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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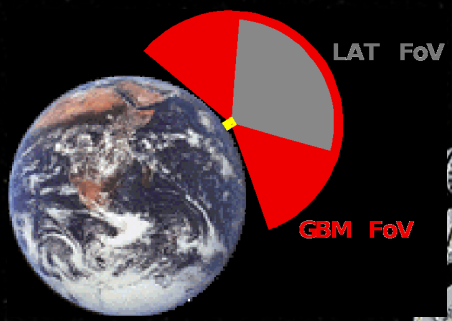
The *Fermi* Space Telescope

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

Fermi LAT as a solar observatory

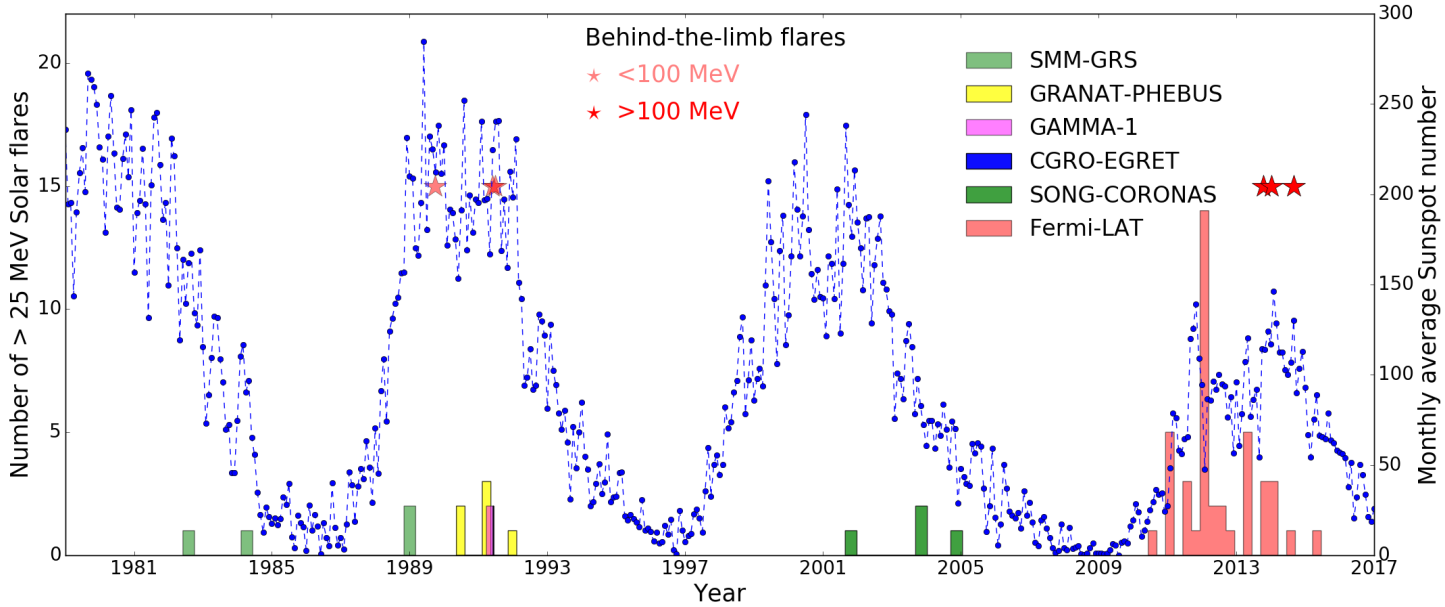
The LAT *standard analysis*

- 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 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

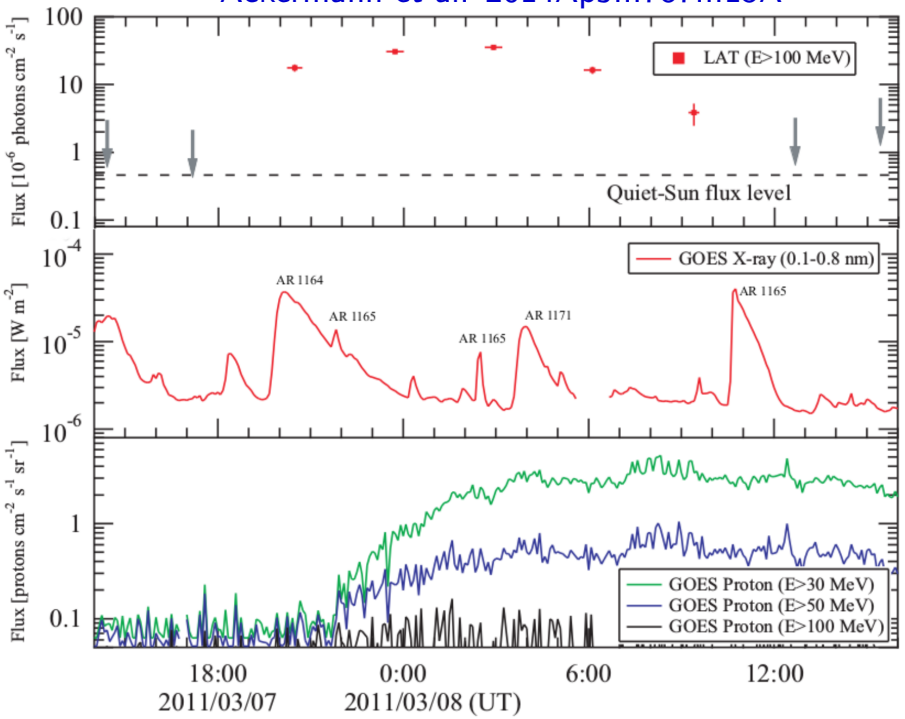
Why study Solar flares with *Fermi*?



- 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
- *Fermi* has detected more than 40 Solar flares in Solar cycle 24
  - 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

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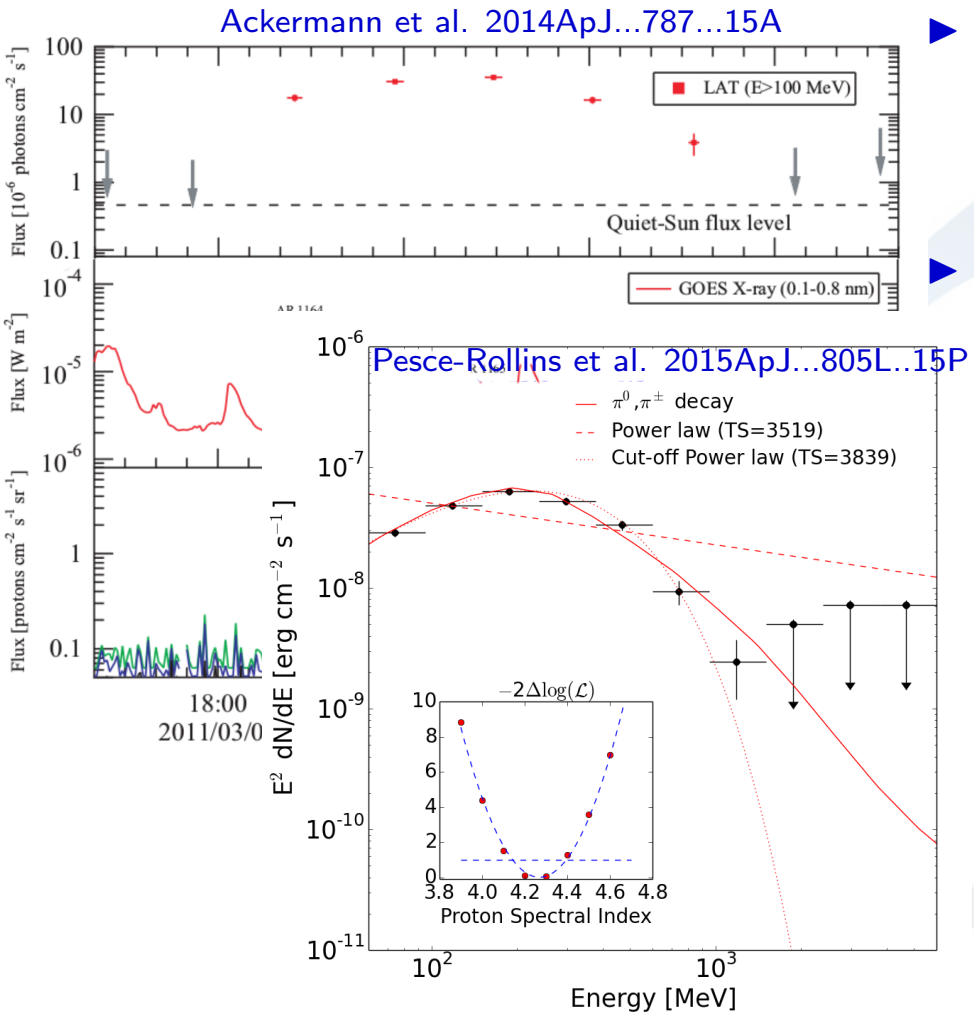

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  - Pion-decay is the most likely origin

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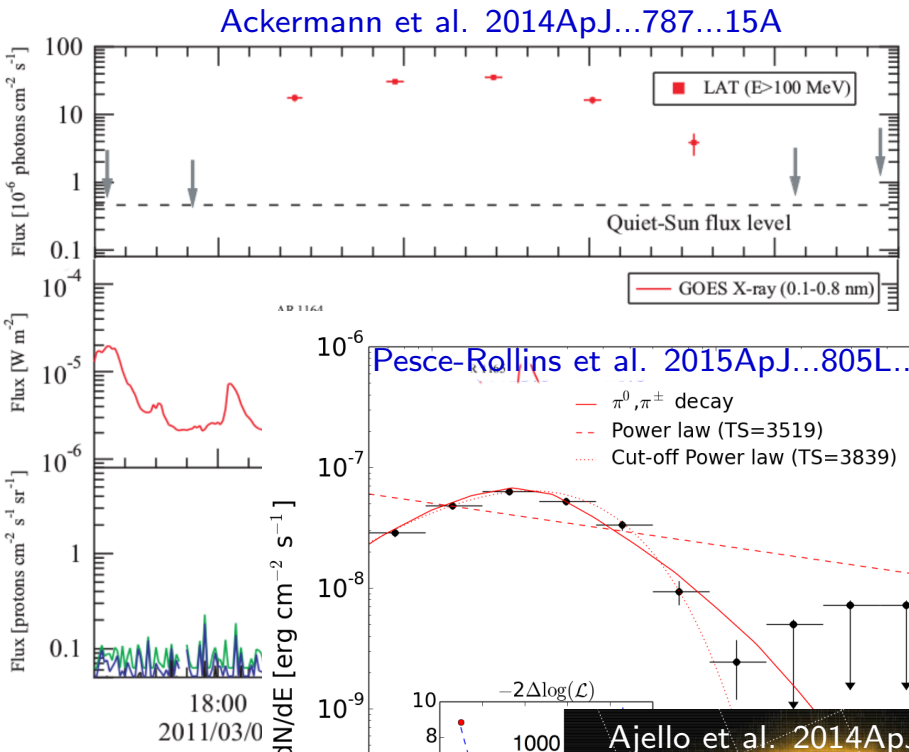

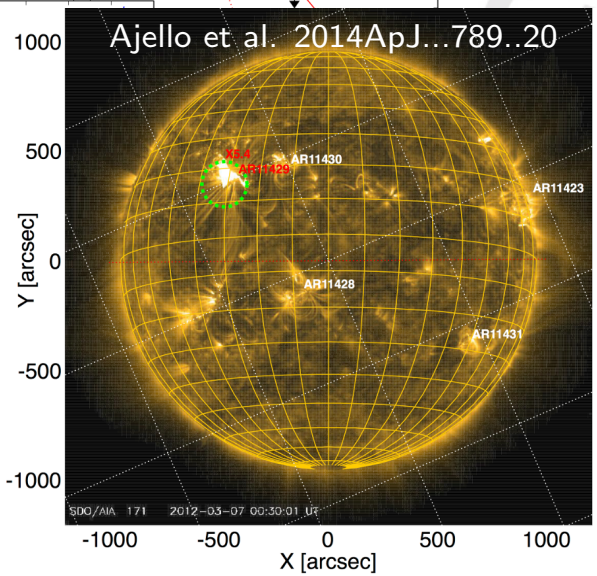

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- >100 MeV emission centroid consistent with active region for most bright flares

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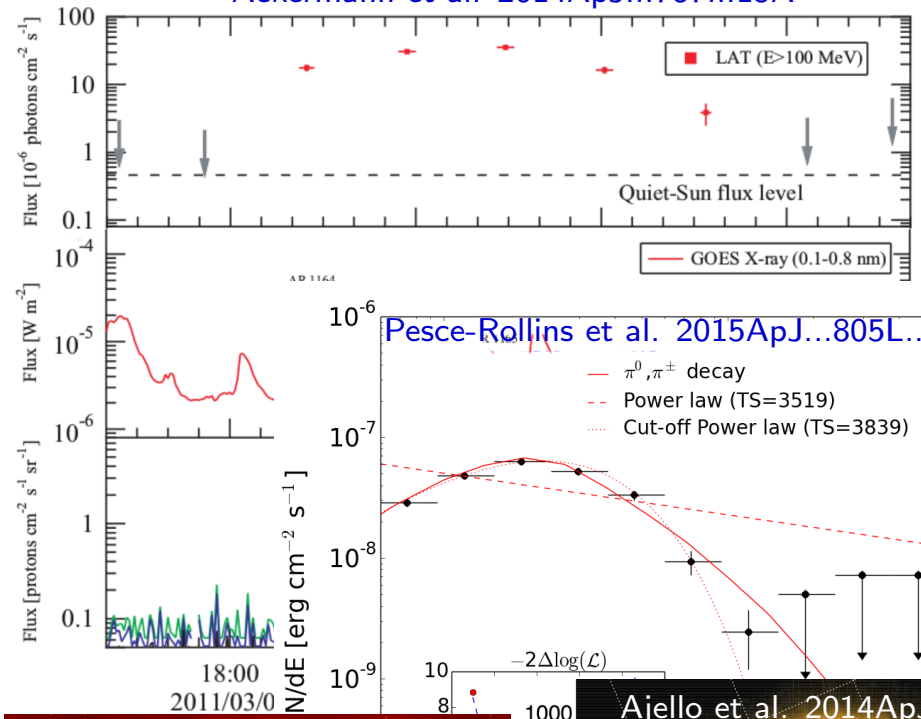

Pesce-Rollins et al. 2015ApJ...805L..15P

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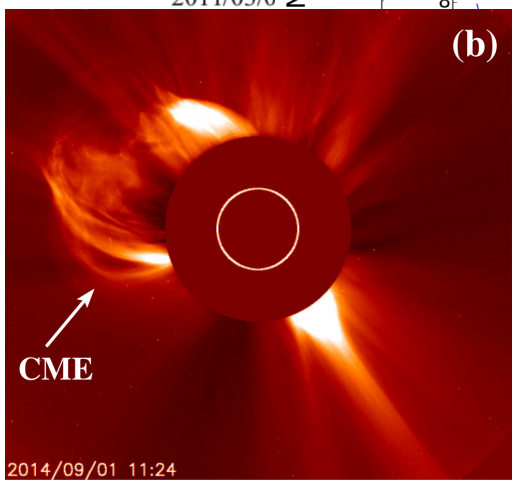
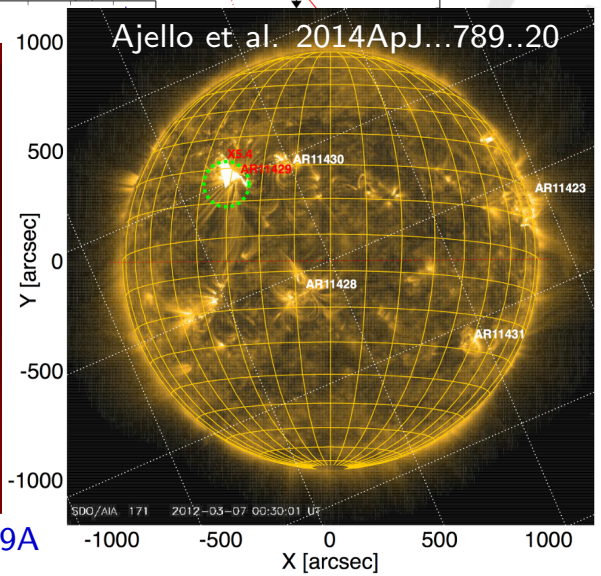


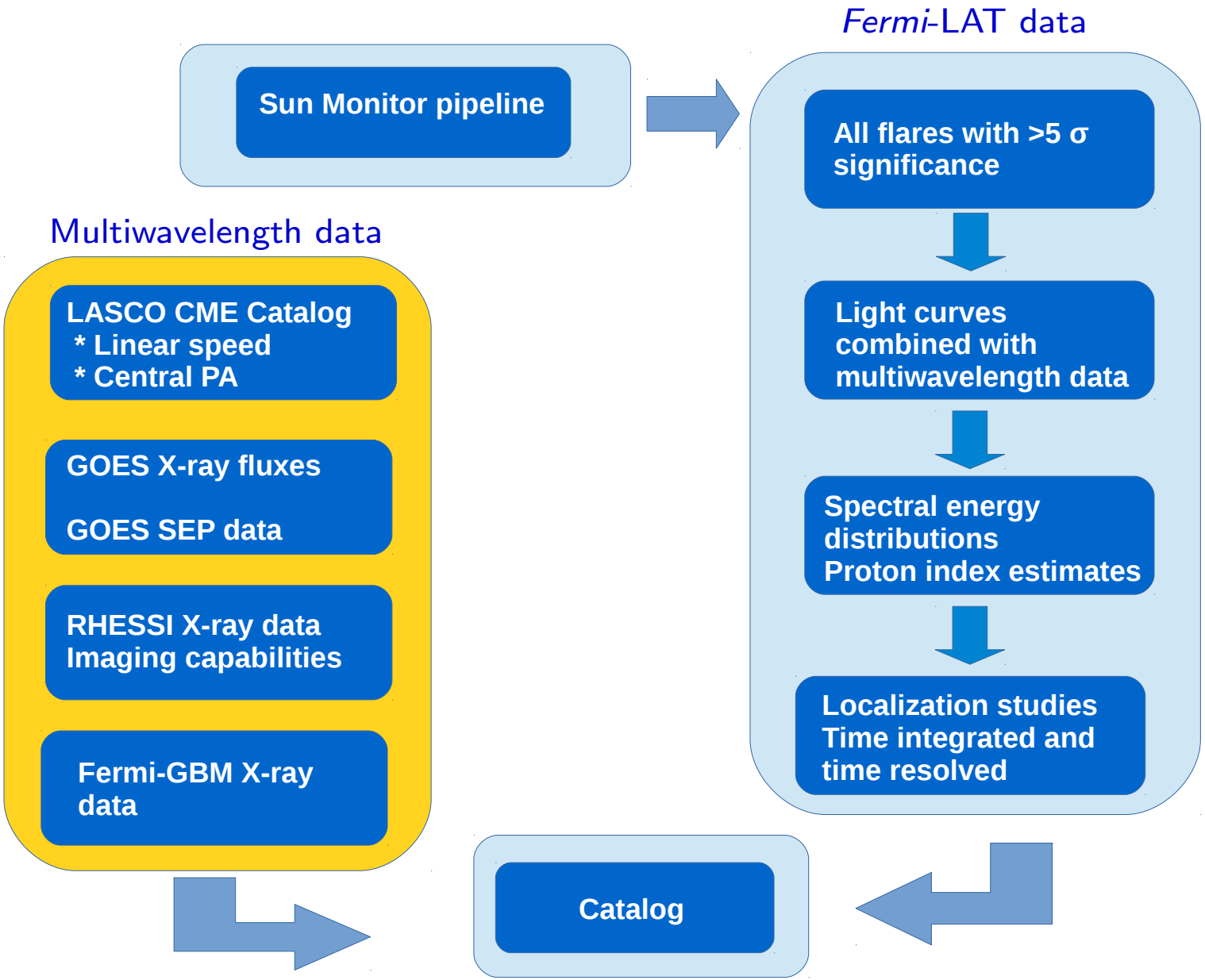
Ackermann et al. 2017ApJ...835..219A

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



- >100 MeV emission centroid consistent with active region for most bright flares
- All long duration LAT flares associated with fast CME's

The First Fermi-LAT solar flare catalog



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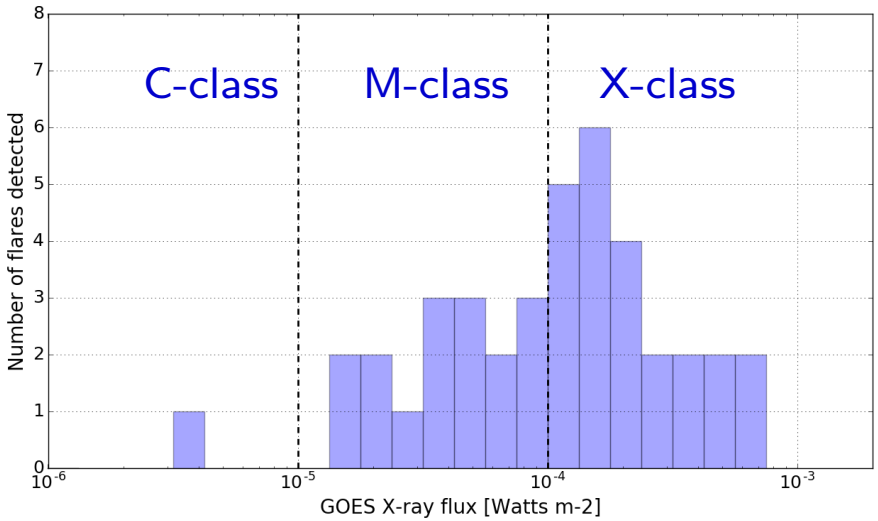
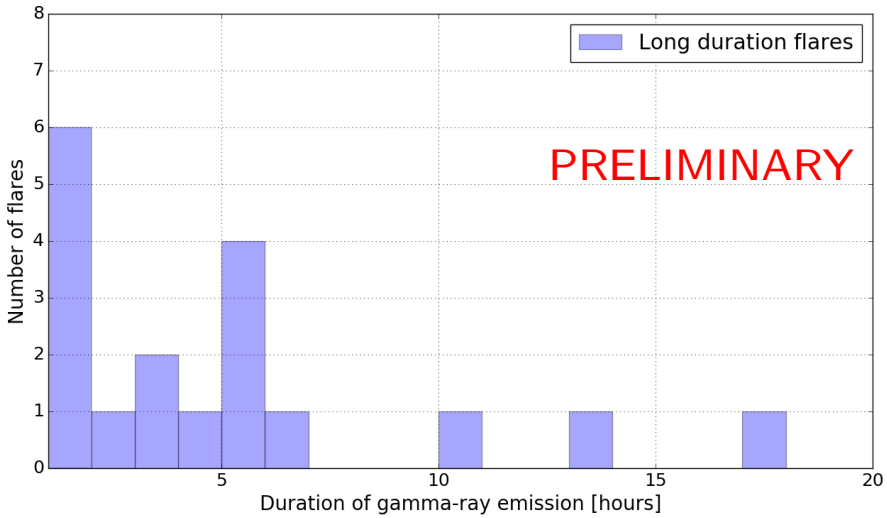
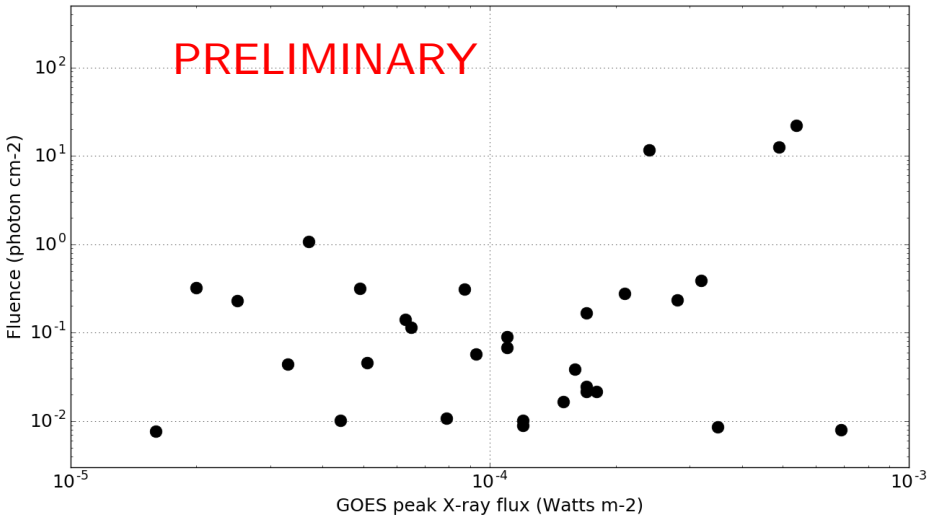
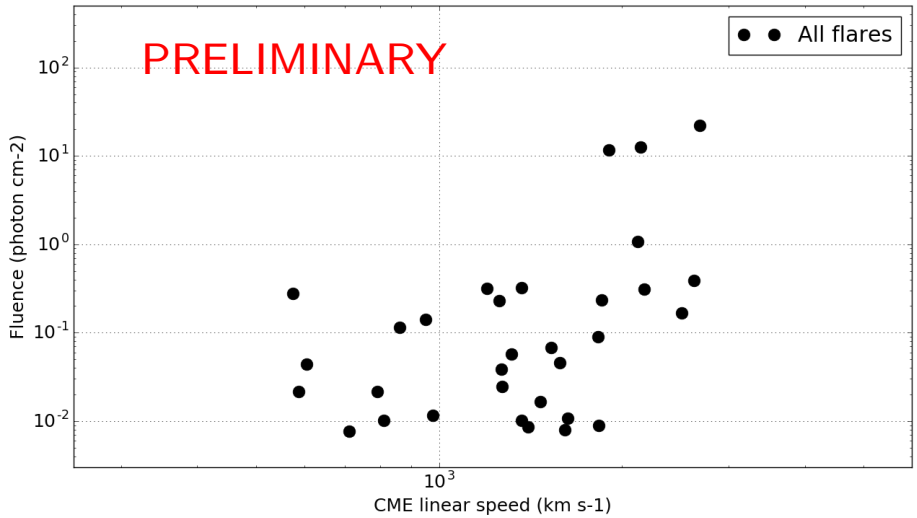




- Total of 42 high significance solar flares detected since 2010
- 3 behind-the-limb flares
  - First detections with emission >100 MeV
- 14 impulsive flares
- 18 with emission lasting $\geq$ 1 hour
- Almost half of the total sample consists of GOES M-class flares
  - 1 GOES C-class flare detected

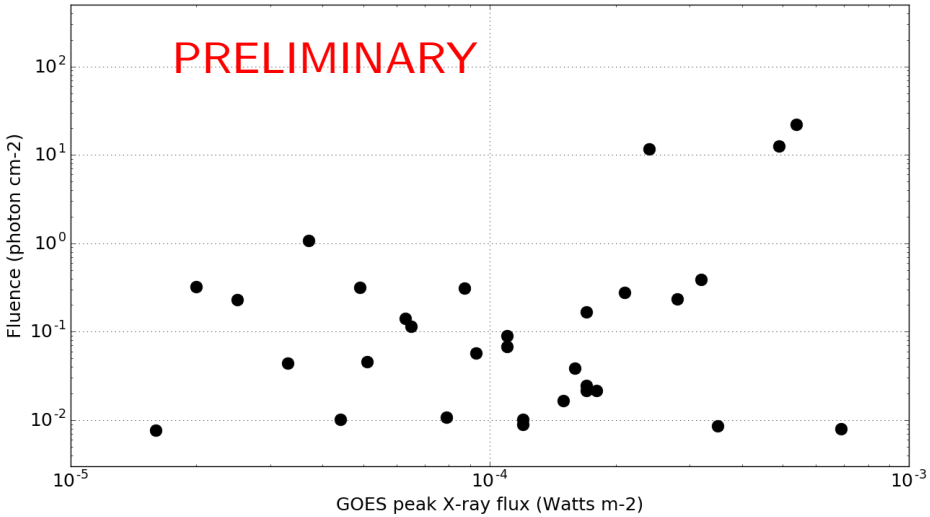
Correlation studies

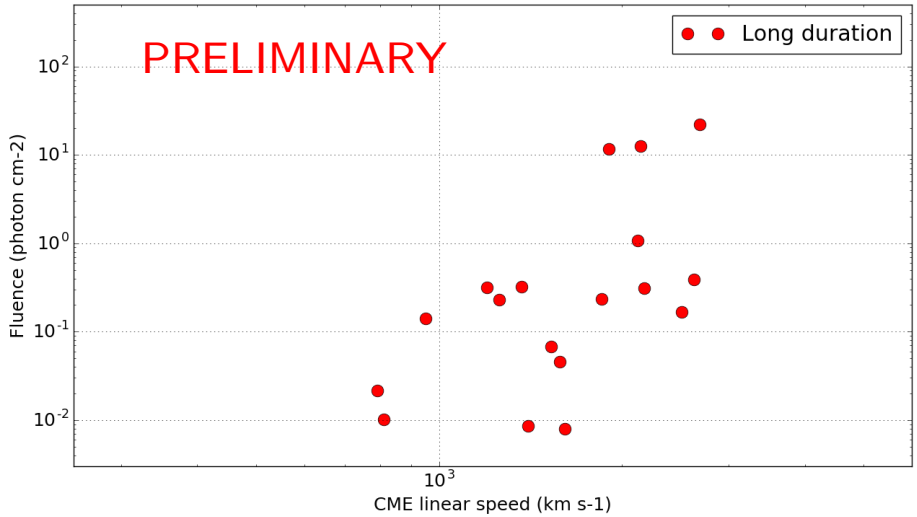




- Compared the fluence of the LAT detected solar flares with the peak GOES X-ray flux
  - Pearson correlation of 0.27 found
- Compared the fluence of the LAT detected solar flares with the LASCO CME linear speed
  - Pearson correlation of 0.46 found

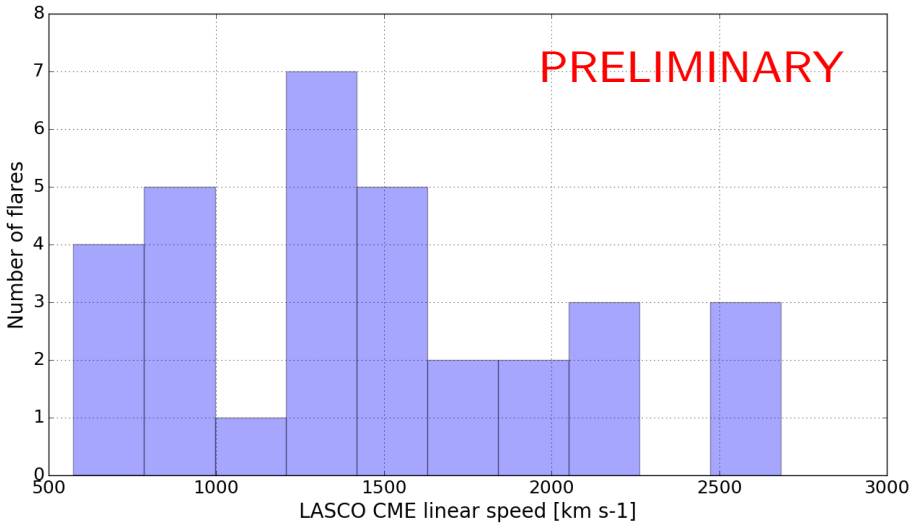
Correlation studies

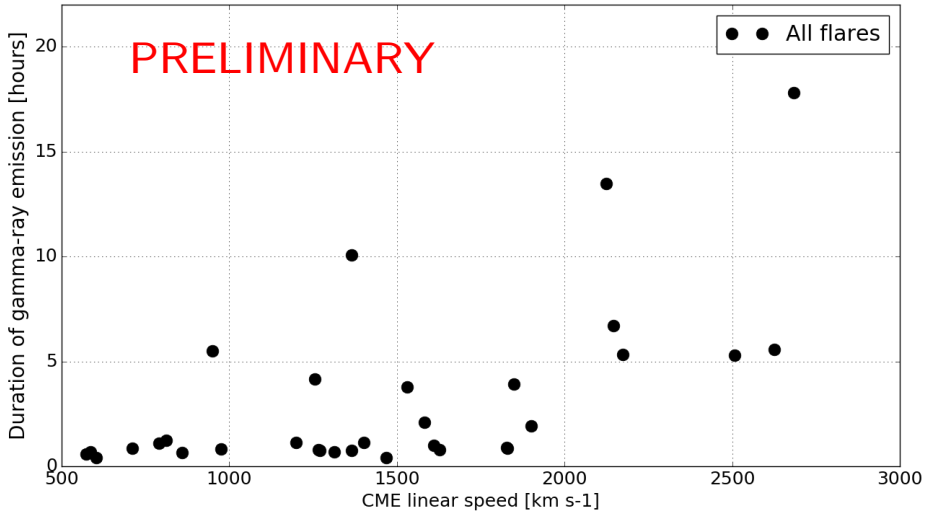




- Compared the fluence of the LAT detected solar flares with the peak GOES X-ray flux
  - Pearson correlation of 0.27 found
- Compared the fluence of the LAT detected solar flares with emission lasting more than 1 hour with the LASCO CME linear speed
  - Pearson correlation of 0.60 found

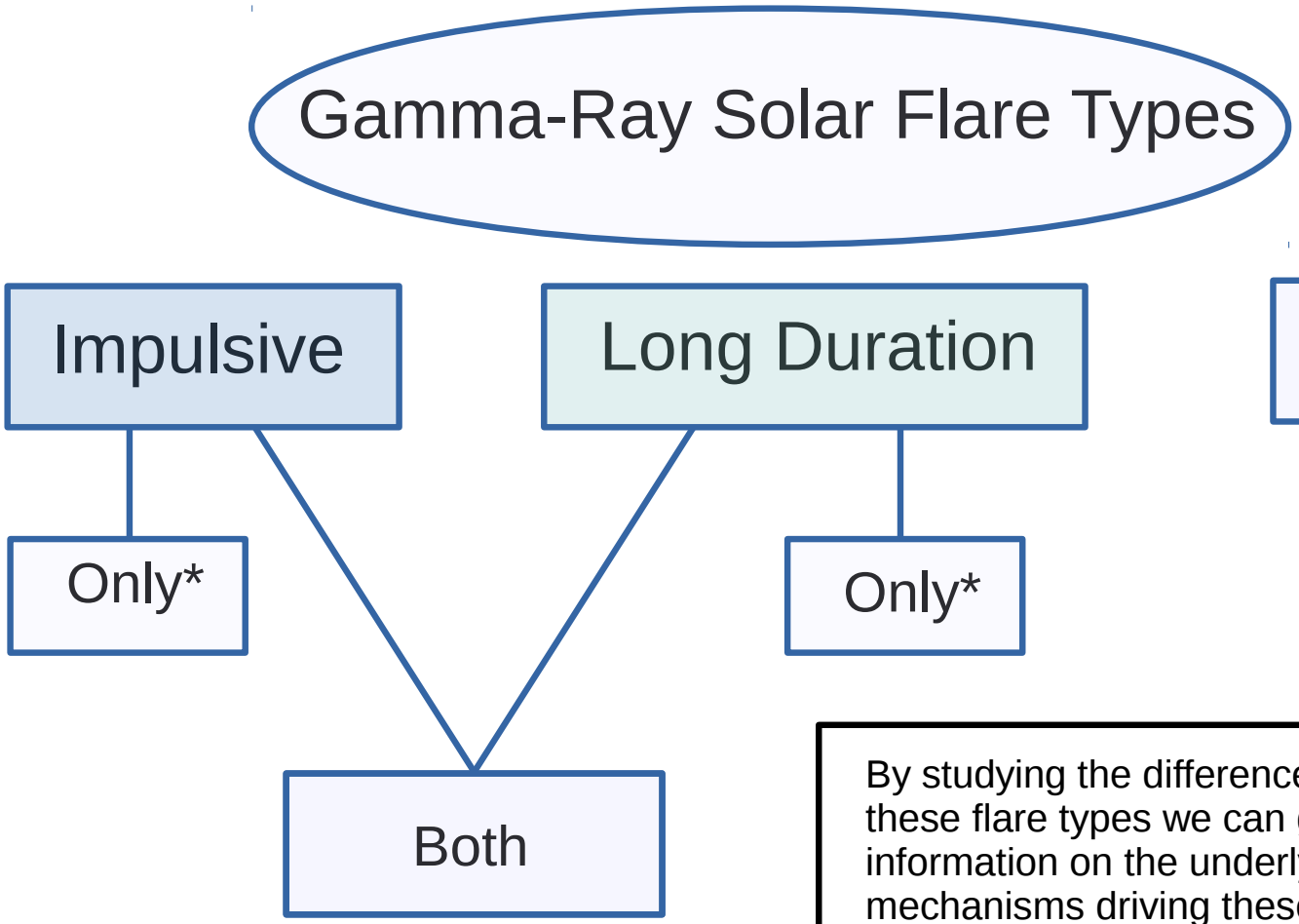
CMEs and Fermi-LAT flares





- Distribution of LASCO CME linear speeds for the solar flares detected by *Fermi*-LAT (left)
- Duration of *Fermi*-LAT flares as a function of CME linear speeds (right)
  - Pearson correlation of 0.60 found

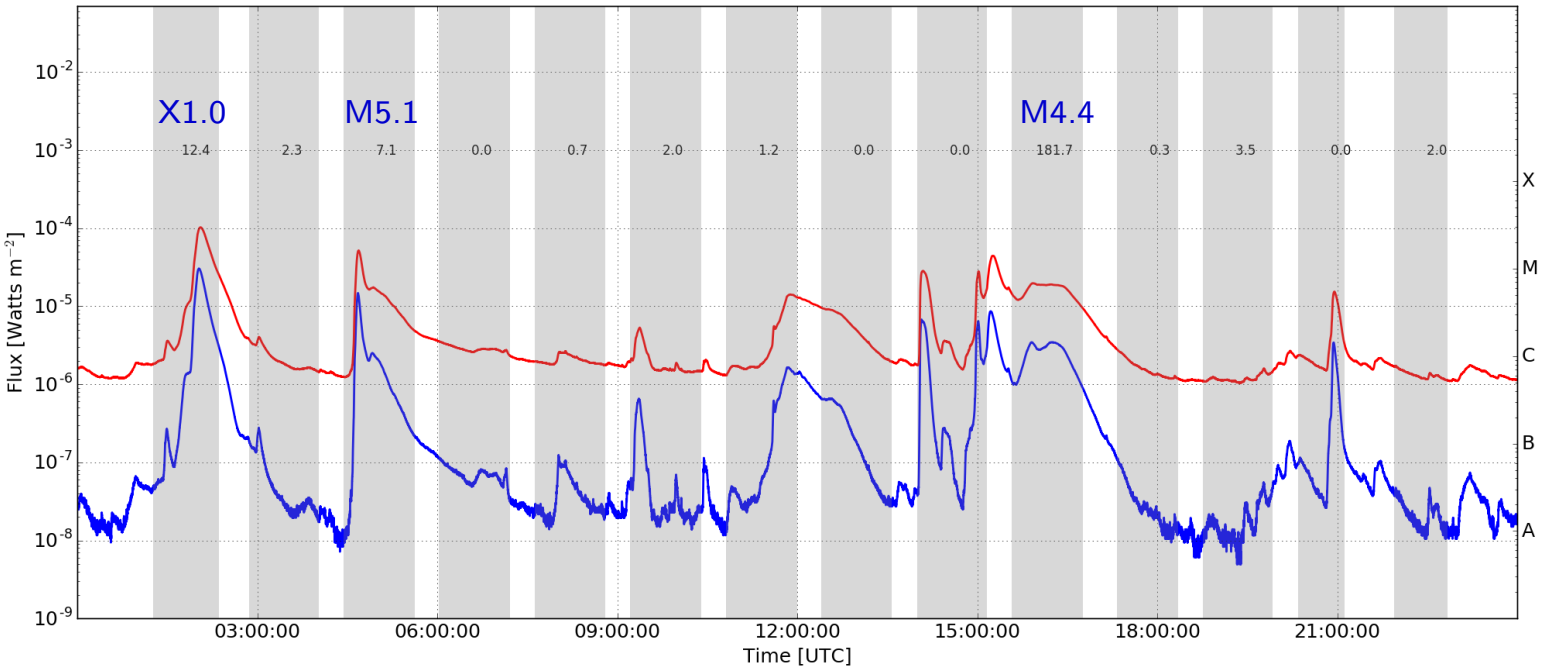
Flare types



By studying the differences between these flare types we can gain valuable information on the underlying mechanisms driving these gamma-ray flares

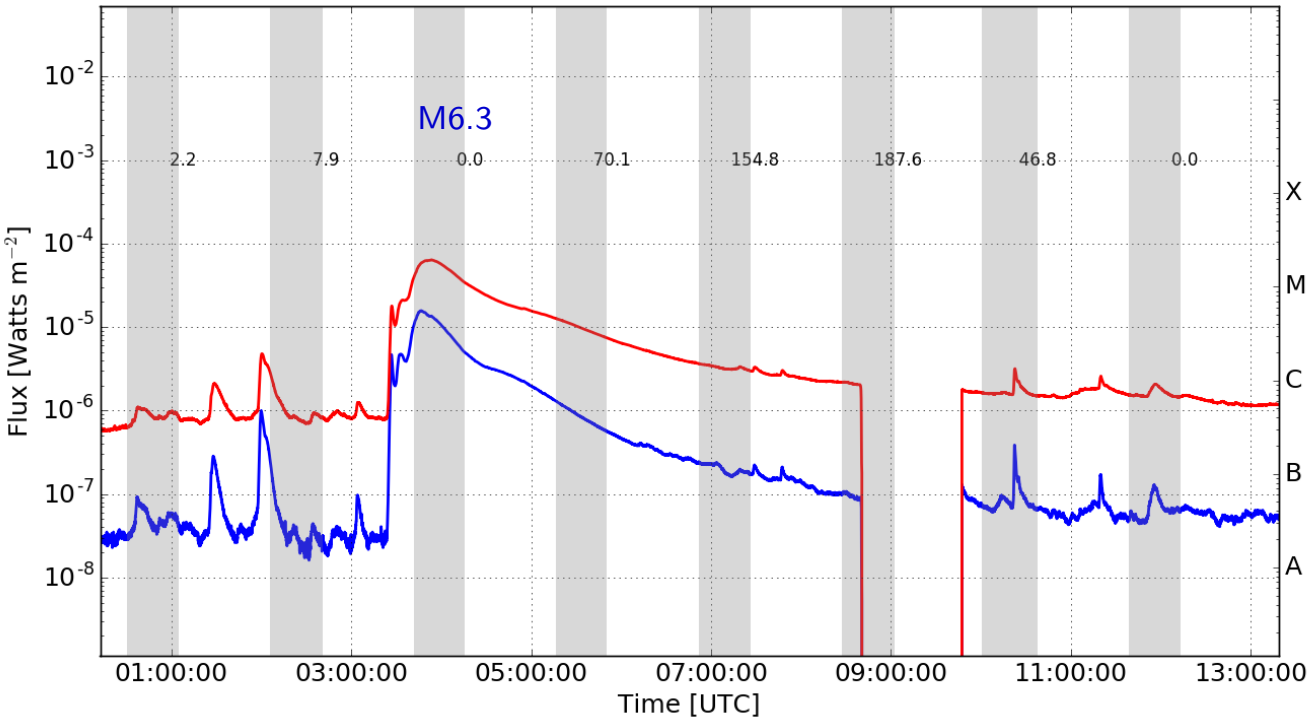
* Even if the Sun was in the field of view of the LAT, no impulsive/long duration emission was detected.

Solar flares of 2013 October 28



- 3 flares were detected on the 28 of October 2013
- The first two were impulsive only
  - Sun in the LAT field of view during X-ray flare and in the decay phase
  - No long duration emission detected
- The Sun was in the field of view ∼15 min after end of the third X-ray flare → impulsive phase missed

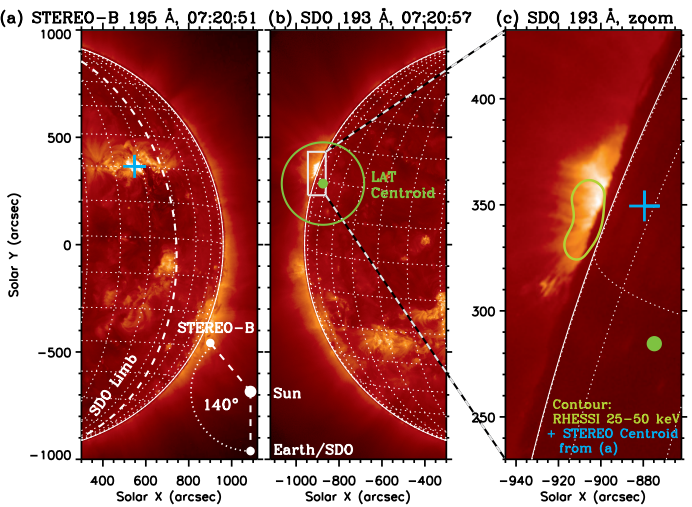
Long duration flare of 2012 March 9



- GOES X-ray flare started at 03:22 peaked at 03:53 and ended at 04:18 UTC
- Sun in the LAT field of view starting at 03:41 and no emission detected
- Significant LAT detection lasting roughly 5 hours
  - Flux peaking around 09:00 UTC $\rightarrow$ almost 5 hours after the X-ray peak

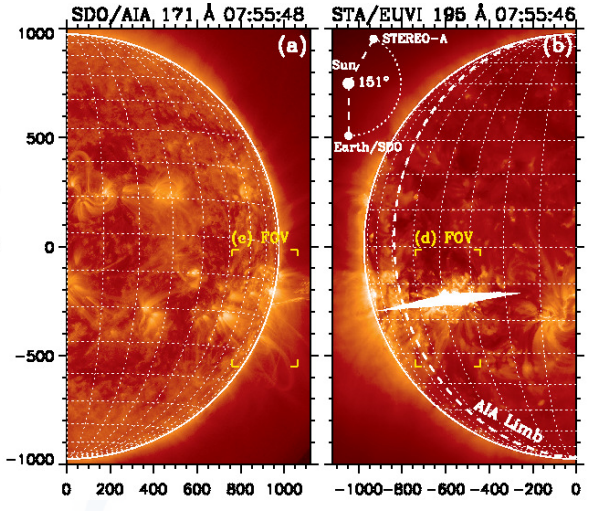
LAT behind-the-limb flares

SOL2013-10-11



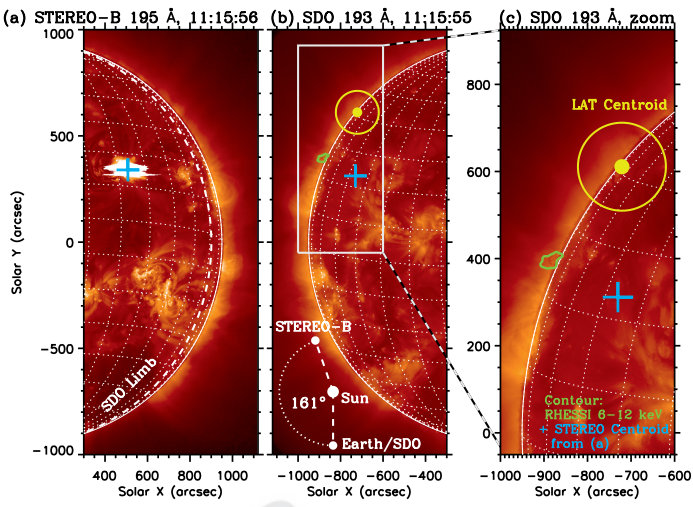
- Located ∼10° behind the eastern limb
- >100 MeV emission for 30 minutes
- *RHESSI* emission consistent with loop top
- Upper limits on nuclear line emission from GBM
- LAT emission centroid consistent with on-disk

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
- Insufficient 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 marginally visible in GBM
- LAT emission centroid consistent with on-disk

LAT behind-the-limb flares

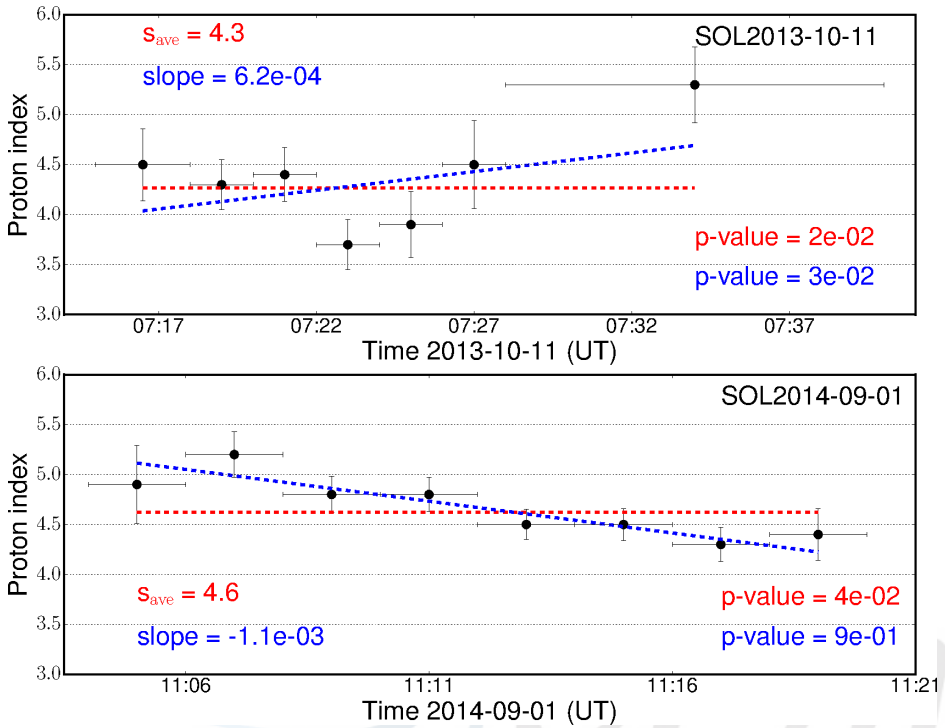
Comparison between behind-the-limb and on-disk flare quantities

Date (UTC)	GOES[a] class	CME speed[b] (km s^{-1})	AR position	Duration (minutes)	Peak Flux[c] (10^{-5} ph cm^{-2} s^{-1})	E_γ >100 MeV[d] (ergs)	Proton[e] index	E_p >500 MeV[f] (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±0.1	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[h]	X5.4	2684	N16E30	45	417±13	3.9×10^{24}	3.90± 0.02	2.1×10^{26}
2012-03-07E[i]	X5.4	2684	N16E30	1068	97±2	1.4×10^{25}	4.3±0.1	9.0×10^{26}

Ackermann et al. 2017ApJ...835..219A

- Comparison between behind-the-limb flare quantities and on-disk flares
- Proton indexes comparable
- Peak fluxes and the total energy released by protons with E>500 MeV for Sep14 and the impulsive phase of SOL2012-03-07 are comparable

LAT BEHIND-THE-LIMB FLARES



- Temporal variation of the proton index for behind-the-limb flares SOL2013-10-11 and SOL2014-09-01
- The temporal variation over tens of minutes is not sufficient to conclude whether a softening or hardening is present
- For the on-disk flare SOL2012-03-07 the spectrum softened with a time scale of a few hours

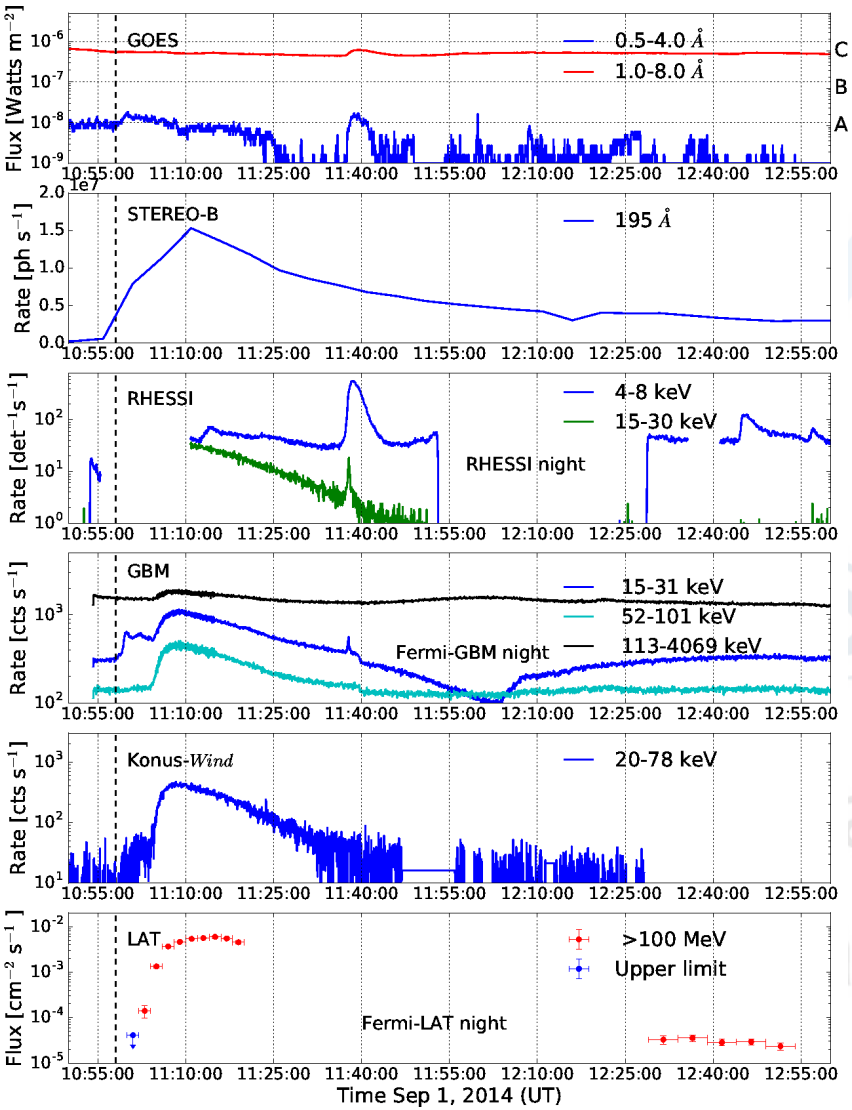
Summary

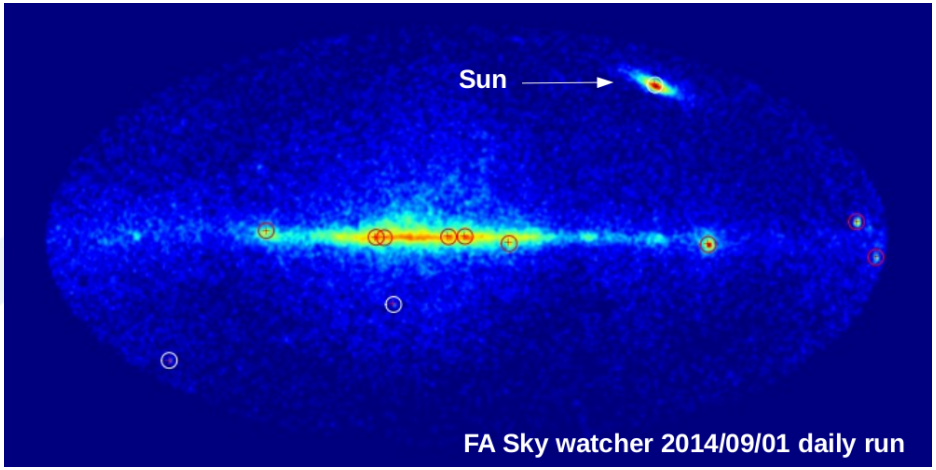
- The *Fermi*-LAT has detected high energy gamma-rays from more than 40 solar flares over the first 8 years of mission
  - Almost half of which are GOES M class
  - Sampling both impulsive and sustained emission
  - Extended emission lasting hours is fairly common
  - $>$100 MeV emission is most likely 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
- The First Fermi-LAT Solar flare catalog is in preparation

Spare slides

Exceptional behind-the-limb flare

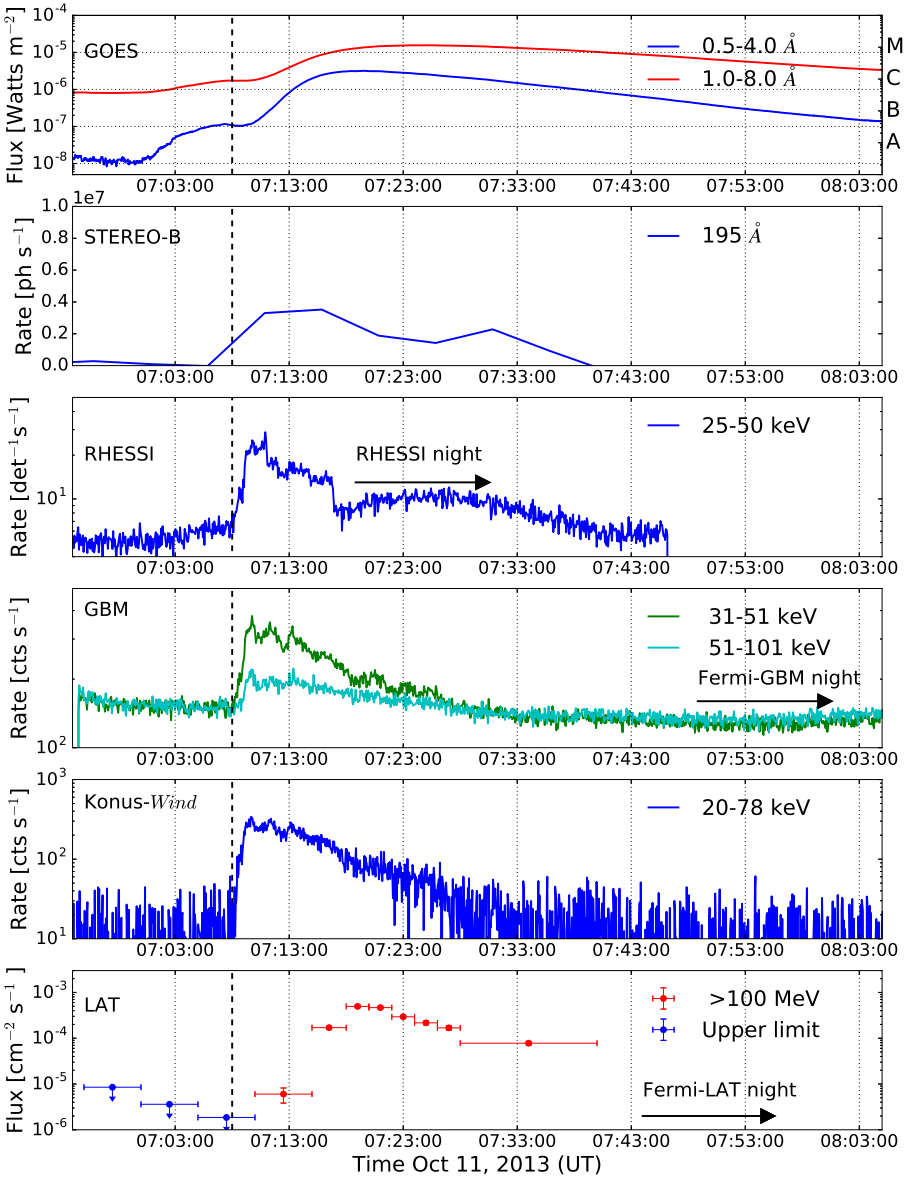
Ackermann et al. 2017ApJ...835..219A





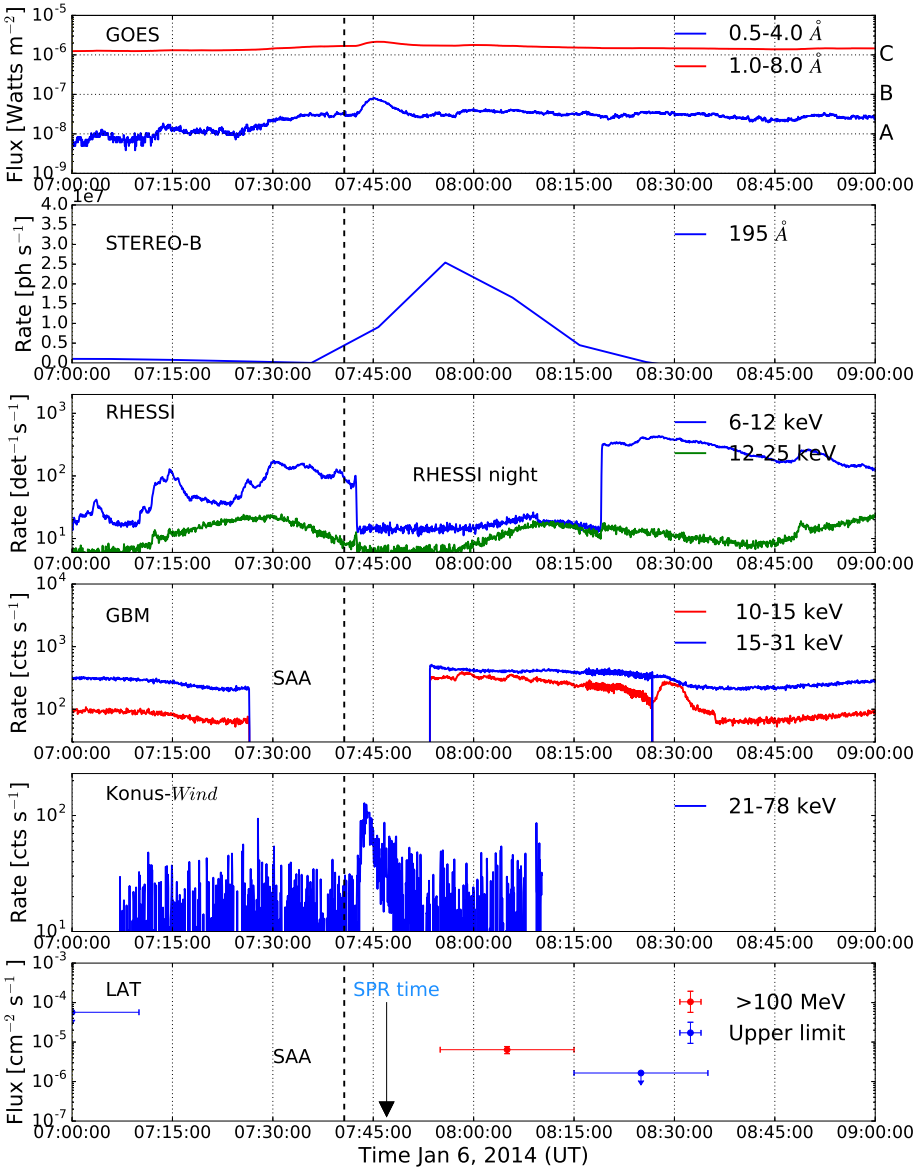
- The September 1st 2014 flare was unleashed from an active region near 40° behind the visible limb
  - More than 500,000 km (300,000 mi) behind the visible side of the Sun
- 15 photons withe E>1 GeV detected during the first 15 minutes (including 3.5 GeV photon)
- Press release at 2017 APS meeting in Washighton D.C

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

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

Impulsive flares and CMEs

LLE flares and CME onsets

Date	CME onset (UTC)	LAT onset (UTC)	LAT-CME (min)	LAT duration (min)
2010-06-12	01:31	00:55	-36	∼1
2011-08-09	08:12	08:01	-11	∼3
2011-09-24	09:48	09:34	-14	∼1
2013-10-25	23:12	20:56	-136	∼1
2013-10-28	04:48	04:37	-11	∼1
2014-02-25	01:25	00:41	-46	∼3

- Six out of 12 LLE flares have onsets prior to the onset of the CME
  - The duration of the LLE flare is much shorter than the difference in onsets
- Indication that the CME probably does not play a role in the acceleration of the particles producing the gamma-ray emission
- These are short flares which have very similar time structures as the hard x-ray flares
  - Indication that they may have acceleration mechanism in common