Probing particle acceleration through gamma-ray Solar flare observations

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on behalf of the *Fermi*-LAT collaboration

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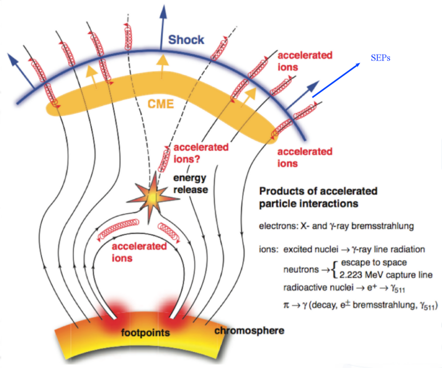
Gamma-ray Solar flares

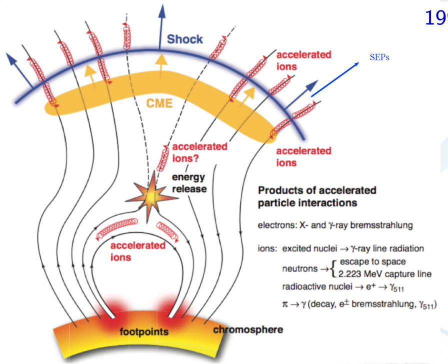


γ-ray emission from Solar flares

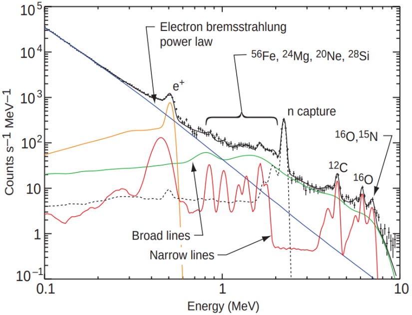
Produced by interactions of high-energy particles with ambient plasma:

1. Bremsstrahlung
   - 10 keV – 1 GeV
2. Nuclear de-excitation
   - $\approx$0.5 – 8 MeV
3. Pion decay
   - $>$10 MeV

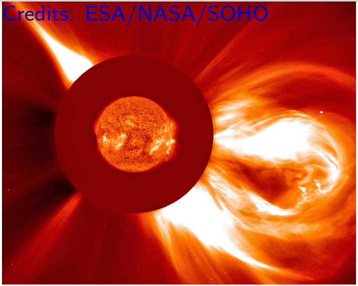
- Magnetic reconnection believed to be at the origin of particle acceleration in Solar flares
- γ-rays provide clues on the properties of the acceleration mechanisms and information on ambient plasma
  - Chromospheric ion abundances
  - Maximum energy of the accelerated charged particles
  - Coronal trapping times



1991 June 4 solar flare observed with CGRO/OSSE



- Particle accelerated are trapped within a loop and interact at the higher densities associated with the footpoints
- Deexcitation lines→ ∼1<E<20 MeV protons interacting with ambient solar material
- Neutron capture line→ up to 100 MeV protons
- Continuum above ∼30 MeV in gamma-rays → >280 MeV protons



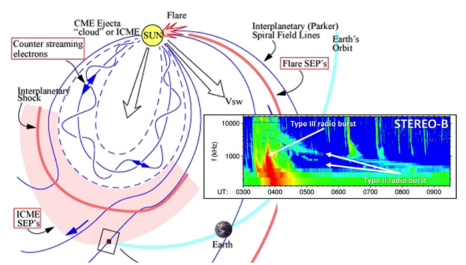
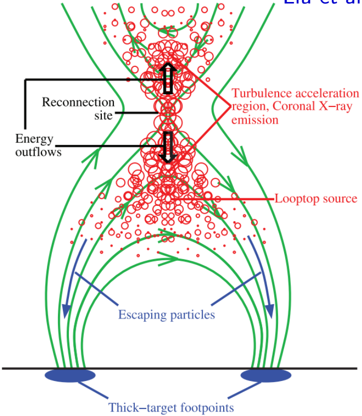


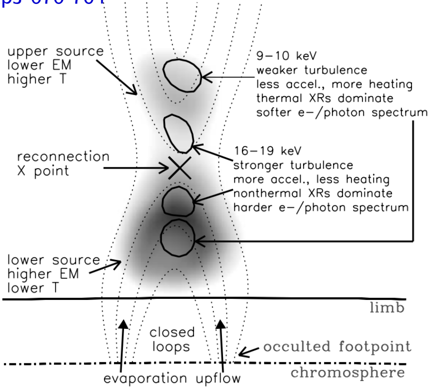
Figure 1. Illustration of ICMEs, solar flares, and associated radio emissions. Image Credits: NASA

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

Evidence for magnetic reconection

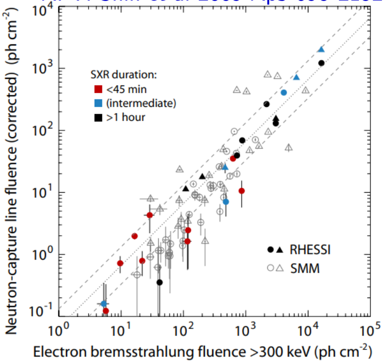


Liu et al 2008 ApJ 676 704

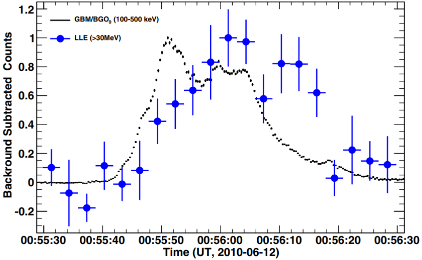


- Outflows in opposite directions can generate turbulence that accelerates particles and heats the background plasma stochastically
  - Two distinct X-ray sources, one above and one below the reconnection region are expected in this scenario
- RHESSI revealed these distinct sources confirming expectations

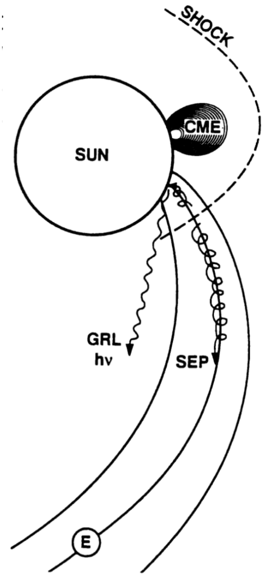
A. Y. Shih et al 2009 ApJ 698 L152



Ackermann et al 2012 ApJ 745 144

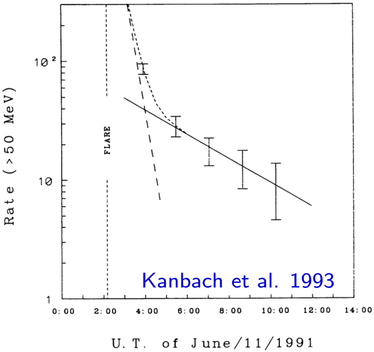


- The acceleration of >0.3 MeV electrons proportional to the acceleration of >30 MeV protons over > 3 orders of magnitude
  - Strongly implying a common acceleration mechanism during the impulsive phase of the flares
- Gamma-ray emission lags the bremsstrahlung by 6±3 sec
  - >280 MeV ions accelerated on similar timescale as 100's keV electrons



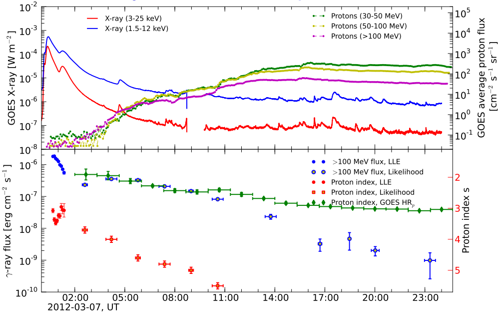
Cliver et al. 1993

- γ-ray emission processes require chromospheric densities
- Measurements of γ-ray line emission are generally consistent with a compact region located close to 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 subtend a large range of heliolongitudes
  - Or acceleration and emission occur in the Corona
- Only 3 cases observed prior to 2008
  - Difficult to identify the origin of the γ-ray emission



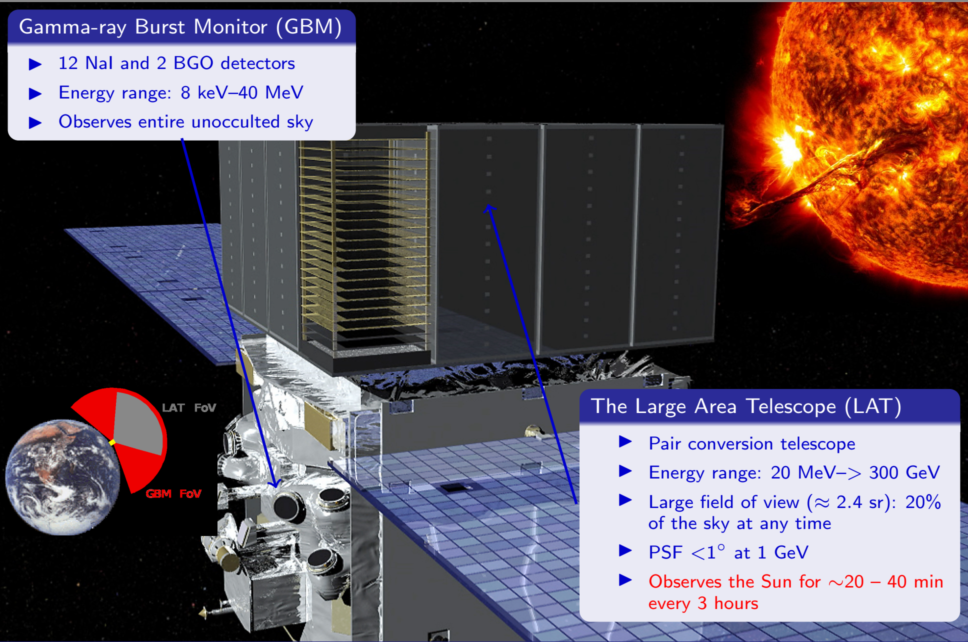
Kanbach et al. 1993

Ajello et al. 2014ApJ...789..20



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

The *Fermi* Space Telescope

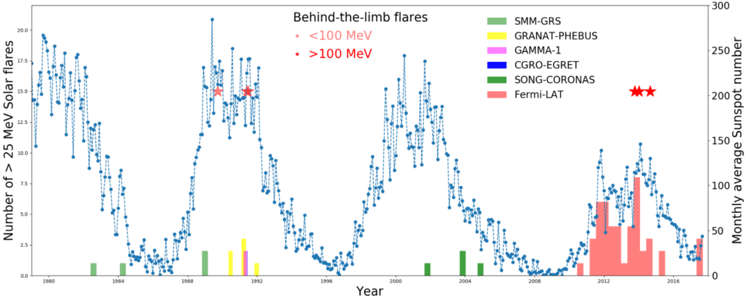


Gamma-ray Burst Monitor (GBM)

- 12 NaI and 2 BGO detectors
- Energy range: 8 keV–40 MeV
- Observes entire unocculted sky

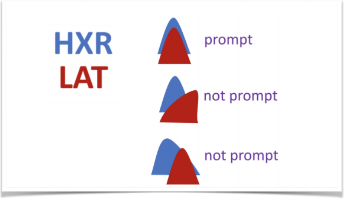
The Large Area Telescope (LAT)

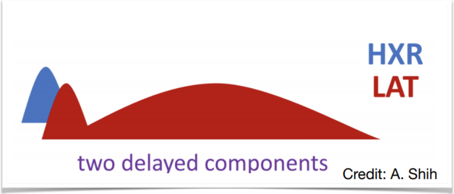
- Pair conversion telescope
- Energy range: 20 MeV–> 300 GeV
- Large field of view ($\approx$ 2.4 sr): 20% of the sky at any time
- PSF $<1^{\circ}$ at 1 GeV
- Observes the Sun for $\sim$20 – 40 min every 3 hours



- 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 45 Solar flares during the 24th Solar cycle
  - More than half are associated with more modest X-ray flares
  - Extended >100 MeV emission observed from 37 flares
  - 3 behind-the-limb flares with >100 MeV emission

Categories of Fermi LAT Solar Flares (FLSF)

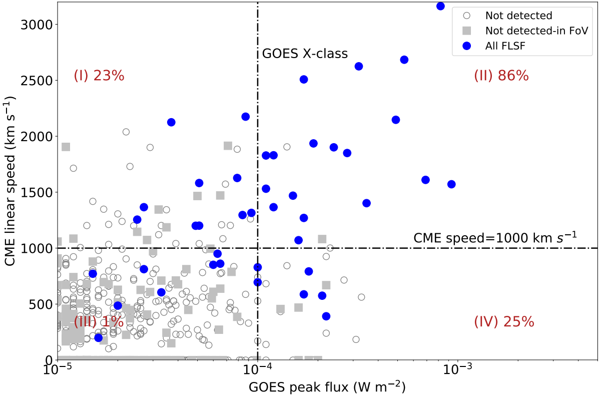




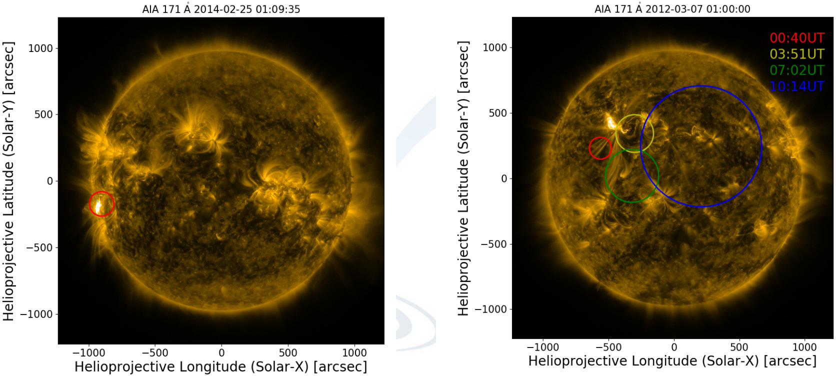
The Fermi-LAT Solar Flare Catalog (Ajello et al 2021 ApJS 252 13) contains 45 flares, revealing a rich sample of events

- 18 with a prompt component synchronized with HXR
- 37 with some delayed component beyond HXR
  - 21 exhibit delayed emission lasting longer than 2 hours
  - 16 exhibit delayed emission lasting less than 2 hours
  - 4 exhibit only delayed emission–no prompt emission detected
- 8 with only a prompt component
- 3 behind the limb

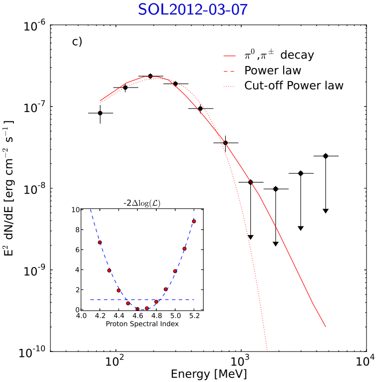
Ajello et al 2021 ApJS 252 13



- CME speed vs soft X-ray peak flux for all flares of Solar cycle 24
- Most favorable condition for γ-ray emission: flares with SXR flux$>10^{-4}$ W m^{-2} and CME with linear speed >1000 km s^{-1}
- Quadrants (I) and (IV) are equally favorable



- 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

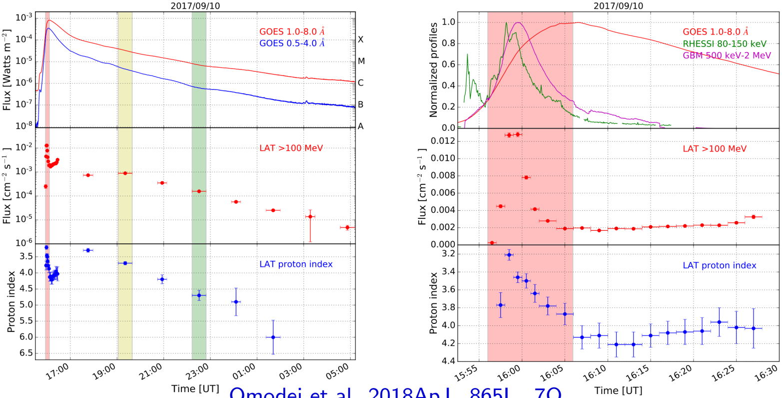


We fit the LAT spectral data between 60 MeV and 10 GeV to test three different emission models:

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

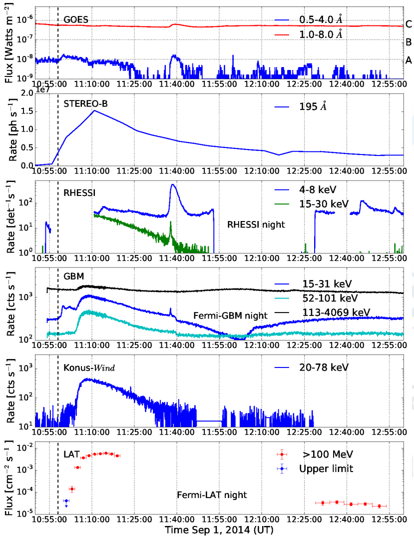
- When model (2) provides a better fit we also fit the data with a series of pion-decay models to determine the best proton spectral index

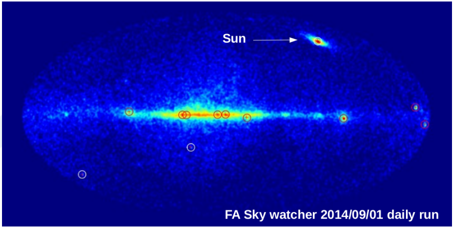


Omodei et al. 2018ApJ...865L...7O

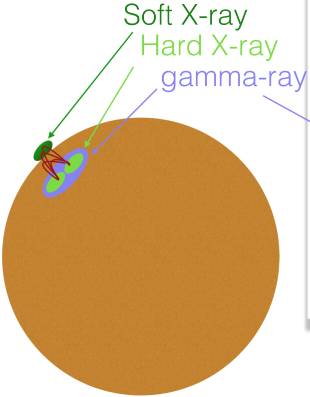
- Data suggests multiple phases in flux and proton index evolution
- Prompt phase light curve follows X-ray
- Intermediate steady phase isolated from X-rays (<20 minutes)
- Delayed phase for around 10 hours

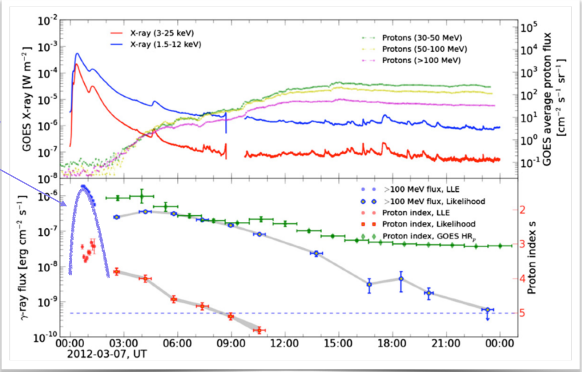
Ackermann et al. 2017ApJ...835..219A



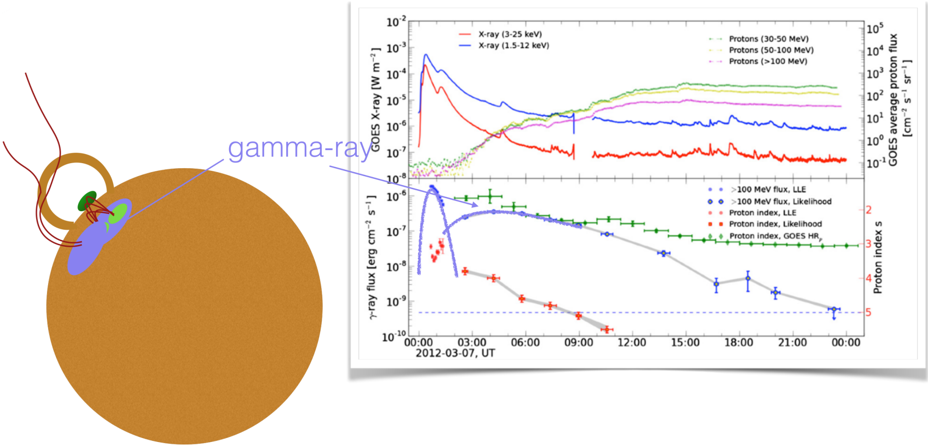


- The September 1st 2014 flare was unleashed from an active region near 40° behind the visible limb
  - More than 500,000 km behind the visible side of the Sun
- 15 photons withe E>1 GeV detected during the first 15 minutes (including 3.5 GeV photon)
- Emission lasted for almost two hours
- Mechanism driving this emission?

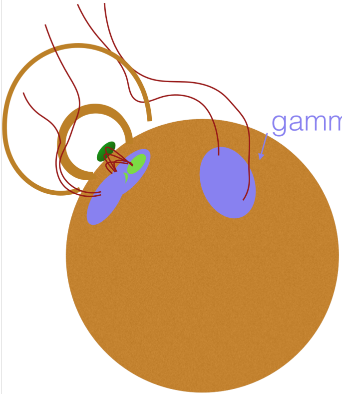


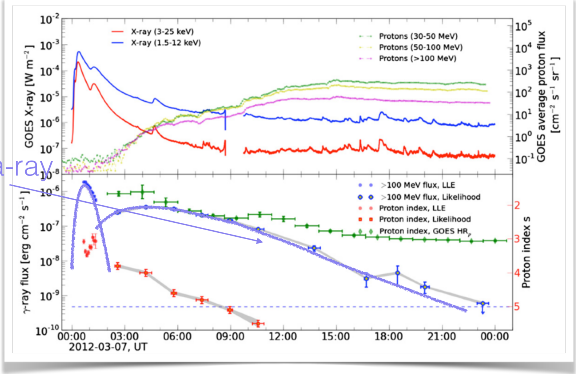


- Soft X-rays emitted from the loop top
- Hard X-rays emitted from the foot points
- Gamma-rays emitted from the chromosphere near the foot points

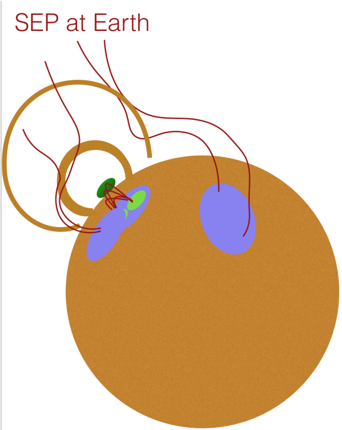


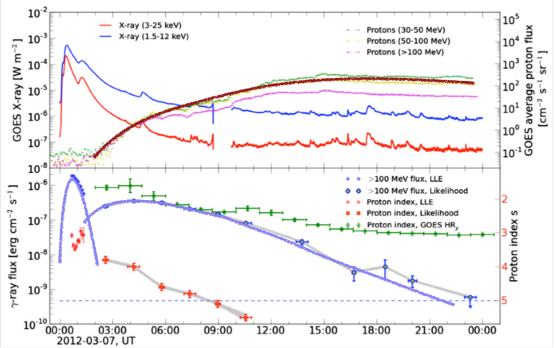
- Long duration gamma-ray emission from particles accelerated at the CME shock front
- Accelerated particles precipitate back to the chromosphere to produce gamma-rays





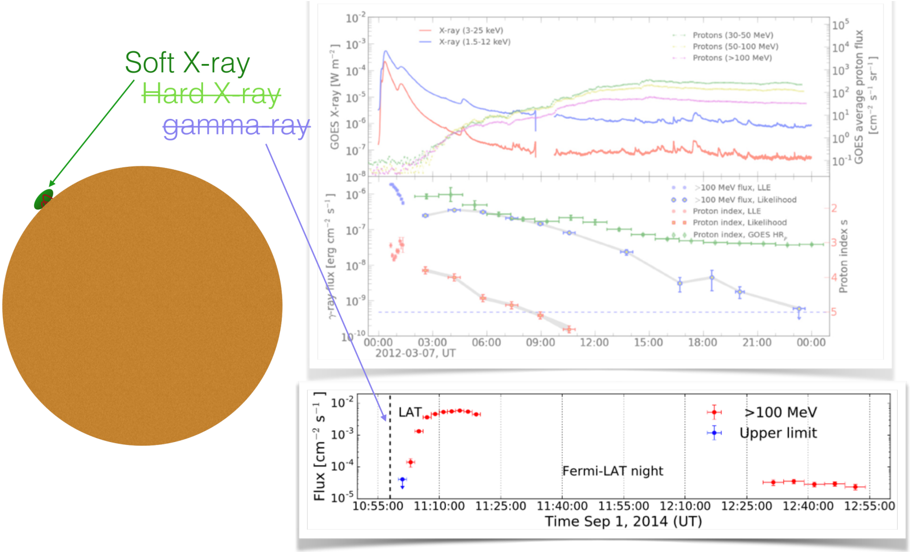
- Long duration gamma-ray emission from particles accelerated at the CME shock front
- Accelerated particles precipitate further away from the active region to produce gamma-rays

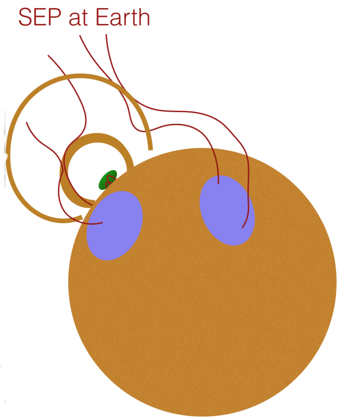


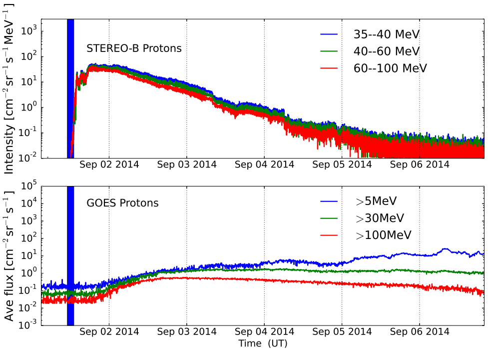


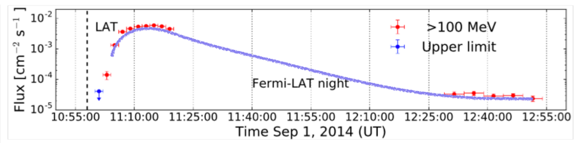
- Long duration gamma-ray emission from particles accelerated at the CME shock front
- Some of the accelerated particles escape from the CME shock front and are detected as SEP at Earth

Possible scenario for behind the limb flares





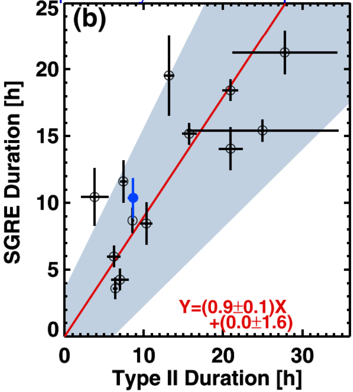




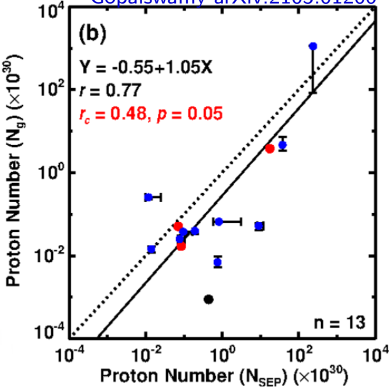
- Accelerated particles access field lines connected to the visible disk and produce gamma-rays

Clues from observations

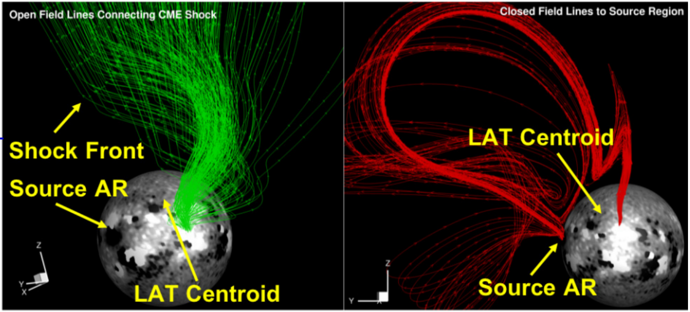
Gopalswamy et al. 2018 ApJL 868 L19



Gopalswamy arXiv:2105:01206



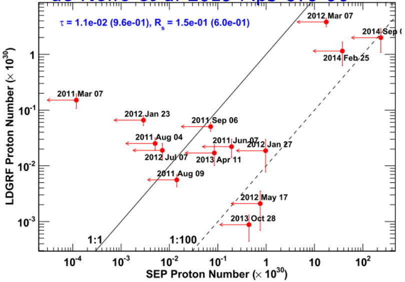
- Duration of >100 MeV gamma-ray solar flares show linear relationship with duration of Type II radio bursts
- Number of protons observed at Earth as SEP and number of protons needed to produce gamma-rays also show correlation
- Strongly suggestive of common acceleration mechanism: CME shock



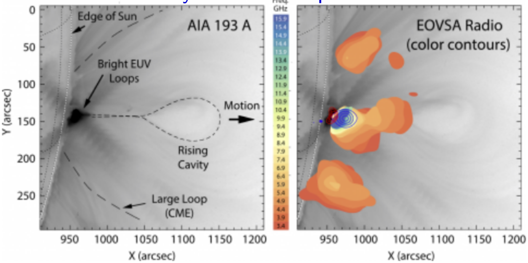
Jin et al 2018 ApJ 867 122

- Simulated CME associated Fermi BTL flare on September 1, 2014 by using a data-driven global MHD model
- Magnetic connectivity established between CME-driven shock and centroid of the Fermi-LAT γ-ray source
- Rate of particle acceleration by the shock closely correlated with the Fermi γ-ray flux
- Supporting evidence for acceleration at CME shock scenario

de Nolfo et al 2019 ApJ 879 90

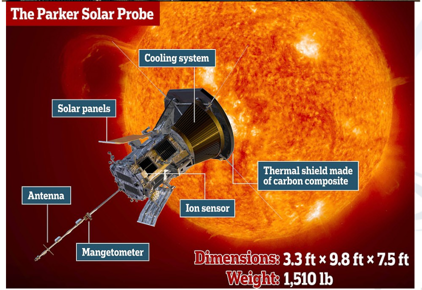


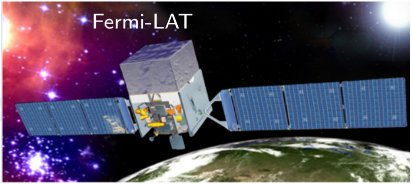
Gary et al 2018 ApJ 863 83



- de Nolfo et al. do not find correlation between SEP and γ's
- Complications with magnetic mirroring preventing back precipitation to the photosphere
  - *Alternative scenario*: Particles accelerated via second-order Fermi mechanism and trapped locally within extended coronal loops
- *Supporting observation*: Microwave observations identified large coronal loop footpoint
  - Microwave emission persisted well into the extended phase of the $>$100 MeV γ-ray emission

Future prospectives





- Expanded Owens Valley Solar Array will continue to provide microwave observations →Help to distinguish acceleration scenario
- Solar Orbiter and Parker Solar Probe will provide full coverage of the solar activity → exquisite data that will unveil needed details

Summary and conclusions

- Gamma-ray observations of solar flares allow us to probe ion acceleration up to GeV energies
- Prompt-impulsive phase most likely driven by magnetic reconnection
- Observations of hour-long delayed emission persistent after all other flaring counterparts have ceased
  - Need for an additional mechanism for driving this emission
- Correlations between duration of Type II bursts and gamma-ray emission suggest a common origin of acceleration → the Coronal Mass Ejection shock front
  - Supported by MHD simulations and observations of BTL flares
- 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
- Exciting times for solar physics with many new observatories working in synergy