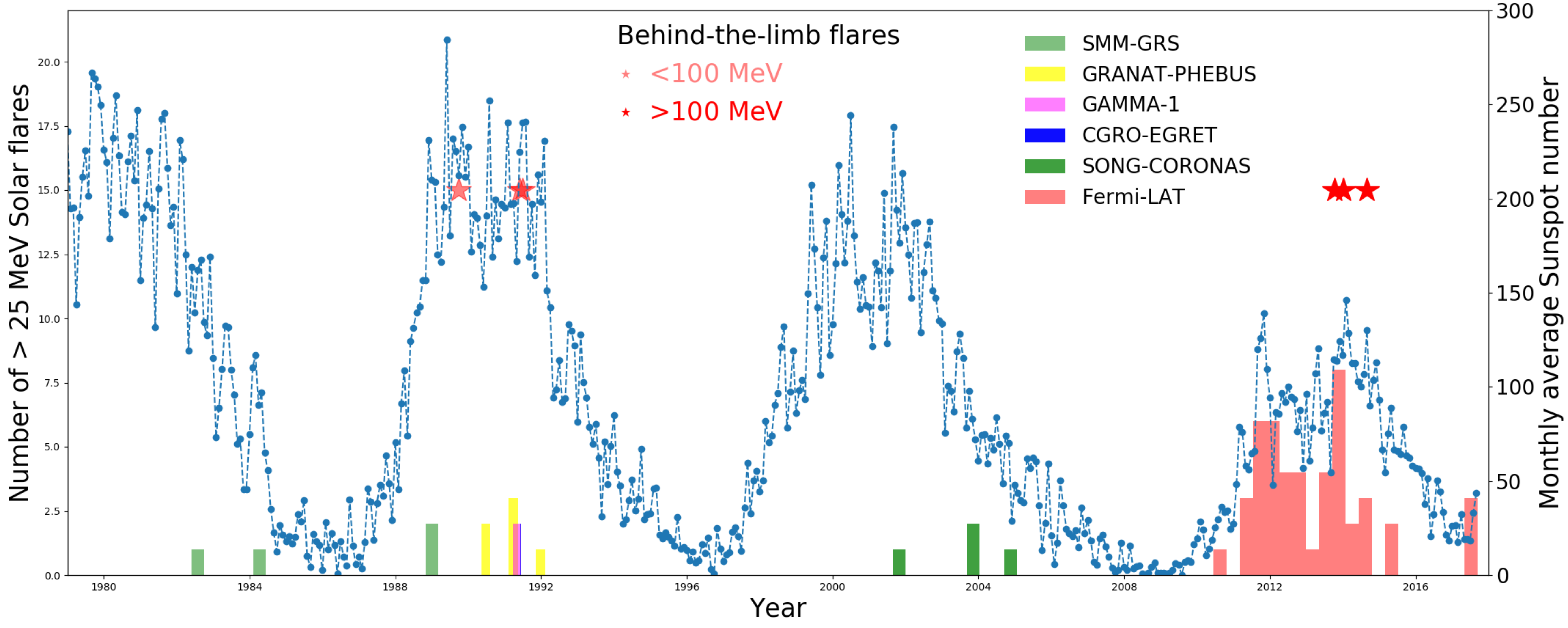
High-energy Observations of Solar Flares During Solar Cycle 24 with the Fermi Large Area Telescope

Nicola Omodei,
Alice Allafort, Melissa Pesce-Rollins, Francesco Longo

on behalf of the Fermi LAT collaboration

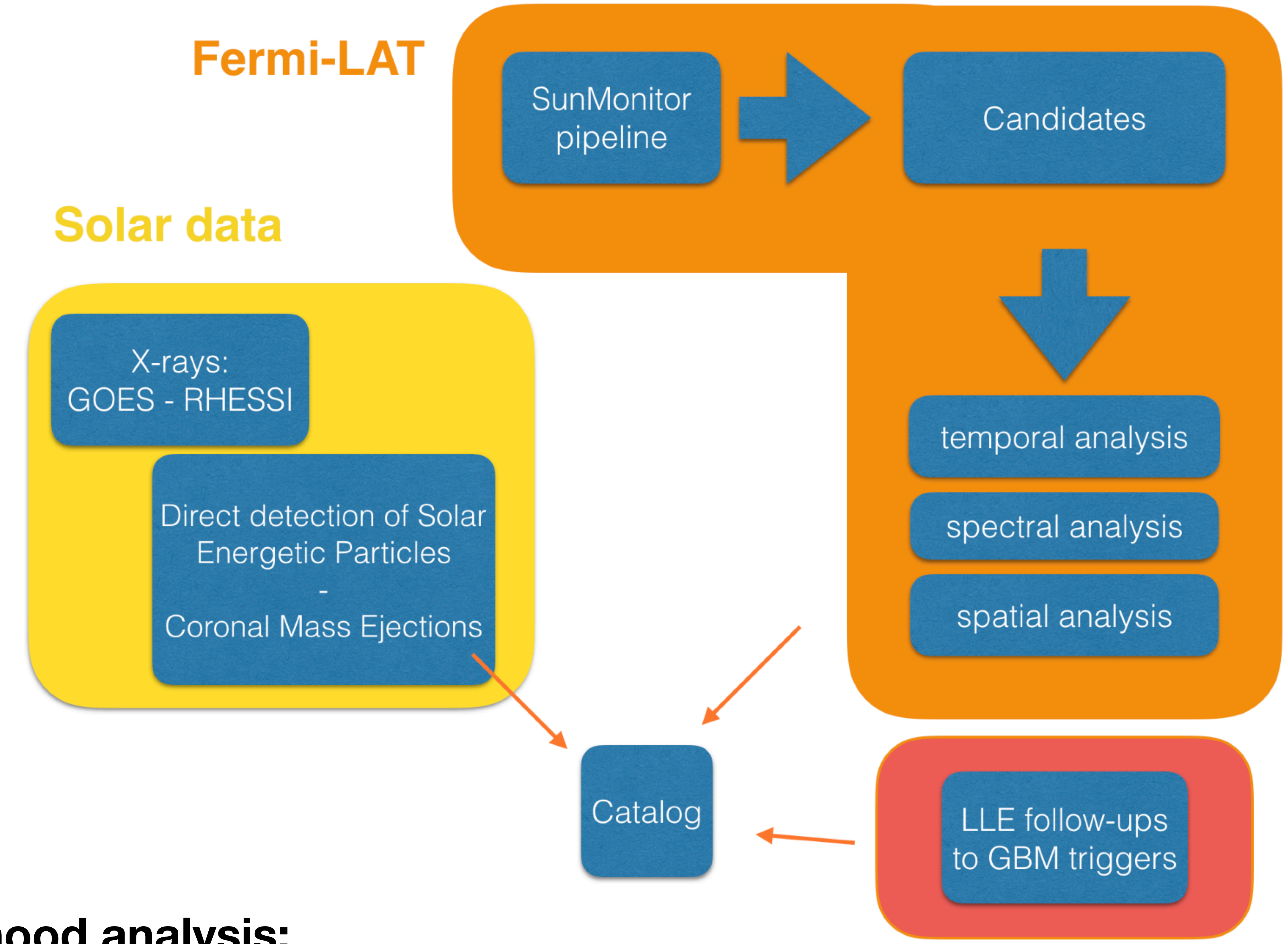
Solar Flares in gamma-rays with Fermi



Cycle 24: Quietest cycle in the last 100 years!

5 papers from the LAT collaboration published on individual flares

Solar Flare Catalog Framework



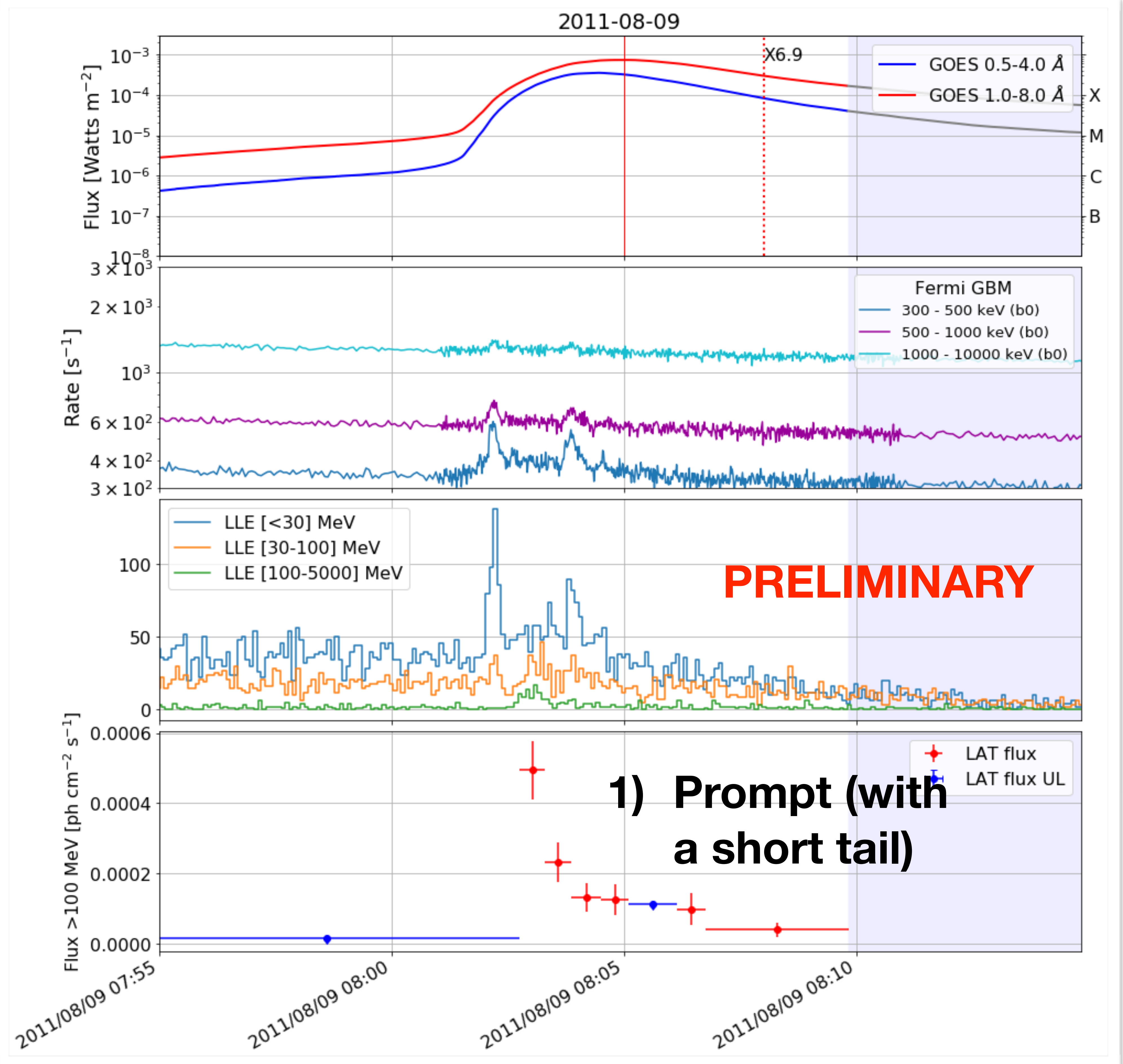
- SunMonitor runs continuously:
- Produces a list of 92 time windows candidates (TS>25)
- Yield 39 flares detections above 60 MeV
- LLE approach detected 6 additional above 30MeV

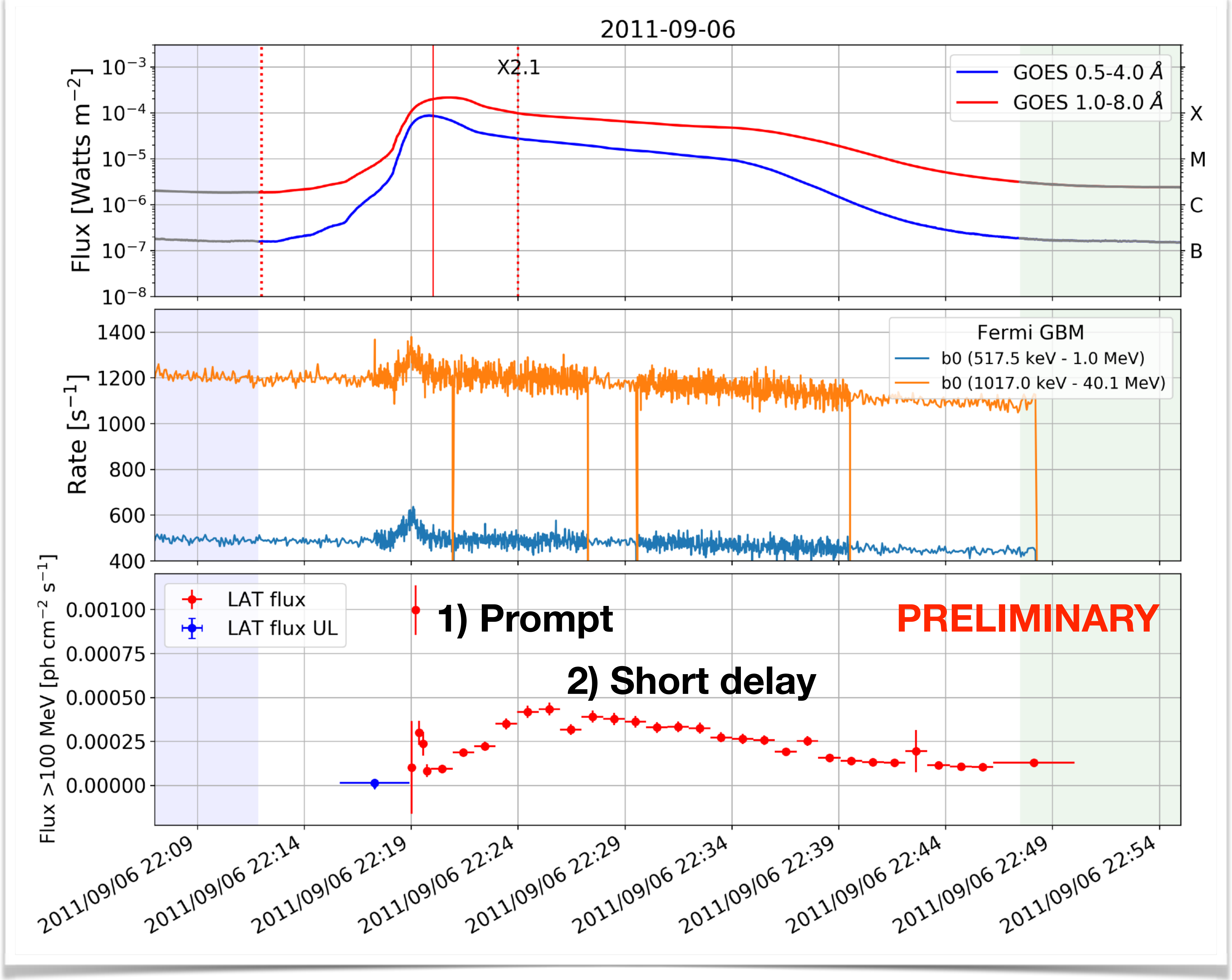
45 Flares total :

- all associated with X-ray flare
- all but 3 associated with CMEs
- 3 from behind the limb (BTL)

- **Detailed likelihood analysis:**
  - **in each time window we independently model the background: galactic, isotropic (extragalactic + unresolved CR) + background sources, quiet Sun;**
  - **Model the source: power law vs Power law with exponential cut off;**
  - **Pion decay template (from Ron Murphy) fitting;**
  - **Compute the localization of the gamma-ray emission, optimize the localization in the analysis.**

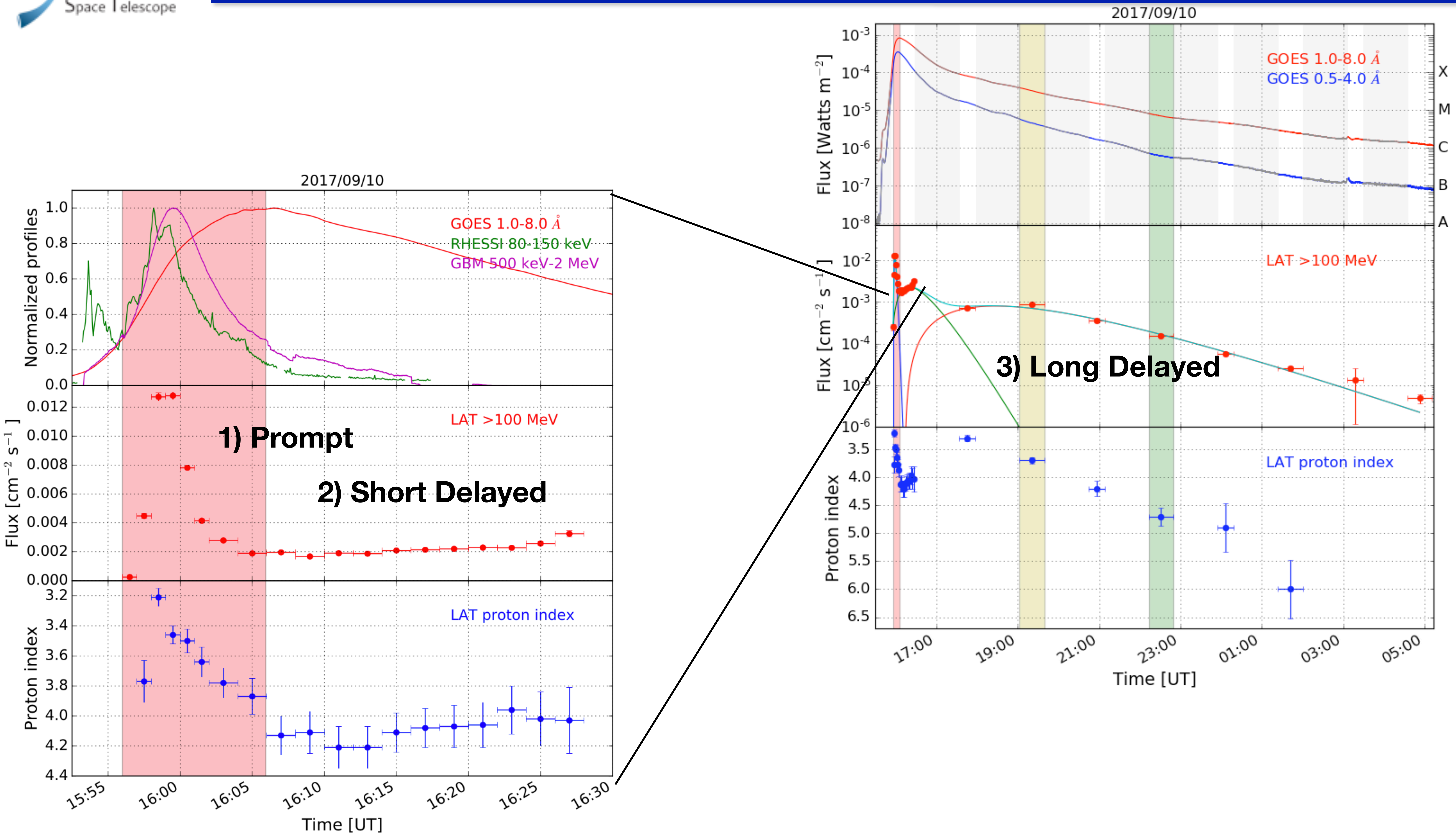
One, or two distinct components





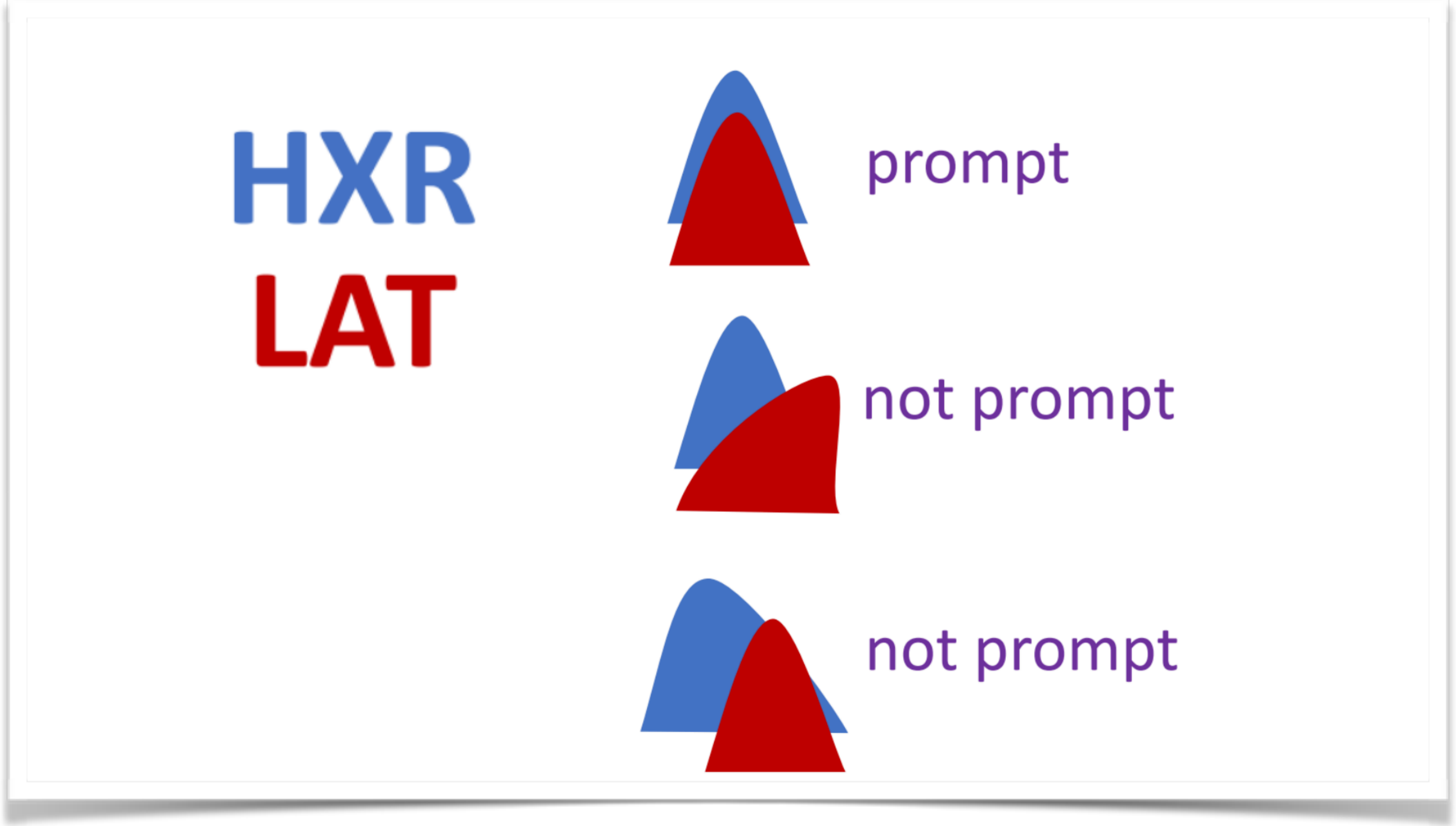
- **LAT Low Energy (LLE) extends the LAT energy range down to 30 MeV**
- **Large effective are <1 GeV**
  - **Larger field of view**
  - **Good for temporal and spectral studies**

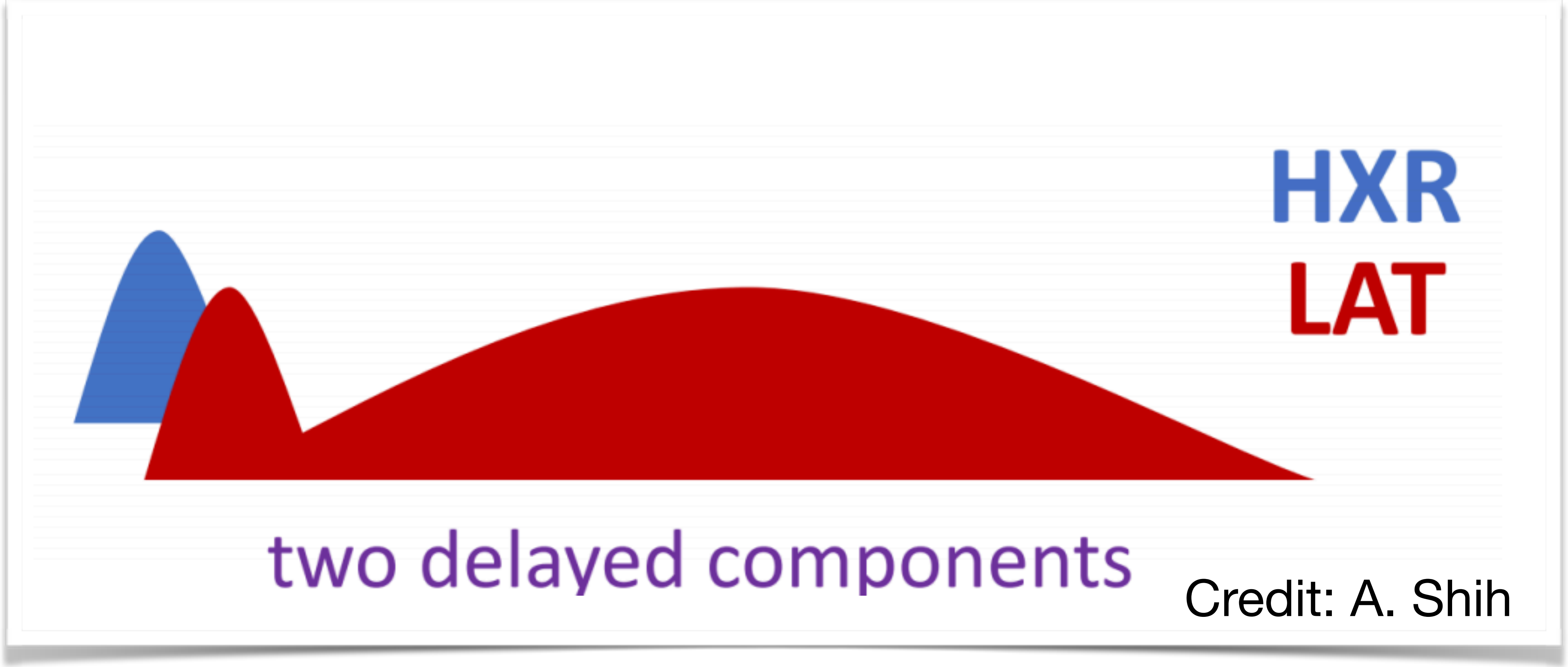
SOL 2017-09-10 shows multiple components



Omodei et al. 2018

Categories of Fermi LAT Solar Flares (FLSF)





Catalog of **45 Flares**:

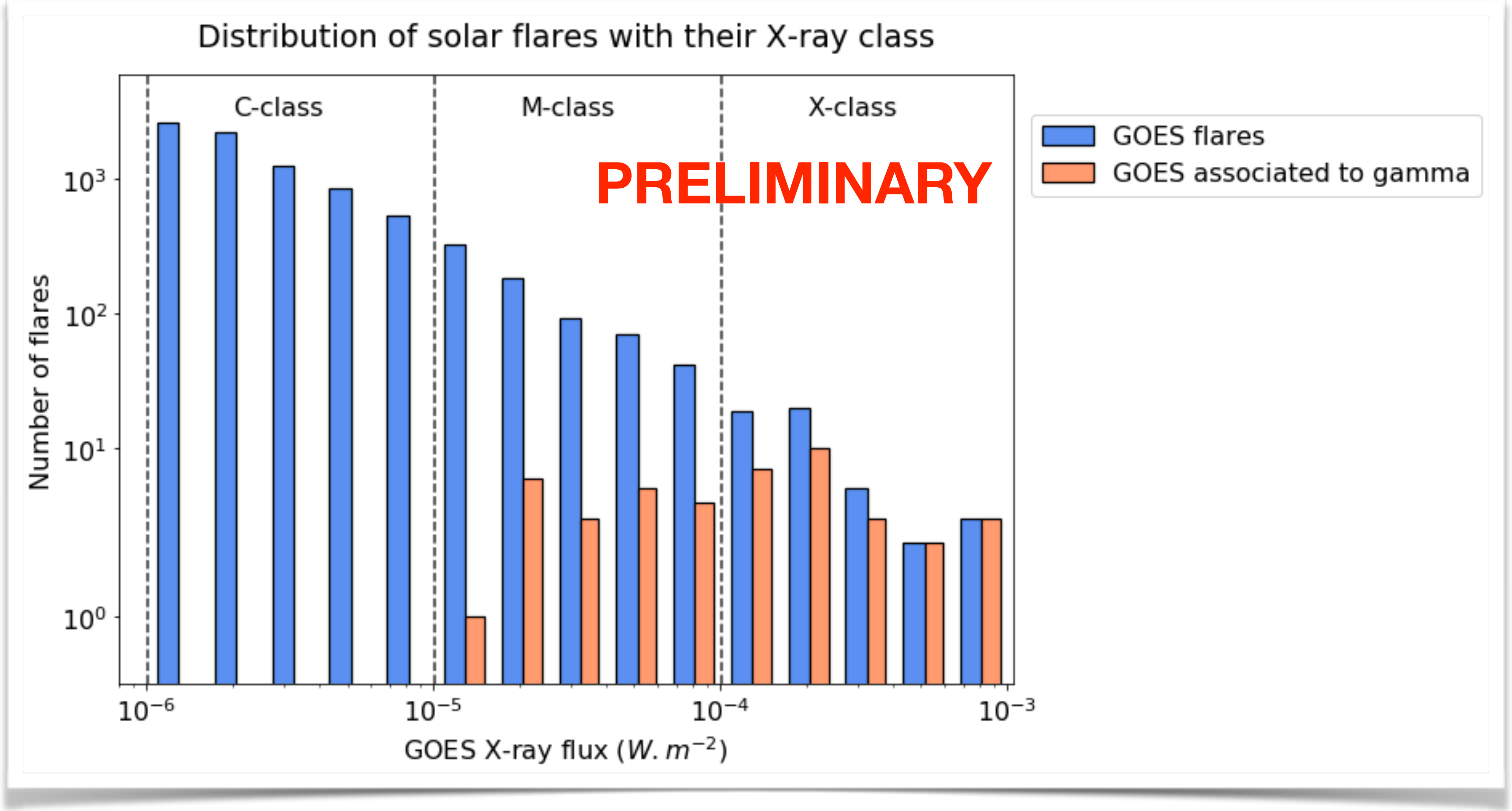
- **18** flares with a **Prompt** component synchronized with HXR
- **37** flares with some **delayed** component beyond HXR
  - **19** exhibit a **delay longer than 2 hours.**
  - **18** exhibit a **delay shorter than 2 hr.**
- **3 Behind The Limb flares**

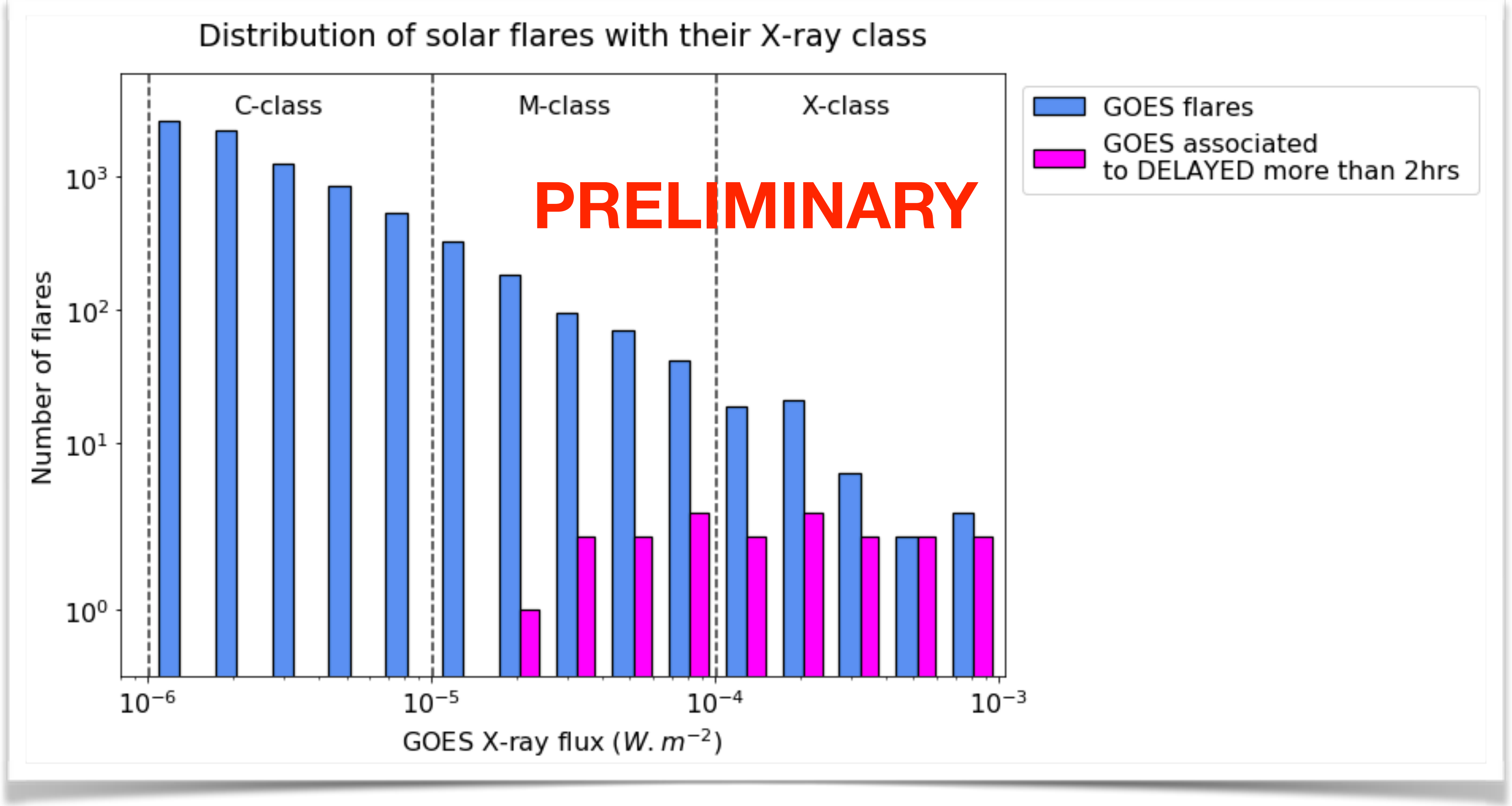
(**4 flares** show no prompt emission but delayed emission)

Population studies: the Fermi LAT Solar Flare (FLSF) Catalog

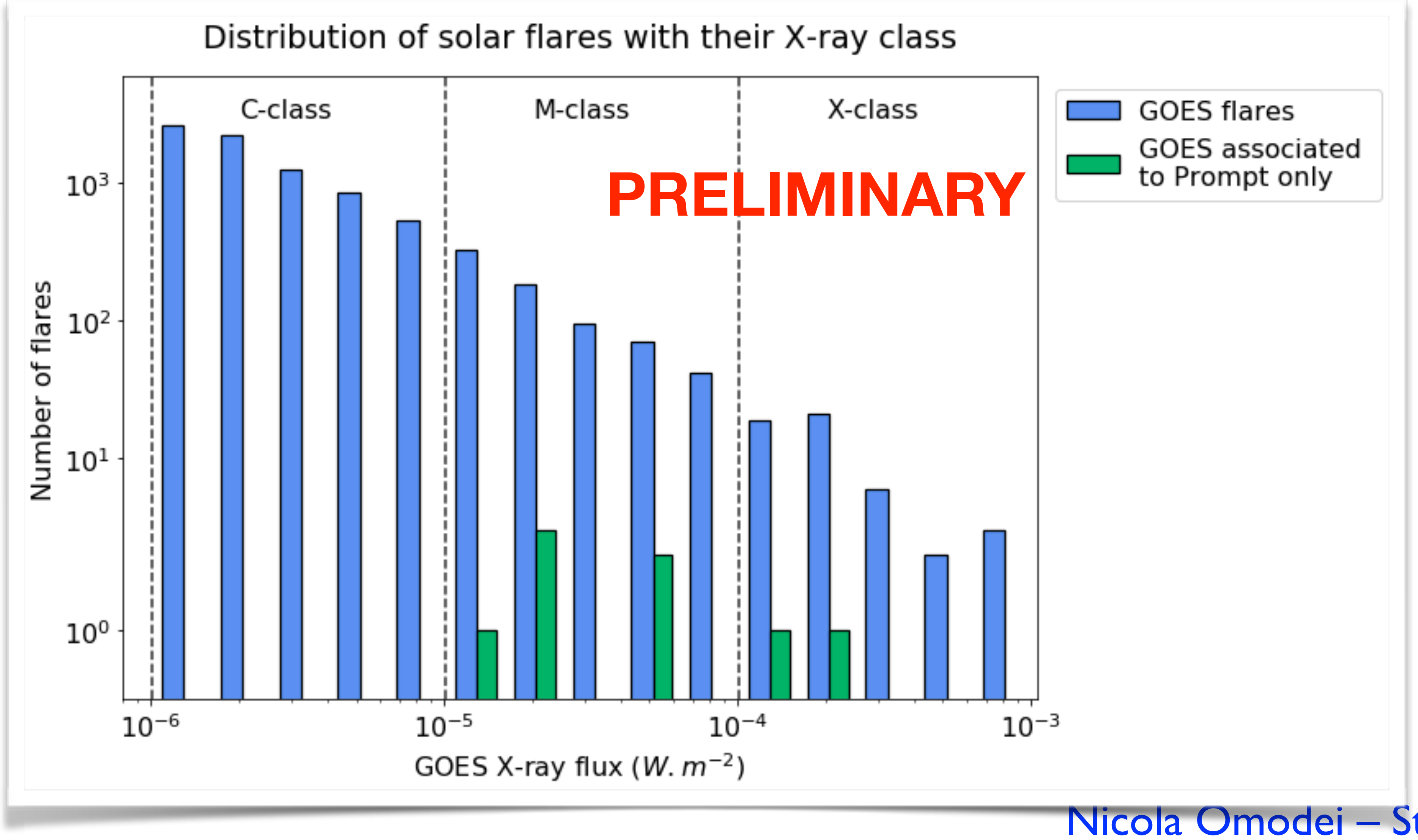
Connection with GOES flares

All flares are associated to GOES, and for the BTL we use the estimated equivalent class from STEREO fluxes



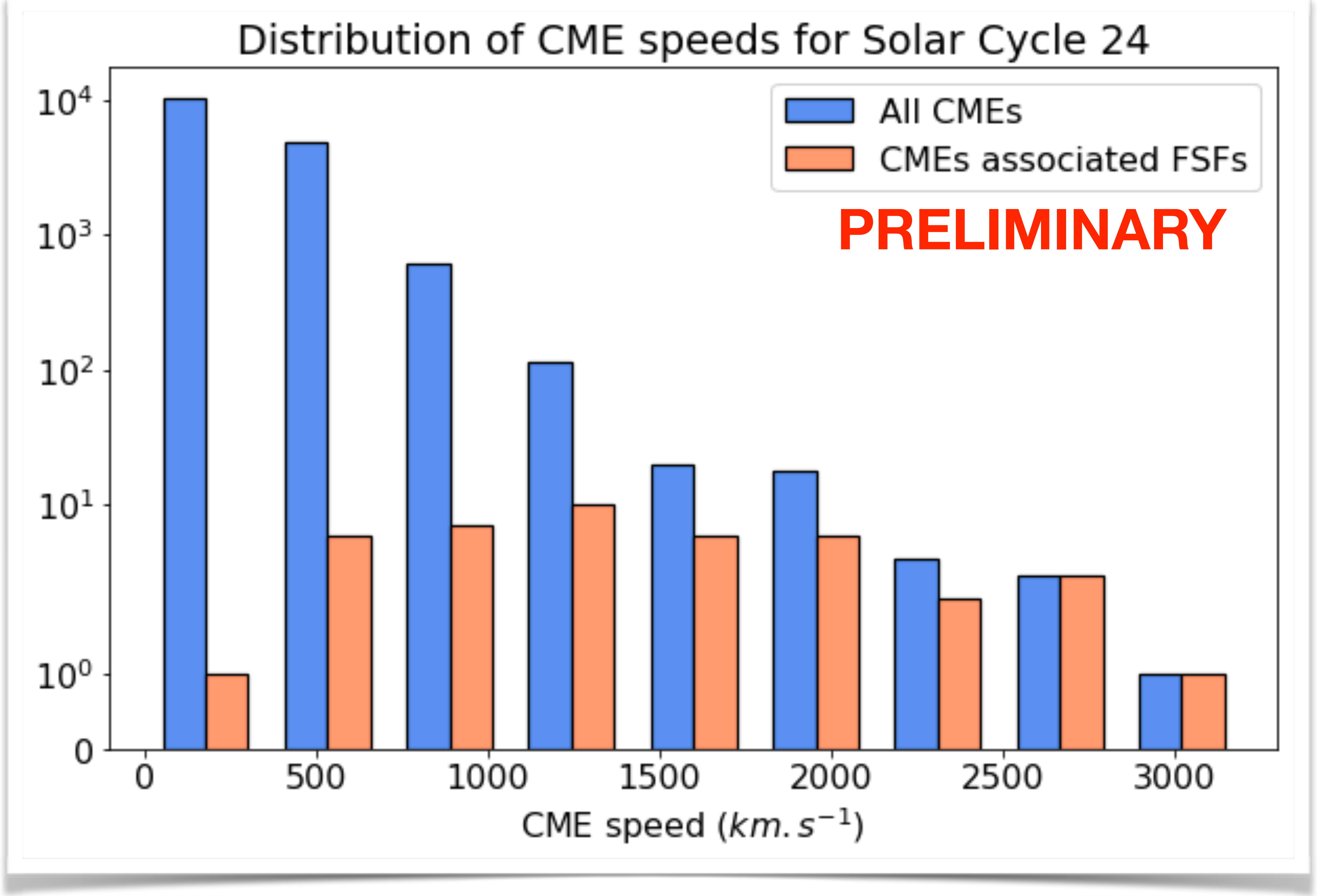


There doesn't seem to be any strong requirement on the GOES flare flux for a FLSF delayed or prompt



Connection with CMEs

Only 3 FSF not associated to CMEs

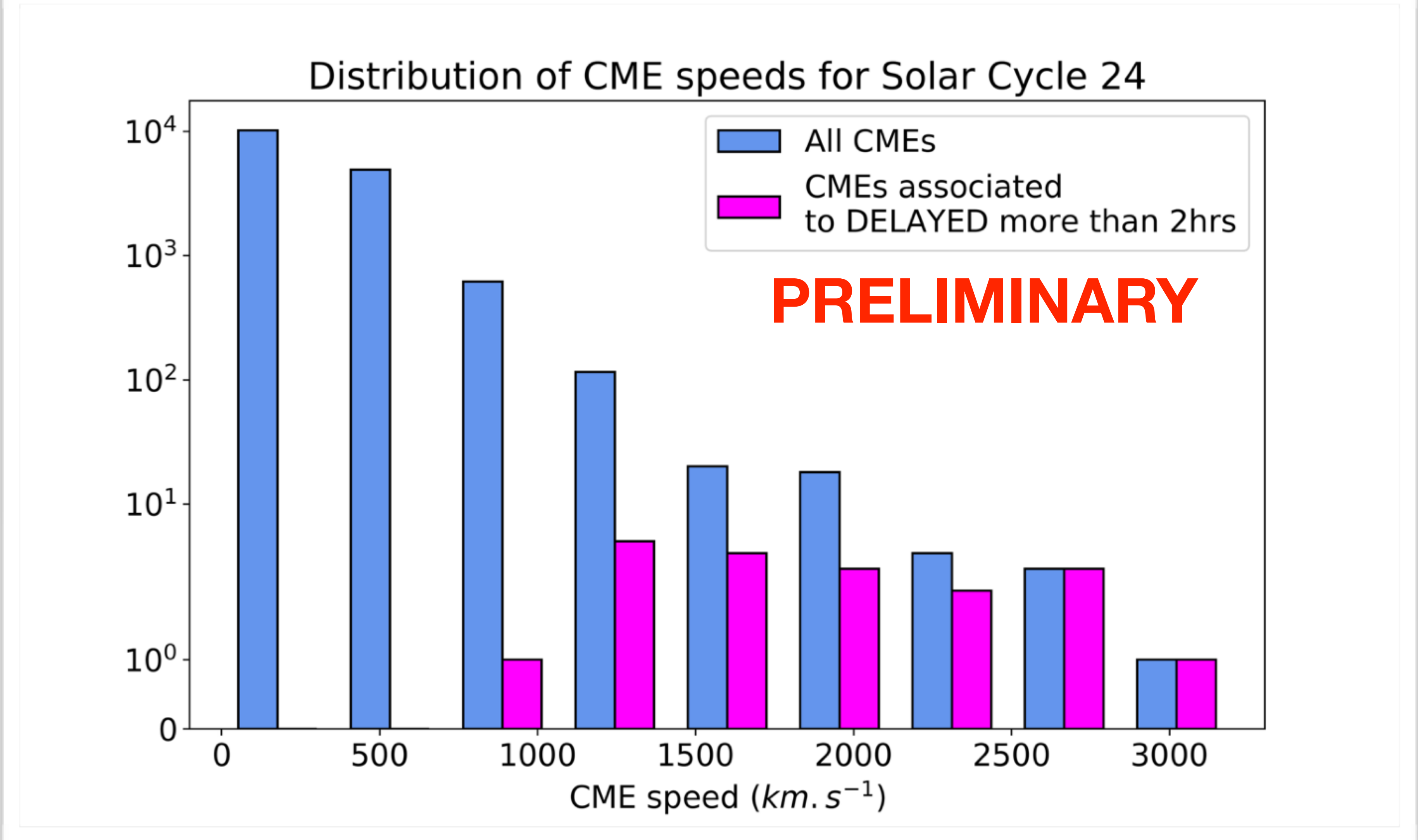


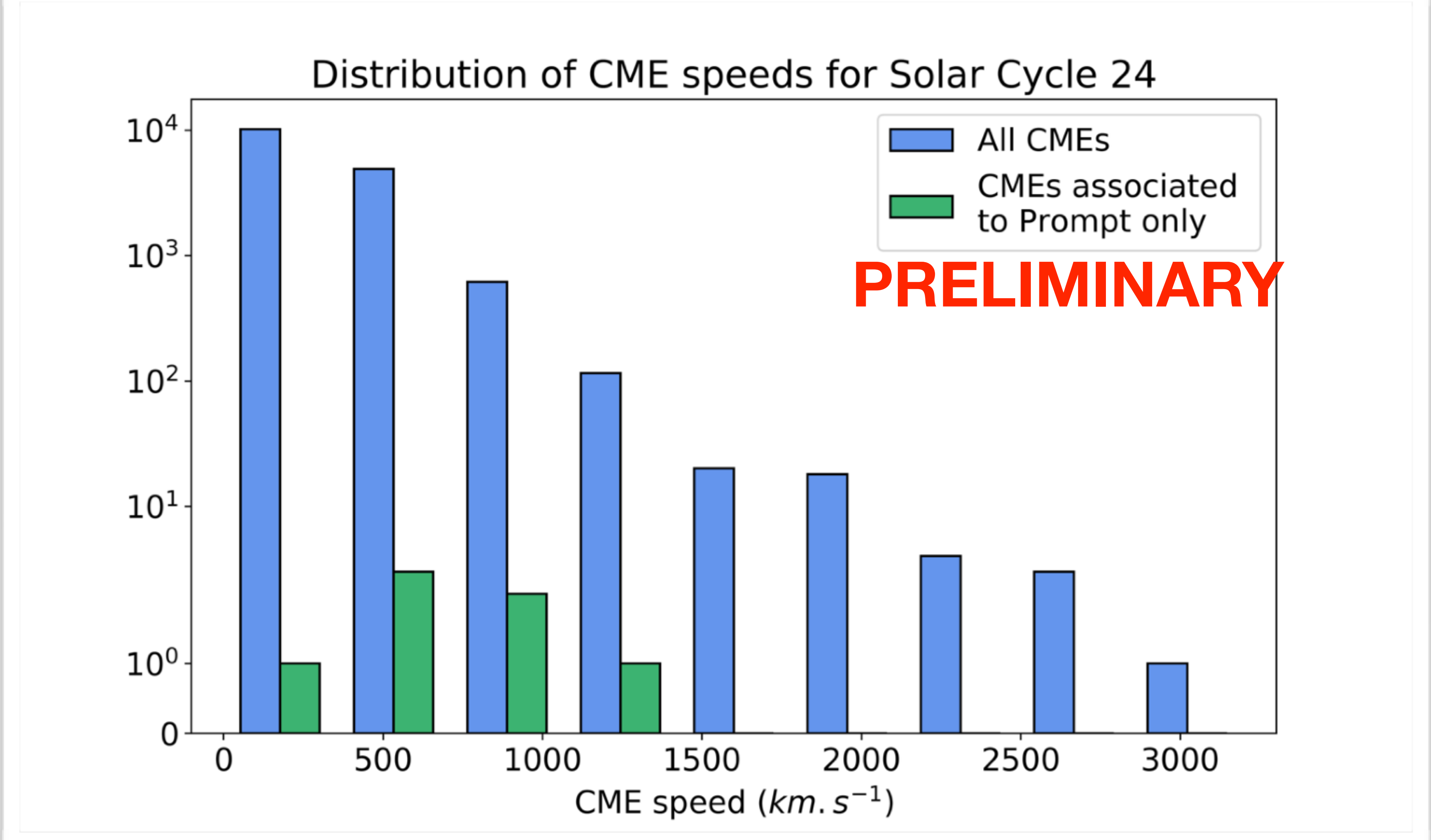
Most are Halo CMEs (all for fast CMEs)

Best predictor:

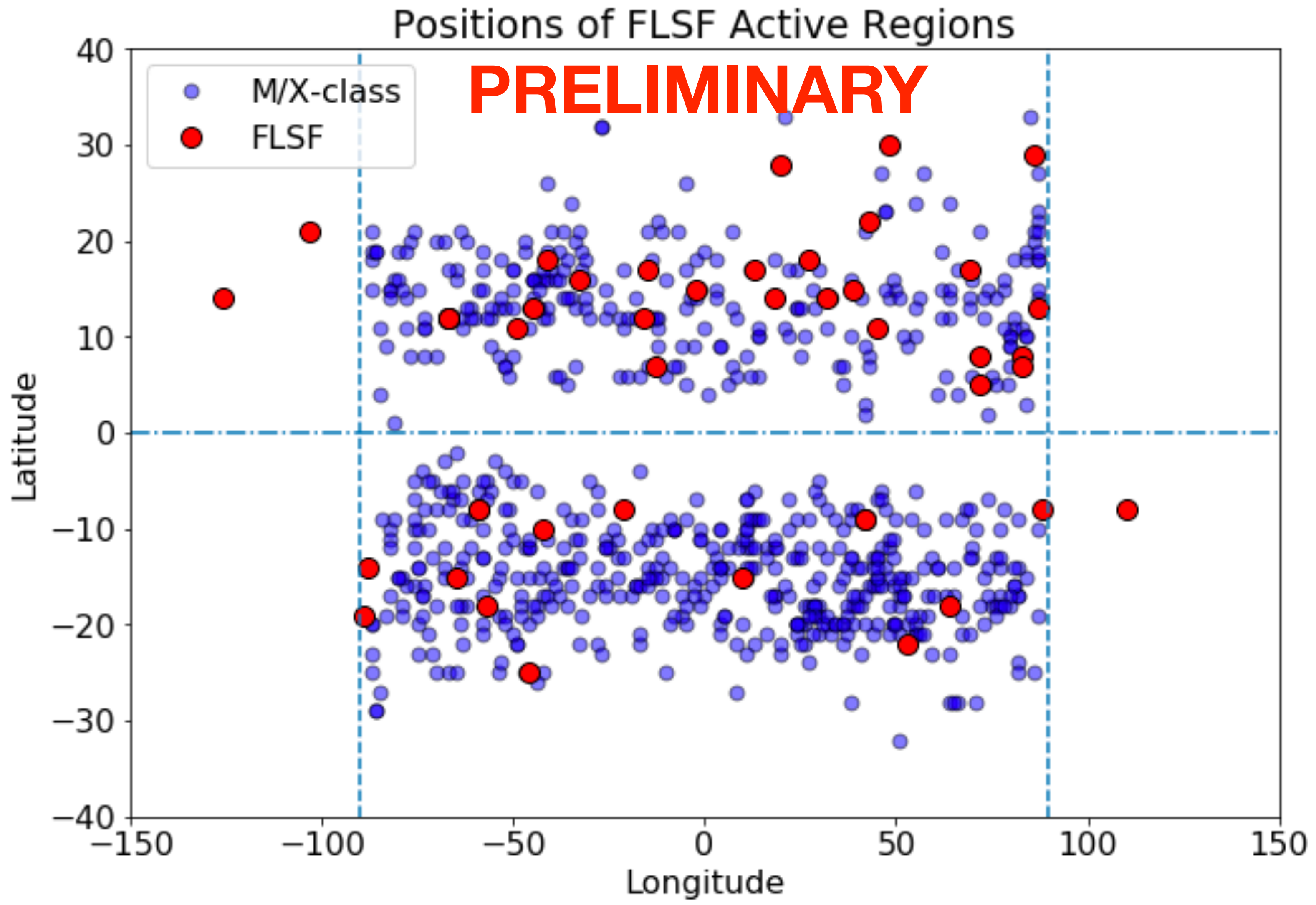
Delay extend beyond two hours

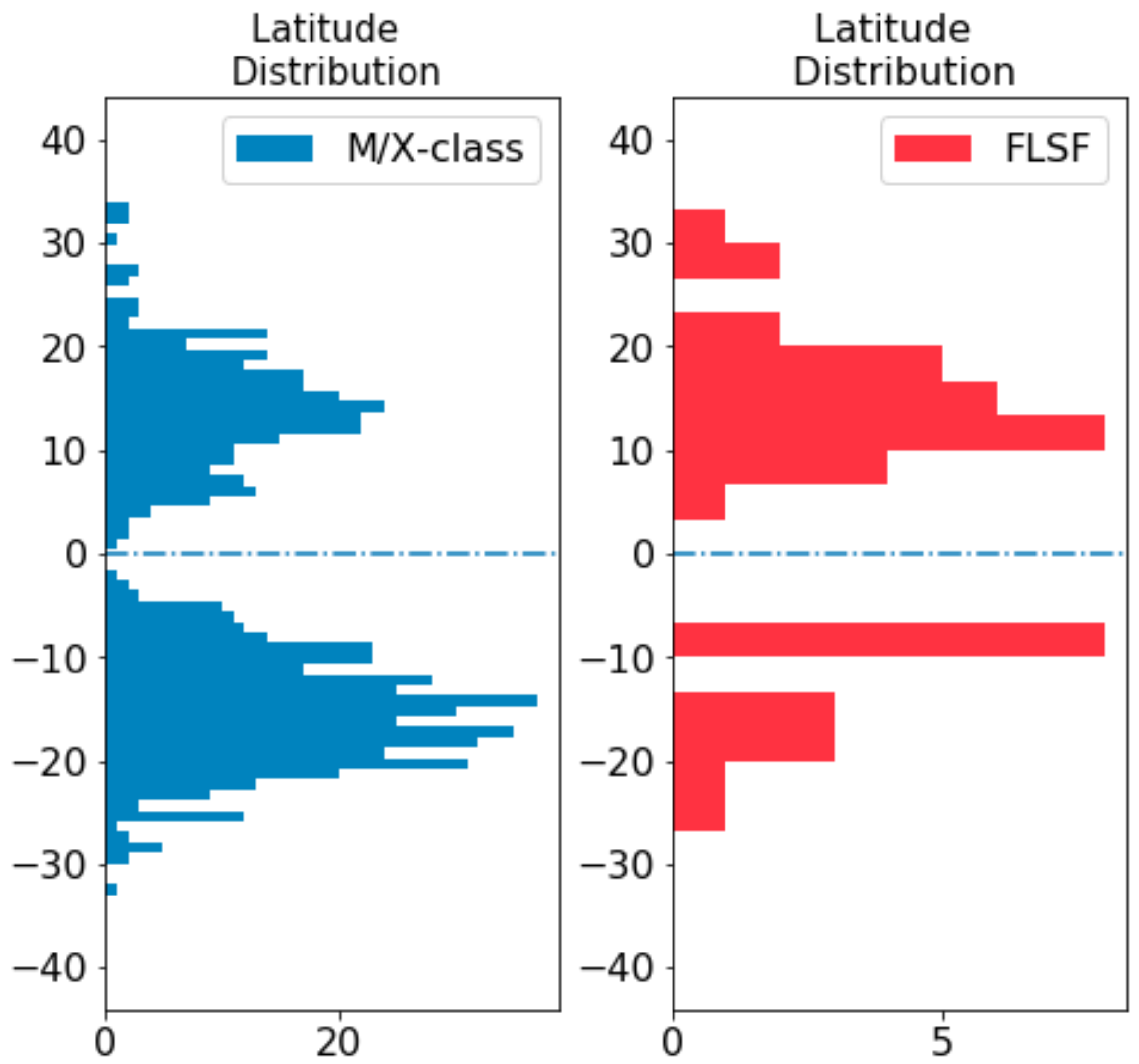
Definite trend for long delayed FLSF to be associated to faster CME

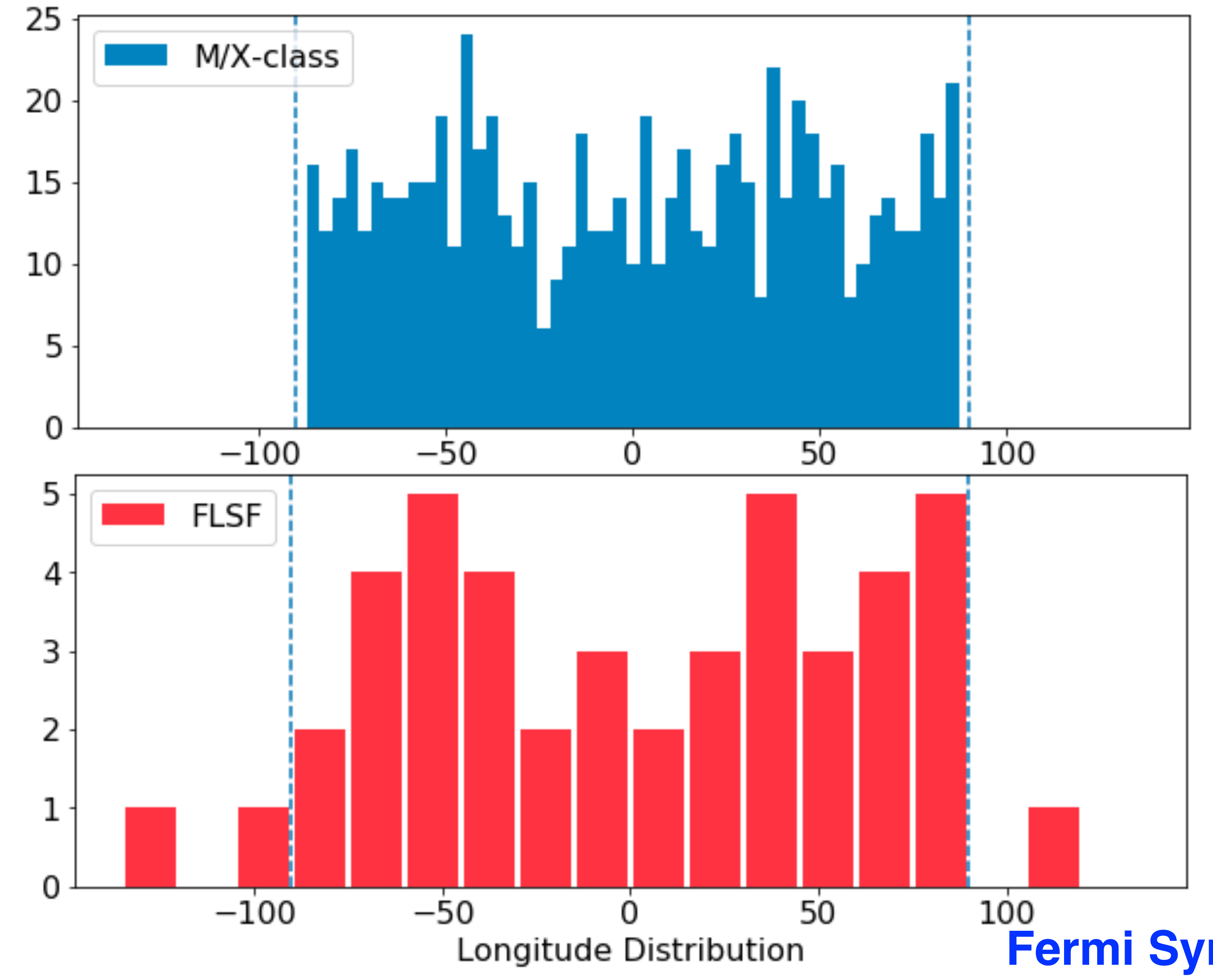




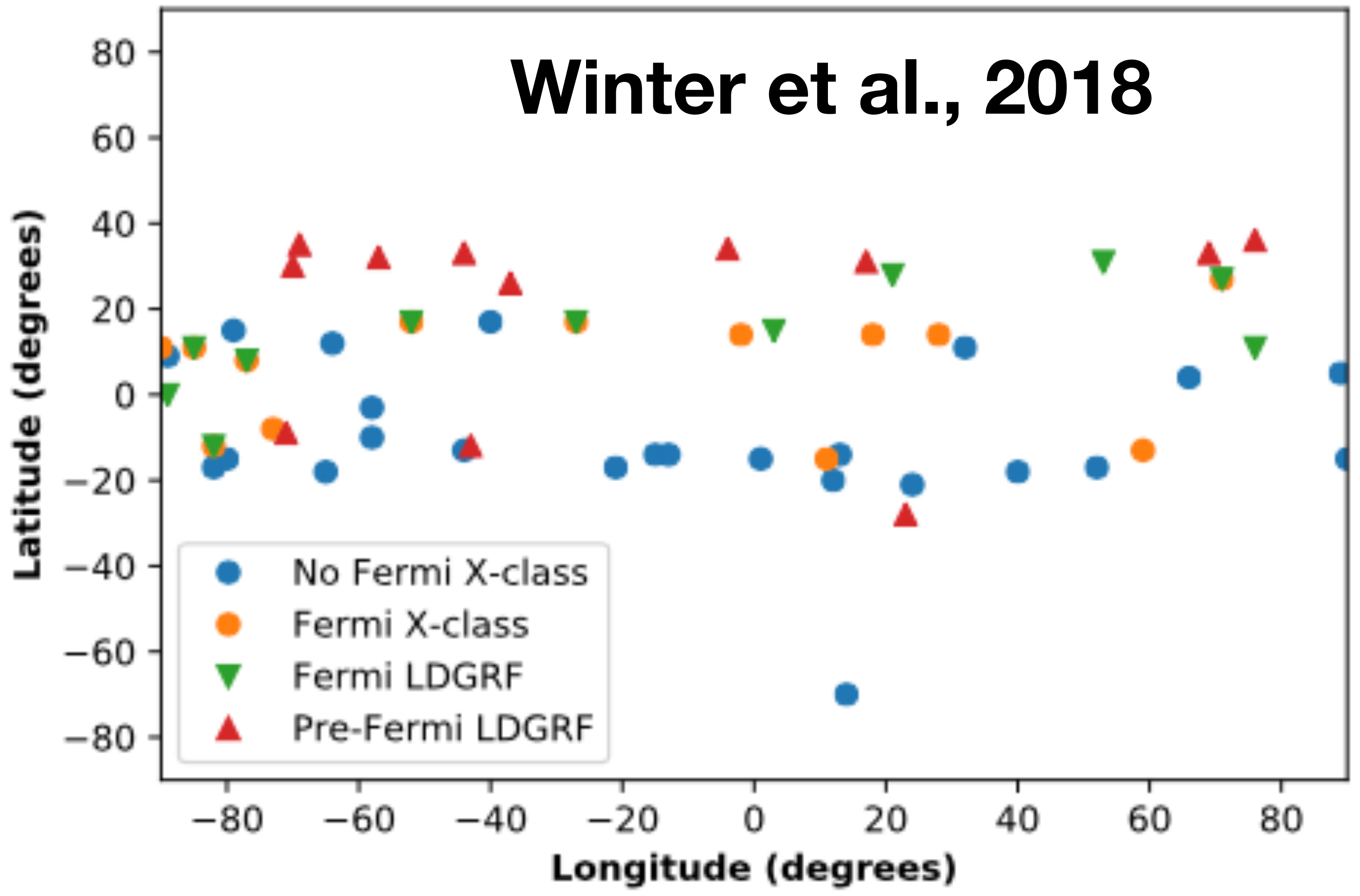
Distribution of the FLSF active regions





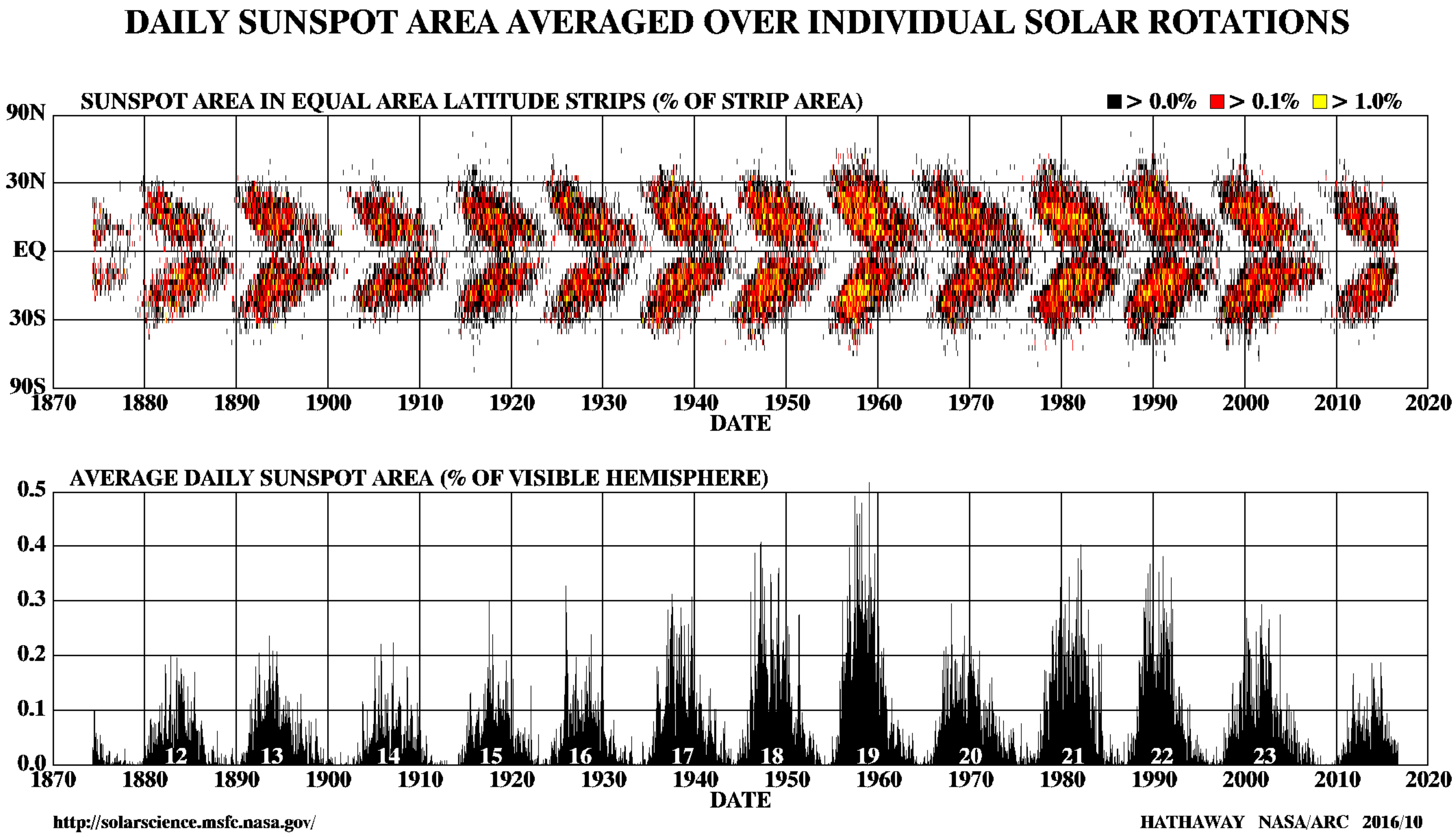


- **North/South asymmetry:** It is known that the distribution of AR shows an asymmetry with one hemisphere dominating at a given time
  - **Opposite in X-rays and gamma-rays!**



- **Longitude distribution:** Deficit at the disk center: Gamma-ray production beamed?

The "butterfly effect" as seen by Fermi LAT



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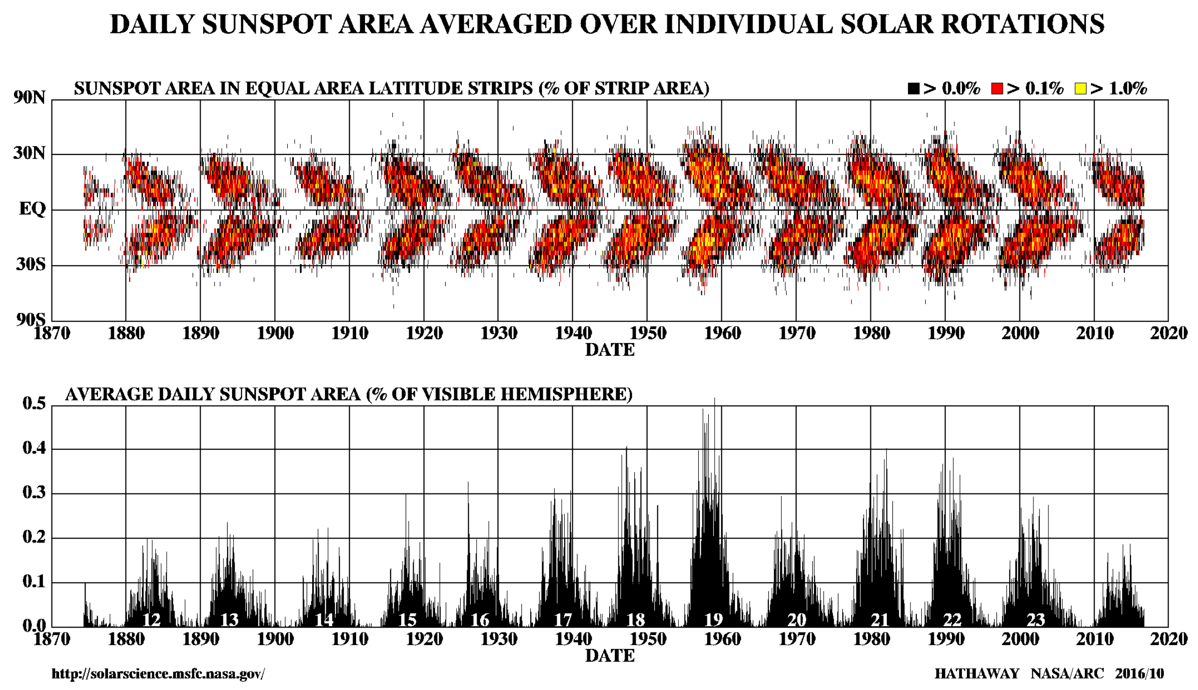
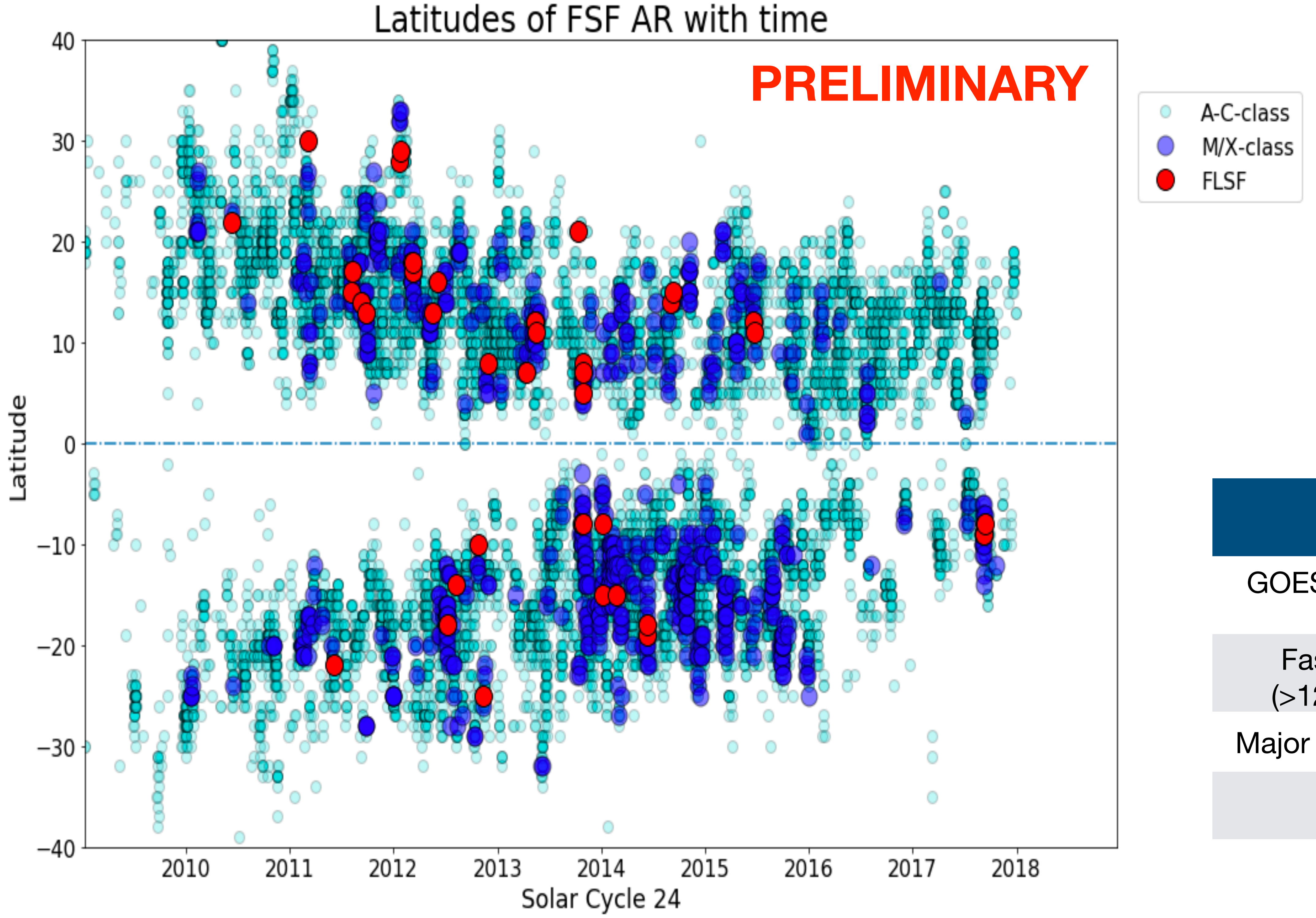
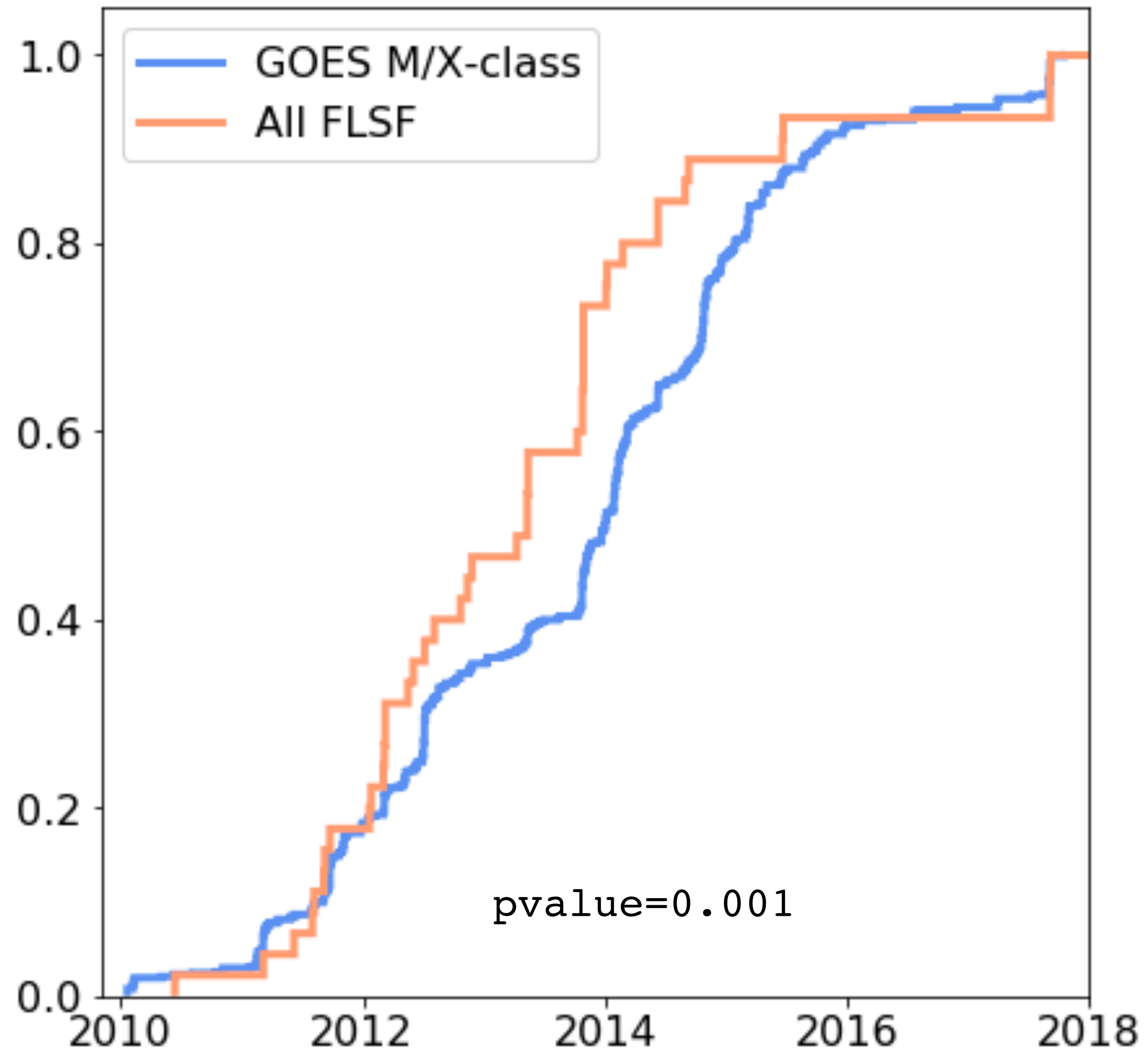
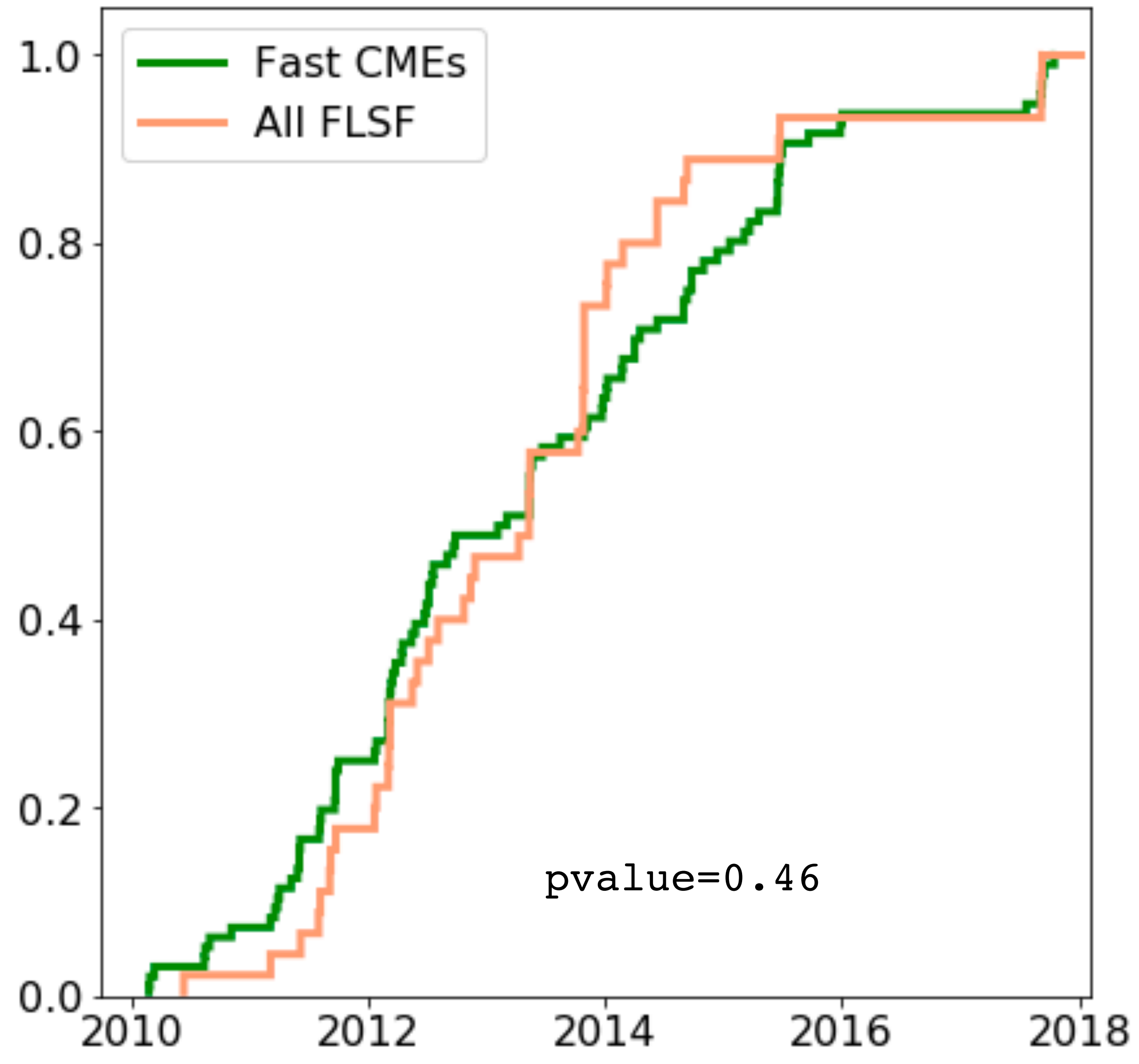




PRELIMINARY





	Total	2010 - 2014	2014 - 2018
GOES M and X-class	773	384	389
Fast CMEs (>1200km/s)	96	**61**	35
Major SEP Events	42	**30**	12
FLSF	45	**33**	12

Summary and Conclusions

- Fermi-LAT is providing valuable observations to understand particle acceleration, transport and gamma-ray emission in Solar Flares;
- Comprehensive study of high-energy solar flares ongoing: toward the first LAT catalog of high-energy solar flares covering Cycle 24
  - Distinct phases observed (prompt vs delayed);
  - Prompt emission observed during on-disc flares suggests acceleration at the flare site
  - Correlation with CME stronger than correlation with GOES X-ray peak flux: acceleration at the CME shock for long duration flares?

- Behind the limb flares: acceleration site likely to be the CME shock, as suggested by Cliver et al. (1993), Pesce-Rollins et al. (2015), and Plotnikov et al. (2017)

- Population studies with CME and X-ray flares:
  - Gamma-ray flare duration better correlates with CME speed than X-ray peak flux;
  - North-south asymmetry also suggest better correlation with CME generating active regions;

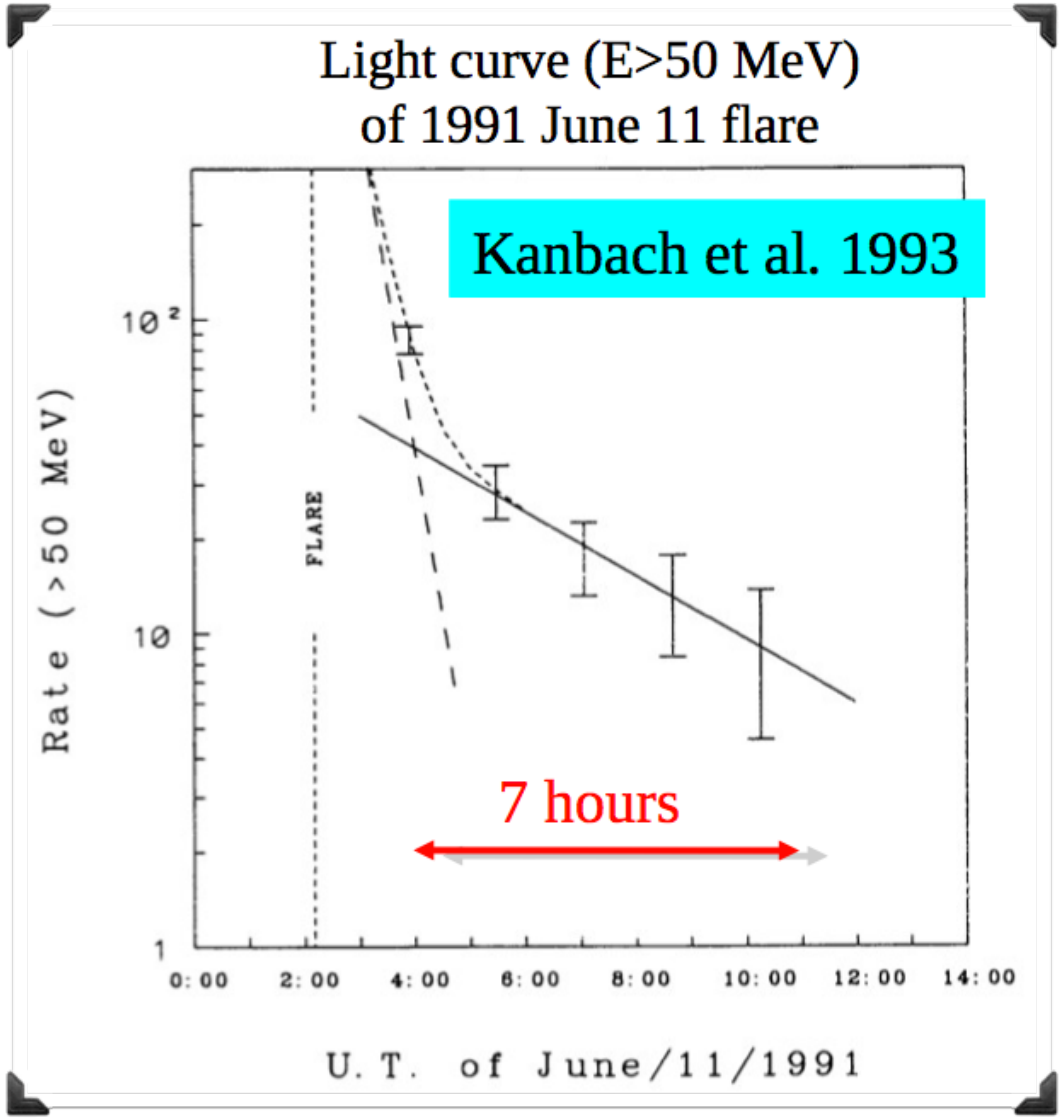

National Aeronautics and Space Administration
NASA
Fermi
Gamma-ray Space Telescope
www.nasa.gov/fermi

Spare


CREDIT: NASA

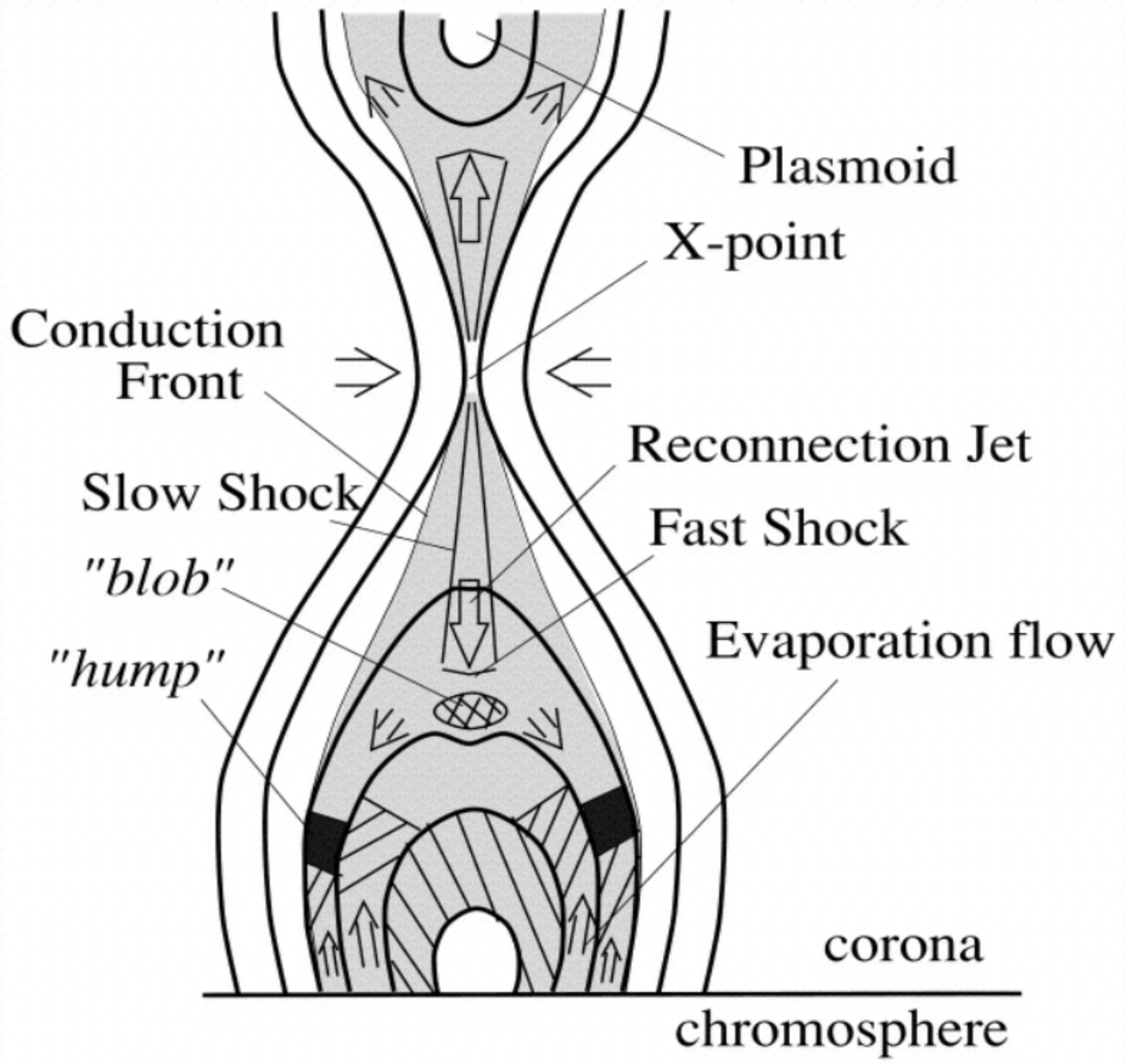
Gamma-ray emission from the Sun

- The sun is a steady, faint source of gamma-rays (produced by the interactions of CR with the solar atmosphere and with the solar radiation field);
- High-energy emission (up to GeV) has been observed during solar flares:
  - In the past decades, only two long-lived (hours long) gamma-ray emissions were observed by EGRET (e.g. Kanbach et al., 1993, Ryan et al. 2000)
  - It was unclear where, when, how the high-energy (HE) particles responsible for gamma-ray emission are accelerated
    - EGRET was saturated during the brightest emission
    - No precise localization available

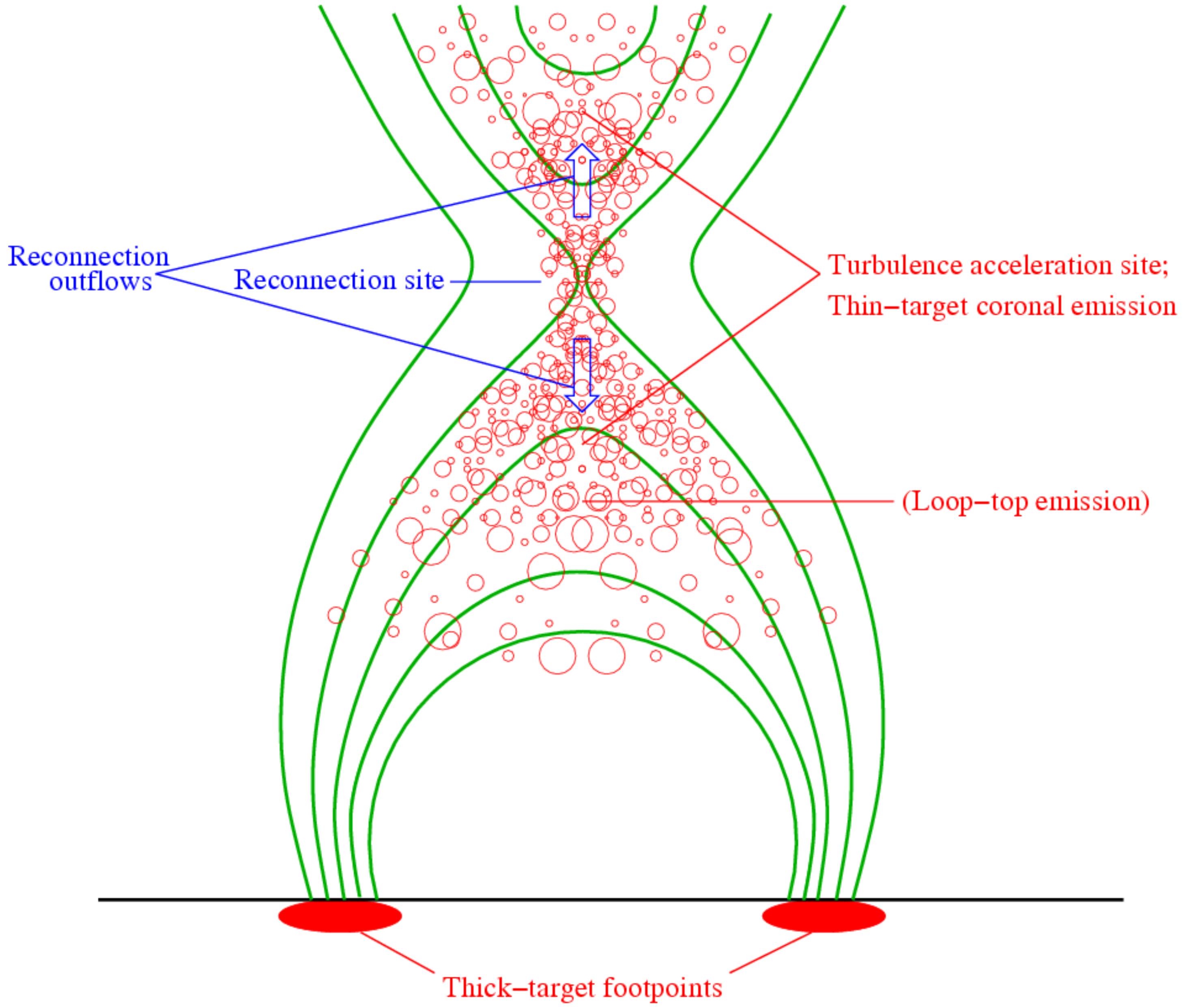


Particle acceleration and gamma-ray emission in solar flares

Accelerated protons and ions must interact in **high dense region** (above the photosphere) to produce gamma-rays via pion decay



- **Trap-precipitation of HE particles produced during the impulsive phase via magnetic reconnection (Kanbach et al. 1993);**
- **In coulomb collision, the trap efficiency increases with energy, and a gradual hardening of the spectrum is expected;**
- **Not observed during the sustained emission;**

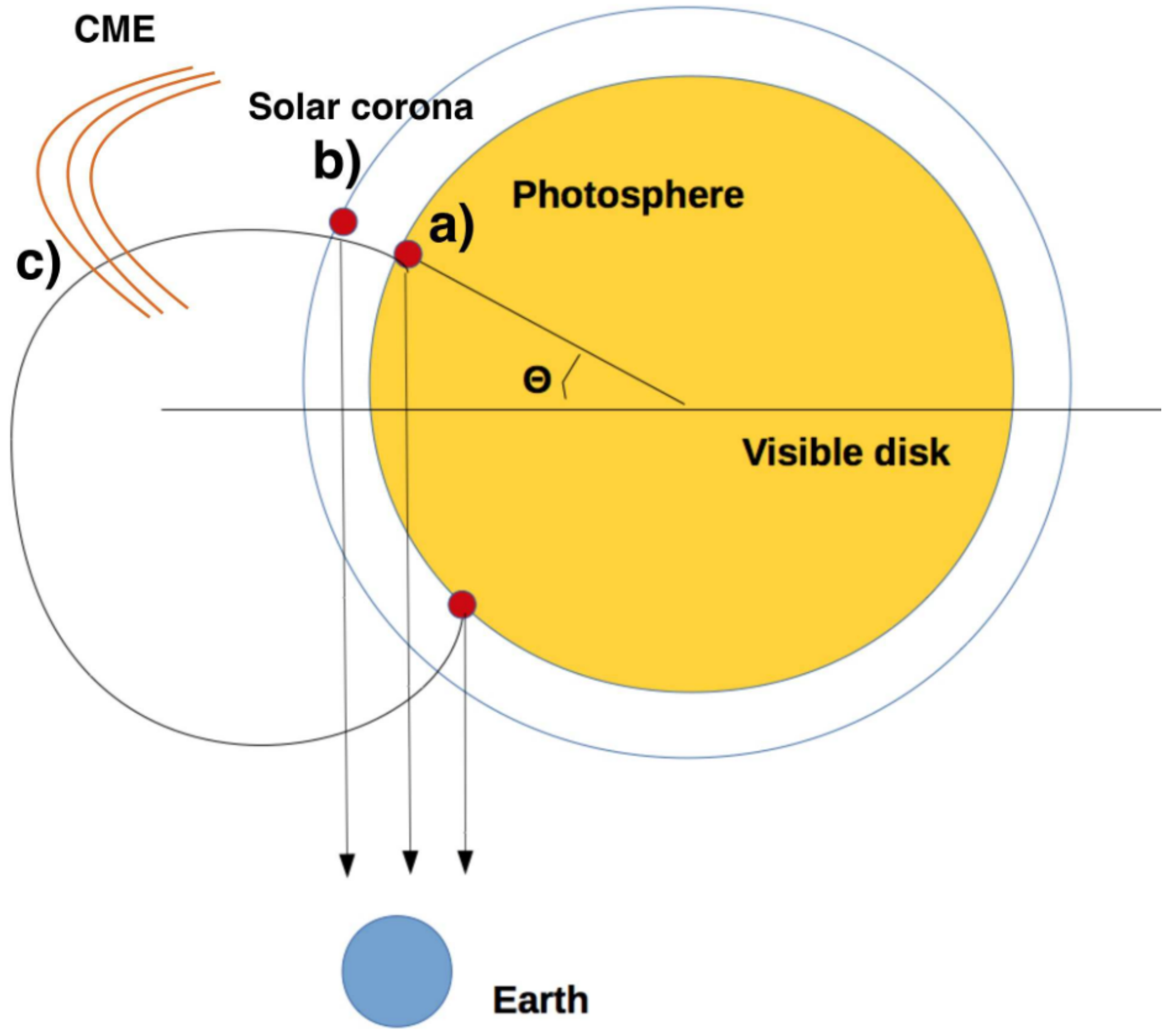


- **Continuous acceleration at flare reconnection region via Stochastic acceleration (Petrosian & Liu 2004);**
- **Accelerated particle spectra become softer as turbulence weakens;**
- **Can explain the spectral evolution seen;**

In both these scenarios the high-energy gamma-ray emission is spatially close to the active region that produced the X-ray flare

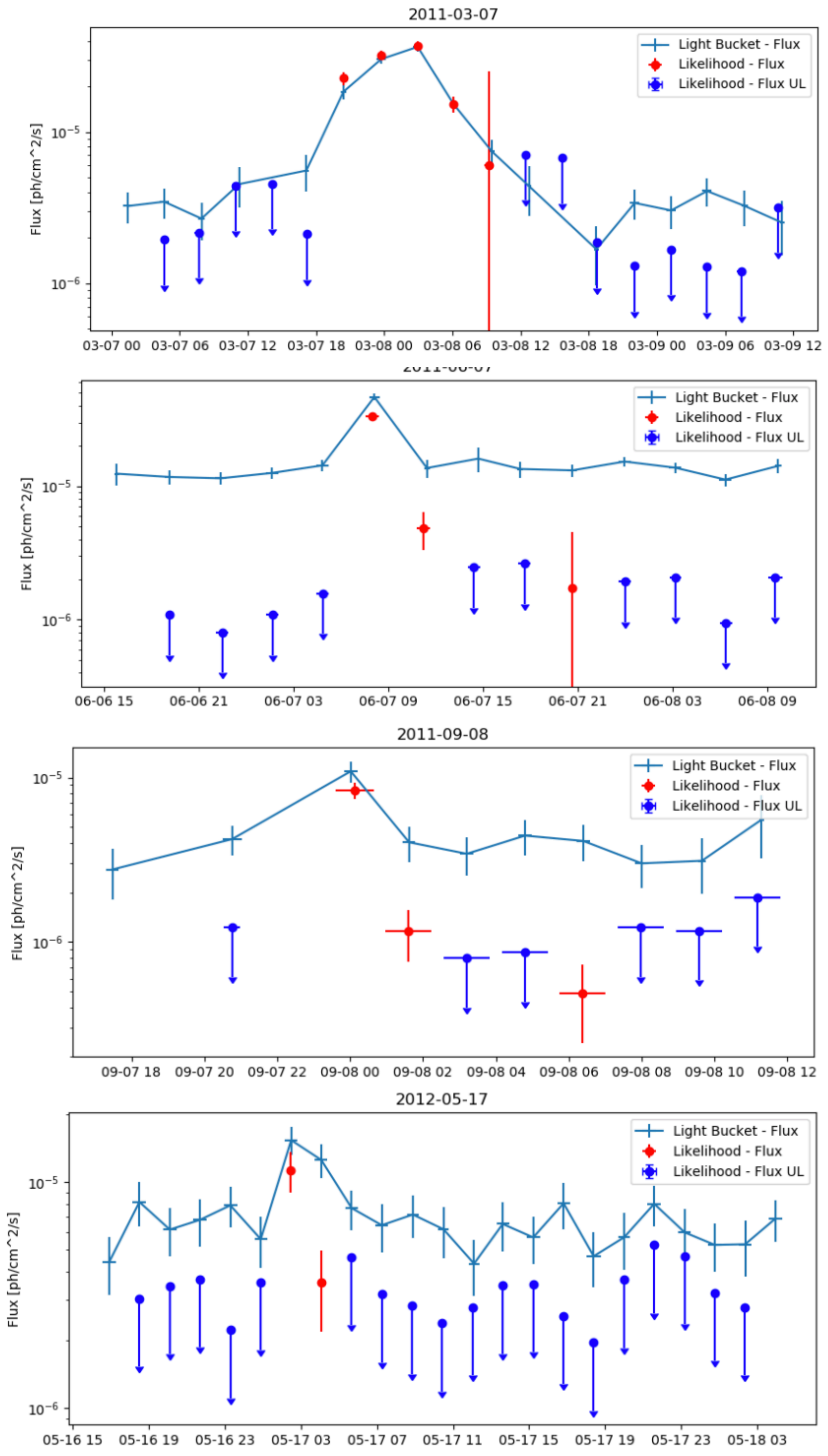
Particle Acceleration & gamma-ray emission in Solar Flares

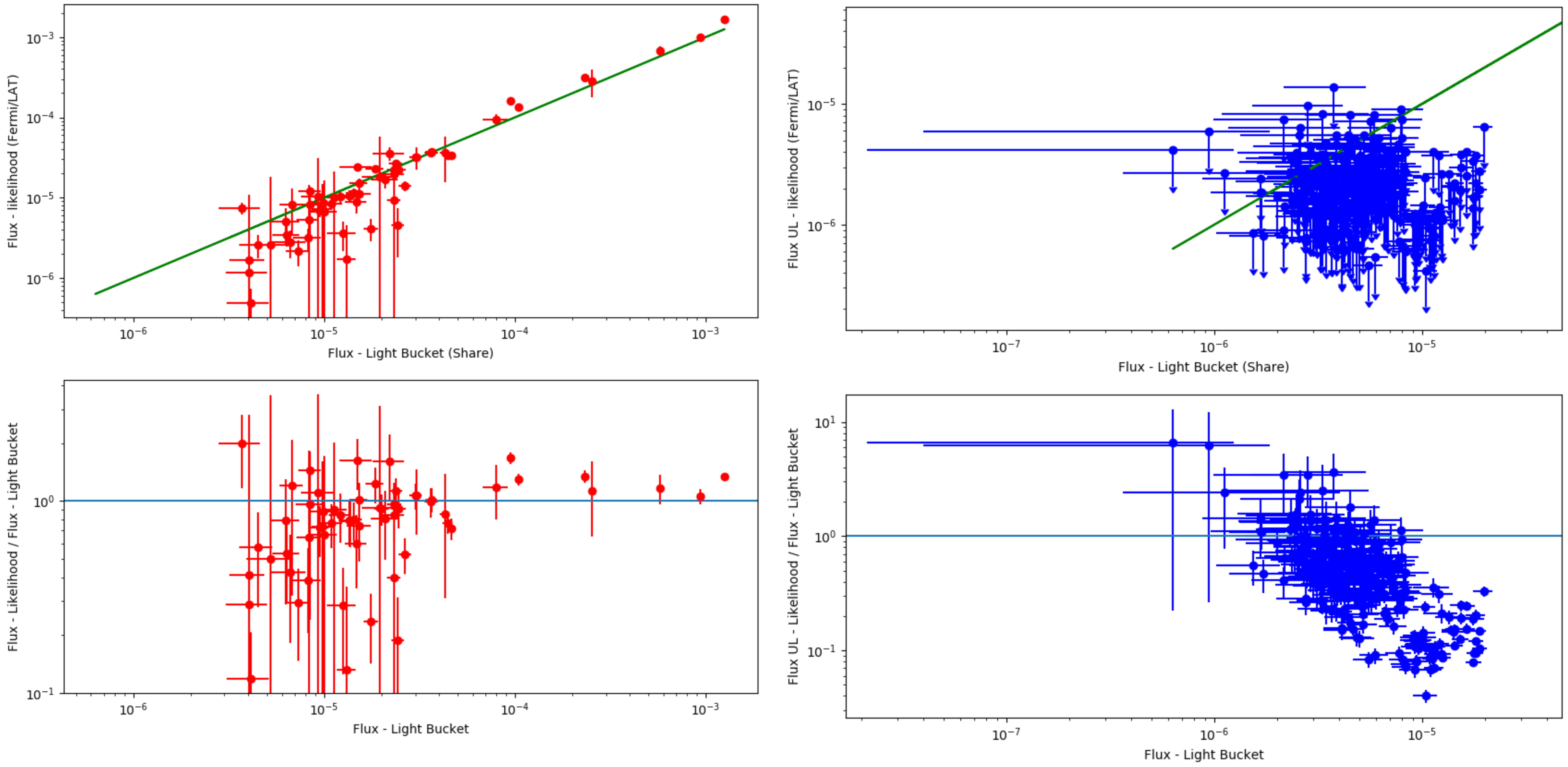
- a) Prompt emission: temporally correlated with the HXR emission
  - proton injection at the flare site, precipitation, emission consistent with the foot-points
  - Occulted in behind the limb flares
- b) Emission at the loop top
  - acceleration at the loop top, trapping
  - visible in behind the limb (if loop is large enough) (see Vahe Petrosian talk)
- c) Acceleration at the CME shock
  - Acceleration at the shock front (~2 solar radii)
  - Trapping and precipitation along large field lines
  - Explain BTL flares (as in Cliver et al., 1993)
  - Correlation with SEP



Omodei et al. 2015 (arXiv:1502.03895)

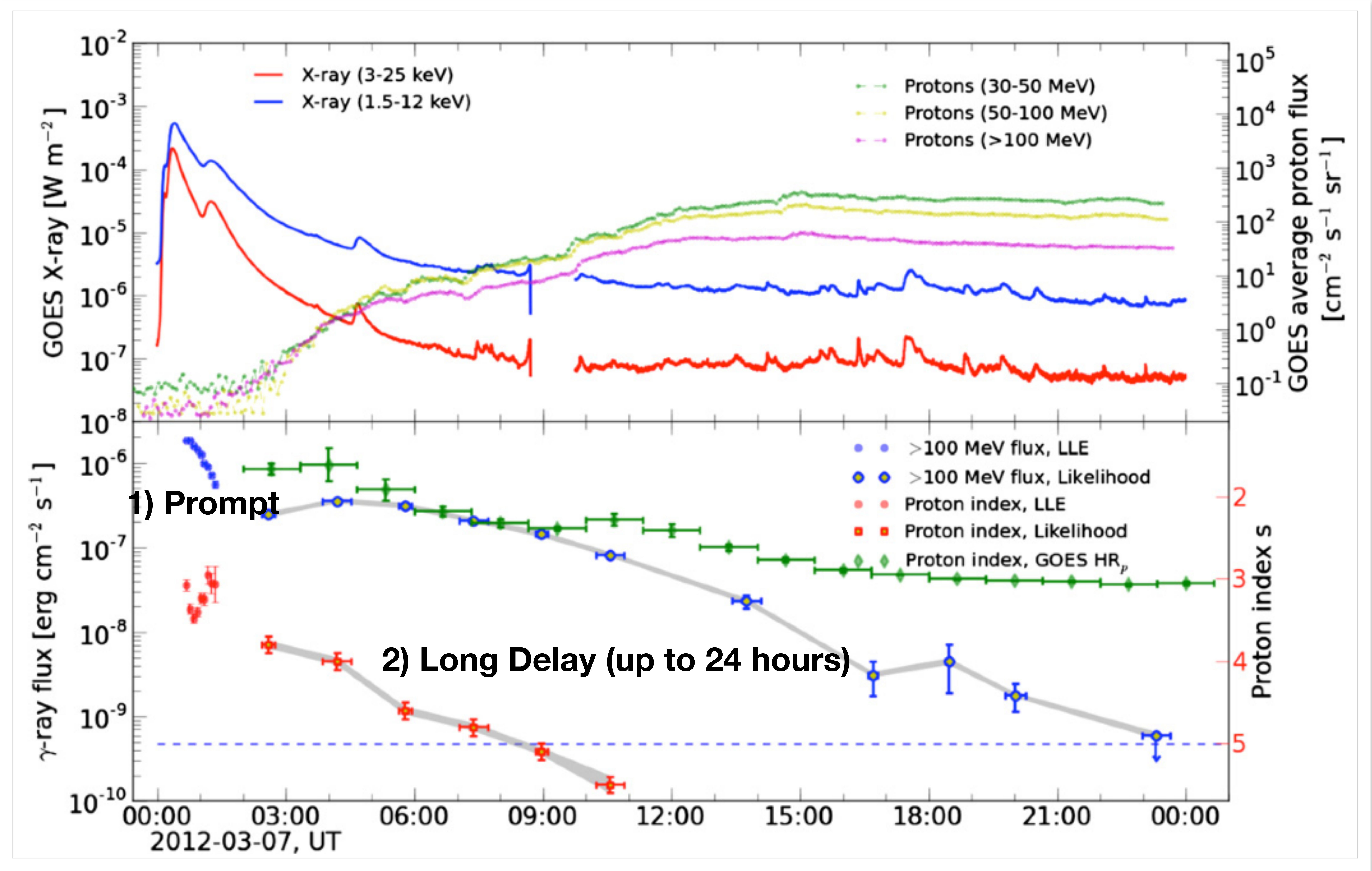
The Likelihood analysis and the “Light bucket” by Share et al.





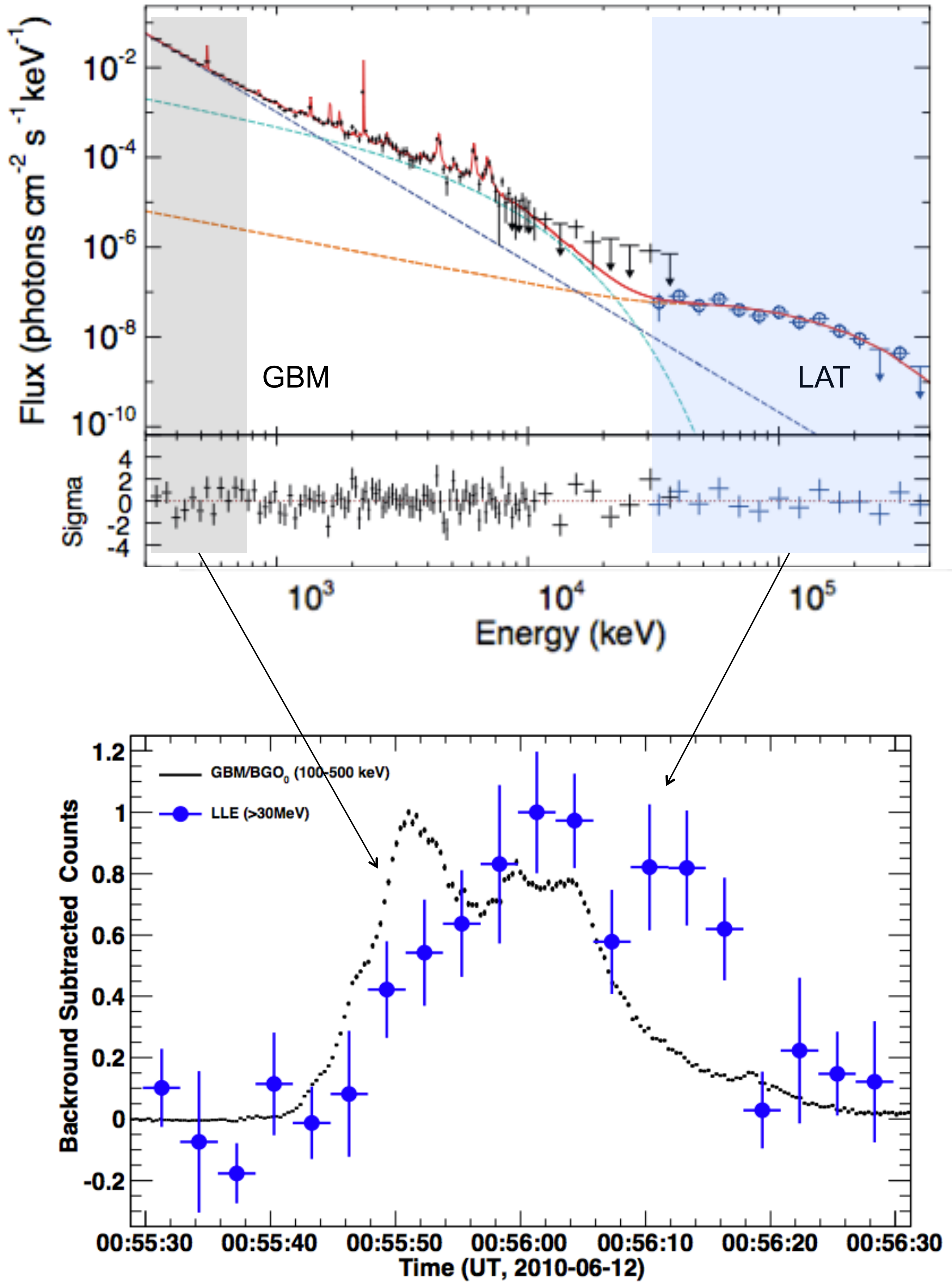
- **The “light bucket” has some issues:**
  - **The background is not fitted (and therefore the flux for dim flares is largely overestimated)**
  - **The exposure is calculated with an assumed (not fitted) spectral model:**
    - **this can explain the discrepancy saw with bright fluxes**

Longest emission



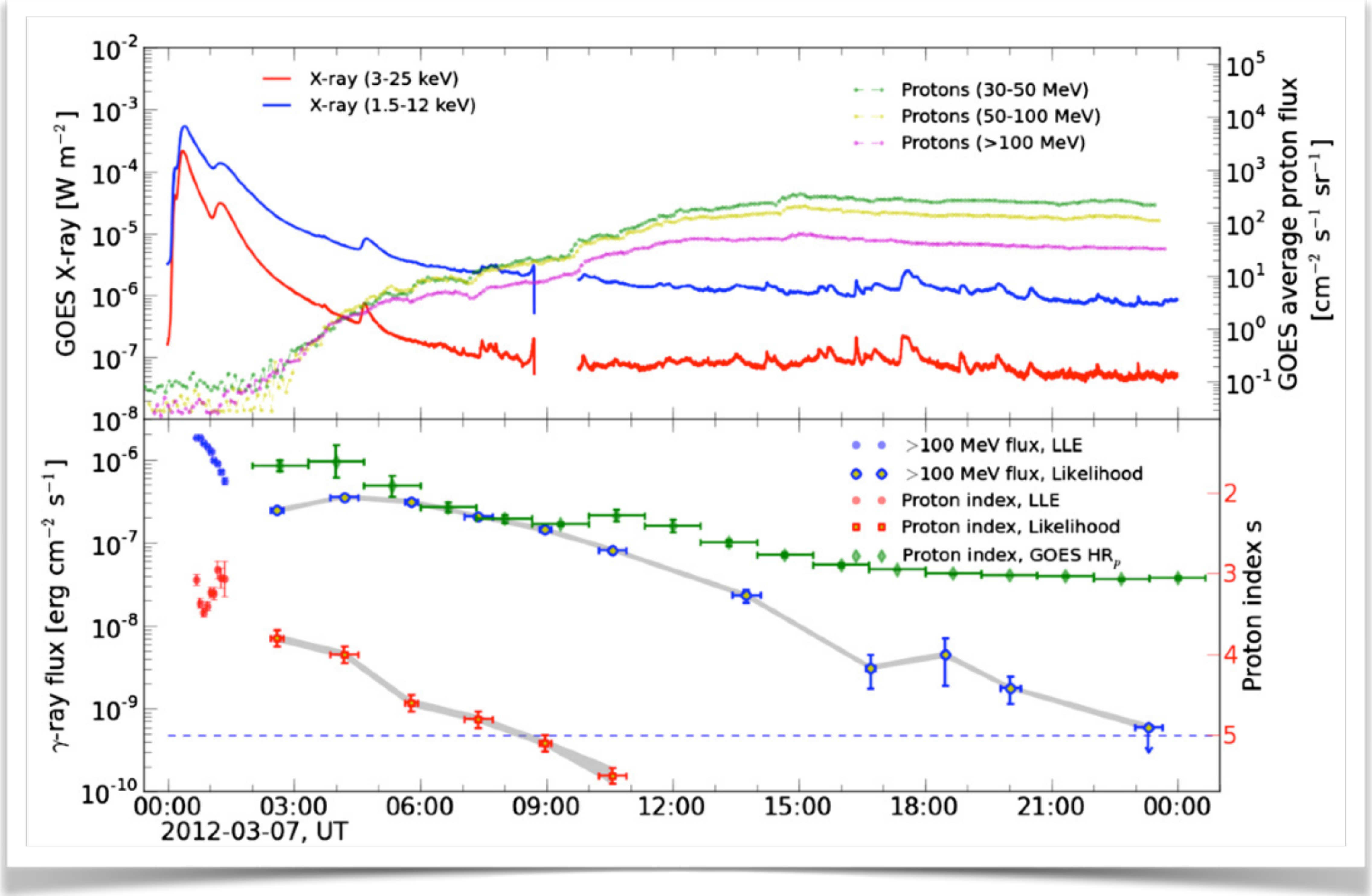
Impulsive & Delayed emission detected by Fermi LAT

Impulsive events



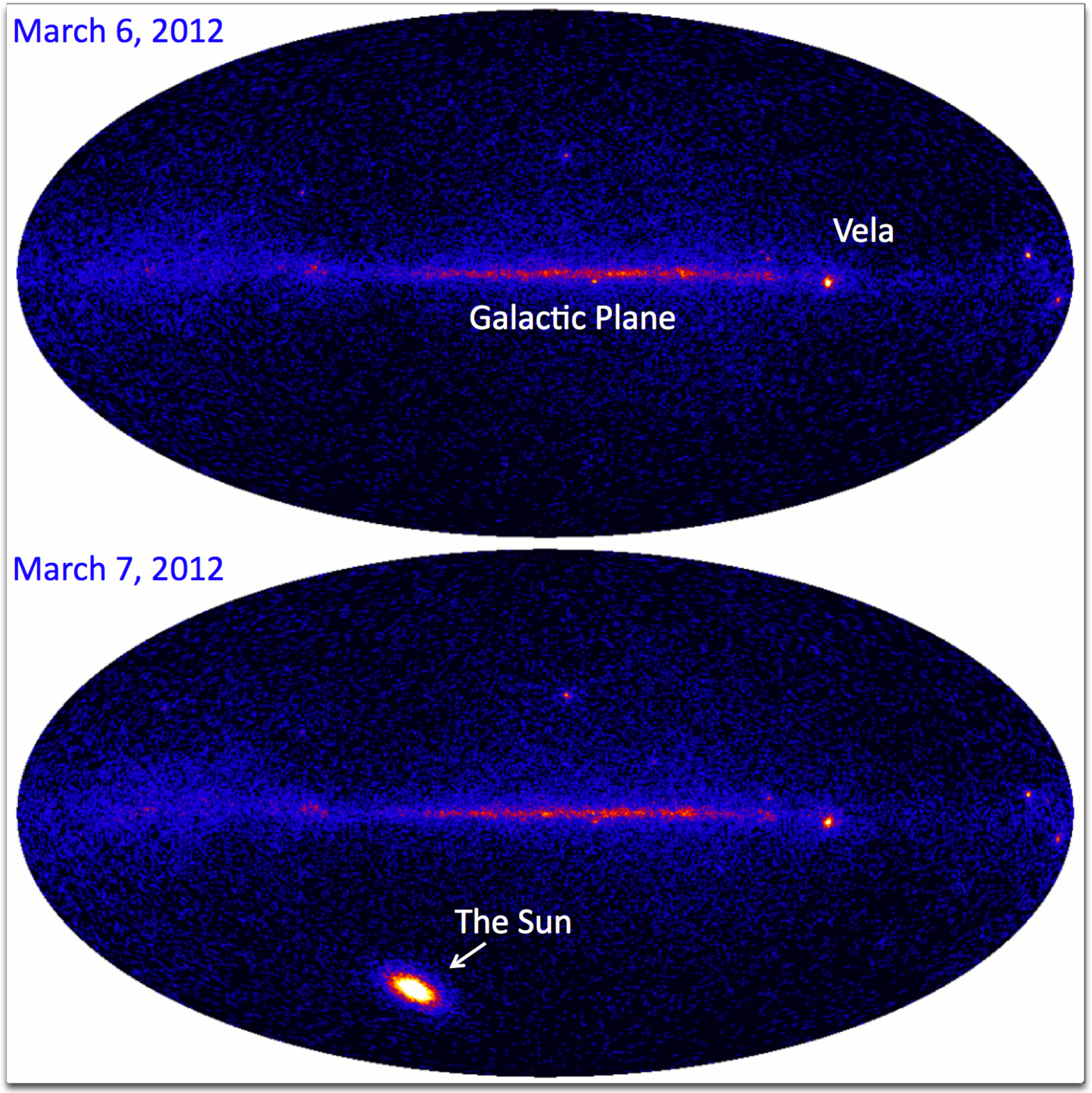
Simultaneous HRX and gamma-ray emission
Ackermann et al. 2012, ApJ...745..144A

Long Lasting emission



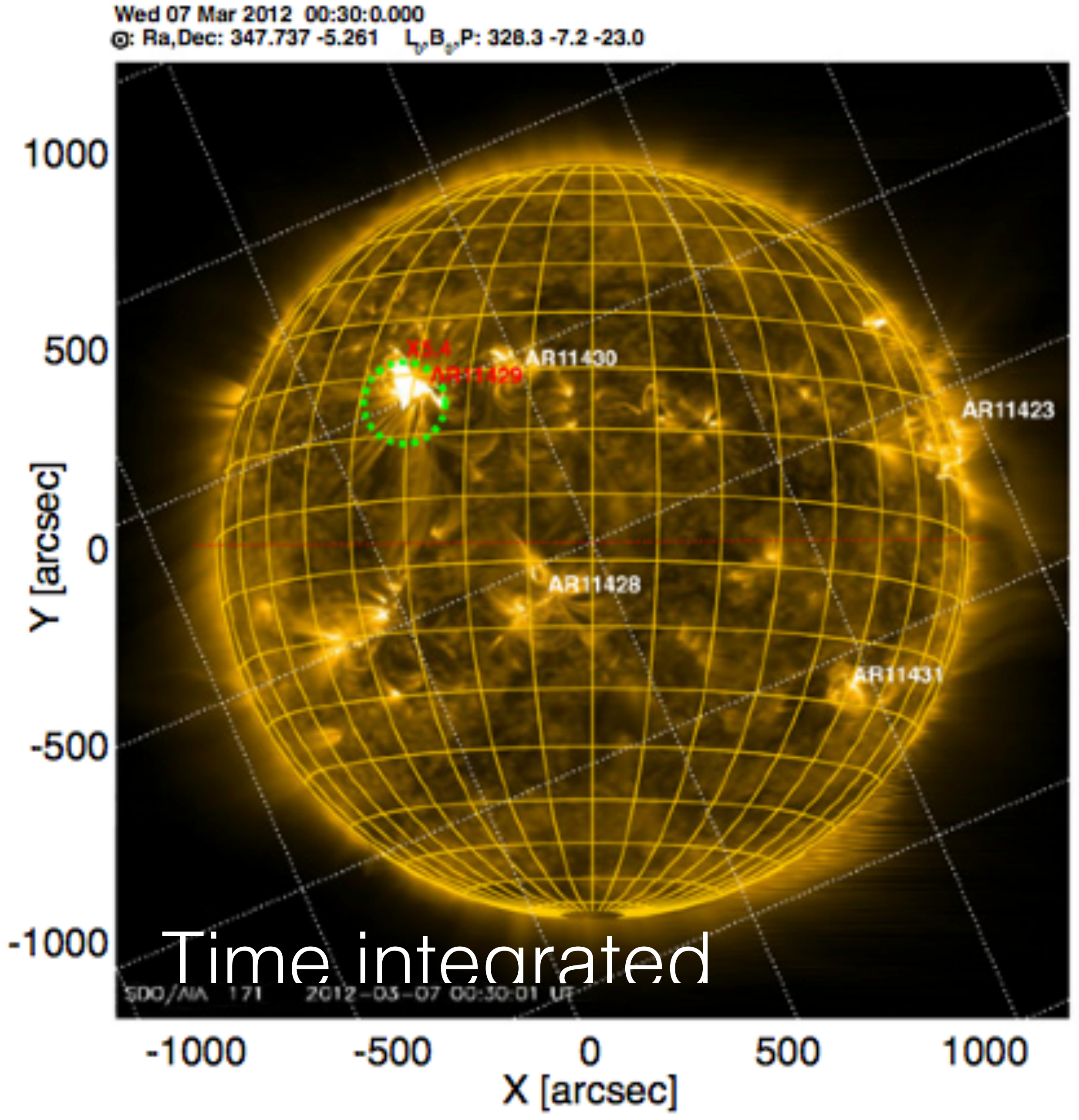
Sustained emission observed up **20 hours**
Ackermann, M. et al. 2014, ApJ, 787, 15

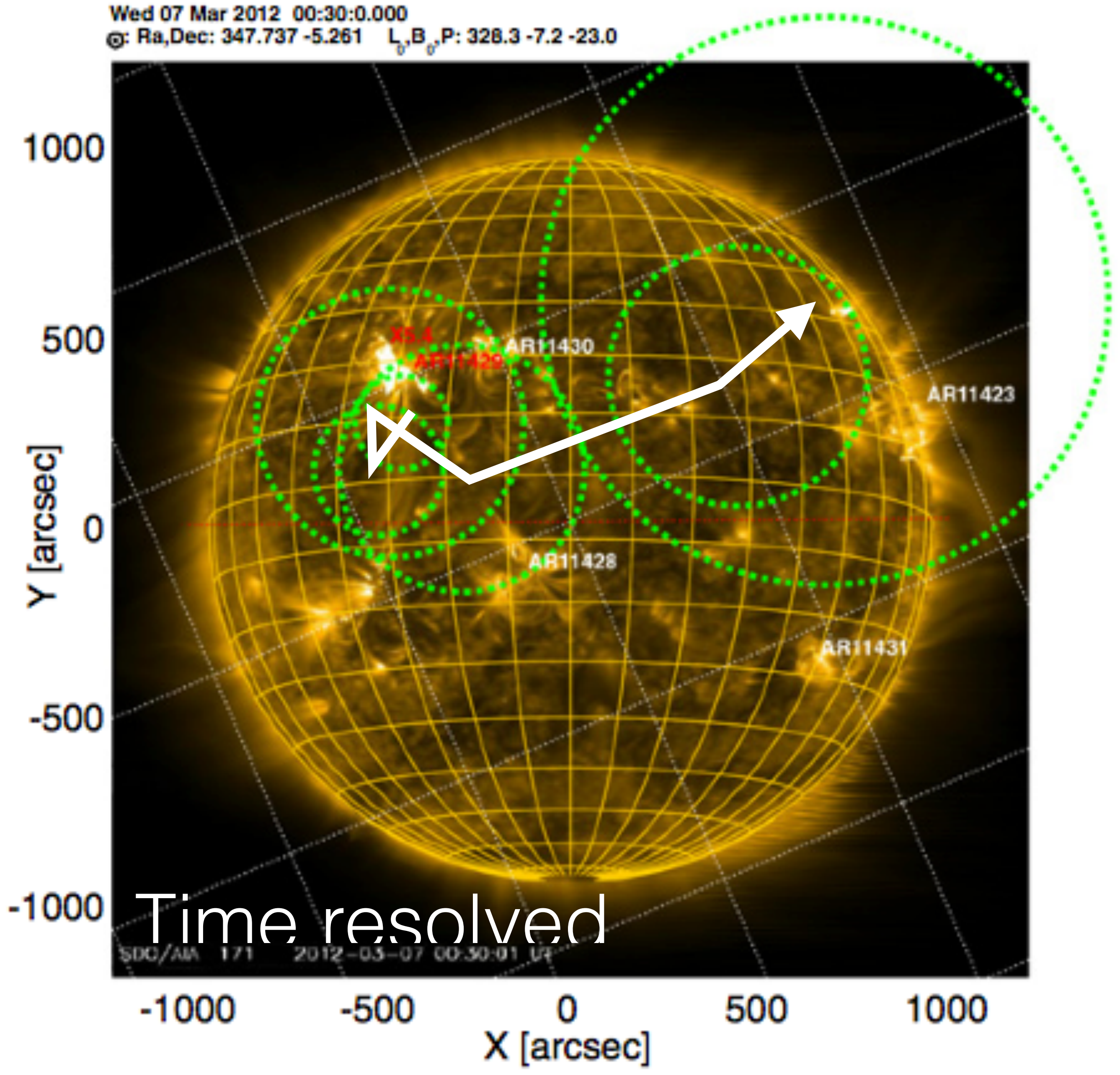
The longest lasting gamma-ray emission: March 7, 2012



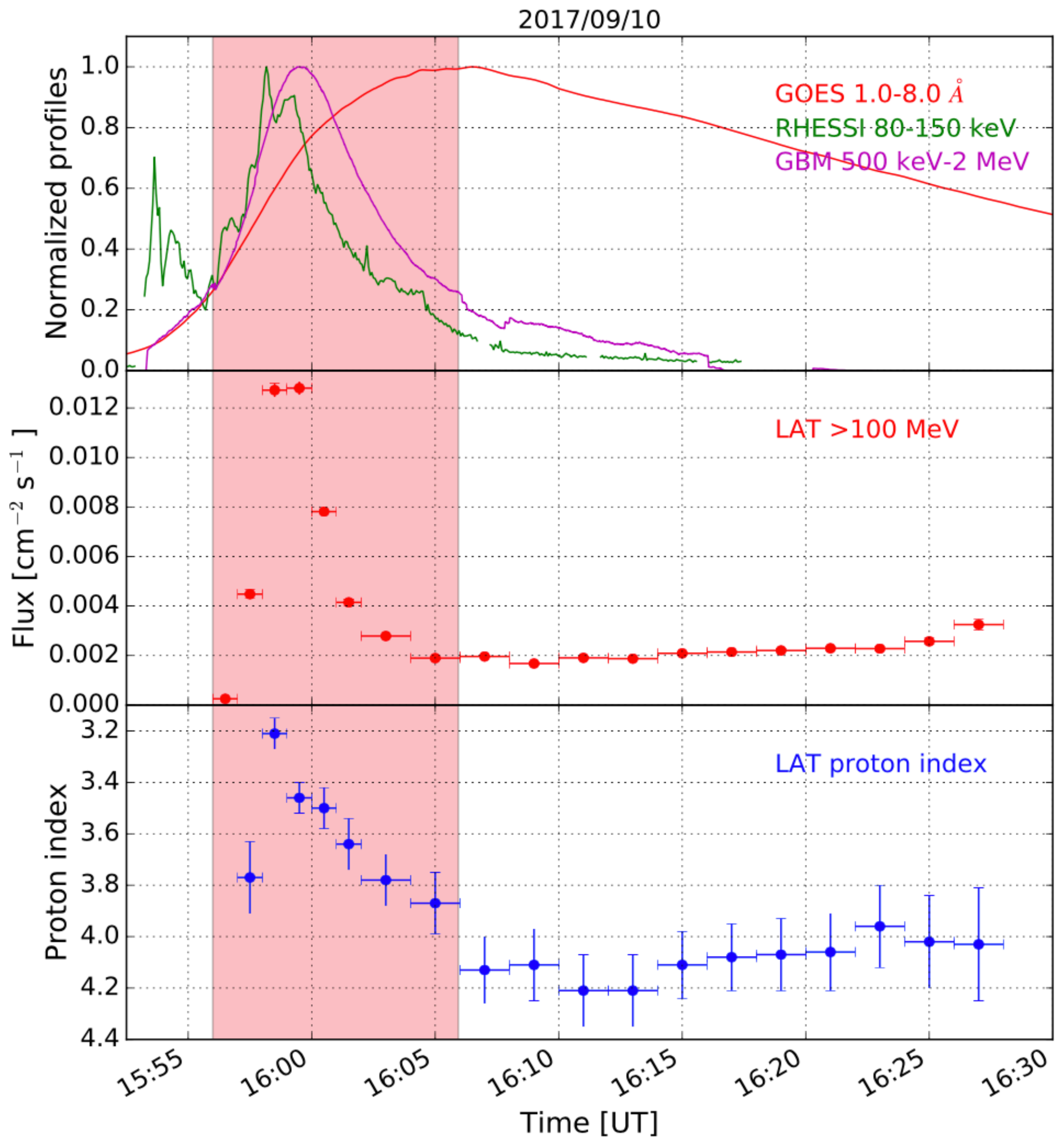
LAT 1 day all sky data >100 MeV

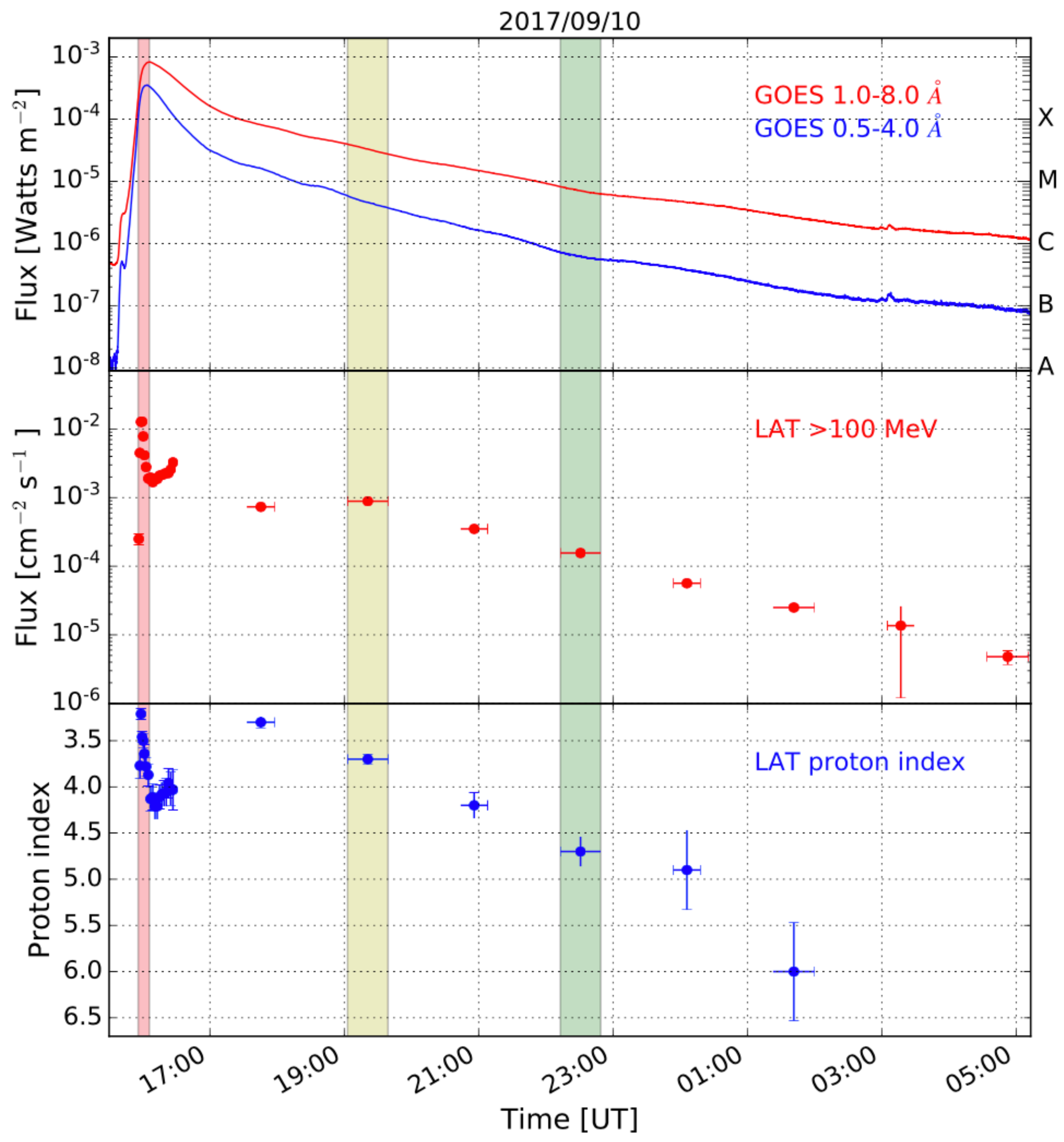
- A very bright Solar Flare was detected on March 7, exceeding:
  - 1000 times the flux of the steady Sun;
  - 100 times the flux of Vela;
  - 50 times the Crab flare;
- High energy emission (>100 MeV, up to 4 GeV) lasts for ~20 hours
- Softening of the spectrum with time

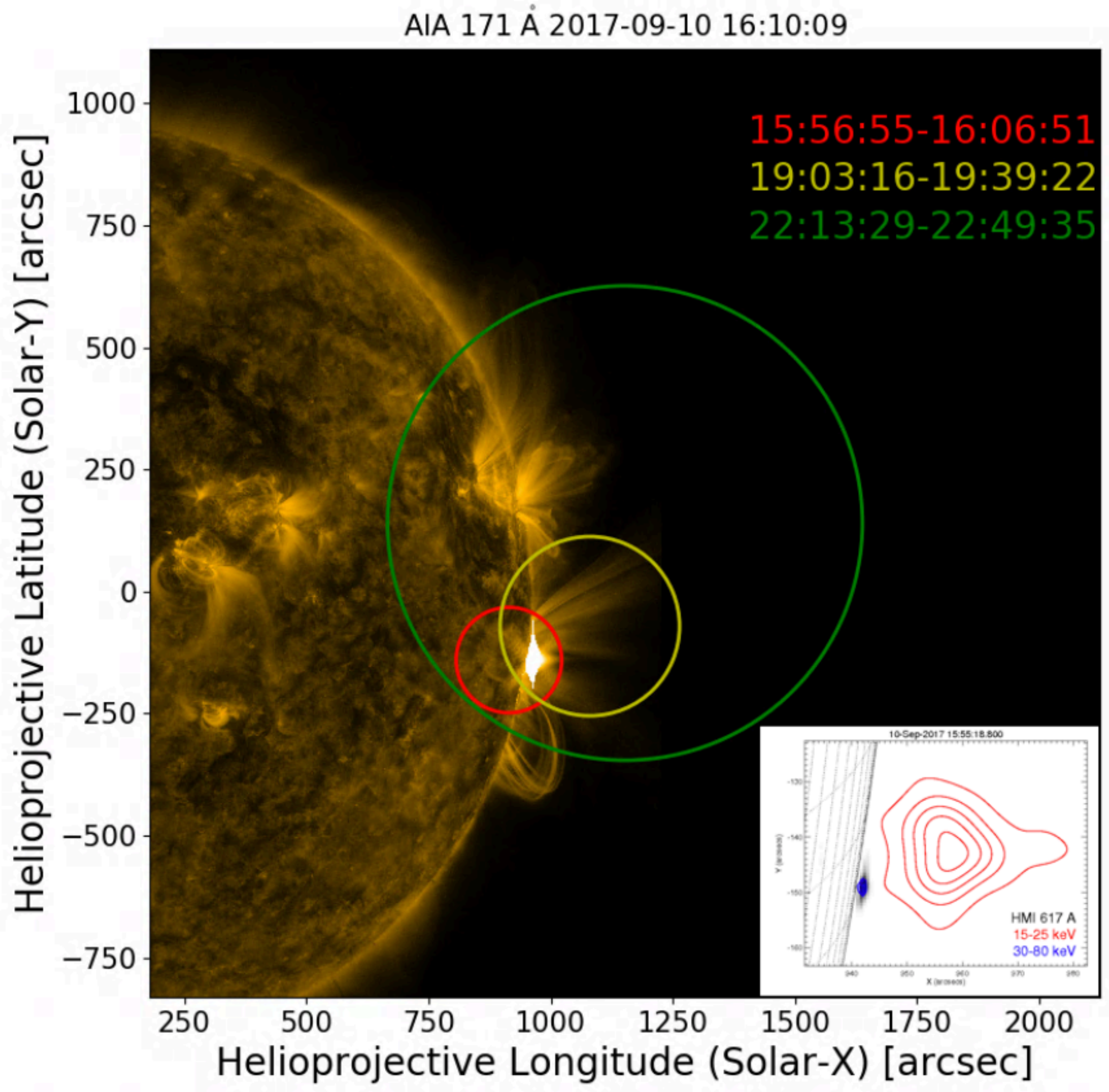




SOL 2017-09-10 localization







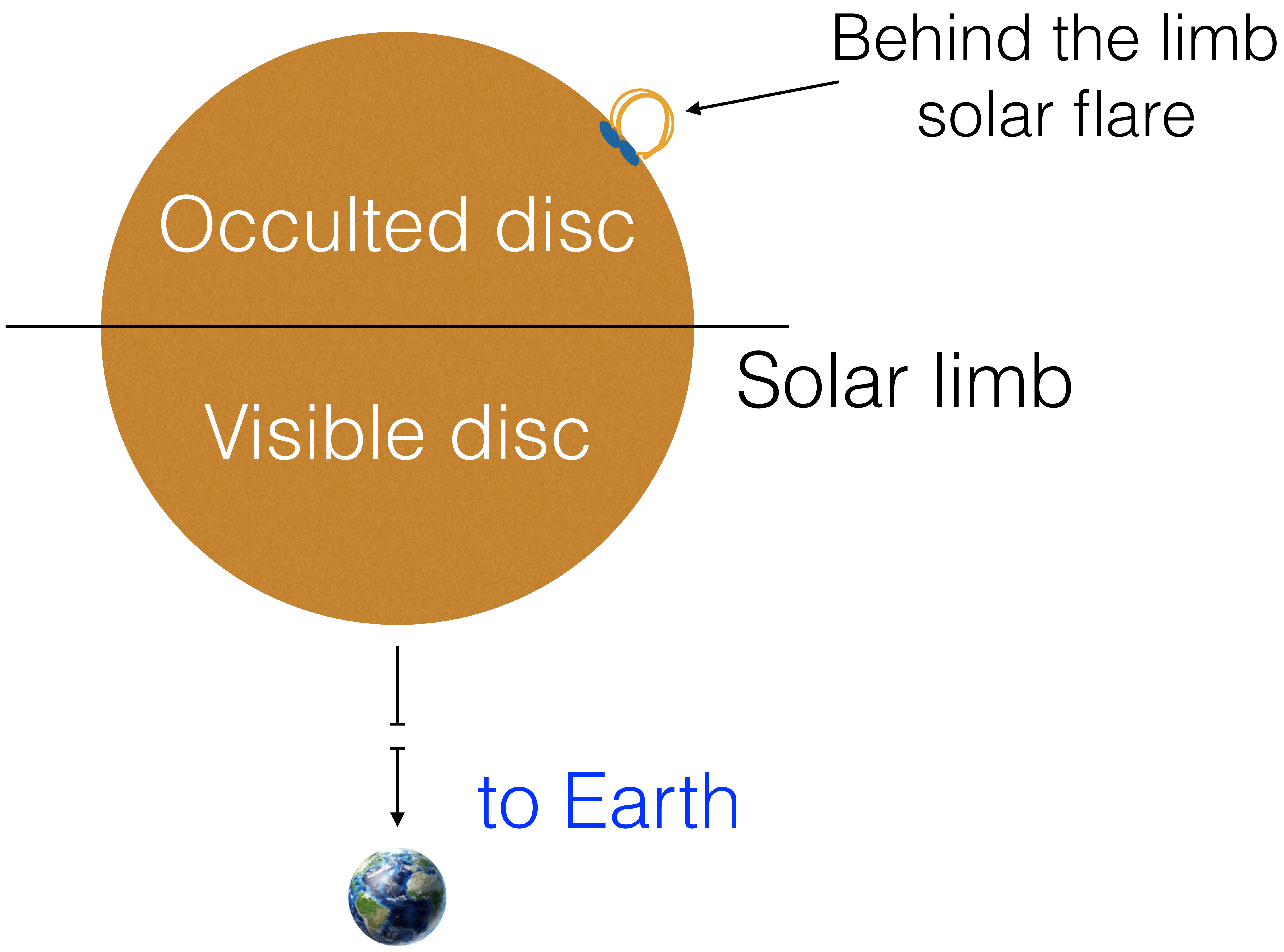
Omodei et al. 2018

- **Exclude the intervals when the sun is more off-axis**
  - **Correction for the fish-eye effect critical**

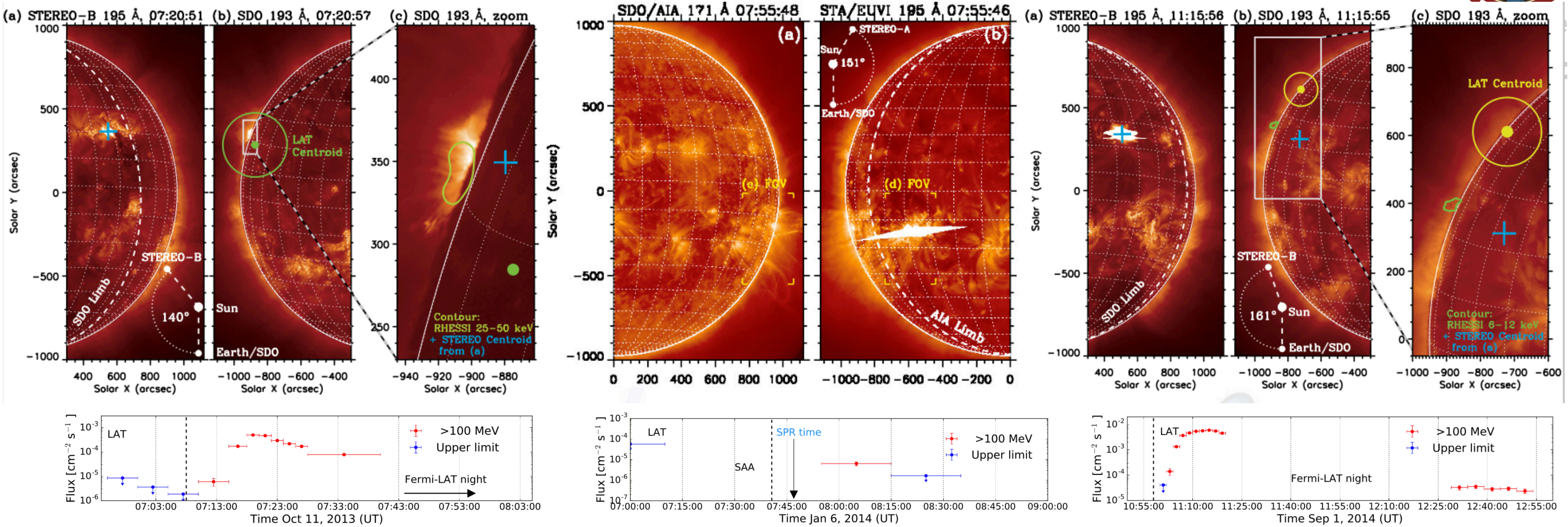
We cannot exclude that the source moved behind the limb -> Spatially extended emission?

Behind-the-limb flares

- **Fermi-LAT is providing detections of >100MeV emission from footpoint occulted flares;**
  - **Pesce Rollins et al. 2015, Ackermann et al., 2017**
- **Gamma-ray emission up to 100 MeV has been detected before from behind-the-limb flares:**
  - **i.e. Vestrand & Forrest 1993, Barat et al. 1994, Vilmer et al. 1999,…**



Behind-the-limb flares



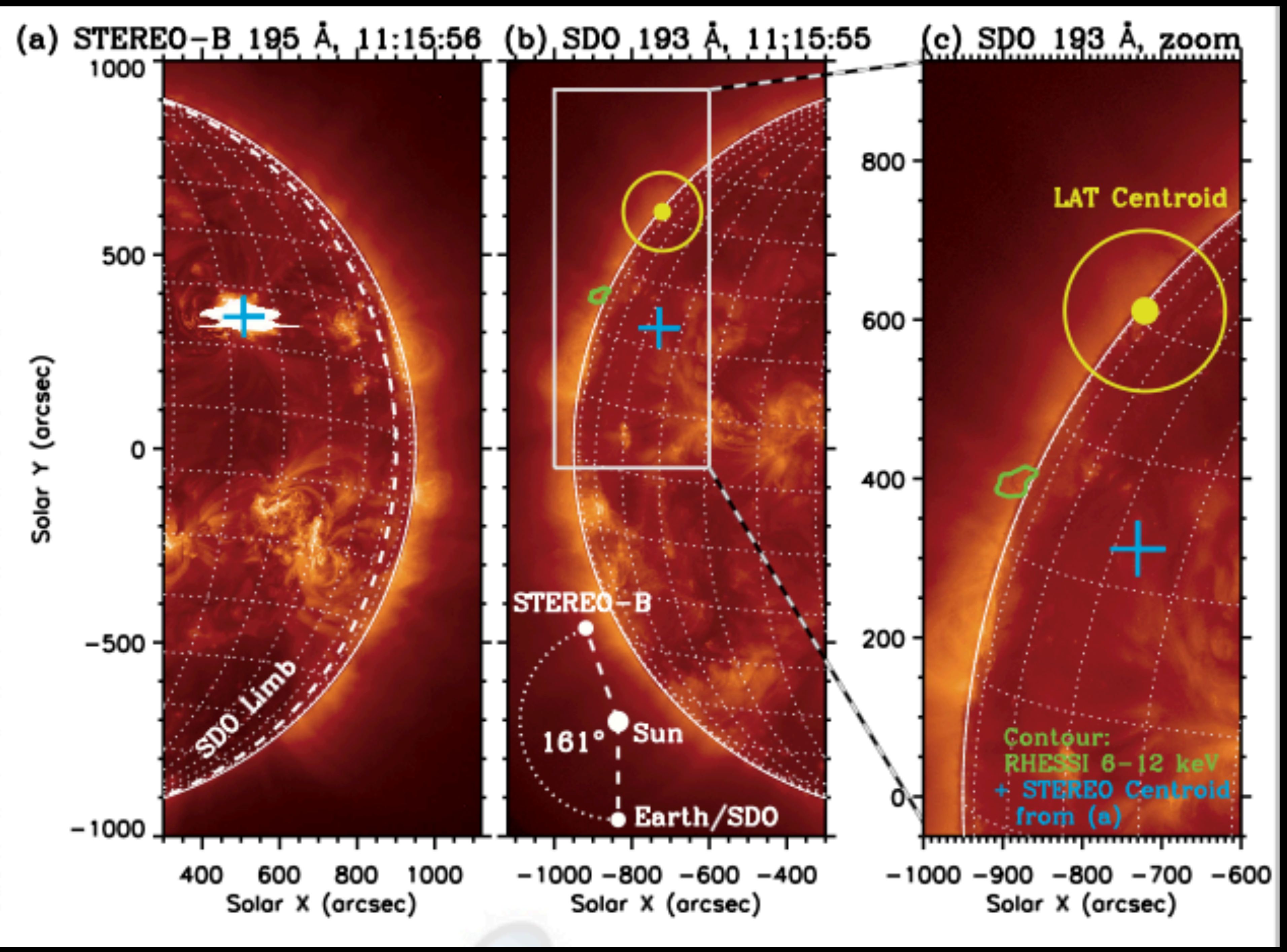
- 10˚ behind the eastern limb;
- RHESSI emission consistent with loop top;

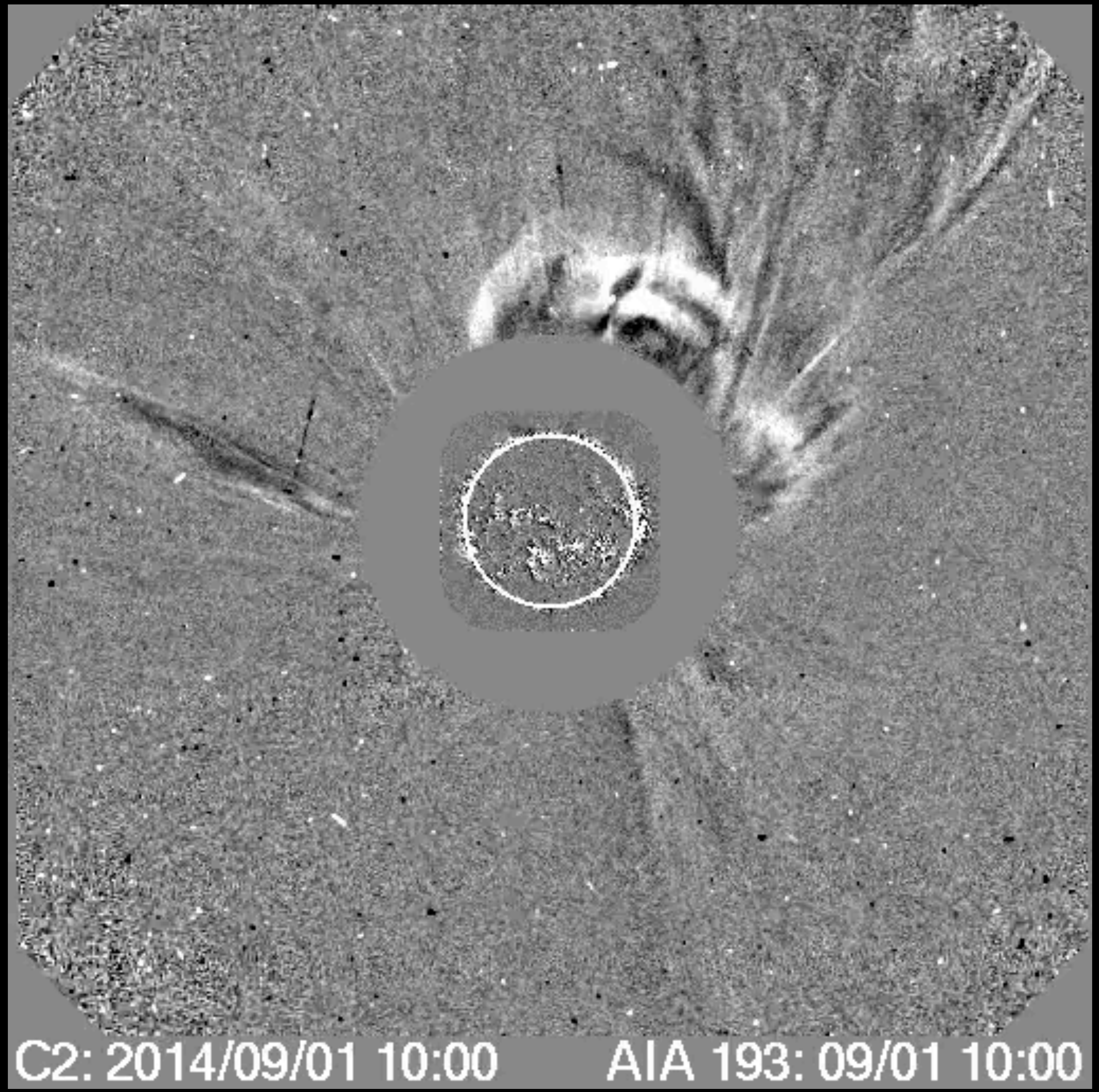
- 20˚ behind the western limb;
- SEP particles with E>=700 MeV detected;

- 43˚ behind the eastern limb;
- Bright LAT emission lasting ~2 hr;

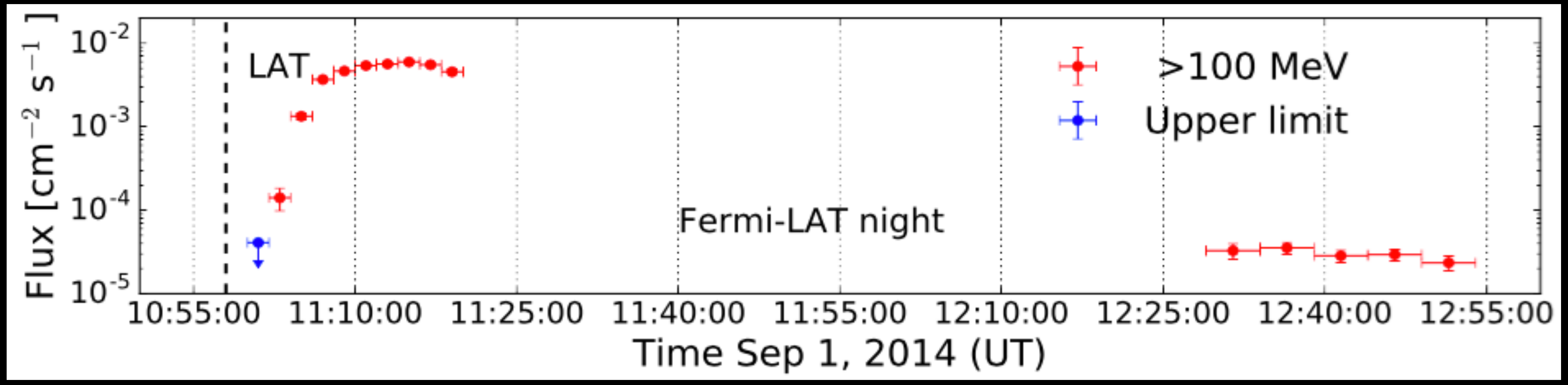
Pesce Rollins et al. 2015, Ackermann et al., 2017

Association with fast CME

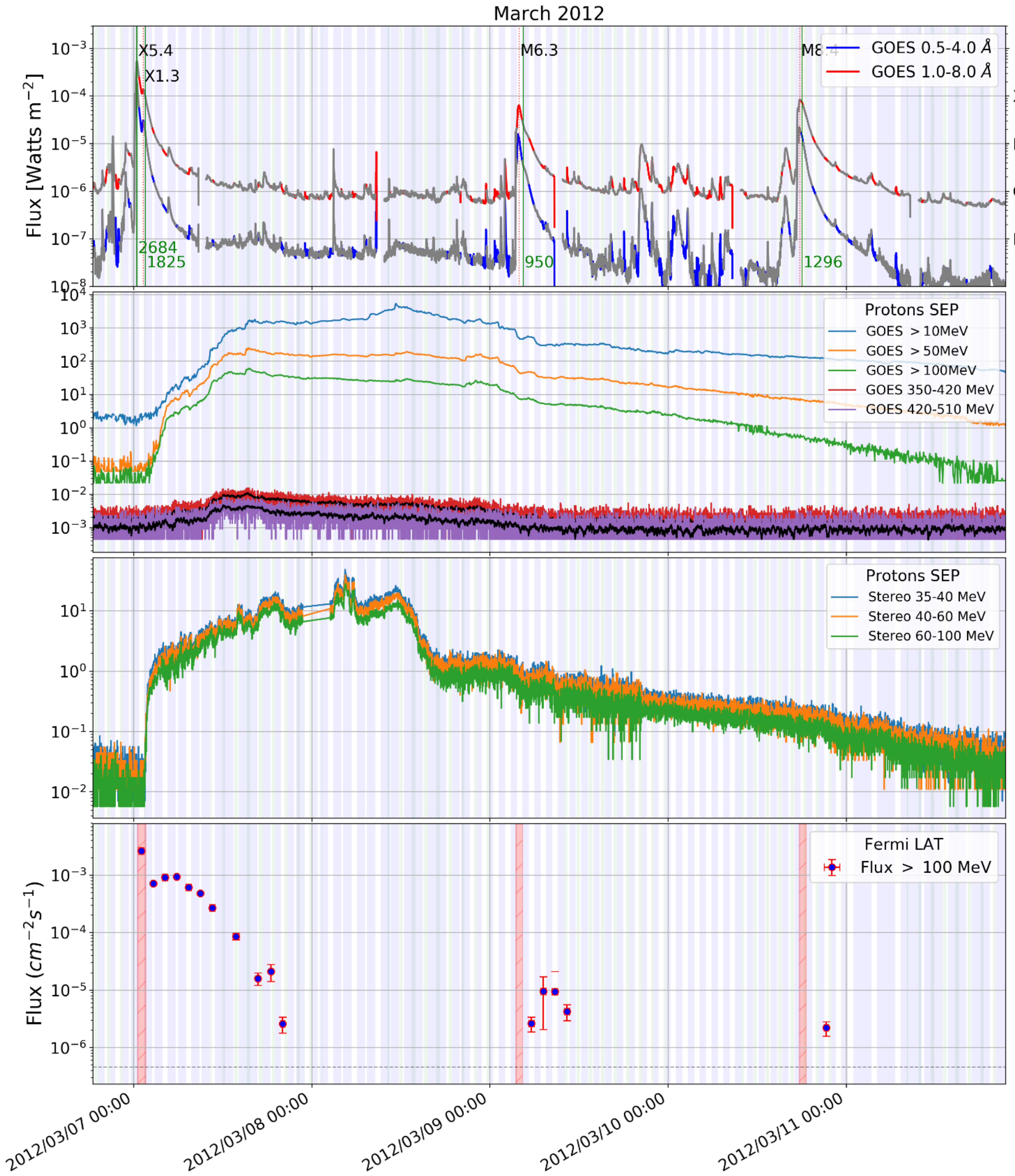


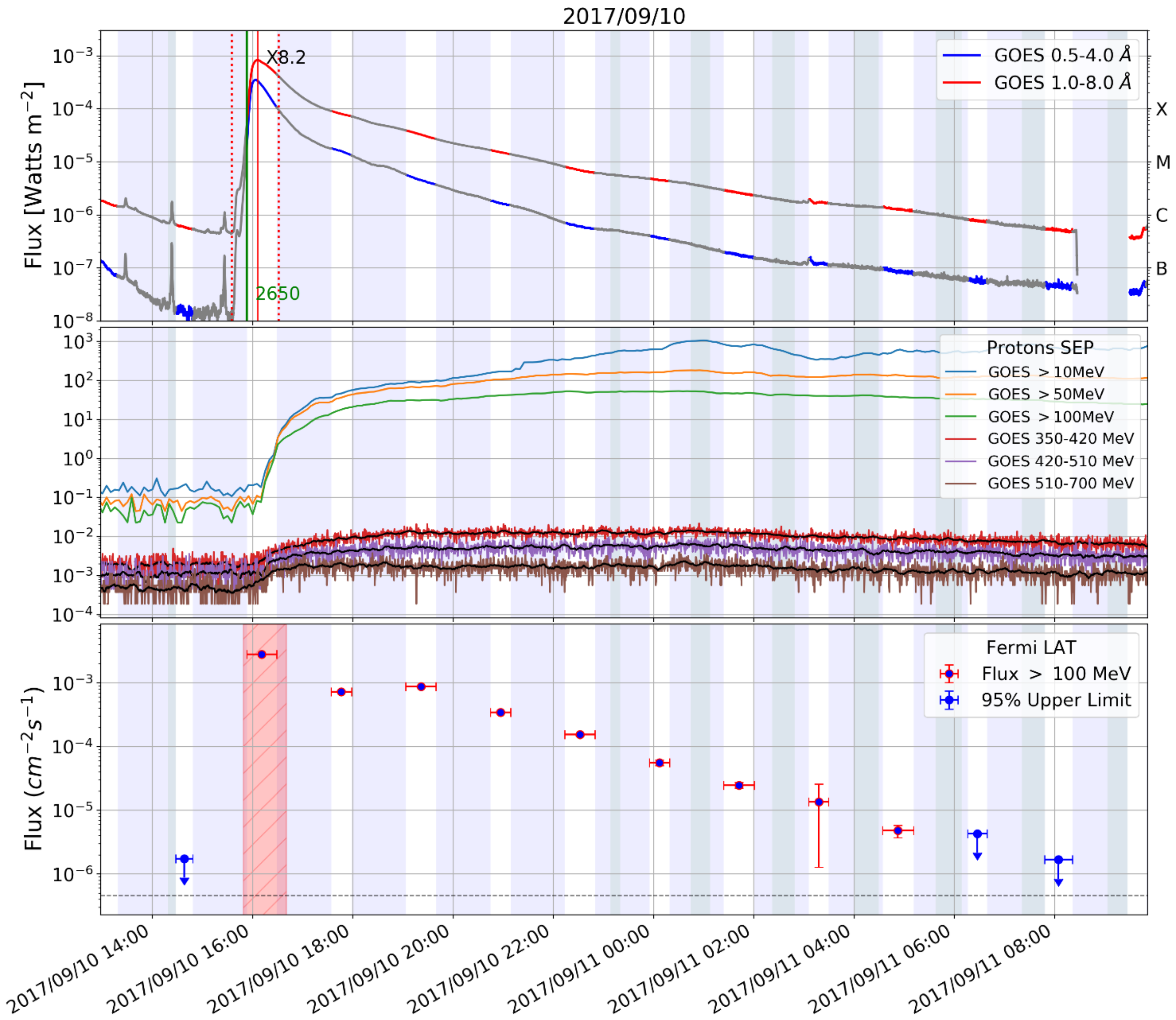


CME speed ~ 1900 km s^{-1}



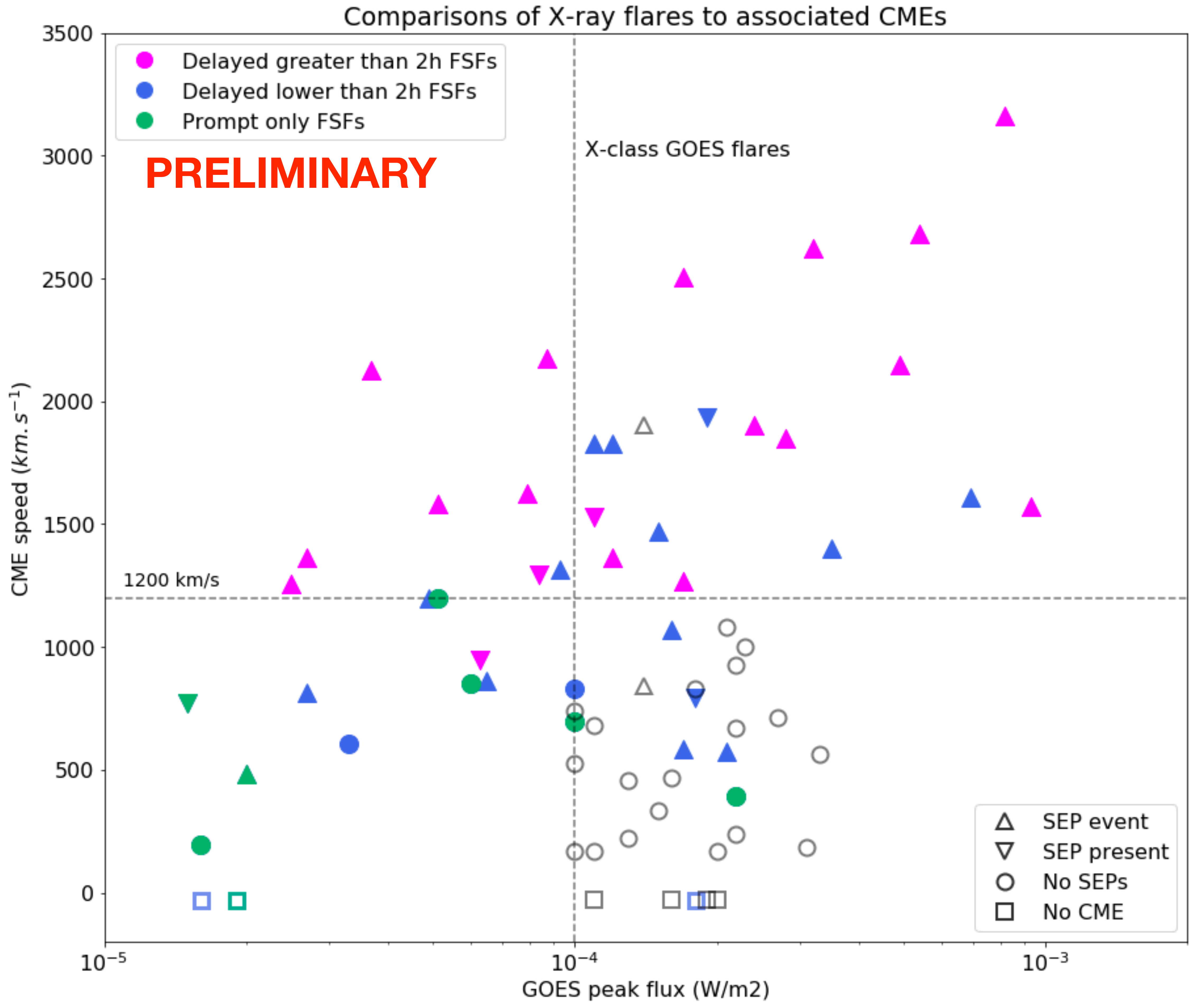
Long gamma-ray emission often associated with fast CME & SEP

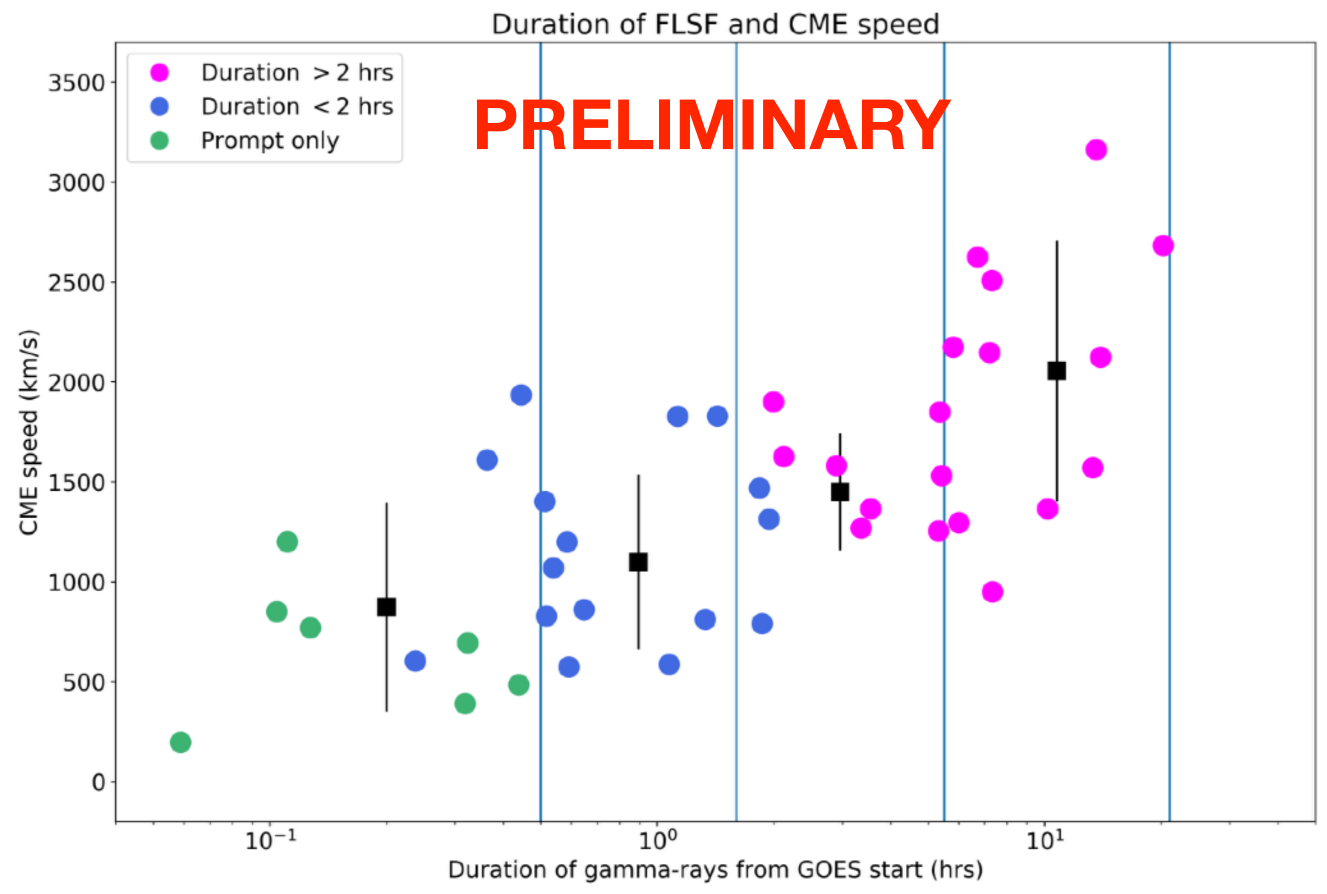




GOES peak/CME speed

- All but one FLSFs with a long delay rank with a CME of speed greater than 1200 km/s
- All flares with a Prompt only component rank below that limit.
- Wider range of behavior in the FLSFs with a delayed emission component shorter than 2 hours
- Non-detected X-class flares (grey) All but one are associated with slow CMEs, (4 are not associated with any CME)





Also reported by Winter et al., 2018