
# Fermi LAT Observation of High-Energy Solar Flares

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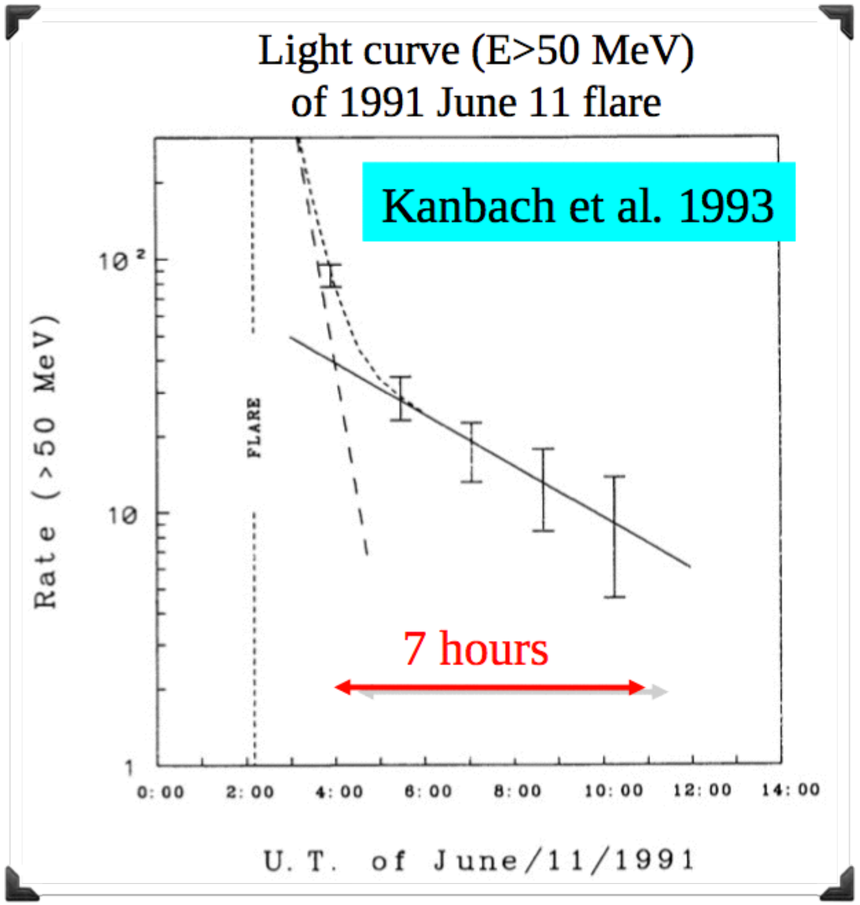
for the Fermi/LAT collaboration


**Solar Energetic Particles (SEP), Solar Modulation and Space Radiation: New Opportunities in the AMS-02 Era #3**

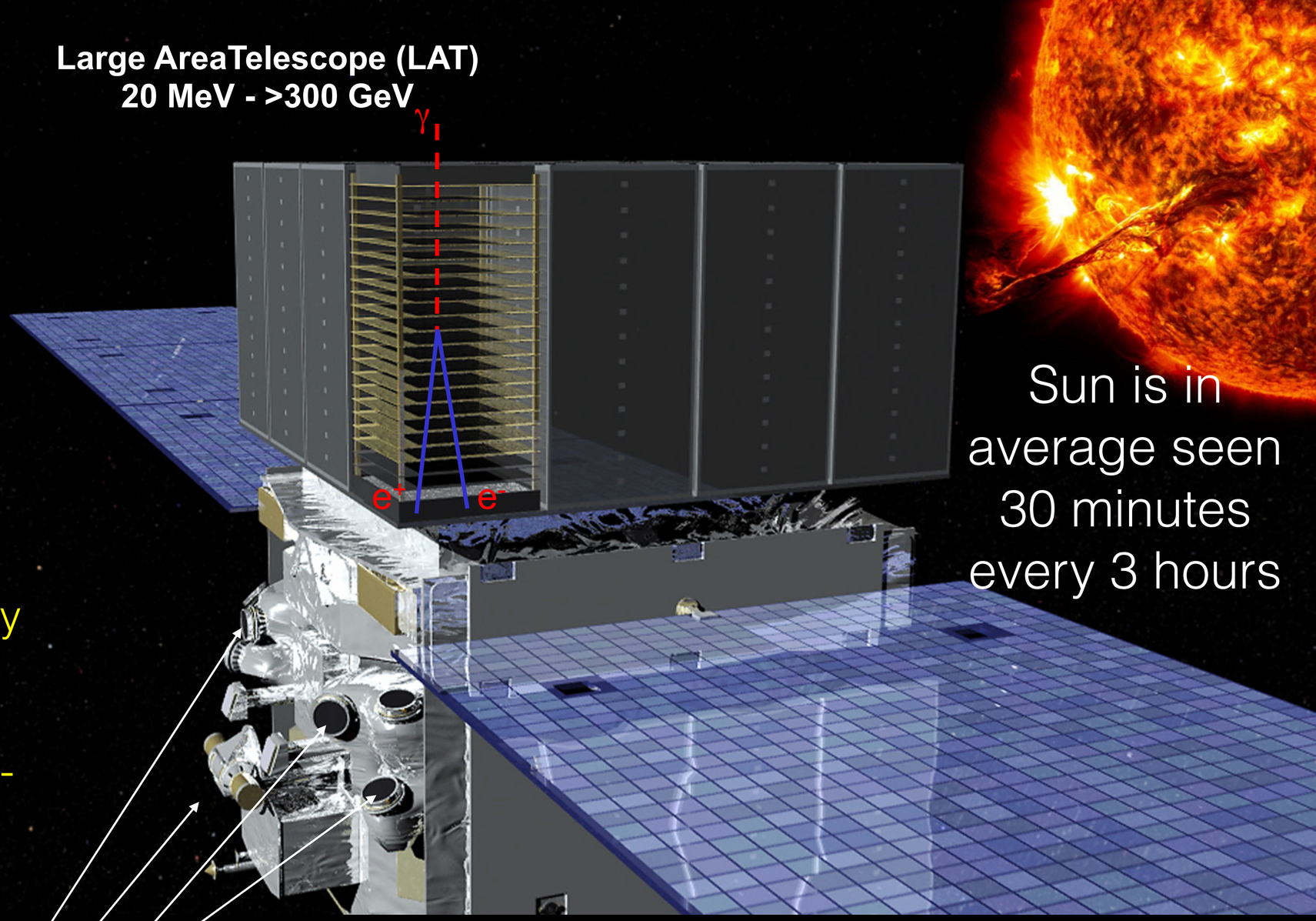
# Gamma-ray emission from the Sun

- **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**



# Fermi-LAT KEY FEATURES

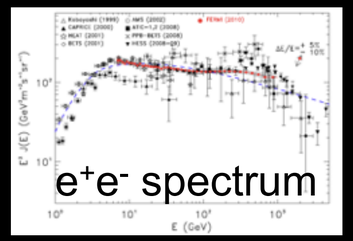
Huge field of view
(LAT: 20% of the sky at any instant)
Good energy resolution
(<15% >100 MeV)
Good Point Spread Function
(~1˚ at 1 GeV)
Large effective area
(>1 GeV is ~8000 $cm^2$ on axis)
GBM: whole *unocculted* sky at any time.
Huge energy range, including largely unexplored band 10 GeV - 100 GeV.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

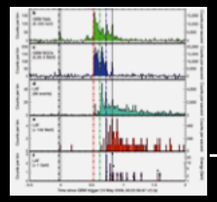



Sun is in average seen 30 minutes every 3 hours

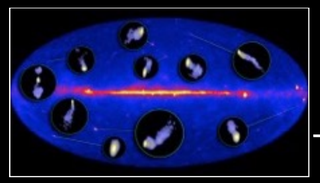
Launched in 2008, continuously monitors the sky

# *Fermi* Highlights and Discoveries

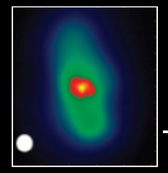


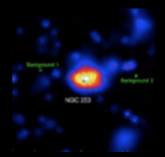
GRBs



Blazars

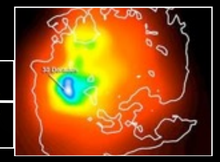


Radio Galaxies

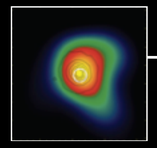


Starburst Galaxies

Extragalactic

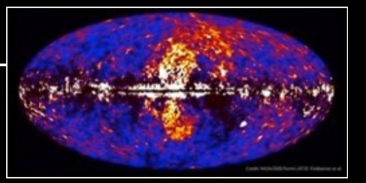


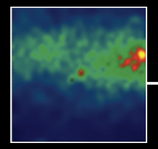
LMC & SMC



Globular Clusters

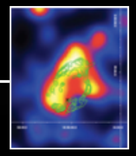
Fermi Bubbles

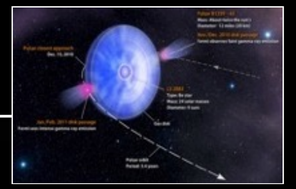




Nova

SNRs & PWN

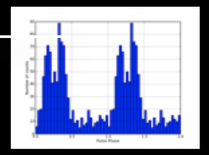




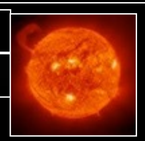
Galactic

γ-ray Binaries

Pulsars: isolated, binaries, & MSPs



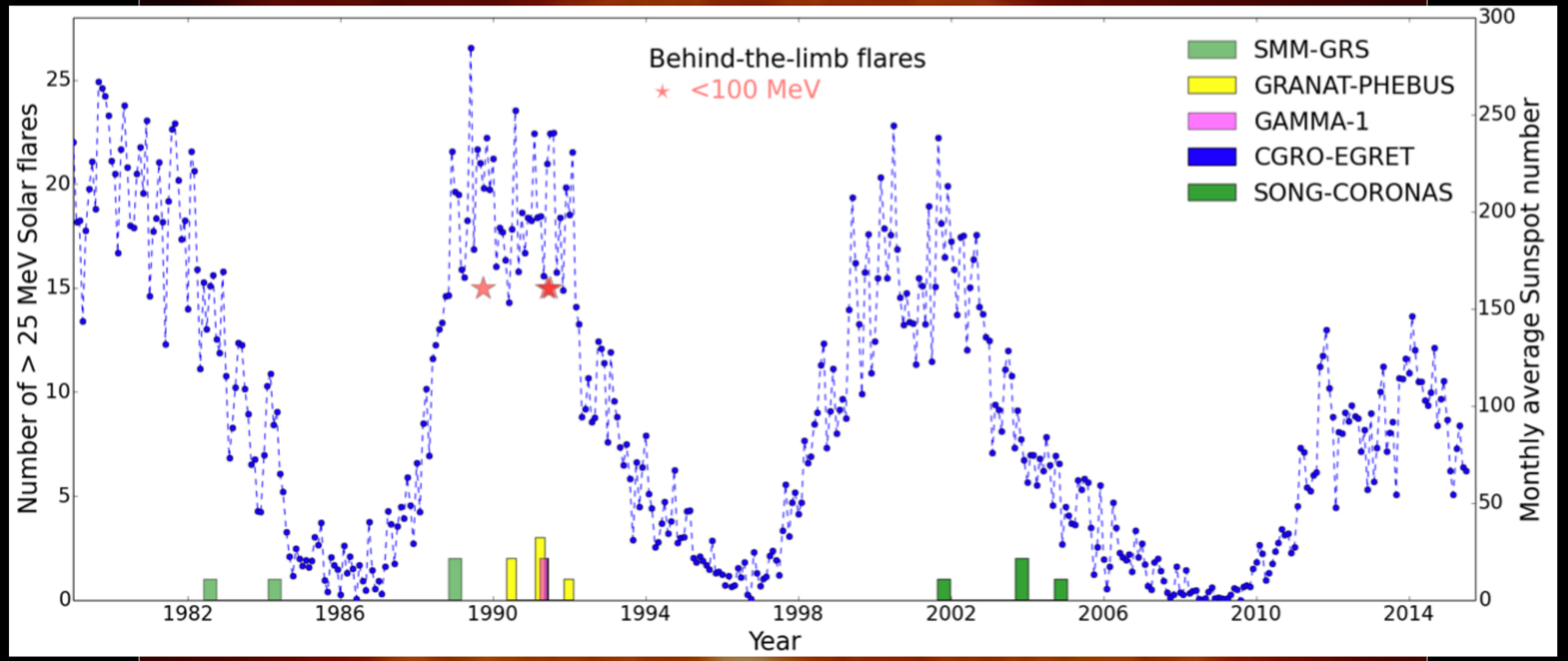
Sun: flares & CR interactions



Terrestrial γ-ray Flashes

Unidentified Sources (577/1873)

# Solar Flares in gamma-rays prior to Fermi



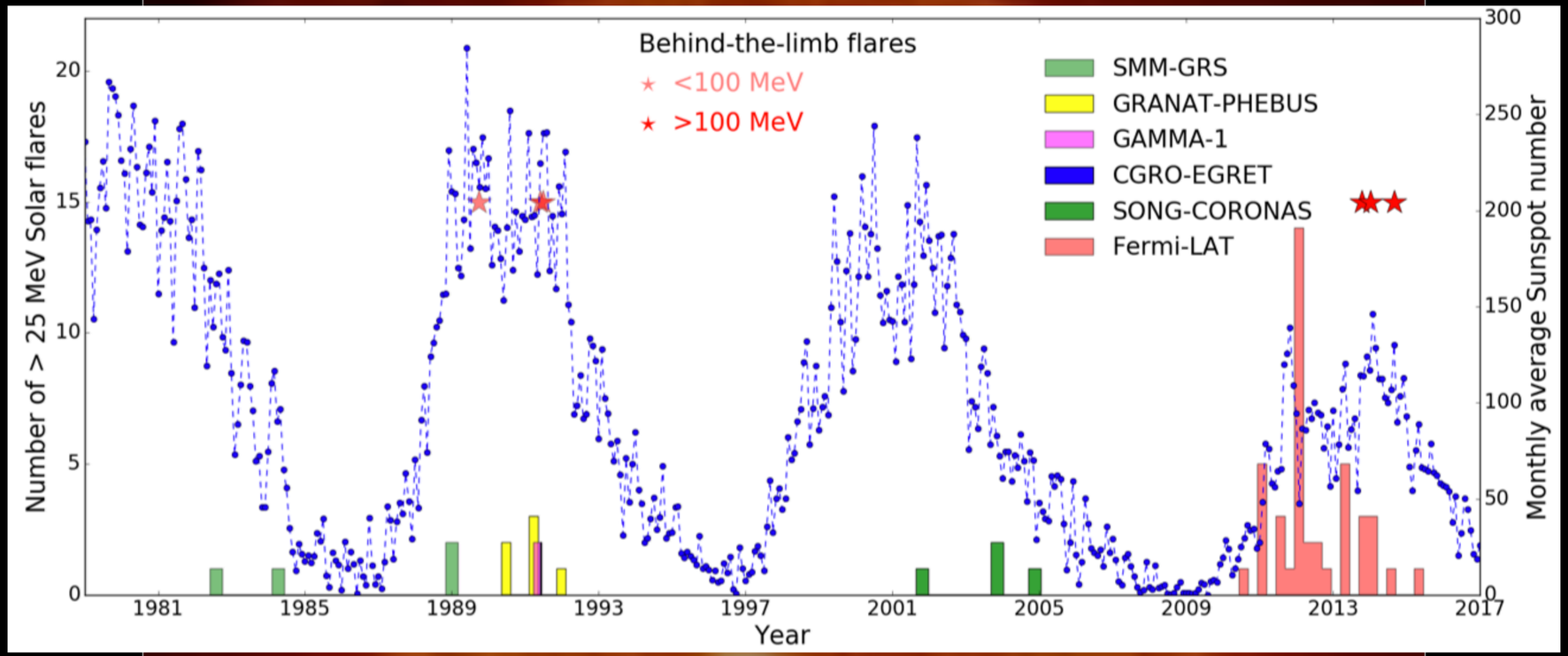

Over the past 30 years limited sampling of solar flares with E>25 MeV

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

# Solar Flares in gamma-rays with Fermi




Fermi-LAT has detected more than 40 Solar flares in first 9 years of mission

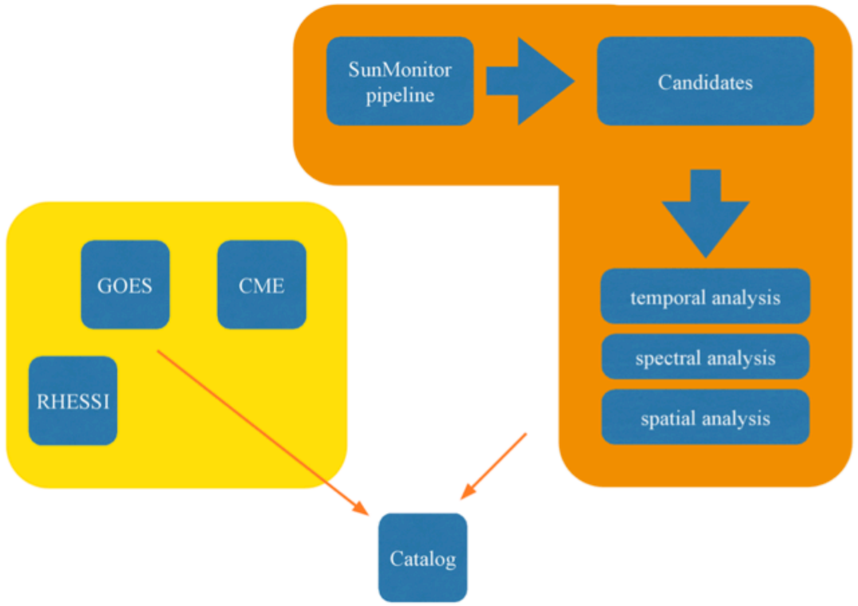
More than half are GOES M class

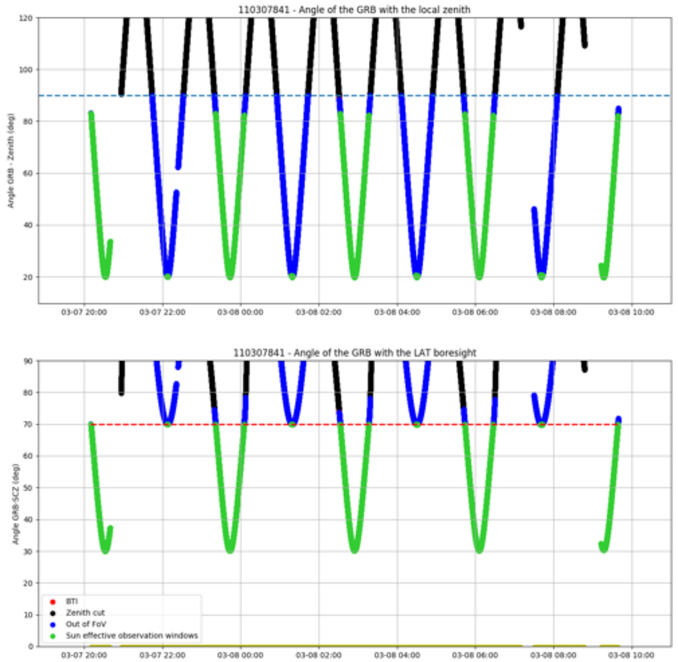
Extended >100 MeV emission for more than 20 hours

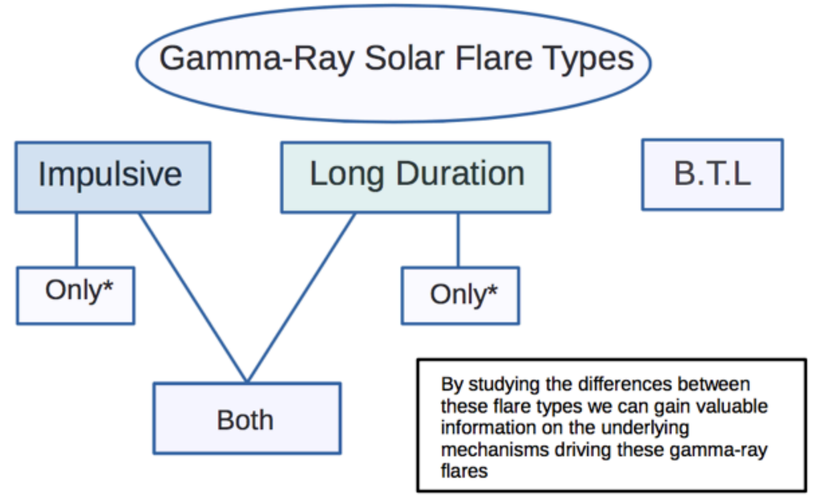
Including 3 behind-the-limb flares with >100 MeV emission

Fermi-GBM: more than 1000 detections

# Catalog of Fermi-LAT Solar Flares



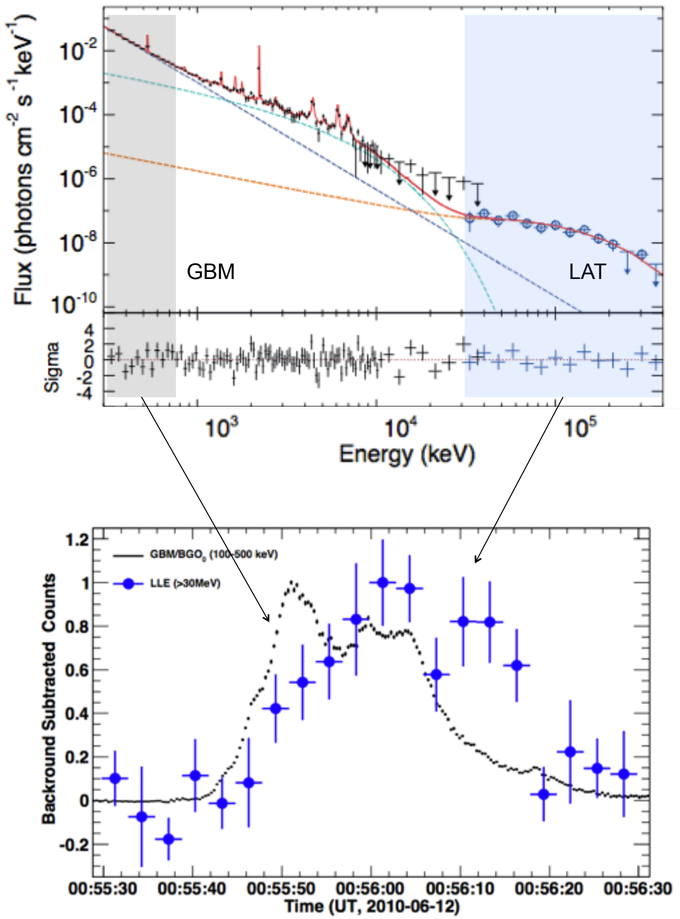

* Even if the Sun was in the field of view of the LAT, no impulsive/long duration emission was detected.

- **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 fitting**
  - **Compute the localization of the gamma-ray emission, optimize the localization in the analysis.**

- **<u>Impulsive</u>: we see gamma-rays in the time window of the X-ray flares**
- **<u>Long Duration</u>: we see gamma rays, after the X-ray flare**

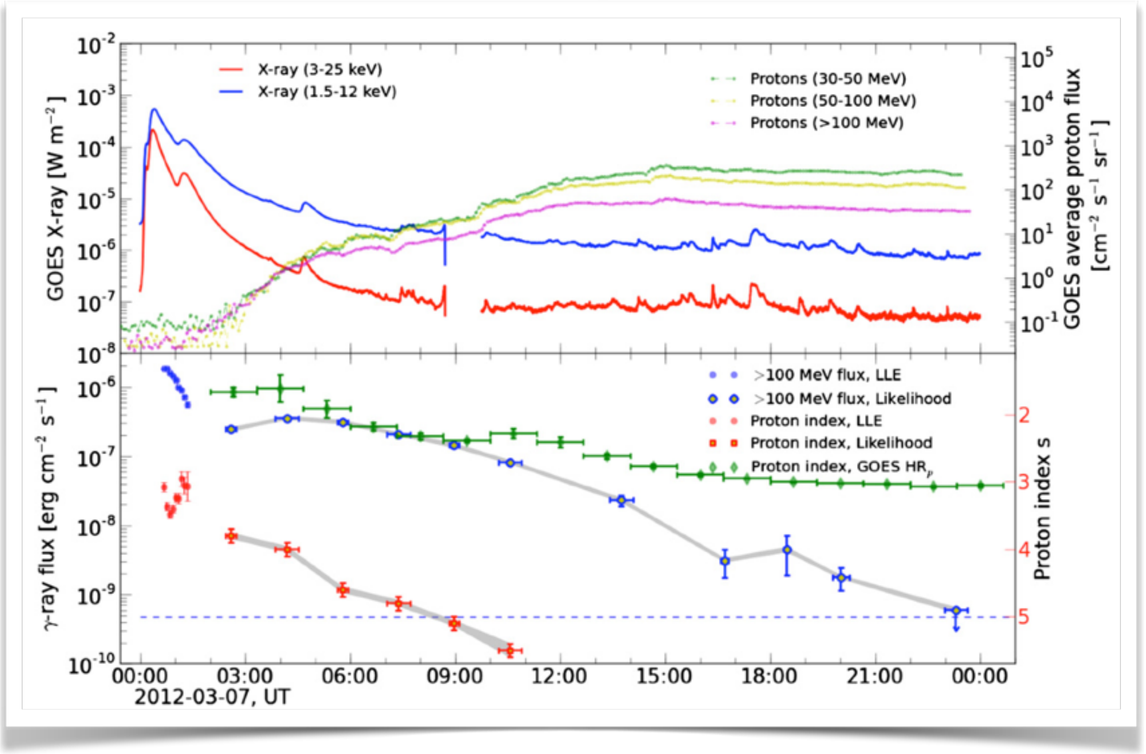
# Impulsive & Delayed emission detected by Fermi LAT

## Impulsive events




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

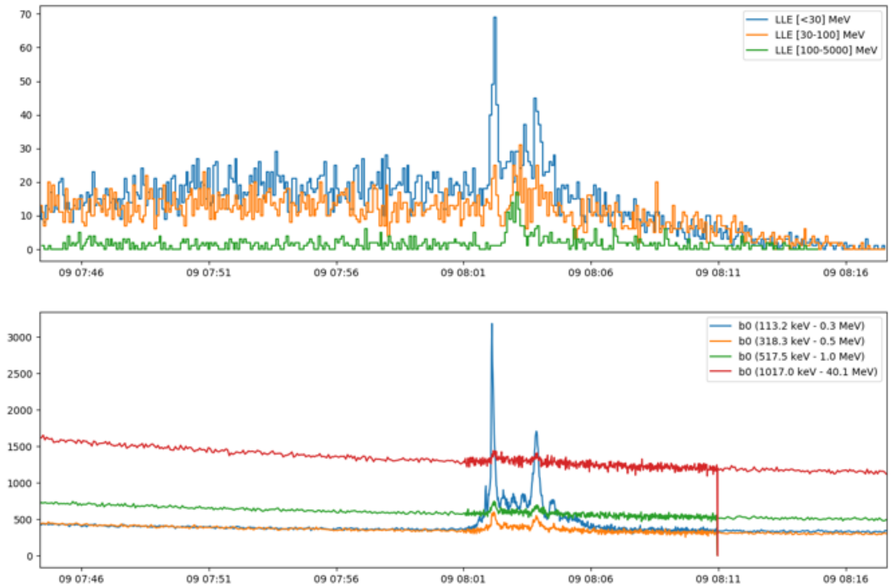
## Long Lasting emission



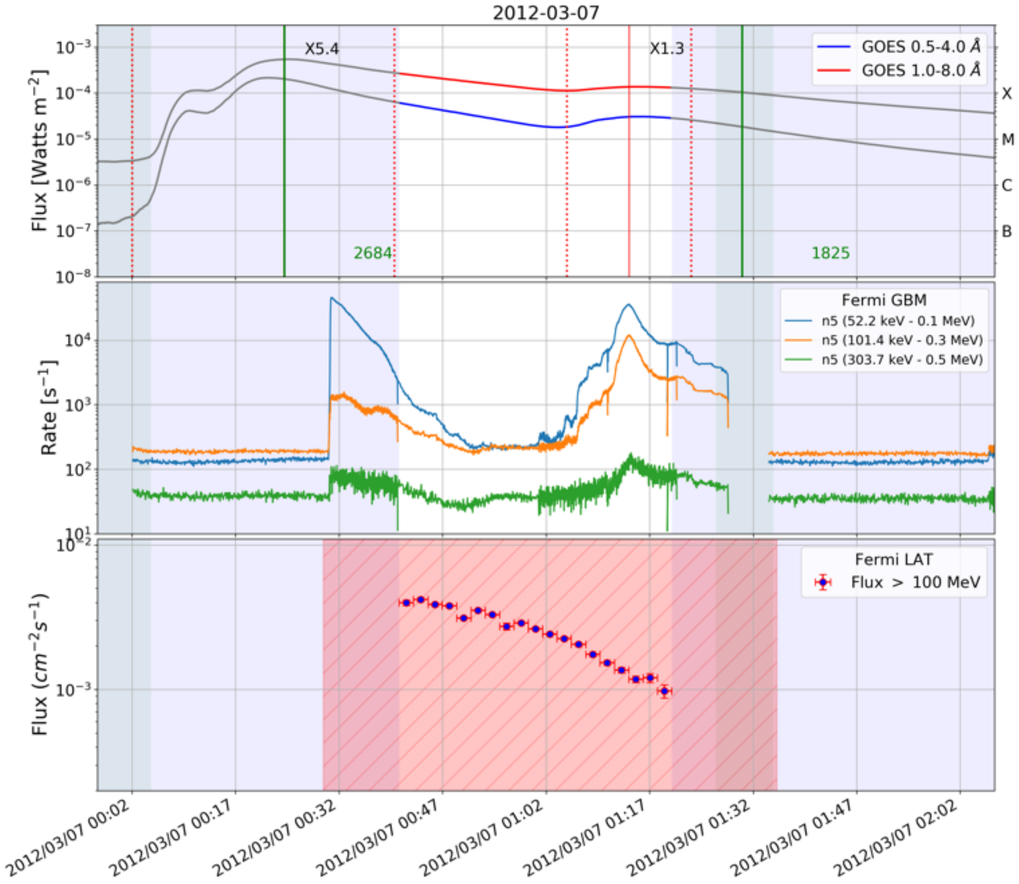

Sustained emission observed up **20 hours**
Ackermann, M. et al. 2014, ApJ, 787, 15

# Impulsive events not necessarily correlated with HXR!

- **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**

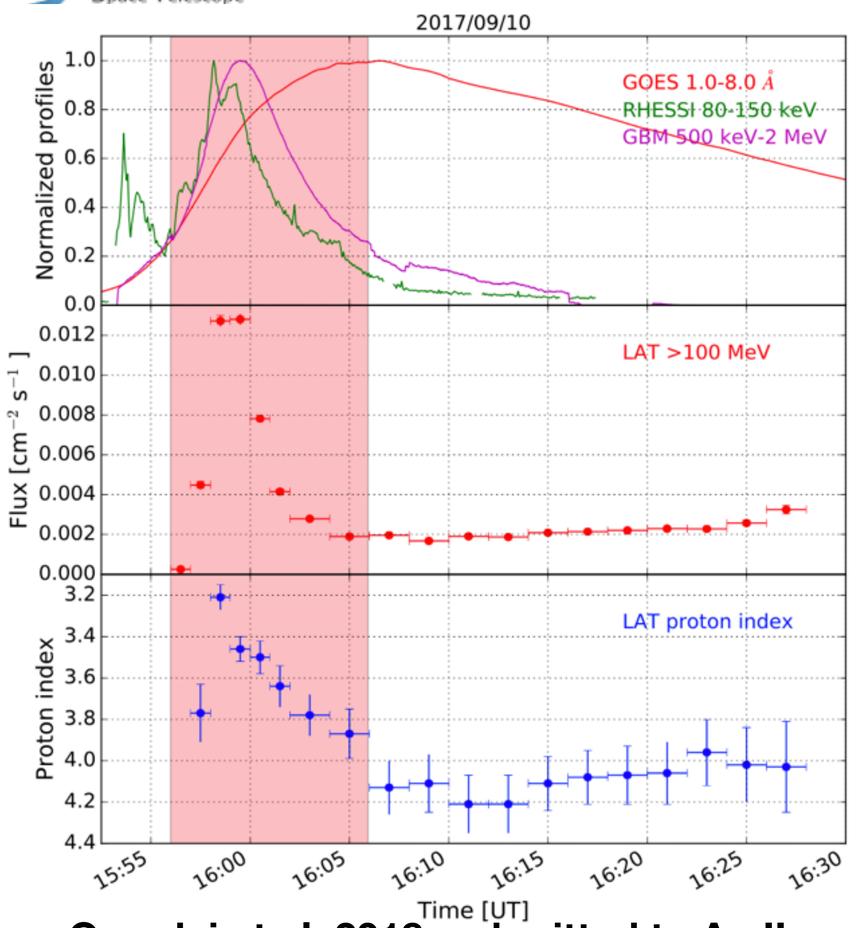


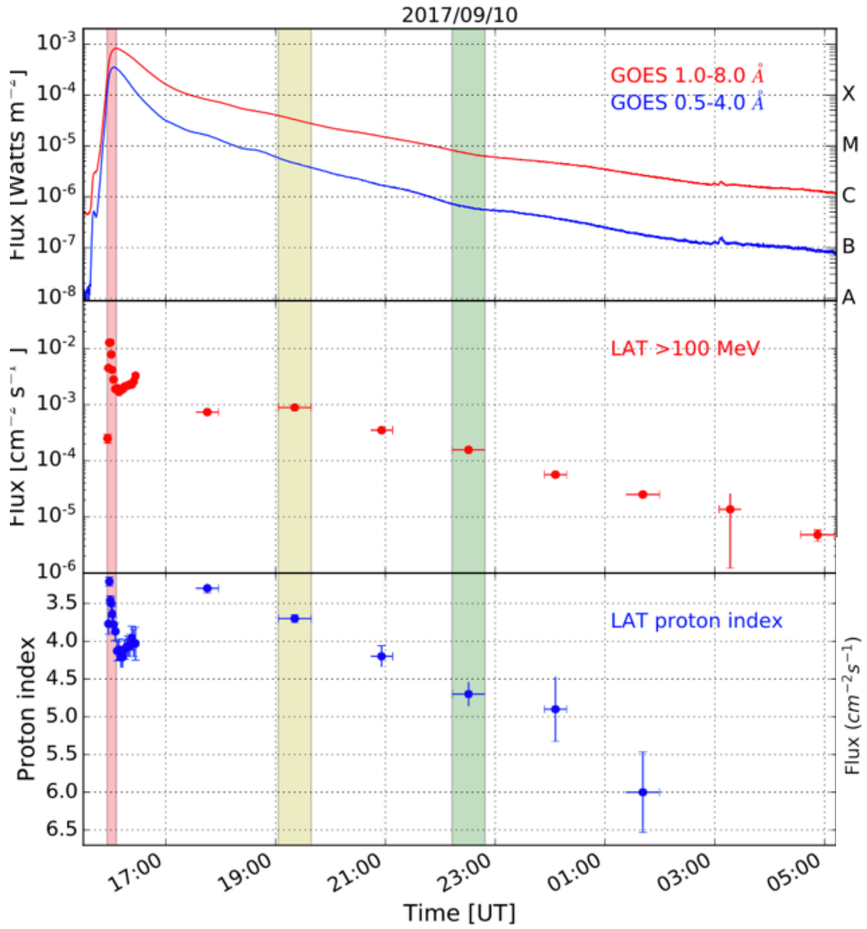

– **Clear temporal correlation between X-ray and gamma-rays**

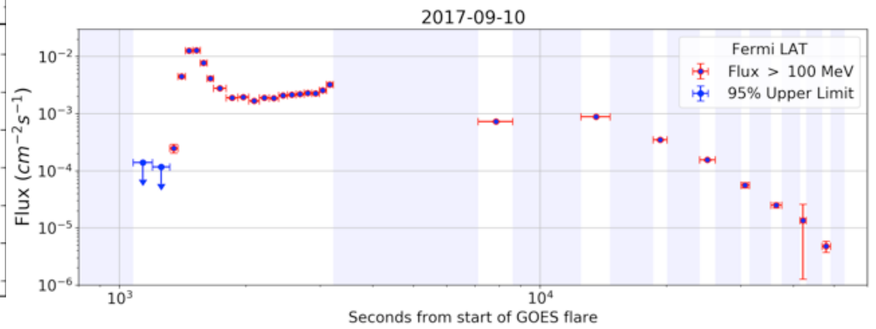



– **Not clear correlation**

# SOL 2017-09-10 shows multiple components



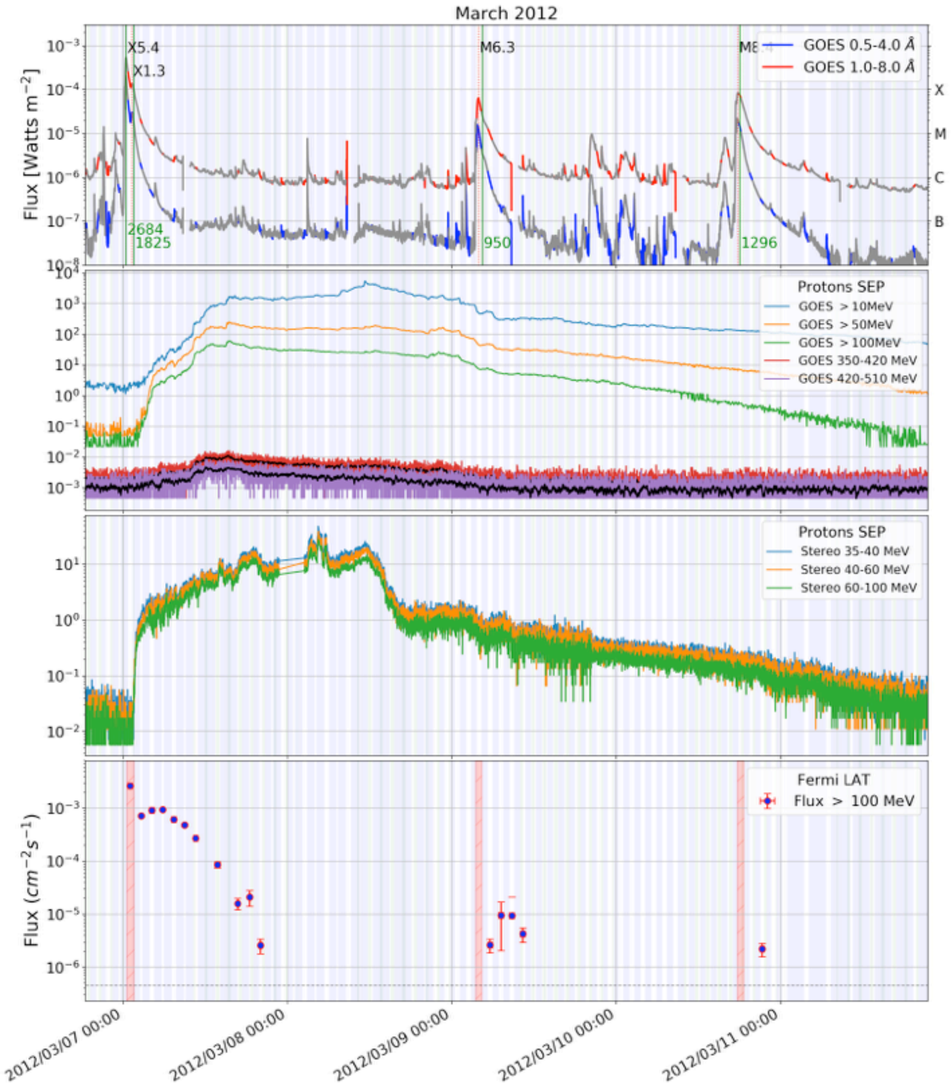



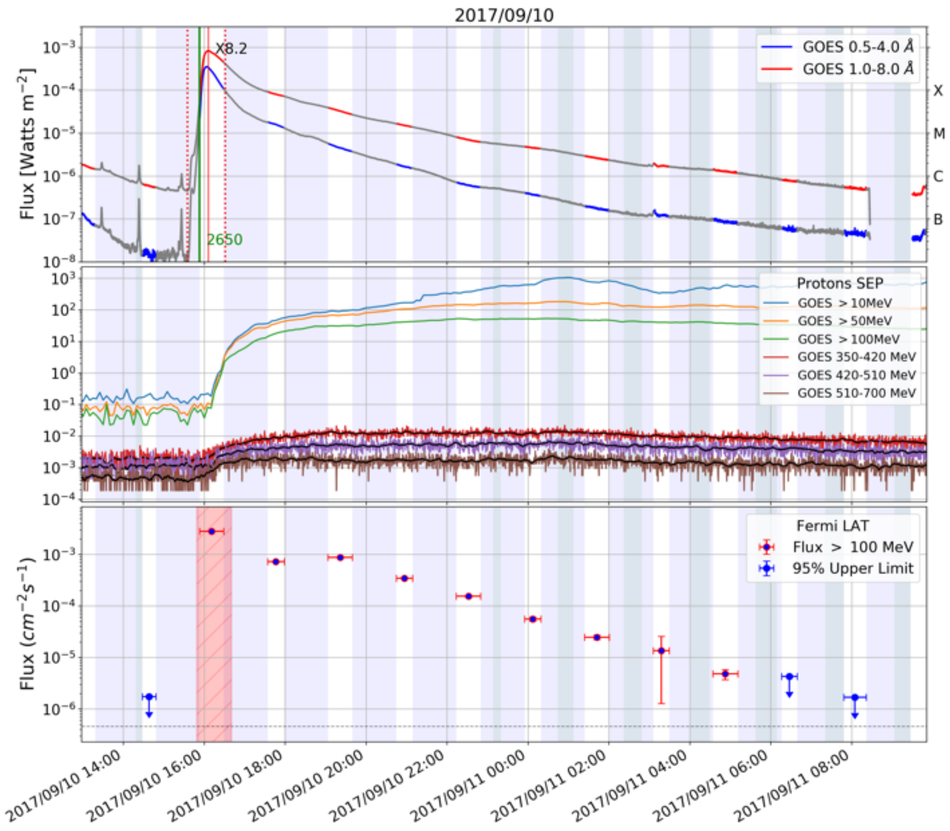




Omodei et al. 2018, submitted to ApJL

- **Prompt component (correlated with HXR)**
- **Delayed component during the impulsive phase**
- **Long lasting component**

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

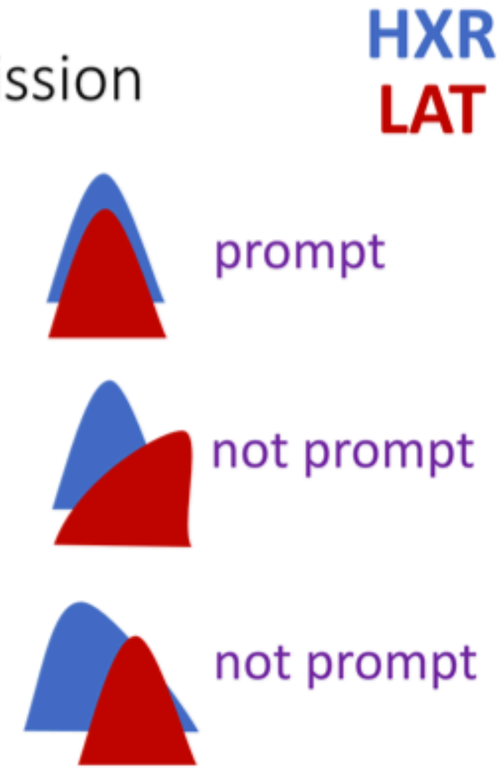


# Prompt & Delayed

## "Prompt" LAT emission

- Prompt LAT emission is correlated with a flare-associated nonthermal signature (e.g., >100 keV bremsstrahlung)
- Suggestive that the flare itself is accelerating ions to hundreds of MeV
- "Impulsive-phase" LAT emission is not necessarily prompt!

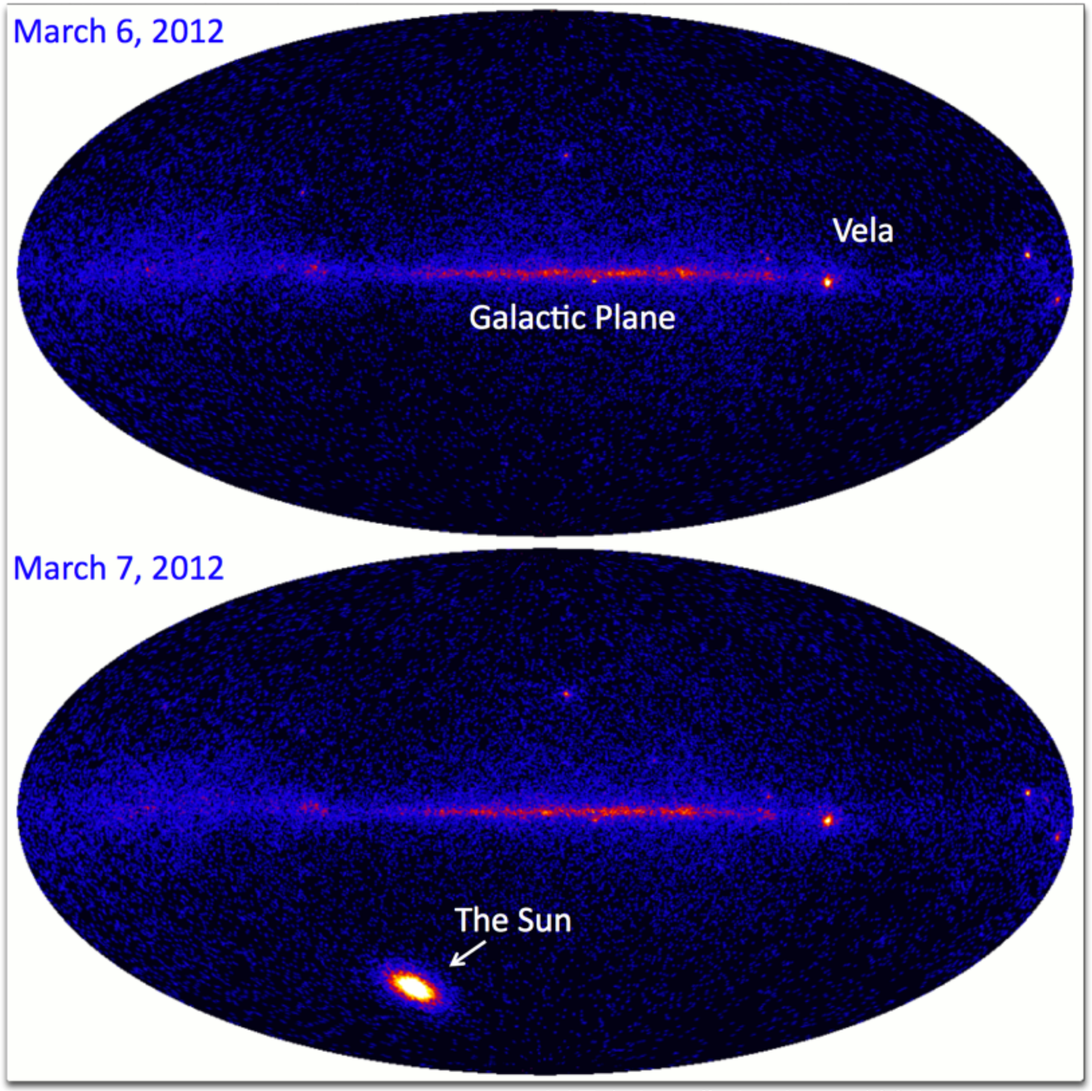



## "Delayed" LAT emission

- Delayed LAT emission is not prompt and peaks after flare-associated nonthermal signatures
- Suggestive of a non-flare origin (e.g., the CME)
- There can be multiple delayed components

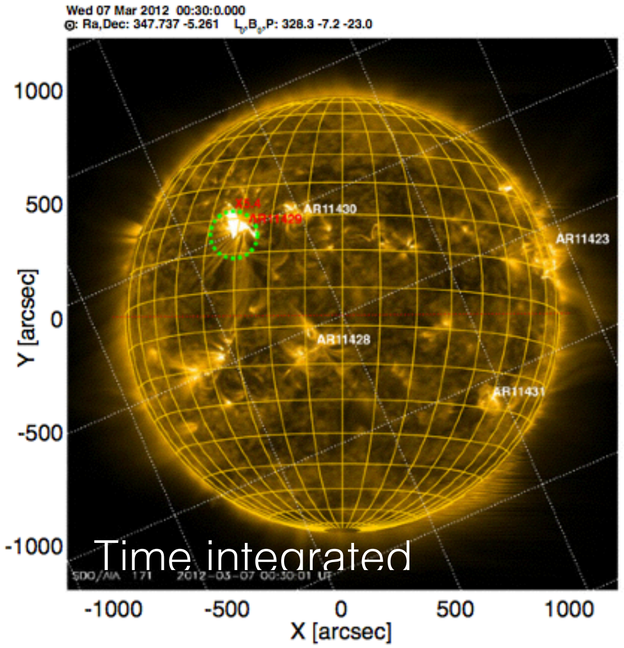

**Credit: A. Shih**

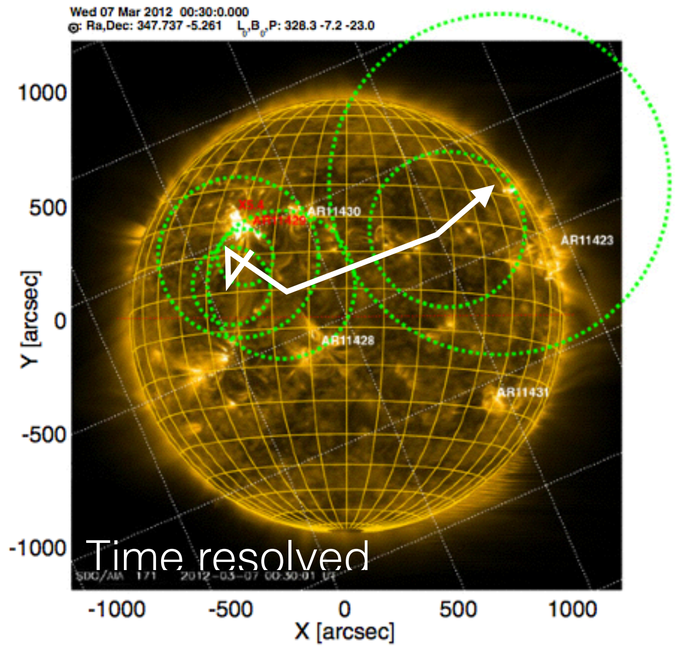
# The longest lasting gamma-ray emission: March 7, 2012




LAT 1 day all sky data >100 MeV

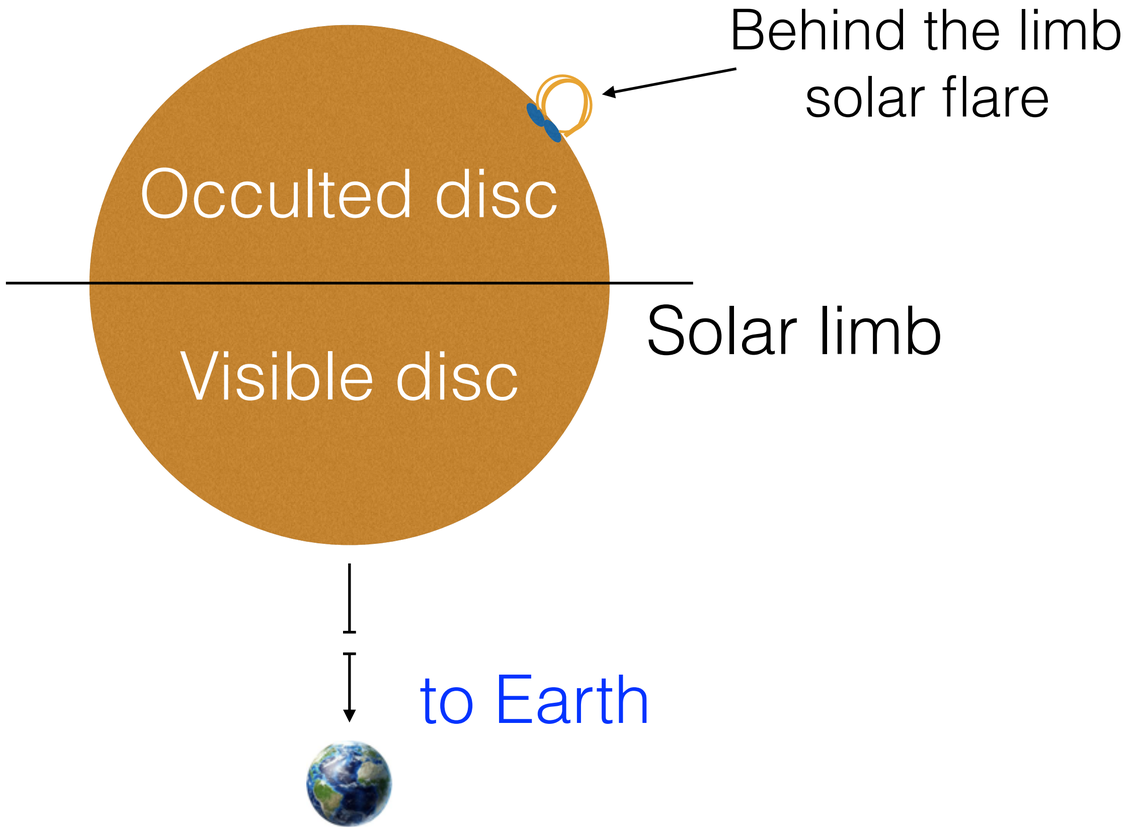
- **A very bright Solar Flare was detected on March 7, exceeding:**
  - **1000 times the flux of the steady Sun;**
  - **100 times the flux of Vela;**
  - **50 times the Crab flare;**
- **High energy emission (>100 MeV, up to 4 GeV) lasts for ~20 hours**
- **Softening of the spectrum with time**



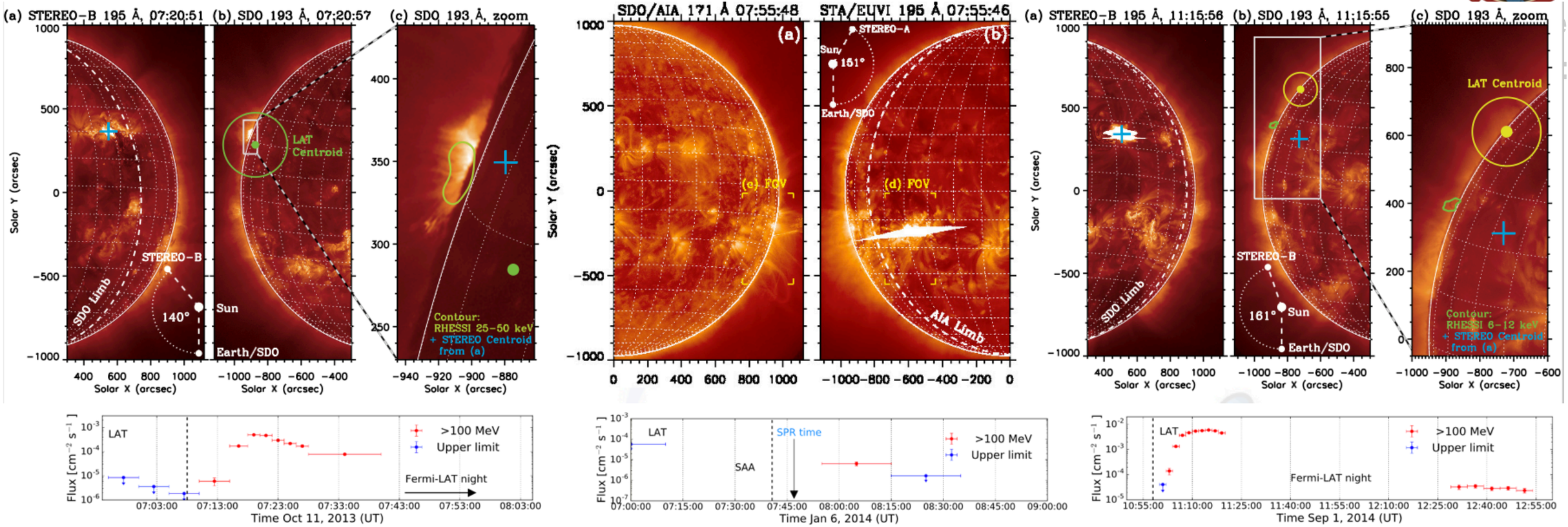



# Behind-the-limb flares

- **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



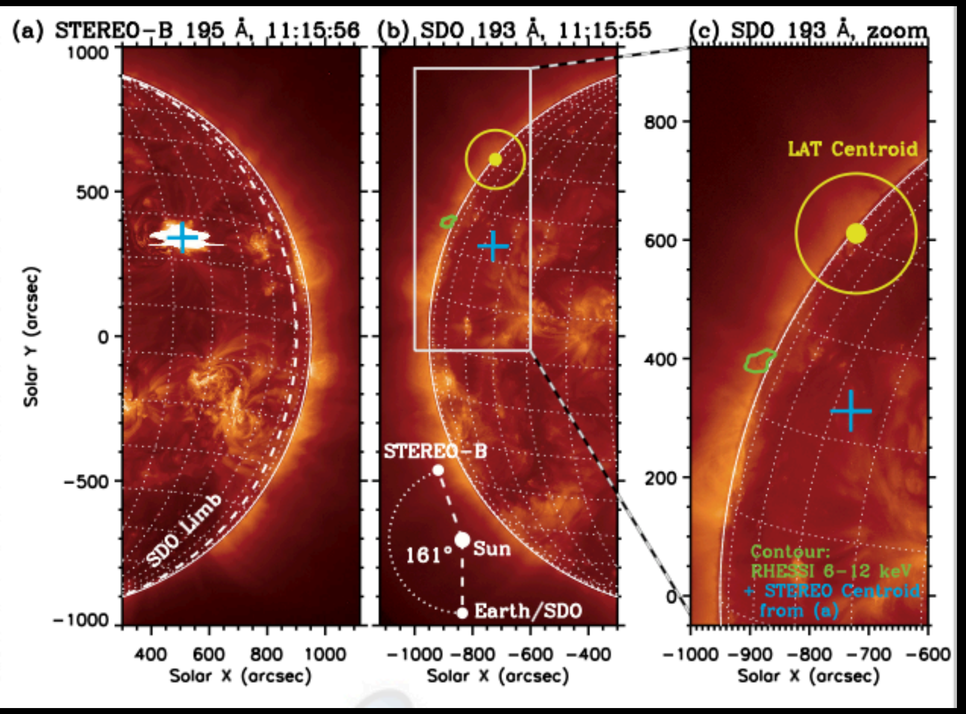

- 10˚ behind the eastern limb;
- RHESSI emission consistent with loop top;

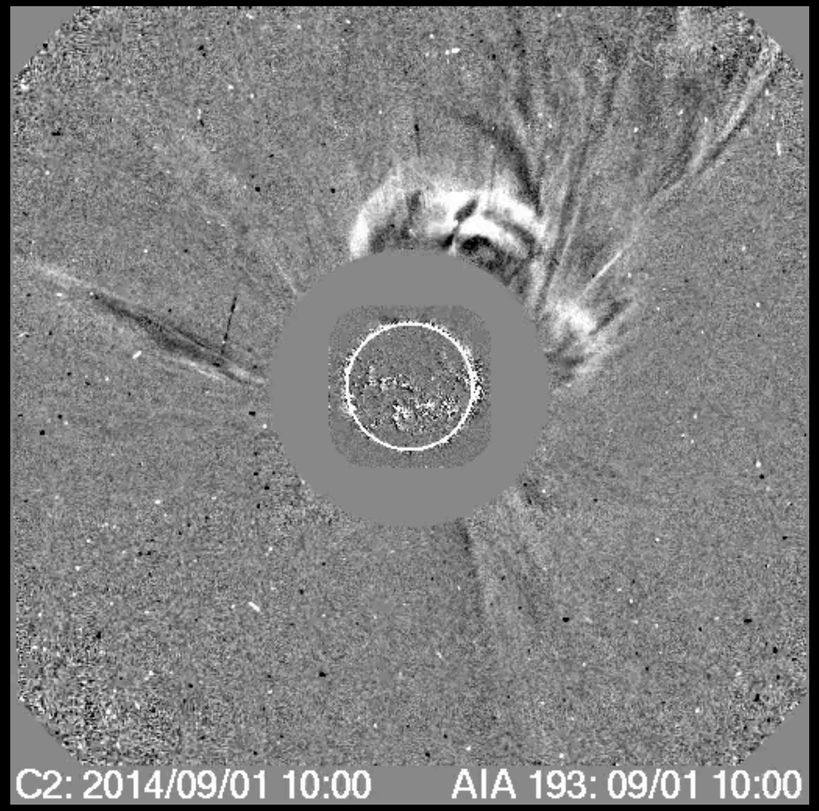
- 20˚ behind the western limb;
- SEP particles with E>=700 MeV detected;

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

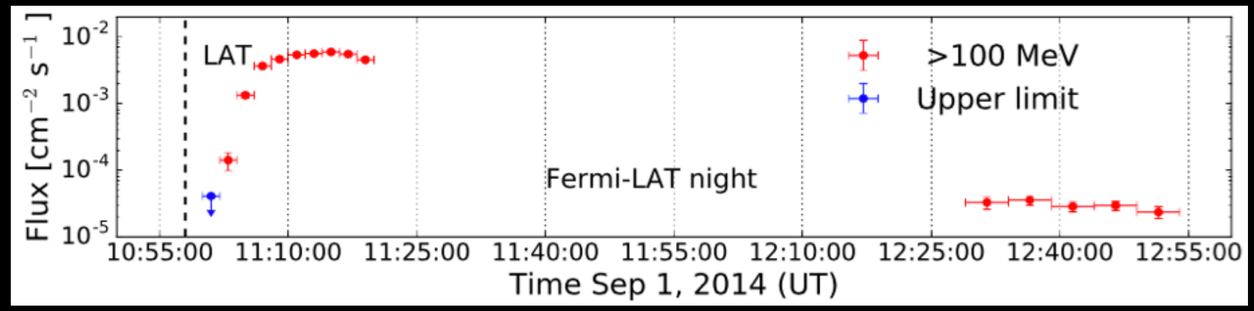
**Pesce Rollins et al. 2015, Ackermann et al., 2017**

# Association with fast CME

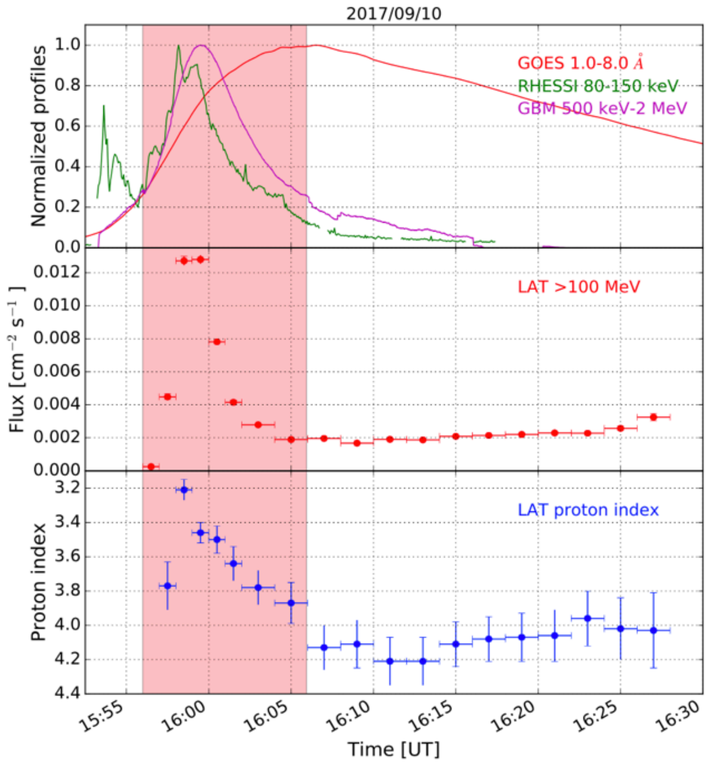


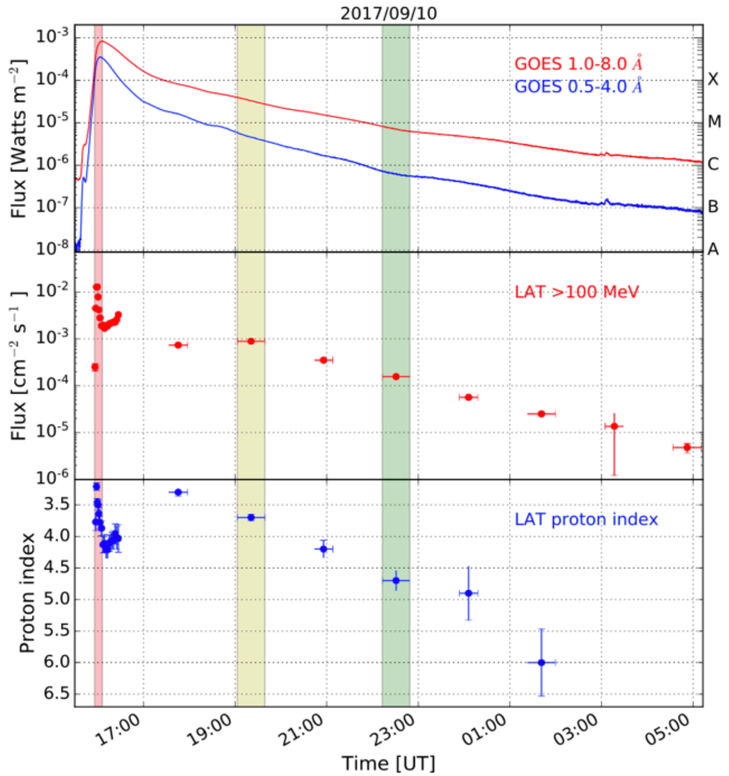



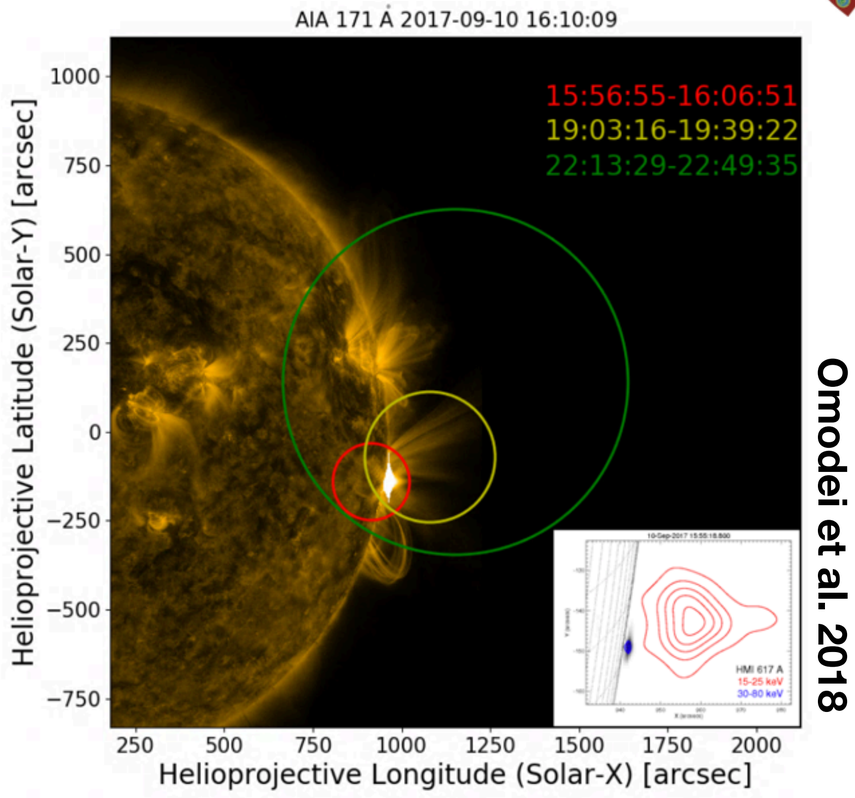

CME speed ~ 1900 km $s^{-1}$



# SOL 2017-09-10 localization



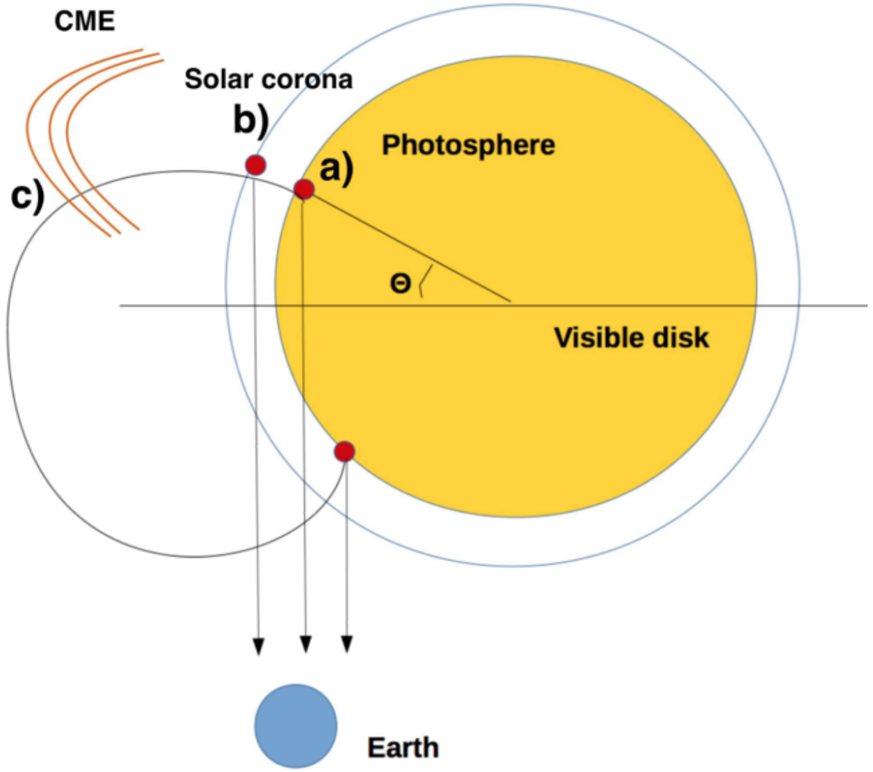

Omodei et al. 2018

- **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?**

# Particle Acceleration & gamma-ray emission in Solar Flares

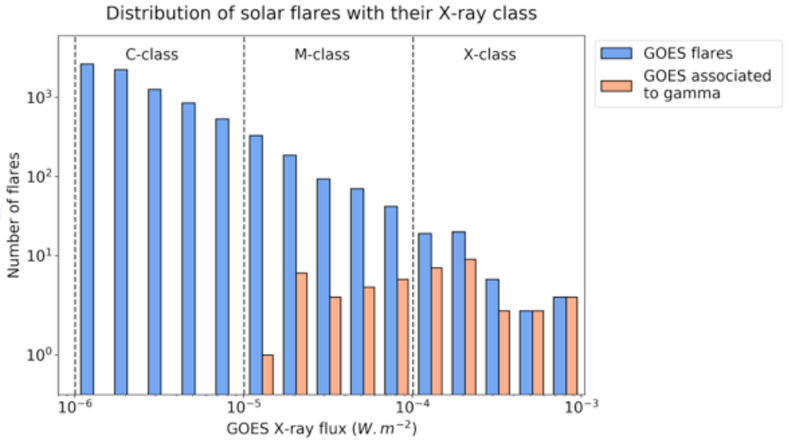
- a) Prompt emission: temporally correlated with the HXR emission
  - proton injection at the flare site, precipitation, emission consistent with the foot-points
  - Occulted in behind the limb flares
- b) Emission at the loop top
  - acceleration at the loop top, trapping
  - visible in behind the limb (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

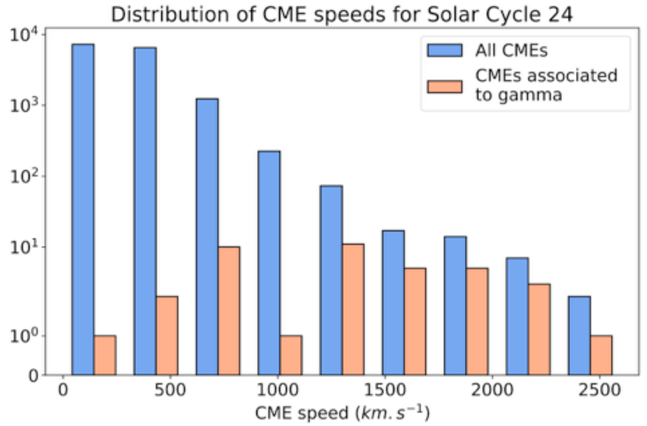


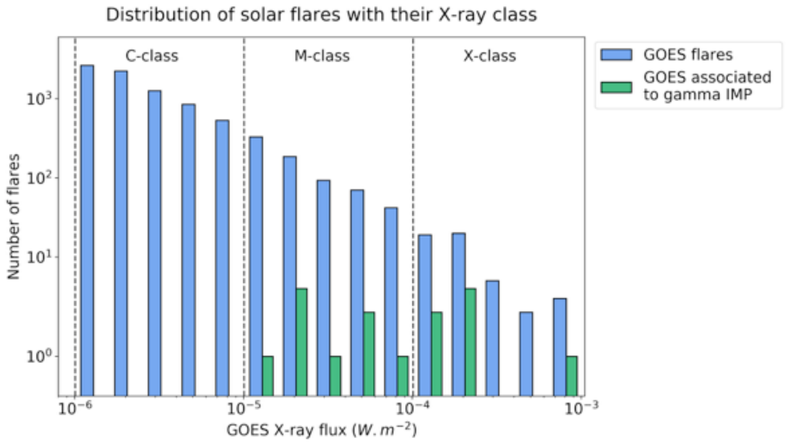

Omodei et al. 2015 (arXiv:1502.03895)

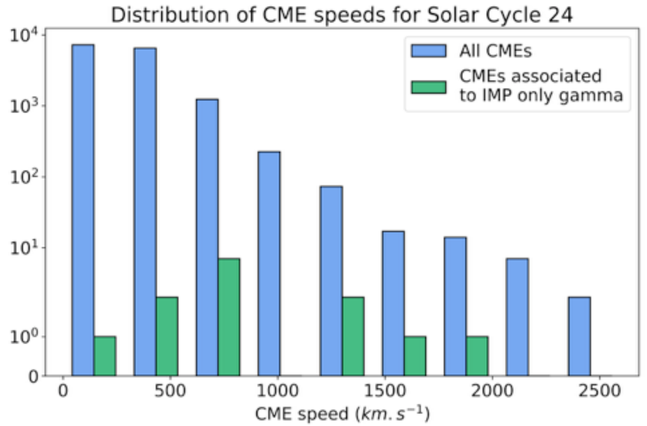
# Fermi-LAT Solar Flares of Cycle 24

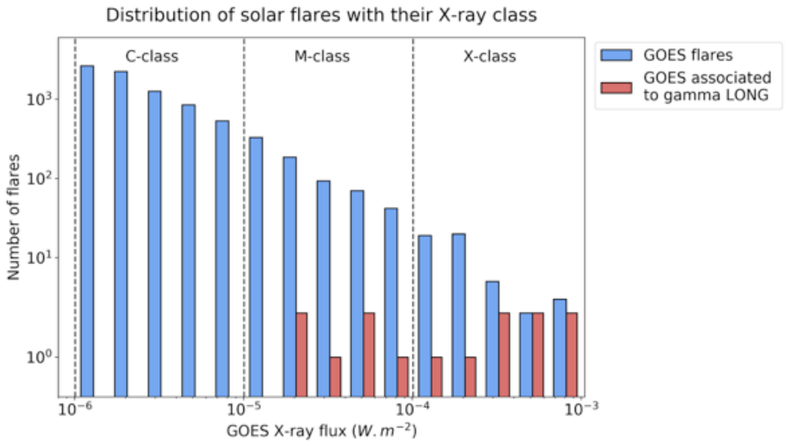
- Total of 45 solar flares detected with High Significance
- 3 behind-the-limb flares
  - First detections with emission >100 MeV
- 16 impulsive flares
- 27 long duration flares
  - 15 with emission lasting > 1 hour
- Almost half of the total sample consists of GOES M-class flares

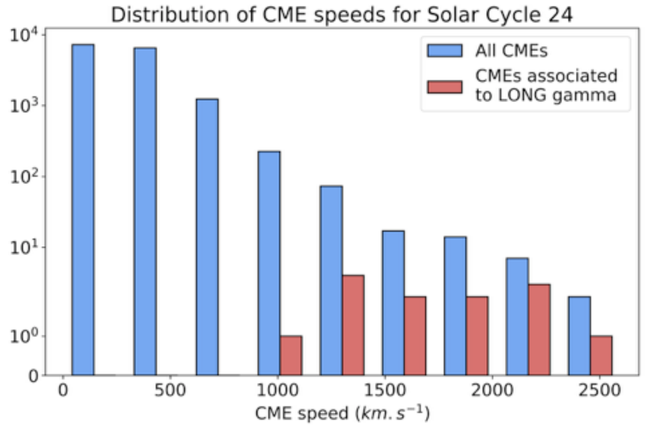


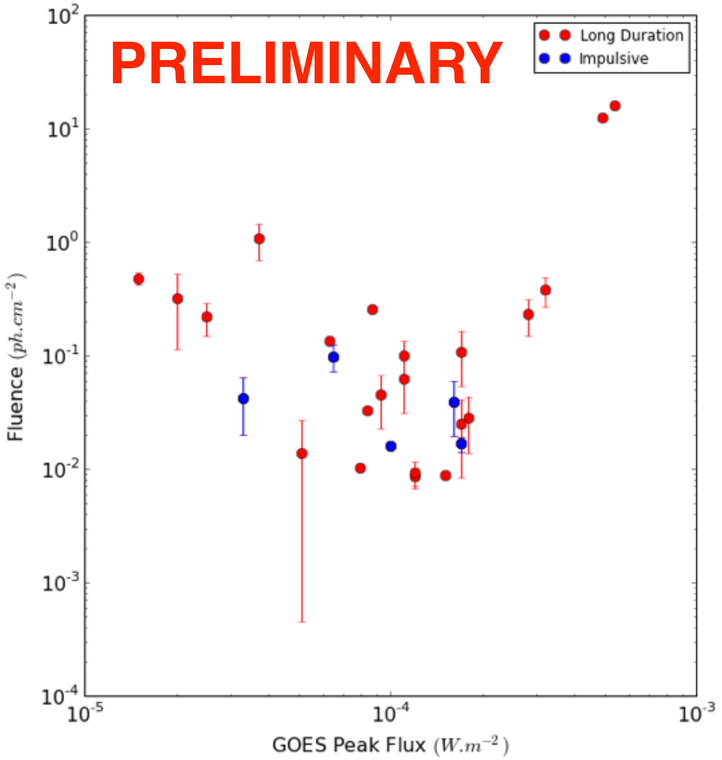



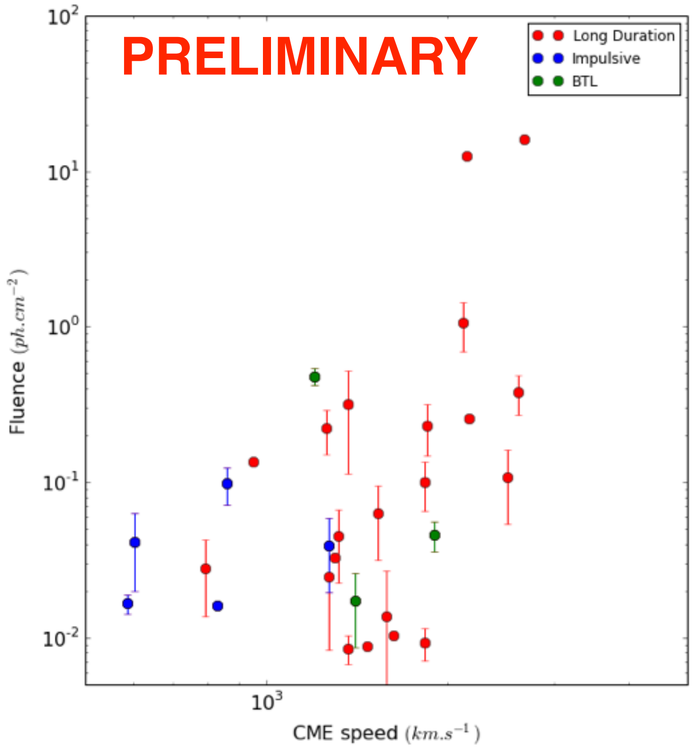




**PRELIMINARY**

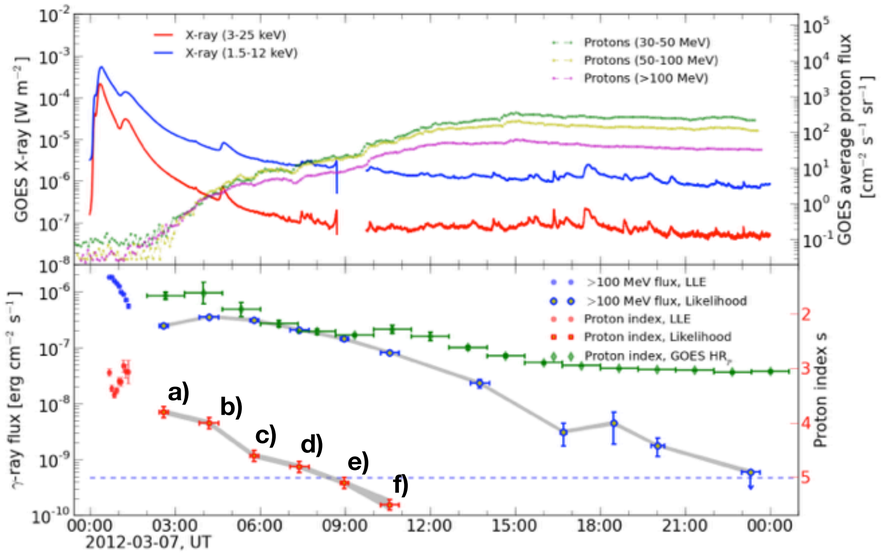
# Correlations Studies

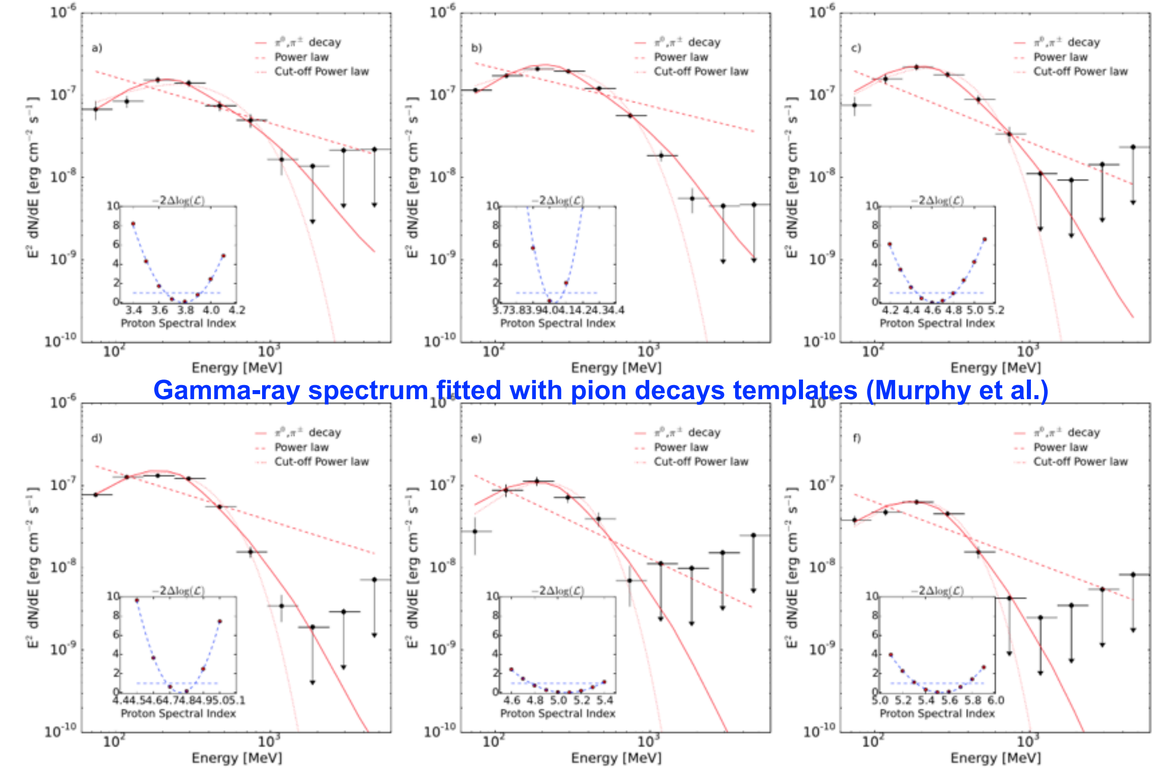


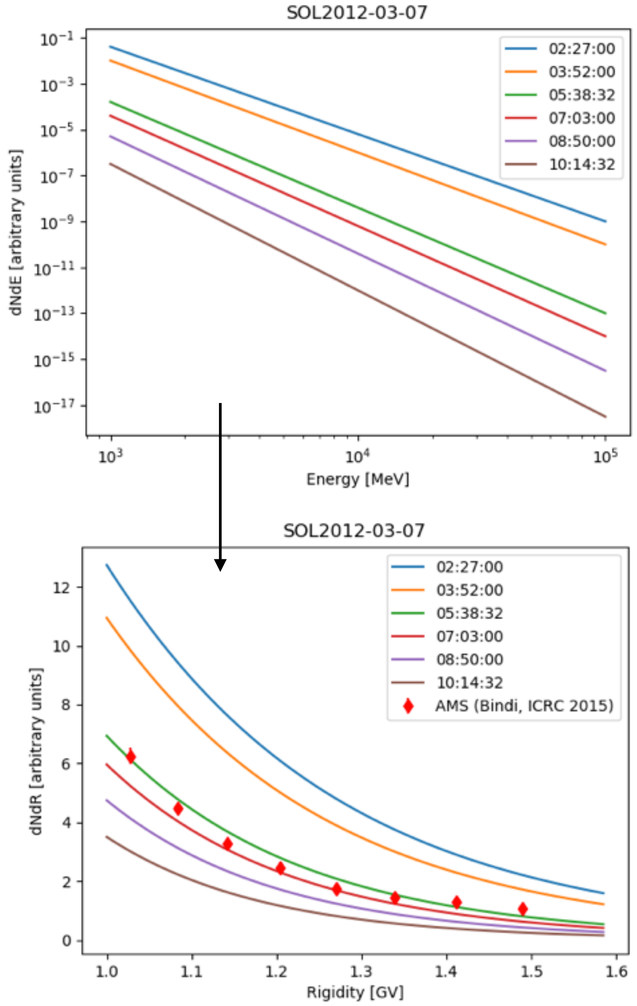

- **Compared the fluence of the LAT detected solar flares with the peak GOES X-ray flux**
  - **Pearson correlation of 0.27 found**
- **Compared the fluence of the LAT detected solar flares with emission lasting more than 1 hour with the LASCO CME linear speed**
  - **Pearson correlation of 0.60 found**

# Synergy with AMS




Gamma-ray spectrum fitted with pion decays templates (Murphy et al.)




Emission well described by pion decay model
Ackermann, M. et al. 2014, ApJ, 787, 15

- **Under the assumption that particles producing gamma-rays at the Sun are correlated with SEP:**
  - **Gamma-ray spectrum fitted provides indirect measurement of the proton spectrum (and rigidity)**
  - **Injected at the source**
- **Can be compared with the measurement by AMS**
  - **Spectrum at Earth**
  - **Case for studying propagation effects, re-acceleration and diffusion**

# 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 phase observed (prompt vs delayed);
  - Prompt emission observed during on-disc flares suggests acceleration at the flare site
  - Correlation with CME stronger than correlation with impulsive flux: acceleration at the CME shock for long duration flares?

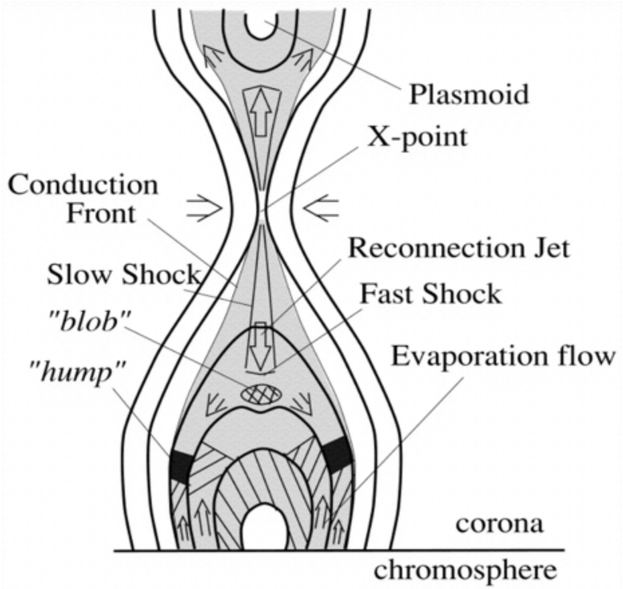
- Behind the limb flares: acceleration site likely to be the CME shock, as suggested by Cliver et al. (1993), Pesce-Rollins et al. (2015), and Plotnikov et al. (2017)

- Synergy with AMS in studying SEP

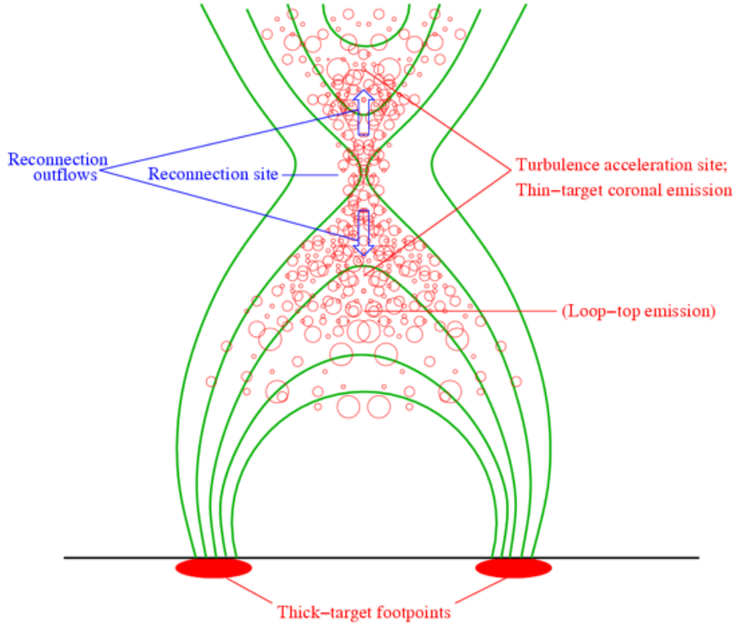
# Spare

# 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



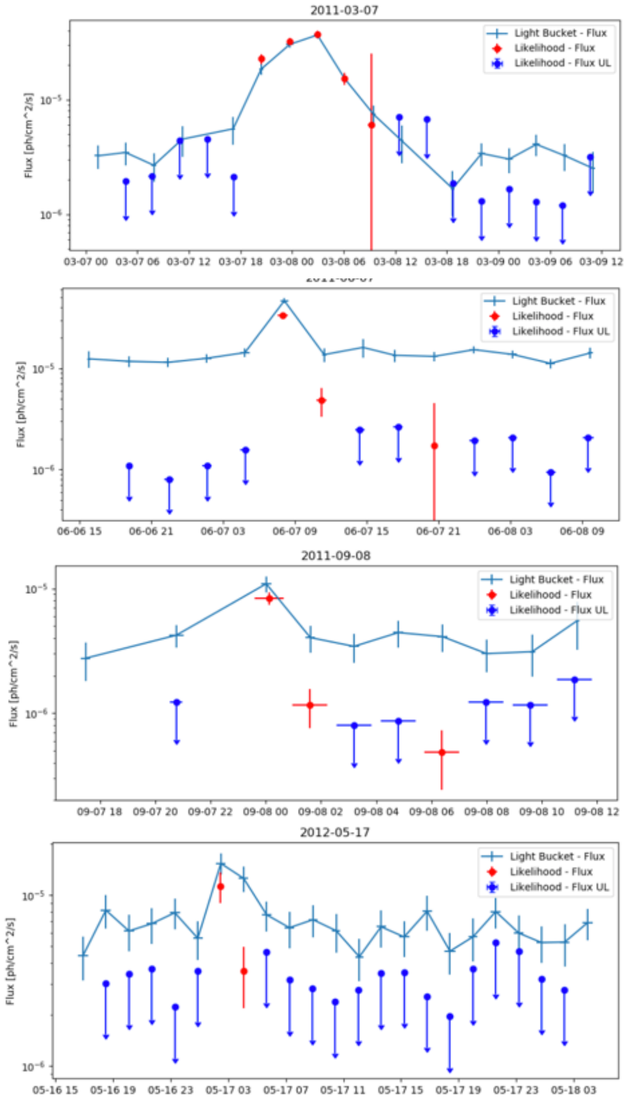

- **Trap-precipitation of HE particles produced during the impulsive phase via magnetic reconnection (Kanbach et al. 1993);**
- **In coulomb collision, the trap efficiency increases with energy, and a gradual hardening of the spectrum is expected;**
- **Not observed during the sustained emission;**

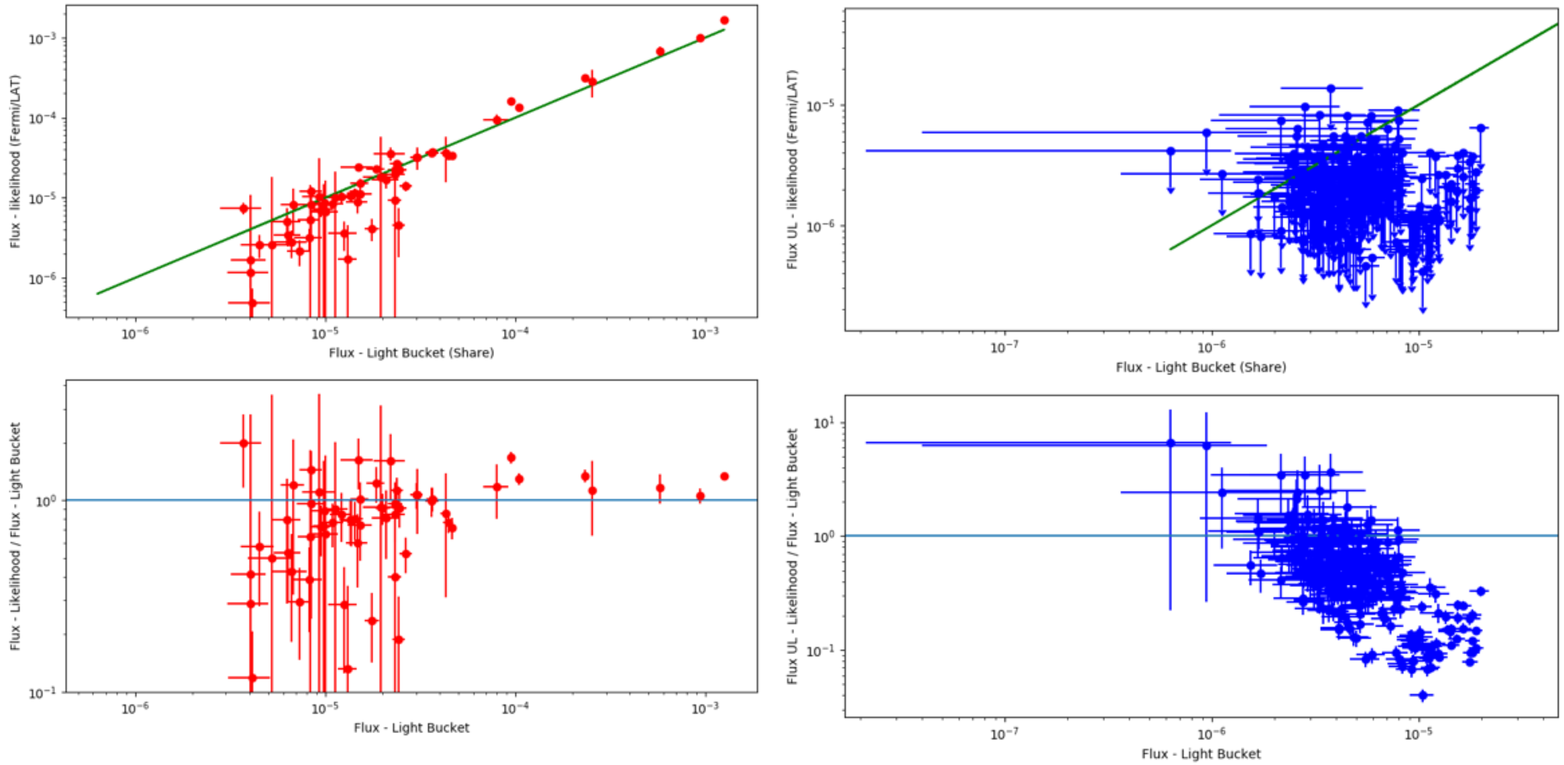



- **Continuous acceleration at flare reconnection region via Stochastic acceleration (Petrosian & Liu 2004);**
- **Accelerated particle spectra become softer as turbulence weakens;**
- **Can explain the spectral evolution seen;**

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

# The Likelihood analysis and the “Light bucket”




- **The “light bucket” has several 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**