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

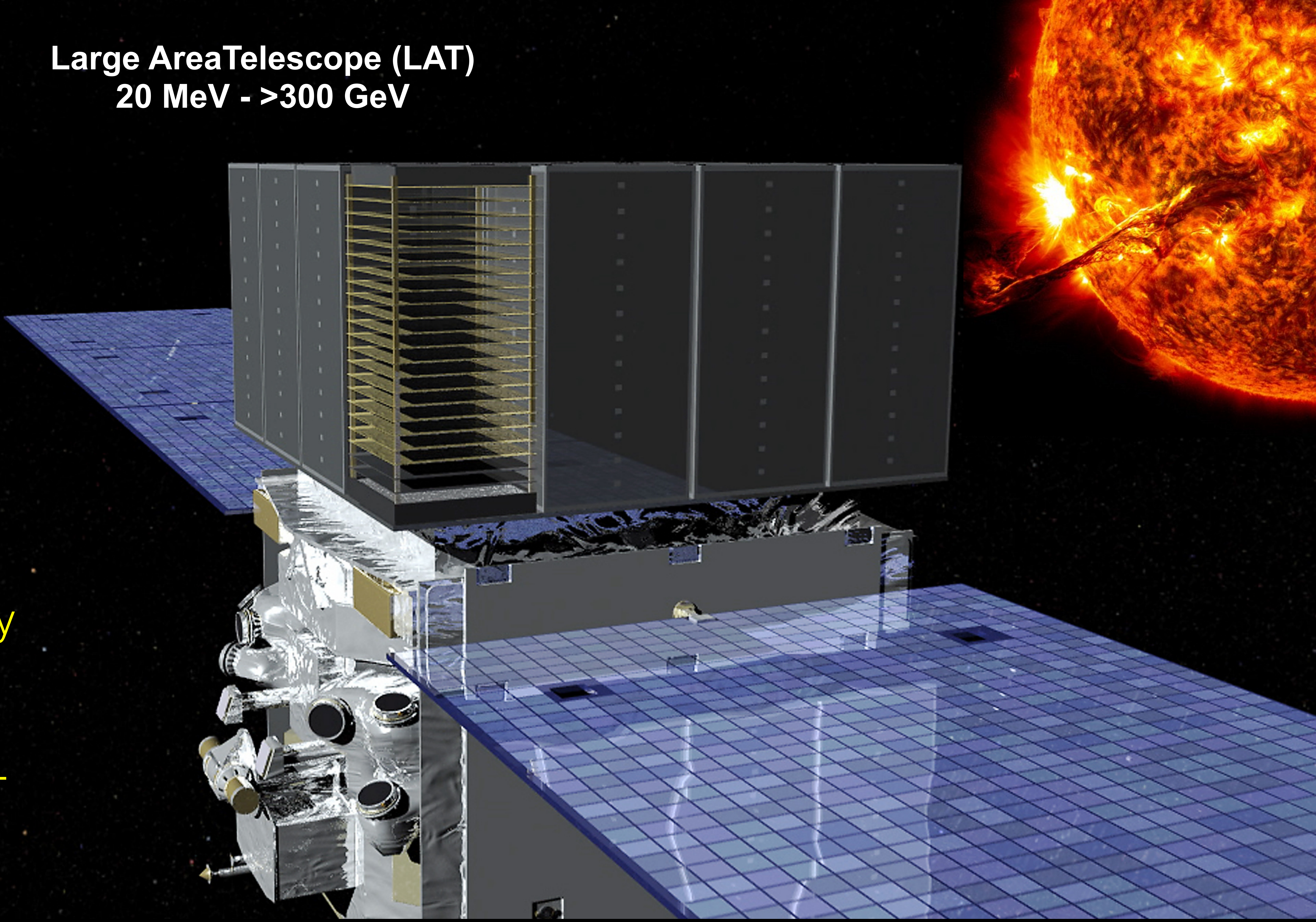
Nicola Omodei,
Melissa Pesce-Rollins, Francesco Longo, Vahe Pertosian

on behalf of the Fermi LAT collaboration

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 cm² 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!

Large AreaTelescope (LAT)
20 MeV - >300 GeV



Launched in 2008, continuously monitors the sky

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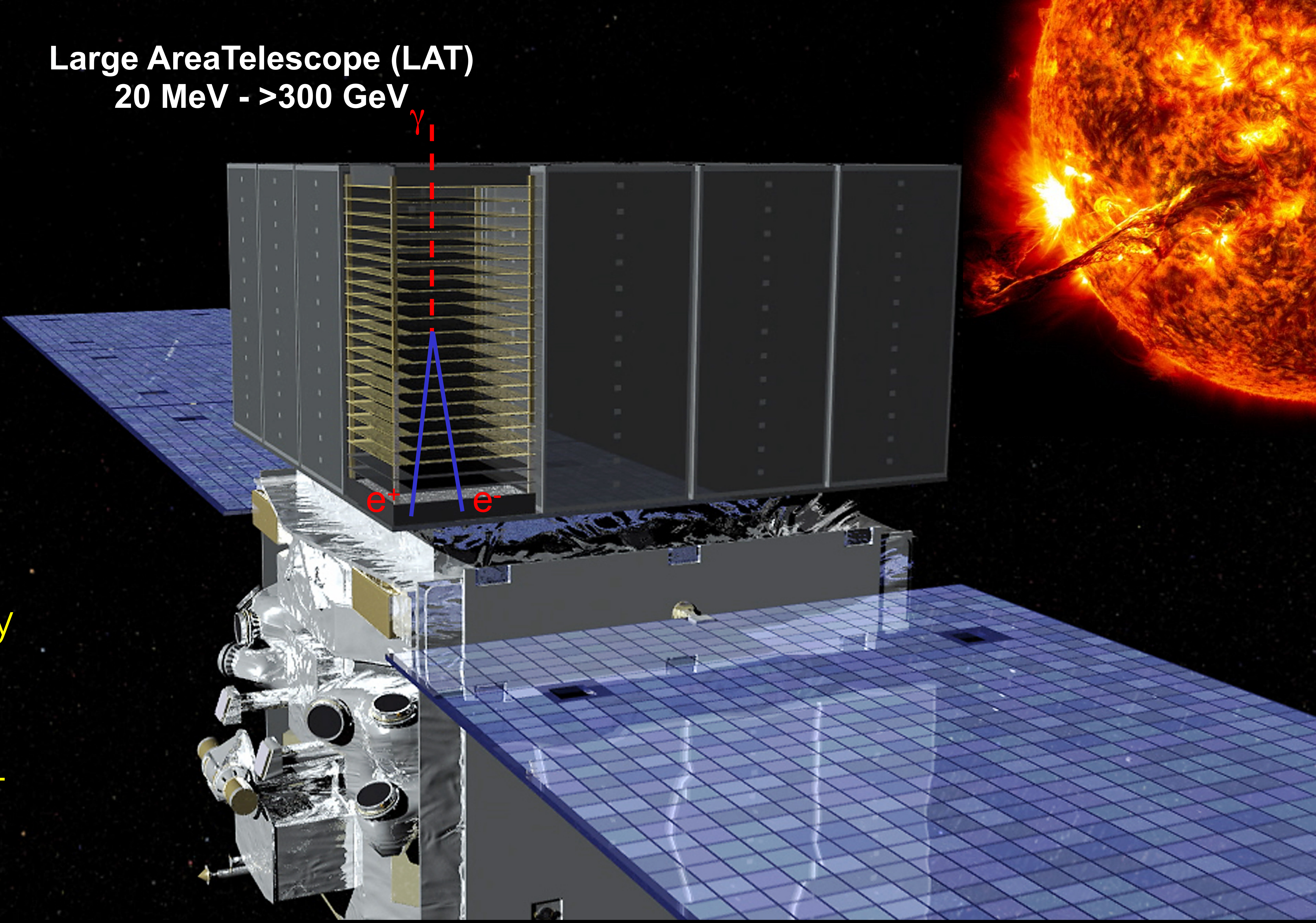

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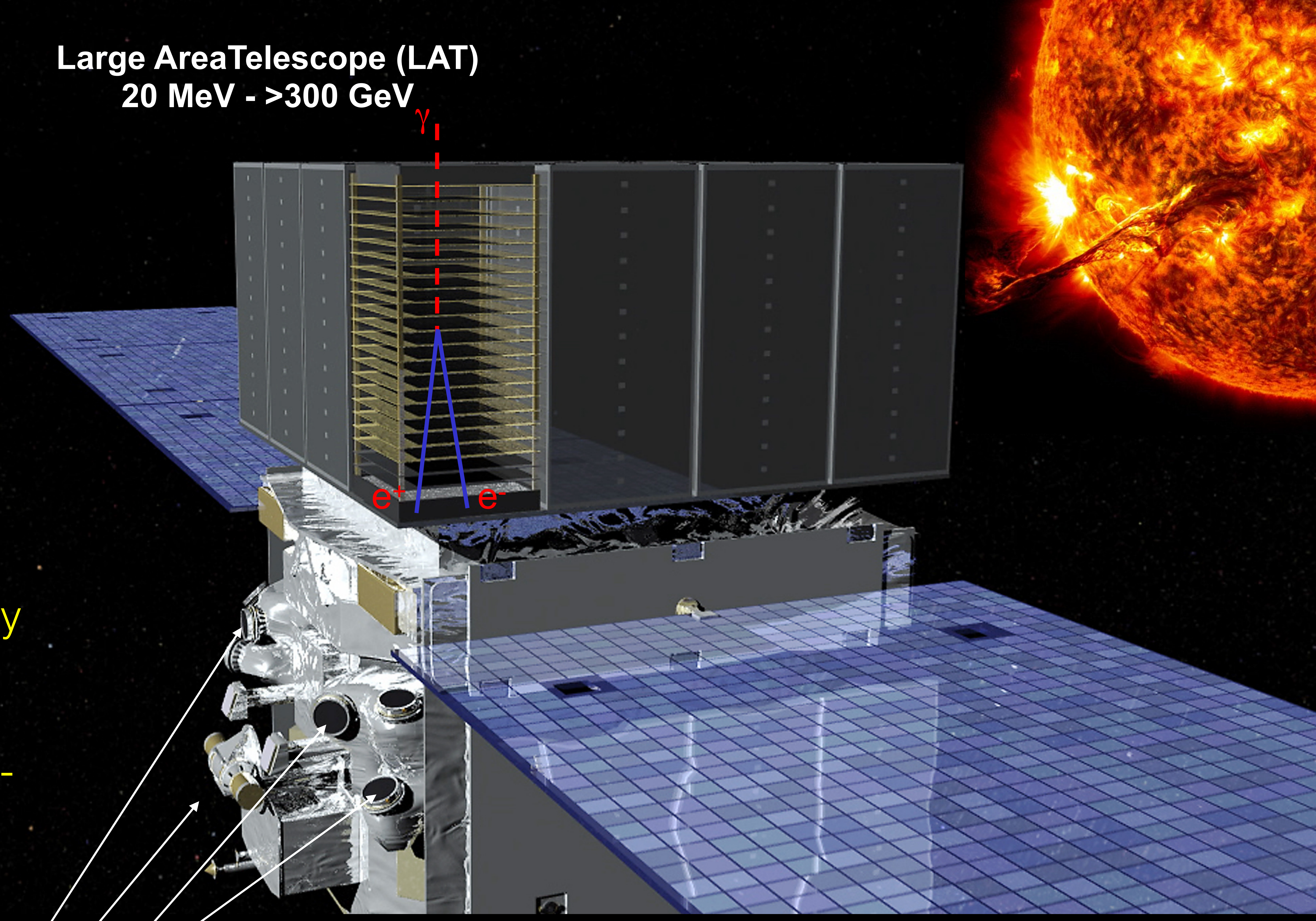

Gamma-ray Burst Monitor (GBM)
NaI and BGO Detectors
8 keV - 40 MeV

Launched in 2008, continuously monitors the sky

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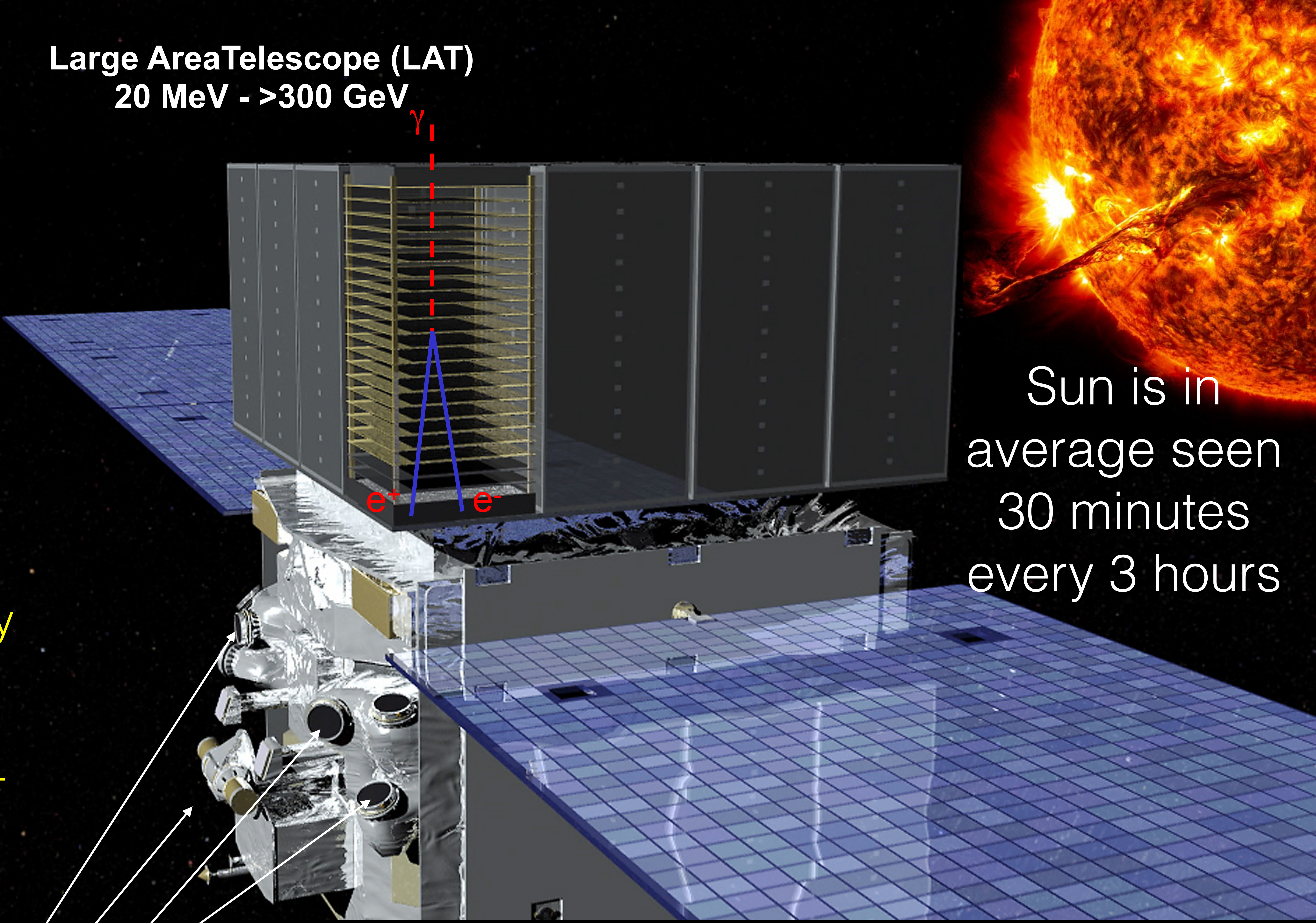

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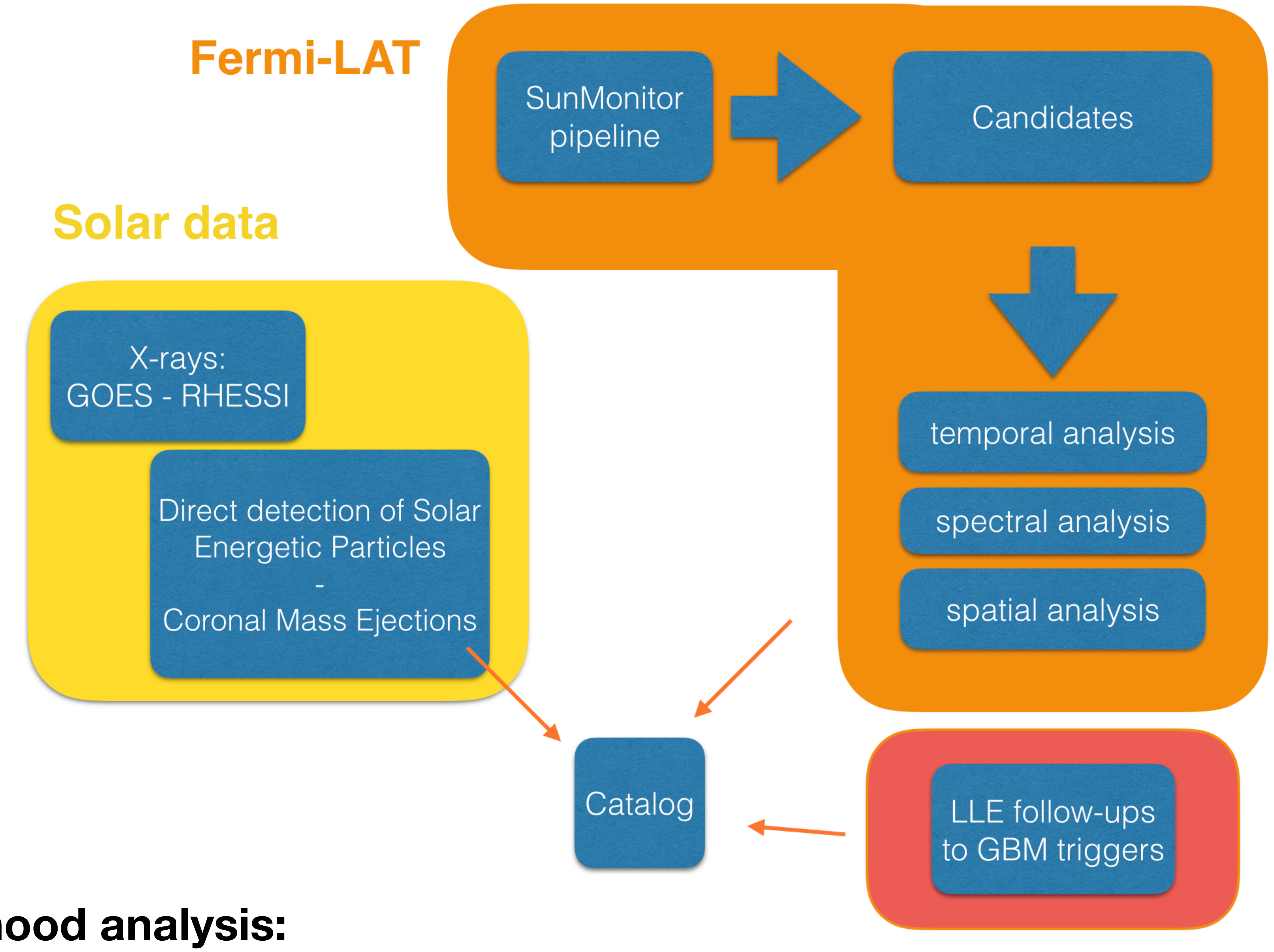
Solar Flare Catalog Framework



- 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.**

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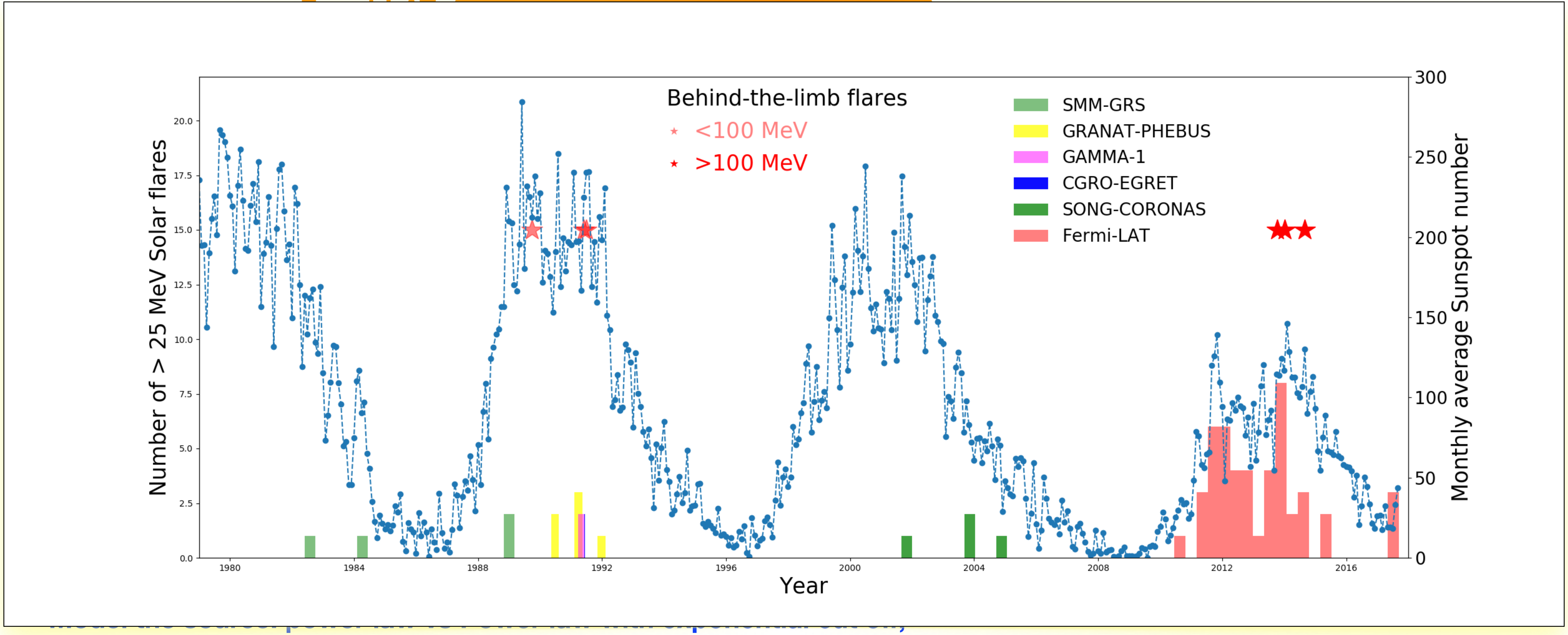

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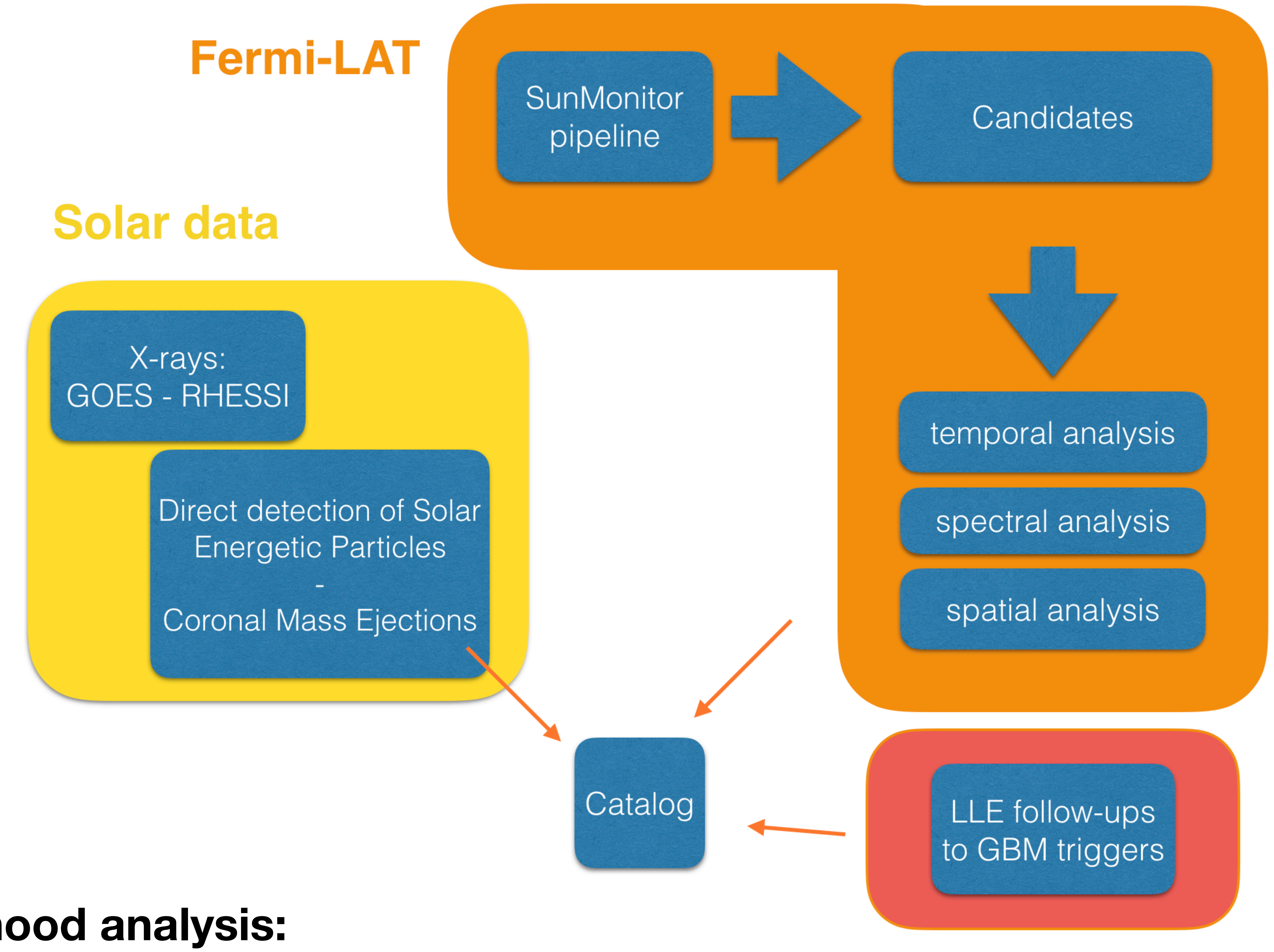

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Temporal Behavior of Fermi LAT Solar Flares (FLSF)

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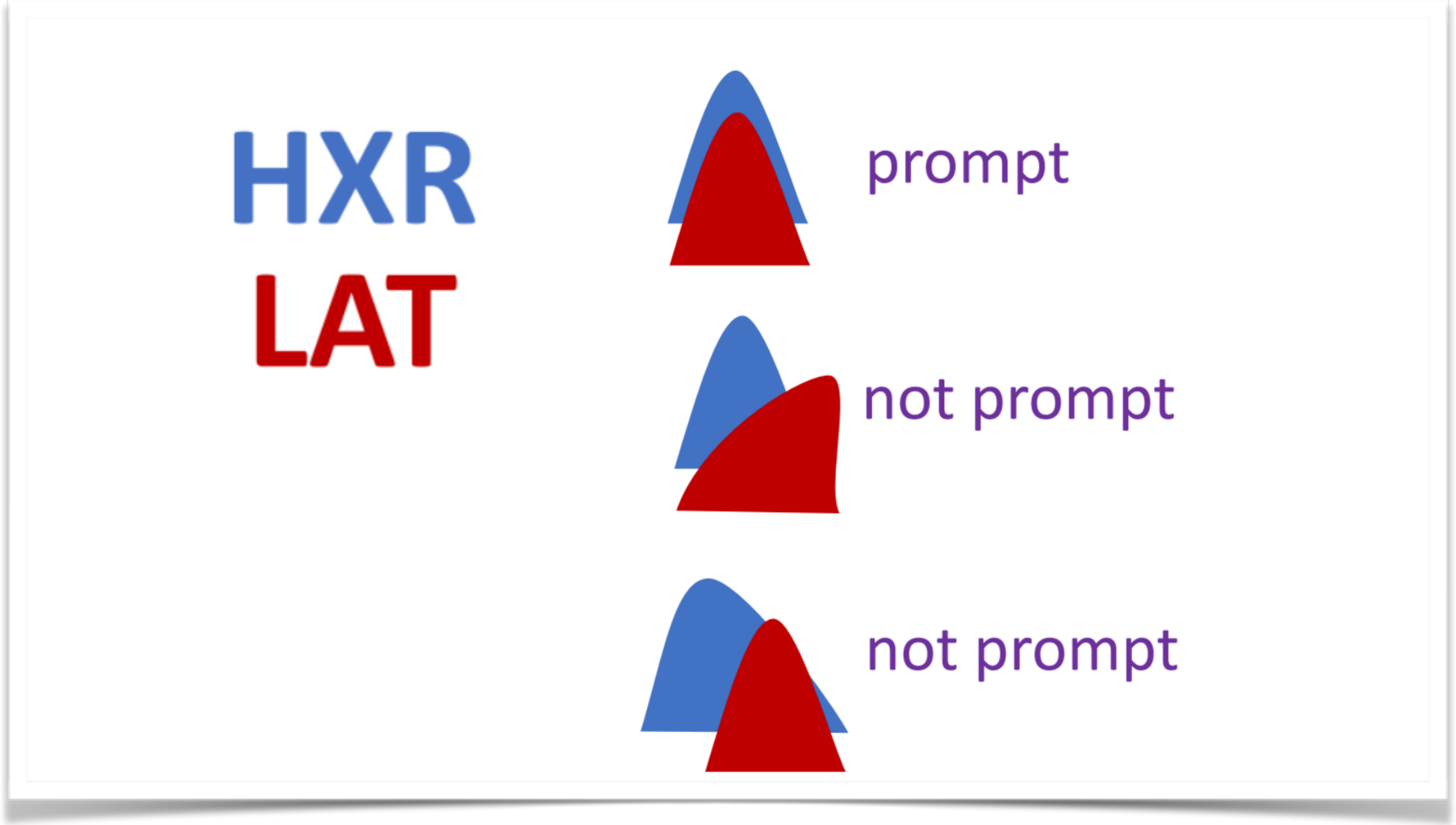

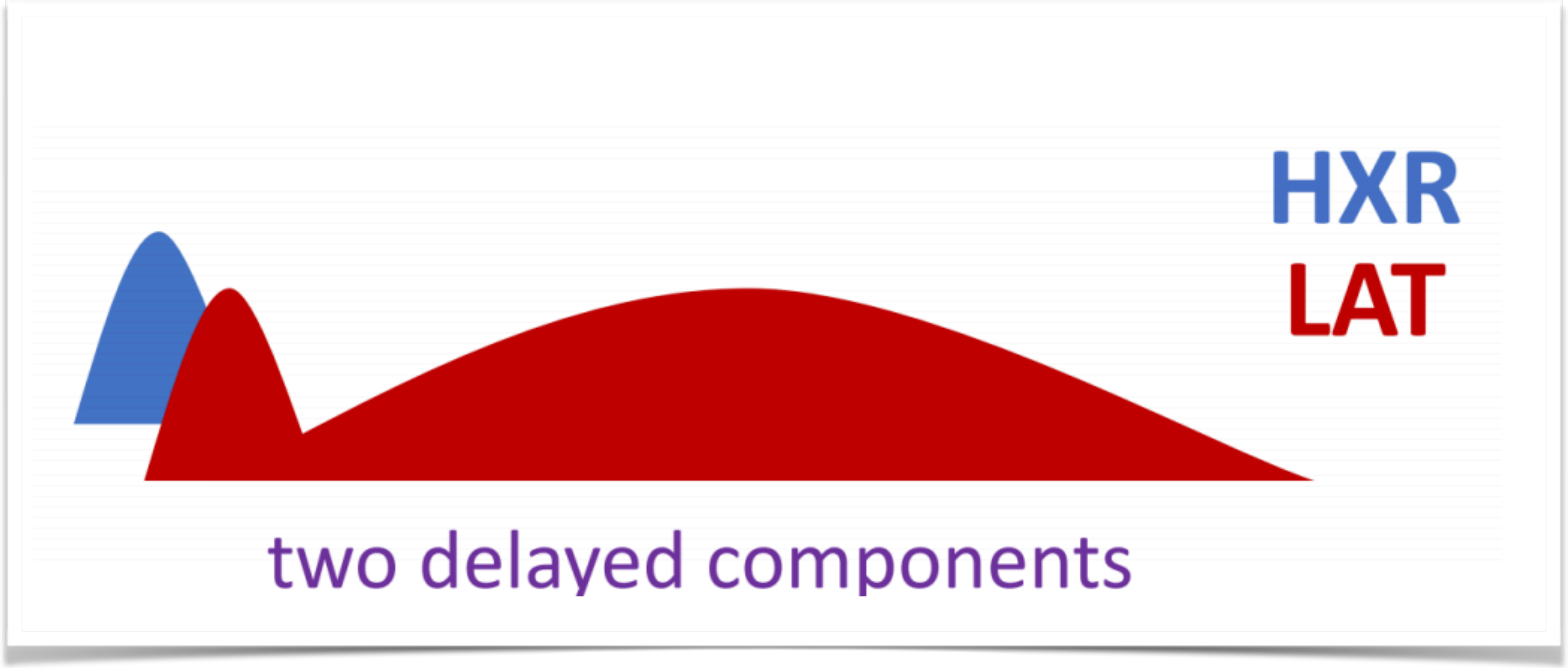

Credit: A. Shih

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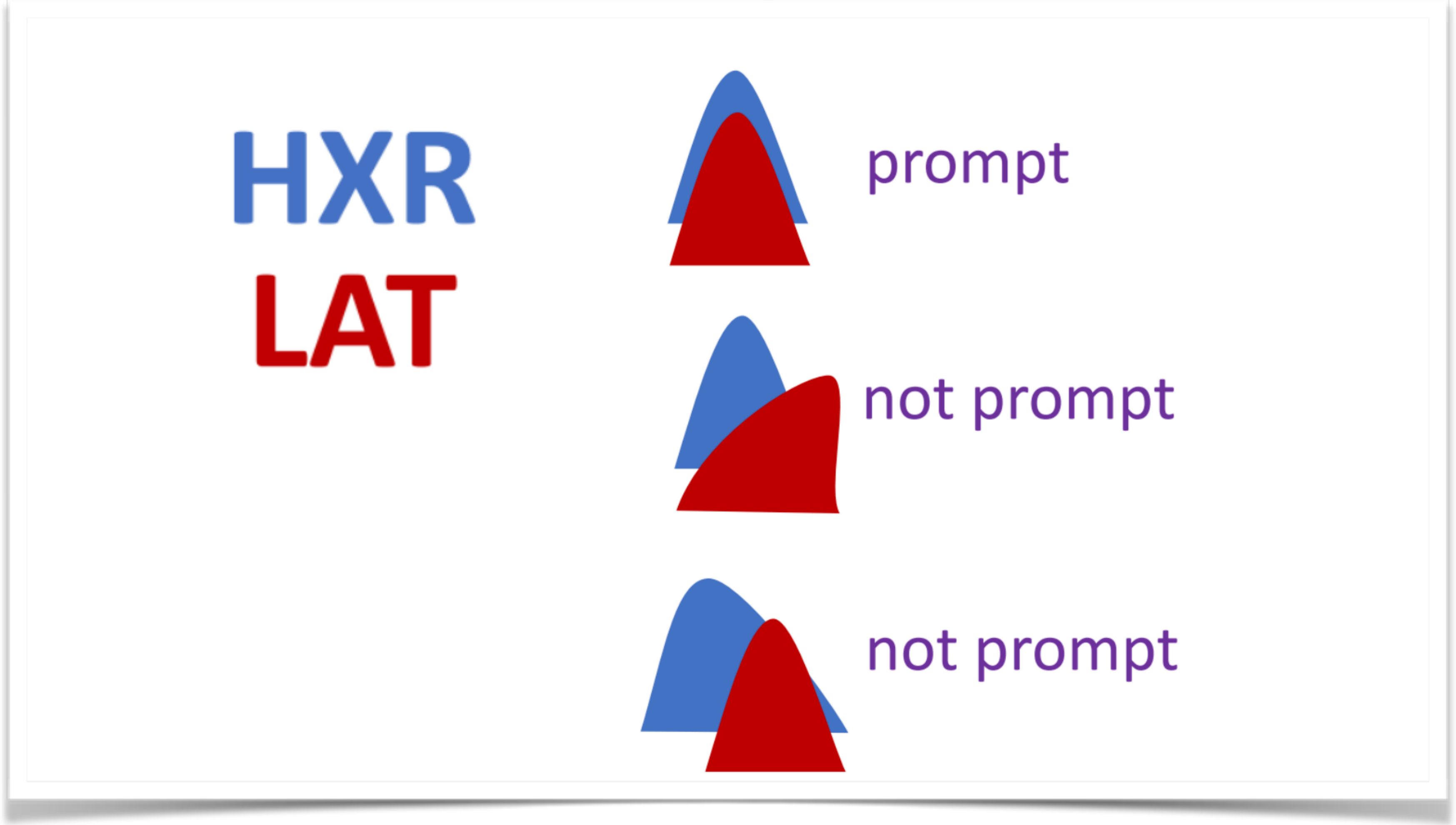

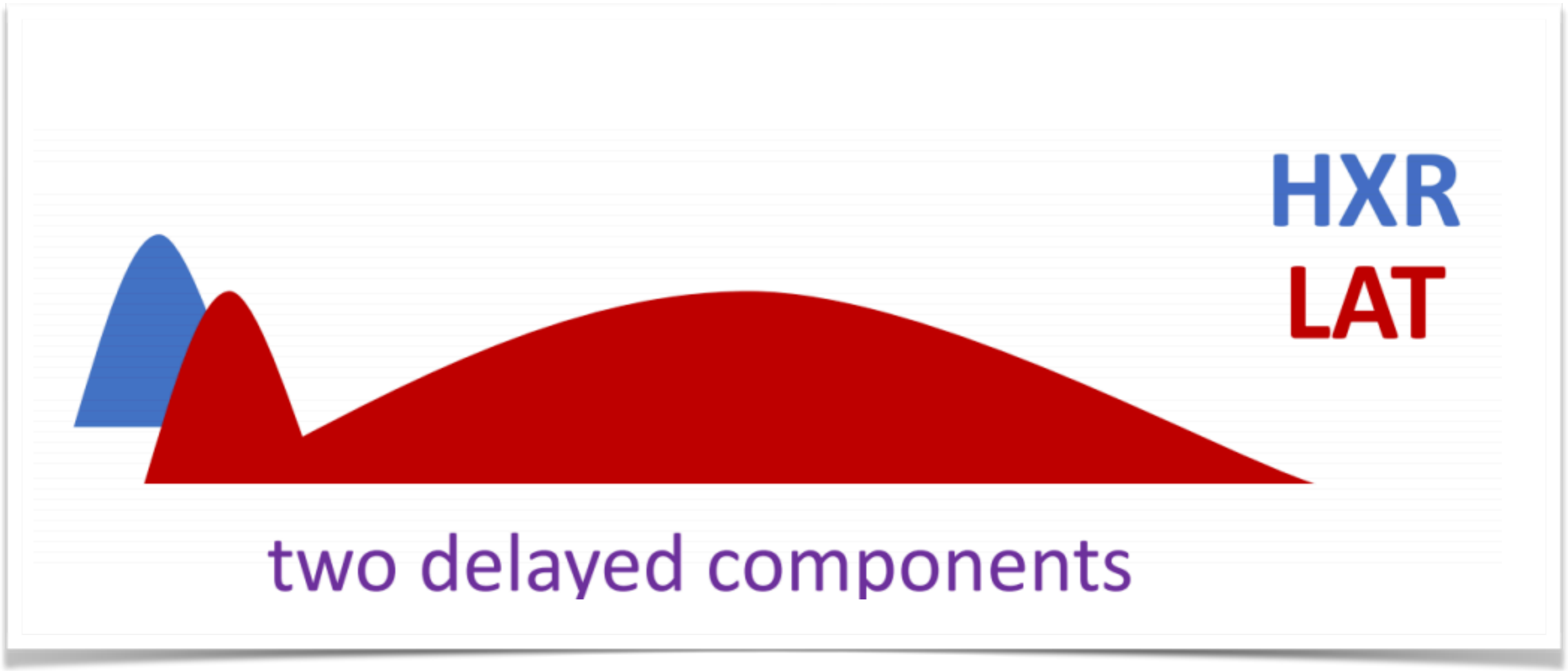

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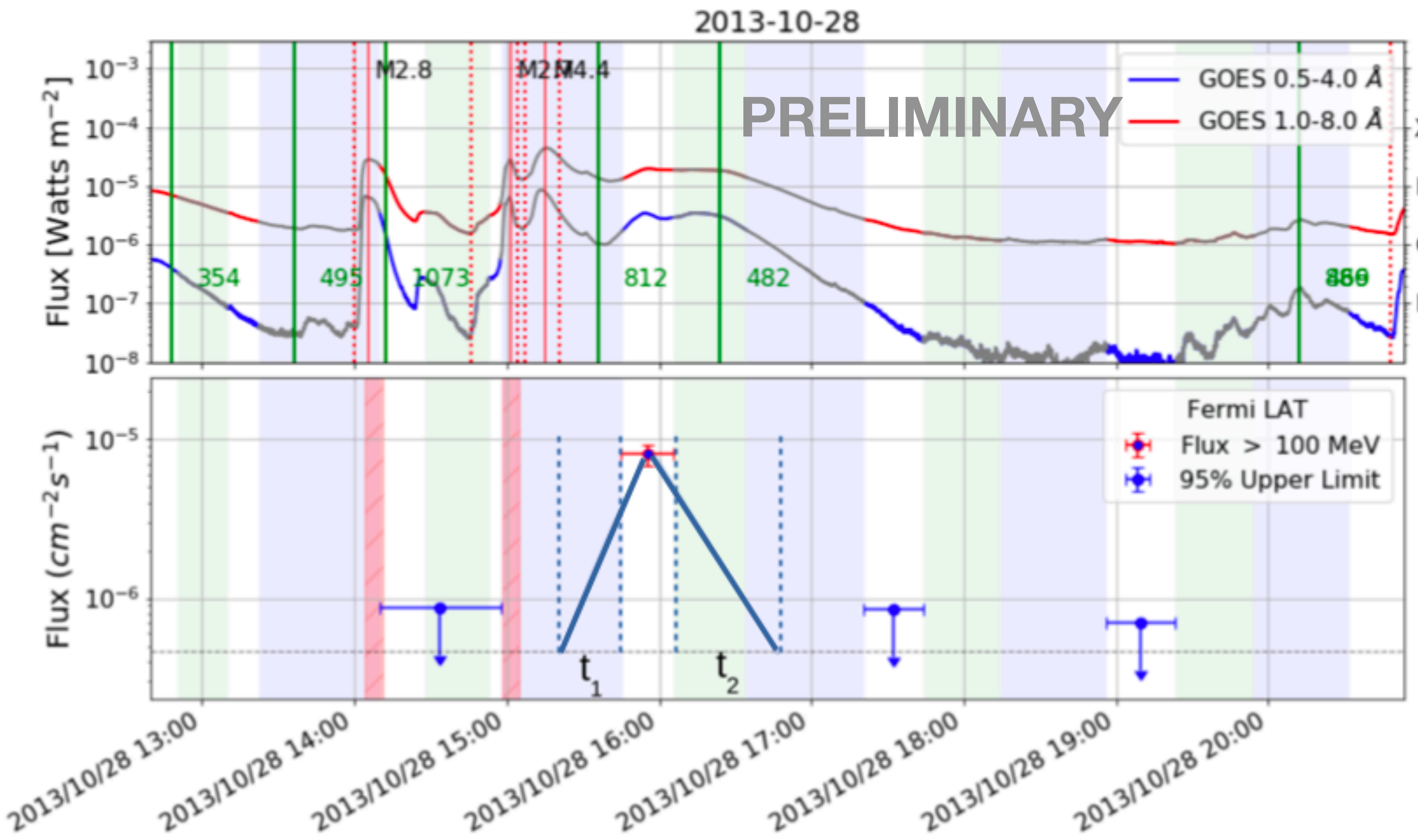
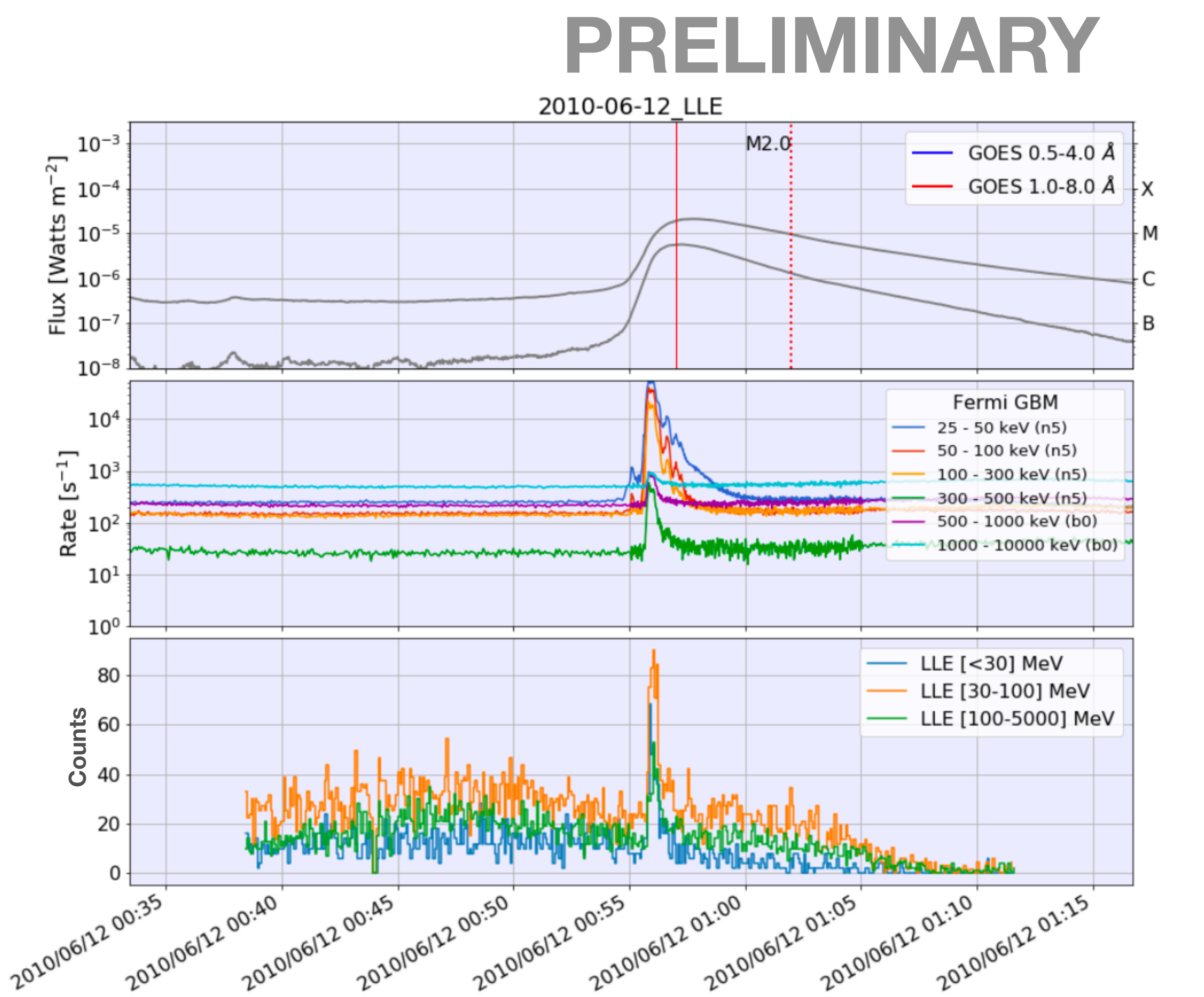


- **Light curve data is sparse.**
- **We interpolate between data and UL with simple assumption.**

<table>
<tr><th></th><th>Prompt-only</th><th>Prompt Short Delayed (<2 hr)</th><th>Prompt Delayed (>2hr)</th><th>Delayed Only</th></tr>
<tr><td>Example</td>
<td>
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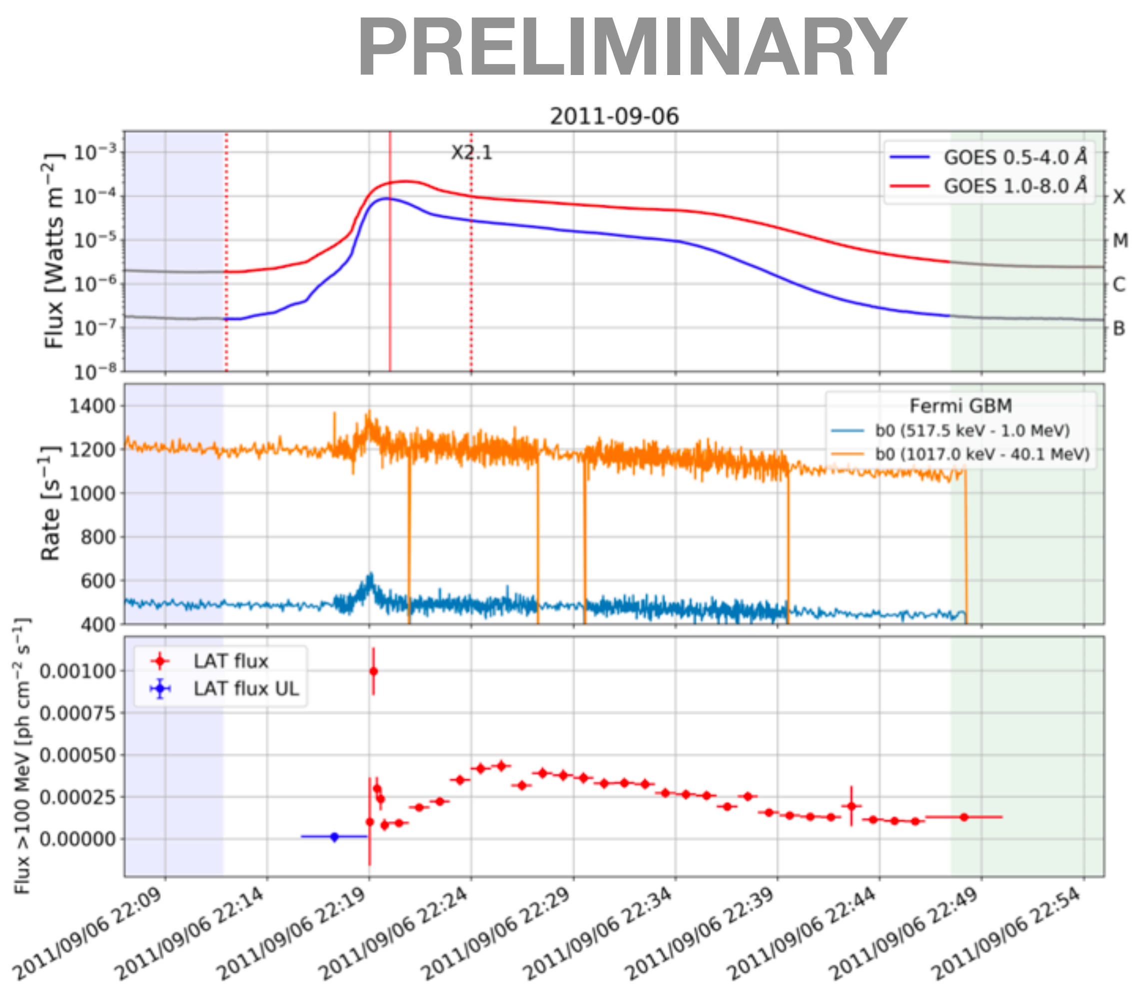
<td>
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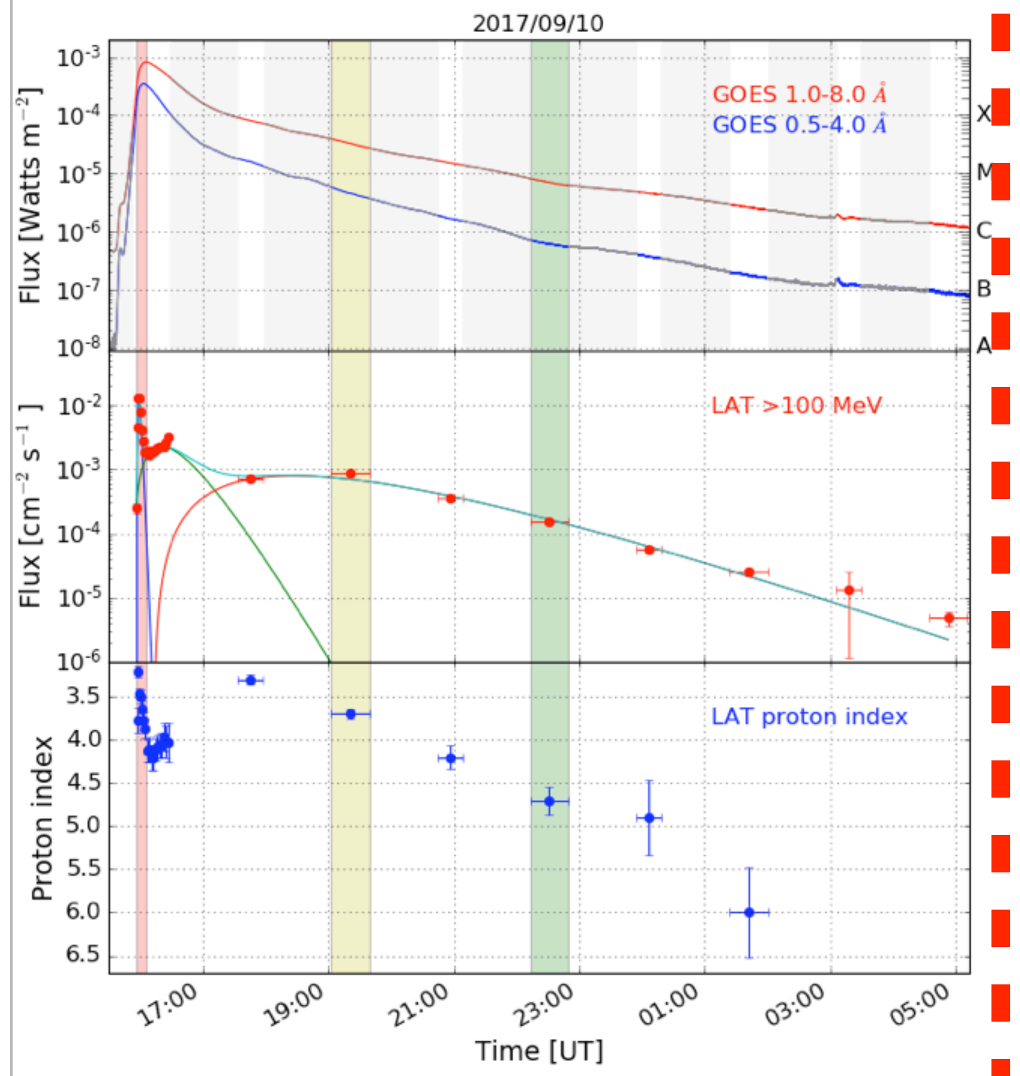
<td>
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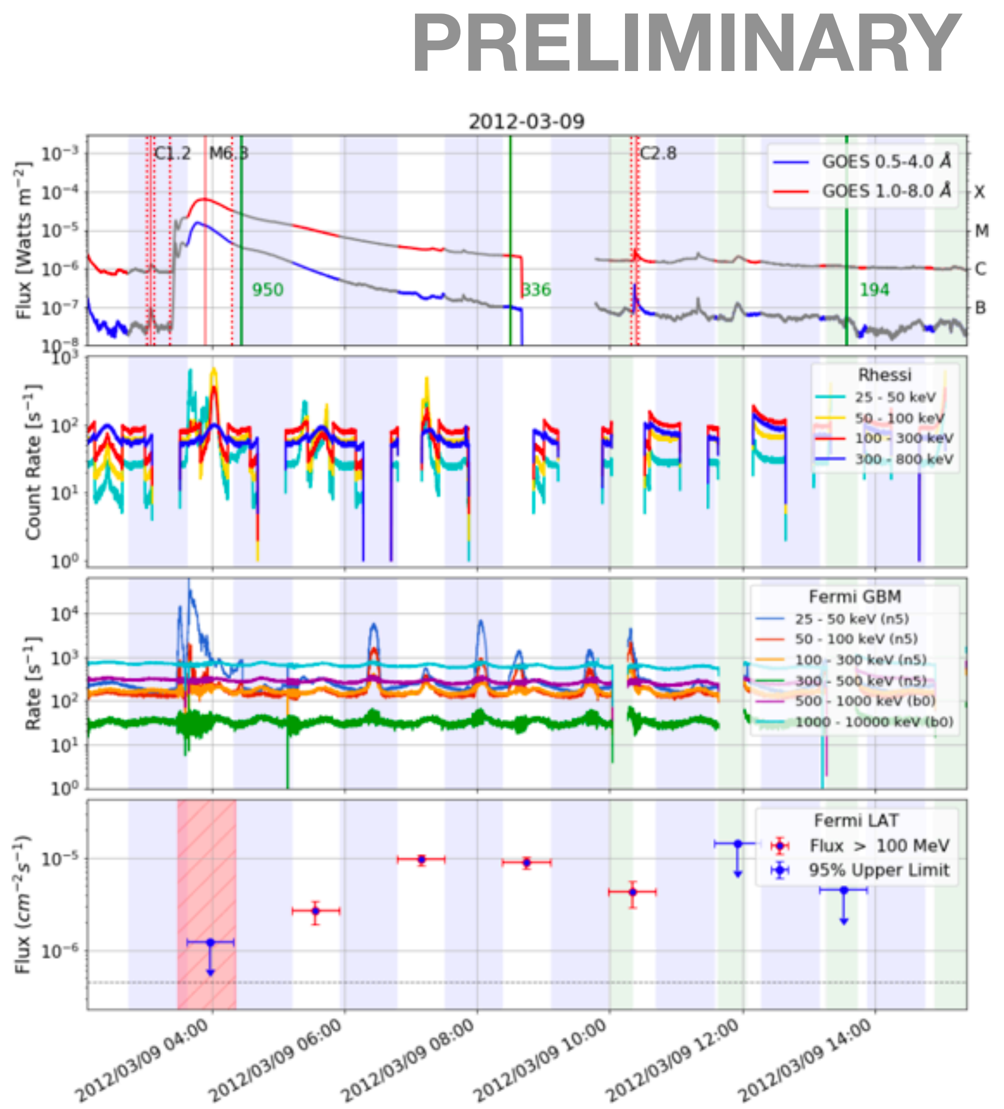
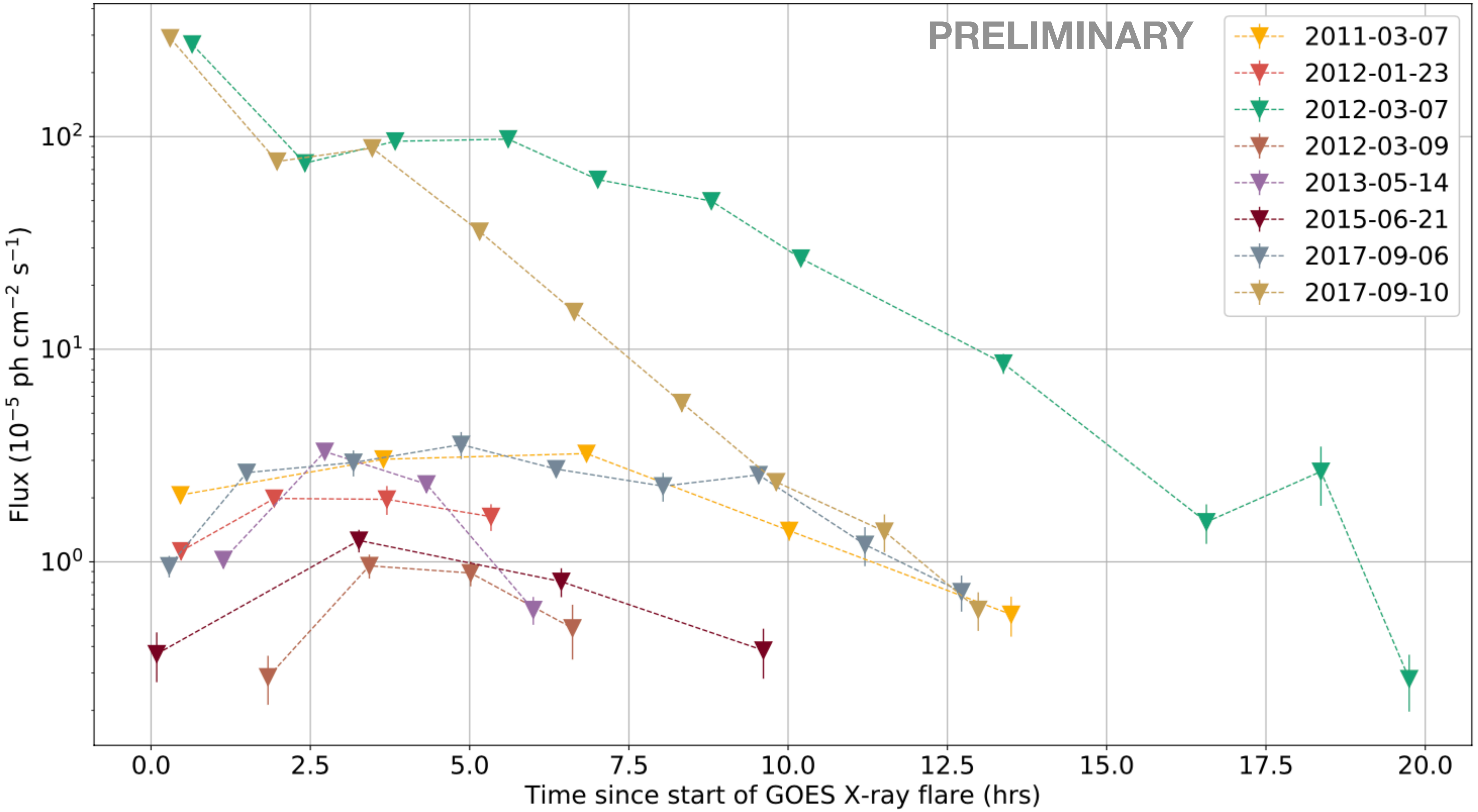
<td>
</td></tr>
<tr><td>FLSFs</td><td>6</td><td colspan="2">10</td><td>4</td></tr>
</table>

For the remaining 25 cases, the prompt emission was not in the field of view, so we cannot conclude anything about the physical presence of it.

- **16 flares detected in >2 time windows (>2hrs)**

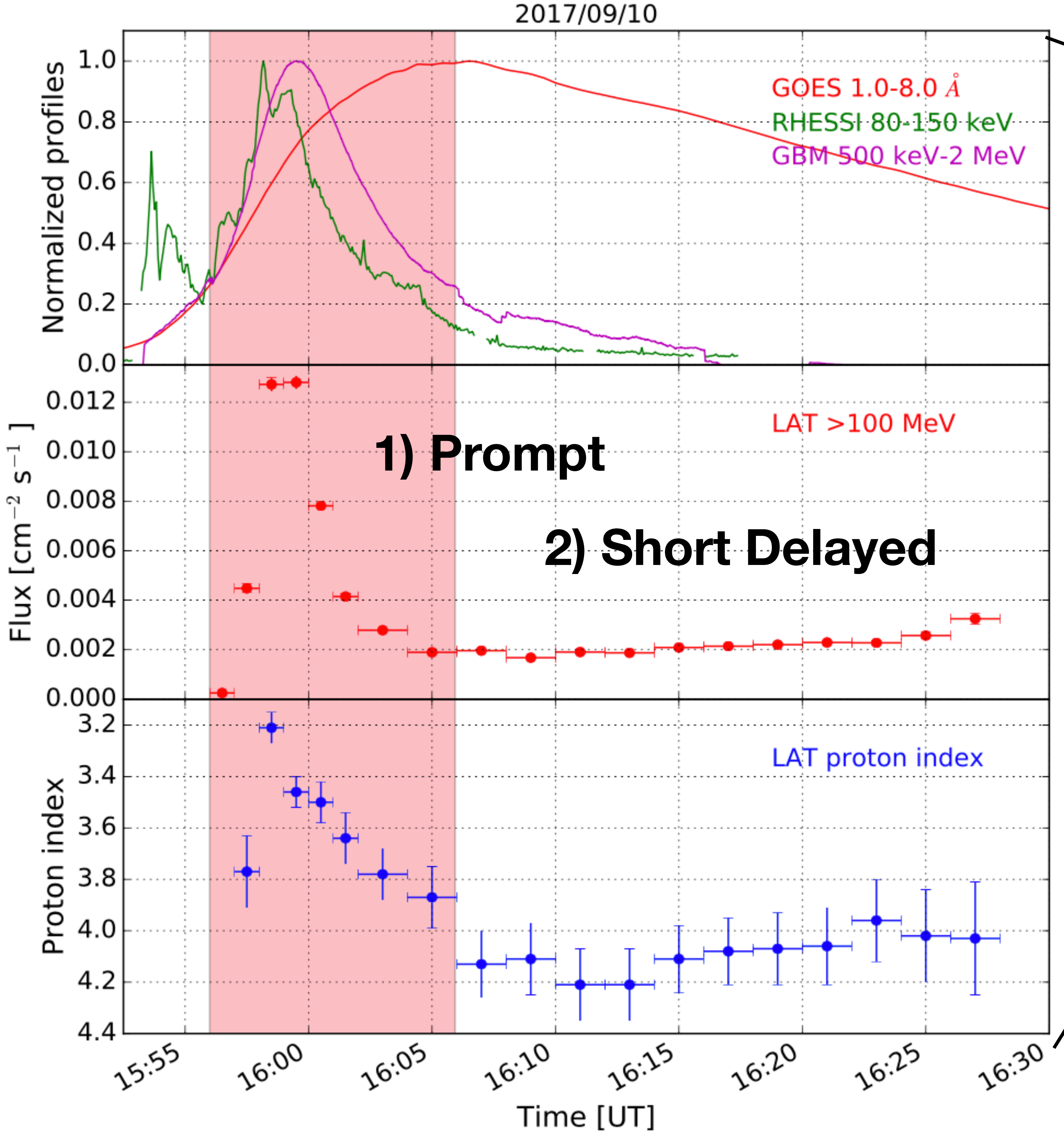
+ 3 BTL

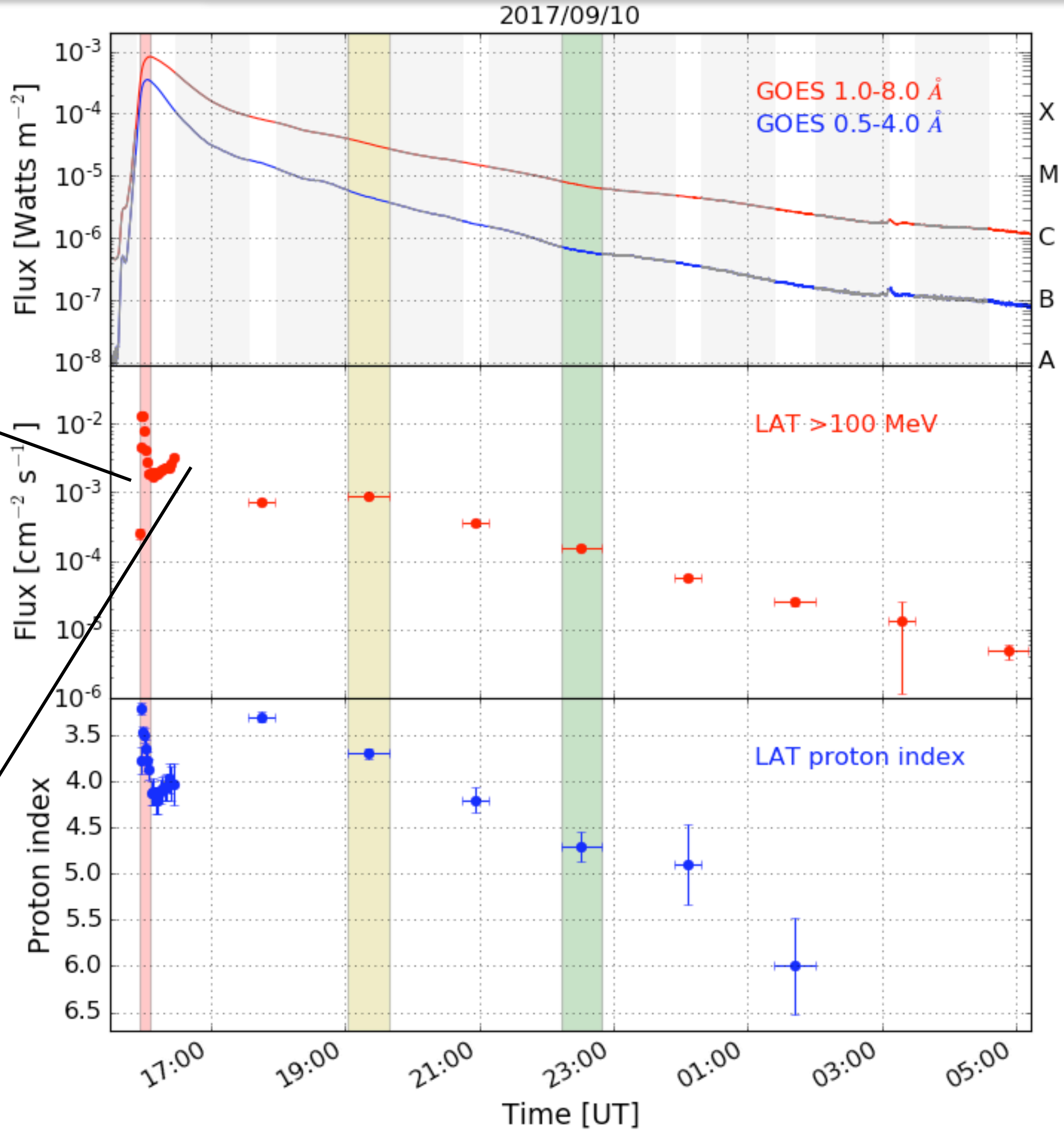
Eight Long Lasting (>4 hr) Solar Flares head to head



- **The GLE event (2017-09-06) and sub-GLE event (2012-03-07) are by far the brightest one.**
- **Rise-time behavior more evident for delayed-only flares**

SOL 2017-09-10 shows multiple components





Omodei et al. 2018

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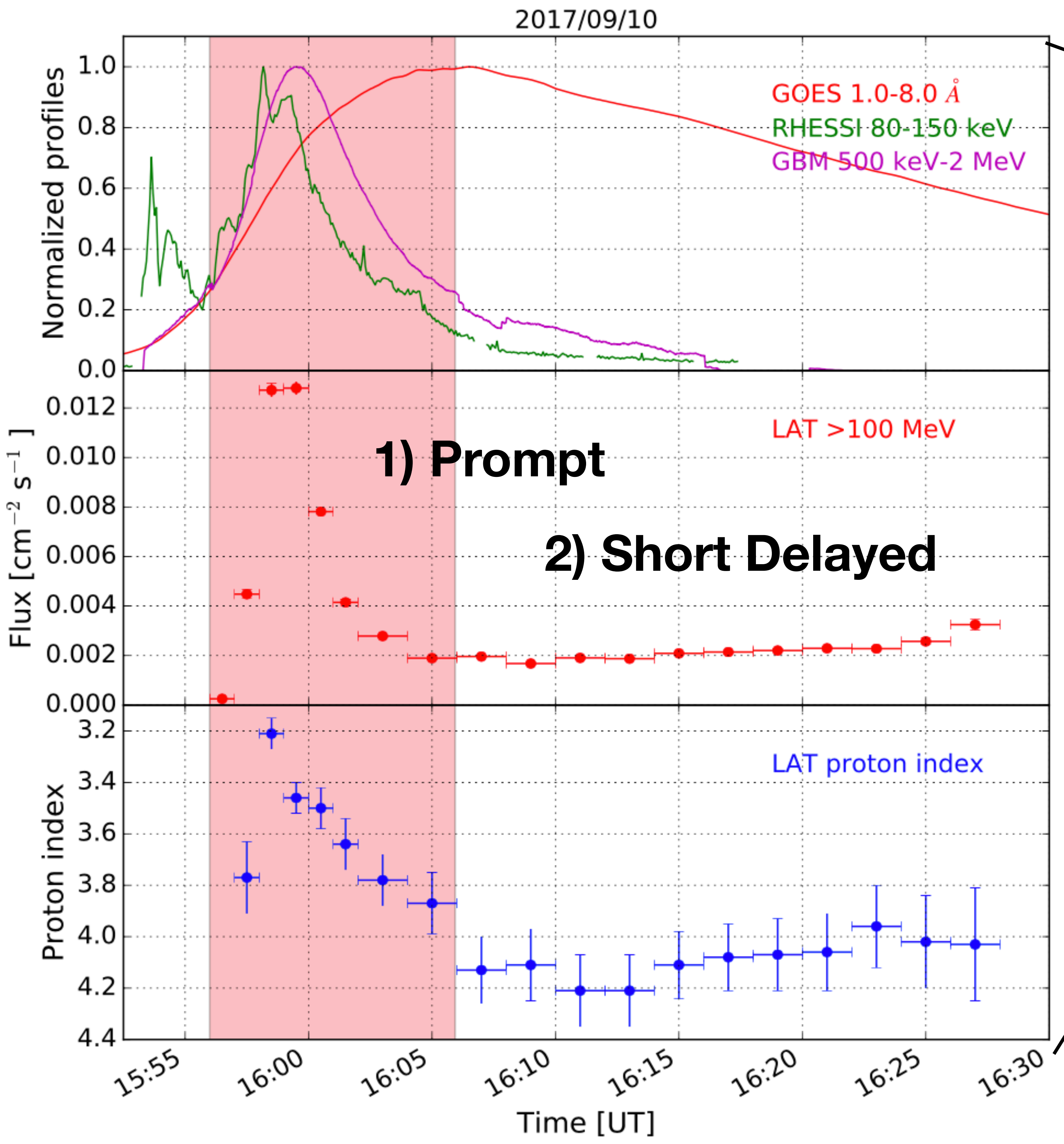
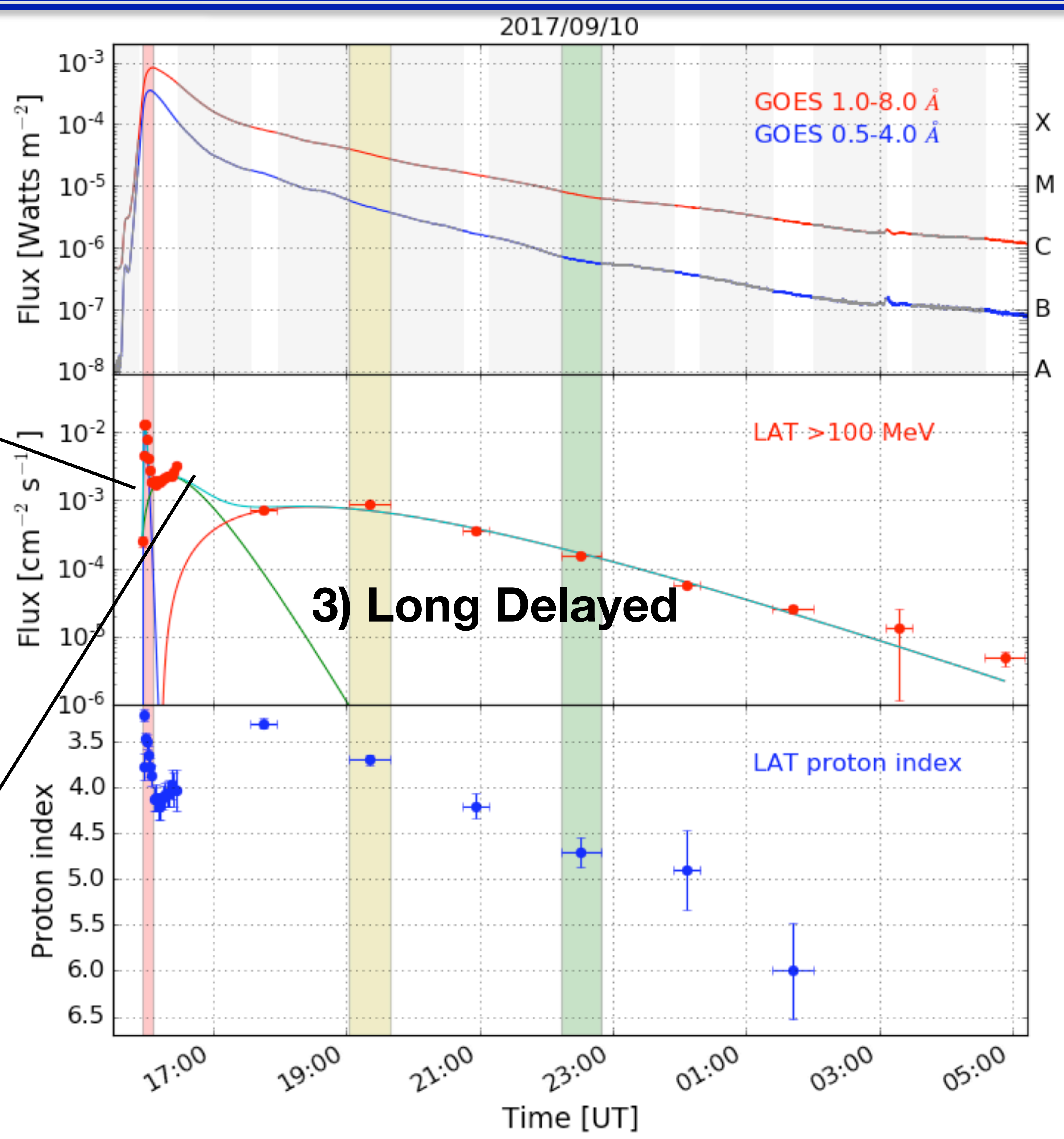
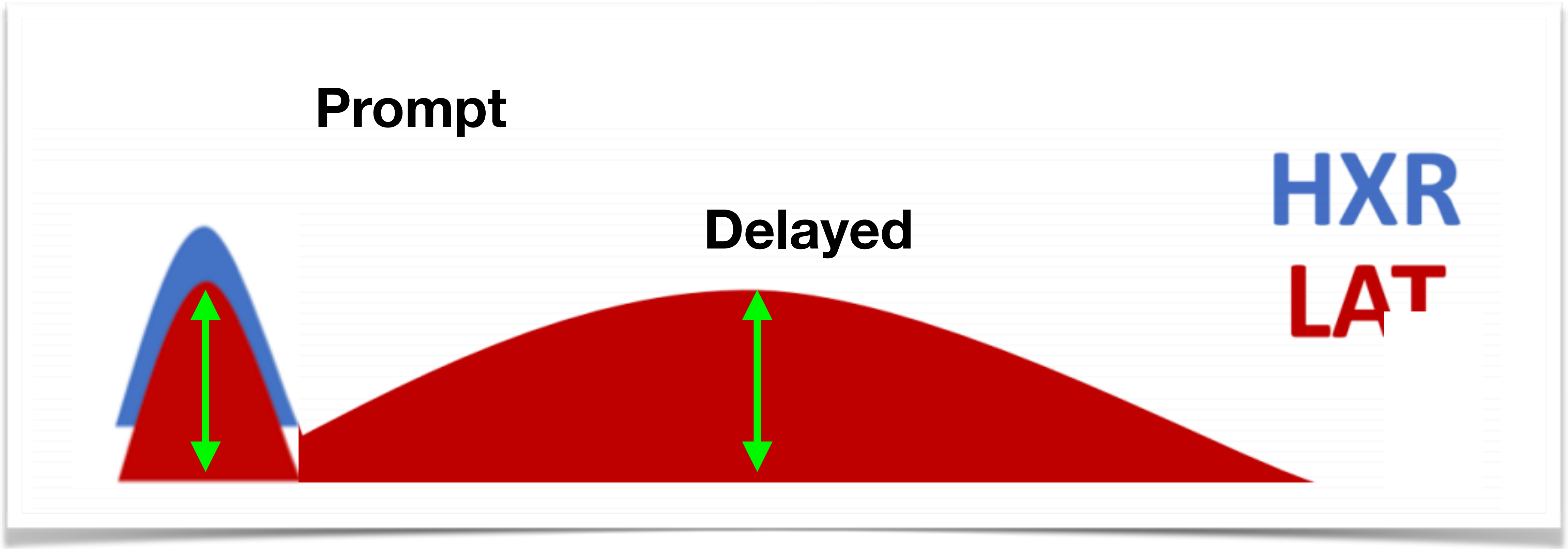
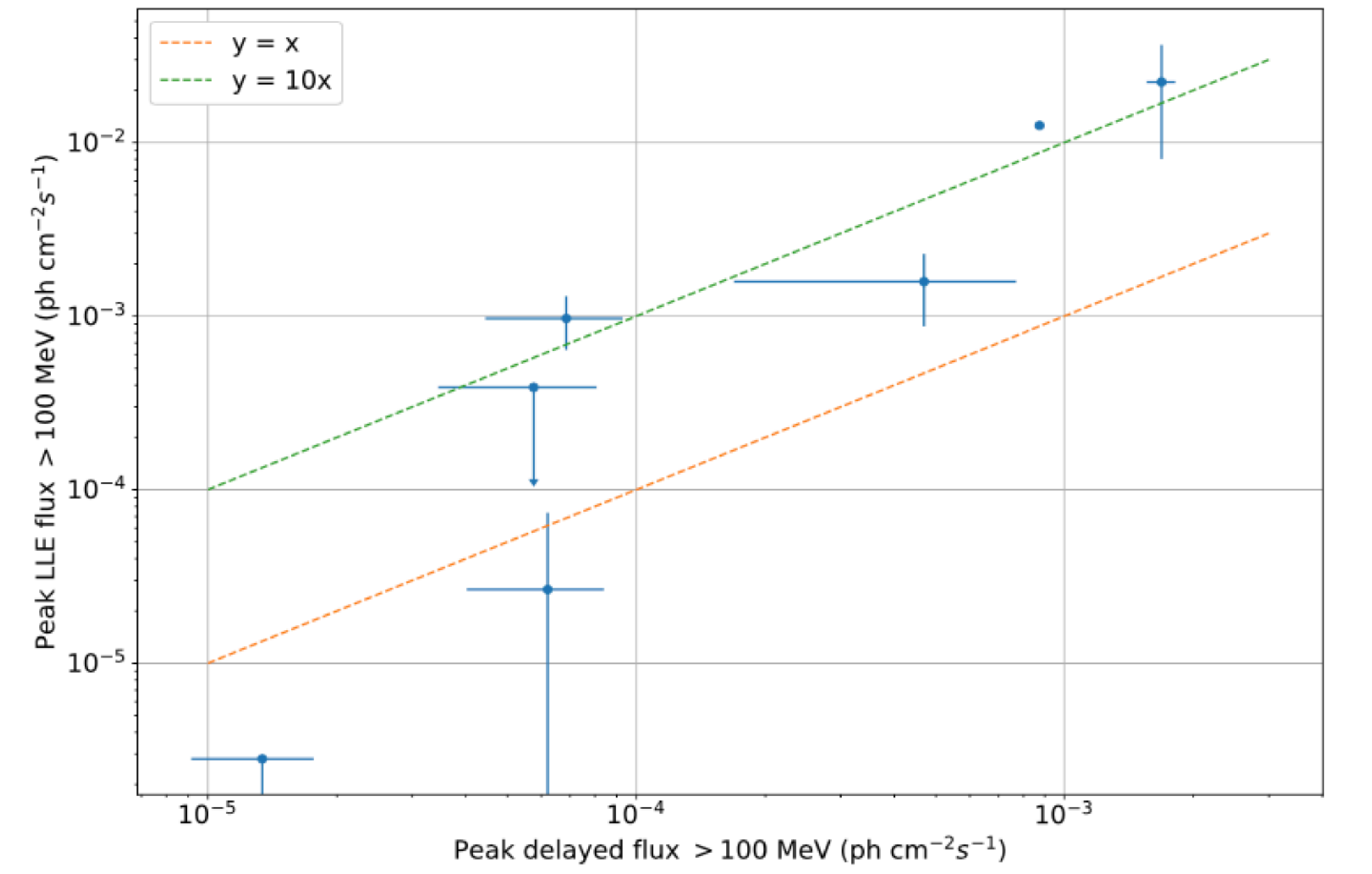




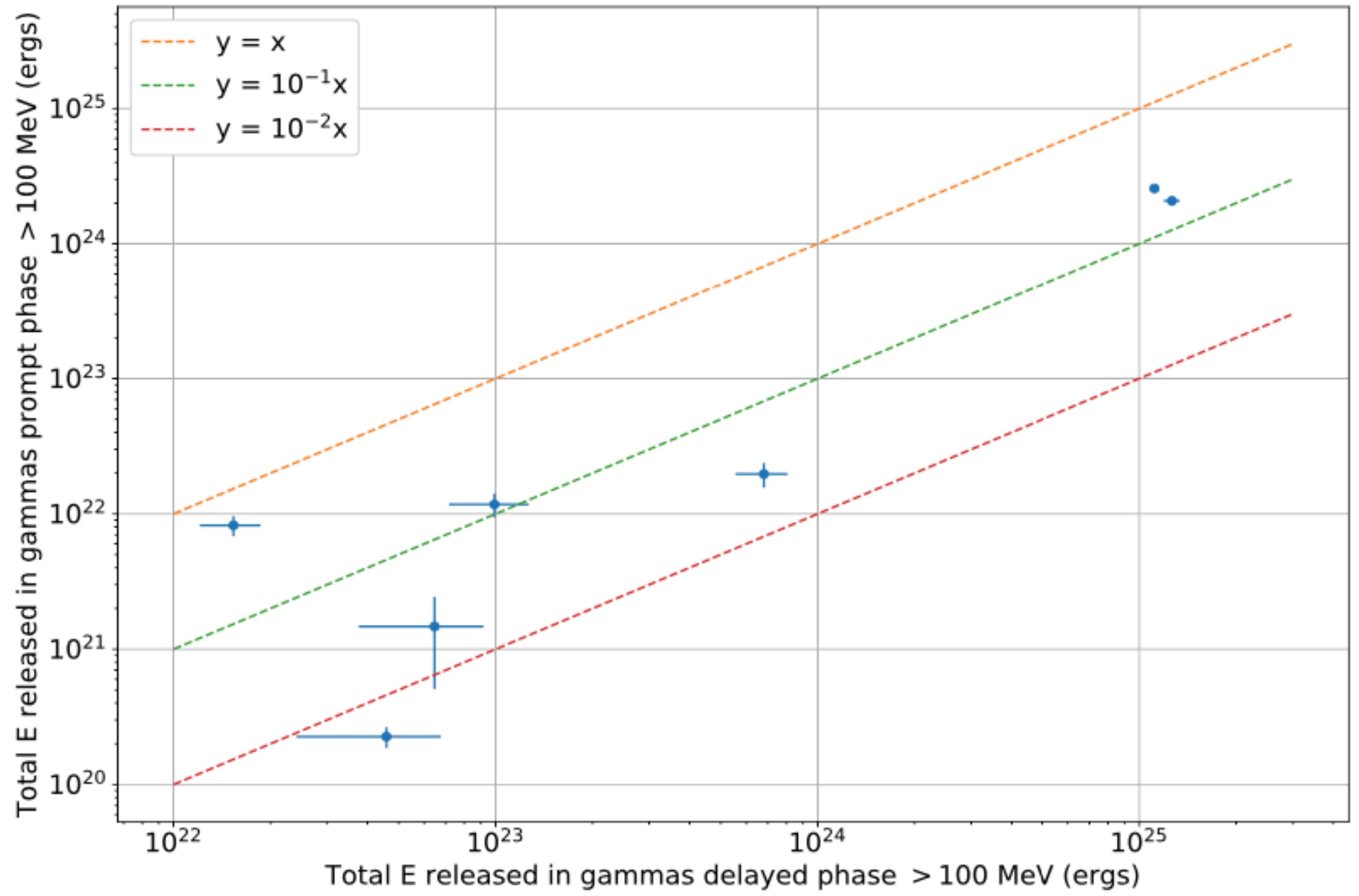
Omodei et al. 2018

Quantifying the prompt phase and delayed phase





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



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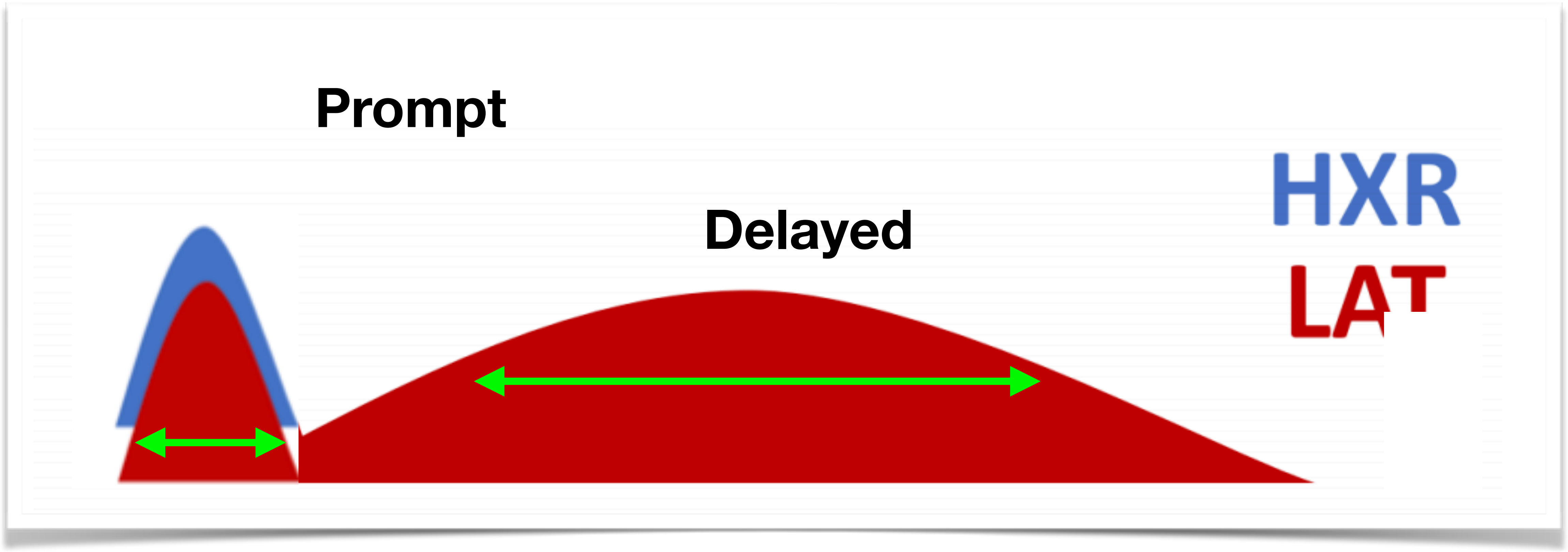
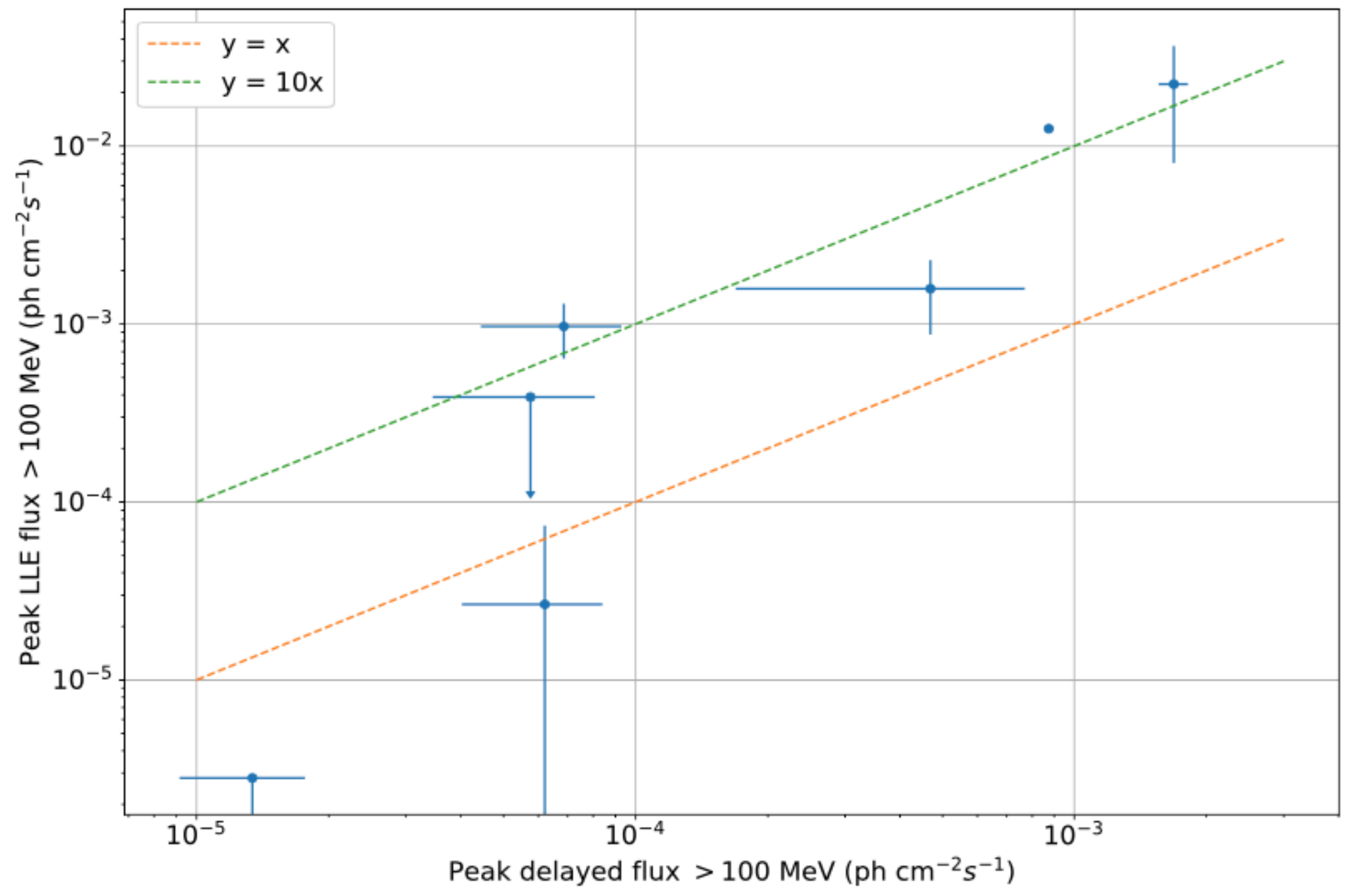
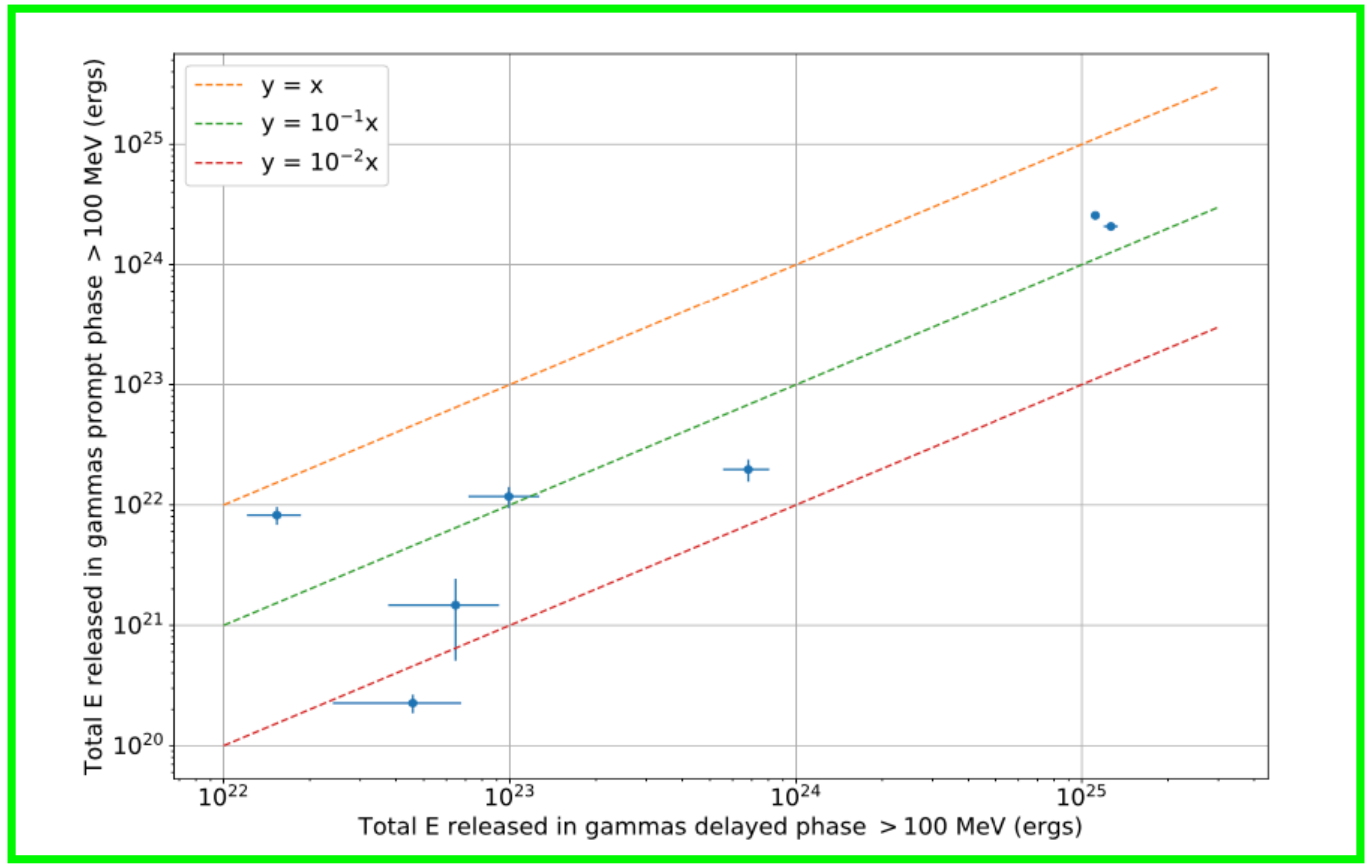






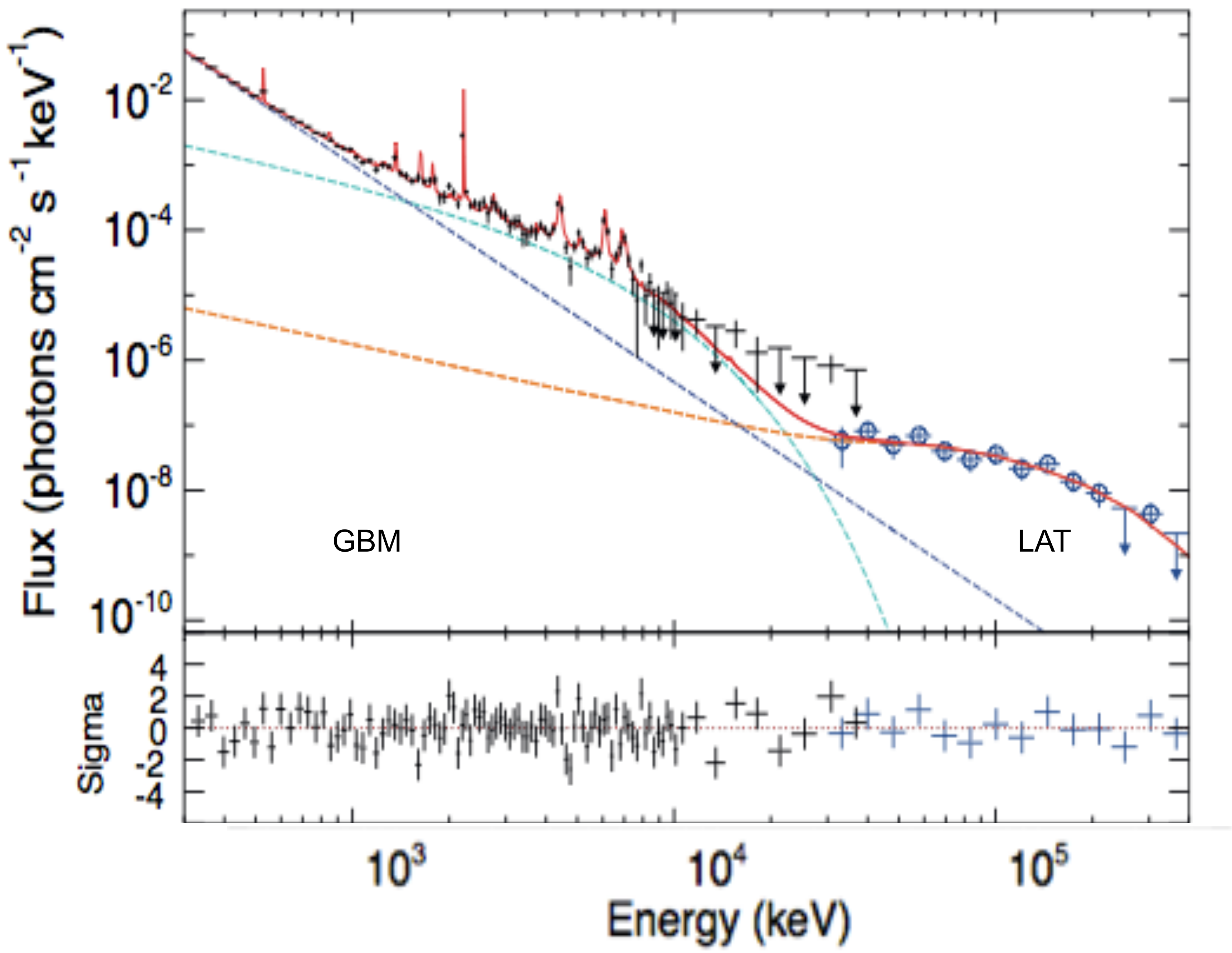
- **Peak flux of the prompt phase > Peak flux of the delayed phase**
- **Energy released in the delated phase > Energy released in the prompt phase**

Spectral analysis

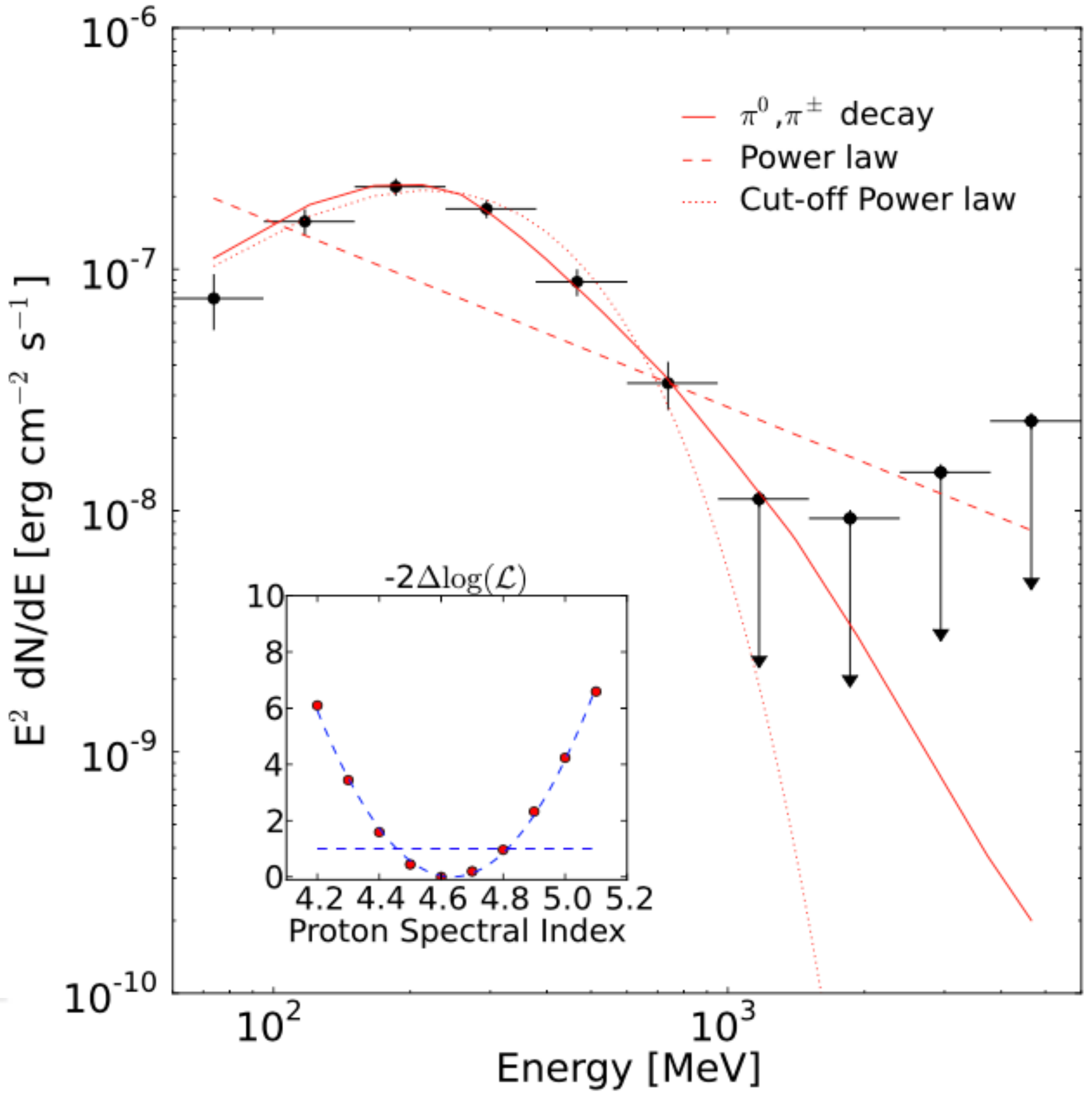
Spectral analysis

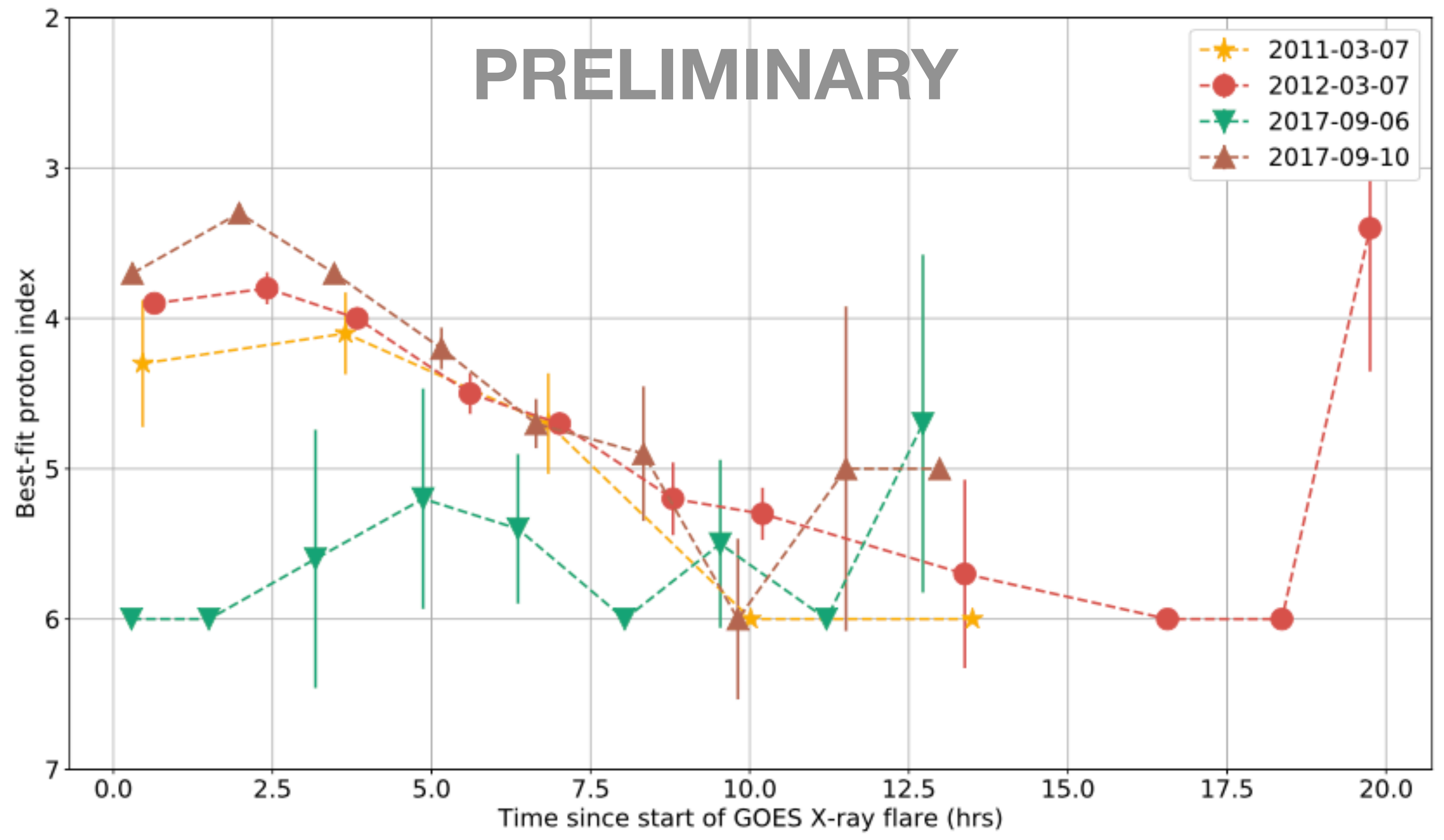
- Both prompt and delayed emissions exhibit curvature in their spectrum.
- Well reproduced (when statistic allows) with pion decay model (Murphy et al. 1987)

2010-06-12 (Prompt)



2012-03-07 (Delayed)





Softening of the p spectrum with time

Where does the gamma-ray emission come from?

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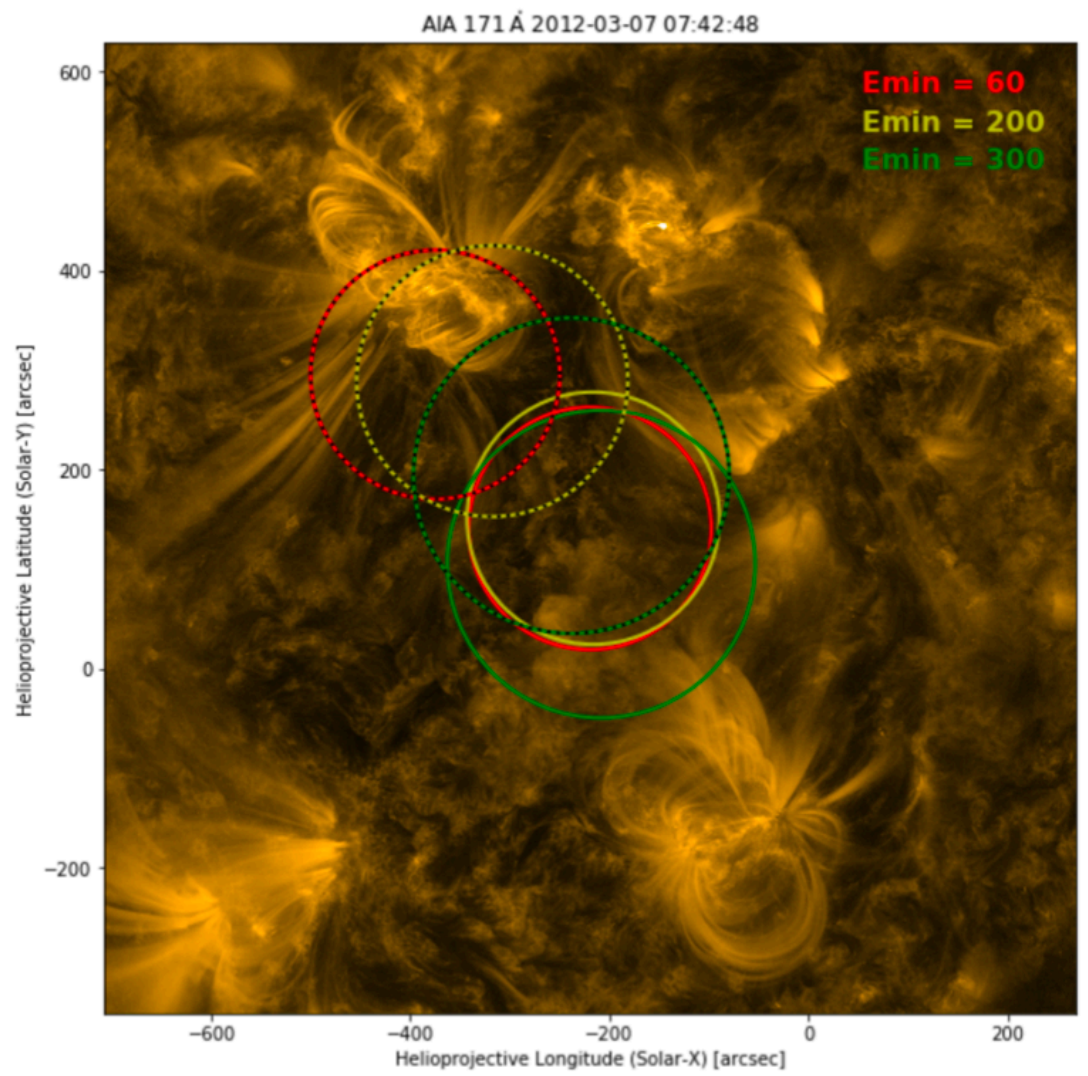
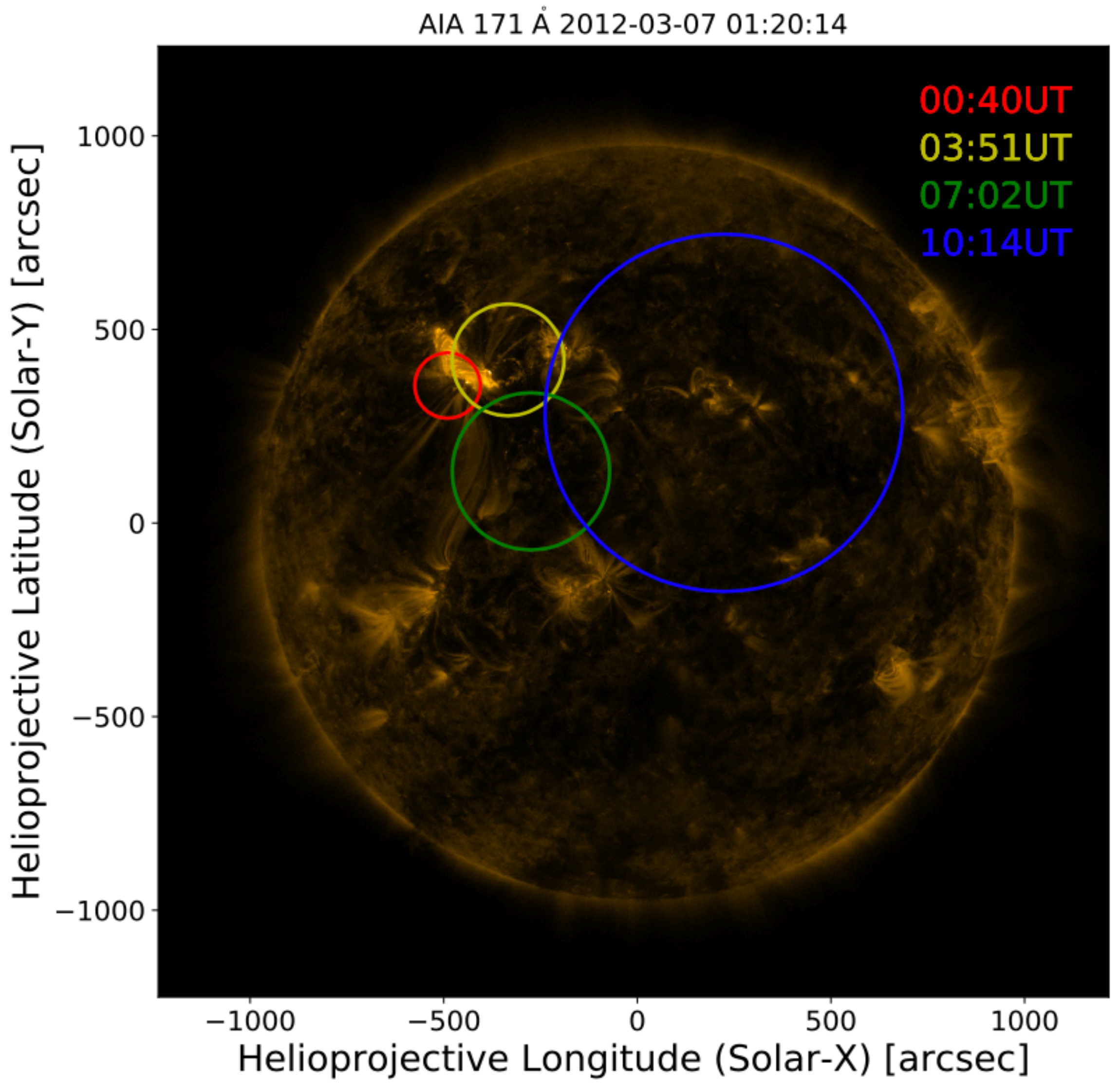
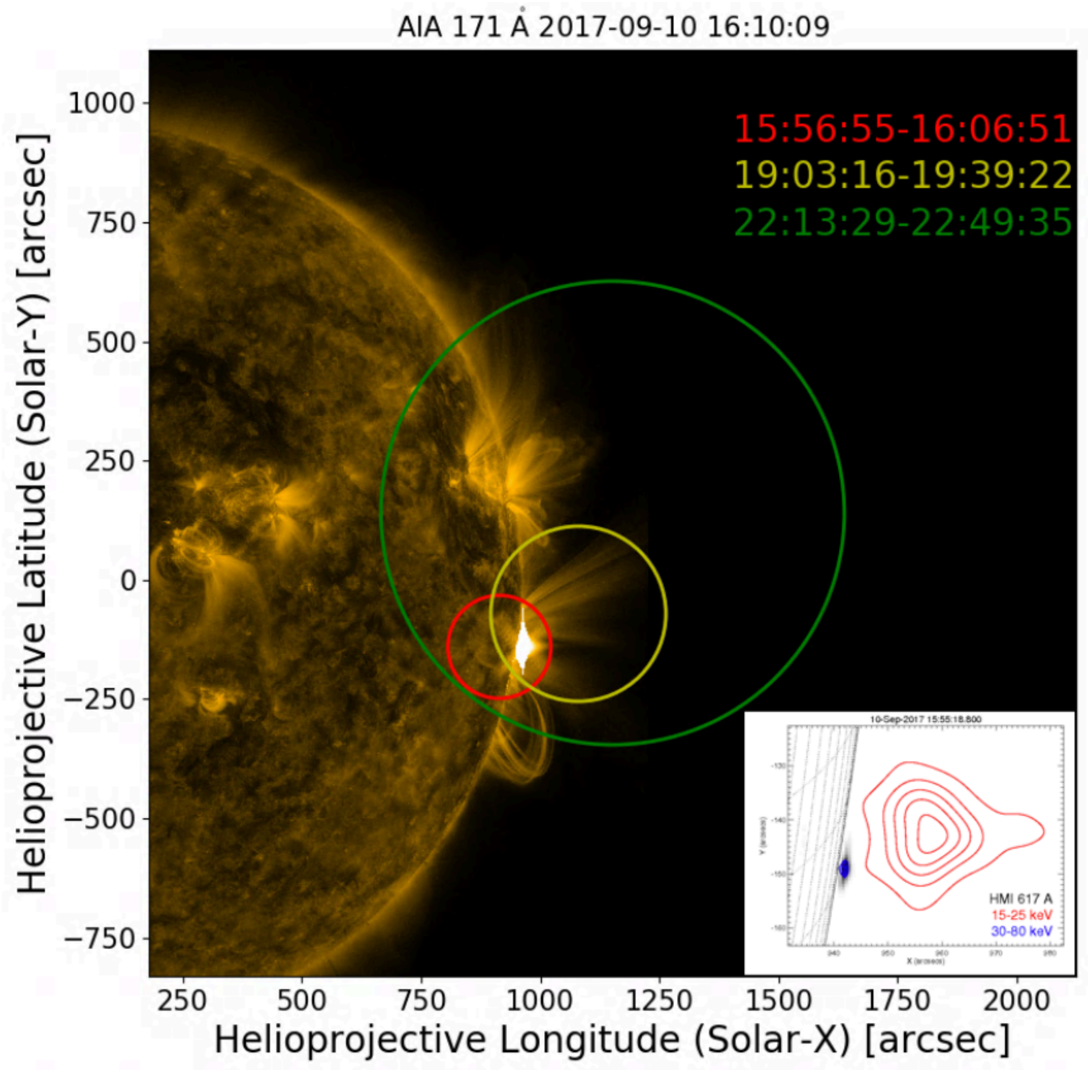
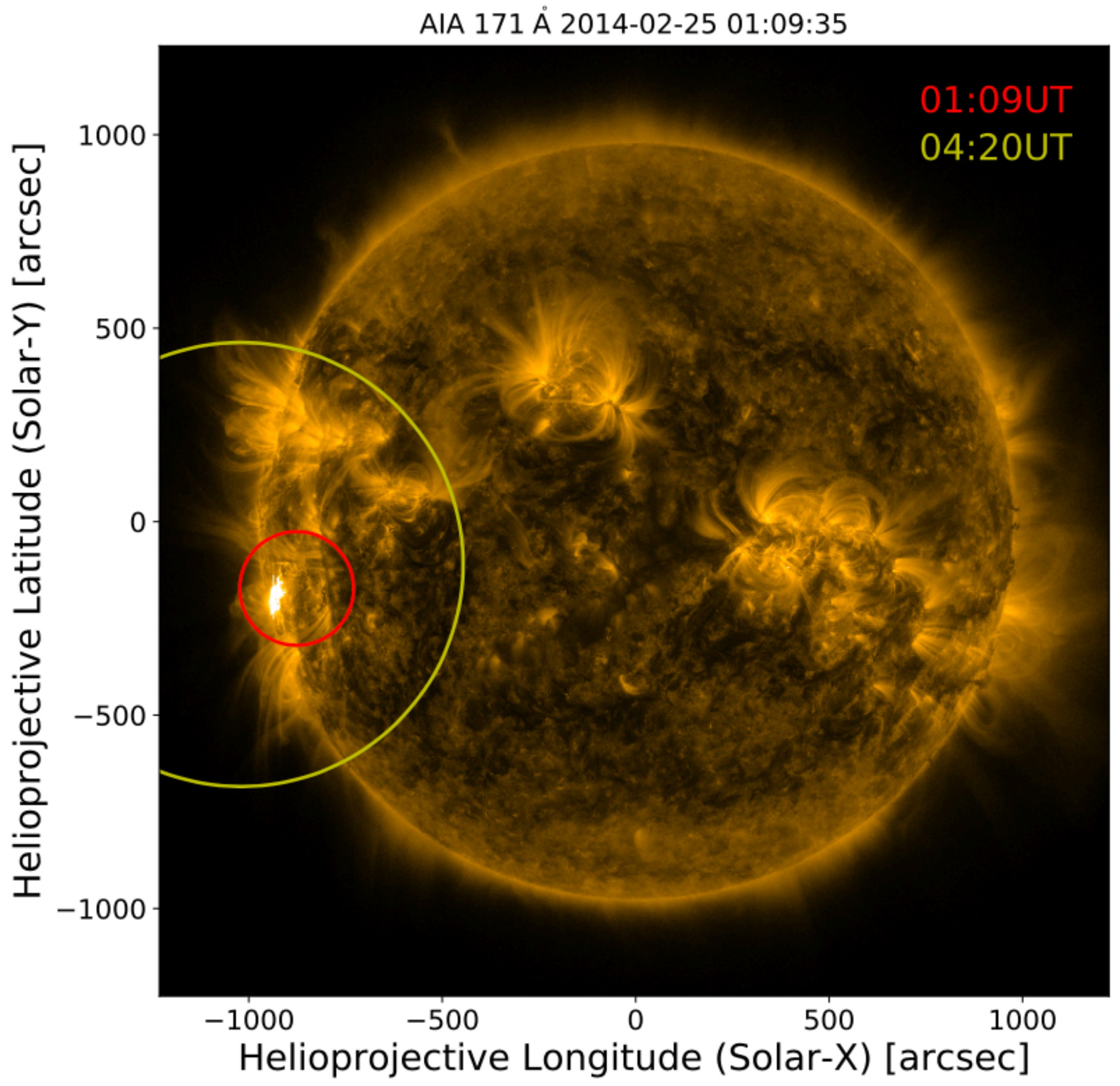


- Correction for fish-eye effect based on Monte Carlo simulations

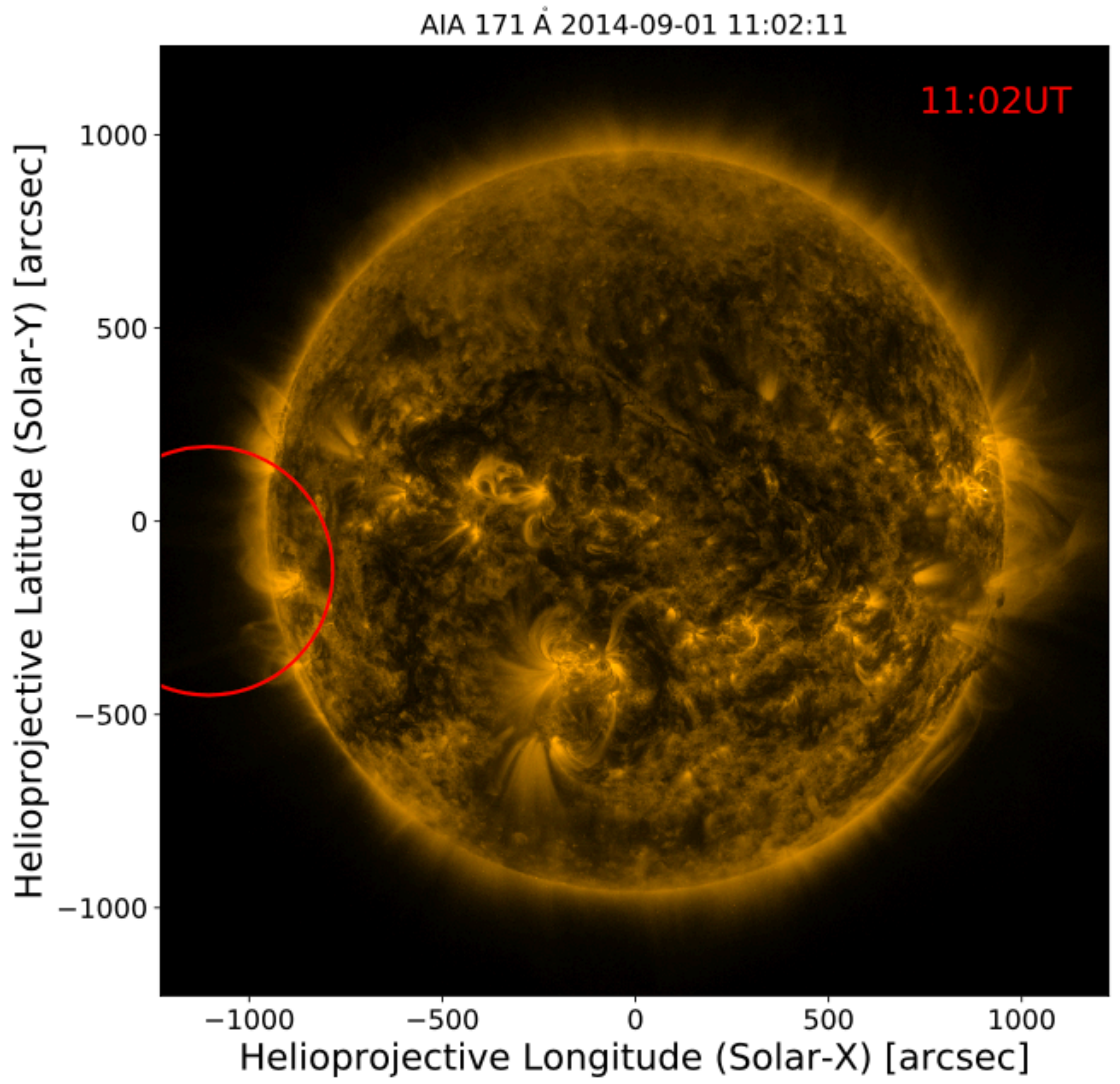


- Late time emission from 2012-03-07 "wonders around”





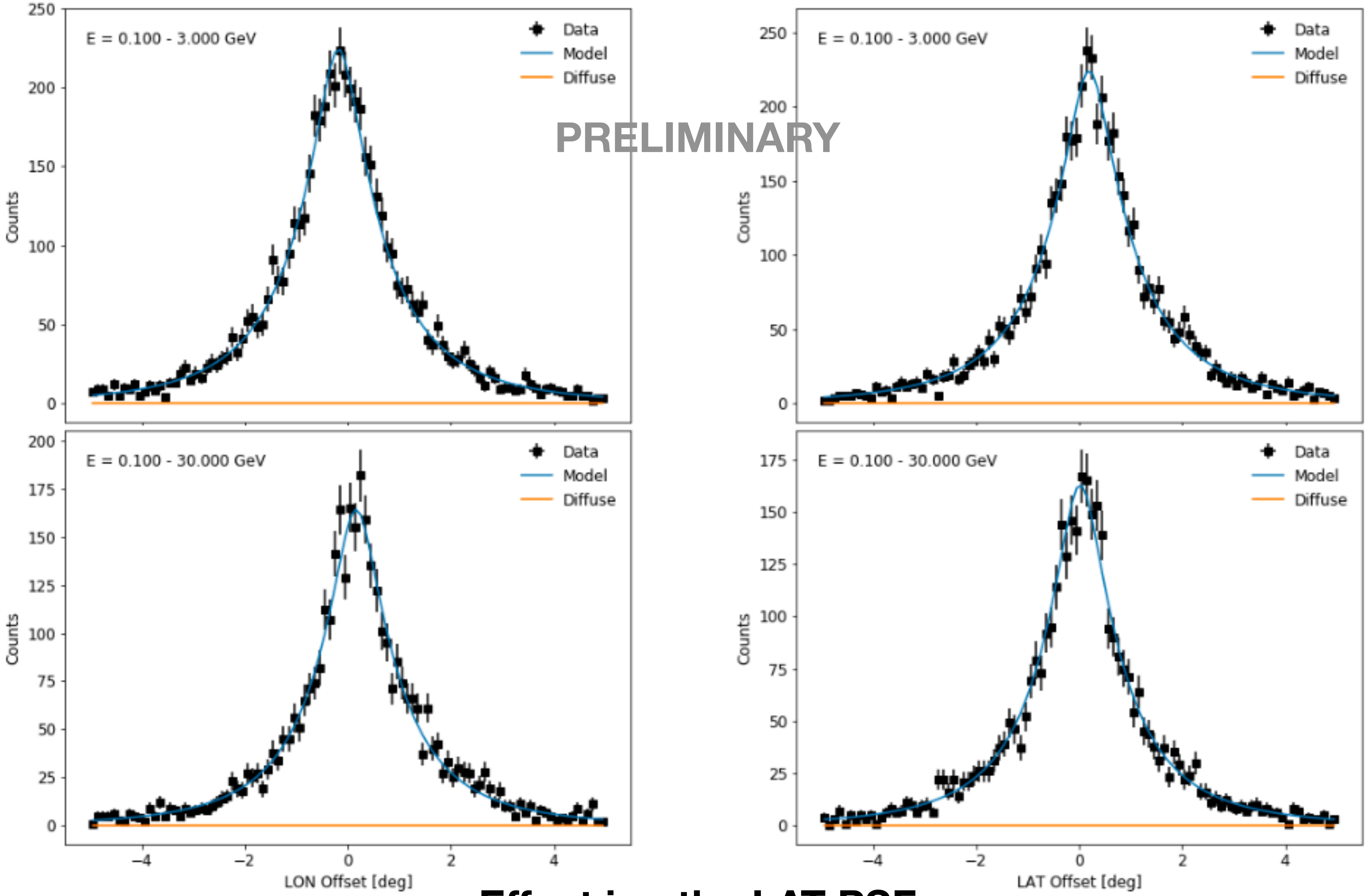
- Location consistent with AR (but on limb!)

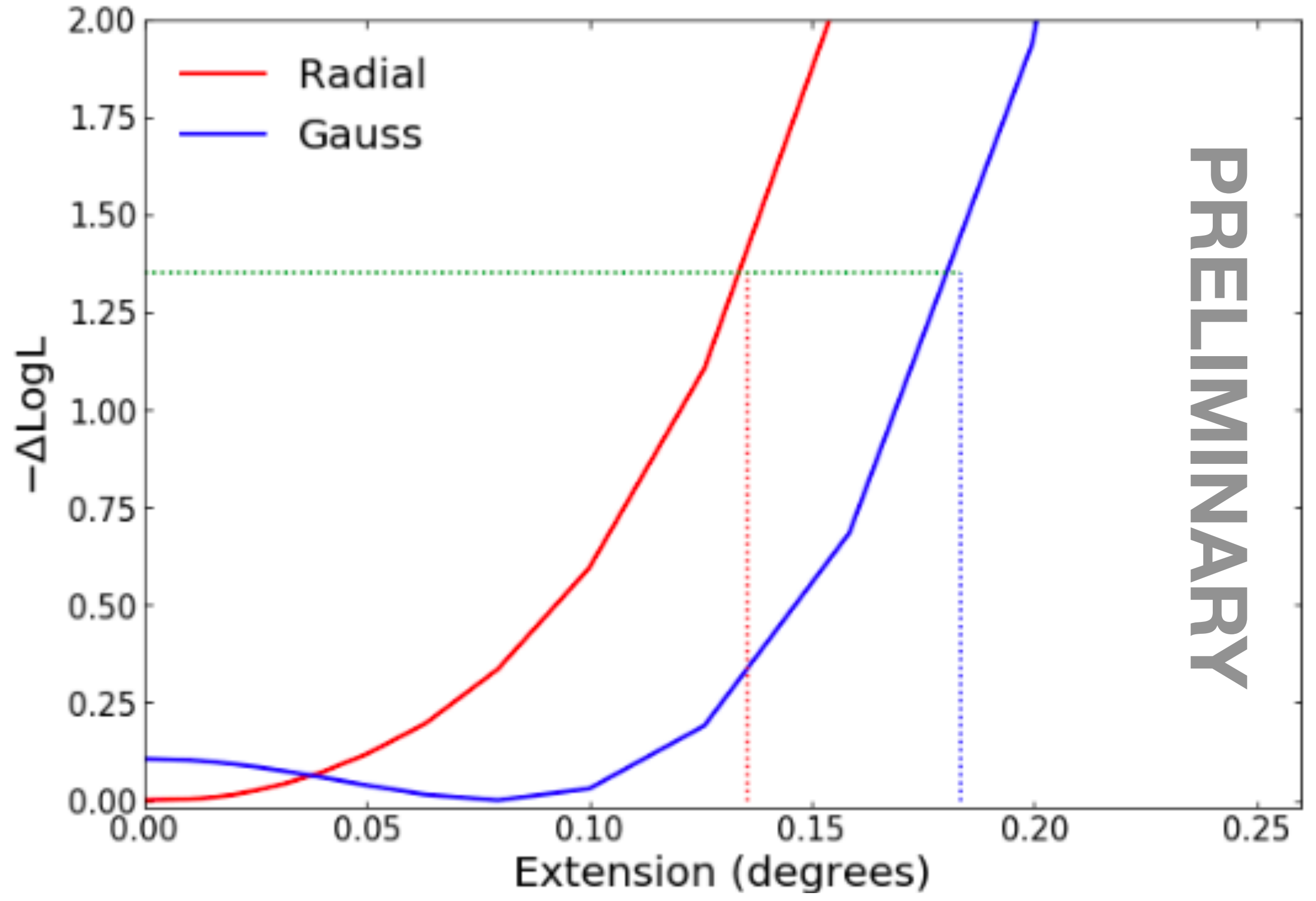


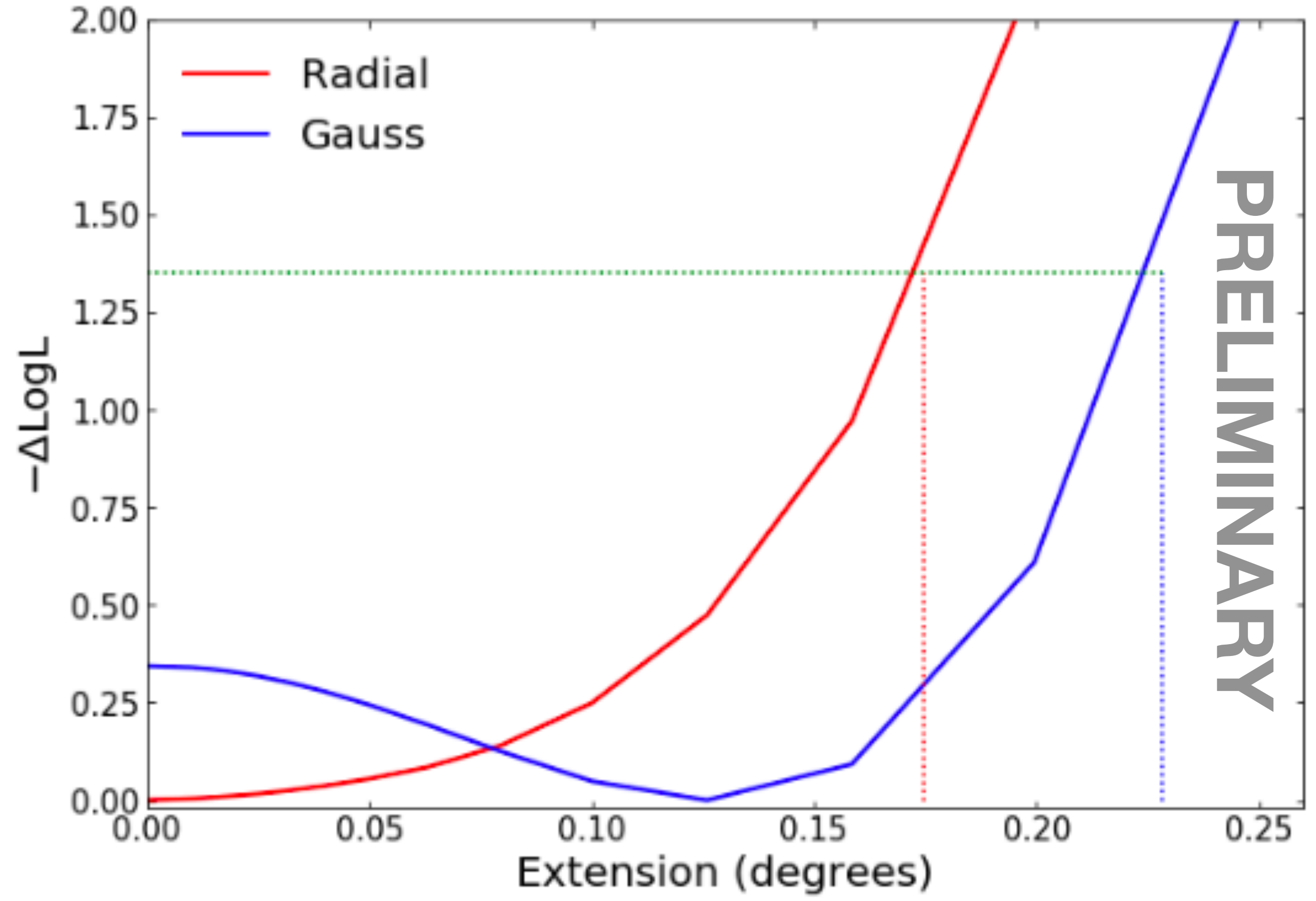
- Updated localization for the BTL flare

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)

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,…**

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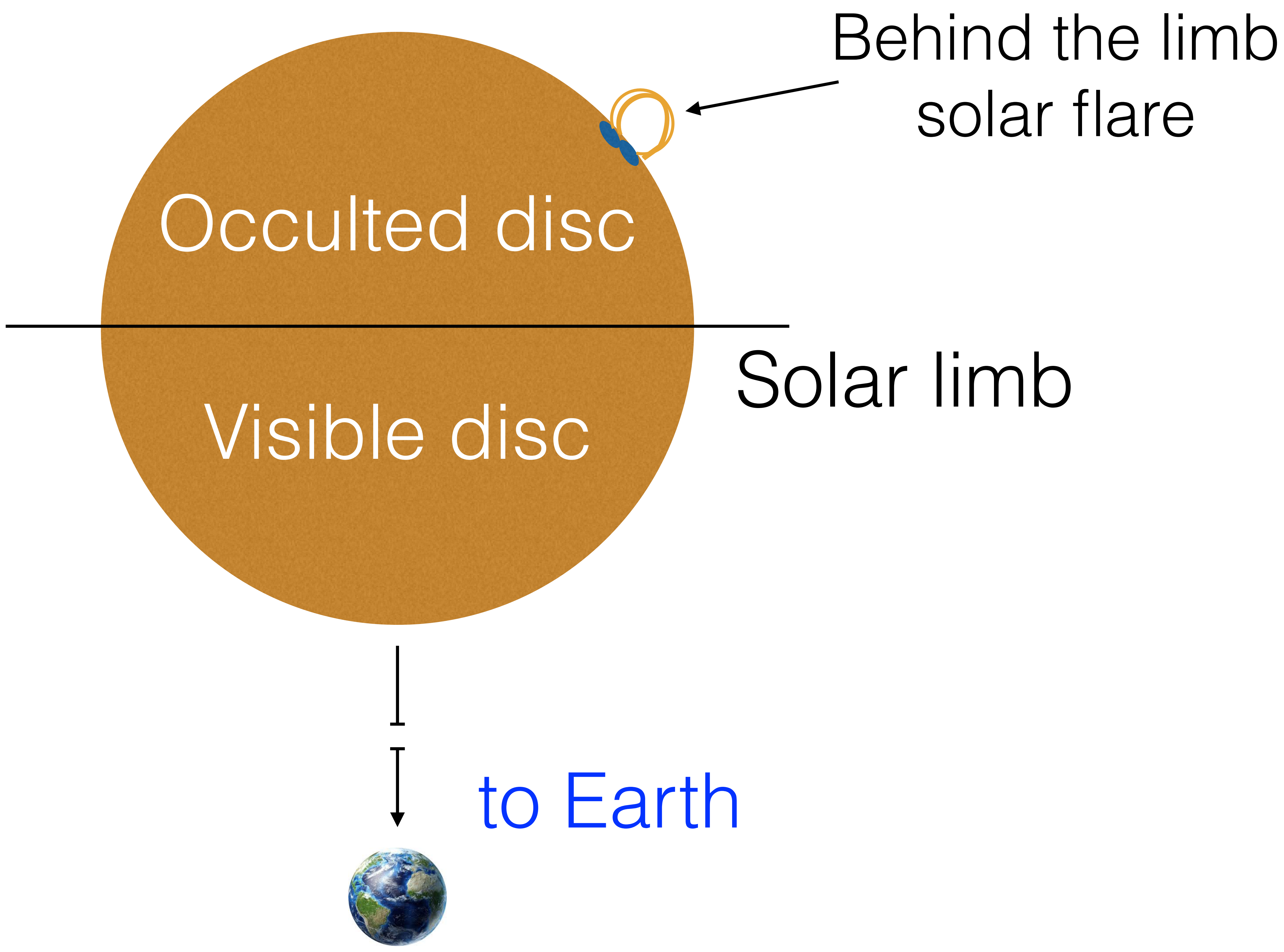

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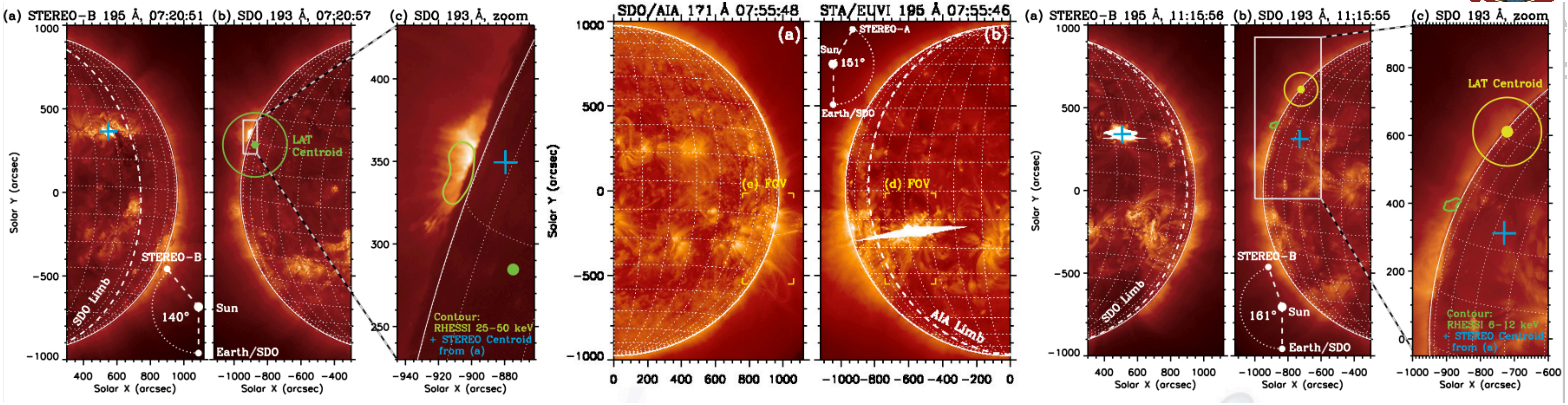
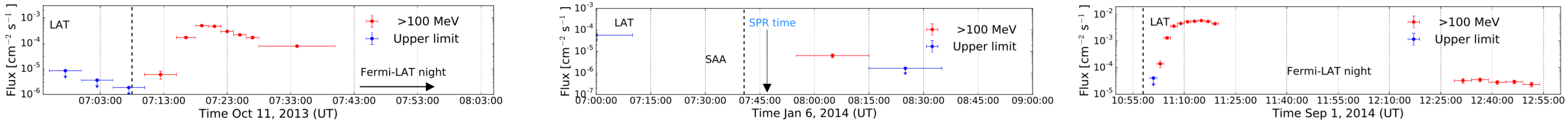




- 10˚ behind the eastern limb;
- RHESSI emission consistent with loop top;

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

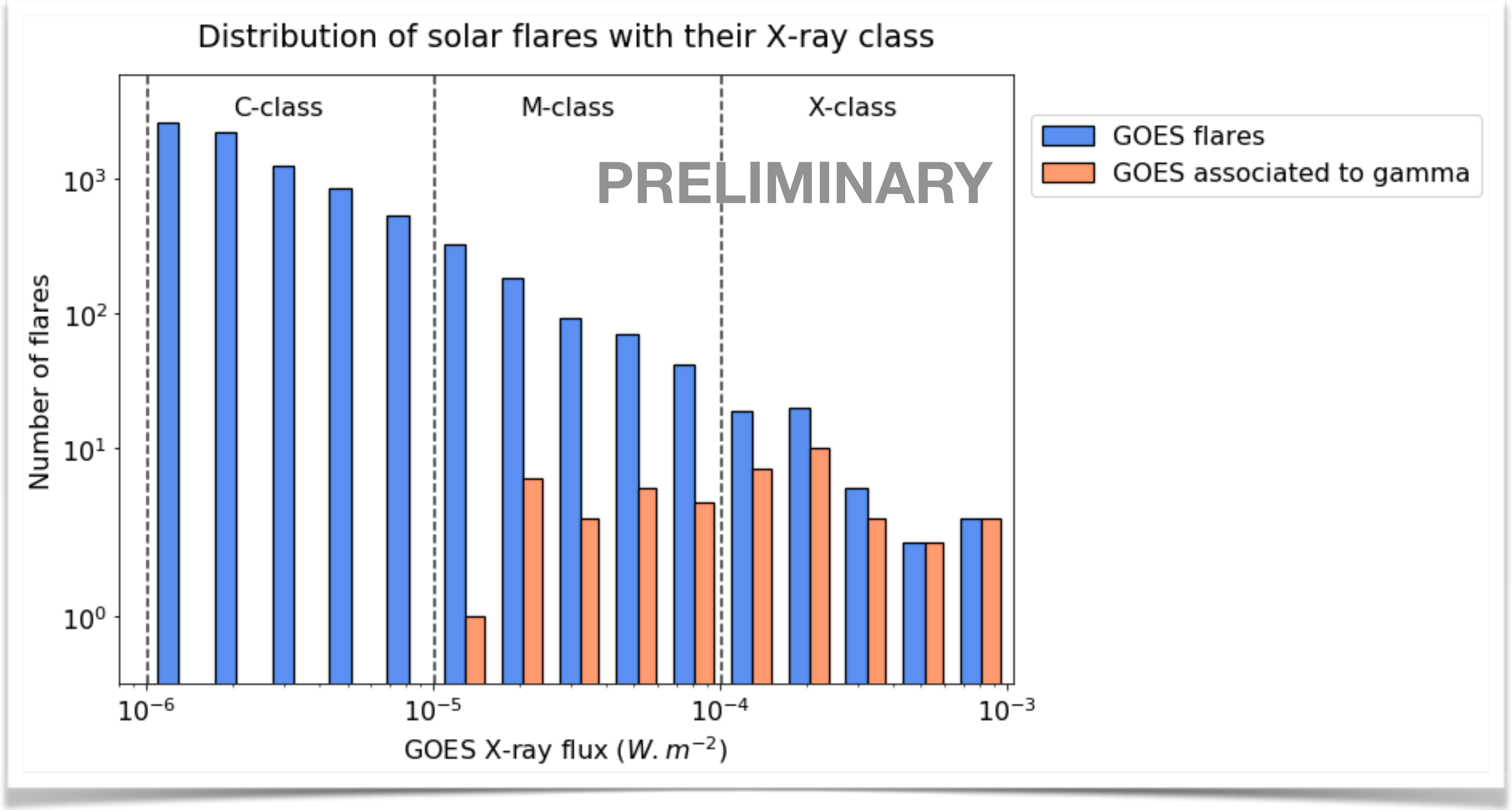
- 43˚ behind the eastern limb;
- Bright LAT emission lasting ~2 hr;

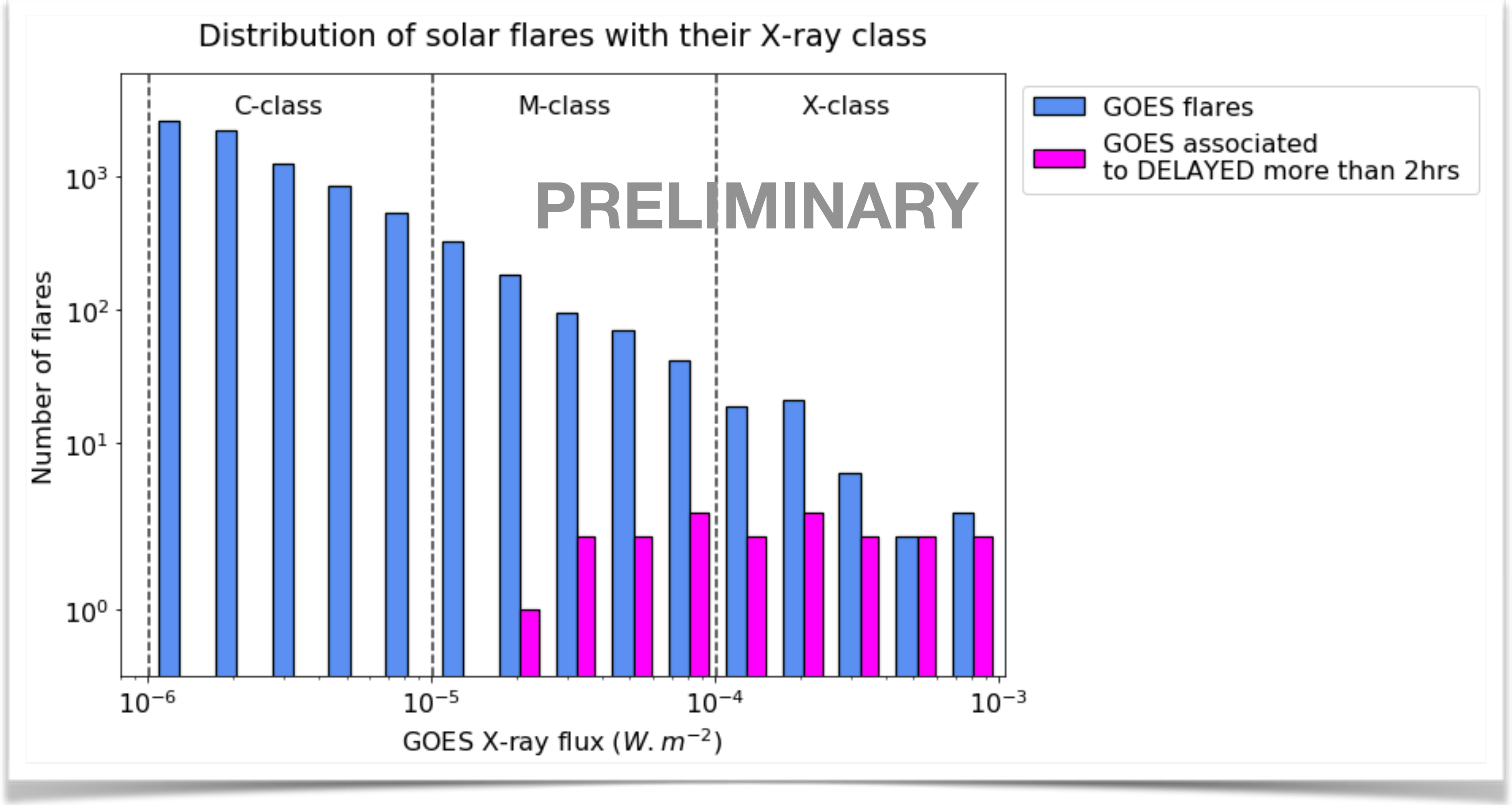
Pesce Rollins et al. 2015, Ackermann et al., 2017

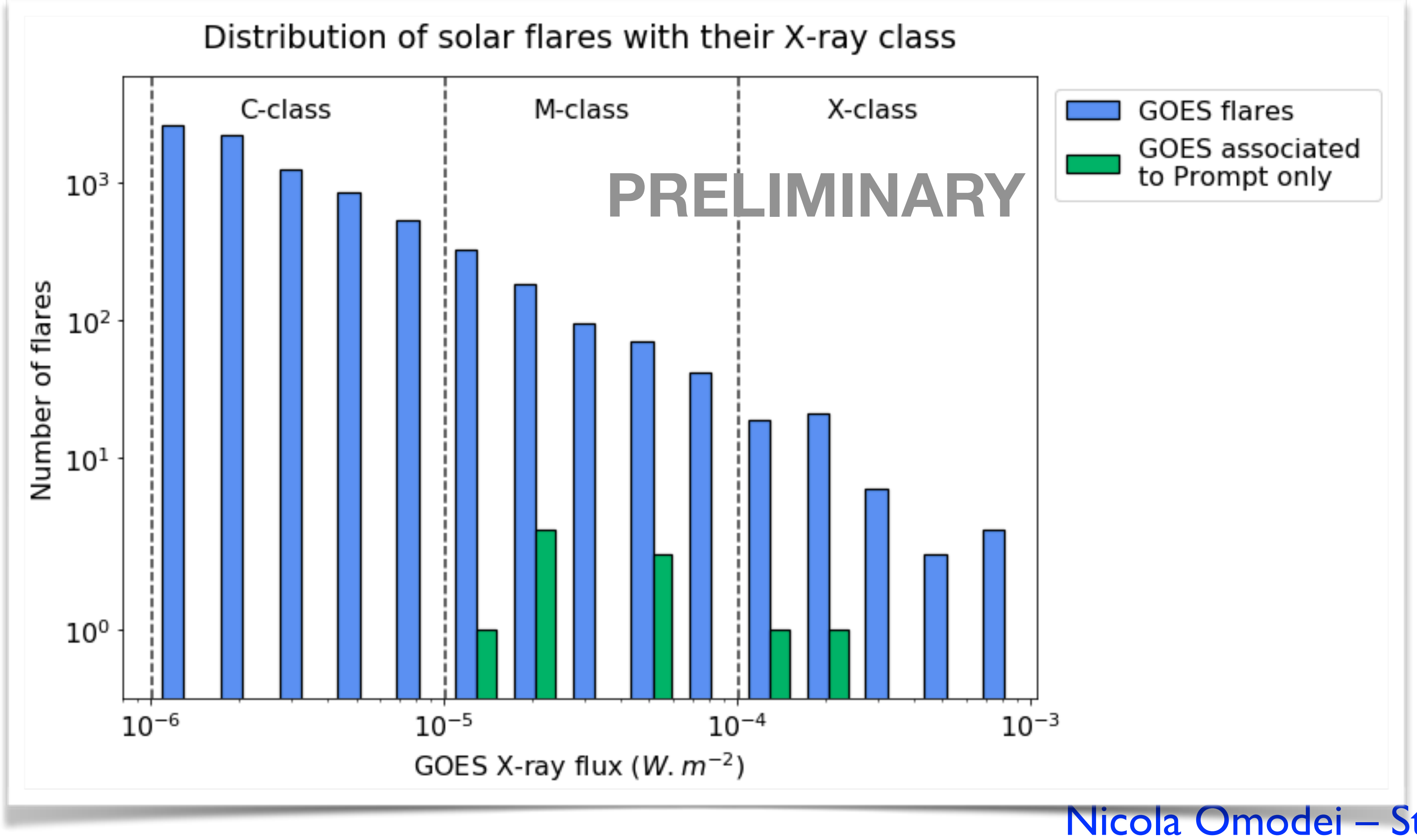
Population studies and correlations with other catalogs

Connection with GOES flares

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



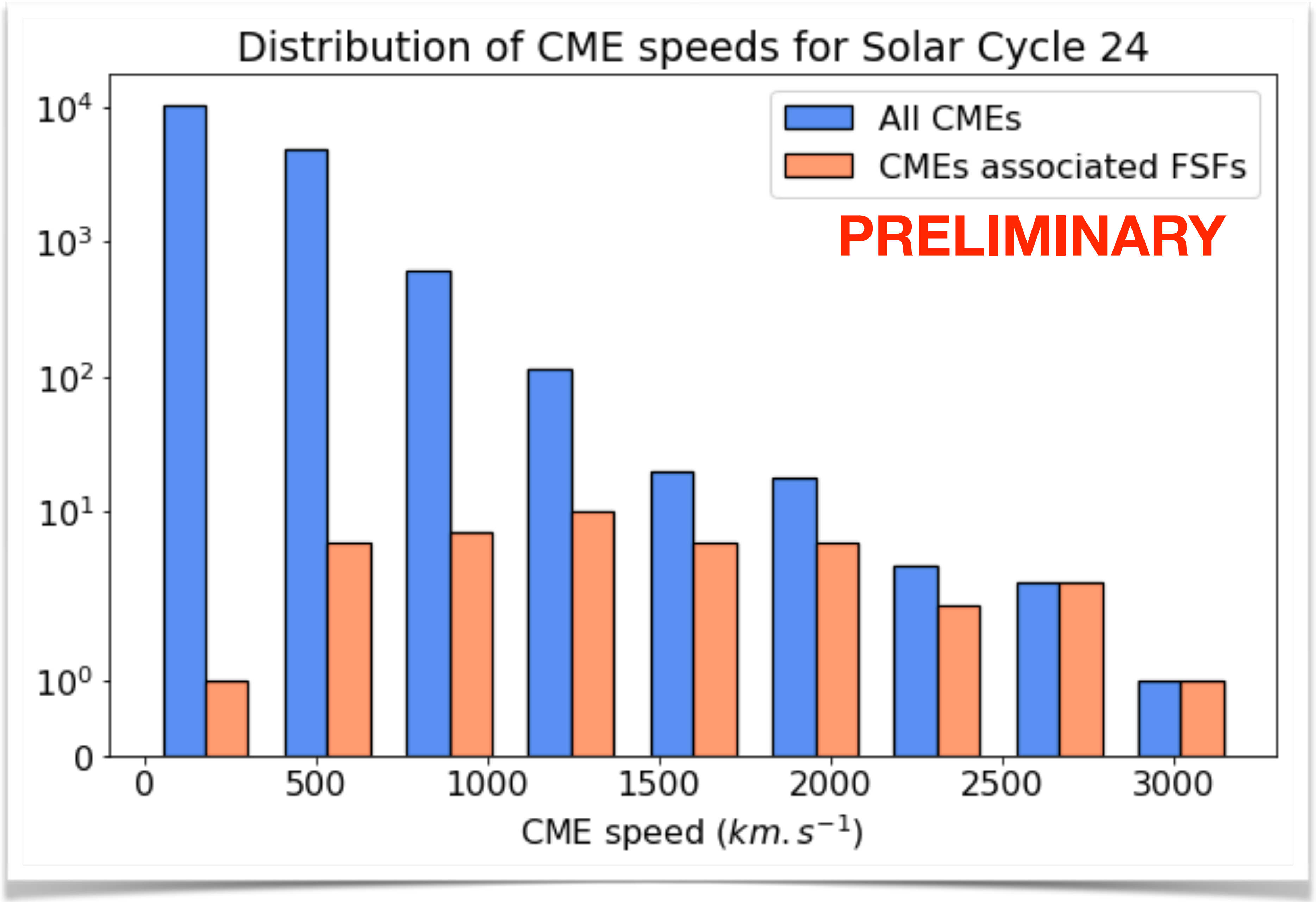




There doesn't seem to be any strong requirement on the GOES flare flux for a FLSF delayed or prompt

Connection with CMEs

Only 3 FLSF not associated to CMEs

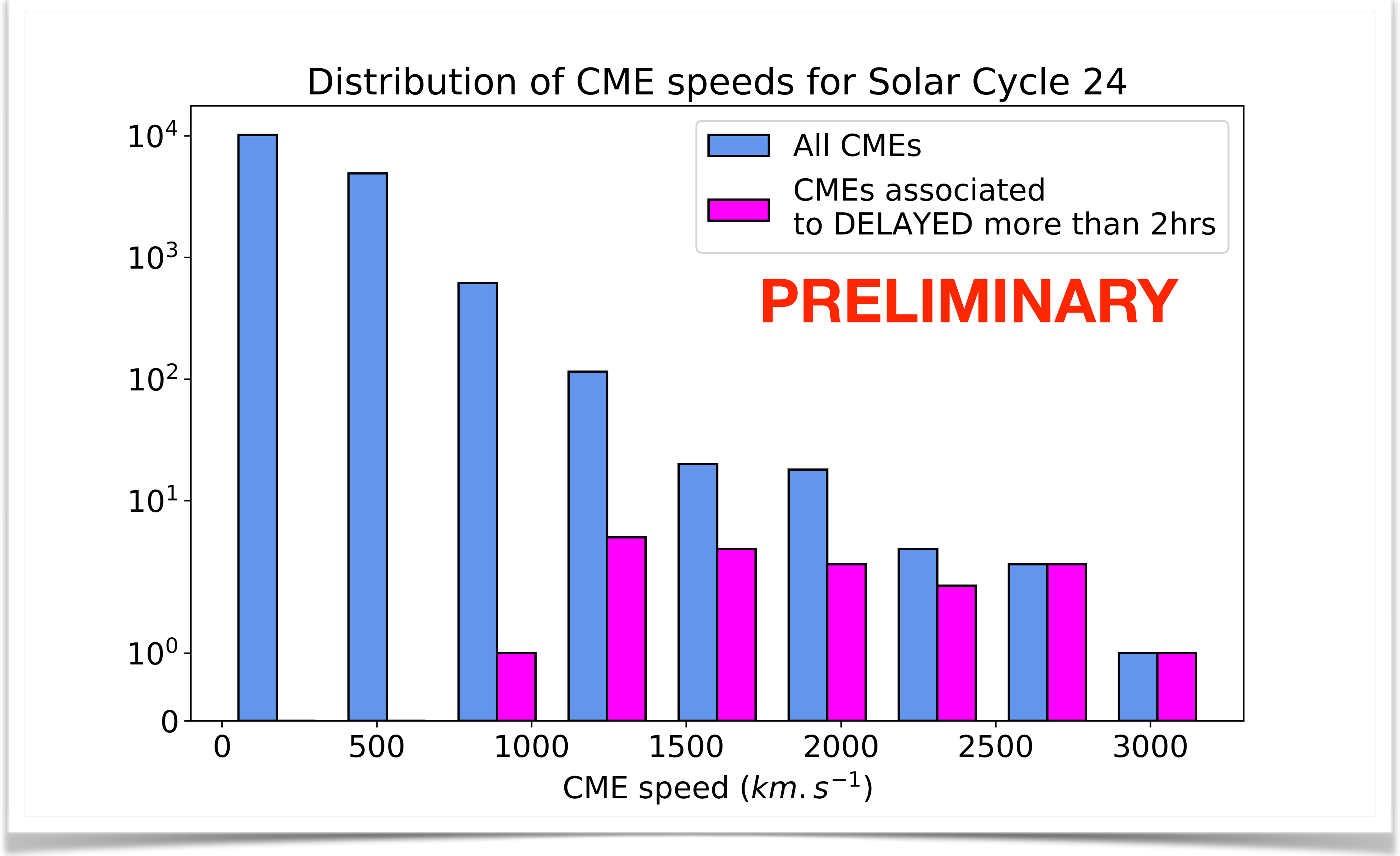


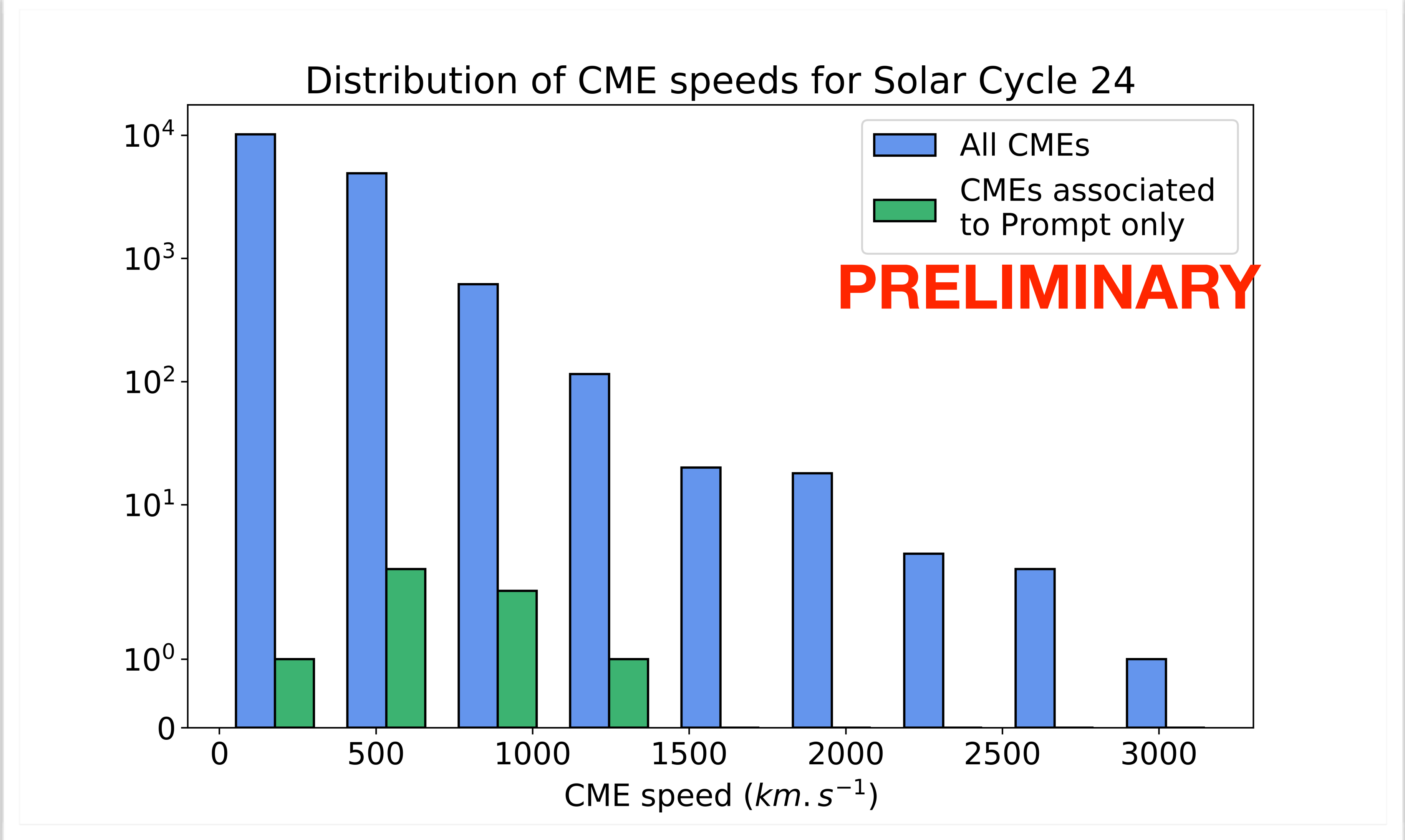
Most are Halo CMEs (all for fast CMEs)

Best predictor:

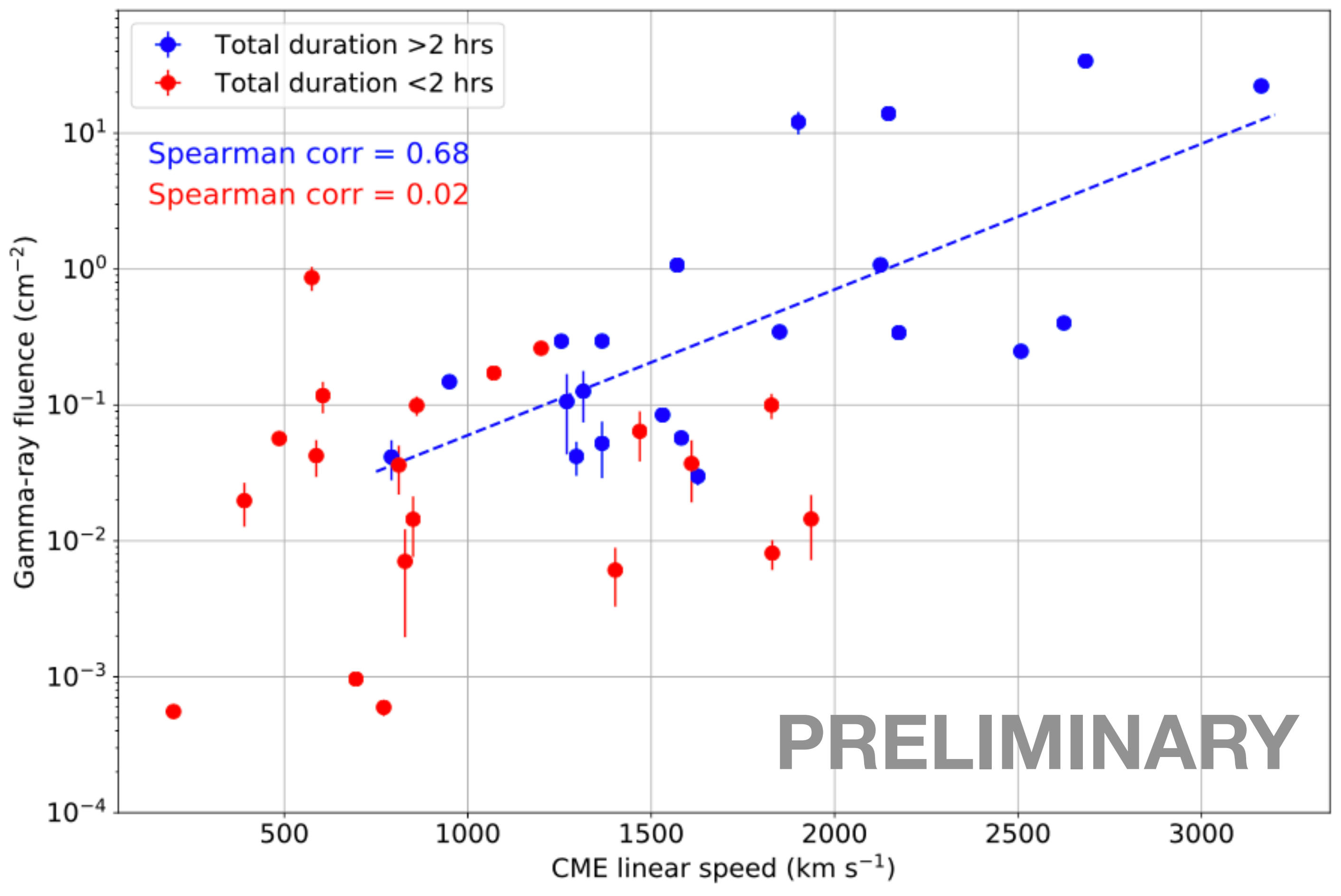
Delay extend beyond two hours

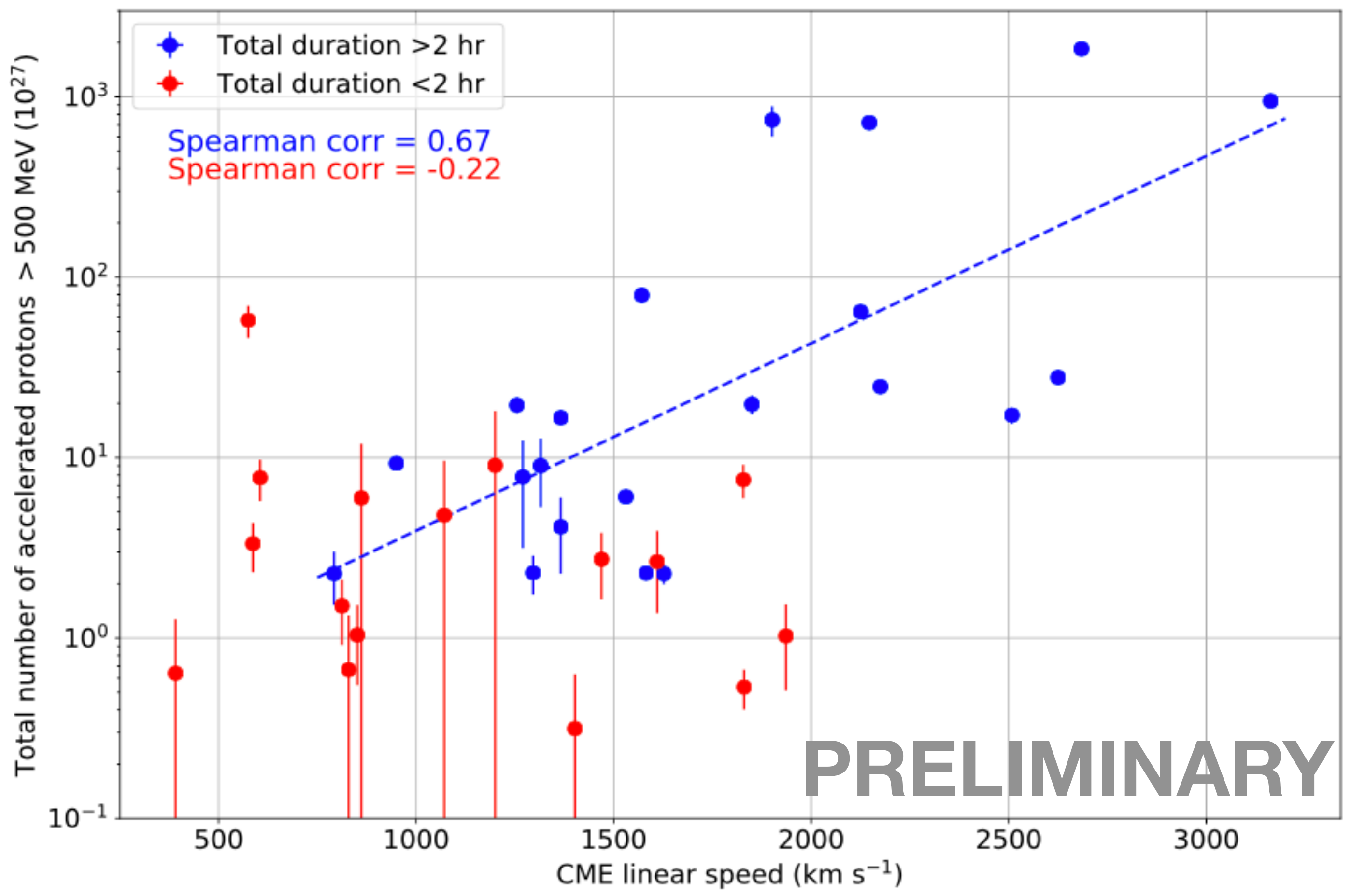
Definite trend for long delayed FLSF to be associated to faster CME

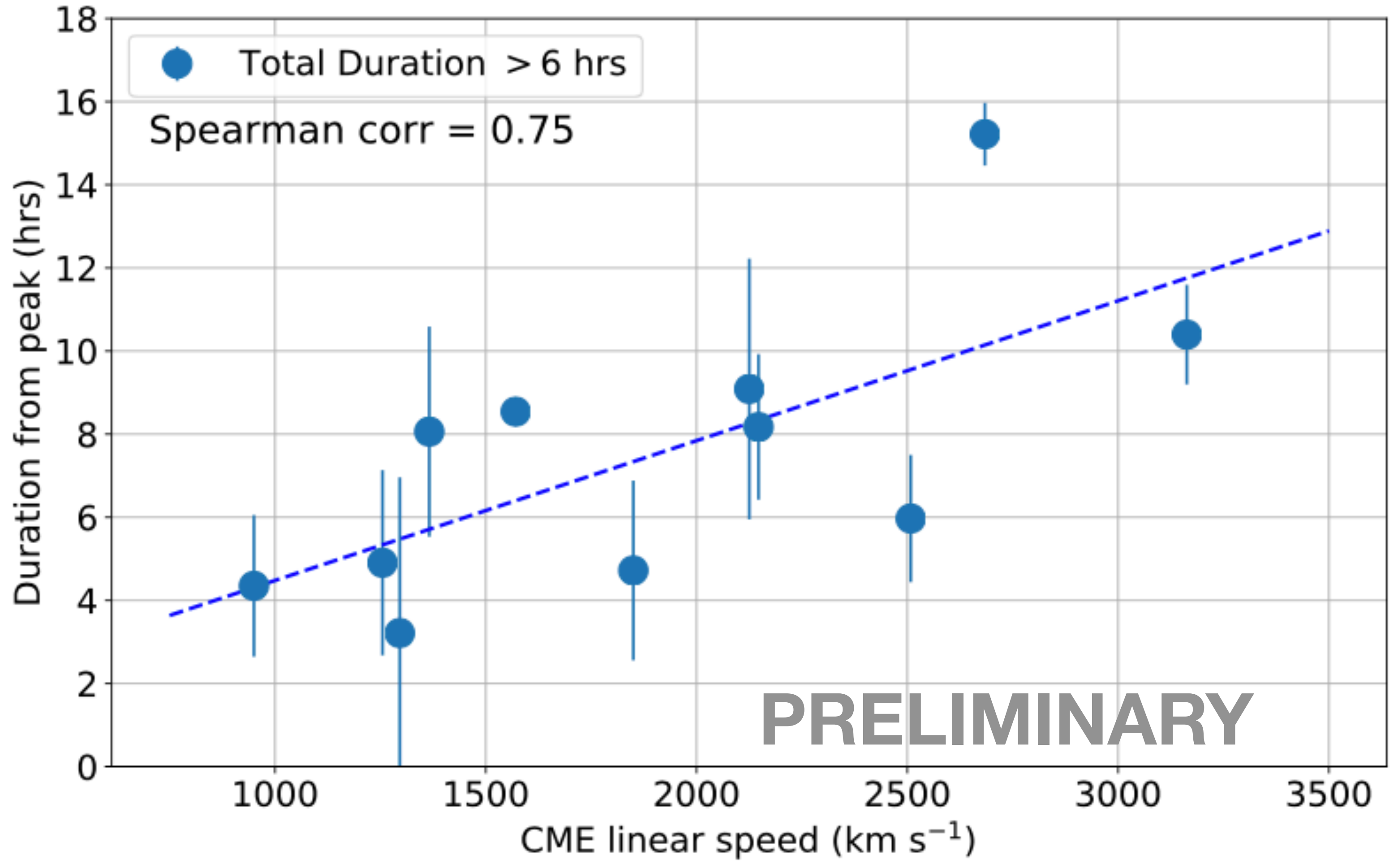




Correlation with CME properties

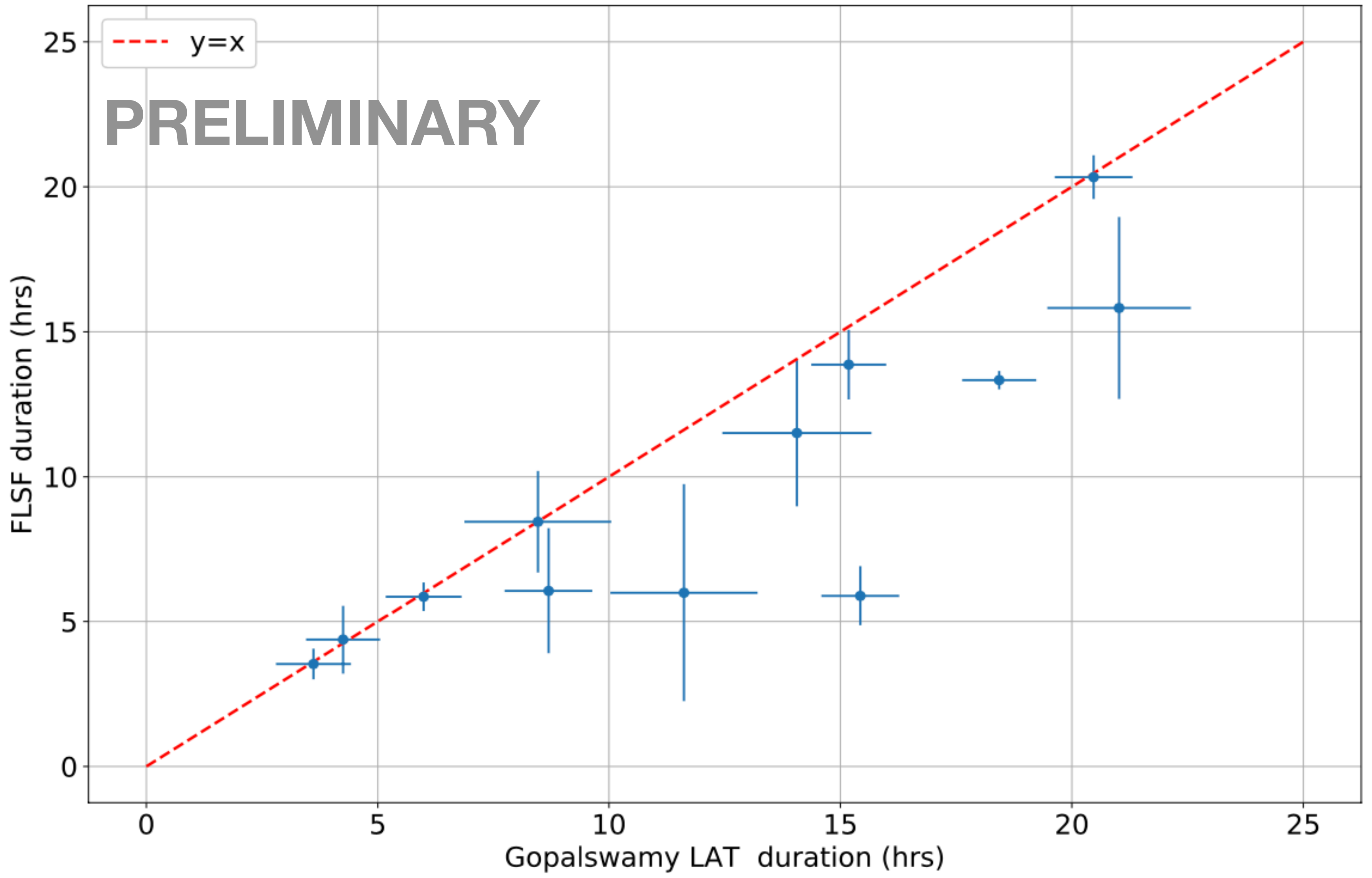


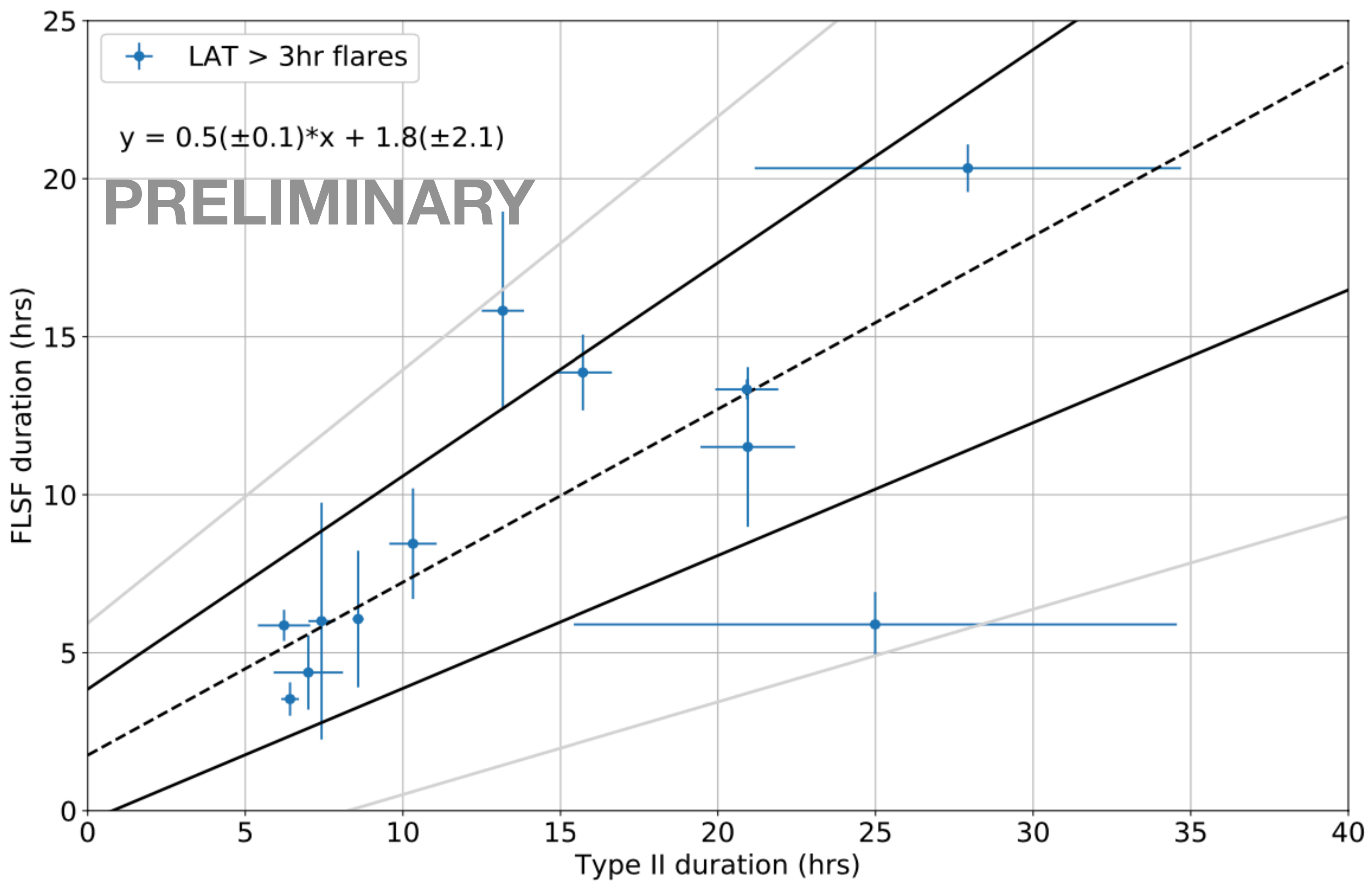




- **CME speed drives duration and energetics in long duration Fermi LAT solar flares**

Connection with type II radio bursts





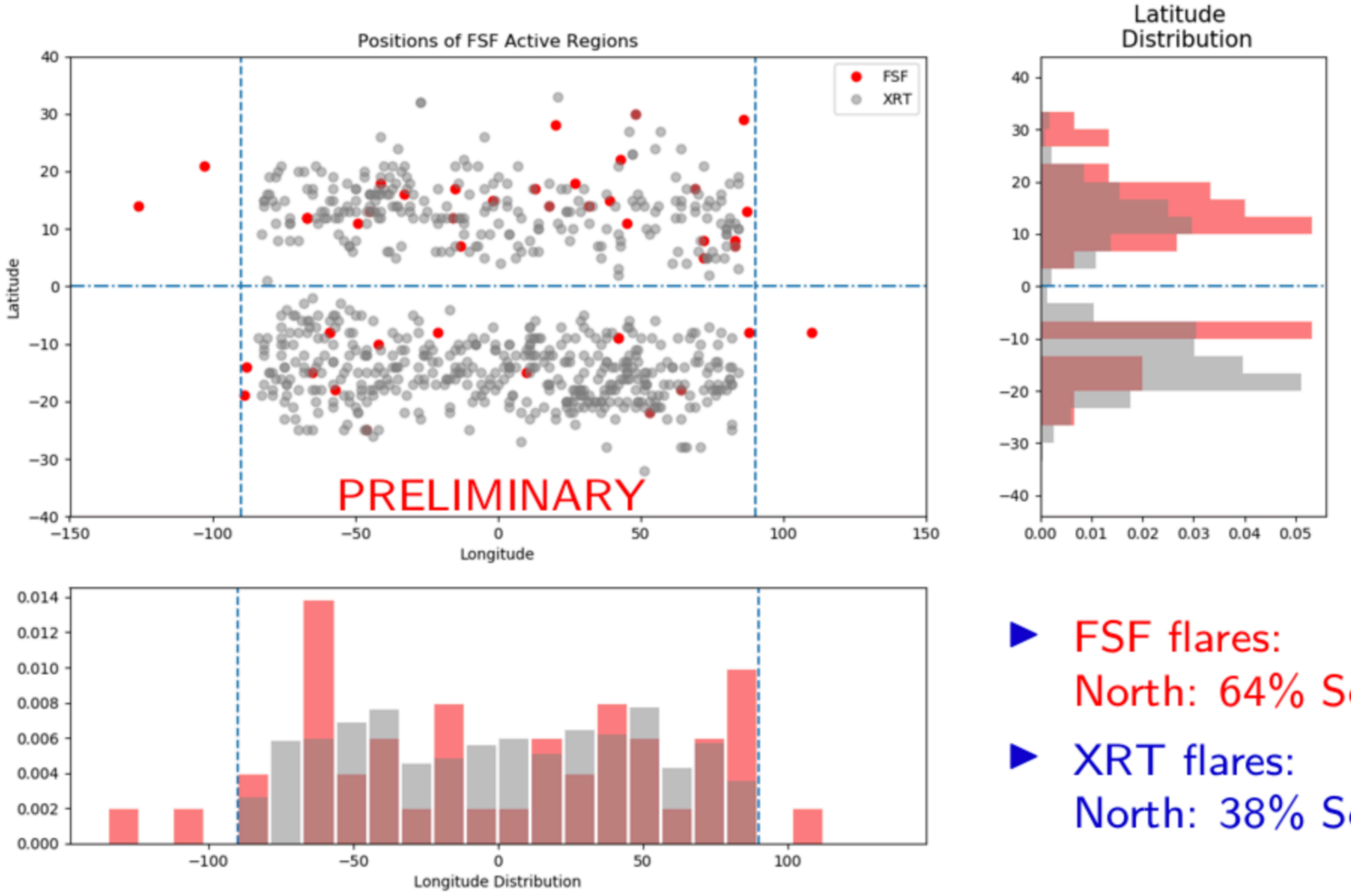
If the gamma-ray production is associated with CME shock, a tight correlation between type II radio burst and gamma-ray propertied should exist.

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:

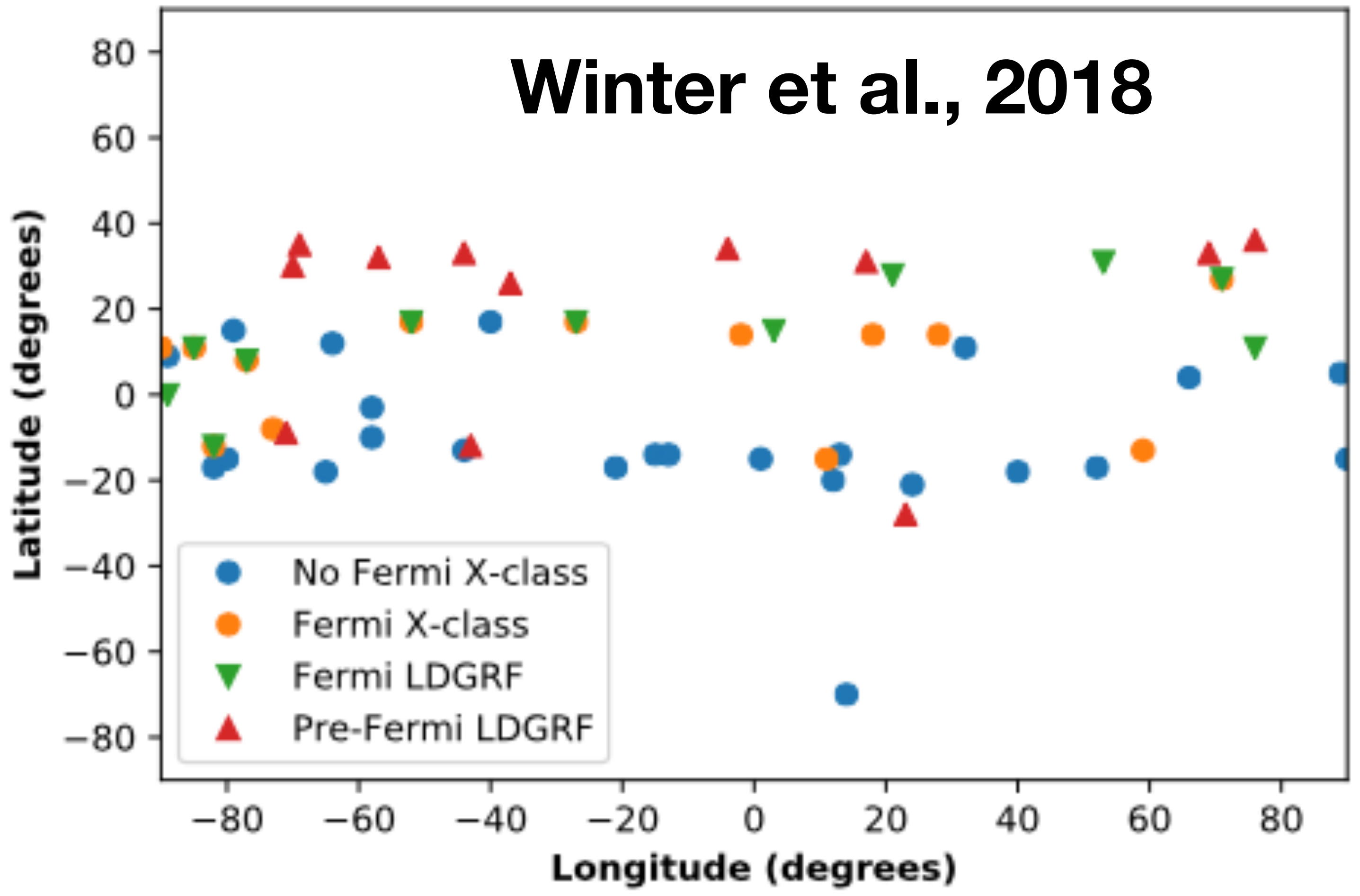
– The resulting best fit line has a softer slope of 0.5±0.1 compared to the 0.9±0.1 reported in Gopalswamy et al. (2018).

Distribution of the FLSF active regions



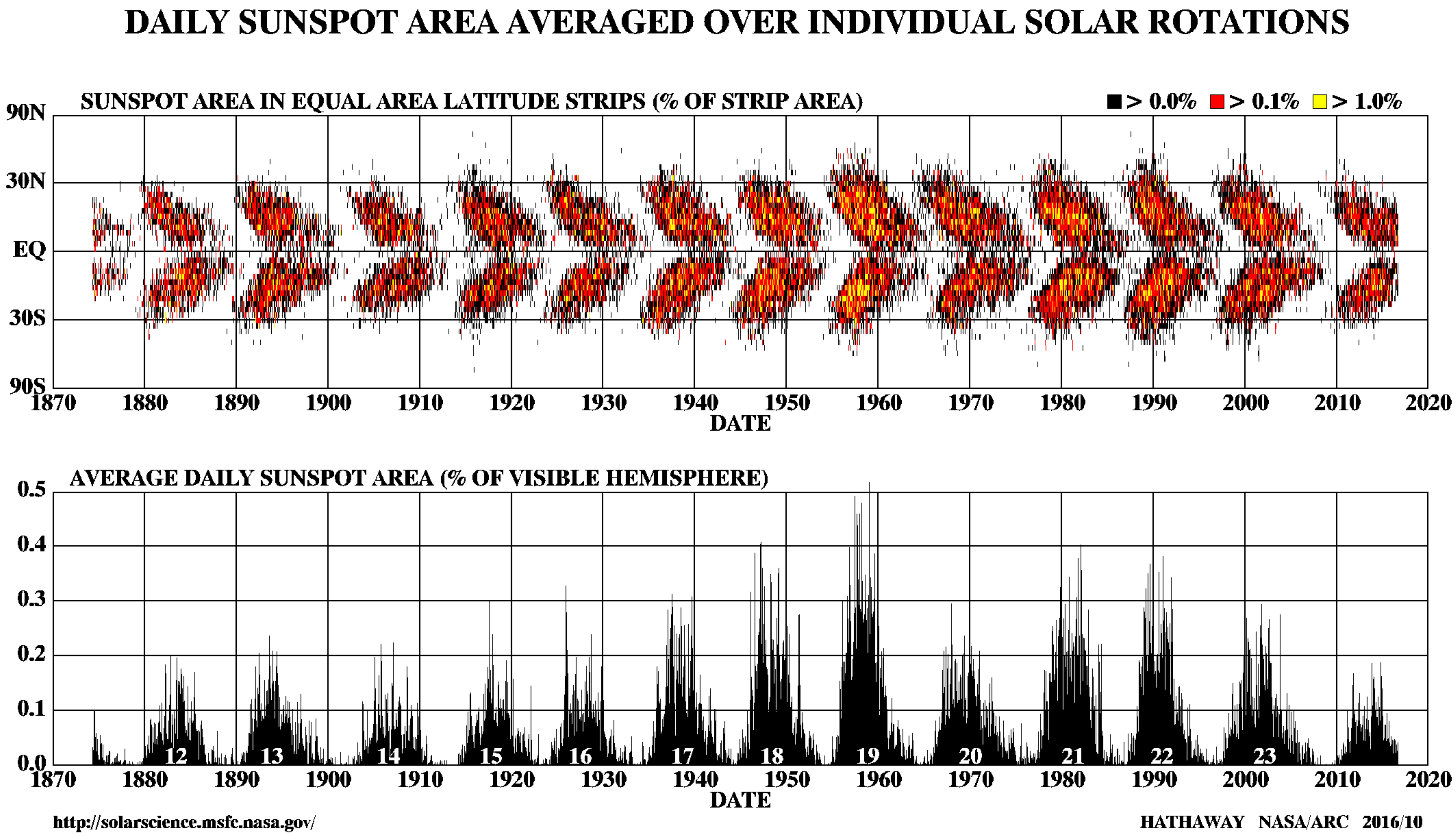
- **North/South asymmetry:** It is known that the distribution of AR shows an asymmetry with one hemisphere dominating at a given time
  - **Opposite in X-rays and gamma-rays!**

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

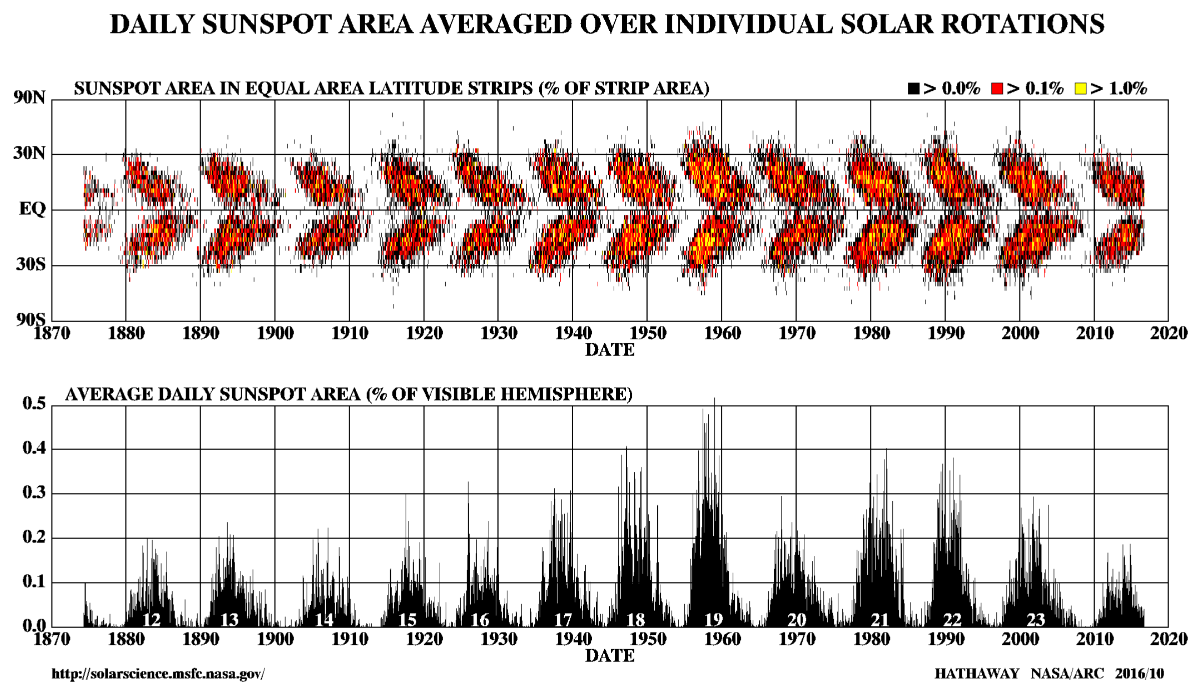


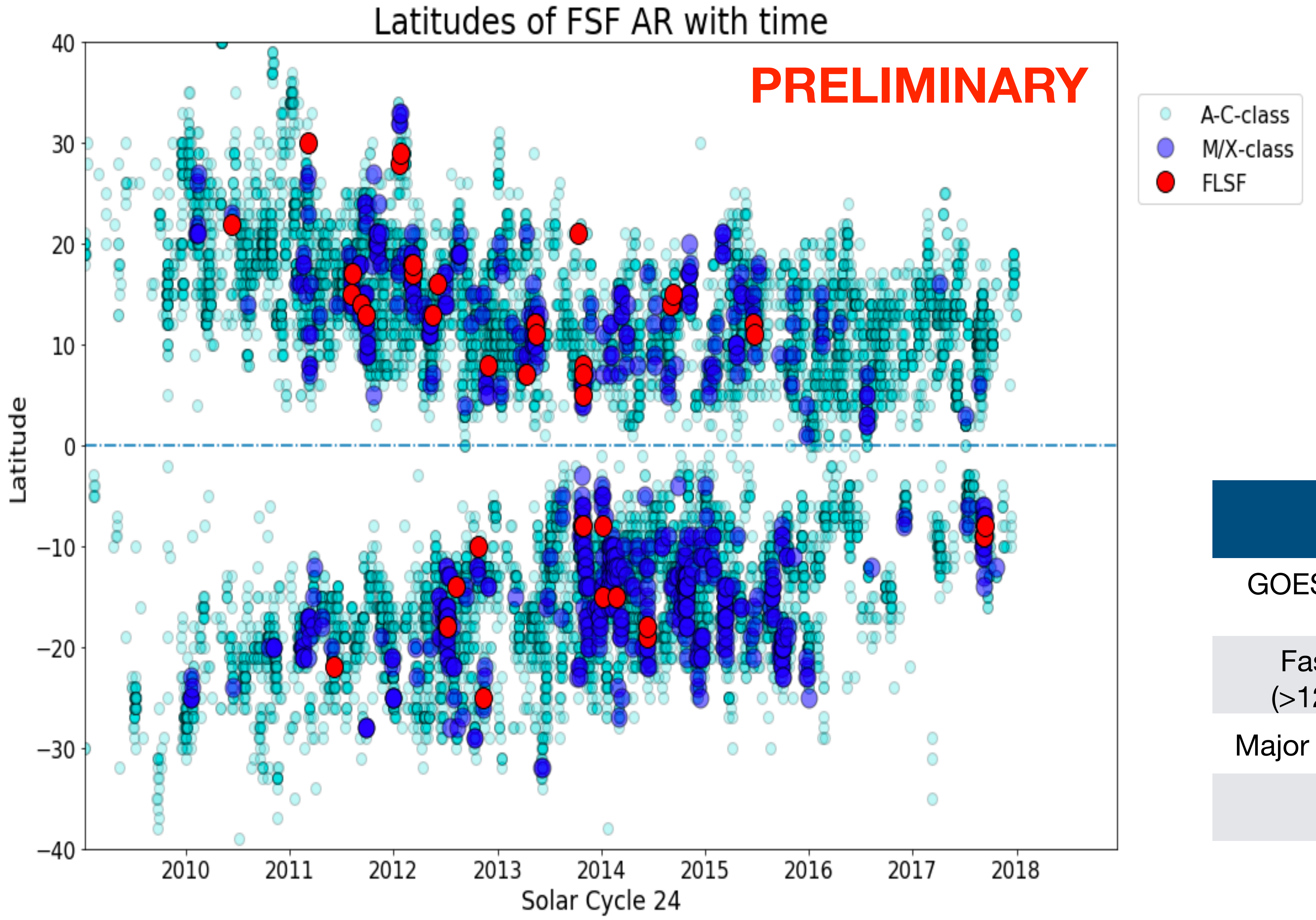
- **Longitude distribution:** Deficit at the disk center: Gamma-ray production beamed?

The “butterfly effect” as seen by Fermi LAT

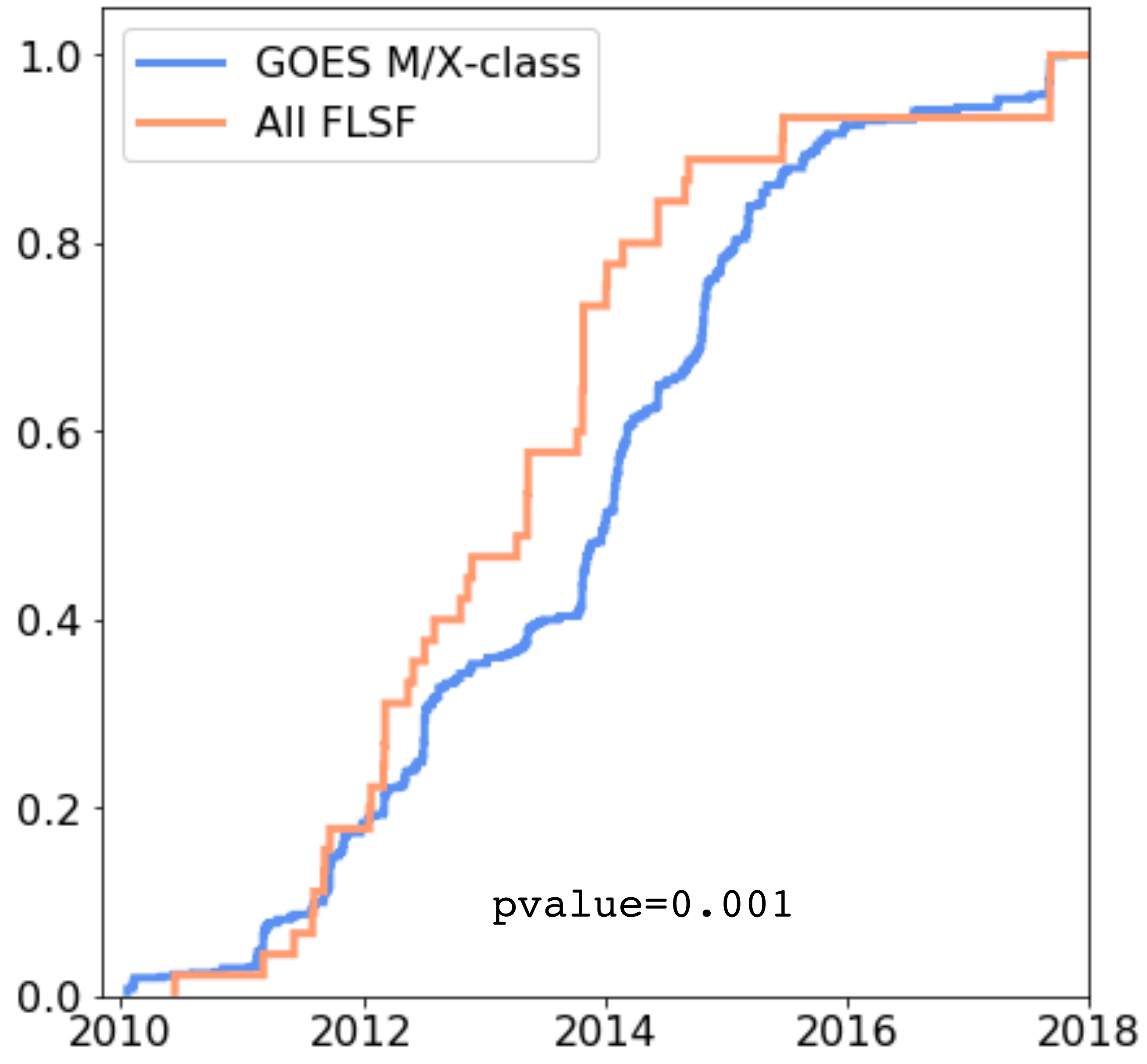


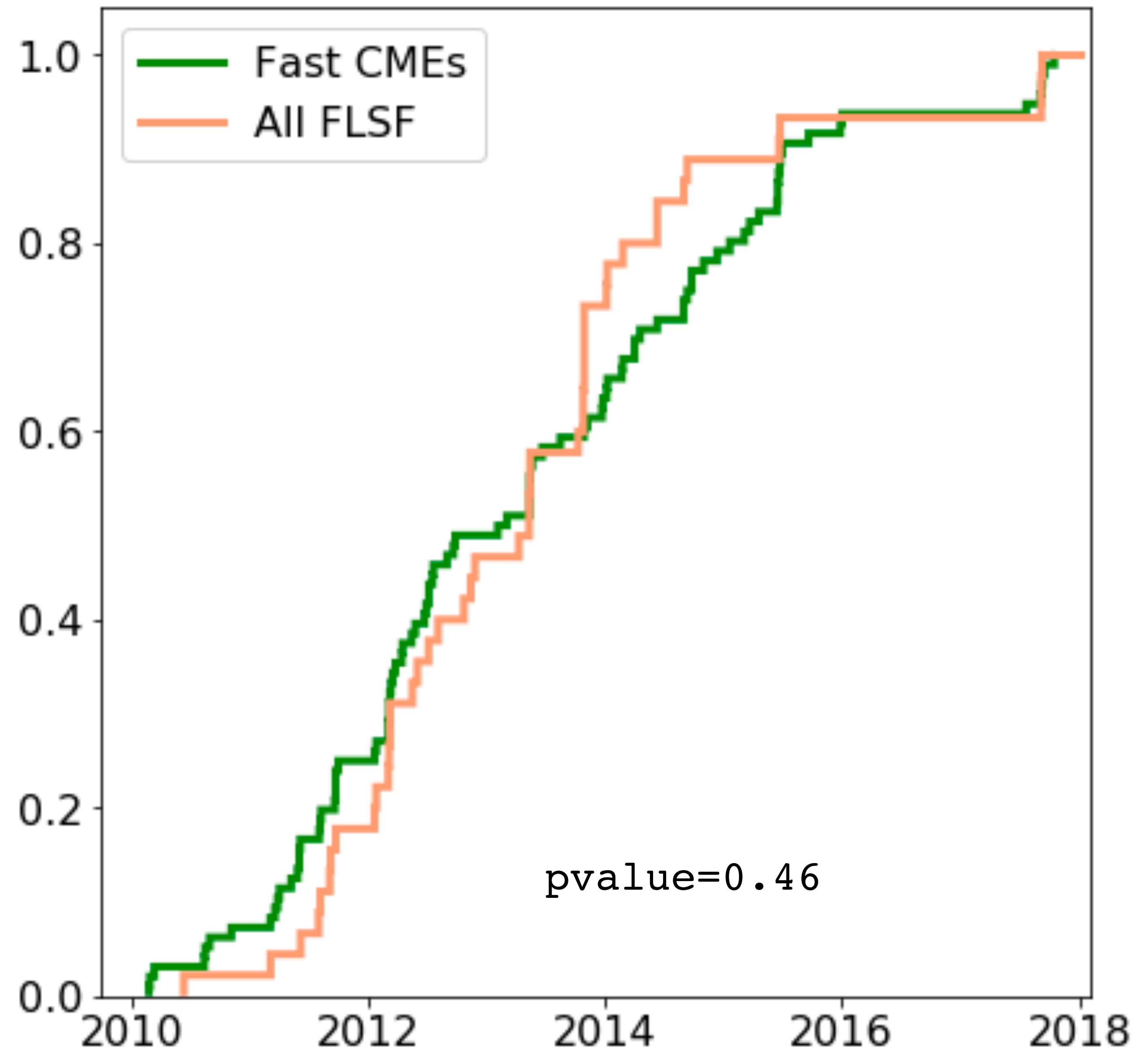
The "butterfly effect" as seen by Fermi LAT





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 (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)

- Population studies with CME, X-ray flares and Type II radio bursts:
  - 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;
  - Correlation with Type II radio bursts (Gopalswamy et al., 2018) also suggests shock driven acceleration.