Characteristics of 29 Sustained >100 MeV γ-Ray Events Associated with Solar Eruptive Events

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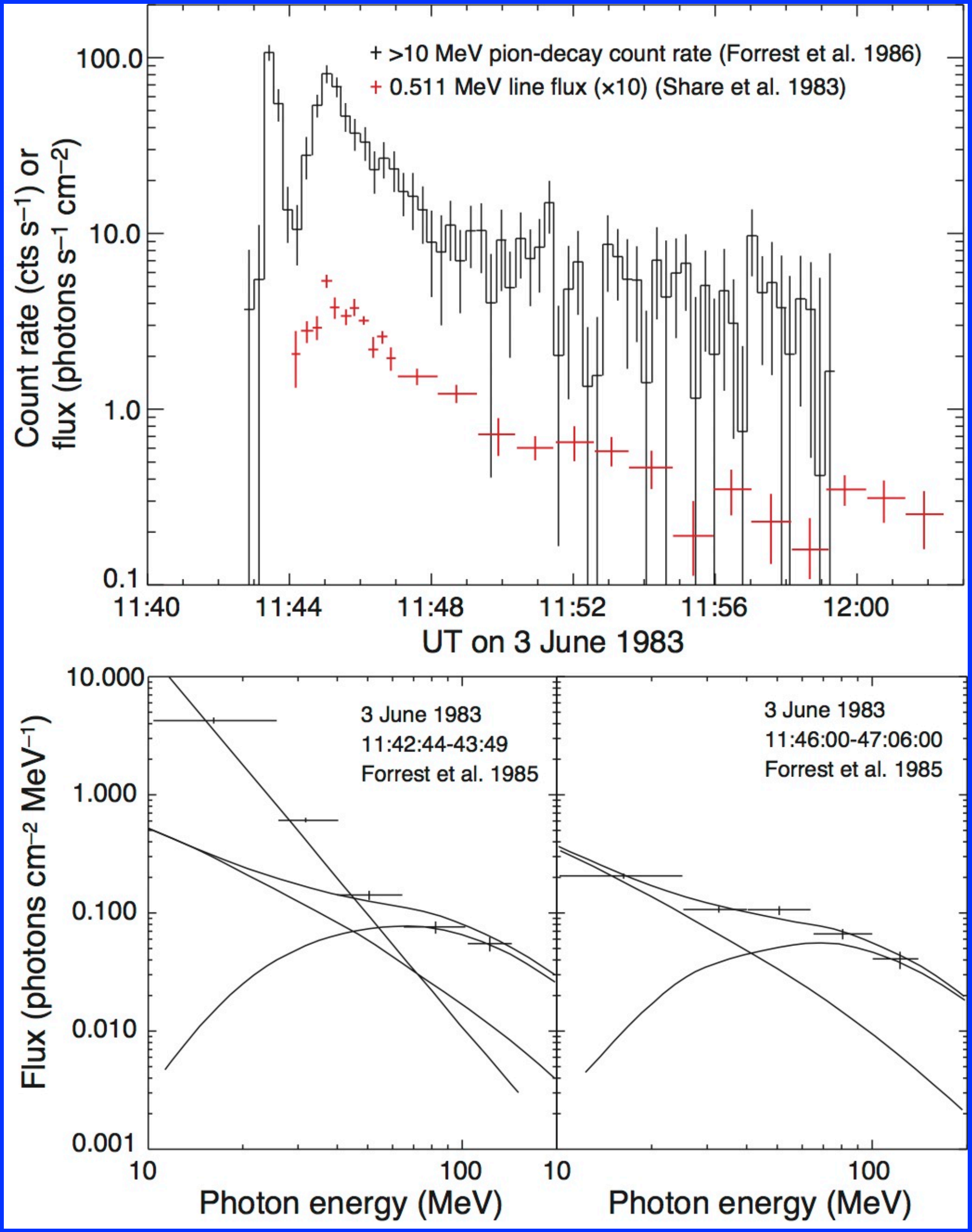
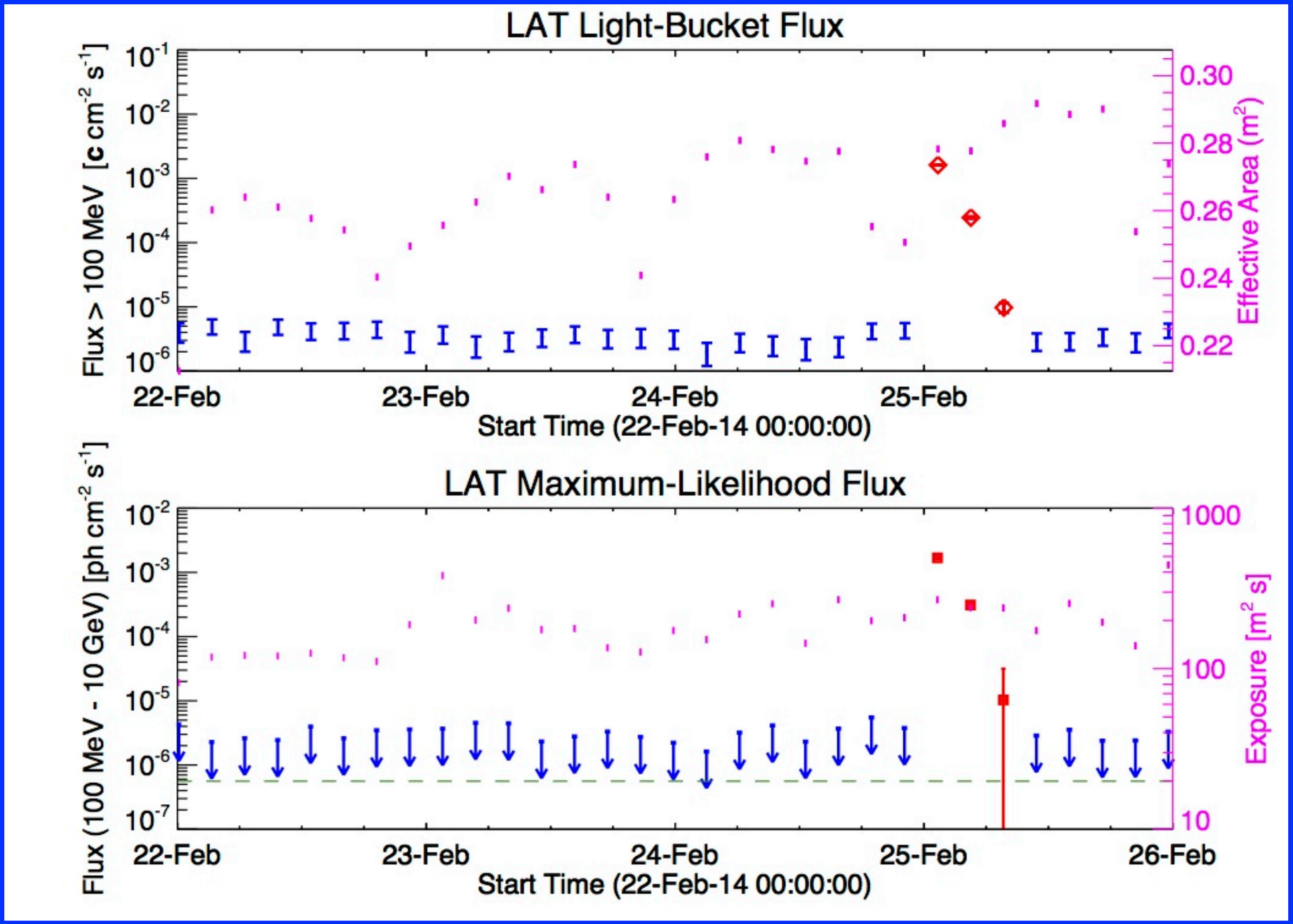
Observations of sustained >100 MeV gamma-rays appear to provide measurements of shock-accelerated >300 MeV protons at the Sun associated with high-energy SEPs

We use the term 'sustained' emission to characterize time-extended >100 MeV γ-ray emission that is distinct from the impulsive emission, as represented by the time profile of non-thermal hard X-rays. The 1982 June 3 flare observed by the *SMM* GRS was first to exhibit the classic time profile for such high-energy emission. In that flare >10 MeV γ rays were observed both in the impulsive flare and in a much harder delayed and temporally distinct stage. This latter emission has also been called Long Duration Gamma Ray Flares discussed by Ryan (2000).





4-day plots of >100 MeV solar gamma-ray fluxes covering the whole Mission are on the RHESSI Browser. Our light-bucket plots (top panel). These data can be analyzed using standard analysis tools operating under SSW/OSPEX. LAT team Maximum Likelihood plots (bottom panel).

Twenty-nine sustained emission >100 MeV γ-ray events were identified in our study from 2008-2016.

Paper about to be submitted detailing the study and cataloging the events.

Where measurements available all events associated with >100 keV flare X-rays. All but two are associated with fast CMEs.

Table 1. LAT Sustained >100 MeV Emission 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}, Width (deg) (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]	10–25[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	2012/01/23, N33W21	M8.7, 03:38–04:34	2175	N, Y	3280, >100	100–300[d,e]
9	2012/01/27, N35W81	X1.7, 17:37–18:56	2508	3, Y	518, >100	100–300[d,e]
10	2012/03/05, N16E54	X1.1, 02:30–04:43	1531	N, Y	<33, >13[b,f]	100–300[d,e]
11	2012/03/07, N17E27	X5.4, 00:02–00:40	2684	2?, Y	1800, >100	>1000[g]
		X1.3, 01:05–01:23	1825	2?, Y	1800, >100	>1000[g]
12	2012/03/09, N16W02	M6.3, 03:22–04:18	950	2, Y	<528, >10[f]	100–300
13	2012/03/10, N18W26	M8.4, 17:15–18:30	1296	N, Y	<115, >10[f]	100–300[d]
14	2012/05/17, N05W77	M5.1, 01:25–02:14	1582	3, Y	180, >100	100–300[c]
15	2012/06/03, N15E38	M3.3, 17:48–17:57	605, 892[b,h]	2, N	0.6, >60[b]	300–800
16	2012/07/06, S17W52	X1.1, 23:01–23:14	1828	3, Y	19.1, >100	100–300[e]
17	2012/10/23, S15E57	X1.8, 03:13–03:21	–	N, N	<0.1, >13[b]	>9000
18	2012/11/27, N05W73	M1.6, 15:52–16:03	–	N, N	<0.1, >10	300–1000
19	2013/04/11, N07E13	M6.5, 06:55–07:29	861	3, Y	184, >60[b]	100–300[d]
20	2013/05/13, N11E89	X1.7, 01:53–02:32	1270	1, Y	9.3, >60[b]	100–300
21	2013/05/13, N10E80	X2.8, 15:48–16:16	1850	2, Y	176, >60[b]	>1000
22	2013/05/14, N10E77	X3.2, 00:00–01:20	2625	1, Y	306, >60[b]	300–1000[d]
23	2013/05/15, N11E65	X1.2, 01:25–01:58	1366	1, Y	<17, >13[b,f]	300–1000
24	2013/10/11, N21E106	M4.9[i], 07:01–07:45	1182	2, Y	156, >60[b]	–[j]
25	2013/10/25, S08E71	X1.7, 07:53–08:09	587	2, Y	32.6, >60[b]	800–7000[c]
26	2013/10/28, S14E28	M4.4, 15:07–15:21	812	2, Y	5.6, >13[b]	100–300[c]
27	2014/02/25, N00E78	X4.9, 00:39–01:03	2147	3,Y	219[b], >700	1000–10000
28	2014/09/01, N14E126	X2.1[i], 10:58–11:34	1901	–,Y	~1000, >13	–[j]
29	2015/06/21, N13E16	M2.6, 02:03–03:15	1434	2?,Y	~40, >10	100-300[d]

[a] *STEREO A*

[b] *STEREO B*

[c] *RHESSI*

[d] *Fermi*/GBM

[e] Missing Data

[f] Preceding SEP

[g] *INTEGRAL*

[h] CACTUS

[i] Pesce-Rollins et al. (2015b)

[j] flare behind solar limb

* 1, 2, 3 ≃ <50, 50–500, >500 $\times 10^{-22}$ W m^{-2} Hz^{-1}

** from neutron-capture line flux assuming accelerated protons follow a power law with index –4.5 >40 MeV

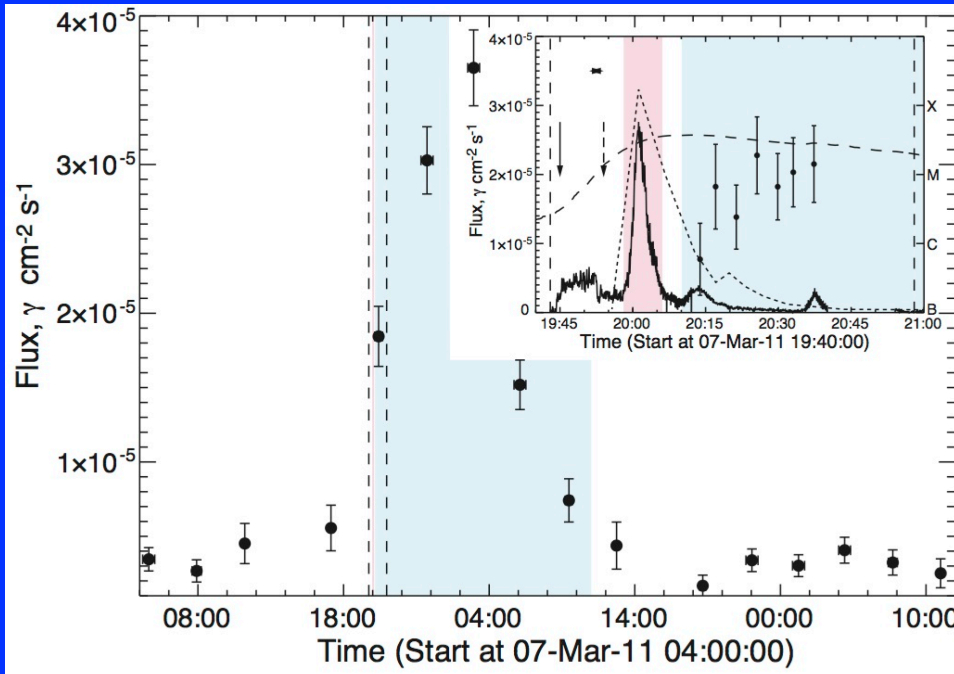
Table 3. Characteristics of Events with HXR Emission <100 keV and >100 keV

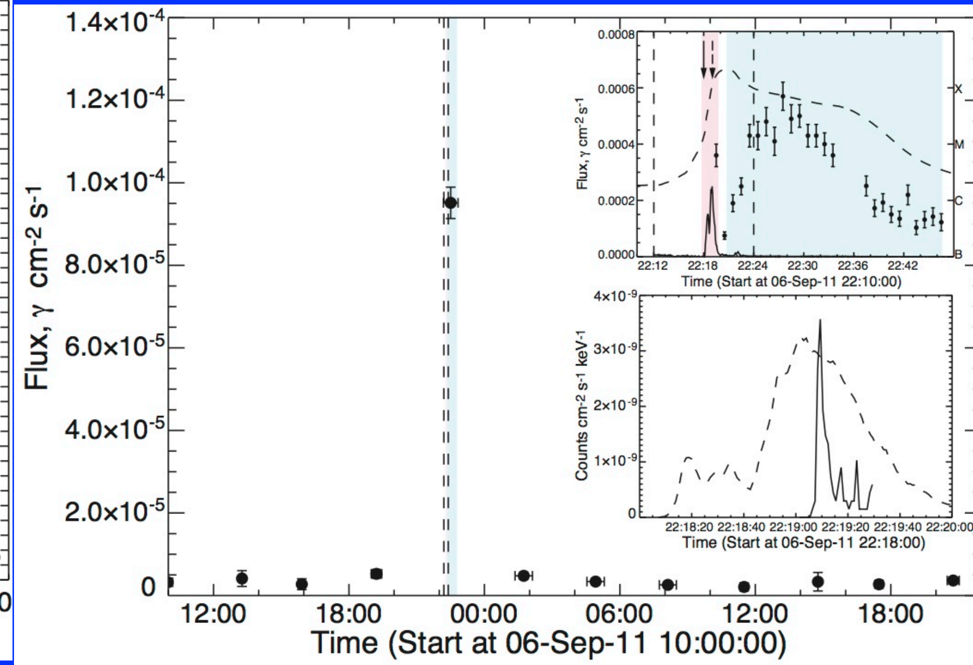
HXR Energy	<100 keV	>100 keV
Number	15	17
Number with sustained >100 MeV	0	12
Mean *GOES* Class	M1.2	X1.5
Mean CME speed, km s^{-1}	1027	1620
Number With Type II radio	4	13
Mean/Median SEP proton flux, pfu	11/ 5[a]	525/75[b]

[a] 6 measured fluxes

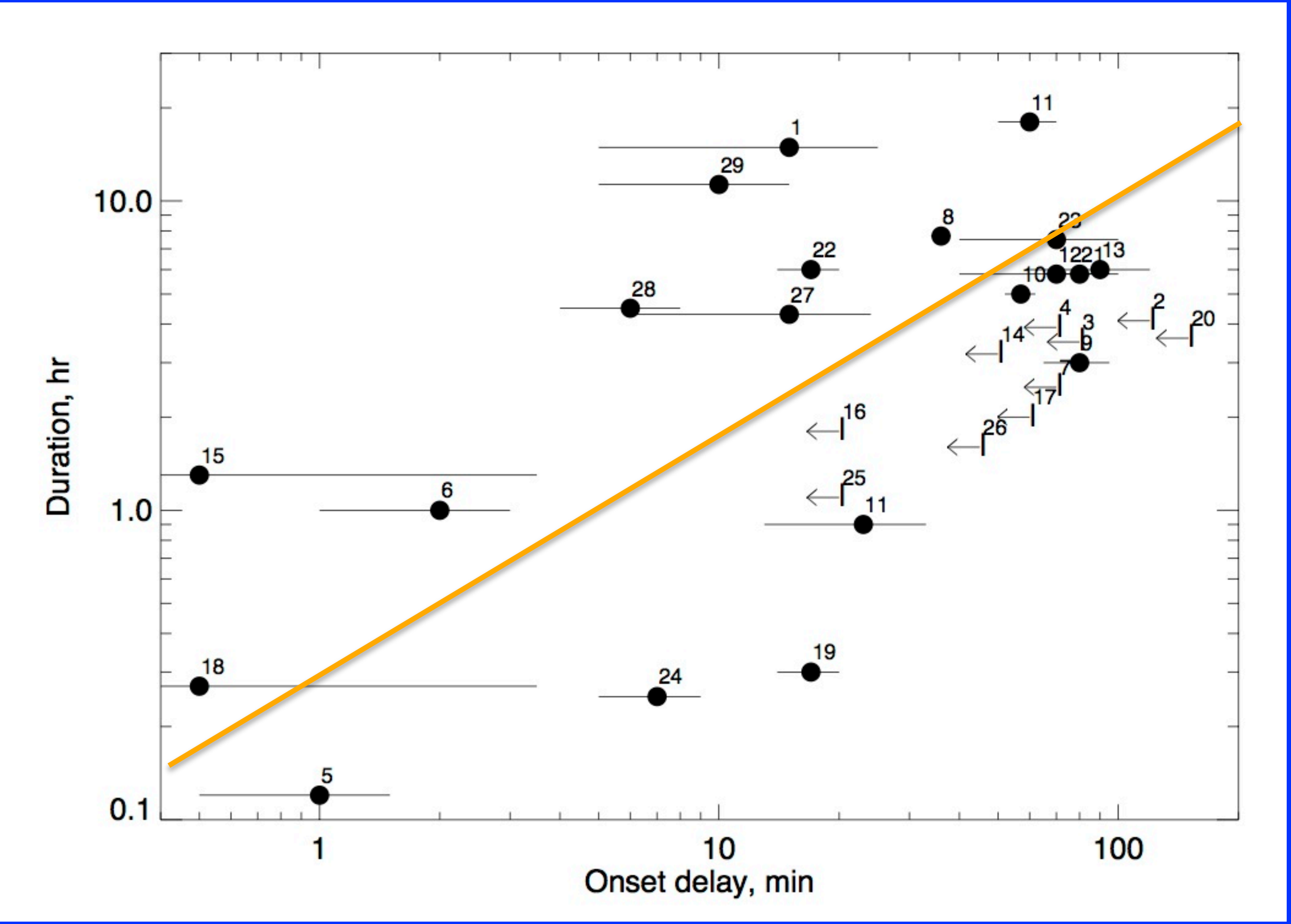
[b] 12 measured fluxes

Is there anything special about flares with >100 keV impulsive hard X-ray emission? 32 flares selected from our 4-yr study with CME speeds >800 km/s with characteristics according to the >100 keV criterion. Is it just the Big Flare Syndrome? Spectroscopic studies suggest otherwise. Of the fifteen events listed in the table with hard X-ray emission that did not exceed 100 keV, only three had emission exceeding 50 keV. Fits to the hard X-ray bremsstrahlung spectra for these three events indicate that the non-thermal electron spectra were steep with electron power-law indices of –5 to –6.

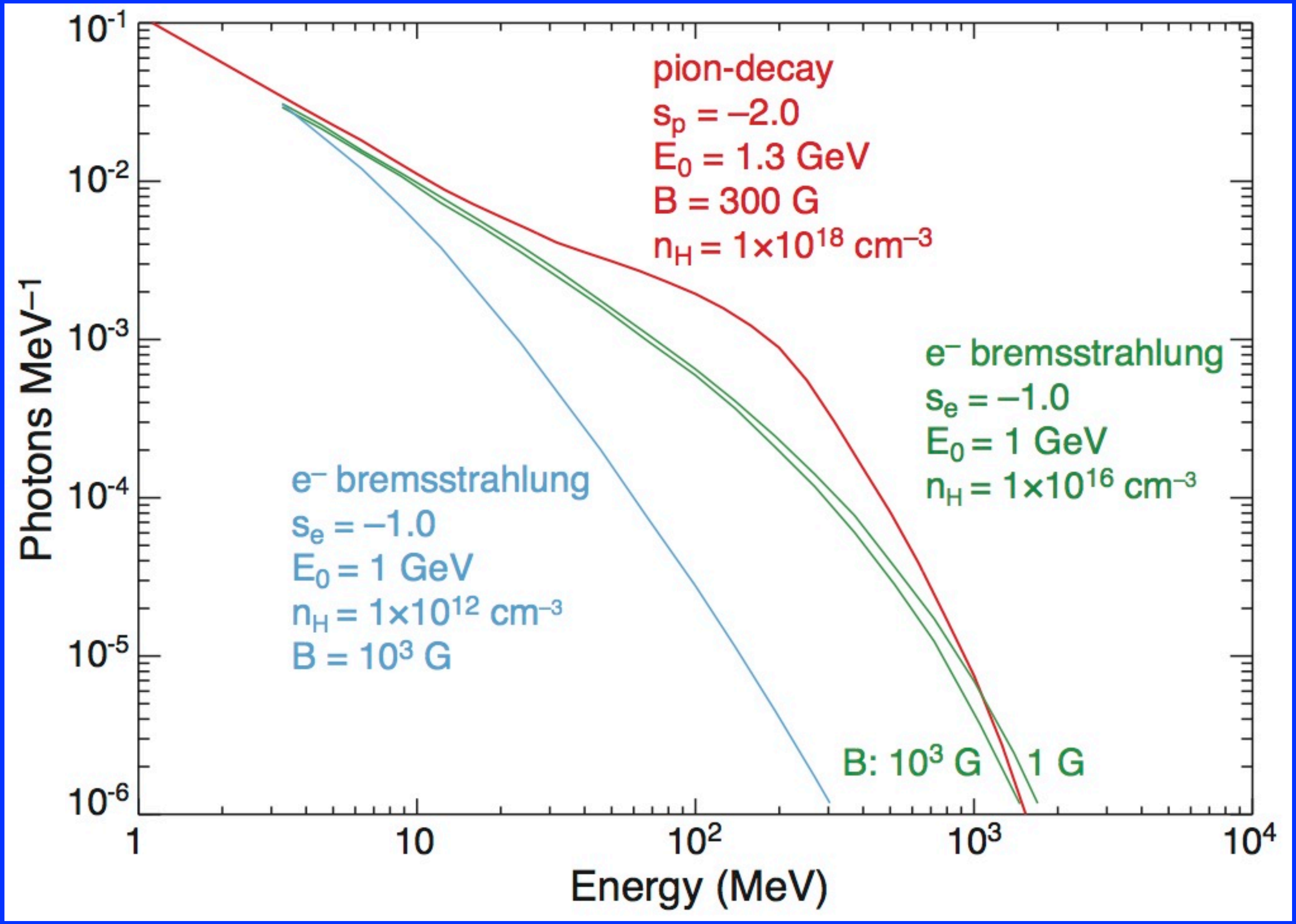




2/3's of the events show clear evidence for >100 MeV gamma-ray time profiles distinctly different than the impulsive phase. We found no case where the emission was the tail of the impulsive flare.



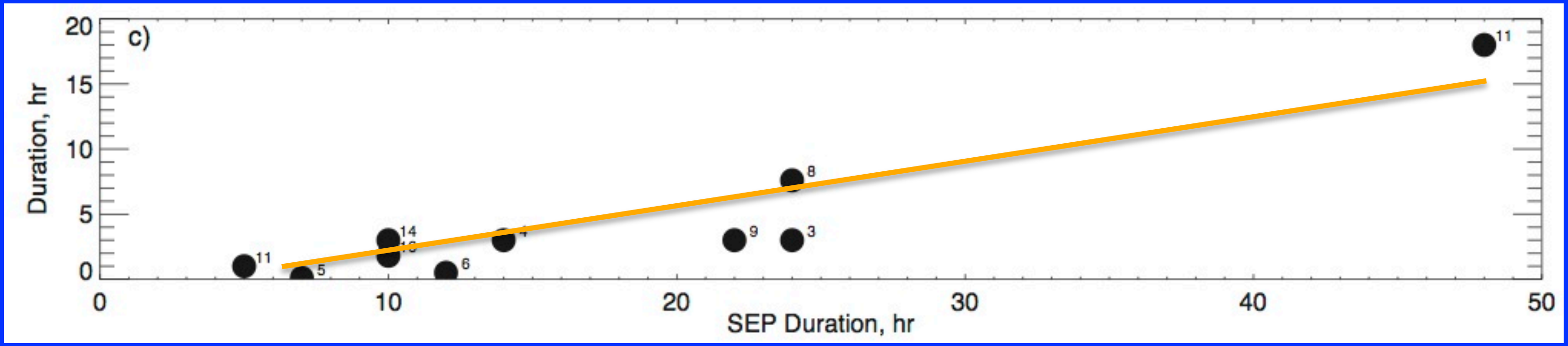
Delay of start of sustained gamma-ray emission from the CME onset vs duration of the sustained emission. Solid circle: onset delay measured. Weak evidence at 98% confidence that delay and duration are correlated. Upper limits on delay also shown. Onset delay can be as short as 1 min and as long as tens of min. Durations can range from ~10 min to 20 hrs.



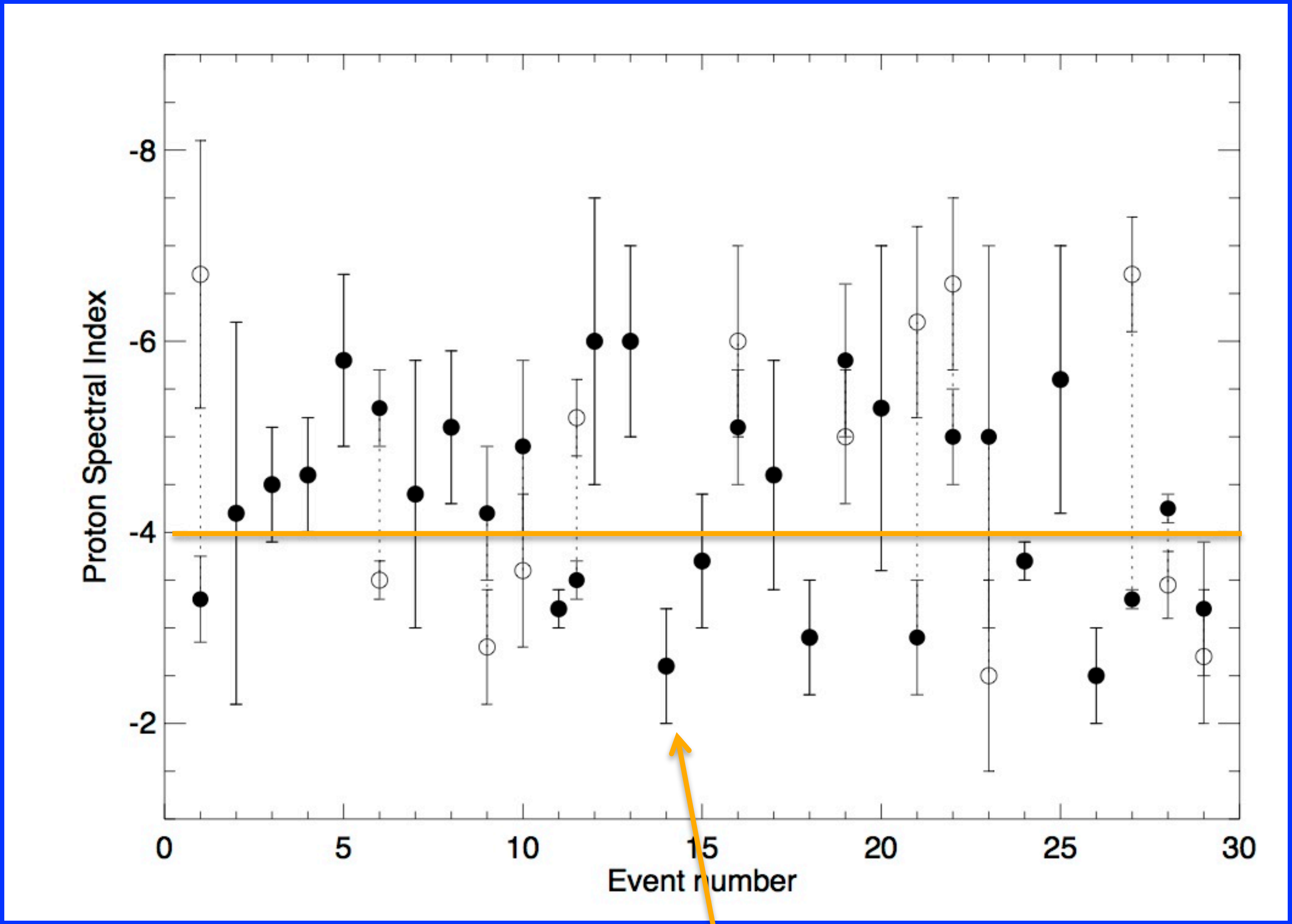
Shown in red is pion-decay photon spectrum that fits the 2014 February 25 event. Electron bremsstrahlung spectra, even with synchrotron losses, cannot fit the LAT >100 MeV spectrum. Electron bremsstrahlung also inconsistent with LAT spectra in 17 solar exposures with peak flux $>10^{-4}$ γ cm^{-2} s^{-1}.

We have fit the spectra of the 29 sustained emission events with pion-decay spectra to obtain >100 MeV fluxes, proton spectral indices >300 MeV, and numbers of >500 MeV protons at the Sun. We have also fit impulsive phase data from LAT, GBM, and RHESSI to obtain similar estimates. For intense events we use GBM and RHESSI to set limits on sustained proton spectra from 30-300 MeV. Spectra appear to soften above ~100 MeV. Estimates of the numbers of protons in SEPs from HEPAD. Better estimates from PAMELA (Georgia De Nolfo:poster)

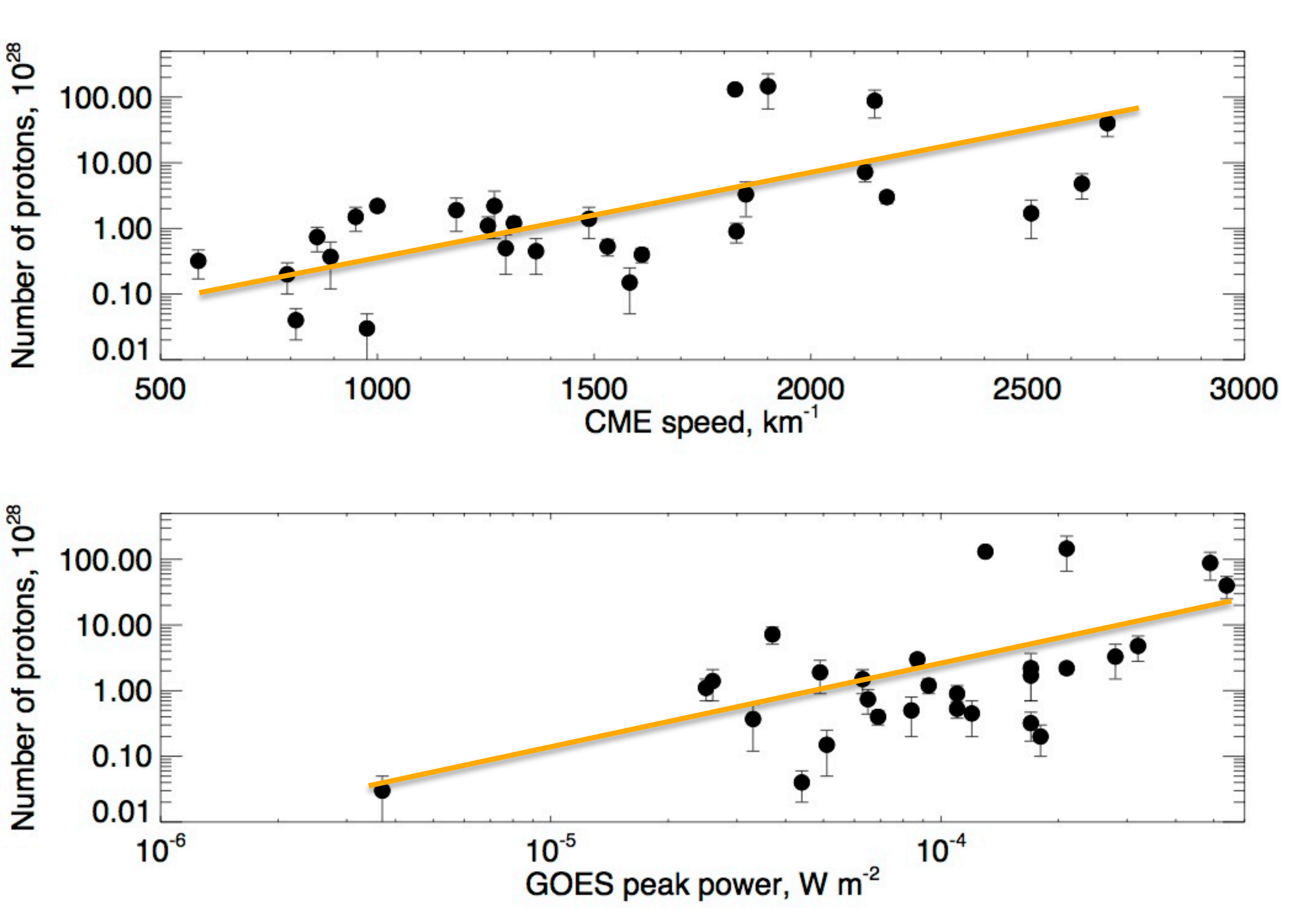
Date yyyy/mm/dd (1)	Time Delay[a] Minutes (2)	Observing Interval, UT (3)	Flux >100 MeV $10^{-4}\gamma\ cm^{-2}\ s^{-1}$ (4)	Proton PL Index >300 MeV (5)	Emission Interval, UT (6)	10^{28} Protons >500 MeV (7)
					09:14–12:00	0.7
					04:20–12:00	3.0 ± 0.6
		M8.7 flare			03:53–04:09	<0.4[b]
					03:45–04:09	<0.7
		SEP				212 ± 88
2012/01/27	80 ± 15	19:36–19:56	0.26 ± 0.05	–4.2 ± 0.7	19:00–19:50	0.5
		21:06–21:37	0.05 ± 0.02	–2.8 ± 0.6	19:50–21:21	1.1
					21:21–22:00	0.08
					19:00-22:00	1.7 ± 1.0
		SEP				656 ± 260
2012/03/05	57 ± 5	05:46–06:12	0.10 ± 0.015	–4.9 ± 0.9	04:45–05:59	0.12
		07:18–07:56	0.075 ± 0.019	–3.6 ± 0.8	05:59–07:36	0.25
					07:36–10:00	0.16
					04:45–10:00	0.53 ± 0.15
		X1.1 flare			03:55–04:35	<0.3[b]
2012/03/07	23 ± 10	00:39–01:24	28.7 ± 0.4	–3.6 +- 0.3	00:28–01:24	40
	60 ± 10	02:18–02:48	5.8 ± 0.3	–3.5 ± 0.2	02:00–02:34	3
				>–3.3[c]		
		03:50–04:34	10.0 ± 0.2	–3.85 ± 0.1	02:34–04:12	23
				>–3.3[c]		
		05:34–06:01	8.7 ± 0.4	–4.25 ± 0.2	04:12–05:46	30
		07:02–07:46	6.2 ± 0.2	–4.5 ± 0.15	05:46-07:24	27
				>–3.3[c]		
		08:42–09:12	4.1 ± 0.3	–4.8 ± 0.5	07:24-08:48	18
				>–3.7[c]		
		10:33–10:58	2.5 ± 0.2	–5.2 ± 0.4	8:48–10:46	17
				>–3.7[c]		
		13:23–13:33	0.6 ± 0.2		10:46–13:27	9
		16:35–16:49	0.22 ± 0.06		13:27–16:41	3
		19:46–20:14	0.07 ± 0.02		16:41-20:01	1
					02:00–20:01	131 ± 15
		X5.4 flare			00:16–00:28	1.4[b]
		X1.3 flare			01:11–01:20	1.1[b]
					01:12–01:17	<0.4
		SEP				13300 (+31800, –9360)
2012/03/09	70 ± 30	05:10–05:58	0.06 ± 0.03	<–6	05:00–06:00	0.1
		06:46–07:32	0.11 ± 0.03	–6 ± 1.5	06:00–07:09	0.3
		08:22–09:08	0.15 ± 0.03	–6.7 ± 1.5	07:09–08:46	0.7
					08:46–10:30	0.4
					05:00–10:30	1.5 ± 0.6
		M6.3 flare			03:40–04:14	<0.1
					03:30–04:06	<0.6[b]
2012/03/10	90 ± 30	20:59–21:33	0.02 ± 0.01	≤–6	20:00–21:15	0.05
		22:35–23:15	0.043 ± 0.027	≤–6	21:15–22:55	0.18



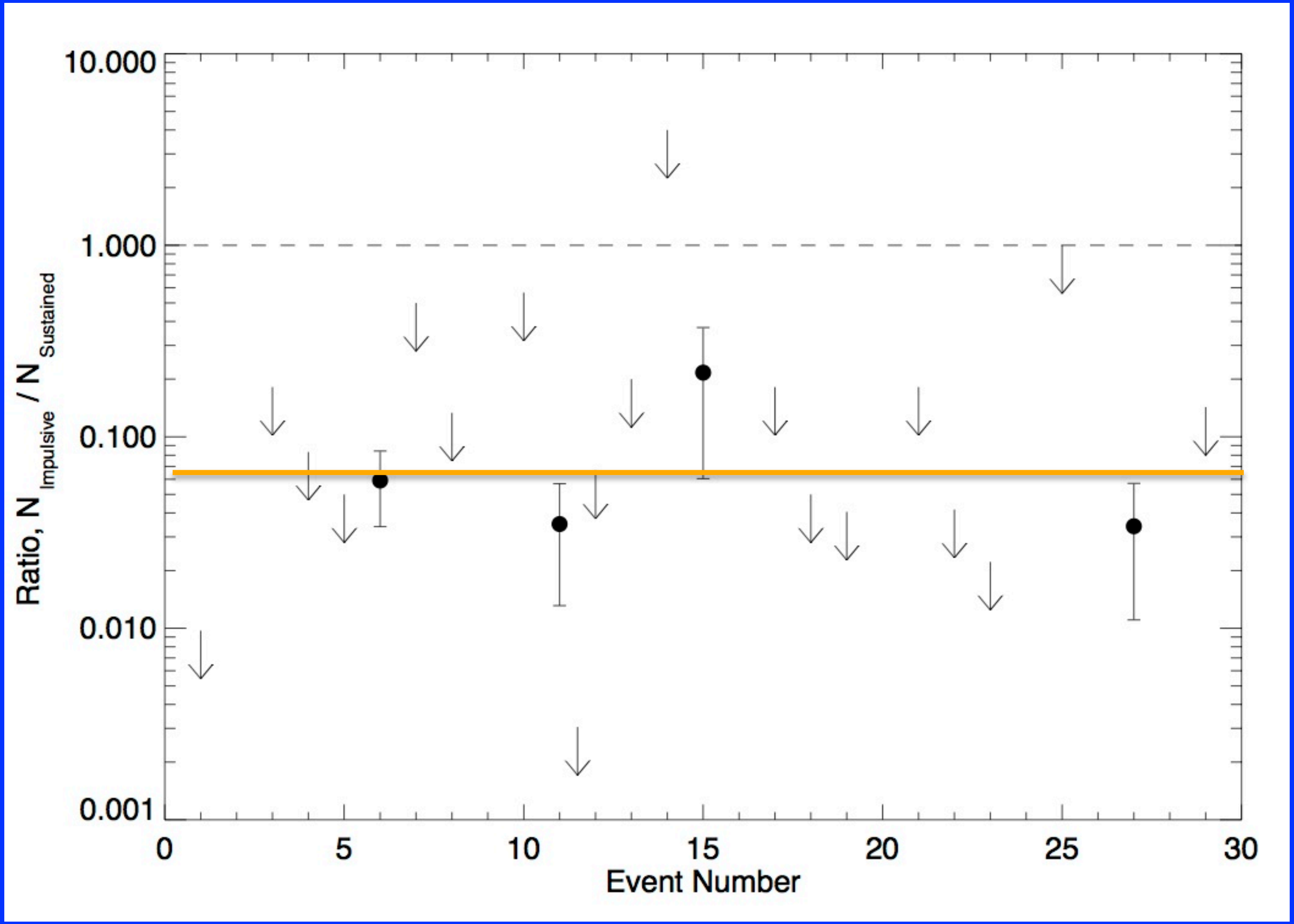
99% probability that duration of LAT events is correlated with duration of associated >100 MeV SEP.



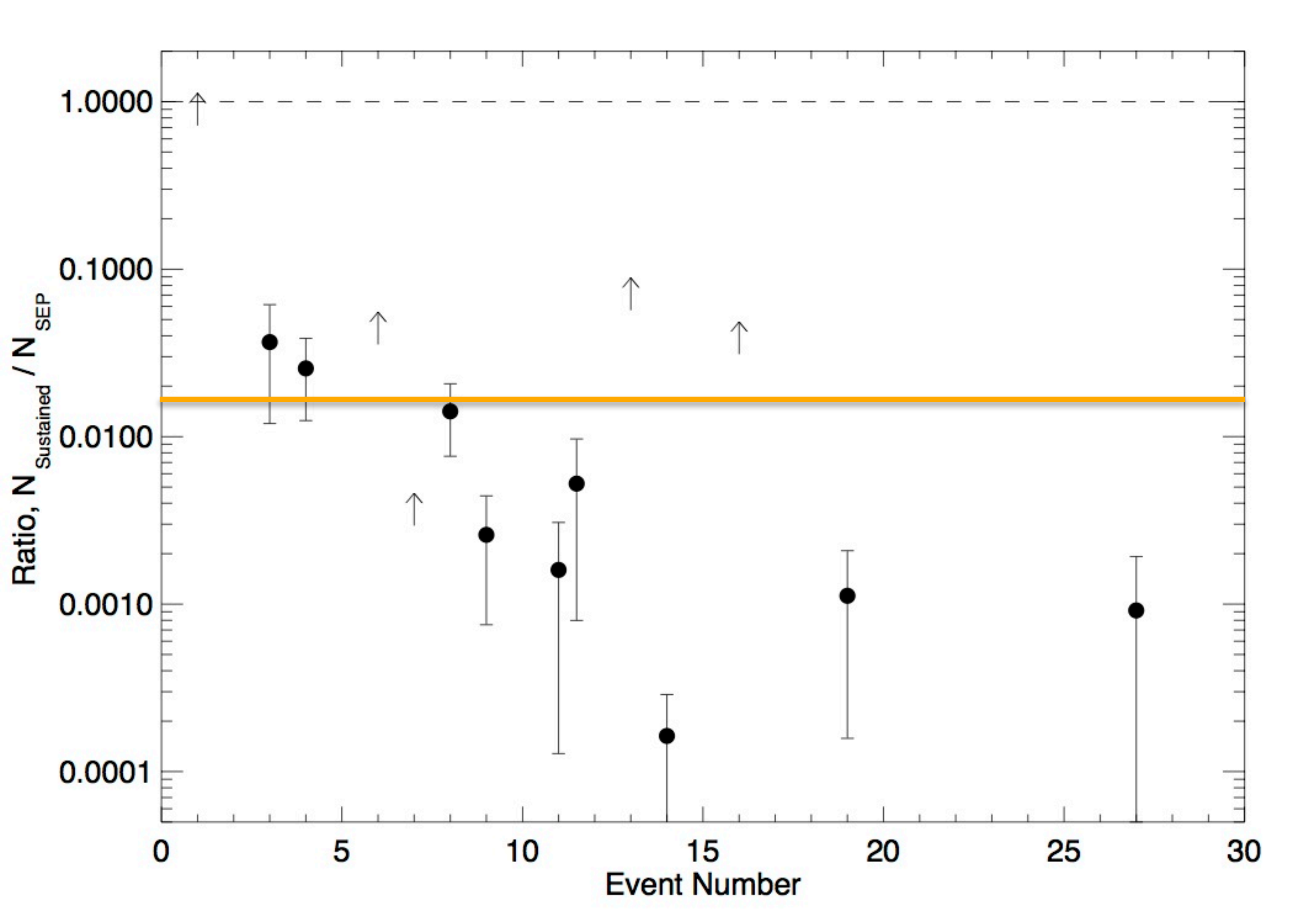
Estimated spectral indices of >300 MeV protons producing sustained γ-ray emission based on fits to the Fermi/LAT spectra. Solid circle: either the event averaged index or value of the first index in an event when the index changed in time. Open circle: value of the last index measured. Mean weighted by uncertainties 3.95+- 0.05. Six events with spectral variation: 4 with durations >1 hr soften; 2 with durations <1 hr harden. Sustained emission proton spectrum for 2012 May 17 GLE is hard.



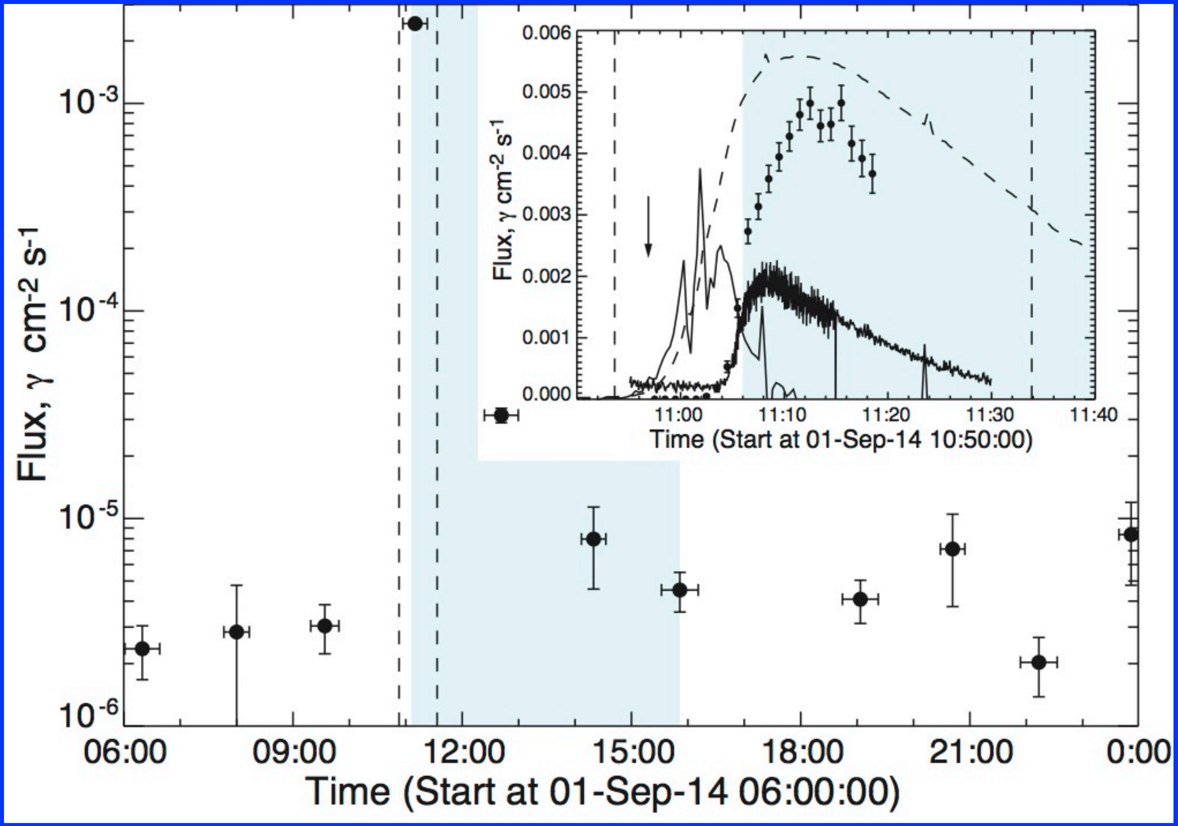
Number of sustained emission protons >500 MeV correlated with CME speed with 99.99% confidence. Correlation with GOES X-ray class is weaker. 98% confidence in correlation if we exclude marginally detected C3.7 flare.



Ratio of number of accelerated >500 MeV solar protons in impulsive phase to that in the sustained phase. Solid circles: impulsive phase proton measurement made, average ratio, 0.07. Upper limit symbols: 95% confidence limits on impulsive phase protons, dominated by 2012 May 17 GLE where the sustained flux was anomalously low; mean upper limit on ratio <0.07. Flare is not the main energy source. Need another energy source ➔CME.



Ratio of number of protons >500 MeV in the sustained gamma-ray emission phase to the number in the associated SEP. Solid circles: SEP proton number measured. Weighted mean of measured ratios 0.017. Lower limit symbols: Only upper limit on SEP number available. Anomalous 2011 March 7 event:SEP proton energies barely exceeded 100 MeV.



Time history of the 2014 September 1 behind-the-limb event lasting for about 2 hr (Ackermann et al 2017). The inset shows 1-min accumulation LAT data fluxes and scaled 100 -- 300 keV count rates observed by GBM. There is compelling evidence that the electrons with energies up to tens of MeV were accelerated along with the protons responsible for producing the sustained gamma-ray emission. The proton/electron ratio at Sun is consistent with the ratio measured in SEPs. Start time of sustained emission consistent with estimates based on shock acceleration onto field lines returning to the Sun.

Conclusions

Compelling evidence that the sustained gamma-ray emission is produced by protons accelerated in a process that is distinct from the impulsive flare and energized by a CME or magnetic eruption. SEP measurement at the Sun?

- Spectra consistent with pion-decay radiation and not electron bremsstrahlung
- Mean >300 MeV proton power-law index ~-4; some spectra vary with time
- Where measurements made, proton spectra are harder below 300 MeV.
- Time histories distinctly different from the associated impulsive flares
- Emission delayed by ~1 min to tens of minutes from CME onset
- Durations from 10 min to 18 hr. Durations correlate with >100 MeV SEP durations.
- More than ten times the number of >500 MeV protons than in the flare
- ~1% of the number of protons >500 MeV in SEPs.
- Tens of degrees spatial distribution around the active region
- Evidence for sustained-emission electrons in 2014 September 1 behind-the-limb event
- Start times of behind-the-limb events explained by shock acceleration onto field lines returning to the Sun (Plotnikov et al 2017)

Interesting twists:
Two sustained-emission events with no associated CME or SEP but had >100 keV HXR.

Why are all sustained-emission events associated with impulsive flares with HXR >100 keV
>100 keV HXR →~ >100 keV ions present at flare site
Shock is quasi-perpendicular for field lines reaching back to the Sun.
Quasi-perpendicular shock acceleration requires high-energy (~>100 keV) seed ions