Working Group 6, WG6:
‘Solar Energetic Particles (SEPs)’

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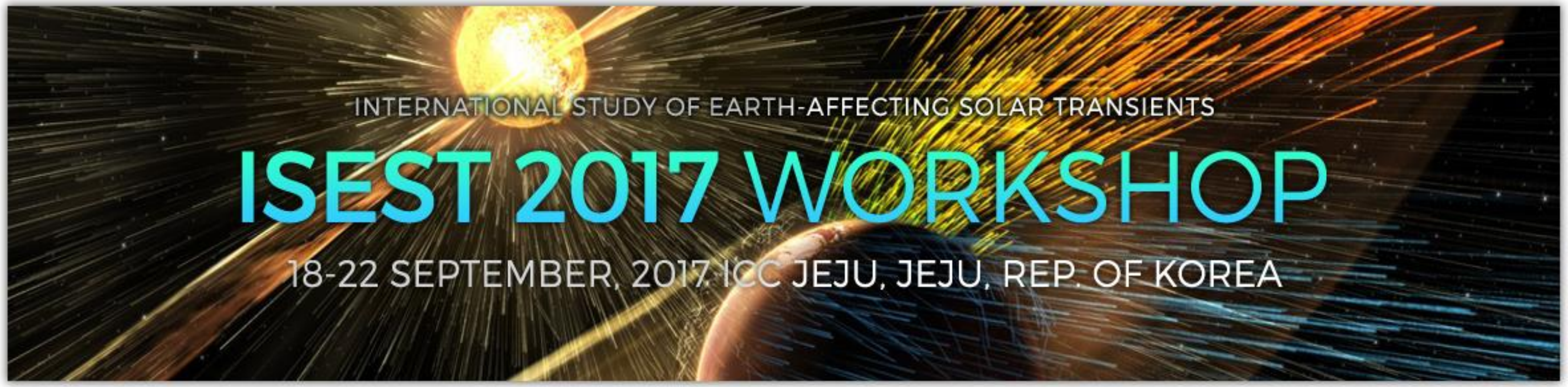


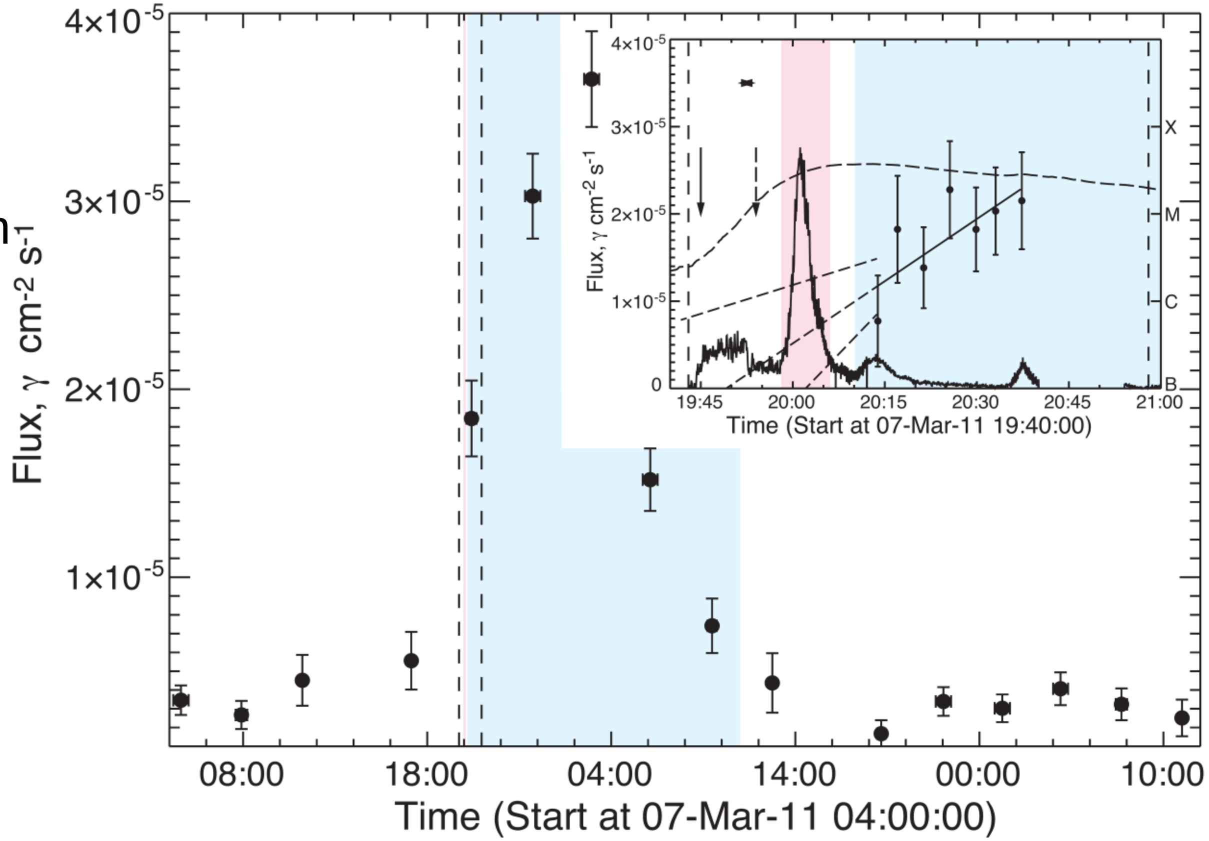
SCIENTIFIC ISSUES REPORTED HERE!

- **Gamma-ray flare events and SEPs: FERMI era**
- Triangulation of shocks in 3-D
- Joint Ne/O and Fe/O Analysis to Diagnose Large Solar Energetic Particle Events during Solar Cycle 23
- **What Governs the Longitudinal Spread of Solar Energetic Particles**
- **3D Modelling of Solar Energetic Particle Propagation within the heliosphere**
- Are Abundance Enhancements Power-Law in A/Q?
- Compare FIP plots of SEPs and slow Solar Wind
- **Flare vs Shock Acceleration of high-energy protons in Solar Energetic Particle Events**
- **High Energy Solar Particle Events Forecasting**
- Small-scale magnetic islands in the solar wind

  and their role in particle acceleration
- CME Kinematics and SEP spectra, 2012 July 23 event
- 2017 September 10 SEP/GLE Event

Sustained Gamma-Ray Emission (SGRE) events

- Example of SOL2011-03-07T19:43 with distinct sustained-emission phase
- First event detected by LAT (Ackermann et al. 2014), 14 hr duration
- **>100 MeV γ-ray flux** plotted before and after the flare
- Dashed vertical lines: GOES SXR start and end times
- Emission began during GOES flare and **rose to peak about 6 hours later**
- **Inset:** >100 MeV 4-min res after hard X-ray peak: SGRE began within min of the hard X-ray peak



Clear that the SGRE is due to a distinct particle acceleration phase and is not just the tail of emission from the impulsive flare

Share et al. submitted, 2017

Sustained Gamma-Ray Emission (SGRE) events: Statistics

Share et al. 2017, submitted

- Identified, catalogued and analyze **30 Sustained Gamma-Ray Emission (SGRE)** events observe by Fermi/LAT from 2008-2016
- Considered CME, type II and SEP association

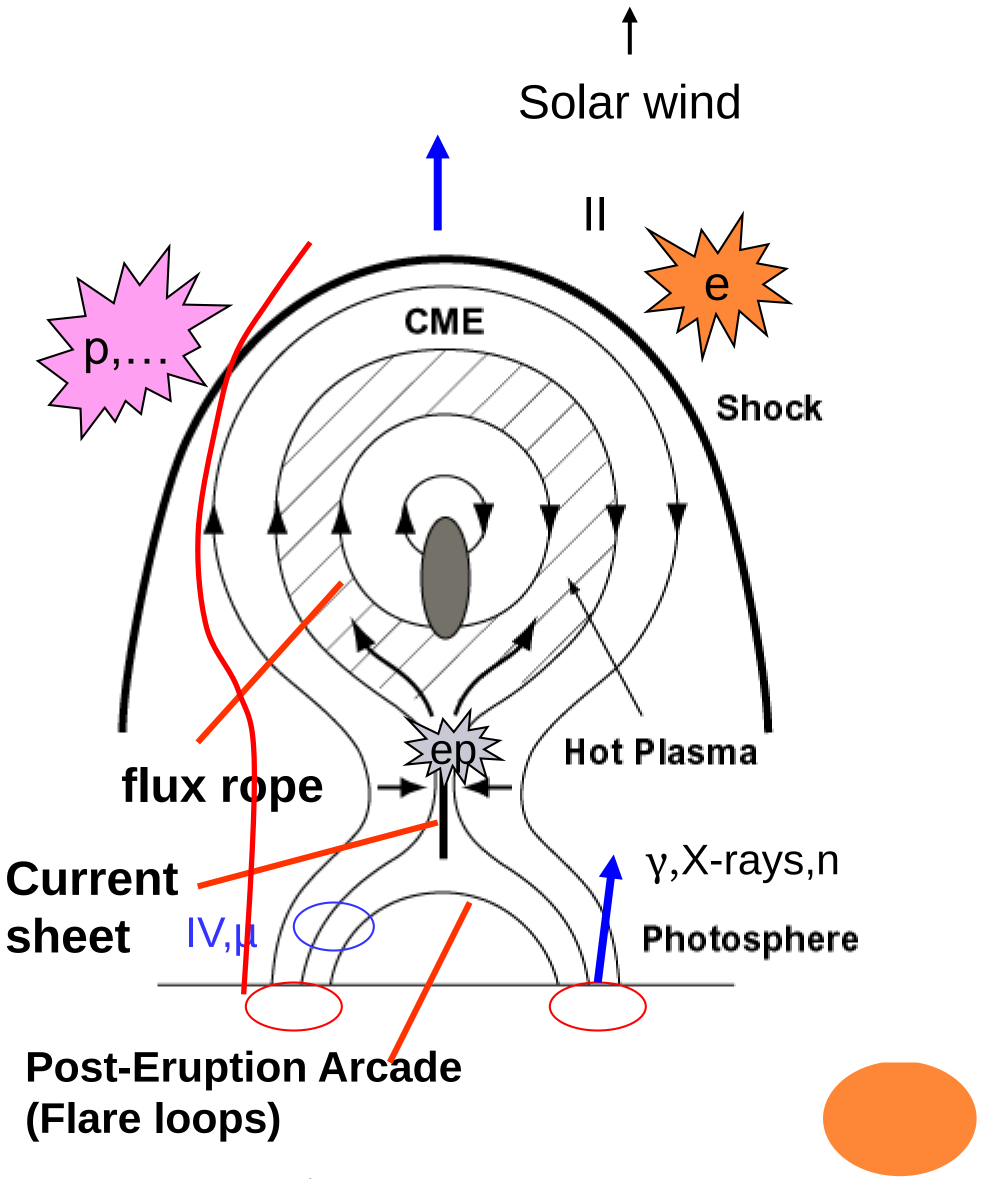
Table 1. LAT Sustained >100 MeV Emission (SGRE) Events from June 2008 to December 2016

Number (1)	Date, Location yyyy/mm/dd, deg (2)	*GOES* X-Ray Class, Start-End (3)	CME Speed, km s^{-1} (4)	Type II M*, DH (5)	SEP Flux (pfu), Energy (MeV) (6)	Hard X-ray Energy (keV) (7)
1	2011/03/07, N30W47	M3.7, 19:43–20:58	2125	3?, Y	39.6, >60	300–1000[d]
2	2011/06/02, S18E22	C3.7, 07:22–07:57	976	N, Y	~0.1, <40[b]	–[e]
3	2011/06/07, S21W54	M2.5, 06:16–06:59	1255	2?, Y	60.5, >100	300–800
4	2011/08/04, N19W46	M9.3, 03:41–04:04	1315	2, Y	48.4, >100	300–1000[d]
5	2011/08/09, N16W70	X6.9, 07:48–08:08	1610	1?, Y	16.3, >10	800–7000
6	2011/09/06, N14W18	X2.1, 22:12–22:24	575, ~1000[a,b,h]	2, Y	5.6, >100	300–1000
7	2011/09/07, N18W32	X1.8, 22:32–22:44	792	1, N	<1.7, >10[f]	300–1000[d]
8	2011/09/24, N14E61	X1.9, 09:21–09:48	1936	2?, N	<77, >13[b,f]	800–7000
9	2012/01/23, N33W21	M8.7, 03:38–04:34	2175	N, Y	3280, >100	100–300[d,e]
10	2012/01/27, N35W81	X1.7, 17:37–18:56	2508	3, Y	518, >100	100–300[d,e]
11	2012/03/05, N16E54	X1.1, 02:30–04:43	1531	N, Y	<33, >13[b,f]	100–300[d,e]
12	2012/03/07, N17E27	X5.4, 00:02–00:40	2684	2?, Y	1800, >100	>1000[g]
		M3, 01:05–01:23	1825	2?, Y	1800, >100	>1000[g]
13	2012/03/09, N16W02	M6.3, 03:22–04:18	950	2, Y	<528, >10[f]	100–300
14	2012/03/10, N18W26	M8.4, 17:15–18:30	1296	N?, Y	<115, >10[f]	100–300[d]
15	2012/05/17, N05W77	M5.1, 01:25–02:14	1582	3, Y	180, >100	100–300[c]
16	2012/06/03, N15E38	M3.3, 17:48–17:57	605, 892[b,h]	2, N	0.6, >60[b]	300–800
17	2012/07/06, S17W52	X1.1, 23:01–23:14	1828	3, Y	19.1, >100	100–300[e]
18	2012/10/23, S15E57	X1.8, 03:13–03:21	–	Y, N	<0.1, >13[b]	>9000
19	2012/11/27, N05W73	M1.6, 15:52–16:03	–	N, N	<0.1, >10	300–1000
20	2013/04/11, N07E13	M6.5, 06:55–07:29	861	3, Y	184, >60[b]	100–300[d]
21	2013/05/13, N11E89	X1.7, 01:53–02:32	1270	1, Y	9.3, >60[b]	100–300
22	2013/05/13, N10E80	X2.8, 15:48–16:16	1850	2, Y	176, >60[b]	>1000
23	2013/05/14, N10E77	X3.2, 00:00–01:20	2625	1, Y?	306, >60[b]	300–1000[d]
24	2013/05/15, N11E65	X1.2, 01:25–01:58	1366	1, Y	<17, >13[b,f]	300–1000
25*	2013/10/11, N21E103	M4.9[i], 07:01–07:45	1182	2, Y	156, >60[b]	–[j]
26	2013/10/25, S08E71	X1.7, 07:53–08:09	587	2, N	32.6, >60[b]	800–7000[c]
27	2013/10/28, S14E28	M4.4, 15:07–15:21	812	2, N	5.6, >13[b]	100–300[c]
28	2014/02/25, N00E78	X4.9, 00:39–01:03	2147	3, Y	219[b], >700	1000–10000
29*	2014/09/01, N14E126	X2.1[i], 10:58–11:34	1901	Y?, Y	~1000, >13	–[j]
30	2015/06/21, N13E16	M2.6, 02:03–03:15	1434	2?, Y	~40, >10	100-300[d]

** Pesce-Rollins et al. 2015, Ackermann et al. 2017*

SGRE Summary from Share et al. 2017

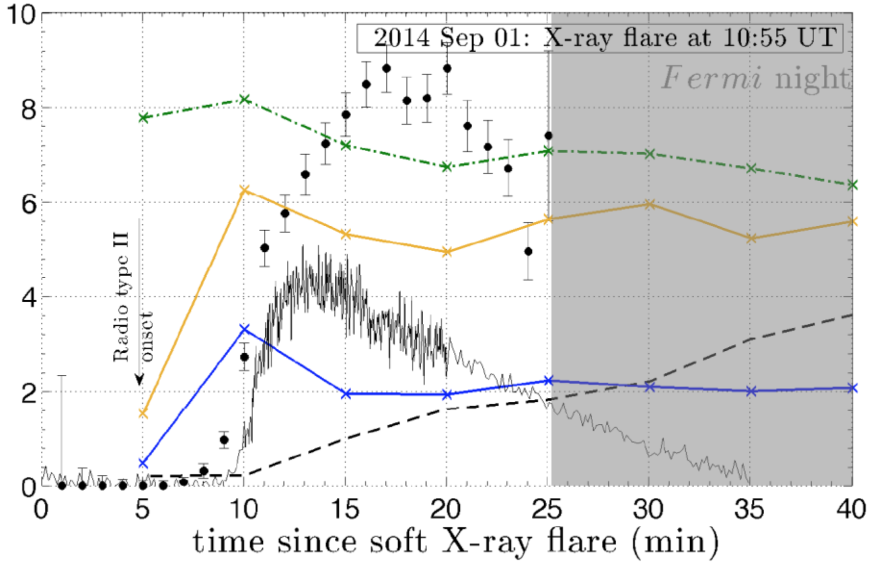
- Detailed spectroscopic studies of many LAT events: the number of >500 MeV protons producing SGRE was typically a factor 10 more than found in the accompanying impulsive flare
- Clear that another energy source is necessary to accelerate protons to energies >300 MeV to produce the pion-decay emission observed in the sustained emission
- Energetic considerations and the rise of sustained γ-ray emission following the impulsive phase suggests **the source of energy is the accompanying fast CME through its driven shock**
- The number of **>500 MeV SEP protons is ~100 times the number returning to the Sun to produce the sustained γ-ray emission**, Consistent with what shock wave models estimate (Kocharov et al. 2015)
- Results consistent with Plotnikov et al. 2017 study of the two behind-the-limb events (Ackermann et al. 2017) : a direct magnetic connection exists between the shock wave and the low solar atmosphere at the onset of the hard X-ray and γ-ray in both events.

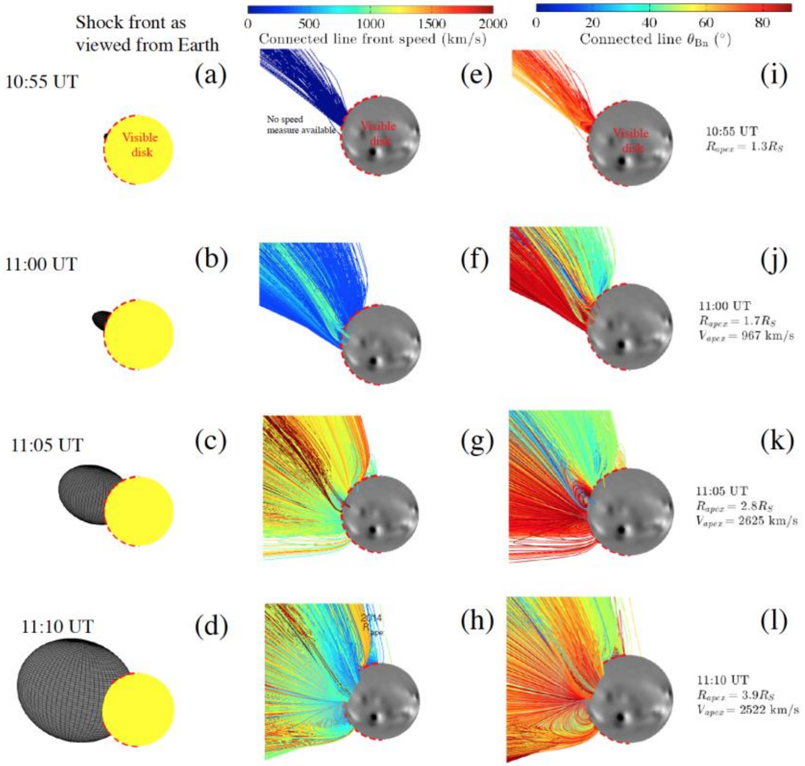


Gopalswamy 2006
adapted from Martens & Kuin 1989

Triangulation of shocks in 3-D: study of the onset of gamma-ray events

01 Sept 2014: Onset of gamma-rays and hard X-rays measured near Earth occurs when the quasi-perp shock connects magnetically with the solar surface visible from Earth.





Plotnikov, Rouillard, Share (2017)

Flare vs Shock Acceleration of high-energy protons in Solar Energetic Particle Events

This study was motivated by three recent papers by

- Dierckxsens et al. (2015)
- Grechnev et al. (2015)
- Trottet et al. (2015)

that provided correlative evidence for a role for a significant contributory, or dominant, flare-resident particle acceleration mechanism in the generation of high-energy protons in large SEP events.

Focused on the Grechnev et al. (2015) study that examined >100 MeV proton events.

E. W. Cliver (2016)

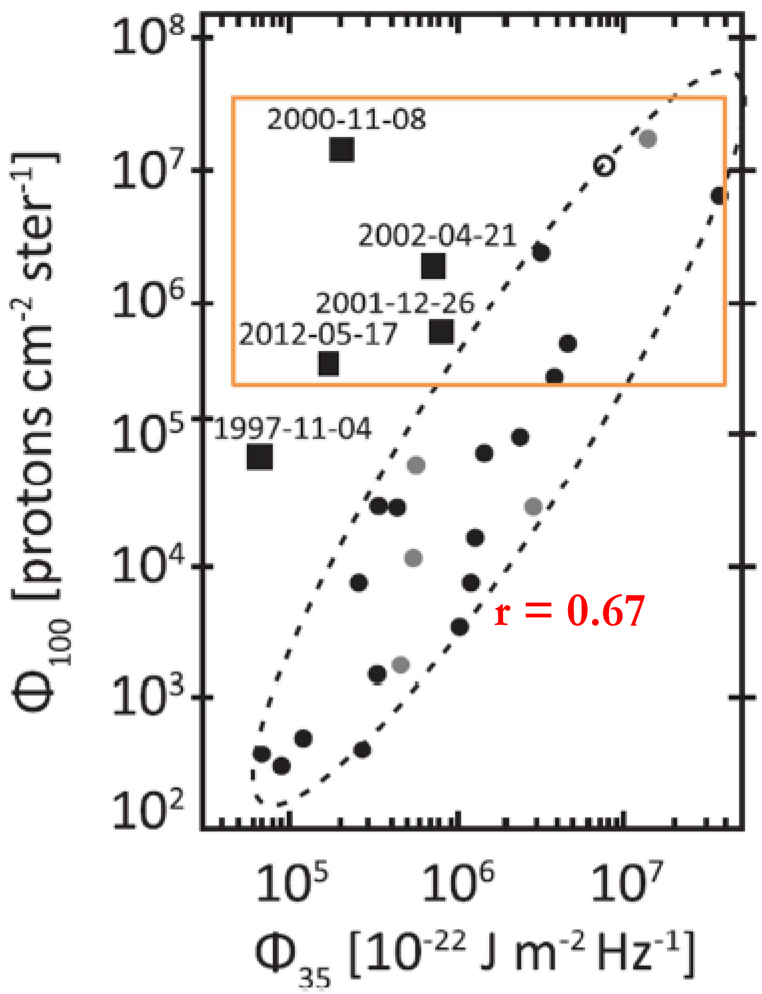


Figure 1. Scatterplot of longitude-corrected >100 MeV proton fluence (Φ_{100}) vs. 35 GHz fluence (Φ_{35}) for solar proton events from 1996 to 2014, adapted from Grechnev et al. (2015; black circles and squares (W21–W90); gray circles (E30–W20); open circles (<E30)). The orange rectangle isolates events with $\Phi_{100} > 2 \times 10^5$ pfu s.

Grechnev et al. (2015)

Grechnev et al. argued that the events indicated by black squares in the figure were events in which CME-driven shocks dominated acceleration of >100 MeV protons while a flare-resident acceleration process dominated the events depicted by circles.

Excluding the “squares” => r = 0.67

In the next slide we compare the CME properties of the square (outliers) and circle events (main sequence) in the orange rectangle.

Table 1

Comparison of Large Outlying and Main Sequence SEP Events with >100 MeV Proton Fluence >2 × 10^5 pfu s in Figure 6 of Grechnev et al. (2015)

Date	SXR Peak Time	SXR Class	SXR Duration	SXR Fluence	35 GHz Fluence	CME Speed	CME Width	>100 MeV Fluence	GLE?/ % Inc.	DH II?	0.5 MeV e- to 10 Mev pr Ratio
Outliers	UT		minutes	10^{-3} J m^{-2}	10^5 sfu s (a)	km s^{-1}	°	10^3 pfu s(b)			
2000 Nov 8	23:27	M7.9	201	66	2.1	1738	>170	13000	yes?/-	yes	4.69E+01
2001 Dec 26	5:36	M7.6	306	110	8.2	1446	>212	600	yes/5	yes	8.44E+01
2002 Apr 21	1:47	X1.6	179	280	7.2	2393	360	1500	no/-	yes	7.13E+01
2012 May 17	1:47	M5.1	141	31	1.7	1582	360	305	yes/16	yes	5.20E+01
Main Sequence											
2001 Apr 2	21:51	X18.4	59	930	38	2505	244	220	no/ -	yes	1.12E+02
2002 Aug 24	1:11	X3.5	83	178	46	1913	360	400	yes/5	yes	1.62E+02
2005 Jan 20	7:00	X7.9	93	500	370	2800	360	6400	yes/269	yes	1.64E+02
2006 Dec 13	2:39	X3.7	82	310	32	1774	360	1900	yes/92	yes	1.78E+02

The main sequence events, attributed to flare-resident SEP acceleration, have slightly faster/wider **CMEs** than the outliers. Both groups of events have associated **DH type II radio bursts** and comparable **>100 MeV proton fluences**.

As noted by Grechnev et al., including the outliers in Figure 1 => r = 0.09.

Summary *Cliver, ApJ, 2016*

(1) The correlation between flare electromagnetic emissions and associated >100 MeV proton events is poor because of a class of large proton events with relatively weak flare emissions (e.g. FE/SEP events – Gopalswamy et al. 2015)

(2) Classic flare-associated impulsive events are poor producers of >100 MeV protons

(3) The existence of >100 MeV proton events associated with weak flares that have fast CMEs and associated DH type II bursts argues that shock acceleration dominates high-energy proton acceleration in solar flares (e.g., Cliver, 1983, 1989)

Correlation of Fe/O ratios with the event duration

✓ An improved ion ratio calculation was carried out by rebinning the ion intensity into the form of equal bin widths in the logarithmic energy scale

✓ Because of the similarity of mass-to-charge (A/Q) ratios between Ne and O ions, we see no substantial time variation of Ne/O ratios $\Rightarrow$ the Ne/O measurement is more accurate and the explanation of Ne/O observations is more straightforward

✓ In particular, we observe a good correlation of the high-energy Ne/O ratio with the source plasma temperature T recently reported by Reames (2016). Therefore the $(Ne/O)_n$ value at high energies should be a proxy of the injection energy in the shock acceleration process, and hence the shock θ_{Bn} according to the models of Tylka & Lee (2006) and Schwadron et al. (2015)

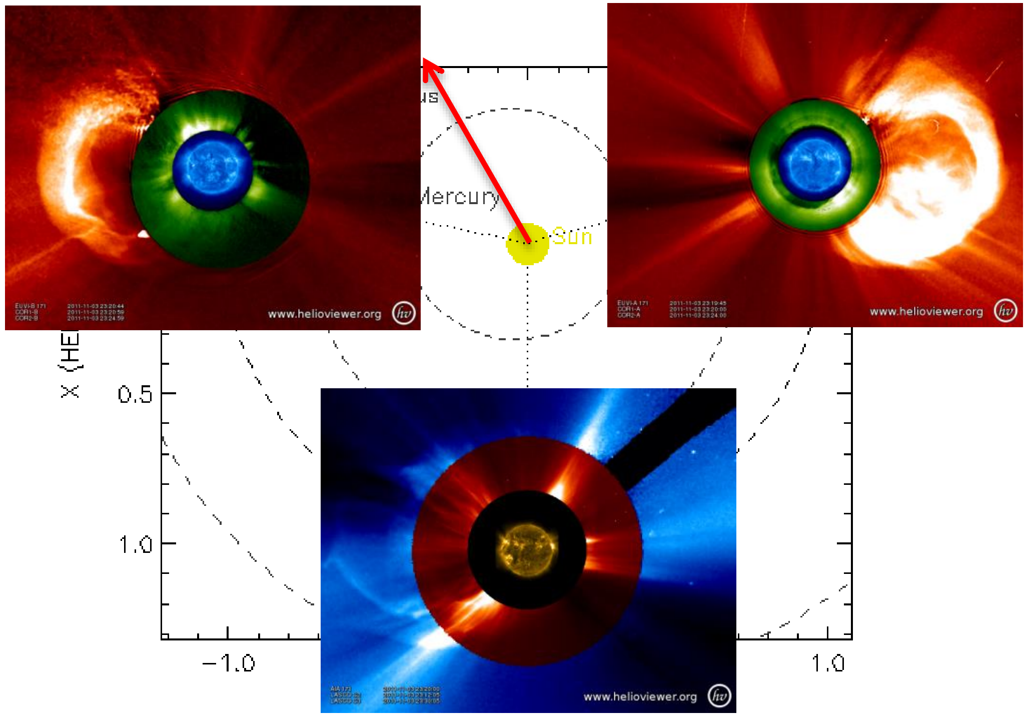
✓ We clarify the explanation on the correlation of Fe/O ratios with the event duration at higher energies. We find that the apparent correlation between $(Fe/O)_n$ and the event duration is caused by a large difference of average $(Fe/O)_n$ values between the Fe-poor and Fe-rich event groups

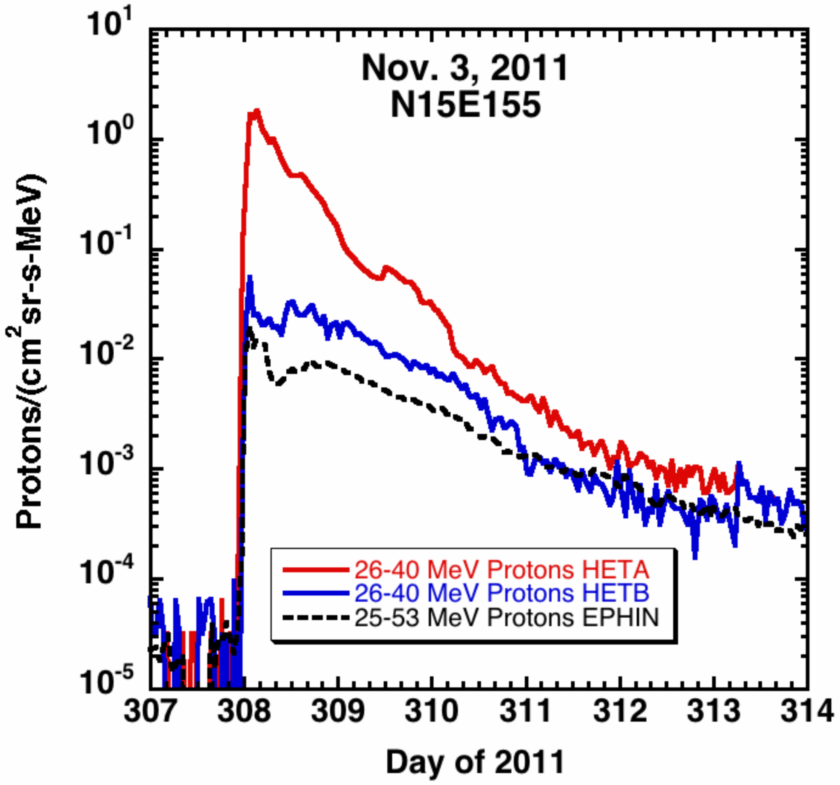
Tan, Malandraki, Shao, ApJ, 2017

What Governs the Longitudinal Spread of Solar Energetic Particles?

Motivation

- Surprises in longitude distribution observations
  - Fast rise times at wide separations





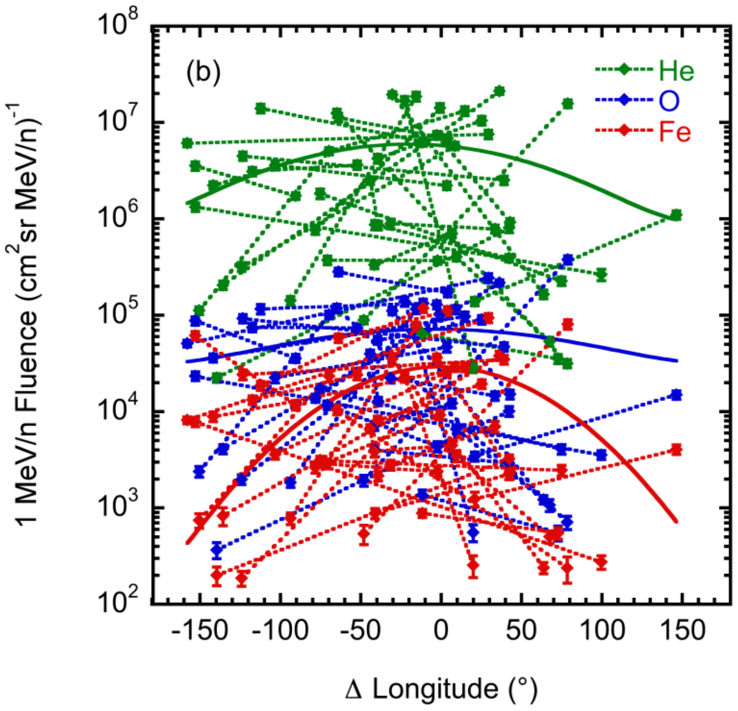
C.M.S. Cohen, G.M. Mason, R.A. Mewaldt

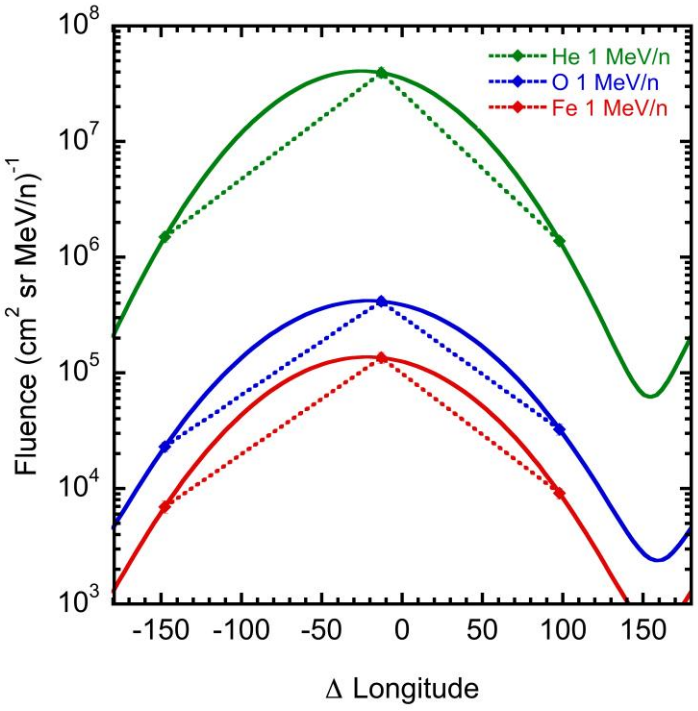
Current Study: Heavy Ions

- Selected events - 41
  - 2 or 3 spacecraft had ≥10 MeV/n O increases
- Determined source regions
- Used Predictive Science models for footpoints
  - Based on measured solar wind Parker spiral to 30 Rs
  - Extrapolation of measured photospheric B field
- Examining
  - Q/M dependence (H, He, O, Fe)
  - E dependence (0.3, 1, 10 MeV/n)

CURRENT STUDY: HEAVY IONS

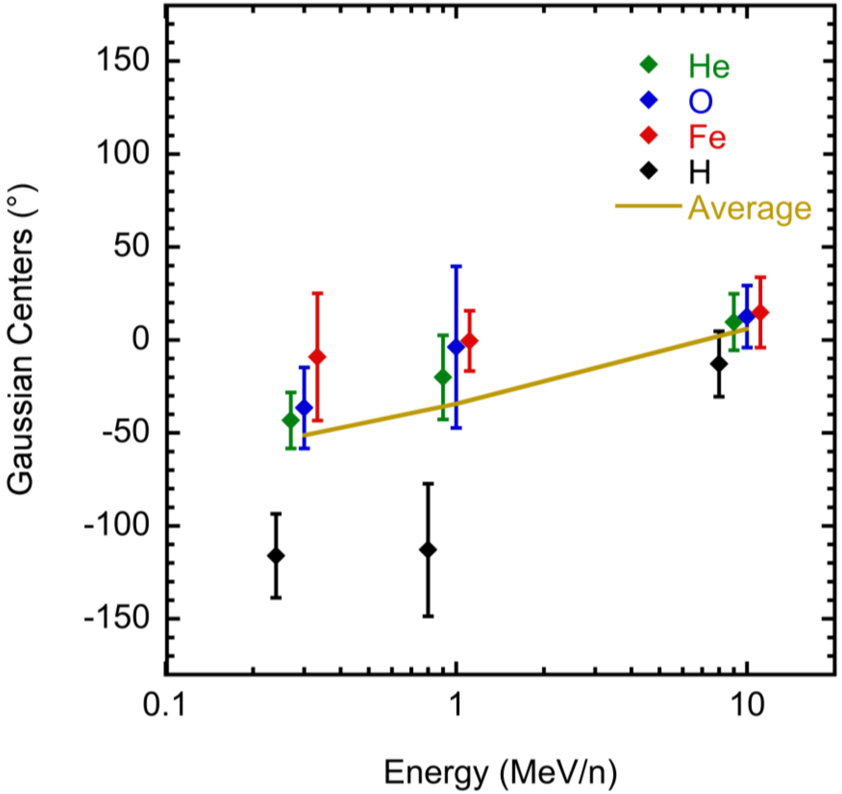
- Fits
  - 2-spacecraft events are fit in ‘aggregate’ with periodic Gaussian
  - – 3-spacecraft events are used to calculate corresponding Gaussian

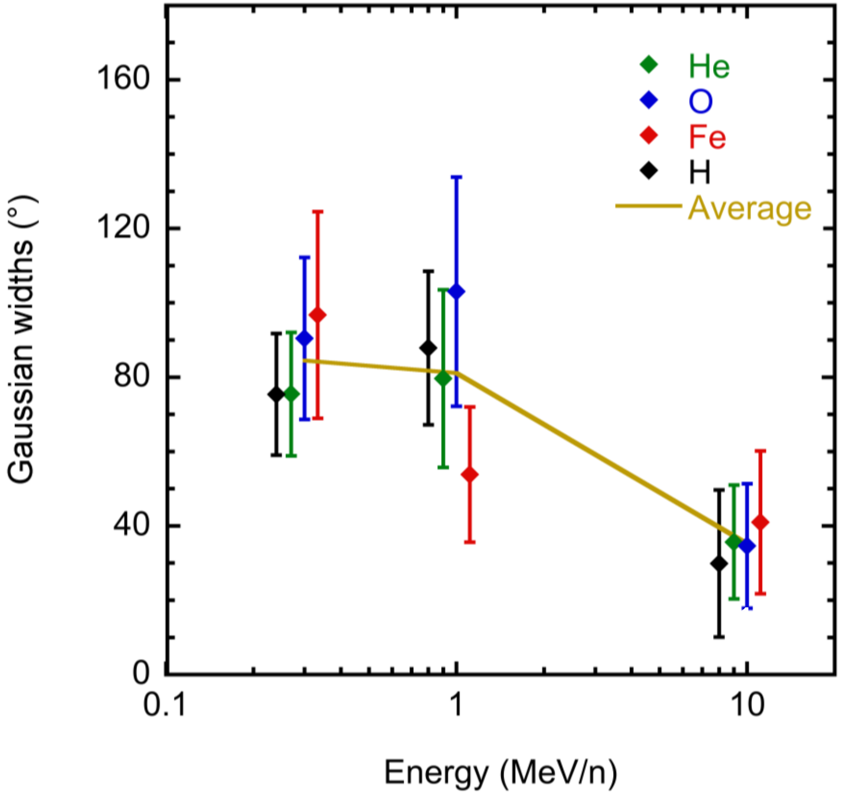




2-Spacecraft Results

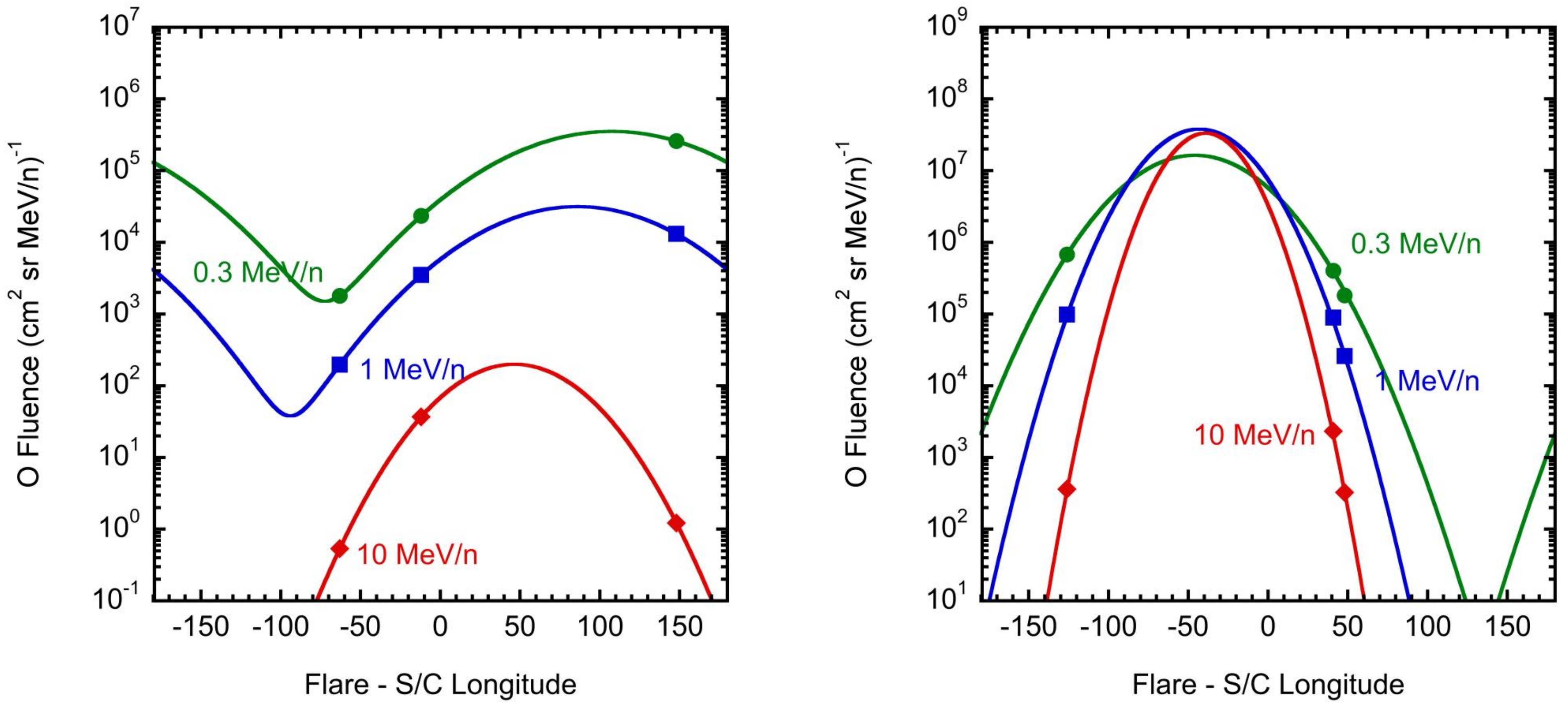
- No clear Q/M dependence
- Centers move towards flare with increasing E
- Sigmas decrease with increasing E





3-Spacecraft Results

- Significant variability



Interpretations

- No strong Q/M dependence
  - Rigidity-related processes probably not dominant
- Wider distributions for lower energy ions
  - Speed related
    - Slower ions will experience more field line co-rotation
  - Energy-related
    - Lower energy ions are accelerated over distances farther from Sun and CME-shock will have more lateral expansion
    - Lower energy ions are accelerated over greater longitude extent of shock
- No support for direct flare contribution scenario

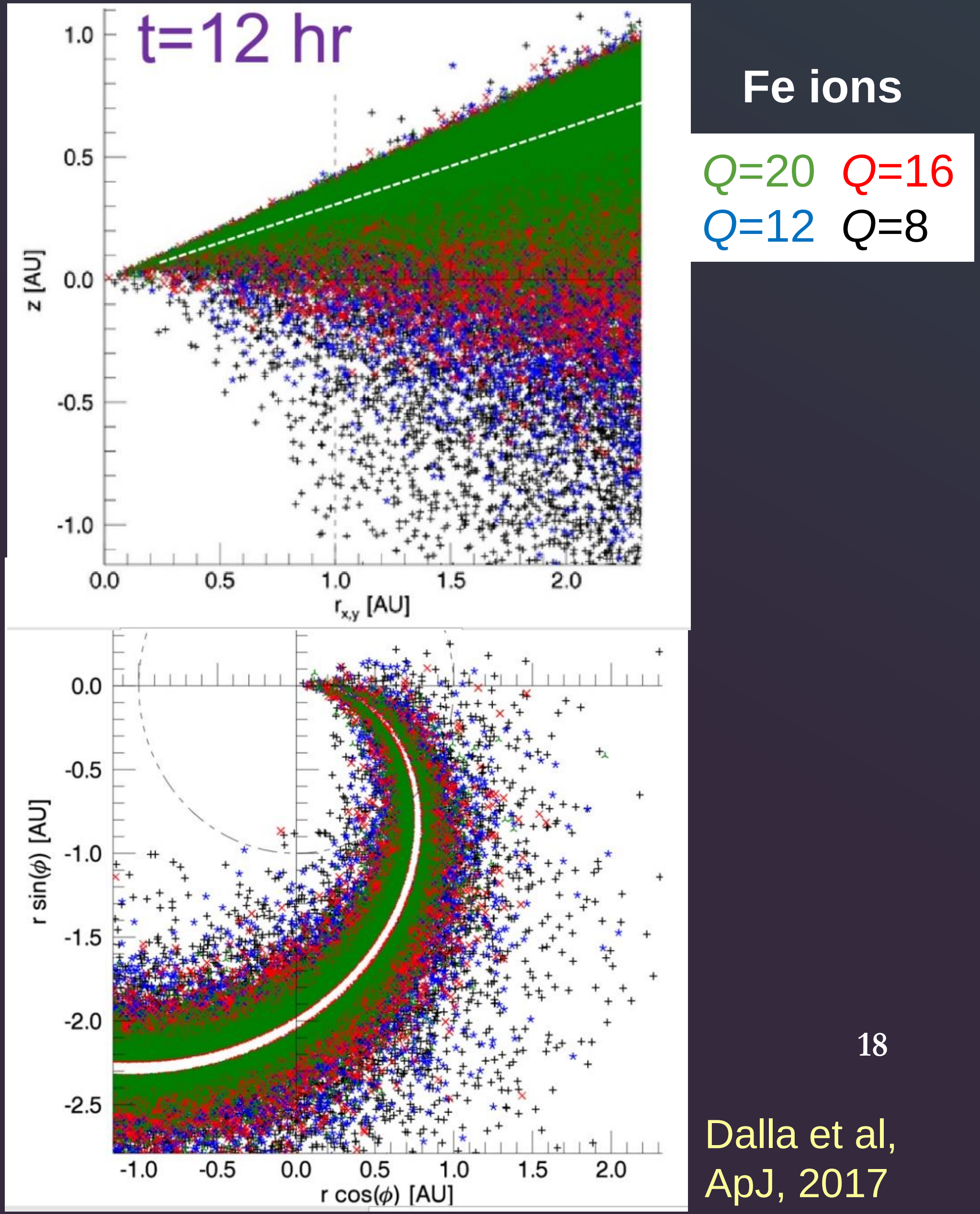
Cohen, Mason, Mewaldt, ApJ, 2017

3D Modelling of Solar Energetic Particle Propagation within the heliosphere

1. Modelling SEPs with 3D test particle model

- Integrate test particle trajectories in heliospheric magnetic and electric fields
- Heavy ion modelling shows that ions do not remain confined within injection flux tube (in white in plots)
- Perpendicular transport seen in plots is due to drifts due to curvature and gradient of Parker spiral (Dalla et al 2013, Marsh et al 2013)

S. Dalla, M. Battarbee, T. Laitinen



Dalla et al, ApJ, 2017

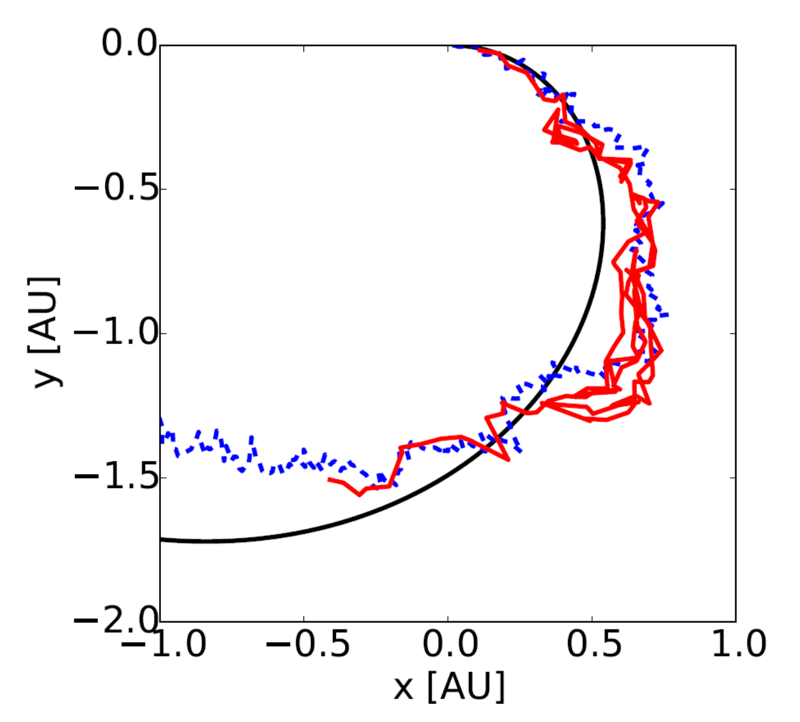
2. Modeling effect of field line meandering on SEPs

- Turbulence produces meandering in the magnetic field lines, and this contributes to particle transport across the mean field

- New model based on focussed transport eqn coupled with field line meandering

$$\frac{\partial f}{\partial t} + (\mu v \boldsymbol{b} + \boldsymbol{V}_{\rm sw}) \cdot \nabla f + \frac{v}{2L}(1-\mu^2)\frac{\partial f}{\partial \mu}$$
$$+ \left[\frac{\mu(1-\mu^2)}{2}(\nabla \cdot \boldsymbol{V}_{\rm sw} - 3\boldsymbol{bb} : \nabla \boldsymbol{V}_{\rm sw})\right]\frac{\partial f}{\partial \mu}$$
$$= \frac{\partial}{\partial \mu}\left(D_{\mu\mu}\frac{\partial f}{\partial \mu}\right) + \nabla \cdot \hat{\kappa}\nabla f + Q(\boldsymbol{r}, \boldsymbol{v}, t),$$

$$\mathrm{d}r_{\perp}(r_{\|}) = \sqrt{2D_{\rm FL}(r_{\|})\mathrm{d}r_{\|}}W_{\perp},$$



Laitinen et al, 2016

- New model is compared with standard approaches that do not include field line meandering

- VIDEO

Summary

- Our simulations show that due to gradient and curvature drifts, and to magnetic field line meandering, a 3D description is needed for SEP propagation

- 3D drift-associated propagation qualitatively reproduces two key heavy ion observations: energy dependence of <Q> and time dependence of Fe/O ratio

- Field line meandering allows particles to reach a much wider range of longitudes than predicted by traditional models

High Energy Solar Particle Events Forecasting

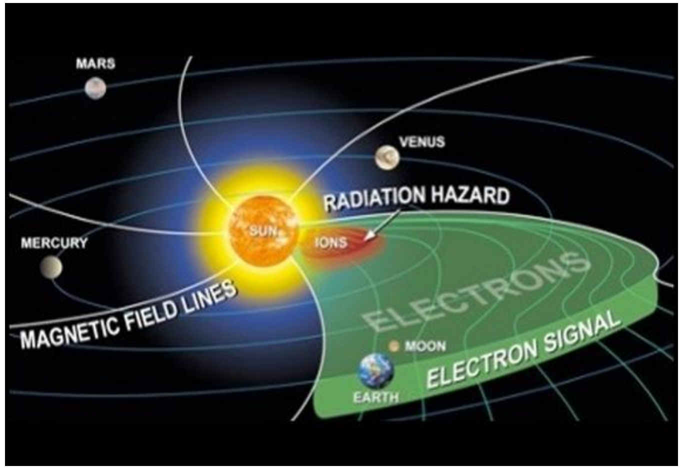
HESPERIA REleASE and HESPERIA UMASEP-500 tools

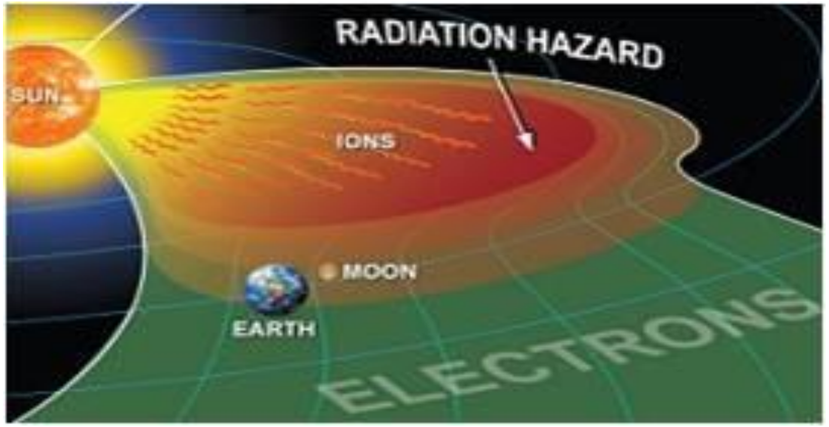
O. Malandraki, M. Nunez, B. Heber, J. Labrenz, N. Milas, E. Pavlos

Activity of the Balkan, Black Sea and Caspian Sea Regional Network on Space Weather Studies (BBC SWS)
http://www.bbc-spaceweather.org/
Chair of Steering Committee: Dr. Olga Malandraki, Greece

HESPERIA REleASE

Predicting 30-50 MeV SEP events by using the Relativistic Electron Alert System for Exploration (REleASE) scheme





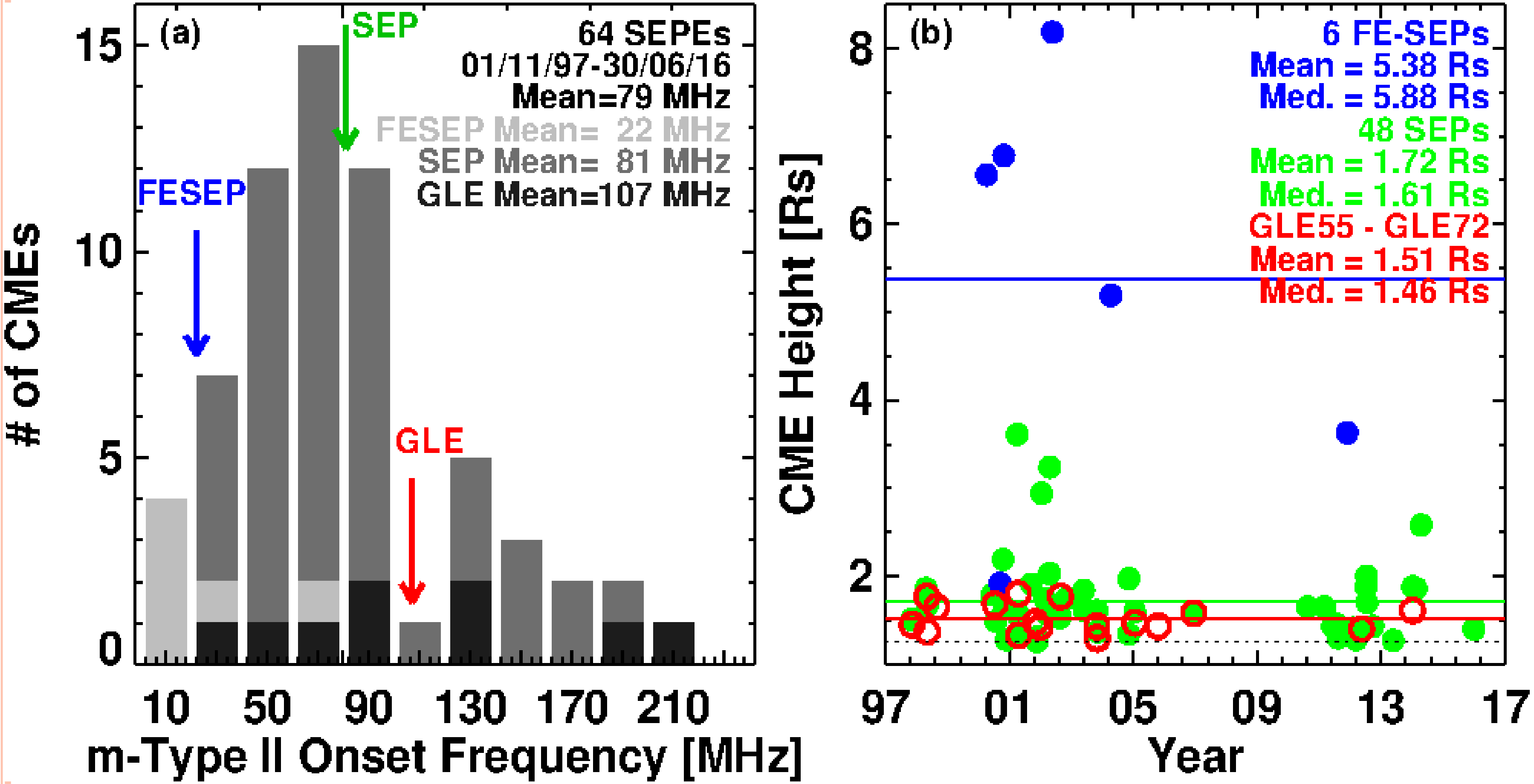
- This tool has been implemented and evaluated a real-time SEP predictor by using the REleASE scheme (Posner, 2007)
- The implemented model infers the maximum proton intensity and onset at 30-50 MeV based on near relativistic and relativistic electron intensity time profiles measured by SOHO/EPHIN and **ACE/EPAM**
- The tool provides advanced nowcasting/forecasting methods
- Validation: POD, FAR, and average warning time.

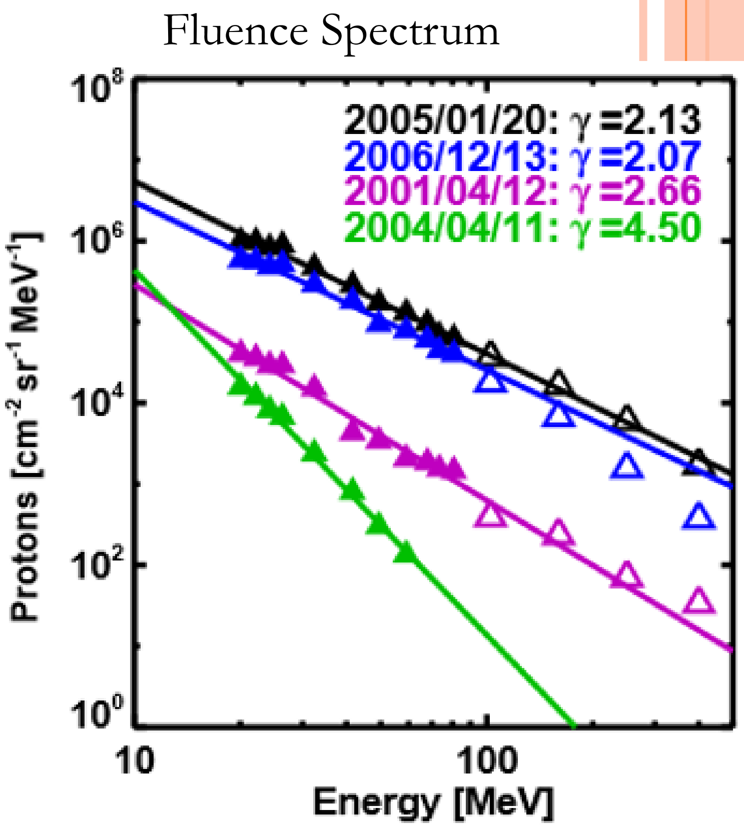
HESPERIA UMASEP-500

CONCLUSIONS

- UMASEP-500 is the only tool that issues warnings **before** NM alerts.
- The main goal of this research has been to provide **valuable added minutes of forewarning** to the users of the service, compared with the current GLE warning systems.
- We found that:
  - the use of neutron data provoked the generation of many false alarms due some quality data problems (mainly spikes) caused by technical issues, such as problems in the neutron sensor tubes and power supplies, among others.
- We consider that the UMASEP-500 and the GLE Alert Plus systems are complementary tools for space weather users to be warned before and during GLE events.

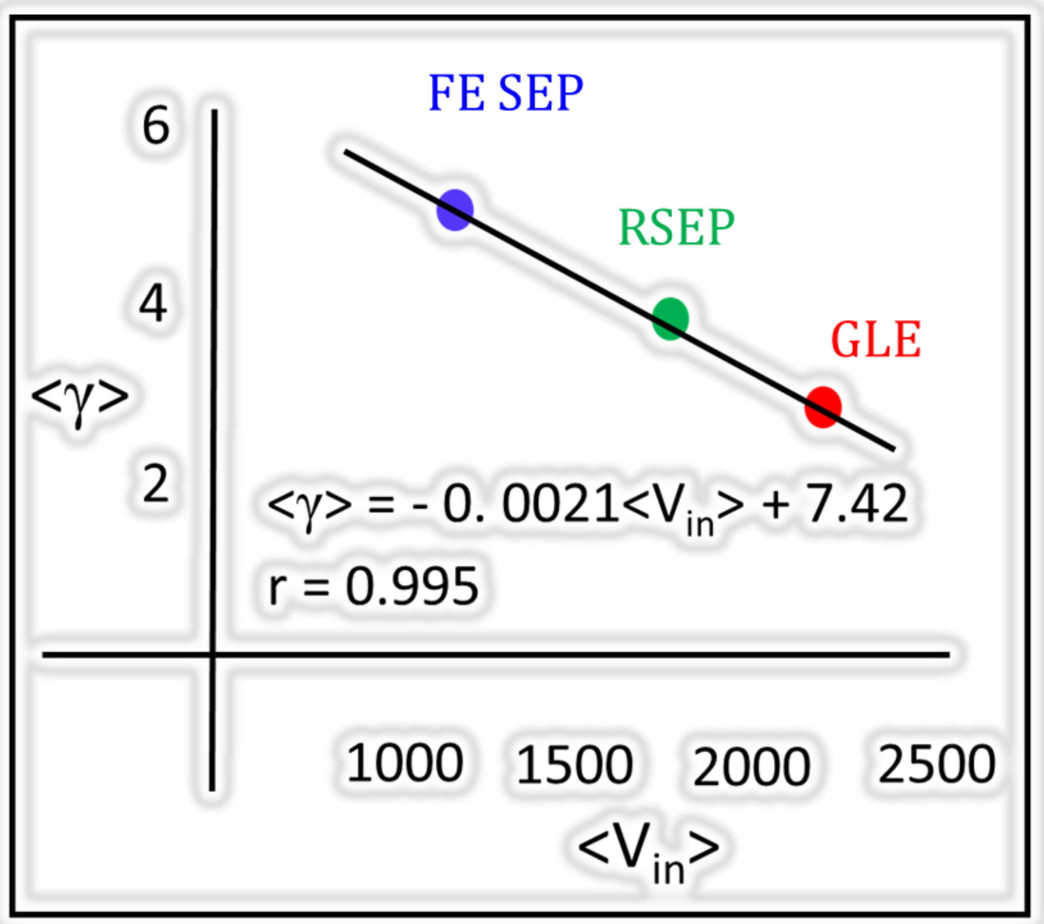
It Matters Where the Shocks Form





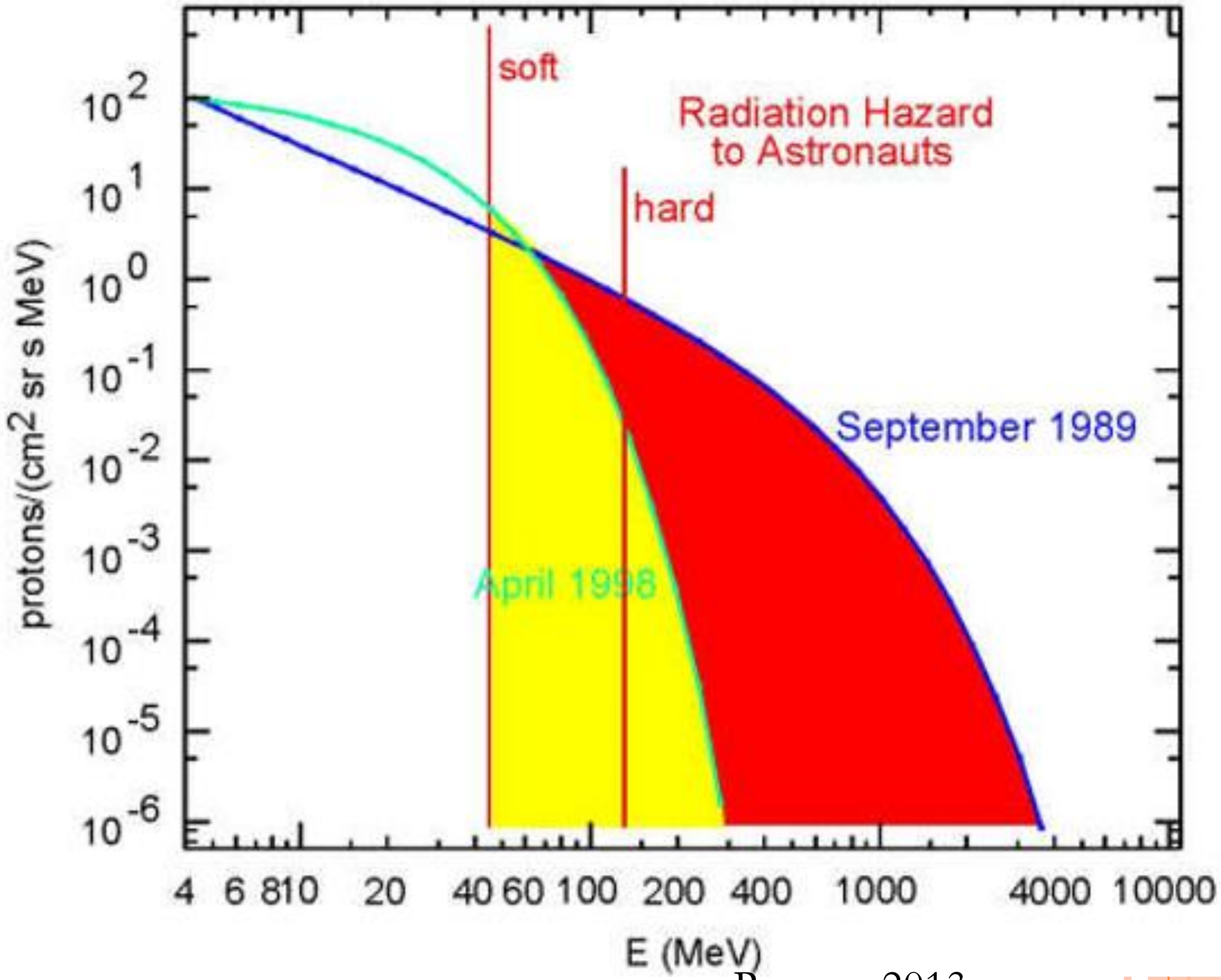
Gopalswamy et al. 2016, 2017

Hard Spectrum Events are more hazardous



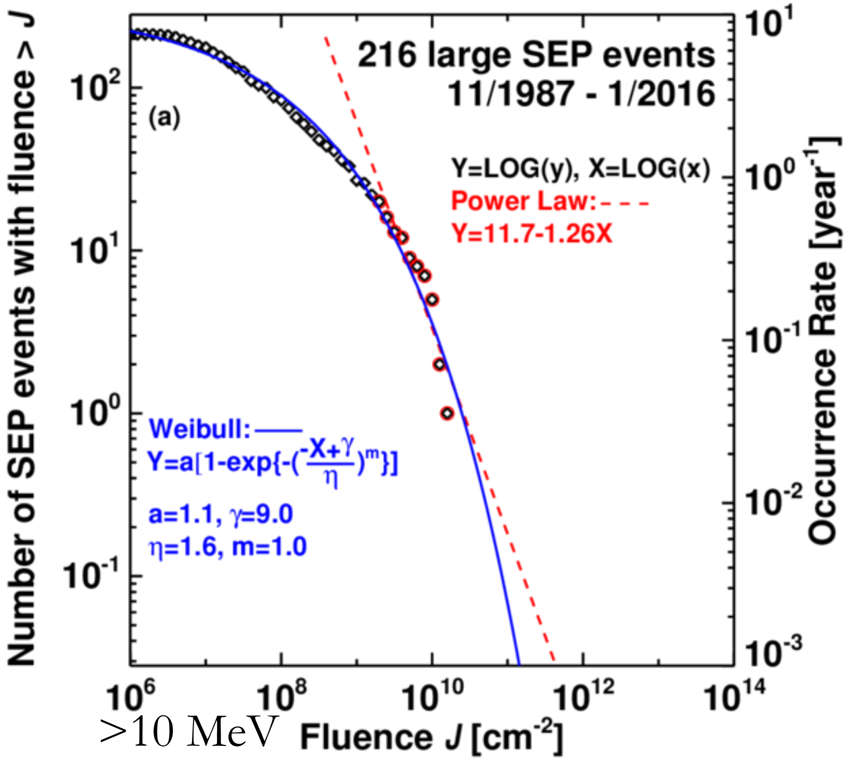
CME Kinematics determines the spectral shape

Gopalswamy et al. 2016

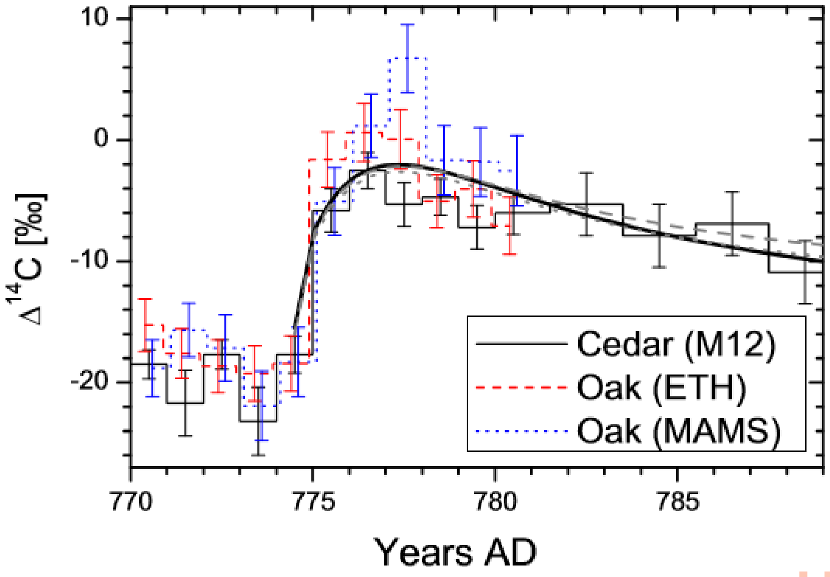


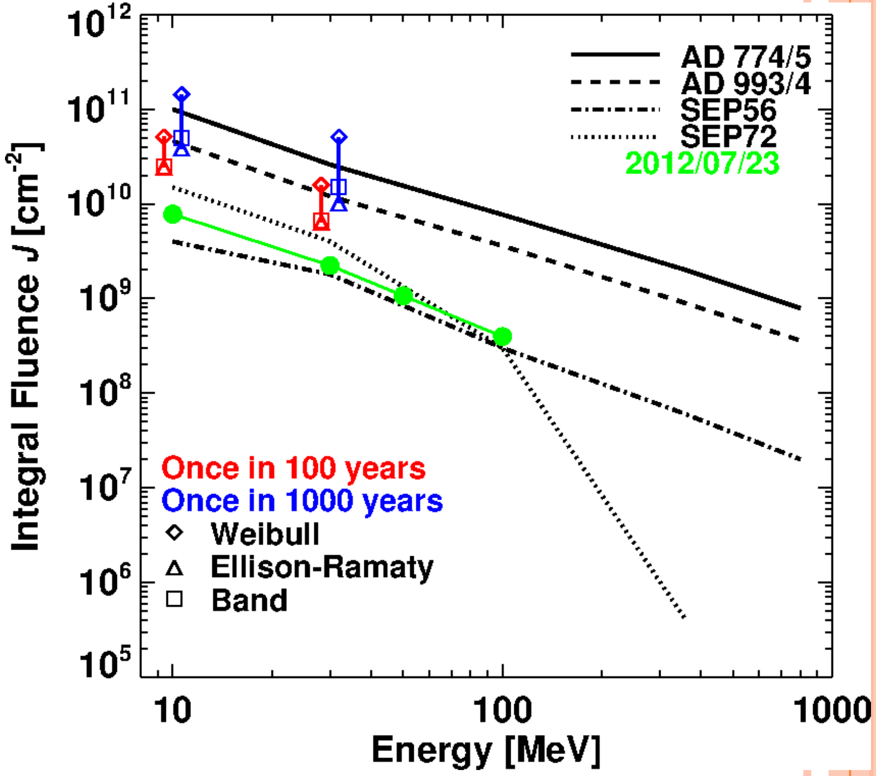
Reames 2013

EXTREME SEP EVENTS



Usoskin et al. 2013

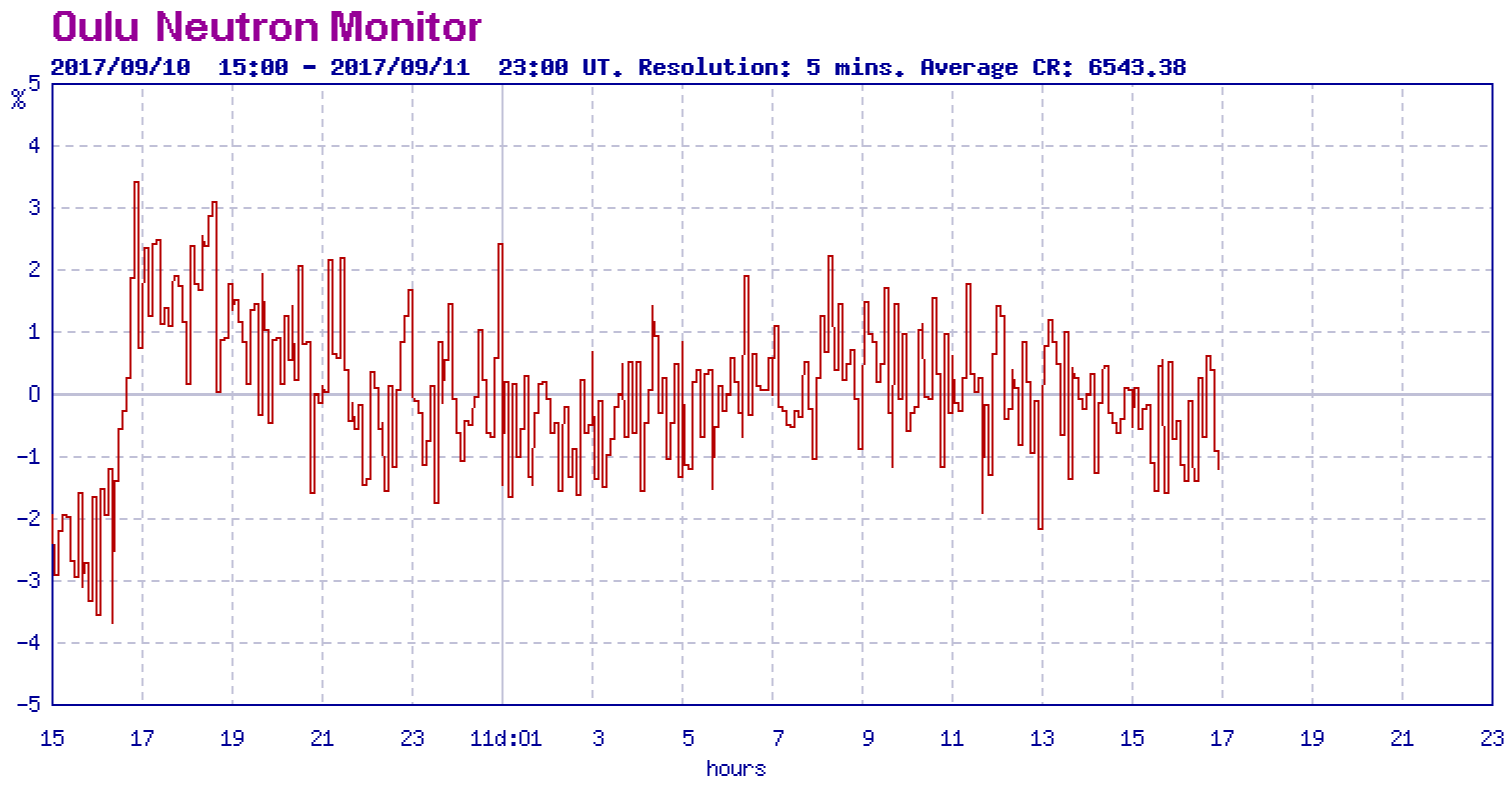




Miyake et al. 2012; Mekhaldi et al. 2015; ; Usoskin 2017; Gopalswamy 2017

20170910 GLE Event

Oulu NM Data showing the GLE on 20170910



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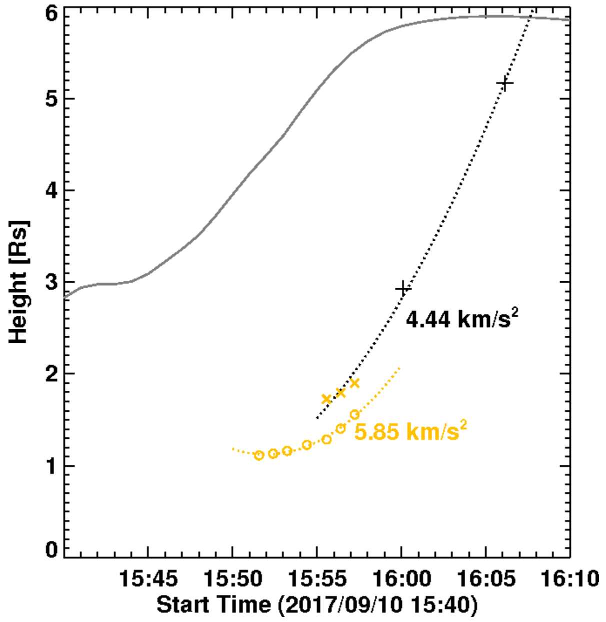
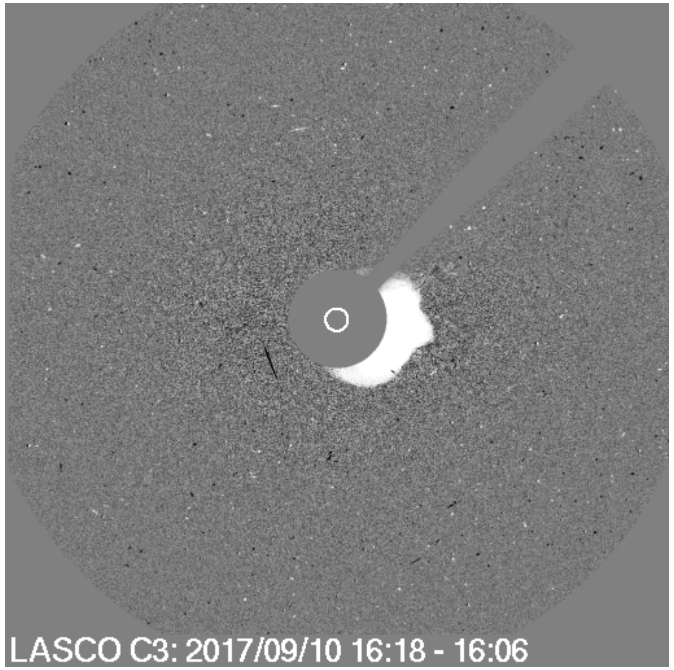
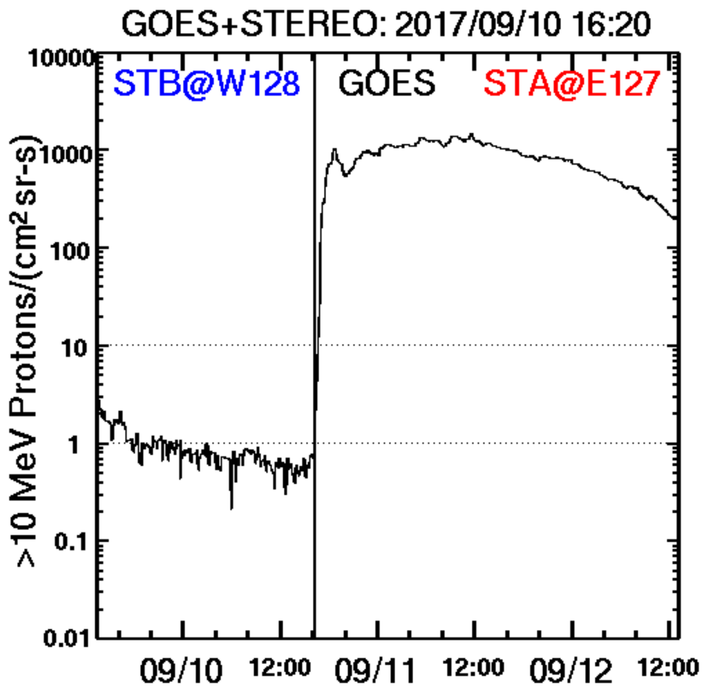
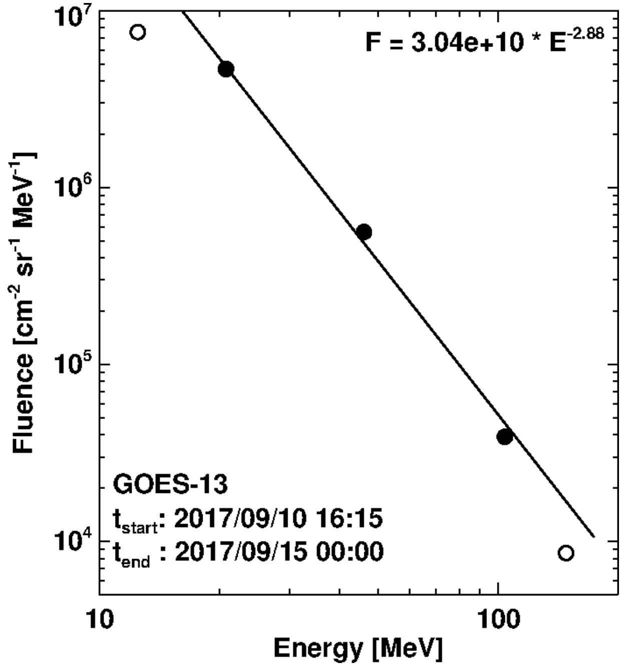
LARGE SEP EVENT WITH I_P >1000 PFU

<V> >3500 km/s
Vin ~ 4000 km/s
Ain ~ 4-5 kms^{-2}
Hard spectrum consistent with GLE event

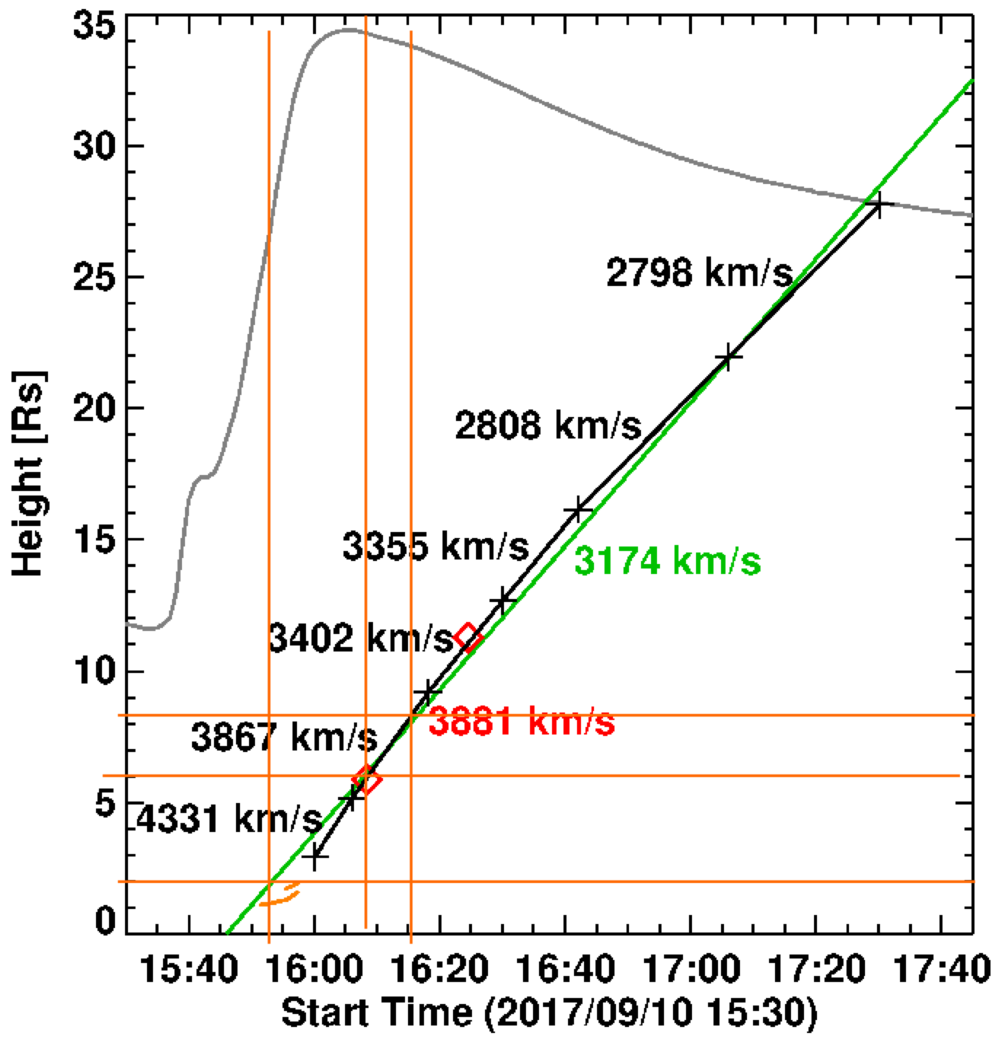








TYPE II BURST AT METRIC WAVELENGTHS

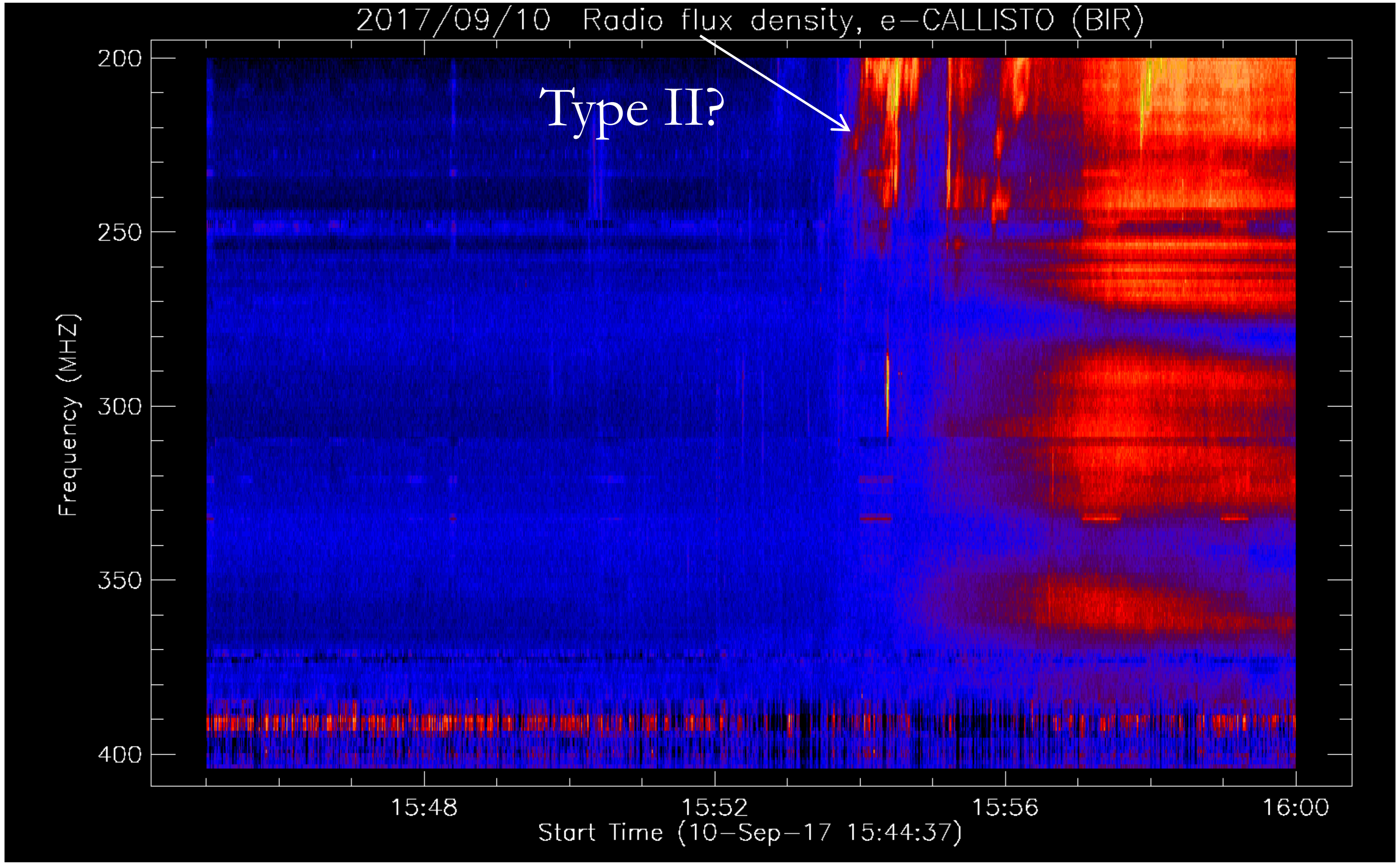


Type II is poorly defined.
Possible type II (225 MHz) at 15:53 UT CME height <2 Rs

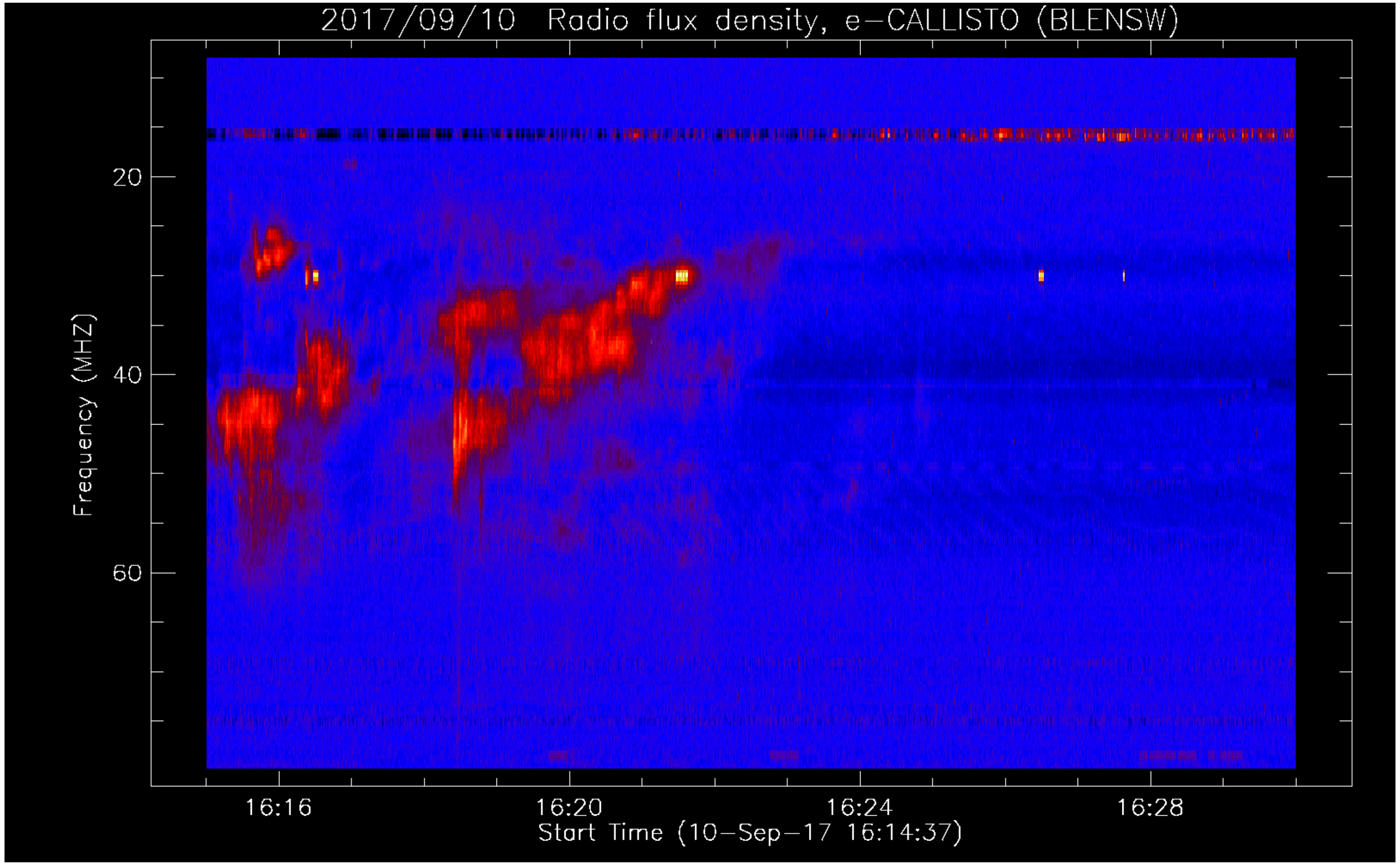
16:08 UT (43 MHz) CME height 6 Rs (NOAA)

16:15 UT (60 MHz H?) CME height 8 Rs

CALLISTO DATA TYPE II BURST @ 225 MHZ 15:53:30?



DEFINITELY TYPE II AT LOWER FREQUENCIES



SUMMARY

- Only nuggets presented
- Need to do a better survey of the literature
- Need to prepare a set of outstanding questions
- Need to provide guidance to immediate problems to address