Properties of The Forbush decreases measured by AMS on the ISS

Matteo Palermo (University of Hawaii)
on behalf of the AMS Collaboration

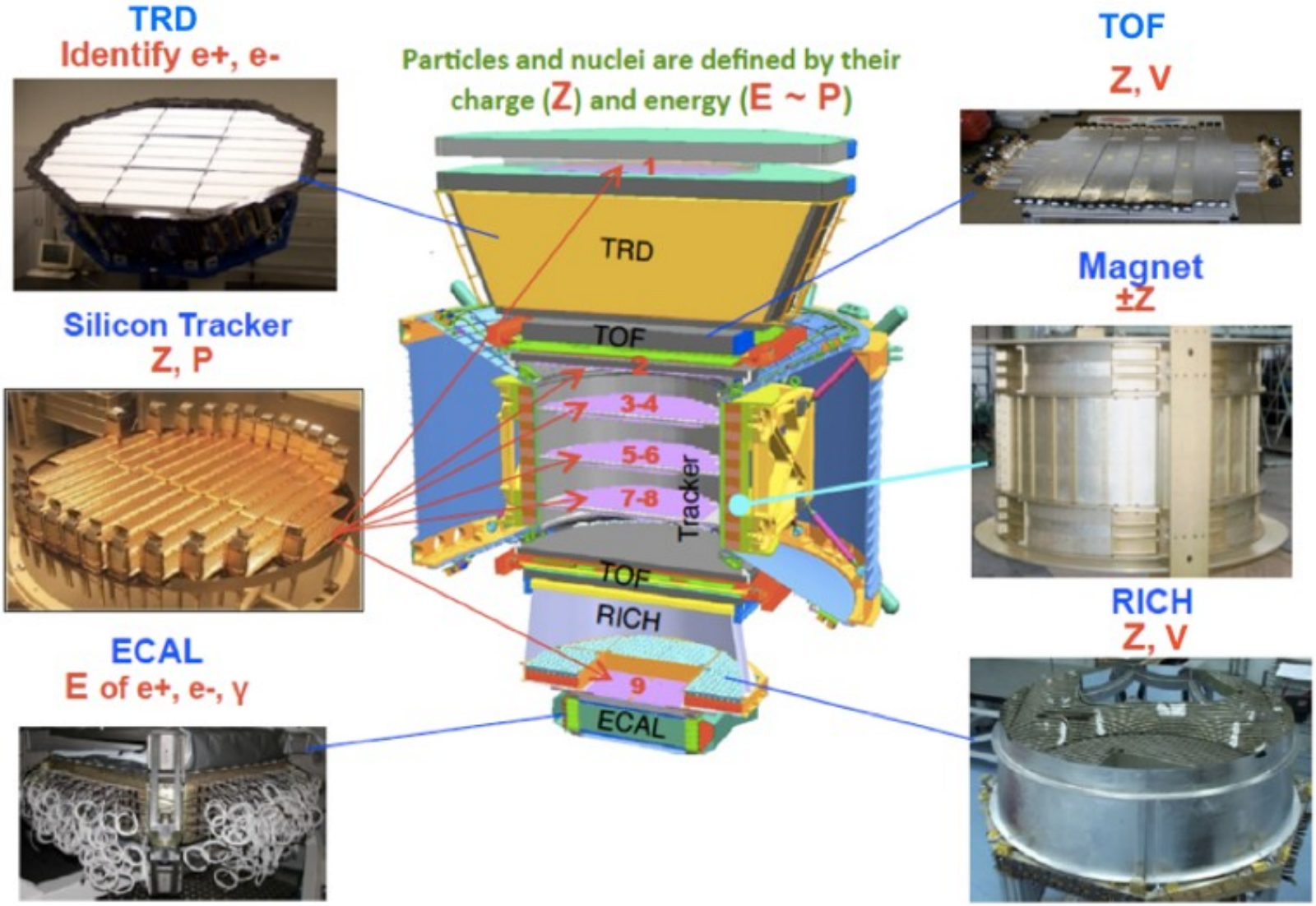
Solar Energetic Particles (SEP), Solar Modulation and Space Radiation: New Opportunities in the AMS-02 Era #3

Washington DC

Physics and Astronomy Department
University of Hawaii at Manoa
Honolulu, Hawaii, US

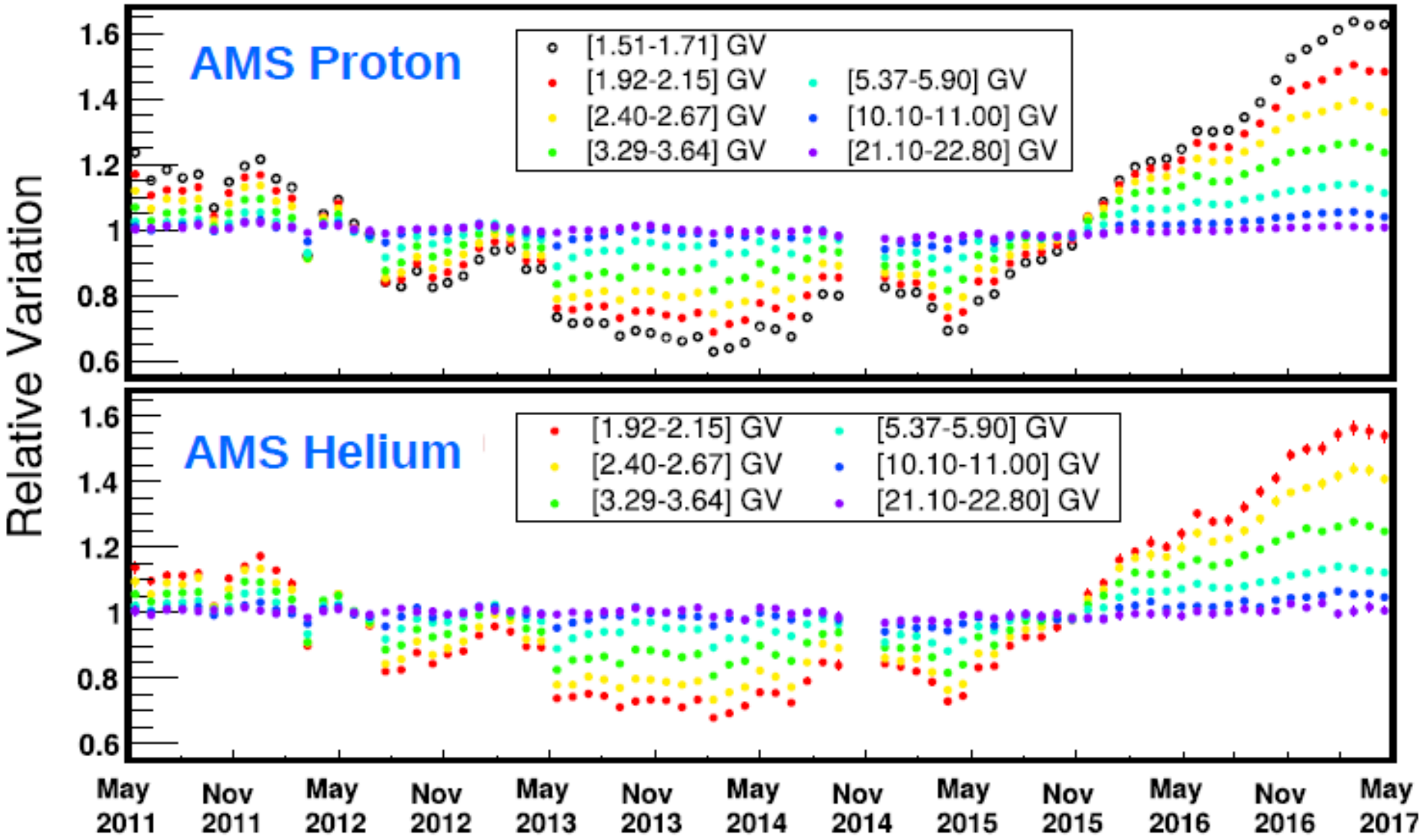
Particle Identification with AMS

AMS is a general purpose detector which measures particles in the GV-TV rigidity range



Proton and He Monthly Fluxes

presentation from C. Consolandi

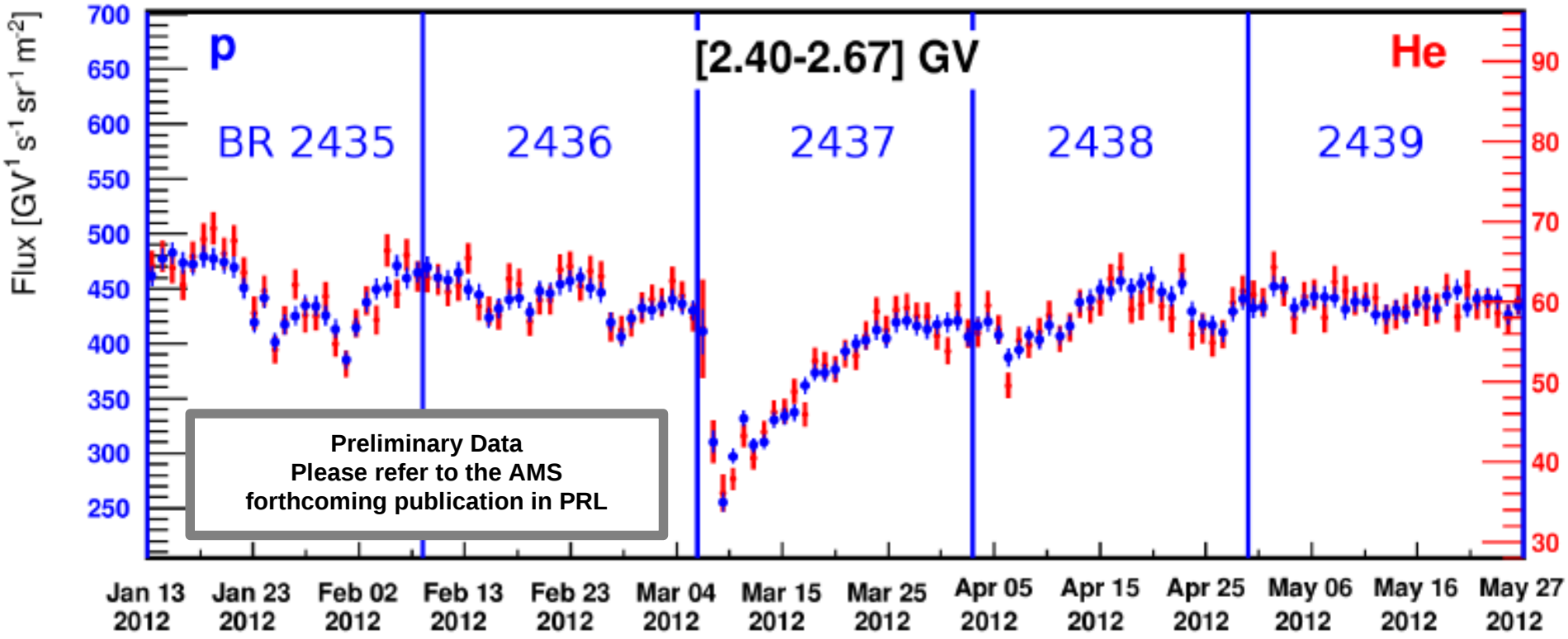


At low rigidities, not only long-term solar modulation but also short-term solar activity

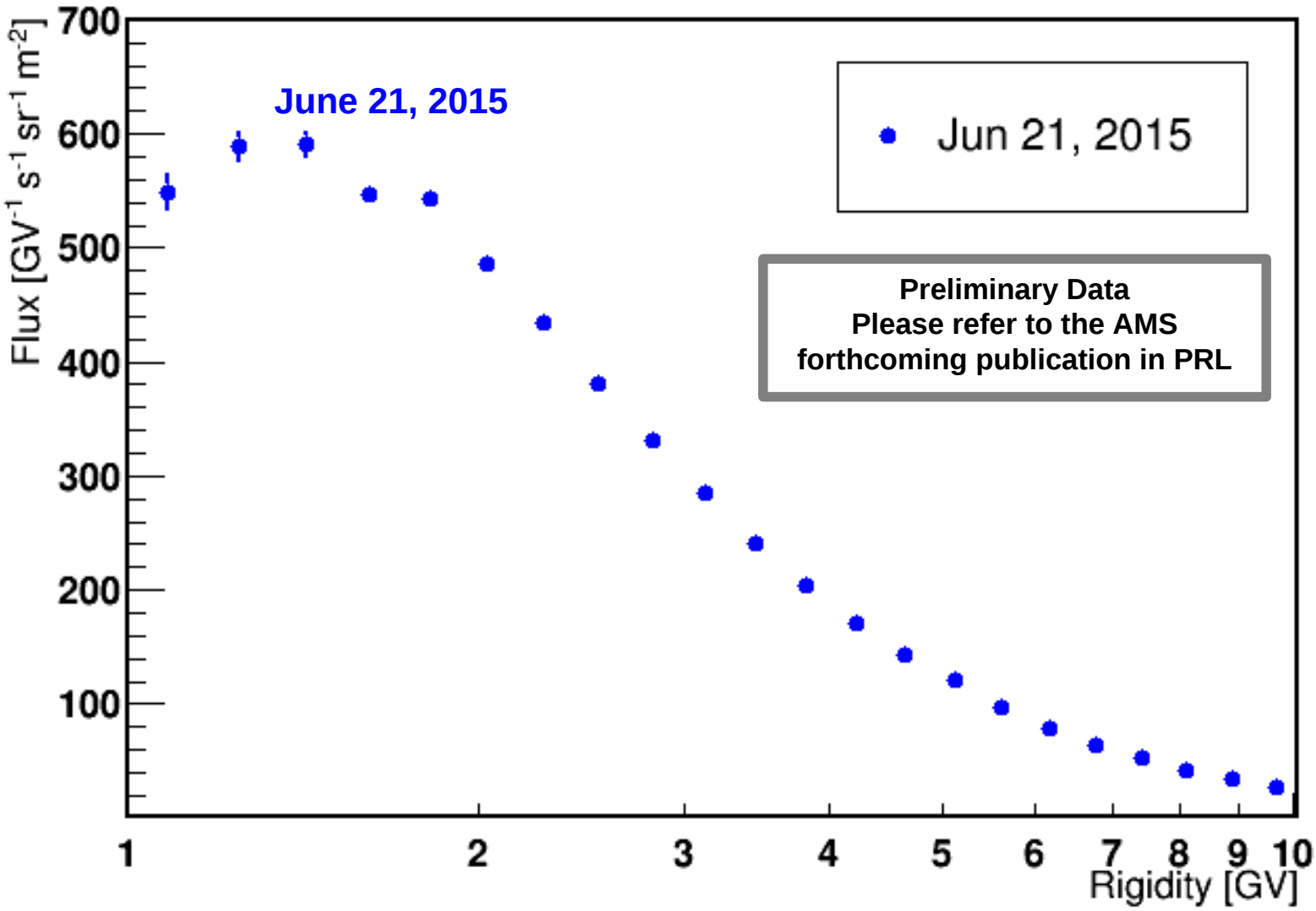
Forbush Decreases (FD)

- **Temporary decreases in the CR flux, followed by gradual recovery**
- **Often associated to passing of Interplanetary Coronal Mass Ejections (ICME) and/or Corotating Interacting Regions (CIR)**
- **Some of them may be associated with the arrival of Solar Energetic Particles (SEP) accelerated at the Sun during CME or solar flares.**

March 2012 Forbush decrease event

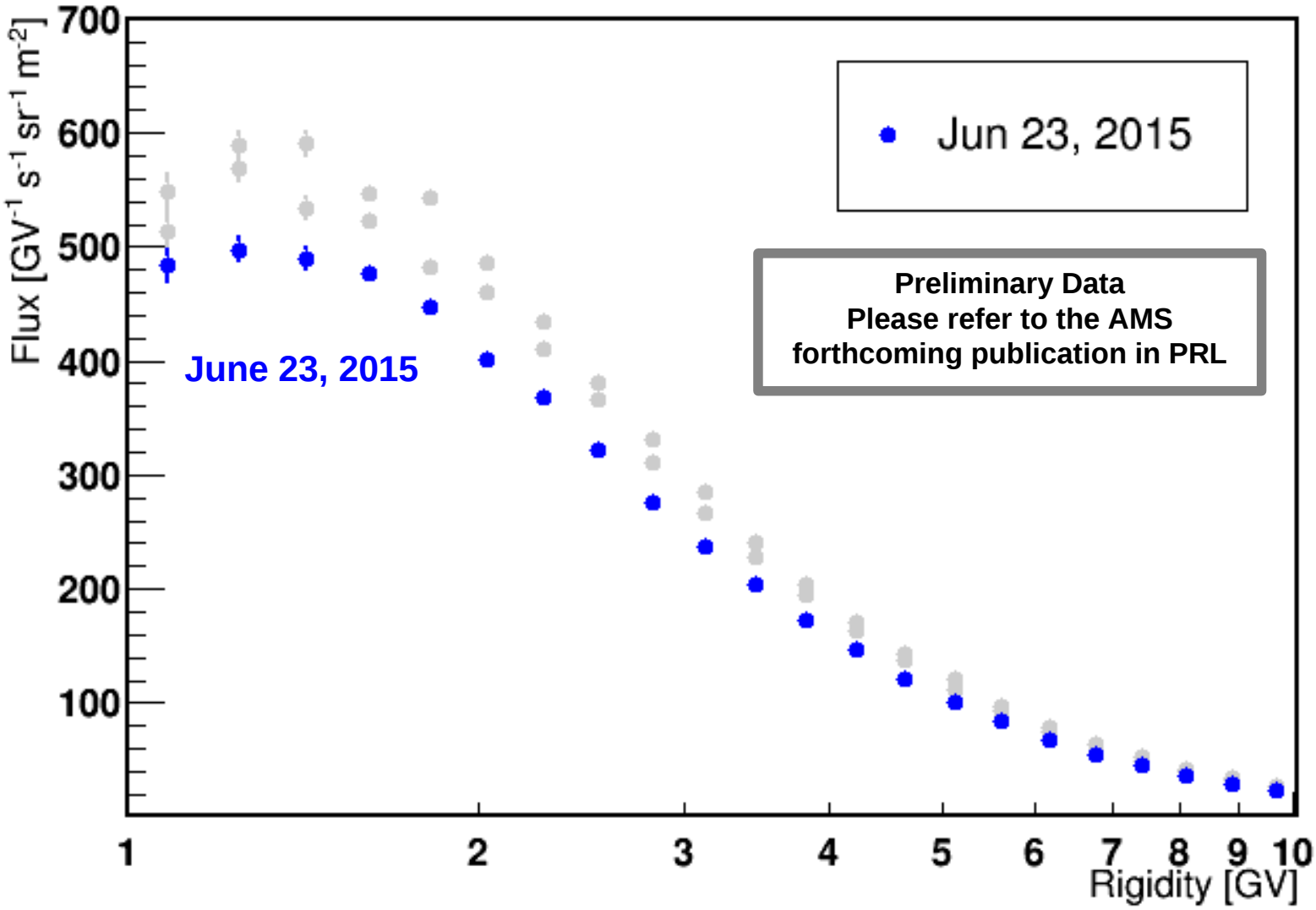


AMS Daily Proton Flux



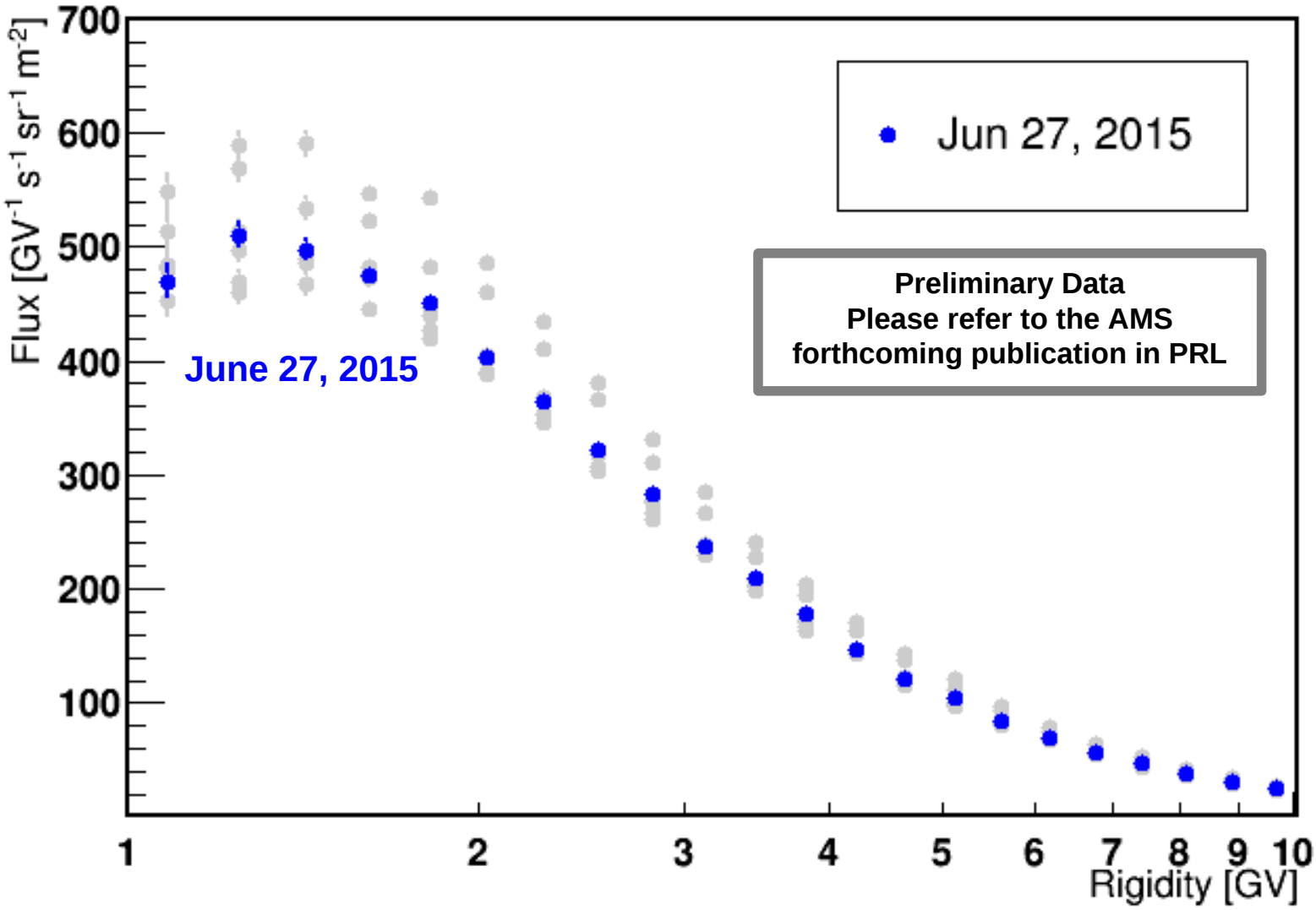
AMS Daily Proton Flux

AMS observed fast decreases in the daily proton flux



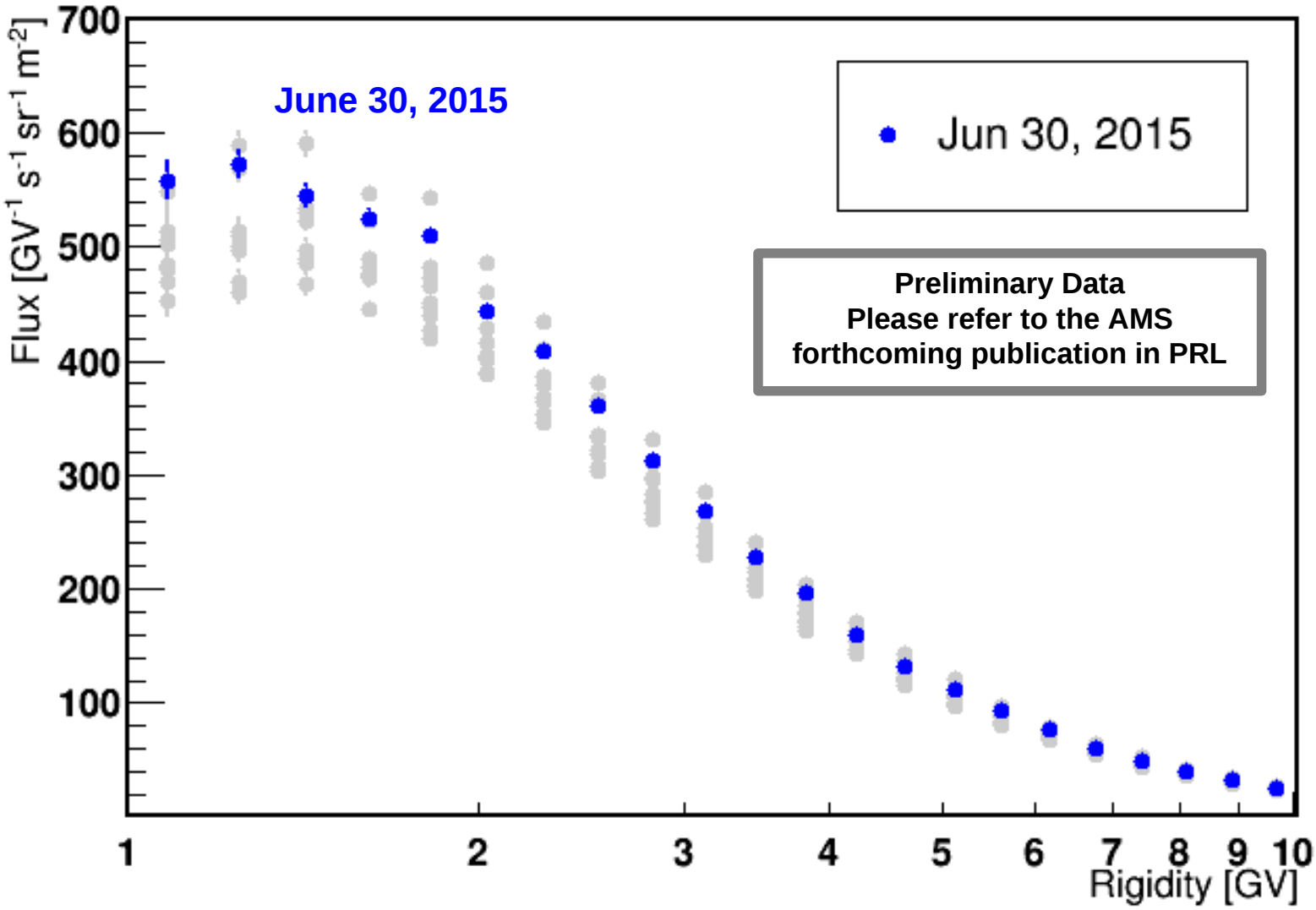
AMS Daily Proton Flux

Decreases may last several days



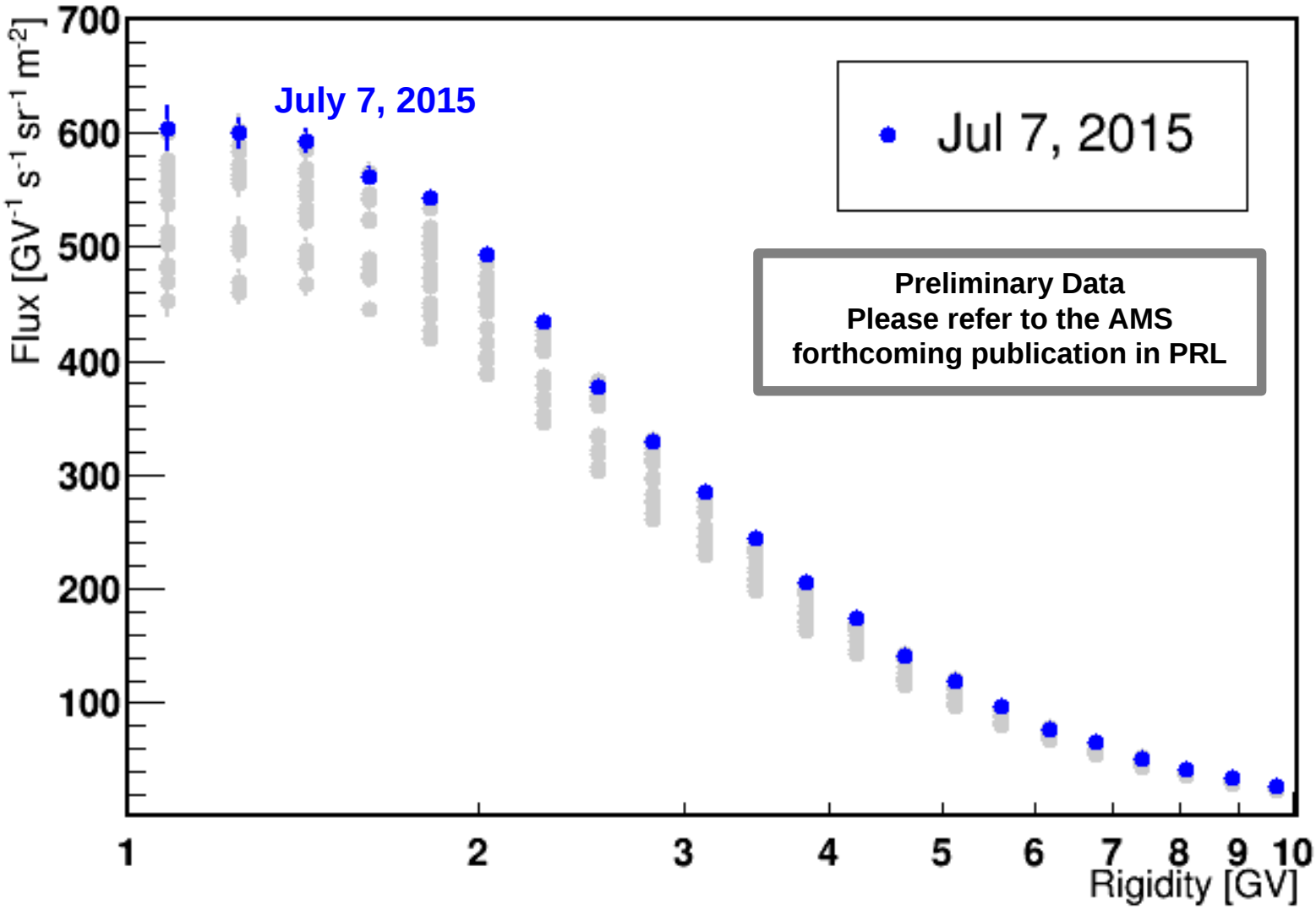
AMS Daily Proton Flux

This decrease lasted for 17 days



AMS Daily Proton Flux

Gradually AMS proton flux recovers to previous conditions



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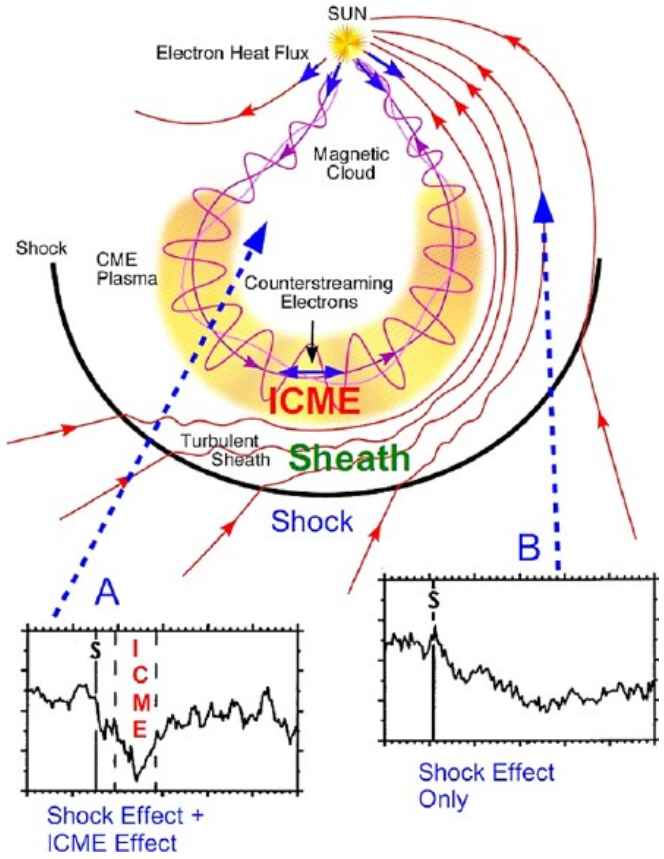

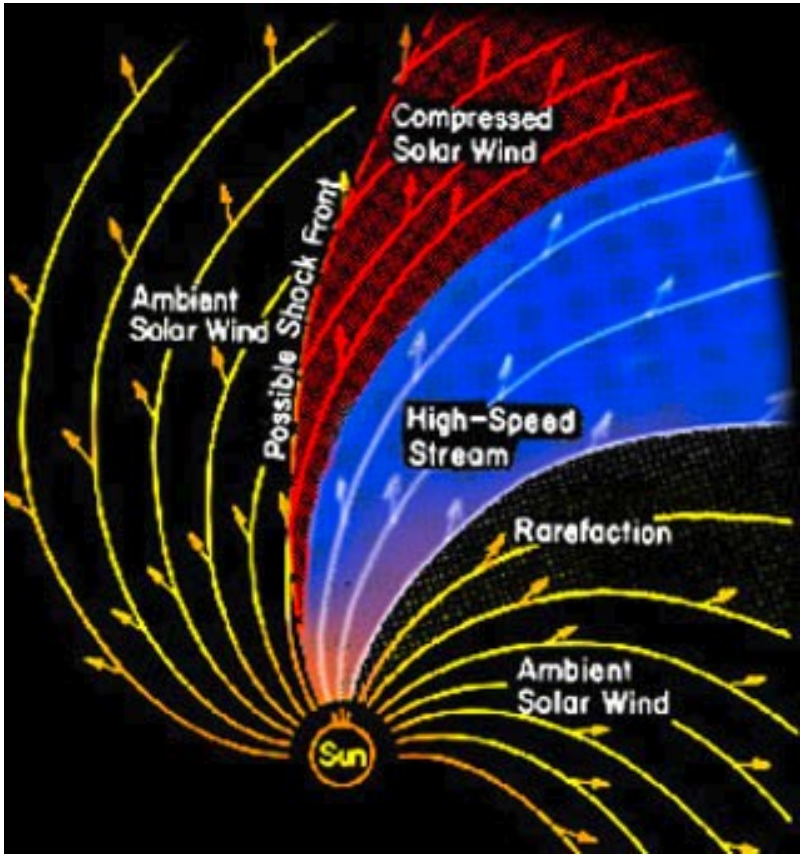

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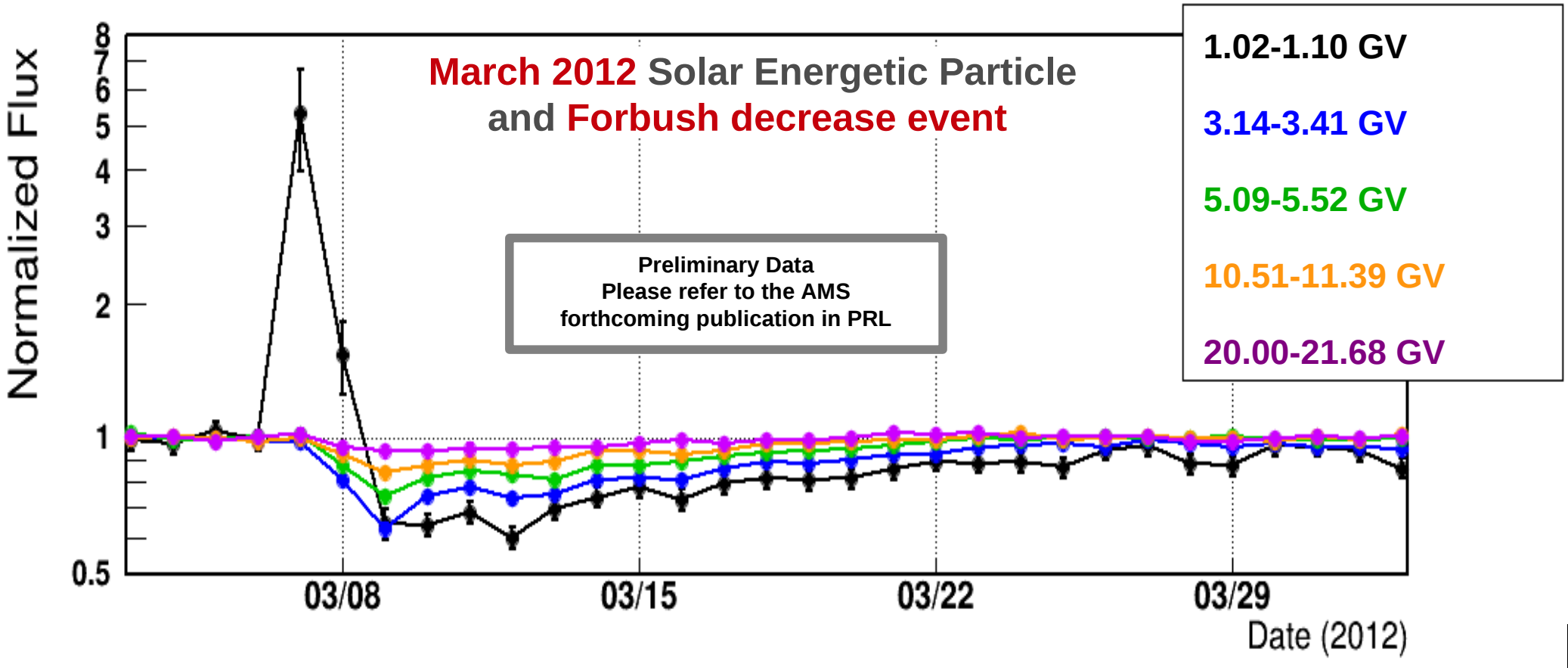
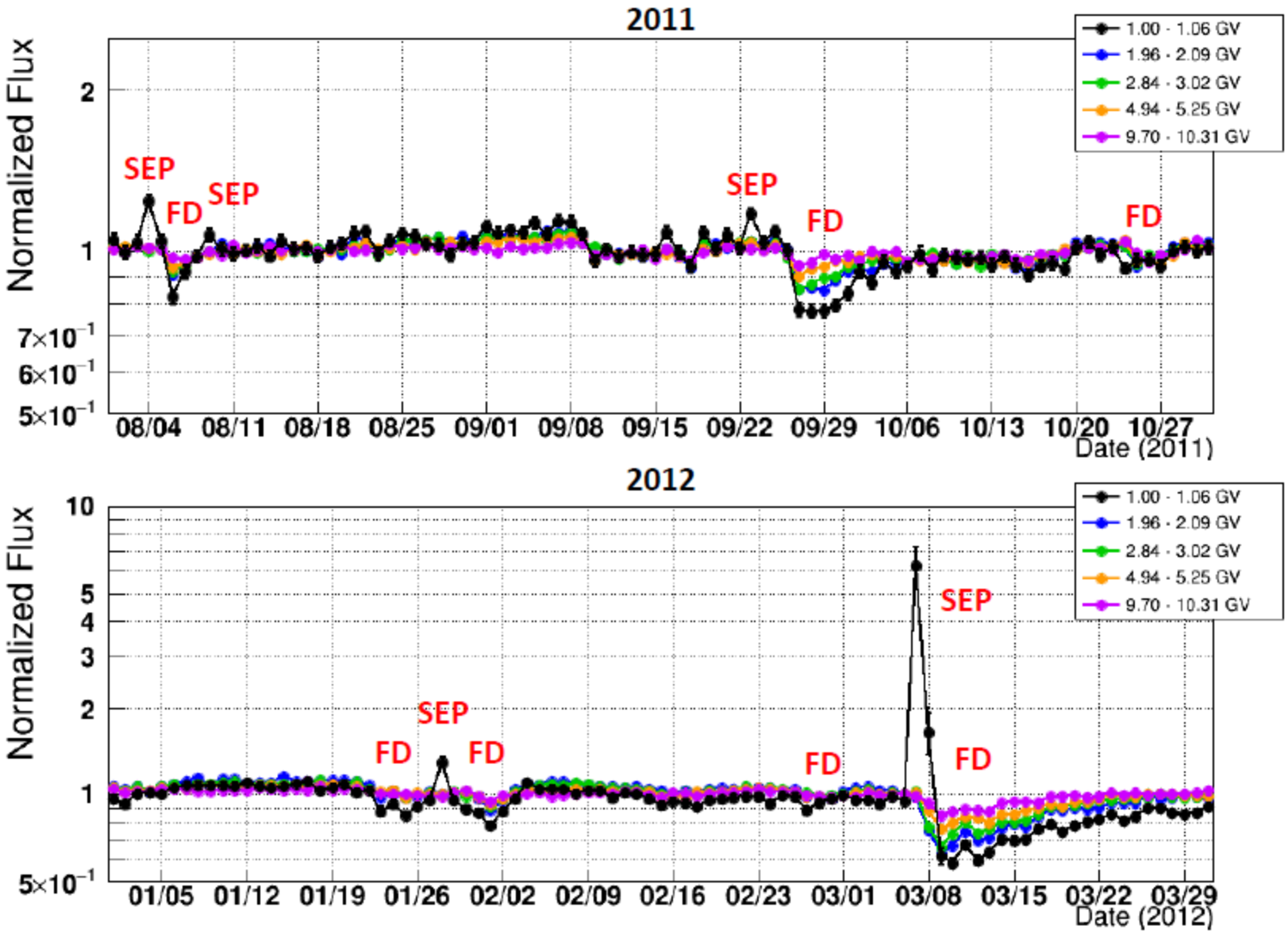


FDs and SEPs

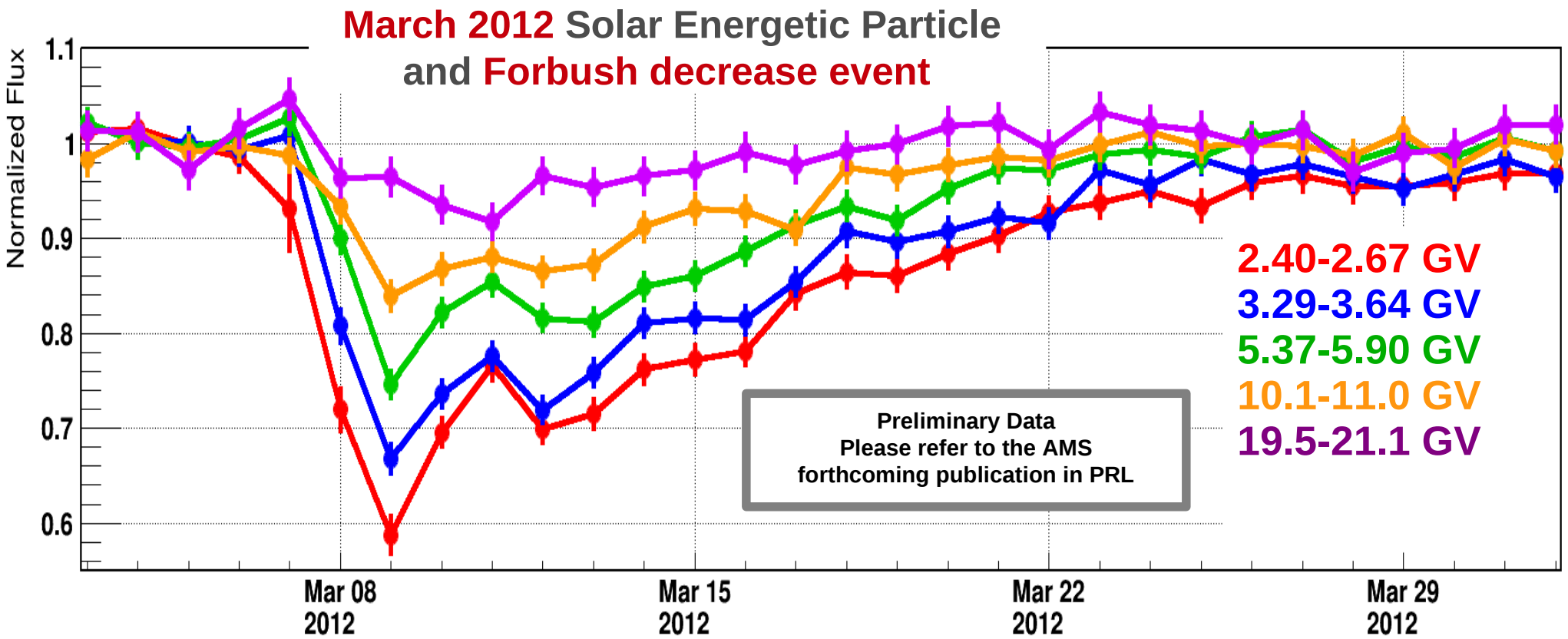

2011
Normalized Flux
2
1
7×10⁻¹
6×10⁻¹
5×10⁻¹
SEP
FD
SEP
SEP
FD
FD
08/04 08/11 08/18 08/25 09/01 09/08 09/15 09/22 09/29 10/06 10/13 10/20 10/27
Date (2011)
1.00 - 1.06 GV
1.96 - 2.09 GV
2.84 - 3.02 GV
4.94 - 5.25 GV
9.70 - 10.31 GV
2012
Normalized Flux
10
5
4
3
2
1
5×10⁻¹
SEP
FD
FD
FD
SEP
FD
01/05 01/12 01/19 01/26 02/02 02/09 02/16 02/23 03/01 03/08 03/15 03/22 03/29
Date (2012)
1.00 - 1.06 GV
1.96 - 2.09 GV
2.84 - 3.02 GV
4.94 - 5.25 GV
9.70 - 10.31 GV

Why studying FDs with AMS?

- Although FDs can be seen also on the ground (e.g by Neutron Monitors), the rigidity spectra of FDs and their time evolution are not precisely known

- The relationship with disturbances measured in the solar wind and FD behavior in rigidity is unknown

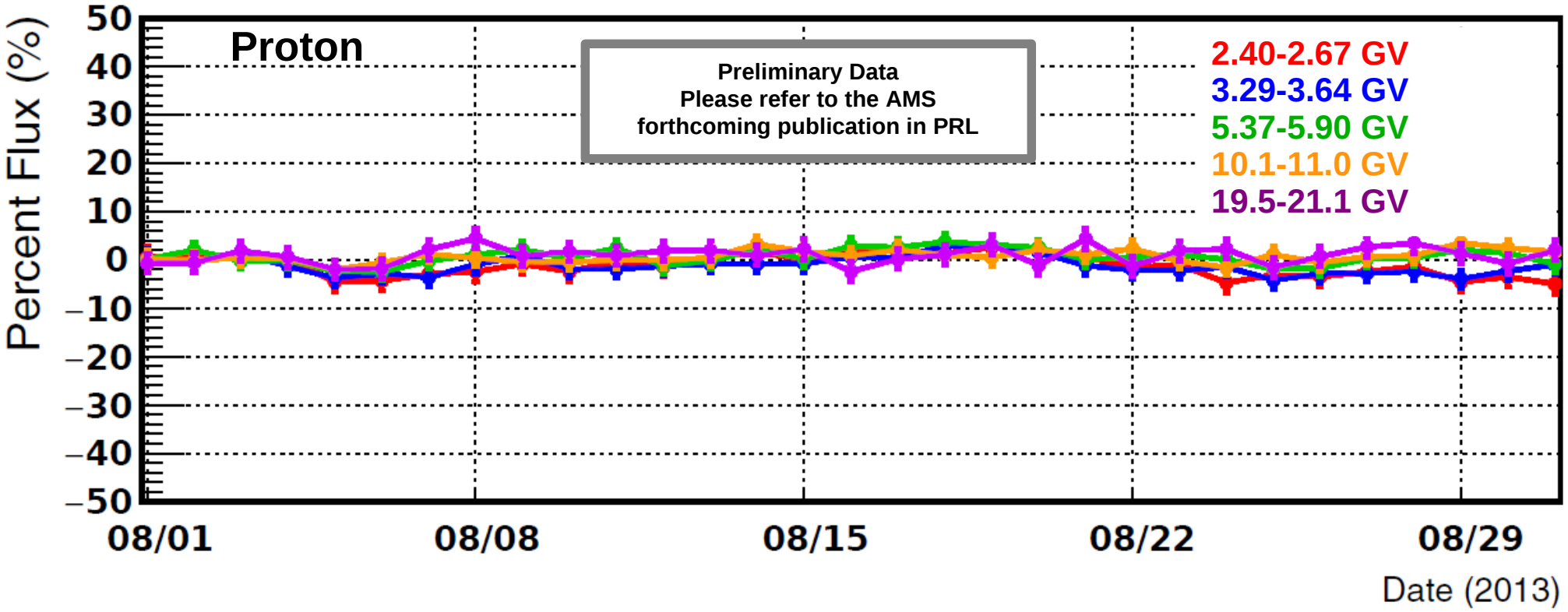
- Remove the short-term effects to better study the long-term solar modulation



Forbush Decreases Study

Characterize the day-to-day variability on AMS proton flux for each rigidity bin

1. Select quiet periods (~ 1 month)
2. Normalize the daily flux to the average of the first 3 days
3. Calculate standard deviation (SD) of the daily flux distribution



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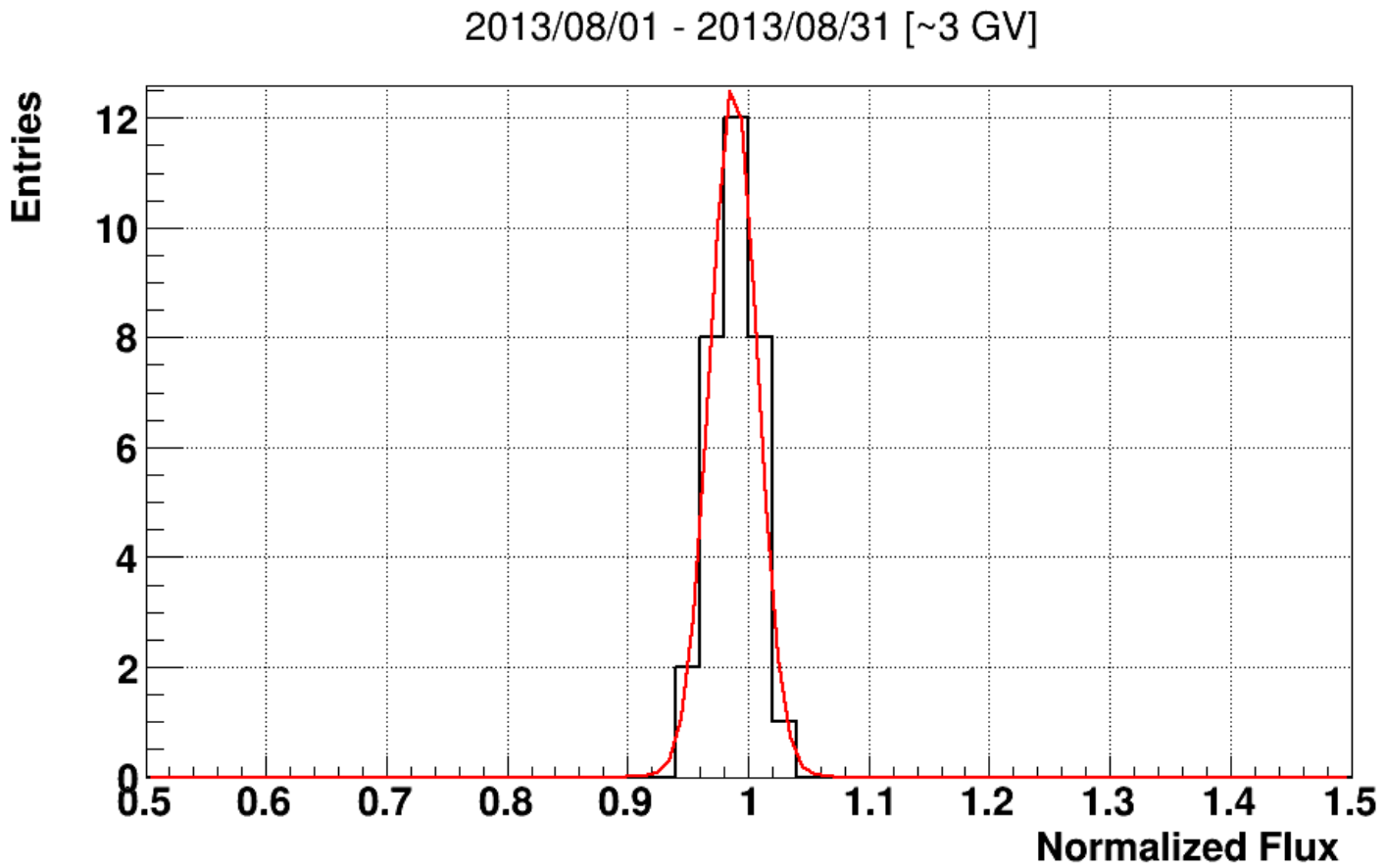

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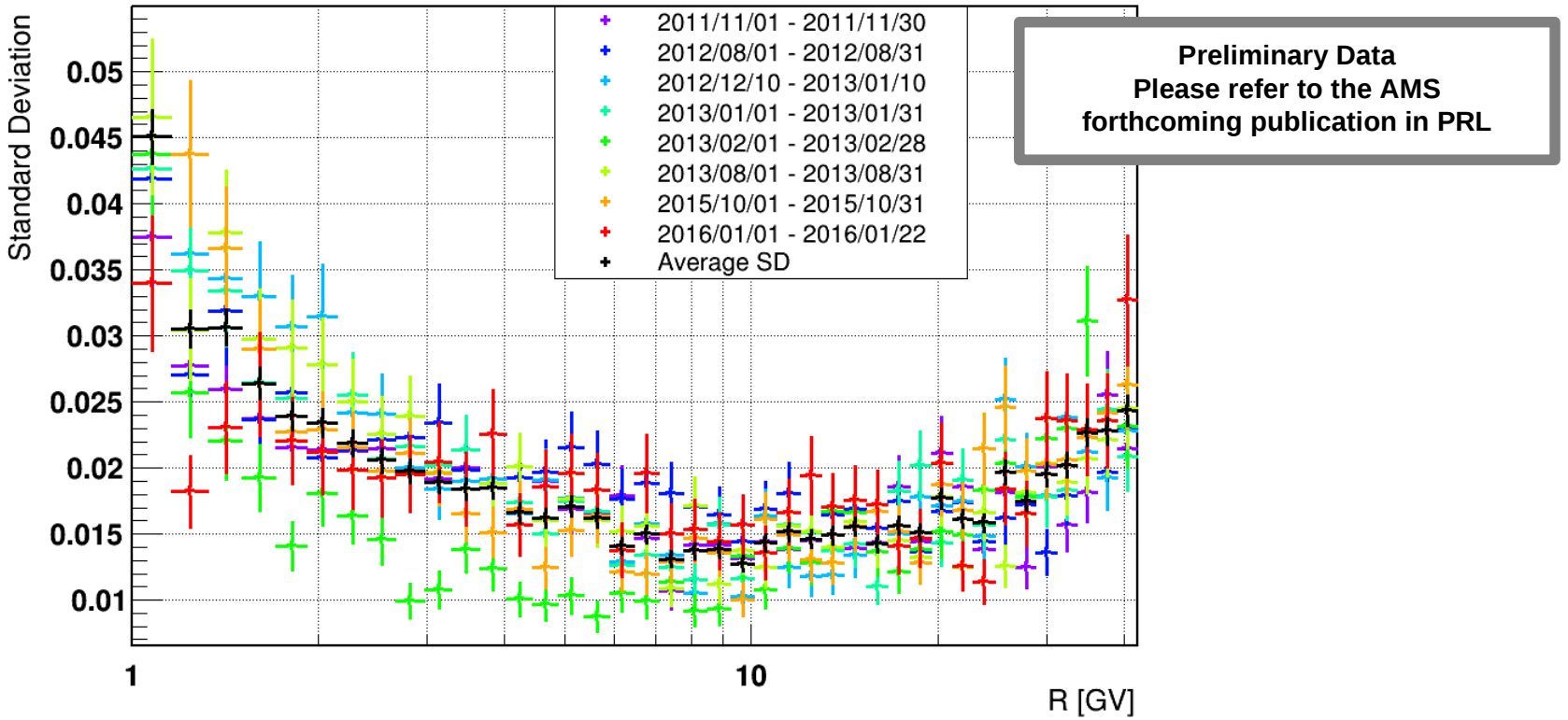
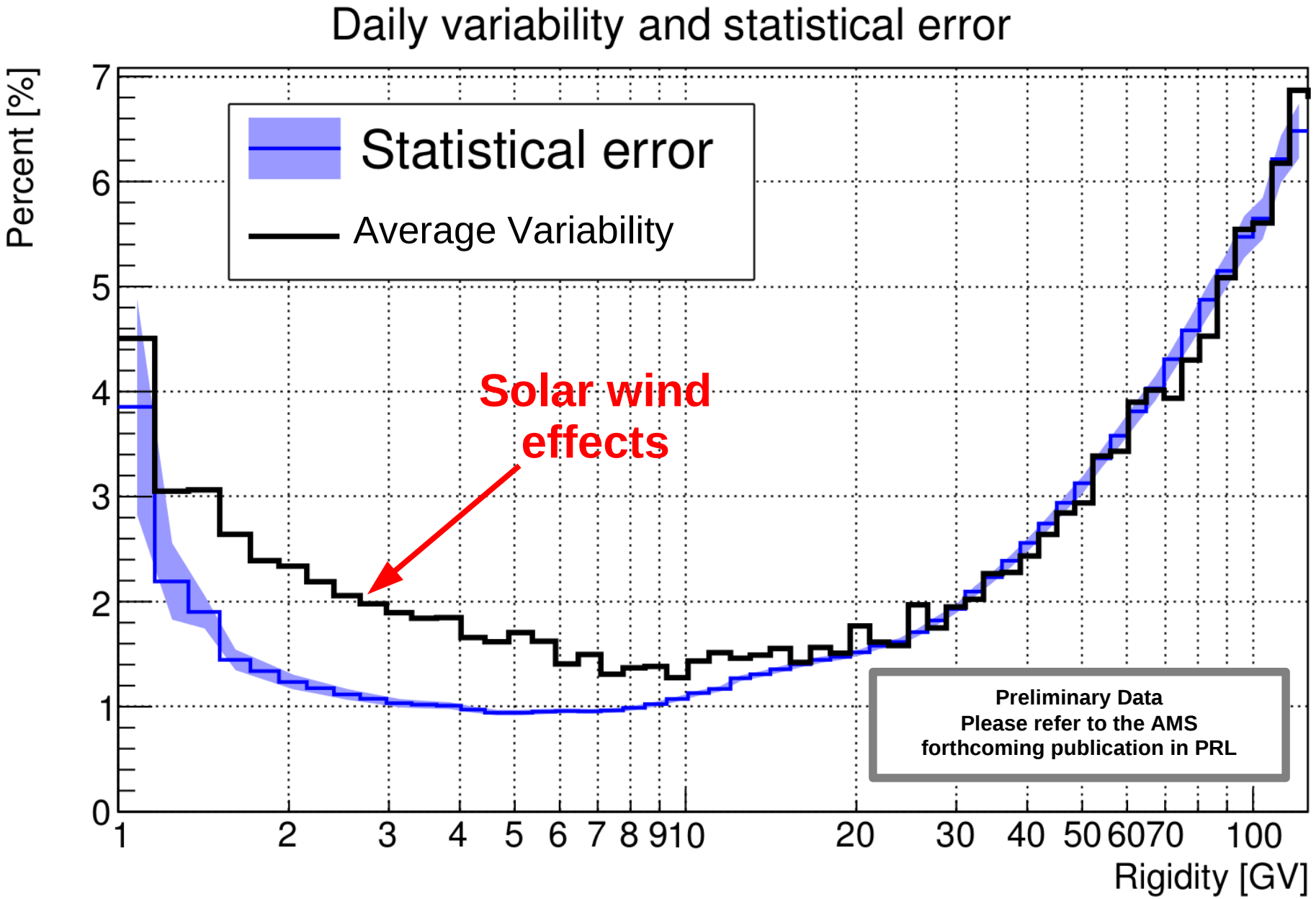
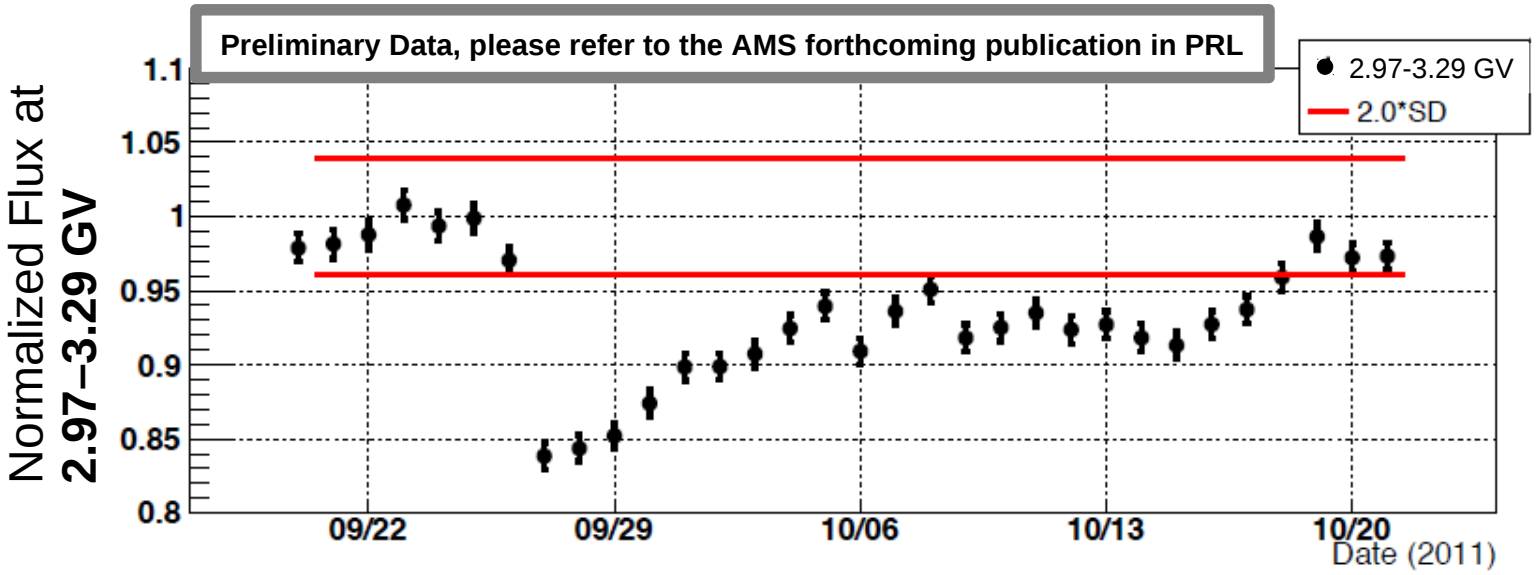


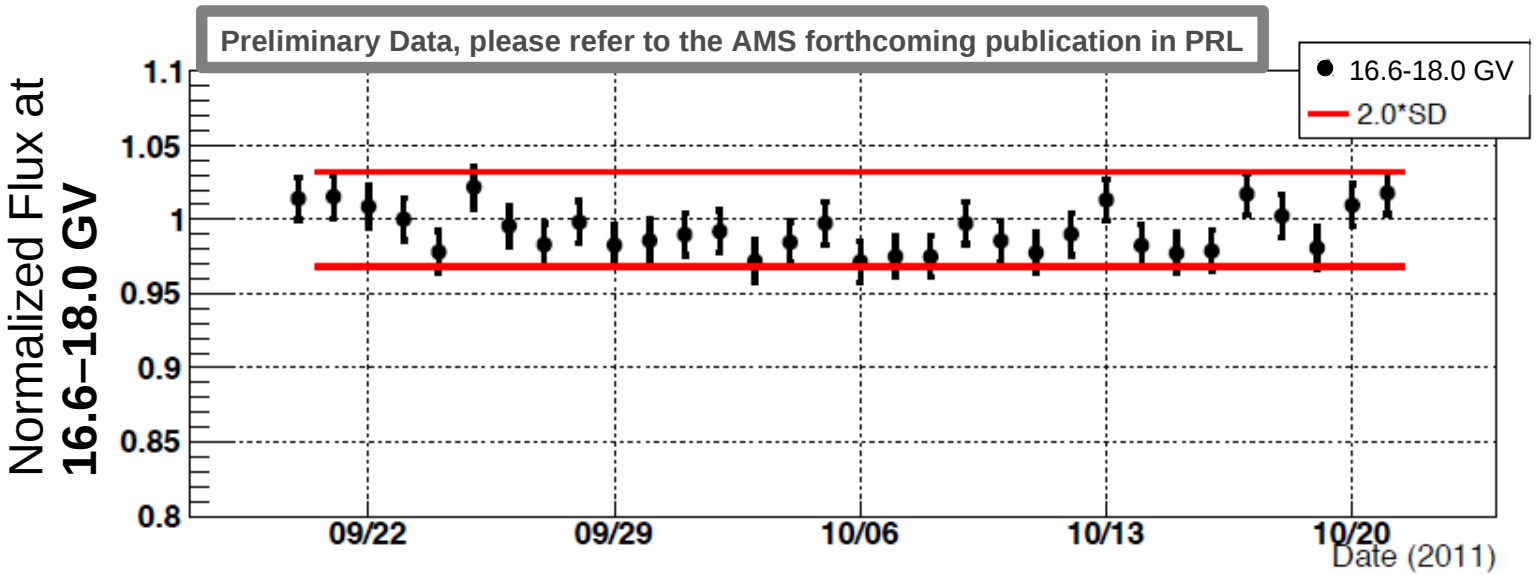
Day-to-day Variability



Forbush Decreases Study

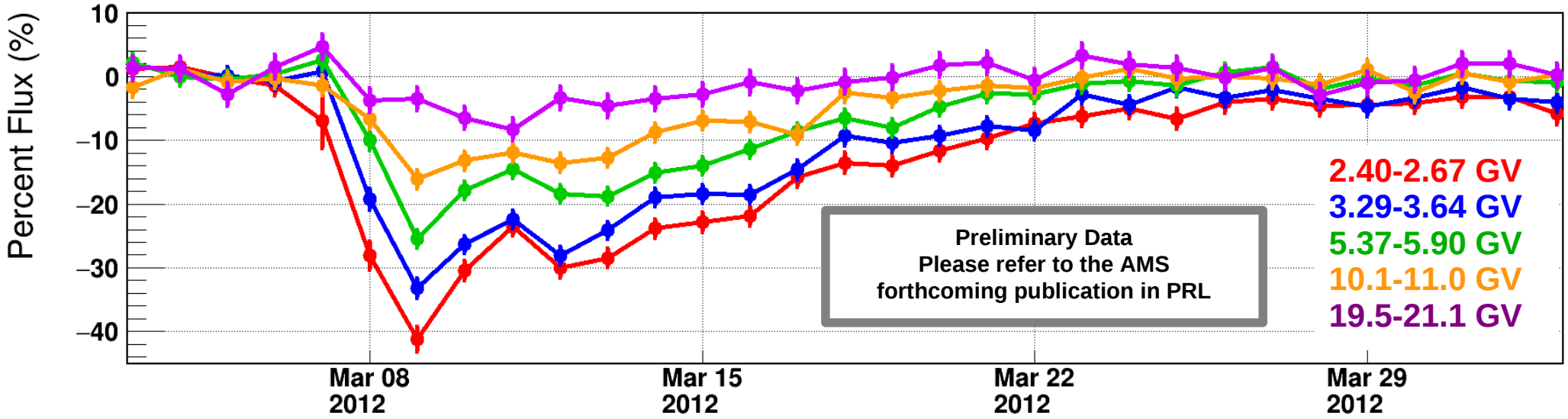
Look for significant decreases in the daily proton flux, for each rigidity bin





FD Characteristics

- **Start date:** date when decrease is first observed
- **Date of minimum:** date when majority of rigidity reach a minimum value
- **Recovery date:** date when normalized flux is within 2 SD of day-to-day variability
- **Duration:** number of days a decrease is observed
- **Maximum rigidity:** highest rigidity that shows a decrease
- **Maximum decrease at 2 GV:** percent decrease of the flux in the rigidity bin around 2 GV on the date of minimum.



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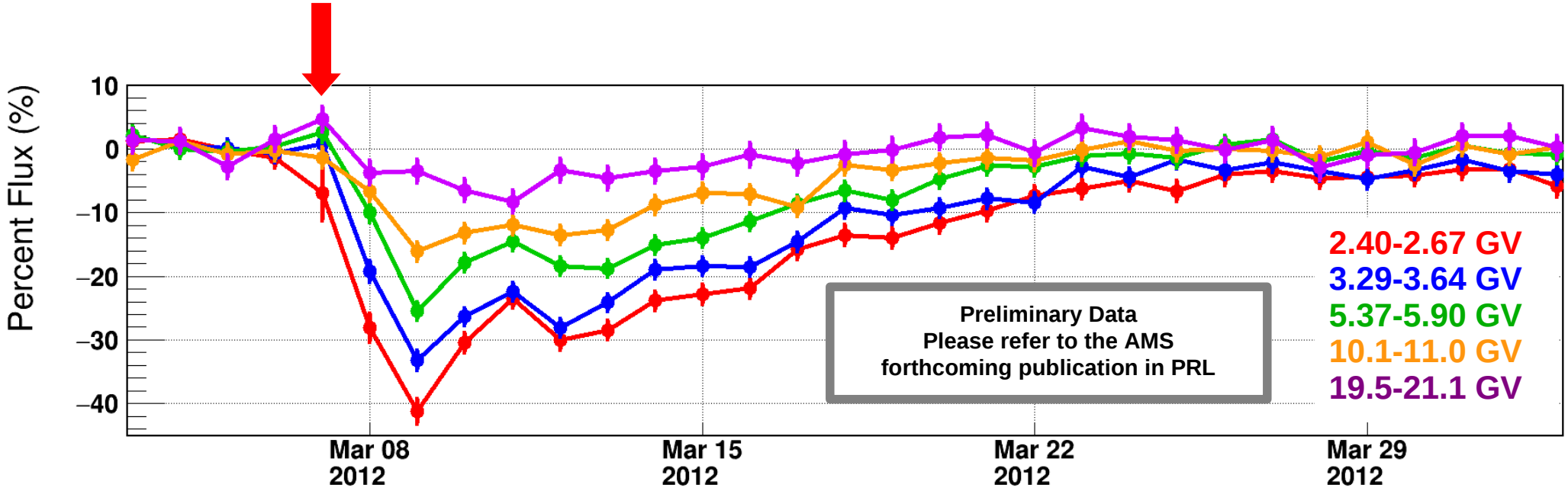

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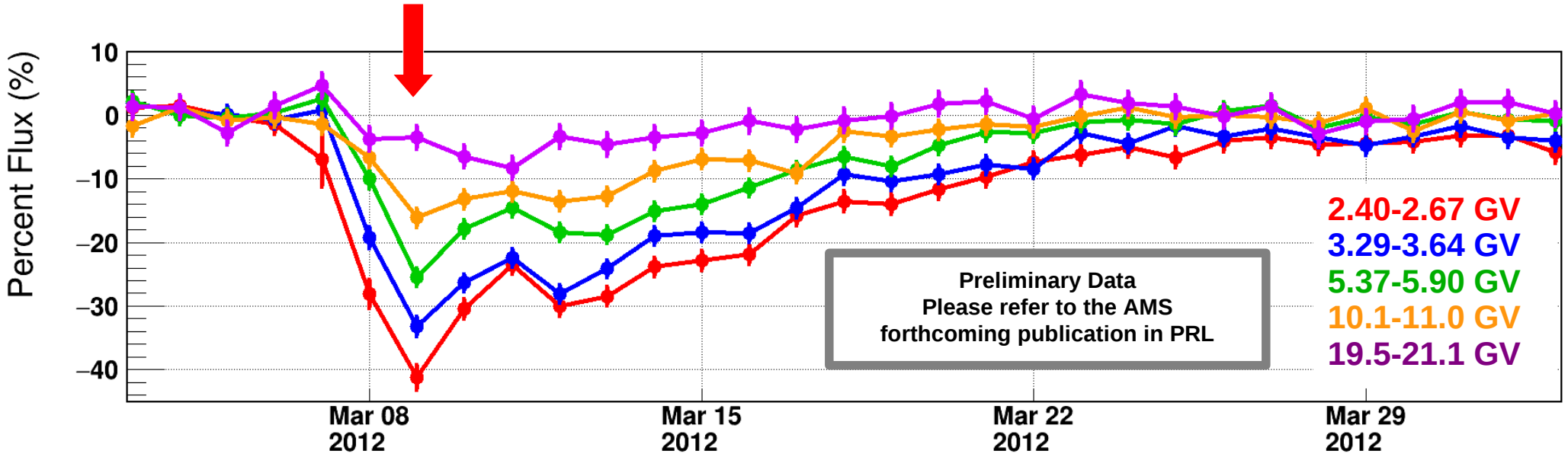

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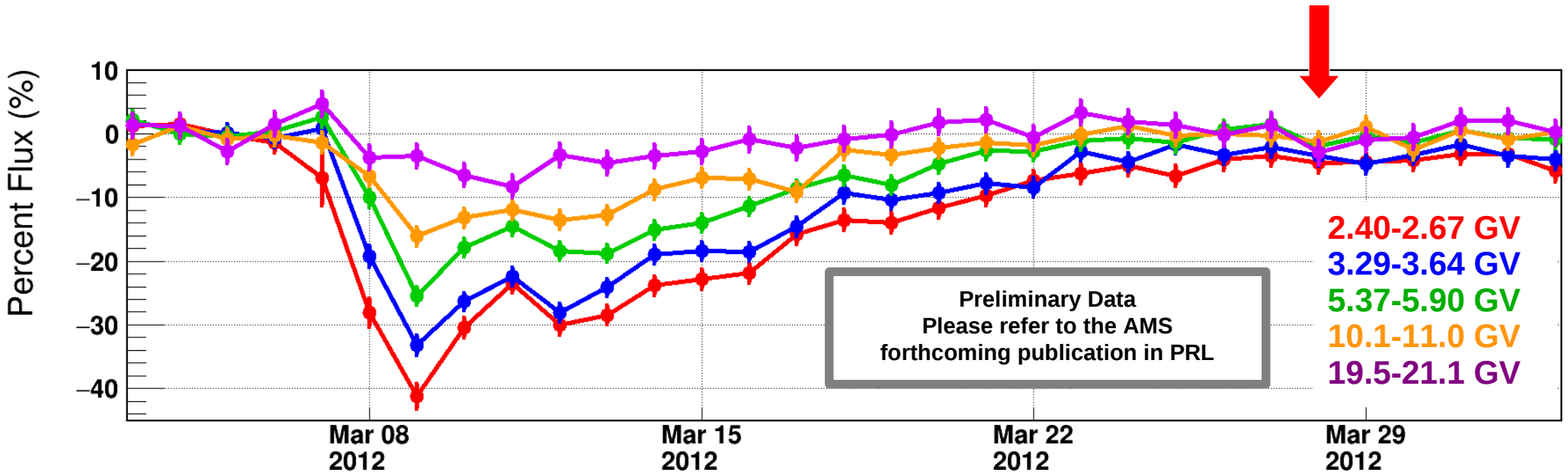

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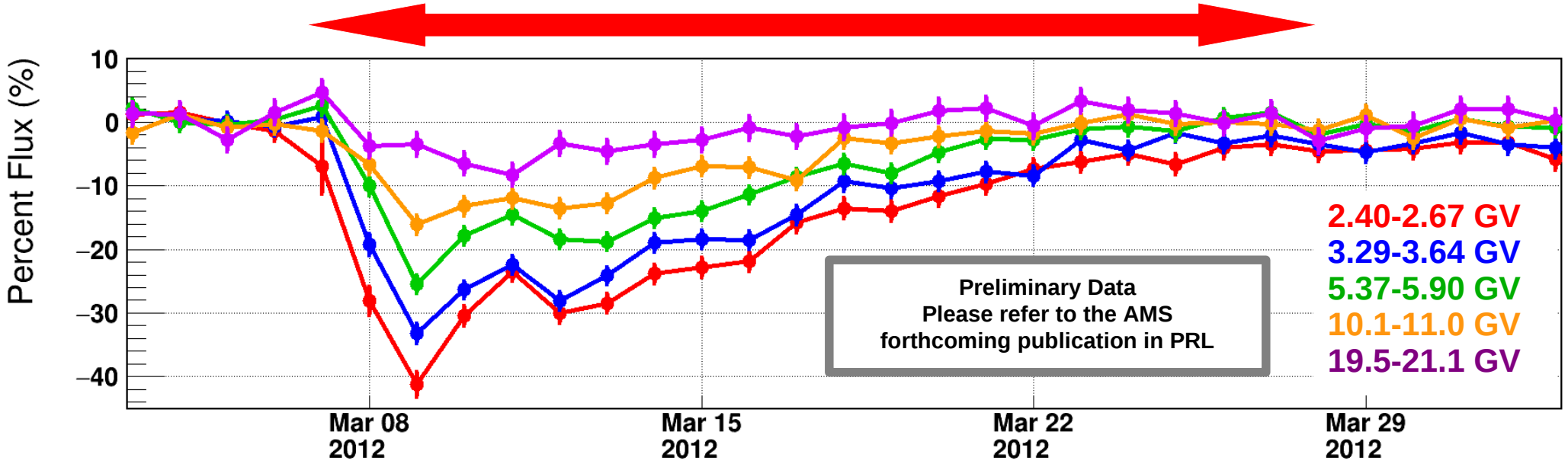

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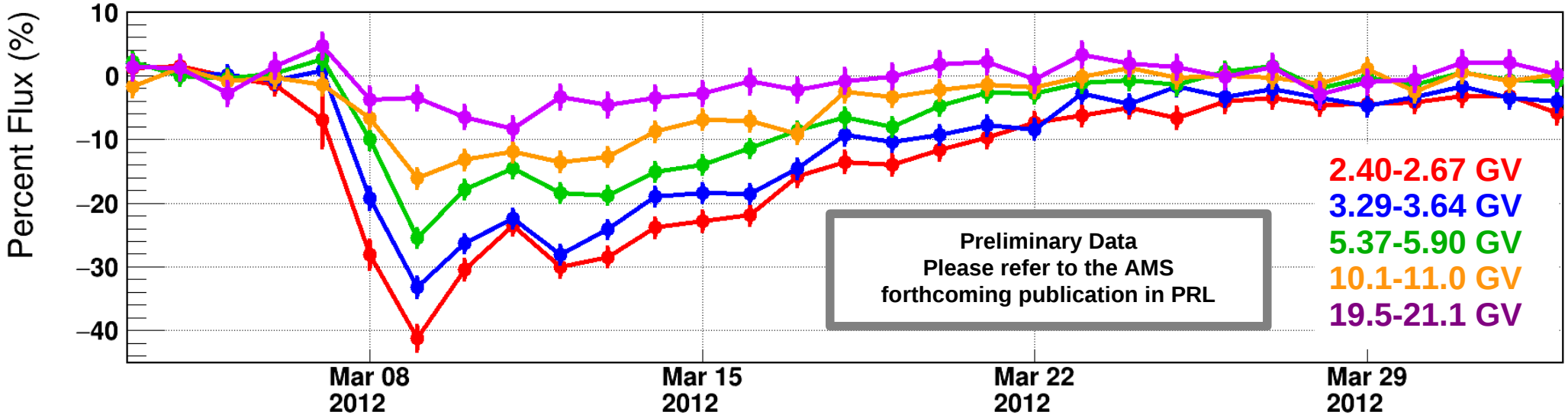

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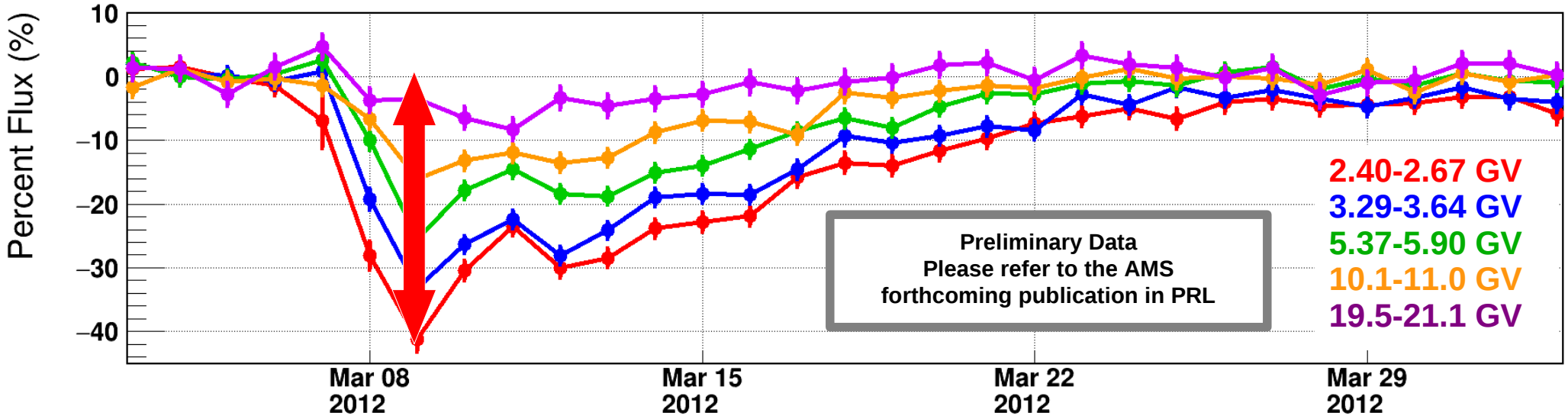


69 FDs Studied by AMS

Since the beginning of operations on **May 20, 2011** until **May 6, 2016**, **69 decreases** in GCR flux have been studied with AMS.

The underlying cause (ICME or CIR) of each FD was determined using **Solar Wind data** and the comprehensive **ICME catalog** compiled by Richardson and Cane (2003 and 2010):

- **43 FDs are attributed to ICMEs,**
- **14 to CIRs,**
- **7 to both,**
- **5 currently have an unclear origin.**

Correlation **studies** with solar wind, CME and Flare parameters are **currently on going** to enable a better understanding of cosmic ray transport within the heliosphere.

FD Characteristics for Selected Events

Longest duration: 23 days

Highest rigidity affected: 28.8 – 31.1 GV

Largest amplitude: 41.5% at ~2 GV

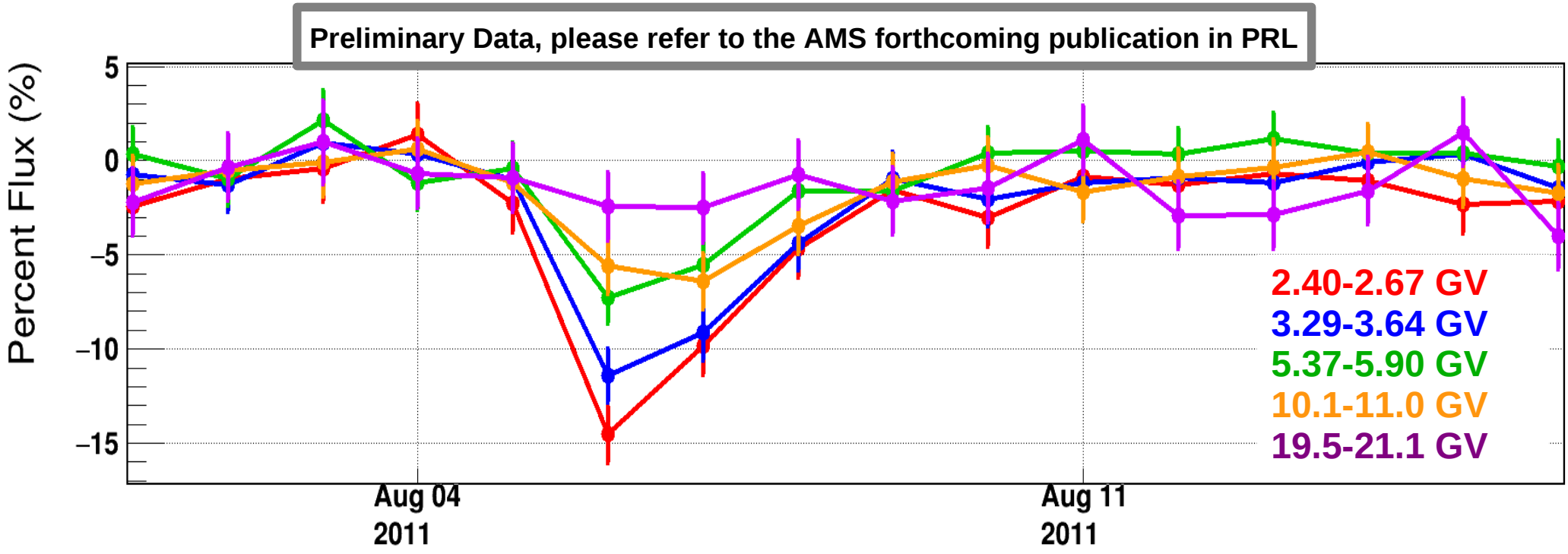
AMS-02 FD	Start Date	Date of Minimum	Duration (Days)	Max Rigidity (GV)	Amplitude 1.92 - 2.15 GV (%)
1	2011/06/23	2011/06/24	6	19.5 - 21.1	8.5 ± 2.2
2	2011/08/06	2011/08/06	4	14.1 - 15.3	16.6 ± 2.0
3	2011/09/26	2011/09/27	23	15.3 - 16.6	20.6 ± 1.9
4	2011/10/25	2011/10/25	3	16.6 - 18.0	9.9 ± 2.1
5	2012/01/22	2012/02/01	13	28.8 - 31.1	21.3 ± 1.9
6	2012/02/27	2012/02/27	4	14.1 - 15.3	8.8 ± 2.2
7	2012/03/08	2012/03/09	20	28.8 - 31.1	41.5 ± 2.8
8	2012/04/06	2012/04/06	4	8.48 - 9.26	7.9 ± 2.2
9	2012/06/17	2012/06/18	5	18.0 - 19.5	10.3 ± 2.4
10	2012/07/15	2012/07/16	9	14.1 - 15.3	20.1 ± 2.0
11	2012/09/04	2012/09/05	4	22.8 - 24.7	14.7 ± 2.1
12	2012/11/24	2012/11/25	5	14.1 - 15.3	8.2 ± 2.2
13	2013/03/17	2013/03/19	16	21.1 - 22.8	17.9 ± 2.0
14	2013/04/15	2013/04/15	3	13.0 - 14.1	10.5 ± 2.2
15	2013/06/23	2013/06/28	9	12.0 - 13.0	12.1 ± 2.2
16	2013/12/15	2013/12/15	4	7.09 - 7.76	6 ± 1.8

FD Rigidity Behavior

Start date:

August 6 2011

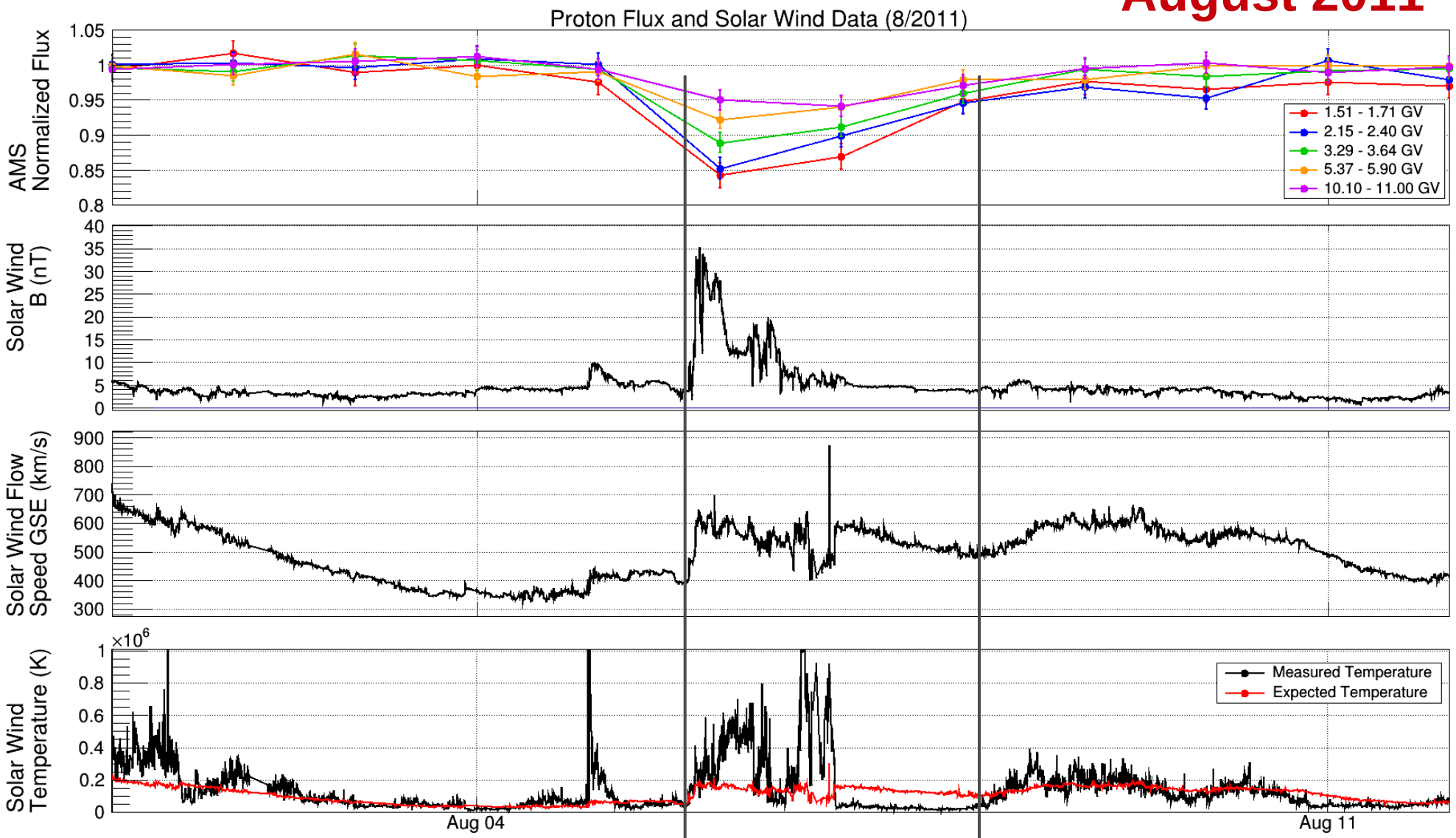
FD with short duration (4 days)
and maximum decrease at 2 GV of 15%



Caused by: ICME

AMS and Solar Wind

August 2011



Preliminary Data, please refer to the AMS forthcoming publication in PRL

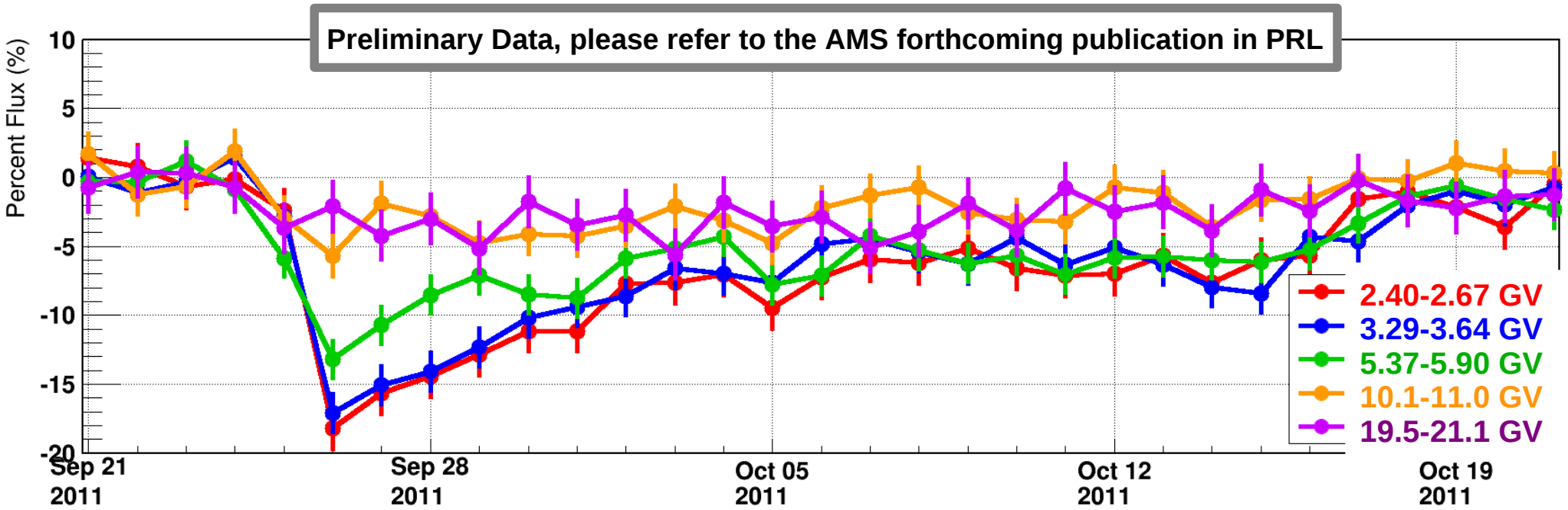
ICME in this time period

FD Rigidity Behavior

Start date:

September 26 2011

FD with longest duration (23 days)
and maximum decrease at 2 GV of 18%



Caused by: Multiple ICMEs

K. Whitman, Phd Thesis

AMS and Solar Wind

Sep.-Oct. 2011

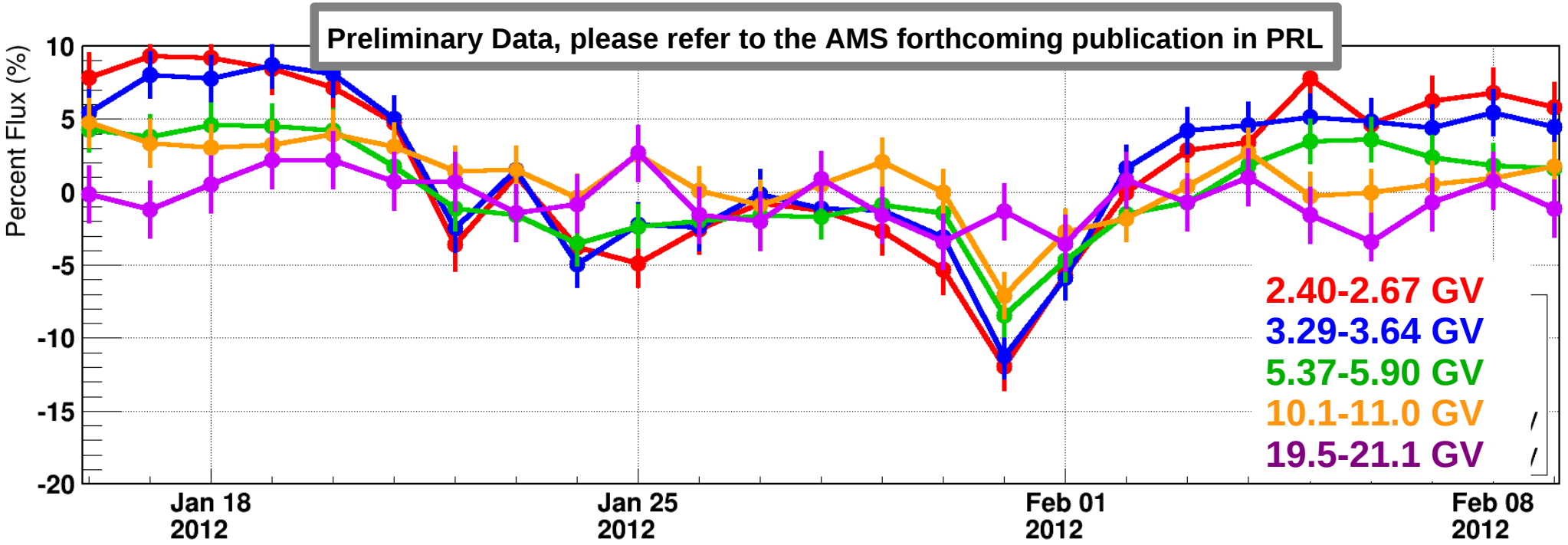
Preliminary Data, please refer to the AMS forthcoming publication in PRL

FD Rigidity Behavior

Start date:

January 22 2012

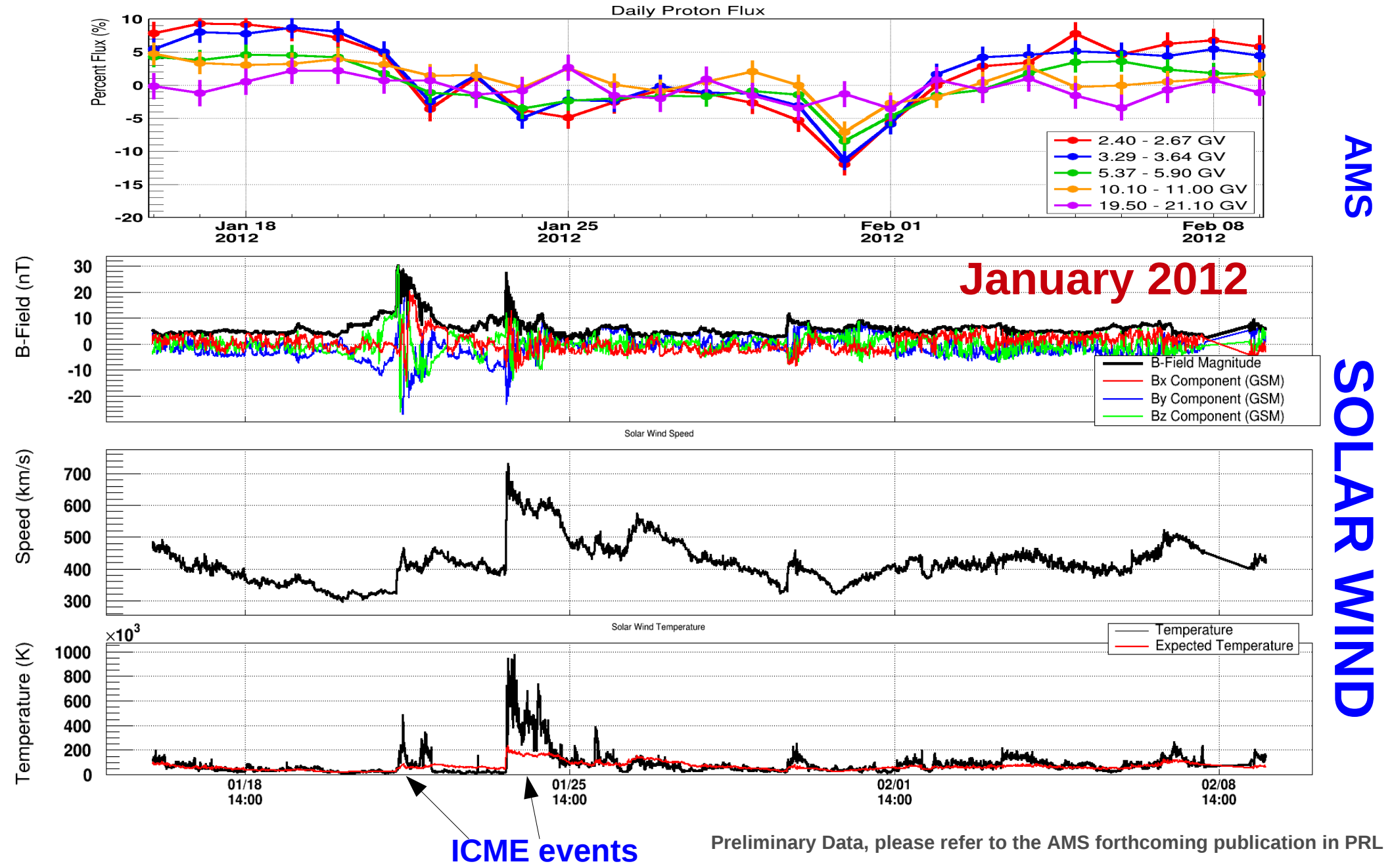
FD with highest rigidity affected (~30 GV)
and maximum decrease at 2 GV of 12%



Caused by: ICME

K. Whitman, Phd Thesis

AMS and Solar Wind



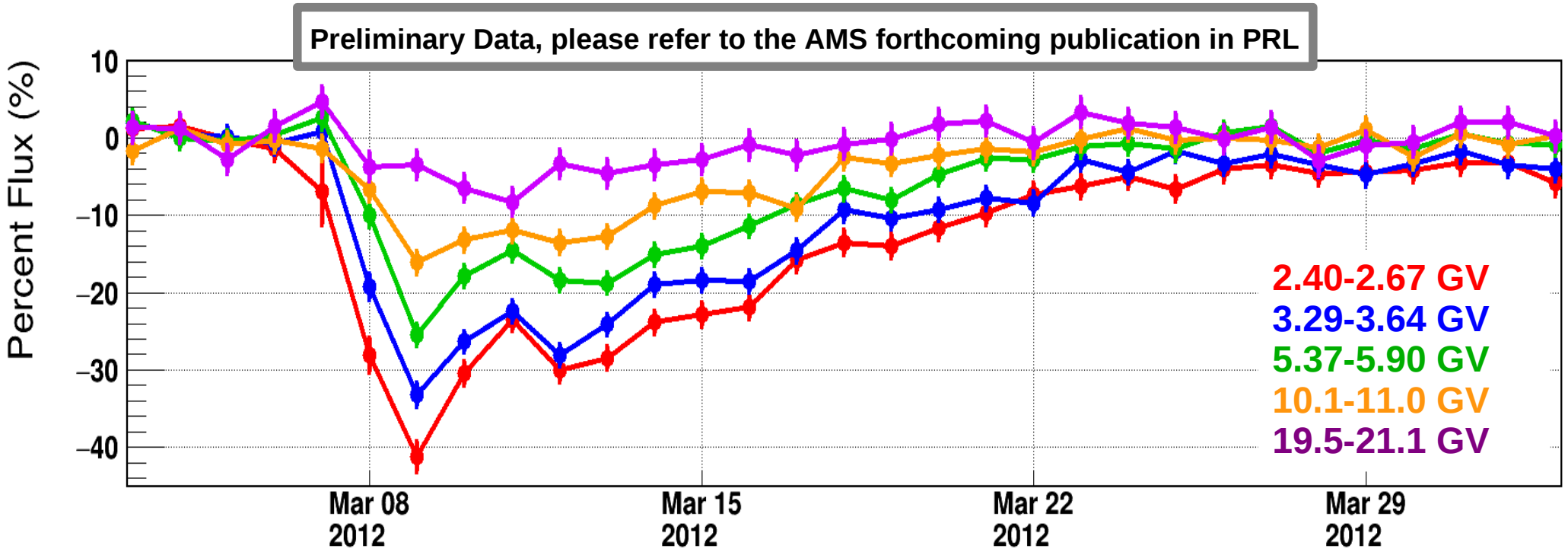
Preliminary Data, please refer to the AMS forthcoming publication in PRL

FD Rigidity Behavior

Start date:

March 8 2012

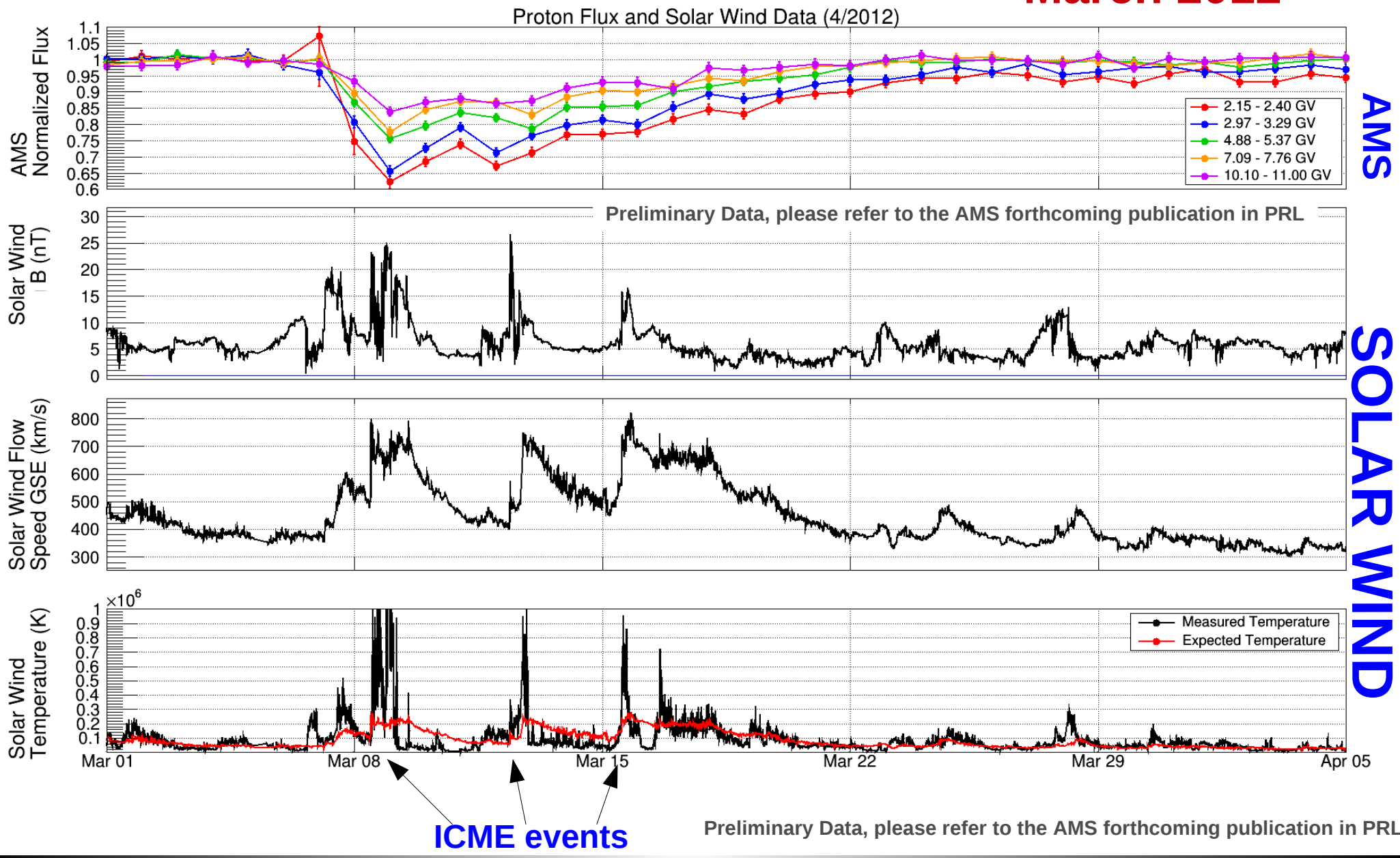
FD with long duration (20 days)
and **largest** maximum **decrease at 2 GV of 40%**



Caused by: Multiple ICMEs

AMS and Solar Wind

March 2012

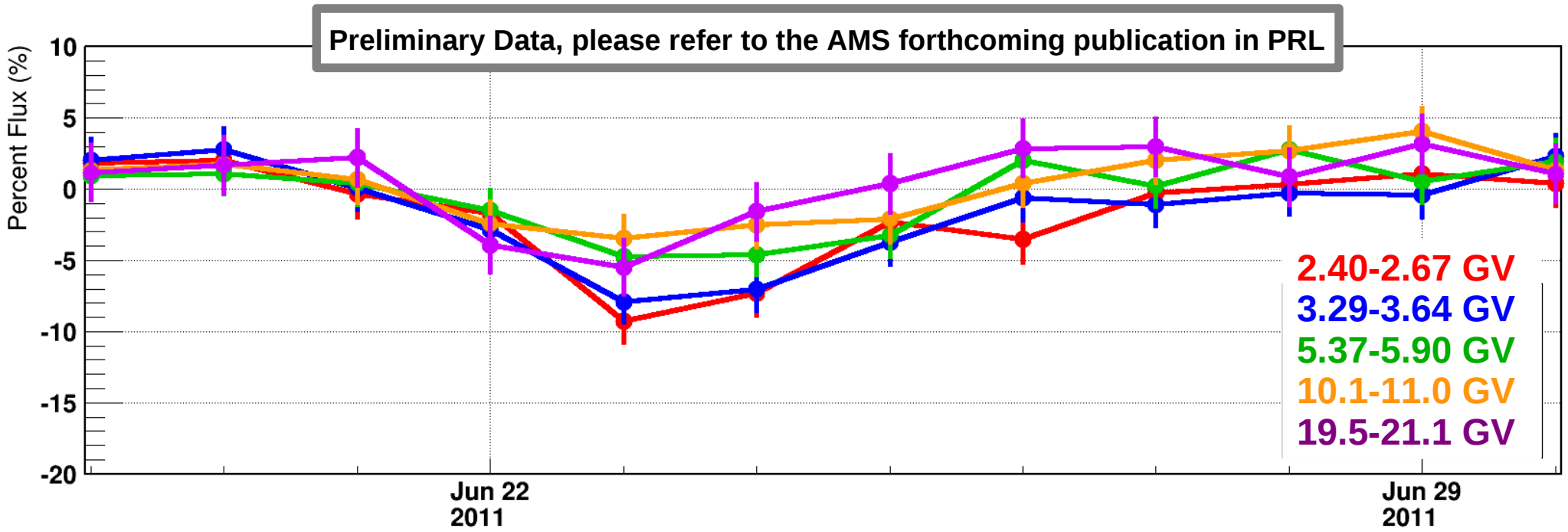


FD Rigidity Behavior

Start date:

June 23 2011

FD with duration of 6 days
and maximum decrease at 2 GV of 9%

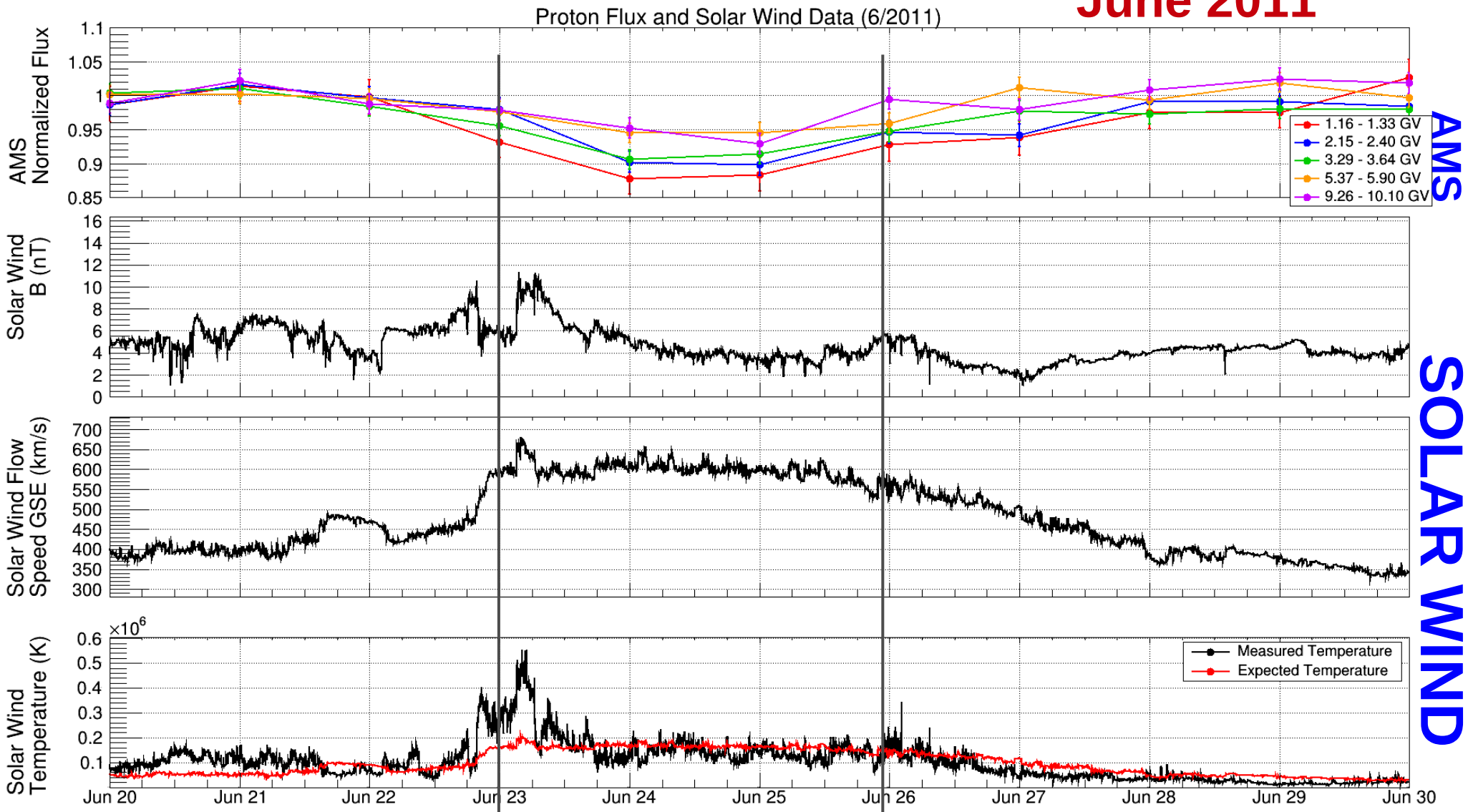


Caused by: CIR

K. Whitman, Phd Thesis

AMS and Solar Wind

June 2011



Preliminary Data, please refer to the AMS forthcoming publication in PRL

CIR signature within this time period

Summary

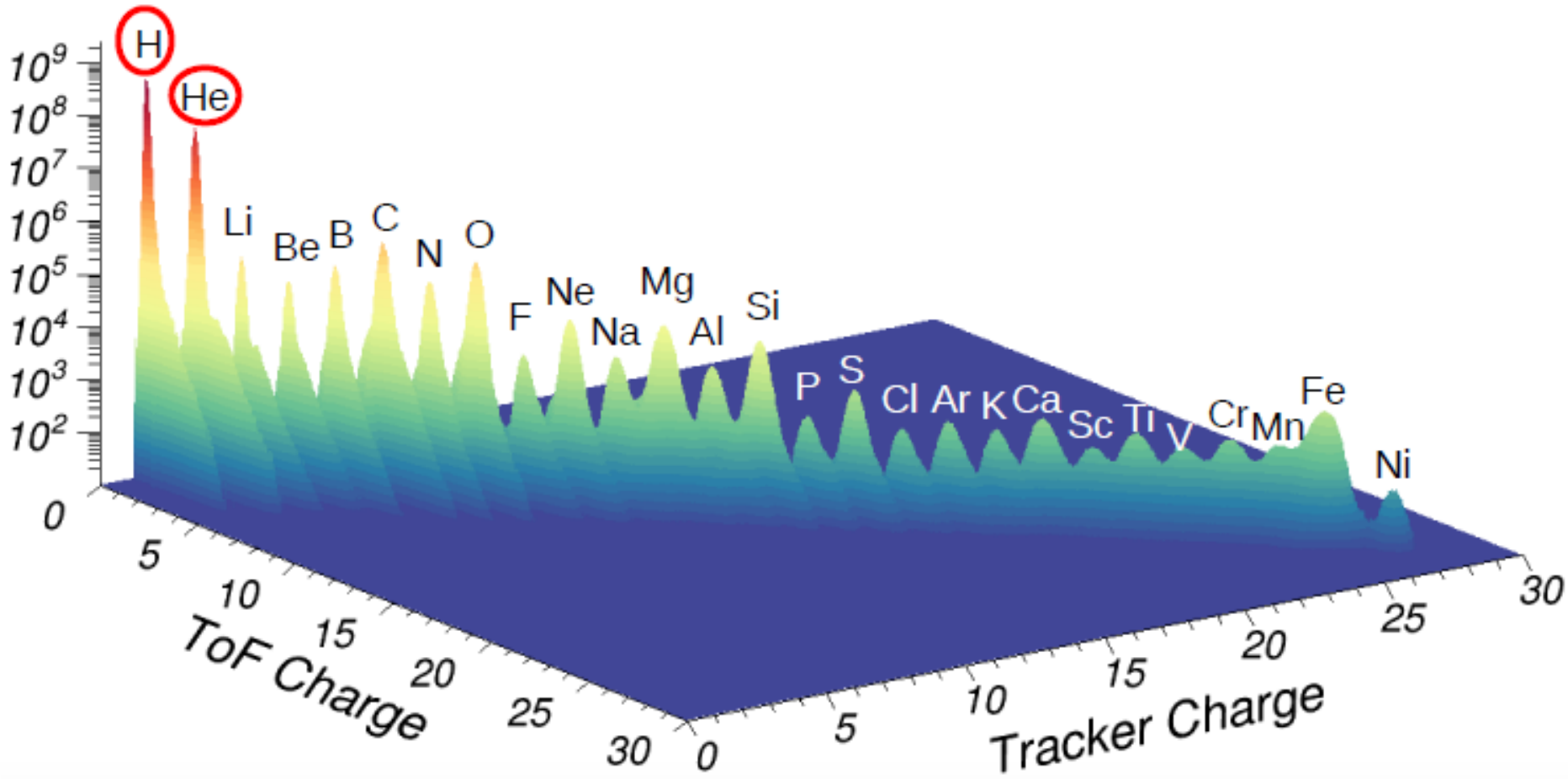
- AMS measures the daily proton flux with high precision and resolution
- A method to study the FD properties of the AMS daily flux was developed
- 69 Forbush decreases between May 2011 and May 2016 have been studied by AMS
- Time evolution in all rigidity bins is now precisely measured

The study of FDs represent an excellent tool for a deeper understanding of the short-term solar activity phenomena

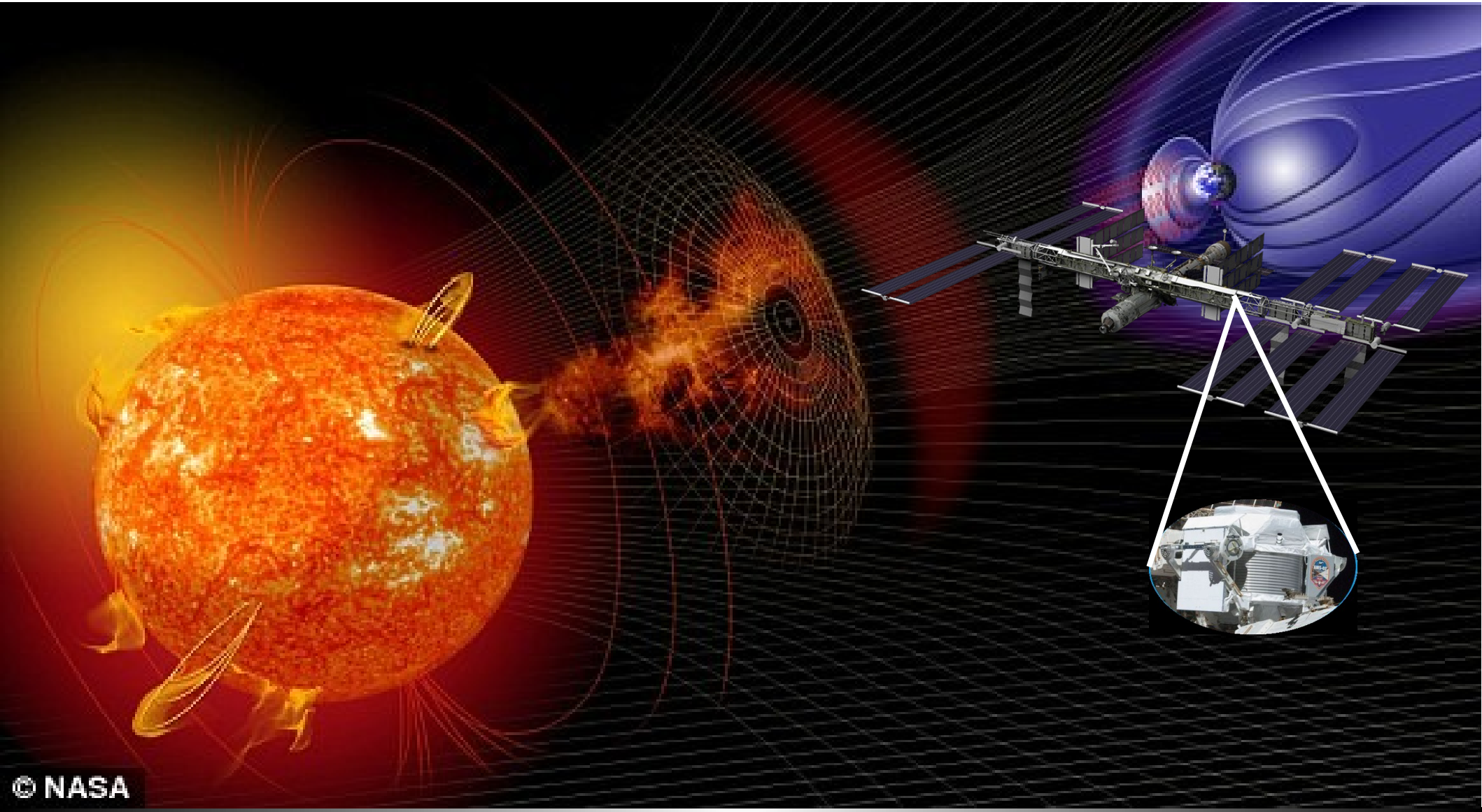
Future Developments

- FD studies with Helium measured by AMS are ongoing

- AMS is also capable to perform FD studies with heavier nuclei and electrons (charge-sign dependence)



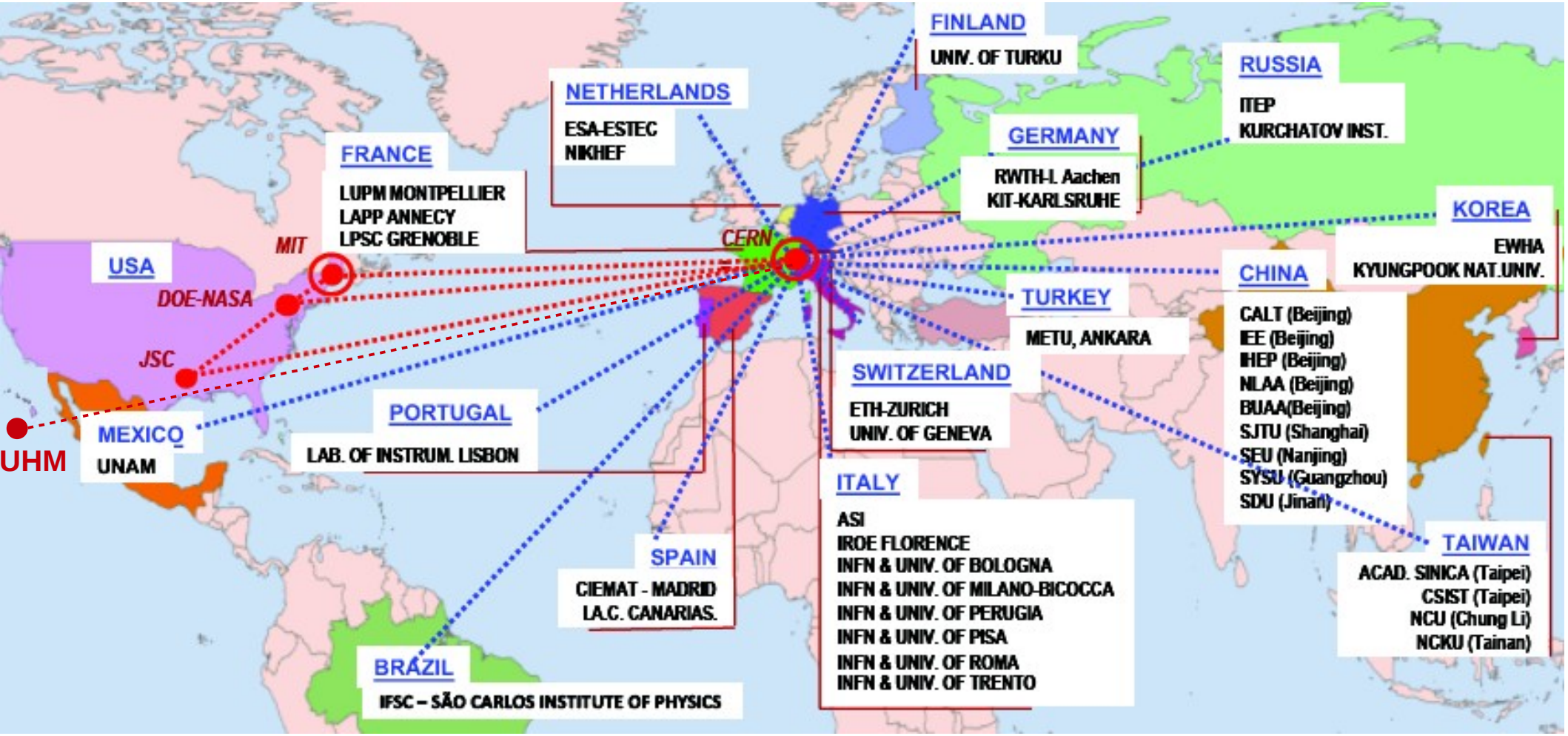
Thanks For Your Attention



Backup

AMS Collaboration
15 Countries, 46 Institutes

AMS is sponsored by US DOE and NASA, and many agencies in the world.



AMS on the ISS

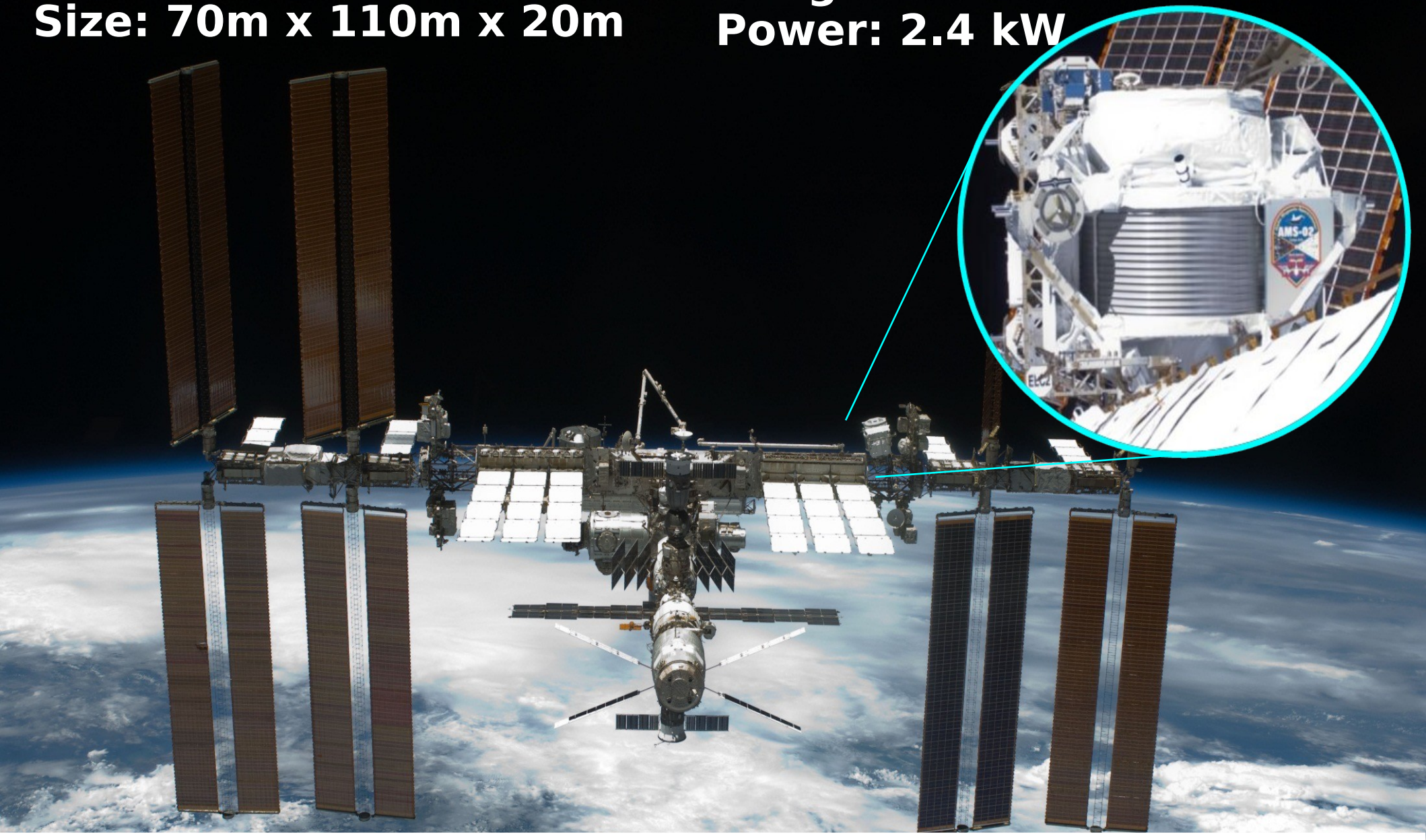
May 16, 2011: AMS Flight, Space Shuttle Endeavor

ISS

Altitude: ~400 km
Orbit: 90 minutes
Size: 70m x 110m x 20m

AMS-02

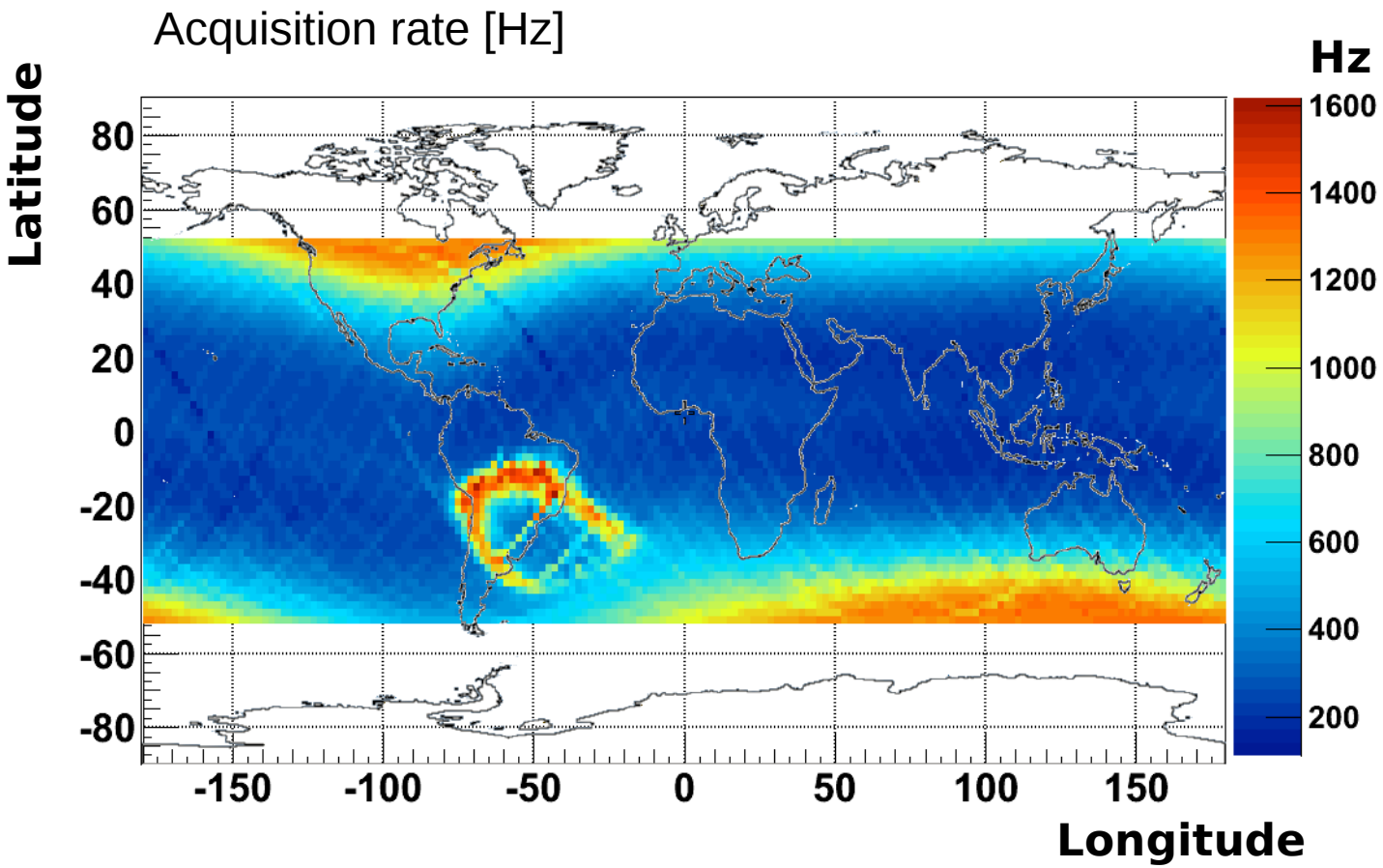
Size: 5m x 4m x 3m
Weight: 7 ton
Power: 2.4 kW



In 6 years of operation, AMS has measured over 100 billion events.
It will continuously take data for the entire duration of the ISS

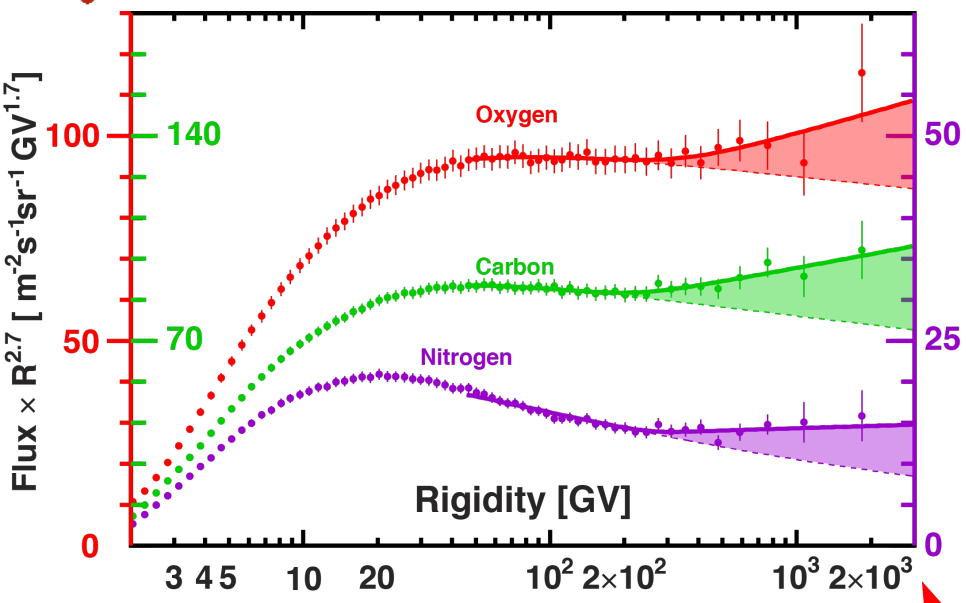
AMS Acquisition Rate

The ISS orbits the Earth at 400 km altitude and 51.6° to the Equator

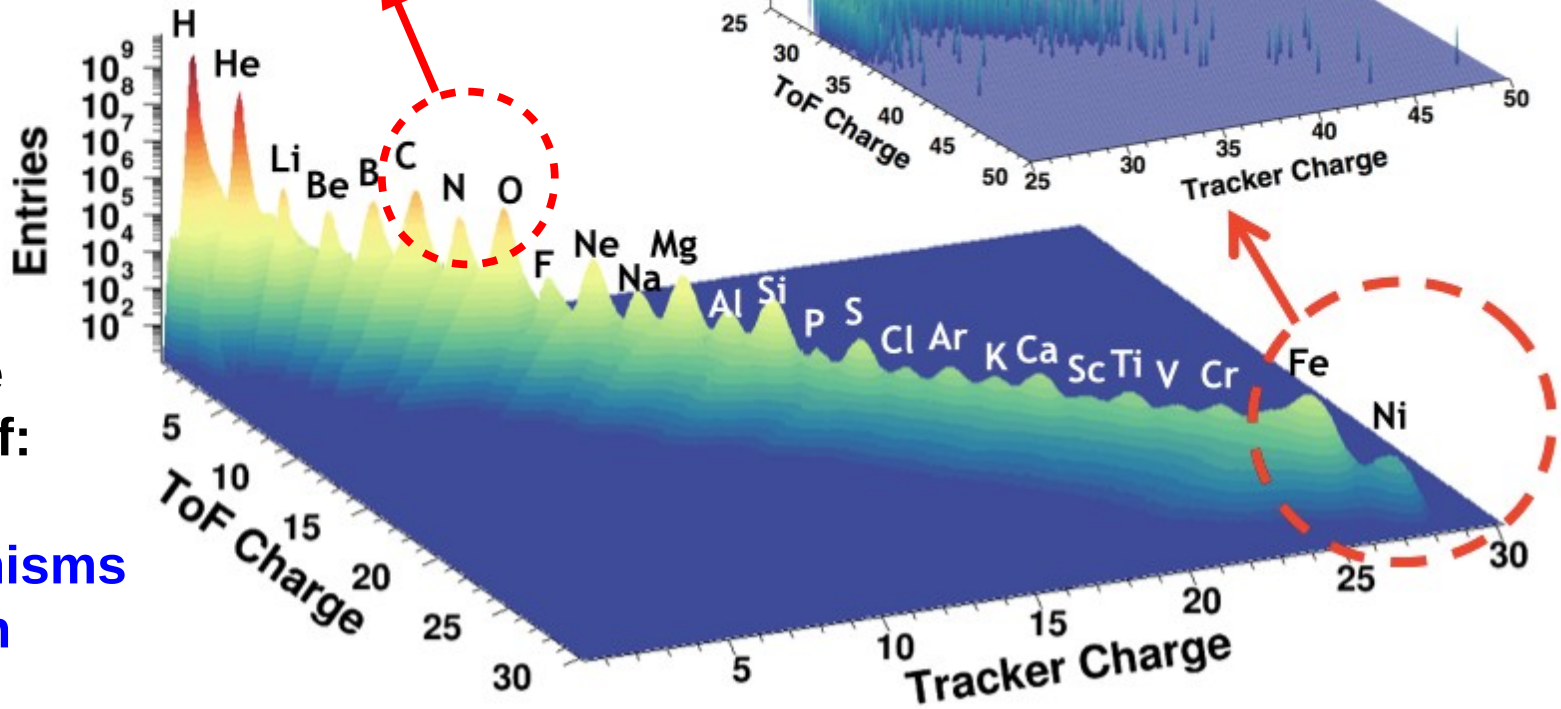


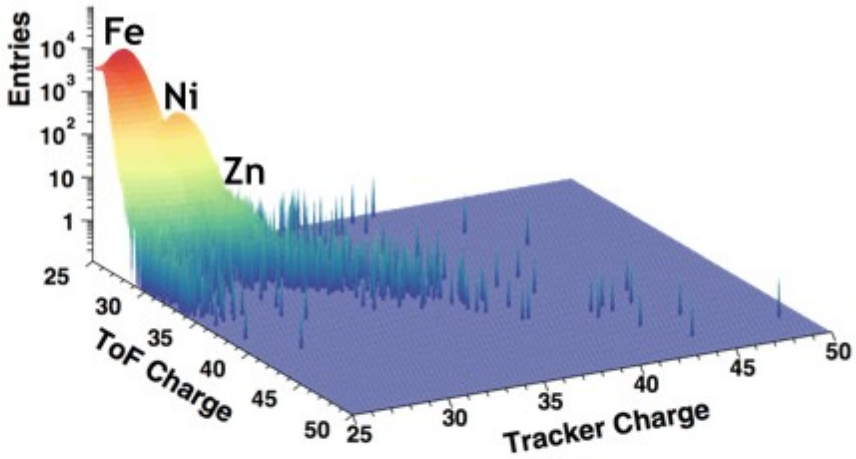
Particle rates vary from 200 to 1600 Hz per orbit

Scientific Goals: GCR Nuclei



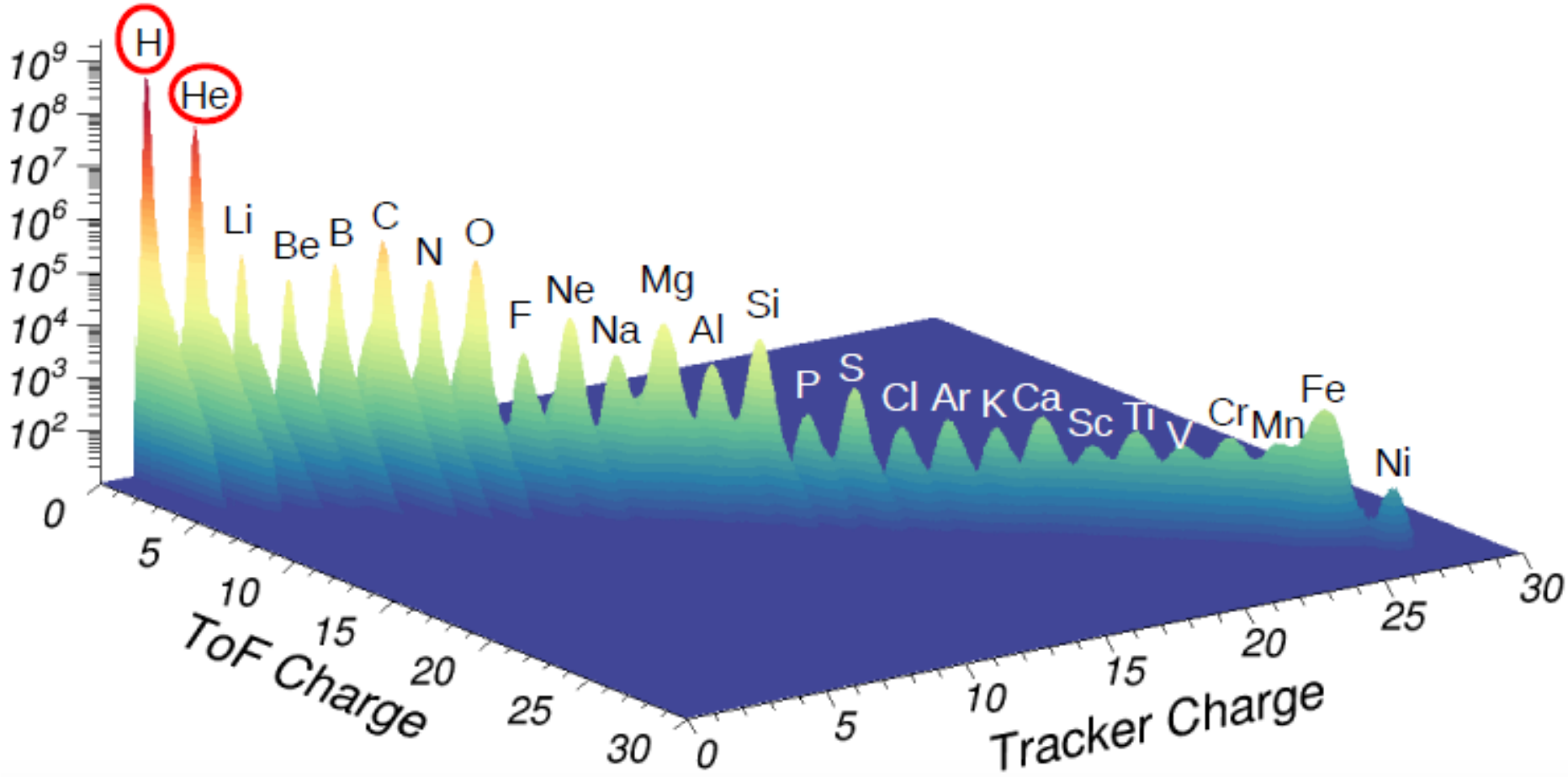
AMS measures all CR species with error at % level up to Fe and above



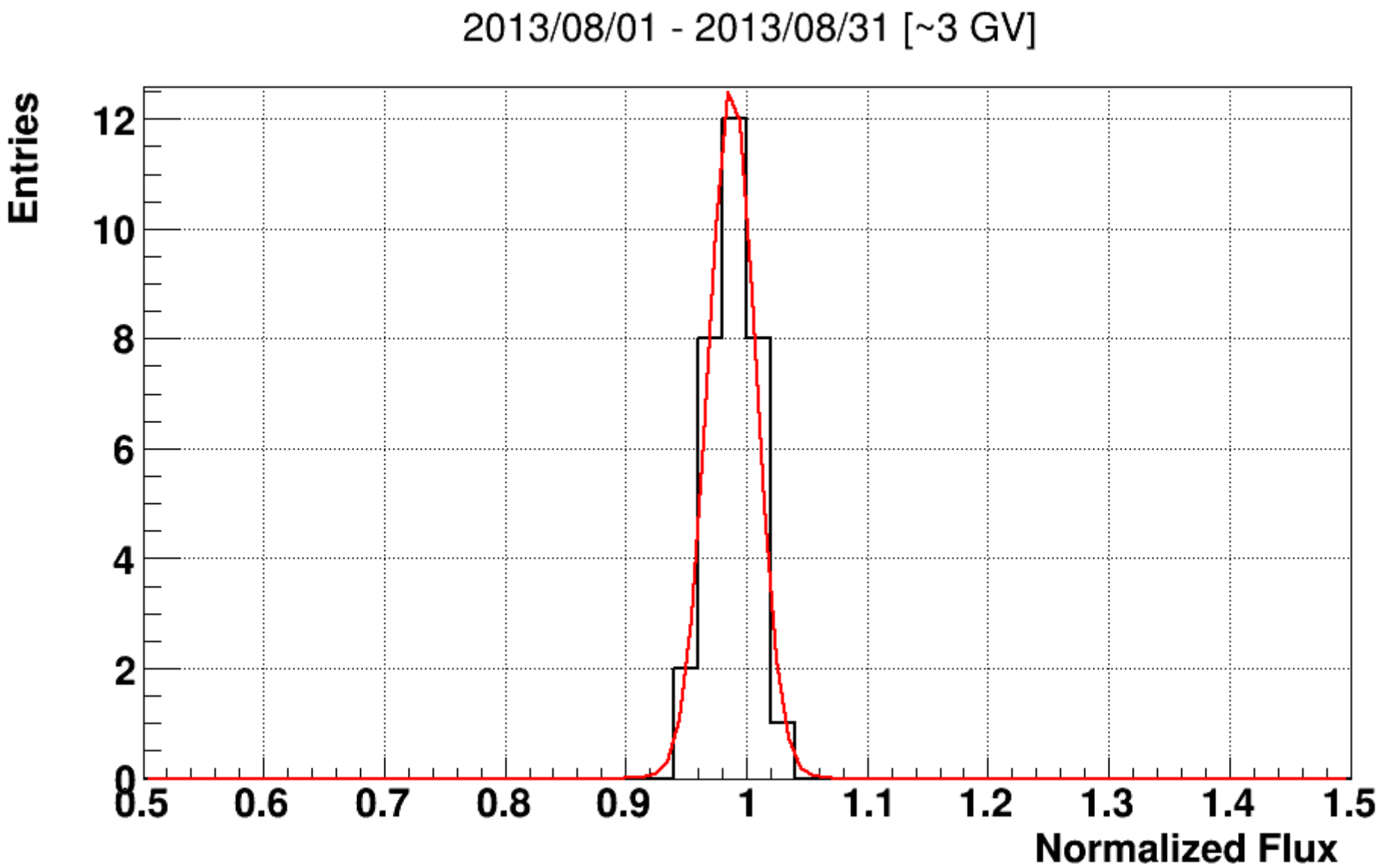


It has improved and will improve our knowledge of: CR sources, acceleration mechanisms and propagation

GCR Nuclei with AMS



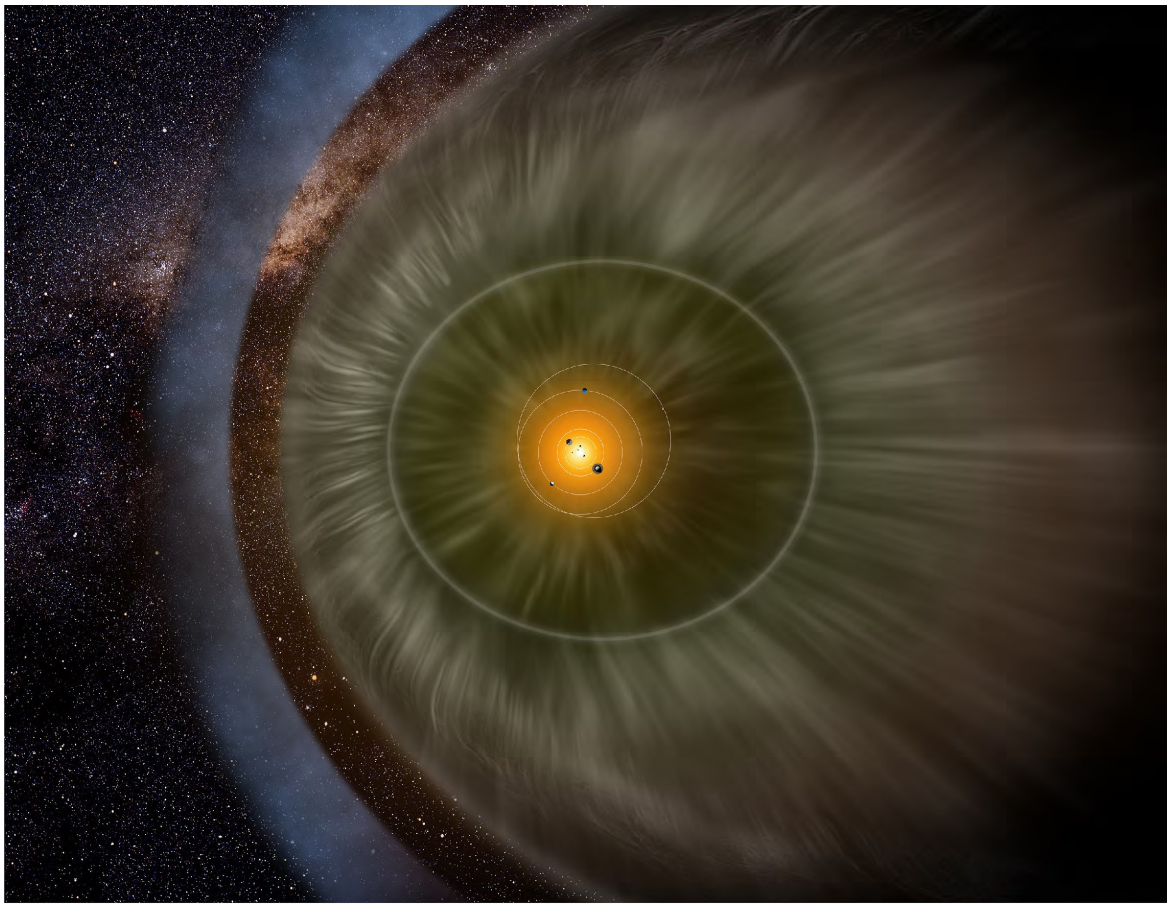
Distribution quiet period



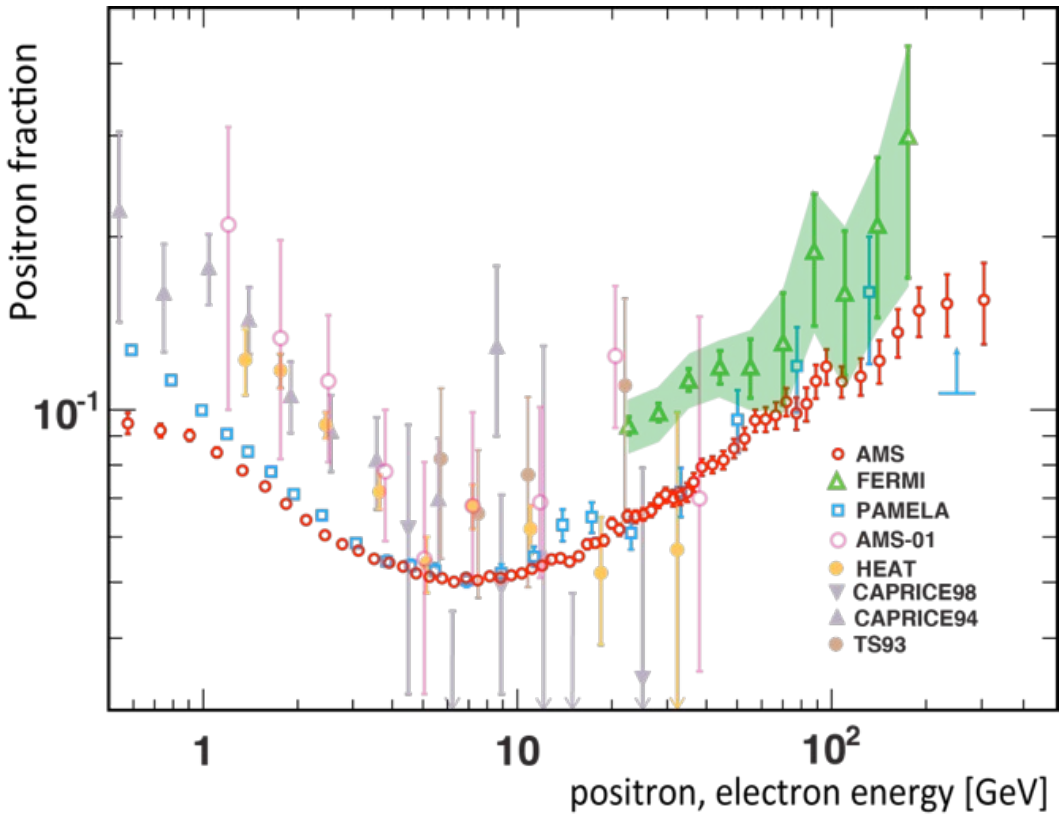
Solar Modulation: GCR in heliosphere

Precise measurements of the time-dependent GCRs spectra are important:

- **to understand the propagation of GCRs in the heliosphere.**
- **to test theories of particles diffusion (charge and mass) and drift (charge-sign).**
- **to study the effect on cosmic rays due to the reversal in the solar polarity.**
- **Space radiation monitoring**



Scientific Goals: Dark Matter search



M. Aguilar
(AMS collaboration)
PRL110,141102 (2013)

Interesting features have been measured at high energies and more will come in the near future.

New Goal: Study of the time variation of the low energy part of the spectrum.

AMS: GCR and SEP studies

Collaboration between
NASA AES (Advanced Exploration Systems) group at JSC
and AMS research group at the University of Hawaii

- AMS measures CR fluxes with unprecedented accuracy

- **University of Hawaii** research group is focused on the **AMS energy range that supports NASA human space exploration missions (unavailable by other satellites)**

Improvement in the accuracy provides new insights in areas such as the study of CR and solar activity, and has **application to NASA space radiation health assessments and shielding design**

Main research studies:

- **GCR fluxes and their changes with solar activity**
- **Heliophysics: study of Solar Energetic Particles**

Solar Modulation: GCR in heliosphere

Precise measurements of the time-dependent GCRs spectra are important:

- **to understand the propagation of GCRs in the heliosphere.**
- **to test theories of particles diffusion (charge and mass) and drift (charge-sign).**
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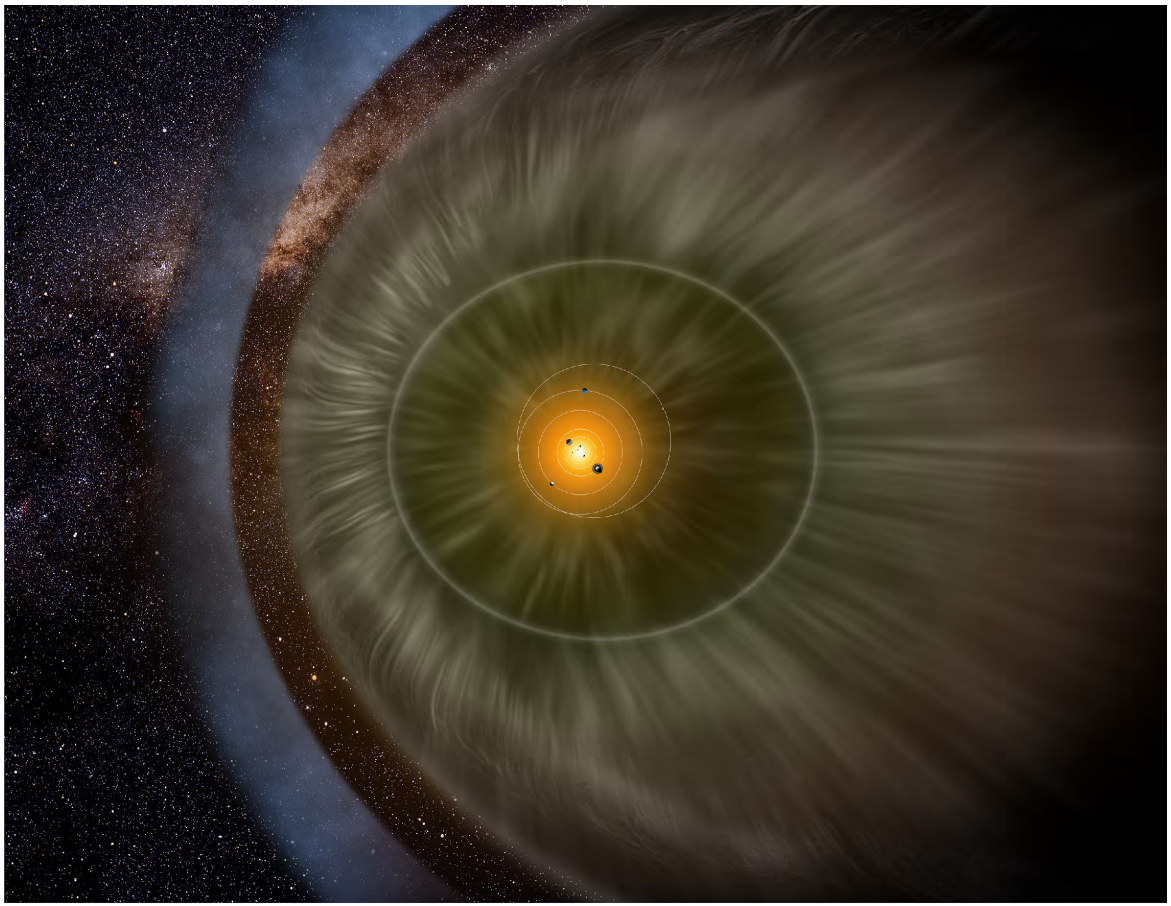


AMS FD Event List

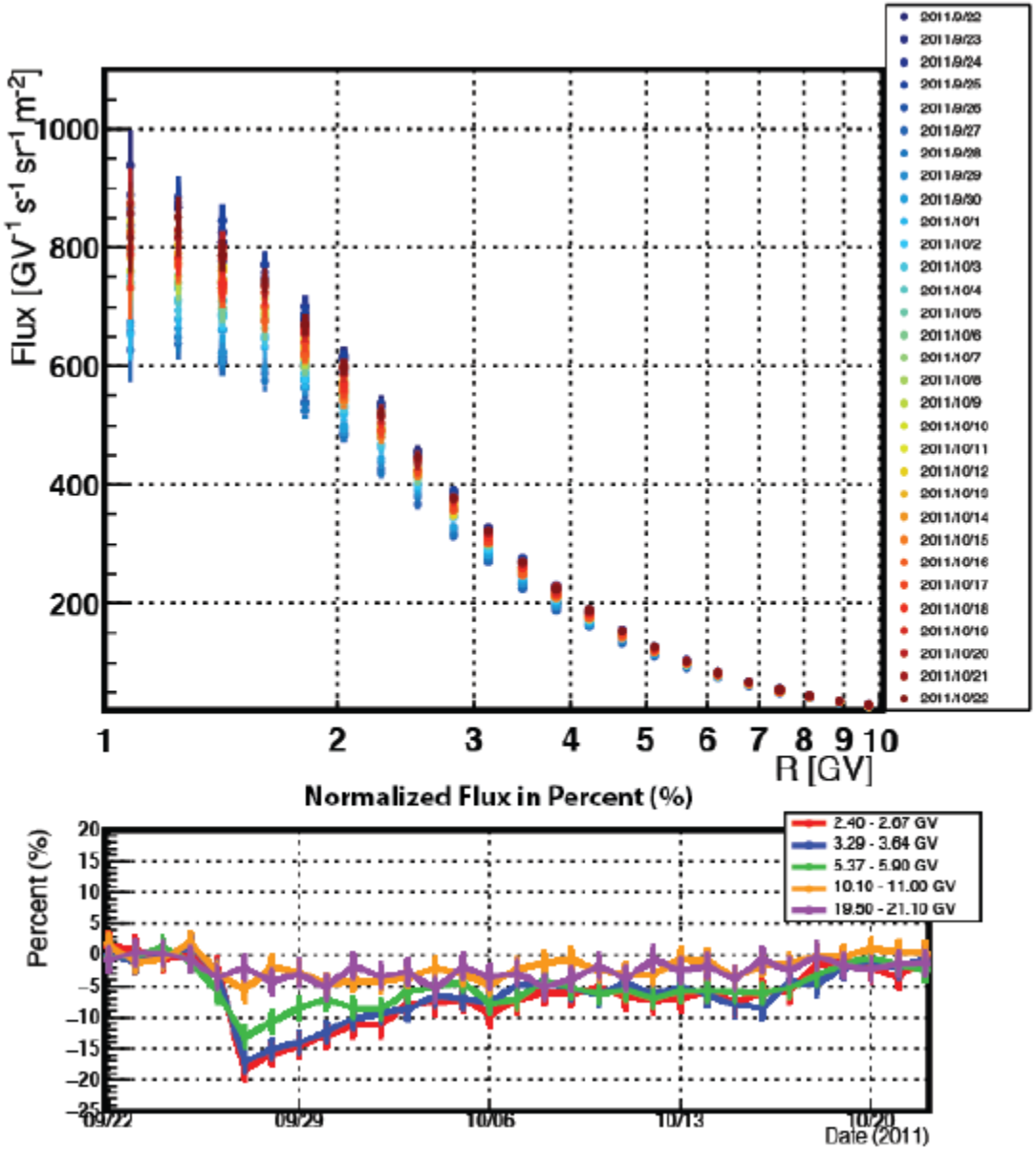
List of FDs studied between May 2011 and May 2016

Number	Start Date	Duration (Days)	Type	Number	Start Date	Duration (Days)	Type
1	2011/06/16	5	ICME	36	2013/10/29	8	–
2	2011/06/24	5	CIR	37	2013/11/08	13	ICME
3	2011/07/10	10	CIR	38	2013/11/30	6	ICME
4	2011/07/19	6	CIR	39	2013/12/07	6	ICME
5	2011/08/06	4	ICME	40	2013/12/14	5	ICME
6	2011/09/09	14	ICME+CIR	41	2013/12/31	6	CIR
7	2011/09/17	6	ICME	42	2014/01/09	8	CIR
8	2011/09/26	25	ICME	43	2014/02/15	4	ICME
9	2011/10/25	3	ICME	44	2014/02/20	7	ICME
10	2011/11/28	3	ICME	45	2014/02/27	15	–
11	2012/01/22	13	ICME	46	2014/04/05	11	ICME
12	2012/02/27	5	ICME	47	2014/04/18	13	ICME
13	2012/03/08	20	ICME	48	2014/05/22	5	CIR
14	2012/04/06	4	–	49	2014/06/07	5	ICME
15	2012/04/20	13	ICME+CIR	50	2014/06/15	21	–
16	2012/04/23	3	ICME	51	2014/09/04	17	–
17	2012/05/30	15	CIR	52	2014/09/12	6	ICME
18	2012/06/17	5	ICME	53	2014/11/30	19	CIR
19	2012/07/04	7	ICME	54	2014/12/21	22	ICME
20	2012/07/15	9	ICME	55	2015/03/16	21	ICME
21	2012/09/04	4	ICME	56	2015/04/09	21	ICME+CIR
22	2012/09/30	5	ICME	57	2015/05/07	10	ICME
23	2012/10/07	18	ICME	58	2015/06/13	7	CIR
24	2012/11/11	7	ICME	59	2015/06/22	17	ICME
25	2012/11/24	5	ICME	60	2015/07/13	4	ICME
26	2013/01/16	8	ICME	61	2015/08/15	4	ICME
27	2013/01/25	6	CIR	62	2015/08/26	4	ICME
28	2013/03/14	22	ICME	63	2015/09/07	12	ICME
29	2013/04/13	14	ICME	64	2015/11/06	11	ICME+CIR
30	2013/06/22	11	ICME+CIR	65	2015/12/06	20	ICME+CIR
31	2013/07/09	11	ICME+CIR	66	2015/12/31	8	ICME
32	2013/08/03	5	CIR	67	2016/03/05	7	ICME
33	2013/08/22	7	ICME	68	2016/03/24	10	CIR
34	2013/08/30	13	CIR	69	2016/04/21	7	CIR
35	2013/10/01	4	ICME				

FD Rigidity Behavior

Start date:
September 26 2011

Caused by:
Multiple ICMEs

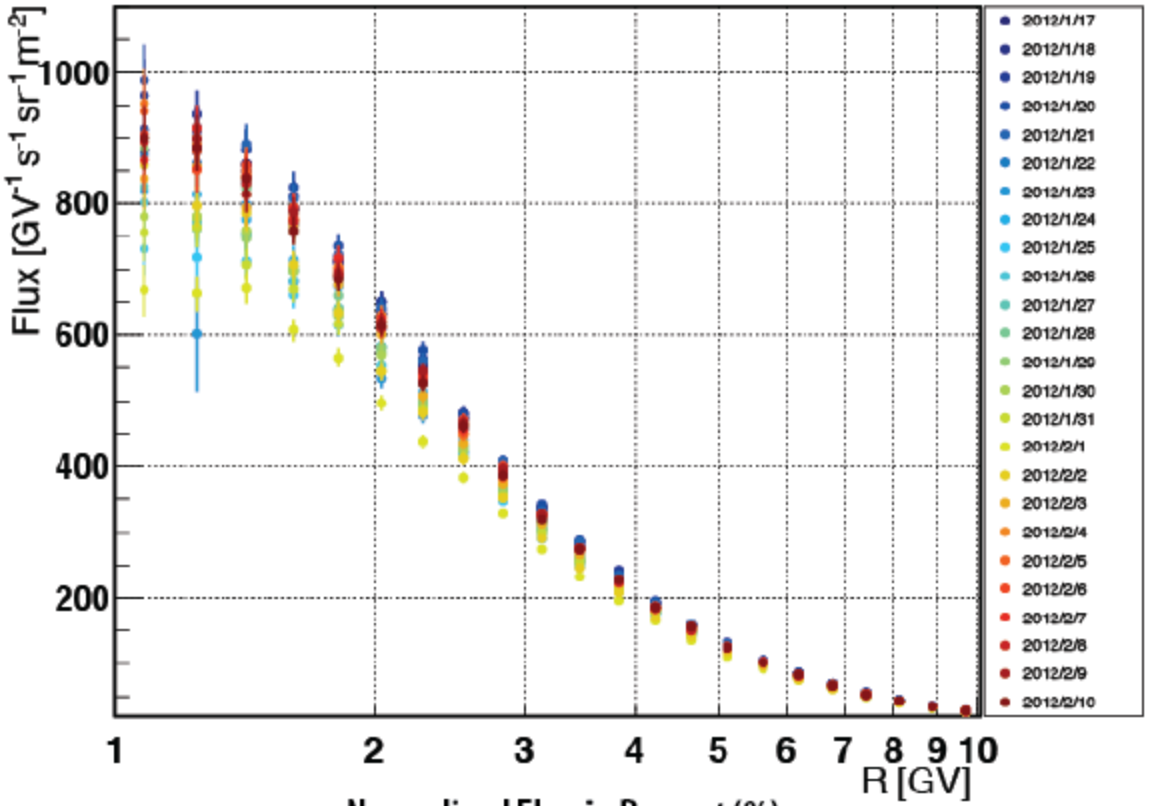


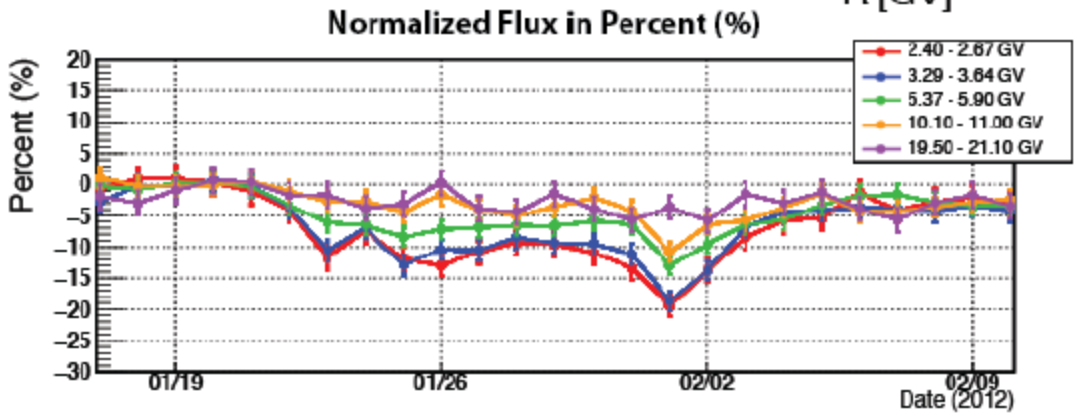
K. Whitman, Phd Thesis

FD Rigidity Behavior

Start date:
January 22 2012

Caused by:
ICME



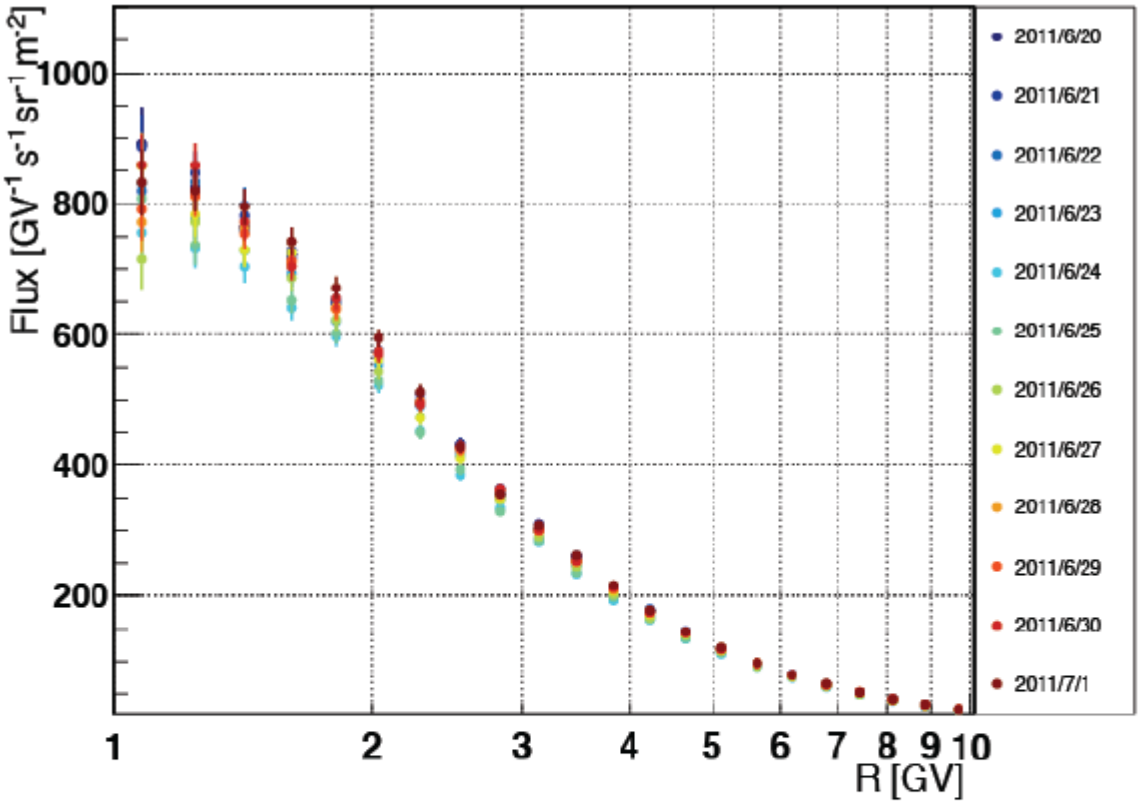


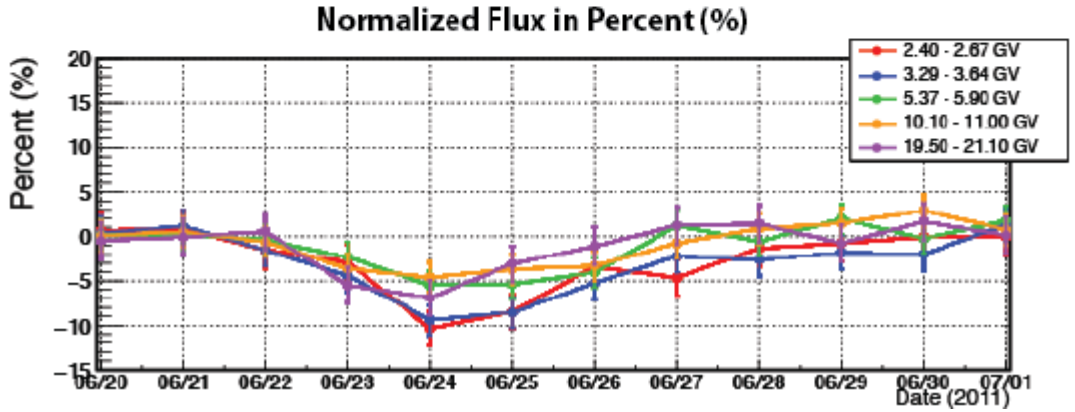
K. Whitman, Phd Thesis

FD Rigidity Behavior

Start date:
June 23 2011

Caused by:
CIR





K. Whitman, Phd Thesis

Summary

- AMS measures the daily proton flux with high precision and resolution
- A method to study the FD properties of the AMS daily flux was developed
- 69 Forbush decreases between May 2011 and May 2016 have been studied by AMS
- Time evolution in all rigidity bins is now precisely measured
- The study of FD represent an excellent tool for a deeper understanding of the short-term solar activity phenomena

Future Developments

- FD studies with Helium measured by AMS are ongoing
- AMS is also capable to perform FD studies with heavier nuclei and electrons (charge-signe dependence)

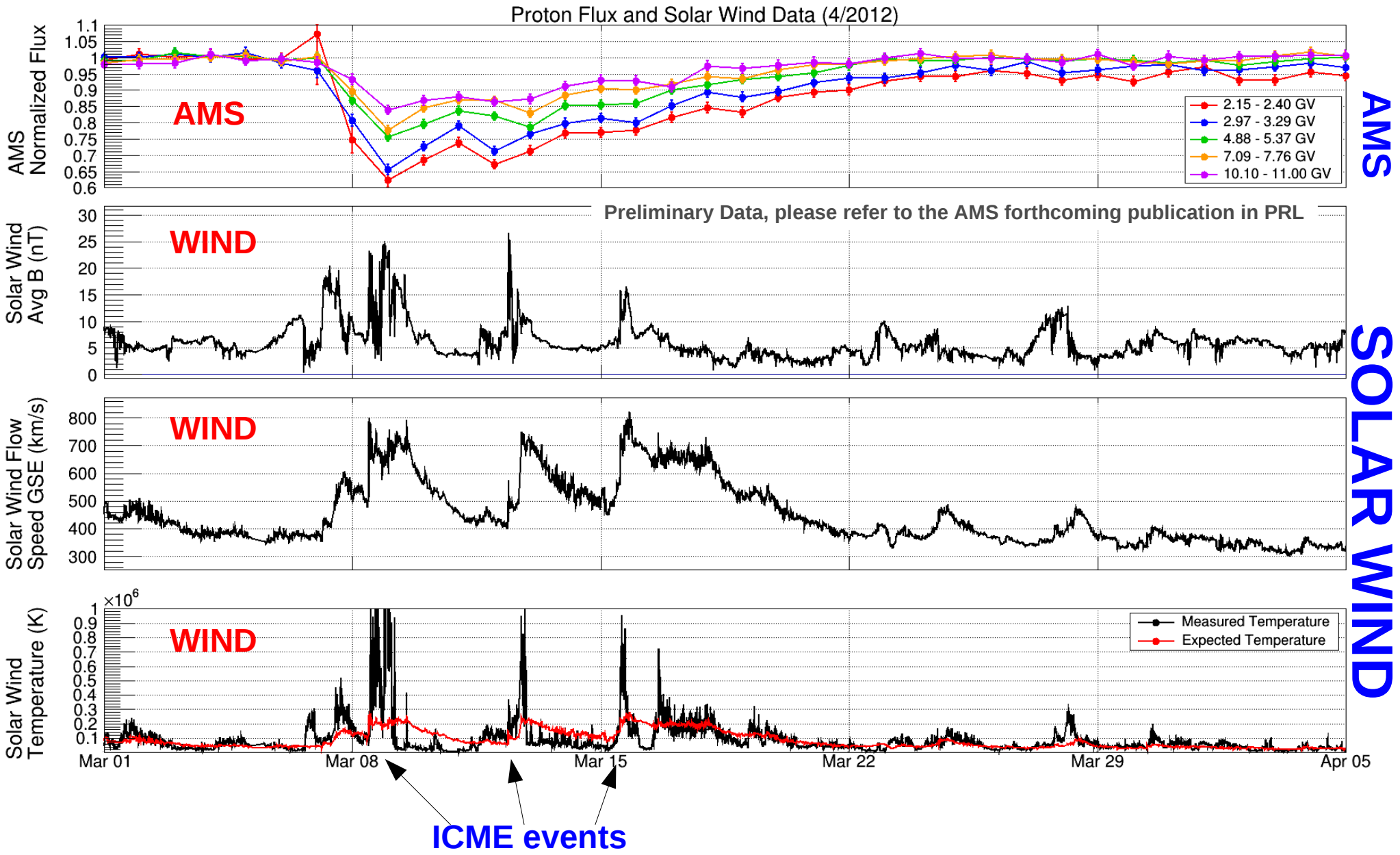
FD Event List

List of FDs between May 2011 and May 2016 studied by AMS with estimated start date and duration.

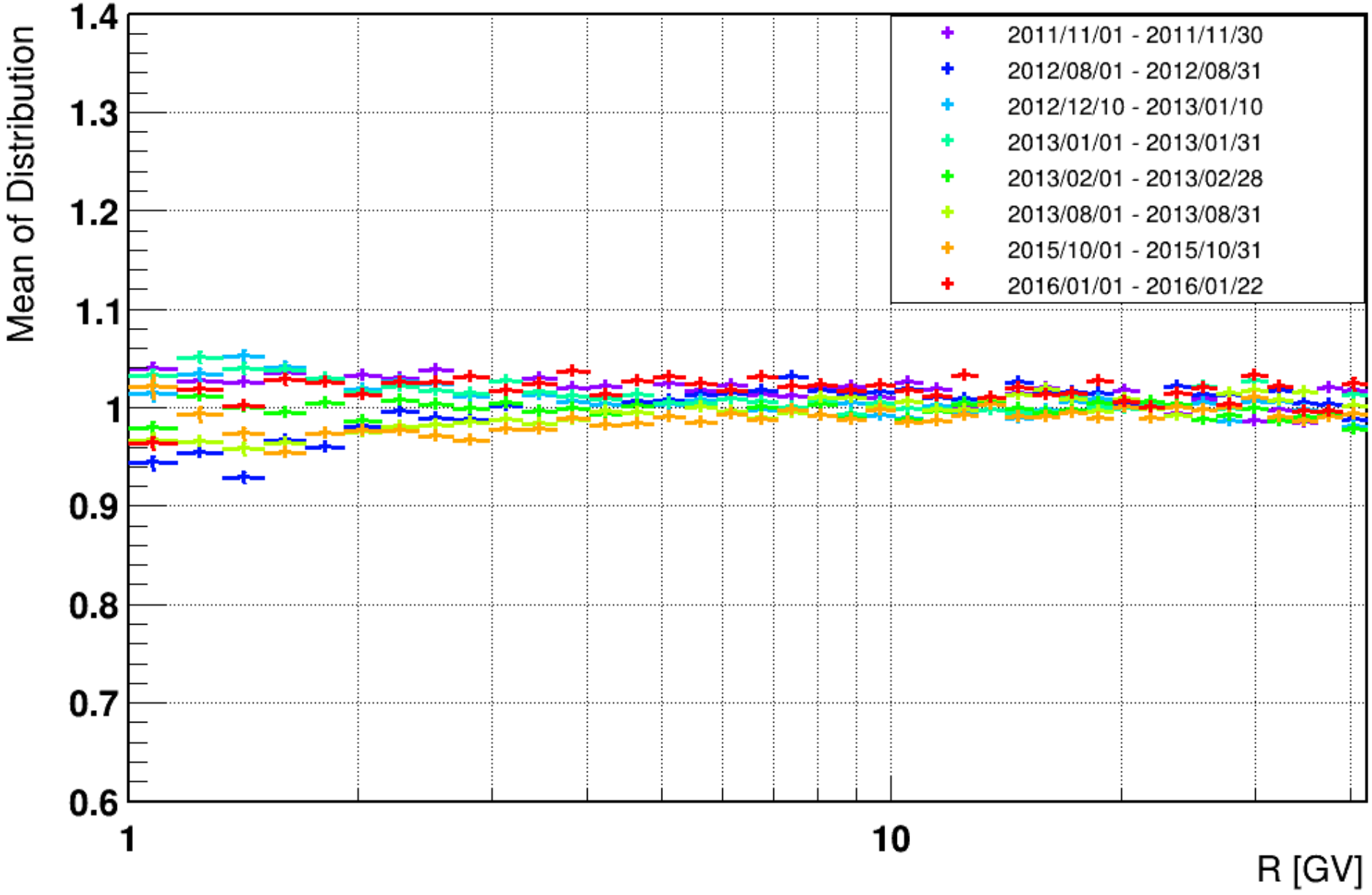
Number	Start Date	Duration Days
1	2011/06/24	5
2	2011/08/06	4
3	2011/09/26	23
4	2011/10/25	3
5	2012/01/22	13
6	2012/02/27	4
7	2012/03/08	20
8	2012/04/06	4
9	2012/06/17	5
10	2012/07/15	9
11	2012/09/04	4
12	2012/11/24	5
13	2013/03/17	16
14	2013/04/15	3
15	2013/06/23	9
16	2013/11/08	13
17	2013/12/15	4

Number	Start Date	Duration Days
18	2014/02/15	5
19	2014/02/20	6
20	2014/02/26	14
21	2014/06/08	4
22	2014/06/18	20
23	2014/09/12	12
24	2014/12/01	17
25	2014/12/21	22
26	2015/03/16	10
27	2015/05/06	8
28	2015/06/22	14
29	2015/08/15	3
30	2015/08/26	3
31	2015/11/07	3
32	2015/12/20	4
33	2015/12/31	8

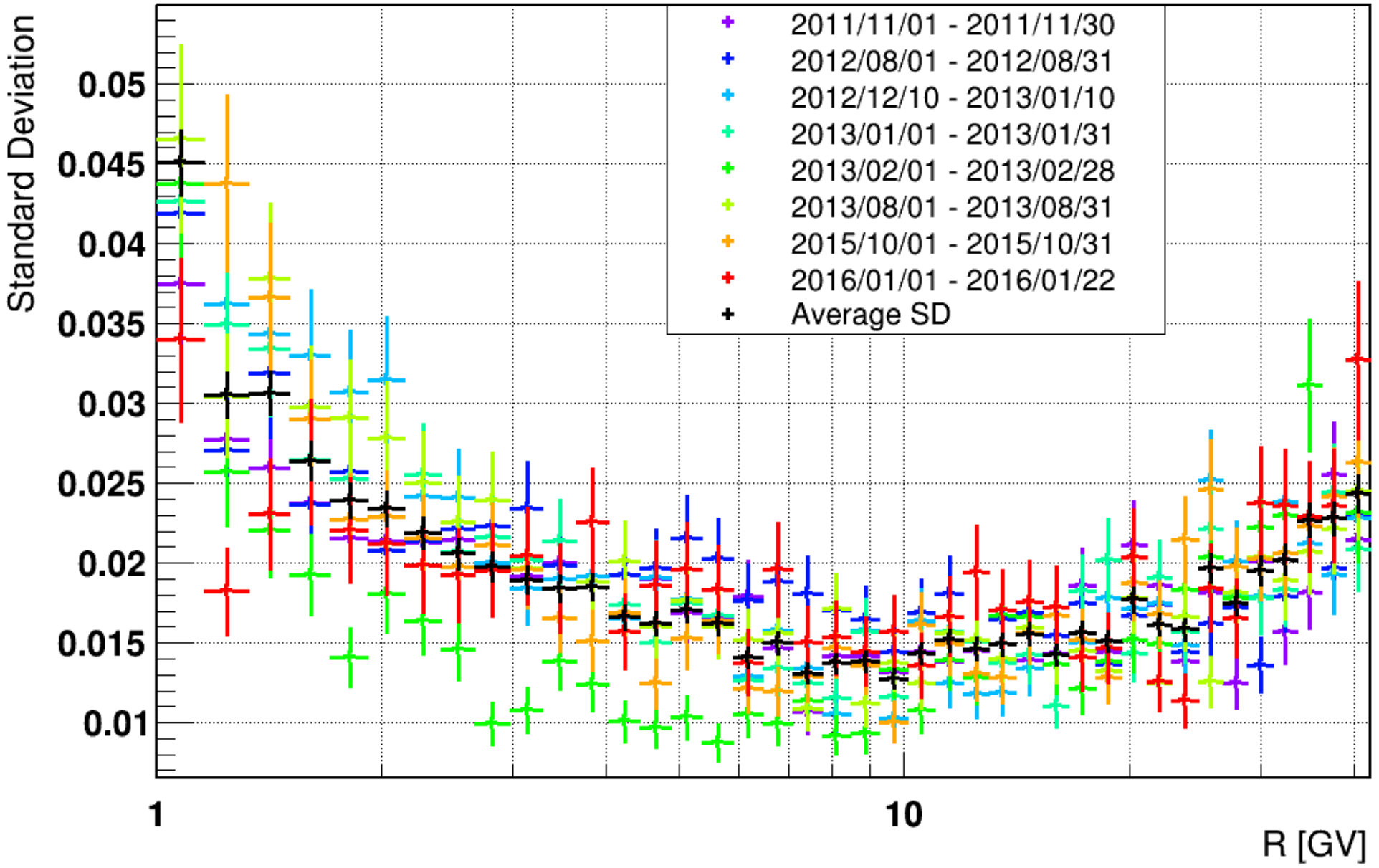
AMS and Solar Wind



Mean of Distribution quite periods vs R



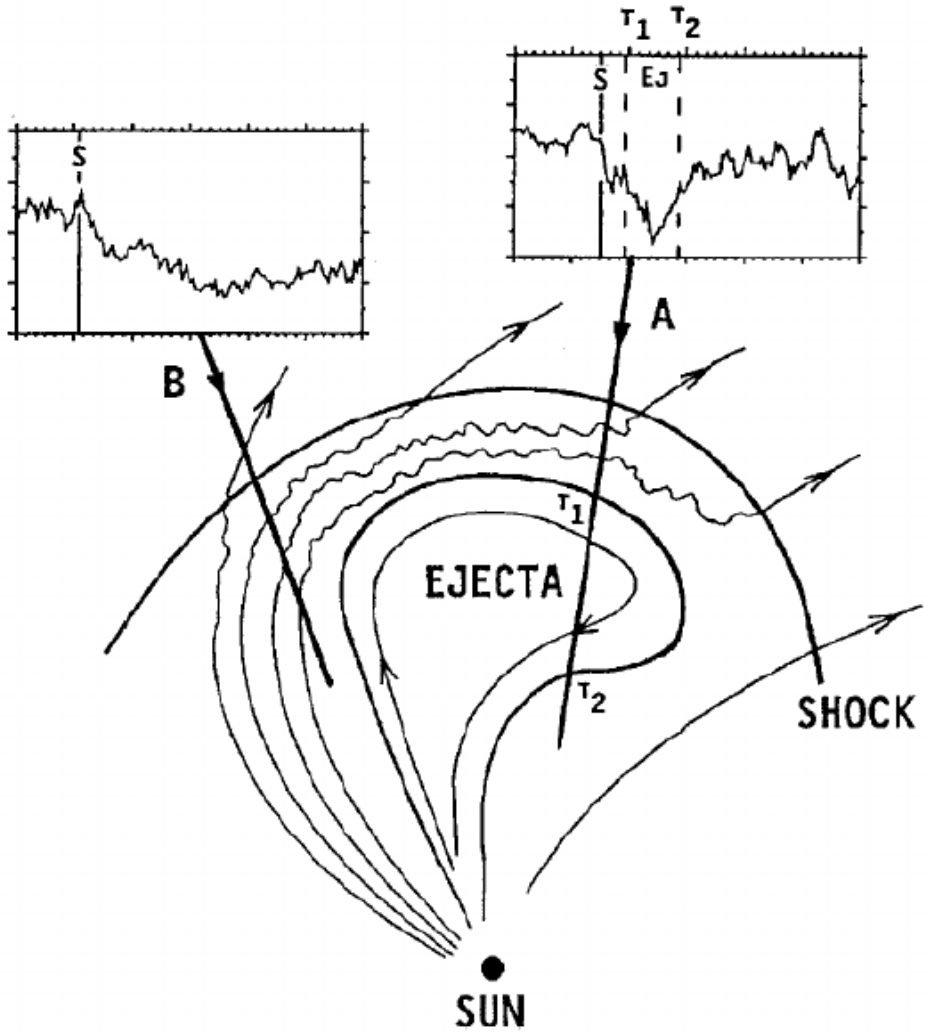
SD quite periods vs R



Correlations with ICMEs

The profile of a FD is influenced by the path through the interplanetary disturbances:

- **The faster the propagation of the interplanetary disturbance, the stronger its magnetic field, the faster the decrease**
- **The FD magnitude is larger for:**
  - **Fast and wide ICME**
  - **Stronger flares**
  - **Source regions close to the center of the solar disk**
- **FDs have generally smaller magnitude when only the forward shock is present**
- **If ICME is preceded by a shock, two-step pattern (1st shock, 2nd ejecta)**



H. V.Cane, "Coronal Mass Ejections and Forbush Decreases". Space Science Reviews, 93: 55-77, 2000
H. V. Cane et al., "Helios 1 and 2 observations of particle decreases, ejecta and magnetic cluds". Journal of Geophysical Research, 99(A11)
A. Devos et al., "Geoeffectiveness of Coronal Mass Ejections in the SOHO era", Solar Physics 290:579-612, 2015
Richardson, Cane, "Near-Earth Interplanetary Coronal Mass Ejections during Solar Cycle 23 (1996-2009): Catolog and Summary of Properties"

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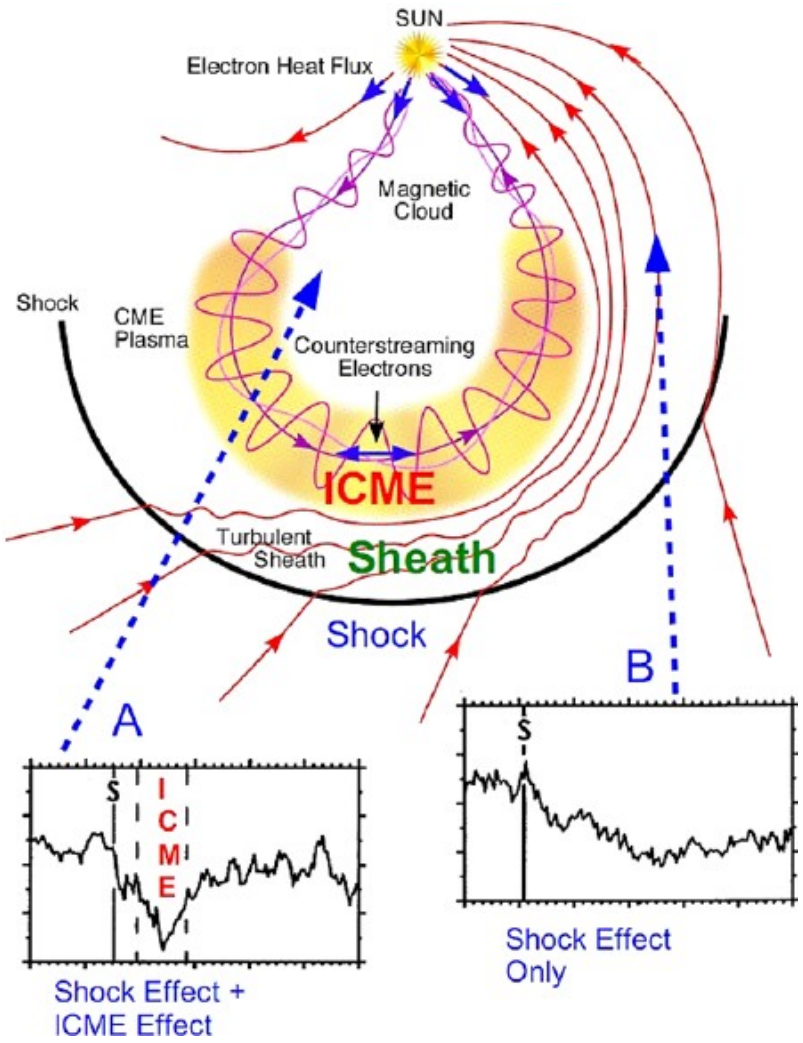

H. V.Cane, "Coronal Mass Ejections and Forbush Decreases". Space Science Reviews, 93: 55-77, 2000

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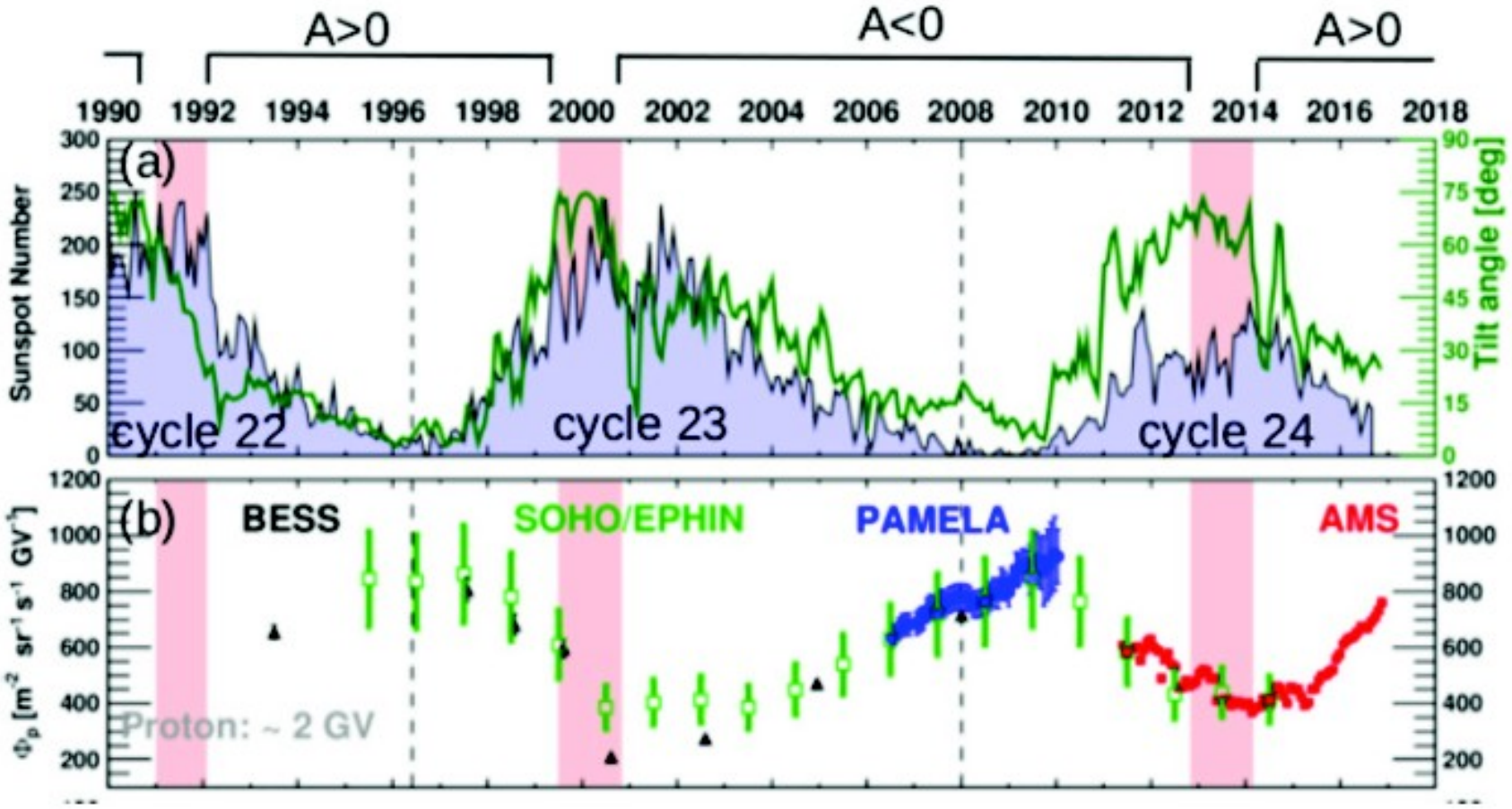
Solar activity measured by AMS

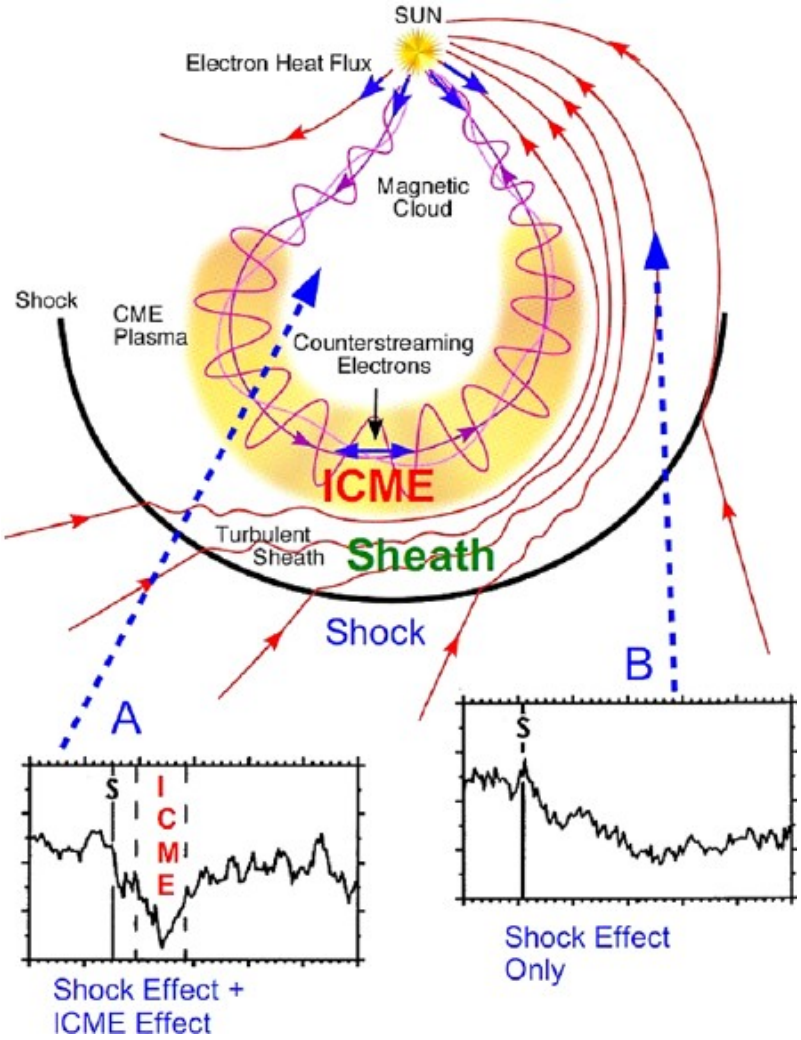
The Sun goes through an 11-year activity cycle shown by sunspots number or the current sheet tilt angle (maximum and minimum).
At each solar maximum the Sun flips its magnetic field polarity (A>0, A<0) showing a periodicity of 22 years.
The flux of galactic cosmic rays is anti-correlated with the intensity of the solar activity.



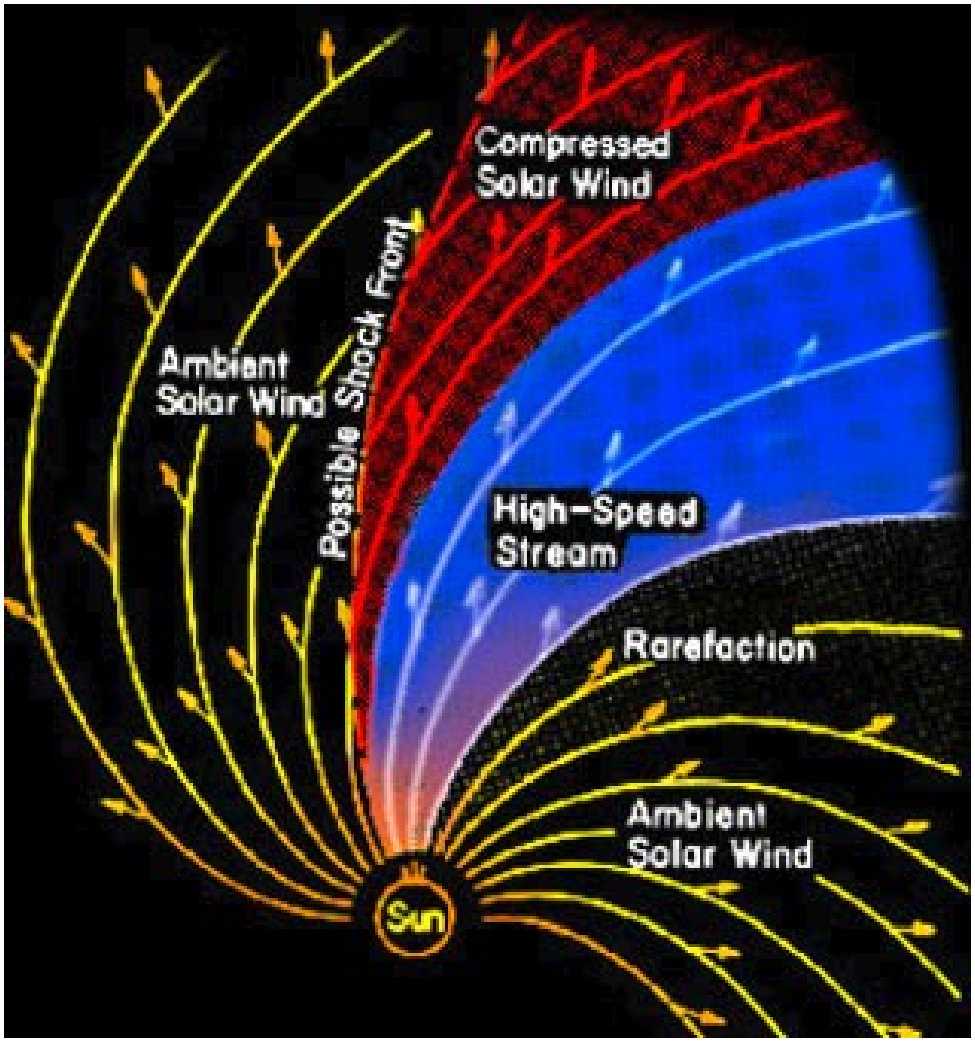
Daily sunspot number: http://www.sidc.be/silso/datafiles

ICME & CIR

Interplanetary Coronal Mass Ejections



Corotating Interacting Regions



ICMEs, CIRs and their shocks are responsible for the majority of Forbush decreases