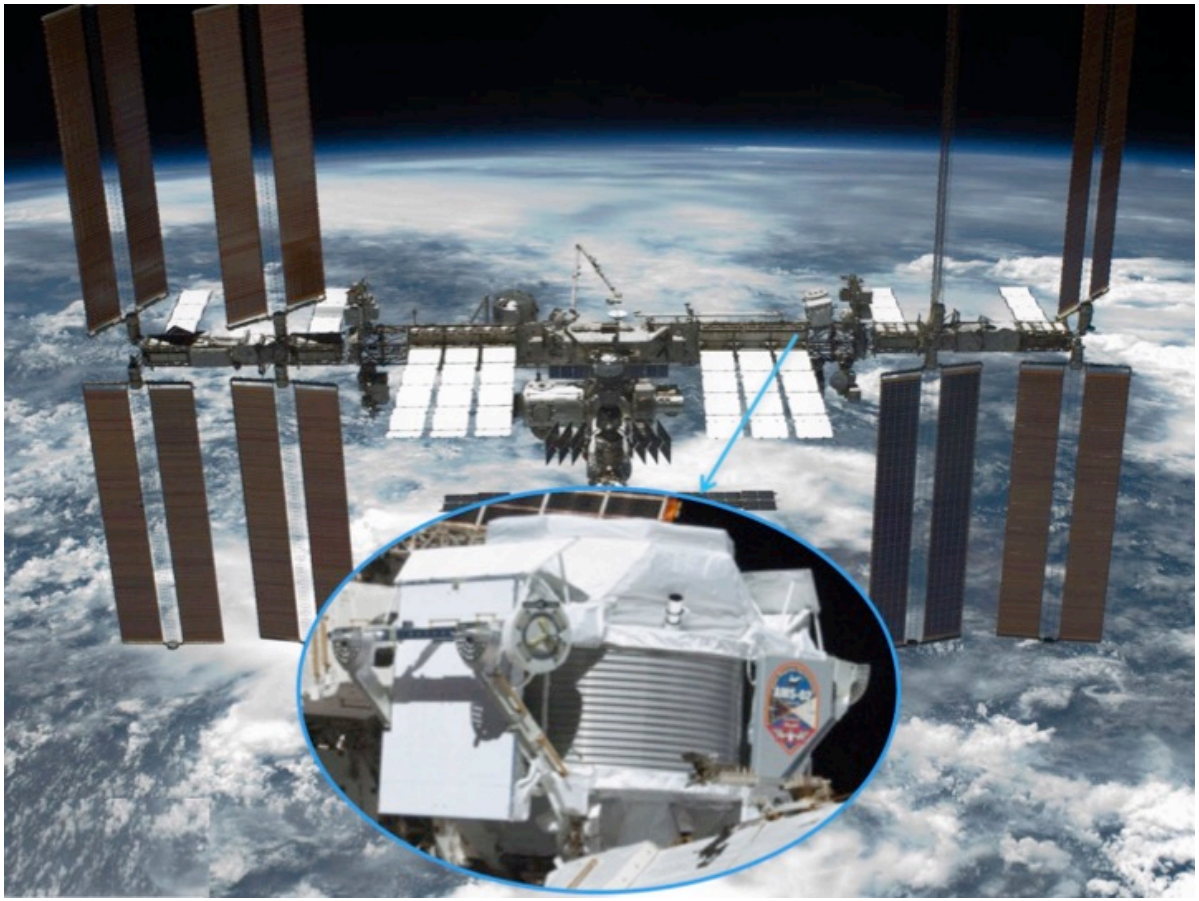
Solar Energetic Particles Measured by AMS

Alexis Popkow – University of Hawaii at Manoa
V.Bindi, C.Consolandi, C.Corti, C.Light, M.Palermo

Solar Energetic Particles (SEP), Solar modulation and Space Radiation: New Opportunities in the AMS-02 Era #3

April 24th Washington DC

AMS on the International Space Station



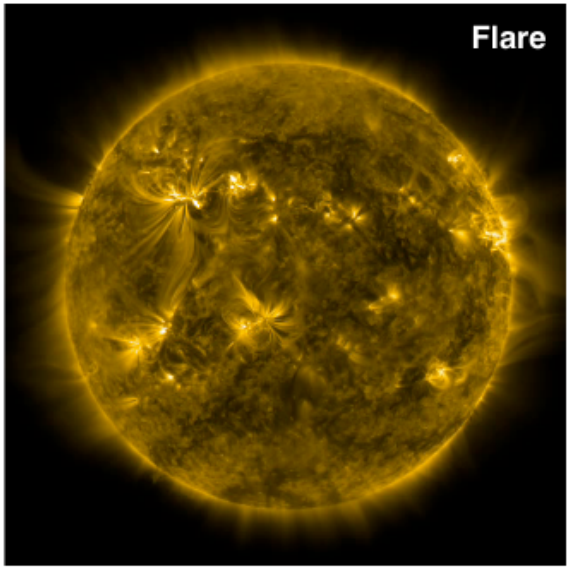
AMS a multipurpose particle detector installed on the ISS on **May 19th , 2011** to measure high energy particles in space from GV to a few TV

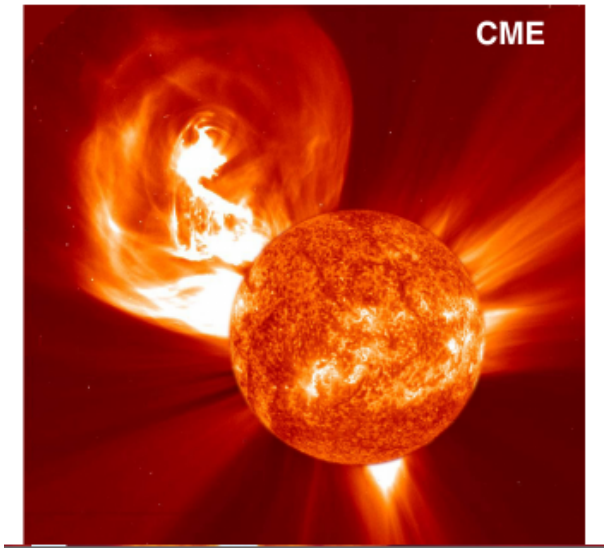
Solar Energetic Particles (SEPs) and Forbush Decreases (FDs) with AMS

AMS is also capable of measuring:

- Solar Energetic Particles
  - Temporary increase in particle flux
  - M- and X-class flares and high speed CMEs generate SEP events measured by AMS-02

- Forbush Decreases
  - Temporary decrease in the galactic cosmic ray flux
  - Caused by a passing Interplanetary Coronal Mass Ejection or Corotating Interacting Regions



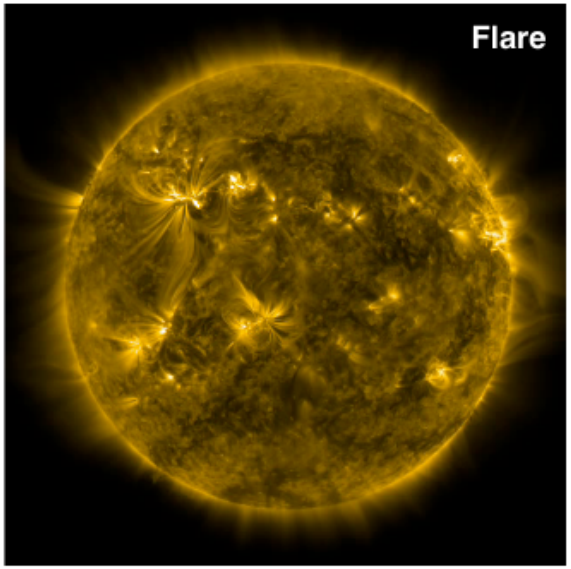


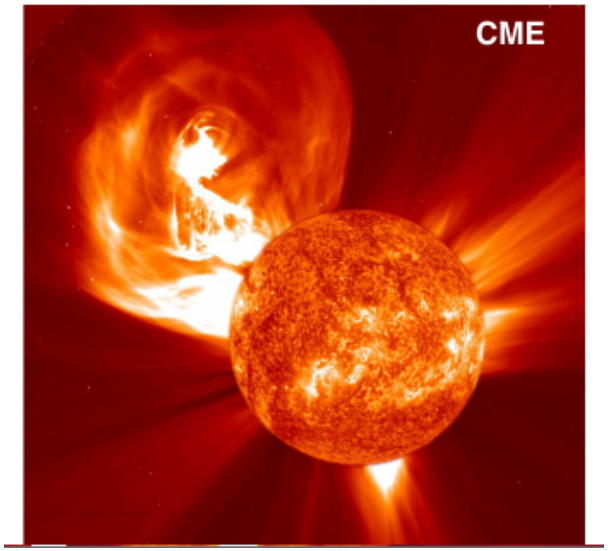
Solar Energetic Particles (SEPs) and Forbush Decreases (FDs) with AMS

AMS is also capable of measuring:

- **Solar Energetic Particles**
  - Temporary increase in particle flux
  - M- and X-class flares and high speed CMEs generate SEP events measured by AMS-02

- Forbush Decreases
  - Temporary decrease in the galactic cosmic ray flux
  - Caused by a passing Interplanetary Coronal Mass Ejection or Corotating Interacting Regions





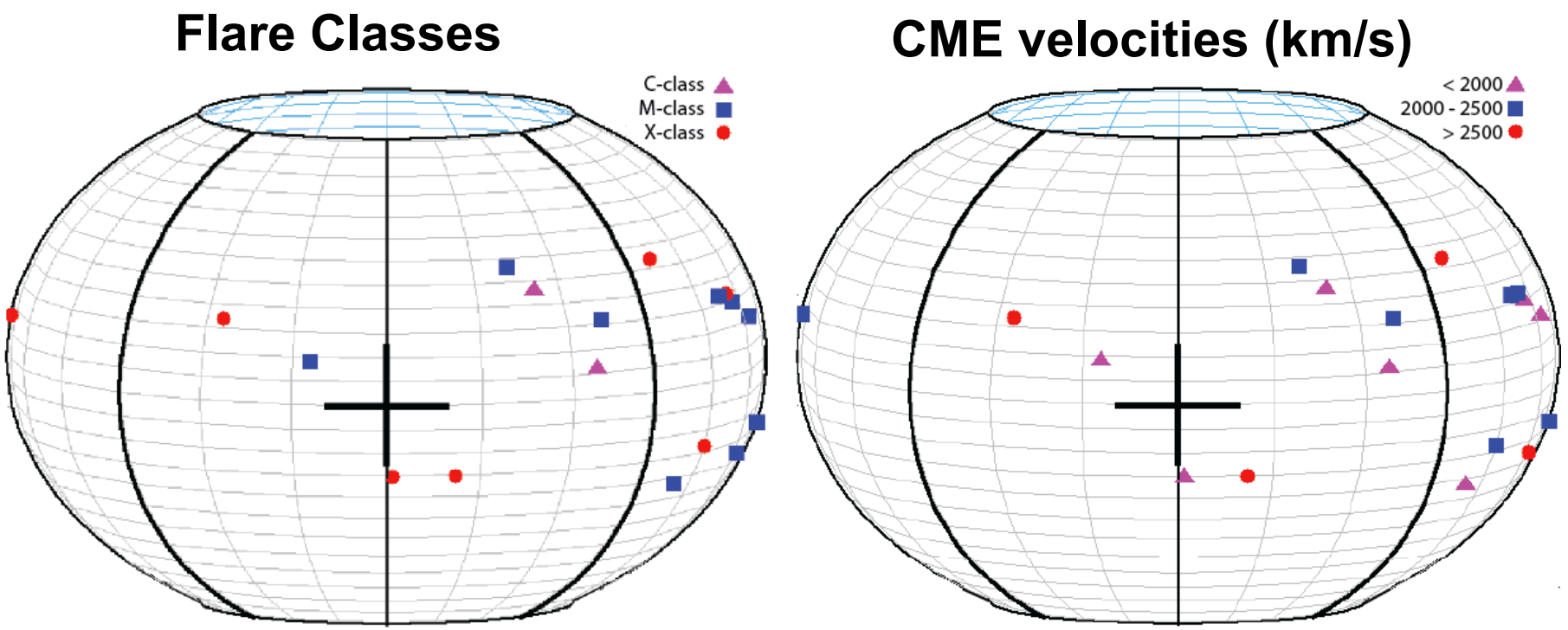
List of SEP Events Observed by AMS

In solar cycle 24 from May 2011 to May 2016 AMS observed **27 high-energy Solar events above 1GV**

AMS SEP events are typically associated with M- and X-class flares and fast CMEs

AMS Event		Event Date	Flare Class	CME Vel. (km/s)
1		**2011/06/07**	**M2.5**	**1255**
2	FD	**2011/08/04**	**M9.3**	**1315**
3		**2011/08/09**	**X6.9**	**1610**
4		2011/09/06	X2.1	575
5		2011/09/22	X1.4	1905
6	FD	**2012/01/23**	**M8.7**	**2175**
7	FD	**2012/01/27**	**X1.7**	**2508**
8	FD	**2012/03/07**	**X5.4, X1.3**	**2684, 1825**
9	FD	**2012/03/13**	**M7.9**	**1884**
10		**2012/05/17**	**M5.1**	**1582**
11		2012 /07/06	X1.1	1854
12		2012/07/08	M6.9	1495
13	FD	**2012/07/19**	**M7.7**	**1631**
14	FD	**2012/07/23**	**backside**	**2003**
15		**2013/04/11**	**M6.5**	**861**
16	FD	**2013/05/22**	**M5.0**	**1466**
17	filament	2013/09/29	C1.2*	1179
18		2013/10/28	M5.1, M2.8, M4.4	1201, 1073, 812
19	FD	2013/11/02	backside	828
20		2013/12/28	backside	1118
21	FD	2014/01/06	backside	1118
22	FD	2014/01/07	X1.2	1830
23	FD	2014/02/25	X4.9	2147
24	FD	2014/04/18	M7.3	1203
25		2014/09/01	backside	1404
26	FD	2014/09/10	X1.6	1267
27		2015/10/29	backside	530**

Locations on the Sun of the Flares and CMEs associated with AMS SEP events

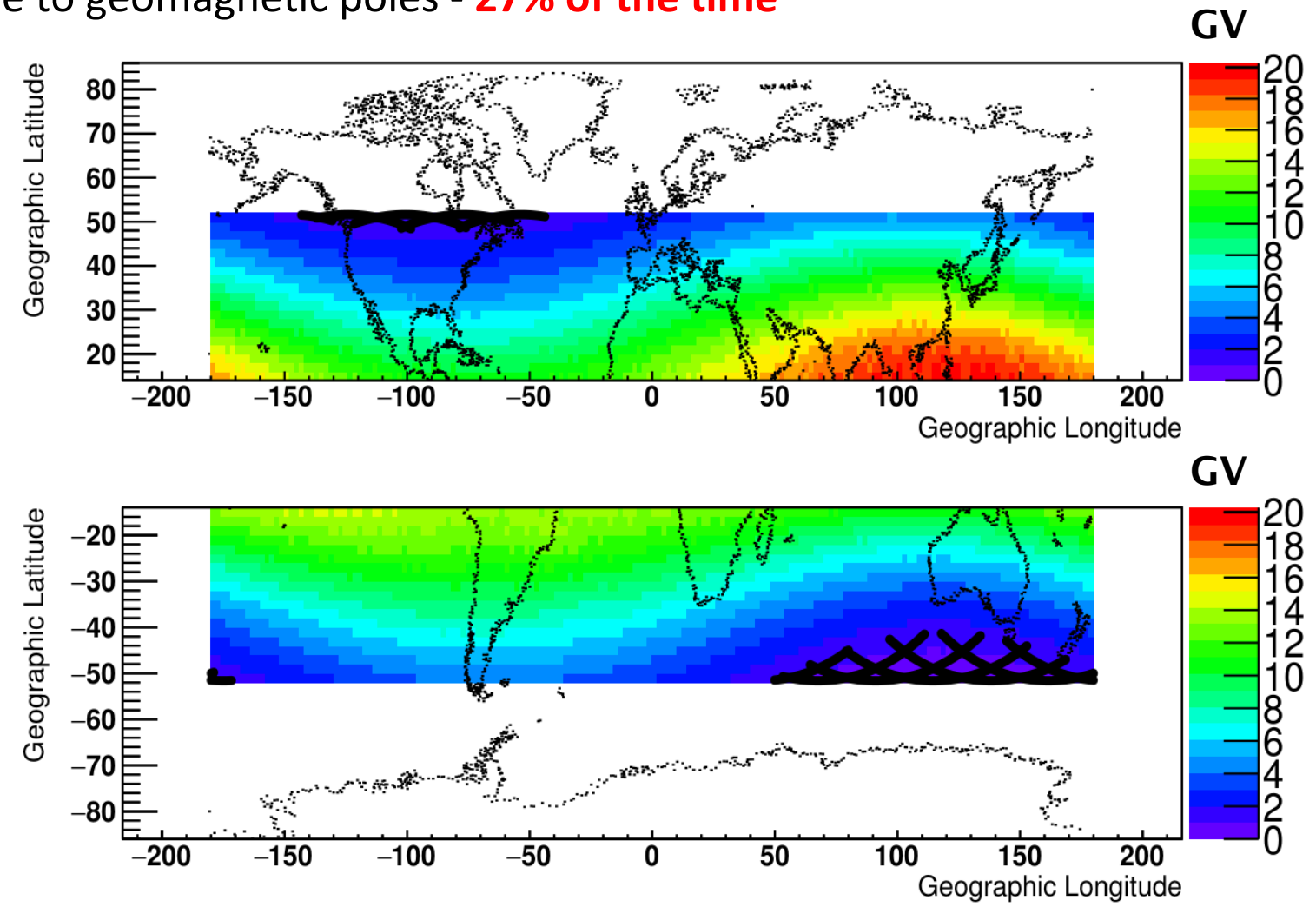


Explosive events on the sun can accelerate and distribute high energy particles over wide longitudes

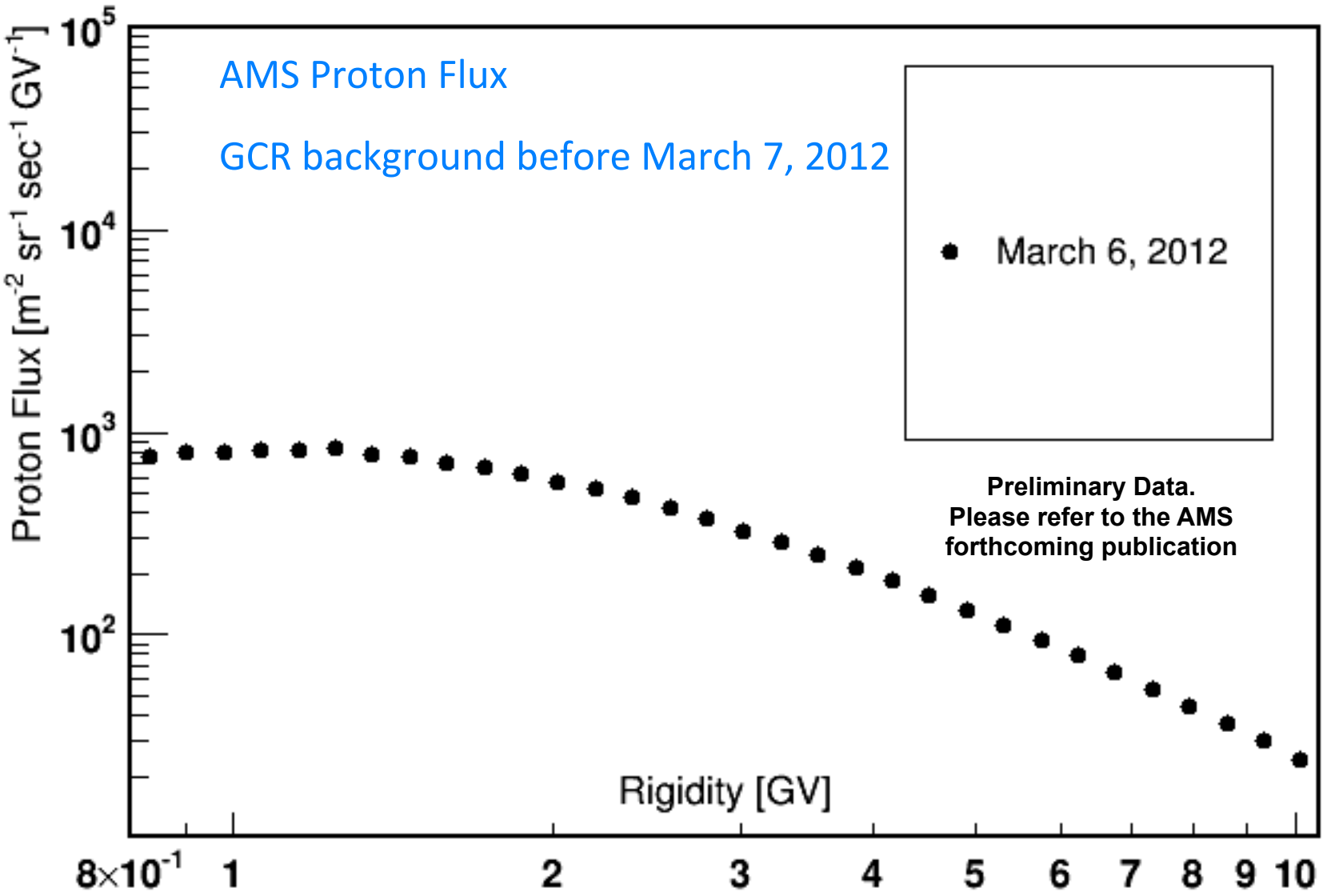
An unexpected radiation hazard over large portions of the inner heliosphere.

Locations where AMS Measures SEPs

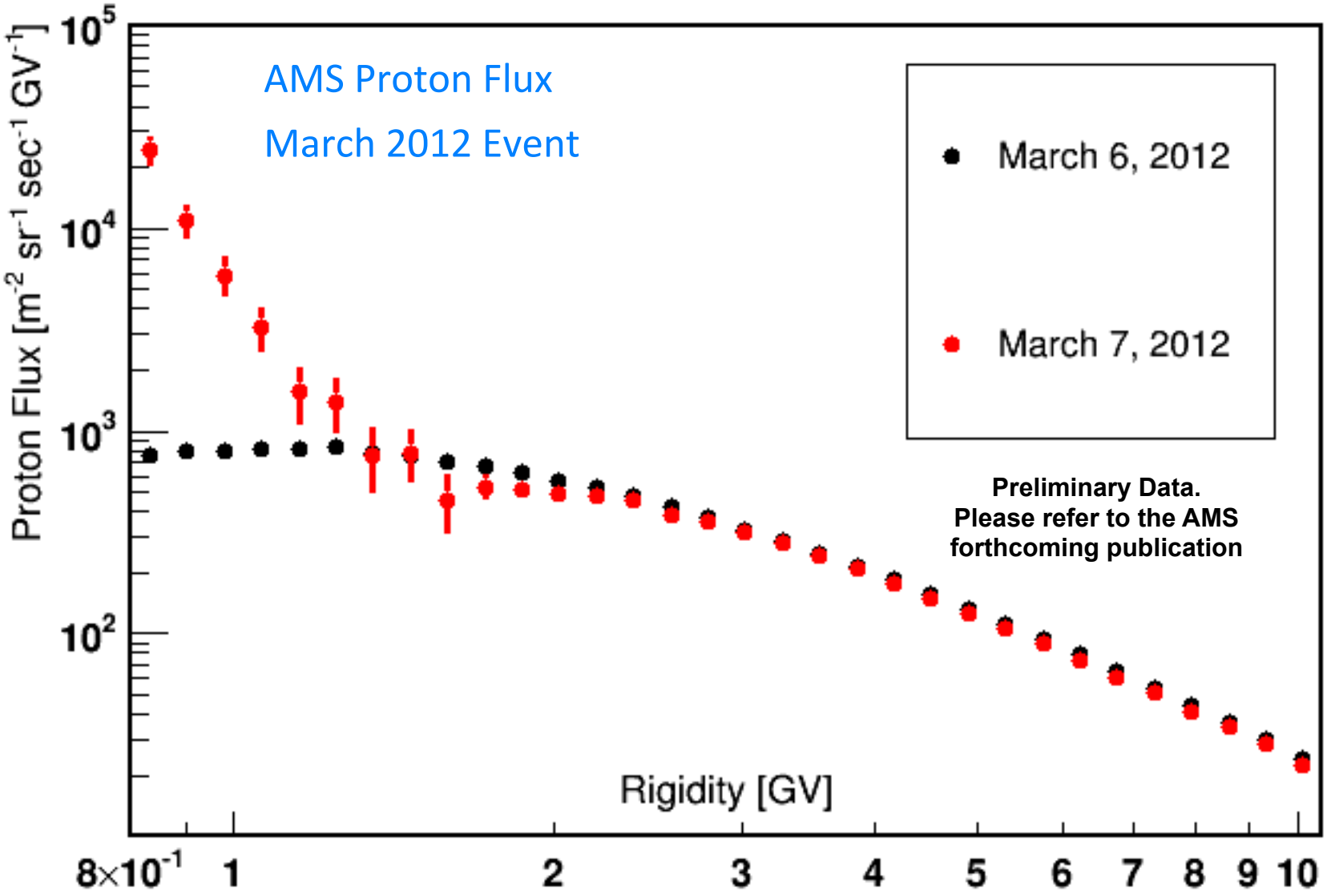
Due to the Earth's geomagnetic field, AMS is sensitive to SEP when is orbiting close to geomagnetic poles - **27% of the time**



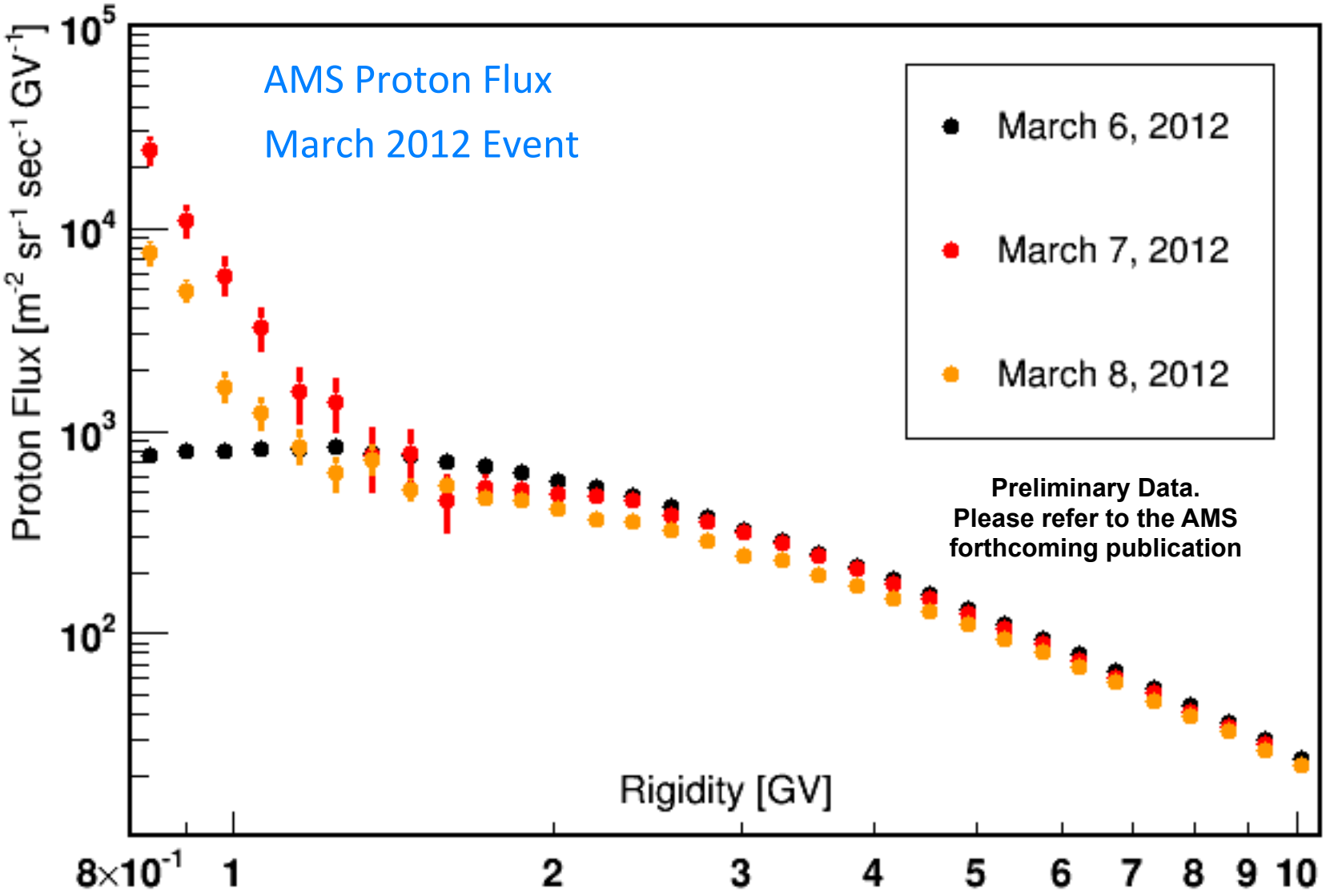
AMS Daily Proton Flux



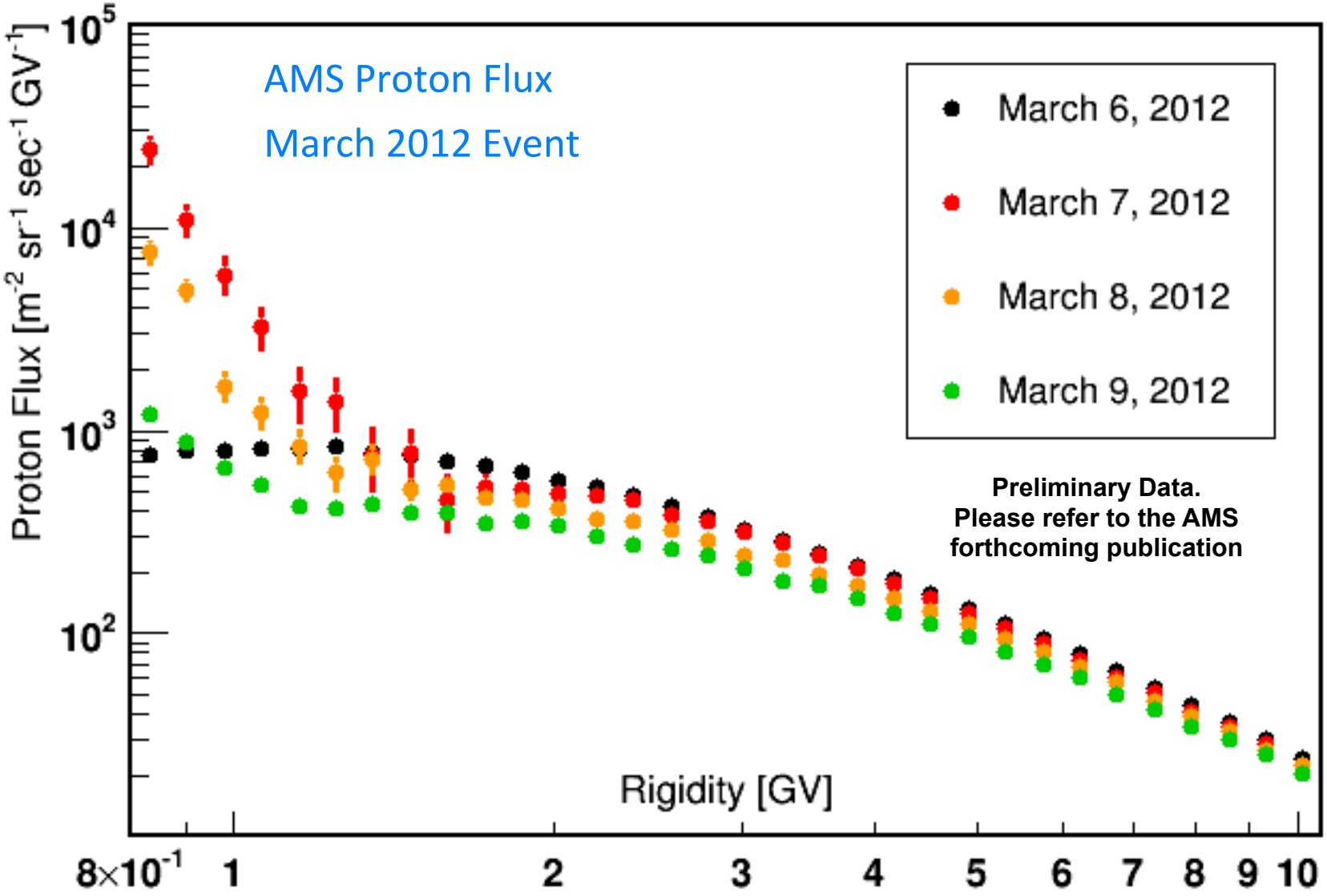
SEPs Observed by AMS as an Excess above the GCR Background



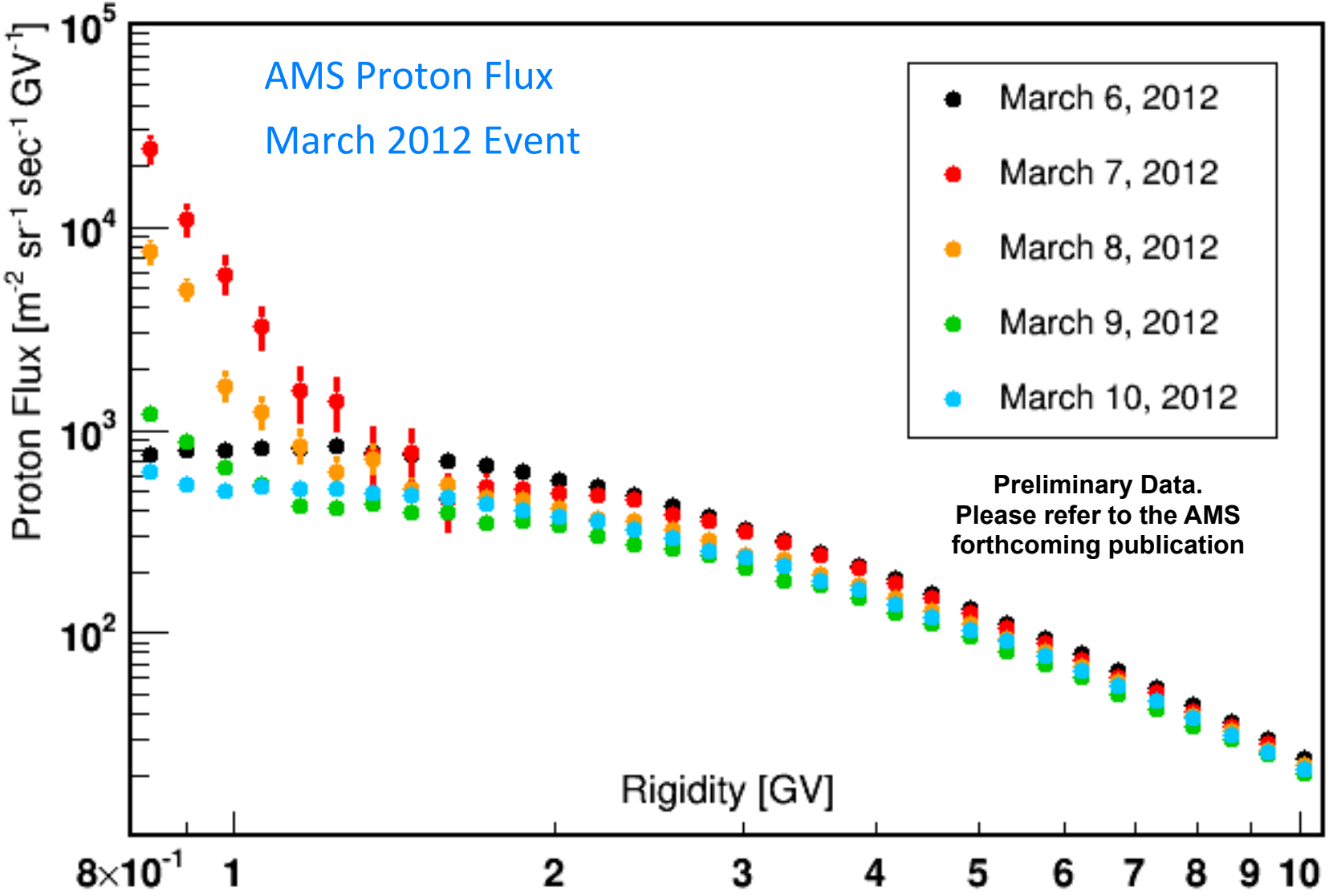
SEPs Observed by AMS as an Excess above the GCR Background



SEPs Observed by AMS as an Excess above the GCR Background

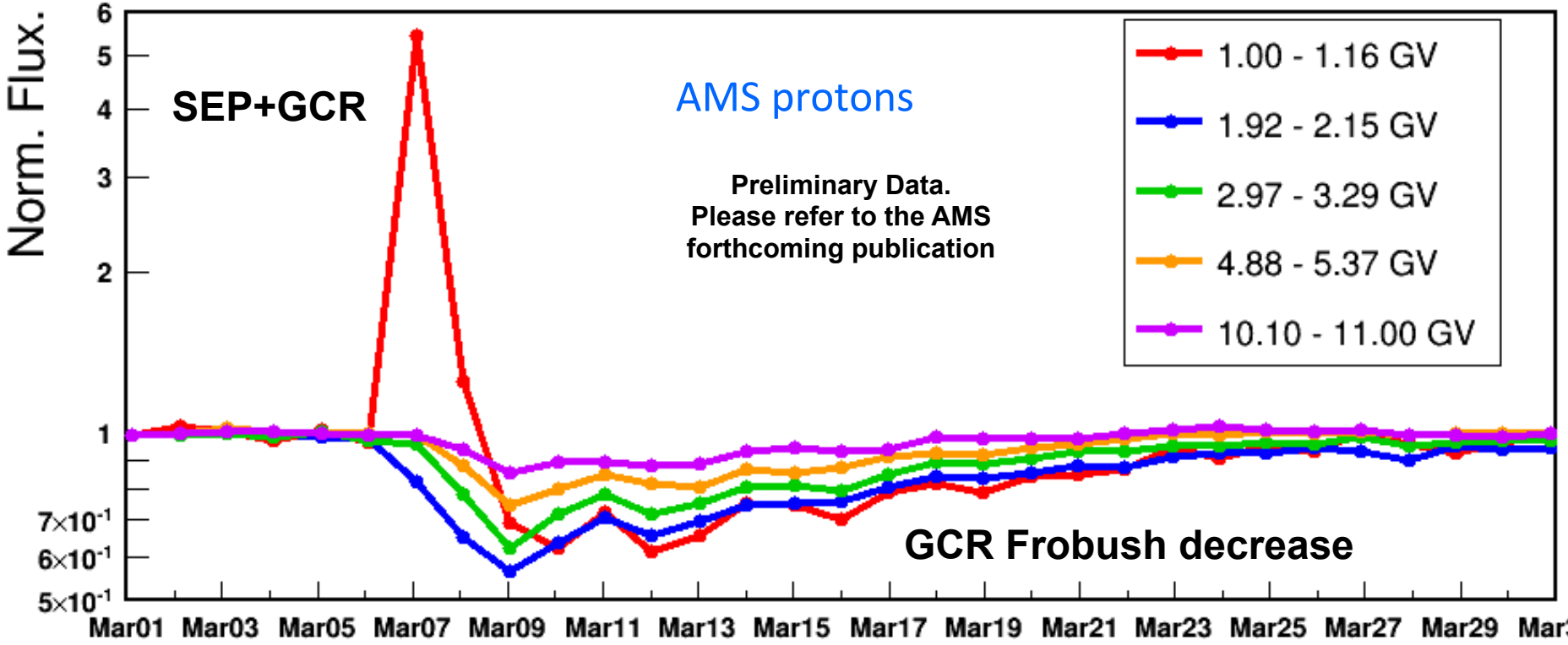


SEPs Observed by AMS as an Excess above the GCR Background



March 7, 2012 Event

In addition to the SEPs AMS registered a strong suppression of the GCR, a **Forbush decrease**, that lasted for about 20 days



Examples of AMS SEP Events

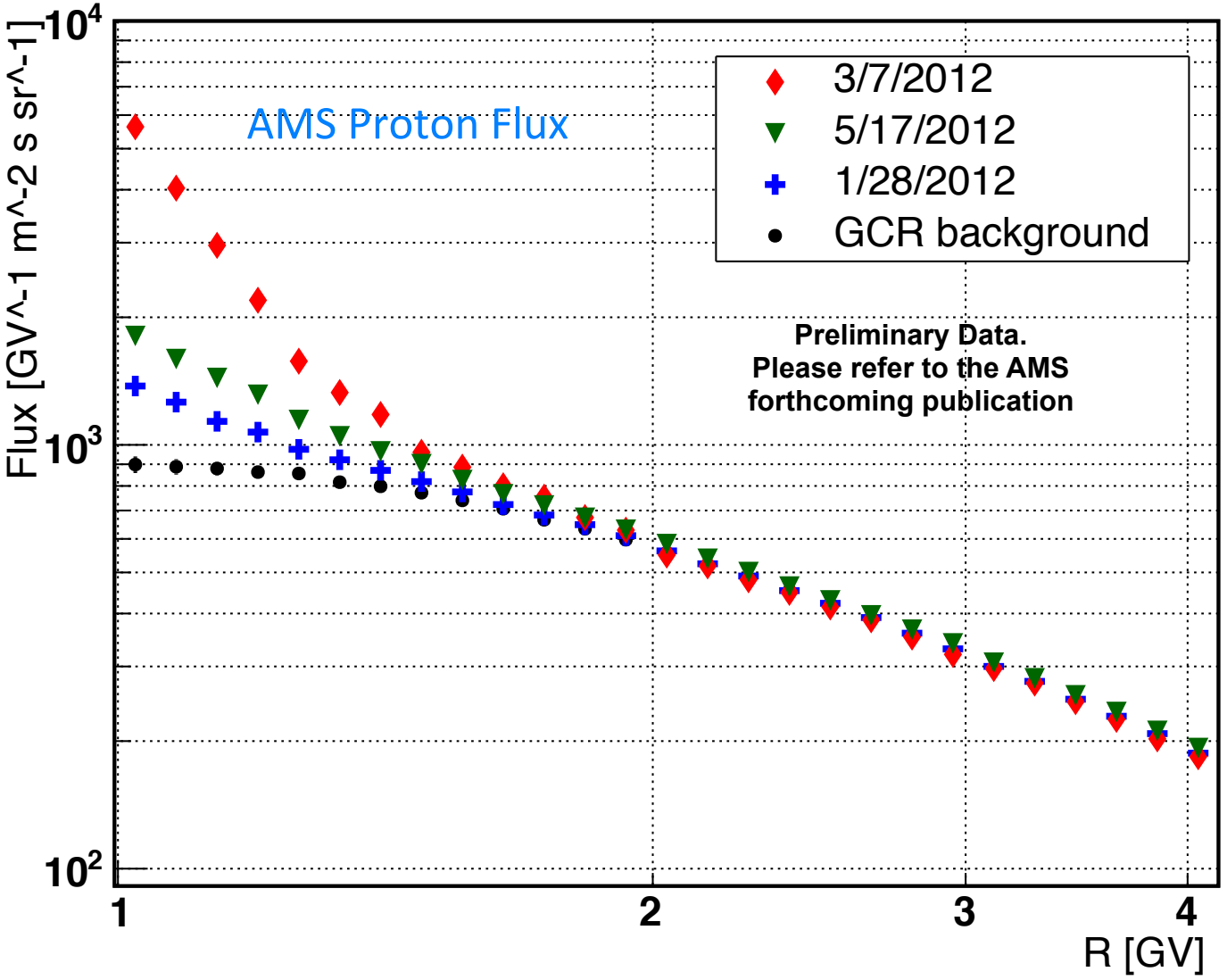
Mar 7, 2012

May 17, 2012

Jan 27, 2012

Quiet Sun

Flux integrated over 24 hours.

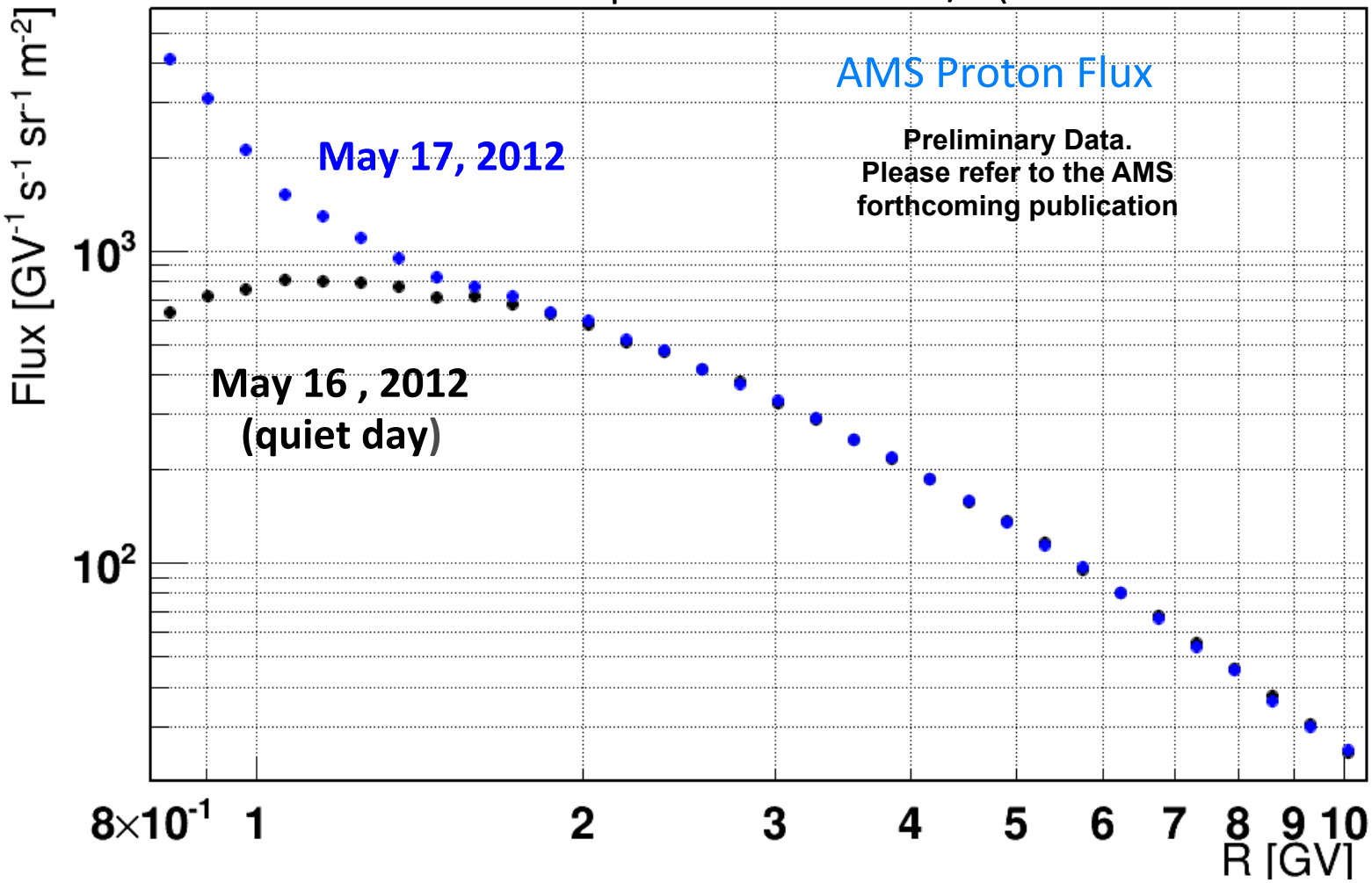


AMS Daily Proton Flux May 17, 2012

May 17, 2012 - Ground Level Enhancement (GLE)

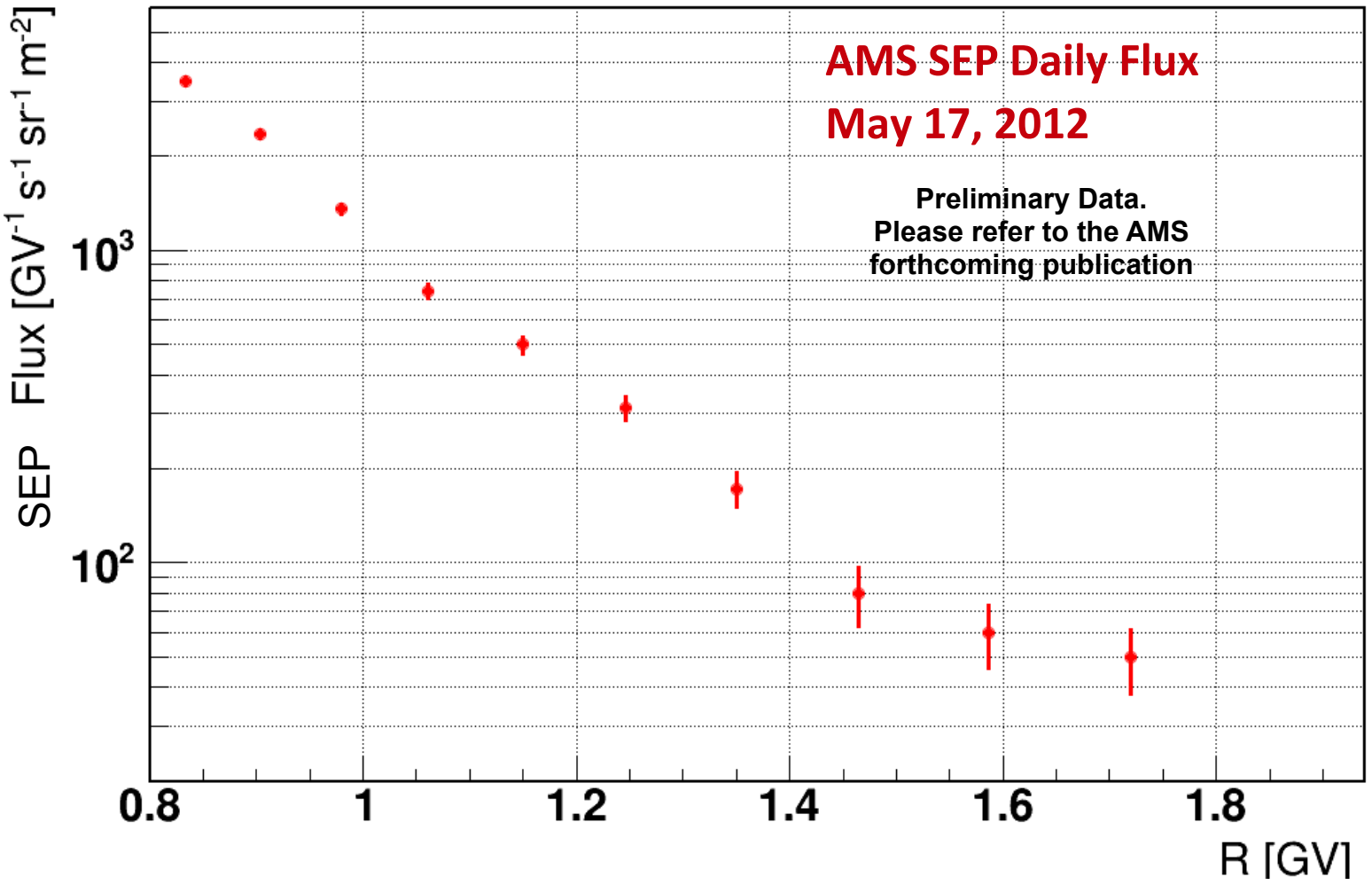
Solar Flare of class M5.1 (XRT Flare catalog)

CME with linear speeds of 1582 km/s (SOHO LASCO CME catalog)

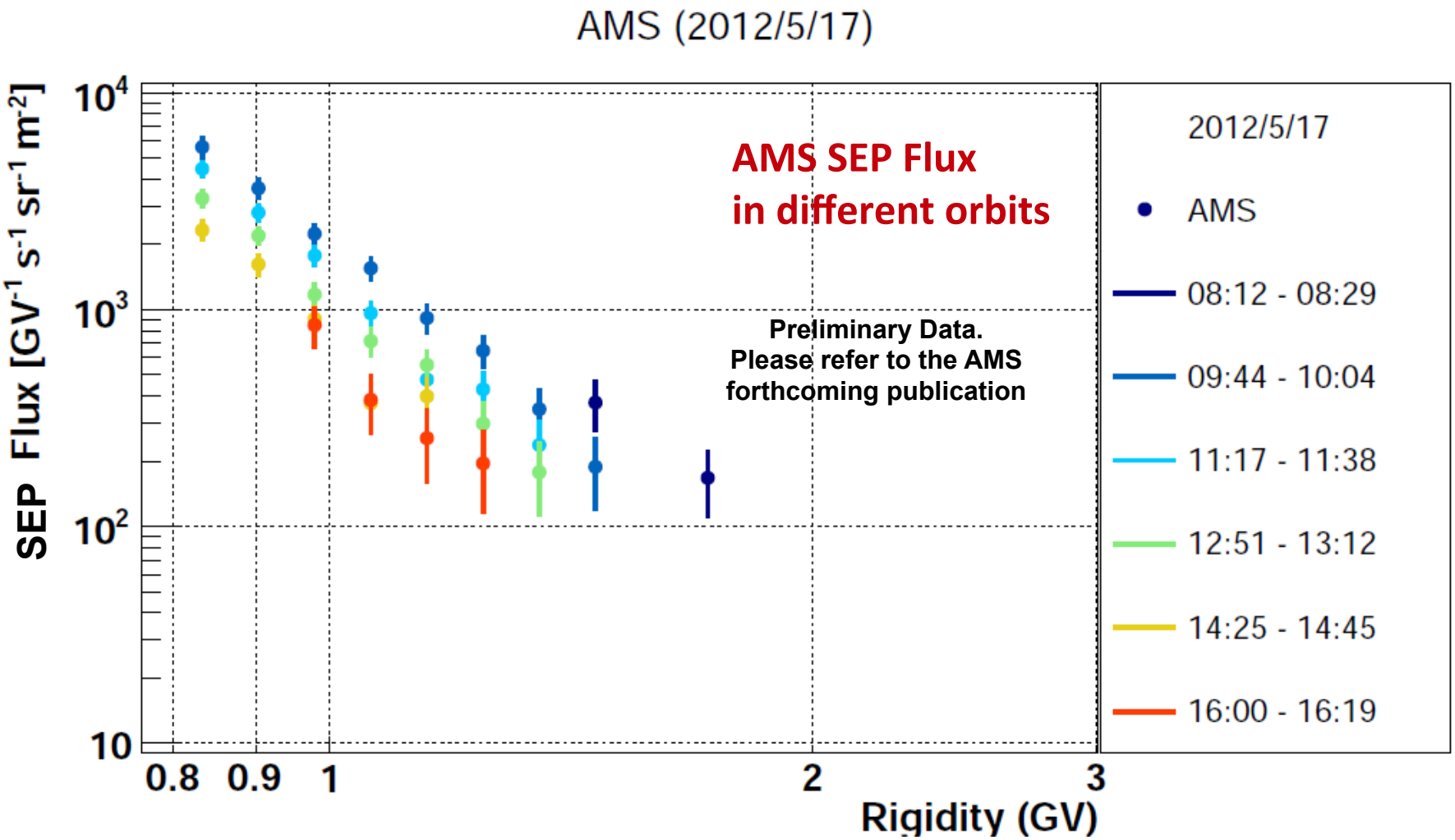


AMS Daily SEP Flux May 17, 2012

SEP flux obtained after subtracting the CGR background



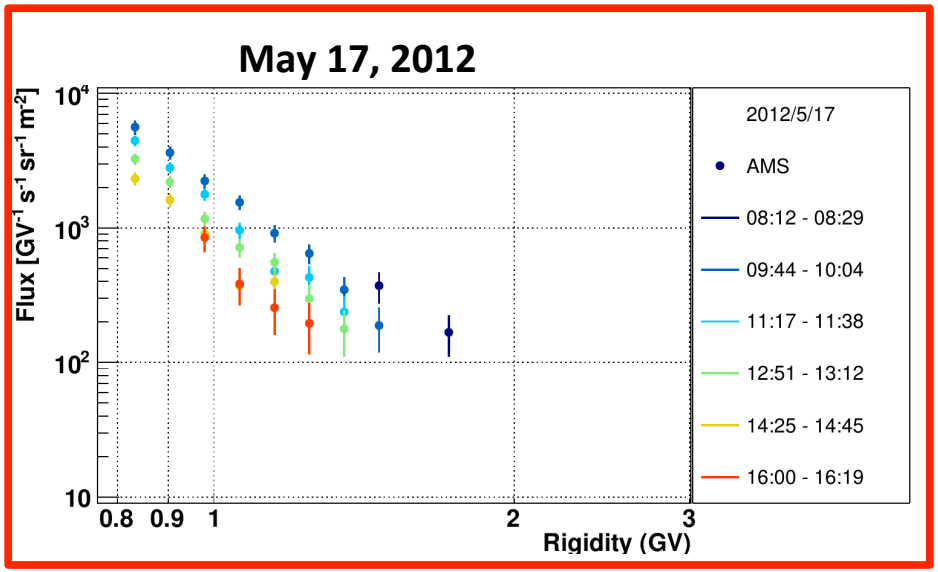
AMS Sub-orbit SEP Flux May 17, 2012

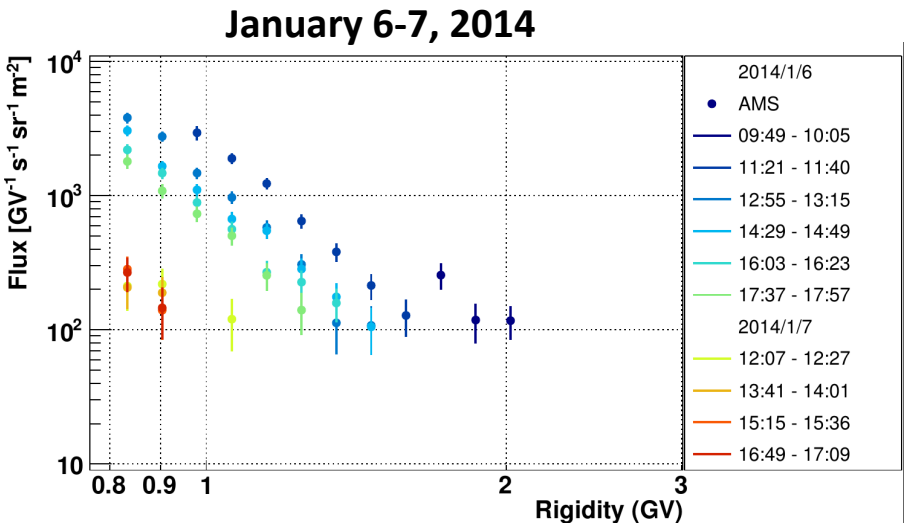


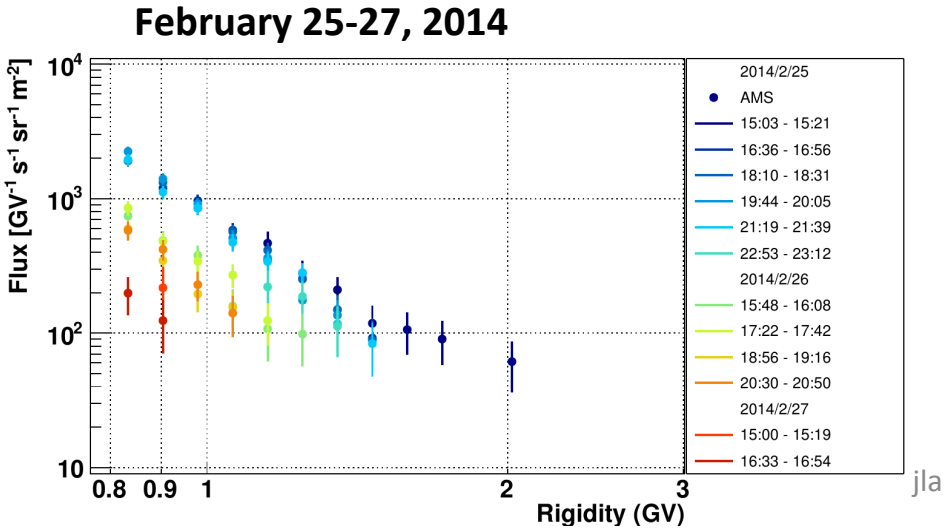
Average integration time about 20 minutes

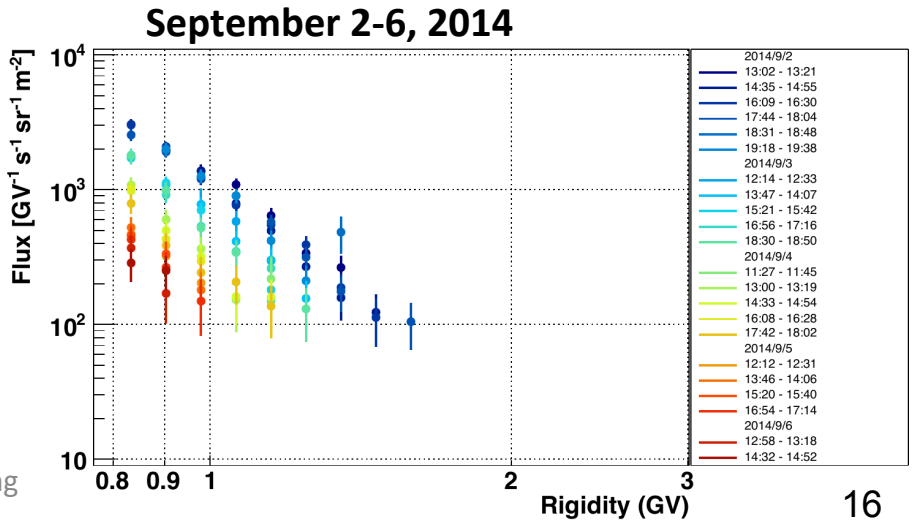
Open Question on GLEs

AMS saw similar fluxes also for other events that were not GLEs







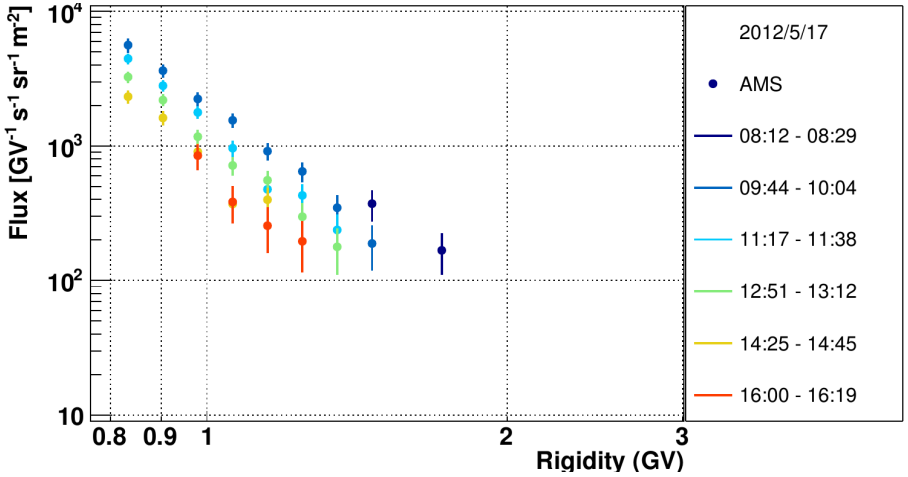


jlang

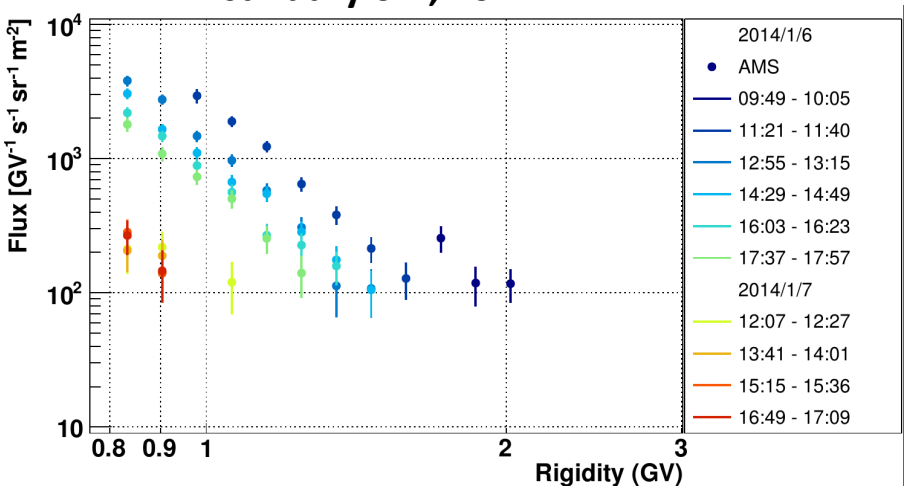
AMS SEP Observations

At AMS energies the spectrum can be described by a **power law**

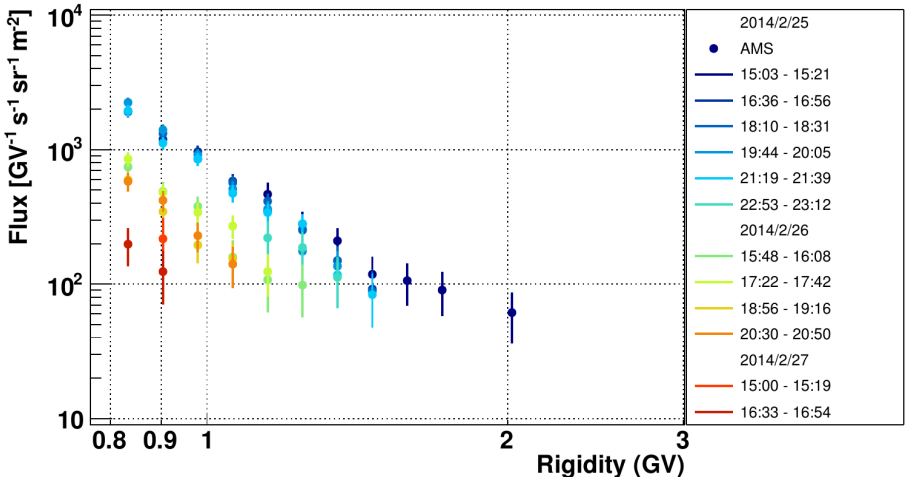
May 17, 2012



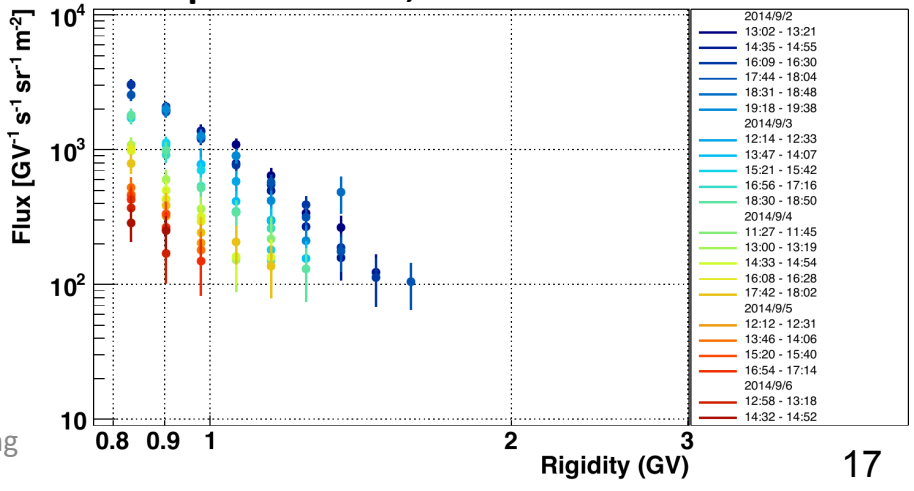
January 6-7, 2014



February 25-27, 2014

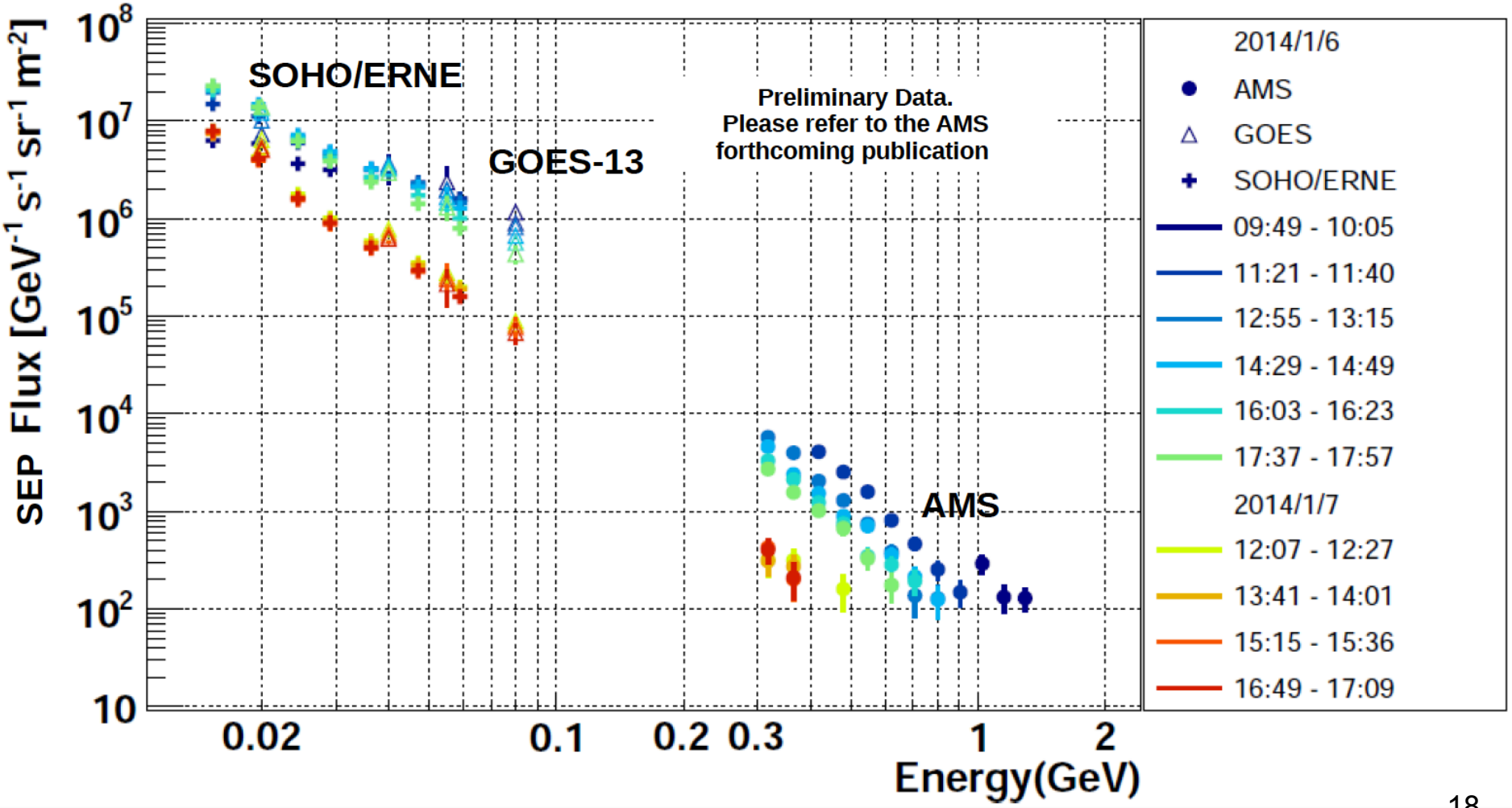


September 2-6, 2014



Multi-Spacecraft SEP observations with SOHO, GOES, and AMS

AMS data combined with lower energy data provides a baseline for the modeling of SEP acceleration

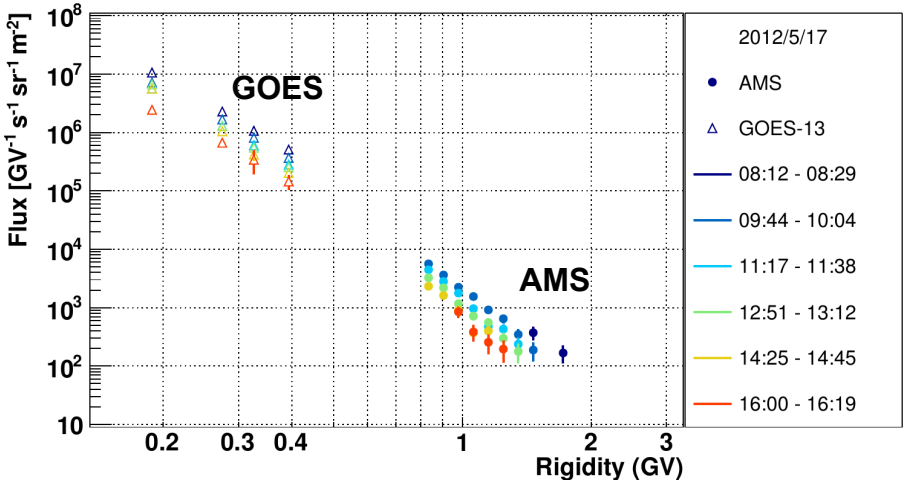


Multi-Spacecraft SEP observations

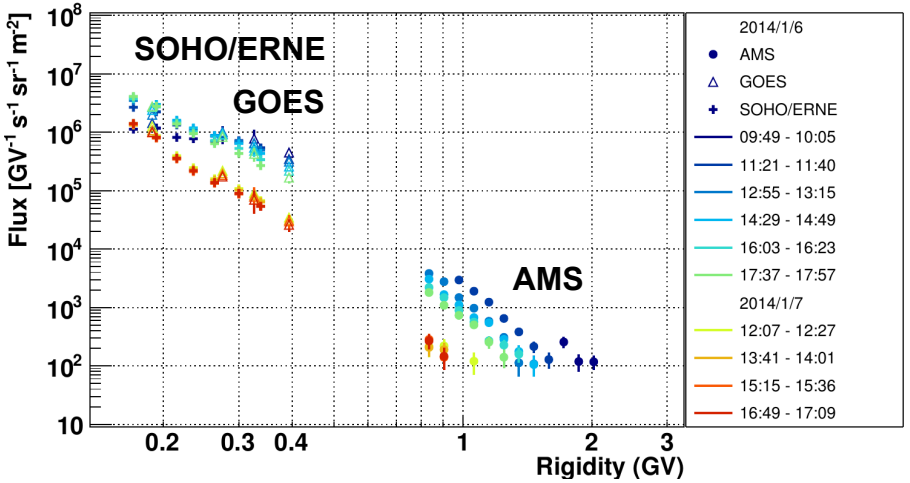
A clear spectral break is observed

The flux cannot be described by a single power law

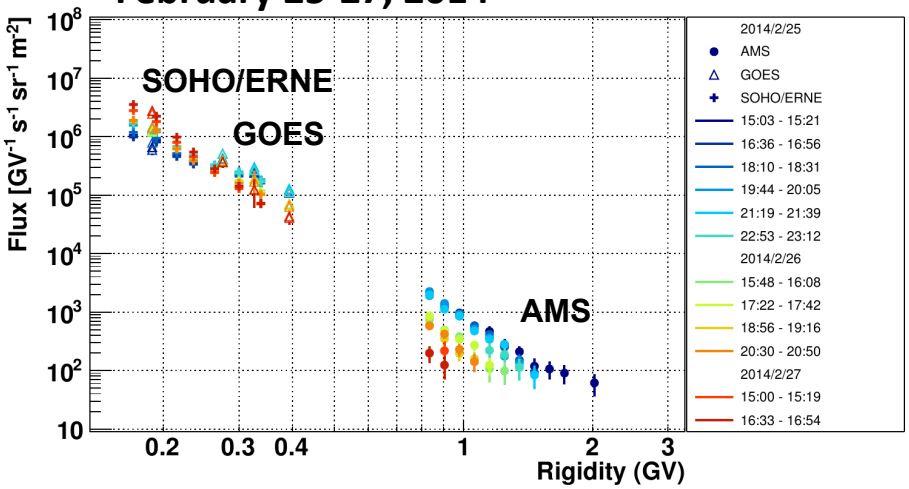
May 17, 2012



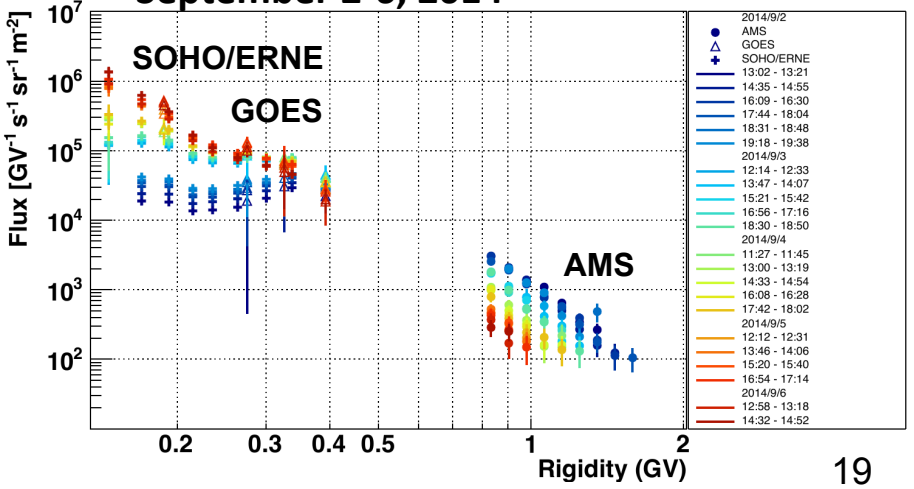
January 6-7, 2014



February 25-27, 2014

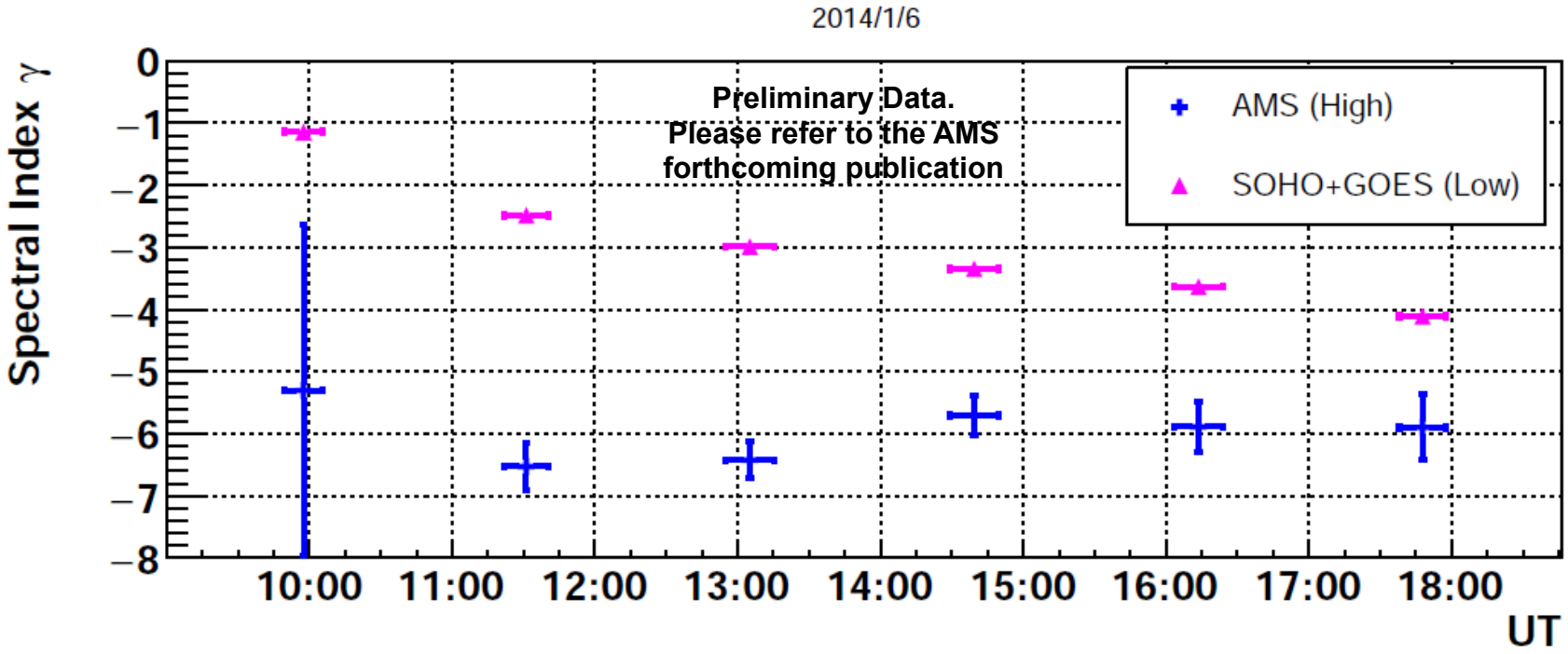


September 2-6, 2014



Time Evolution of SEP Spectral Index
January 6, 2014

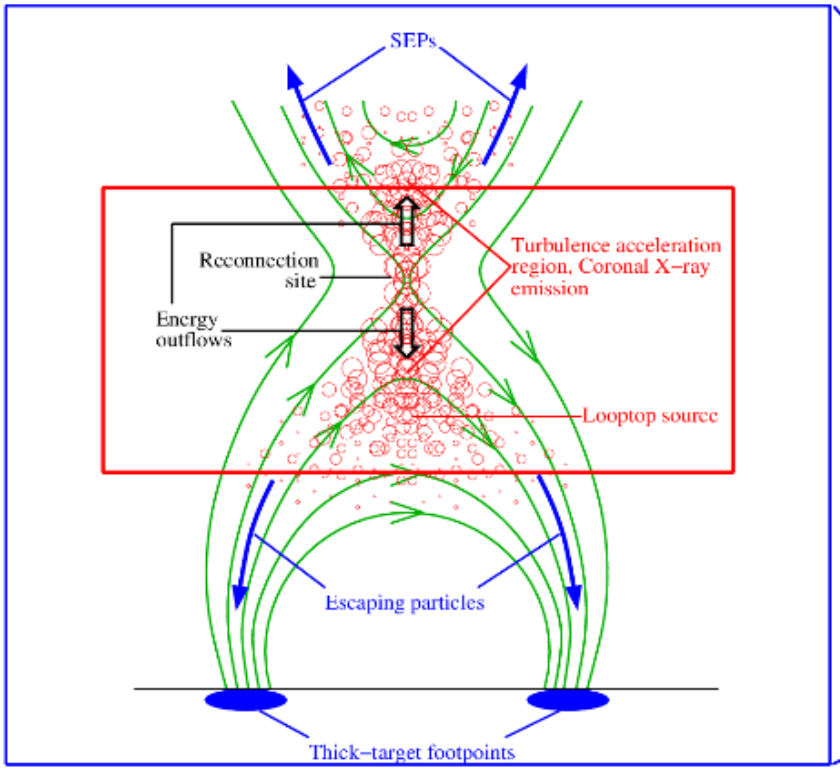
Spectral index from a fit with a power law for the **Low** (SOHO+GOES) and **High** (AMS) energy spectra **separately**



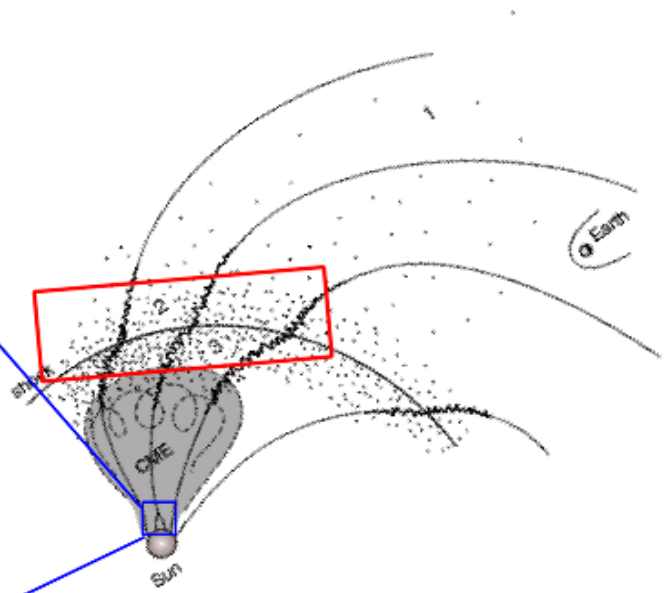
At **low** energy the spectral index **changes** with time
At **high** energy it remains fairly **constant** with time

High Energy SEP Acceleration Mechanisms

Acceleration in Flares



Diffusive shock acceleration in CMEs



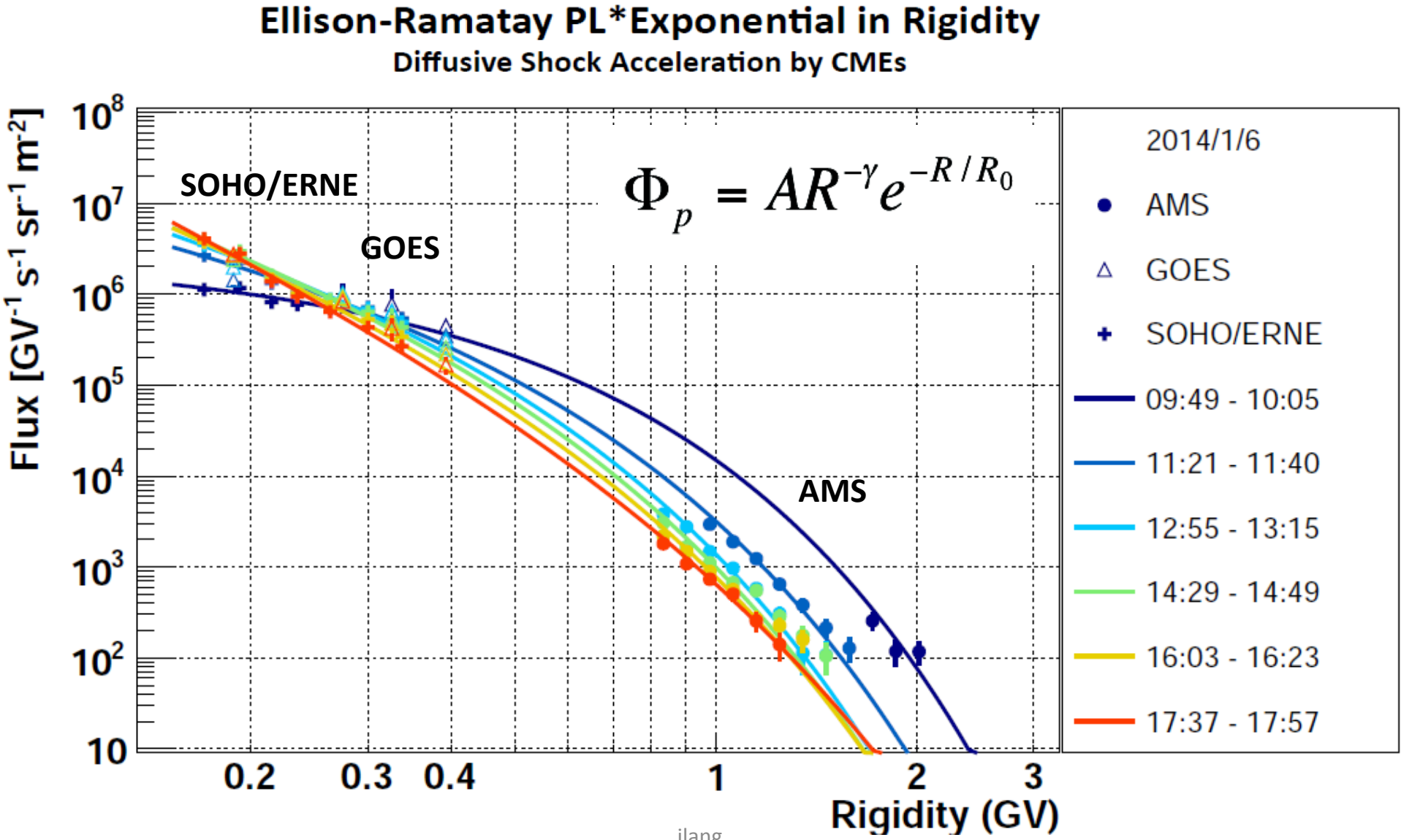
AMS measurements will help us understand the acceleration mechanisms of High Energy SEPs

Some Models Used to Describe SEP Data

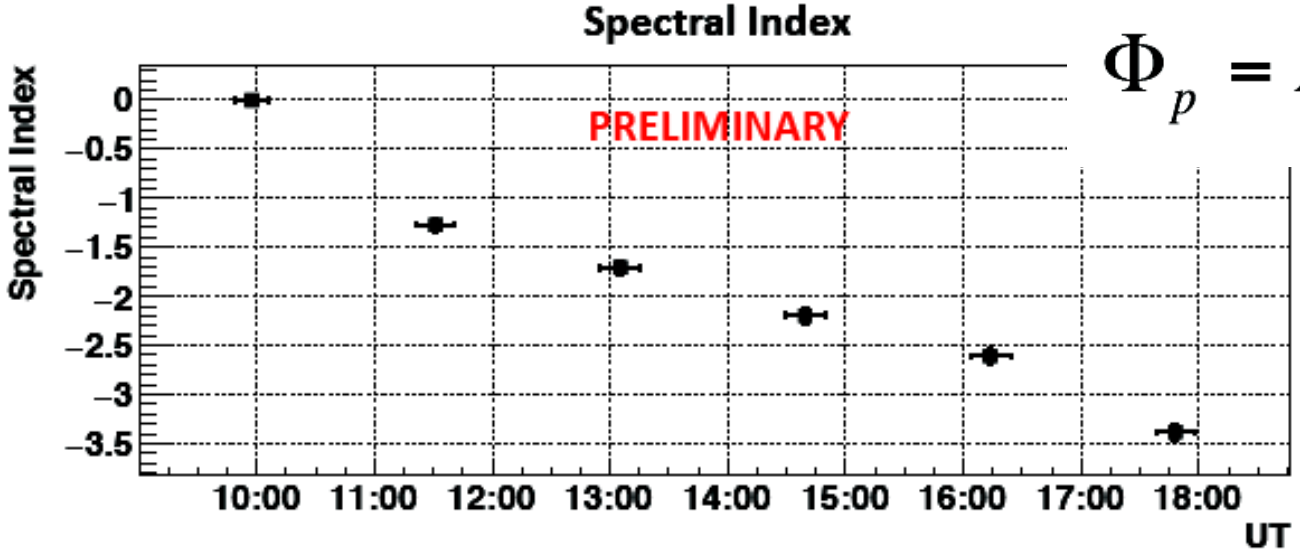
Function/Model in Rigidity	Mathematical Form
Power Law	$\frac{dJ}{dR} = A\left(\frac{R}{R_0}\right)^{-\gamma}$
Power Law times Exponential	$\frac{dJ}{dR} = Ae^{-R/R_0}$
Modified Power Law	$\frac{dJ}{dR}_{\|\|} = KR^{[\gamma-\Delta\gamma(R-1)]}$
Band Function	$\frac{dJ}{dR} = \begin{cases} AR^{-\gamma_1}e^{-R/R_0} & \text{if } R \le (\gamma_2-\gamma_1)R_0 \\ A[(\gamma_2-\gamma_1)R_0]^{(\gamma_2-\gamma_1)}e^{\gamma_2-\gamma_1}R^{-\gamma_2} & \text{if } R > (\gamma_2-\gamma_1)R_0 \end{cases}$
Second-order Bessel Function	$\frac{dJ}{dE} = ARK_2\left(2\left[\frac{3p}{m_pc\alpha T}\right]^{1/2}\right)$

Function/Model in Energy	Mathematical Form
Power Law	$\frac{dJ}{dE} = A\left(\frac{E}{E_0}\right)^{-\gamma}$
Ellison & Ramatay Spectrum	$\left(\frac{dJ}{dE}\right)_0 \propto n_{inj}(E_{inj}^2 + 2E_{inj}m_0c^2)^{3/[2(r-1)]}(E^2 + 2Em_{inj}c^2)^{-(1/2)[(r+2)/(r-1)]}$
Coupled Wave-Particle Acceleration Model at an Evolving Shock by Lee (2005)	$G_p(v > \bar{v}_p) = 1 - \beta\left(\frac{v}{2V}\right)\epsilon\left[\frac{(v/\bar{v}_p)^{\beta-3}-1}{\beta-3} - \frac{(v/\bar{v}_p)^{\beta+\delta-6}-1}{\beta+\delta-6}\right]$
Model of Stochastic Acceleration by Gallegos-Cruz and Pérez-Peraza (1995, 2006)	$N(E) = kq_0\left(\frac{3}{4\pi a}\right)^{1/2}\frac{\epsilon^{3/4}[\epsilon^2-m^2c^4]^{-\frac{3\rho}{2\alpha}}}{(\epsilon^2-m^2c^4)^{1/8}}e^{-(3a/\alpha)^{1/2}J}$

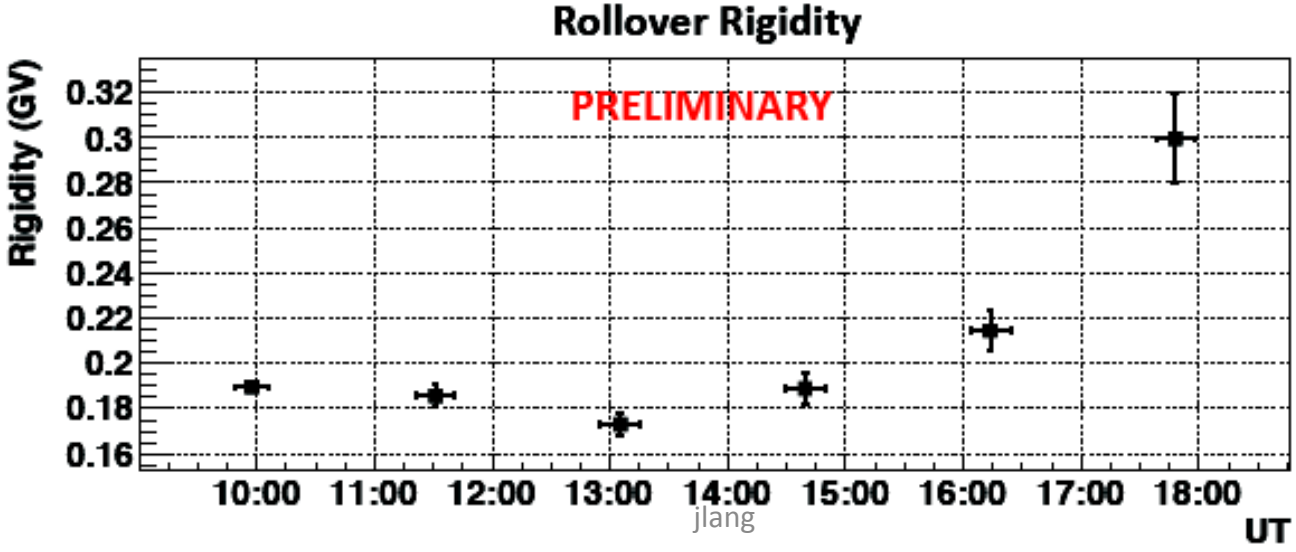
January 6, 2014 Event – Power law*Exponential



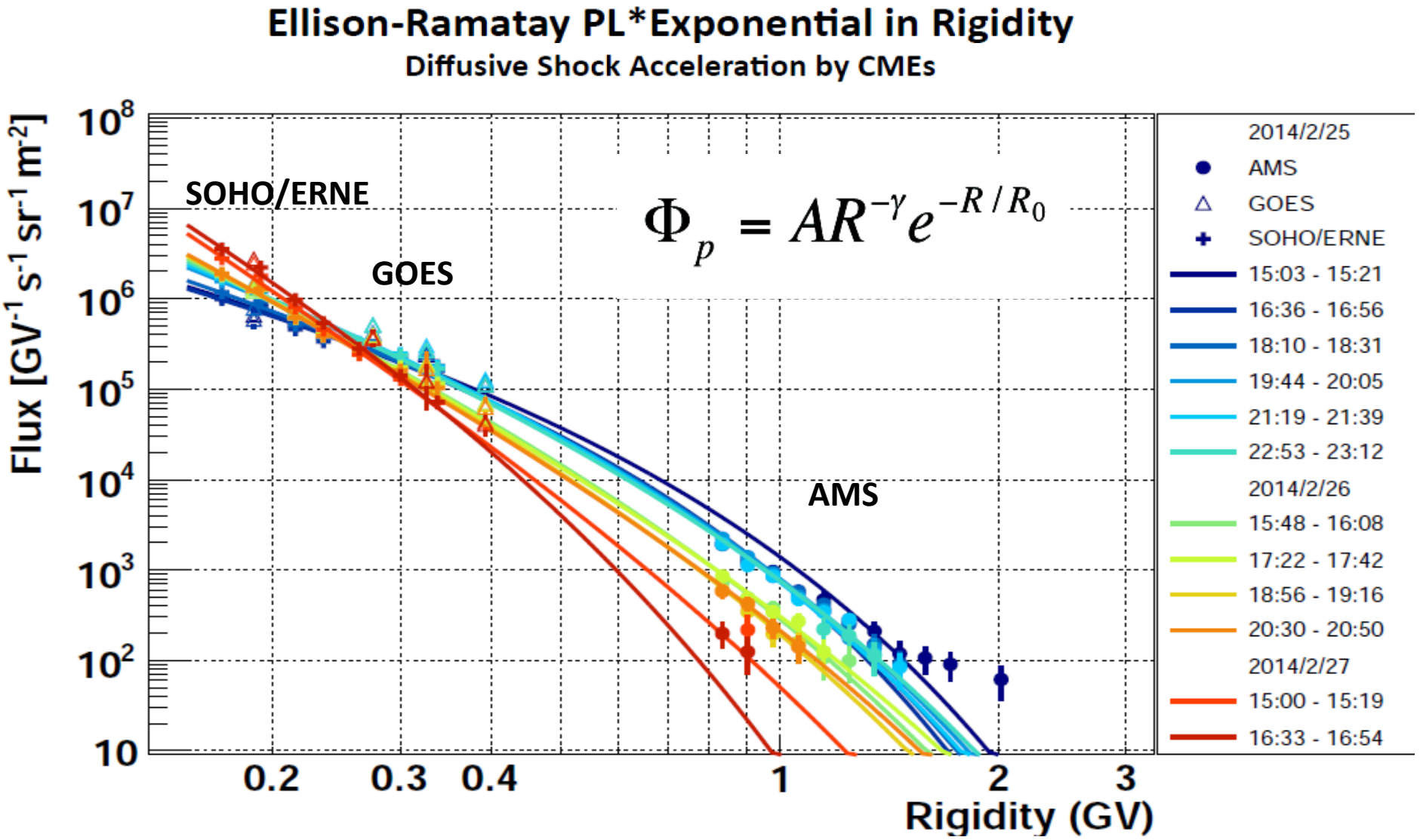
Time Evolution of Power law*Exponential Fit January 6, 2014



$$\Phi_p = AR^{-\gamma}e^{-R/R_0}$$



February 25, 2014 Event – Power law*Exponential



Improved fit analysis with different models is ongoing

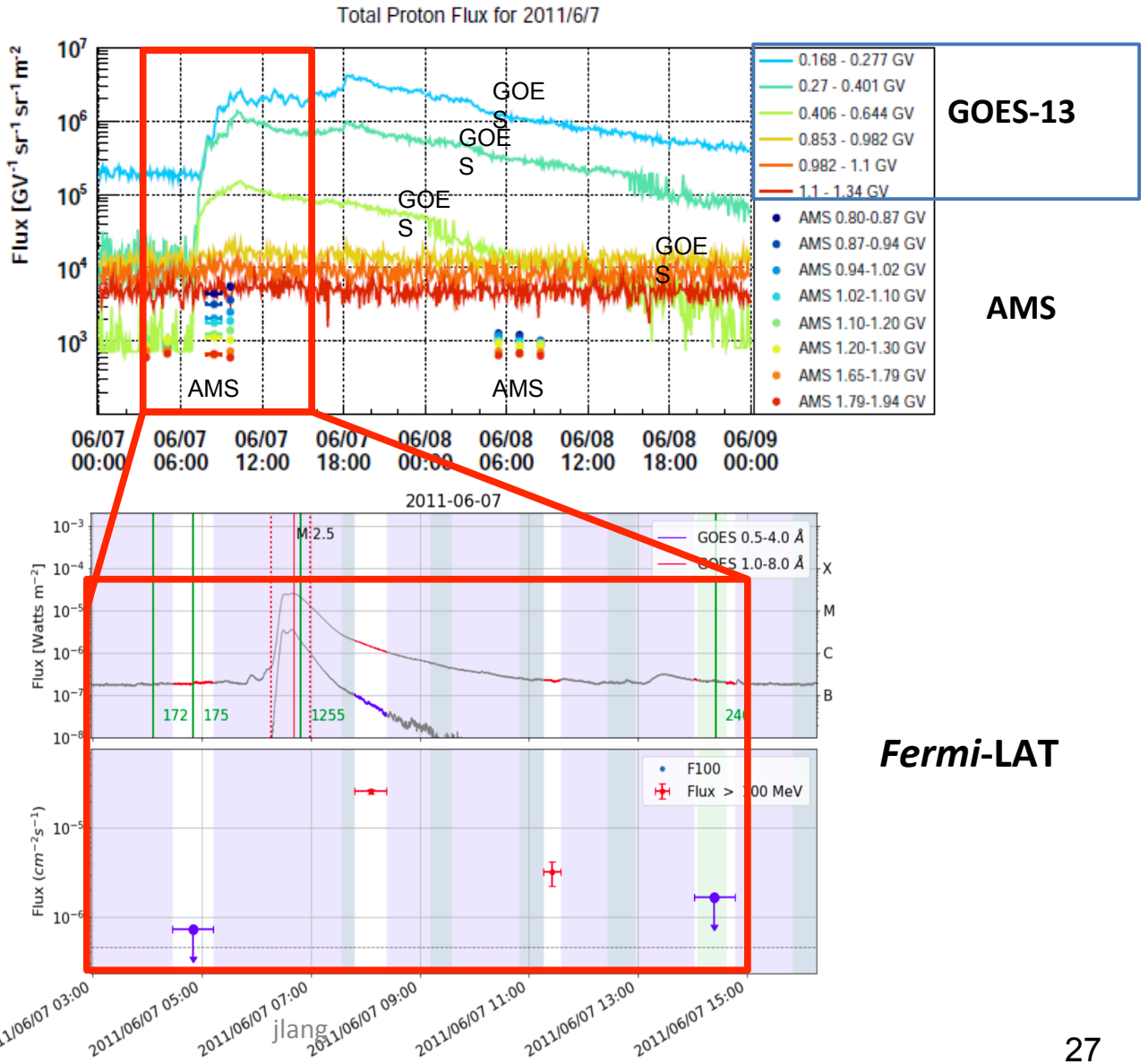
AMS SEP List and *Fermi* long-duration Gamma-ray flares

Preliminary list of AMS SEP events with measured *Fermi* long-duration gamma-ray flares (ongoing work)

AMS Event		Event Date	Flare Class	CME Vel. (km/s)
1		2011/06/07	M2.5	1255
2	FD	2011/08/04	M9.3	1315
3		2011/08/09	X6.9	1610
4		2011/09/06	X2.1	575
5		2011/09/22	X1.4	1905
6	FD	2012/01/23	M8.7	2175
7	FD	2012/01/27	X1.7	2508
8	FD	2012/03/07	X5.4, X1.3	2684, 1825
9	FD	2012/03/13	M7.9	1884
10		2012/05/17	M5.1	1582
11		2012 /07/06	X1.1	1854
12		2012/07/08	M6.9	1495
13	FD	2012/07/19	M7.7	1631
14	FD	2012/07/23	backside	2003
15		2013/04/11	M6.5	861
16	FD	2013/05/22	M5.0	1466
17	filament	2013/09/29	C1.2*	1179
18		2013/10/28	M5.1, M2.8, M4.4	1201, 1073, 812
19	FD	2013/11/02	backside	828
20		2013/12/28	backside	1118
21	FD	2014/01/06	backside	1118
22	FD	2014/01/07	X1.2	1830
23	FD	2014/02/25	X4.9	2147
24	FD	2014/04/18	M7.3	1203
25		2014/09/01	backside	1404
26	FD	2014/09/10	X1.6	1267
27		2015/10/29	backside	530**

AMS, GOES SEP and *Fermi*-LAT – June 7, 2011 Event

Study of AMS SEP and *Fermi*-LAT gamma-ray predicted proton spectral indices is ongoing.



GOES-13

AMS

***Fermi*-LAT**

Presented at the workshop on **The Solar Sources of GeV Gamma-Rays**
Leiden - Holland
February 26- March 2, 2018

Summary and Conclusions

- AMS is sensitive to SEPs when orbiting close to geomagnetic poles **(27% of orbiting time)**
- From May 2011 to May 2016 AMS has measured **27 high-energy SEP events**
- AMS provides SEP flux and time evolution at **high rigidity with fine rigidity resolution**
- **AMS SEP fluxes have a power law** spectrum with a spectral index that remains fairly constant with time
- Multi-spacecraft analysis (GOES-13, SOHO and AMS) shows that the broader energy spectrum cannot be described by a single power law
- AMS measurements will help to understand the acceleration mechanisms of high-energy SEPs