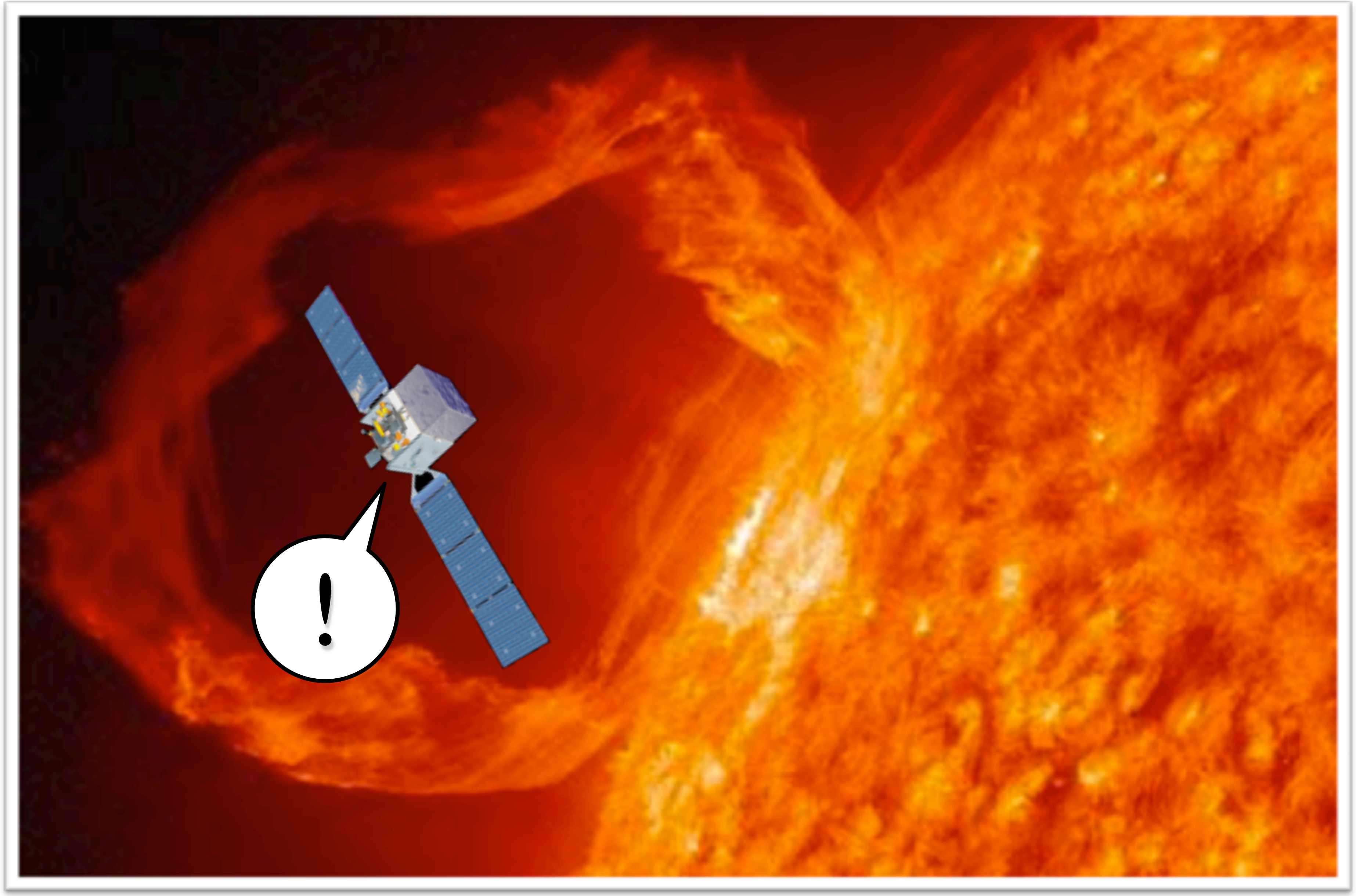
Fermi-LAT Observation of Impulsive Solar Flares



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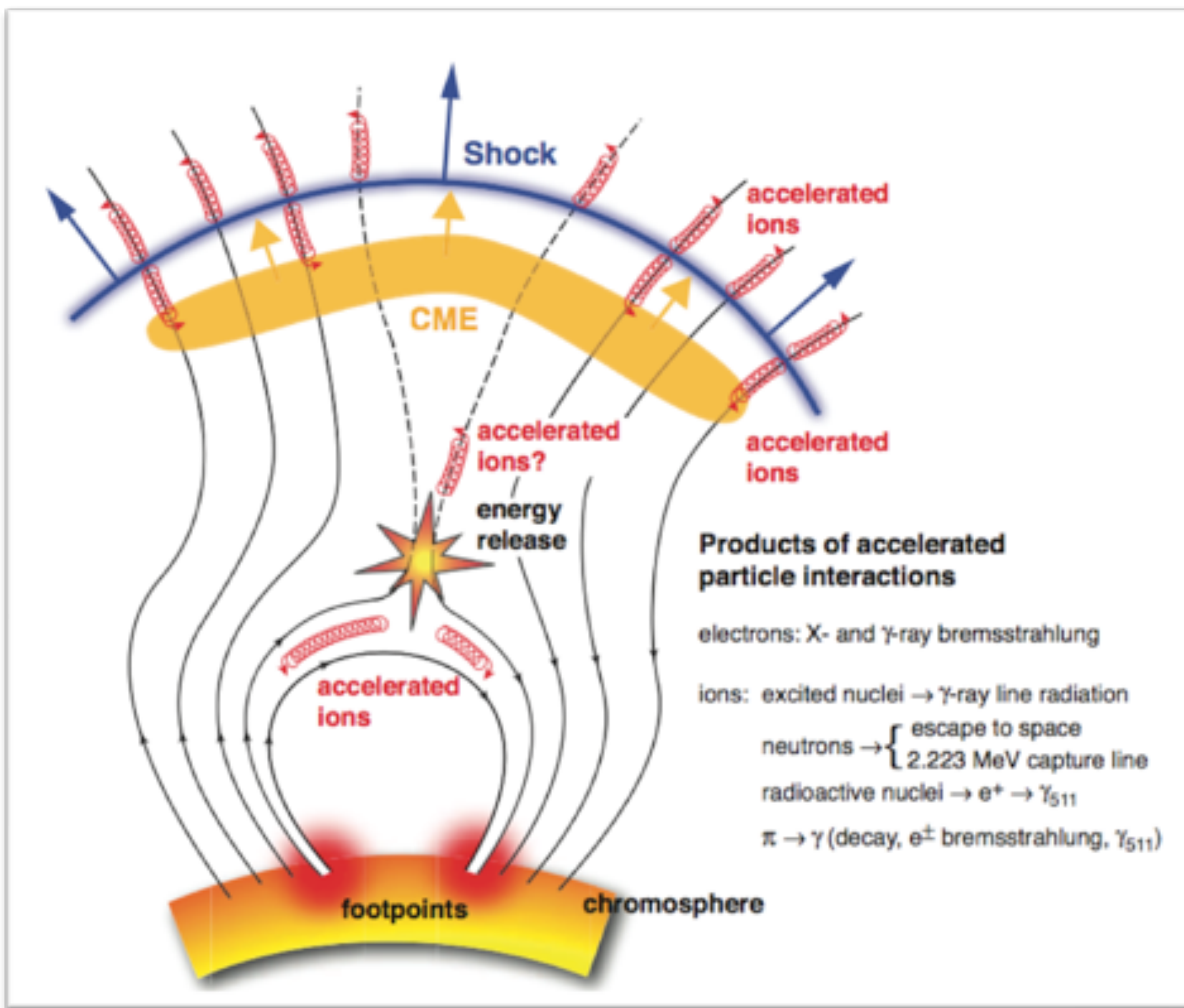
for the

Fermi LAT Collaboration

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)

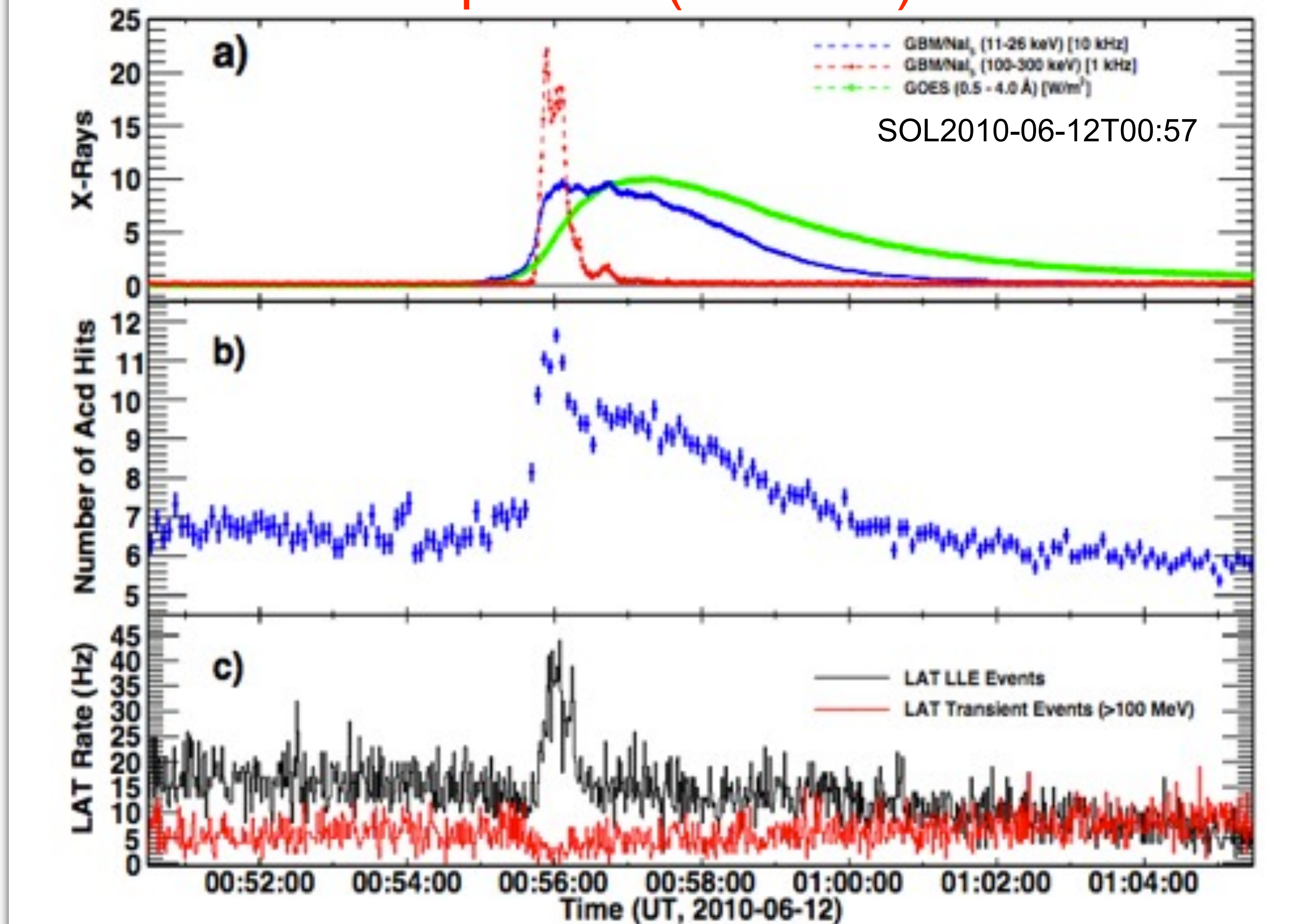


- **Acceleration at the flare site:**
  Energy release probably by magnetic field reconnection;
  Particles are trapped by magnetic field lines and interact with the solar atmosphere, **producing gamma-rays;**
  Some of the particles have access to an open field line and escape into interplanetary space;

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

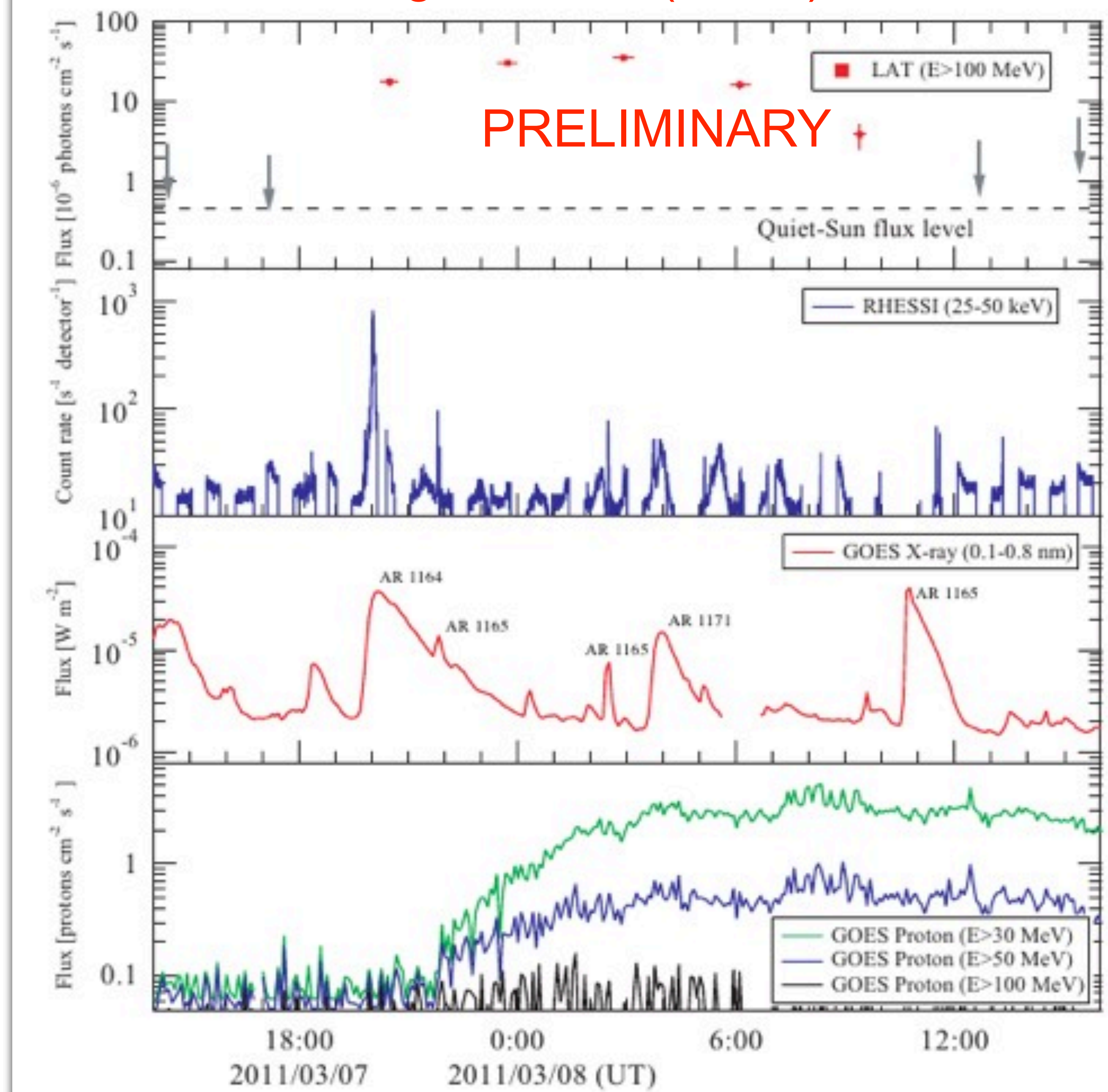
Impulsive vs Long Duration flares >100 MeV

Impulsive (minutes)



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

Long Duration (hours)



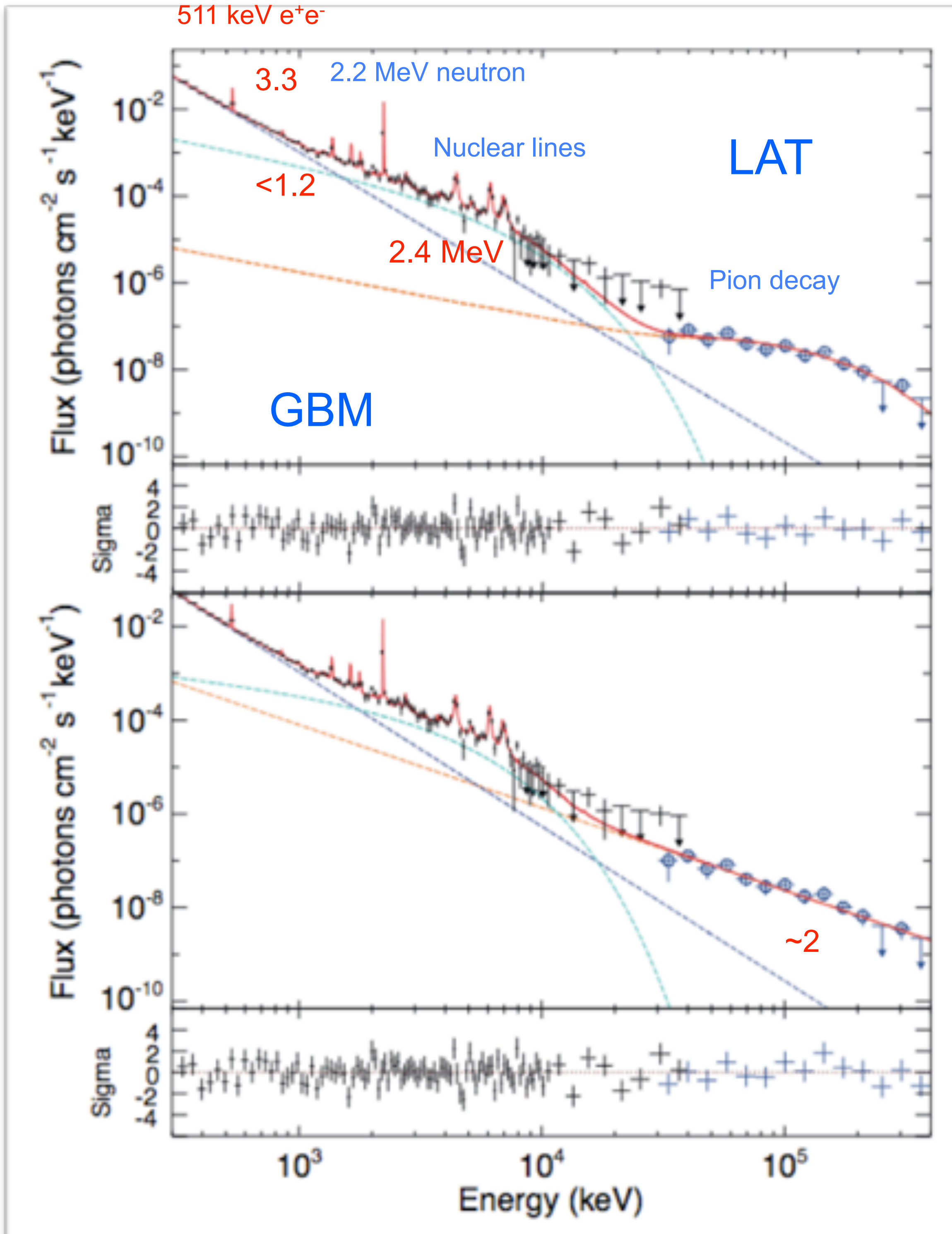
June 12, 2010: Gamma-Ray temporally associated with impulsive hard X-ray emission. Particles accelerated up to ~ 300 MeV in few seconds;
Hard X-ray pile up in ACD causes suppression of the standard LAT event rate (on-ground classification of gamma-rays)
Signal recovered in LAT Low Energy Events (looser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

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;

6 Impulsive solar flares to date

~13 long lasting emission (high significance)

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



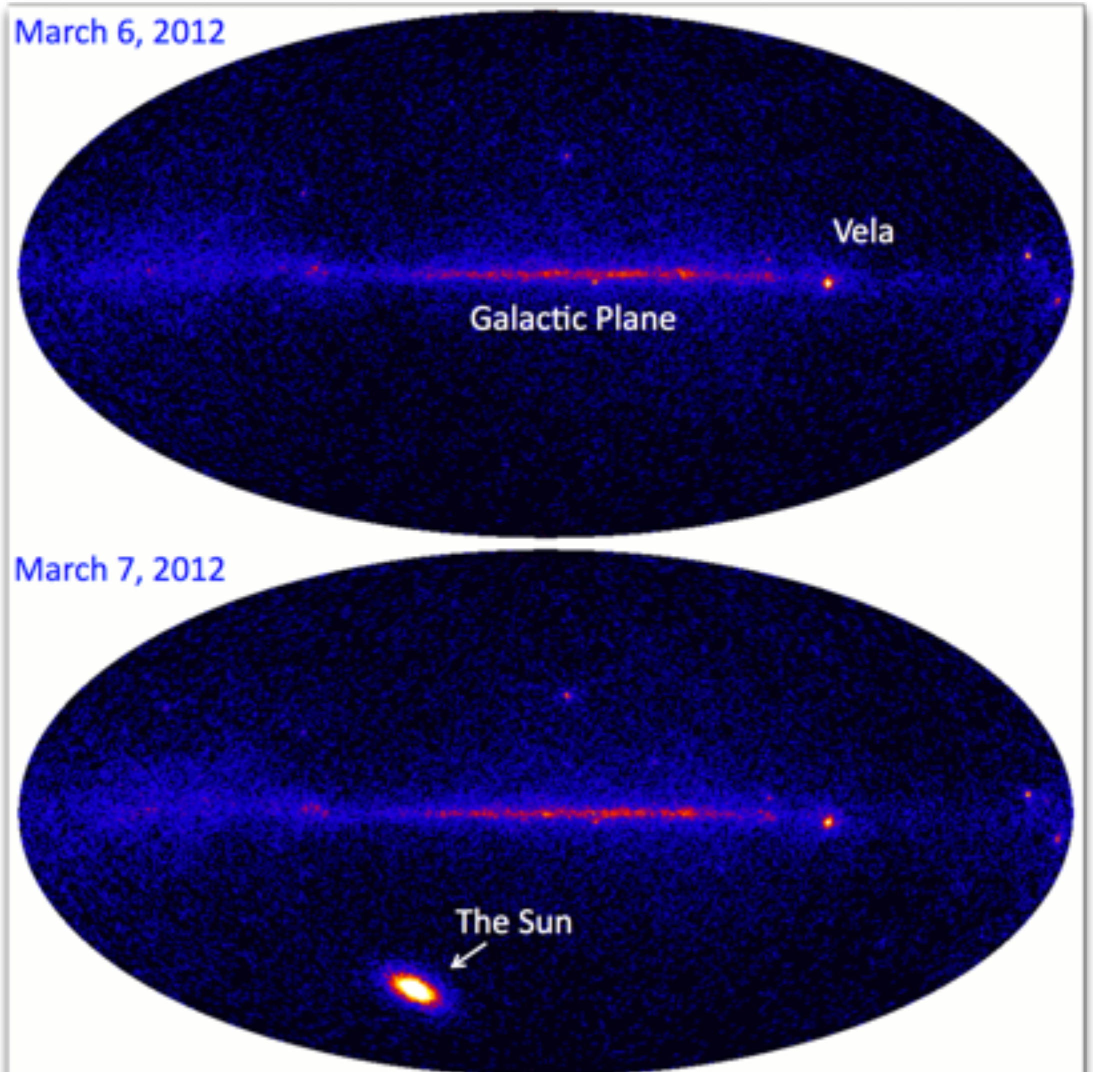
Ackermann et al. 2012, ApJ...745..144A

- **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**

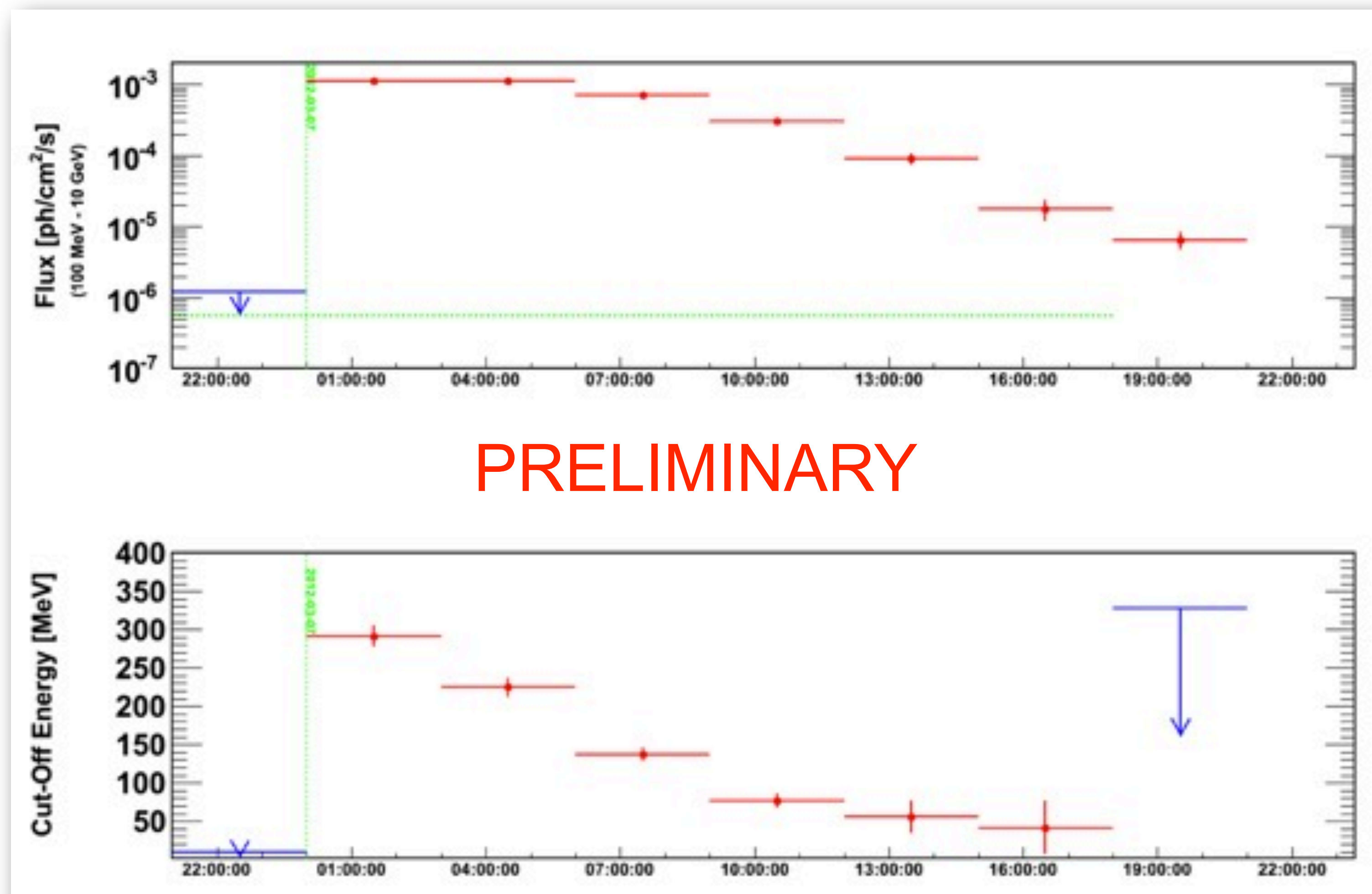
Component	Energy of gamma-ray	Energy of the ions	Derived accelerated ion spectral index
Neutron Capture	2.2 MeV	10-50 MeV	~3.2 (10-50 MeV)
Nuclear lines	5-20 MeV	50-20 MeV	~4.3 (50 -300 MeV)
Pions	>300 MeV	>280 MeV	~4.5 (>300 MeV)

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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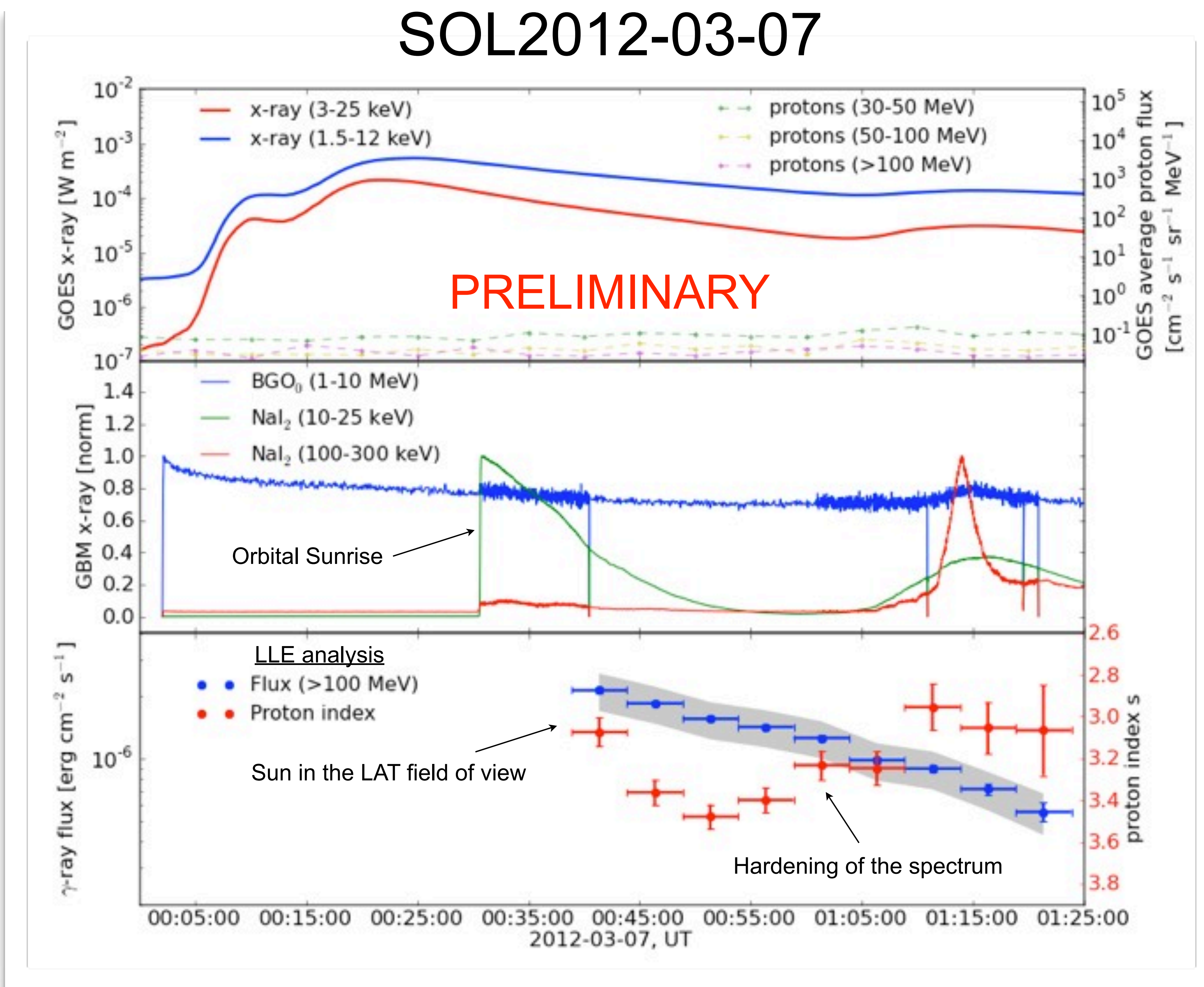
The "impulsive" phase: the first orbit



Particle trapping time ~ Energy of the protons

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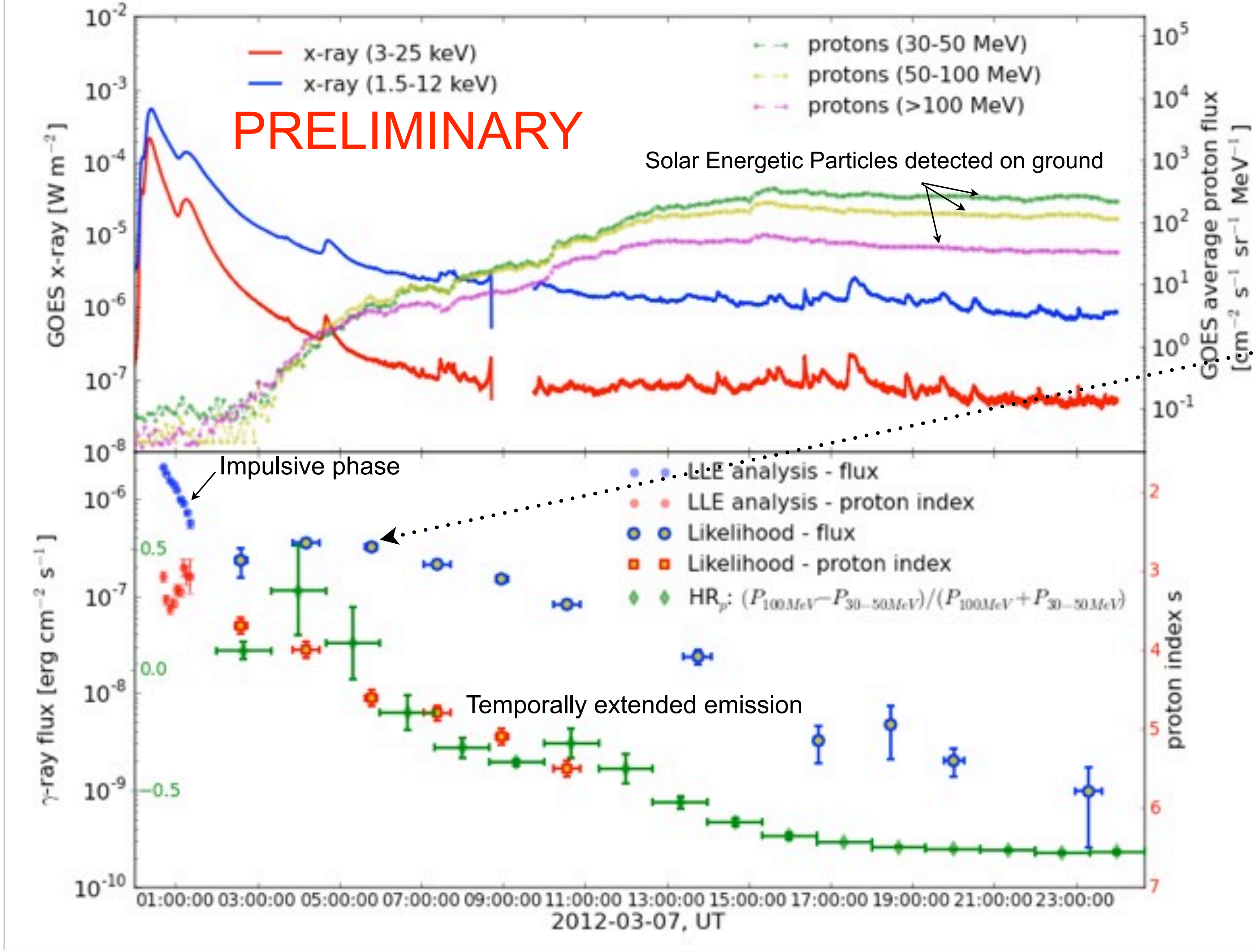
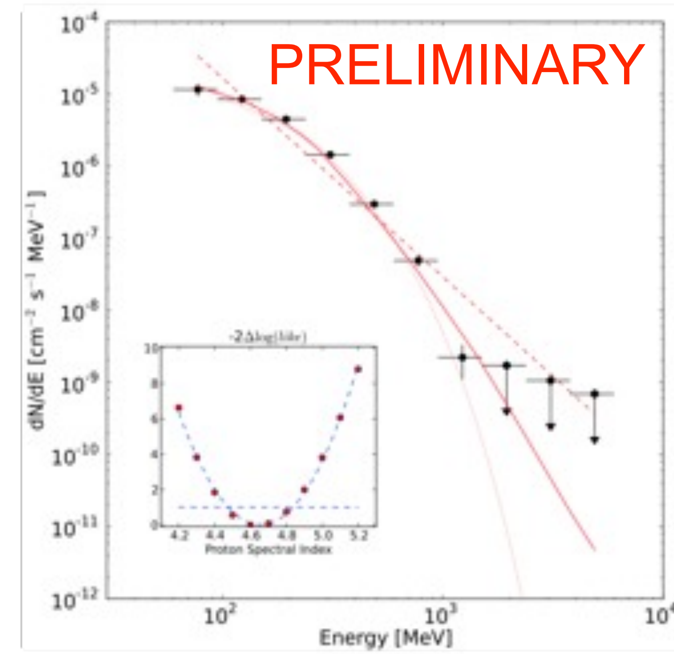
Long Lasting emission

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**

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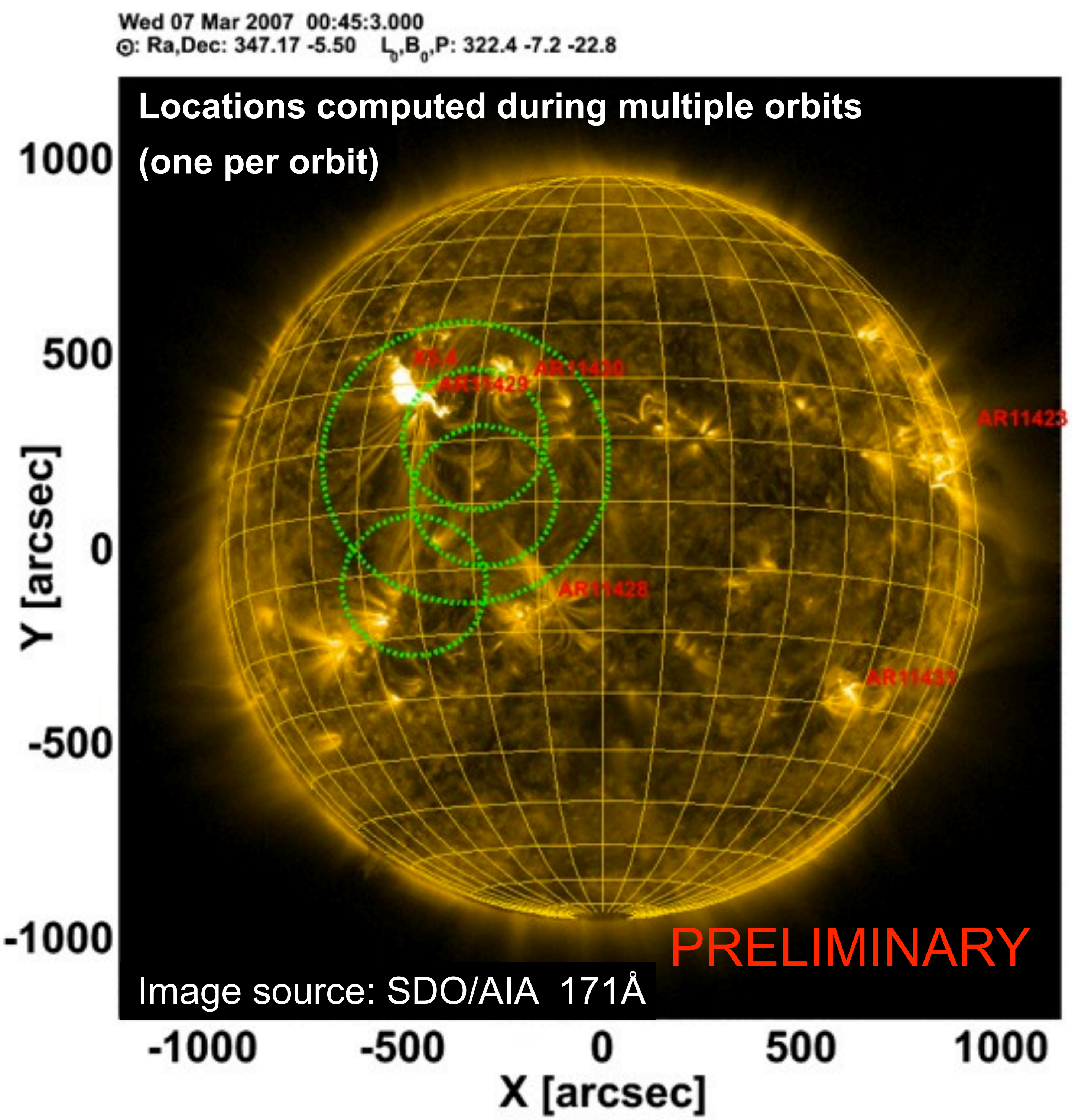
Localization



- **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

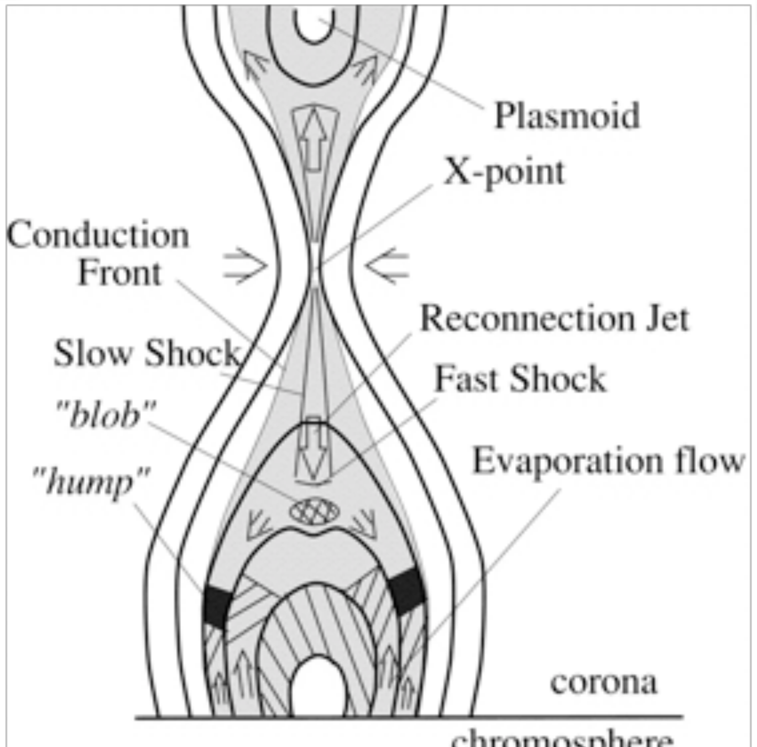
(e.g., Kanbach et al. 1993)

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

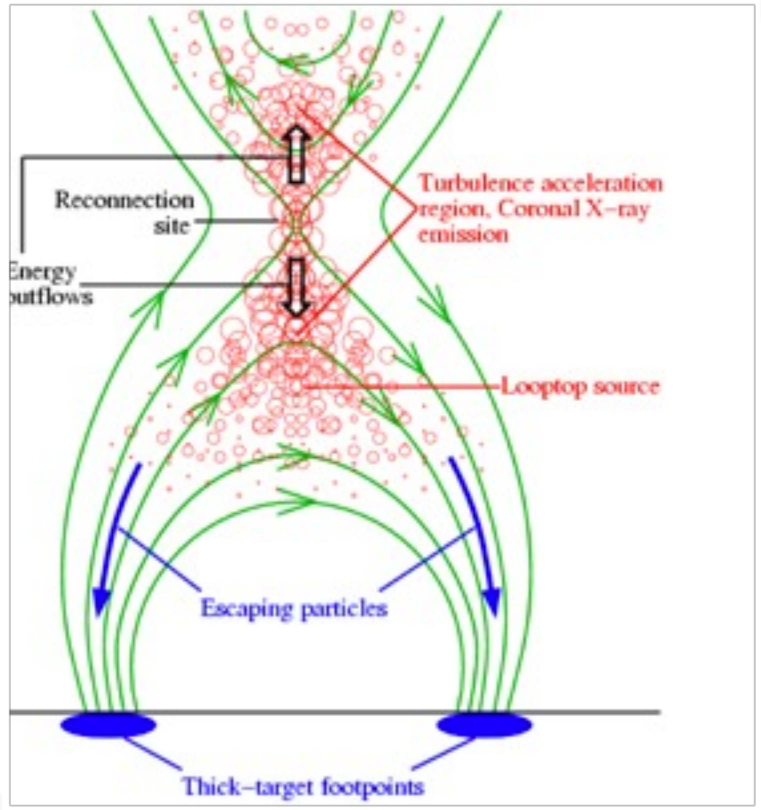
(e.g. Petrosian and Liu 2004)

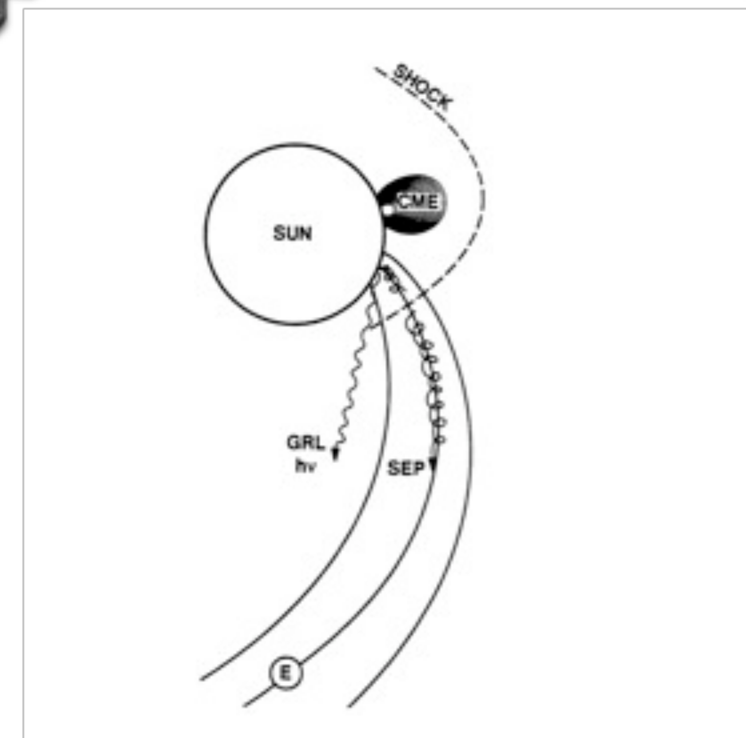
Return of protons accelerated by CME-driven shock (1st order Fermi)

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



Yokoyama & Shibata 2001





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;