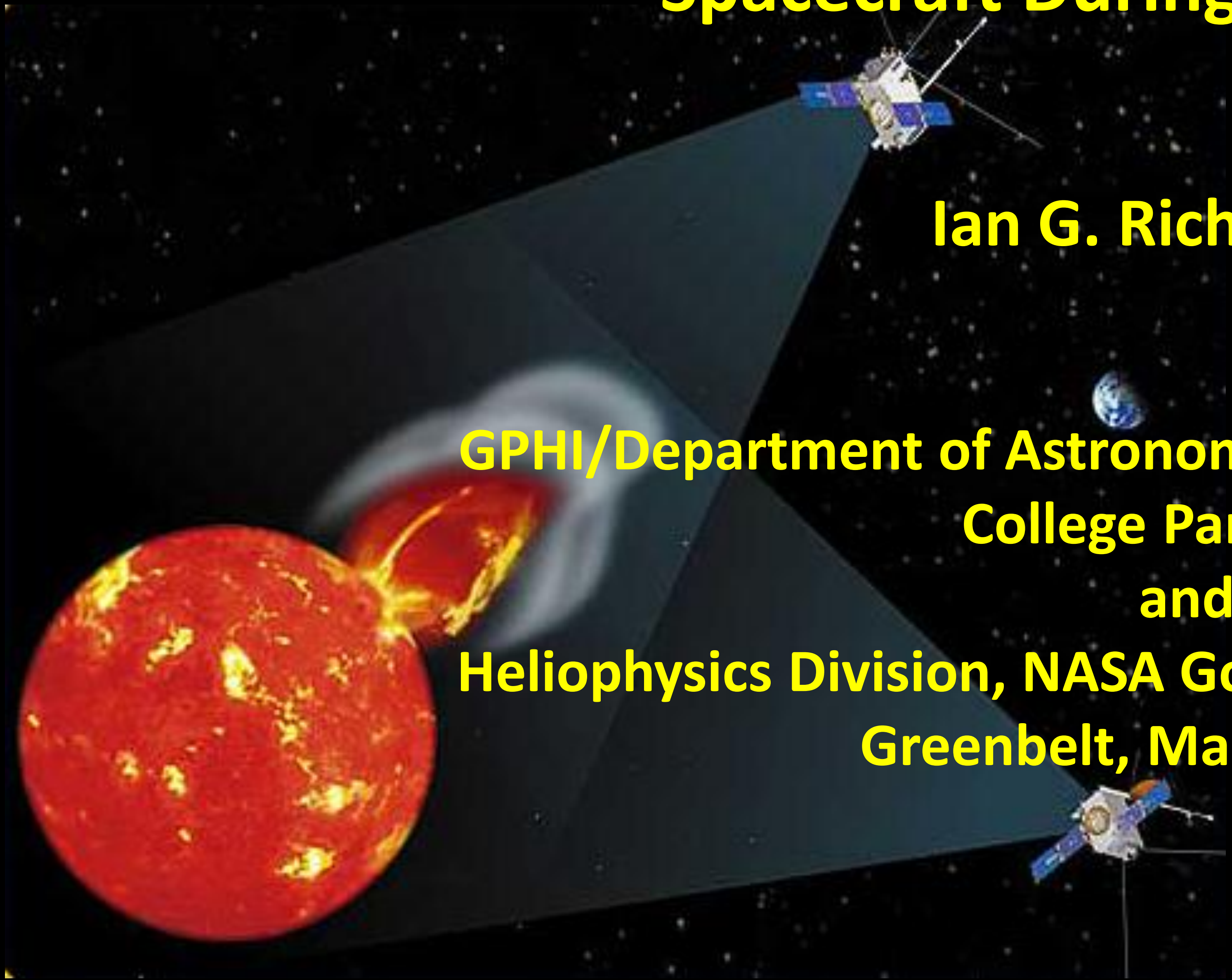
Solar Energetic Particles Observed by the STEREO Spacecraft During Solar Cycle 24



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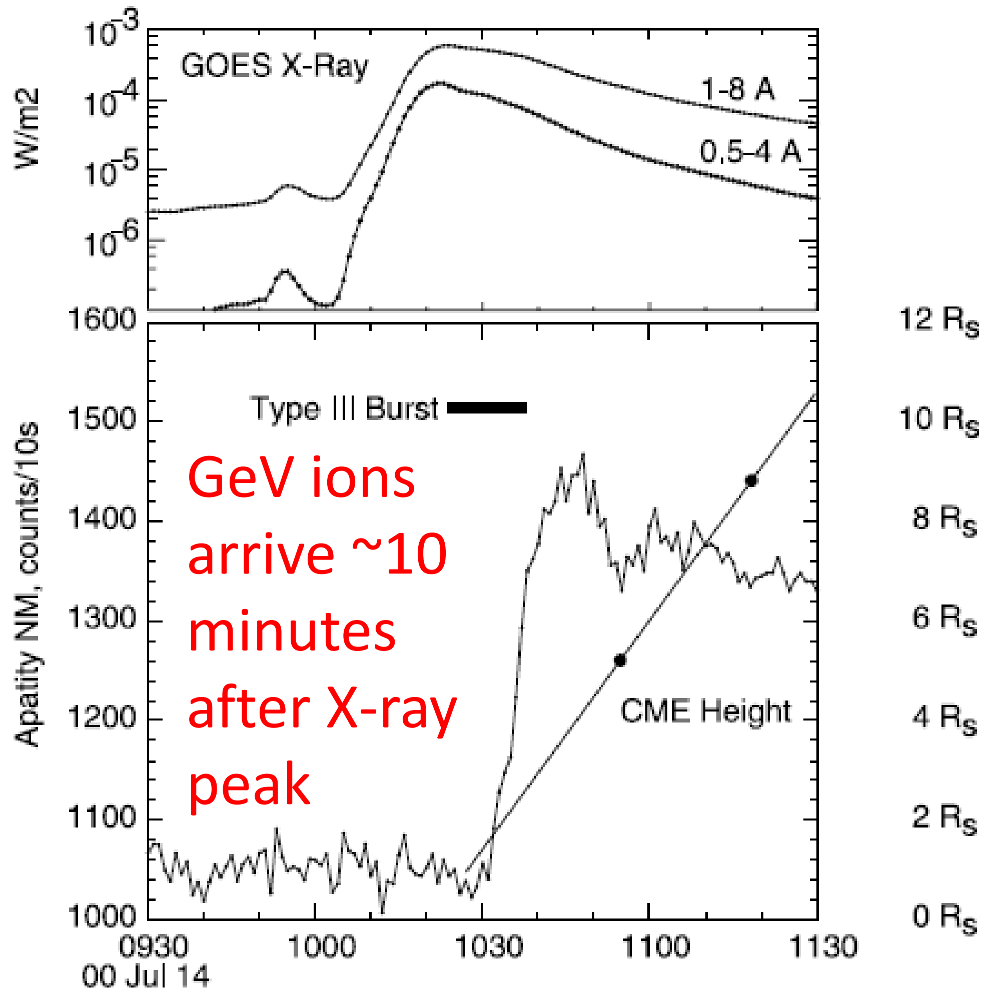
Solar energetic particle (SEP) events are temporary enhancements in the proton, heavy ion and electron intensity resulting from the **acceleration** of particles by solar flares and/or shocks driven by coronal mass ejections and their subsequent **release** and **transport** through the heliosphere.

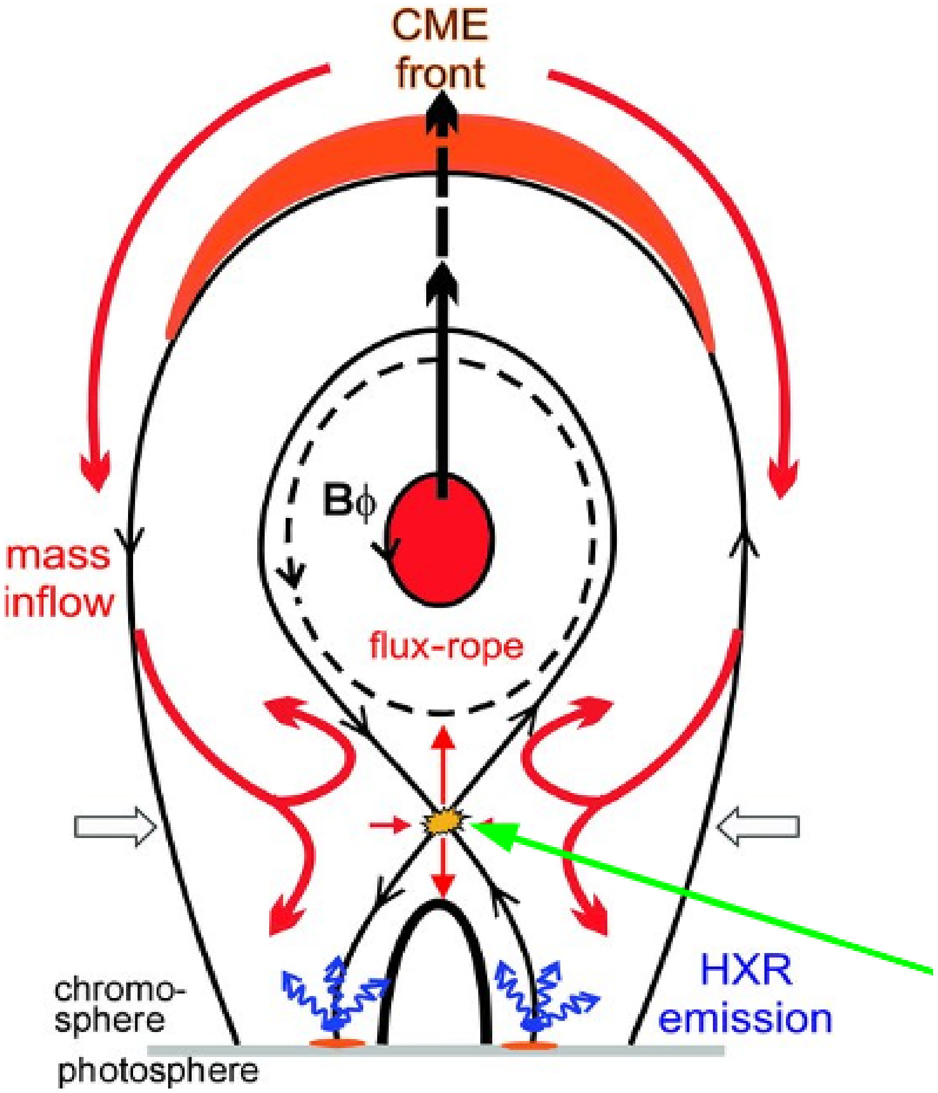
Range in energy from ~10s of keVs to GeVs.

A significant hazard to space-based assets, in particular outside the shield of Earth's magnetosphere, and to aircraft at high latitudes (e.g., polar routes).

Occur ~randomly and with little warning – the fastest particles can arrive at Earth's orbit within minutes of the solar event.



Richardson et al., 2003



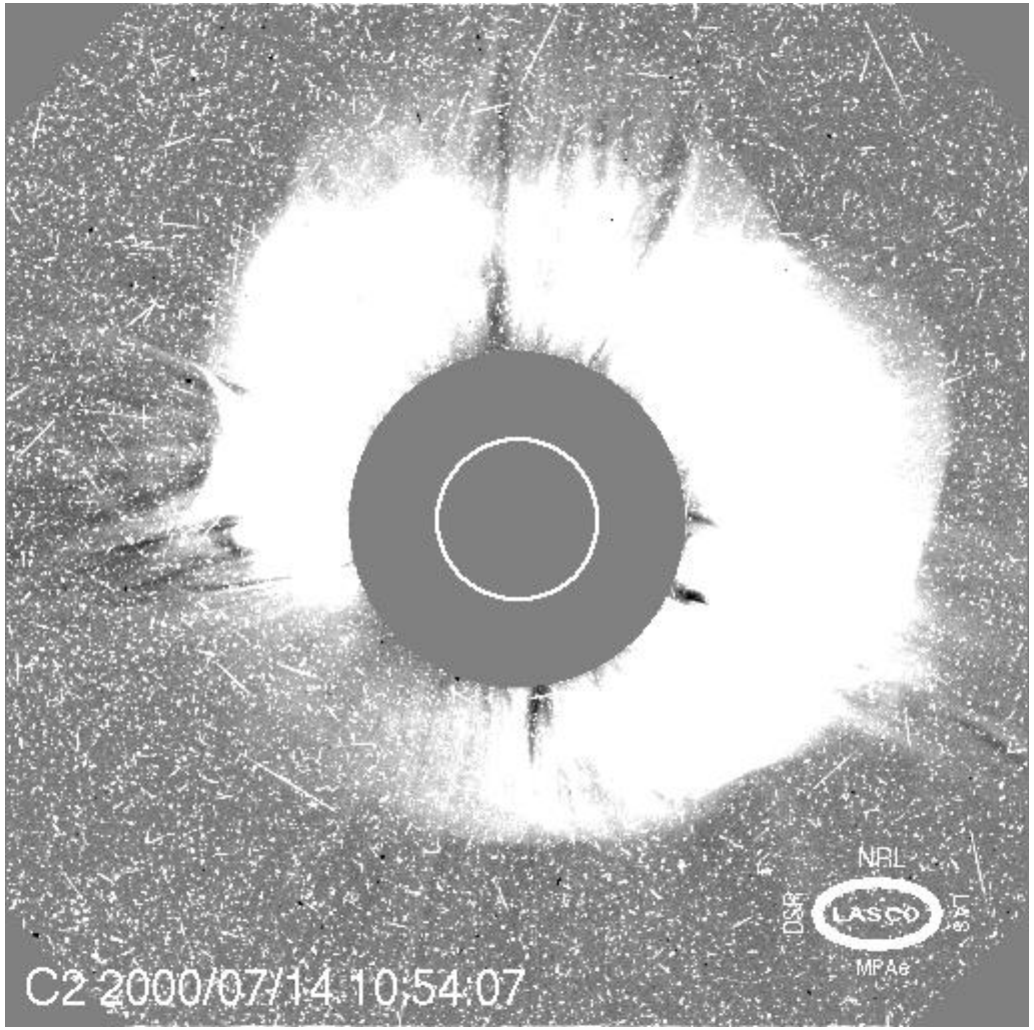
Temmer et al., 2010

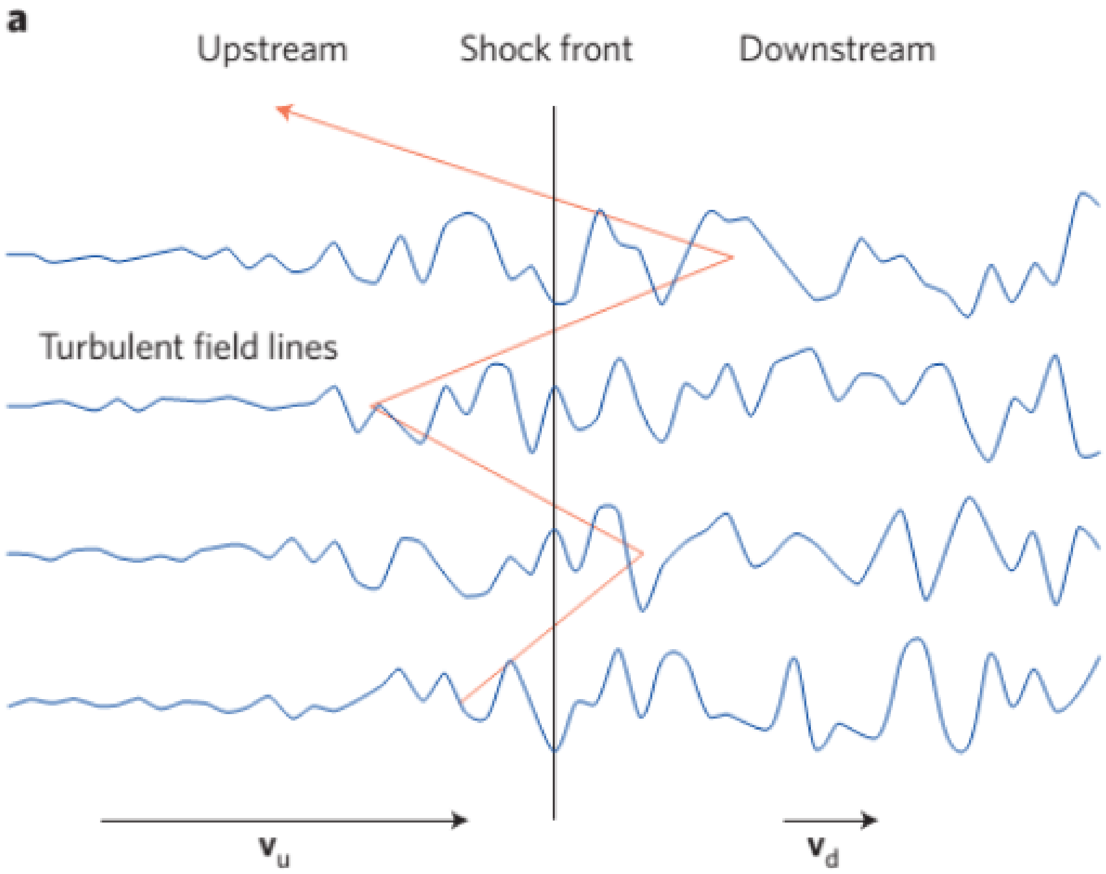
SEP acceleration mechanisms are still the topic of heated debate!

Acceleration in solar flares by magnetic reconnection, wave-particle interactions.

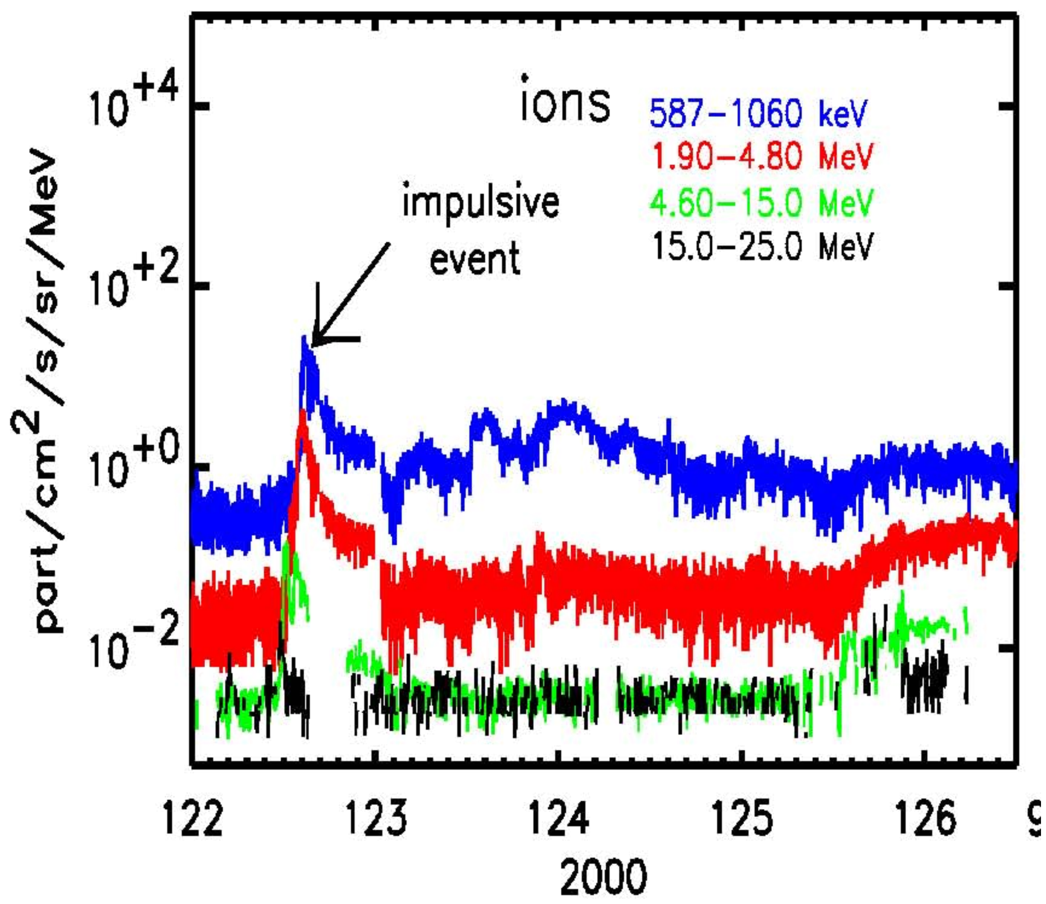
Acceleration at the CME-driven shock

Particle Acceleration by Bouncing Between Converging Scattering Centers Upstream and Downstream of a (Quasi-Parallel) Shock



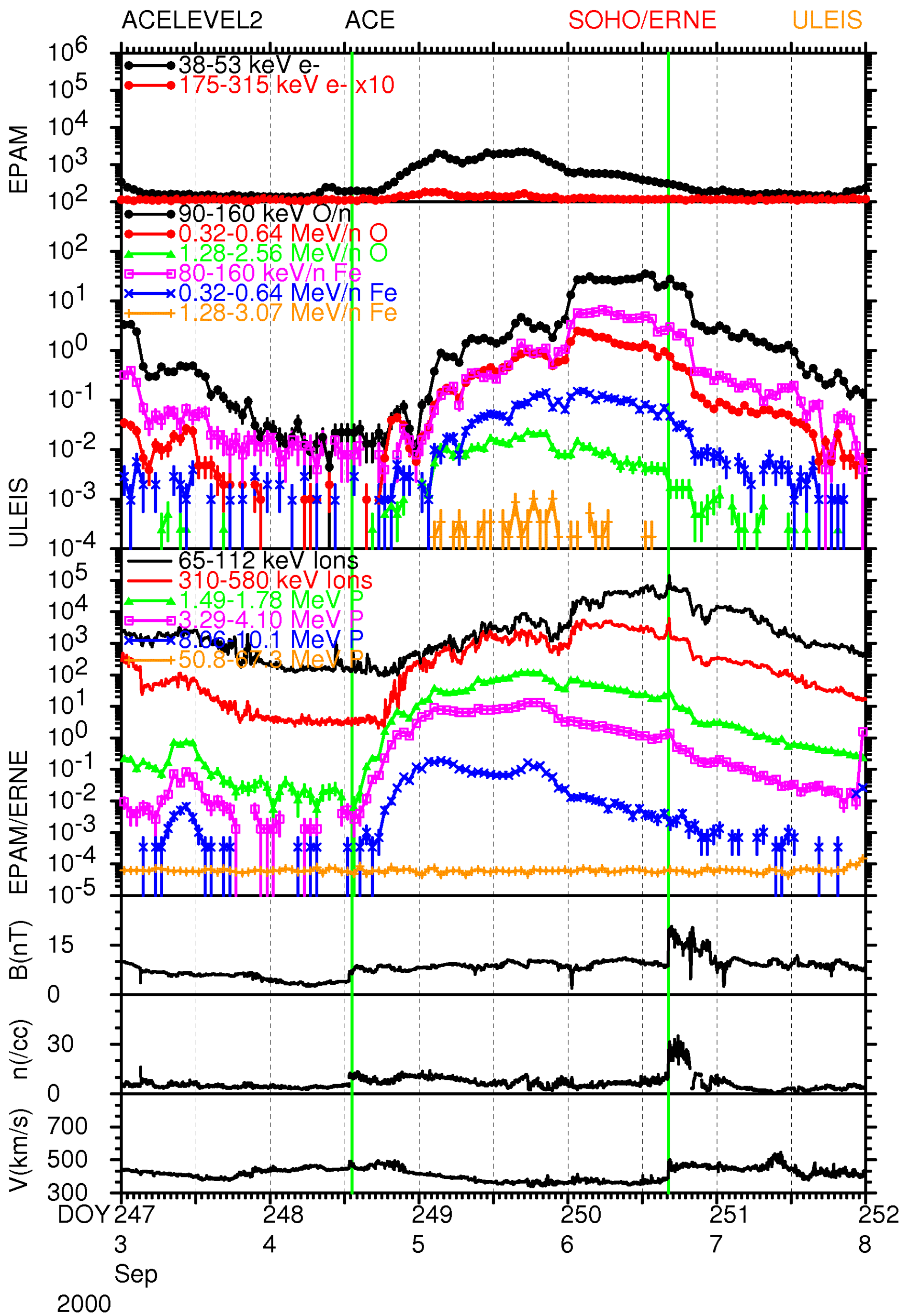


Richardson, Nature Physics, 2013



Tylka and Lee, 2006

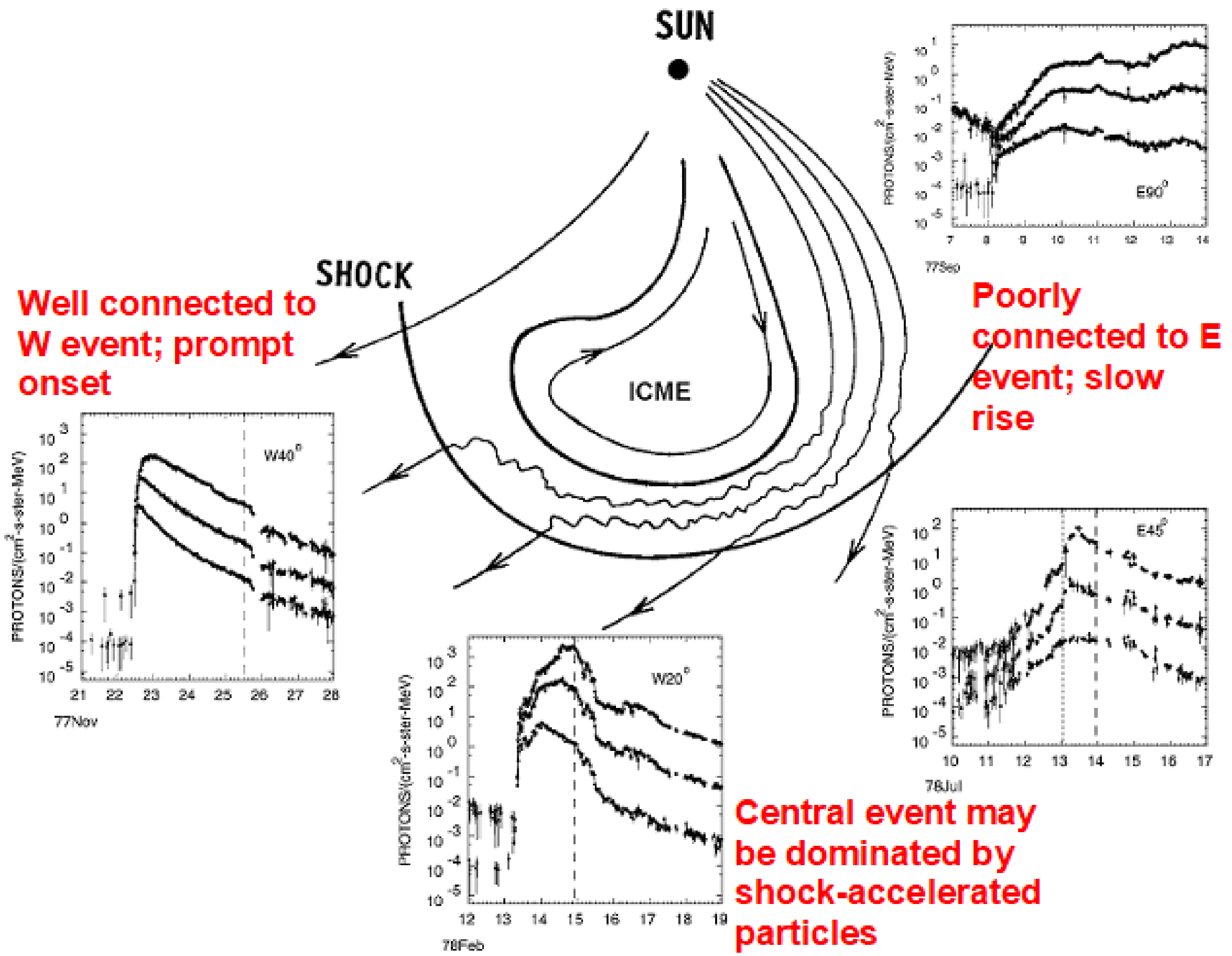
- Short durations of a few hours to ~1 day;
- Associated with impulsive (brief) solar flares. Hence, are usually termed **"impulsive" events**;
- Usually attributed to flare acceleration;
- Electron rich;
- Enhanced in ^{3}He (rare in the photosphere/solar wind);
- Fe-rich; higher Fe/O than the photosphere, solar wind;
- Flare-accelerated electrons => Type III (fast-drift) radio emission.



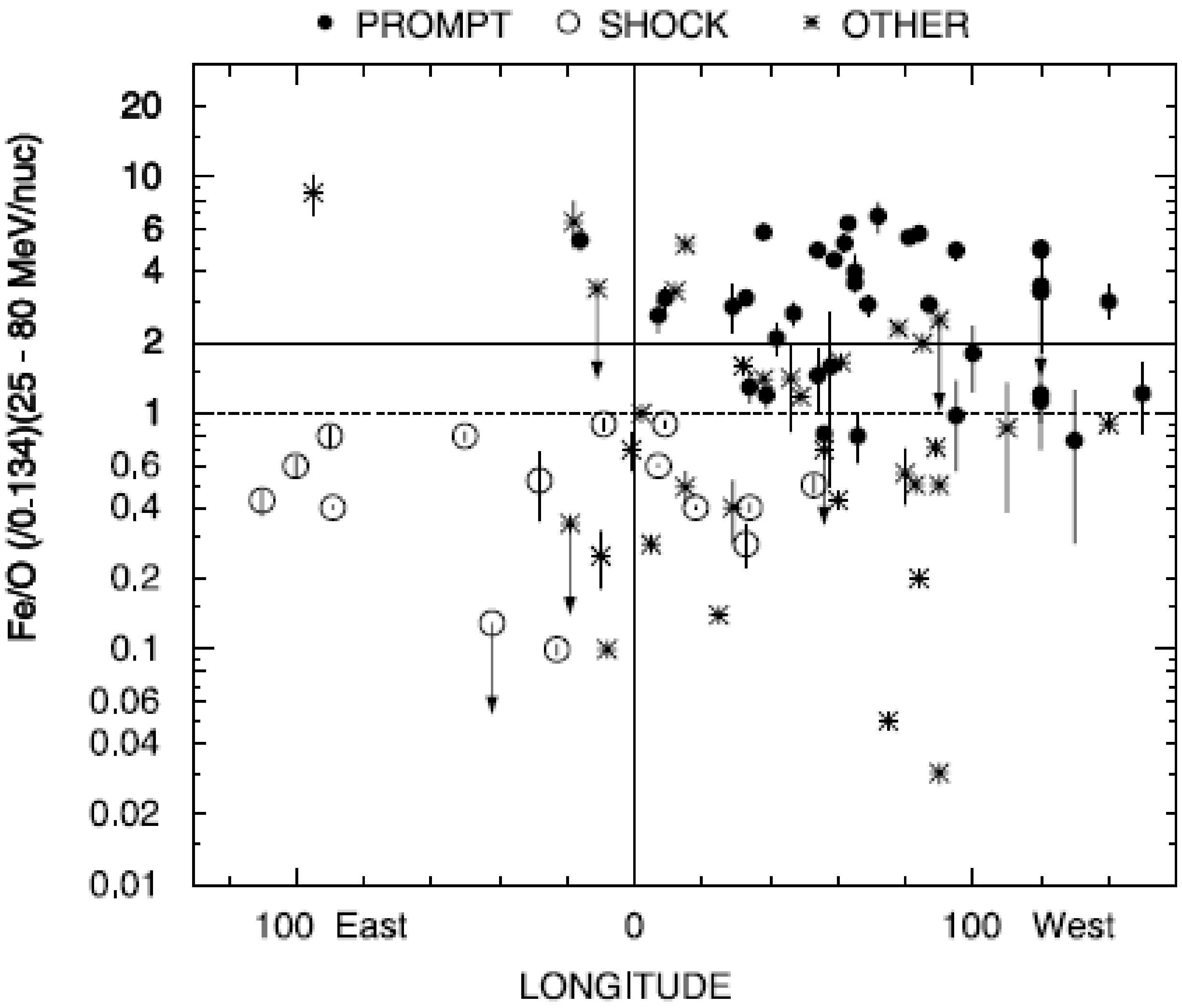
- Durations of several days;
- Associated with longer duration flares, hence **<u>“gradual” events</u>**;
- May have intensity peak at passage of CME-driven shock (“Energetic Storm Particle (ESP) Event”);
- Electron poor;
- ~Photospheric/solar wind abundances + re-accelerated minor ions e.g. ^{3}He;
- Fe/O ~ solar wind;
- Type II (slow drift) radio emission associated with shock;
- Type III radio emissions, stronger for larger SEP events;

Not two distinct classes of events, many show “mixed” properties

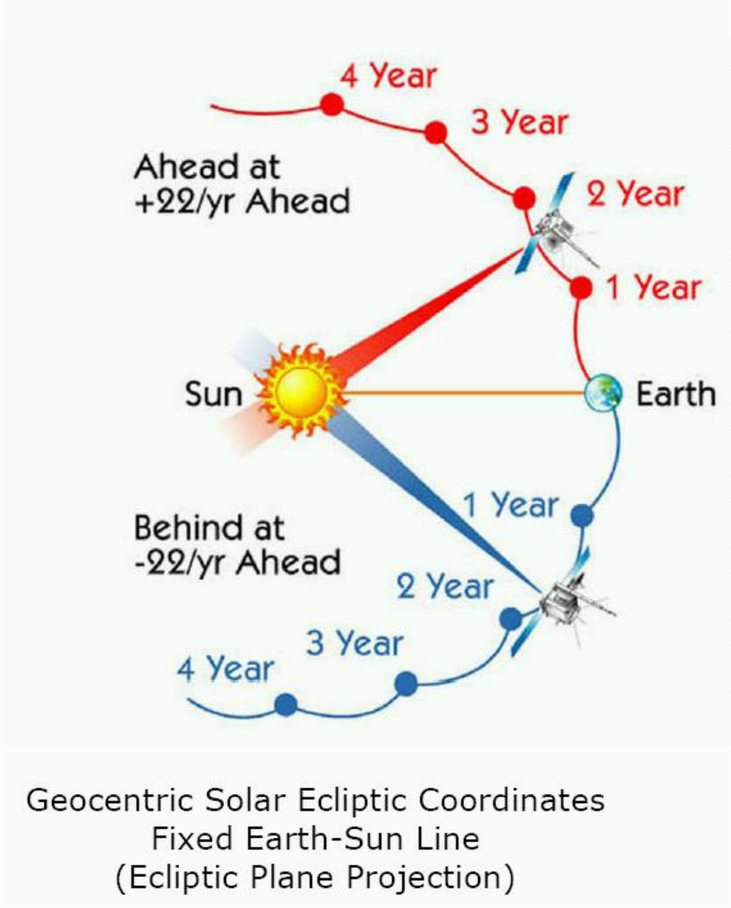
Differences in SEP (~5, 15, 30 MeV Proton) Intensity-Time Profiles for Western, Central and Eastern Solar Events (Cane and Lario, 2006, adapted from Cane et al. 1988)



Longitudinal-dependence of Fe/O Ratio at 25-80 MeV/n (*Cane et al.,* 2006)

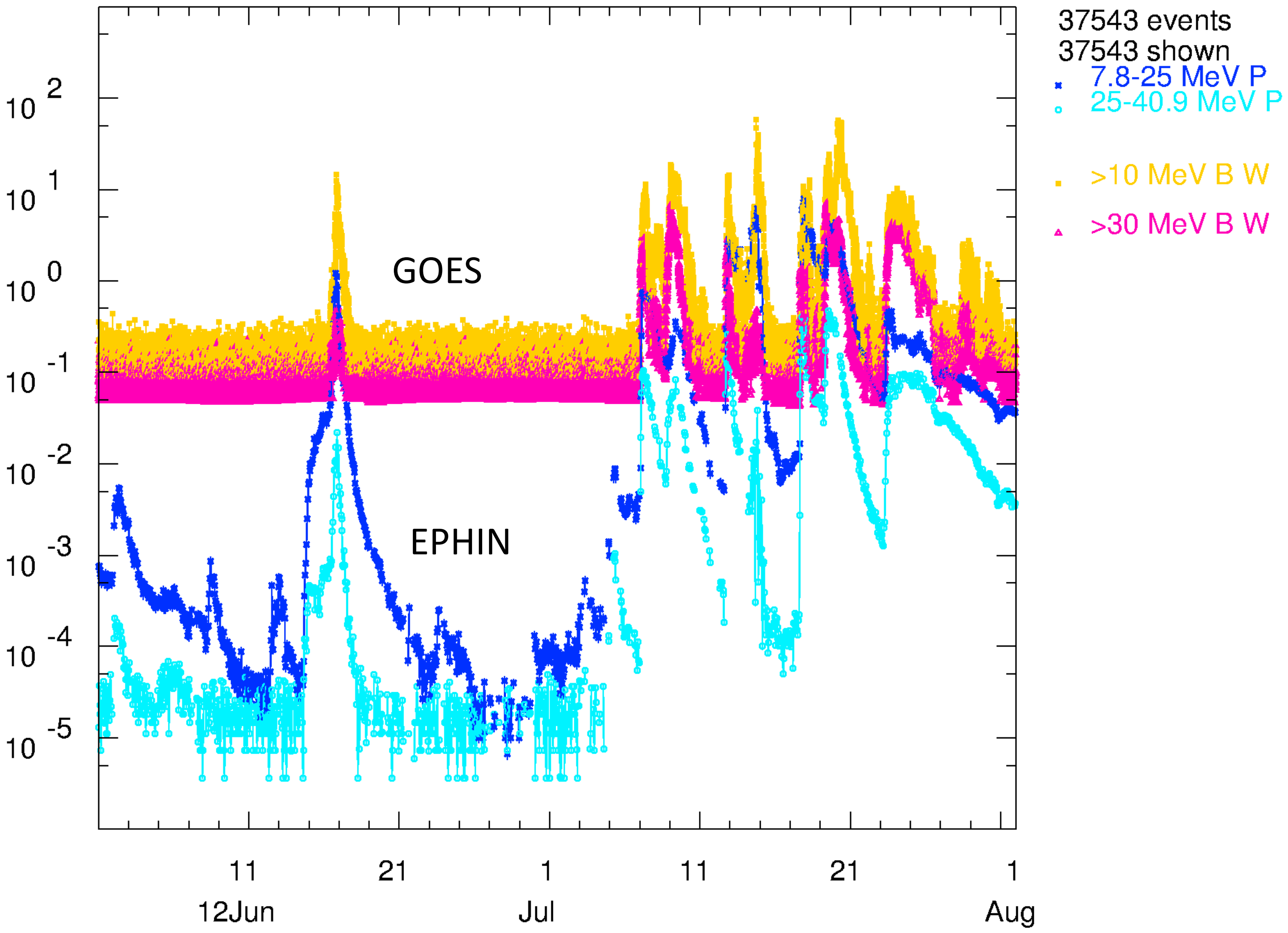


STEREO – Two Spacecraft in Heliocentric Orbits at ~1 AU, Launched October, 2006



Study SEPs using observations from the High Energy Telescopes (HETs) on STEREO A and B together with similar observations from near-Earth spacecraft (e.g., from ERNE and EPHIN on SOHO).

Why I Don't Use GOES For Near-Earth Proton Data (If I Have a Choice)!

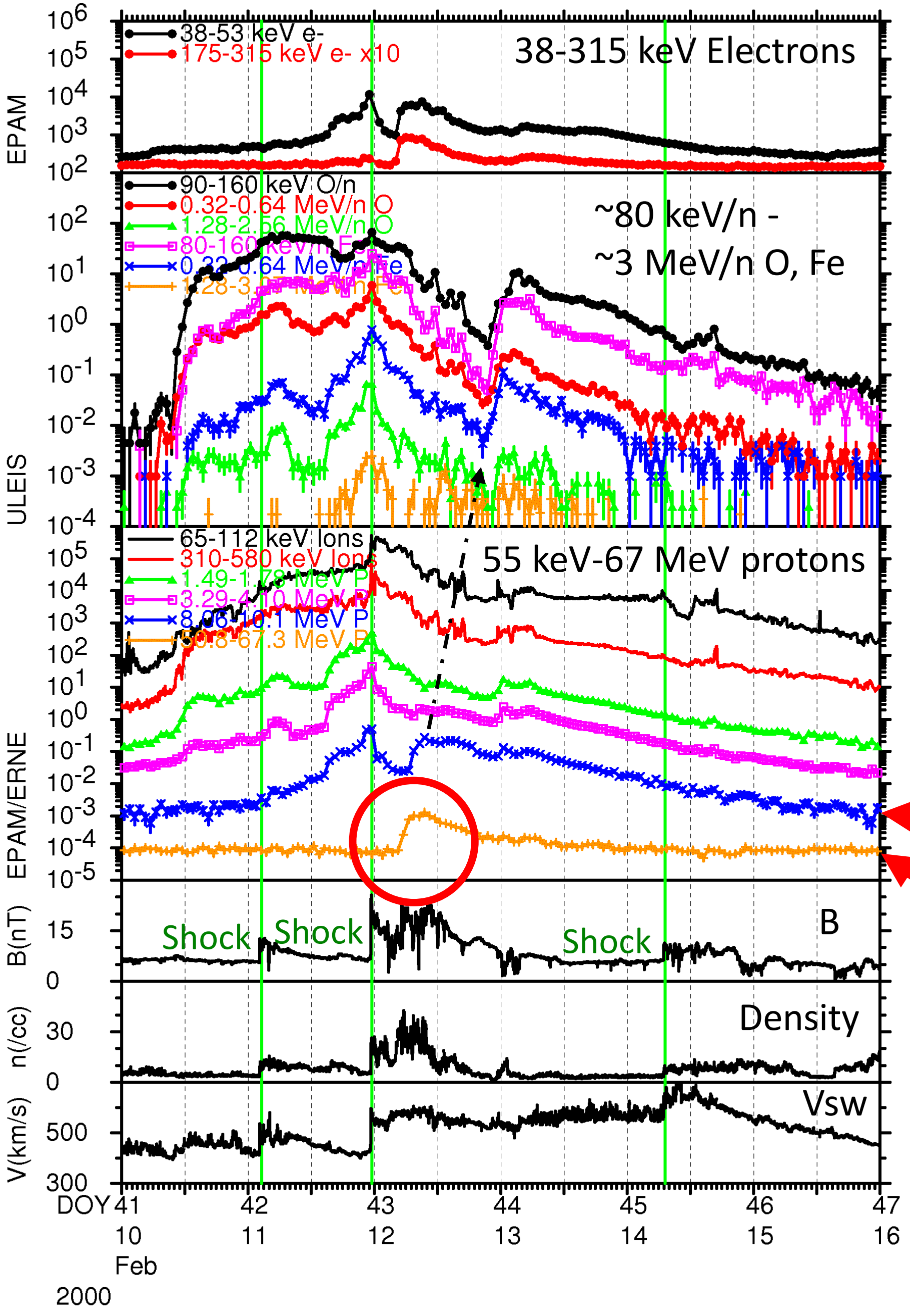


Comparison of GOES and SOHO/EPHIN shows the high background in GOES.

Many more features, including small SEP events, are visible in the EPHIN (and ERNE, not shown) data

We focus on solar particle events that include 25 MeV protons. Why?

- The intensity-time profile at 25 MeV is less frequently dominated by ions associated with local interplanetary shocks than e.g., the "standard" GOES >10 MeV proton flux;
- It is relatively easy to identify event onsets and the related solar event;
- Energy range of interest for radiation hazards;
- Associated with relatively energetic solar events (e.g., nearly all have CMEs);
- Events since 1967 have been recorded in several studies.



8-10 MeV Protons

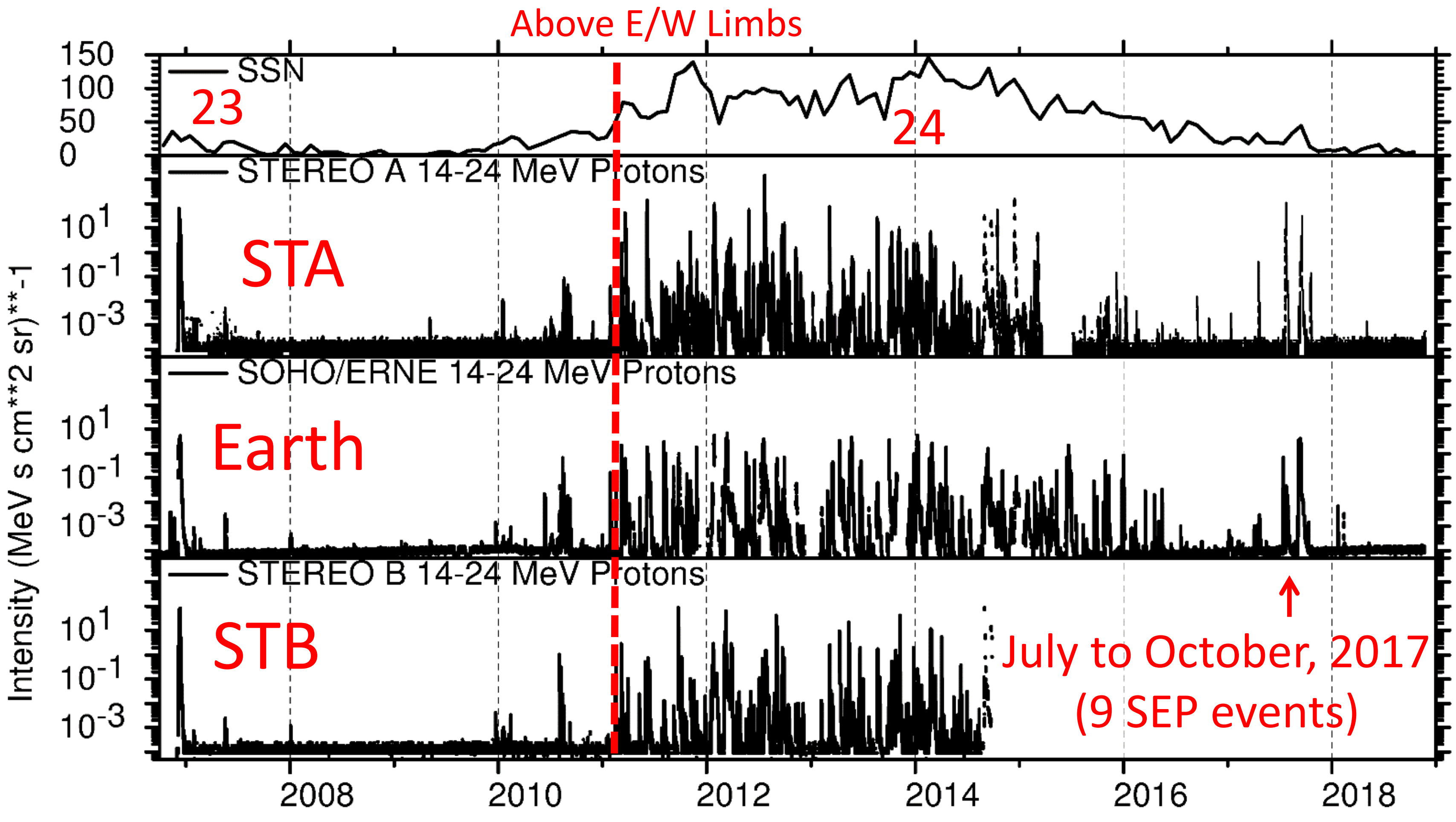
51-67 MeV Protons

Richardson et al. (2017)

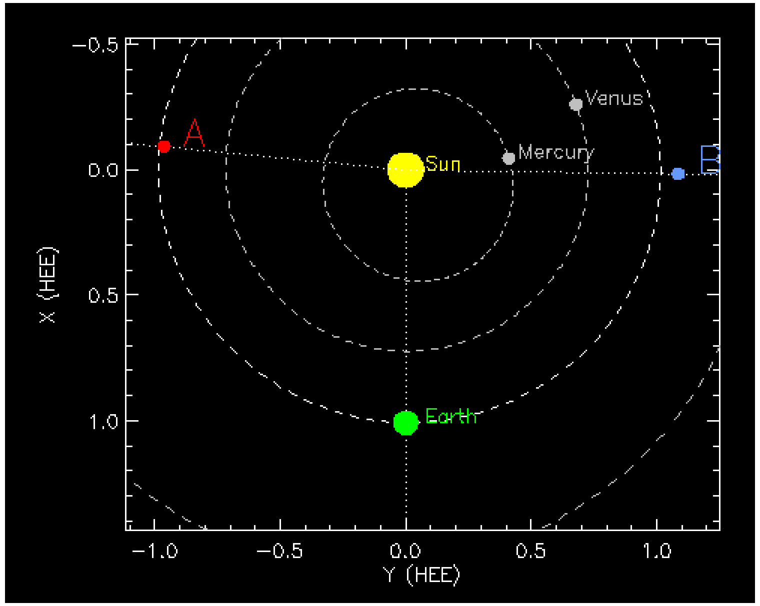
Example of an SEP event onset that is harder to identify at lower energies where an ongoing shock-associated event dominates.

M1 Flare at W24°, 0351 UT, February 12, 2000. LASCO CME: 0431 UT, 1107 km/s (*Cane et al.*, 2010). Particle data from ACE/EPAM, ACE/ULEIS, SOHO/ERNE; ACE plasma and field observations.

Overview of 14-24 MeV Proton Intensities at STEREO A, B and at Earth (SOHO/ERNE) From STEREO Launch (October, 2006) to November 2018



STEREO Locations 29 April 2019



Updated from *Richardson et al.,* 2014; ~400 individual SEP events

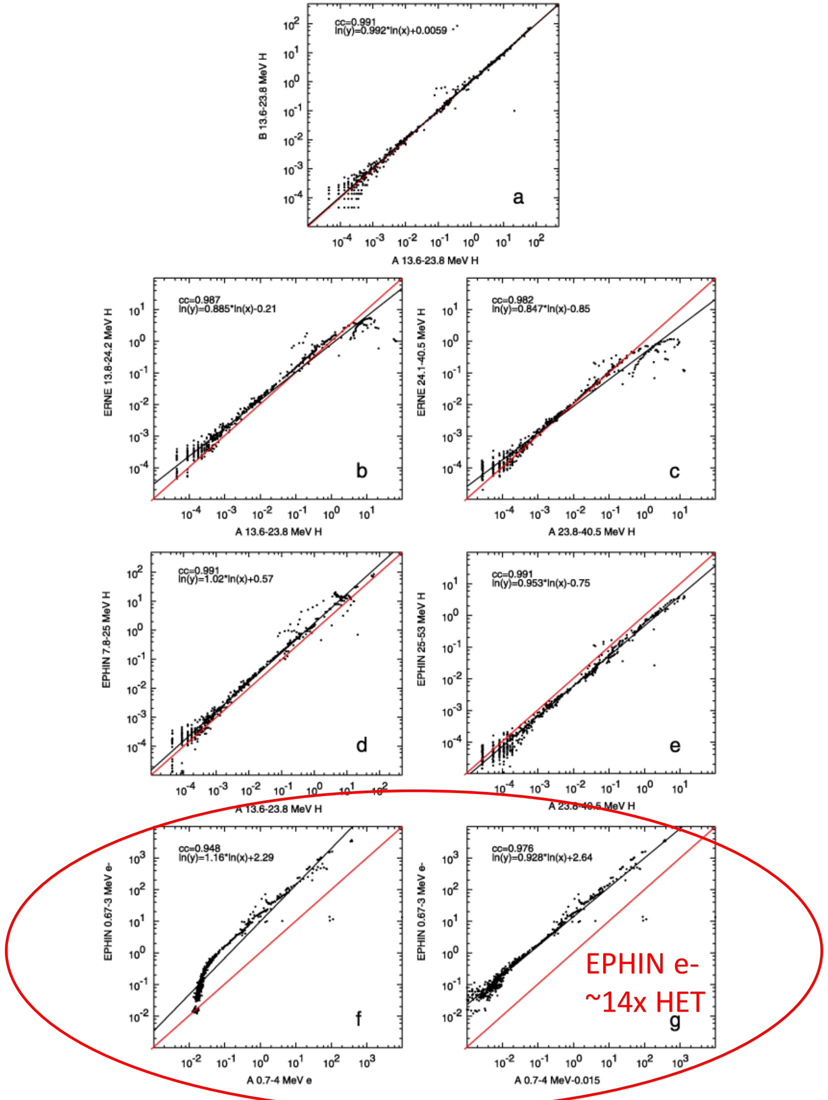


Figure 3 Comparison of the STEREO HETs, SOHO/ERNE E, and SOHO/EPHIN proton and electron intensities (in $(\mathrm{MeV\,s\,cm^2\,sr})^{-1}$) using observations during December 2006. (a) HET B *vs.* HET A for 13.6 – 23.8 MeV protons; (b) ERNE 13.8 – 24.2 MeV protons *vs.* HET A 13.6 – 23.8 MeV protons; (c) ERNE 24.1 – 40.5 MeV protons *vs.* HET A 23.8 – 40.5 MeV protons; (d) EPHIN 7.8 – 25 MeV protons *vs.* HET A 13.6 – 23.8 MeV protons; (e) EPHIN 25 – 53 MeV protons *vs.* HET A 23.8 – 40.5 MeV protons; (f) EPHIN 0.67 – 3.0 MeV electrons *vs.* HET A 0.7 – 4.0 MeV electrons, and (g) with a HET background of 0.015 $(\mathrm{MeV\,s\,cm^2\,sr})^{-1}$ subtracted. Black lines are least-squares fits to the data, while red lines indicate equal values.

Richardson et al. (2014)

It was fortuitous that the large December 2006 SEP events occurred soon after launch when the STEREO spacecraft were still close to Earth:

• Allowed the HET calibration to be checked relative to instruments on near-Earth spacecraft over a large dynamic range.

• Identified an unexpected (and still unexplained) factor of ~14 reduction in the HET electron intensity relative to other instruments.

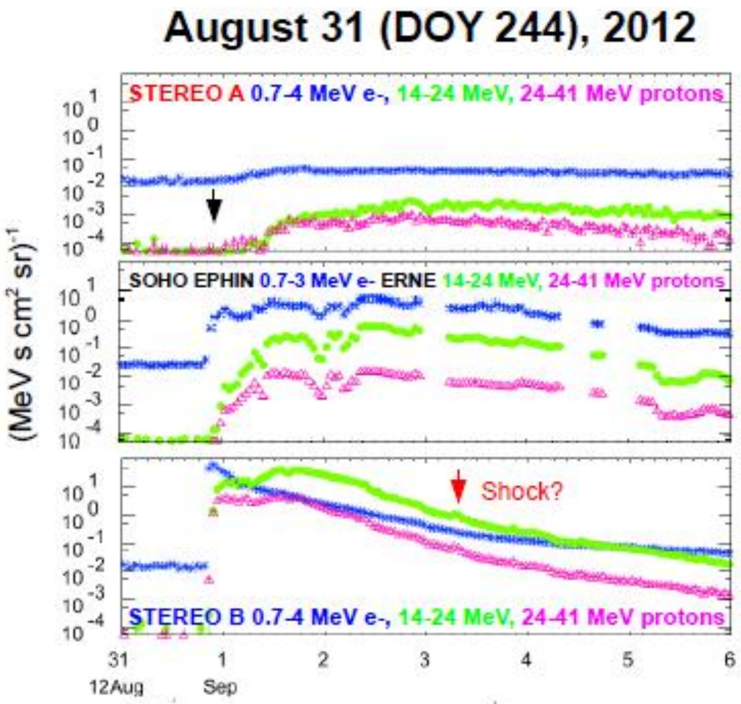
•If not identified, this would have led to errors in the longitudinal distribution of electrons based on combined STEREO and near Earth observations, errors in electron/proton ratios, etc.

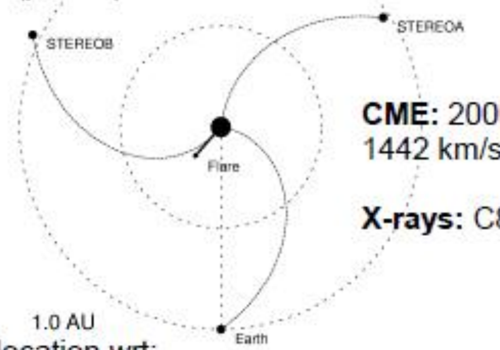
Example of a Solar Particle Event Detected at Both STEREO Spacecraft and at Earth ("3-Spacecraft Event")

STEREO A

EARTH/SOHO

STEREO B

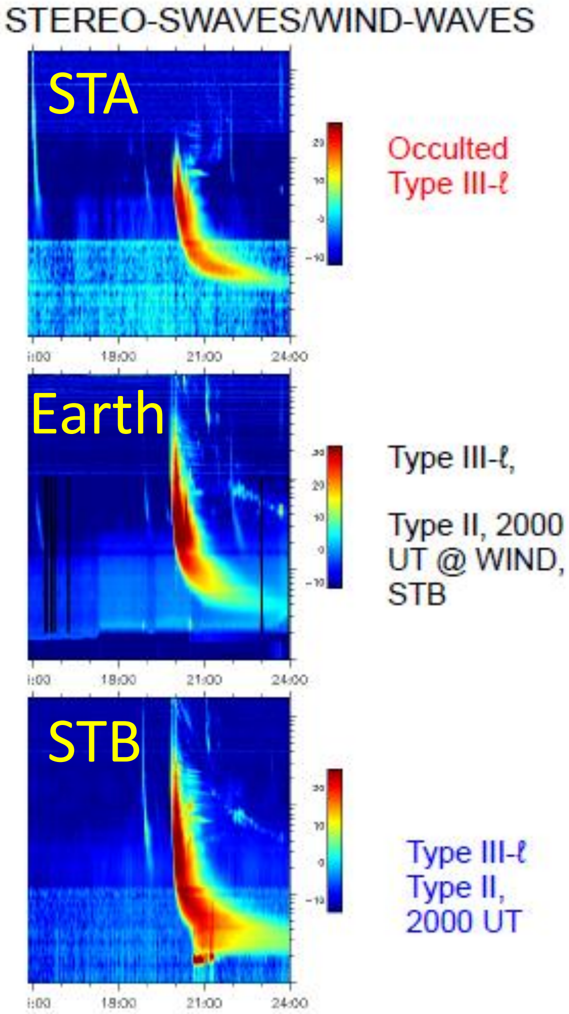




CME: 2000 UT, 360º, 1442 km/s (CDAW)

X-rays: C8.4

Flare location wrt:
STEREO B: W74º Earth: E42º STEREO A: E165º

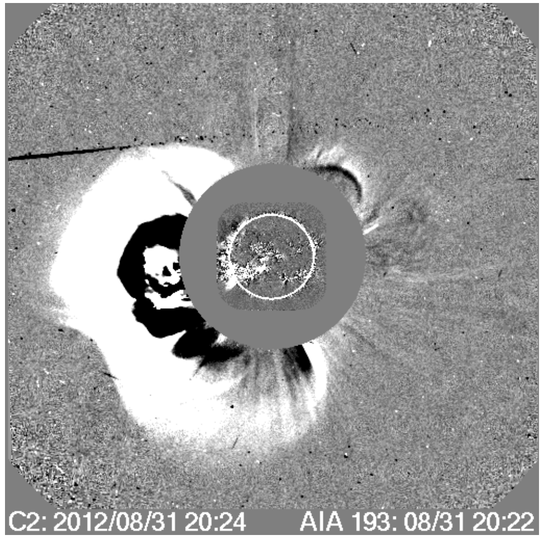


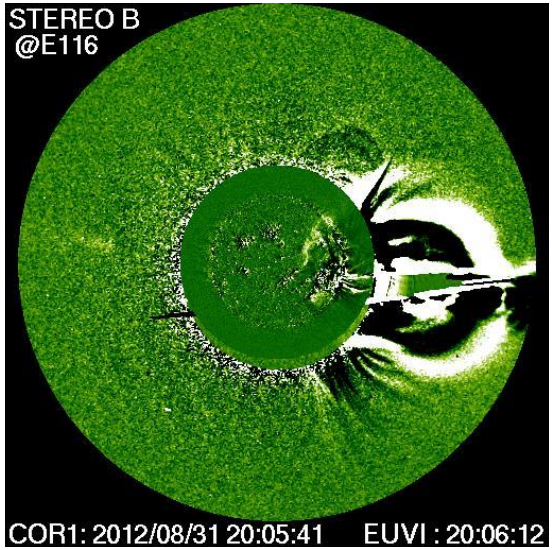
Occulted Type III-ℓ

Type III-ℓ,

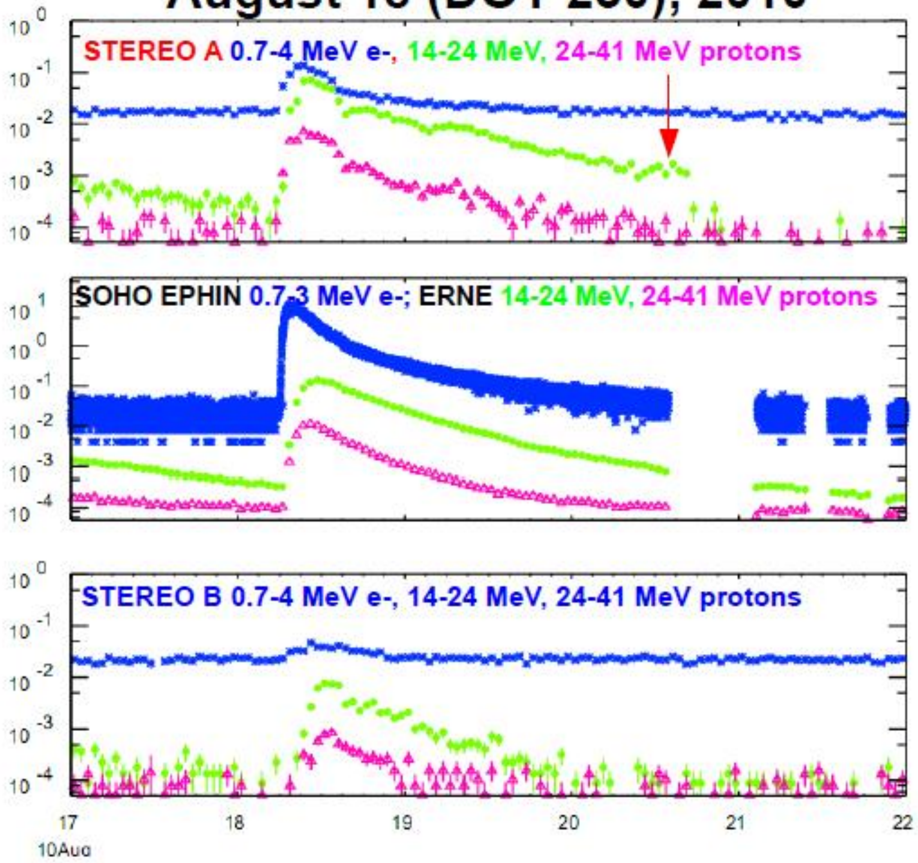
Type II, 2000 UT @ WIND, STB

Type III-ℓ
Type II,
2000 UT

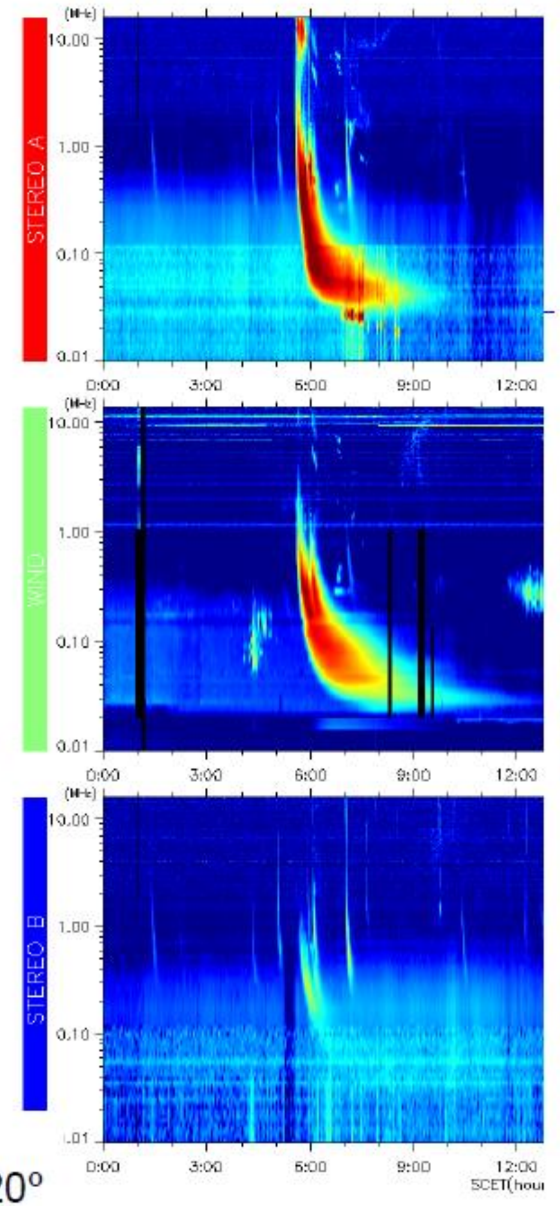




August 18 (DOY 230), 2010



STEREO-SWAVES/WIND-WAVES

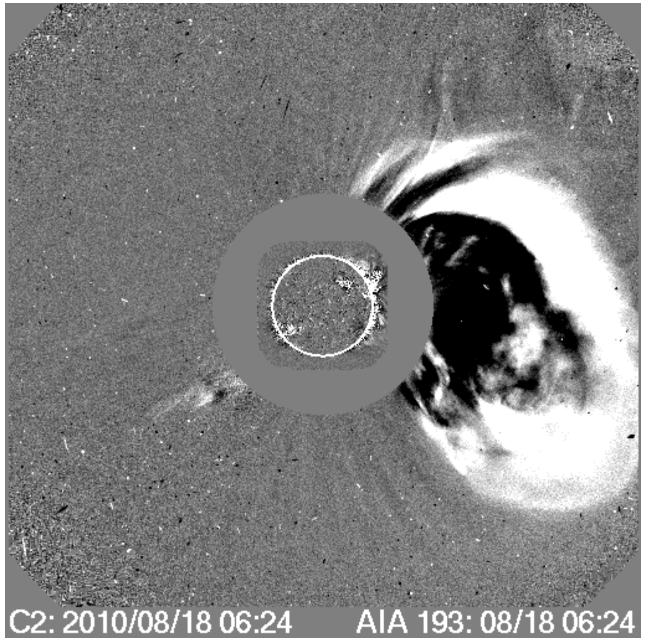


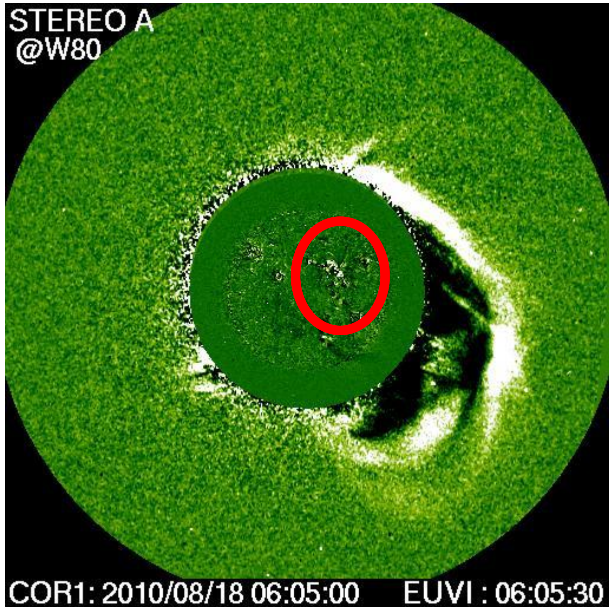
Type III-ℓ

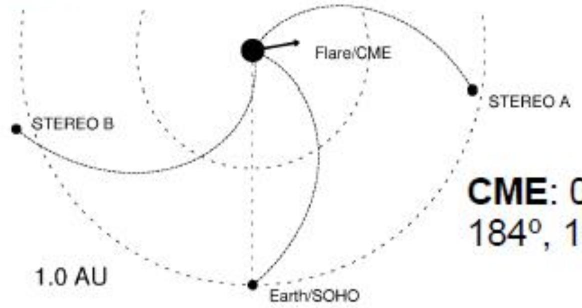
Occulted Type III-ℓ

Type II, all S/C, 0605 UT

Weak, occulted Type III

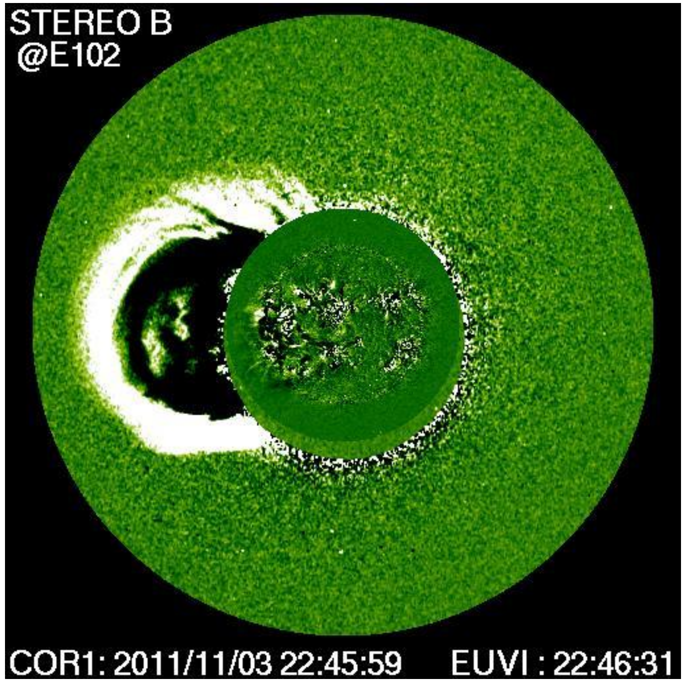


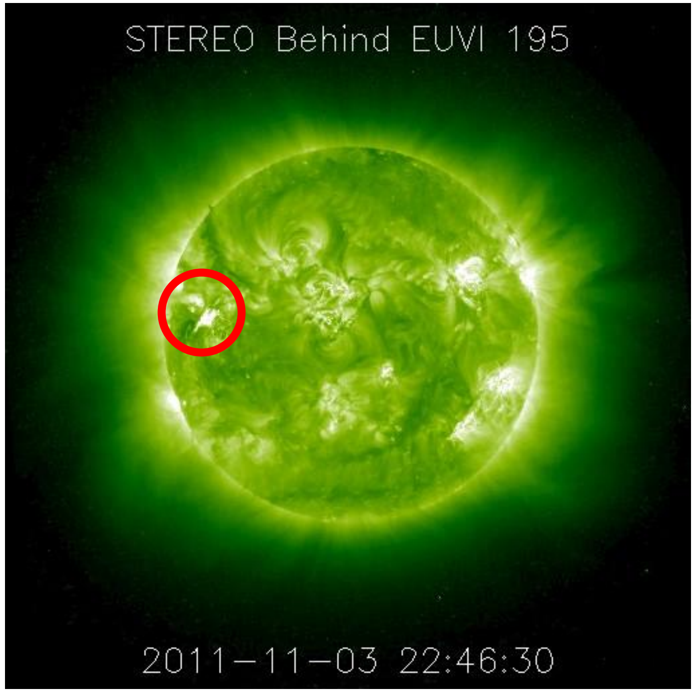


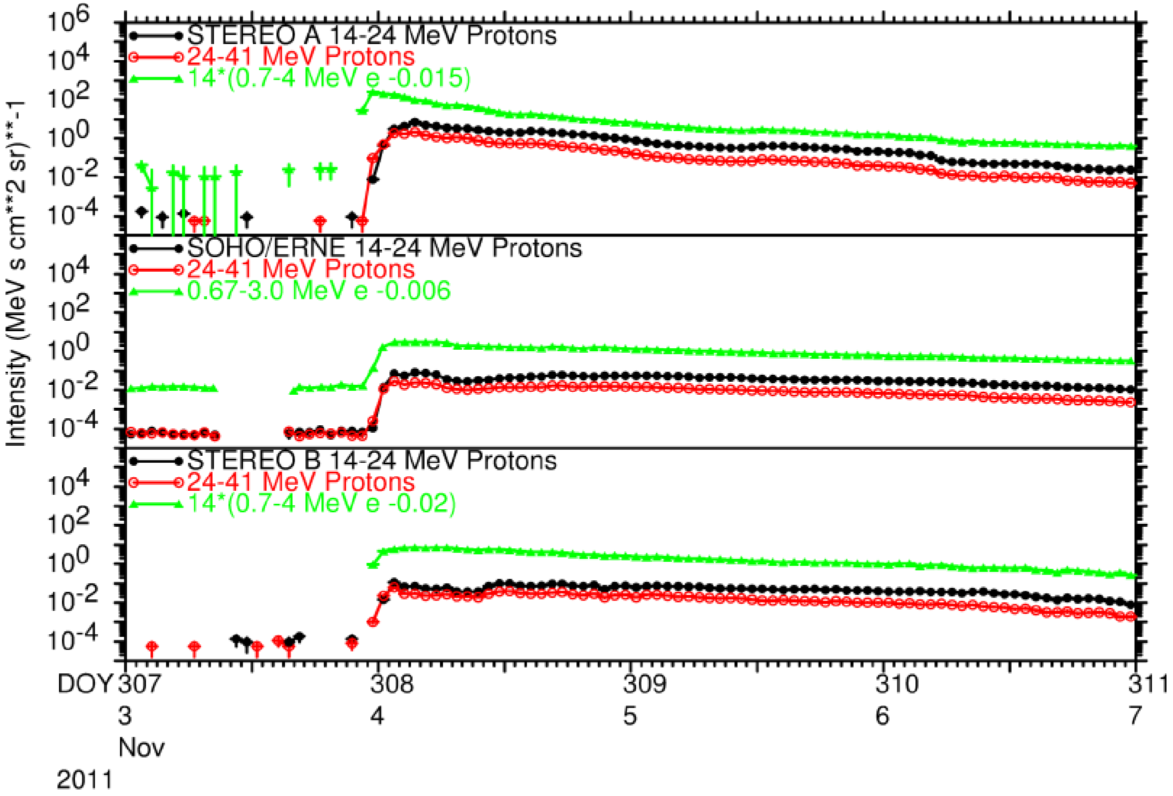


CME: 0548 UT, 184°, 1471 km/s (CDAW)

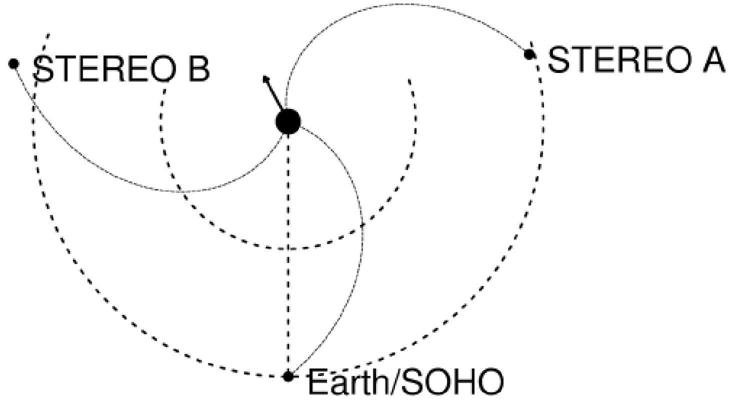
Flare location wrt:
STEREO B: W172° Earth: W100° STEREO A: W20°





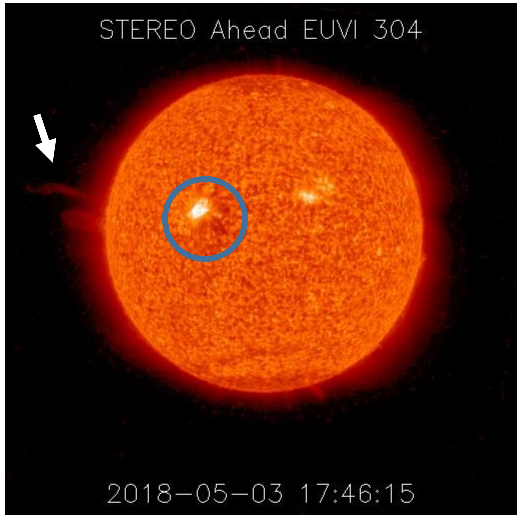


Nov. 3, 2011: Rapid onset at Earth and both STEREOs following a solar event behind the east limb.

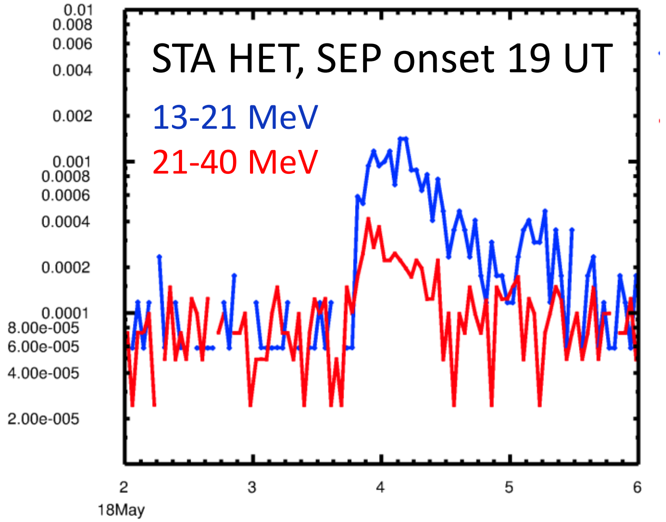


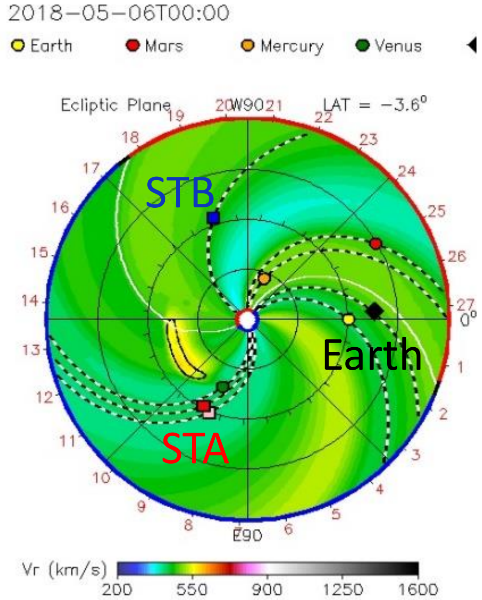
STEREO B Observations

Most Recent 25 MeV Proton Event, on May 3, 2018, at STEREO A

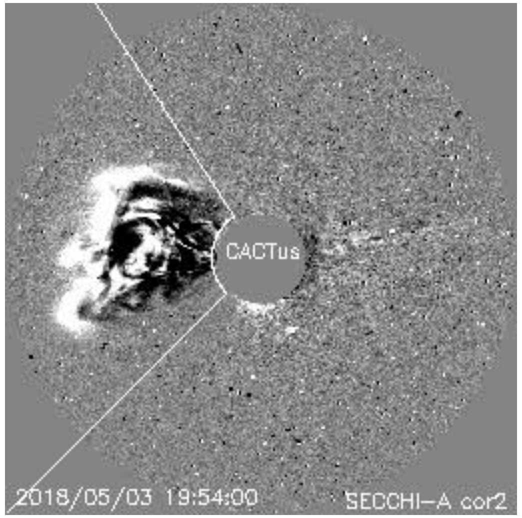


Flaring (~E136°) and erupting filament (STA EUVI)

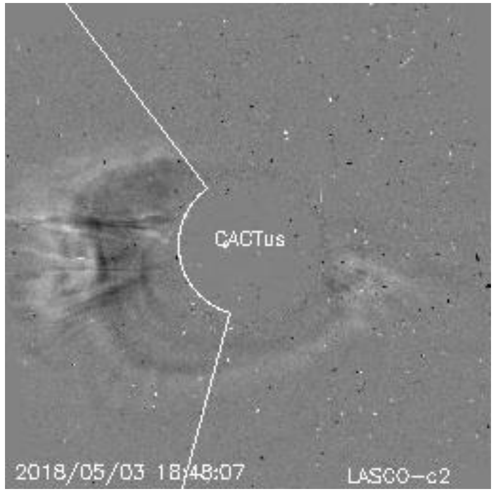




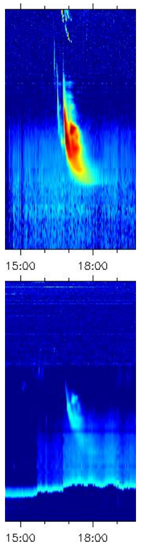
ENLIL+CONE simulation of CME (DONKI database) E155°, 650 km/s



CME observed by STA COR 2; CACTUS width= 102°, 581 km/s



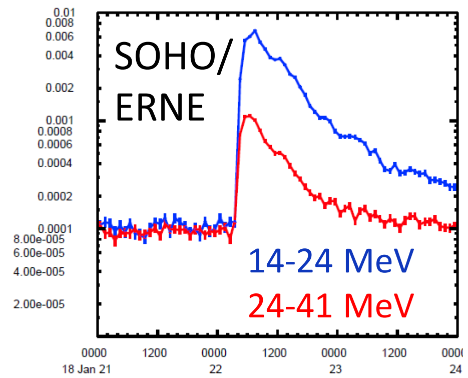
CME (~halo) observed by LASCO; CACTUS width= 128°, 374 km/s

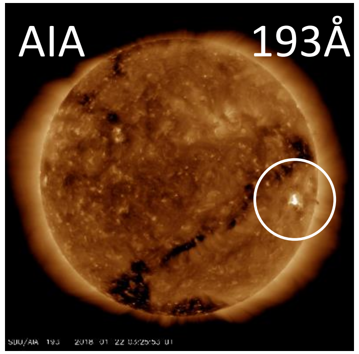


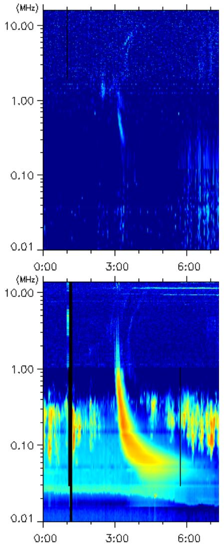
Type III radio emission observed at STA (top) and WIND (bottom).

Two Other Recent 25 MeV Proton Events, January 22 and February 12, 2018, at Earth

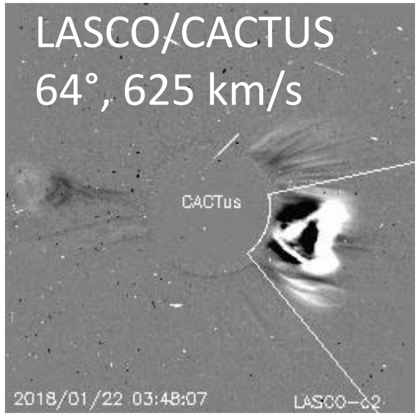
W55°, B9.5 flare



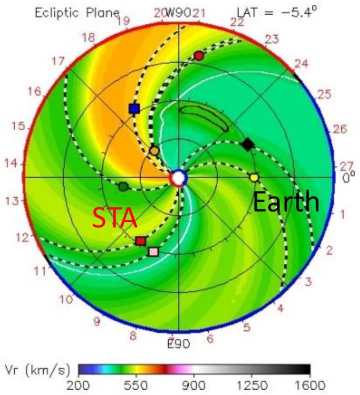




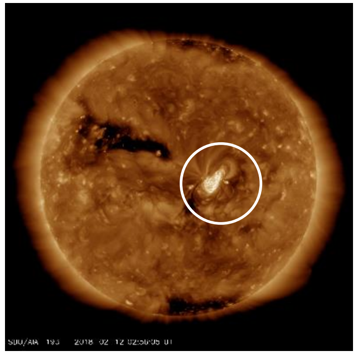
Type III
@
WIND

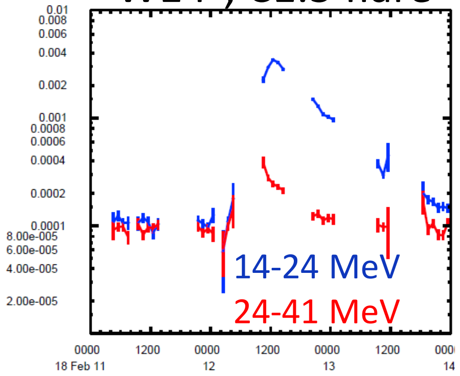


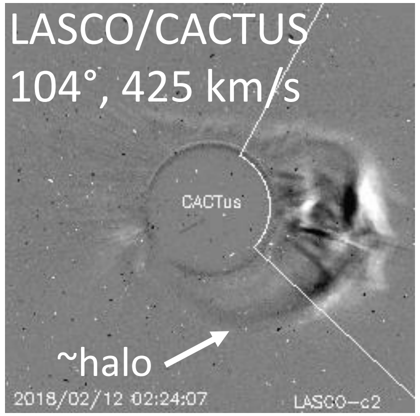
ENLIL+CONE
(from DONKI):
W66°, 560 km/s



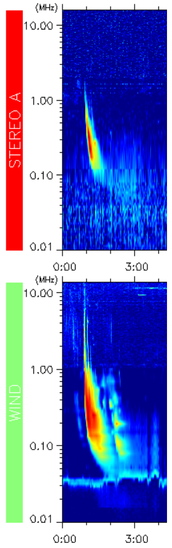
W14°, C1.5 flare

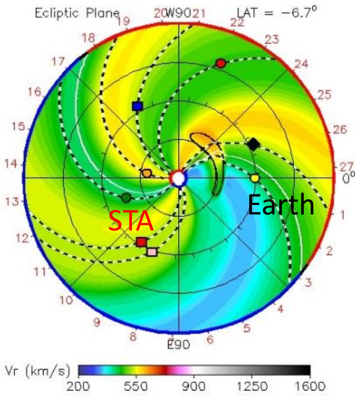






Type III
@
STA,
WIND

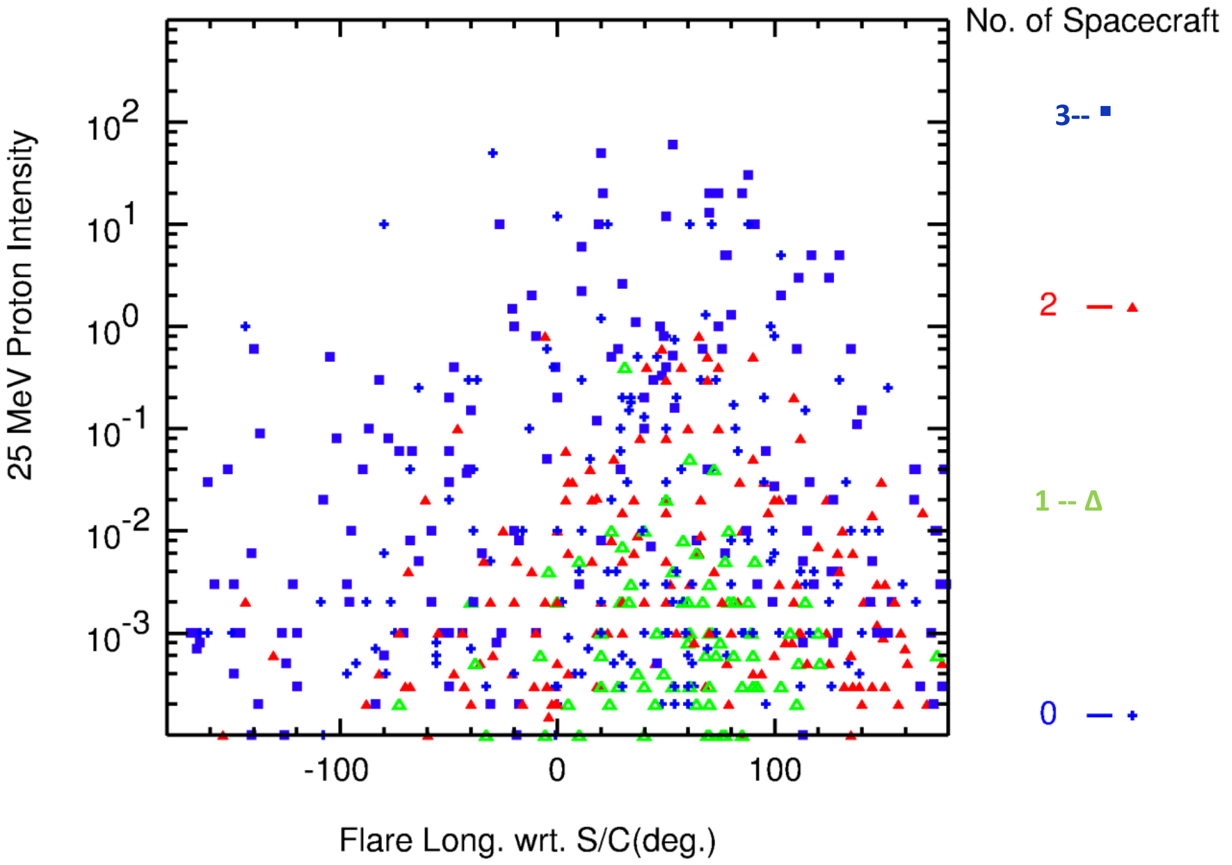




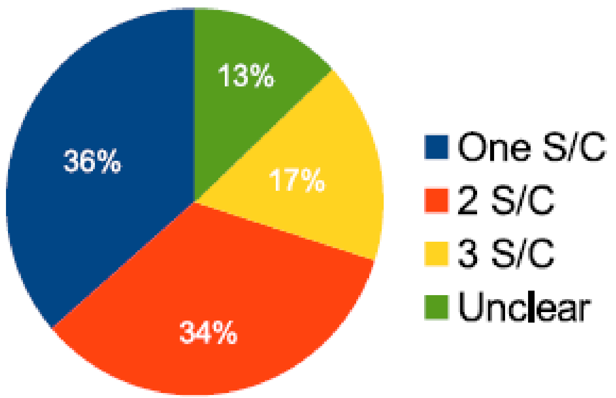
ENLIL+CONE
(from DONKI):
W22°, 554 km/s

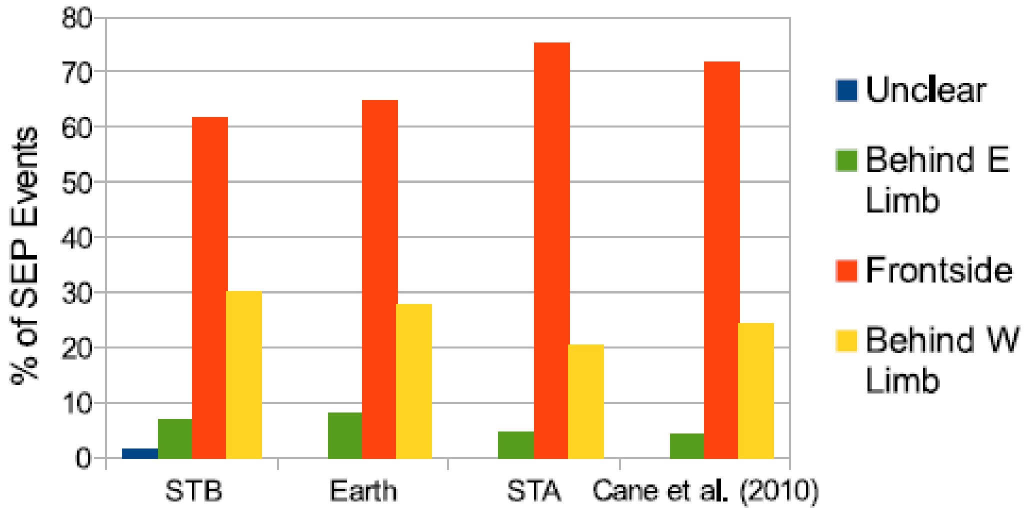
Peak 25 MeV Proton Intensity vs. Solar Event Longitude Relative to the Observing Spacecraft

SEPs can arrive from anywhere on the Sun!



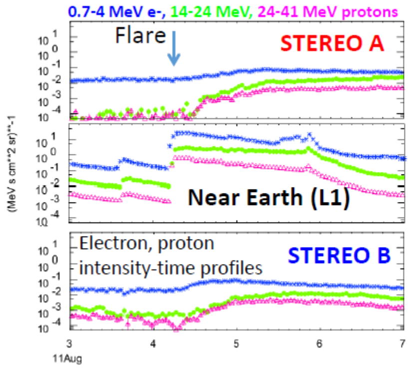
Richardson et al., 2014

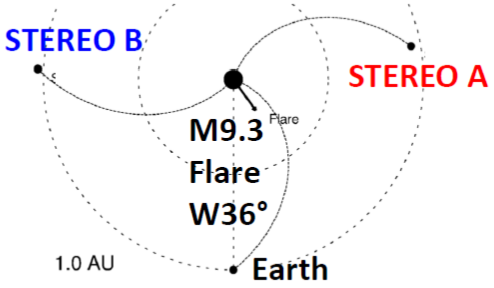


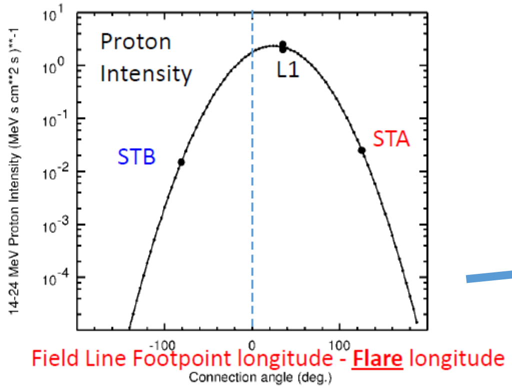


Three viewpoints (two STEREOs and another, e.g. Earth) are insufficient to characterize the longitudinal dependence of SEP events, especially when well separated.

Assume a simple longitudinal dependence, such as a Gaussian fit to peak intensities mapped to the magnetic field line footpoint longitude relative to the solar event (“connection angle”, CA).



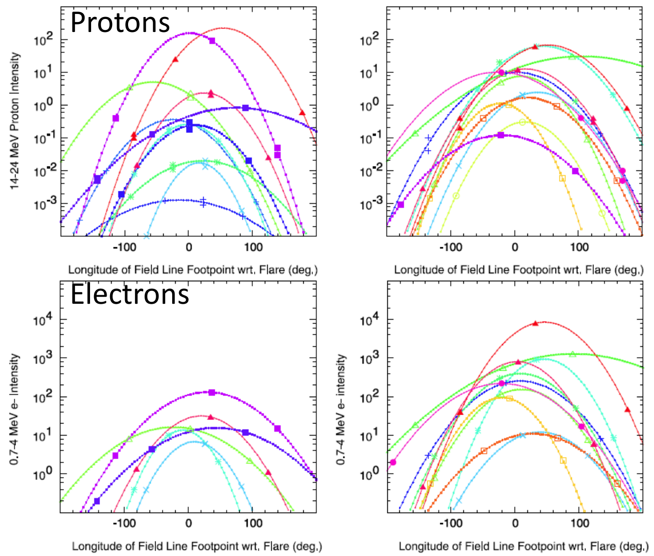




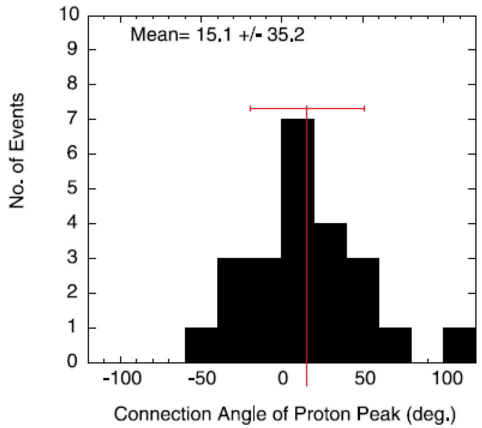
14-24 MeV proton intensities at Earth (two observations from different instruments) and at STEREO A and B *vs.* Connection Angle (CA) wrt. flare (Gaussian fit).

Peak Intensity is at CA = 24.8°; i.e., *the SEP peak is on field lines connected to the west of the flare.* Full Width at Half Maximum = 78.4°

Examples of Gaussian fits to 3-spacecraft proton and electron intensities for several events



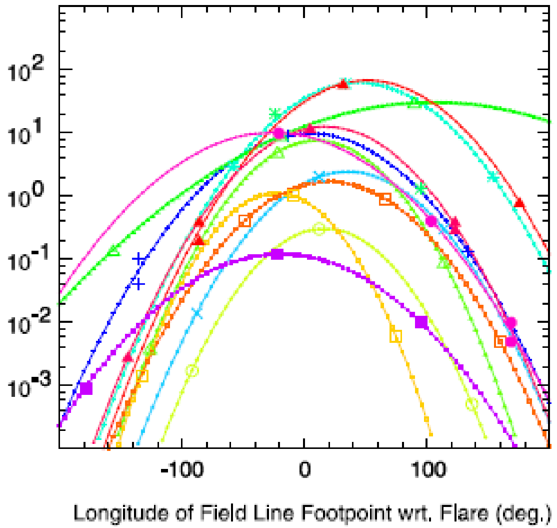
Distribution of connection angles of 14-24 MeV proton peaks for a sample of three spacecraft events. While the Gaussian peak is most frequently near the field line connecting to the solar event, there are also events that appear to be significantly asymmetric.



Richardson et al., 2014

SEP Proton Intensity Formula (*Richardson et al.,* 2014)

14-24 MeV Proton Intensity Gaussian fit vs. φ for 3 spacecraft (STEREOs + near Earth) events



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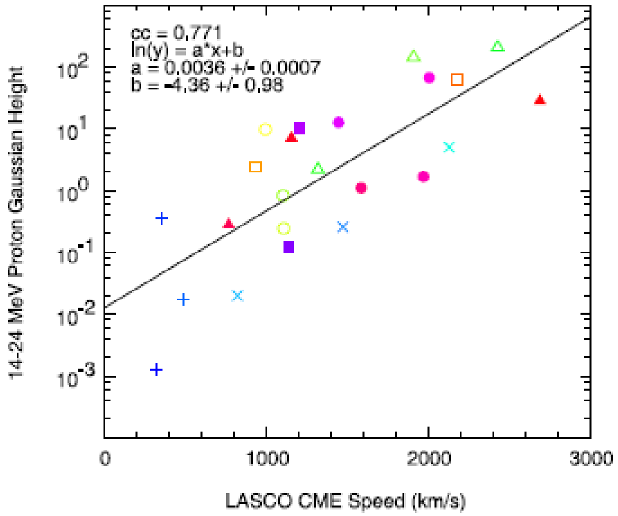
Gaussian peak intensity vs. LASCO CME speed



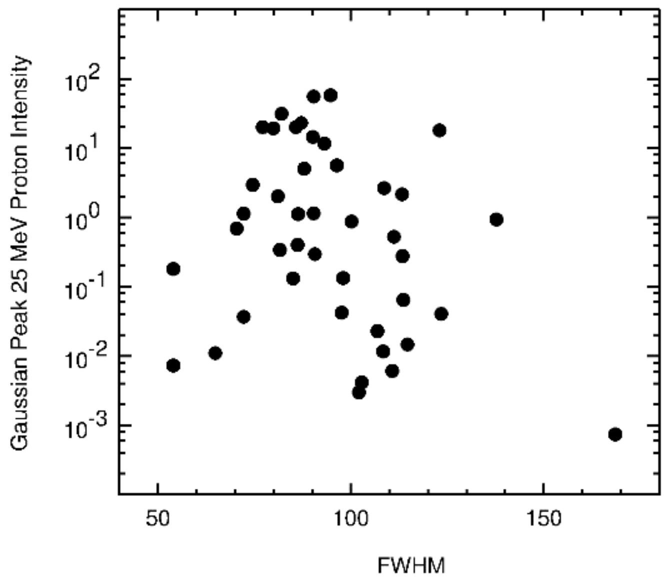
=>

***I* (φ) (MeV s cm² sr)⁻¹ ≈ 0.013 exp(0.0036*V* −φ²/2σ²)), σ = 43°, where:**

φ is the angle (longitude) between the solar event and the solar footpoint of the spiral magnetic field line passing the observing spacecraft, and

σ is the Gaussian width; 43° is the average value.

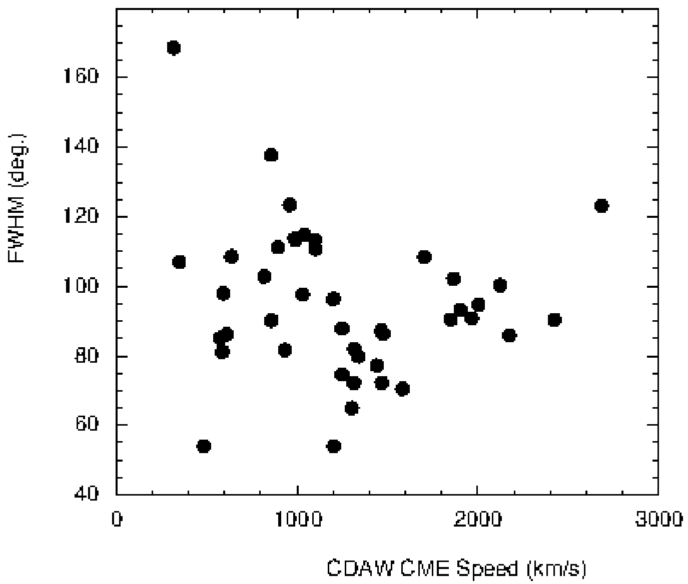
Relationship of 25 MeV Proton Gaussian Features with Event Intensity and CME Speed



Gaussian Peak 25 MeV proton intensity vs. Gaussian Full Width at Half Maximum (=2.355σ).

Most events lie in the FWHM=70-120° range (σ=30-51°).

Maybe an increase in FWHM for decreasing event size. This could be a selection effect since, for an intrinsically small event to be detectable as a 3 S/C event, a larger FWHM (wider Gaussian) is advantageous.



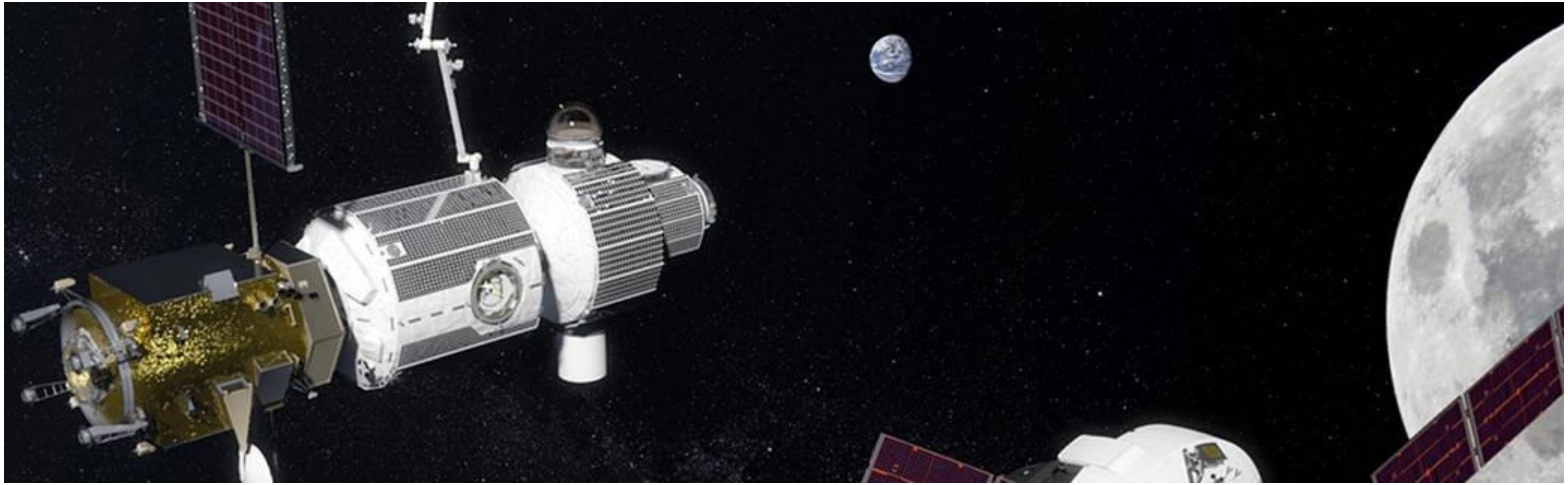
von Rosenvinge et al., 2015

FWHM vs. CME speed

There is no correlation.

However, combined with the tendency for the proton intensity to be correlated with the CME speed, the proton intensity will tend to exceed a particular threshold over a wider longitude range as the CME speed increases.

SEP Prediction for NASA's Lunar Outpost to Extend Human Presence in Deep Space, and Missions to Moon/Mars

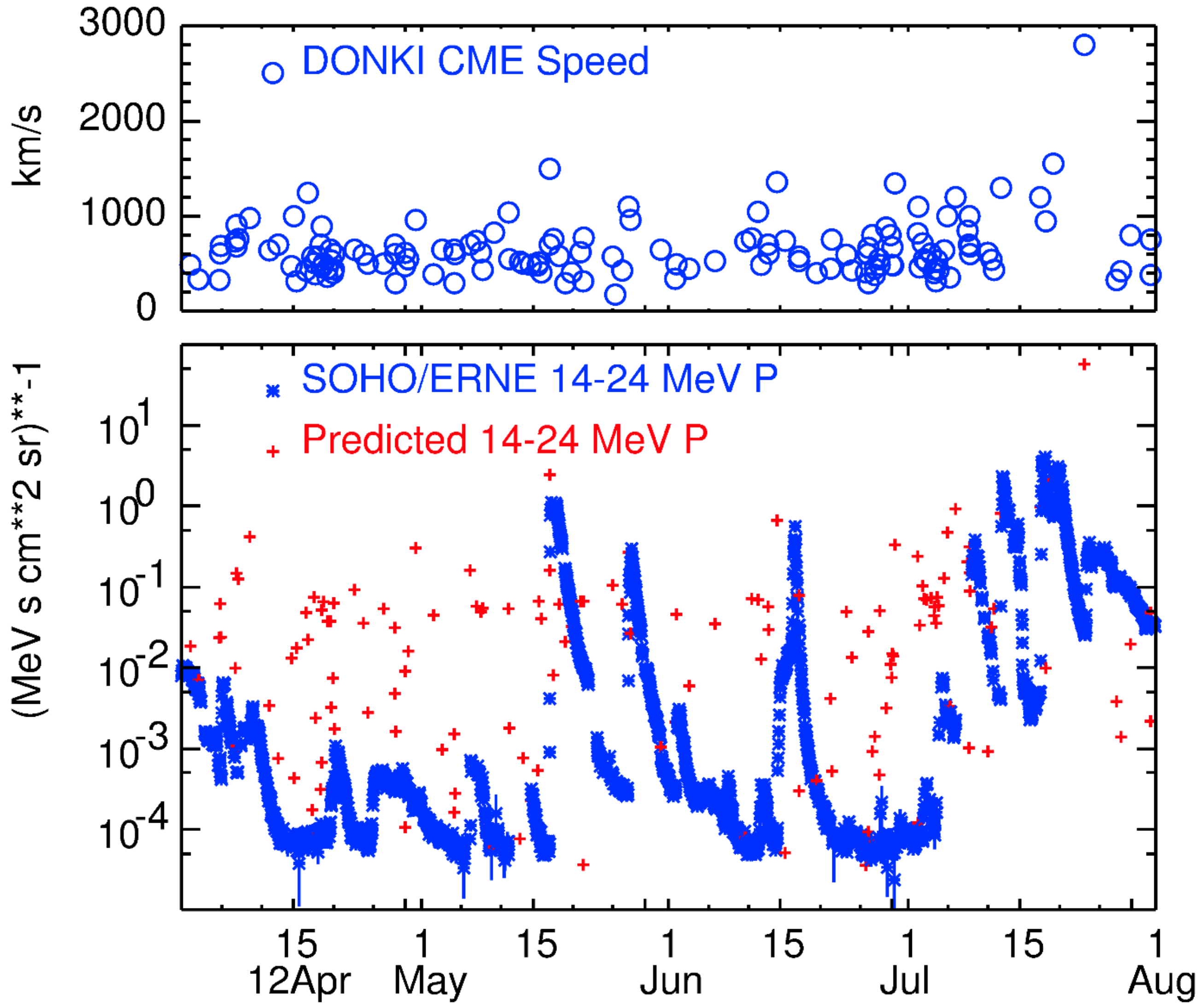


- Greater radiation hazard from Galactic Cosmic Rays and SEPs than for the ISS in LEO (less shielding from vehicle and geomagnetic cut off).

SEPs

- Only an occasional concern and lower energies than GCRs but little warning.
- Astronauts can reduce radiation exposure by building a shelter from supplies already on the vehicle in ~15 minutes.
- The Space Radiation Analysis Group (SRAG) at Johnson SFC is charged with issuing timely SEP warnings to astronauts with a low false alarm rate.
- SRAG are working with CCMC to select several SEP forecast models to develop an operational “scoreboard” to issue an SEP alert or “all-clear”.
- One of these is “SEPSTER” (SEP prediction based on STEReo observations) (*Richardson et al.,* Space Weather, 16, 1862, 2018)

Observed and Predicted SEP intensities at Earth in April-July, 2012



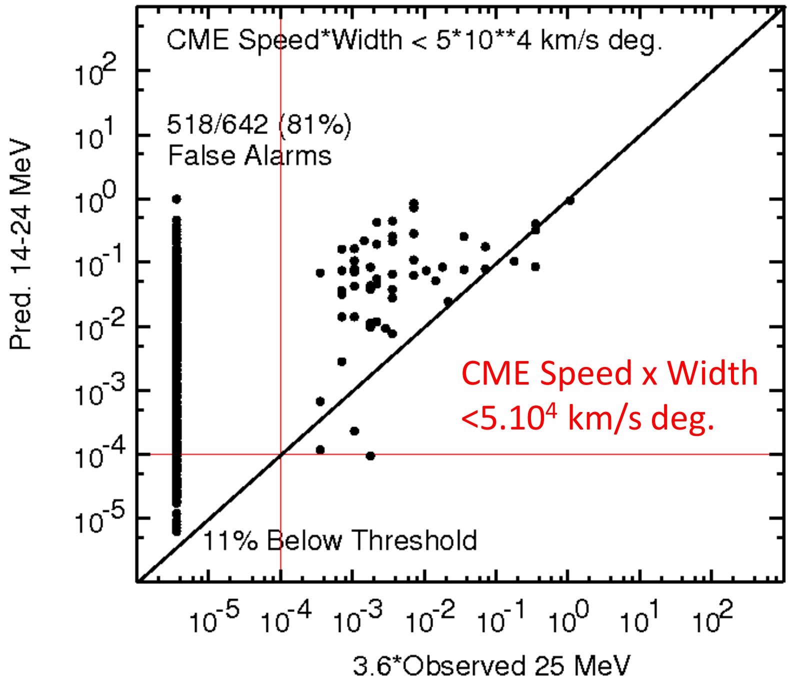
Problem: Most CMEs (~85%) are NOT accompanied by an SEP event.

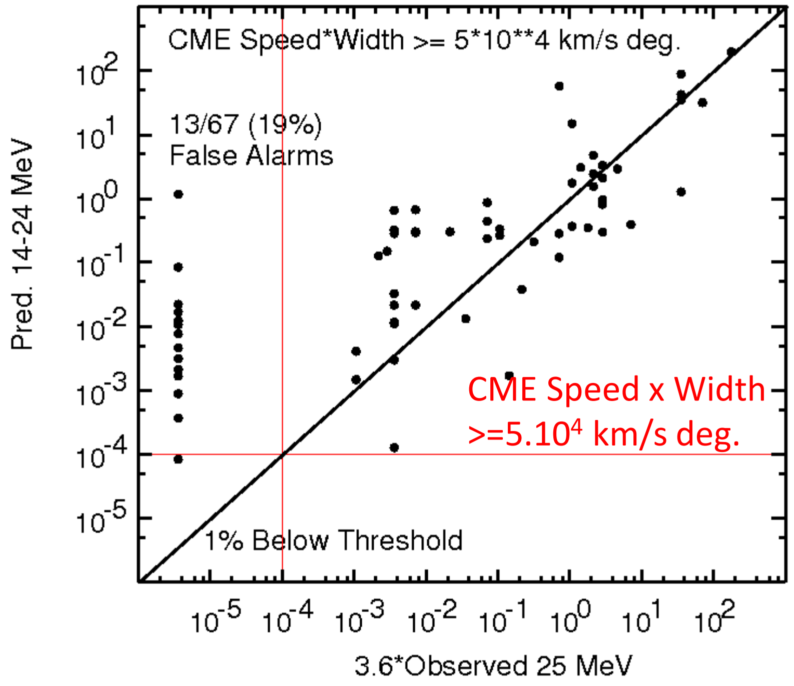
Hence, there are many cases when a predicted event is not observed.

Major problem: Only ~15% of CMEs are actually associated with 25 MeV proton events.

Filter using e.g., the presence of type II or type III radio emissions, or the CME speed and width, to reduce “false alarms”

Filtering by DONKI CME Speed x Width



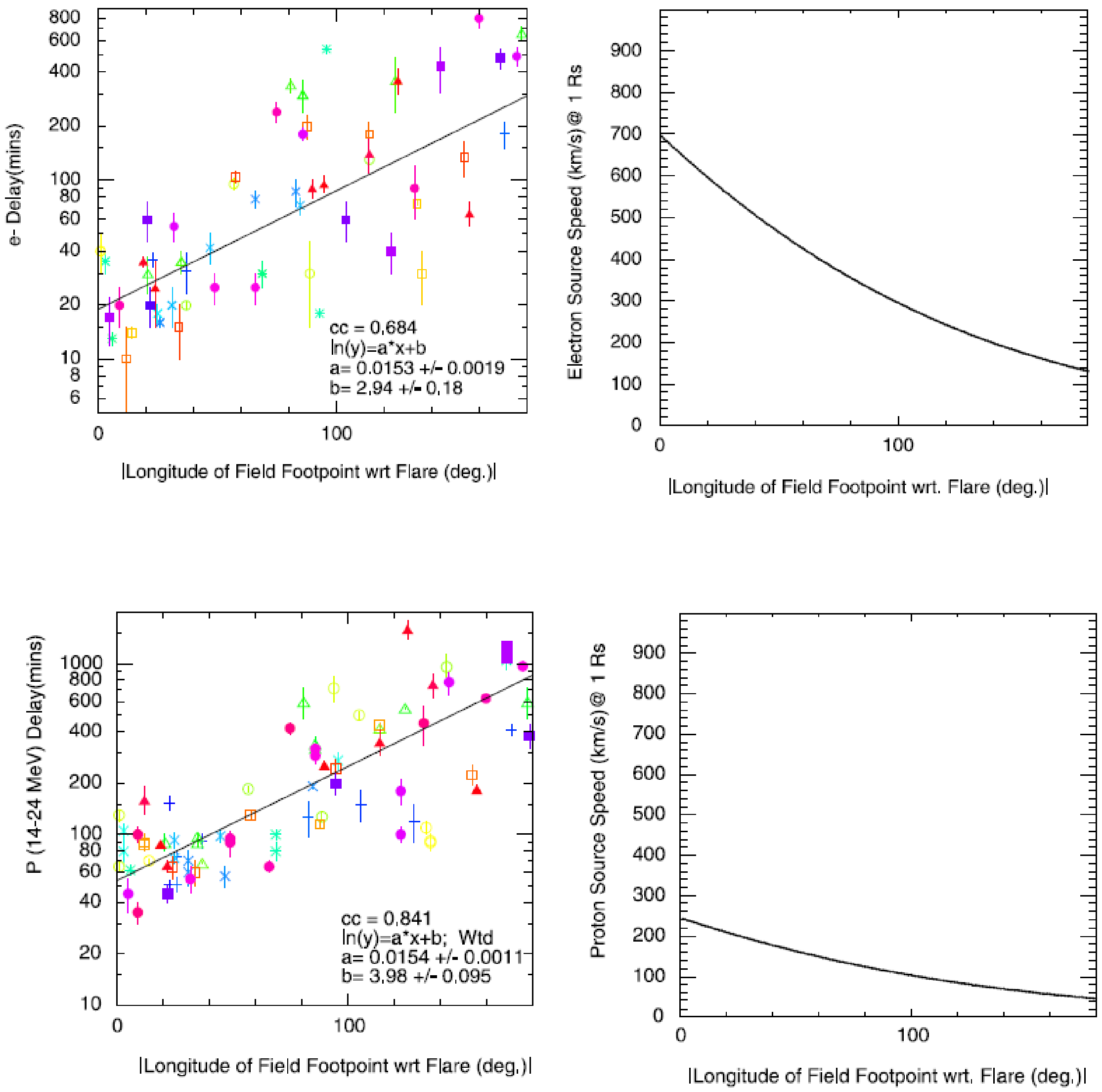


Currently running in real time at the CCMC, GSFC

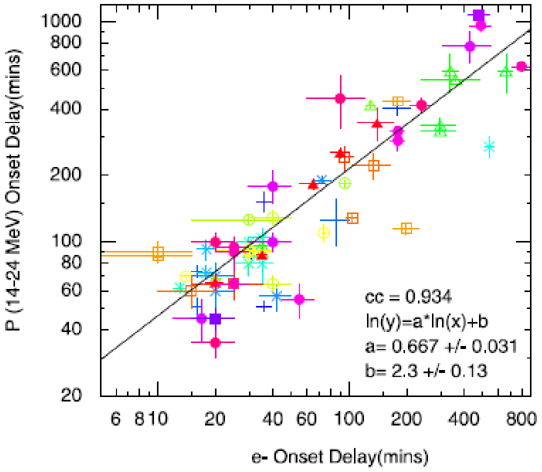
How are energetic particles transported in longitude in extended events?

- **An apparent effect due to "sympathetic" flares (*Richardson*, 1936)?** **X ?** No clear evidence that multiple solar events usually contribute to widespread SEP events (*Richardson et al*., 2014), though suggested for the November 3, 2011 event (and others) by *Park et al.,* 2013, *Prise et al.,* 2014.
- **Particle transport to remote longitudes by large scale magnetic loops?** **X ?** No clear evidence but not ruled out.
- **Diffusion near/at the Sun, e.g. Coronal propagation?** **?** Particles appear to spread rapidly in longitude near the Sun, but does diffusion play a role?
- **Acceleration by coronal waves?** **?** Particles are observed beyond the range of coronal waves; waves may be the "skirts" of CMEs.
- **Connection to an expanding 3-dimensional CME shock?** ✓**?** Could explain the rapid transport of particles near the Sun, but some events extend beyond the connected region
- **Cross-field transport/diffusion in the Solar Wind?** ✓ **?** Used to model some events. (Are the assumed parameters realistic?)
- **Acceleration by expansive interplanetary shocks?** ✓ Clearly observed in the heliosphere
- **Guidance by non-Parker spiral interplanetary magnetic fields, e.g. in ICMEs?** ✓ Clearly observed, but only operates at individual spacecraft in certain events.

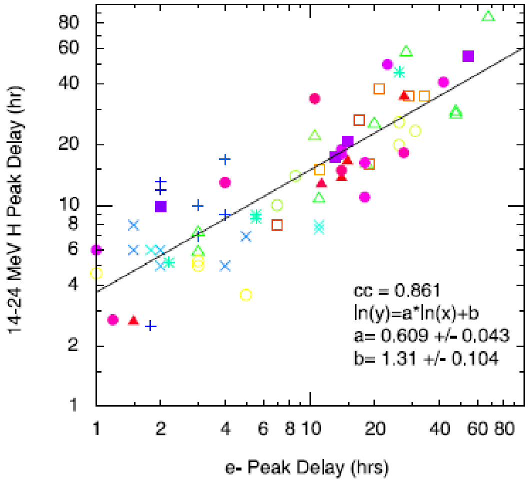
Different Longitudinal Source Speeds For Protons and Electrons



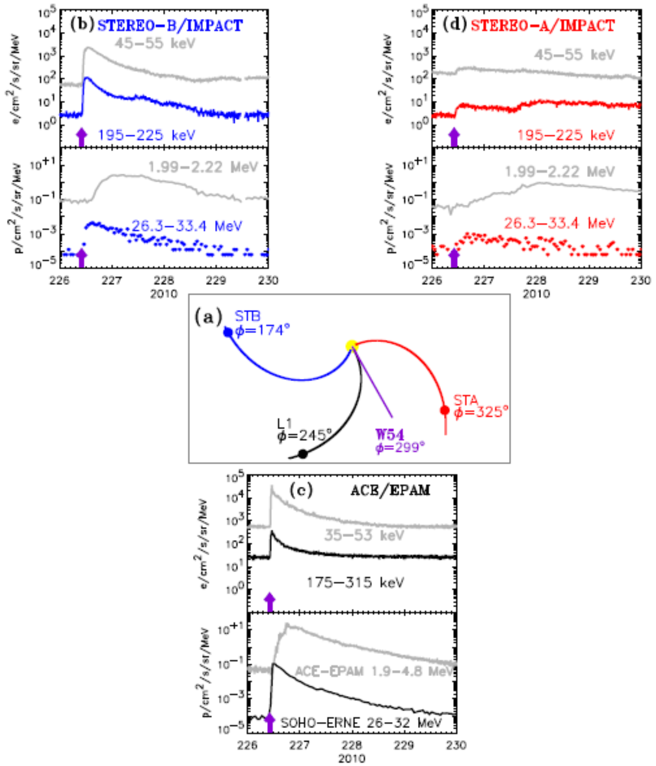
Electron and Proton Onset Delays are Correlated

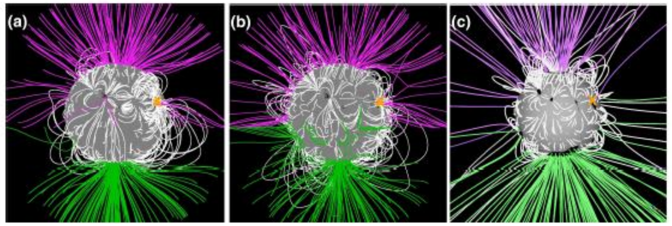


Electron and Proton Times to Peak Intensity are Correlated



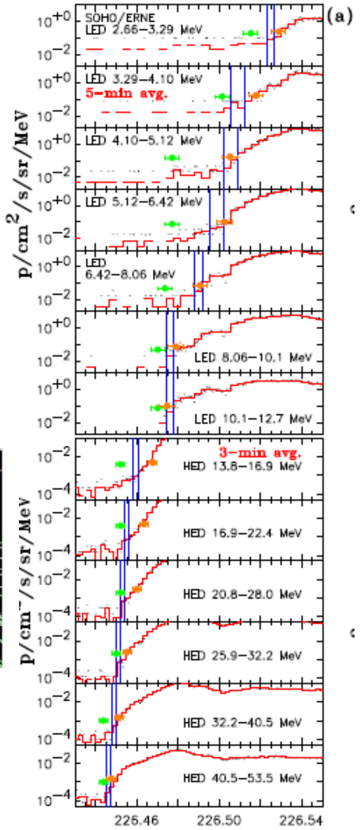
August 14, 2010 SEP Event Observed at Both STEREOs and at Earth (*Lario et al.,* 2017)

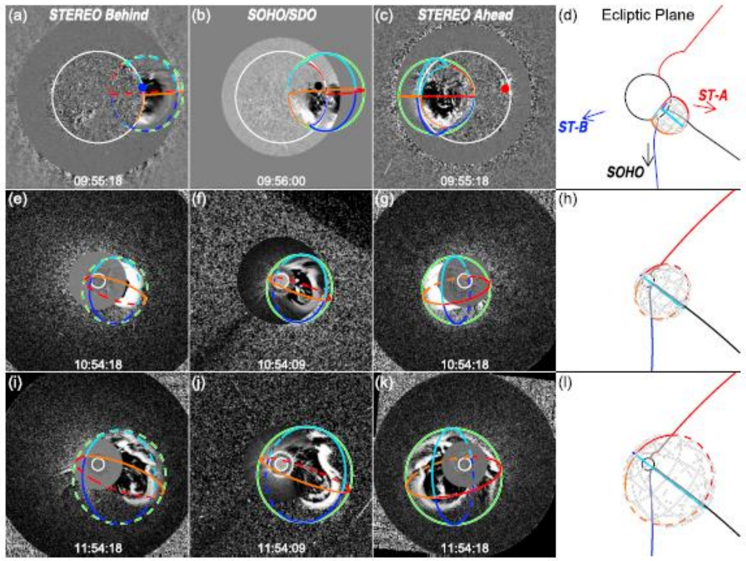




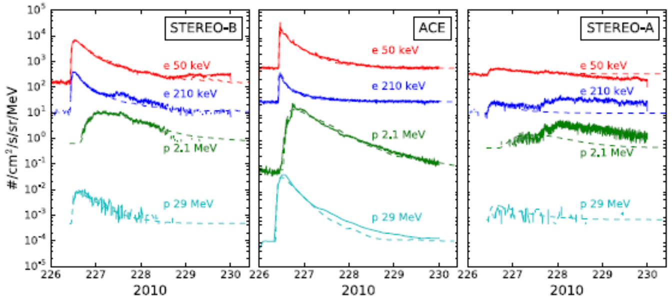
Different coronal fields obtained using different models/magnetograms: a)PFSS+HMI; b)PFSS+GONG; c)MAS+HMI

Different estimates of onset times using different methods: Blue lines=uncertainty "by eye"; green dots=Poisson-CUSUM; orange dots=Fixed onset level method.



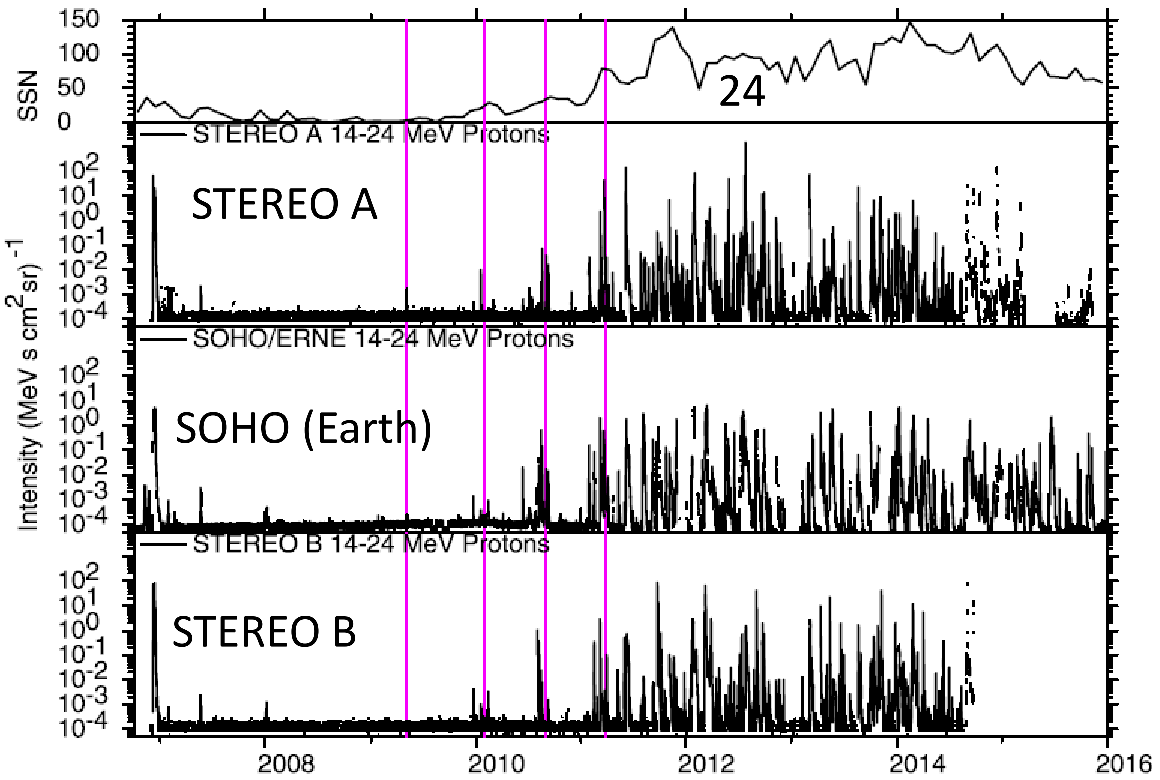


Evolving magnetic connection to an expanding ellipsoidal model shock front *assuming a PFSS+GONG coronal field*



A particle transport model including cross field diffusion may also account for the particle profiles, in particular the onset at STEREO A which does not connect to a fast section of the shock.

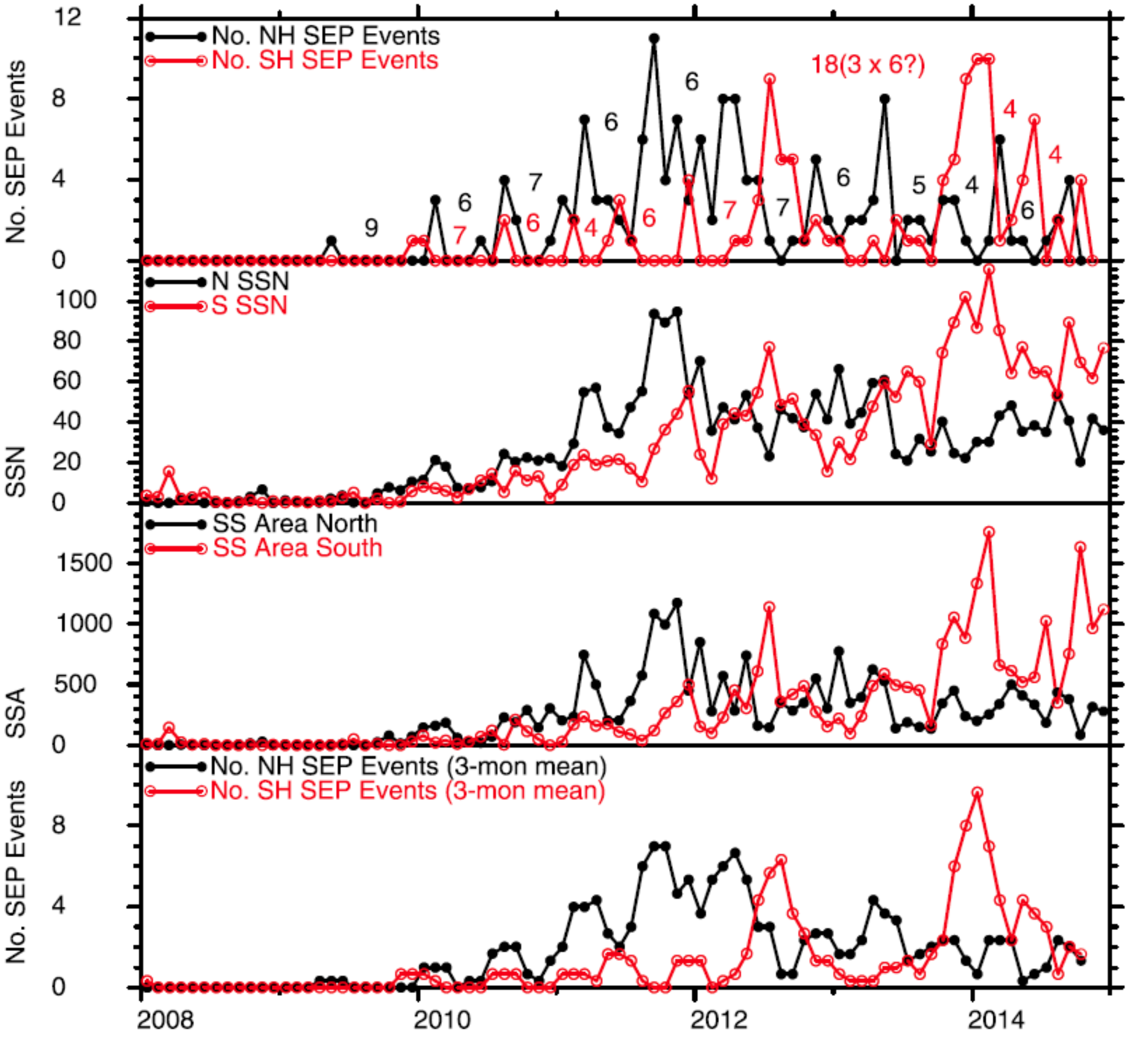
Overview of 14-24 MeV Proton Intensities at STEREO A, B and at Earth (SOHO/ERNE) From STEREO Launch to 2016

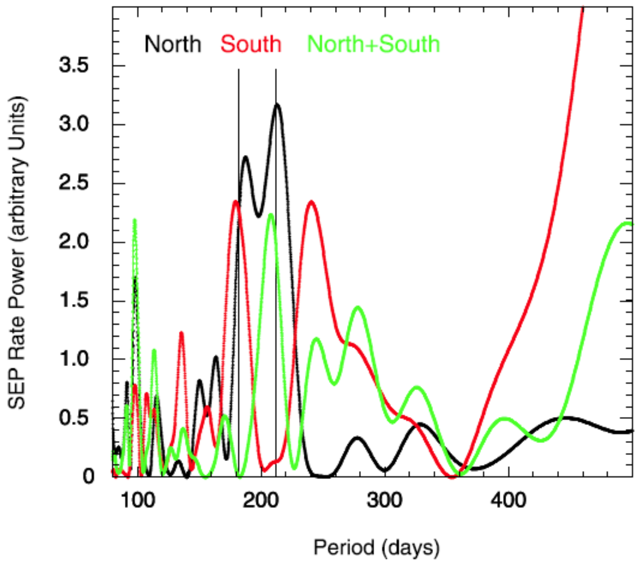


Updated from Richardson et al., 2014

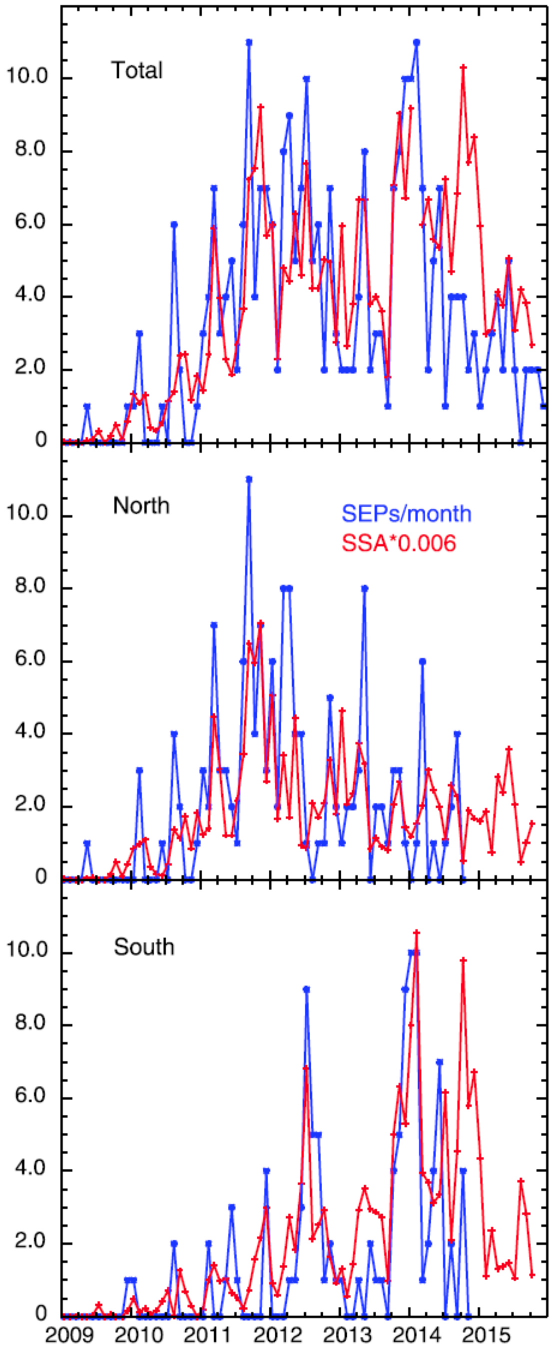
The first 25 MeV proton event detected at both STEREOs and at Earth occurred on December 22, 2009, when the STEREO A and B spacecraft were ~65° ahead or behind the Earth in longitude, respectively. This event occurred in one of several brief intervals of enhanced SEP occurrence (indicated by vertical lines) separated by similar several (~6)-month periods with relatively few SEP events. These intermittent intervals with SEPs characterize the rise of Cycle 24

~Six Month Periodicity in the Hemispheric SEP (25 MeV Proton) Event Rate in 2008-2014





Richardson et al., Solar Physics, 291, 2117-2134, 2016, doi:10.1007/s11207-016-0948-4.

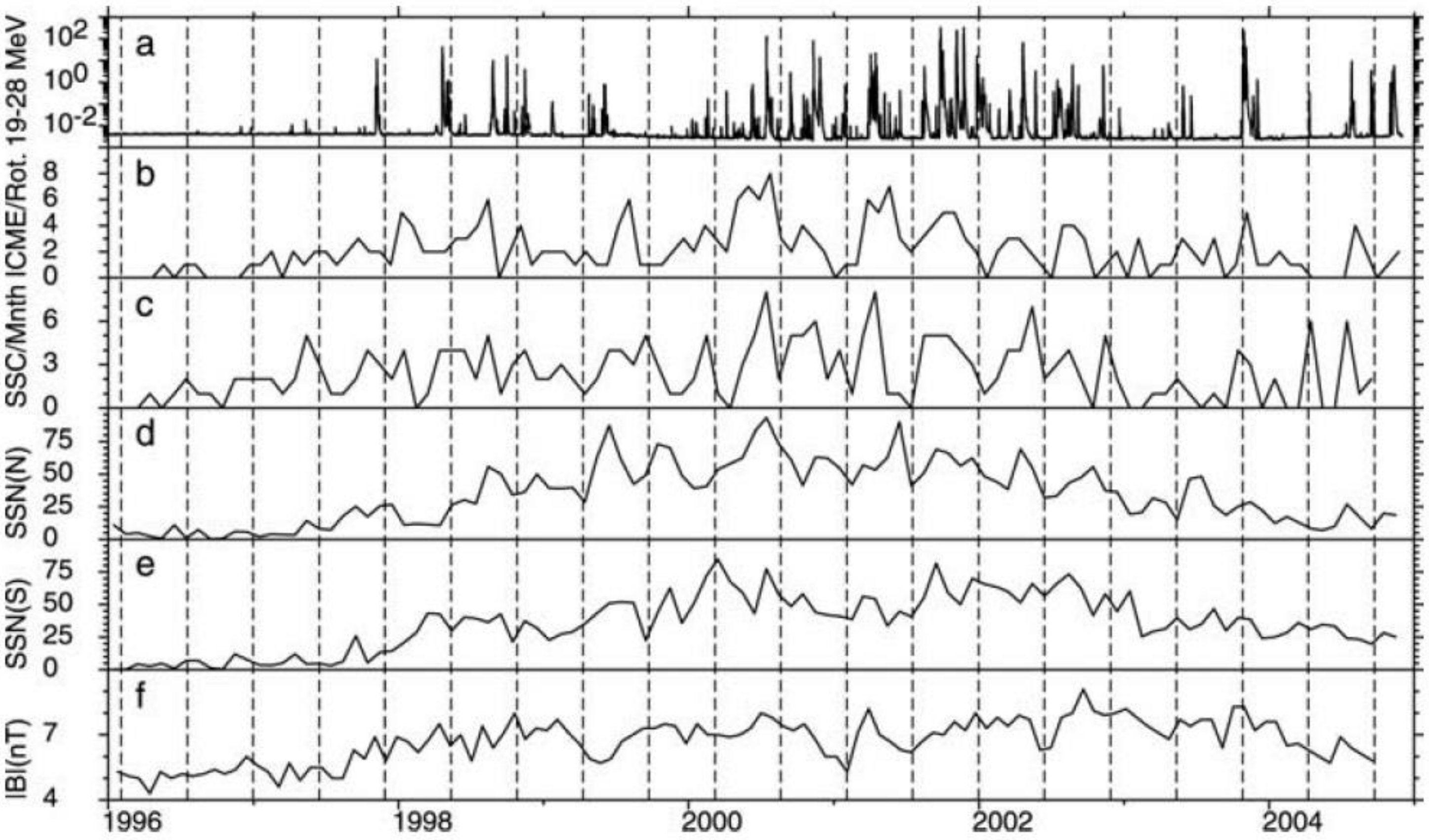


Monthly rate of 25 MeV proton events (blue) plotted with the monthly-averaged sunspot area (from David Hathaway) multiplied by 0.006, for the whole Sun, and Northern and Southern hemisphere separately.

Note the excellent correlation except in late 2014, when a large southern sunspot region was associated with non-erupting flares.

(*Richardson et al.*, 2016)

Evidence for periodicities in SEPs in Cycle 23 were discussed by *Richardson and Cane* (2005).



19-28 MeV proton intensity (from IMP 8) in 1996-2004 and rotation/monthly averages of several parameters. **The vertical lines are separated by 166 days**, the prominent period found in the ICME rate at Earth around solar maximum, where they approximately align with local minima in the ICME rate. During the early phase of the cycle, the SEP events were clustered with a similar period, as was the case in Cycle 24 where the period was also comparable (~6 months).

And in Cycle 21 SEPs and IMF by *Cane et al.* (1998):

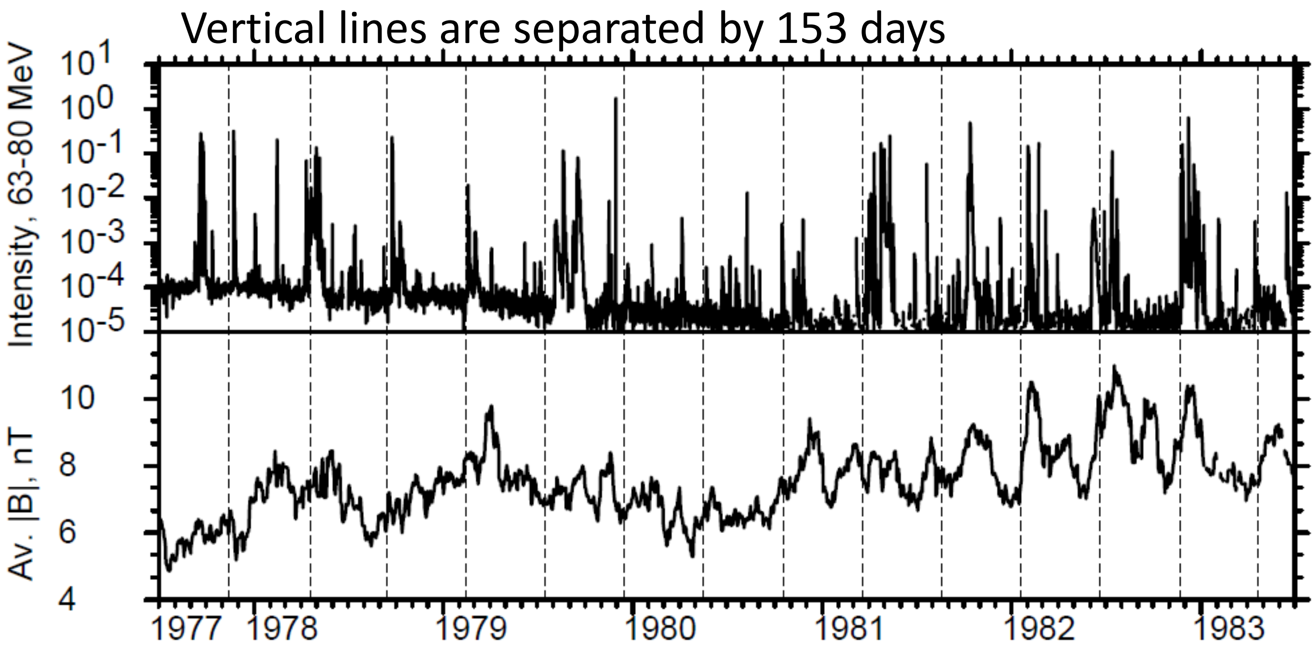
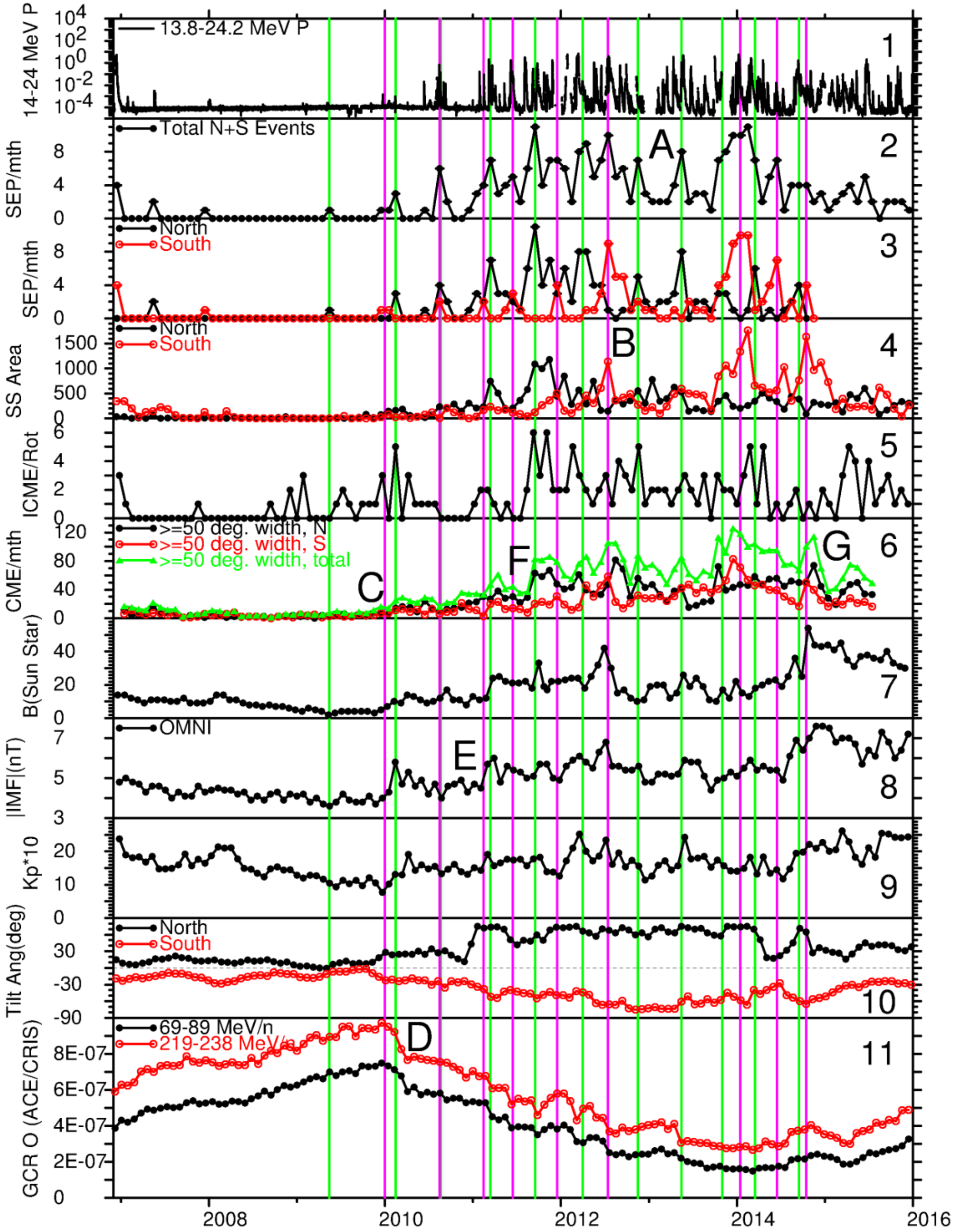


Figure 1. The lower panel shows daily-averages of the magnetic field strength at 1 AU in nT for July, 1977 to June, 1983, running averaged over a 27-day (∼solar rotation) period. The upper panel shows 8-hour averages of the intensity of 63-82 MeV protons at 1 AU.

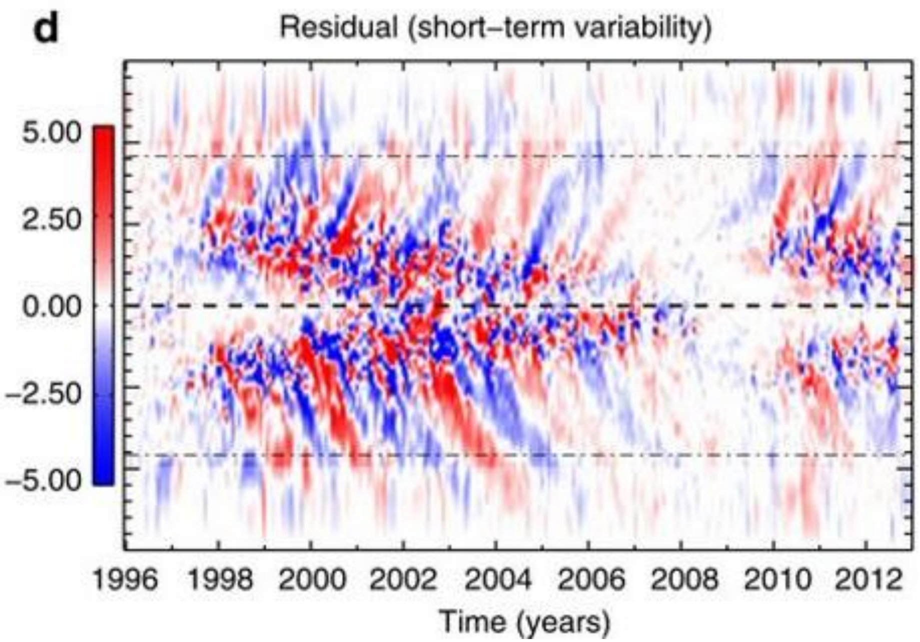
And e.g., by *Rieger et al.* (1984) in X-ray flares*,* *Lean* (1990) (who identified periods of ∼130 – 185 days in a survey of multiple solar cycles), *Bai and Cliver* (1990) (proton flares), *Dalla et al.* (2001) (SEPs), *Richardson and Cane* (2005) (see above), *Richardson and Cane* (2010) (ICMEs), and references therein, so Cycle 24 shows evidence of a similar phenomenon.

The periodicities are related to variations in other solar and interplanetary parameters during cycle 24 (Richardson et al., 2016).

Green (purple) vertical lines are times of North (South) SEP rate maxima.



Richardson et al., 2016



Photospheric magnetic field (McIntosh et al., 2015)

“SDO Global Energetics Survey Project” (*Aschwanden et al.*, 2017)

(http://www.lmsal.com/~aschwand/RHESSI/flare_energetics.html)

Project: Survey the global energetics of solar flares and CMEs observed with SDO, including data from AIA, HMI, EVE, STEREO/EUVI, RHESSI, GOES, etc.

Data set: 2010-2014, first 5 years of SDO mission; 398 GOES flares (28 X- and 370 M-class);177 flares near disk center (<45° longitude)

Energy parameters :	Instruments :	Collaborators :
Nonpotential magnetic energy	HMI, AIA (NLFFF codes)	Xu, Jing, Aschwanden
Potential field magnetic energy	HMI (PFSS or NLFFF codes)	Xu, Jing, Welsch, Aschwanden
...	...	...
HXR fluence >25 keV	RHESSI	Kontar, O'Flannagain
SXR fluence 1-8 A	GOES	Ryan, Aschwanden
EUV fluence 94-335 A	AIA	Aschwanden
SXR+EUV+UV fluence 1-1060 A	EVE	Woods
Bolometric fluence	SORCE	Kretzschmar, C.S.Moore
...	...	...
EUV peak thermal energy	AIA (DEM), AIA(area)	Aschwanden
SXR peak thermal energy	GOES (T, EM), AIA (area)	Ryan
SXR+EUV peak thermal energy	GOES+EVE (DEM), AIA (area)	Warren
HXR+EUV peak thermal energy	RHESSI+EVE (DEM), AIA (area)	Caspi, McTiernan, Warren
...	...	...
HXR nonthermal electrons >25 keV	RHESSI	Kontar, O'Flannagain, Guo
Gamma-ray producing ions >1 MeV	RHESSI, FERMI	Share, Shih
SEP particle energies	ACE, GOES, STEREO	Mewaldt
...	...	...
CME kinetic + potential energy	COR1+2/STEREO, LASCO/SOHO	Temmer, Vourlidas, Zhang, Warmuth
CME thermal energy	STEREO/EUVI, AIA (EUV Dimming, DEM)	Aschwanden, Vourlidas
CME thermal energy	UVCS/SOHO	Raymond
...	...	...

Solar Energetic Particle (SEP) Component:

Dick Mewaldt (leader): Scattering correction, total energy calculation

Christina Cohen: He, heavier ions

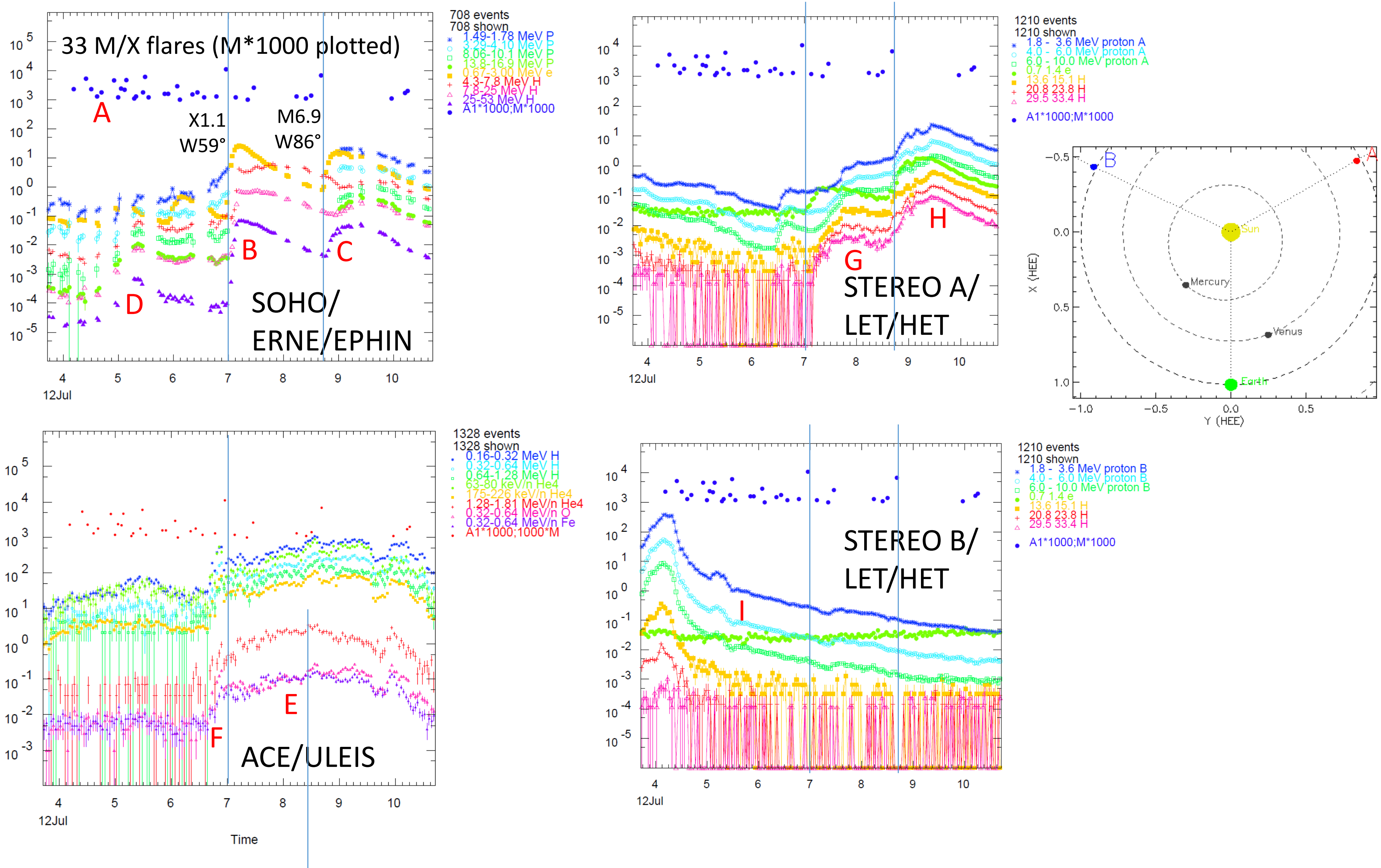
Mihir Desai: H, heavy ion spectra

Glenn Mason, George Ho: Low energy H, heavy ions.

David Lario: Electrons

Ian Richardson: SEP/flare/CME associations, identify usuable events, spectral fitting.

SEP Observations During a 7-day Period in July, 2012 With 33 M/X Flares



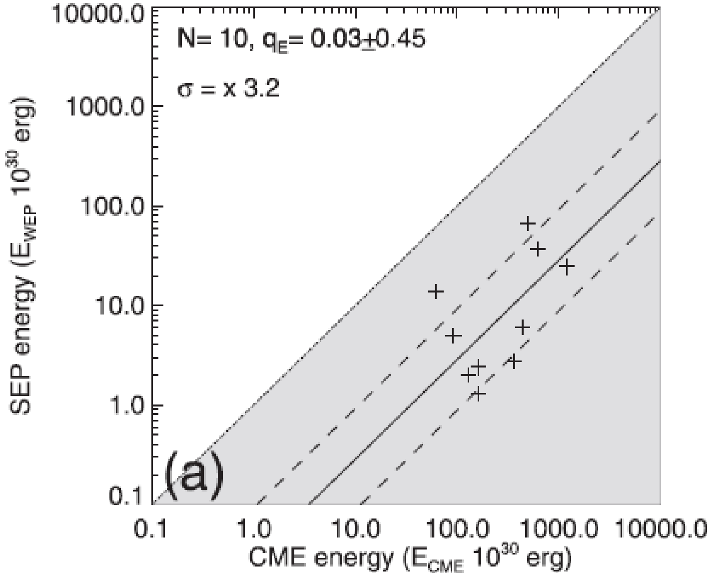
Results for Three-Spacecraft Events as Reported in Aschwanden et al. (2017)

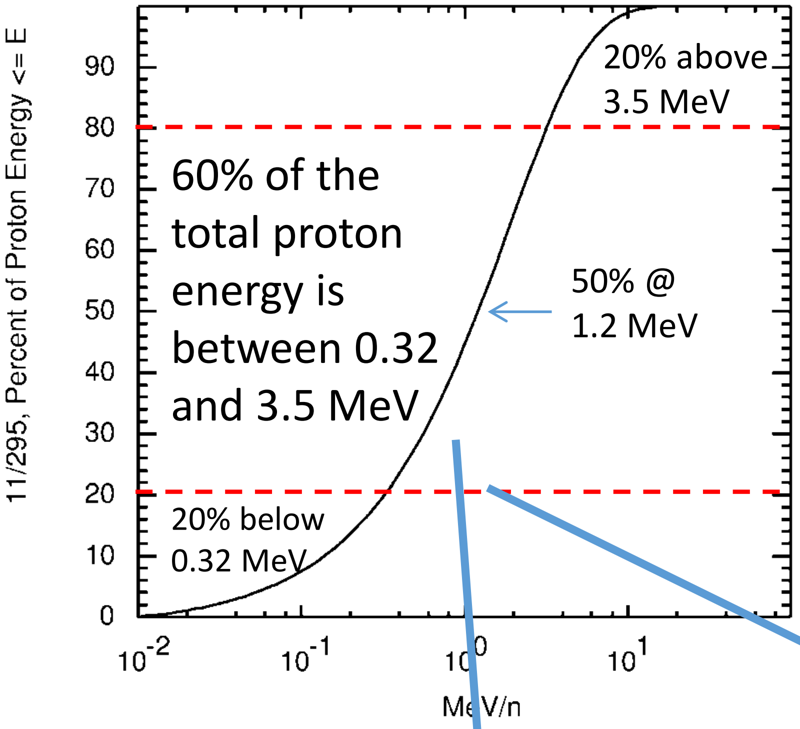
Table 1
SEP Kinetic Energies for Selected Three-spacecraft Events From 2011 to 2013

#	Flare Date	*GOES* Class	Heliographic Position	SEP kinetic Energy (10^{30} erg)	CME/LASCO Energy (10^{30} erg)	CME/AIA Energy (10^{30} erg)	SEP/CME Energy Ratio
12	2011 Feb 15	X2.2	S21W12	1.3	>1.6	161.0	0.008
58	2011 Aug 04	M9.3	N18W36	4.9	45.0	>15.0	0.110
74	2011 Sep 22	X1.4	N08E89	2.8	265.0	>14.0	0.011
102	2011 Oct 22	M1.3	N27W87	13.6	22.0	>17.0	0.620
131	2012 Jan 23	M8.7	N33W21	37.3	413.0	>19.0	0.090
132	2012 Jan 27	X1.7	N33W85	24.5	819.0	>41.0	0.030
148	2012 Mar 07	X1.3	N18E29	67.6	362.0	>12.0	0.190
169	2012 May 17	M5.1	N07W88	6.0	251.0	>14.0	0.024
284	2013 May 13	X1.7	N11W89	2.0	61.0	>11.0	0.033
296	2013 Jun 21	M2.9	S14E73	2.4	100.0	>12.0	0.024
	Logarithmic	mean					$0.03 \div 3.2$

Note. The higher value of the two lower limits of CME/LASCO (sixth column) and CME/AIA energies (seventh column) is used in the SEP/CME ratio (eighth column).

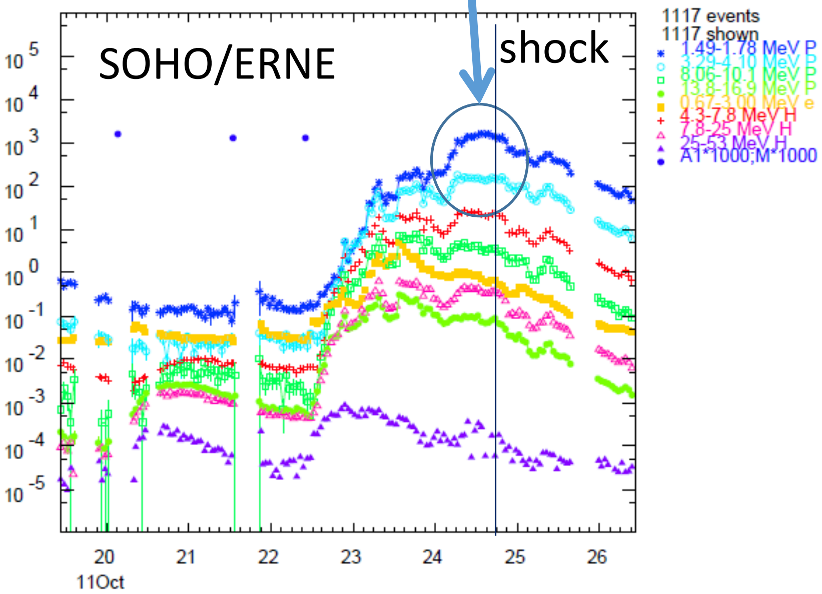
The SEP energy is typically only a few percent of the CME energy.

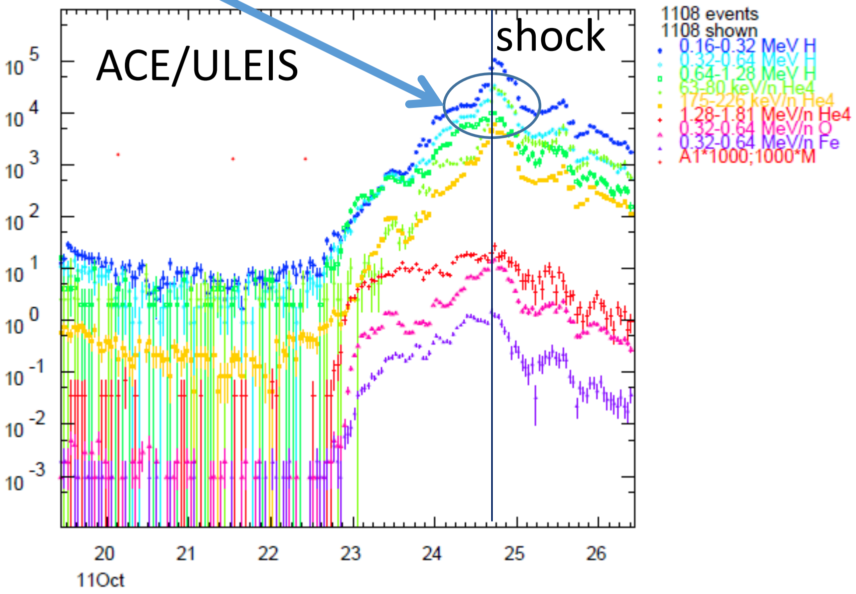




How is the Event-Integrated SEP Energy Distributed in Energy?

The top left figure shows the percentage of the total integrated proton energy that lies *below* a given energy, for the Oct 22 (day 295), 2011 flare. 60% of the total energy in this event is contributed by 0.32-3.5 MeV protons. The intensity at these energies is greatest in the local enhancement associated with passage of the flank of the interplanetary shock (10/24, 18 UT) related to this W77° M1.3 flare. Hence, this local shock-associated particle increase dominates the SEP energetics in this event.





The STEREO mission has made significant contributions to understanding SEPs.

Observations confirm that SEPs can be detected from anywhere on the Sun (as strongly suspected from previous observations at Earth), though they are most intense on field lines well connected to the solar event.

The rapid spread of SEPs over large longitudinal extents places significant constraints on mechanisms of particle transport near the Sun and/or in the solar wind.

Field line connection to expanding shocks is the simplest explanation, but cross-field transport may be required to explain cases where connection appears to be unlikely.

Because of its launch at solar minimum, STEREO could not satisfactorily address the variations in SEP properties with longitude anticipated from previous statistical studies. However, STEREO A is approaching the Earth again, and may be favorably placed for such studies as the next solar cycle ramps up.

The > factor of 2 increase in SEP event statistics available with the STEREO observations improves studies of for example, variations in the SEP rate, showing quasi-periodicities that are probably a manifestation of the evolution of solar magnetic fields during the solar cycle. Observing and understanding this evolution may be a significant advance in space weather forecasting, including the longer-term (several months) prediction of SEPs.