15 years of Fermi-Large Area Telescope observations of high energy gamma-ray Solar flares

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on behalf of the *Fermi*-LAT collaboration

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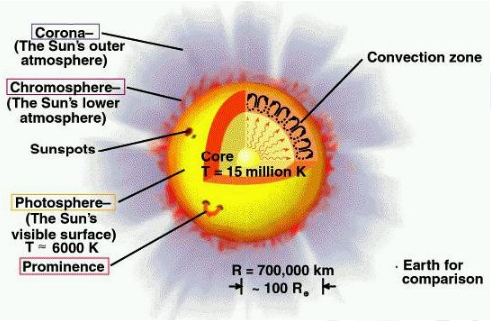
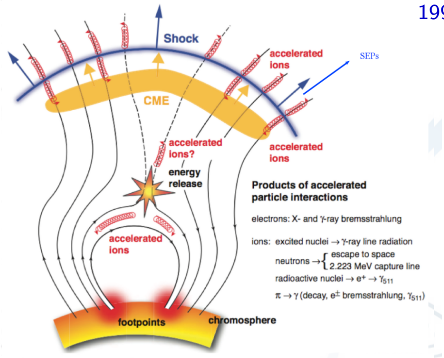


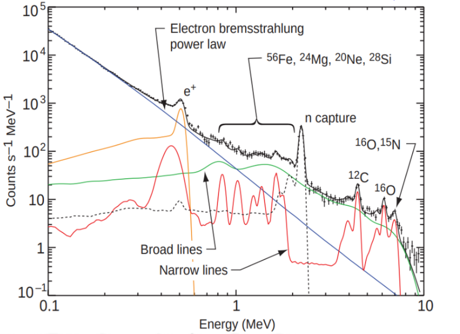
- Density variation from the chromosphere to the Corona is ~8 orders of magnitude
- Sunspots result from the internal magnetic field bursting through photosphere and out into the corona
- The number of sunspots are used as a marker for solar activity

- Sunspots are generally where flares originate from
- Flares are powered by the sudden release of magnetic energy stored in the corona capable of accelerating particles up to relativistic energies

ACCELERATED PARTICLE SIGNATURES: FLARE SITE

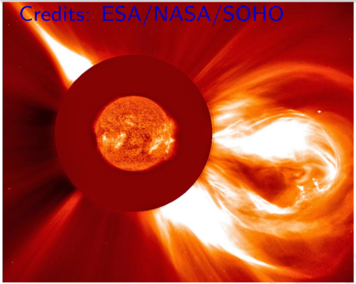


1991 June 4 solar flare observed with CGRO/OSSE



- Magnetic reconnection believed to be at the origin of particle acceleration in solar flares
- Deexcitation lines between 1-8 MeV in gamma-rays→ ∼1<E<20 MeV protons interacting with ambient solar material
- Neutron capture line at 2.223 MeV→ up to 100 MeV protons
- Continuum above ∼30 MeV in gamma-rays → >280 MeV protons

Accelerated particle signatures: far from flare site



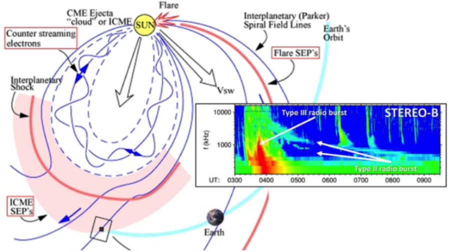
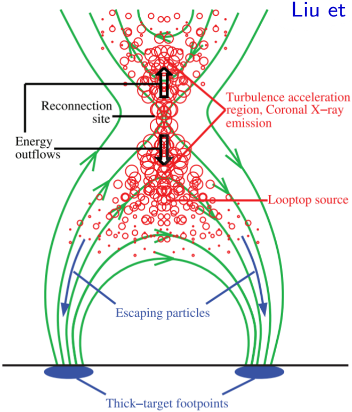


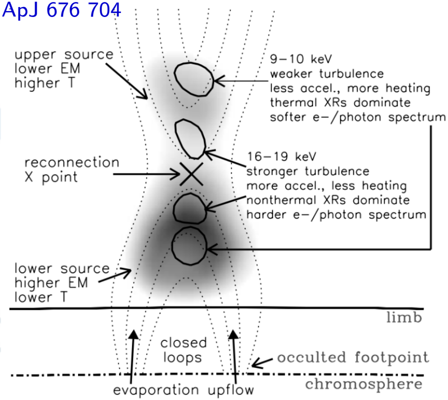
Figure 1. Illustration of ICMEs, solar flares, and associated radio emissions. Image Credits: NASA

- Coronal Mass Ejections (CMEs): significant release of plasma/accompanying magnetic field from the solar corona, shock waves are formed
- Radio bursts caused by non-thermal electrons accelerated at coronal/interplanetary (IP) shocks often associated with CMEs
- Solar Energetic Particles (SEP) observed at Earth found to be accelerated at the CME shock front
  - Evidence for ion acceleration up to GeV energies

Evidence for magnetic reconection



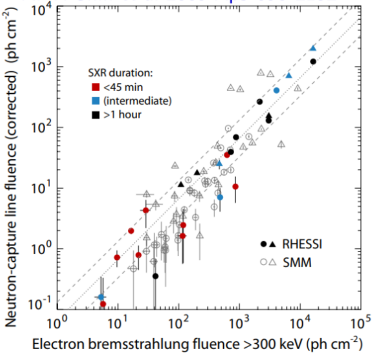
Liu et al 2008 ApJ 676 704



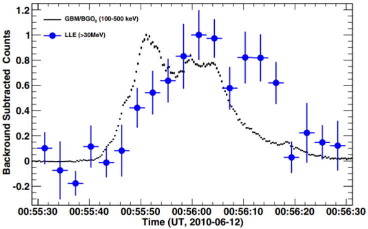
- Outflows in opposite directions can generate turbulence that accelerates particles and heats the background plasma stochastically
  - Two distinct X-ray sources, one above and one below the reconnection region are expected in this scenario
- RHESSI revealed these distinct sources confirming expectations

Connection between X-ray and γ-rays

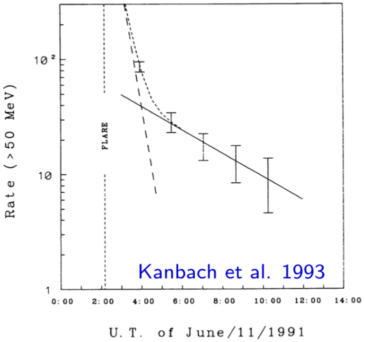
A. Y. Shih et al 2009 ApJ 698 L152

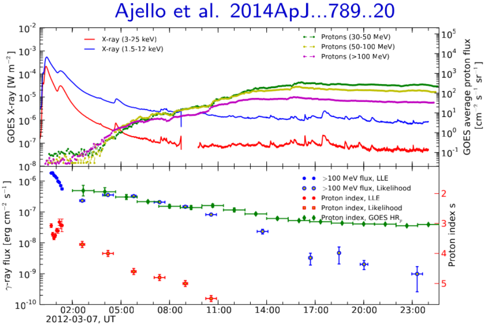


Ackermann et al 2012 ApJ 745 144



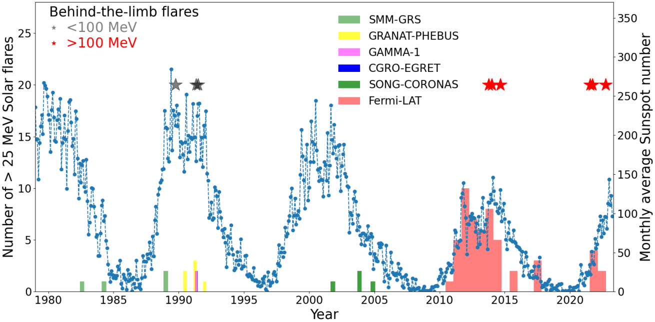
- The acceleration of >0.3 MeV electrons is proportional to the acceleration of >30 MeV protons over >3 orders of magnitude
  - Strongly implies a common acceleration mechanism during the impulsive phase of solar flares
- Gamma-ray emission lags the bremsstrahlung by 6±3 secs



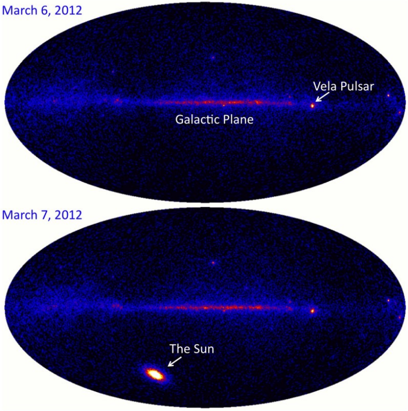


- Observations indicate that gamma-ray flares have an additional phase lasting hours after the impulsive phase
  - And after all the other flaring counterparts have ceased
- Need to understand what mechanism is driving this hour-long emission
- The limited statistsics prior to 2008 made it very difficult to investigate

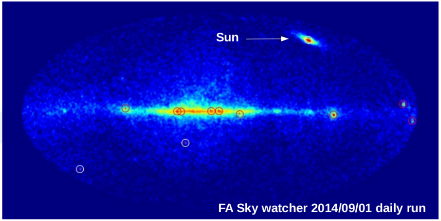
Gamma-ray Solar flares with *Fermi*



- Over past 30 years limited sampling of solar flares with E>25 MeV
  - All associated with brightest X-ray flares
  - Extended >100 MeV emission observed from 5 flares
  - 3 behind-the-limb flares with E<100 MeV
- *Fermi* has detected 53 Solar flares during the past 15 years in orbit
  - More than half are associated with modest X-ray flares
  - Extended >100 MeV emission observed from 40 flares
  - 6 behind-the-limb flares with >100 MeV emission

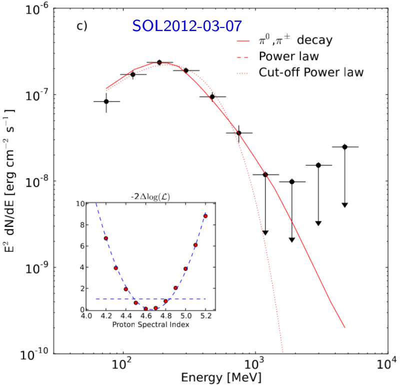


APOD March 15^{th}, 2012



- Solar flares can cause the Sun to be the brightest gamma-ray source in the sky
- Behind-the-limb flare of 2014 Sept 1^{st}

- The flare of 2012 March 7^{th} lasted for more than 20 hours
  - And was more than 100 times brighter than the Vela pulsar

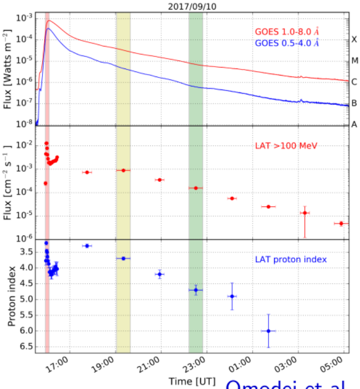


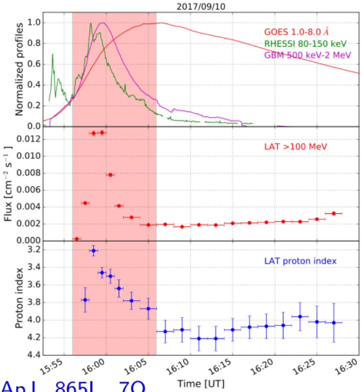
We fit the LAT spectral data between 60 MeV and 10 GeV to test three different emission models:

1. Pure power-law
2. Power-law with exponential cut-off
3. Templates to describe emission from pion decay based on Murphy et al. 1987

We rely on the likelihood ratio test (TS) to estimate the significance of the source and whether the curved model provides a better fit

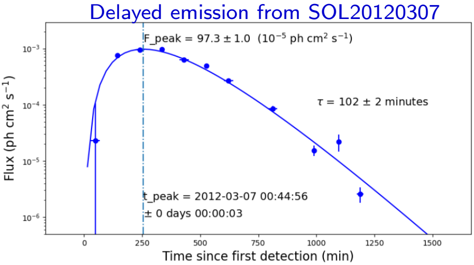
- When model (2) provides a better fit we also fit the data with a series of pion-decay models to determine the best proton spectral index

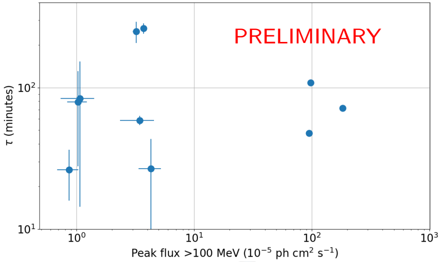




Omodei et al. 2018ApJ...865L...7O

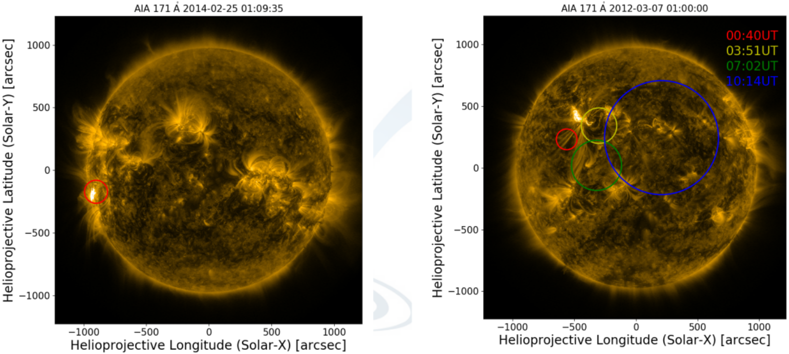
- Data suggests multiple phases in flux and proton index evolution
- Prompt phase (coincident with X-rays), delayed and intermediate (no obvious counterpart)
- Intermediate steady phase isolated from X-rays (<20 minutes)
- Delayed phase for around 10 hours





- Delayed emission exponential decay, τ, and peak flux obtained by fitting with model:
  - $\mathrm{P}(\mathrm{t}\,|\,\mathrm{F_p}, \mathrm{t_p}, \tau) = \mathrm{F_p}\left(\frac{\mathrm{t}}{\mathrm{t_p}}\right)^{\mathrm{t_p}/\tau} \exp\left(-\frac{\mathrm{t}-\mathrm{t_p}}{\tau}\right) + \mathrm{C}$
- τ values span over at most an order of magnitude
- While peak flux values can vary up to three orders of magnitude
  - What mechanism regulates the flux intensity over such a wide range?
  - While maintaing the decay so similar?

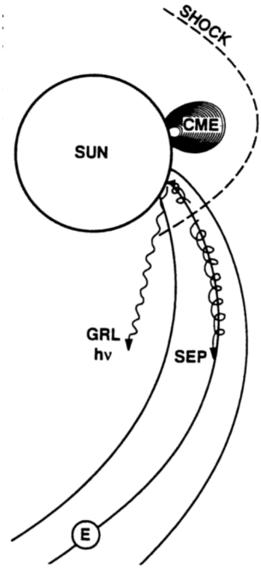
What does the localization of the gamma-ray emission tell us?



Ajello et al. 2021ApJS...252...13

- Prompt emission centroids coincide with the Active Region from which lower energy counterparts originate
- The delayed emission centroids of SOL20120307 illustrate an east-west movement across the solar disk
  - Suggestive of a spatially extended component

Why are behind-the-limb flare interesting?

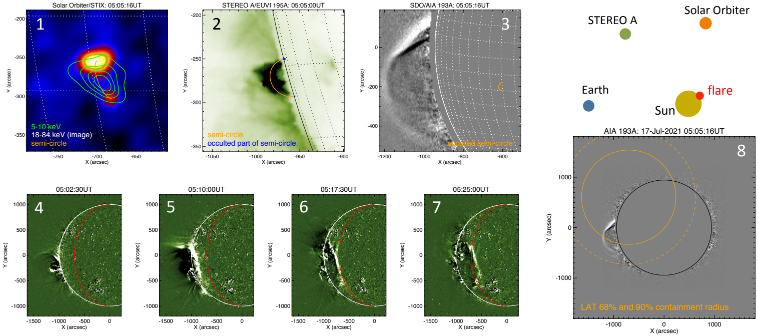


Cliver et al. 1993

- γ-ray emission processes require chromospheric densities
- Measurements of γ-ray line emission are generally consistent wit a compact regions located close the active region
- Observations of γ-rays (both line emission and pion produced) from behind-the-limb flares can imply:
  - A spatially extended flare component that can subtent a large range of heliolongitudes
    - Allowing the particles to interact at the visible disk
  - Or acceleration and/or emission occur in the Corona
    - requires larger than usual Coronal densities or very large loops

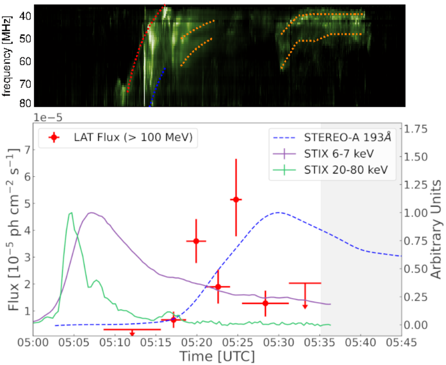
The BTL flare of July 17, 2021

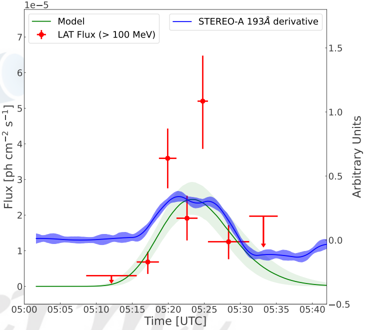
Pesce-Rollins et al. 2022 ApJ 929 172



- Thanks to STIX we were able to localize position of the active region to be 50° behind the visible limb
- Flare detected Fermi-LAT with a significance $>15\sigma$
  - The most distant behind-the-limb flare ever observed in gamma-rays!
- Combined observations with STEREO and SDO indicate that the onset of coronal wave coincides with LAT onset on visible limb

Relation between Coronal wave and LAT flux



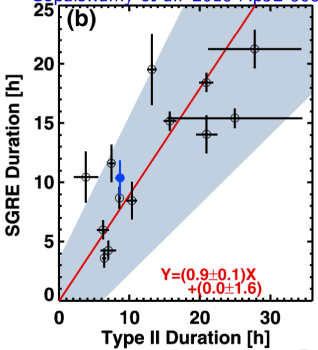


Pesce-Rollins et al. 2022 ApJ 929 172

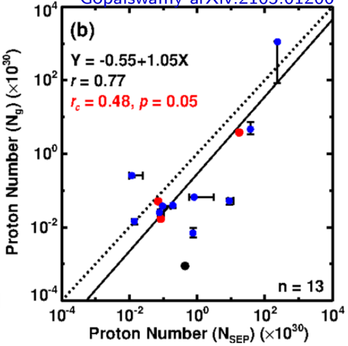
- Radio spectrum from the Gauribidanur Low-Frequency Solar Spectrograph showing Type II radio burst
- The time derivative of the coronal wave light curve peaks at the same time as the LAT flux
  - Probing the rate of particles precipitating to the visible disk
  - Accelerated protons are coupled with the coronal wave

Additional clues from obsevrations on delayed emission

Gopalswamy et al. 2018 ApJL 868 L19

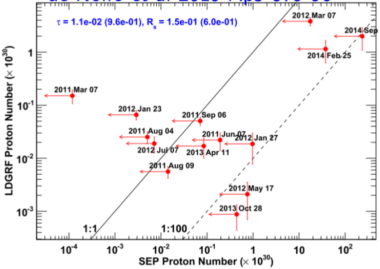


Gopalswamy arXiv:2105:01206

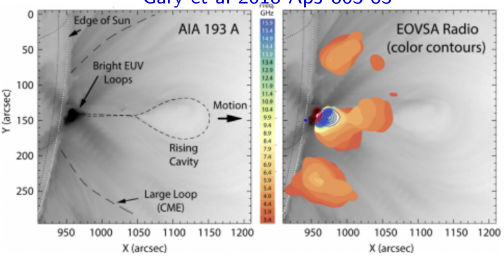


- Duration of >100 MeV gamma-ray solar flares show linear relationship with duration of Type II radio bursts
- Number of protons observed at Earth as SEP and number of protons needed to produce gamma-rays also show correlation
- Strongly suggestive of a common acceleration mechanism

de Nolfo et al 2019 ApJ 879 90



Gary et al 2018 ApJ 863 83

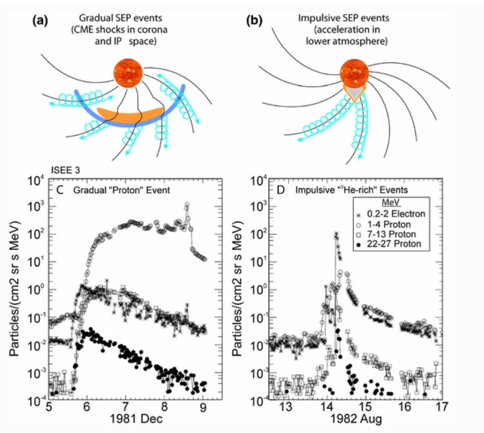


- Complications with magnetic mirroring preventing back precipitation to the photosphere
  - Proposed scenario: Particle accelerated via second-order Fermi mechanism and trapped locally within extended coronal loops
- EOVSA microwave observations identified large coronal loop footpoint
  - The microwave emission persisted well into the extended phase of the $>$100 MeV γ-ray emission

Summary

- The first 15 years of *Fermi*-LAT observations of gamma-ray solar flares have revealed a rich and diverse sample of events
- Emission observed during the prompt-impulsive phase correlates with Hard X-rays and appears to be tied to the flaring activity
- Long and short delayed emission may require an additional mechanism for accelerating the particles
- Behind-the-limb gamma-ray emission is coupled with EUV coronal waves and support the CME-shock acceleration scenario as the most likely mechanism for these events
- Correlations between the durations of Type II bursts and the duration of the gamma-ray emission suggest a common origin of acceleration $\rightarrow$ the Coronal Mass Ejection shock front
- Particle accelerated via second-order Fermi mechanism and trapped locally within extended coronal loops also a possibility
  - Need additional observations to help solidify this scenario

Spare slides



Desai & Giacalone 2016

- The gradual event is produced by a large-scale CME-driven shock wave that accelerates the SEPs and populates interplanetary magnetic field (IMF) lines over a large longitudinal area
- The impulsive event is produced by a solar flare that populates only those IMF lines well-connected to the flare site

Correlation also in other BTL flares

Gamma-ray behind-the-limb flares

Flare	LAT peak flux time (UT)	EUV peak time (UT)
FLSF 2013-10-11	07:19 ± 1 minute	07:16
FLSF 2014-09-01	11:11 ± 1 minute	11:14
FLSF 2021-07-17	05:23 ± 1 minute	05:21
FLSF 2021-09-17	04:17 ±0.5 minute	04:17

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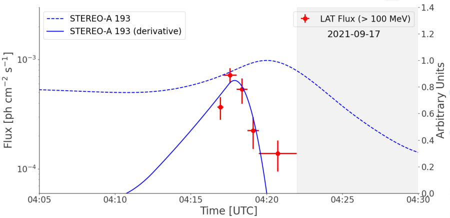

- At the time of the study, a total of 5 BTL flares had been detected by the LAT
- Analyzed EUV coronal wave data for these flares and found same correlation to be present in four of the flares
  - Flare of 2014-01-06 was lacking gamma-ray statistics to perform the study
- CME-shock acceleration is most likely the driving mechanism for the γ-rays observed in btl flares