Fermi Large Area Telescope observations of the flaring Sun: The first ten years

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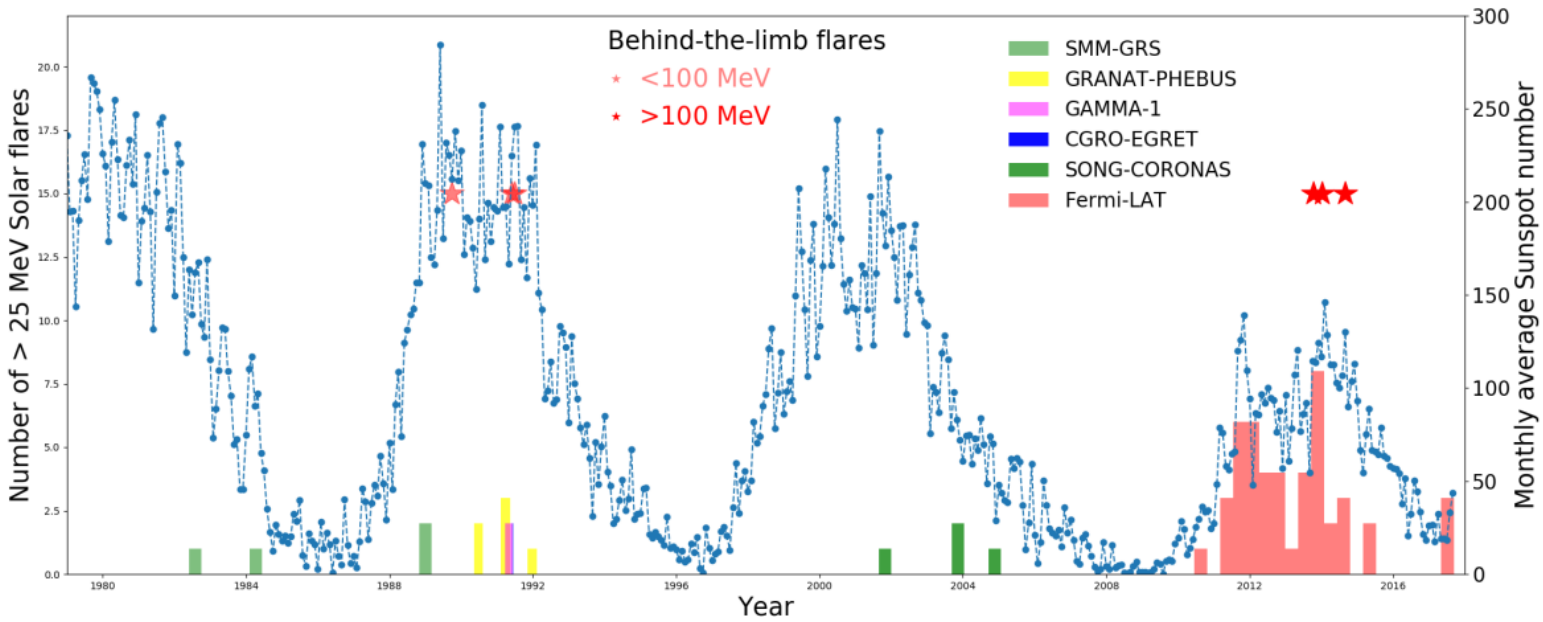
on behalf of the *Fermi*-LAT collaboration

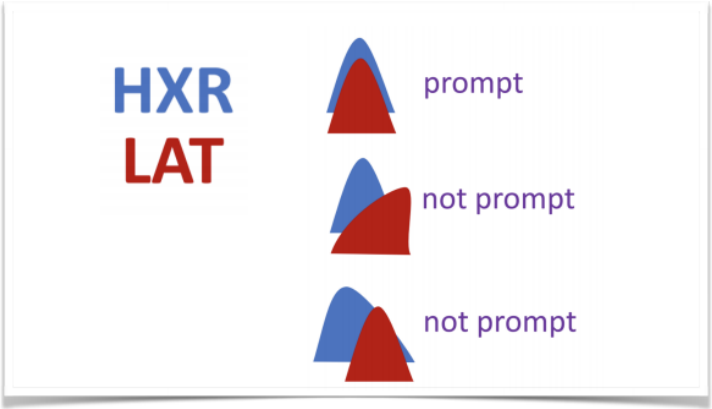
Konus-Wind 2019

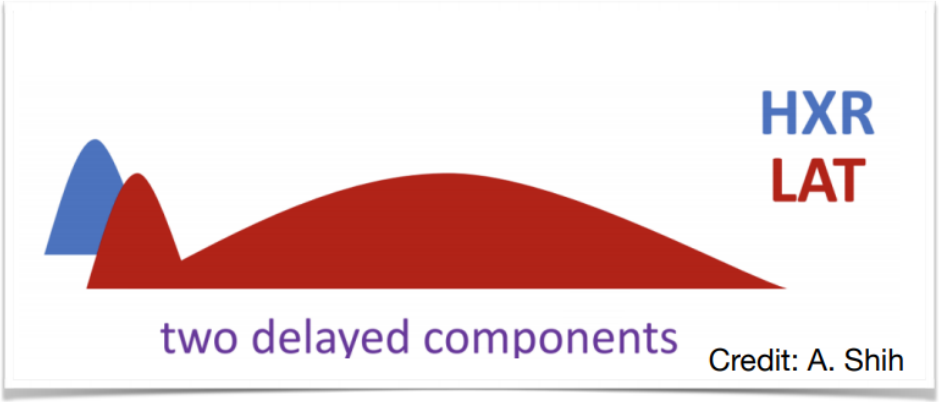
Fermi-LAT as a Solar observatory



- Fermi-LAT is by no means a Solar observatory!
  - On average the Sun is in the field of view (FoV) only 40% of the orbit
- Nonetheless the number of > 30 MeV γ-ray flares has drastically increased after the launch of Fermi
  - First detection of >100 MeV emission from behind-the-limb flares
  - Extended >100 MeV emission for more than 20 hours
  - Wide sampling of M-class flares

Categories of Fermi LAT Solar Flares (FLSF)

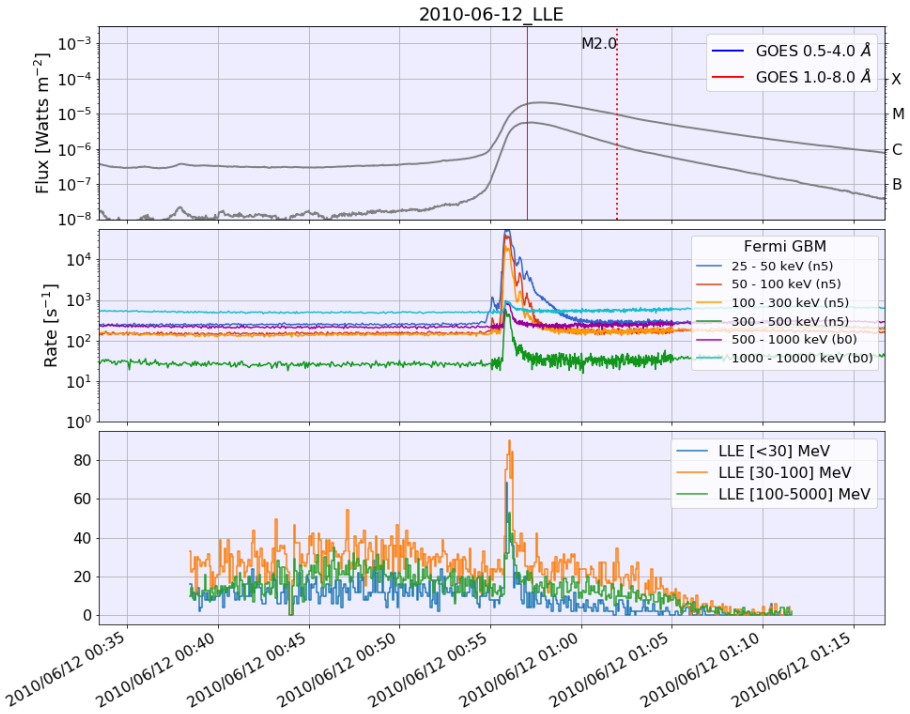


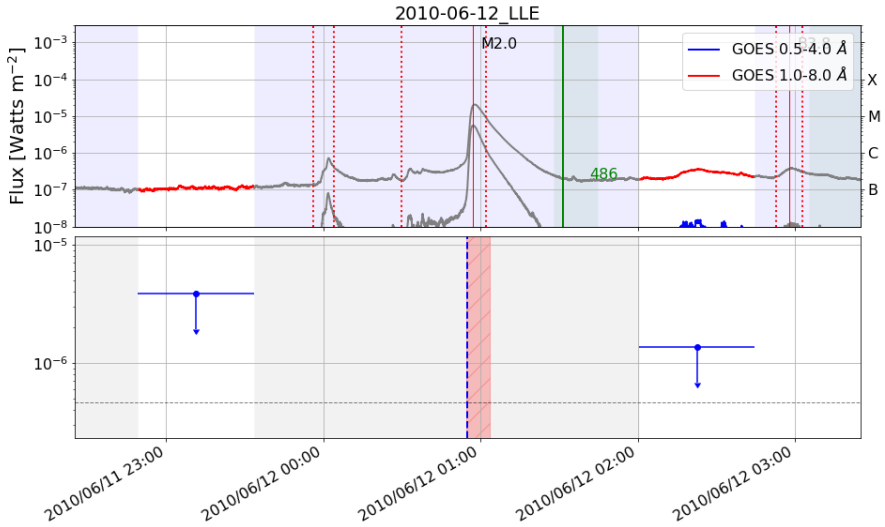


Fermi-LAT Solar Flare (FSF) Catalog contains 45 flares

- 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

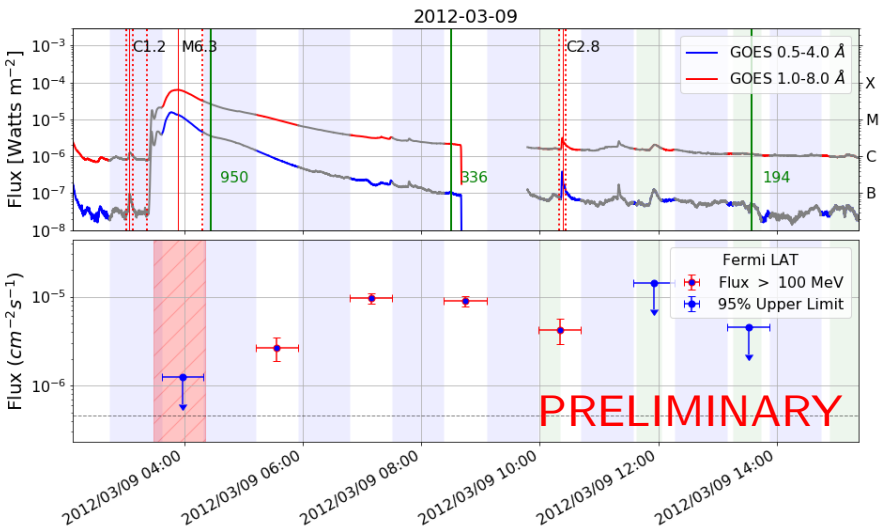


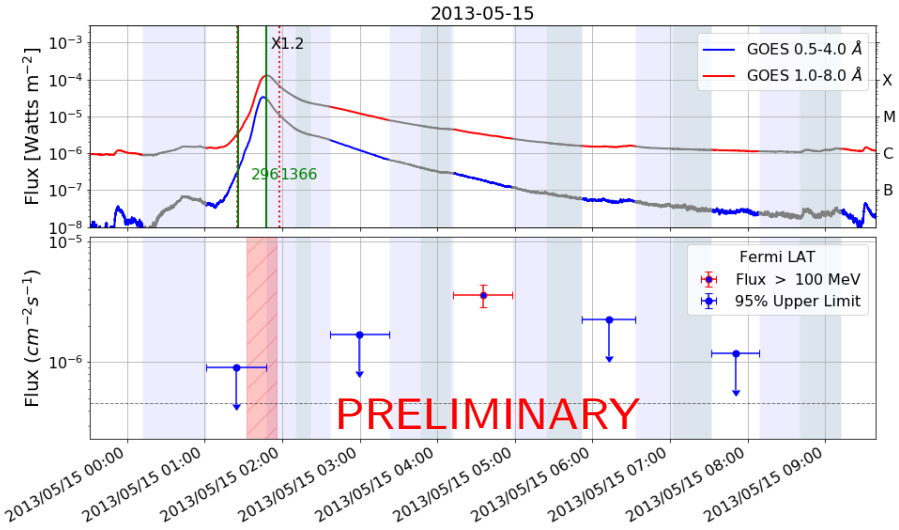


Ackermann et al. 2012

- 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

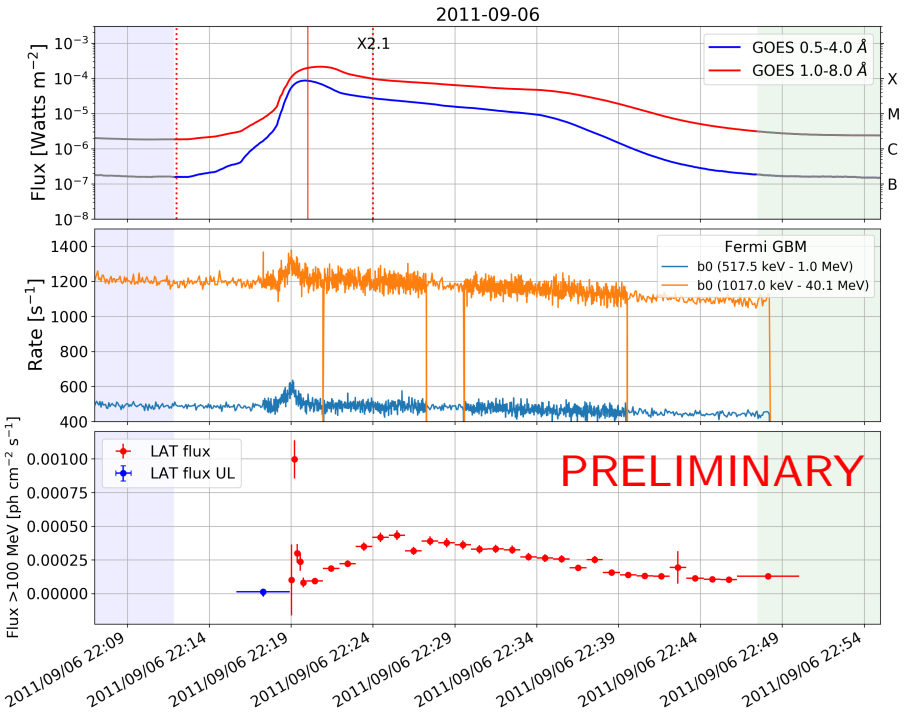
Examples of flare types: Delayed only

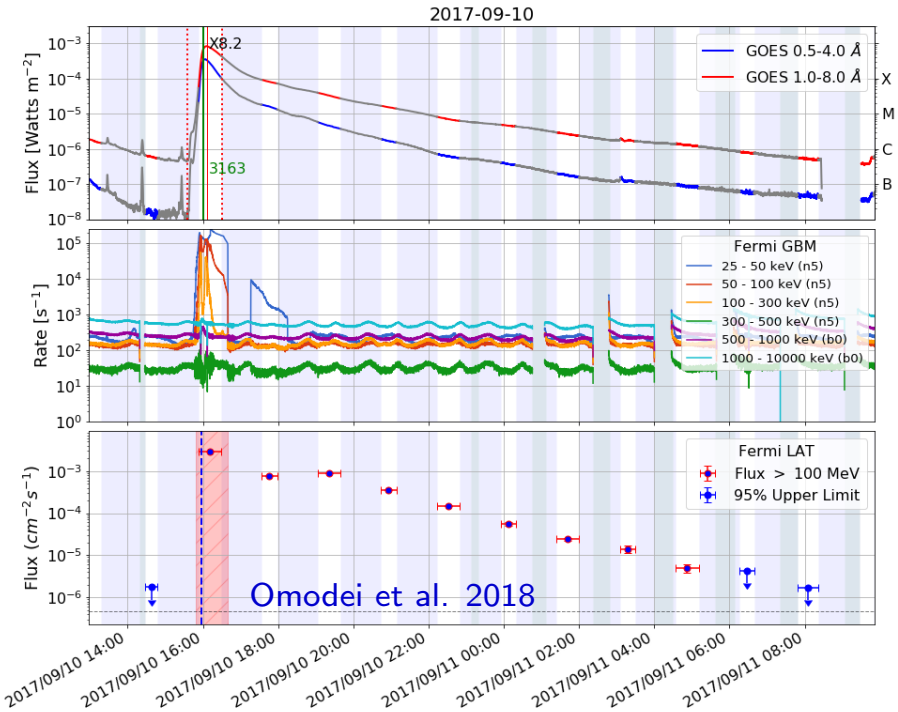




- 4 of the FSF in catalog have no-prompt delayed component, or delayed-only
  - These are the cases where the Sun was in the FoV when the GOES X-ray flare occurred
  - And no >30 MeV emission was observed during the prompt phase
- For most of the FSF with a delayed component the Sun was not in the FoV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

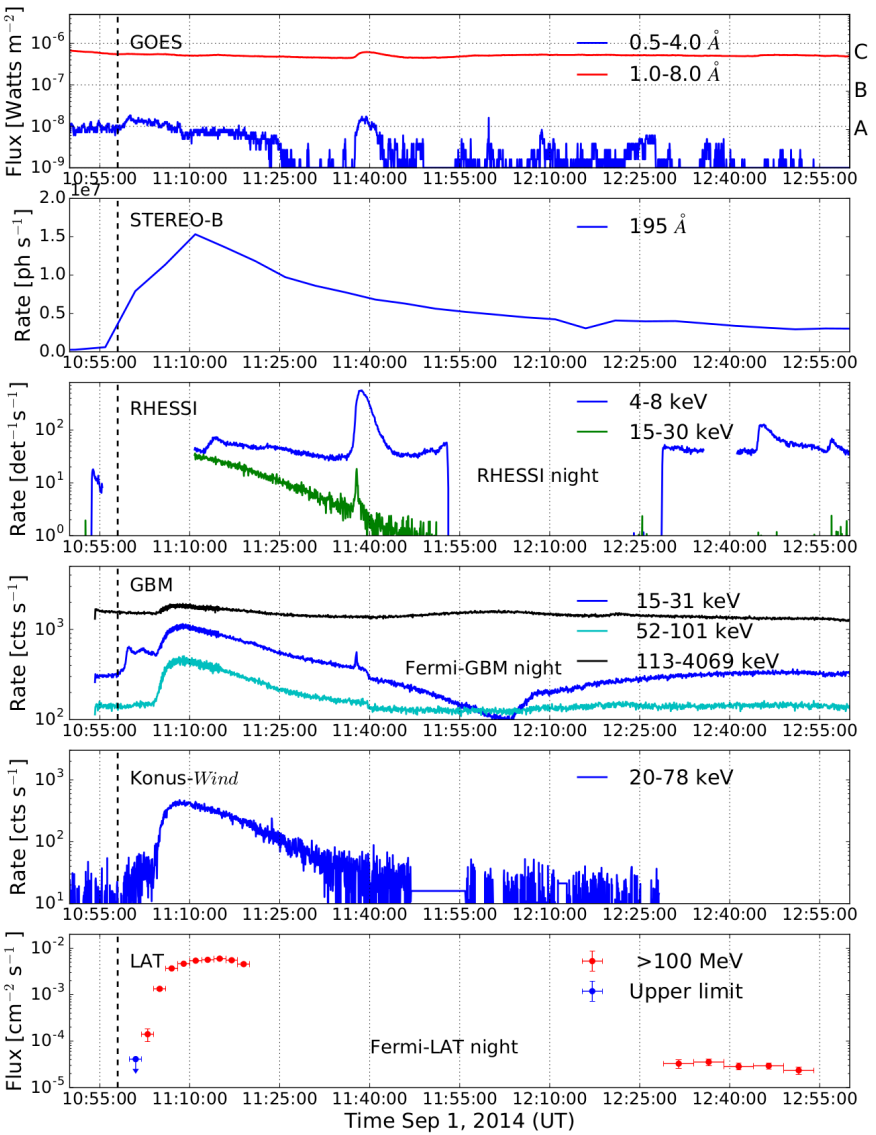
Examples of flare types: Prompt and Delayed





- 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

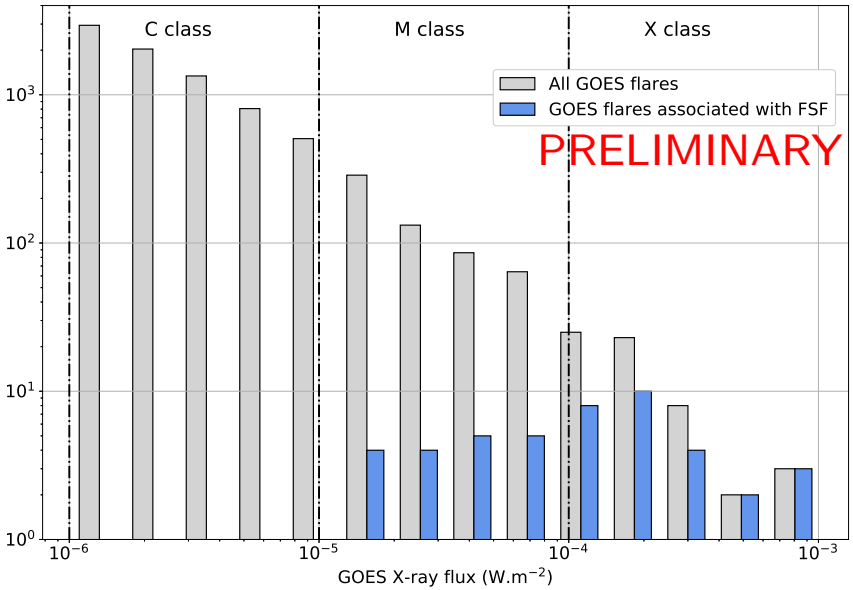
Examples of flare types: Behind-the-limb

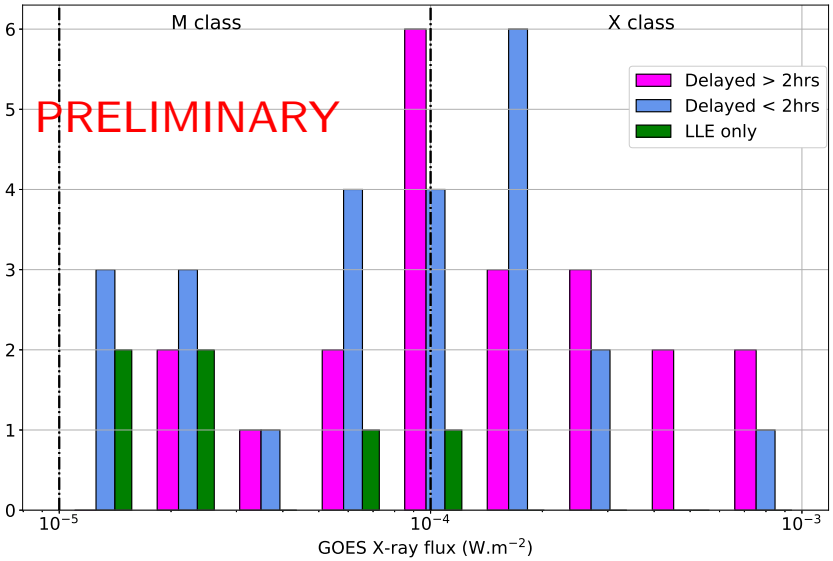


Ackermann et al. 2017

- 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

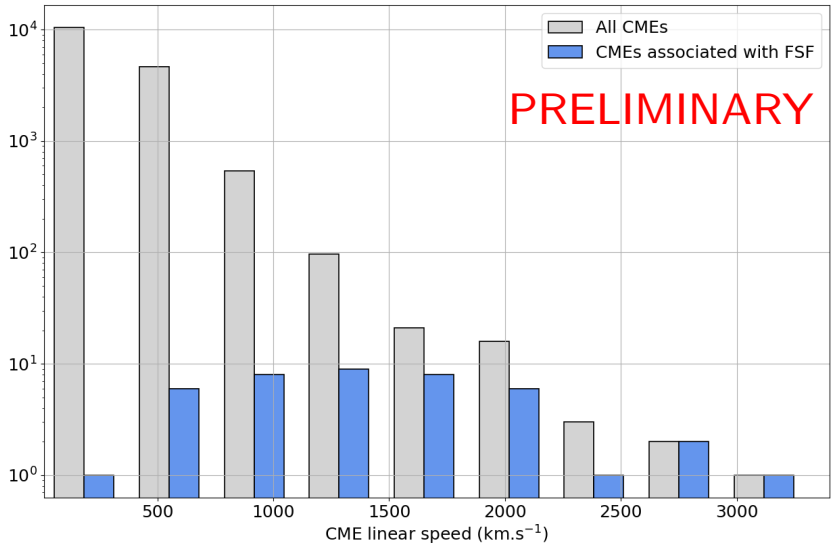
FSF GOES X-ray characteristics

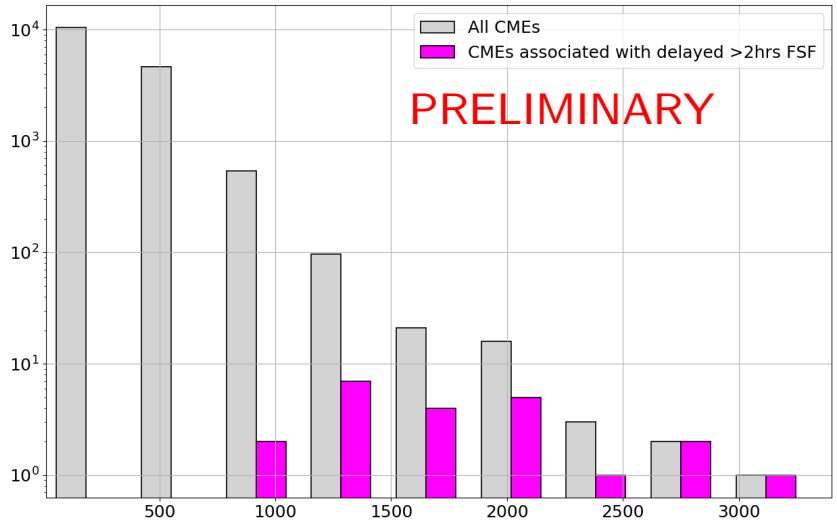




- FSF in the catalog associated with both M and X-class GOES flares
  - Gamma-ray emission >100 MeV more common that previously thought
- Prompt-only flares predominately associated with weaker GOES flares

Connection with CMEs

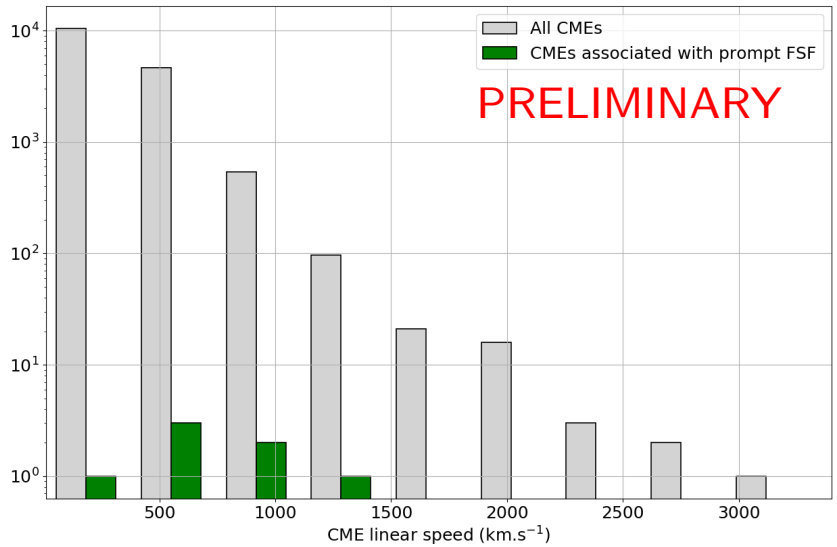




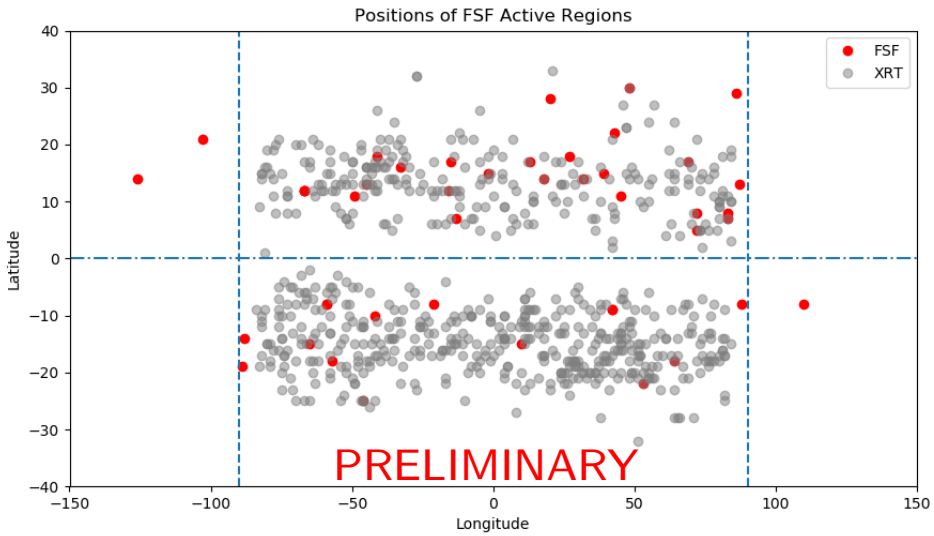
Only 3 FSF in the catalog are not associated with a CME.

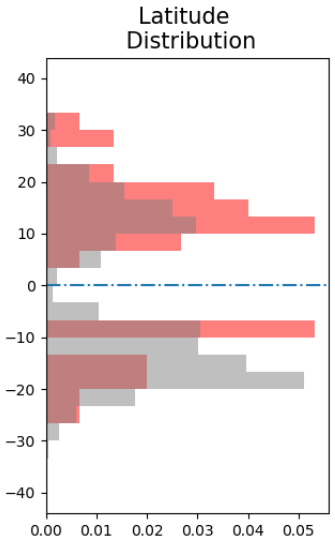
Mean Speeds for

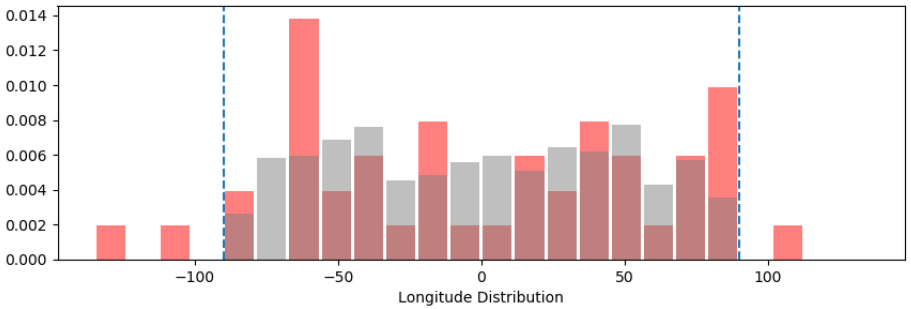
- All CMEs = 342 km/s
- All FSF = 1388 km/s
- FSF delayed >2 hours = 1766 km/s
- FSF prompt = 656 km/s



AR positions



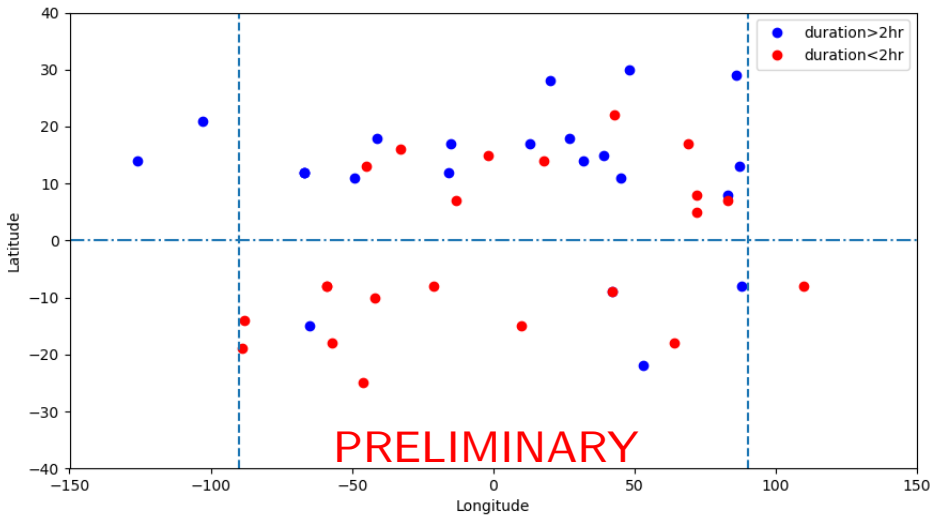


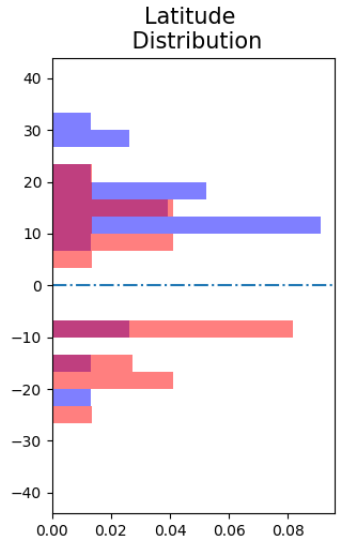


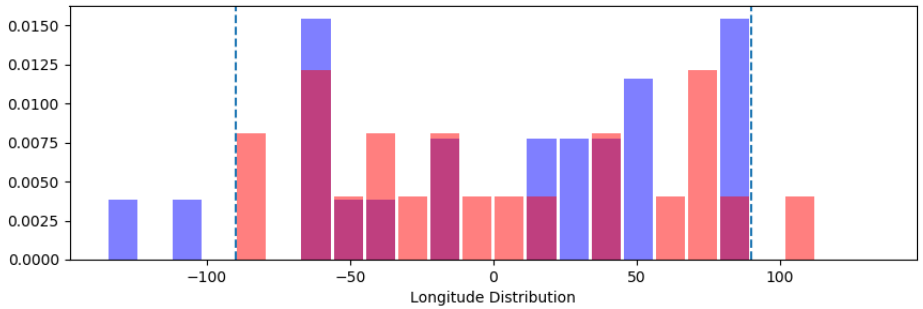
- FSF flares:
  North: 64% South: 36%
- XRT flares:
  North: 38% South: 62%

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

AR positions: delayed flares



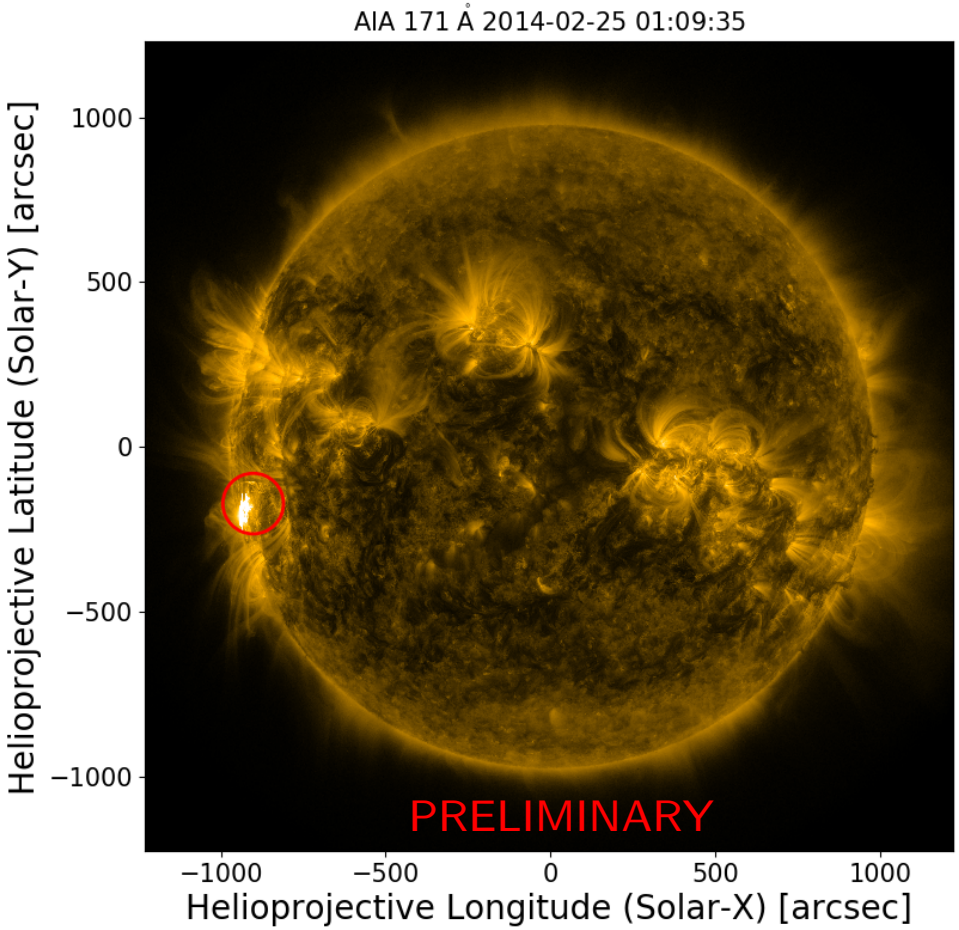




- Duration >2 hrs:
  North: 80% South: 20%
- Duration <2 hrs:
  North: 50% South: 50%

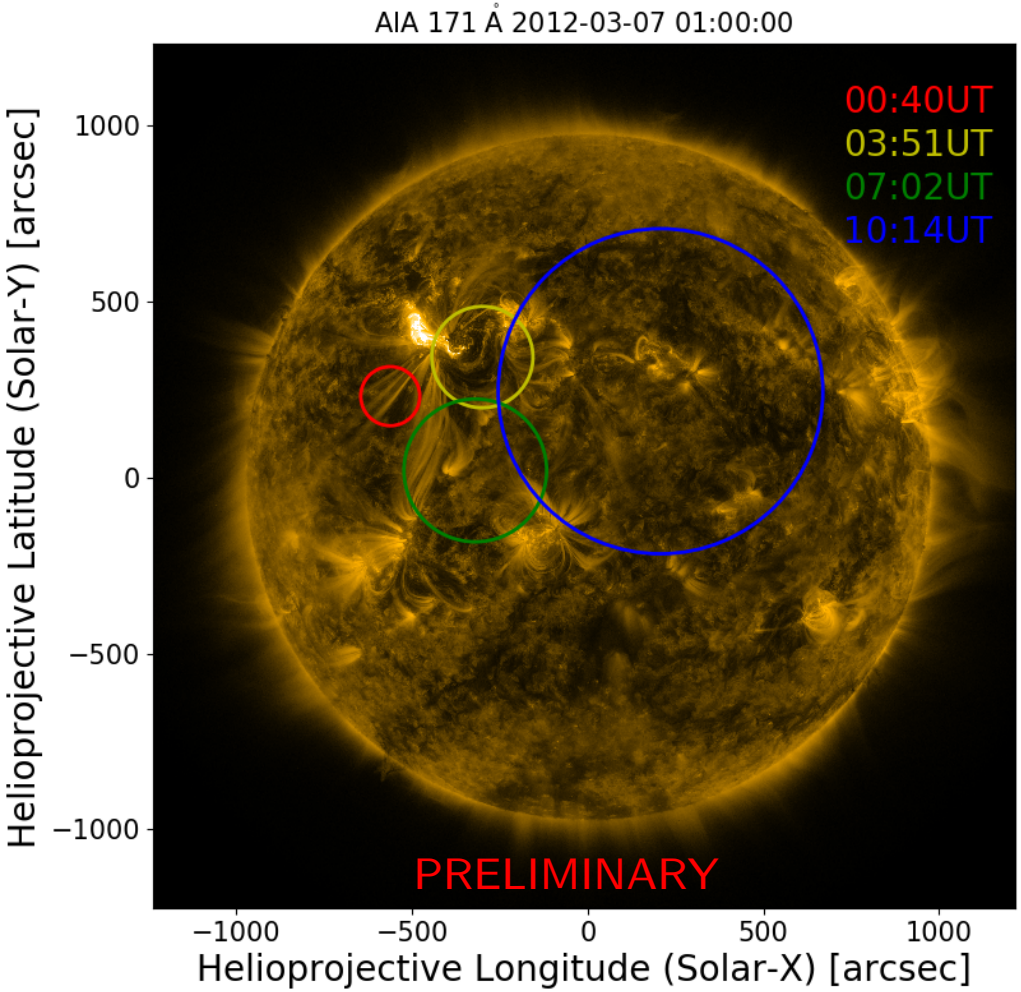
- FSF flares with emission lasting more than 2 hours are preferentially associated with AR in the northern heliosphere
- FSF flares with emission lasting less than 2 hours are evenly distributed over the heliosphere

Localization of the gamma-ray emission



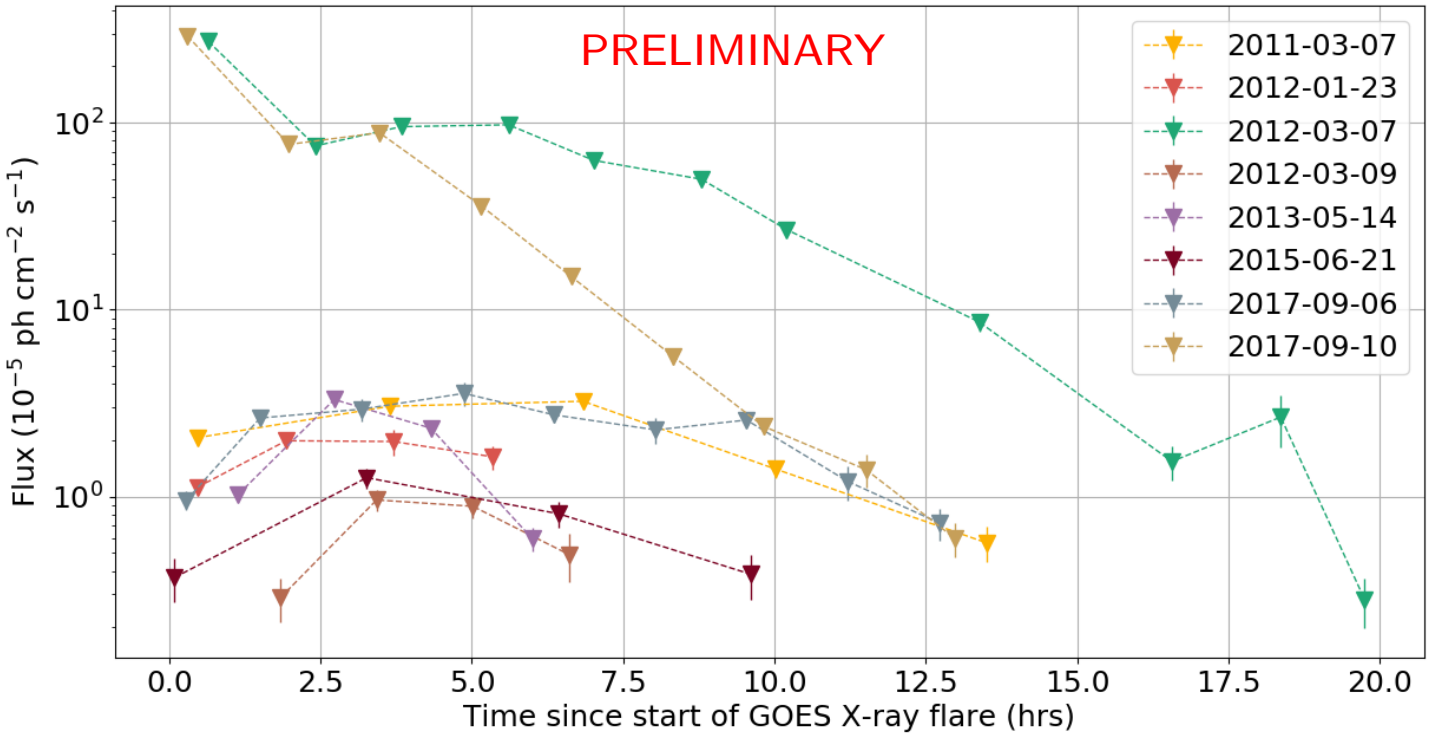
- 8 of the FSF have localization with a 68% uncertainty $\leq 360''$
- 3 of these flares were bright enough to have localization in multiple windows
- 2 flares originated from AR's behind-the-limb
- 5 flares originated from AR's from the eastern quadrant
- 3 flares originated from AR's from the western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

Localization of the gamma-ray emission



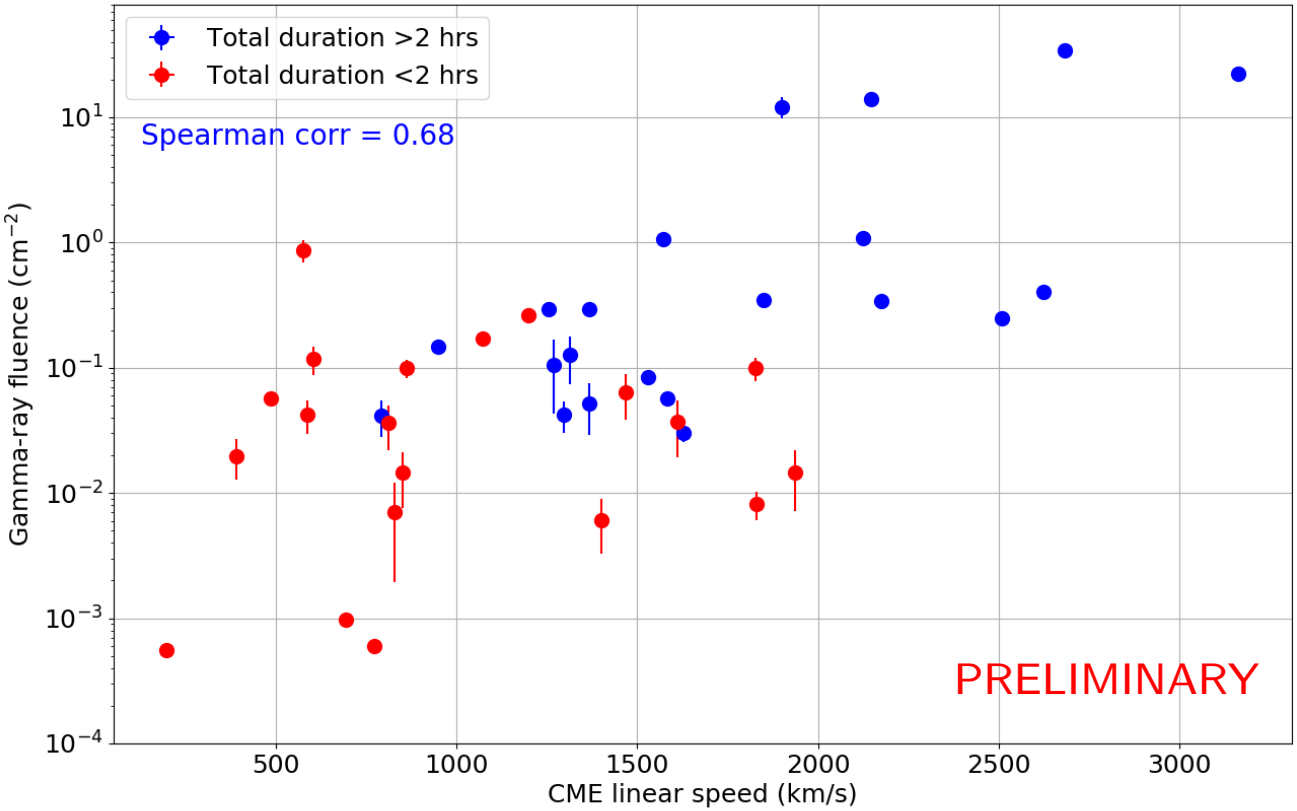
- SOL20120307, SOL20140225 and SOL20170910 were bright enough to have localization results in multiple windows
- The emission centroids of SOL20120307 illustrate an east-west movement across the solar disk with time
- SOL20140225 did not show any movement across the disk
- SOL20170910 was on the western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

Delayed flares characteristics



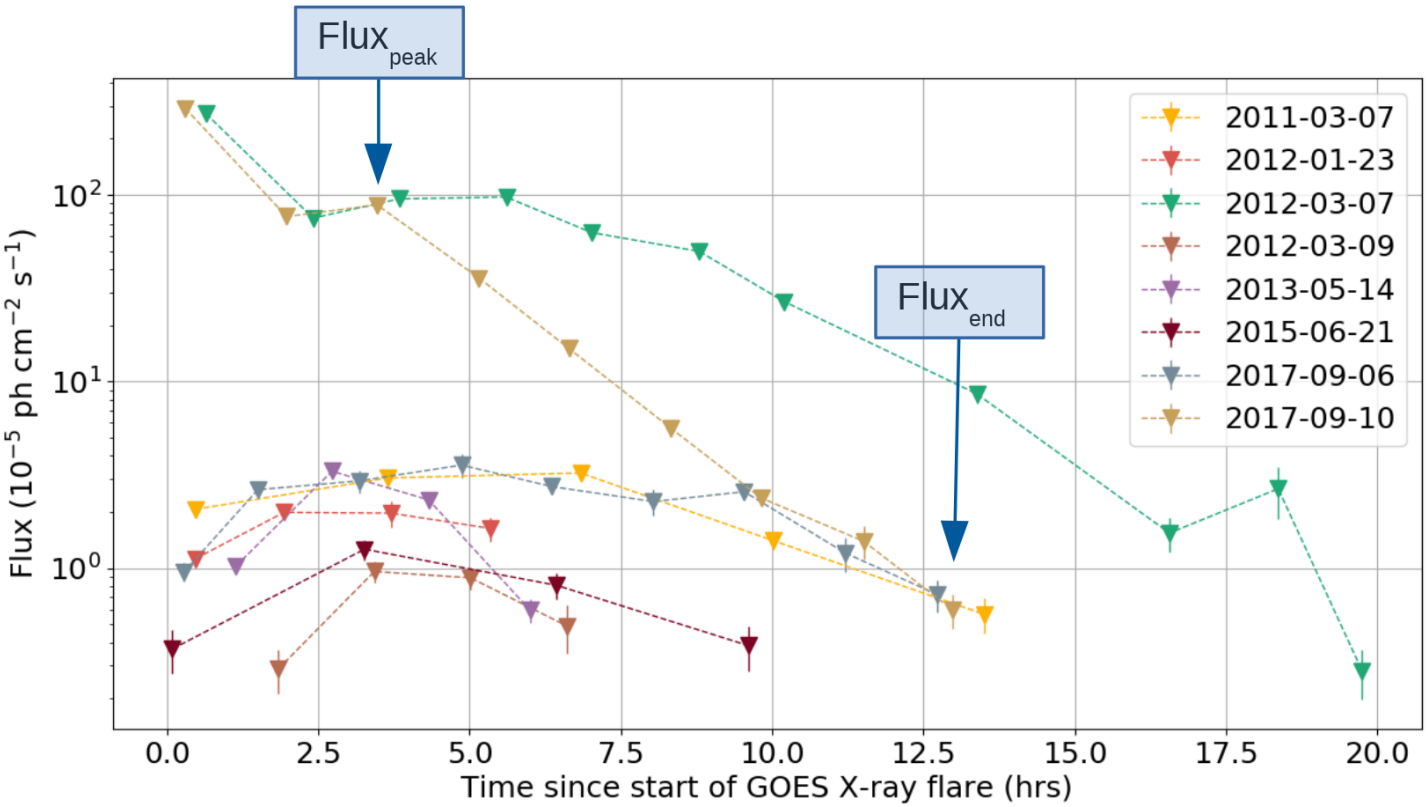
- FSF in the catalog with a detection in 4 or more *Fermi*-LAT observing windows
- Fluxes for all flares show the *rise-and-fall* behavior with time
- Peak flux values span up to two orders of magnitude

Delayed flares characteristics



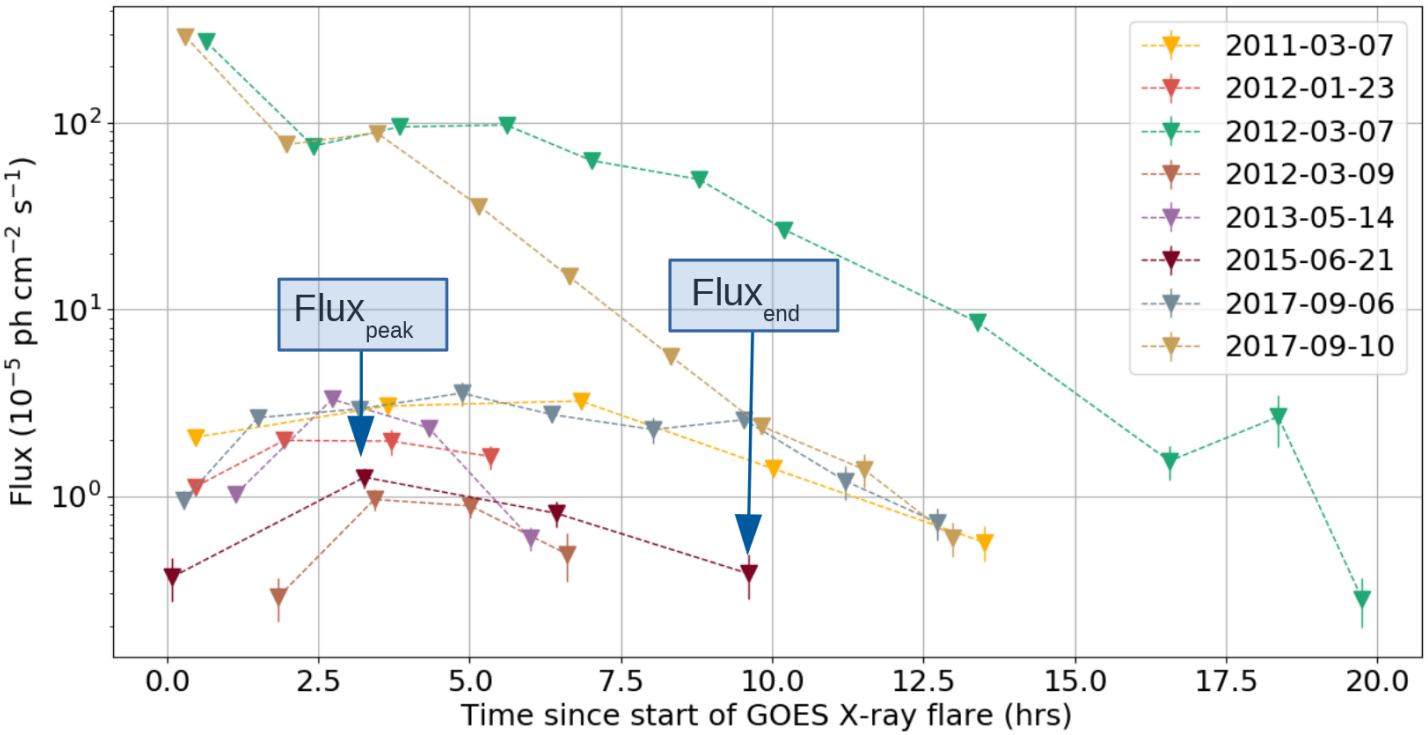
- >100 MeV fluence for all the FSF in the catalog versus the CME speed
- FSF with delayed emission lasting more than 2 hrs show a positive correlation with CME speed

Delayed flares characteristics



- 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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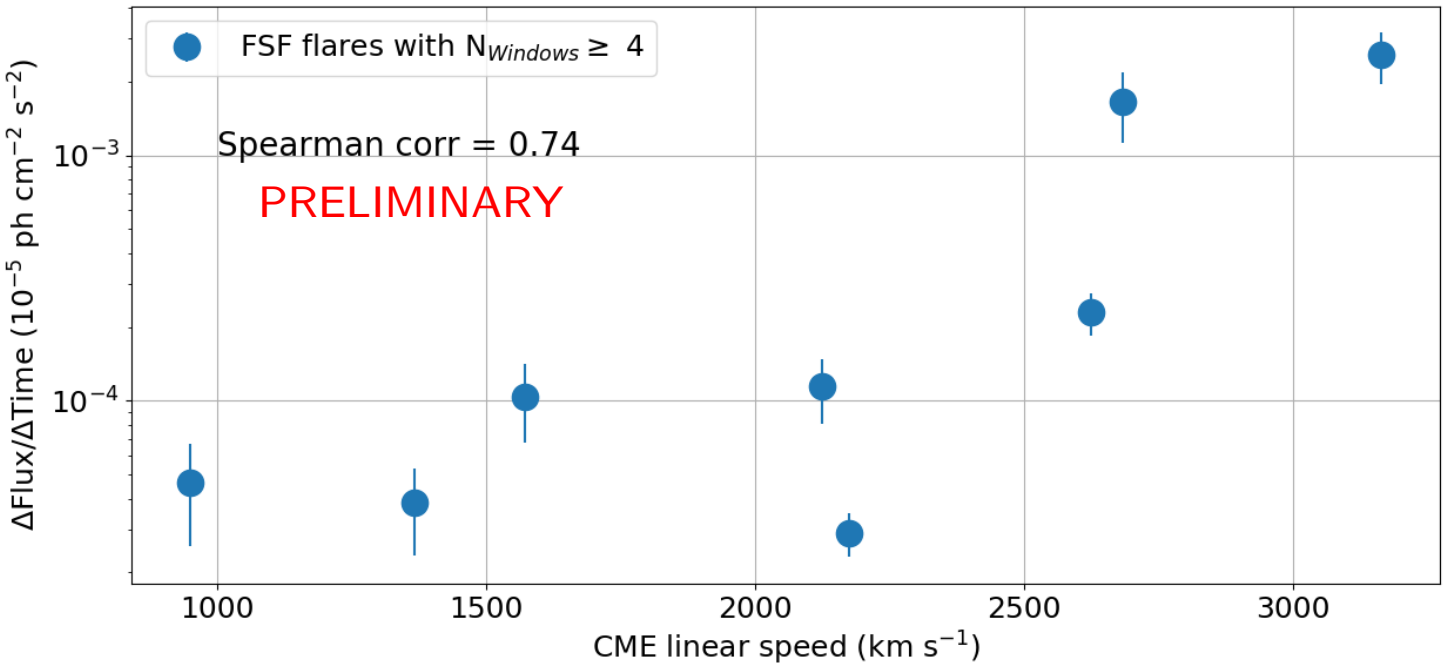
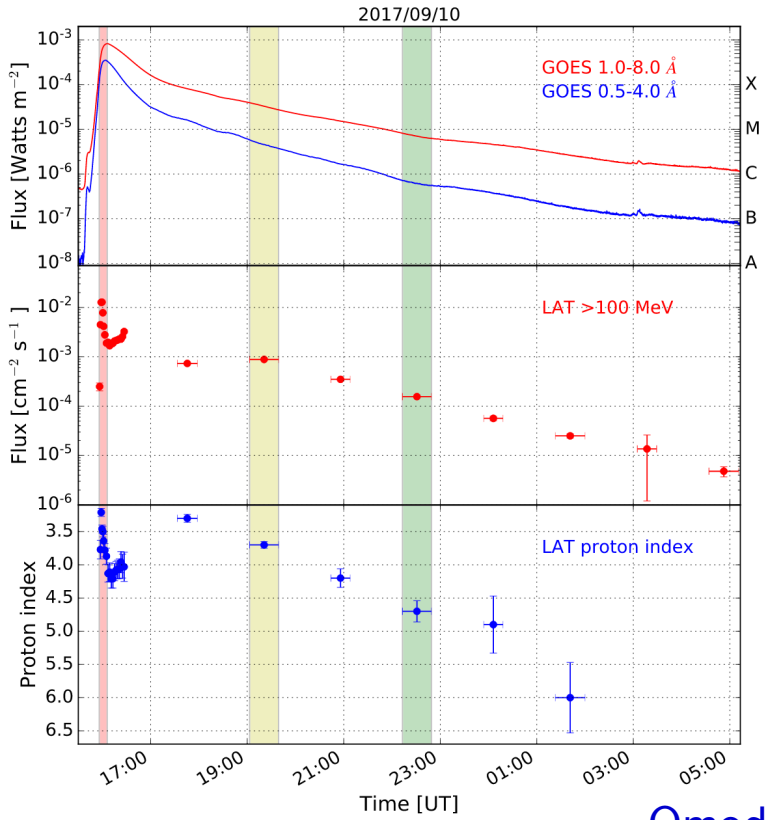
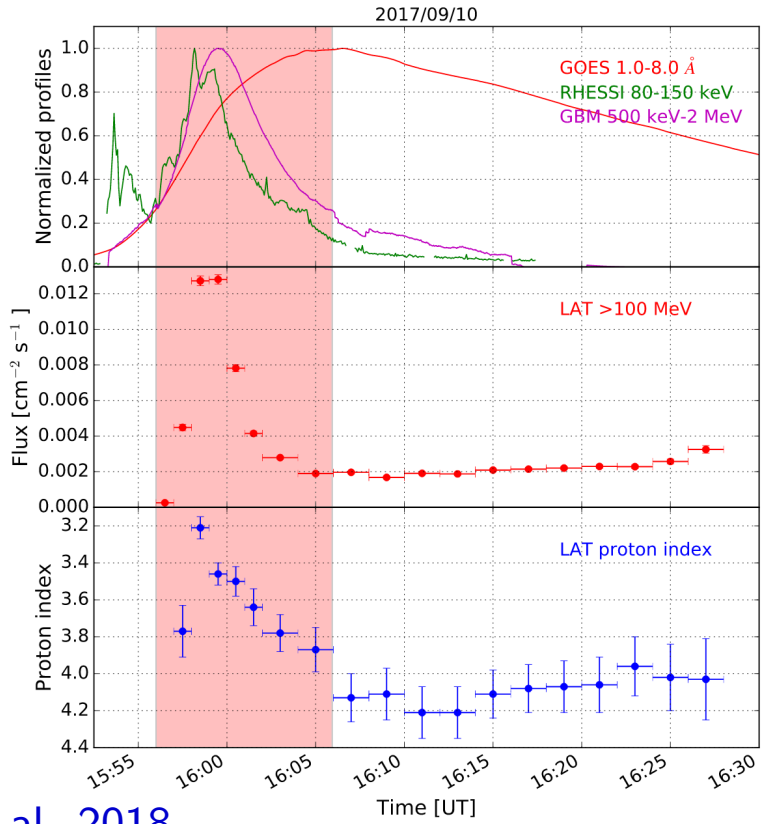
Delayed flares characteristics



- 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

Inferred proton properties

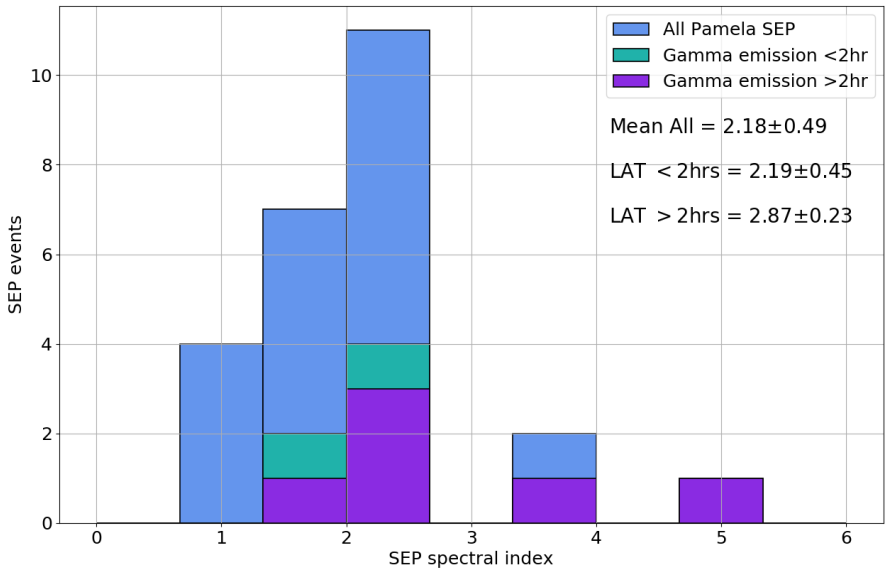


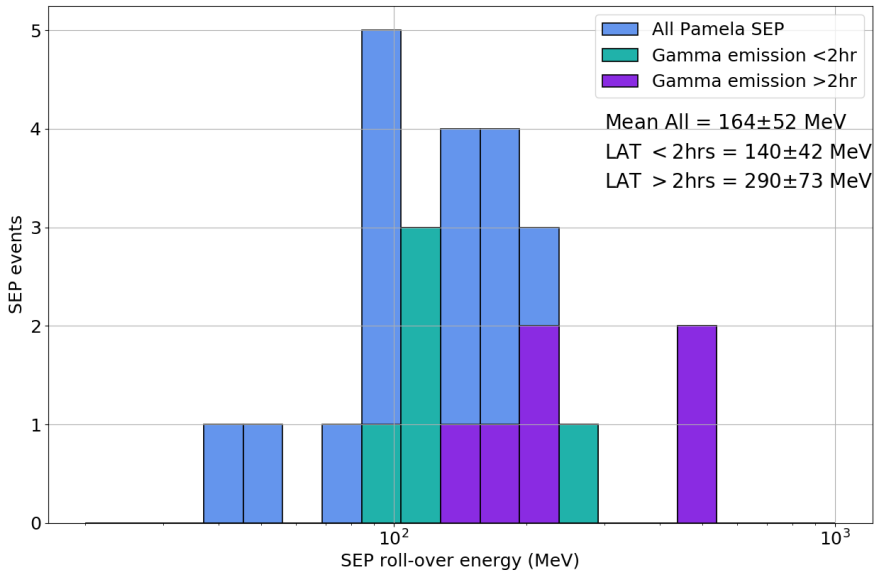


Omodei et al. 2018

- 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
  - Contrary to what is seen for other LAT flares where proton index softens with time as flux gets dimmer

SEP PROPERTIES



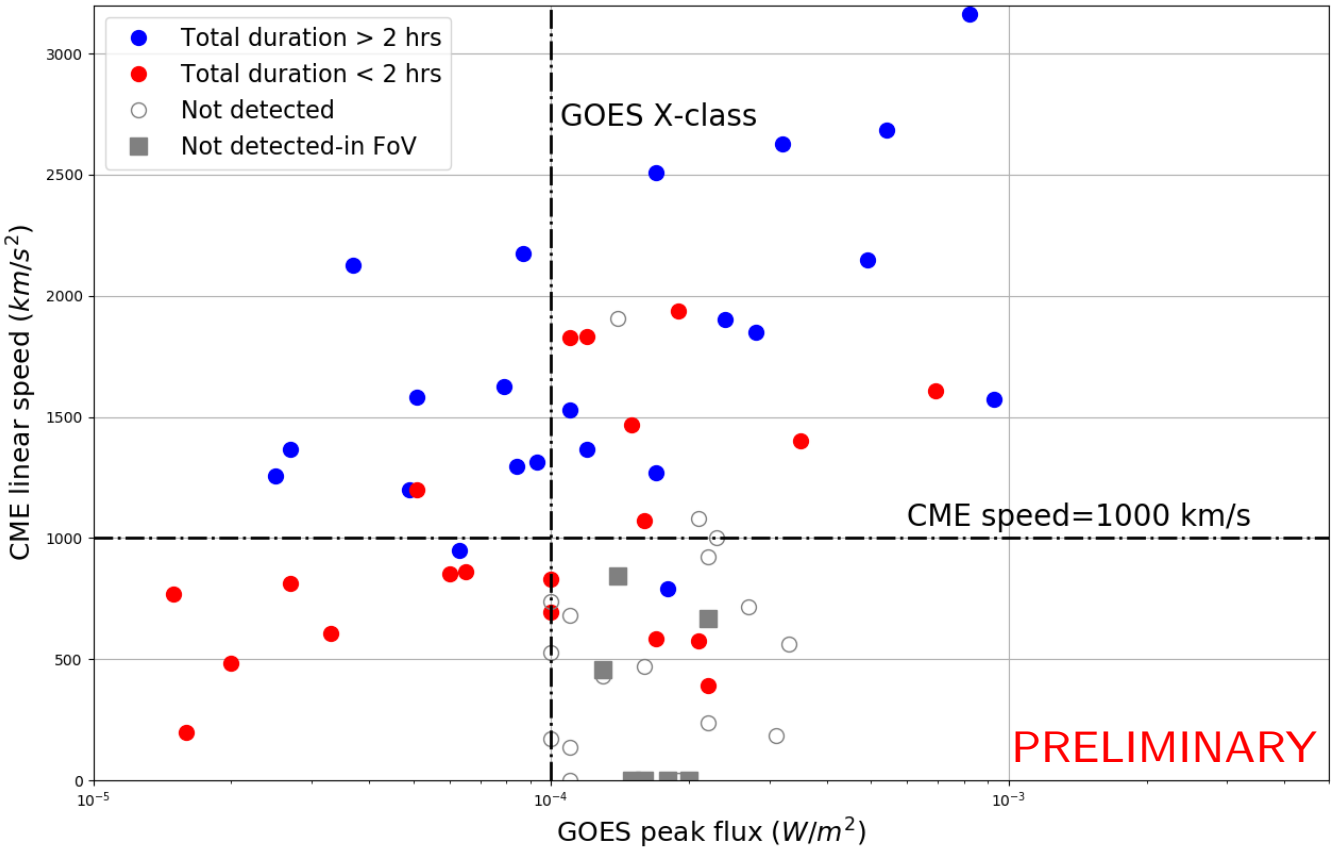


SEP data from Bruno et al. 2018

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?



- Out of 49 X-class flares in Solar cycle, 24 were detected by the LAT
- Only 3 of non-detected X-class flares had CME speed >1000 km/s
  - Not in the LAT field of view during prompt phase
  - Marginal detection for the flare with highest CME speed
- Delayed gamma-ray flares are some how tied to fast CMEs

Summary

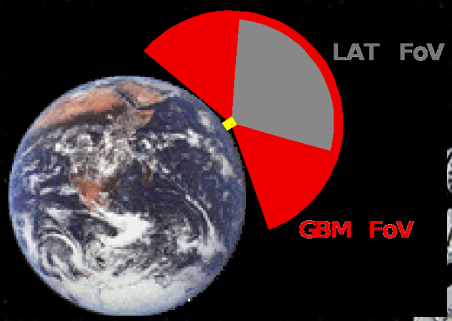
- The First *Fermi*-LAT Solar flare catalog has a total 45 flares with emission >30 MeV
  - Wide variety of types of flares
  - Two main classes of flares: *prompt* and *delayed*
  - The data suggests that there are at least two acceleration mechanisms driving these classes
- The properties of FSF with emission lasting more than 2 hrs show a positive correlation with CME speed
  - Not the case for FSF with shorter duration emission
- All but one of the GOES X-class flares not detected by the LAT were associated with slow CMEs
  - Marginal detection by the LAT of the X-class flare with CME speed 1900 km/s
- Behind-limb-flares also suggest the need for a spatially extended component to bring the accelerated particles to the visible disk

Spare slides

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
- PSF $<1^\circ$ at 1 GeV

The LAT *standard analysis*

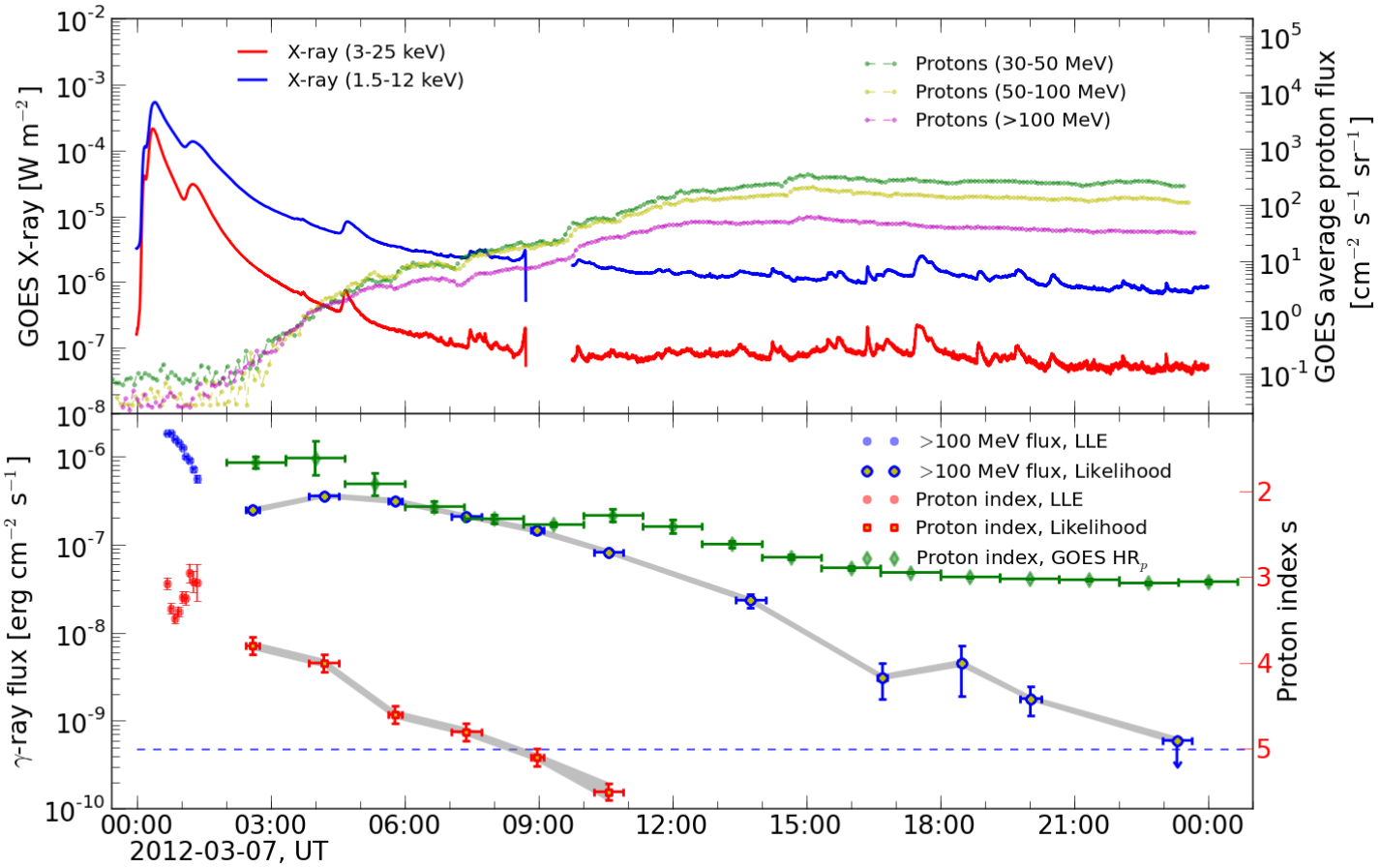
- Event classification (photon vs. bkg) on event-by-event basis
  - Use classification trees to reject bkg and give high-quality photon data
  - Likelihood fit of spatial and spectral model of region around Sun
    - We typically take a circle with radius of 10° centered on the Sun
    - All known gamma-ray 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 ACD
  - Problem solved with the dedicated 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

Inferred proton properties

Ajello et al. 2014



- 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