

Fermi
Gamma-ray Space Telescope

Fermi LAT Observations of Solar Flares

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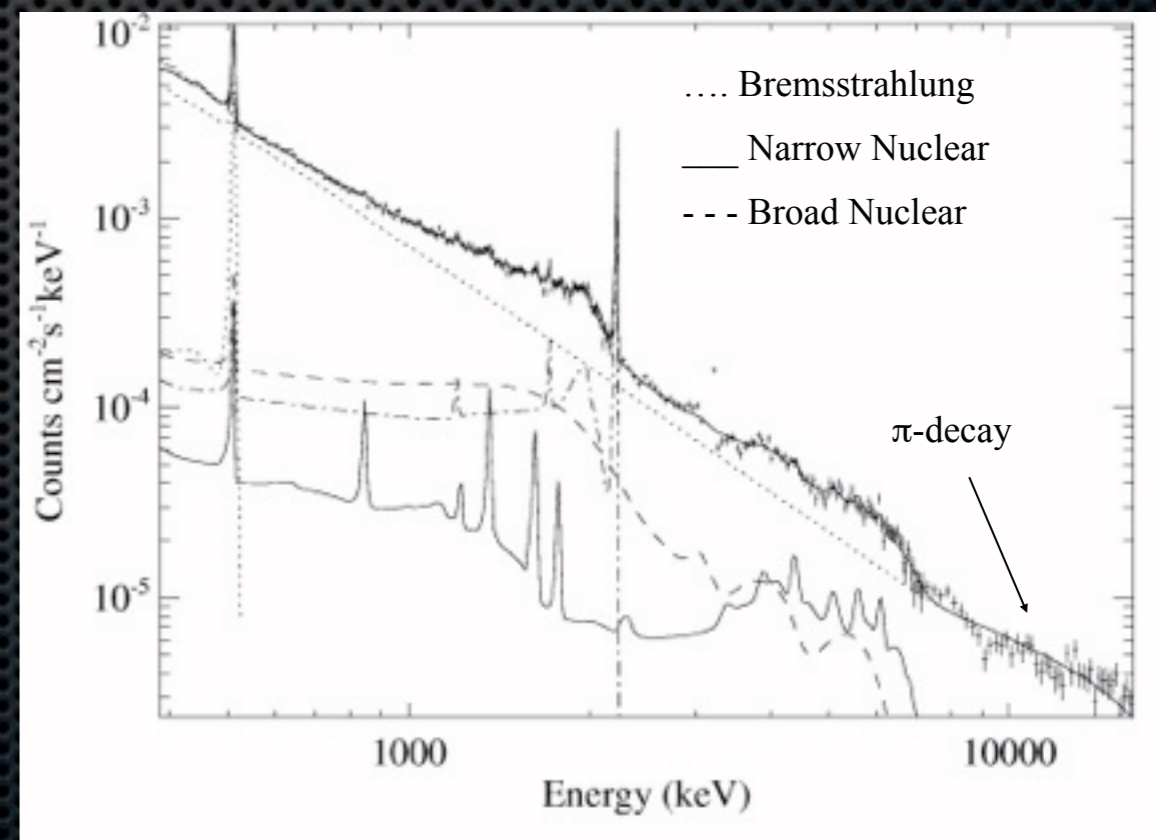
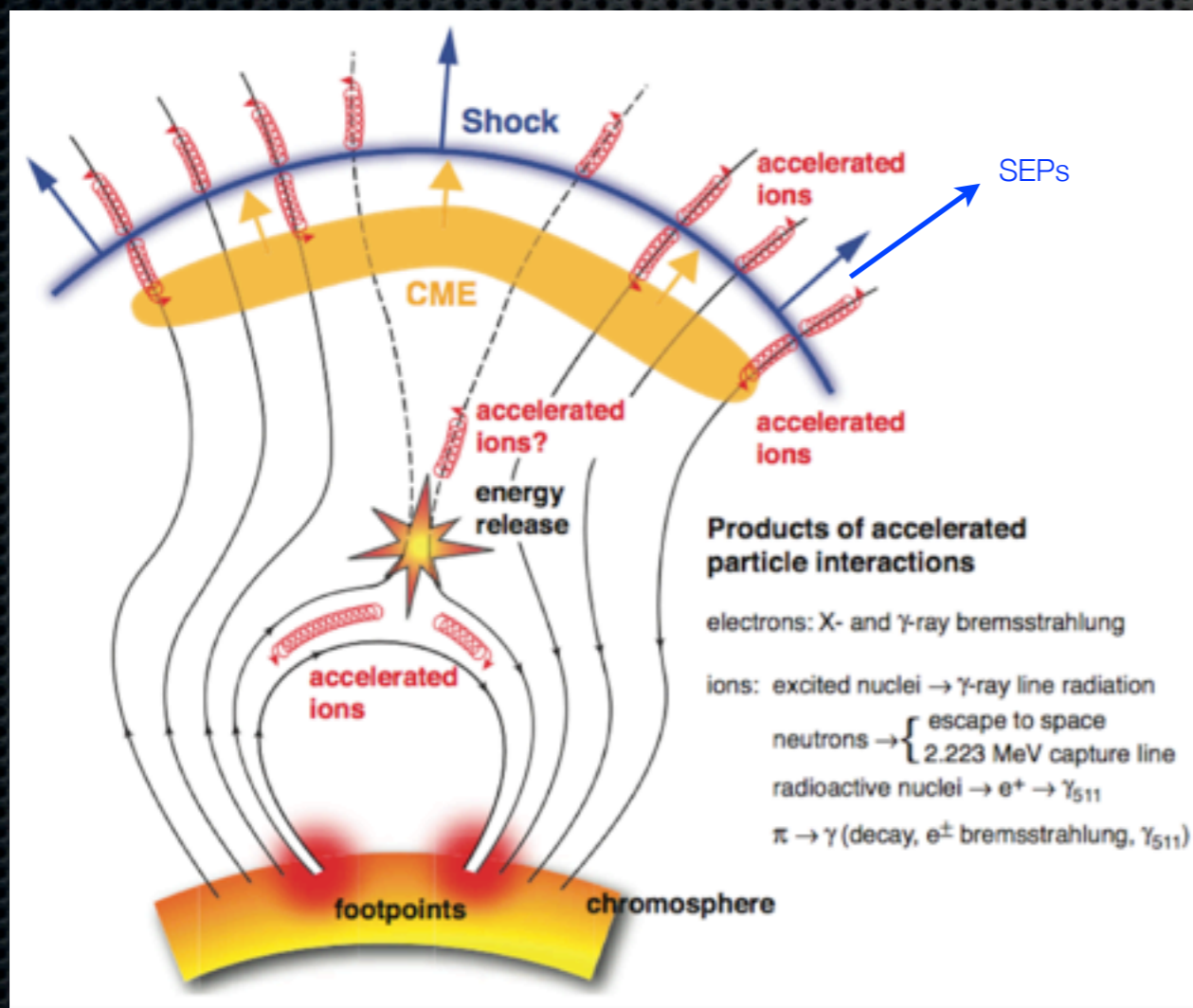
on behalf of the Fermi-LAT
collaboration

¹Stanford U., ²SLAC



- Observations of solar flares in γ rays since the 70s (SMM, EGRET, ...) for bright X-ray flares

- Evidence for nuclear lines ($\sim 1-10$ MeV), and continuum (up to 100MeV):
 - in the impulsive phase
 - sustained emission



RHESSI observations of 2005 Jan. 20 flare (Share et al., 2005)



- List of flares with sustained emission

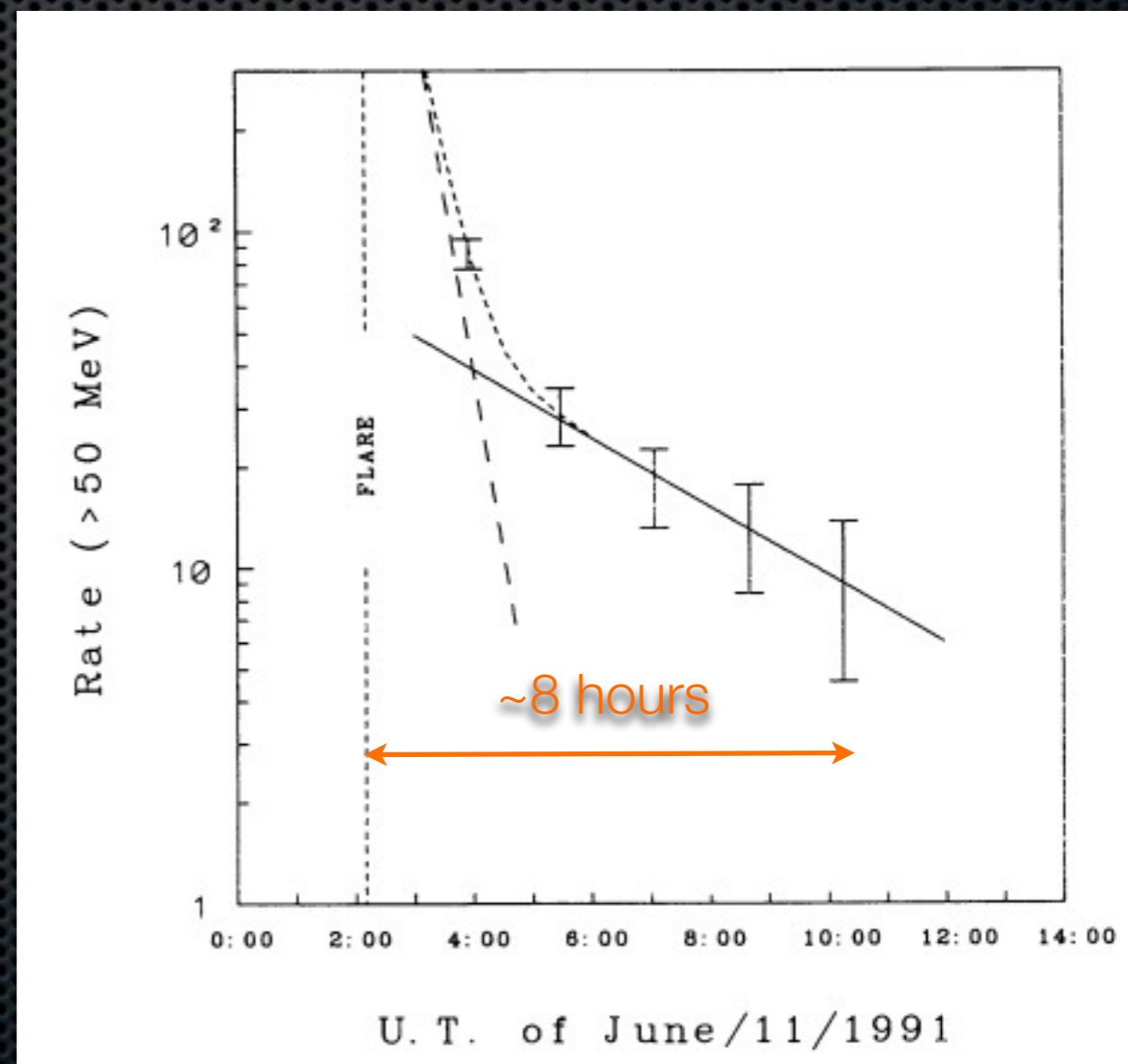
TABLE I

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

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

Ryan et al. 2000

- 1991 June 11 X12.0 flare: monotonic decay for 8 hours above 50MeV



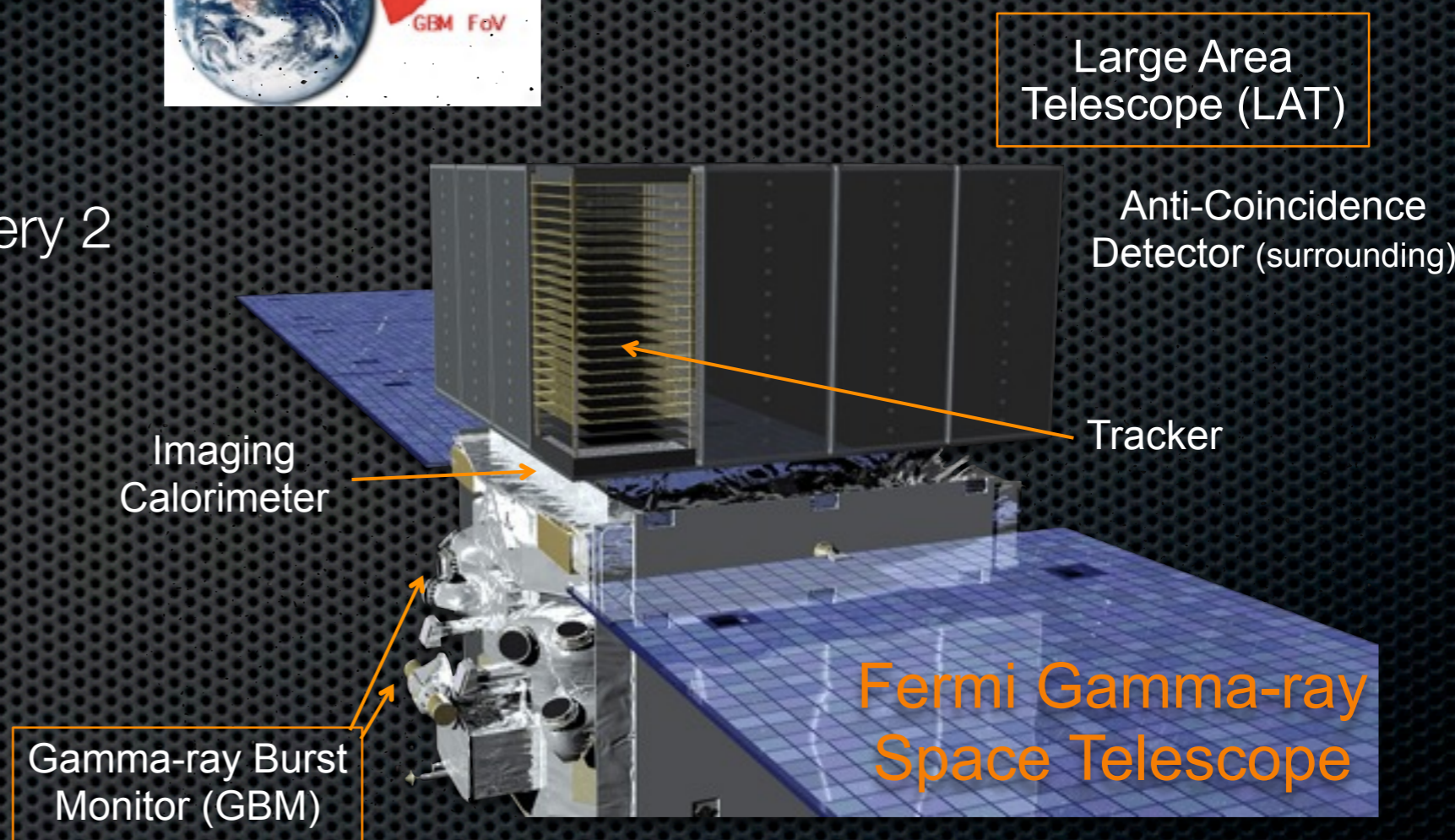
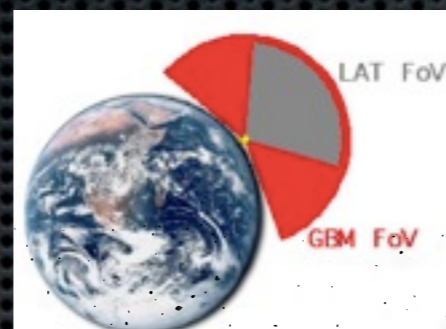
EGRET observation of 1991 June 11 flare (Kanbach et al., 1993)

Unclear **where and how** γ rays are produced

Fermi LAT as solar observatory



- High sensitivity above 100MeV
- Wide Field of View
- Observes the entire sky every 2 orbits:
 - Sun in the FoV about 30min every 3 hours
- Adapting the pointing strategy to high solar activity period



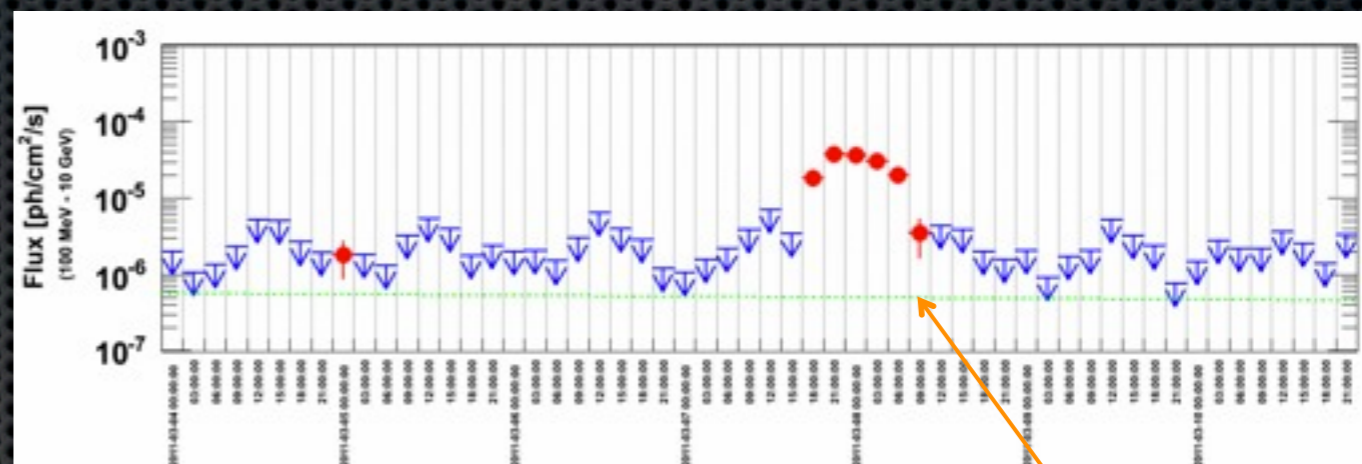
Fermi Gamma-ray Space Telescope

LLE events now available

- Intense X-ray flux: pile-up in the ACD \Rightarrow γ -ray suppression.
 - Recover the signal with looser selection technique: LAT Low Energy events (LLE)



- Each passage of the Sun in the LAT FoV yields a measurement: γ -ray flux coincident with the Sun position



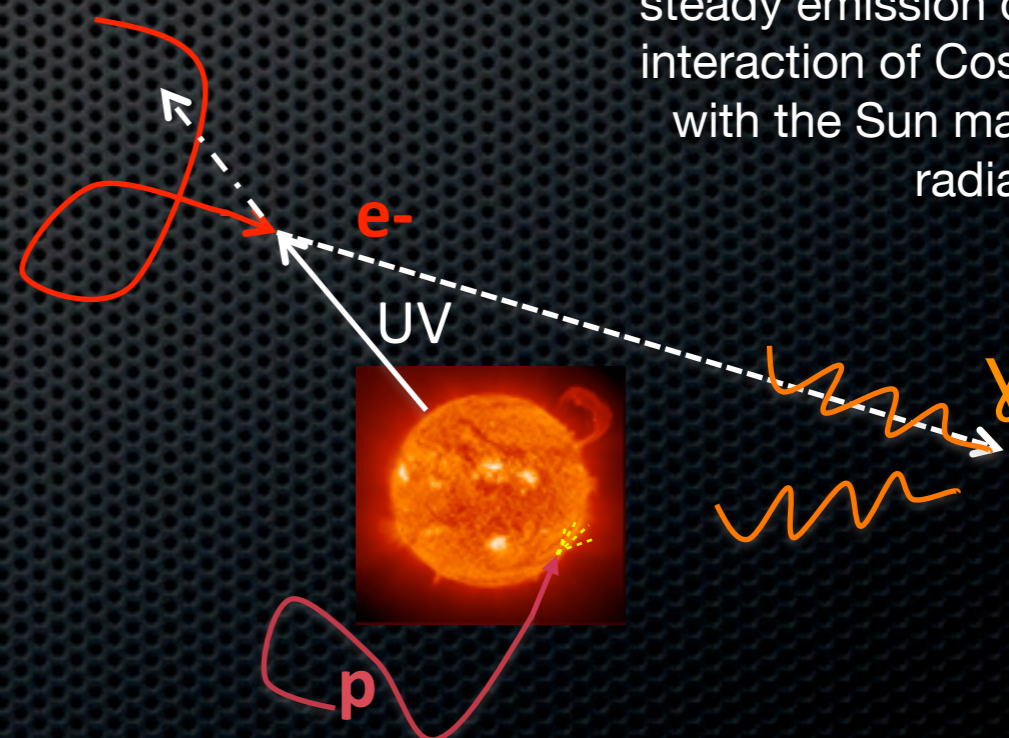
LAT SunMonitor output example

- Also check all GBM solar flares for LLE data.

Quiet Sun γ -ray flux: steady emission due to the interaction of Cosmic Rays with the Sun material and radiation field.



High confidence detections of 18 flares in the first 4 years of the Fermi mission



Solar Flares detected $>100\text{MeV}$



Date	GOES X-ray Class, Start-End (UT)	Type	Duration (hr)	CME [†] Speed, km/s
2010-06-12	M2.0, 00:30-01:02	I	–	486
2011-03-07	M3.7, 19:43-20:58	I/S	10.7	2125
2011-03-08		S		
		S		
		S		
2011-06-02	C2.7, 09:42-09:50	I/S	0.8	976
2011-06-07	M2.5, 06:16-06:59	S	2.2	1255
2011-08-04	M9.3, 03:41-04:04	S	1.9	1315
2011-08-09	X6.9, 07:48-08:08	I	–	1610
2011-09-06	X2.1, 22:12-22:24	I	0.6	575
		I/S		
2011-09-07	X1.8, 22:32-22:44	S	2.1	792
2011-09-24	X1.9, 09:21-09:48	I	–	1936
2012-01-23	M8.7, 03:38-04:34	I/S	5.7	1953
		S		
		S		
		S		
2012-01-27	X1.7, 17:37-18:56	D	4.0	1930
		S		
2012-03-05	X1.1, 02:30-04:43	I/S	5.3	1602
		S		
		S		
2012-03-07	X5.4, 00:02-00:40	S	20.2	2684
	X1.3, 01:05-01:23	I/S		1785
		S		
		S		
		S		
		S		
		S		
2012-03-09	M6.3, 03:22-04:18	D	5.7	844
		S		
		S		
2012-03-10	M8.4, 17:15-18:30	D	4.3	1379
2012-05-17	M5.1, 01:25-02:14	I/S	1.2	1582
2012-06-03	M3.3, 17:48-17:57	I	0.3	605
		I/S		
2012-07-06	X1.1, 23:15-23:49	I/S	0.9	892

- ✦ Not all flares are bright X-ray flares.
- ✦ Different types of emission:
 - ✦ Impulsive (duration $\lesssim 1$ min)
 - ✦ Sustained
 - ✦ Delayed
- ✦ All flares are associated with fairly fast CMEs

Solar Flares detected $>100\text{MeV}$



Date	GOES X-ray Class, Start-End (UT)	Type	Duration (hr)	CME [†] Speed, km/s	Fermi Time Window Start (UT), Duration (min.)	TS	Flux ($>100\text{ MeV}$) $\times 10^{-5}\text{ ph cm}^{-2}\text{ s}^{-1}$
2010-06-12	M2.0, 00:30-01:02	I	–	486	00:55, –	LLE*	–
2011-03-07	M3.7, 19:43-20:58	I/S	10.7	2125	20:15, 25	230	1.9 ± 0.3
2011-03-08		S			23:26, 36	520	3.5 ± 0.3
		S			02:38, 35	450	3.5 ± 0.3
		S			05:49, 35	200	1.9 ± 0.3
2011-06-02	C2.7, 09:42-09:50	I/S	0.8	976	09:43, 45	35	0.4 ± 0.2
2011-06-07	M2.5, 06:16-06:59	S	2.2	1255	07:34, 53	570	3.6 ± 0.3
2011-08-04	M9.3, 03:41-04:04	S	1.9	1315	04:59, 34	390	2.5 ± 0.3
2011-08-09	X6.9, 07:48-08:08	I	–	1610	08:01, –	LLE*	–
2011-09-06	X2.1, 22:12-22:24	I	0.6	575	22:17, –	LLE*	–
		I/S			22:13, 35	2600	‡
2011-09-07	X1.8, 22:32-22:44	S	2.1	792	23:36, 63	350	1.0 ± 0.1
2011-09-24	X1.9, 09:21-09:48	I	–	1936	09:34, –	LLE*	–
2012-01-23	M8.7, 03:38-04:34	I/S	5.7	1953	04:07, 51	180	0.8 ± 0.1
		S			05:25, 69	650	2.1 ± 0.2
		S			07:26, 16	69	3.7 ± 0.9
		S			08:47, 35	97	2.6 ± 0.5
2012-01-27	X1.7, 17:37-18:56	D	4.0	1930	19:45, 11	78	3.2 ± 0.8
		S			21:13, 24	47	1.0 ± 0.3
2012-03-05	X1.1, 02:30-04:43	I/S	5.3	1602	04:12, 49	69	0.5 ± 0.1
		S			05:26, 71	250	0.9 ± 0.1
		S			07:23, 28	39	0.8 ± 0.2
2012-03-07	X5.4, 00:02-00:40 X1.3, 01:05-01:23	S	20.2	2684	00:46, 31	22000	‡
		I/S			00:46, –	LLE*	–
		S			03:56, 32	16000	113.1 ± 2.0
		S			07:07, 32	8900	71.9 ± 1.6
		S			10:18, 32	1900	30.1 ± 1.5
		S			13:29, 32	120	8.9 ± 1.9
2012-03-09	M6.3, 03:22-04:18	D	5.7	844	05:17, 34	51	0.6 ± 0.2
		S			06:52, 35	100	0.9 ± 0.2
		S			08:28, 34	159	1.4 ± 0.2
2012-03-10	M8.4, 17:15-18:30	D	4.3	1379	21:05, 30	43	0.4 ± 0.1
2012-05-17	M5.1, 01:25-02:14	I/S	1.2	1582	02:18, 22	45	1.0 ± 0.3
2012-06-03	M3.3, 17:48-17:57	I	0.3	605	17:52, –	LLE*	–
		I/S			17:40, 23	300	3.2 ± 0.4
2012-07-06	X1.1, 23:15-23:49	I/S	0.9	892	23:19, 52	930	3.5 ± 0.2

Flux measured for each Time Window

Solar Flares detected $>100\text{MeV}$



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2011-08-04	M9.3, 03:41-04:04	S	1.9	1315	04:59, 34	390	2.5 ± 0.3
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2011-09-06	X2.1, 22:12-22:24	I	0.6	575	22:17, –	LLE*	–
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		I/S			00:46, –	LLE*	–
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First impulsive event
Ackermann et al. 2012

First long duration event
Ackermann et al. 2013

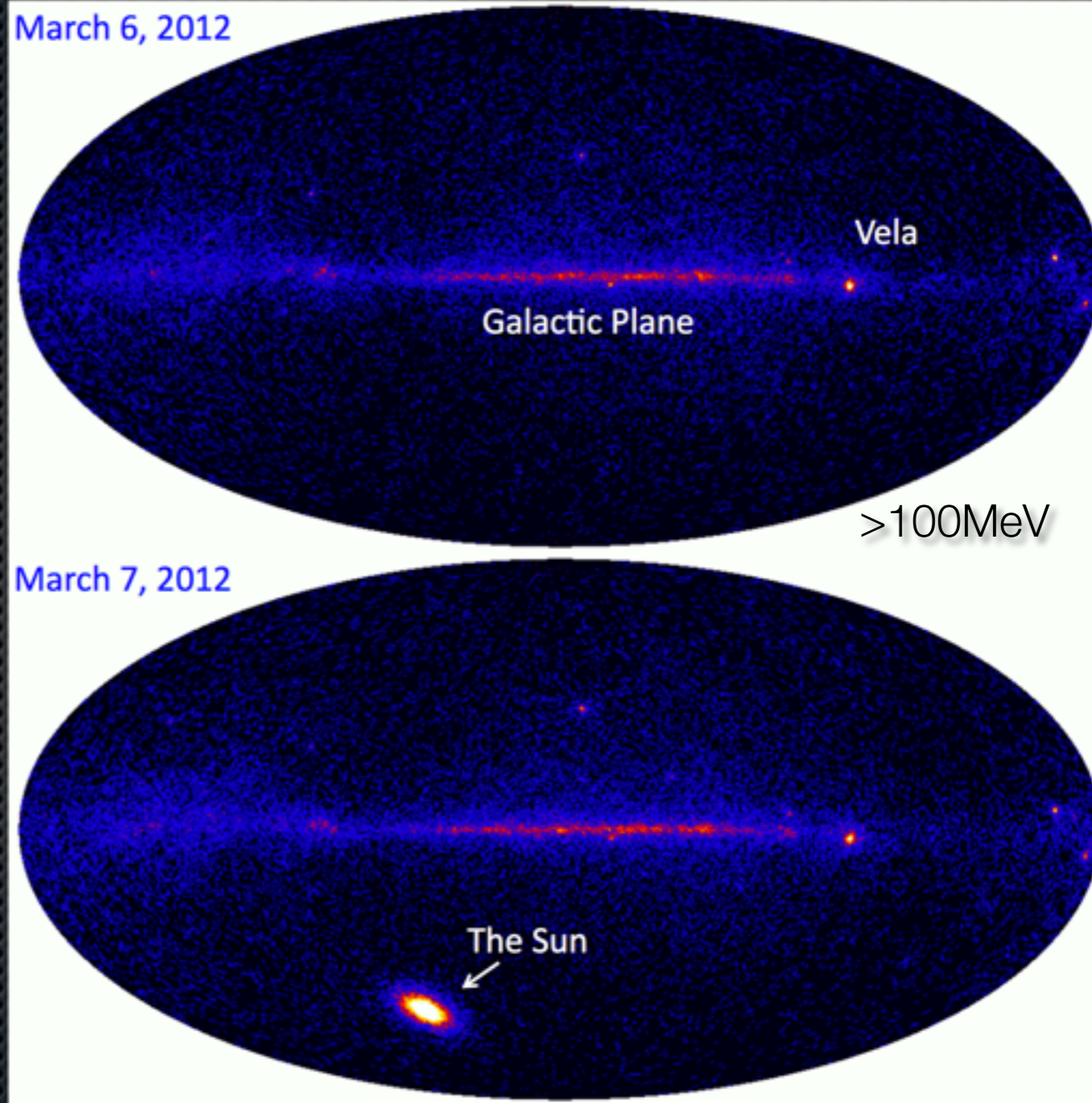
Longest and brightest event
Ajello et al. 2013



2012 March 7 flare

Astronomy Picture Of the Day:

On March 7, the Sun was 100 times brighter than the Vela pulsar (the brightest steady γ -ray source).



Two all-sky γ -ray images integrated over 1 day



2012 March 7 flare

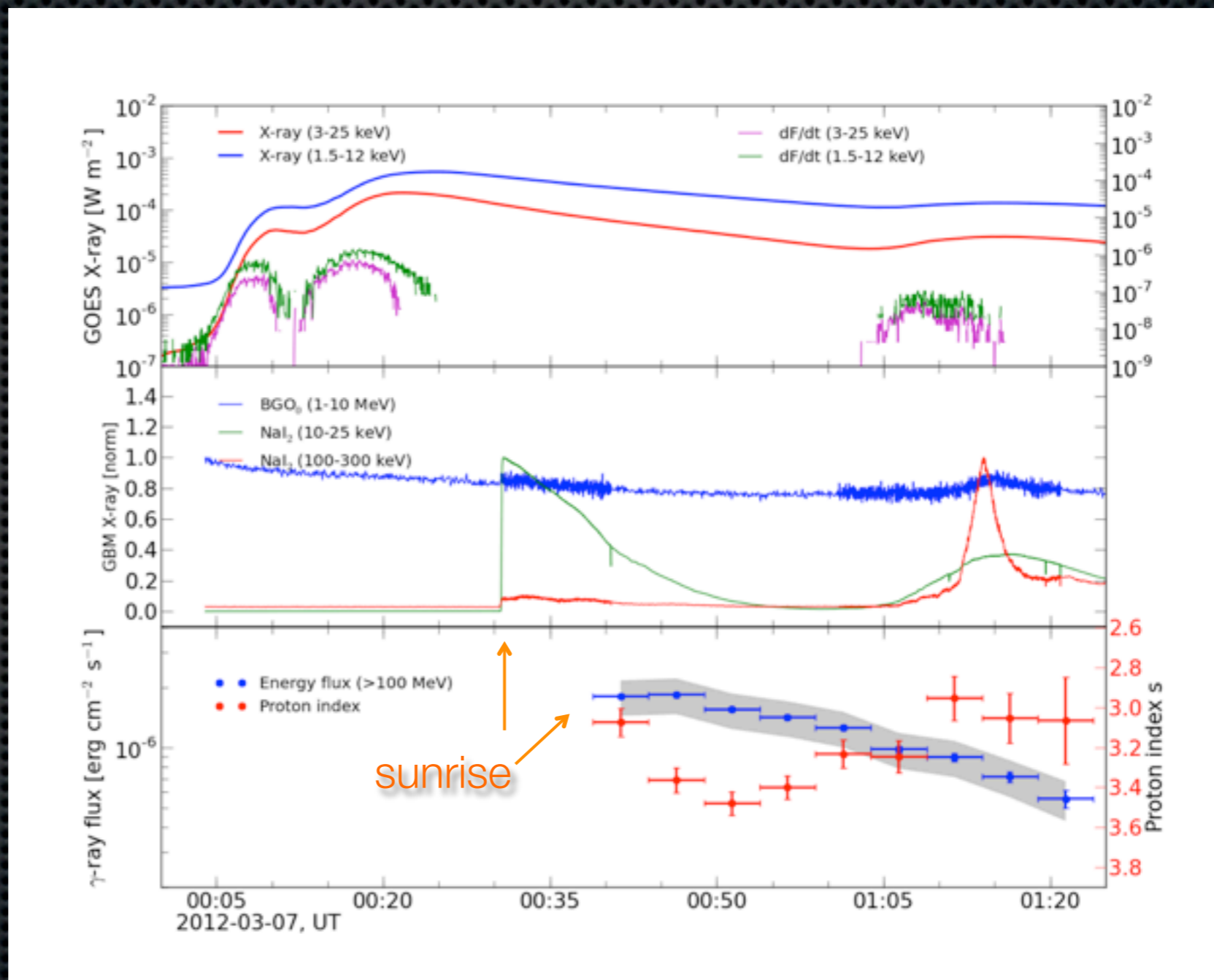
Impulsive phase:

GOES flares:

X5.4 (peak at 00:40 UT)

X1.3 (peak at 01:23 UT)

Preliminary detection by the *Fermi* GBM - but analysis has not yet been finalized

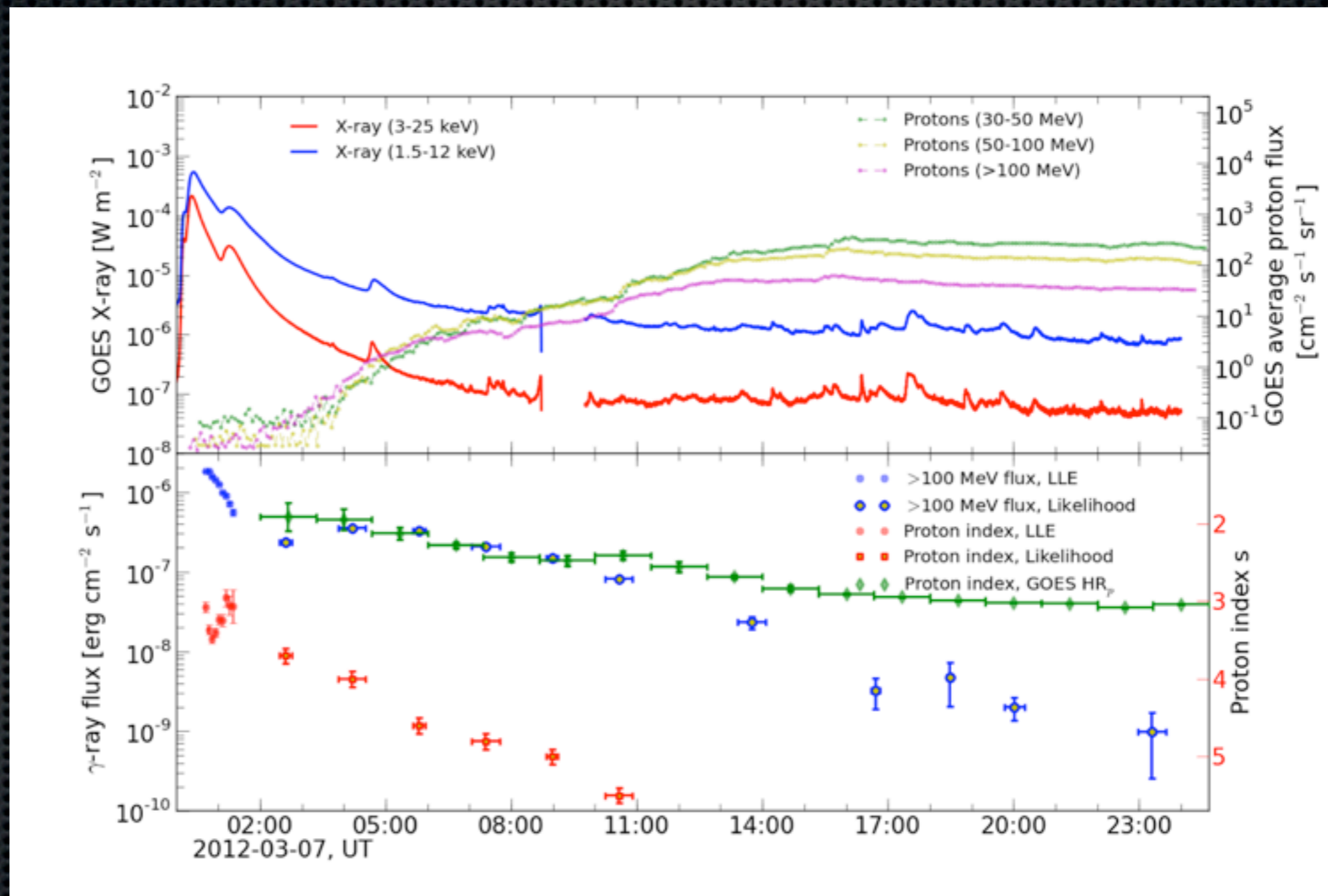




2012 March 7 flare

Sustained emission: **~20 h. detection**

- Two Fast CMEs interacting
- Second largest SEP event in cycle 24

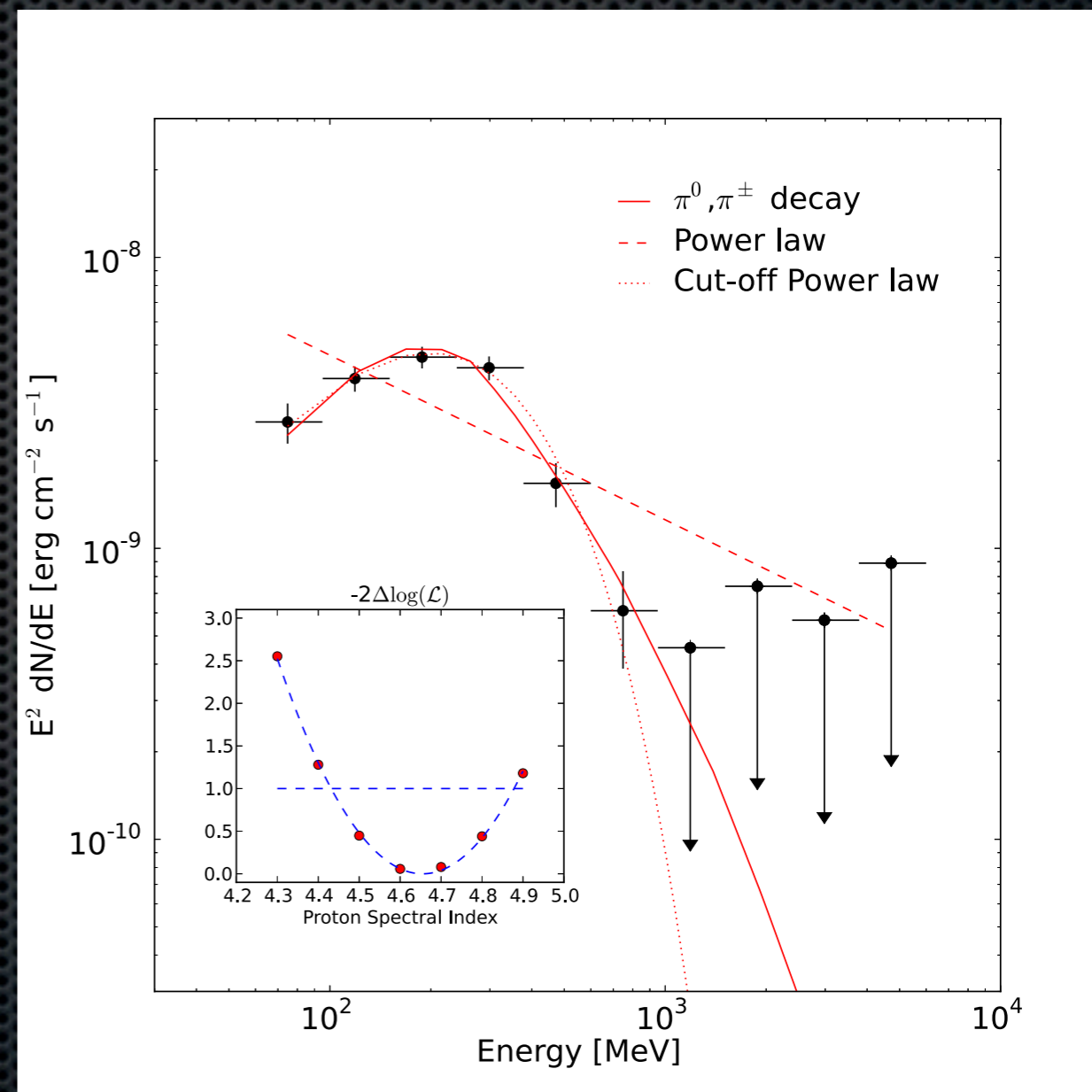




- ✦ Detection **up to 4GeV** (2012 flare)
- ✦ Consistent with pion decay template (assuming power-law proton distribution; based on Murphy et al. 1987)
- ✦ Electron bremsstrahlung possible with a cutoff
- ✦ First observations of spectral evolution in γ rays:

Hard to soft

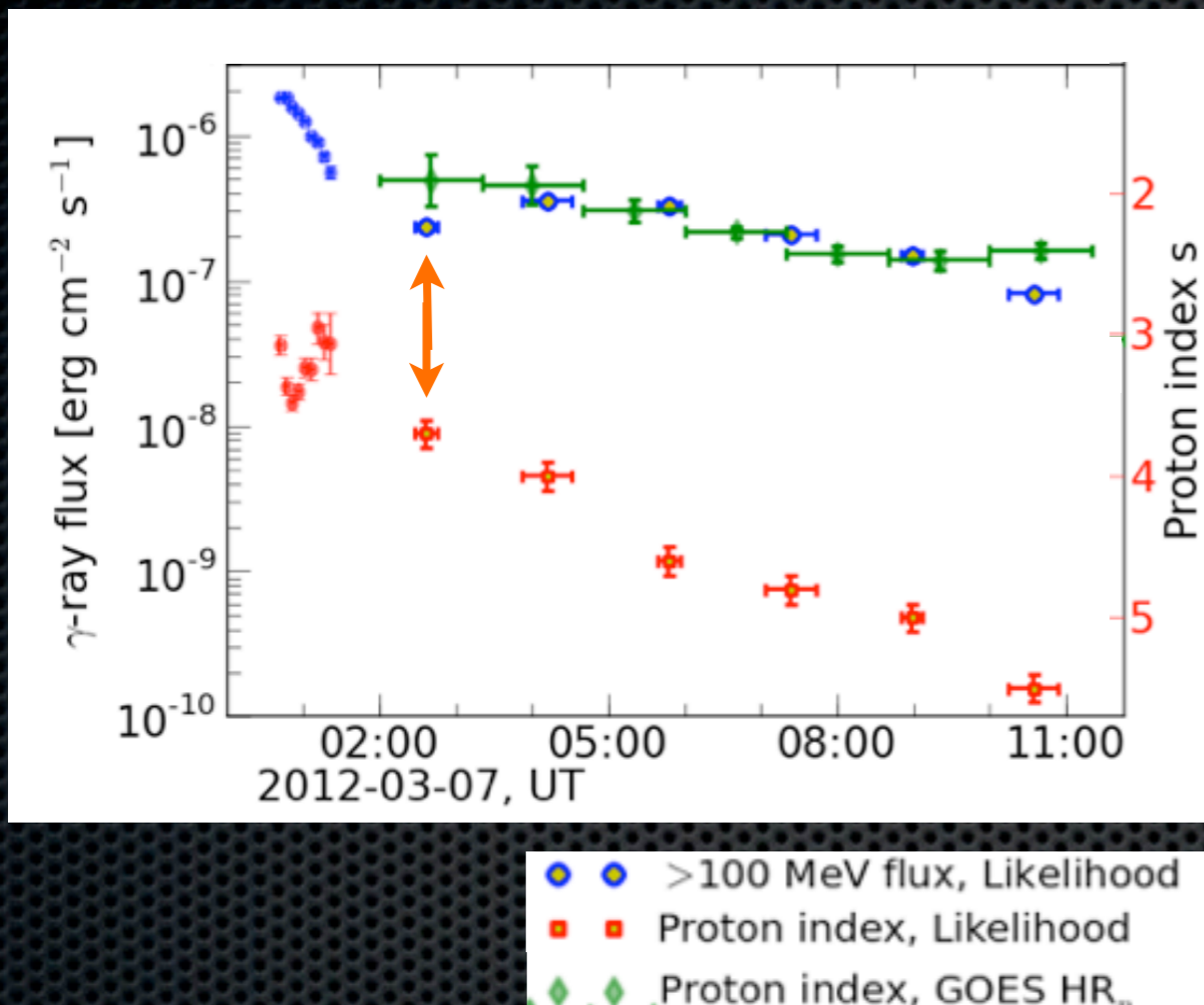
Time integrated spectrum ($>60\text{MeV}$)



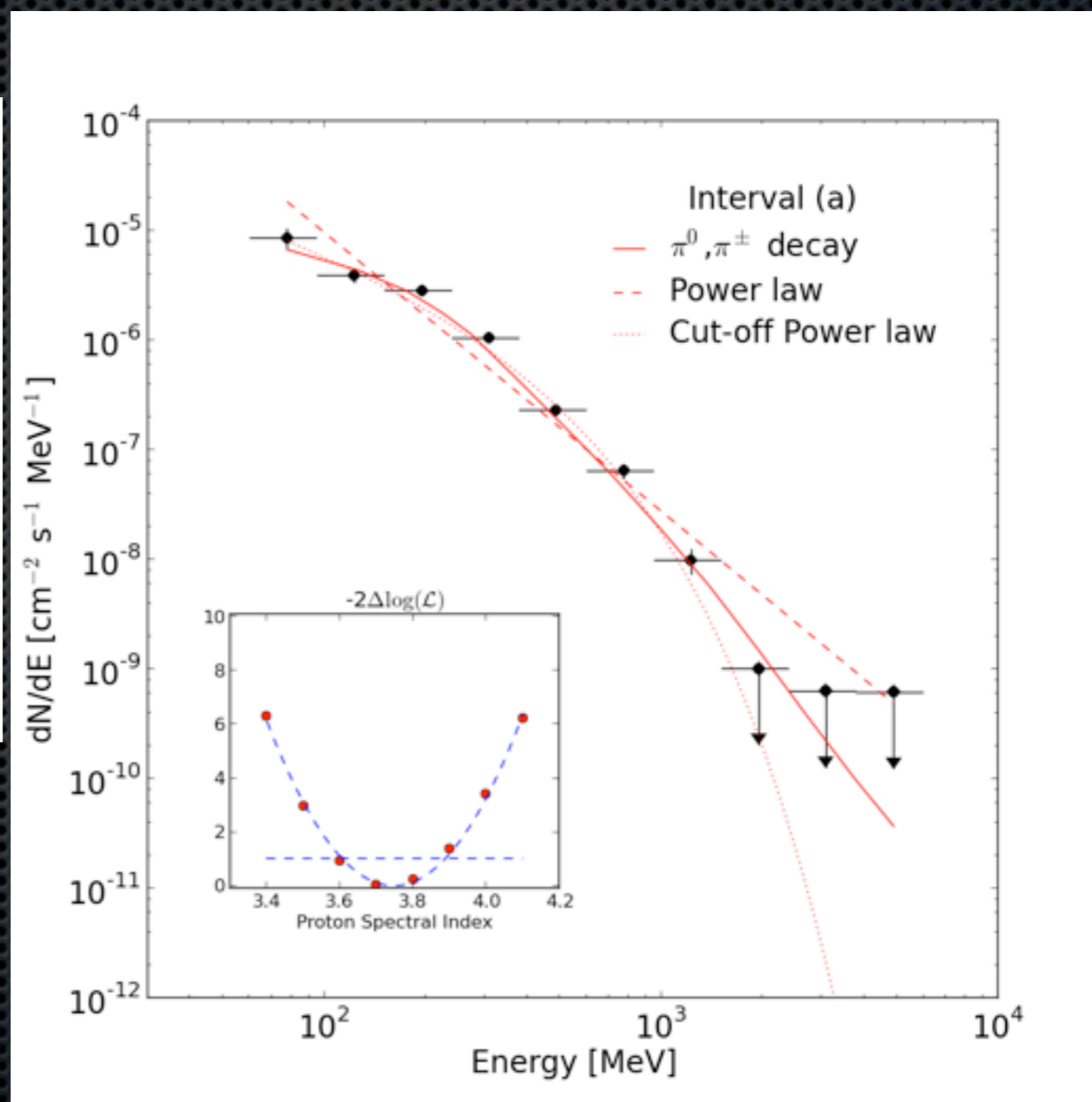
2011-03-07 flare



2012-03-07 flare



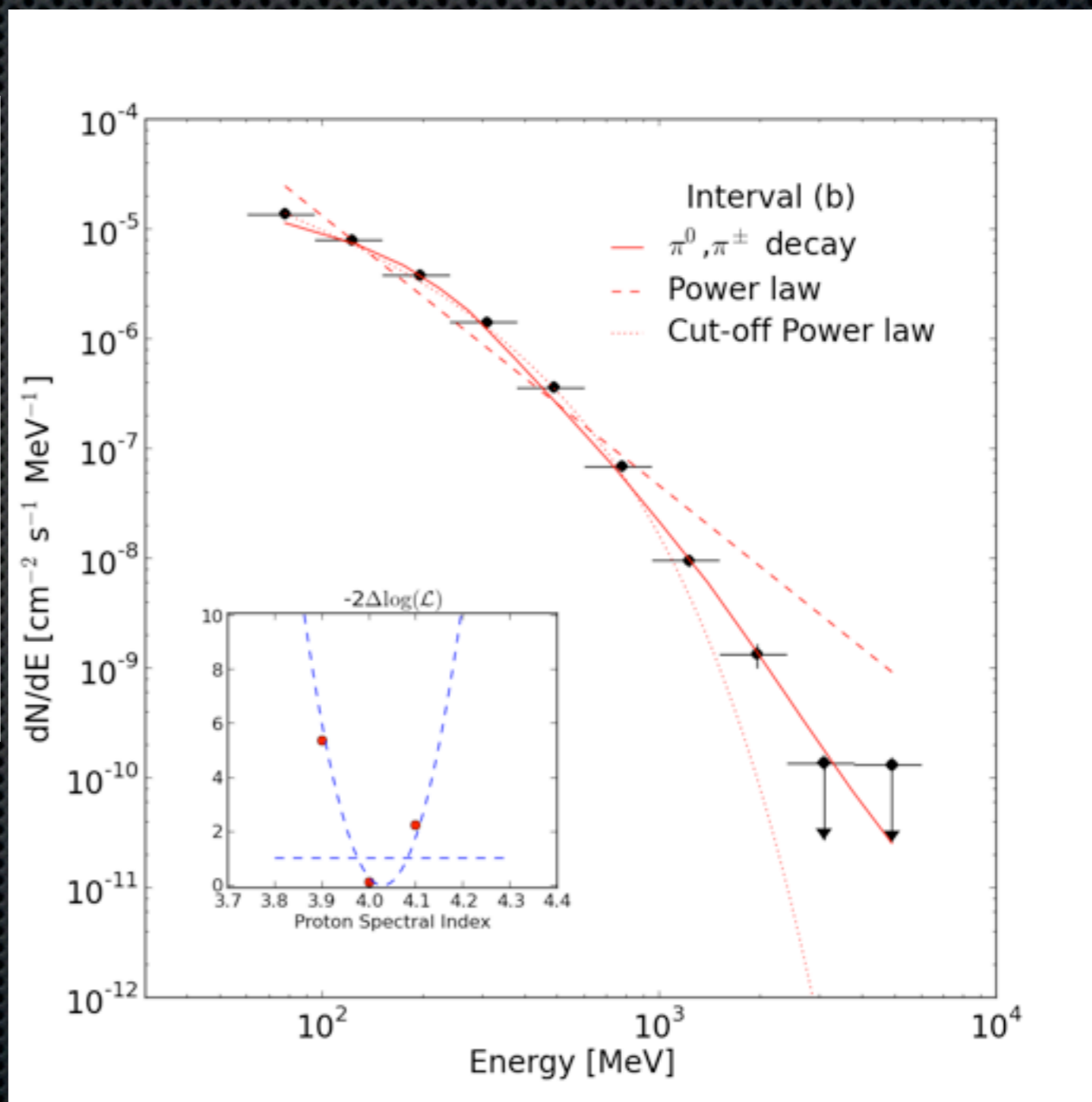
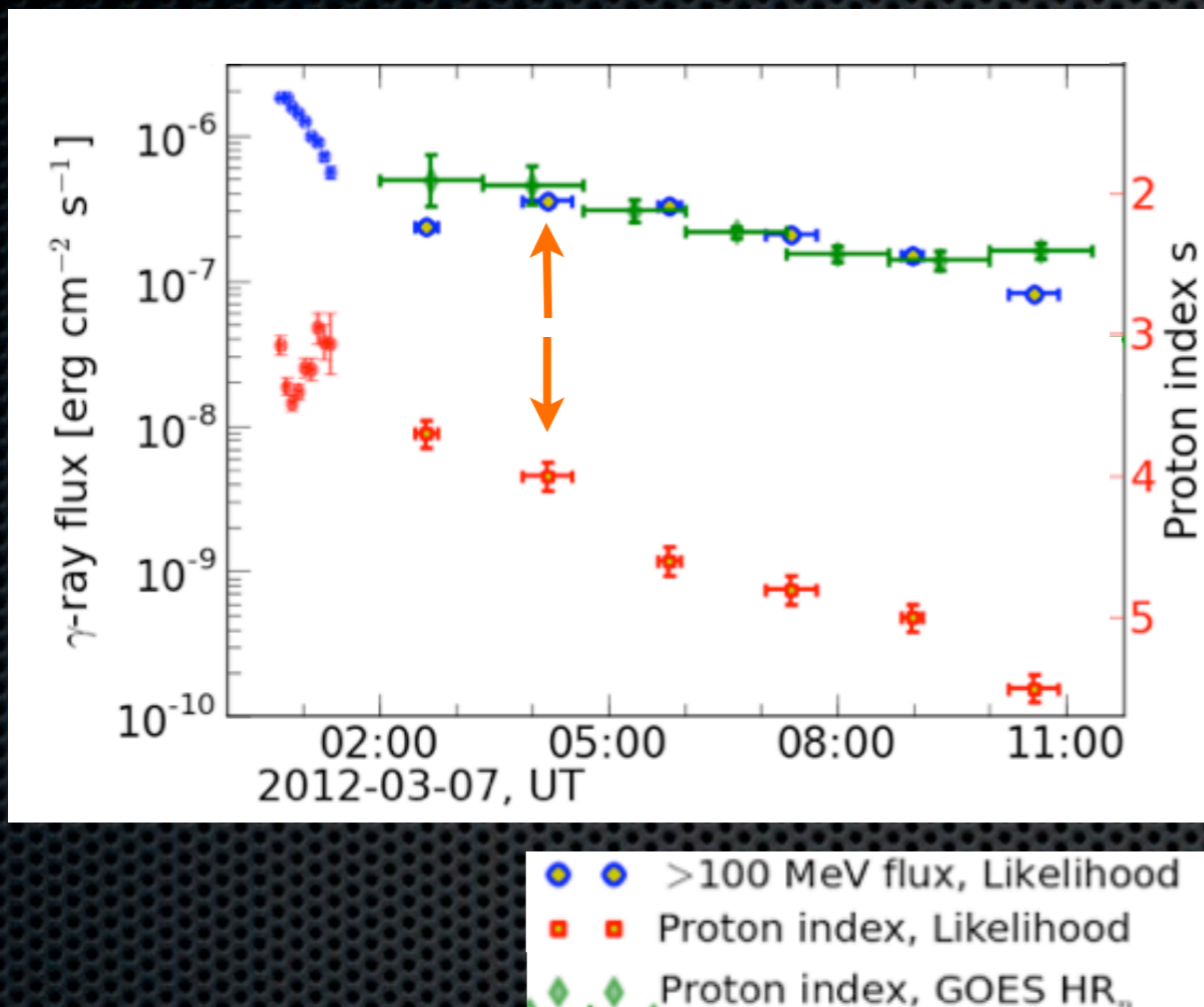
Time resolved spectra ($>60\text{MeV}$)





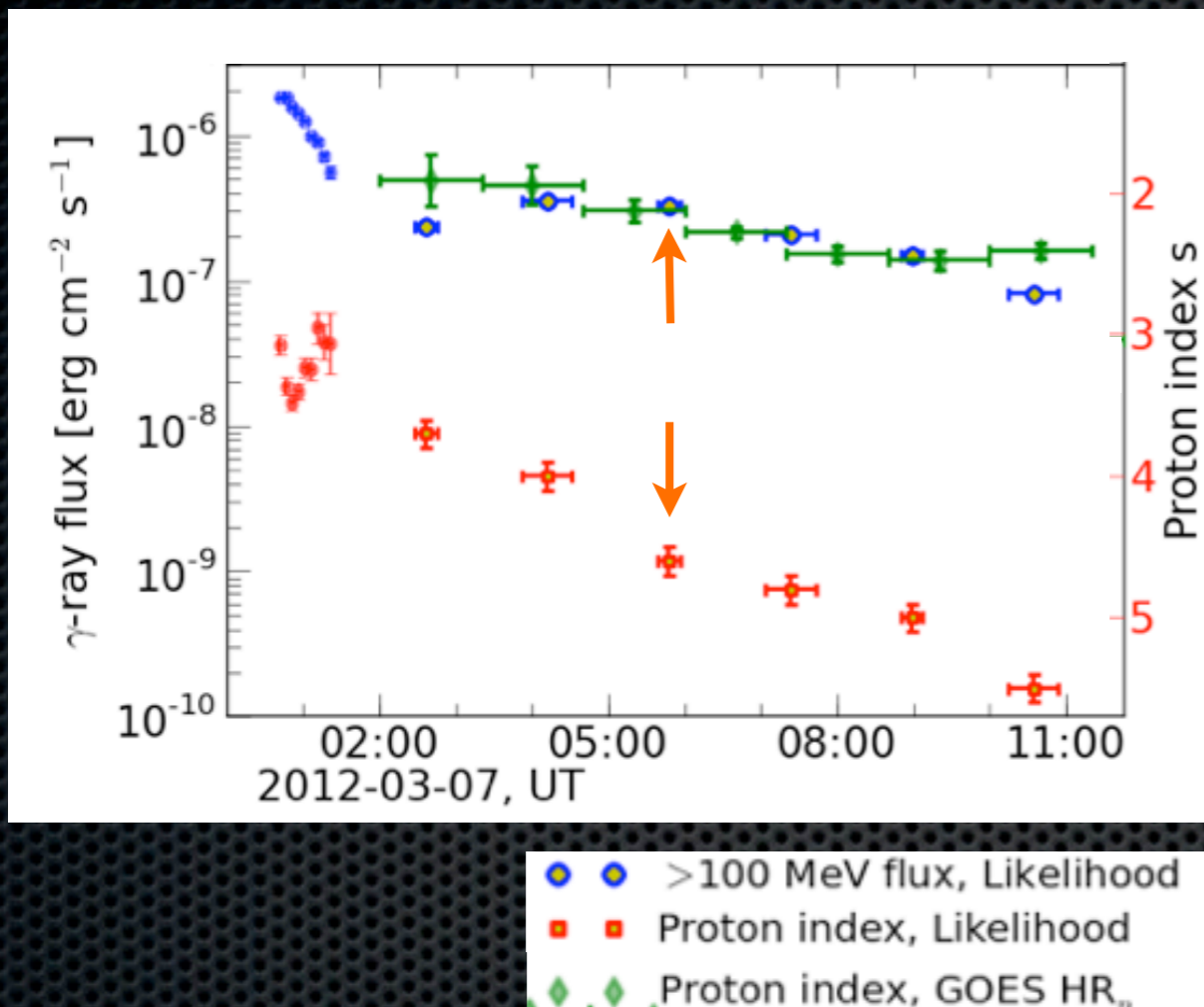
2012-03-07 flare

Time resolved spectra (>60MeV)

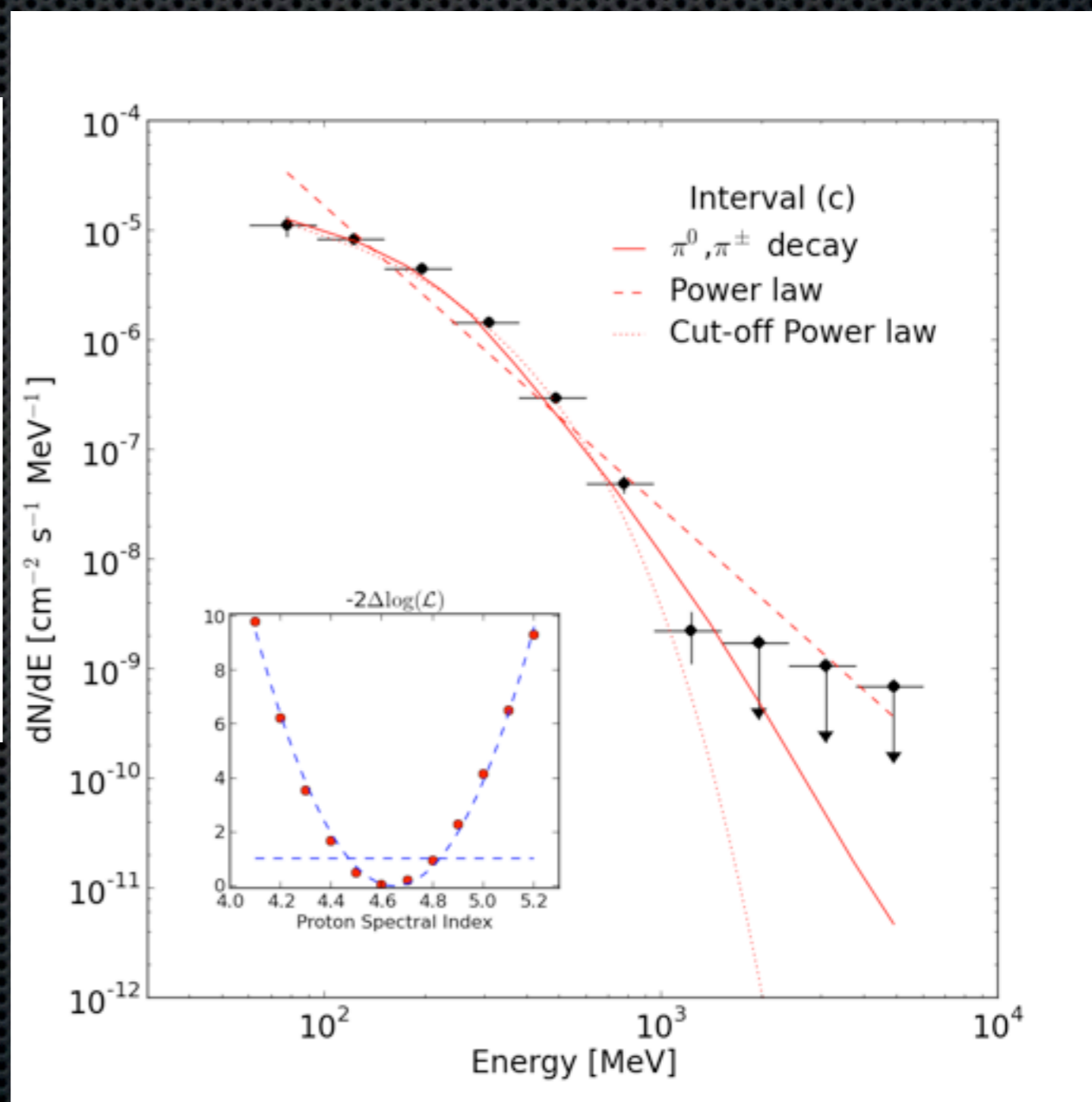




2012-03-07 flare

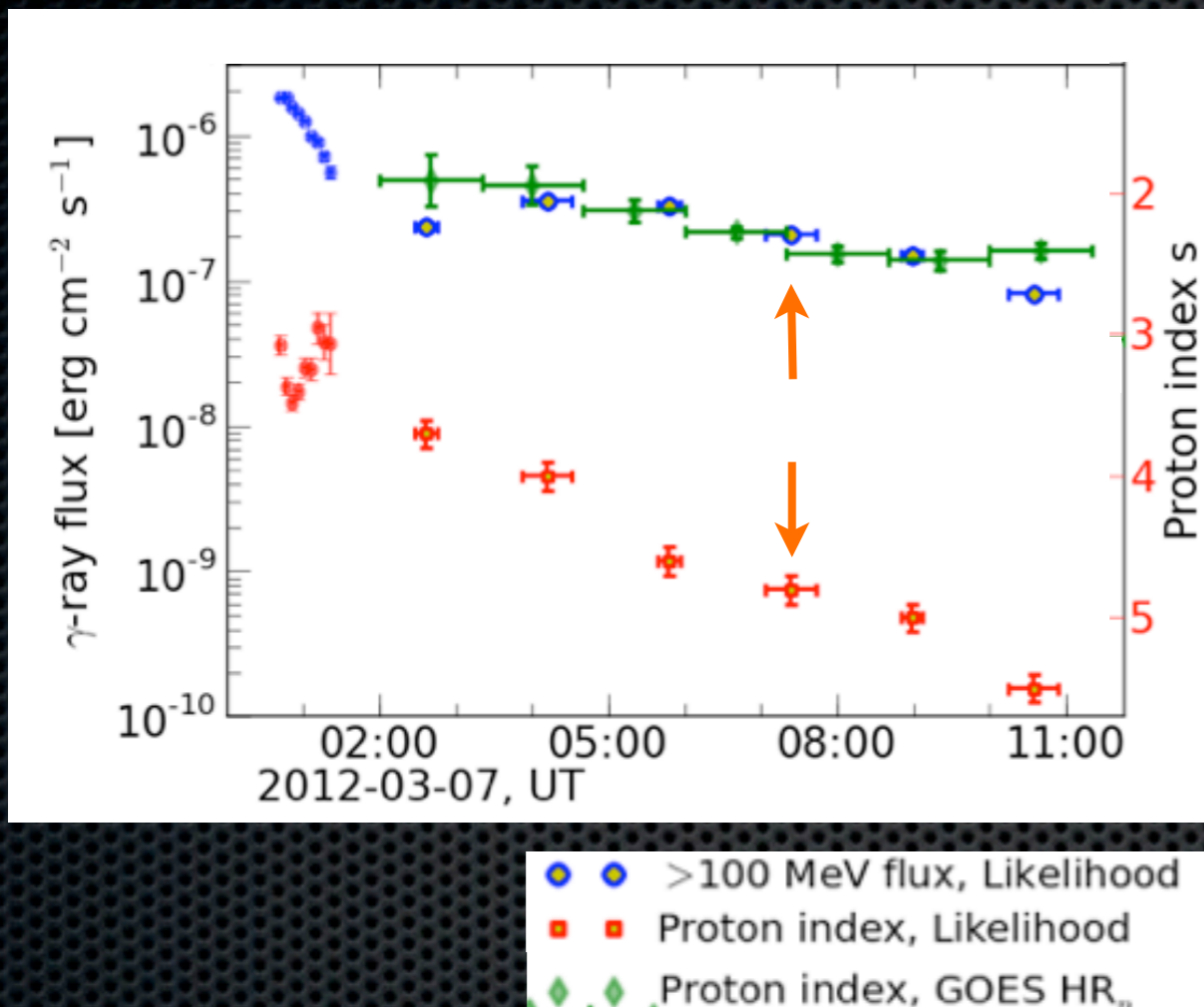


Time resolved spectra (>60MeV)

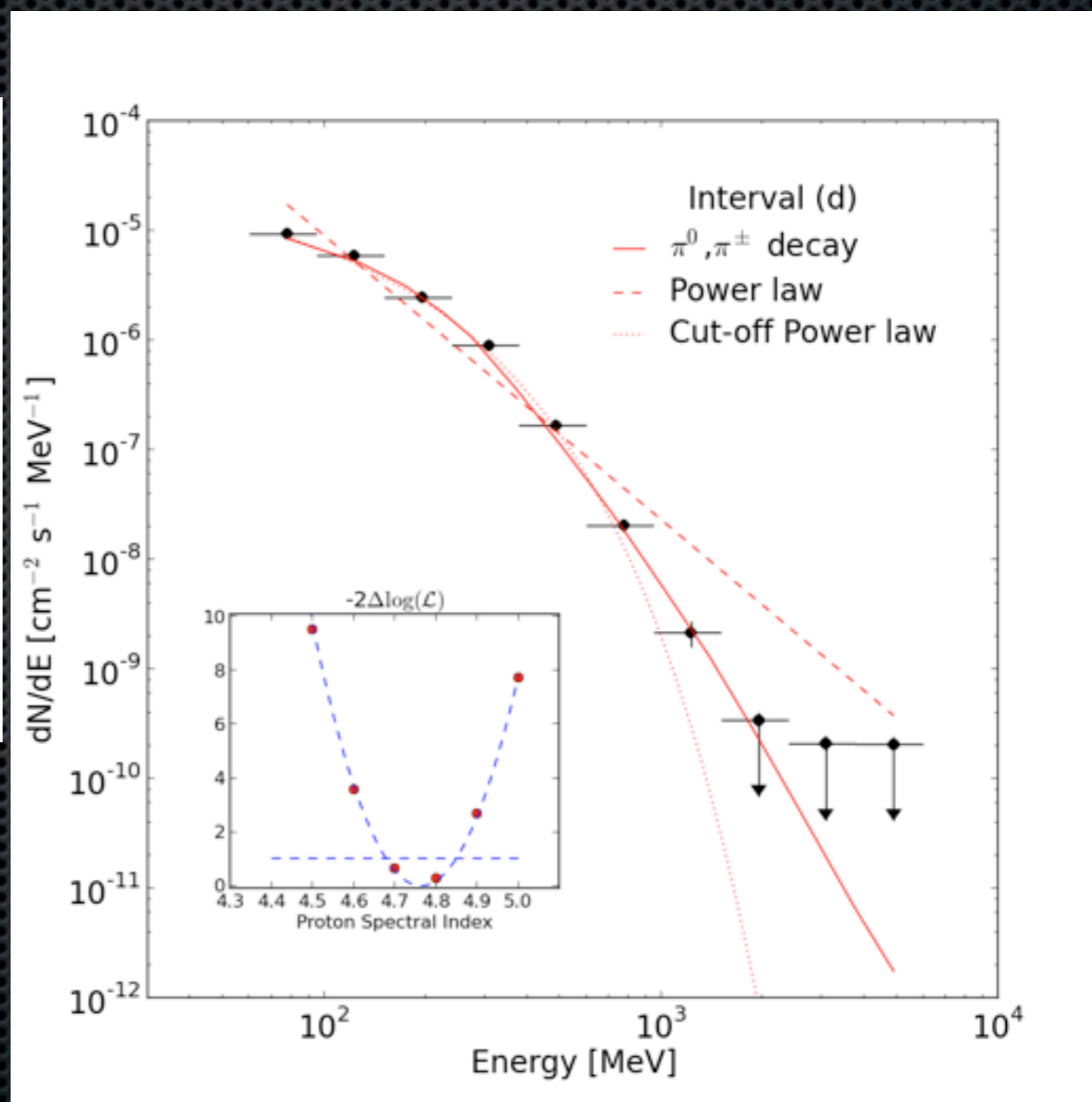




2012-03-07 flare

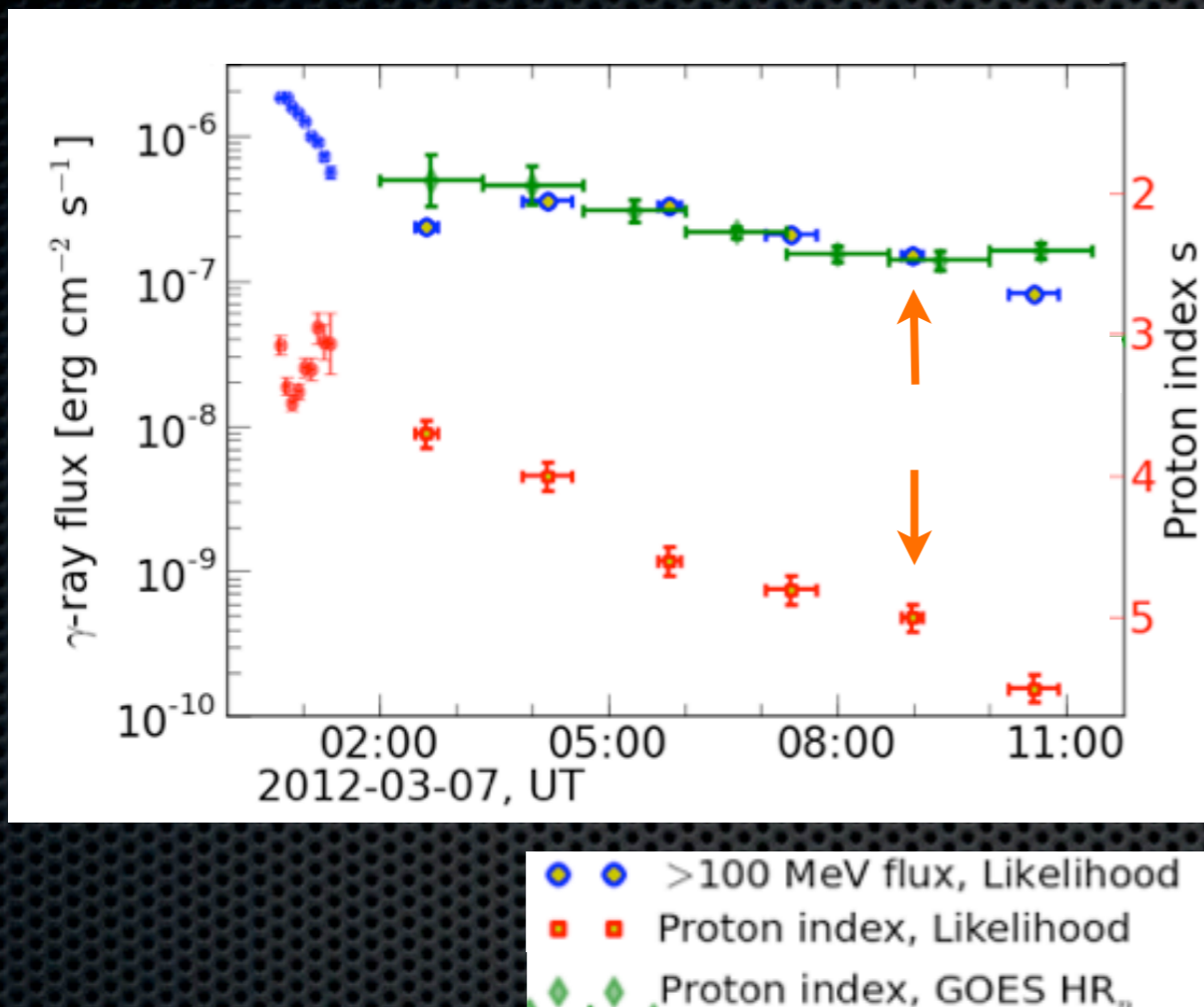


Time resolved spectra (>60MeV)

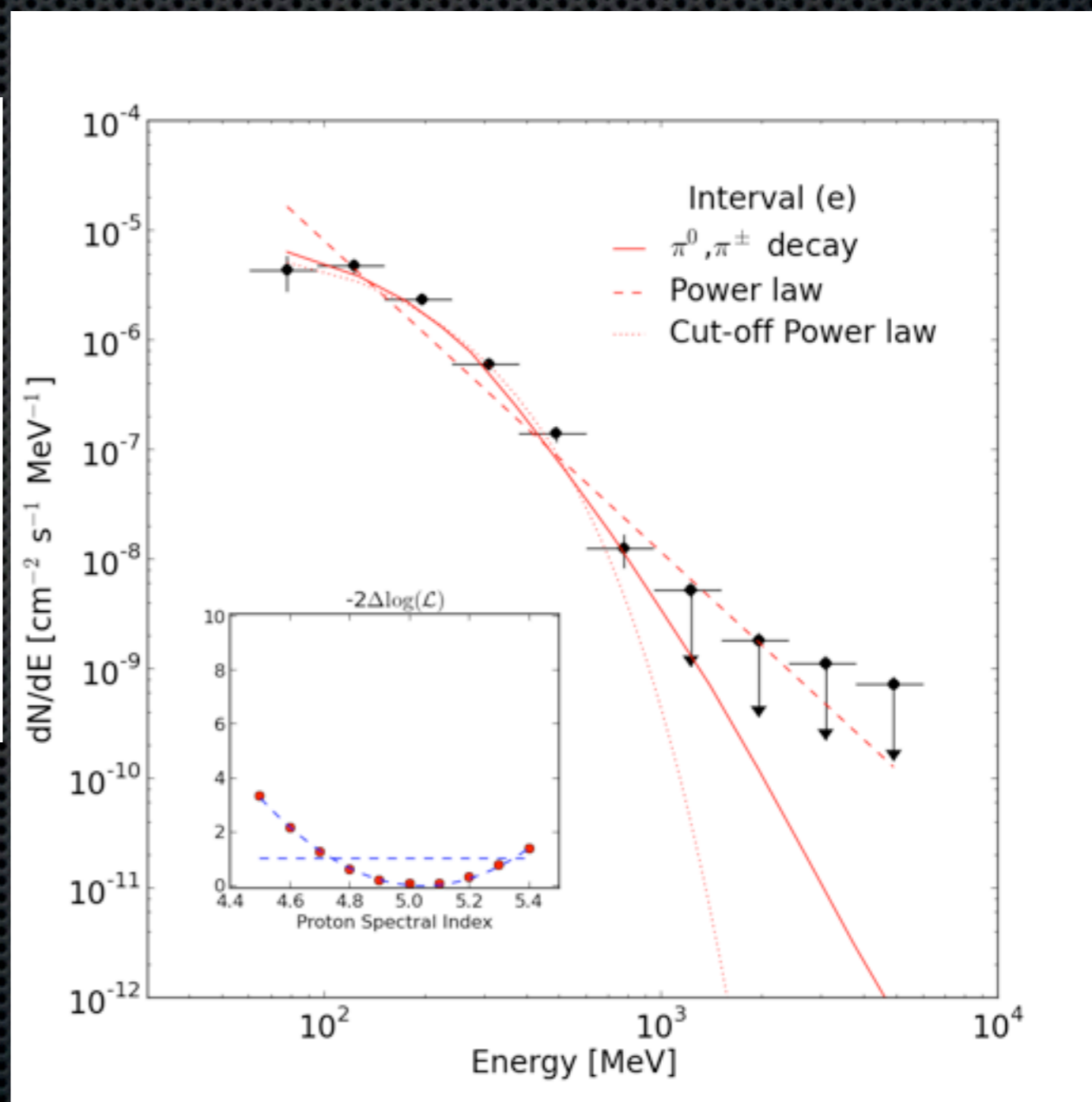




2012-03-07 flare

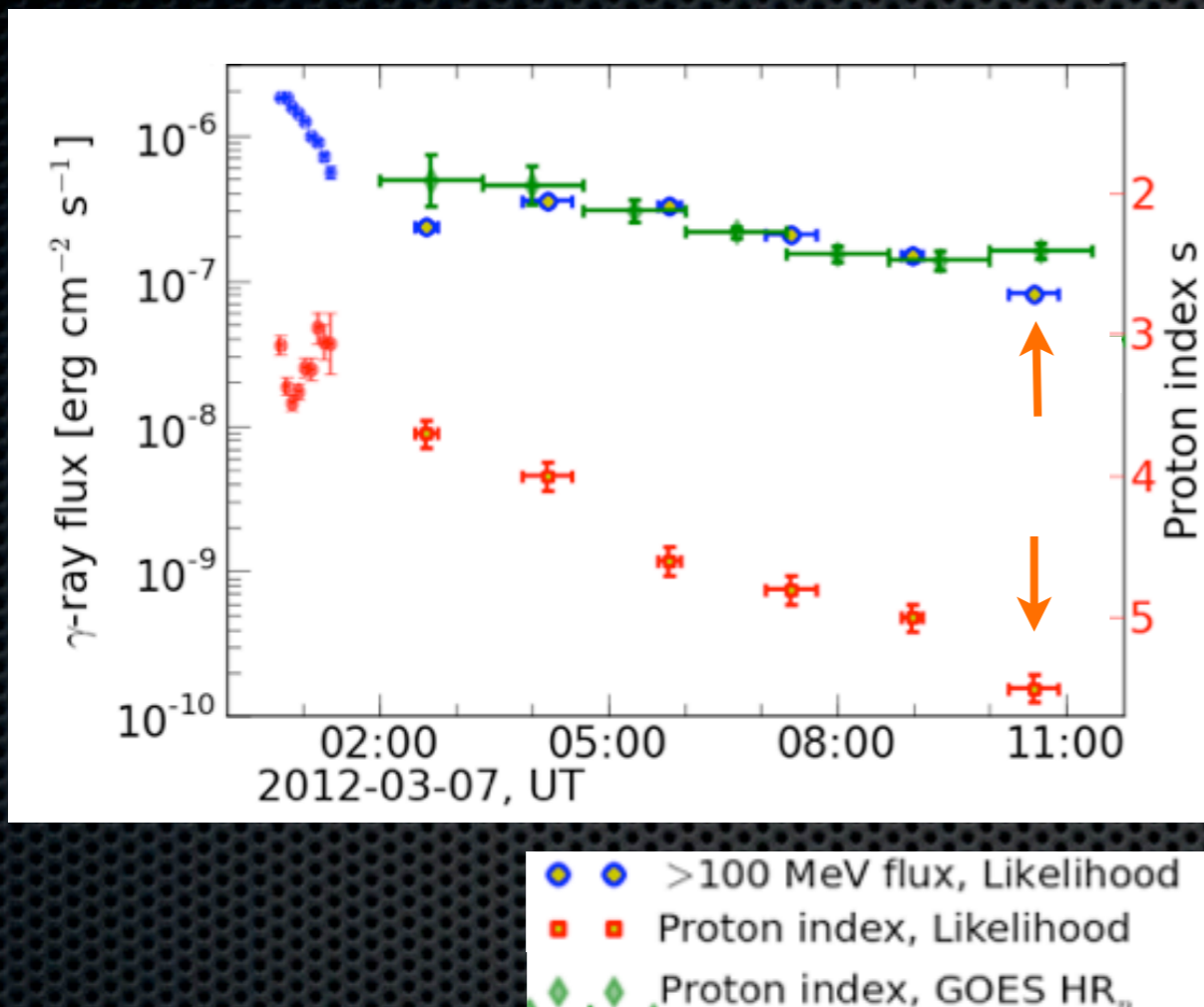


Time resolved spectra (>60MeV)

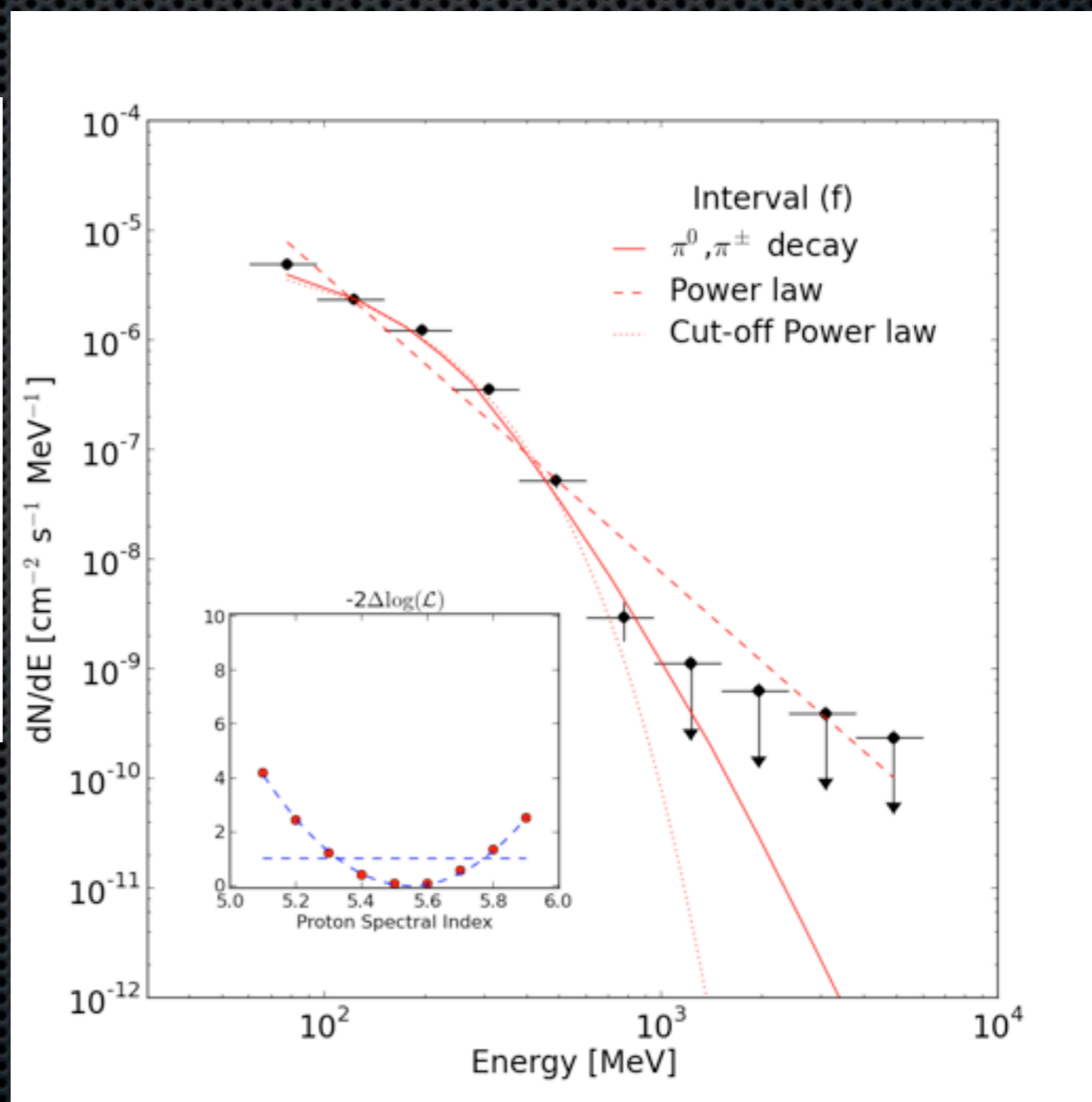




2012-03-07 flare



Time resolved spectra (>60MeV)

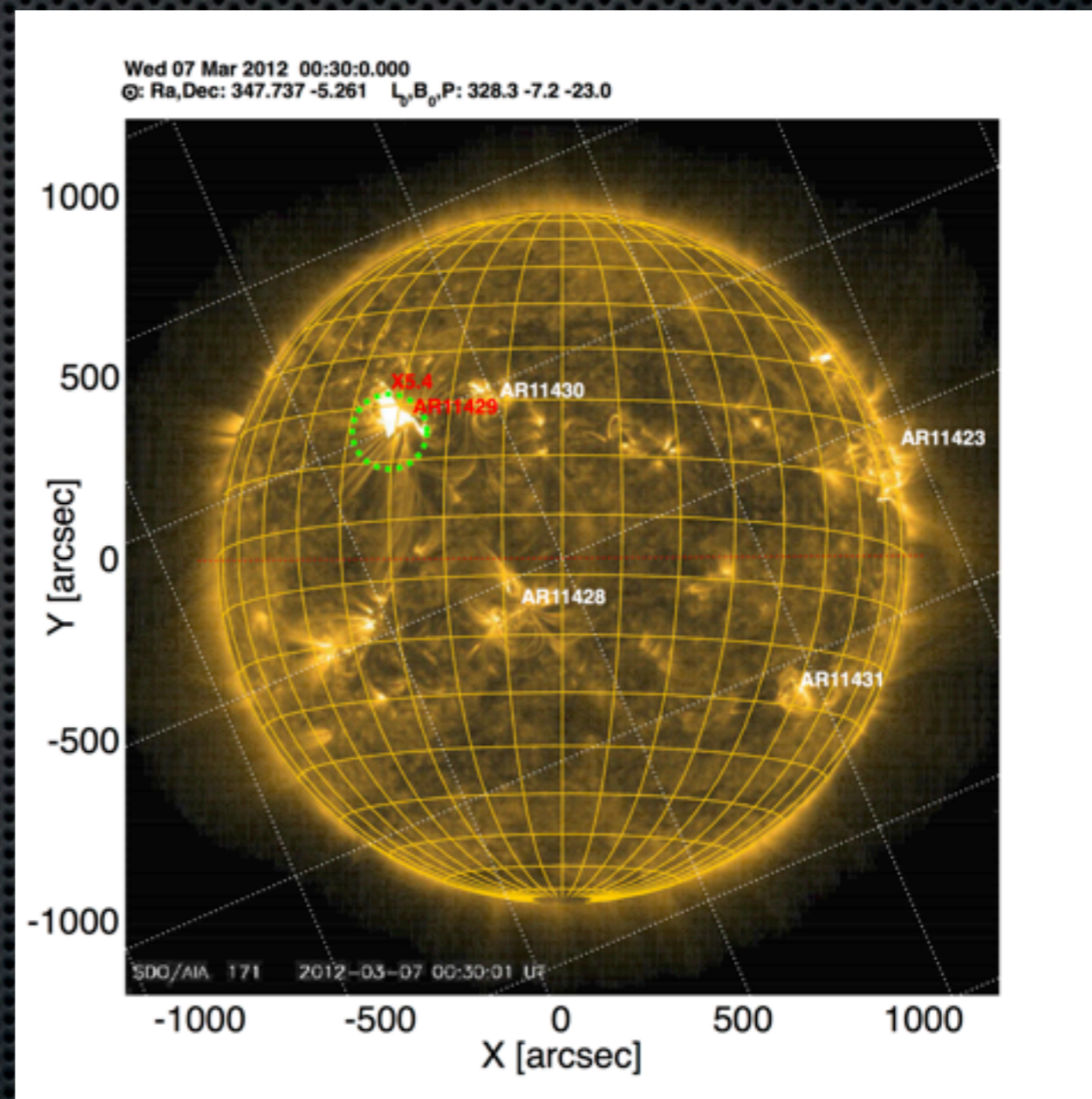




2012-03-07 flare

68% error circle

- Time **integrated** localization
- Consistent with the flare site
- Way to exclude contribution of other flares at other sites



Ajello et al. 2013



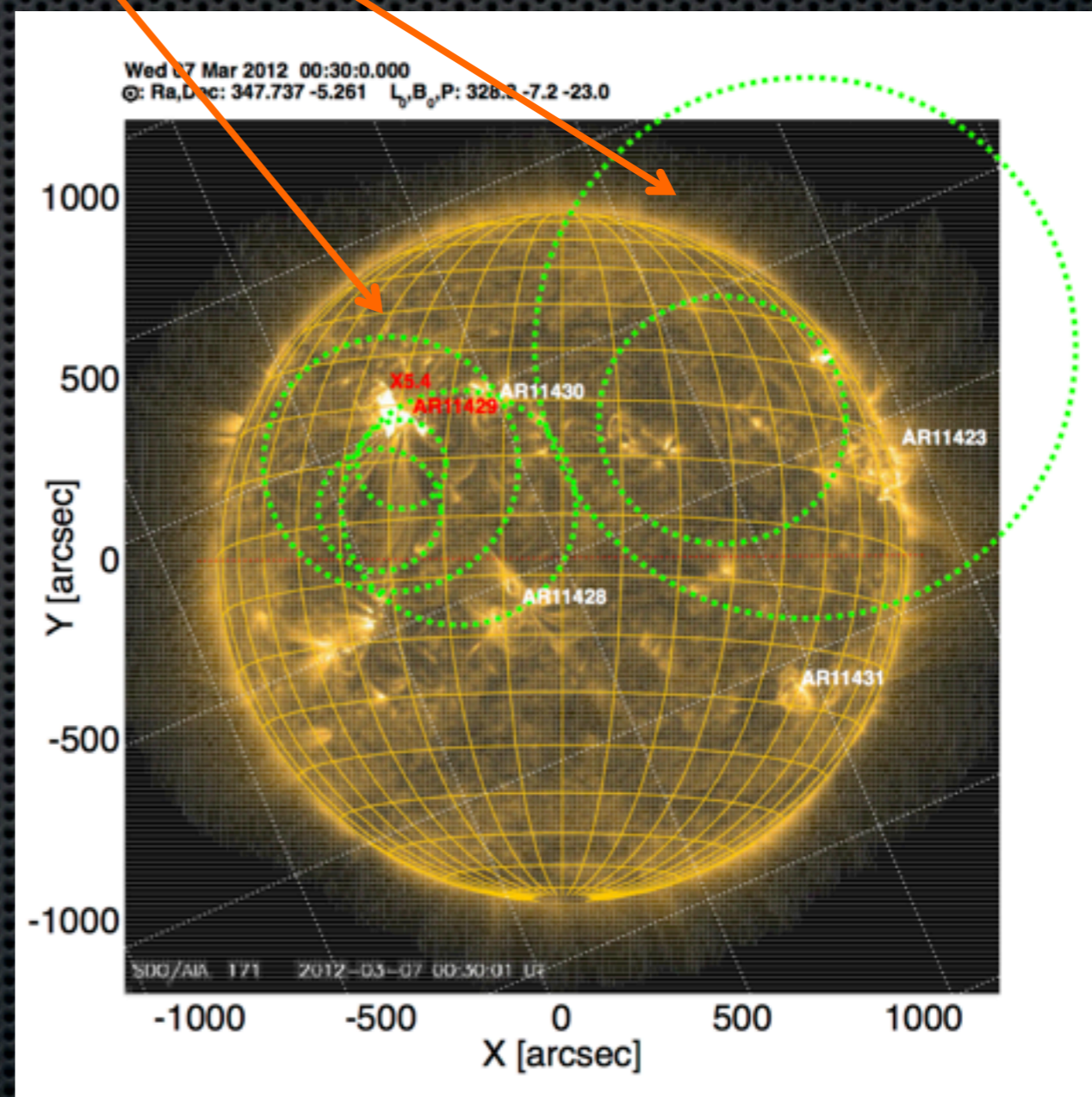
2:00 -> 7:40 UT

8:50 -> 11:00 UT

2012-03-07 flare

68% error circles

- Time **resolved** localization
- All sites are consistent with the flare site - ***Hint of an evolution (?)***
- Statistics limited**



Ajello et al. 2013

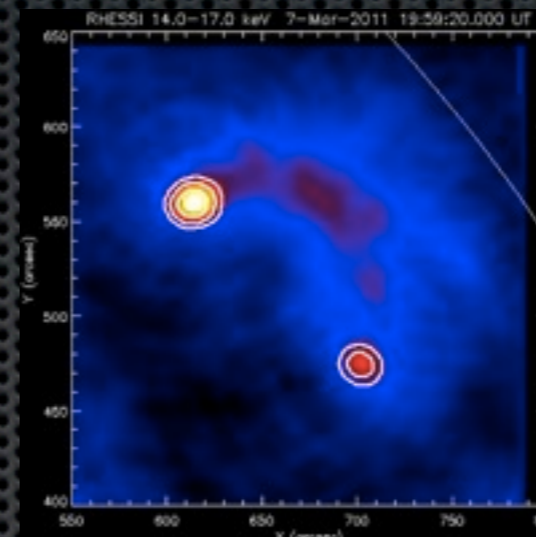


- Total energy in γ rays is much less than in HXR
($\sim 7 \times 10^{22}$ erg - 200x less than between 20-300keV)
- Leptonic scenario seems unlikely :
 - Brem. requires >100 MeV electrons whose lifetime is ~ 10 s thru synchrotron losses [maybe more in low B fields - large loop]
 - High energy electrons would lose most of their energy in sub-mm, far IR via synchrotron
- Hadronic scenario:
 - in good agreement with data
 - requires modest number of accelerated protons
($\sim 10^{34}$ protons >30 MeV - 10x less than SEP protons)



- ✦ Initial acceleration and trapping - Coulomb losses for protons would induce a hardening

⇒ Continuous acceleration seems more plausible

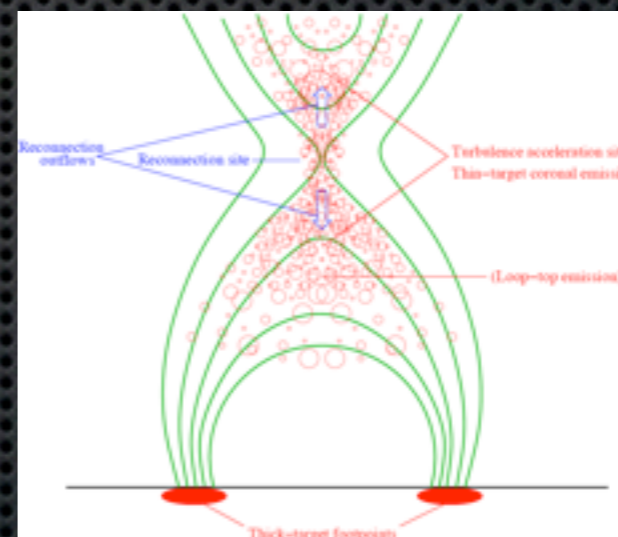


RHESSEI loop for 2011 March 7

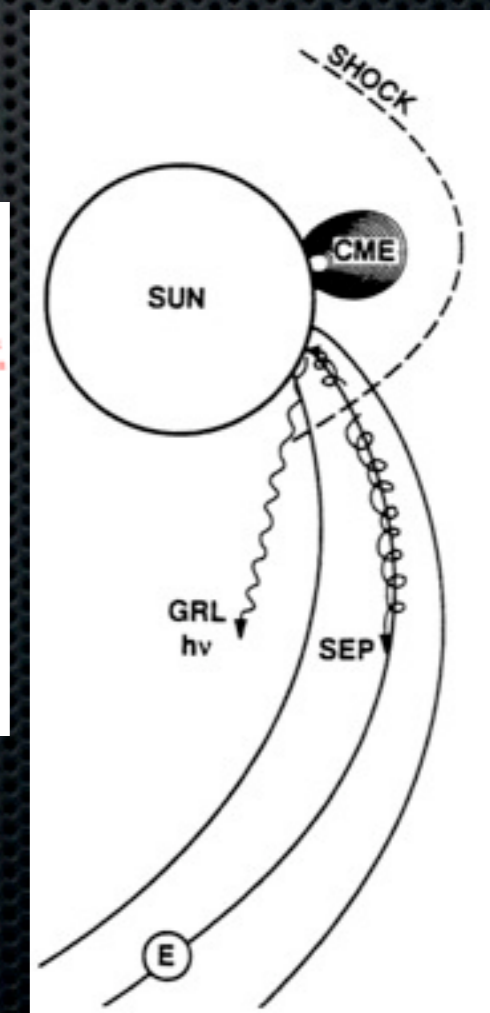
- ✦ CME shock accelerates SEPs

⇒ Accelerated particles transport back to Sun surface [emission site]

(e.g. Murphy et al. 1987, Cliver et al. 1993)



stochastic acceleration by turbulence, e.g., Petrosian & Liu, 2004



Cliver et al. 1993



- ✦ Fermi LAT observations reveals new **temporal** and **spectral** properties of high energy particles accelerated in solar flares.
- ✦ High energy γ -ray emission is more common than previously observed - even for modest X-ray flares: **18 flares** so far.
- ✦ Long sustained γ -ray emission raises a lot of questions on acceleration scenarios.
- ✦ CME connection

Ackermann et al., ArXiv:[1304.3749](https://arxiv.org/abs/1304.3749)
 Ajello et al., ArXiv: [1304.5559](https://arxiv.org/abs/1304.5559)
 Both submitted to ApJ



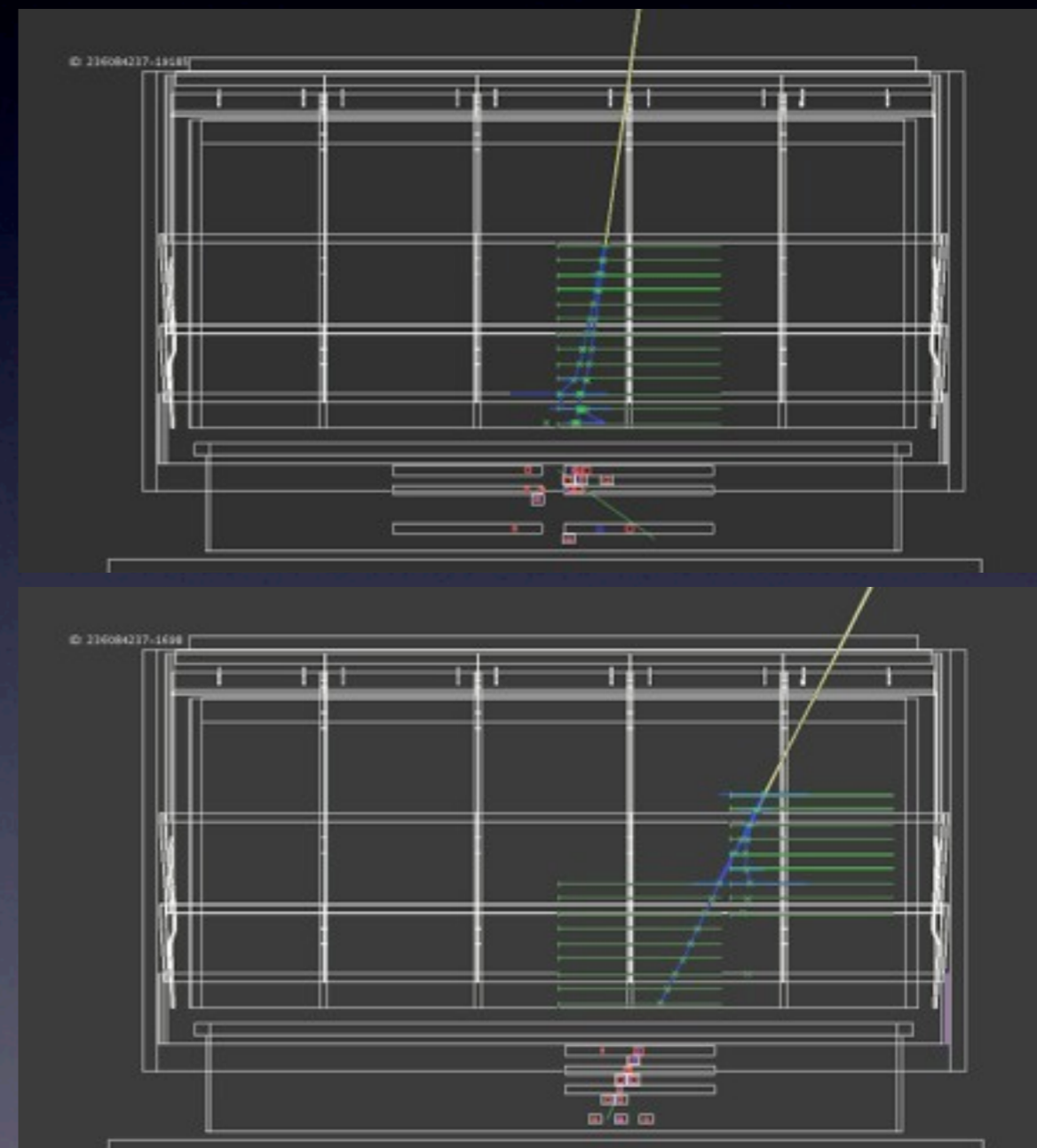


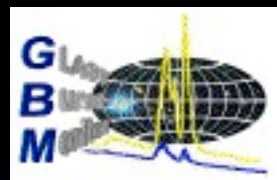
Backup

The LAT real view

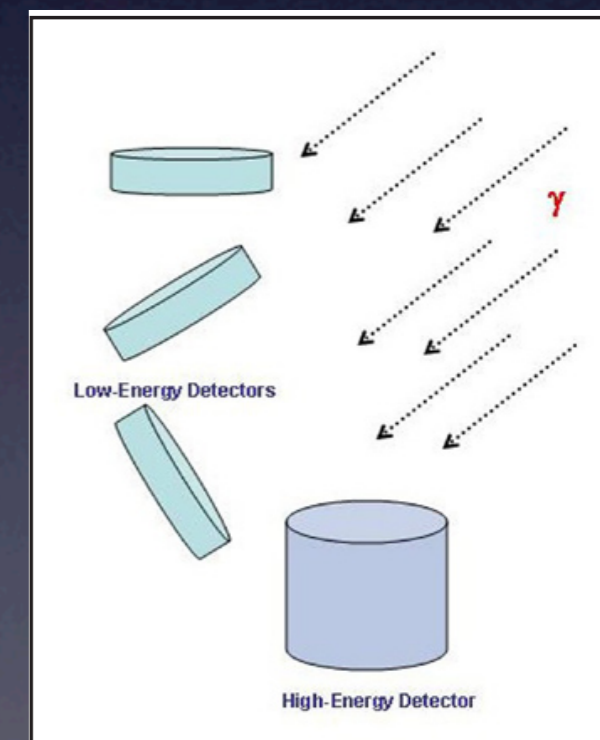
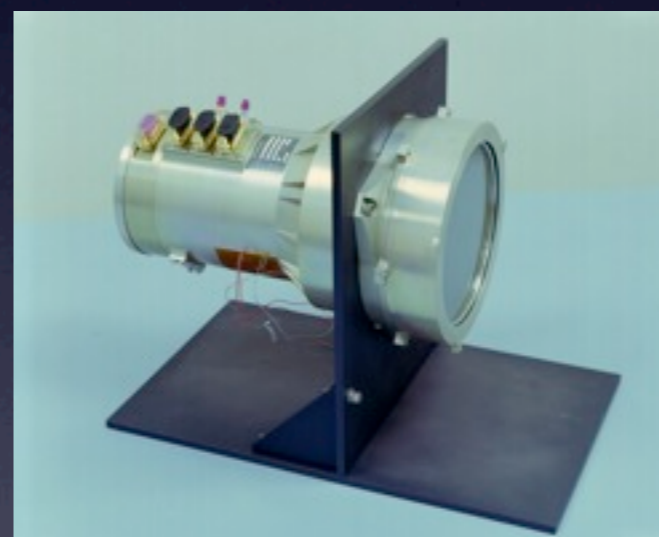
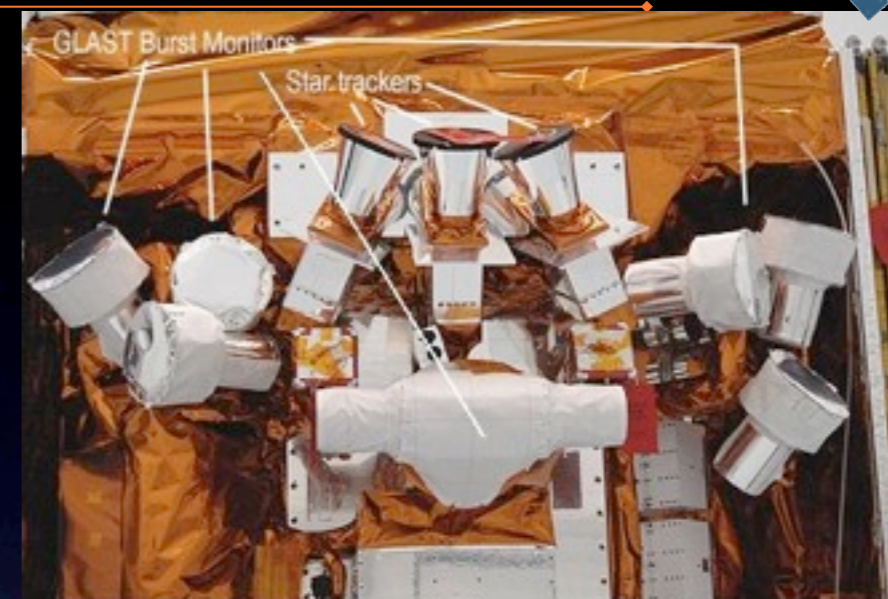


The LAT has 16 towers of particle detectors, seen here before the installation of the Anticoincidence Detector. Each tower contains a Tracker module and a Calorimeter module. The Data Acquisition System is located underneath the towers.





- 12 low-energy sodium iodide detectors
 - 8 keV (X-ray) - 1 MeV (gamma)
 - 3 on each corner of the LAT -> full sky coverage.
- 2 high-energy detectors: bismuth germanate
 - 150 keV - 30 MeV
 - good overlap with the low- energy detectors at the bottom end of the gamma-ray energy range, and with the LAT at the high end.
- Trigger System on Transient
- Onboard Processing and Repointing of whole spacecraft to source of interest



Credit: NASA / David Thompson

γ rays from the quiet Sun



- Cosmic-ray interactions with the sun:

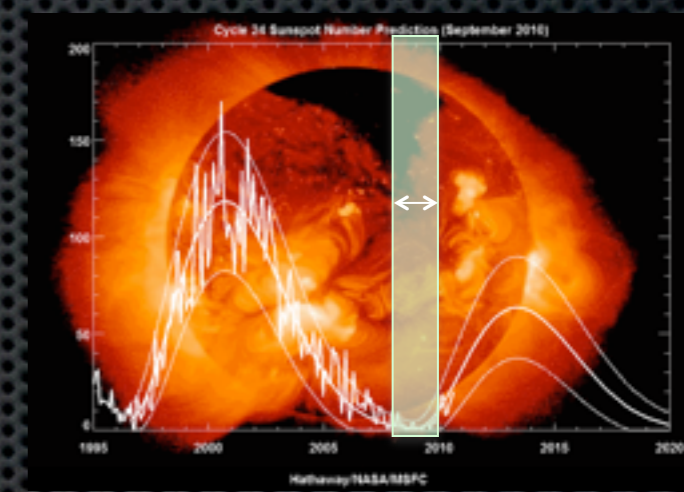
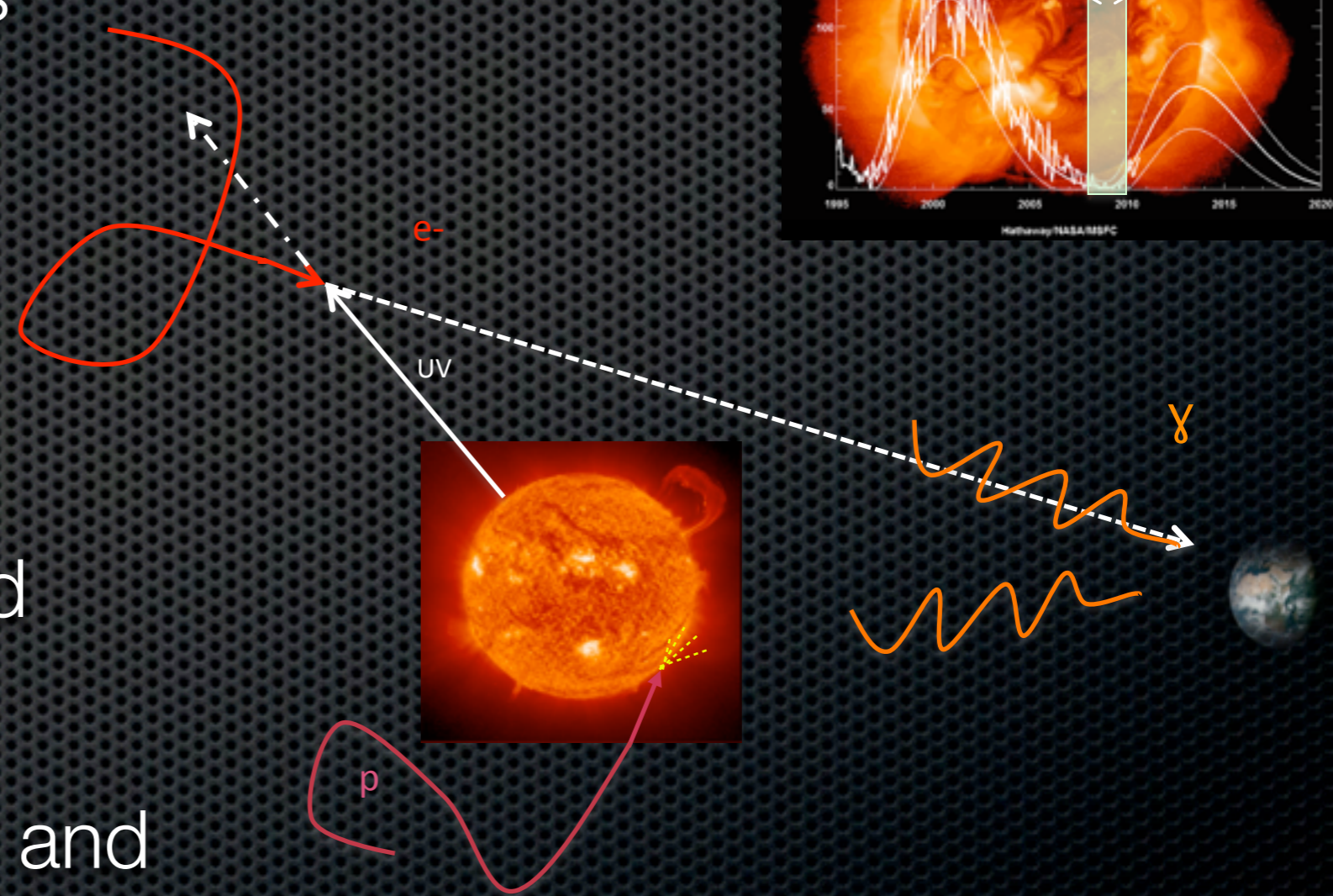
- Hadronic showers in the solar atmosphere

(Seckel 91, Thompson 97)

- Inverse Compton of electrons and solar radiation field

(Moskalenko et al. 2006, Orlando & Strong 2007, 2008)

- Fermi LAT detection and separation of both components (Abdo et al. 2011)

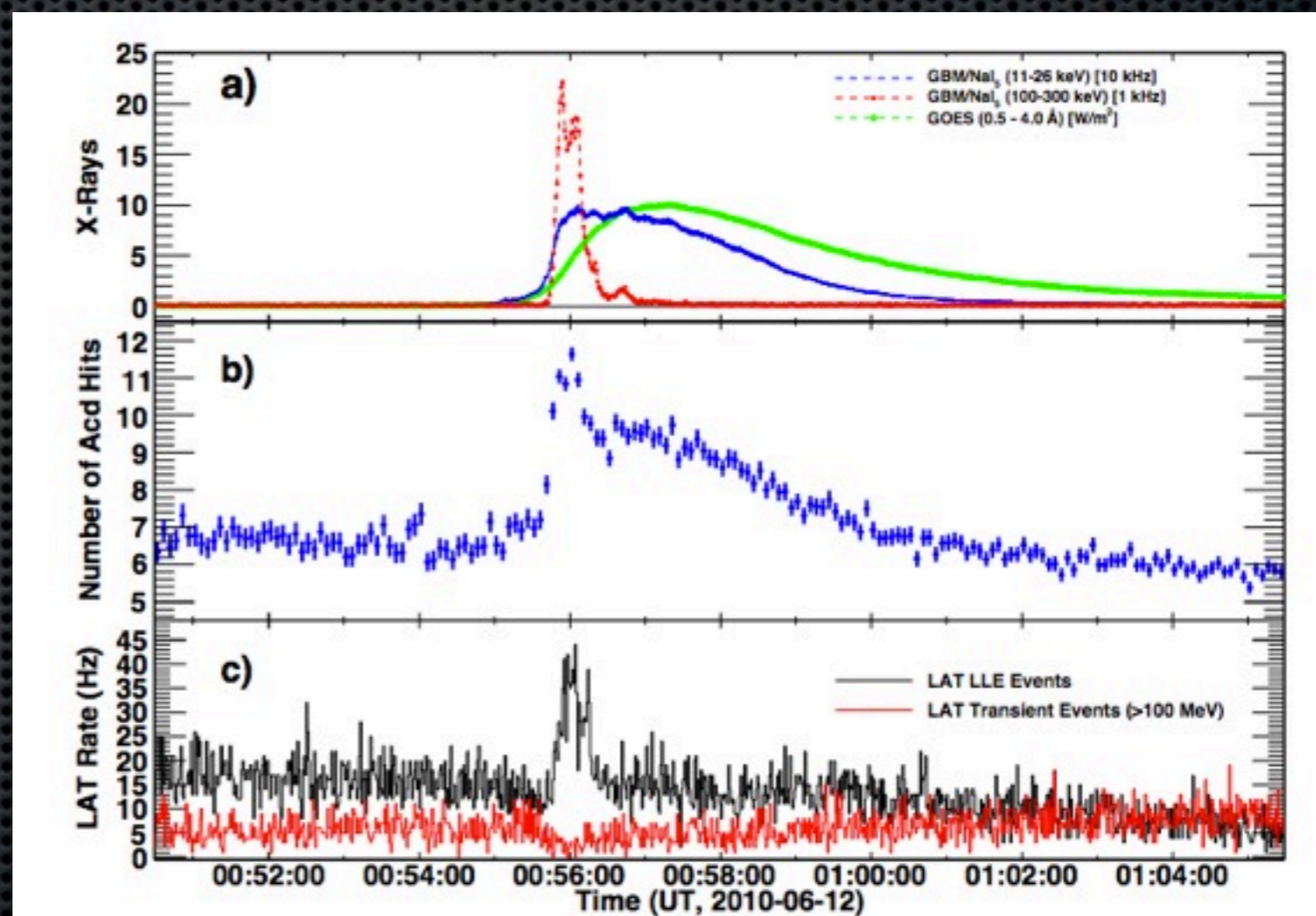




2010 June 12 flare

- GOES M2 class
- Hard Xray and γ rays lasted for ~ 50 s
- LLE analysis
- Localization consistent with the Sun
- No evidence of sustained emission

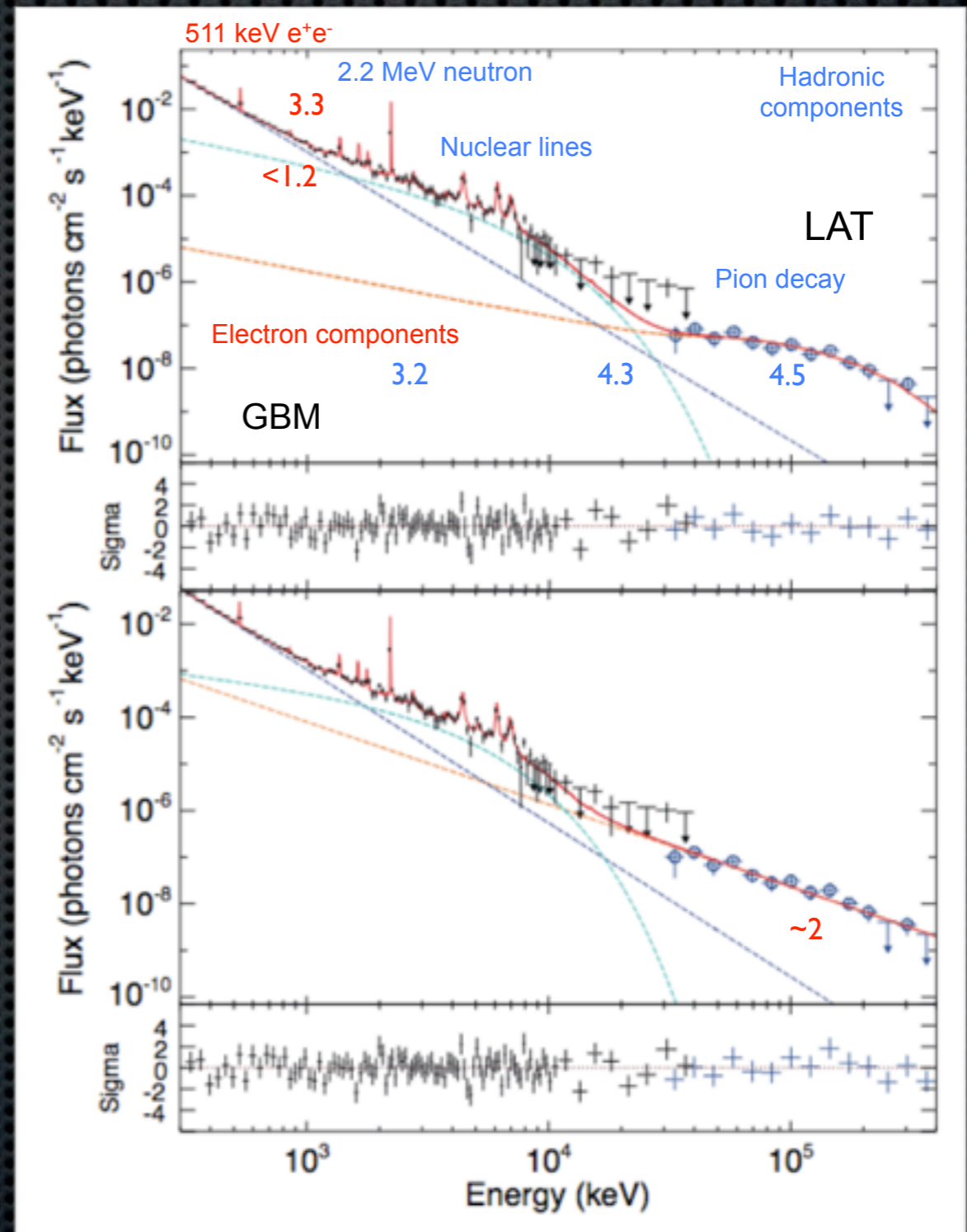
Detected by the Fermi LAT and GBM



Ackermann et al. 2012



- ✦ Electron bremsstrahlung dominates $< 1\text{MeV}$
- ✦ Several electron populations
- ✦ Nuclear lines
- ✦ High energy component up to 400 MeV: modeled by Pion decay or electron brem.

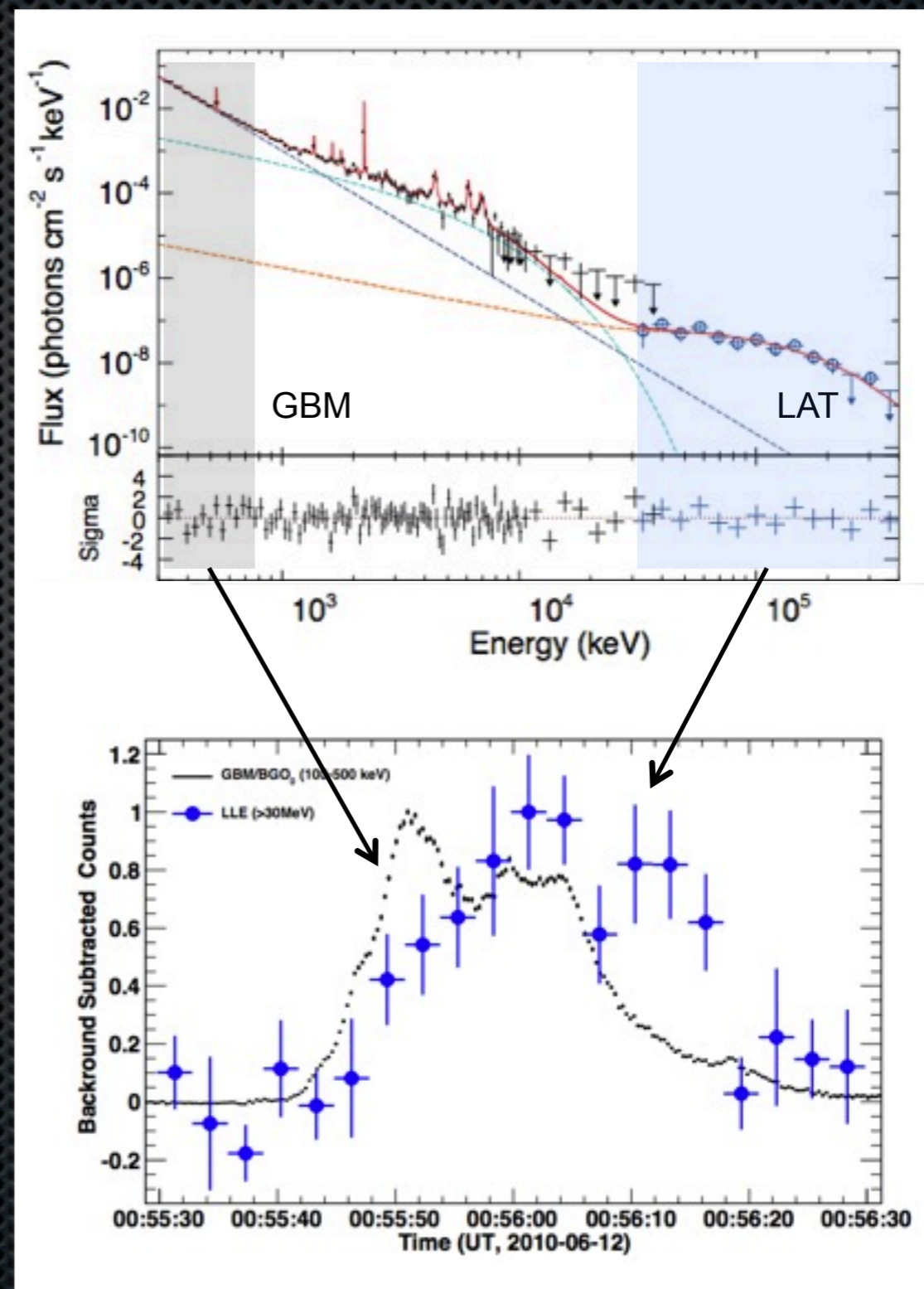


Ackermann et al. 2012



2010 June 12 flare

- High-energy γ rays are delayed by a few seconds:
 - ~ 3 sec at onset and ~ 10 sec at the peak time.
 - Similar ‘double peak’ structure
- Indicate a build-up process for >100 MeV electrons or protons

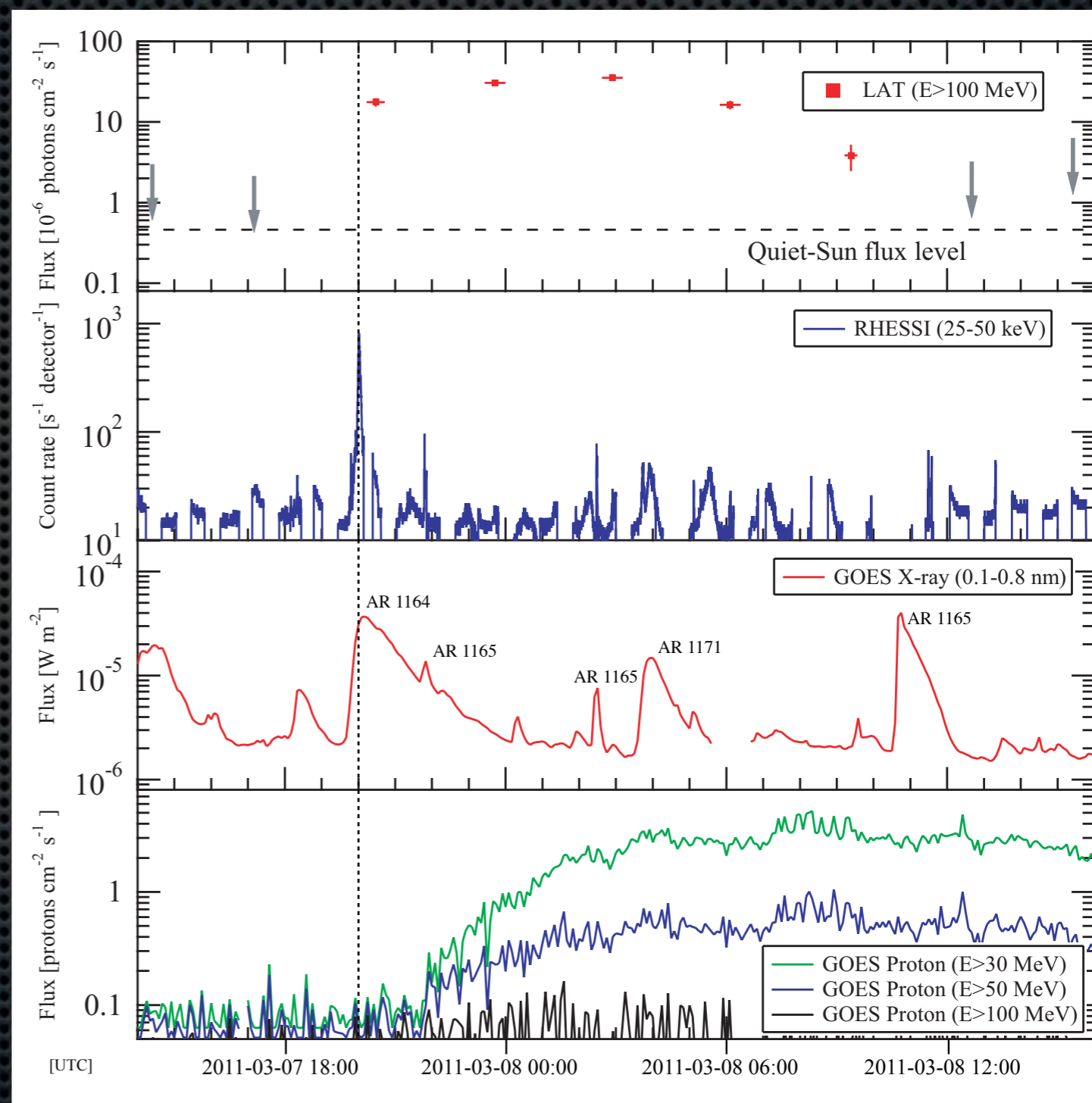


Ackermann et al. 2012



2011 March 7 flare

- GOES M3.7 class
- Impulsive phase not visible
- No detection of HXR above 300 keV
- SEPs
- ~13 h. detection (peak reached 6 h. after impulsive phase)



Ackermann et al. 2013