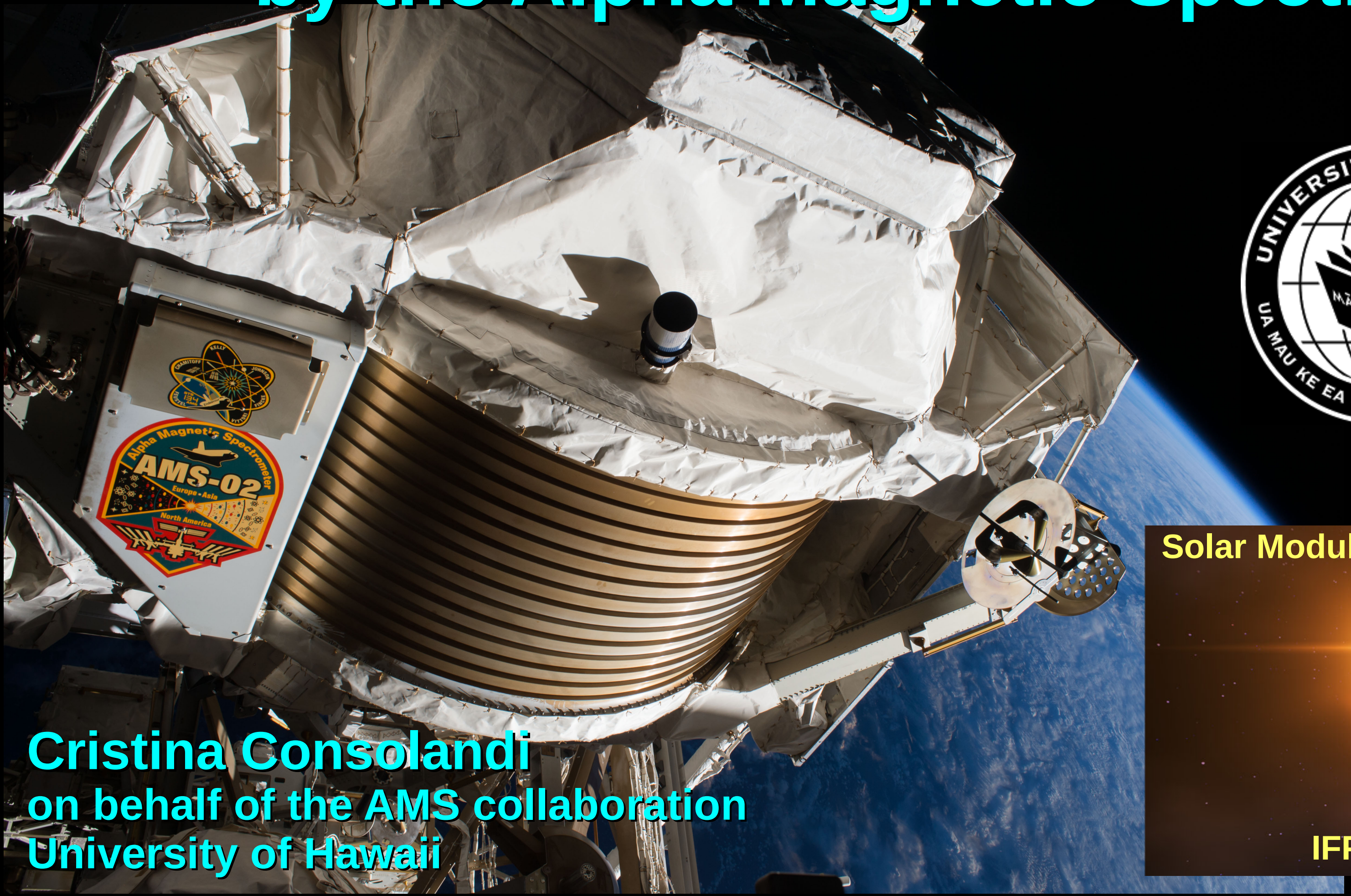
Time Dependent Measurements by the Alpha Magnetic Spectrometer

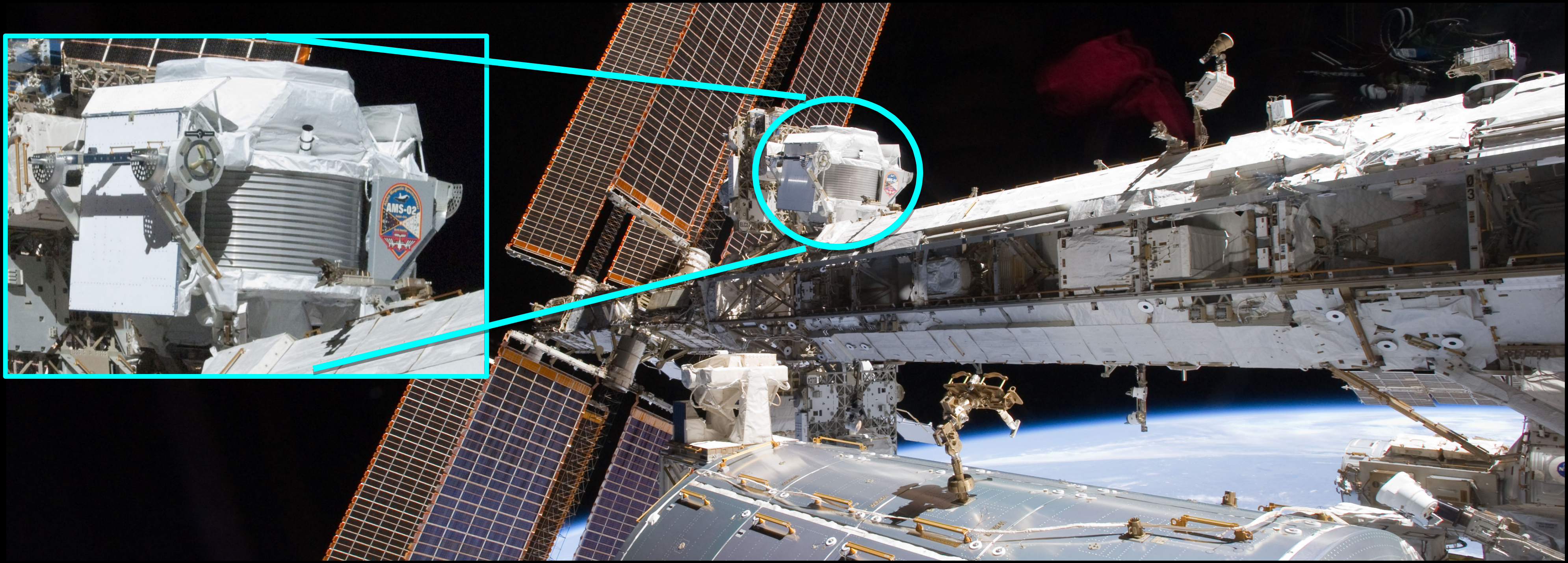


Cristina Consolandi
on behalf of the AMS collaboration
University of Hawaii

Solar Modulation and Dark Matted Workshop

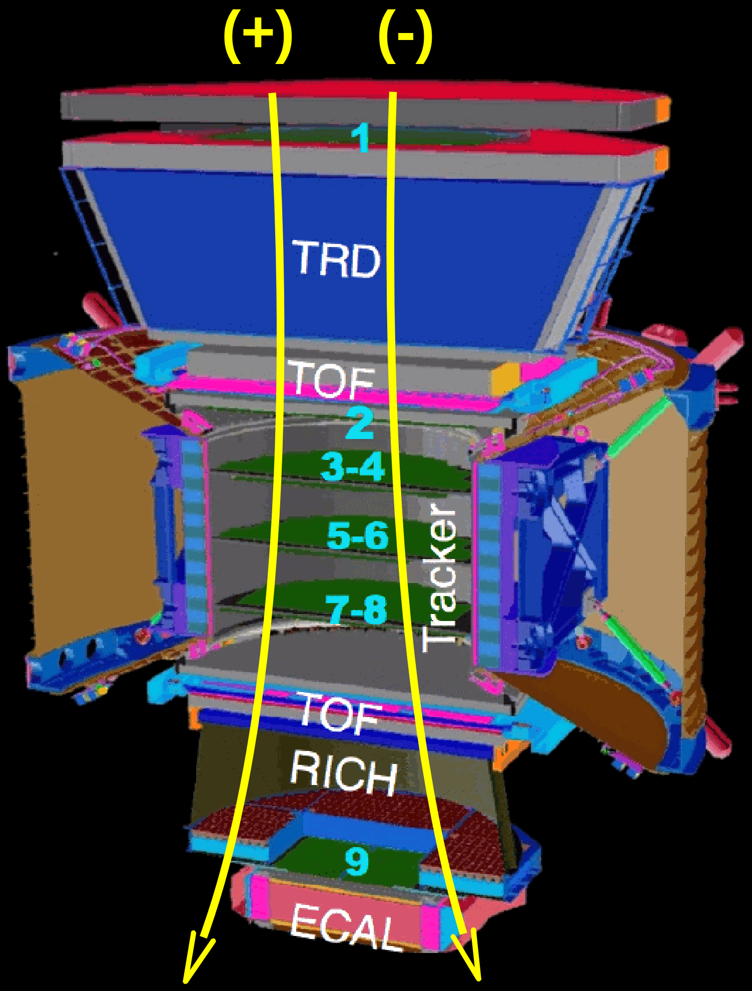
IFPU-Trieste, November 15-19, 2021

Alpha Magnetic Spectrometer
on the International Space Station since May 2011



Over 180 billion charged particles have been measured

AMS Particle Detector



Transition Radiation Detector

- e+ e- identification

Time-of-Flight counter

- Trigger
- Velocity
- Charge
- Particle flight direction

Silicon Tracker + Magnet

- Rigidity
- Charge & sign

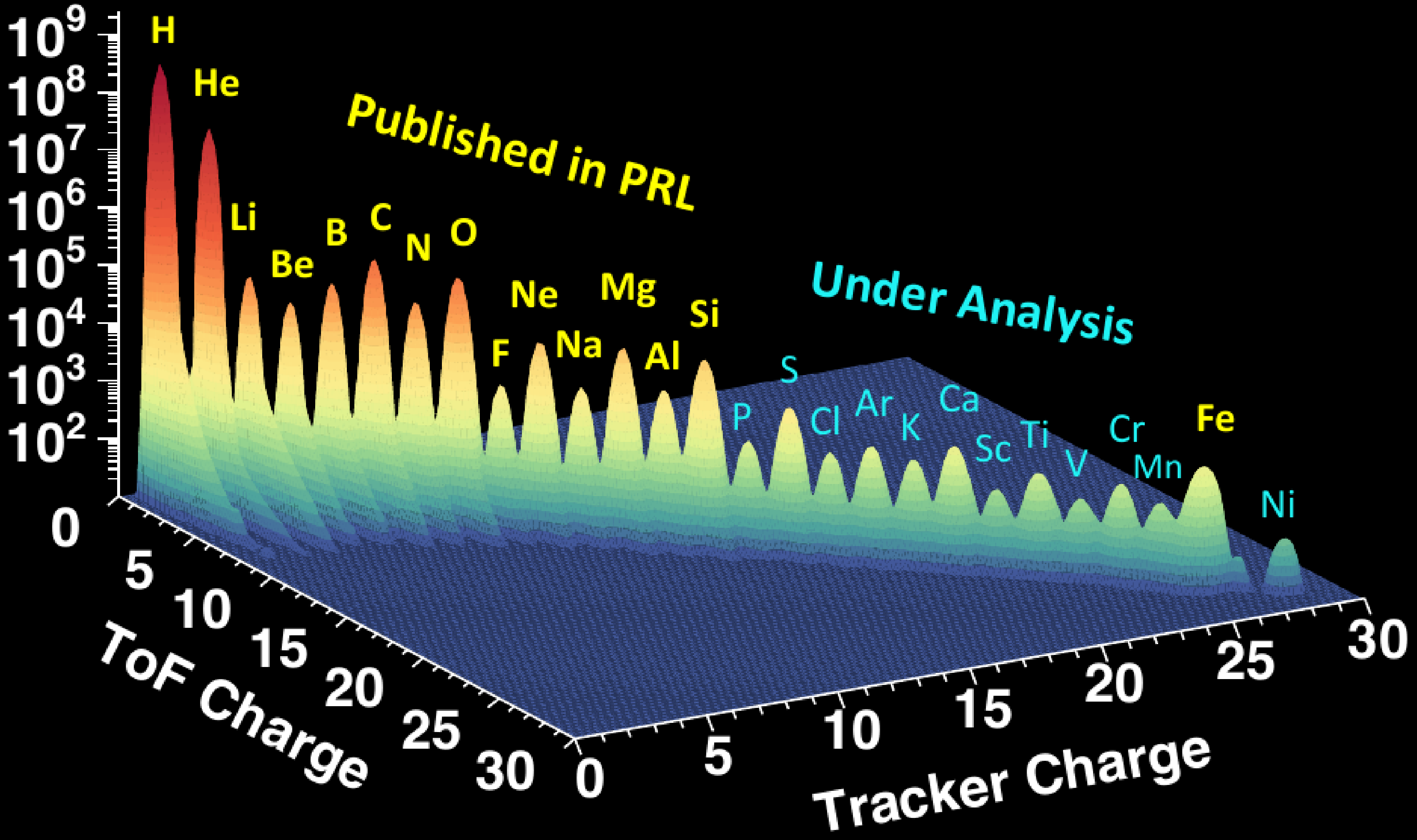
Ring Imaging Cherenkov detector

- Velocity
- Charge

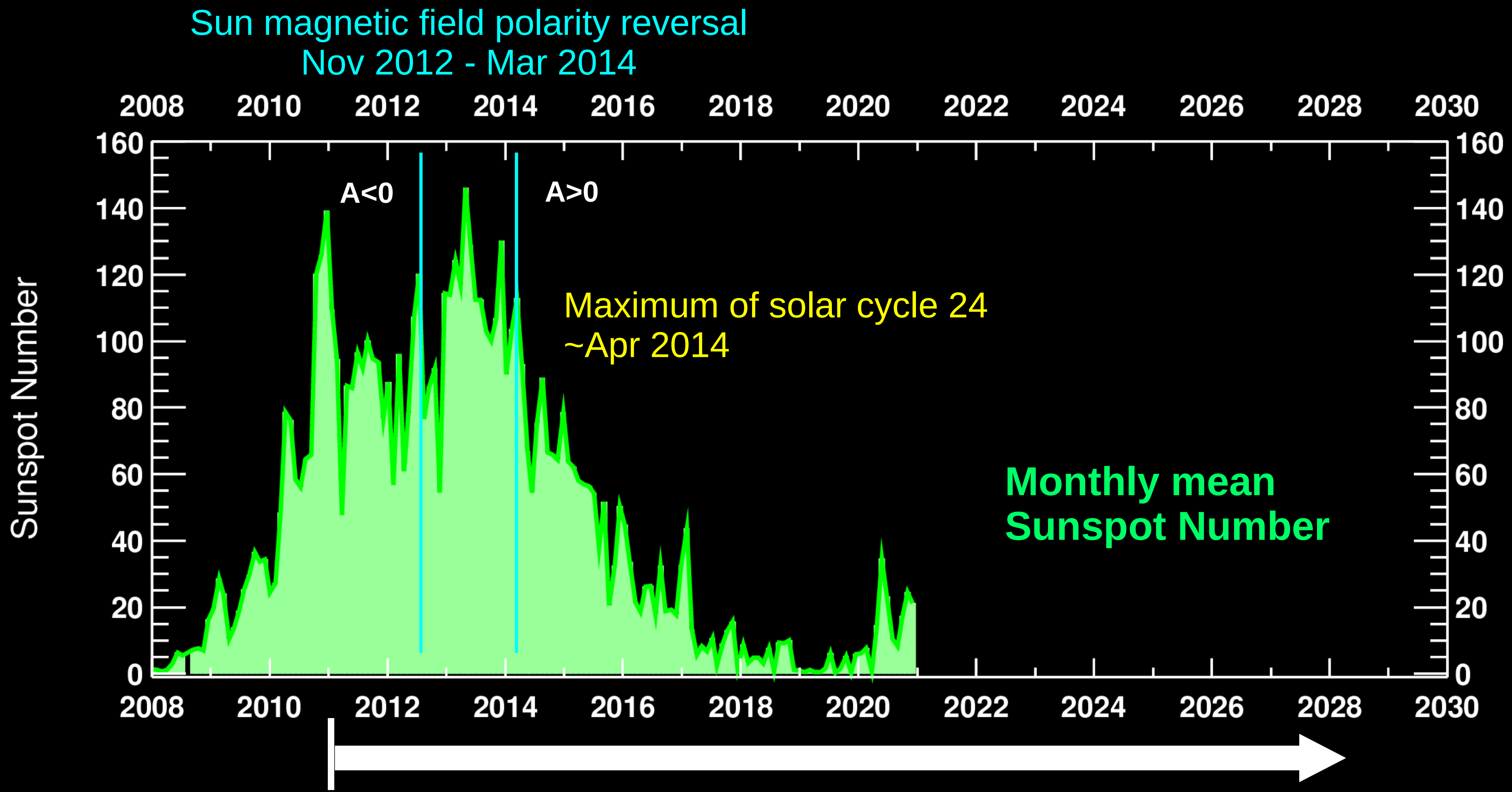
Electromagnetic Calorimeter

- e+ e- identification
- e+ e- Energy

AMS Nuclei "Periodic Table"

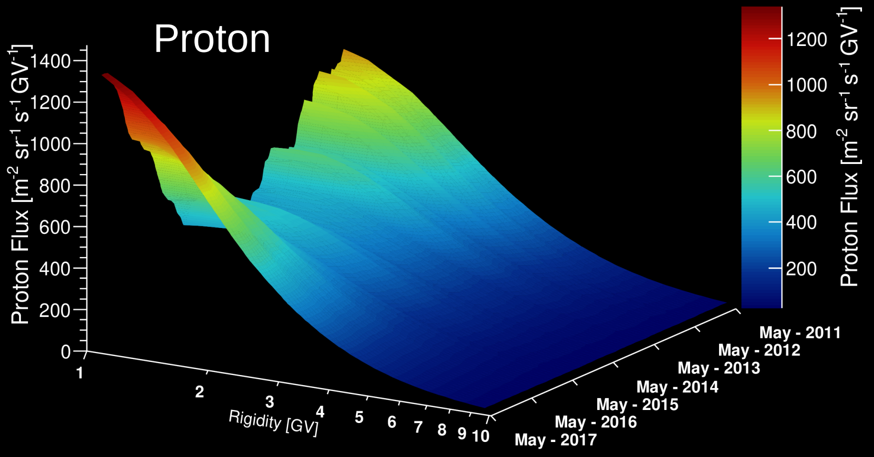


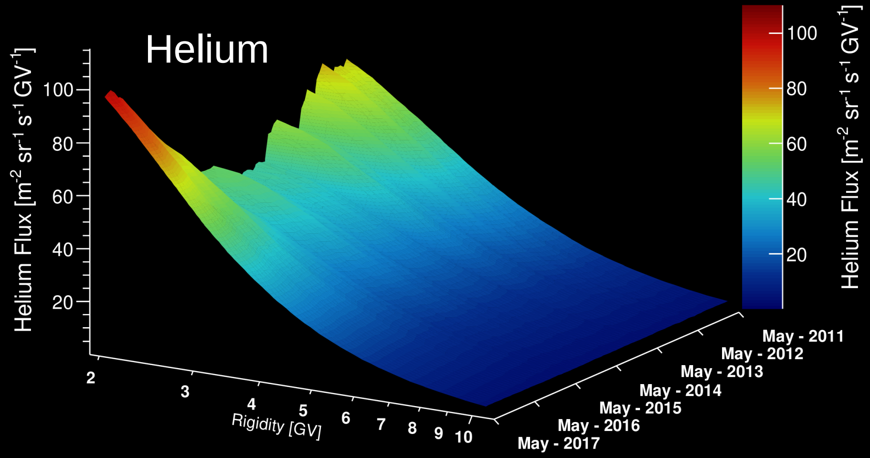
AMS Period of Observation



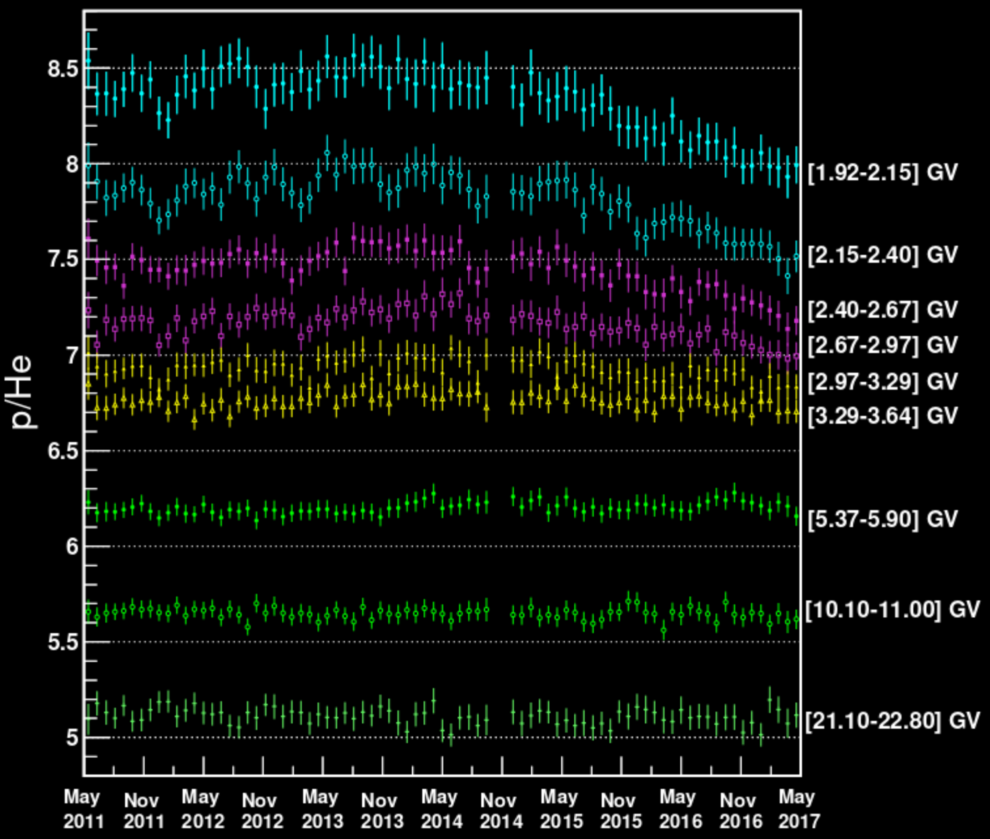
AMS will continue through the lifetime of the ISS

Previous Measurements: Monthly p and He Fluxes



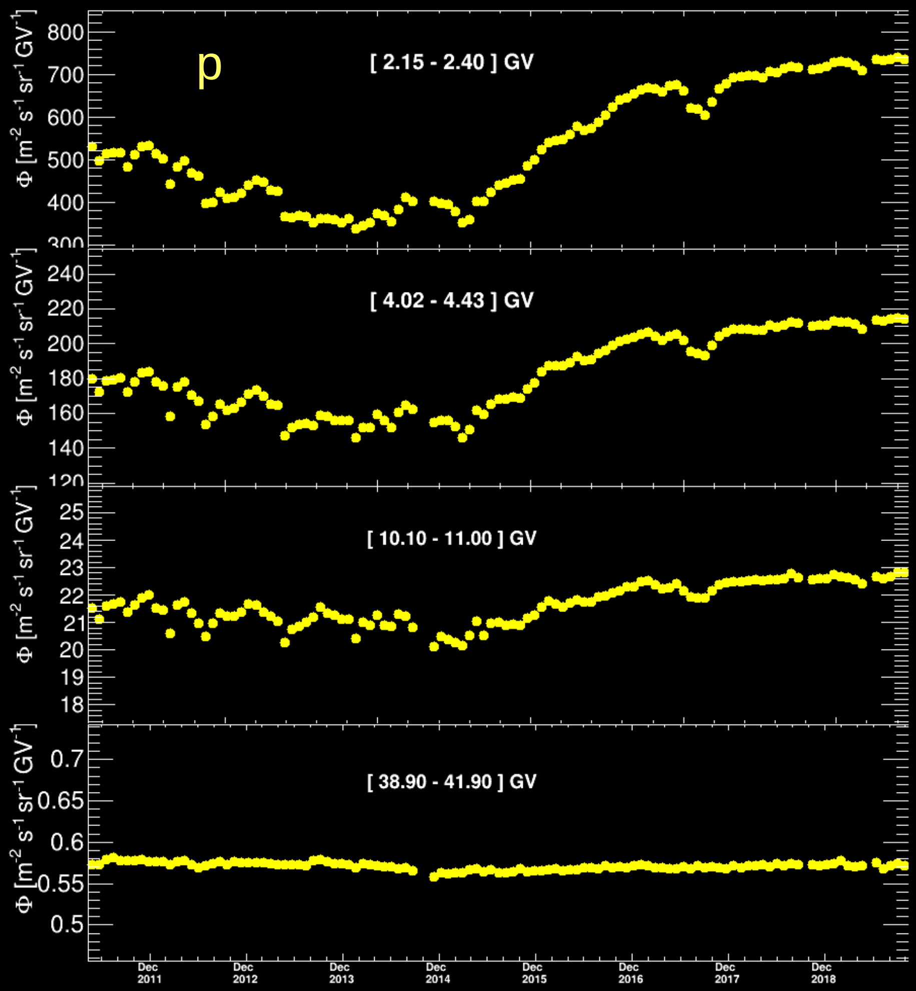


PRL 121, 051101 (2018)



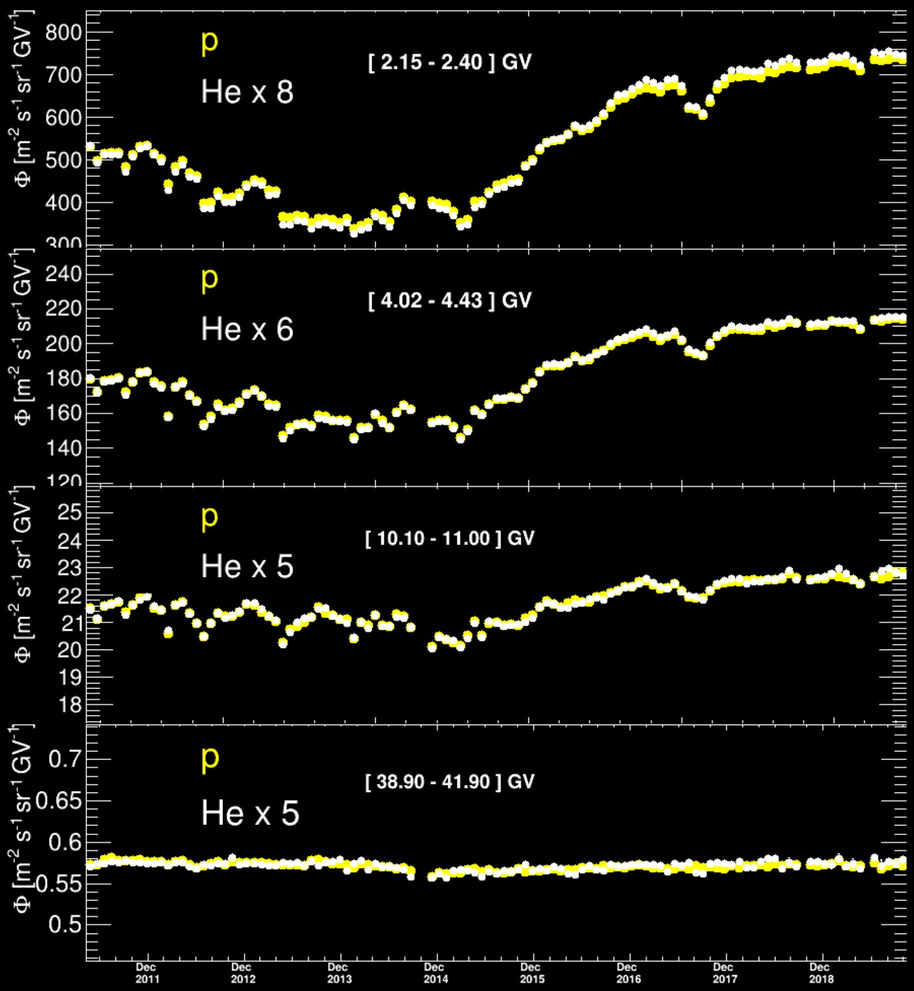
Monthly Fluxes: p (May 2011 - Nov 2019)

Preliminary data, refer to upcoming AMS publication



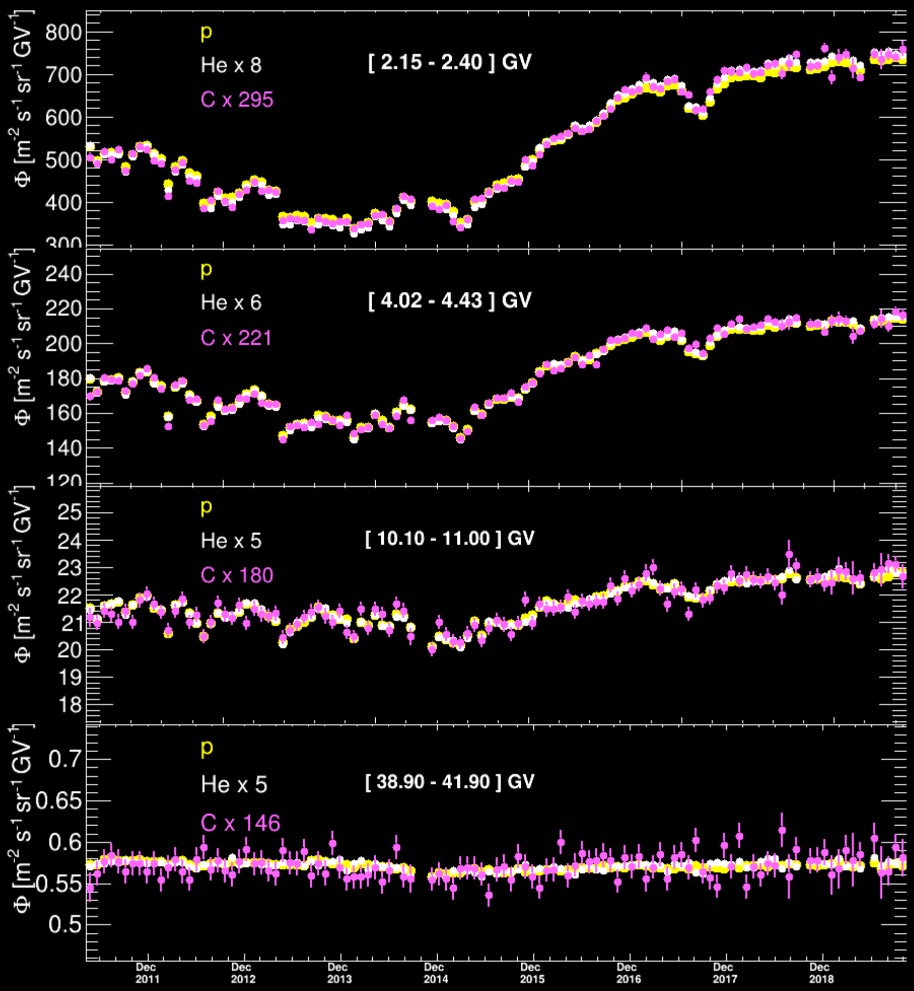
Monthly Fluxes: p, He (May 2011 - Nov 2019)

Preliminary data, refer to upcoming AMS publication



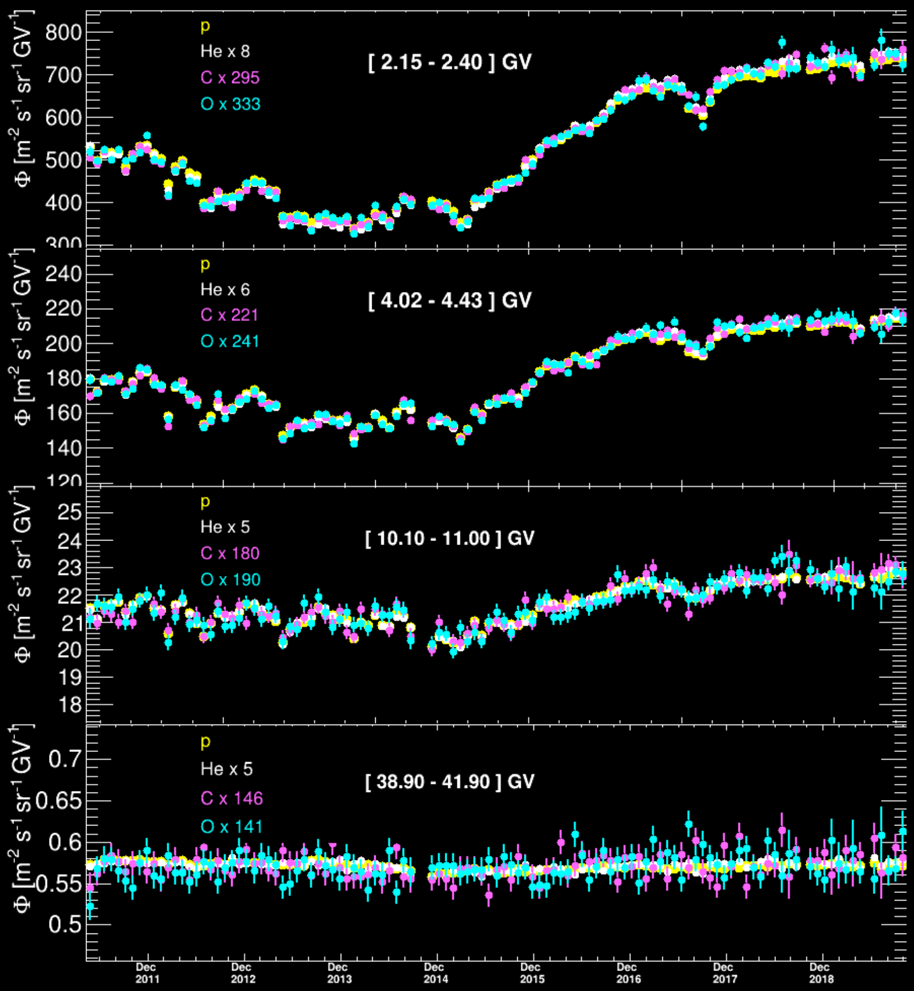
Monthly Fluxes: p, He, C (May 2011 - Nov 2019)

Preliminary data, refer to upcoming AMS publication



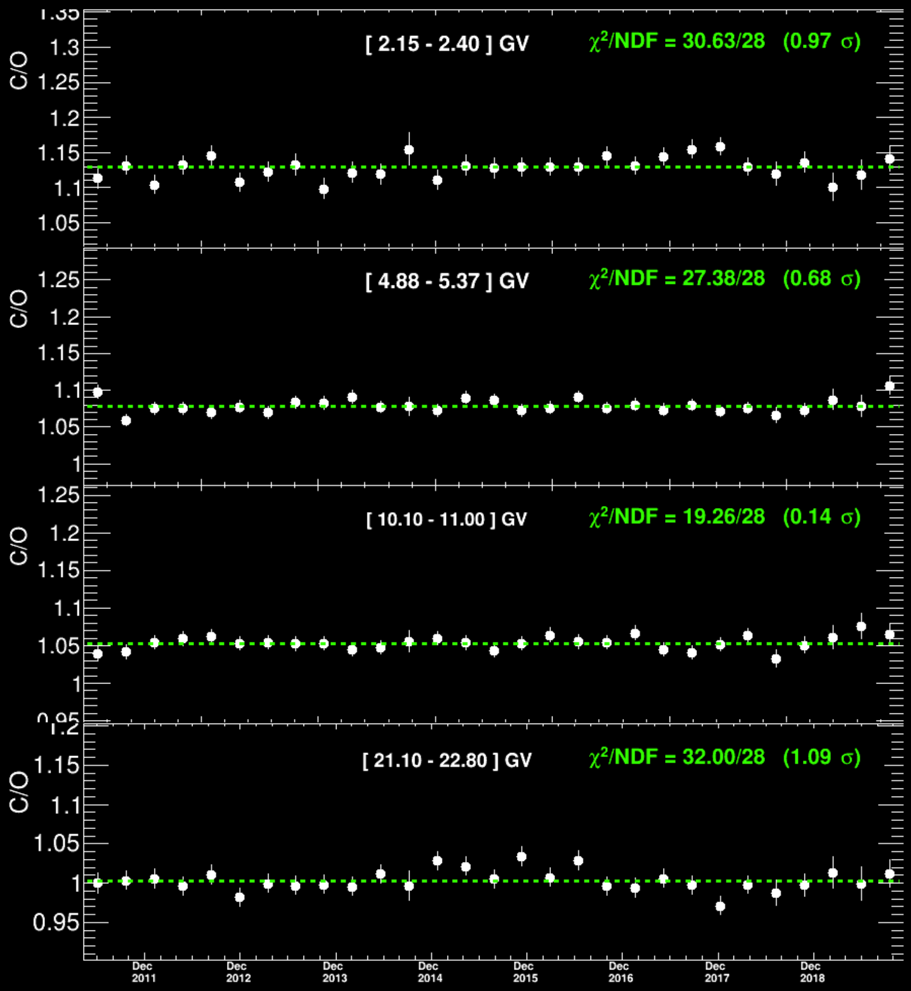
Monthly Fluxes: p, He, C, O (May 2011 - Nov 2019)

Preliminary data, refer to upcoming AMS publication



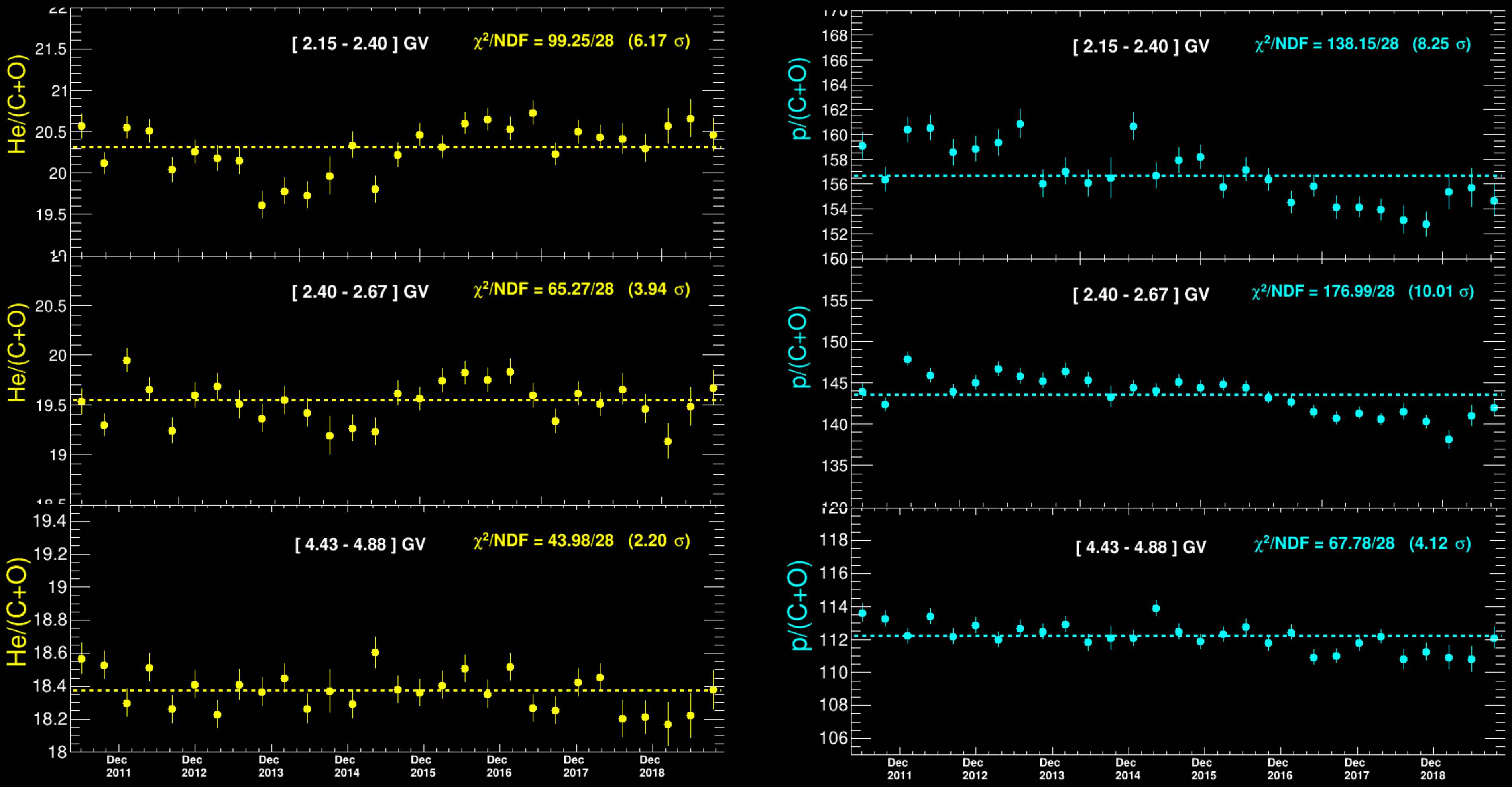
Monthly Flux Ratio: C/O

Preliminary data, refer to upcoming AMS publication



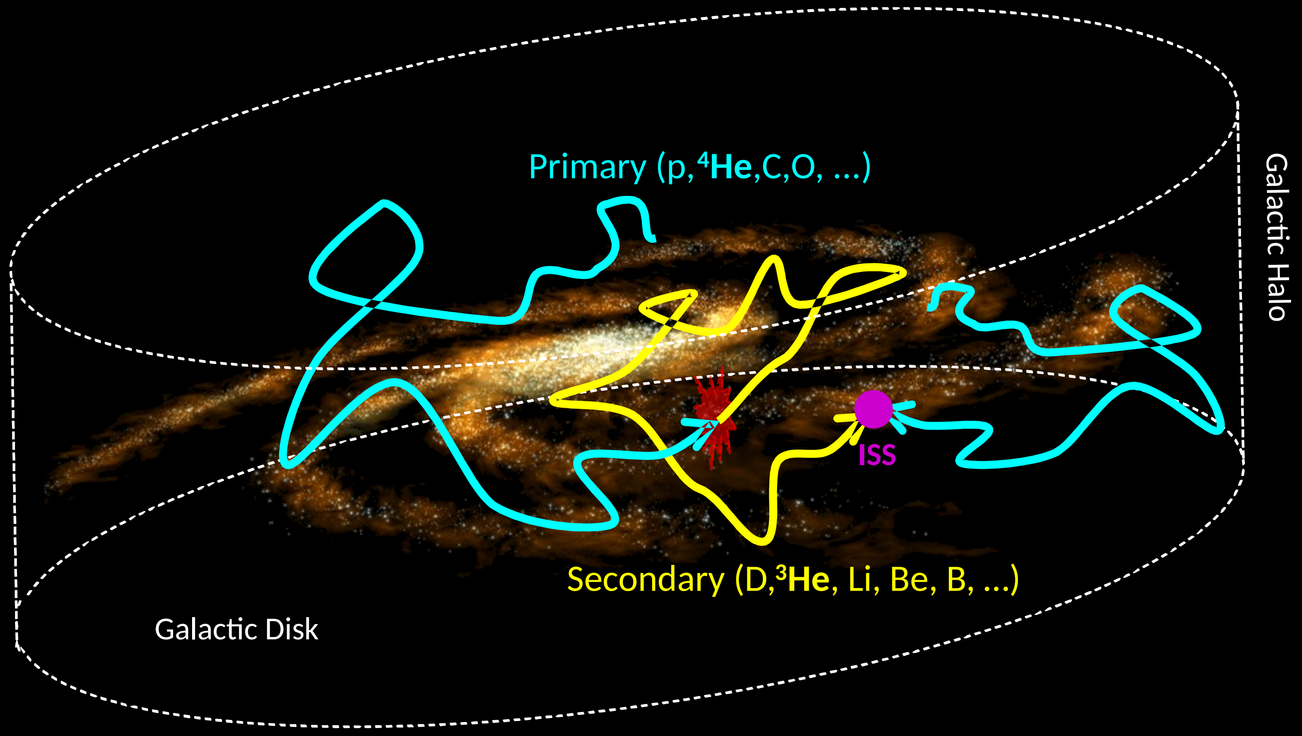
Monthly Flux Ratios: He/(C+O) & p/(C+O)

Preliminary data, refer to upcoming AMS publication

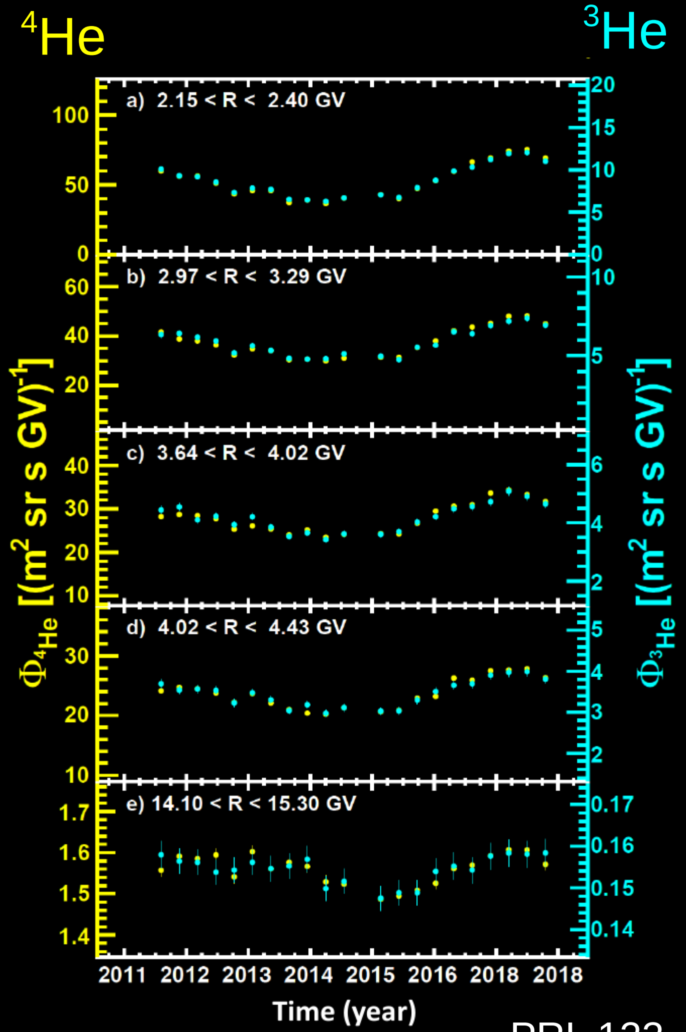


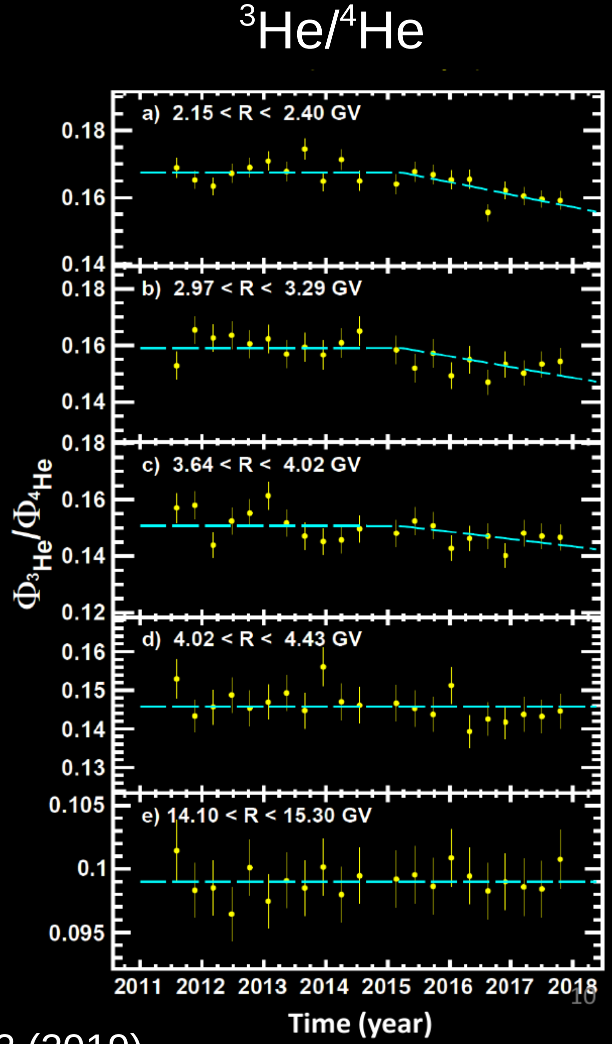
Primary and Secondary Cosmic Rays

Precise measurements of **primaries** and **secondary** elemental fluxes by AMS
give important information to understand the origin and the propagation of Cosmic Rays



4-Month Fluxes ^{3}He and ^{4}He (May2011-Nov2017)

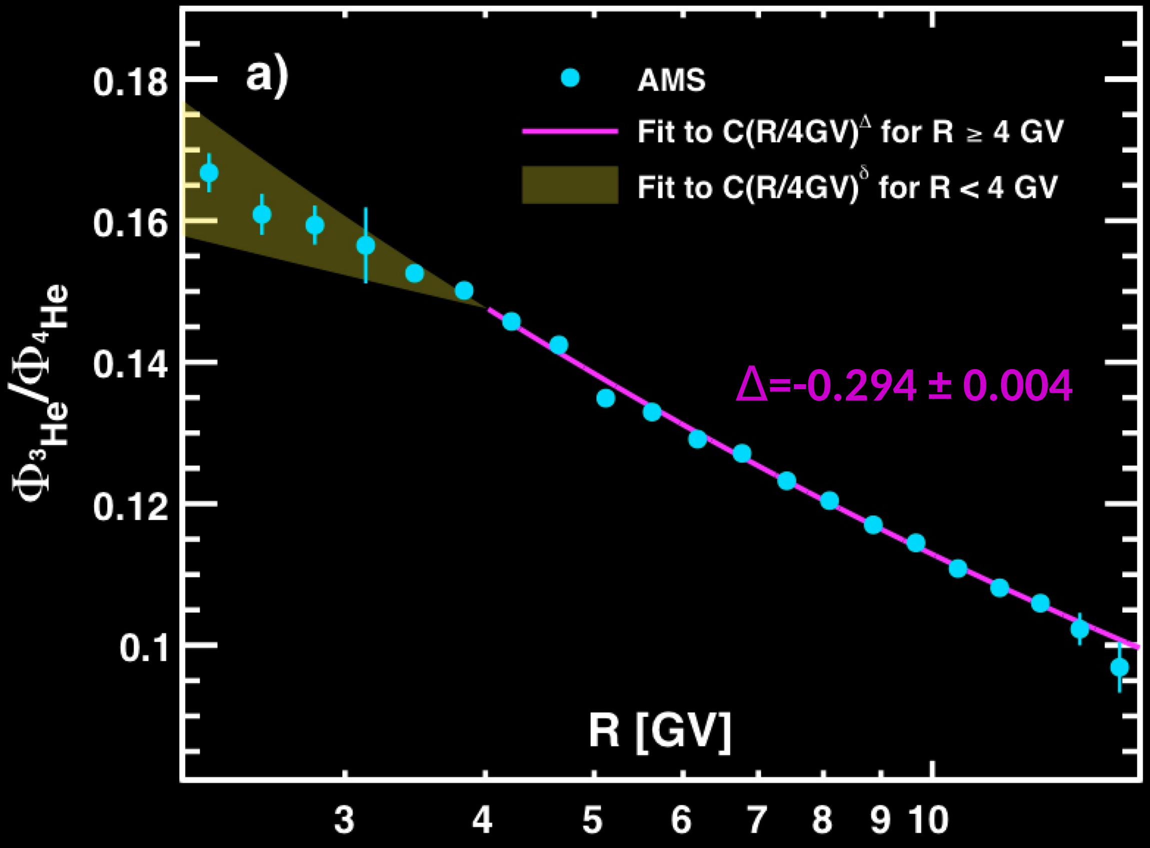




PRL 123, 181102 (2019)

^{3}He and ^{4}He Ratios versus Rigidity

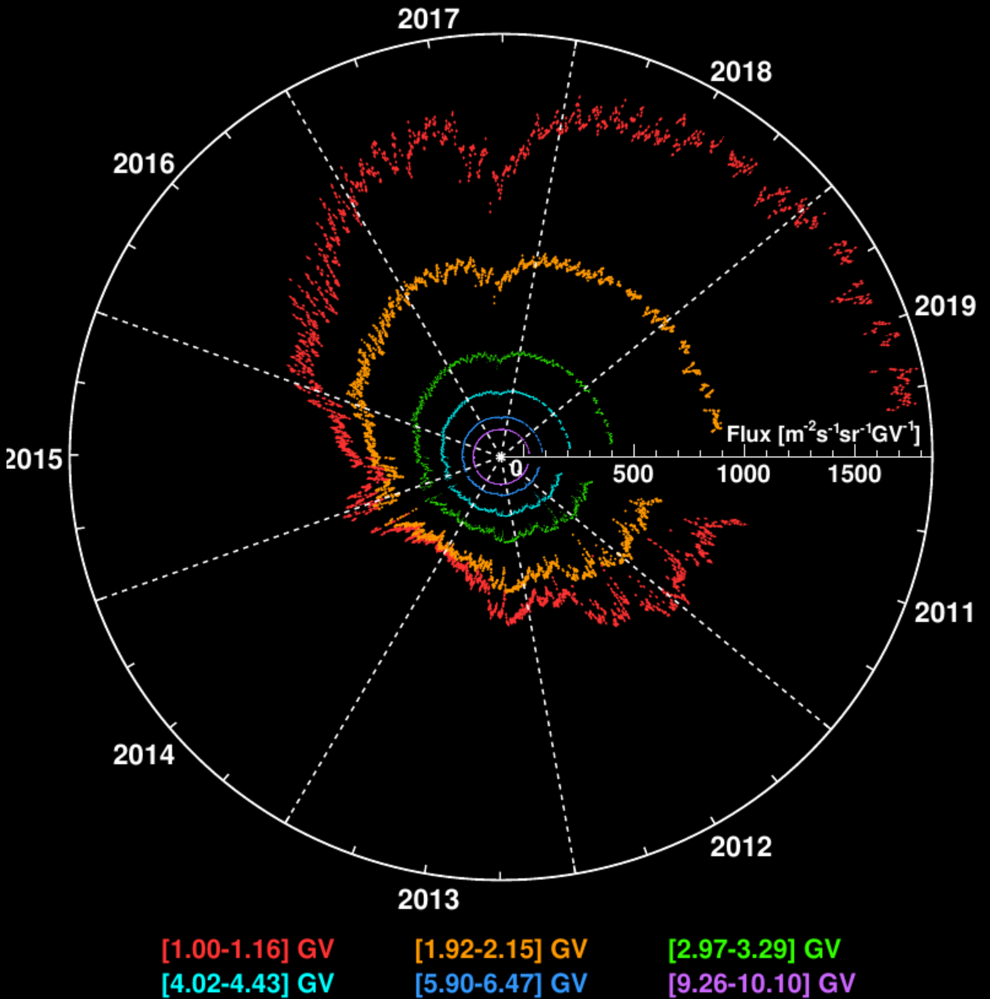
The time-averaged isotops ratio flux ratio as function of rigidity [2.1-15GV]



PRL 123, 181102 (2019)

Daily Proton Fluxes: May 20, 2011 - Oct 29, 2019

Accepted for publication in PRL



Daily Proton Fluxes: May 20, 2011 - Oct 29, 2019

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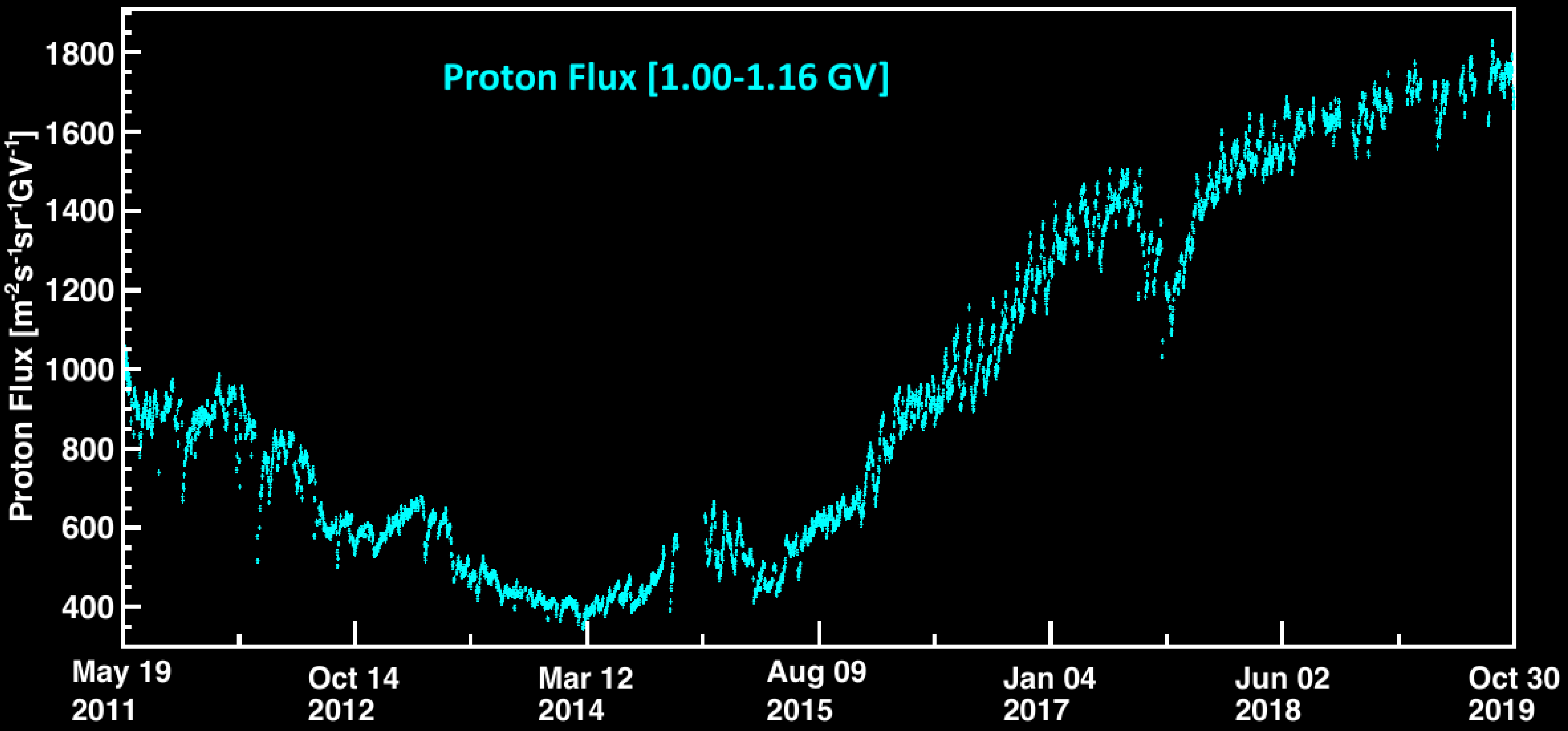
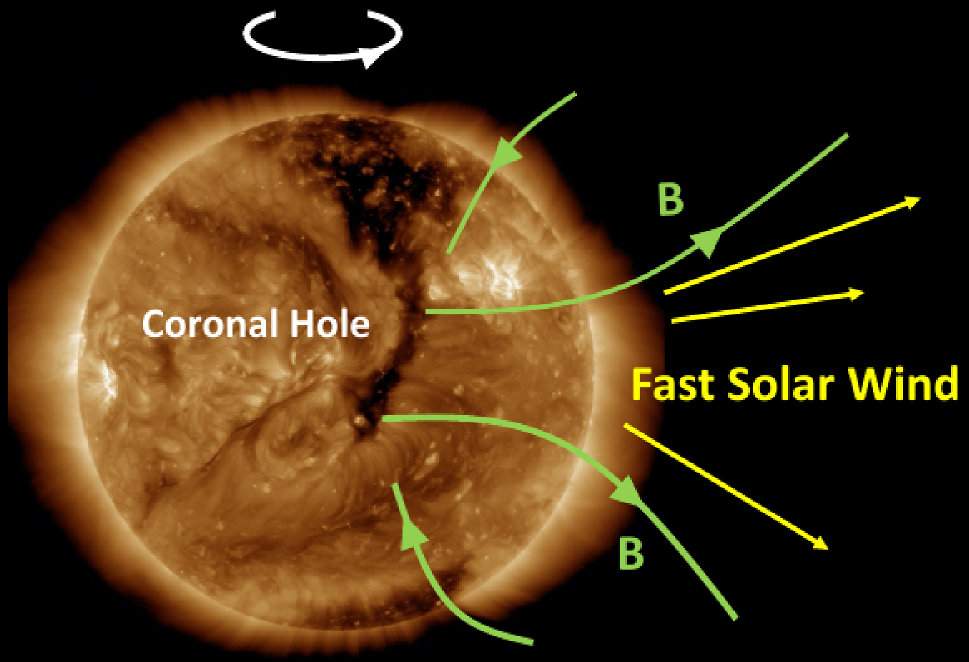
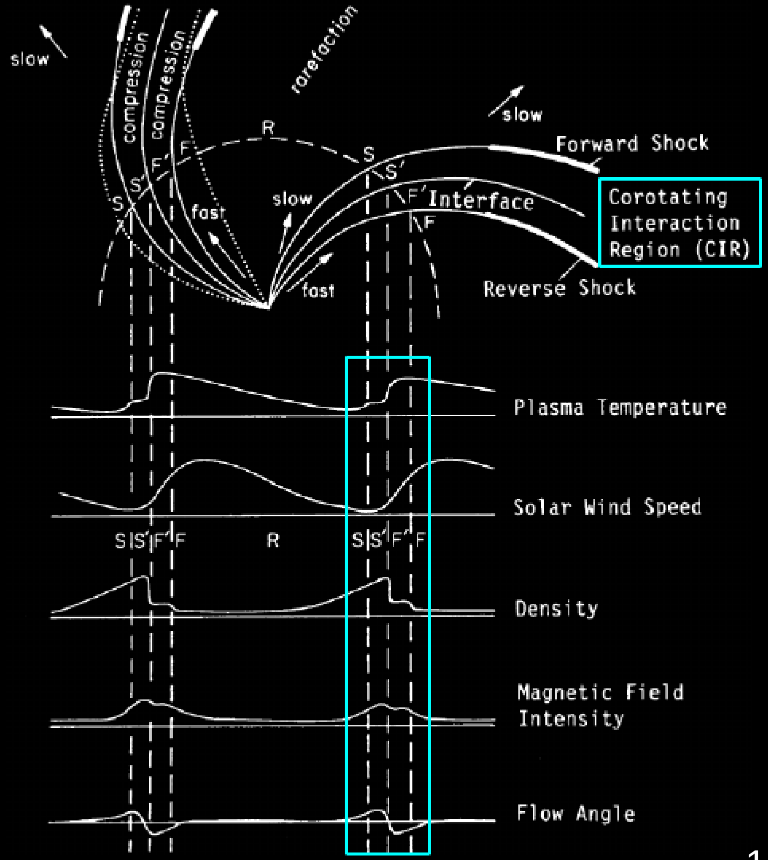


Recurrent Flux Variations

Recurrent variations in cosmic rays with a period of 27, 13.5, and 9 days are related to one or more coronal holes on the surface of the Sun.



2016-03-26, Image Credit: Solar Dynamics Observatory (SDO), NASA

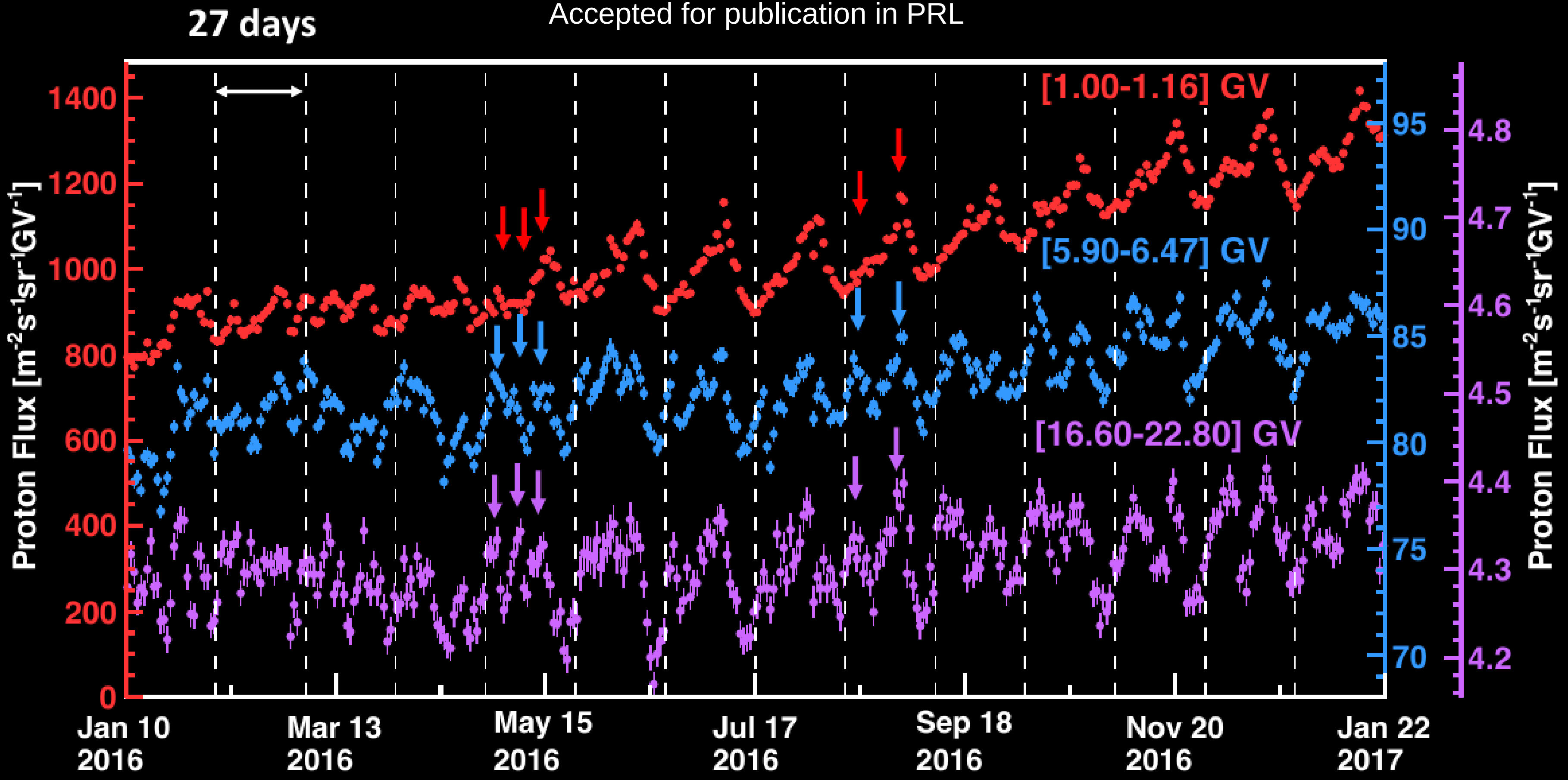


Richardson, Space Science Reviews volume 111, pages 267–376 (2004)

Recurrent Flux Variations Daily Proton Fluxes

Recurrent Flux Variation with Periods of 9, 13.5, and 27 days in 2016

Accepted for publication in PRL



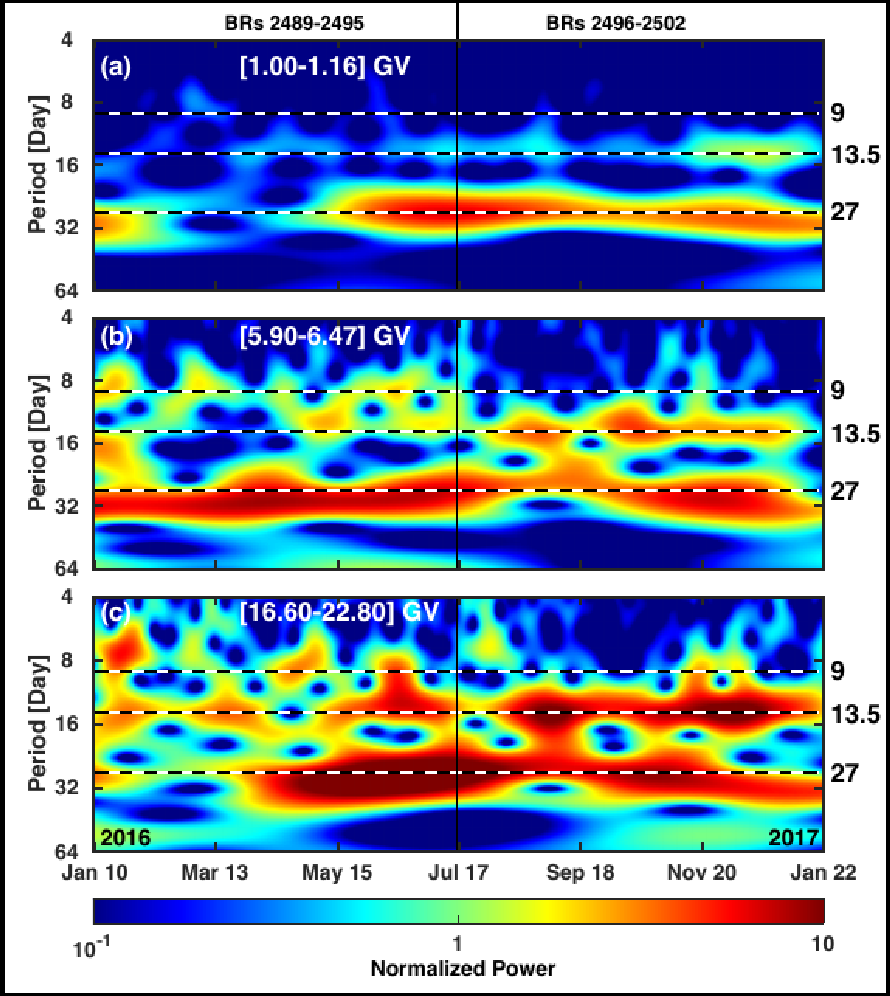
Daily Proton Fluxes: Wavelet Analysis

Wavelet Analysis of Proton Fluxes in 2016

Power is normalized by the variance of flux in the corresponding time interval to show the strength of the periodicities.

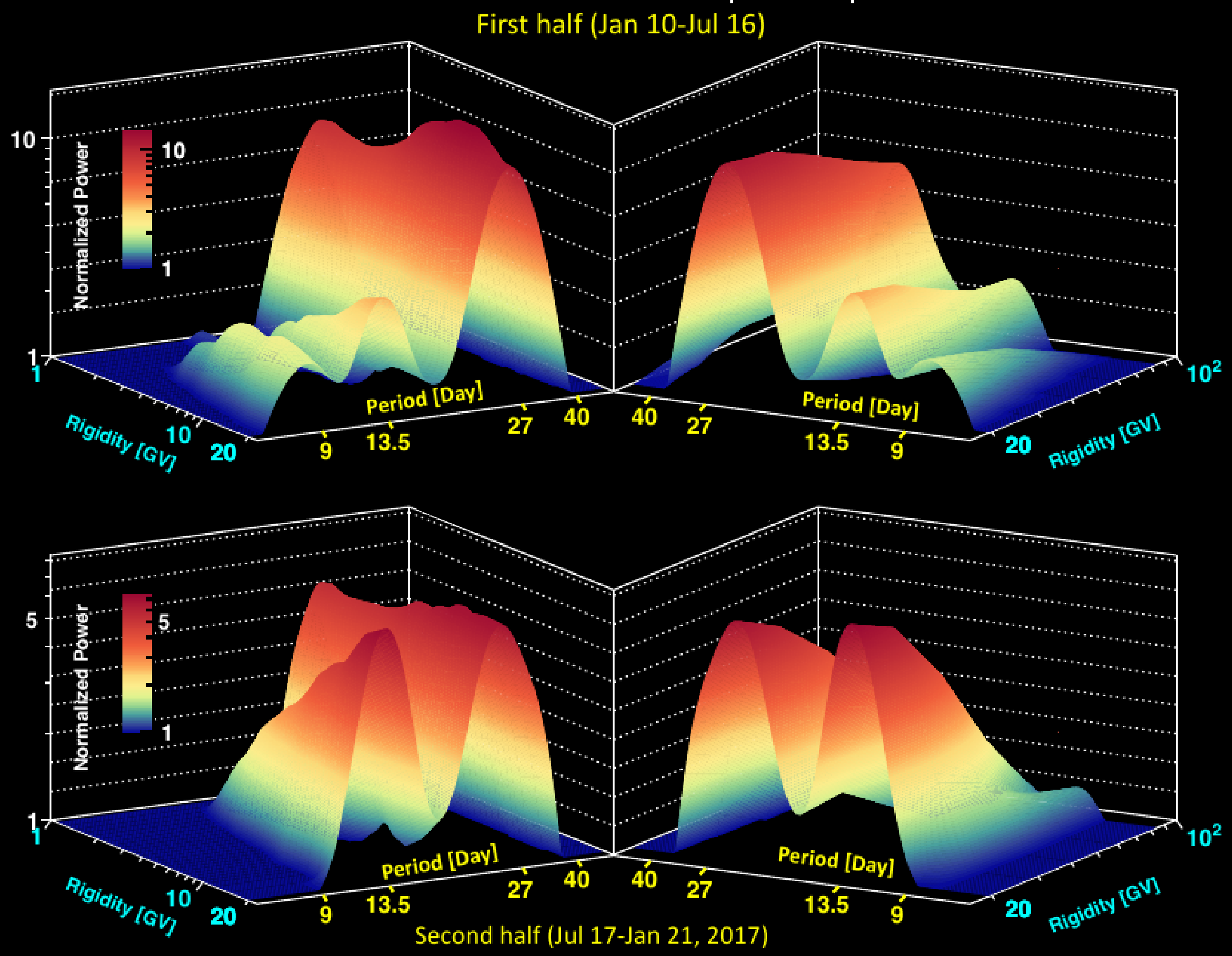
Periods of 9, 13.5, and 27 days are observed in 2016. The strength of all three periodicities change with time and rigidity. In particular, shorter periods of 9 and 13.5 days, when present, are more visible at 6~GV and 20~GV compared to 1 GV.

Accepted for publication in PRL



Daily Proton Fluxes: Normalized Power

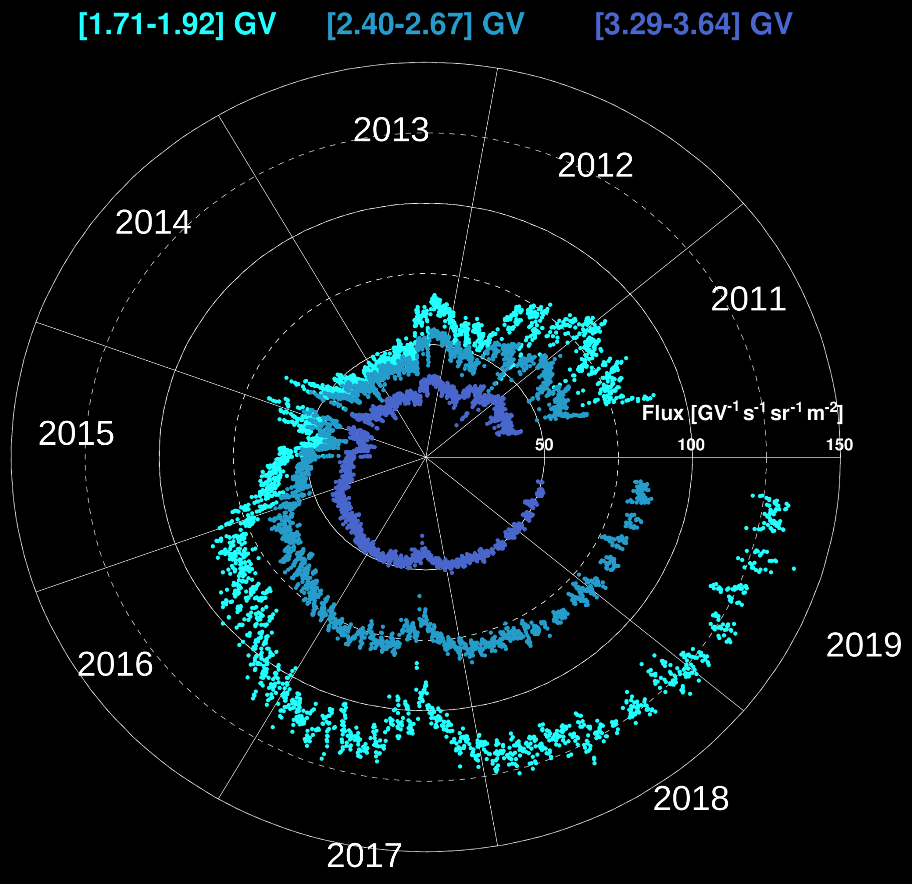
Accepted for publication in PRL

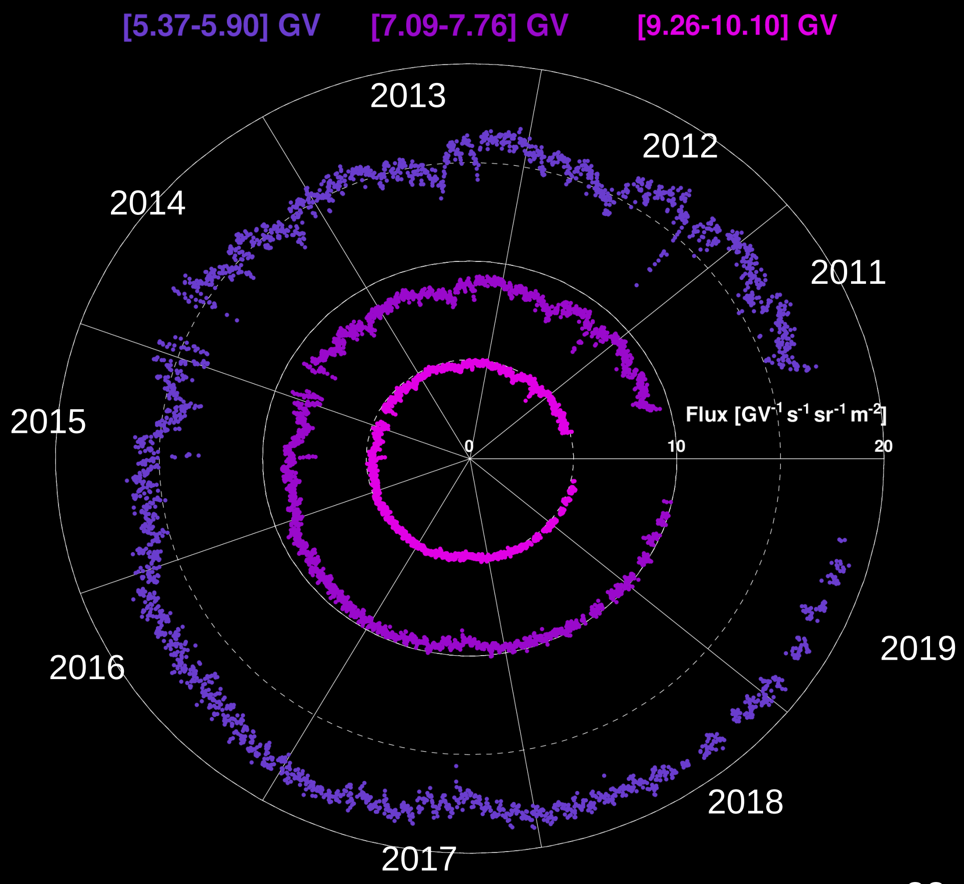


The strength of all three periodicities is rigidity dependent.

In particular, the strength of **9-day and 13.5-day periodicities** increases with increasing rigidity up to **~10 GV and ~20 GV** respectively, and then decreases with increasing rigidity up to **100 GV.**

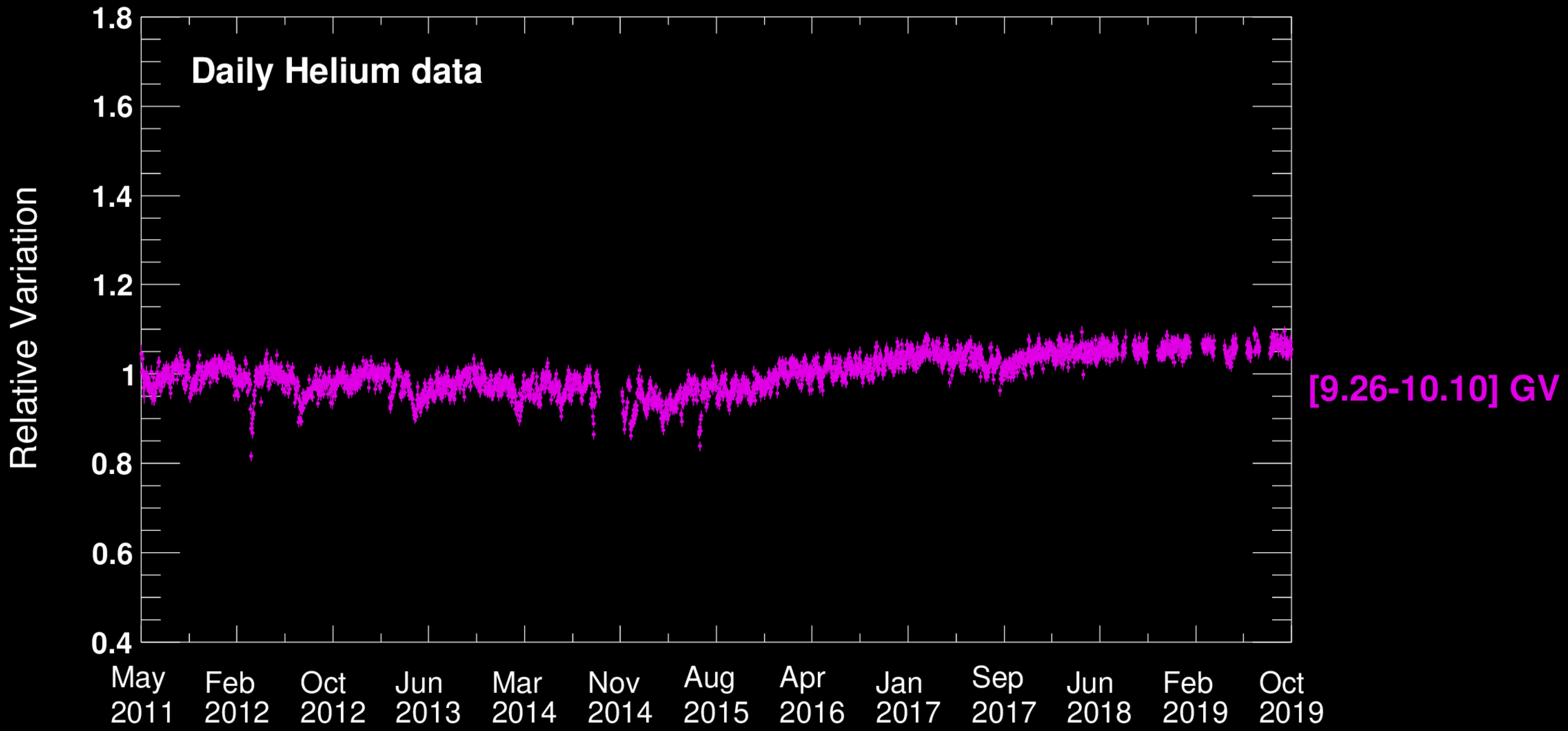
Daily Helium Fluxes: May 20, 2011 - Oct 29, 2019





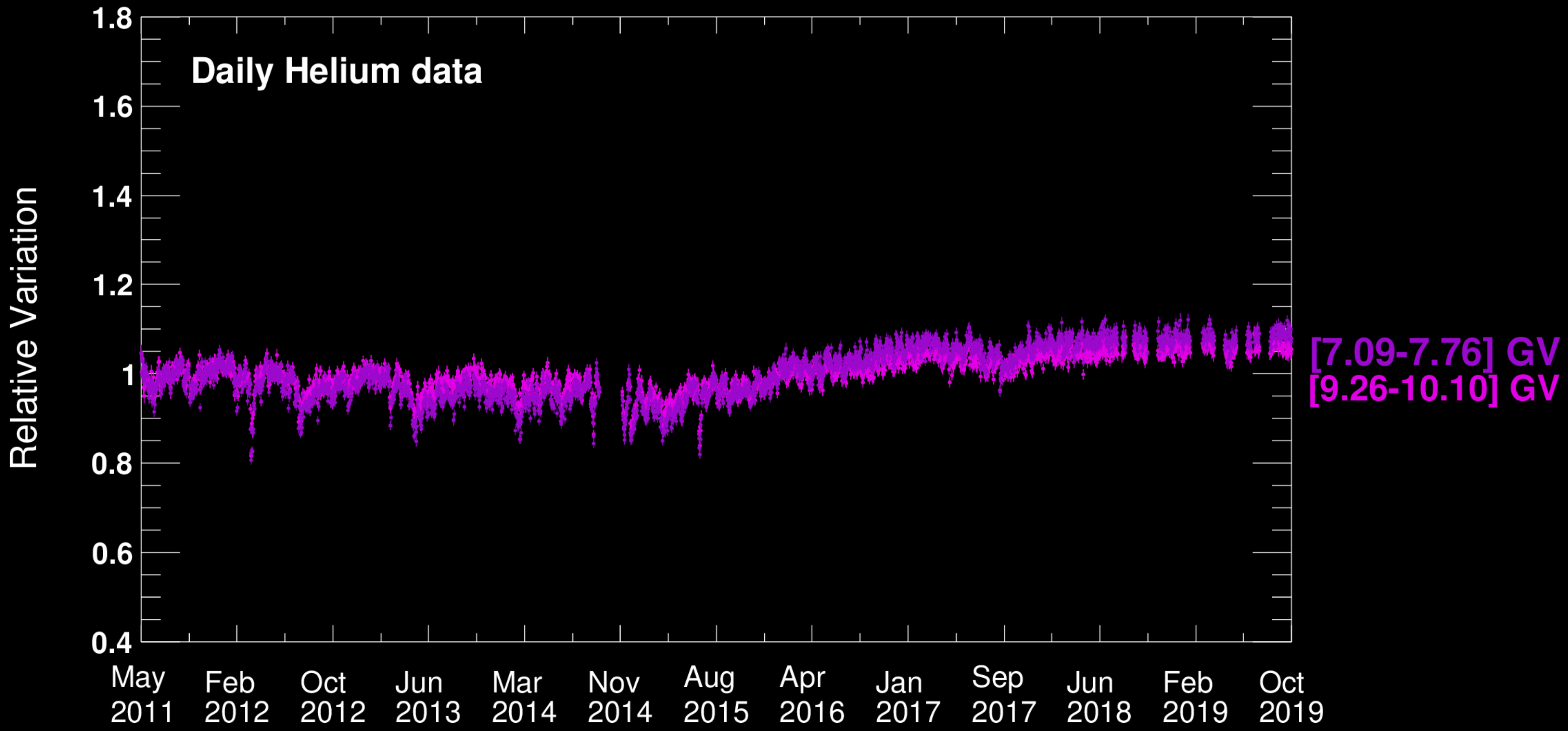
Preliminary data, refer to upcoming AMS publication

Daily Helium Fluxes Relative Variation



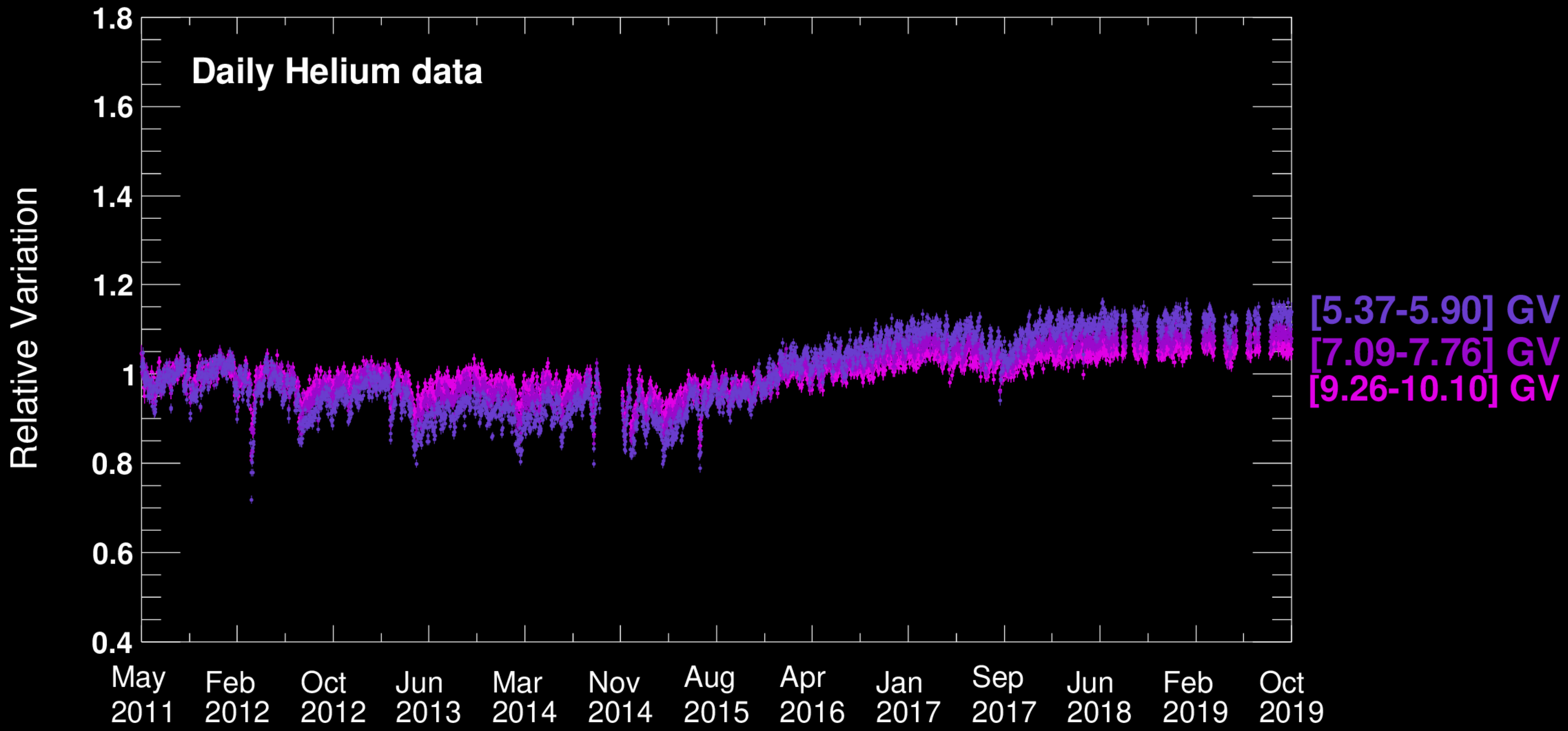
Preliminary data, refer to upcoming AMS publication

Daily Helium Fluxes Relative Variation



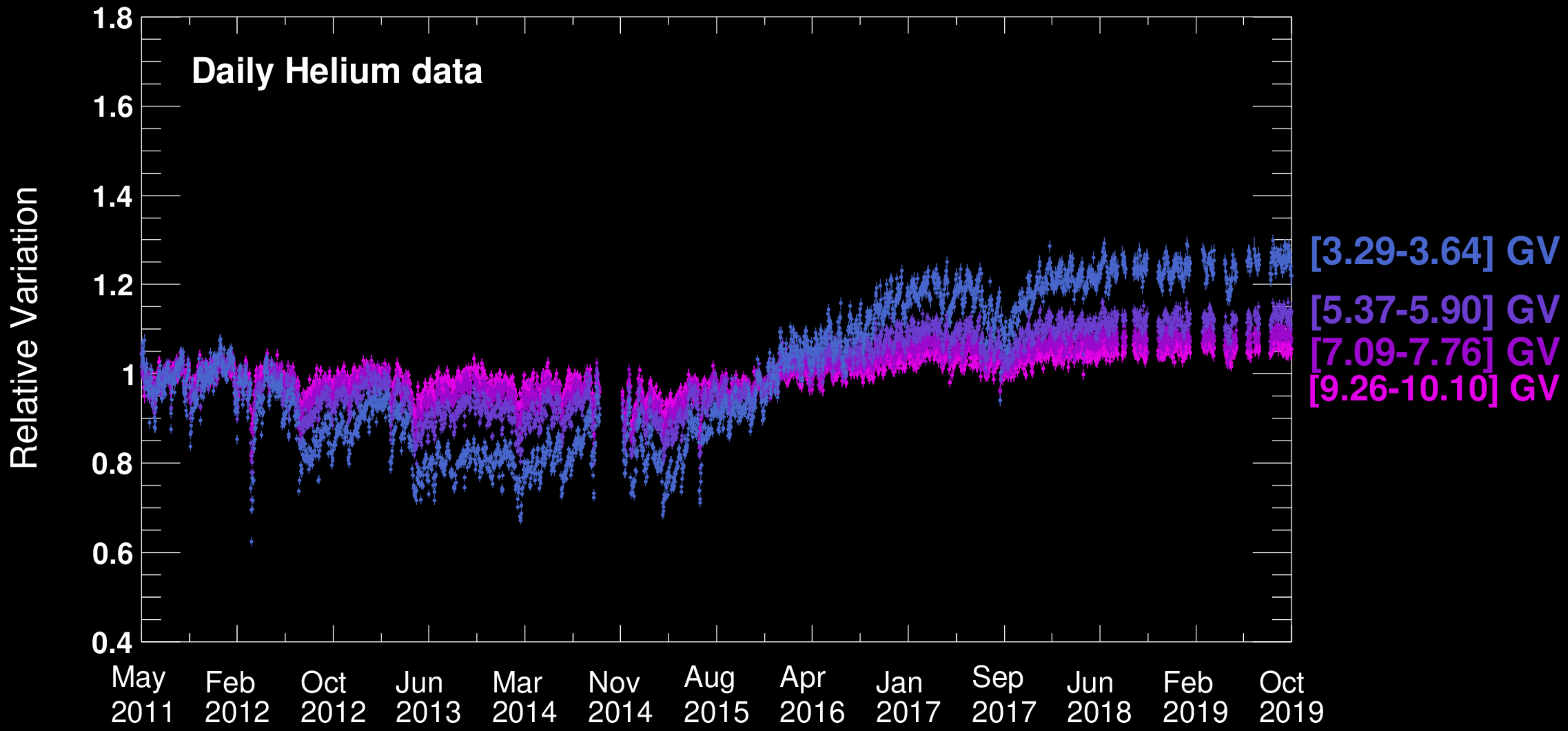
Preliminary data, refer to upcoming AMS publication

Daily Helium Fluxes Relative Variation



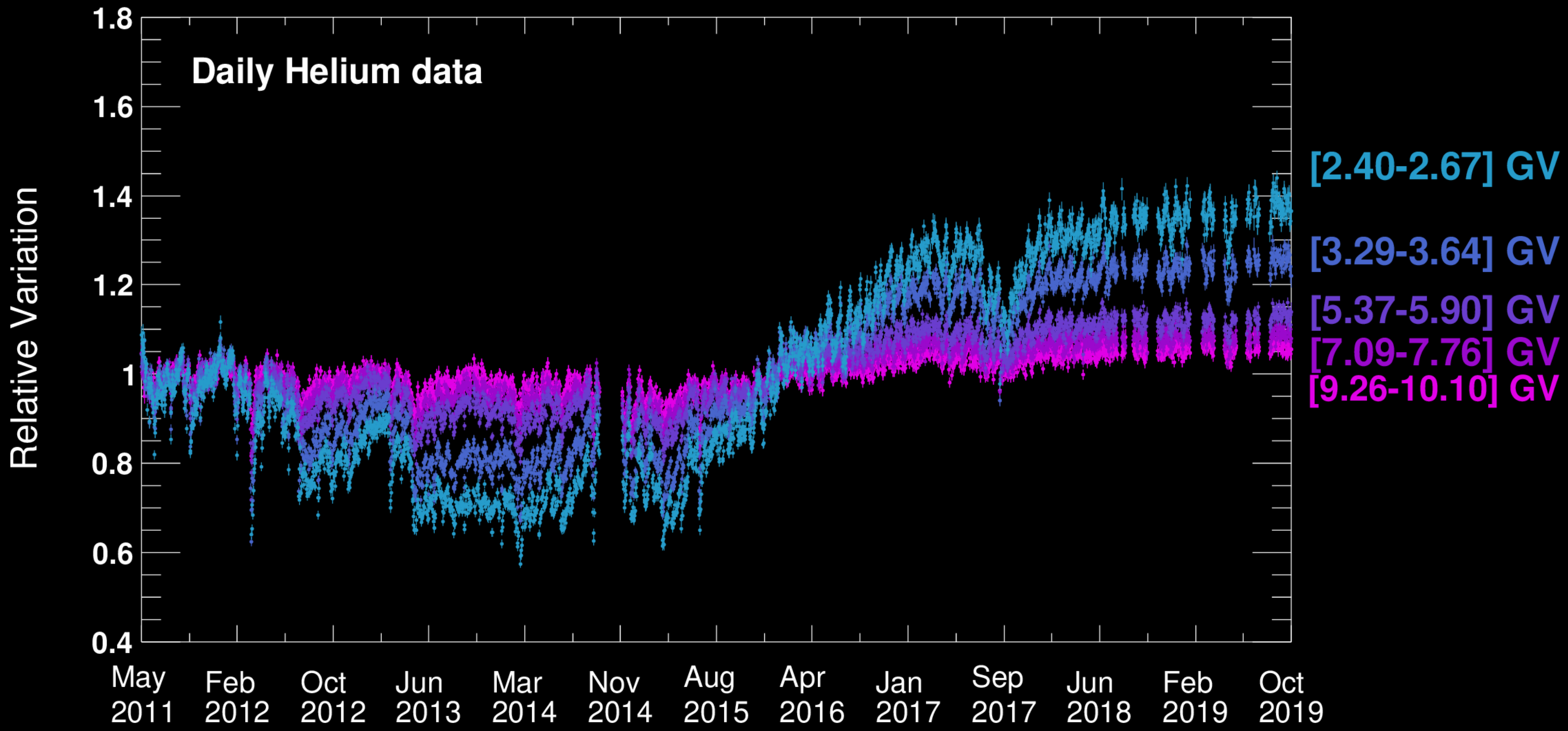
Preliminary data, refer to upcoming AMS publication

Daily Helium Fluxes Relative Variation



Preliminary data, refer to upcoming AMS publication

Daily Helium Fluxes Relative Variation



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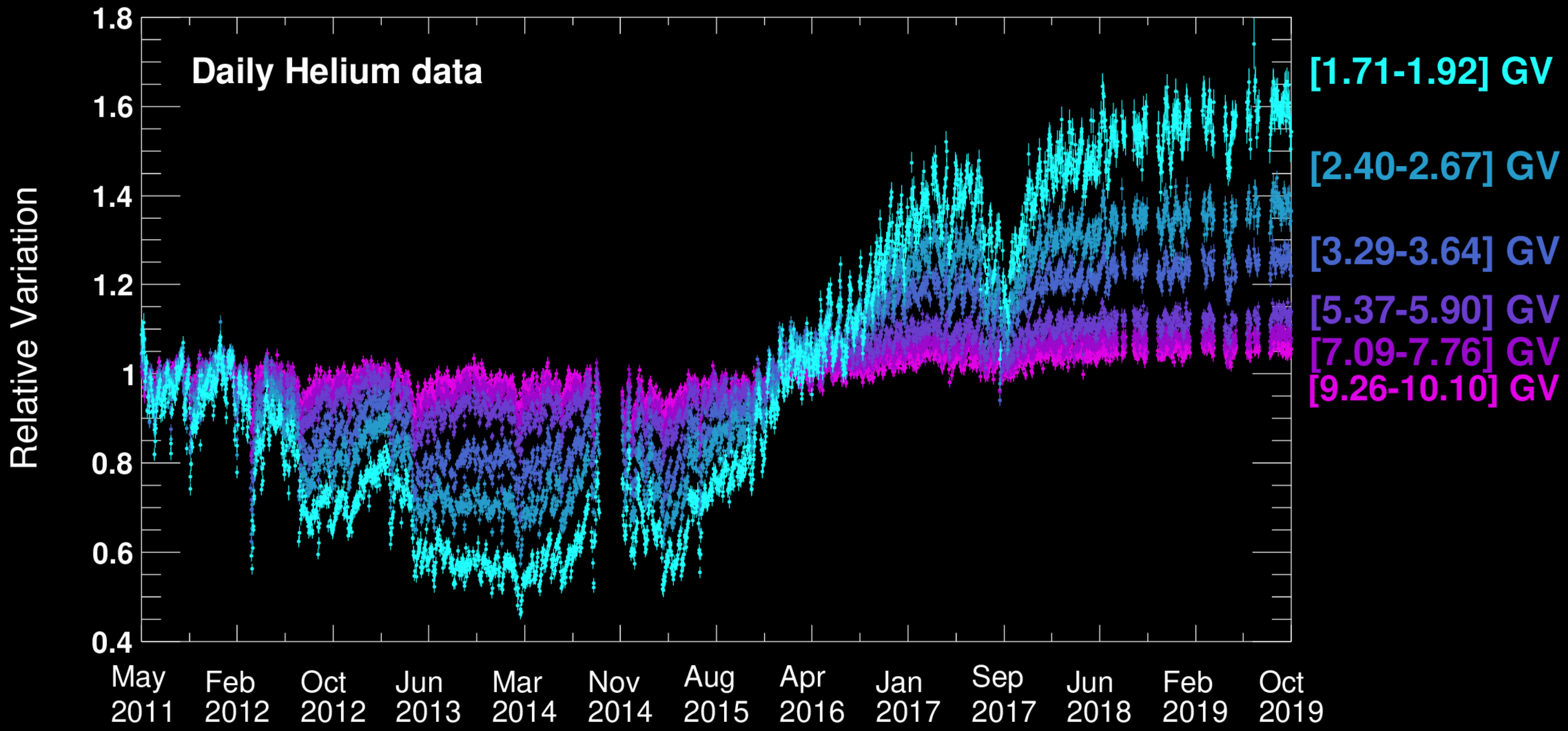
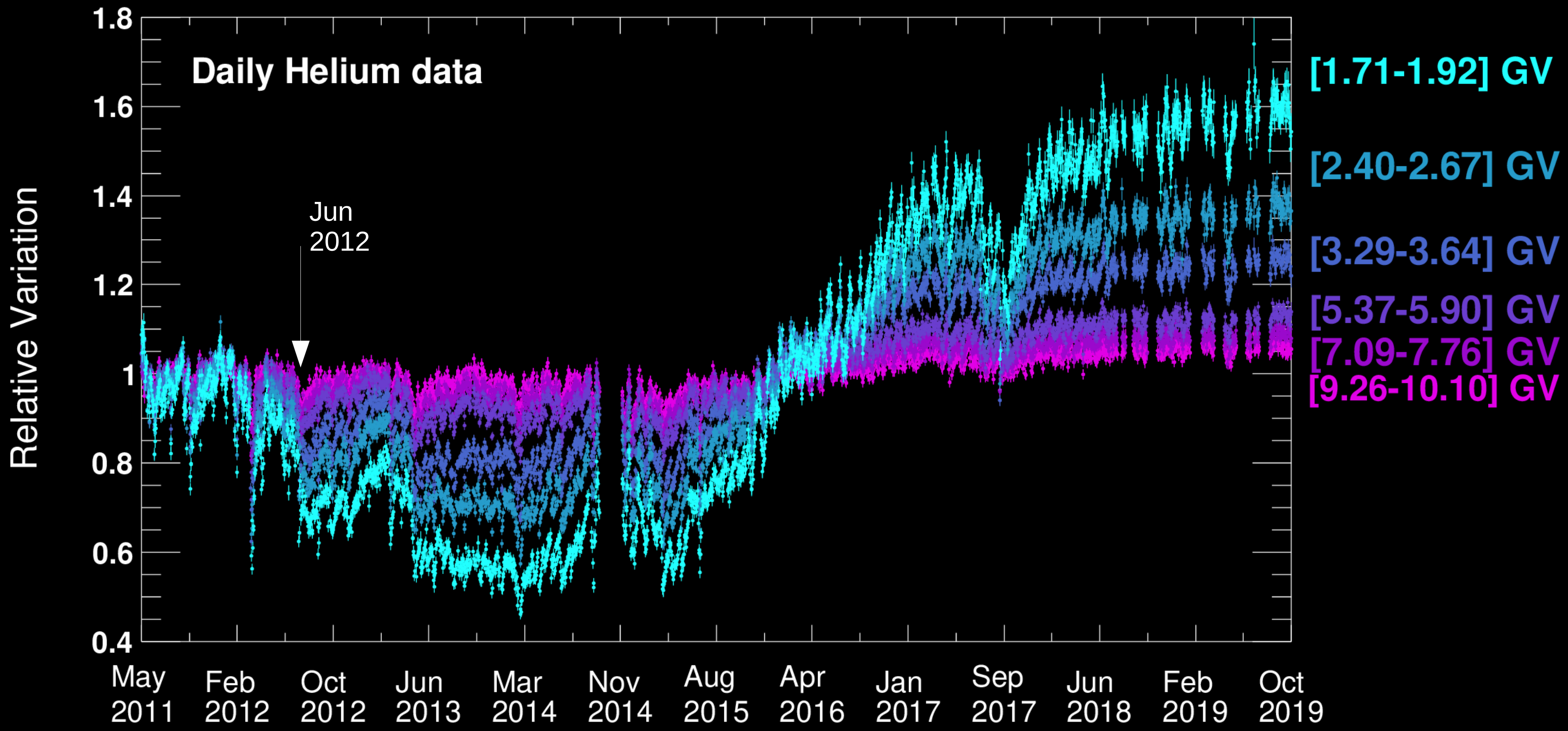
Daily Helium Fluxes Relative Variation



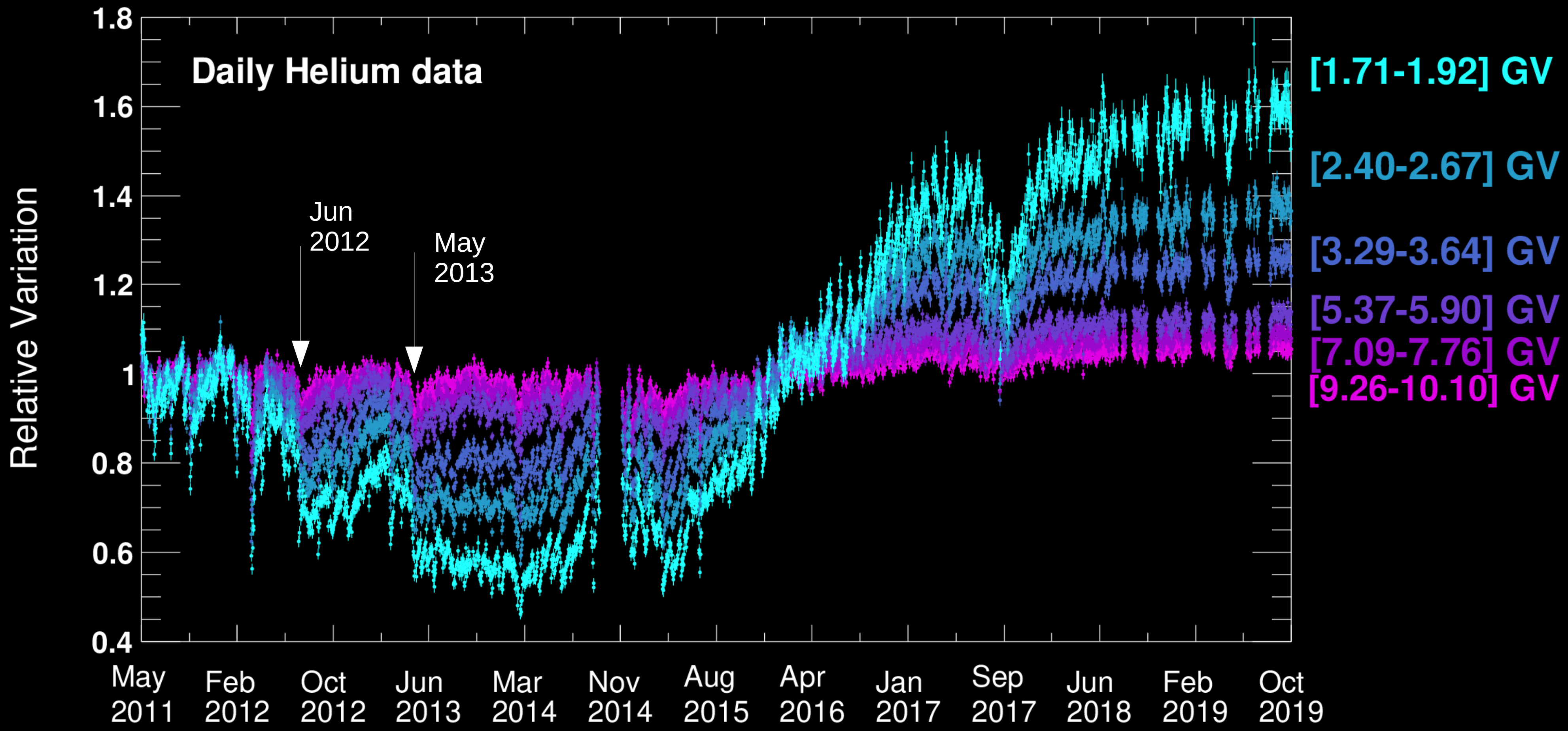
Preliminary data, refer to upcoming AMS publication

Daily Helium Fluxes Relative Variation



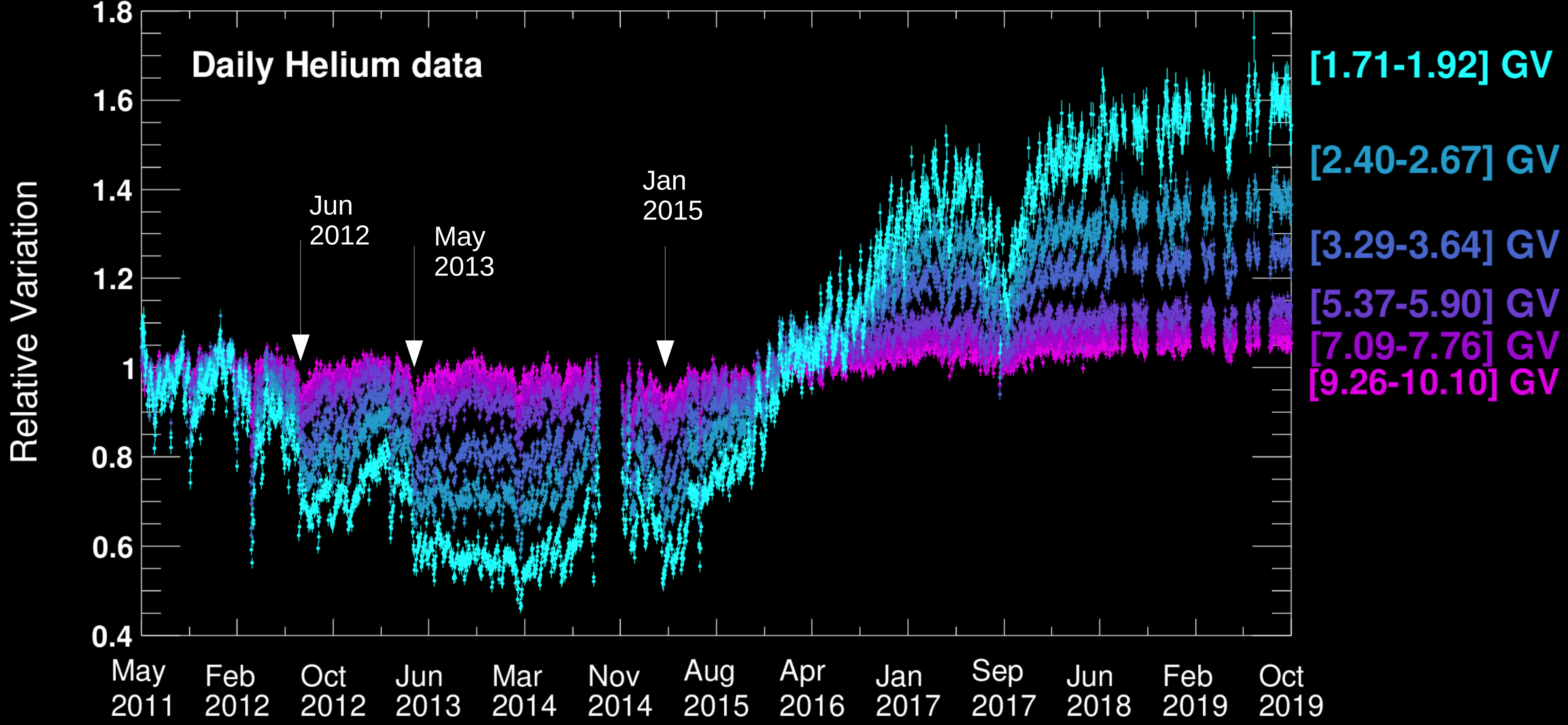
Preliminary data, refer to upcoming AMS publication

Daily Helium Fluxes Relative Variation



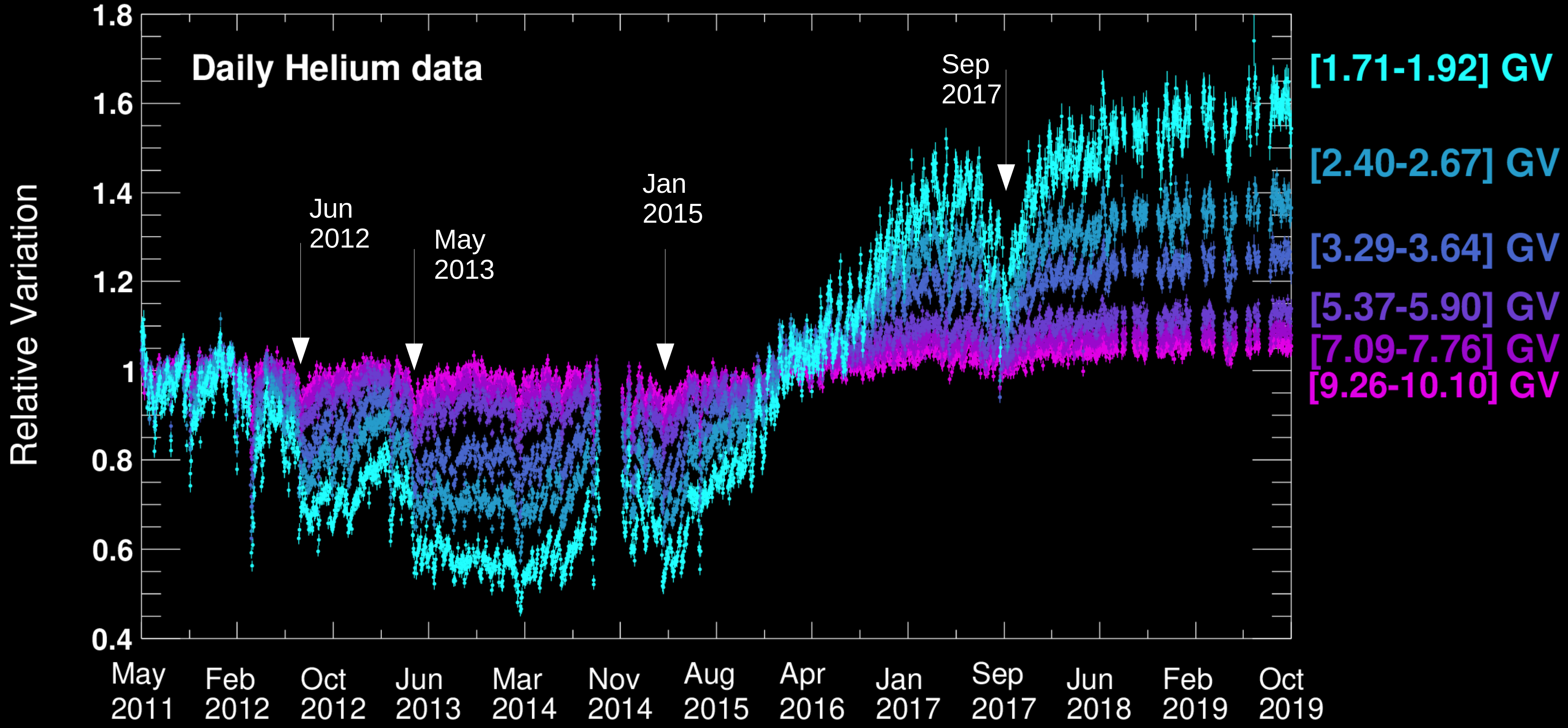
Preliminary data, refer to upcoming AMS publication

Daily Helium Fluxes Relative Variation



Preliminary data, refer to upcoming AMS publication

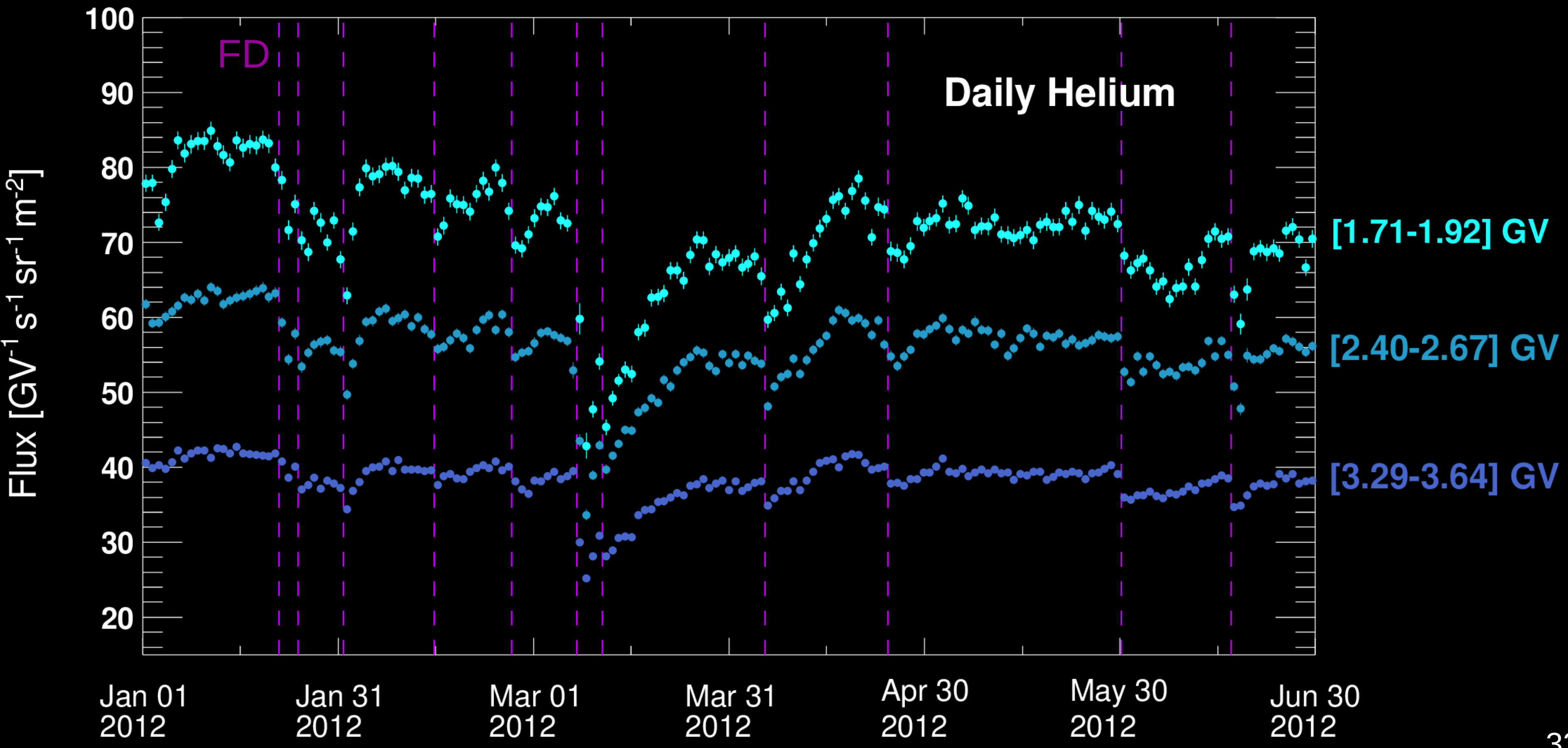
Daily Helium Fluxes Relative Variation



Preliminary data, refer to upcoming AMS publication

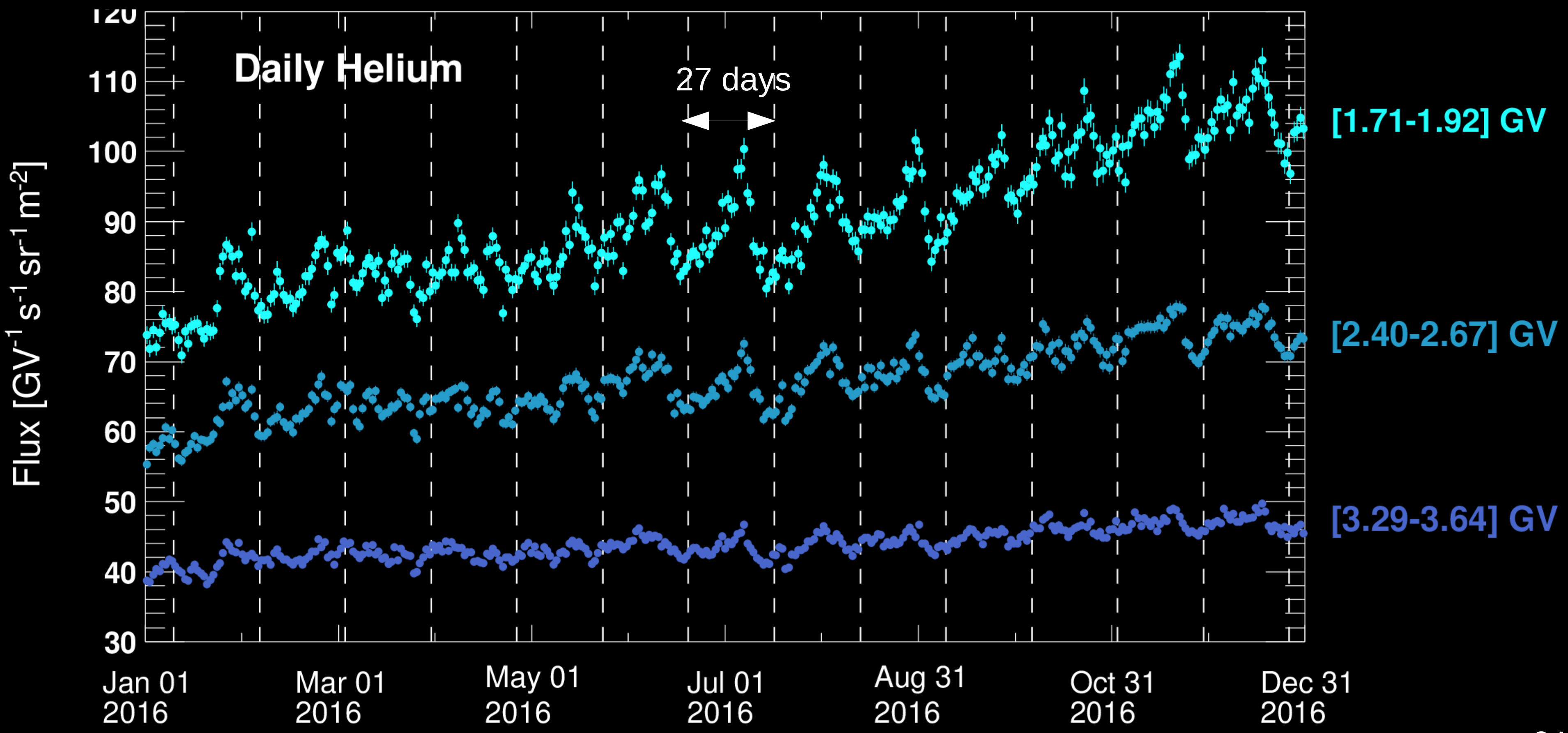
Helium Forbush Decreases

Over 100 Forbush decrease events were observed.



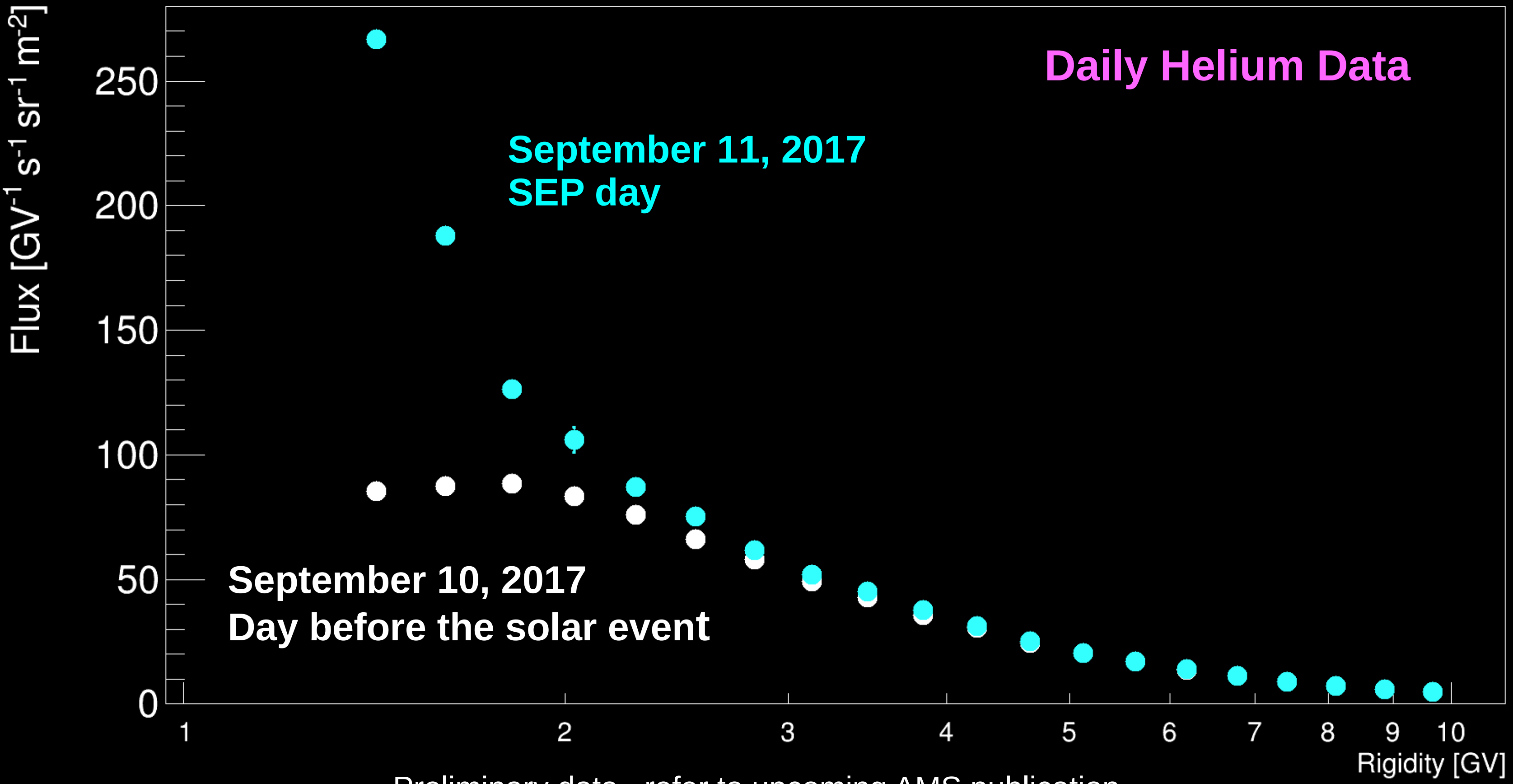
Preliminary data, refer to upcoming AMS publication

Daily Helium Periodicities



Preliminary data, refer to upcoming AMS publication

Helium Solar Energetic Particles
Sep 11, 2017



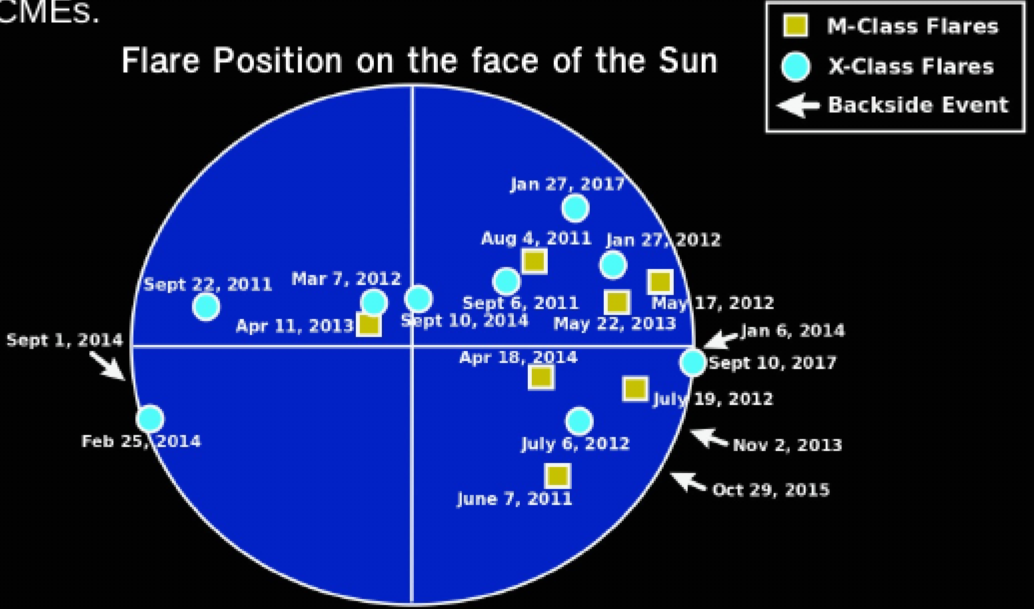
Preliminary data, refer to upcoming AMS publication

AMS Proton SEP List

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
28		2017/9/11	X8.2	2868

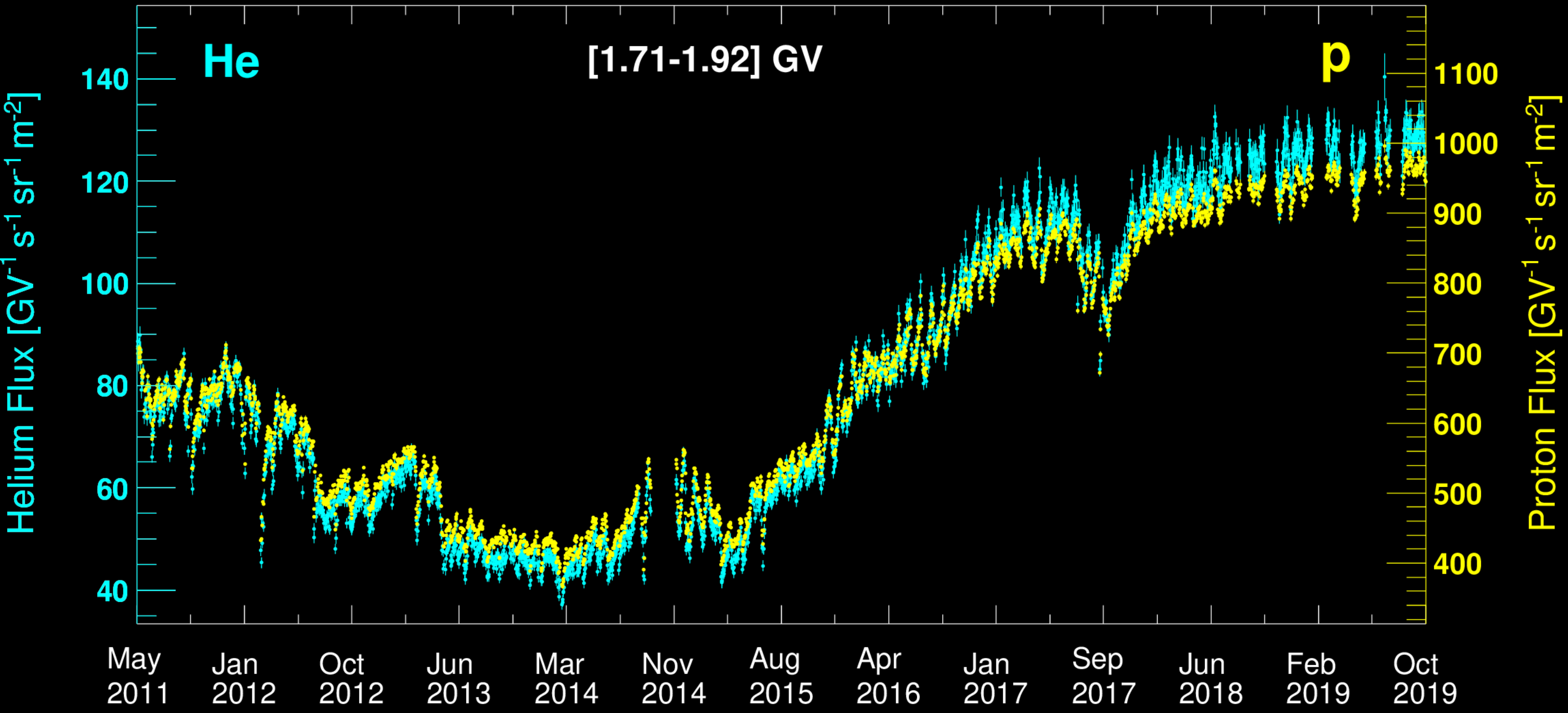
Solar Energetic Particle Events Observed by AMS

SEP events detected by AMS are a subset of events with a very hard spectrum, they are typically associated with M- and X-class flares and fast CMEs.



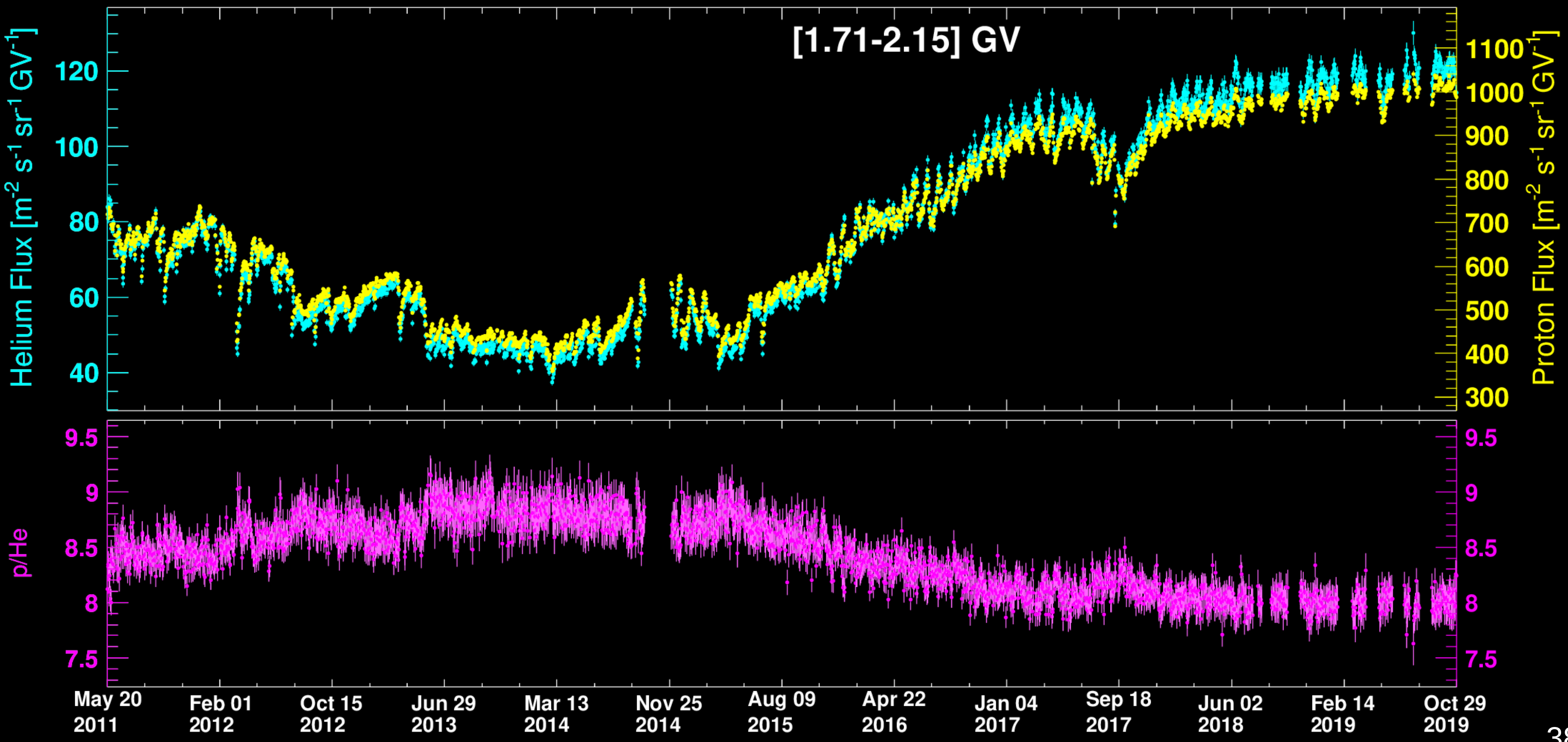
Flare class taken from the hinode catalogue:
https://hinode.isee.nagoya-u.ac.jp/flare_catalogue/
CME speed taken from the CDAW CME catalogue:
https://cdaw.gsfc.nasa.gov/CME_list/

Daily Helium and Proton Flux Comparison



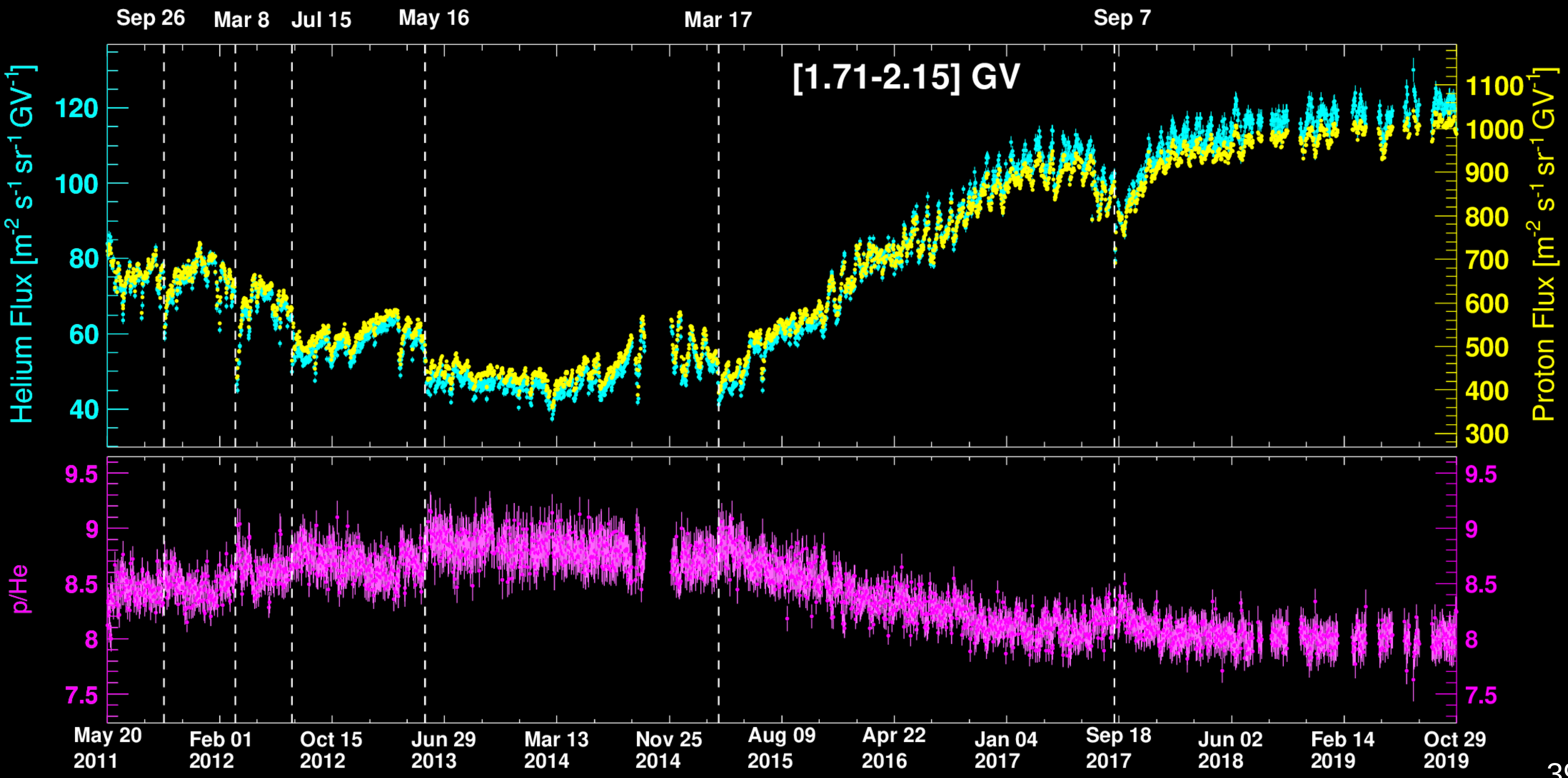
Preliminary data, refer to upcoming AMS publication

Daily p/He Flux Ratio



Preliminary data, refer to upcoming AMS publication

Daily p/He Flux Ratio



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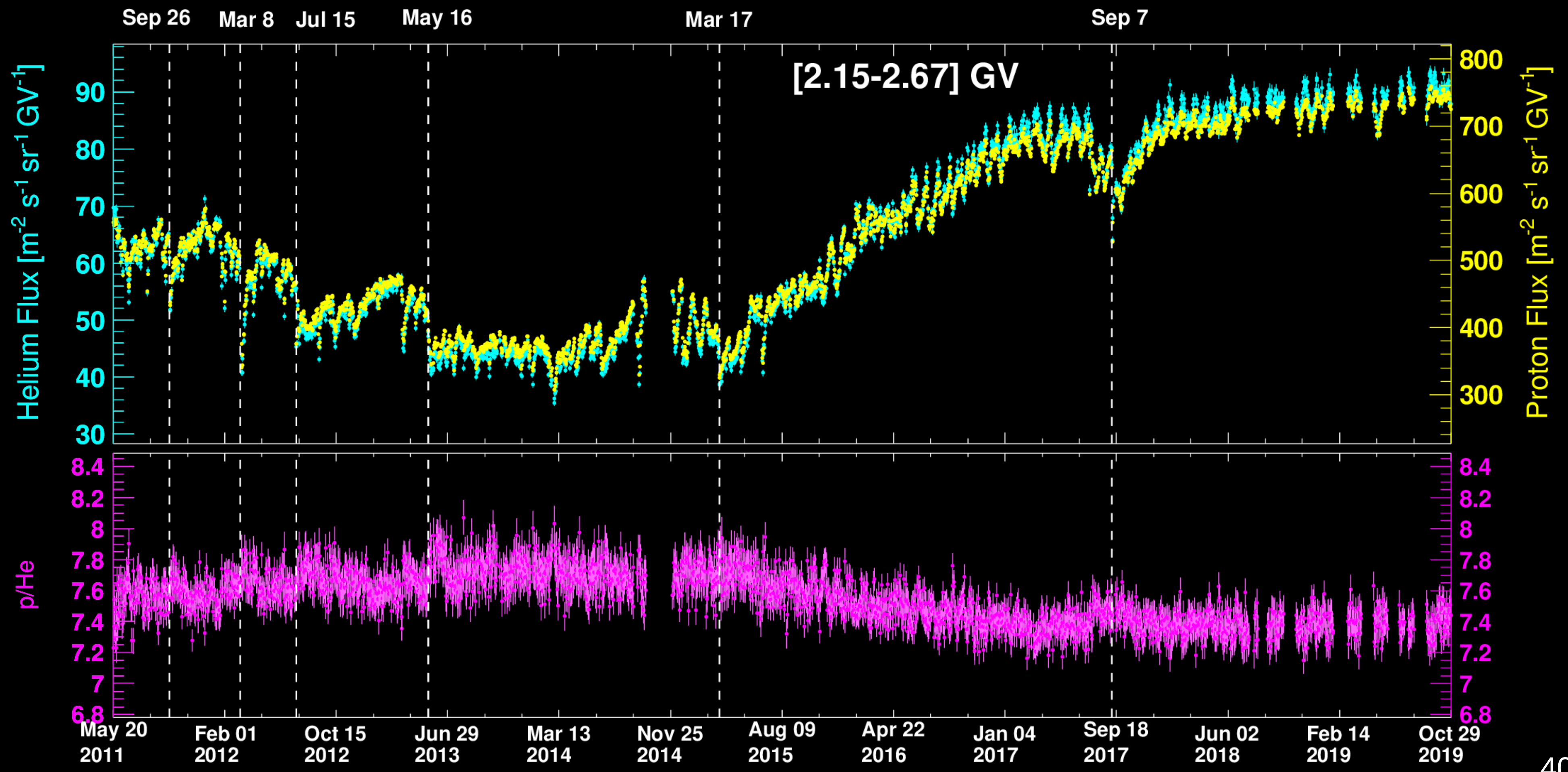
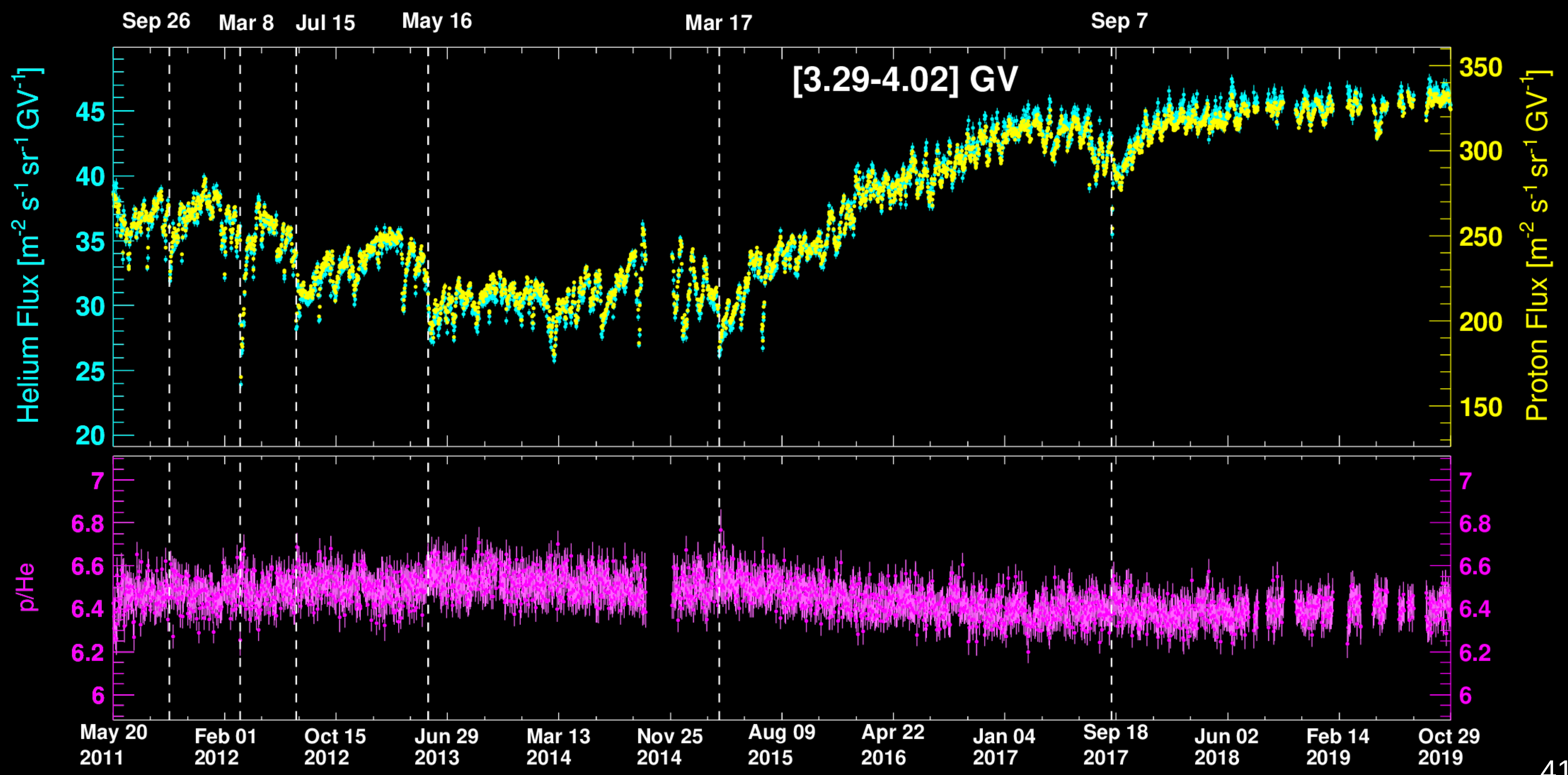
Daily p/He Flux Ratio



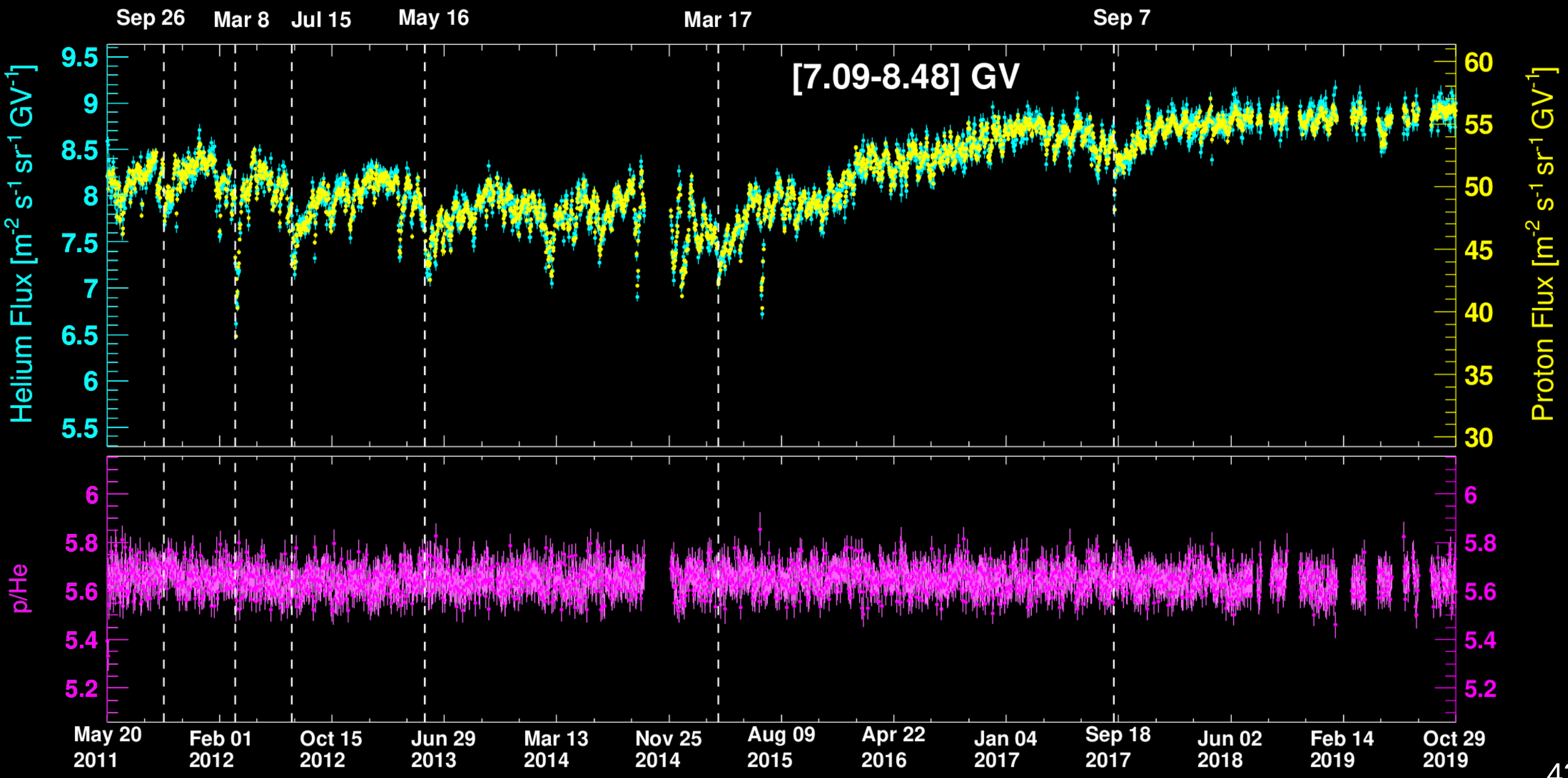
Preliminary data, refer to upcoming AMS publication

Daily p/He Flux Ratio



Preliminary data, refer to upcoming AMS publication

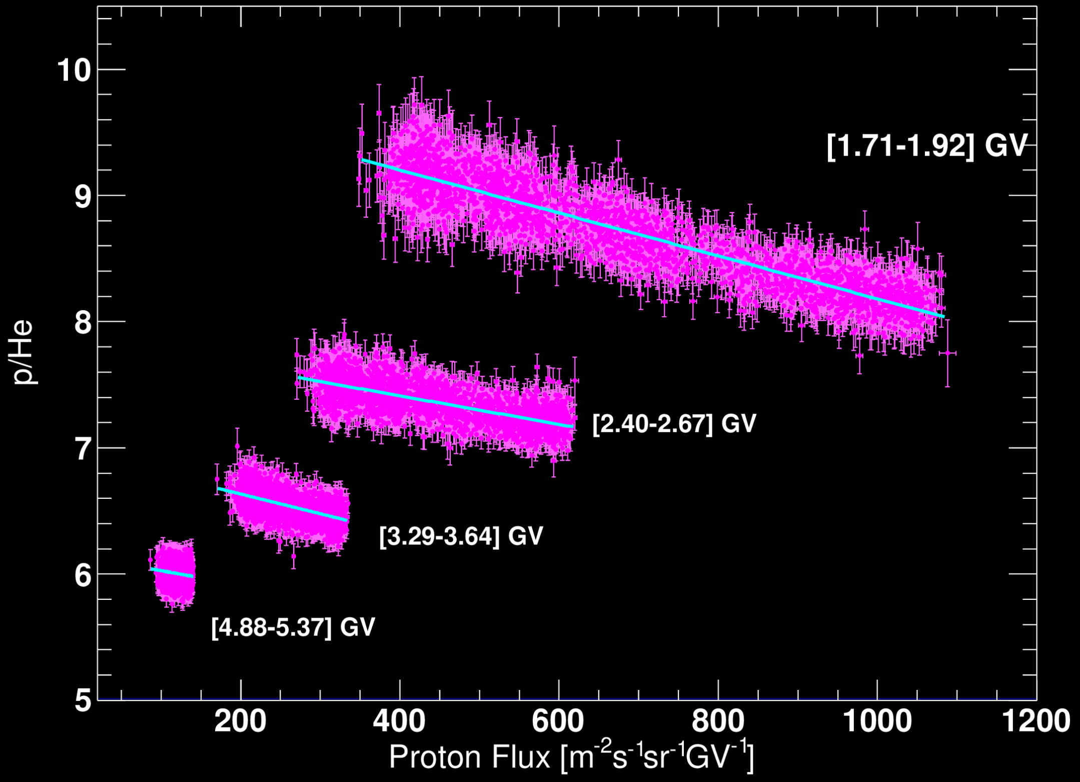
Daily p/He Flux Ratio

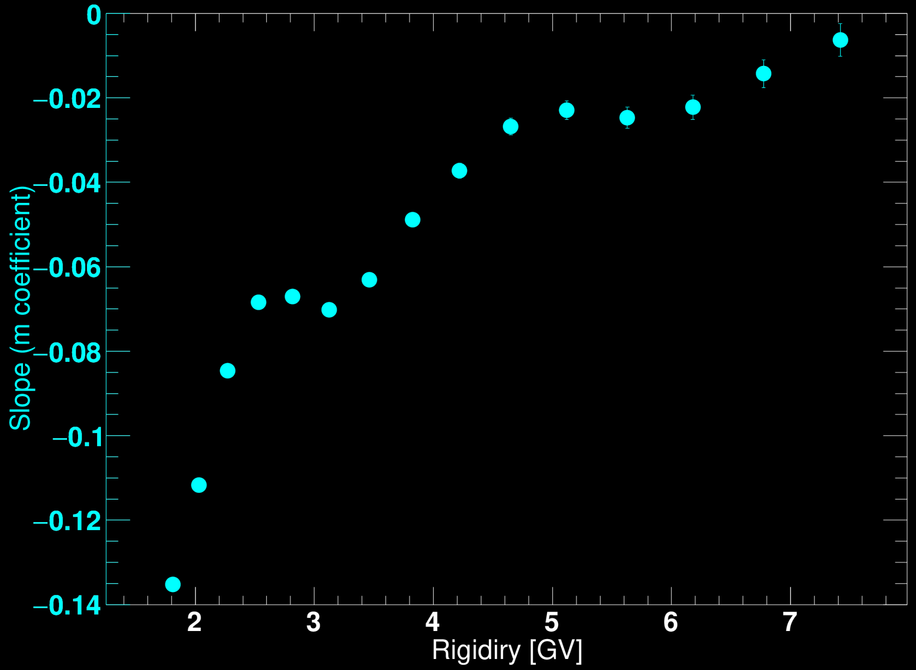


Preliminary data, refer to upcoming AMS publication

Daily p/He Flux Ratio
Anti-correlation with the Absolute Flux

$$\frac{p/He}{\langle p/He \rangle} - 1 = m\left(\frac{p}{\langle p \rangle} - 1\right)$$





Preliminary data, refer to upcoming AMS publication

Propagation of GCR in Heliosphere - Parker Equation

$$\frac{\partial f}{\partial t} = \underbrace{-\vec{V}_{SW}\cdot\vec{\nabla} f}_{\text{Solar wind convection}} \underbrace{-\vec{V}_{D}\cdot\vec{\nabla} f}_{\text{Particle drifts}} + \underbrace{\vec{\nabla}\cdot(K\cdot\vec{\nabla} f)}_{\text{Particle diffusion}} + \underbrace{\frac{1}{3}\vec{\nabla}\cdot\vec{V}_{SW}\frac{\partial f}{\partial \ln R}}_{\text{Adiabatic energy changes}}$$

- Particle drifts due to heliospheric magnetic field gradients, curvatures and heliospheric current sheet.
- K = diffusion tensor, due to scattering on magnetic irregularities
- Adiabatic energy losses/gains due to expansion/compression of solar wind, proportional to spectral index.

Hypotheses for p/He time dependent behavior

$$\frac{\partial f}{\partial t} = \underbrace{-\vec{V}_{SW}\cdot\vec{\nabla} f}_{\text{Solar wind convection}} \underbrace{-\vec{V}_{D}\cdot\vec{\nabla} f}_{\text{Particle drifts}} + \underbrace{\vec{\nabla}\cdot(K\cdot\vec{\nabla} f)}_{\text{Particle diffusion}} + \underbrace{\frac{1}{3}\vec{\nabla}\cdot\vec{V}_{SW}\frac{\partial f}{\partial \ln R}}_{\text{Adiabatic energy changes}}$$

1) Velocity dependence of the diffusion coefficient: $k(r,R) = \beta k_1(r) k_2(R)$
Even if k_2 is the same for all nuclei, the beta multiplying it will change the divergence of the diffusive flux term in the Parker equation for nuclei with different A/Z.
A/Z(p) = 1; A/Z(^{3}He) = 3/2; A/Z(^{4}He) = 2

2) Difference in the LIS shape: the adiabatic energy change term in the Parker equation depends on the spectral index, so if two nuclei have the same A/Z, but different spectral index, the last term will be different.

Hypotheses for p/He time dependent behavior

$$\frac{\partial f}{\partial t} = \underbrace{-\vec{V}_{SW}\cdot\vec{\nabla} f}_{\text{Solar wind convection}} \underbrace{-\vec{V}_{D}\cdot\vec{\nabla} f}_{\text{Particle drifts}} + \underbrace{\vec{\nabla}\cdot(K\cdot\vec{\nabla} f)}_{\text{Particle diffusion}} + \underbrace{\frac{1}{3}\vec{\nabla}\cdot\vec{V}_{SW}\frac{\partial f}{\partial \ln R}}_{\text{Adiabatic energy changes}}$$

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N. Tomassetti et al., PRL, 121, 251104 (2018)
C. Corti et al. The Astrophysical Journal, 871:253 (2019)

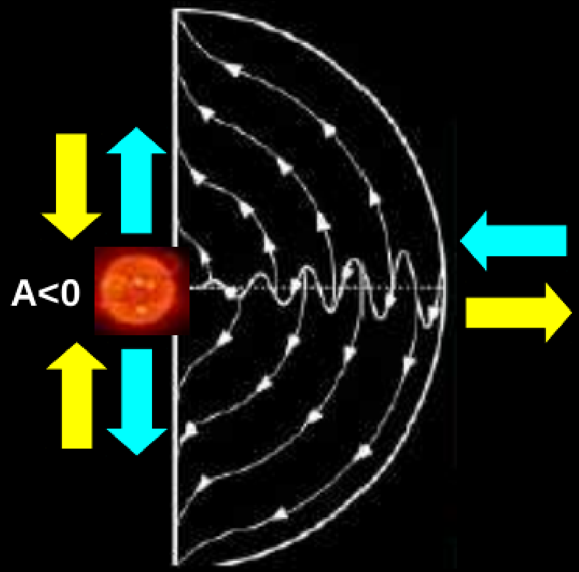
Propagation of GCR in Heliosphere - Parker Equation

$$\frac{\partial f}{\partial t} = \underbrace{-\vec{V}_{SW}\cdot\vec{\nabla} f}_{\text{Solar wind convection}} \underbrace{-\vec{V}_{D}\cdot\vec{\nabla} f}_{\text{Particle drifts}} + \underbrace{\vec{\nabla}\cdot(K\cdot\vec{\nabla} f)}_{\text{Particle diffusion}} + \underbrace{\frac{1}{3}\vec{\nabla}\cdot\vec{V}_{SW}\frac{\partial f}{\partial \ln R}}_{\text{Adiabatic energy changes}}$$

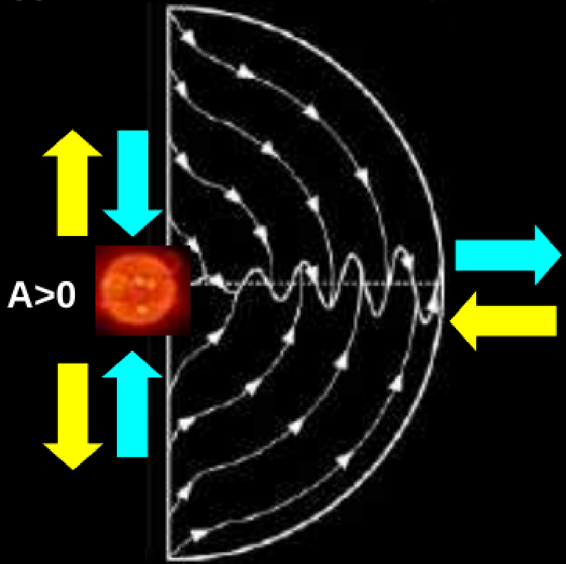
- Particle drifts due to heliospheric magnetic field gradients, curvatures and heliospheric current sheet.

Drift Effect of Opposite Charged Particles

During negative epochs (A<0) positive charged particles mainly drift in the heliosphere from the equator and drift out trough the poles. The opposite is true for negative charged particles.



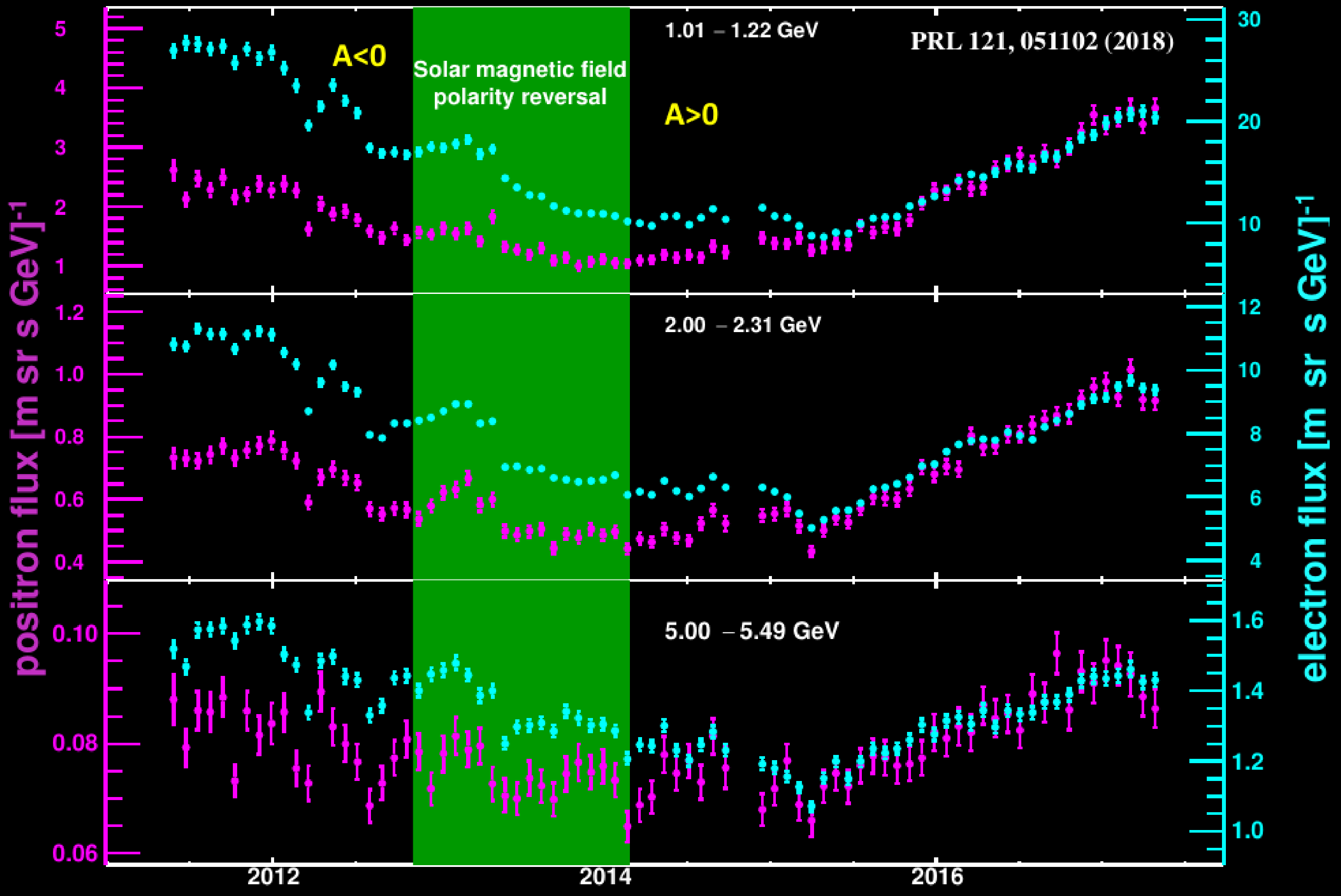
During positive epochs (A>0) positive charged particles mainly drift in the heliosphere from the poles and drift out trough the equator. The opposite is true for negative charged particles.



A<0 positive particles are more modulated than negative particles

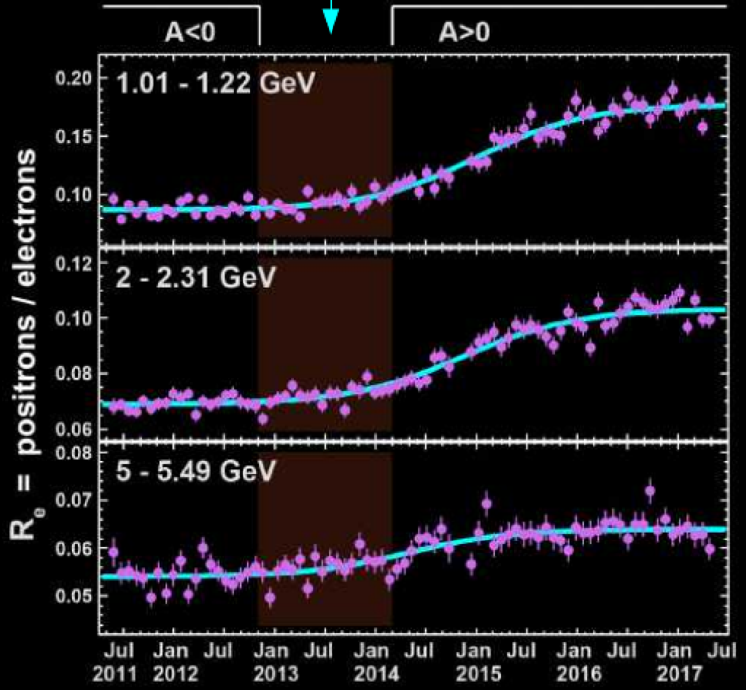
A>0 positive particles are less modulated than negative particles

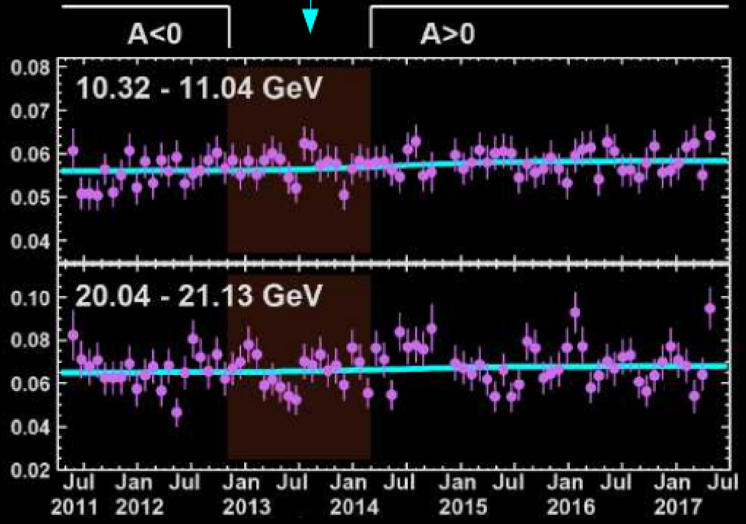
Electron and Positron Monthly Flux (May2011-May 2017)



AMS Positron/Electron Flux Ratio (May2011-May 2017)

Polarity reversal of solar magnetic filed
Nov 2012 - Mar 2014





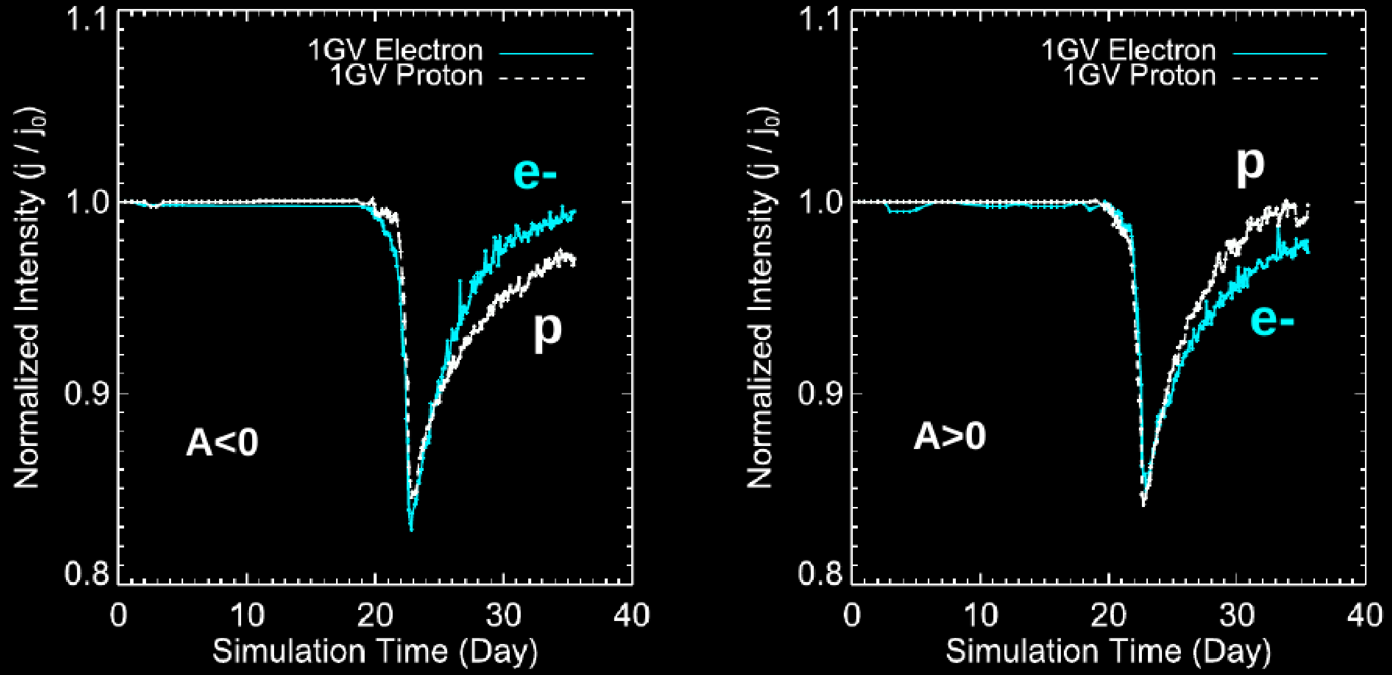
Fit performed with a logistic function

$$R_e(t,E) = R_0(E)\left[1 + \frac{C(E)}{\exp\left(-\frac{t-t_{1/2}(E)}{\Delta t(E)/\Delta_{80}}\right)+1}\right].$$

PRL 121, 051102 (2018)

Charge Sign Effects during Forbush Decreases

Xi Luo's (2018) numerical study of electron and proton Forbush decreases with time-dependent, 3D stochastic differential equation model , shows that if drift effects are important in the local environment at 1AU then **during an A<0 epoch, the FD recovery time of 1 GV electrons is expected to be faster than 1 GV protons. The opposite is expected for A>0 epoch.**

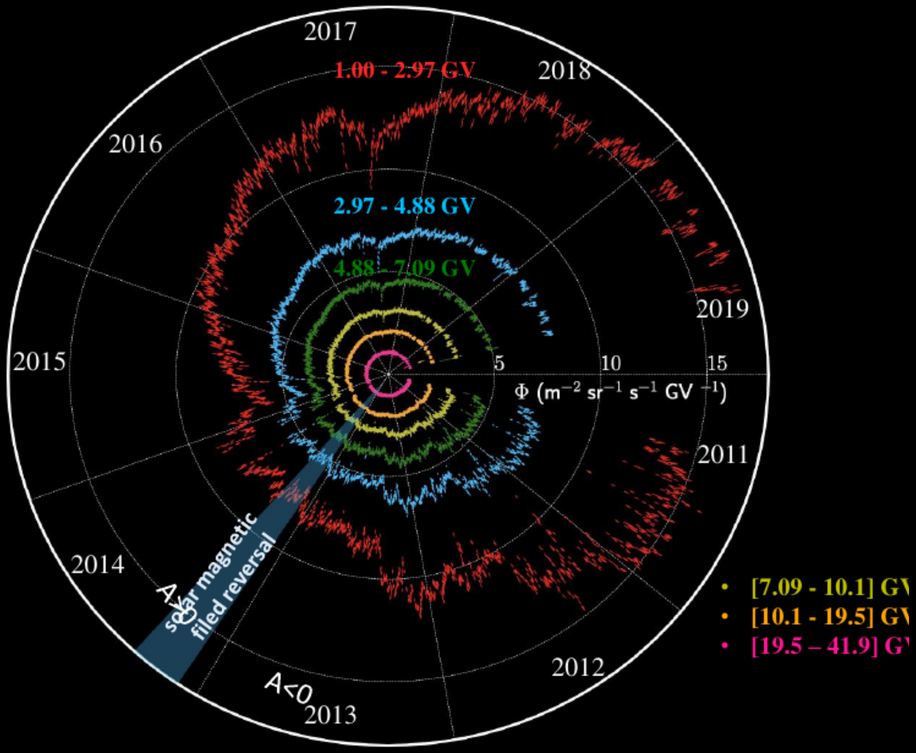


Xi Luo et al. (2018)
The Astrophysical Journal, 860:160 (9pp),

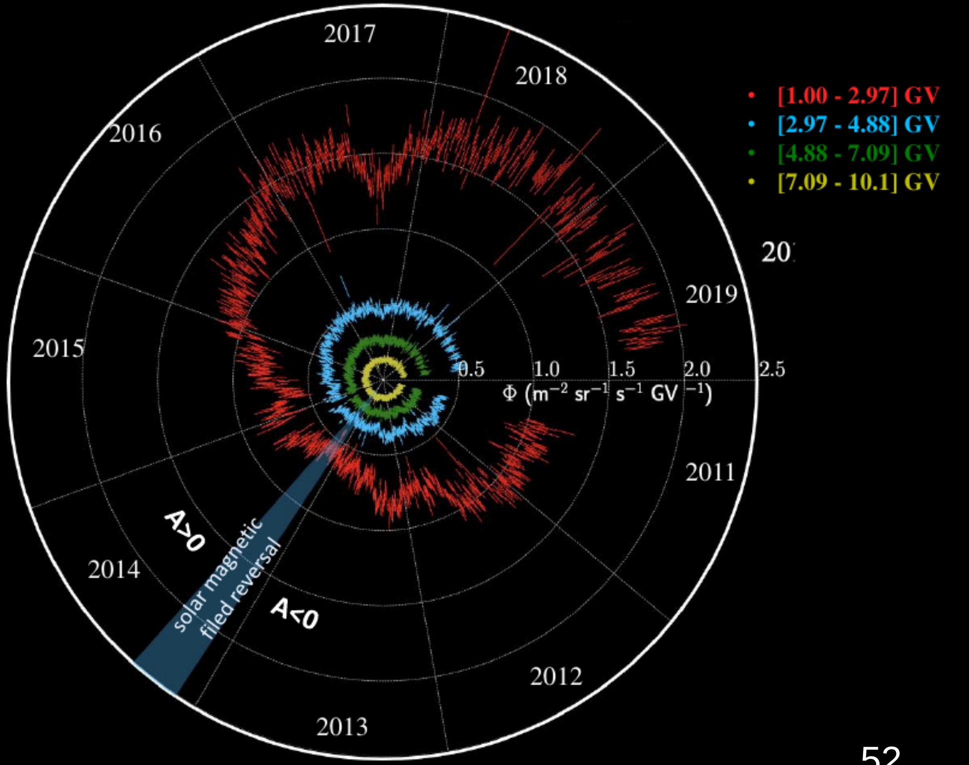
AMS Daily Electron & Positron Fluxes

Preliminary data, refer to upcoming AMS publication

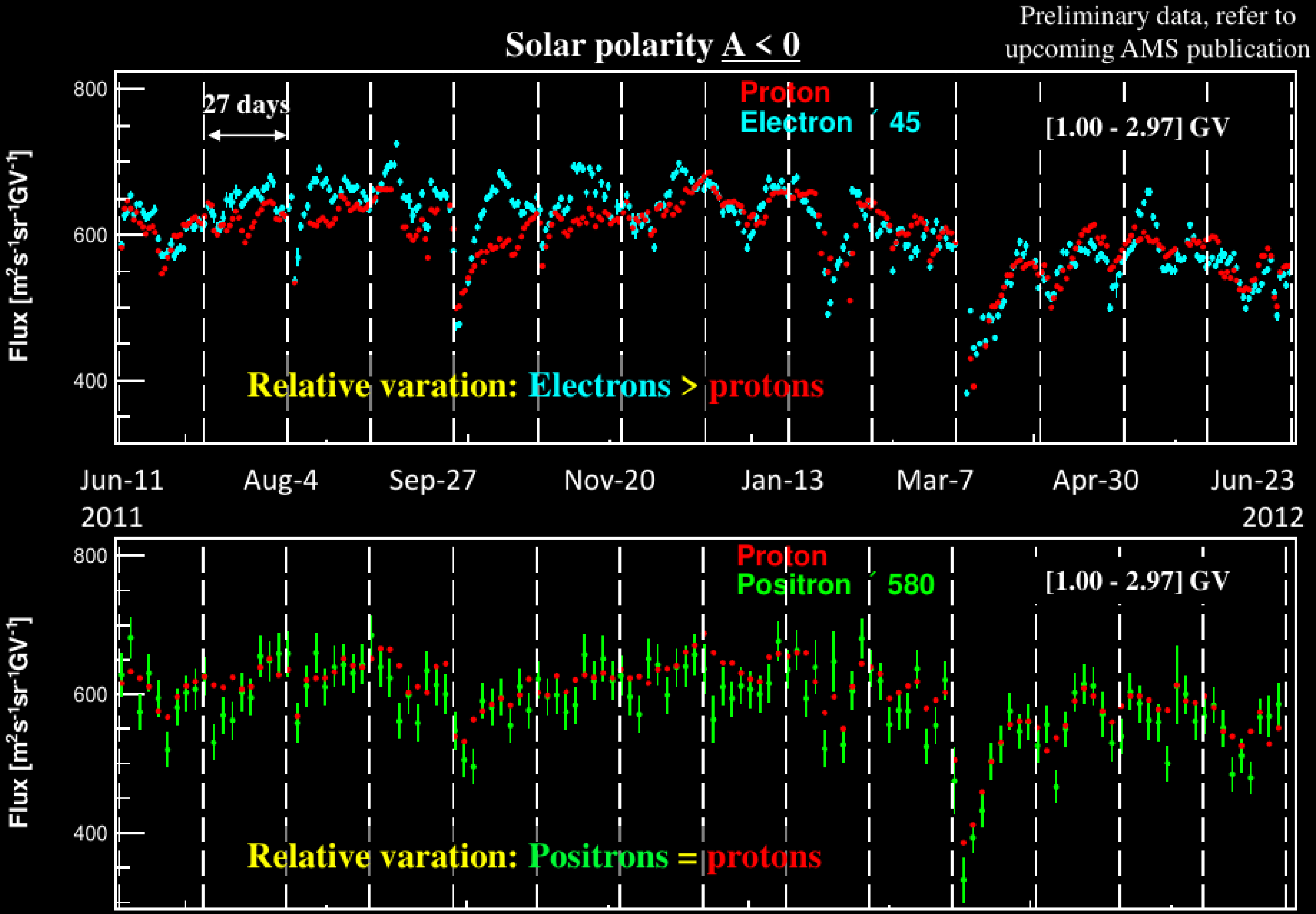
Daily Electron Fluxes



3-Days Positron Fluxes

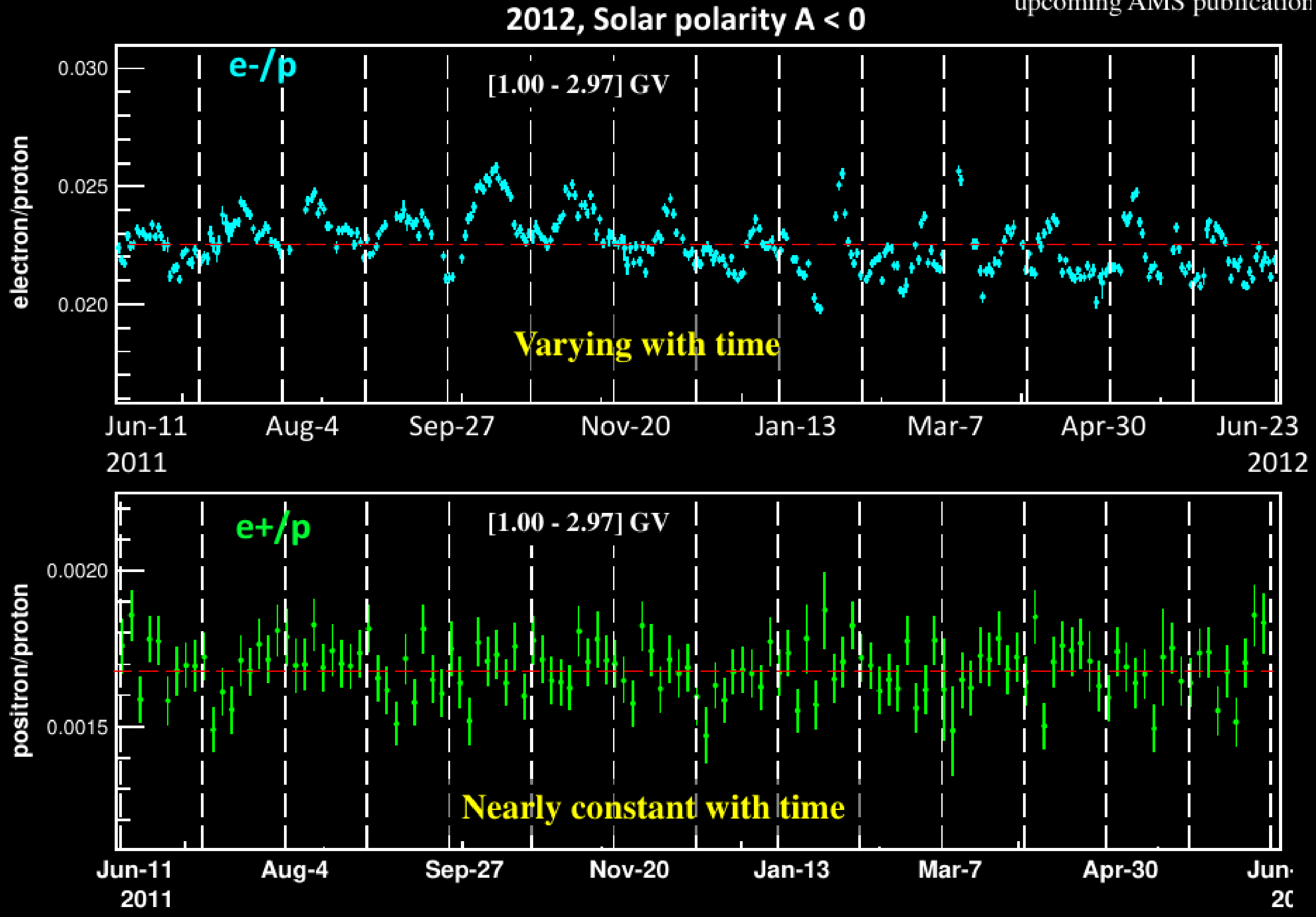


Electron, Positron and Proton (A<0)

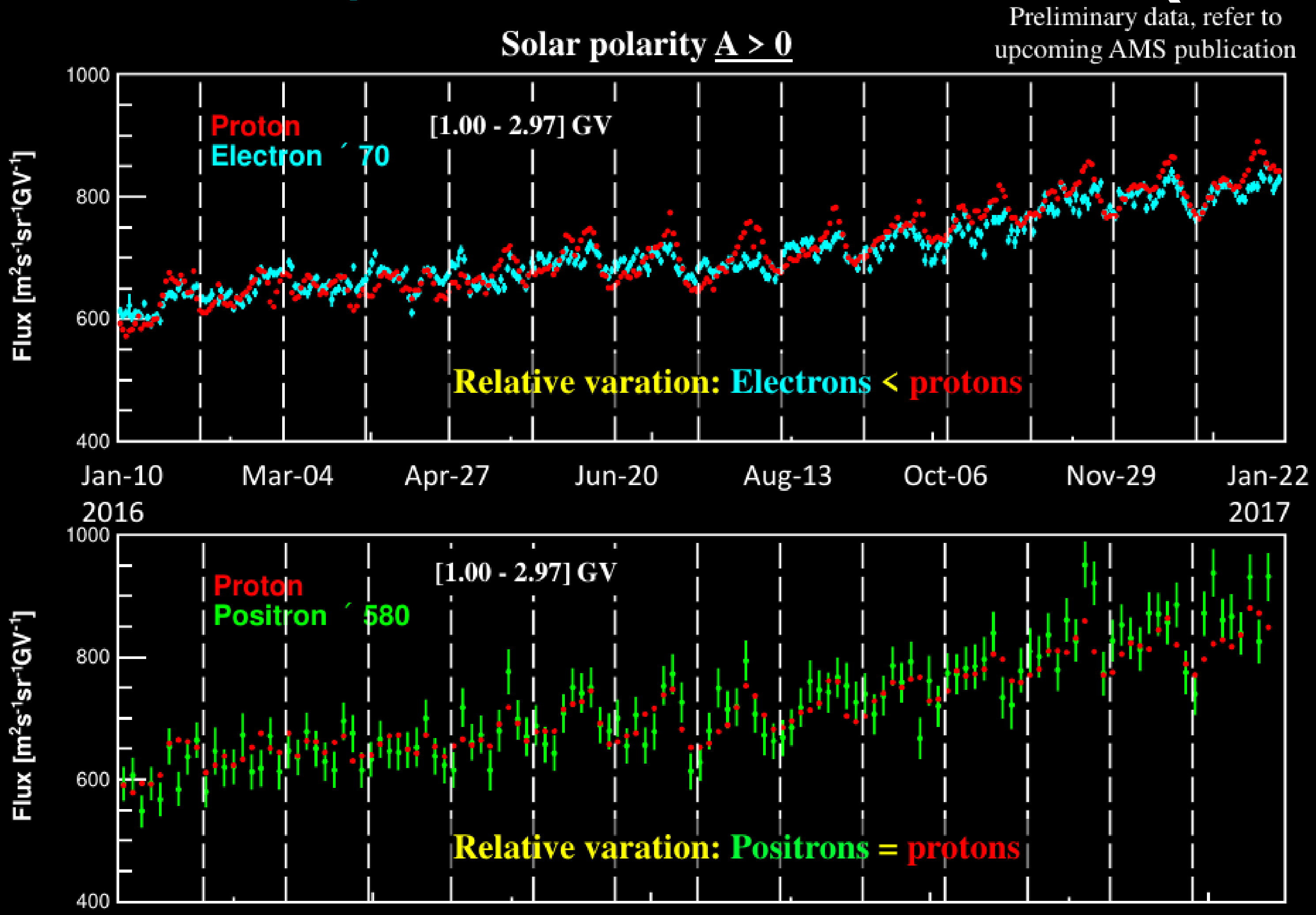


Electron, Positron and Proton Ratios (A<0)

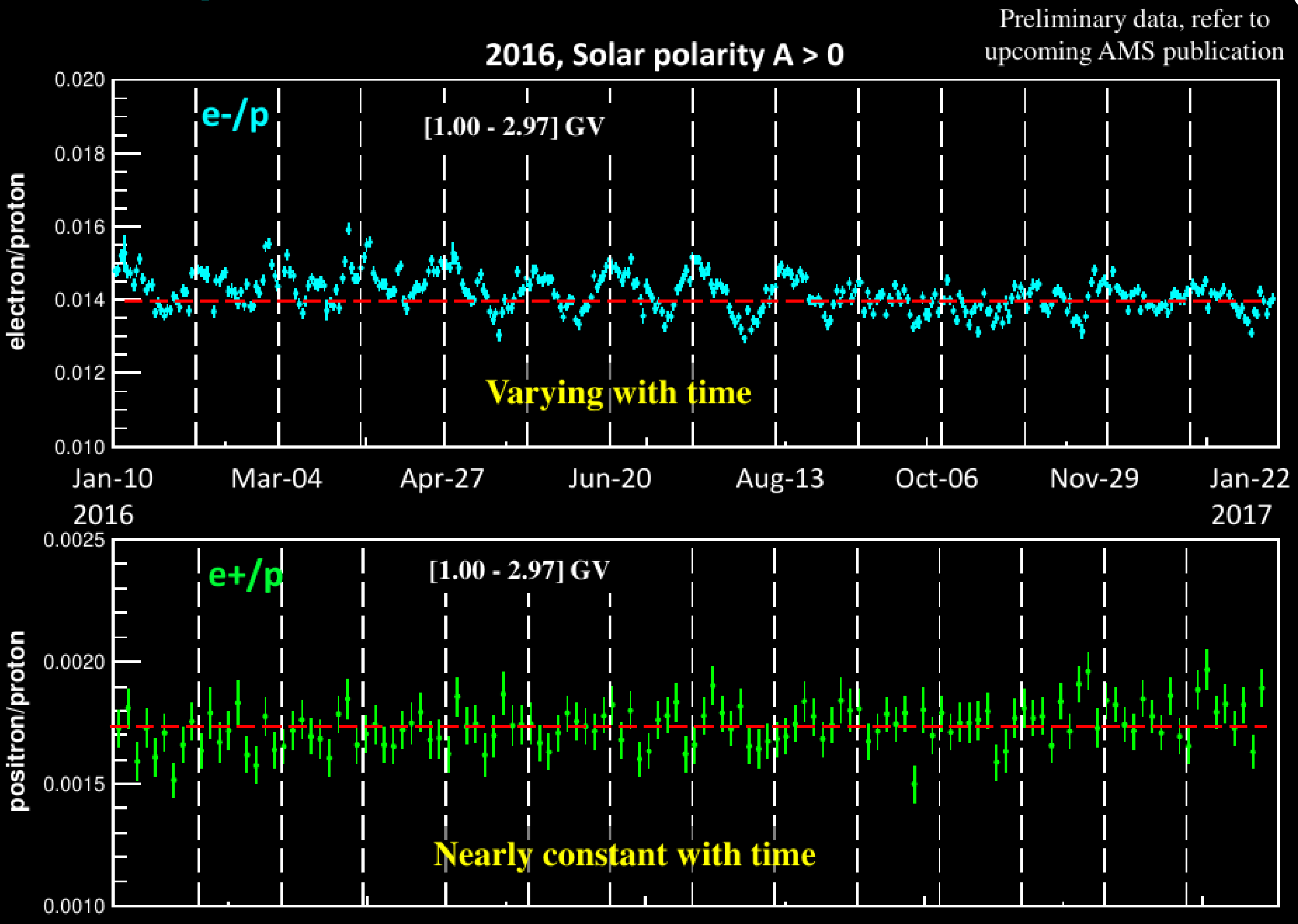
Preliminary data, refer to upcoming AMS publication



Electron, Positron and Proton (A>0)



Electron, Positron and Proton Ratios (A>0)



Summary

During the fist 10 years of operation, AMS has performed multiple
flux measurements of nuclei, isotops, electron and positron,
on different time scales.

Long- and short-time scale variations, due to the solar modulation effect,
were observed in all particle species.
SEP events were also detected.

AMS will continue taking data through the lifetime of the ISS.

Backup

Wavelet Analysis of Proton Fluxes

The continuous wavelet transform W_n of a time series x_n with equal time interval δt is defined as:

$$W_n(s)=\sum_{n'=1}^{N} x_{n'}\psi^*\left[\frac{(n'-n)\delta t}{s}\right],$$

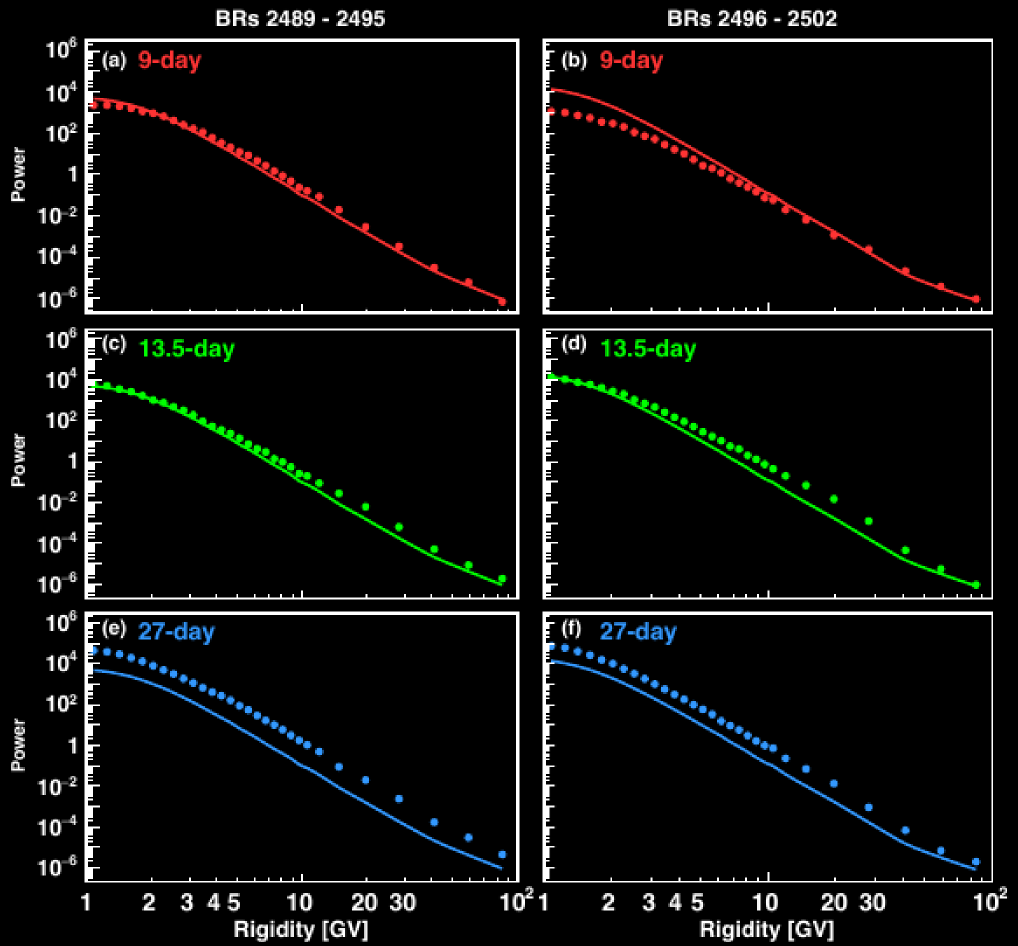
where ψ^* is the complex conjugate of the wavelet function ψ, s is the period, and n is the time index of the wavelet. The wavelet power is given by $|W_n(s)|^2$.

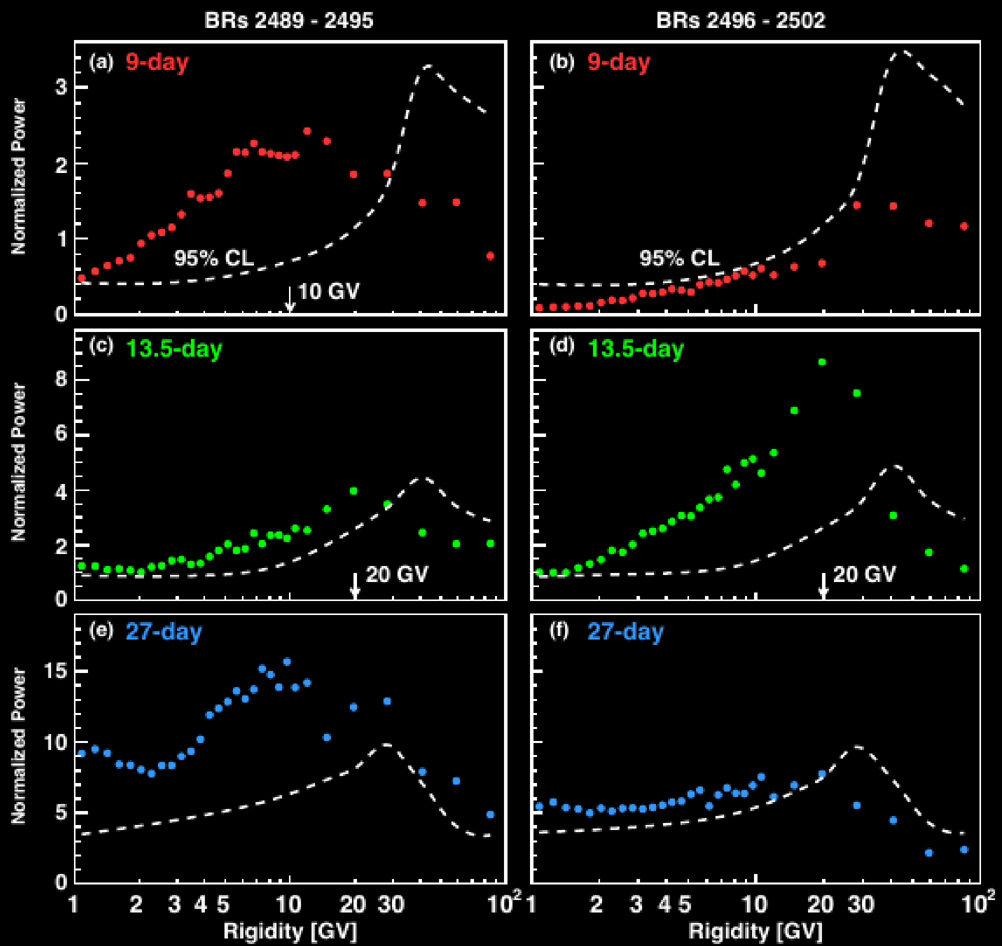
The time-averaged power spectrum over a certain time interval from index n_1 to n_2 is

$$\overline{W}_n^2(s) = \frac{1}{n_2-n_1+1}\sum_{n=n_1}^{n_2} |W_n(s)|^2.$$

To show the strength of the periodicity, **the normalized power** is defined by the wavelet power divided by **the variance** of the time series in the corresponding time interval. Background based on lag-1 autoregressive process is used to determine the **significance levels** of the periodic structure.

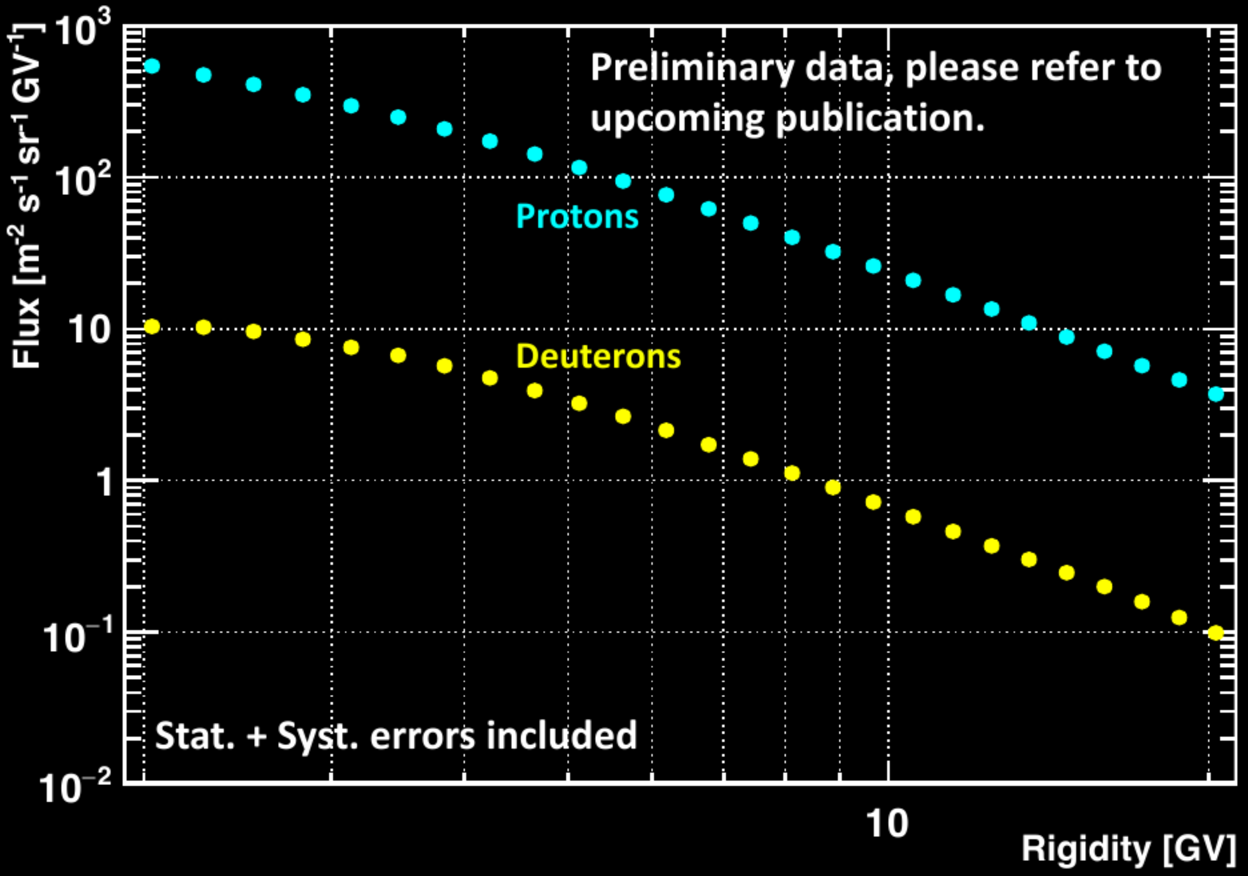
C. Torrence and G. P. Compo, Bull. Am. Meteorol. Soc. 79, 61 (1998)


BRs 2489 - 2495
BRs 2496 - 2502
(a) 9-day
(b) 9-day
(c) 13.5-day
(d) 13.5-day
(e) 27-day
(f) 27-day
Power
Rigidity [GV]

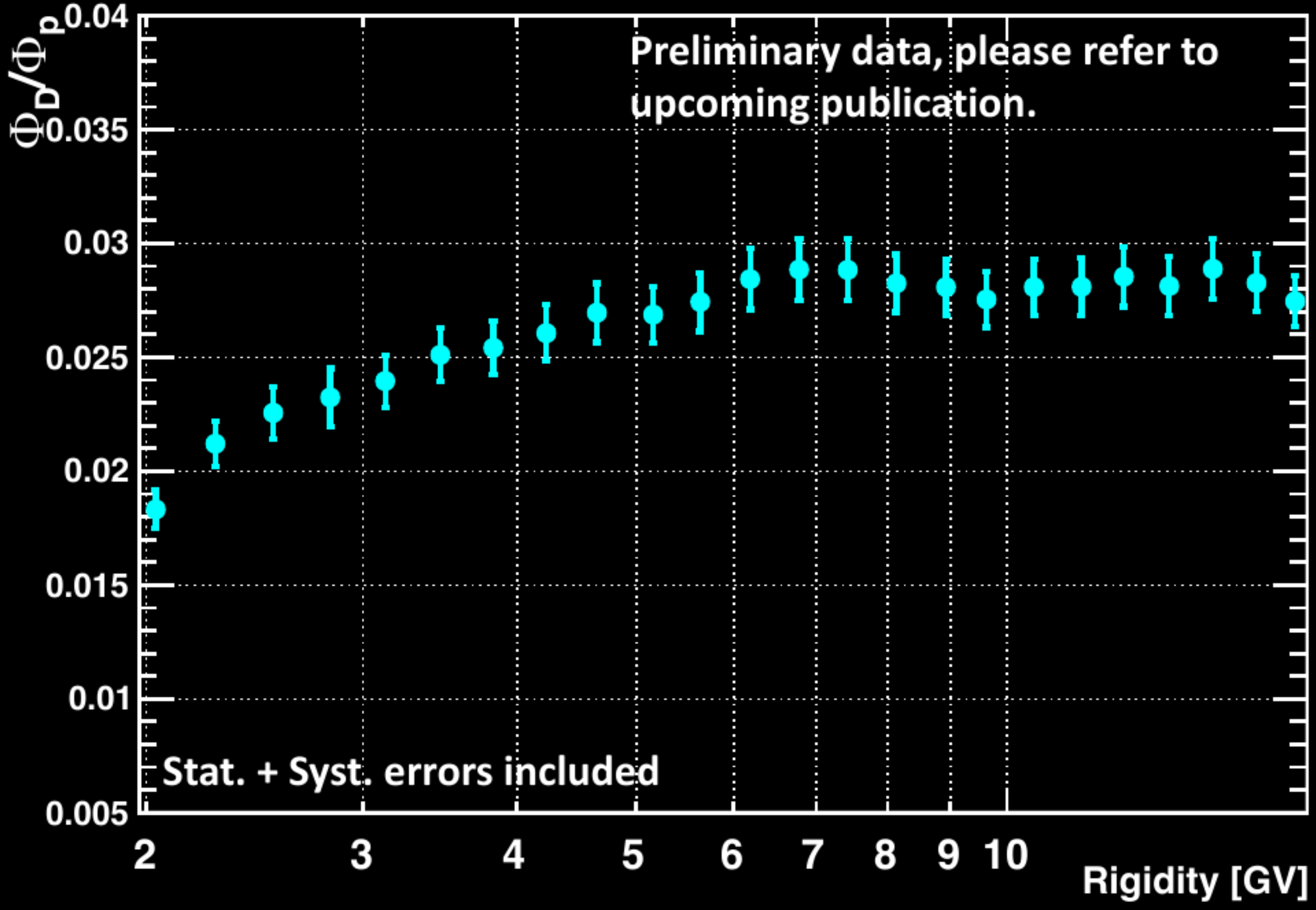

BRs 2489 - 2495
BRs 2496 - 2502
(a) 9-day
(b) 9-day
95% CL
10 GV
(c) 13.5-day
(d) 13.5-day
20 GV
(e) 27-day
(f) 27-day
Normalized Power
Rigidity [GV]

Proton and Deuteron Fluxes (May2010-Jan2020)

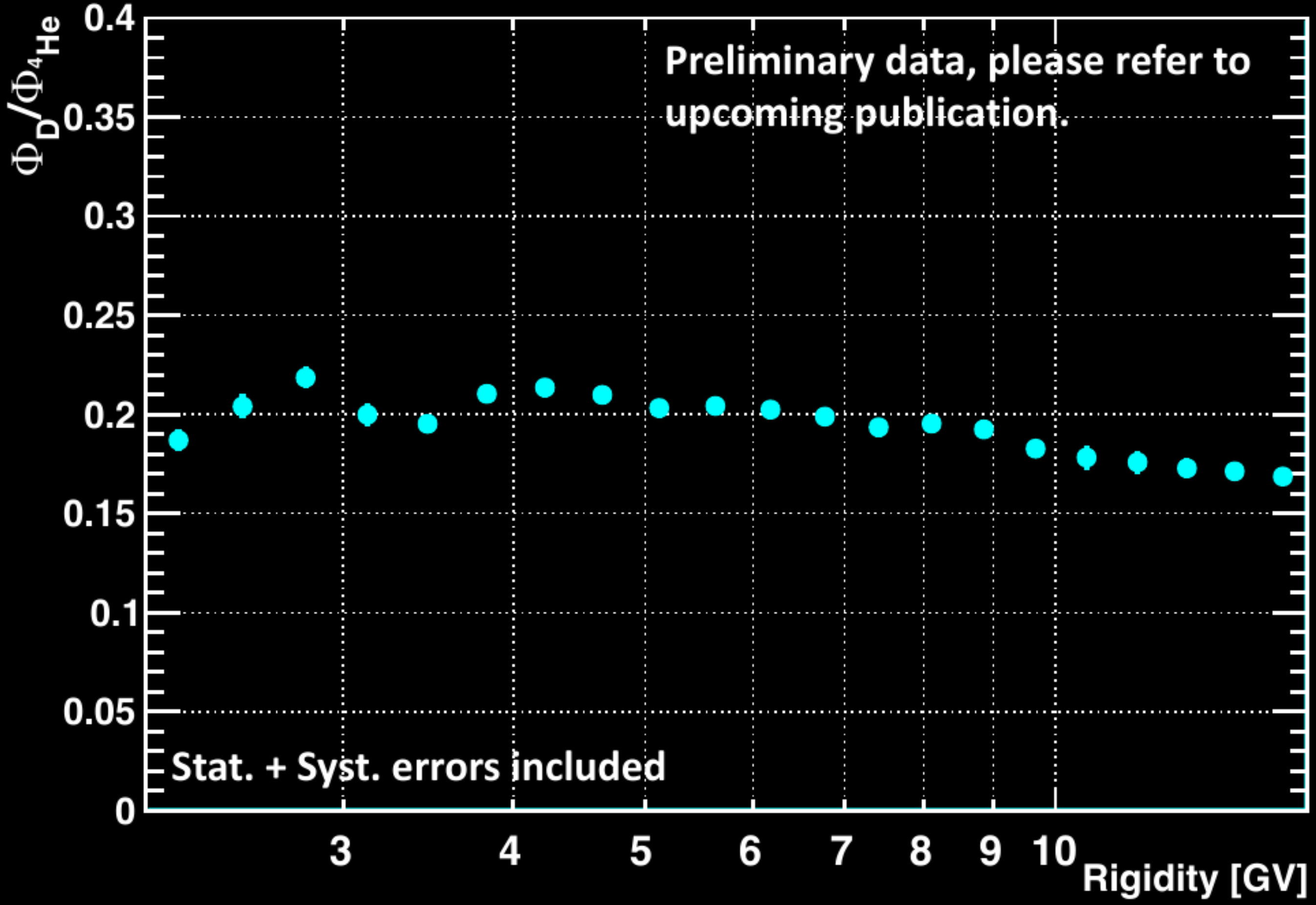
15 x 10⁶ deuteron events collected in 8.5 years



Deuteron over Proton Flux Ratio (May2010-Jan2020)



Deuteron over 4He Flux Ratio (May2010-Jan2020)



AMS Electron Flux Periodicity

Preliminary data, refer to upcoming AMS publication