Solar Protons above 500 MeV in the Sun's Atmosphere and in Interplanetary Space

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Overview

There are at least two sites for particle acceleration at or near the Sun:

- at the coronal reconnection site that launches the CME
- at the CME-driven shock
- perhaps others?

The relationship and relative contributions of these different sites to the energetic particle population is still a matter of debate, particular at the highest energies, i.e., protons at >500 MeV.

"Routine", precise Fermi observations of >100 MeV solar gamma-rays offer a new avenue of investigation, including the distinction between the impulsive and sustained (or "extended") phases of the flare.

Long-duration solar gamma-ray flares have been observed before (i.e., Kanbach et al. 1992), but never in the numbers and with the precision of Fermi. These observations permit more detailed analysis than ever before.

In this work, we compare estimates of the number of >500 MeV protons:

- in interplanetary space (in-situ measurements by satellites & by neutron monitors)
- in the solar atmosphere (remotely-sensed, derived from gamma-rays)

Outline

1. **>500 MeV protons at the Sun**: Review of the Fermi observations of sustained emission of >100 MeV gamma-rays in solar events.

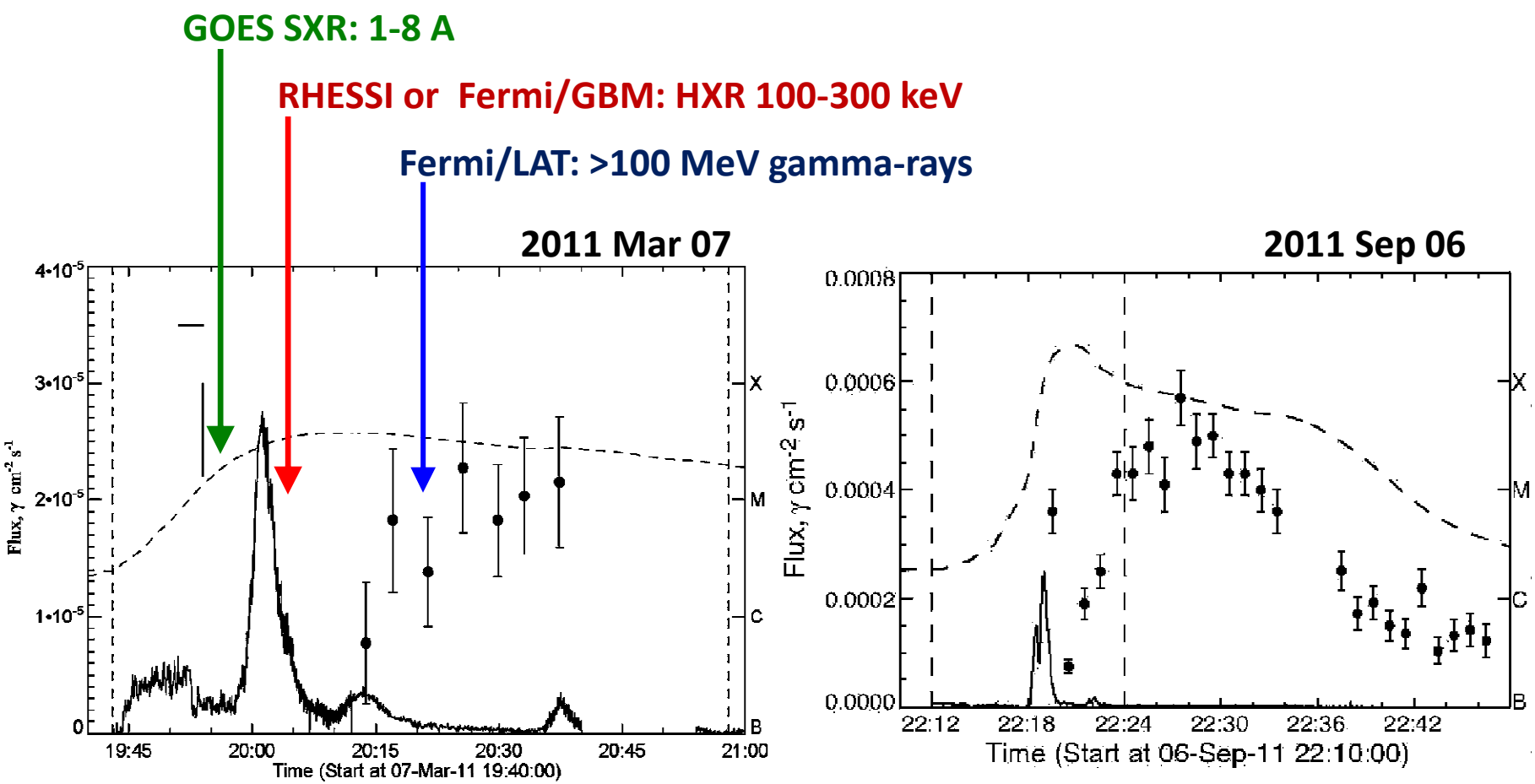
2. **>500 MeV Solar Protons in Interplanetary Space:**
   - GOES/HEPAD data
   - Transport Corrections
   - Spatial Distributions

   How obtained?
   Systematic Uncertainties?

3. **Quantitative Comparisons: Number of >500 MeV protons at the Sun and in IP Space**

4. **Implications:**
   - **Origin of the Fermi sustained–emissions**
   - **Acceleration processes for high-energy solar protons**

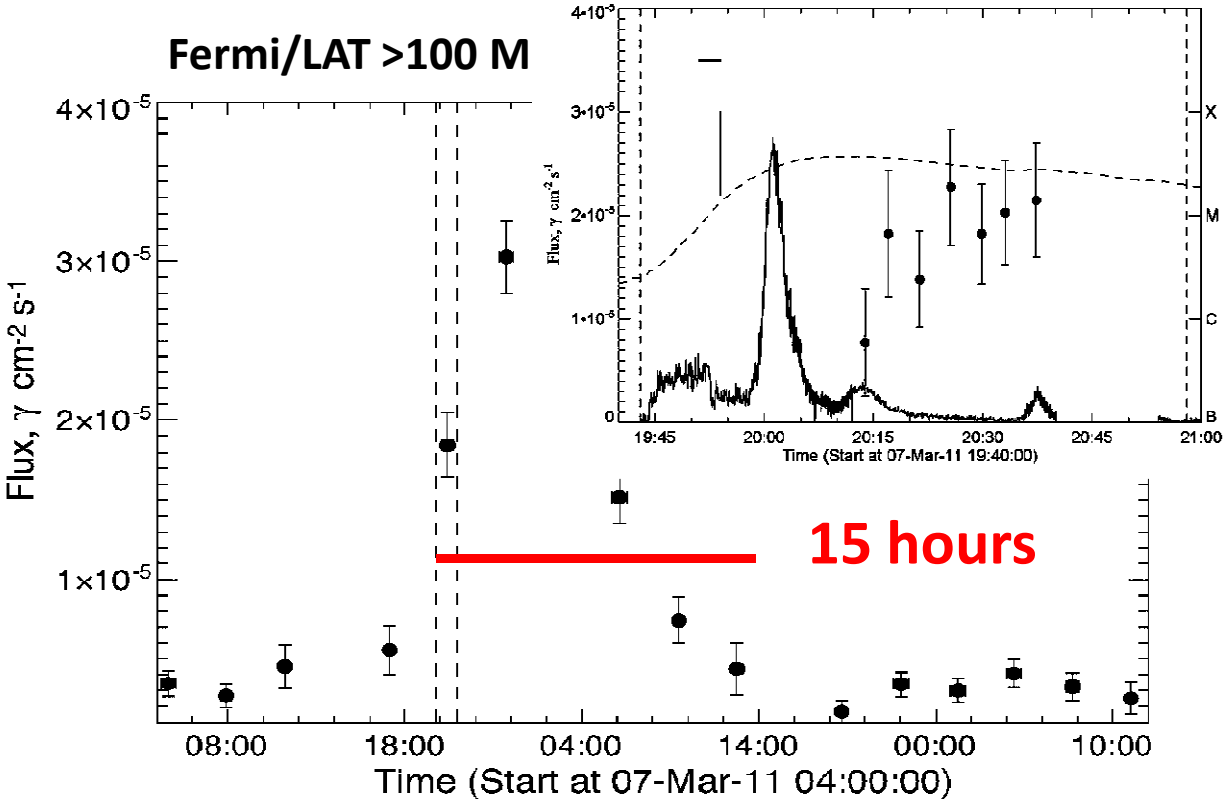
A Brief Review of Fermi/LAT Observations



These are short time intervals: first ~30-40 minutes of the event.

But there's more…

A Brief Review of Fermi/LAT Observations



In 2011-2014, Fermi has observed 20 sustained-emission events, with >100 MeV γ-ray emissions lasting more than 1 hour after the HXRs .

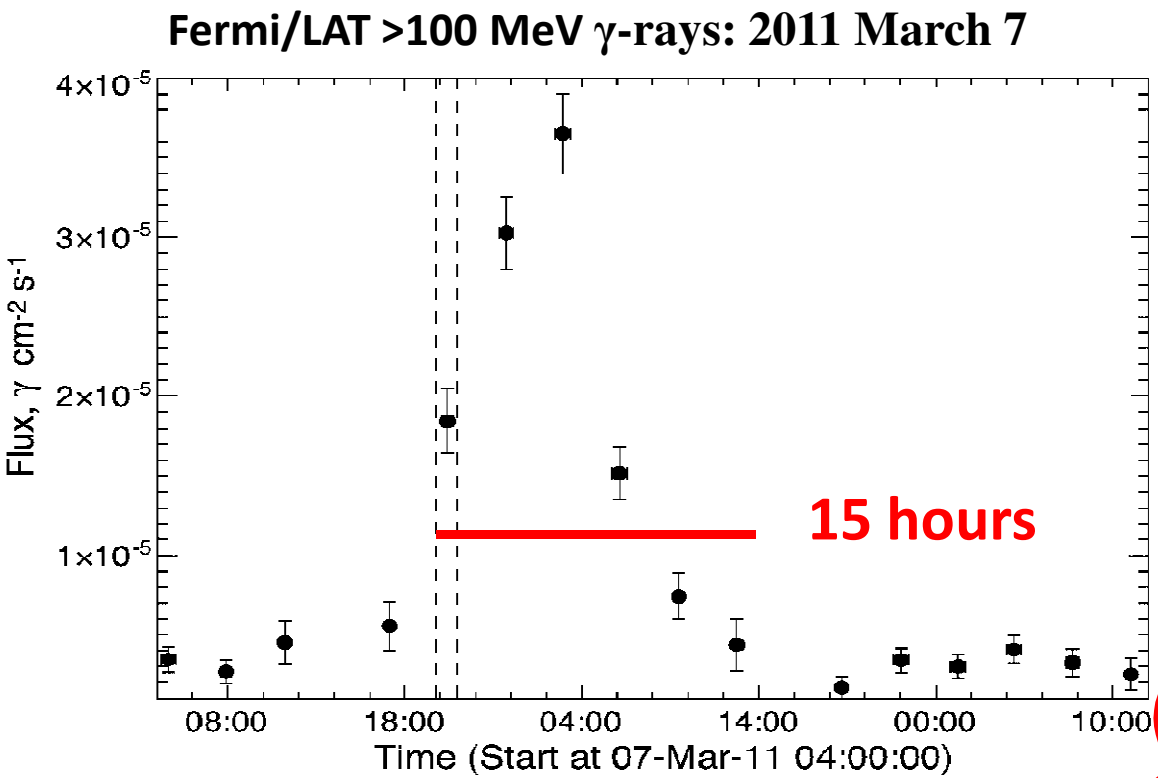
In these 20 events:

Delays between peak of HXRs and onset of >100 MeV γ-ray range from <1 minute to several 10s of minutes.

All of the sustained-emission events are accompanied by a broad, fast (>800 km/s) CME and HXRs (>100 keV).

But not all events with a broad, fast CME and/or >100 keV HXRs show sustained >100 MeV γ-ray emission.

A Brief Review of Fermi/LAT Observations



>100 MeV γ-rays are produced by nuclear interactions of >300 MeV protons that generate pions in the solar atmosphere

By modeling the observed gamma-ray emission, we can obtain information on:

- The number of high-energy protons hitting the Sun's atmosphere (i.e., >500 MeV)
- Their spectral shape

This report

Future work

On the spatial localization of the source-region of the Fermi sustained emissions….

There is no evidence – *for or against* – the sustained emission coming from a compact source region:

- **At 100 MeV, Fermi point-spread function is ~0.5 degree, which is also the size of the Sun.**

- **Even in the strongest events with the best gamma-ray statistics, the *centroid* of the >100 MeV emission is probably localized to within only a quadrant (octant?) of the Sun**

- **More information on this issue will come from the Fermi team.**

On the spatial localization of the source-region of the Fermi sustained emissions….

However, in at least some events, the source of the sustained emission <u>cannot</u> be only at the associated Active Region (AR):

- **Fermi saw sustained emission in the event of 2013 October 11, where STEREO-B EUV observations put the associated AR at E106.**

- **Other sustained-emission events were seen from ARs very near to the limb, where the gamma-rays headed toward Earth would have been absorbed in the solar-atmosphere (i.e, "limb darkening") :**

  27 Jan 2012 at W85, 2012 May 17 at W77, 13 May 2013 at E80, 14 May 2013 at E77, 25 Feb 2014 at E82

These events indicate that the source of the sustained emission can be as much as 20-30 degrees away from the AR.

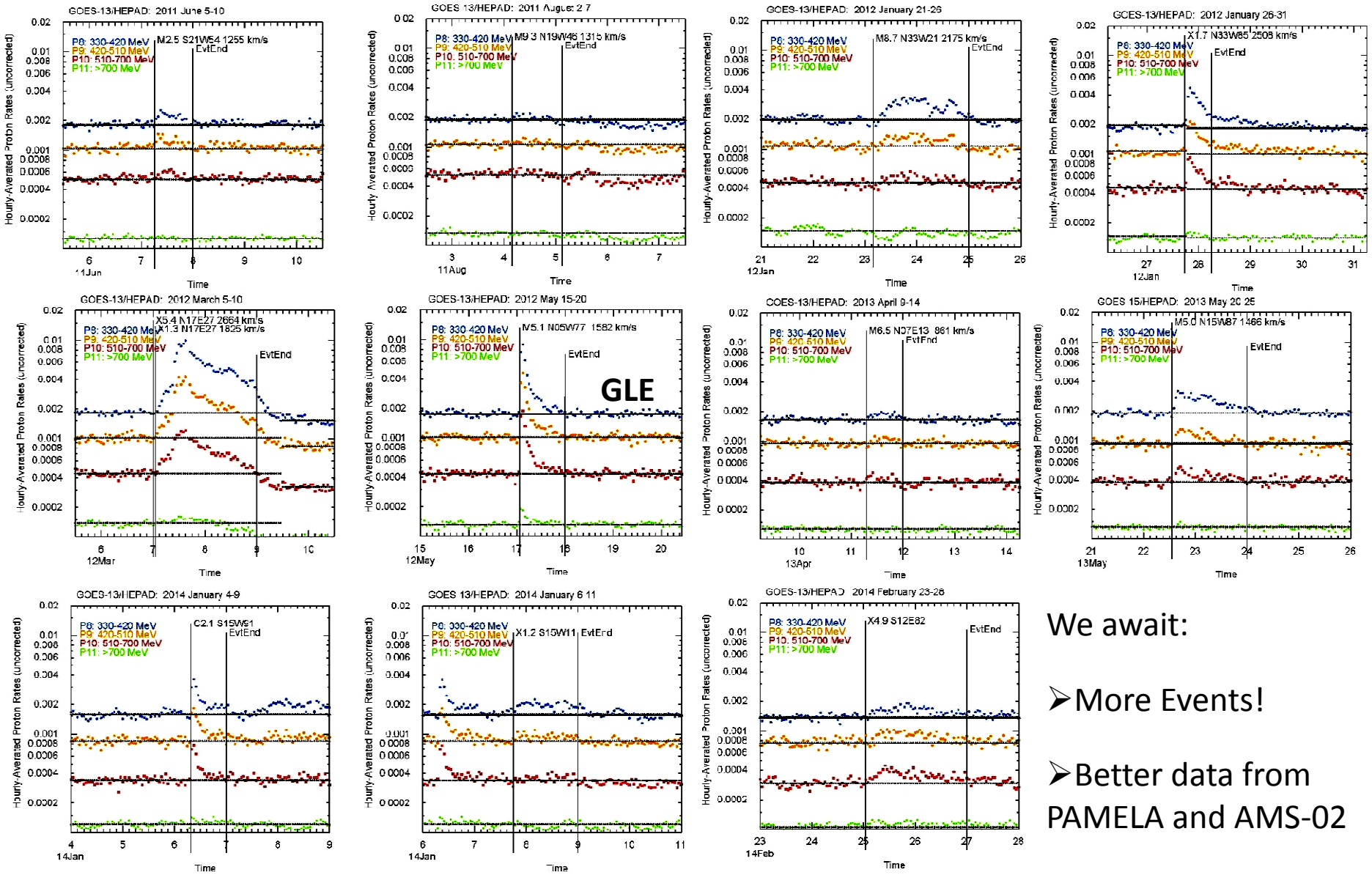
>500 MeV Solar Protons in Interplanetary Space

Very high energy solar proton measurements are available only at Earth:

- Neutron monitors in Ground-Level Events (GLEs)
- **GOES/HEPAD**
- PAMELA
- AMS-02

Note: STEREO reports protons only up to 100 MeV

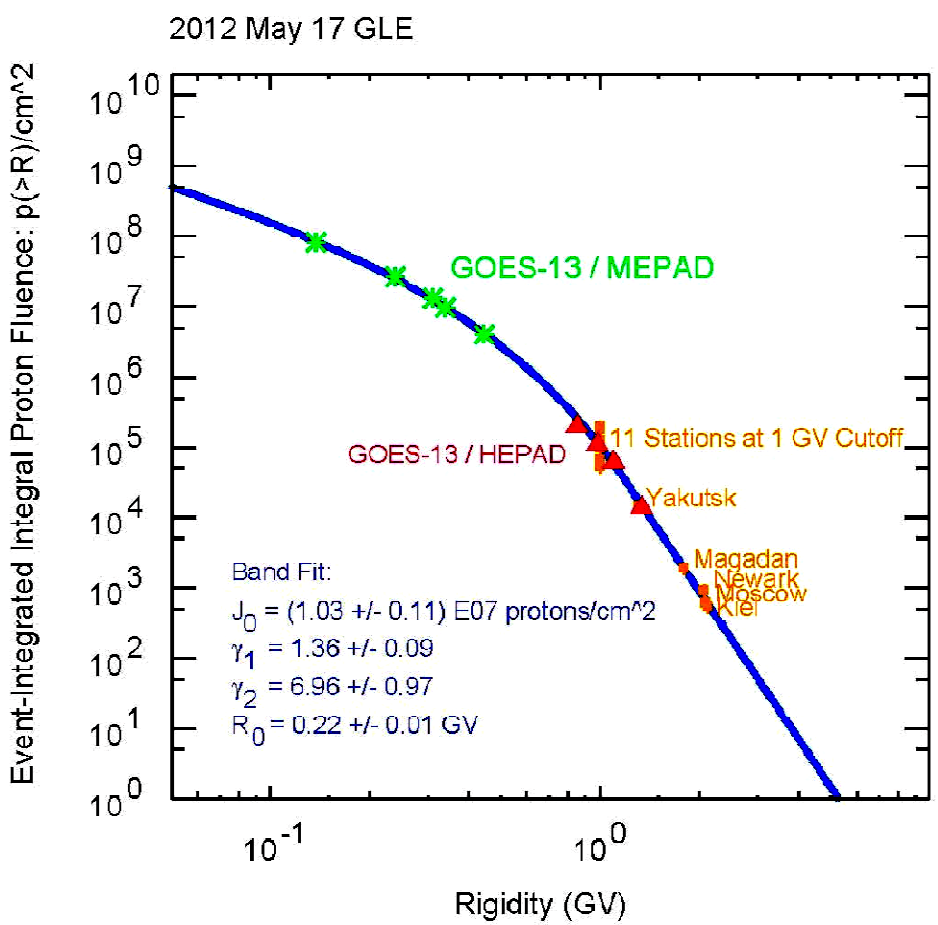
>500 MeV Protons from GOES/HEPAD: 2011-2014



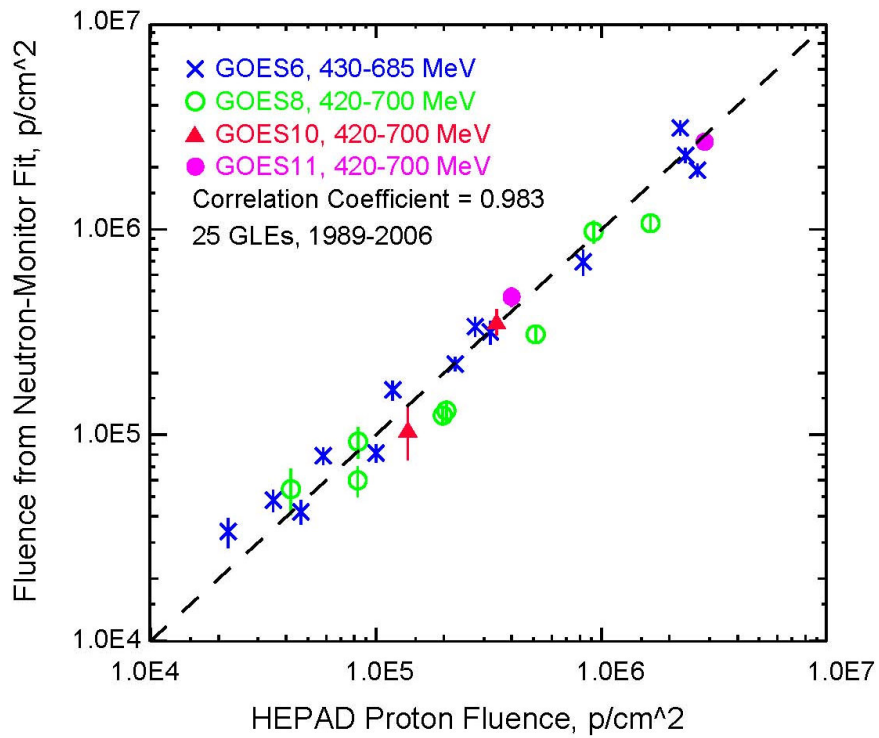
We await:

- More Events!
- Better data from PAMELA and AMS-02

Neutron Monitors and GOES/HEPAD



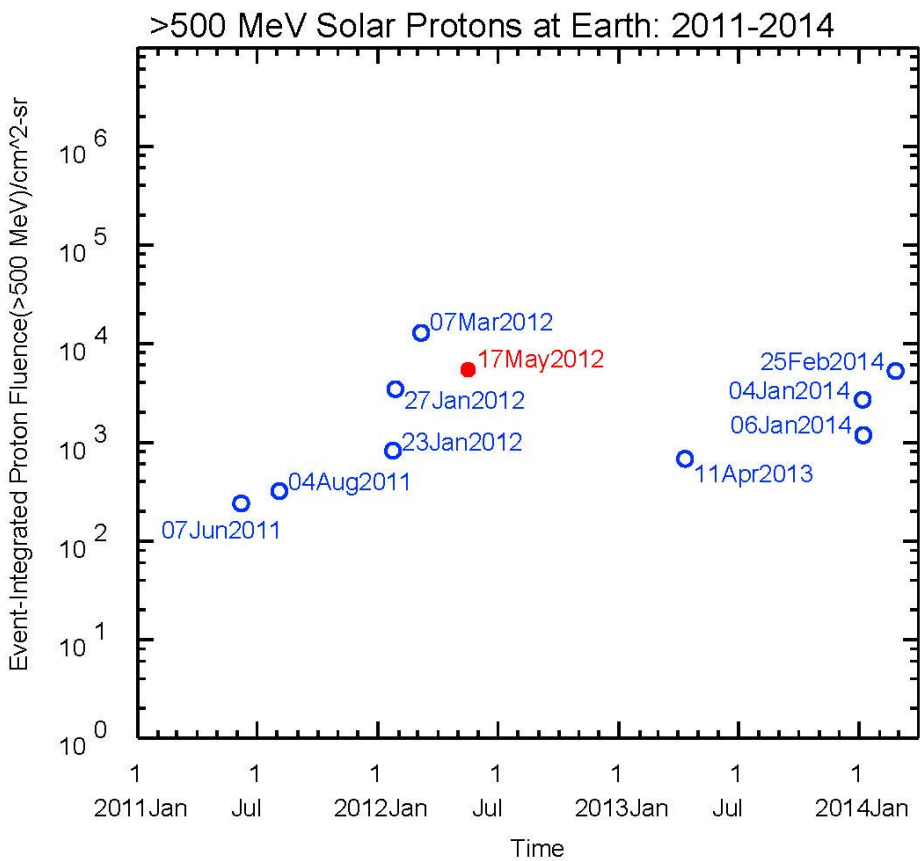
NMs vs. HEPAD: 25 GLEs, 1989-2006

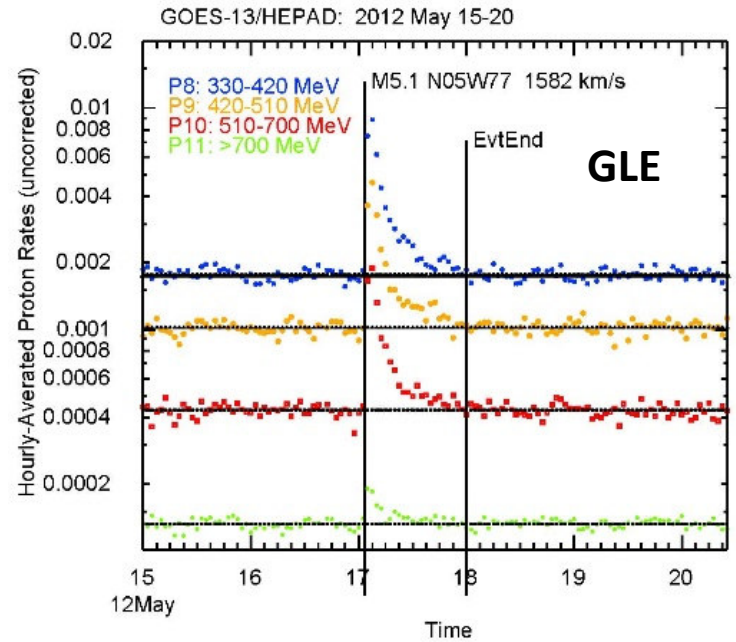


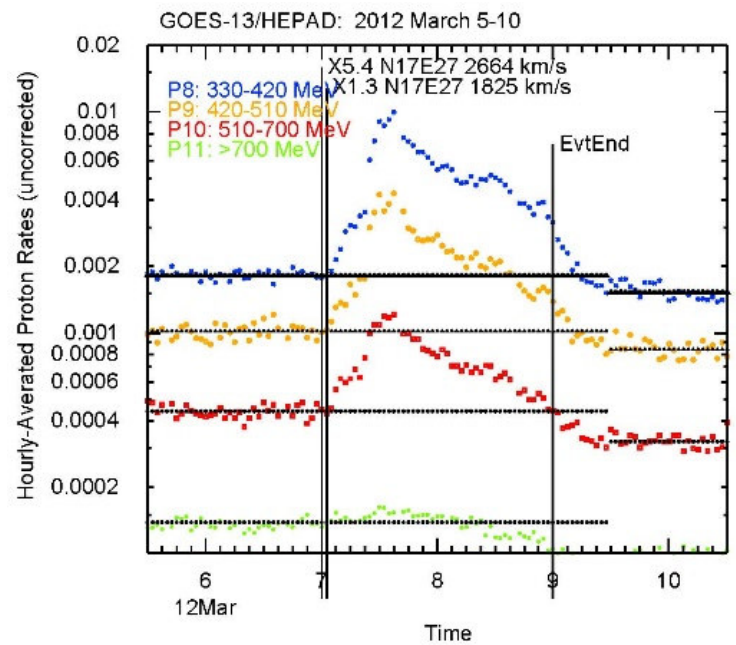
HEPAD data from NGDC
Reprocessed per Sauer Memo (unpublished, 2007)
Independent of the NM analysis

HEPAD and NM estimates of >500 MeV fluence typically agree to within ~30%.

>500 MeV Protons from GOES/HEPAD: 2011-2014







We will come back to these two events:

We now have estimates for the fluence of >500 MeV protons in IP space at Earth.

The gamma-ray analysis estimates the TOTAL NUMBER of protons IN THE SOLAR ATMOSPHERE.

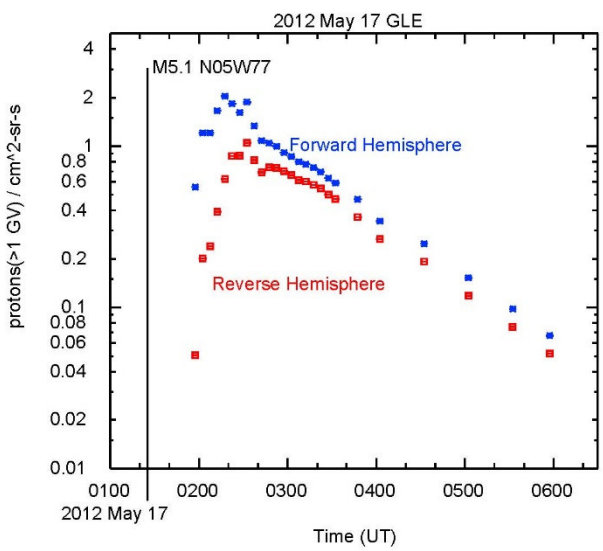
We need an analogous estimate of the TOTAL NUMBER of protons IN INTERPLANETARY SPACE.

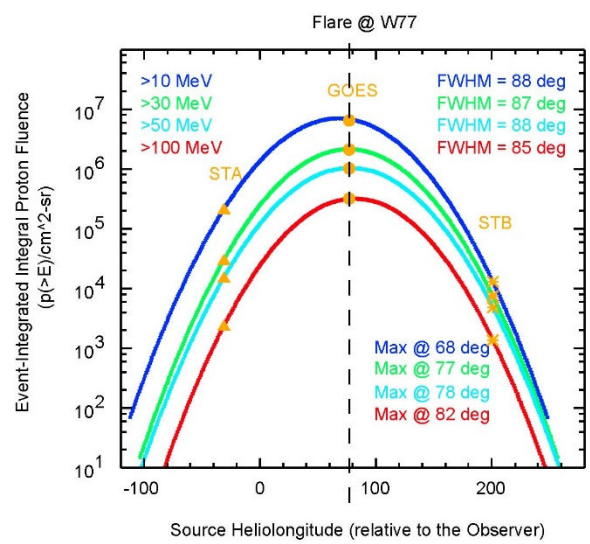
Mewaldt et al. (2005) outlined a heuristic approach to this problem:

$$N_{IP} = 2\pi R_0^2 J_{Earth} C_{spatial} / C_{transport} \quad (\text{where } R_0 = 1 \text{ AU})$$

" Crossing Correction"

Large-Scale Distribution of SEPs

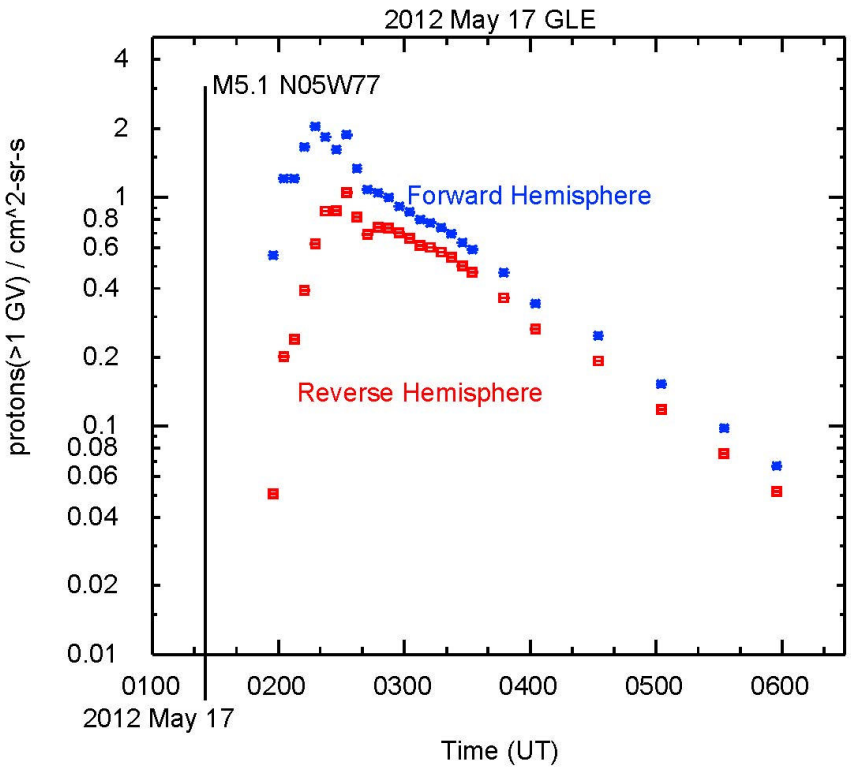




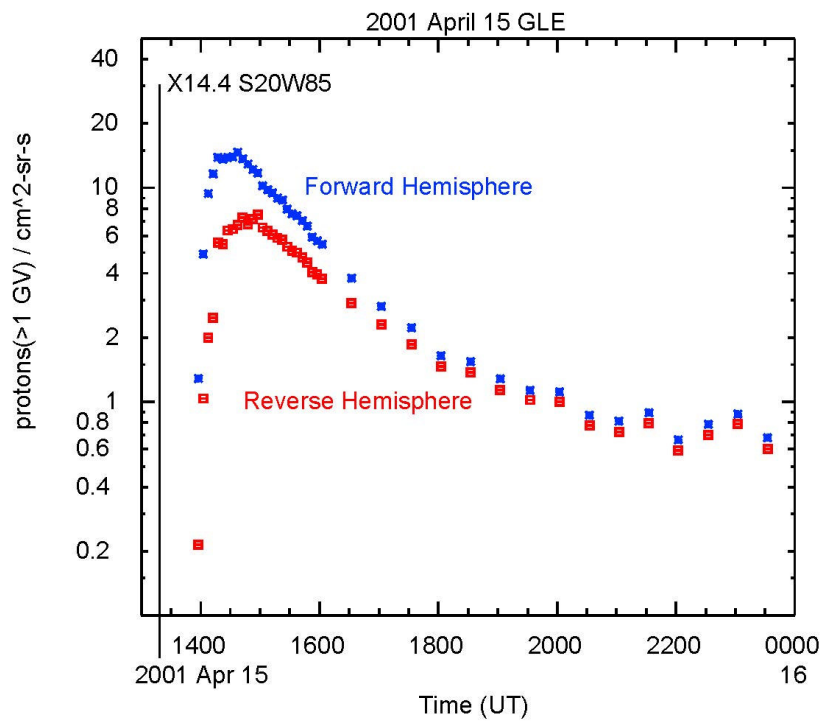
Interplanetary Protons: "Crossing Correction" at >500 MeV

$$C_x = \frac{J_{omni}}{|J_{forward}| - |J_{reverse}|} = \frac{0.5^*(|J_{forward}| + |J_{reverse}|)}{|J_{forward}| - |J_{reverse}|}$$

$C_x = 1.9 \pm 0.3$



$C_x = 2.3 \pm 0.3$



Analysis of the world-wide Neutron Monitor Network by D. F. Smart & M.A. Shea.

Interplanetary Protons: "Crossing" Correction" at >500 MeV

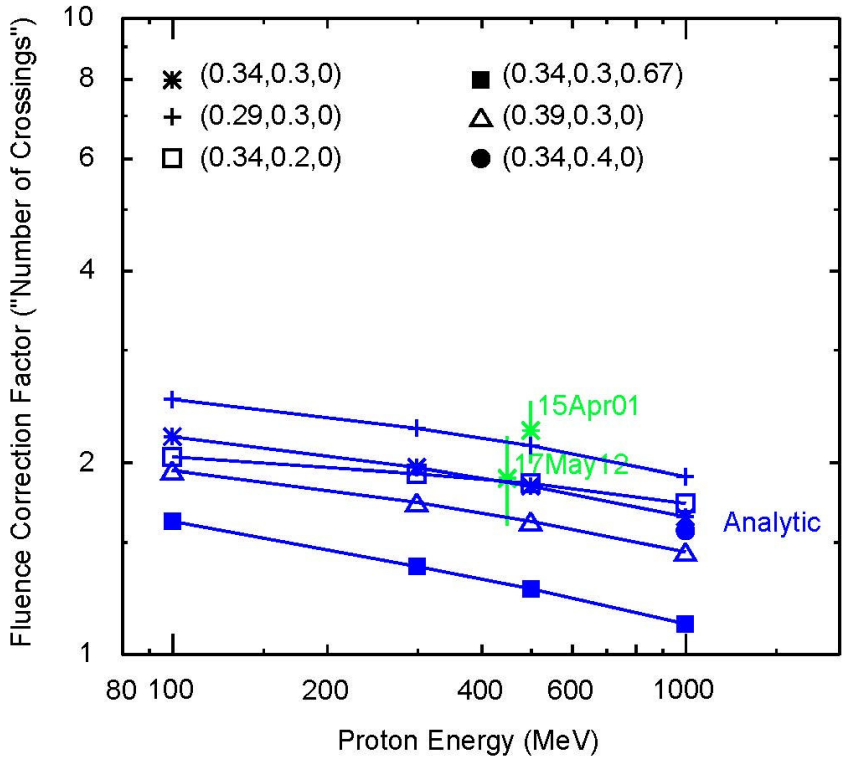
Analytic Calculations

Analytic crossing-correction calculations by Chee K. Ng, assuming:

- **Delta-function injection of particles at the Sun, i.e. short duration**
- **IP transport according to:**
  - $\lambda = \lambda_0 (P/GV)^{\alpha} (R/AU)^{\beta}$

  with various parameter values.

  Bieber et al. (2004) modeled intensities and anisotropies observed by the Spaceship Earth NM network on 2001 April 15 with λ_0 = 0.34 AU, α=0.3, and β=0.
- **Observations over 1 day**



Interplanetary Protons: "Crossing" Correction" at >500 MeV

Analytic & Monte Carlo Calculations

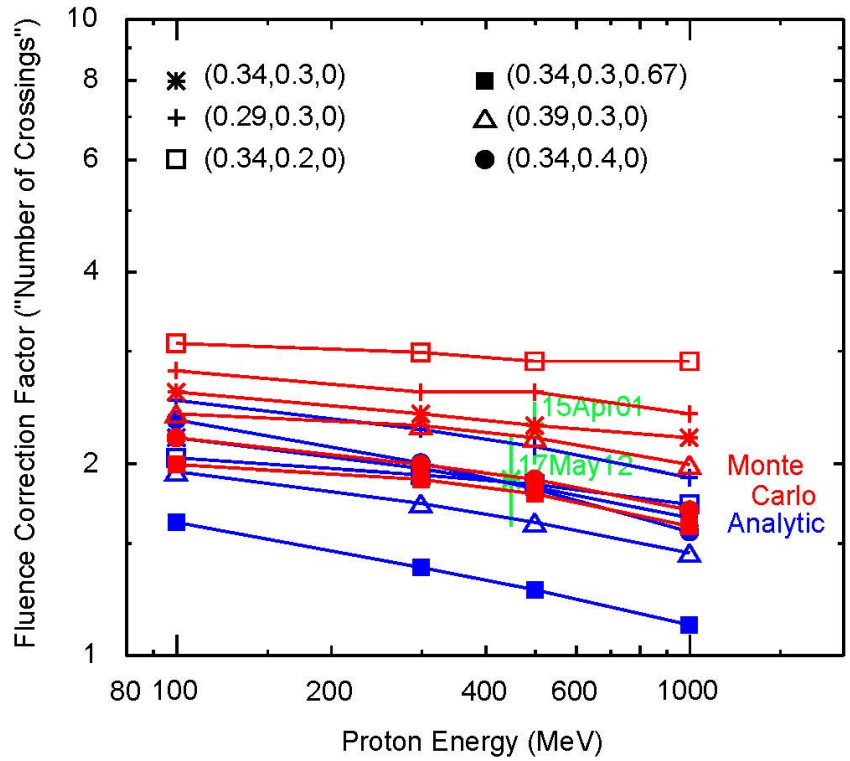
Analytic crossing-correction calculations by Chee K. Ng, assuming:

- **Delta-function injection of particles at the Sun, i.e. short duration**
- **IP transport according to:**
  - $\lambda = \lambda_0 (P/GV)^{\alpha} (R/AU)^{\beta}$

  with various parameter values.

  Bieber et al. (2004) modeled intensities and anisotropies observed by the Spaceship Earth NM network on 2001 April 15 with λ_0 = 0.34 AU, α=0.3, and β=0.
- **Observations over 1 day**

Monte-Carlo crossing-correction calculations by Eileen Chollet (Chollet et al. *JGR*, 2010), using the same scattering law & parameters.

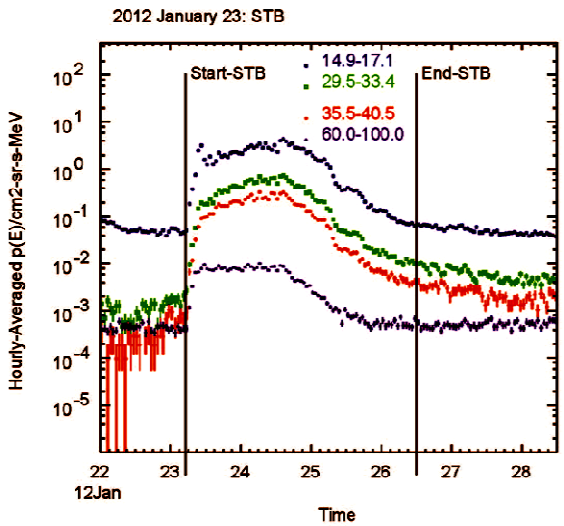


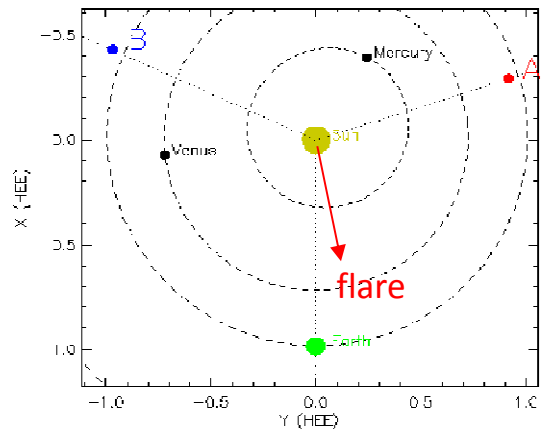
Analysis of NM data and two different theoretical techniques all confirm C_x ~ 2, with a factor of 2 systematic uncertainty

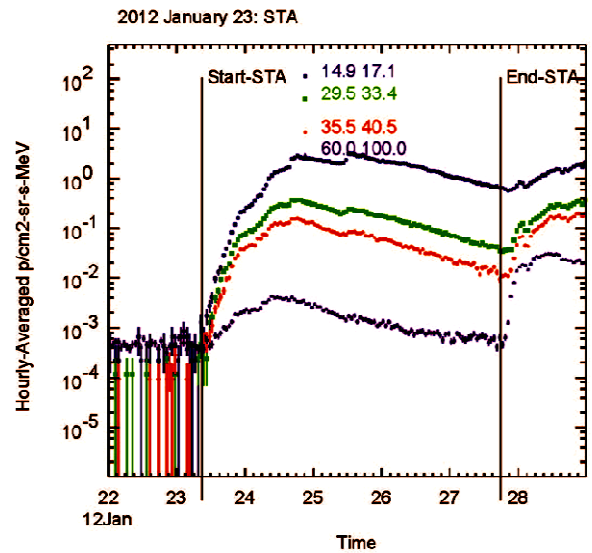
We henceforth assume that C_x ~ 2 is also applicable to other events for protons at >500 MeV.

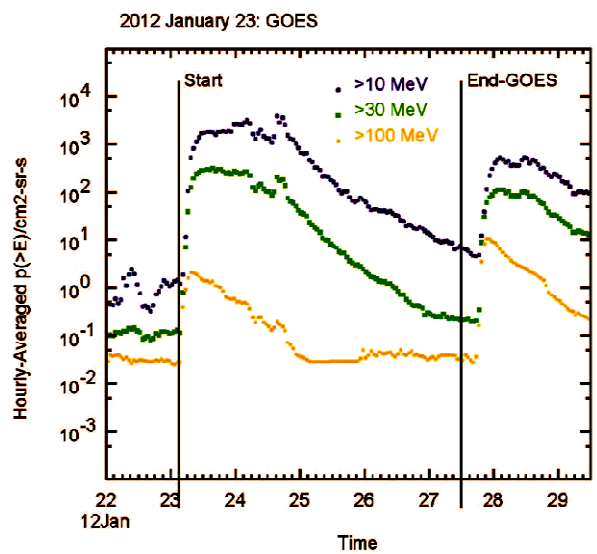
Interplanetary Protons: Spatial Distribution

2012 January 23 Solar Energetic Protons from STEREOs and GOES

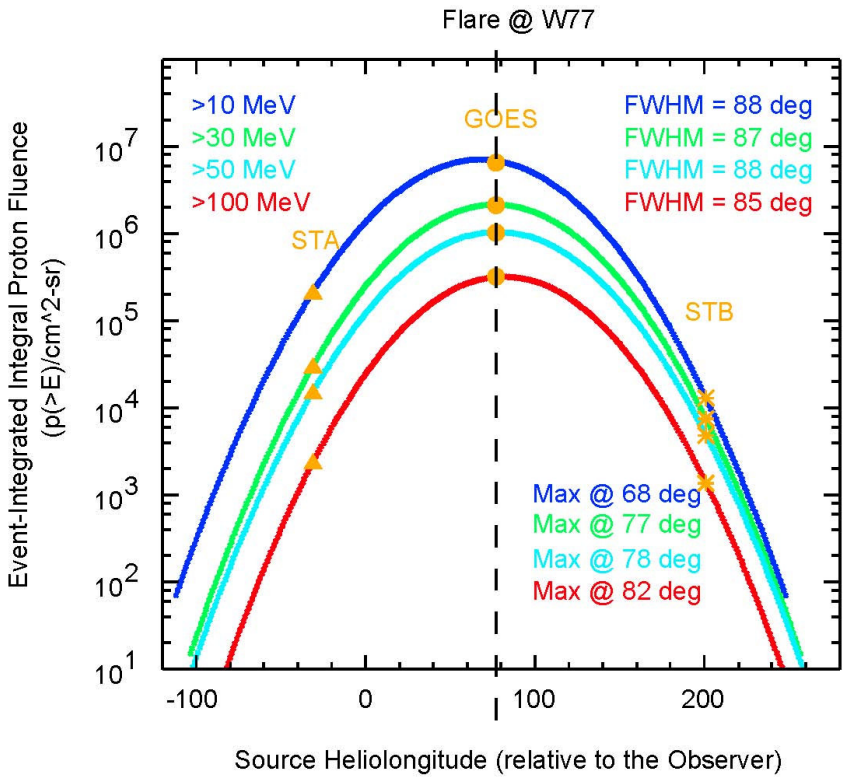


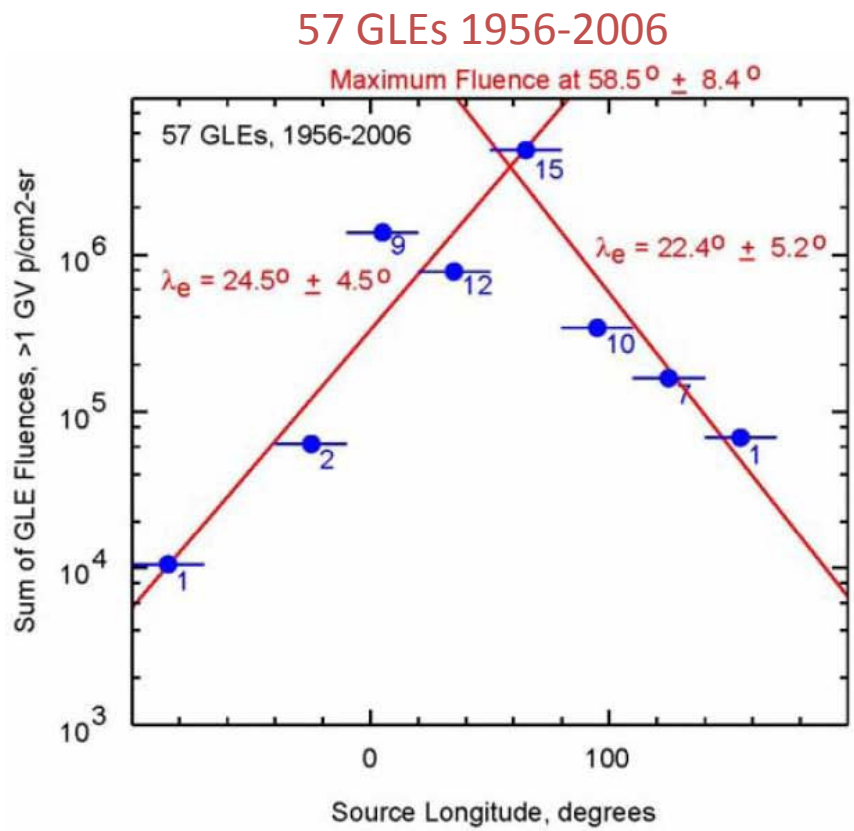






Interplanetary Spatial Distribution: Two Methods





Gaussian fits to GOES & STEREOs

Available only for energies well below 500 MeV

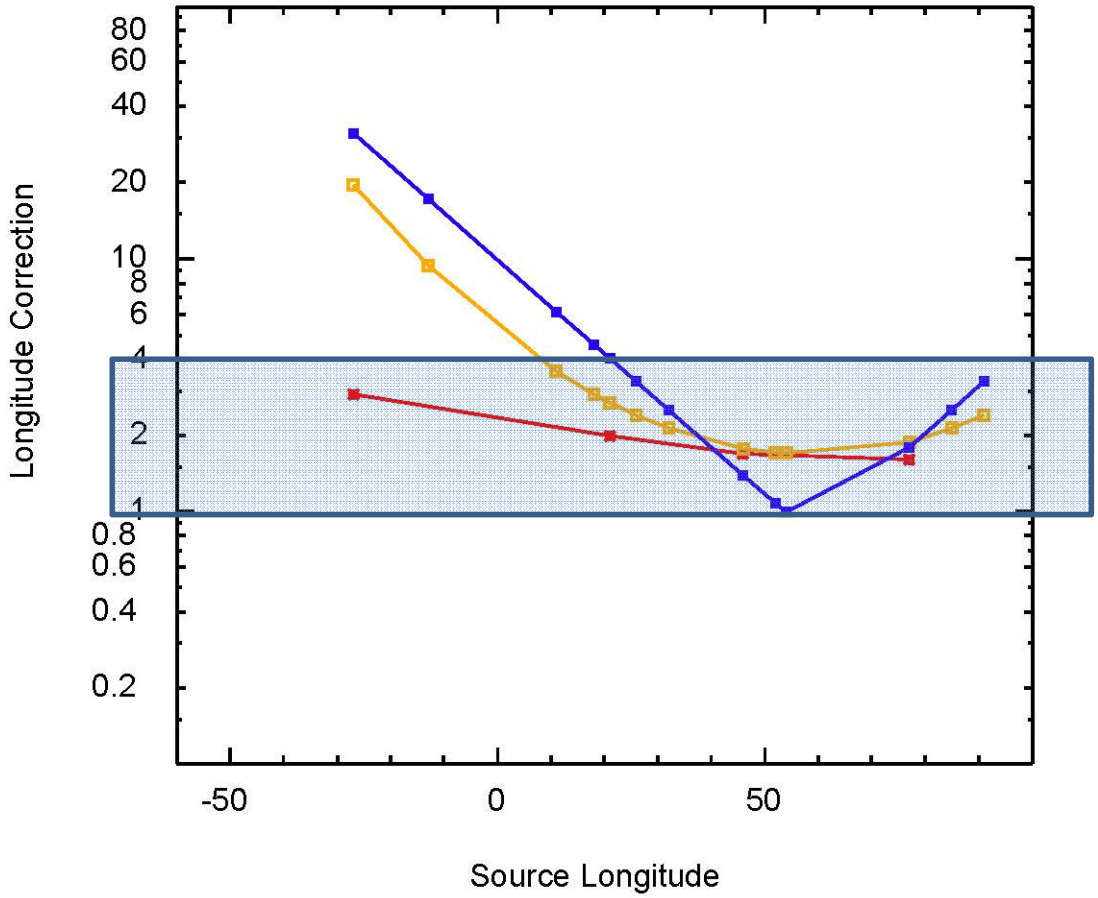
Not available for all events

Distribution centered at $\Phi_0 = 58^o$

Symmetric fall-off $\Lambda_\Phi = 23^o$

$J(\Phi) = J_0 \exp(-|\Phi-\Phi_0|/\Lambda_\Phi) \rightarrow C_{spatial}$

Spatial Correction Factor



For sources at ~W20-W90, models agree to within a factor of two.

For eastern sources , larger systematic uncertainty in this correction:

- **07 March 2012, at E27**
- **11 April 2013, at E13**

Extremely large systematic uncertainty causes some events to be omitted:

- **25 Feb 2014, at E82**

Models for Source Location Correcton:

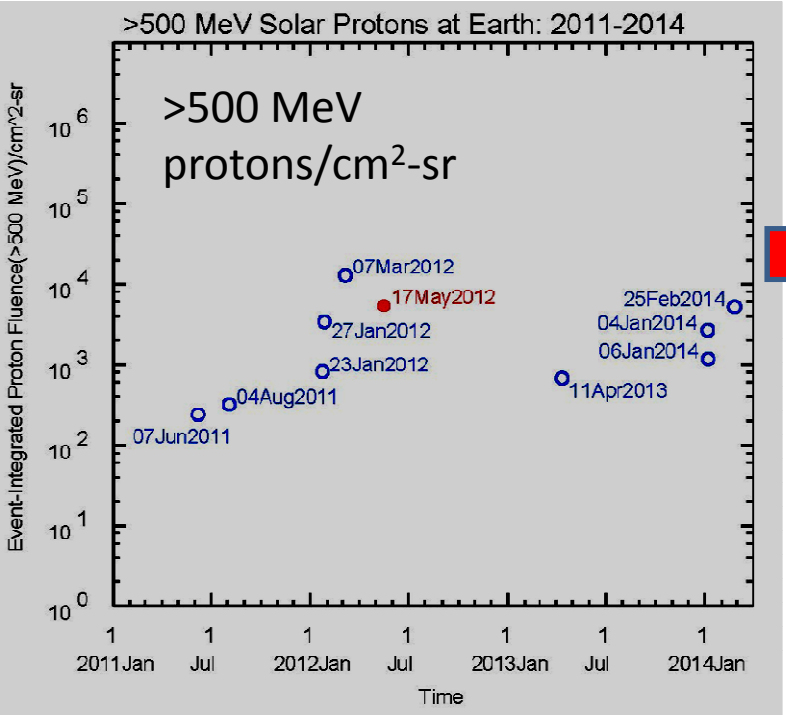
Exponential, peak at W58, based on historical GLEs

Gaussian, peak at W58, use average width from STEREO-era Events

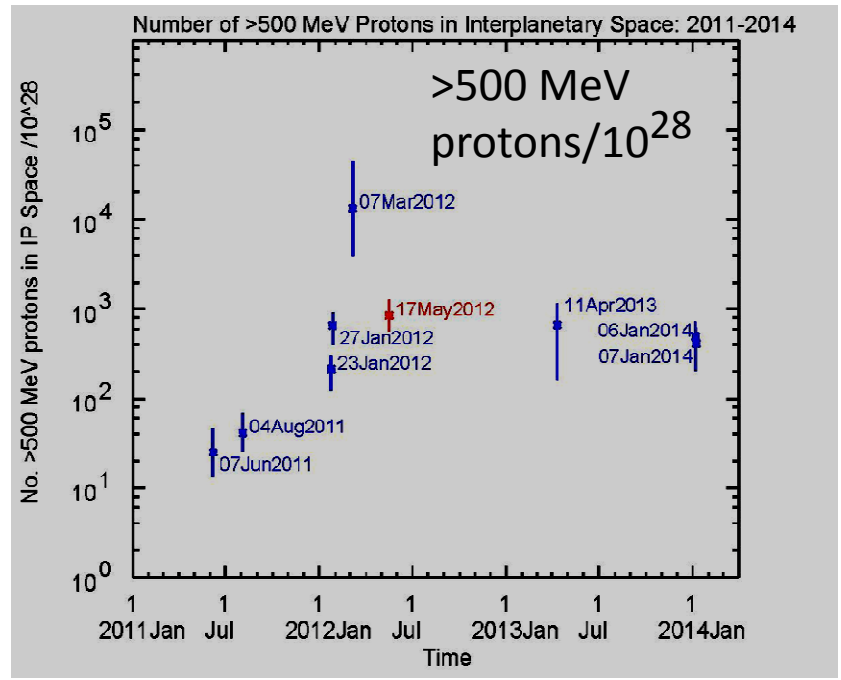
Gaussians from STEREO-era Events, peak and width different in each event

Results

Fluence at Earth



Number of Interplanetary Protons

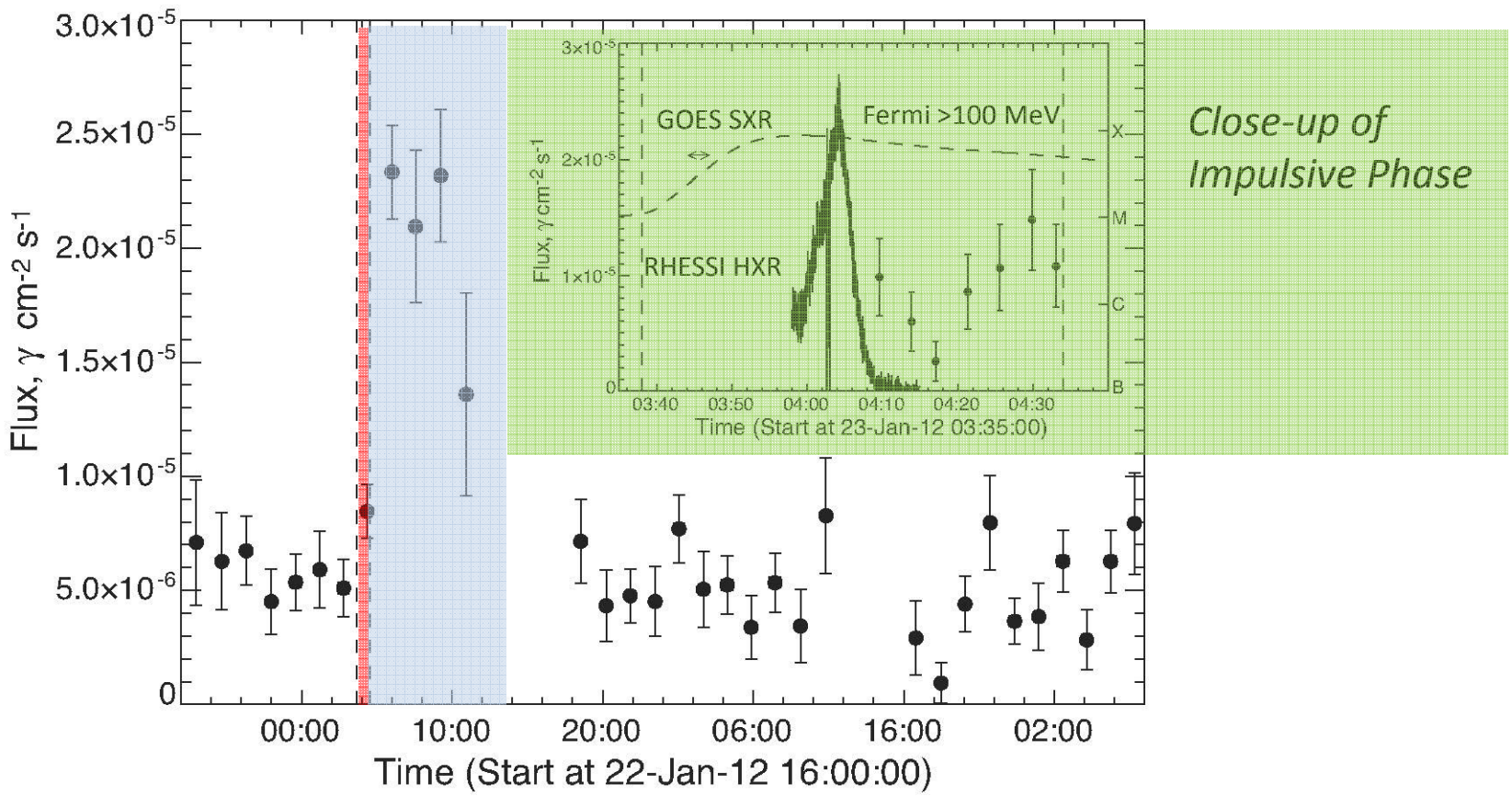


We can now compare $N_{protons}$(>500 MeV) at the Sun (from Fermi) and in Interplanetary space (from this analysis).

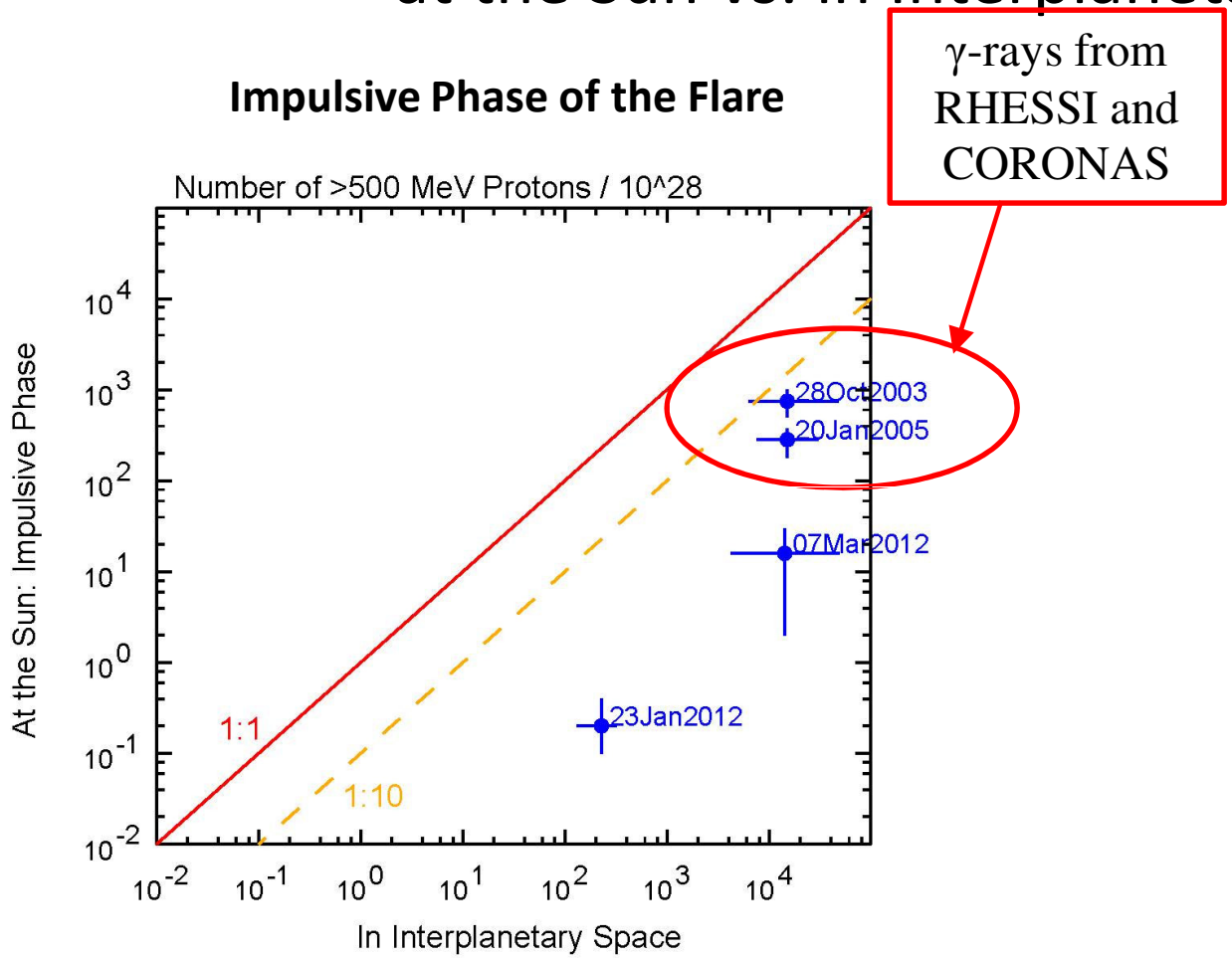
The Fermi γ-ray analysis (Share et al., in preparation) provides separate estimates for >500 MeV protons at the Sun in the impulsive and sustained phases of the flare.

Impulsive Phase (hard x-ray emission, ~10 minutes)

Sustained Phase (>100 MeV gamma-rays, ~4 hours in this event)

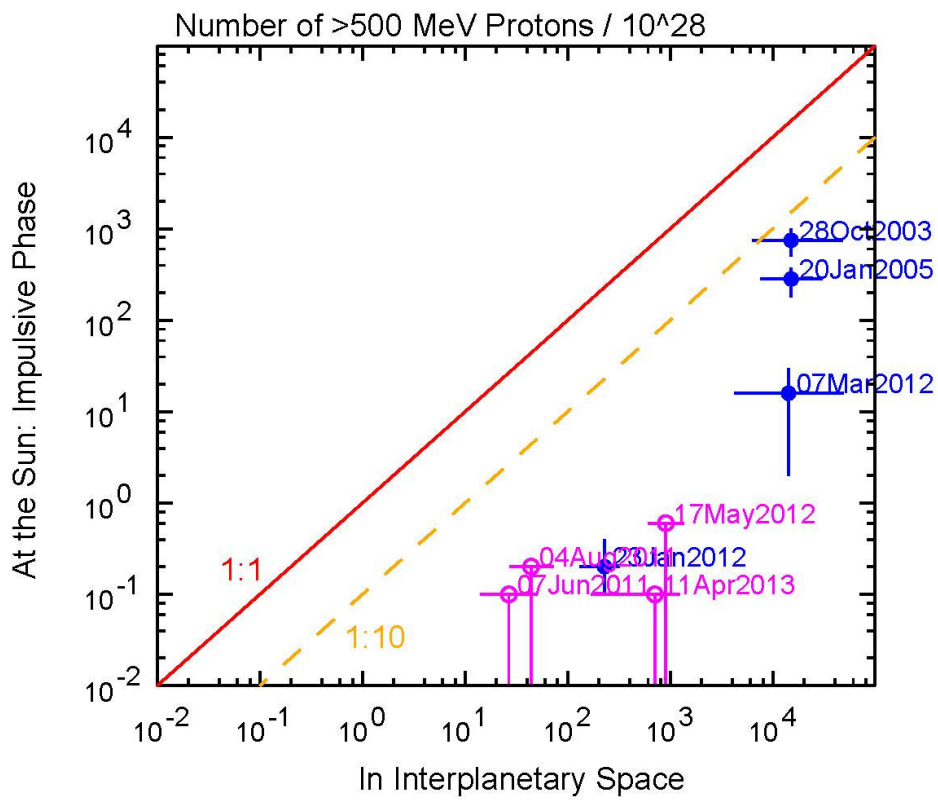


Number of >500 MeV Protons: at the Sun vs. in Interplanetary Space



Number of >500 MeV Protons: at the Sun vs. in Interplanetary Space

Impulsive Phase of the Flare

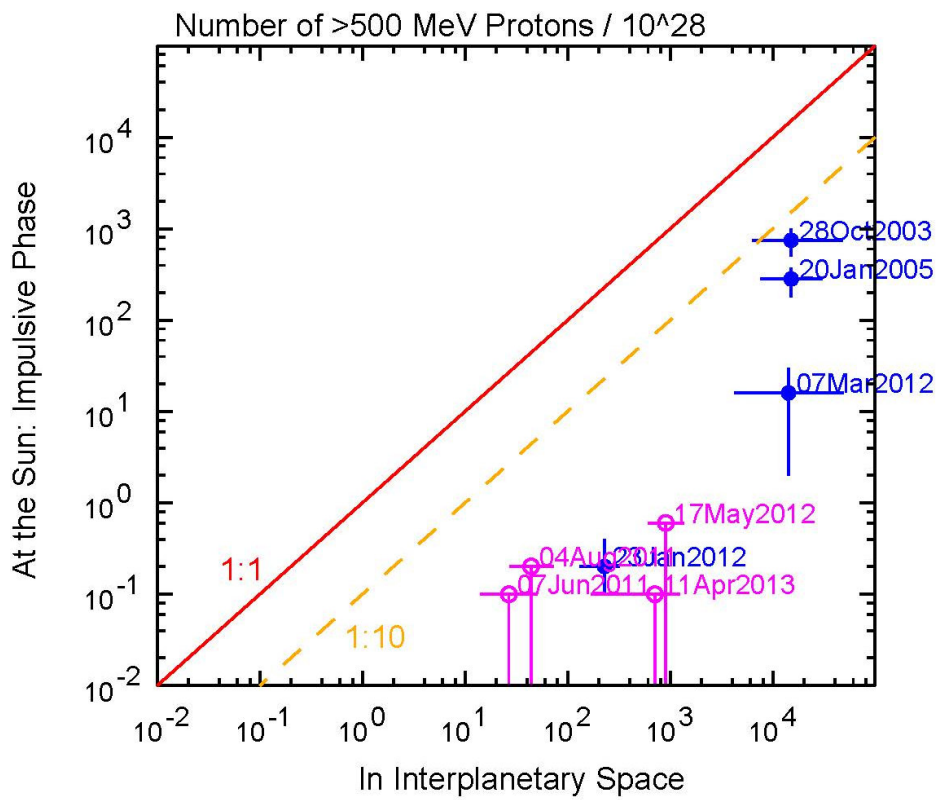


Purple: upper limits

Blue: measurements

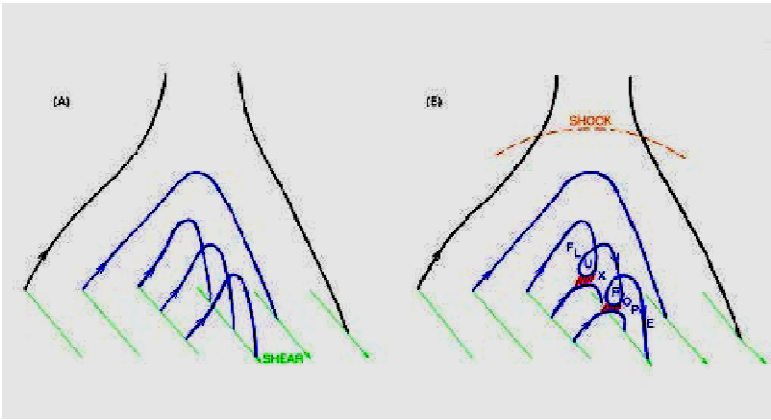
Implications: for the impulsive flare

Impulsive Phase of the Flare



>500 MeV protons in the **impulsive flare** are typically **~1% or less** of the interplanetary protons.

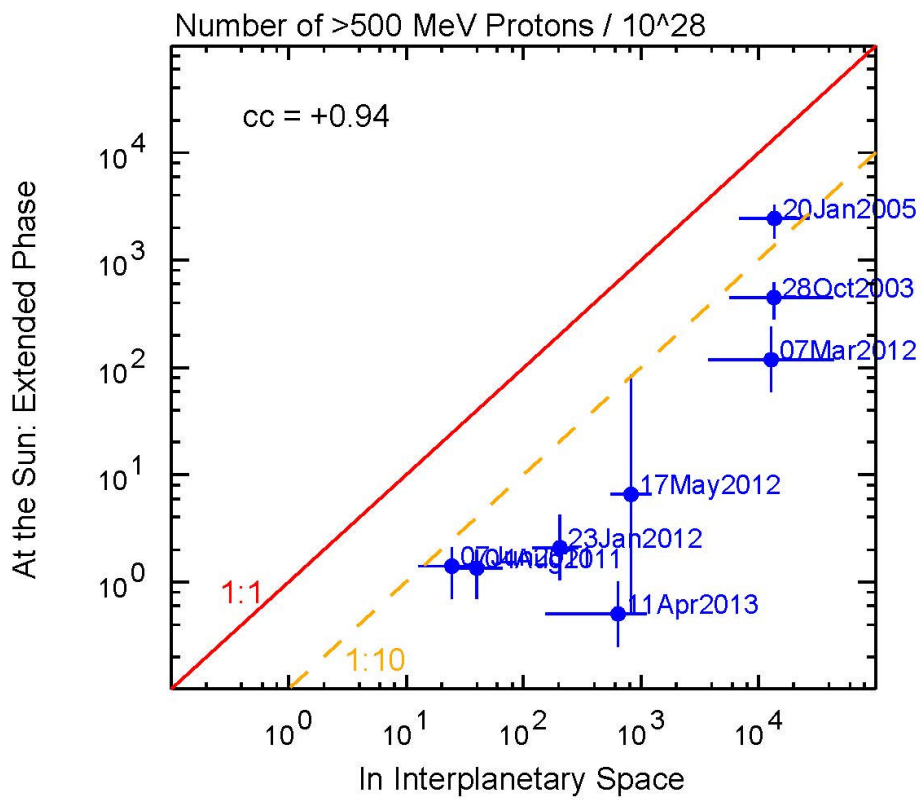
This makes it **EXTREMELY UNLIKELY** that the impulsive flare is the primary source of the interplanetary protons at >500 MeV.



Energetic particles primarily on closed loops

Number of >500 MeV Protons: at the Sun vs. in Interplanetary Space

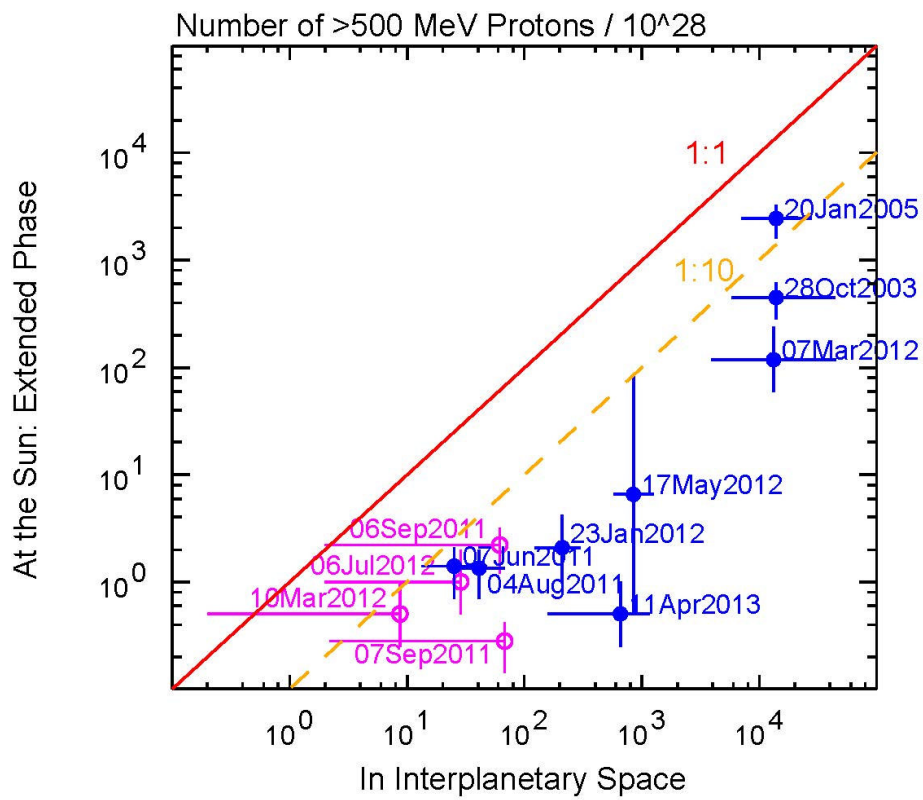
Sustained Phase of the Flare



17 May 2012: Large uncertainty in gamma-ray analysis due to location and possibly extended source.

Number of >500 MeV Protons: at the Sun vs. in Interplanetary Space

Sustained Phase of the Flare

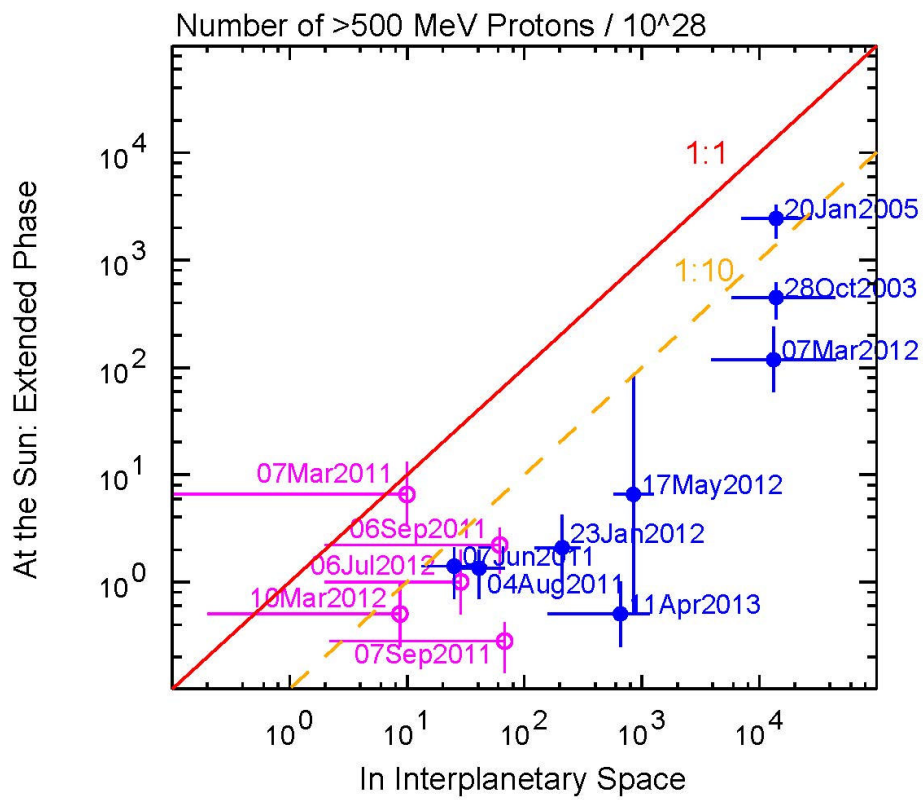


Purple: upper limits

Blue: measurements

Number of >500 MeV Protons: at the Sun vs. in Interplanetary Space

Sustained Phase of the Flare



07 March 2011: Upper-limit on IP protons but a typical number of sustained phase protons.

Implications: for the sustained emission

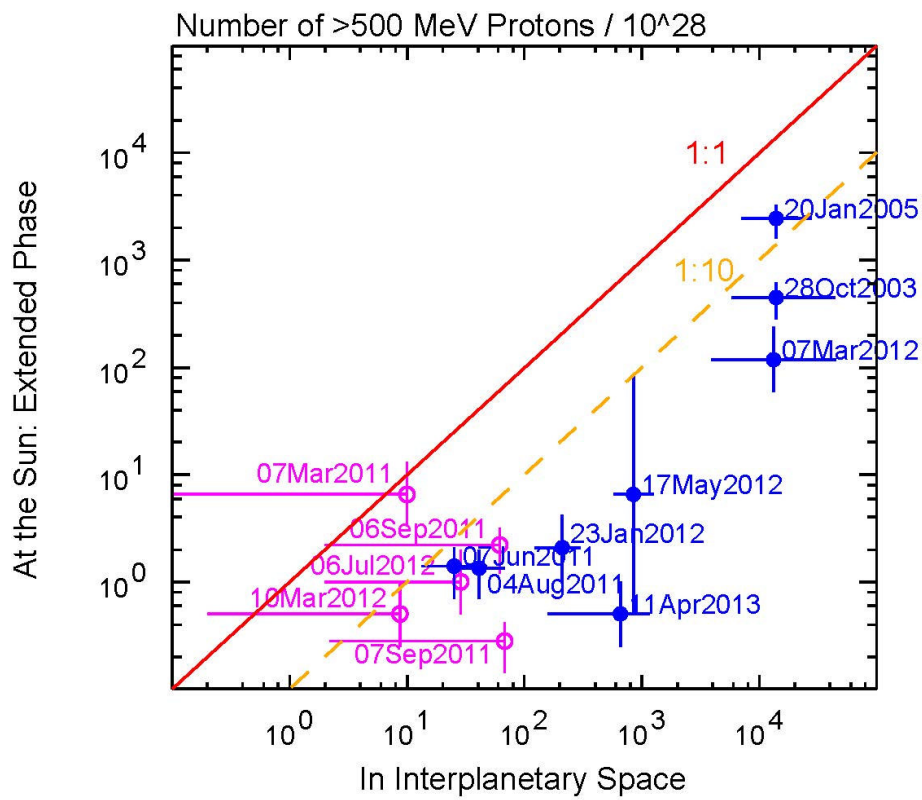
>500 MeV protons in the sustained emission are typically 5-10% of the interplanetary protons.

The sustained emission arises from the interplanetary proton population:

- a highly plausible idea.

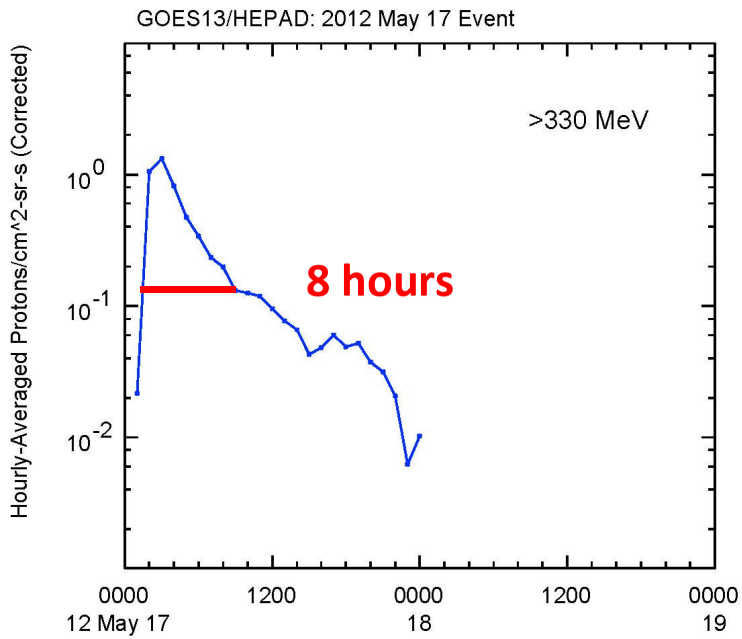
But how?

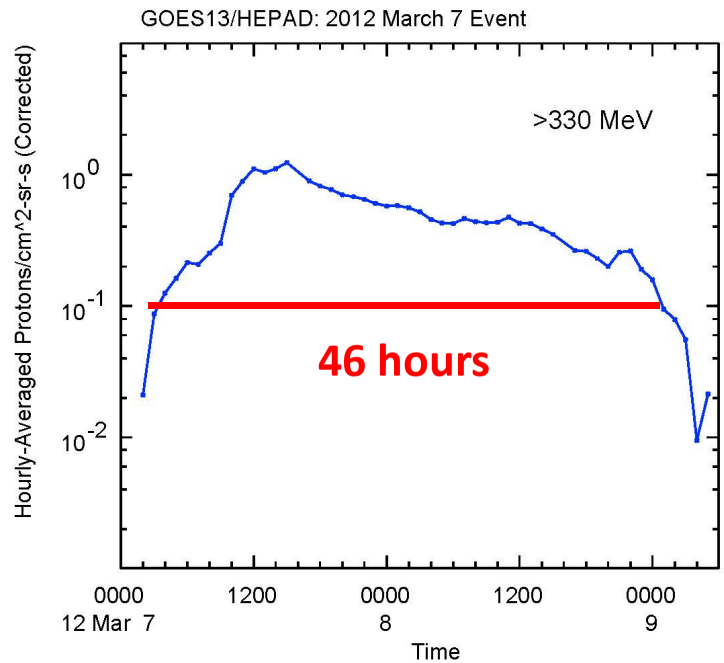
Sustained Phase of the Flare



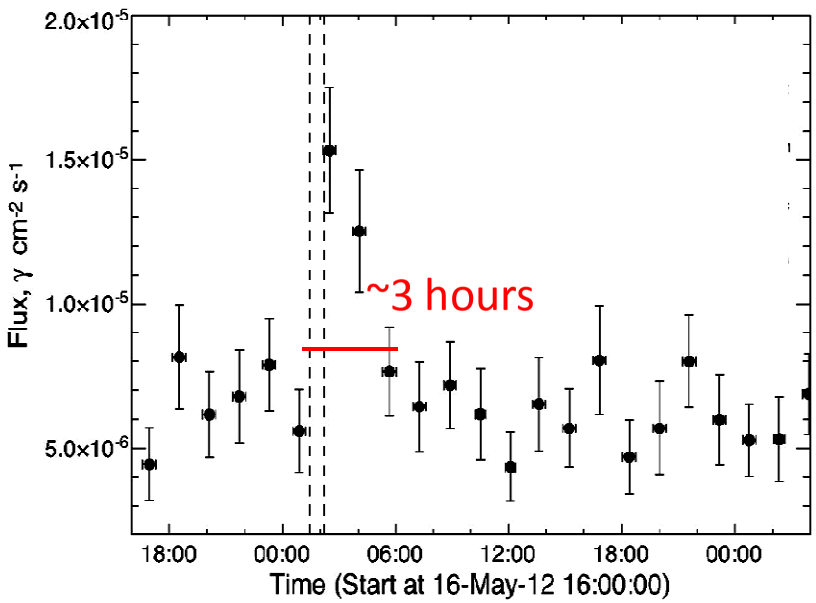
Time-Scale Comparisons:

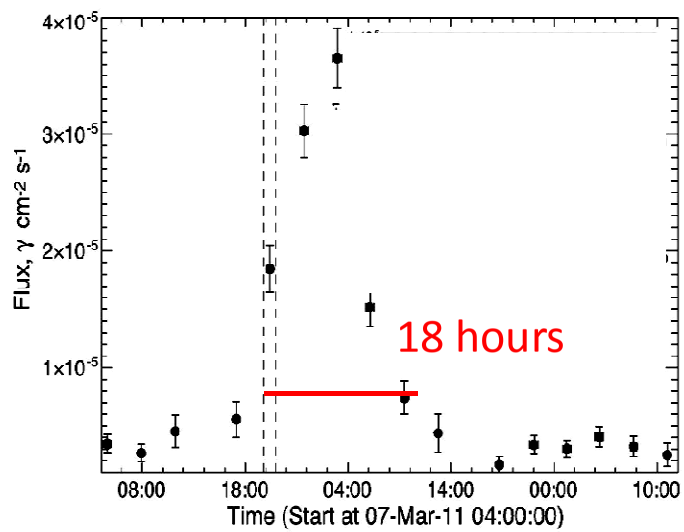
GOES/HEPAD >330 MeV Protons





Fermi >100 MeV gamma-rays

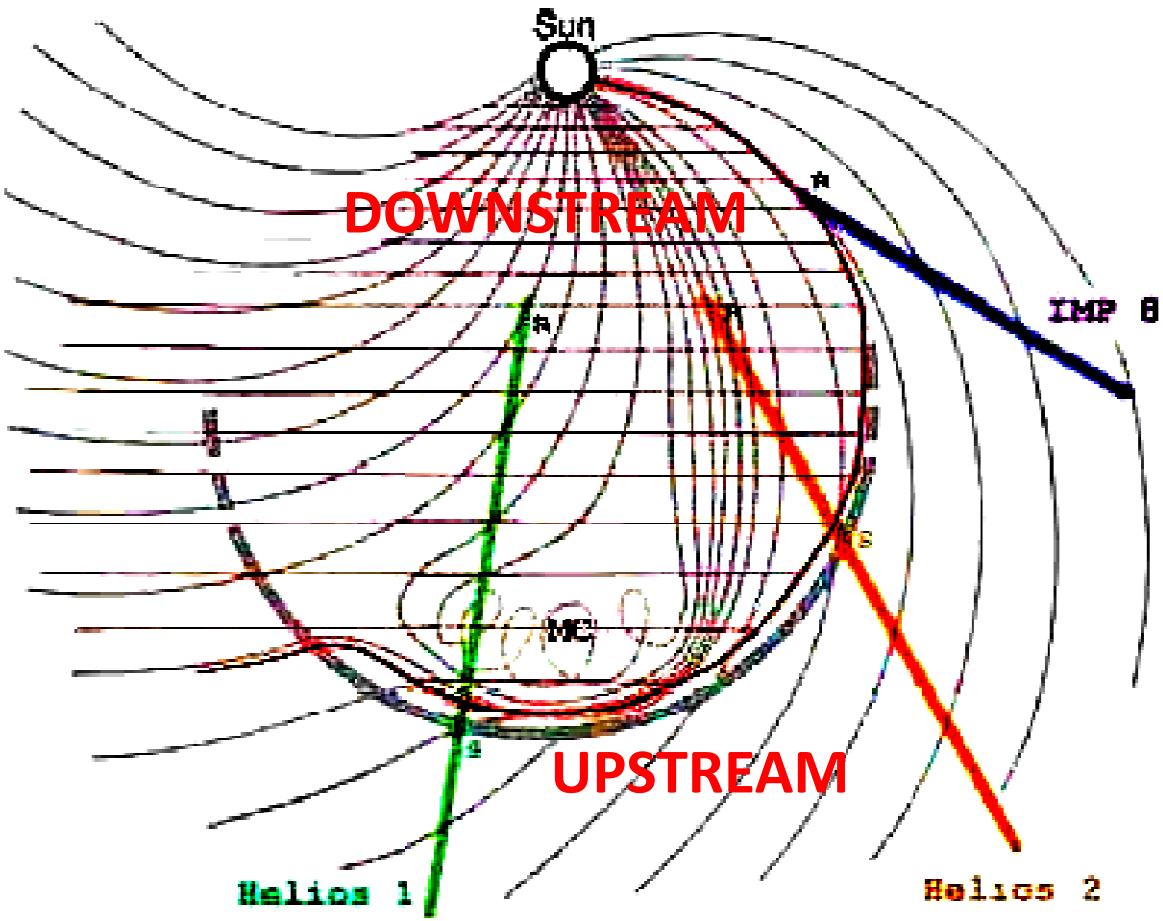




The SEP Reservoir

The CME-driven shock produces SEPs in the upstream region ahead of the shock.

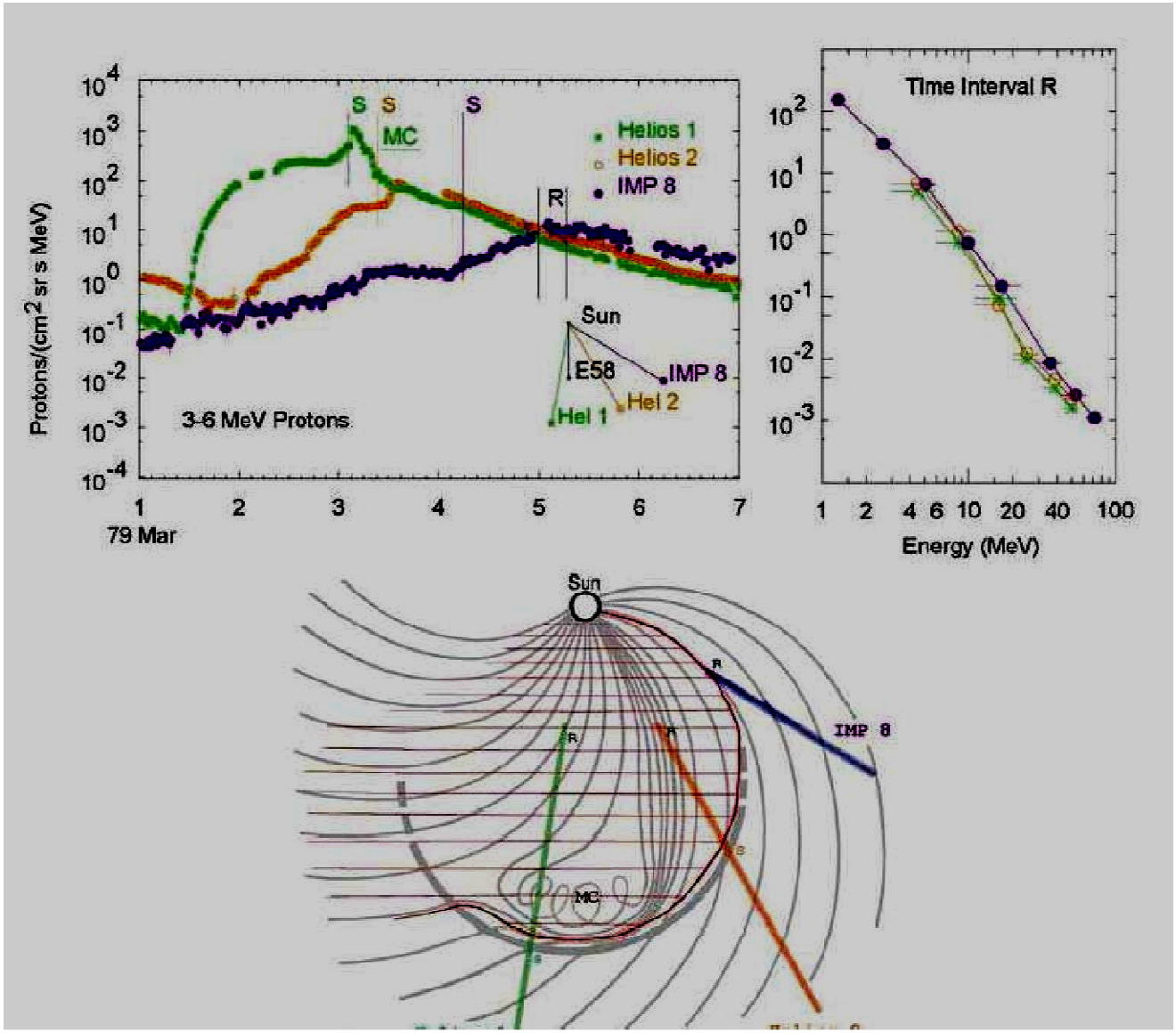
But the CME-driven shock also releases SEPs into the downstream region, where they effectively become trapped in the expanding “bottle” between the Sun and the shock.



The formation of the downstream SEP reservoir was first discovered through multi-spacecraft observations at 1 AU and beyond (McKibben 1972; Roelof et al. 1992, Reames et al. 1996, 1997, 2010, 2013; Lario 2010).

But the formation of the reservoir presumably begins much closer to the Sun.

The SEP Reservoir: *interesting things happen there!*



Cross-field transport occurs in the turbulence in the downstream region, leading to the formation of large-scale intensity and spectral invariance.

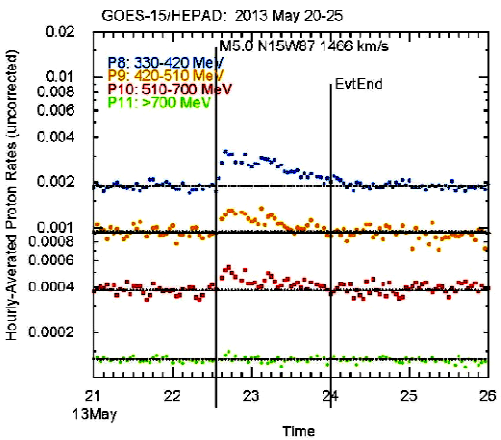
These same processes occur for high energy particles early in the event. Some of the particles in **the nascent reservoir** arrive on field lines that lead them back to the Sun, where they generate the Fermi sustained -emission

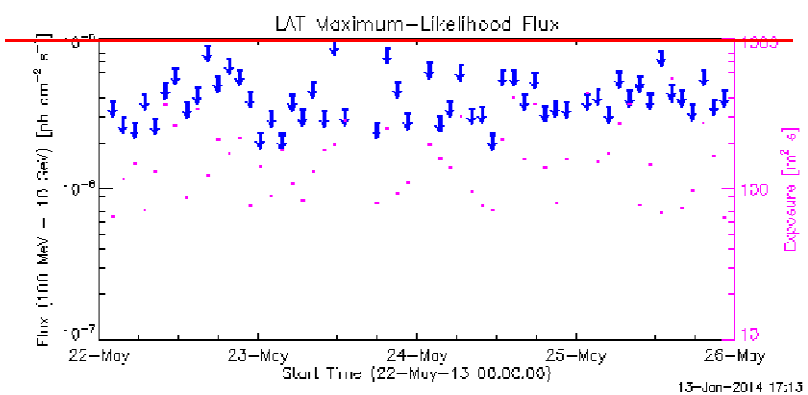
The Devil is in the Details…

2013 May 22

SXR: M5.0, N14W87. CME: 1466 km/s

Seen in HEPAD; but not in Fermi

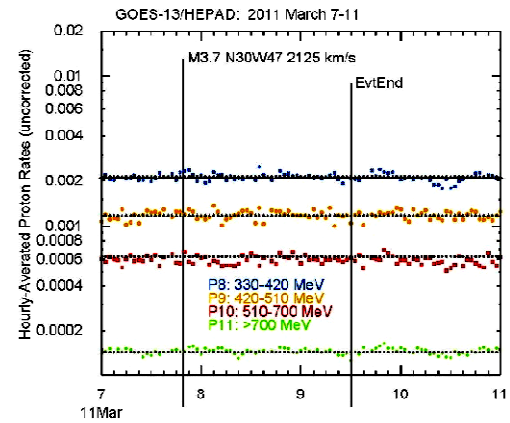


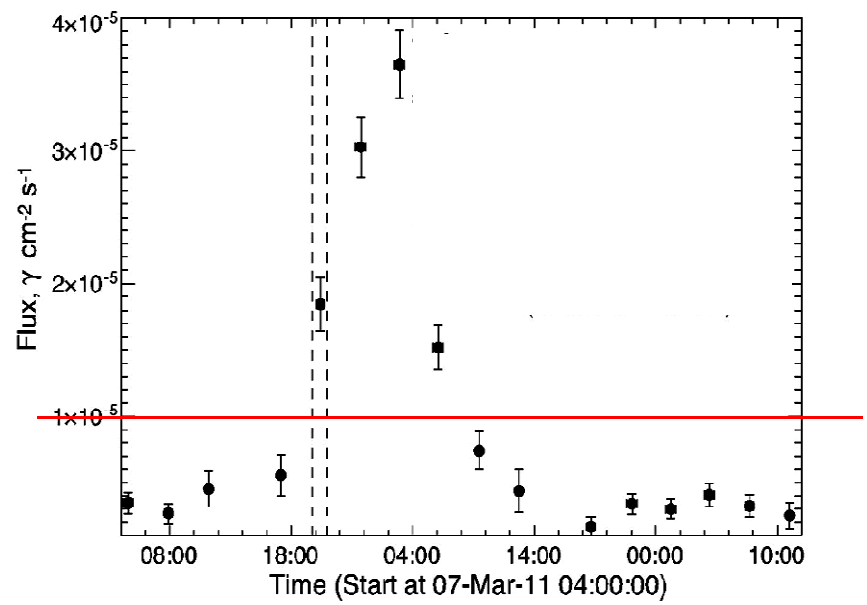


2011 March 07

SXR: M3.5, N30W47. CME: 2125 km/s

Seen in Fermi; but not in HEPAD





Summary

Temporal structure of Fermi observations of >100 MeV solar gamma-rays provide unambiguous evidence for two distinct particle acceleration processes operating at/near the Sun:

- The impulsive flare, coincident with the HXR emission, typically lasting ~10 minutes
- The sustained emission, lasting for ~ 1-20 hours after the HXR emission

We estimated the total number of >500 MeV protons:

in the solar atmosphere (from the >100 MeV gamma-rays) of ~10^{28} to 10^{31}
In interplanetary space (from observations at Earth) of ~10^{29} to 10^{32}

with large event-to-event variation.

Typically, the relative number of >500 MeV protons is

Interplanetary Space : Sustained Emission : Impulsive Flare = 100 : 5 – 10 : 0.1 - 1

The comparatively small number of >500 MeV protons in the Impulsive Flare make it **highly-unlikely that the impulsive flare is a significant contributor to the interplanetary population.**

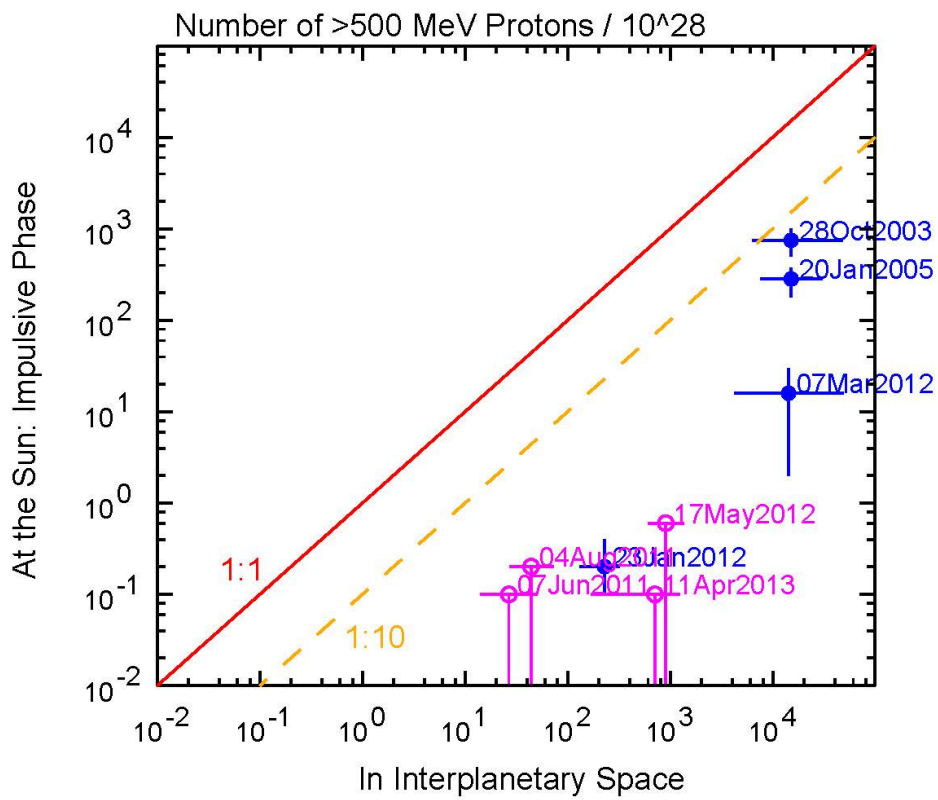
The number of >500 MeV protons in the Sustained Emission make **it highly plausible that they come from the interplanetary population, most likely via the nascent SEP reservoir** that forms downstream of the CME-driven shock,

The CME-driven shock is the primary source of solar energetic protons, both at the Sun and in interplanetary space, even at >500 MeV.

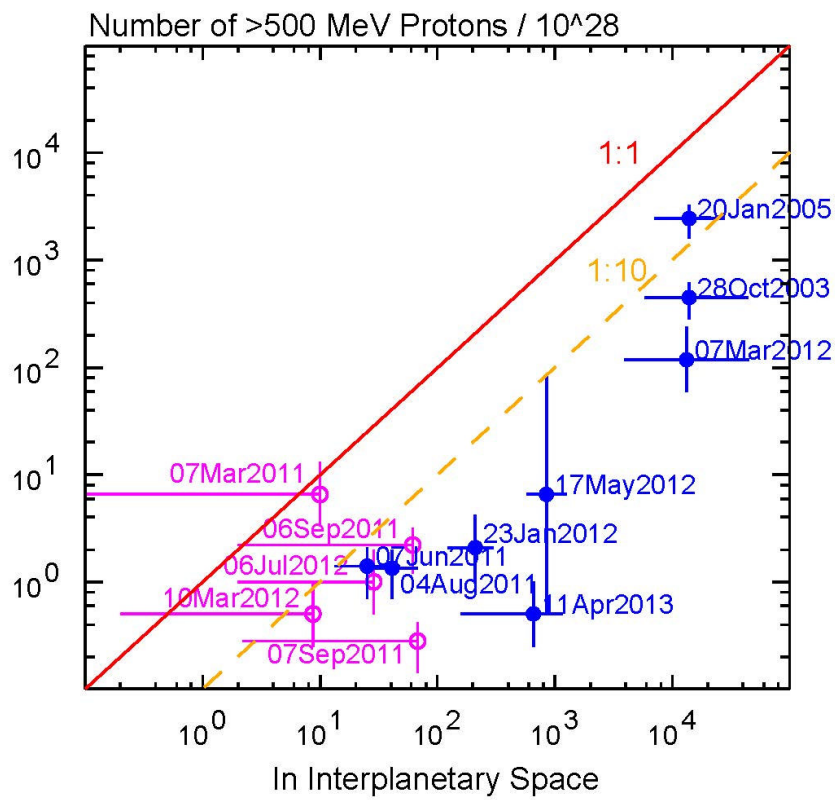
Back-ups

Number of >500 MeV Protons: at the Sun vs. in Interplanetary Space

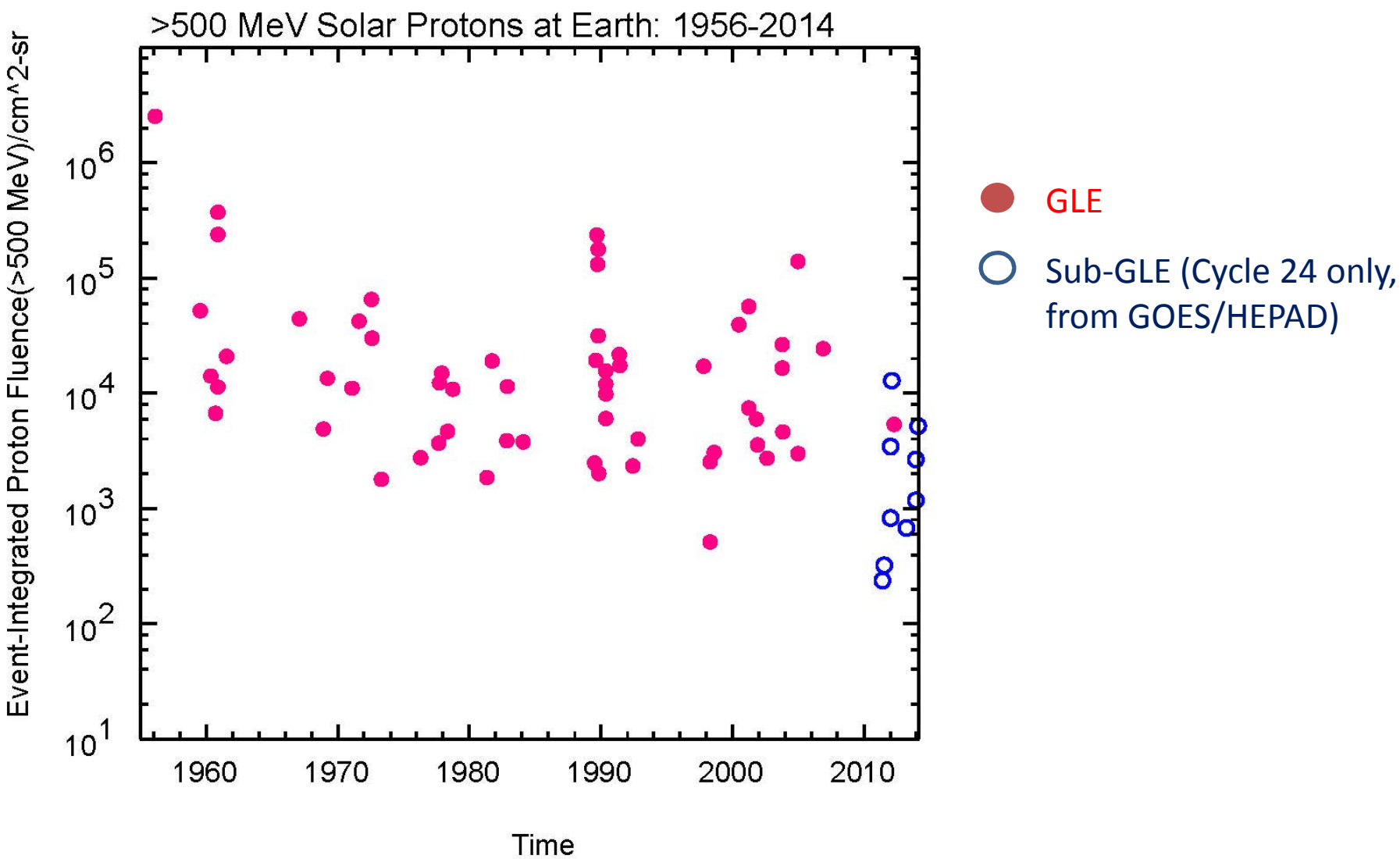
Impulsive Phase of the Flare



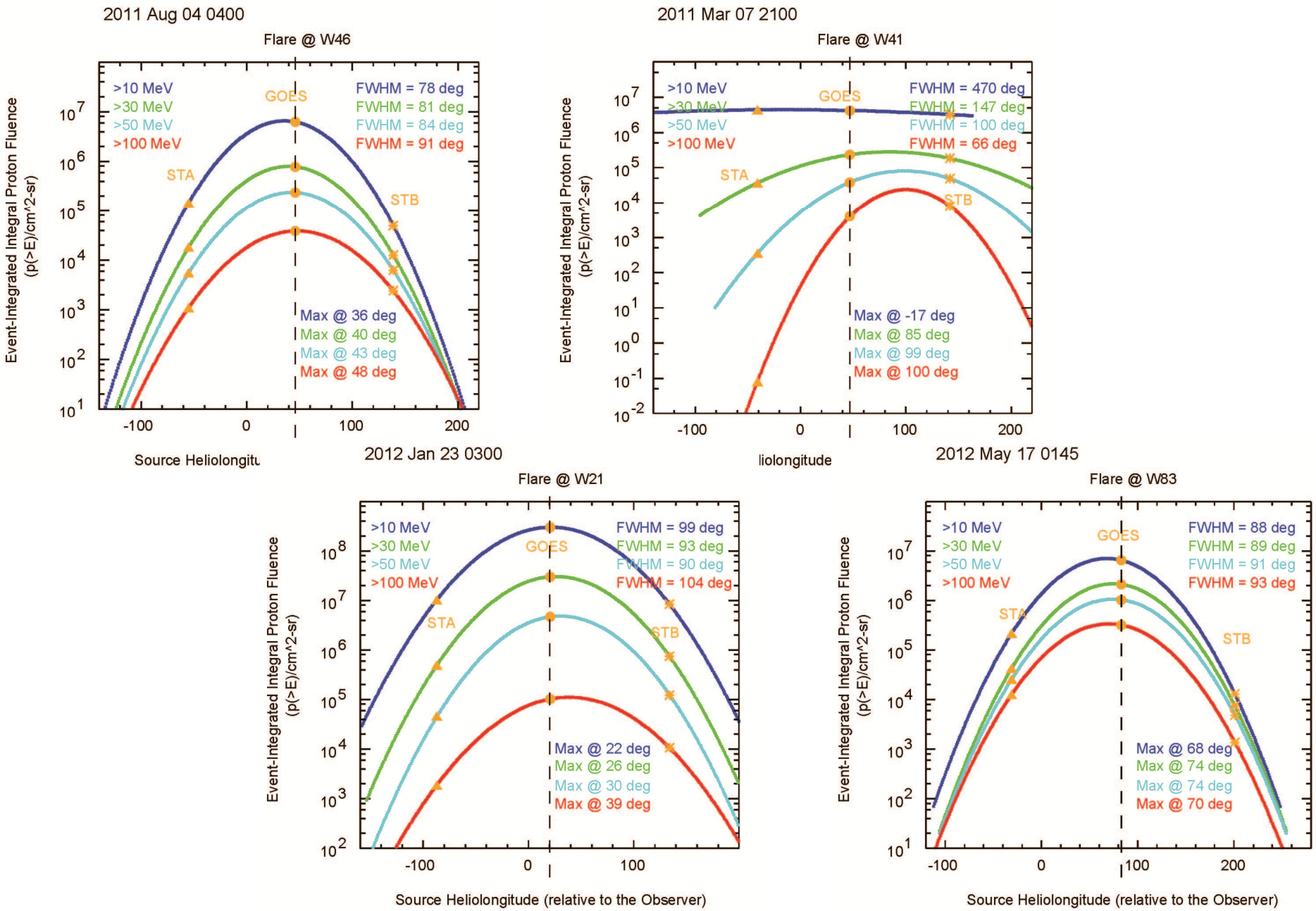
Sustained Phase of the Flare



Cycle 24 has been a disappointment…

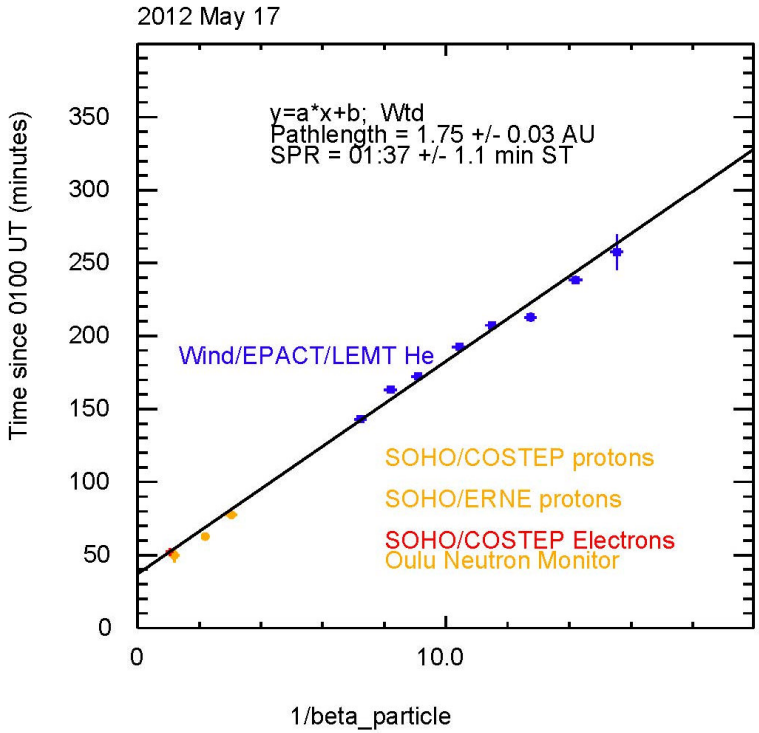


Gaussian Fits to Observed Longitude Distributions

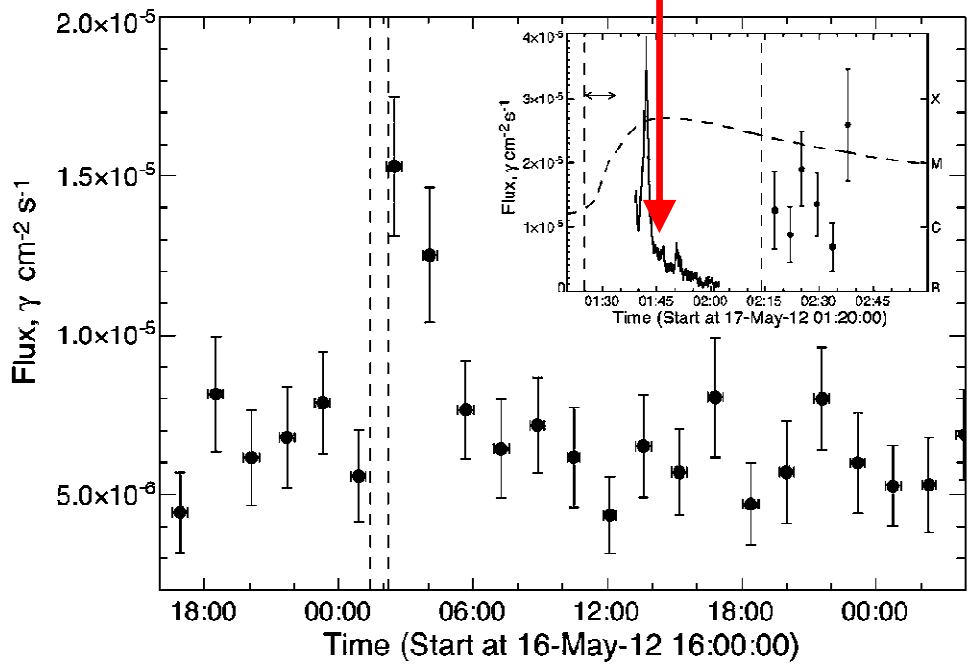


Onset Timing in the 2012 May 17 Ground-Level Event

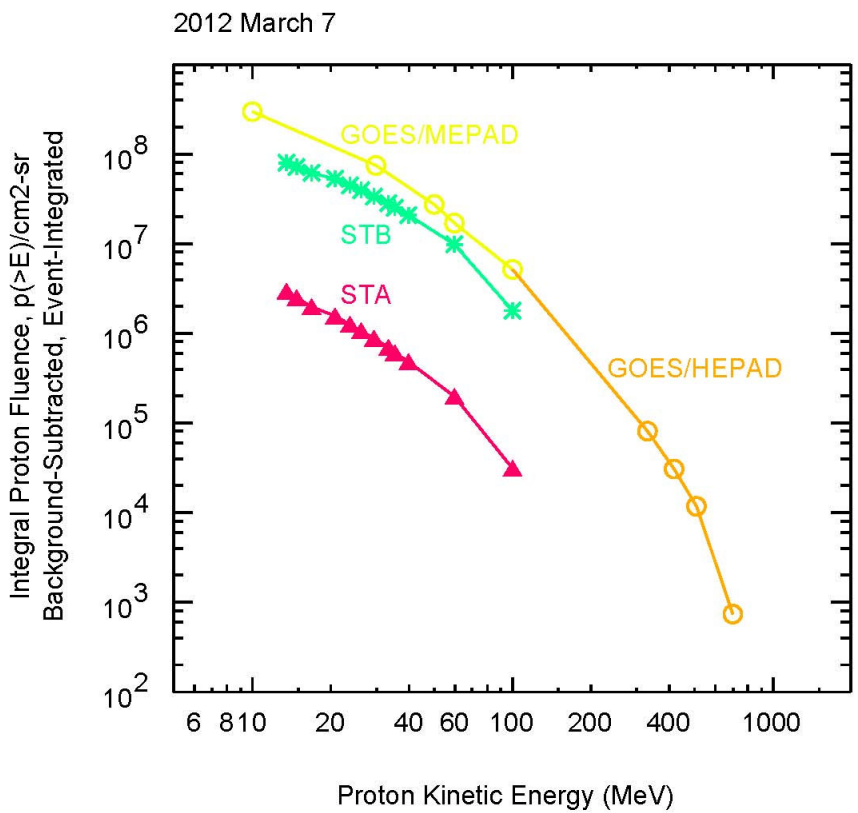
SEP Velocity Dispersion Analysis

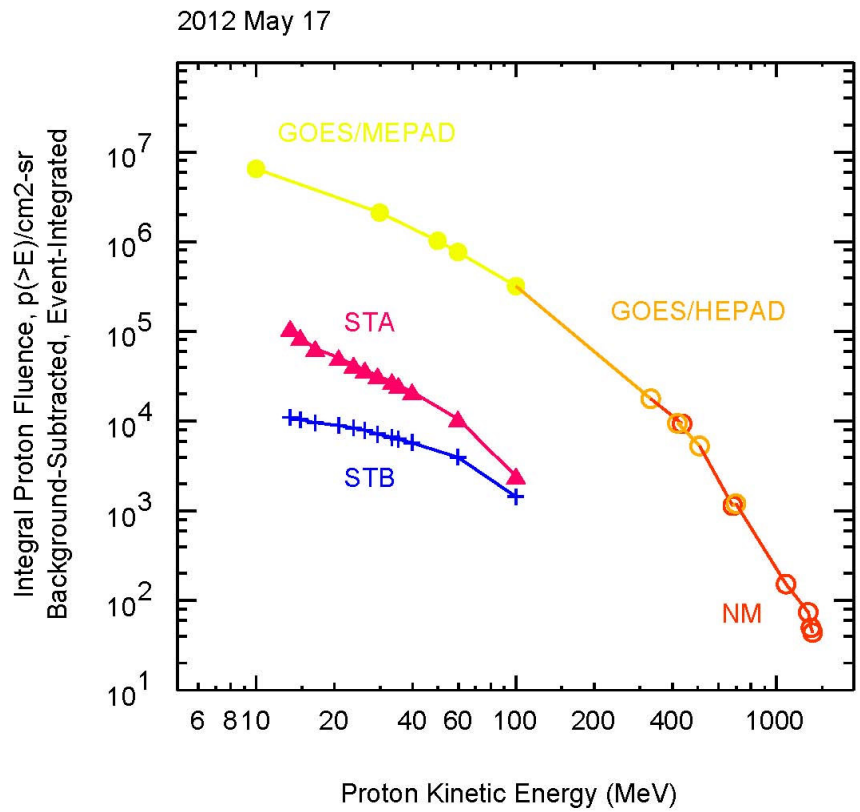


Solar Particle Release:
01:45.3 UT ± 1.1 minutes

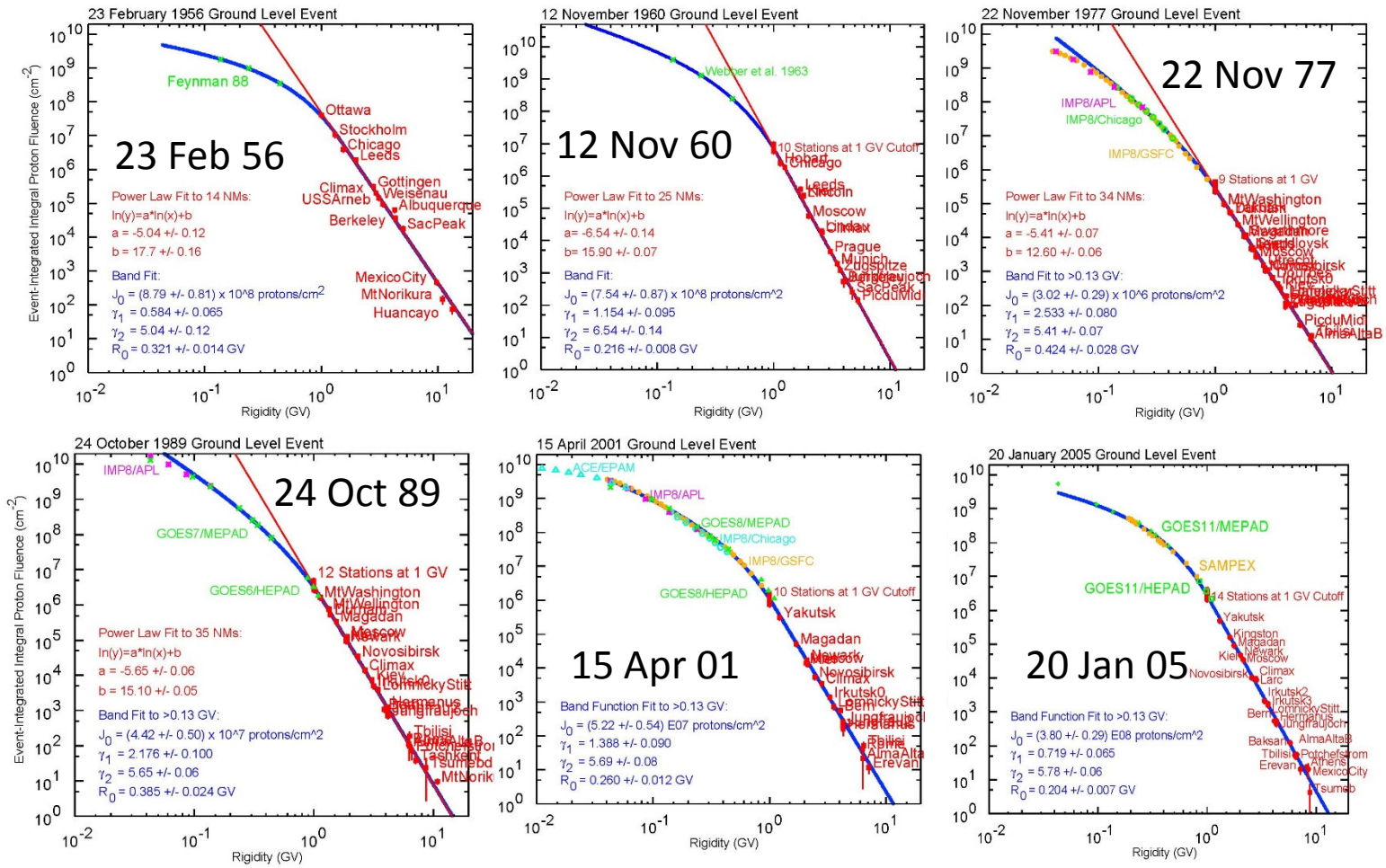


Compare: 2012 March 7 (non-GLE) and 2012 May 17 (GLE)





Band-Function Fits to Event-Integrated GLE Spectra at 10 to ~5000 MeV



- We have combined satellite/riometer and neutron-monitor data to derive absolutely normalized, event-integrated proton spectra for GLEs.
- Spectra have been derived for 59 (out of 67) GLEs since 1956.
- See Herbst et al. (SH31C-07) for another application of our GLE catalogue.

Interplanetary Protons: Spatial Distribution

2012 May 17 Solar Energetic Protons from STEREOs and GOES