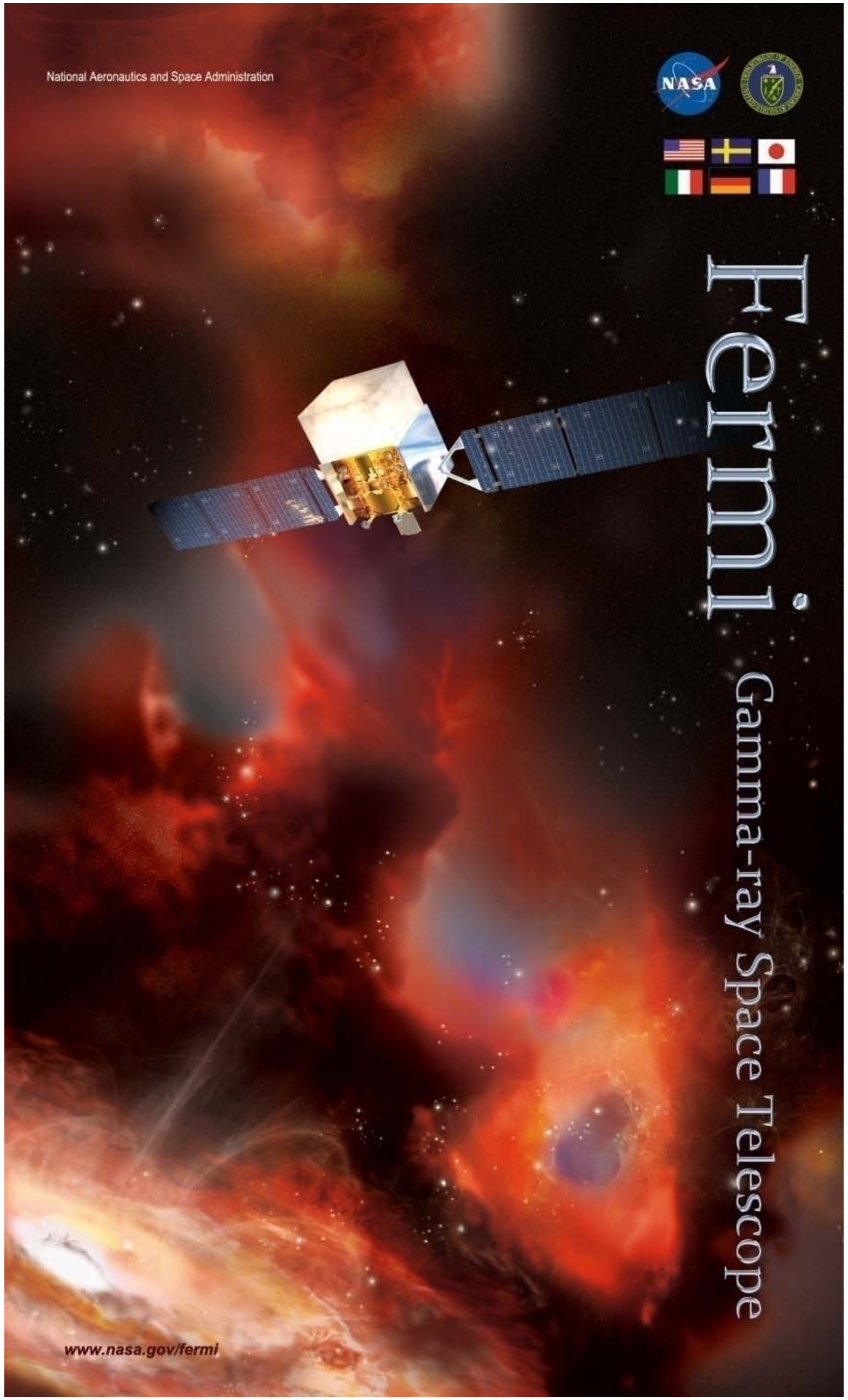

Long-lived solar gamma-ray emission during 2011 March 7 to 8 detected by Fermi-LAT

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G. H. Share (NRL), H. Takahashi (Hiroshima U.)
on behalf of Fermi/LAT collaboration

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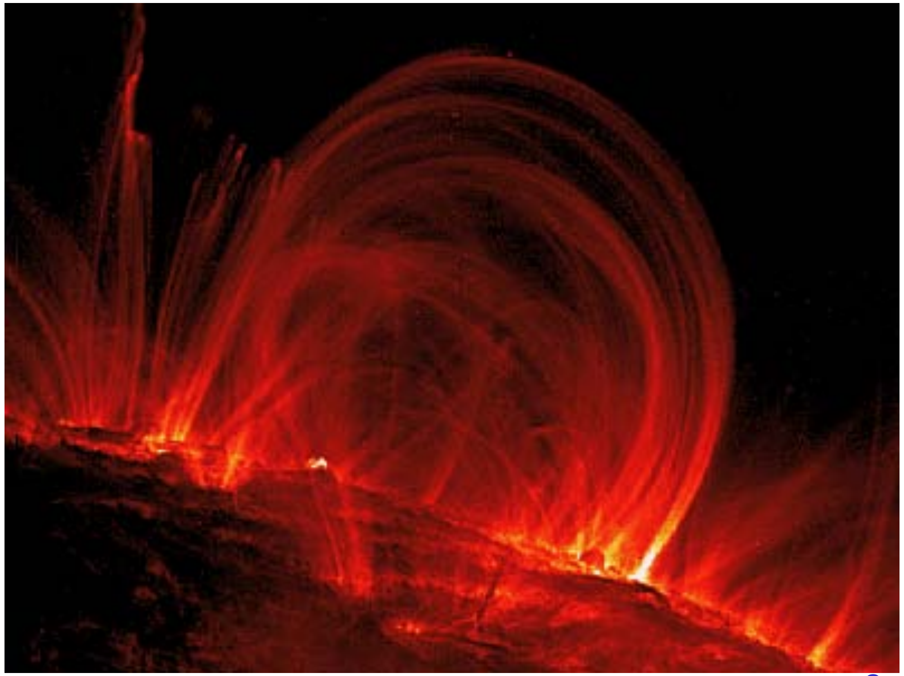
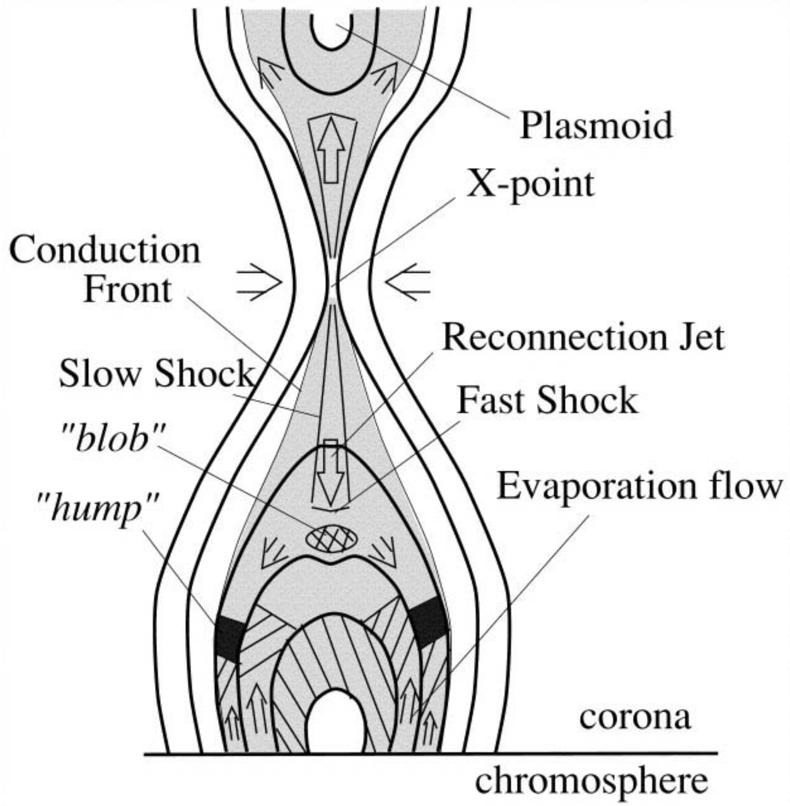


EUV (171A) image by TRACE

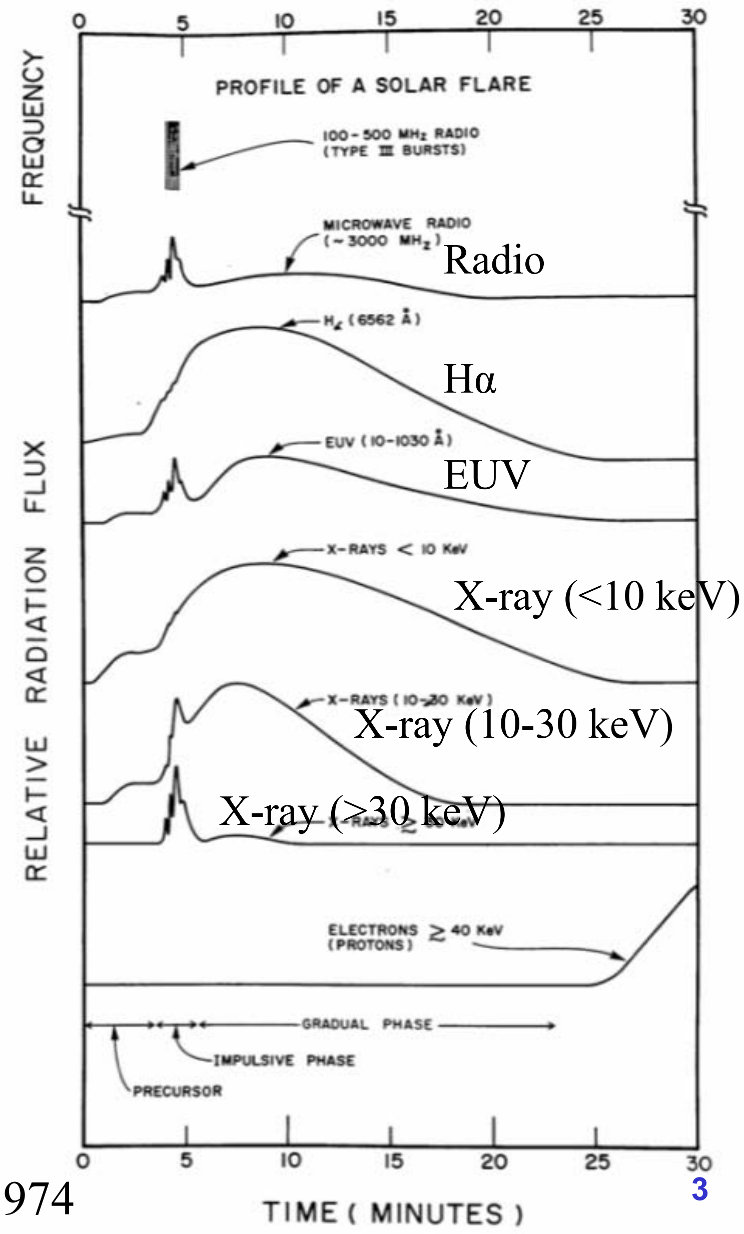
http://soi.stanford.edu/results/SolPhys200/Schrijver/TRACEpodarchive.html

Current understanding of solar flare

Release of magnetic energy via reconnection



Yokoyama & Shibata 2001



Kane 1974

Long-lasting solar gamma-ray emission

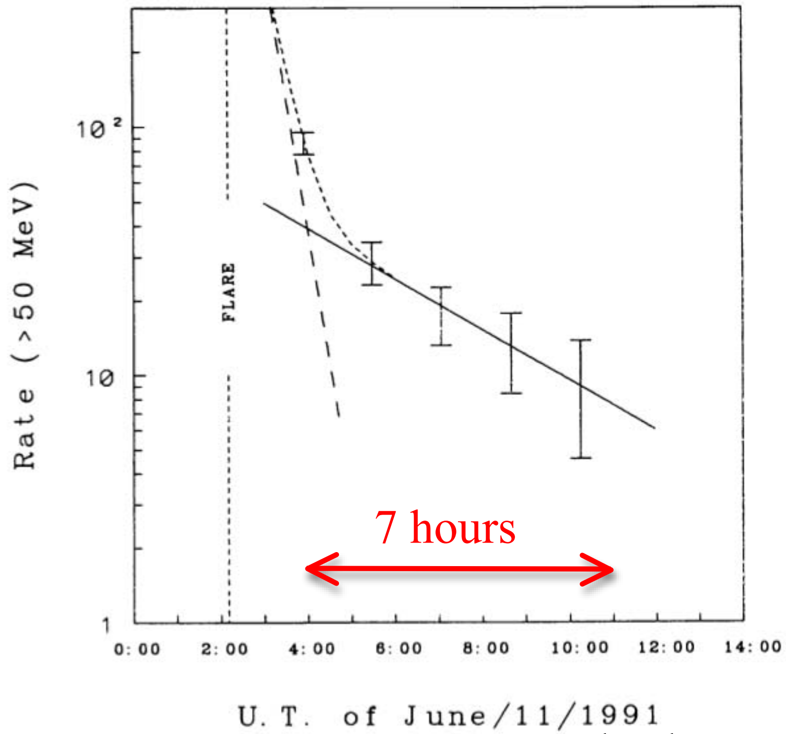
- **In the past decades, only two long-lived (hours long) gamma-ray emissions were observed by EGRET (e.g. Kanbach+93, Ryan00)**

Year	Month	Day	Duration (s)	τ_1 (min)	τ_2 (min)	Ref.
1982	6	3	1200	1.15 ± 0.14	11.7 ± 3.0	1, 2
1984	4	24	900	3.23 ± 0.07	≥ 10	2
1988	12	16	600	3.34 ± 0.30		2
1989	3	6	1500	2.66 ± 0.27		2
1989	9	29	>600			3
1990	4	15	1800			5
1990	5	24	500	0.35 ± 0.02	22 ± 2	4, 5, 6
1991	3	26	600			7, 8
1991	6	4	10000	7 ± 0.8	27 ± 7	9, 10
1991	6	6	1000			9
1991	6	9	900			9, 11
1991	6	11	30000	9.4 ± 1.3	220 ± 50	9, 12, 13
1991	6	15	5000	12.6 ± 3.0	180 ± 100	7, 8, 12

[1]Chupp (1990); [2]Dunphy and Chupp (1994); [3]Vestrand and Forrest (1993); [4]Debrunner et al. (1997); [5]Trottet (1994); [6]Debrunner et al. (1998); [7]Akimov et al. (1991); [8]Akimov et al. (1994c); [9]Schneid et al. (1996); [10]Murphy et al. (1997); [11]Ryan et al. (1994a); [12]Rank et al. (1996); [13]Kanbach et al. (1993)

Ryan 2000

Light curve (E>50 MeV) of 1991 June 11 flare



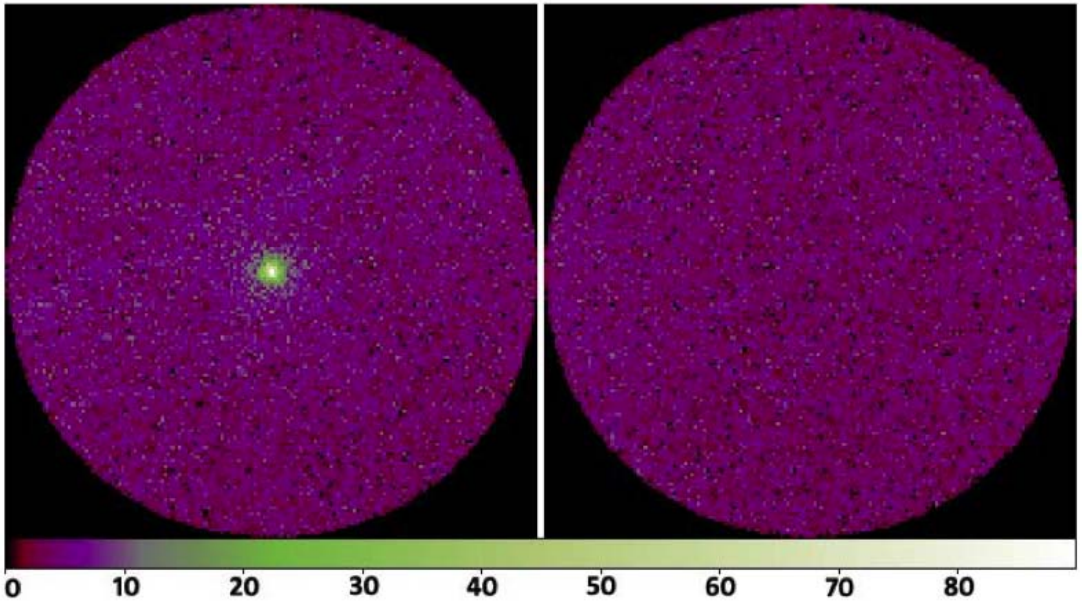
Kanbach+1993

- **It is unclear where, when, how the high-energy (HE) particles responsible for gamma-ray emission are accelerated**

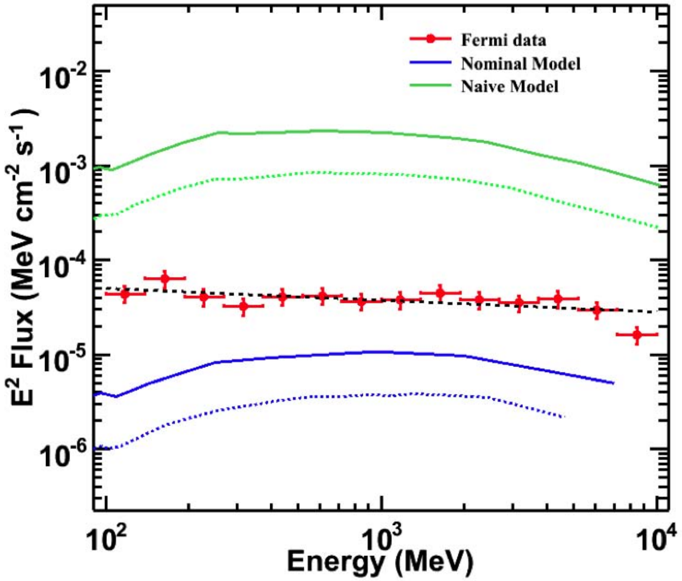
Fermi-LAT detection of quiet-Sun

(Abdo et al. 2011, ApJ in press, astroph/1104.2093)

Count map of the Sun (left) and background (right)

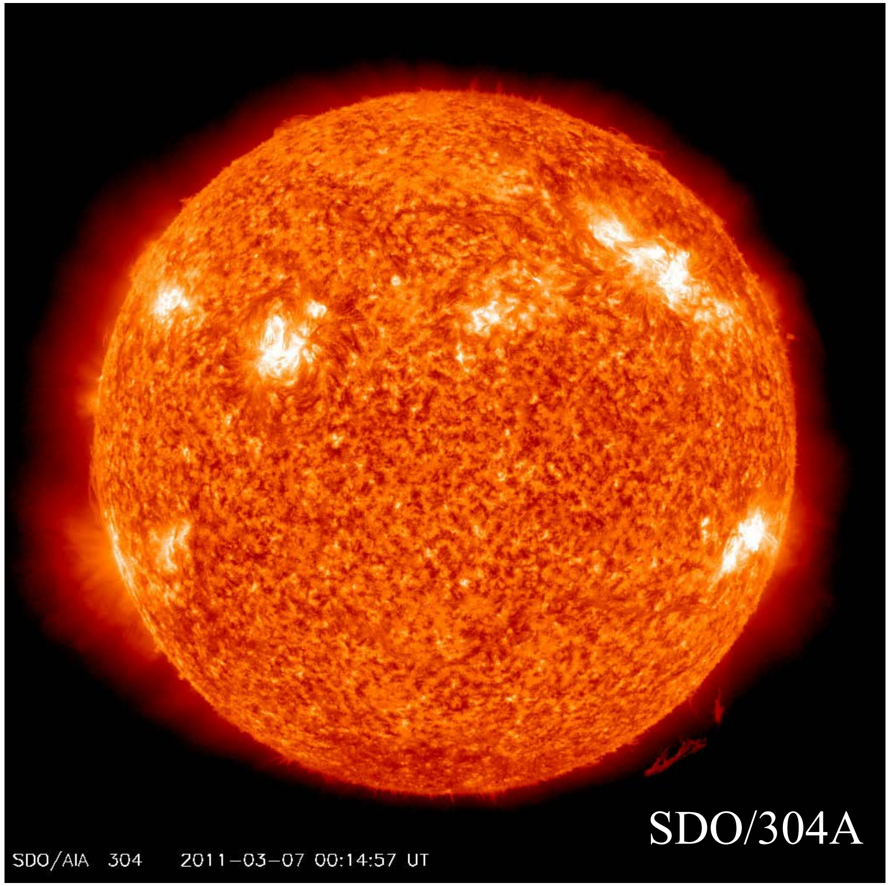


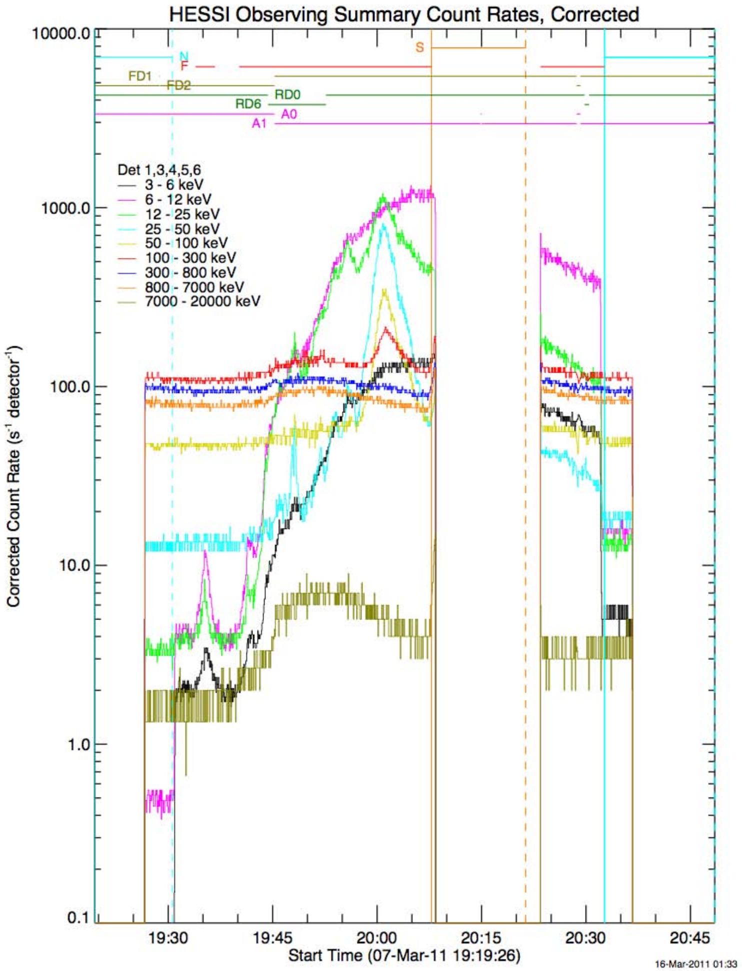
Spectrum of disk component



- **MeV/GeV emission coming from solar disk are due to cosmic-ray cascade in the solar atmosphere**
- **The power-law index is 2.11 +/- 0.73**
- **The flux (E>100 MeV) is (4.6 +/- 0.2 +1.0/-0.8)x10^{-7} photons/cm2/s**

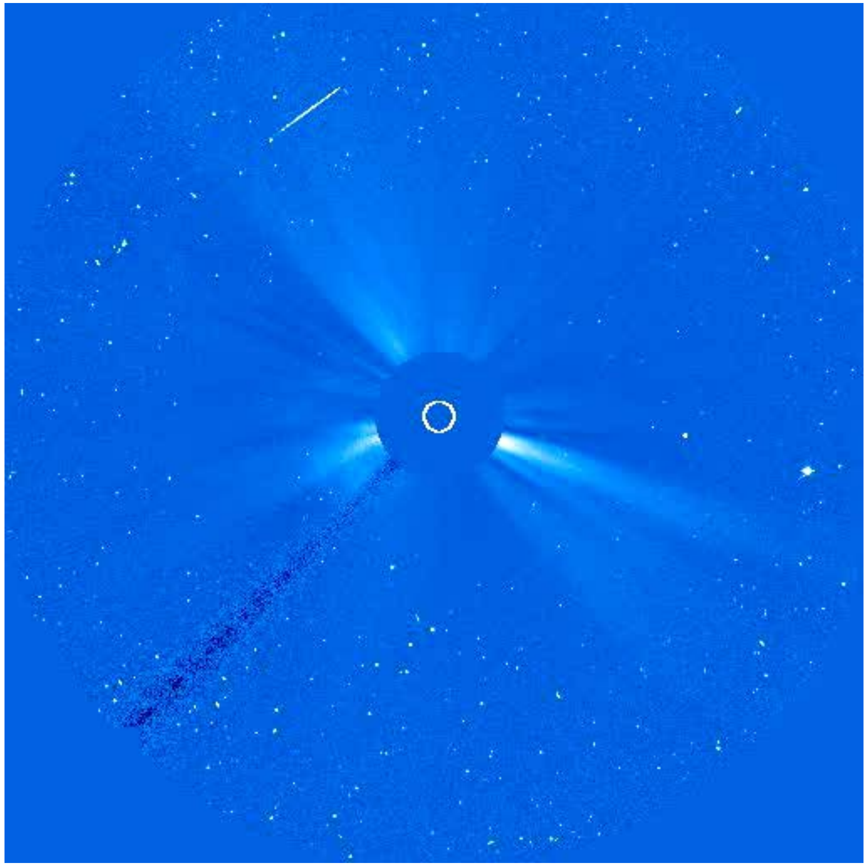
2011 March 7 flare

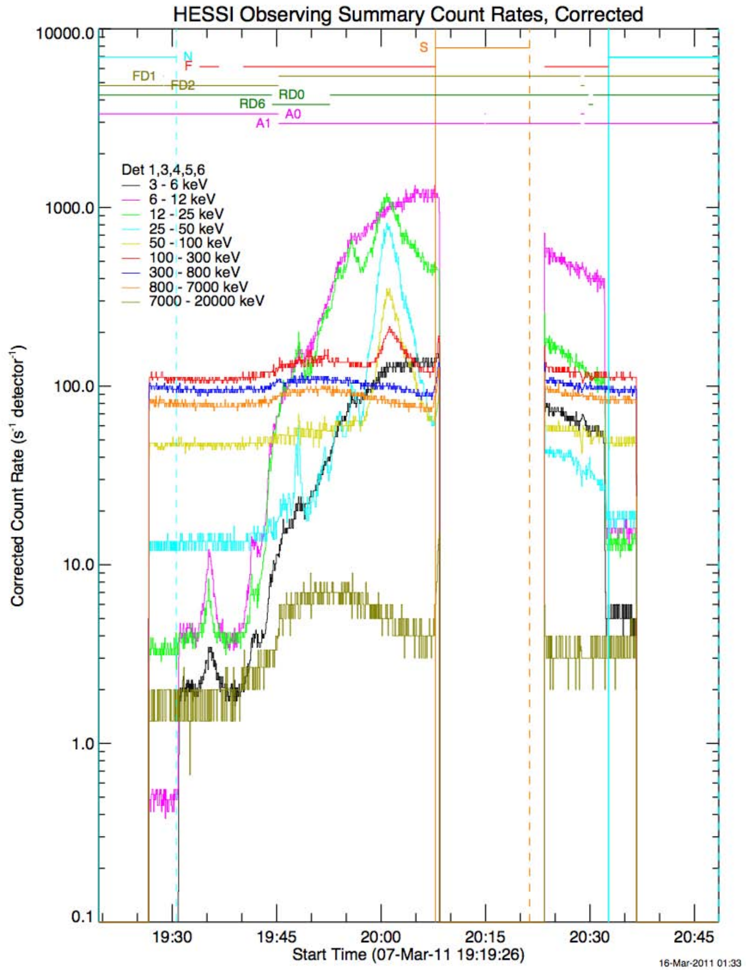




- **GOES class M3.7 flare started at 19:43 UT on Active Region 11164 (North-Western part)**
- **RHESSI detected hard X-rays up to 300 keV during the impulsive phase**
- **The flare ended in hard X-rays around 20:10 UT**

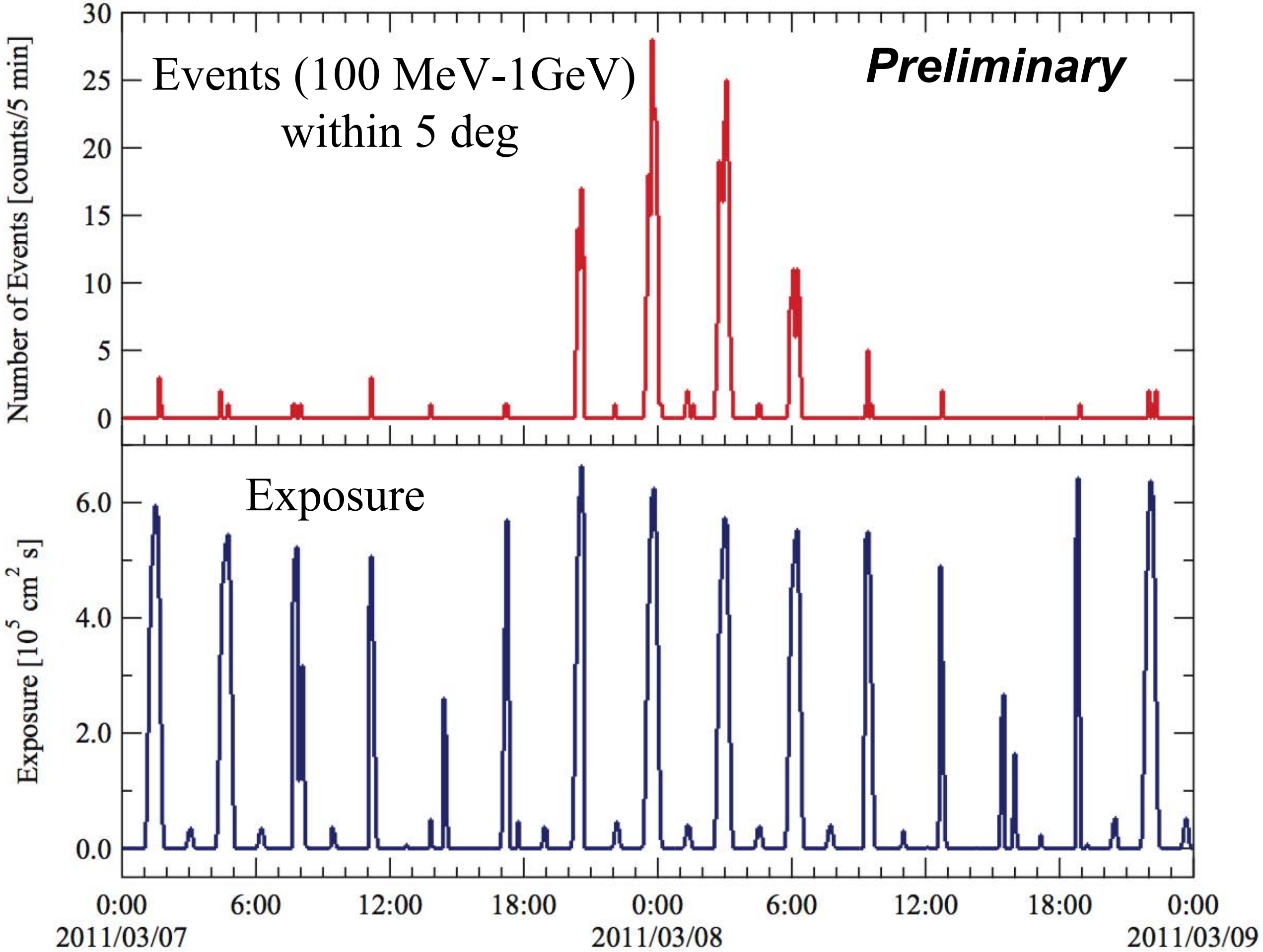
Remarkable features of the March 7 flare





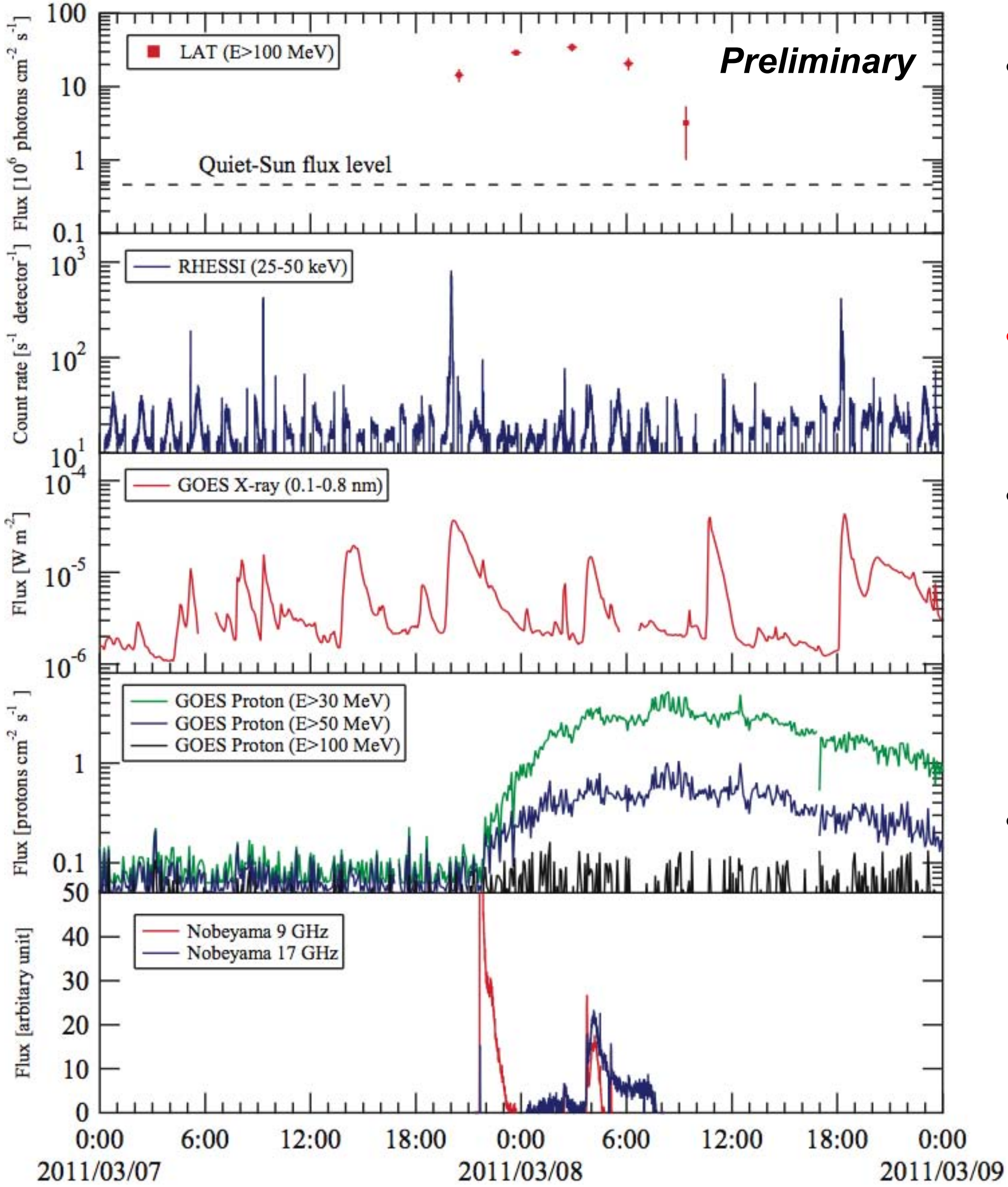
- **Following the M3.7 flare, large coronal mass ejection (CME) was observed by SOHO/LASCO**
- **The velocity is ~2200 km/s, which is the highest since 2005 September (http://www.spaceweather.com)**
- **Neither neutron capture line nor gamma-ray lines was detected by RHESSI during the impulsive phase (Priv. comm., G. Share and R. Murphy)**

Fermi-LAT observation of long-lasting emission



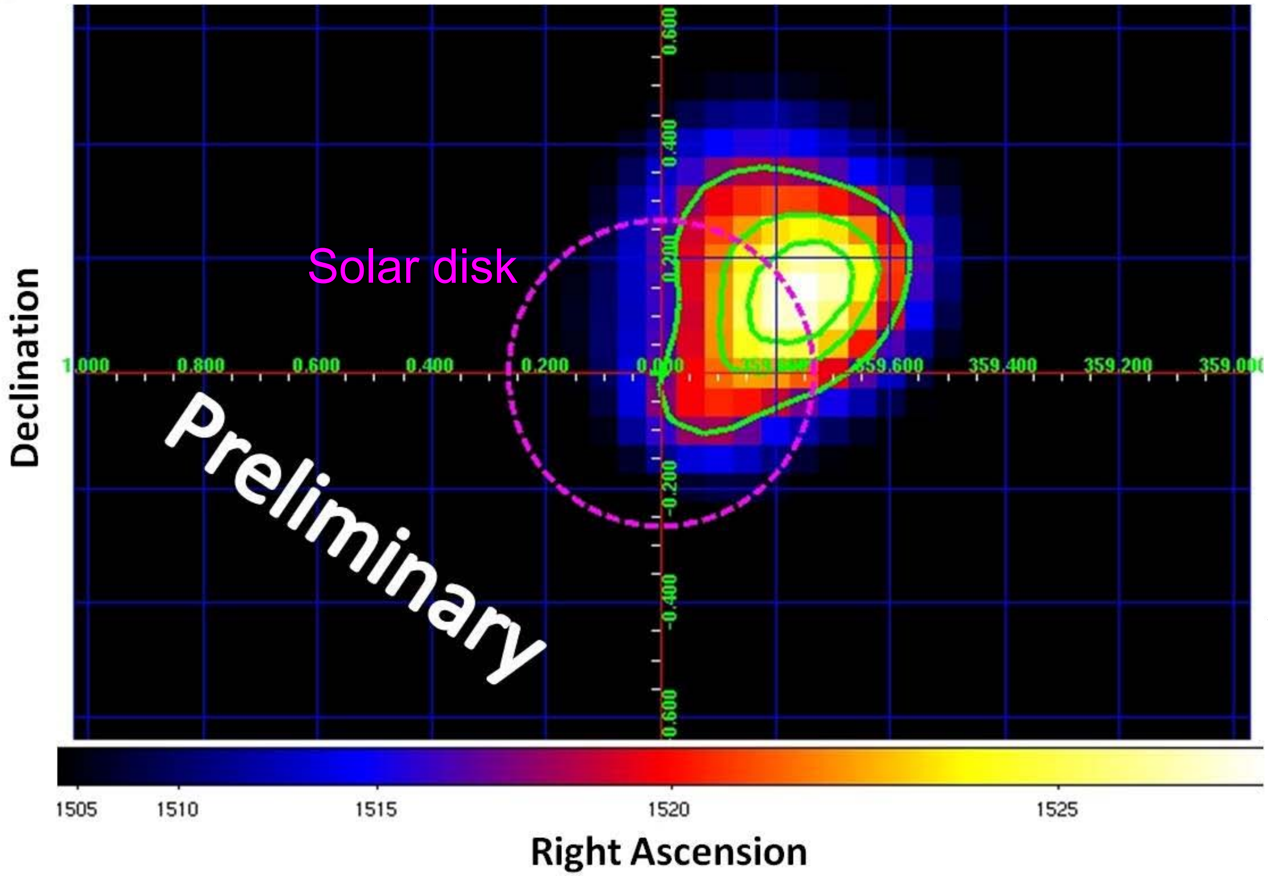
- **The Sun was NOT in the FoV of Fermi-LAT during the impulsive phase, and entered the FoV from 20:08 UT**
- **High-energy photons (100 MeV – 1 GeV) were significantly detected in the subsequent 5 periods, suggesting that the high-energy (HE) radiation lasts for ~12 hours**

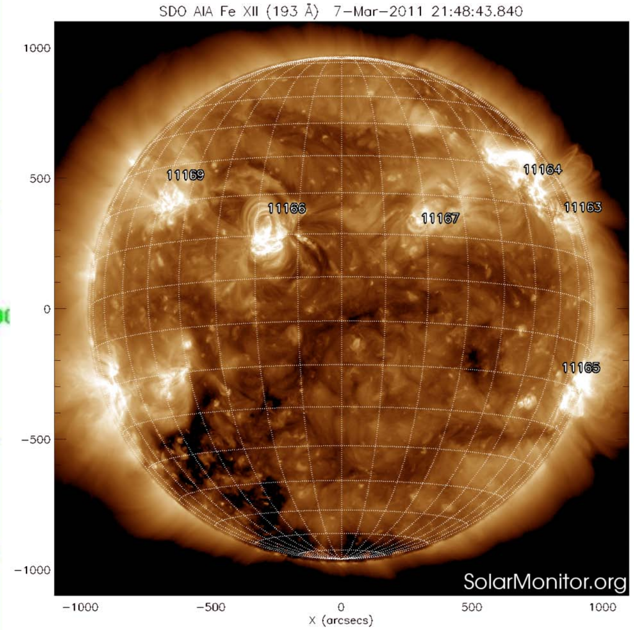
Multi-wavelength light curve



- Following M3.7 flare at ~20 UT on March 7, Fermi-LAT detected long-lasting HE emission over ~12 hours
- LAT flux showed clear rising profile
- No corresponding long-lasting enhancements were seen in hard X-ray (RHESSI), soft X-ray (GOES), and radio (Nobeyama) bands
- GOES proton monitor at 1AU detected solar energetic protons above 50 MeV, suggesting that CME-driven shock indeed accelerated protons

Gamma-ray emission region

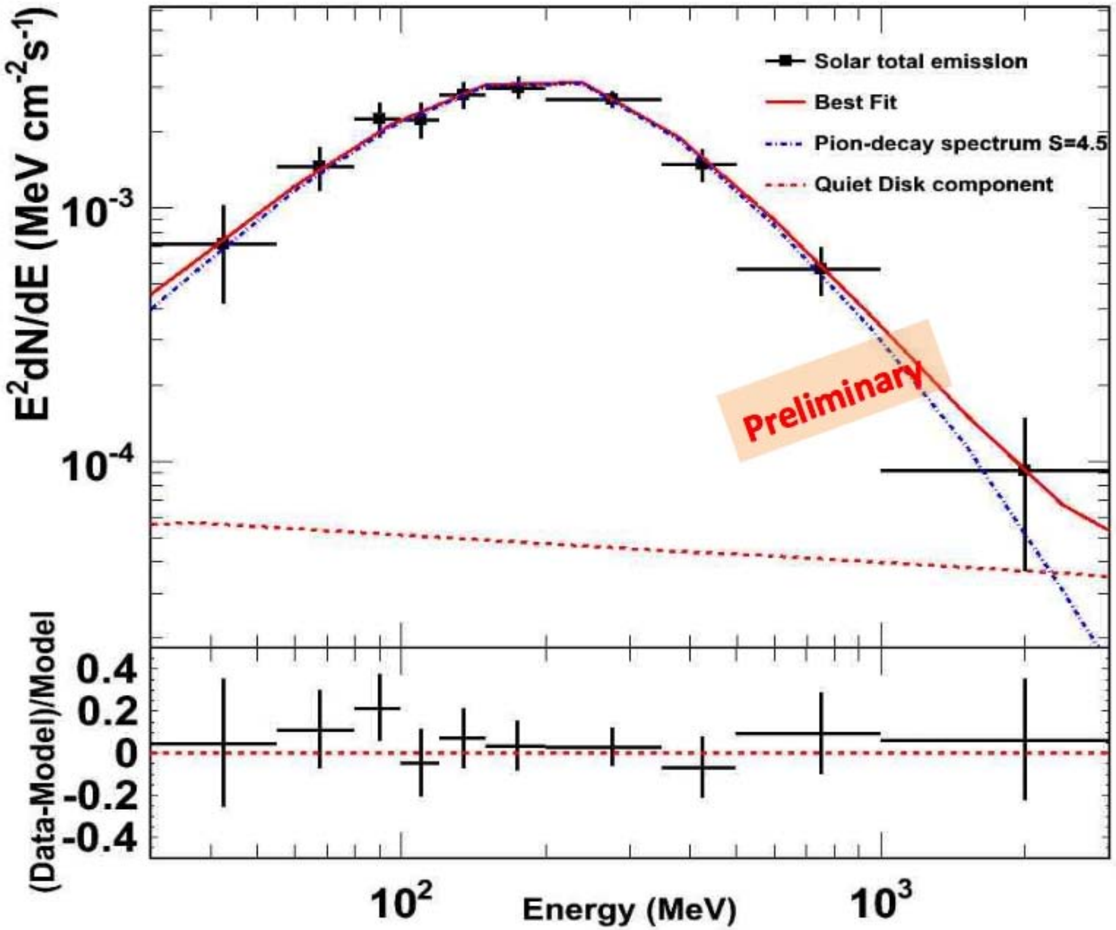




SDO/193A image

- **Sigificance map (so-called TS map) was produced for the LAT data accumulated during the whole duration**
- **Green lines show the 1sigma, 2sigma, 3sigma contours**
- **The LAT HE photons came from the North-western part of the Sun, from where M3.7 flare was emitted (active region 11164)**

LAT spectrum



- The LAT data are accumulated for the whole flare duration
- The LAT spectrum showed clear turn over around 200 MeV
- Pion decay model of proton index s=4.5 (Murphy et al. 1987) well represents the LAT spectrum
- Broken power-law model also provides reasonable likelihood values

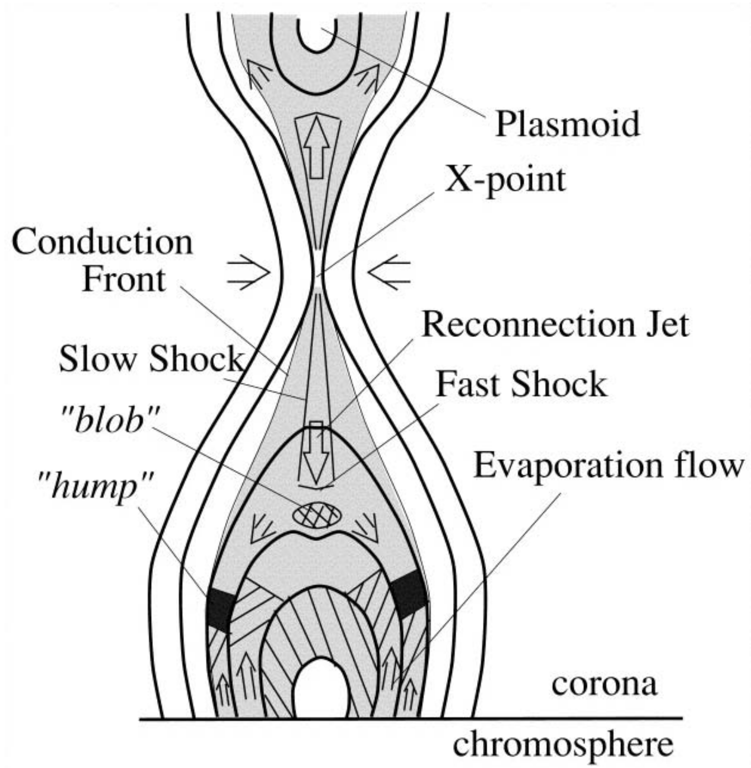
Possible scenario 1

- **Trap and precipitation of HE protons produced during the impulsive phase via magnetic reconnection (e.g., Kanbach et al. 1993)**

✧ Quantitative estimation of total number of accelerated protons during the impulsive phase as well as the LAT emission is needed

✧ RHESSI detected no evidence of gamma-ray line emissions during the impulsive phase. From the RHESSI data, upper limit of the total number of accelerated protons produced during the impulsive phase is being estimated

✧ Comparison with the total number of protons responsible for the LAT emission would provide constraints on this scenario



Yokoyama & Shibata 2001

Possible scenario 2

- **Precipitation of HE protons accelerated stochastically within the loop (2nd order Fermi) (e.g., Ryan & Lee 1991)**

✧ Application of the observed time scales

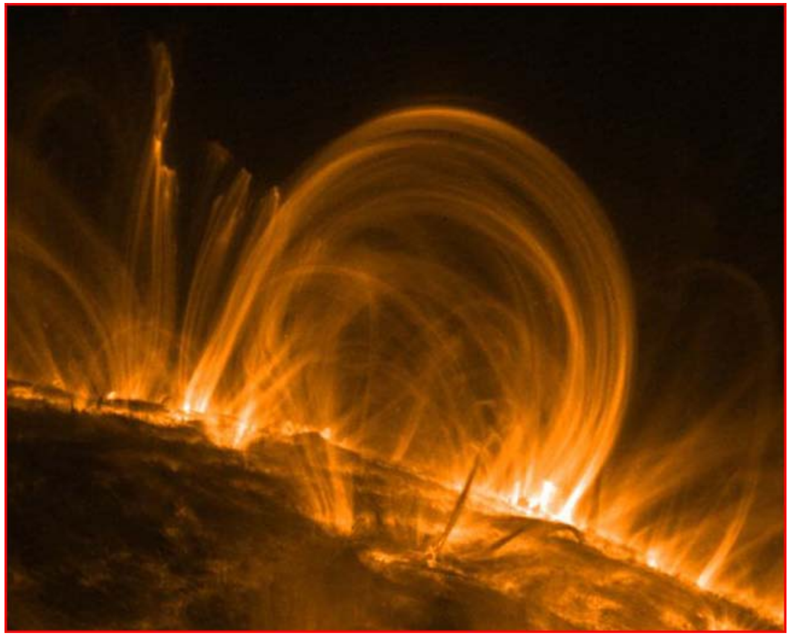
$$t_{\rm acc} = \frac{9D}{V_{\rm A}^2} \sim 10^4 \ {\rm sec} \Leftrightarrow D \sim 10^{19} \left(\frac{t_{\rm acc}}{10^4 \ {\rm s}}\right)\left(\frac{V_{\rm A}}{10^3 \ {\rm km/s}}\right)^2 \ {\rm cm^2/s}$$

$$t_{\rm diff} = \frac{L^2}{\pi^2 D} \sim 10^4 \ {\rm sec} \Leftrightarrow L \sim 10^{12} \left(\frac{t_{\rm diff}}{10^4 \ {\rm s}}\right)^{1/2}\left(\frac{D}{10^{19} \ {\rm cm^2/s}}\right)^{1/2} \ {\rm cm}$$

✧ Unreasonably large loop size (c.f. solar radius: ~10^11 cm)

✧ Assuming the loop size of 10^5 km and Alfven velocity of 1000 km/s, MHD turbulence is maintained only for ~100 s, unless there is an energizing process in flaring loops

✧ How the MHD turbulence is maintained? (Is it possible to explain the long-lived signature?)



SOHO EUV image © NASA

Possible scenario 3

- **Return of protons accelerated by CME-driven shock (1st order Fermi) (Murphy et al. 1987, Cliver et al. 1993)**

✧ Maximum energy of protons

$$E_{\rm max} = \frac{3}{20}\frac{V_{\rm shock}}{c} eBR\,\xi$$
$$\simeq 20 \left(\frac{V_{\rm shock}}{2200\ {\rm km/s}}\right)\left(\frac{B}{10\ {\rm G}}\right)\left(\frac{R}{0.1R_\odot}\right)\xi\ {\rm GeV}$$

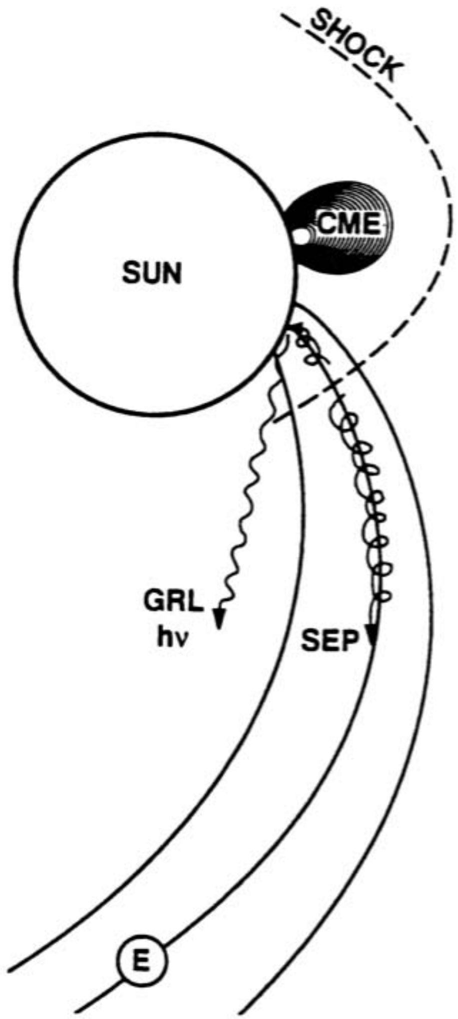
✧ Acceleration time of 1 GeV proton

$$t_{\rm acc} = \frac{20}{3}\frac{c\,r_{\rm gyro}}{V_{\rm shock}^2}\frac{1}{\xi}$$
$$\simeq 2\left(\frac{2200\ {\rm km/s}}{V_{\rm shock}}\right)^2\left(\frac{10\ {\rm G}}{B}\right)\left(\frac{1}{\xi}\right)\ {\rm sec}$$

✧ The fast CME-driven shock can easily and immediately accelerate protons up to >300 MeV

✧ Note that the CME-driven shock proceeds away from the Sun

✧ Is it possible to explain the LAT rising profile?



Cliver+1993

Summary

- Fermi-LAT detected the longest HE emission from the Sun following the 2011 March 7 flare. The duration was ~12 hours.
- The LAT emission came from the North-West part of the Sun, from where the M3.7 flare is emitted
- The LAT spectrum showed clear turnover around 200 MeV, suggesting that pion decay is promising
- The March 7 flare is associated with a fast CME of 2200 km/s
- We considered three possible scenarios which might explain the long-lived LAT emission
- Further quantitative discussion is ongoing, and paper is now being prepared

Extra slides

Possible scenarios

- **Trap and precipitation of HE protons produced during the impulsive phase via magnetic reconnection (e.g., Kanbach et al. 1993)**

  ✧ RHESSI detected no evidence of gamma-ray line emissions during the impulsive phase

  ✧ Quantitative estimation of total number of accelerated protons from RHESSI upper limit of gamma-ray lines is now ongoing

- **Precipitation of HE protons accelerated stochas within the loop (e.g., Ryan & Lee 1991)**

  ✧ Assuming the loop size of 10^5 km and Alfven velocity of 1000 km/s,
  MHD turbulence maintained only for ~100 s, unless there is an energizing process
  in flaring loops

  ✧ Is it possible to explain the long-lived signature?