Fermi Large Area Telescope observations of solar flares during the 24th solar cycle

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on behalf of the *Fermi*-LAT collaboration

Solar Webinar
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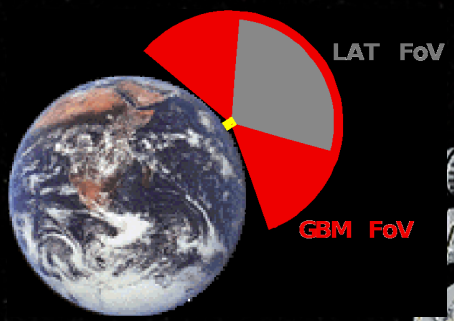
The *Fermi* Space Telescope

Gamma-ray Burst Monitor (GBM)

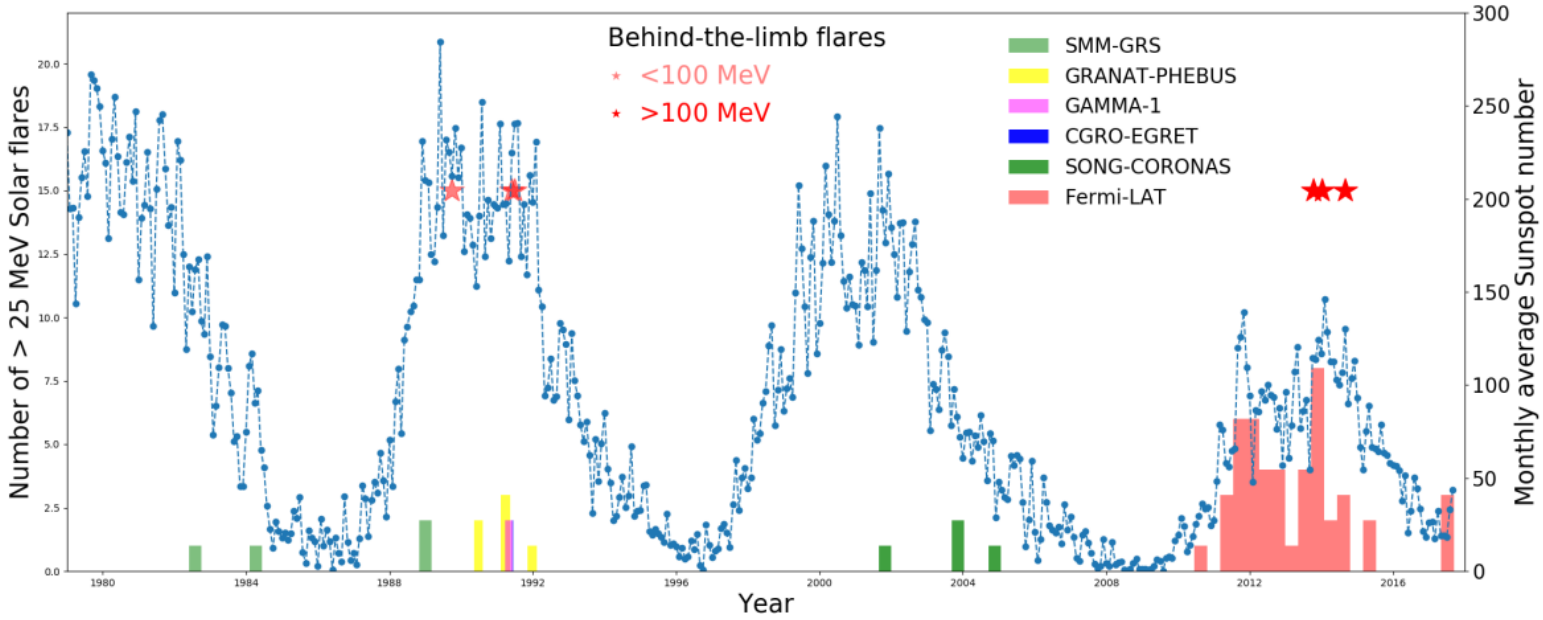
- 12 NaI and 2 BGO detectors
- Energy range: 8 keV–40 MeV
- Observes entire unocculted sky



The Large Area Telescope (LAT)

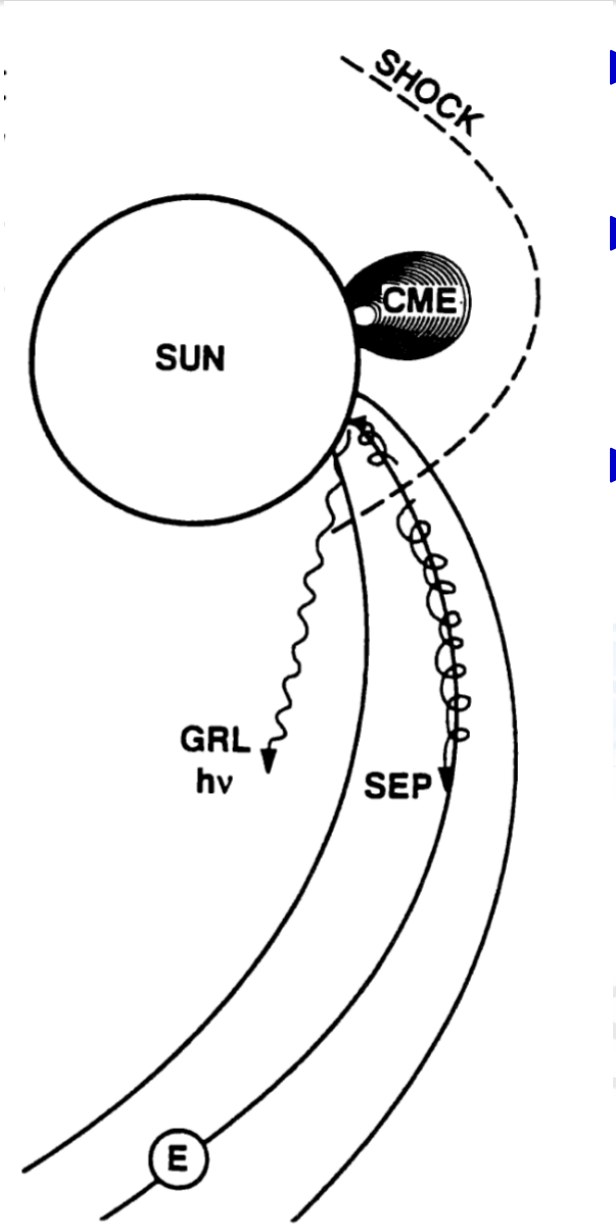
- Pair conversion telescope
- Energy range: 20 MeV–> 300 GeV
- Large field of view ($\approx$ 2.4 sr): 20% of the sky at any time
- PSF $<1^\circ$ at 1 GeV
- Observes the Sun for $\sim$20 – 40 min every 3 hours

Why study Solar flares with *Fermi*?



- Over 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 45 Solar flares during the 24^{th} Solar cycle
  - More than half are associated with GOES M class flares
  - Extended >100 MeV emission for more than 20 hours
  - Including 3 behind-the-limb flares with >100 MeV emission

Why are behind-the-limb flares interesting?



Cliver et al. 1993

- γ-ray emission processes require chromospheric densities
- Measurements of γ-ray line emission are generally consistent with a compact region located close to the active region
- 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

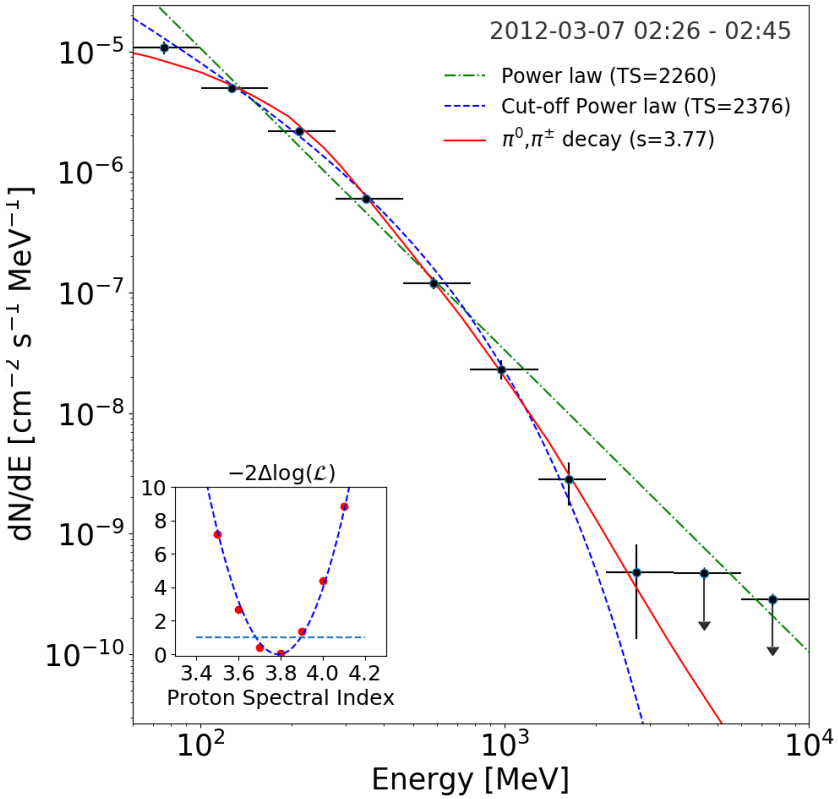
The LAT *standard analysis*

- Event classification (photon vs. 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
    - We typically take a circle with radius of 10° centered on the Sun
    - All known gamma-ray sources (including the quiet Sun) and background (galactic, isotropic) are modeled in our region
  - High flux of hard x-rays during solar flares can cause pile-up in the anti-coincidence detector (ACD) of the LAT
    - Problem solved with Solar flare event classes released in 2015

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
- Higher effective area but lower signal to noise w.r.t to standard analysis
  - Immune to potential pile-up in the ACD

Testing the emission models



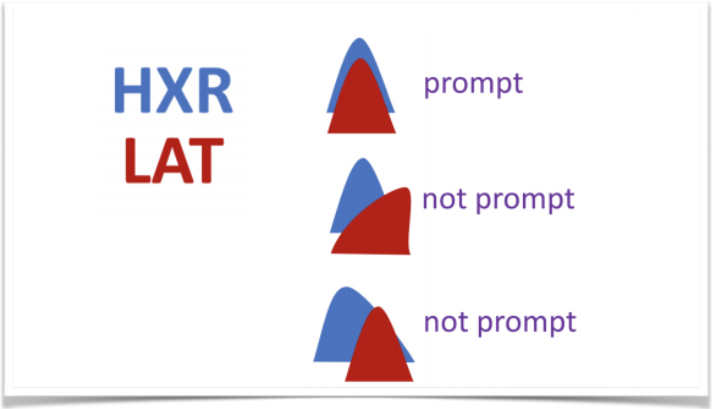
We fit the LAT spectral data between 60 MeV and 10 GeV to test three different emission models:

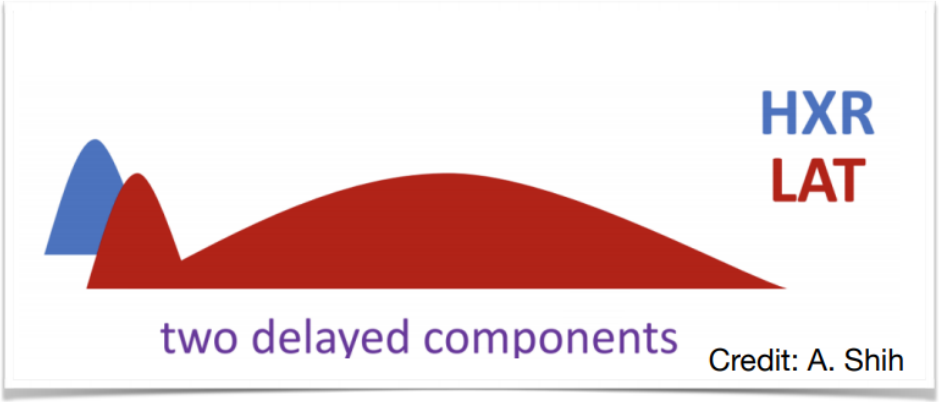
1. Pure power-law
2. Power-law with exponential cut-off
3. Templates to describe emission from pion decay based on Murphy et al. 1987

We rely on the likelihood ratio test 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

Categories of Fermi LAT Solar Flares (FLSF)

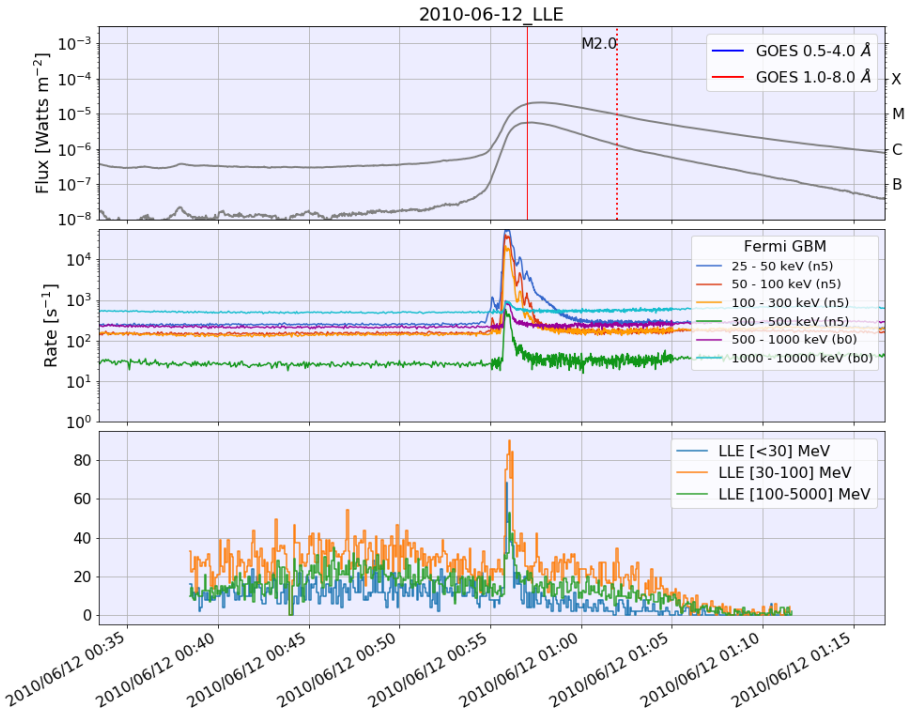


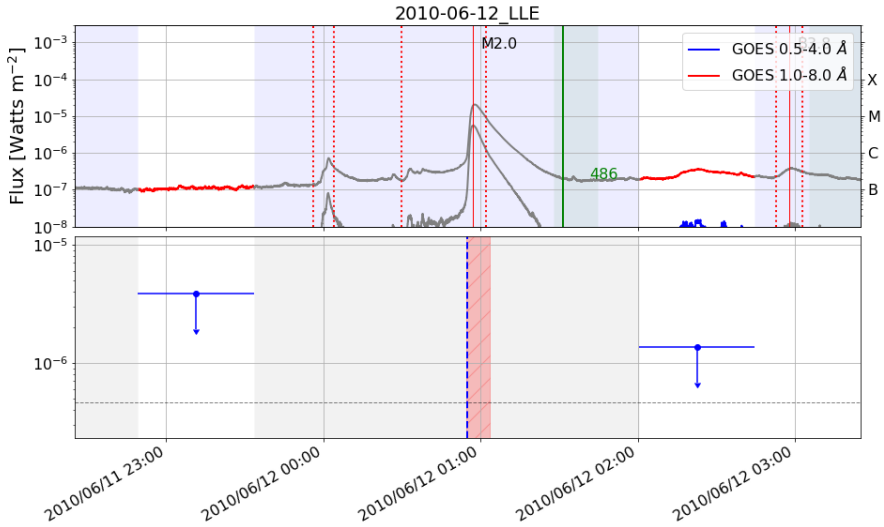


Fermi-LAT Solar Flare (FSF) Catalog contains 45 flares

- 18 with a prompt component synchronized with HXR
- 37 with some delayed component beyond HXR
  - 21 exhibit delayed emission lasting longer than 2 hours
  - 16 exhibit delayed emission lasting less than 2 hours
  - 4 exhibit only delayed emission–no prompt emission detected
- 8 with only a prompt component
- 3 behind the limb

Examples of flare types: Prompt only

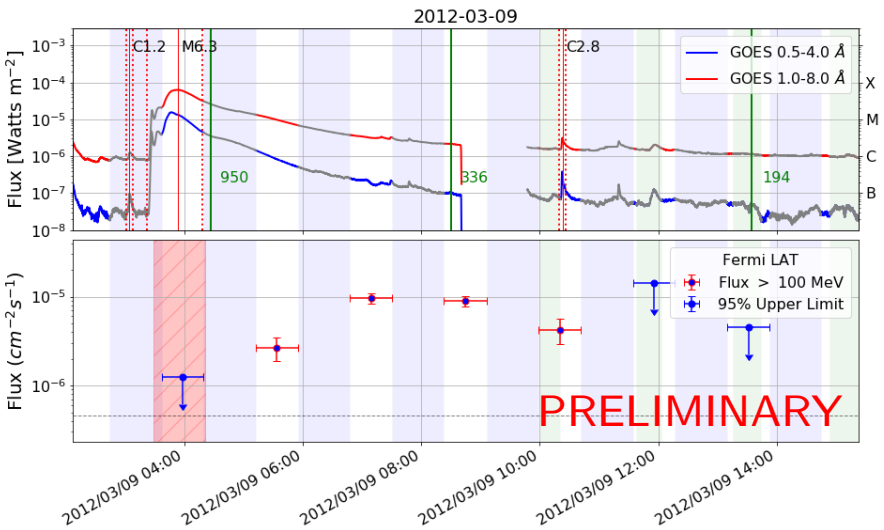


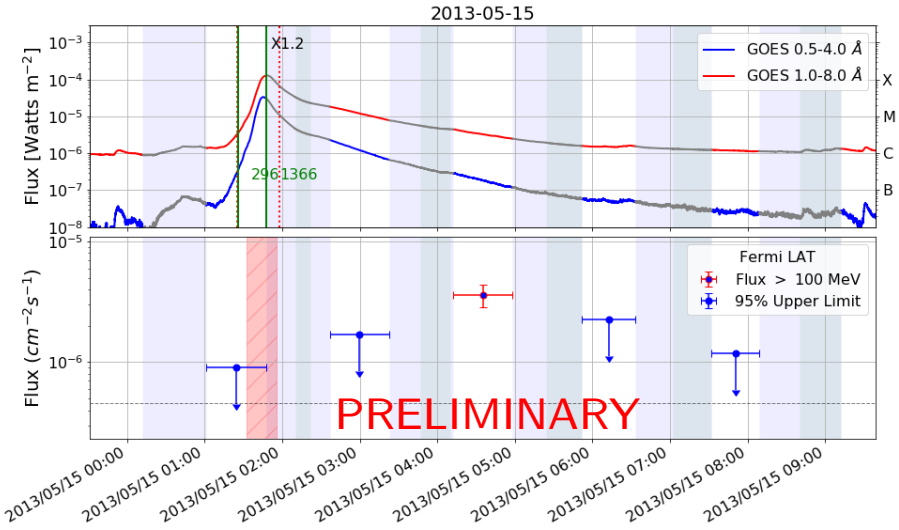


Ackermann et al. 2012ApJ...745..144A

- 8 of the FSF in catalog have only a prompt component
- These are detected either in LLE-only or with the standard likelihood analysis
- We always search in the following windows for any delayed emission

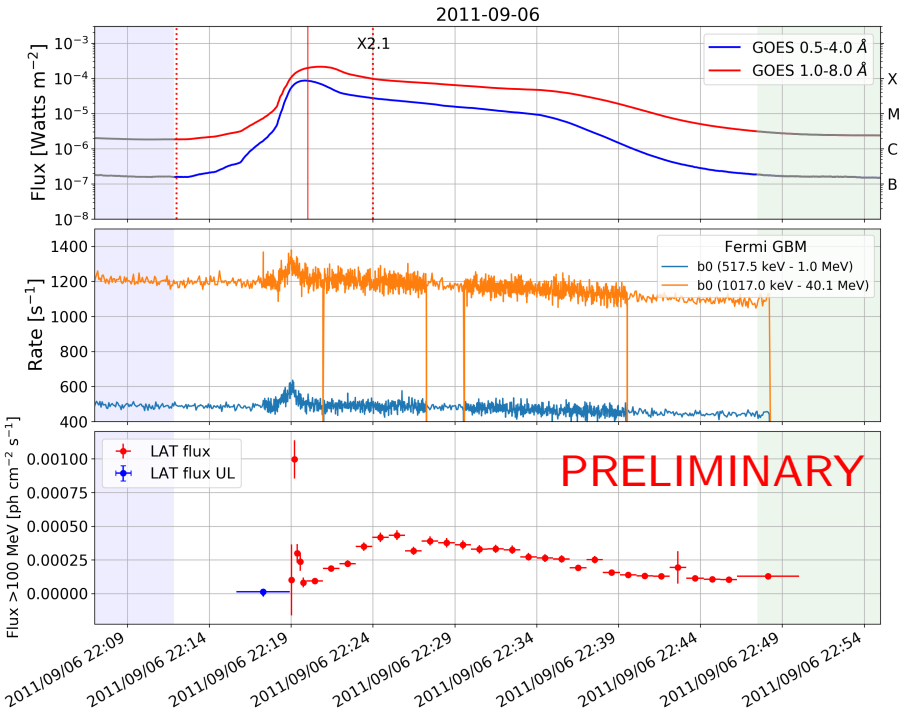
Examples of flare types: Delayed only

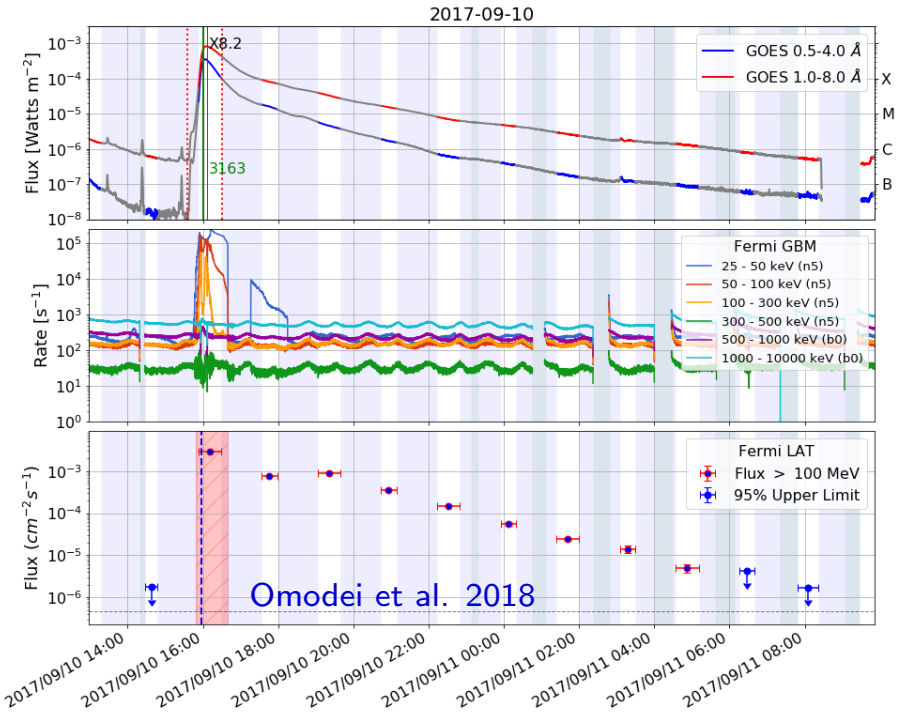




- 4 of the FSF in catalog have no-prompt delayed component, or delayed-only
  - These are the cases where the Sun was in the FoV when the GOES X-ray flare occurred
  - And no >30 MeV emission was observed during the prompt phase
- For most of the FSF with a delayed component the Sun was not in the FoV when the GOES X-ray flare occurred
  - Impossible say if any prompt emission was present or not

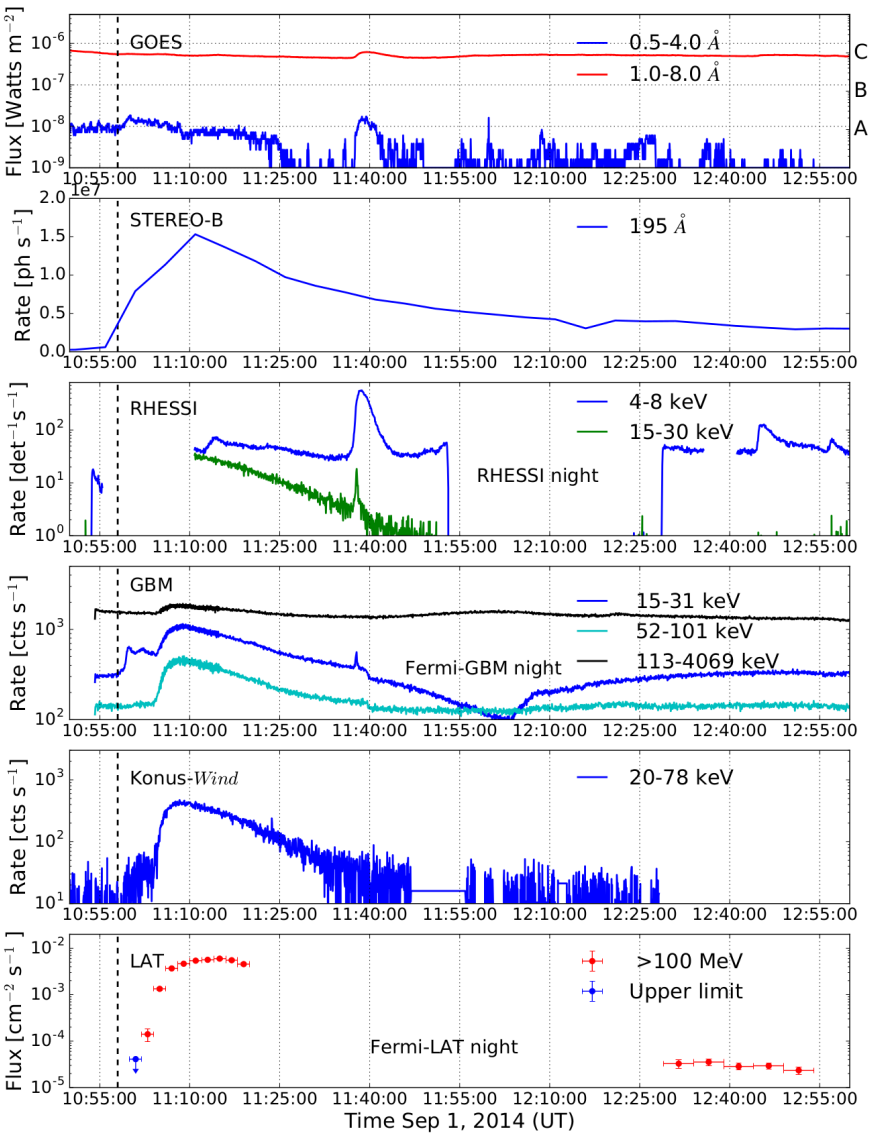
Examples of flare types: Prompt and Delayed





- 10 of the FSF in catalog have a prompt and delayed component
  - These are the cases where the Sun was in the FoV when the GOES X-ray flare occurred
  - And >30 MeV emission was observed during the prompt phase
  - And a delayed component following the prompt phase
- Two types of components observed: short-delayed and delayed

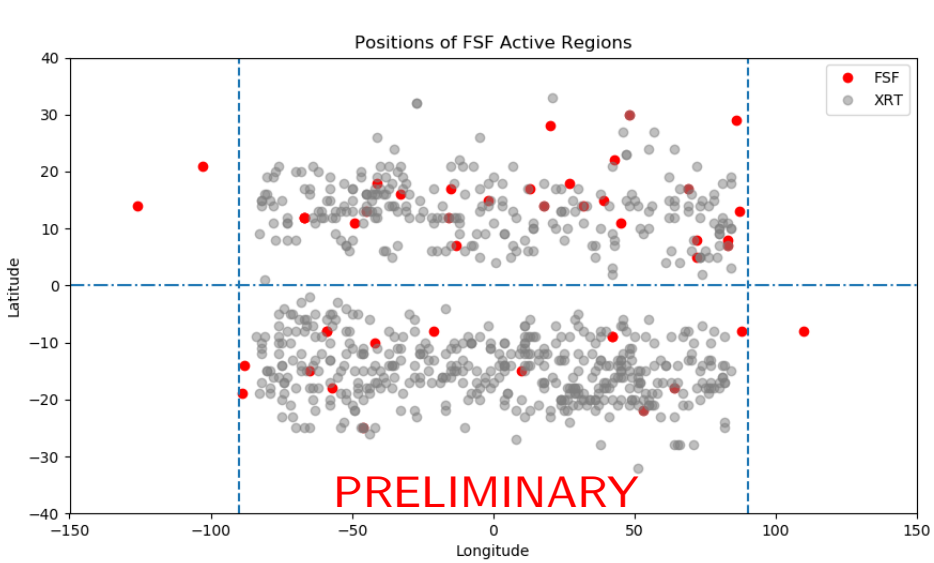
Examples of flare types: Behind-the-limb

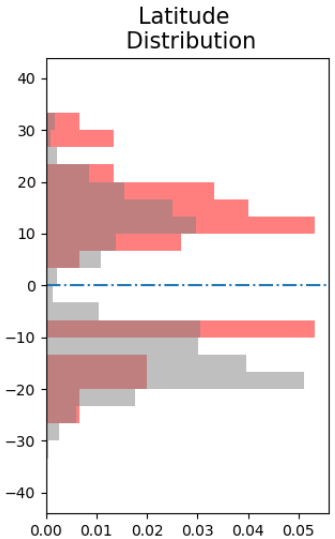


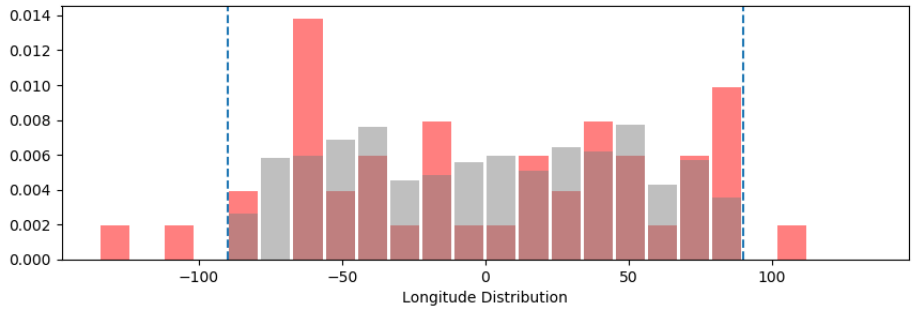
Ackermann et al. 2017

- A total of 3 bind-the-limb flares with emission >100 MeV have been detected with the LAT
- SOL2013-10-11, SOL2014-01-06 and SOL2014-09-01
- Two originated from AR's behind the eastern limb and one behind the western
  - Distances ranging from 10° to ∼40° degrees behind the limb
- >100 MeV emission lasting up to 2 hours!
- Suggesting the need for a spatially extended component to aid the accelerated particles to the visible disk

AR positions



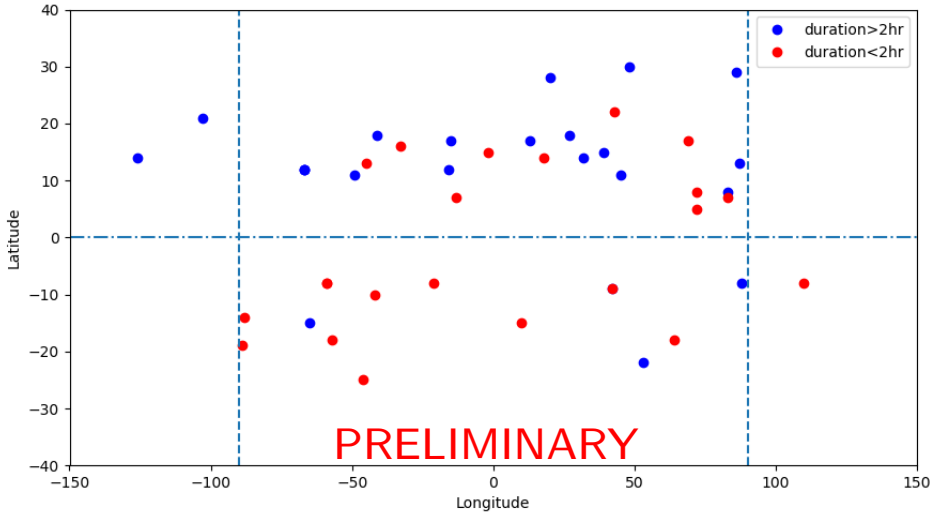


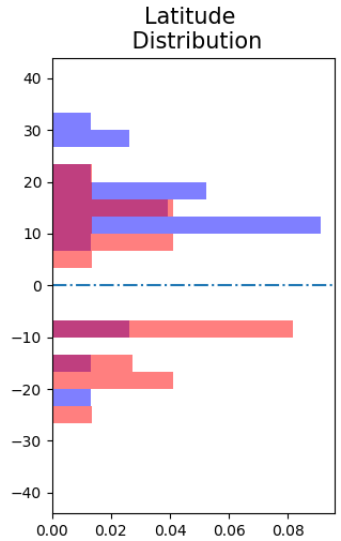


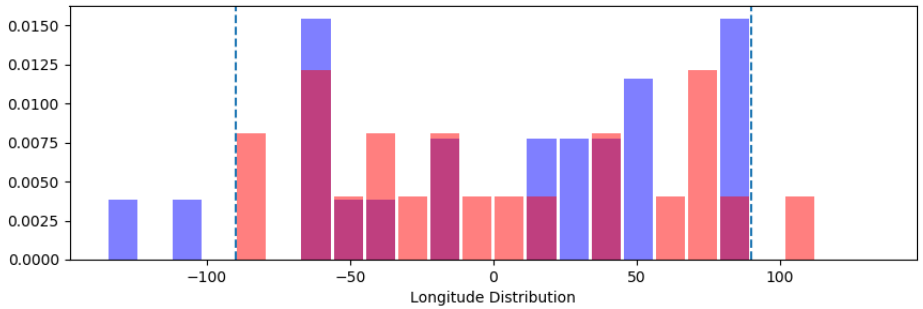
- FSF flares:
  North: 64% South: 36%
- XRT flares:
  North: 38% South: 62%

- FSF have the opposite trend as seen for the XRT detected M/X class flares
- CMEs also have similar distribution, i.e. predominately from northern heliosphere

AR positions: delayed flares



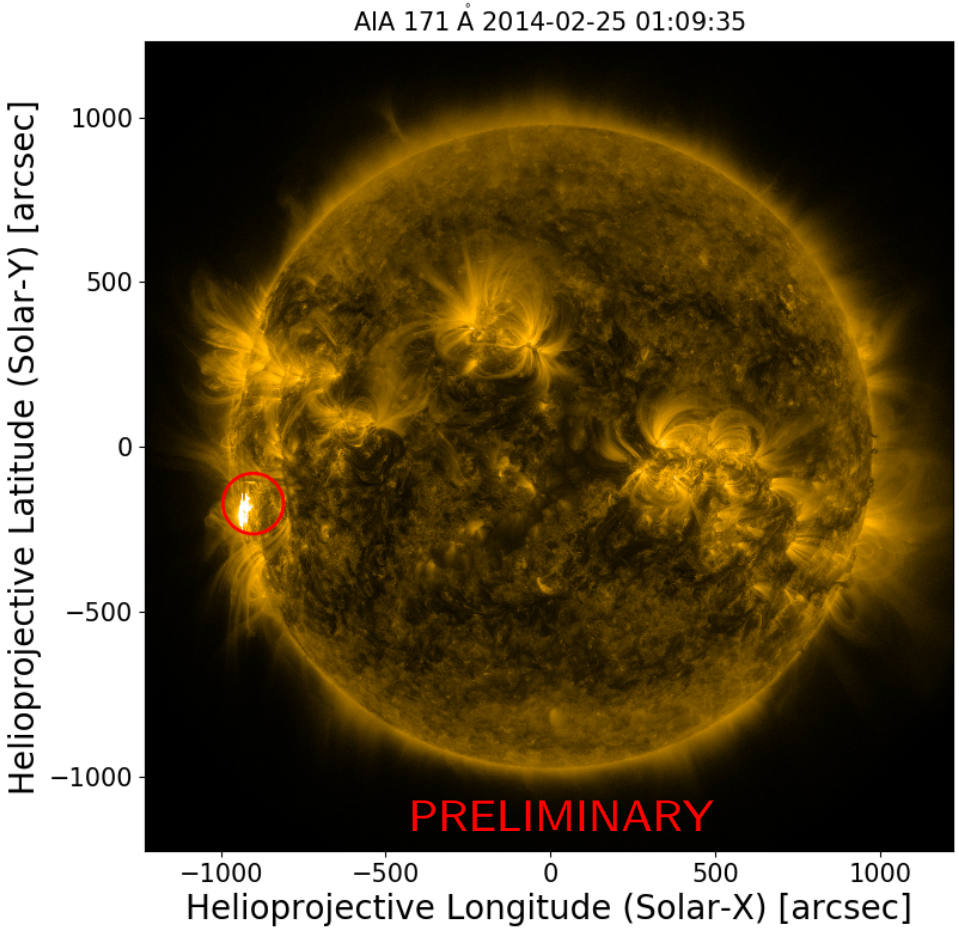




- Duration >2 hrs:
  North: 80% South: 20%
- Duration <2 hrs:
  North: 50% South: 50%

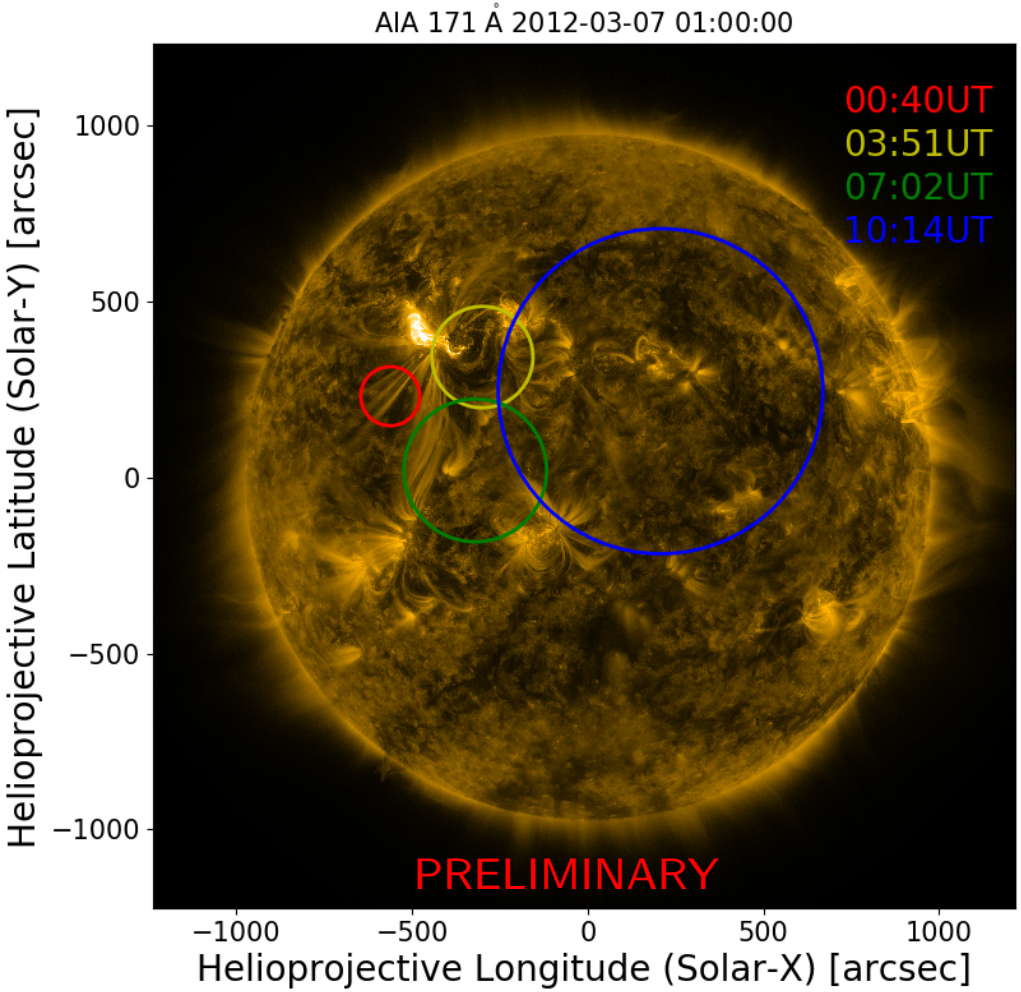
- FSF flares with emission lasting more than 2 hours are preferentially associated with AR in the northern heliosphere
- FSF flares with emission lasting less than 2 hours are evenly distributed over the heliosphere

Localization of the gamma-ray emission



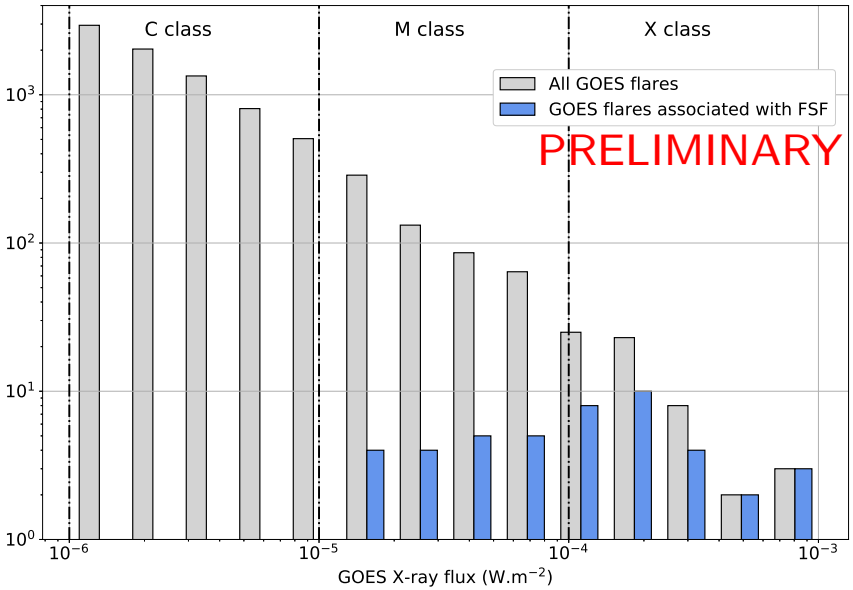
- 8 of the FSF have localization with a 68% uncertainty $\leq 360''$
- 3 of these flares were bright enough to have localization in multiple windows
- 2 flares originated from AR's behind-the-limb
- 5 flares originated from AR's from the eastern quadrant
- 3 flares originated from AR's from the western quadrant

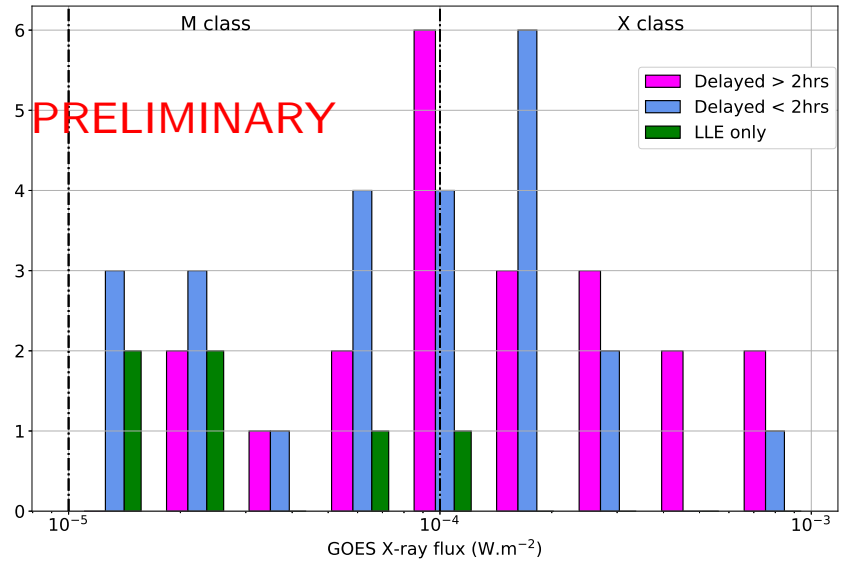
Localization of the gamma-ray emission



- SOL20120307, SOL20140225 and SOL20170910 were bright enough to have localization results in multiple windows
- The emission centroids of SOL20120307 illustrate an east-west movement across the solar disk with time
- SOL20140225 did not show any movement across the disk
- SOL20170910 was on the western limb so not possible to detect any movement

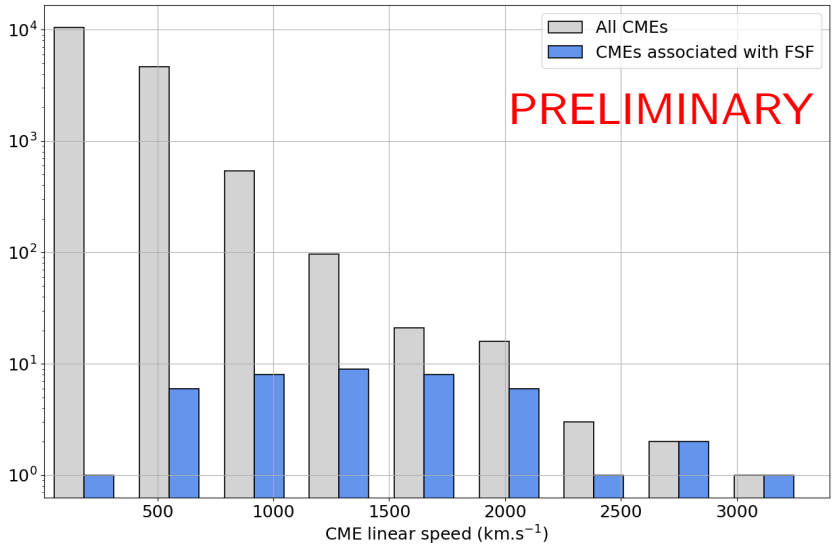
FSF GOES X-ray characteristics

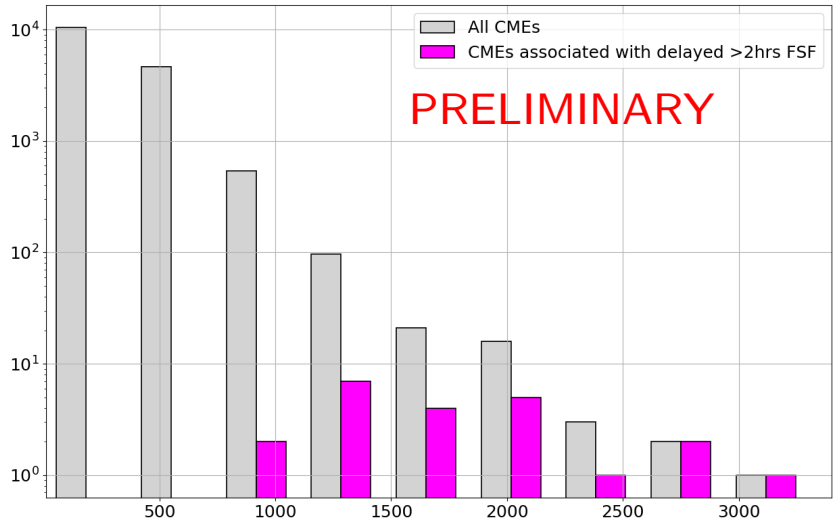




- FSF in the catalog associated with both M and X-class GOES flares
  - Gamma-ray emission >100 MeV more common that previously thought
- Prompt-only flares predominately associated with weaker GOES flares

Connection with CMEs

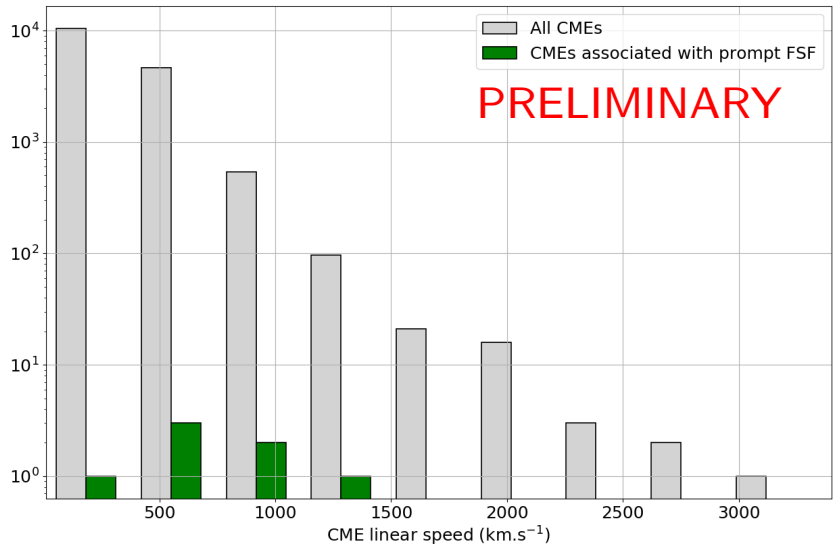




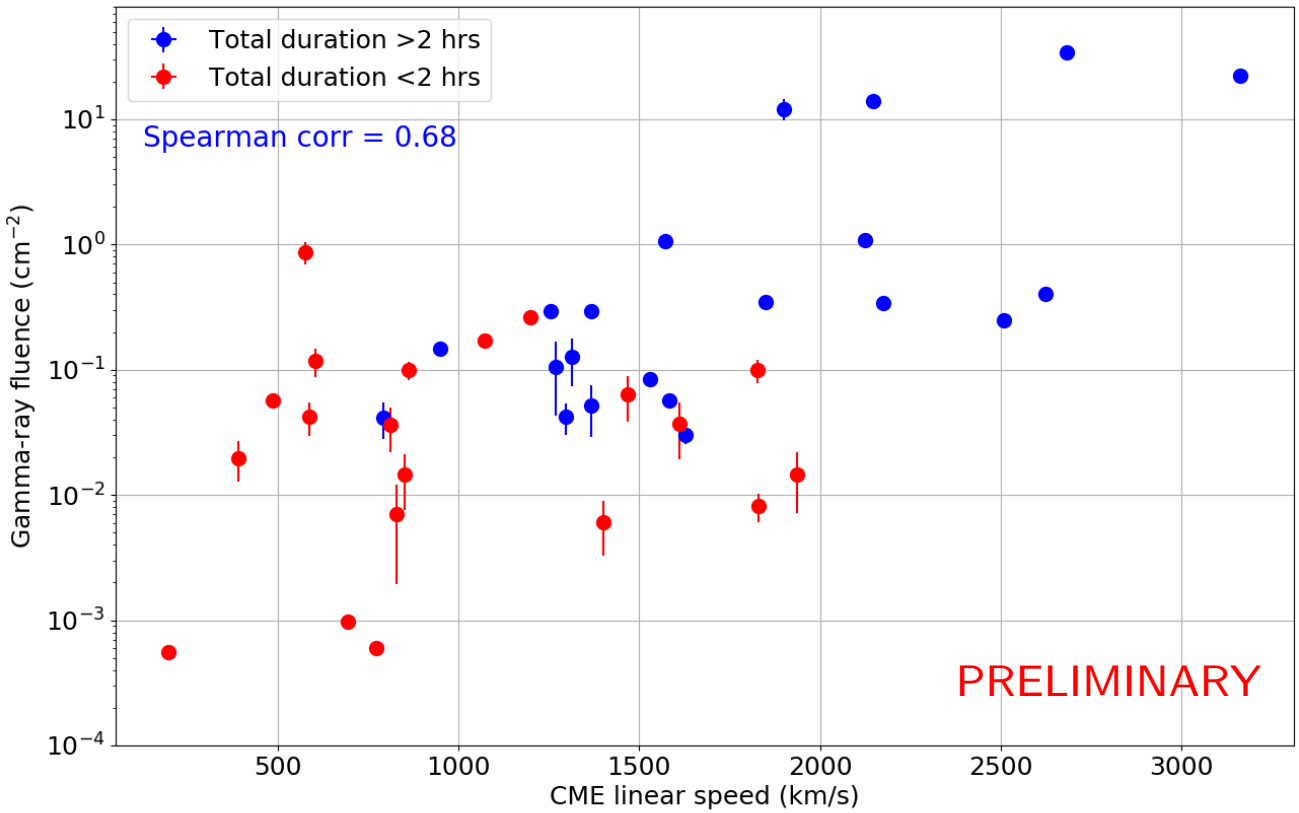
Only 3 FSF in the catalog are not associated with a CME.

Mean Speeds for

- All CMEs = 342 km/s
- All FSF = 1388 km/s
- FSF delayed >2 hours = 1766 km/s
- FSF prompt = 656 km/s

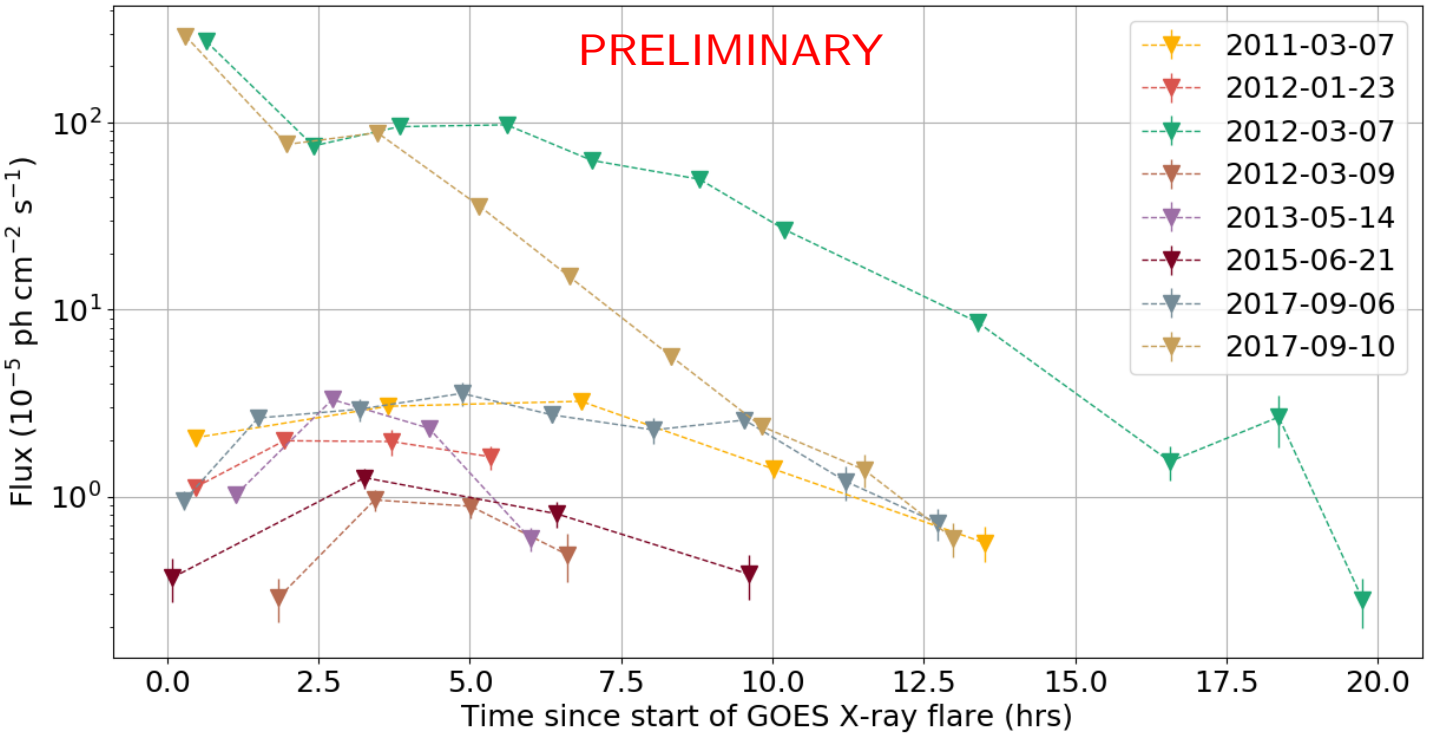


Delayed flares characteristics



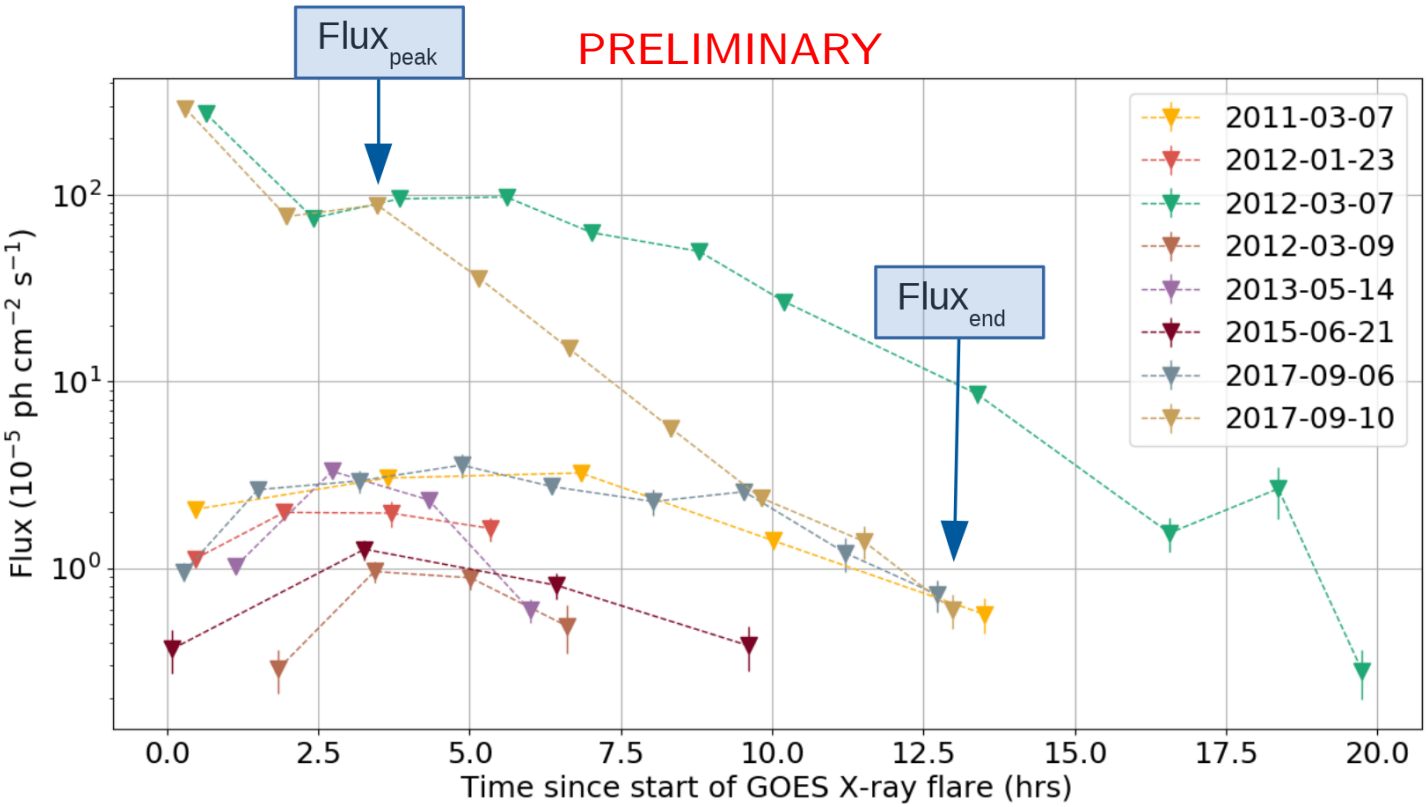
- >100 MeV fluence for all the FSF in the catalog versus the CME speed
- FSF with delayed emission lasting more than 2 hrs show a positive correlation with CME speed

Delayed flares characteristics



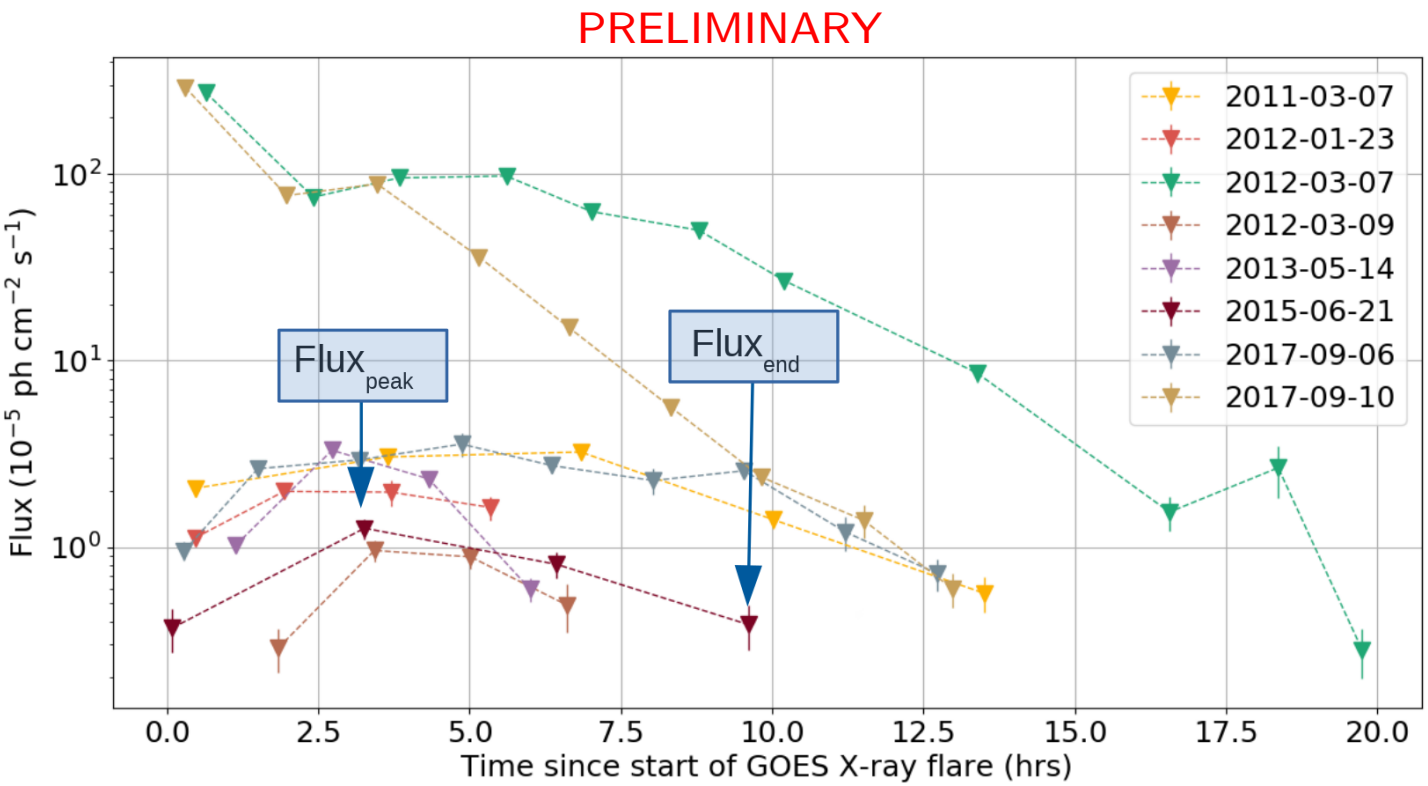
- FSF in the catalog with a detection in 4 or more *Fermi*-LAT observing windows
- Fluxes for all flares show the *rise-and-fall* behavior with time
- Peak flux values span up to two orders of magnitude

Delayed flares characteristics



- Change in flux from peak to end vs the change in time varies dramatically from flare to flare
- No connection with the GOES X-ray flare class

Delayed flares characteristics



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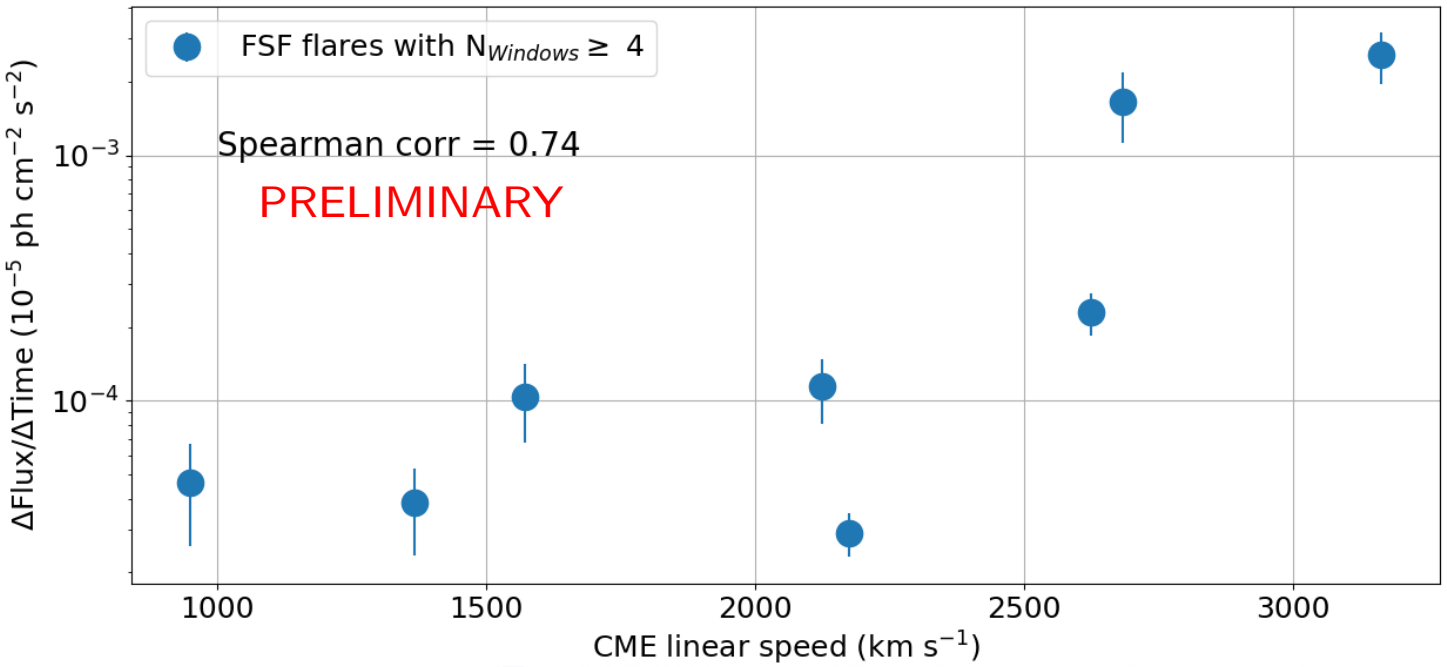
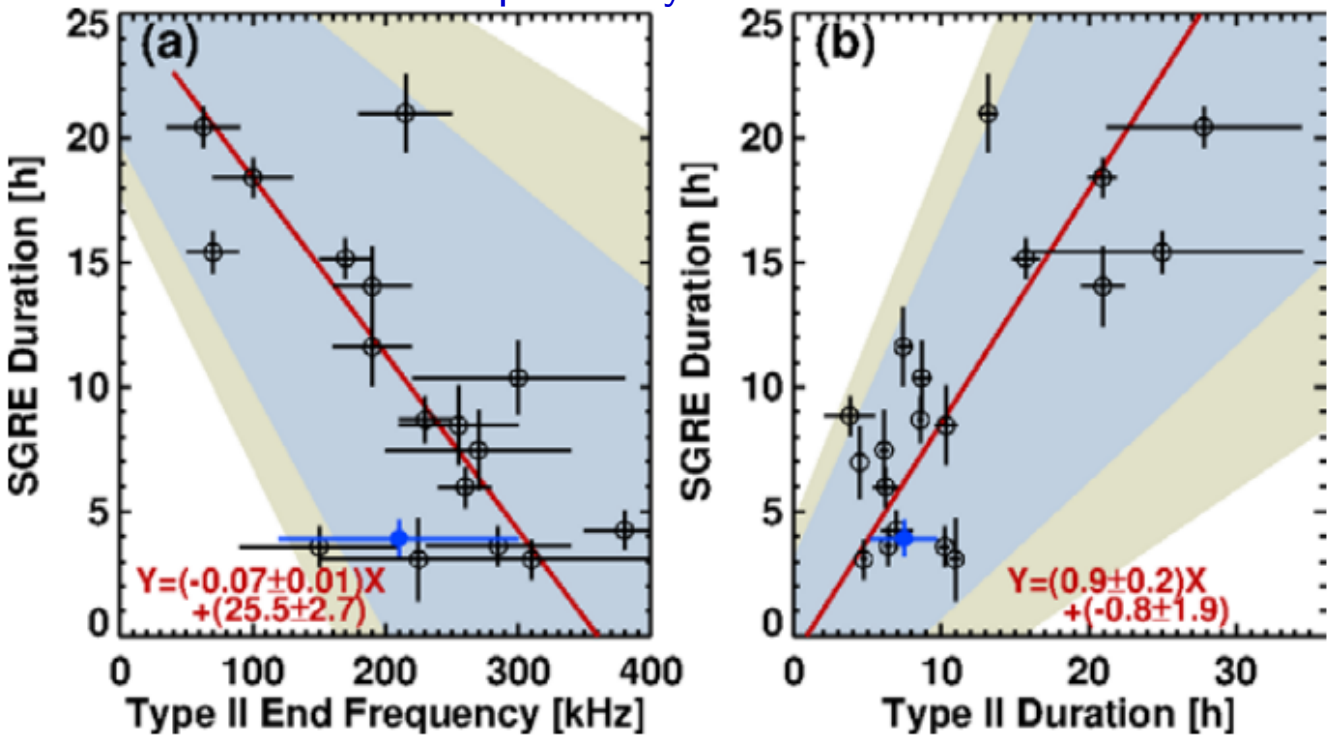
Delayed flares characteristics



- The change in flux over the change in time from peak to end versus CME speed
- Positive correlation found between these two quantities
  - The faster the CME the faster the flux drops with time from the peak

Relationship with Type II bursts

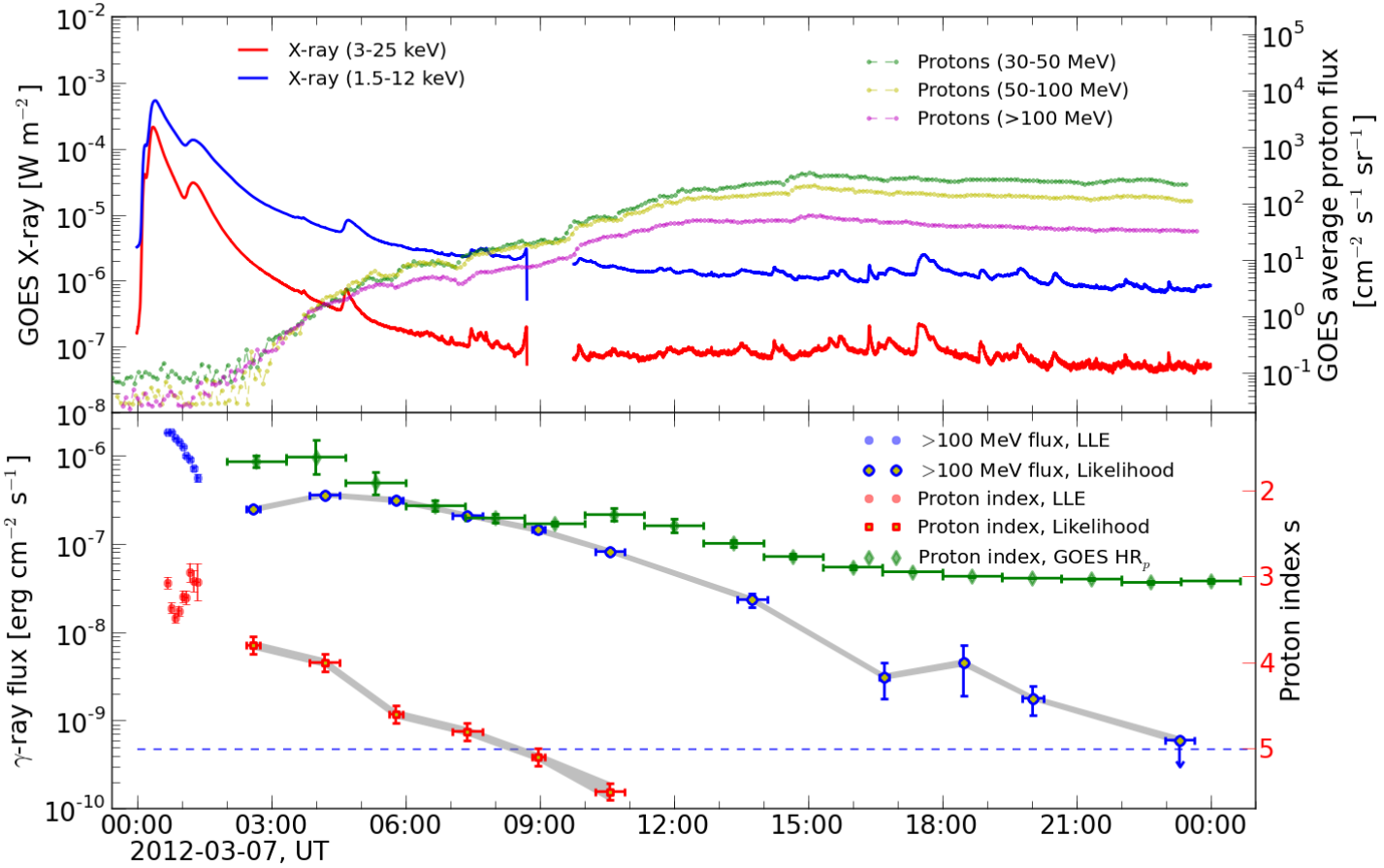
Gopalswamy et al. 2018



- Linear relation between Type II duration and LAT delayed emission
  - Also between the Type II ending frequency and LAT duration
- Strong support that same shock accelerates electrons to produce type II bursts and protons (>300 MeV) that propagate from the shock to the solar surface to produce SGRE via pion decay

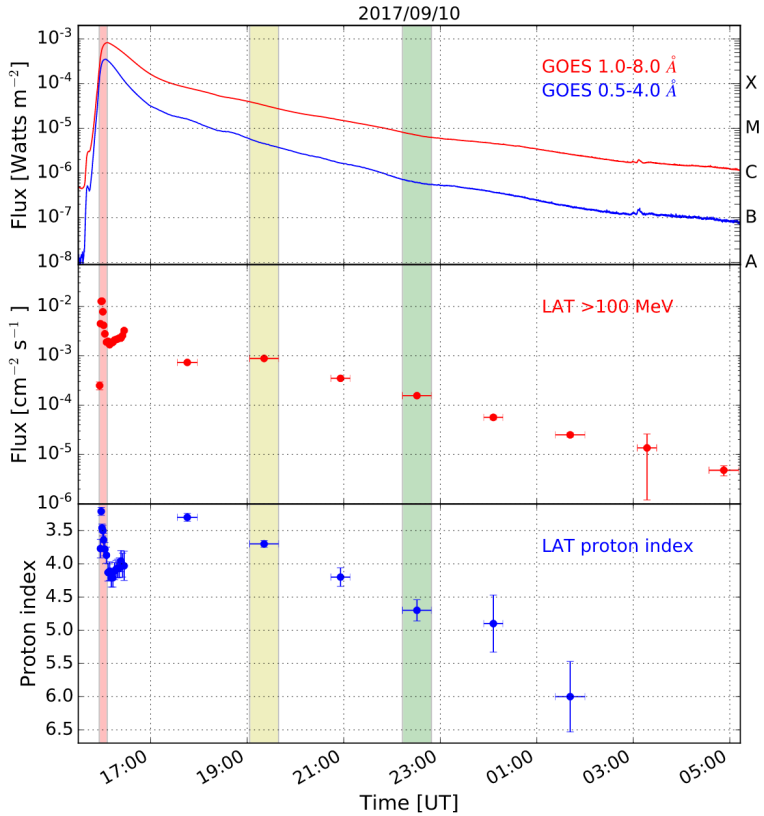
Inferred proton properties

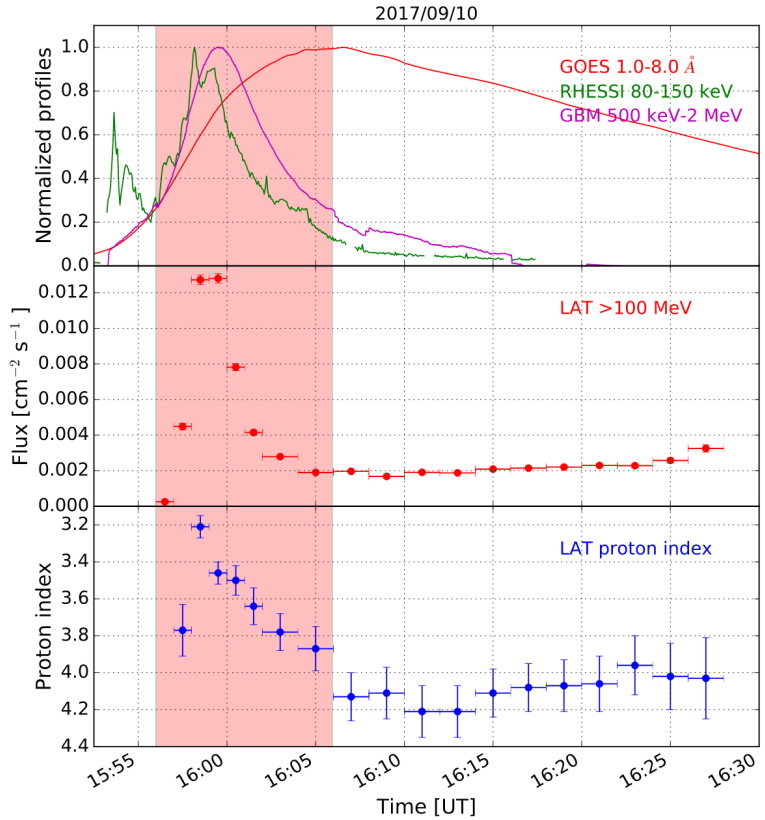
Ajello et al. 2014ApJ...789..20



- Multiple X class flares and fast CMEs
- >100 MeV emission lasted for more than 20 hr
- Proton index evolution softens with time as the flux dimmens

Inferred proton properties

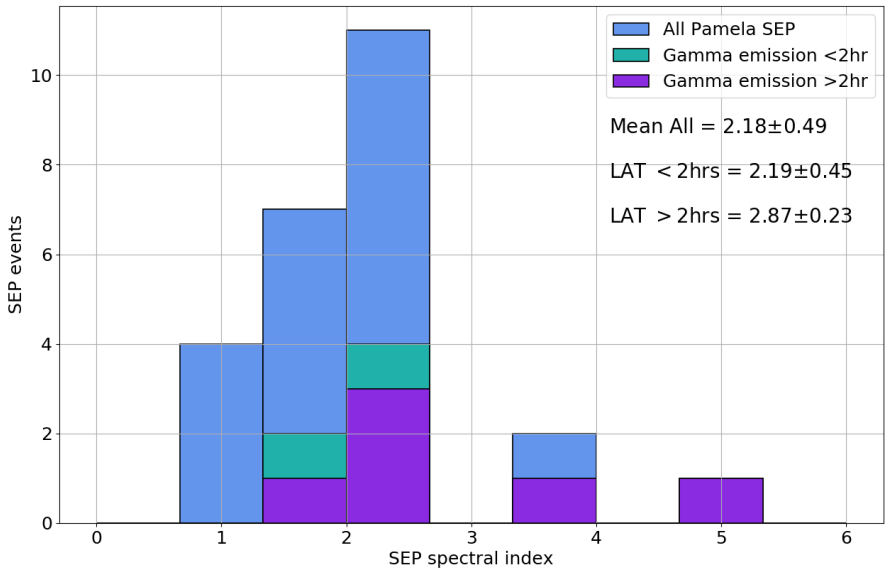


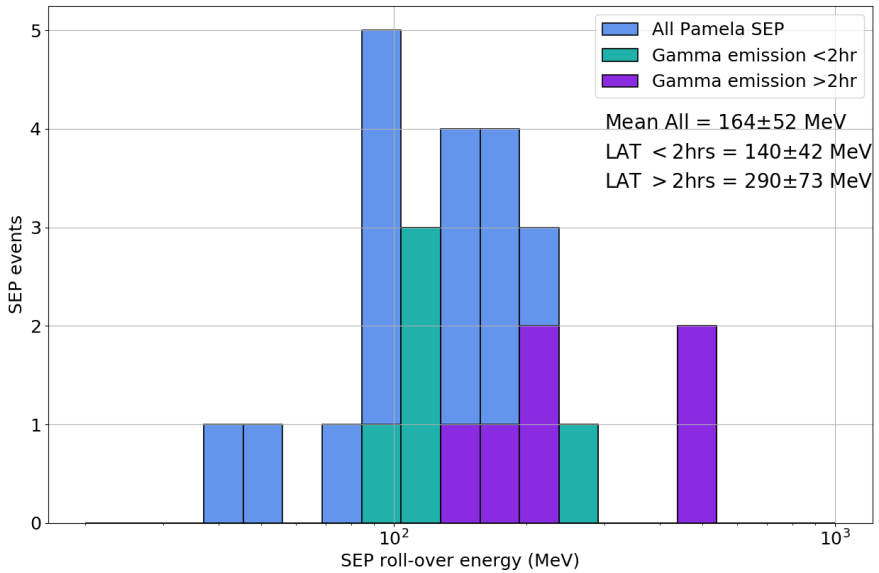


Omodei et al. 2018ApJ...865L...7O

- GOES X8.2 class flare associated with GLE72
- >100 MeV emission lasted for more than 12 hr
- Data suggests multiple phases in proton index evolution with time
  - Both *prompt* and *delayed* phases observed for this flare

SEP PROPERTIES





SEP data from Bruno et al. 2018

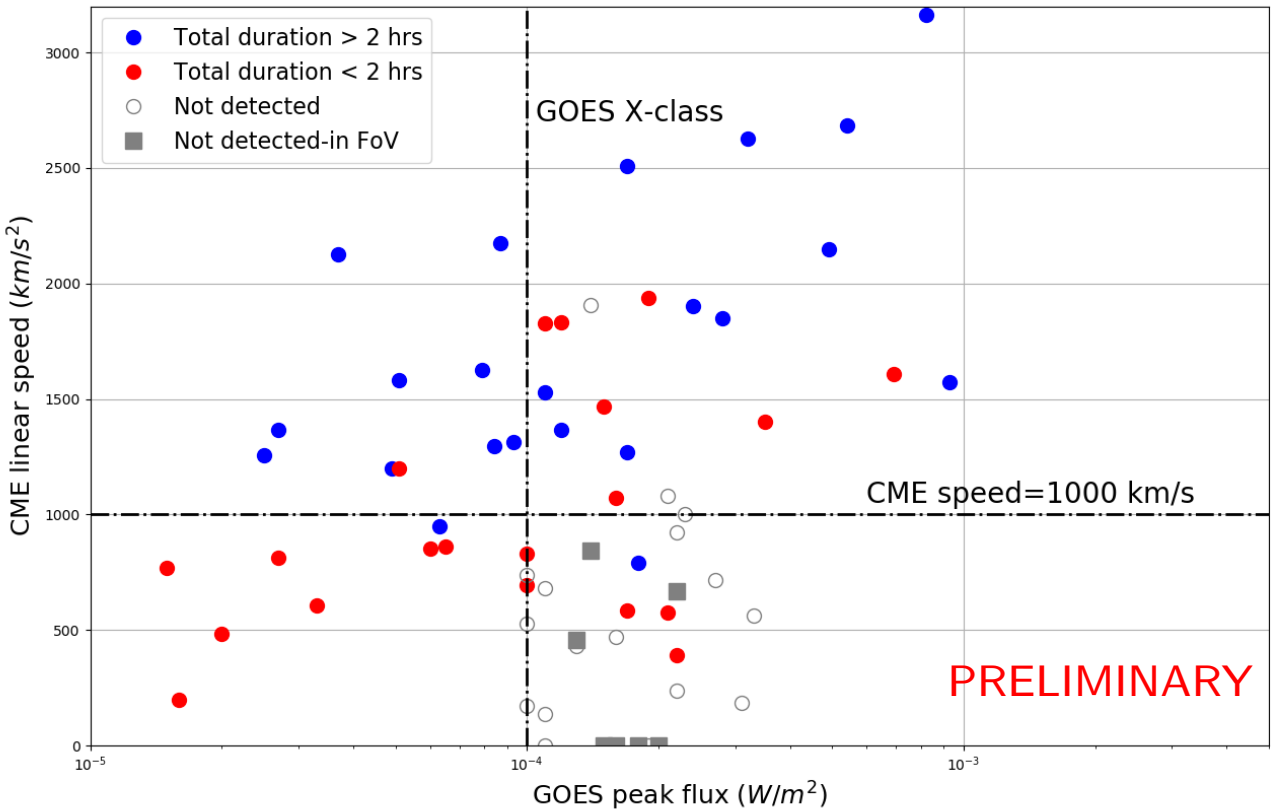
SEP events detected by PAMELA from 2011-2014

- All SEP events with fluence above 1 GeV were LAT gamma-ray flares
- SEP events coincident with LAT flares with emission lasting >2 hrs have softer spectral index and higher roll-over energies
  - Similar to the values for GLE and sub-GLE events
- What ever is driving the GLE/sub-GLE SEPs is also driving the high-energy gamma-ray flares

Flares not detected by the LAT?

- Looked at all the X-class GOES flares of the 24th Solar cycle
  - Cross checked if they were detected by *Fermi*-LAT
  - If not then investigated the properties of the flare
- There were 49 X-class flares
- 24 are associated to FSF
- Out of the 25 not detected by the LAT
  - Only 7 were in the field of view during the prompt phase
  - And these 7 were all associated with slow CMEs (or not at all)
  - Providing support for the need of a fast CME to produce a delayed gamma-ray flare
  - Question still remains as to why the prompt emission was not detected

FSF CHARACTERISTICS



- Only 3 of the 25 non-detected X-class flares had CME speed >1000 km/s
- Marginal LAT detection for flare with CME speed 1905 km/s in following observing windows

Summary

- The First *Fermi*-LAT Solar flare catalog has a total 45 flares with emission >30 MeV
  - Wide variety of types of flares
  - Two distinct phases observed: *prompt* and *delayed*
  - The data suggests that there are at least two acceleration mechanisms driving these phases
- Prompt emission observed during on-disc flares suggests acceleration at the flare site
  - LAT emission is correlated with flare associated non-thermal signature
- Correlation with CME speed stronger for the *delayed* flux than with the *prompt* supporting acceleration at the CME shock scenario
  - Relationship with Type II burst duration/ending frequency also supportive
  - Behind-limb-flares also suggest the need for a spatially extended component to bring the accelerated particles to the visible disk
  - All but one of the GOES X-class flares not detected by the LAT were associated with slow CMEs