The Sun and the Solar System in Gamma Rays

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on behalf of the Fermi-LAT collaboration

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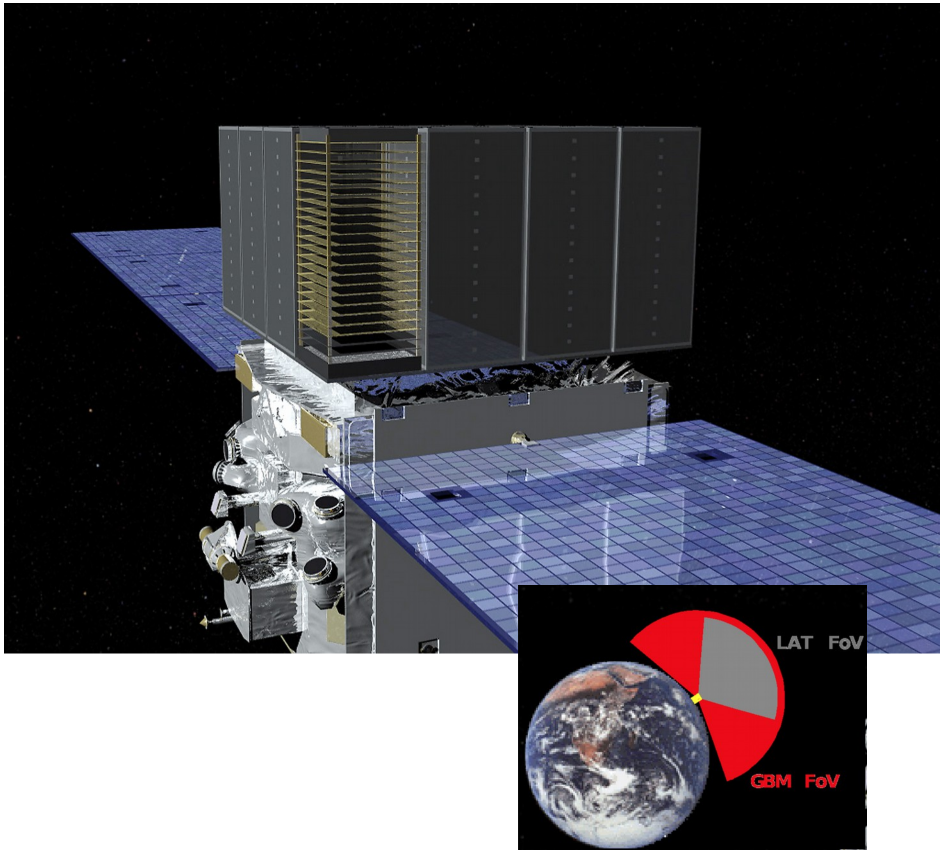
Outline

- Introduction
  - The *Fermi* Gamma-Ray Space Telescope
- The active Sun as seen in gamma rays:
  - *Fermi* observation of solar flares:
  - Pass8 improvements
  - some interesting cases
- *Fermi* observation of the quiet Sun
- The Solar System observed in gamma rays:
  - Moon
  - Earth-Limb
  - Terrestrial Gamma-ray Flashes (TGFs)
- Prospects and Conclusions

The *Fermi* observatory



- Large Area Telescope (LAT)
  - 30 MeV - ~1 TeV
  - observes ~ 20% of the sky at any instant, exposing all part of the sky for 30 min every 3 hrs
- Gamma-ray Burst Monitor (GBM)
  - 8keV - 40 MeV
  - 12 NaI + 2 BGO detectors
  - looks at the whole unocculted sky

➡ **Great discovery potential**
➡ **Perfect observatory to constantly monitor the solar activity and to study transients events like solar flares!**

Solar Flares @ high-energies

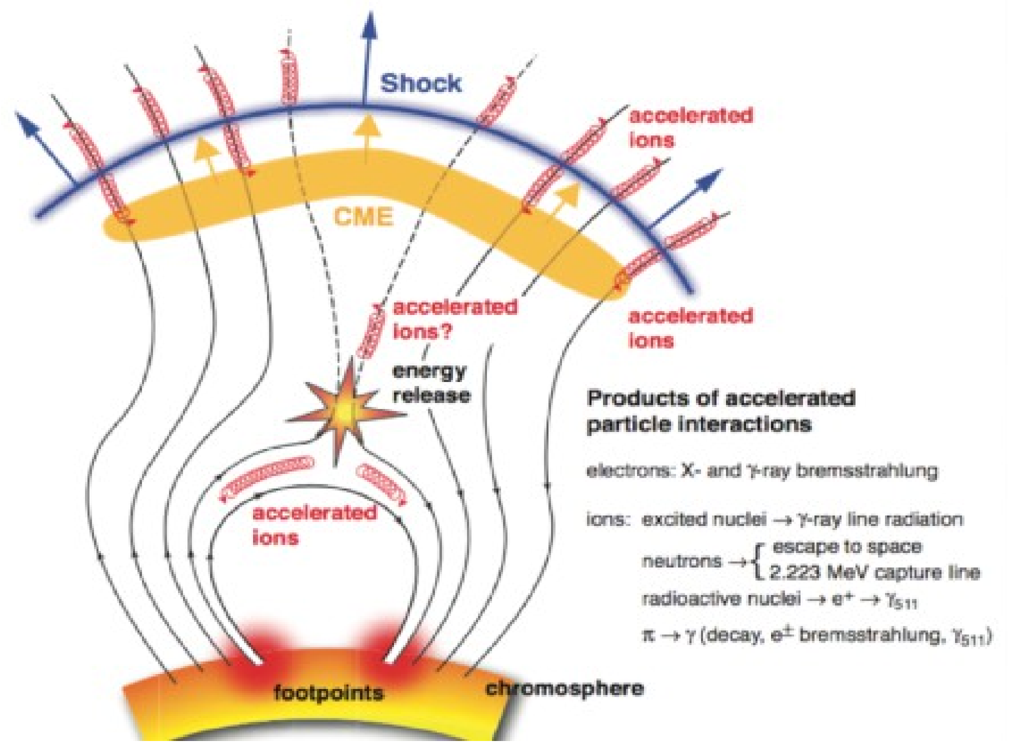
- Magnetic fields reconnect releasing energy which

  accelerate particles

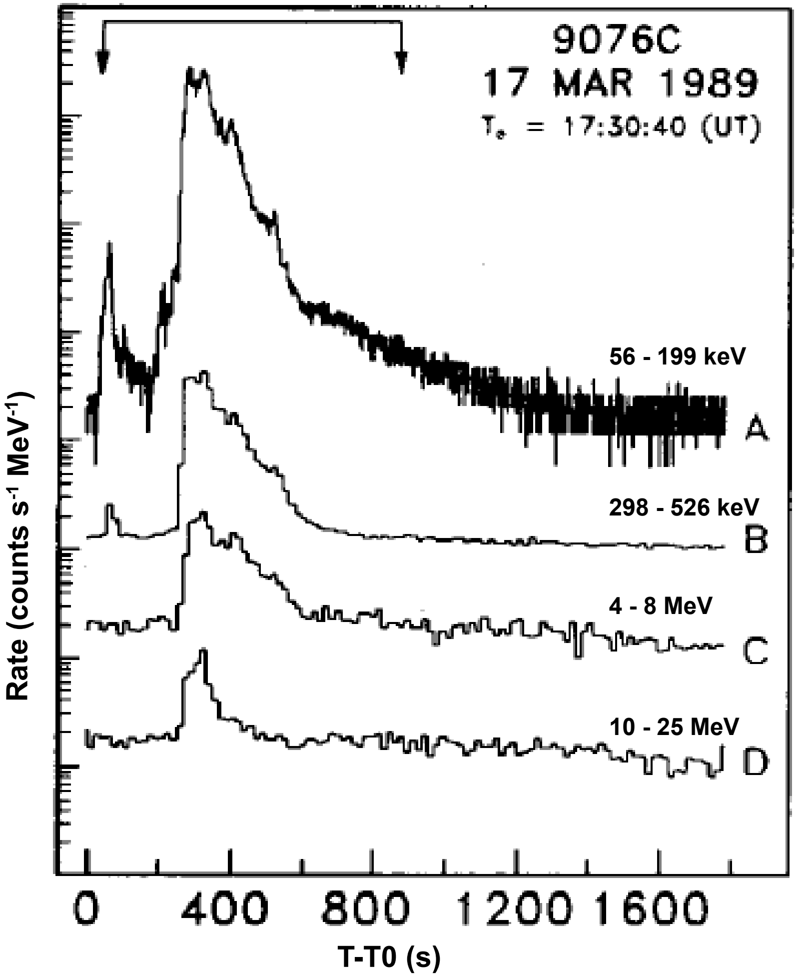
- Particles trapped by magnetic field lines interact with solar atmosphere, producing gamma-rays

- Some of these particles can escape into interplanetary space

- They can also be accelerated by the CME shock

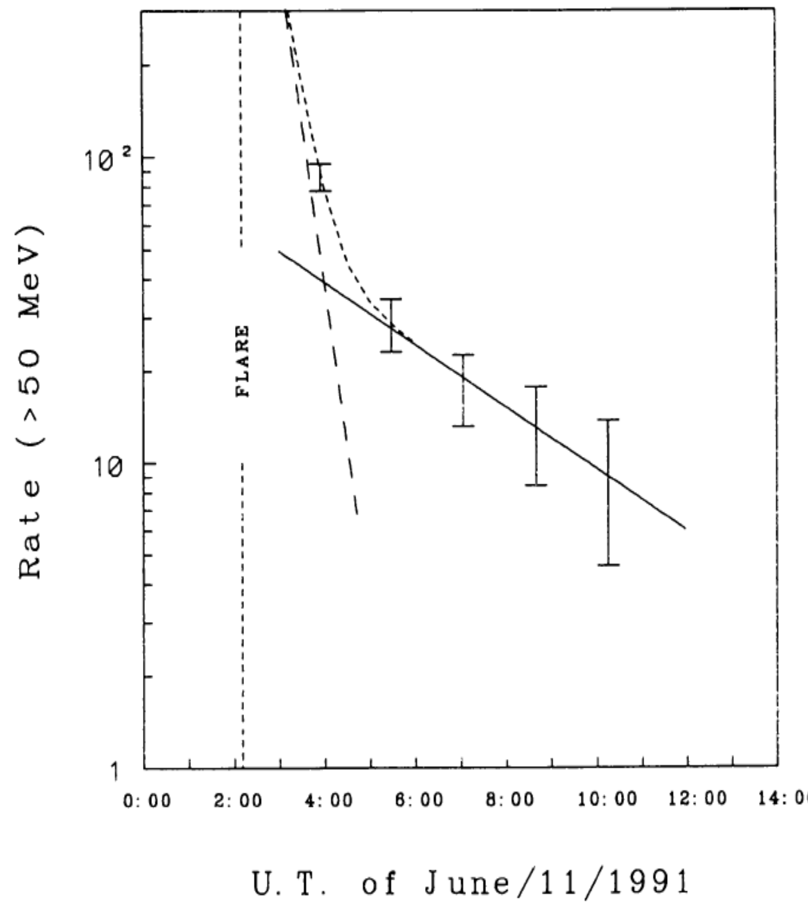


Solar Flares in Gamma-rays



SMM Atlas of Solar Flares
(Vestrand et al. 1999) Up to 25 MeV

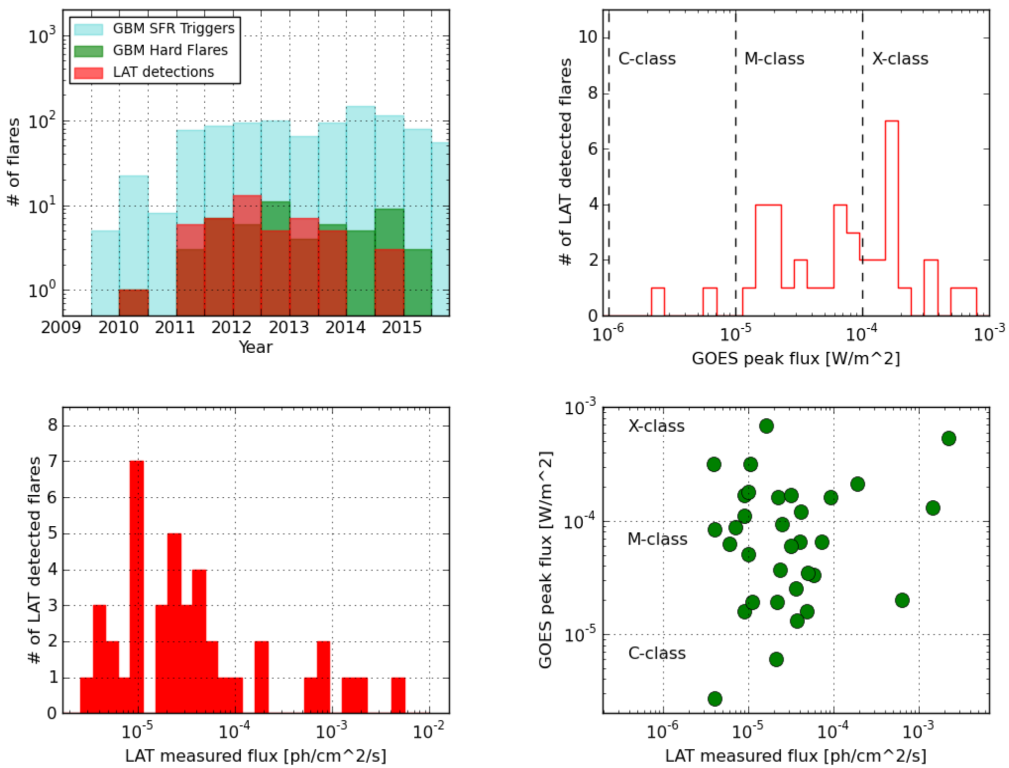
EGRET detection of June 11, 1991 Solar Flare
(Kanbach et al 1993)
..one of two lasting for several hours



Fermi observation of Solar Flares

- **Only 9 solar flares have been detected with E>25 MeV before Fermi (SMM, EGRET in ~ 20 years of observations); only X-class**

- **Up to now, the LAT detected more than 40 solar flares, from C to X GOES class**
- **GBM detects ~ one hundred of solar flare yr $^{-1}$**



Fermi observation of Solar Flares

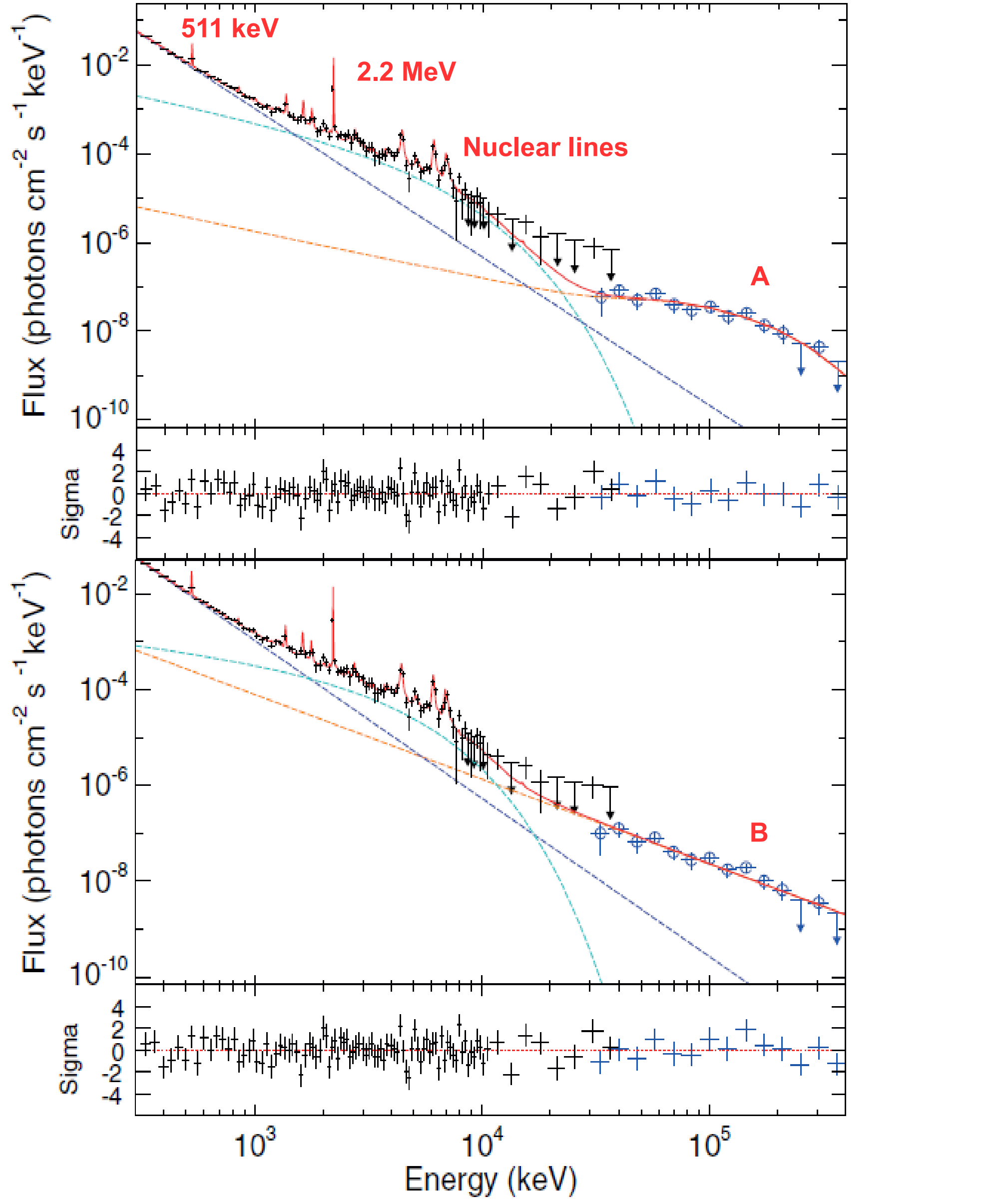
- The LAT detected eXtreme and Moderate class flares
- All these flares are associated with fairly fast CME
- Impulsive Emission
- Long-duration (Sustained) emission
- Delayed Emission: the Sun was in the LAT FOV at the time of the impulsive flare, but the LAT did not detect it

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

Ackermann et al. (2014)

Fermi observation of Solar Flares
SOL 2010-06-12

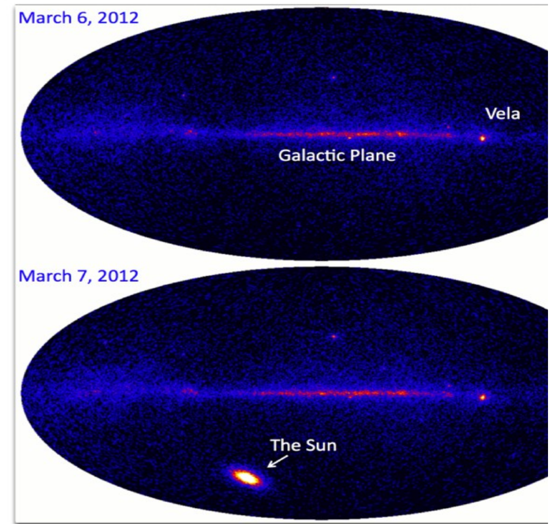
- **GBM and LAT joint spectral analysis**
  - **Electron bremstrahlung for E < 1MeV**
    two components: hardening followed by a roll-off at 2.4 MeV
  - **Ions/protons lines:**
    - **2.23 MeV neutron capture line**
    - **511 keV e^+e^- annihilation line**
    - **4-7 MeV de-excitation nuclear lines**
- **Spectral analysis > 30 MeV**
  - **Pion decay component (A) or HE bremsstrahlung component (B)**



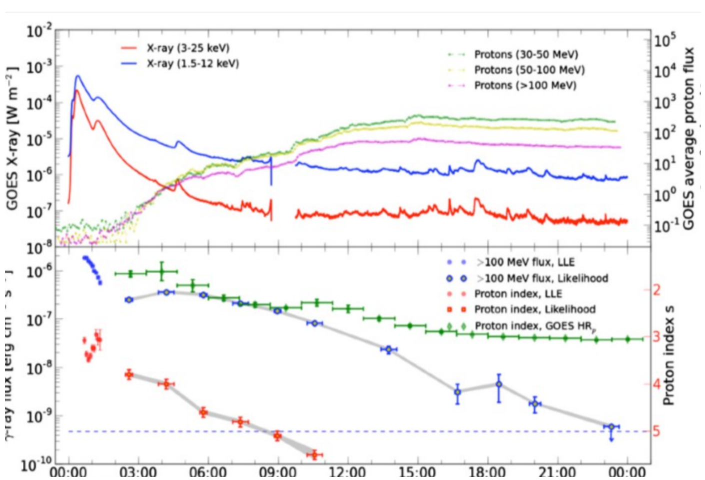
Ackermann et al. (2012)

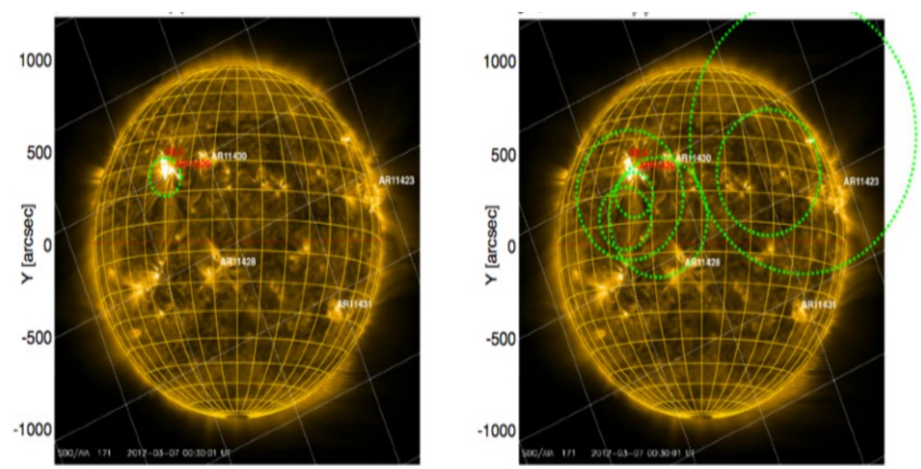
Fermi observation of Solar Flares SOL 2012-03-07

- Very bright Solar Flare:
  - > 1000 times the flux of the steady Sun
- Light-curves and spectra:
  - High energy emission (>100 MeV - 4 GeV) lasts for ~20 hours
  - Softening of the spectrum with time
  - Impulsive emission correlated with X-ray flux
  - Sustained emission better correlated with SEP
- Localization studies
  - Correction of the "fish-eye effect"
  - Location of the gamma-ray emission consistent with the AR 11429
  - Time resolved localization



LAT 1 day all sky data

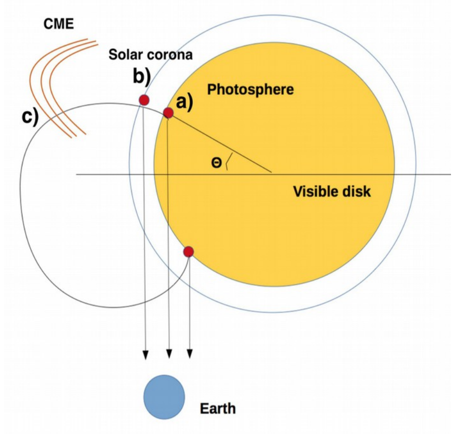


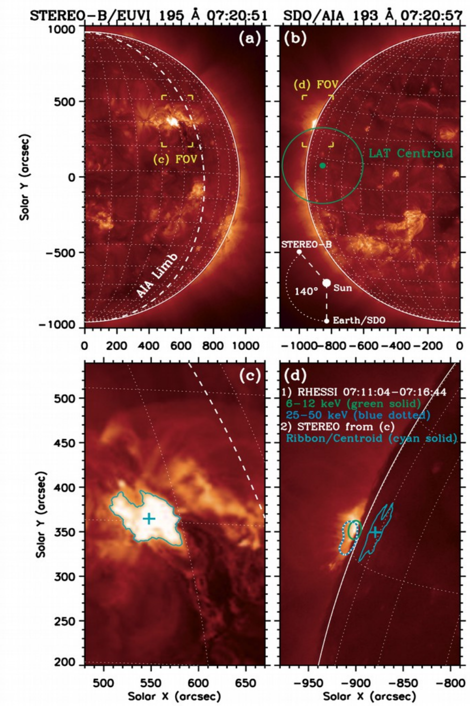


Ackermann et al. (2014)

Fermi observation of Solar Flares
SOL 2013-10-11

- **The first >100 MeV *behind-the-limb* flare (θ ~10 deg)**
- **Emission scenarios:**
  - **Footpoints not visible at the time of the gamma-ray detection**
    - **If HE emission occurs in photosphere at flare site: the optical depth makes a detection from |θ| >2 deg impossible**
  - **High density region required for gamma-ray production**
  - **CME shock accelerated particles travel to the front side of the Solar disk**
- **Open questions:**
  - **How are protons travelling to the visible disk?**
  - **What is causing this migration?**
  - **Diffusion along field lines?**

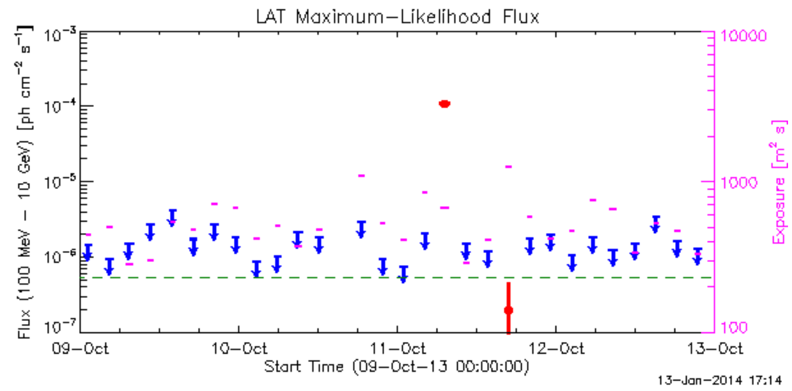




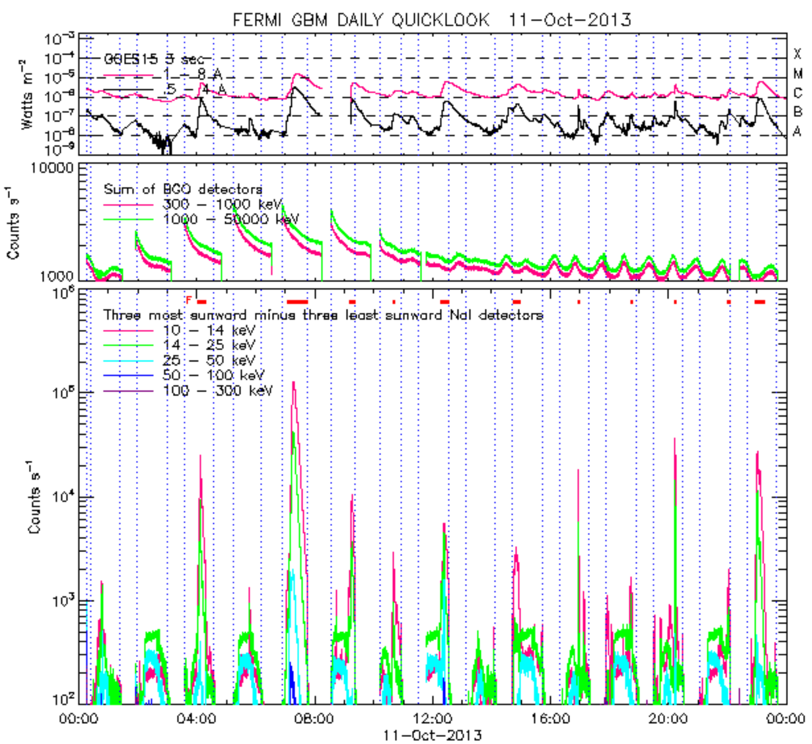
Pesce-Rollins et al. (2015)

The Online LAT Sun Monitor (credit to N. Omodei)

- **LAT data light-curve @ hesperia Fermi Solar website**
  http://hesperia.gsfc.nasa.gov/fermi_solar/
  - **> 100 MeV data**
  - **variable time-bins**
  - **Flux and uncertainty for points with significance >~ 4 sigma**

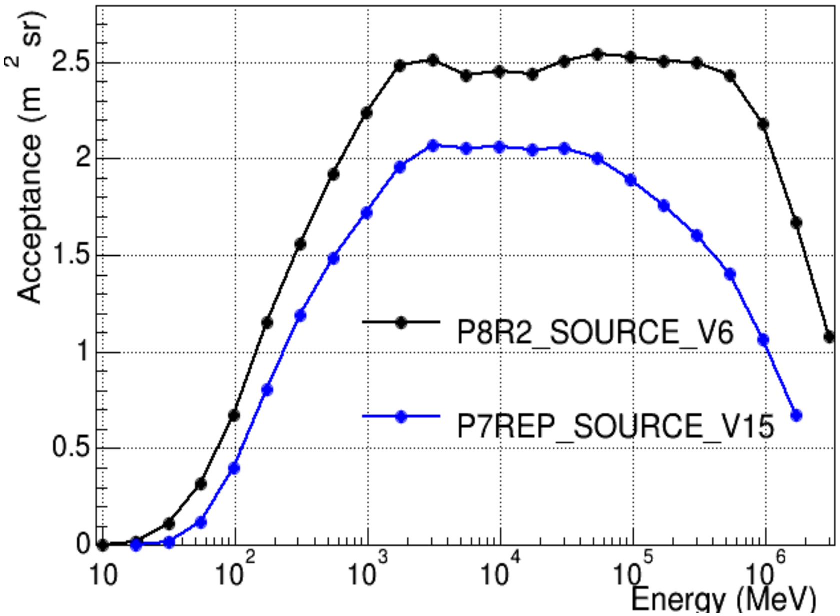


- **Quick-look on data taken at the same time from other instruments (GBM, RHESSI, GOES, ..)**



Pass 8 LAT data

- **Pass 8 is a comprehensive revision of the entire analysis chain that yields substantial gains in instrument performance:**
  - **Larger acceptance**
  - **Better PSF**
  - **Wider energy range**
  - **Better bkg rejection**
  - **Better control of systematic uncertainties**

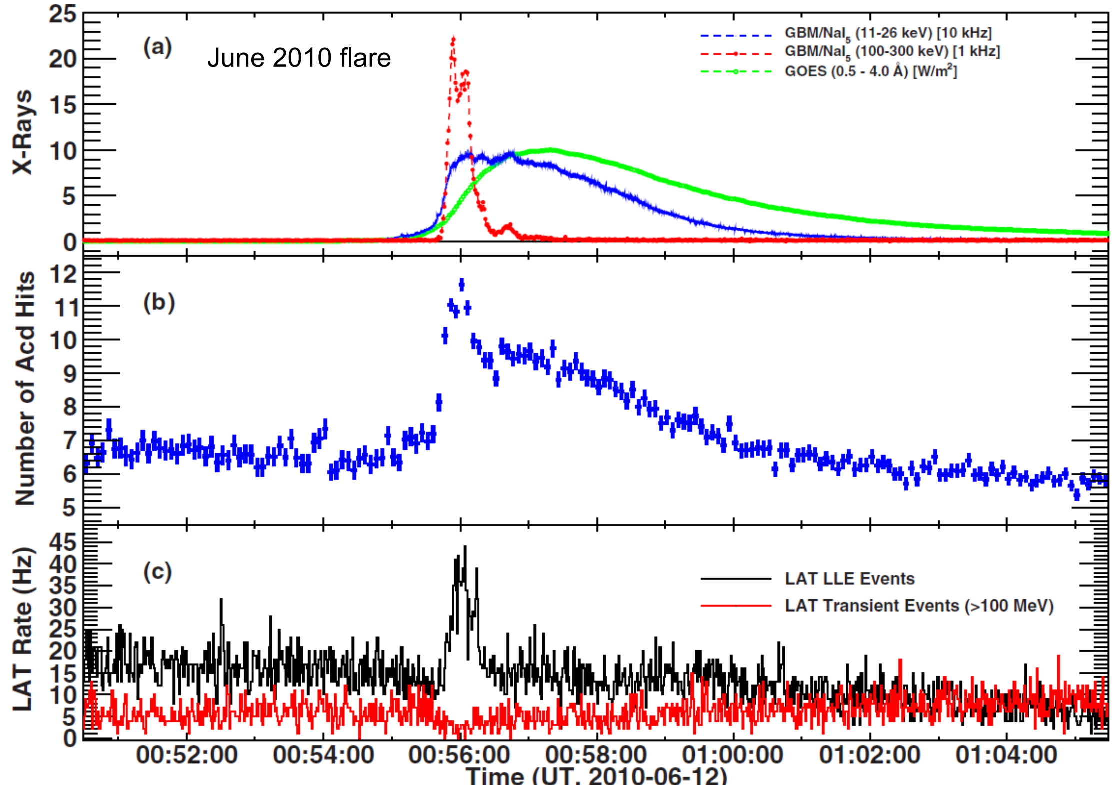


- **Effectively a “new" LAT**

- **Development of Solar-Flare dedicated event classes with better treatment of ACD pile-up**

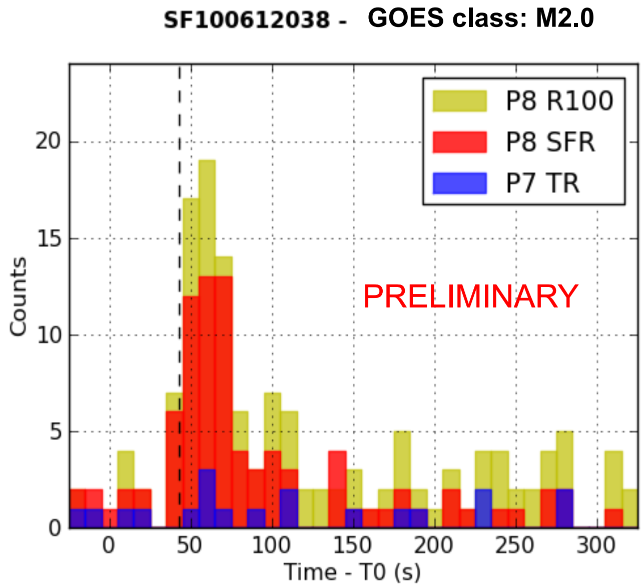
The LAT Low Energy Technique

- Intense X-ray flux during the impulsive phase caused pile-up in the ACD and suppression of the standard LAT event rate.
- Recover the signal with looser selection technique
  - LAT Low Energy data (LLE)

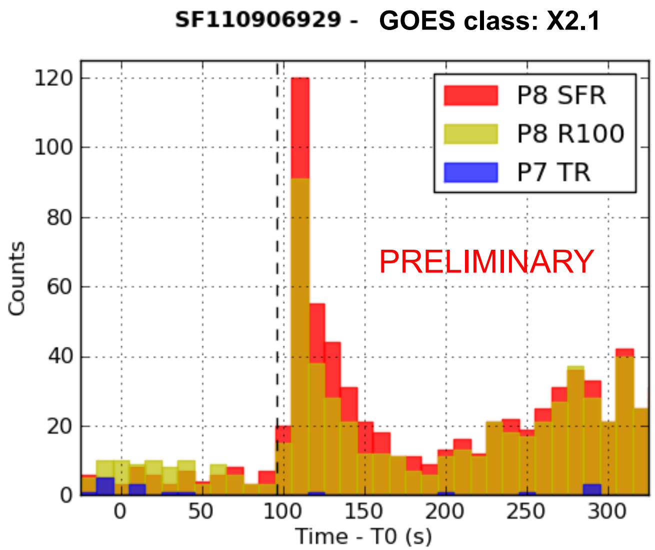


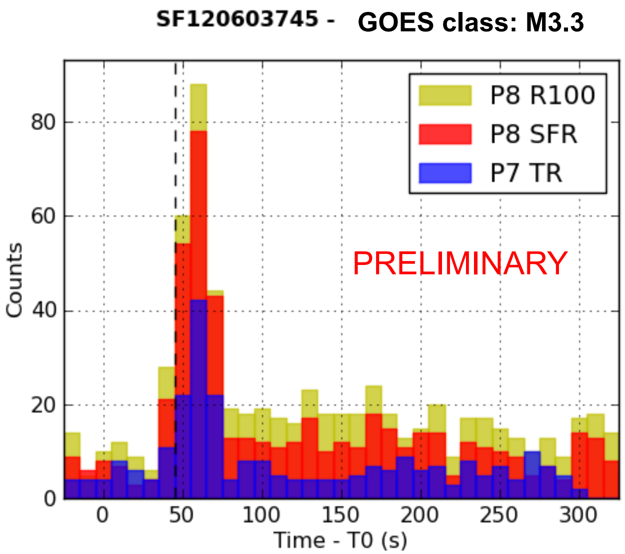
Ackermann et al. (2012)

Pass 8 Analysis of Solar Flares



- **R100: Loosest Pass 8 TRANSIENT class**
- **SFR: Pass 8 class dedicated to Solar Flare analysis**





Desiante et al. (2015)

The Quiet Sun

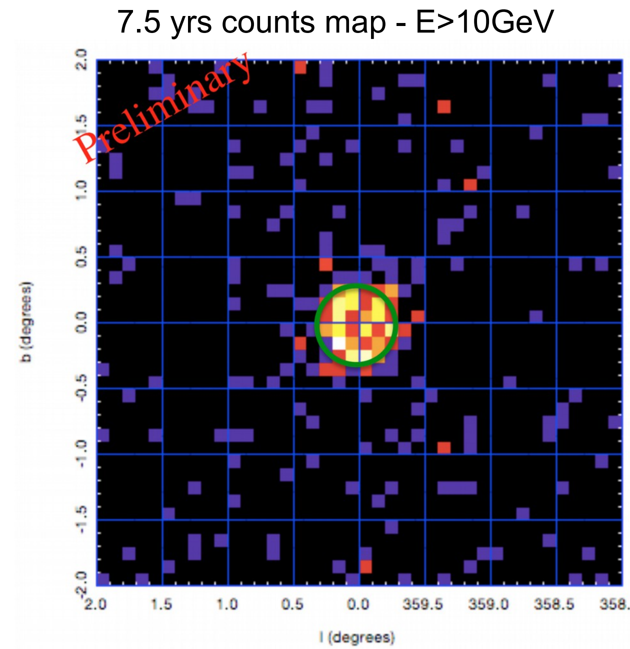
- Gamma-ray emission from the steady sun:
  - interaction of charged CRs with the solar atmophere (point-like emission)
  - Inverse Compton emission due to CR-electrons scattering off photons in the heliosphere (extended emission)
- Probe for CR fluxes in the solar system and for electrons in the inner heliosphere
- IC solar emission is extended: background for many studies
- The gamma-ray flux depends on CRs flux intensities
- Gamma-ray flux measurements depend on the solar cycle

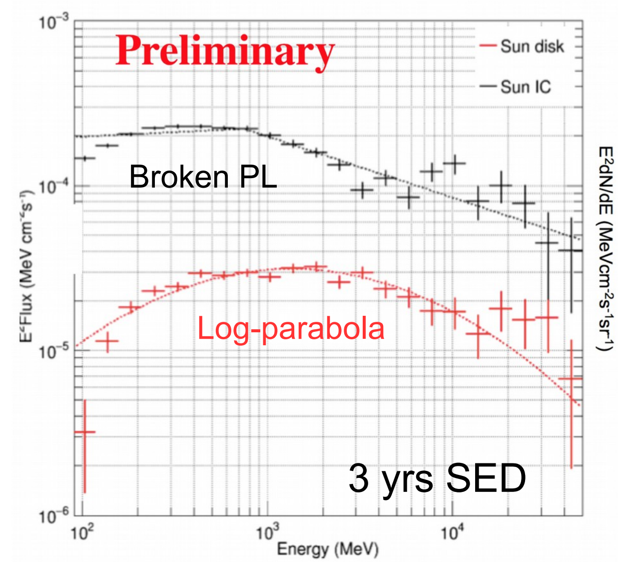
The Quiet Sun

- First 18 months data results in Abdo et al. 2011 - arXiv: 1104.2093

- First 8 years analysis ongoing Preliminary results: (Raino' et al. CRIS 2106)
  - IC profile: in agreement to what predicted by the models
  - Disk: flux similar to that published on the first analysis ($1.93 \pm 0.07 \ 10^{-7}$ ph $cm^{-2}s^{-1}$)
  - The solar disk component demonstrates a clear trend in anticorrelation with solar activity

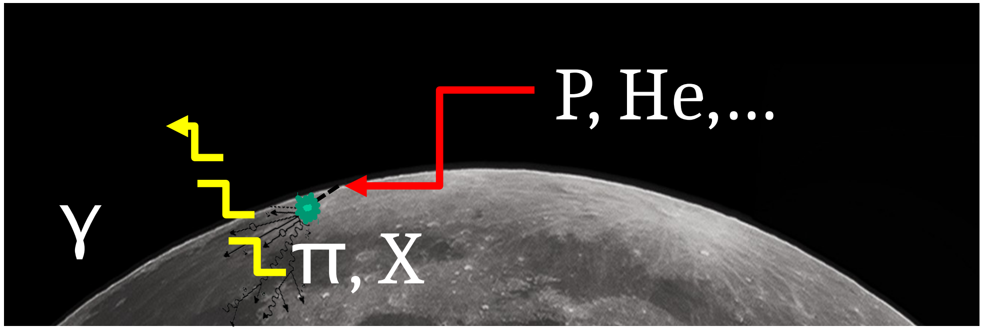
7.5 yrs counts map - E>10GeV

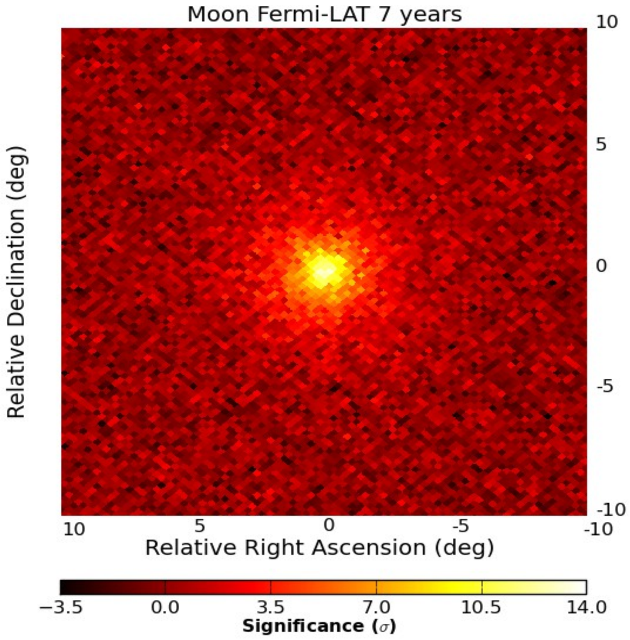




Gamma rays from the Moon

- Gamma-ray are produced in the interactions of primary CRs with the lunar surface via π^0 decays
- The lunar gamma-ray flux is sensitive to:
  - primary CRs composition and spectra
  - lunar surface composition
- Time evolution of gamma-ray intensity of the Moon shows a correlation with the solar activity
- The Moon gamma-ray data allow to reconstruct the local CR p and He spectra
- Details in Ackermann et al. 2016 (arXiV 1604.03349)





APOD 2016 Apr 29

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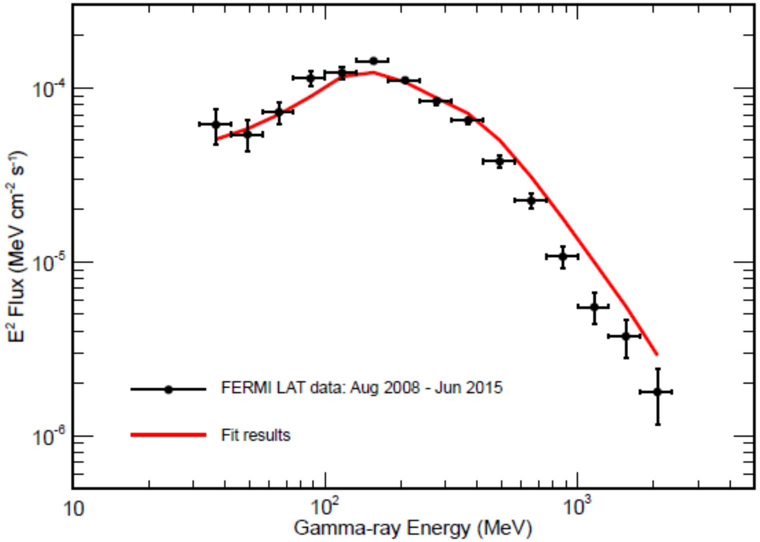
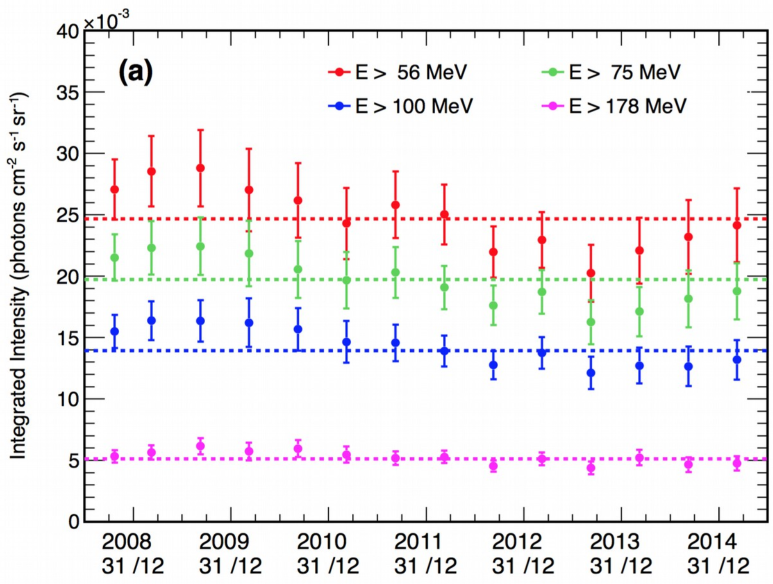
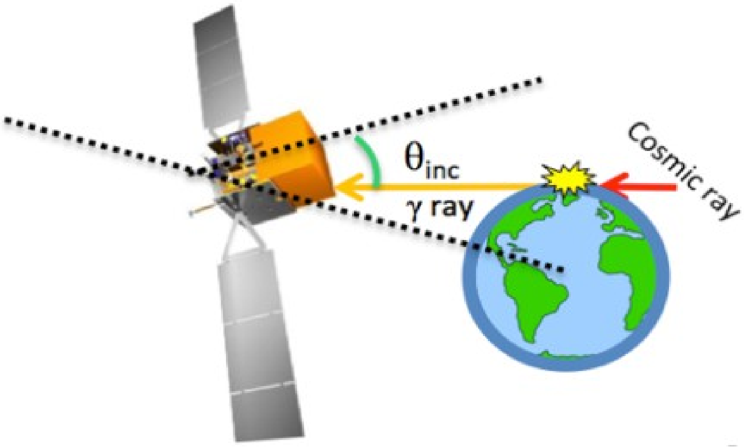
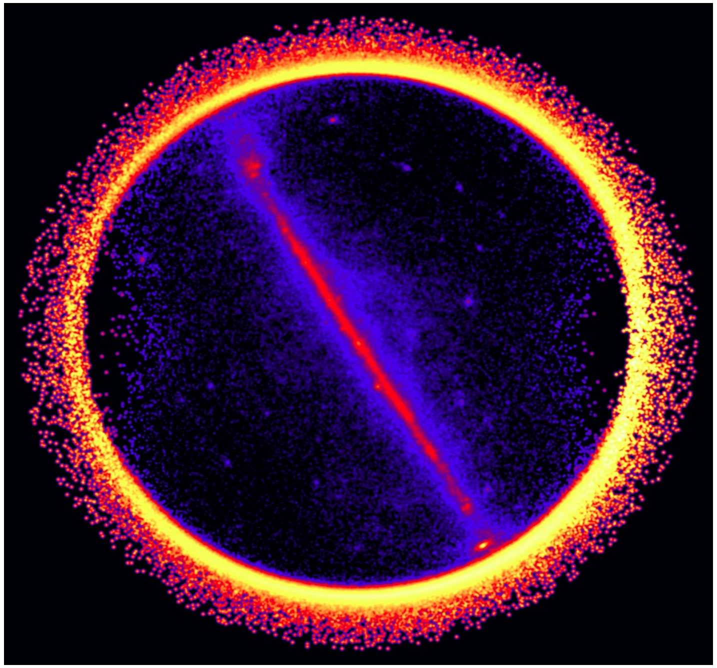




The Earth Limb

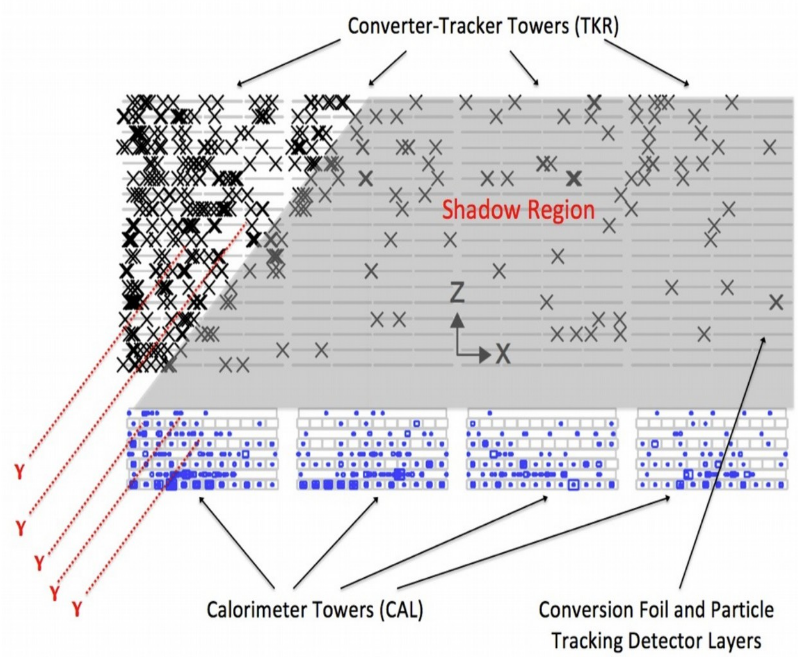
- **Gamma rays from charged cosmic rays (mainly protons) interactions in the upper atmosphere**
  - **visible at the horizon**
- **The horizon has essentially a fixed angular distance from the zenith**
  - **for a satellite at 560 km orbit altitude the limb emission is visible at a zenith angle of ~ 110 deg**
- **LAT data in the range 15 GeV - 1 TeV used to derive the proton energy spectrum in the range 90 GeV - 6 TeV**
  - **indicate a flattening of the proton spectrum at high energies**
- **Details in Ackermann et al. 2014 (arXiv: 1403.5372)**





Terrestrial Gamma-ray Flashes

- The LAT regurarly detects upward-going ~ 10 MeV gamma-rays in coincidence with GBM detected TGFs:
  - effective area for triggering: ~500 cm^2
  - clear excess in the LAT trigger rate during TGFs
- TGFs are bright, so events are complex!
  - not single-photon events
  - Tens or hundreds of γ-rays in one LAT "event"



- Thick calorimeter casts shadow on tracker for upward-going MeV gamma rays

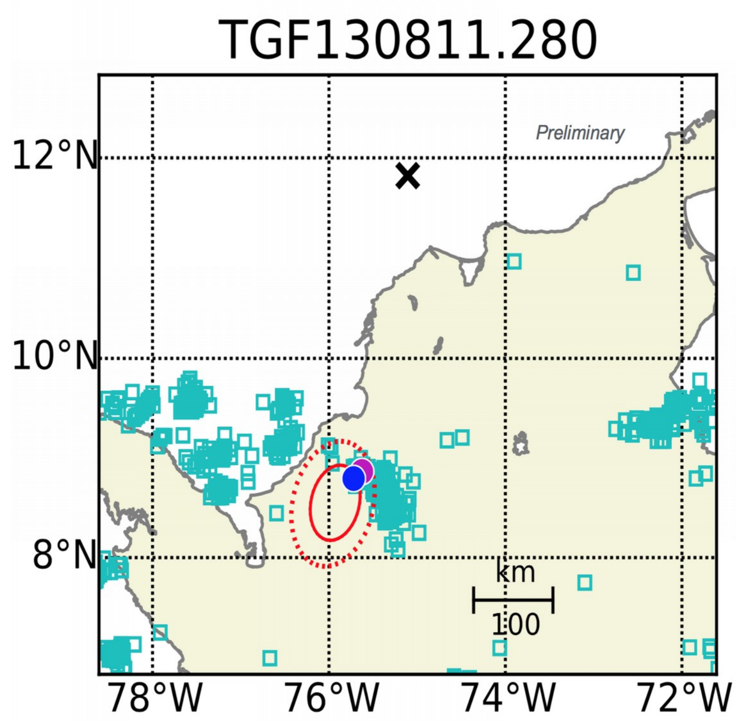
Grove et al. *Fermi* Symp. 2015

Terrestrial Gamma-ray Flashes

- >~ 150 TGFs can be geolocated from LAT signal (5yrs sample)
  - 19 TGFs with good γ-ray geolocations (<15 km uncertainties) have VLF/LF radio geolocations

- Gamma rays and VLF/LF pulse are spatially and temporally coincident:
  - common origin in relativistic electron avalanche
    (Cummer et al. 2011, Connaughton et al. 2013, Dwyer and Cummer 2013)
  - Gamma rays from bremsstrahlung
  - Radio from pulse of secondary ionization electrons

- Thunderstorms with modest lightning activity can produce bright TGFs



- LF/VLF in blue and magenta
  - ~10 km uncertainty
  - LAT local. (68%, 95% confidence)
  - ~ ±50 km uncertainty
- Lightning in cyan
  - Within 10 minutes of TGF

Grove et al. *Fermi* Symp. 2015

Conclusions and Future Steps

- Catalog of LAT flares is in preparation
  - Explore correlation with CME and SEP
  - Pass8 Improvements allow to better study the low energy gamma-ray part of the spectrum and improve the localization and duration measurements
  - Constrain emission models

- Detailed paper on MWL observations of the three behind-the-limb flares just submitted to ApJ!

- Papers with upadated analysis on the gamma-ray emission from the earth-limb and the quiet sun in preparation using Pass 8 data (stay tuned!)