Recent Developments in Solar Energetic Particle Research

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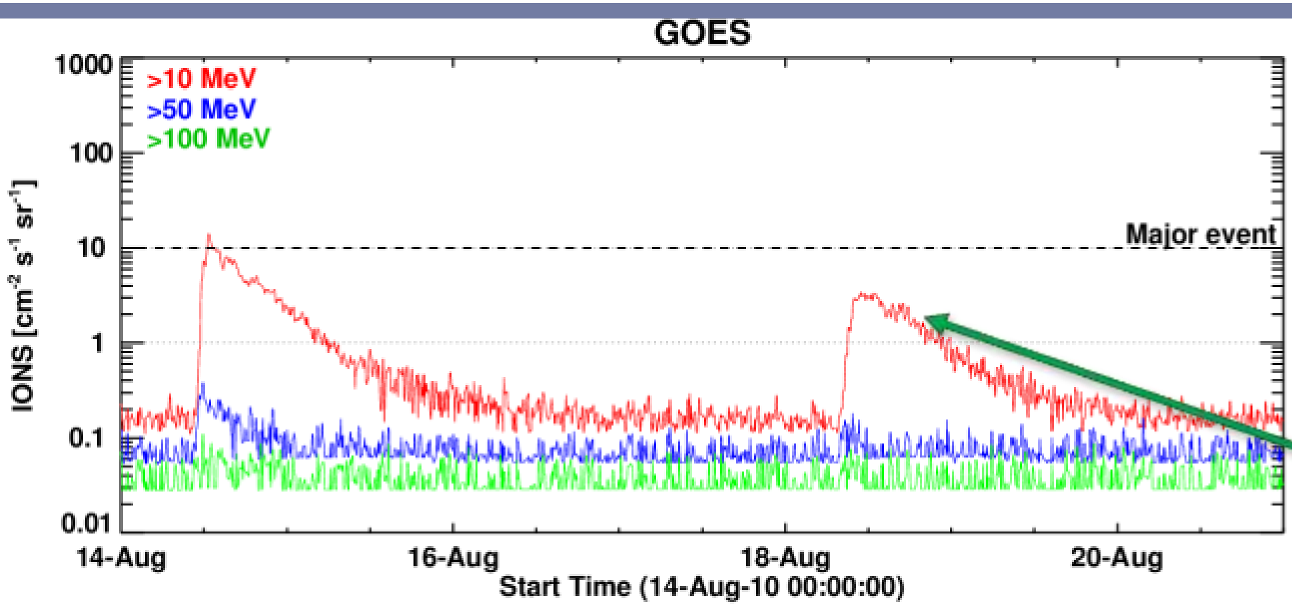
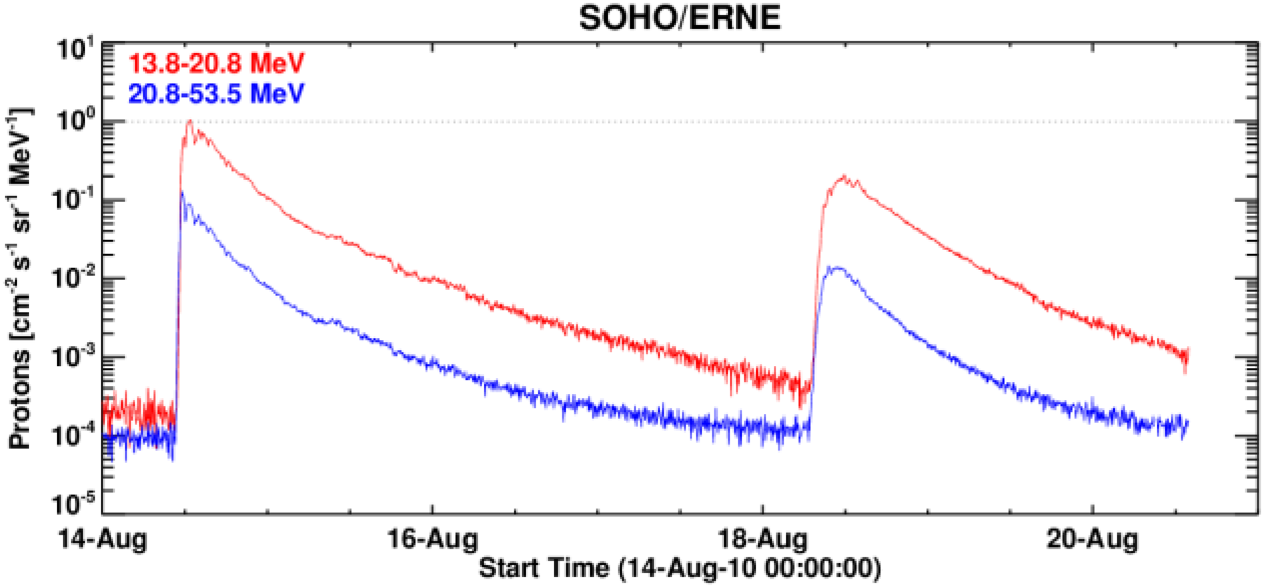
Recent Books/Reviews

- Malandraki, O. E., Crosby, N. B. (eds), Solar Particle Radiation Storms Forecasting and Analysis, The HESPERIA HORIZON 2020 Project and Beyond, *Astrophys. Space Sc. L.*, 444, 2018, DOI:10.1007/978-3-319-60051-2
- Reames, D. V., Solar Energetic Particles, A Modern Primer on Understanding Sources, Acceleration and Propagation, *Lect. Note Phys.*, 932, 2017, DOI:10.1007/978-3-319-50871-9
- Simnett, G. M., Energetic Particles in the Heliosphere, *Astrophys. Space Sc. L., 438, 2017,* DOI:10.1007/978-3-319-43495-7
- Desai, M., Giacalone, J., Large gradual solar energetic particle events, *Living Rev. Sol. Phys.*, 3, 2016, DOI:10.1007/s41116-016-0002-5
- Miroshnichenko, L., Solar Cosmic Rays, Fundamentals and Applications, *Astrophys. Space Sc. L.*, 405, 2015, DOI:10.1007/978-3-319-09429-8

SEP Event Definition





Large (major) SEP event (CME shock-accelerated):

GOES >10 MeV peak integral flux ≥ 10 pfu.

pfu = particle flux unit

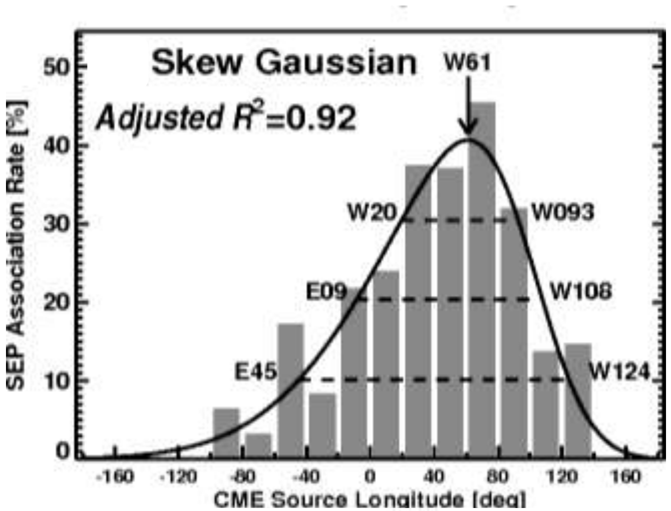
1 pfu = 1 particle per $(cm^2\ s^1\ sr^1)$

Small event (flare accelerated if ^{3}He/heavy ion flux enhancements)

GOES measurements are not good for detecting small SEP events due to high background levels.

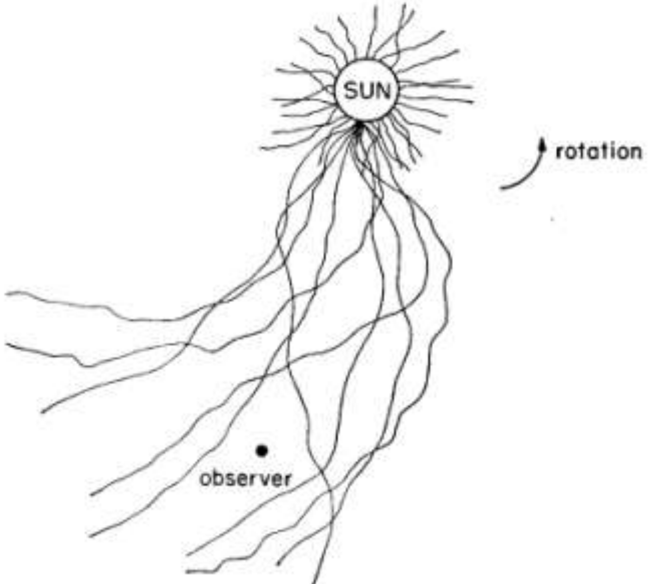
High-energy SEPs can penetrate into the Earth's ionosphere and atmosphere causing ionization, changing chemical processes and producing nuclear reactions (ground level enhancement events)

SEP Propagation

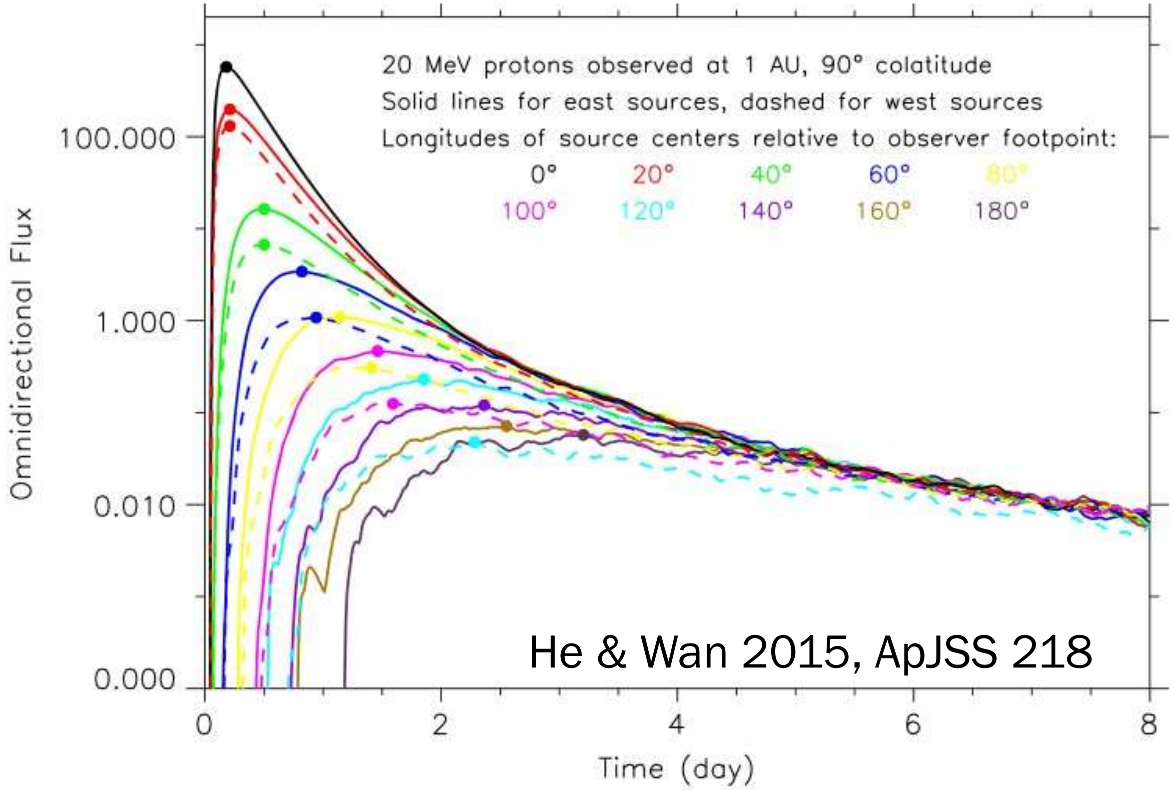


- 196 Fast and Wide (Speed ≥ 900 km/s; Width ≥ 60 °) CMEs during 2007-2014
- SEP association rate as a function of the CME source longitude is skewed
- The eastern wing drops slowly compared to the western wing

East-west asymmetry of flux-time profiles due to longitudinal locations of solar sources relative to the magnetic footpoint of the observer at 1 AU



Jokipii & Parker, 1969 ApJ 155



He & Wan 2015, ApJSS 218

Type II Radio Bursts and SEPs

Type II emission is produce by CME shock-accelerated electrons.

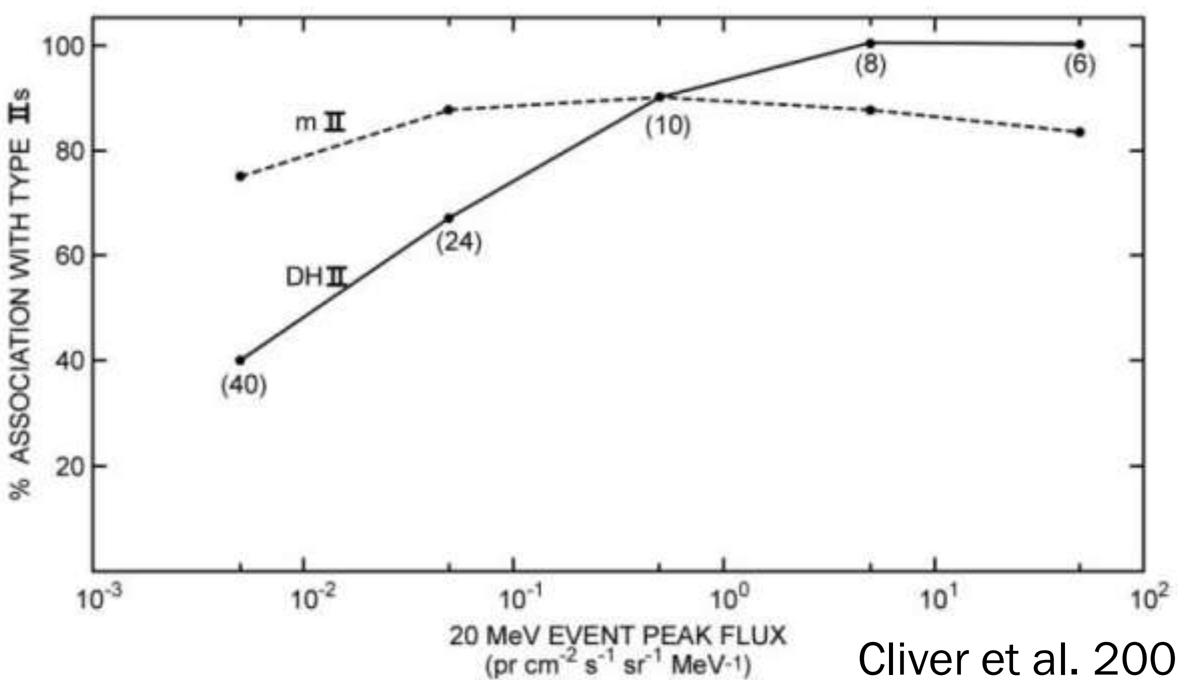
$f = A\sqrt{n}$, where *f* is the frequency in kHz, *n* the electron number density in cm^{-3} of the ambient plasma and A=9 (18) for fundamental (harmonic) emission.

~80% of ~ 20 MeV SEP events associated with metric type II bursts (Cliver et al., 2004).

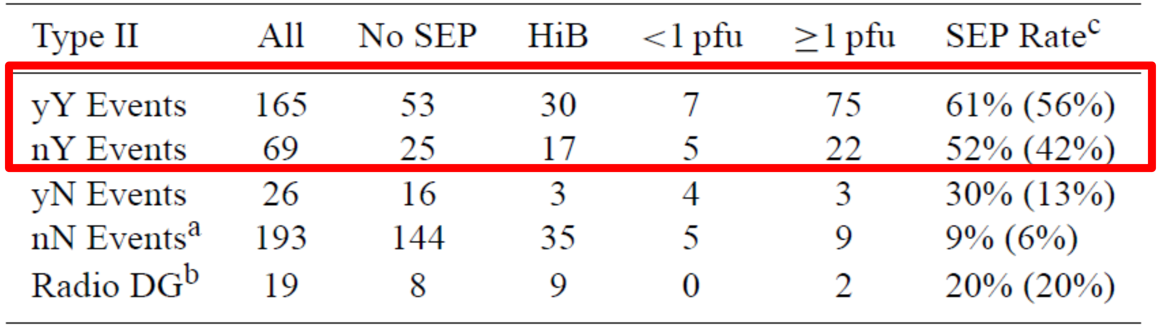
~100% association between intense SEP events and decameter-hectometric (DH) type II bursts (Gopalswamy, 2003; Cliver et al., 2004).

Metric-DH (yY) and DH (nY) type II bursts associated with fast and wide CMEs have high SEP event rates.

DH type IIs are good indicators of large SEP events, but give a short/none lead time for prediction because SEPs arrive at 1 AU around the same time as the DH type II bursts are observed.



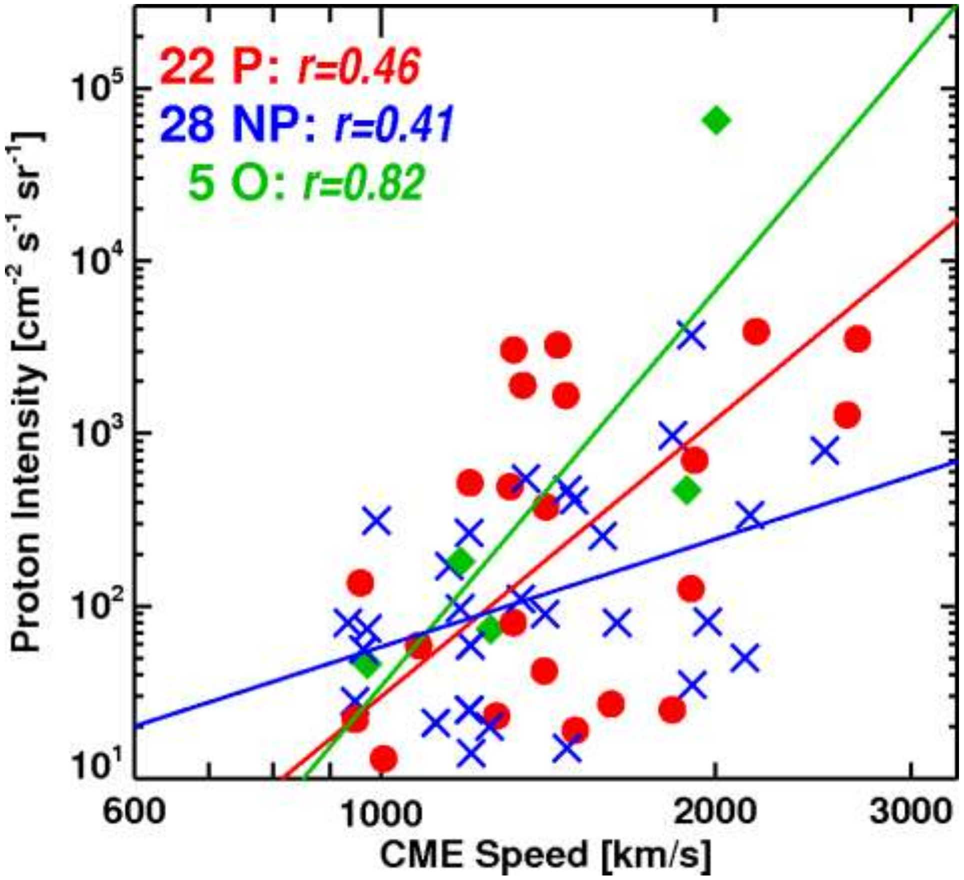
Cliver et al. 2004



Type II	All	No SEP	HiB	<1 pfu	≥1 pfu	SEP Rate[c]
yY Events	165	53	30	7	75	61% (56%)
nY Events	69	25	17	5	22	52% (42%)
yN Events	26	16	3	4	3	30% (13%)
nN Events[a]	193	144	35	5	9	9% (6%)
Radio DG[b]	19	8	9	0	2	20% (20%)

Gopalswamy et al. 2008

Preconditioning

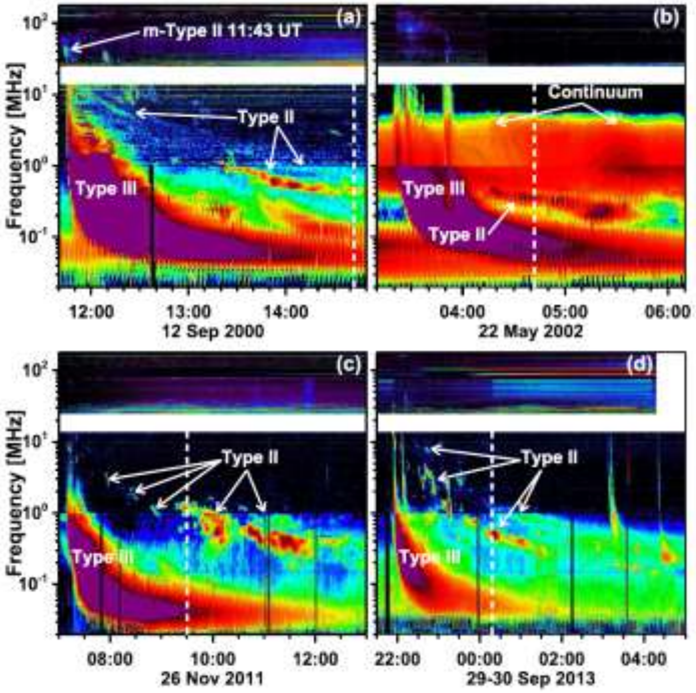


- P: Preceding CME from the same active region ≤ 24 hours
- Cycle -24 large SEP events analyzed for preconditioning
- All but one huge SEP event (Ip≥1000 pfu) in cycle 24 were preconditioned
- The result is consistent with Gopalswamy et al. (2004) who considered cycle 23 events, but the cycle 24 distributions overlap more than cycle 23 ones

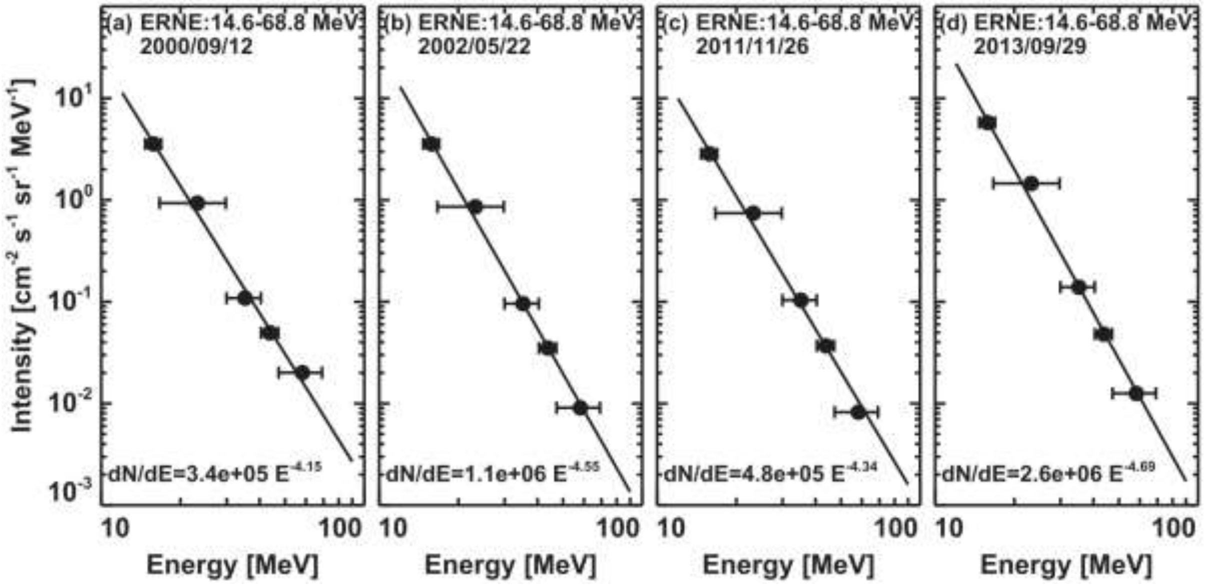
Yashiro et al. 2015

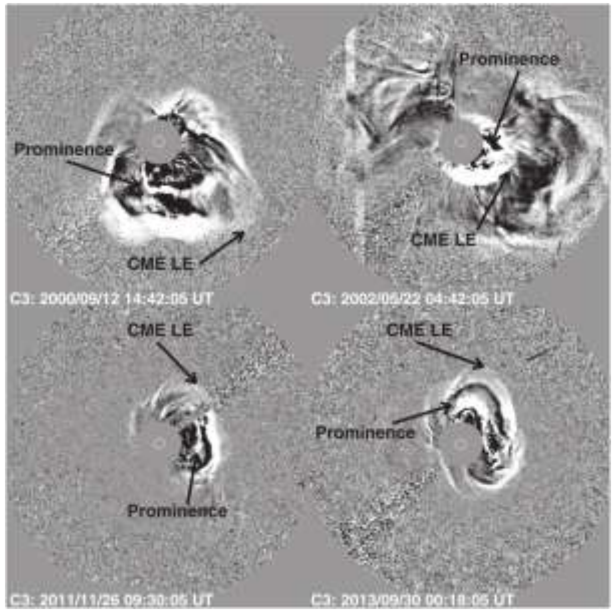
Filament Eruption SEPs

- First reported by Kahler et al. (1986; ApJ 302)
- Gopalswamy et al. (2015; ApJ 806) identified four filament eruptions (FEs) outside active regions (ARs) that were associated with major (GOES >10 MeV flux ≥ 10 pfu) SEP events and interplanetary type II radio bursts (no metric type II bursts except during one event).
- Spectral index in the 10–100 MeV range typically >4 for the FE-SEP events. → Soft energy spectrum



Time-of-Maximum (TOM) spectra





Fluence Spectral Index

Systematic increase in spectral index as one goes from the ground level enhancement (GLE) events to regular SEP events and to FE SEP events (Gopalswamy et al. 2016, ApJ 833)

Large SEP events

	Cycle 23	Cycle 24	Cycles 23 and 24
FE SEP	4.72	5.41	4.89
Regular SEP	3.85	3.78	3.83
GLE	2.70	2.51	2.68

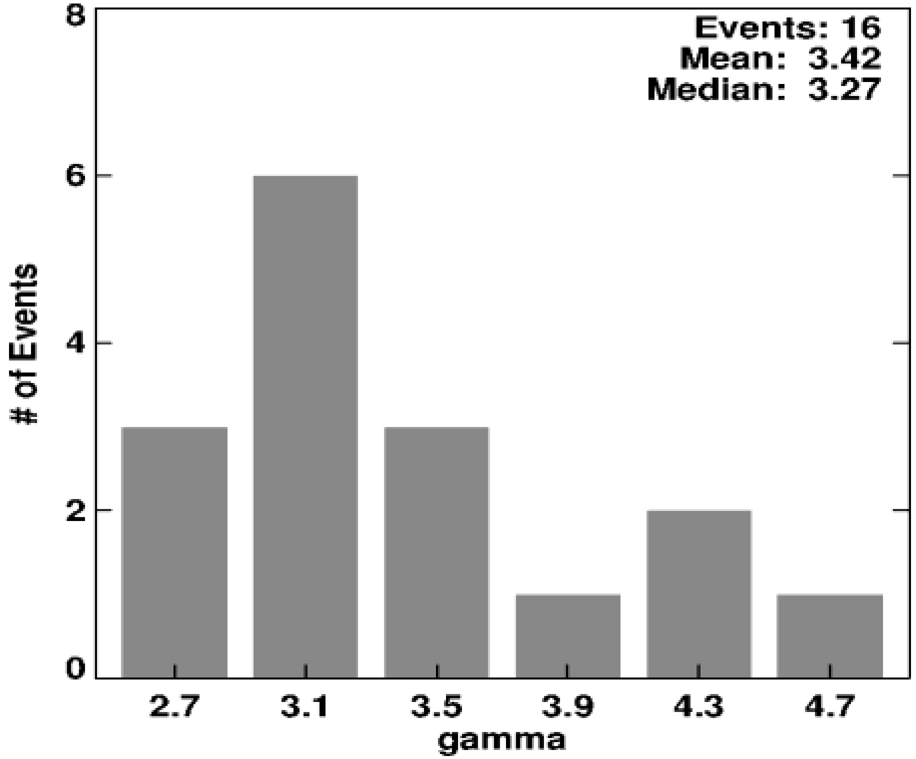
Fluence spectra

Soft

Intermediate

Hard

Small SEP events



Small SEP events follow the spectral index hierarchy

CME Kinematics

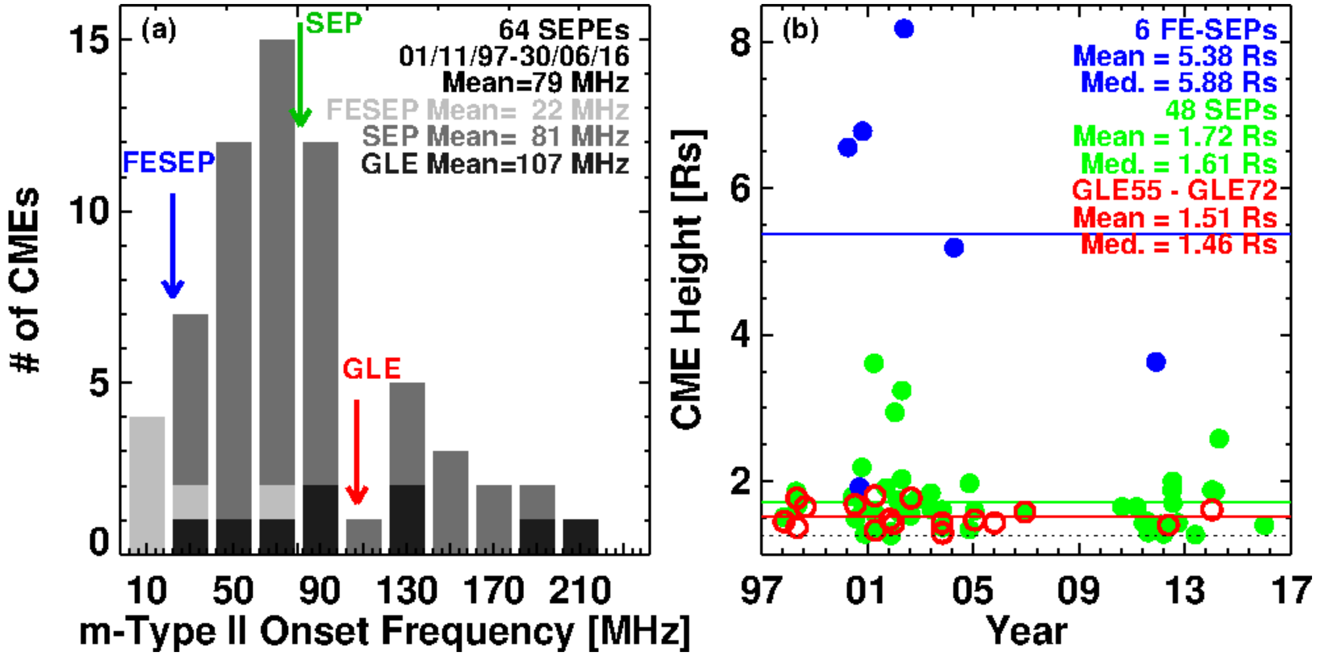
Hierarchical relationship between CME kinematics and the spectral index of SEP events

- In GLE events the shock forms close to the Sun—about half a solar radius above the solar surface.
- Particles accelerated efficiently to GeV energies (hard spectrum) because of the high ambient magnetic field near the Sun.
- The low shock-formation height implies impulsive CME acceleration (initial acceleration ~2 km/s^2).
- In FE SEP events, the shock forms at much larger heights—either in the outer corona or in the interplanetary medium (Mäkelä et al. 2015, ApJ 806).
- Particles are not accelerated to high energies (soft spectrum; Gopalswamy et al. 2015, Prog EP&S 2).
- The regular major SEP events show intermediate behavior in shock-formation height, initial acceleration, and spectral hardness.

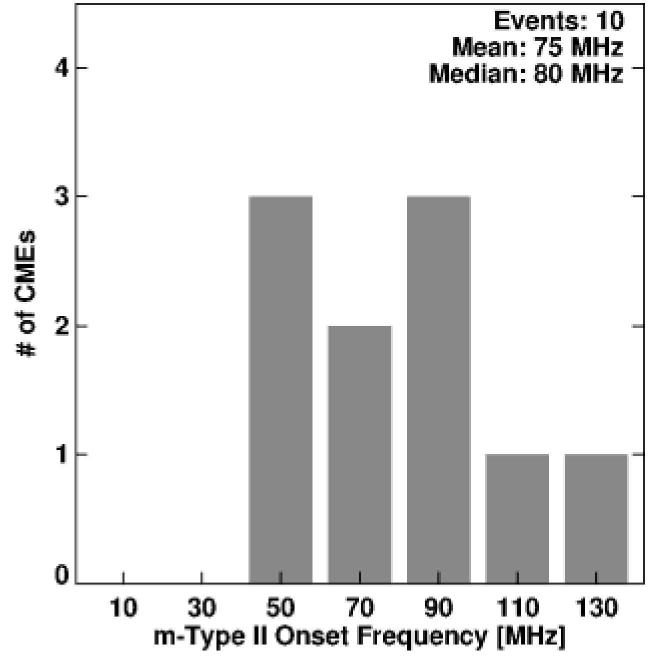
Type II Burst Onset Frequency

- Average onset frequencies of type II radio bursts associated with the GLE, FE SEP and major SEP events have a hierarchy (Gopalswamy et al. 2017, JPCS, Proc 16th AIAC).
- The shock formation heights are also organized accordingly.
- Small SEP events resemble regular large SEP events

Major SEP events



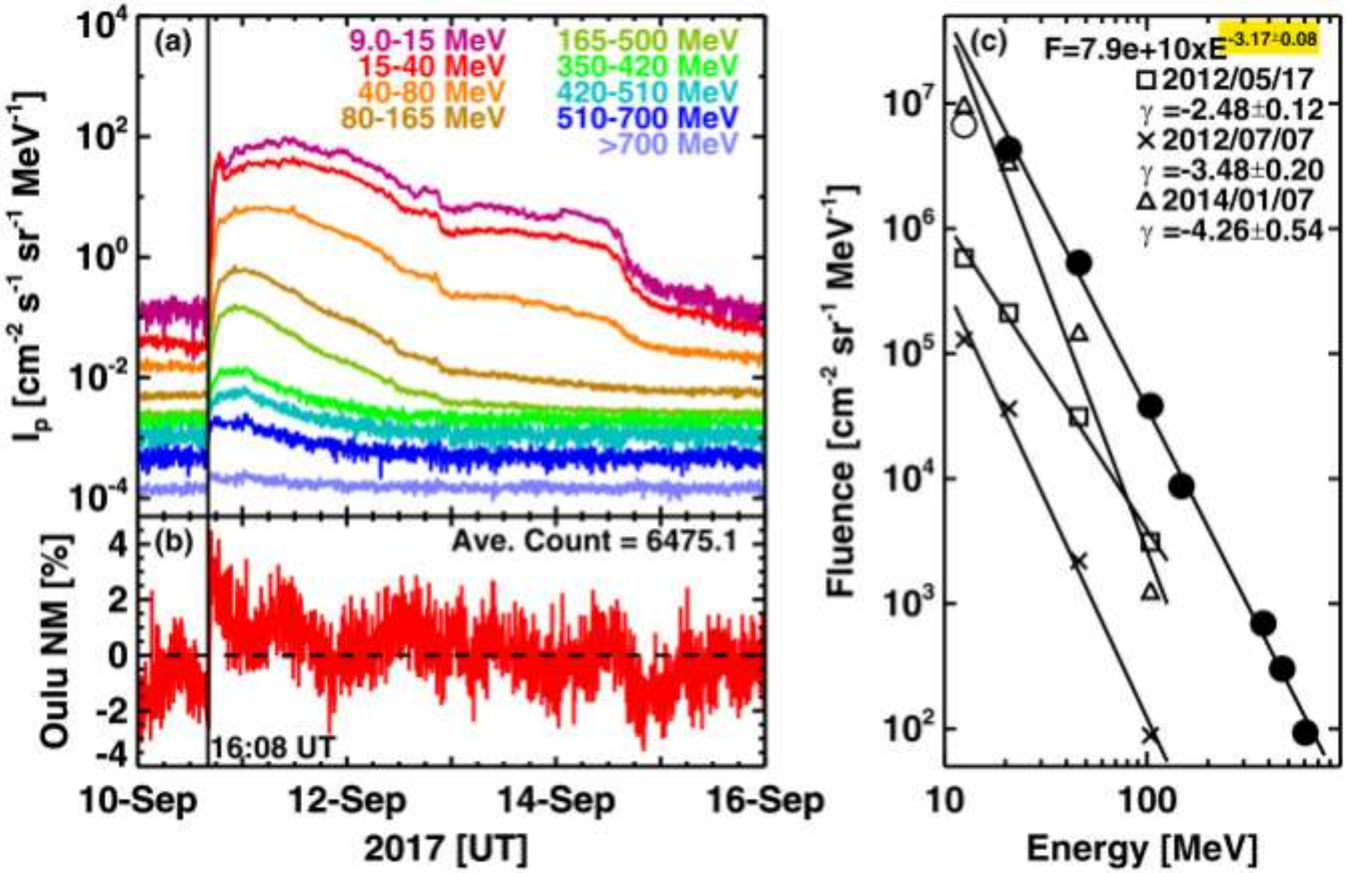
Small SEP events

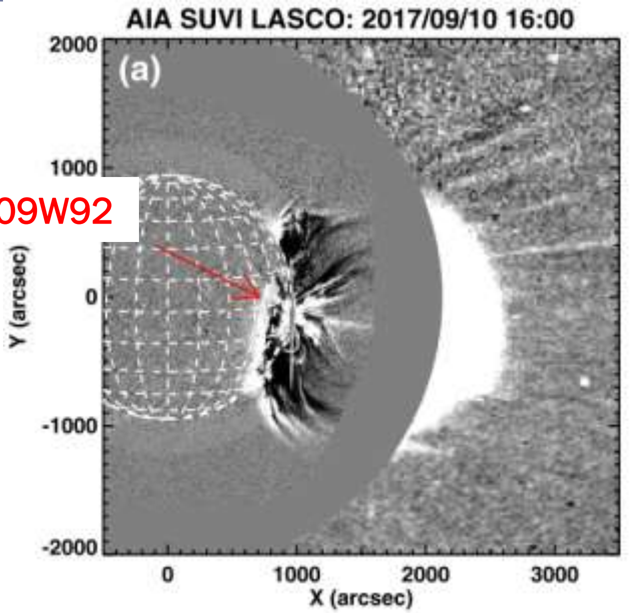


2017 September 10 GLE

Softer fluence spectrum (3.17) than that of the 2012 May 17 GLE (2.48), but harder than those of the two non-GLE events (3.48; 2012 July 7 and 4.26; 2014 January 7)

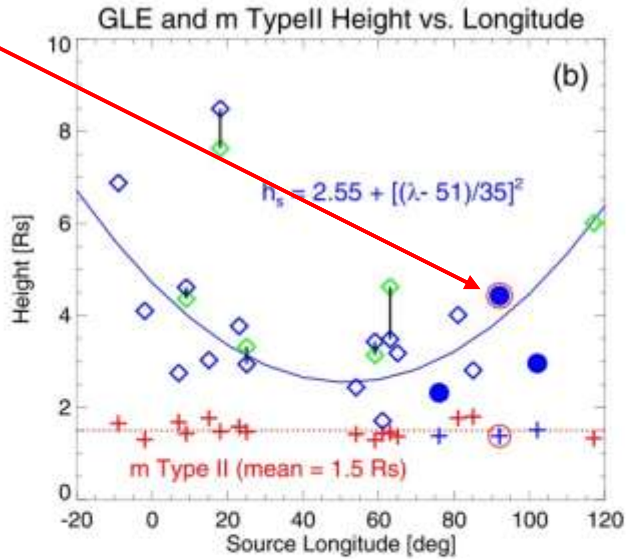
Low intensity GLE (neutron monitor count rate ~4.4% above background)





S09W92

The shock height at the solar particle release time consistent with the relationship between shock height and source longitude derived from cycle-23 GLE events.

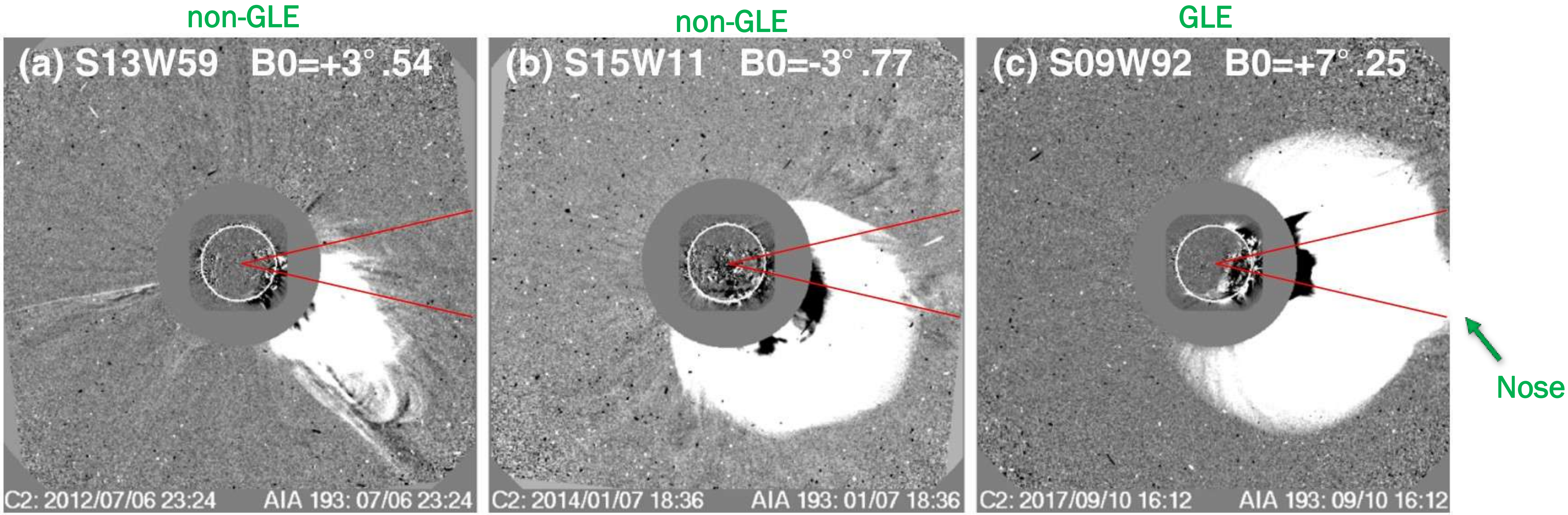


Gopalswamy et al. 2018, ApJL 863

Connection to the Shock Nose

SOHO/LASCO CMEs in two non-GLE SEP events (a, b) with similar initial speeds as the Sep 10 CME (c). The red lines represent a cone of half angle of 13° based on the latitudes of cycle-23 GLEs

The nose of the GLE CME is closer to the ecliptic than those of the other two that did not produce GLE, but the latitudinal and longitudinal connectivity is still less than ideal → lower intensity and softer fluence spectrum

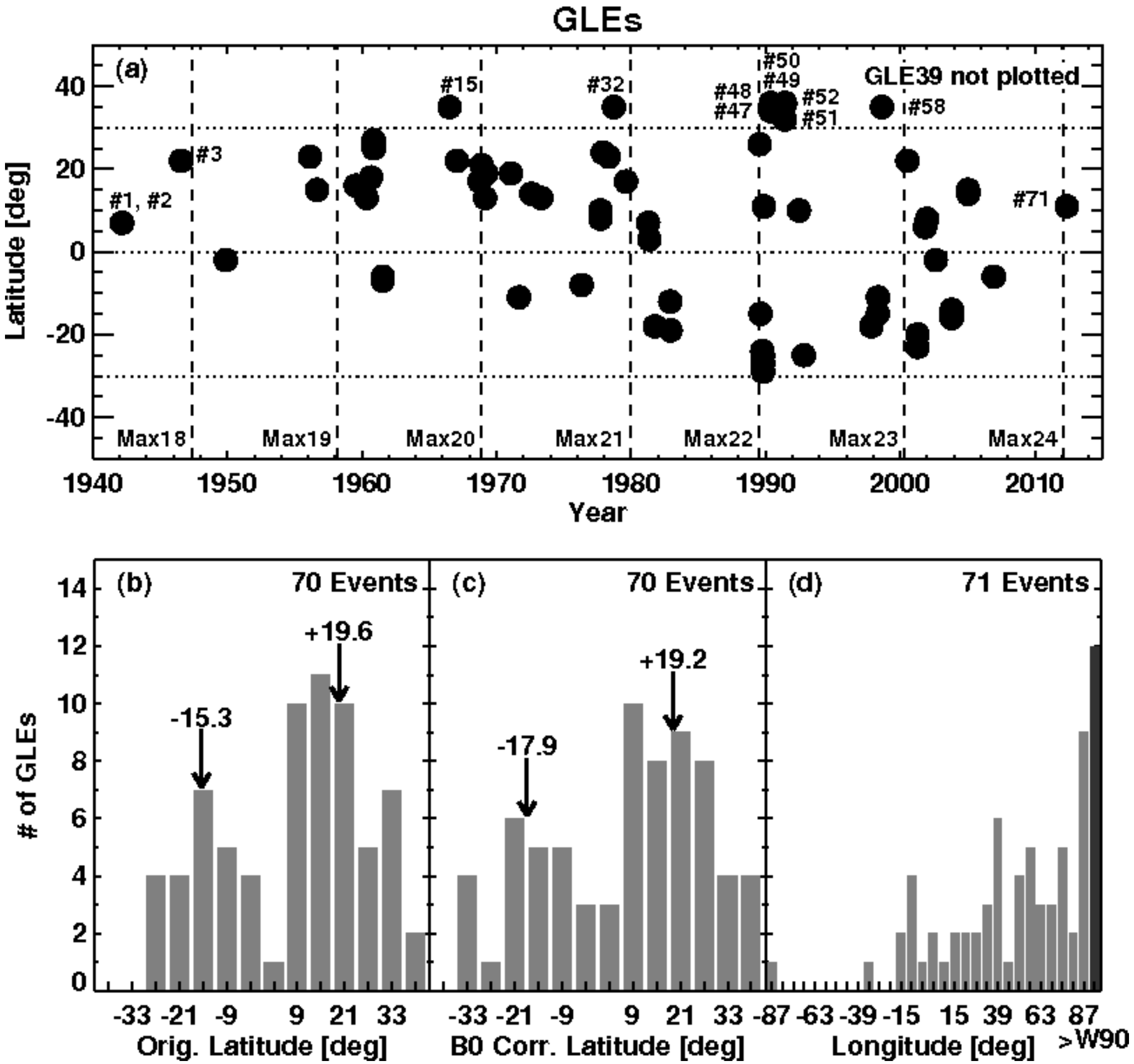


Gopalswamy et al. 2018, ApJL 863

Latitudinal Connectivity in Historical GLE Events

13 historical GLE events with flare latitudes >30 deg

Non-radial motion of GLE-producing CMEs towards lower latitudes is likely due to deflection by large-scale magnetic structures in coronal holes or in streamers.



Gopalswamy and Mäkelä, 2014, ASP Conf. Ser. 484

Longitudinal Distribution

Xie et al. 2019, JGR submitted

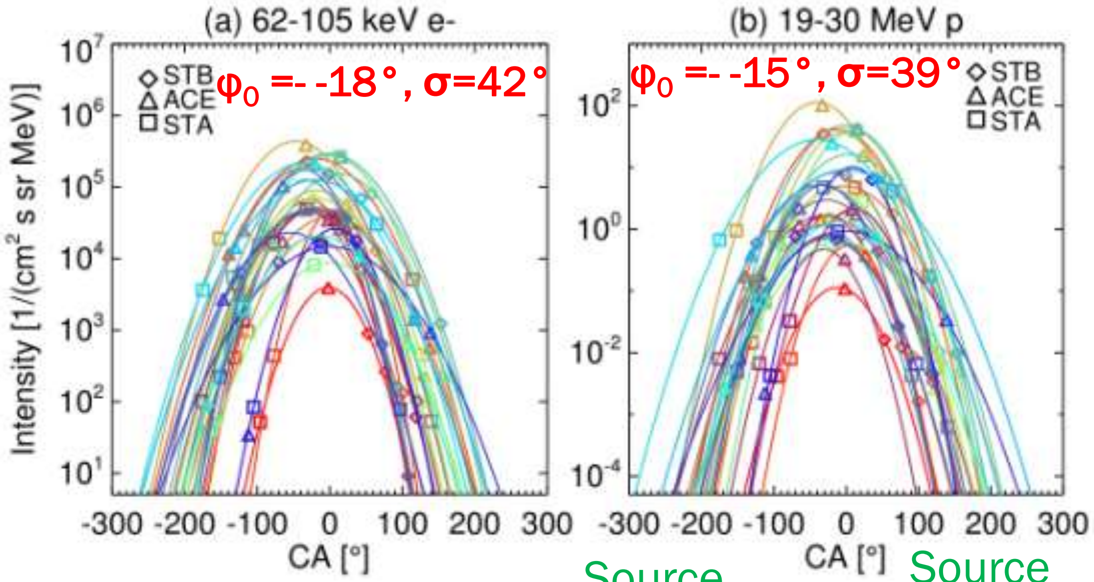
$$I(\phi) = I_0 \exp[-CA^2/2\sigma^2], \text{ where } I_0 = 10^{4.26+0.7v^2\kappa^2\omega_{FO}}$$

$$\sigma = \begin{cases} 7.1 + 0.26CA, & \text{if } CA \geq 0 \\ 12.9 - 0.28CA, & \text{if } CA < 0 \end{cases}$$

$$I(\phi) = I_0 exp[-CA^2/2\sigma^2], \text{ where } I_0 = 10^{-0.27+1.09v^2\kappa^2\omega_{FO}}$$

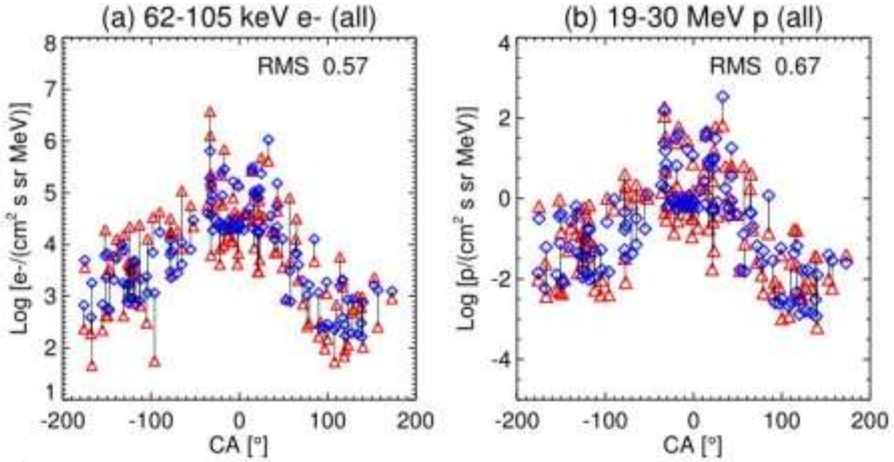
$$\sigma = \begin{cases} 8.4 + 0.21CA, & \text{if } CA \geq 0 \\ 7.9 - 0.28CA, & \text{if } CA < 0 \end{cases}$$

where (v, ω_{FO}, CA) are in units of $(10^{-3}km/s, 10^{-2}\text{deg, deg})$, respectively.

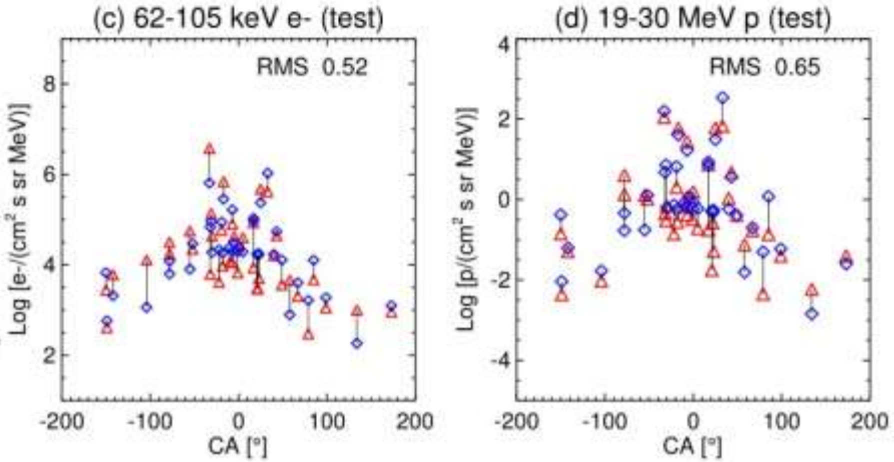


Source eastward

Source westward of obs. footpoint



Observations Predictions



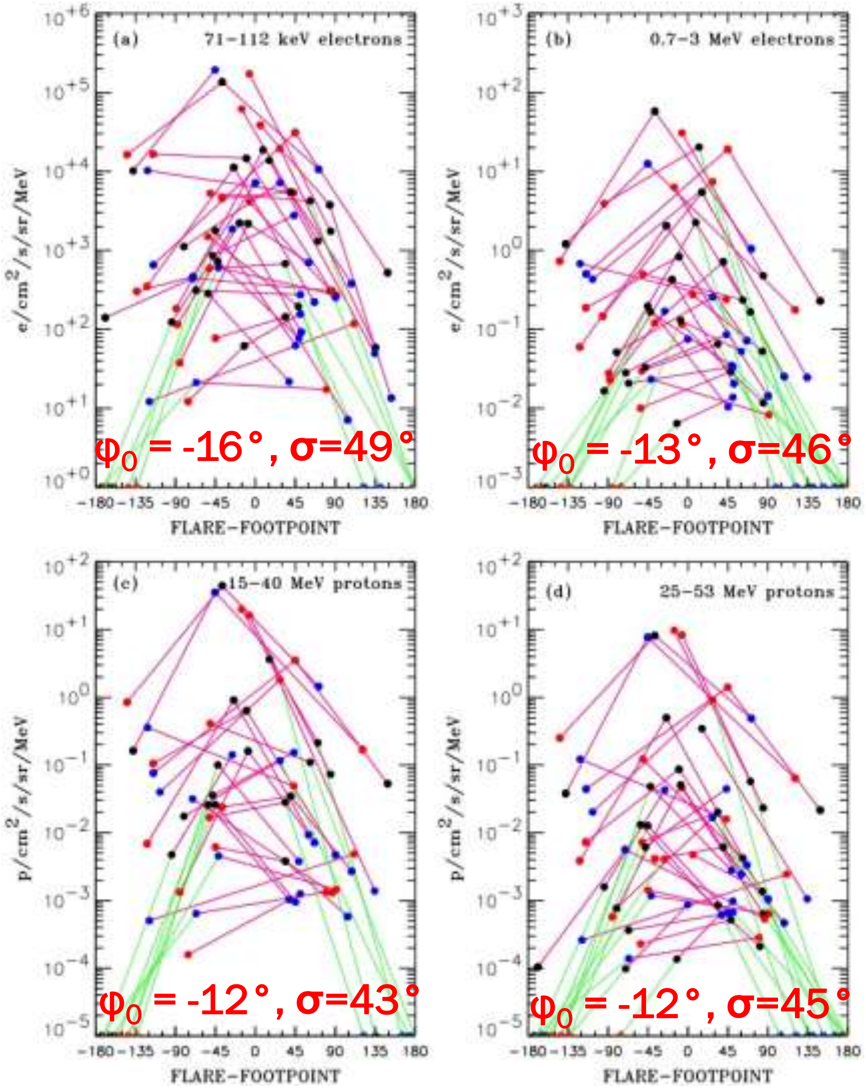
Richardson et al. (2014, SolPhys 289) for 25 MeV proton peak intensity (also Richardson et al. 2018, Space Weather 16)

$$I(\phi) = I_0 \exp[-CA^2/2\sigma^2], \; I_0 = exp(-4.36 + 3.6v_{sky})$$

where v_{sky} is the sky-plane speed of the CME in units of $(10^{-3}km/s)$ and $\sigma = 43°$

Longitudinal Distribution

Lario et al. 2013, ApJ 767



φ_0 = -16°, σ=49°

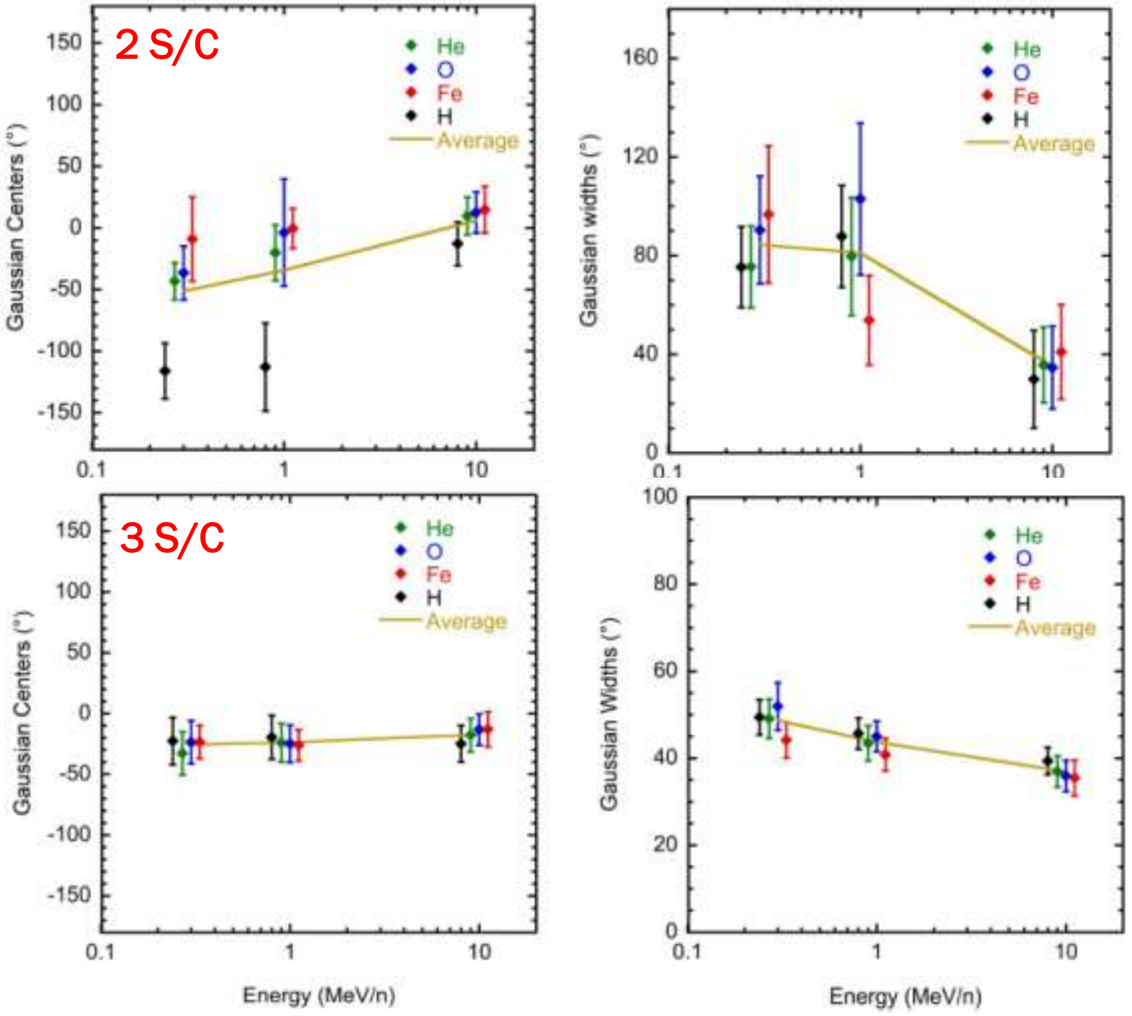
φ_0 = -13°, σ=46°

φ_0 = -12°, σ=43°

φ_0 = -12°, σ=45°

Cohen et al. 2017, ApJ 843

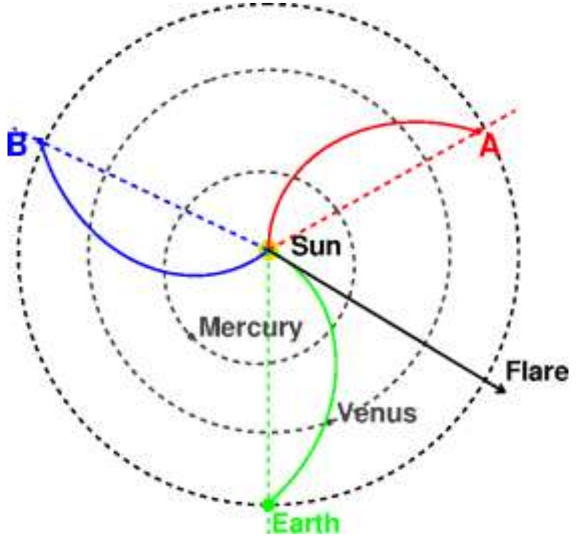
3 S/C dist. φ_0 =-22°, σ=43° wide on average; 2 S/C distr. wider



2 S/C

3 S/C

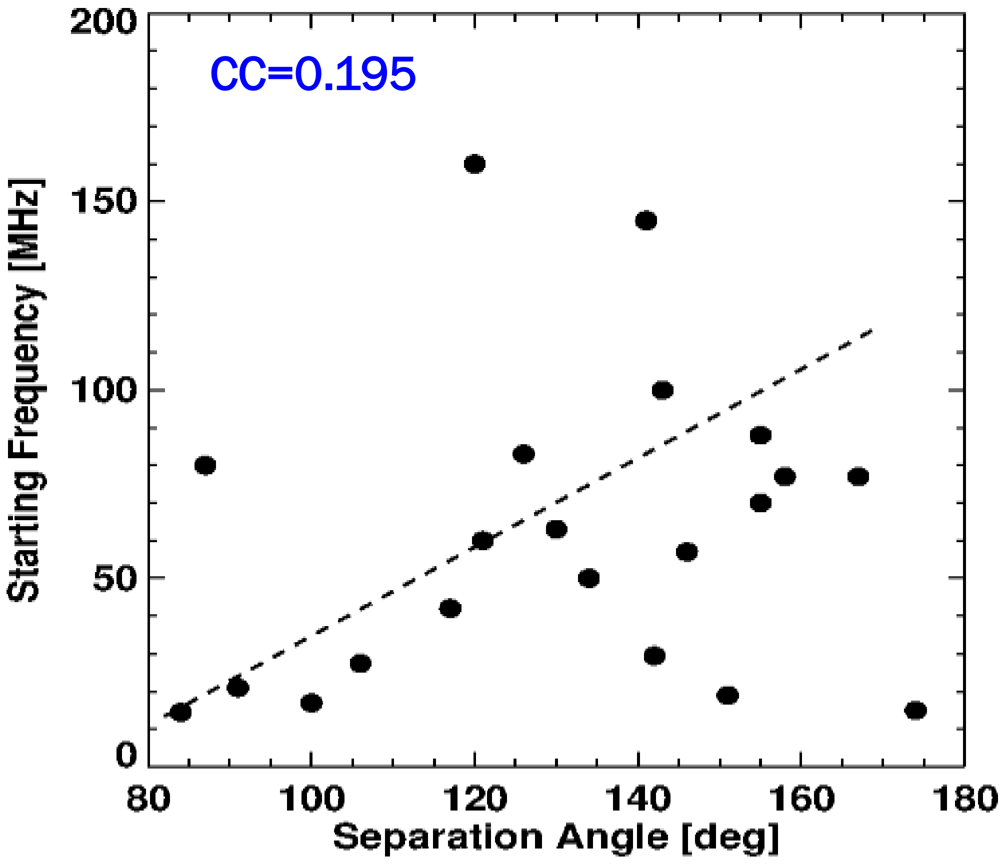
Type II Onset Frequency Correlation



1. Shifted spacecraft longitude according to the Parker spiral for the 400 km/s solar wind.
2. Assumed that the flare location is the solar location from were the SEP source expands.

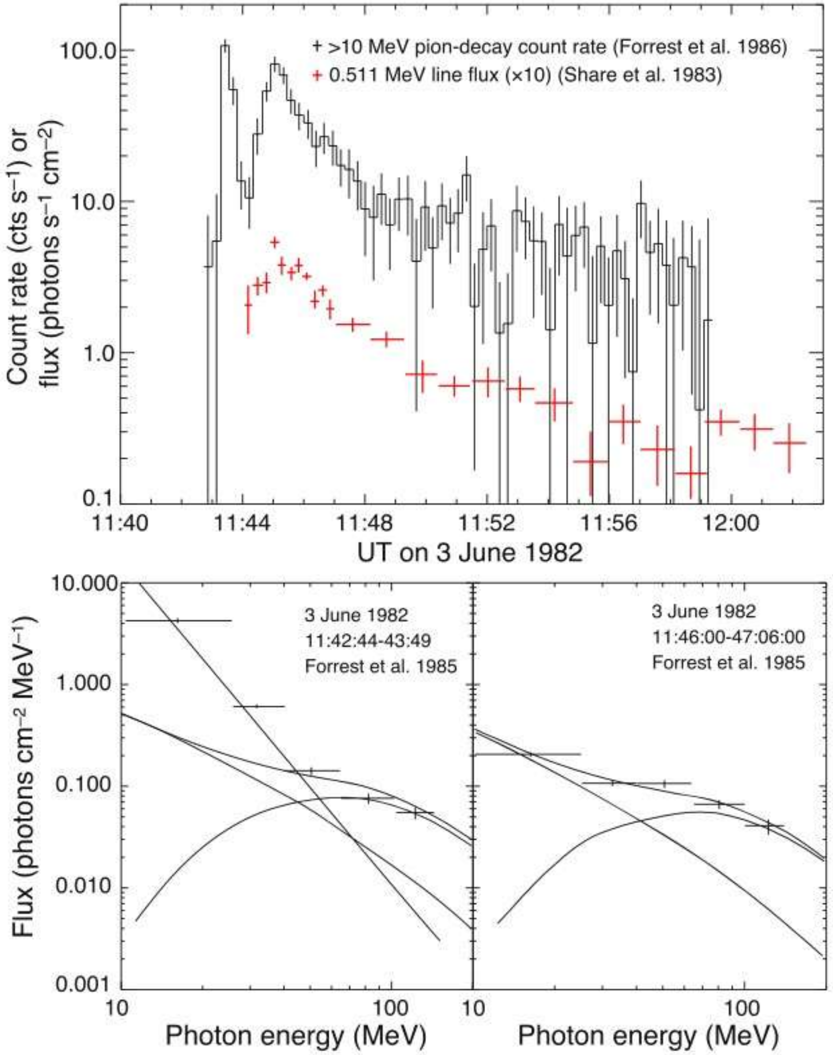
3 S/C (from Richardson et al. 2014, SolPhys 289) : Lower limit for the longitudinal extent of the SEP event: longitudinal separation angle between the farthemost SEP-observing spacecraft and the flare

3 S/C including single lane type IIs assumed to be harmonic emission



Sustained Gamma-Ray Emission

- Sustained gamma-ray emission (SGRE) events show prolonged >100 MeV gamma-ray emission lasting up to several hours after the impulsive phase
- First detected during the 1991 June 15 (Akimov et al. 1991 22nd ICRC) and June 11 gamma-ray flares (Kanbach et al. 1993, A&ASS 97)
- Large Area Telescope (LAT) of the Fermi satellite has detected several SGRE events (Share et al. 2018, ApJ 869)
- 13 long-duration gamma-ray flares (LDGRF) events between 1982–1991 (Ryan 2000, SSRv 93)
- Emission of neutral pion-decay gamma-rays produced by >300 MeV proton interactions in the dense low solar atmosphere
- Suggested particle sources: flares and shocks driven by CMEs



Share et al. 2018, ApJ 869

Pion Decay

p+p → p+ π+ X

E >300 MeV

$$\pi^0 \rightarrow 2\gamma \qquad 98.8\%$$

$$\pi^0 \rightarrow e^- + e^+ + \gamma \qquad 1.2\%$$

$$\pi^{+/-} \rightarrow \mu^{+/-} + \bar{\nu}_\mu$$

neutral pion life time ~ 10^{-16} s. charged pion lifetimes of about 2.6 x 10^{-8} s.

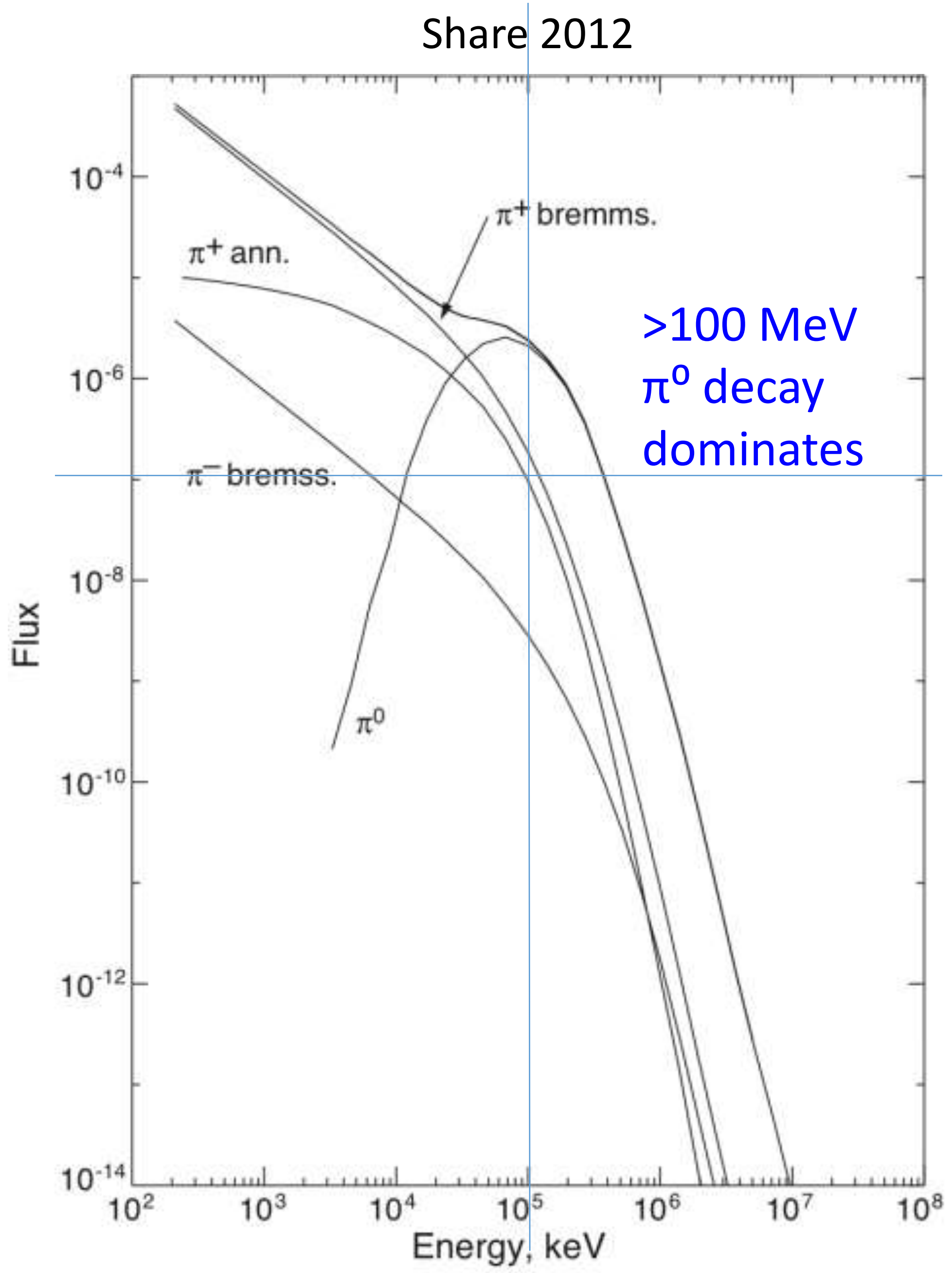
$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

muon life time 2.2x 10^{-6} s

http://hyperphysics.phy-astr.gsu.edu/hbase/Particles/hadron.html#c2

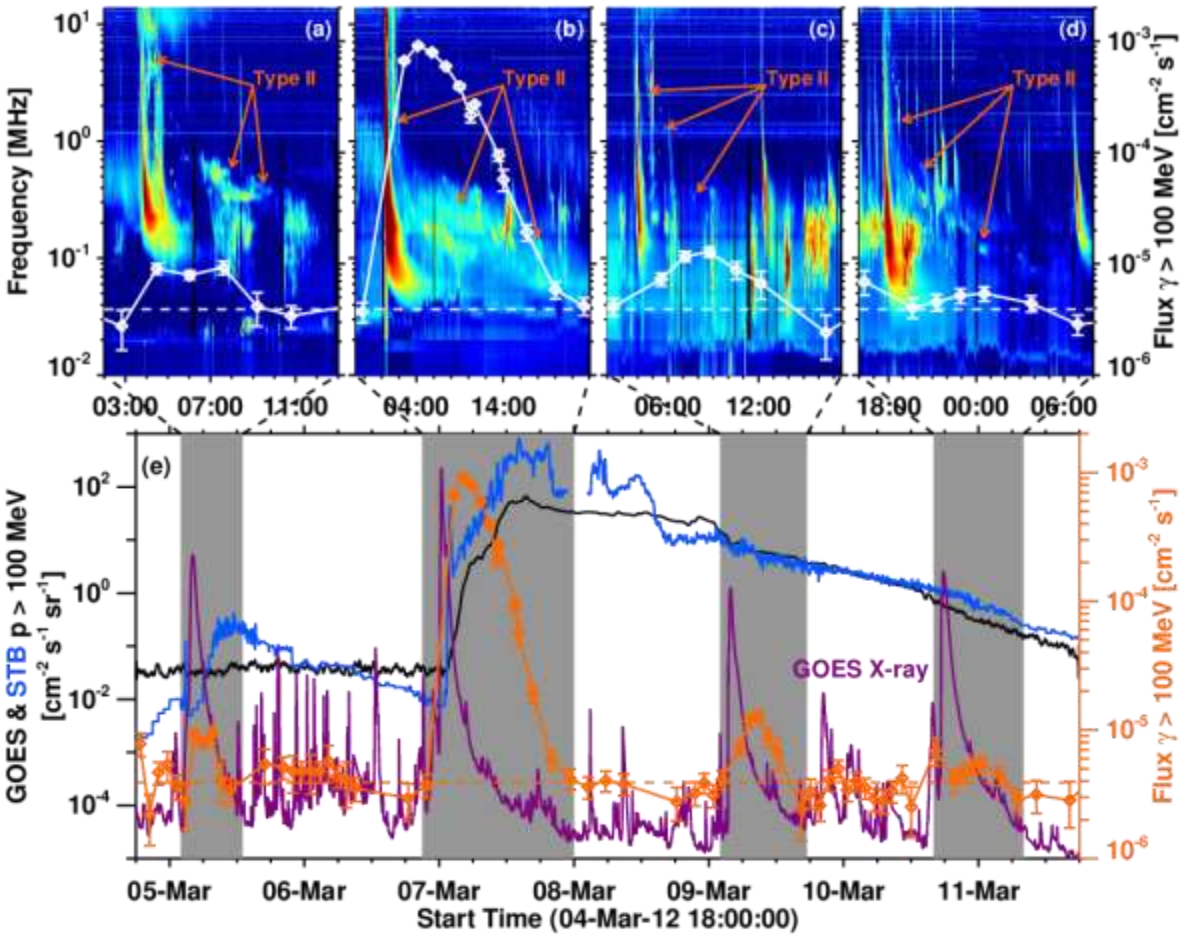
Share 2012

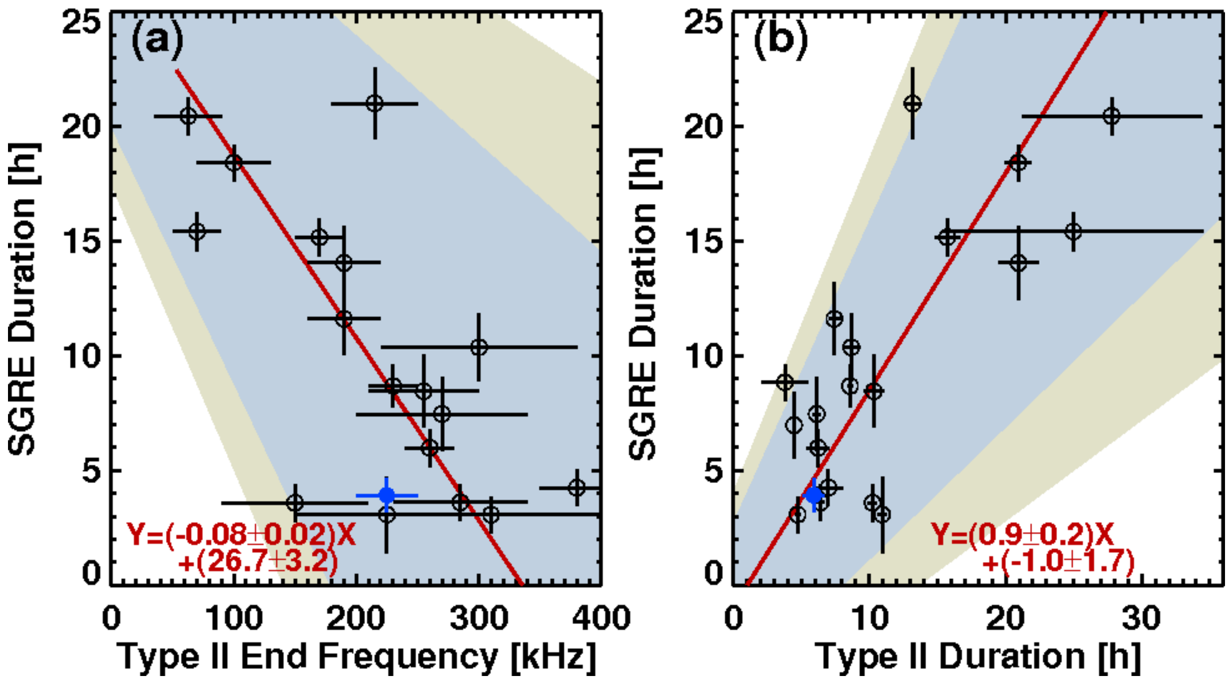


>100 MeV π^0 decay dominates

Lingenfelter & Ramaty (1967)

SGRE Events vs Type II Burst





- All SGRE events were associated with interplanetary (IP) type II bursts
- Durations of type II radio bursts and SGRE have a linear relationship, the same shock accelerating both e^- & p
- Type II ending frequency has inverse linear relation with SGRE duration the IP shocks remain strong over larger distances from the Sun

Gopalswamy et al. 2018, ApJ 868
Gopalswamy et al. 2018, arXiv:1810.08958

Conclusions

1. Observed SEP intensities and energy spectra depend on multiple factors (magnetic connection, shock strength, CME acceleration, preceding activity etc.)
2. Proper interpretation of SEP events requires multi-spacecraft measurements over wide ranges of energy, wavelength, elements/isotopes, etc.
3. Prediction of SEP peak intensities is still difficult, but some simple formulas based on statistical studies can give upper boundaries