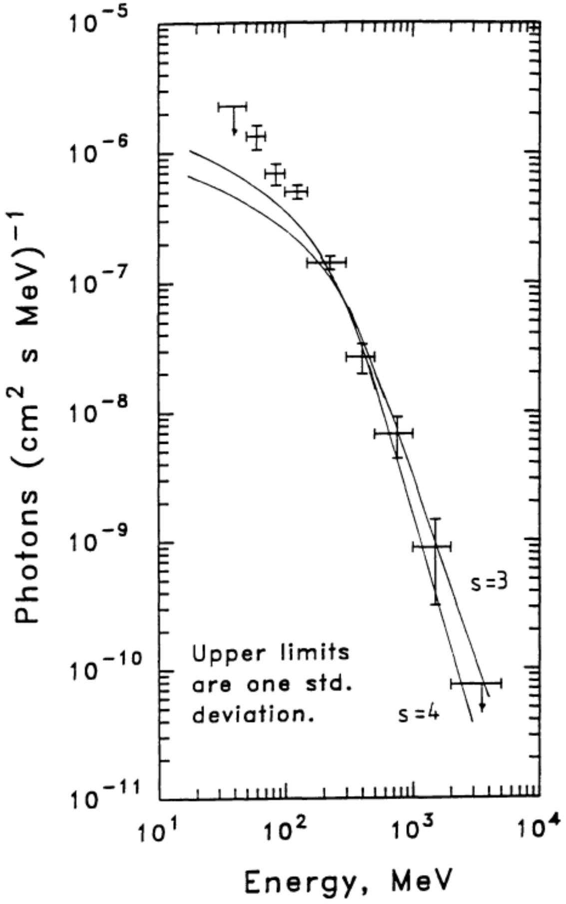
SGRE with Duration >8 h from CGRO/EGRET

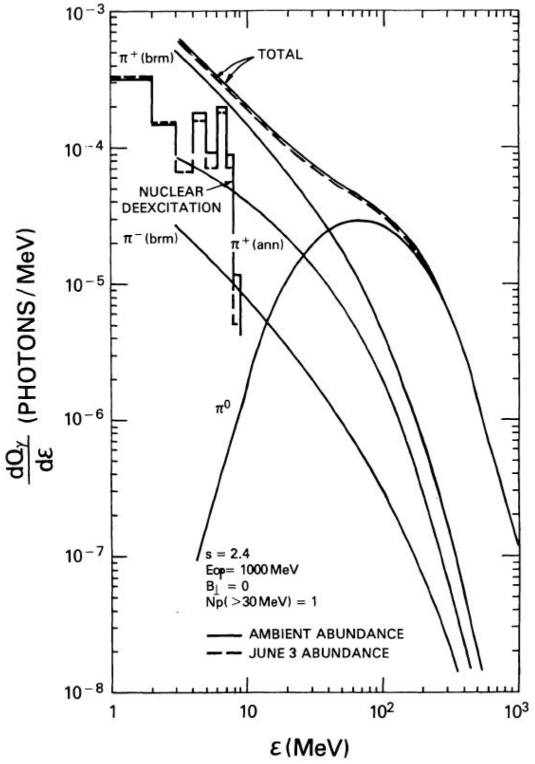
- The same AR as the Akimov event
- The largest-duration gamma ray event observed by CGRO/EGRET
- Gamma rays detected at energies >2.0 GeV
- Spectrum similar to Akimov et al. 1991
- Turbulence-free trap suggested to explain the long duration



Kanbach et al. 1993
N31W17 AR 6659
X12 flare:
1:56-2:09-02:20 UT

>8 h





Murphy et al. 1987

Fermi Sky

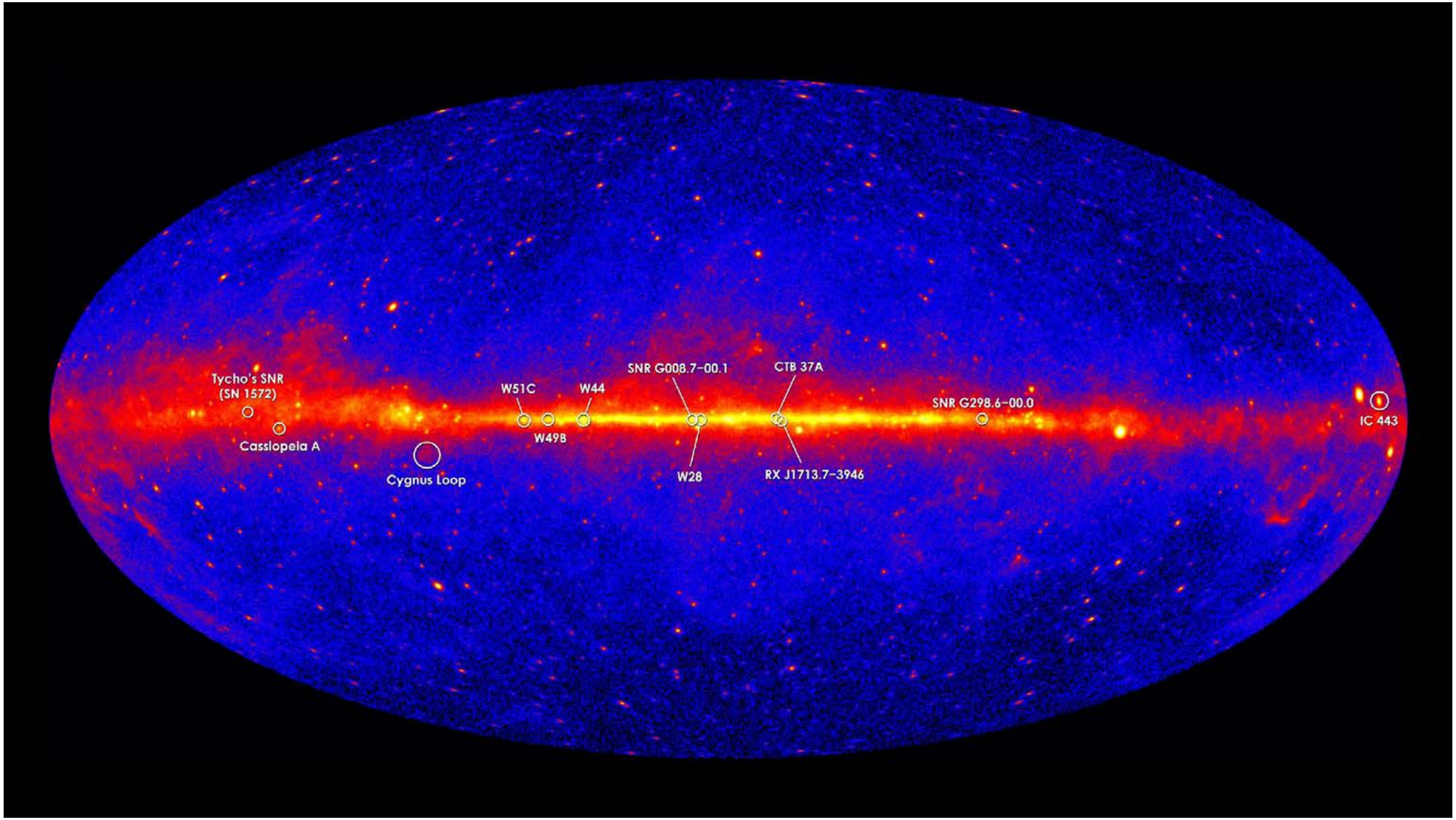
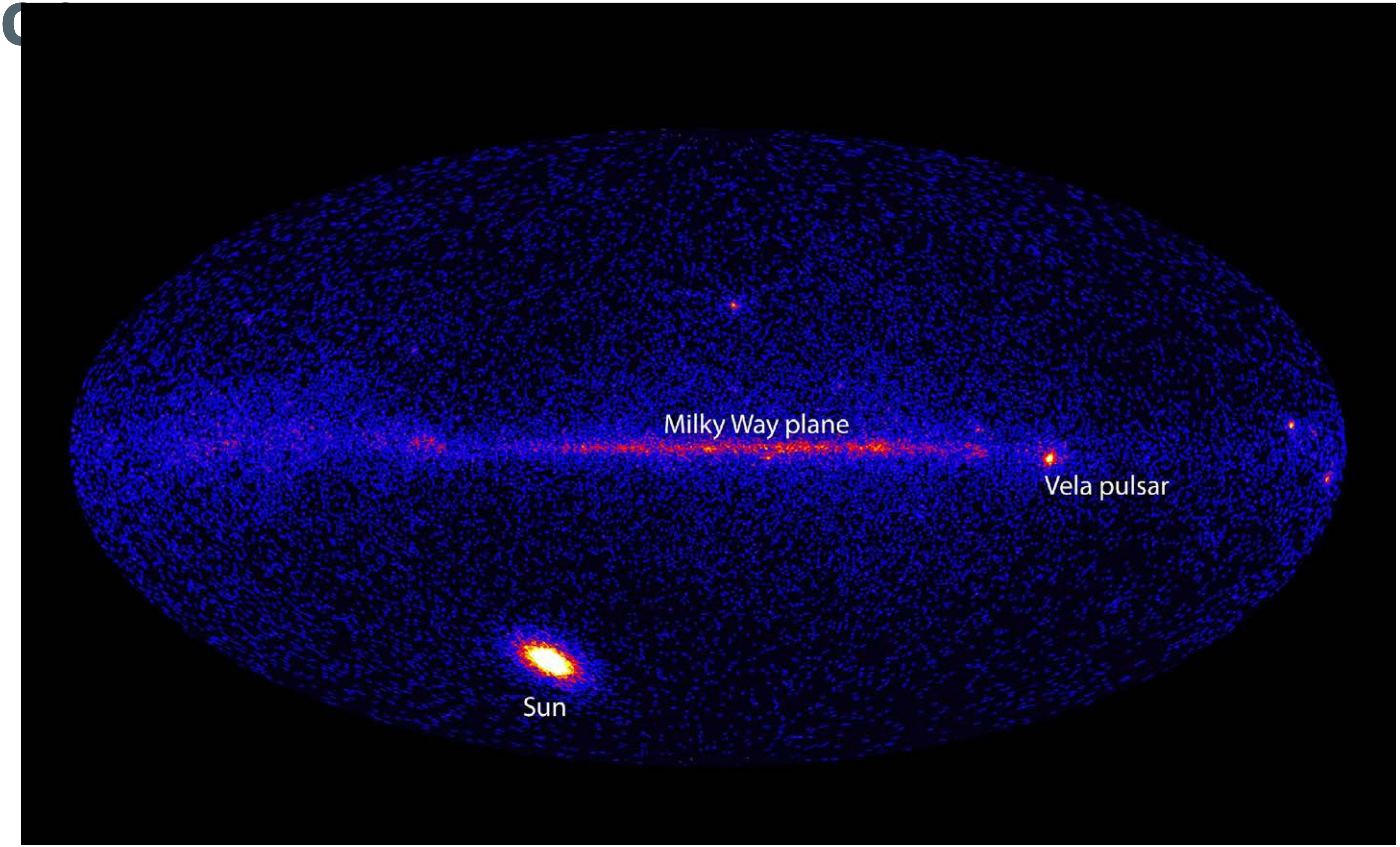
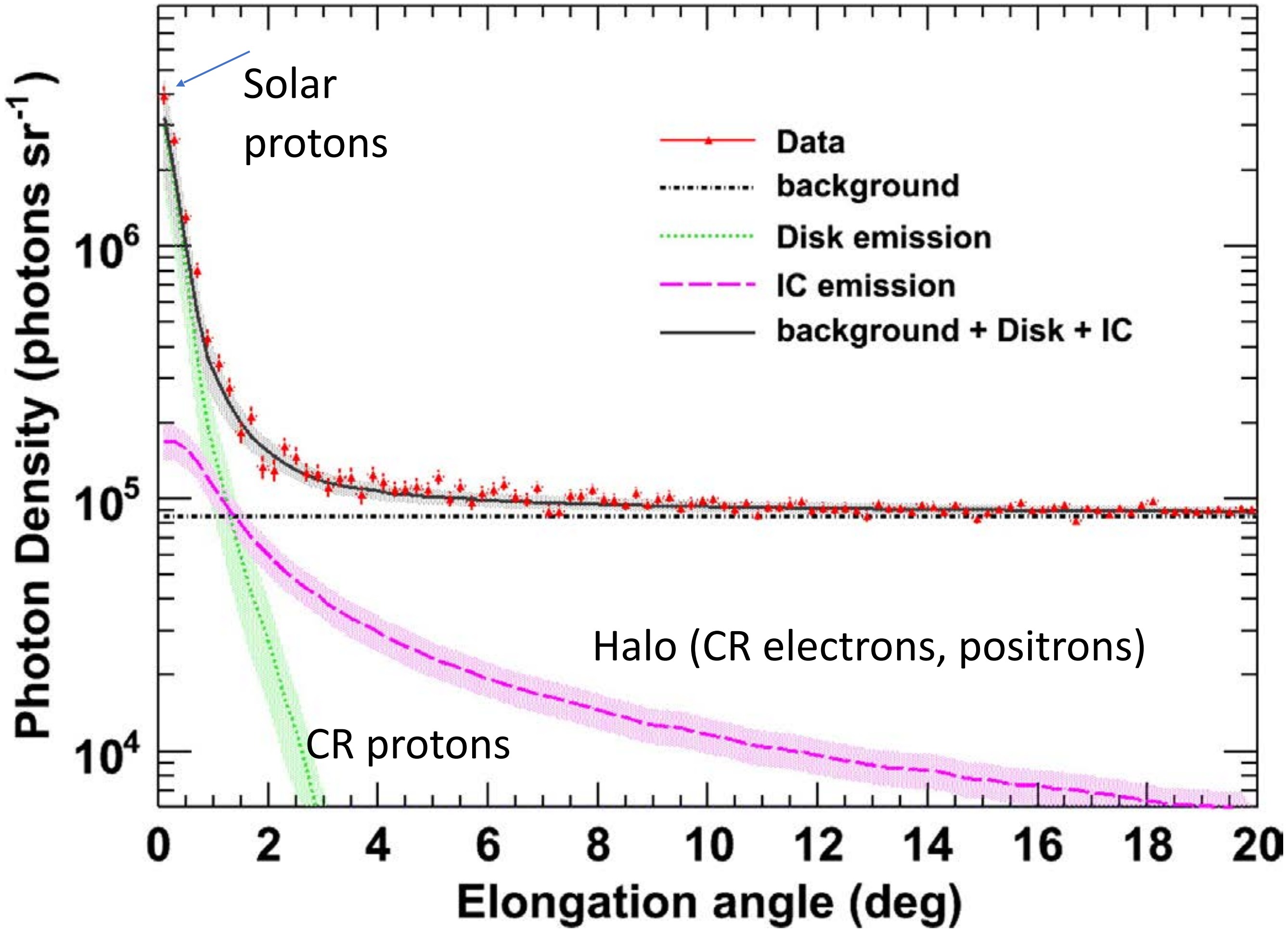


Image credit: NASA/DOE/Fermi LAT Collaboration

Sun can be temporarily the brightest γ-ray sourc



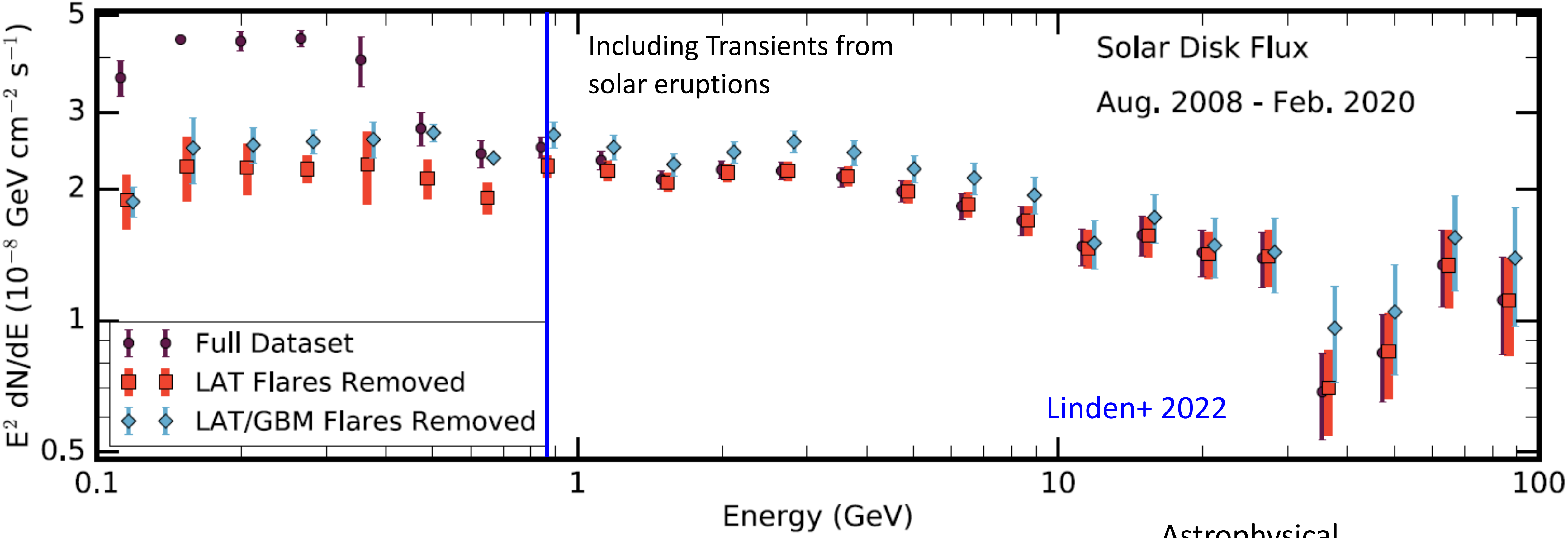
Processes for Solar γ-rays



Giglietto +
2012

Solar Disk Emission Spectrum

dN/dE ~ $E^{-2.03}$ (100MeV – 10 GeV)

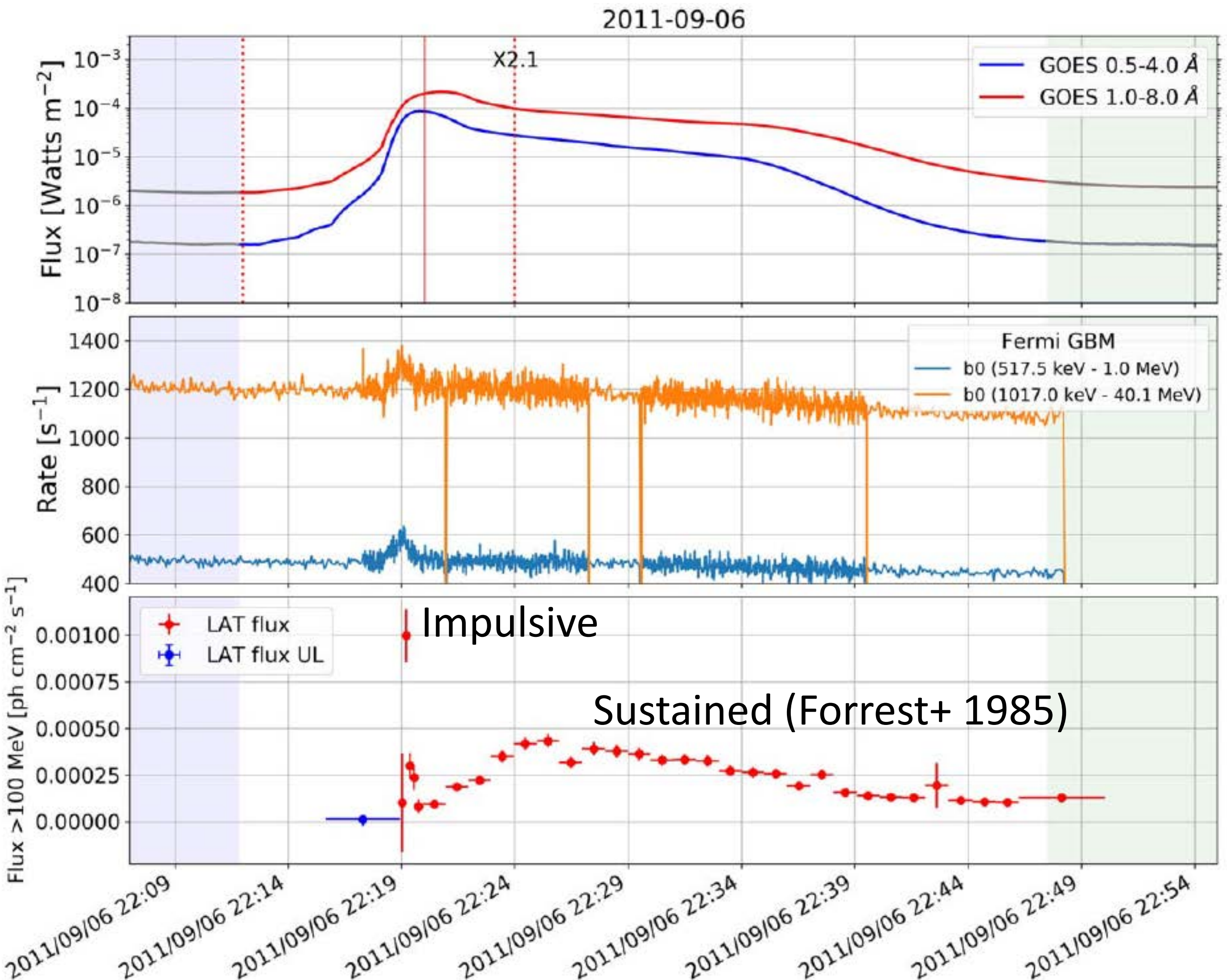


Solar energetic particles
Cosmic rays

Petrosian: Quiet Sun
Jin: CME shocks
Mäkelä Poster

Astrophysical
background subtracted

Example of a Solar γ-ray Event



Impulsive

Sustained (Forrest+ 1985)

Ajello+ 2021

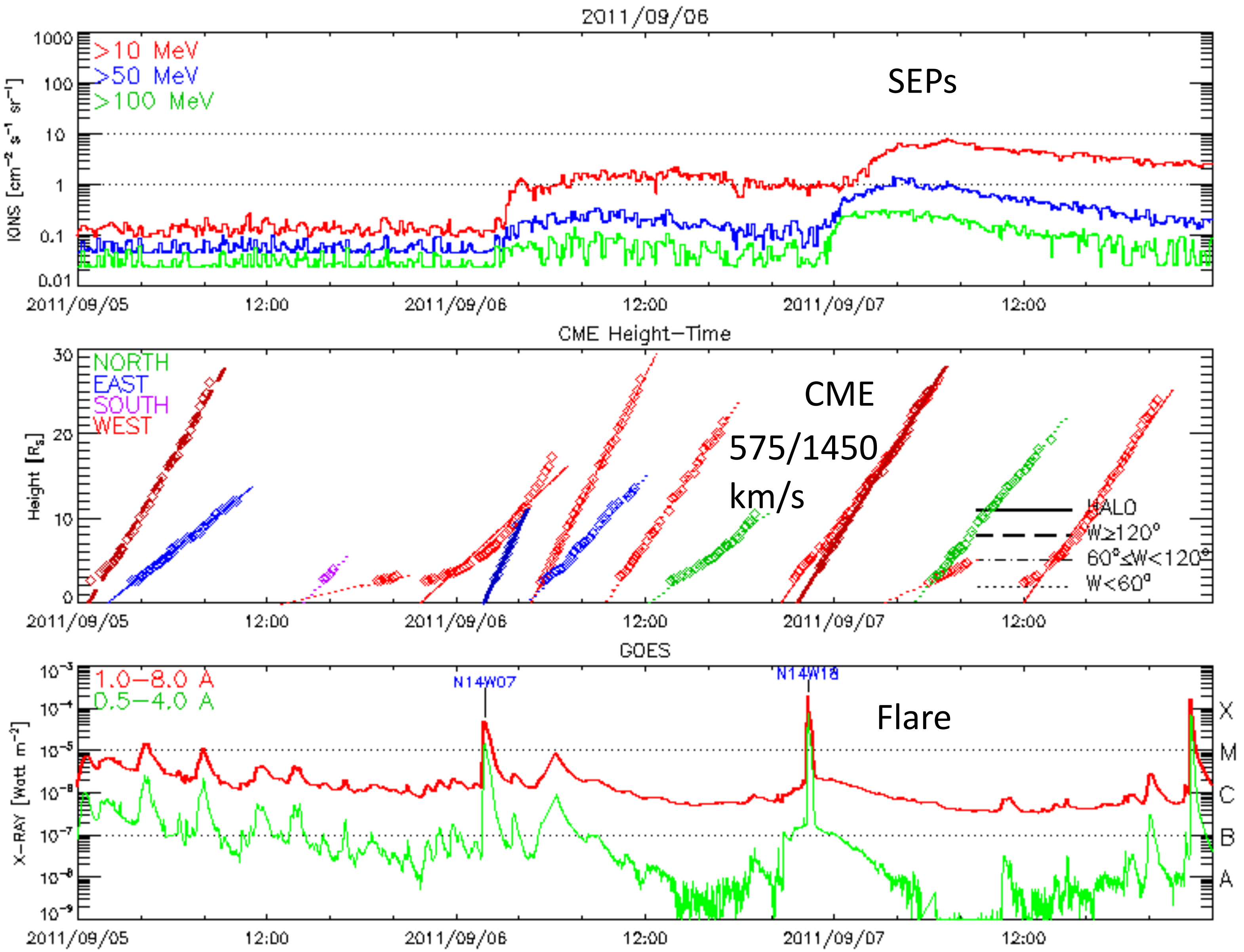
Impulsive component: coincident with flare hard X-rays

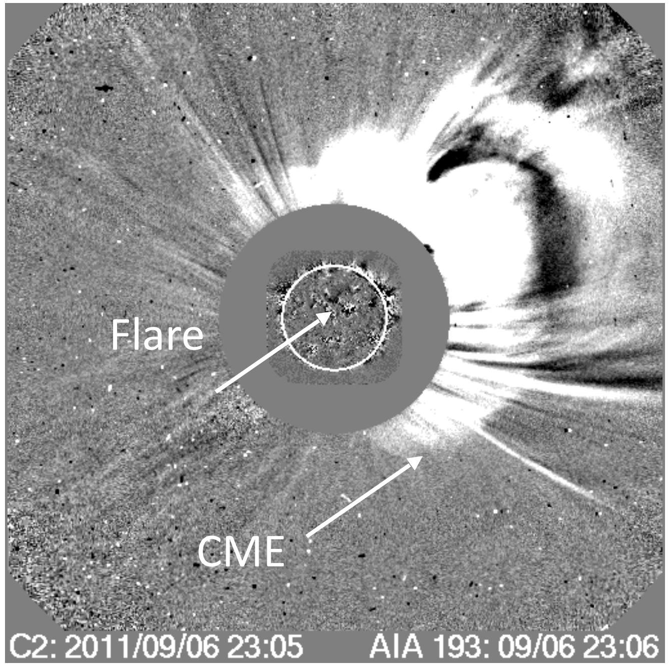
Sustained component: peaks well beyond the soft X-ray peak (2 hr); in some events the emission can last up to a day

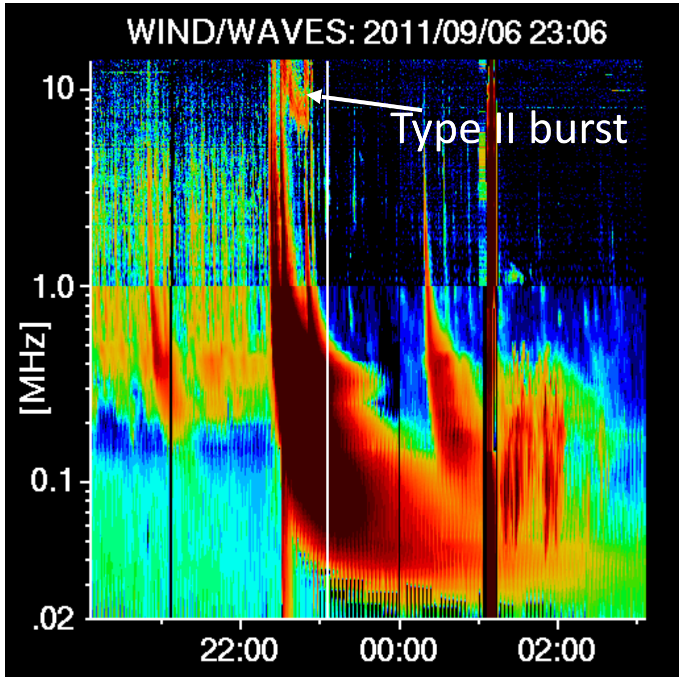
Problem: Origin of >300 MeV protons that cause these emissions
Two possibilities:

- Particles producing the impulsive component also produce the sustained component via trapping in flare loops (LDGRF)
- Particles accelerated in the CME-driven shock diffuse back to the Sun and produce γ-rays (SGRE, LPGRE)

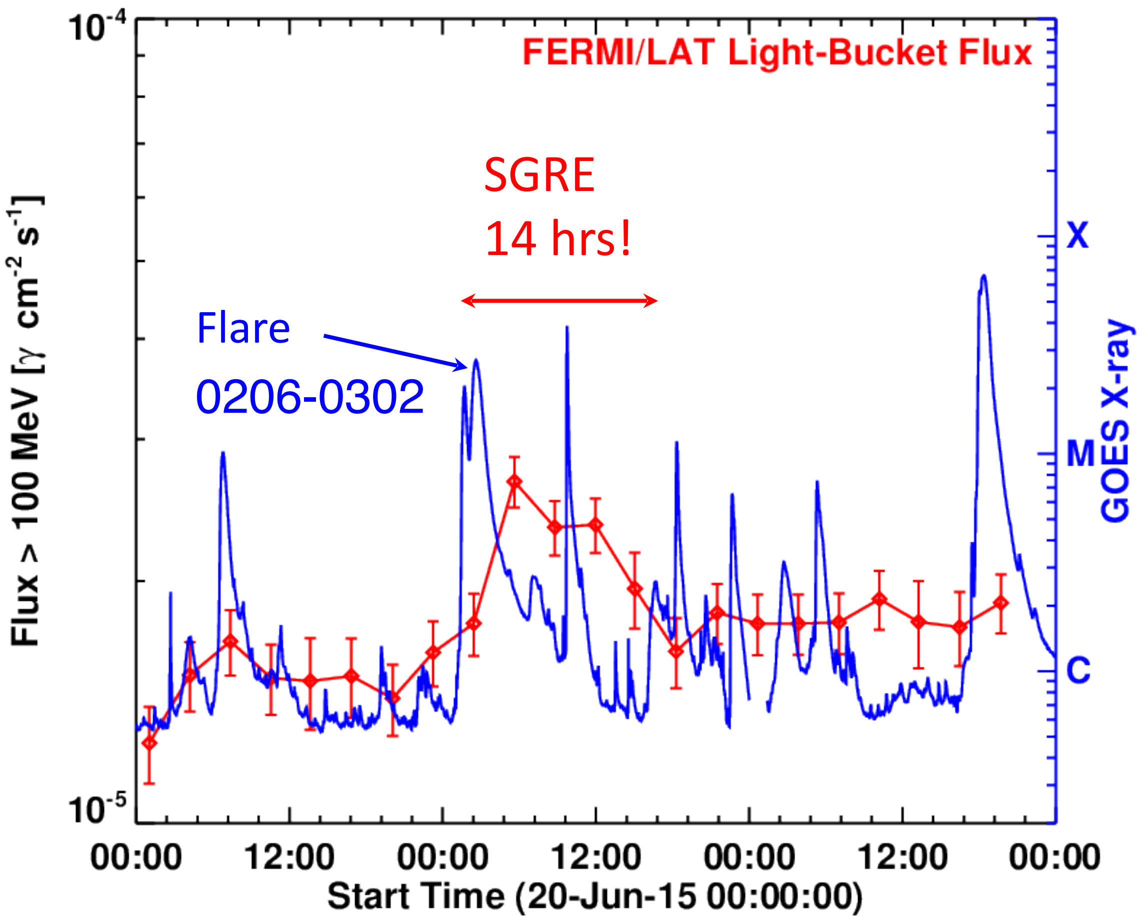
Associated Phenomena

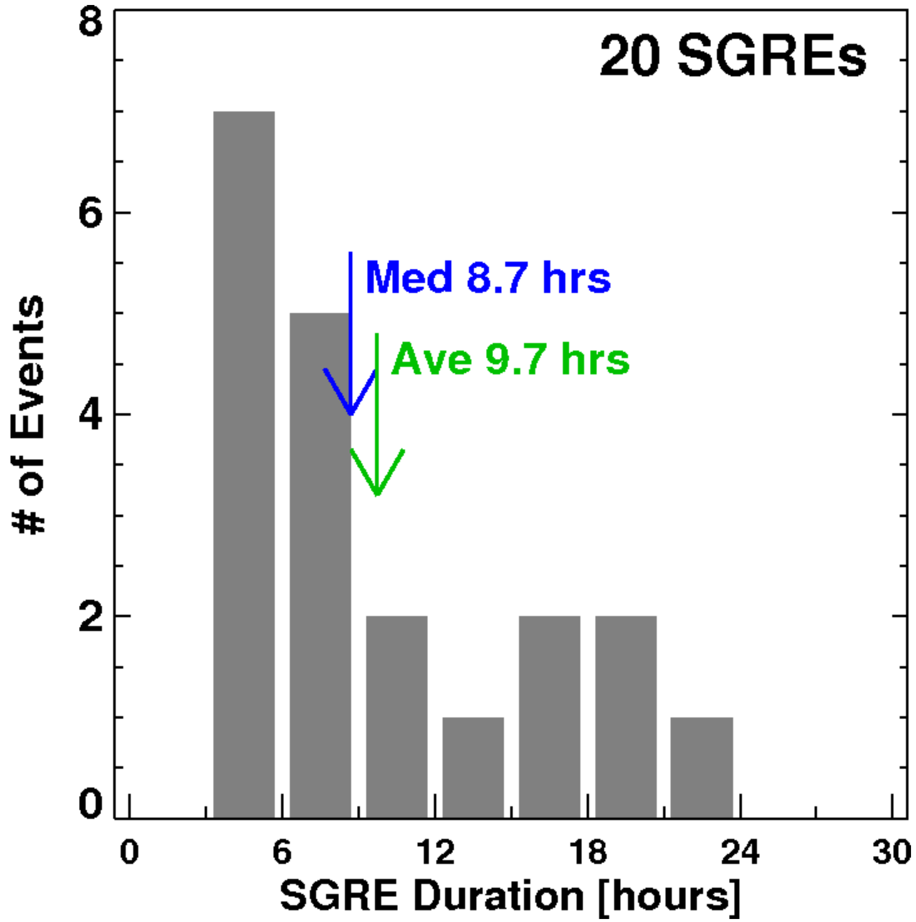






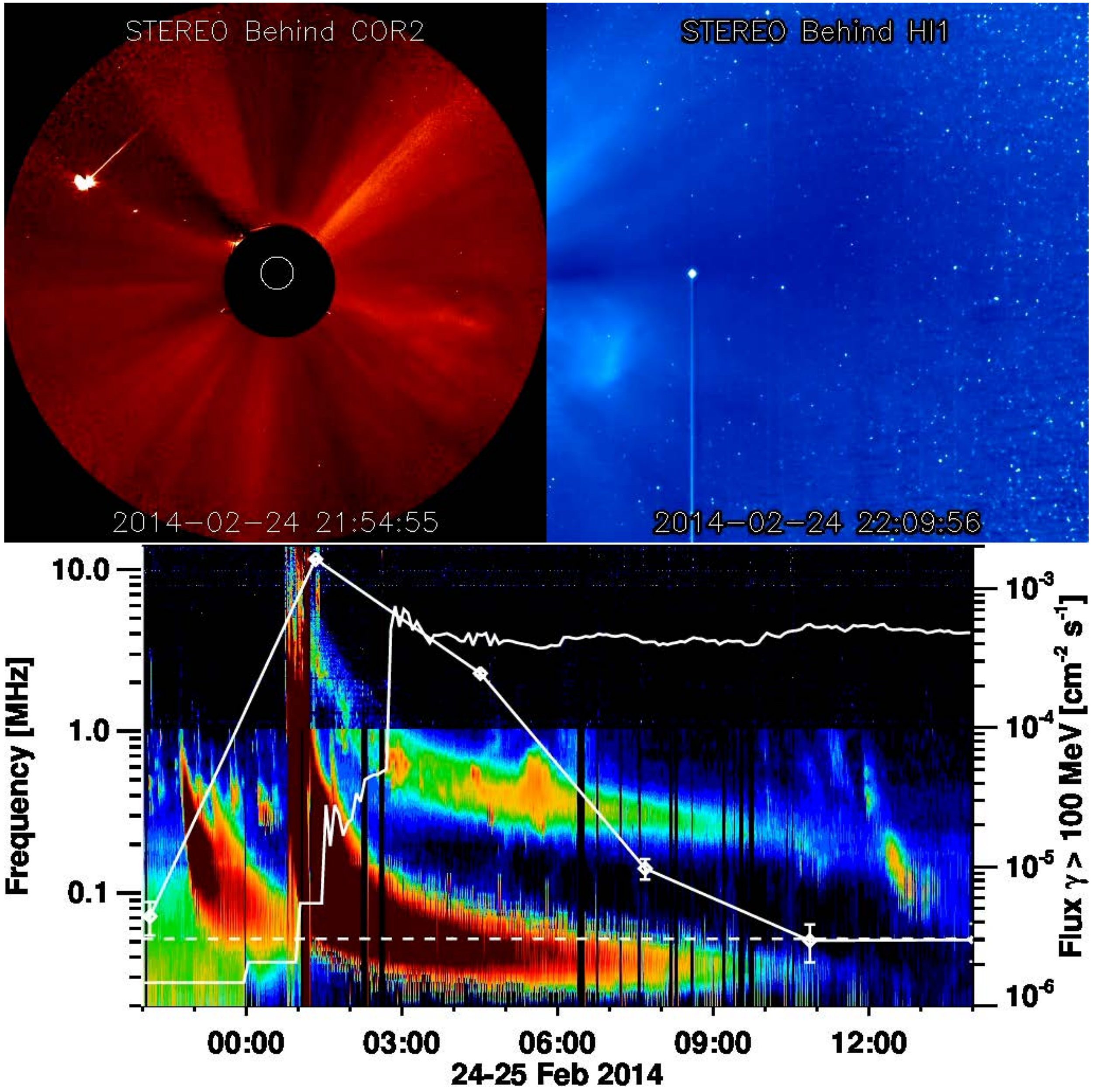
Fermi/LAT Gamma-ray Events





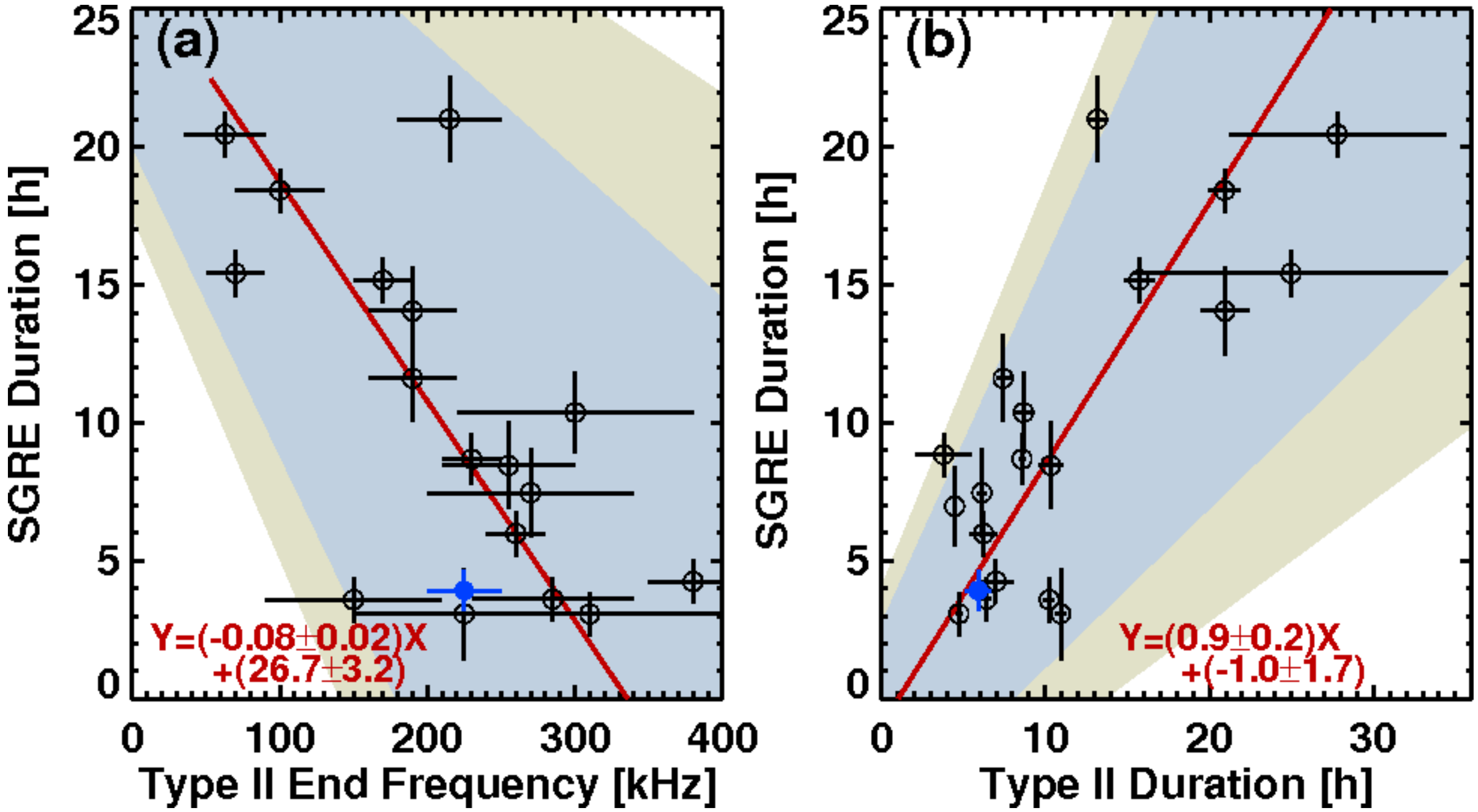
Fermi/LAT showed that SGRE events are rather common

Gopalswamy+ 2019



- SGRE ends when Type II ends
- CME at ~65 Rs when type II & SGRE end
- Large distances also indicated by the ending frequency of type II (~200 kHz)
- Copious >100 MeV particles from STEREO-B

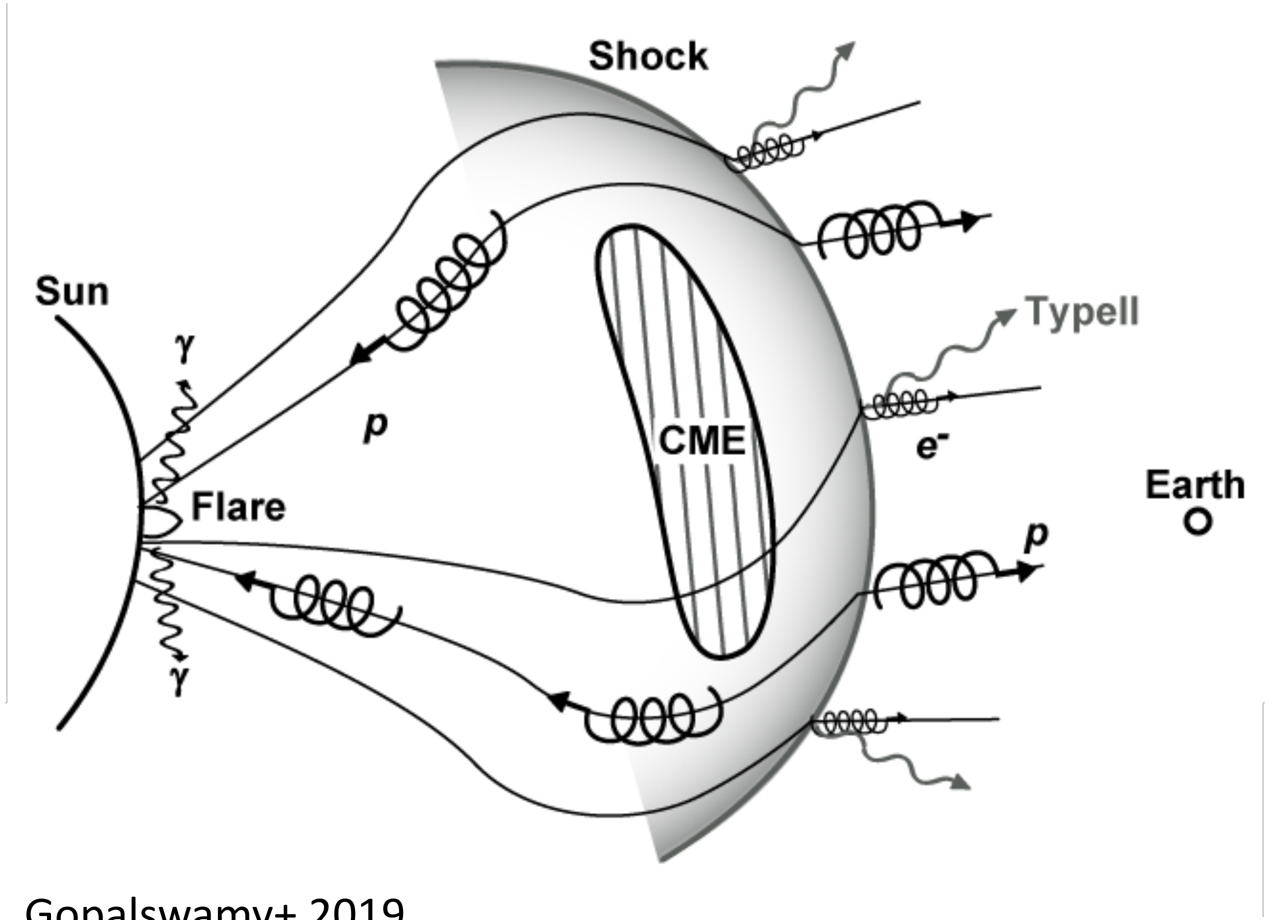
SGRE Duration directly related to Type II duration & Inversely related to the Type II ending frequency



● Backside event 2014 Sep 01

The same shock accelerates electrons producing type II bursts and protons producing SGRE

Scenario: SGRE source particles from IP shock



Gopalswamy+ 2019

Over the SGRE duration the shock accelerates ~10 KeV electrons, it also accelerates >300 MeV protons

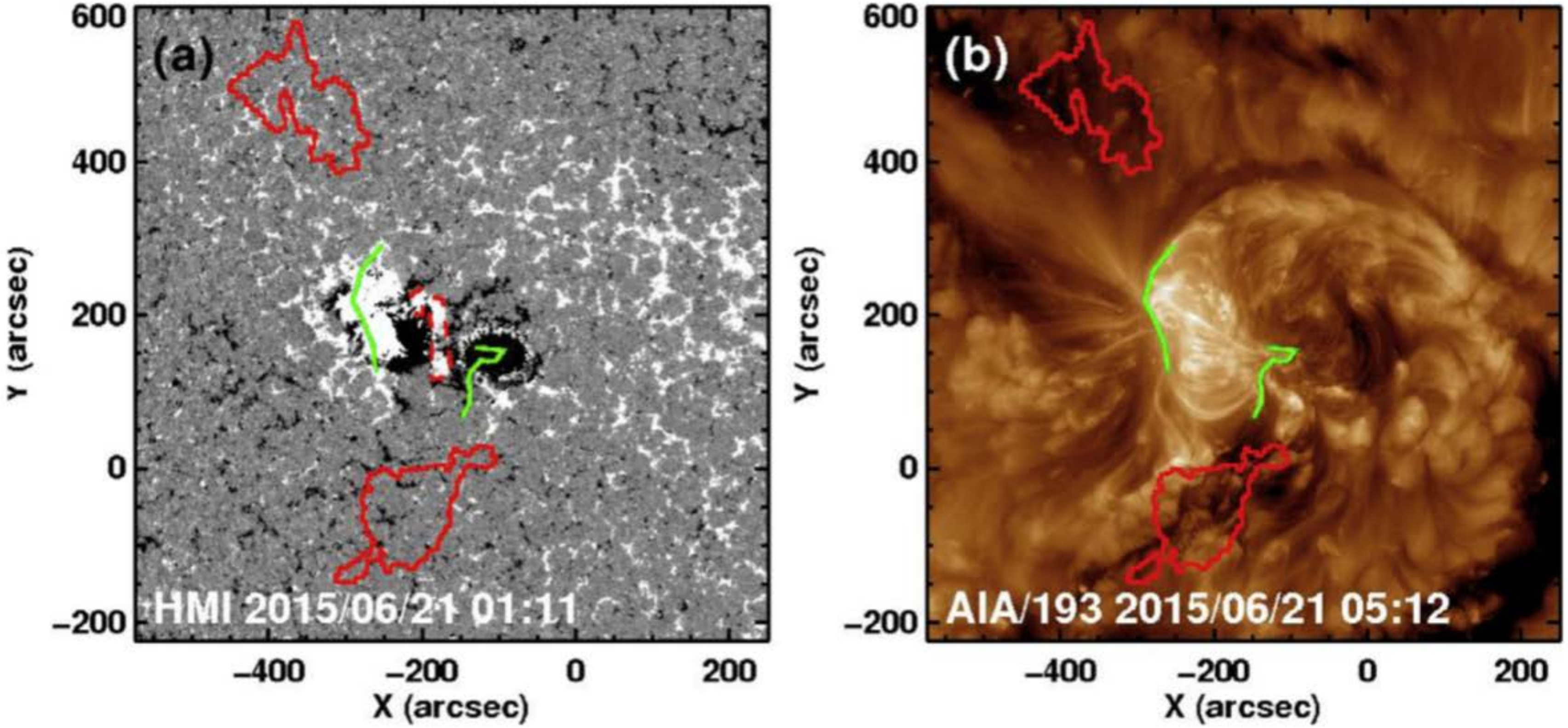
Energetic protons and electrons travel away and toward the Sun; protons traveling toward the Sun cause the gamma-ray emission

Shock-nose has the highest-energy particles, so the precipitation is still in the vicinity of the CME flux rope feet (spatially extended compared to the flare arcade)

Spatial-extended emission expected from the shock scenario

CME Flux rope spatially more extended than the flare structure (post-eruption arcade)

Hard X-rays (& impulsive γ) confined to flare ribbons

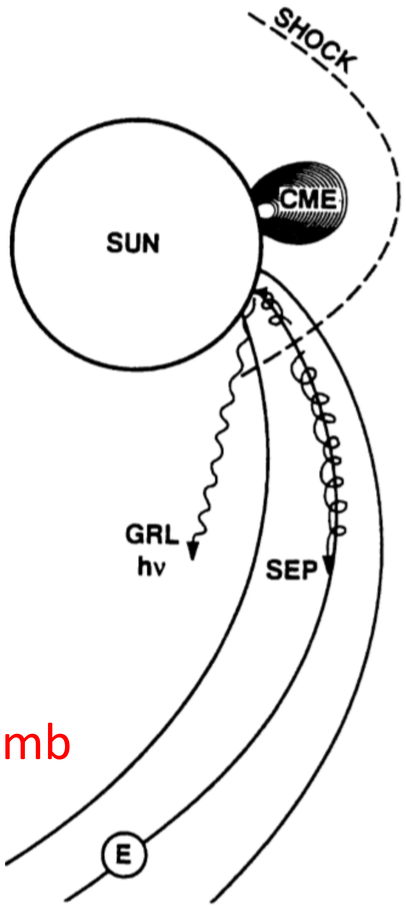


2015 June 21 CME speed: 1366 km/s, M2.6 flare; SGRE 14 h; type II 21 h

Flare Sizes: 12 X, 7 M, 1 C

Sources of Particle Acceleration

Spatially extended GRL emission



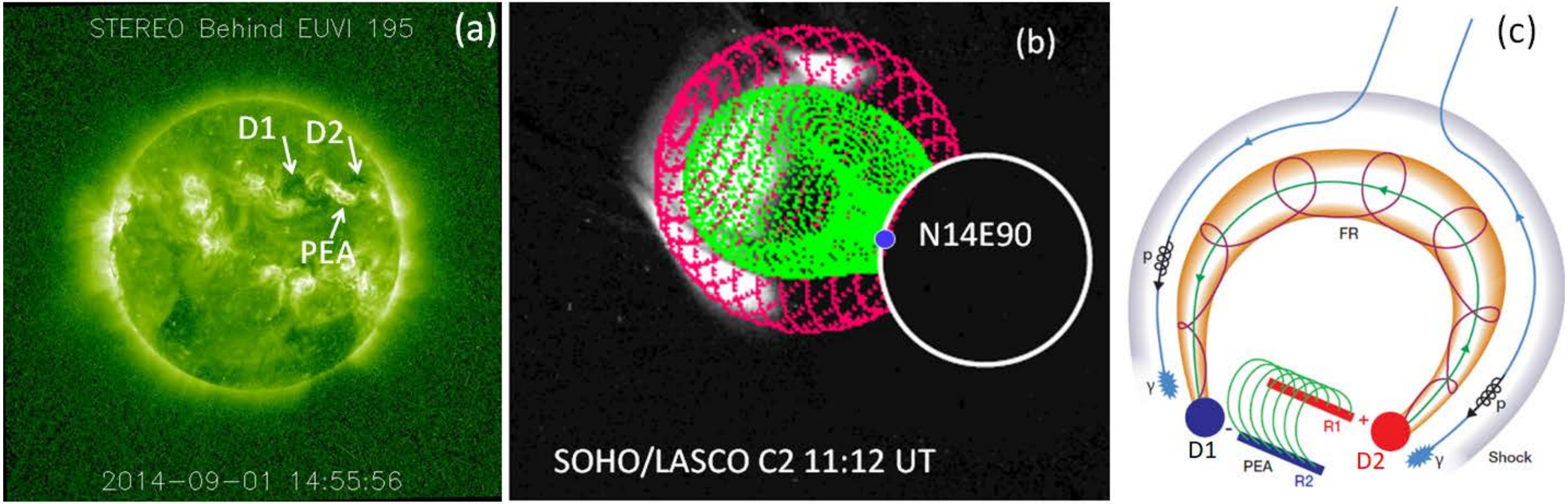
1989 Sep 29 GRL emission
X9.8 flare
S25W98
1800 km/s CME
8 deg behind the limb

- 2.223 MeV GRL detected on the disk from a backside eruption
- >30 MeV protons need to precipitate on the frontside
- Extended shock can do this
- Did not conclude on SGREs (>300 MeV protons needed)
- Fermi/LAT detected 3 behind-the-limb events (Pesce-Rollins+ 2015) ⍰ CME-driven shock
- 2014 Sep 1: eruption ~40 deg behind the limb

Cliver et al. 1993 ICRC; Vestrand & Forrest 1993
Murphy et al. 1987; Ramaty et al. 1987

Spatially-extended Gamma-rays: 2014/09/01

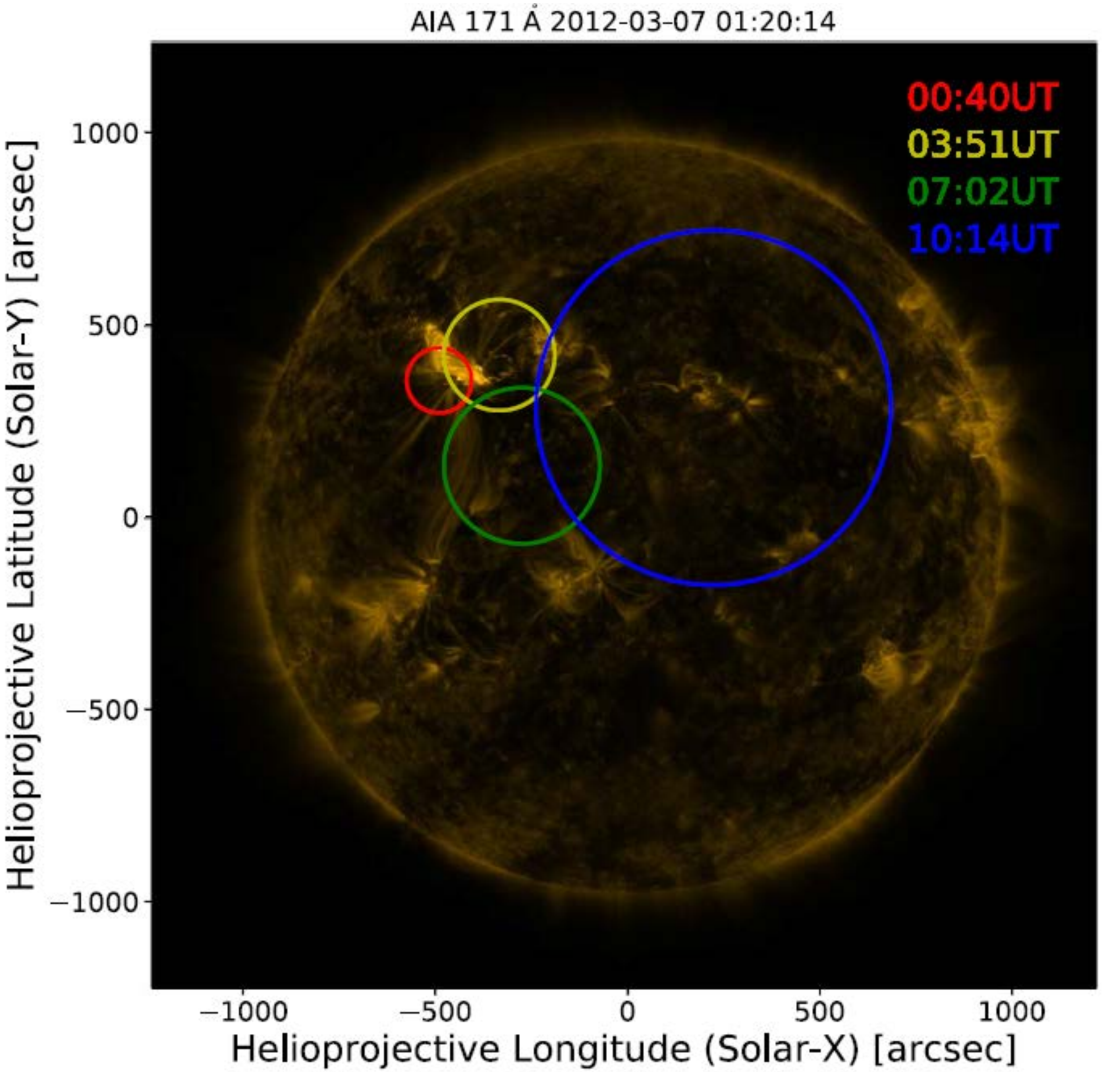
Flares: compact source; shock: extended source



Most of the gamma-ray photons must be occulted

Gopalswamy+ 2020

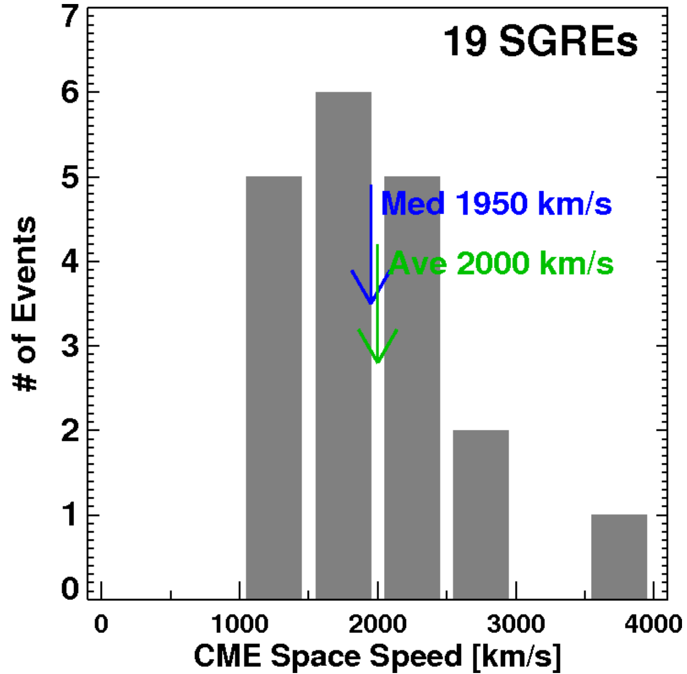
Shift in Centroid: Problem for stochastic spectrum from flare loops

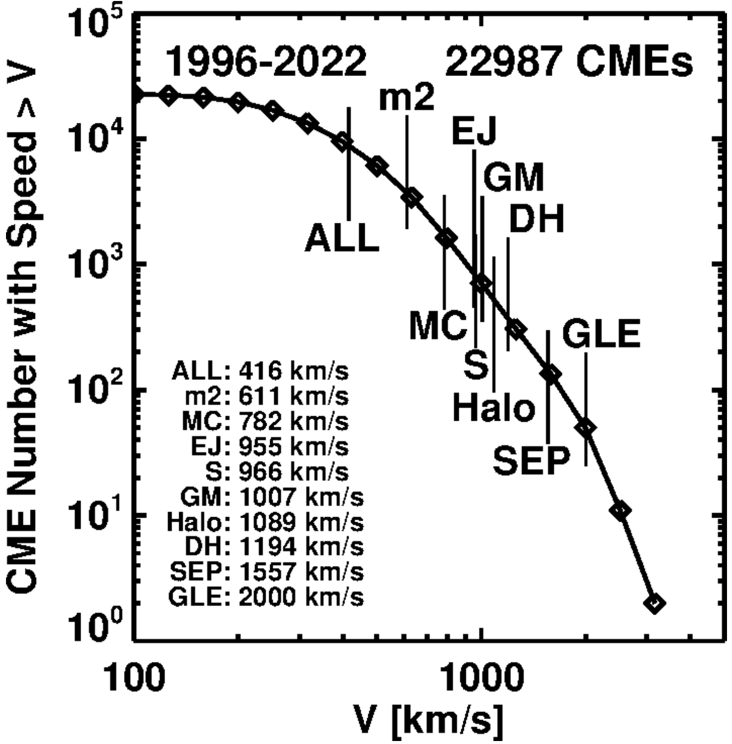


Omodei+ 2018
Ajello+ 2021

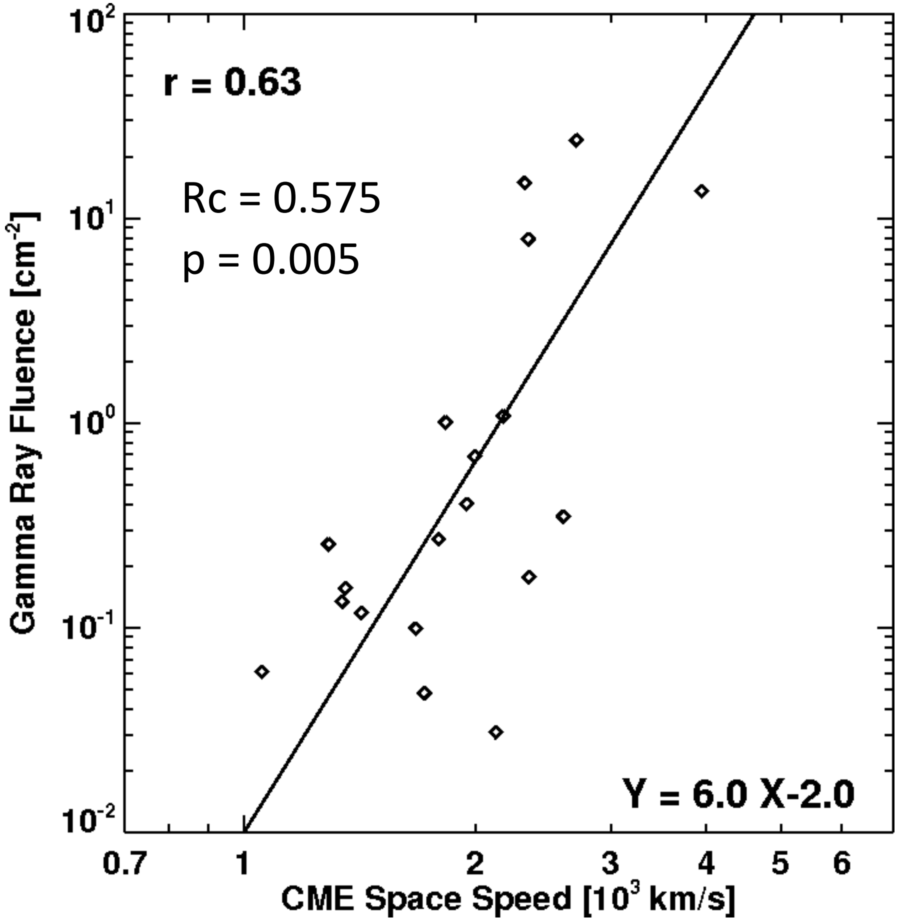
The SGRE CMEs are like GLE CMEs

- The CME speeds average to 2000±600 km/s - above the average speed (~1500 km/s) of CMEs producing large SEP events (see e.g., Gopalswamy et al. 2004)
- All SGRE CMEs (100%) are halo CMEs
- All SGRE CMEs have Type II bursts extending to kilometric wavelengths
- Mostly M and X class flares
- These properties are similar to GLE-associated CMEs implying GeV particles are accelerated but may not be detected due to connectivity
- SGRE duration of 10 hr and a CME speed of 2000 km/s imply that the shock supplies >300 MeV particles until ~100 Rs (midway between Sun and Earth!)

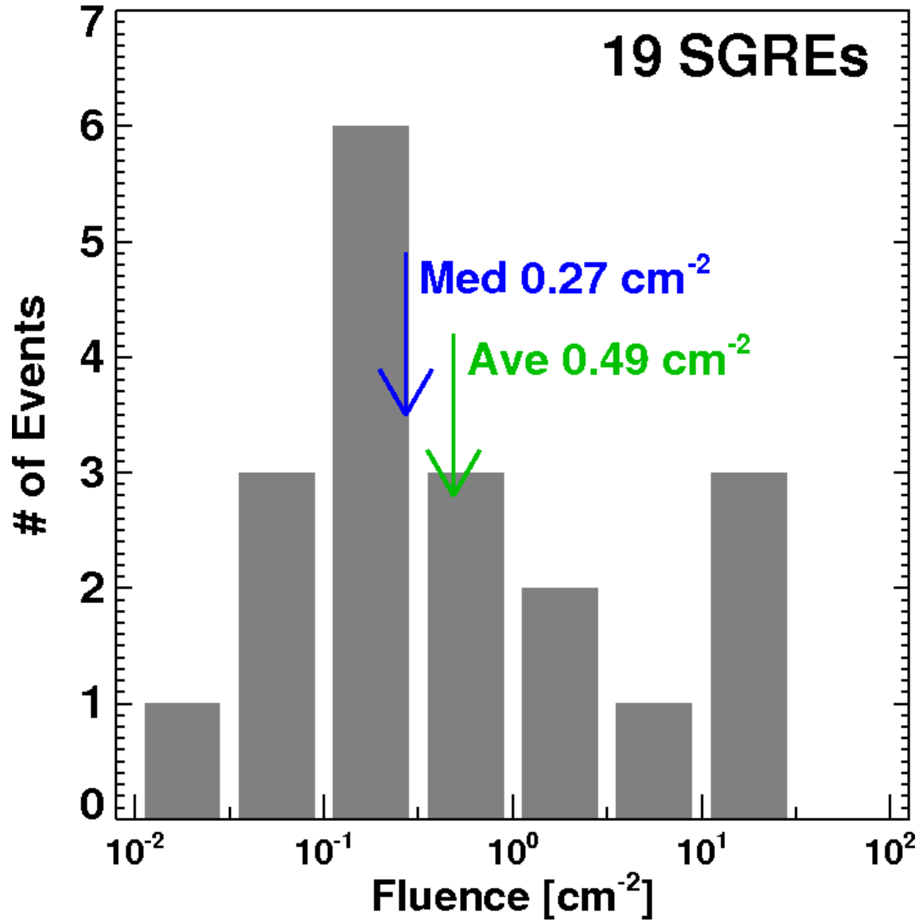




SGRE Fluence has Good Correlation with CME Speed

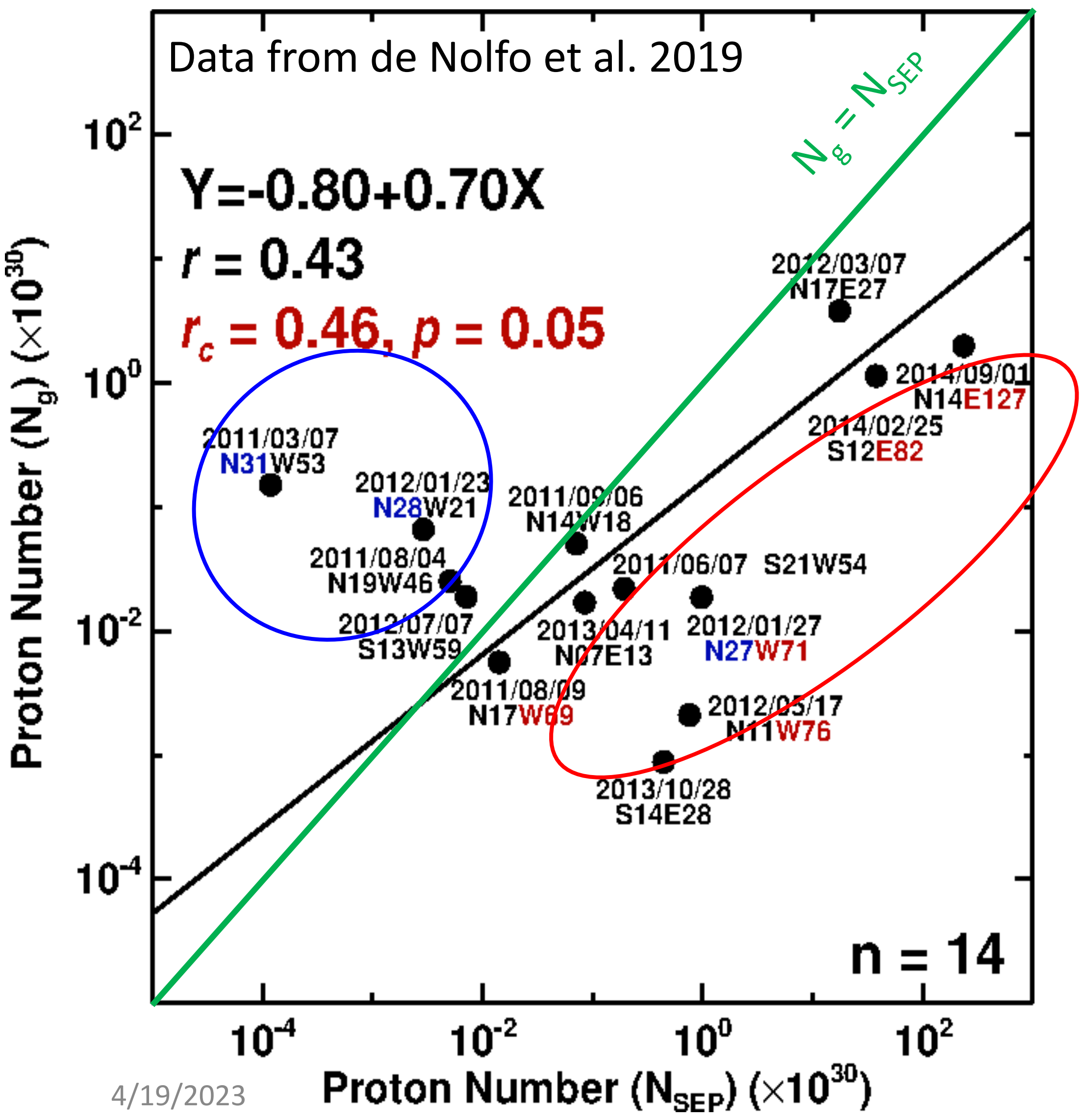


Rc = 0.575
p = 0.005



Close connection to shock strength, SEP events, and type II radio bursts

>500 MeV proton numbers from SEP event and SGRE


Data from de Nolfo et al. 2019

If the shock paradigm is correct, one expects a correlation between the number of >500 MeV protons inferred from the SEP event (N_{SEP}) and the number derived from the observed gamma-ray flux (N_g).

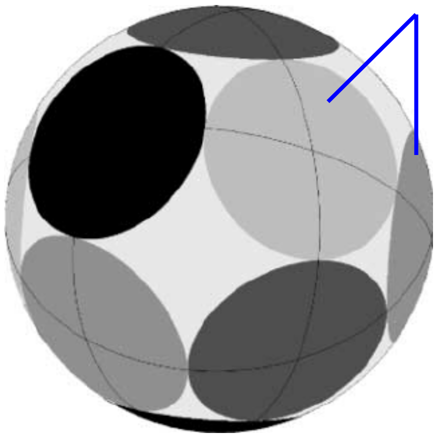
De Nolfo et al. (2019a,b) pointed out that N_{SEP} and N_g are uncorrelated, thus questioning the shock paradigm

However, we notice a **systematic pattern** in the plot:

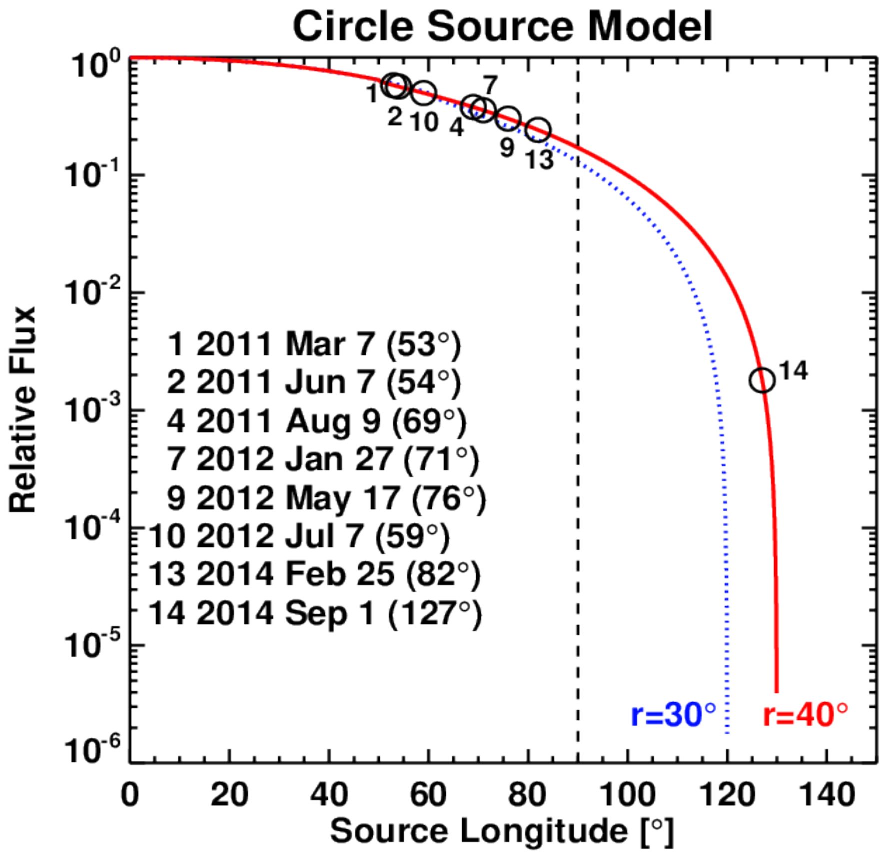
- rightmost events originate from close to the limb; data points lie below the equal-number line
- leftmost events originate at relatively high latitudes; data points lie above the equal-number line

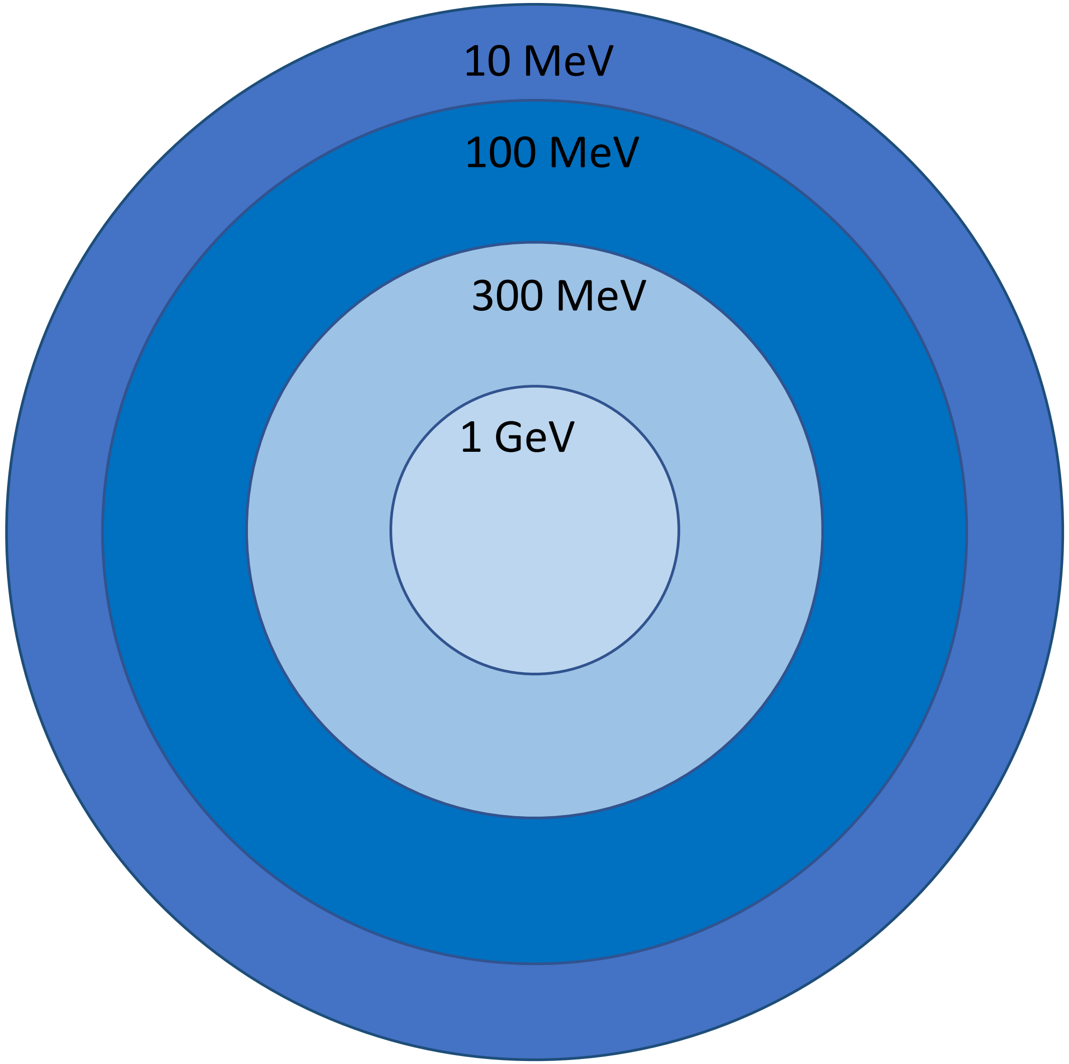
- N_g is underestimated in limb events (partial occultation because of the extended source)
- N_{SEP} is underestimated in higher-latitude events (higher than 13^o, typical of GLE events)

Partial occultation of limb gamma-ray sources



- Assume the gamma-ray source to be a circular disk with a radius of 40^0 (heliographic), equivalent to ~0.6 Rs
- As the CMD of eruptions increases, the gamma-ray flux decreases by cos φ, where φ is the CMD (foreshortened source area).
- Inverse of the flux reduction gives the correction factor, which ranges from 1.7 for a source at $\varphi = 53^0$ to ~560 for the backside eruption at $\varphi = 127^0$
- The same correction factor applies to the number of >500 MeV particles
- The 2014 Sep 1 SGRE would not have been observed if the source circle has a radius of 30^0





Looking from above the shock nose

The distribution of accelerated particles:

- energy-dependent Gaussians centered at the shock nose
- width decreasing with increasing energy
- W ~ (E/100)

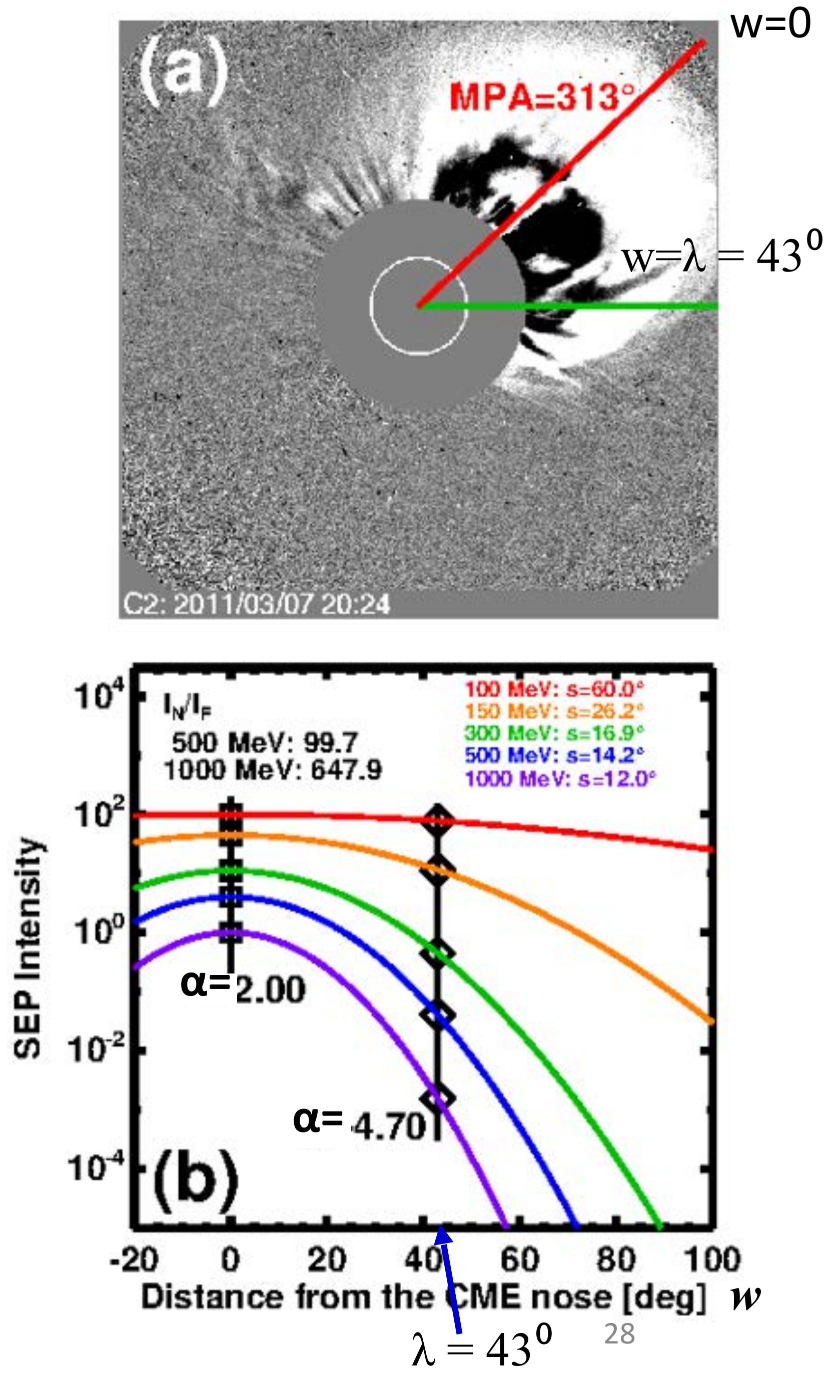
- Spectral hardness depends on the connectivity
- Hard spectrum when connected to nose
- Soft spectrum when connected to flank

Modeling energy-dependent widths

- Particle intensity as a function of the angle from the CME nose:

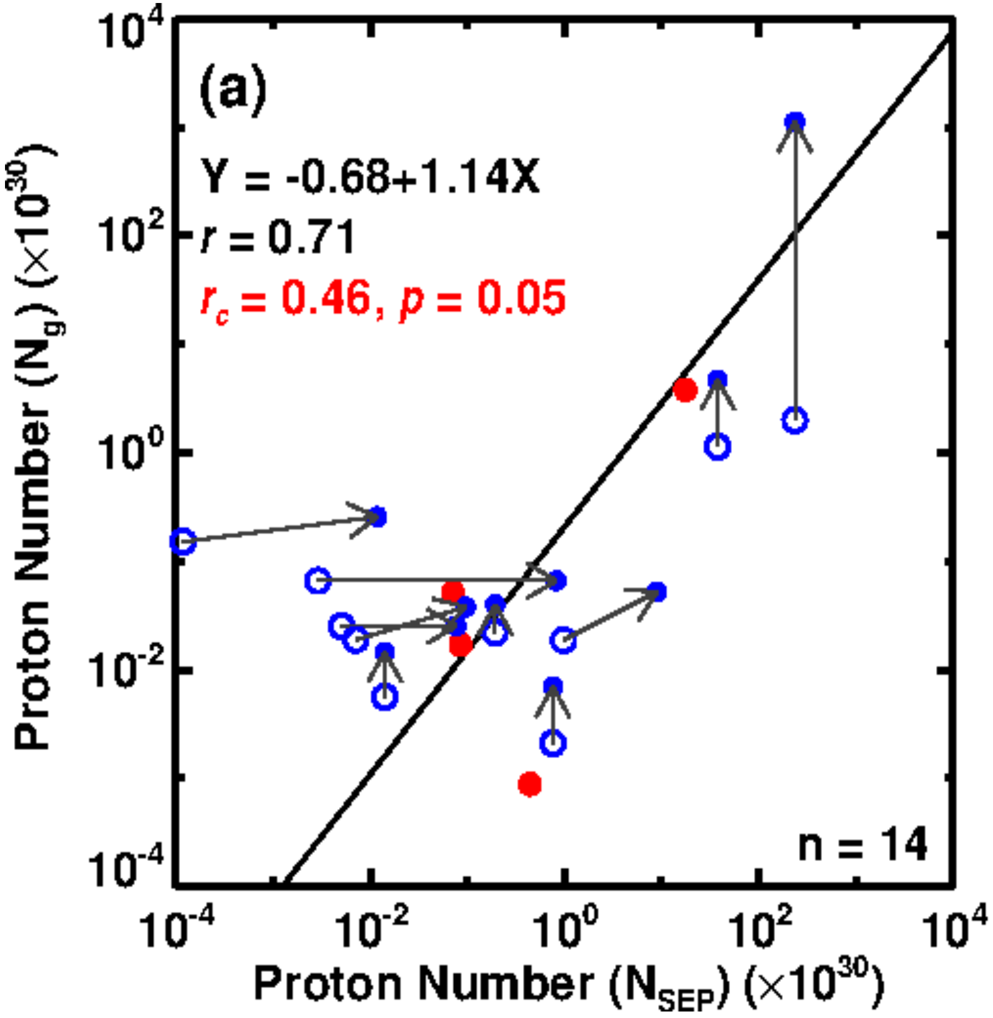
$I_E = A_E e^{-\frac{1}{2}(w/s_E)^2}$ (1) (w = 0 is the nose; w = λ is the observer position, S_E is Gaussian width)

- Assume α =2 at the nose and normalize the 1-GeV nose intensity to 1 so I_E at lower E are known from the power law spectrum (~$E^{-\alpha}$)
- Assume the low-energy (100 MeV) Gaussian width (say $s_{100} = 60^o$), get flank I_E at 100 MeV from (1).
- Obtain the flank intensities at higher energies from the flank spectrum (e.g., α = 4.70 for the 2011 March 7 event with λ = 43^o).
- Determine the Gaussian width s_E for different E. Nose to flank intensity ratio is the correction factor



The N_{SEP} – N_g correlation

r = 0.43 (uncorrected) vs. 0.71 (corrected)

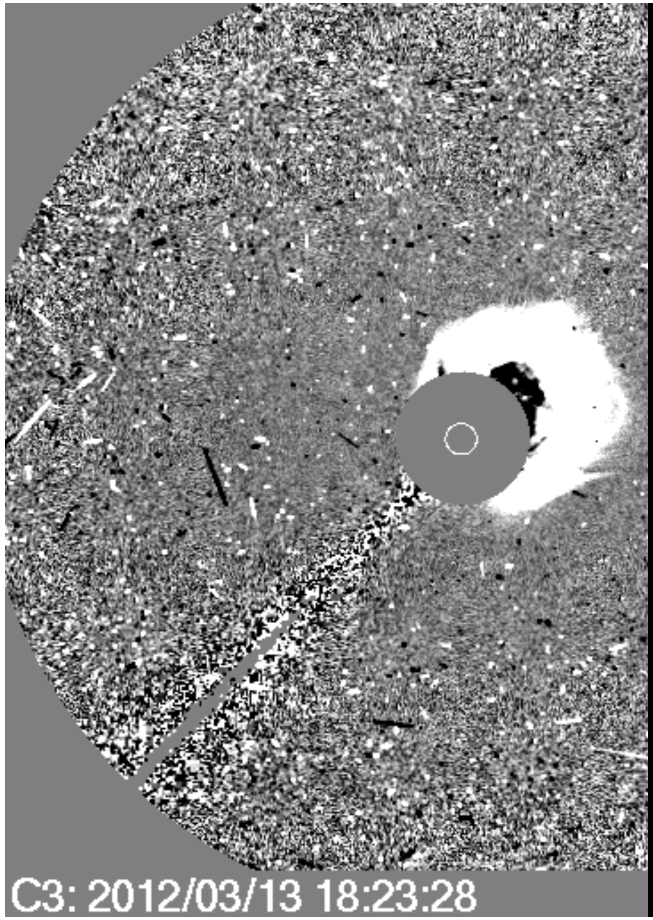


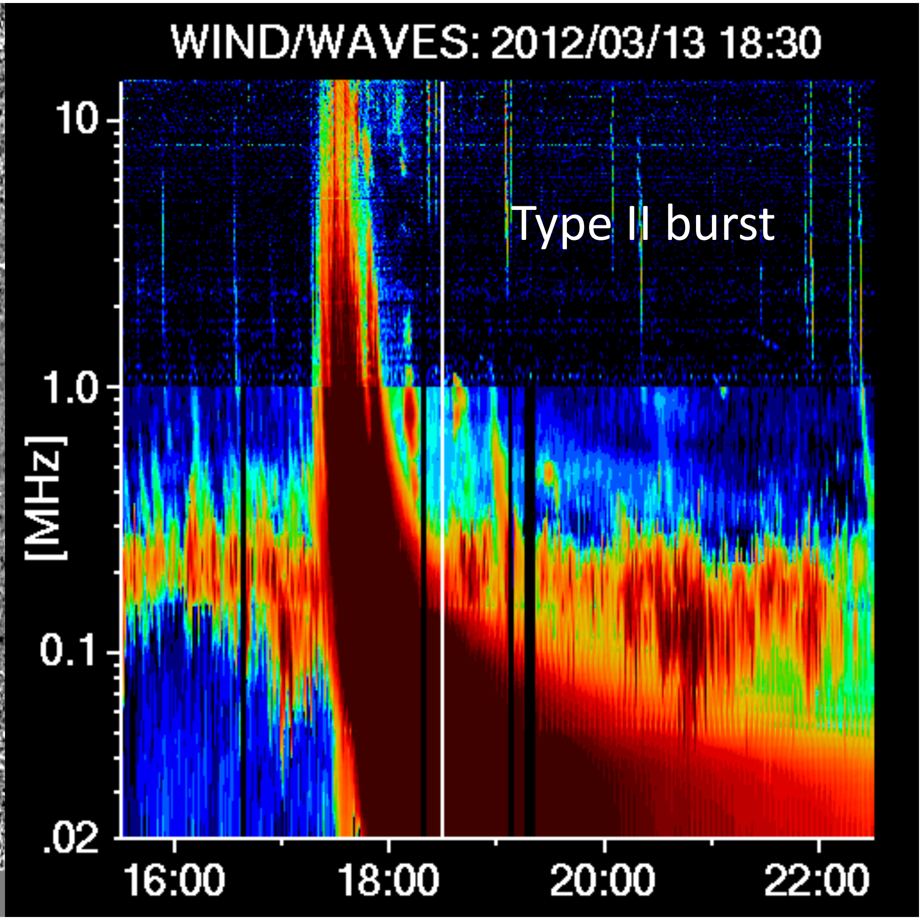
Good correlation supports shock paradigm

Why no SGRE during the 2012/03/13 SEP event

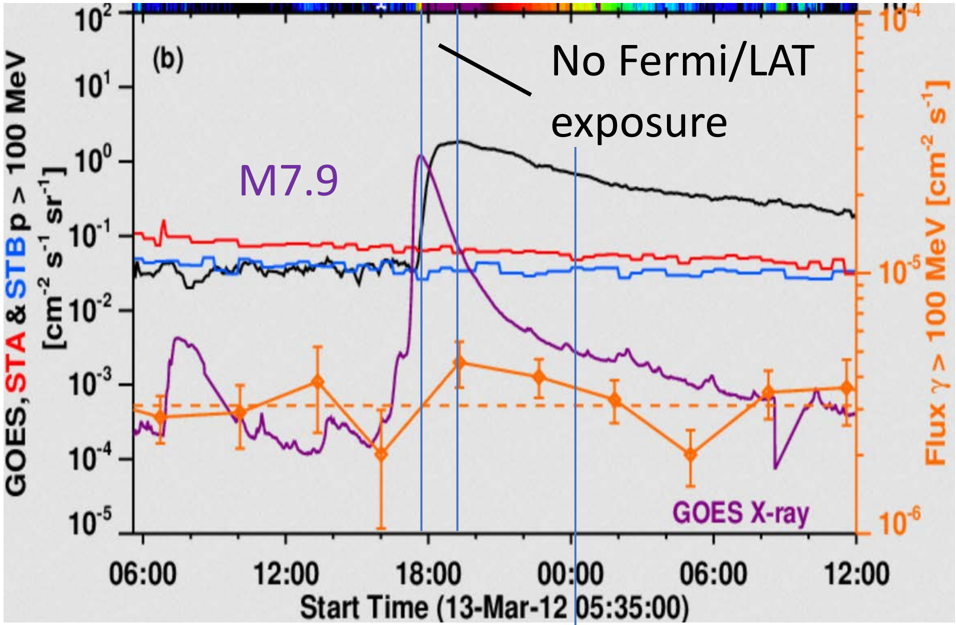
Cannot say whether there was no SGRE during 17:21 – 19:30 UT because Fermi/LAT was not pointed to the Sun until ~19:15 (Share+2018)

Weak SGRE possible during the subsequent exposures (19:30, 22:30 UT), but the level of confidence is low.





Type II burst



No Fermi/LAT exposure

M7.9

CME speed: 1884 km/s (sky plane) and 2333 km/s (3D)

Type II: 17:30 to 21:30 UT ? 4 hours

SGRE 17:41 to 00:15 or 4 hr and 34 min

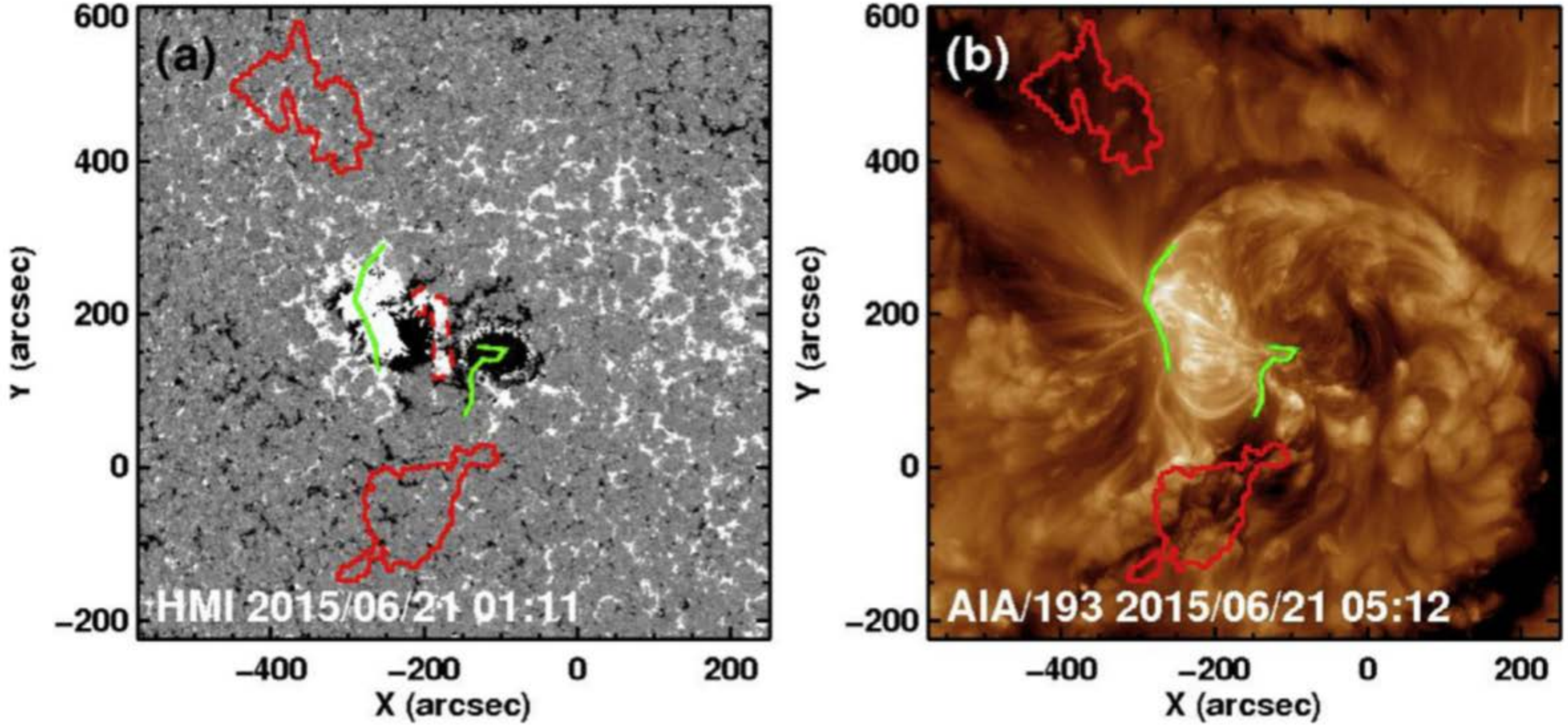
Some Outstanding Issues

- Two SGRE events without CMEs or SEPs (2012/10/23 & 2012/11/27)
- There are indications of CMEs in EUV images; 2012/10/23 event had shock close to the Sun (meter wavelength type II burst)
- Slower CMEs associated with SGRE: CME interactions; seed particles – similar to some GLE events associated with slower CMEs
- Mirroring (Hutchinson+ 2022) – may not be an issue if it happens deep in the solar atmosphere – even better for upward photons (Seckel+ 1991)

Spatial-extended emission expected from the shock scenario

CME Flux rope spatially more extended than the flare structure (post-eruption arcade)

Hard X-rays (& impulsive γ) confined to flare ribbons

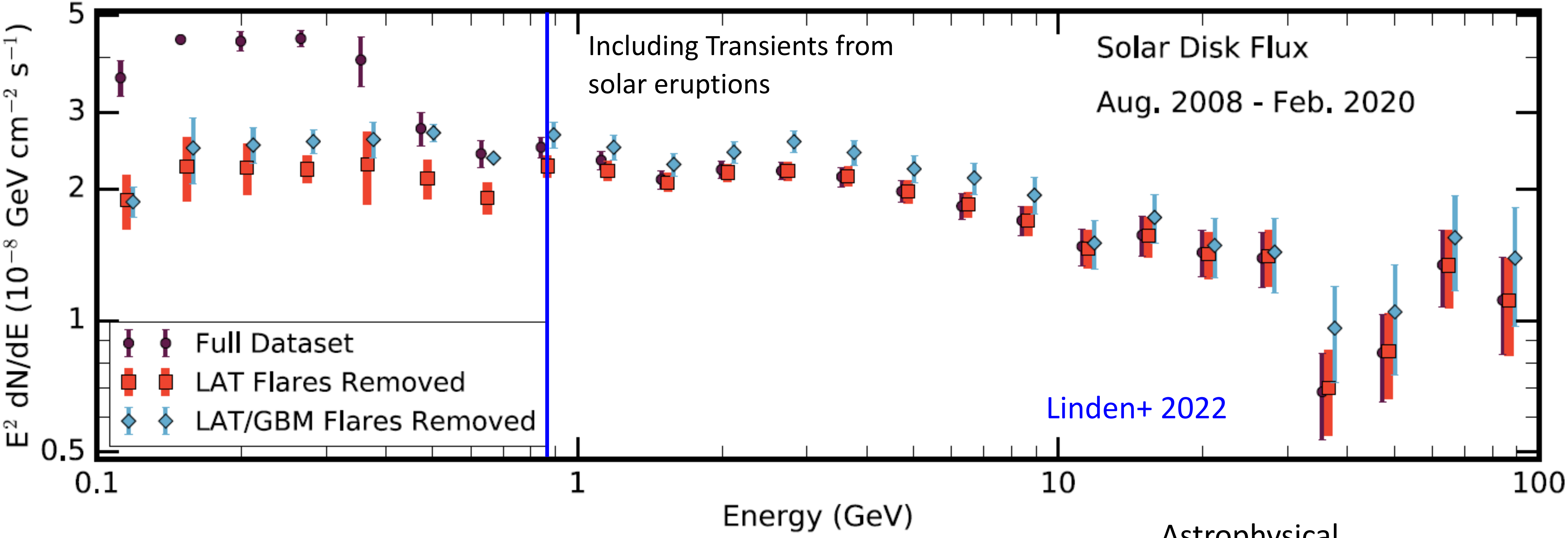


2015 June 21 CME speed: 1366 km/s, M2.6 flare; SGRE 14 h; type II 21 h

Flare Sizes: 12 X, 7 M, 1 C

Solar Disk Emission Spectrum

$dN/dE \sim E^{-2.03}$ (100MeV – 10 GeV)



Including Transients from solar eruptions

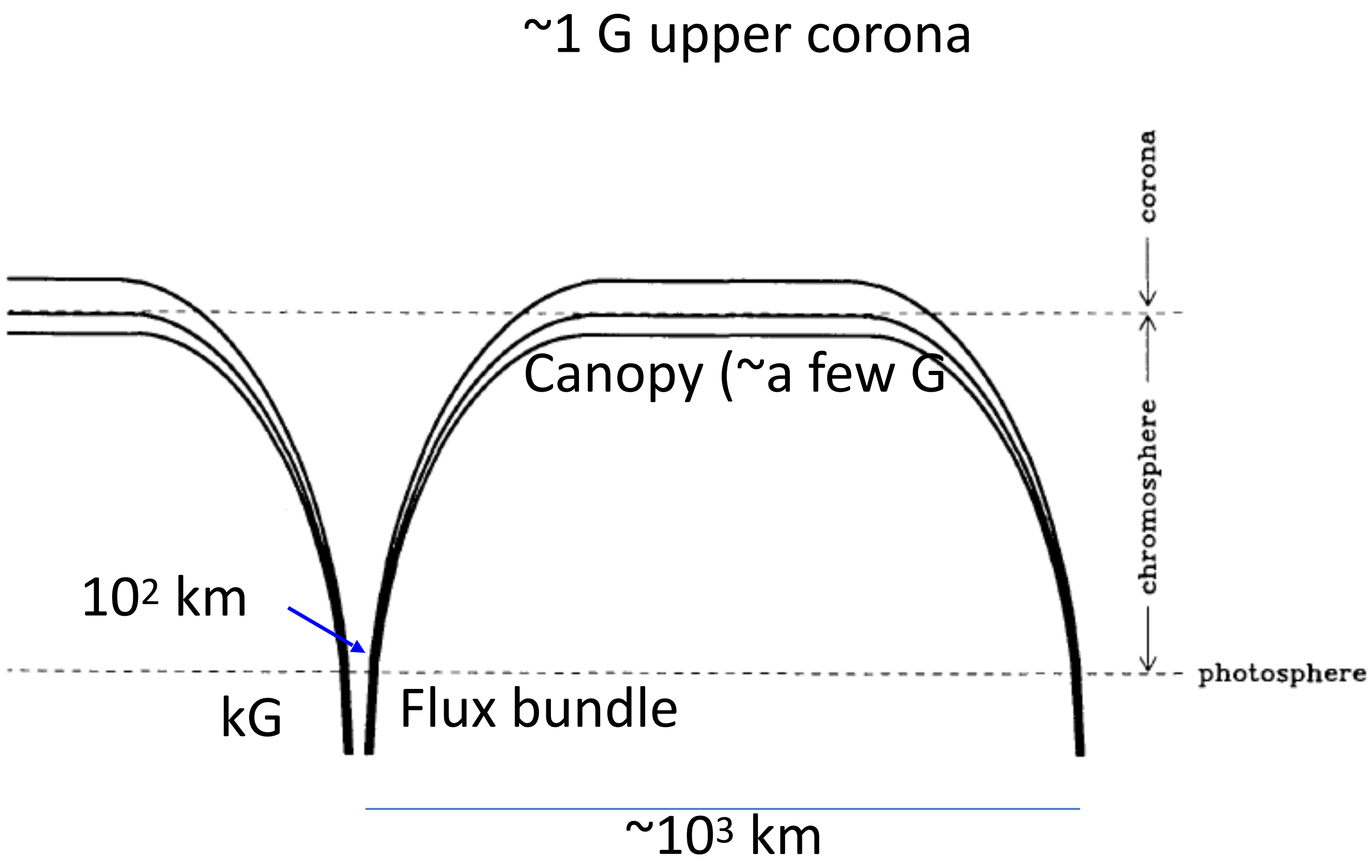
Linden+ 2022

Astrophysical background subtracted

Solar energetic particles
Cosmic rays

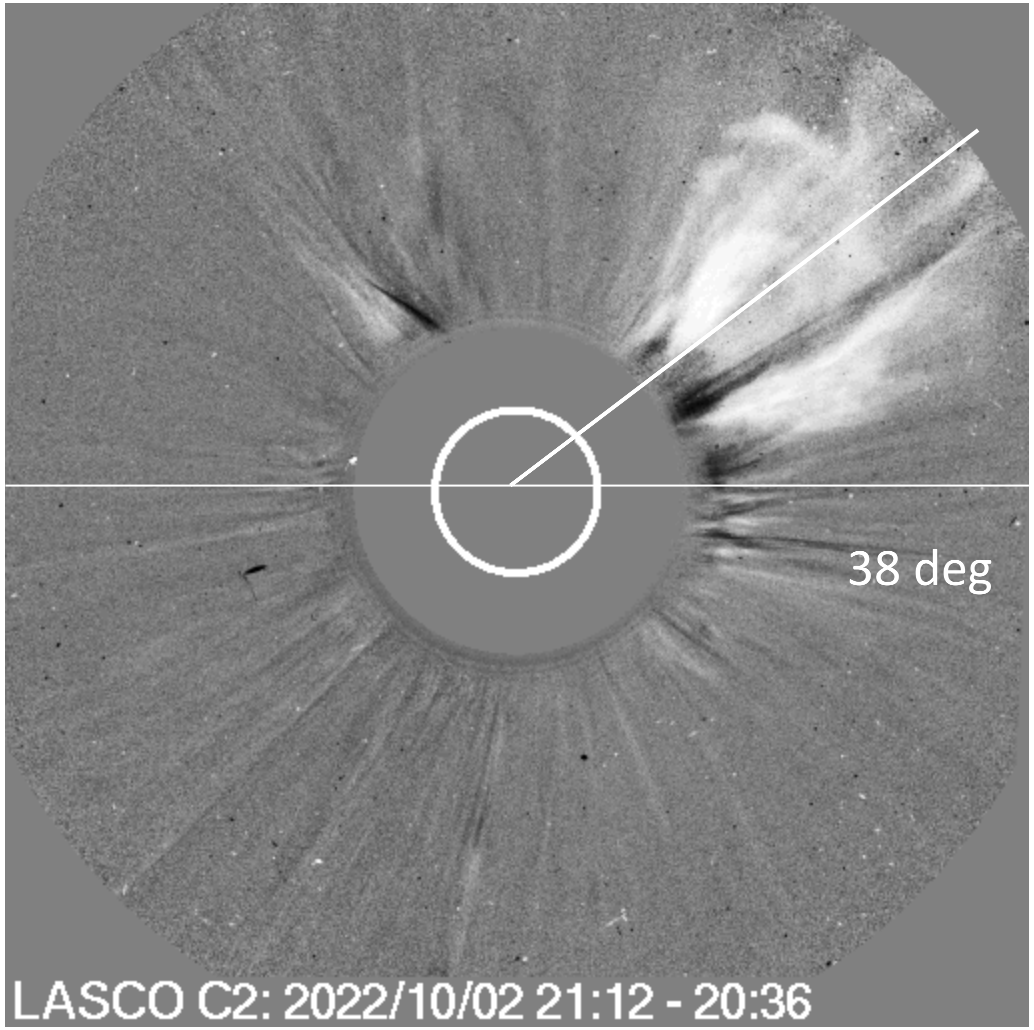
Petrosian: Quiet Sun
Jin: CME shocks
Mäkelä Poster

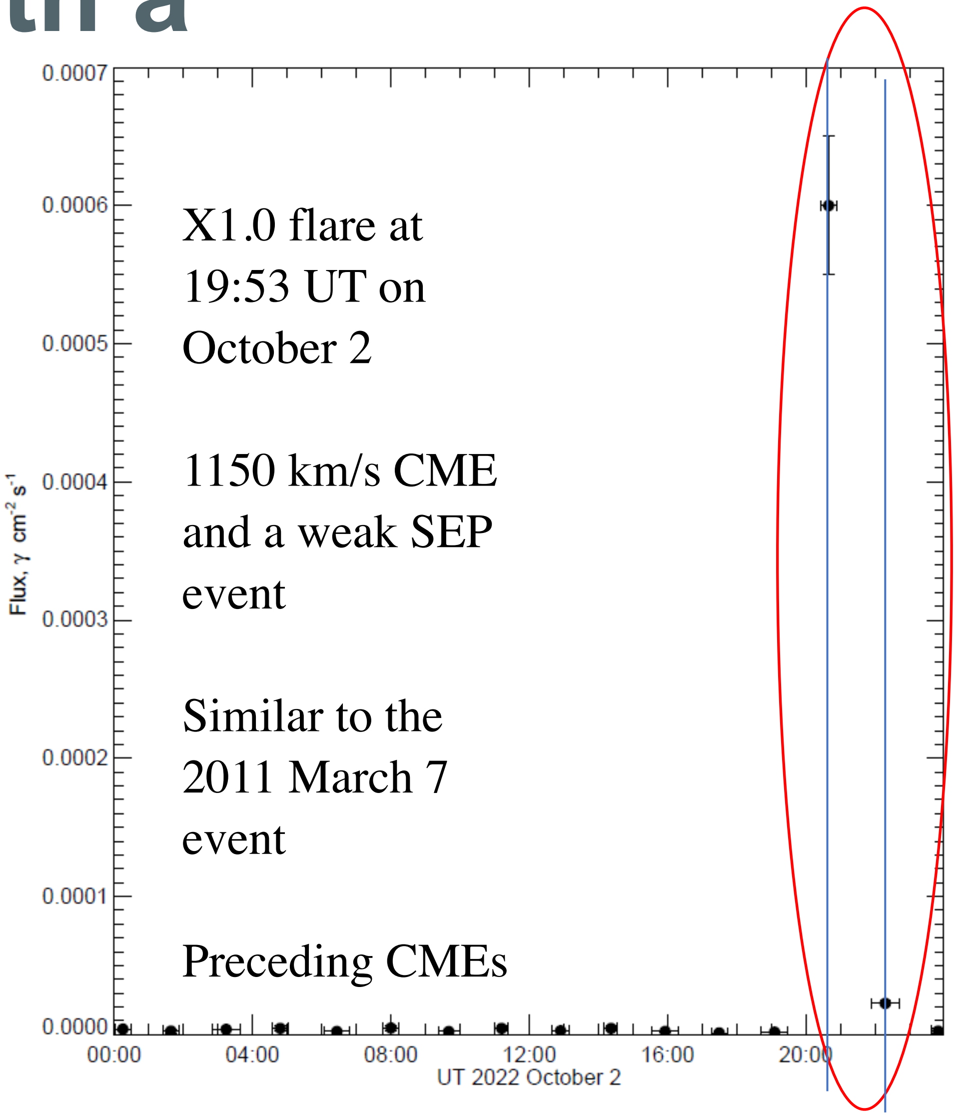
Mirroring Issue



Active regions not important

Cycle 25 SGRE associated with a weak SEP event





X1.0 flare at 19:53 UT on October 2

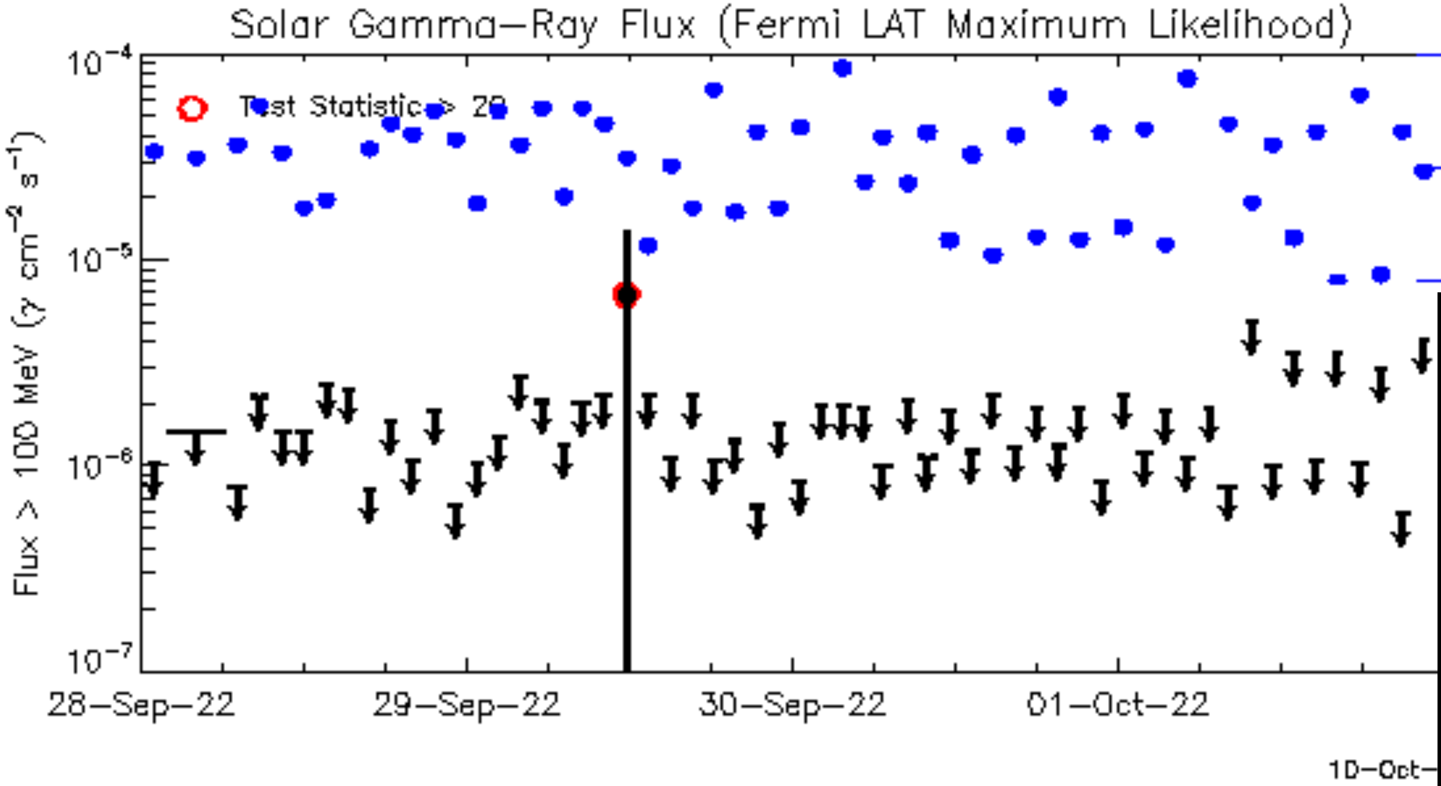
1150 km/s CME and a weak SEP event

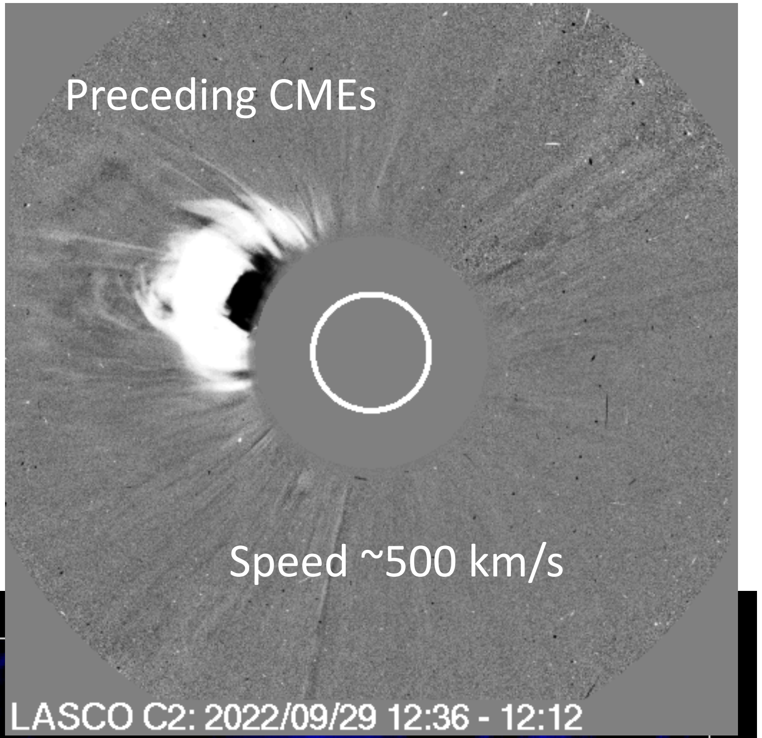
Similar to the 2011 March 7 event

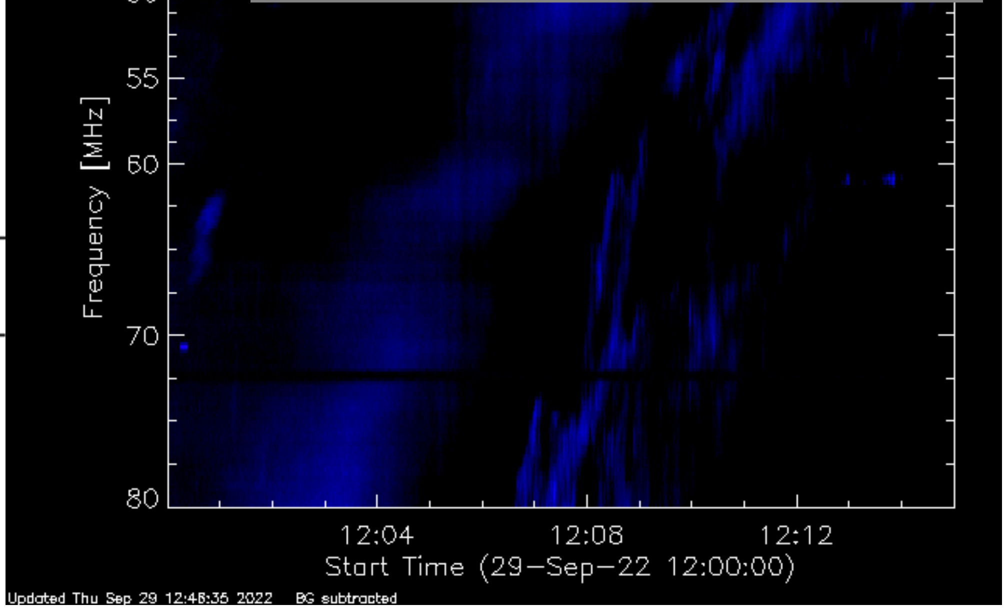
Preceding CMEs

Courtesy: G. Share

Cycle 25 SGRE associated with a slow CME







~10deg behind the limb

Effect of CME interaction?

Summary

- Fermi/LAT observations have revived the issue of source of high-energy particles required for sustained gamma-ray emission
- The close connection among SGRE, CME, SEP, and type II bursts favors the shock paradigm
- The SGRE CMEs are similar to GLE CMEs ⍰ High energy SEPs are guaranteed; the CME speed is closely correlated with the SGRE fluence
- The flare size is not a critical parameter: 7M and 1 C class flares (40%)
- Soft-spectrum SEP events at Earth with SGRE: poor latitudinal connectivity to the shock nose results in soft spectrum although high-energy particles are accelerated at the shock but do not arrive at the particle detector.
- The extended source expected from shock particles explains backside events and the N_{SEP} – N_g correlation
- The extended gamma-ray emission is similar to the quiet-Sun emission due to galactice cosmic rays (Seckel+ 1991)
- Need to explain SGRE during a couple of CME-less flares (although CME signatures exist)