Fermi Large Area Telescope observations of high-energy gamma-ray emission from solar flares

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on behalf of the *Fermi*-LAT collaboration

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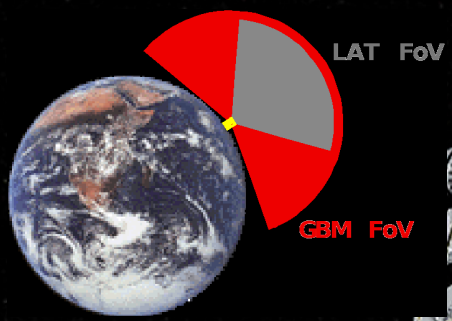
The *Fermi* Space Telescope

Gamma-ray Burst Monitor (GBM)

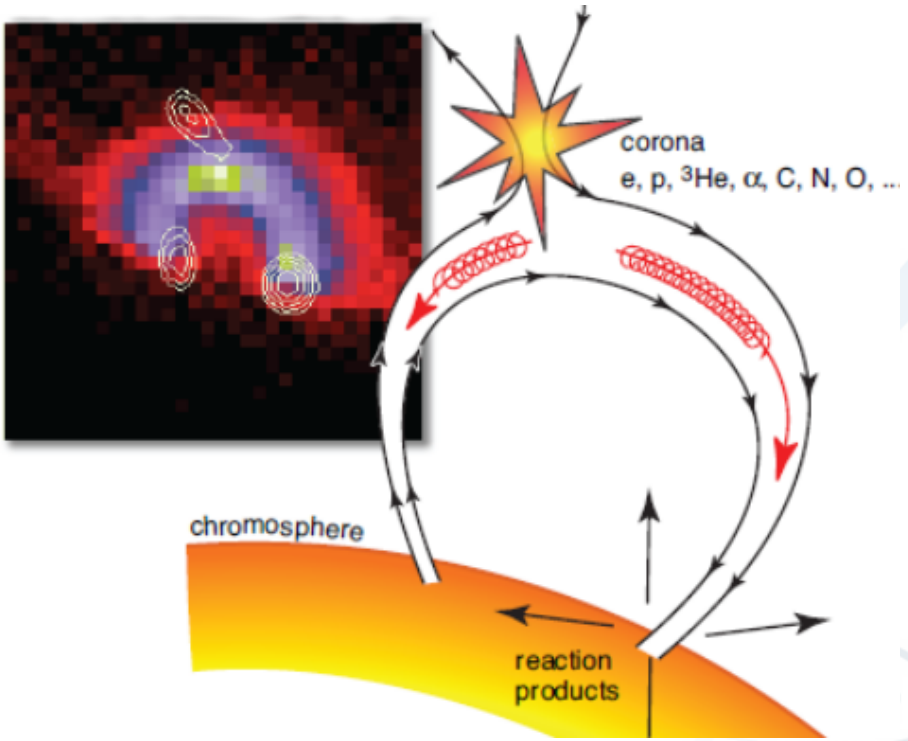
- 12 NaI and 2 BGO detectors
- Energy range: 8 keV–40 MeV
- Observes entire unocculted sky



The Large Area Telescope (LAT)

- Pair conversion telescope
- Energy range: 20 MeV–> 300 GeV
- Large field of view ($\approx$ 2.4 sr): 20% of the sky at any time, all parts of the sky for 30 minutes every 3 hours
- Observes the Sun for $\sim$20 – 40 min every 3 hours

Gamma-ray Solar flares



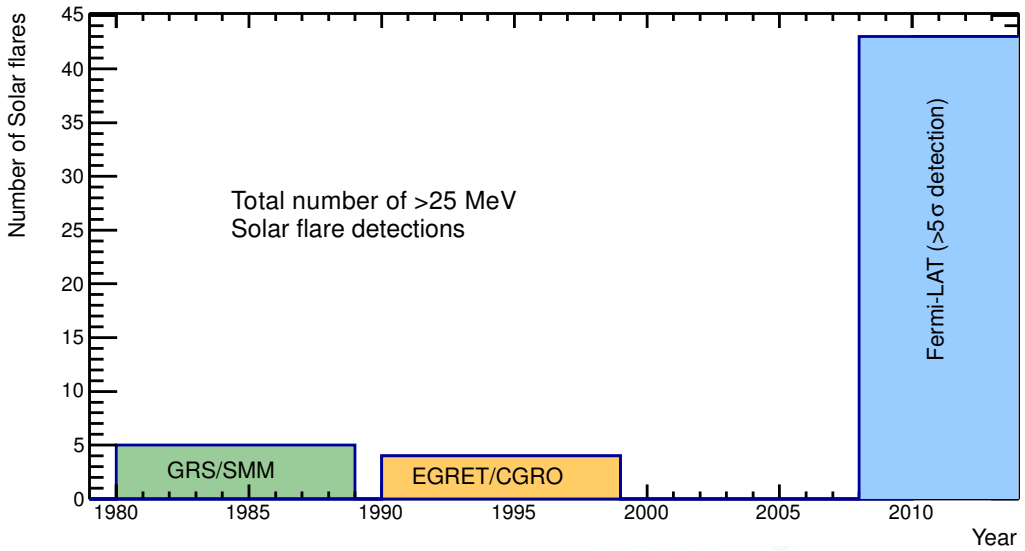
γ-ray emission from Solar flares

Produced by interactions of high-energy particles with ambient plasma:

1. Bremsstrahlung
   - 10 keV – 1 GeV
2. Nuclear de-excitation
   - $\approx$0.5 – 8 MeV
3. Pion decay
   - $>$10 MeV

- Magnetic reconnection believed to be at the origin of particle acceleration in Solar flares
- γ-rays provide clues on the properties of the acceleration mechanisms and information on ambient plasma
  - Chromospheric ion abundances
  - Maximum energy of the accelerated charged particles
  - Coronal trapping times

Why study Solar flares with *Fermi*?



GOES spacecraft Classification

Classification	Peak flux at 100-800 pm (Watts m^{-2})
A	$< 10^{-7}$
B	10^{-7}–10^{-6}
C	10^{-6}–10^{-5}
M	10^{-5}–10^{-4}
X	10^{-4}–10^{-3}

- Only 9 Solar flares have been detected with E>25 MeV prior to the launch of *Fermi*
  - All of which were classified as GOES X class flares
- *Fermi* has detected more than 40 Solar flares with E>25 MeV in first 6 years of mission
  - More than half are classified as GOES M class flares

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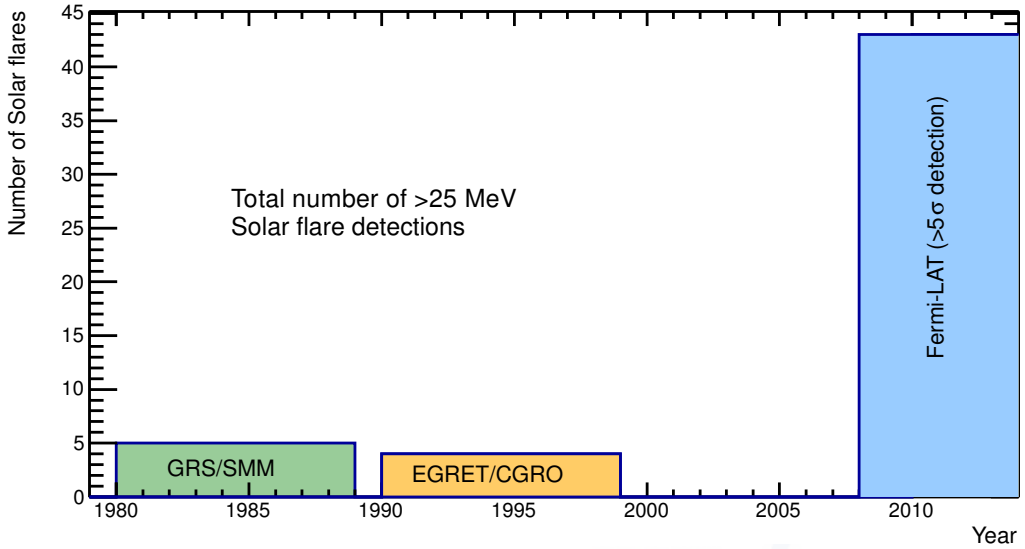

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  - More than half are classified as GOES M class flares
- Sampling a wider range of Solar flares providing a new piece to the puzzle of the acceleration mechanisms at work

Fermi LAT as a solar observatory

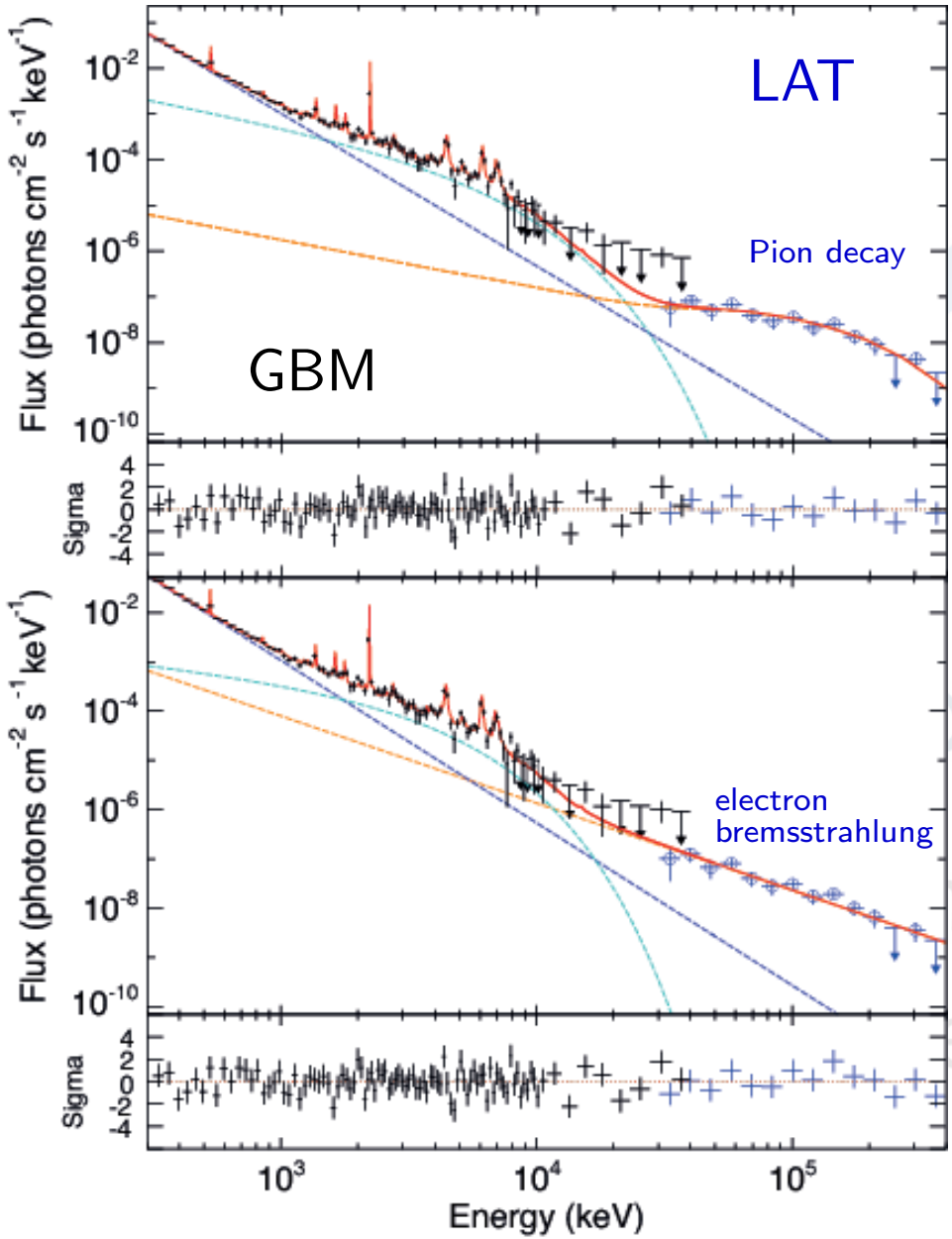
The LAT *standard analysis*

- Likelihood fit of spatial and spectral model of region around sun
- Event classification (photon v. bkg) on event-by-event basis
  - Use classification trees to reject bkg and give high-quality photon data
- High flux of hard x-rays during solar flares causes pile-up in the ACD
  - High probability of mis-classifying good photons as background

The LAT Low Energy (LLE) analysis

- Useful only for short transients (10s of minutes or less)
- Model the background by fitting time series of LAT events from region around sun
- Relaxed event classification gives high effective area but lower signal to noise
- Immune to the pile-up effect in the ACD!

Impulsive flares: SOL2010-06-12T00:57

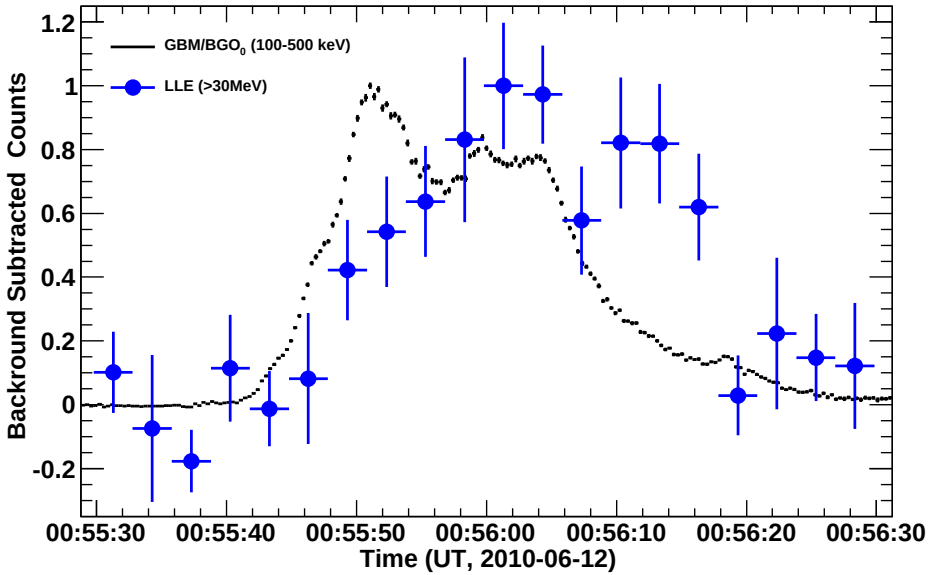


Ackermann et al. 2012ApJ...745..144A

- Narrow and broad nuclear line emission detected by GBM
  - Protons and ions accelerated above ∼30 MeV
- Emission up to ∼400 MeV detected by LAT
  - What physical process?
- Fit GBM and LAT to investigate the origin
  - Pion decay radiation
  - Bremsstrahlung from power-law electron spectrum

Parameter	Value
Power-law index (blue)	3.31
Power-law with exp cutoff (cyan)	$\leq$ 1.2 2.4 $\pm$0.8 MeV
Pion decay (top panel)	-4.5
Power-law at 30 MeV	1.9$\pm$0.2

Timing gamma-rays and Hard X-rays: SOL2010-06-12T00:57



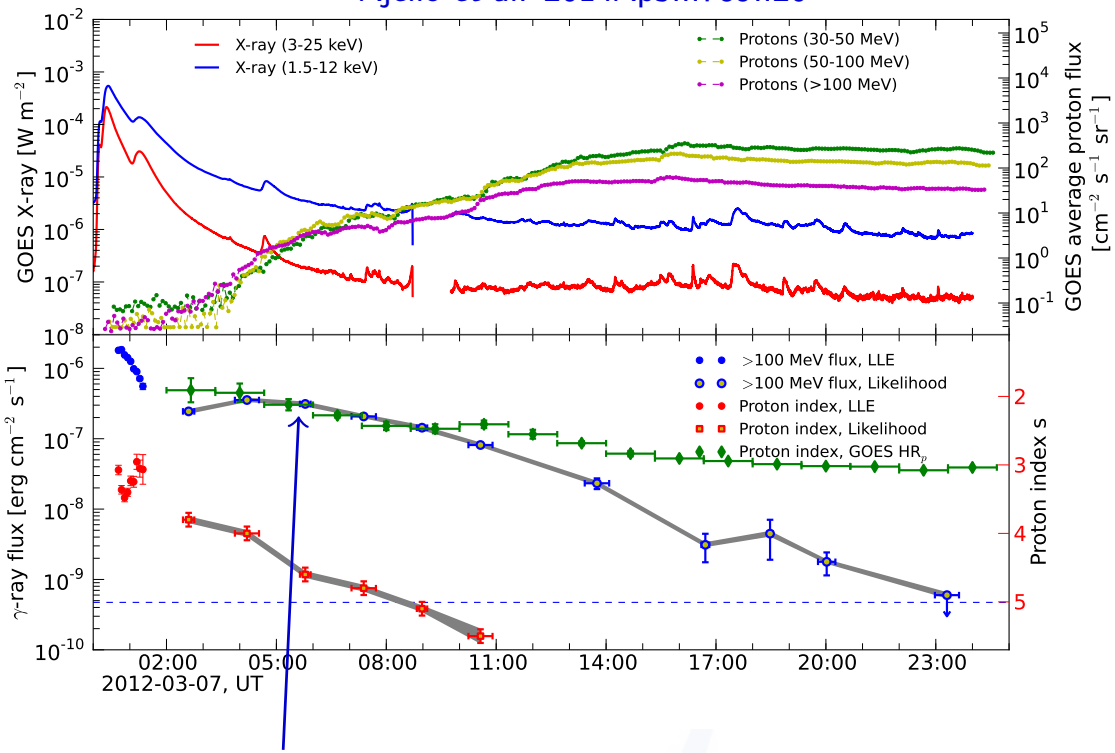
- Electron dominated GBM/BGO 100–500 keV counting rates at 320 sec resolution
- LAT LLE >30 MeV at 3 second resolution
- LLE profile is delayed relative to HXR profile
  - Weak evidence for double-peaked profile
- From a cross correlation analysis we find >30 MeV emission lags the bremsstrahlung by 6±3 seconds

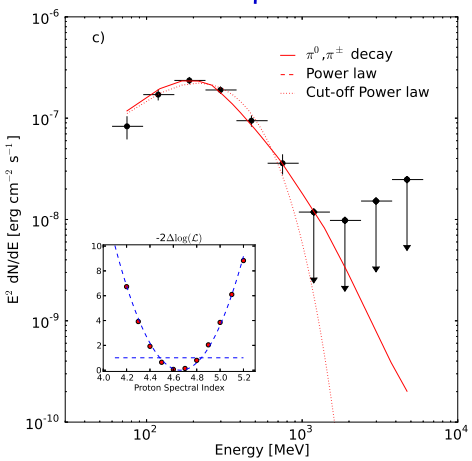
Implications of time profiles

- protons and/or electrons reach E>100 MeV w/in few seconds of the time it takes electrons to reach 100's of keV
- Acceleration time scales of >100 MeV particles is similar to 100's of keV electrons, but delayed by ≈10 sec

Sustained emission: SOL2012-03-07

Ajello et al. 2014ApJ...789..20



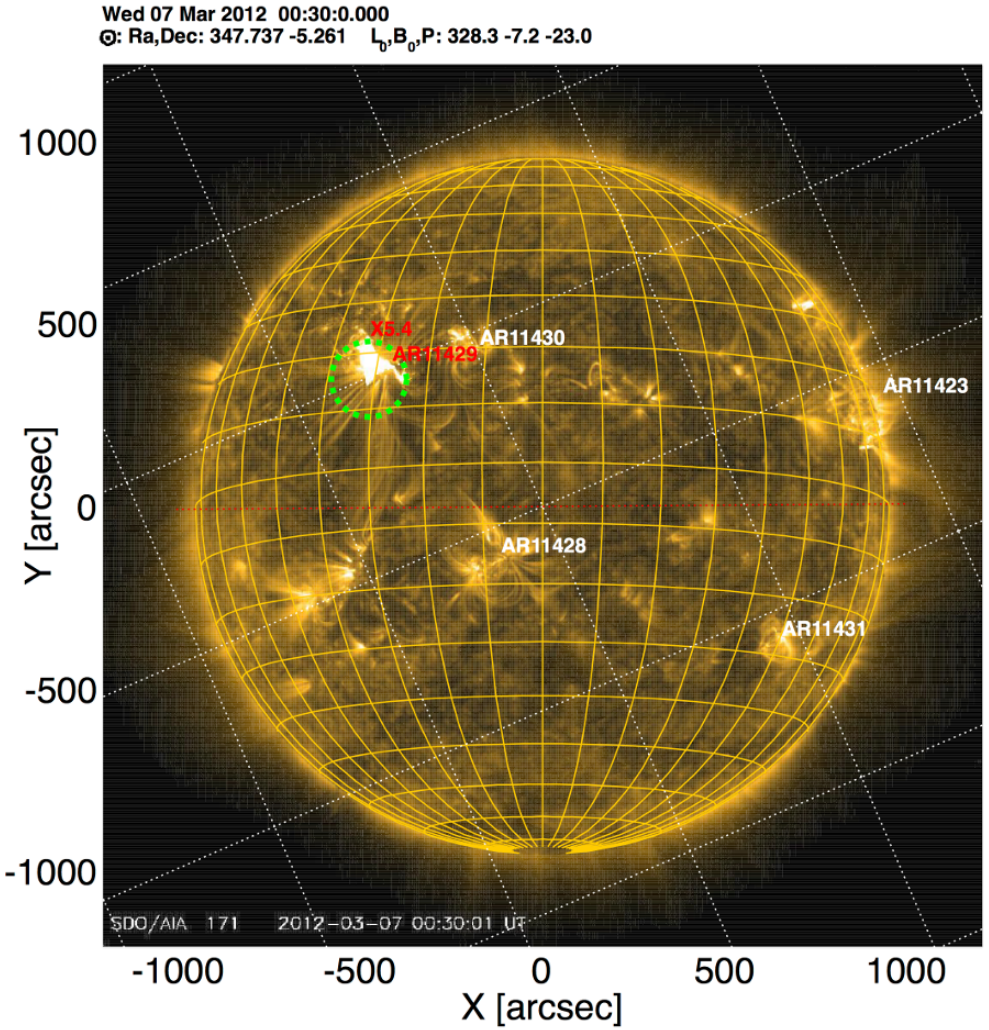


- *Fermi*-LAT detected >100 MeV emission for more than 20 hours
- Including the most energetic photon (4.5 GeV) ever detected during a flaring episode

- High-energy gamma-ray spectrum is curved, consistent with:
  - Pion decay spectrum, or
  - Electron spectrum with cutoff

Localizing the high energy gamma-rays

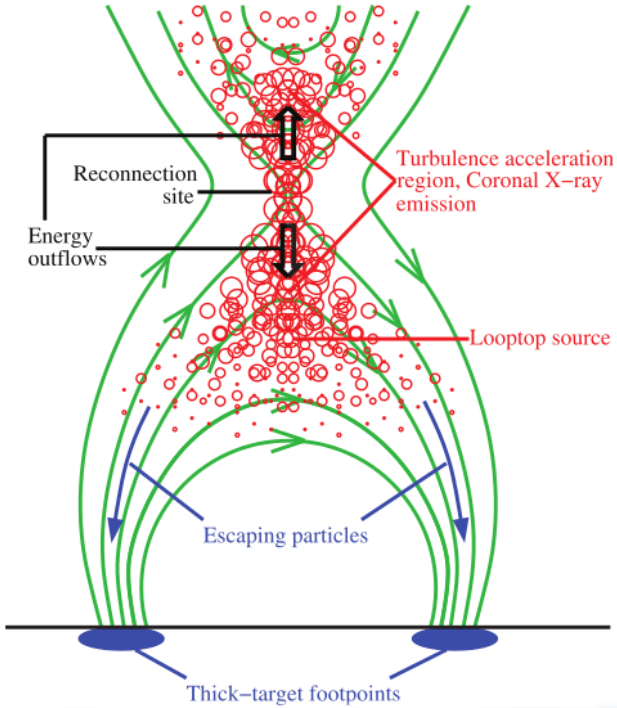
SOL2012-03-07

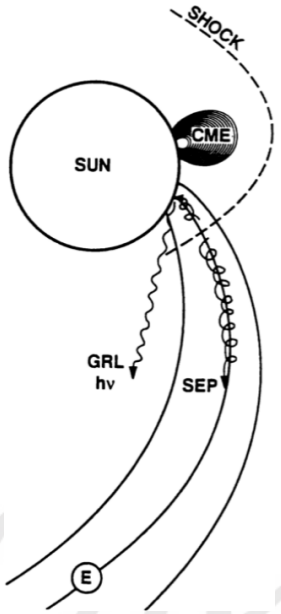


- Localization studies provide insight to the source of the accelerated particles
- We measure the direction of the emission centroid via a *likelihood* analysis
- For the brightest flares we find the >100 MeV emission centroid to be consistent with location of the active region on the solar disk

Ajello et al. 2014ApJ...789..20

How to explain the long duration >100 MeV emission?





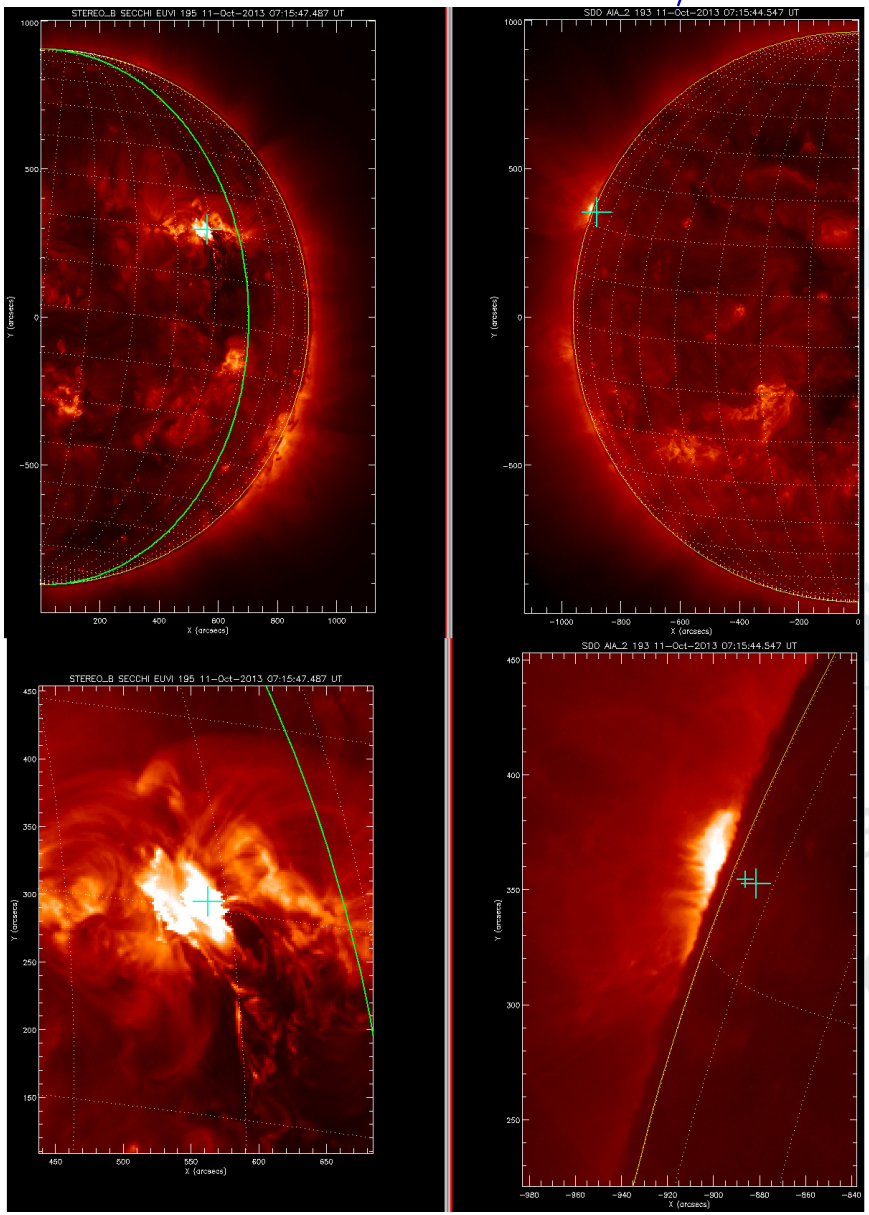
- Continuous acceleration at flare reconnection region via Stochastic acceleration (Petrosian & Liu 2004)
- Accelerated particle spectra become softer as turbulence weakens.
- Can explain the spectral evolution seen for SOL2012-03-07

- Coronal Mass Ejection-driven shock (Murphy et al. 1987) can accelerate particles
- γ emission cannot occur at CME site (density too low)
- Particles must travel back to the Sun
- Could explain long lasting emission

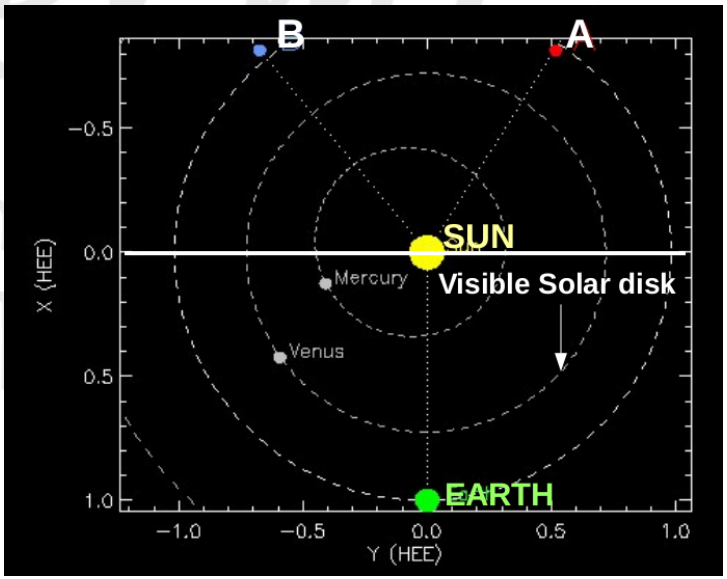
Complementary EUV and HXR data

STEREO B

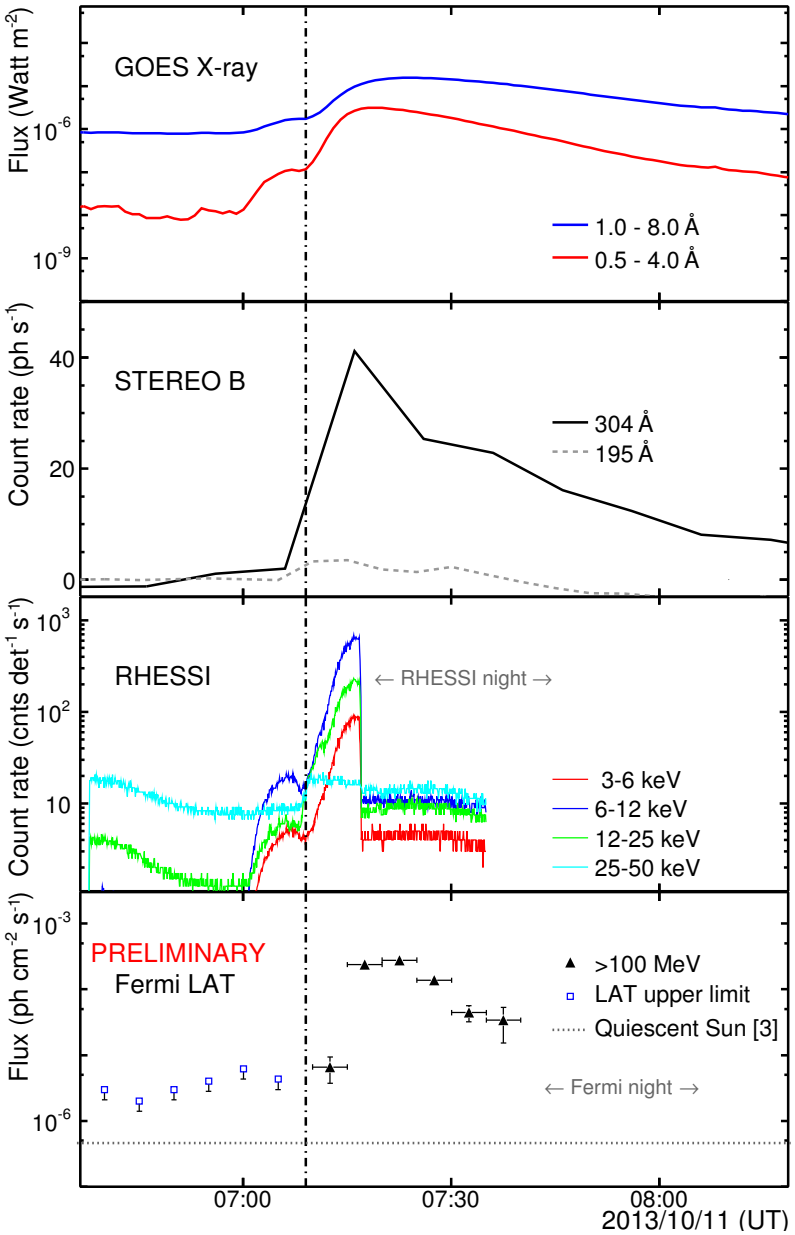
SDO/AIA



- M1.5 *GOES* class flare erupted at 7:01:00 UT
- EUV and HXR data reveal that the active region is $\sim 8^{\circ}$ behind the visible Solar limb at the time of the flare
- HXR footpoints were occulted during RHESSI coverage

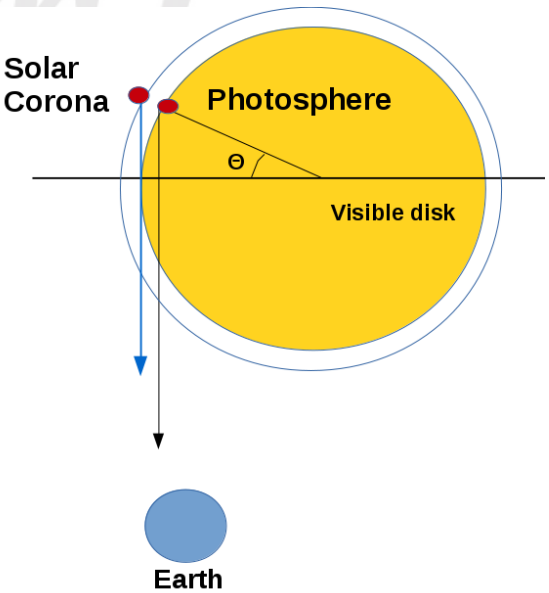


First >100 MeV behind the limb flare

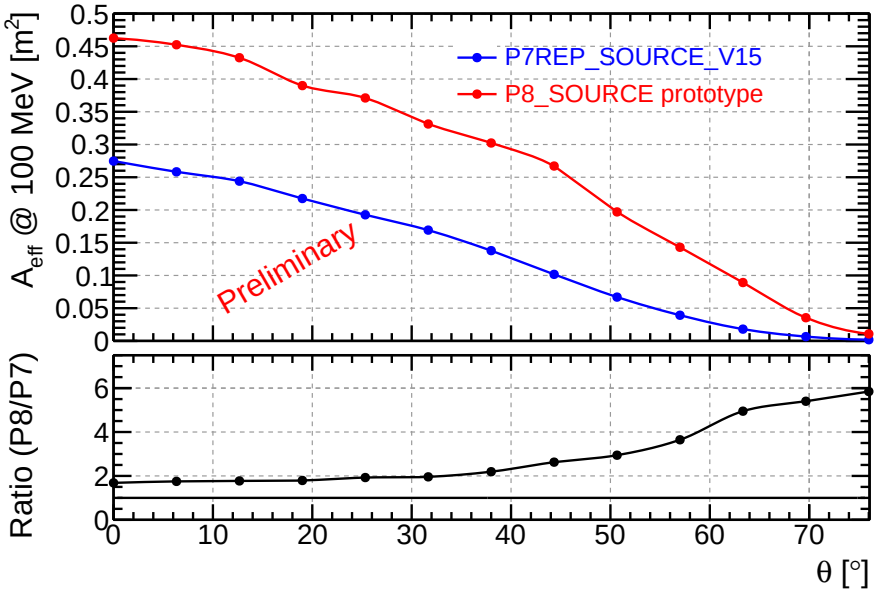


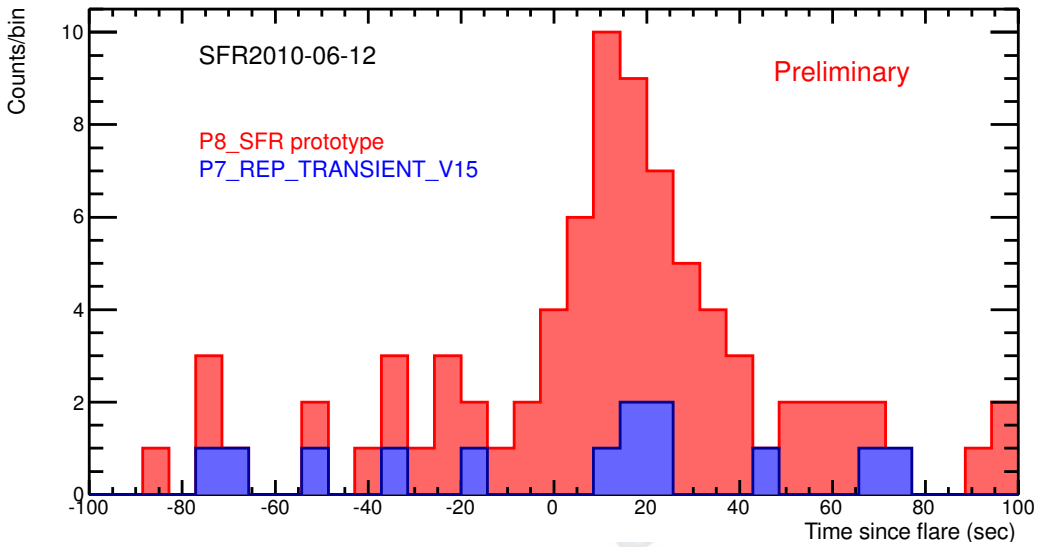
- Surprising >100 MeV emission detected by *Fermi*-LAT from 7:10 UT for ∼30 min
  - Including a ∼3 GeV photon
  - LAT emission centroid coincides with the flaring region location
- How to explain this LAT detection?
- γ's produced in the Corona or photosphere?

Paper in preparation



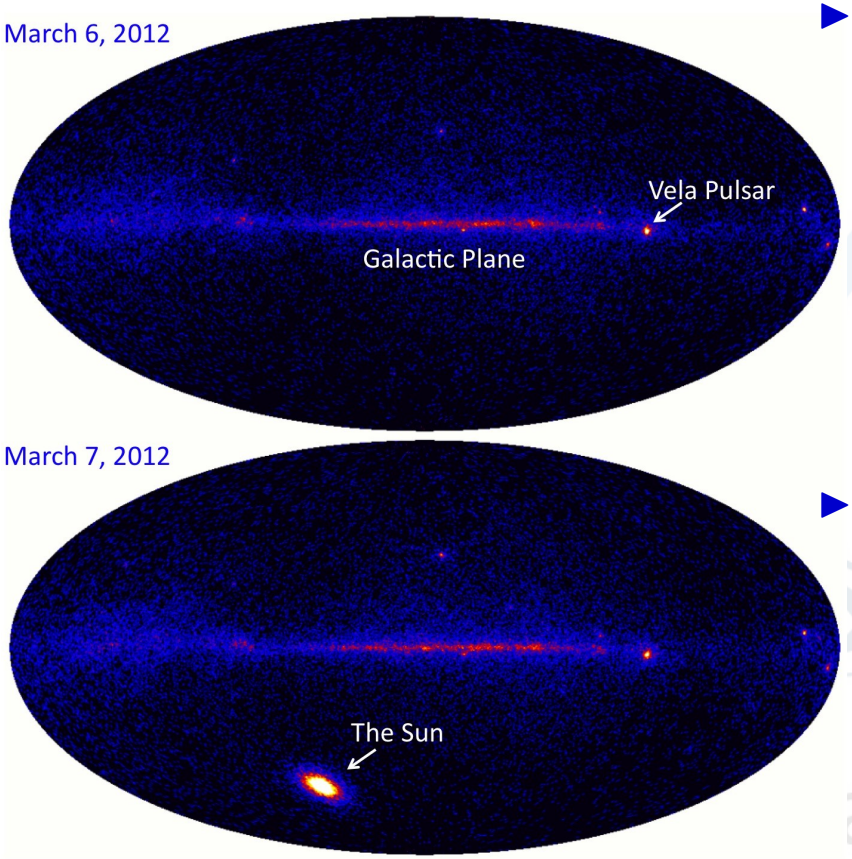
Improvements with Pass8





1. Increase in Pass8 effective area for low energies will greatly improve the Solar flare detection capabilities
2. We have also developed a Solar flare dedicated event selection
   - Will alleviate the pile-up effect often present during impulsive Solar flares
   - Increase the number of Solar flares sample for localization studies

Summary



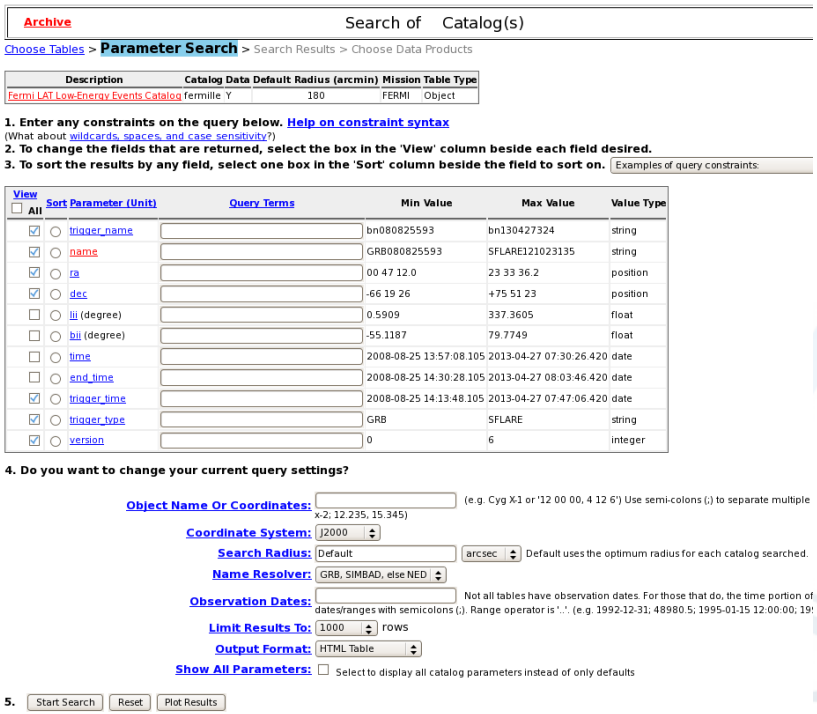
March 15, 2012 Astronomy picture of the day
http://apod.nasa.gov/apod/ap120315.html

- The *Fermi*-LAT has detected high energy gamma-rays more than 40 solar flares
  - Almost half of which are GOES M class
  - Sampling both impulsive and sustained emission
  - Opening a new high-energy window for Solar physics!
- Data and tools are publicly available!
  - `http://heasarc.gsfc.nasa.gov/W3Browse/fermi/fermille.html`
  - `http://hesperia.gsfc.nasa.gov/fermi_solar/`
  - `http://fermi.gsfc.nasa.gov/ssc/data/analysis/`

Stay tuned for more exciting Solar results from the *Fermi* Space Telescope!

Backup slides

Fermi LAT Solar flare public data



Archive — Search of Catalog(s)

Choose Tables > **Parameter Search** > Search Results > Choose Data Products

Description	Catalog Data	Default Radius (arcmin)	Mission	Table Type
Fermi LAT Low-Energy Events Catalog	fermille Y	180	FERMI	Object

1. Enter any constraints on the query below. Help on constraint syntax
(What about wildcards, spaces, and case sensitivity?)
2. To change the fields that are returned, select the box in the 'View' column beside each field desired.
3. To sort the results by any field, select one box in the 'Sort' column beside the field to sort on. Examples of query constraints:

View All	Sort	Parameter (Unit)	Query Terms	Min Value	Max Value	Value Type
☑	○	trigger_name		bn080825593	bn130427324	string
☑	○	name		GRB080825593	SFLARE121023135	string
☑	○	ra		00 47 12.0	23 33 36.2	position
☑	○	dec		-66 19 26	+75 51 23	position
☐	○	lii (degree)		0.5909	337.3605	float
☐	○	bii (degree)		-55.1187	79.7749	float
☐	○	time		2008-08-25 13:57:08.105	2013-04-27 07:30:26.420	date
☐	○	end_time		2008-08-25 14:30:28.105	2013-04-27 08:03:46.420	date
☑	○	trigger_time		2008-08-25 14:13:48.105	2013-04-27 07:47:06.420	date
☑	○	trigger_type		GRB	SFLARE	string
☑	○	version		0	6	integer

4. Do you want to change your current query settings?

Object Name Or Coordinates: (e.g. Cyg X-1 or '12 00 00, 4 12 6') Use semi-colons (;) to separate multiple x-2; 12.235, 15.345)
Coordinate System: J2000
Search Radius: Default arcsec Default uses the optimum radius for each catalog searched.
Name Resolver: GRB, SIMBAD, else NED
Observation Dates: Not all tables have observation dates. For those that do, the time portion of dates/ranges with semicolons (;). Range operator is '..'. (e.g. 1992-12-31; 48980.5; 1995-01-15 12:00:00; 19
Limit Results To: 1000 rows
Output Format: HTML Table
Show All Parameters: Select to display all catalog parameters instead of only defaults

5. Start Search | Reset | Plot Results

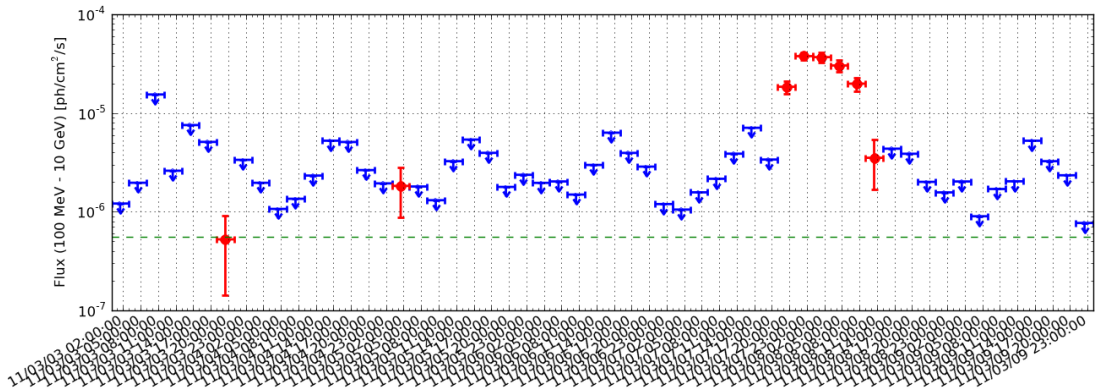
Fermi LLE public data

- LLE catalog of Solar flares and GRBs
- 6 impulsive solar flares and 29 GRBs
- `http://heasarc.gsfc.nasa.gov/W3Browse/fermi/fermille.html`
- All LLE data products publicly available
  - LLE event file
  - spectrum files (PHAII,PHAI and RSP)
  - Quick look files
- LLE data can be analyzed with `XSPEC` and rmfit

Fermi LAT SunMonitor

- Fermi-LAT SunMonitor continuously monitors the Sun
- `http://hesperia.gsfc.nasa.gov/fermi_solar/`
- `http://www.asdc.asi.it/gbmsolar/`

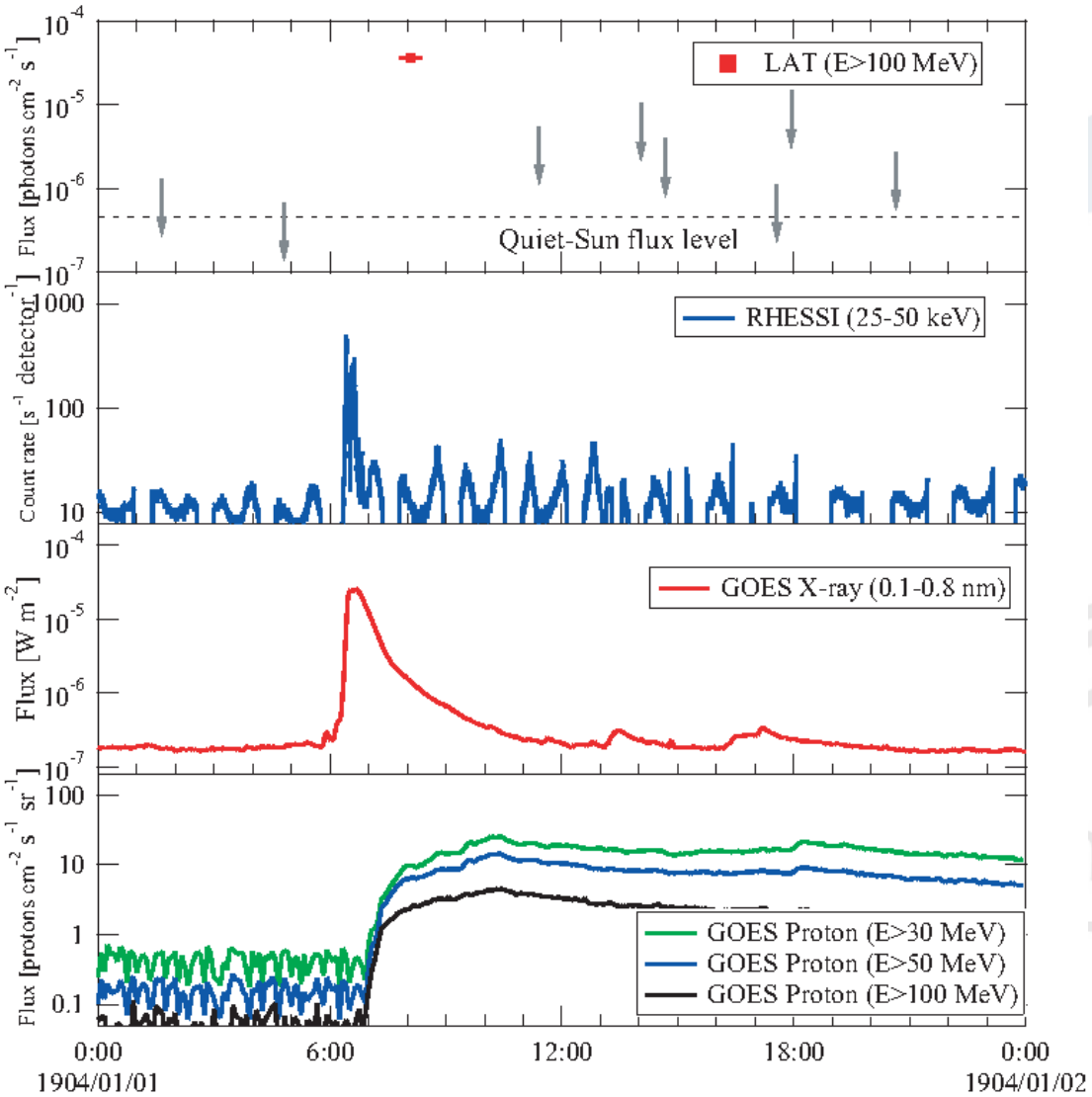
March 7, 2011 M3.7 class flare



Leptonic vs. hadronic emission processes

- For the SOL2011-03-07, SOL2011-06-7 and SOL2012-03-07 flares a power-law with exponential cutoff provides a better fit to the data than a simple power-law
- A challenge for the leptonic scenario?
  - High energy electrons would loose most of their energy in sub-mm, far IR via synchrotron
  - A multiwavelength analysis is necessary in order to rule out this scenario
- Hadronic scenario for these flares seems more plausible
  - In good agreement with data
- The proton spectral index inferred from the pion decay templates is >4 in all three cases
  - Hard to soft spectral evolution for March 7, 2011 and 2012 flares
  - New clues for the underlying acceleration mechanisms?

Long duration flare of June 7, 2011



- Sustained emission associated to impulsive M2.5 X-ray flare
- Accompanied by fast CME ($\sim$1250 km/s)
- $\sim$36 minutes of $>$100 MeV gamma-ray emission detected with Fermi LAT
- Peak flux ($3.4 \pm 0.2 \times 10^{-5}$ph s^{-s}cm^{-2})

Submitted to ApJ (arXiv:1304.3749)