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

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OUTLINE:

(1) Motivations: Applications & Physics
(2) GOES/HEPAD: strengths & weaknesses, viz a viz AMS-02 & Pamela
(3) Results:

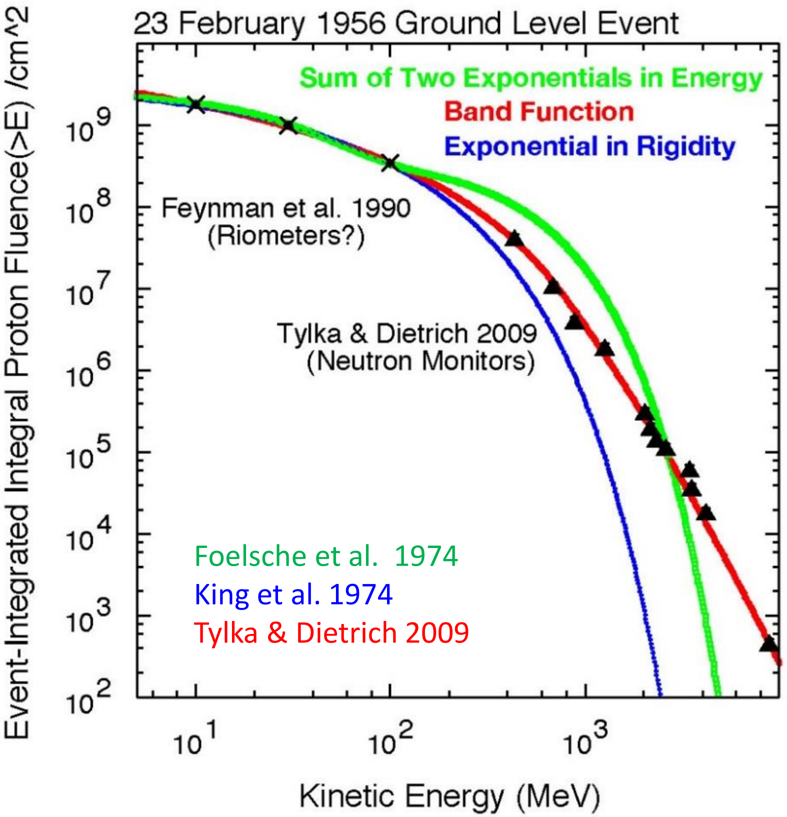
AMS-02 Workshop
22 October 2015

5:05 PM

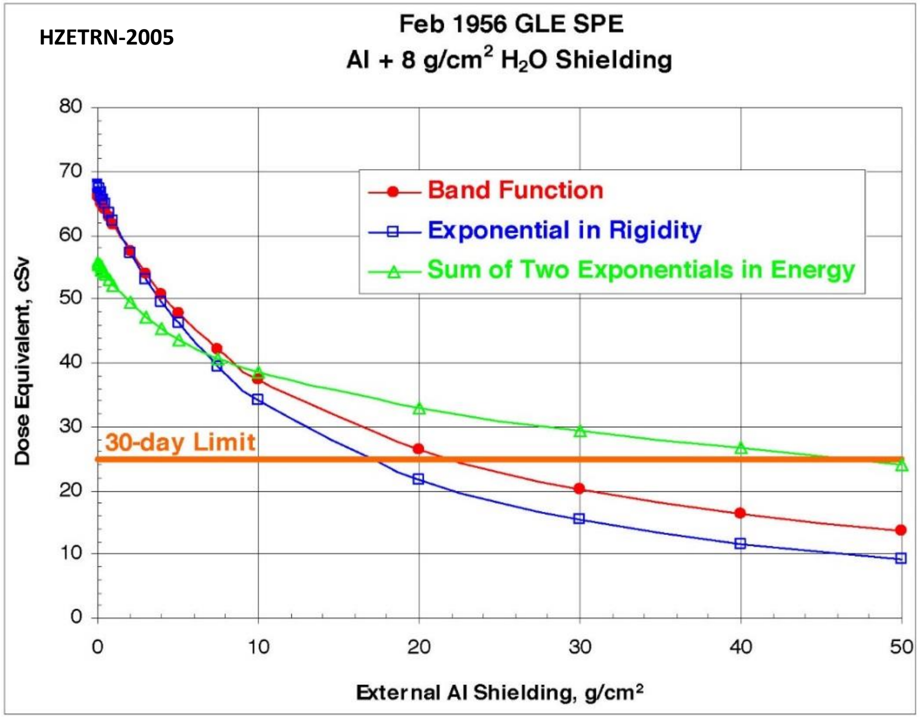
Radiation Hazard from High-Energy SEPs

➢ Designing a "Storm Shelter" for Astronauts

Solar-Proton Energy Spectrum

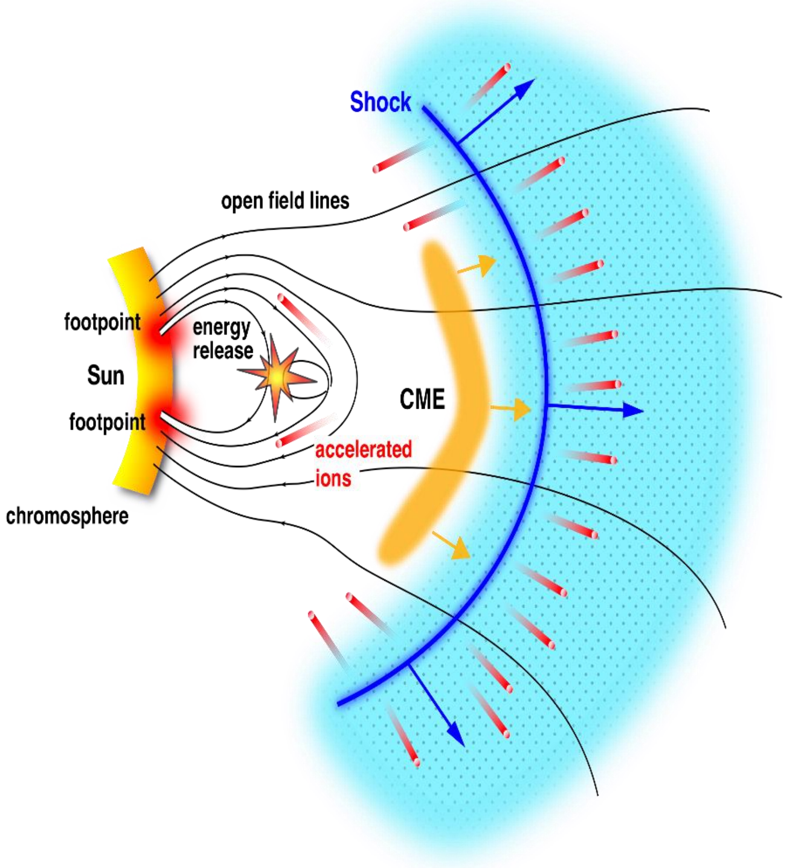


Dose-Depth Curves



Inaccurate spectral forms can lead to either under- or over-estimate of shielding required to reduce dose to an acceptable level.

Overview



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

- at the coronal reconnection site that launches the CME (the 'flare')
- 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 **quantitative** avenue of investigation.

- Gamma-rays are produced by energetic particles impinging on the solar atmosphere.

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

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

NOAA /GOES/ HEPAD

NOAA: National Oceanic and Atmospheric Administration
GOES: Geostationary Operational Environment Satellite
HEPAD: High Energy Proton and Alpha Detector

- **HEPAD** measures protons above ~330 MeV and alphas above ~ 640 MeV/nuc, using a Cerenkov detector
- Also on GOES: “**EPS**” (aka “**MEPAD**”) instrument measures ~1-100 MeV protons

HEPAD strengths:

- In geostationary orbit:
  - No geomagnetic cutoff losses or magnetospheric background for >10 MeV protons
- GOES spins: 100 rpm, ~axis parallel Earth rotation axis
  - Particle instruments have axes perpendicular to the spin axis
  - HEPAD Conical FOV: +/- 35 degrees
  - Captures particles from ~60 % of the sky

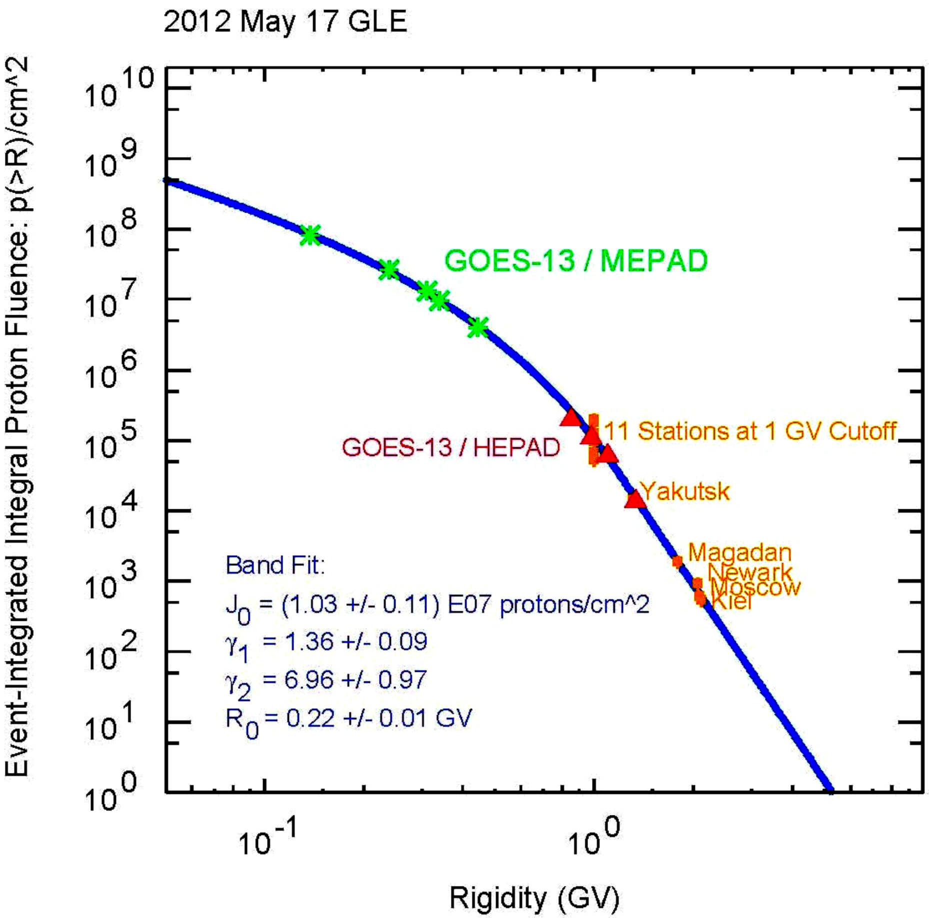
  Continuous, nearly-omnidirectional particle measurements

HEPAD weaknesses:

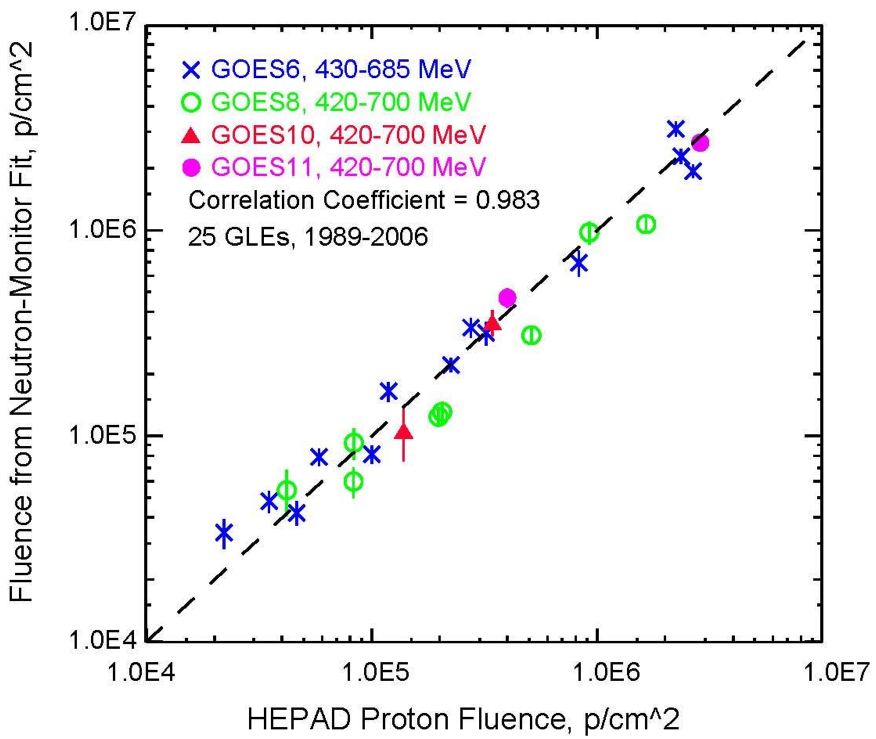
- Small: 0.73 cm^2-sr, compared to PAMELA (20 cm^2-sr) and AMS-02 (4500 cm^2-sr)
- Poor Energy Resolution: 4 wide, non-uniform energy bins
- High GCR background through sides and back of instrument.

How reliable is GOES/HEPAD?

Neutron Monitors and GOES/HEPAD



NMs vs. HEPAD: 25 GLEs, 1989-2006



HEPAD data from NGDC

Reprocessed per Sauer Memo (unpublished, 2007)

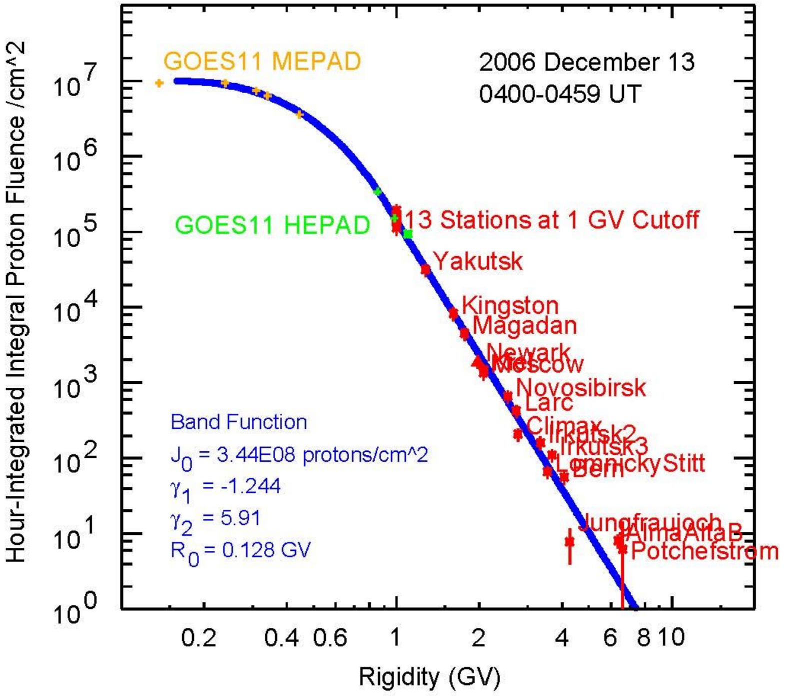
Independent of the NM analysis

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

How reliable is GOES/HEPAD?

Another Validation Study:
Proton Measurement from PAMELA on 2006 December 13
(Second Hour of the Event ~4-5 UT)

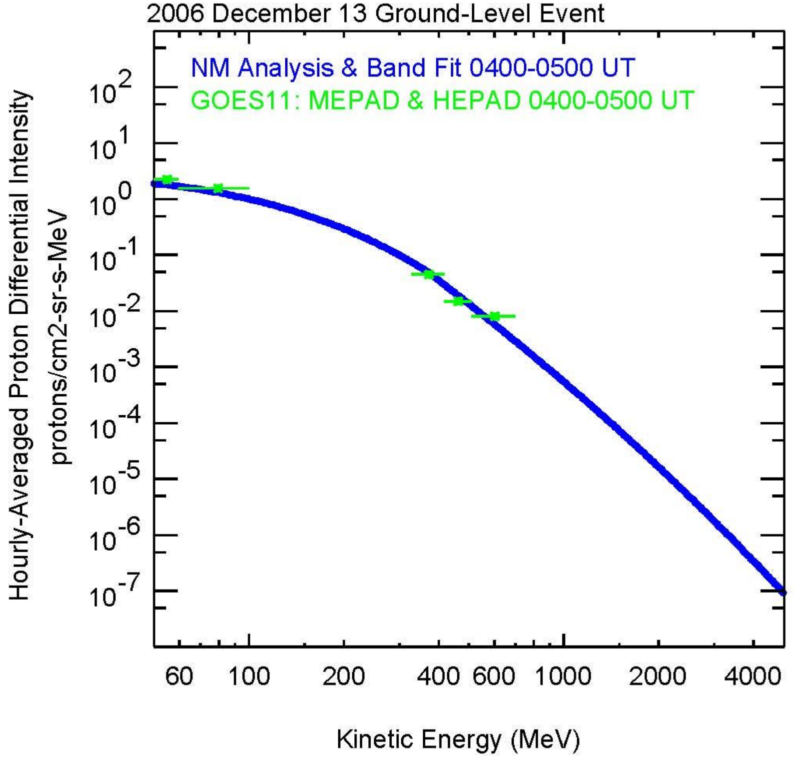
Integral Spectrum in Rigidity
(our analysis)



differentiate

divide by $4\pi\beta(E)\Delta t$

Differential Spectrum in Energy



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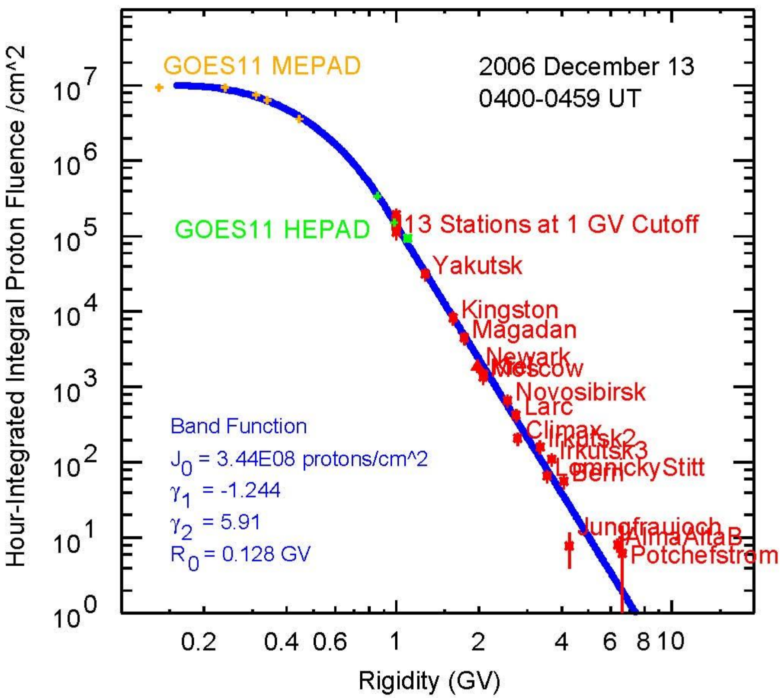

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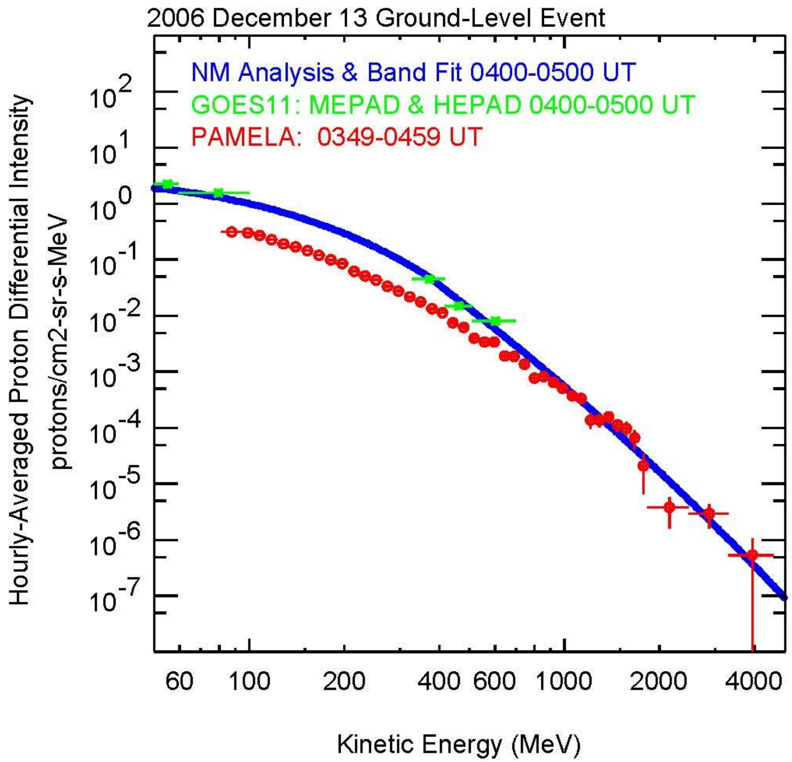
Differential Spectrum in Energy



- Excellent agreement between PAMELA and our NM analysis above ~800 MeV.
- At lower energies, factor ~2 disagreement between PAMELA and GOES.
- *Thanks to Prof. Marco Cassolino for providing these preliminary(?) PAMELA data.*

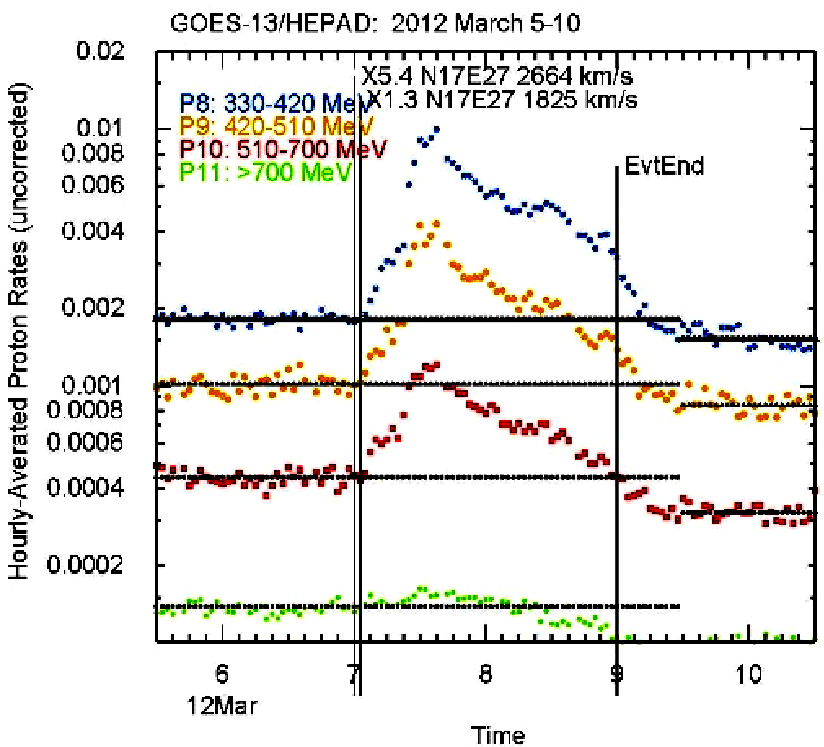
>500 MeV Solar Protons in Interplanetary Space in Cycle 24

Measurements of >500 MeV solar protons are ***available only at Earth***:

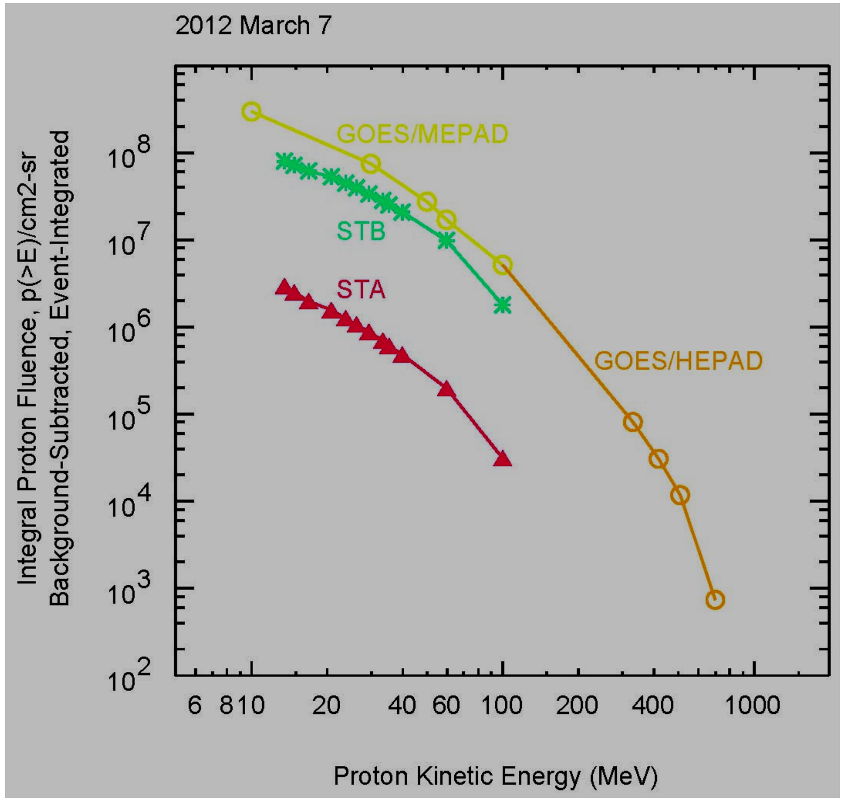
- Neutron monitors in Ground-Level Events (GLEs)
- **GOES/HEPAD: We use these data.**
- PAMELA & AMS-02: ***We're eager to see them!***

The Very Large Event of 2012 March 7

Intensity vs. Time



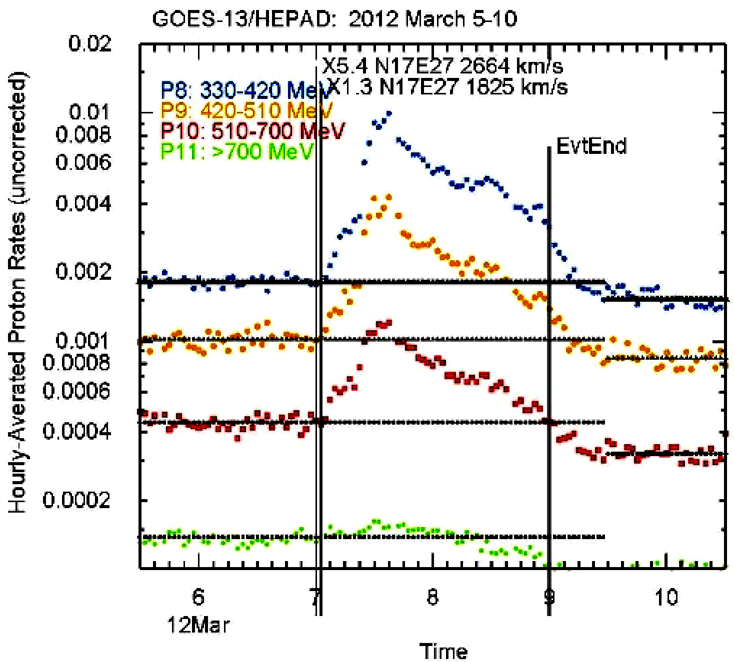
Event-Integrated Proton Spectrum

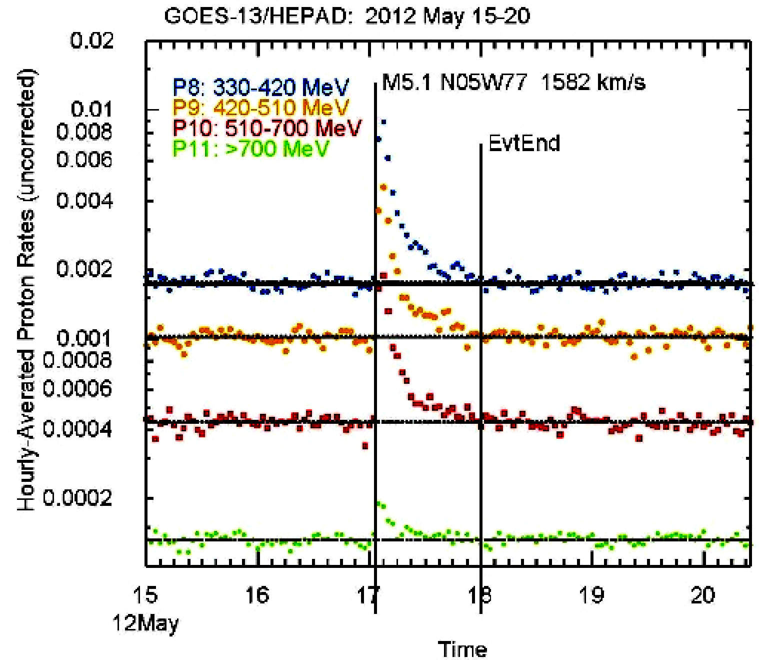


2012 March 7

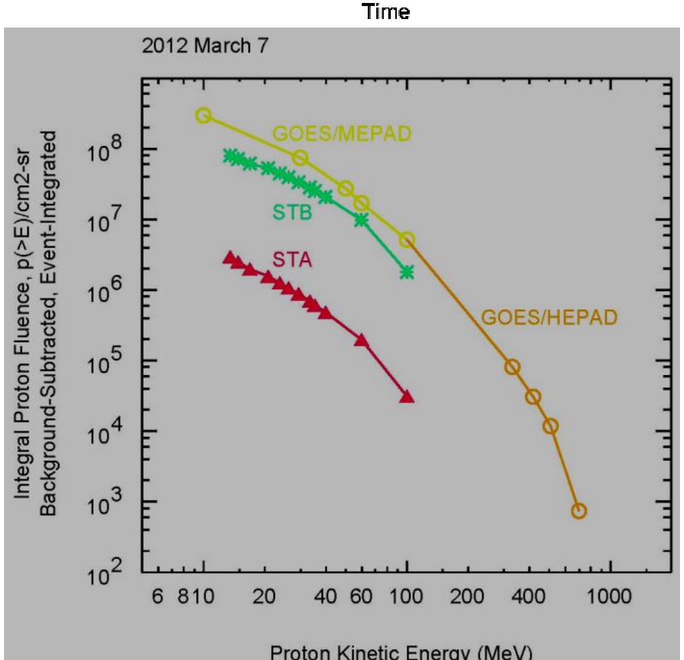
2012 May 17

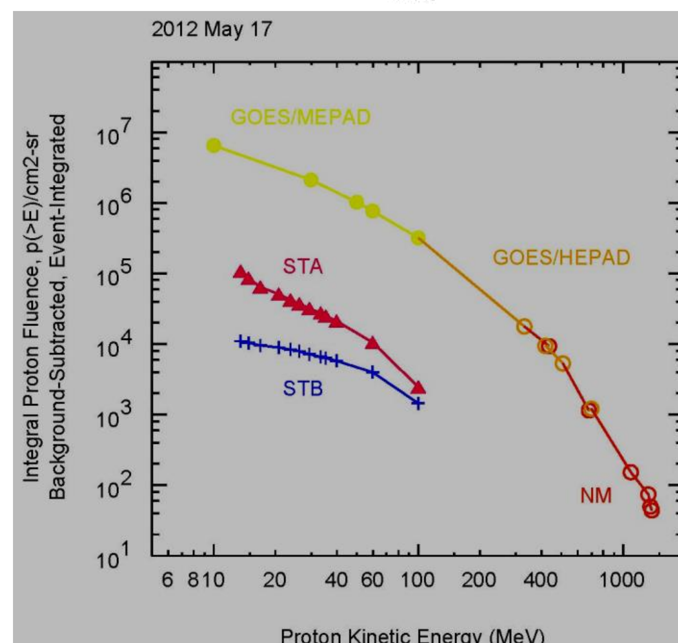
Intensity vs. Time



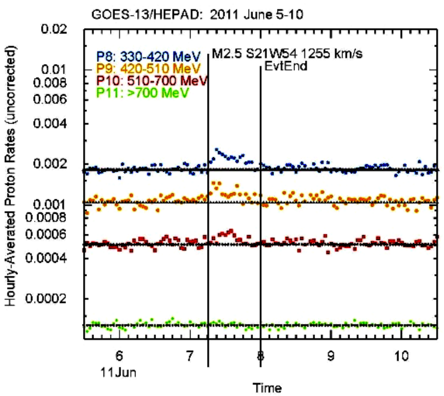


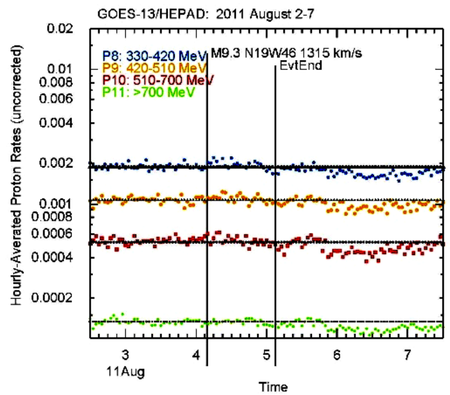
Event-Integrated Proton Spectrum

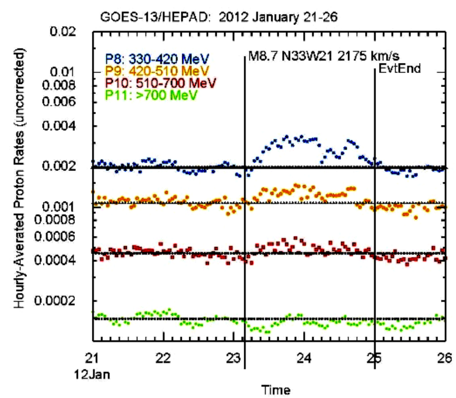


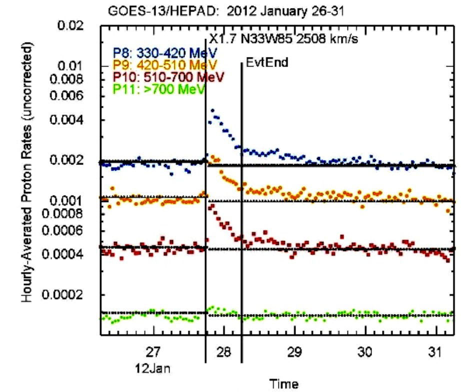


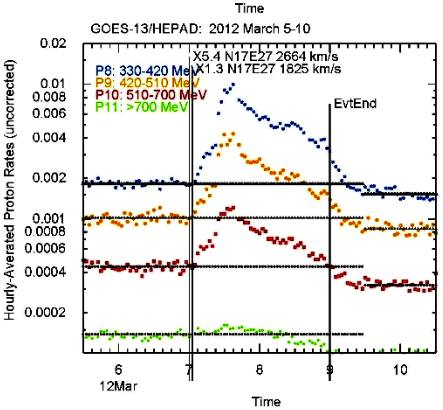
>500 MeV Protons from GOES/HEPAD: January 2008- February 2014

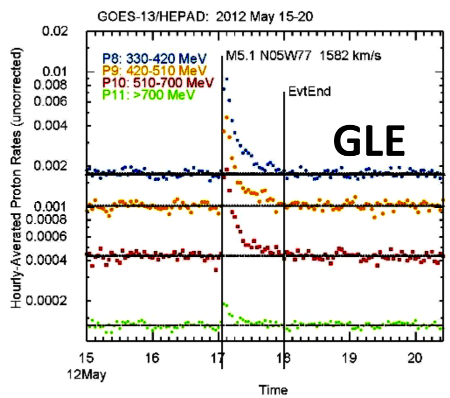


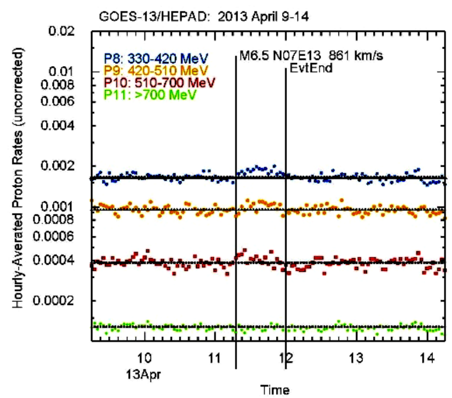


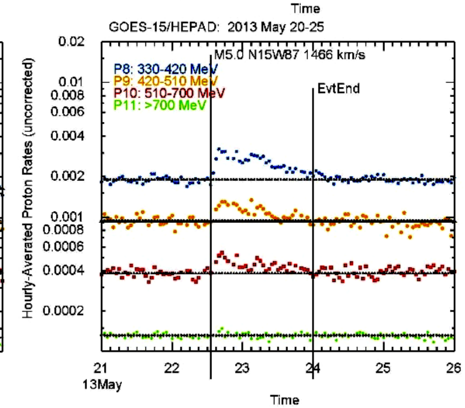


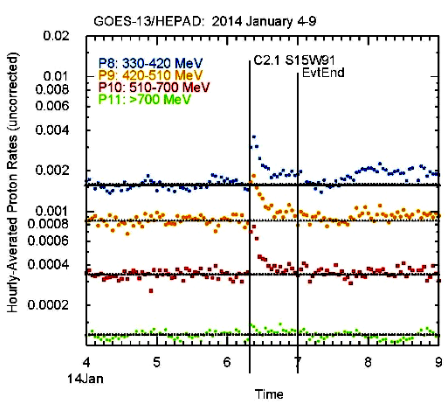


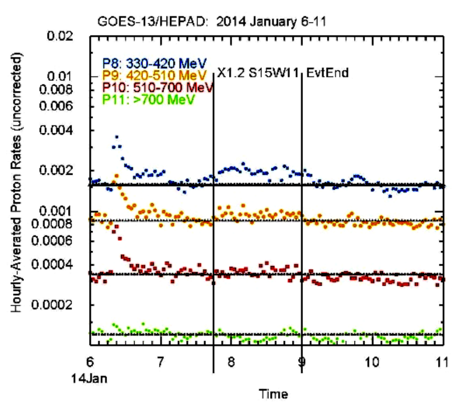


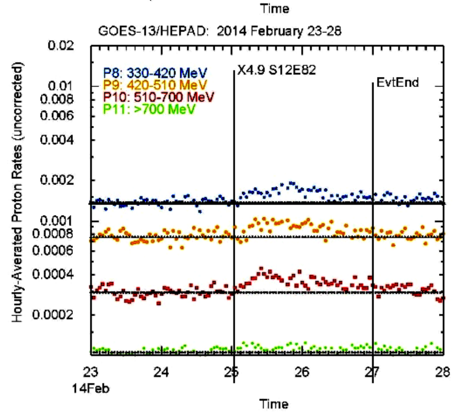






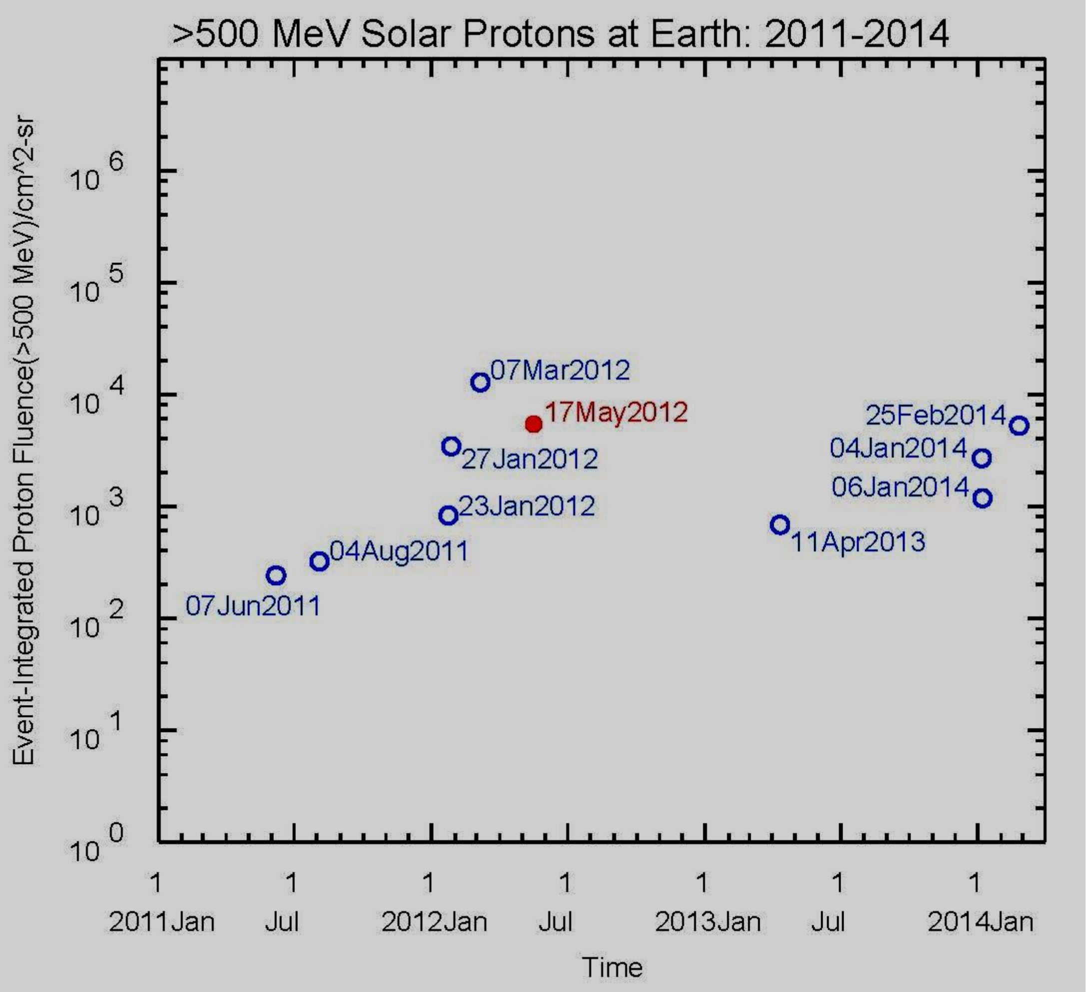






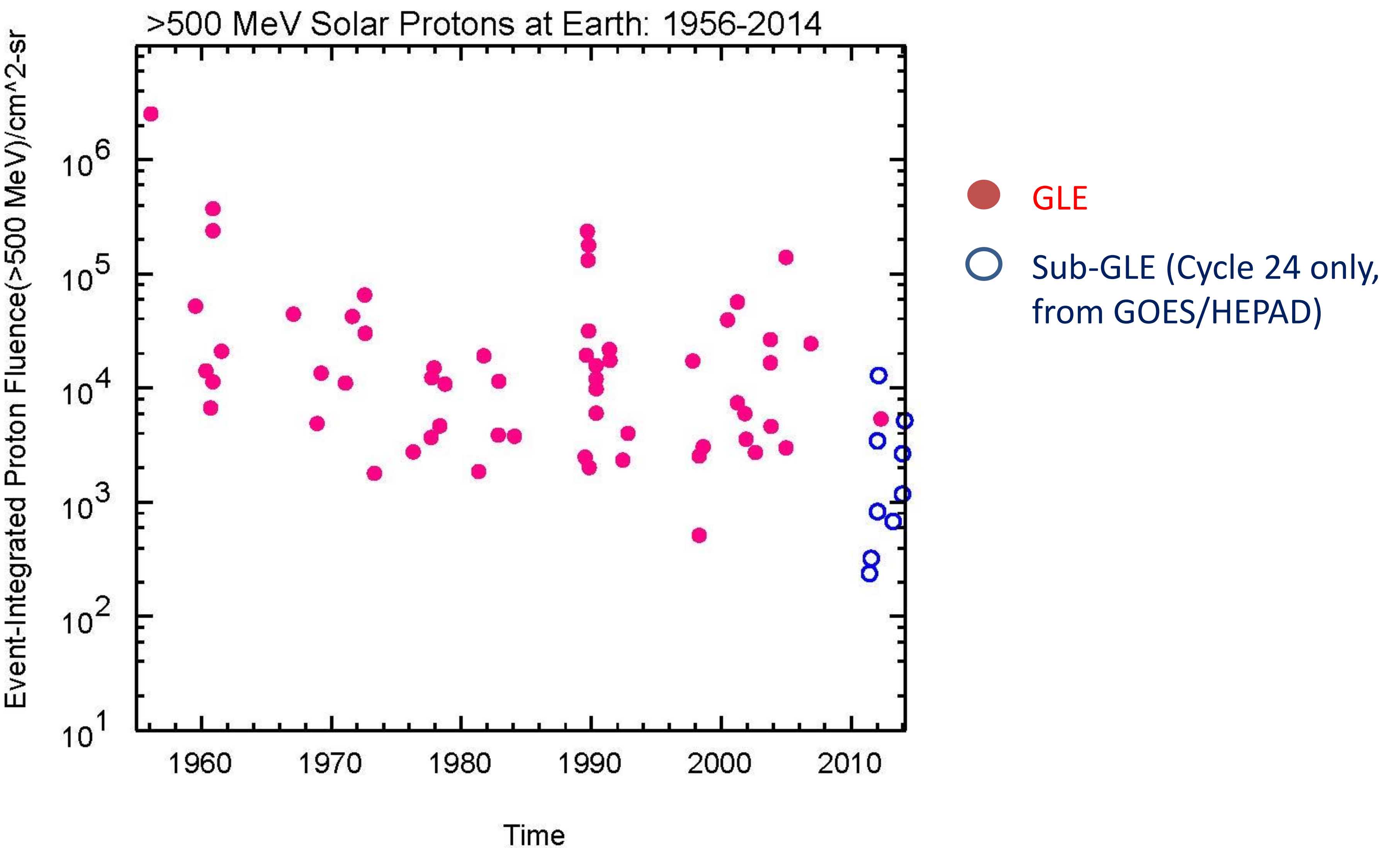
All of these events also observed by AMS-02, plus at least 7 more.

Results



>500 MeV Solar Protons at Earth: 2011-2014
Event-Integrated Proton Fluence(>500 MeV)/cm^2-sr
10^6
10^5
10^4
10^3
10^2
10^1
10^0
07Mar2012
17May2012
27Jan2012
23Jan2012
04Aug2011
07Jun2011
25Feb2014
04Jan2014
06Jan2014
11Apr2013
1 2011Jan
1 Jul
1 2012Jan
1 Jul
1 2013Jan
1 Jul
1 2014Jan
Time

Cycle 24 has been a disappointment…



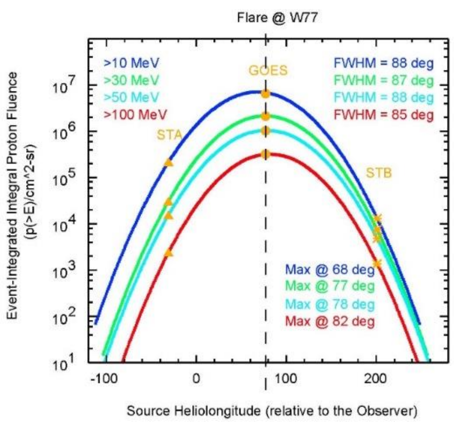
The gamma-ray analysis estimates the TOTAL NUMBER of protons IN THE SOLAR ATMOSPHERE.
We need an analogous estimate of the TOTAL NUMBER of protons IN INTERPLANETARY SPACE.

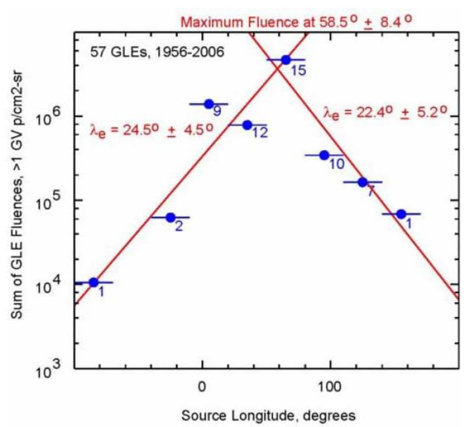
We adopt a heuristic approach to this problem (Mewaldt et al. 2005):

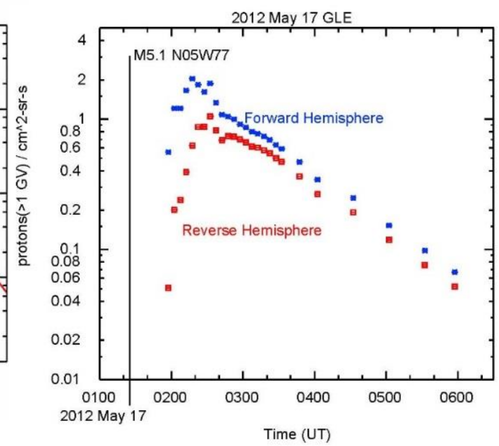
What we measure

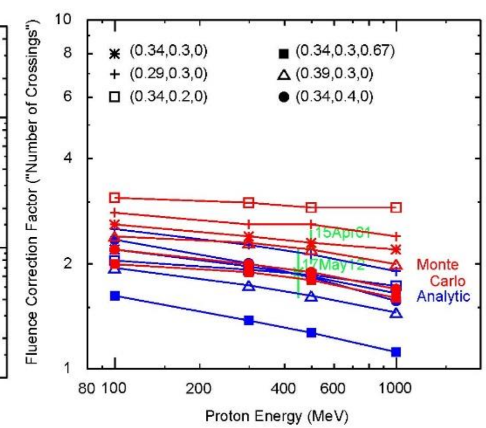
Calculated Correction Factors

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









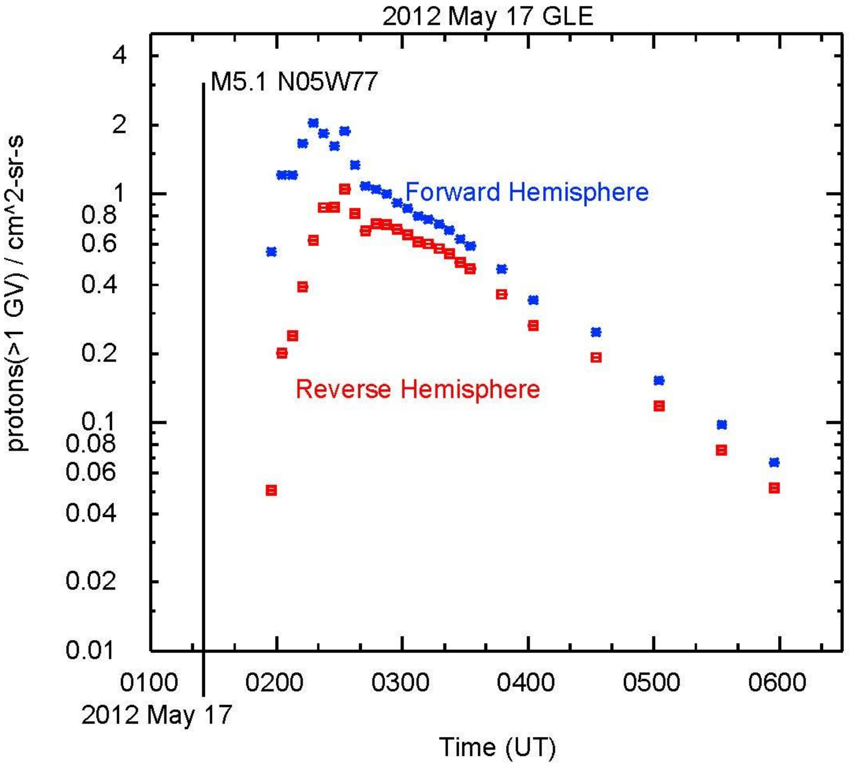
We have approached these correction factors in a variety of ways, using both observations and theoretical modeling, and combining both recent data (from STEREO) and the 60-year historical record from neutron monitors.

Correction factors are determined to within modest systematic uncertainties (typically factor of ~2, larger in a few events).

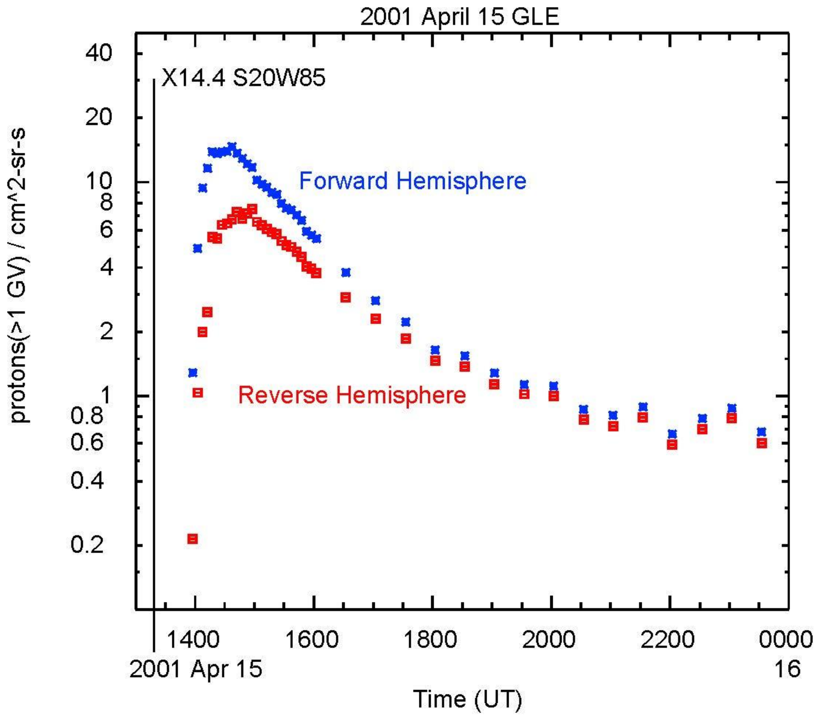
Interplanetary Protons: "Crossing Correction" at >500 MeV

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

$C_x = 1.9 \pm 0.3$



$C_x = 2.3 \pm 0.3$



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

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

Analytic & Monte Carlo Calculations

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

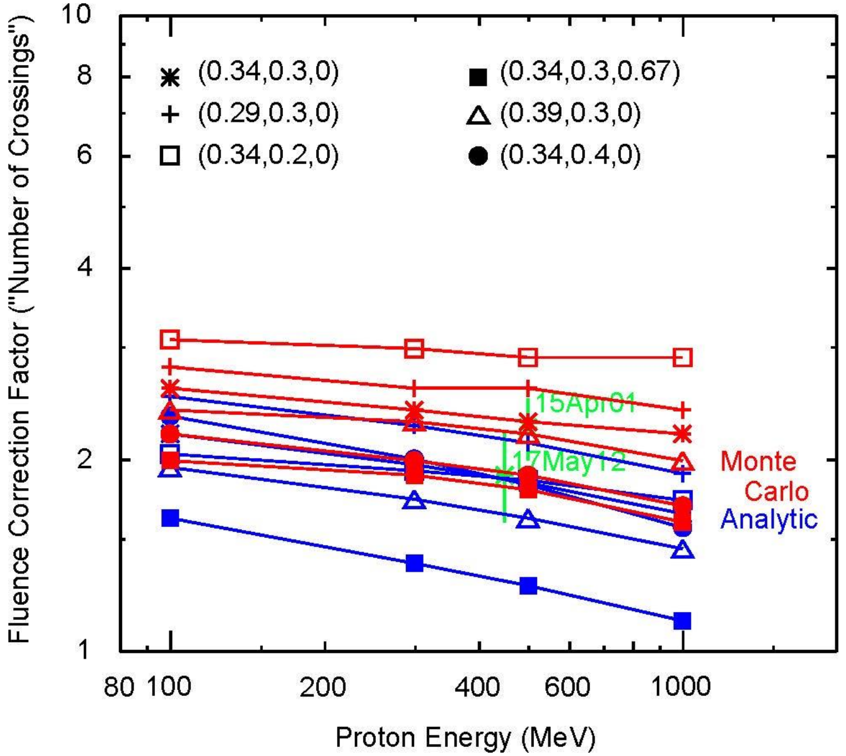
- **Delta-function injection of particles at the Sun, i.e. short duration**
- **IP transport according to:**
  - $\lambda = \lambda_0 \, (P/GV)^{\alpha} \, (R/AU)^{\beta}$

  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.

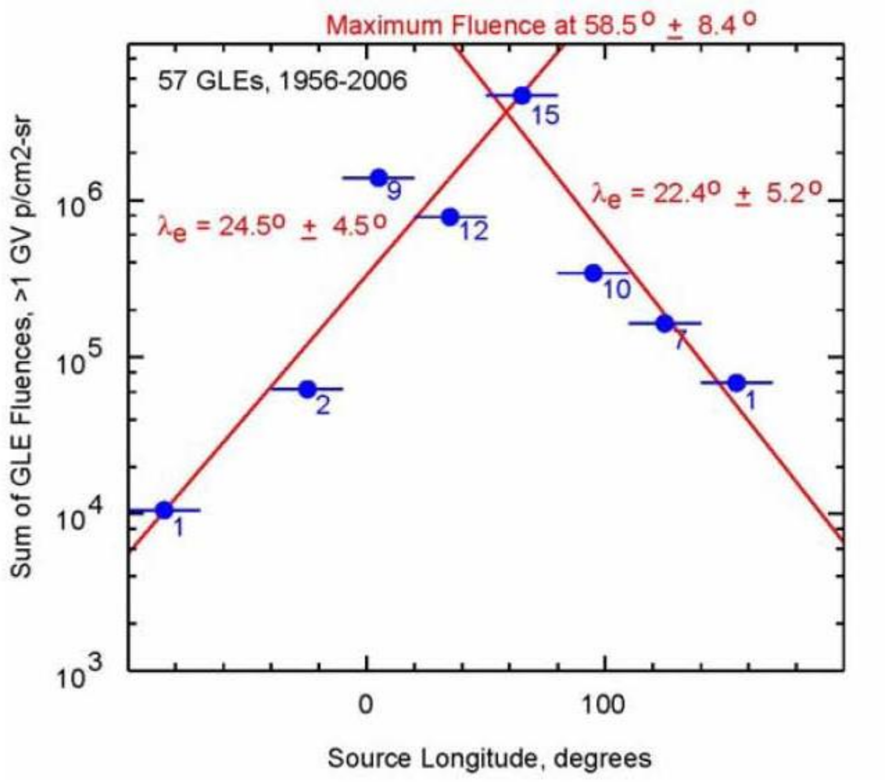


Analysis of NM data and two different theoretical techniques all confirm C_x ~ 2, with a <2 factor of systematic uncertainty

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

Interplanetary Spatial Distribution: From GLEs

57 GLEs 1956-2006



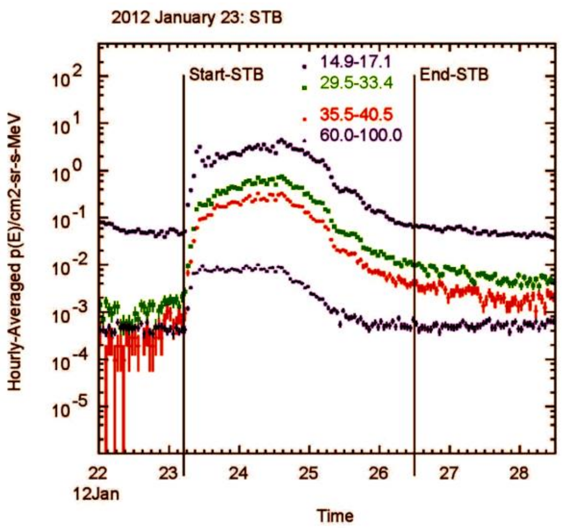
Distribution centered at $\Phi_0 = 58^o$

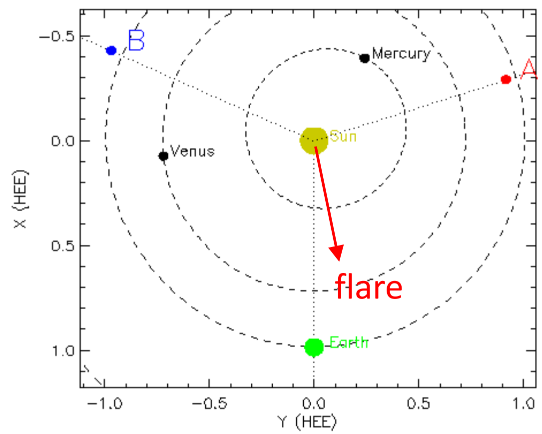
Symmetric fall-off $\Lambda_\Phi = 23^o$

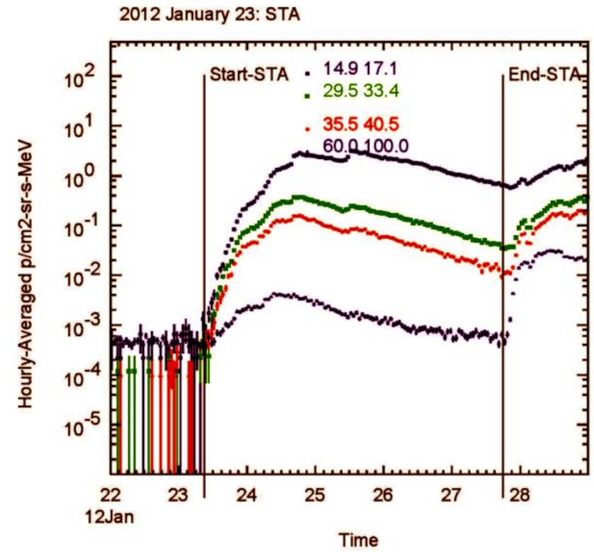
$J(\Phi) = J_0 \exp(-|\ \Phi-\Phi_0\ |/\Lambda_\Phi) \rightarrow C_{spatial}$

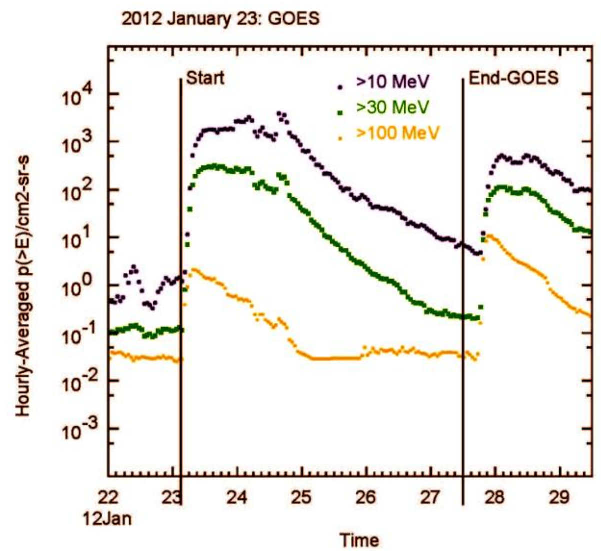
Interplanetary Spatial Distribution: from STEREO & GOES

2012 January 23 Solar Energetic Protons from STEREOs and GOES

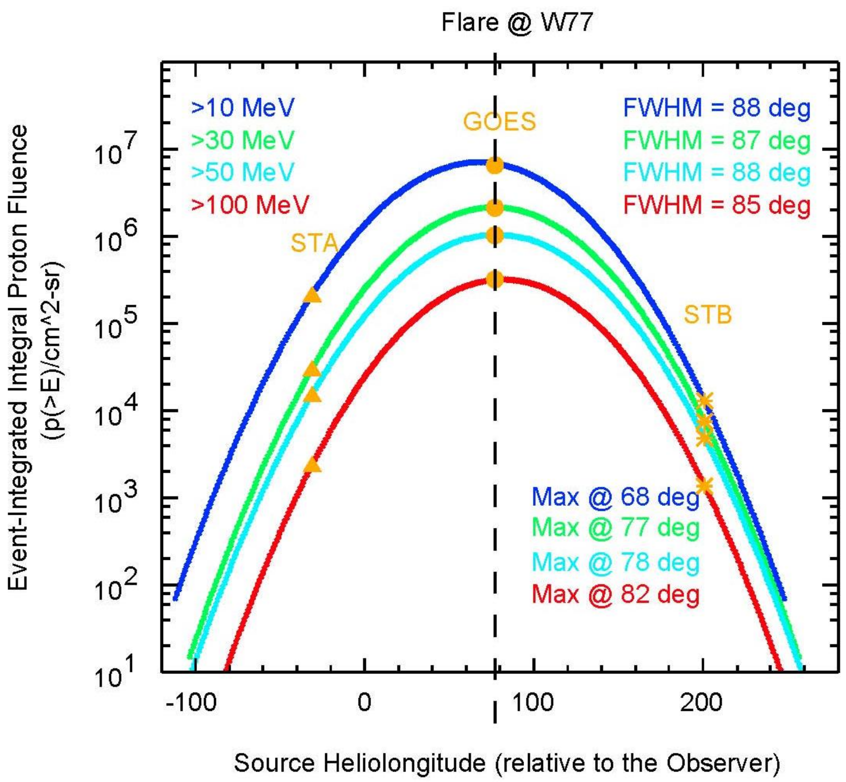








Interplanetary Spatial Distribution: from STEREO & GOES



Note: STEREO measures protons only up to 100 MeV. We use a power-law fit at 30-100 MeV to *estimate* >100 MeV fluence at STEREOs.

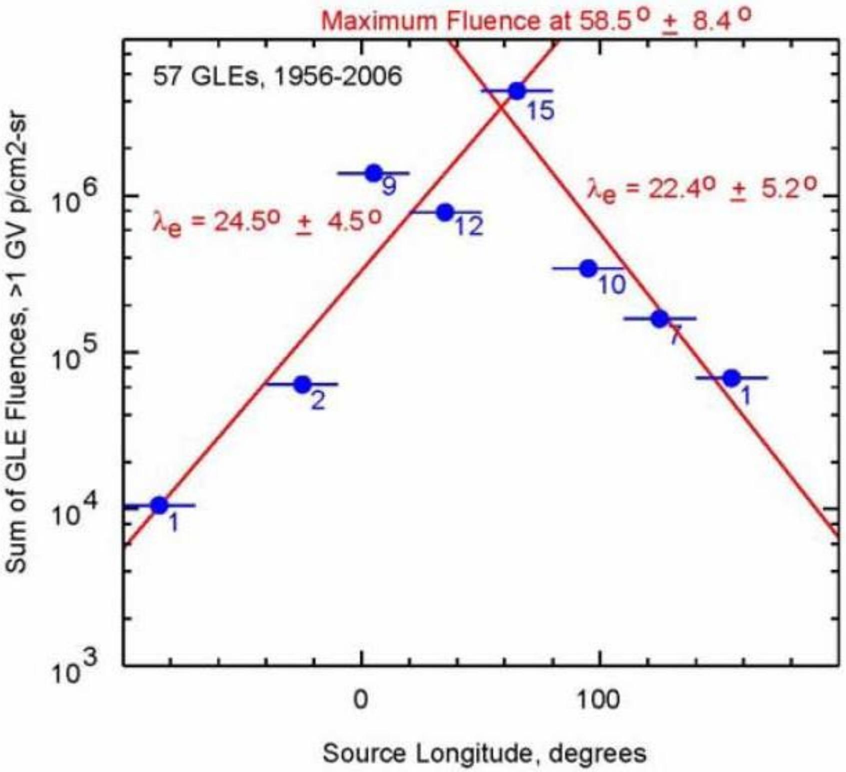
Gaussian fits to GOES & STEREOs

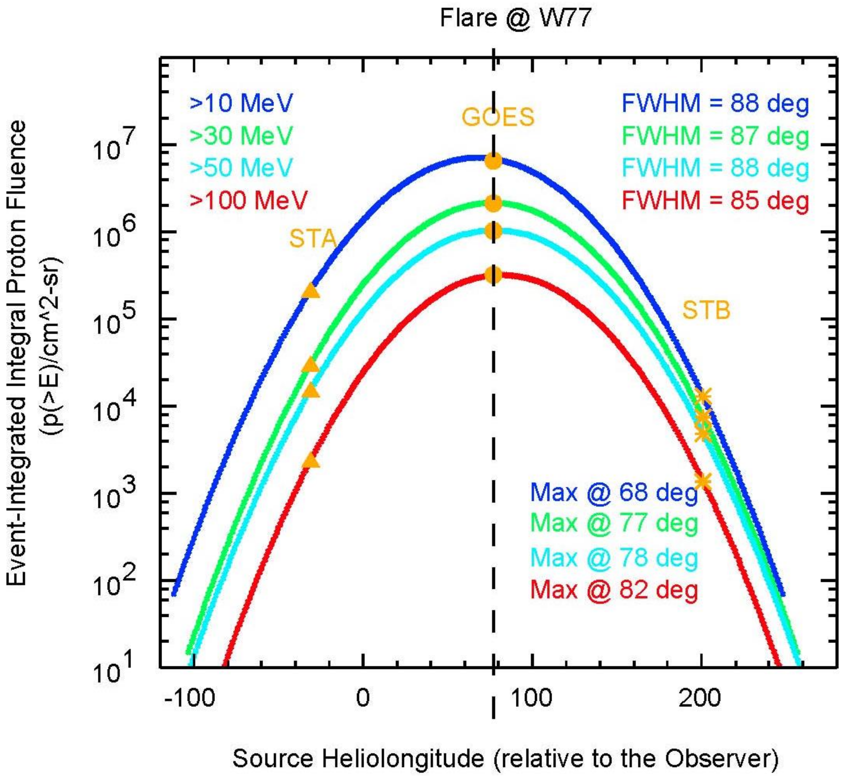
Available only for energies well below 500 MeV

Not available for all events

Interplanetary Spatial Distribution: Two Methods

57 GLEs 1956-2006

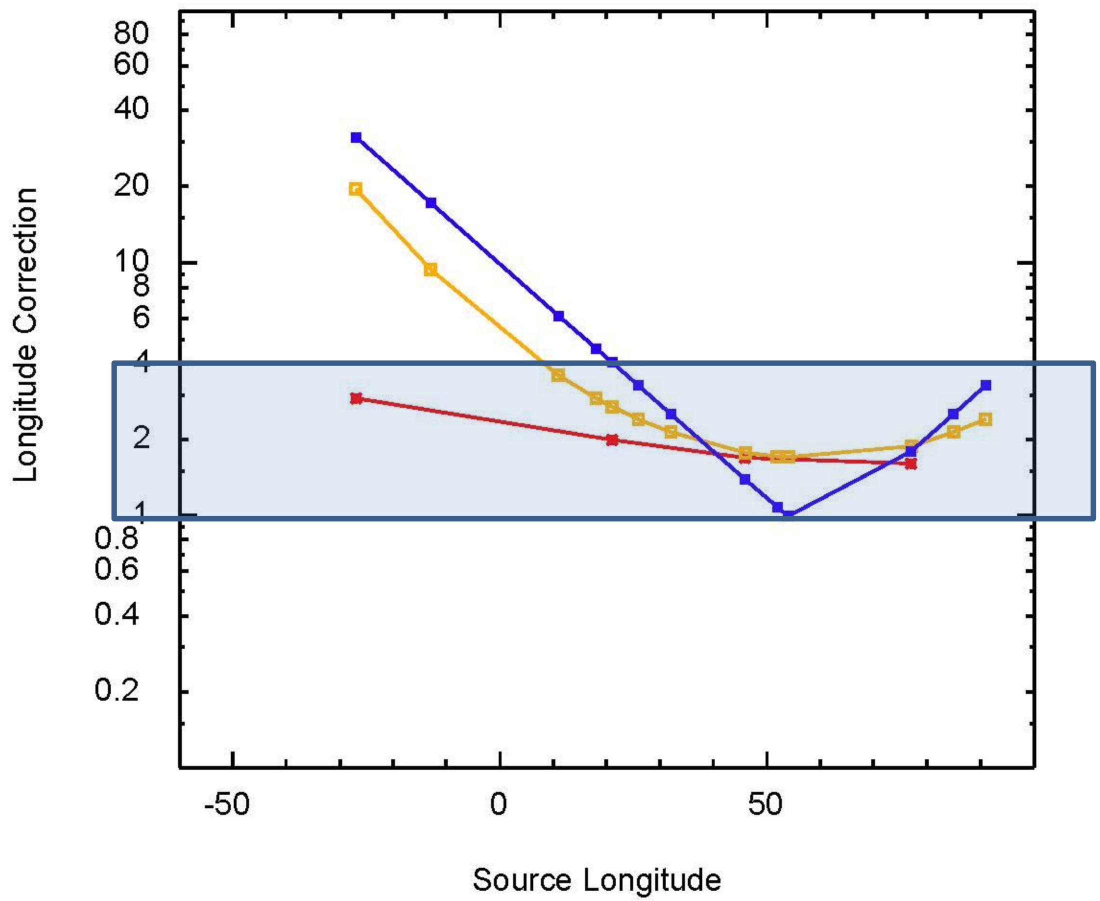




These results are models for the spatial distribution of the proton fluence in solar longitude.

We assume that the spatial distribution in solar latitude also has these forms, with maximum fluence observed in the ecliptic.

Spatial Correction Factor



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

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

For eastern sources , larger systematic uncertainty in this correction:

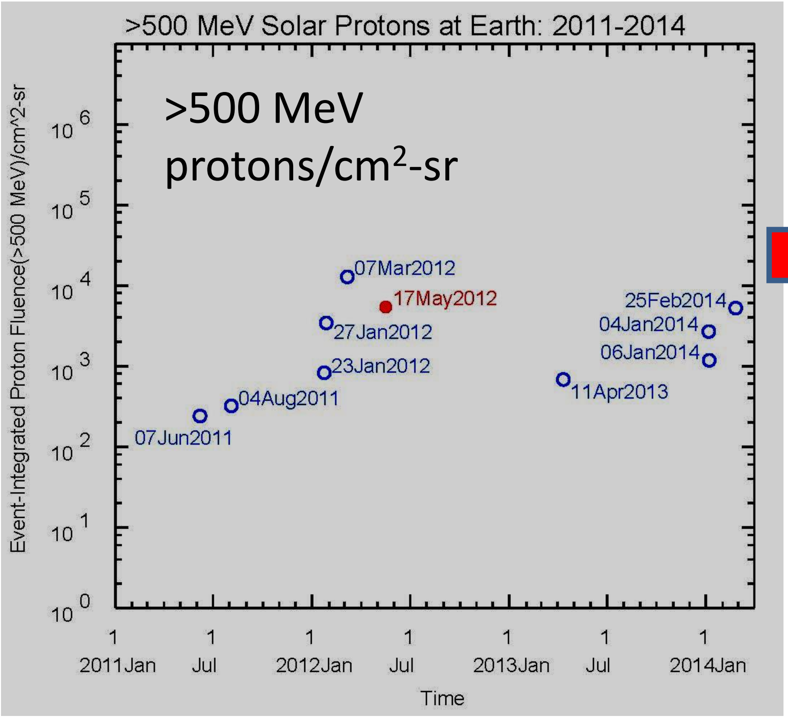
- **07 March 2012, at E27**
- **11 April 2013, at E13**

Extremely large systematic uncertainty causes some events to be omitted:

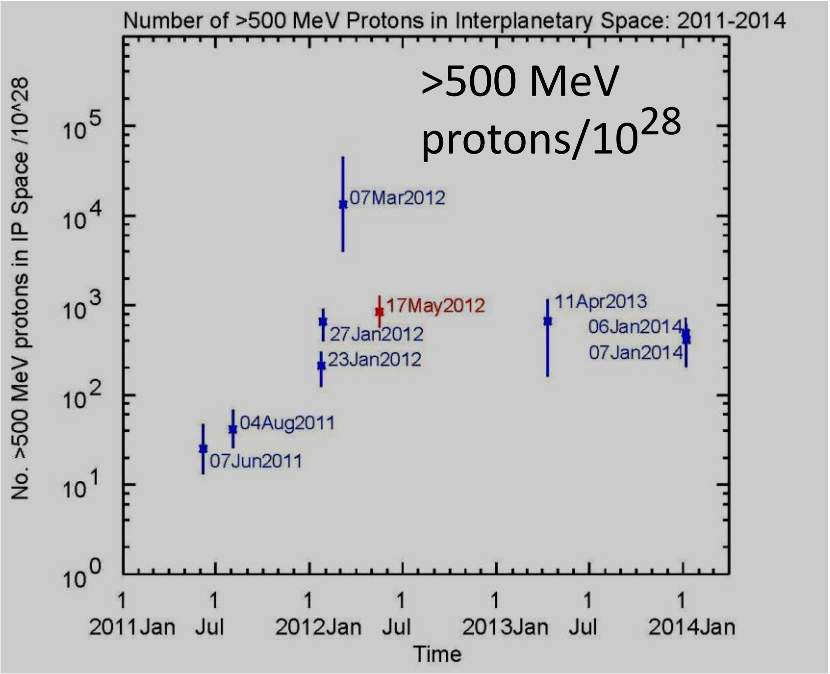
- **25 Feb 2014, at E82**

Results

Fluence at Earth



Number of Interplanetary Protons

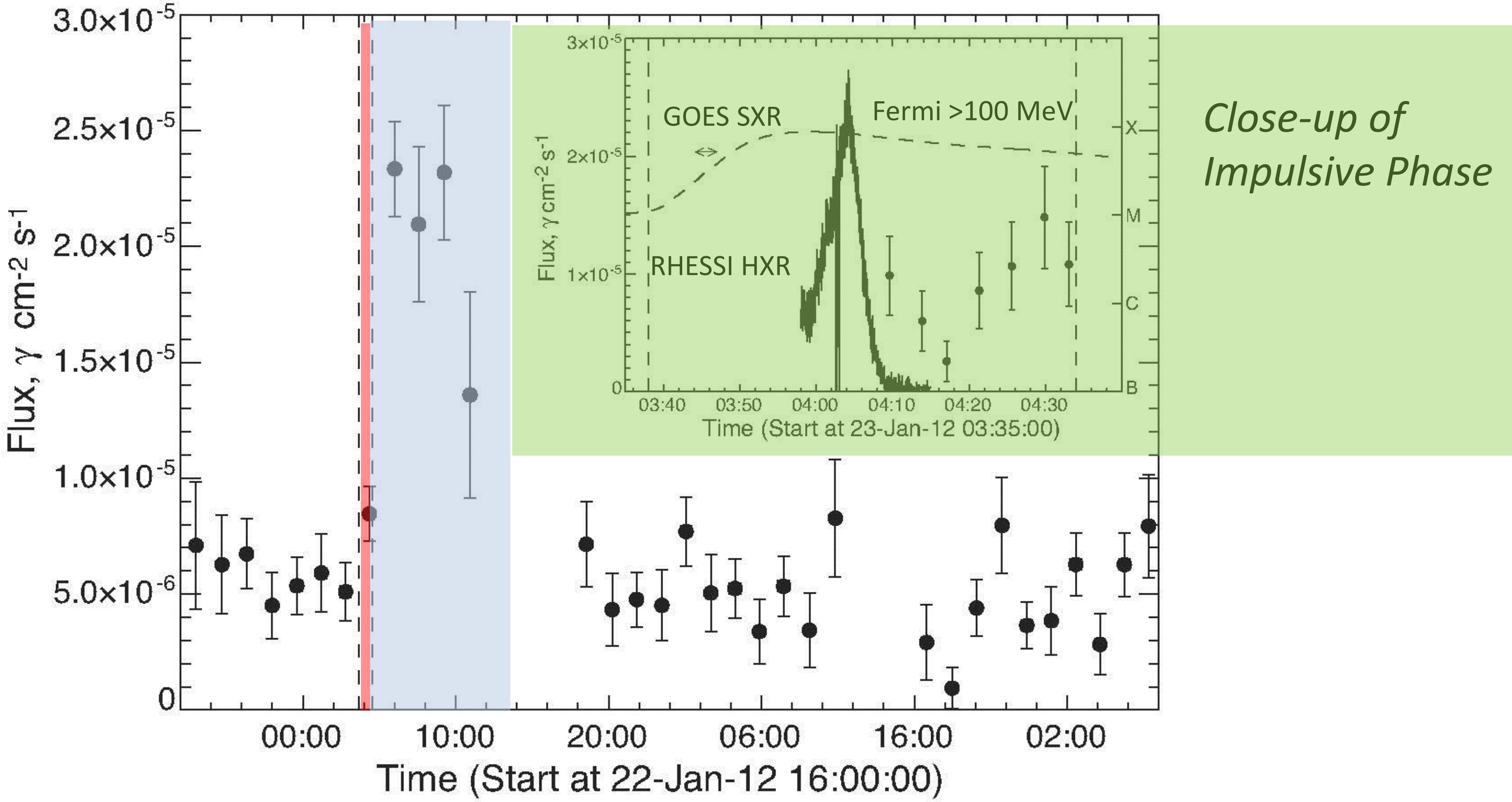


We can now compare $N_{protons}$(>500 MeV) at the Sun (from Fermi) and in Interplanetary space (from this analysis).

The Fermi γ-ray analysis provides separate estimates for >500 MeV protons at the Sun in the impulsive and sustained phases of the emission.

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

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



Gerry Share will report tomorrow: for >500 MeV protons at the Sun:

typically sustained/impulsive ~10

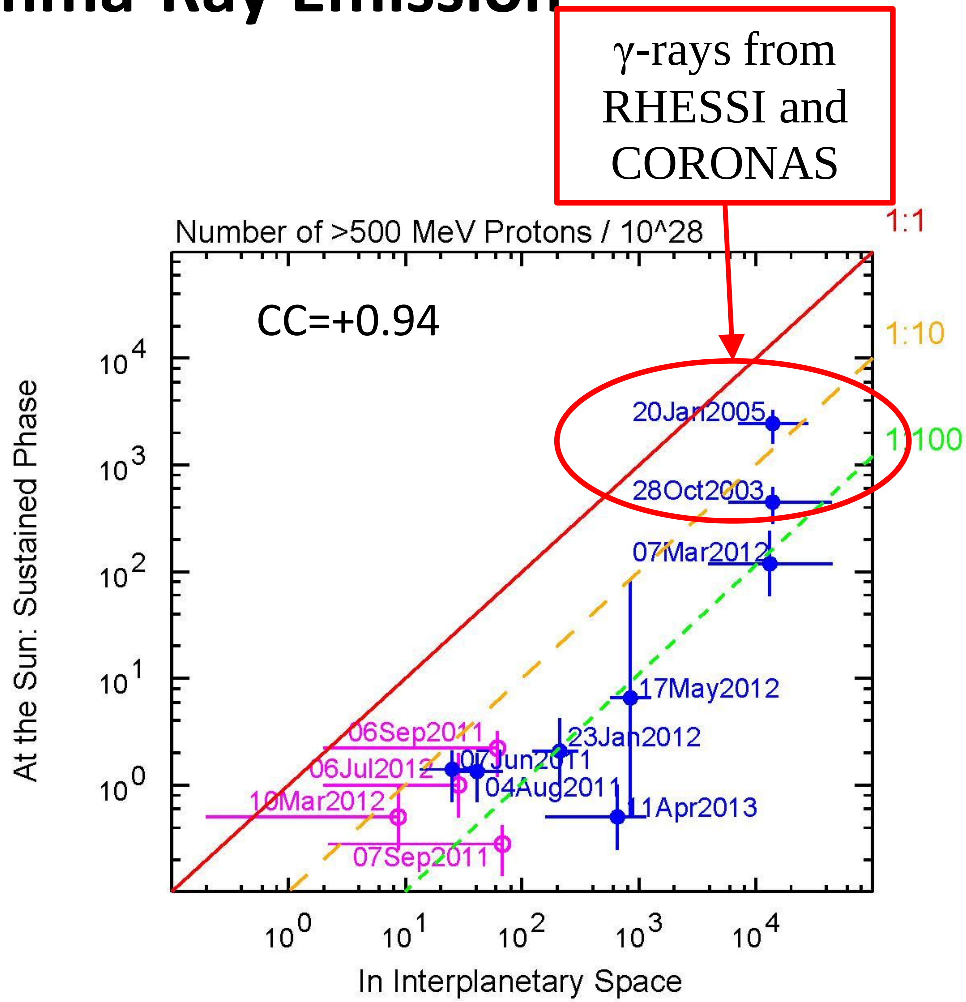
It is unlikely that the flare is the source of the sustained emission

Number of >500 MeV Protons:
at the Sun vs. in Interplanetary Space:
Sustained Gamma-Ray Emission

>500 MeV protons in the sustained emission are typically ~1-10% of the interplanetary protons.

These results suggest that the sustained emission arises from the interplanetary proton population:

But how?

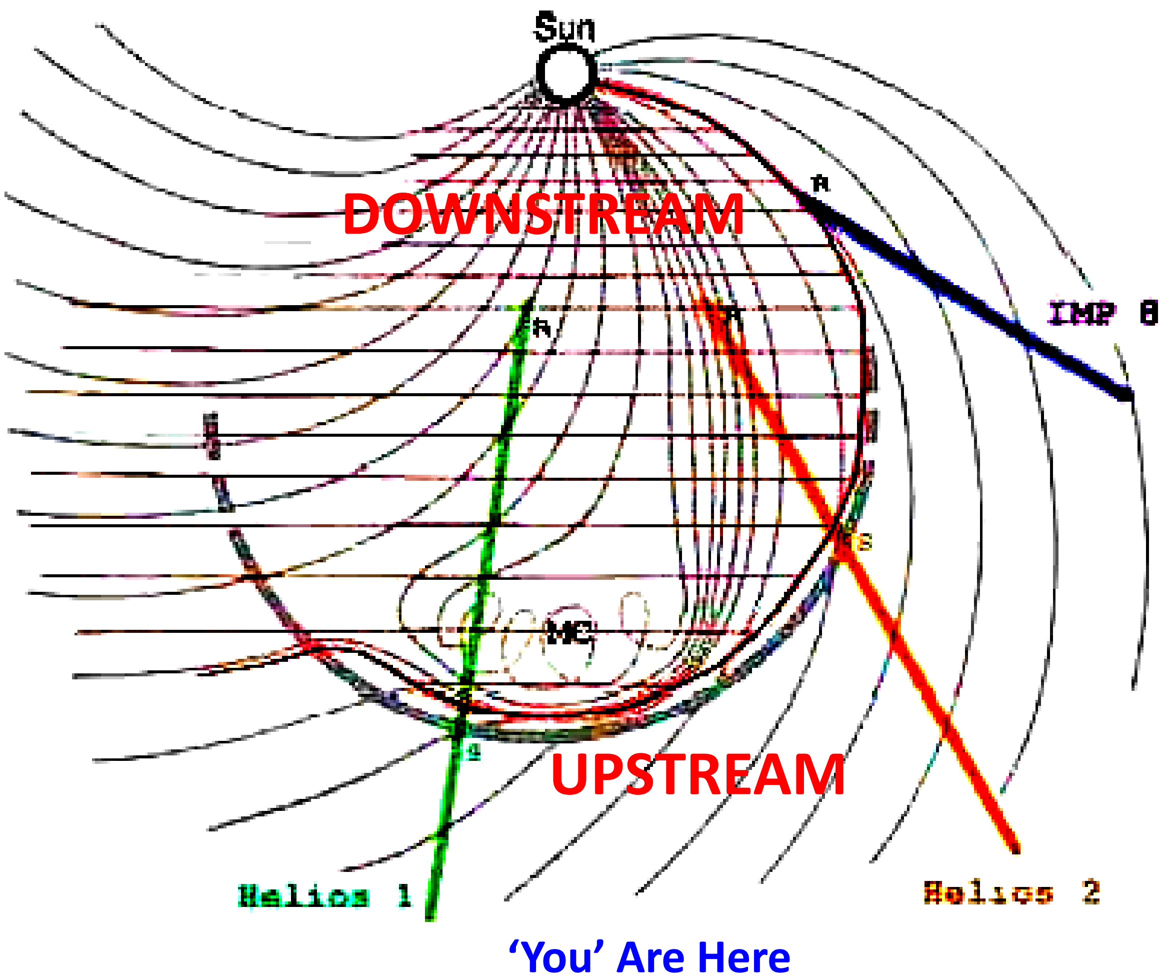


Purple: upper limits Blue: measurements

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.

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

The SEP Reservoir

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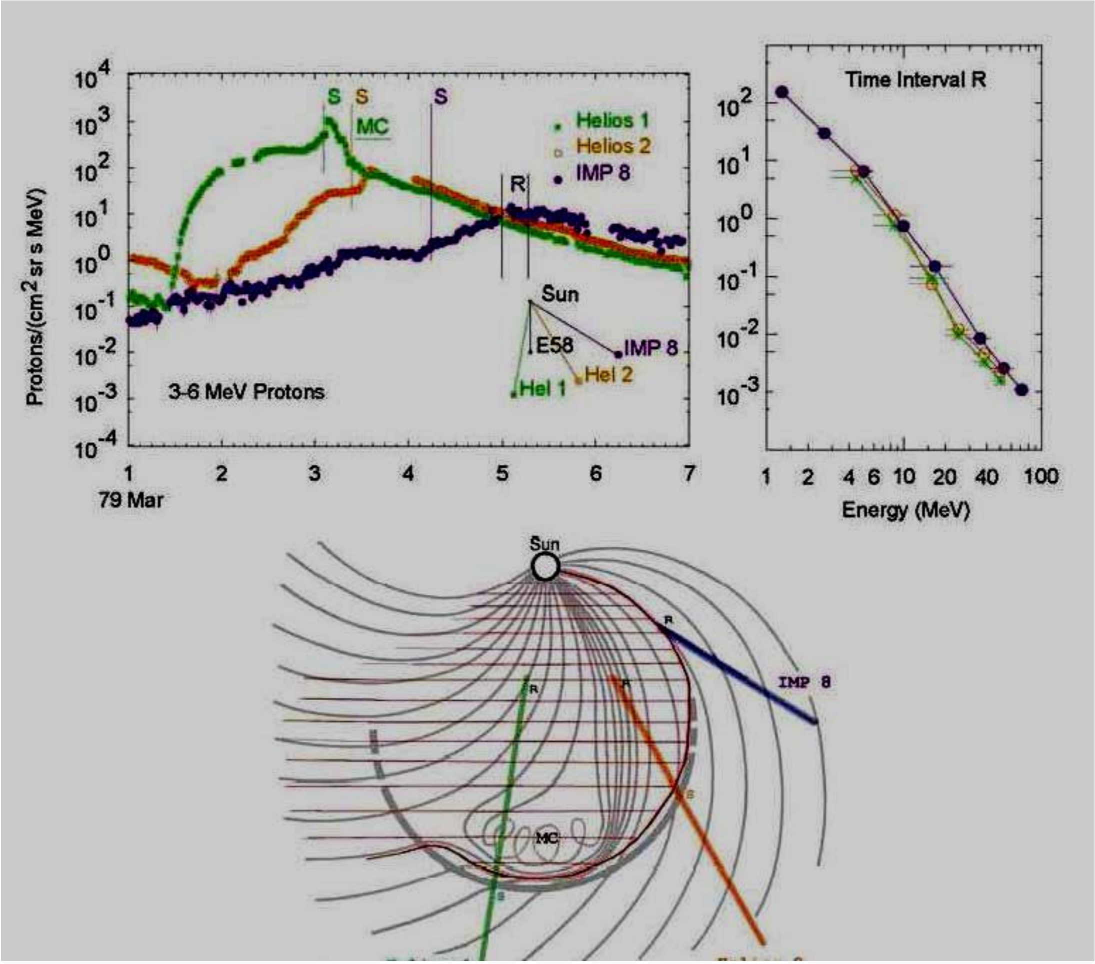


Cross-field transport occurs in the turbulence in the downstream region, leading to the formation of large-scale intensity, spectral, and compositional invariance.

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

Summary

Solar protons above 500 MeV are important both for practical concerns (e.g., storm-shelter implementation for astronauts) and for physics (e.g., probes of acceleration processes that occur near the Sun).

We can learn things from spectral shapes, temporal evolution, anisotropies. But **ABSOLUTE NORMALIZATION** (*how many protons/cm2-sr?)* is also important for some studies and applications.

In the past, our knowledge of these high energies has come primarily from **Neutron Monitors** and **GOES/HEPAD.**

AMS-02 and PAMELA will greatly enhance our knowledge of these high energies, (although perhaps limited by the comparatively low-level and diminished strength of solar activity).

But both NM-network and GOES/HEPAD have characteristics that complement those of AMS-02 and PAMELA. Cross-checks should be done whenever possible.

We derived from measurements at Earth (from GOES/HEPAD) estimates for

N_{IP}(>500 MeV) = the total number of protons above 500 MeV in interplanetary space.

using empirically-estimated correction factors for transport effect and large-scale spatial distribution

For 10 events in 2011-2014, we find

N_{IP}(>500 MeV) ~ 10^{29} to 10^{32}

Summary

Tomorrow, ***Gerry Share*** will present **Fermi/LAT** results on **the number >500 MeV protons in the solar atmosphere** during both the ***impulsive-flare*** and ***sustained-emission*** phases.

We find that the relative numbers of >500 MeV protons are:

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

These comparative sizes imply:

• It is highly unlikely that the Impulsive Flare is a significant contributor to the interplanetary population.

• It is likely that the Sustained Emission arises from the interplanetary population. In particular, a small fraction of the protons in the nascent SEP reservoir downstream of the CME-drivne shock find field lines that carry them into the solar atmosphere.

This suggestion should be tested by quantitative modeling, as well as more detailed analysis of the Fermi observations.

Our results suggest that

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

We welcome future tests of our results and conclusions, using other data sources and independent analyses methods

Introducing my granddaughter…

Isabel Rodriguez-Tylka

Born 28 September 2015

Introducing my granddaughter…

Isabel Rodriguez-Tylka

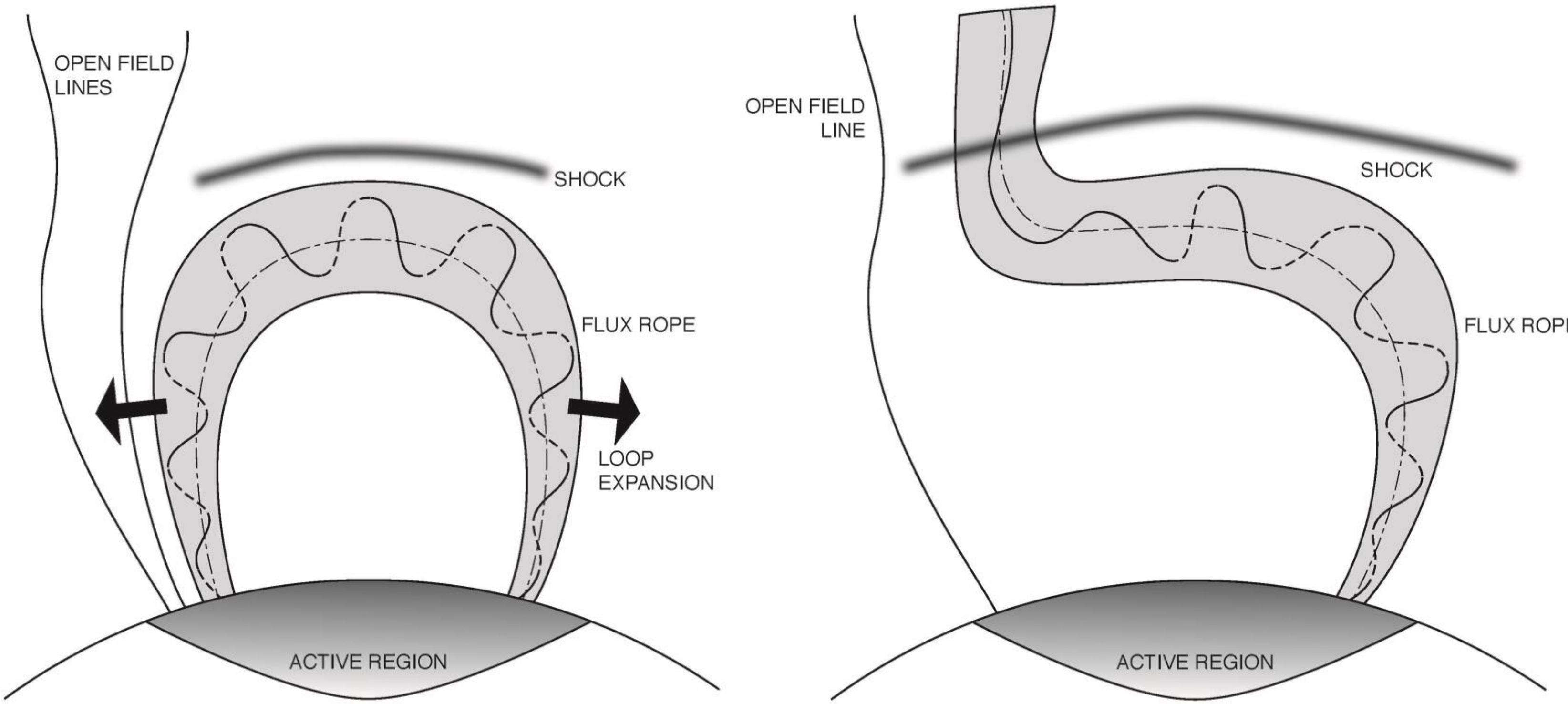
Born 28 September 2015

Mahalo, Veronica!

(Today's picture, from Facebook)

Back-ups

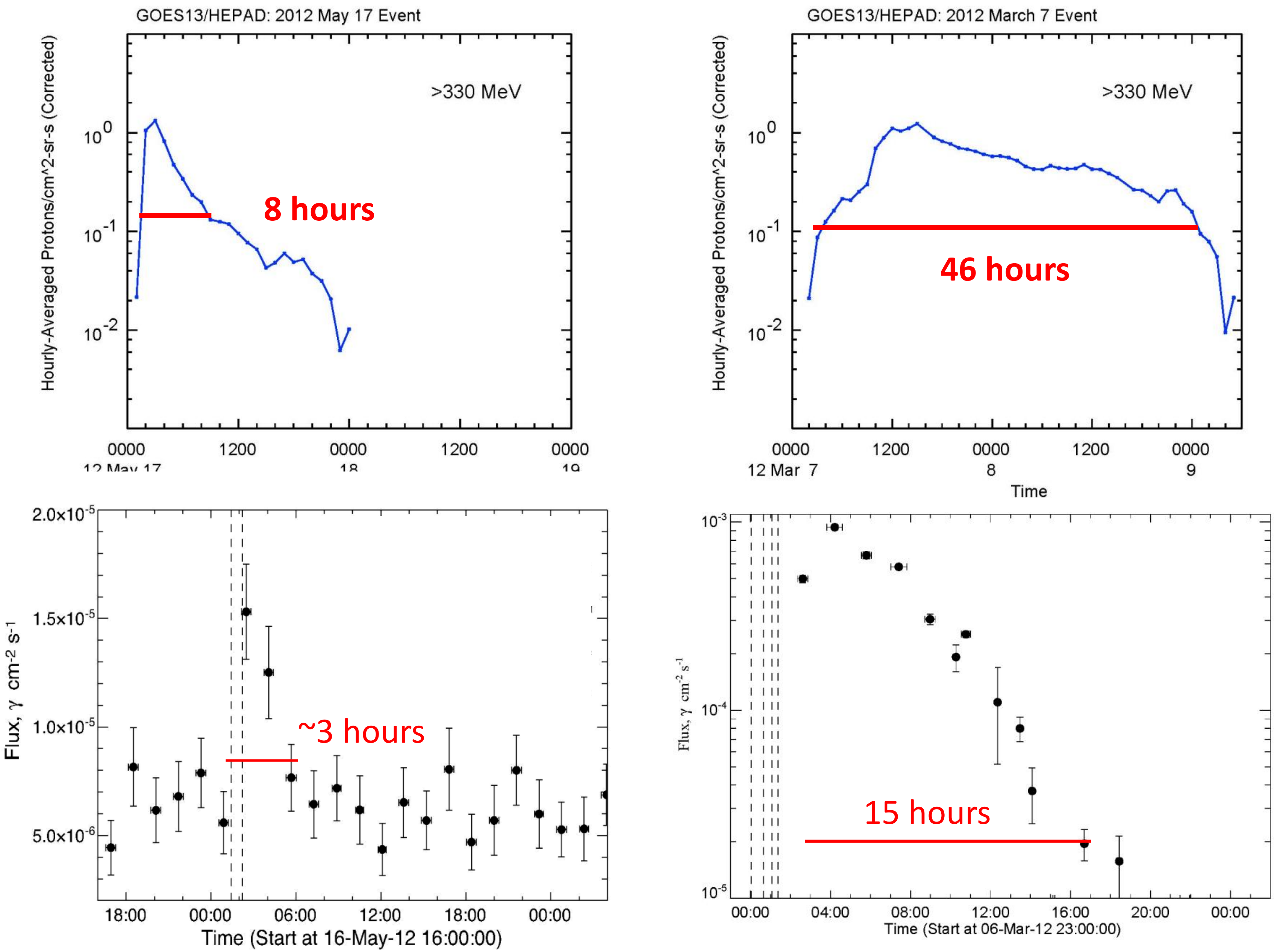
A way in which this might happen…



Time-Scale Comparisons:

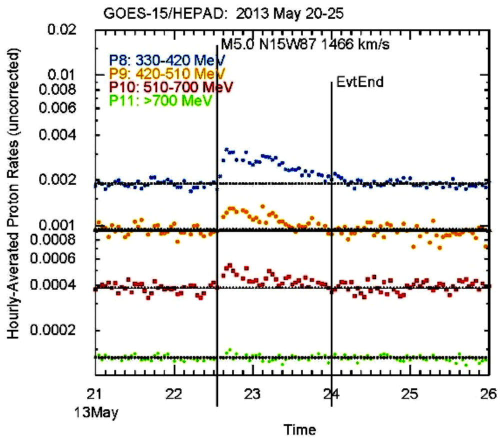
GOES/HEPAD >330 MeV Protons

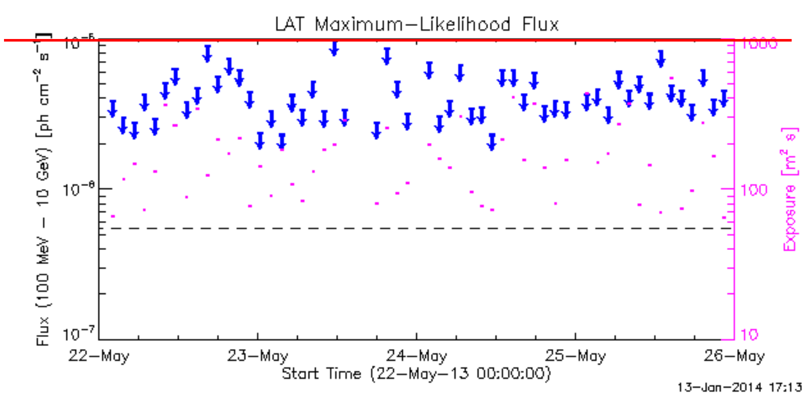
Fermi >100 MeV gamma-rays



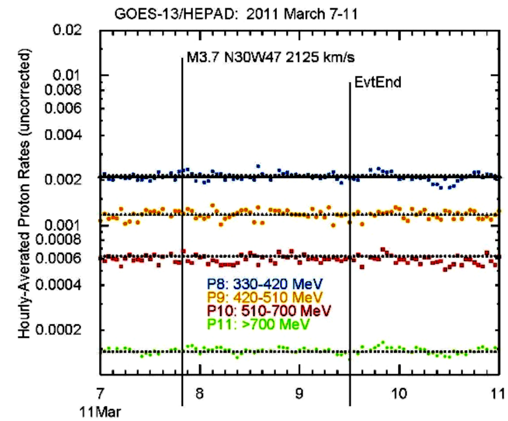
The Devil is in the Details…

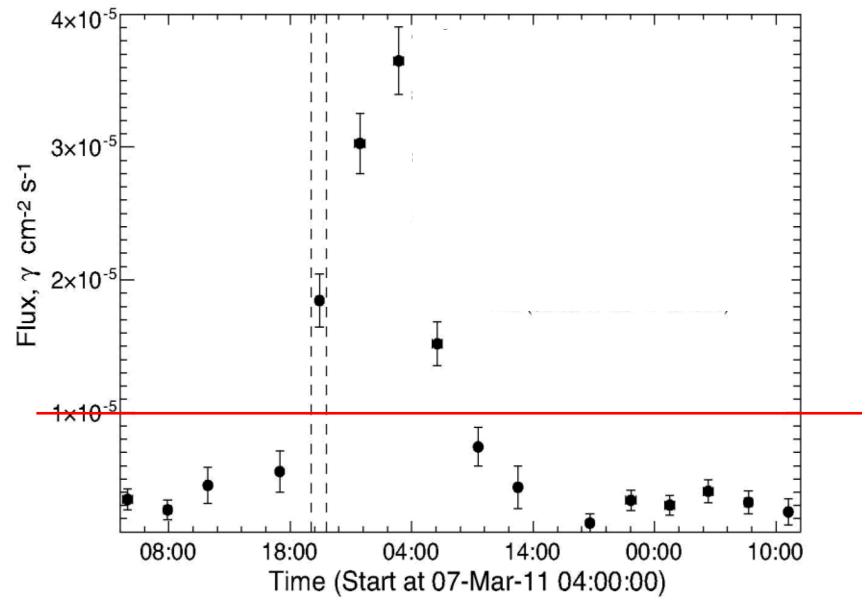
2013 May 22
SXR: M5.0, N14W87. CME: 1466 km/s
Seen in HEPAD; but not in Fermi



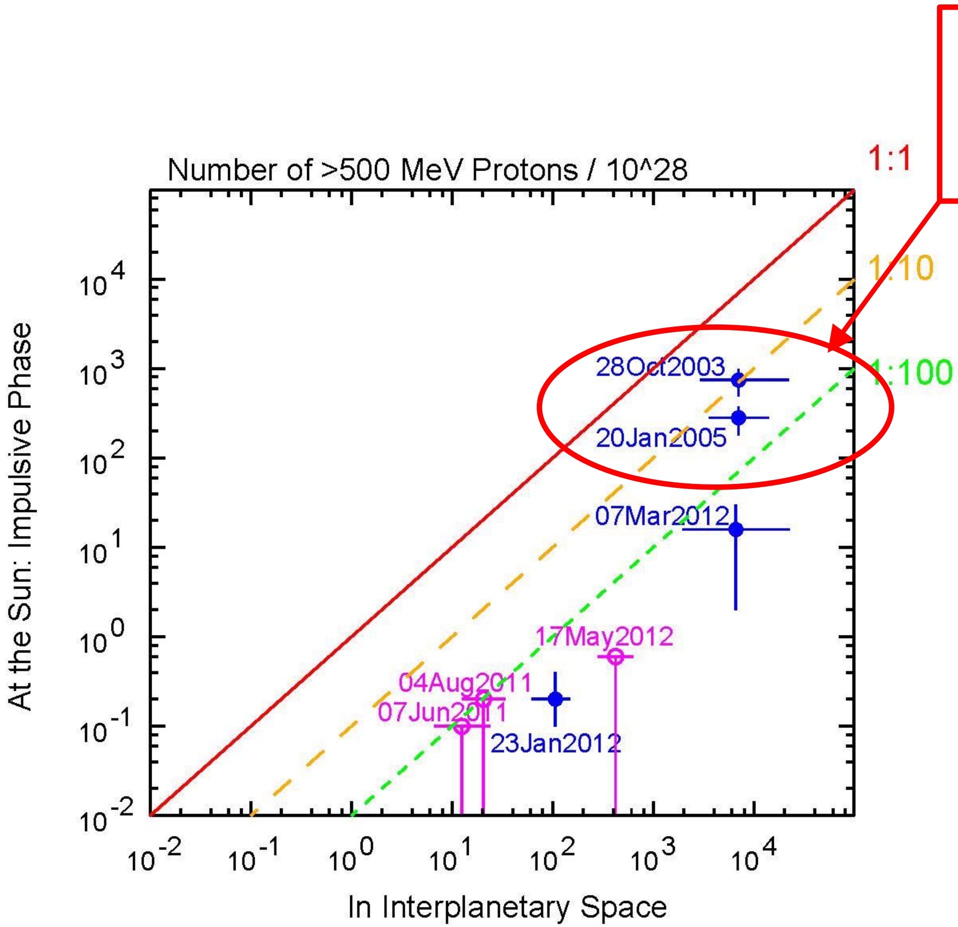


2011 March 07
SXR: M3.5, N30W47. CME: 2125 km/s
Seen in Fermi; but not in HEPAD





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



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

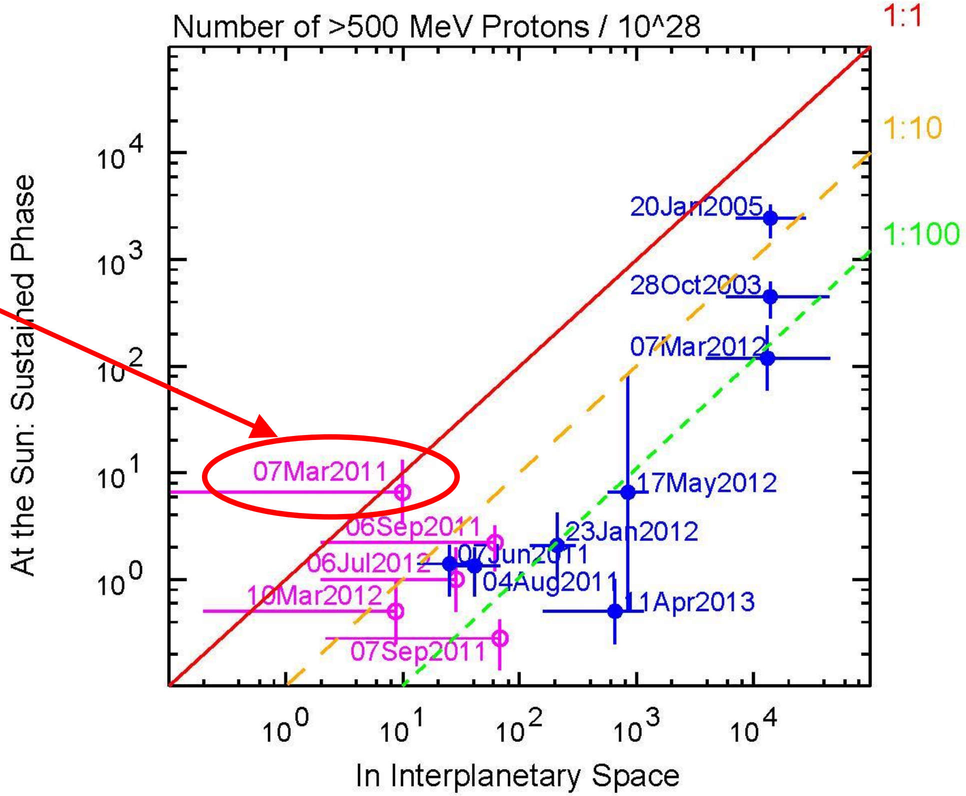
This makes it **EXTREMELY UNLIKELY** that the flare is the primary source of the interplanetary protons at >500 MeV.

Purple: upper limits Blue: measurements

Number of >500 MeV Protons:
at the Sun vs. in Interplanetary Space:
Sustained Gamma-Ray Emission

An Exception:

- Strong sustained >100 MeV gamma-ray emission
- No >500 MeV Interplanetary protons, at least, not at Earth.



Purple: upper limits Blue: measurements

Gaussian Fits to Observed Longitude Distributions