Fermi LAT Observations of Solar Flares

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on behalf of the Fermi-LAT collaboration

Ackermann et al., submitted to ApJ
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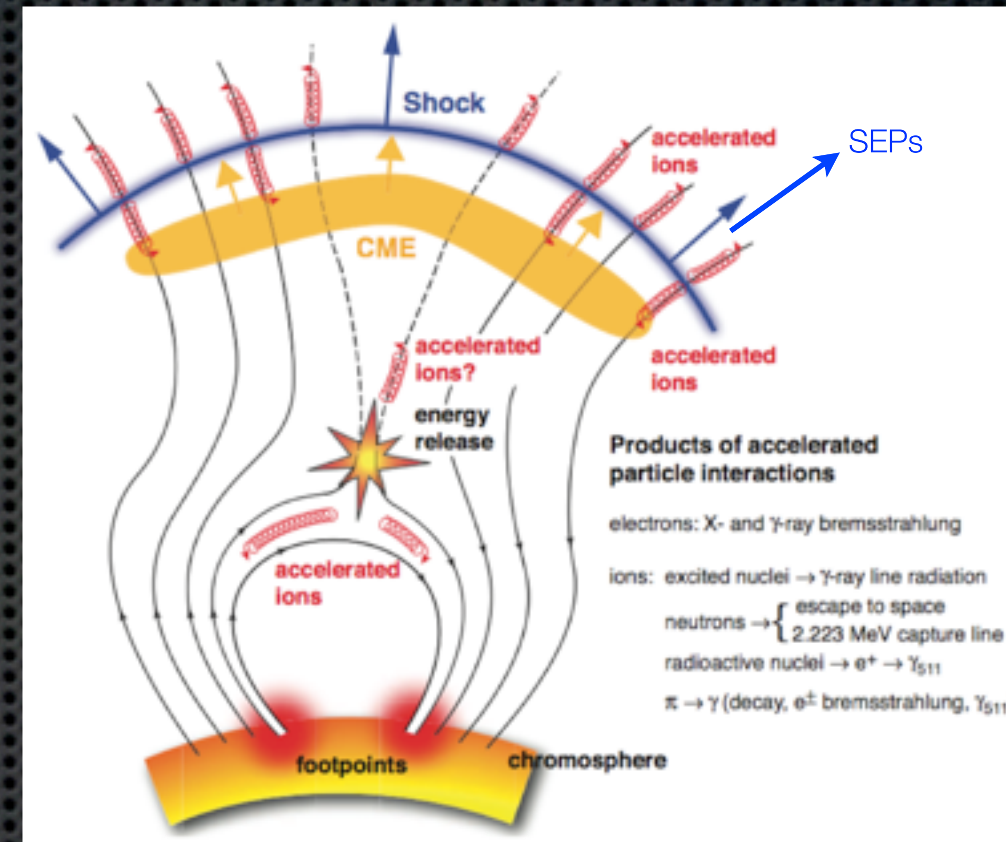
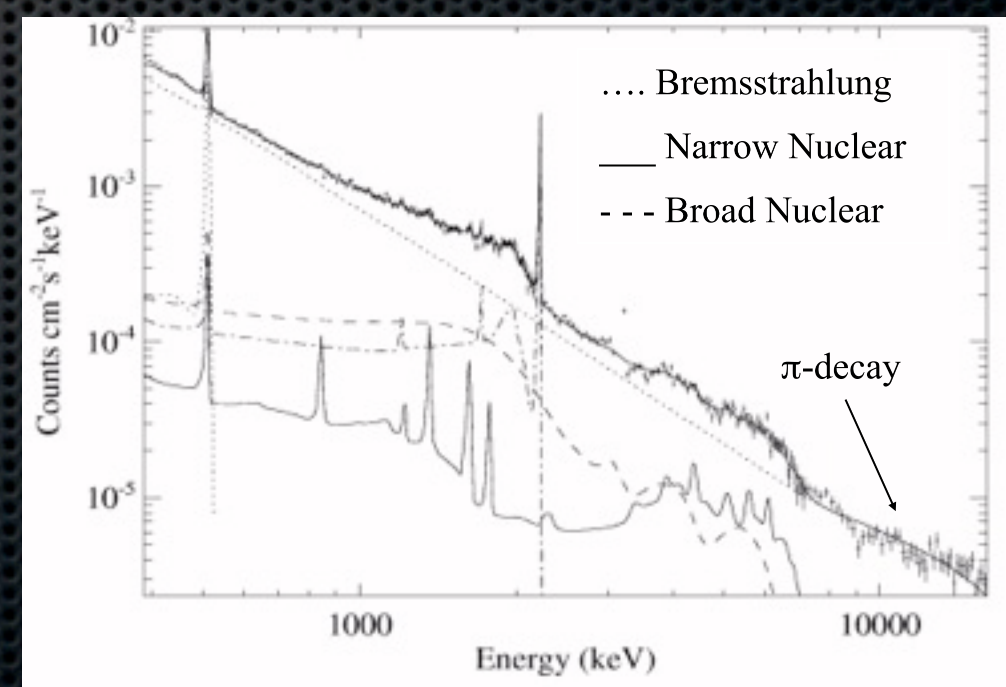
Solar Flares at High-energy

- Observations of solar flares in γ rays since the 70s (SMM, EGRET, ...) for bright Xray flares
- Evidences for nuclear lines (~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)

Sustained high-energy ɣ-ray emission

- List of flares with sustained emission

TABLE I

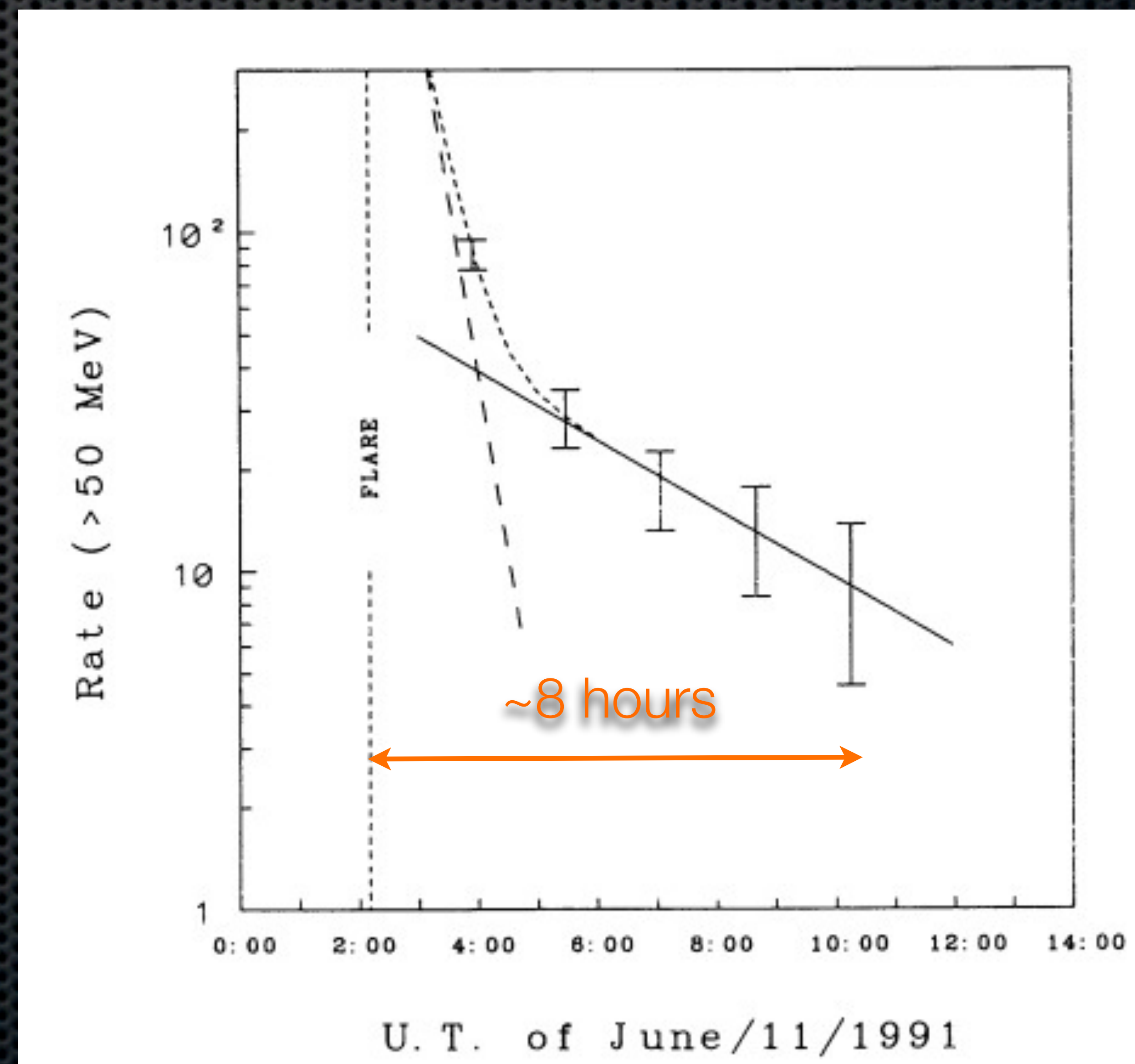
Year	Month	Day	Duration (s)	τ_1 (min)	τ_2 (min)	Ref.
1982	6	3	1200	1.15 ± 0.14	11.7 ± 3.0	1, 2
1984	4	24	900	3.23 ± 0.07	≥ 10	2
1988	12	16	600	3.34 ± 0.30		2
1989	3	6	1500	2.66 ± 0.27		2
1989	9	29	>600			3
1990	4	15	1800			5
1990	5	24	500	0.35 ± 0.02	22 ± 2	4, 5, 6
1991	3	26	600			7, 8
1991	6	4	10000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

[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 et al. 2000

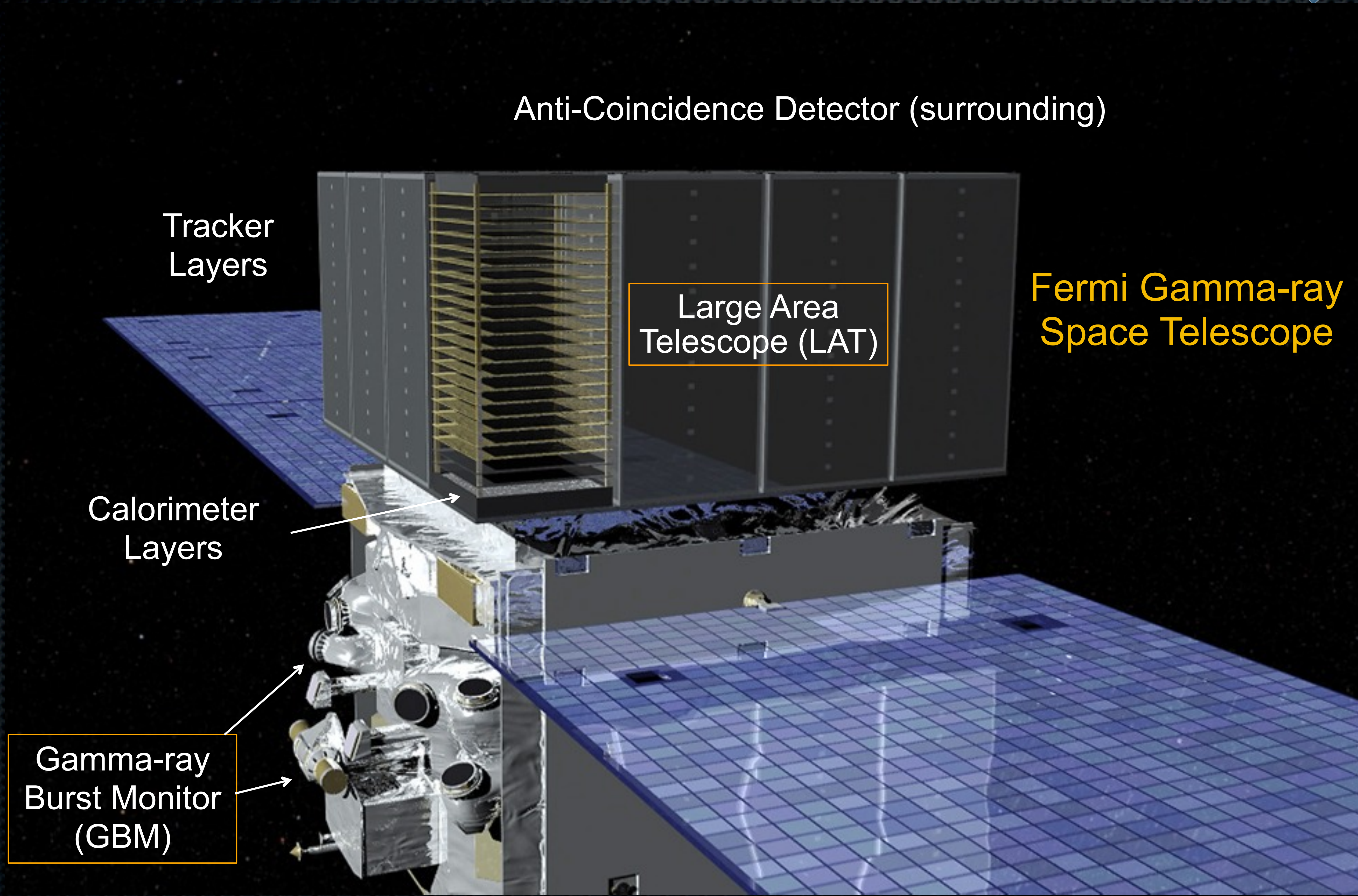
Unclear where and how ɣ rays are produced

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

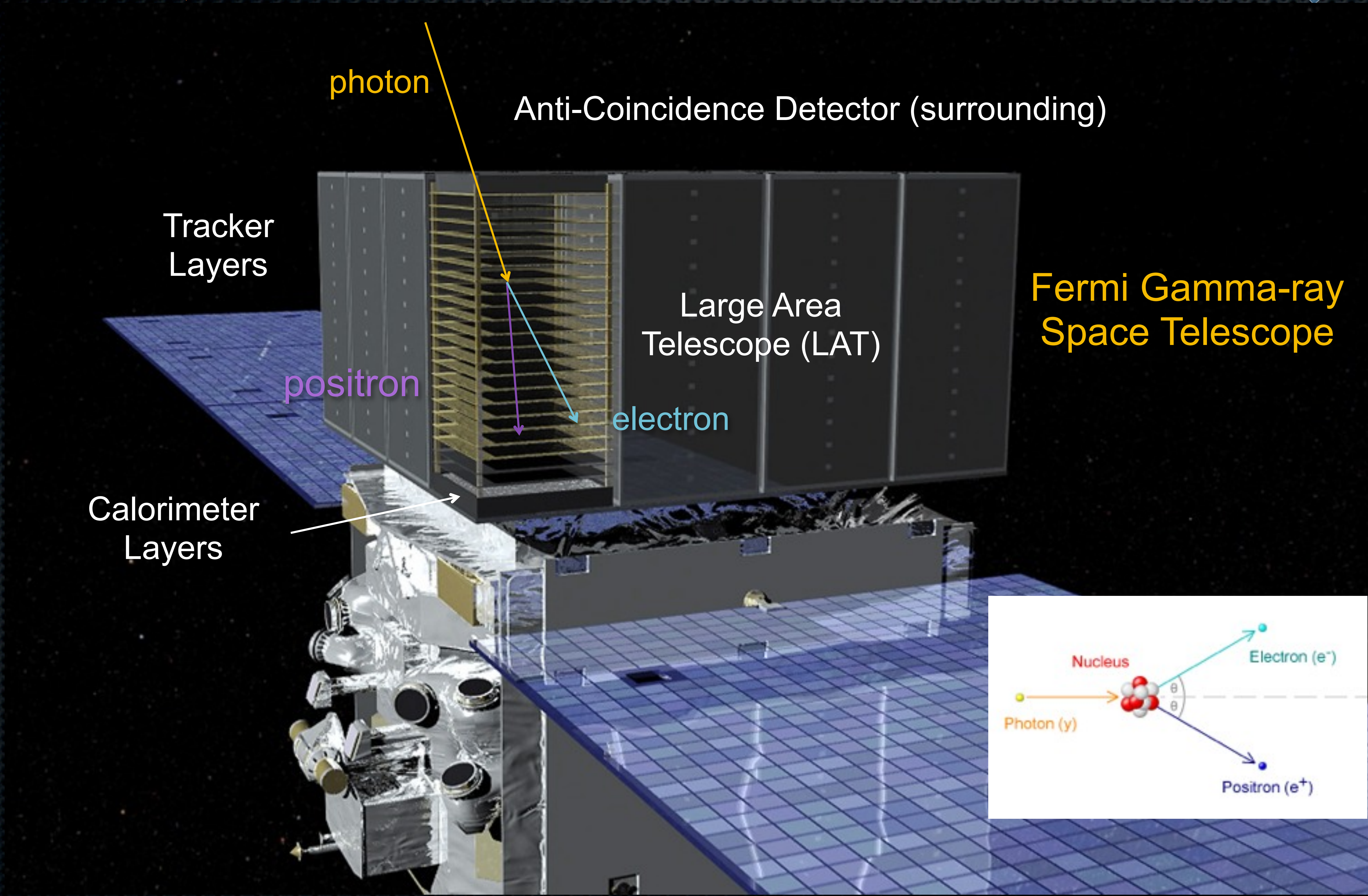


EGRET observation of 1991 June 11 flare (Kanbach et al., 1993)

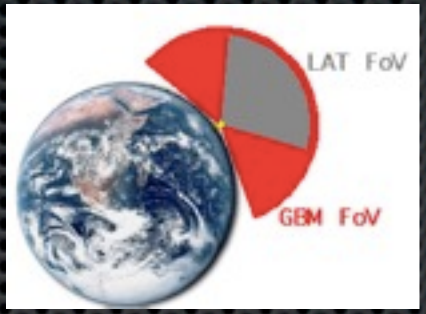
The Fermi Observatory



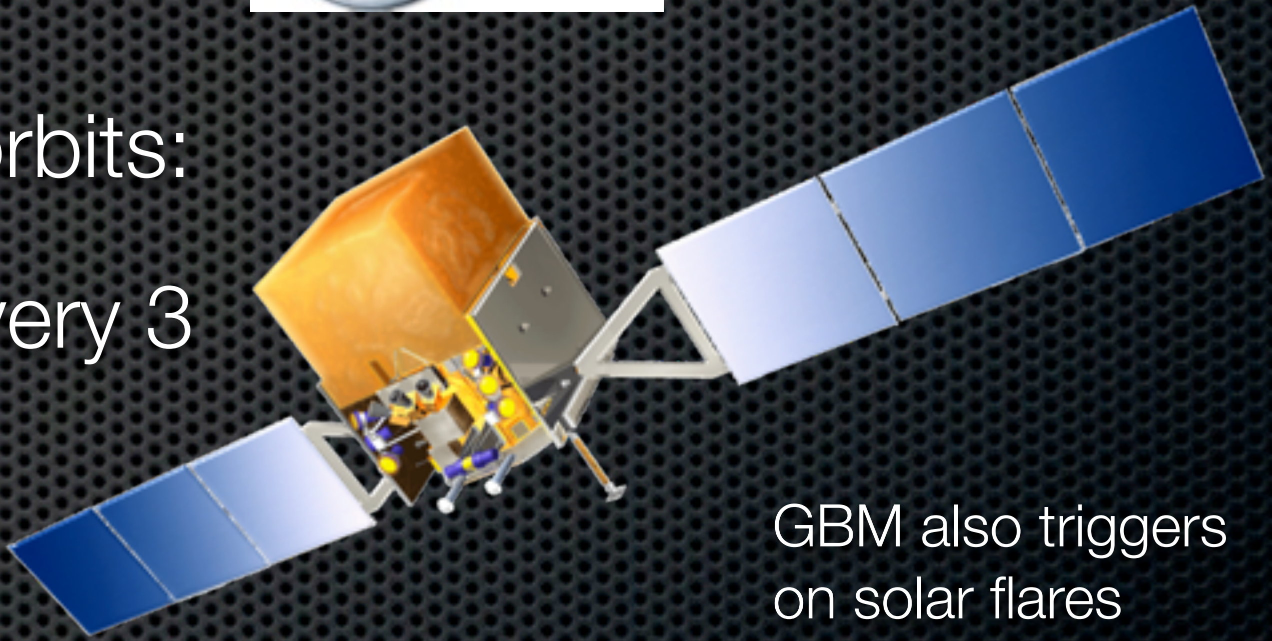
Particle Detector as a Telescope



Fermi LAT as solar observatory



- Wide Field of View
- High sensitivity above 100MeV
- Observes the entire sky every 2 orbits:
    - Sun in the FoV about 30min every 3 hours [data public].



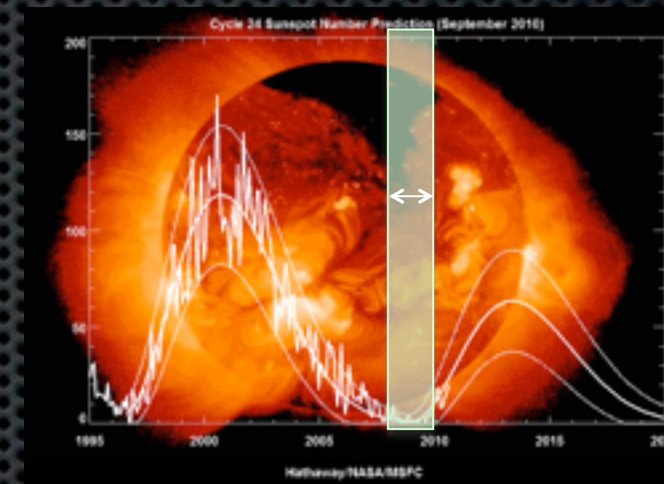
GBM also triggers on solar flares

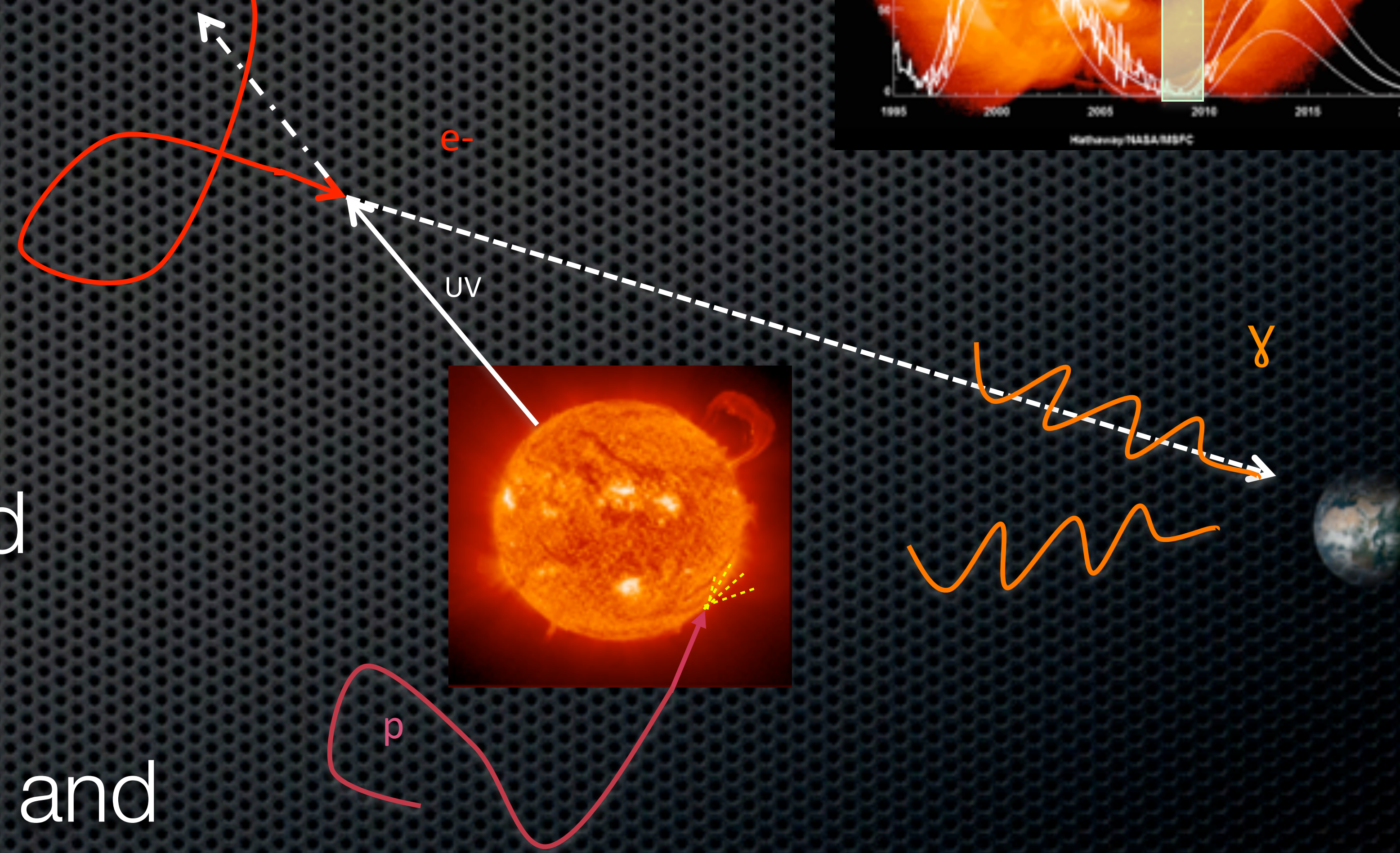
- Intense Xray flux: pile-up in the ACD ➩ ɣ-ray suppression.
    - Recover the signal with looser selection technique: LAT Low Energy events (LLE)

LLE events now available

ɣ rays from the quiet Sun

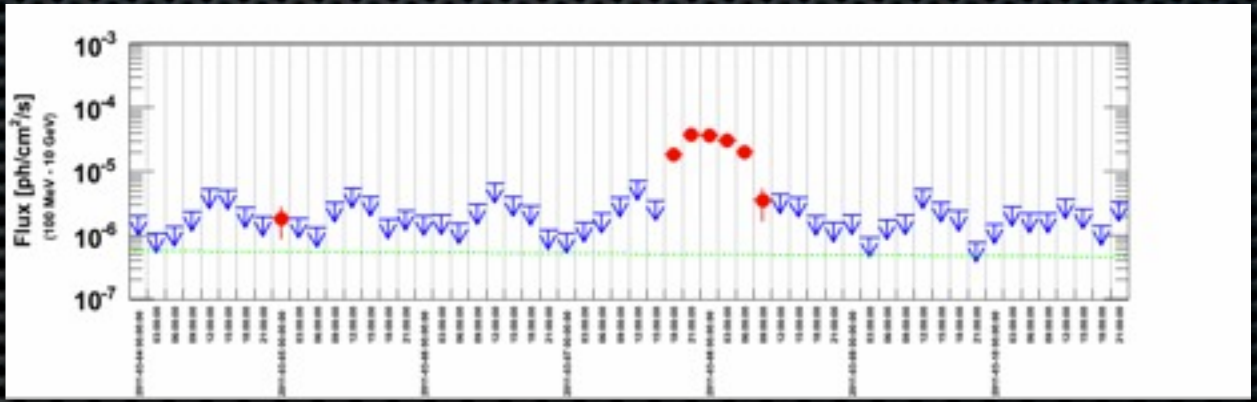
- Cosmic-ray interactions with the sun:
  - Hadronic showers in the solar atmosphere (Seckel 91,Thompson 97)
  - Inverse Compton of electrons and solar radiation field (Moskalenko et al. 2006, Orlando & Strong 2007, 2008)
- Fermi LAT detection and separation of both components (Abdo et al. 2011)





Monitoring the Solar Activity

- Principle:
  - Each passage of the Sun in the LAT FoV yields a measure
  - Also check for all GBM solar flares for LLE data.
- High confidence detection of 19 flares in 4 years of mission



LAT Sun Monitor output example: ɣ-ray flux concident with the Sun position

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Solar Flares detected >100MeV

- For each flare: flux and duration
- Different types of emission:
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  - Sustained
  - Delayed

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Solar Flares detected >100MeV

- Not all flare are bright Xray flares.
- All flares associated with fairly fast CMEs

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Solar Flares detected >100MeV

- 4 individual flares published in 3 papers:
  - First impulsive flare: 2012 June 10
  - First two sustained flares: 2011 March 7 and June 7
  - The brightest and longest recorded so far: 2012 March 7

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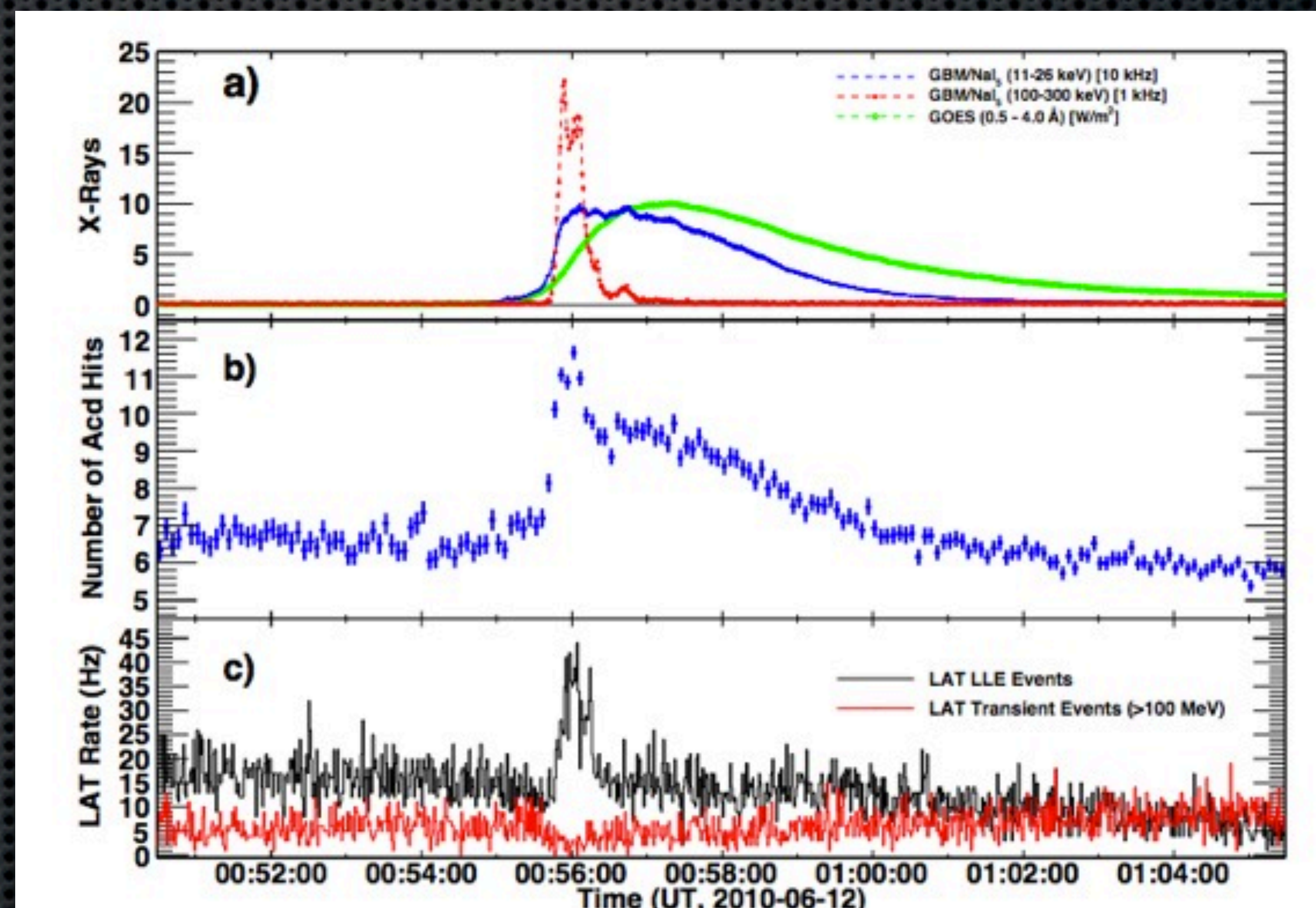
ɣ rays in the impulsive phase

2010 June 12 flare

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

Detected by the Fermi LAT and GBM



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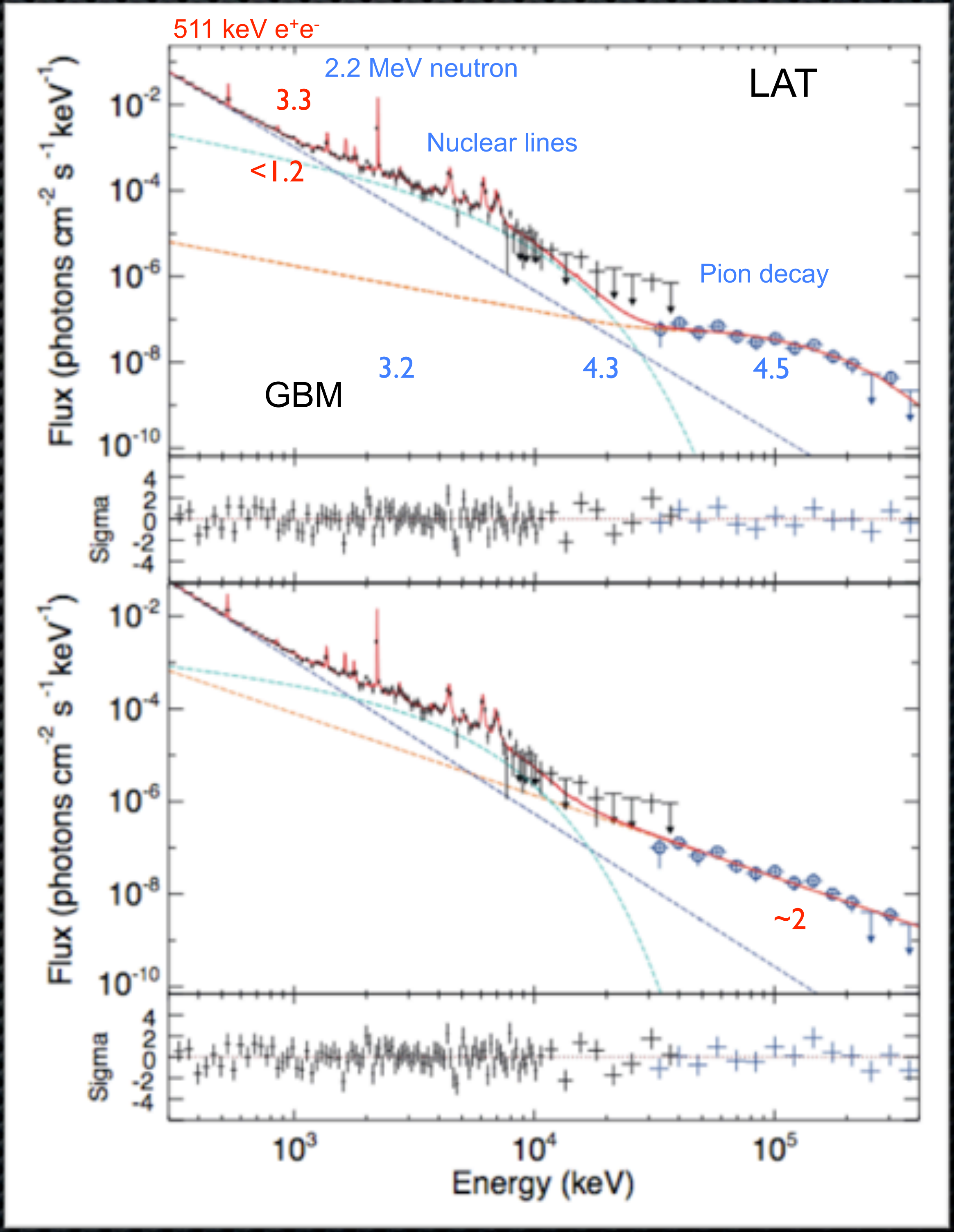
2010 June 12 spectral analysis

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



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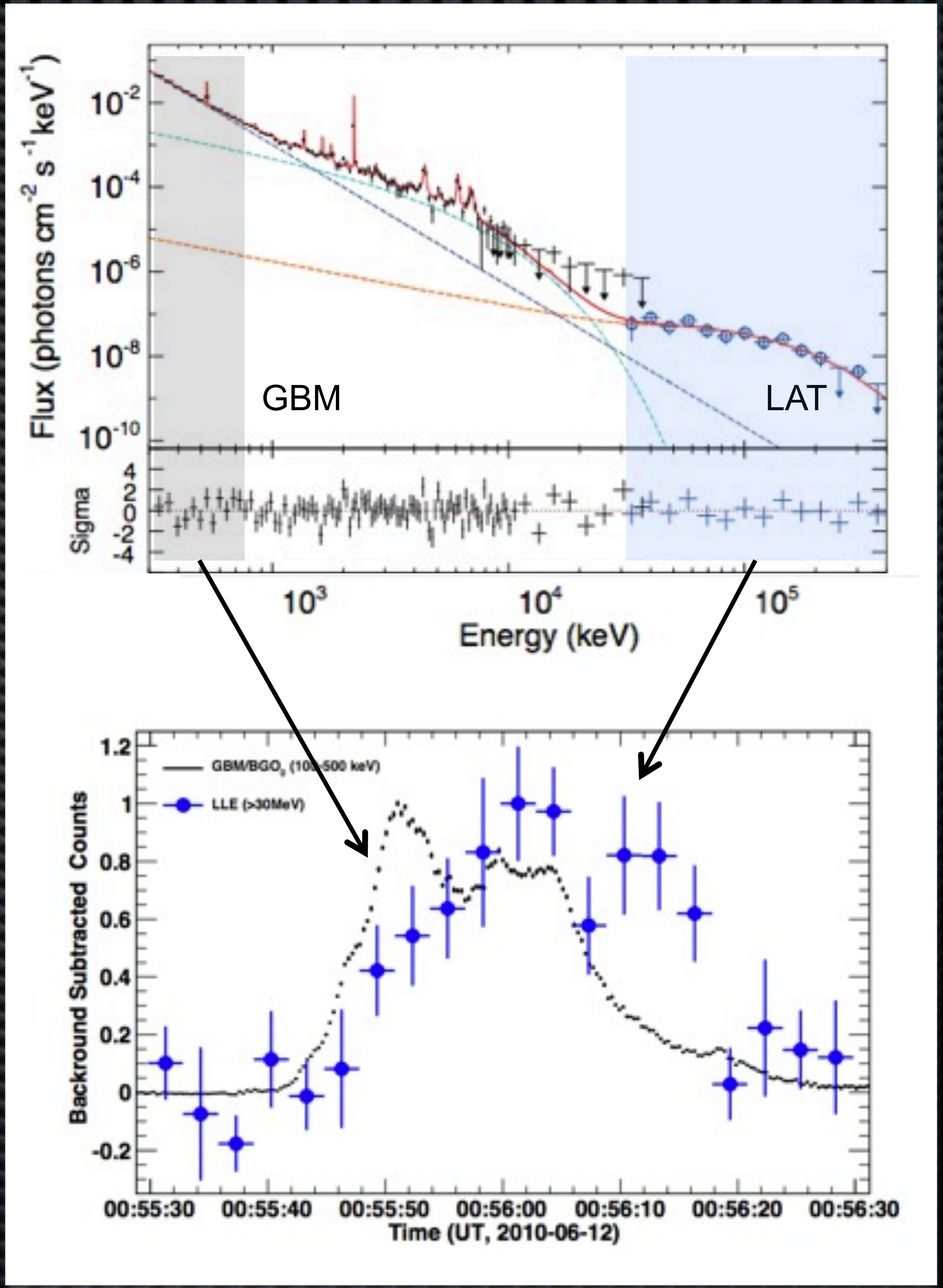
Timing ɣ rays and HXR

- High-energy ɣ 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 >100MeV electrons or protons

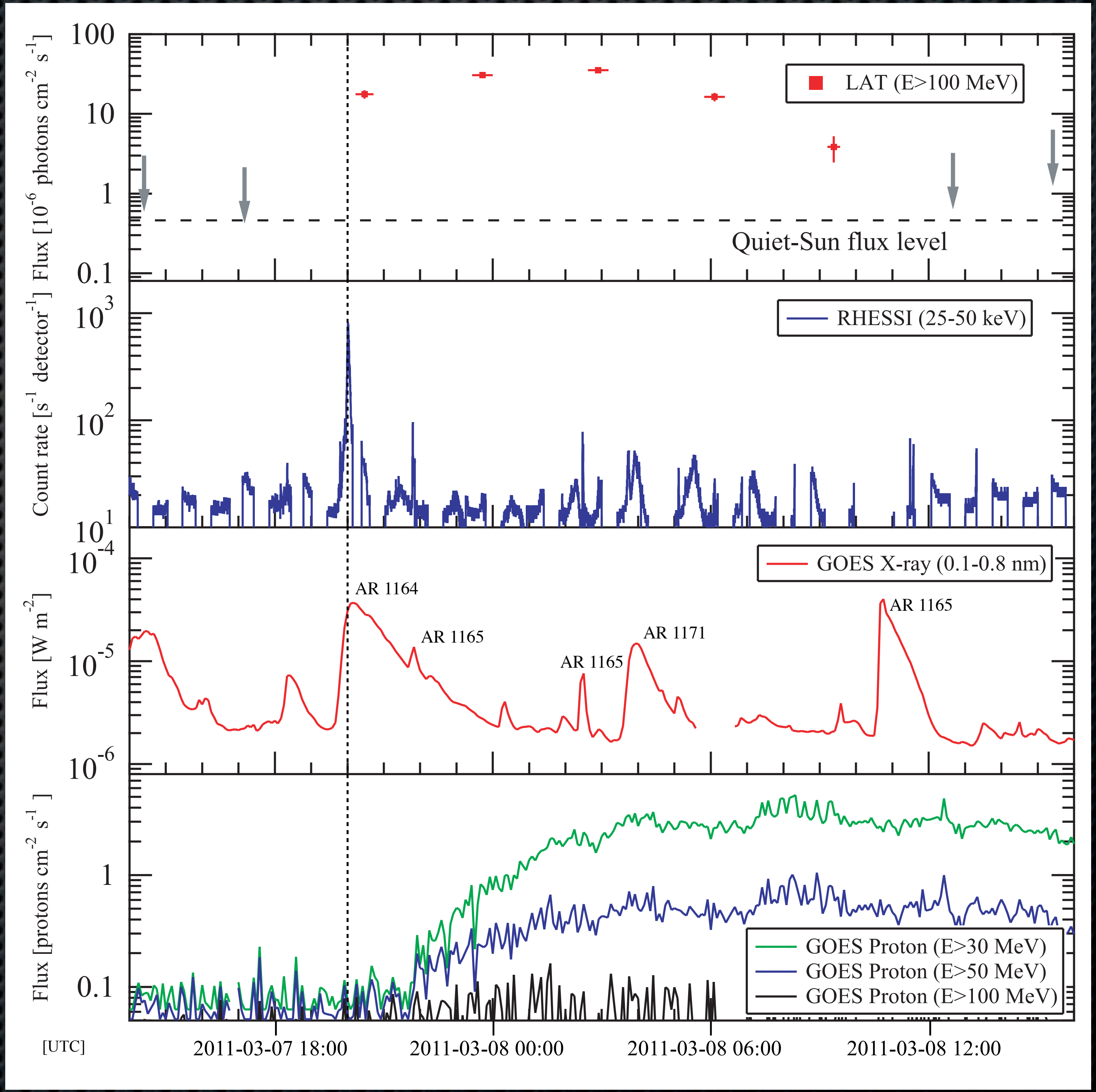


Ackermann et al. 2012

Sustained γ-ray emission

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)



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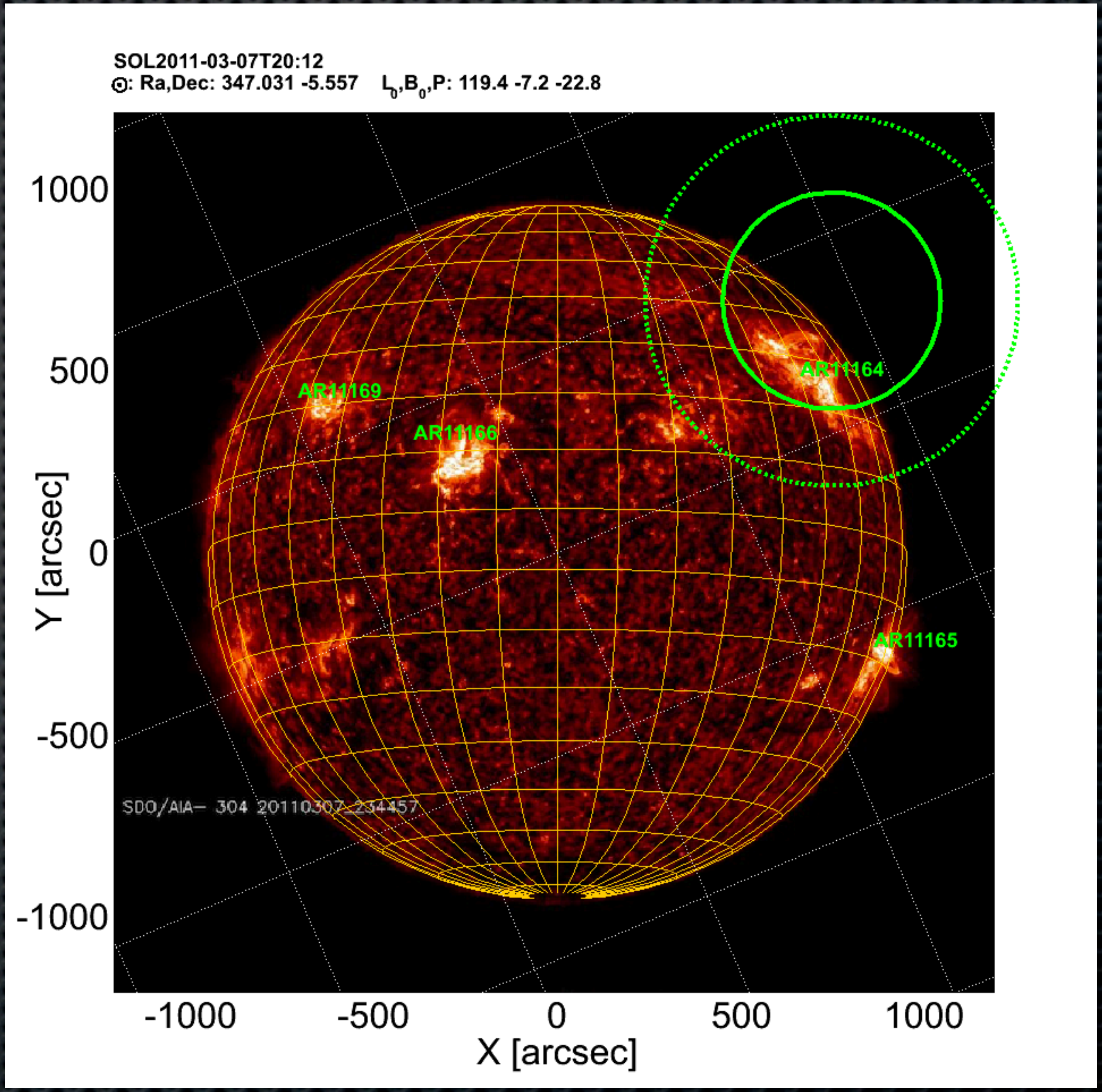
Localization of the γ rays

- Time integrated localization
- Consistent with the flare site
- Exclude contribution of other flares at other sites

68 and 95% error circles



Ackermann et al. 2013

LAT spectrum

- Detection up to 1GeV
- Consistent with pion decay template with proton index 4.5
  (based on Murphy et al. 1987)
- Electron bremsstrahlung possible with a cutoff
- Hard to soft spectral evolution

Time integrated spectrum (>60MeV)

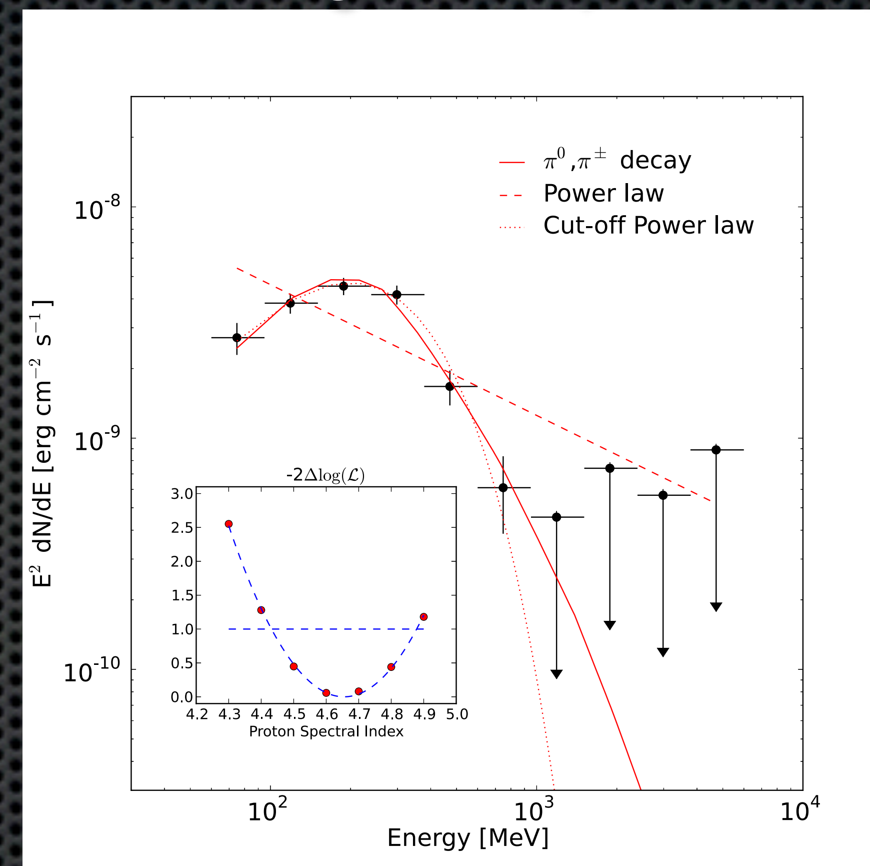


TABLE 2
Fermi-LAT OBSERVING WINDOWS, DURATION, γ-RAY FLUX, AND BEST-FIT PROTON SPECTRAL INDEX.

Date (UT)	Duration min.	Flux (>100 MeV) $\times10^{-5}$ ph cm^{-2} s^{-1}	Proton index
GOES M3.7 flare, SOL2011-03-07T20:12			
2011-03-07 20:15:42.6	24	$1.7\pm0.2^{+0.2}_{-0.1}$	$4.0\pm0.5^{+0.2}_{-0.3}$
2011-03-07 23:26:51.6	33.5	$3.3\pm0.3^{+0.3}_{-0.2}$	$4.6\pm0.3^{+0.2}_{-0.2}$
2011-03-08 02:37:37.6	34	$3.5\pm0.3^{+0.3}_{-0.3}$	$4.9\pm0.3^{+0.2}_{-0.2}$
2011-03-08 05:49:03.6	34	$1.8\pm0.2^{+0.2}_{-0.1}$	>5.6
2011-03-08 09:13:06.7	21	$0.4\pm0.1^{+0.04}_{-0.03}$	†
GOES M2.5 flare, SOL2011-06-07T06:41			
2011-06-07 07:47:40	36	$3.1\pm0.2^{+0.3}_{-0.2}$	$4.3\pm0.3^{+0.2}_{-0.2}$

† In this time interval, the number of γ-rays is small and the pion-decay template spectrum does not produce a statistically satisfactory fit. The best-fit model to the γ-ray data is described by a power-law with spectral index Γ=2.7±0.4 with the reported flux.

Ackermann et al. 2013

Emission processes

- Total energy in ɣ rays is 200 times less than in HXR (20-300keV)
  - Leptonic scenario is unlikely :
    - Brem. requires >100MeV electrons whose lifetime is ~10s [low B fields - large loop]
    - Inverse Compton requires GeV electrons
    - High energy electrons would loose most of their energy in sub-mm, far IR via synchrotron
  - Hadronic scenario:
    - in good agreement with data
    - requires modest number of accelerated protons

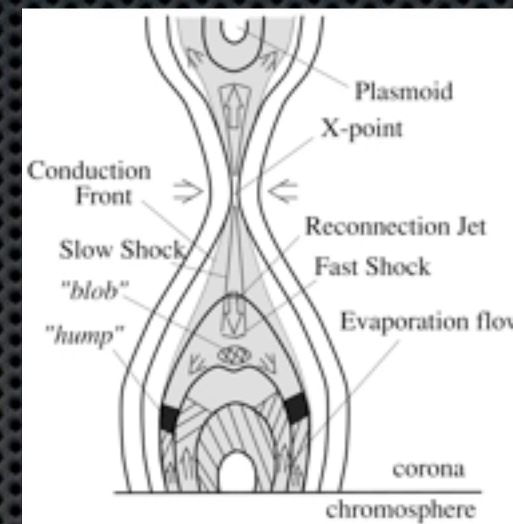
Possible acceleration mechanism

- Initial acceleration and trapping model challenged by long sustained emission

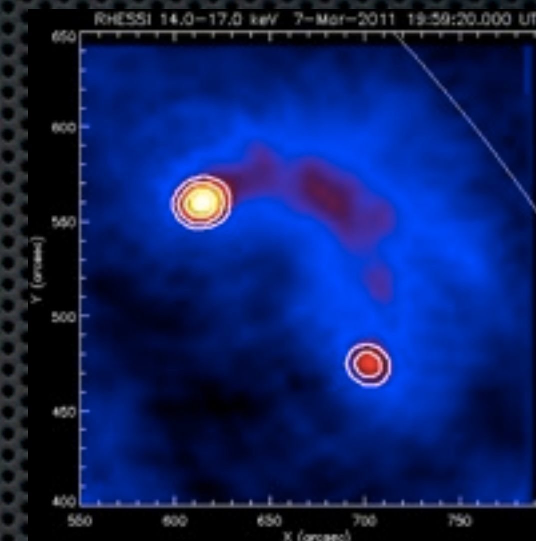
➪ Continuous acceleration seems more plausible

- CME shock accelerates SEPs

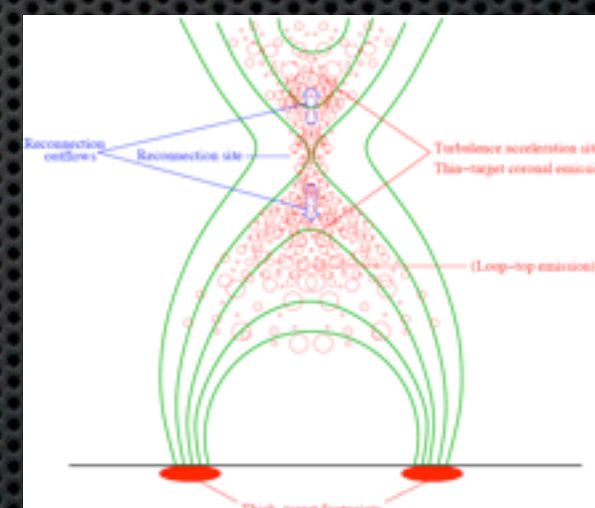
➪ Accelerated particles transport back to Sun surface [emission site]
(e.g. Murphy et al. 1987, Cliver et al. 1993)

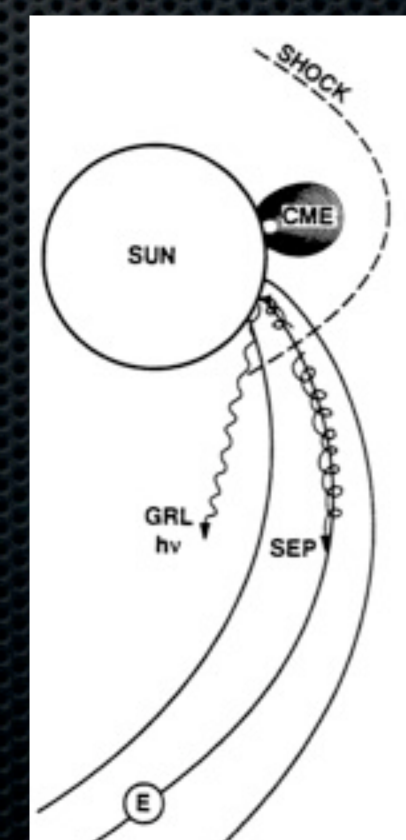


Yokoyama & Shibata, 2001



RHESSI loop for 2011 March 7


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



Cliver et al. 1993

More to come...

- The brightest of all: 2012 March 7 flare
- GOES X5.4 and X1.3 class flares
- Impulsive phase AND the longest sustained emission of 20 hours

Impulsive phases detected by the Fermi LAT and GBM

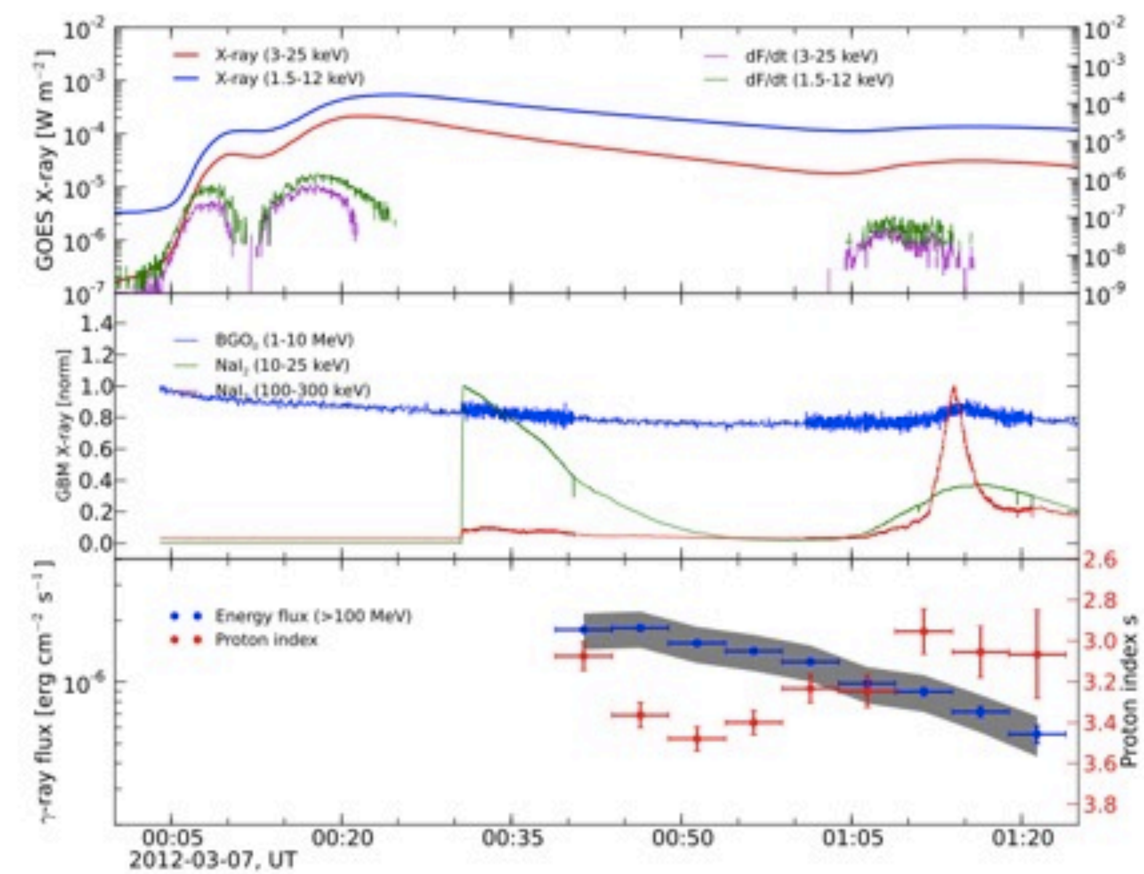
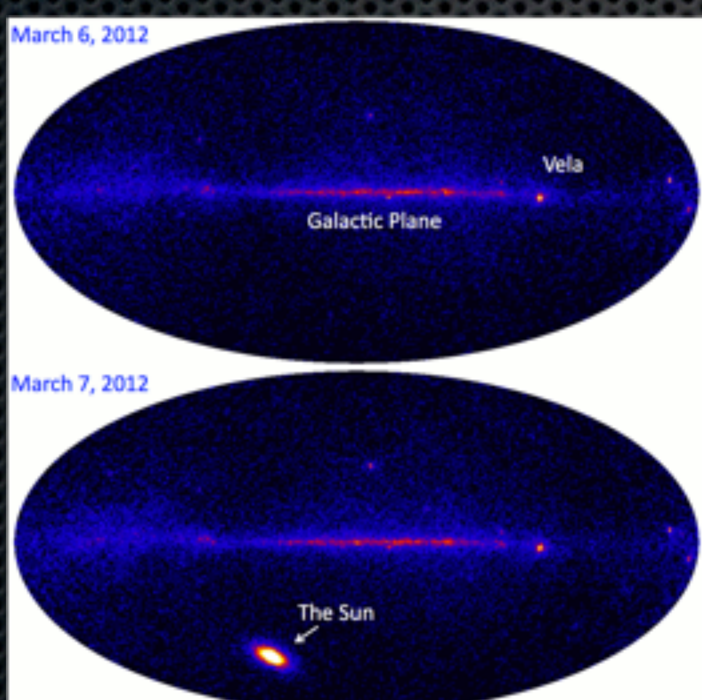


Figure 3: PRELIMINARY: Composite light curves for 2012 March 7 flare, covering the first ~80 minutes. **Top panel**: Soft X-rays (red: 1.5–12 keV, blue: 3–25 keV) from the GOES 15 satellite. On the right axis are the first derivatives of the soft X-rays fluxes (magenta: 1.5–12 keV, green: 3–25 keV). These curves approximate accelerated electron impulsive lightcurves [Neupert 1968]. **Middle panel**: Hard X-rays count rates from the GBM; green and red for NaI_2 10–25 keV and 100–300 keV energy channels, and blue for the BGO_0 detector. **Bottom panel**: LAT (>100 MeV) gamma-ray flux (blue) and derived proton spectral index (red). The gray band represents the systematic uncertainties associated to the flux measurement, and it is obtained by adding 20% systematic error in quadrature.

Omodei et al, Fermi Symp. proc. 2012



APOD: 1 day all sky data
100 times brighter than Vela

A new era in high-energy study of solar flares

- Fermi LAT reveals new temporal and spectral properties of the highest energy particles.
- High-energy γ rays emission is rather common - even for modest Xray flares: 19 flares so far.
- Long sustained γ-ray emission put real constraints on acceleration and emission scenarios.
- CME connection