Characteristics of Sustained >100-MeV Gamma-Ray Emissions Observed by Fermi and their Association with Solar Explosive Events

Gerry Share[1], Ron Murphy[3], Allan Tylka[2], Kim Tolbert[2], Richard Schwartz[2], Brian Dennis[2], and Stephen White[4]

[1]University of Maryland
[2]Goddard Spaceflight Center
[3]Naval Research Laboratory
[4]Kirtland AFB

Work supported by the NSF and Fermi GI program.

New Opportunities in the AMS-02 Era, Oct 19-23,2015

INTRODUCTION

Fermi detection of sustained >100 MeV gamma-ray emission following solar flares (Ackermann et al. 2014). Most likely origin is from neutral and charged pions produced when >300 MeV protons interact deep in the solar atmosphere. Long Duration Gamma-Ray Flares (Ryan 2000).

AMS/PAMELA provide unique observations of >300 MeV protons in space; these are the same energies producing the pion-decay radiation observed by Fermi.

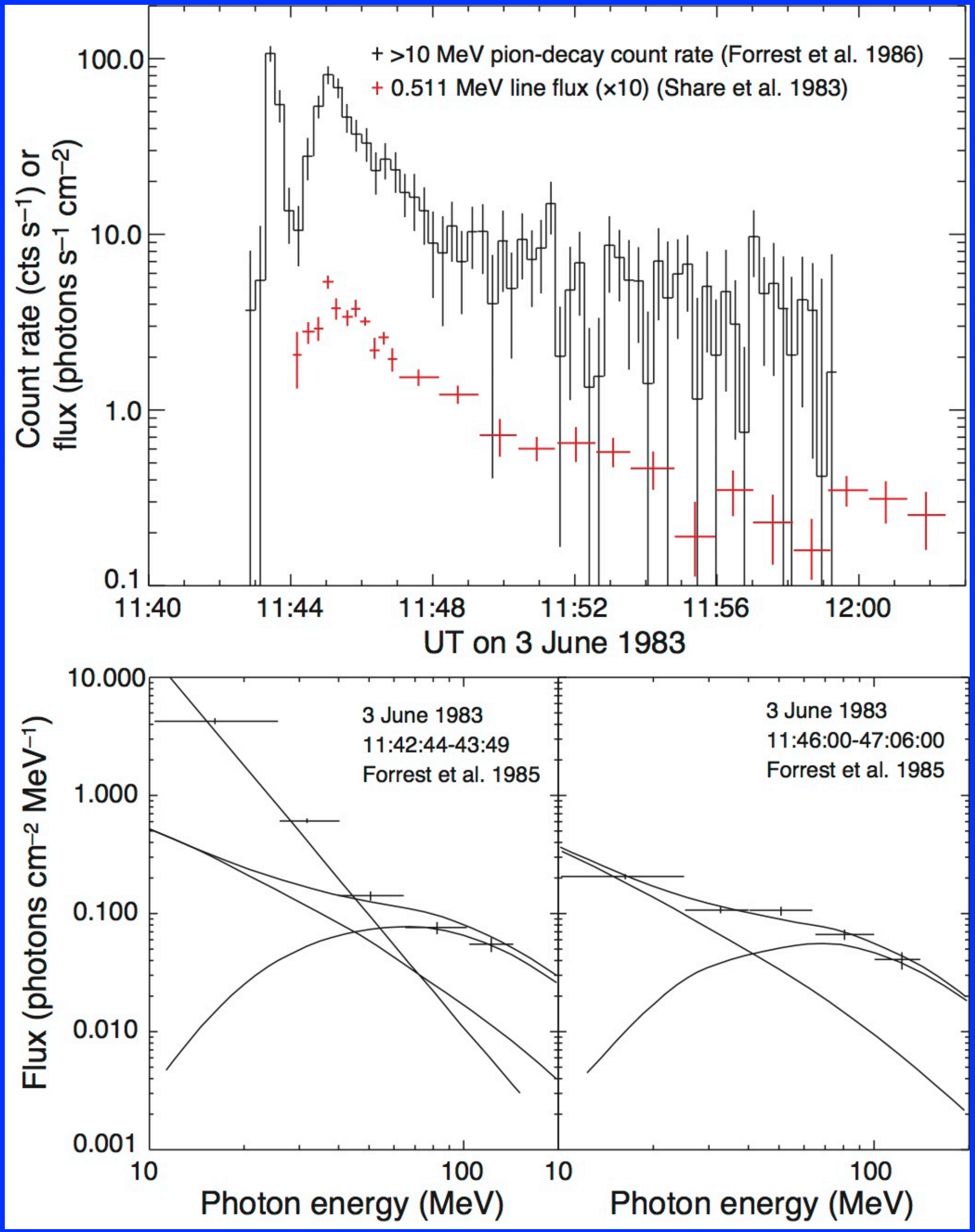
Example: the 2014 February 25 event that was one of the largest observed by Fermi. Time history and spectral studies

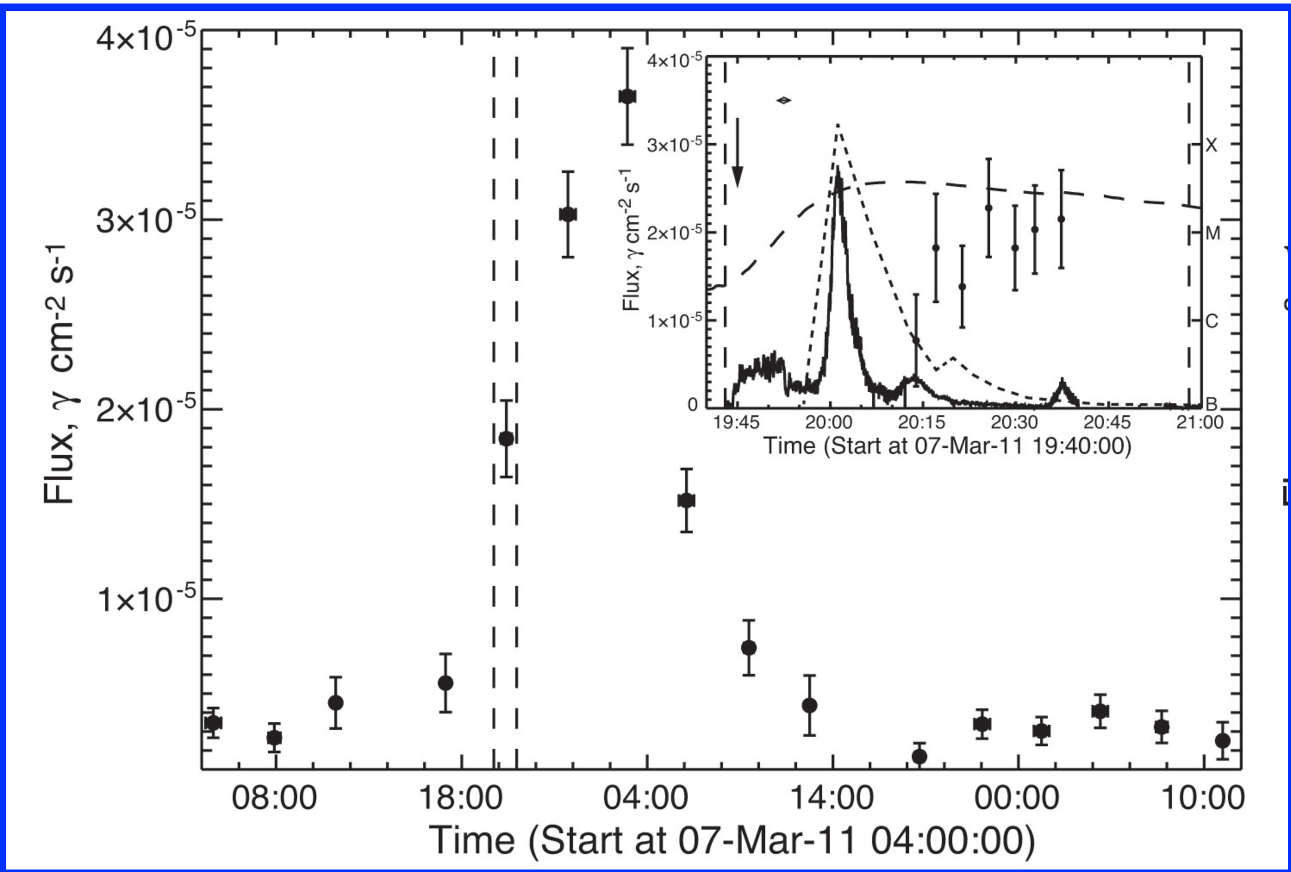
Results of systematic study of 95 Solar Explosive Events from June 2008 to May 2012 and their association with LAT >100 MeV sustained gamma-ray events.

Twenty-six Fermi events studied from 2008 to 2015: numbers of protons, spectral indices, onset times and durations. Comparisons with flares and SEPs.

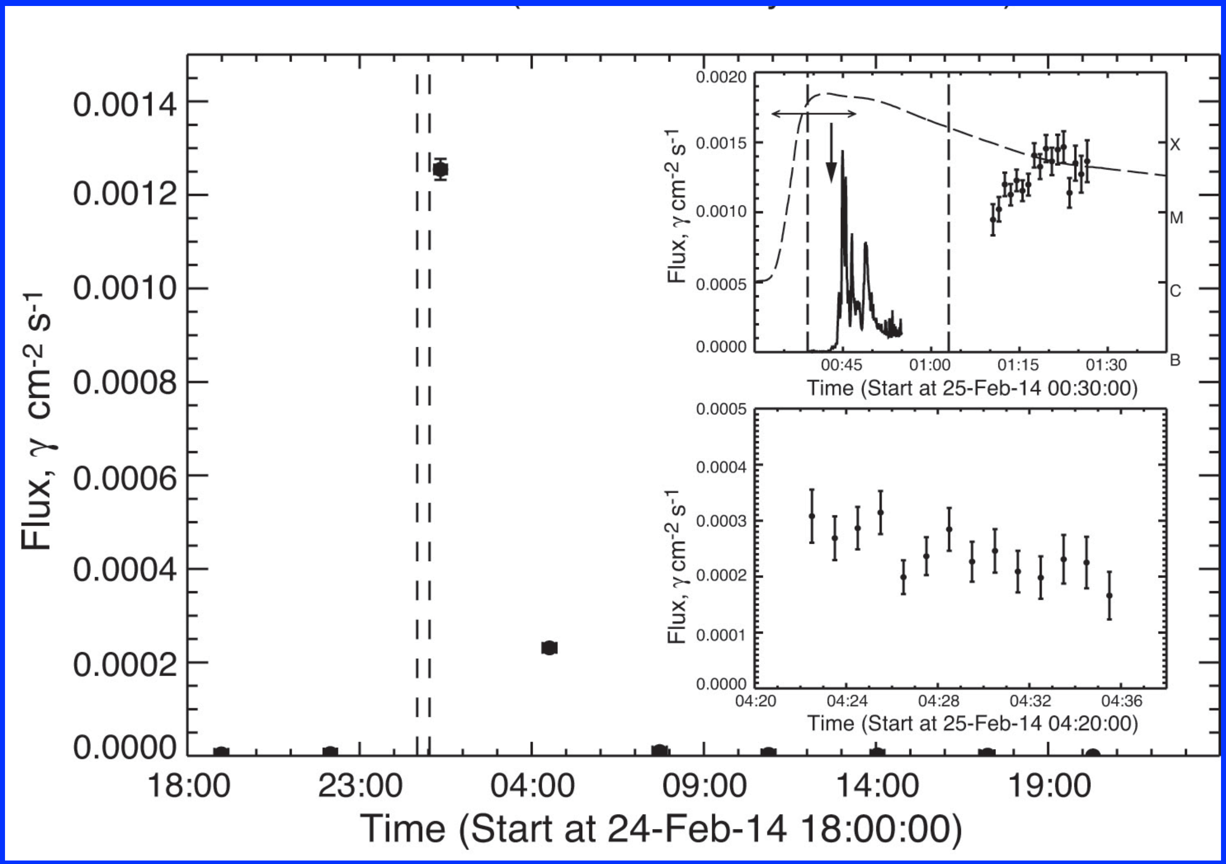
LAT >100 MeV gamma-ray fluxes from 2008 to 2015 on RHESSI Browser page. Spectroscopic analysis using SSW/OSPEX.

Observations of high-energy emission from the 1982 June 3 flare made by the SMM} GRS. a) Time history of the pion-decay γ-ray count rate revealing two clear phases of emission. b) γ-ray spectra observed during the impulsive phase (left panel) and during the second phase (right panel). The solid curves show the different components of the spectrum, including: bremsstrahlung from primary electrons and electrons and positrons from pion-decay and neutral pion-decay bump. Shown in red, and scaled arbitrarily, is the count rate observed in the 511 keV annihilation line





The first LDGRF observed by Fermi and reported by the Fermi/LAT team in Ackermann et al. (2014). Note that the flare was only an M3.7. Plot made using a 'light-bucket' analysis technique different than the Maximum Likelihood technique used by LAT team. Emission lasted at least 14 hrs. Dashed lines show extent of soft X-ray flare; details in inset: 100-300 keV rate, 4 min LAT data suggesting the emission begins within 15 min of HXR peak. Dotted curve 1991 June 11 profile. No 2.223 MeV or nuclear line emission during impulsive phase ➔ estimate of >100 MeV γ-rays. Spectral softening observed in protons >300 MeV at Sun. Is the gamma-ray onset associated with the SEP release time?



>100 MeV time profile of 2014 Feb. 25 event, one of most intense LAT events. Inset shows high-time resolution rise and fall. Strong nuclear line radiation during the impulsive phase but no LAT solar exposure. Spectral softening with time again observed in >300 MeV protons producing gamma rays. Can estimate >100 MeV gamma-ray emission during impulsive phase using 2.2 MeV capture line or LLE data where available.

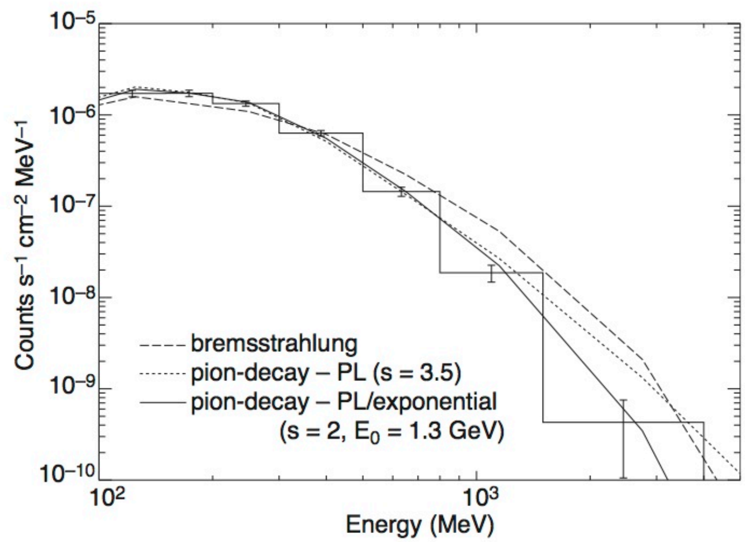
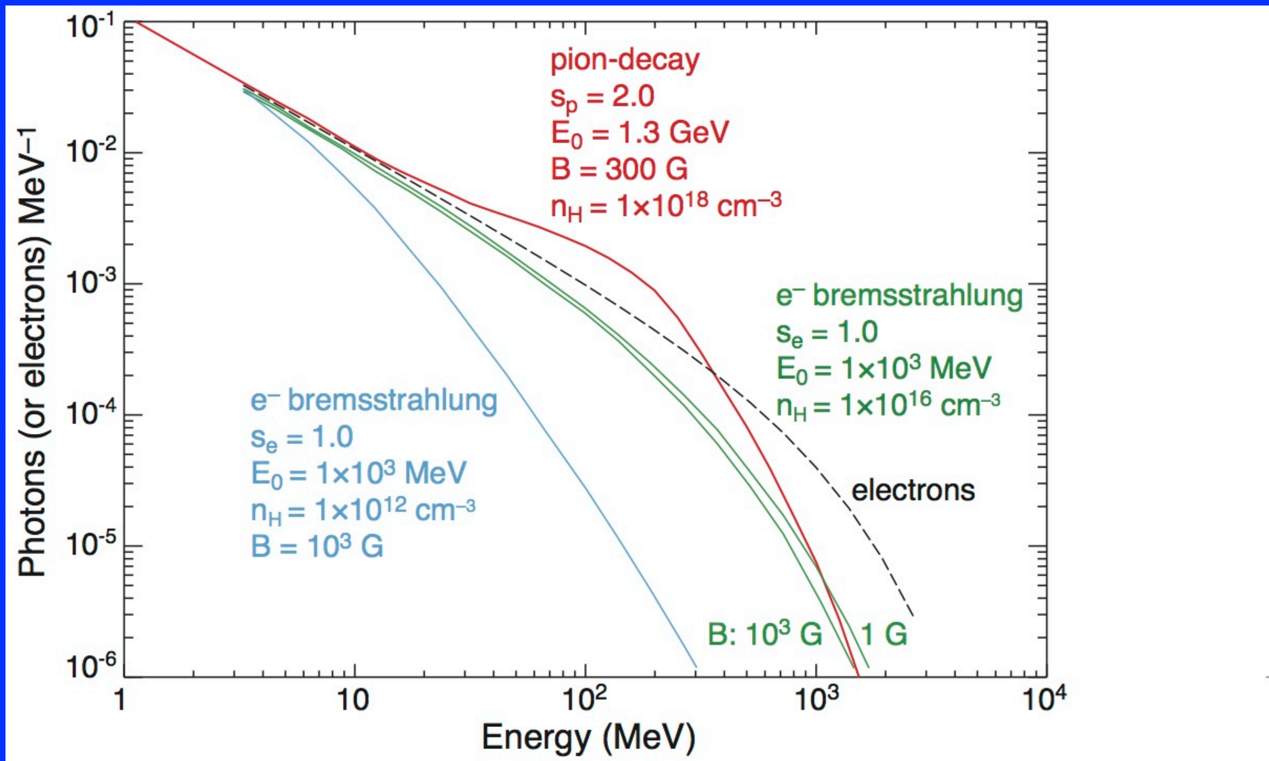


Fig. 4.— Background-subtracted γ-ray spectrum observed by LAT between 01:13:30 and 01:17:30 UT on 2014 February 25 during its peak exposure to the Sun. Best fits to the spectrum for: a pion-decay spectrum produced by a power-law spectrum of protons with spectral index –3.5, dotted curve; a pion-decay spectrum produced by a power-law spectrum of protons with spectral index –2 and 1.3 GeV exponential cutoff energy, solid curve; and a bremsstrahlung spectrum produced at a density 10^{16} cm^{-3} from a power-law spectrum of electrons with index –1 and 1 GeV exponential cutoff energy in a 10^3 G magnetic field, dashed curve.

Count spectrum best fit by a >300 MeV power-law proton spectrum with exponential cutoff. Electron bremsstrahlung does not provide a good fit to the data.



Best fit gamma-ray photon spectrum from pion decay produced by protons following a power-law energy spectrum with exponential cutoff. No plausible electron bremsstrahlung spectrum fits data. We therefore fit the LAT spectra using pion-decay templates calculated by Ron Murphy for different proton power-law spectral indices.

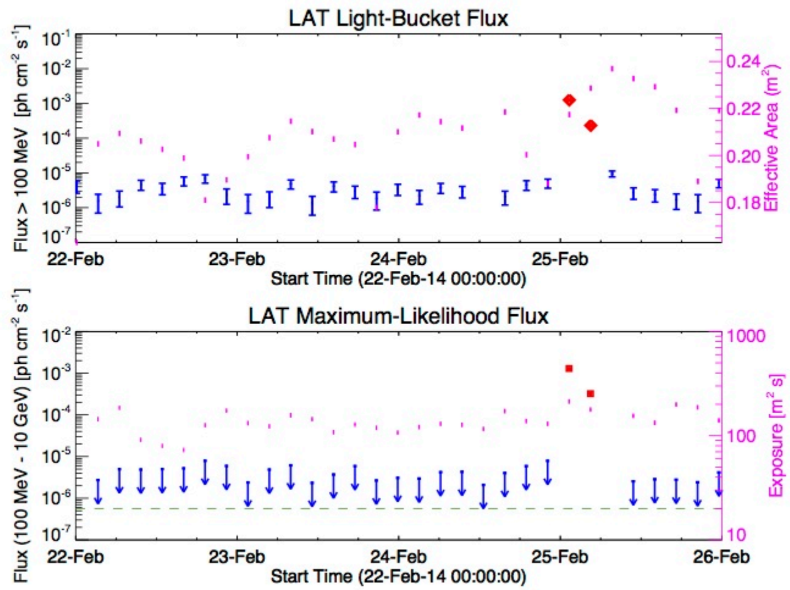
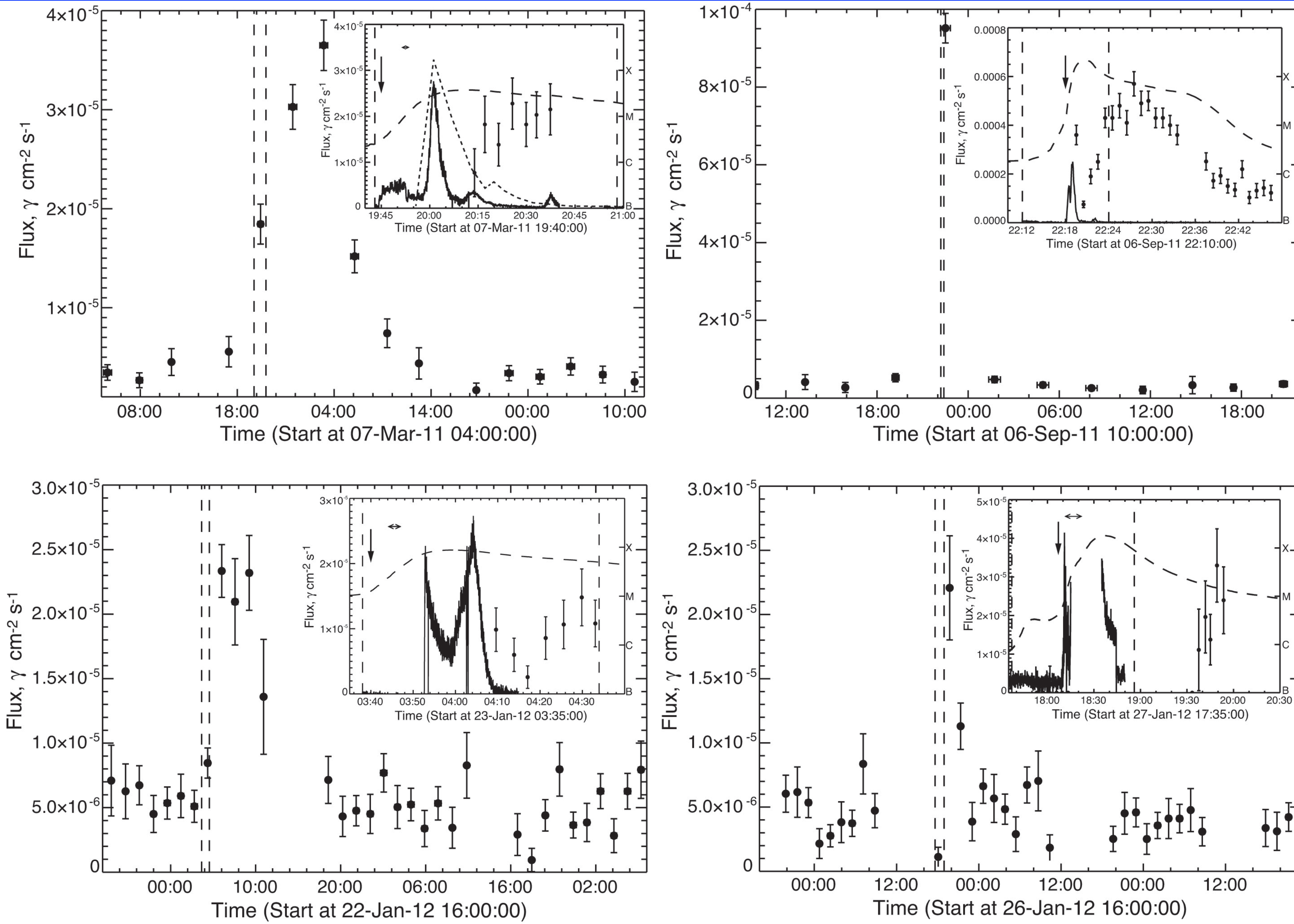


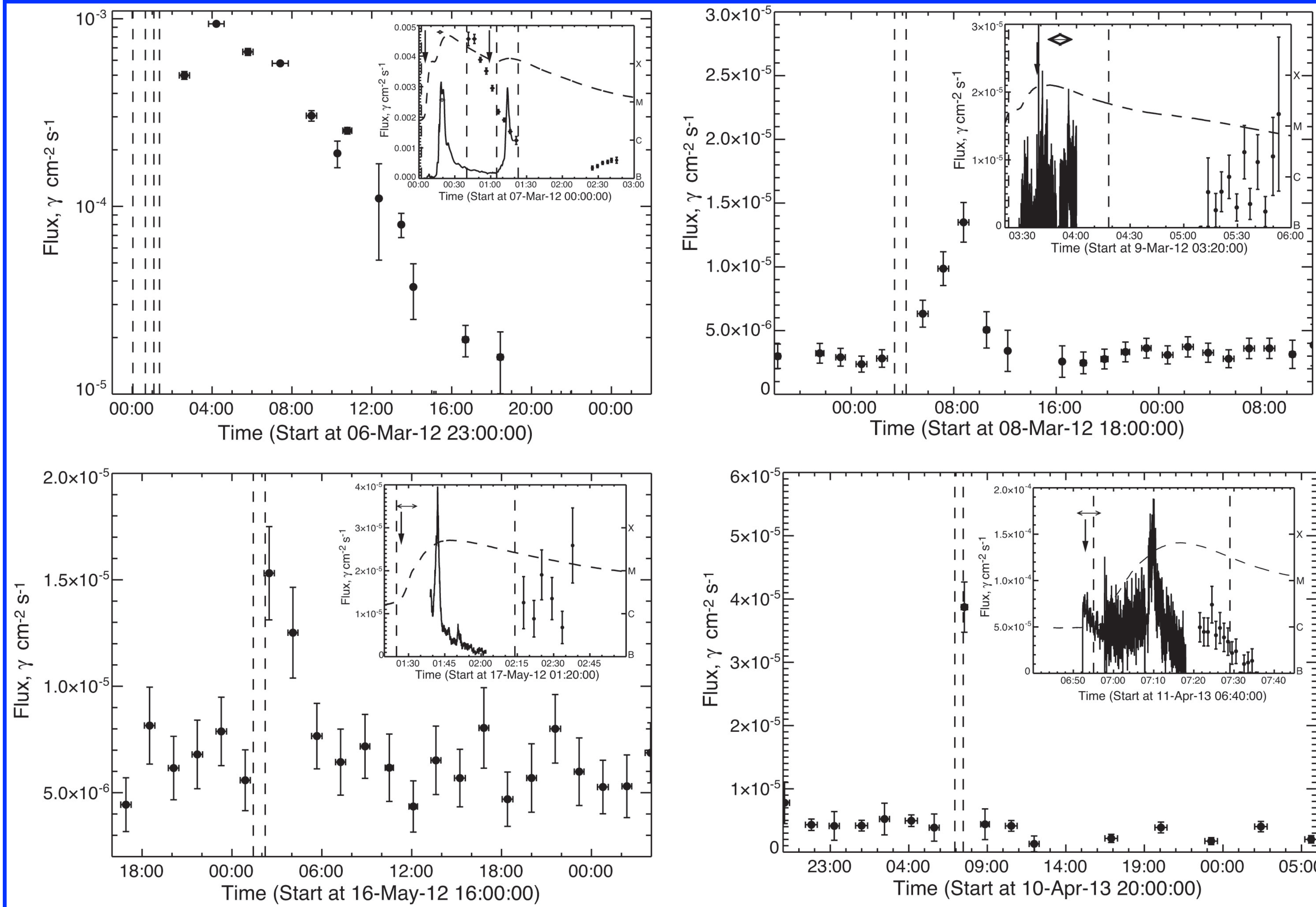
Fig. 3.— *RHESSI* Browser plots of LAT >100 MeV fluxes using the 'Light Bucket' technique used in this paper and Maximum Likelihood technique developed by Ackermann & et al. (2014); Ajello & et al. (2014). Shown is the 4-day time period that includes the sustained emission event observed by *Fermi* 2014 February 25.

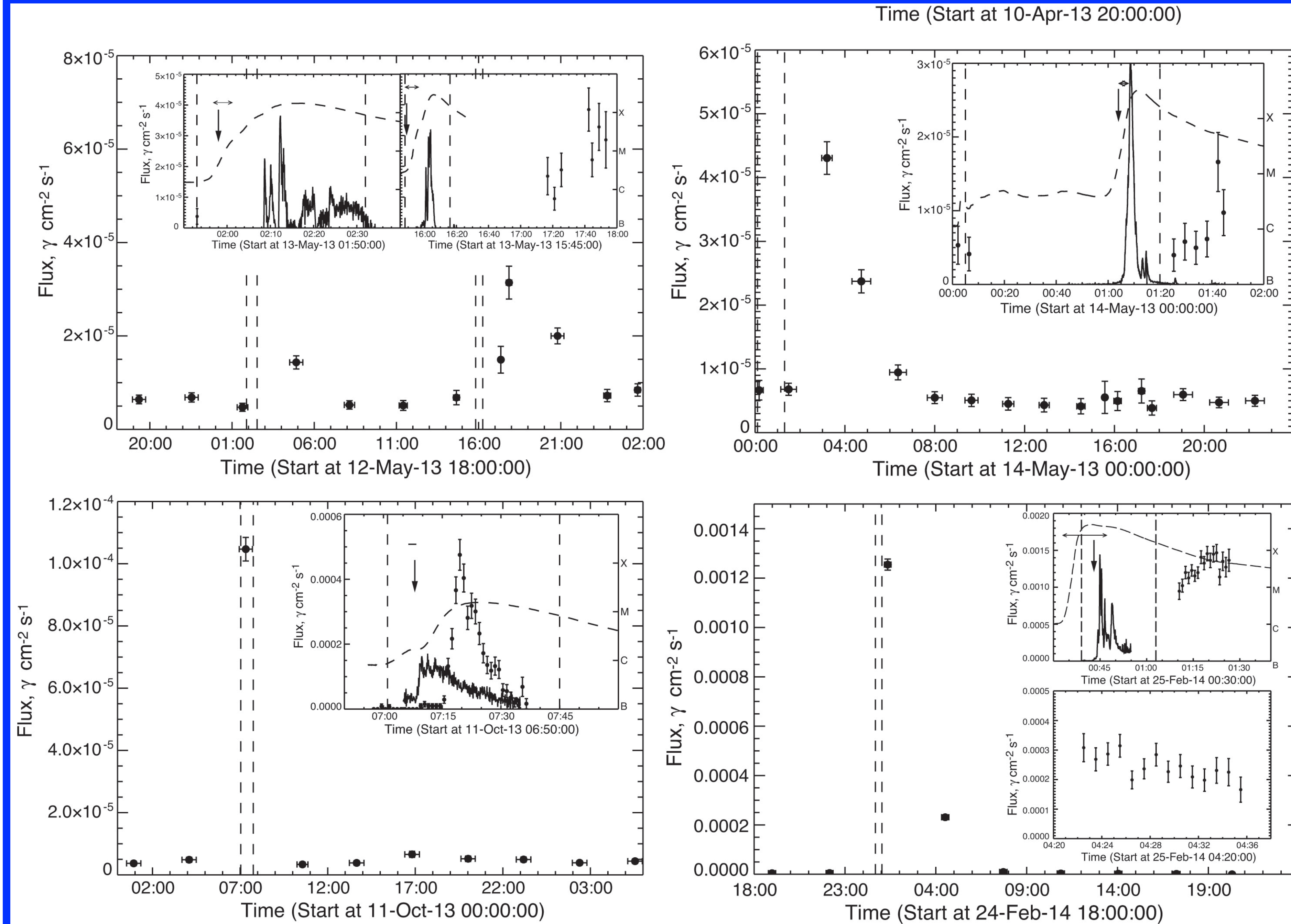
Example of RHESSI Browser plots of Fermi-LAT >100 MeV photons within 10^o of the Sun. Maximum Likelihood plots provided by the LAT Team are more sensitive than the simple the 'Light Bucket' plots. All Fermi solar data using the 'Light Bucket' approach can be spectroscopically analyzed using OSPEX and SSW.

Many of the flares reveal a distinct phase for the sustained emission similar to what was first observed in the 1982 June 3 flare. Examples below show other clear onsets following the impulsive phase. Delay of onset from peak of impulsive phase varies from ~1 min to over an hour.

Are these onset times related to the release of solar energetic particles/return of SEP particles to the Sun/acceleration of protons in large loops (Ryan)?


Flux, γ cm-2 s-1
Time (Start at 07-Mar-11 04:00:00)
Time (Start at 07-Mar-11 19:40:00)
Time (Start at 06-Sep-11 10:00:00)
Time (Start at 06-Sep-11 22:10:00)
Time (Start at 22-Jan-12 16:00:00)
Time (Start at 23-Jan-12 03:35:00)
Time (Start at 26-Jan-12 16:00:00)
Time (Start at 27-Jan-12 17:35:00)
X
M
C
B


Flux, γ cm-2 s-1
Time (Start at 06-Mar-12 23:00:00)
Time (Start at 07-Mar-12 00:00:00)
Time (Start at 08-Mar-12 18:00:00)
Time (Start at 9-Mar-12 03:20:00)
Time (Start at 16-May-12 16:00:00)
Time (Start at 17-May-12 01:20:00)
Time (Start at 10-Apr-13 20:00:00)
Time (Start at 11-Apr-13 06:40:00)
X
M
C
B

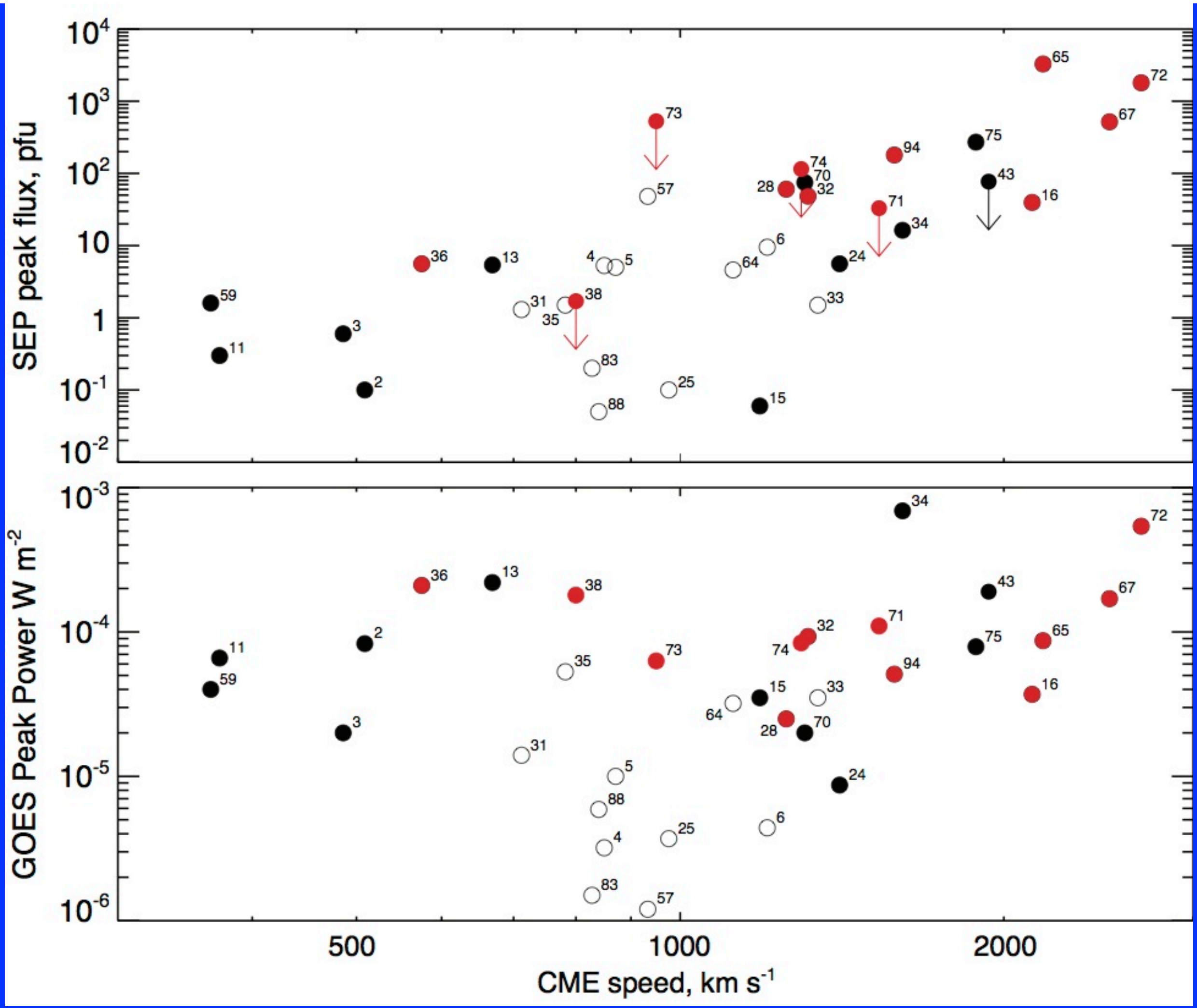

Time (Start at 10-Apr-13 20:00:00)
Flux, γ cm-2 s-1
Time (Start at 12-May-13 18:00:00)
Time (Start at 13-May-13 01:50:00)
Time (Start at 13-May-13 15:45:00)
Time (Start at 14-May-13 00:00:00)
Time (Start at 14-May-13 00:00:00)
Time (Start at 11-Oct-13 00:00:00)
Time (Start at 11-Oct-13 06:50:00)
Time (Start at 24-Feb-14 18:00:00)
Time (Start at 25-Feb-14 00:30:00)
Time (Start at 25-Feb-14 04:20:00)
X
M
C
B

Systematic study: We developed a list of 95 high-energy Solar Explosive Events from 2008 June to 2012 May with following properties:
broad CME with speed above ~800 km/s
or >100 keV impulsive hard X-ray emission
or SEP with fluxes >1 proton flux unit (pfu) >10 MeV.

Table 1. Solar Eruptive Events from June 2008 to May 2012

Number	Date, Location yyyy/mm/dd, deg	*GOES* X-Ray Class, Start-End	CME Speed, km s^{-1}	Type II M*, DH	SEP Flux (pfu)**, Max. Energy (MeV)	Hard X-ray Energy (keV)
1	2010/02/08, N22W02	M4.0, 07:36–07:46	N	N, N	<0.2, <10	100–300[d]
2	2010/02/12, N25E11	M8.3, 11:19–11:28	735[b]	N, N	0.1, <35[b] ; <0.2, <10	300–800[c]
3	2010/06/12, N22W57	M2.0, 00:30–01:02	486	2, N	0.6, <60	1000–50000
4	2010/08/01, N13E21	C3.2, 07:55–09:35	1562[a]	N, Y	5.3, <60[b]	12–25
5	2010/08/07, N12E31	M1.0, 17:55–18:47	871	2, Y	5.0, >60[b]	12–25[e]
6	2010/08/14, N11W65	C4.4, 09:38–10:31	1205	1, N	9.5, >100	25–50
7	2010/08/18, N17W91	C4.5, 04:45–06:51	1471	1, Y	2.5, <60	12–25[c]
8	2010/08/31, S20W145	?, ∼ 20:41	1304	N, N	0.6, >60[a]	–
9	2010/12/14, N20W56	C2.3, 15:03–16:55	835	N, N	<0.2, <10	6–12
10	2011/01/28, N17W87	M1.3, 00:44–01:10	606	1, N	1.9, >100	25–50[c]
11	2011/02/13, S20E04	M6.6, 17:28–17:47	595[a]	1, Y	0.3, <60[b]	100–300[d]
12	2011/02/14, S19W05	M2.2, 17:20–17:32	1249[a,h]	2, N	<0.2, <10	100–300[d]
13	2011/02/15, S20W12	X2.2, 01:44–02:06	669	2, Y	5.4, >60[b]	100–300
14	2011/02/18, S20W55	M6.6, 09:55–10:15	N, N	N	<0.2, <10	100–300[c]
15	2011/02/24, N16E87	M3.5, 07:23–07:42	1186	2, Y	0.06, <35[b] ; <0.2,<10	800–7000
16	2011/03/07, N30W47	M3.7, 19:43–20:58	2125	3, Y	39.6, >60	300–1000[d]
17	2011/03/09, N09W11	X1.5, 23:13–23:29	332	N, N	<14.7, >10[f]	100–300[d]
18	2011/03/14, N15W49	M4.2, 19:30–19:54	N	N, N	<0.2, <10	100–300[d]
20	2011/03/21, N17W129	?, ∼ 02:13	1341	N, N	702, >60[a]	–
21	2011/03/27, N19E101	?, ∼ 05:16	877	1, N	<0.2, <10	–
22	2011/03/29, N21E115?	?, ∼20:14	1264	N, N	1.3, >60[b]	–
23	2011/04/27, N19E59	C2.0, 02:26–03:01	924	2, N	<0.2, <10	25–50
24	2011/05/09, N19,E91	C5.4, 20:42–21:19	1318	N, Y	0.3, <41[b]	25–50

Events (2008-2012) with measured SEP fluxes >10 MeV (GOES/STEREO) and compare with CME speeds (top panel). Correlation observed. GOES peak soft X-ray power for same events compared with CME speed (bottom panel). Open circles, flare HXR <100 keV; filled black circles flare HXR >100 keV and no >100 MeV sustained emission; red-filled circles, flare HXR >100 keV and >100 MeV sustained emission. Added 4 LAT events with SEP upper limits.



Two populations of >100 keV HXR's associated with gradual and impulsive SEPs.

Gap in HXR's >100 keV for CME speeds 700-800 km s^{-1} just due to small soft X-flares (BFS). Concentrate on study of events with CME speeds >800 km s^{-1} and HXR >100 keV to understand LAT emission.

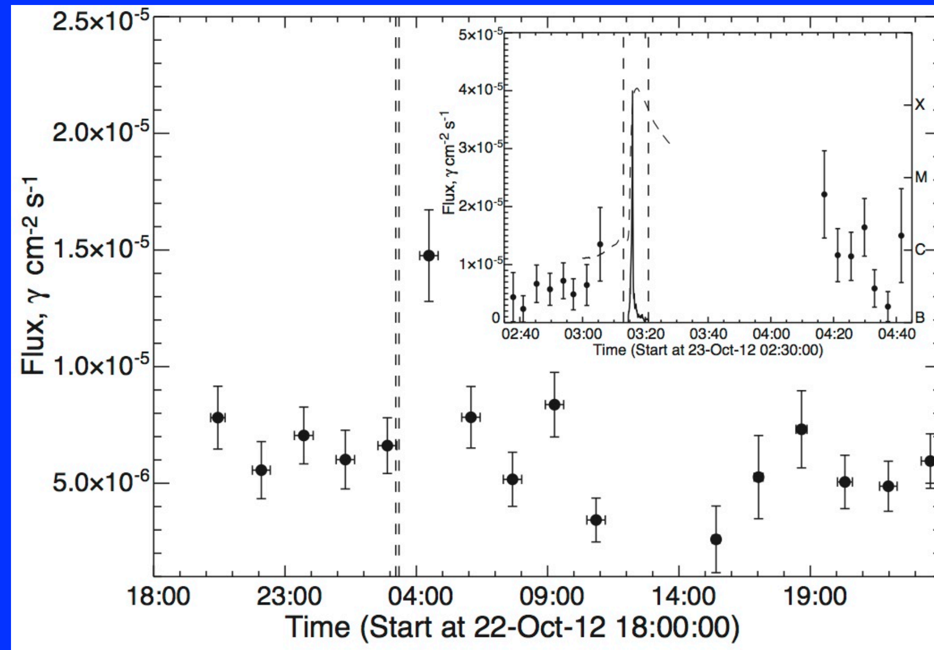
Results of Systematic Study

Sustained >100 MeV emission appears to require both a broad-fast CME and a flare with impulsive HXR emission >100 keV.

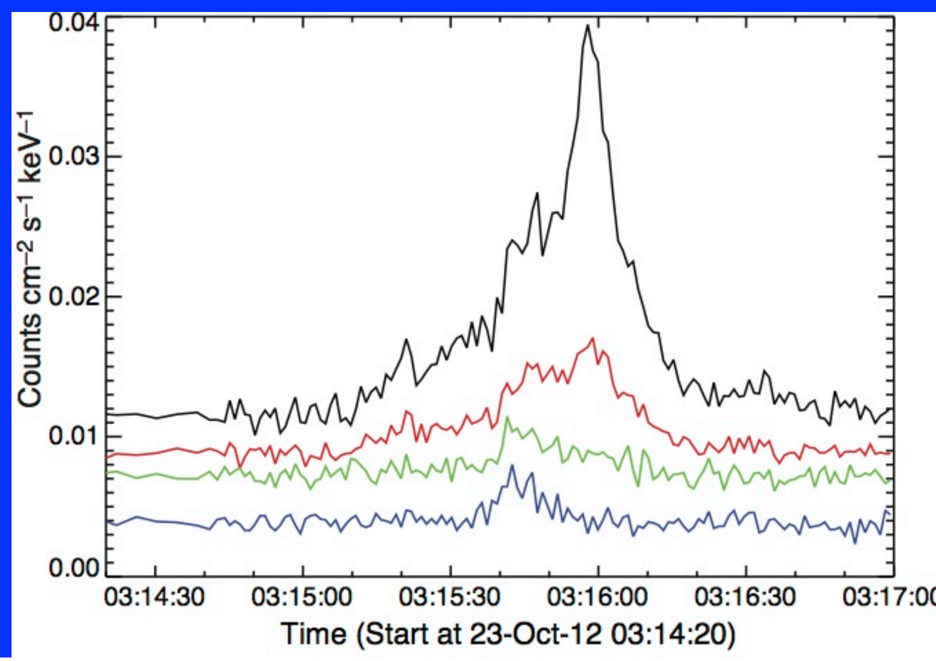
Possible reasons why 6 events meeting the two requirements were not observed by Fermi above 100 MeV: 1) no physical relationship between the requirements and sustained >100 MeV emission, 2) these 6 events were closer to the limb of Sun where emission was attenuated, 3) these 6 events were associated with weaker SEP events (assuming a relationship between protons in space and at the Sun), 4) these 6 events may have had short duration >100 MeV emission and were missed due to LAT solar duty cycle.

Wait a minute!!

New weak event on 2012 October 23 just found in Pass8 data with no associated CME or SEP. No evidence for nuclear emission in flare so not likely to be tail of impulsive phase. Impulsive phase emission best fit by power-law electron spectra extending to tens of MeV interacting in a thick target



Time profile of flare measured by GBM in different energy channels revealing two peaks. The first is harder than the second, giving the impression of the early onset of the high-energy component. Black 0.4-0.6 MeV, red 0.6-1.1 MeV (x1.5), green 2.4-7.4 MeV (x20), blue 9-40 MeV (x300).



Information on location of proton interactions producing the >100 MeV sustained gamma-ray emission from 4 year study:

Not one of the 35 events with broad CME's >800 km/s occurring beyond the limb of the Sun was detected >100 MeV by Fermi/ LAT (19 <30^{o} beyond the limb).

➔Interacting protons typically not distributed over visible disk such as in polar coronal holes (Hudson et al.) or regions >40^{o} from active region.

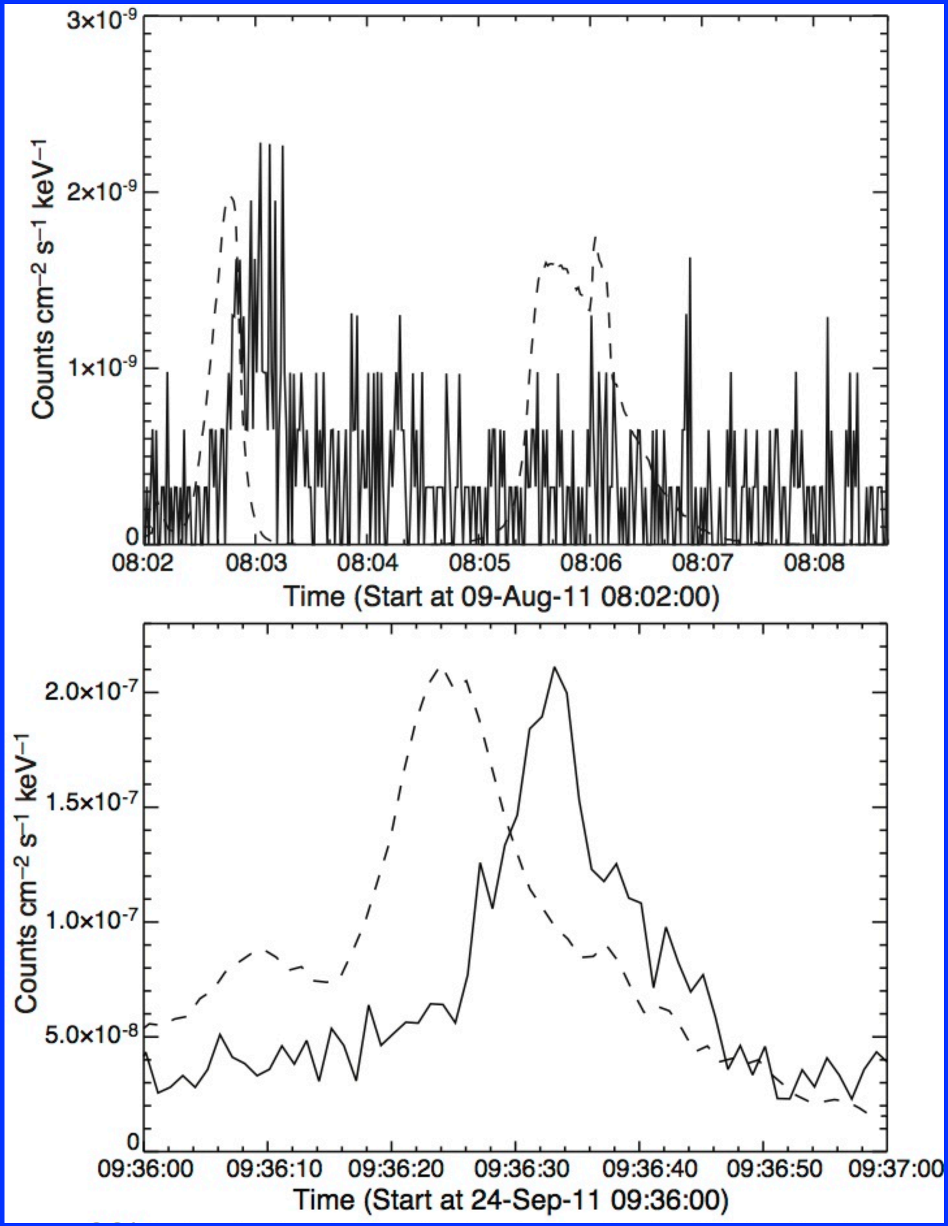
➔Some evidence that sustained emission might not always be associated with flare footpoint.

Picture clarified with over-the-limb flares observed after 2012 (Pesce-Rollins).

Interesting side light on acceleration delays first discussed by Ackermann et al for 2010 June 12 flare from two of the six flares with no sustained emission.

2011 August 9 flare exhibited impulsive nuclear line emission and gamma-ray emission >30 MeV. >30 MeV spectrum in 24 September is clearly electron bremsstrahlung. ~10 sec delays of >30 MeV emission (solid) from >100 keV HXR (dashed) in both flares.

10-sec time to accelerate electrons (protons?) to tens of MeV.



I

Table 2. LAT LDGRF's from June 2008 to February 2015

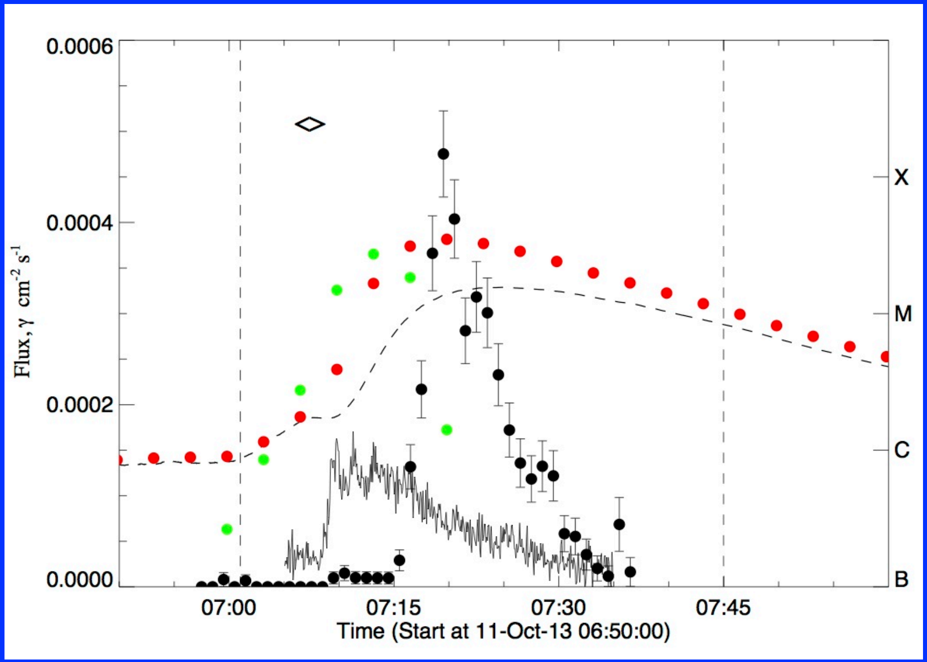
Number	Date, Location yyyy/mm/dd, deg	*GOES* X-Ray Class, Start-End	CME Speed, km s^{-1}, Width (deg)	Type II M^* , DH	SEP Flux (pfu), Energy (MeV)	Hard X-ray Energy (keV)
1	2011/03/07, N30W47	M3.7, 19:43–20:58	2125	3, Y	39.6, >60	300–1000[d]
2	2011/06/07, S21W54	M2.5, 06:16–06:59	1255	2?, Y	60.5, >100	300–800
3	2011/08/04, N19W46	M9.3, 03:41–04:04	1315	2, Y	48.4, >100	300–1000[d]
4	2011/09/06, N14W18	X2.1, 22:12–22:24	575 (∼1000[a,b])[h]	2, Y	5.6, >100	800–7000
5	2011/09/07, N18W32	X1.8, 22:32–22:44	792	1, N	<1.7, >10[f]	300–1000[d]
6	2012/01/23, N33W21	M8.7, 03:38–04:34	2175	N, Y	3280, >100	100–300[d,e]
7	2012/01/27, N35W81	X1.7, 17:37–18:56	2508	3, Y	518, >100	100–300[d,e]
8	2012/03/05, N16E54	X1.1, 02:30–04:43	1531	N, Y	<33, >13[b,f]	100–300[d,e]
9	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]
10	2012/03/09, N16W02	M6.3, 03:22–04:18	950	2, Y	<528, >10[f]	100–300
11	2012/03/10, N18W26	M8.4, 17:15–18:30	1296	N, Y	<115, >10[f]	100–300[d]
12	2012/05/17, N05W77	M5.1, 01:25–02:14	1582	3, Y	180, >100	100–300[c]
13	2012/06/03, N15E38	M3.3, 17:48–17:57	605 (892[b,h])	2, N	0.6, >60[b]	300–800
14	2012/07/06, S17W52	X1.1, 23:01–23:14	1828	3, Y	19.1, >100	–[e]
15	2013/04/11, N07E13	M6.5, 06:55–07:29	861	3, Y	184, >60[b]	100–300[d]
16	2013/05/13, N11E89	X1.7, 01:53–02:32	1270	1, Y	9.3, >60[b]	100–300
17	2013/05/13, N10E80	X2.8, 15:48–16:16	1850	2, Y	176, >60[b]	>1000
18	2013/05/14, N10E77	X3.2, 00:00–01:20	2625	1, Y	306, >60[b]	300–1000[d]
19	2013/05/15, N11E65	X1.2, 01:25–01:58	1366	1, Y	<17, >13[b,f]	300–1000
20	2013/10/11, N21E106	M1.5, 07:01–07:45	1200	2, Y	156, >60[b]	50-100
21	2013/10/25, S08E71	X1.7, 07:53–08:09	587	2, Y	32.6, >60[b]	800 – 7000[c]
22	2013/10/28, S14E28	M4.4, 15:07–15:21	812	2, Y	5.6[b]	100–300[c]
23	2014/02/25, N00E78	X4.9, 00:39–01:03	2147	3,Y	219[b] , >700	1000–10000
24	2014/09/01, N12E138	?, 10:58–11:34	1901	–,Y	∼1000, >13	—
25	2015/06/21, N13E16	M2.6, 02:03–03:15	1488[h]	2,?	∼40, >10	100-300[d]

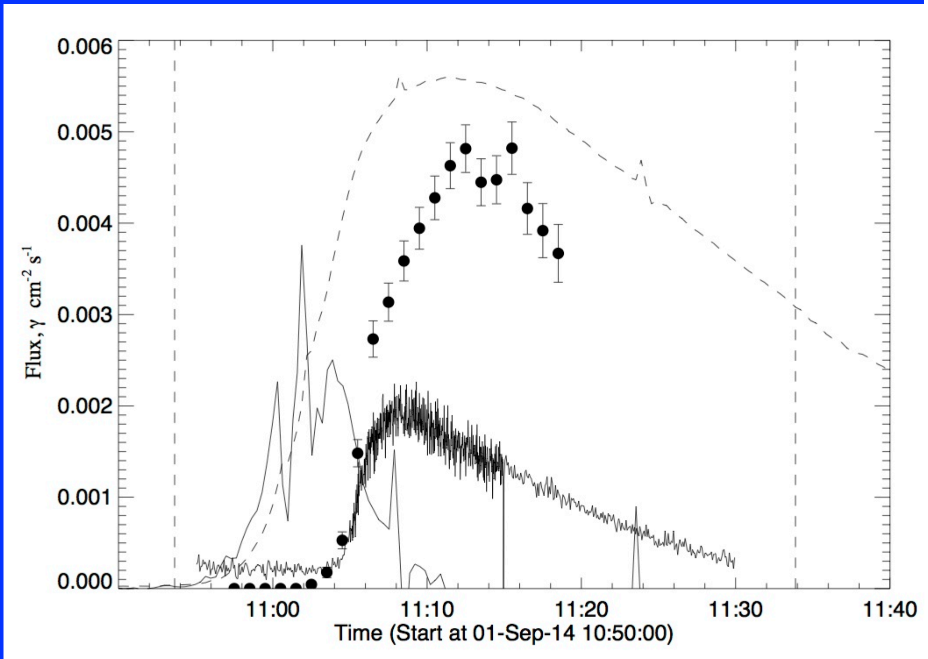
Using the LAT 'Light Bucket' solar fluxes on the RHESSI browser we have identified 13 new sustained emission events from June 2012 until the present. Two events are associated with flares at heliocentric angles >80^o where gamma-ray attenuation is strong, again suggesting that the interaction site may not have been at the flare footpoints.

Two of the events occurred for flares beyond the limb at E106^o (2013/10/11 Pesce-Rollins et al 2014) and E138^o (Pesce-Rollins et al. 2015 and previous talk).

Where measurements are available, all of the sustained emission events are associated with impulsive phase >100 keV emission and all but one, 2013 October 25 are associated with >800 km/s CMEs.

DETAILED TIME PROFILES OF BEHIND THE LIMB EVENTS





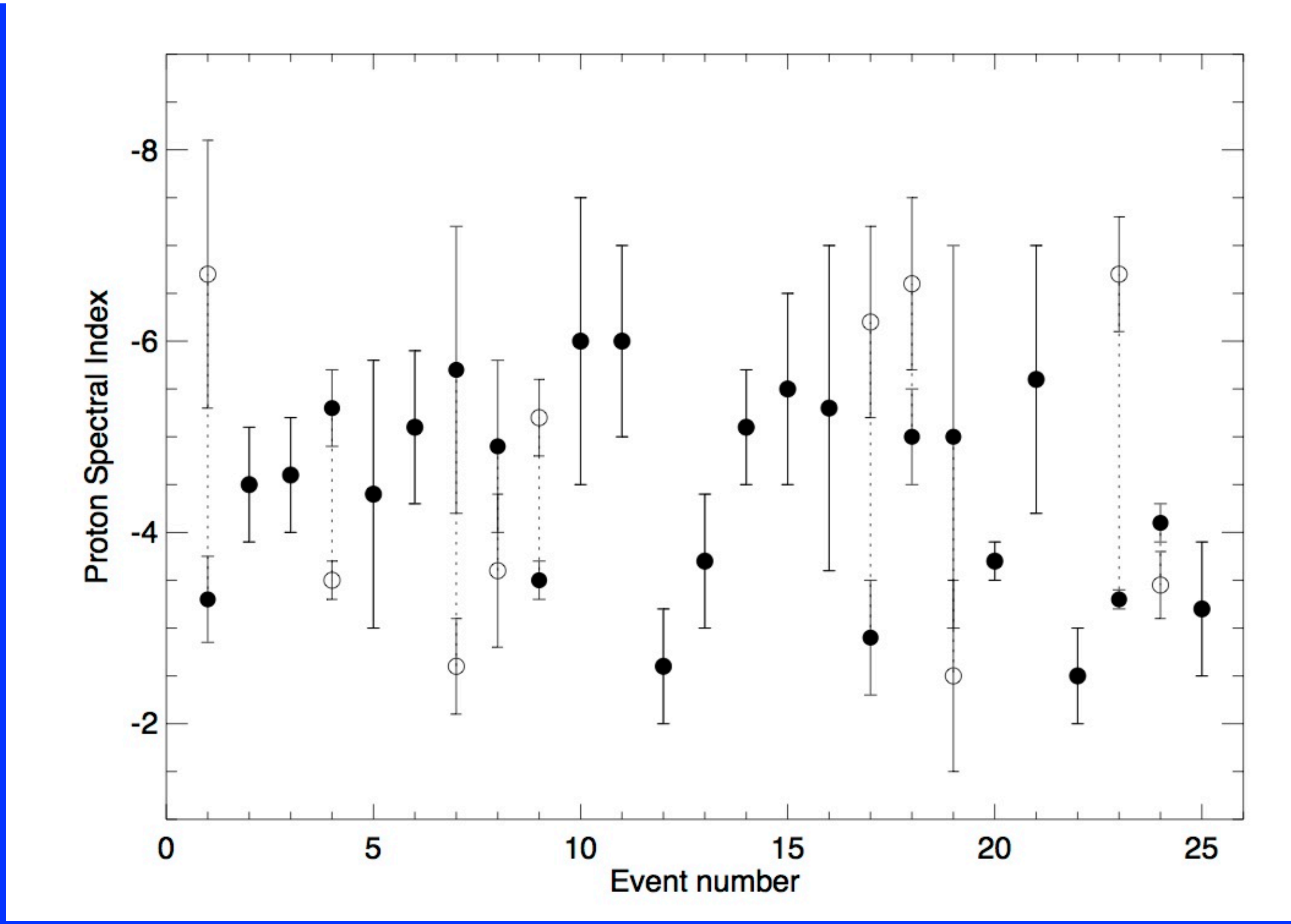
Flare site about 15° behind East limb. GOES dashed curve. MESSENGER/SAX soft X-rays (red dots) and derivative (green dots) reflecting impulsive HXRs. HXRs at flare site starts before rise in 100-300 keV flux observed by GBM. Suggests that emission is coming from source rising above limb of Sun. Note clear delay in rise of >100 MeV emission.

This was one of the most intense events observed by LAT even though it was 40° behind the limb. 1-min accumulation LAT data points and arbitrarily scaled 100 -- 300 keV count rates observed by GBM. The dashed curve shows the soft X-ray profile measured by MESSENGER/SAX. The dashed vertical lines show the inferred GOES start/stop times. The solid curve shows the derivative of the soft X-ray flux that is a proxy for the impulsive hard X-rays.

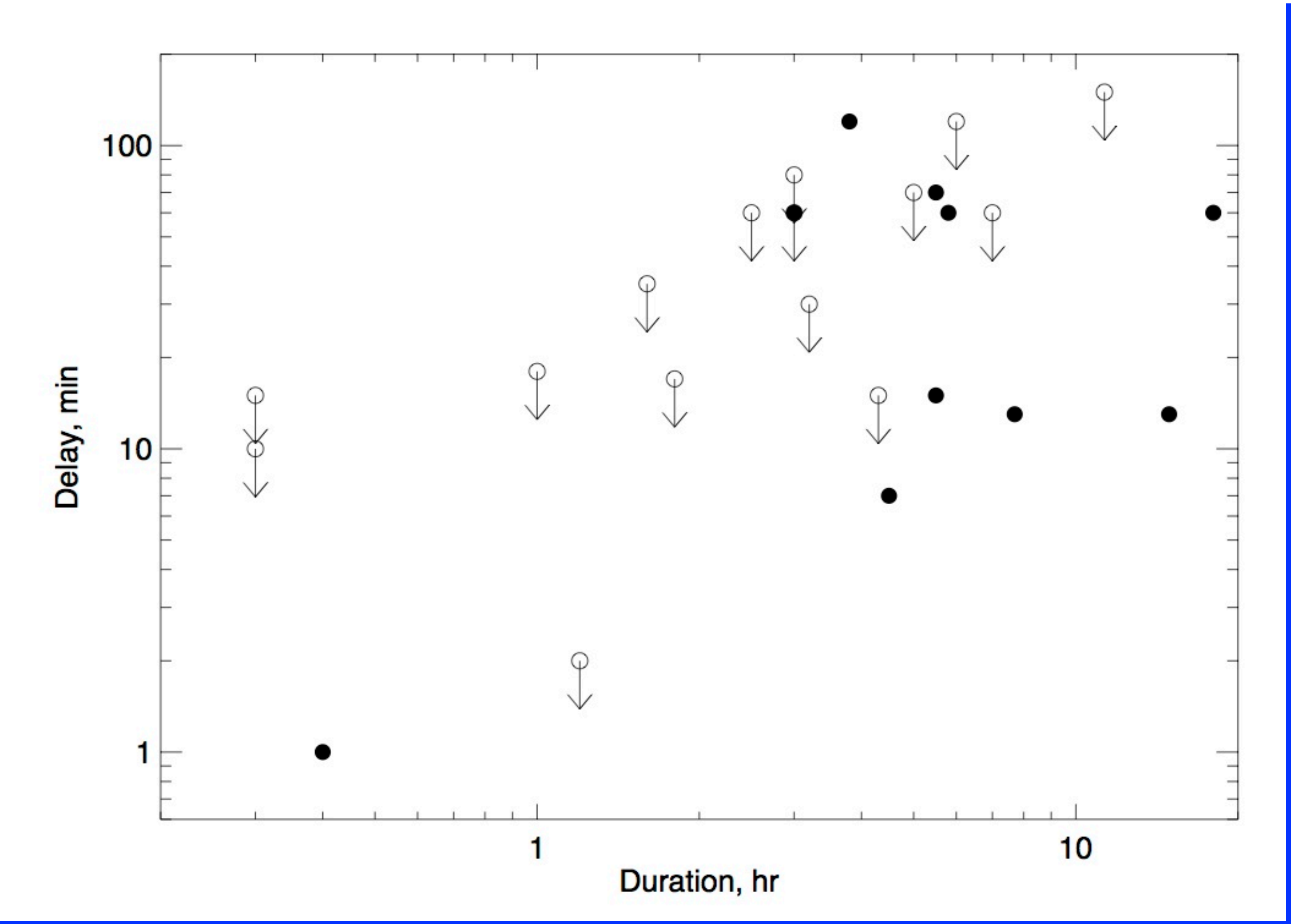
Table 5. Characteristics of LAT Detected Events

Date yyyy/mm/dd	Time Delay* Minutes	LAT Observed Interval, UT	Flux >100 MeV $10^{-4}\gamma$ cm^{-2} s^{-1}	Index	Emission Interval, UT	10^{28} Protons >500 MeV
2011/03/07	$\leqslant$13	20:10–20:39	0.17 ± 0.03	–3.3 ± 0.45	20:10–20:39	0.1
		23:21–00:03	0.29 ± 0.03	–4.1 ± 0.4	20:39–00:03	1.6
		02:32–03:13	0.35 ± 0.03	–4.3 ± 0.4	00:03–03:13	2.4
		05:43–06:25	0.14 ± 0.02	–6.7 ± 1.4	03:13–06:25	2.0
					06:25–11:00	1.1
					20:10–11:00	7.2 ± 2.1
		M3.7 flare			19:58–20:06	<0.07
2011/06/07	<80	07:48–08:19	0.29 ± 0.03	–4.5 ± 0.6	07:00 – 08:20	0.5
					08:20–10:00	0.6
					07:00–10:00	1.1 ± 0.4
		M2.5 flare			06:24–06:45	< 0.2
		SEP				12 ± 4
2011/08/04	<60	04:56–05:37	0.28 ± 0.03	–4.6 ± 0.6	04:10–05:10	0.4
					05:10–07:10	0.8
					04:10–07:10	1.2 ± 0.3
		M9.3 flare			03:48–04:00	< 0.1
		SEP				15 ± 7.5
2011/08/09		08:00–12:00	< 0.03		08:00–12:00	< 0.3
		X6.9 flare	1.2 ± 0.2	–5.0 ± 0.7	08:02–08:08	0.4

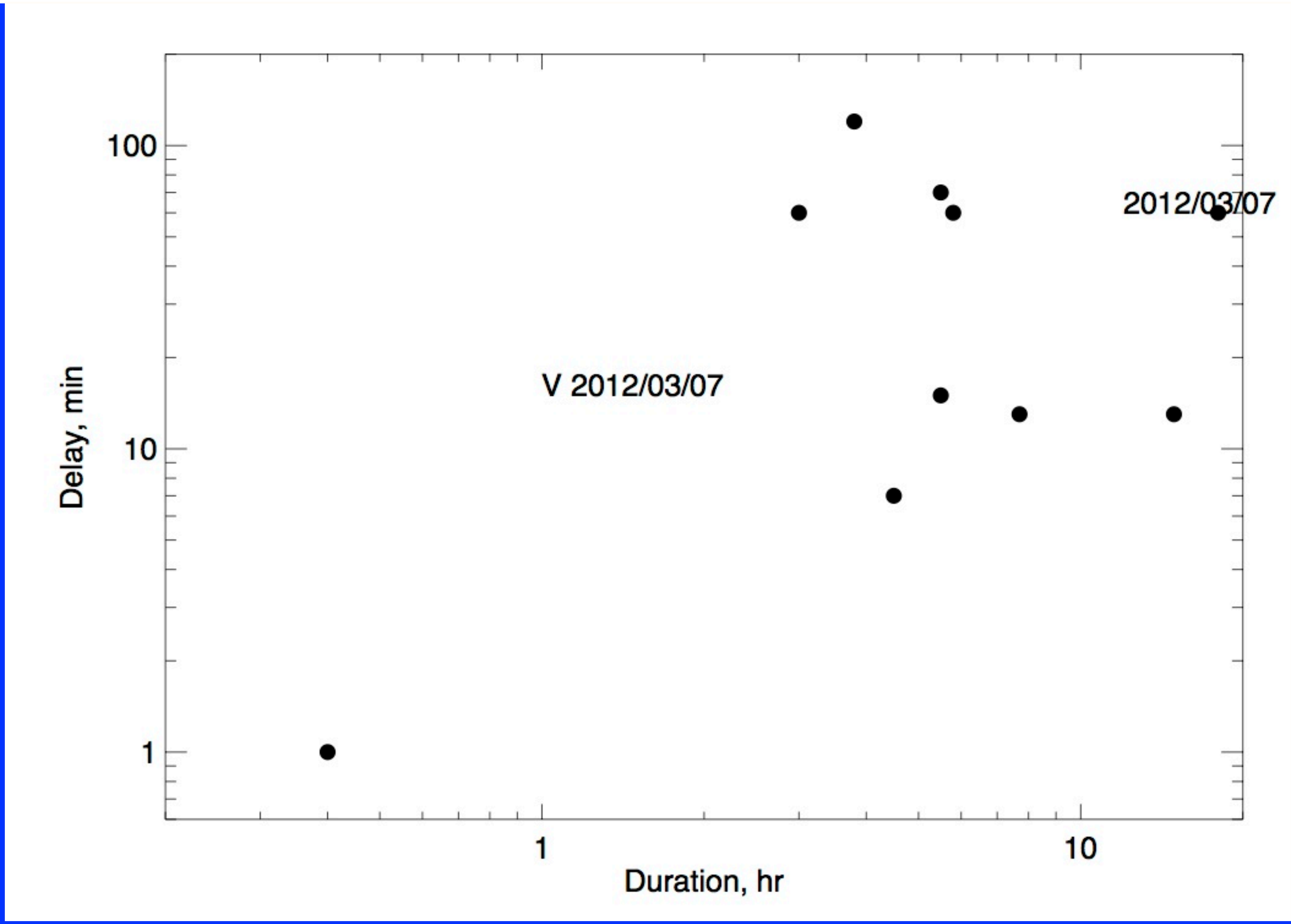
We have fit the spectra of the 26 sustained emission events to obtain >100 MeV fluxes, spectral indices and numbers of >500 MeV protons at the Sun. We have also fit impulsive phase data from LAT, GBM, and RHESSI to obtain similar estimates. Allan Tylka has obtained estimates of the numbers of protons >500 MeV in SEPs.



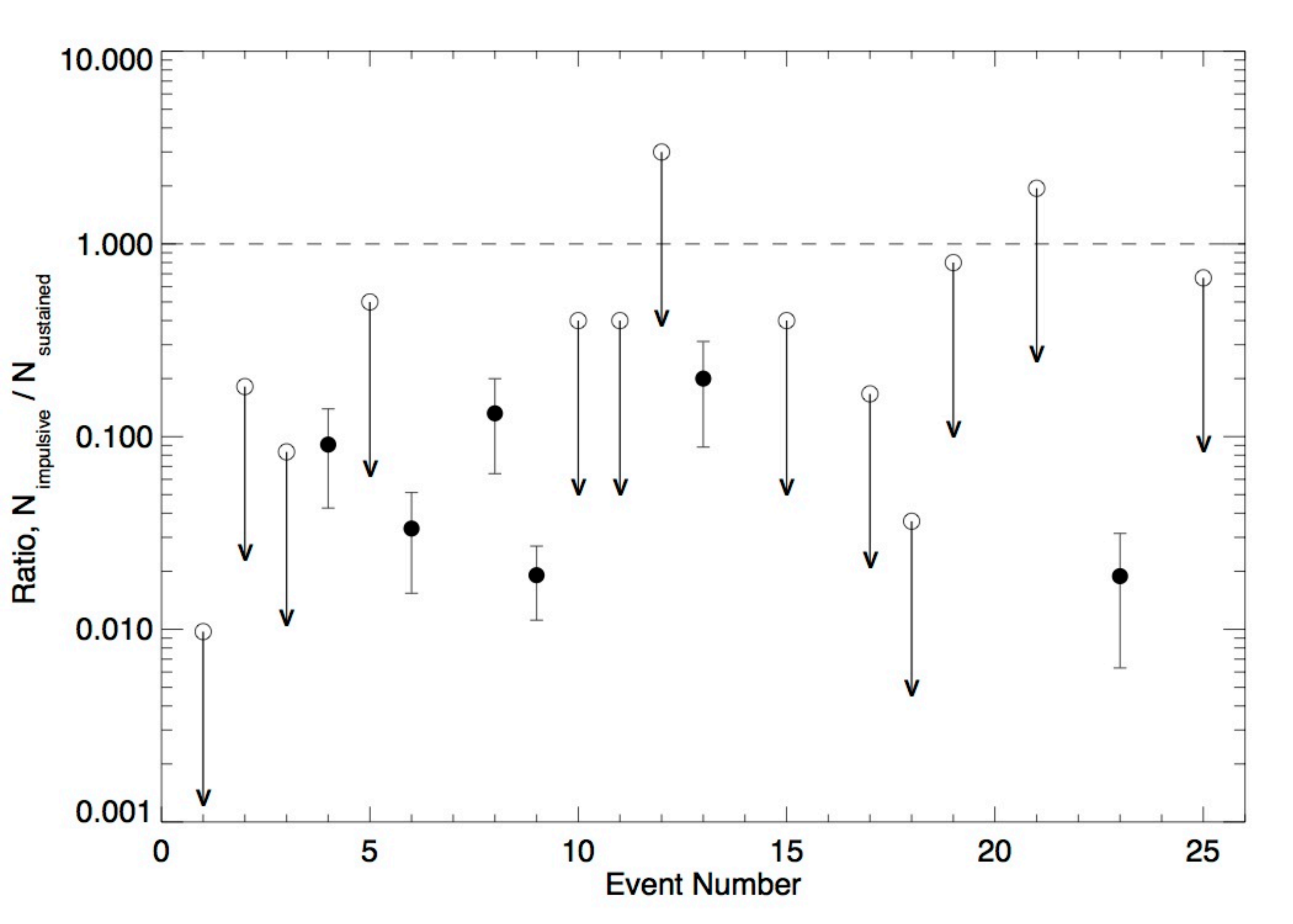
Estimated spectral indices of >300 MeV protons producing sustained γ-ray emission based on fits to the Fermi/LAT spectra. Solid circle: either the event averaged index or value of the first index in an event when the index events varied in time: 5 softened and 5 hardened. Average index –4.5



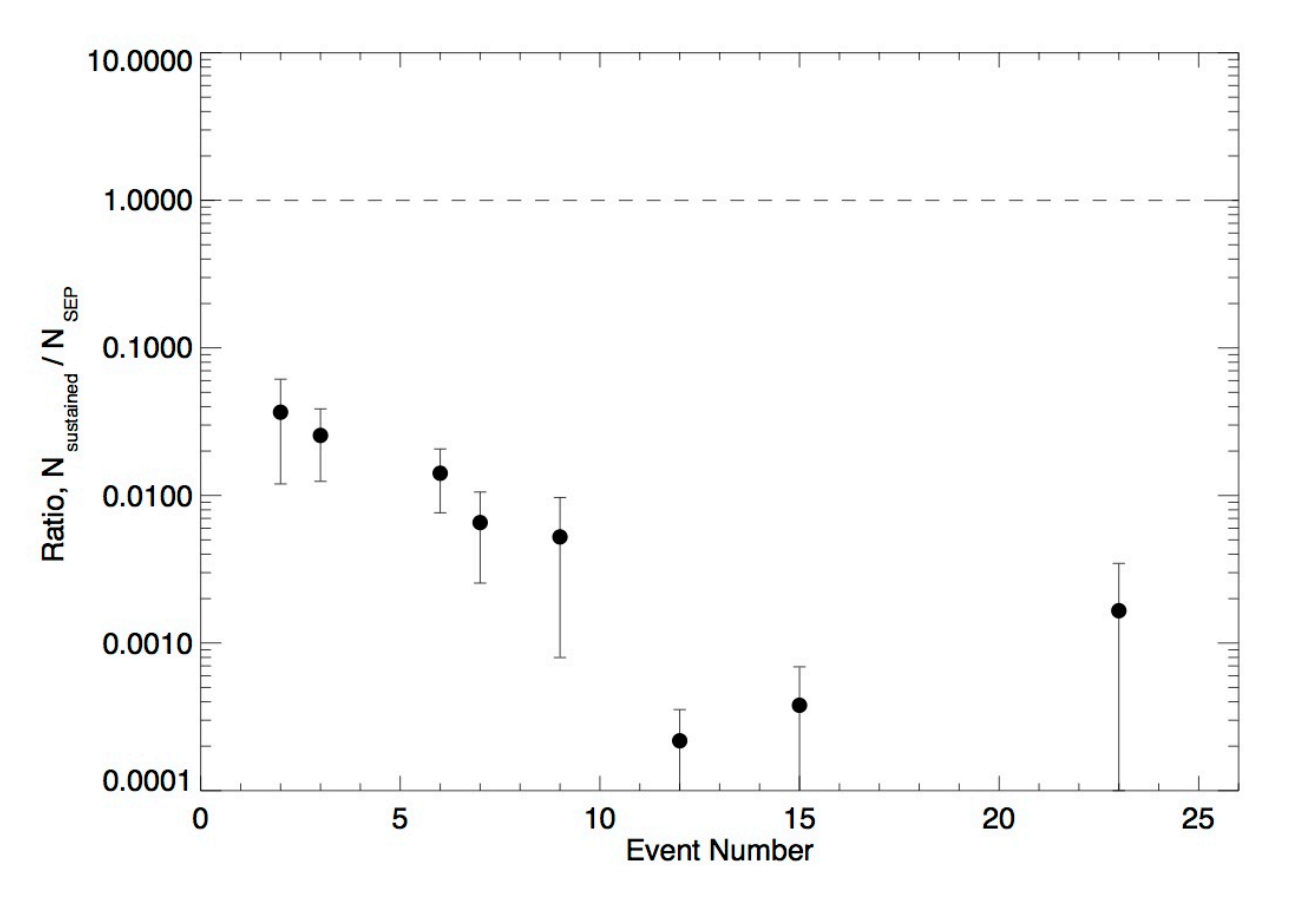
Delay of onset of sustained gamma-ray emission from the peak of impulsive phase vs duration of the sustained emission. Some durations are upper limits. Solid circle: delay measured. Open circle: Upper limit on delay. Orbital duty cycle effects limit accuracy. Delays can be as short as 1 min and as long as tens of min. Minutes long delays are compatible with SEP onset times but longer delays suggest a different origin, e.g. as SEP return. Durations can range from ~20 min to ~20 hrs. Evidence for a fast class of event?



2012 March 7 also had a 60 min duration event with <20 min delay and 20 times the number of protons in the preceding X5.4 flare. Are there two classes of events based on delay from the impulsive phase or is it due to duty cycle effects, e.g. one related to SEP onset and the other with SEP return from a reservoir (Tylka's talk). But durations of both classes of events appear to be similar.



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. Open circles: 95% confidence limits on impulsive phase protons. Average ratio is 8%. ➔ Flare is not the main energy source. Need another energy source ➔CME/SEP return.



Ratio of number of protons >500 MeV in the sustained gamma-ray emission phase to the number in the associated SEP (Allan) Tylka.

Average ratio about 1%.

Dates of events: (2) 2011/06/07, (3) /08/04; (6) 2012/01/23, (7) 01/27, (9) /03/07, (12) /05/17 (GLE; anomalously low ratio, although >300 MeV spectrum is hard), (15) 2013/04/11 (short duration event), (23) 2014/02/25

Summary and Questions

Sustained >100 MeV gamma-ray events appear to normally require a broad/fast CME and a flare with HXR >100 keV. One exception is 2012 October 23 where no CME observed. What is special about >100 keV HXR? Seed population of sub-MeV ions?

>300 MeV protons producing sustained emission typically interact within about 40° of the active region, but not necessarily at the HXR footpoints.

Onset times of the >300 MeV proton interactions range from ~1 min to tens of min after the peak of the HXR flare. Durations last from a few tens of minutes to 20 hours. Are there two classes of onset delays: <15 min and >50 min? Two different sources of protons: CME/shock and return SEPs? Acceleration in large loops (Ryan)?

Power-law spectral indices of >300 MeV protons range from -2.5 to -7 with average of -4.5. Five events show spectral softening in time and five show spectral hardening. Interpretation?

Numbers of >500 MeV solar protons producing sustained emission typically ten-times larger than those in impulsive flare, (including the 2012 October 23 flare without a CME). This suggests that another energy source (eg CME/shock or returning SEP particle flux) is required to produce the sustained gamma-ray emission at the Sun.

Number of >500 MeV protons producing sustained emission is only about 1% of the number in SEP events. Variable ratio.

For 2012 March 7 sustained emission proton spectrum is harder than a power-law with index -3.7 between 40-300 MeV and steepens to an index of about -4.5 above 300 MeV.

Put event dates on all the points of the slides
Two classes of onset times-CME/Shock, SEP return?

Where does the 10/23/12 plot fall on the delay/duration plot? Only limits
Check Li and Lee ApJ paper on hardening spectrum below 20 MeV in SEPs