Characteristics of Thirty Second-Stage >100 MeV γ-Ray Events Accompanying Solar Flares[a]

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[a] ApJS in review, arXiv 1711.01511v1

We acknowledge the Fermi LAT Team for the excellent performance of the instrument and quality of the data. Special thanks to Melissa Pesce-Rollins, Nicola Omodei, and Eric Grove

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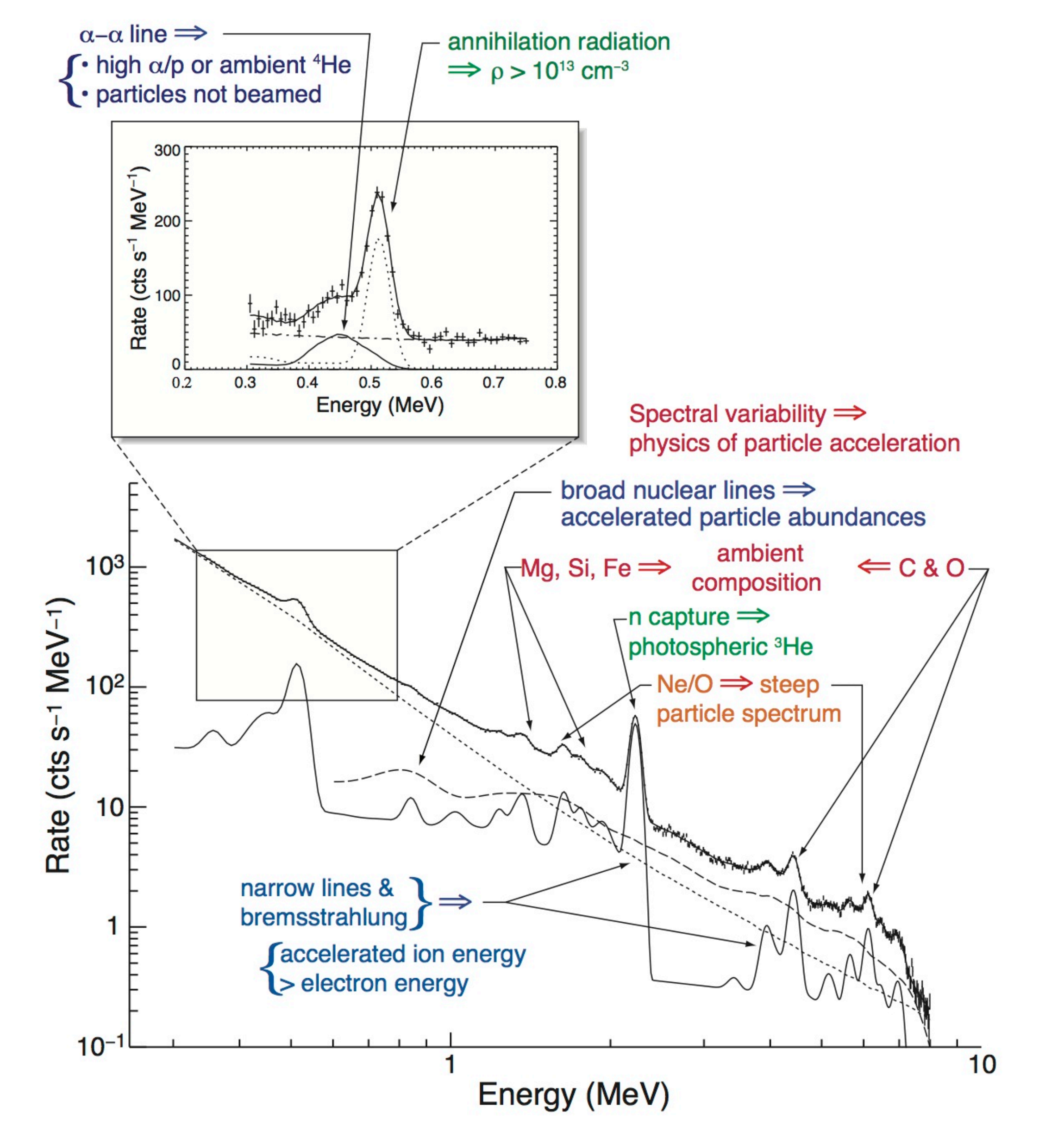
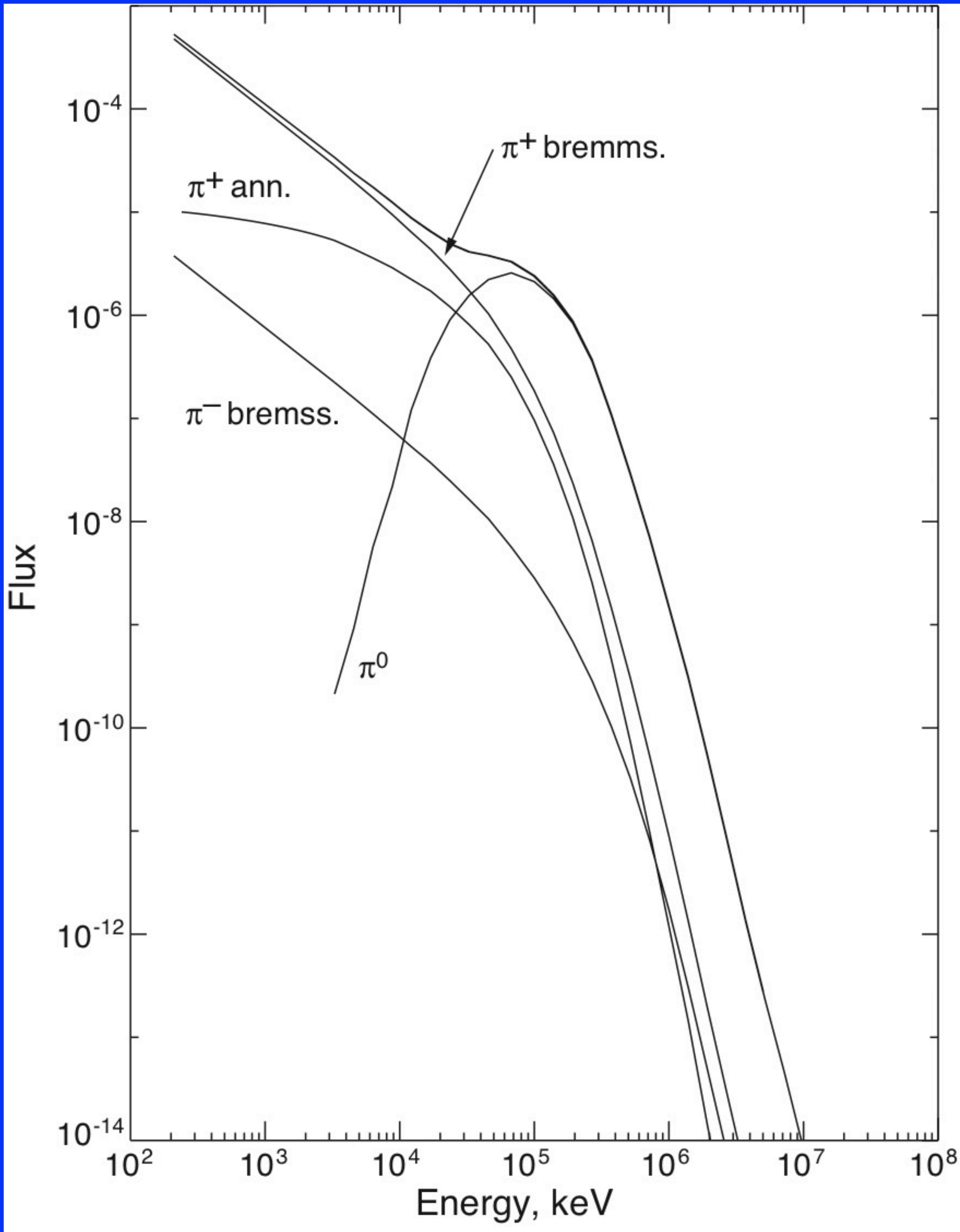
What γ-Rays Tell us About Accelerated Particles at the Sun

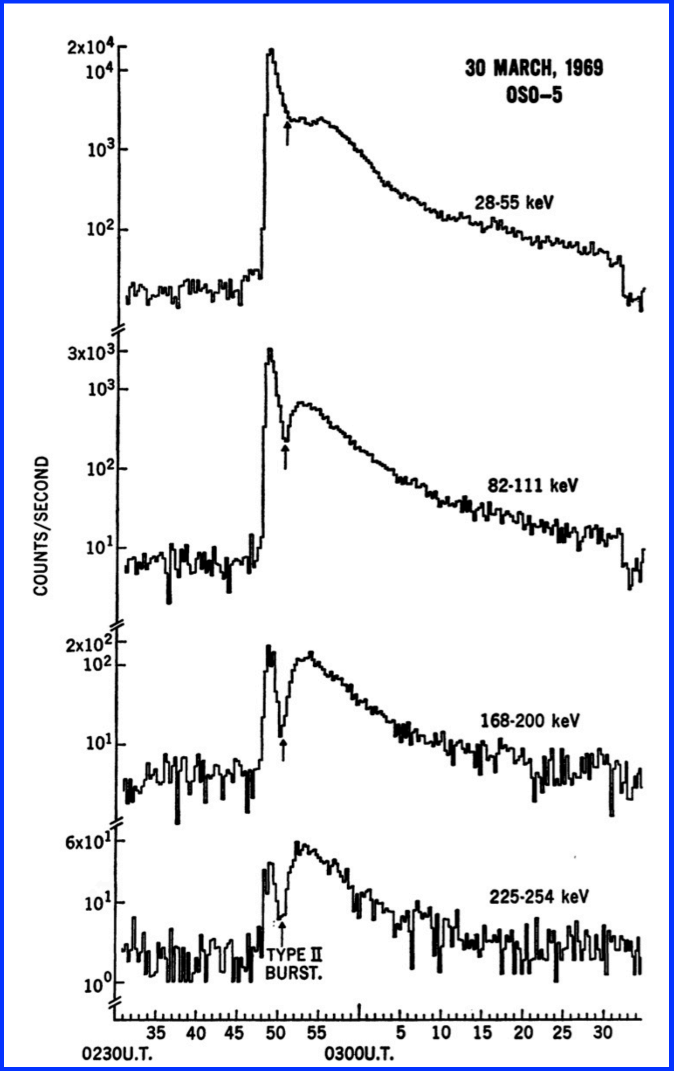
Summed γ-ray spectrum between 0.3 and 8 MeV from 19 solar flares observed by SMM. The contributing components are identified: electron bremsstrahiung, narrow nuclear lines from p's and α's, broad lines from heavy ions, e^+-e^- annihilation line, neutron capture line, and α-α fusion lines.



Calculated pion-decay spectrum from >300 MeV p-H and >200 MeV/nucleon α/H interactions (Murphy, Dermer, & Ramaty 1987) showing the contributions from neutral and charged pion decays for an isotropic angular distribution. The pion-decay emission below the peak at ~70 MeV is dominated by both bremsstrahlung and annihilation in flight of positrons from positive pion-decays. At energies >100 MeV gamma rays from neutral pion decays dominates.

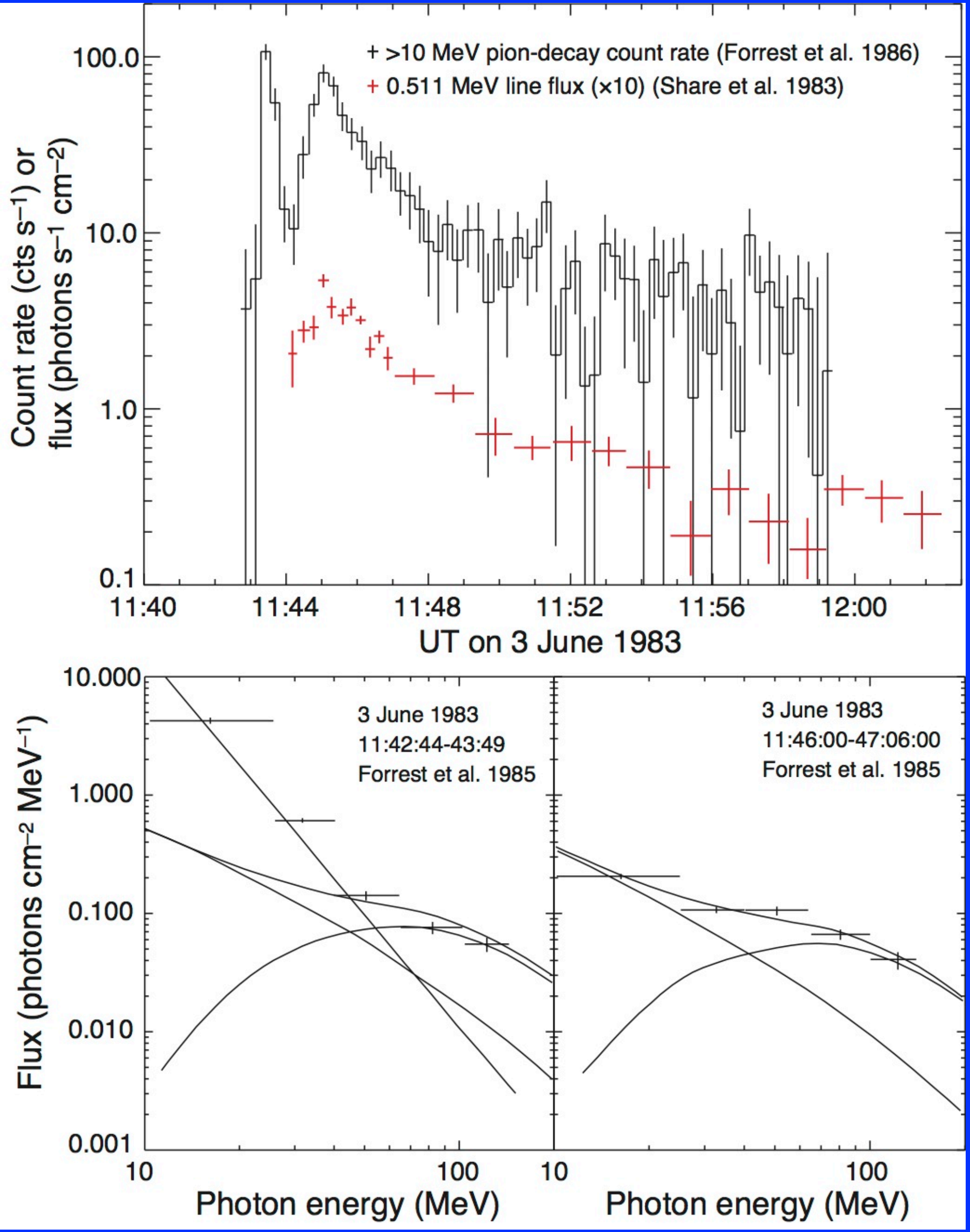


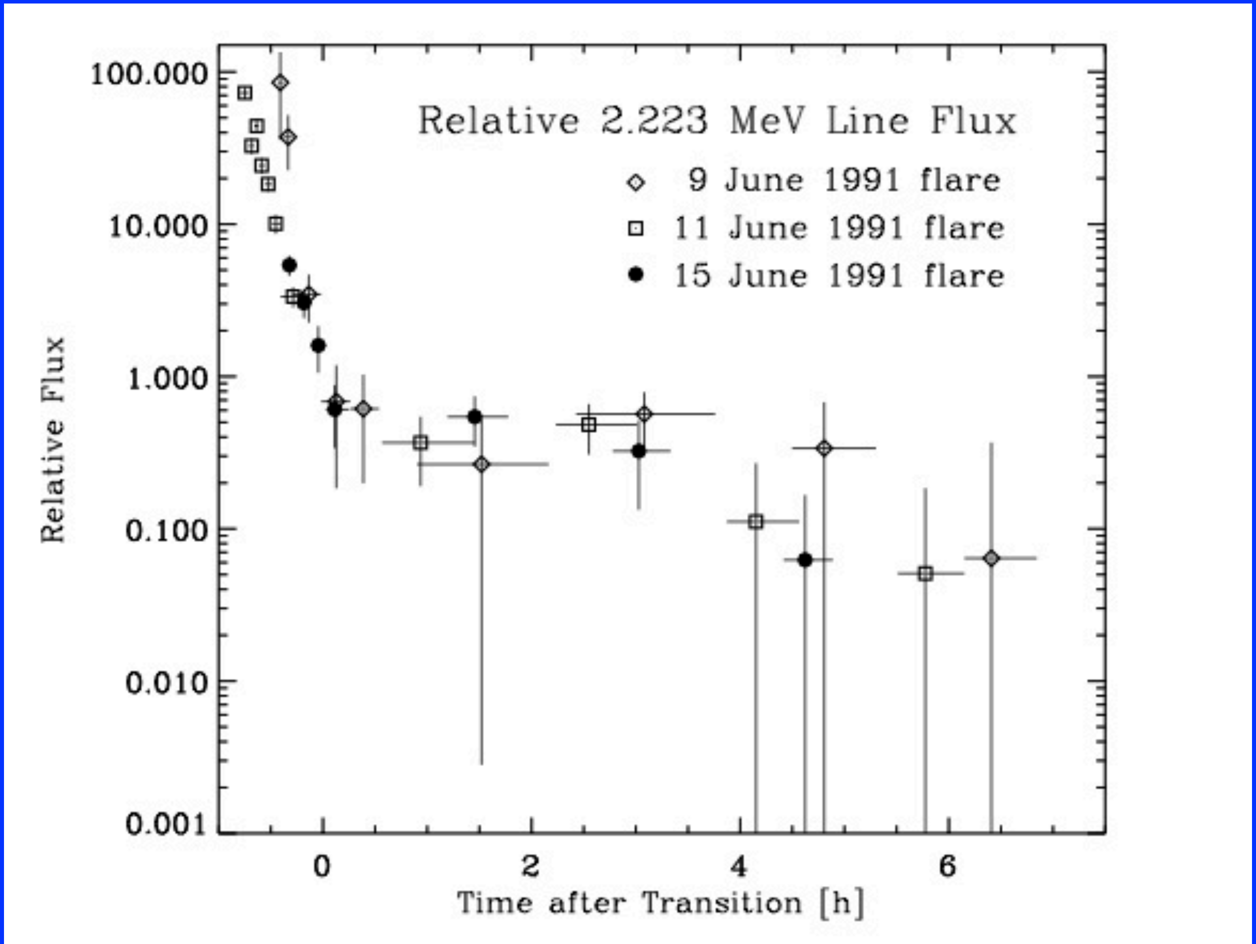
There is a history of flares with what appear to be two stages of emission: impulsive and time extended. First example observed by Frost and Dennis (1971). The second stage is clearly harder and they suggested it might be due to particle acceleration in a shock front.



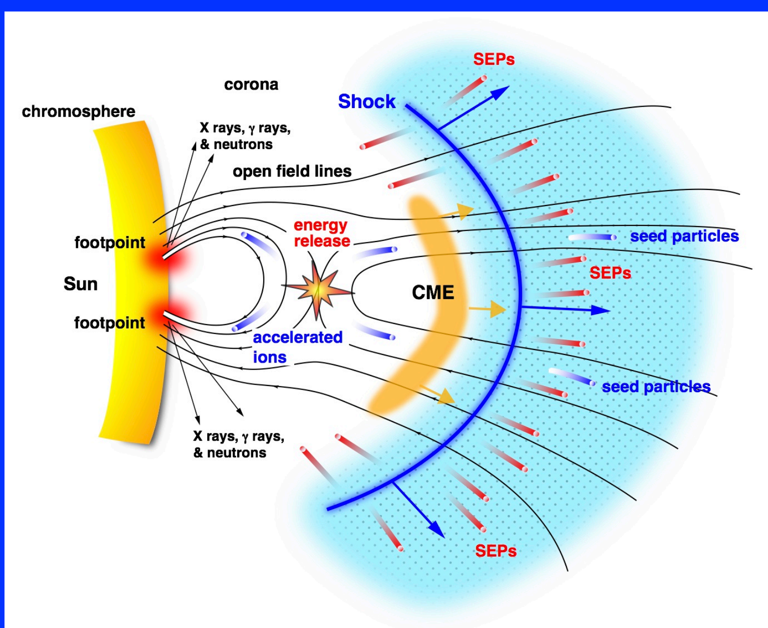
The 1982 June 3 flare observed by the *SMM* GRS was first to exhibit these two stages above 10 MeV. The measured spectra in both phases exhibit pion decay components.

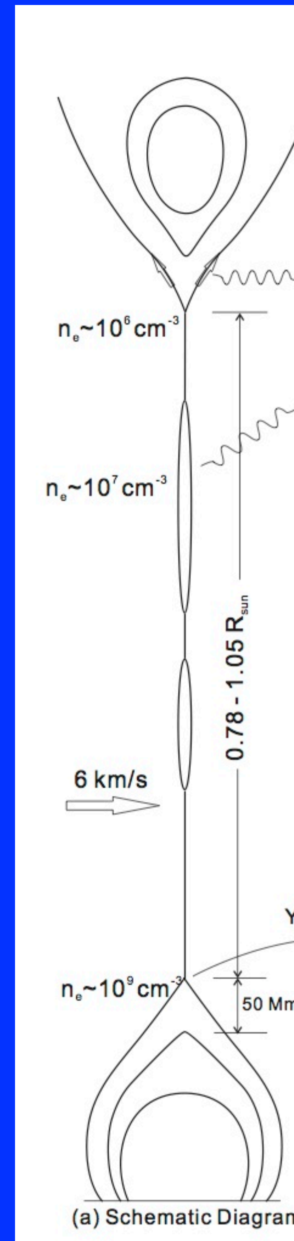
The presence of an annihilation line with similar time profile is consistent with a pion origin.





Other gamma-ray events observed in the 1980's and 1990's contained these two component, e.g. 2.223 MeV line observations from Comptel Rank et al 2001. This provided evidence for the nuclear origin of the events. Long Duration Gamma Ray Flares (LDGRFs) were characterized by Ryan (2000) as those that have long term hard X-gamma-ray and neutron emissions extending well after (hours) after the impulsive phase. See also Chupp and Ryan (2009). All the accompanying flares were X-class.





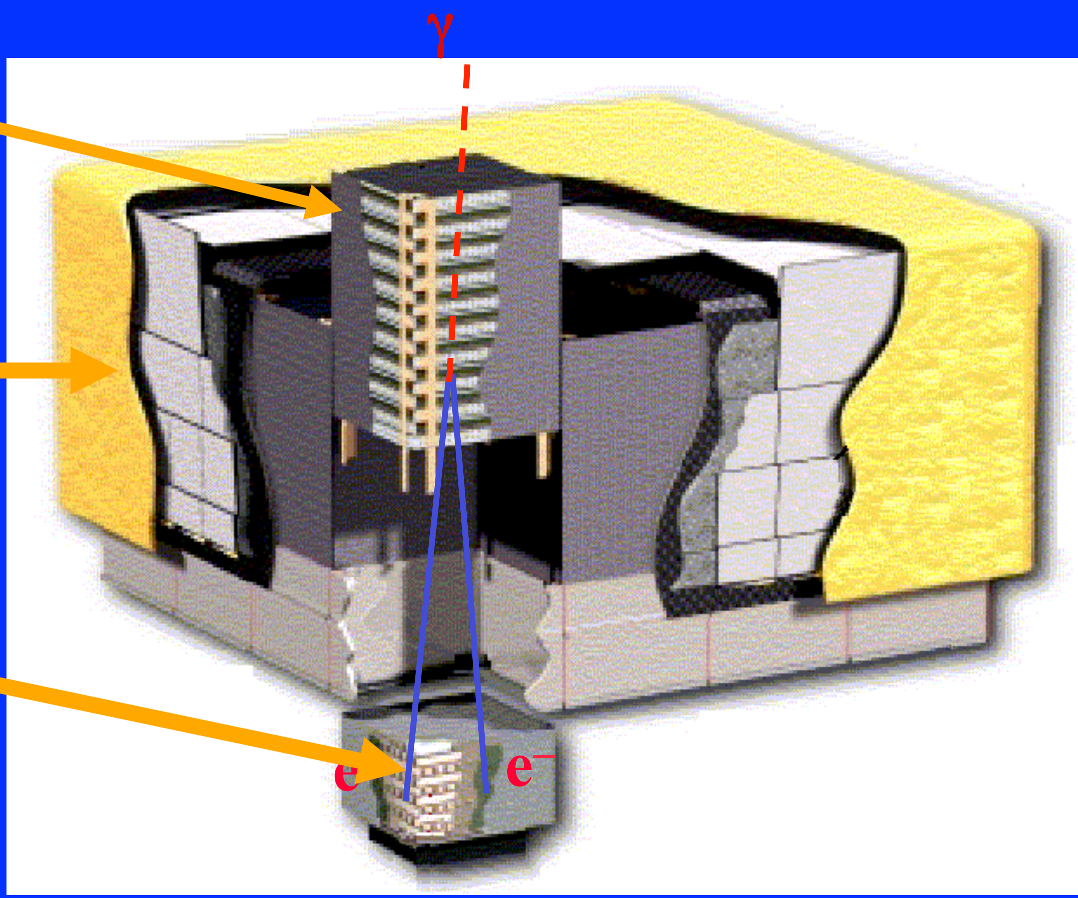
Three possible origins suggested: continuously accelerated ions from impulsive phase population in turbulent magnetic loops, downstream particles from CME shock, and particles accelerated by reconnection in the current sheet produced behind the receding CME.

Fermi Changes the Ballgame

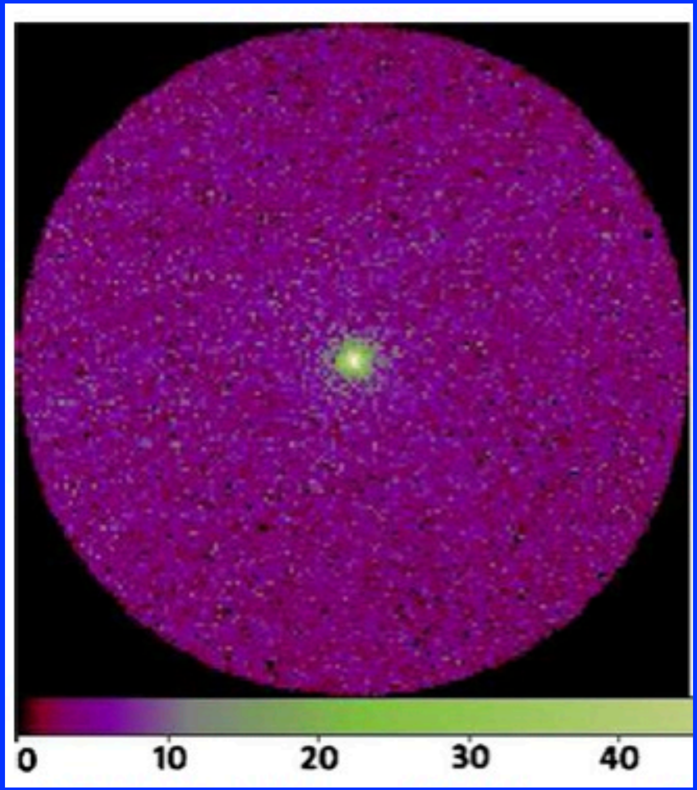
Precision Si-strip Tracker

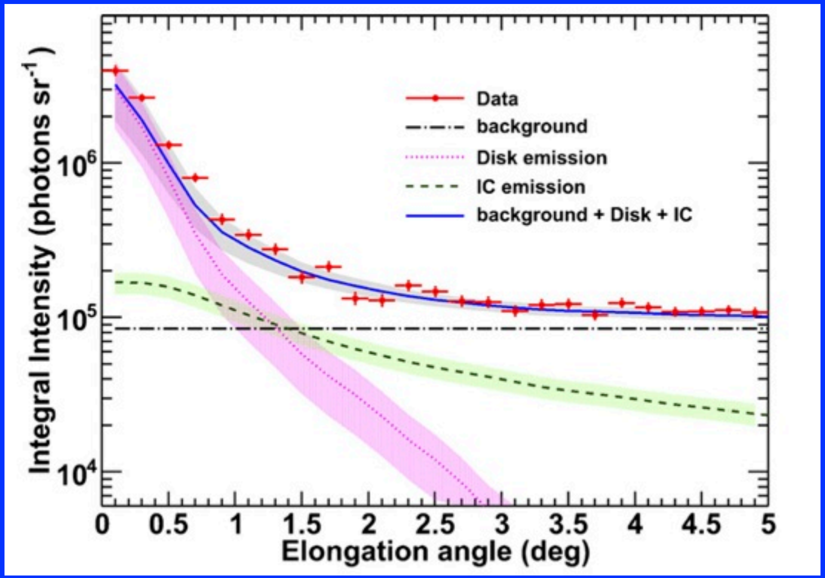
Segmented Anticoincidence Detector

CsI Calorimeter



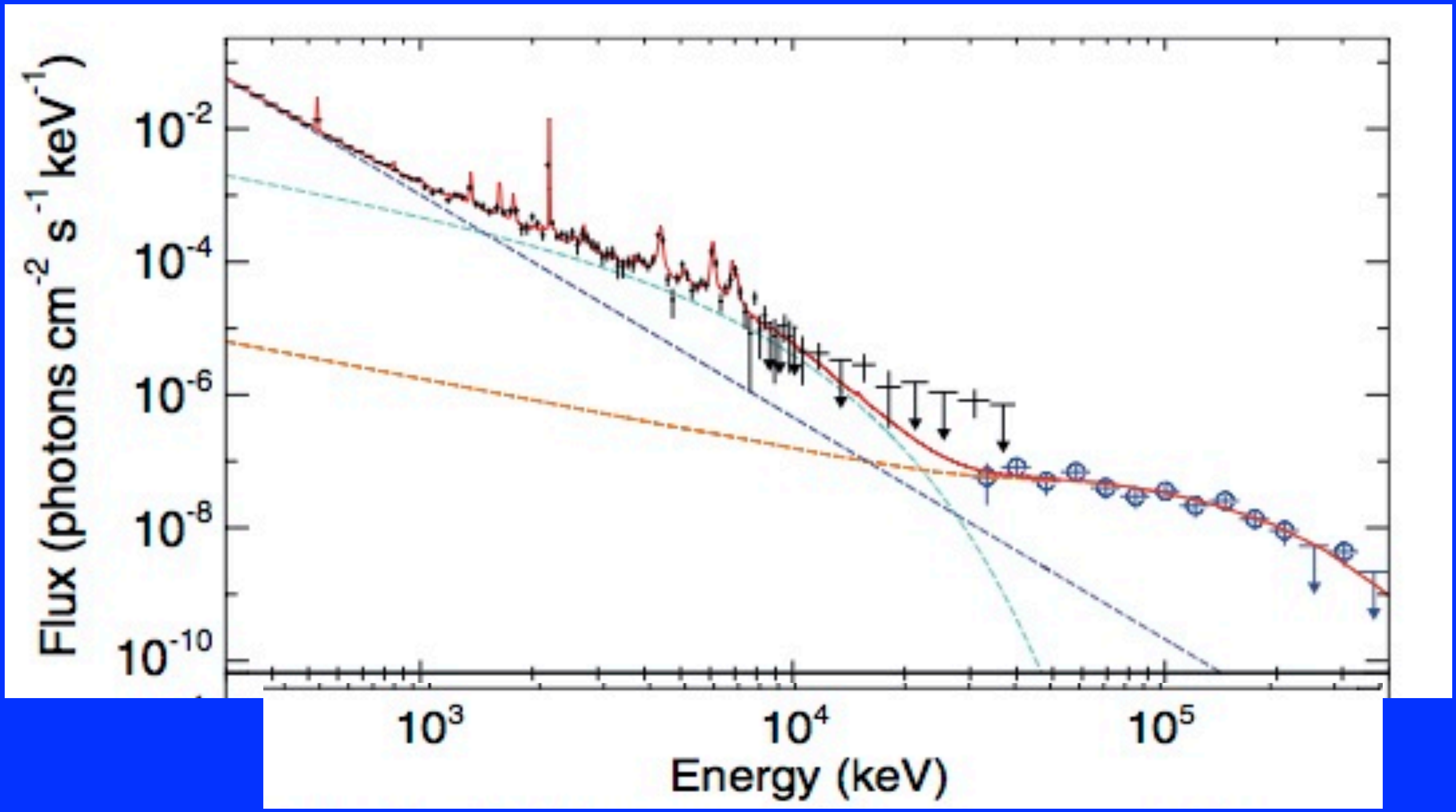
FERMI: Most sensitive space detector for gamma rays with energies 30 MeV - >300 GeV. Detects quiescent solar emission on a near daily basis.



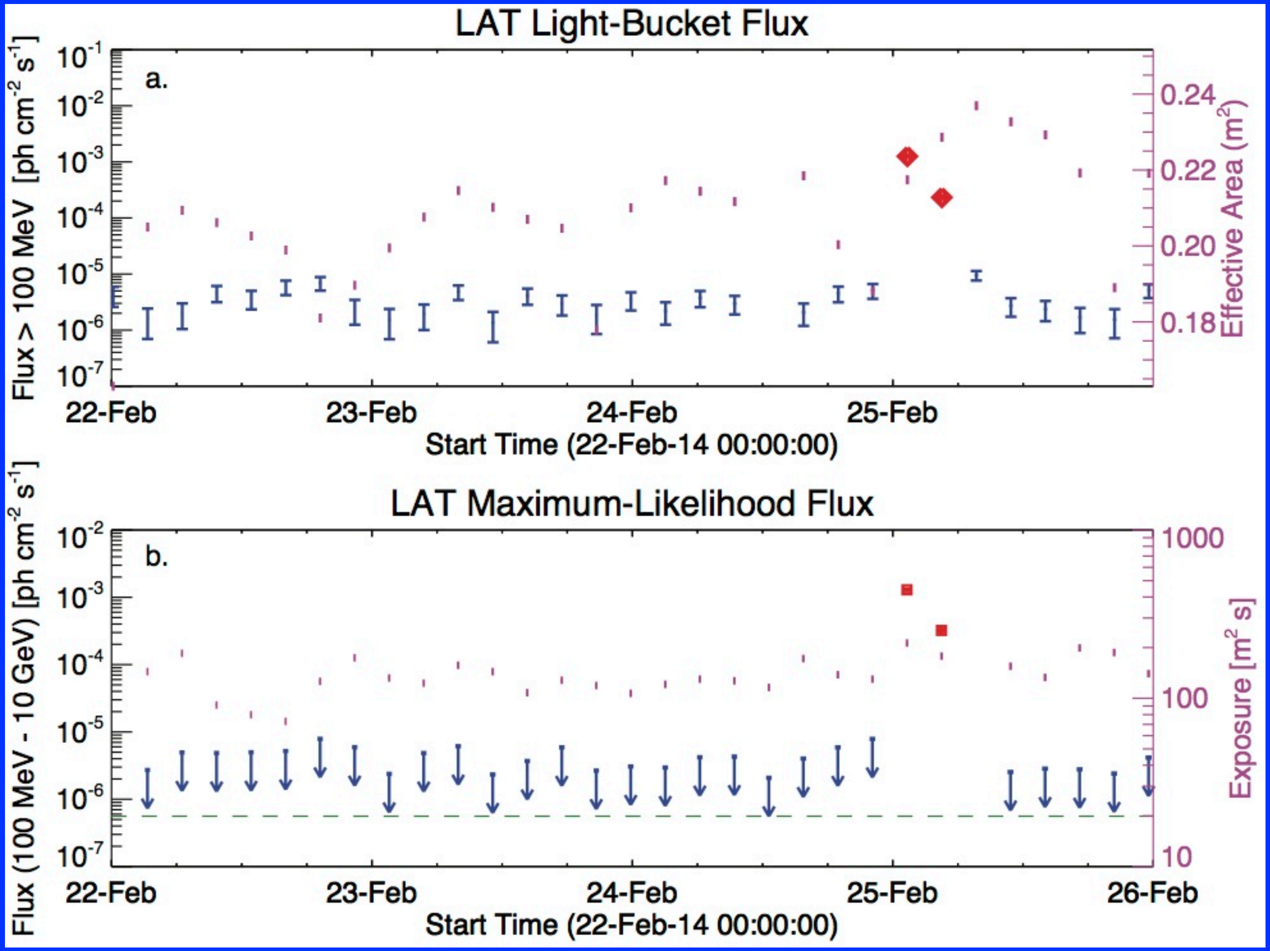


Fermi LAT is so sensitive that it observes quiescent solar emission on a near daily basis that originates from cosmic-ray proton collisions in the photosphere (producing pion-decay radiation) and from Compton up-scattering of solar blackbody photons by cosmic-ray electrons. Background in public data almost entirely due to galactic and extragalactic point sources and diffuse components.

Gamma-ray Spectrum of an Impulsive Flare



Composite GBM/LAT spectrum of the impulsive phase of the 2010 June 12 flare (Ackermann et al. 2012). The flare proton spectrum is consistent with a series of power laws with indices ~3.2 from 3-50 MeV, ~4.3 from 50-300 MeV, and softer than 4.5 >300 MeV. No time-extended second stage was observed.



Example of our-day plots of >100 MeV solar gamma-ray fluxes covering the whole mission that are on the RHESSI Browser. Top panel: simple 'light-bucket' accumulation of photons within a 10° circle of the Sun. The data can be analyzed using standard analysis tools operating under SSW/OSPEX. Lower panel: LAT team Maximum Likelihood plots. Impulsive phase flares can be missed because of ACD effects.

32 sustained emission or second stage acceleration events were discovered in LAT data from 2008-2017 (including two in September not included in Table).

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	–[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]

[a] *STEREO A*

[b] *STEREO B*

[c] *RHESSI*

[d] *Fermi*/GBM

[e] Missing HXR data due to night time or SAA passage

[f] Preceding SEP

[g] *INTEGRAL*

[h] CACTUS

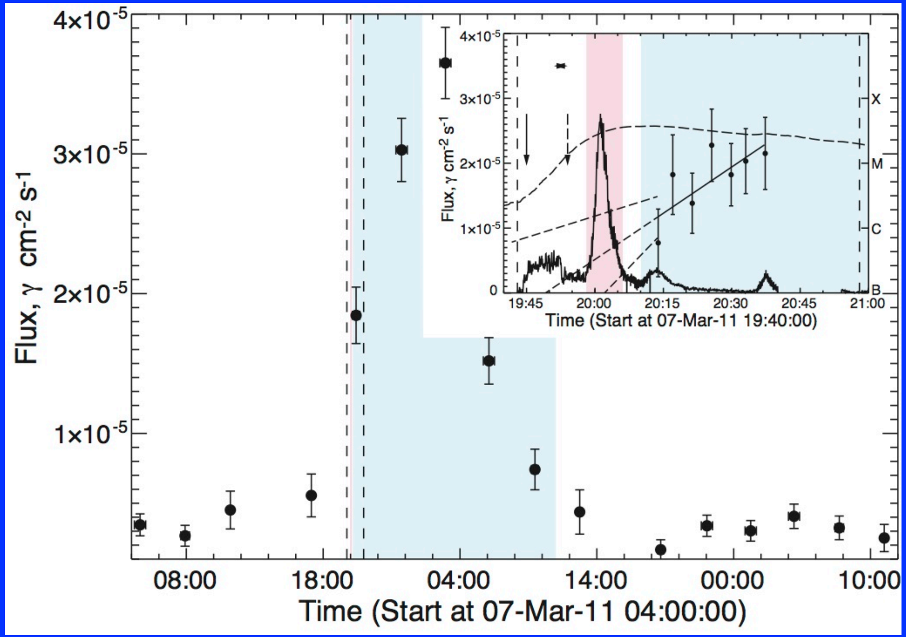
[i] Pesce-Rollins et al. (2015b)

[j] flare behind solar limb

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

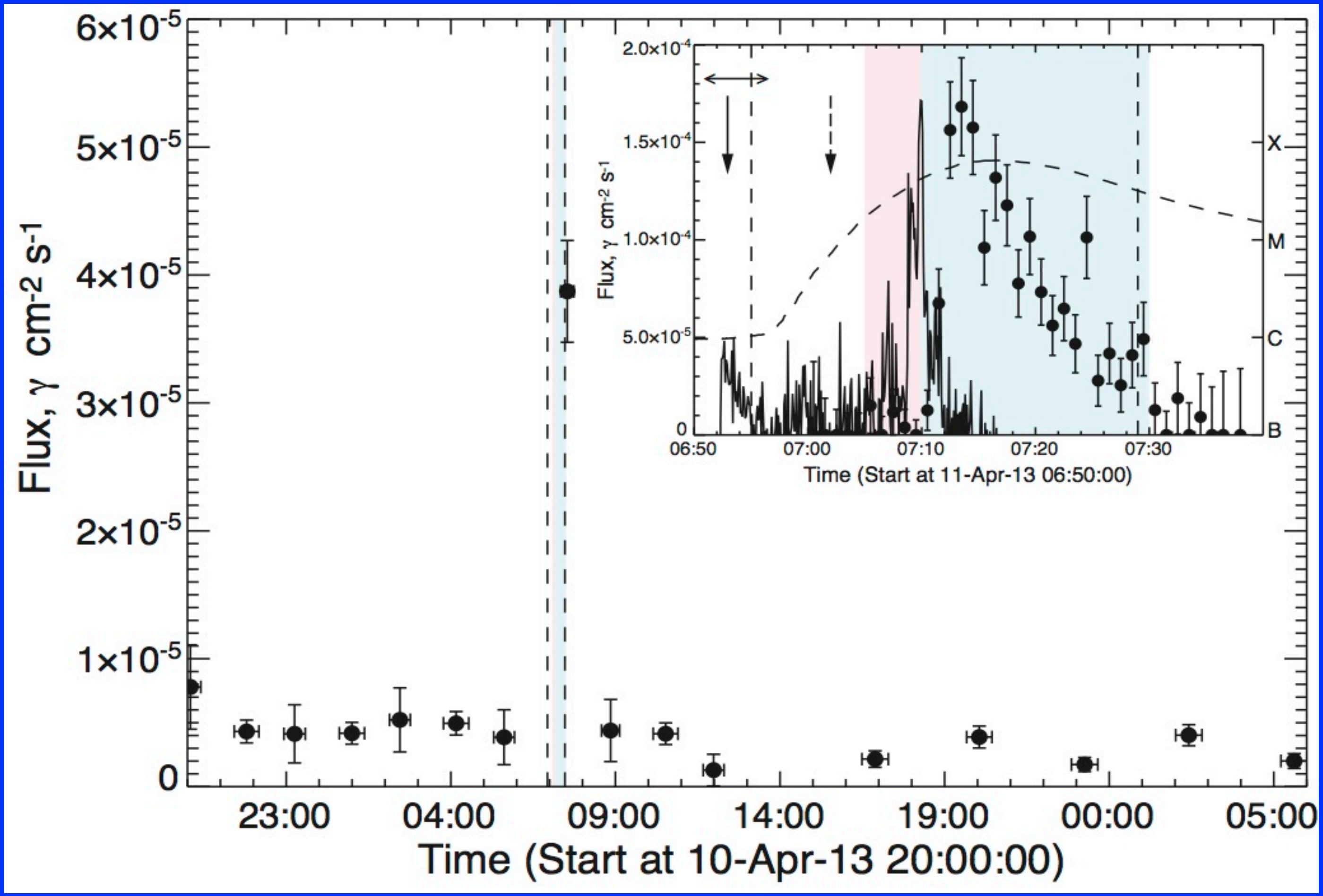
Representative Time Histories of SSGRE Events

Fermi/LAT has only detected three other impulsive flares with protons producing pion-decay γ-rays, but it has detected 32 >100 MeV events with time-extended emission that Ackermann et al. (2014) called sustained emission. The first such event is plotted.
We identifiy them as
Second Stage Gamma-Ray Emission (SSGRE) events,
We feel that this is a more appropriate name than Long Duration Gamma-Ray Flares because they have temporal and spectral characteristics distinct from the accompanying impulsive flare, and, although they most often extend well past the end of the flare, they are not always of long duration.

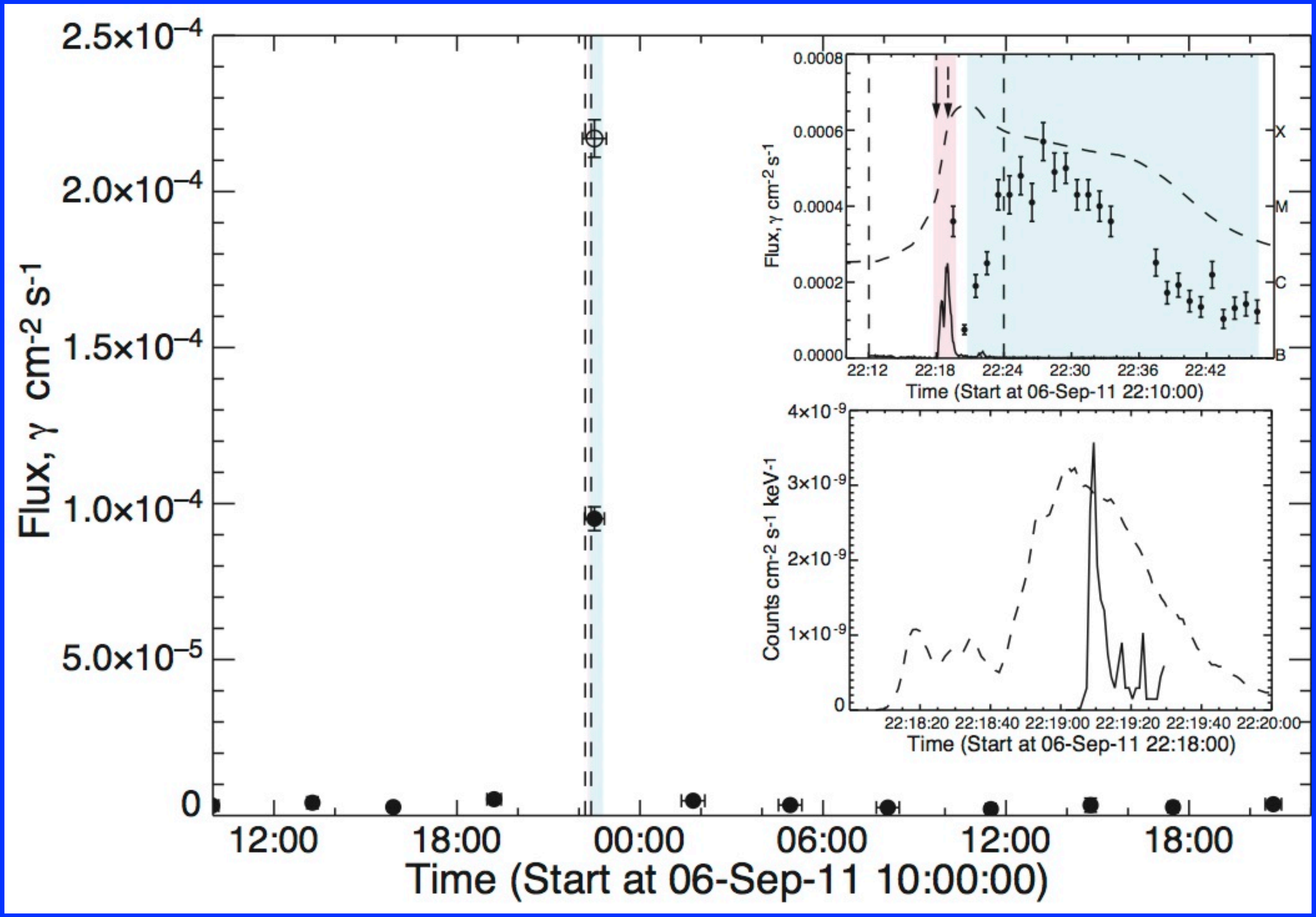


SSGRE can begin within a minute of CME onset and up to two hours later.

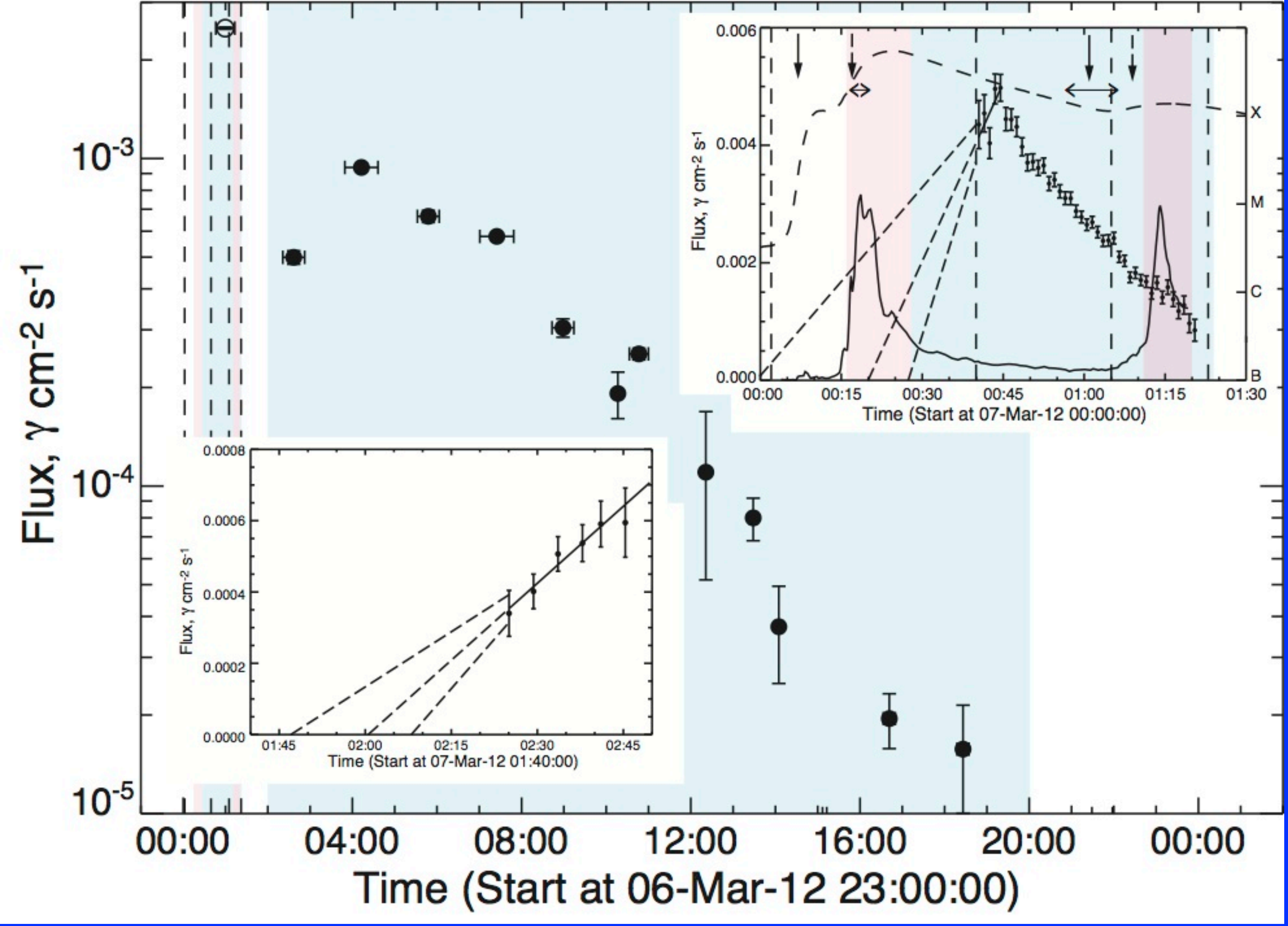
SSGRE have durations of 4 minutes to 20 hours.



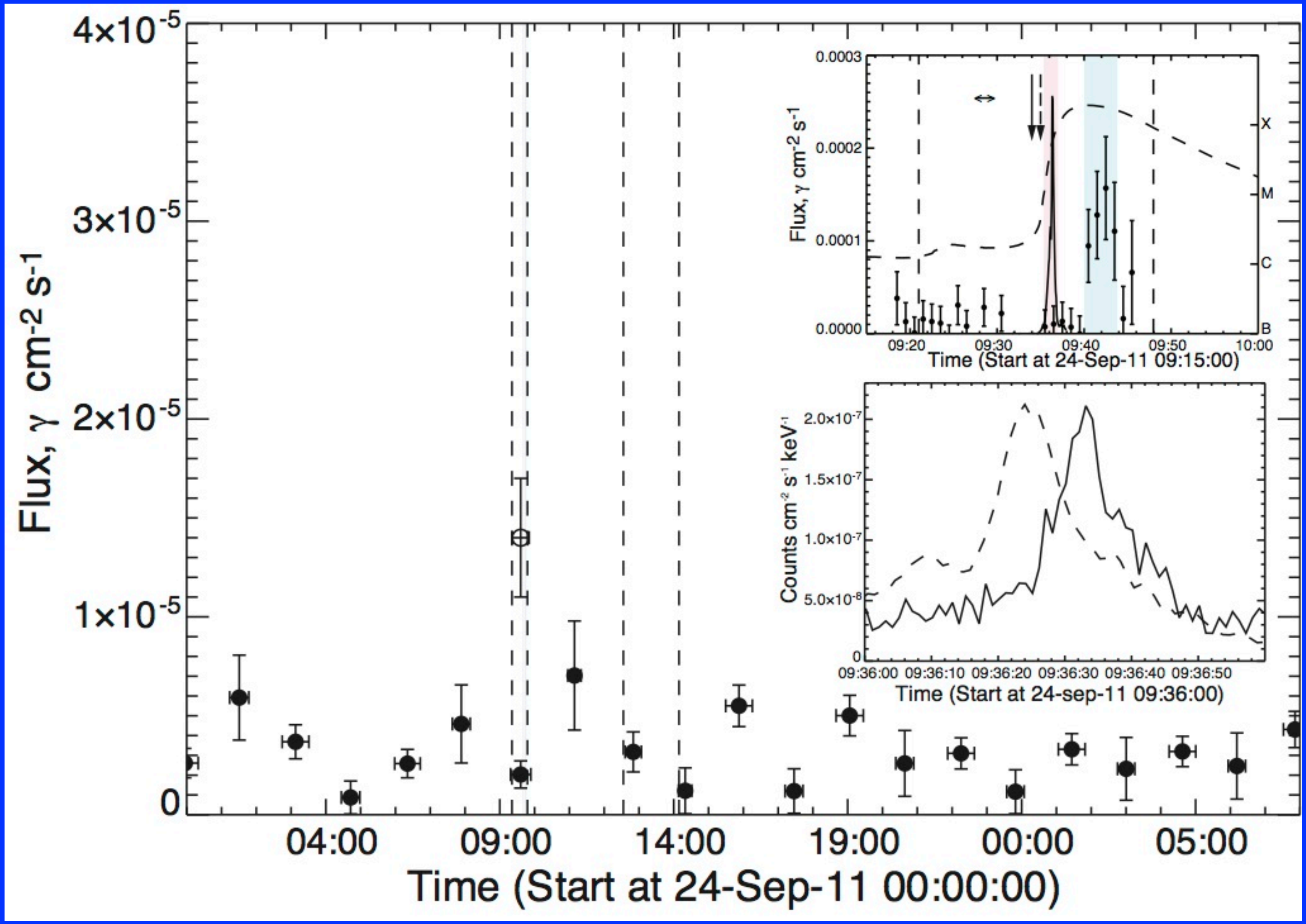
No evidence for >100 MeV γ-rays during impulsive flare. SSGRE begins just after the flare.



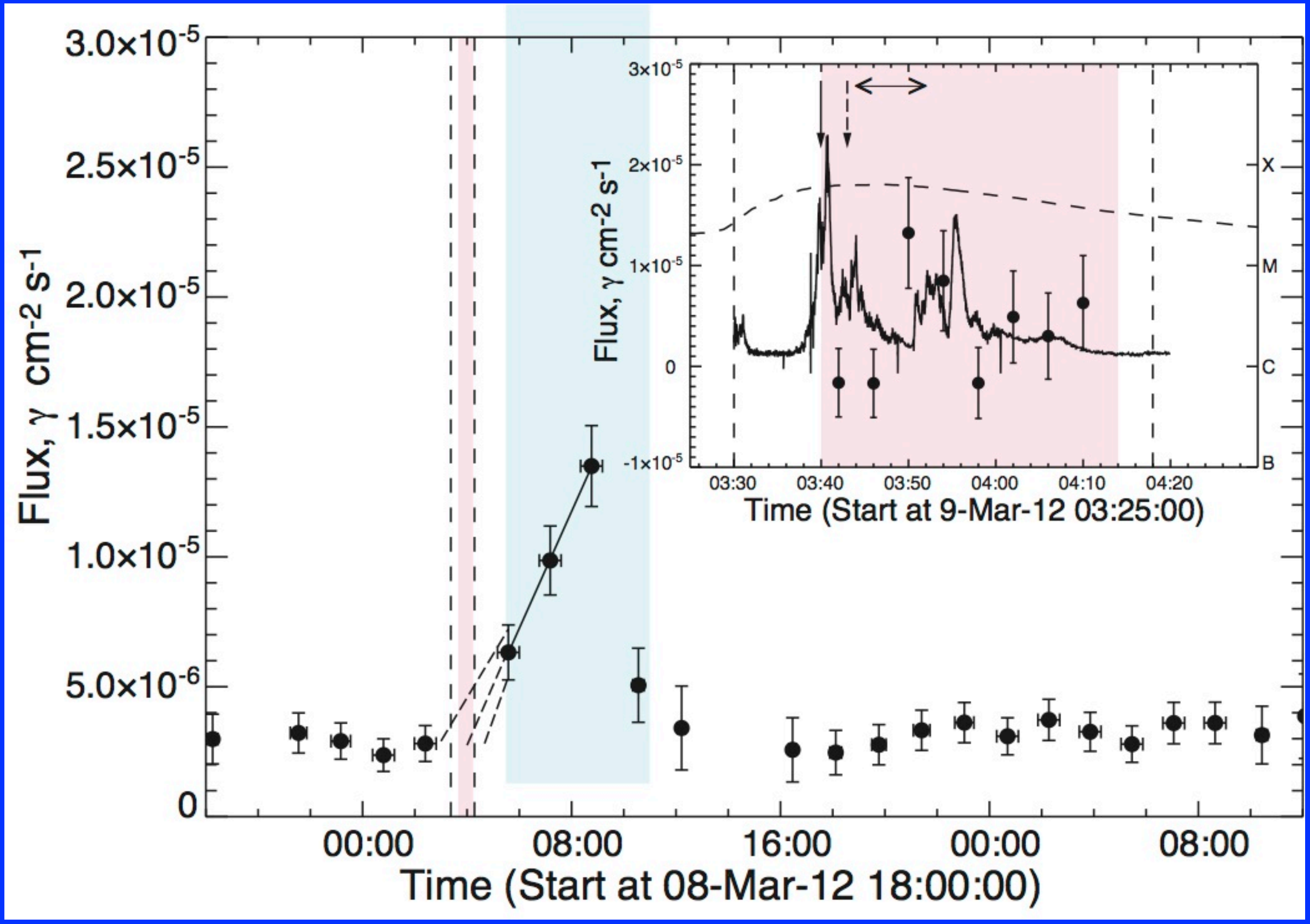
SSGRE onset just after impulsive flare observed in nuclear and >100 MeV γ-rays. Steep impulsive >100 MeV emission occurs just after the hard X-ray peak.



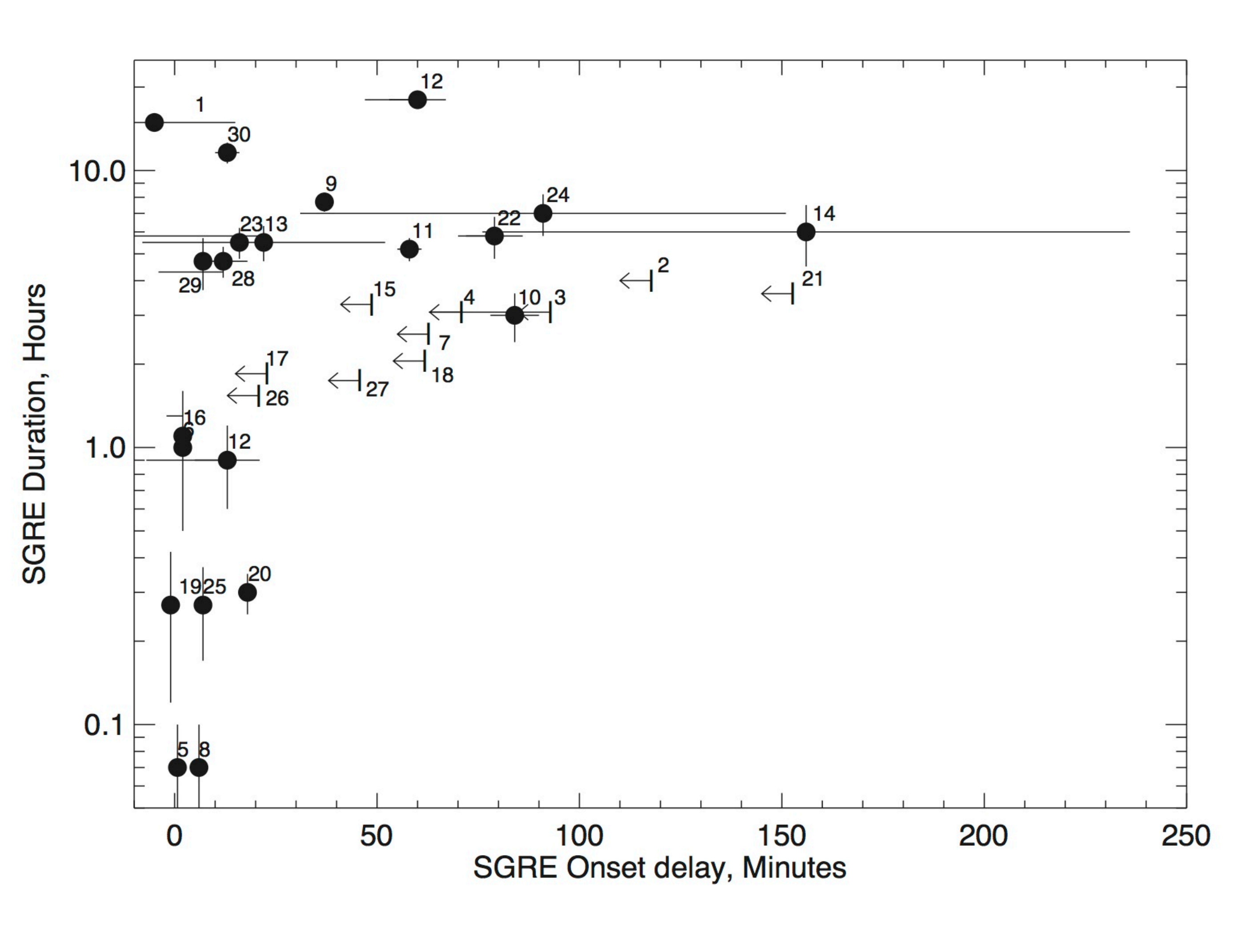
Evidence for two SSGRE events associated with two flares and CMEs. Longest duration and one of the most intense SSGRE events.



The shortest duration SSGRE that begins after the impulsive flare. No evidence for >100 MeV emission in impulsive phase but there is 10-60 MeV emission delayed by about 8 s from the HXR. Not found in daily plots.

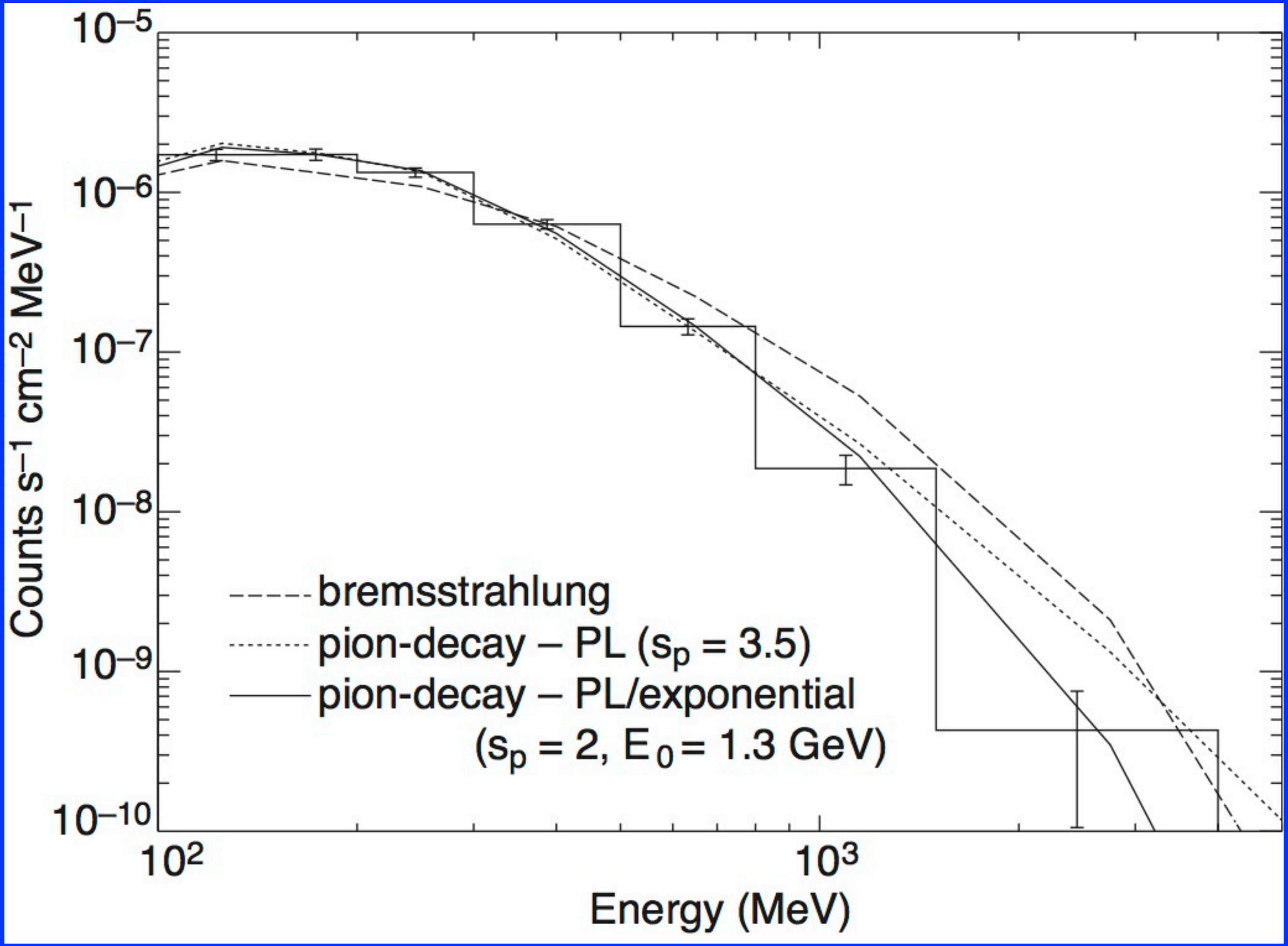


Hours long rise in the SSGRE. No evidence for >100 MeV γ-rays during the impulsive flare.

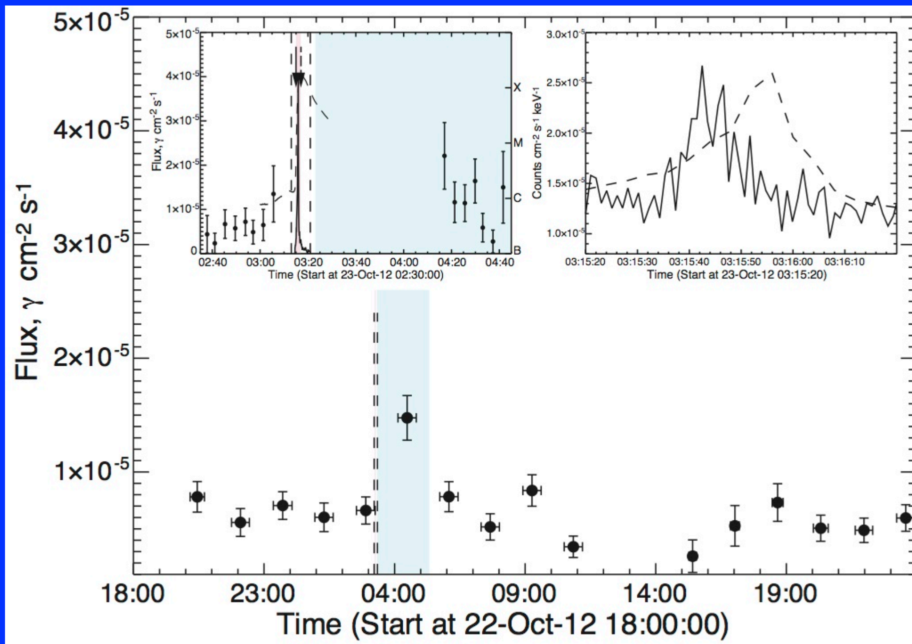


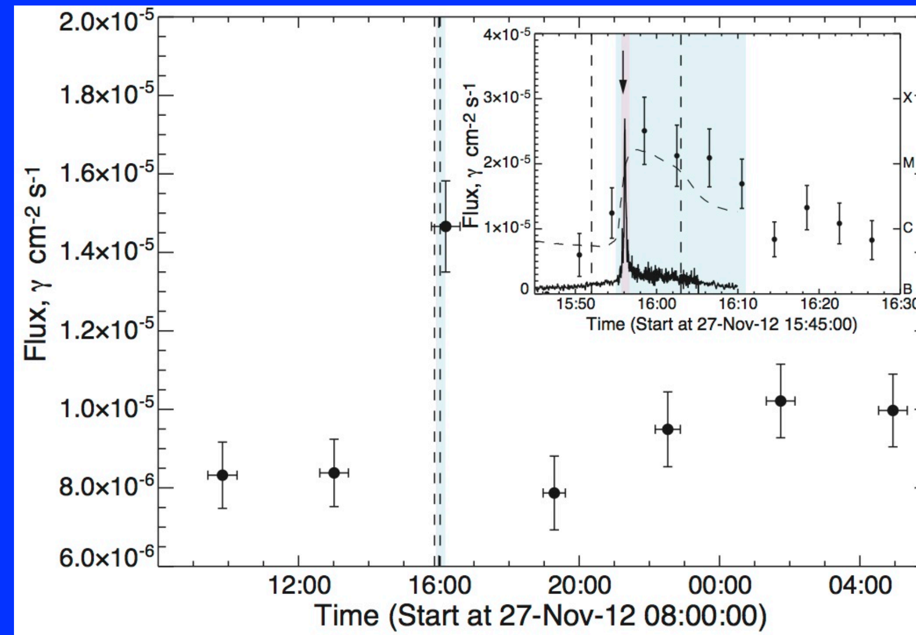
SSGRE begins within a minute of CME onset and up to two hours later.
SSGRE lasts 4 minutes to 20 hours.

Spectroscopy



Fits to the 2014 February 25 event. Best fit is for pion decay produced by a proton power law spectrum with an exponential role over. Bremsstrahlung spectra even with synchrotron losses cannot fit the spectrum. Electron bremsstrahlung cannot fit LAT spectra in 17 solar exposures with peak flux >$10^{-4}\,\gamma\ cm^{-2}\ s^{-1}$ consistent with pion decay and not bremsstrahlung.

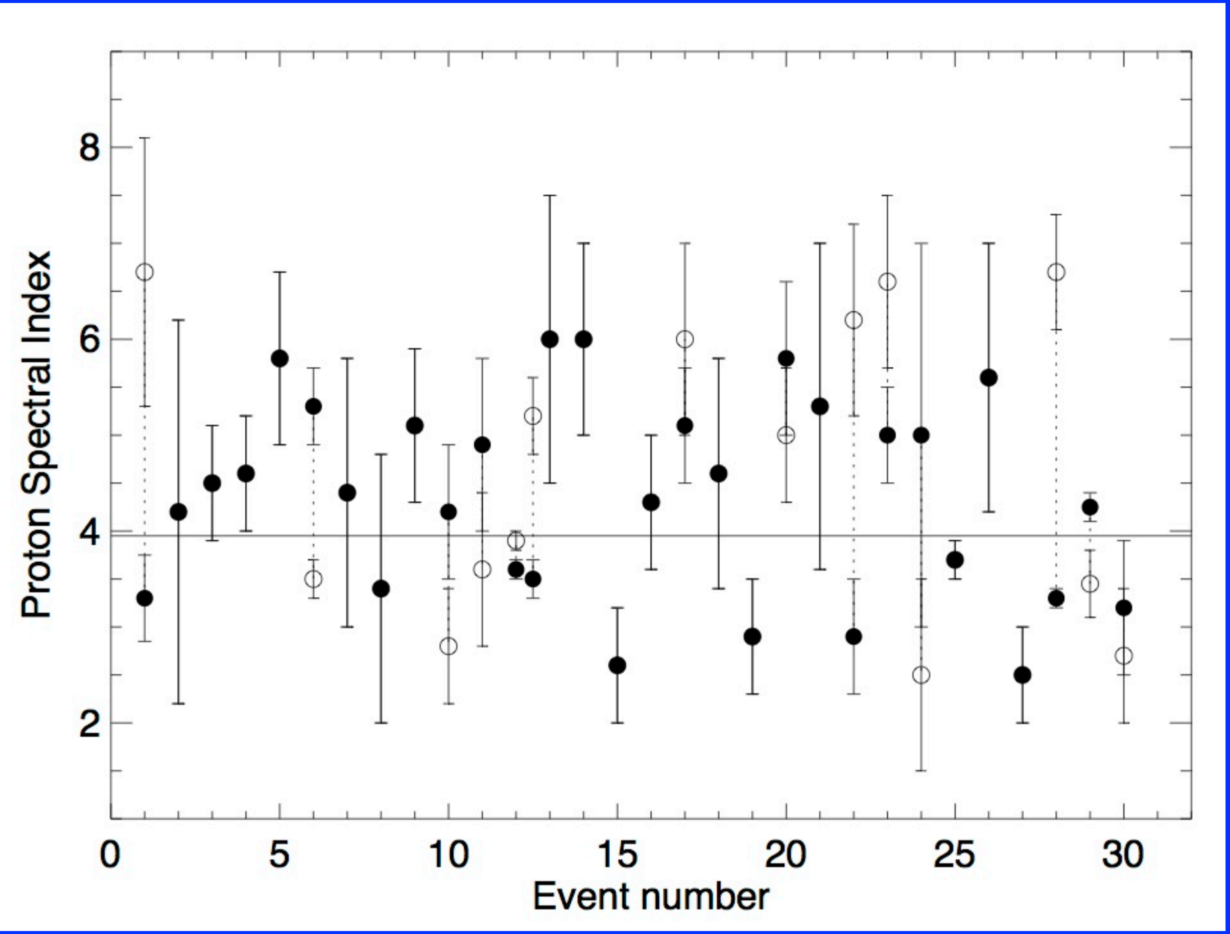




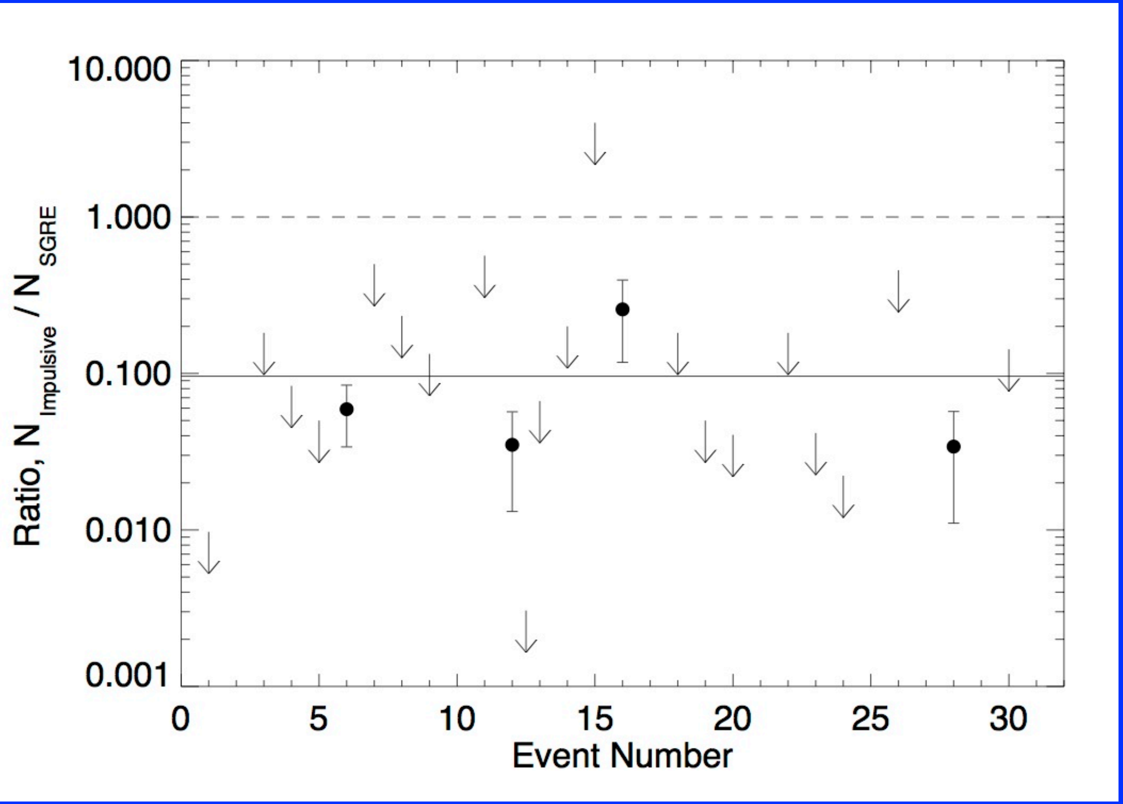
Two SSGRE events without accompanying CMEs or SEP. There was Type II radio emission associated with the 2012 Oct. 12 event. The inset compares 100-300 keV and >9 MeV rates during the impulsive flare. The 2012 Nov. 27 SSGRE appears to begin before the peak of the impulsive hard X-rays.

We have fit the spectra of the 30 SSGRE 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 below 300 MeV. Allan Tylka obtained estimates of the numbers of protons in SEPs using GOES HEPAD data

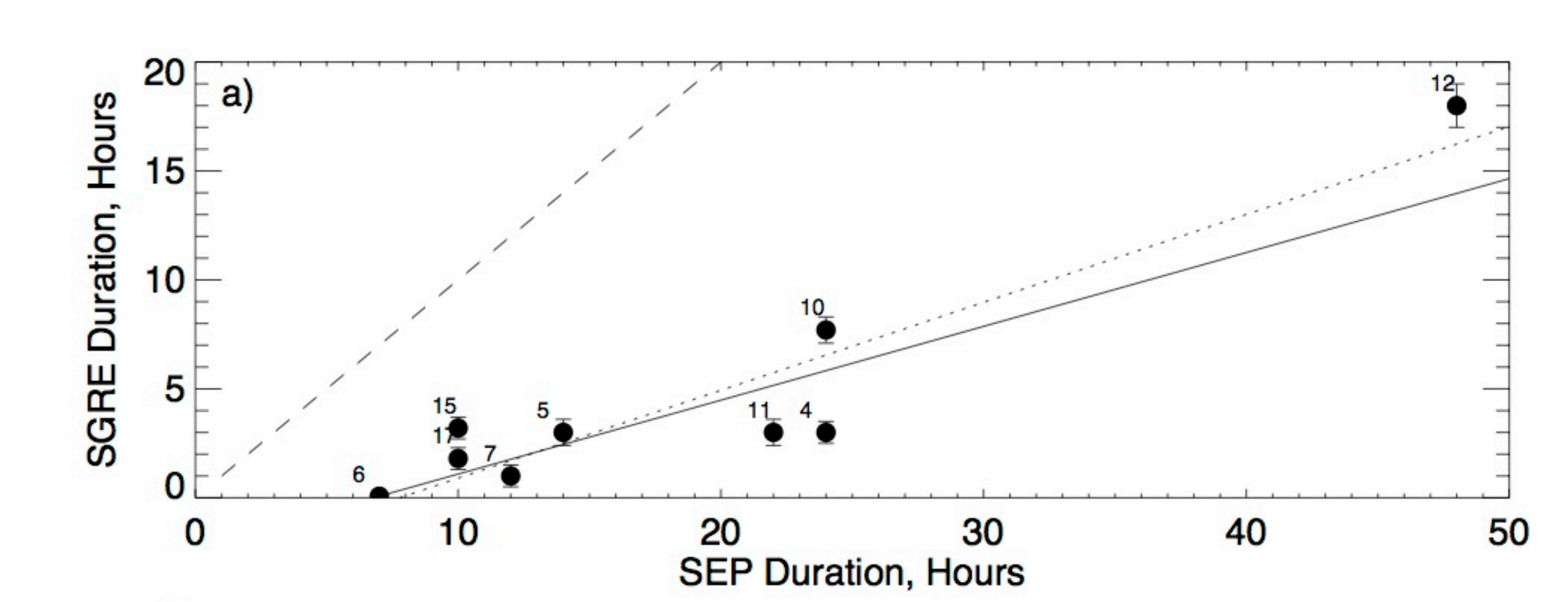
Date yyyy/mm/dd (1)	Time Delay[a] Minutes (2)	Observing Interval, UT (3)	Flux >100 MeV $10^{-4} \gamma$ cm^{-2} s^{-1} (4)	Proton PL Index >300 MeV (5)	Emission Interval, UT (6)	10^{28} Protons >500 MeV (7)
					09:14–12:00	0.7
					04:20–12:00	3.0 ± 0.6
		M8.7 flare			03:53–04:09	<0.4[b]
					03:45–04:09	<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



Average power-law index of >300 MeV protons 4.0 with a range from 2.5 to 6.5. Spectra of 4 softened and 2 hardened. Proton spectra 20-300 MeV flatter than >300 MeV.



Number of >500 MeV protons producing SSGRE typically 10X number producing the flare γ-ray emission during the associated. Flare not the primary source of energy for the SSGRE. Caveat: All of our proton number estimates are based on calculations for an isotropic distribution of protons. For other broad angular distributions the numbers of protons will be higher (up to a factor of four).

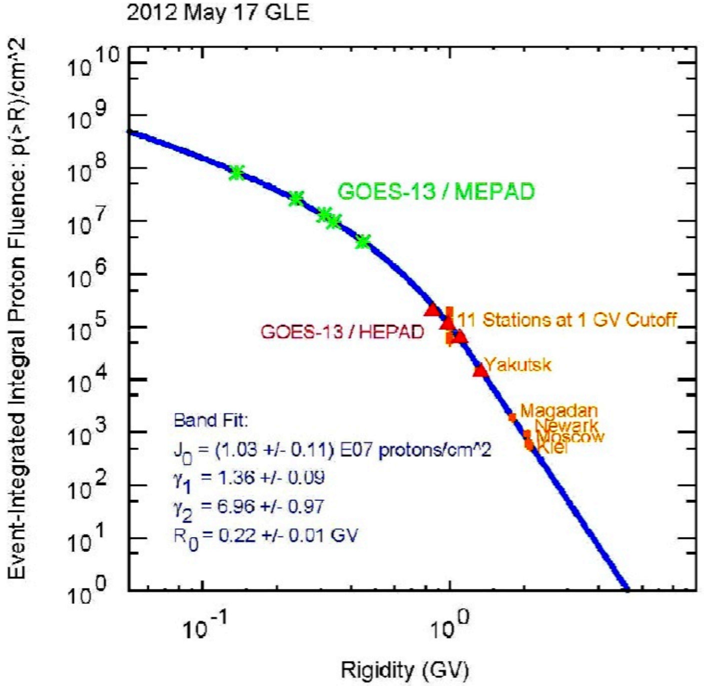


SSGRE durations are correlated with the durations of accompanying >100 MeV solar energetic proton events but SEP durations 5X larger. The associated >100 MeV proton events typically last no more than 1 day.

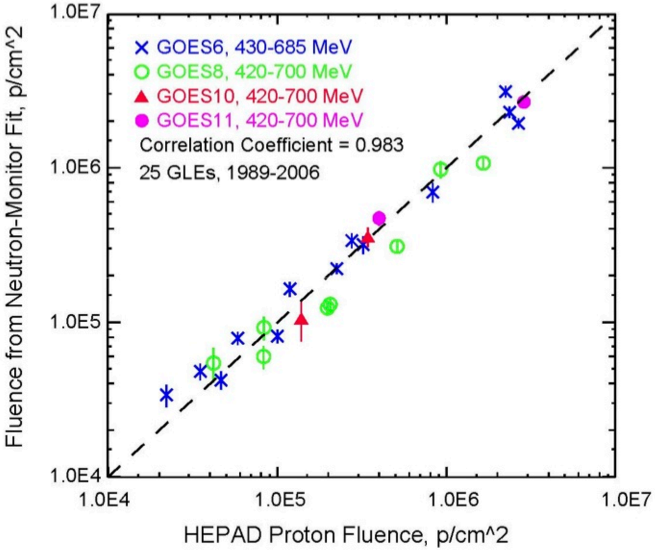
There were two flares and two fast CMEs associated with the event on March 7, 2012.

SEP Proton Estimates using GOES HEPAD (Tylka)

Neutron Monitors and GOES/HEPAD



NMs vs. HEPAD: 25 GLEs, 1989-2006



HEPAD data from NGDC
Reprocessed per Sauer Memo (unpublished, 2007)
Independent of the NM analysis

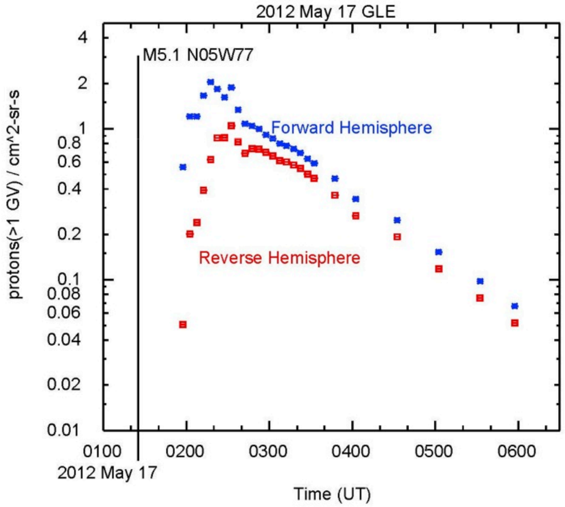
HEPAD and NM estimates of >500 MeV fluence typically agree to within ~30%.

Georgia De Nolfo is obtaining solar energetic proton numbers using PAMELA.

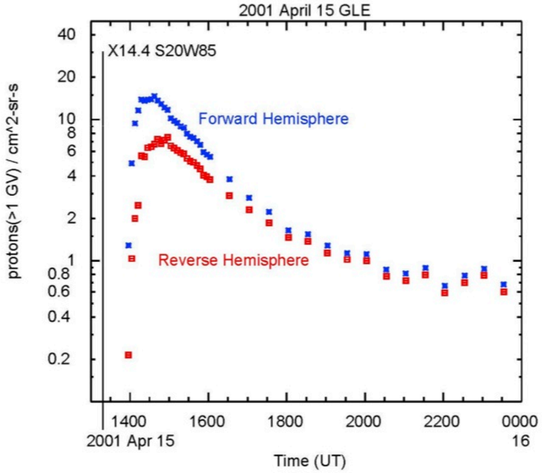
Interplanetary Protons: "Crossing Correction" at >500 MeV

$$C_x = \frac{J_{omni}}{|J_{forward}| - |J_{reverse}|} = \frac{0.5^*(|J_{forward}| + |J_{reverse}|)}{|J_{forward}| - |J_{reverse}|}$$

$C_x = 1.9 \pm 0.3$



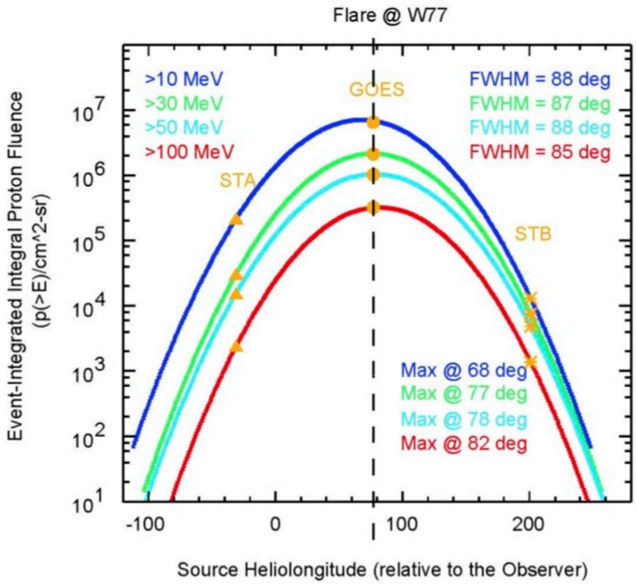
$C_x = 2.3 \pm 0.3$



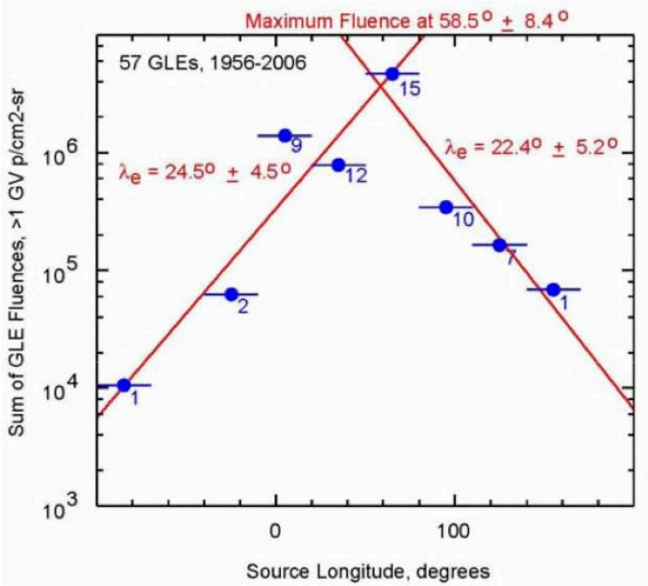
Analysis of the world-wide Neutron Monitor Network by D. F. Smart & M.A. Shea.

Consistent with analytic and Monte Carlo calculations for one day.

Interplanetary Spatial Distribution: Two Methods



57 GLEs 1956-2006



Gaussian fits to GOES & STEREOs

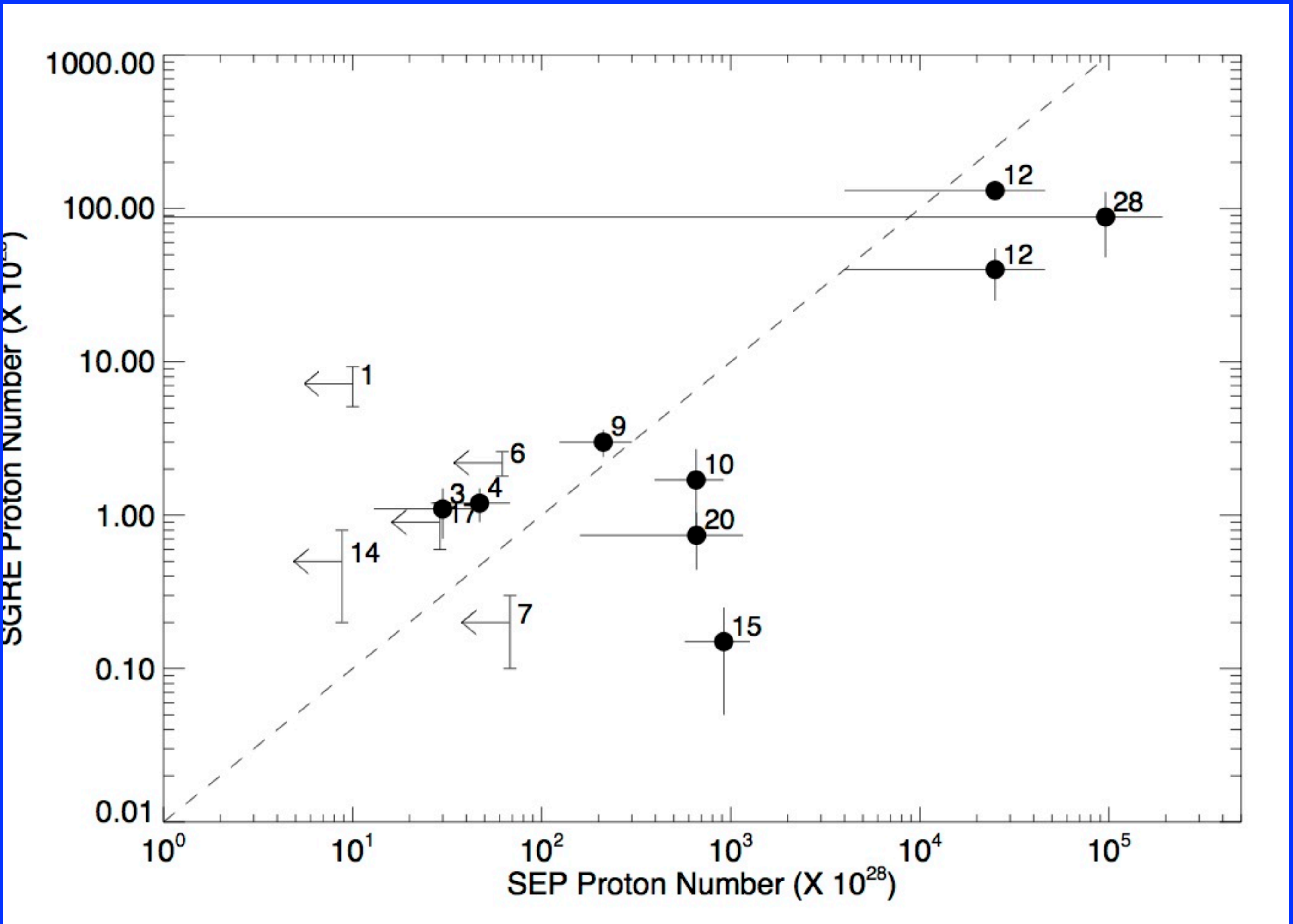
Available only for energies well below 500 MeV

Not available for all events

Distribution centered at $\Phi_0 = 58^o$

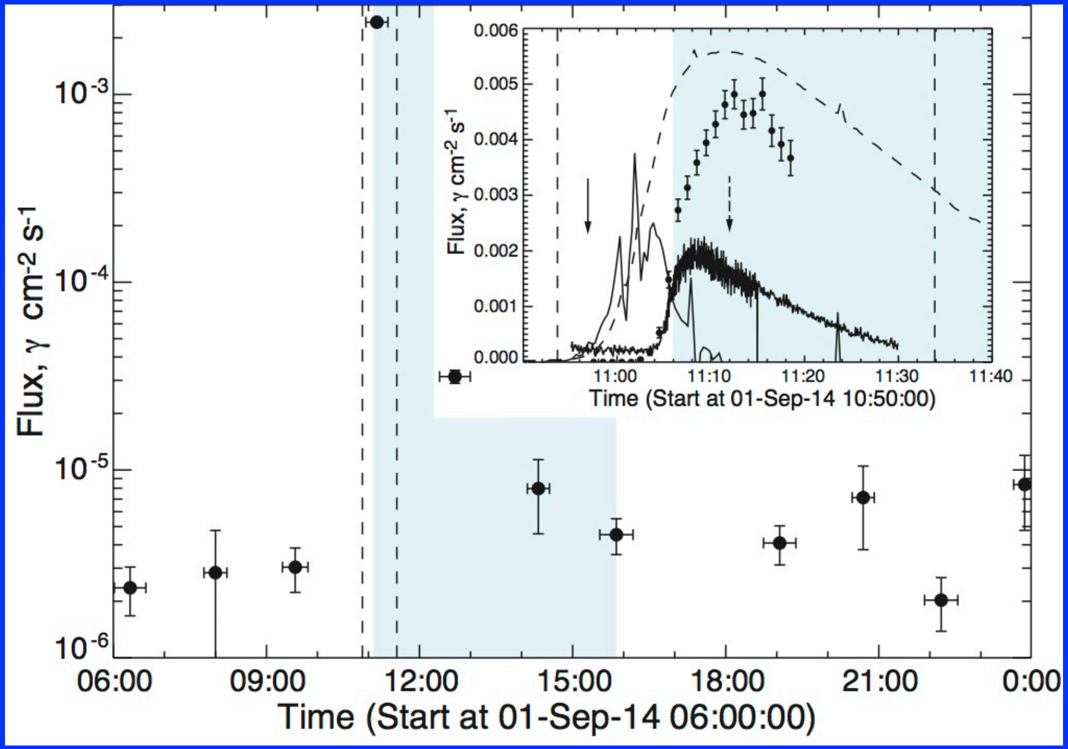
Symmetric fall-off $\Lambda_\Phi = 23^o$

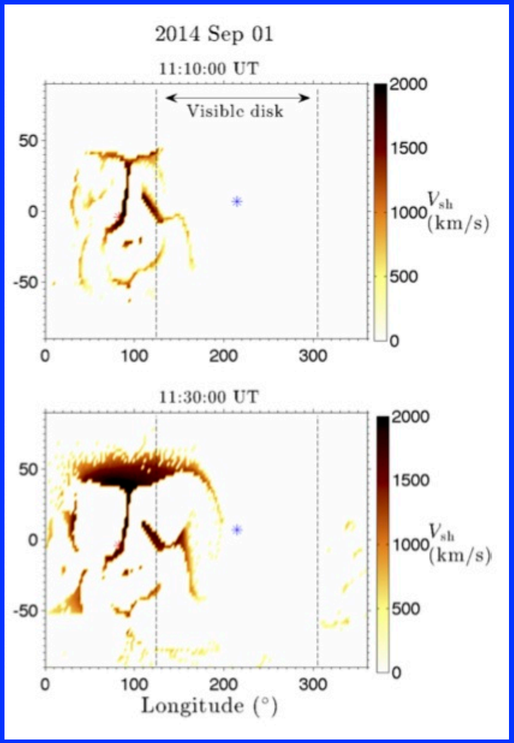
$J(\Phi) = J_0 \exp(-|\Phi-\Phi_0|/\Lambda_\Phi) \rightarrow C_{spatial}$



Number of >500 MeV protons producing SSGRE is on average 1-2% of number of protons observed in accompanying SEP event.

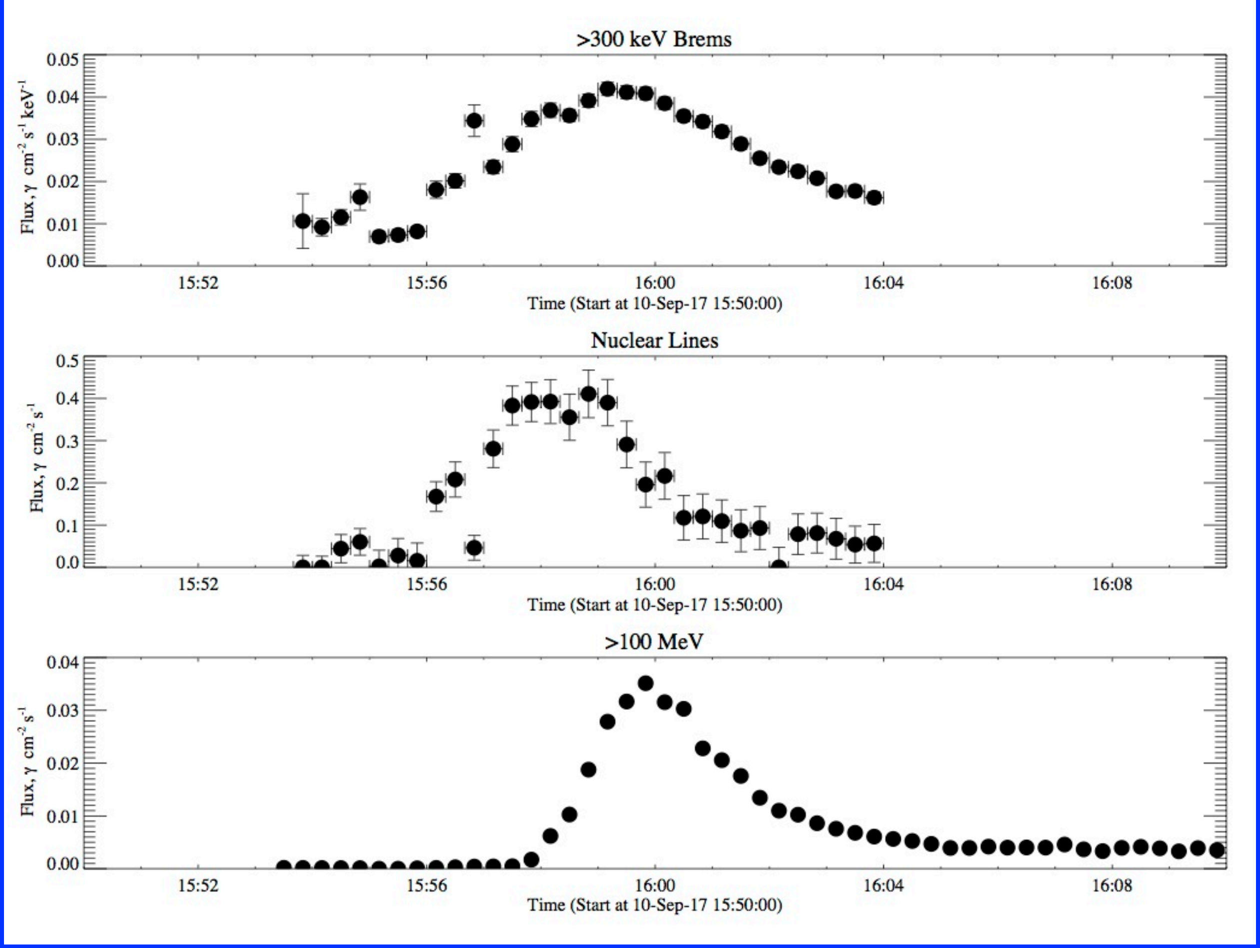
What We Have Learned about SSGRE from a Behind-the-Limb Flare



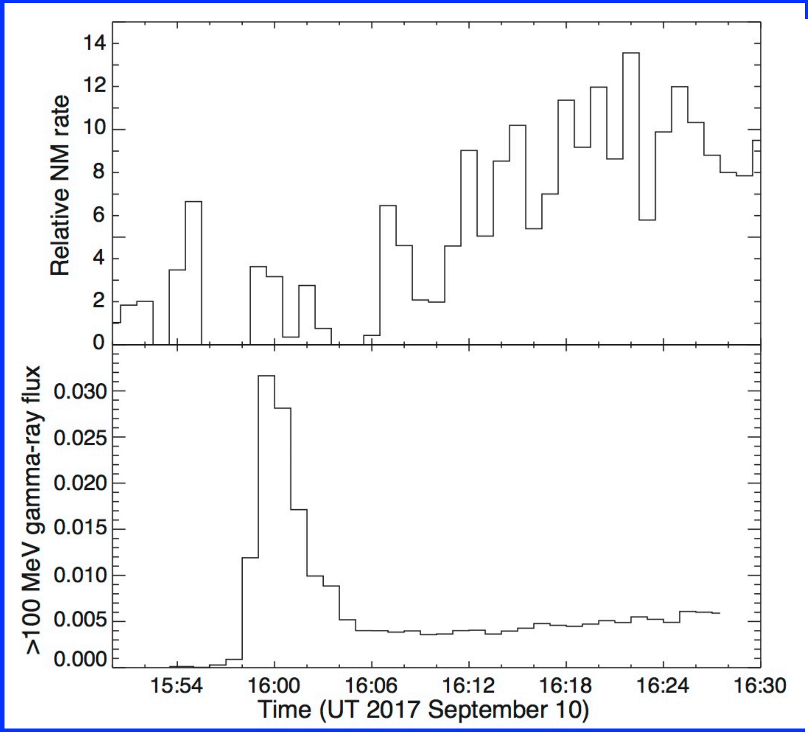


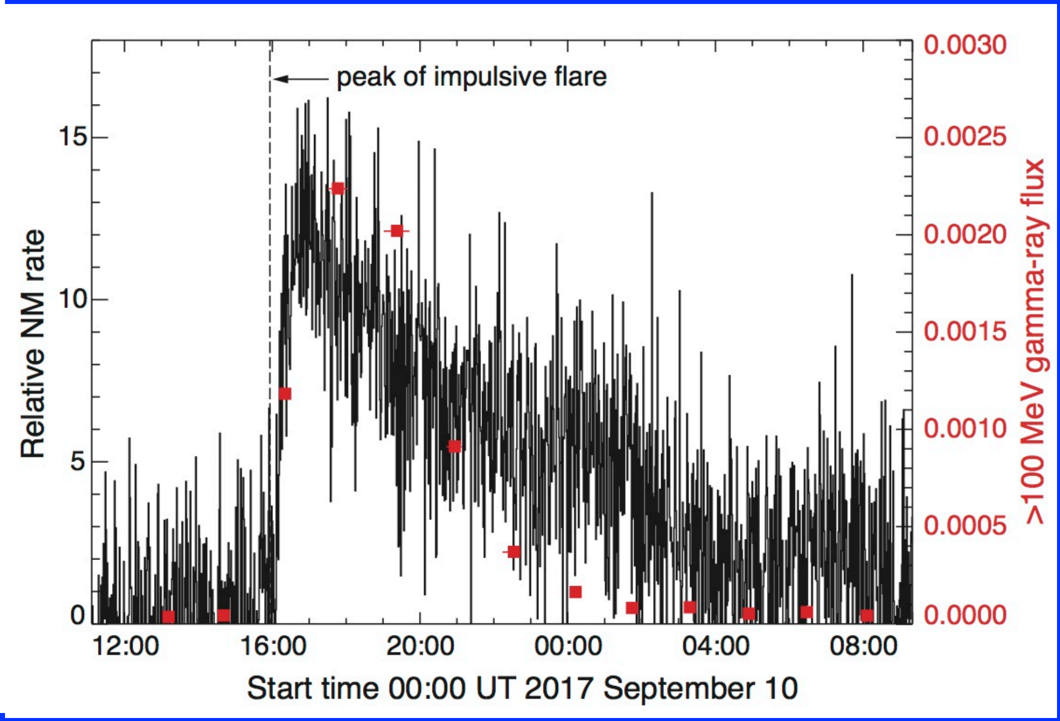
Behind-the-limb events (Ackermann et al. 2017) indicate that SGRE can extend up to a few tens of degrees from the active region. Second stage bremsstrahlung from electrons with energies in excess of 10 MeV observed. RHESSI imaging indicates that bremsstrahlung distributed over tens of heliographic degrees. SSGRE onset consistent with time when high Mach number CME shocks first intersected with magnetic field lines returning to the Sun (Plotnikov et al. 2017)

Surprising Burst of Solar Activity in September



Flare on 2017 September 10 had impulsive nuclear-line gamma-rays. The >100 MeV emission started minutes later suggesting a second-stage origin. Another, slower rising acceleration stage began later.





2017 September 10 X8.2 flare was accompanied by two SSGRE events and a ground level neutron monitor event. Ft. Smith neutron monitor data (R. Pyle and P. Evenson).

SUMMARY of SSGRE Characteristics

- 20 of 30 SSGRE events clearly distinct from impulsive flare; none of other 10 events are clearly the decay of impulsive flare; nuclear radiation only detected during the impulsive flare in five of the events.
- >100 keV impulsive flare emission was observed in all 26 SGRE events with HXR observations. In only 4 events was impulsive phase nuclear line or pion-decay emission observed.
- CMEs were observed in 28 of the 30 SGRE events
- SEP were observed in all SSGRE events with accompanying CMEs except when following a strong particle event.
- Type II metric or DH radio emission observed in all but one event.
- Spectra from pion-decay; power-law index of protons as hard as 2.5 and as soft as 6.5 with a weighted mean of 4; proton spectrum softens above 100 MeV; spectral variability observed during some of the events.
- Number of impulsive flare >500 MeV protons ~10% of SSGRE protons.
- Number of SSGRE protons ~1-2% of interplanetary protons.
- SGRE can extend up to a few tens of heliographic degrees from the AR and can be broadly distributed (tens of degrees).
- Sustained bremsstrahlung emission observed in one behind-the-limb flare.

CONCLUDING REMARKS

The SSGRE appears to be associated with magnetic eruptions, CMEs, and related shocks. The distinctly different impulsive and second time profiles and the 10X small number of protons in the impulsive phase suggest that the impulsive flare is not the primary source for energizing the protons producing the SSGRE. The inferred broad spatial distribution (behind-the-limb flares) suggests shock acceleration onto field lines returning to the Sun. Hours long durations may be explained by a reservoir of accelerated particles behind the CME that interact over broad regions on the Sun. There appears to be an association with SEP, although SSGRE are not always detected when a >100 MeV SEP event was observed (LAT duty cycle, magnetic connectivity back to the Sun, mirroring in solar atmosphere, proton energy spectra differences at different locations). Why impulsive >100 keV X-rays are observed in all SSGRE events is interesting. Could they suggest the presence of a seed population of sub-MeV ions emitted from the flare site?