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

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on behalf of the *Fermi*-LAT collaboration

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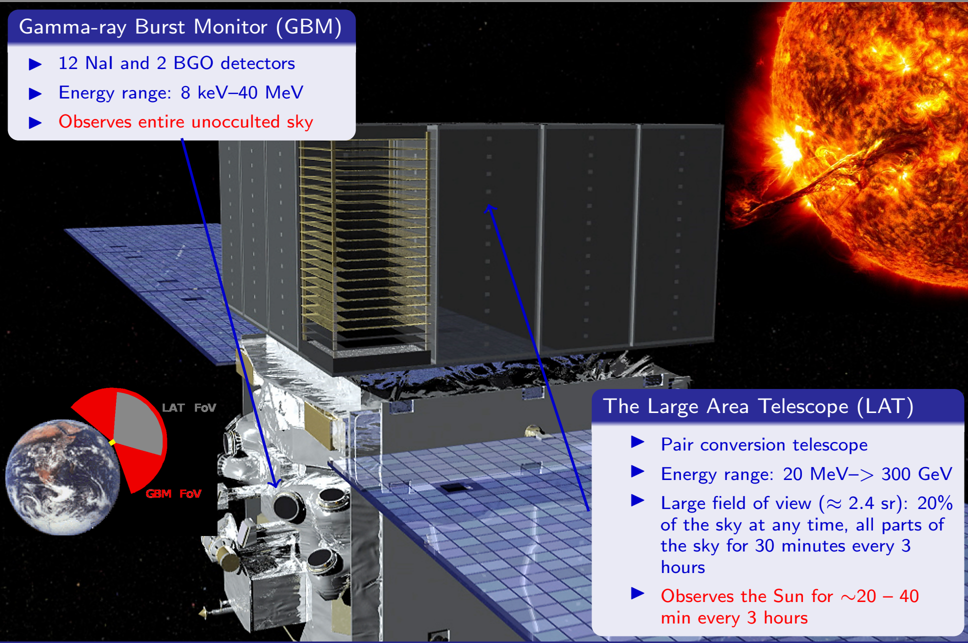
The *Fermi* Space Telescope

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

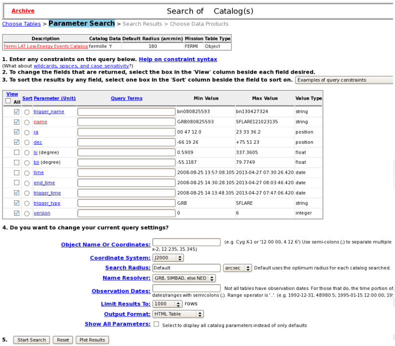
The LAT *standard analysis*

- 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 can cause pile-up in the ACD
  - With Pass7 high probability of mis-classifying good photons as background
  - Problem solved with new Solar flare event classes in Pass8

The LAT Low Energy (LLE) analysis

- Most Useful 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

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

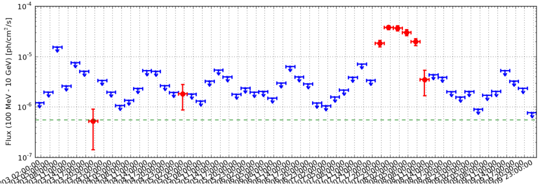
Fermi LLE public data

- LLE catalog of Solar flares and GRBs
- 11 impulsive solar flares and 56 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

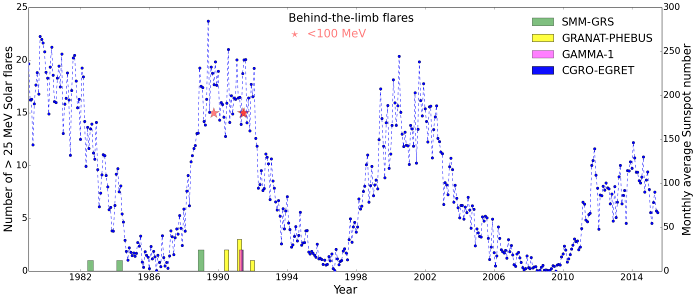
Fermi LAT SunMonitor

- Fermi-LAT SunMonitor continuously monitors the Sun
- >100 MeV gamma-ray flux from the Sun in fixed 3 hour time intervals
- All available online!

March 7, 2011 M3.7 class flare

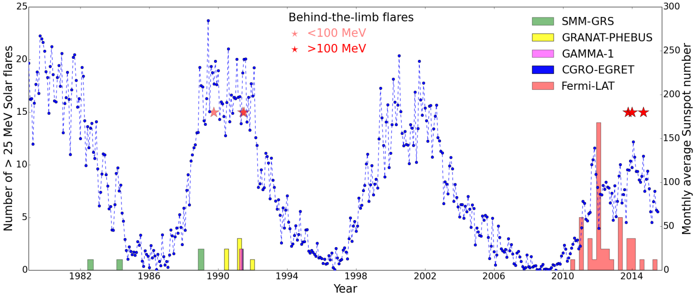


`http://sprg.ssl.berkeley.edu/~tohban/browser`



- In the 1980's and 1990's limited sampling of solar flares with E>25 MeV
  - All of which were classified as GOES X class flares
  - Extended >100 MeV emission for ∼8 hours detected by EGRET
  - 3 behind-the-limb flares with E<100 MeV

Why study Solar flares with *Fermi*?



- In the 1980's and 1990's limited sampling of solar flares with E>25 MeV
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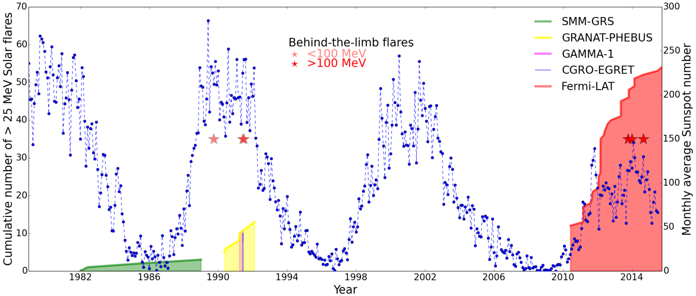
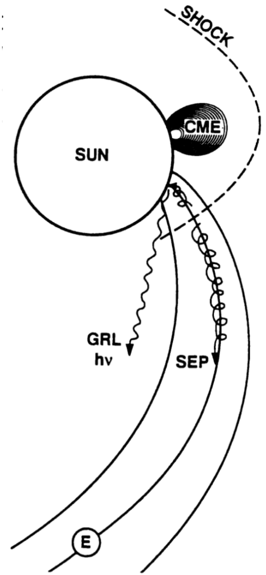
  - 3 behind-the-limb flares with E<100 MeV
- *Fermi* has detected more than 40 Solar flares in first 7 years of mission
  - More than half are GOES M class
  - Extended >100 MeV emission for more than 20 hours
  - Including 3 behind-the-limb flares with >100 MeV emission



- *Fermi* has detected more than 40 Solar flares in first 7 years of mission
  - More than half are GOES M class
  - Extended >100 MeV emission for more than 20 hours
  - Including 3 behind-the-limb flares with >100 MeV emission
- Sampling a wider range of Solar flares provides a new piece to the puzzle of the acceleration mechanisms at work during these explosive phenomena

Why are behind-the-limb flares interesting?

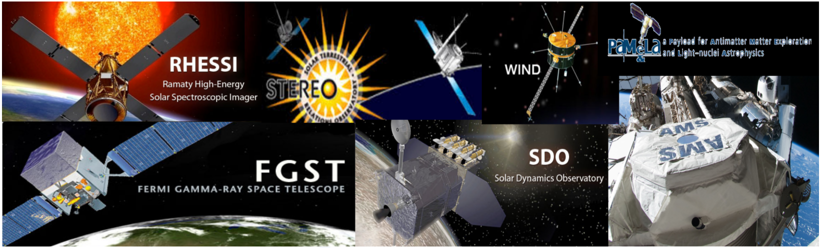


Cliver et al. 1993

- γ-ray emission processes require densities greater than 10^{12} cm^{-3}
- Measurements of γ-ray line emission are generally consistent with a compact region located in the chromosphere
- Observations of γ-rays (both line emission and pion produced) from behind-the-limb flares can imply
  - A spatially extended flare component that can subtend a large range of heliolongitudes
    - Allowing the particles to interact at the visible disk
  - Or acceleration and emission occur in the Corona
    - Requires larger than usual Coronal densities

A total of 3 behind-the-limb flares were detected with emission below 100 MeV by space based observatories

1. 1989 September 29 flare detected by GRS on SMM
    - Vestrand & Forrest 1993, Cliver et al., 1993
    - Intense gamma-ray line emission in the 1-8 MeV range
    - Strong 2.2 MeV neutron capture line
    - Observations required spatially extended flare loop
2. 1991 June 1 flare detected by PHEBUS on GRANAT
    - Barat et al. 1994, Ramaty et al. 1997
    - Intense gamma-ray line emission in the 1-8 MeV range
    - No 2.2 MeV neutron capture line detected
    - Coronal origin for the emission was concluded
3. 1991 June 30 flare detected by PHEBUS, BATSE and EGRET
    - Vilmer et al. 1999, Trottet et al. 2003
    - No detectable line emission or 2.2 MeV line
    - Emission detected up to almost 100 MeV
    - Debate on Coronal or/and extended flare loop emission



Several new instruments in space provide additional valuable information

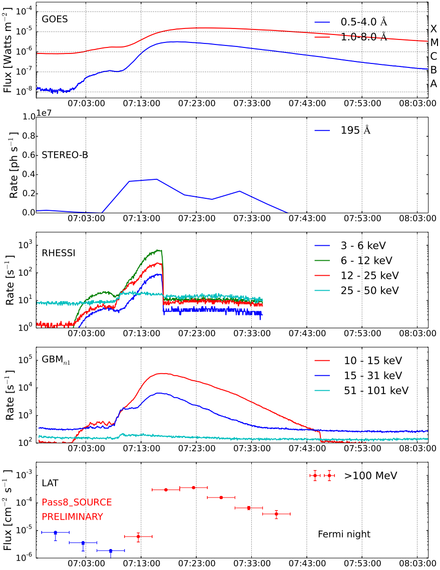
- *RHESSI* launched in 2002 – HXR imaging spectroscopy
- *WIND* at L1 since 2004 – HXR/γ view in steady background
- *STEREO* launched in 2006 – 3D view of the Sun and Heliosphere
- *PAMeLA* launched in 2006 – High energy SEP flux measurements
- *Fermi* launched in 2008 – Monitoring the highest energy flares
- *SDO* launched in 2010 – Full disk observations in EUV
- *AMS* launched in 2011 – High energy SEP flux measurements

A total of 3 behind-the-limb flares with E>100 MeV have been detected so far by *Fermi*-LAT

1. 2013 October 11 – located $\sim 10^\circ$ behind the eastern limb
2. 2014 January 6 – located $\sim 20^\circ$ behind the western limb
3. 2014 September 1 – located $\sim 40^\circ$ behind the eastern limb

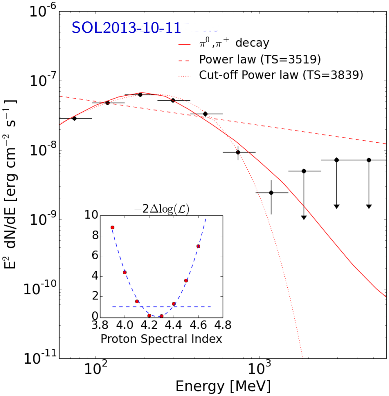
Thanks to the combined observations by the *STEREO* spacecraft, *RHESSI*, *Fermi*-GBM and *Konus* we have:

- the estimated GOES class for each flare based on *STEREO* 195 Å emission
- imaging and position of the behind-the-limb active region
- imaging of the X-ray source
- and full X-ray coverage of the flares (combined observations from *RHESSI*, *Fermi*-GBM and *Konus*)



- Estimated GOES class from STEREO EUV emission is M4.9
- *RHESSI* and GBM detected emission up to 50 keV above the chromospheric limb
- >100 MeV emission detected for 25 minutes by LAT
- Pass7_REP data published in ApJL, 805, L15
- Re-analyzed the flare with new *Fermi*-LAT Pass 8 data
  - Gained 5 minutes of detection with respect to Pass7_REP
  - Detection from 07:10 - 07:40 UT

Testing the emission models



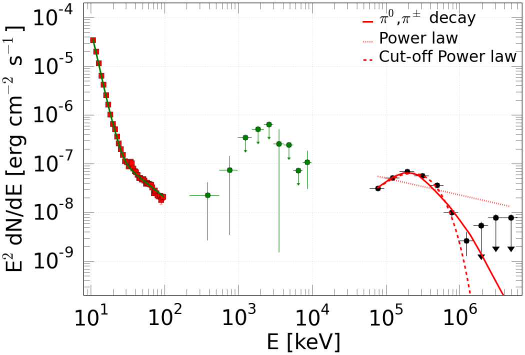
We fit the LAT spectral data between 60 MeV and 10 GeV to test three different emission models:

1. Pure power-law
2. Power-law with exponential cut-off
3. Templates to describe emission from pion decay based on Murphy et al. 1987

We rely on the likelihood ratio test (TS) to estimate the significance of the source and whether the curved model provides a better fit

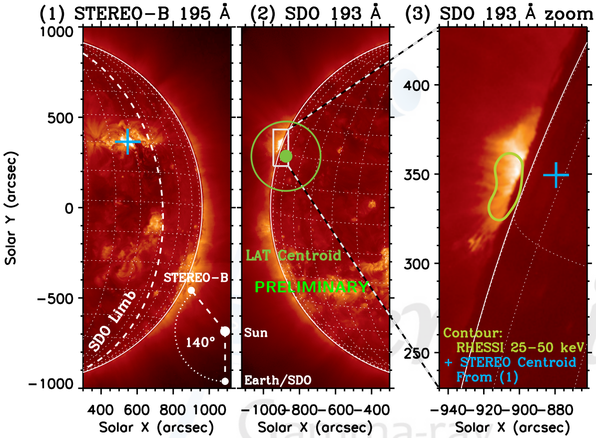
- When model (2) provides a better fit we also fit the data with a series of pion-decay models to determine the best proton spectral index

Spectral energy distribution of SOL2013-10-11

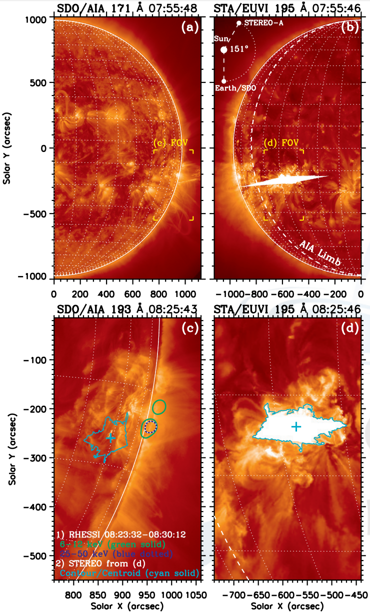


- LAT spectra is curved – increase in significance of $\sim 18\sigma$
  - Best proton spectral index is 4.3 ± 0.1
- Only upper limits on the nuclear lines and neutron capture from GBM
- Broken power-law fit to $<$100 keV GBM emission
  - Photon index 3.22 ± 0.005
  - $E_{break} = 20 \pm 8$ keV

SOL2013-10-11

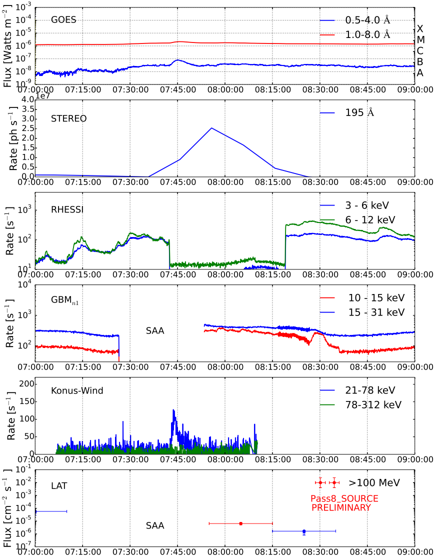


- *RHESSI* source lies within 68% error circle of Fermi-LAT Pass8 emission centroid
- LAT emission error circle consistent with on-disk emission
- Detected 7 photons with measured energies greater than 1 GeV



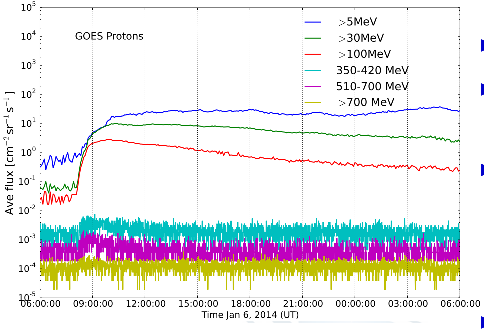
- On Jan 6, 2014 07:42 a flare erupted from an active region located S8W110
  - 20° behind the western limb
- A fast CME (speed ∼1400 km/s) was reported by LASCO
- Filament eruption detected from the visible limb by SDO
- *RHESSI* 6-12 keV source located above the limb
- LAT statistics insufficient to provide localization information

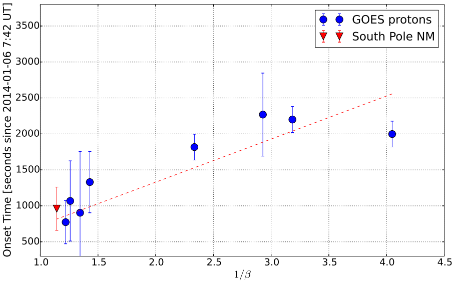
SOL2014-01-06



- Estimated GOES class based on STEREO EUV emission is X3.5
- Konus detected emission up to 78 keV
- *RHESSI* detected emission after 8:20 UT
- *Fermi* satellite was in the SAA from 7:25 - 7:55 UT
- Both detectors on-board *Fermi* detected emission from this flare upon exiting the SAA:
  - GBM detected emission in the 10's of keV range
  - LAT detected >100 MeV emission for ∼20 minutes

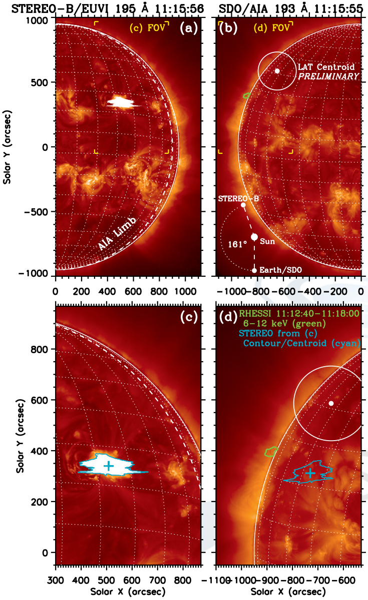
SOL2014-01-06





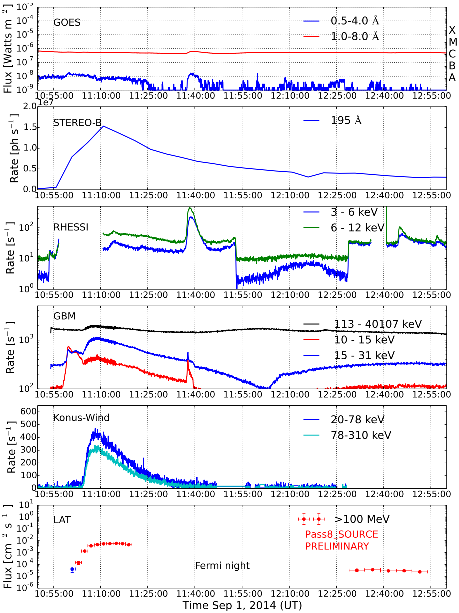
- Very strong SEP event
- Use SEP onset times to estimate the acceleration time at the Sun
- Fit with a straight line assuming 1.2 AU propagation length gives 07:44 UT on Jan 6, 2014 ($\pm$ 3 minutes)
- In agreement with the Solar particle release time 07:47 UT reported by Thakur et al. ApJL 790, L13
- LAT detection starts 8 minutes later
  - *Fermi* in SAA until 7:55 UT
  - SEP and γ-producing ions accelerated at the same time?

SOL2014-09-01



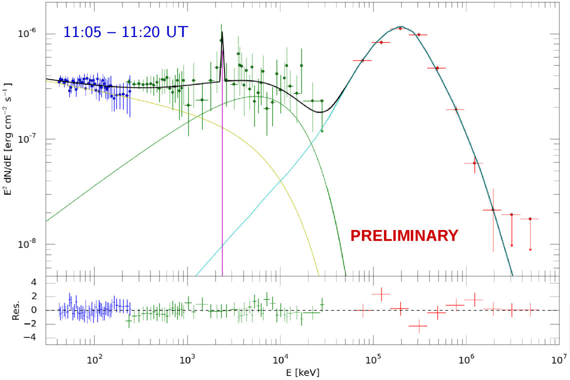
- On Sep 1, 2014 11:01 a flare erupted from an active region located N14E126
  - 36° behind the eastern limb
- A fast CME (speed ∼2000 km/s) was reported by LASCO
- *RHESSI* detected emission from this flare in the 10's of keV range above the limb
  - Minimum loop size of $\sim 10^{10}$ cm
- Fermi-LAT 68% error circle slightly offset with respect to *RHESSI* source
- LAT emission centroid consistent with on-disk emission

SOL2014-09-01



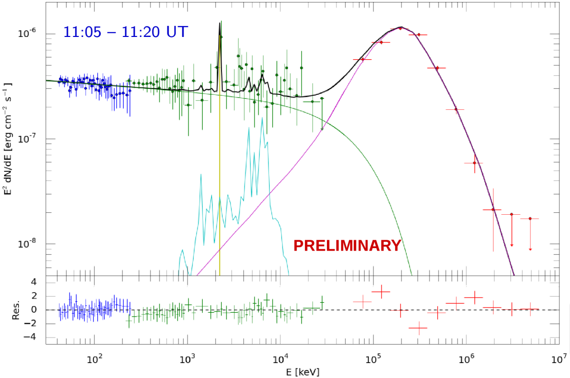
- Estimated GOES class based on STEREO 195 Å emission is X2.1
- *RHESSI* detected faint signal up to ∼12 keV upon exiting the SAA at 11:11 UT
- GBM emission up to few MeV for ∼ 15 minutes
- Konus detected emission up a few 100's keV for more than 20 minutes
- LAT detected emission for almost 2 hours from 11:02 to 12:55
  - 15 photons with E>1 GeV detected during first 15 minutes
  - Including a 3.5 GeV photon

SOL2014-09-01 Spectral energy distribution



1. Pion decay template
2. 2.23 MeV line (gaussian)
3. Power-law exponential cut-off
4. Power-law exponential cut-off

- LAT data is well described by a curved spectrum
  - Best proton spectral index from fit 4.4±0.1
- Power-law (3) index 1.4±0.1, power-law (4) index 2.7±0.1
- Folding energy 8.2±0.2 MeV
- Significance of 2.23 MeV line is $\sim 4\sigma$

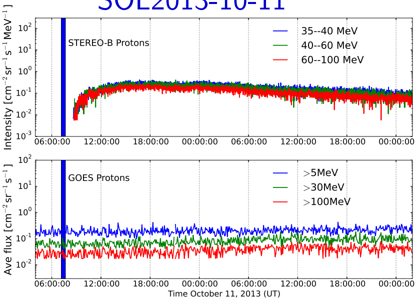


1. Pion decay template
2. 2.2 MeV line (gaussian)
3. Narrow lines template
4. Power-law with EXP cut-off

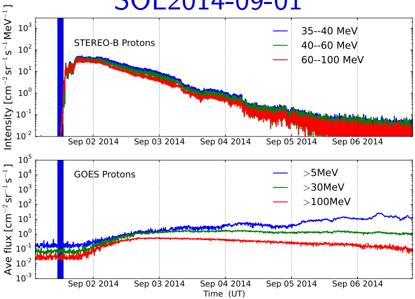
- LAT data is well described by a curved spectrum
  - Best proton spectral index from fit 4.4 ± 0.1
- Photon spectral index 2.1 ± 0.1
- Folding energy 6.7 ± 0.4 MeV
- Significance of 2.23 MeV line and narrow lines is $\sim 7\sigma$

STEREO and GOES protons

SOL2013-10-11



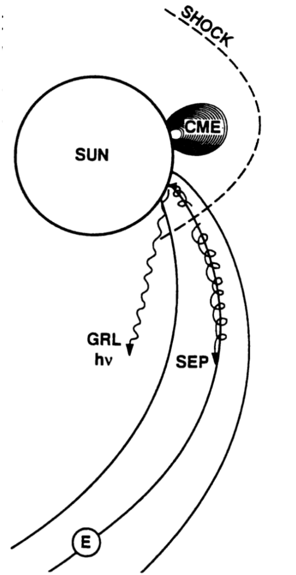
SOL2014-09-01



Proton intensity-time profiles provide information on magnetic connectivity and SEP propagation

- SOL2013-10-11
  - Active region located 10° behind eastern limb
  - Poorly connected to Earth – no GOES signal following the flare
- SOL2014-09-01
  - Active region located 36° behind eastern limb
  - Protons reach Earth ∼9 hours after flare

Connection between SEP and Gamma-rays



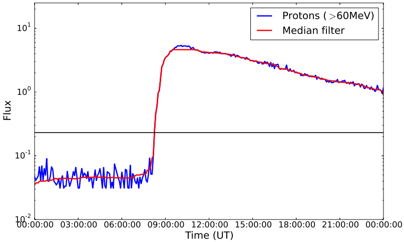
Cliver et al. 1993

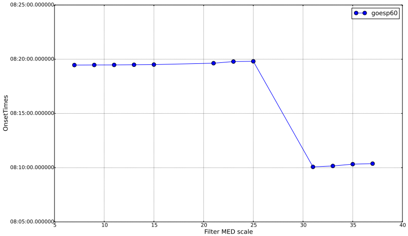
- All three flares are associated with fast CME's and Type II bursts
  - SOL2014-01-06 associated with GLE (?)
  - GLE SEPs most likely accelerated by CME-driven shock
- Particles producing the γ-ray emission accelerated by the CME-driven shock
  - This shock can extend over a wide range of heliolongitudes
  - Allowing the particles to reach the visible disk
- Gamma-ray producing particles and SEP properties should correlate
  - Important to study SEPs measured by PAMeLA and AMS-02
- Working on simulations to test this hypothesis

Summary

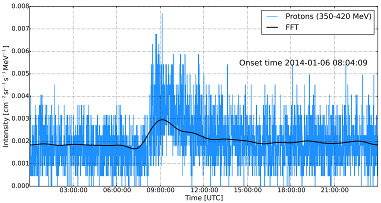
- *Fermi*-LAT has detected for the first time >100 MeV emission from behind-the-limb Solar flares
  - Flares originate from behind both eastern and western limbs
  - Photons with energies up to 3 GeV measured from two of these flares
  - And 2.2 MeV neutron capture line from SOL2014-09-01
- LAT data is well described by pion-decay templates
  - Emission must be produced on disk
  - LAT emission centroid position consistent with on-disk origin
- Observations seem to suggest a spatially extended component for high-energy gamma-rays
  - This component must subtend more 30° heliolongitude
  - Similar conclusion for lower energies reached by Vestrand & Forrest 1993

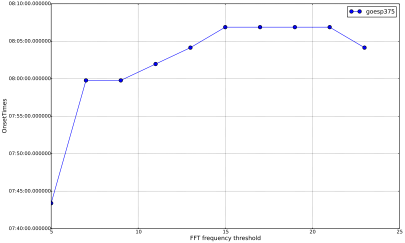
Spare slides



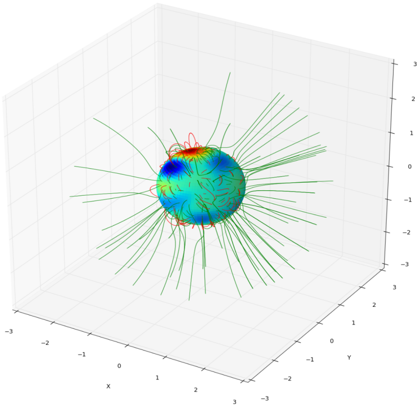


- For GOES SEP we apply a median filtering algorithm to help smooth out the data
- Take the onset time to be the point of 5% max intensity
- We scan over a series of values for the median filter window
- Take median window 25 to be the onset time
- Take the difference in times over the scan values to be the error associated with the onset time





- For GOES HE SEP we run an FFT on the data
- Take the onset time to be the point where second derivative is max
- We scan over a series of values for the frequency threshold
- Take frequency threshold of 13 to be the onset time
- Take the difference in times over the scan values to be the error associated with the onset time



Toy model simulations

- Spherical harmonics expansion of the magnetic field ($R<R_\odot$)
  - First proposed by Newkirk et al. 1968
- Parker field for $R>R_\odot$
  - Parker 1958, Giacalone & Jokipi 2004
- Particle propagation
  - Ray tracing of particles in magentic field
  - Developing code to take into account the effects of scattering and turbulence