Gamma-Ray and Neutron Monitor Observations of the 2017 September 10 Solar Eruptive Event

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SEP, Solar Modulation, and Space Radiation

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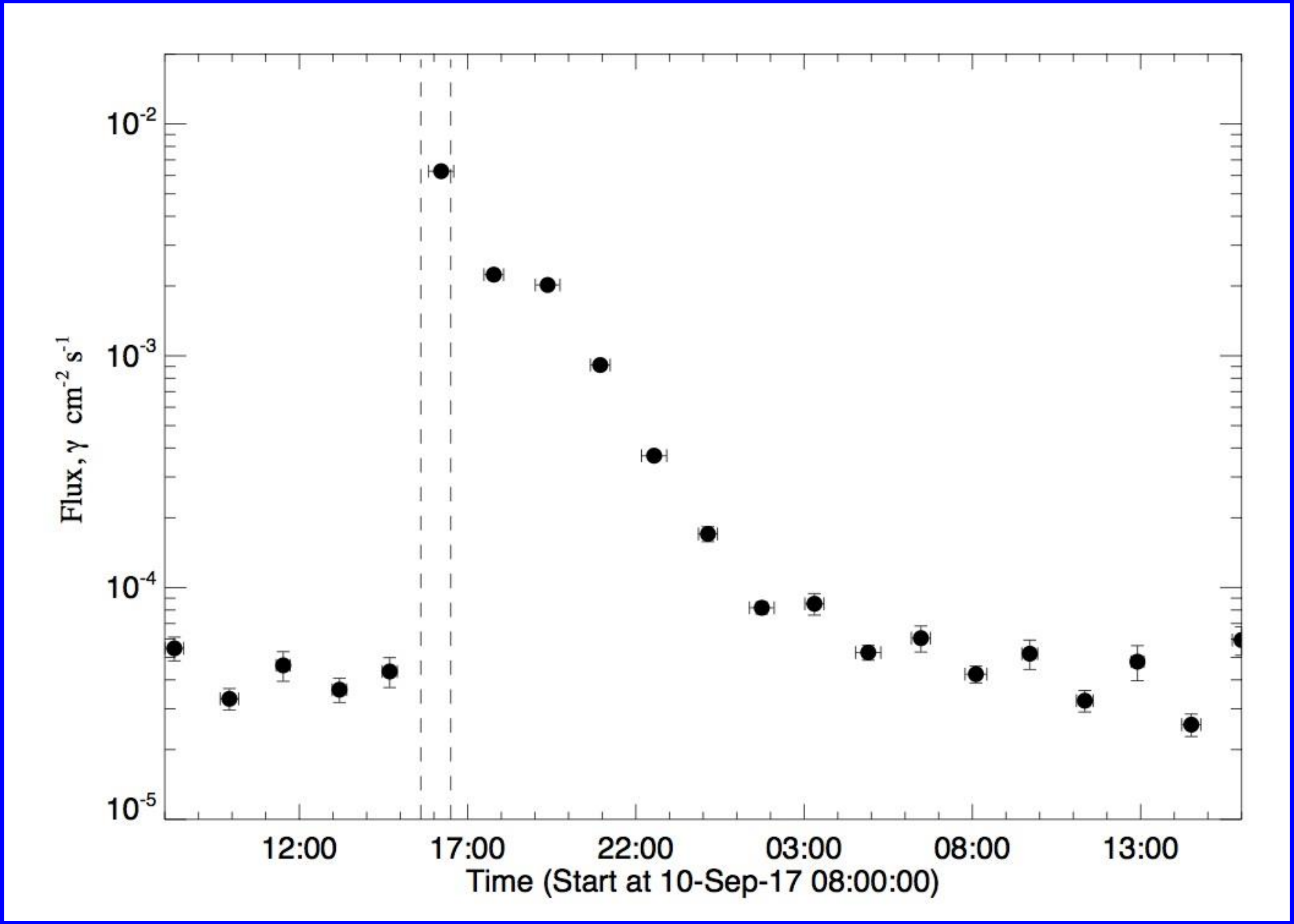
Introduction

We have independently analyzed 30 solar eruptive events observed by Fermi from 2008-2016 with late phase gamma-ray emission temporally and spectrally distinct from impulsive phase emission (arXiv:1711.0111v, 5 Nov. 2017, being revised for ApJ) found in 'long duration gamma ray flares' observed prior to Fermi (see Ryan 2000, Ryan and Chupp 2009).

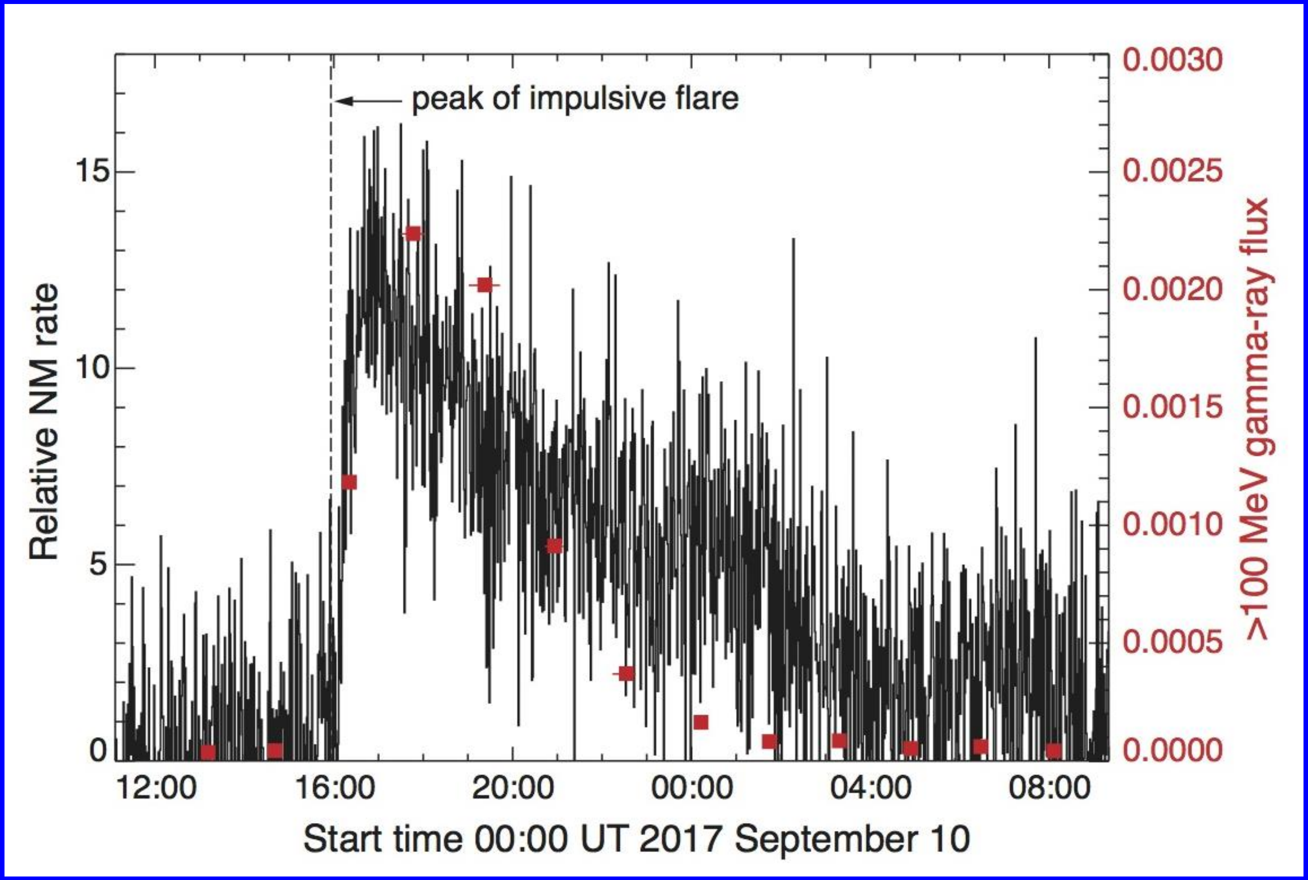
Here we discuss observations of the 2017 September 10 limb event and provide evidence that there are three phases of >100 MeV emission. Omodei et al 2018 discuss timing, spectral, and localization studies.

We provide preliminary studies comparing the >100 MeV and neutron monitor time histories.

We also discuss related studies of proton directivity producing the pion-decay emission and of gamma-ray attenuation.

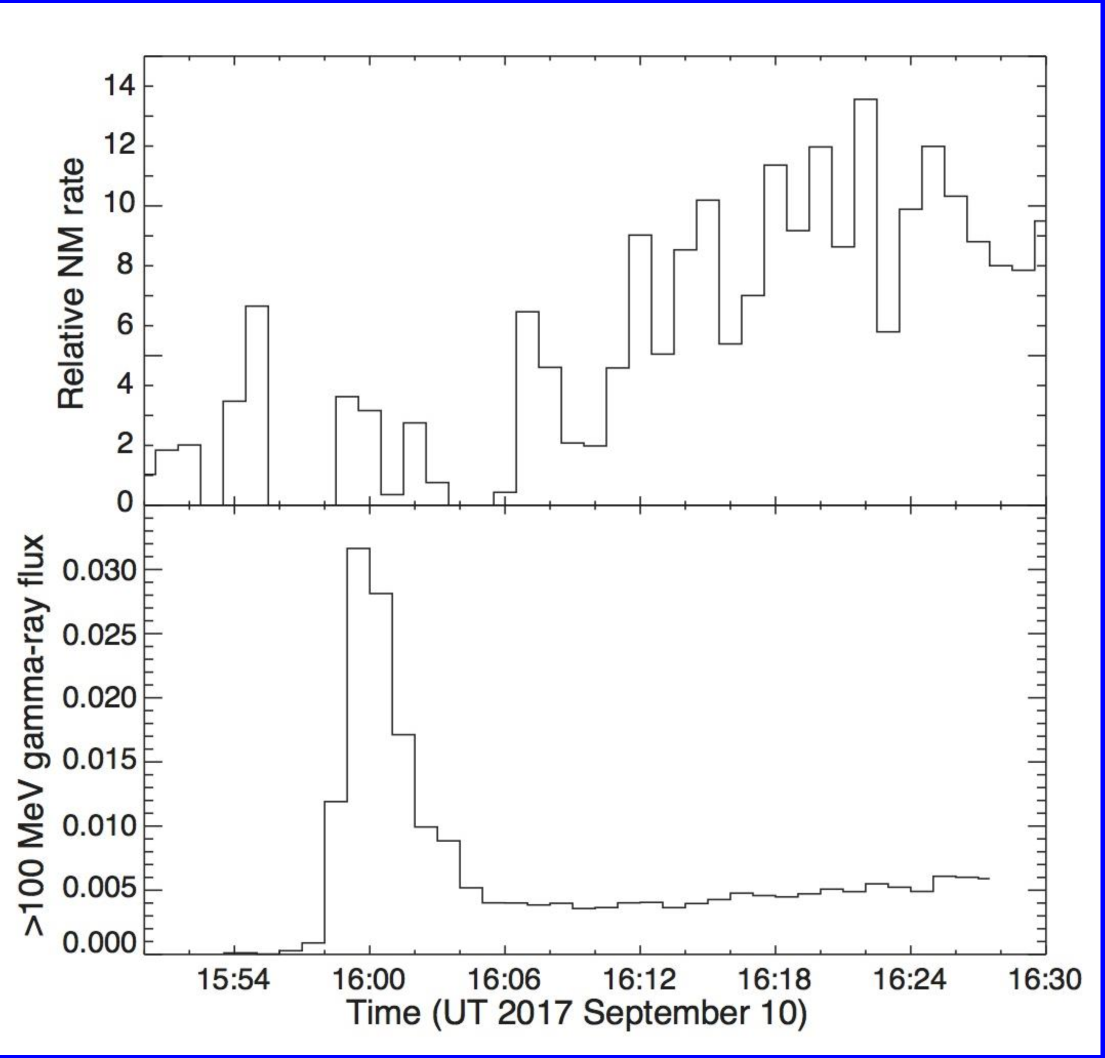


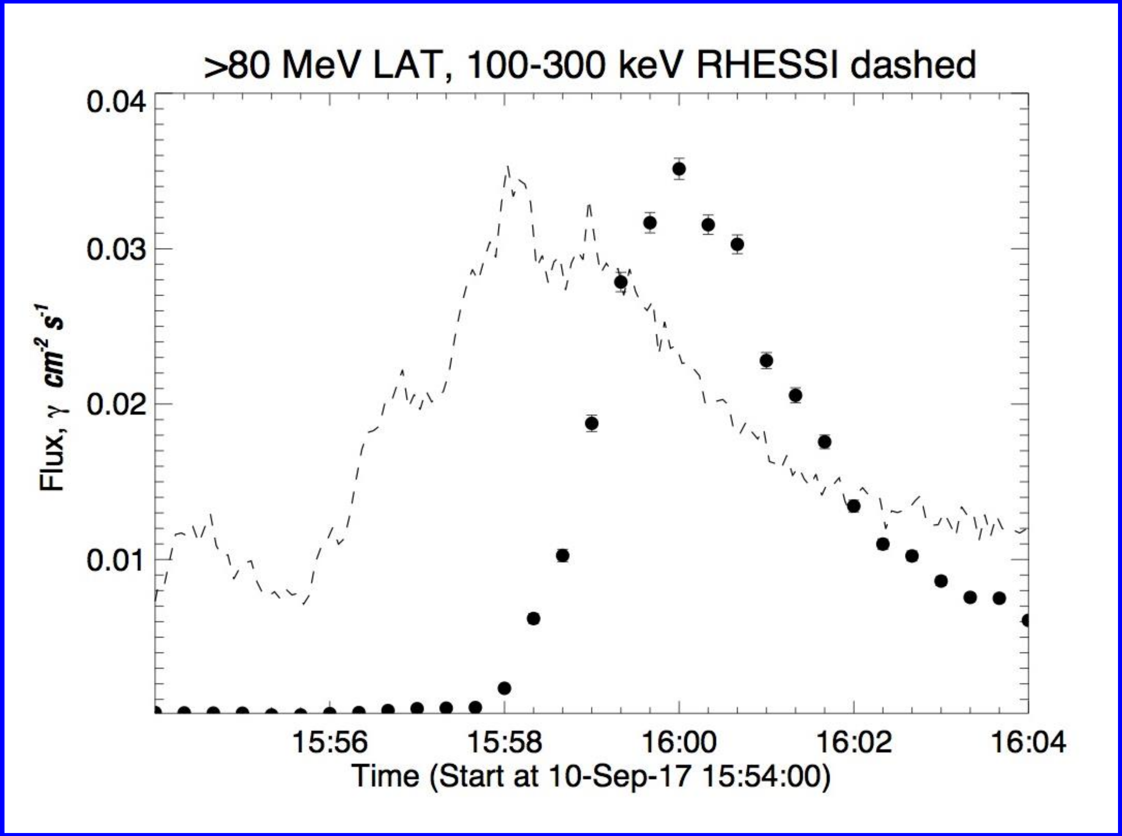
Time history of LAT observations of >80 MeV gamma-ray fluxes in the hours around the 2017 September 10 solar eruption associated . Dashed lines: X-ray flare. The >300 MeV proton spectrum softened from 17 Hr to 23 Hr.



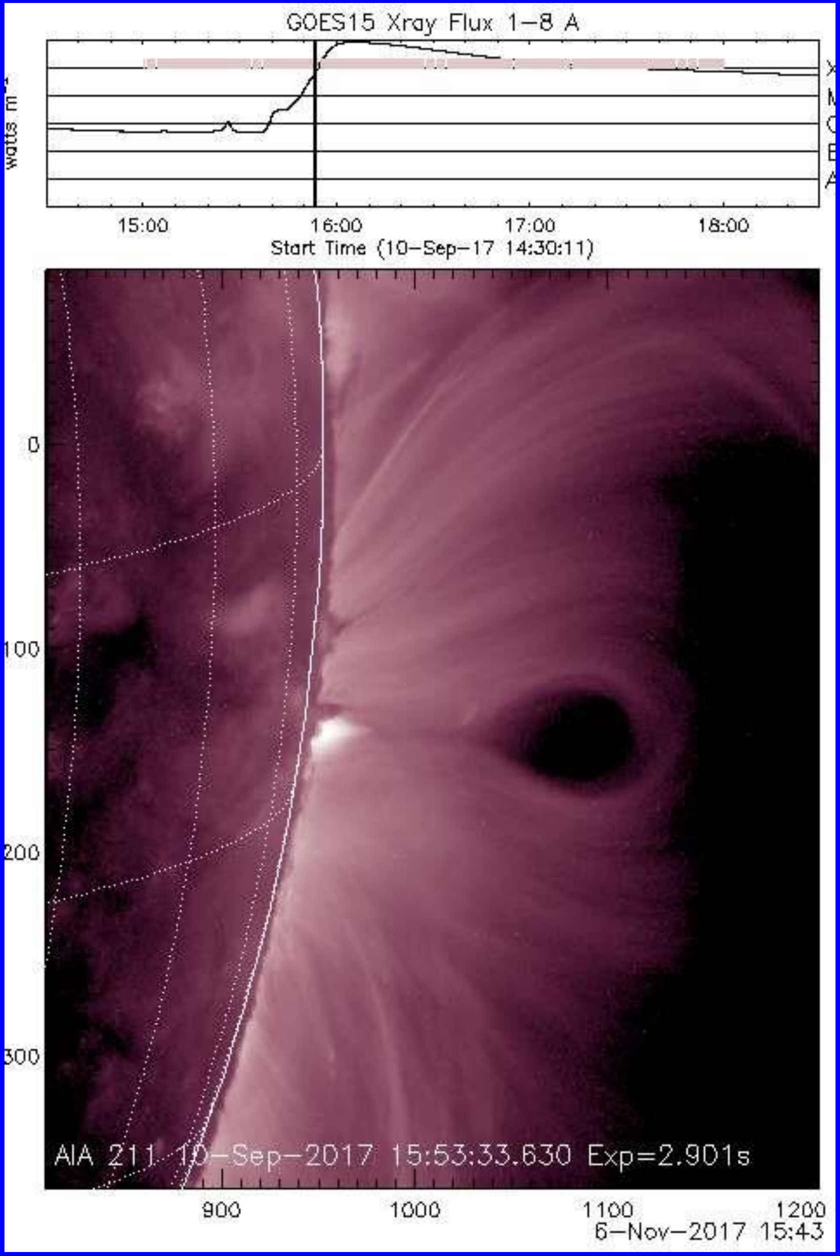
17 hr comparison of the Fort Smith neutron monitor rate (>500 MeV protons) and the long duration >100 MeV gamma-ray flux (first two components removed). The gamma-ray flux falls more rapidly.

Comparison of the Fort Smith neutron monitor rate (>500 MeV protons; R. Pyle and P. Evenson) in the top panel and the >80 MeV gamma-ray rate which monitors protons >300 MeV at the Sun. Is the rise in the ground level event consistent with particle release at the time of the gamma-ray peak? David Ruffolo is studying this.

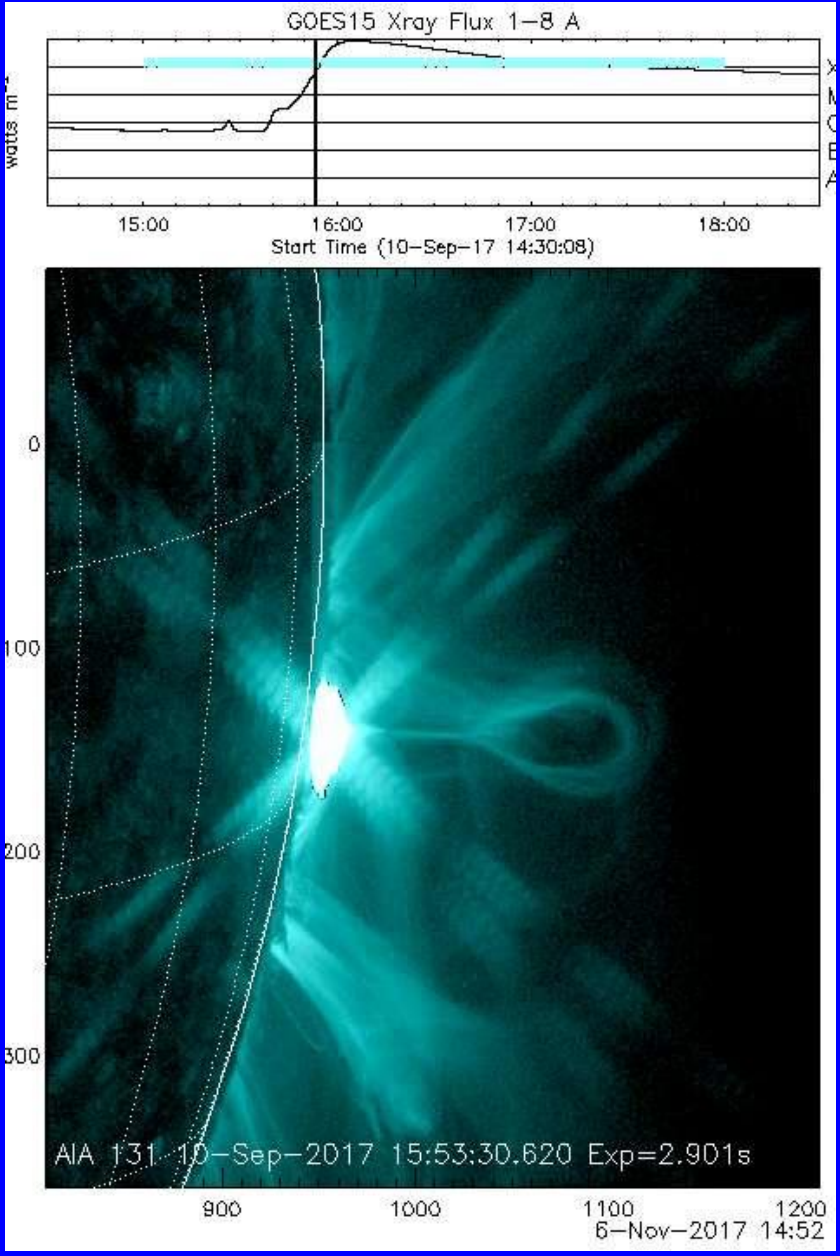




>80 MeV fluxes at 20 s cadence compared with impulsive 100-300 keV hard X-ray emission. The gamma-ray peak is delayed by about two minutes from that of the X-rays. >100 keV emission begins at ~15:45 UT.



2 x 10^6K



0.4 x 10^6K, 20 x10^6 K

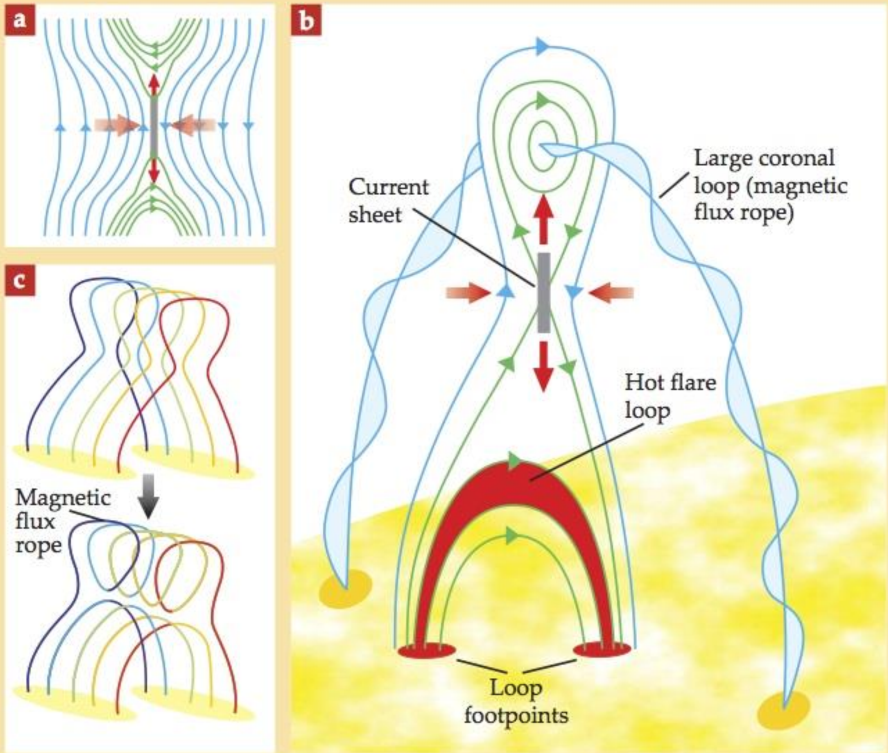
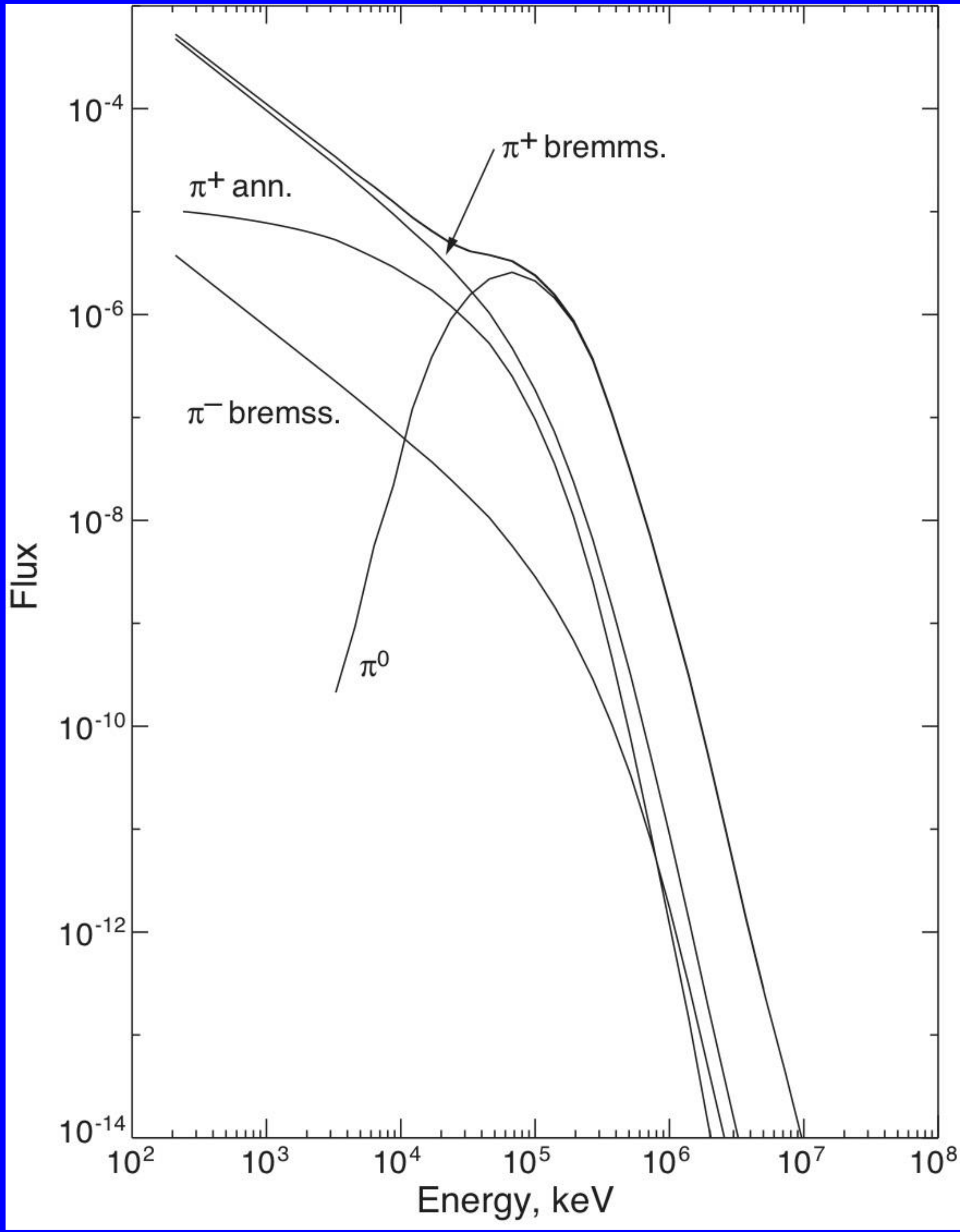


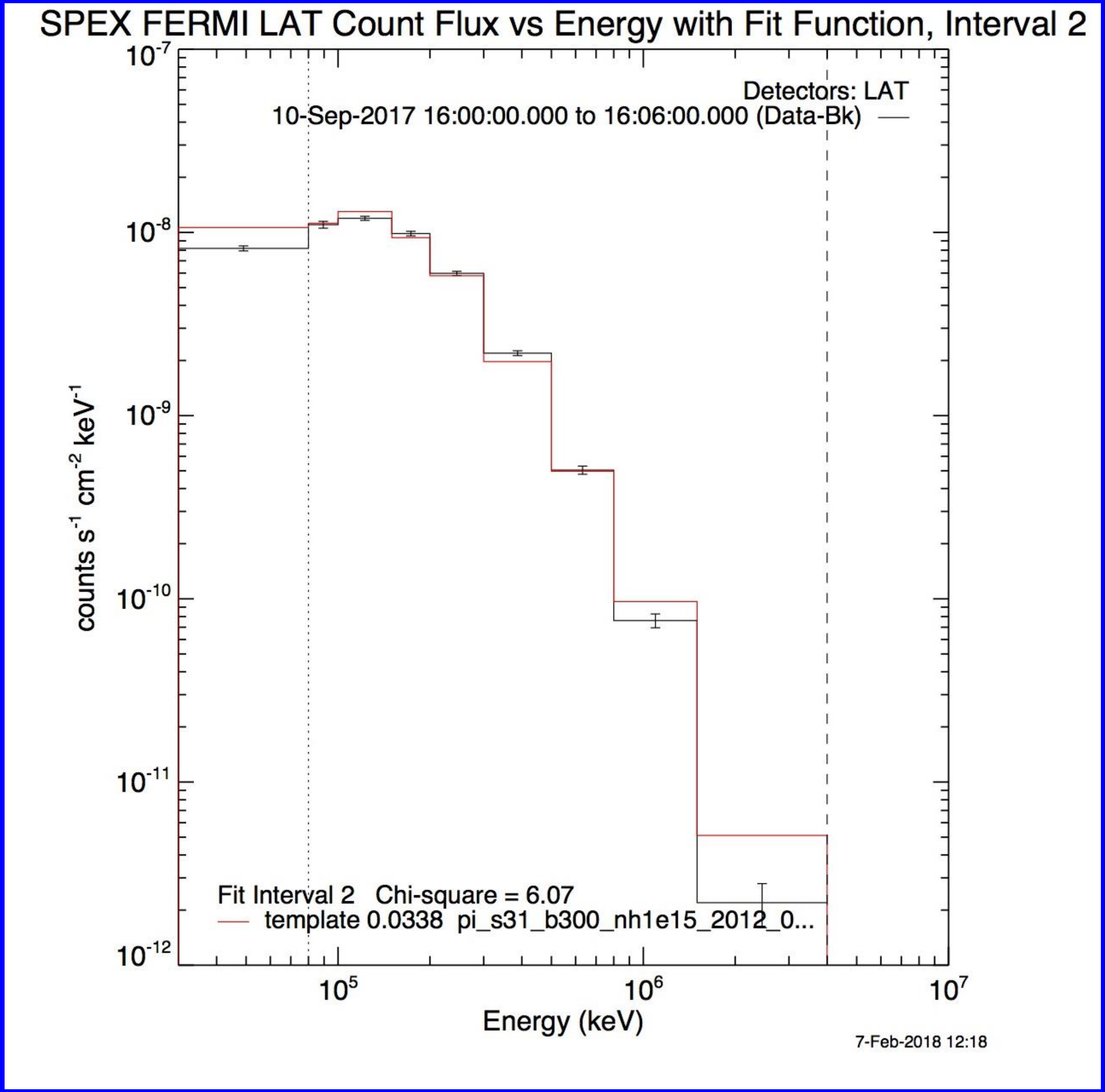
Figure 1. Magnetic reconnection and the standard model for solar eruptive events. **(a)** In magnetic reconnection, oppositely directed magnetic field lines (blue) flow inward and reconnect, releasing much of their magnetic energy to the ambient plasma. The reconnected field lines (green) flow outward, and their associated plasma is ejected in reconnection jets. In the reconnection region (gray), a sheet of current flows perpendicular to the plane of the page. **(b)** In a solar eruptive event, reconnection occurs in an arcade of loops rising above the visible surface of the Sun. **(c)** Because of shearing of the original arcade, the loops generally reconnect with their neighbors, not with themselves. A twisted magnetic flux rope forms and expands upward to become a coronal mass ejection.

Holman, Physics Today, 2012

Calculated pion-decay spectrum from >300 MeV p-H and >200 MeV/nucleon α/H interactions (Murphy, Dermer, & Ramaty 1987) showing the contributions from neutral and charged pion decays for an isotropic angular distribution. The pion-decay emission below the peak at ~70 MeV is dominated by both bremsstrahlung and annihilation in flight of positrons from positive pion-decays. At energies >100 MeV gamma rays from neutral pion decays dominates.

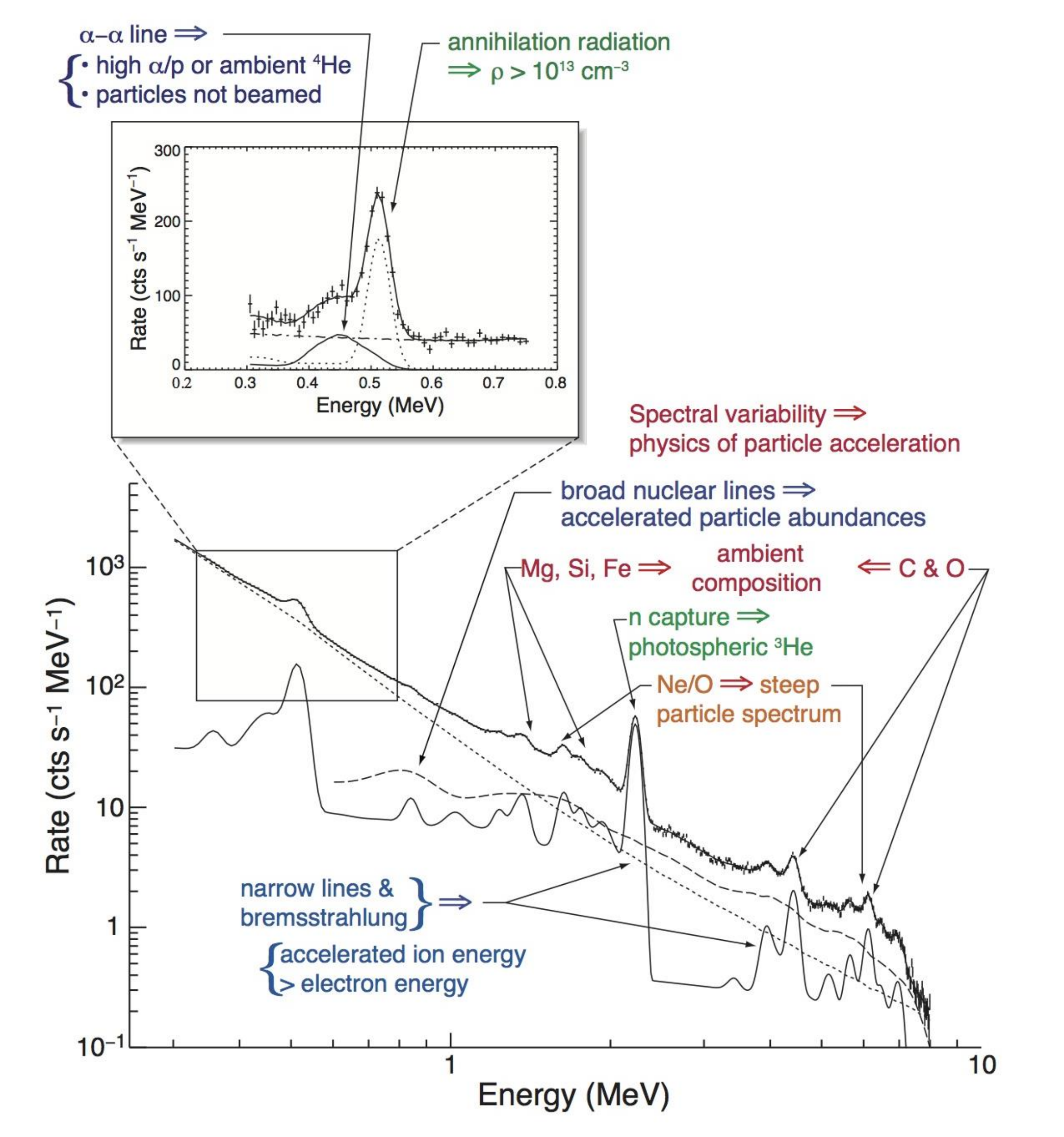


Fit to the LAT gamma-ray spectrum after the peak of >80 MeV emission at 16 hr with a template from neutral and charged pions and their products. This spectrum is fit with a >300 MeV proton spectrum following a power-law with an index 3.1.

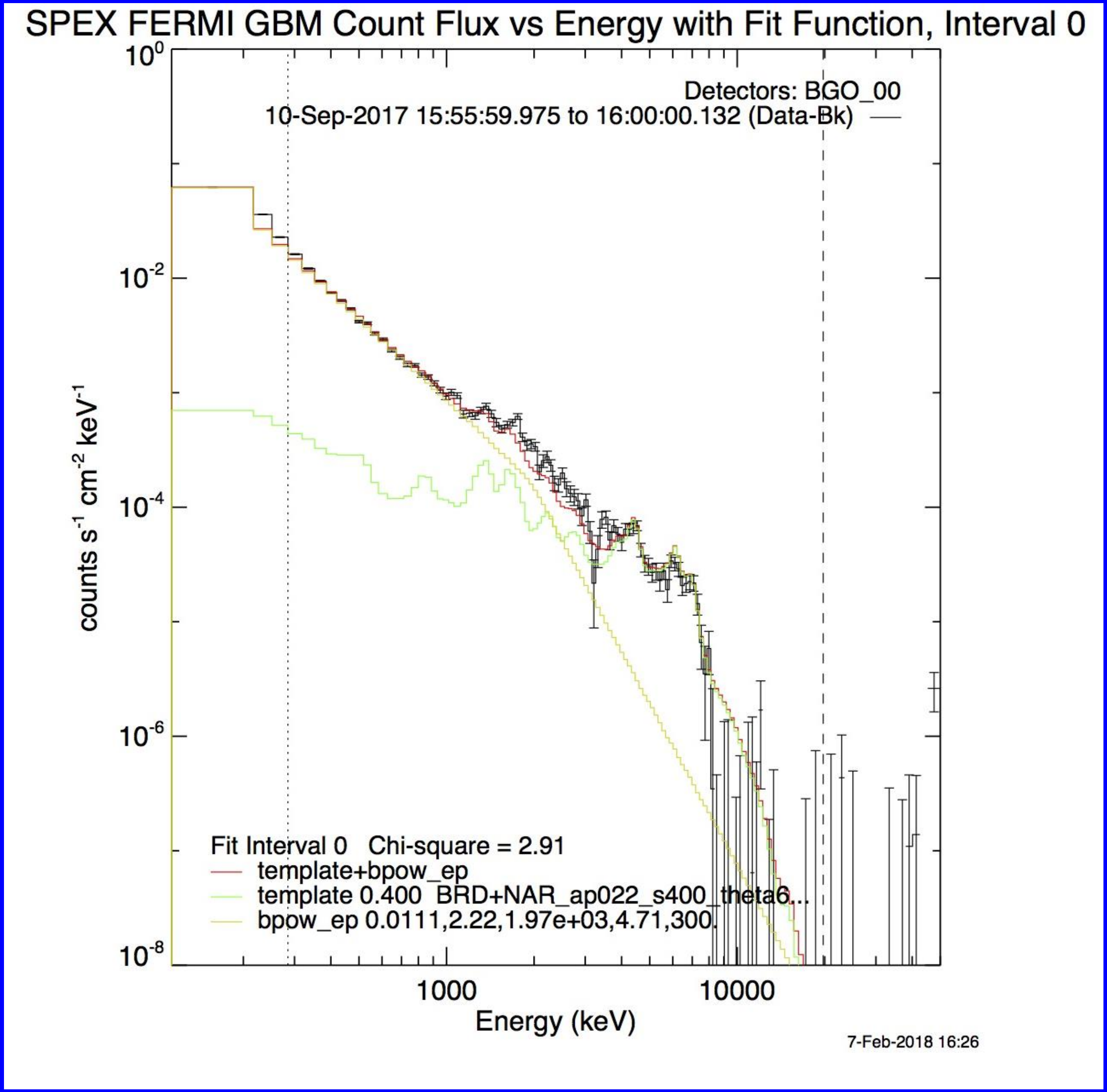


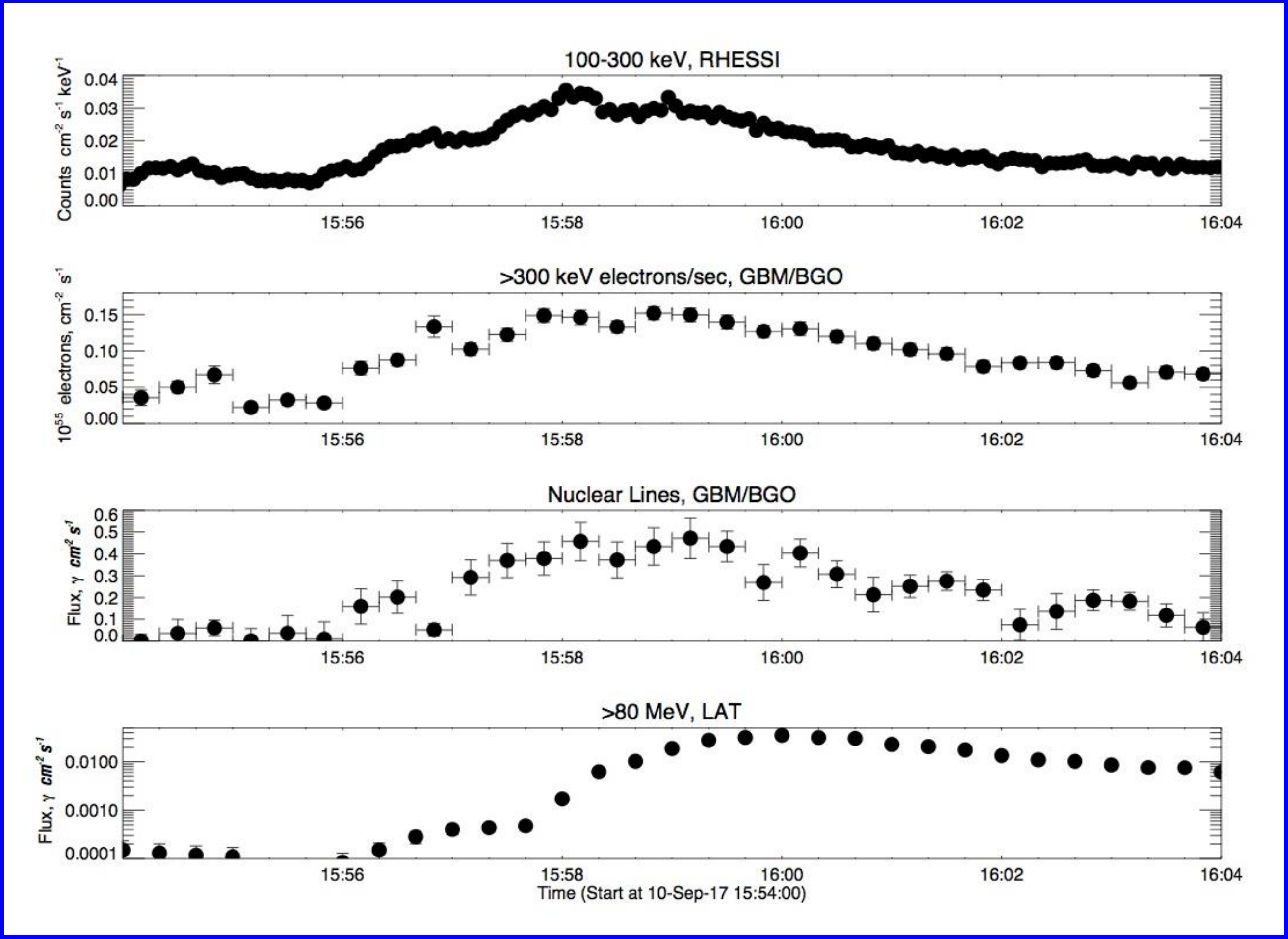
What γ-Rays Tell us About Accelerated Particles at the Sun

Summed γ-ray spectrum between 0.3 and 8 MeV from 19 solar flares observed by SMM. The contributing components are identified: electron bremsstrahiung, narrow nuclear lines from p's and α's, broad lines from heavy ions, e^+-e^- annihilation line, neutron capture line, and α-α fusion lines.



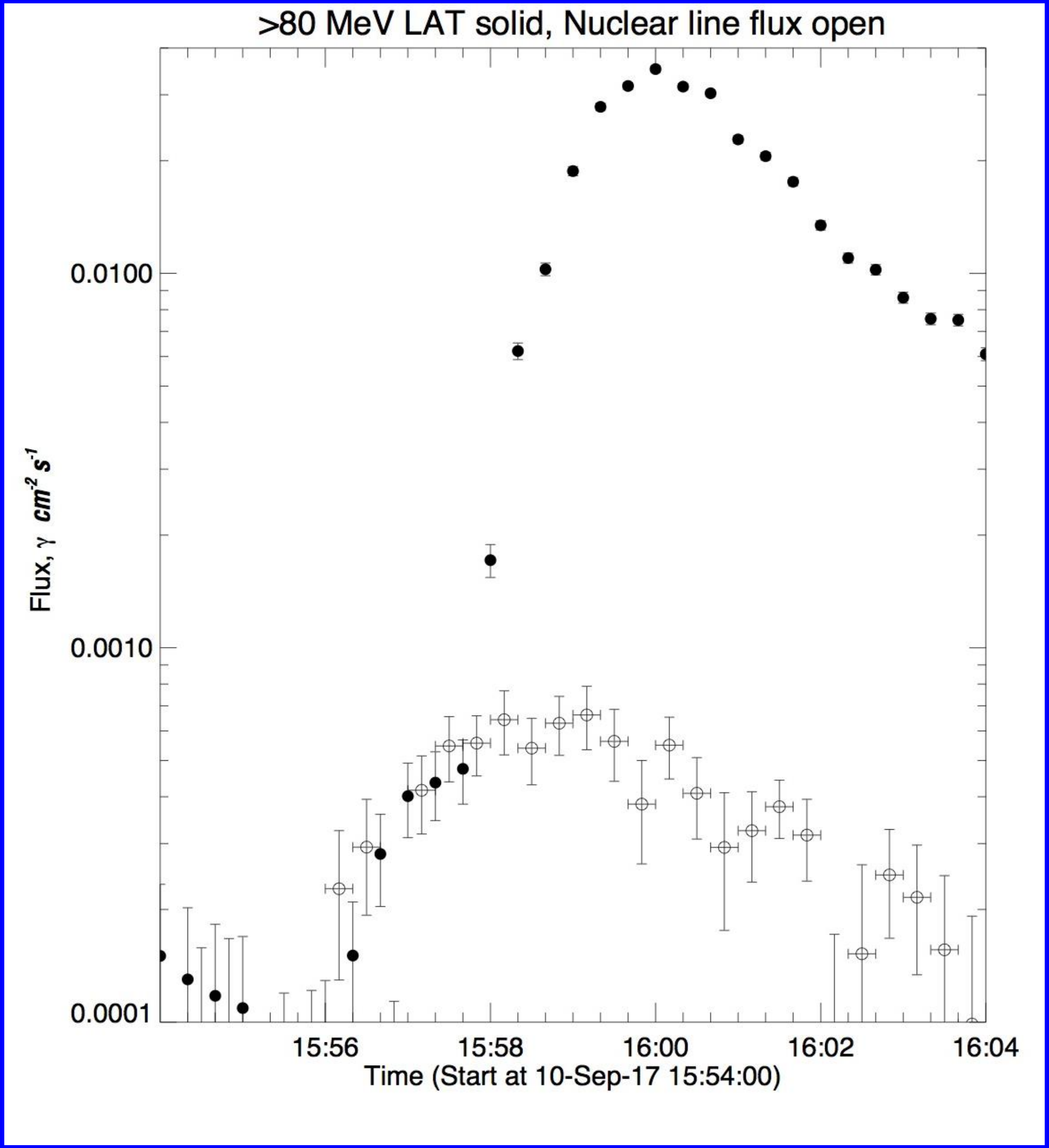
Fit to GBM/BGO gamma-ray spectrum with a broken power-law bremsstrahlung component and a nuclear line spectrum. Note the characteristic fall off in gamma rays >7 MeV. The GBM spectrum has some unfortunate artifacts. The neutron capture line is not visible because of severe limb darkening.



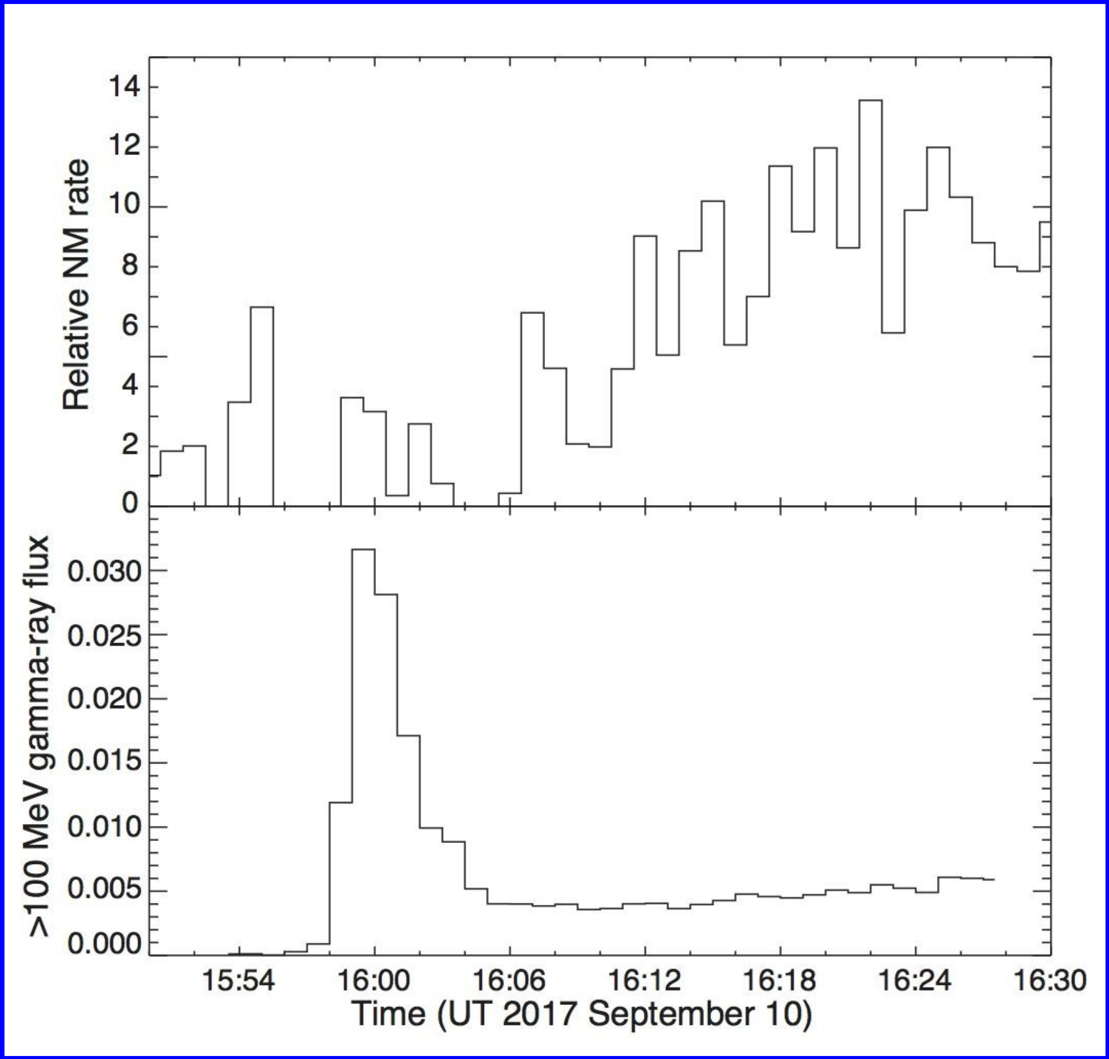


Comparison of time histories of 100-300 keV bremsstrahlung(RHESSI), >300 keV electrons producing bremsstrahlung (GBM), nuclear de-excitation line flux (GBM), and >80 MeV gamma-ray flux (LAT). This provides evidence that the early pion-decay emission is composed of impulsive and late phase emission. A second late phase of emission starts about 16:08 UT.

Evidence for an impulsive >80 MeV emission phase preceding the first late emission phase.



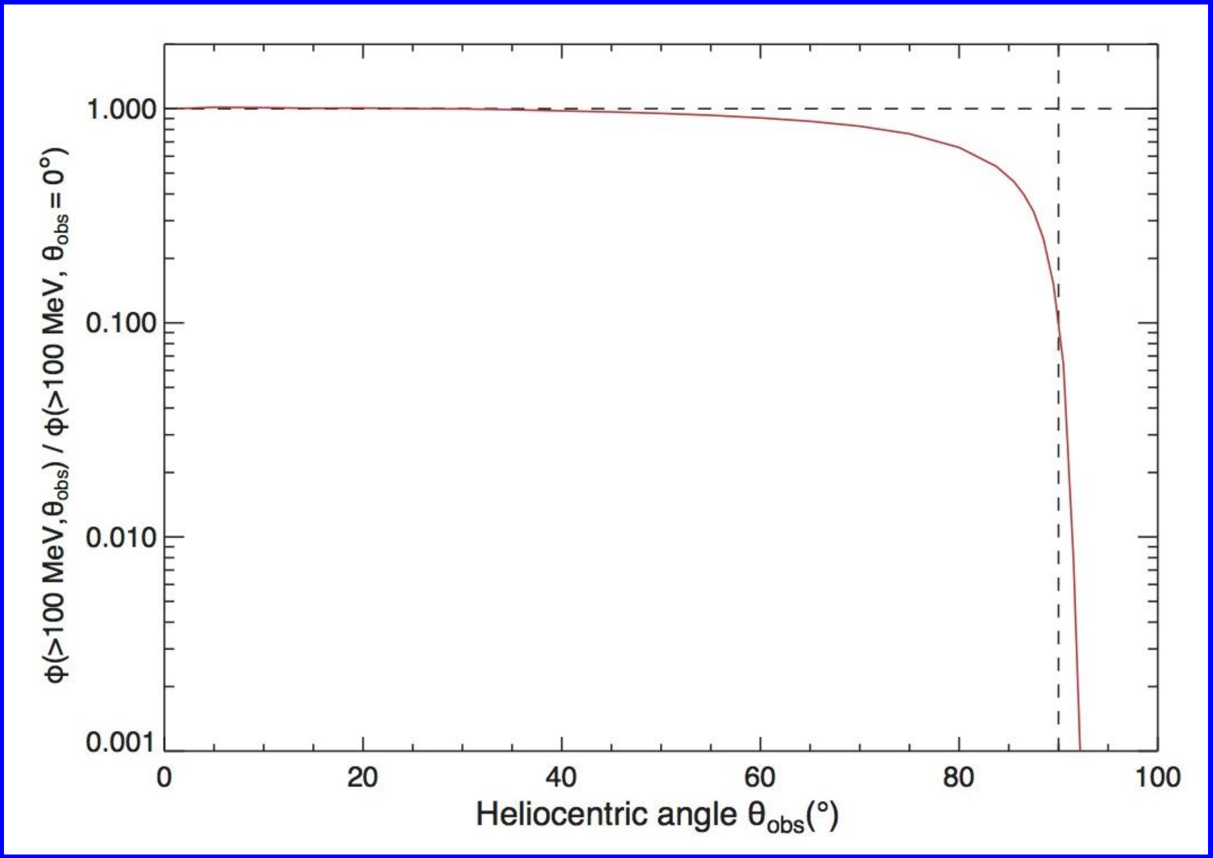
Comparison of the Fort Smith neutron monitor rate (>500 MeV protons; R. Pyle and P. Evenson) in the top panel and the >80 MeV gamma-ray rate which monitors protons >300 MeV at the Sun. Is the rise in the ground level event consistent with particle release at the time of the gamma-ray peak? David Ruffolo is studying this.



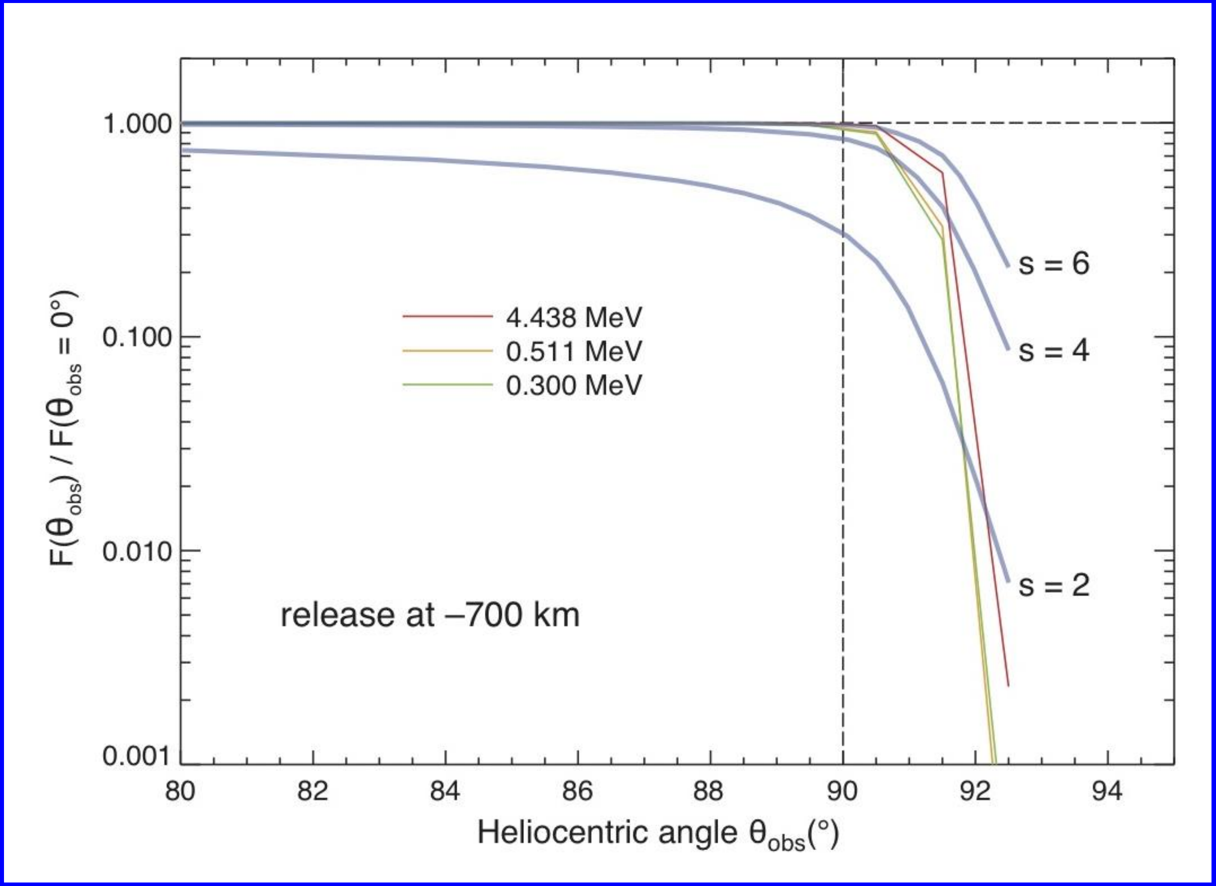
Summary

There appear to be three distinct phases of >100 MeV gamma-ray emission, each with energy spectra consistent with the decay of neutral and charged pions produced by protons above a few hundred MeV. The early part of the first >100 MeV phase began at about 15:56 UT, about one minute after the onset of the CME, and followed the time history of the impulsive flare phase as observed in hard X-rays and nuclear de-excitation line gamma rays that lasted until about 16:05 UT. The second phase of the >100 MeV gamma-ray emission began at 15:58 UT and peaked two minutes later at the highest solar flux level ever recorded by LAT. This emission was observed until

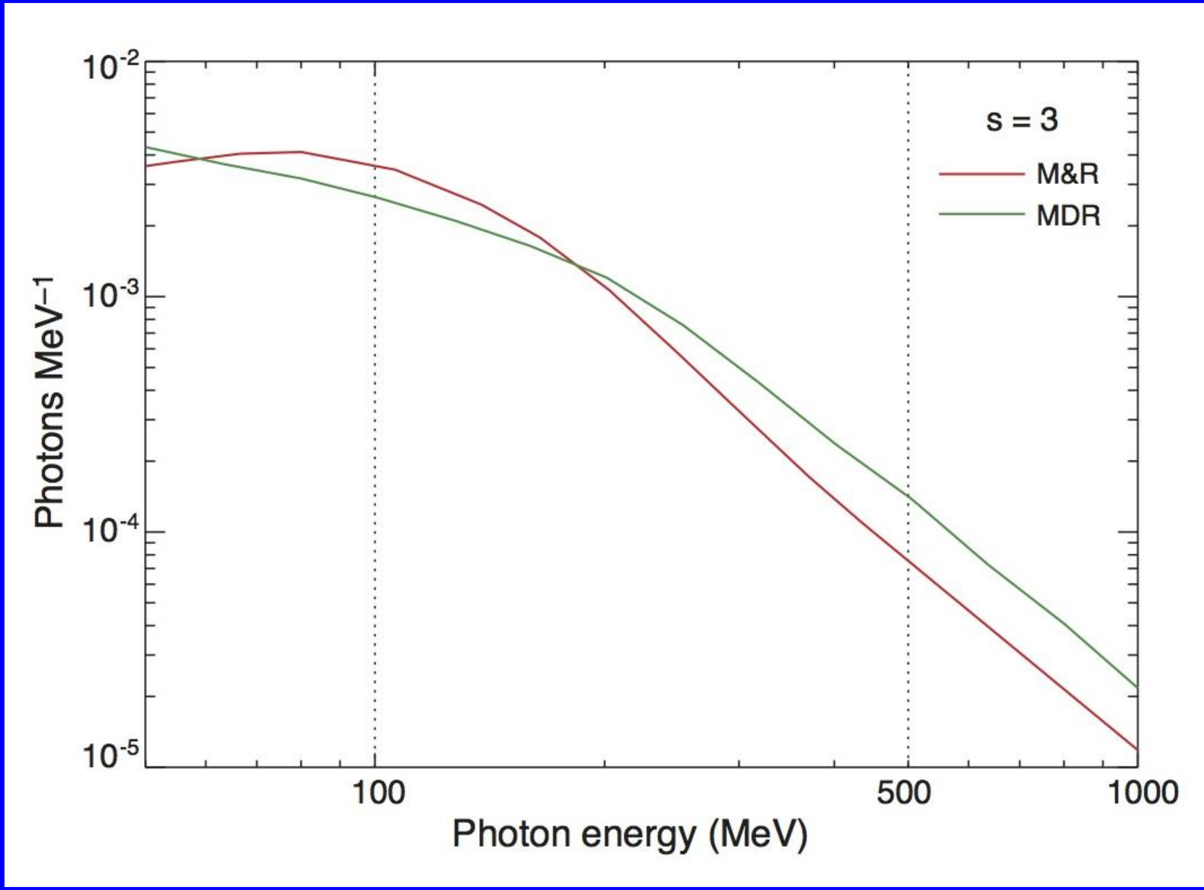
about 16:08 UT when the slow onset of the third >100 MeV phase, lasting about 10 hours, became dominant. This is the same time when Type II radio emission, indicating the presence of a shock, was observed. These latter two phases of>100 MeV emission were not detected in hard X-rays and nuclear de-excitation line gamma-rays observed by RHESSI and GBM.



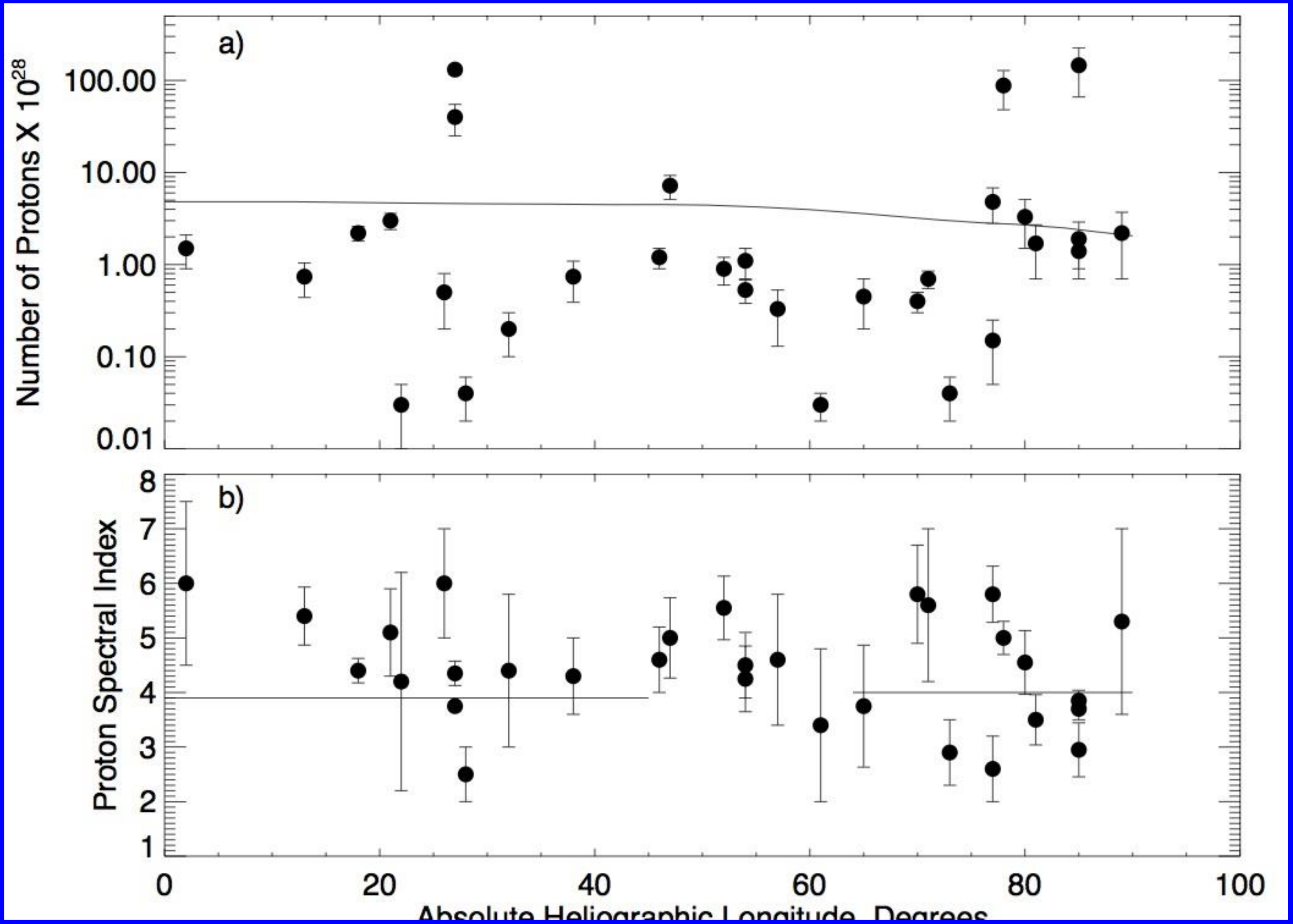
Pion-decay gamma-radiation that is produced deep in the chromosphere and in the photosphere is strongly attenuated near the solar limb.



No significant attenuation of line emission up to 90° for release deep in the chromosphere. More significant attenuation of nuclei de-excitation line emission for hard ion spectra where release can be at greater depths in the atmosphere.



Comparison of the pion-decay gamma-ray spectra calculated for protons following a proton power-law spectrum with index 3 for an isotropic distribution, MDR, and downward particle distribution (Mandzhavidze and Ramaty 1992).



Directivity of ions producing pion-decay emission in late phase emission. Expect lower fluxes and softer gamma-ray spectra for disk flares if protons have a downward or fan beam distribution. We studied longitude distributions of proton number and spectral index. Large spread in proton numbers compared with factor of two change expected for downward distribution (Mandzavidze and Ramaty, 1992). No evidence for disk center to limb change in spectral index.