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

Melissa Pesce-Rollins,
N. Omodei, V. Petrosian,
W. Liu, F.R. da Costa,
S. Krucker, L. Kashapova,
V. Pal'shin
INFN–Pisa
melissa.pesce.rollins@pi.infn.it

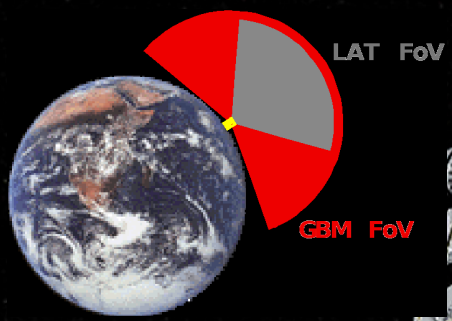
on behalf of the *Fermi*-LAT collaboration

RHESSI Workshop Graz
2016

The *Fermi* Space Telescope

Gamma-ray Burst Monitor (GBM)

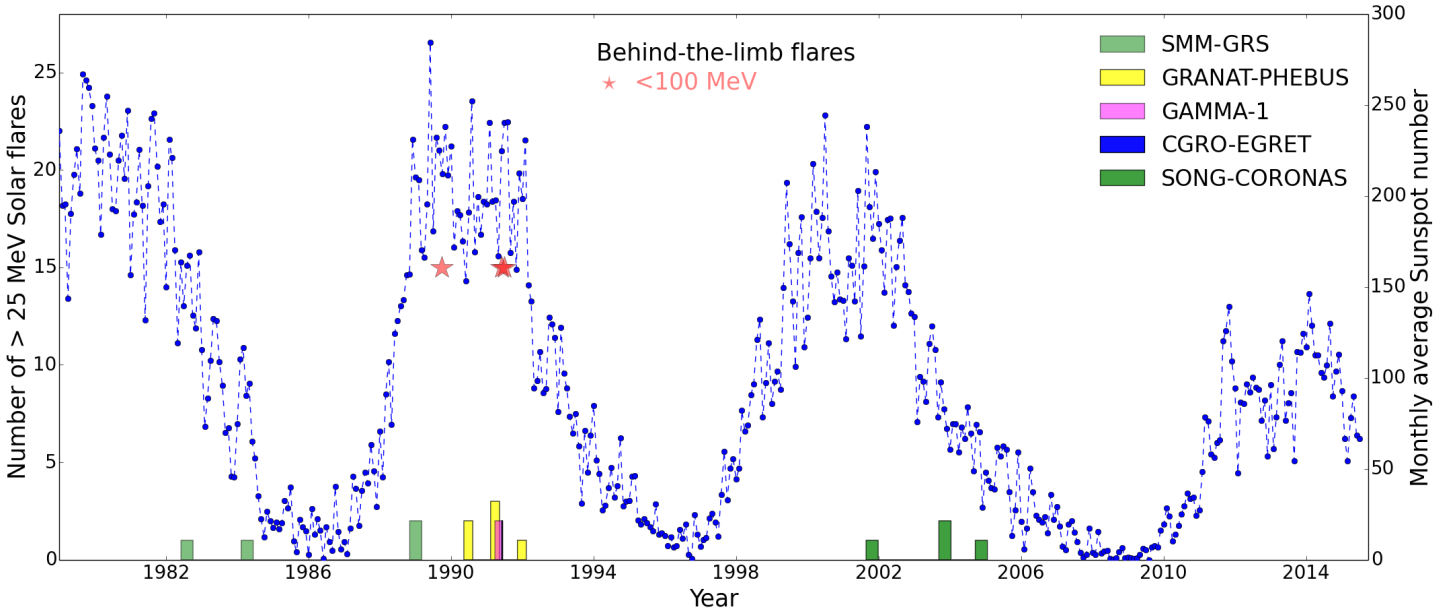
- 12 NaI and 2 BGO detectors
- Energy range: 8 keV–40 MeV
- Observes entire unocculted sky



The Large Area Telescope (LAT)

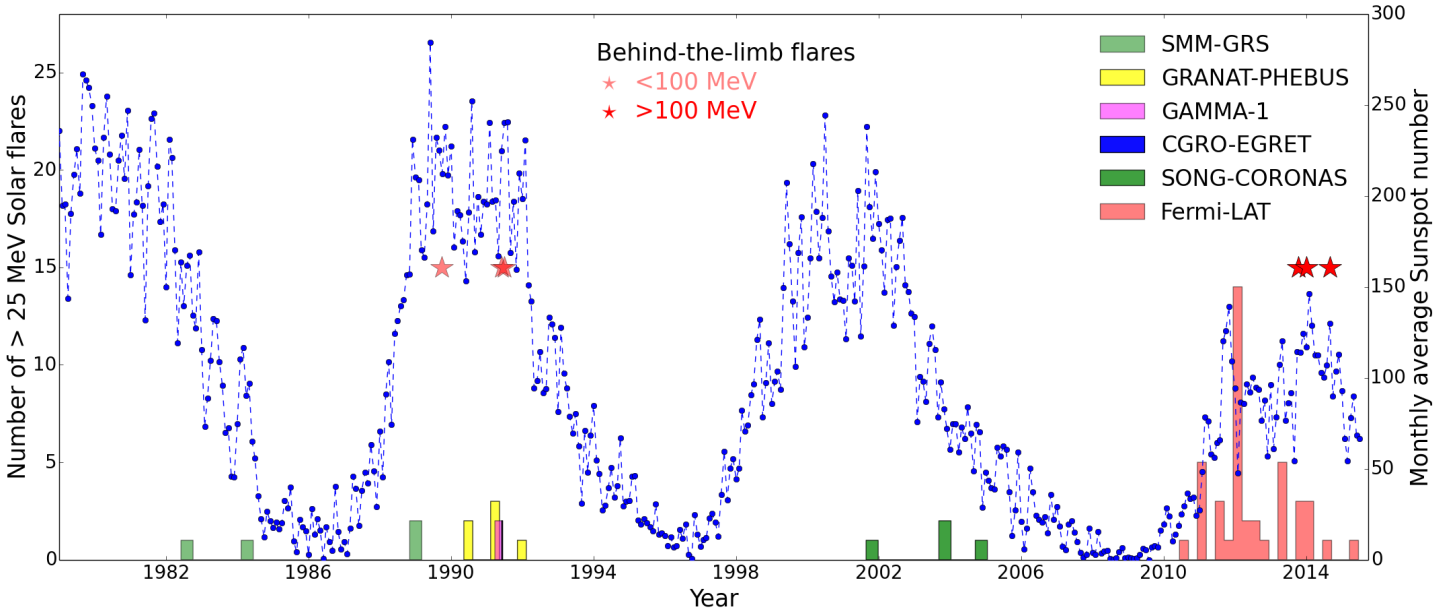
- Pair conversion telescope
- Energy range: 20 MeV–> 300 GeV
- Large field of view ($\approx$ 2.4 sr): 20% of the sky at any time, all parts of the sky for 30 minutes every 3 hours
- Observes the Sun for $\sim$20 – 40 min every 3 hours

Why study Solar flares with *Fermi*?



- Over the past 30 years 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

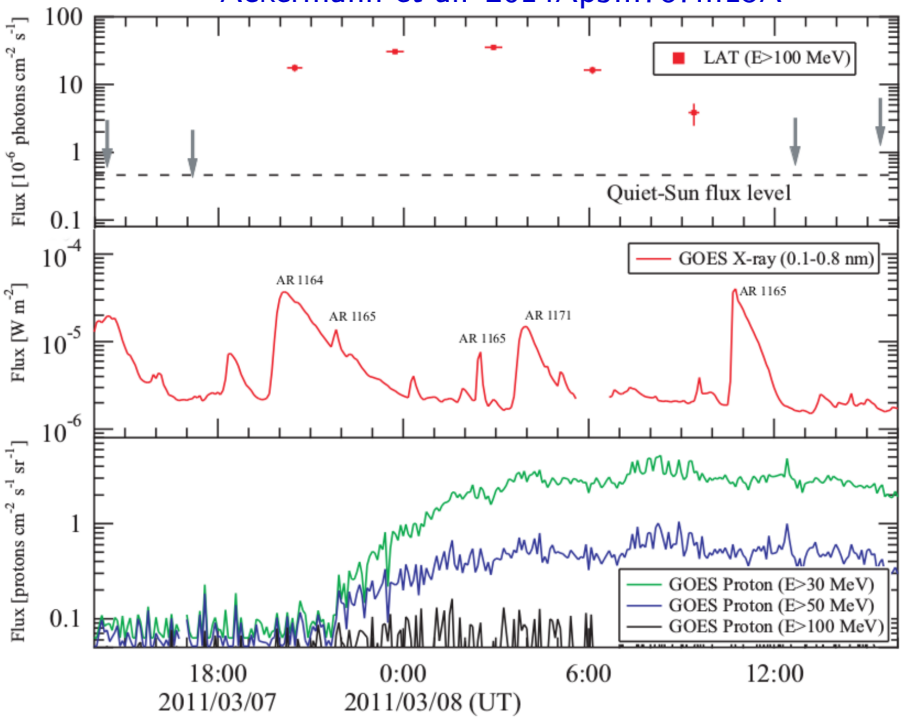
Why study Solar flares with *Fermi*?



- Over the past 30 years 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
- *Fermi* has detected more than 40 solar flares in 8 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

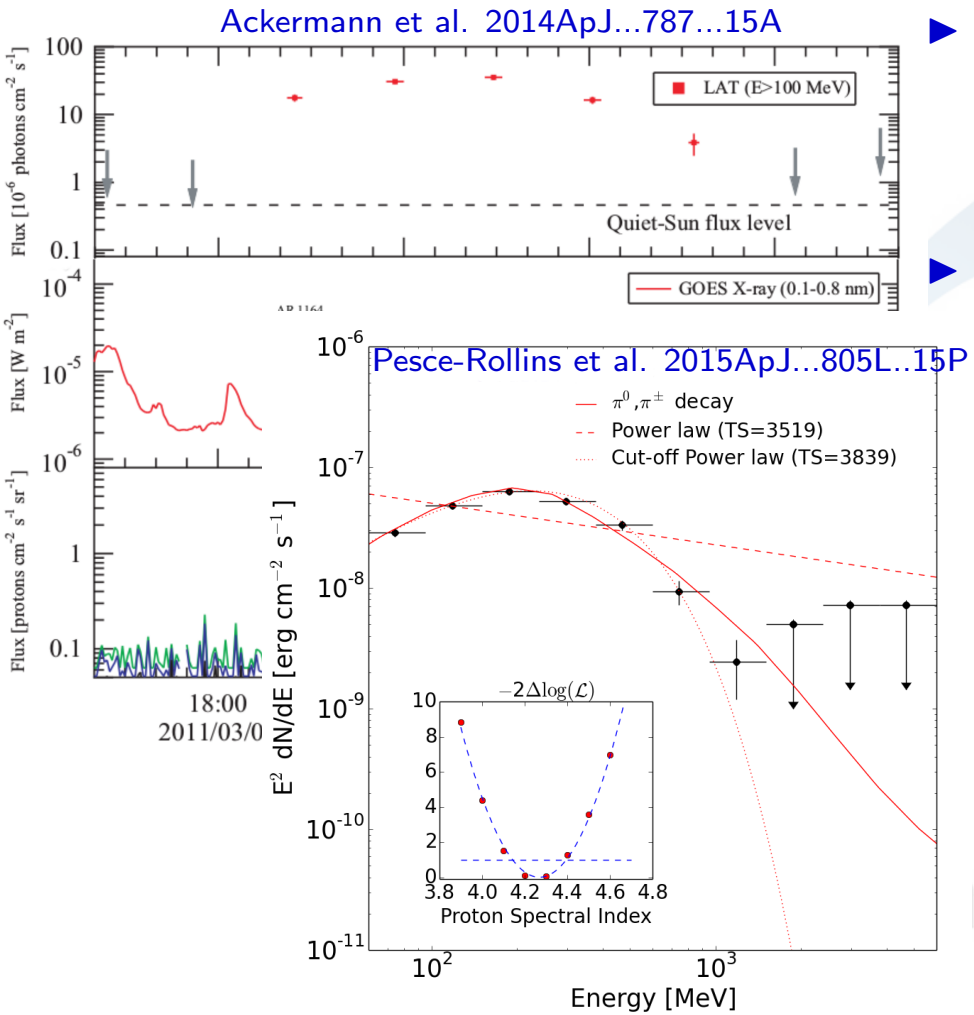
What have we learned so far?

Ackermann et al. 2014ApJ...787...15A



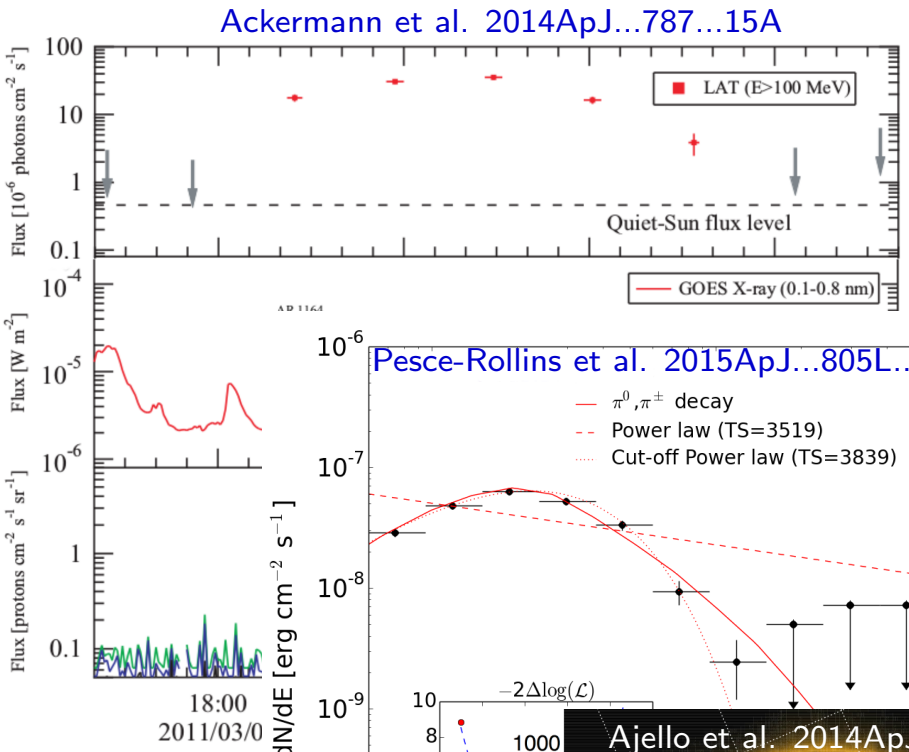
- >100 MeV lasting ~hours from moderate GOES class flares is fairly common
- 13 hours of emission from the M3.7 GOES flare of 2011 March 7

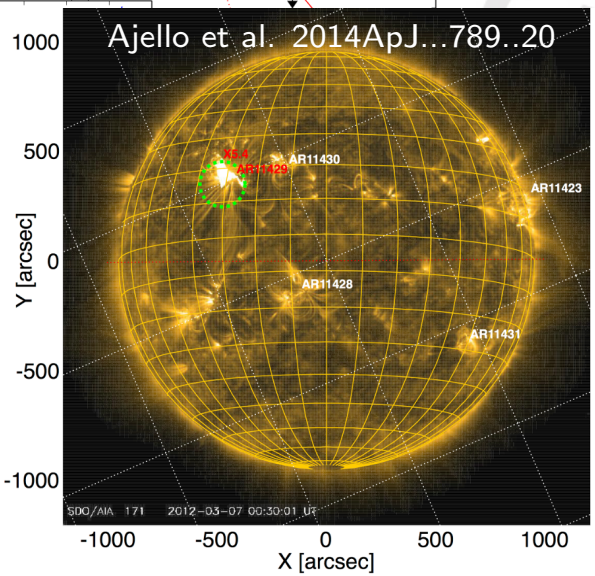
What have we learned so far?



- >100 MeV lasting ∼hours from moderate GOES class flares is fairly common
- 13 hours of emission from the M3.7 GOES flare of 2011 March 7
  - Emission is well described by curved spectrum
  - Pion-decay is the most likely origin

What have we learned so far?

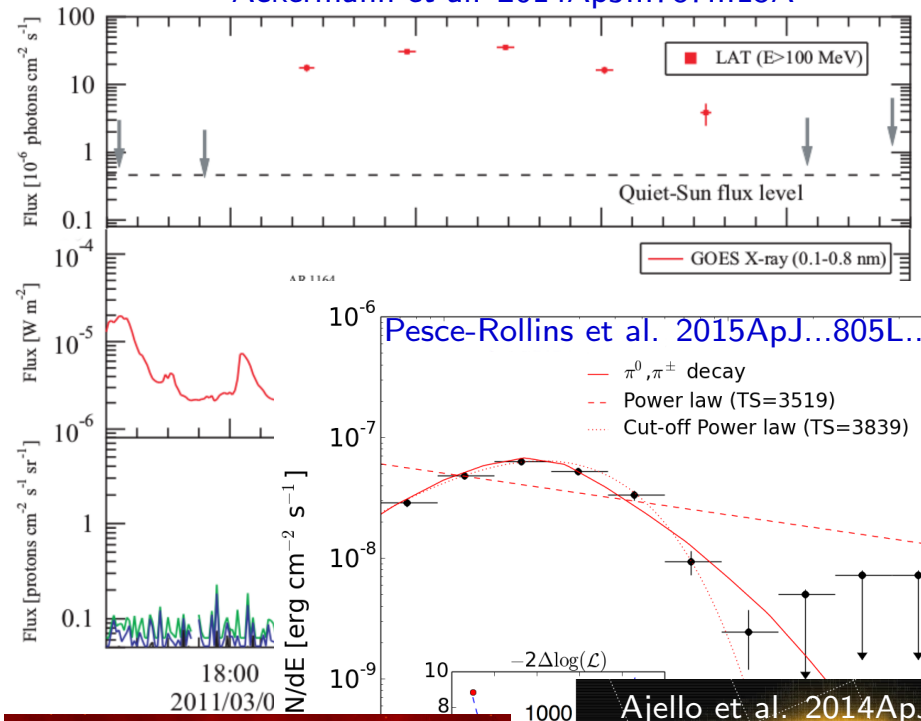




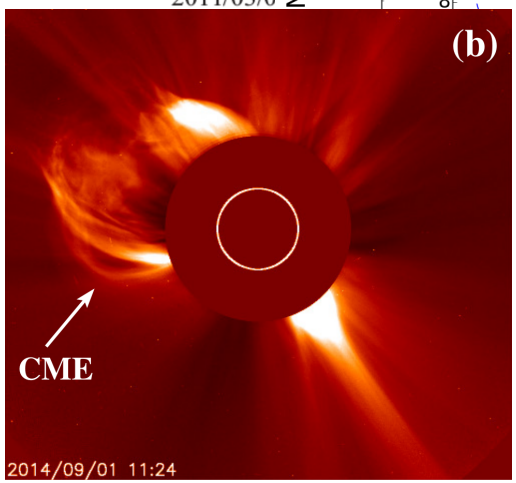
- >100 MeV lasting ∼hours from moderate GOES class flares is fairly common
- 13 hours of emission from the M3.7 GOES flare of 2011 March 7
  - Emission is well described by curved spectrum
  - Pion-decay is the most likely origin
- >100 MeV emission centroid consistent with active region for most bright flares

What have we learned so far?

Ackermann et al. 2014ApJ...787...15A

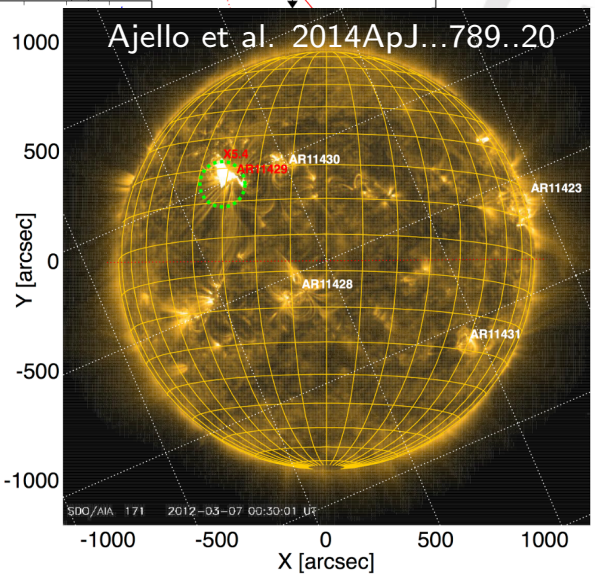


Pesce-Rollins et al. 2015ApJ...805L..15P



Paper in preparation

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



- >100 MeV lasting ∼hours from moderate GOES class flares is fairly common
- 13 hours of emission from the M3.7 GOES flare of 2011 March 7
  - Emission is well described by curved spectrum
  - Pion-decay is the most likely origin
- >100 MeV emission centroid consistent with active region for most bright flares
- All long duration LAT flares associated with fast CME's

Fermi-LAT BEHIND-THE-LIMB FLARES

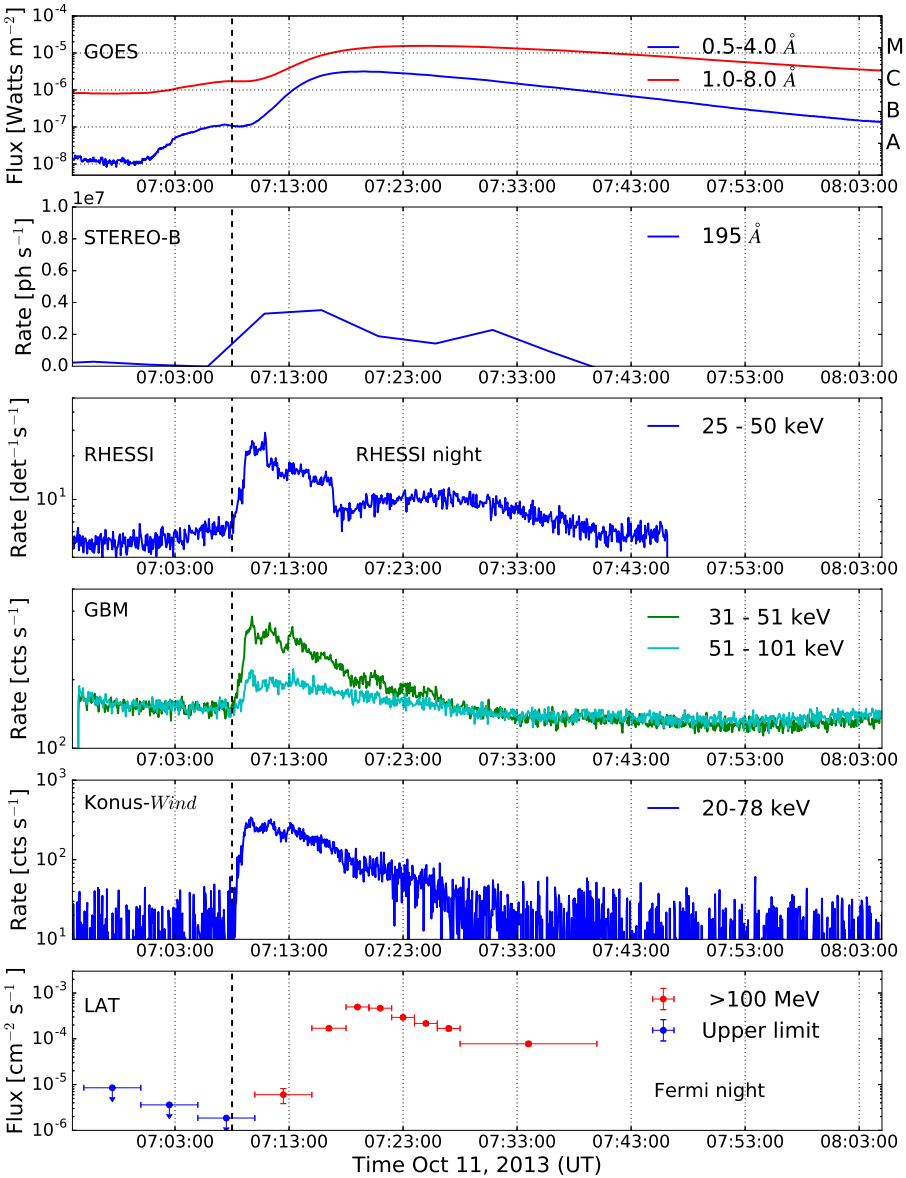
A total of 3 behind-the-limb flares with E>100 MeV have been detected so far by *Fermi*-LAT

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:

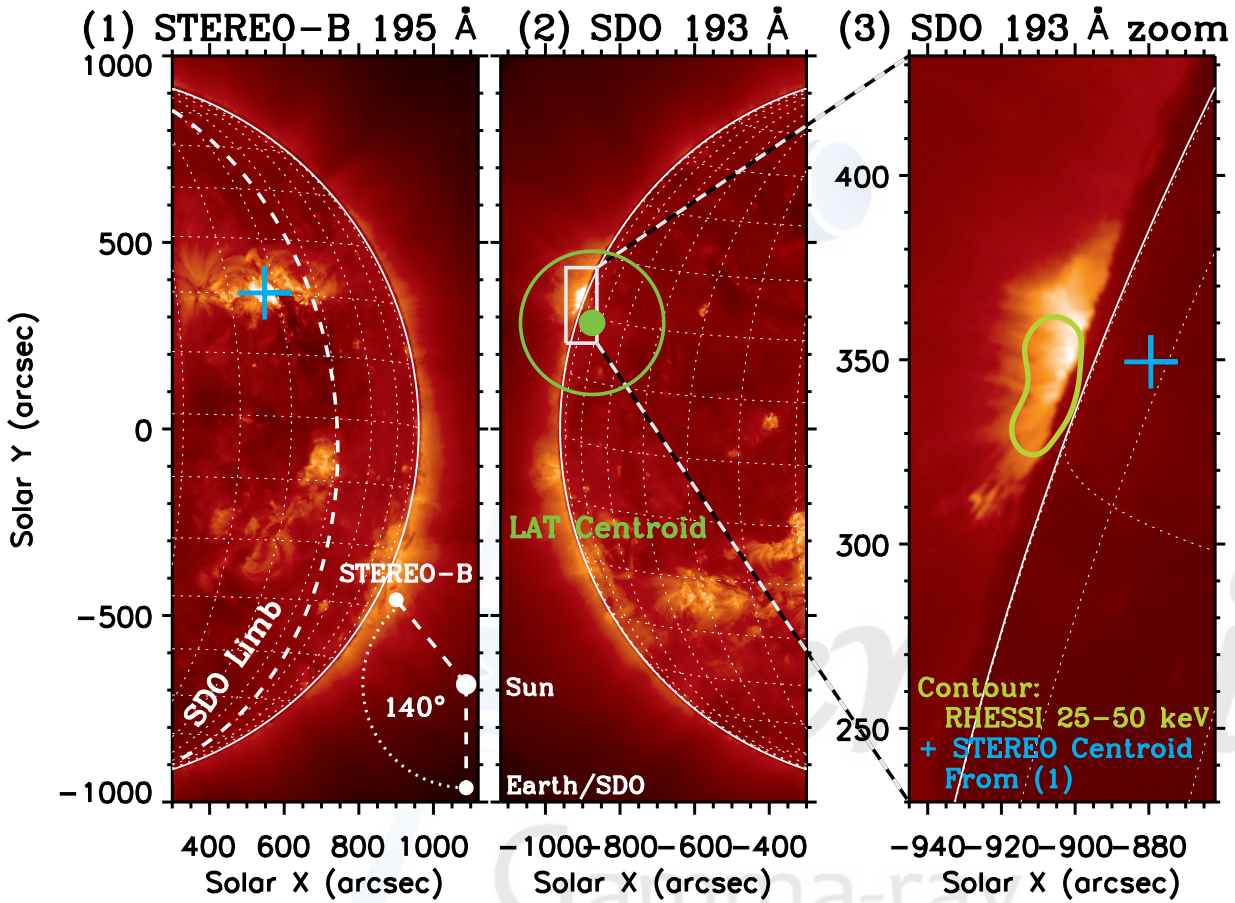
- the estimated GOES class for each flare based on *STEREO* 195 $\mathring{\mathrm{A}}$ emission
- imaging and position of the behind-the-limb active region
- imaging of the X-ray source
- and full X-ray coverage of the flares (combined observations from *RHESSI*, *Fermi*-GBM and *Konus*)

First >100 MeV behind the limb flare



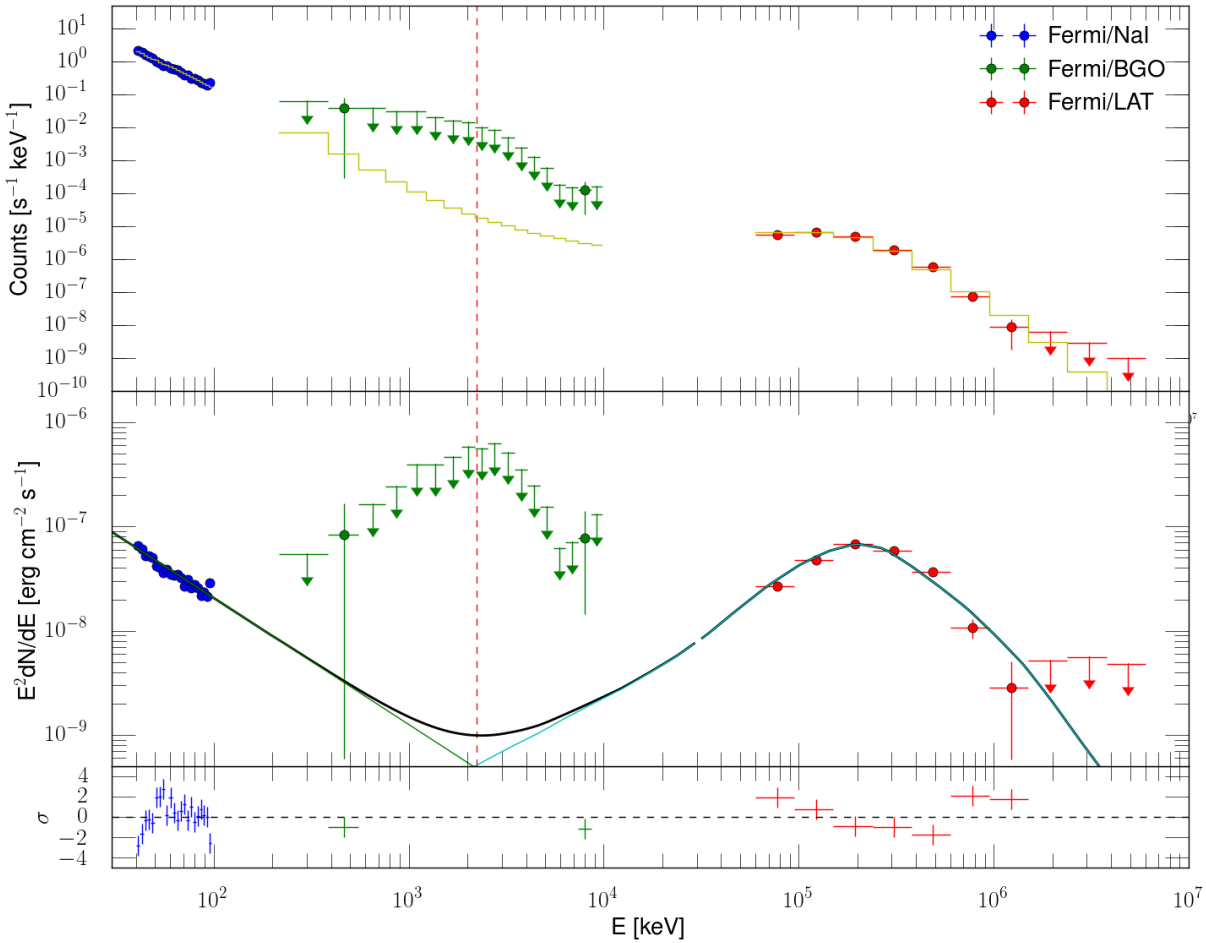
- Estimated GOES class from STEREO EUV emission is M4.9
- *RHESSI* and GBM detected emission up to 50 keV above the chromospheric limb
- >100 MeV emission detected for 25 minutes by LAT
- Pass7_REP data published in ApJL, 805, L15
- Re-analyzed the flare with new *Fermi*-LAT Pass 8 data
  - Gained 5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

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

Spectral energy distribution of SOL2013-10-11



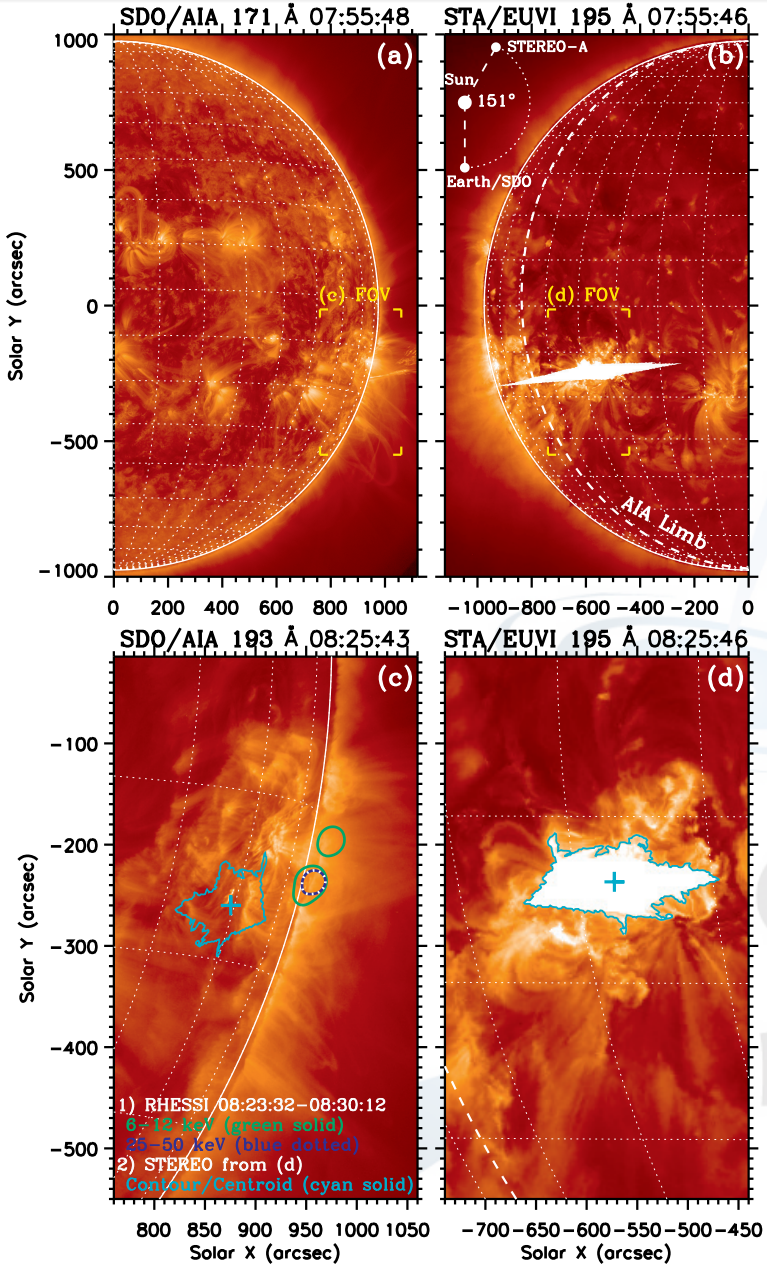
Best fit model

simple power-law + pion template

Parameter	Value
Power-law index	3.2±0.1
Proton index	4.1±0.1

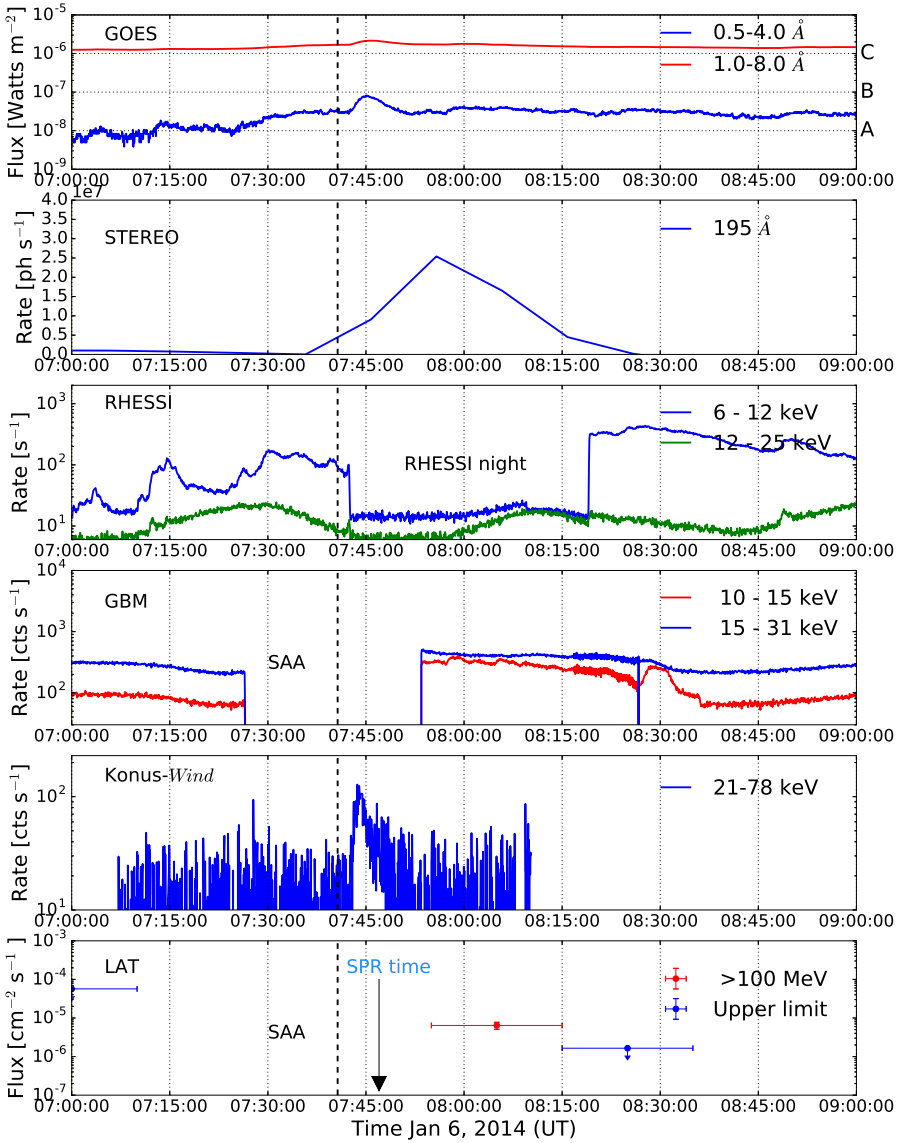
- 2.223MeV line – represented by red dashed line – is not significant
- Nuclear de-excitation lines are not significant

SOL2014-01-06



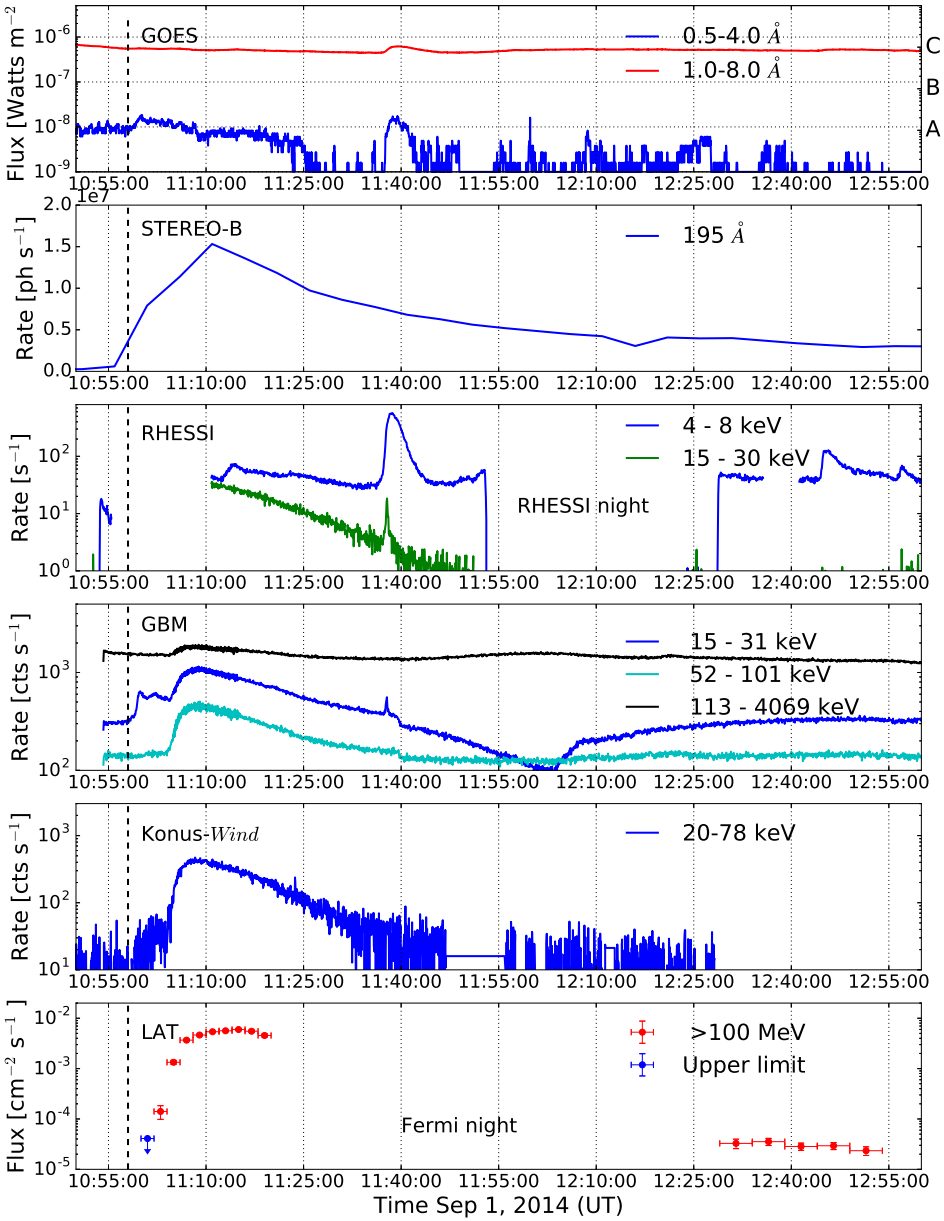
- On Jan 6, 2014 between 07:35 and 7:45 a flare erupted from an active region located S8W110
- A fast CME (speed ∼1400 km/s) was reported by LASCO
- Filament eruption detected from the visible limb by SDO
- *RHESSI* 6-12 keV source located above the limb
- LAT statistics insufficient to provide localization information

SOL2014-01-06



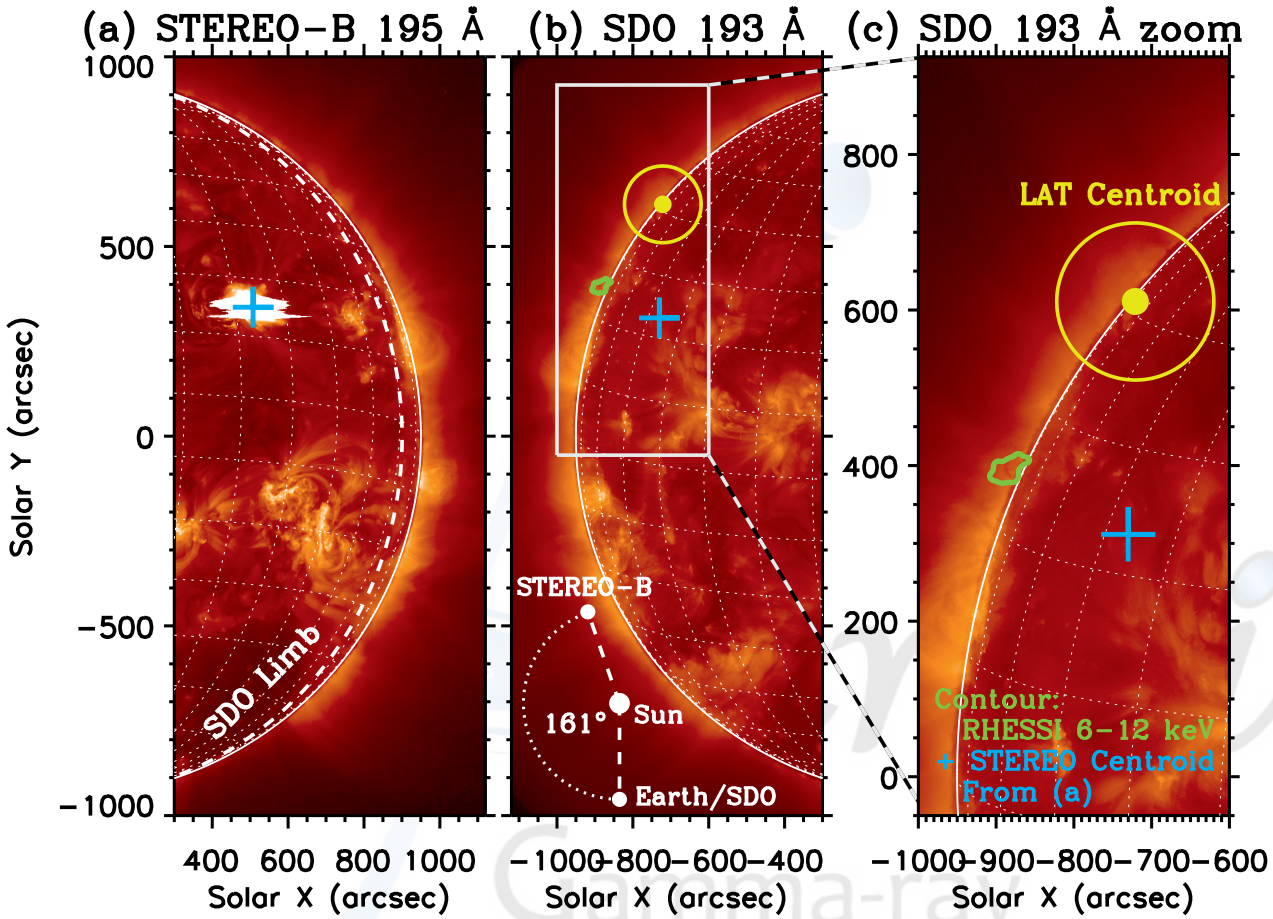
- Estimated GOES class based on STEREO EUV emission is X3.5
- Konus detected emission up to 78 keV
- *RHESSI* detected emission after 8:20 UT
- *Fermi* satellite was in the SAA from 7:25 - 7:55 UT
- Both detectors on-board *Fermi* detected emission from this flare upon exiting the SAA:
  - GBM detected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

SOL2014-09-01



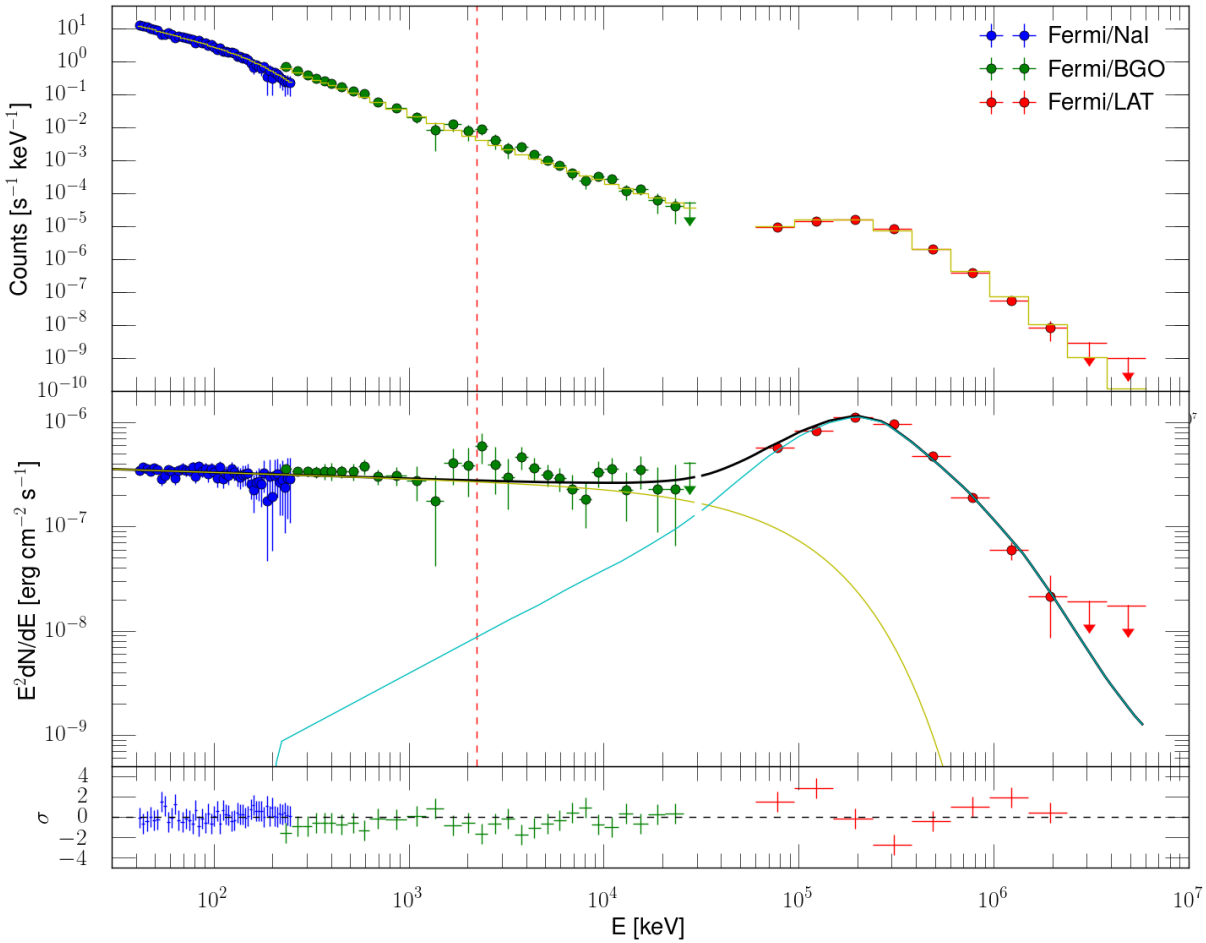
- Estimated GOES class based on STEREO 195 Å emission is X2.1
- *RHESSI* detected signal upon exiting the SAA at 11:11 UT
- GBM emission up to few MeV for $\sim$ 15 minutes
- Konus detected emission up a few 100's keV for more than 20 minutes
- LAT detected emission for almost 2 hours from 11:02 to 12:55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

SOL2014-09-01



- On Sep 1, 2014 between 10:55 and 11:00 a flare erupted from AR located N14E126
- A fast CME (speed ∼2000 km/s) was reported by LASCO
- Fermi-LAT emission centroid is slightly offset from *RHESSI* source

Spectral Energy Distribution SOL2014-09-01



Best fit model

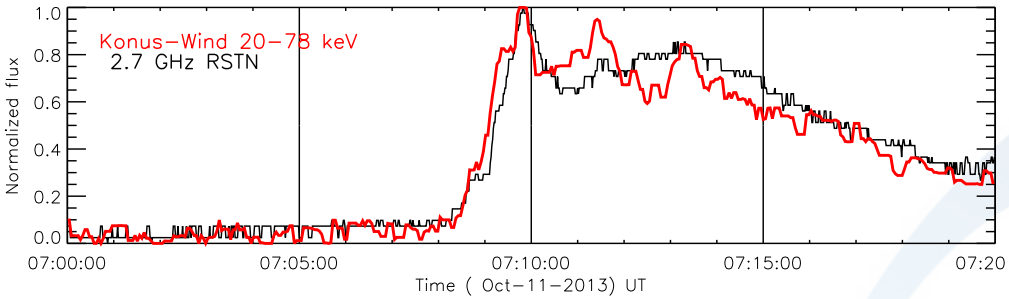
power-law with exp cutoff + pion template

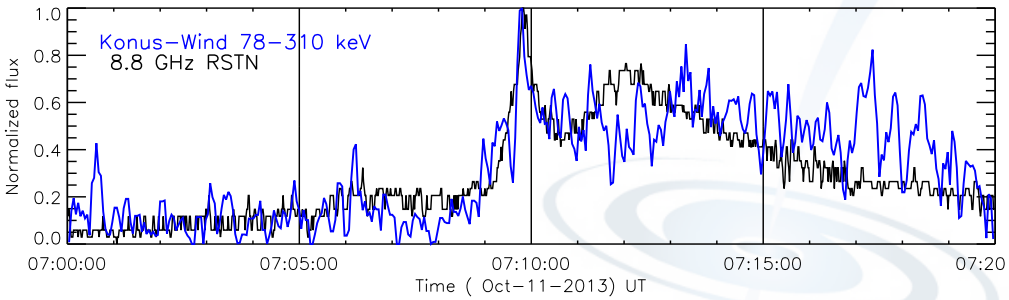
Parameter	Value
Power-law index	2.06±0.01
Folding energy	90±7 MeV
Proton index	4.4±0.1

- Significance of the 2.223MeV line is $\sim 2\sigma$
- Nuclear de-excitation lines are not significant

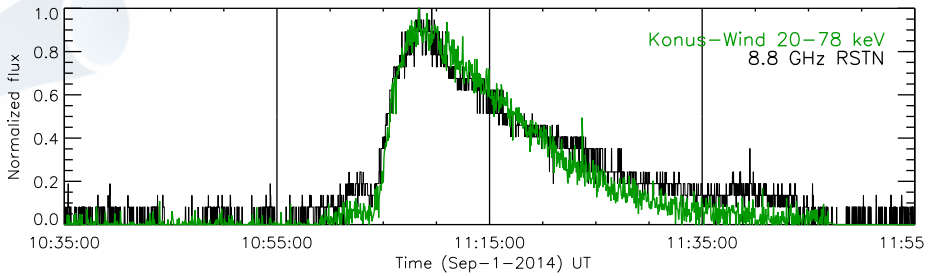
Radio data

SOL2013-10-11





SOL2014-09-01



- HXR and radio time profiles for SOL2013-10-11 and SOL2014-09-01
- SOL2013-10-11:
  - First peak in 8.8 GHz well aligned with 78-310 keV HXR peak
  - No apparent correlation between the remaining peaks
- SOL2014-09-01
  - 20-78 keV HXR light curve well aligned with 8.8 GHz radio emission
  - Smooth time profiles for both HXR and radio

Comparison with on-disk flares

Comparison between behind-the-limb and on-disk flare quantities

Date (UTC)	GOES[a] class	CME speed[b] (km s^{-1})	AR position	*Fermi*-LAT detection (minutes)	Peak Flux (10^{-5} ph cm^{-2} s^{-1})	E_γ >100 MeV[c] (ergs)	Proton[d] index	E_p >500 MeV[e] (ergs)
2013-10-11	M4.9	1200	N21E103	30	49±2	1.5×10^{23}	4.3±0.1	9.8×10^{24}
2014-01-06	X3.5	1400	S8W110	20	0.8±0.6	4.2×10^{21}	5.3±0.4[g]	3.5×10^{23}
2014-09-01	X2.4	2000	N14E126	113	565±14	1.4×10^{24}	4.7±0.1	7.0×10^{25}
On-disk flares								
2011-03-07	M3.7	2125	N30W48	798	3±1	5.1×10^{23}	4.7±0.2	3.6×10^{25}
2011-06-07	M2.5	1255	S22W53	38	3±1	3.2×10^{22}	5.0 ±0.3	2.5×10^{24}
2012-03-07I[f]	X5.4	2684	N16E30	45	417±13	3.9×10^{24}	3.90± 0.02	2.1×10^{26}
2012-03-07E	X5.4	2684	N16E30	1068	97±2	1.4×10^{25}	4.3±0.1	9.0×10^{26}

[a] GOES class for behind-the-limb flares is estimated based on the *STEREO* 195 Å flux.
[b] Speed is the linear speed reported by the LASCO CME catalog.
[c] Total energy released in >100 MeV gamma-rays integrated over the time interval where ΔTS>25.
[d] Proton index in time same interval as (c).
[e] Total energy released by protons with E>500 MeV estimated over the same interval as in (c). Values may be underestimated for flares with centroids at heliocentric angles >75°.
[f] Impulsive phase of the flare, *Fermi*-LAT detection from 00:38:52 - 01:23:52 UT. Note that the peak of the GOES X-ray flare occurred ∼6 minutes prior to *Fermi* orbital sunrise.

- On-disk and behind-the-limb flares have have similar characteristics
- Similar *GOES* class flares have similar peak photon fluxes
- Underlying acceleration and emission processes are most likely similar
- But the transport path of the radiating particles (presumably protons) from the acceleration to the emission site must be different

Summary

- The *Fermi*-LAT has detected high energy gamma-rays from ∼40 solar flares in 8 years of mission
  - Almost half of which are GOES M class
  - Sampling both impulsive and sustained emission
  - Extended emission lasting hours is fairly common
  - >100 MeV emission is most likely due to pion-decay
- First detection of >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
- Behind-the-limb flare observations seem to suggest a spatially extended component for high-energy gamma-rays
  - This component must subtend more 30° heliolongitude
  - Coronal Mass Ejection (CME) generated shocks could accelerate the particles over such a large range
  - Paper on LAT behind-the-limb flares close to publication

Spare slides

Fermi LAT as a solar observatory

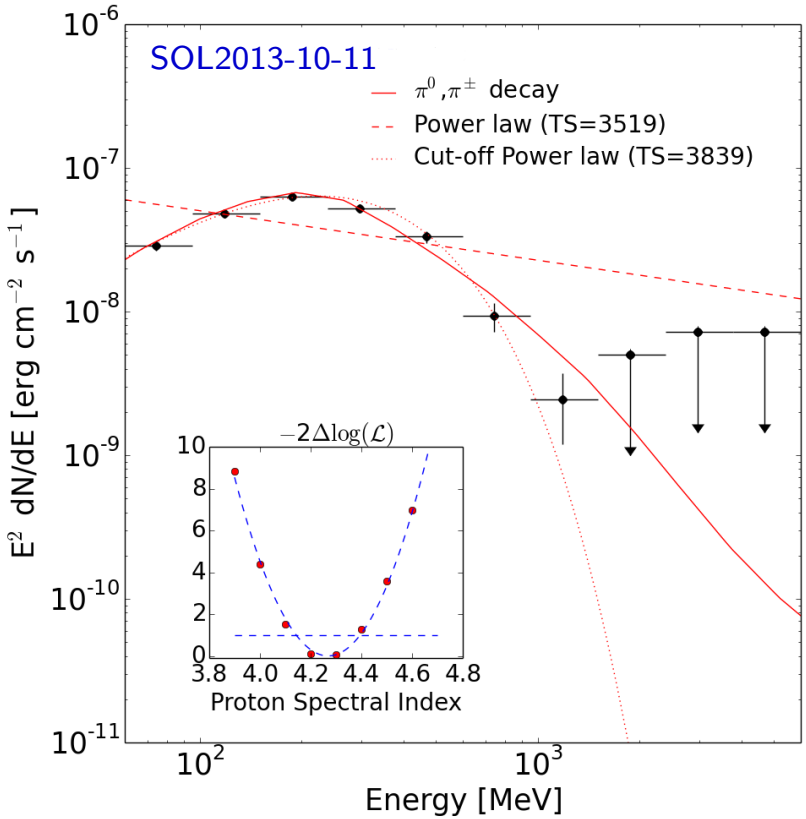
The LAT *standard analysis*

- Event classification (photon v. bkg) on event-by-event basis
  - Use classification trees to reject bkg and give high-quality photon data
- Likelihood fit of spatial and spectral model of region around sun
- 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

Testing the emission models



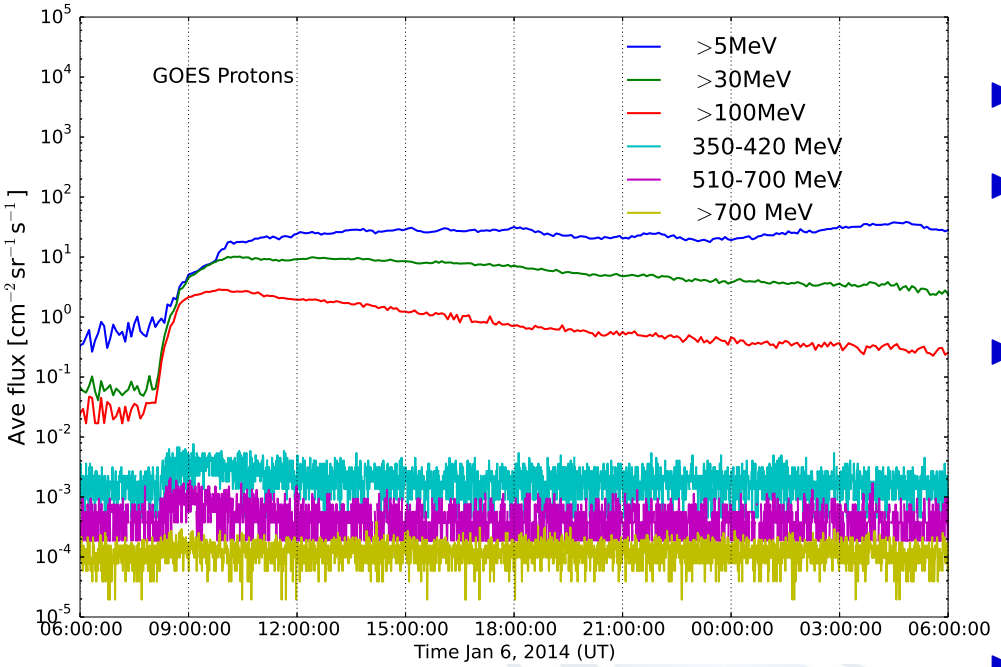
We fit the LAT spectral data between 60 MeV and 10 GeV to test three different emission models:

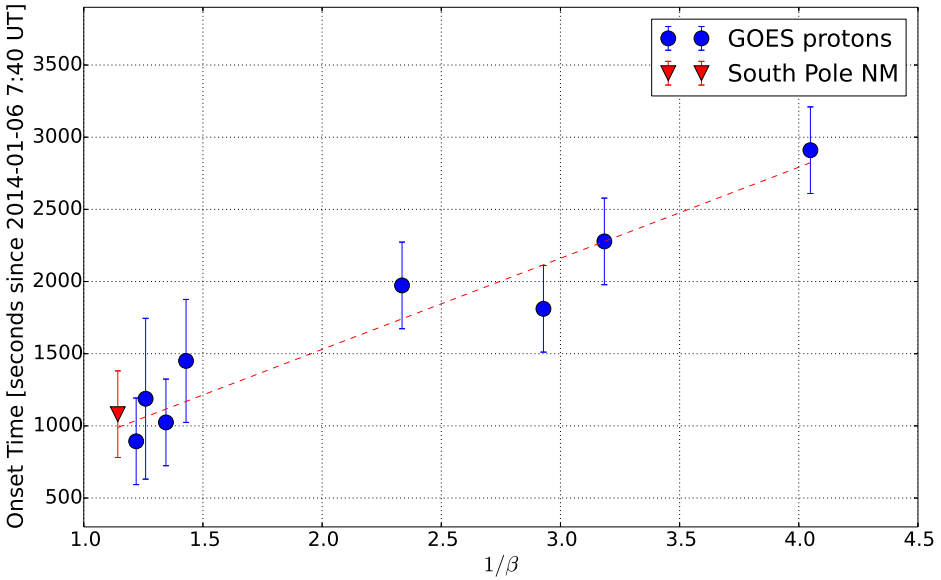
1. Pure power-law
2. Power-law with exponential cut-off
3. Templates to describe emission from pion decay based on Murphy et al. 1987

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

SOL2014-01-06

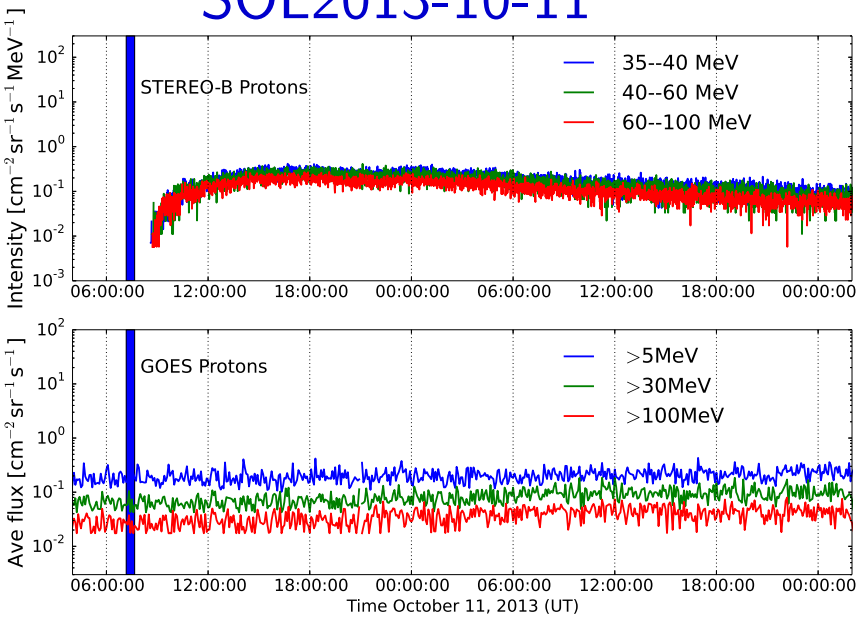




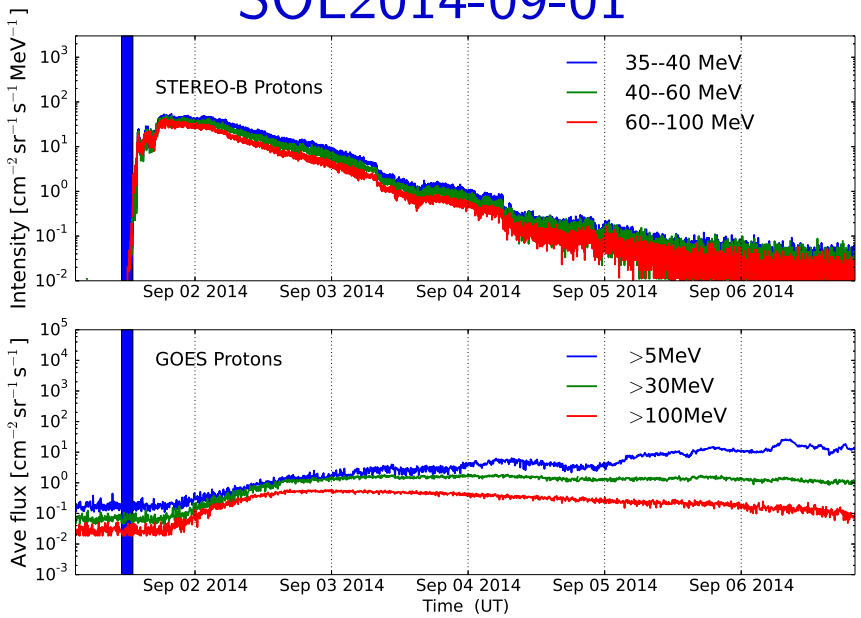
- Very strong SEP event
- Use SEP onset times to estimate the acceleration time at the Sun
- Fit with a straight line gives propagation length of 1.3±0.2 AU and onset time of 7:55 on Jan 6, 2014 (± 5 minutes)
- In agreement with the Solar particle release time 07:47 UT reported by Thakur et al. ApJL 790, L13
- LAT detection starts at 7:55 UT
  - When *Fermi* exited the SAA
  - SEP and γ-producing ions accelerated at the same time?

STEREO and GOES protons

SOL2013-10-11



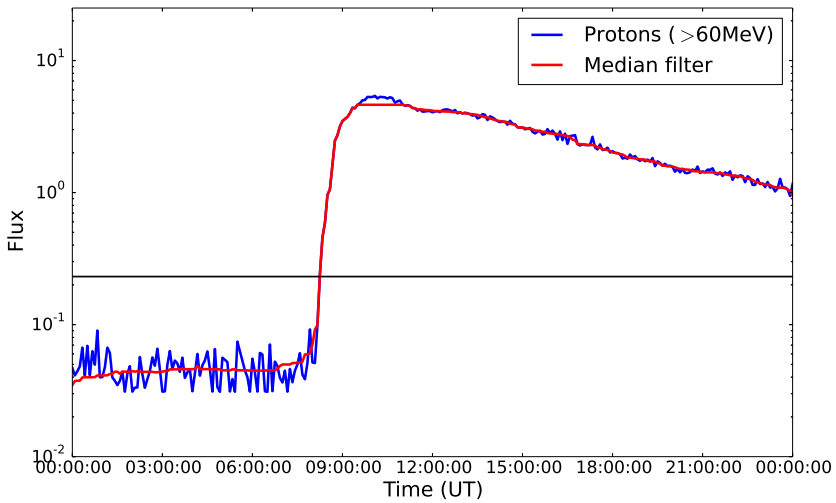
SOL2014-09-01

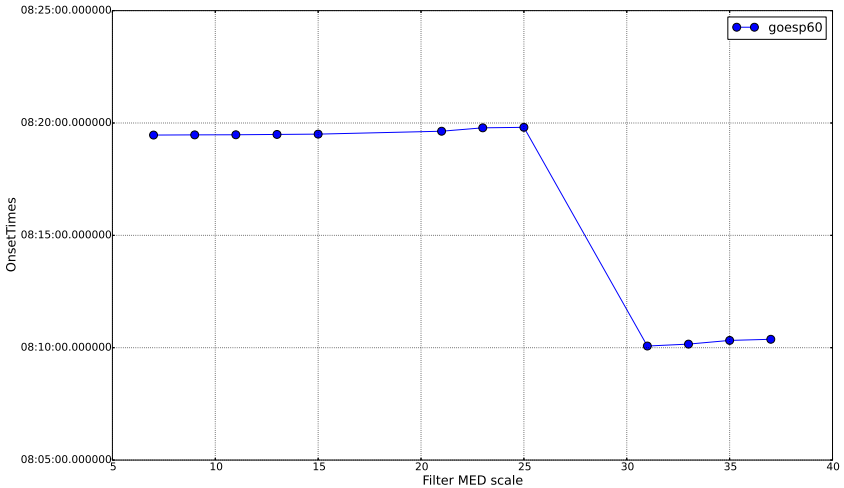


Proton intensity-time profiles provide information on magnetic connectivity and SEP propagation

- 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

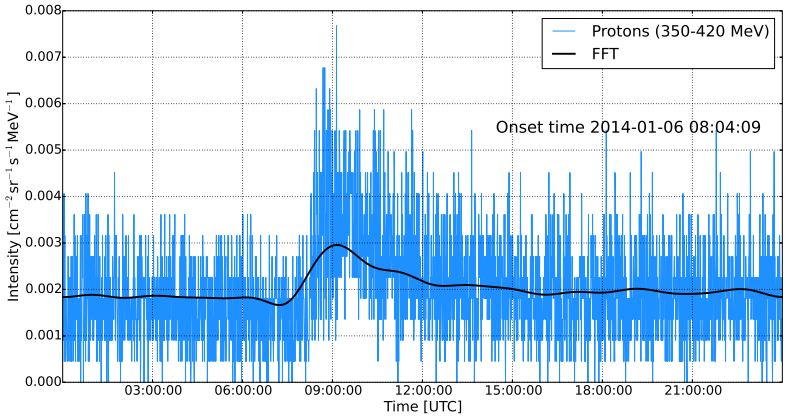
Finding the onset times

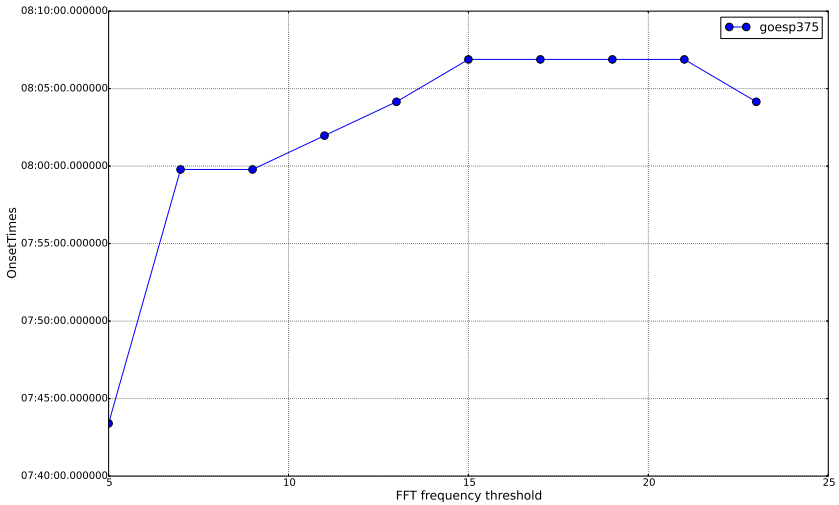




- For GOES SEP we apply a median filtering algorithm to help smooth out the data
- Take the onset time to be the point of 5% max intensity
- We scan over a series of values for the median filter window
- Take median window 25 to be the onset time
- Take the difference in times over the scan values to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

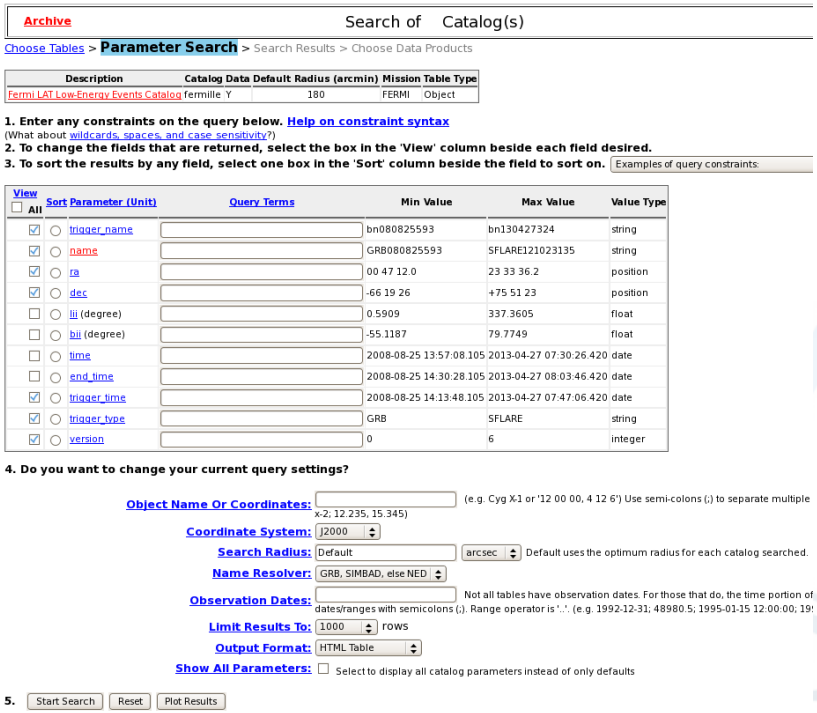
Finding the onset times for HE





- 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

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

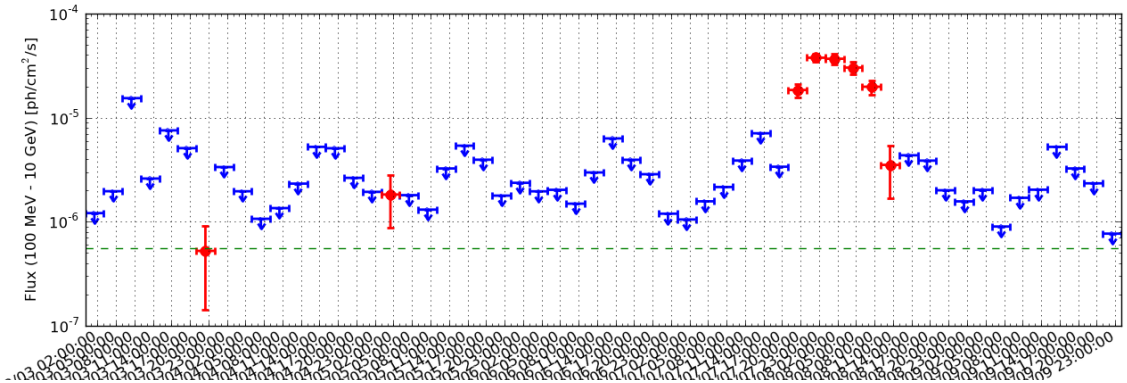
Fermi LLE public data

- 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`