Recent result of Solar flare Observation by Fermi-LAT and GBM

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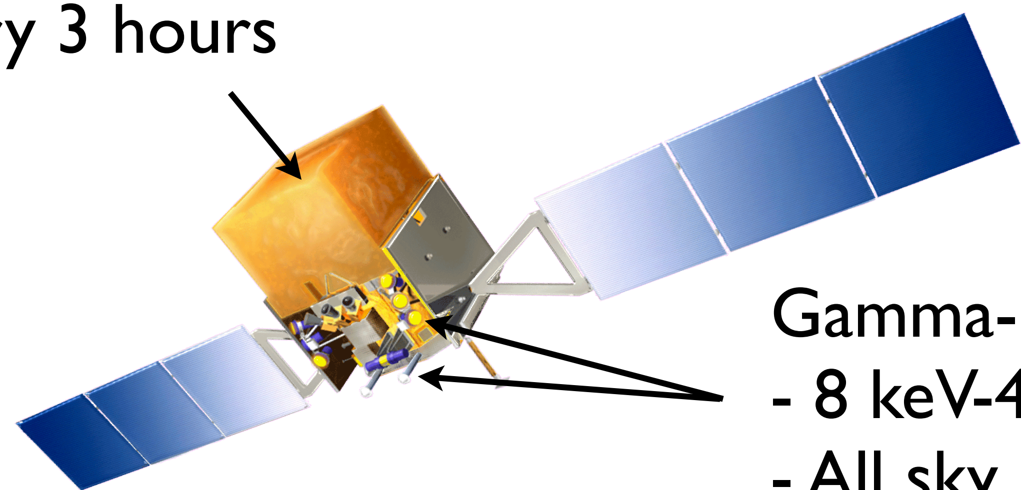
Fermi Gamma-ray Space Telescope

- Launched on 2008 June 11
- All-sky survey mode
- Observation has continued without any critical problems

Large Area Telescope (LAT)

- 20 MeV-300 GeV

- Thanks to the wide FoV (2.4 str), all sky is scanned every 3 hours

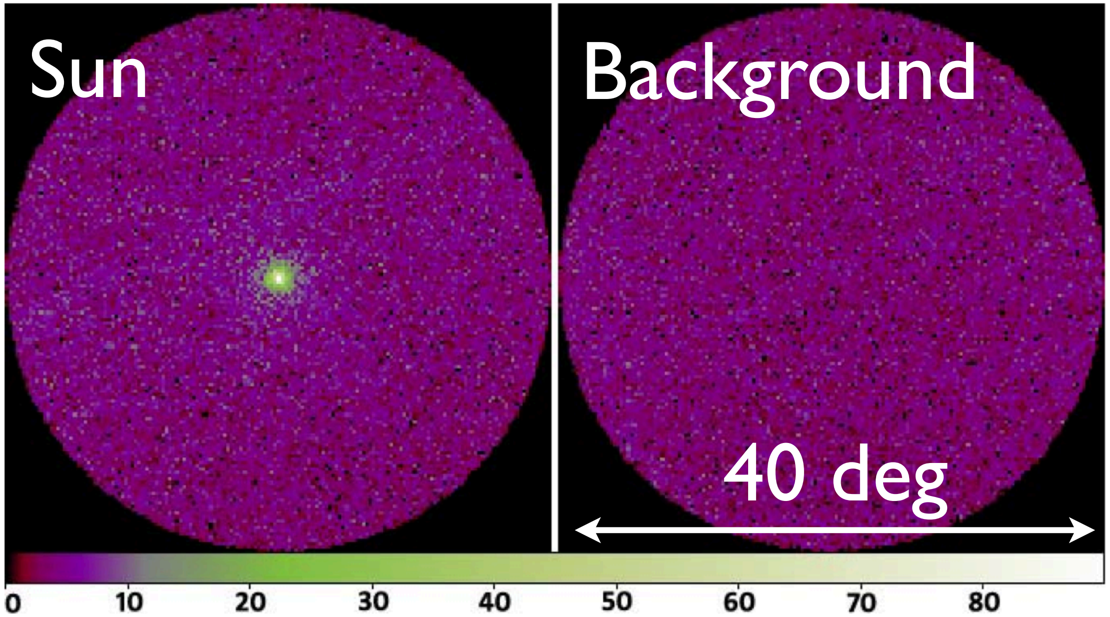


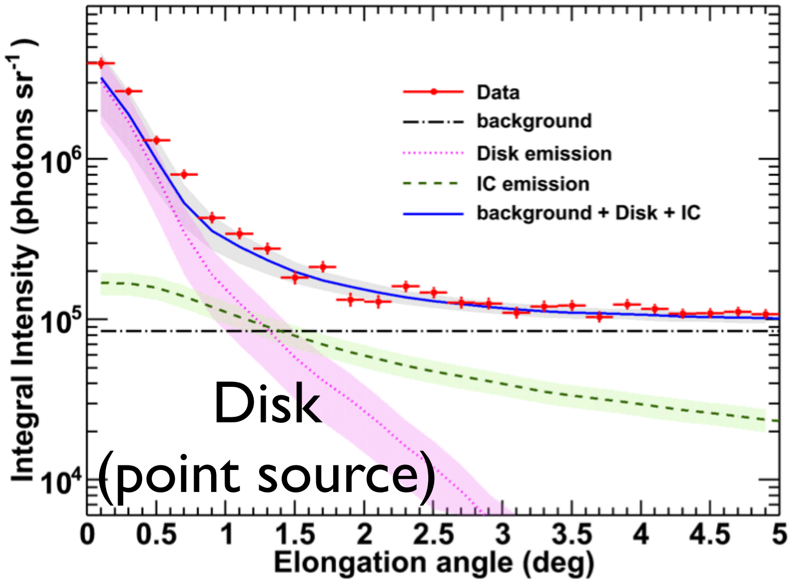
Gamma-ray Burst Monitor (GBM)

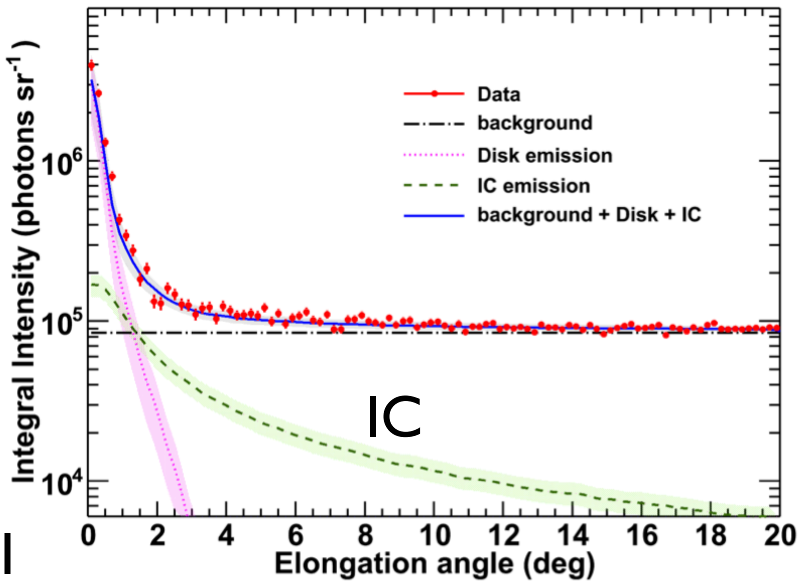
- 8 keV-40 MeV
- All sky monitor

Steady MeV/GeV emission from Quiet Sun

Count map (E>100 MeV, 18 months data)



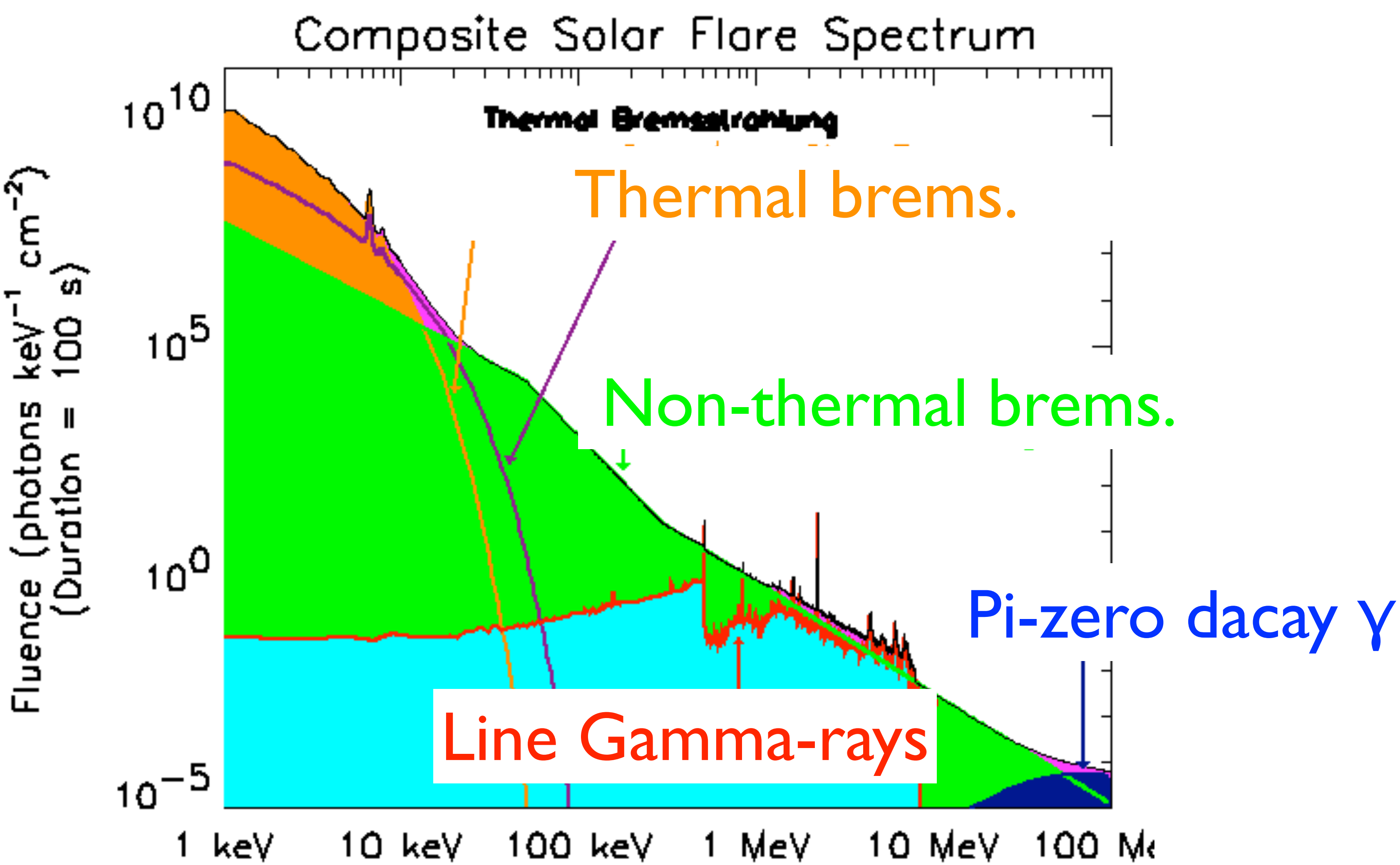




1. Cascade by CR protons
2. Inverse Compton of solar photons by CR electrons

Abdo et al. 2011

Solar Flare X-ray~Gamma-ray spectrum



- Thanks to Yohkoh and RHESSI, solar flare gamma-rays up to several MeV were detected many times

Taken from http://hesperia.gsfc.nasa.gov/hessi/flares.htm

Pre-Fermi EGRET/CGRO result

Long-lasting solar gamma-ray emission

Fermi Gamma-ray Space Telescope

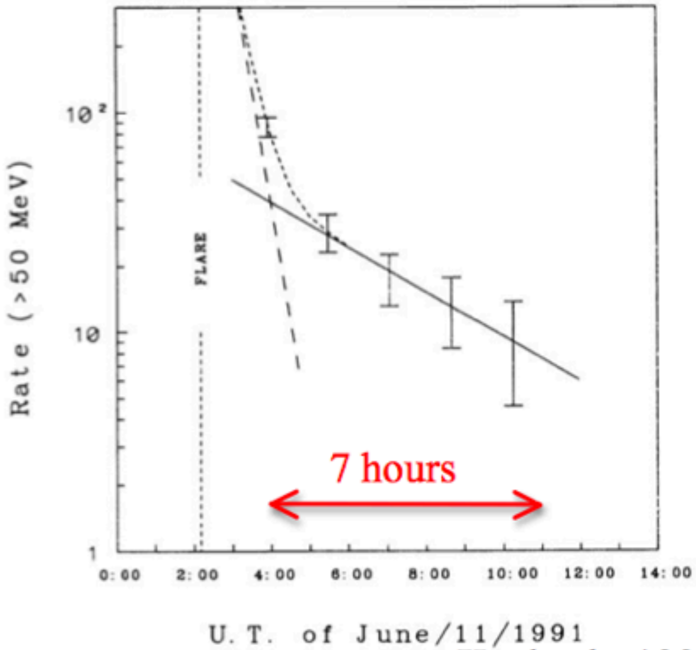
- **In the past decades, only two long-lived (hours long) gamma-ray emissions were observed by EGRET (e.g. Kanbach+93, Ryan00)**

Year	Month	Day	Duration (s)	τ_1 (min)	τ_2 (min)	Ref.
1982	6	3	1200	1.15 ± 0.14	11.7 ± 3.0	1, 2
1984	4	24	900	3.23 ± 0.07	≥ 10	2
1988	12	16	600	3.34 ± 0.30		2
1989	3	6	1500	2.66 ± 0.27		2
1989	9	29	>600			3
1990	4	15	1800			5
1990	5	24	500	0.35 ± 0.02	22 ± 2	4, 5, 6
1991	3	26	600			7, 8
1991	6	4	10000	7 ± 0.8	27 ± 7	9, 10
1991	6	6	1000			9
1991	6	9	900			9, 11
1991	6	11	30000	9.4 ± 1.3	220 ± 50	9, 12, 13
1991	6	15	5000	12.6 ± 3.0	180 ± 100	7, 8, 12

[1] Chupp (1990); [2] Dunphy and Chupp (1994); [3] Vestrand and Forrest (1993); [4] Debrunner et al. (1997); [5] Trottet (1994); [6] Debrunner et al. (1998); [7] Akimov et al. (1991); [8] Akimov et al. (1994c); [9] Schneid et al. (1996); [10] Murphy et al. (1997); [11] Ryan et al. (1994a); [12] Rank et al. (1996); [13] Kanbach et al. (1993)

Ryan 2000

Light curve (E>50 MeV) of 1991 June 11 flare



Kanbach+1993

- **It is unclear where, when, how the high-energy (HE) particles responsible for gamma-ray emission are accelerated**

Taken from my slide at Fermi symposium 2011

LAT-detected solar flares (~2012 August)

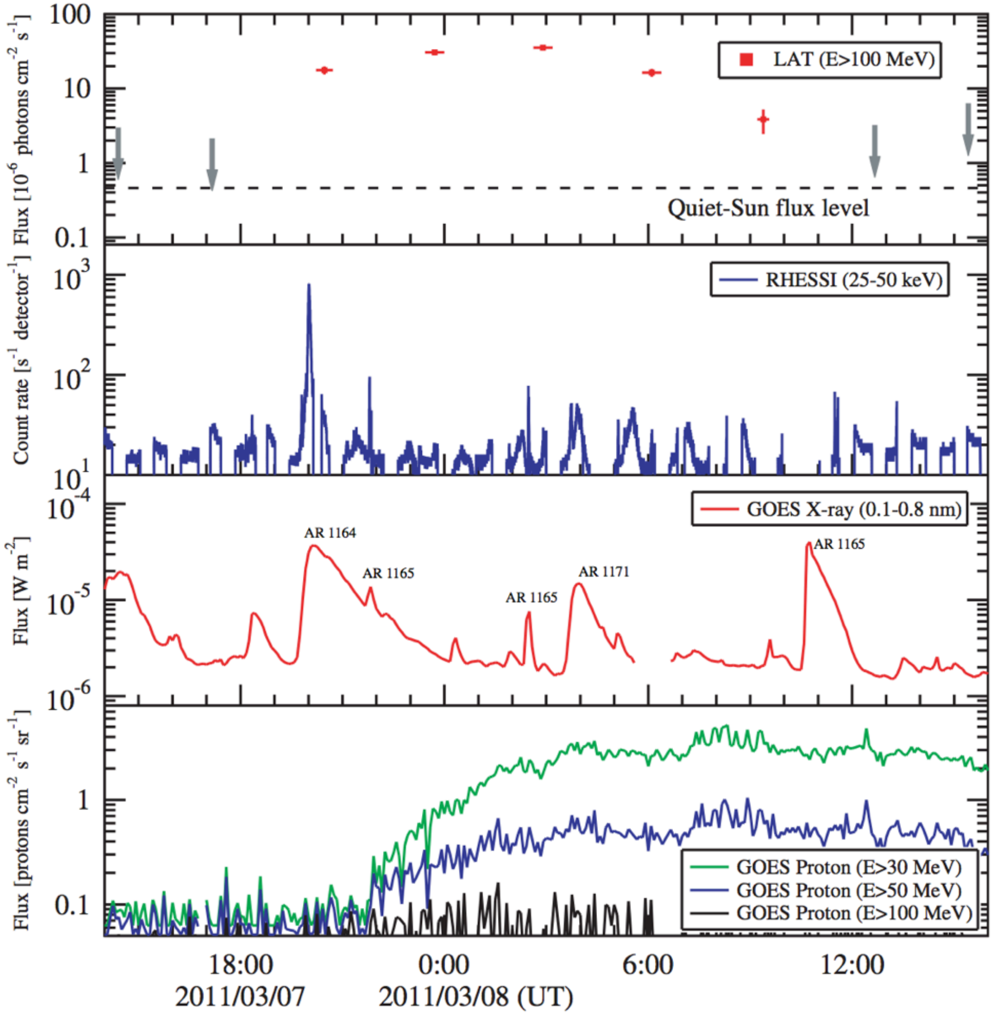
Table 1
Solar Flares Detected by the *Fermi* LAT from 2008 August to 2012 August

Date	*GOES* X-Ray Class, Start–End[d]	Type	Duration (hr)	CME Speed[a] (km s^{-1})	*Fermi* Time Window Start[d], Duration (minutes)	TS[b]	Flux[c]	Energy Flux[c]
2010 Jun 12	M2.0, 00:30-01:02	I	...	486	00:55, 0.8	LLE[e]	...	...
2011 Mar 7	M3.7, 19:43-20:58	I/S	10.7	2125	20:15, 25	230	1.9 ± 0.3	6.7 ± 1.0
		S			23:26, 36	520	3.5 ± 0.3	11.9 ± 1.1
2011 Mar 8		S			02:38, 35	450	3.5 ± 0.3	11.6 ± 1.1
					05:49, 35	200	1.9 ± 0.3	5.4 ± 0.7
2011 Jun 2	C2.7,9:42-9:50	I/S	0.8	976	09:43, 45	35	0.4 ± 0.2	1.4 ± 0.5
2011 Jun 7	M2.5, 06:16-06:59	S	2.2	1255	07:34, 53	570	3.6 ± 0.3	11 ± 0.9
2011 Aug 4	M9.3, 03:41-04:04	S	1.9	1315	04:59, 34	390	2.5 ± 0.3	7.9 ± 0.8
2011 Aug 9	X6.9, 07:48-08:08	I	...	1610	08:01, 3.3	LLE[e]	...	...
2011 Sep 6	X2.1, 22:12-22:24	I	0.6	575	22:17, 0.2	LLE[e]	...	...
		I/S			22:13, 35	[f]	[f]	
2011 Sep 7	X1.8, 22:32-22:44	S	2.1	792	23:36, 63	350	1.0 ± 0.1	3.5 ± 0.4
2011 Sep 24	X1.9, 09:21-09:48	I	...	1936	09:34, 0.8	LLE[e]	...	...
2012 Jan 23	M8.7, 03:38-04:34	I/S	5.7	1953	04:07, 51	180	0.8 ± 0.1	2.7 ± 0.4
		S			05:25, 69	650	2.1 ± 0.2	6.6 ± 0.5
		S			07:26, 16	69	3.7 ± 0.9	9.6 ± 2.2
		S			08:47, 35	97	2.6 ± 0.5	7.0 ± 1.3
2012 Jan 27	X1.7, 17:37-18:56	D	4.0	1930	19:45, 11	78	3.2 ± 0.8	9.6 ± 2.2
		S			21:13, 24	47	1.0 ± 0.3	2.8 ± 0.8
2012 Mar 5	X1.1, 02:30-04:43	I/S	5.3	1602	04:12, 49	69	0.5 ± 0.1	1.5 ± 0.3
		S			05:26, 71	250	0.9 ± 0.1	2.5 ± 0.3
		S			07:23, 28	39	0.8 ± 0.2	2.4 ± 0.7
2012 Mar 7	X5.4, 00:02-00:40	S	20.2	2684	00:46, 31	22000	[f]	[f]
	X1.3, 01:05–01:23	I/S		1785	00:46, 60	LLE[g]	...	...
					03:56, 32	16000	113.1 ± 2.0	400.5 ± 6.6
					07:07, 32	8900	71.9 ± 1.6	232.6 ± 4.9
					10:18, 32	1900	30.1 ± 1.5	91.9 ± 4.3
					13:29, 32	120	8.9 ± 1.9	29.9 ± 5.9
					19:51, 25	50	0.4 ± 0.1	1.7 ± 0.5
2012 Mar 9	M6.3, 03:22-04:18	D	5.7	844	05:17, 34	51	0.6 ± 0.2	2.0 ± 0.5
		S			06:52, 35	100	0.9 ± 0.2	2.8 ± 0.6
		S			08:28, 34	159	1.4 ± 0.2	4.3 ± 0.7
2012 Mar 10	M8.4, 17:15-18:30	D	4.3	1379	21:05, 30	43	0.4 ± 0.1	1.0 ± 0.3
2012 May 17	M5.1, 01:25-02:14	I/S	1.2	1582	02:18, 22	45	1.0 ± 0.3	3.4 ± 0.9
2012 Jun 3	M3.3, 17:48-17:57	I	0.2	605	17:52, 0.6	LLE[e]	...	...
		I/S			17:40, 23	300	3.2 ± 0.4	10.6 ± 1.2
2012 Jul 6	X1.1,23:15-23:49	I/S	0.9	892	23:19, 52	930	3.5 ± 0.2	10.4 ± 0.7

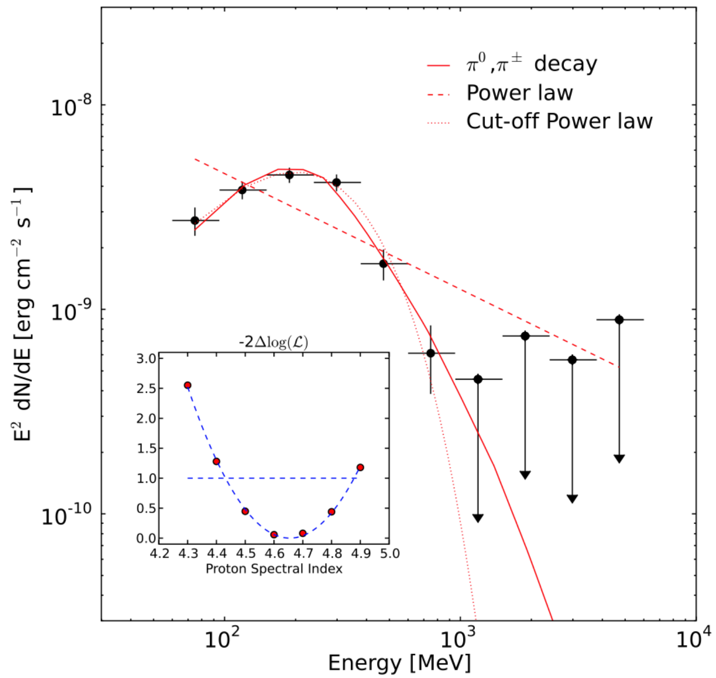
- **I: impulsive emission**
- **I/S: we cannot distinguish between impulsive and Sustained.**
- **S: We don't see the impulsive emission because the Sun was not in the FoV, but we detect sustained emission**
- **D: Delayed: The sun was in the field of view at the time of the impulsive emission, but we do not detect any emission.**
- **All associated with fast CME**

Ackermann+14

M3.7 flare on 2011 March 7



~12 hour long-lasting emission

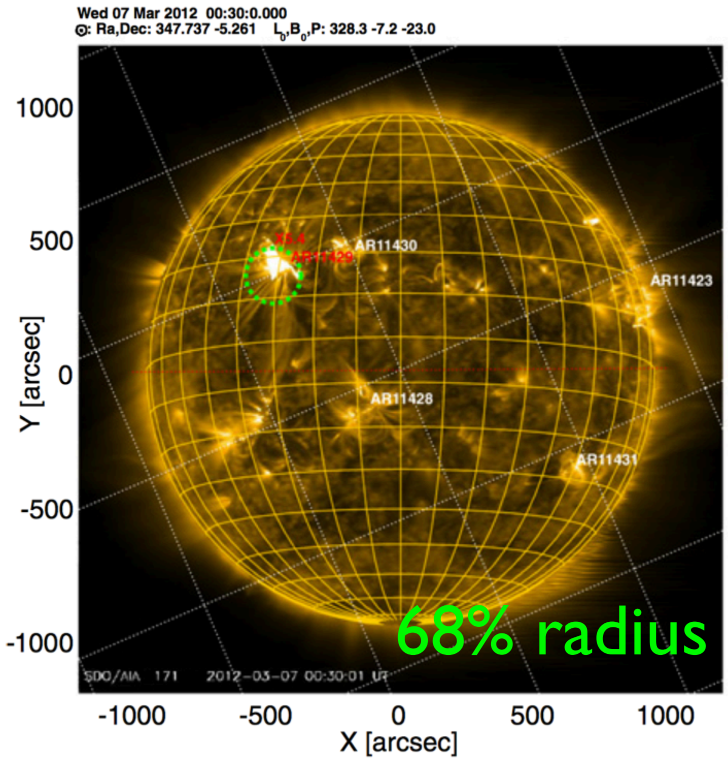


Total emitted energy (E>100 MeV); 9.7E+23 erg

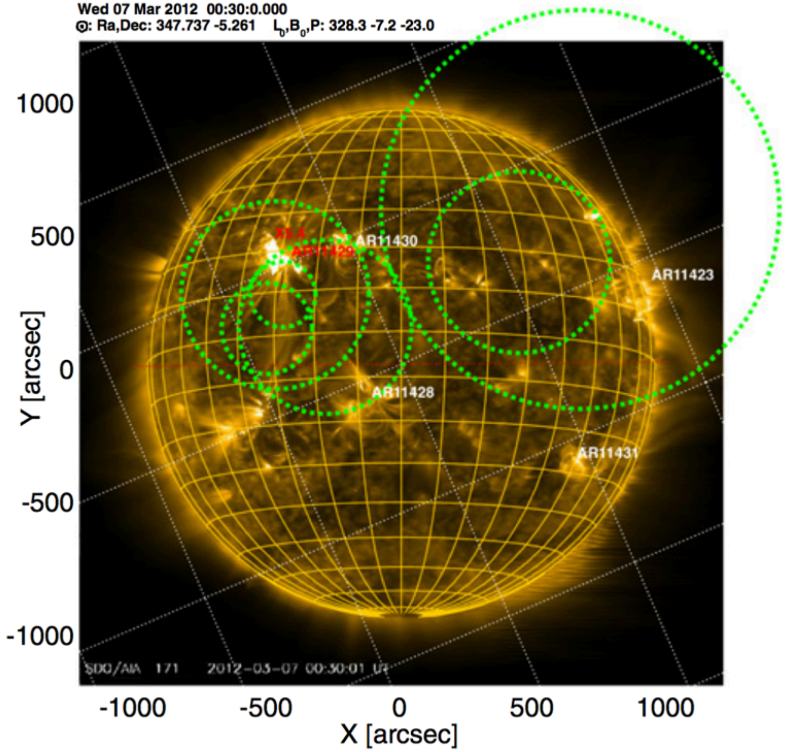
Power-law is significantly rejected
Cutoff PL and Pion-decay (s=4.6, solid line) models are favored

LAT-brightest 2012 March 7 solar flare

By using all LAT events



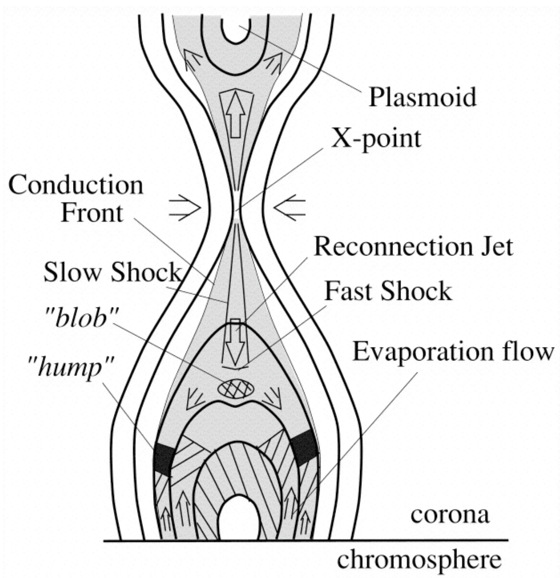
Positions for every 90 minutes



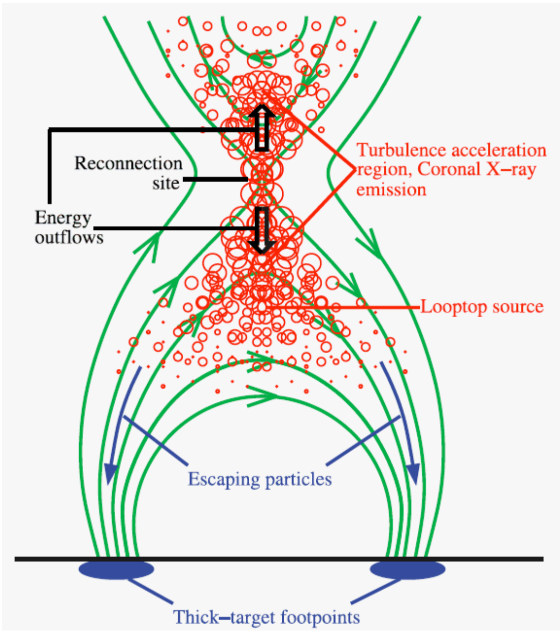
- Clear association with flare-produced AR 11429
- Time-resolved localization shows clear association with AR in earlier times, but later the association becomes less significant

Possible acceleration mechanisms

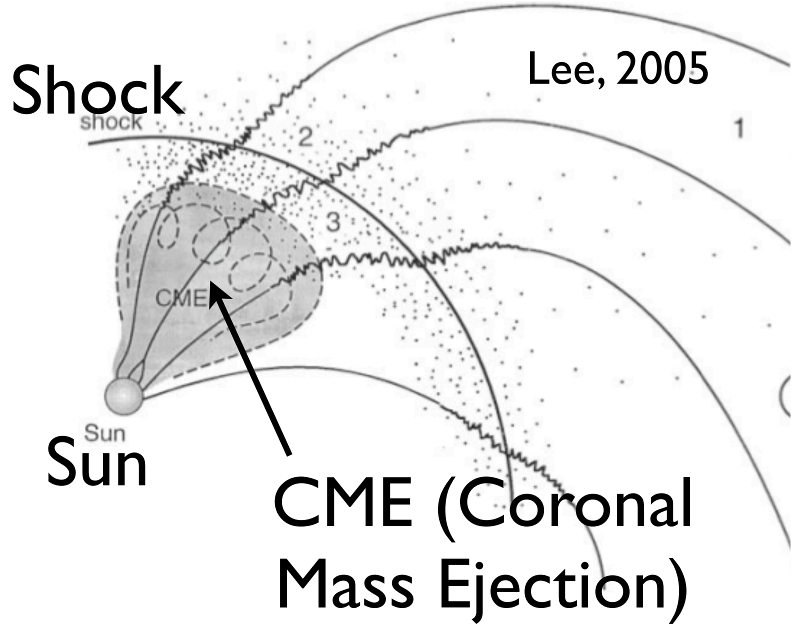
Reconnection	Turbulent acc.	CME shock acc.
	(2nd order Fermi)	(1st order Fermi)



Yokoyama & Shibata, 2001



Liu+2008



Lee, 2005

- Impulsive acceleration+trapping would be rejected
- Continuous acceleration by turbulence or CME shock seems preferred

Recent Fermi-LAT papers related to solar system objects

2016

Measurement of the high-energy gamma-ray emission from the Moon with the Fermi Large Area Telescope (Accepted for publication)
Ackermann, M. et al. 2016, Phys. Rev. D Show links

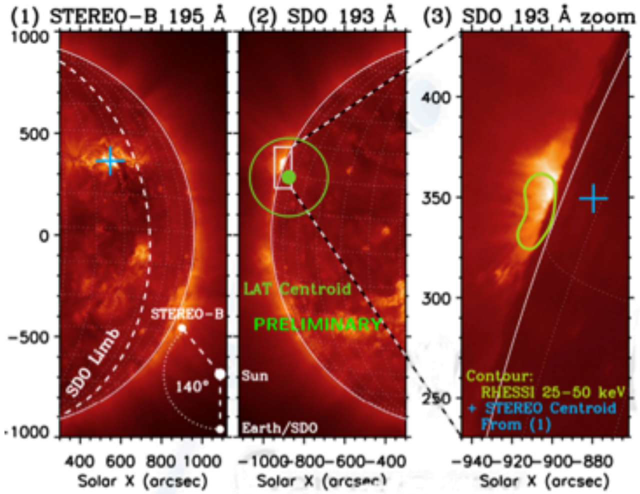
2015

First detection of >100 MeV gamma rays associated with a behind-the-limb solar flare
Pesce-Rollins, M. et al. 2015, ApJL, 805, L15 Hide links
doi: 10.1088/2041-8205/805/2/L15
arXiv: 1505.03480 INSPIRE
ADS: 2015ApJ...805L..15P BibTeX Citations

- See Fermi-LAT publication page
- https://www-glast.stanford.edu/cgi-bin/pubpub

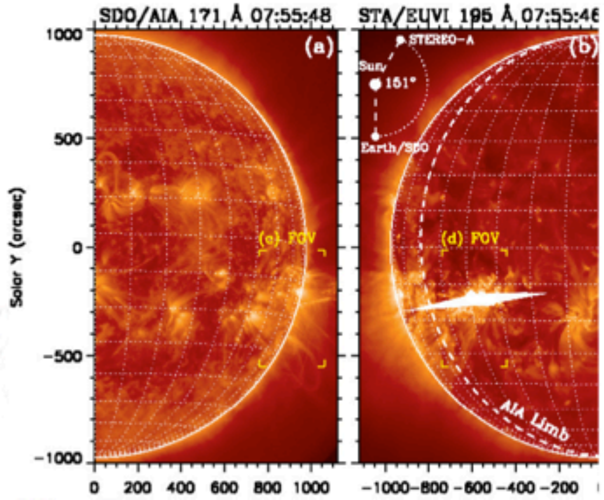
LAT BEHIND-THE-LIMB FLARES

SOL2013-10-11



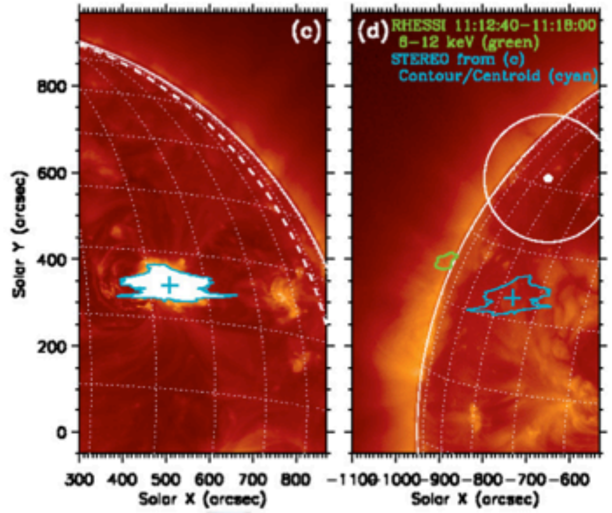
- Located ∼10° behind the eastern limb
- >100 MeV emission for 30 minutes
- *RHESSI* emission consistent with loop top
- Upper limits on nuclear line emission from GBM
- LAT emission centroid consistent with on-disk

SOL2014-01-06



- Located ∼10° behind the western limb
- >100 MeV emission for 20 minutes
- Associated with very strong SEP event
- Gamma-ray onset time consistent with Solar Particle Release time
- Insuffencent statistics for localization

SOL2014-09-01



- Located ∼40° behind the eastern limb
- >100 MeV emission for ∼ 2 hours
- *GBM* and *Konus* emission up to few MeV
- 2.23 MeV line visible in GBM
- LAT emission centroid consistent with on-disk

Taken from M. Pesce-Rollins's presentation at Fermi symposium 2015

FIRST DETECTION OF > 100 MEV GAMMA RAYS ASSOCIATED WITH A BEHIND-THE-LIMB SOLAR FLARE

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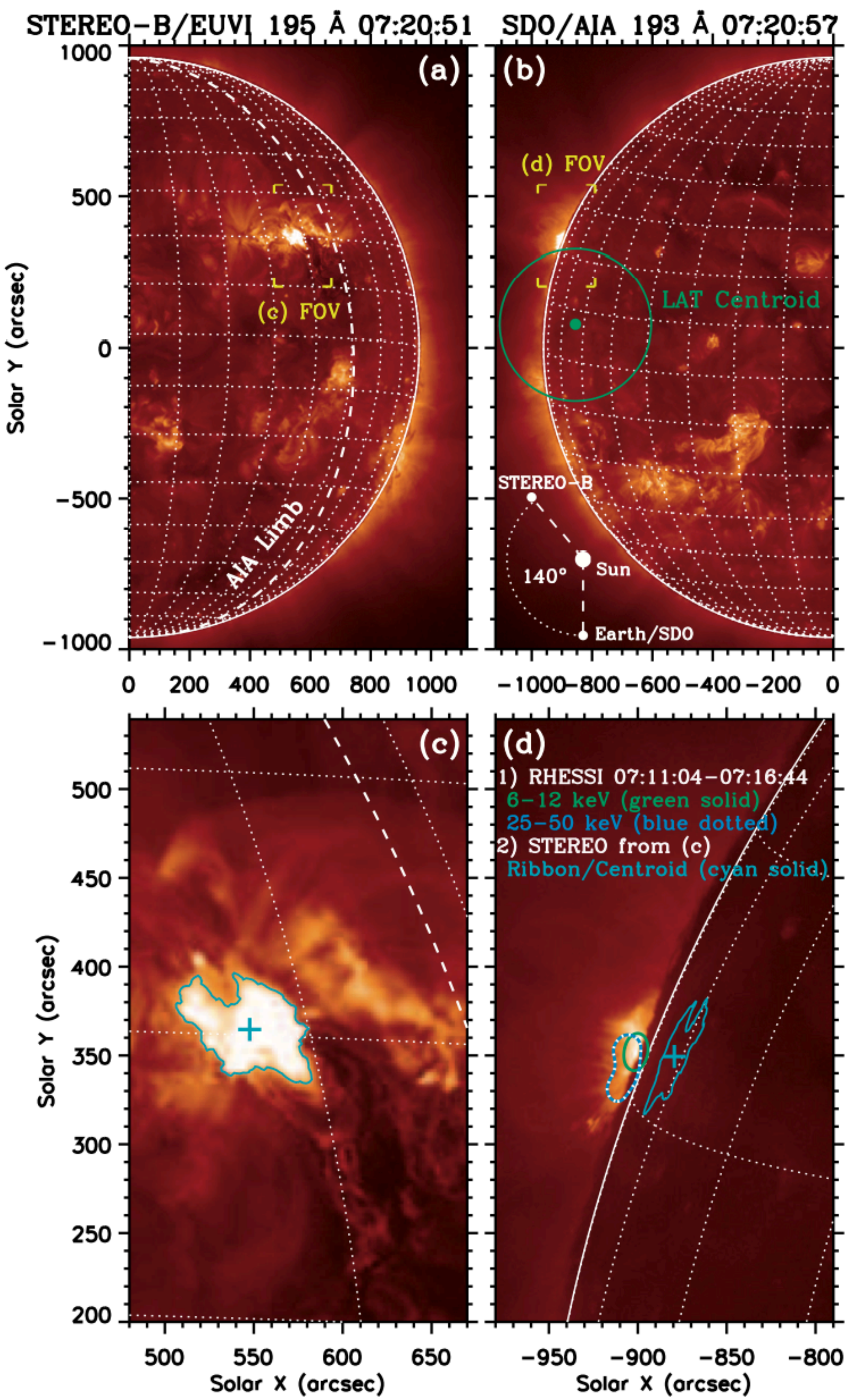
Draft version May 14, 2015

ABSTRACT

We report the first detection of >100 MeV gamma rays associated with a behind-the-limb solar flare, which presents a unique opportunity to probe the underlying physics of high-energy flare emission and particle acceleration. On 2013 October 11 a GOES M1.5 class solar flare occurred $\sim 9^\circ.9$ behind the solar limb as observed by *STEREO*-B. *RHESSI* observed hard X-ray emission above the limb, most likely from the flare loop-top, as the footpoints were occulted. Surprisingly, the *Fermi* Large Area Telescope (LAT) detected >100 MeV gamma-rays for ~30 minutes with energies up to 3 GeV. The LAT emission centroid is consistent with the *RHESSI* hard X-ray source, but its uncertainty does not constrain the source to be located there. The gamma-ray spectra can be adequately described by bremsstrahlung radiation from relativistic electrons having a relatively hard power-law spectrum with a high-energy exponential cutoff, or by the decay of pions produced by accelerated protons and ions with an isotropic pitch-angle distribution and a power-law spectrum with a number index of ~3.8. We show that high optical depths rule out the gamma rays originating from the flare site and a high-corona trap model requires very unusual conditions, so a scenario in which some of the particles accelerated by the CME shock travel to the visible side of the Sun to produce the observed gamma rays may be at work.

Subject headings: Sun: flares: Sun: X-rays, gamma rays



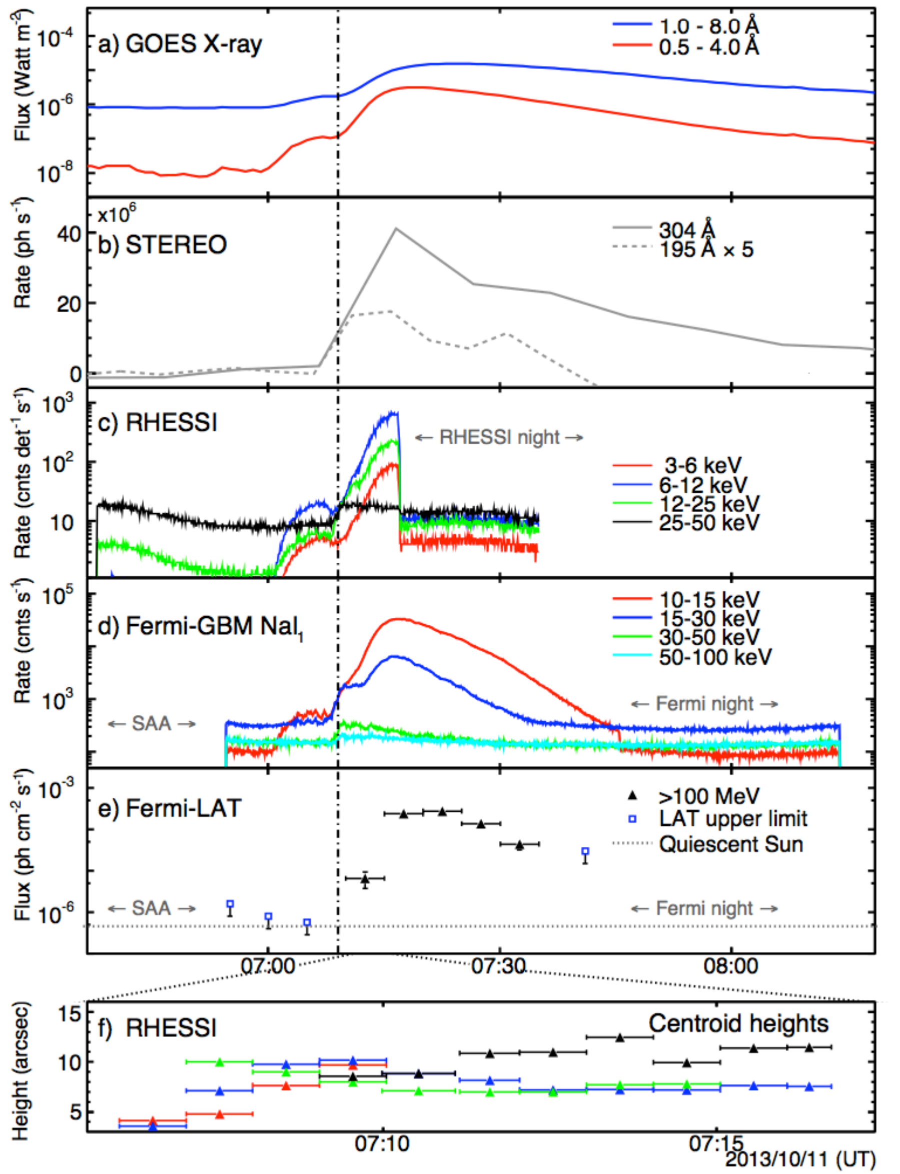


FIG. 1.— Light curves of the 2013 October 11 flare as detected by a) *GOES*, b) *STEREO*, c) *RHESSI*, d) GBM, e) LAT, and heights of the *RHESSI* emission centroid (f) with the same color coding as in c). *Fermi* exited the South Atlantic Anomaly (SAA) at 06:57:00 UT. The vertical dashed line represents flare start time (7:01 UT).

RHESSI+Fermi/GBM+Fermi-LAT
Spectral evolution

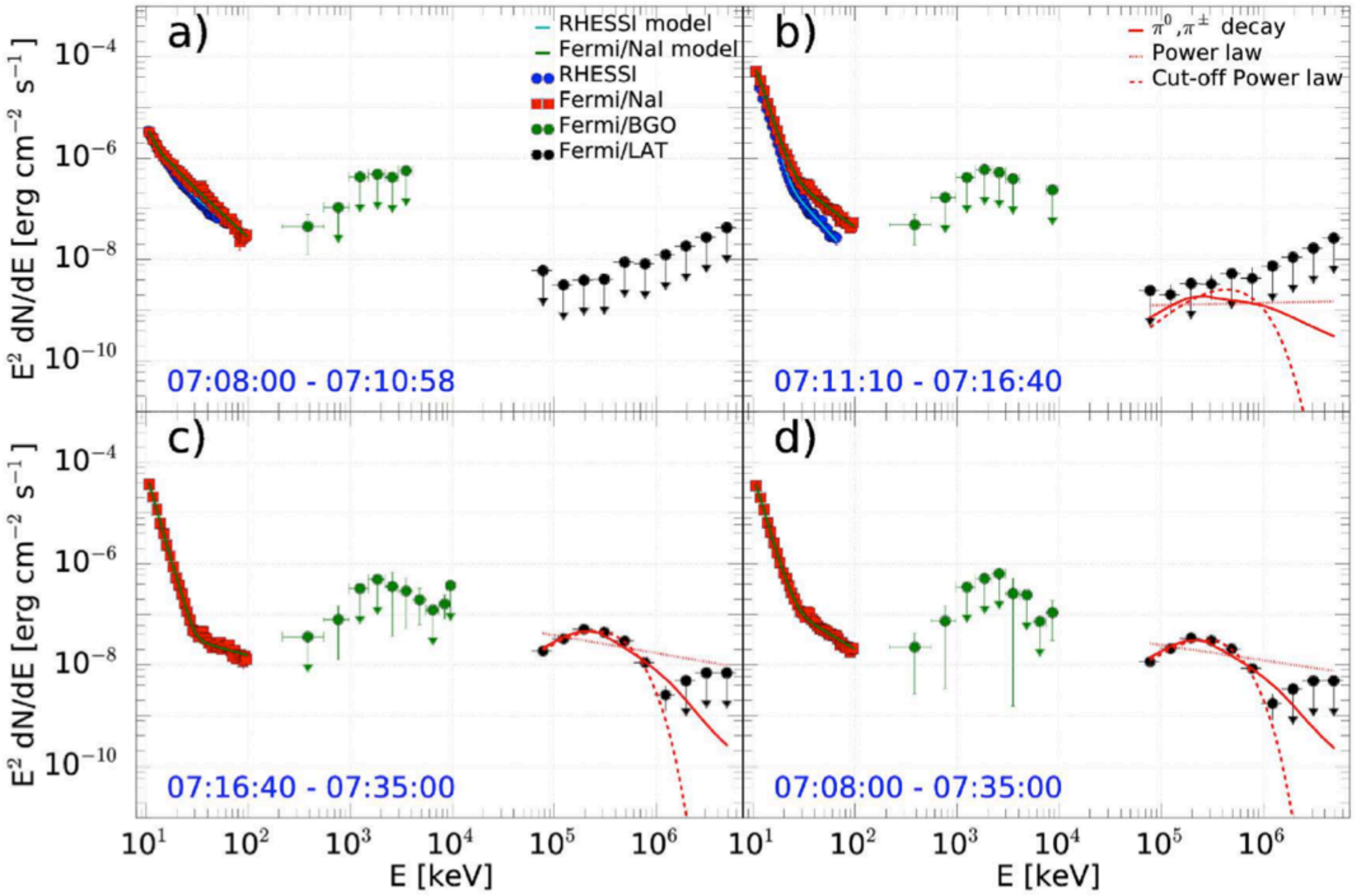


TABLE 1
SPECTRAL ANALYSIS OF LAT, GBM AND *RHESSI* DATA

LAT time intervals						
Time Interval (2013/10/11 UT)	TS_{PL}	ΔTS[a]	Photon index	Cutoff energy[b] (MeV)	Proton index	Flux[c] (10^{-5} ph cm^{-2} s^{-1})
07:10:00–07:15:00	16	5	$1.80\pm0.35^{+0.02}_{-0.02}$[d]	–	–	$0.60\pm0.26^{+0.05}_{-0.04}$
07:15:00–07:20:00	987	22	$0.21\pm0.34^{+0.16}_{-0.14}$	$145\pm27^{+9}_{-8}$	3.7±0.2±0.1	$24.1\pm1.5^{+1.6}_{-1.4}$
07:20:00–07:25:00	1146	92	$0.23\pm0.27^{+0.11}_{-0.11}$	$162\pm26^{+7}_{-7}$	3.5±0.2±0.1	$28.2\pm1.7^{+1.7}_{-1.5}$
07:25:00–07:30:00	435	45	$-0.42\pm0.58^{+0.14}_{-0.15}$	$95\pm21^{+4}_{-4}$	4.3±0.4±0.1	$13.7\pm1.33^{+0.8}_{-0.7}$
07:30:00–07:35:00	55	4	$2.36\pm0.24^{+0.03}_{-0.02}$[d]	–	–	$4.1\pm1.1^{+0.4}_{-0.3}$
07:08:00– 07:35:00	2885	233	$0.2\pm0.2^{+0.135}_{-0.132}$	$147\pm15^{+1}_{-3}$	$3.7\pm0.2^{+0.1}_{-0.1}$	$14.2\pm0.5^{+0.9}_{-1.2}$
07:16:40– 07:35:00	2855	204	$0.4\pm0.2^{+0.134}_{-0.128}$	$155\pm16^{+1}_{-2}$	$3.8\pm0.2^{+0.1}_{-0.1}$	$22.1\pm0.8^{+1.5}_{-1.8}$

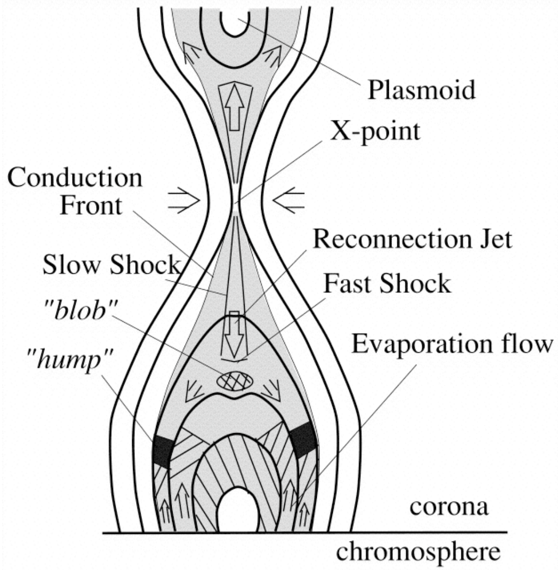
RHESSI and GBM time intervals					
	Broken power law E_{break} (keV)	Broken power law Index	1^{st} thermal component Plasma temperature (keV)	2^{nd} thermal component Plasma temperature (keV)	Flux[e] (ph cm^{-2} s^{-1})
07:08:00–07:10:58*	17.9±0.5	3.76±0.04	2.23±0.06	–	52±1
07:08:00–07:10:58	17.9±0.9	3.88±0.03	1.9±0.1	–	55±1
07:11:10–07:16:40*	16±2	4.24±0.07	1.92±0.02	0.62±0.03	253±5
07:11:10–07:16:40	21±5	3.52±0.05	2.9±0.4	1.54±0.16	630±10
07:16:40–07:35:00	20 (fixed)	2.56±0.06	2.71±0.07	1.27±0.04	399±8
07:08:00–07:35:00	20±8	3.22±0.05	2.8±0.2	1.34±0.08	388±8

[a] $\Delta TS = TS_{PLEXP} - TS_{PL}$
[b] From the fit with PLEXP model.
[c] Integrated flux between 100 MeV and 10 GeV calculated for the best fit model.
[d] Photon index from the fit with PL.
[e] Integrated flux between 10 and 100 keV calculated for the best fit model.
* *RHESSI* spectral fit results. At 07:10:59 UT *RHESSI* changed its attenuator.
Intervals a) and b) of Figure 3 excluded due to lack of statistics. Statistical errors are shown first and systematic errors follow.

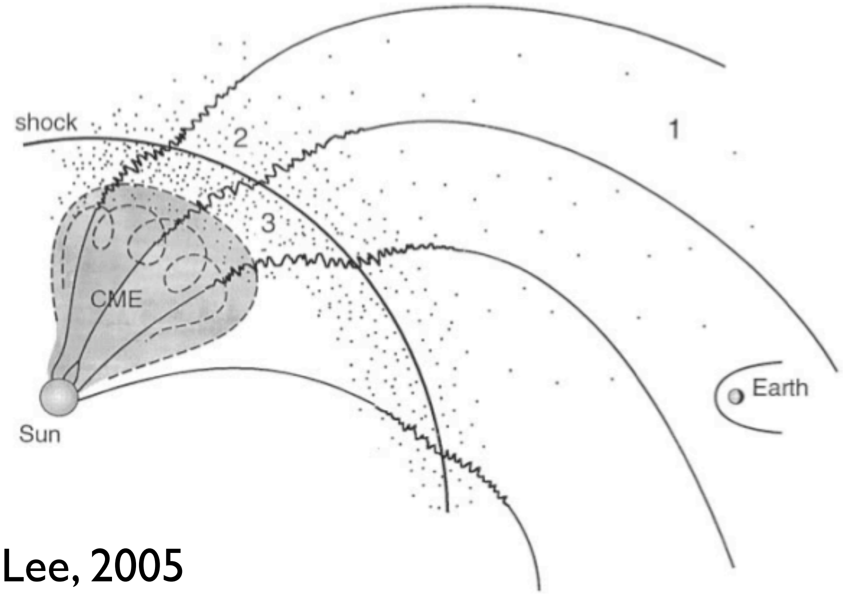
- Cutoff PL is significantly favored over PL
- Sqrt(TS)~sigma
- Very hard photon index, indicating the very hard electron index
- Pion-decay gamma would be most plausible (my personal view)

Possible scenarios

- Electrons or Protons? Possibly protons are responsible for LAT emission, given the very hard PL index for PL-cutoff model
- Deep below the photosphere of the flare site
- In the corona above the limb (suggestive of trapping particles)
- CME-shock accelerated particles traveling back to the Sun



Yokoyama & Shibata, 2001



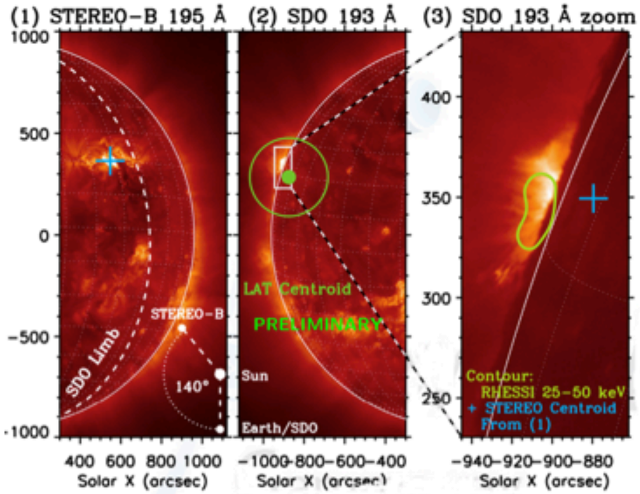
Lee, 2005

Rough estimation

- LAT emission need to be emitted from deep inside the photosphere at the column depth of N>10^25 cm-2, compared to HXR-producing site (depth) of 10^20 cm-2
- Detailed calculation for ~1 GeV protons and electrons are described in the LAT paper
- Energy loss time for 1 GeV proton is ~2x10^15/n s. To sustain the emission for ~2000 sec, the required density is >10^12 cm-3, which is much larger than the typical coronal density at >10^9 cm

LAT behind-the-limb flares

SOL2013-10-11



- Located ∼10° behind the eastern limb
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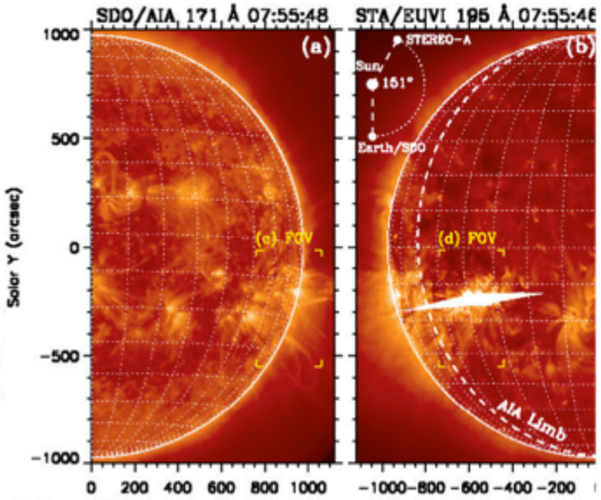
- Upper limits on nuclear line emission from GBM
- LAT emission centroid consistent with on-disk

SOL2014-01-06



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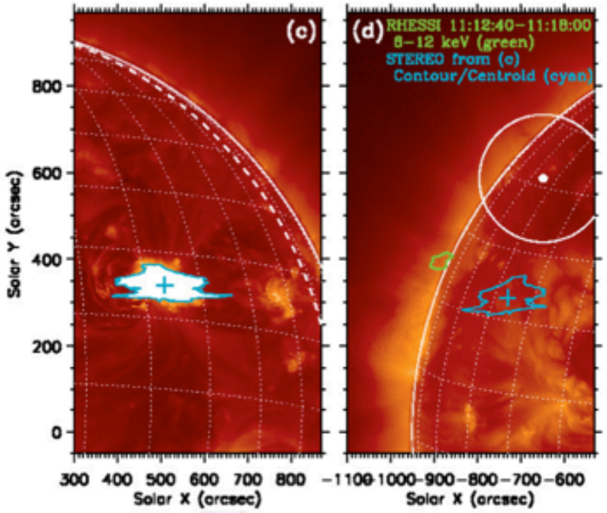
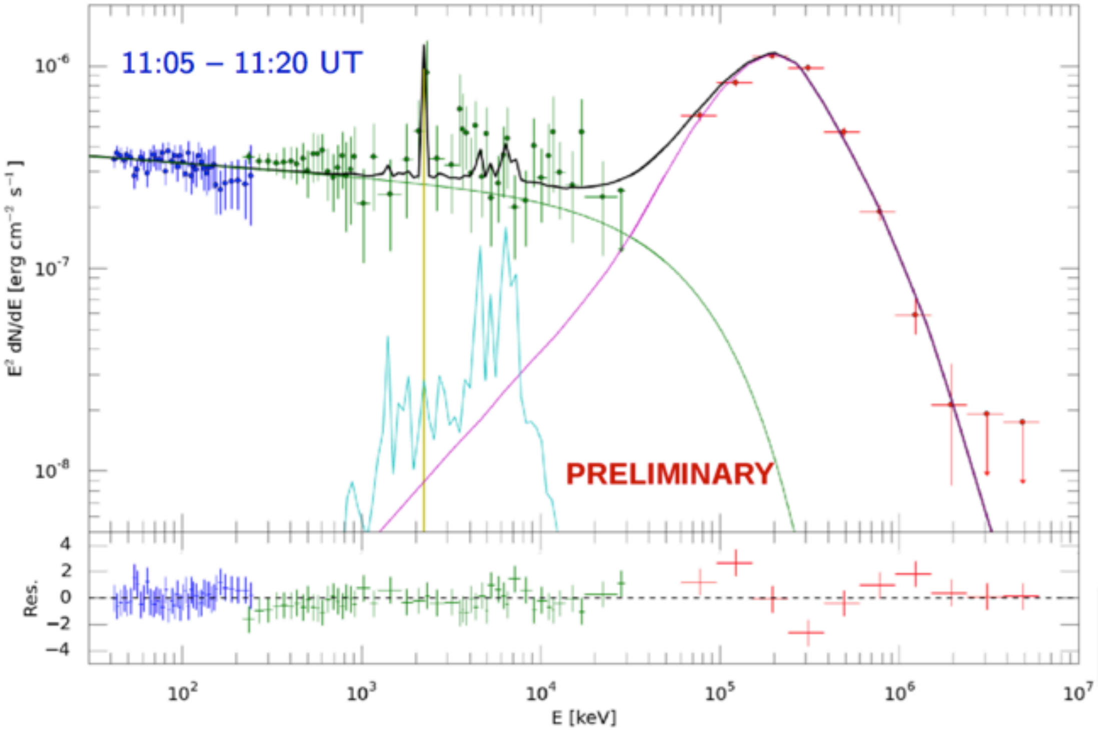
SOL2014-09-01



- Located ∼40° behind the eastern limb
- >100 MeV emission for ∼ 2 hours
- *GBM* and *Konus* emission up to few MeV
- 2.23 MeV line visible in GBM
- LAT emission centroid consistent with on-disk

Taken from M. Pesce-Rollins's presentation at Fermi symposium 2015

SOL2014-09-01 Spectral energy distribution



1. Pion decay template
2. 2.2 MeV line (gaussian)
3. Narrow lines template
4. Power-law with EXP cut-off

- LAT data is well described by a curved spectrum
  - Best proton spectral index from fit 4.4±0.1
- Photon spectral index 2.1±0.1
- Folding energy 6.7±0.4 MeV
- Significance of 2.23 MeV line and narrow lines is $\sim 7\sigma$

Summary

- Behind-the-limb flare was detected several times by Fermi-LAT
- Location of the LAT emission is consistent with RHESSI hard X-ray position
- LAT spectrum is represented by either cutoff-PL or pion-decay
- Detailed calculation of optical depth rule out the flare site origin
- high-corona trap model requires very unusual condition
- Thus, CME-shock accelerated particles traveling back to the Sun would be the most plausible