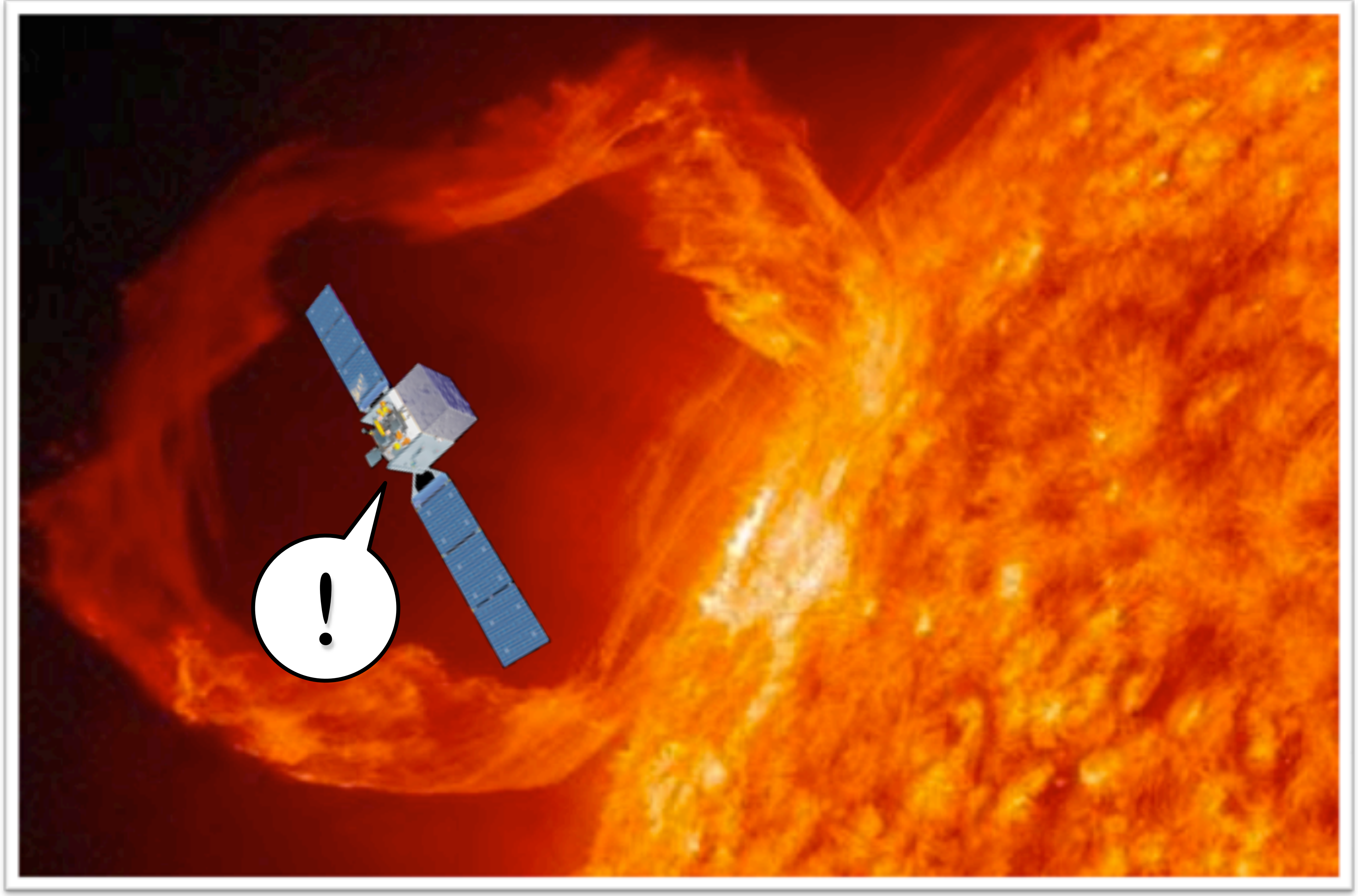
Fermi-LAT Observation of Impulsive Solar Flares



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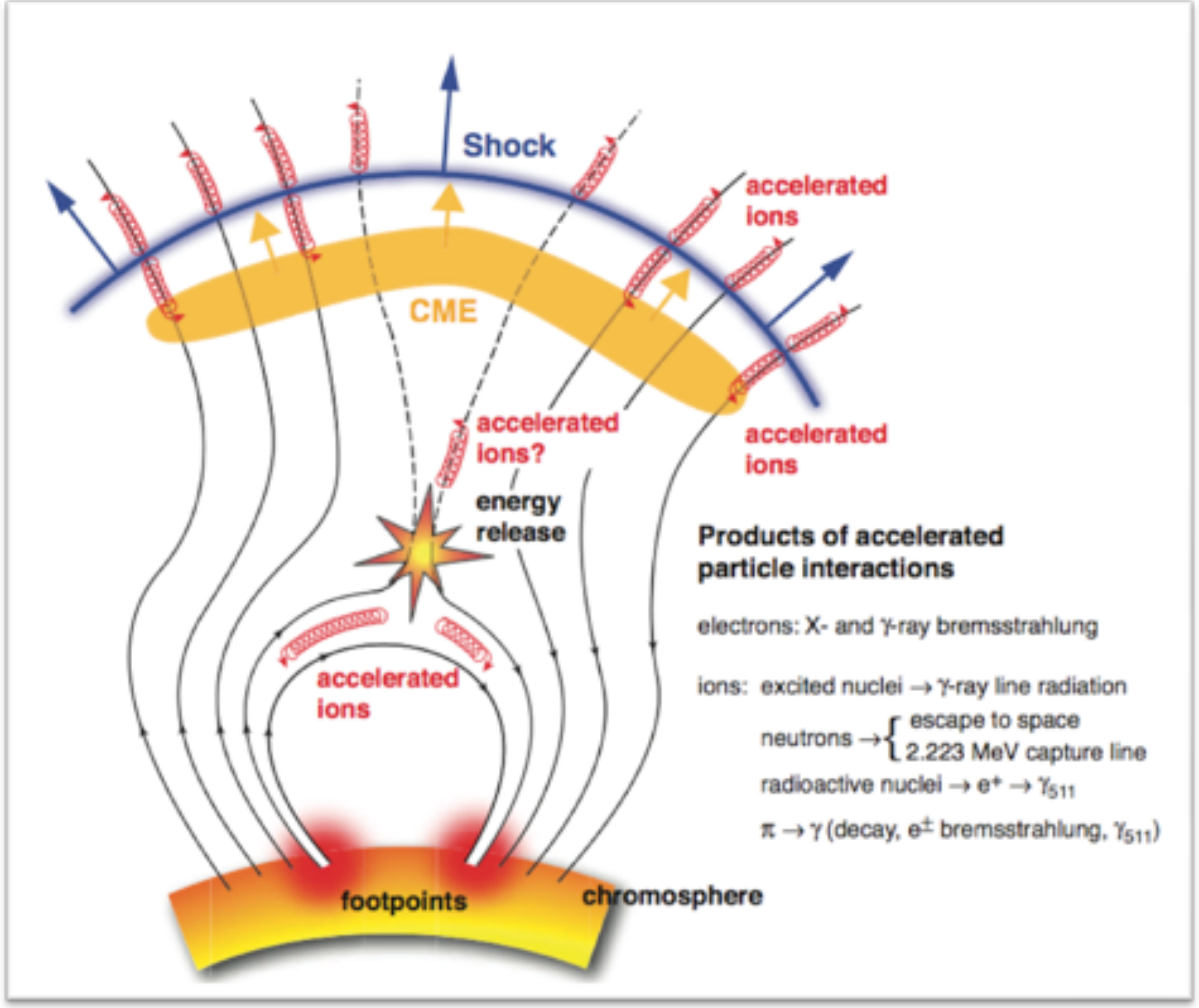
Gamma-ray emission from the Sun

- 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)
  - (Poster Orlando & Strong);
- High-energy emission (up to GeV) from solar flares has been observed by EGRET
  - (e.g. Kanbach+93, Ryan00)

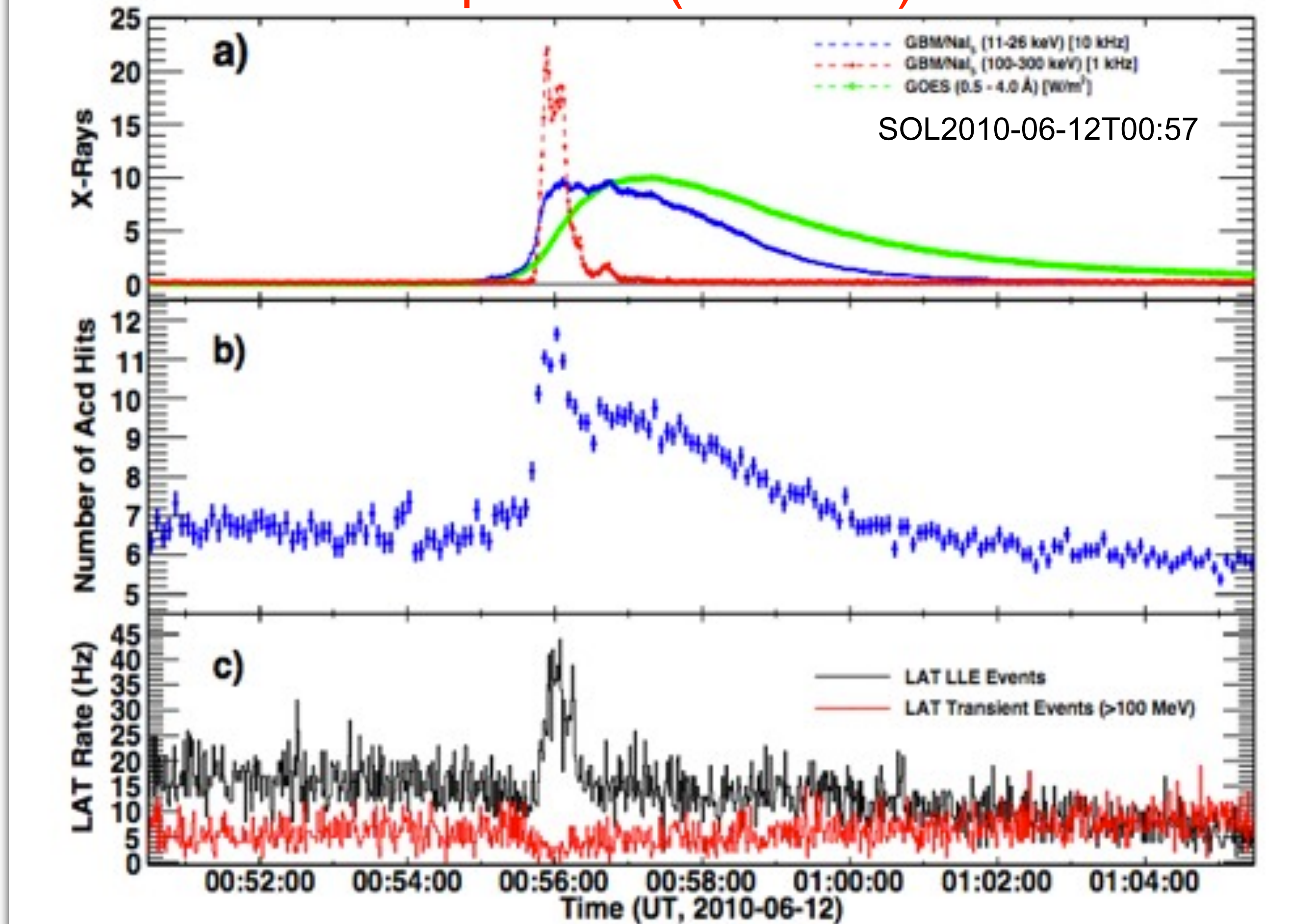


- **Acceleration at the flare site:**
  Energy release probably by magnetic field reconnection;
  Particles are trapped by magnetic field lines and interact with the solar atmosphere, **producing gamma-rays;**
  Some of the particles have access to an open field line and escape into interplanetary space;

- Acceleration **at the CME shock**:
  Solar Energetic Particles (SEP) measured at the Earth over longer time scales.

Impulsive vs Long Duration flares >100 MeV

Impulsive (minutes)

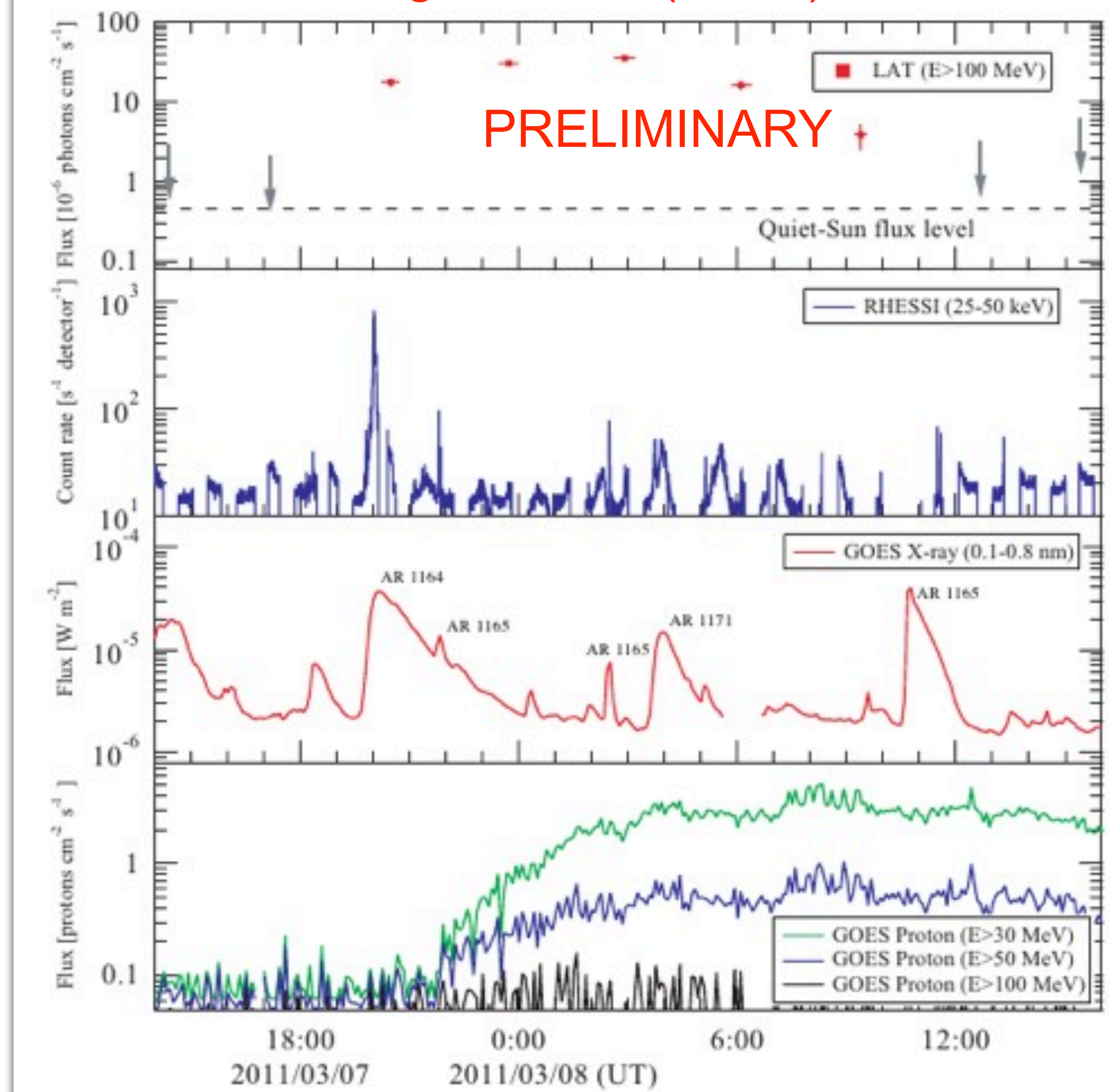


Ackermann et al. 2012, ApJ...745..144A

June 12, 2010: Gamma-Ray temporally associated with impulsive hard X-ray emission. Particles accelerated up to ~ 300 MeV in few seconds;
Hard X-ray pile up in ACD causes suppression of the standard LAT event rate (on-ground classification of gamma-rays)
Signal recovered in LAT Low Energy Events (looser selection cut)
<u>Sustained gamma-ray emission not observed</u>

6 Impulsive solar flares to date

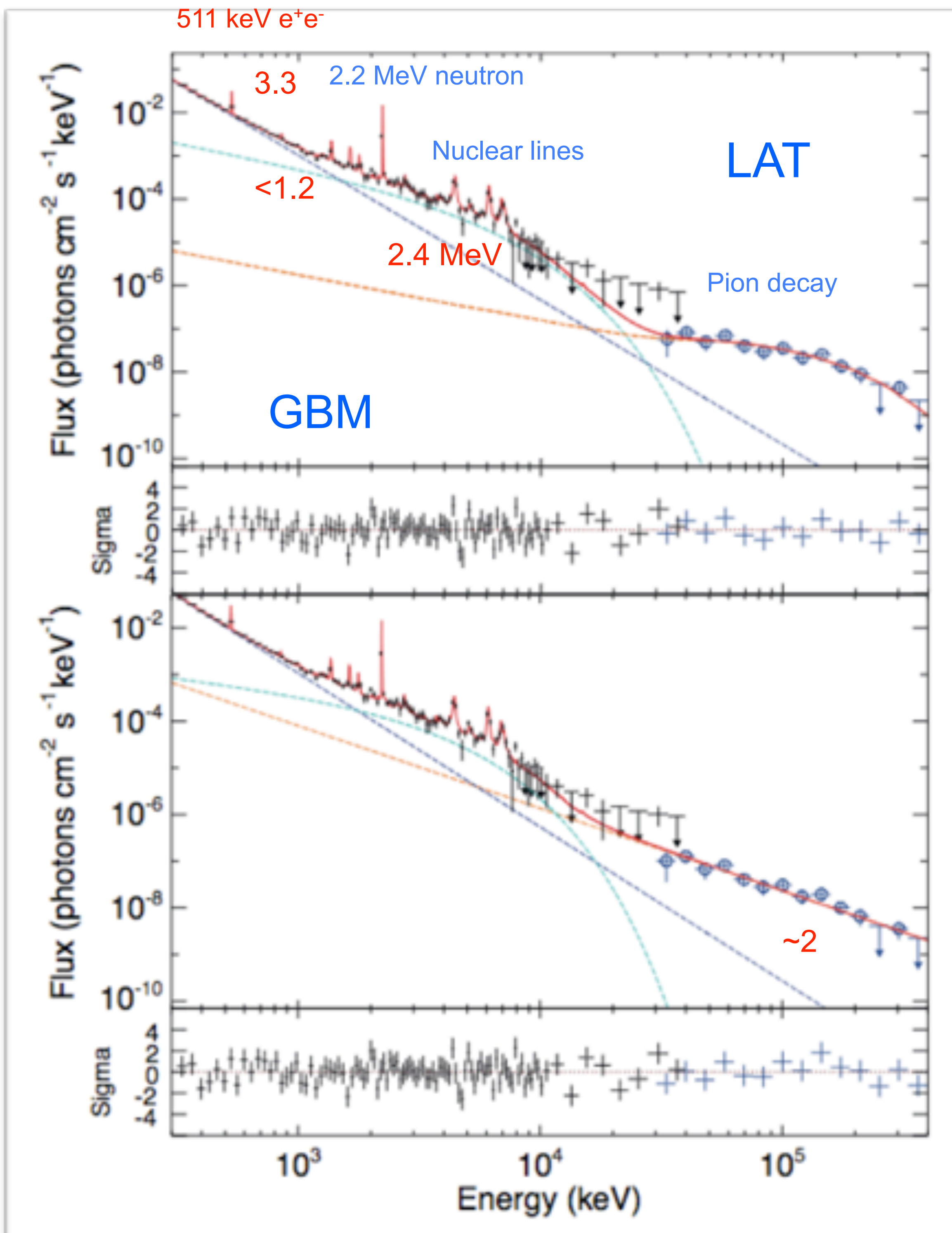
Long Duration (hours)



March7/8 2011: Sustained emission associated to one impulsive episode in X-rays;
Accompanied by modest SEP, but very fast (~2000 km/s) CME;
Continuous interaction of particles with the Sun for hours after the impulsive flare;

~13 long lasting emission (high significance)

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

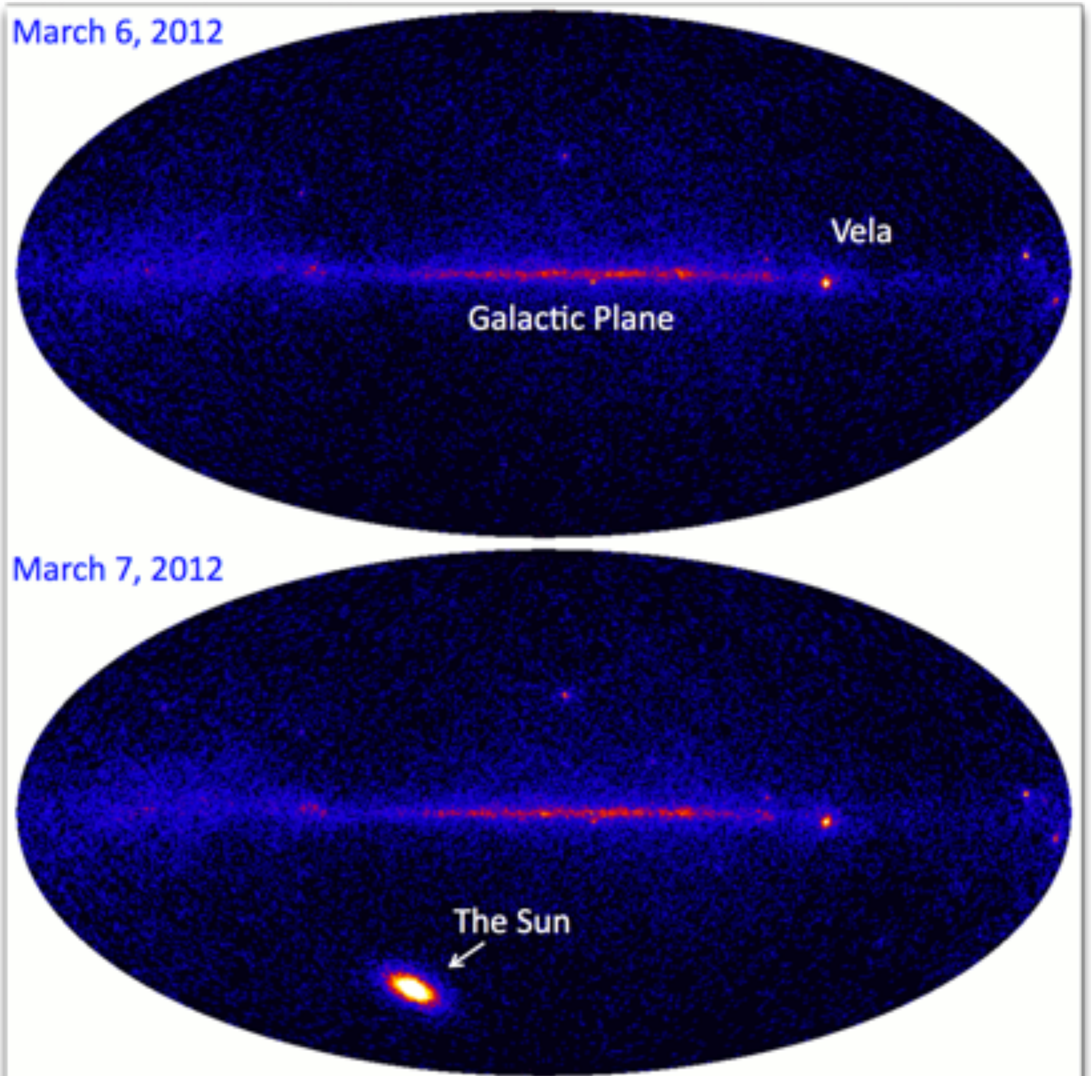


Ackermann et al. 2012, ApJ...745..144A

- **Joint GBM and LAT analysis provides useful information about the underlying accelerated particle distributions:**
  - **Electron Bremsstrahlung dominates at < 1 MeV energies**
    Not a simple power law: 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 for the accelerated ion spectrum**

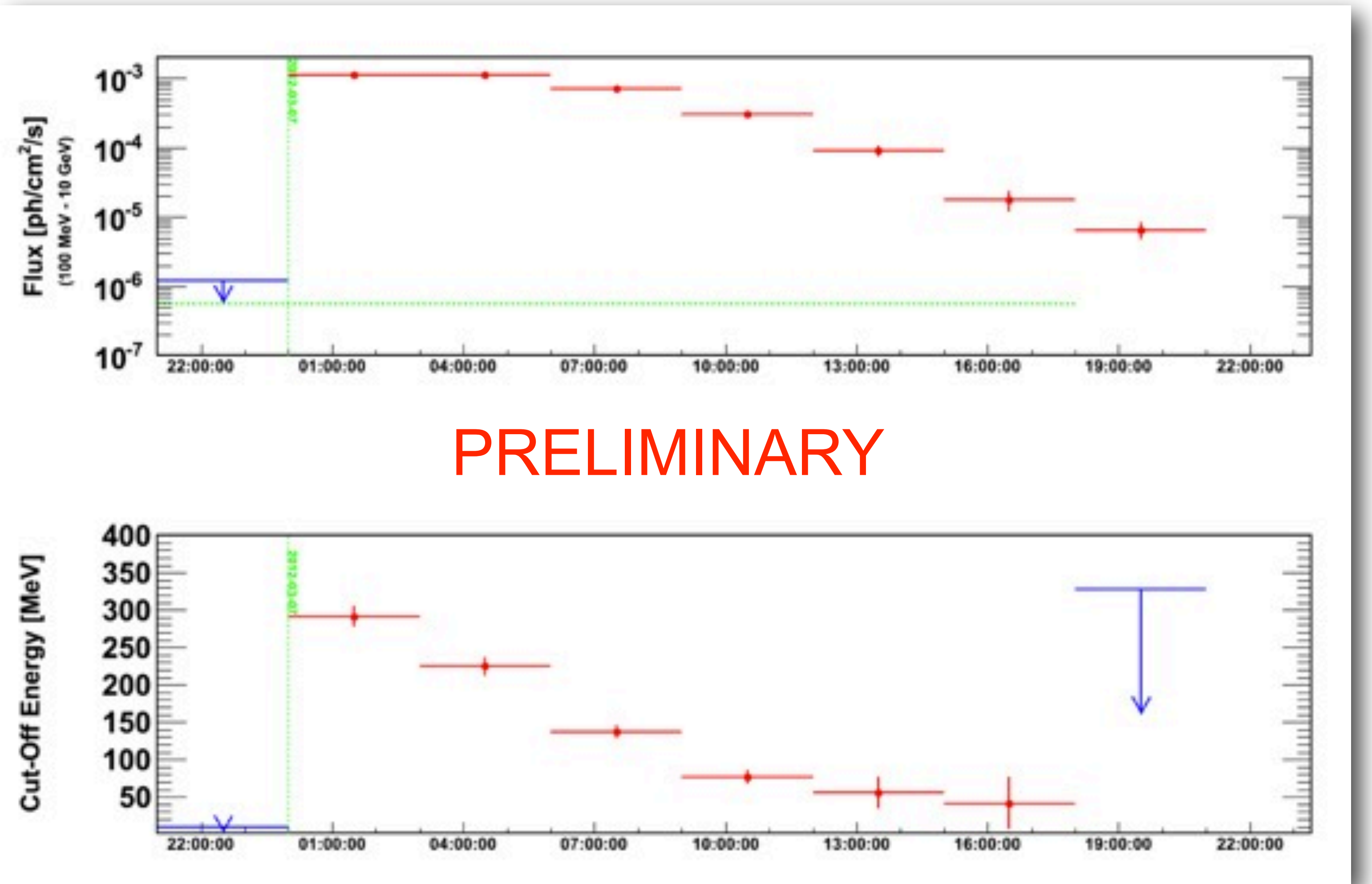
Component	Energy of gamma-ray	Energy of the ions	Derived accelerated ion spectral index
Neutron Capture	2.2 MeV	10-50 MeV	~3.2 (10-50 MeV)
Nuclear lines	5-20 MeV	50-20 MeV	~4.3 (50 -300 MeV)
Pions	>300 MeV	>280 MeV	~4.5 (>300 MeV)

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



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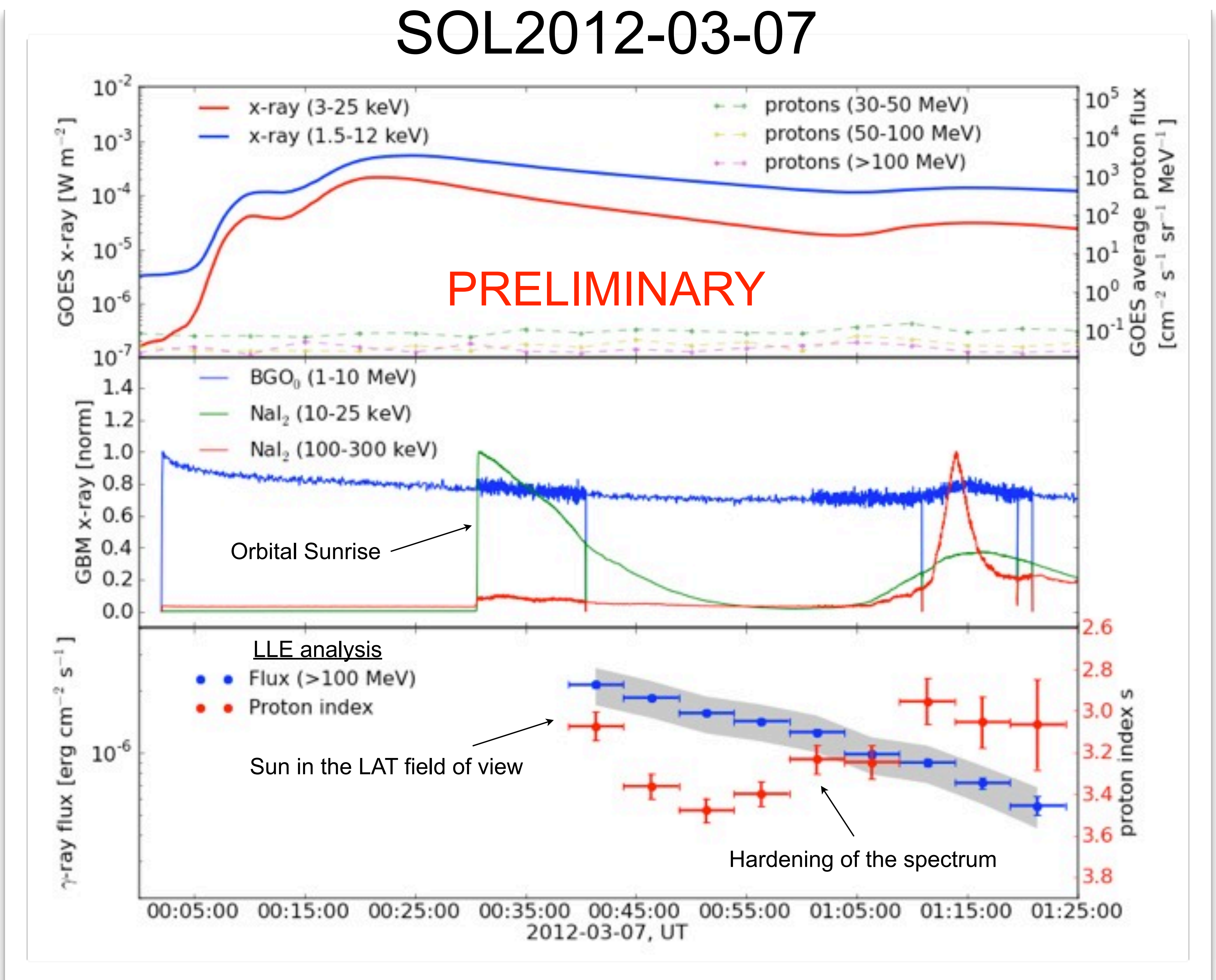
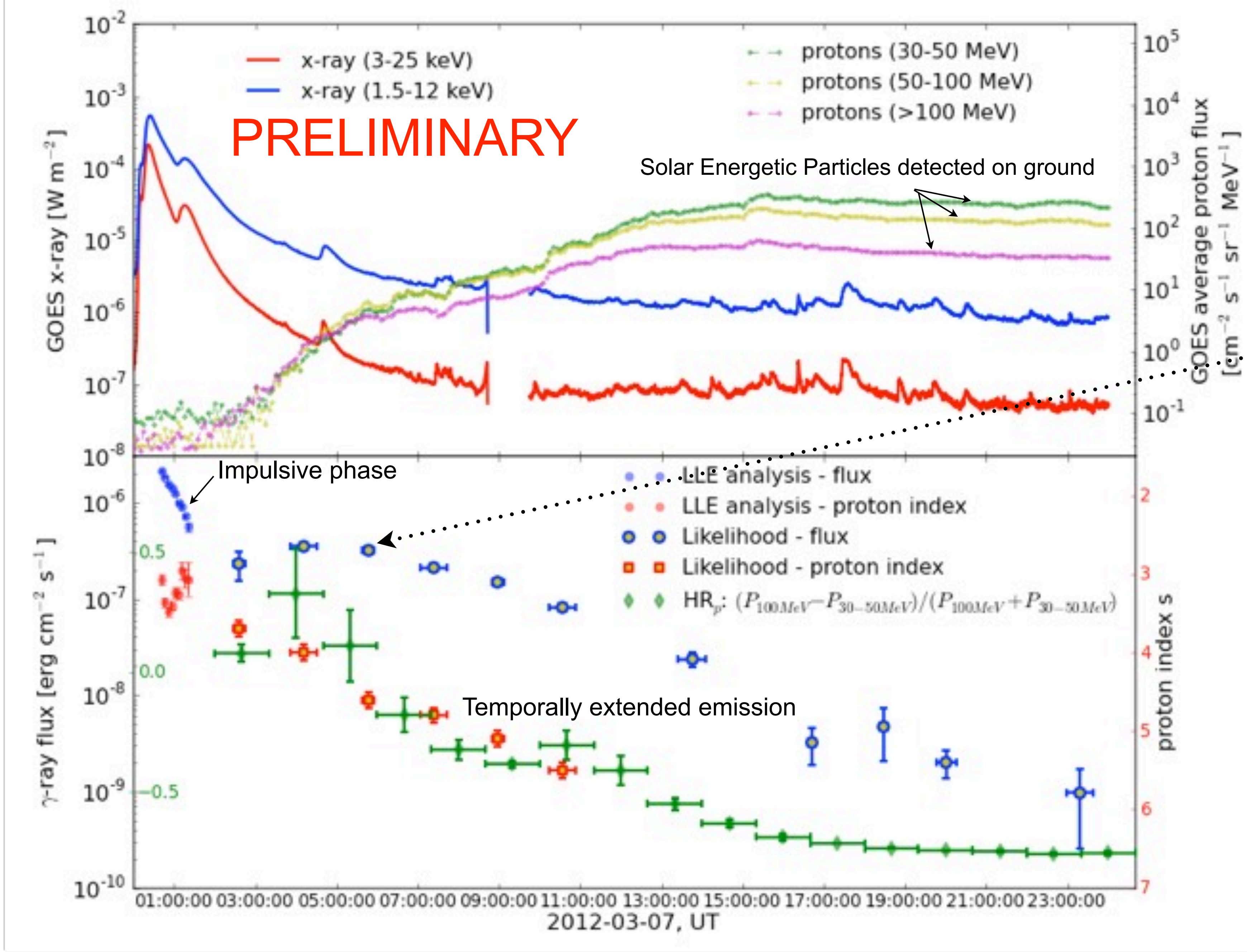
The “impulsive” phase: the first orbit

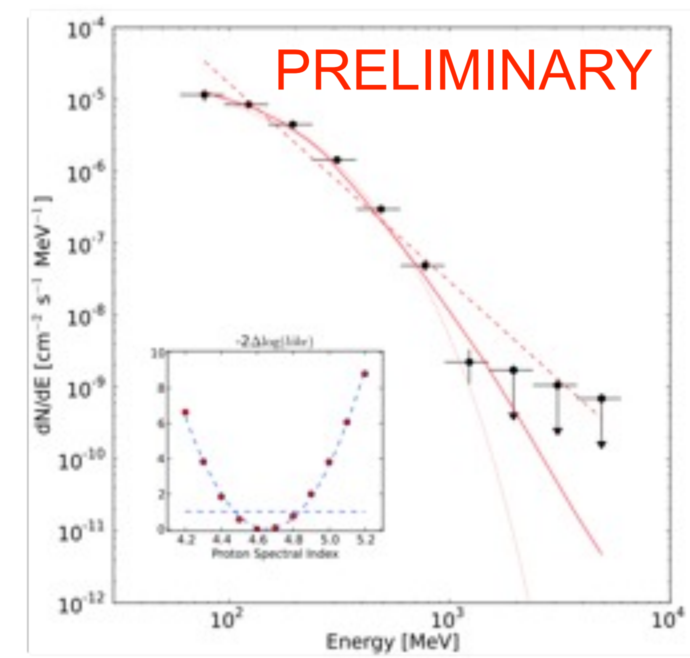


Particle trapping time ~ Energy of the protons

Long Lasting emission

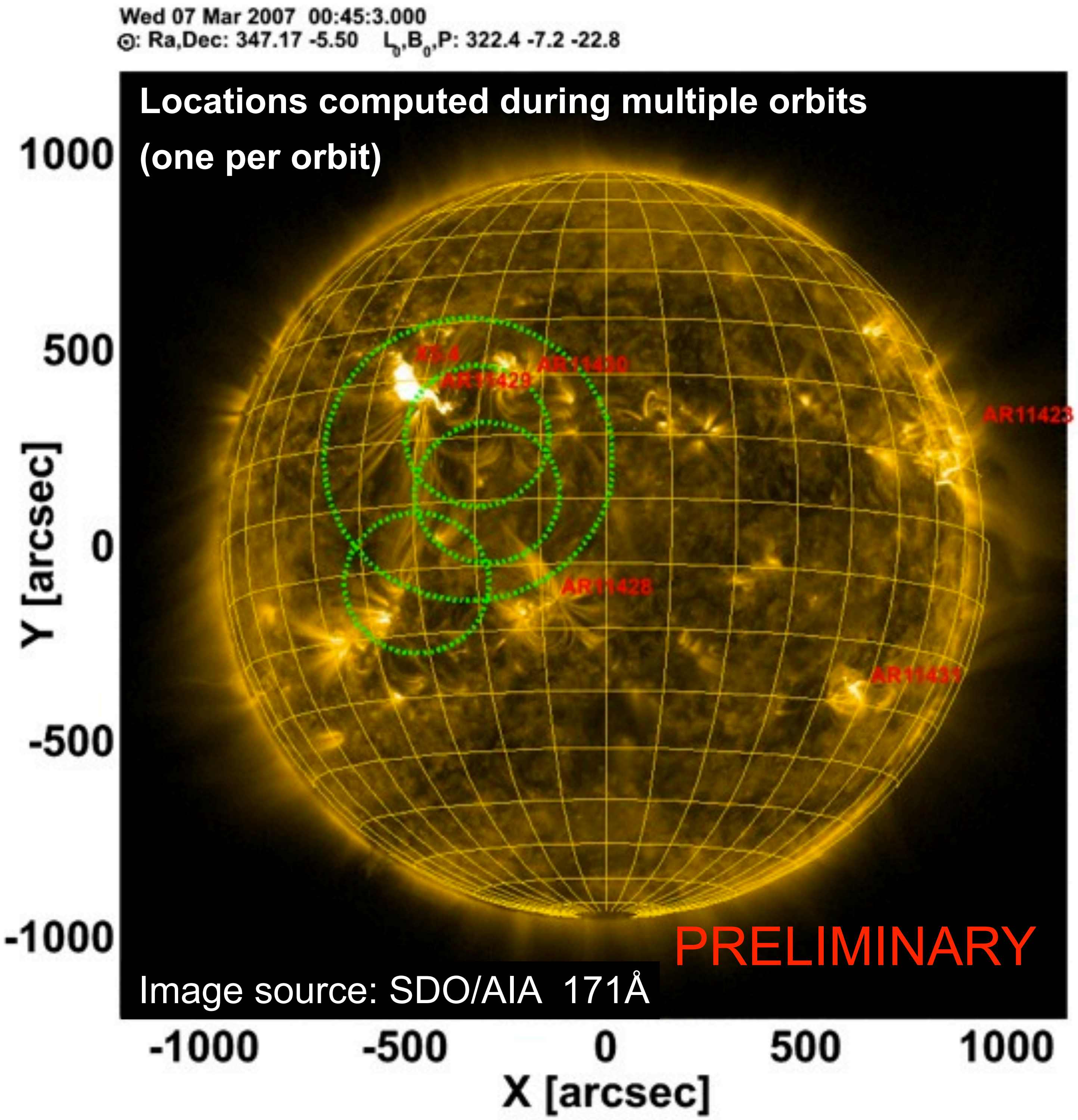
SOL2012-03-07





- **Impulsive & Time extended emission spectra compatible with pion decay spectrum=> information on the underlying accelerated proton distribution**
- **Softening of the gamma-ray spectrum on long time scales, correlated at later time with the softening of the proton spectrum**

Localization

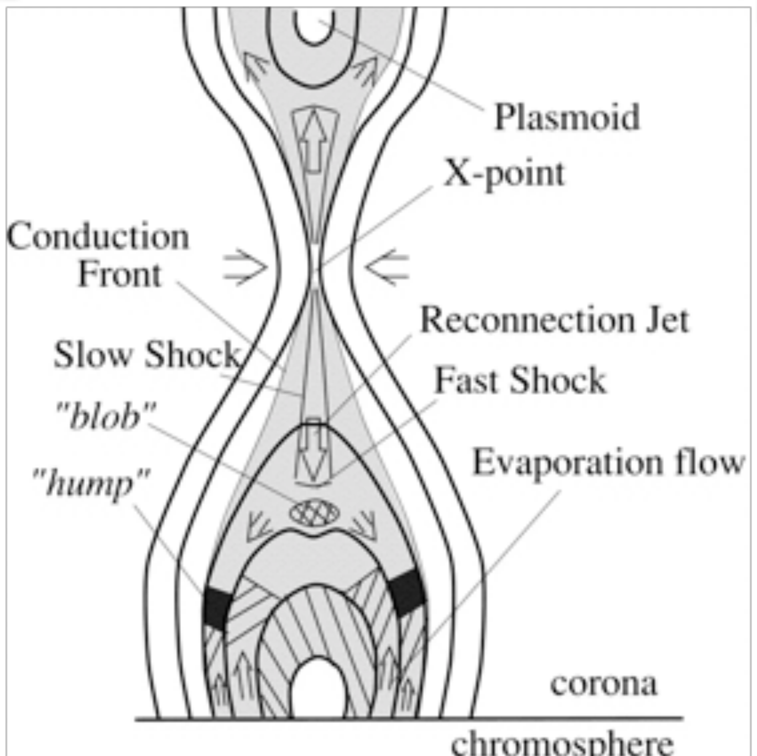


- **Events corrected for the "fish-eye-effect"**
  - **(Ackermann et al. 2012, ApJS)**
- **68% CL error circle with systematic error added in quadrature**
- **Location of the gamma-ray emission ~ consistent with the location of the Active Region 11429**

The big picture

Trap and precipitation of HE particles produced during the impulsive phase via magnetic reconnection

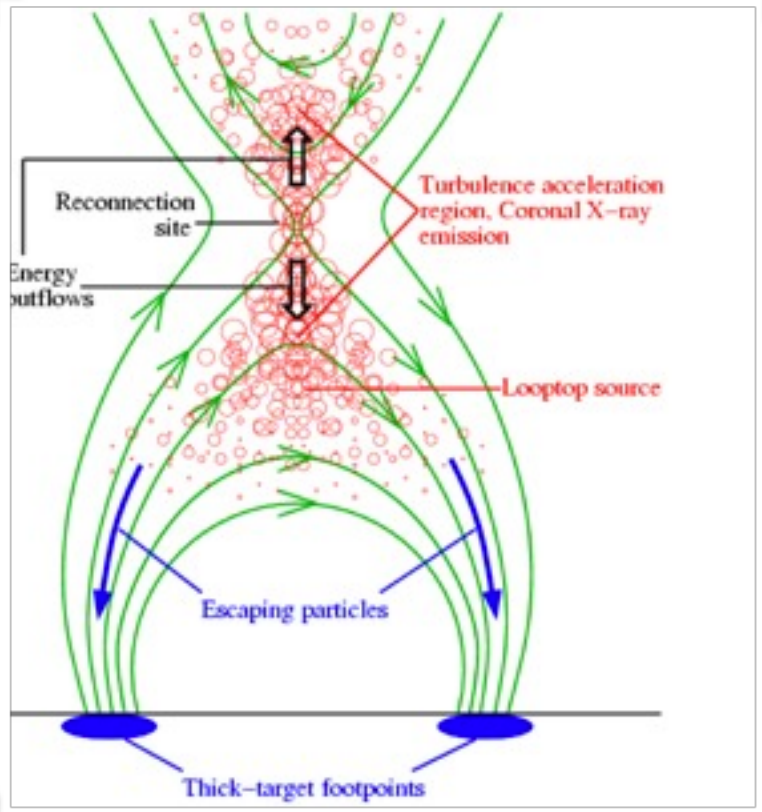
(e.g., Kanbach et al. 1993)



Yokoyama & Shibata 2001

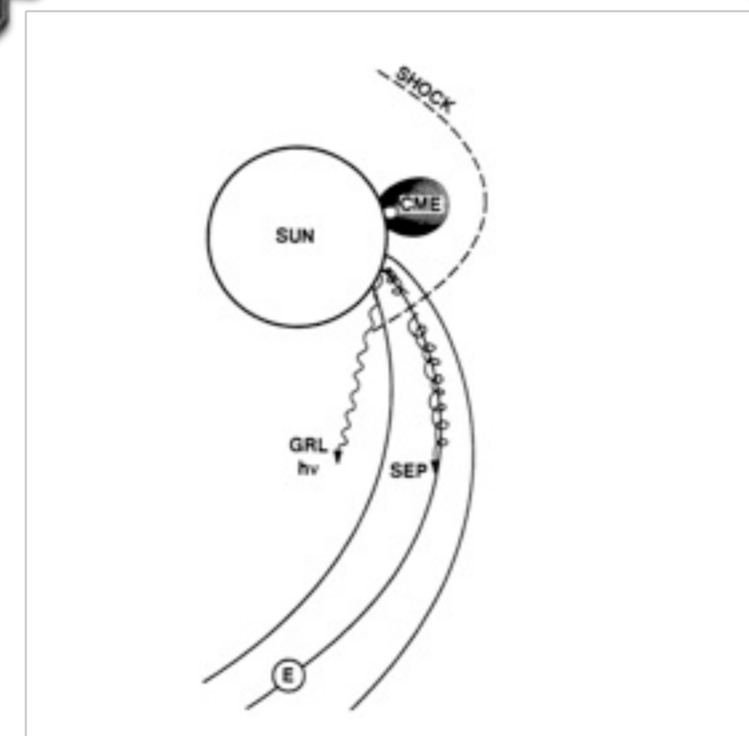
Continuous acceleration at the Sun can be explained by stochastic acceleration mechanism

(e.g. Petrosian and Liu 2004)



Return of protons accelerated by CME-driven shock (1st order Fermi)

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



Cliver+1993

The observed duration of ~20 hours requires very low coronal density
In coulomb collision, the trap efficiency increases with energy => gradual hardening of the spectrum;

Might be ok for the impulsive phase (~3 hours)

Stochastic acceleration provides the correct scenario for SHORT acceleration time scales, but LONG trapping of particles
However we expect accelerated electrons as well !
Might be ok for the impulsive phase (~3 hours)

CME acceleration can easily accelerate 10 GeV protons within few seconds,
Gamma-ray emission cannot occur at the acceleration site (density is too low)
Protons must travel back to the Sun along the current sheath (~100 solar radii)
Could explain the long lasting emission

Summary

- Fermi LAT has detected >100 MeV gamma-rays from solar flares, including the most energetic gamma-rays and the longest-duration emission;
  - Long Lasting emission flare and Impulsive flare events detected;
  - Joint LAT-GBM observations unveil the properties of the accelerated particles, such as spectrum and time scales of the accelerated particles;
  - Thanks to the LAT's improved angular resolution, we can now localize time-extended gamma-ray emission to the site of the X-ray flare for the first time;
  - As the solar cycle progresses toward the maximum of Cycle 24 (mid-2013), the number of extreme energetic flares will increase;