Shedding new light on the Sun with the Fermi LAT

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Fifth international Fermi Symposium - Nagoya University

Gamma-ray emission from the Sun

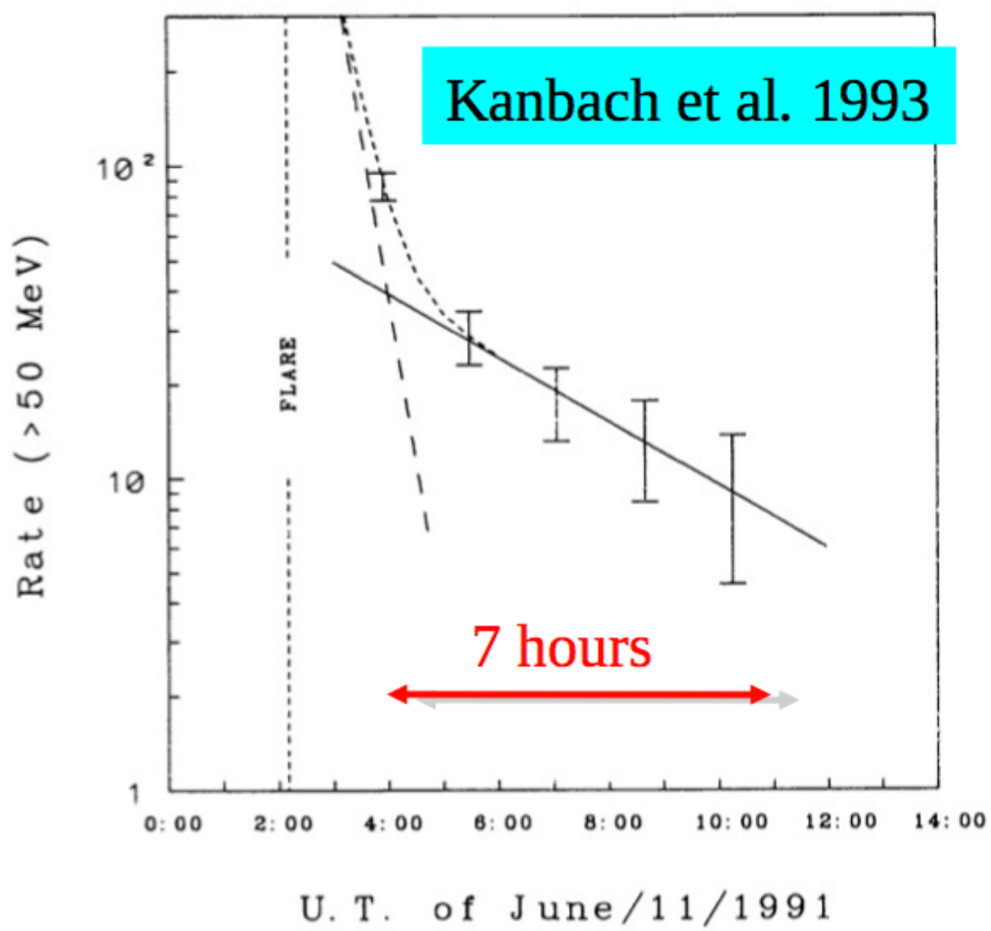
- The sun is a steady, faint source of gamma-rays (produced by the interactions of CR with the solar atmosphere and with the solar radiation field);
- High-energy emission (up to GeV) has been observed in solar flares:
  - In the past decades, only two long-lived (hours long) gamma-ray emissions were observed by EGRET (e.g. Kanbach+93, Ryan00)
  - It was unclear where, when, how the high-energy (HE) particles responsible for gamma-ray emission are accelerated

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



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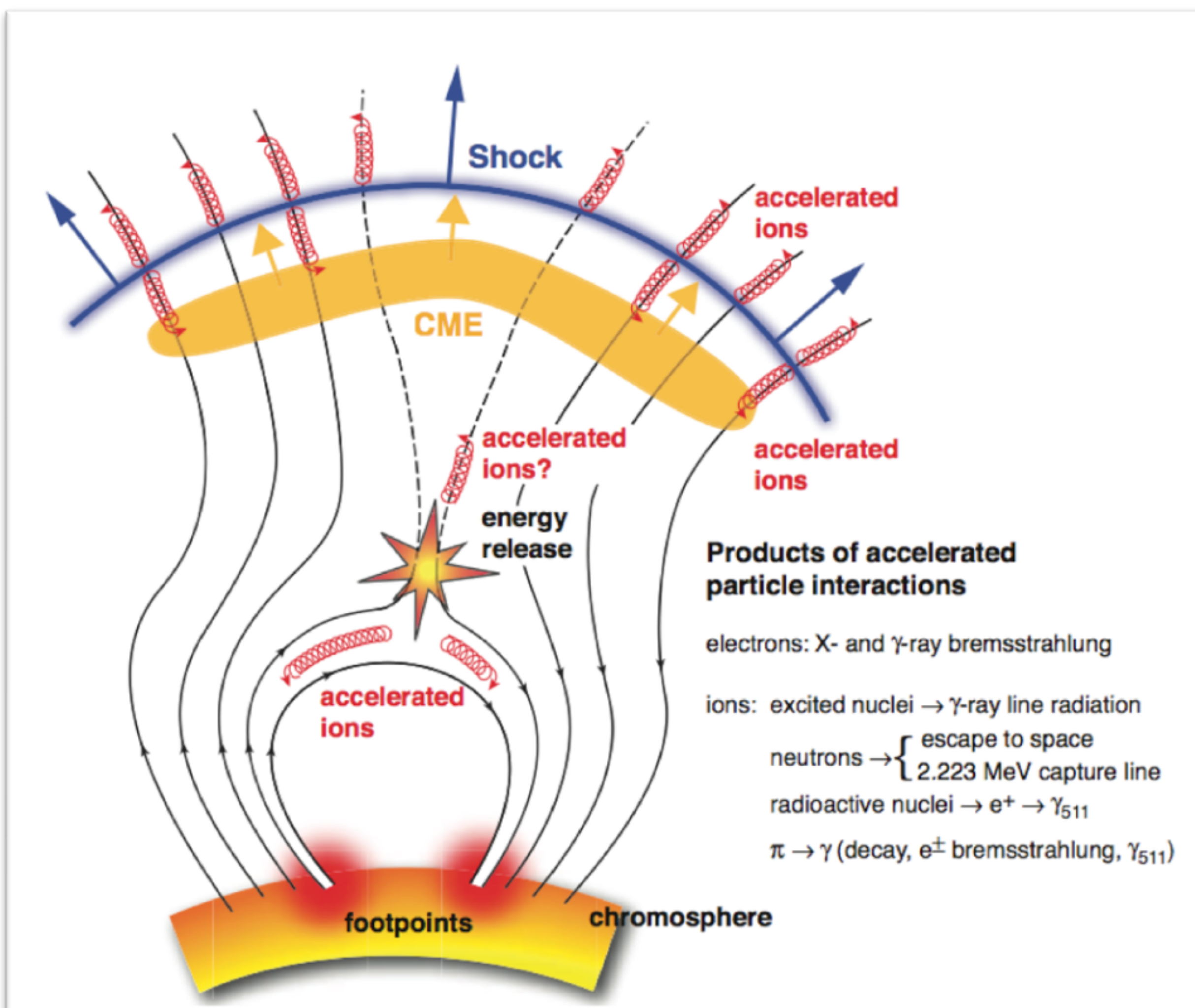
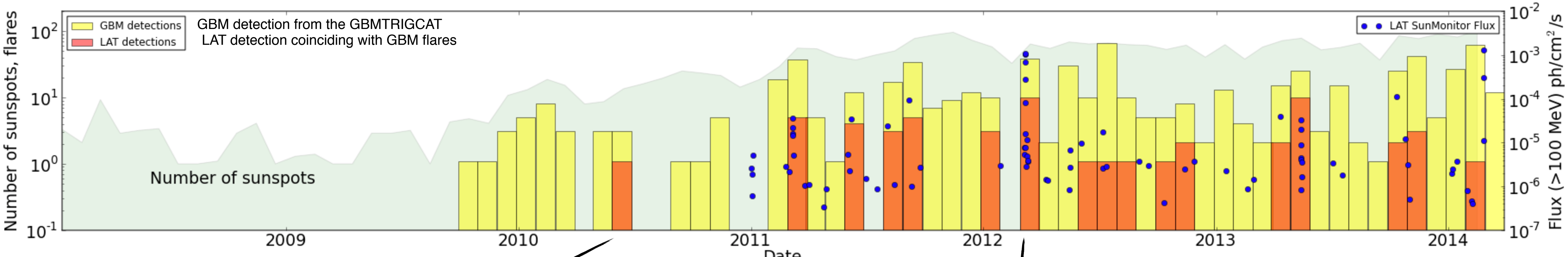
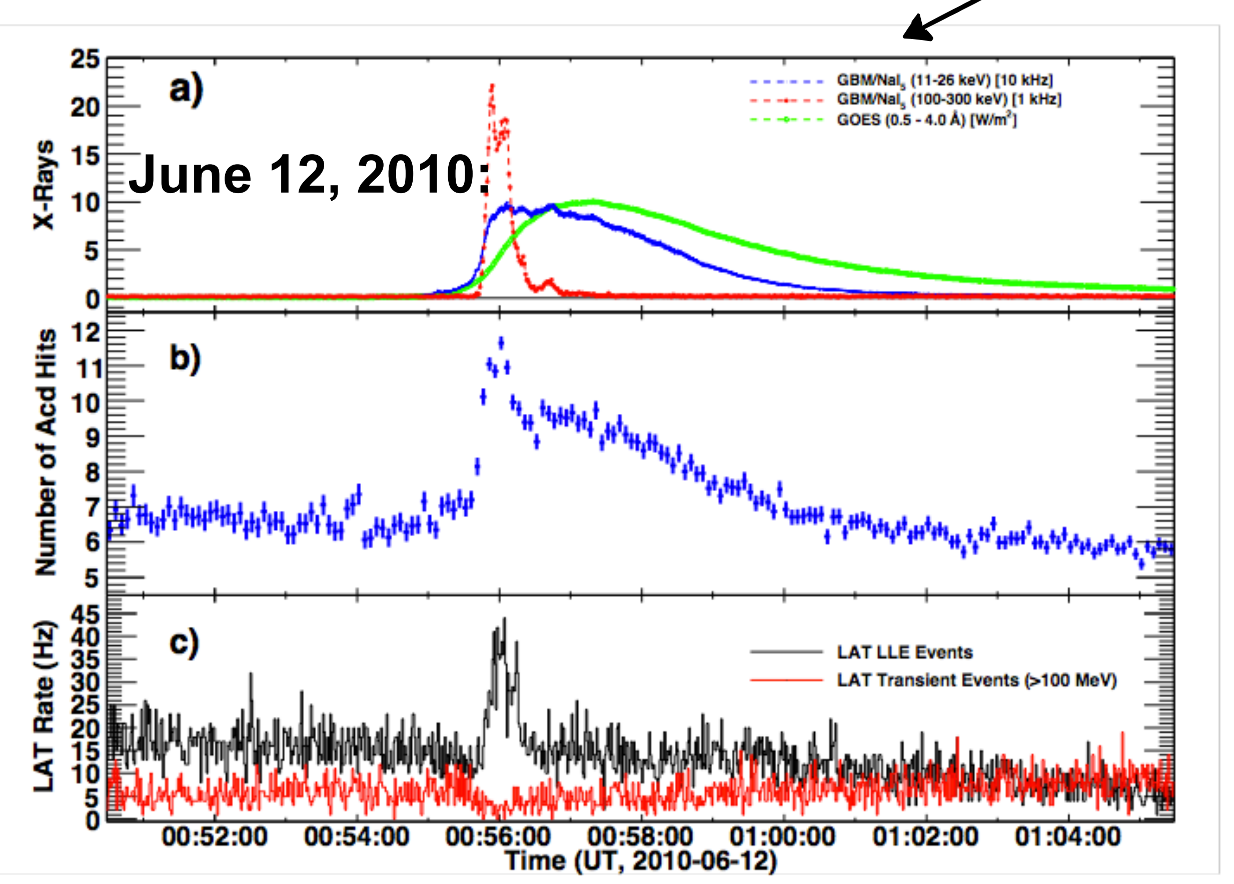
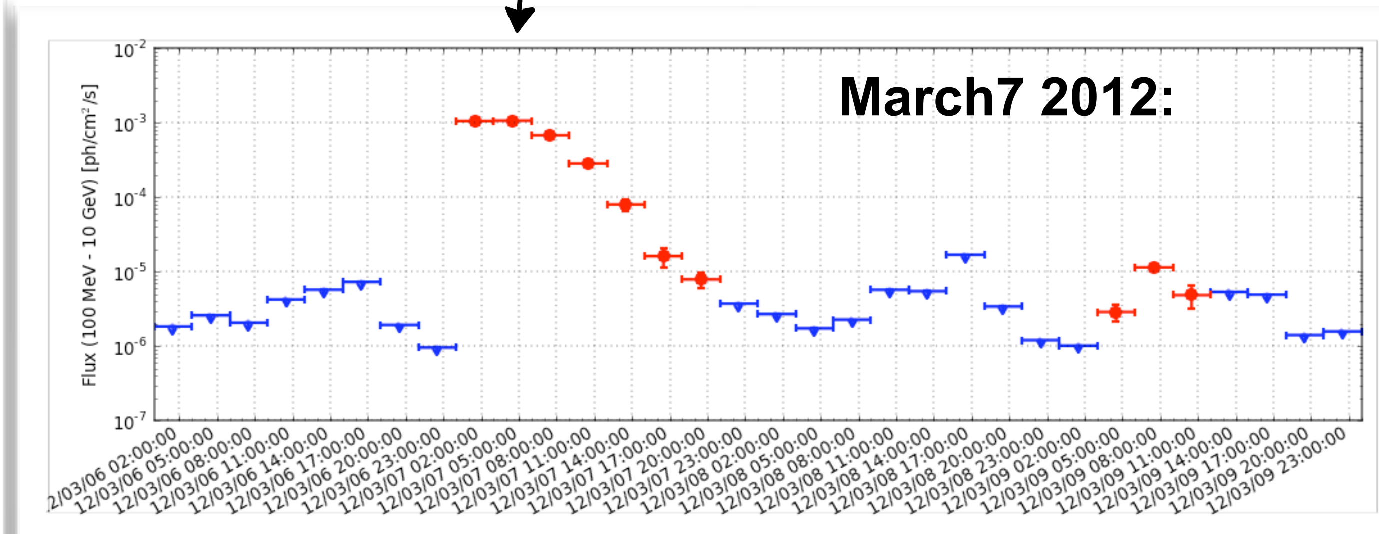


- Complex flare build up (magnetic filed structures, loops and Active Region);
- Magnetic fields reconnect releasing energy which accelerate particles;
- Particles are trapped by magnetic field lines and interact with the solar atmosphere, **producing gamma-rays;**
- Some of the particles have access to the open filed line and escape into interplanetary space;
- They can also be accelerated by the CME shock;

Impulsive & Sustained flares with Fermi LAT







Sustained emission observed up **20 hours**

Ackermann, M. et al. 2014, ApJ, 787, 15

Ackermann et al. 2012, ApJ...745..144A

See the poster 11.03 on the SunMonitor for more details on the continuous monitor of the sun with Fermi LAT!

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The Astrophysical Journal, 787:15 (13pp), 2014 May 20 Ackermann et al.

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2011 Aug 9	X6.9, 07:48-08:08	I	...	1610	08:01, 3.3	LLE[e]	...	...
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		I/S			17:40, 23	300	3.2 ± 0.4	10.6 ± 1.2
2012 Jul 6	X1.1,23:15-23:49	I/S	0.9	892	23:19, 52	930	3.5 ± 0.2	10.4 ± 0.7

- **Xtreme and Moderate flares detected**
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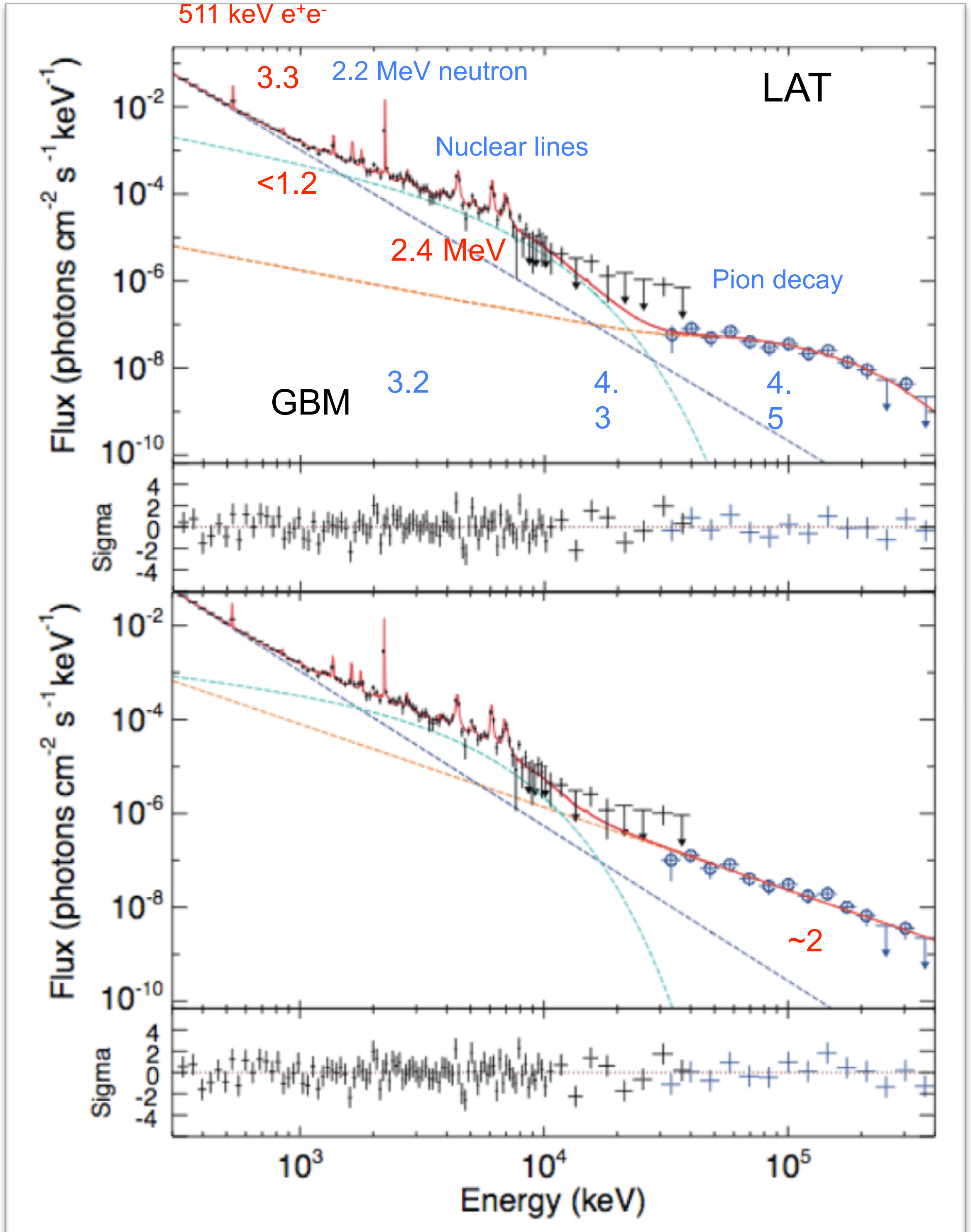
2012 Jun 3	M3.3, 17:48-17:57	I	0.2	605	17:52, 0.6	LLE[e]	...	...
		I/S			17:40, 23	300	3.2 ± 0.4	10.6 ± 1.2
2012 Jul 6	X1.1,23:15-23:49	I/S	0.9	892	23:19, 52	930	3.5 ± 0.2	10.4 ± 0.7

- **Xtreme and Moderate flares detected**
- **I: impulsive emission**
- **I/S: we cannot distinguish between impulsive and Sustained.**
- **S: We don't see the impulsive emission because the Sun was not in the FoV, but we detect sustained emission**
- **D: Delayed: The sun was in the field of view at the time of the impulsive emission, but we do not detect any emission.**
- **All associated with fast CME**

Ackermann, M. et al. 2014, ApJ, 787, 15

Let's focus on impulsive events: SOL2010-06-12T00:57



Ackermann et al. 2012, ApJ...745..144A

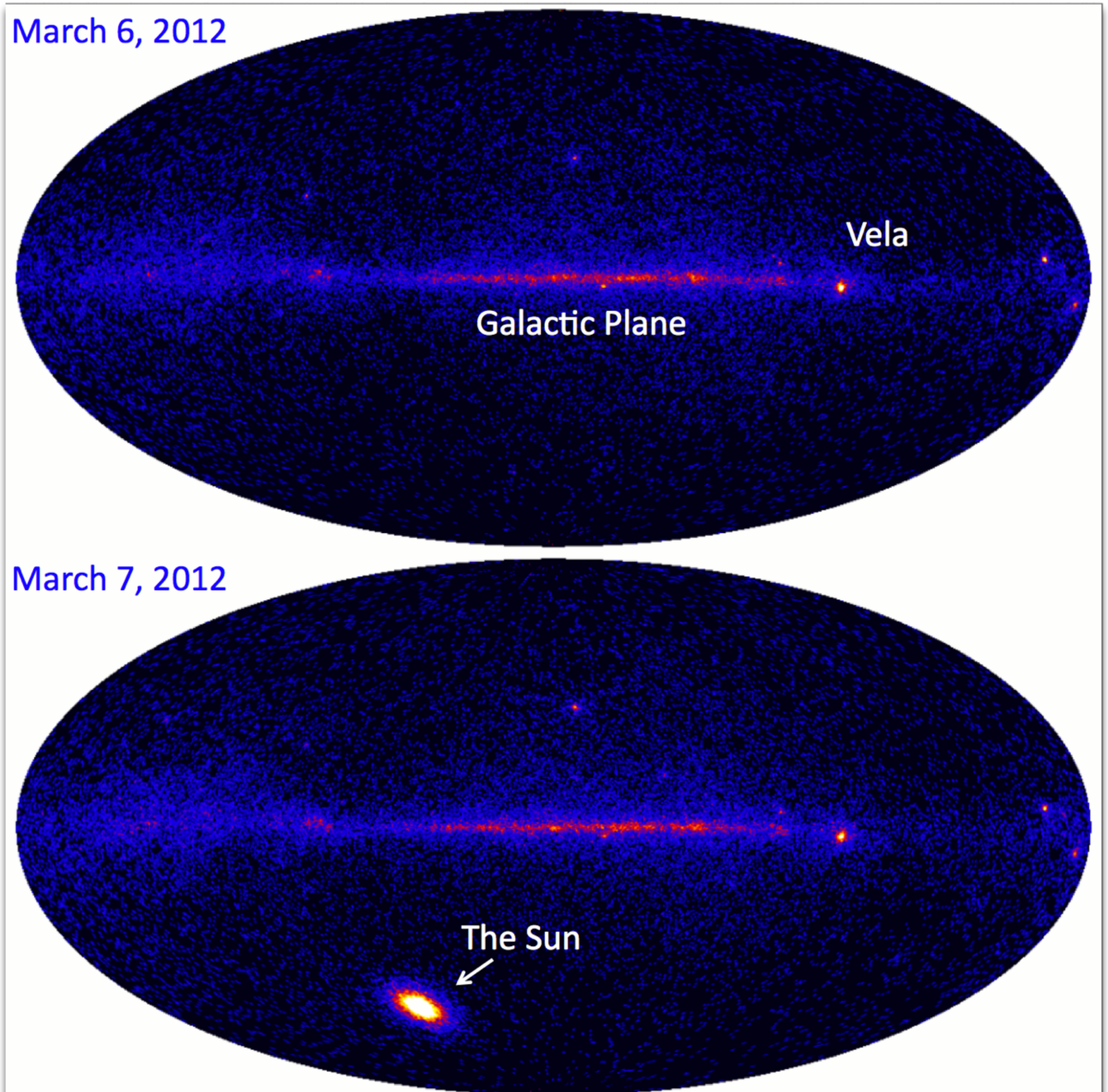
- **Data analysis of the joint GBM and LAT data provides useful information about the underlying accelerated particle distributions:**
  - **Electron Bremsstrahlung dominates at < 1 MeV energies**

    Not a simple powerlaw: hardening followed by a roll-off (at 2.4 MeV); not compatible with transport effects alone;
  - **Protons/ions: gamma-ray spectral features as a proxy of the accelerated ion spectrum**

Component	Energy of gamma-ray	Energy of the ions	Derived accelerated ion spectrum
Neutron Capture	2.2 MeV	10-50 MeV	3.2 (10-50 MeV)
Nuclear lines	5-20 MeV	50-20 MeV	4.3 (50 -300 MeV)
Pions	>300 MeV	>280 MeV	4.5 (>300 MeV)

See the R. Desiante talk on Impulsive flare at Parralel 13A on Thursday (GRB & SF)

The longest lasting gamma-ray emission: March 7, 2012



LAT 1 day all sky data >100 MeV

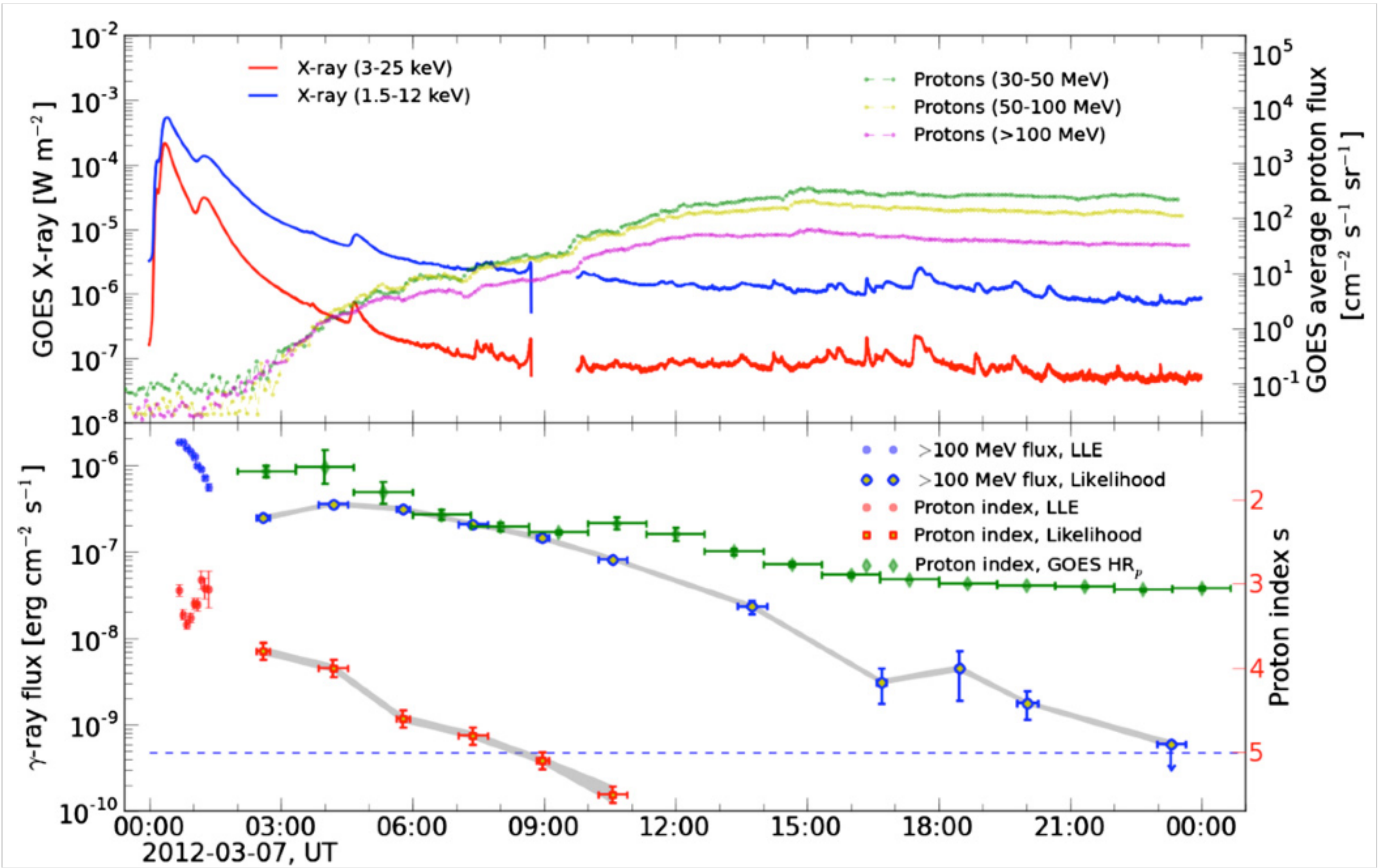
- A very bright Solar Flare was detected on March 7, exceeding:
  - 1000 times the flux of the steady Sun;
  - 100 times the flux of Vela;
  - 50 times the Crab flare;
- High energy emission (>100 MeV, up to 4 GeV) lasts for ~20 hours
- Softening of the spectrum with time

TABLE 4
HIGH ENERGY EVENTS

Arrival Time 2012/03/07 UT	Energy GeV	Distance (deg)	θ (deg)	Event Class	Conversion	$PSF^{a}_{68\%}$ (deg)
0:49	2.8	0.2	49	SOURCE	FRONT	0.3
1:18	4	0.6	66	ULTRACLEAN	BACK	0.5
2:35	2.9	0.6	62	SOURCE	BACK	0.6
4:12	2.9	0.5	36	ULTRACLEAN	BACK	0.6
7:30	4.5	0.8	44	ULTRACLEAN	FRONT	0.2

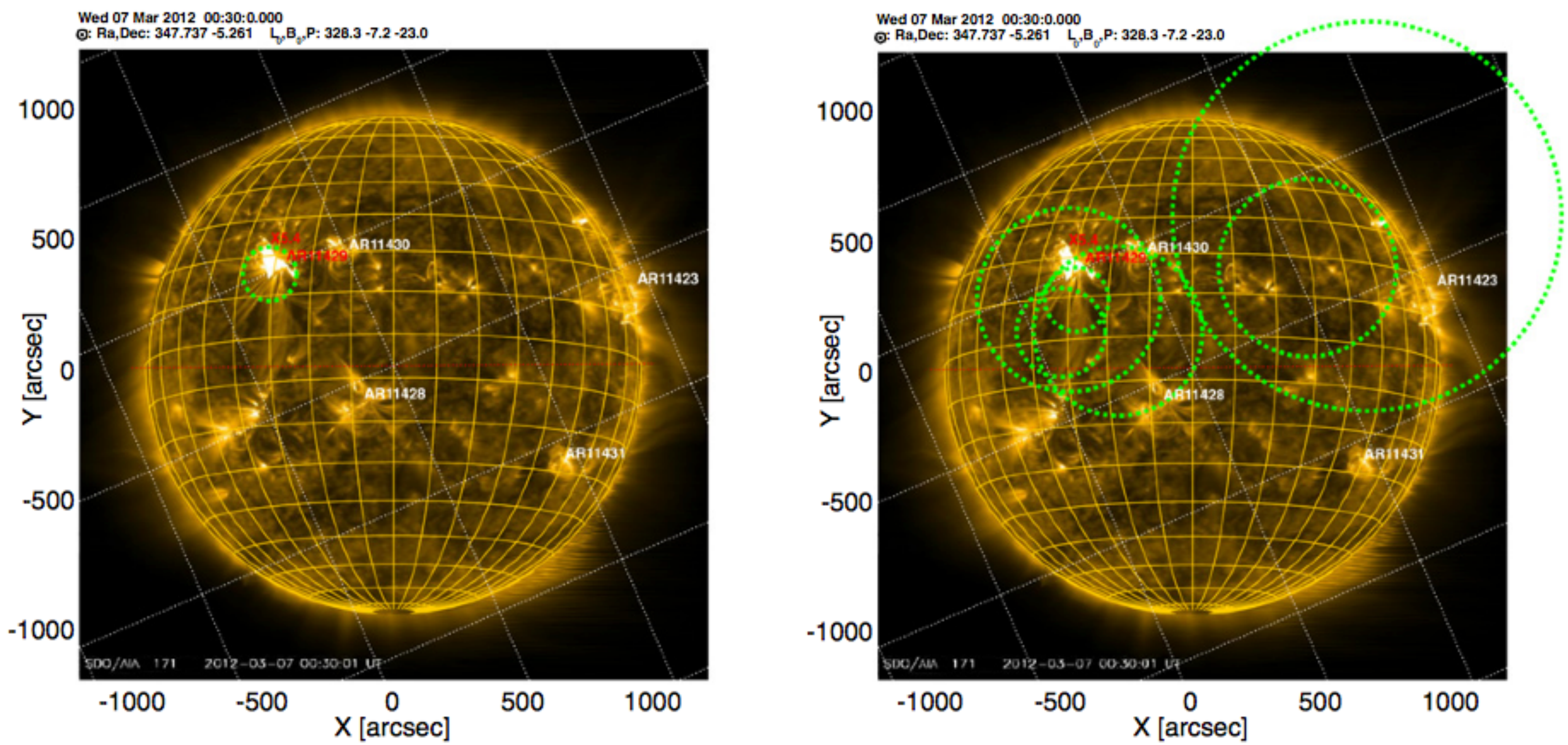
[a] $PSF_{68\%}$ corresponds to the 68% containment radius calculated from the PSF of the instrument for an energy and direction equal to the energy and direction of the event.

The longest lasting gamma-ray emission: March 7, 2012



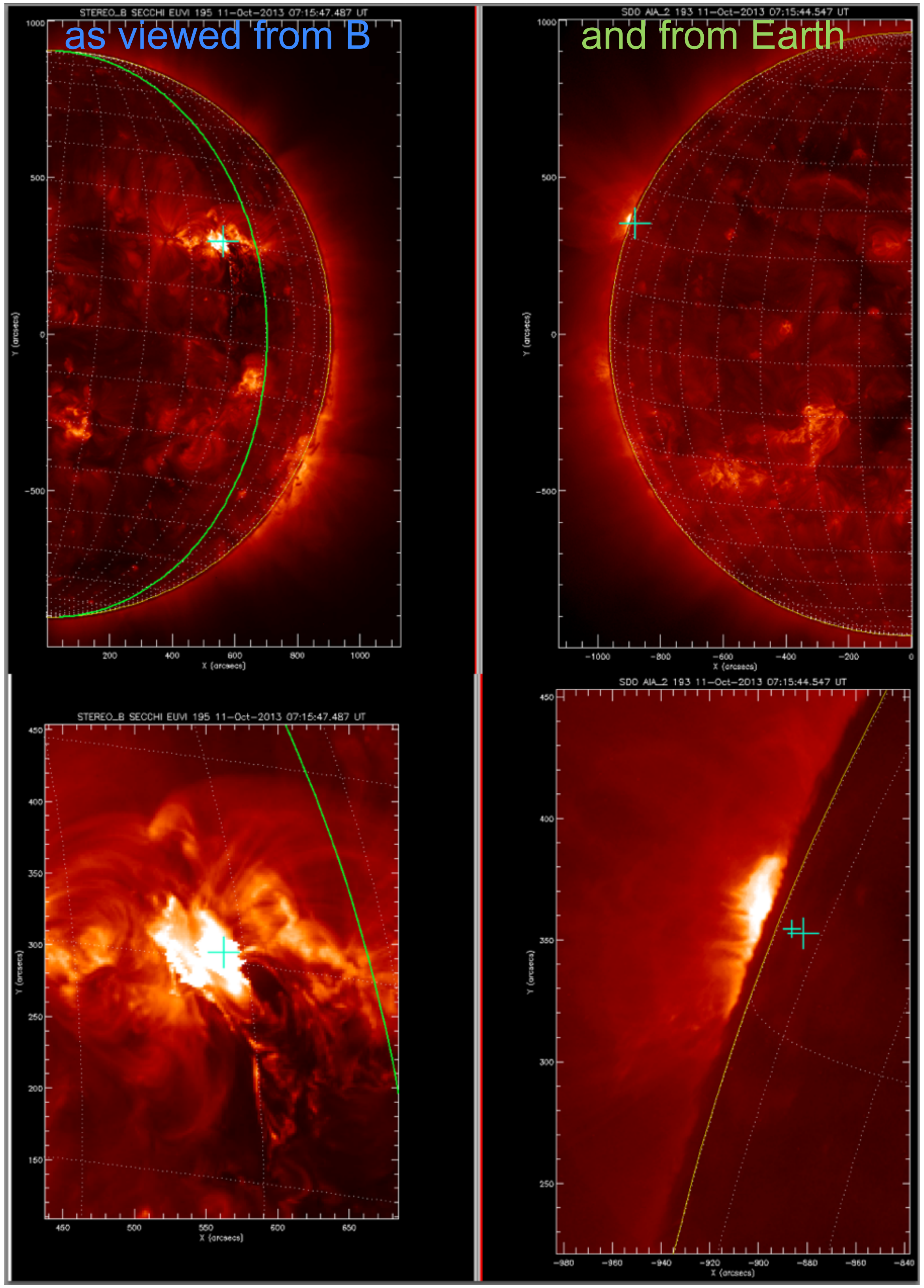
- **Impulsive emission correlated with X-ray flux;**
- **Sustained Gamma-ray flux better correlated with SEP rather than X-ray**

Localization, SOL120307

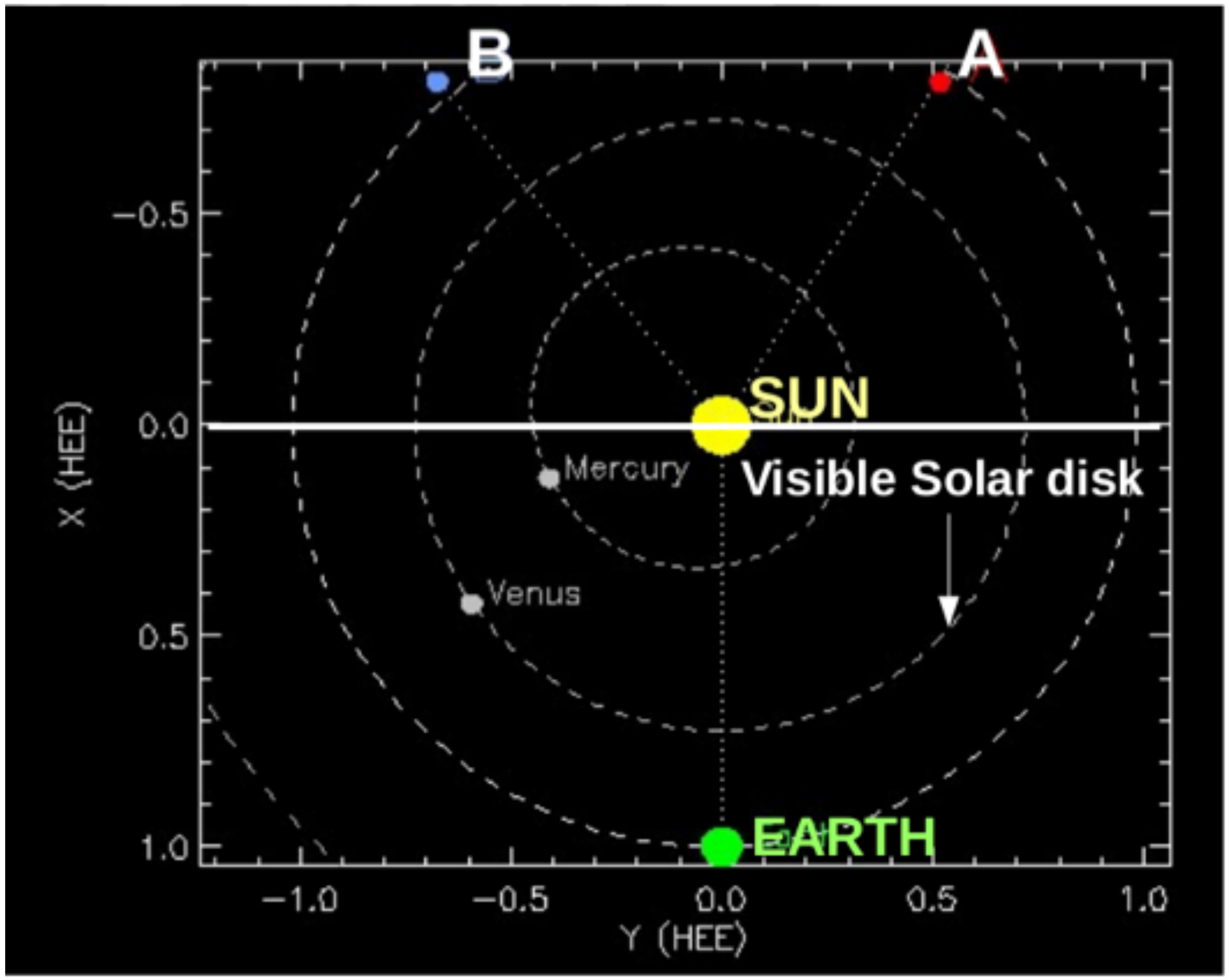


- **Events corrected for the “fish-eye-effect”**
- **95% CL error circle with systematic error added in quadrature**
- **Location of the gamma-ray emission consistent with the location of the Active Region 11429**
- **Time resolved localization shows consistency with the AR at earlier times, becoming less constrain at later times**

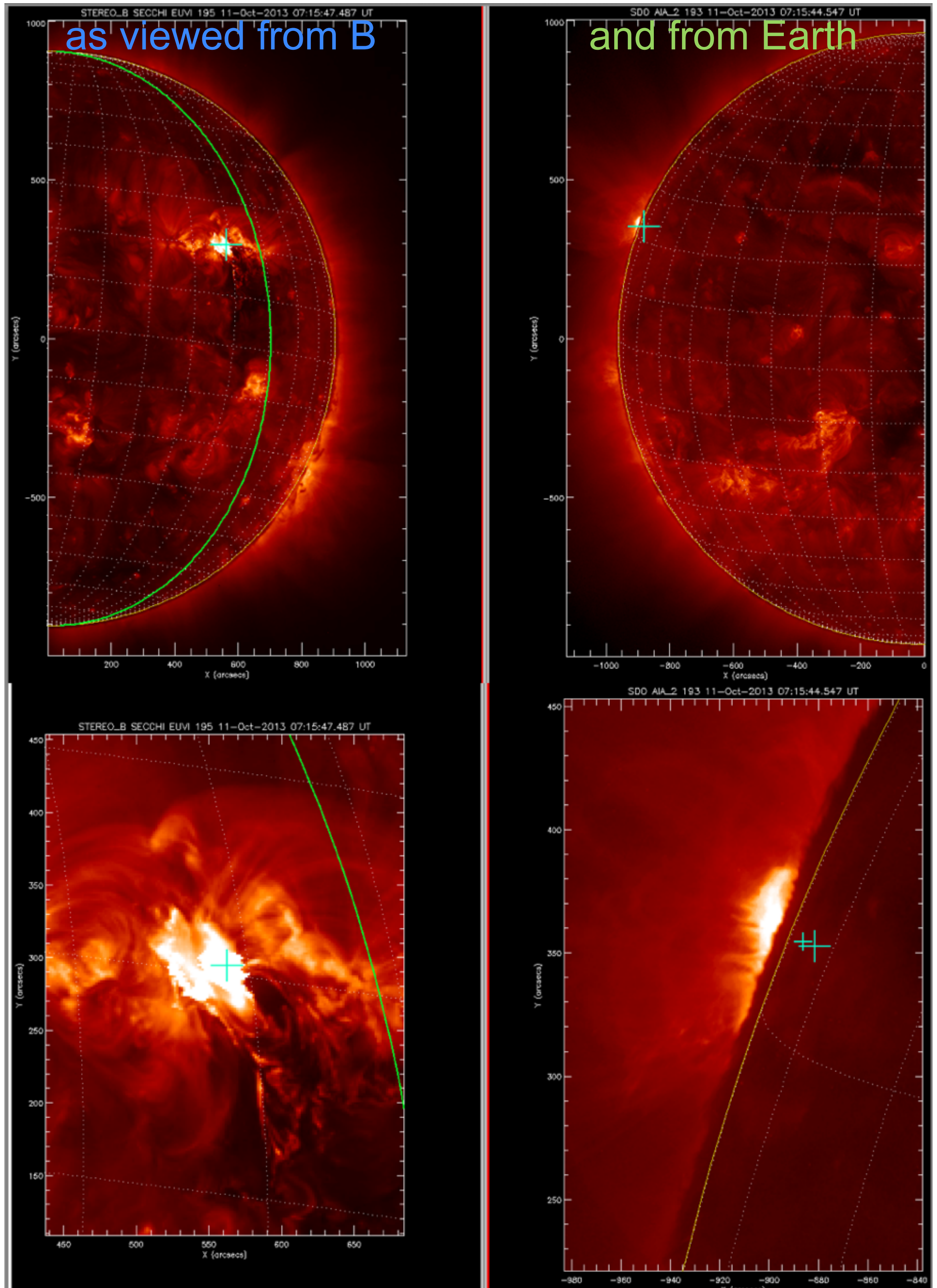
Behind-the-Limb flares



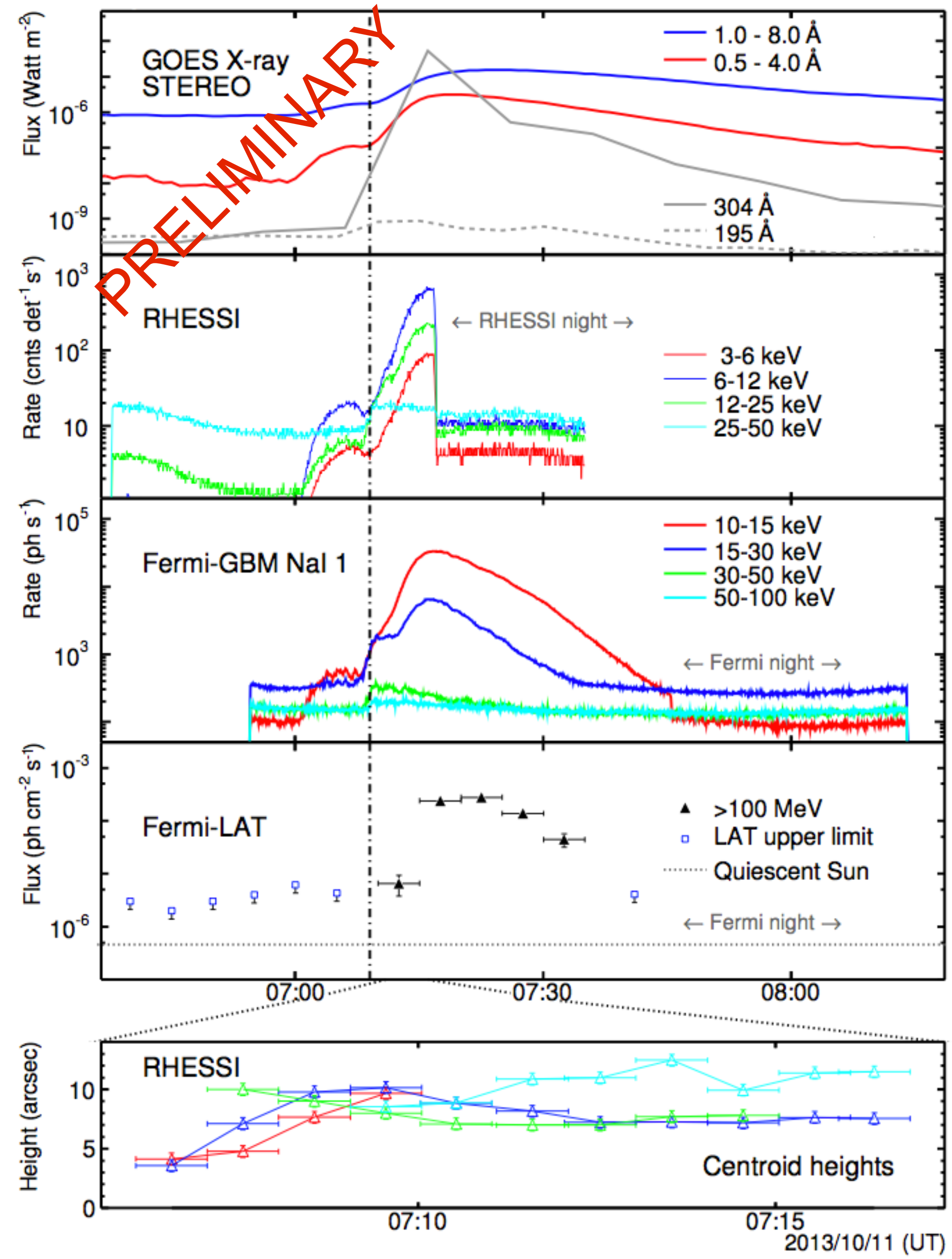
- **SOL131011: M1.5 GOES class flare erupted at 7:01:00 UT**
- **EUV and HXR data reveal that the active region is ~11˚ behind the visible Solar limb at the time of the flare;**
- ***Other behind the limb flares have been detected, stay tuned!***



Behind-the-Limb flares



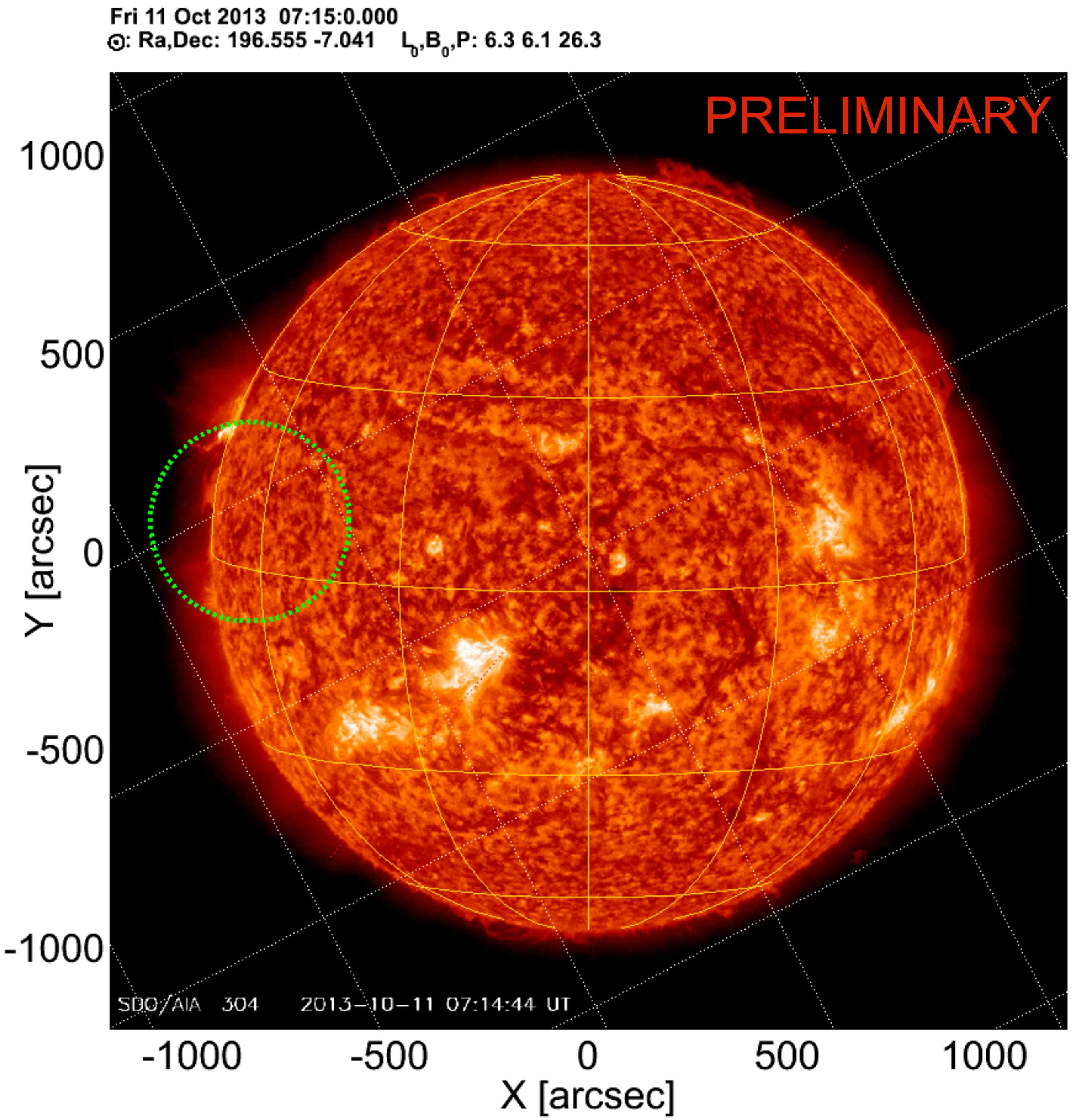
SOL131011

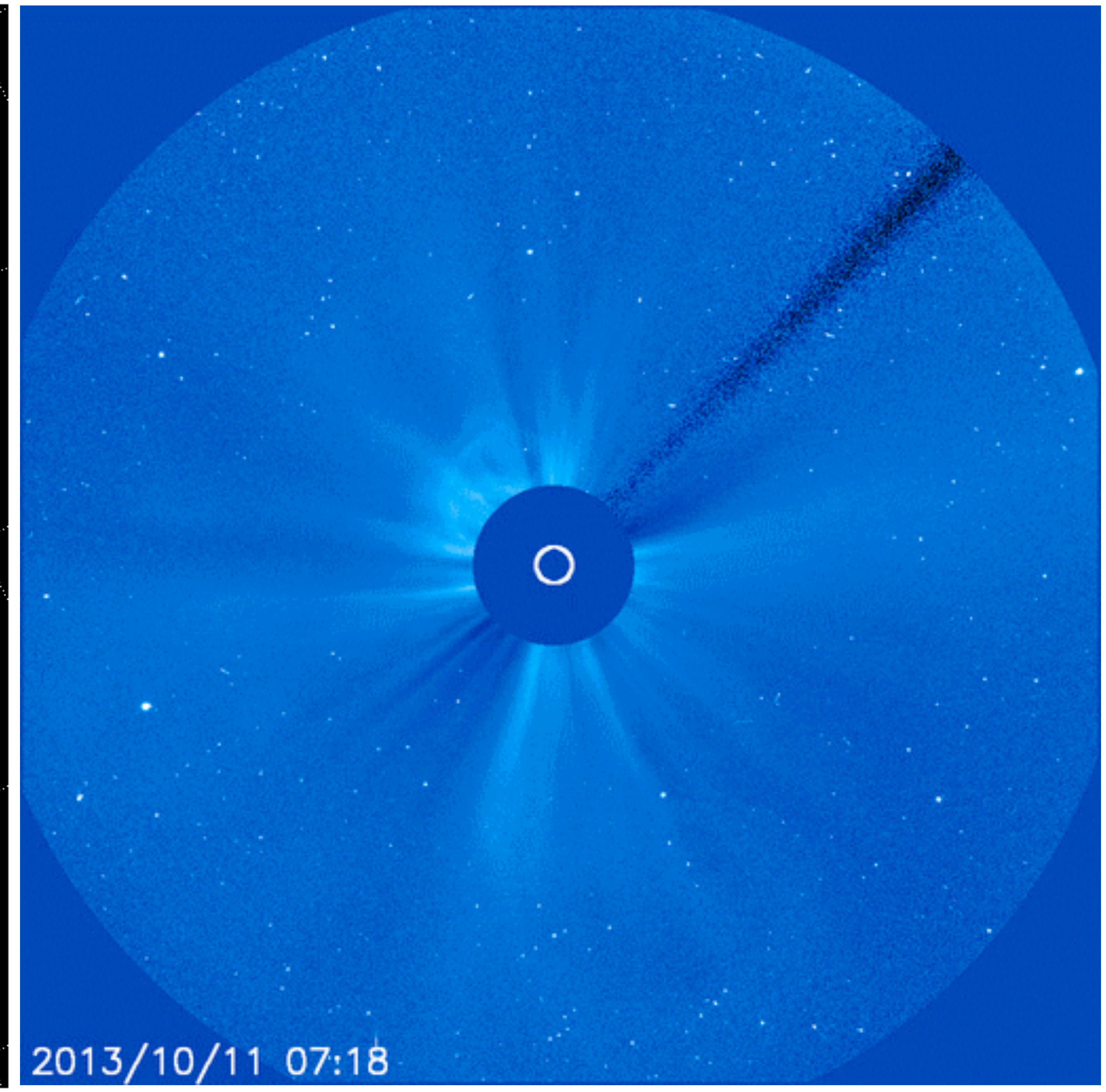


- **HXR *footpoints* were occulted during RHESSI coverage and part of LAT detection**

Nicola Omodei – Stanford/KIPAC

Where does the gamma-ray emission come from?

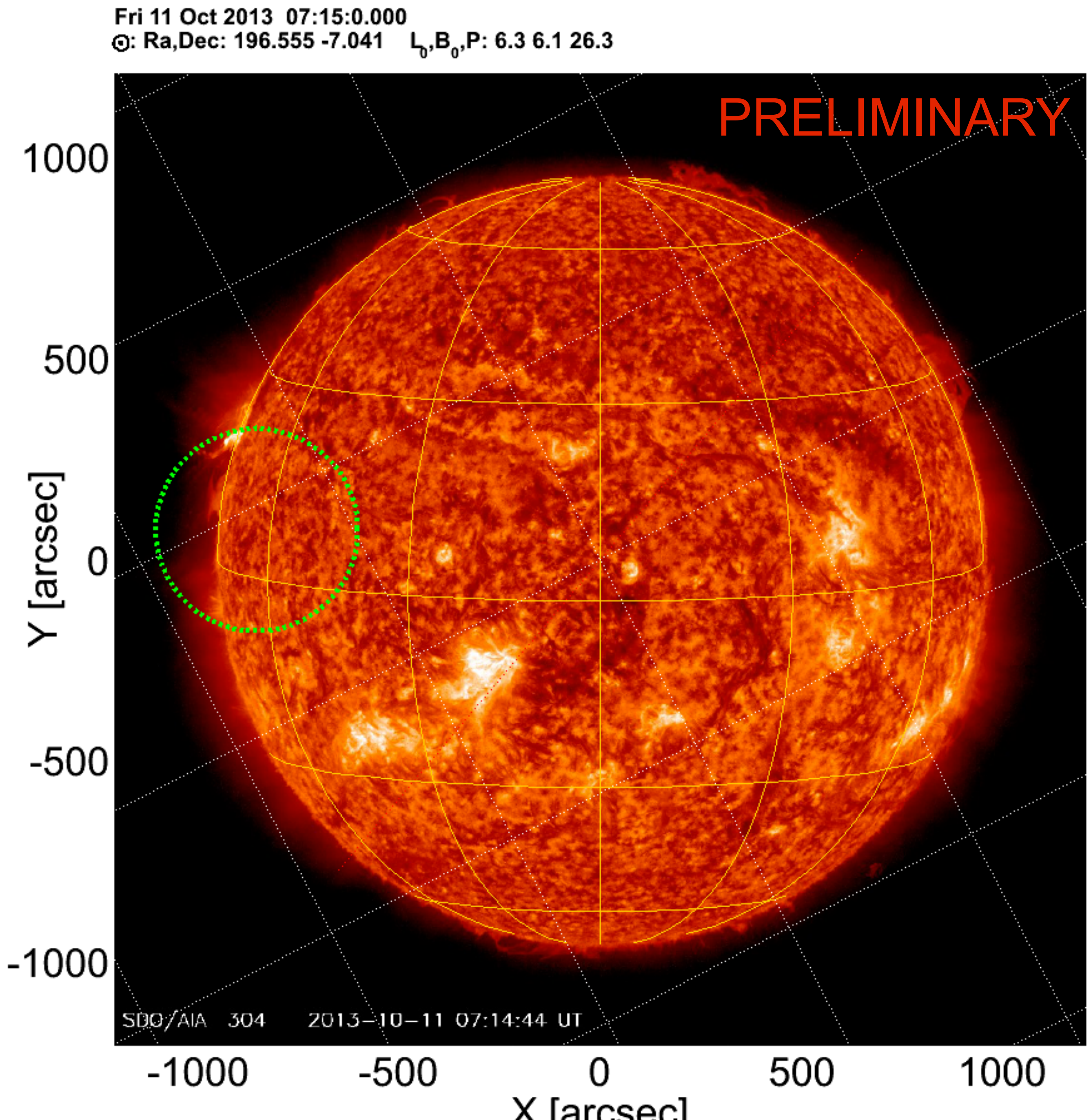


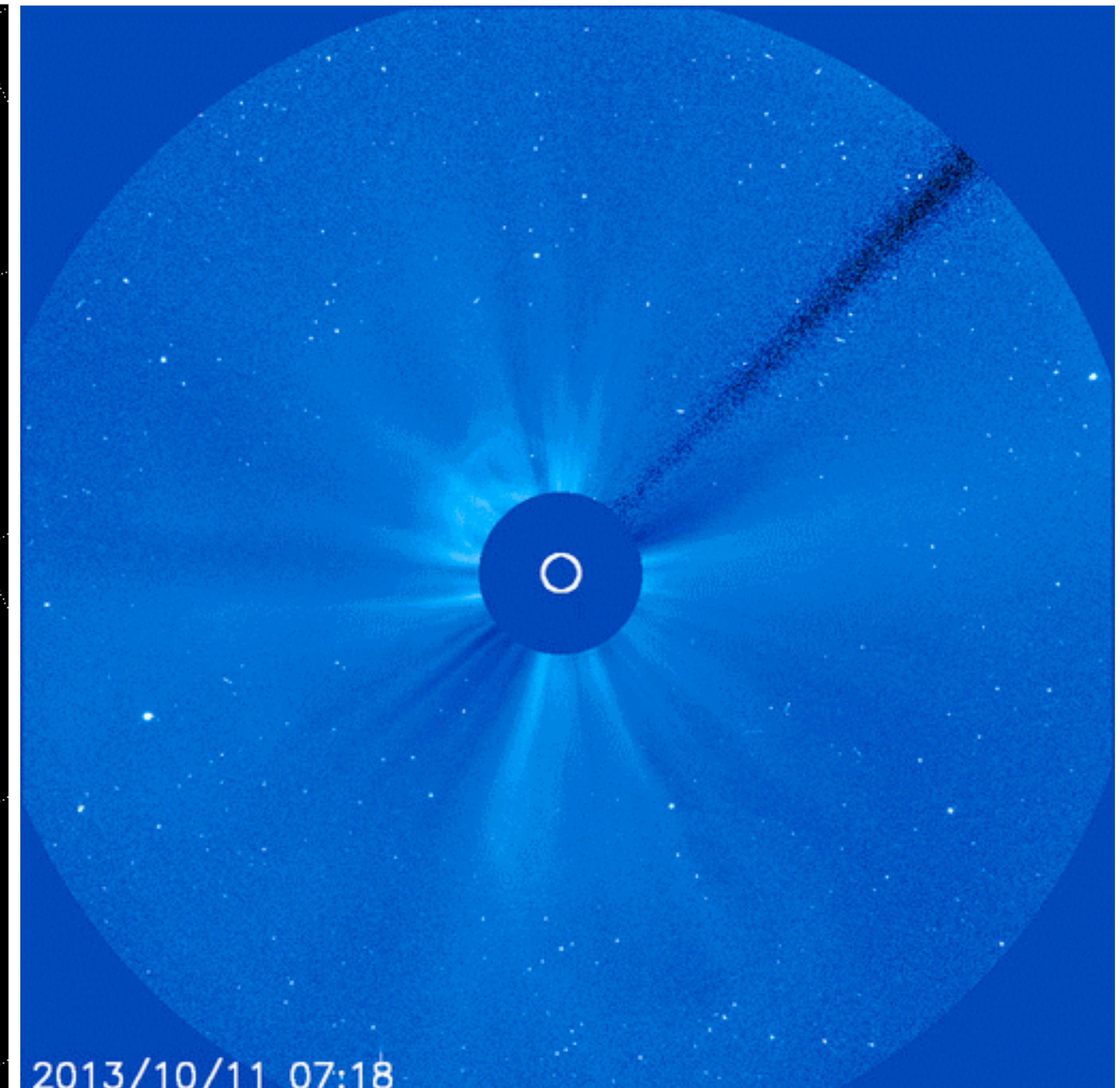


Footpoints not visible at the time of the gamma-ray detection

High density region required for gamma-ray production

Where does the gamma-ray emission come from?





Footpoints not visible at the time of the gamma-ray detection

High density region required for gamma-ray production

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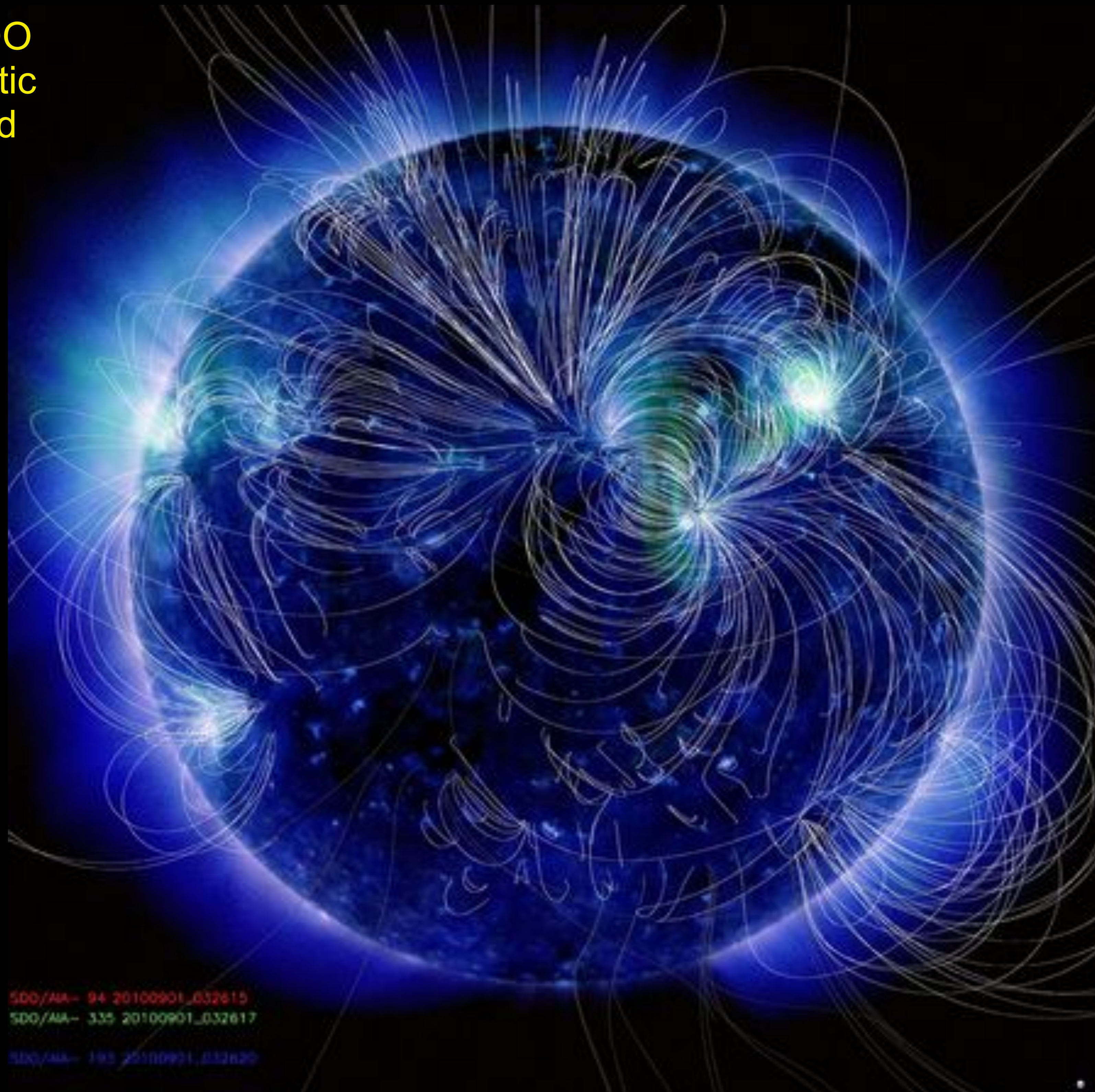
Solar Spaghetti

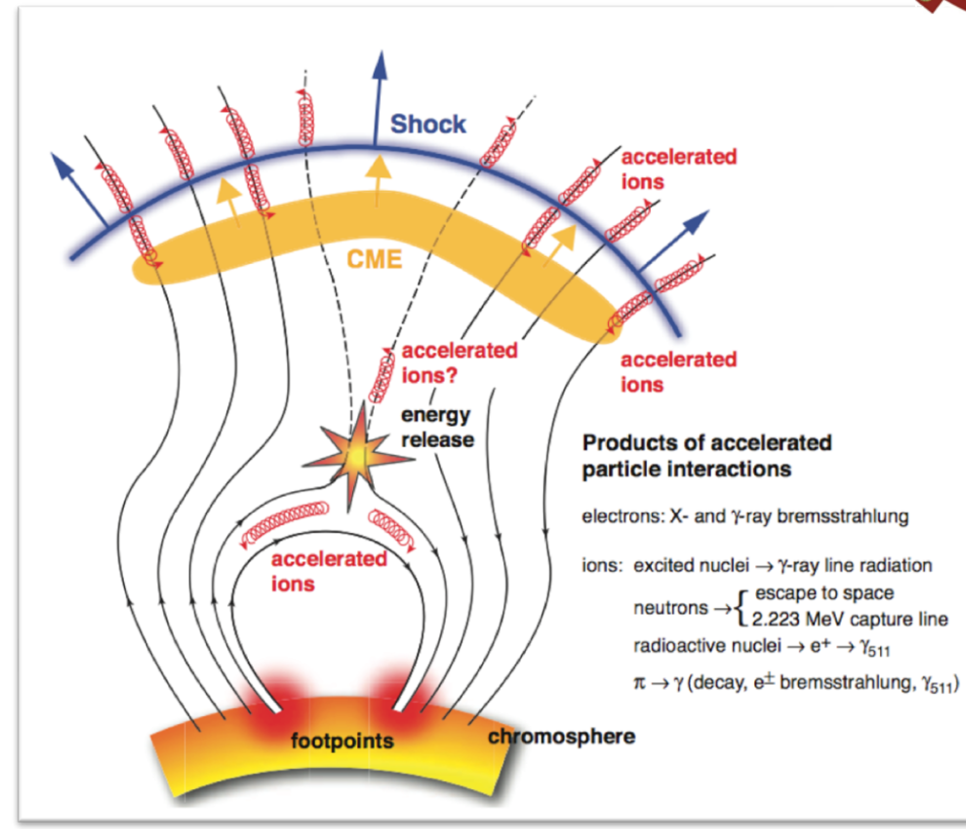
Composite AIA SDO image with magnetic field model overlaid

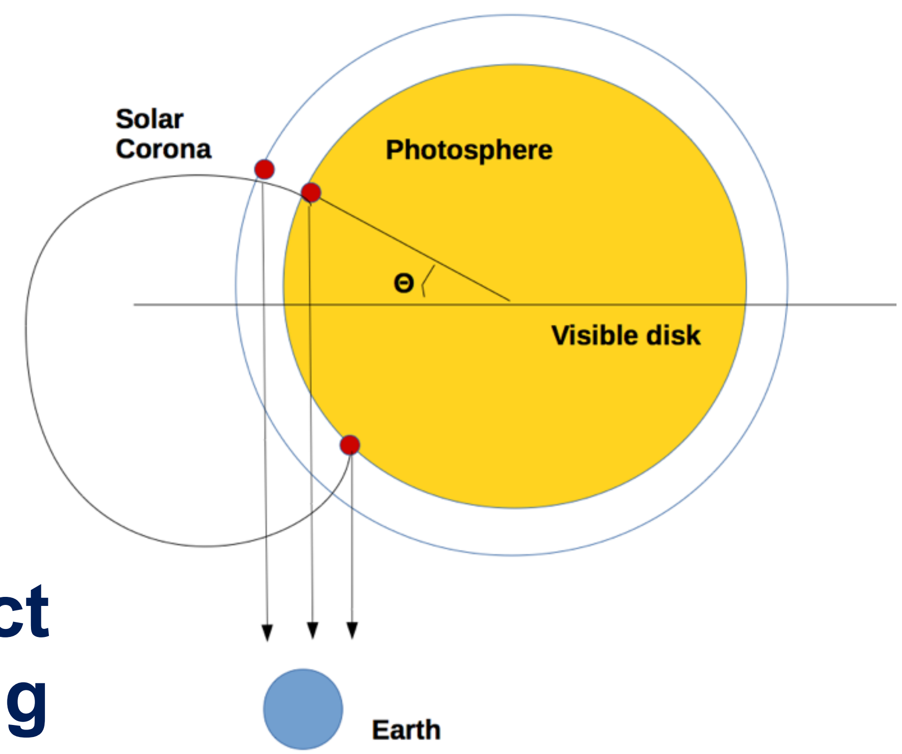


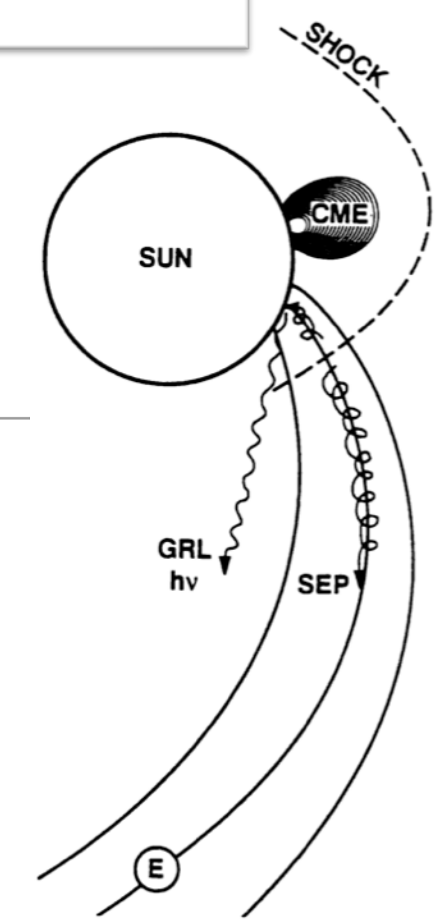
Magnetic field lines connect different regions across the solar surface

Understanding particle acceleration and gamma-ray emission at the Sun

- Particles accelerated during the <u>impulsive phase</u> interact with the solar surface (right below the photosphere) producing gamma-rays (pion production most likely)
- Part of the accelerated particles can escape and eventually can be re-accelerated by the CME shock (This also explains the correlation with SEP)
- <u>Continuously accelerated</u> particles can travel along magnetic field lines, and interact with the dense solar surface in front of the solar limb.
- Alternatively, CME re-accelerated particles can travel back to the Sun along magnetic field lines and interact with dense region, explaining the long lasting emission.







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