Fermi Gamma-ray Space Telescope

Theoretical Interpretation of Solar Flares Observed by Fermi-LAT and Other Instruments

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And

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Melissa Pesce-Rollins and Fatima Rubio da Costa

on behalf of Fermi/LAT collaboration

Prague, 2014

OUTLINE

I. Fermi and Solar Observations

II. Gamma-ray Producing Processes

III. Data

IV. Interpretation

V. Summary

I. Past Flare Gamma-ray Observations

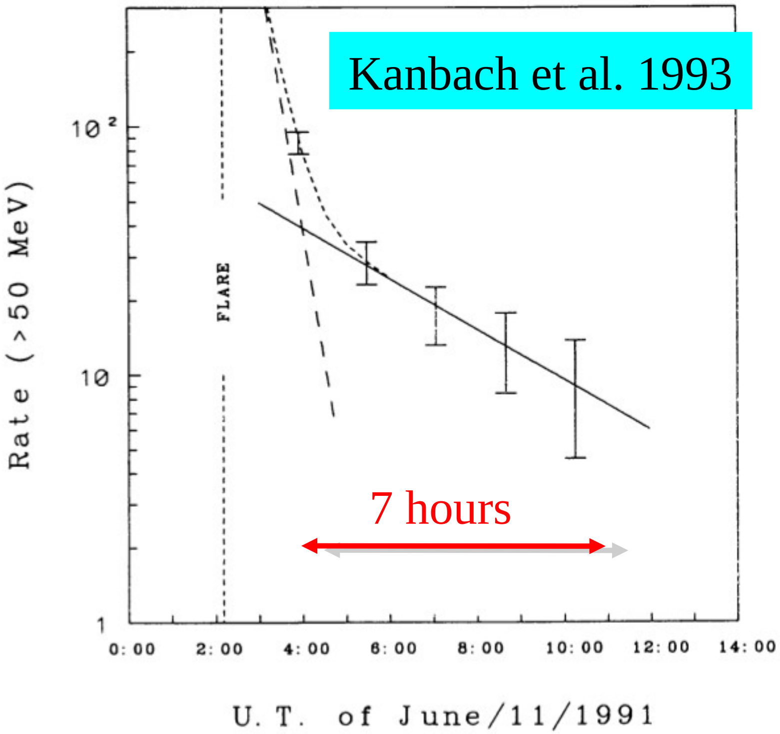
- EGRET observed several flares; *Two lasting several hours*

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

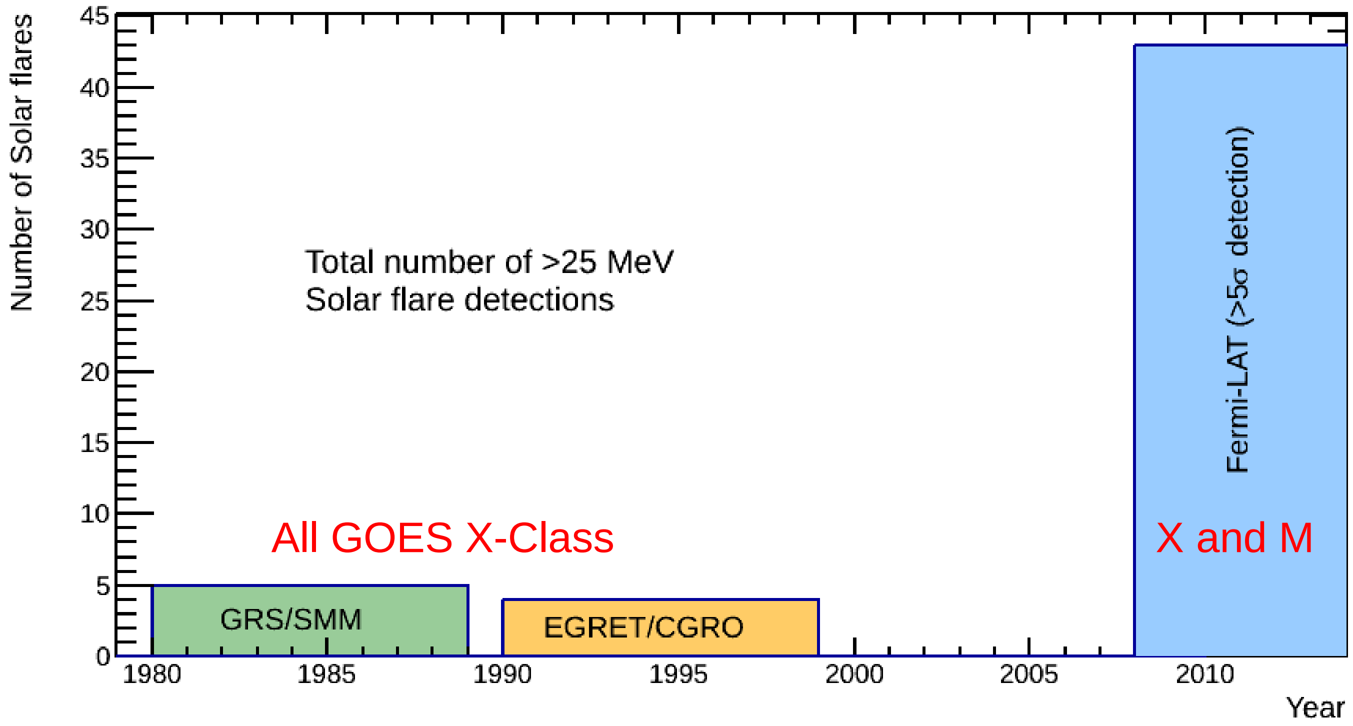
[1]Chupp (1990); [2]Dunphy and Chupp (1994); [3]Vestrand and Forrest (1993); [4]Debrunner et al. (1997); [5]Trottet (1994); [6]Debrunner et al. (1998); [7]Akimov et al. (1991); [8]Akimov et al. (1994c); [9]Schneid et al. (1996); [10]Murphy et al. (1997); [11]Ryan et al. (1994a); [12]Rank et al. (1996);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

Ryan 2000

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

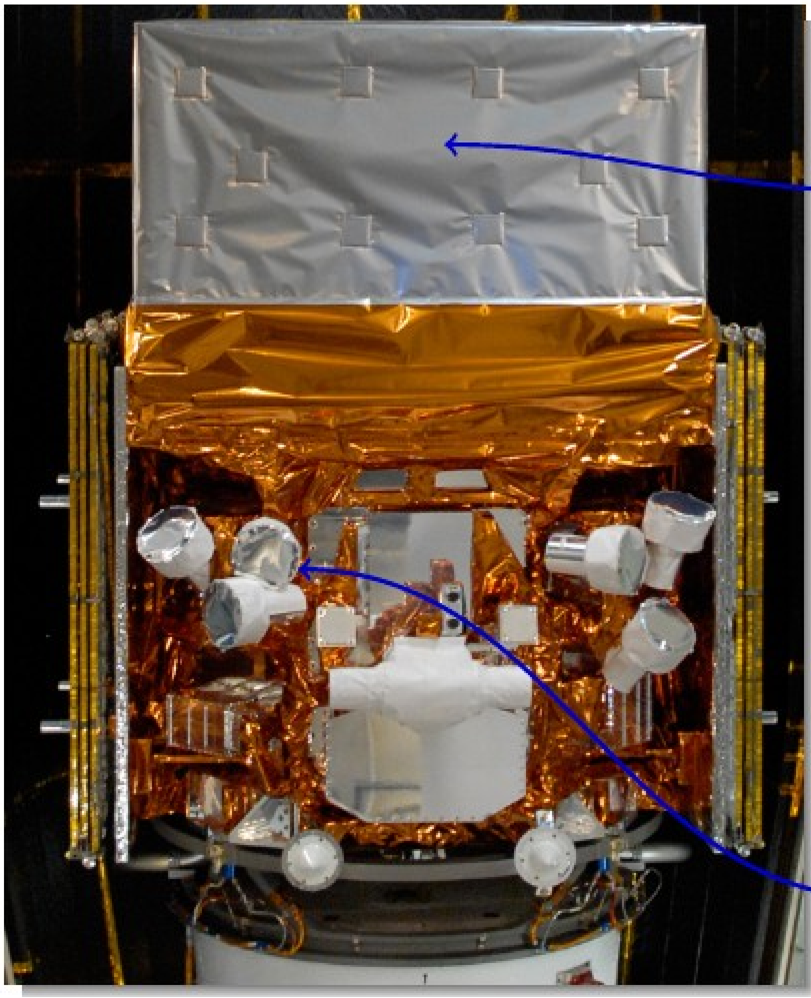


I. Fermi Flare Gamma-ray Observations



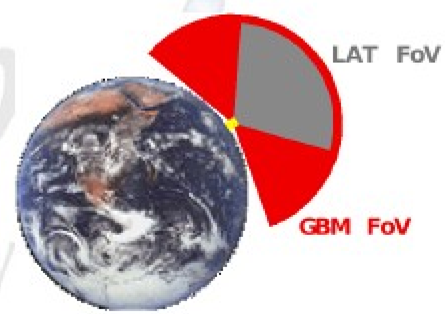
Fermi Observatory and Detectors

The Fermi observatory



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, all parts of the sky for 30 minutes every 3 hours.
- Observes the Sun for $\sim$20 – 40 min every 3 hours



Gamma-ray Burst Monitor (GBM)

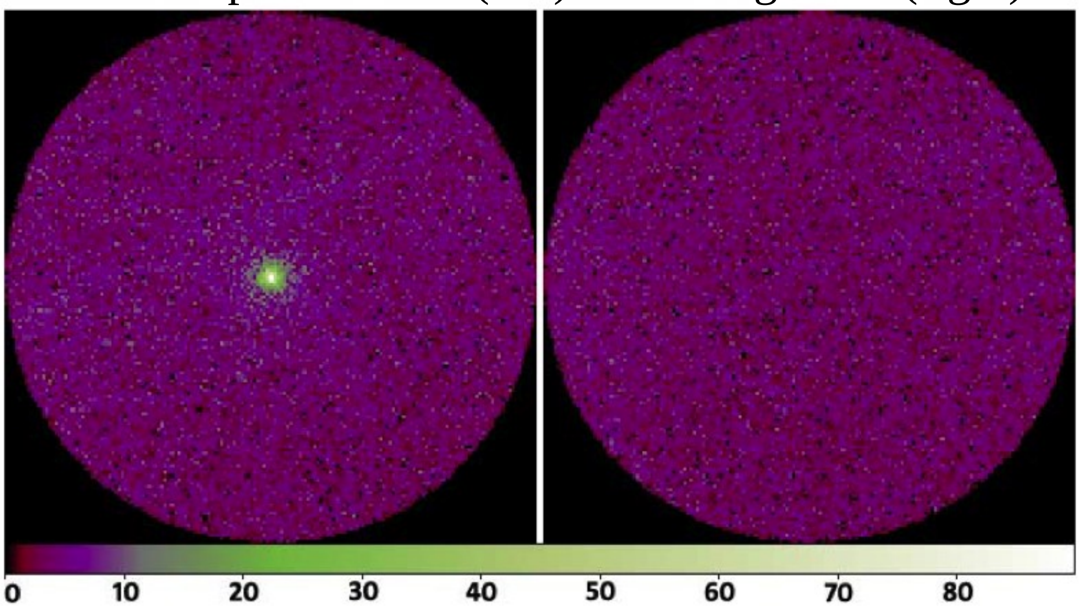
- 12 NaI and 2 BGO detectors.
- Energy range: 8 keV–40 MeV.

Solar Gamma-rays: *A. From Quiet Sun*

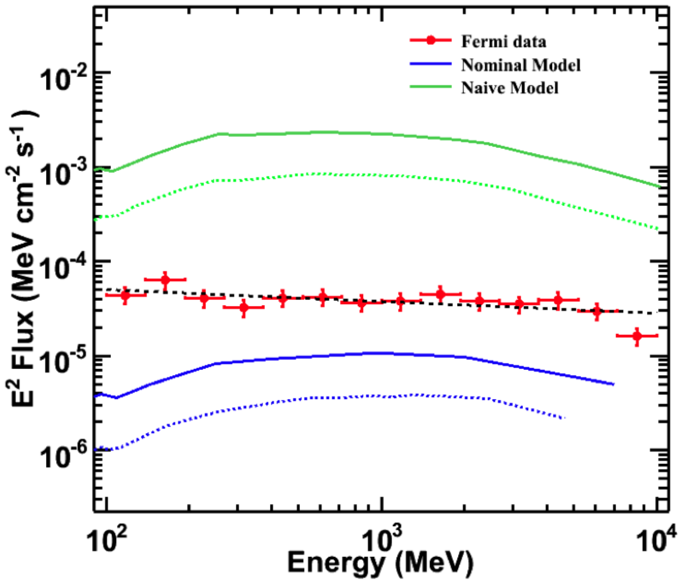
Fermi-LAT detection of quiet-Sun

(Abdo et al. 2012, ApJ; astroph/1104.2093)

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



Spectrum of disk component

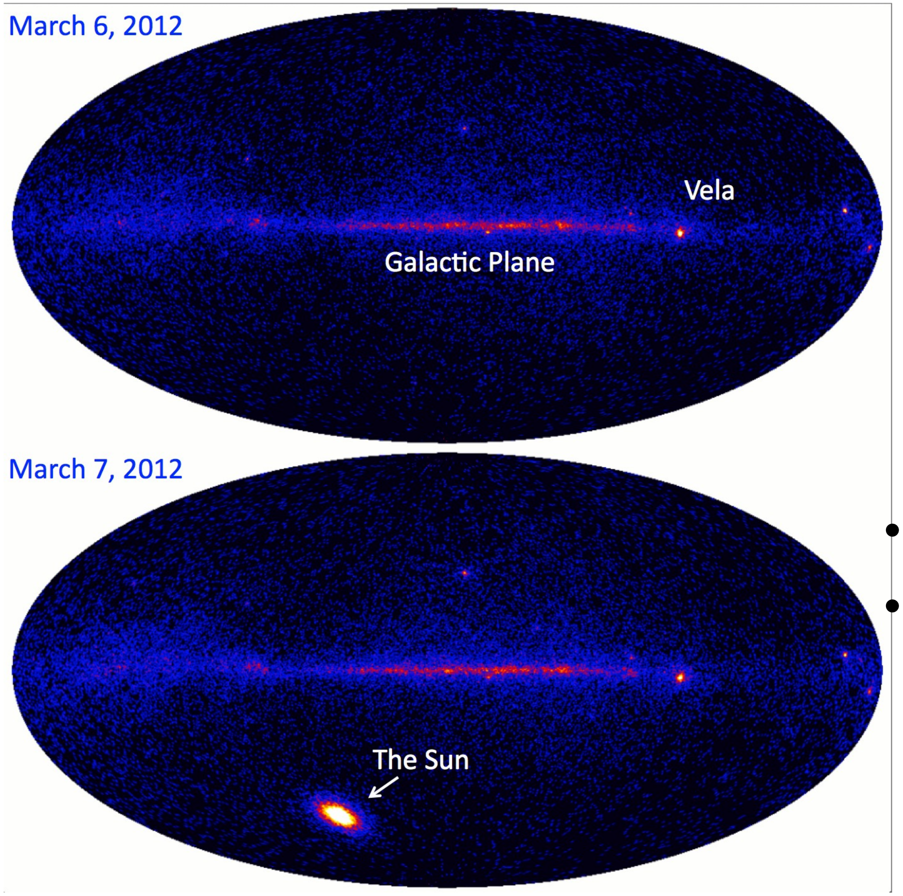


MeV/GeV emission due to cosmic-ray proton and electron interactions with solar matter and radiation

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

Solar Gamma-rays: *B. From Flares*



Brightest Flare; 2012, March 7:

- **1000 times the quiet Sun;**
- **100 times the Vela;**
- **50 times the Crab flare;**

- **Emission up to 4 GeV**
- **Lasting for ~20 hours**

List of Flares detected by Fermi-LAT

TABLE 1
SOLAR FLARES DETECTED BY *Fermi* LAT FROM 2008 AUGUST TO 2012 AUGUST.

Date (UT)	Duration min.	GOES X-ray Class, Start–End	CME[†] Speed, km s^{-1}	TS	Type	Flux (>100 MeV) $\times 10^{-5}$ ph cm^{-2} s^{-1}
2010-06-12 00:55	~1	M2.0, 00:30–01:02	486	LLE*	I	(−)
2011-03-07 20:15	25	M3.7, 19:43–20:58	2125	230	I/S	(1.9± 0.3)
23:26	36			520	S	(3.5± 0.3)
2011-03-08 02:38	35			450	S	(3.5± 0.3)
05:49	35			200	S	(1.9± 0.3)
2011-06-02 09:43	45	C2.7,9:42–9:50	976	35	I/S	(0.4±0.2)
2011-06-07 07:47	53	M2.5, 06:16–06:59	1255	570	S	(3.6 ± 0.3)
2011-08-04 04:59	34	M9.3, 03:41–04:04	1315	390	S	(2.5 ± 0.3)
2011-08-09 08:01	$\lesssim 1$	X6.9, 07:48–08:08	1610	LLE*	I	(−)
2011-09-06 22:17	$\lesssim 1$	X2.1, 22:12–22:24	575	LLE*	I	(−)
2011-09-06 22:13	35			2600	I/S	‡
2011-09-07 23:36	63	X1.8, 22:32–22:44	792	350	S	(1.0 ± 0.1)
2011-09-24 09:35	~1	X1.9, 09:21-09:48	1936	LLE*	I	(−)
2012-01-23 04:07	51	M8.7, 03:38–04:34	1953	180	I/S	(0.8 ± 0.1)
05:25	69			650	S	(2.1±0.2)
07:26	16			69	S	(3.7±0.9)
08:47	35			97	S	(2.6±0.5)
2012-01-27 19:45	11	X1.7, 17:37–18:56	1930	78	D	(3.2±0.8)
21:13	24			47	S	(1.0±0.3)
2012-03-05 04:12	49	X1.1, 02:30–04:43	1602	69	I/S	(0.5±0.1)
05:26	71			250	S	(0.9±0.1)
07:23	28			39	S	(0.8±0.2)
2012-03-07 00:46	31	X5.4, 00:02–00:40	1785	22000	S	‡
		X1.3, 01:05–01:23			I/S	
2012-03-07 03:56	32			16000	S	(113.1±2.0)
07:07	32			8900	S	(71.9±1.6)
10:18	32			1900	S	(30.1±1.5)
13:29	32			120	S	(8.9±1.9)
19:51	25			50	S	(0.4±0.1)
2012-03-09 05:17	34	M6.3, 03:22–04:18	844	51	D	(0.6±0.2)
06:52	35			100	S	(0.9±0.2)
08:28	34			159	S	(1.4±0.2)
2012-03-10 21:05	30	M8.4, 17:15–18:30	1379	43	D	(0.4±0.1)
2012-05-17 02:18	22	M5.1, 01:25–02:14	1582	45	I/S	(1.0±0.3)
2012-06-03 17:52:33	~1	M3.3, 17:48–17:57	605	LLE*	I	(−)
17:40	23			300	I/S	(3.2±0.4)
2012-06-14 14:48	49	M1.9,12:52–15:56	987	49	I/S	(1.1±0.3)
2012-07-06 23:19	52	X1.1,23:15–23:49	892	930	I/S	(3.5±0.2)

† CME data are available at the following url: http://cdaw.gsfc.nasa.gov/CME_list/.
‡ The flux estimate is unreliable because of X-ray pile-up in the ACD.
* LLE detections are >30 MeV while TS values are calculated for >100 MeV.

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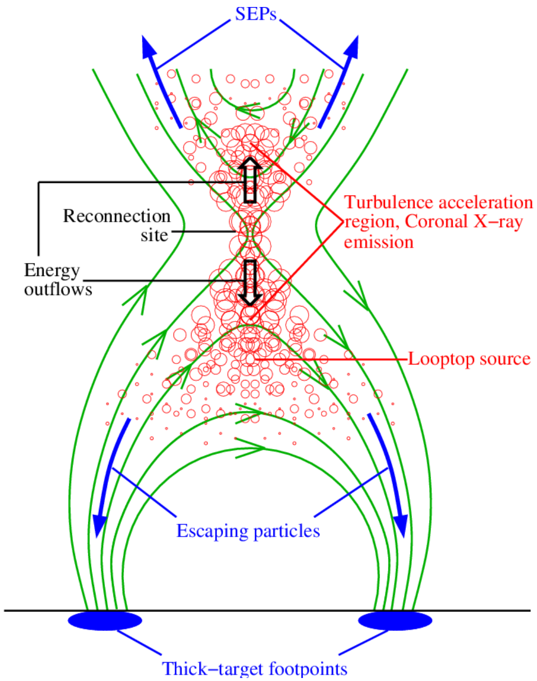
II. The Processes Involved in Gamma-ray Production

A. Acceleration Site and Mechanisms

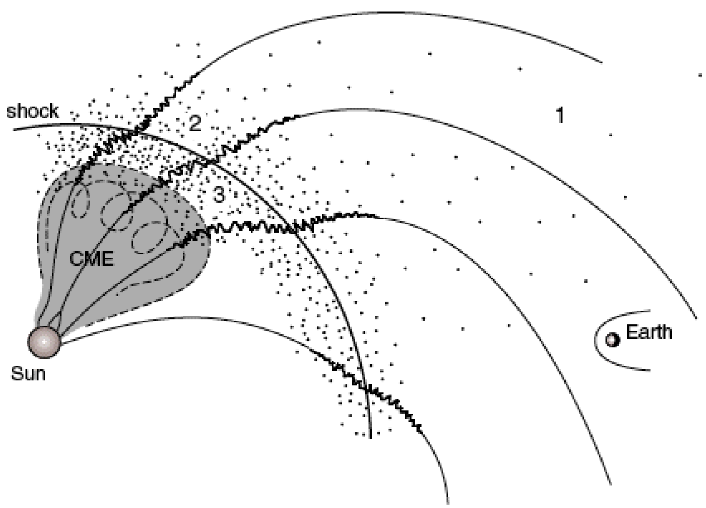
1. Flare loop reconn. site

2^{nd} order Fermi



2. CME shock

1^{st} order Fermi

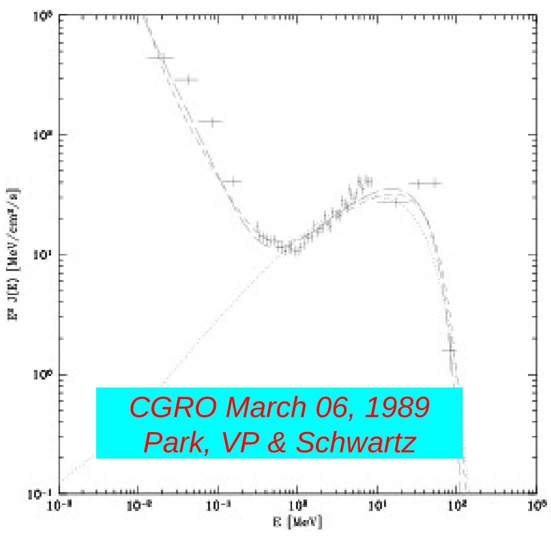


B. Emission Processes

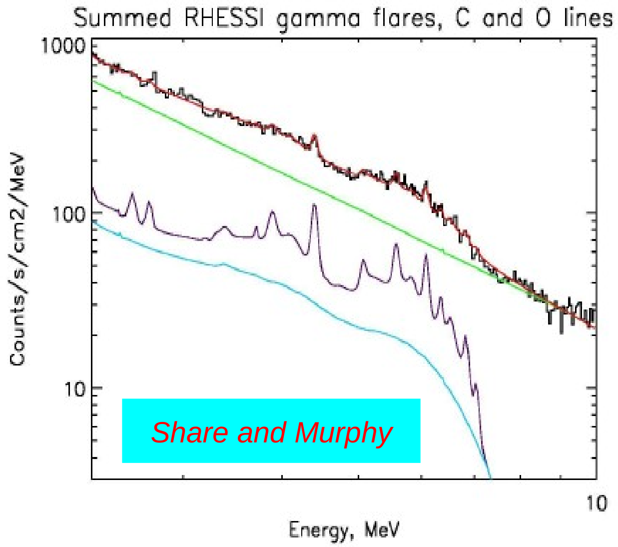
1. Bremsstrahlung by > 10's of MeV ELECTRONS

Also Hard X-rays (Inverse Compton) and Submm-IR (synchrotron)

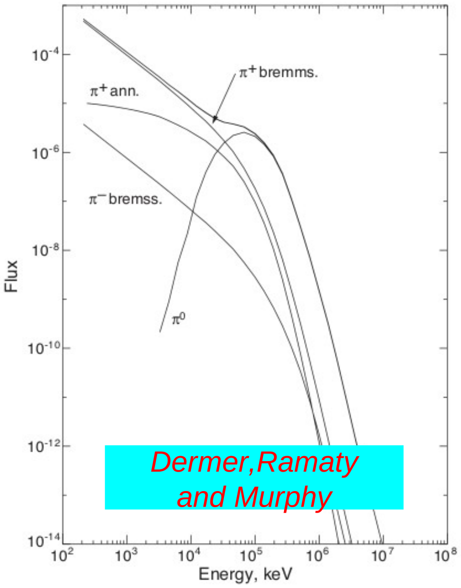
2. Nuclear Line De-excitation and Pion Decay Continuum by > Few MeV PROTONS (and ions)



CGRO March 06, 1989
Park, VP & Schwartz



Share and Murphy



Dermer,Ramaty and Murphy

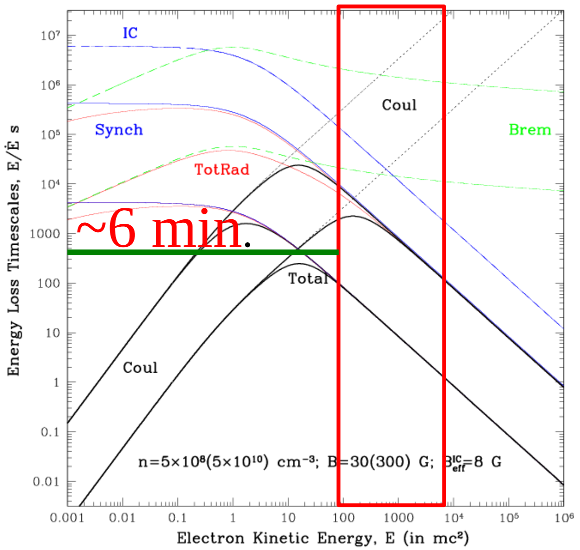
C. Transport Processes; *in the corona*

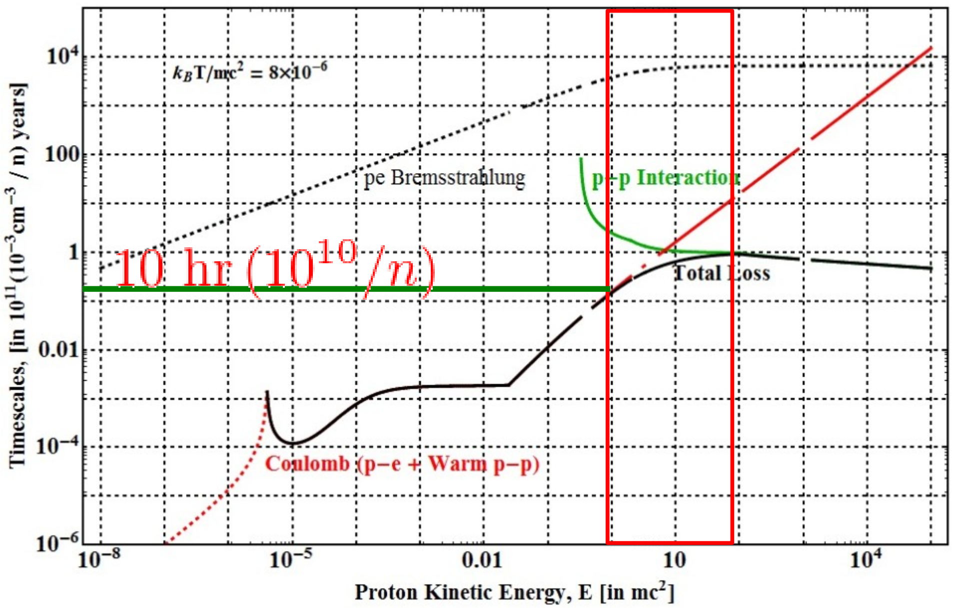
1. Electron Energy Losses

Coulomb, Synchrotron, Inverse Compton, e-p Brem.

2. Proton Energy Losses:

Coulomb, p-p Interactions p-e (Inverse) Brem.





C. Transport Processes; *in the photosphere*

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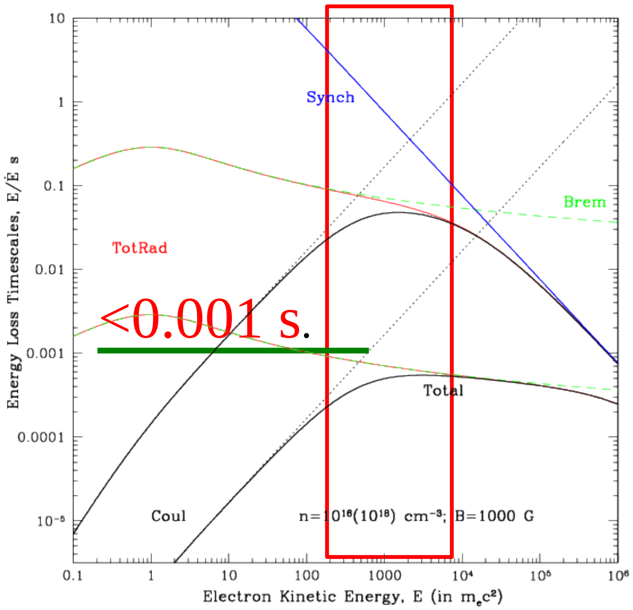
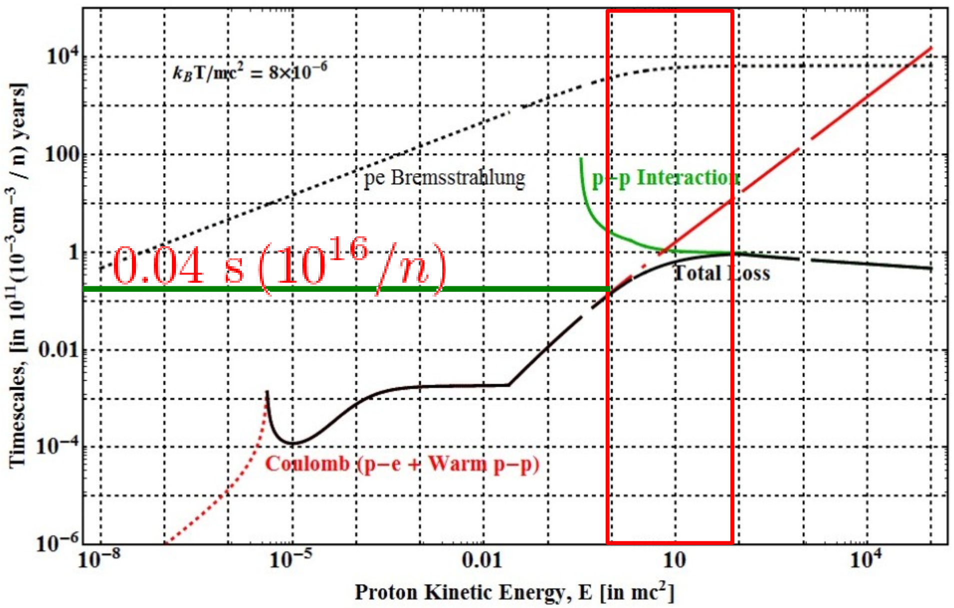
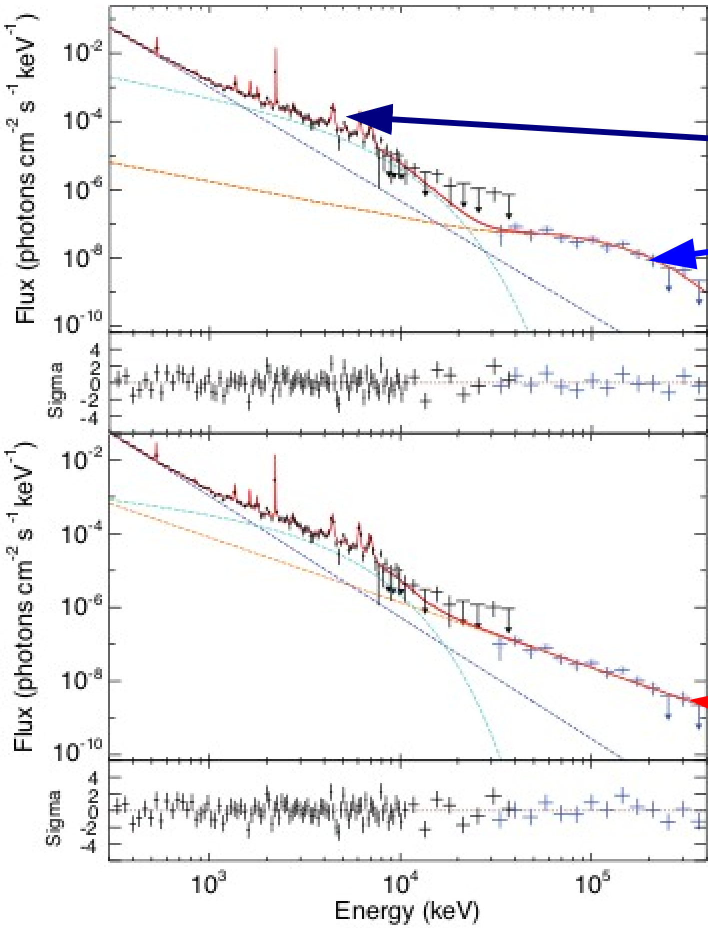




III. Data

A. June 12, 2011: *Impulsive phase only*
Radiation Mechanisms (Ackermann et al. ApJ 2011)



Electron Bremsstrahlung
(2 components: blue and green)
Nulear lines (black)
Pion decay continuum

Nuclear lines + three separate electron bremsstrahlung components
3rd Requires > 1 GeV Electrons

A. June 12, 2011 impulsive flare

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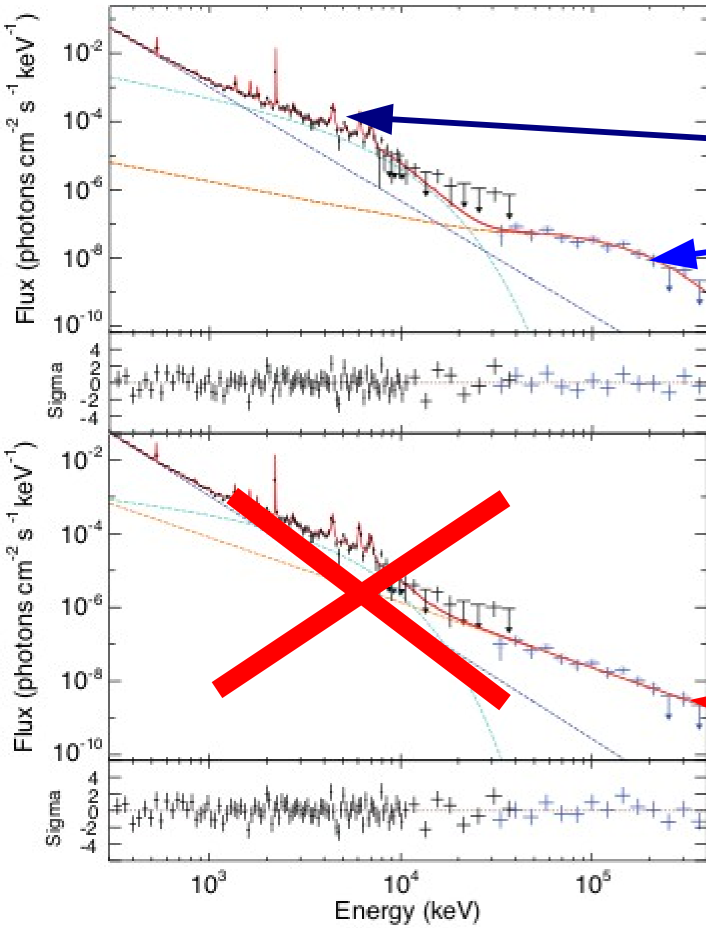

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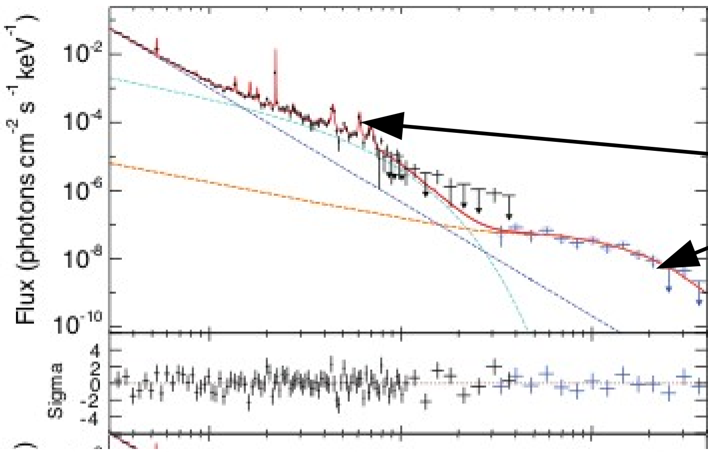
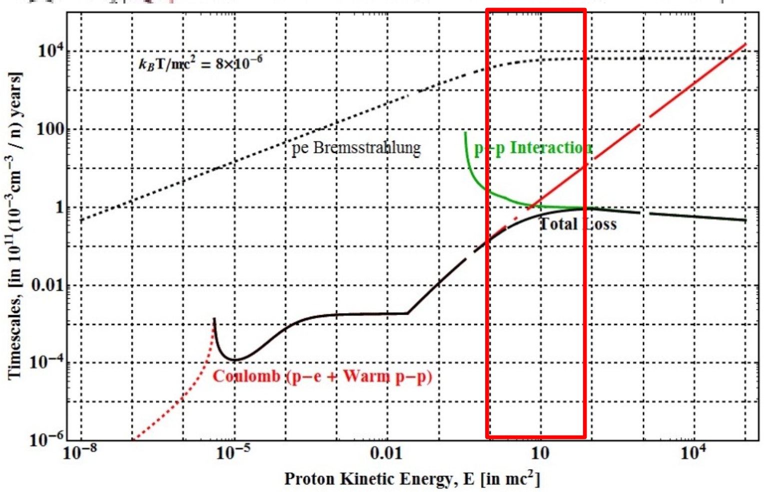
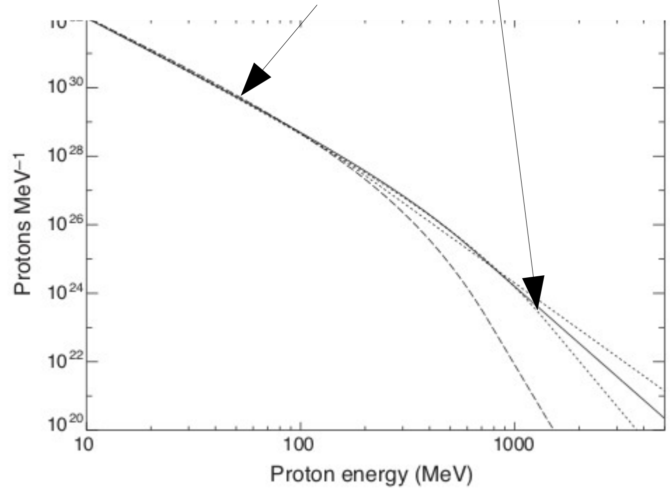




Index 3.5 to >4.5

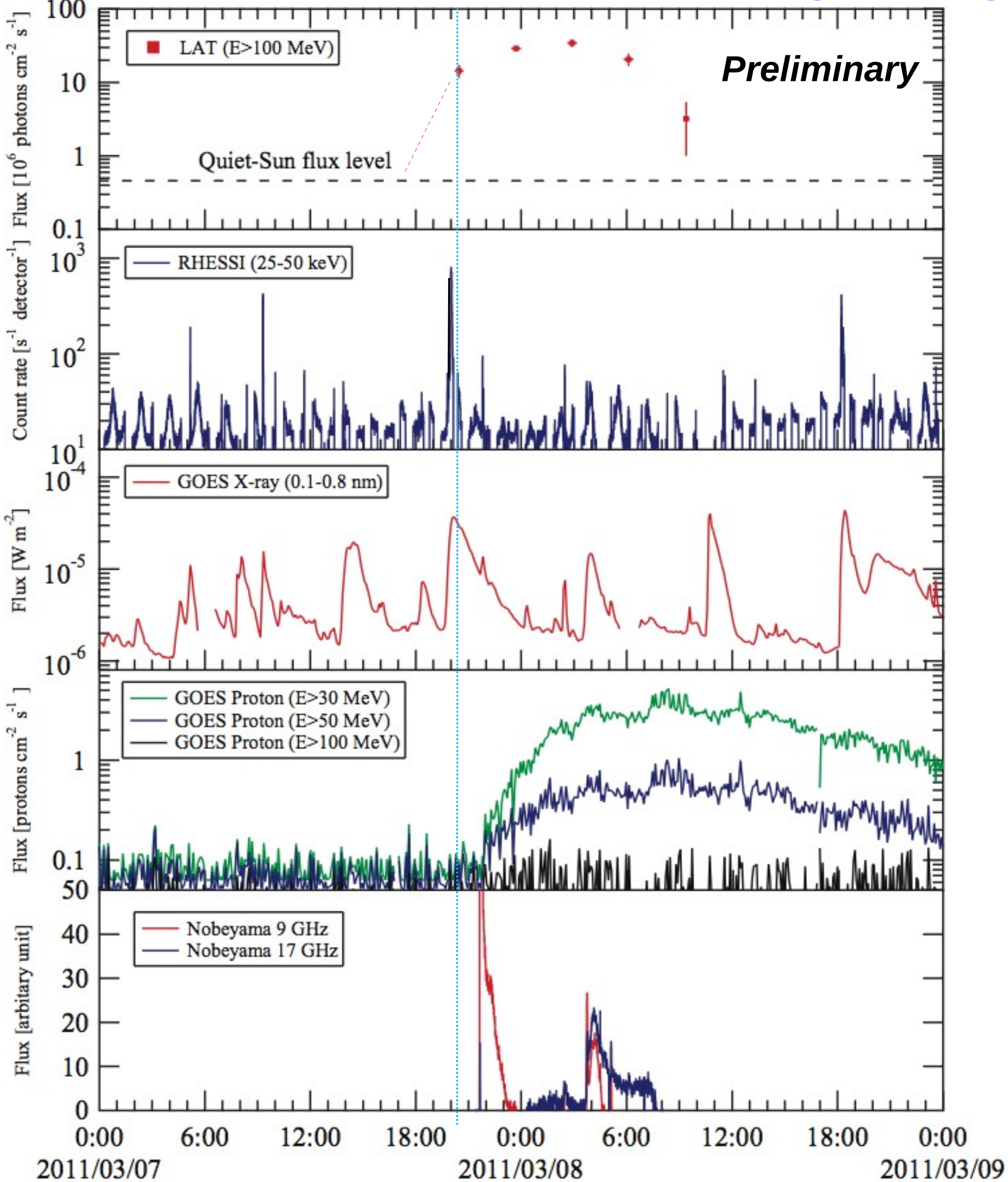


Effects of energy loss in transport

$$N_{\rm eff}(E) = \frac{\tau_L(E)}{E} \int_E^{\infty} \dot{Q}(E')dE$$

Expect steepening by 1.0 to 1.5

B. March 7-8, 2011: *Long Duration Only*
Multi-Wavelength light Curves



GOES M 3.7

LAT detection for ~12 hours just after the peak of the RHESSI impulsive phase.

Implies significant emission during the impulsive phase also.

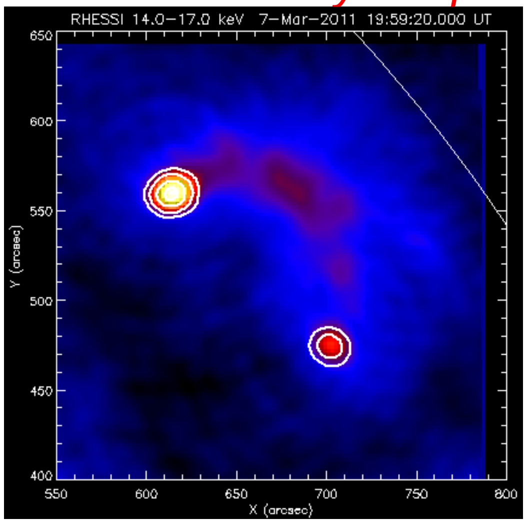
SEP Protons up to ~100 MeV with long duration

2200 km/s CME

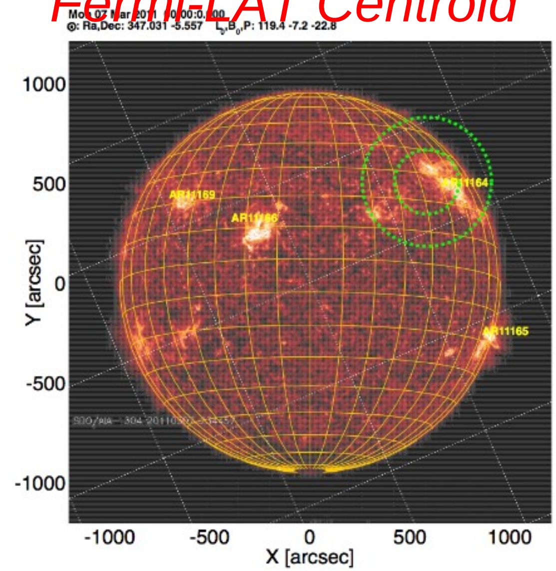
B. March 7-8, 2011: *Long Duration Only*

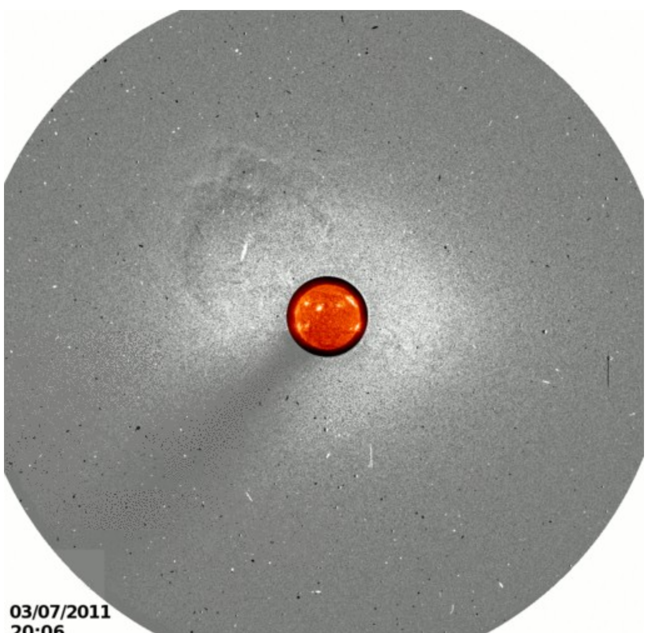
Multi-Wavelength Images (Active Region 11164)

RHESSI X-ray Loop

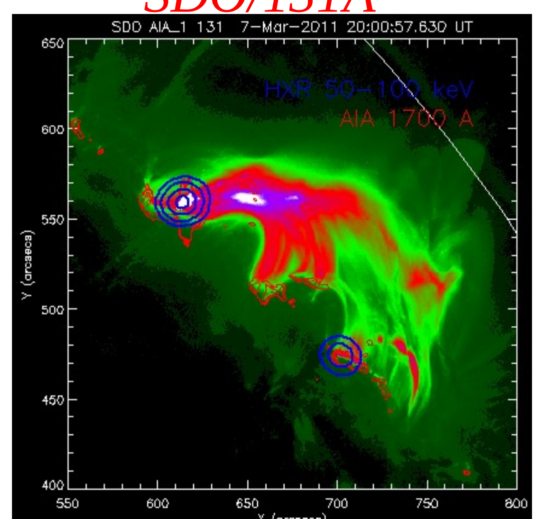


Fermi-LAT Centroid



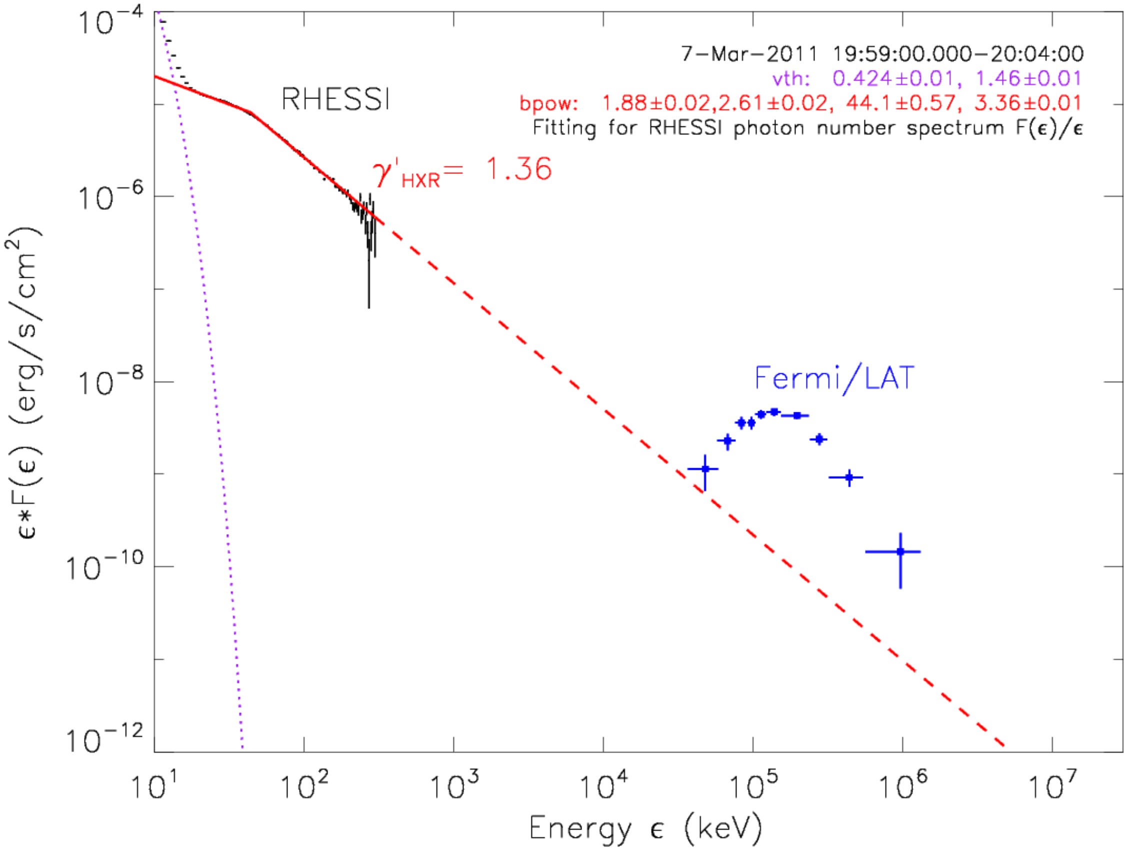


SDO/131A



B. March 7-8, 2011 Long Duration Flare

Spectrum: Electrons or Protons



$$\mathcal{E}^{tot}_{\gamma-ray} = 10^{-3}\,\mathcal{E}^{tot}_{HXR}$$

Considering the differences In durations and yields of (Brem.) HXRs And (Pion decay) Gamma-rays we get

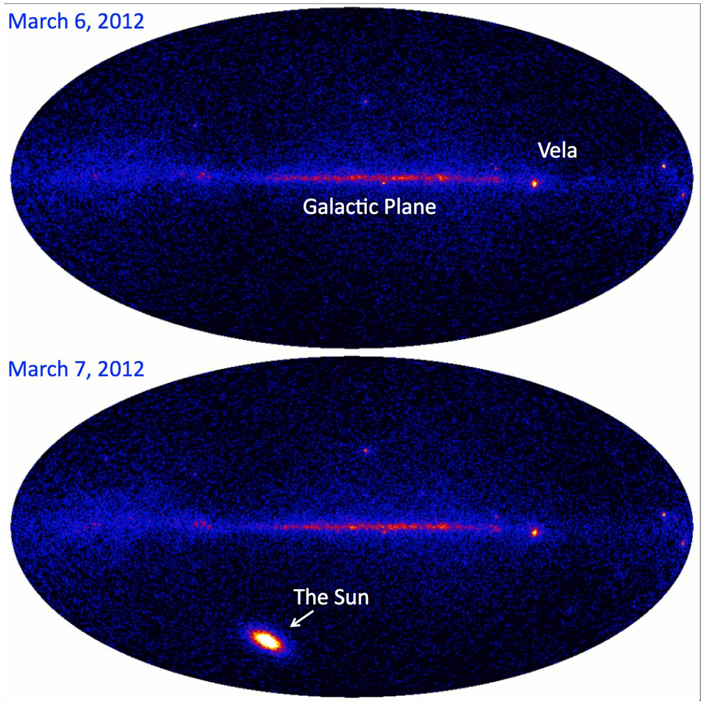
$$\varepsilon_e \sim \mathcal{E}_{HXR} \times Y_{HXR} \times \Delta t_{HXR}$$

$$\varepsilon_p \sim \mathcal{E}_{\gamma-ray} \times Y_{\gamma-ray} \times \Delta t_{\gamma-ray}$$

$$\varepsilon_p \sim 10^{-2}\varepsilon_e$$

C. March 7, 2012 X5.4 Class Flare

Localization (Time integrated)



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1000 times the quiet Sun;

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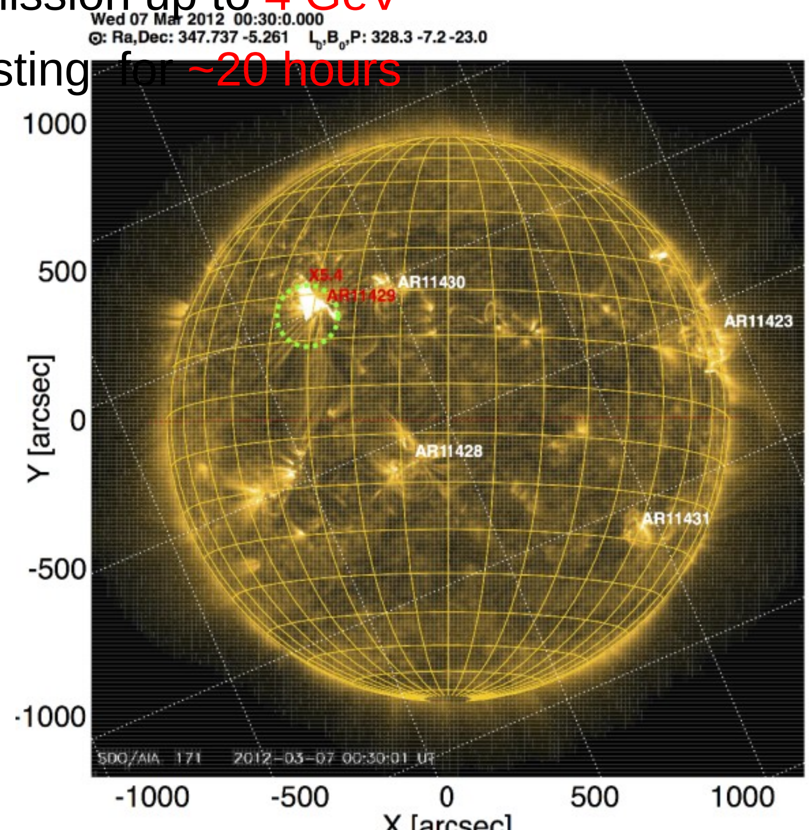
50 times the Crab flare;

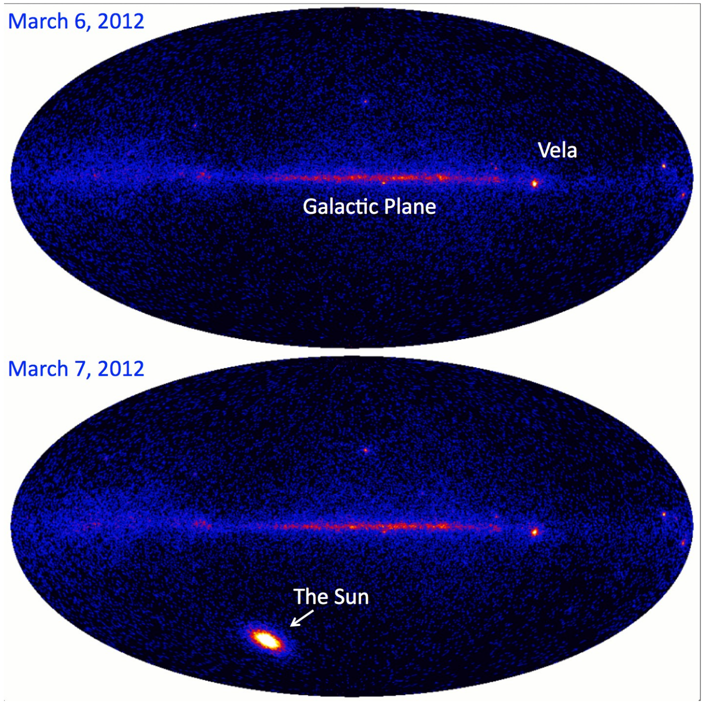
Emission up to 4 GeV

Lasting for ~20 hours



C. March 7, 2012 X5.4 Class Flare

Localization (Time resolved)



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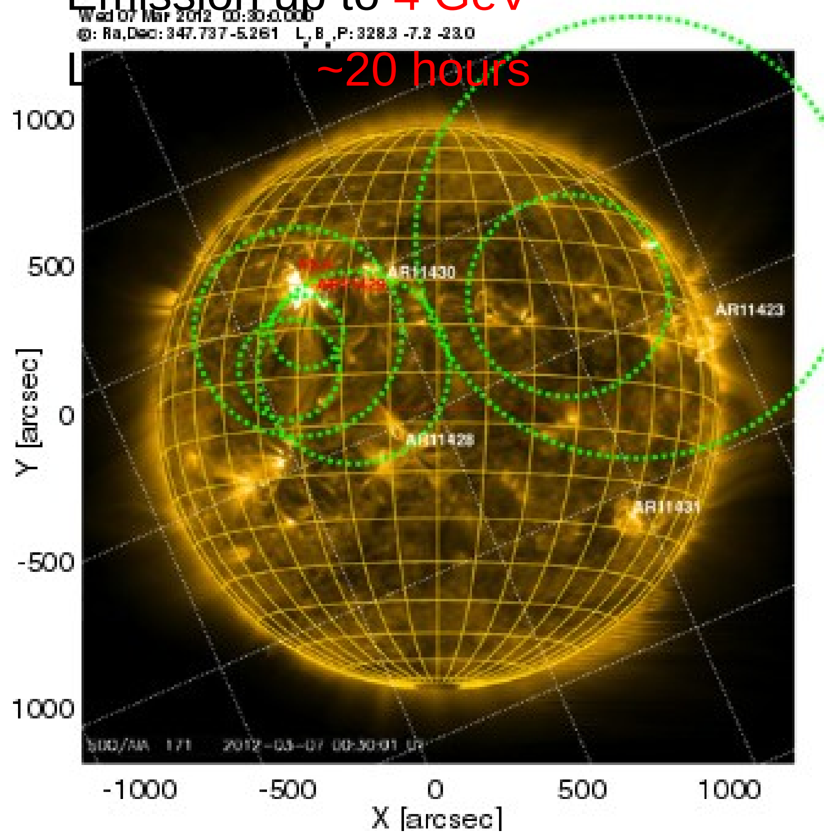


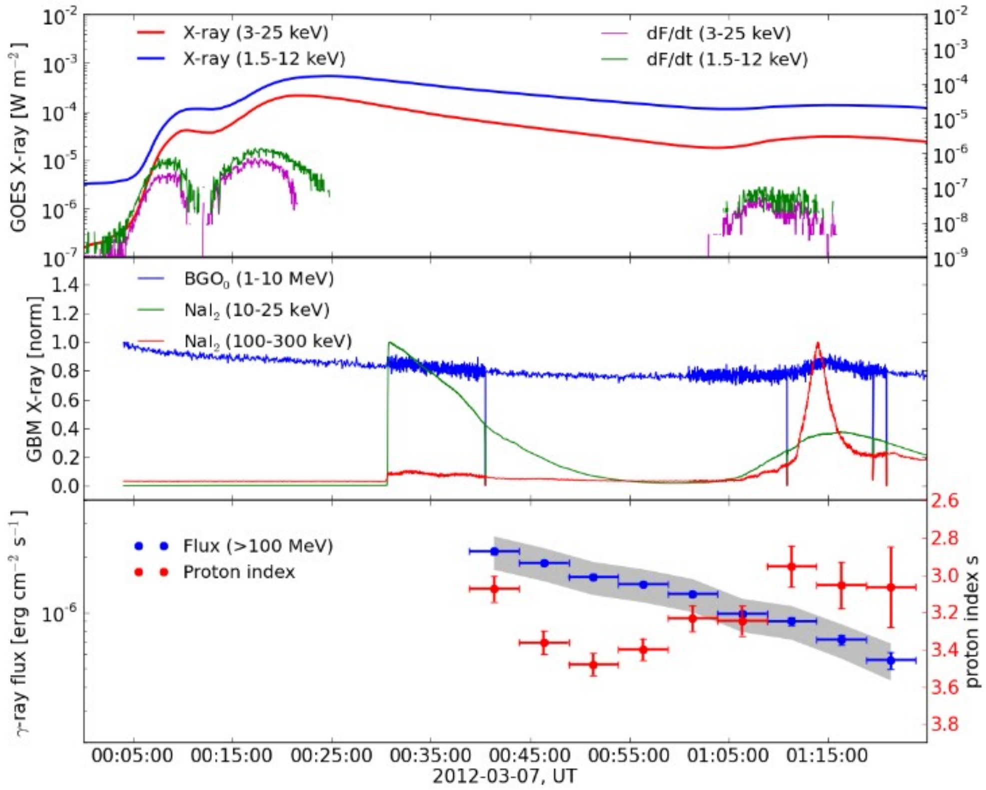
Five Photons > 2.5 GeV

Localization: > 4.5 sigma

that are coming from the Sun

C. March 7, 2012 X5.4 Class Flare

Light curve and Spectral index: *Impulsive phase*



GOES: *soft X-ray*

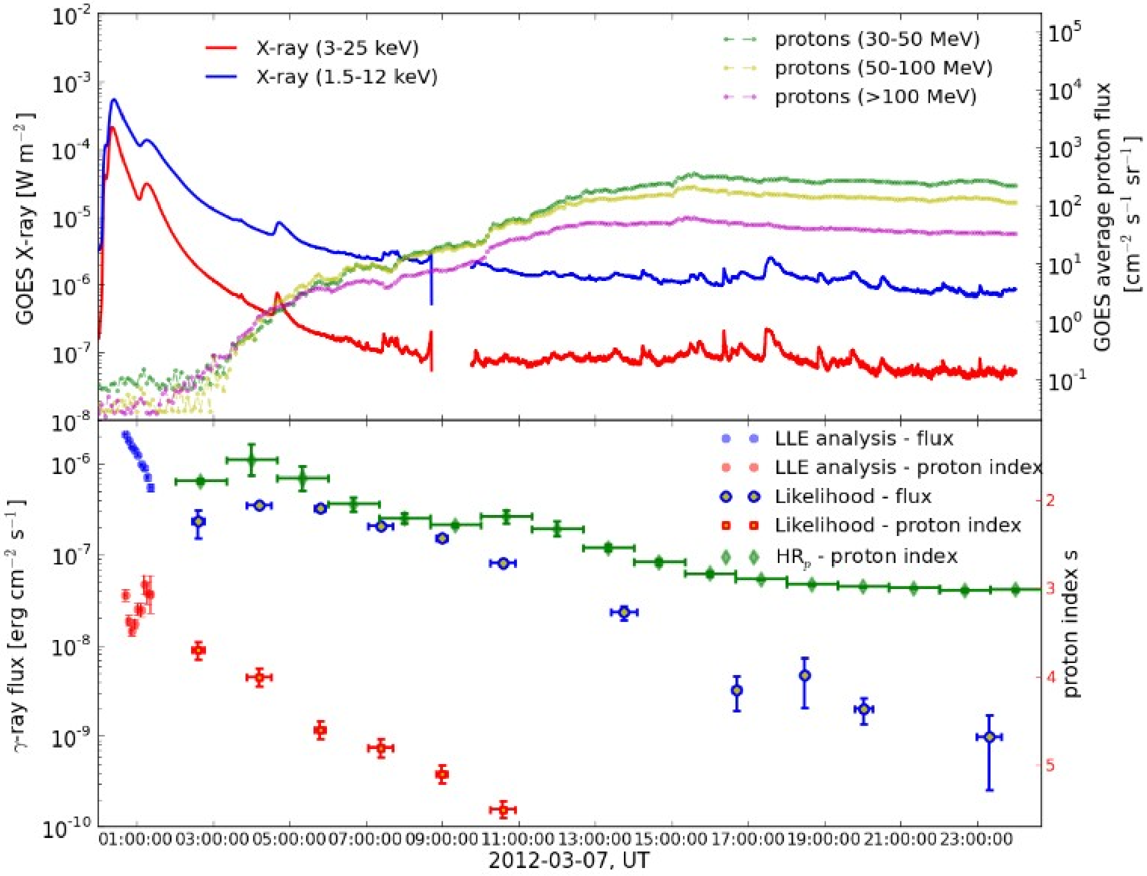
Goes Derivative

GBM: *hard X-rays*

LAT: *gamma-rays*

C. March 7, 2012 X5.4 Class Flare

Light curve and Spectral index: *Extended phase*



SEP: *proton flux*

GOES: *soft X-ray*

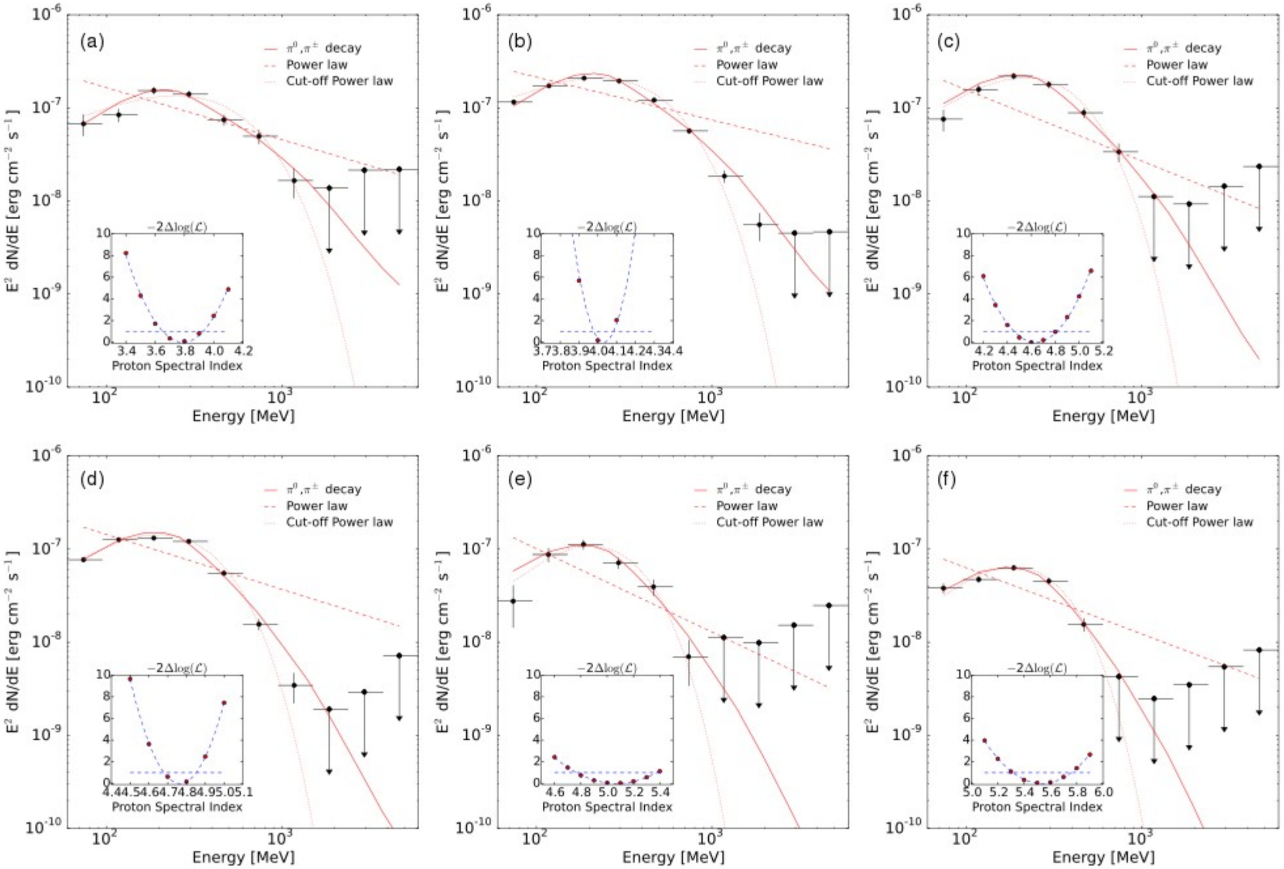
SEP: *proton index*

LAT: *Flux*

LAT: *proton index*

C. March 7, 2012 X5.4 Class Flare

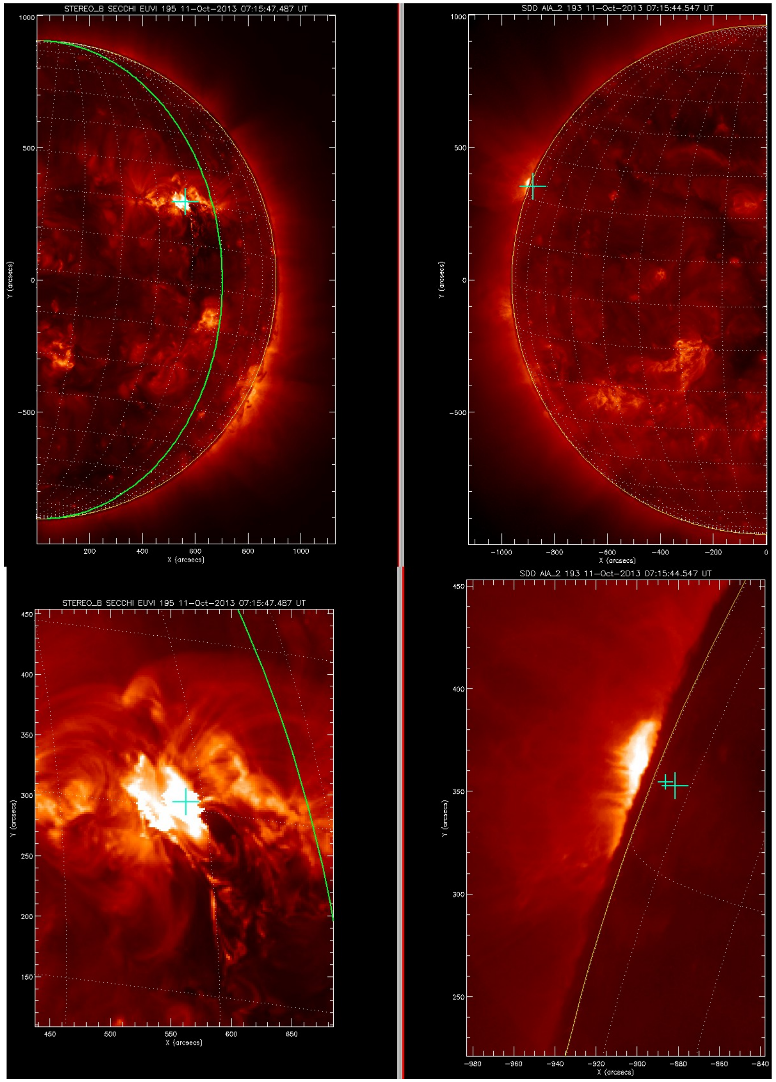
Spectrum and Proton Index: *Extended Emission*

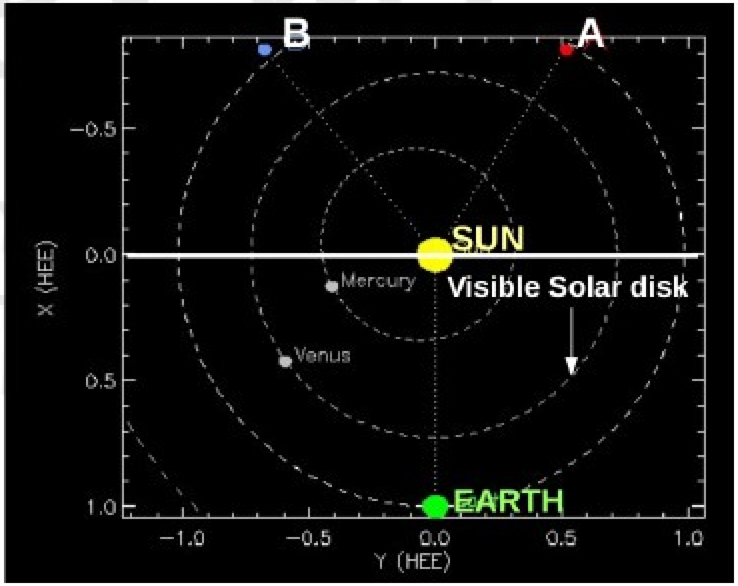


D. Oct. 11, 2013 M1.2 Class Flare

A behind the limb flare

Stereo B SDO/AIA

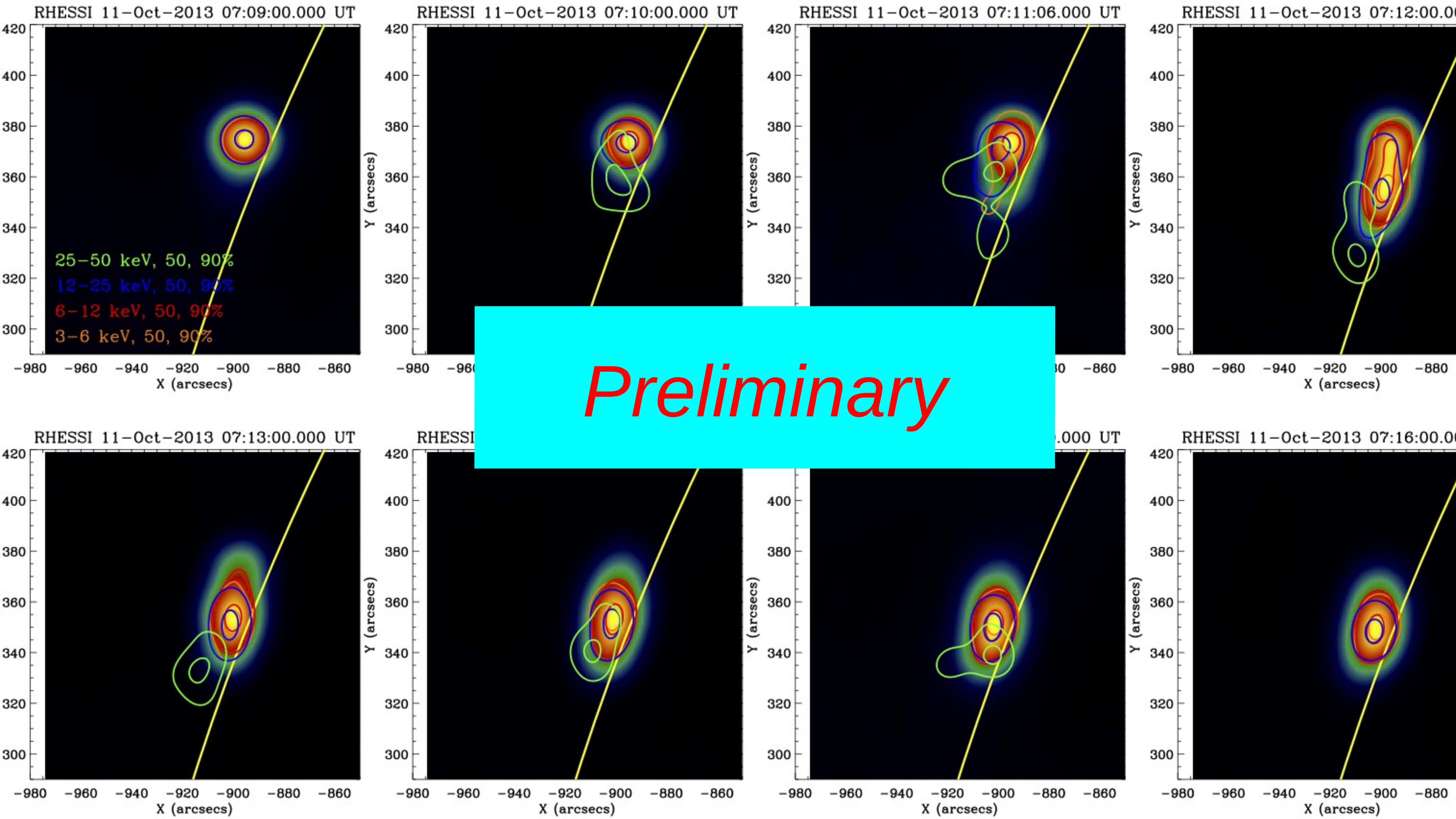




Preliminary

D. Oct. 11, 2013 M1.2 Class Flare

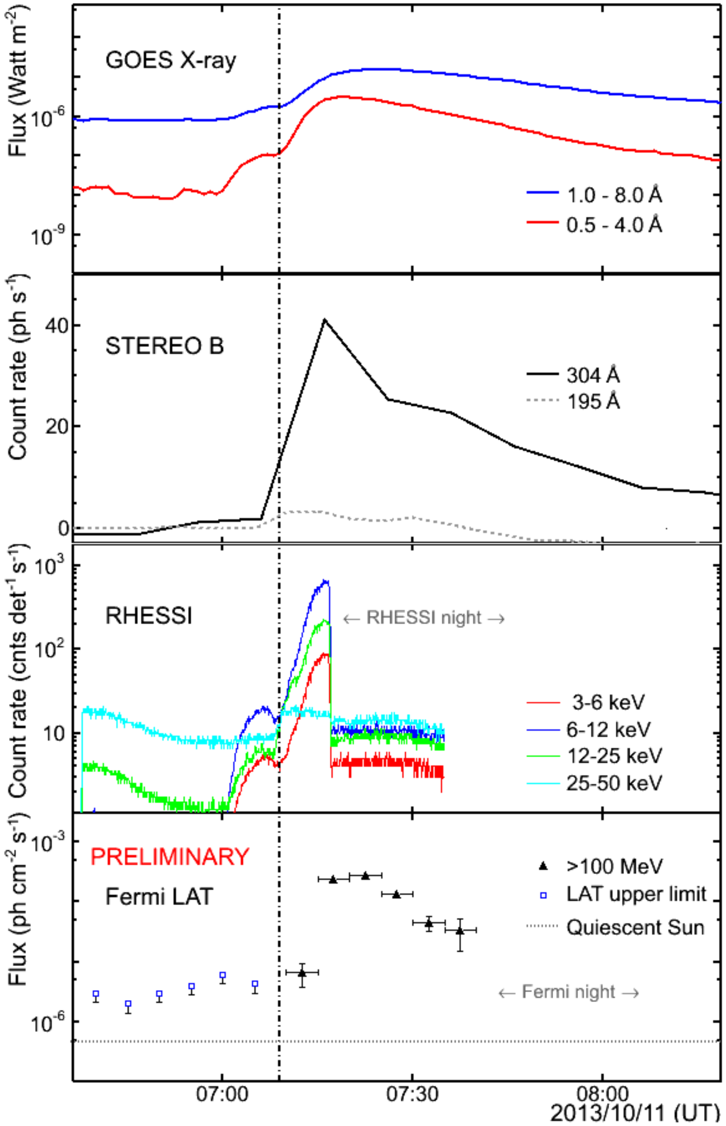
A behind the limb flare



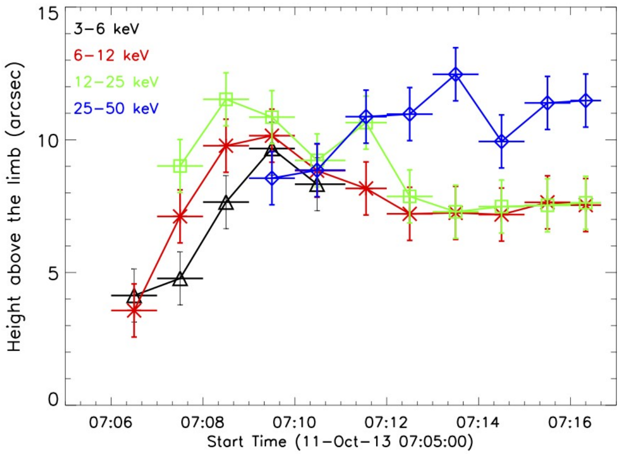
Preliminary

D. Oct. 11, 2013 M1.2 Class Flare

A behind the limb flare



Preliminary



IV. Interpretation

Interpretation: *Models*

1. Prompt injection $\dot{Q}(E,t) = Q_o(E/Ep)^{-p_0}\delta(t-t_0)$

   and transport $\dot{E} = -(E_p/\tau_0)[(1+(E/E_p)^{\delta}]$

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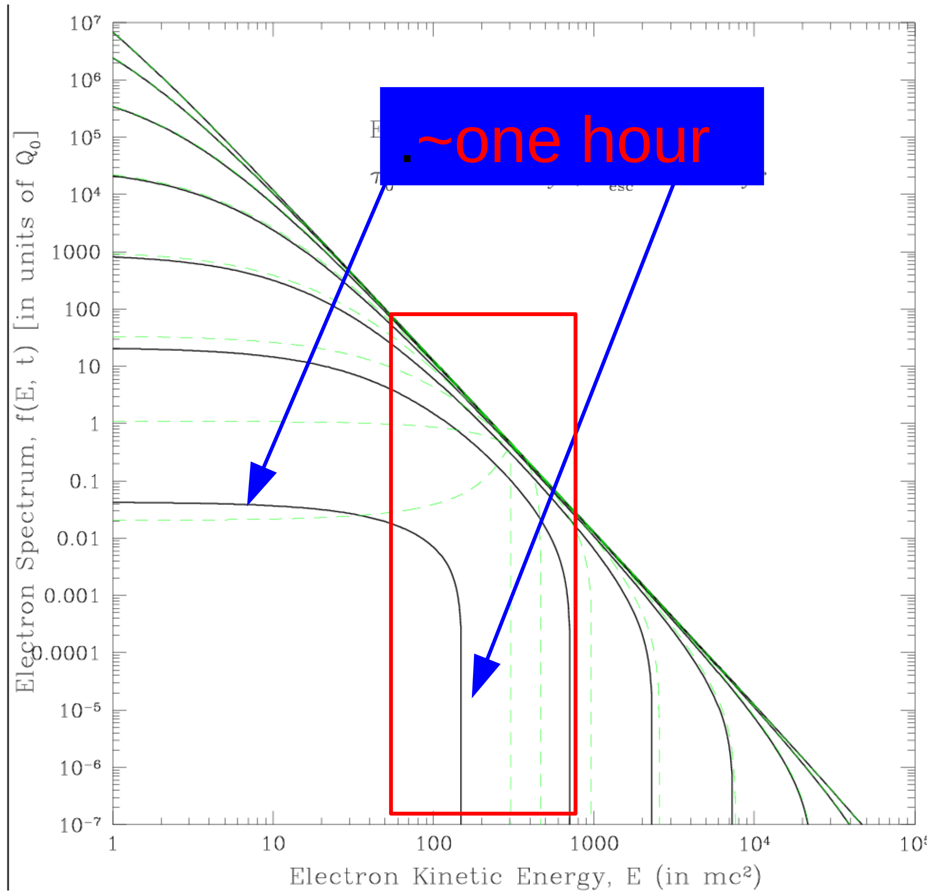
and transport $\dot{E} = -(E_p/\tau_0)[(1+(E/E_p)^{\delta}]$

ELECTRON $\delta = 2$

$$N(E,t) = Q_0 \frac{[1-(E/E_p)\tan(t/\tau_0)]^{p_0-2}}{\cos^2(t/\tau_0)[E/E_p+\tan(t/\tau_0)]^{p_0}}.$$



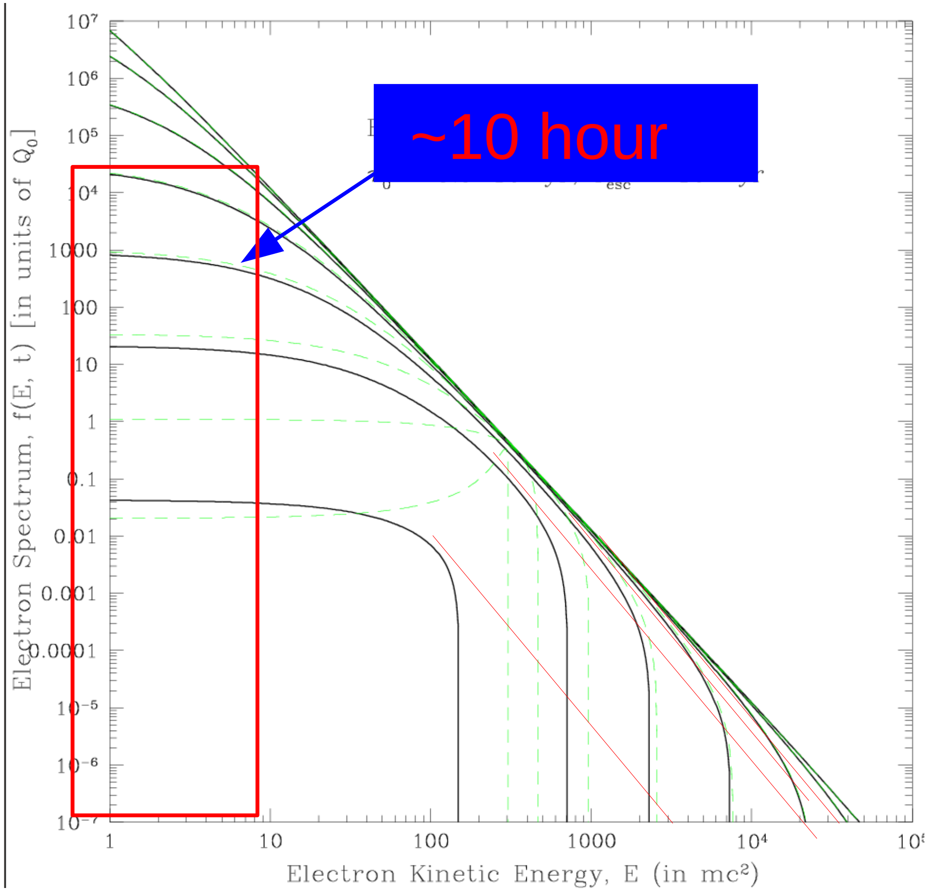
Interpretation: *Models*

1. Prompt injection $\dot{Q}(E,t) = Q_o(E/Ep)^{-p_0}\delta(t-t_0)$

and transport $\dot{E} = -(E_p/\tau_0)[(1+(E/E_p)^{\delta}]$

PROTON $\delta = 1$

$$N(E,t) = Q_0 \frac{e^{-(p_0-1)t/\tau_0}}{(E/E_p + 1 - e^{-t/\tau_0})^{p_0}}$$



Interpretation: *Models*

2. Trap-Percipitation in converging fields:

Need strong scattering

a. Coulomb Collisions: *slower than energy loss*

b. Scattering by turbulence: *also acceleration*

Need scattering time decreasing with energy

Steeper than Kolmogorov spectrum

Also expect spectral hardening: *Not observed*

Interpretation: *Models*

3. Continuous acceleration on a time scale comparable to loss timescale with a rapid transport of particles into the chromosphere and below as in *the standard thick-target model.*

4. Difficult to distinguish between acceleration by

   1. the CME shock

   2. turbulence at lower corona

V. Summary

IV. Summary: *Observations*

Fermi-LAT detected gamma-ray emission from several modest M-class and strong X-class solar flares with some lasting as long as a day.

The combined GBM and LAT observations set significant constraints on the emission processes.

The excellent LAT spatial resolution locates the flare within an active region associated with fast CME and other emissions.

Observations of the behind the limb flare imposes some challenges

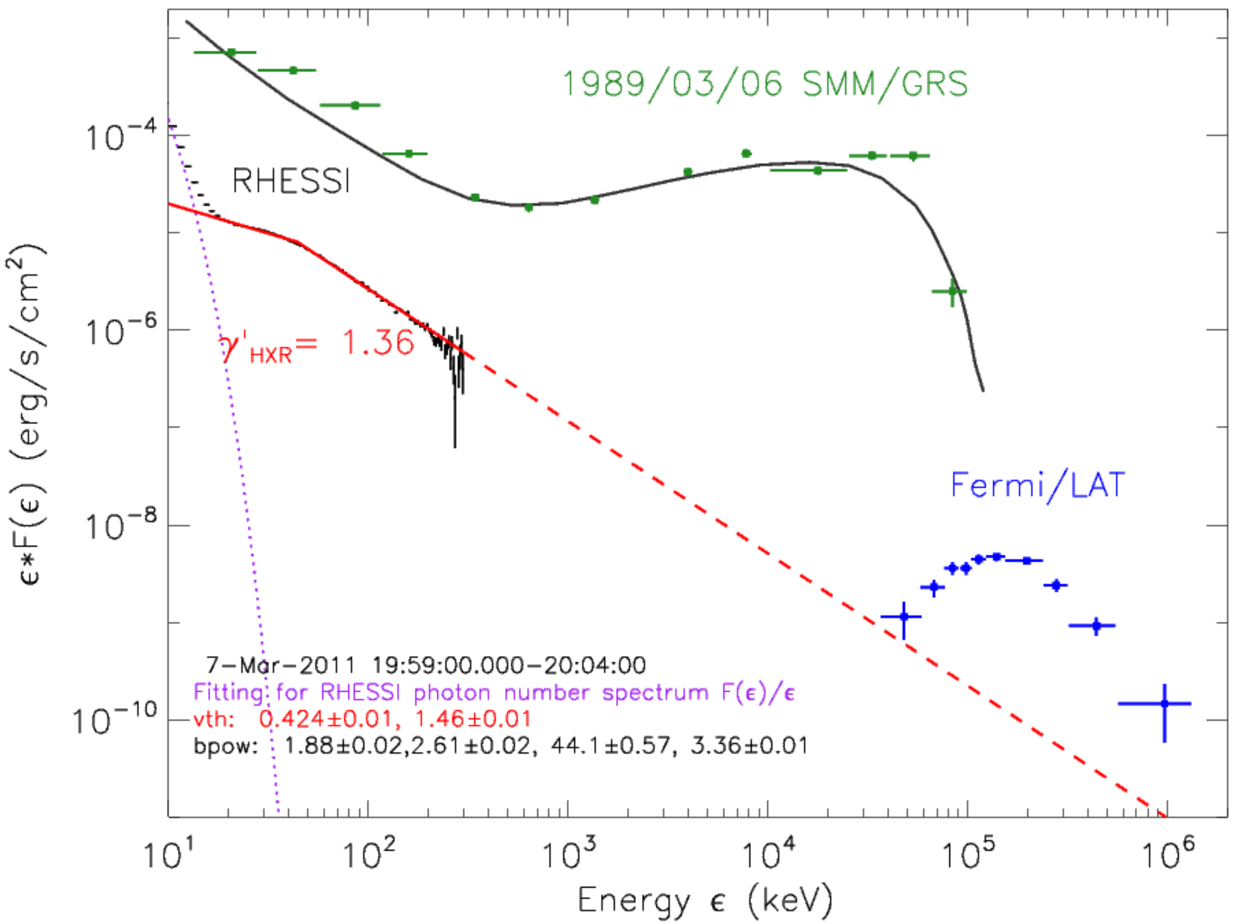
IV. Summary of Emission Processes

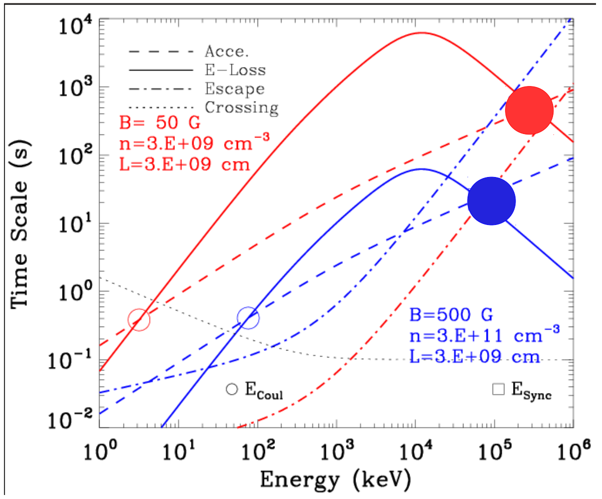
1. Bremsstrahlung by > several 100MeV electrons is a viable model

BUT

B. March 7-8, 2011 Long Duration Flare

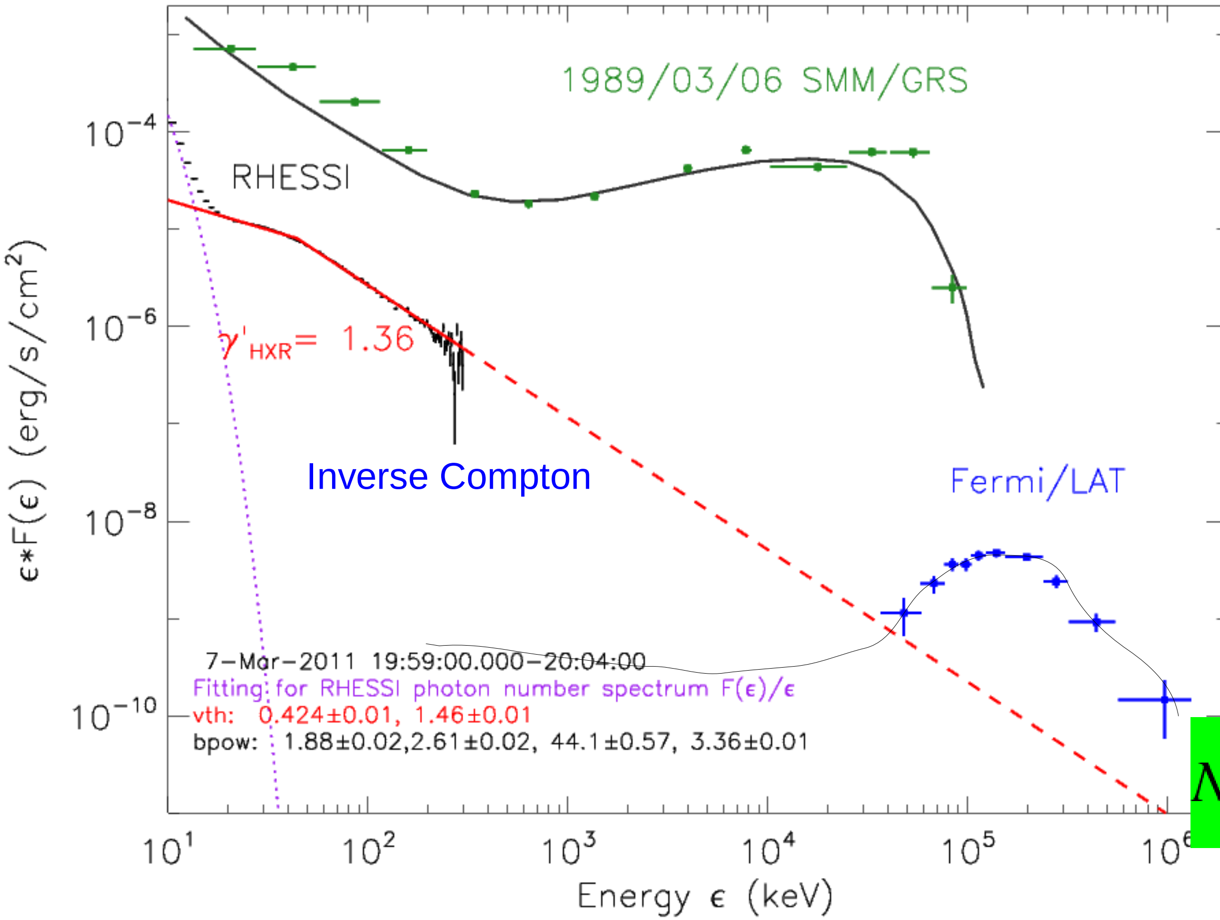
Electron acceleration to MeV range

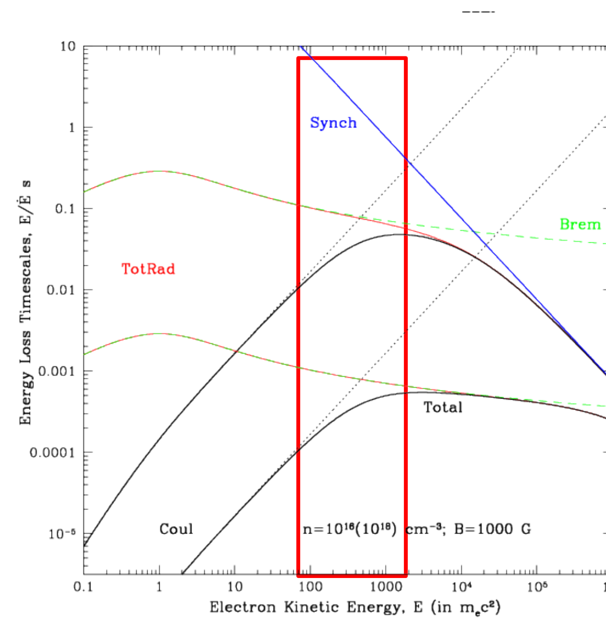




B. March 7-8, 2011 Long Duration Flare

Multi-Wavelength light Curves (Paper in preparation)





$$N_{\rm eff}(E)=\frac{\tau_L(E)}{E}\int_E^{\infty}\dot{Q}(E')\,dE$$

IV. Summary of Emission Processes

1. Bremsstrahlung by > several 100MeV electrons is a viable model

2. Decay of pions produced by high energy protons is a more likely scenario

BUT

How do we deal with the behind the behind the limb flare?

Absorption of gamma-rays

1. The column depth of emission

$$N(E) = \int n(s)ds = N_0 \int_0^E \beta'^2 dE'/(mc^2) = N_0(m/m_e)(E/mc^2)^2/(E/mc^2+1) \text{ with } N_0 = (4\pi r_0^2 \ln\Lambda)^{-1} = 5\times10^{22}\,\mathrm{cm}^{-2}$$

Protons: 0.3-10 GeV N=(6.4-82.5)x10^{24}

Electrons: 0.1-5 GeV N=(10-600)x10^{24}

Electrons 25-300 keV N=(0.2-17)x10^{20}

Absorption of gamma-rays

2. Optical depth from flare at a small angle behind the limb

$$\tau(E,\theta) \sim \sigma(E) n_0(E) R_\odot \theta \left(1 + \sqrt{h_0/(\theta R_\odot)}\right) \exp^{\theta^2 R_\odot/(2h_0)}$$

increases rapidly with angle and energy

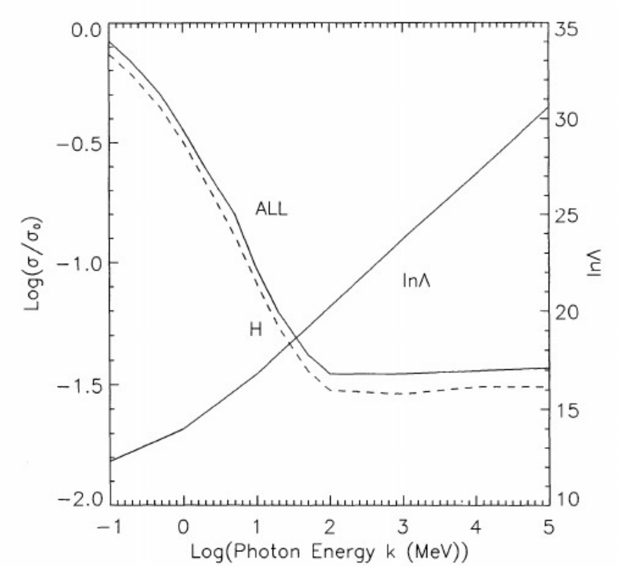


FIG. 5.—Variation with photon energy of the Coulomb logarithm ln Λ and total cross section (in units of Thompson cross section σ_0), primarily due to Compton scattering at low energies and pair production at high energies. The dashed line shows the cross section for hydrogen, and the solid line includes contribution of He and heavy elements for solar abundances calculated from compilation of cross sections by Hubbel et al. (1980).