Fermi-LAT Solar Flare Catalog: Observations of Solar Flares at High Energy During Solar Cycle 24th

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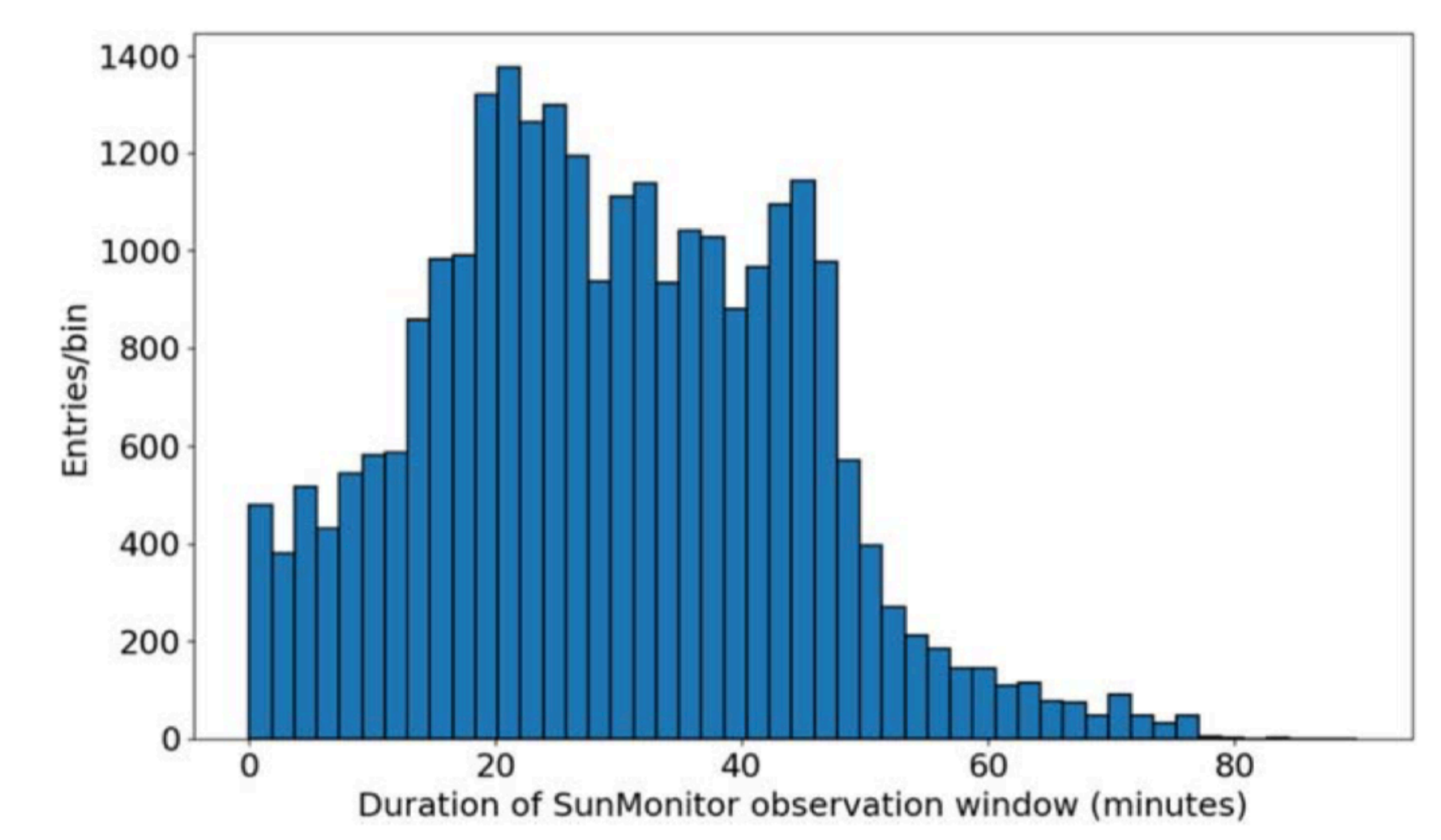
Melissa Pesce-Rollins, Francesco Longo, Vahe Petrosian

on behalf of the Fermi LAT collaboration

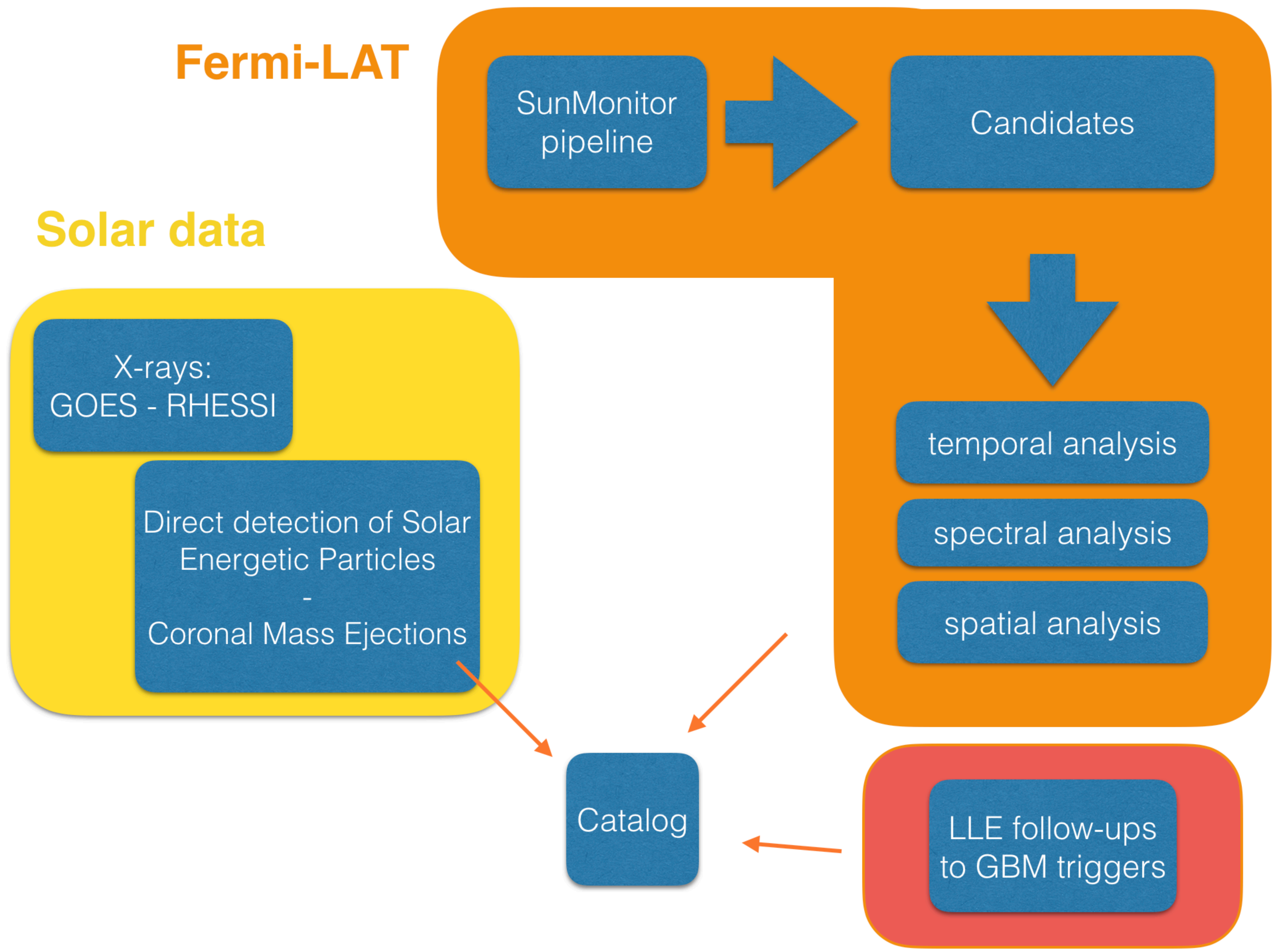
9th International Fermi Symposium

Fermi-LAT as Solar Observer

SunMonitor: pipeline that continuously monitor the Sun using Fermi-LAT data (standard likelihood analysis)



Solar Flare Catalog Framework

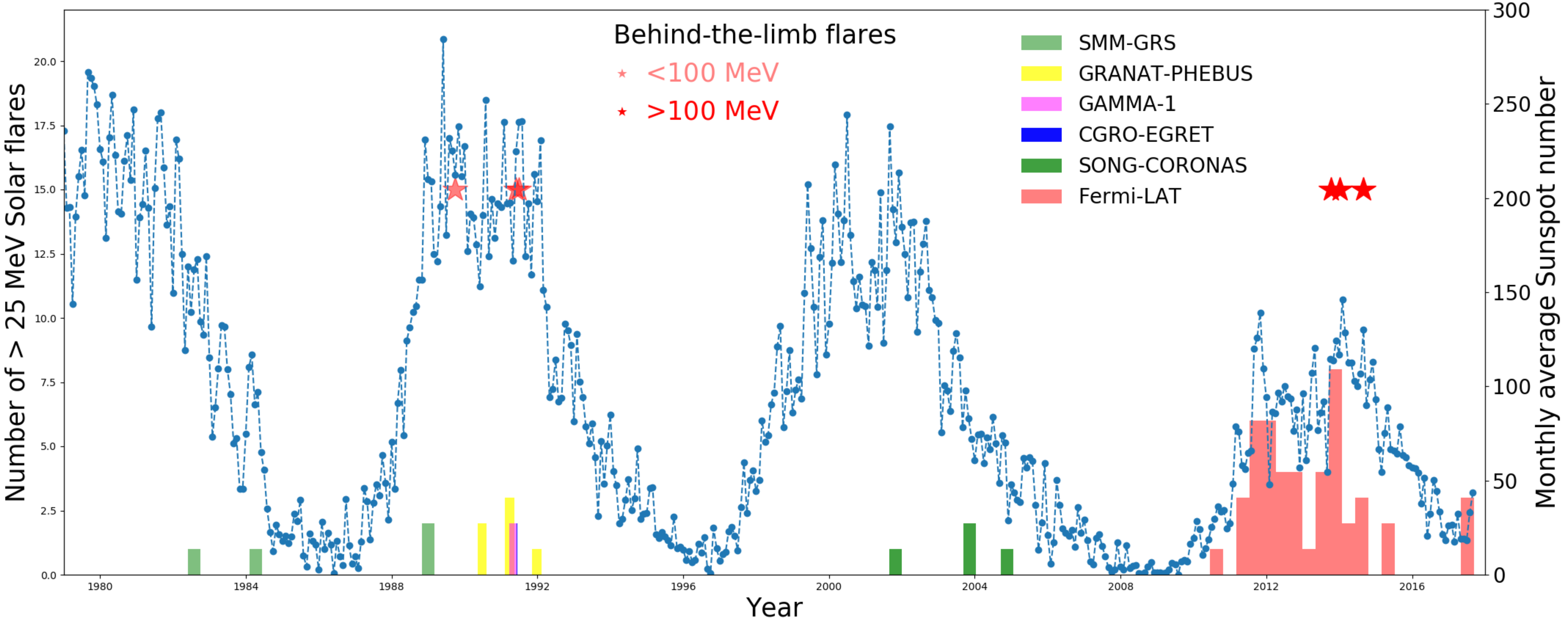


- **SunMonitor**:
  - 92 time windows candidates (TS>25)
  - 39 flares detections above 60 MeV
- **LLE approach** detected 6 additional above 30MeV

45 Flares total :

- all associated with X-ray flare
- all but 3 associated with CMEs

The impact of Fermi-LAT



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Temporal Behavior of Fermi LAT Solar Flares (FLSF)

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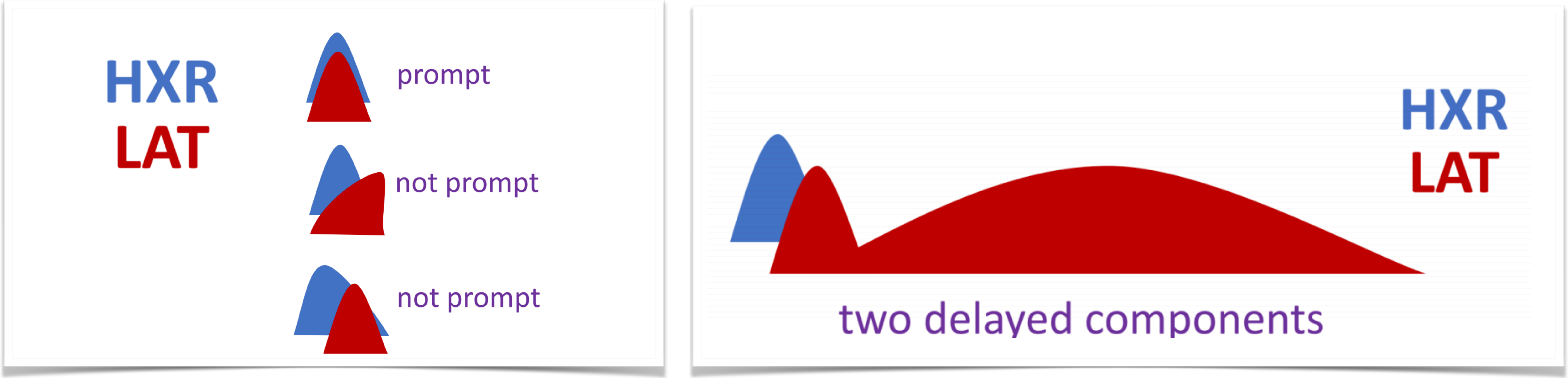

Credit: A. Shih

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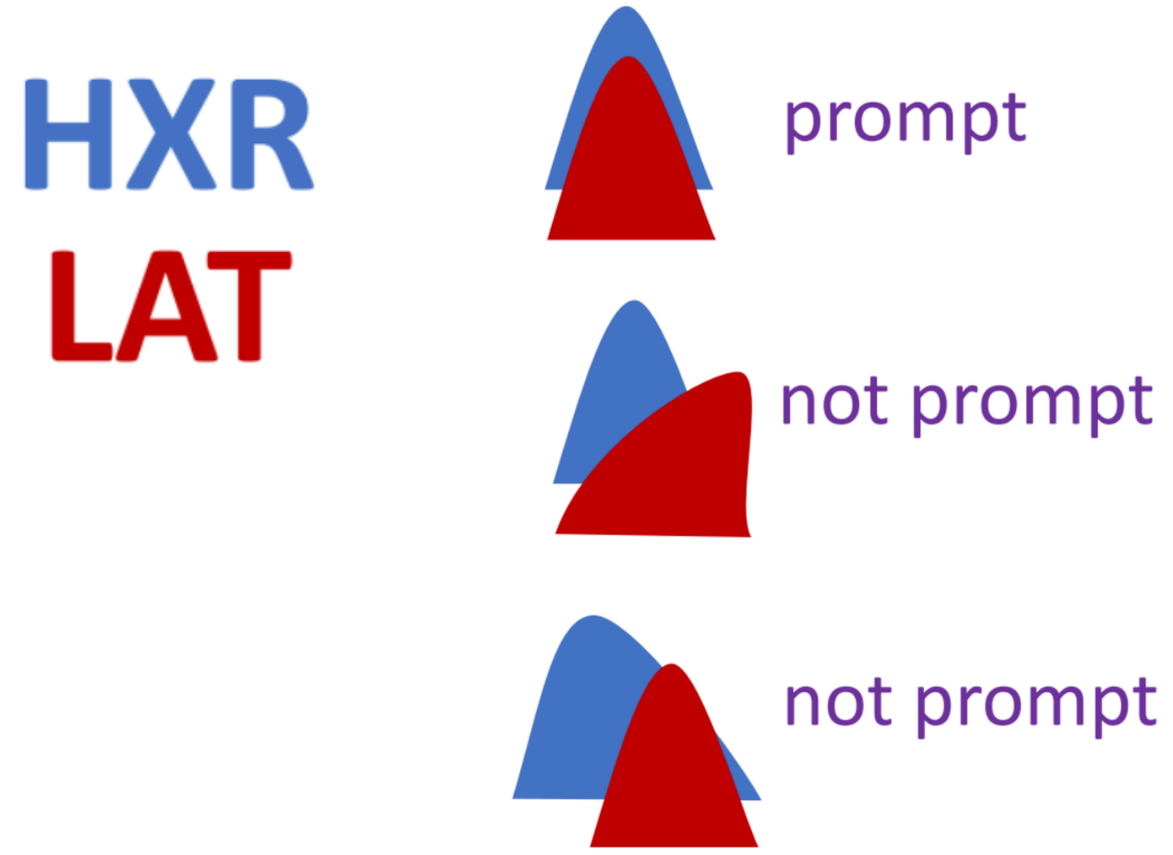
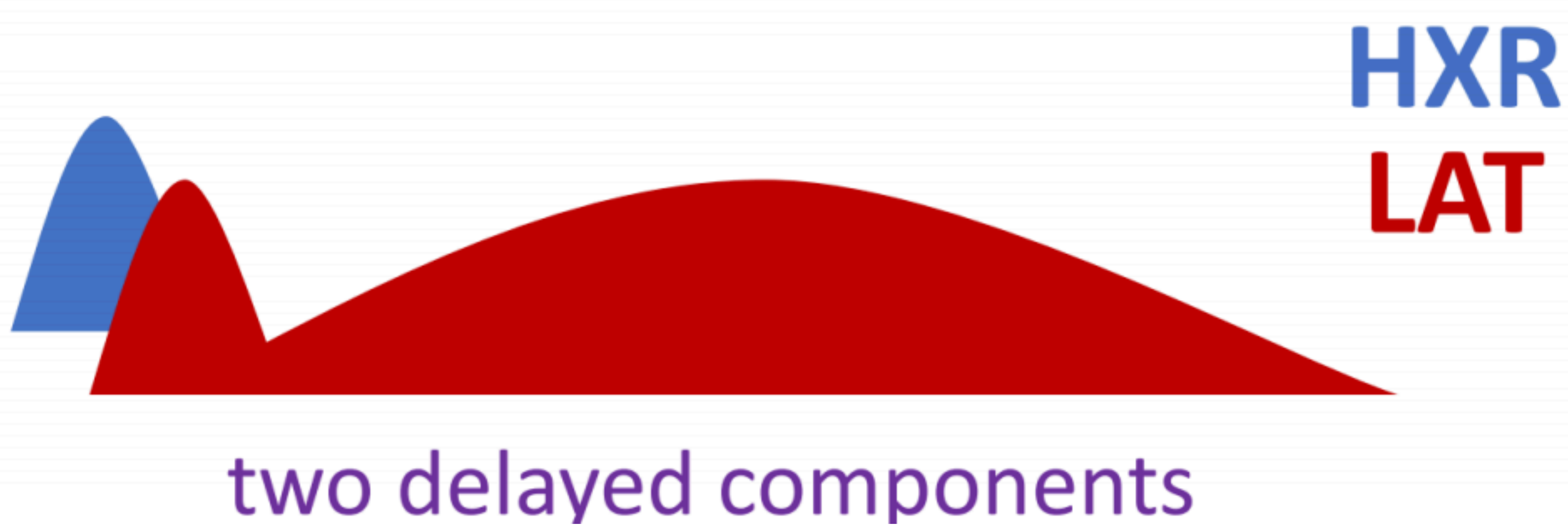
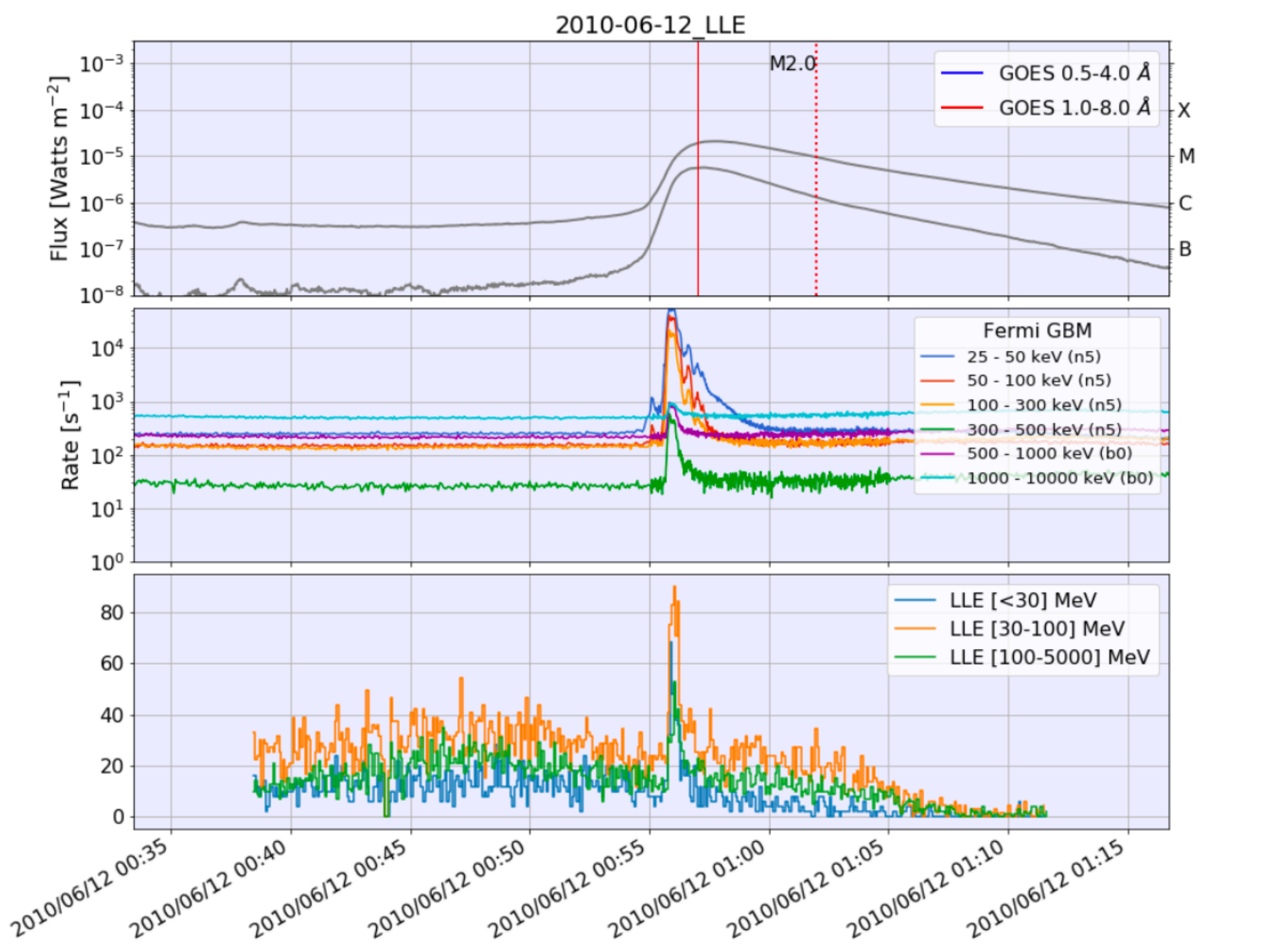
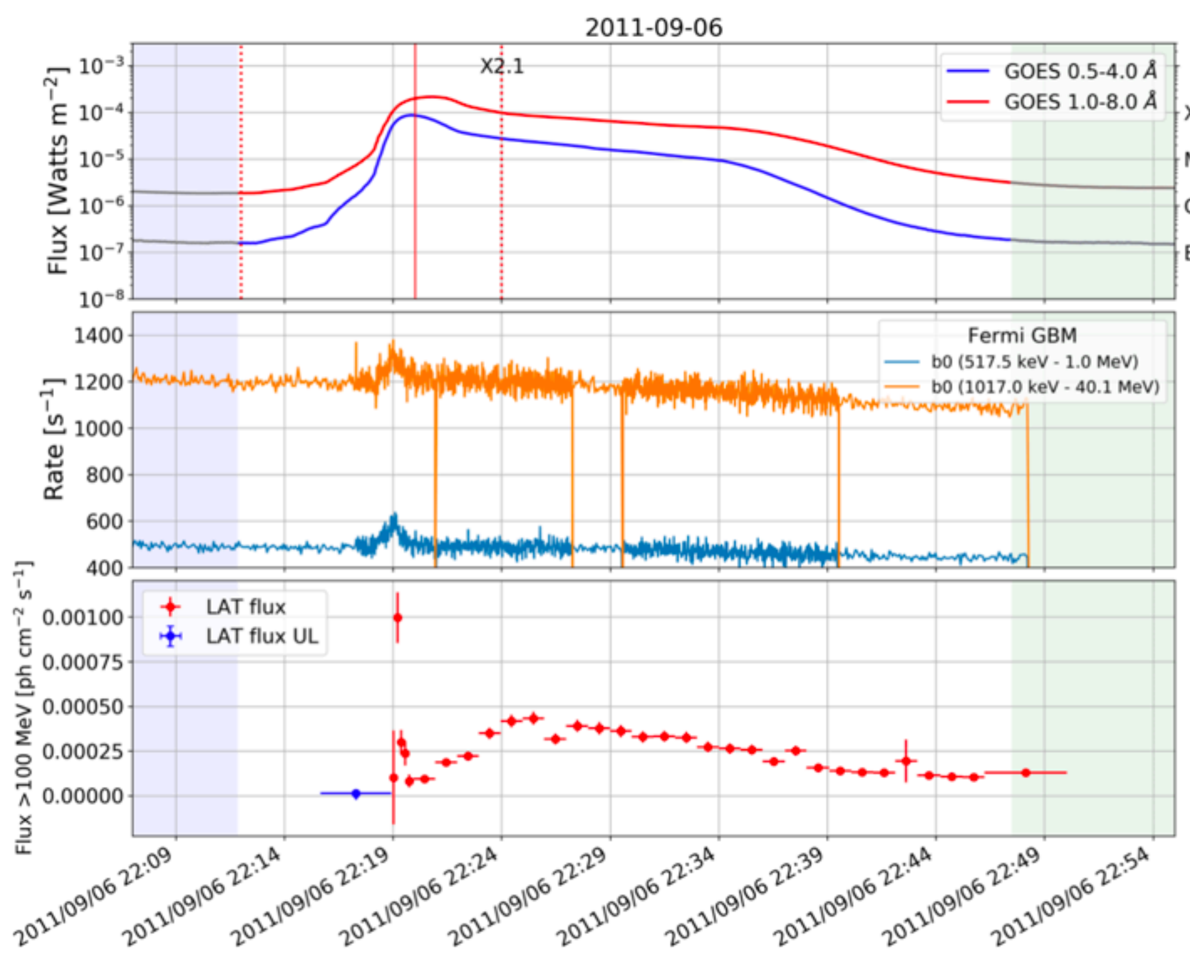
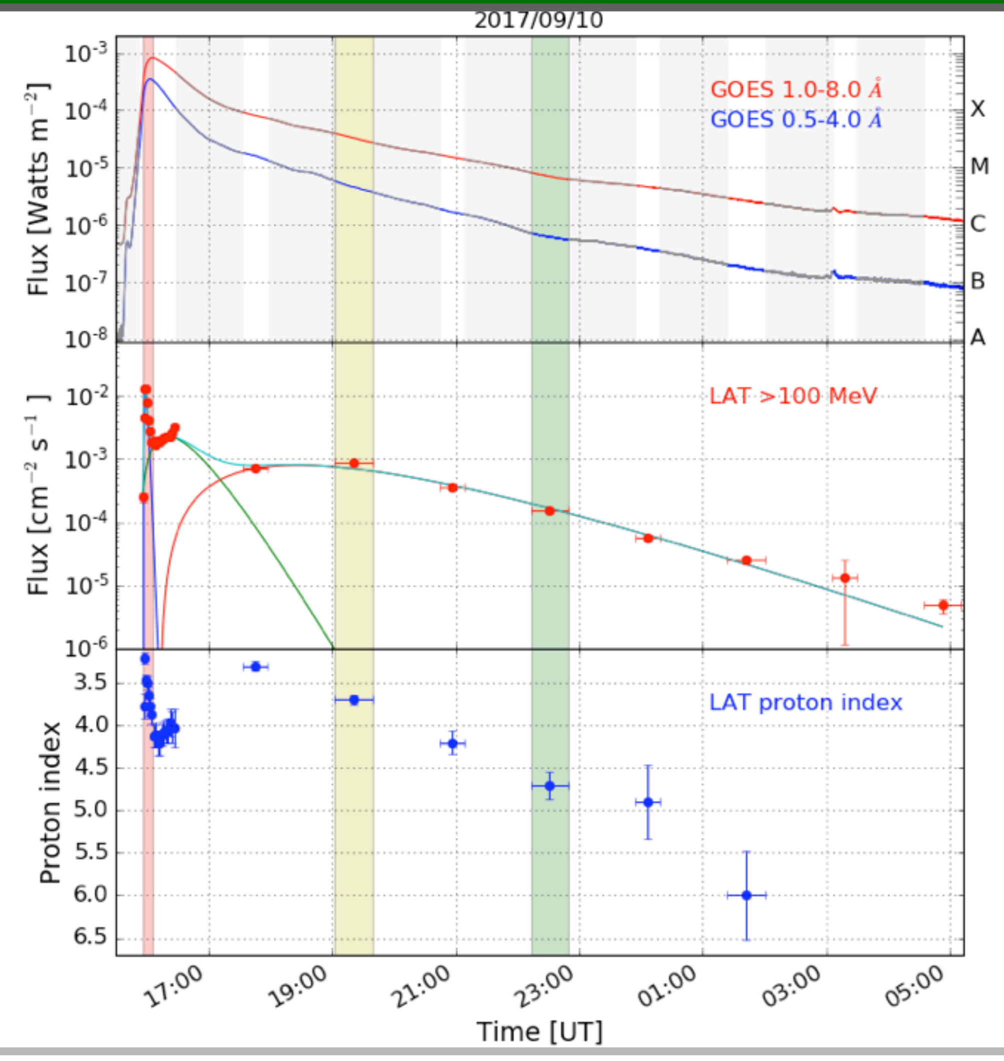


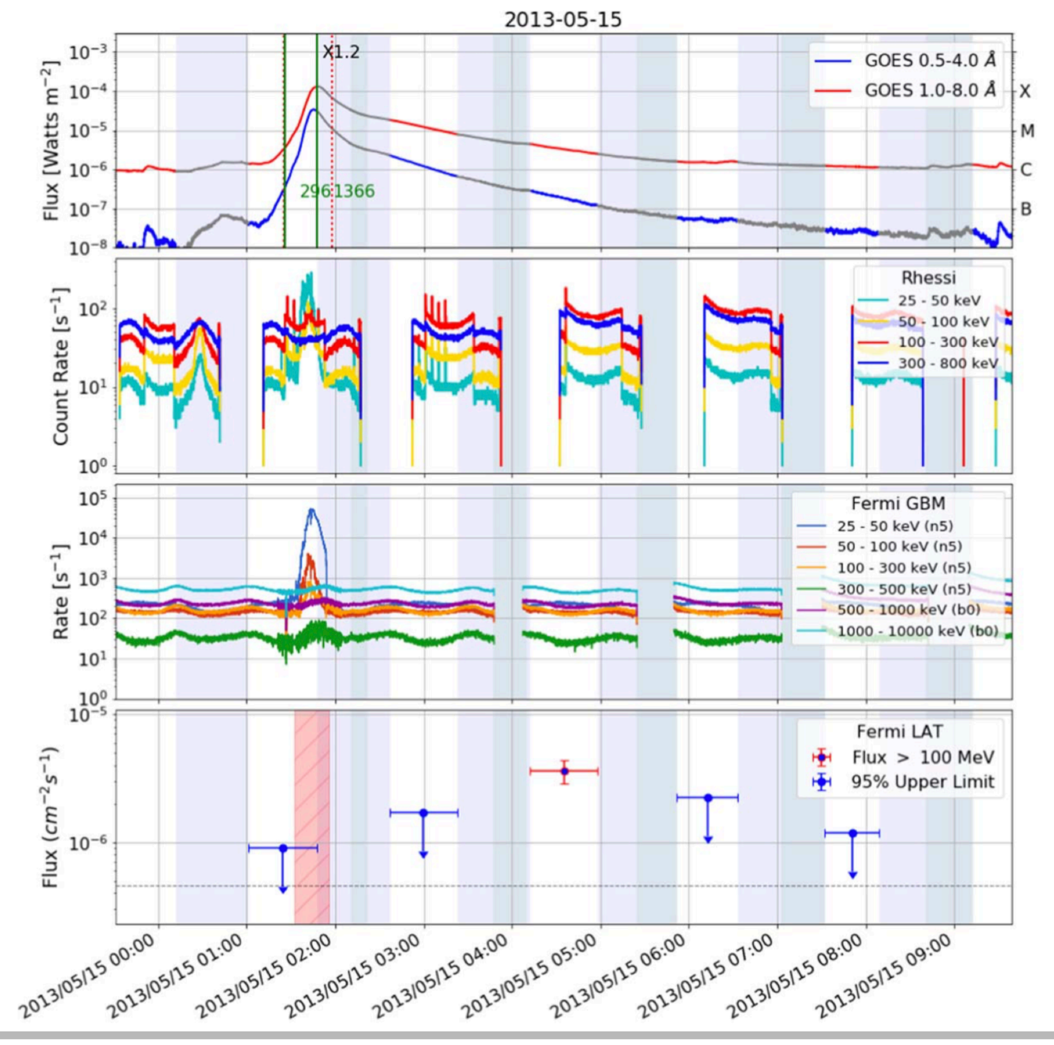


Prompt-only	Prompt Short Delayed (<2 hr)	Prompt Delayed (>2hr)	Delayed Only

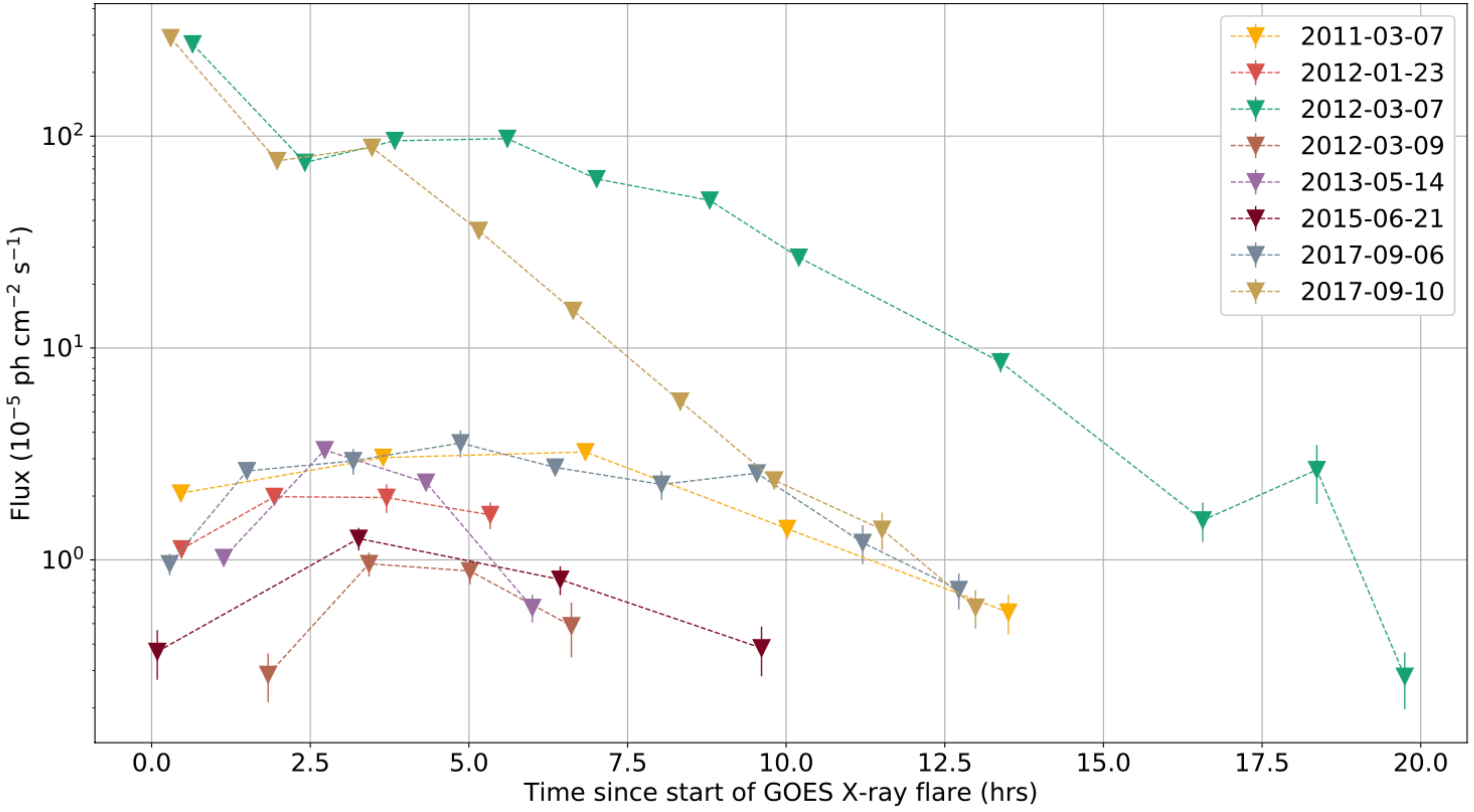








Eight Long Lasting (>4 hr) Solar Flares head to head



Ajello et al. 2021

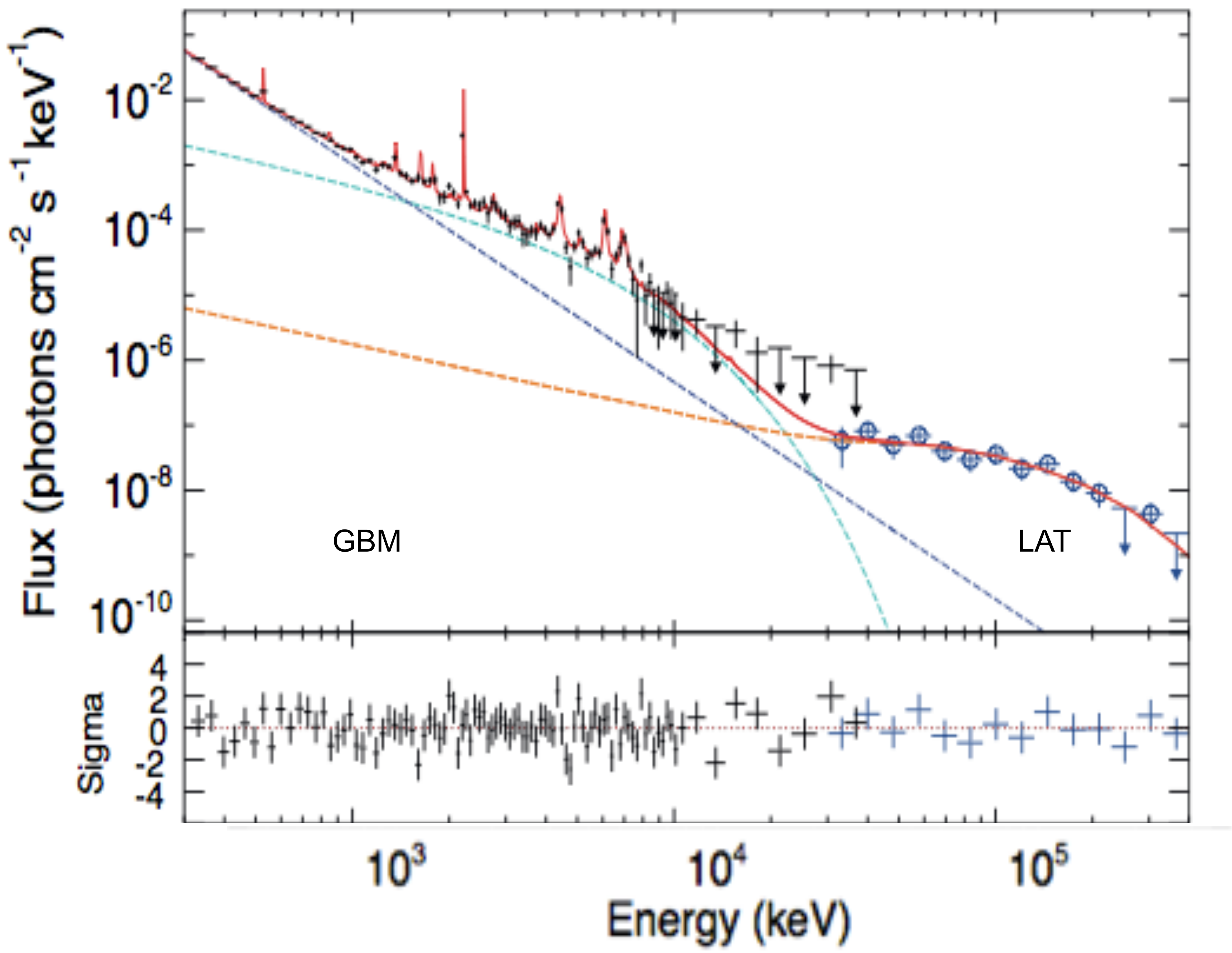
- **The GLE event (2017-09-10) and sub-GLE event (2012-03-07) are by far the brightest one.**
- **Rise-time behavior more evident for delayed-only flares**

Spectral analysis

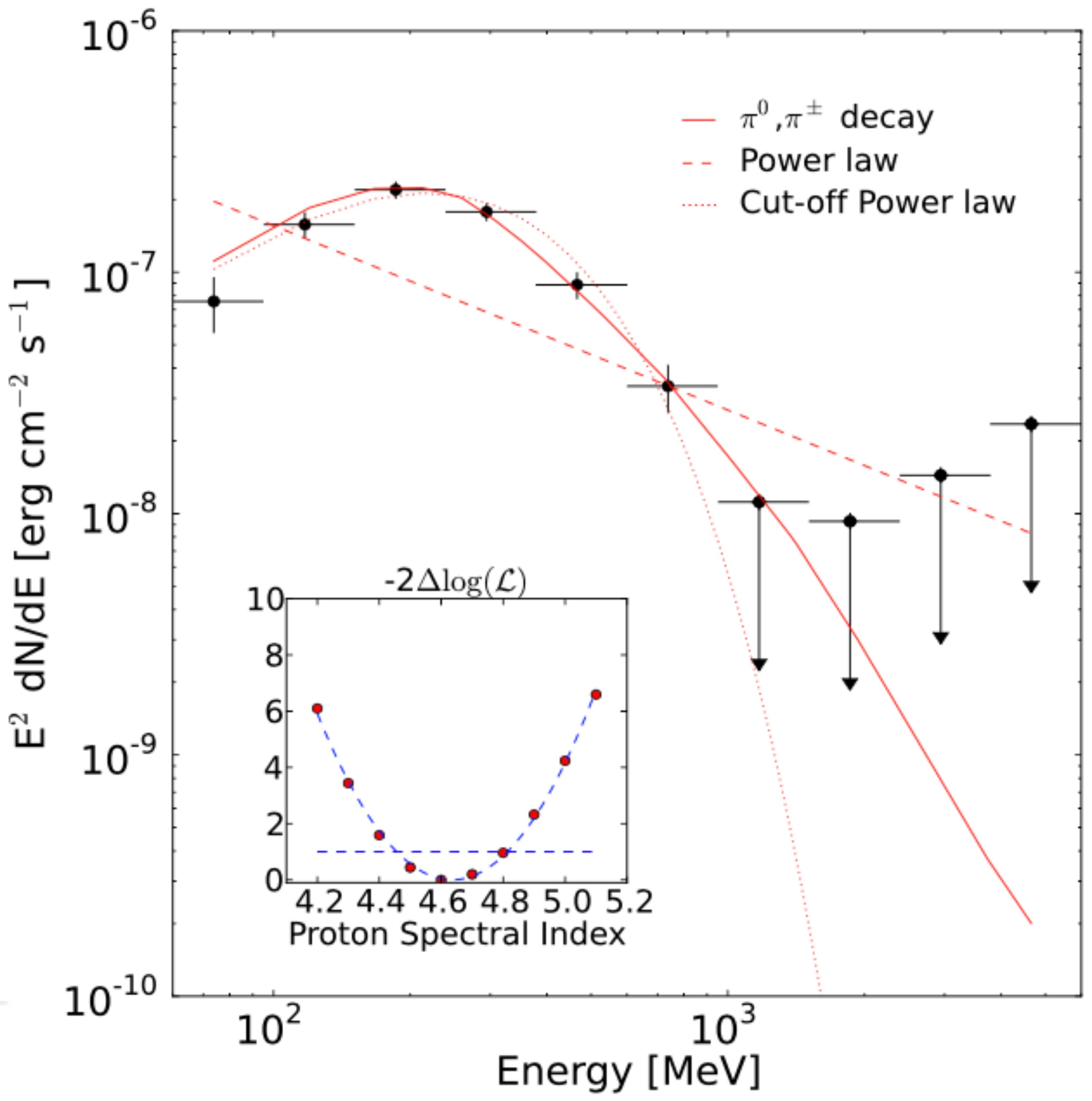
Spectral analysis

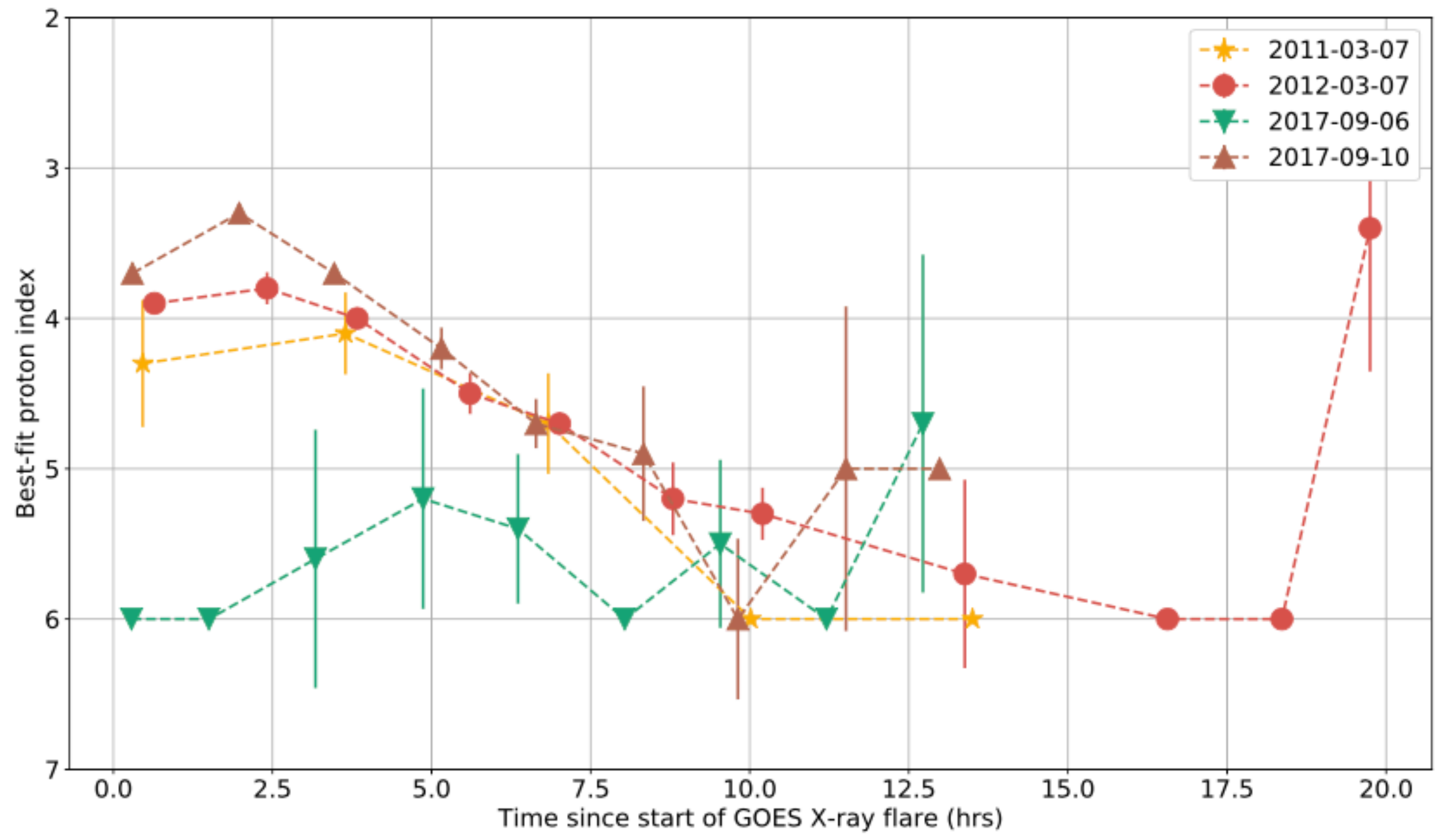
- **Both prompt and delayed emissions exhibit curvature in their spectrum.**
- **Well reproduced (when statistics allows) with pion decay model (Murphy et al. 1987)**

2010-06-12 (Prompt)



2012-03-07 (Delayed)





Softening of the p spectrum with time

Ajello et al. 2021

Where does the gamma-ray emission come from?

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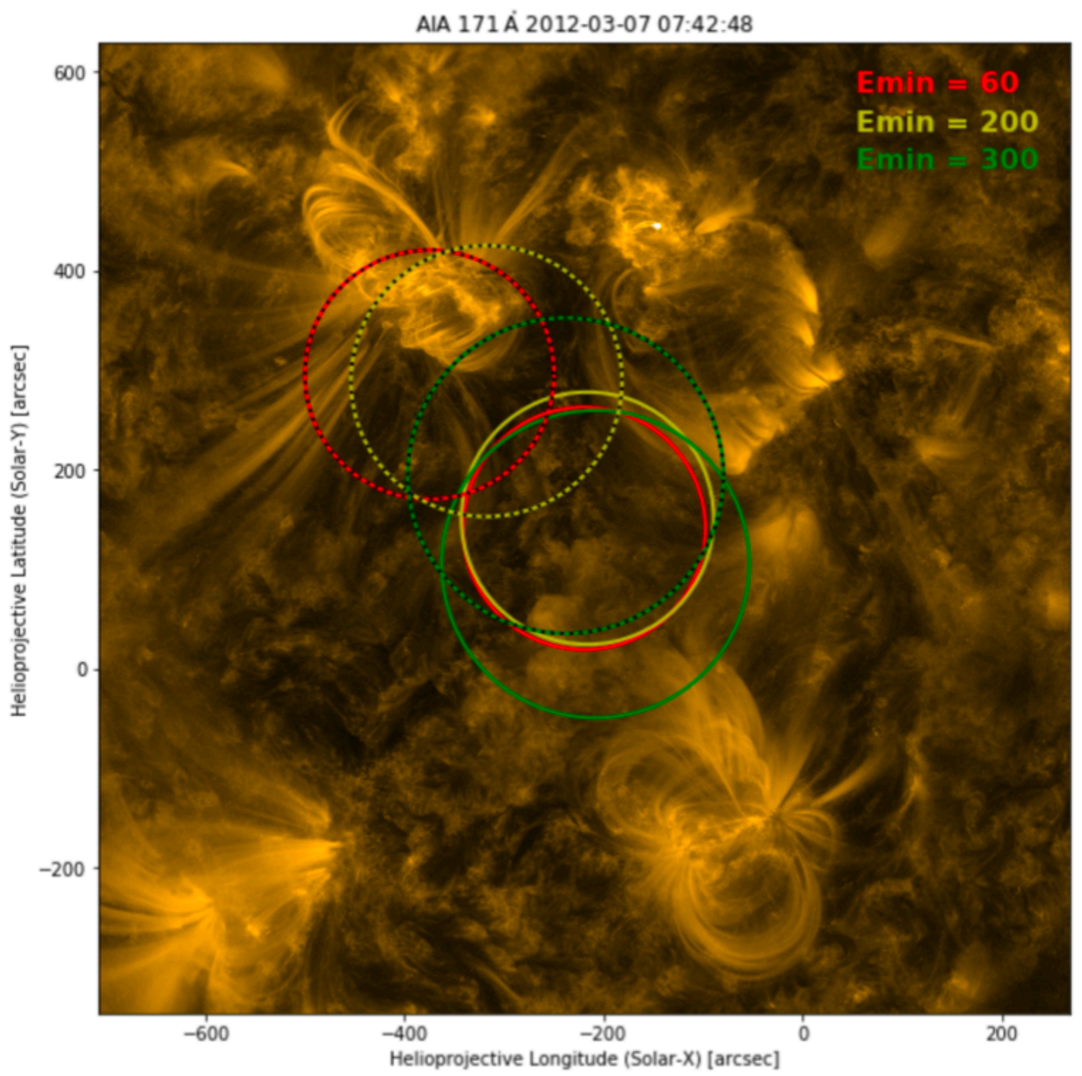
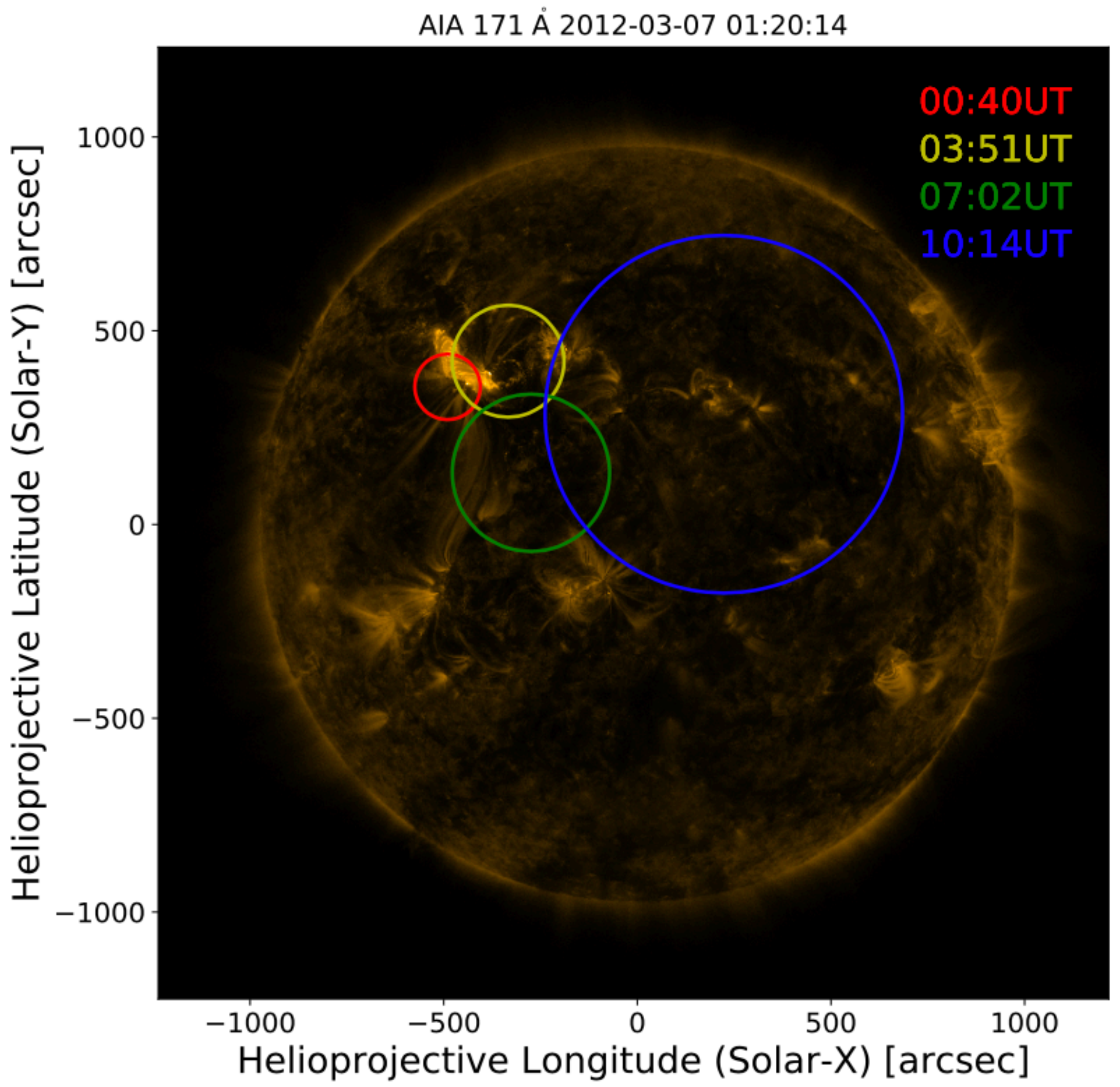
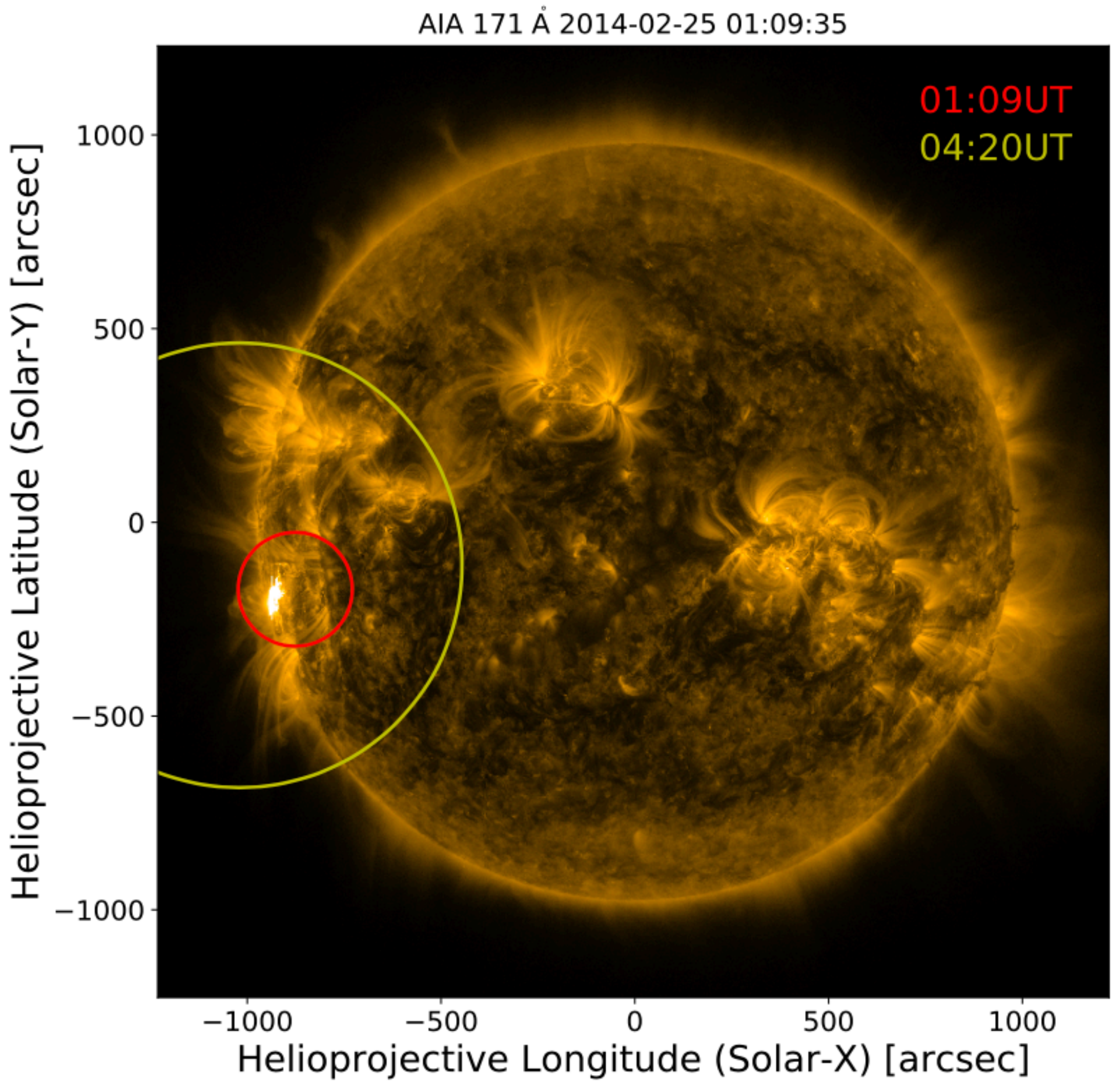
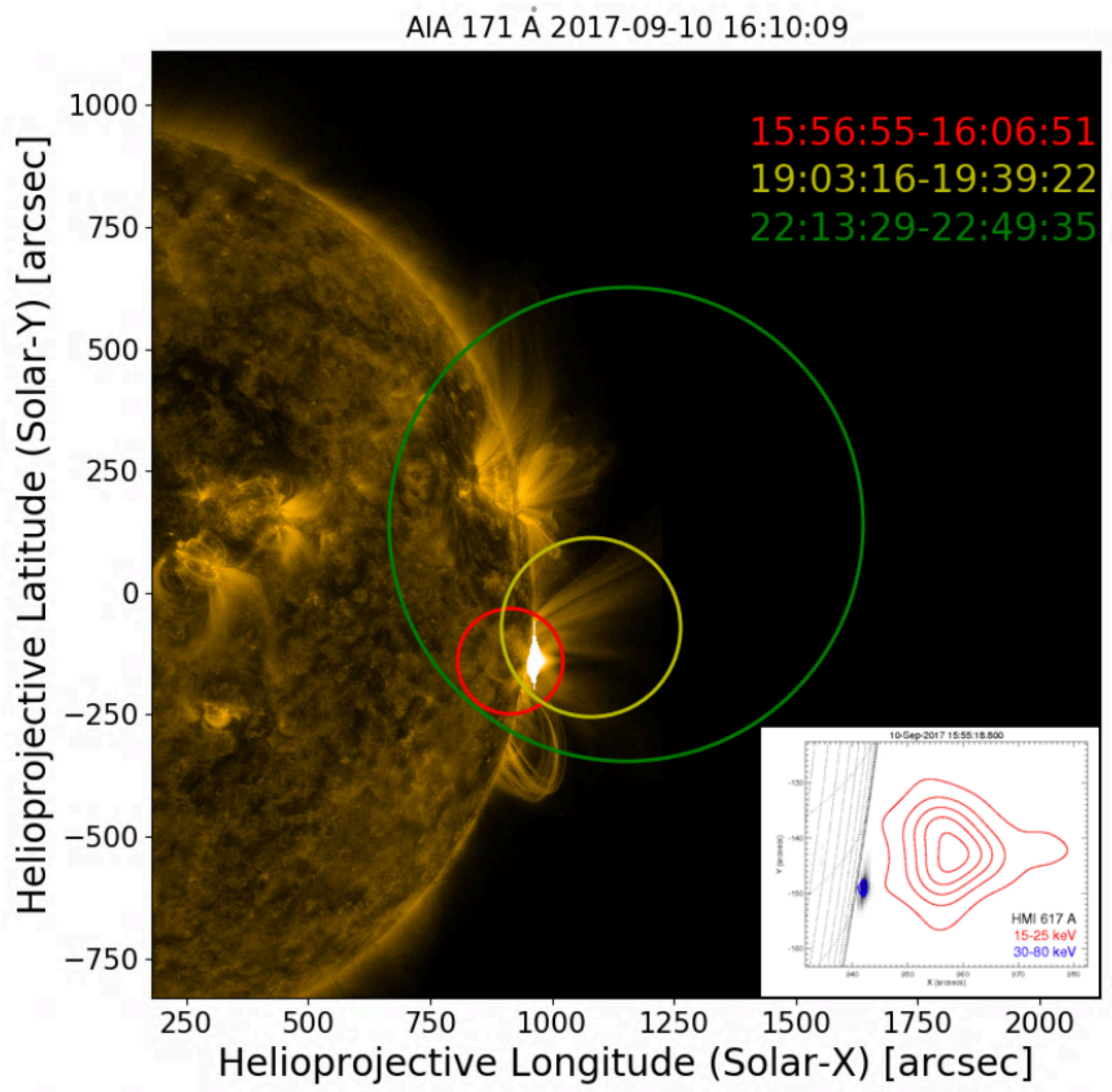






Ajello et al. 2021

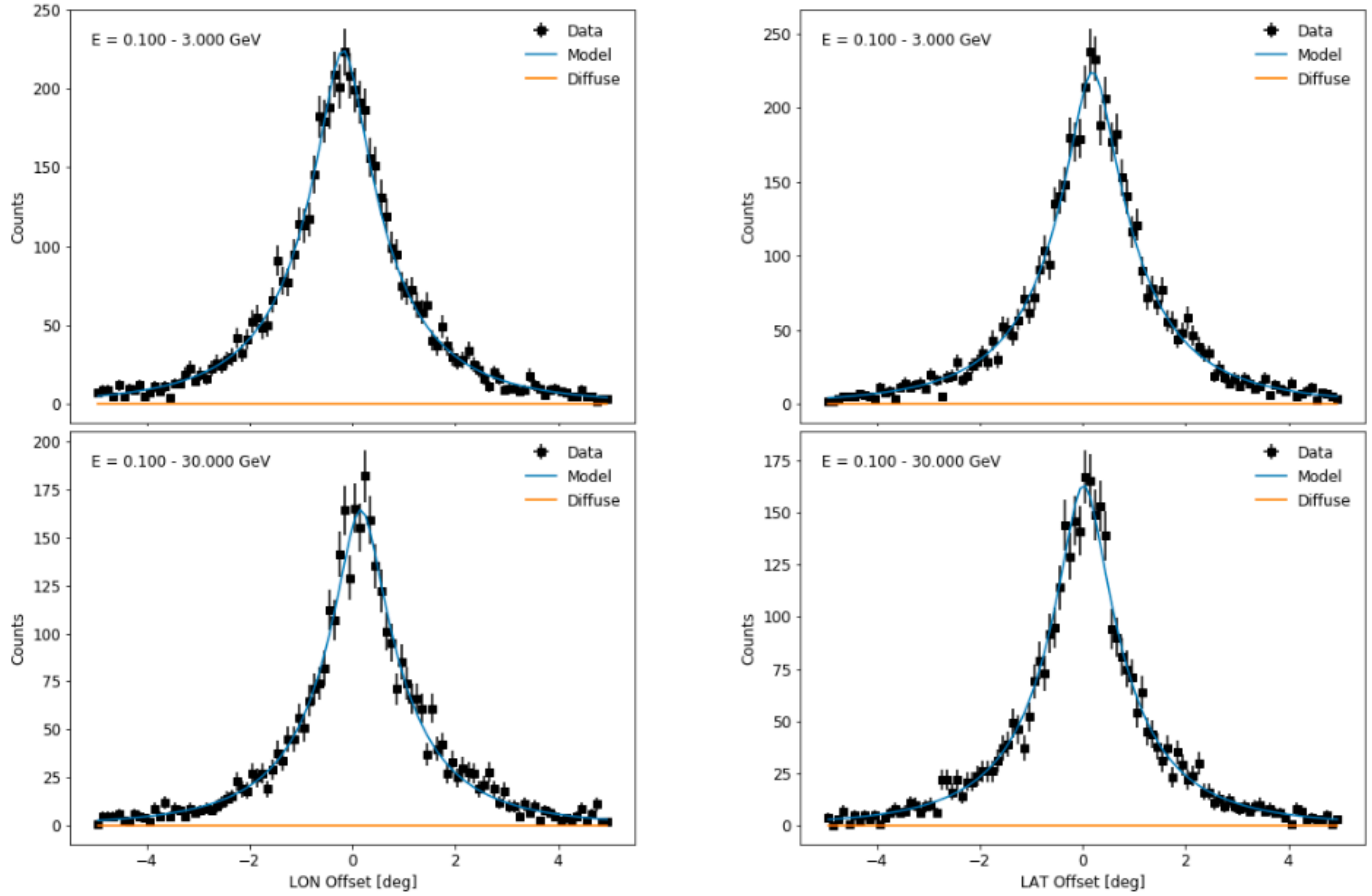


Omodei et al. 2018

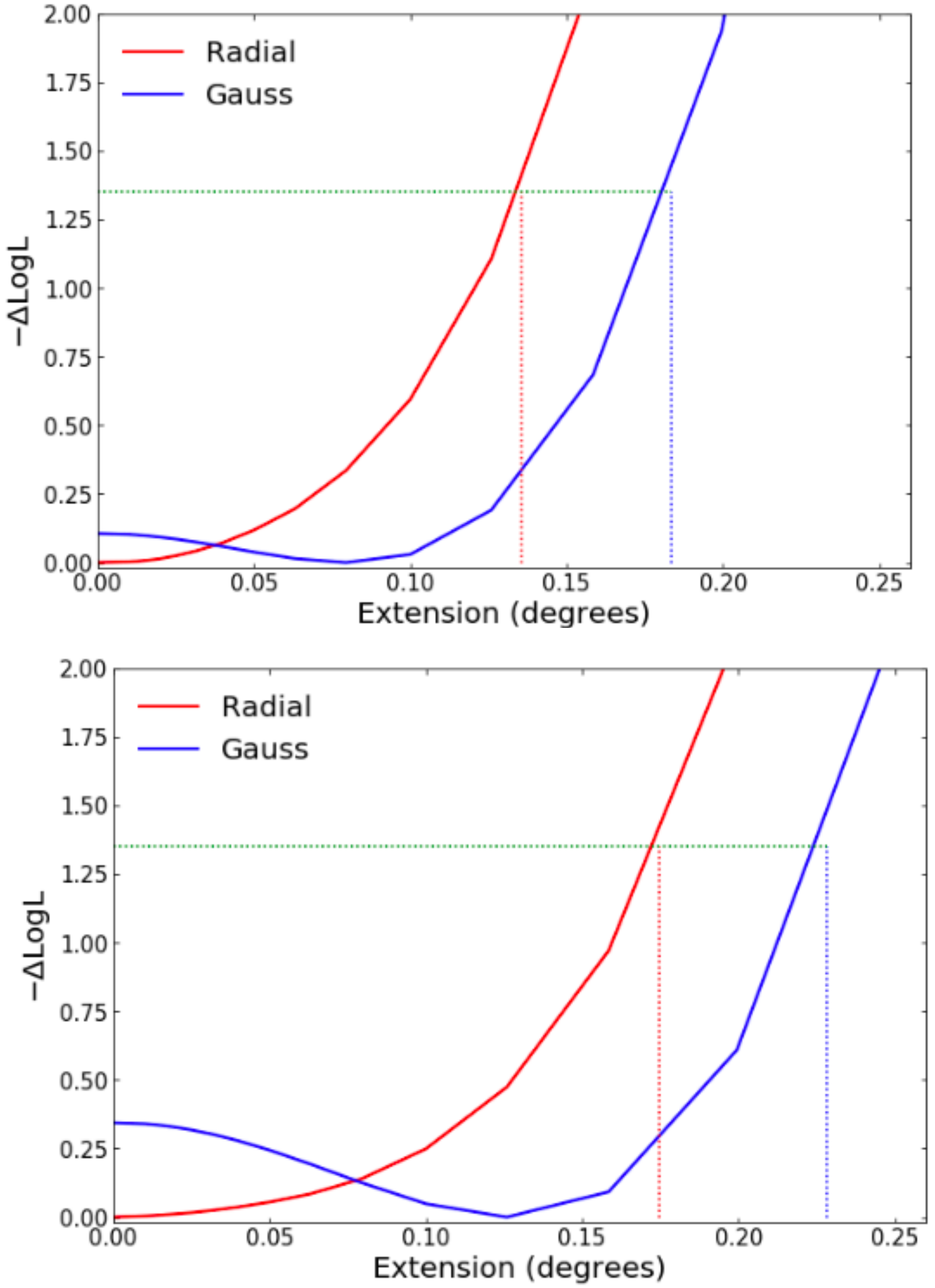
- **Correction for fish-eye effect based on Monte Carlo simulations**
- **Late time emission from 2012-03-07 "wonders around"**
- **Location consistent with AR (but on limb!)**

Is it extended?

- **Fermipy to study the extension of the gamma-ray source (on 2012-03-07 and 2017-09-10).**
  - **Fit with Gaussian and Disk templates, profiling the likelihood by varying the radius.**



Effect ion the LAT PSF (mostly low energy gamma-rays)



Ajello et al. 2021

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
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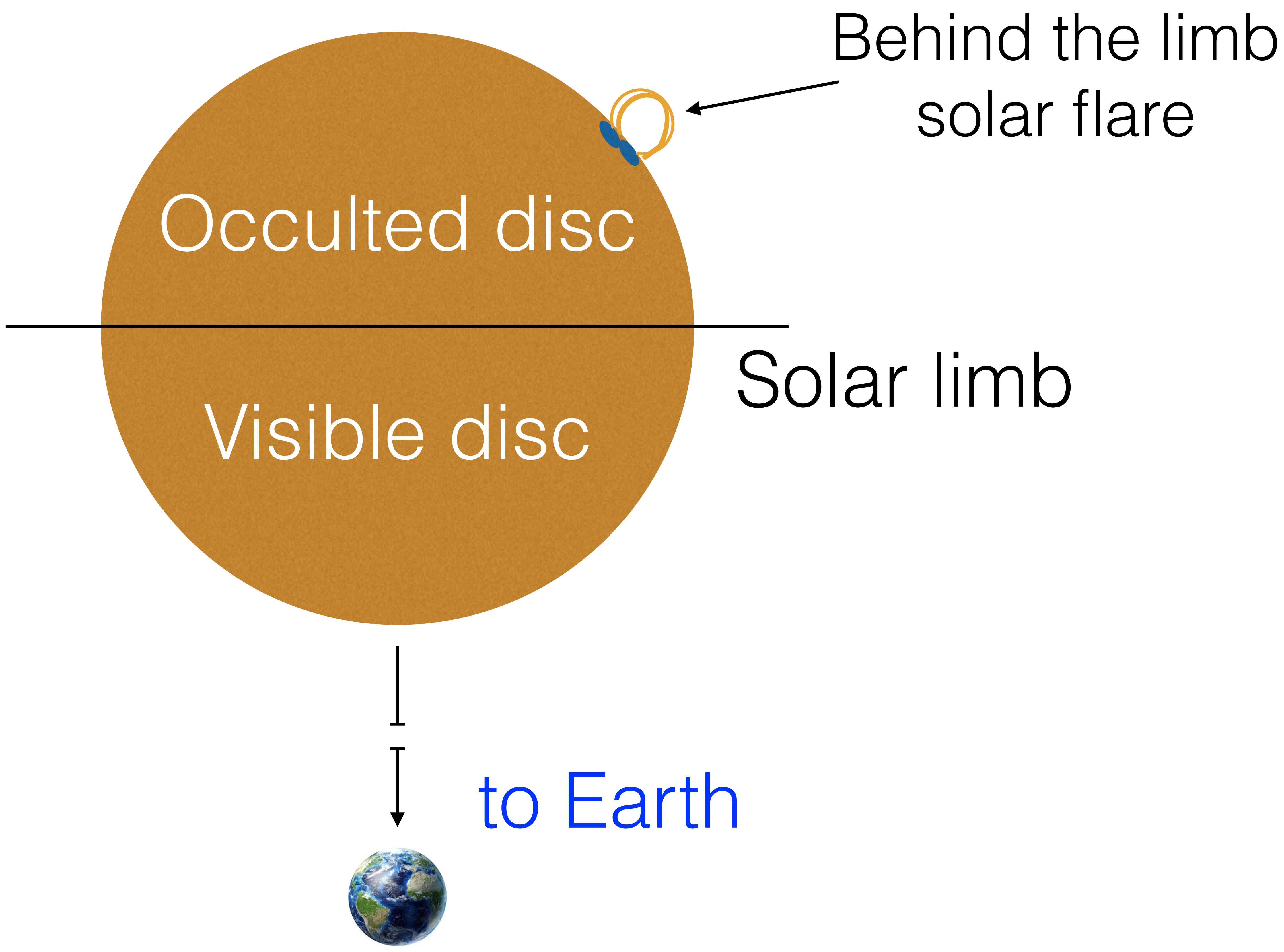

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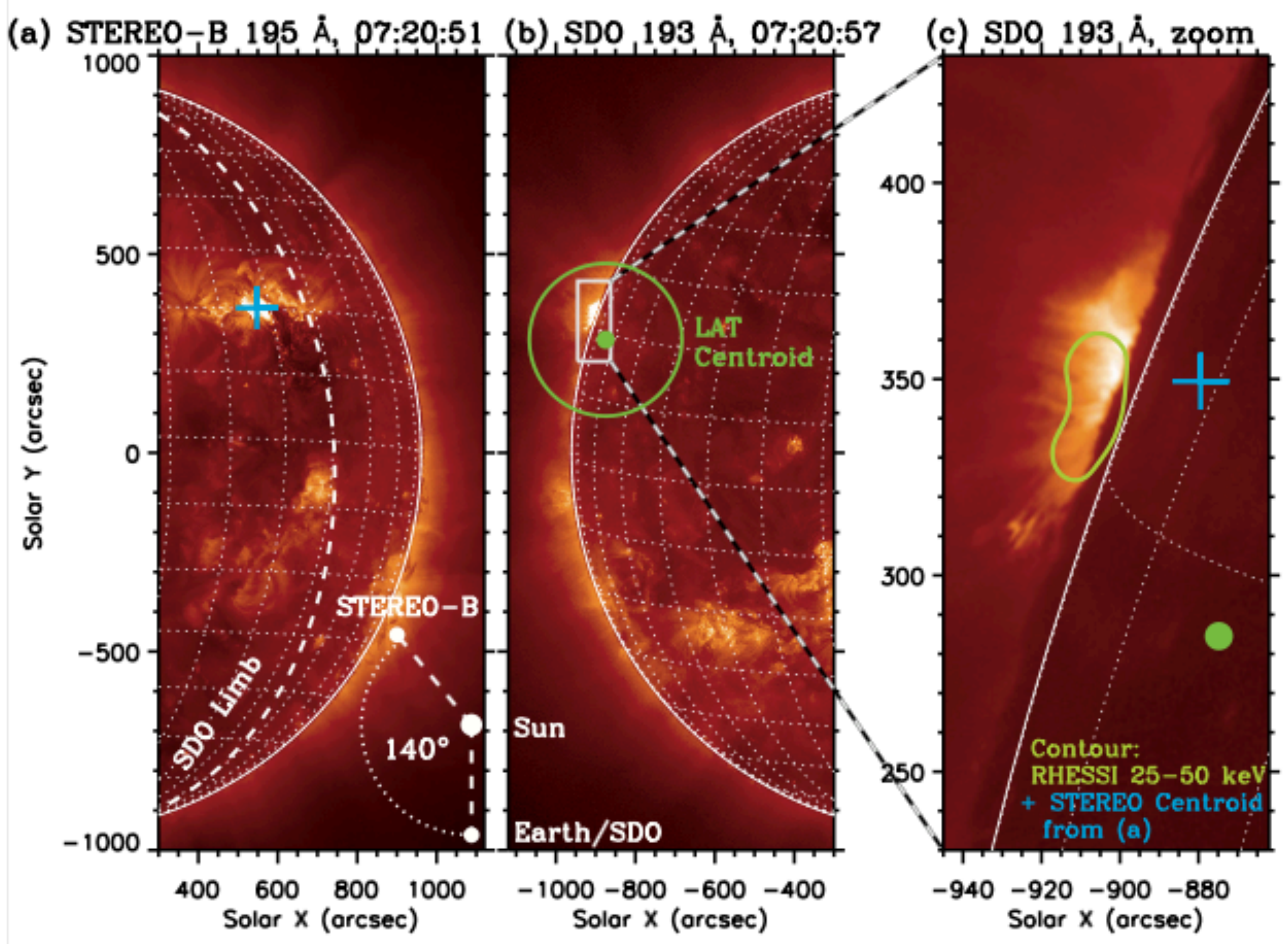
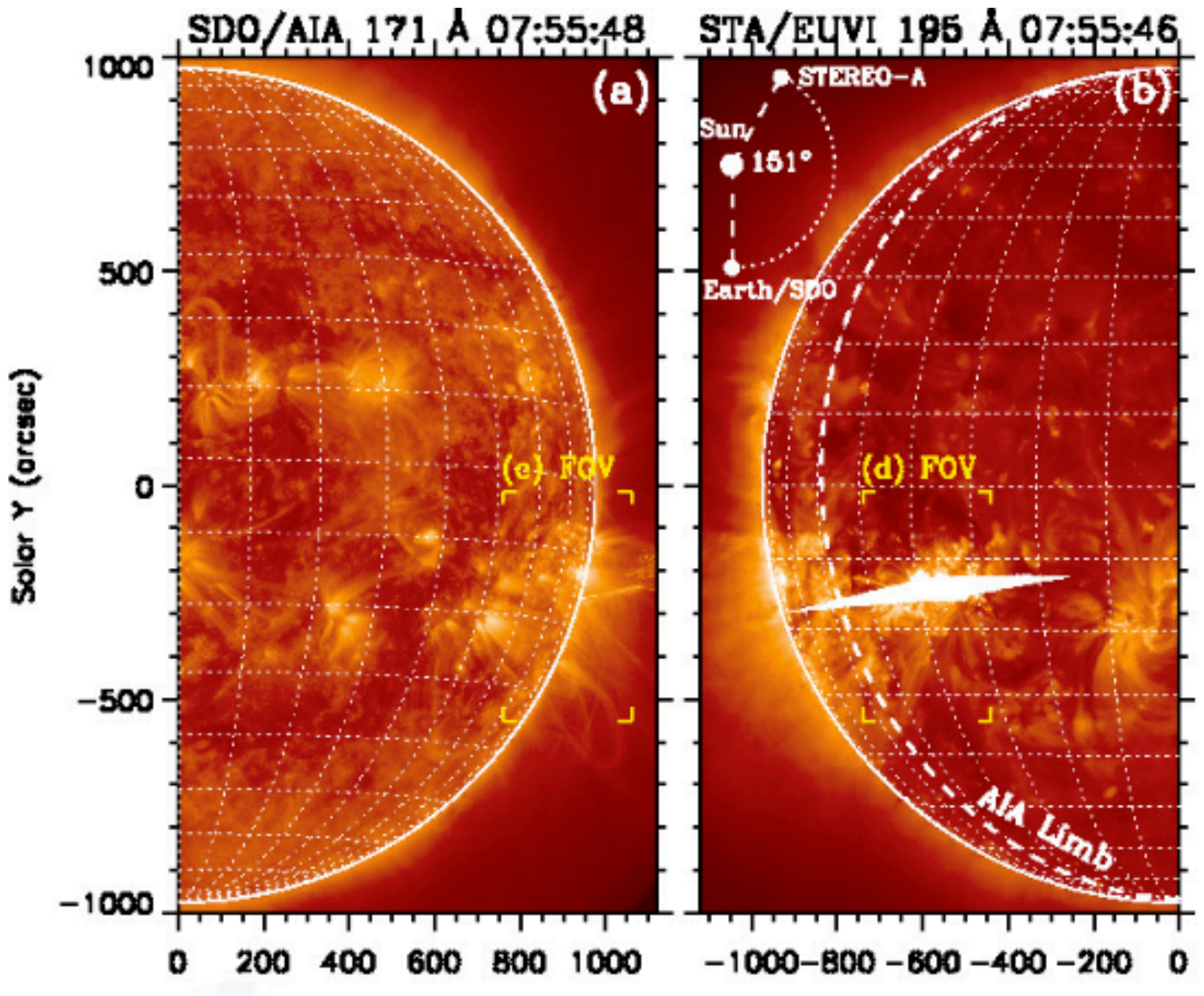
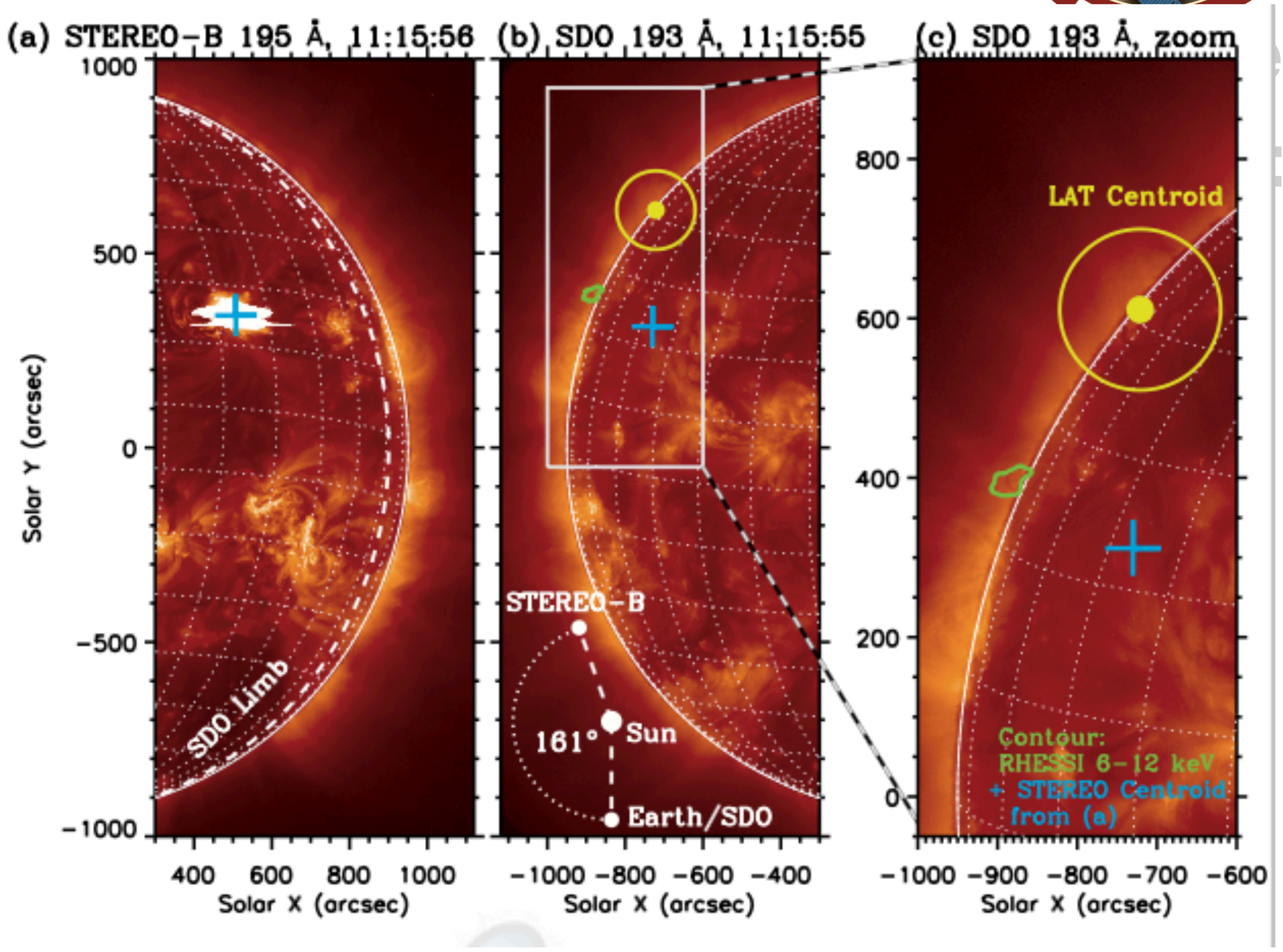
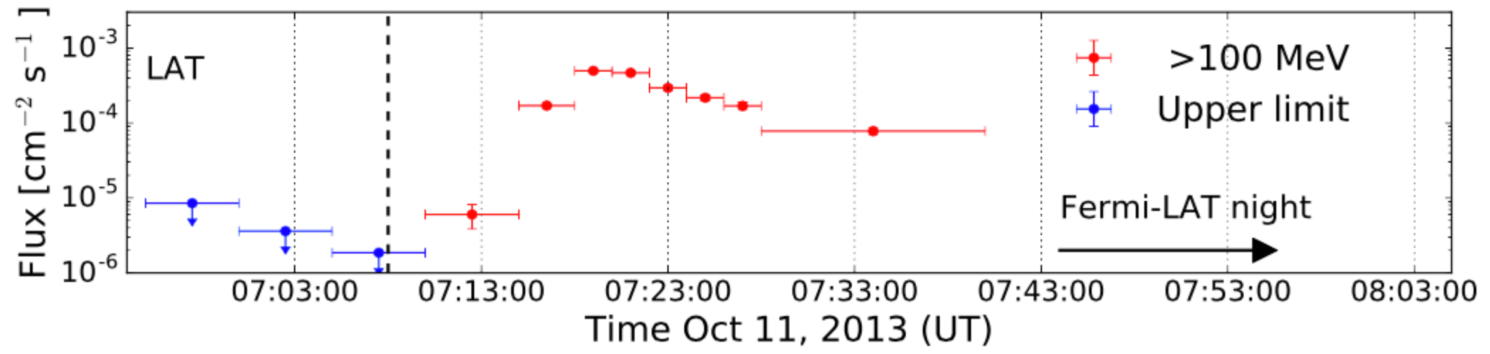
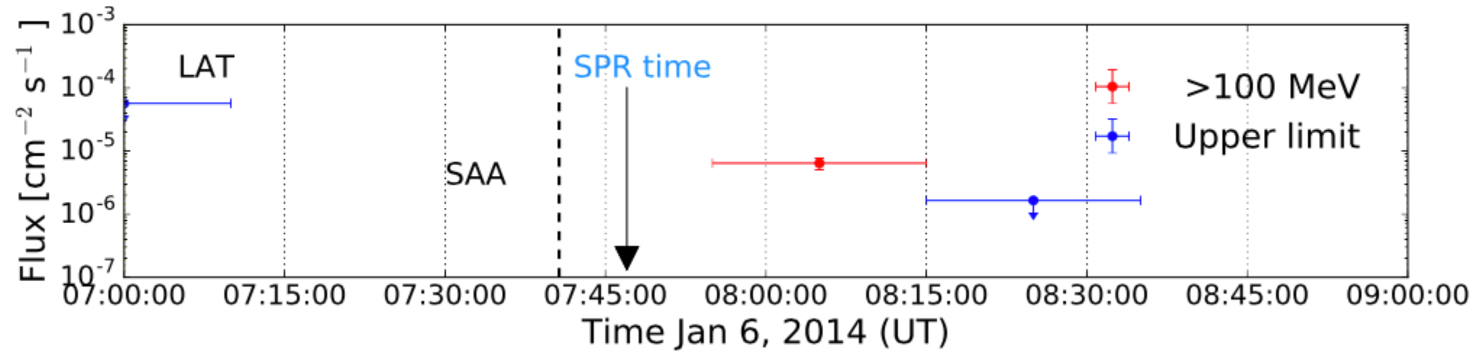
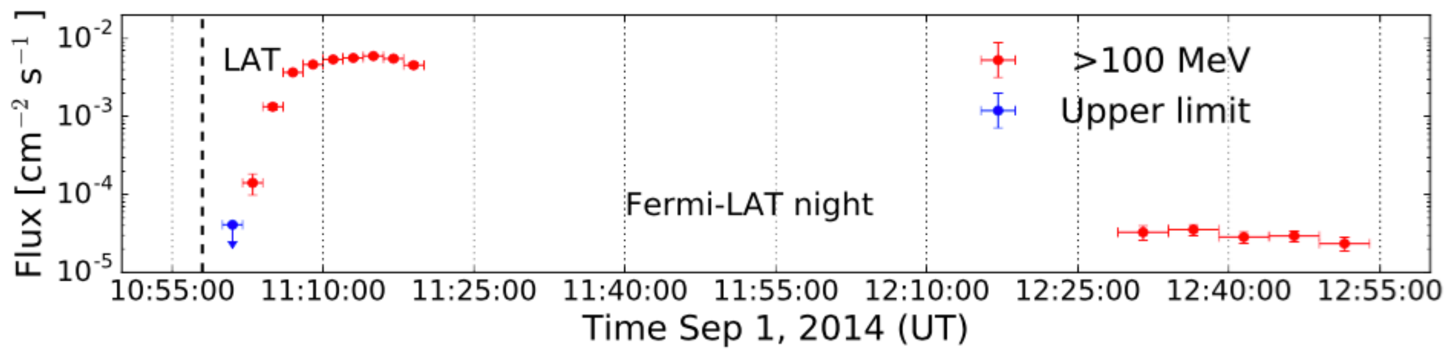












- 10˚ behind the eastern limb;
- RHESSI emission consistent with loop top;

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

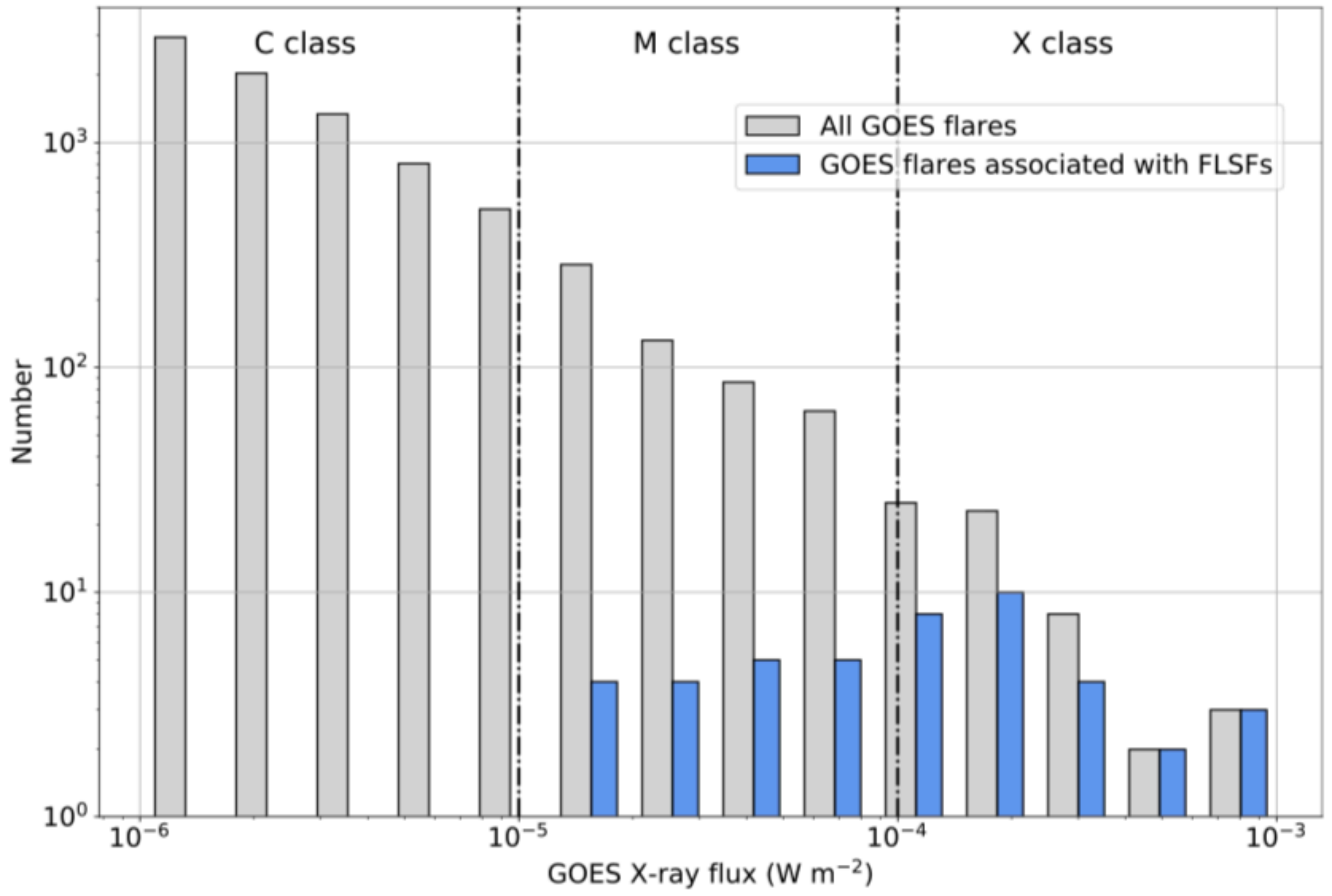
- 43˚ behind the eastern limb;
- Bright LAT emission lasting ~2 hr;

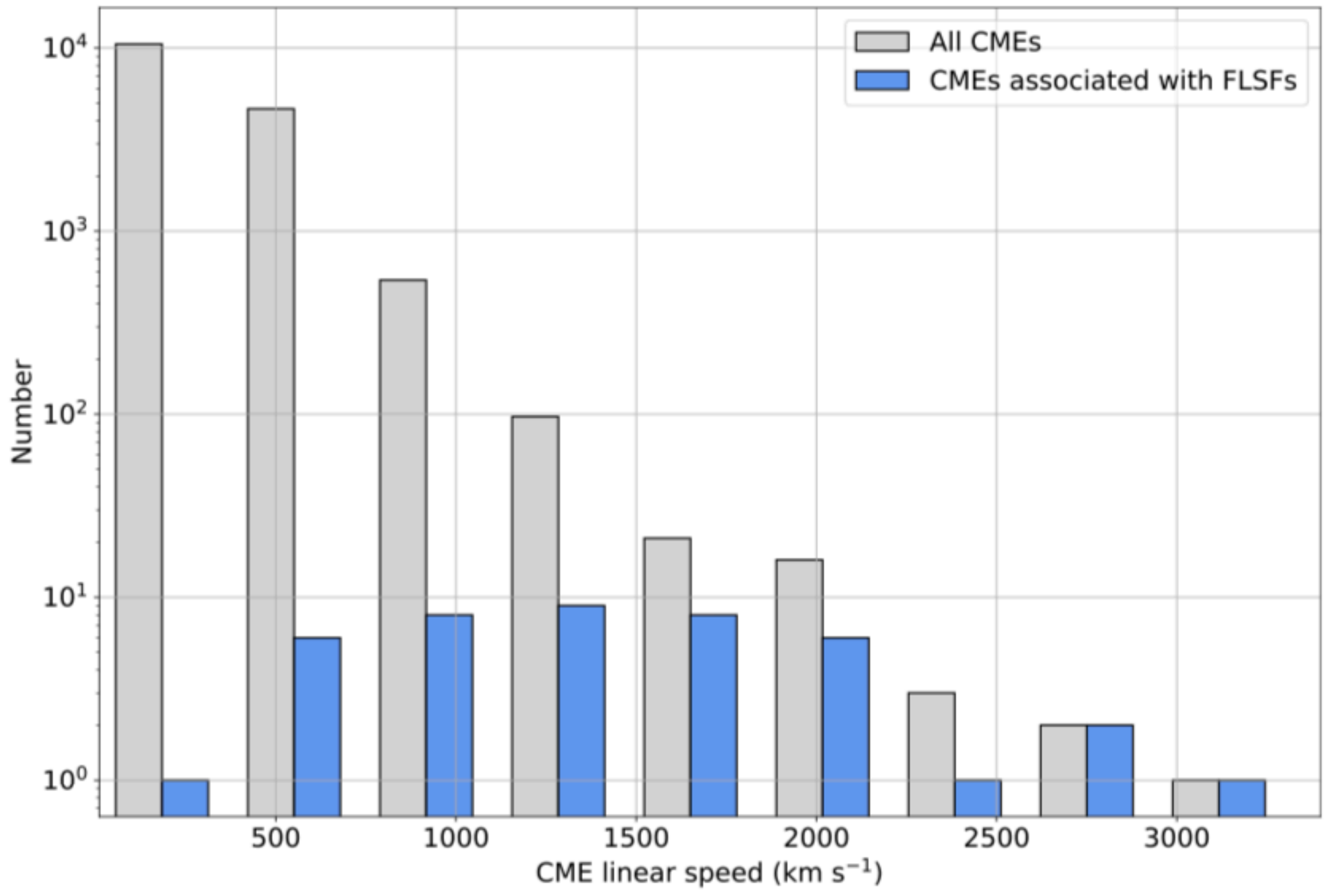
Lack of prompt emission: gamma ray emitting region occulted!

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

Population studies and correlations with other catalogs

Connection with GOES flares





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

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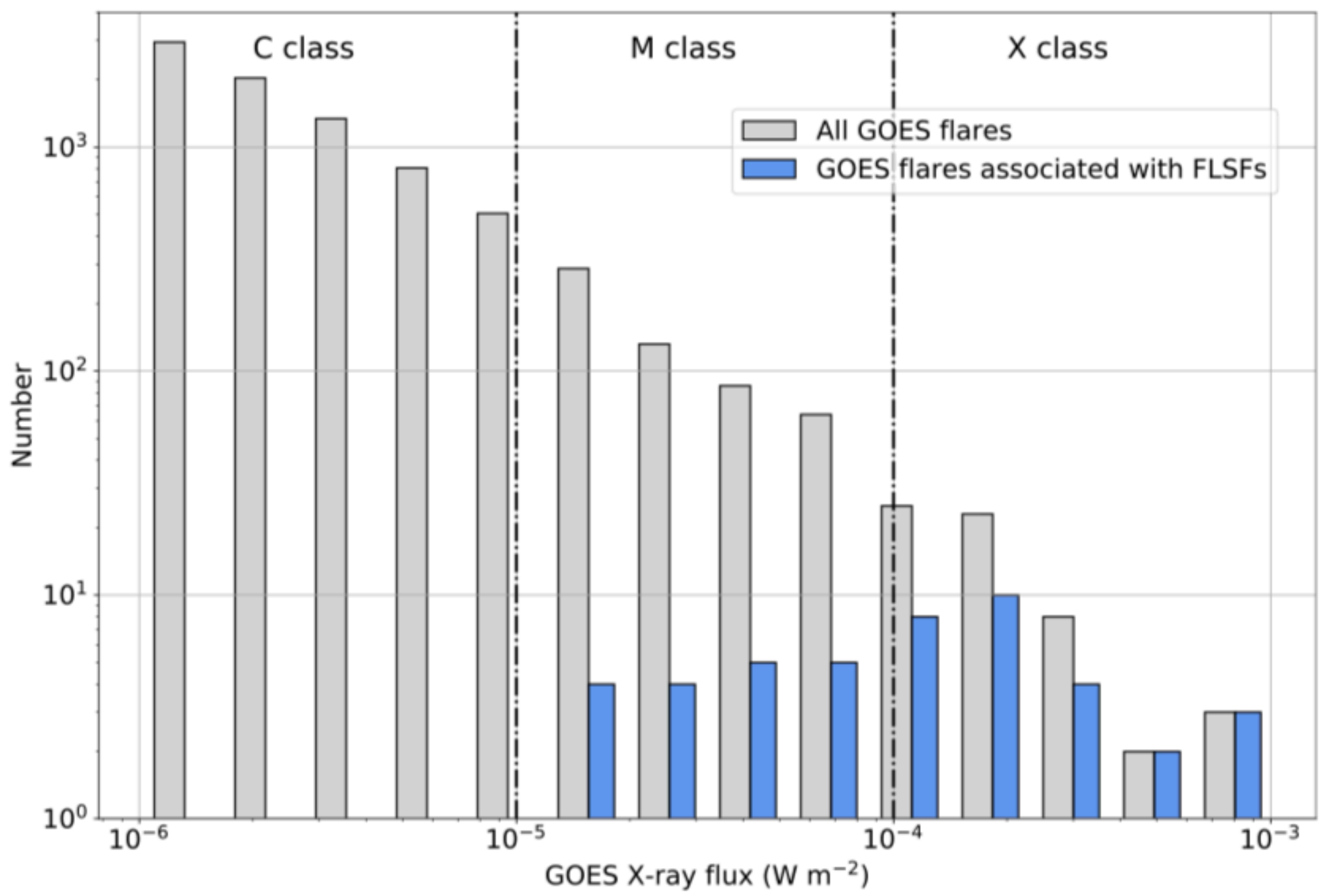

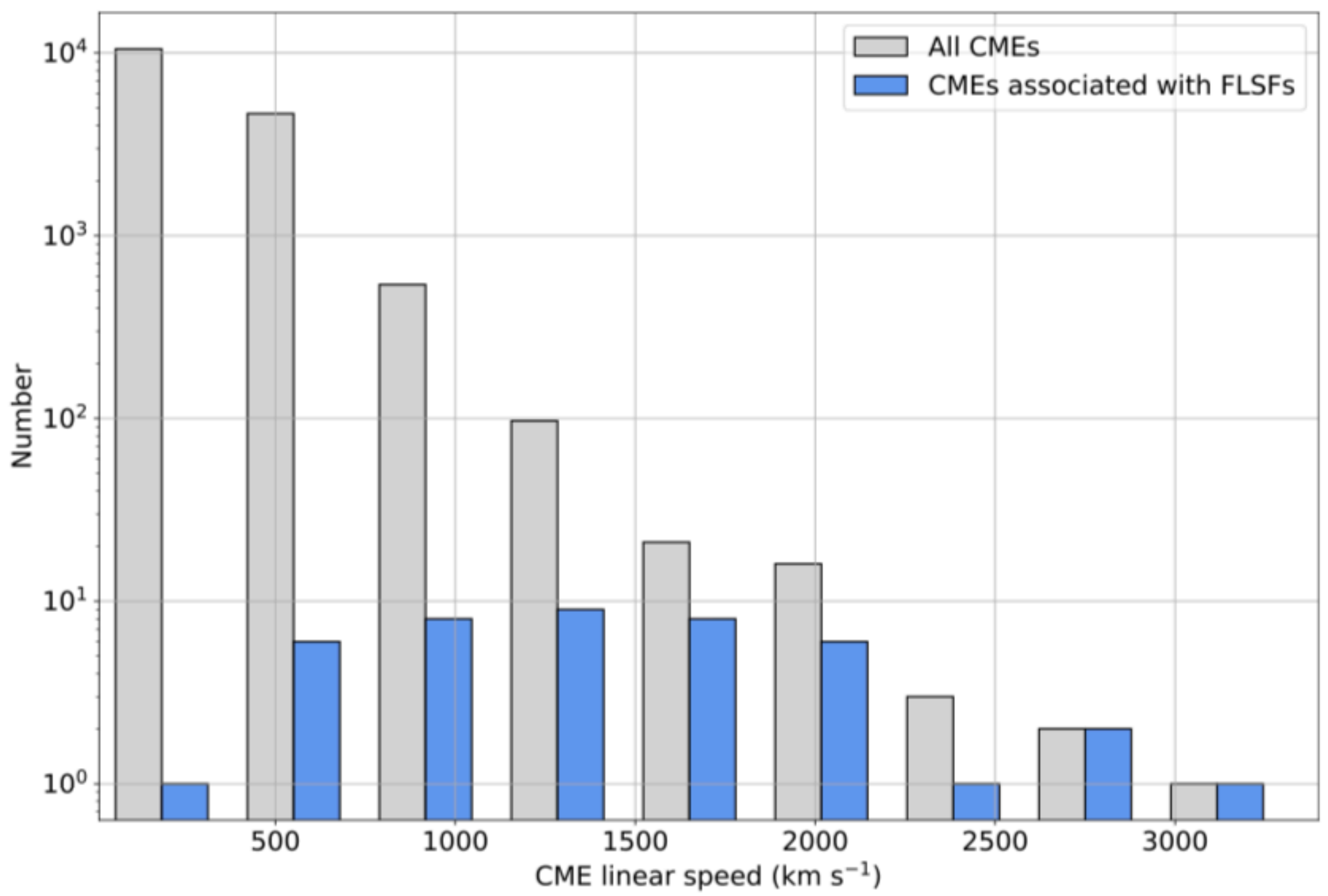

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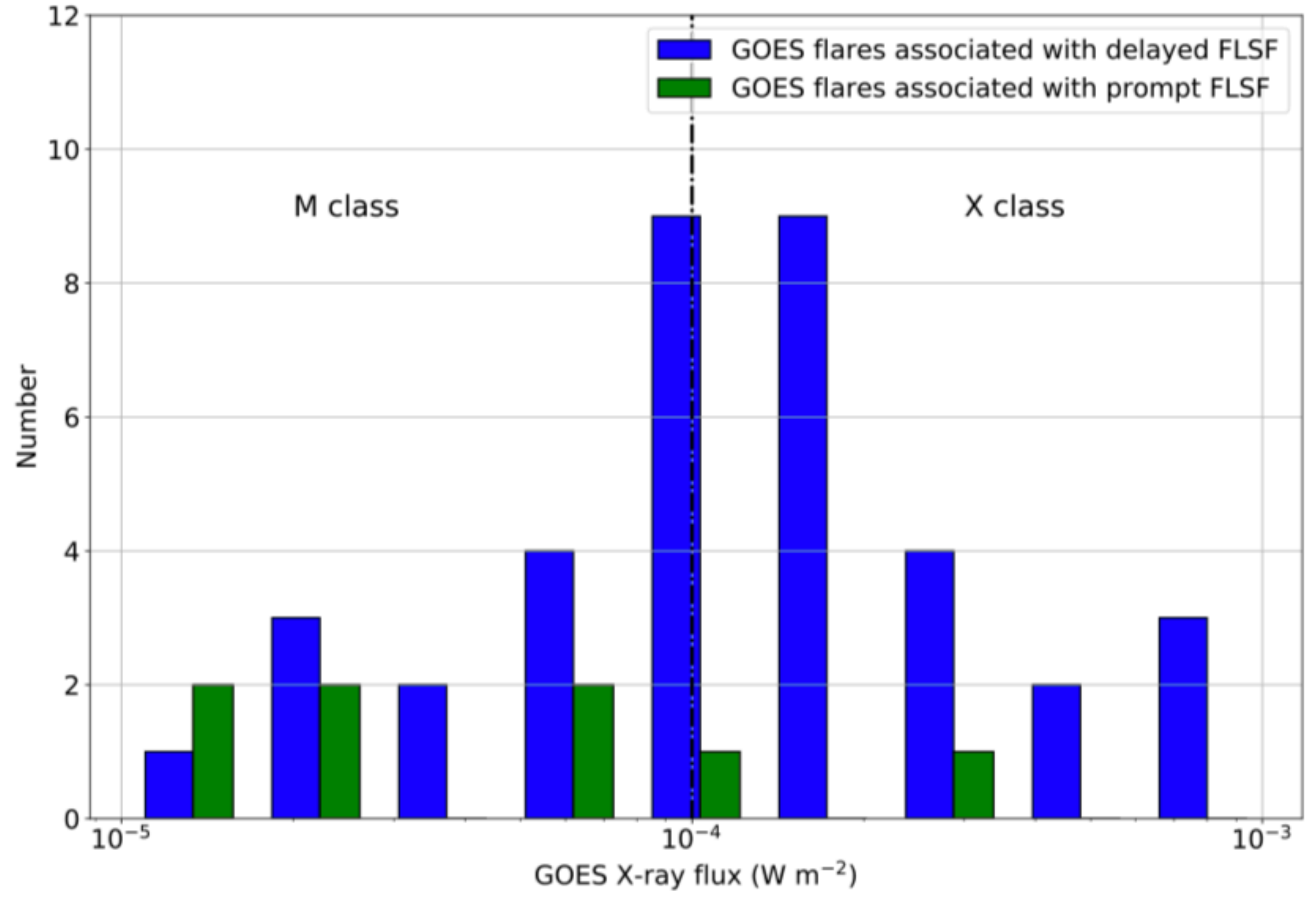
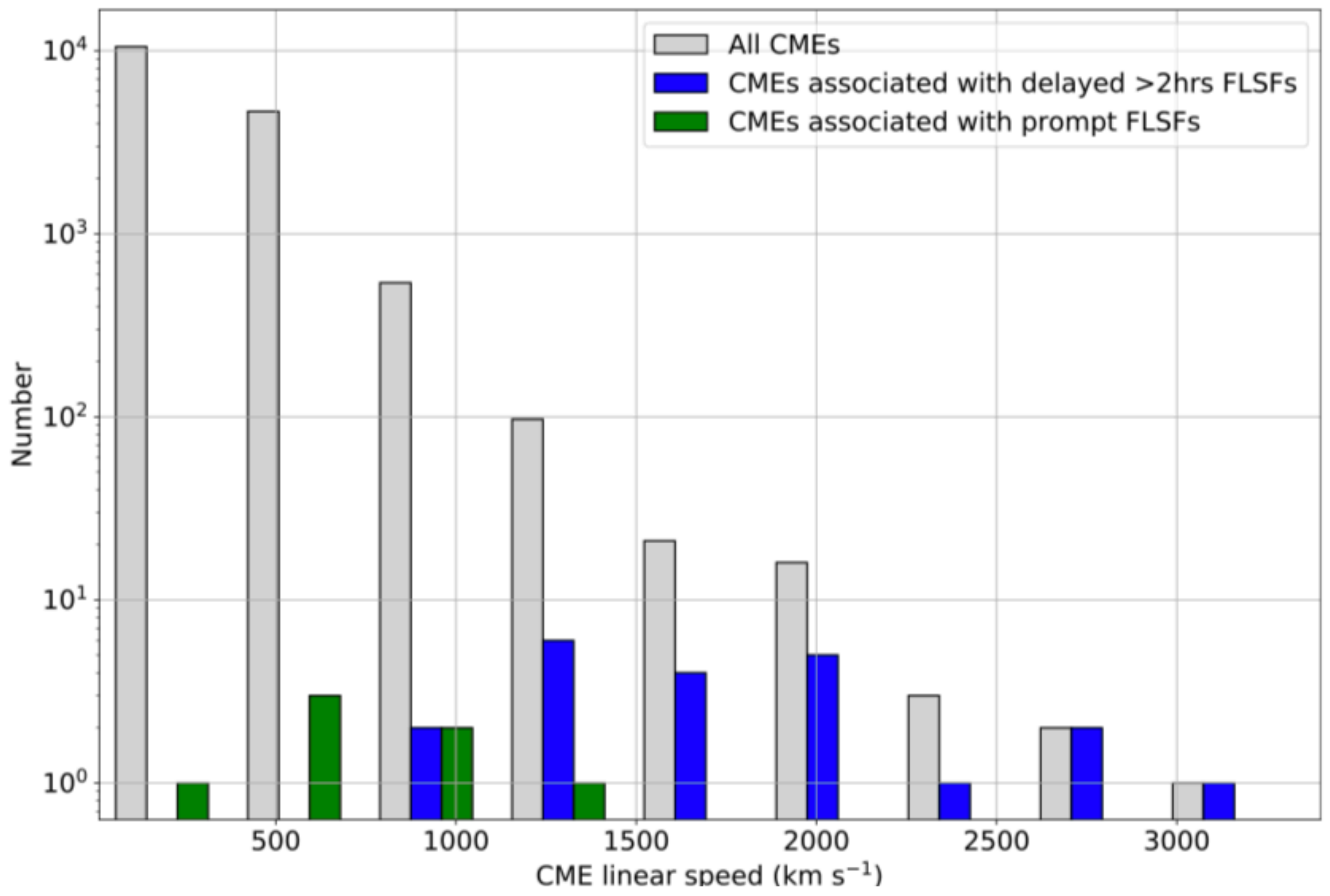
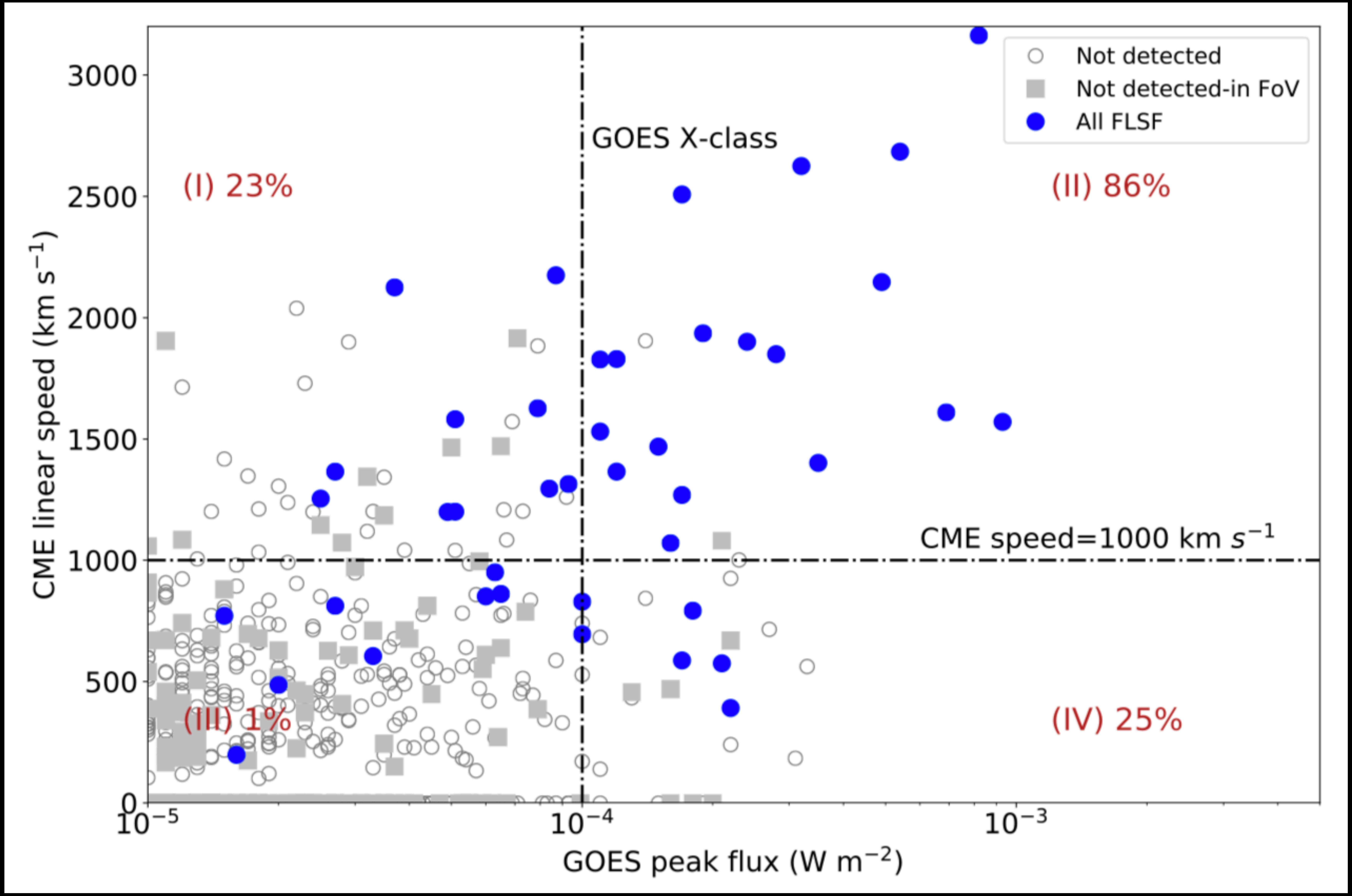


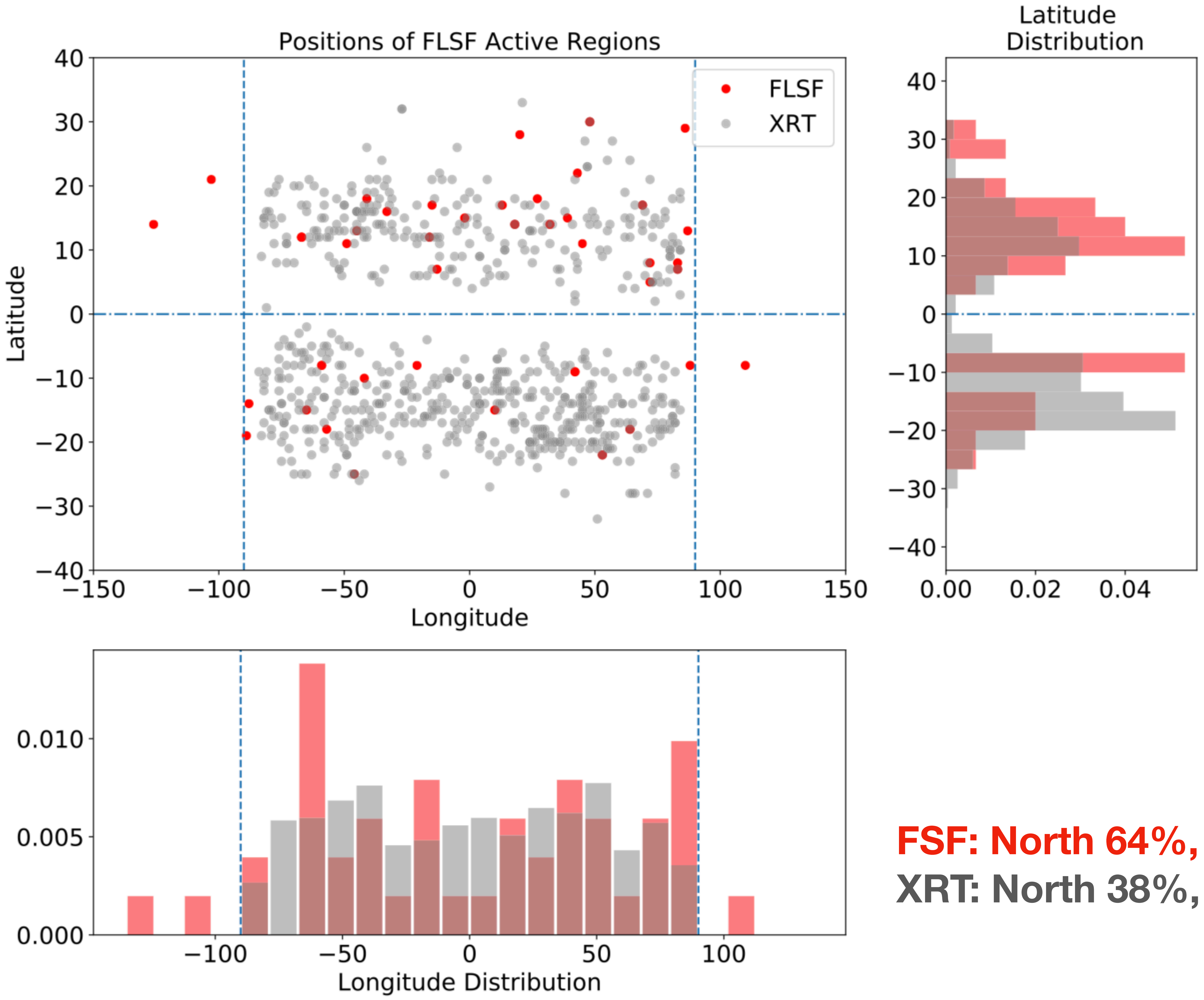


There doesn't seem to be any strong requirement on the GOES flare flux for a FLSF delayed or prompt

Which Solar Flares does Fermi LAT detect?



Distribution of the FLSF active regions

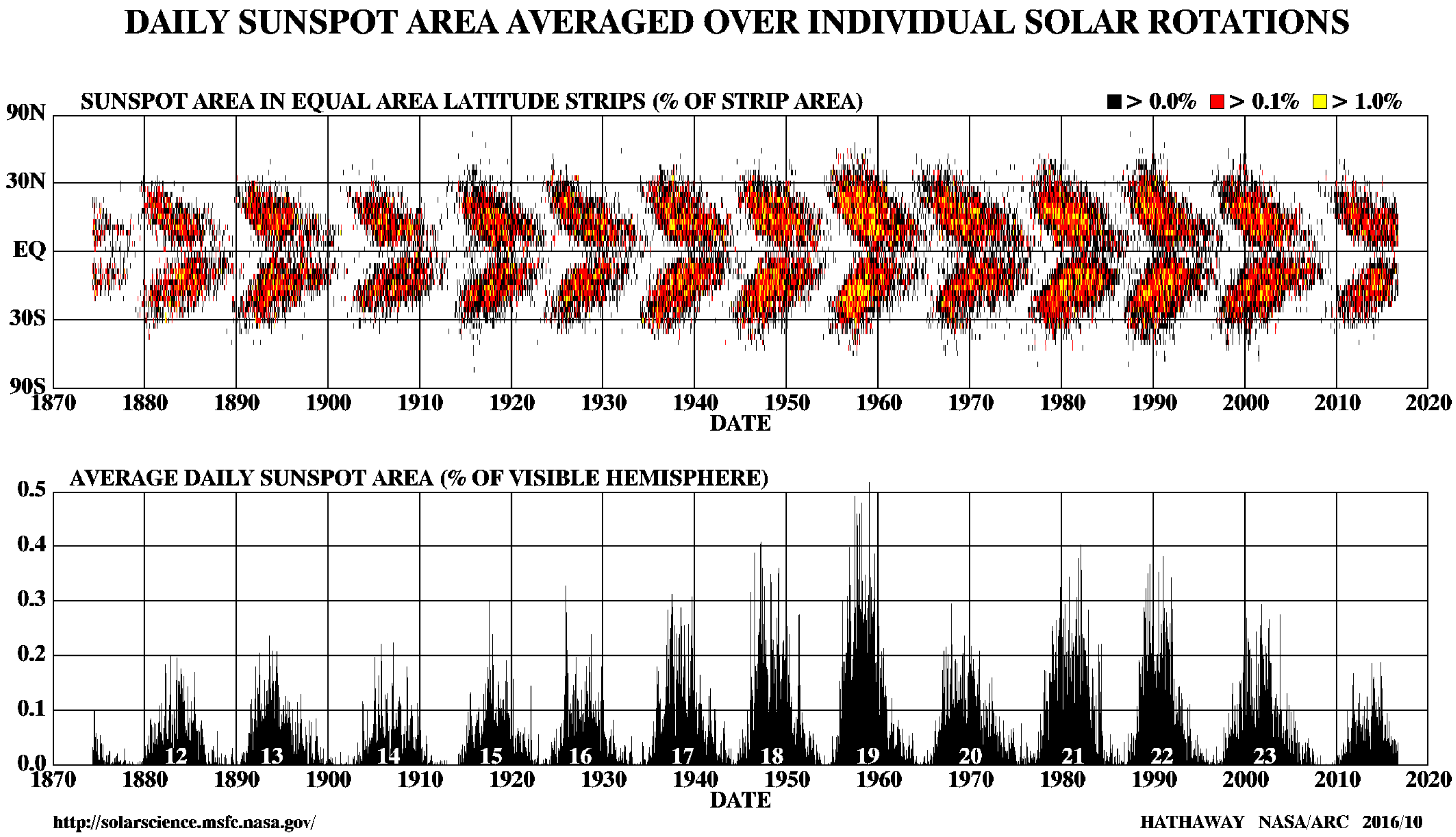


- **North/South asymmetry:** It is known that the distribution of AR shows an asymmetry with one hemisphere dominating at a given time
  - **Opposite in X-rays and gamma-rays!**
- **See also Winter et al., 2018**

FSF: North 64%, South: 36%

XRT: North 38%, South 62%

The "butterfly effect" as seen by Fermi LAT



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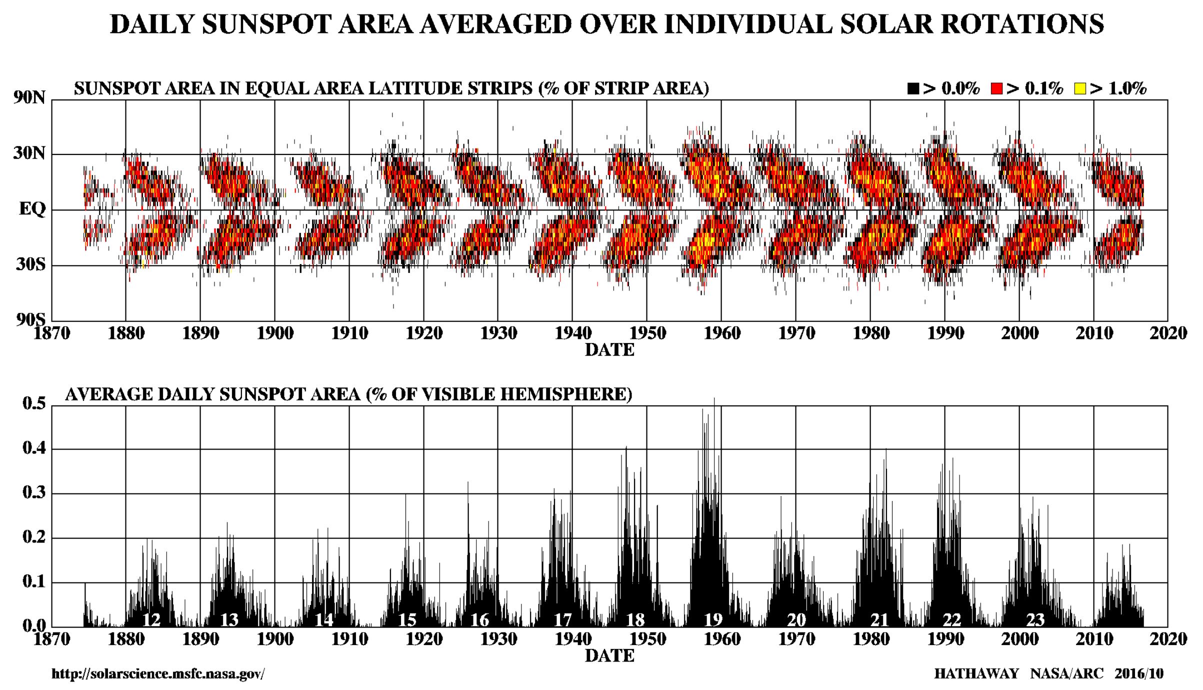
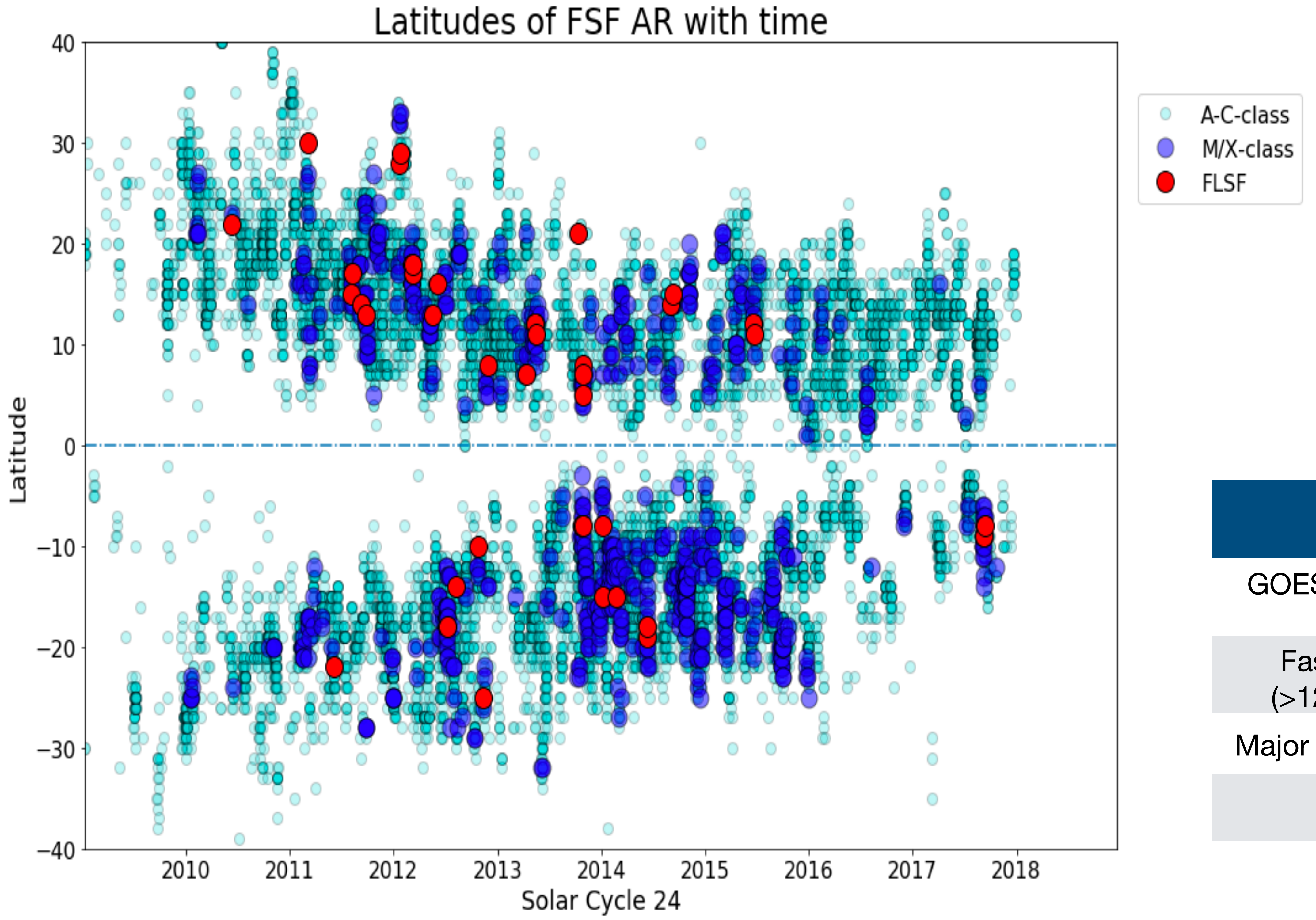
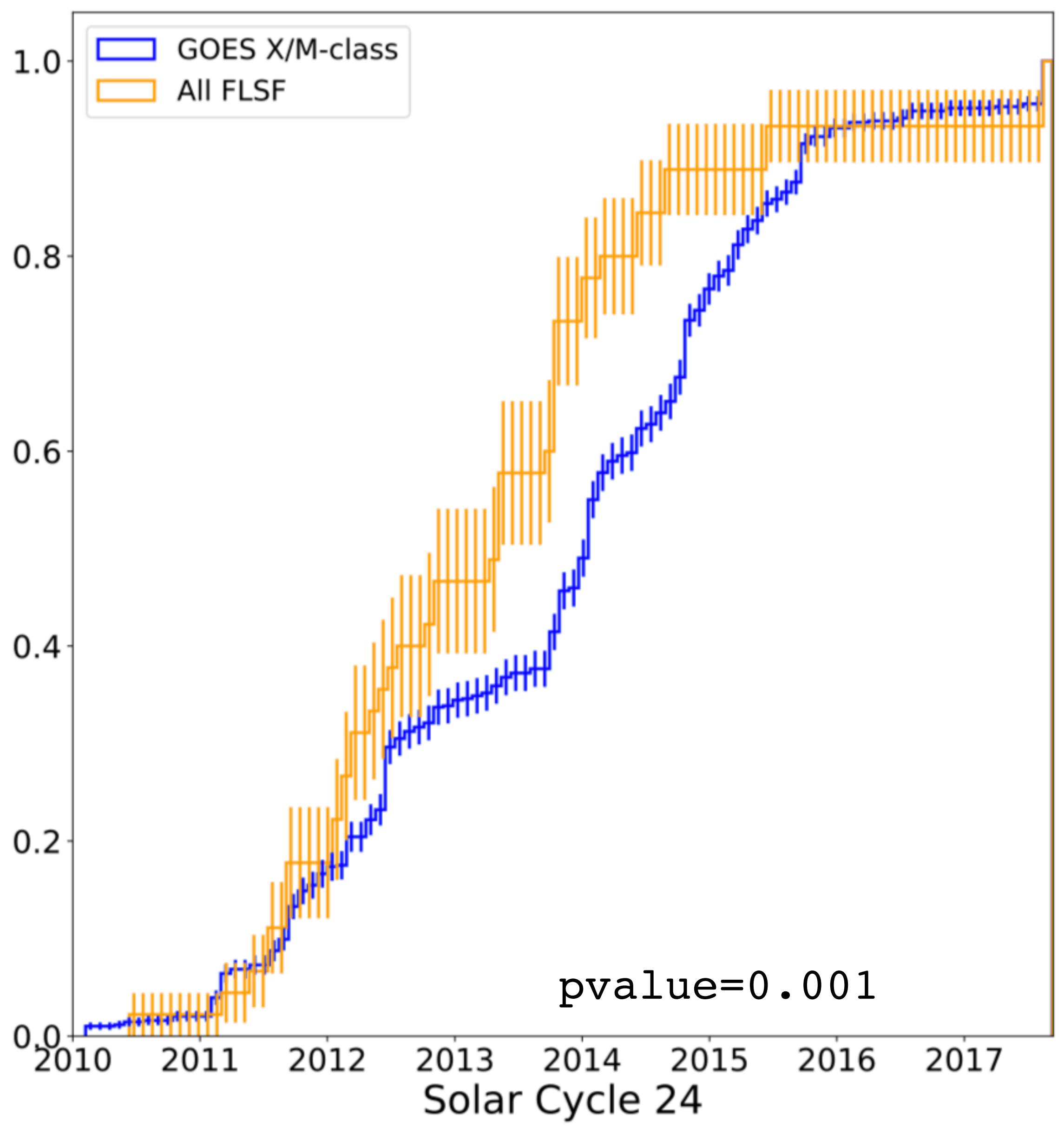
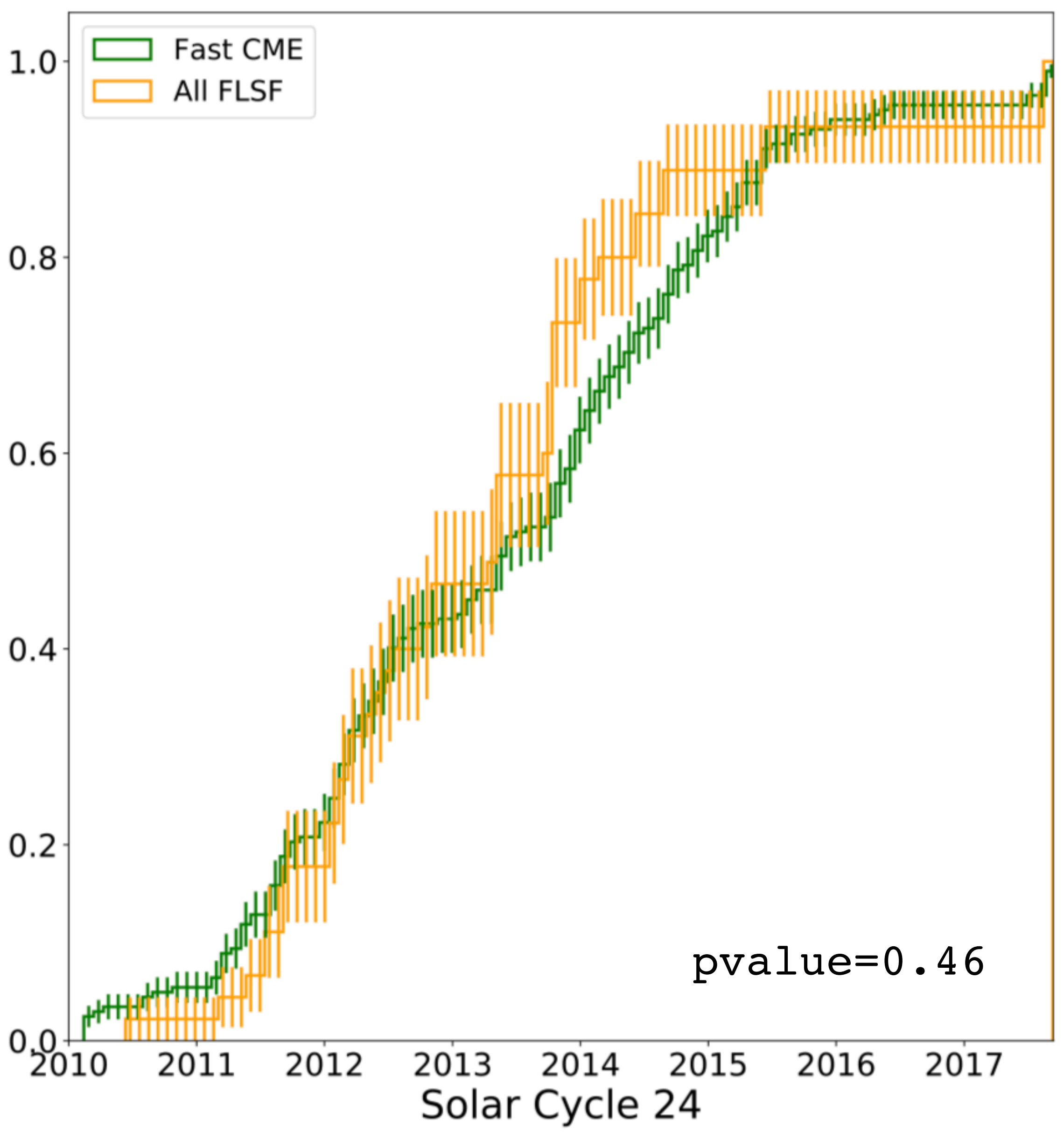


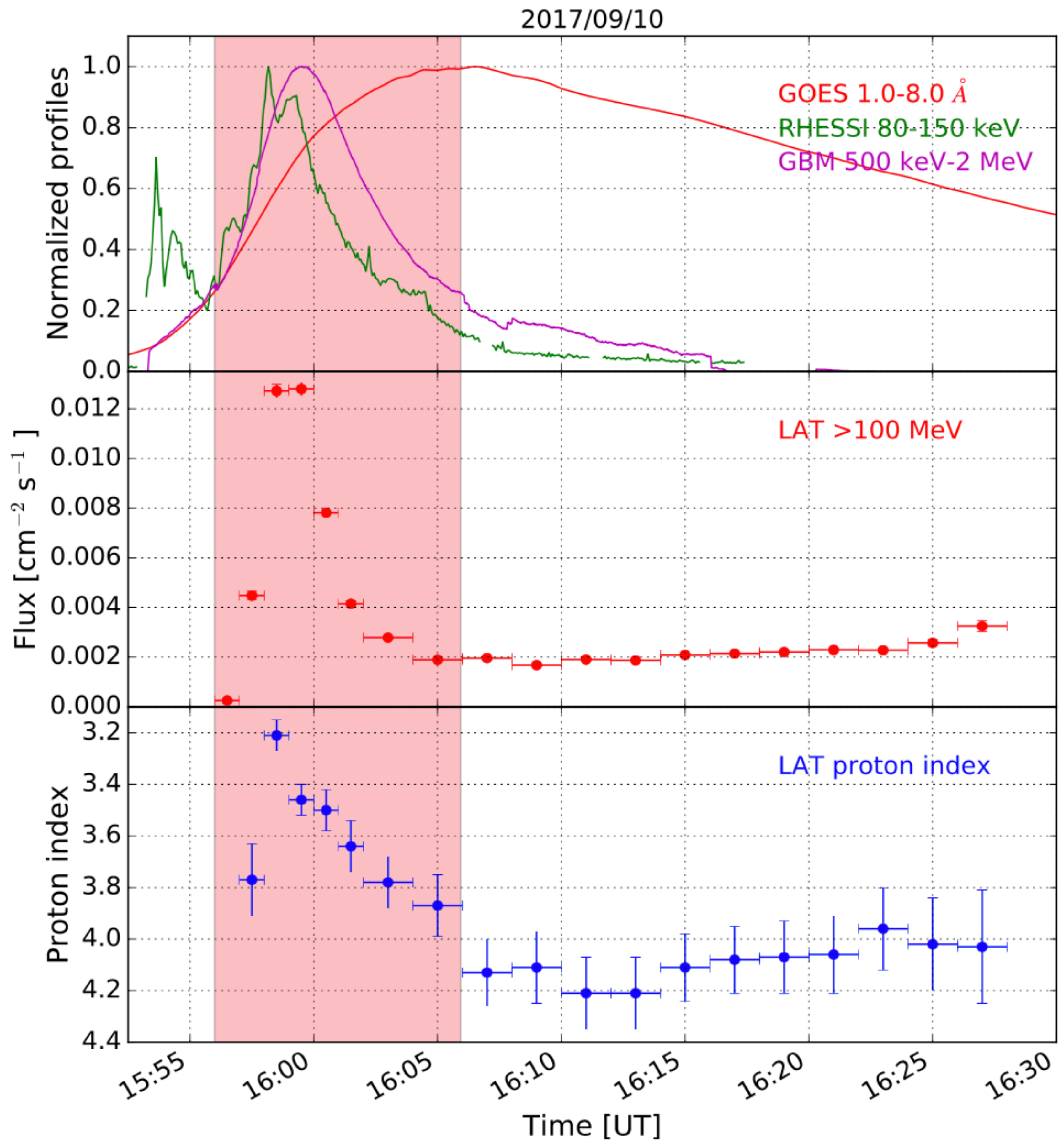


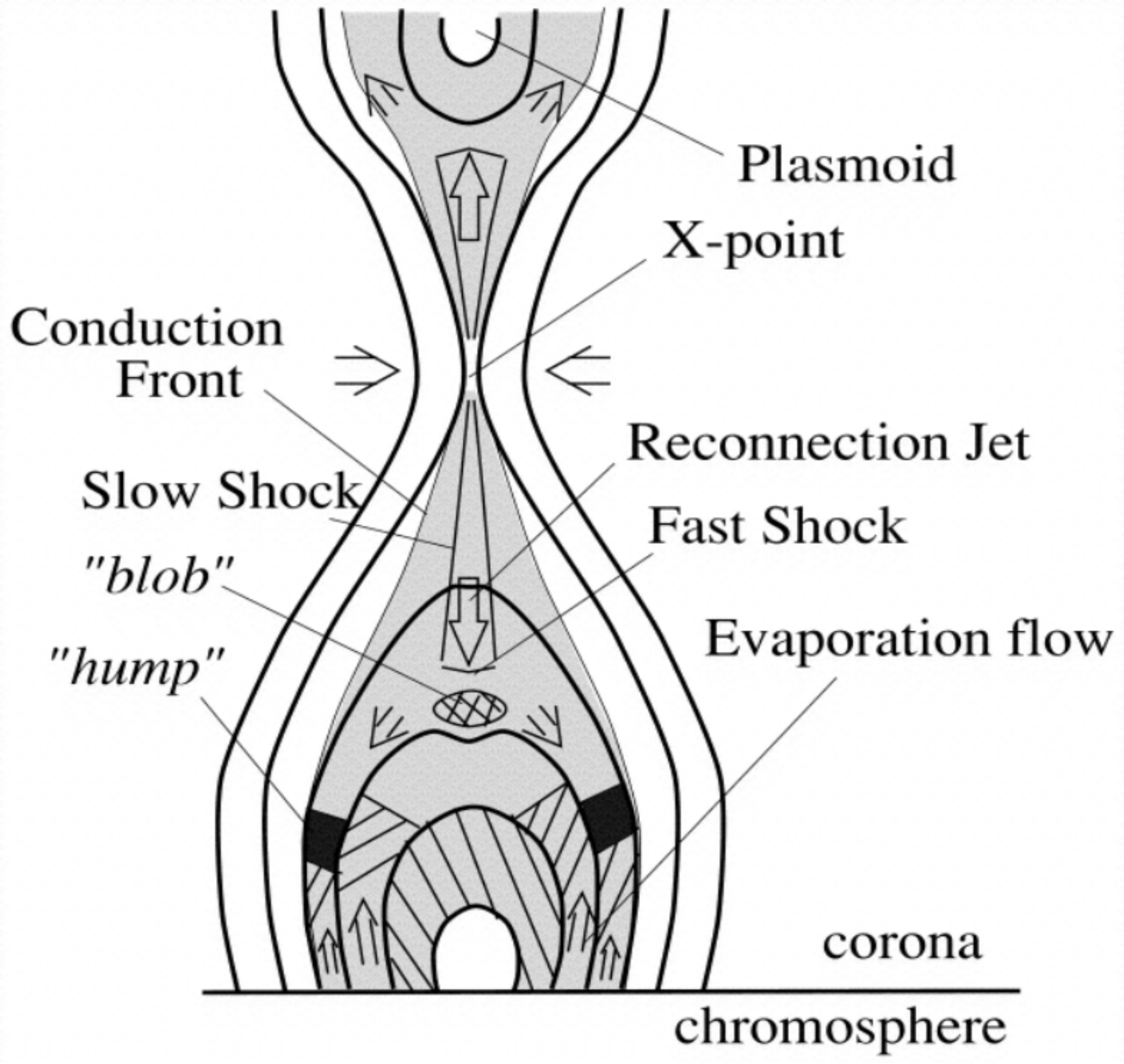


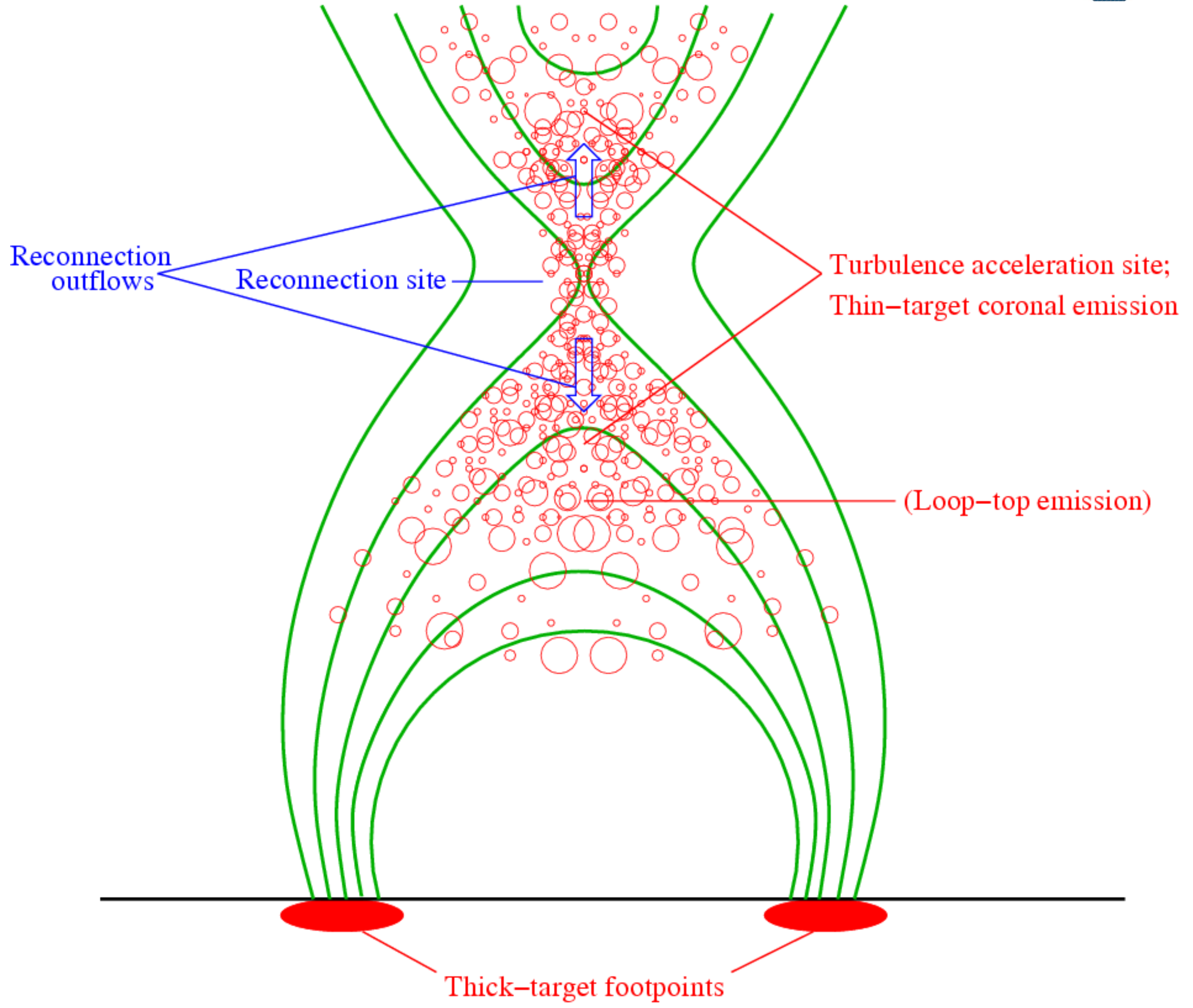


	Total	2010 - 2014	2014 - 2018
GOES M and X-class	773	384	389
Fast CMEs (>1200km/s)	96	**61**	35
Major SEP Events	42	**30**	12
FLSF	45	**33**	12

Possible Scenario - Prompt



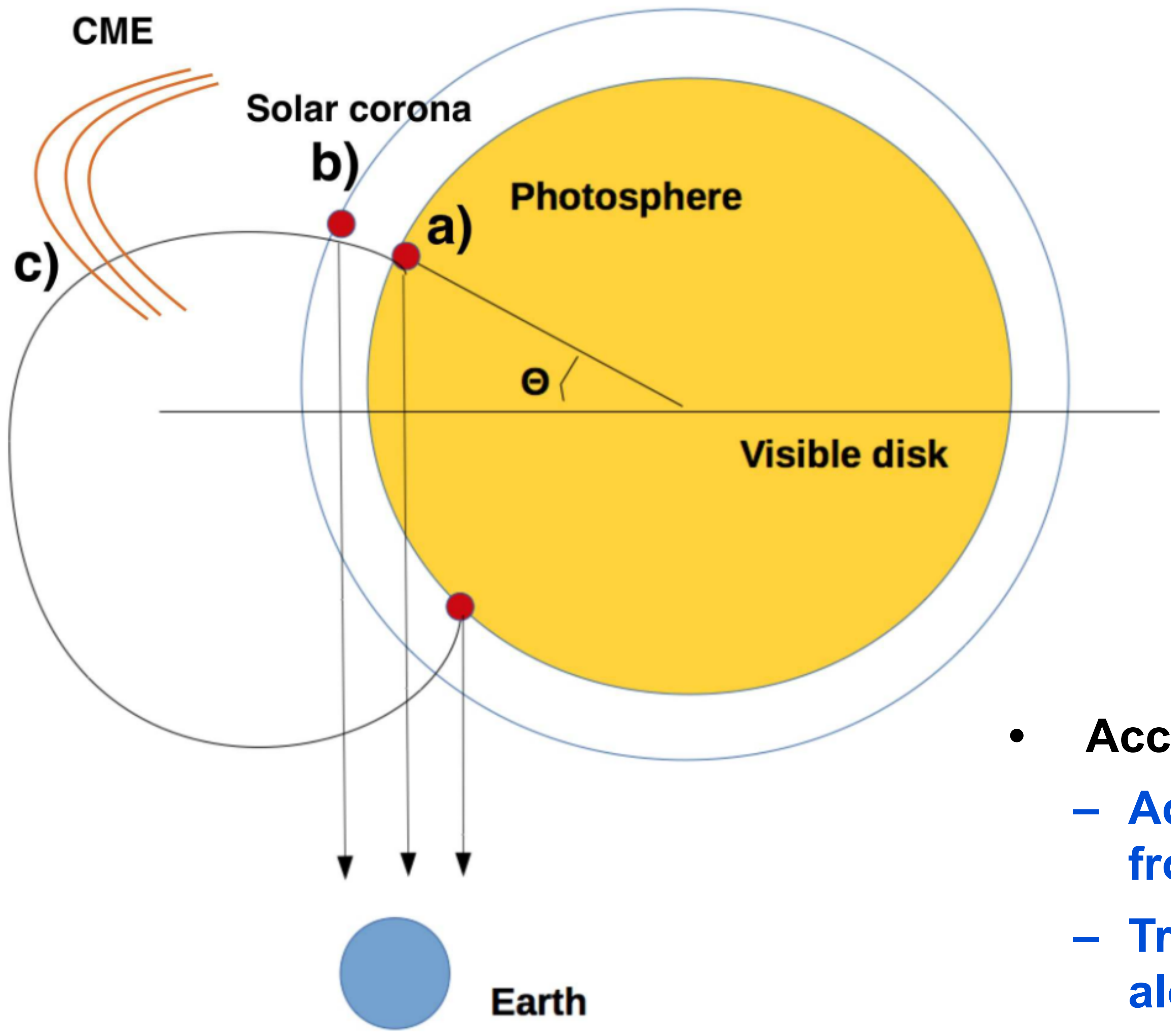




- **Trap-precipitation of HE particles produced during the impulsive phase via magnetic reconnection (Kanbach et al. 1993);**
- **In coulomb collision, the trap efficiency increases with energy, and a gradual hardening of the spectrum is expected;**
- **Not observed during the sustained emission;**

- **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;**

Possible Scenario - Delayed



Omodei et al. 2015 (arXiv:1502.03895)

- 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 CME speed & SEP

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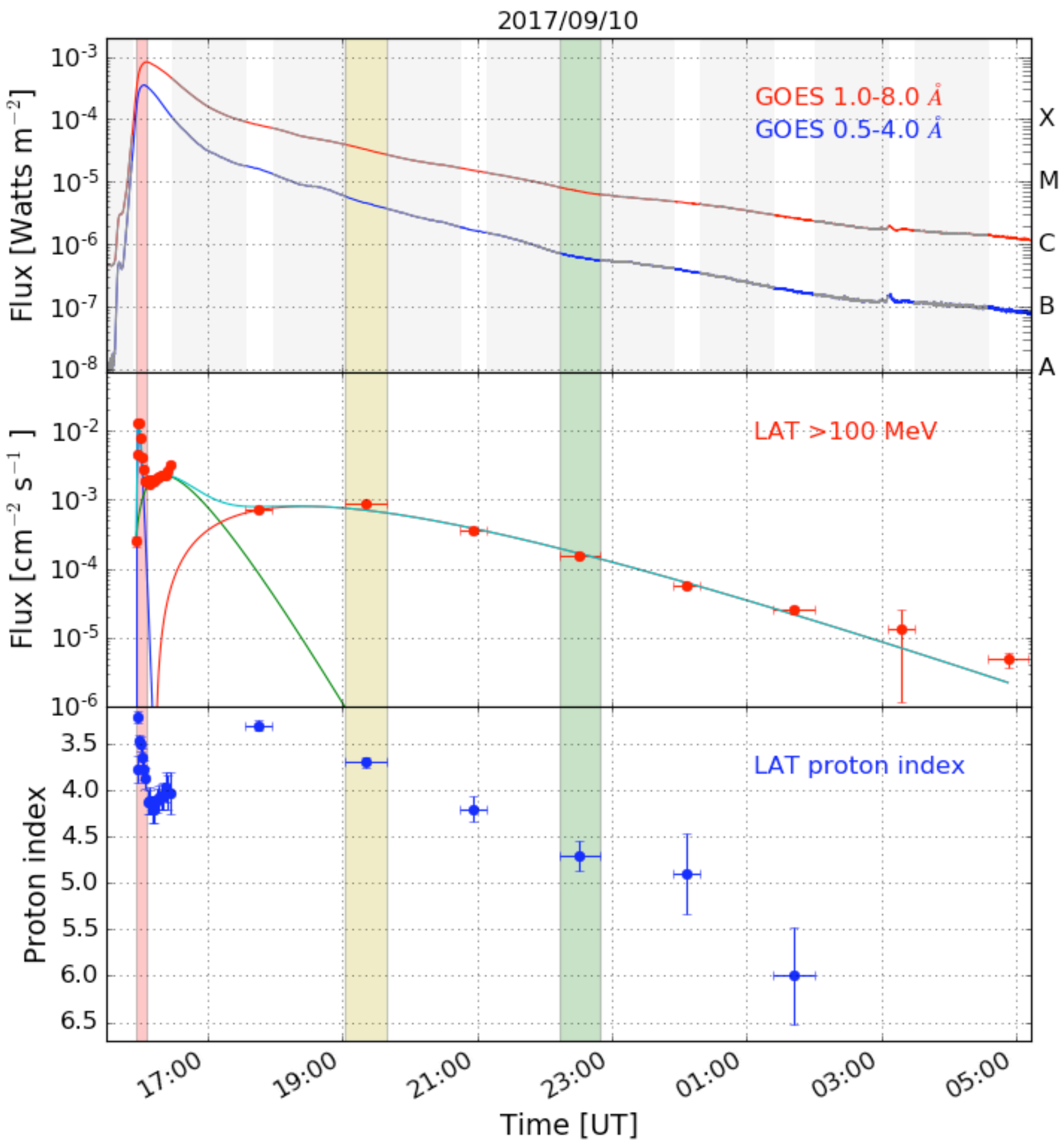

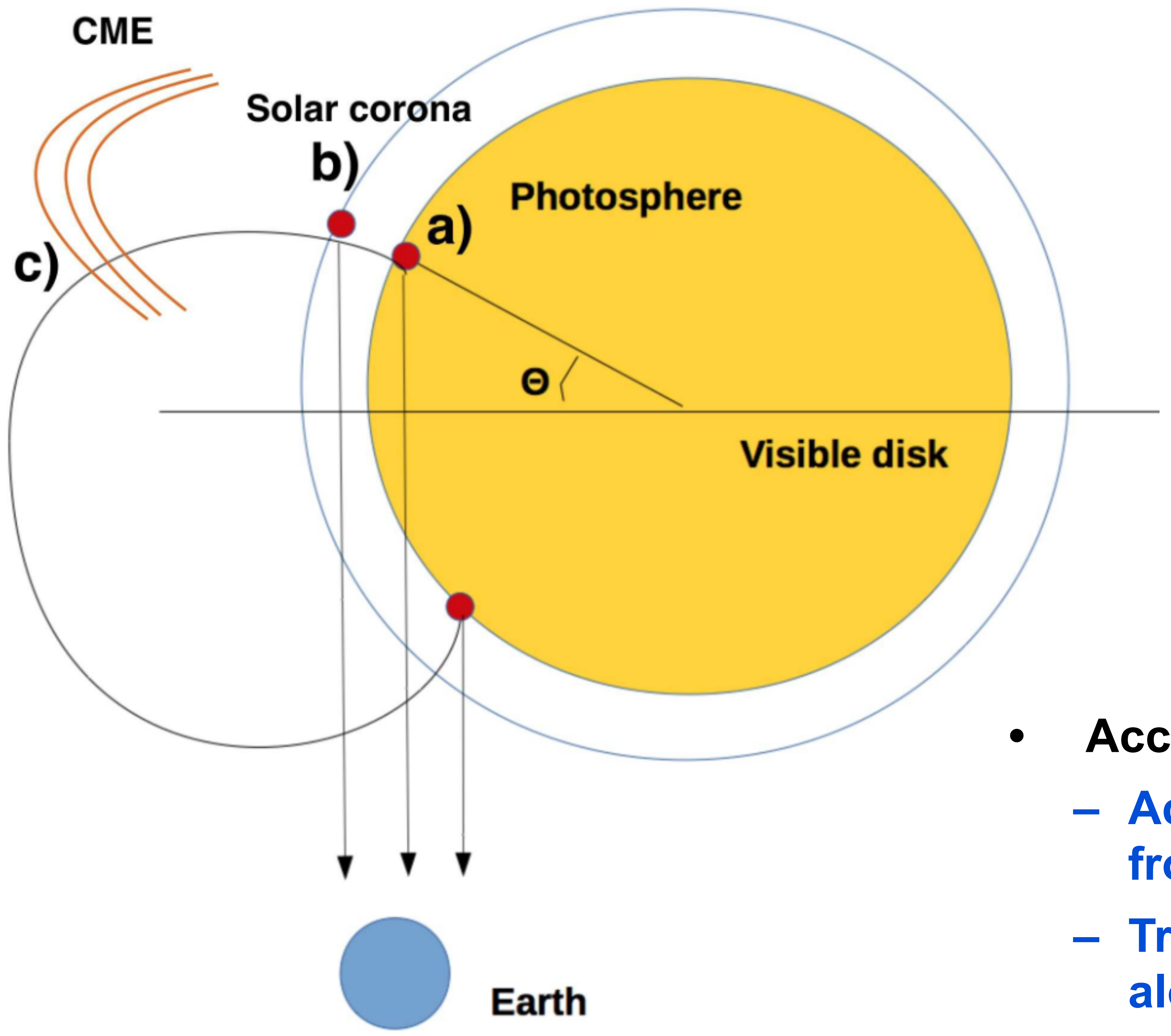

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Summary and Conclusions

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- Comprehensive study of high-energy solar flares: First Fermi-LAT Solar Flare Catalog (FLSF)
  - Distinct phases observed (prompt vs delayed);
  - Prompt emission observed during on-disc flares suggests acceleration at the flare site
  - Long emission: Correlation with CME stronger than correlation with GOES X-ray peak flux
- 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)

M. Ajello *et al* 2021 *ApJS* 252 13
https://doi.org/10.3847/1538-4365/abd32e
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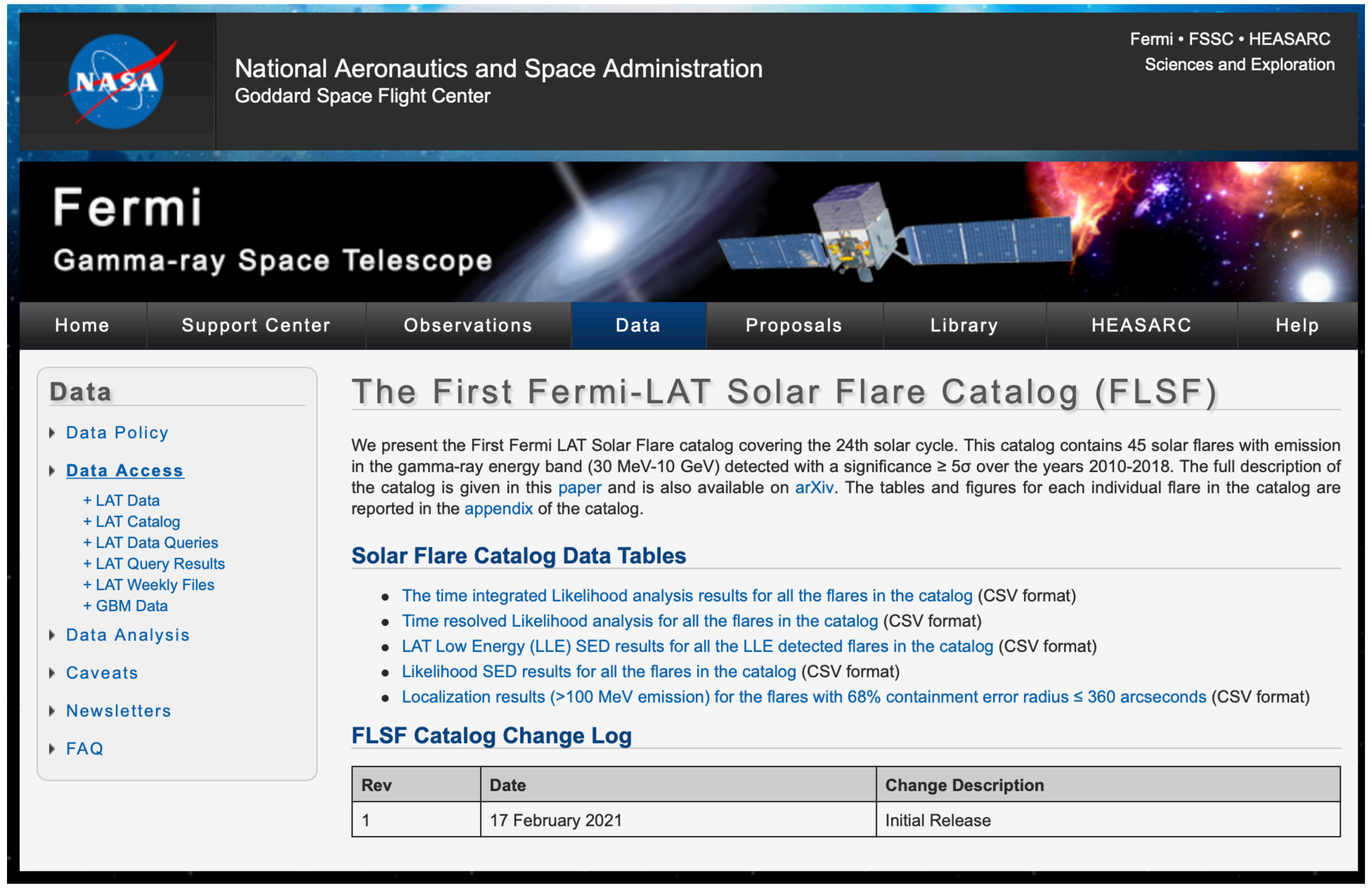

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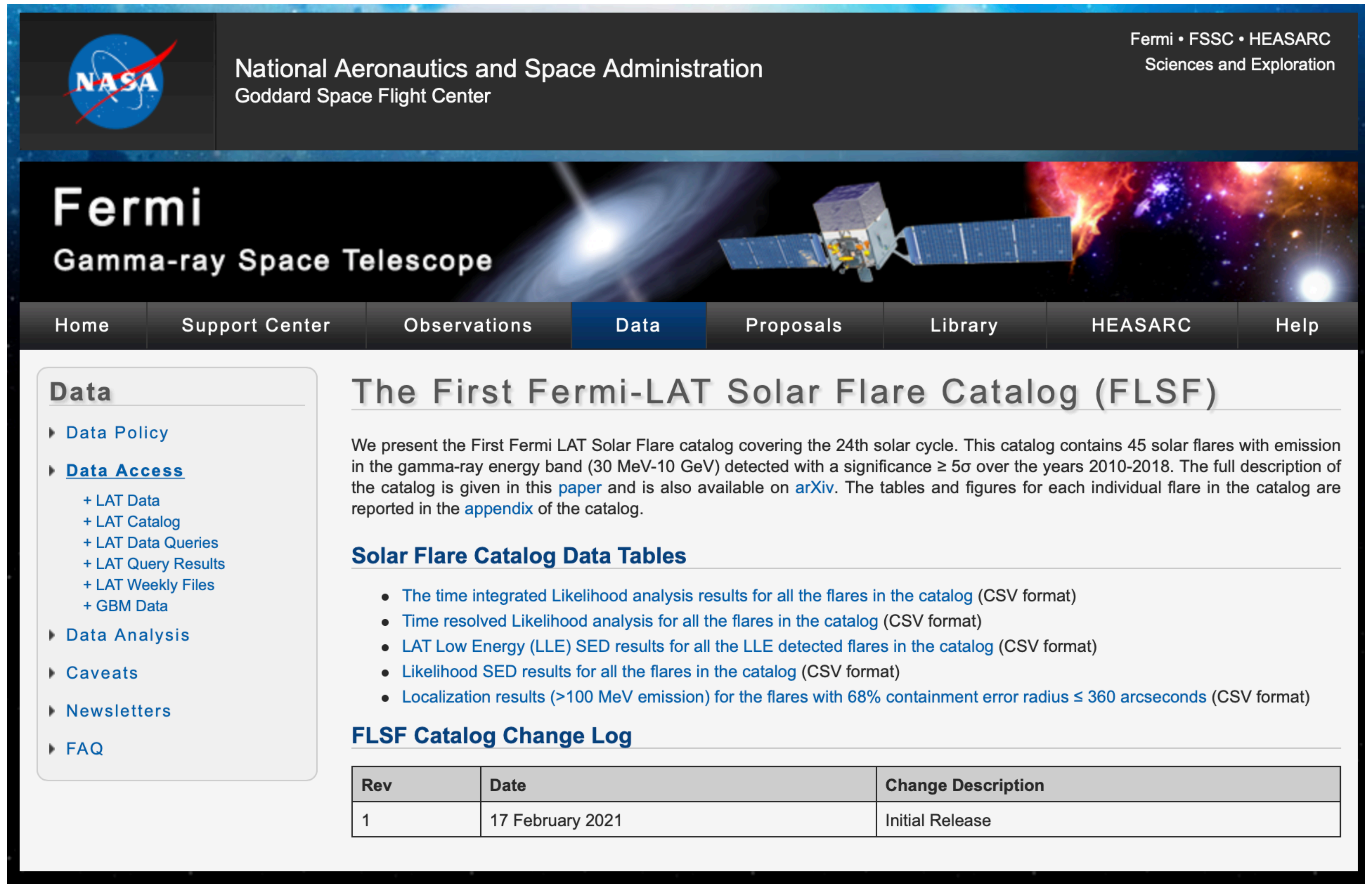

https://fermi.gsfc.nasa.gov/ssc/data/access/lat/FLSF/


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NASA
Fermi
Gamma-ray Space Telescope
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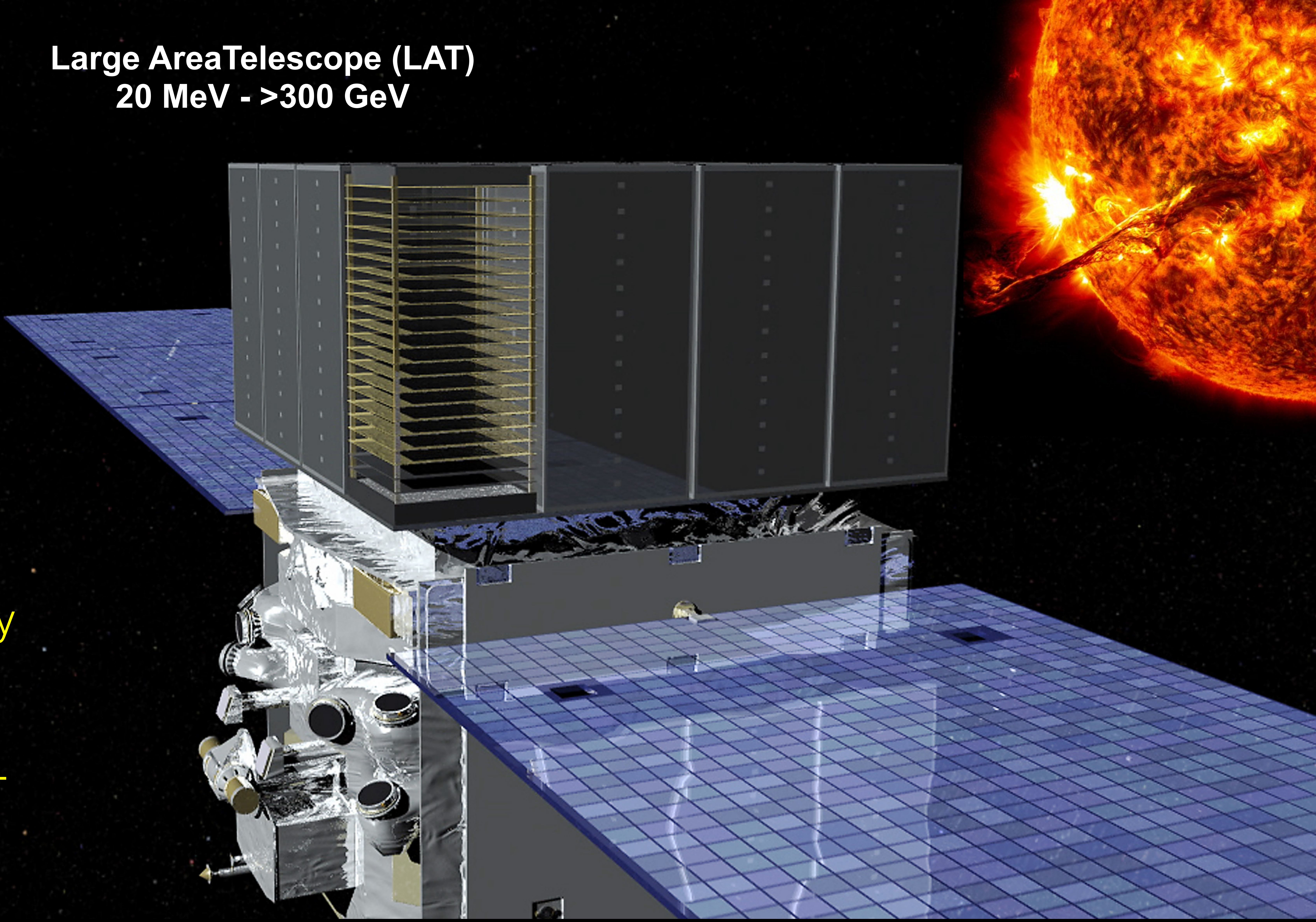
Spare


CREDIT: NASA

Fermi-LAT KEY FEATURES

Huge field of view
(LAT: 20% of the sky at any instant)
Good energy resolution
(<15% >100 MeV)
Good Point Spread Function
(~1° at 1 GeV)
Large effective area
(>1 GeV is ~8000 cm^2 on axis)
GBM: whole *unocculted* sky at any time.
Huge energy range, including largely unexplored band 10 GeV - 100 GeV. Total of >7 energy decades!



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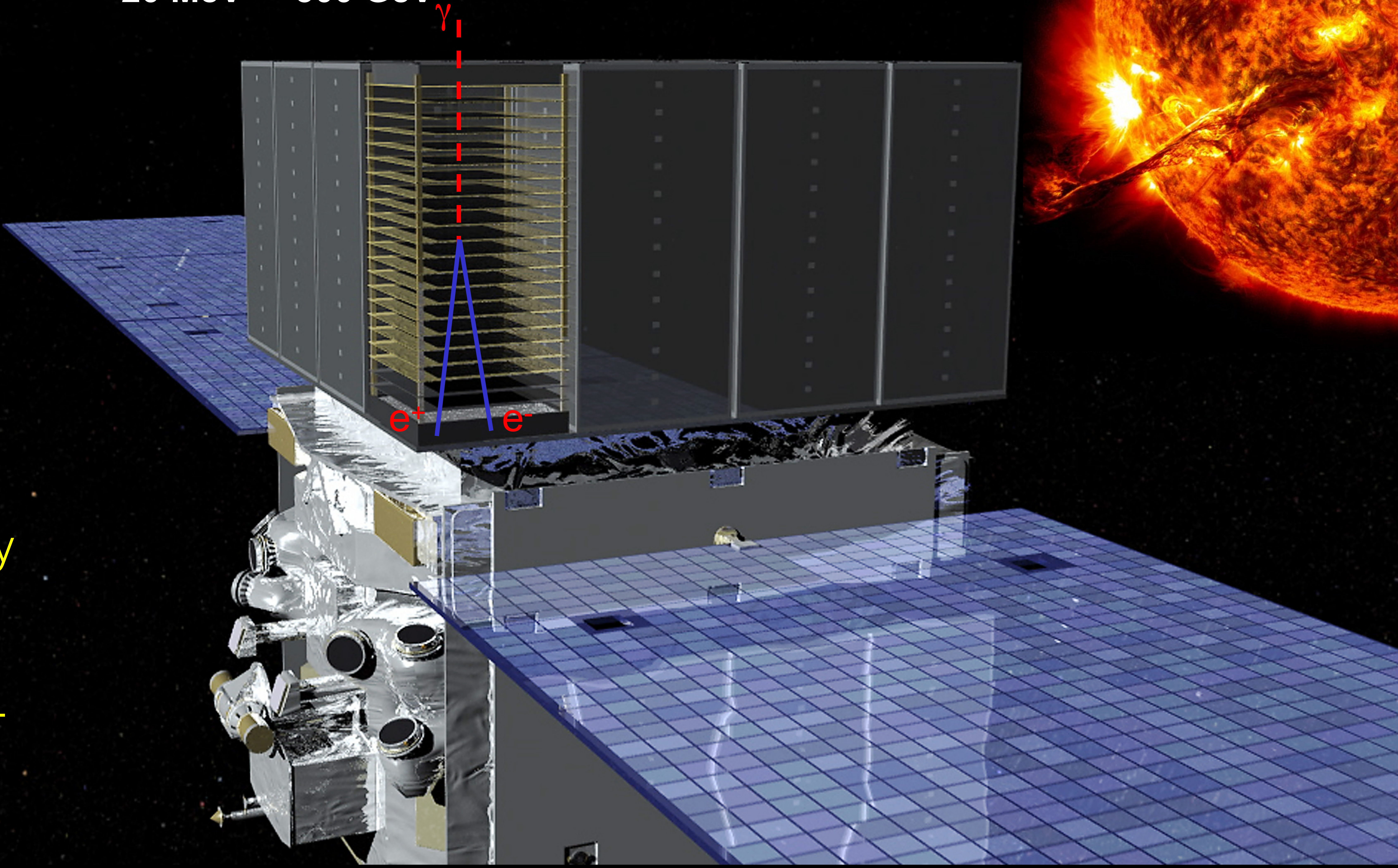

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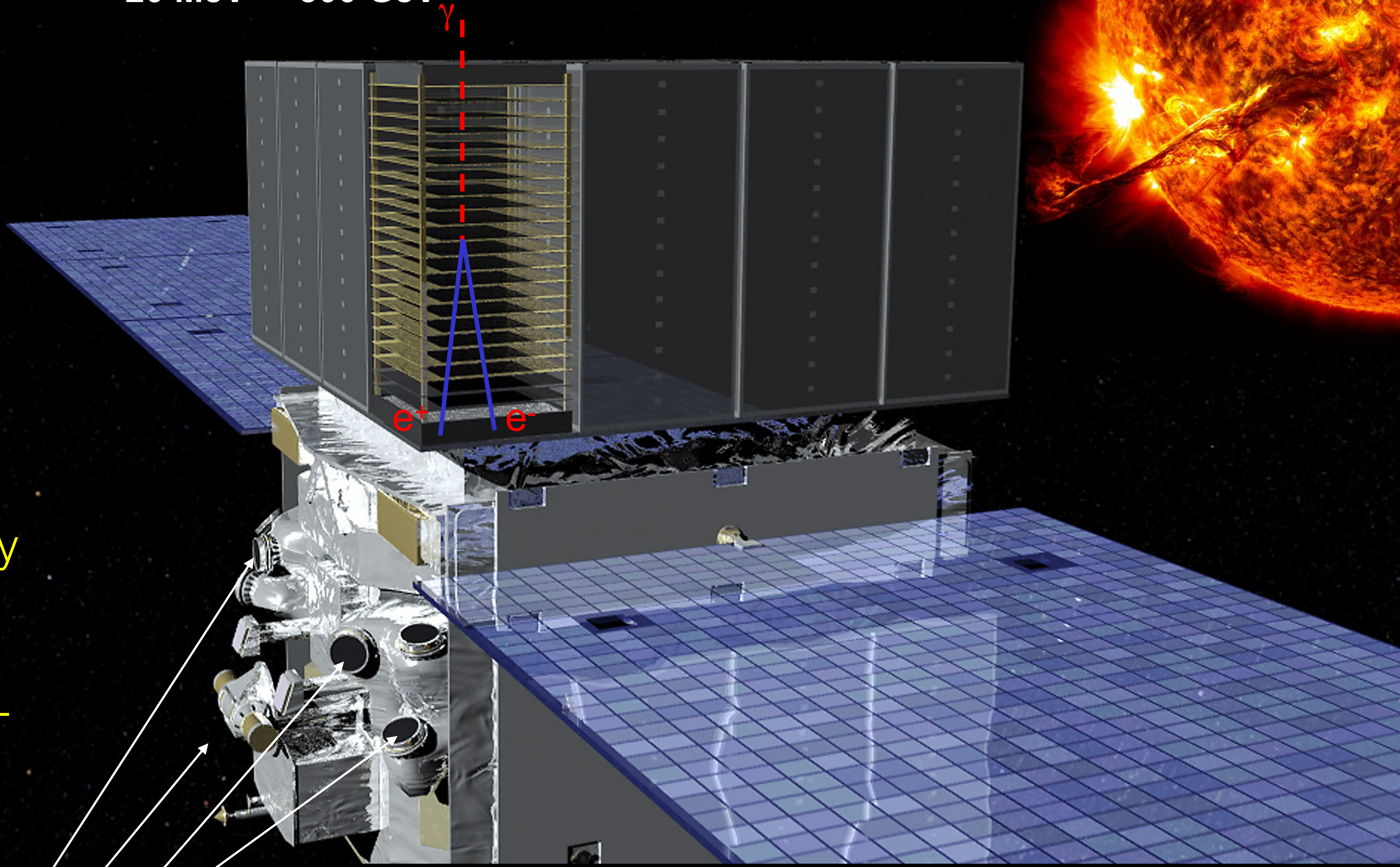

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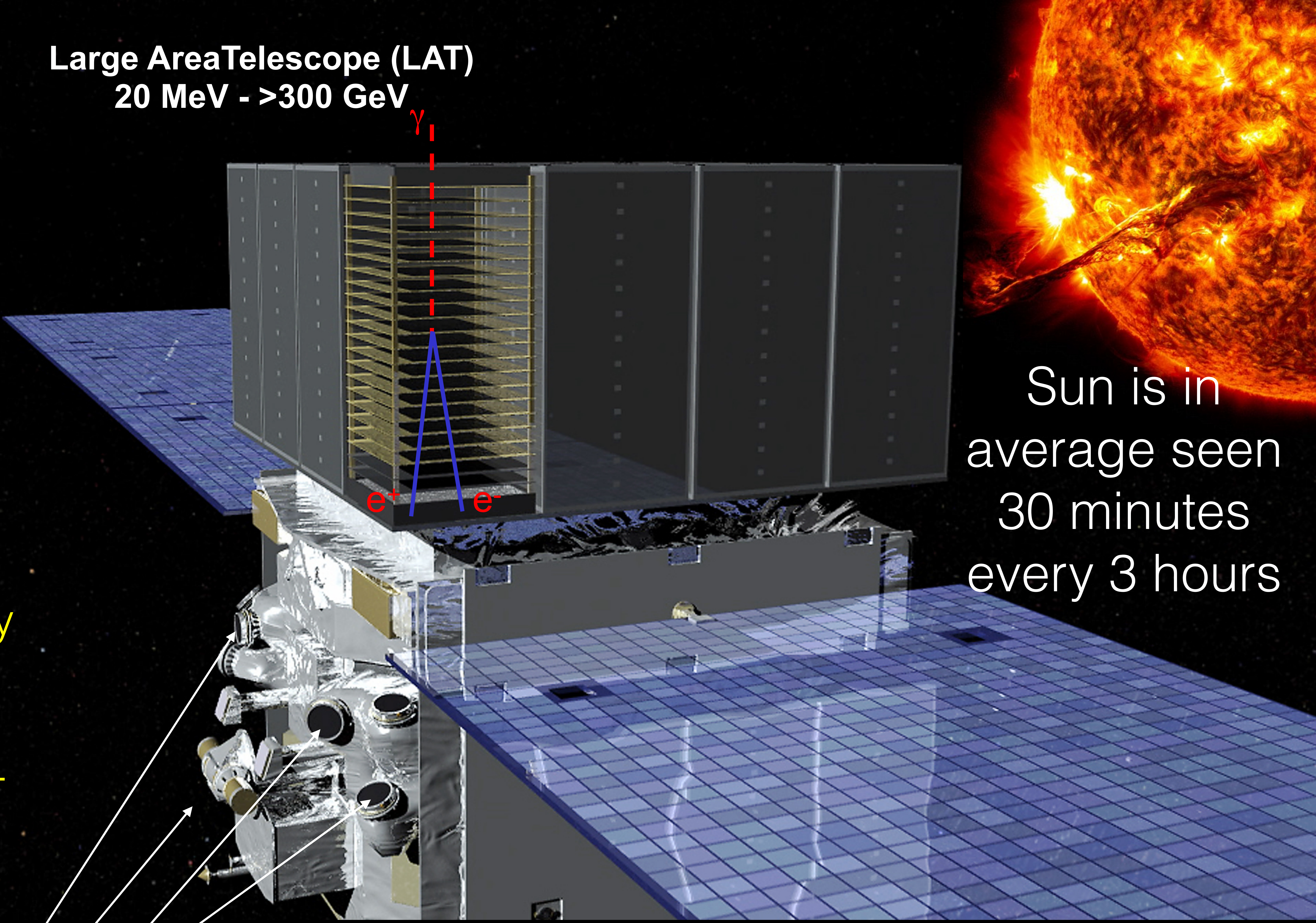
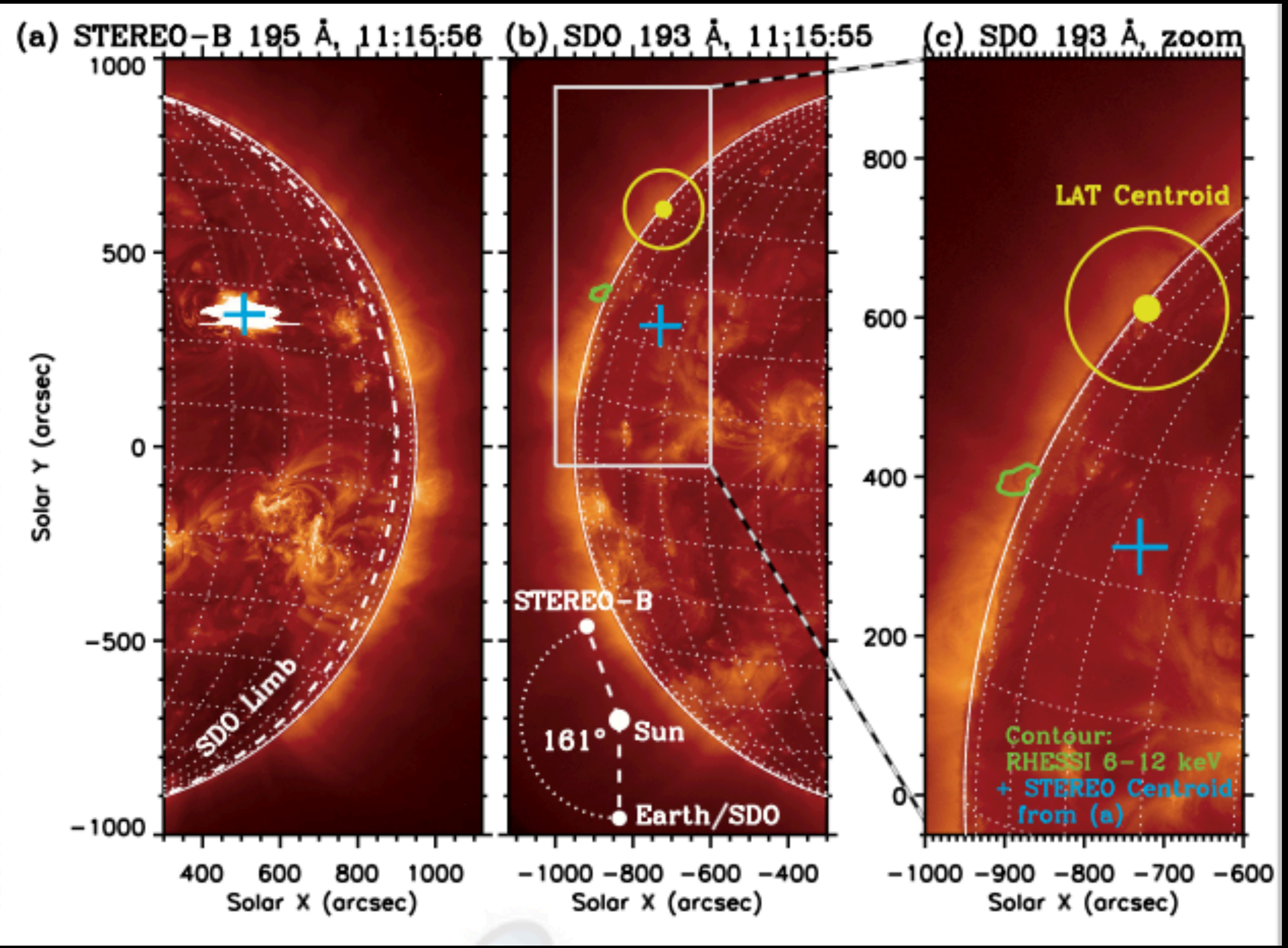
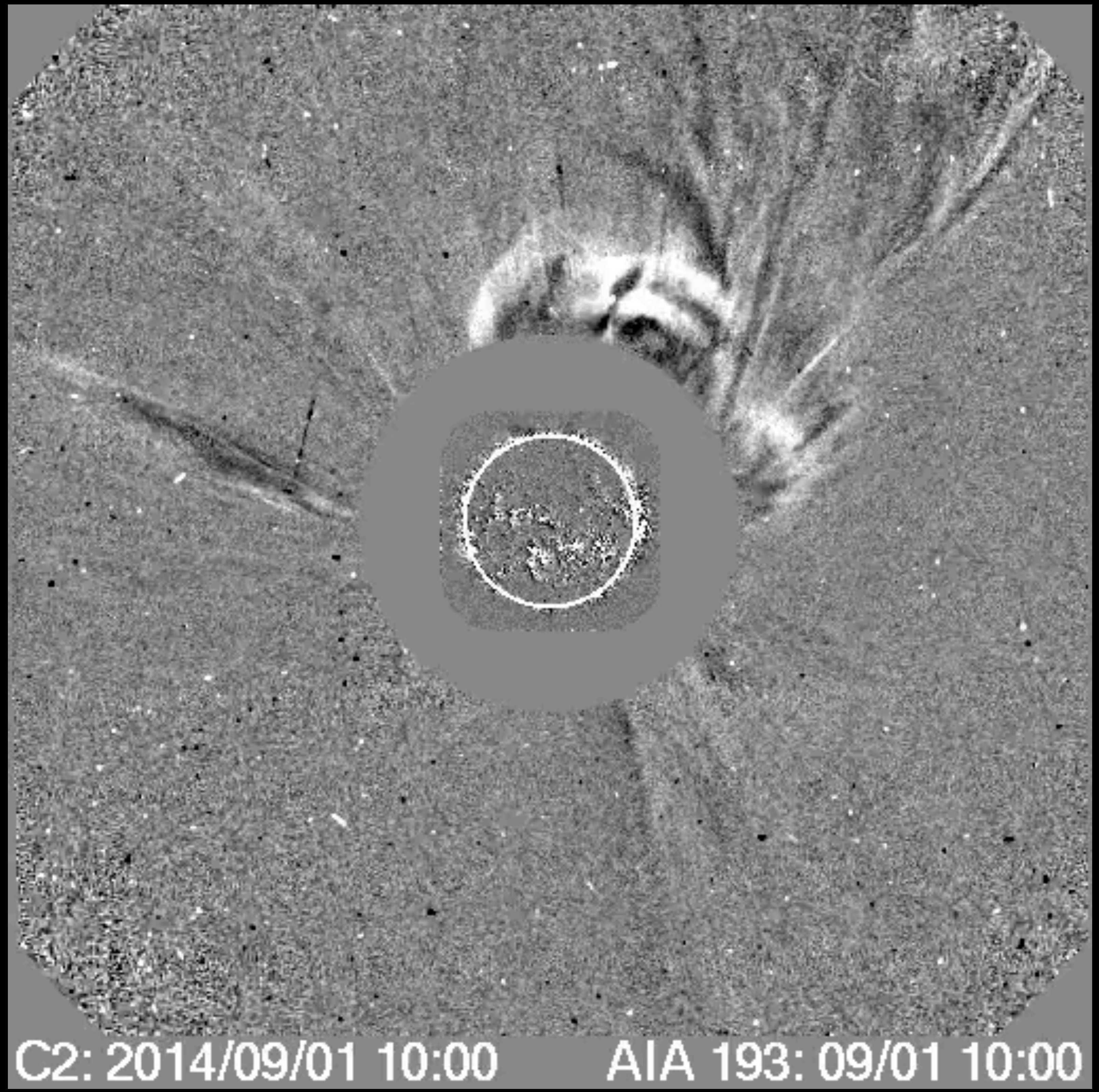
Huge energy range, including largely unexplored band 10 GeV - 100 GeV. Total of >7 energy decades!



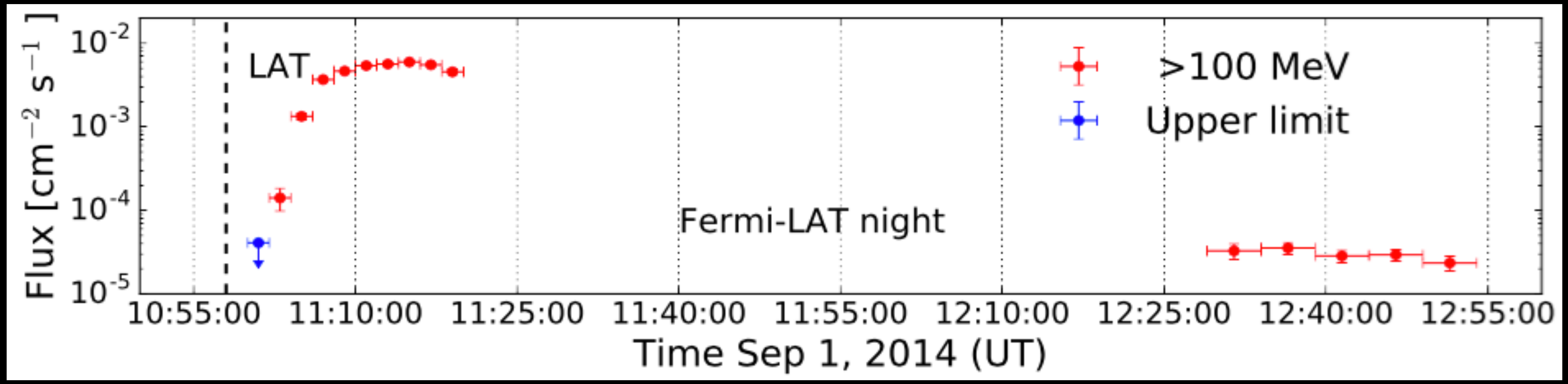
Launched in 2008, continuously monitors the sky

Association with fast CME

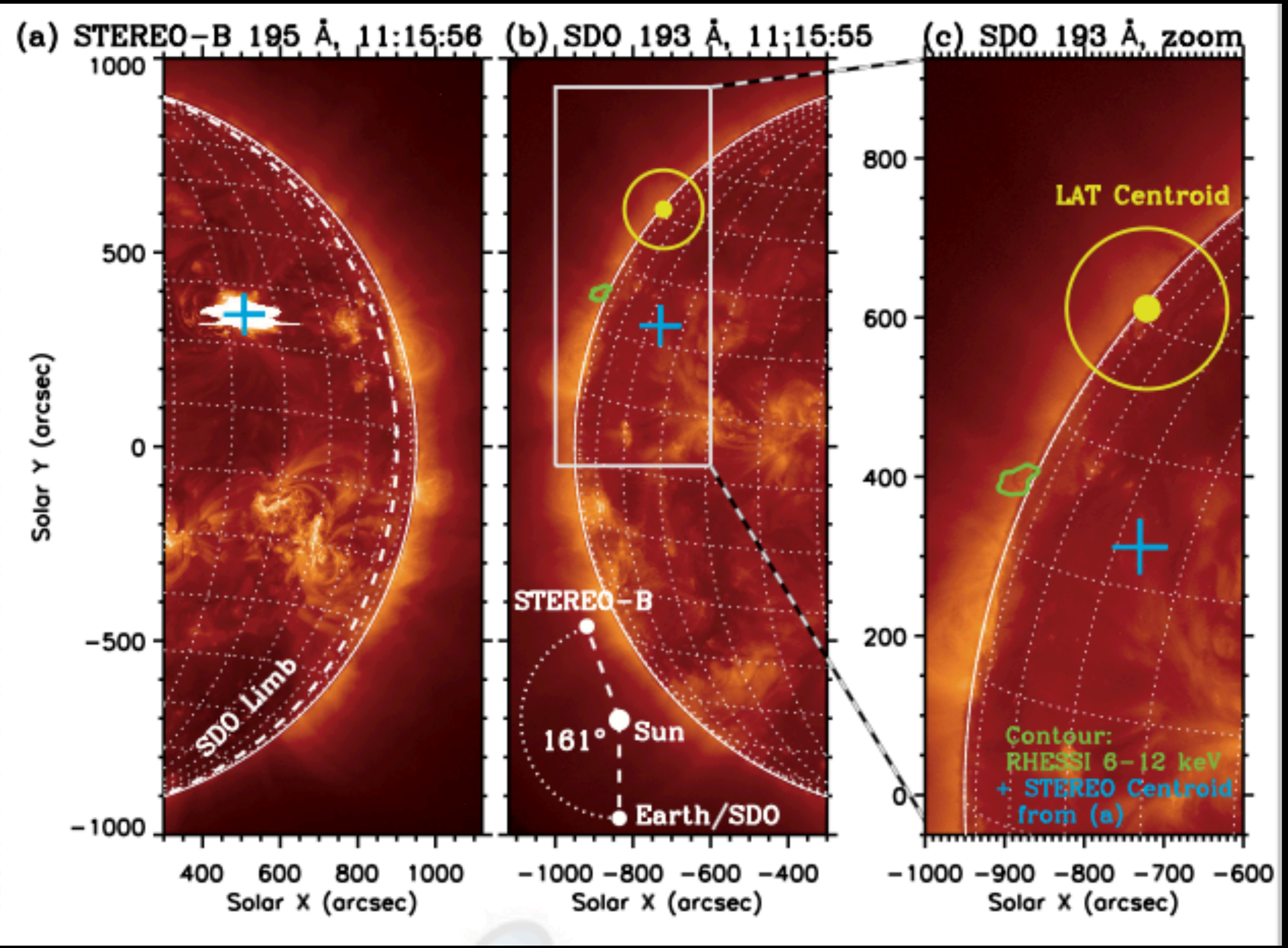


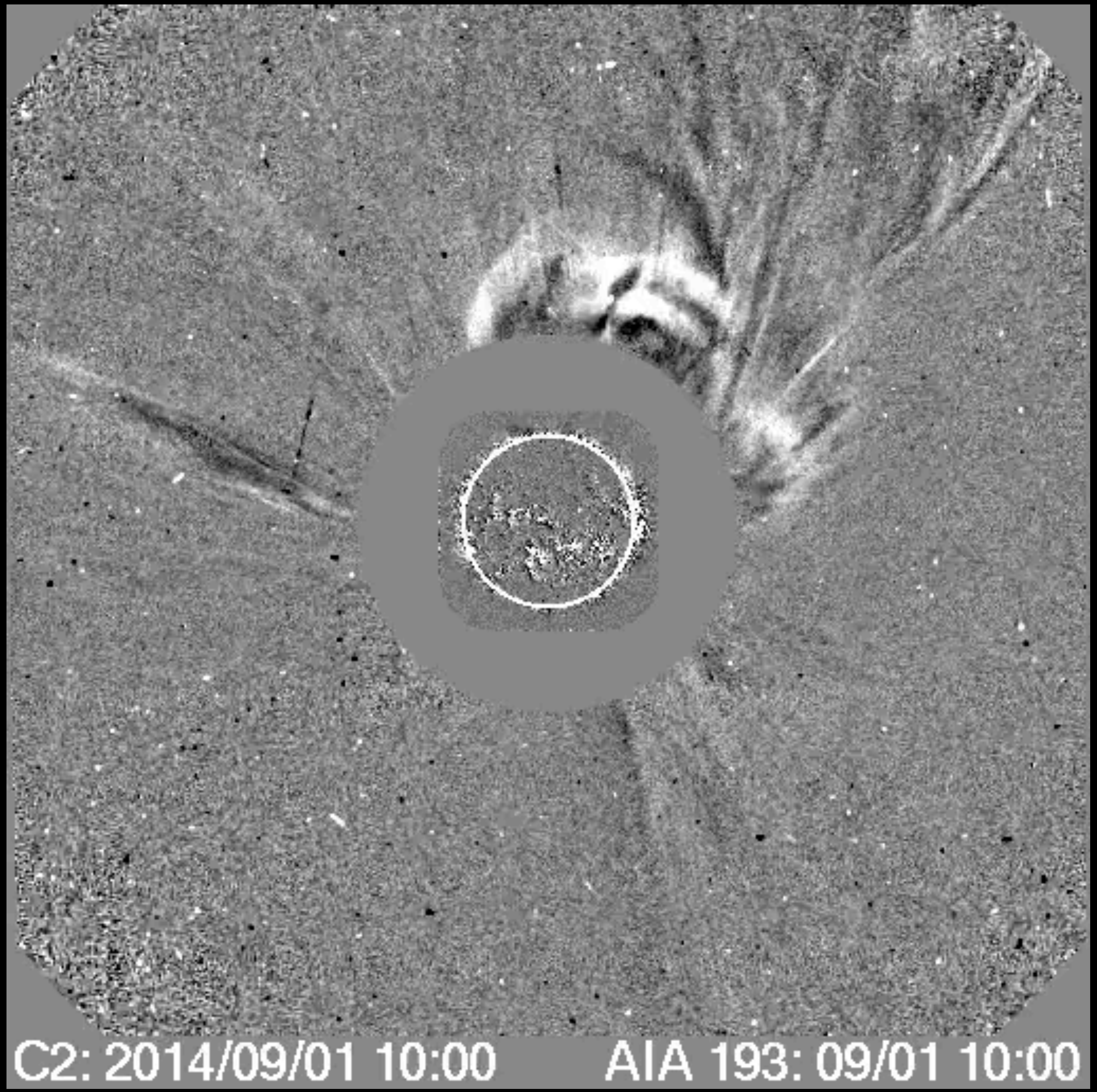


CME speed ~ 1900 km s⁻¹

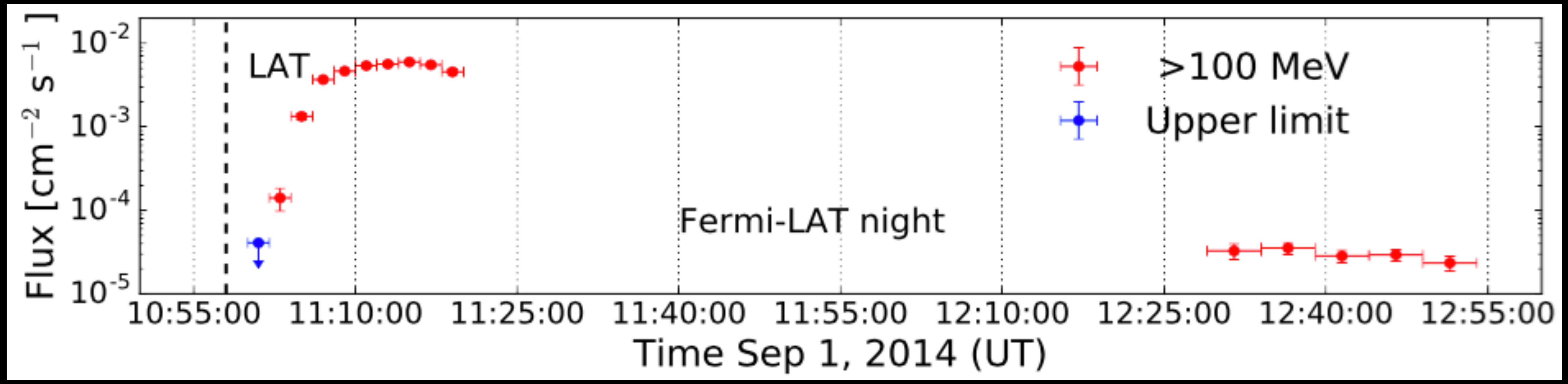


Association with fast CME



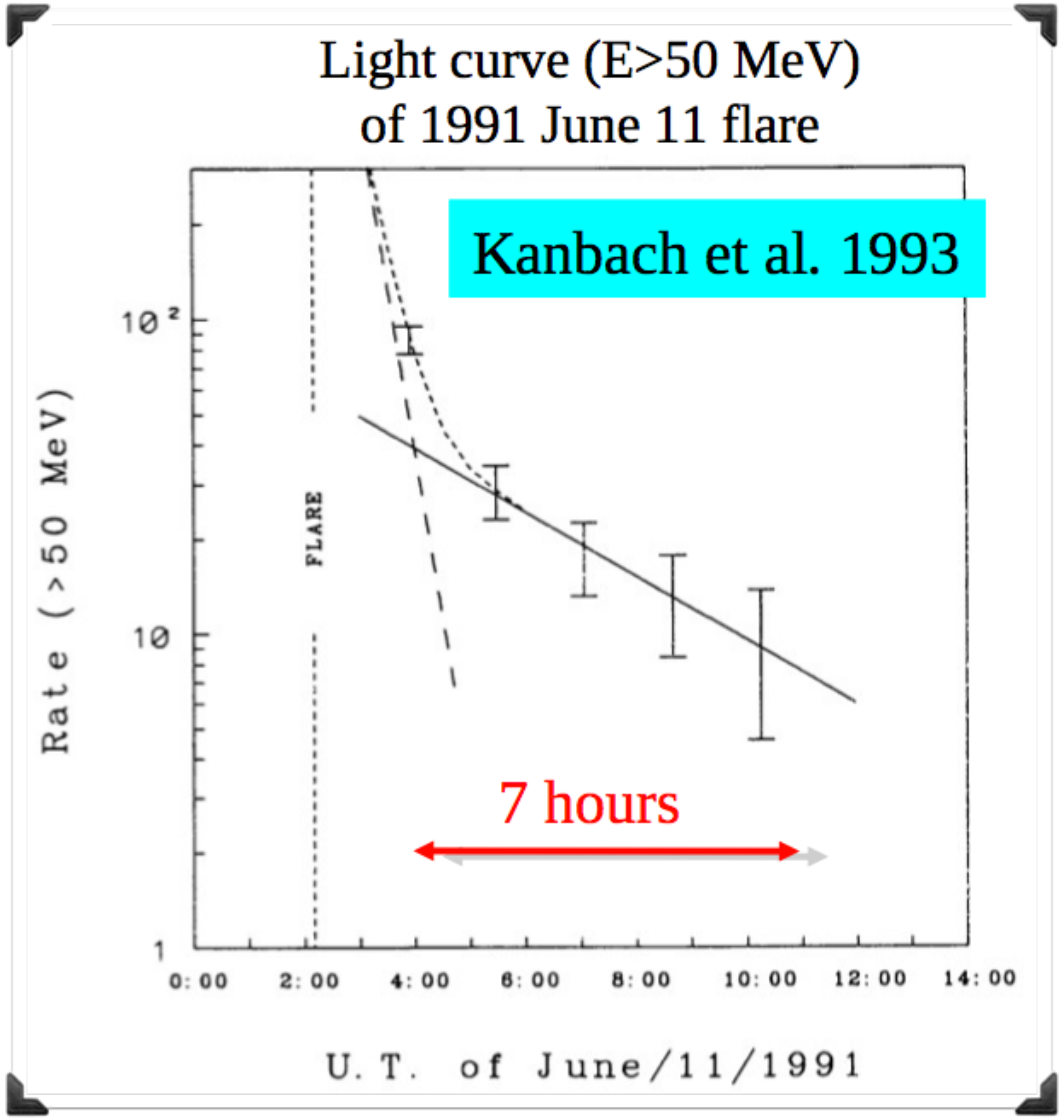


CME speed ~ 1900 km s^{-1}

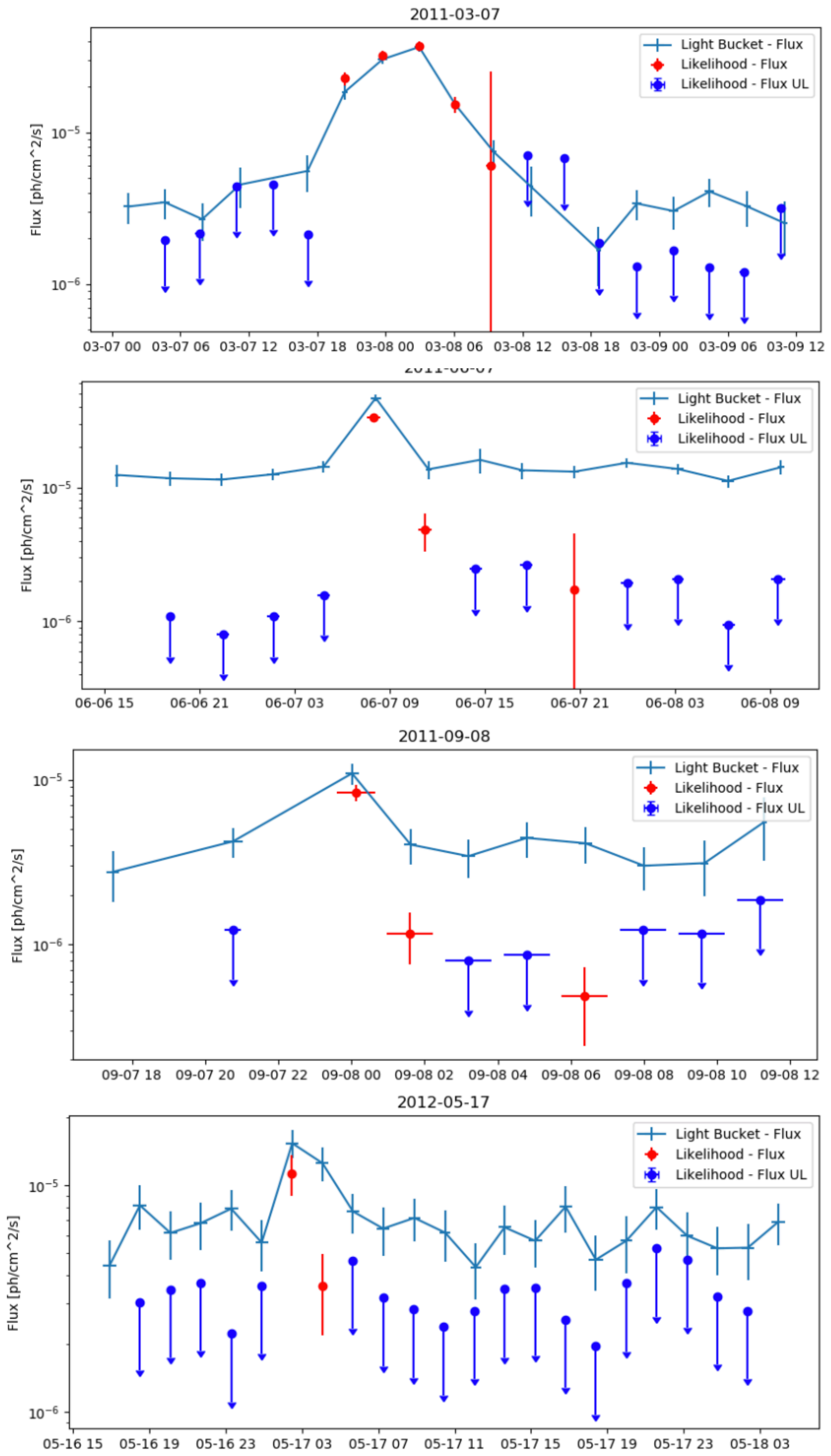


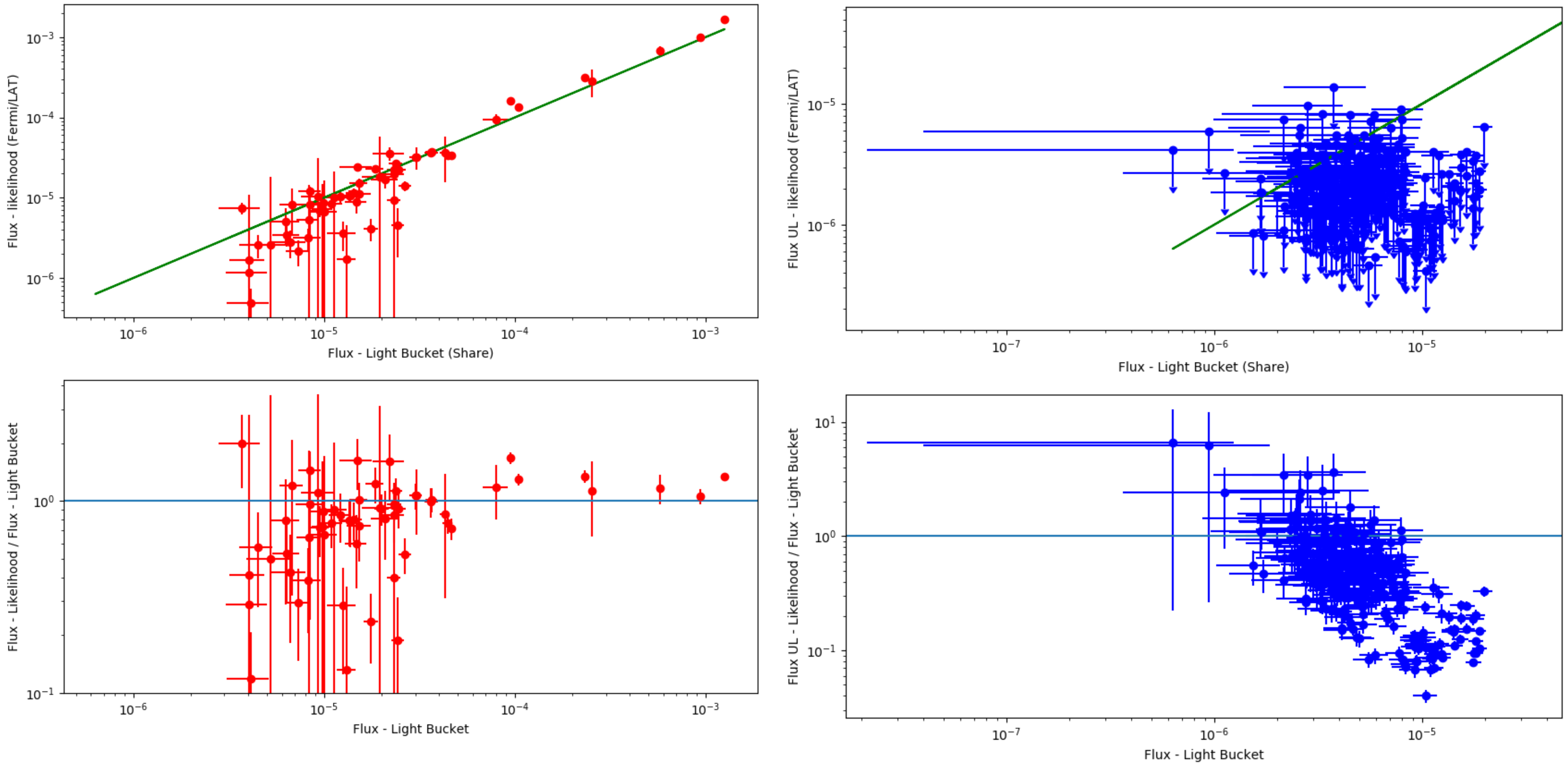
Gamma-ray emission from the Sun

- 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



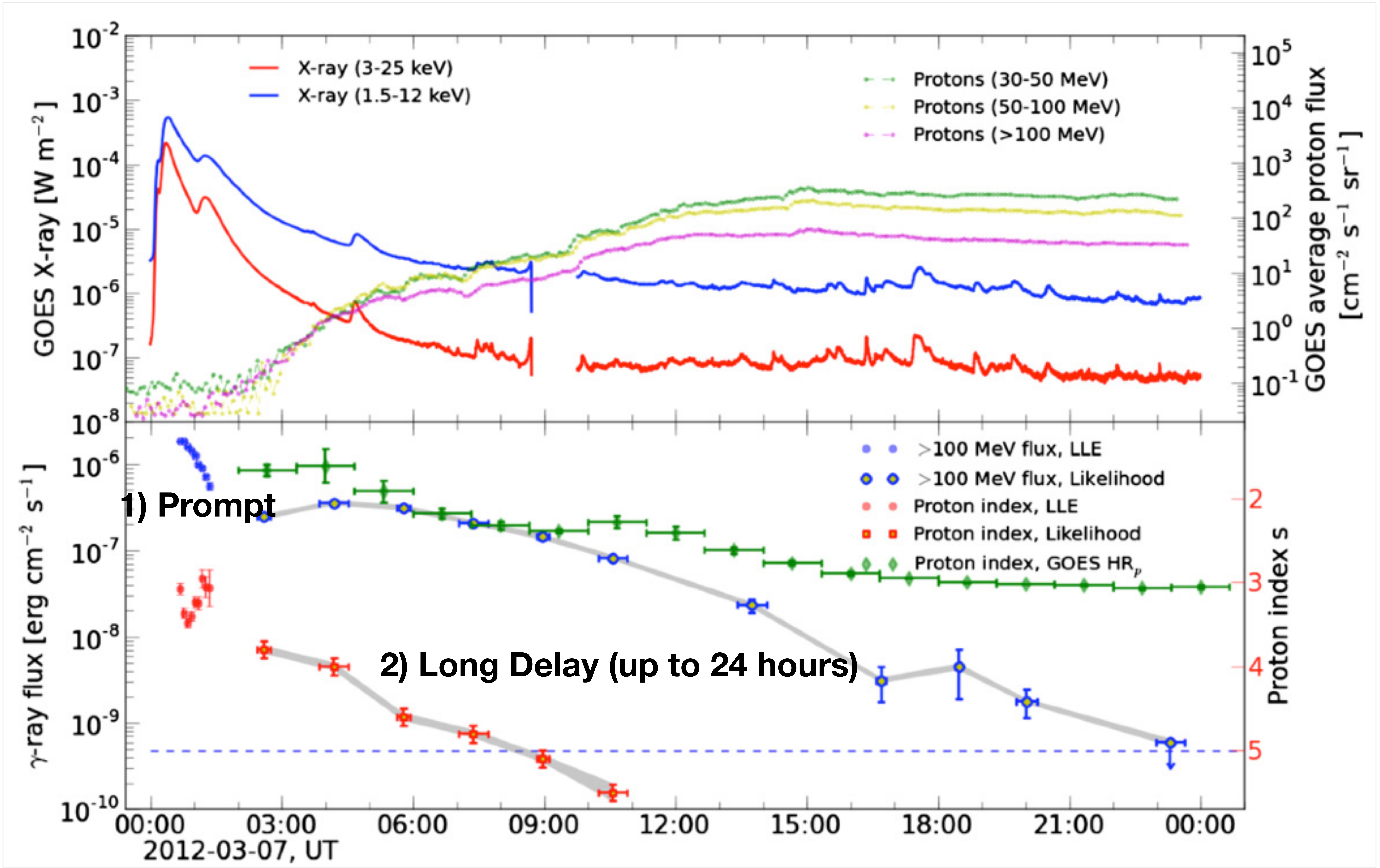
The Likelihood analysis and the “Light bucket” by Share et al.





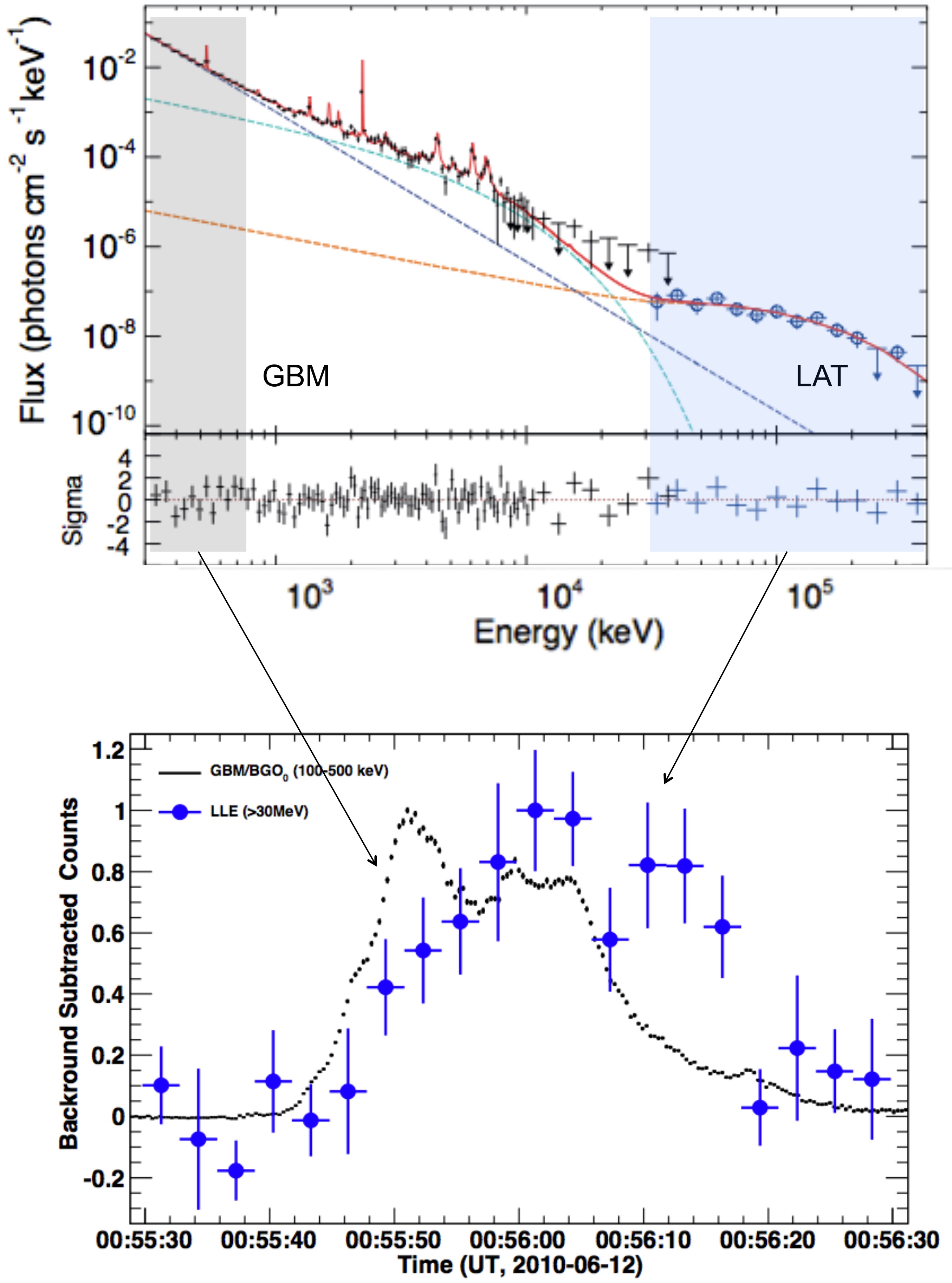
- **The “light bucket” has some issues:**
  - **The background is not fitted (and therefore the flux for dim flares is largely overestimated)**
  - **The exposure is calculated with an assumed (not fitted) spectral model:**
    - **this can explain the discrepancy saw with bright fluxes**

Longest emission



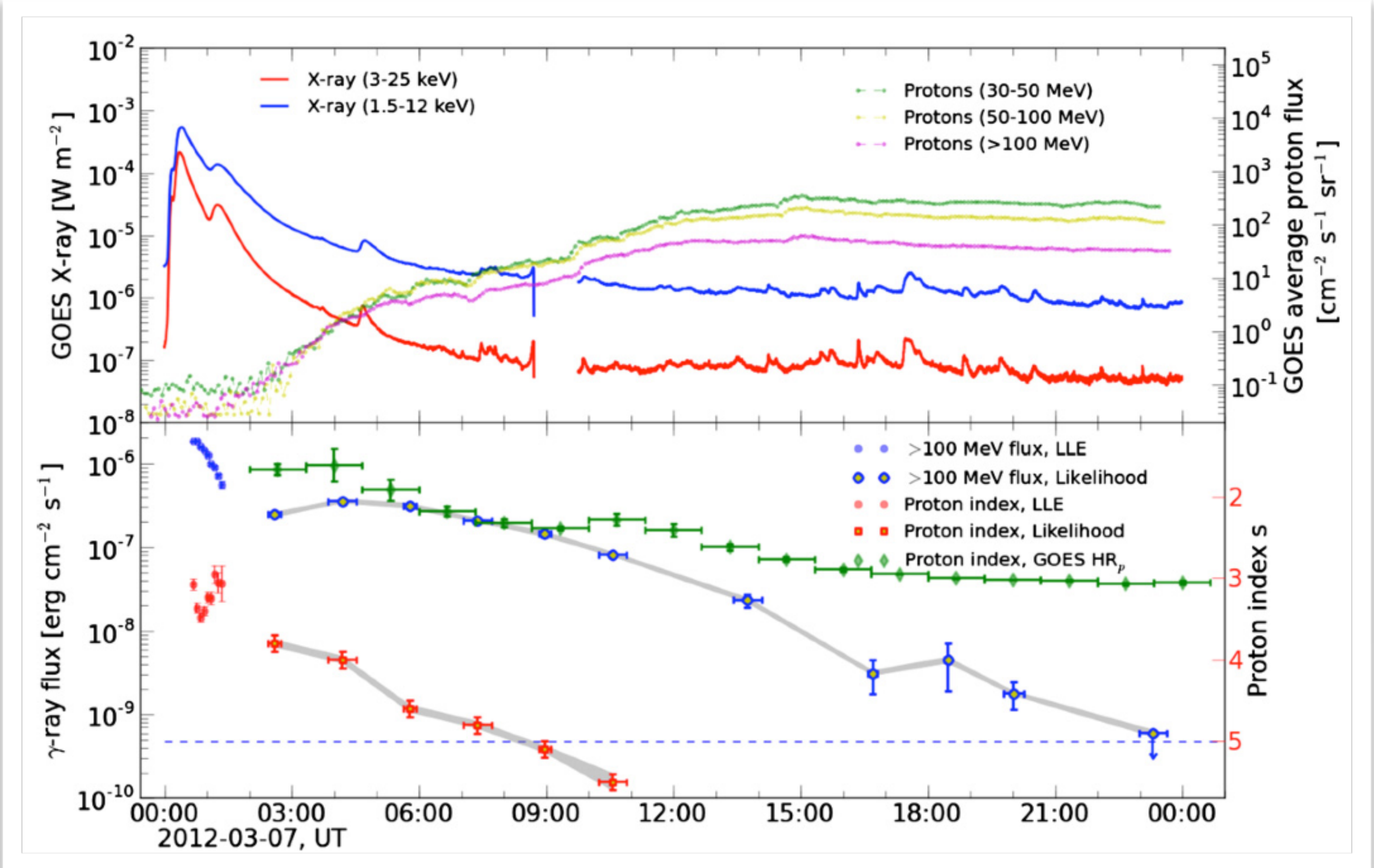
Impulsive & Delayed emission detected by Fermi LAT

Impulsive events



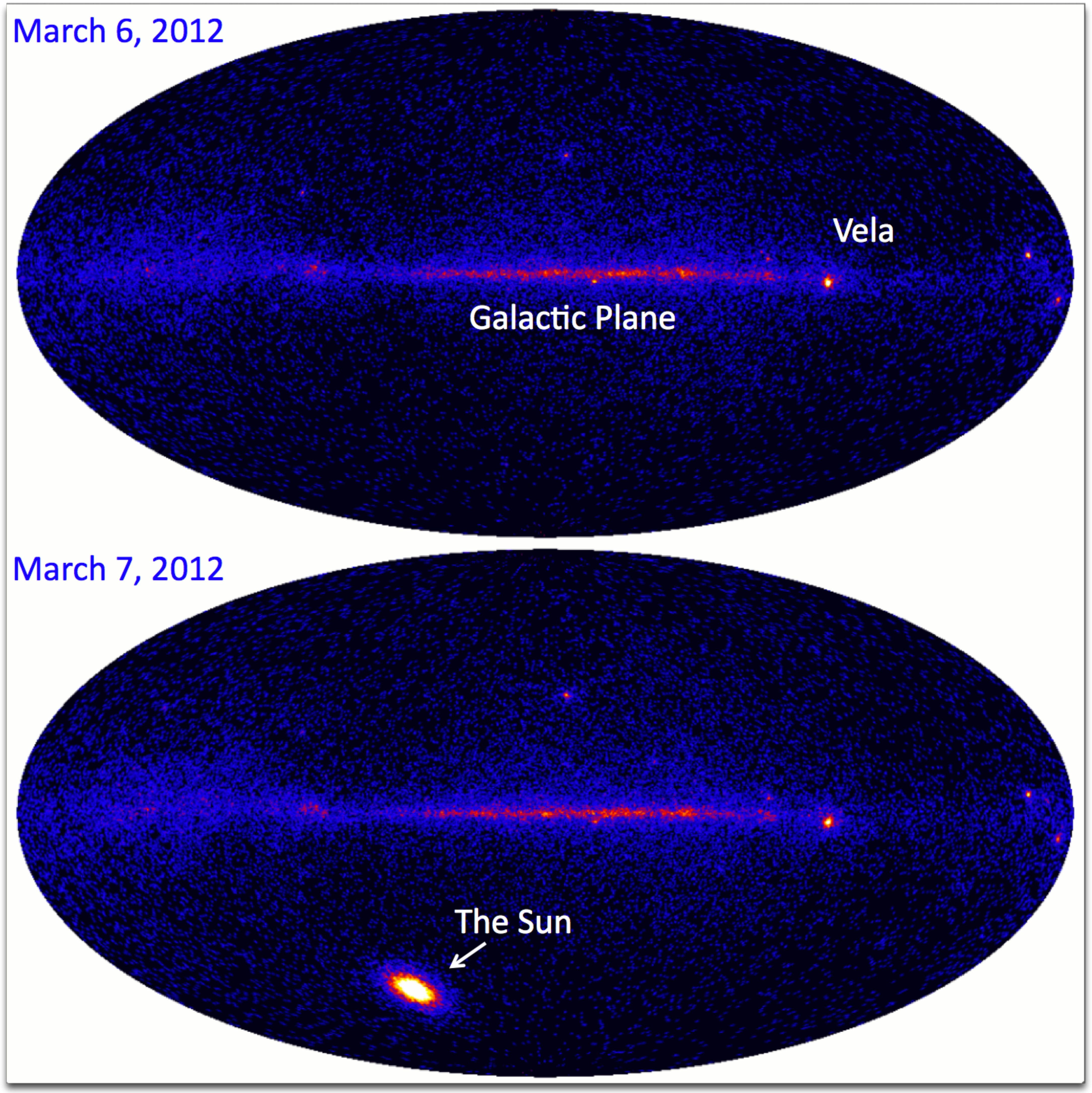
Simultaneous HRX and gamma-ray emission
Ackermann et al. 2012, ApJ...745..144A

Long Lasting emission



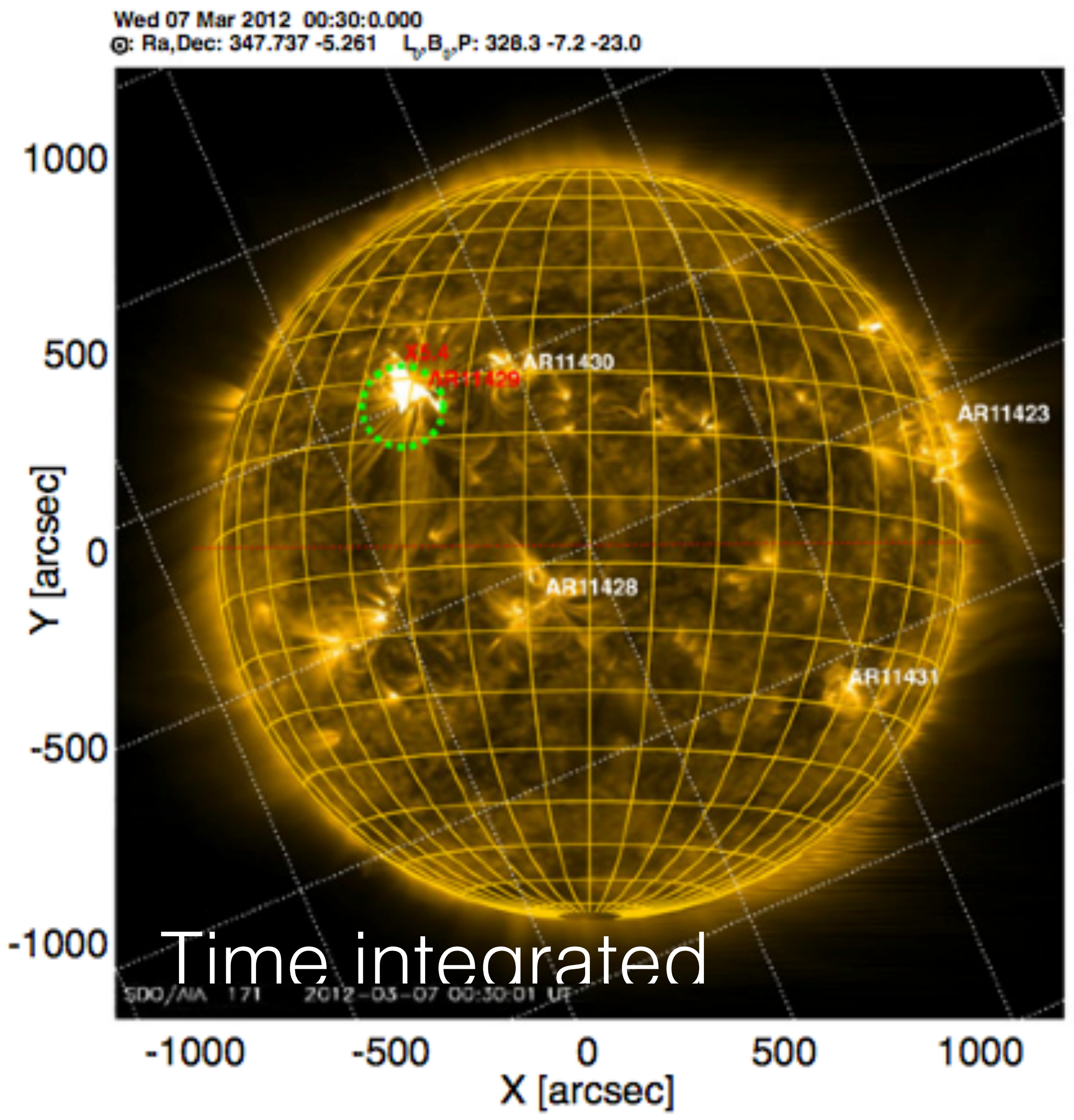
Sustained emission observed up **20 hours**
Ackermann, M. et al. 2014, ApJ, 787, 15

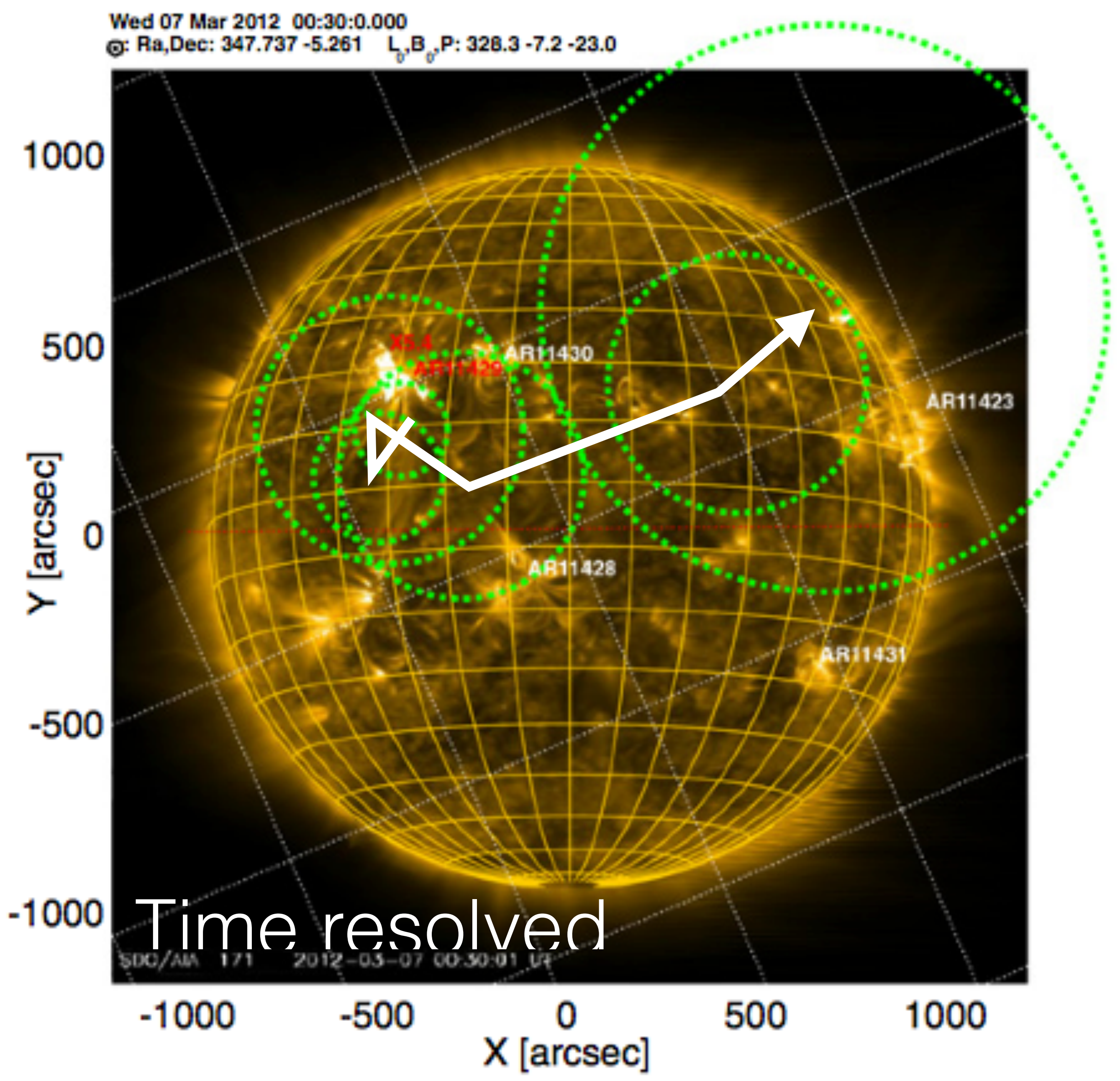
The longest lasting gamma-ray emission: March 7, 2012



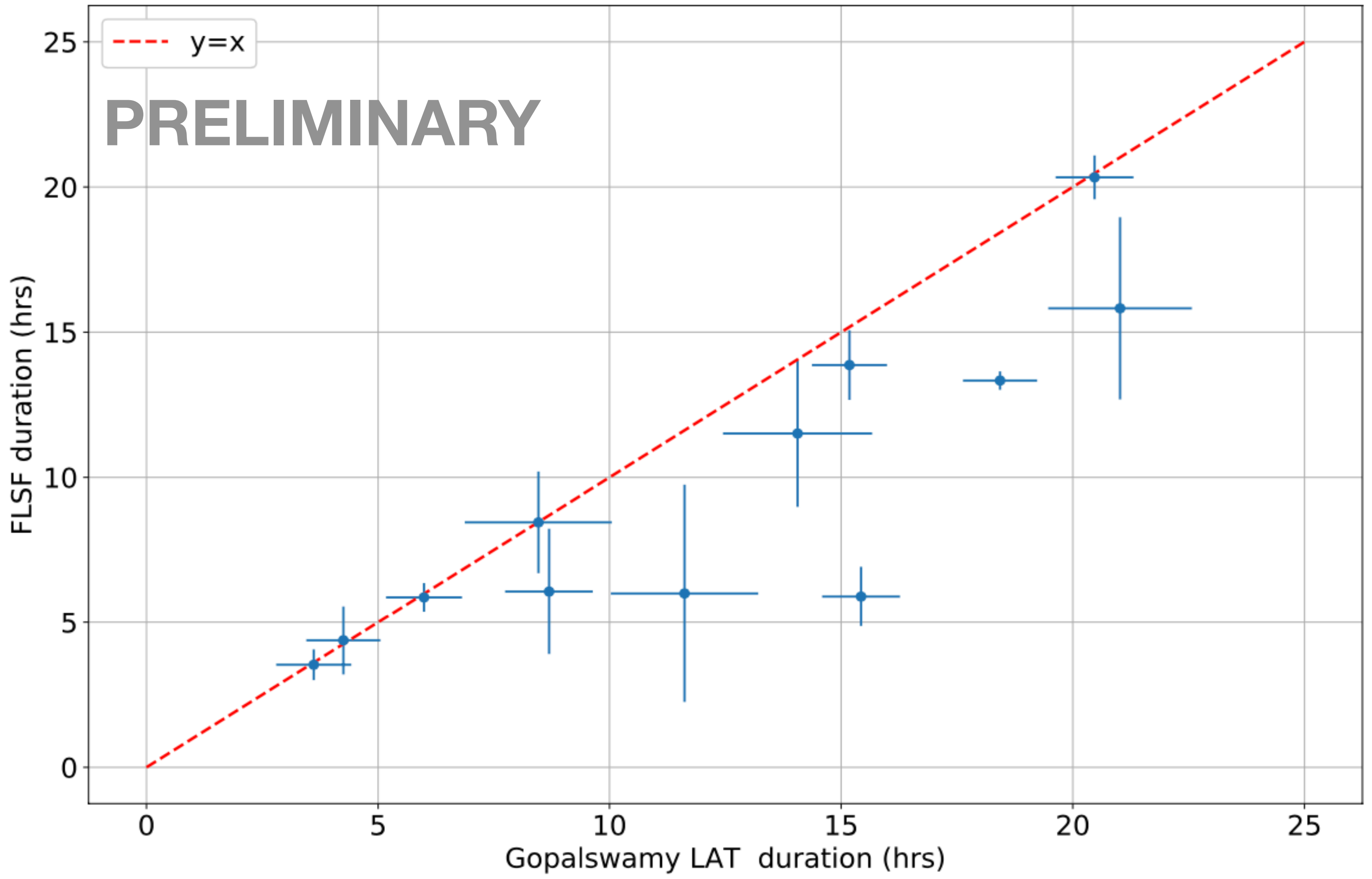
LAT 1 day all sky data >100 MeV

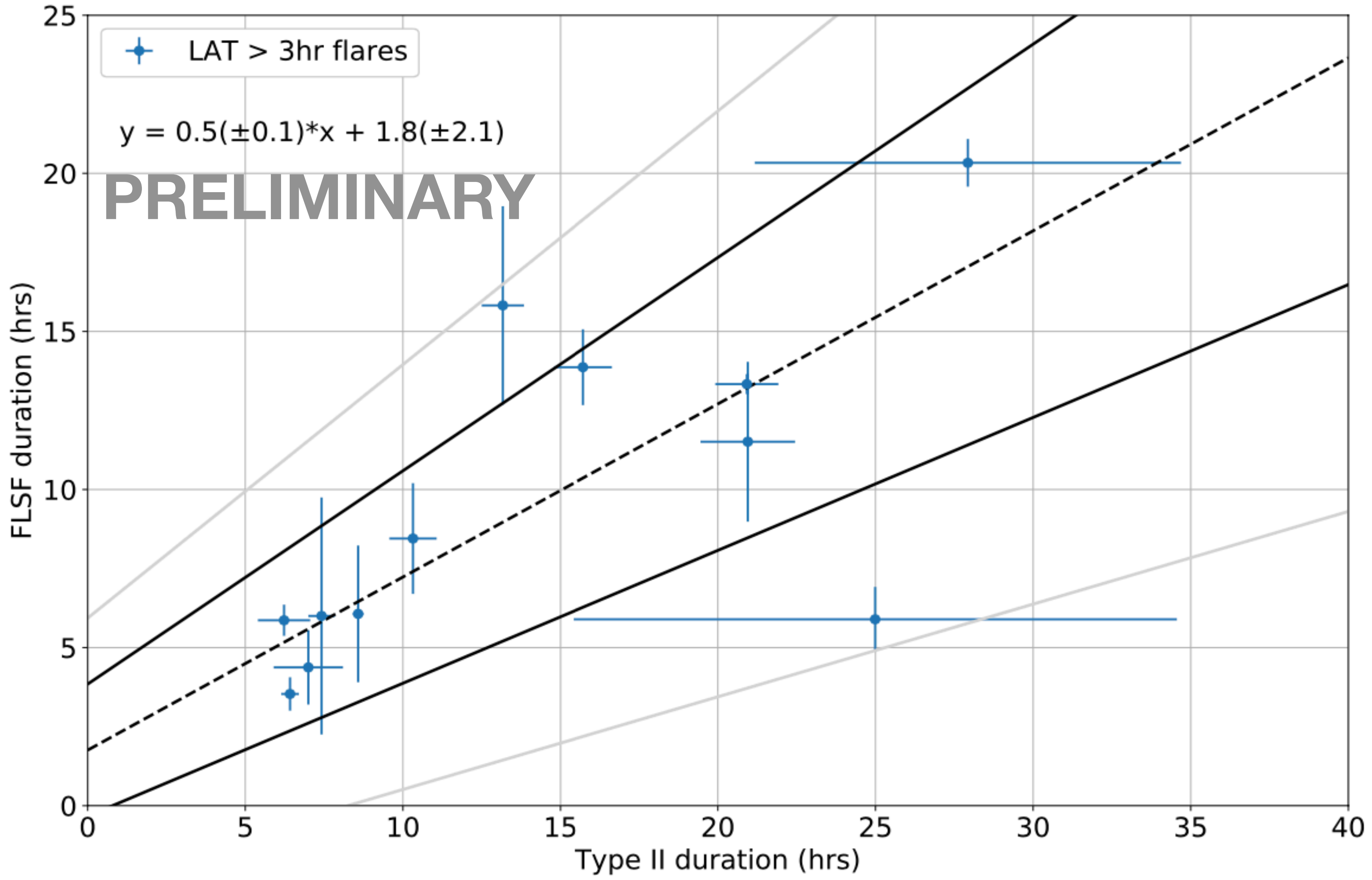
- A very bright Solar Flare was detected on March 7, exceeding:
  - 1000 times the flux of the steady Sun;
  - 100 times the flux of Vela;
  - 50 times the Crab flare;
- High energy emission (>100 MeV, up to 4 GeV) lasts for ~20 hours
- Softening of the spectrum with time





Connection with type II radio bursts





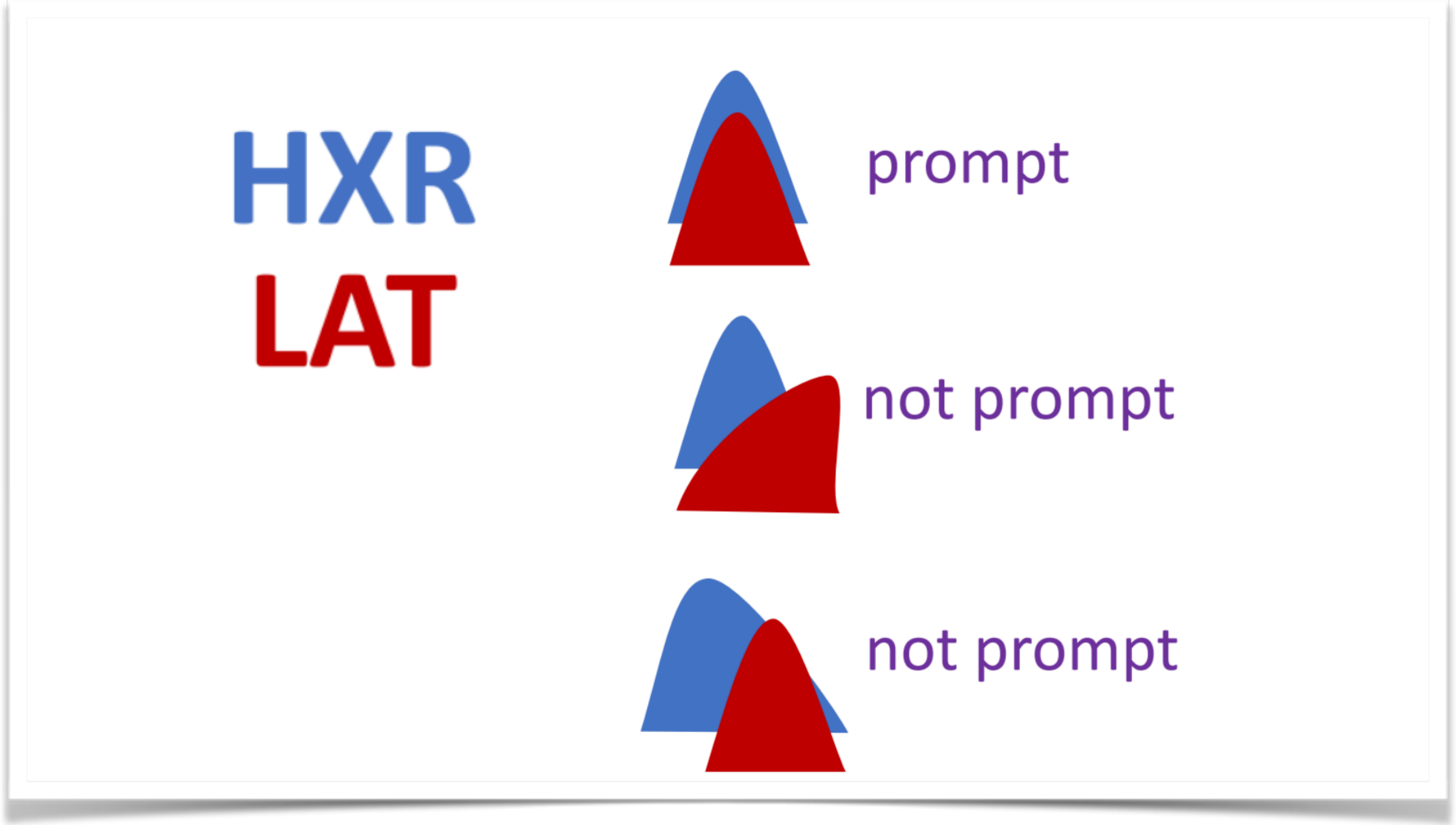
If the gamma-ray production is associated with CME shock, a tight correlation between type II radio burst and gamma-ray propertied should exist.

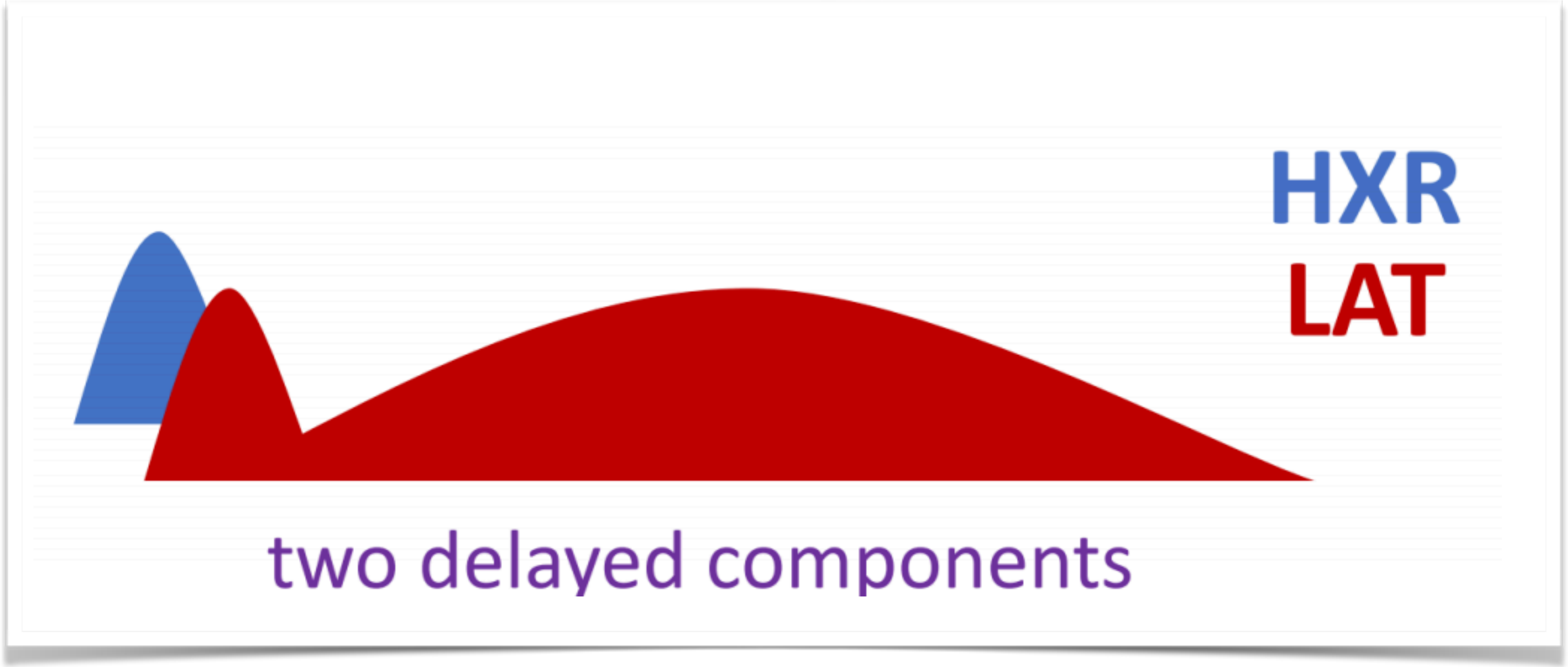
Gopalswamy et al. (2018) indeed study this using the duration from the Share et al. 2017 paper.

Share et al. 2017 are systematically longer than the ones in this work:

– The resulting best fit line has a softer slope of 0.5±0.1 compared to the 0.9±0.1 reported in Gopalswamy et al. (2018).

Temporal Behavior of Fermi LAT Solar Flares (FLSF)

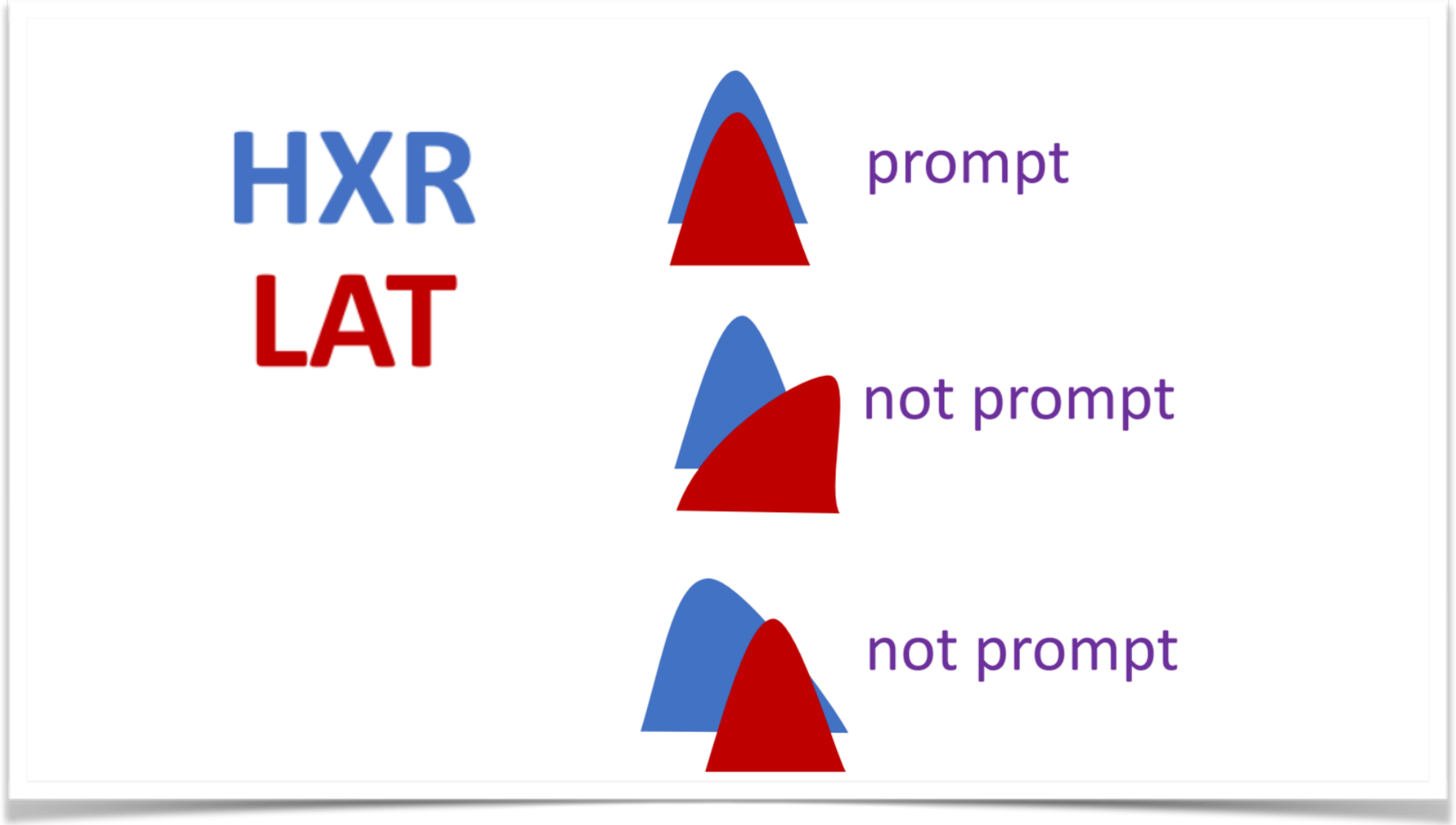


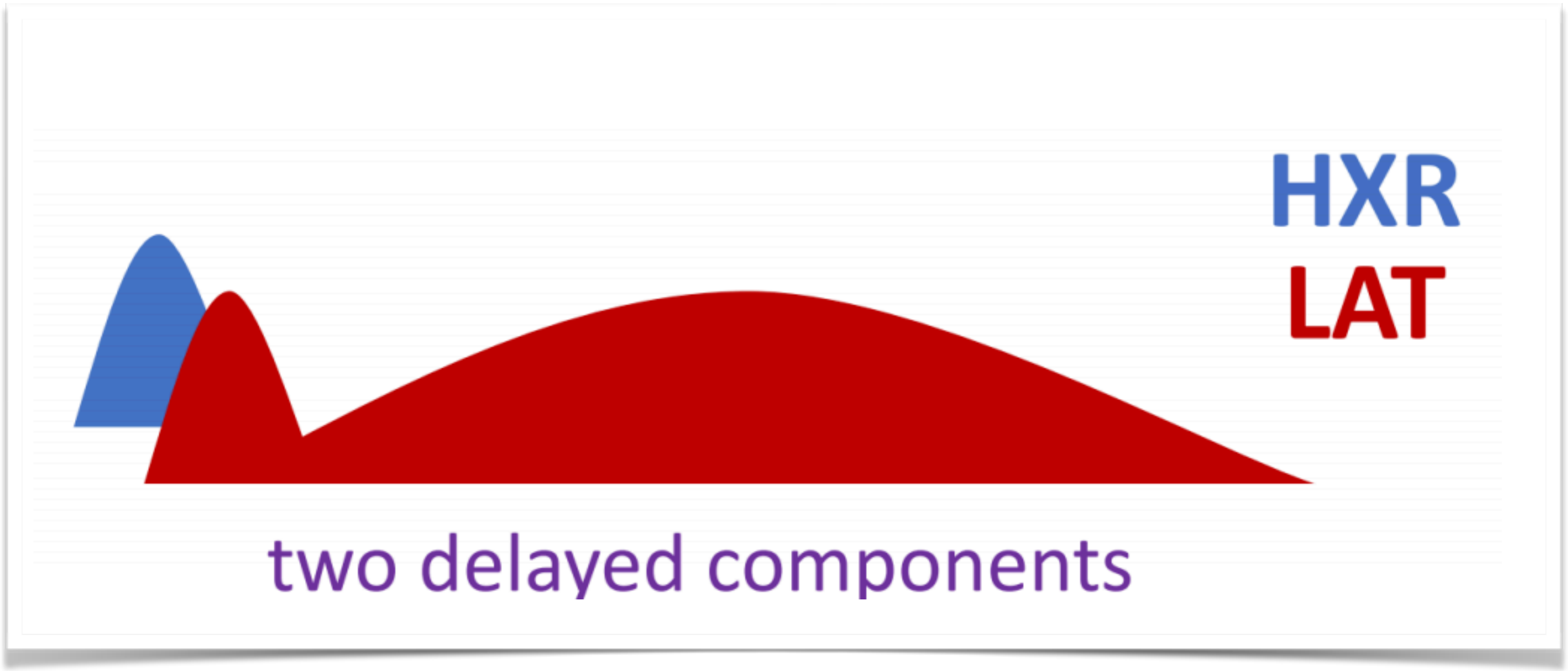


Credit: A. Shih

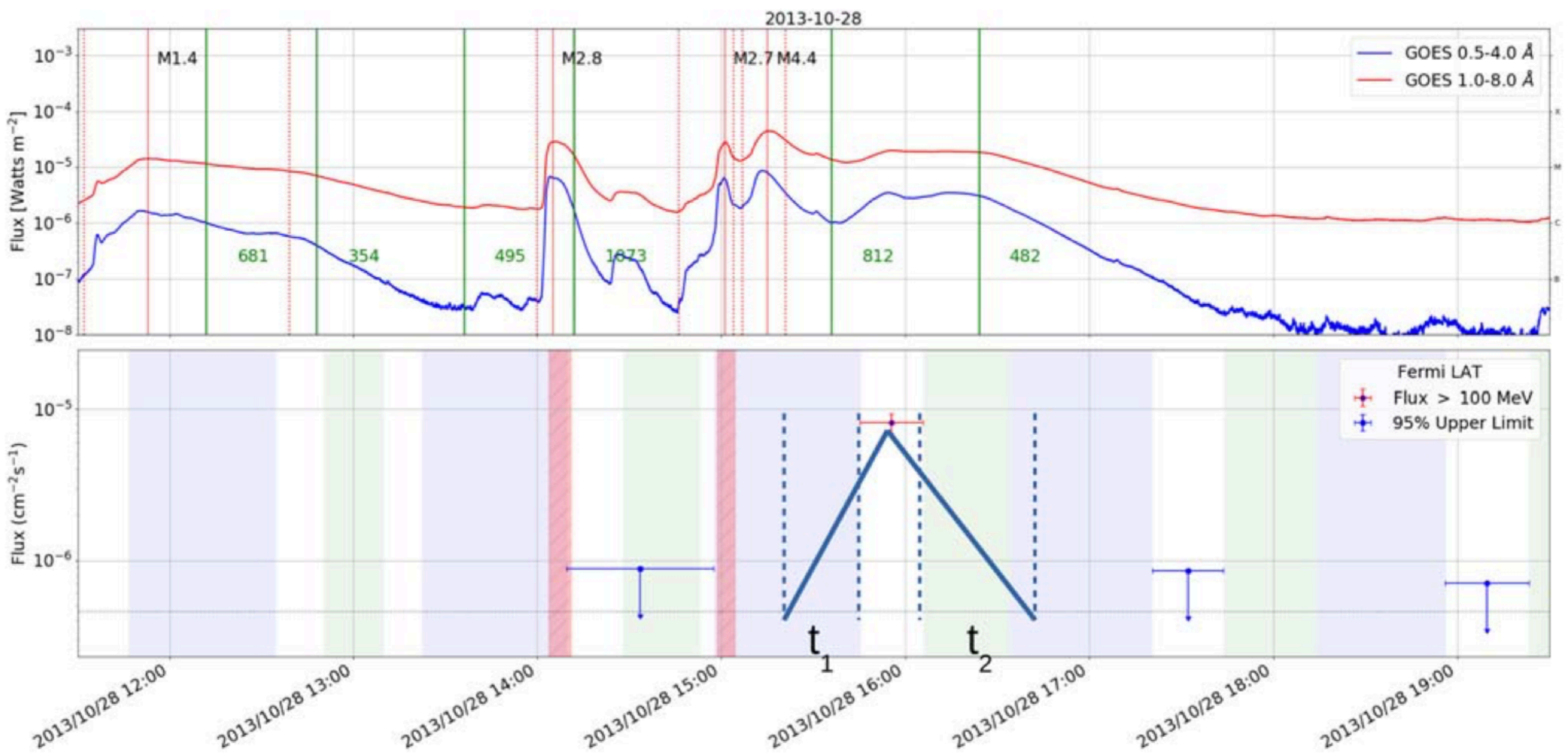
Ajello et al. 2021

Temporal Behavior of Fermi LAT Solar Flares (FLSF)





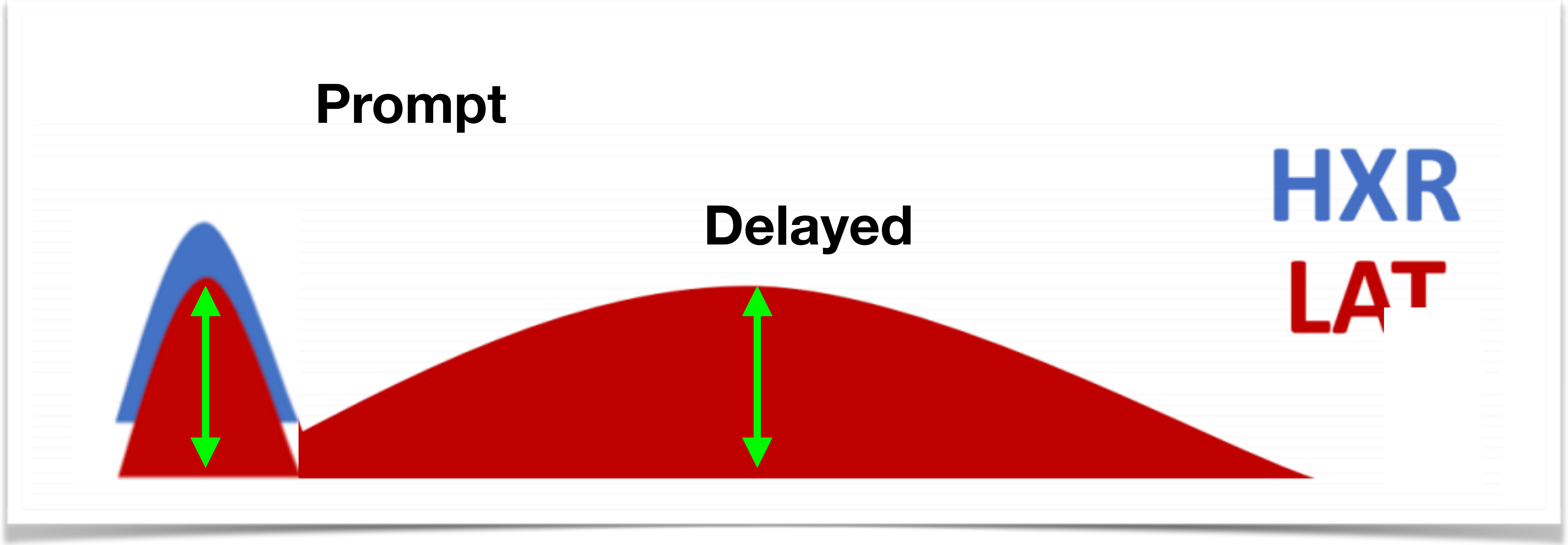
Credit: A. Shih

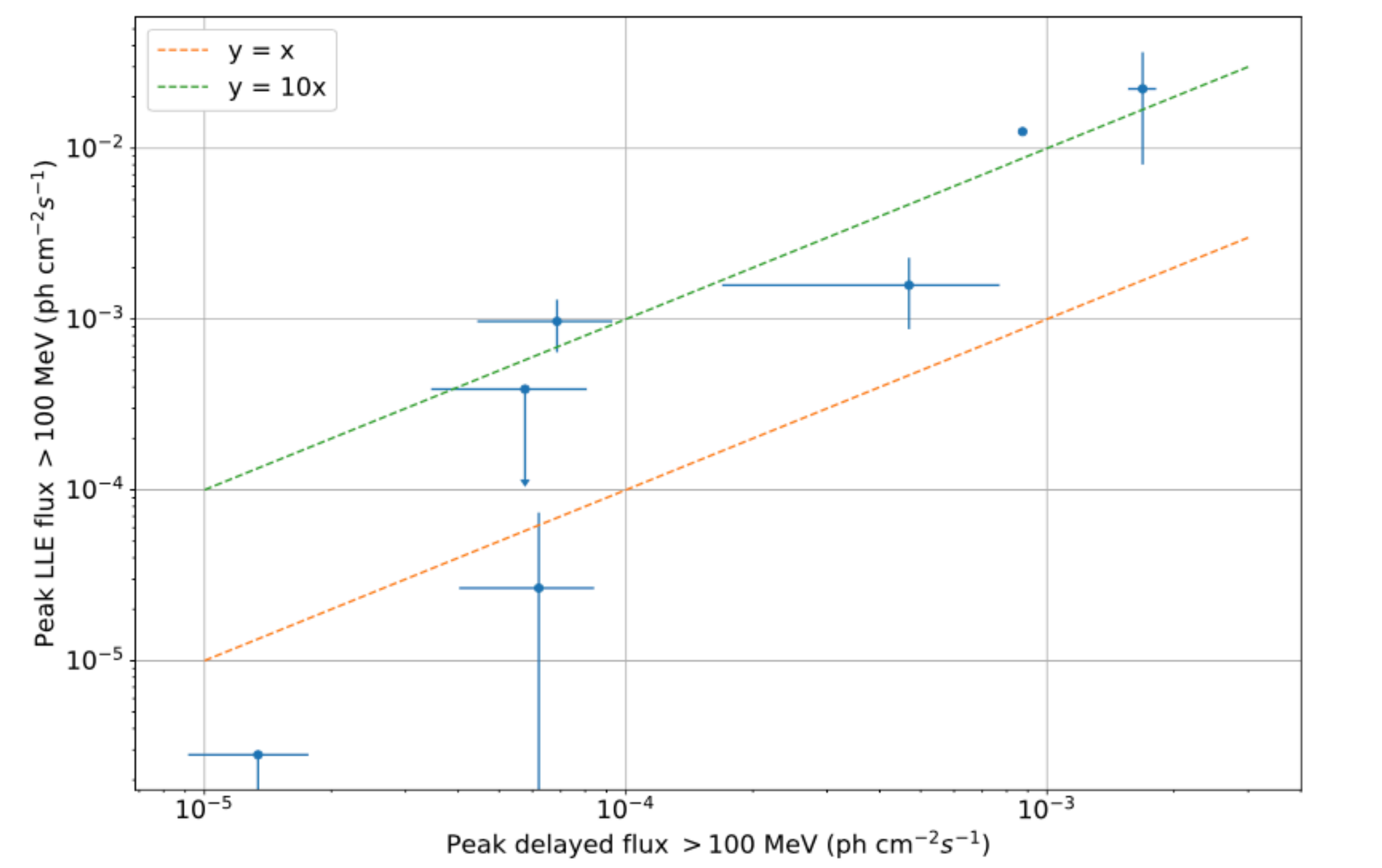


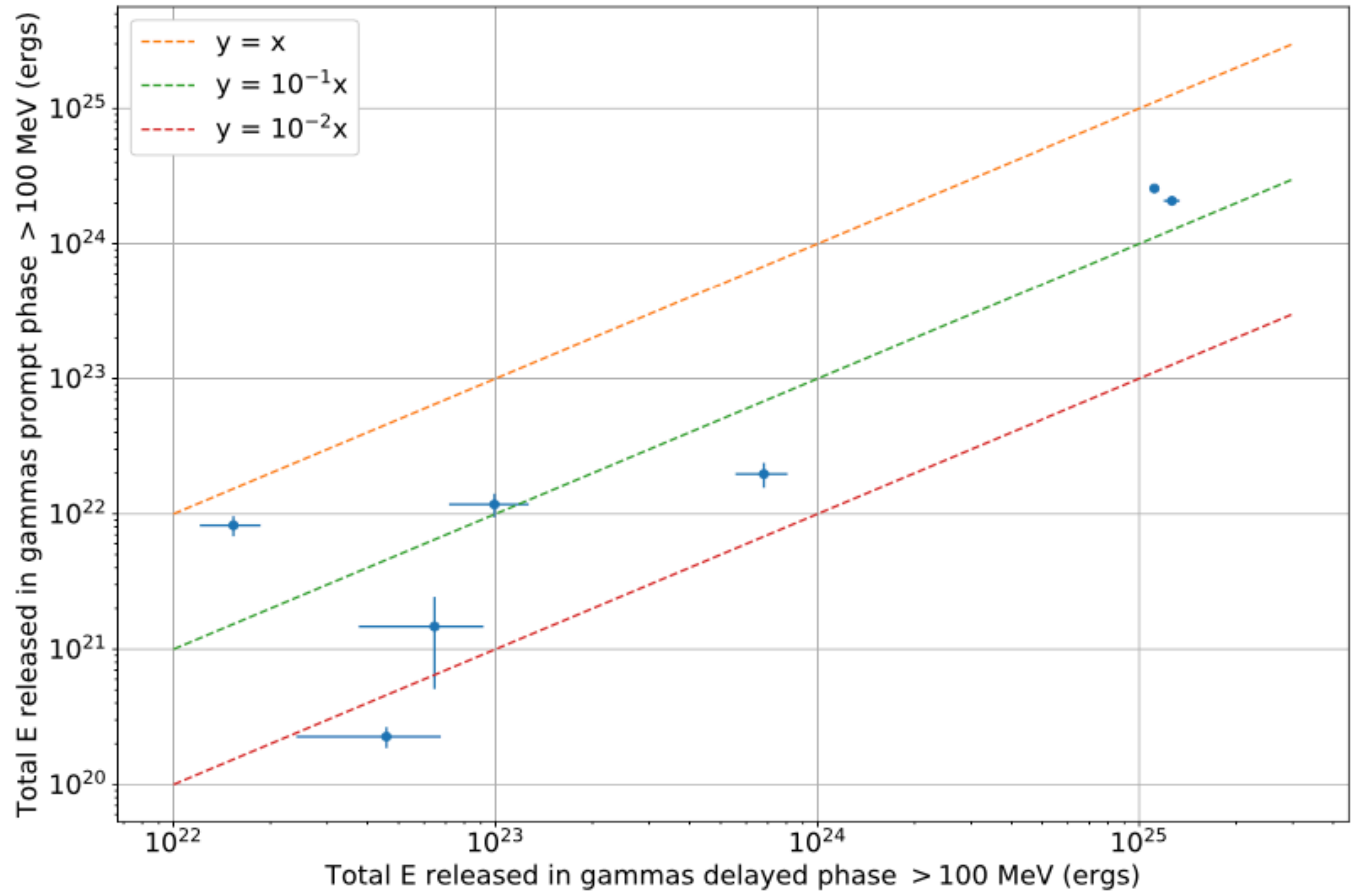
Ajello et al. 2021

- **Light curve data is sparse.**
- **We interpolate between data and UL with simple assumption.**

Quantifying the prompt phase and delayed phase

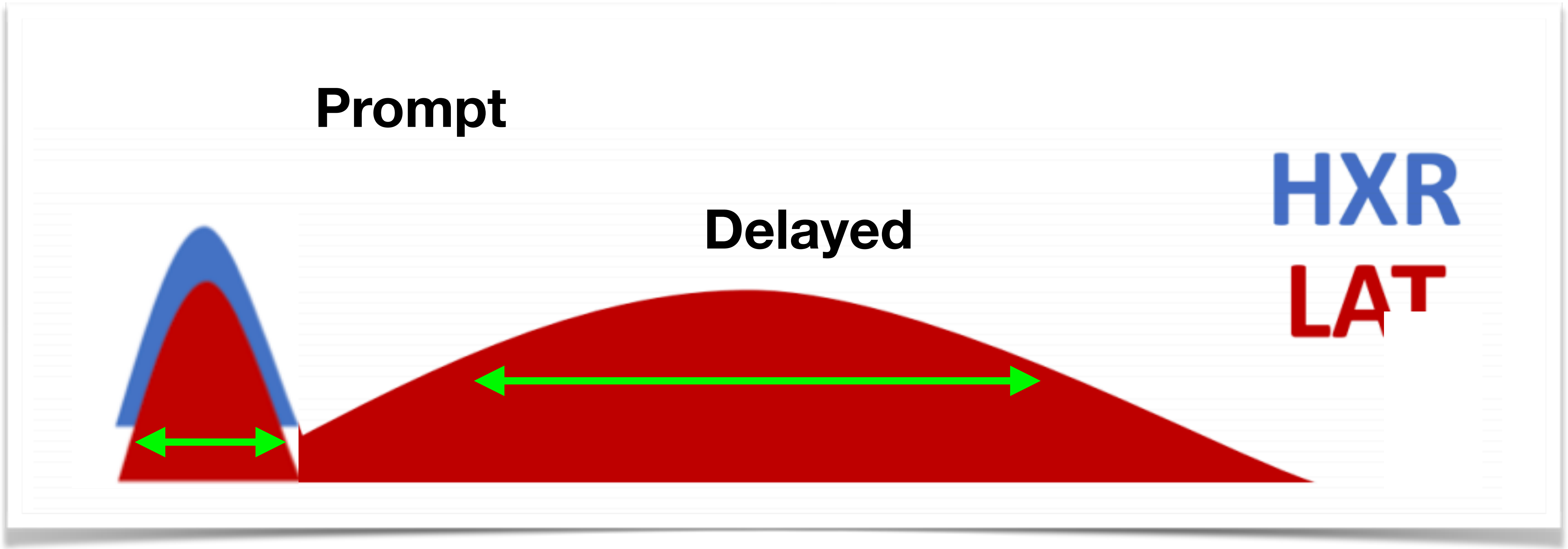


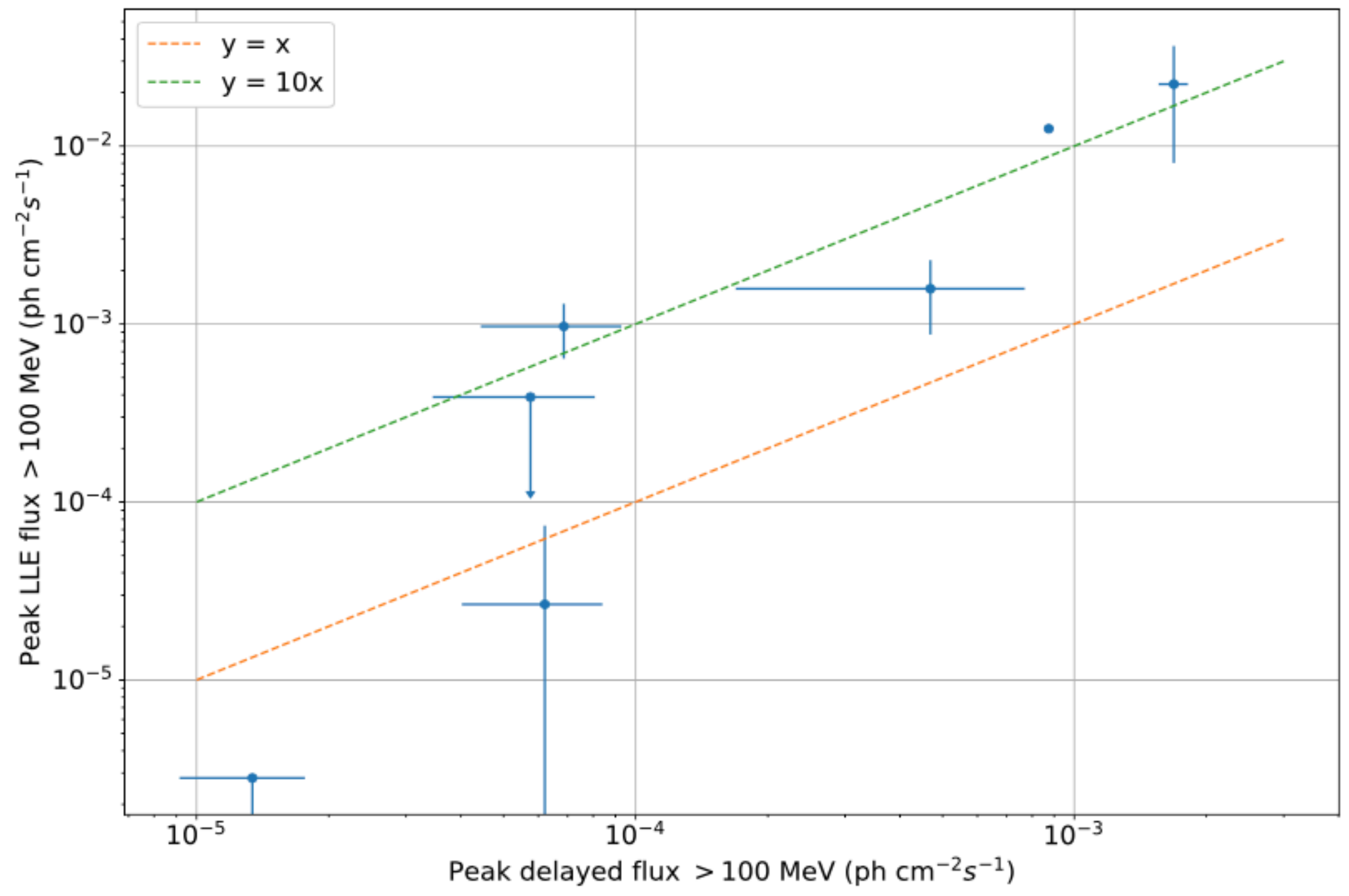




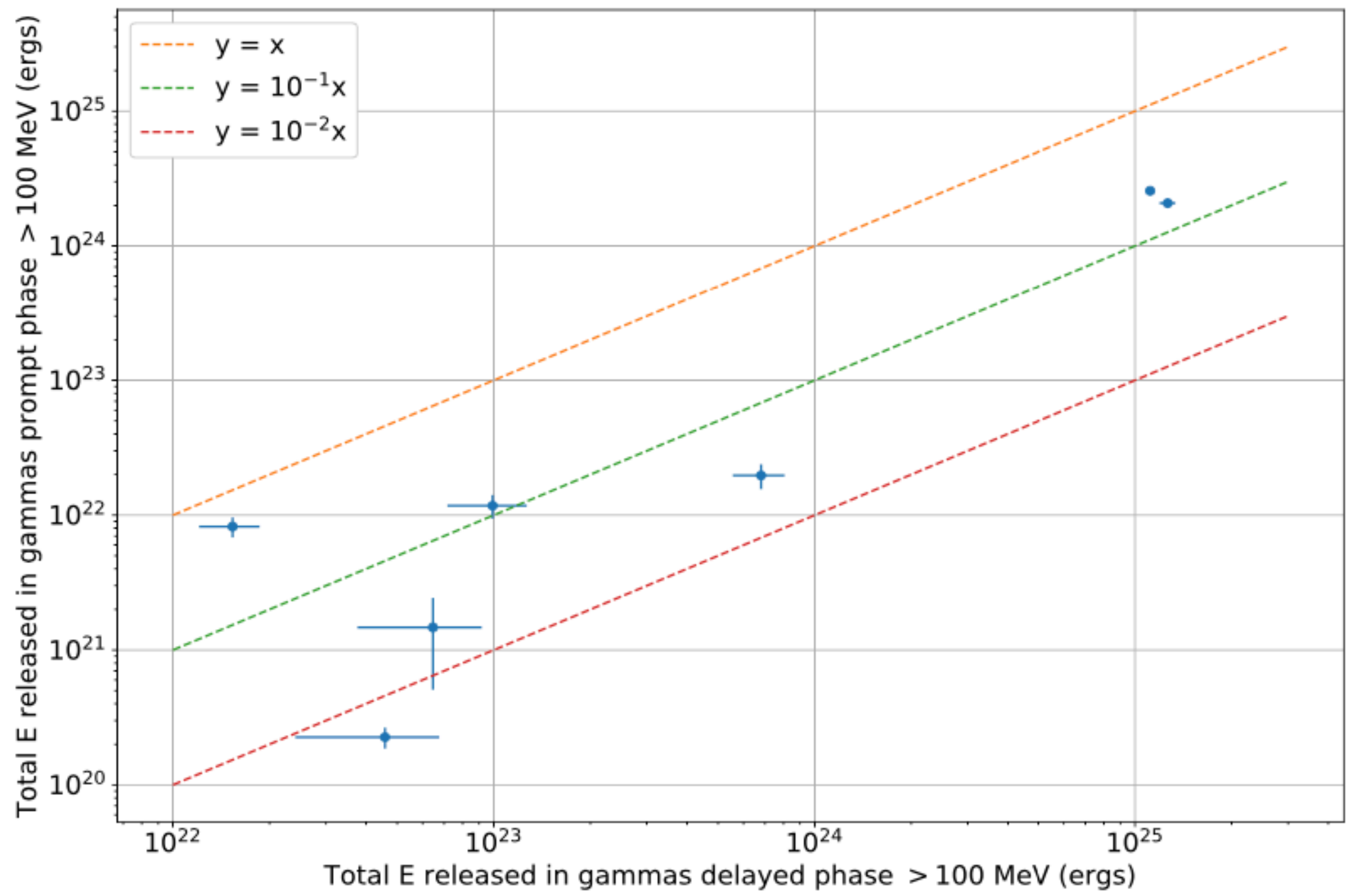
- **Peak flux of the prompt phase > Peak flux of the delayed phase**

Quantifying the prompt phase and delayed phase

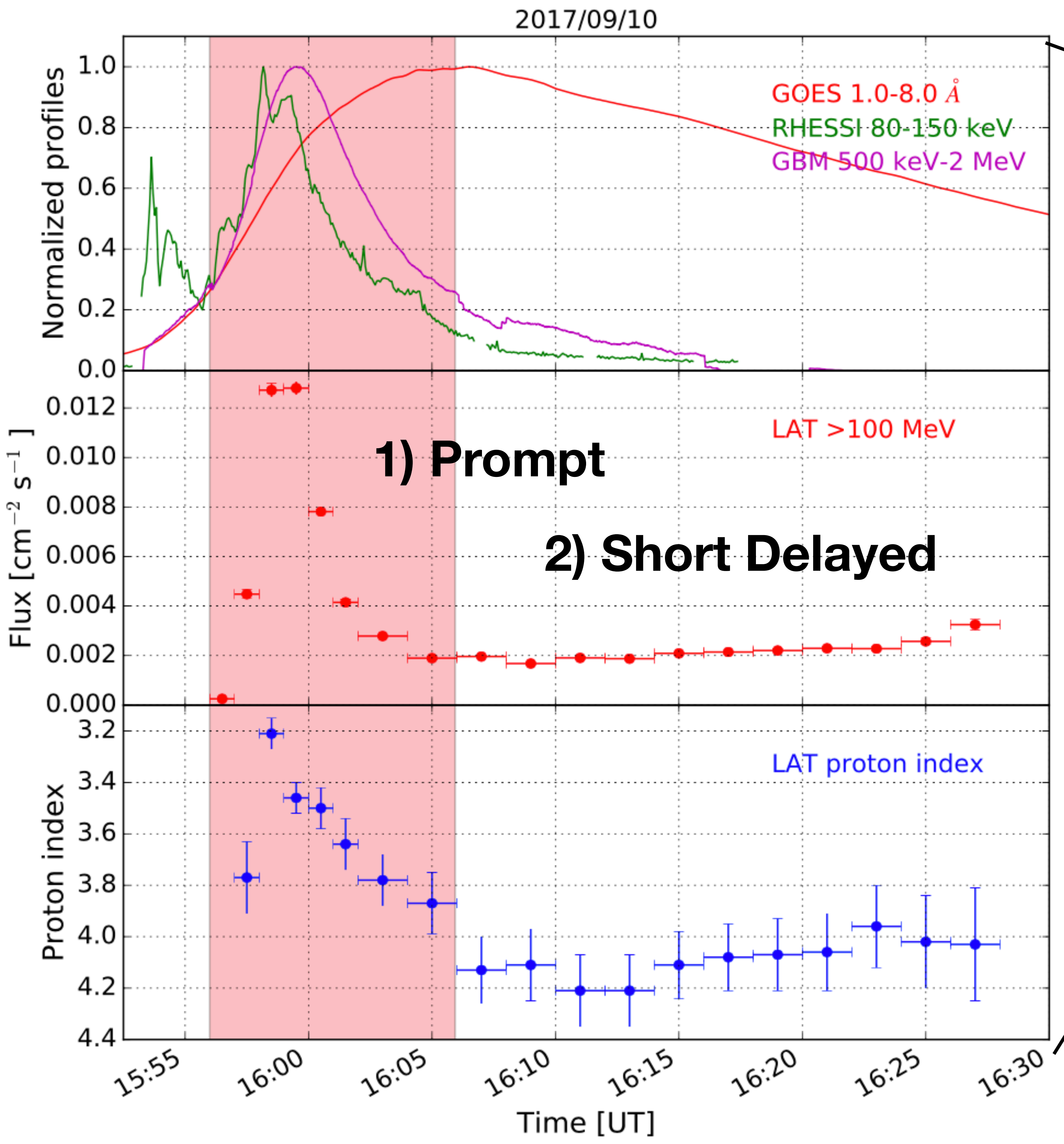


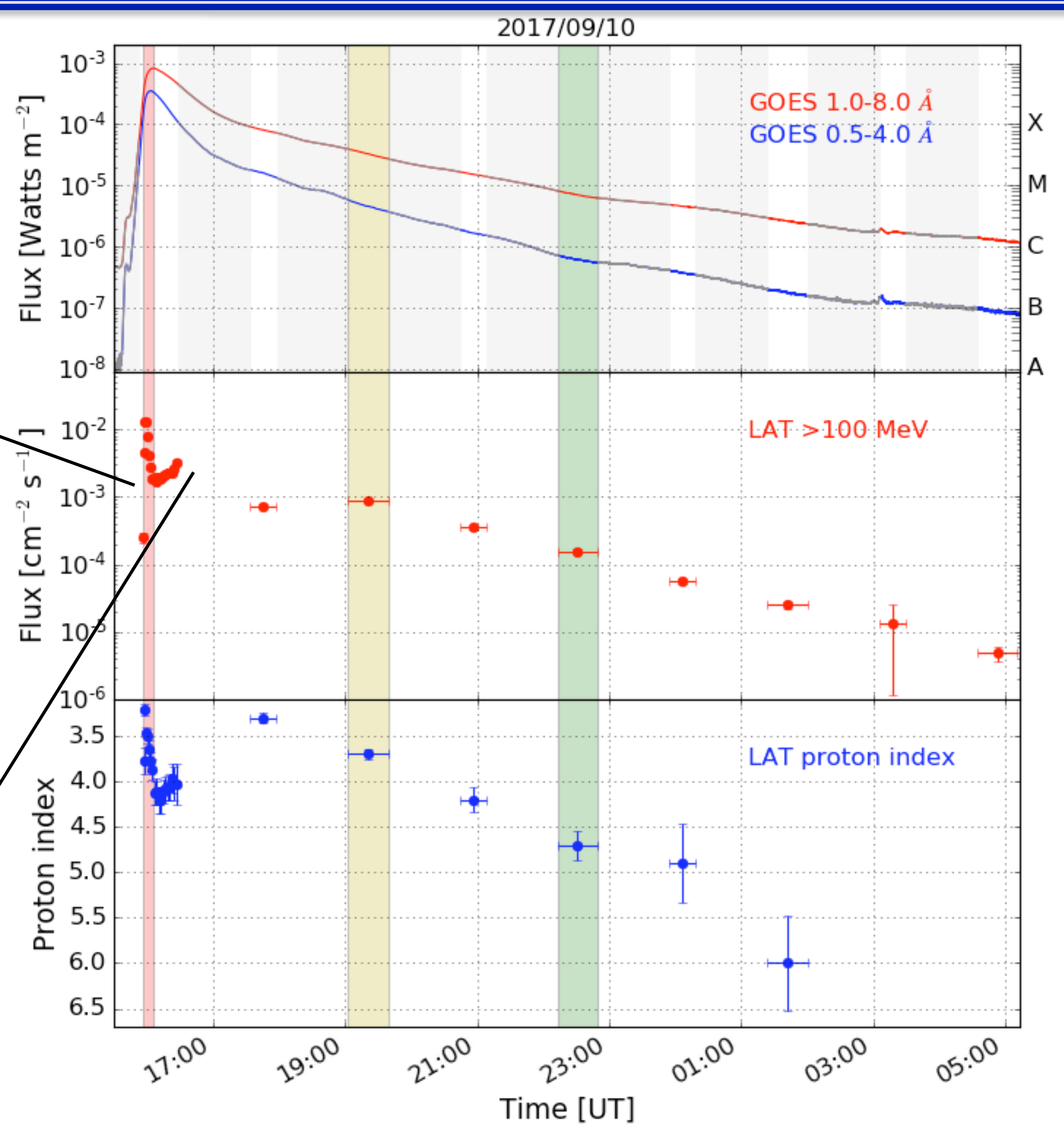


- **Peak flux of the prompt phase > Peak flux of the delayed phase**
- **Energy released in the delated phase > Energy released in the prompt phase**



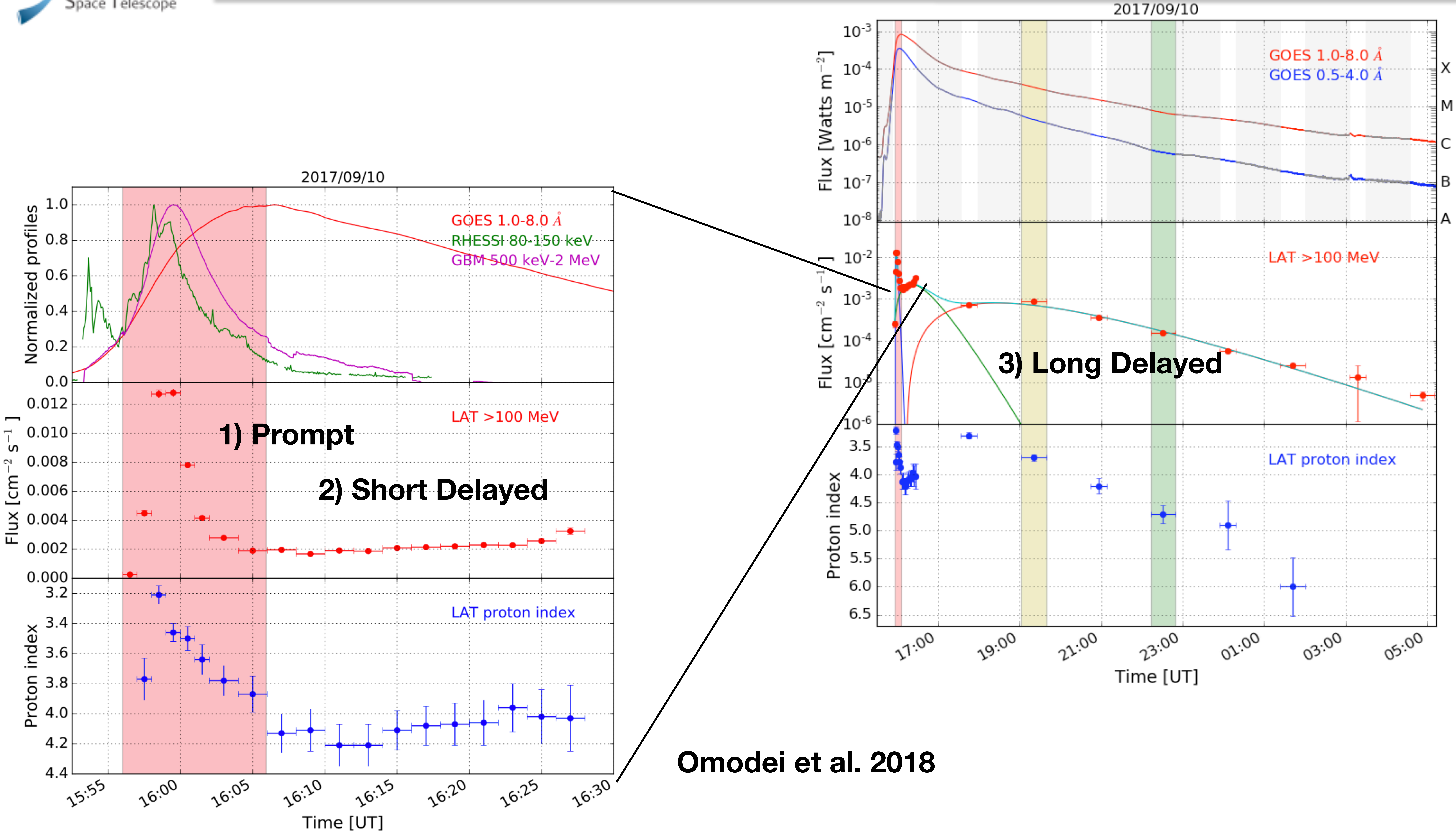
SOL 2017-09-10 shows multiple components





Omodei et al. 2018

SOL 2017-09-10 shows multiple components



Omodei et al. 2018