Precision Measurement of the Monthly Proton, Helium, Carbon and Oxygen Fluxes in Cosmic Rays with the Alpha Magnetic Spectrometer on the International Space Station

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on behalf of the AMS-02 collaboration

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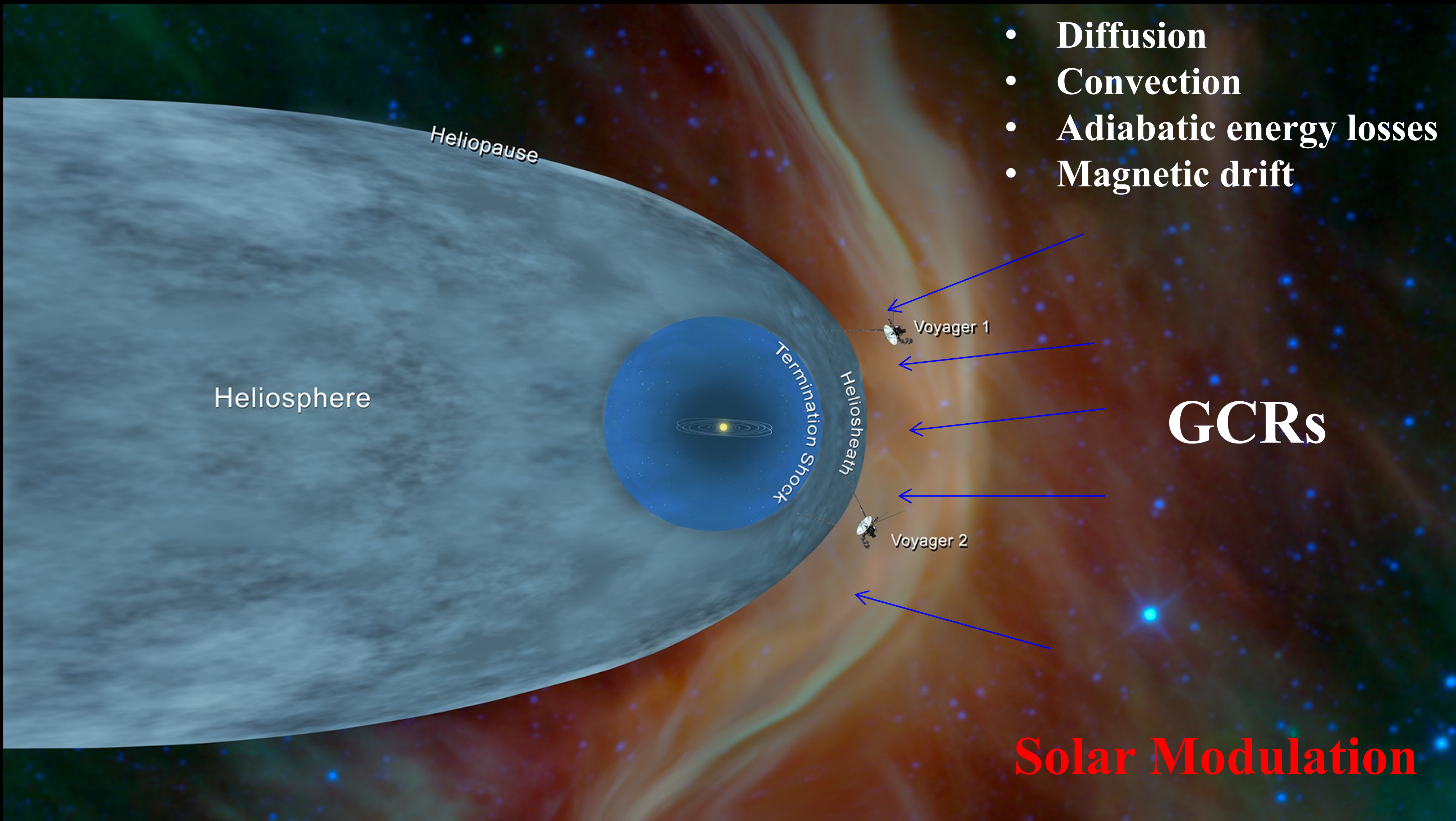
07/09/2022, Rome

GCRs Propagation inside the Heliosphere



GCRs Propagation inside the Heliosphere: Parker's Equation

$$\frac{\partial f}{\partial t} + \underbrace{\vec{V}_{sw} \cdot \vec{\nabla} f}_{\text{Solar wind plasma convection}} - \underbrace{\vec{\nabla} \cdot (K \cdot \vec{\nabla} f)}_{\text{Diffusion and drifts}} - \underbrace{\frac{1}{3} \vec{\nabla} \cdot \vec{V}_{sw} \frac{\partial f}{\partial \ln R}}_{\text{Adiabatic energy losses and gains}} = 0$$

GCRs Propagation inside the Heliosphere: Parker's Equation

Phase-space density distribution of GCRs

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GCRs Propagation inside the Heliosphere: Parker's Equation

Time Evolution

Phase-space density distribution of GCRs

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Velocity dependence of the diffusion tensor:

$$k(r, R) = \beta k_1(r) k_2(R)$$

Nuclei with distinct A/Z result in different velocity

GCRs Propagation inside the Heliosphere: Parker's Equation

Time Evolution

Phase-space density distribution of GCRs

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Solar wind plasma convection

Diffusion and drifts

Adiabatic energy losses and gains

Velocity dependence of the diffusion tensor:

$$k(r, R) = \beta k_1(r) k_2(R)$$

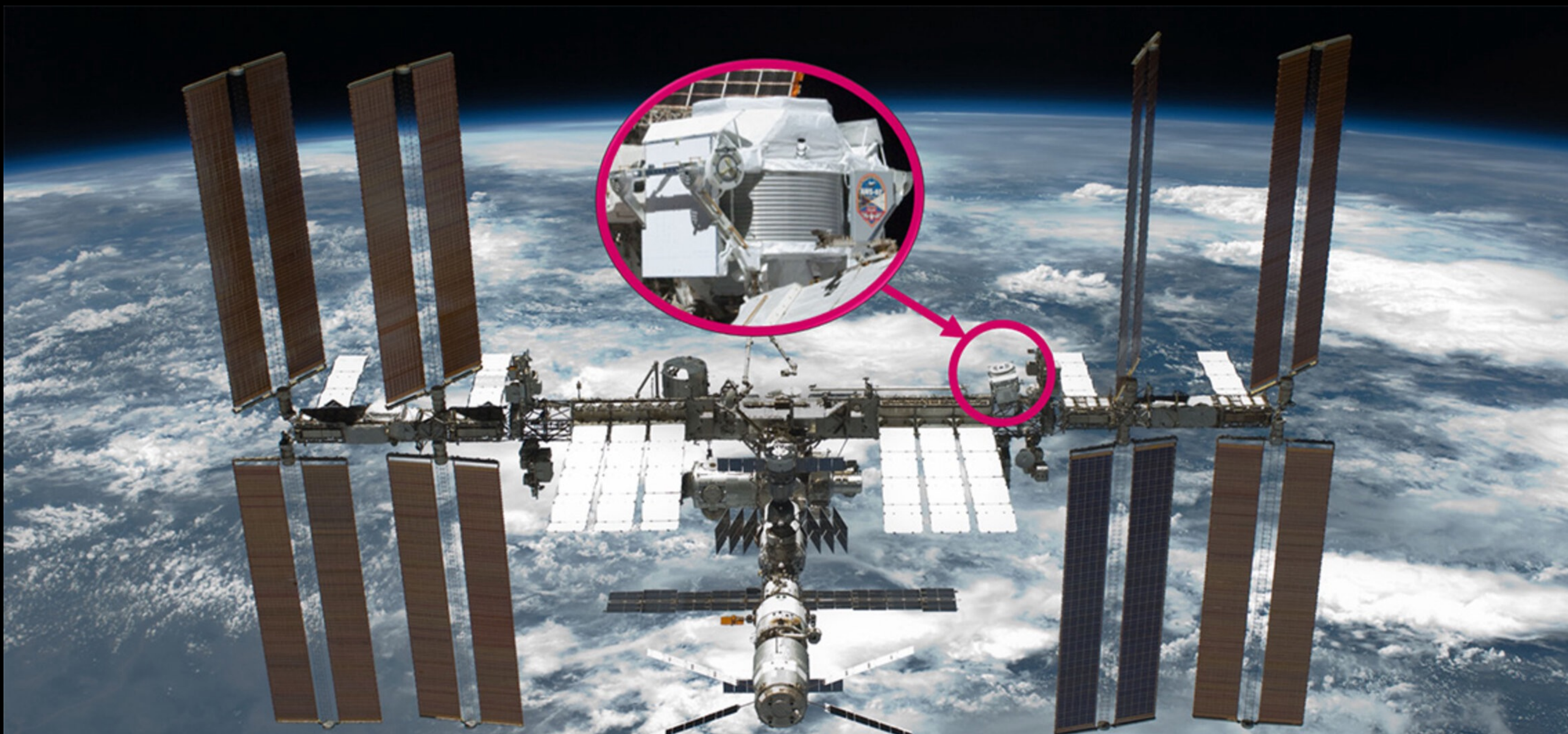
Nuclei with distinct A/Z result in different velocity

Difference in the spectral shape outside the heliosphere (Local Interstellar Spectrum, LIS):

the adiabatic energy changes term depends on the LIS shape

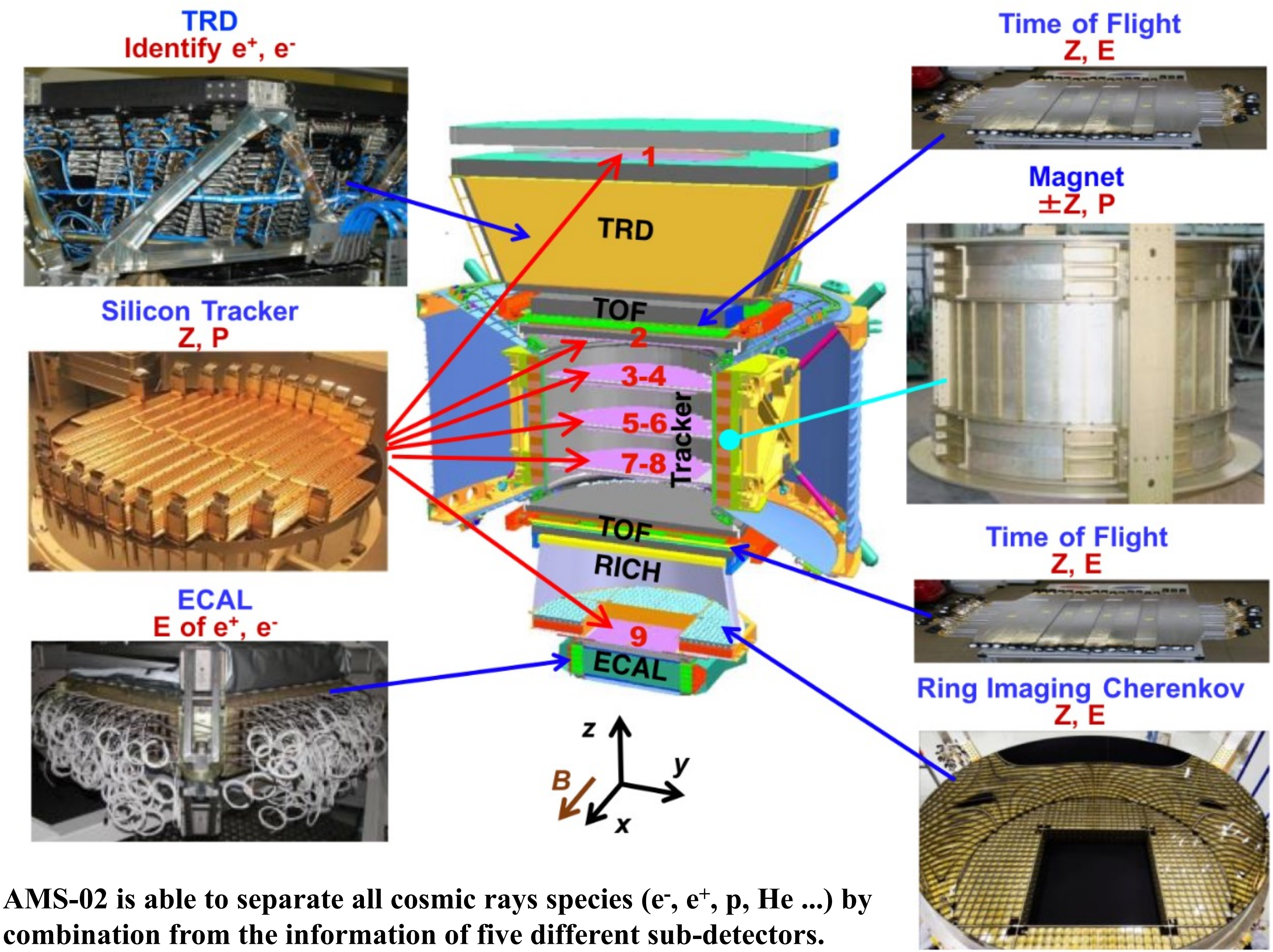
The Alpha Magnetic Spectrometer (AMS-02)

AMS-02 is a high energy particle physics experiment operating continuously on board of the International Space Station since May 2011.



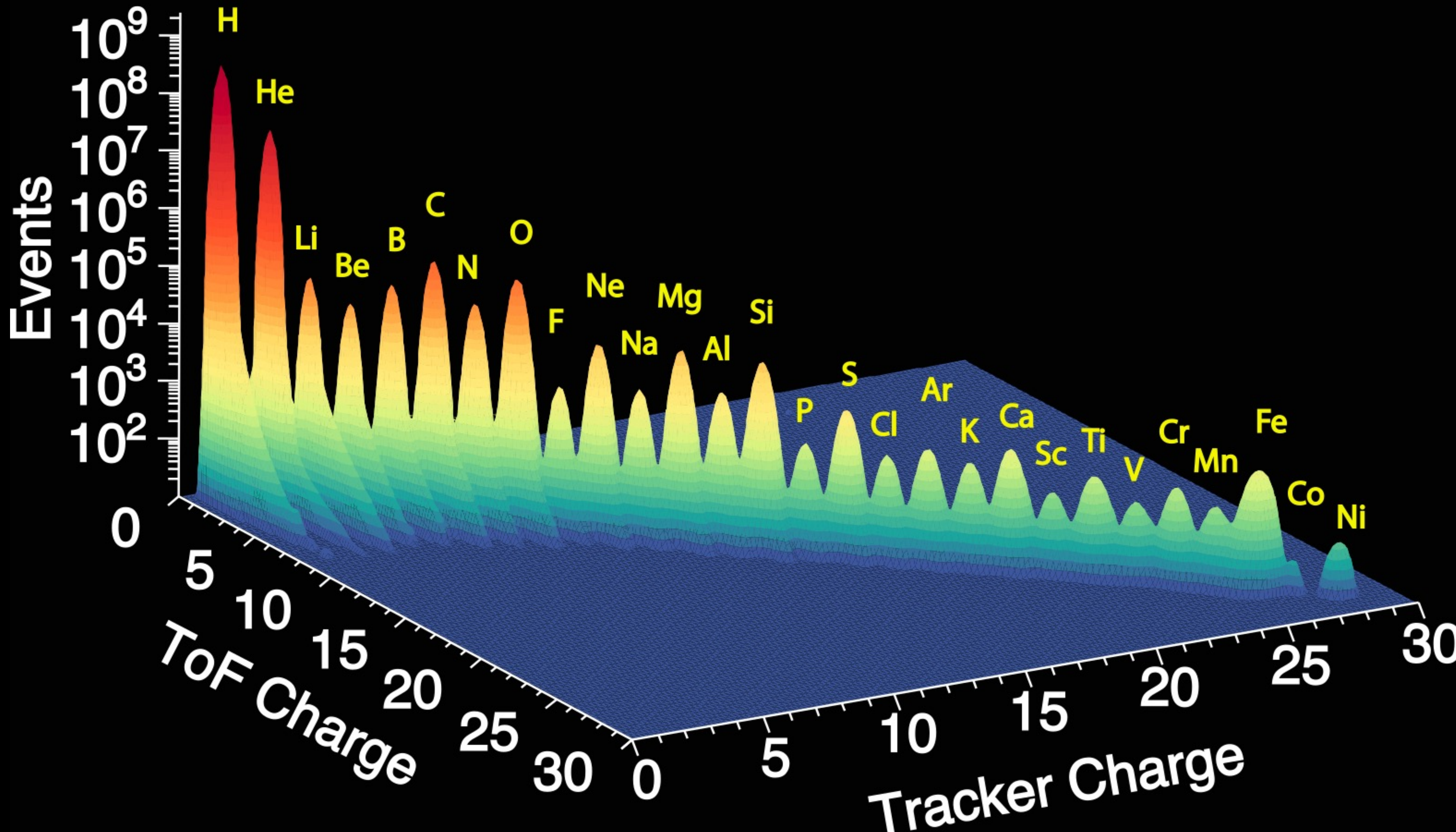
AMS-02 has collected more than 208 billions events up to now.

AMS-02: a multi-TV particle spectrometer



AMS-02 is able to separate all cosmic rays species (e^-, e^+, p, He ...) by combination from the information of five different sub-detectors.

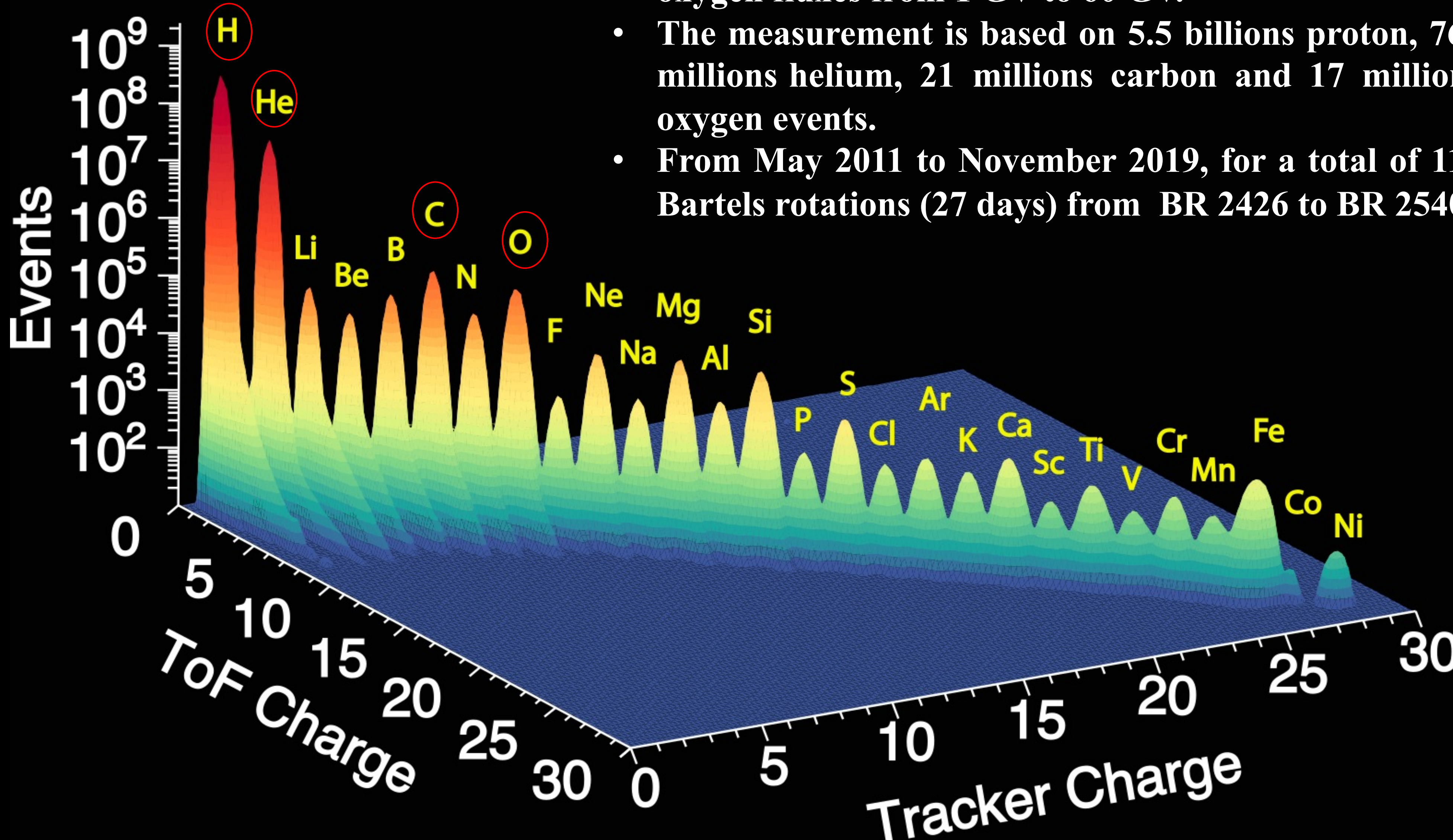
Cosmic Rays chemical composition with AMS



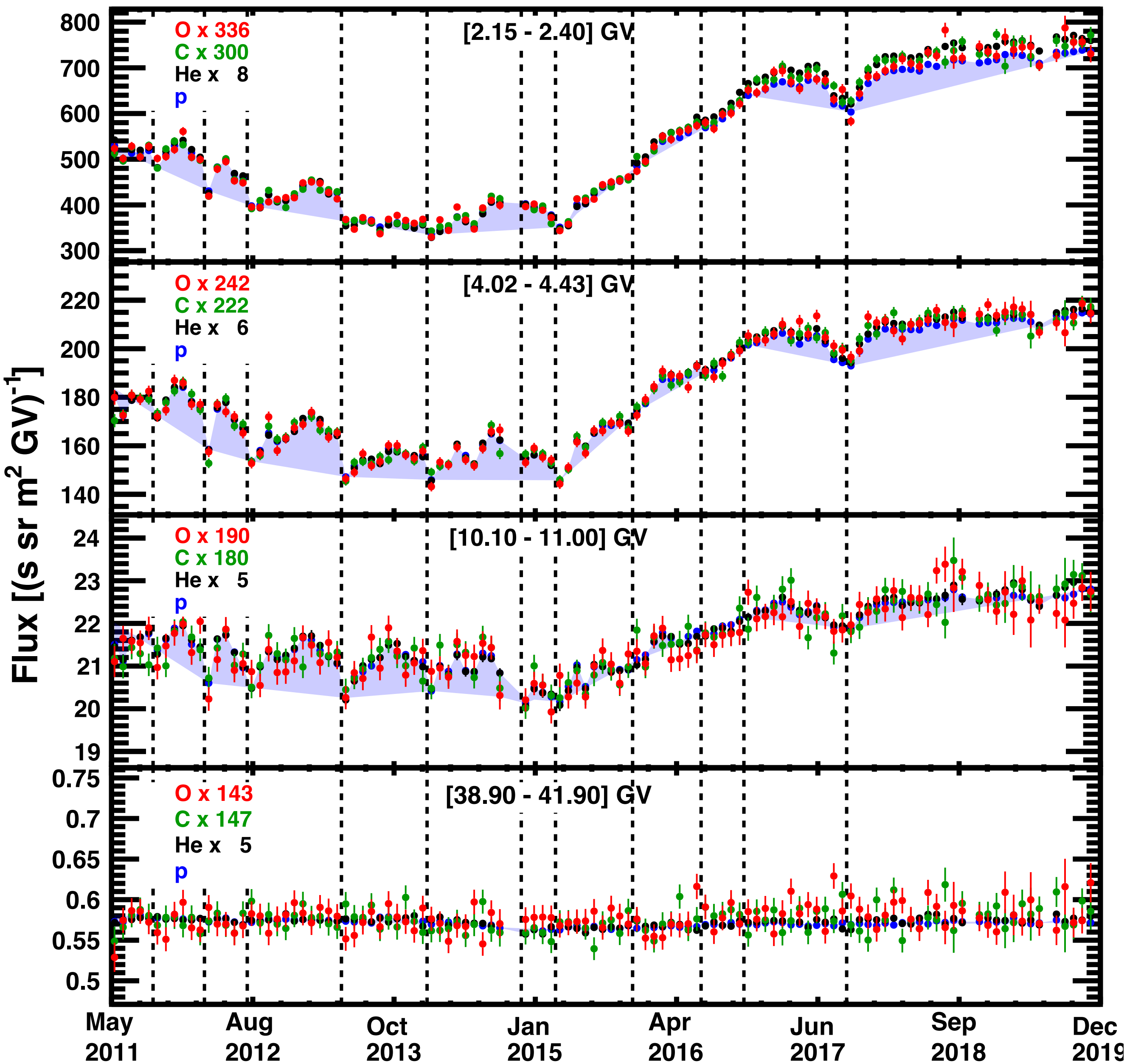
Cosmic Rays chemical composition with AMS

In this talk

- **Time evolution of the proton, helium, carbon, and oxygen fluxes from 1 GV to 60 GV.**
- **The measurement is based on 5.5 billions proton, 760 millions helium, 21 millions carbon and 17 millions oxygen events.**
- **From May 2011 to November 2019, for a total of 115 Bartels rotations (27 days) from BR 2426 to BR 2540.**

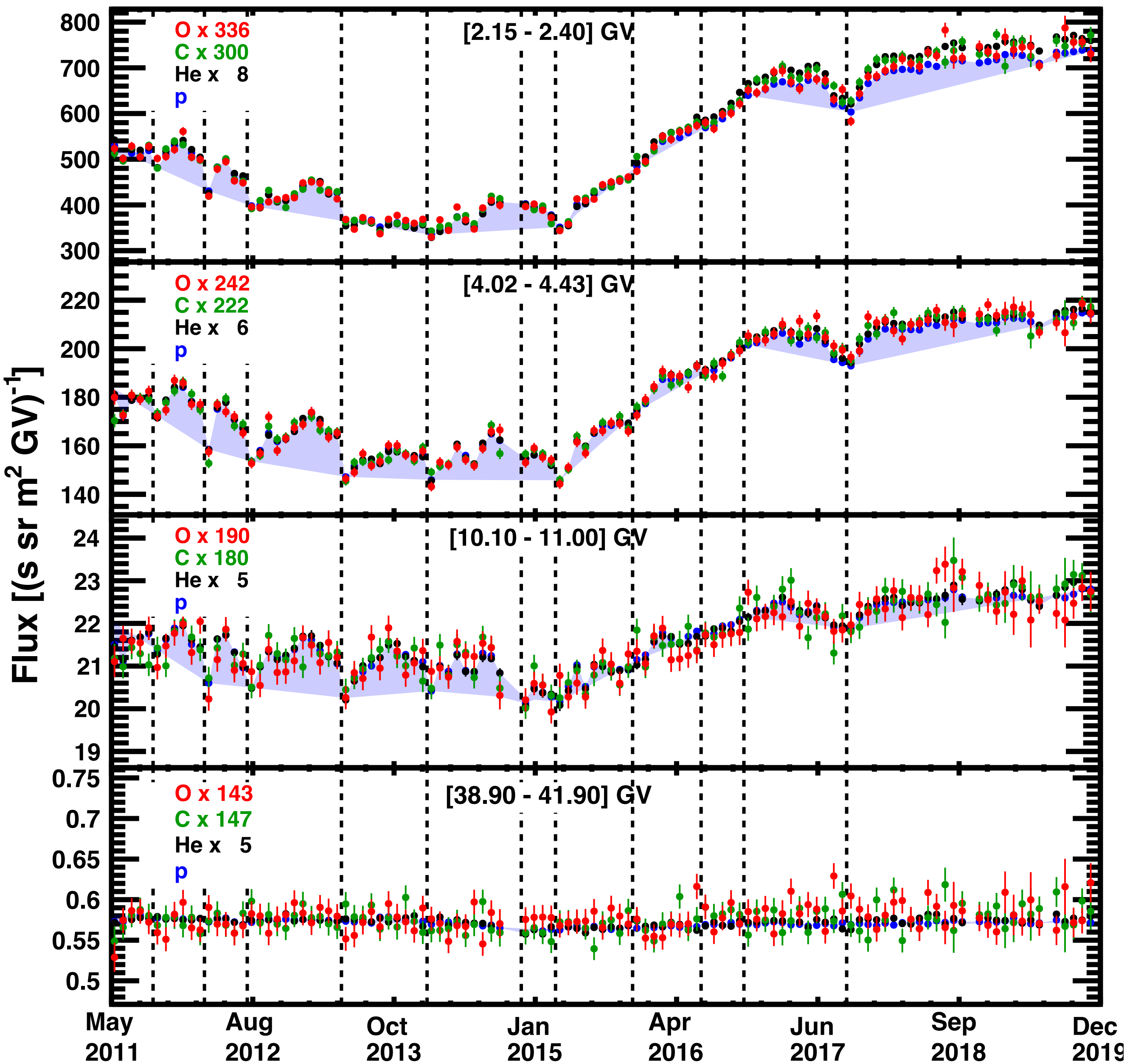


Fluxes vs Time



The proton, helium, carbon, and oxygen fluxes as a function of time for four characteristic rigidity bins.

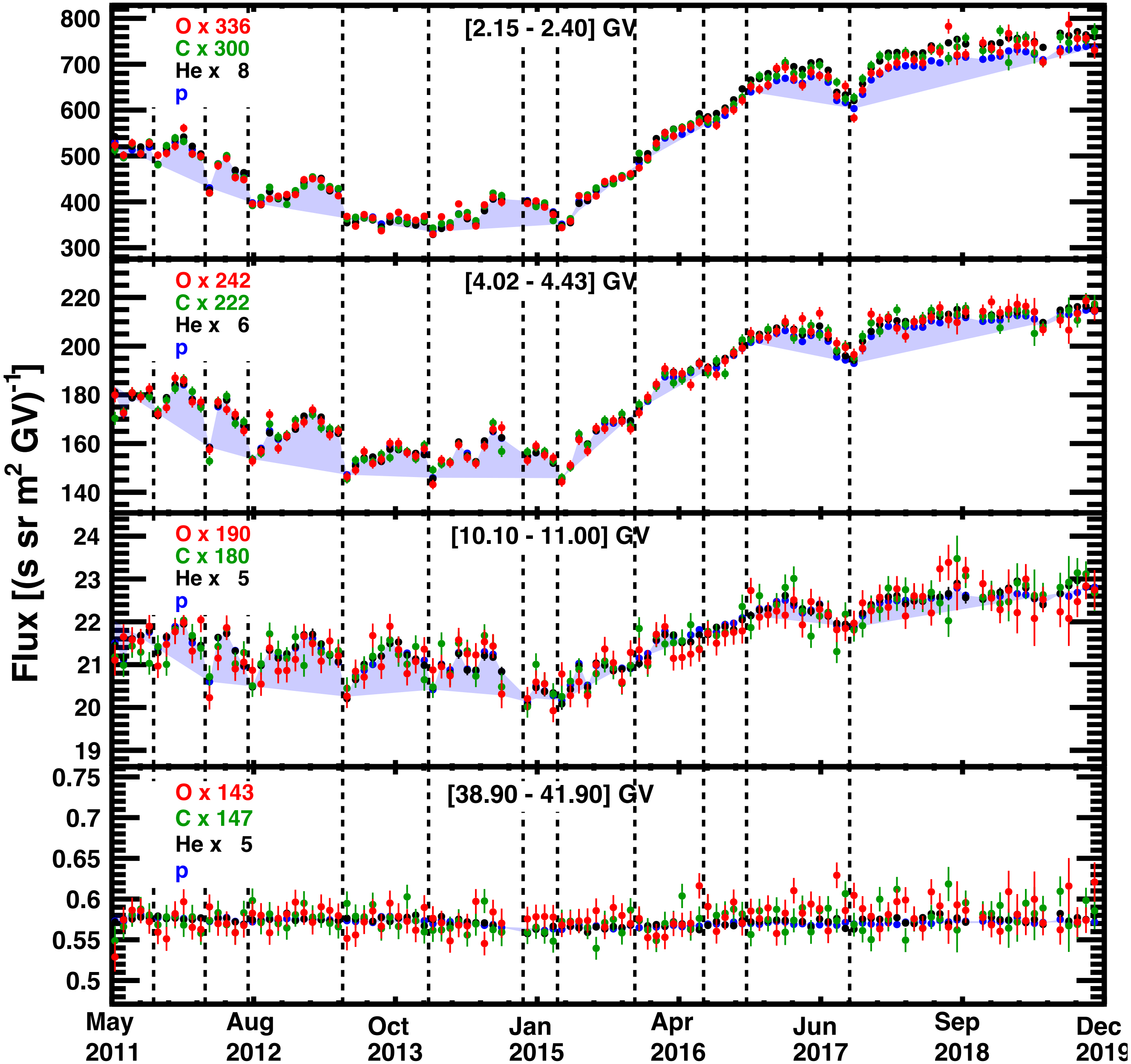
Fluxes vs Time



The proton, helium, carbon, and oxygen fluxes as a function of time for four characteristic rigidity bins.

The fluxes exhibit similar long-term and short-term time dependences.

Fluxes vs Time



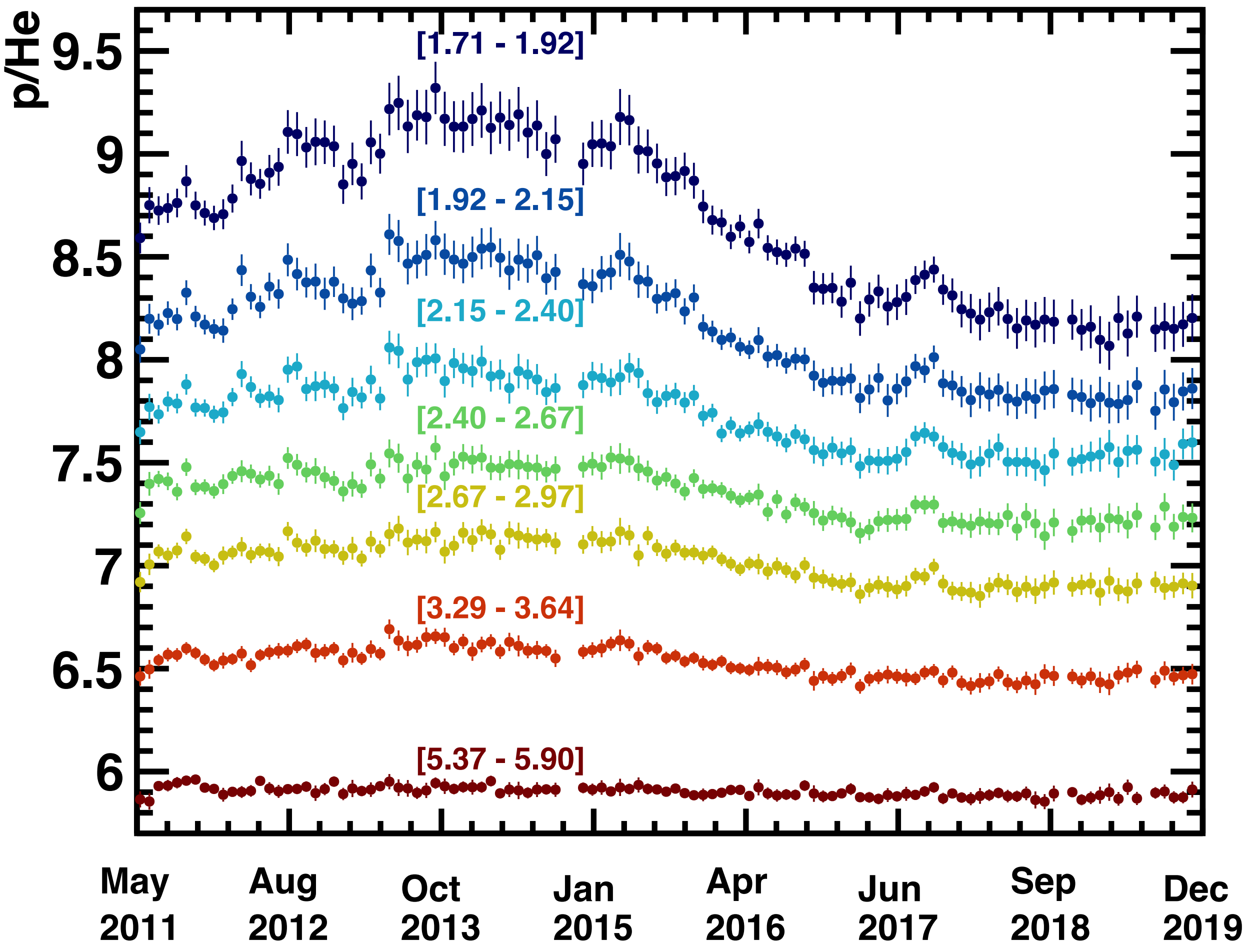
The proton, helium, carbon, and oxygen fluxes as a function of time for four characteristic rigidity bins.

The fluxes exhibit similar long-term and short-term time dependences.

The amplitude of these structures decreases with increasing rigidity and are observed up to ~25 GV for carbon and oxygen, ~50 GV for helium, and over the entire rigidity range for protons (up to 60 GV).

p/He vs Time

A clear long-term time dependence is visible; the p/He flux ratio increases up to the beginning of 2014 and then steadily decreases reaching a plateau in the middle of 2018.



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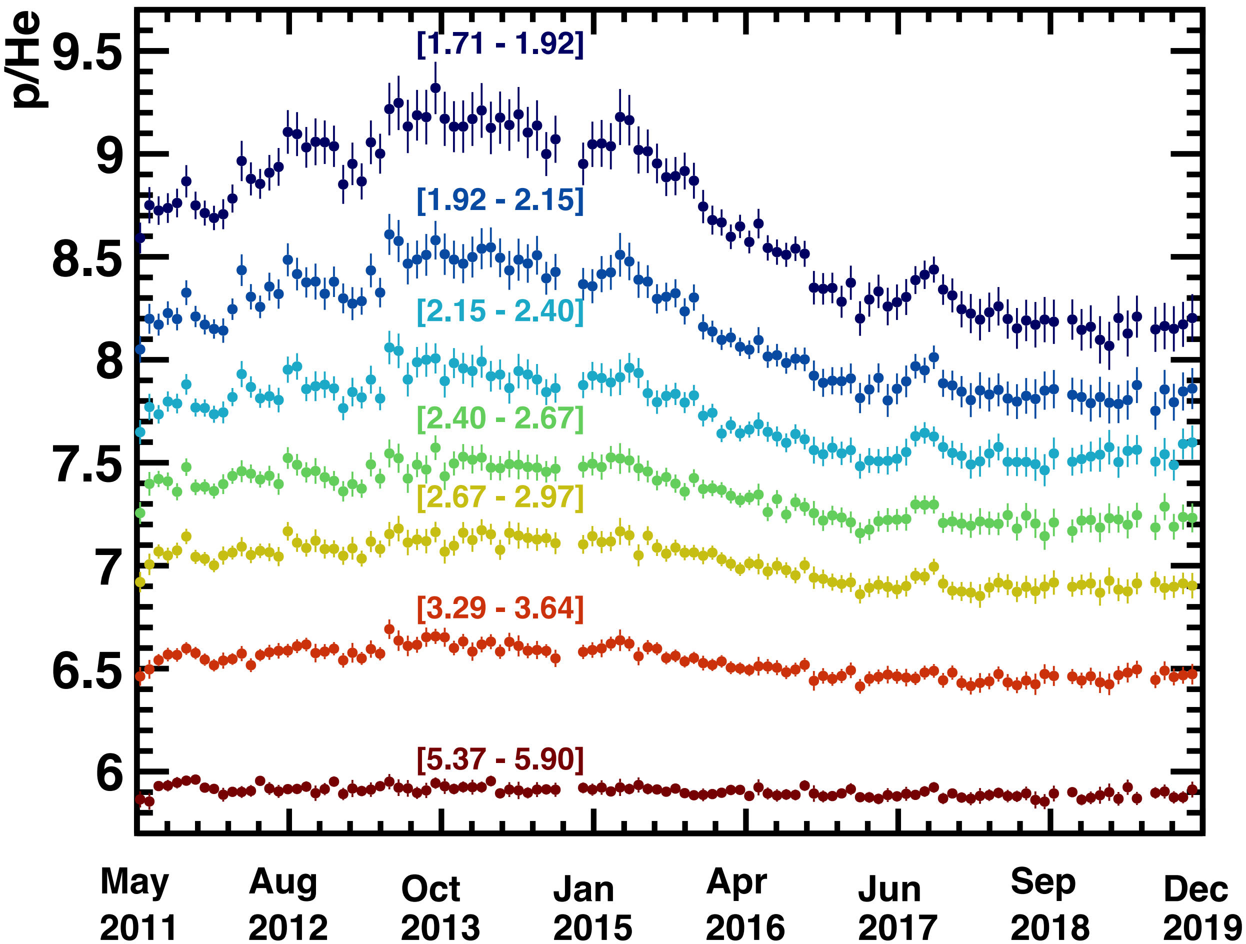

This ratio is not compatible with a constant value at the 5σ level below ~5 GV.

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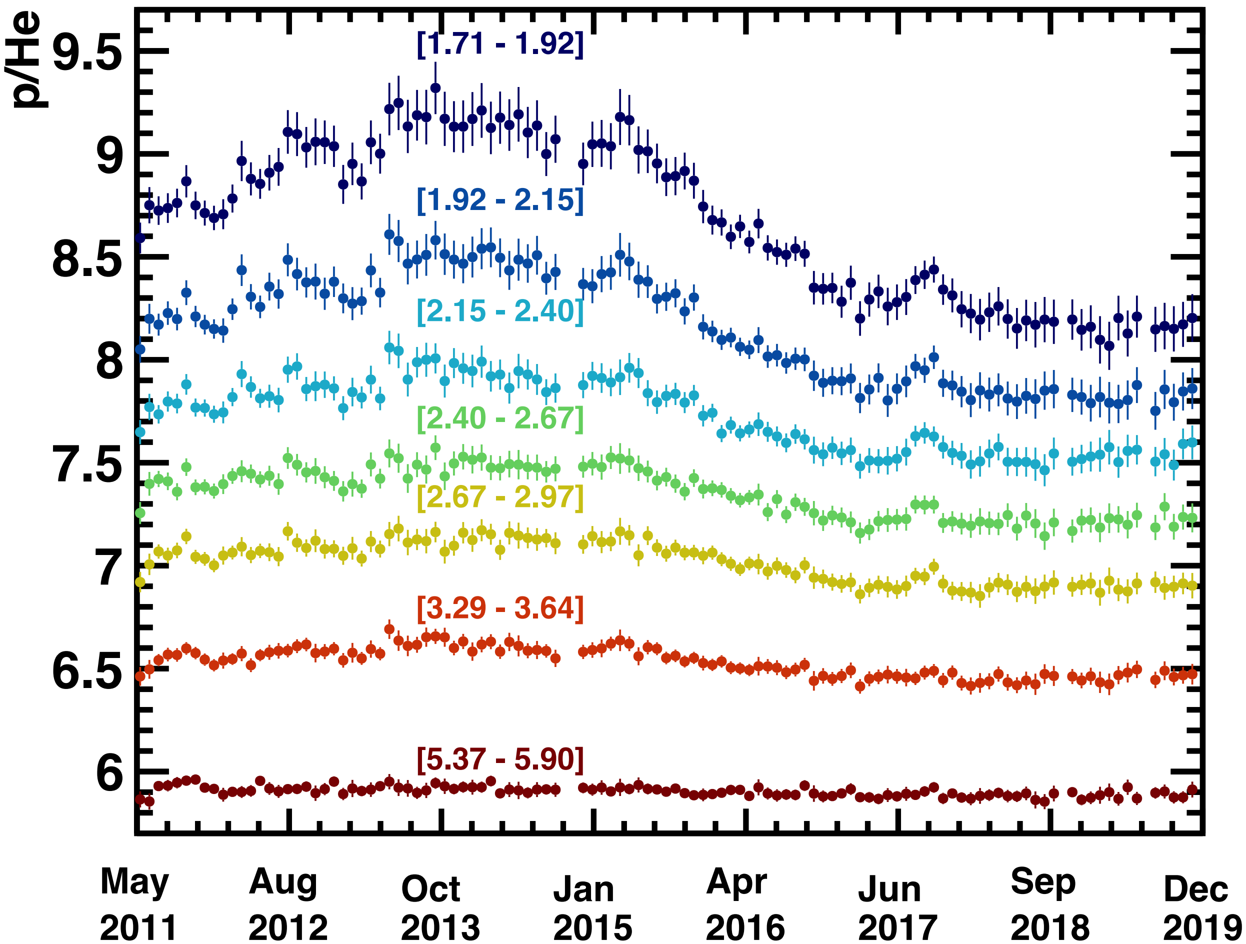

This ratio is not compatible with a constant value at the 5σ level below ~5 GV.

The proton mass-to-charge ratio is significantly different from the one of He. Therefore, both LIS flux rigidity dependence and velocity, factor into the time dependence of the p/He flux ratio.

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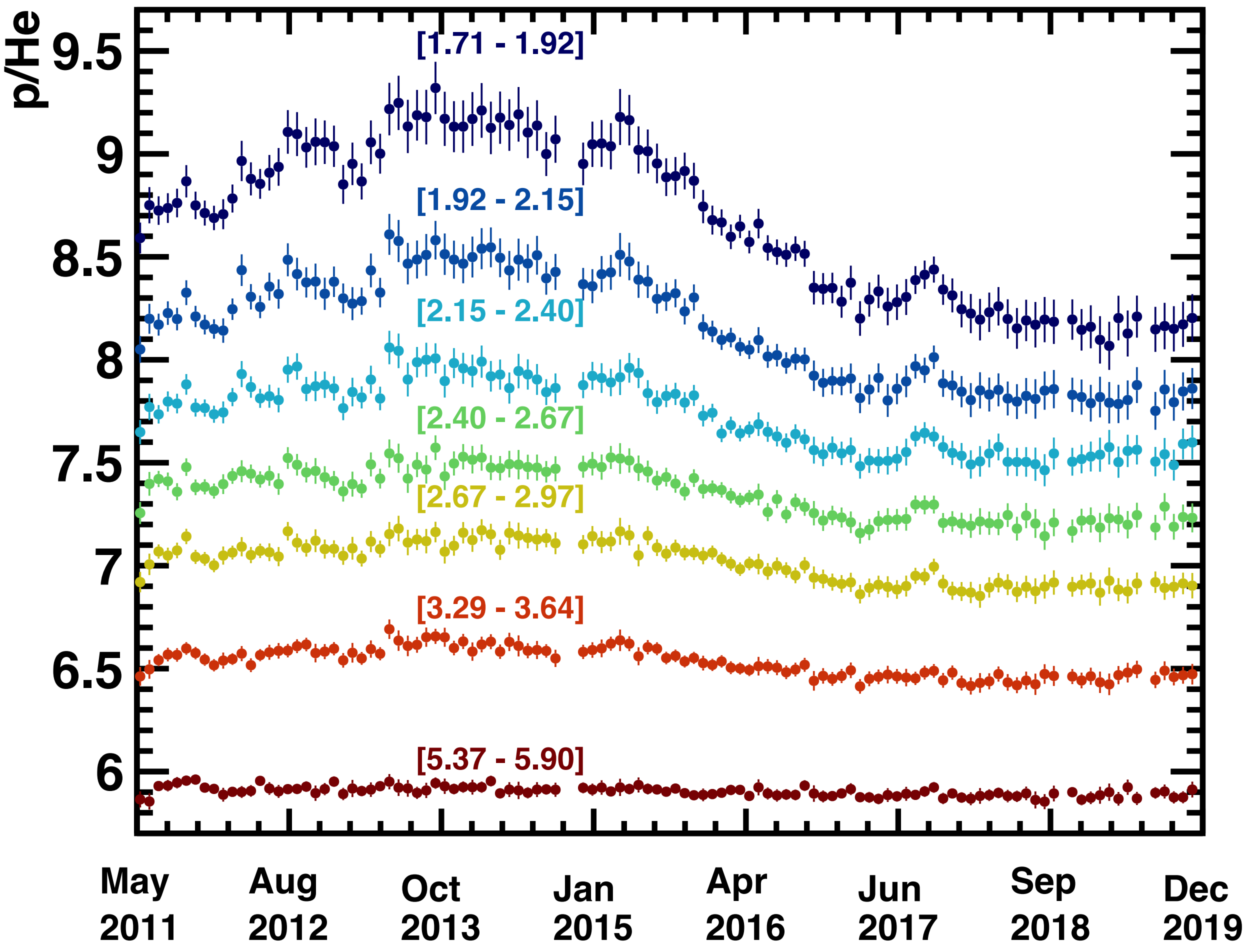

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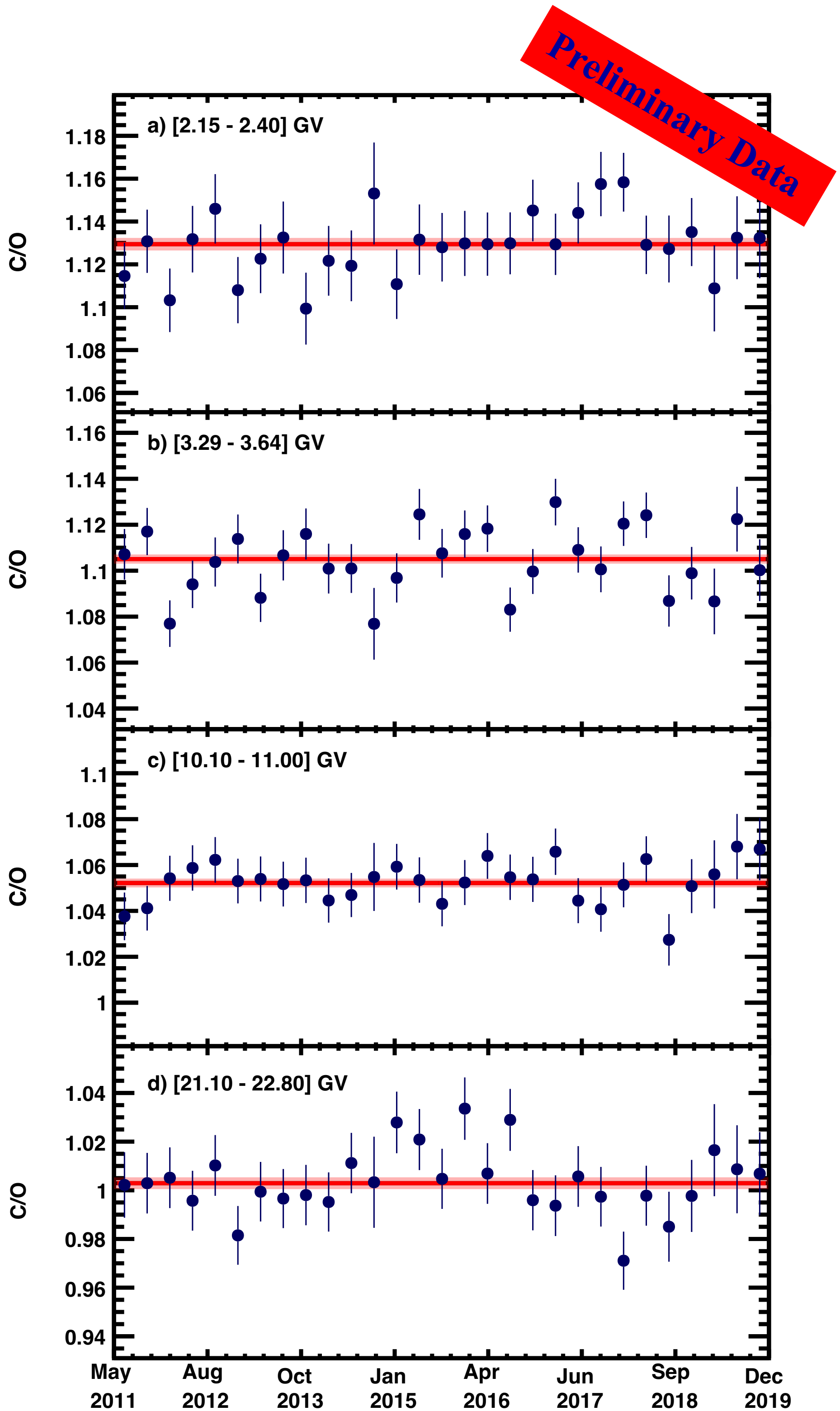
Daily protons: Phys. Rev. Lett. 127, 271102 (2021)

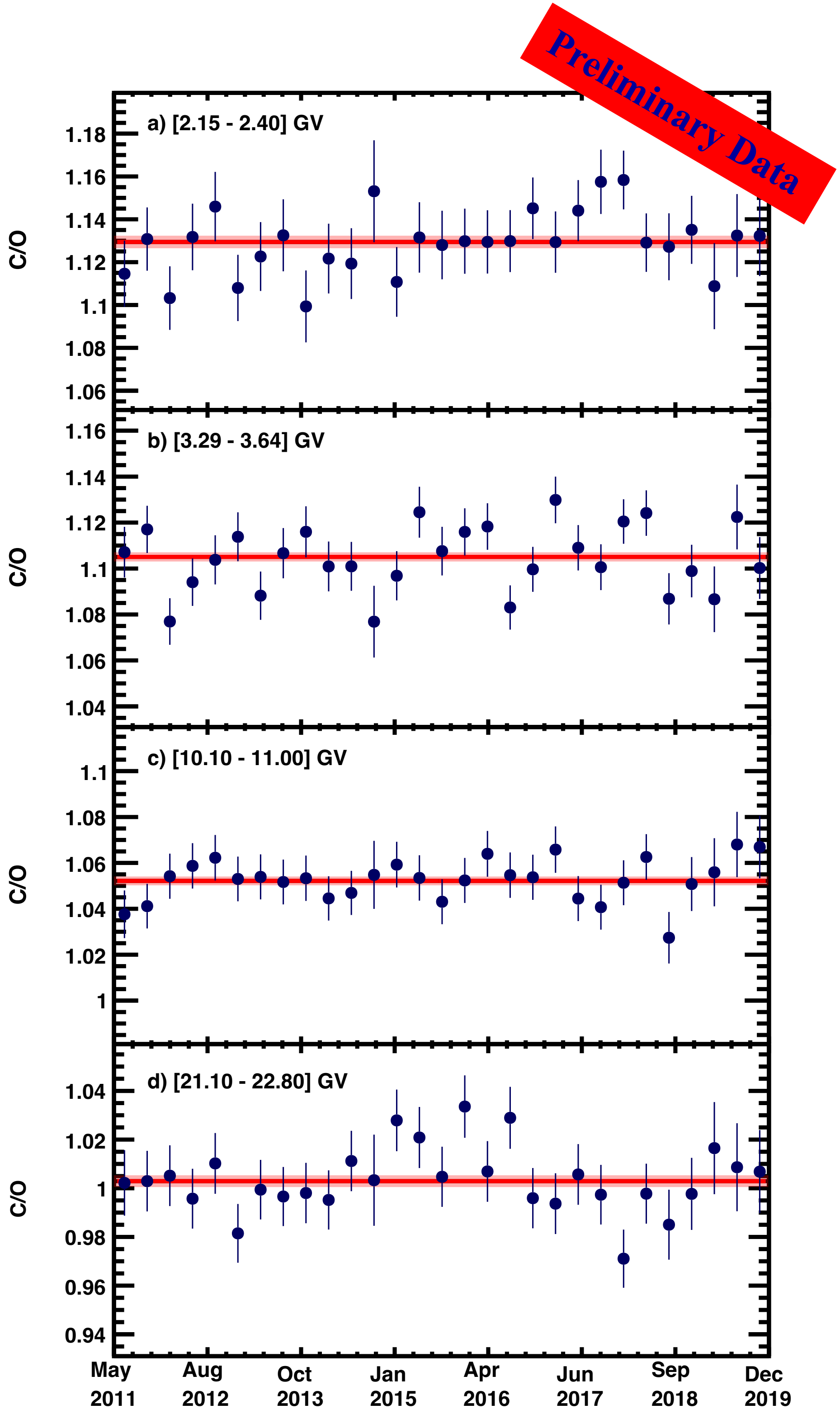
Daily Helium: Phys. Rev. Lett. 128, 231102 (2022)

C/O vs time



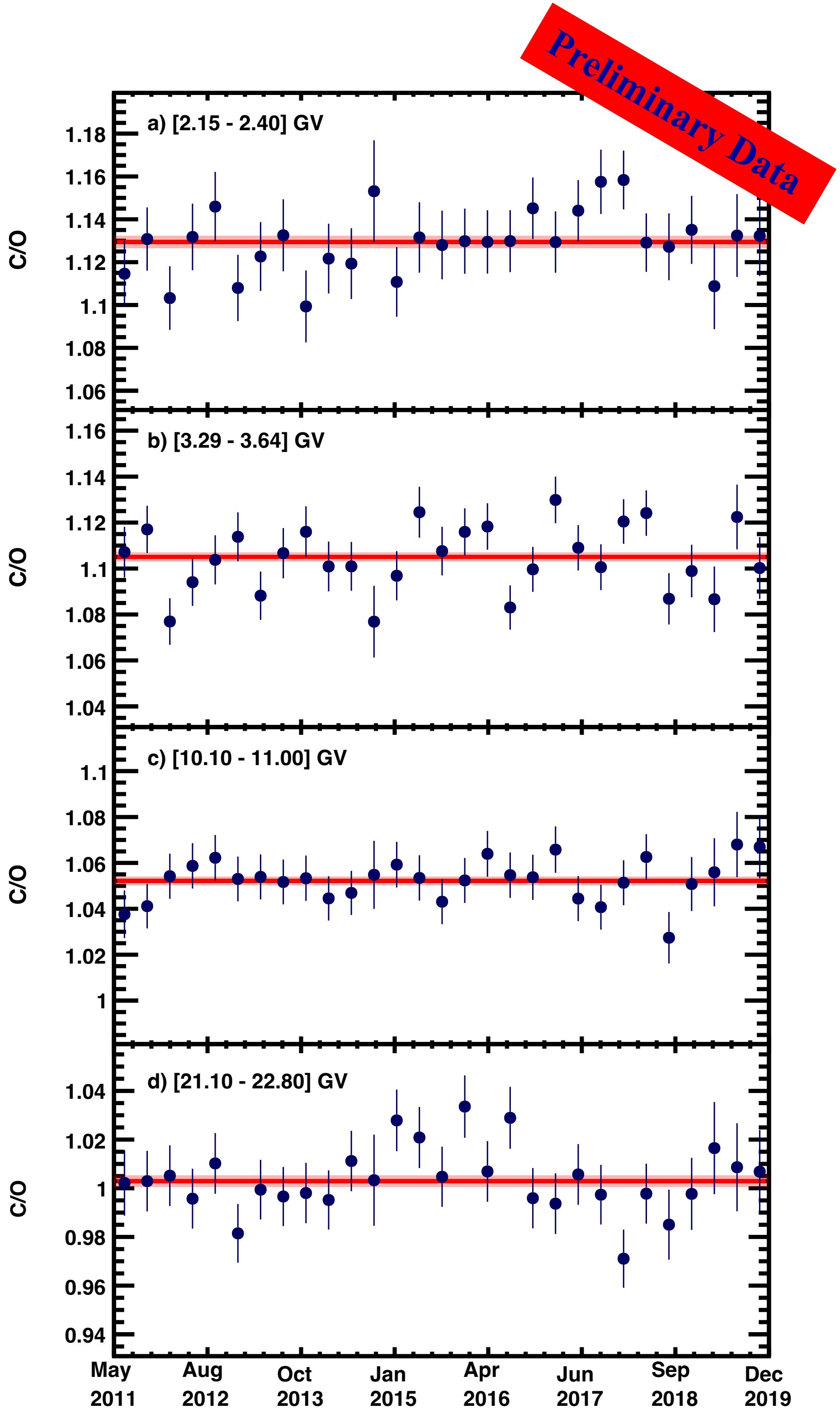
The AMS C/O flux ratio as a function of time in units of 4 Bartels rotations.

C/O vs time



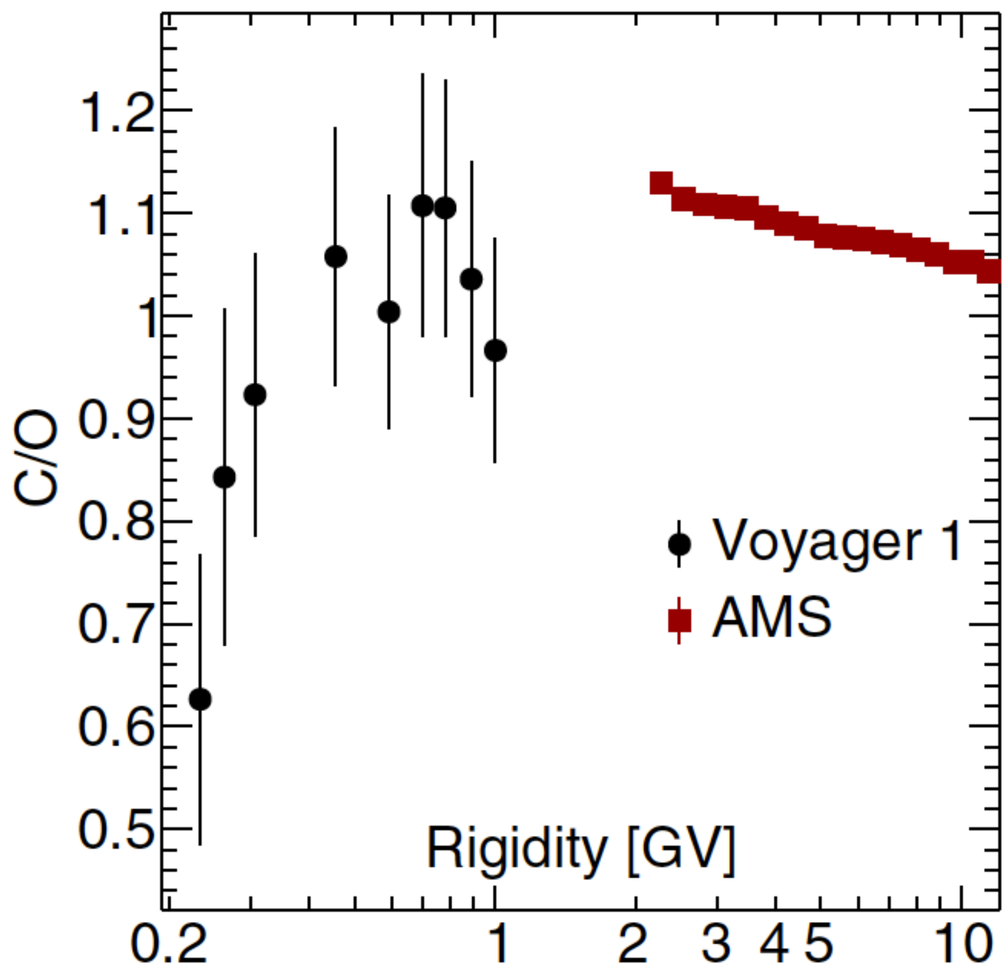
The AMS C/O flux ratio as a function of time in units of 4 Bartels rotations.

The carbon and oxygen fluxes have identical time dependence in the whole rigidity range, between 2 and 60 GV.

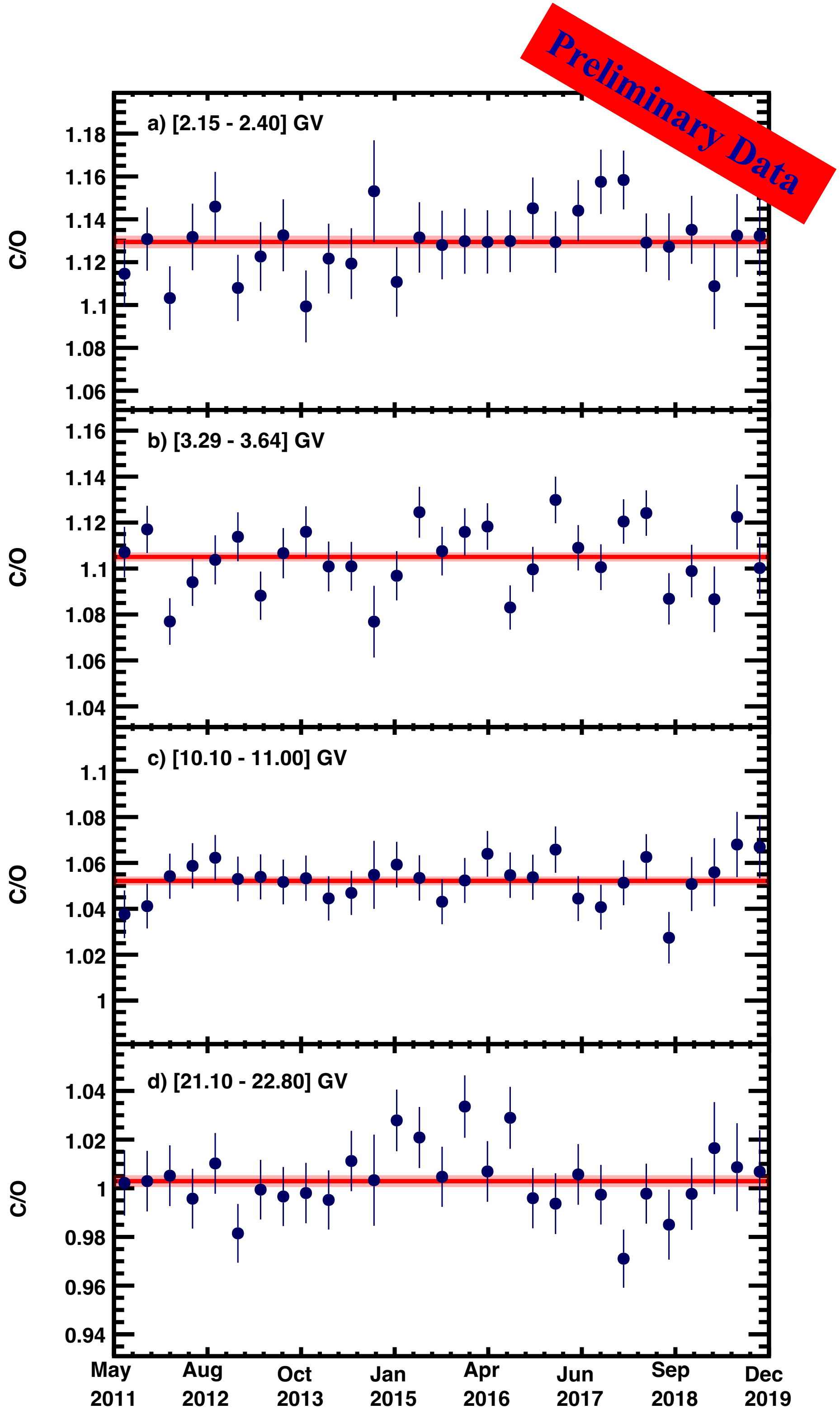


C/O vs time

C and O have the same mass-to-charge ratio. The observation that the C/O flux ratio is constant in time implies that the C and O LIS have very similar rigidity dependence above 2 GV, as observed by Voyager 1 below 1 GV.



C/O vs time

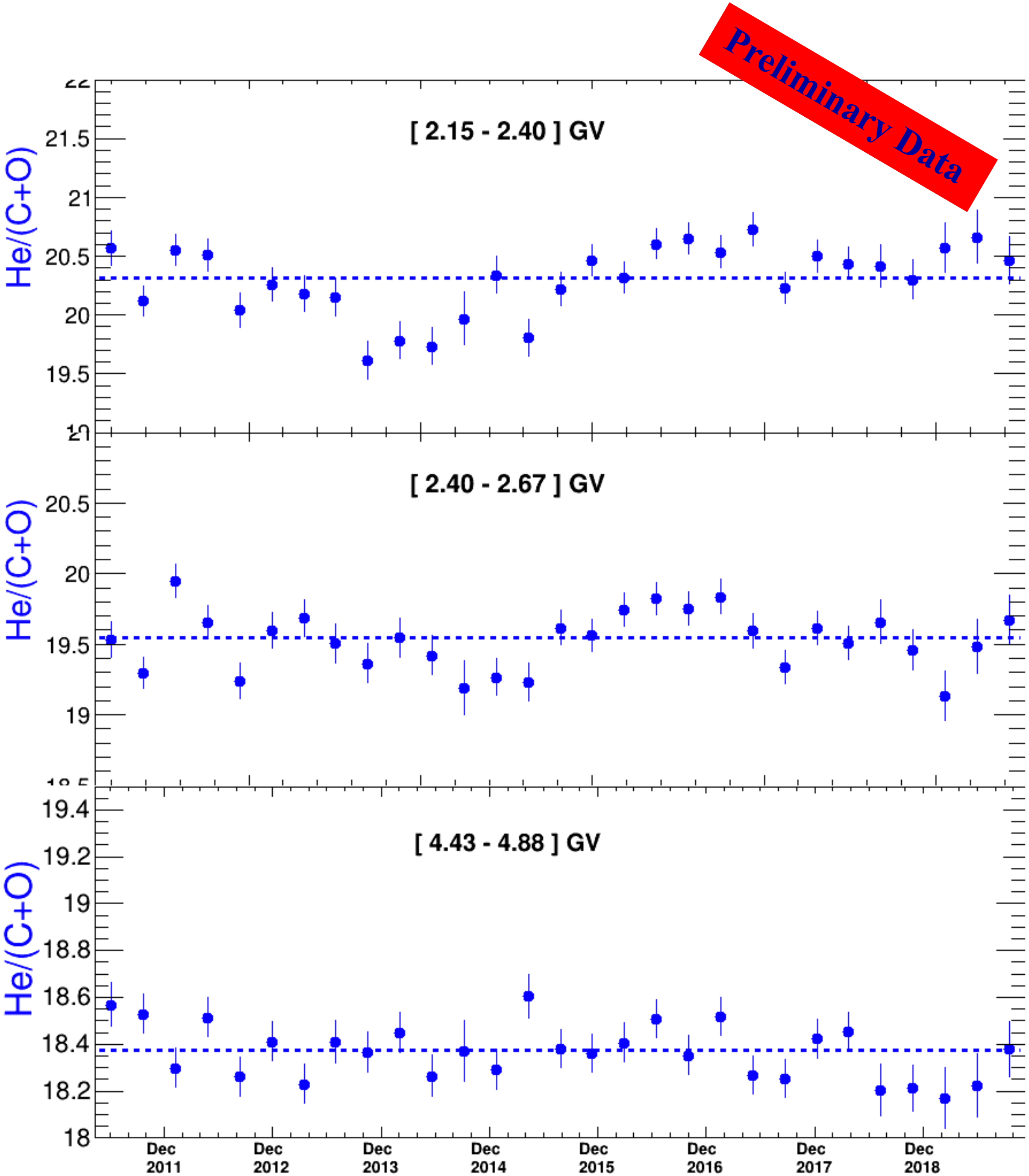


The AMS C/O flux ratio as a function of time in units of 4 Bartels rotations.

The carbon and oxygen fluxes have identical time dependence in the whole rigidity range, between 2 and 60 GV.

Given the identical behavior in time of carbon and oxygen, we will use the sum of the carbon and oxygen fluxes (C+O) for the comparison with p and He.

He/(C+O) vs Time



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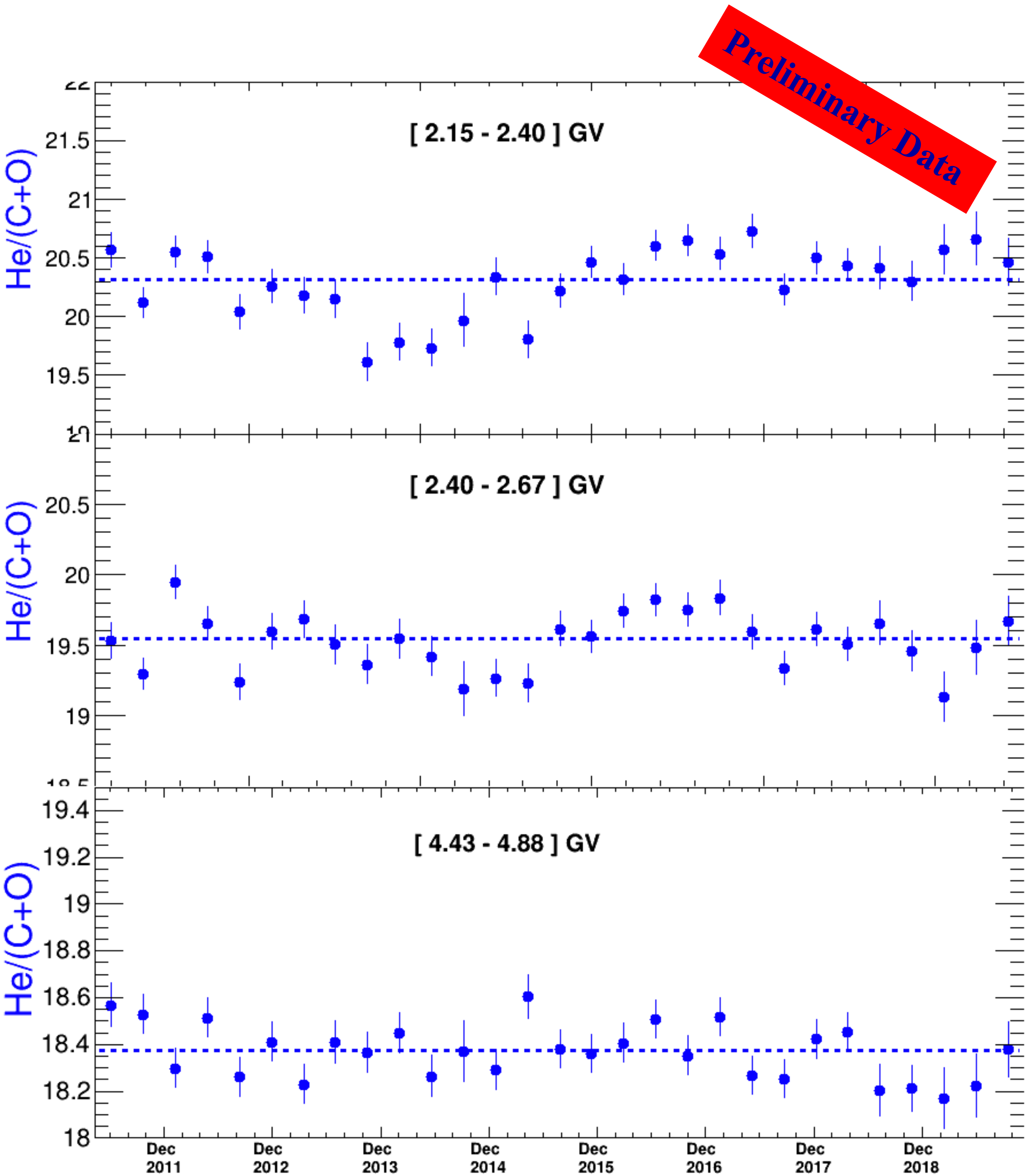
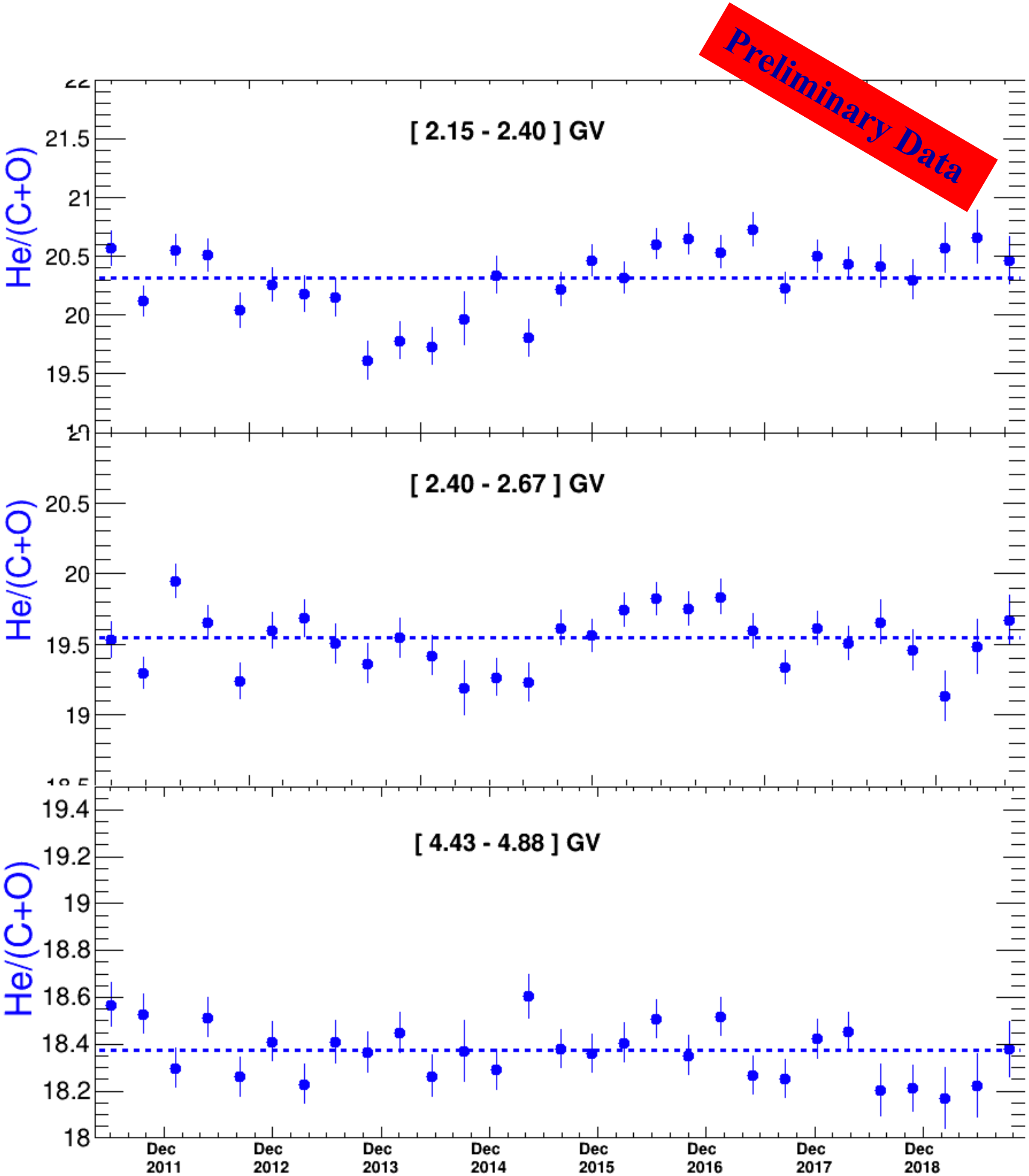
He/(C+O) vs Time



The He/(C+O) flux ratio as function of time in units of 4 Bartels rotations.

The He/(C+O) ratio doesn't show any particular variation from the constant behavior in the whole rigidity range at the 5σ level.

He/(C+O) vs Time



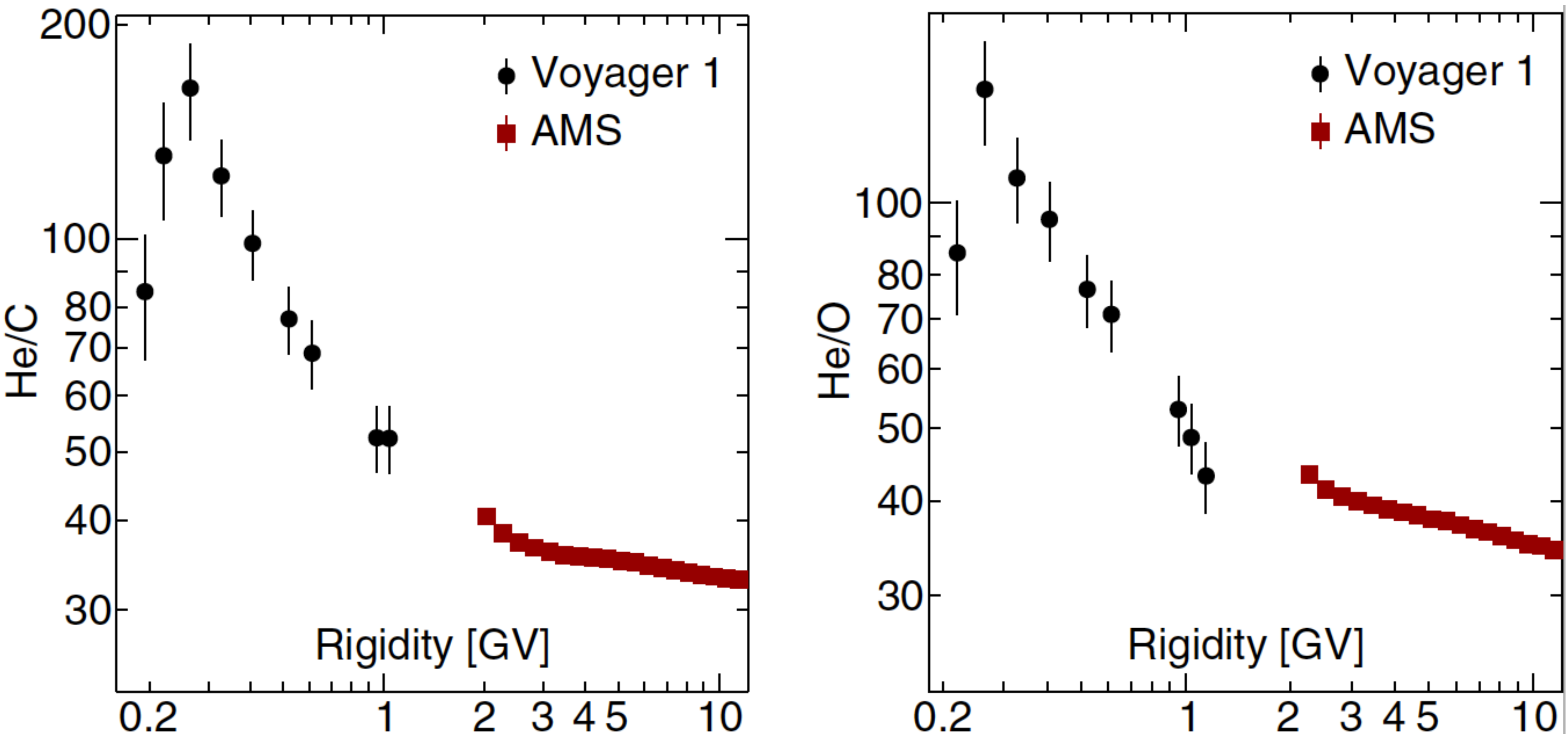
The He/(C+O) flux ratio as function of time in units of 4 Bartels rotations.

The He/(C+O) ratio doesn't show any particular variation from the constant behavior in the whole rigidity range at the 5σ level.

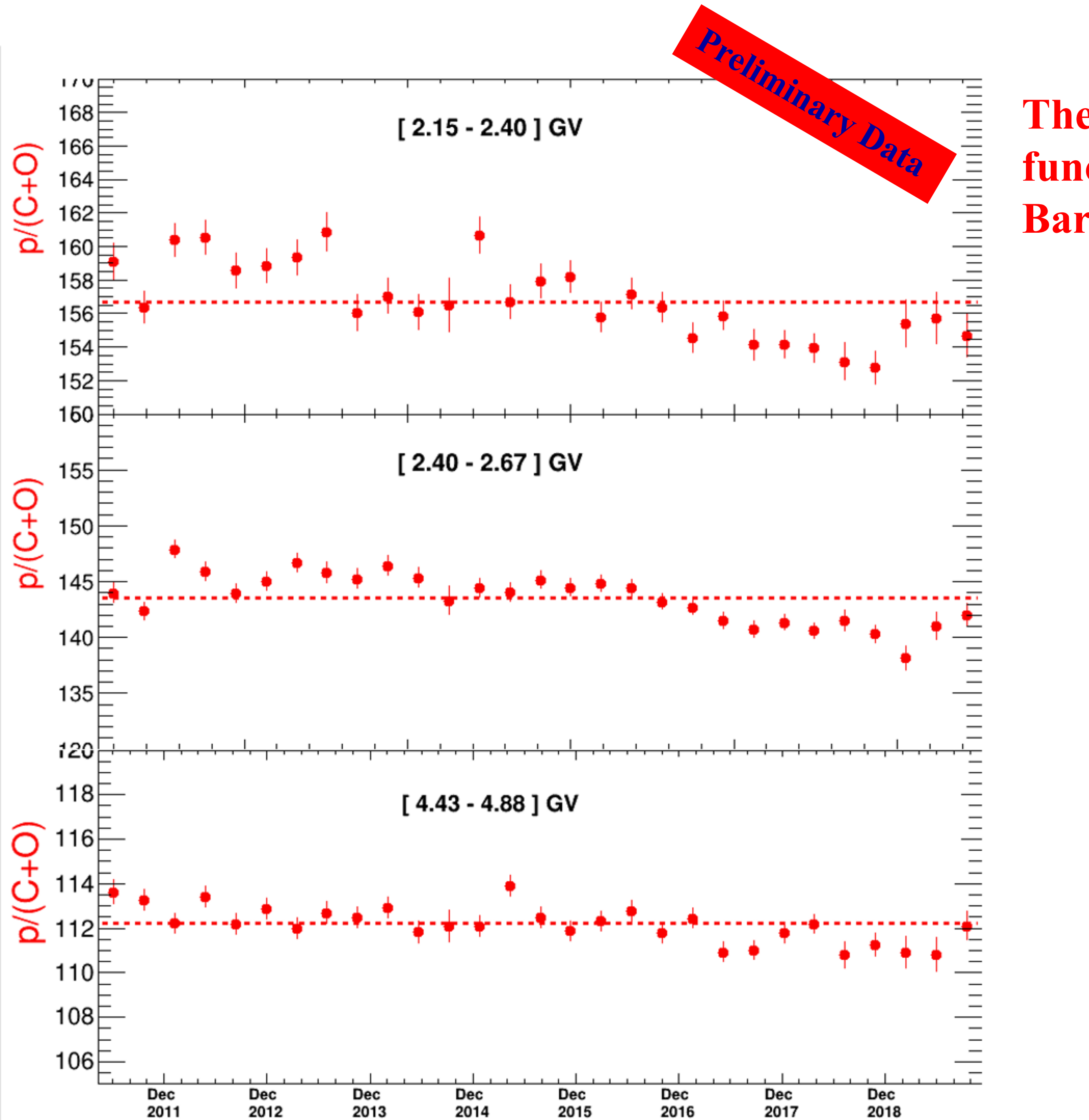
He, C and O have similar mass-to-charge ratio, Δ(A/Z) = -0.07 ± 0.03.

AMS-02 and Voyager 1: He/C and He/O ratios

The observation that the He/(C+O) flux ratio is constant in time implies that LIS have similar rigidity dependence. Meanwhile, Voyager 1 observations below 1 GV contradict this.



p/(C+O) vs Time



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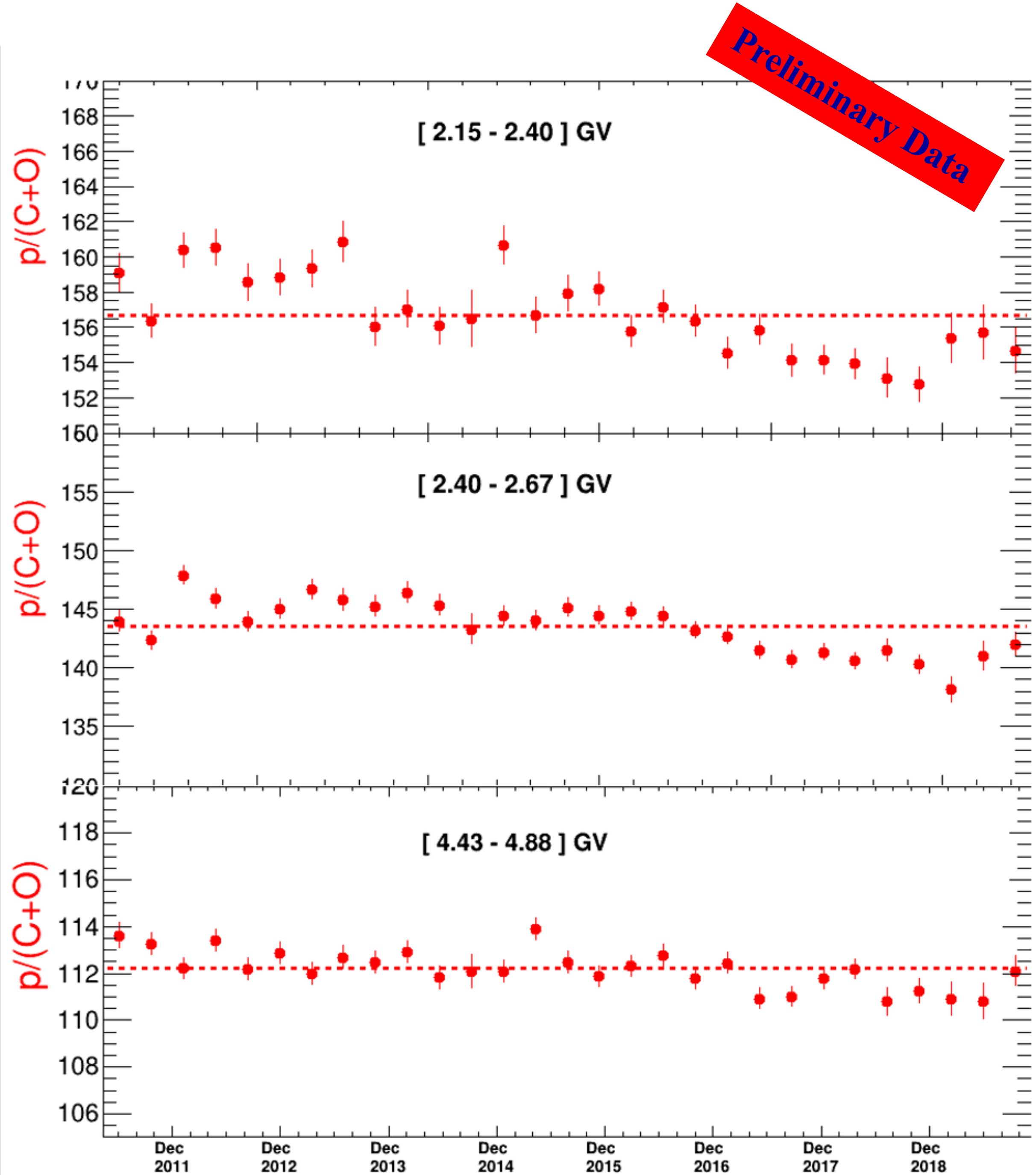
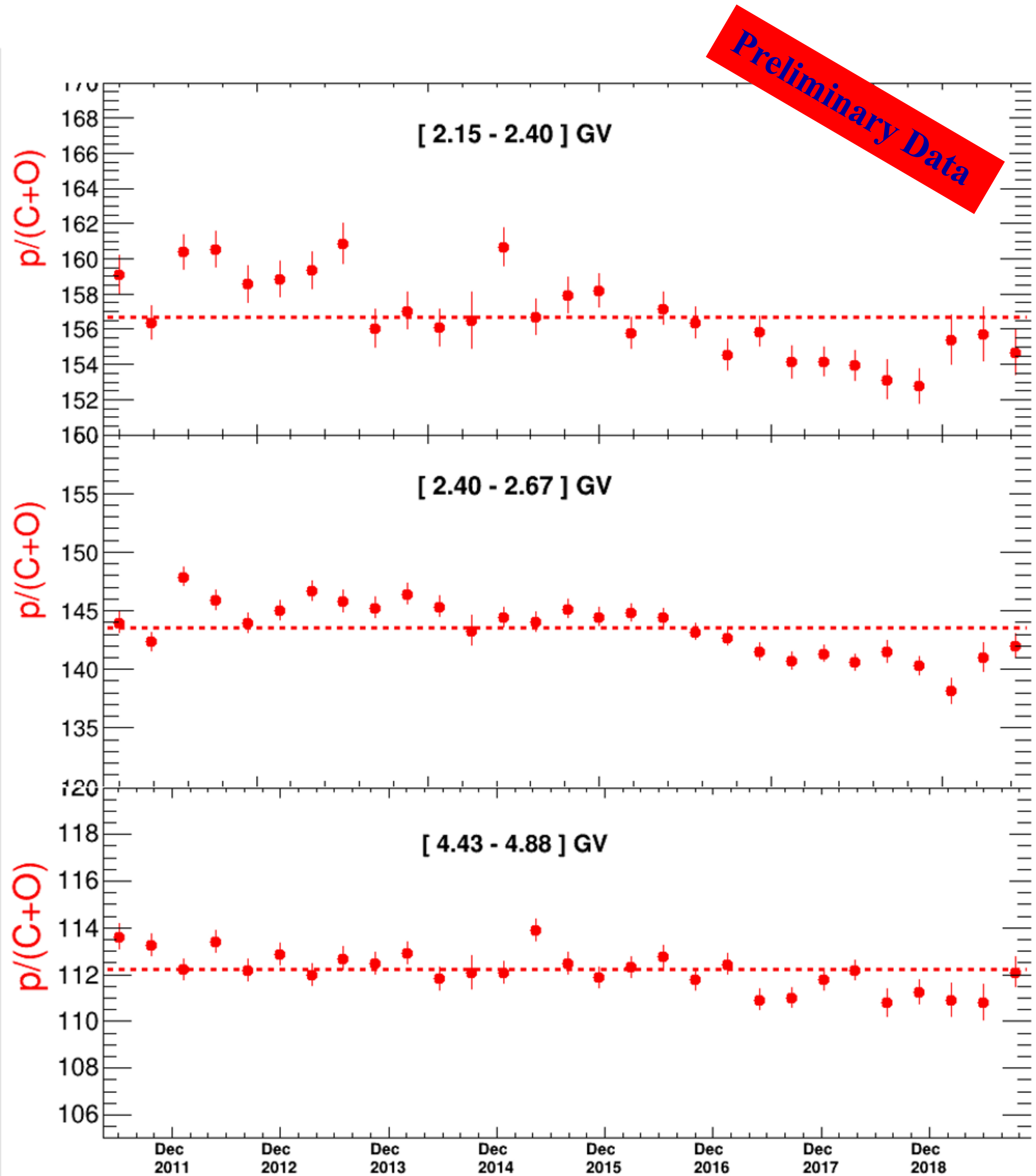
p/(C+O) vs Time



The p/(C+O) flux ratio as function of time in units of 4 Bartels rotations.

The p/(C+O) ratio is not compatible with a constant value at the 5σ level up to ~3.3 GV.

p/(C+O) vs Time

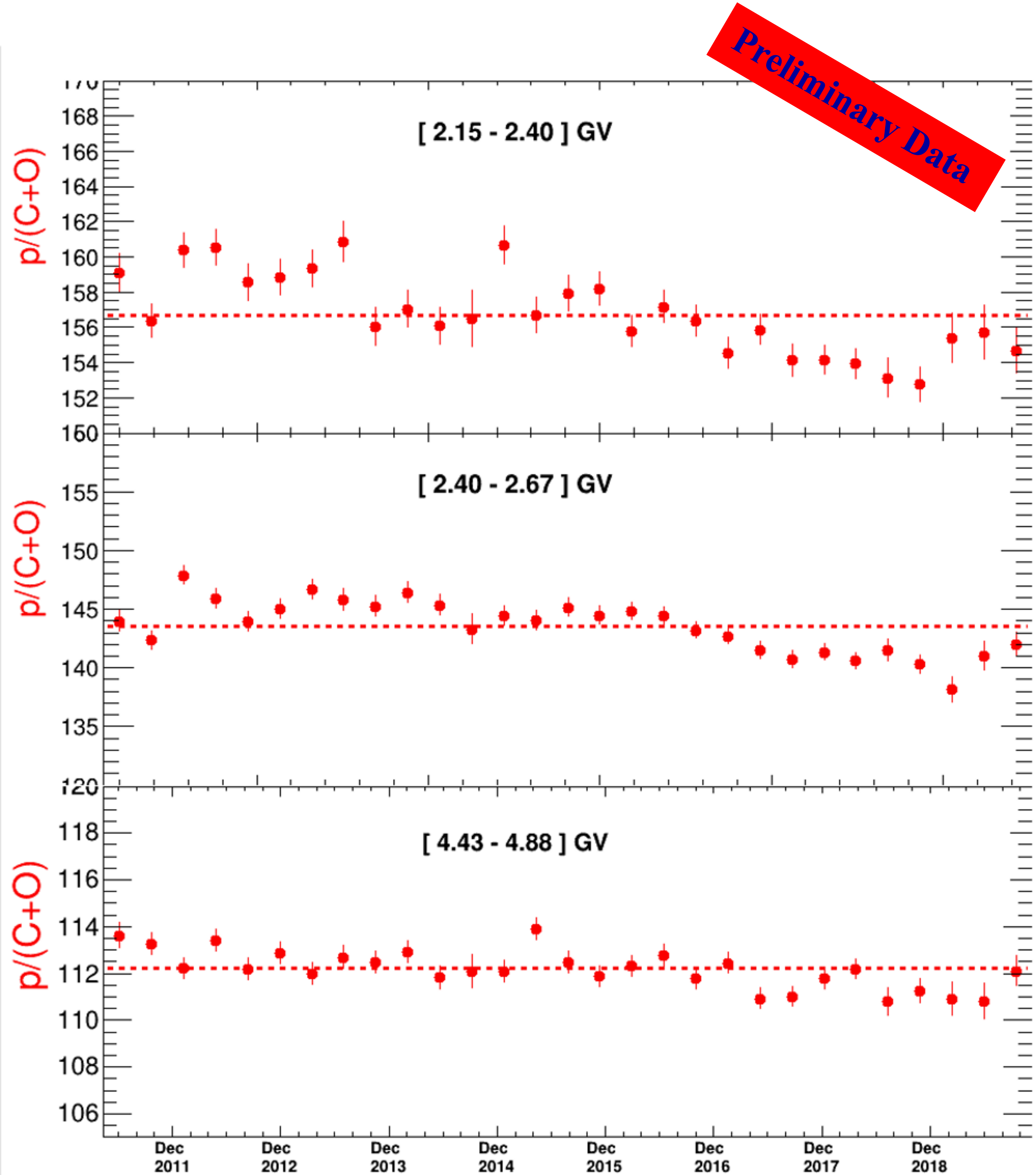


The p/(C+O) flux ratio as function of time in units of 4 Bartels rotations.

The p/(C+O) ratio is not compatible with a constant value at the 5σ level up to ~3.3 GV.

The proton mass-to-charge ratio is significantly different from the one of He, C, and O.

p/(C+O) vs Time



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The p/(C+O) ratio is not compatible with a constant value at the 5σ level up to ~3.3 GV.

The proton mass-to-charge ratio is significantly different from the one of He, C, and O.

Hence both effects, LIS flux rigidity dependence and velocity, factor into the time dependence of the p/(C+O).

Conclusions

- **The precision proton, helium, carbon, and oxygen fluxes and their ratios have been measured in Bartels rotations between May 2011 and Nov 2019 over rigidities from 1 GV to 60 GV.**

- **The carbon and oxygen fluxes presented are the first measurements as a function of time in this rigidity range.**

- **The 4 nuclei species exhibit similar behavior in time. The amplitude of the time variations of the fluxes decreases with increasing rigidity.**

- **The p/He flux ratio is not compatible with a constant value below ~5 GV.**

- **C&O have an identical time behavior, indicating a very similar rigidity dependence of their LIS above ~2GV.**

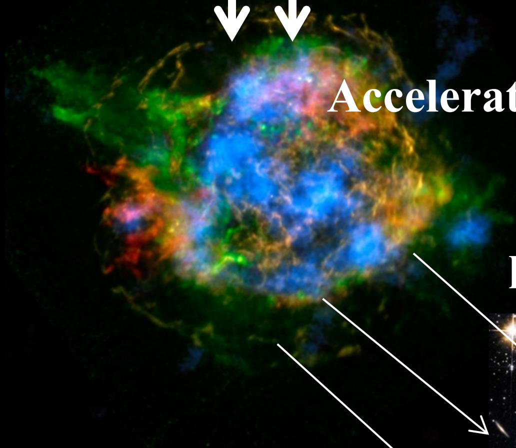
- **The He/(C+O) flux ratio exhibit no time dependence, but this has to be revised in more detail.**

- **The p/(C+O) flux ratio also shows a time dependence up to ~3.3 GV. Both LIS rigidity dependence and velocity contribute to this time behavior.**

Backup

Galactic Cosmic Rays Origin and Acceleration

Primaries CRs are mostly created inside stars



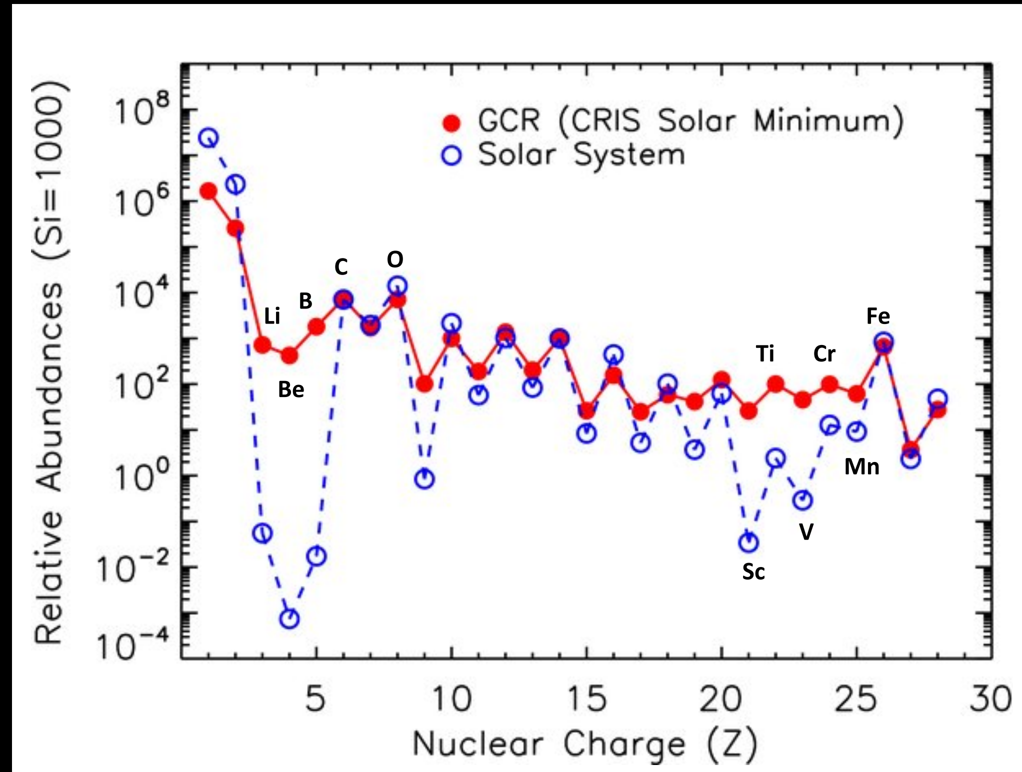
Accelerated in supernovae

p, He, C, O...

Secondaries are mostly produced by the collisions of primaries with the ISM

Interstellar medium (ISM)

Li, Be, B...

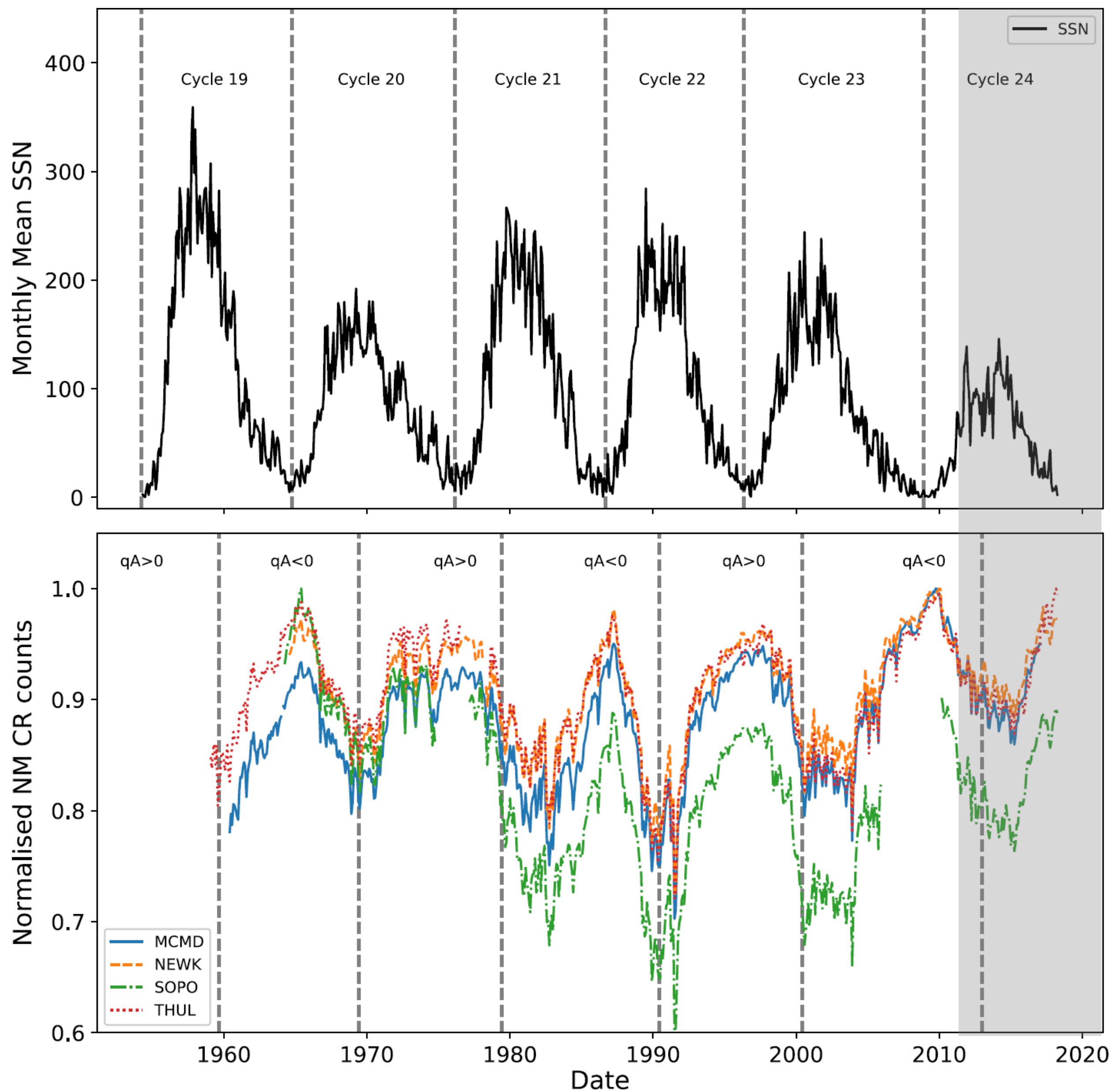


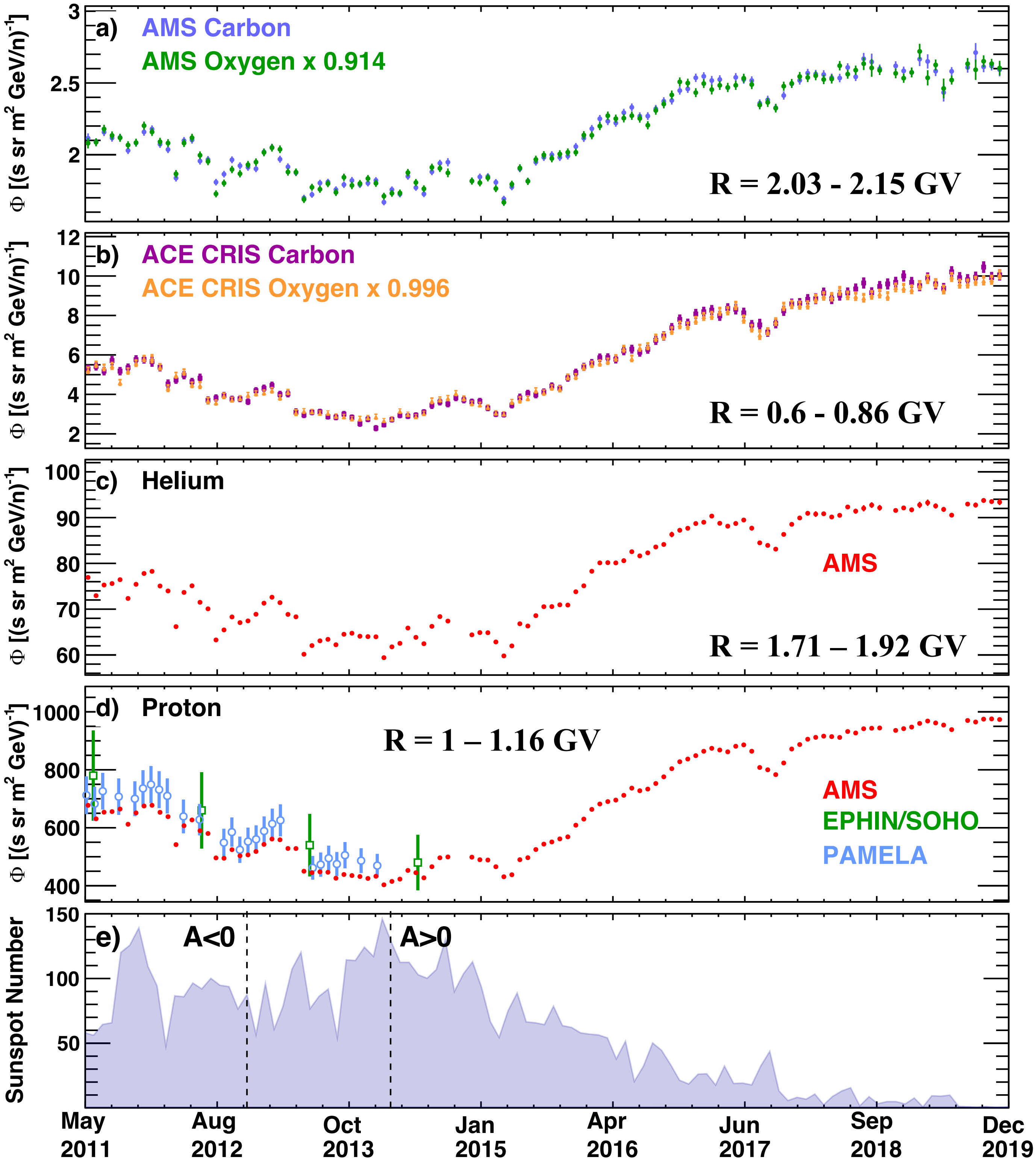
Solar Modulation

The solar modulated energy spectra of GCRs is **anti-correlated** with the solar activity, i.e. the measured flux is **higher** at epochs of **less solar activity** and **lower** at epochs of **higher solar activity**.

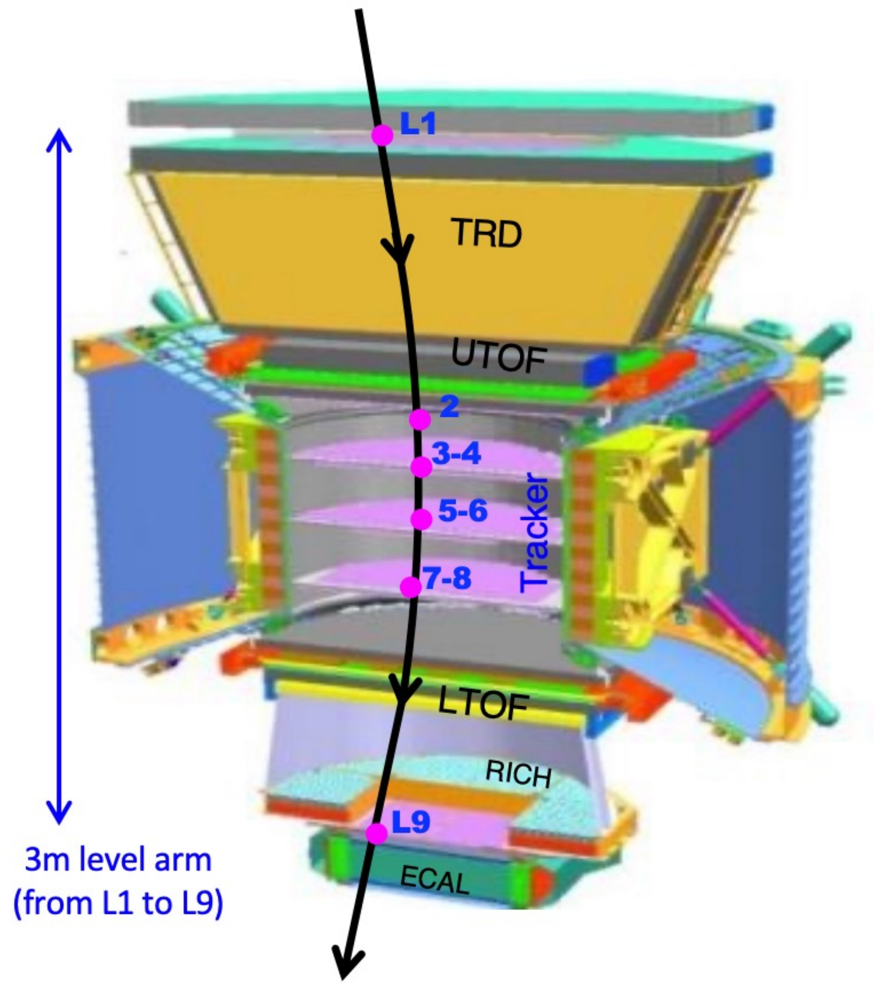
The solar modulation effect decreases with the CR energy. Solar modulation is known to be dependent on the GCRs charge sign, energy, and its also time and space dependent.

AMS-02




a) AMS Carbon
AMS Oxygen x 0.914
R = 2.03 - 2.15 GV
b) ACE CRIS Carbon
ACE CRIS Oxygen x 0.996
R = 0.6 - 0.86 GV
c) Helium
AMS
R = 1.71 – 1.92 GV
d) Proton
R = 1 – 1.16 GV
AMS
EPHIN/SOHO
PAMELA
e) A<0 A>0
Sunspot Number
Φ [(s sr m² GeV/n)⁻¹]
Φ [(s sr m² GeV)⁻¹]
May 2011
Aug 2012
Oct 2013
Jan 2015
Apr 2016
Jun 2017
Sep 2018
Dec 2019

AMS Nuclei Measurement

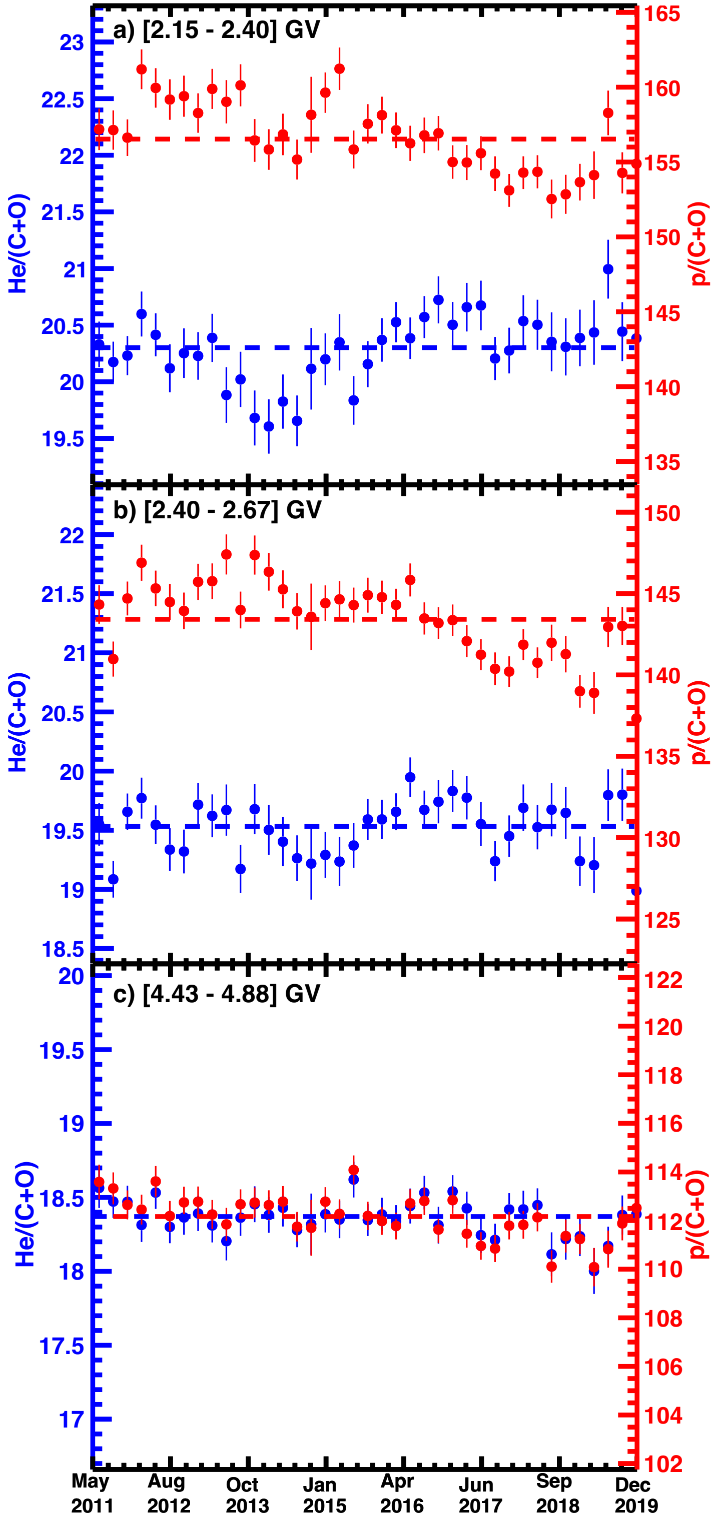


Particle Rigidity (momentum/charge) is measured combining Tracker (9 Layers) + Magnet

	Coordinate Resolution	MDR
Z =1	10 μm	2 TV
$2 \leq Z \leq 8$	5-7 μm	3.2-3.7 TV
$9 \leq Z \leq 14$	6-8 μm	3-3.5 TV

Particle is identified using consistency of charge measured in L1, UTOF, Inner Tracker (L2-L8), LTOF and L9.

	Tracker L2-L8 Charge Resolution (c.u.)
$1 \leq Z \leq 8$	$\Delta Z \approx 0.05\text{-}0.12$
$9 \leq Z \leq 14$	$\Delta Z \approx 0.13\text{-}0.17$



He/(C+O) and p/(C+O) vs Time

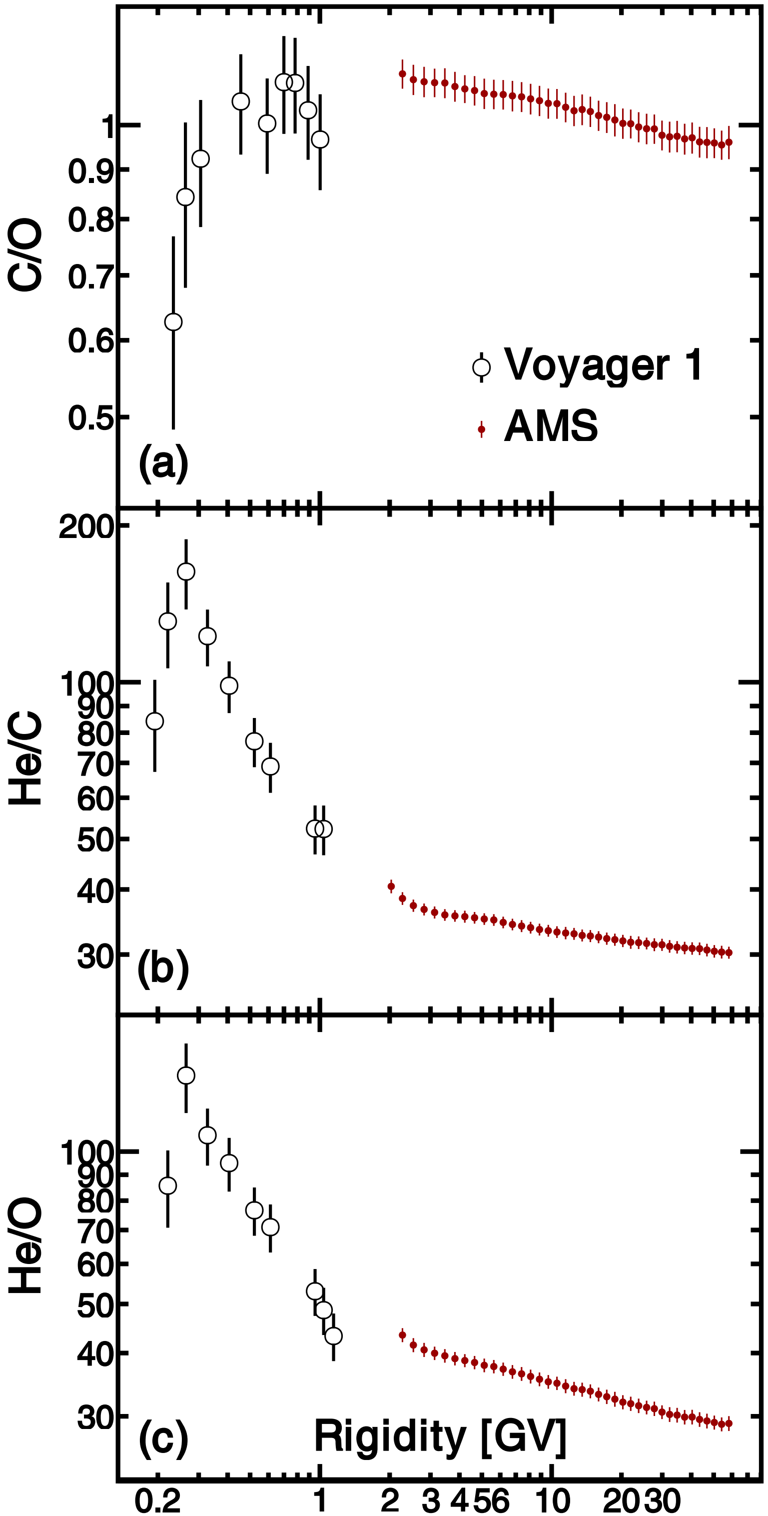
The He/(C+O) and p/(C+O) flux ratios as function of time in units of 3 Bartels rotations.

The He/(C+O) ratio doesn't show any particular variation from the constant behavior in the whole rigidity range at the 5σ level.

The p/(C+O) ratio is not compatible with a constant value at the 5σ level up to ~3.3 GV.

The proton mass-to-charge ratio is significantly different from the one of He, C, and O.

Hence both effects, LIS flux rigidity dependence and velocity, factor into the time dependence of the p/(C+O) and p/He flux ratios.



The (a) C/O, (b) He/C and (c) He/O flux ratios as a function of rigidity measured by AMS, at 1 AU, from May 2011 to November 2019 compared with Voyager-1 data, outside the heliosphere, converted from kinetic energy per nucleon E_k using

$$R = A/Z\sqrt{E_K(E_K + 2M/A)}$$

where Z is the atomic number, while M and A are, respectively, the mass, and the mass number averaged assuming an isotopic composition for each element of:

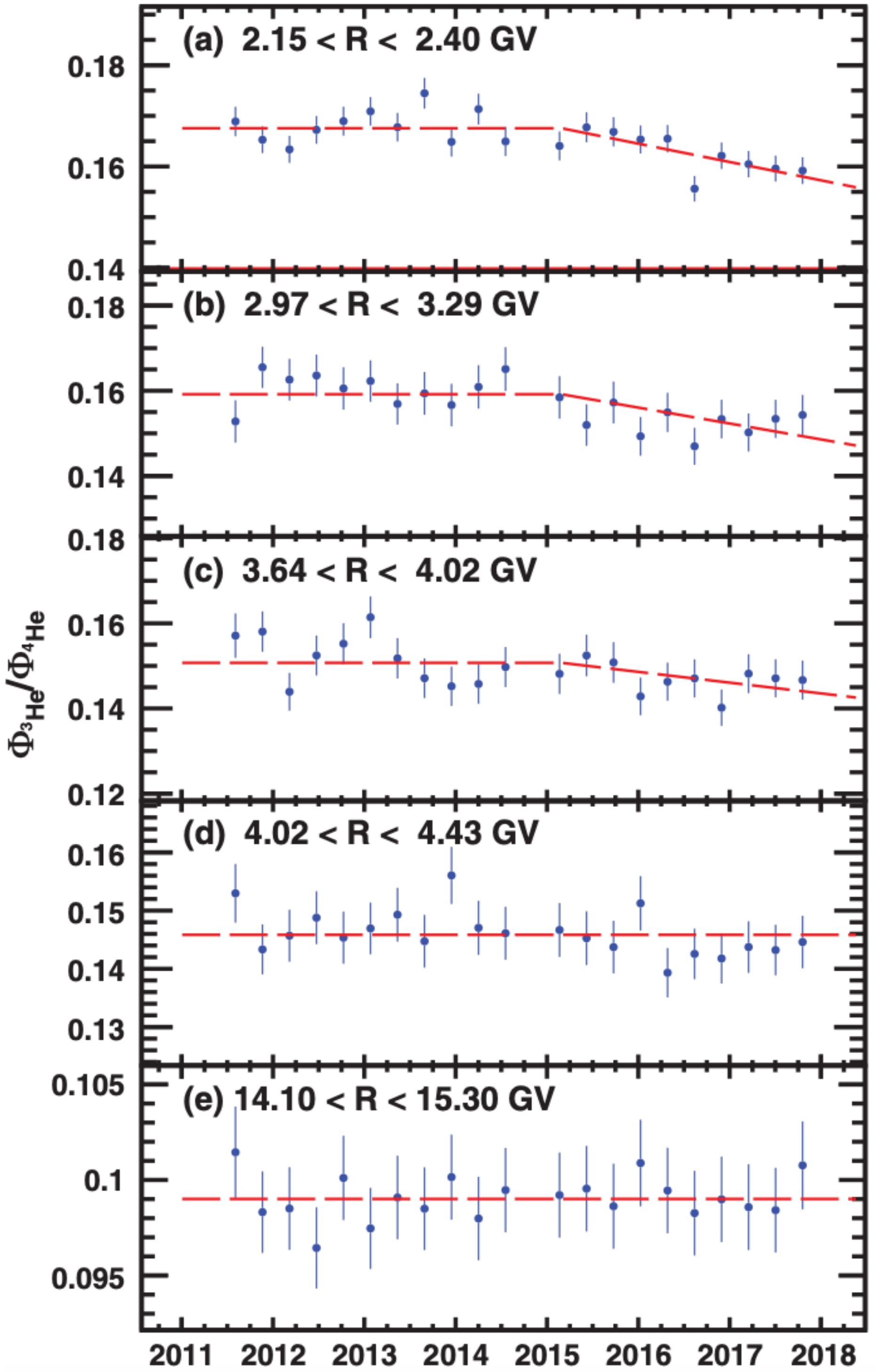
^{3}He/He = 13±4%,

^{13}C/C = 10±10%,

^{17}O/O = 1.5±1.5%,

and ^{18}O/O = 1.5±1.5%

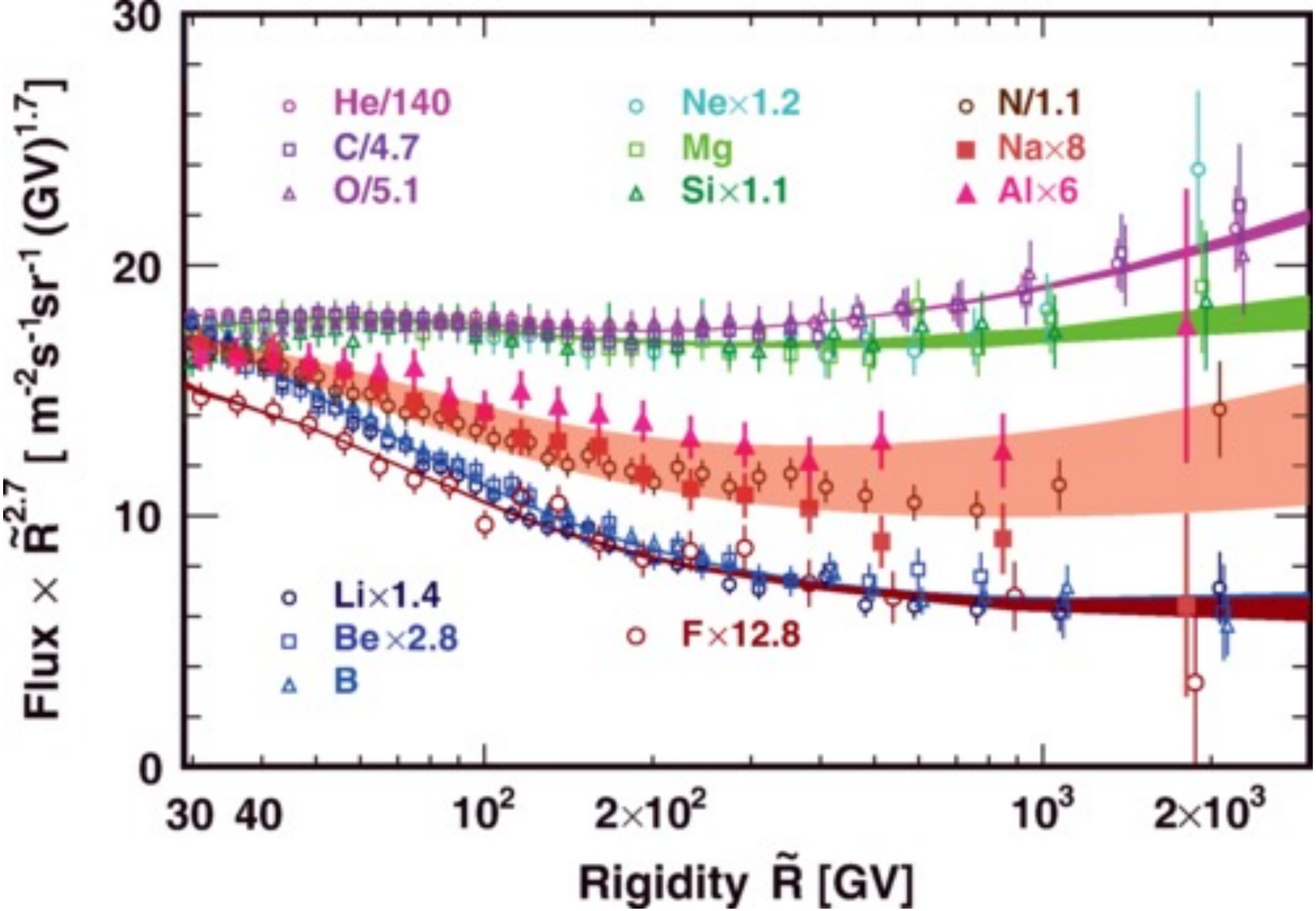
(as estimated from https://lpsc.in2p3.fr/crdb).



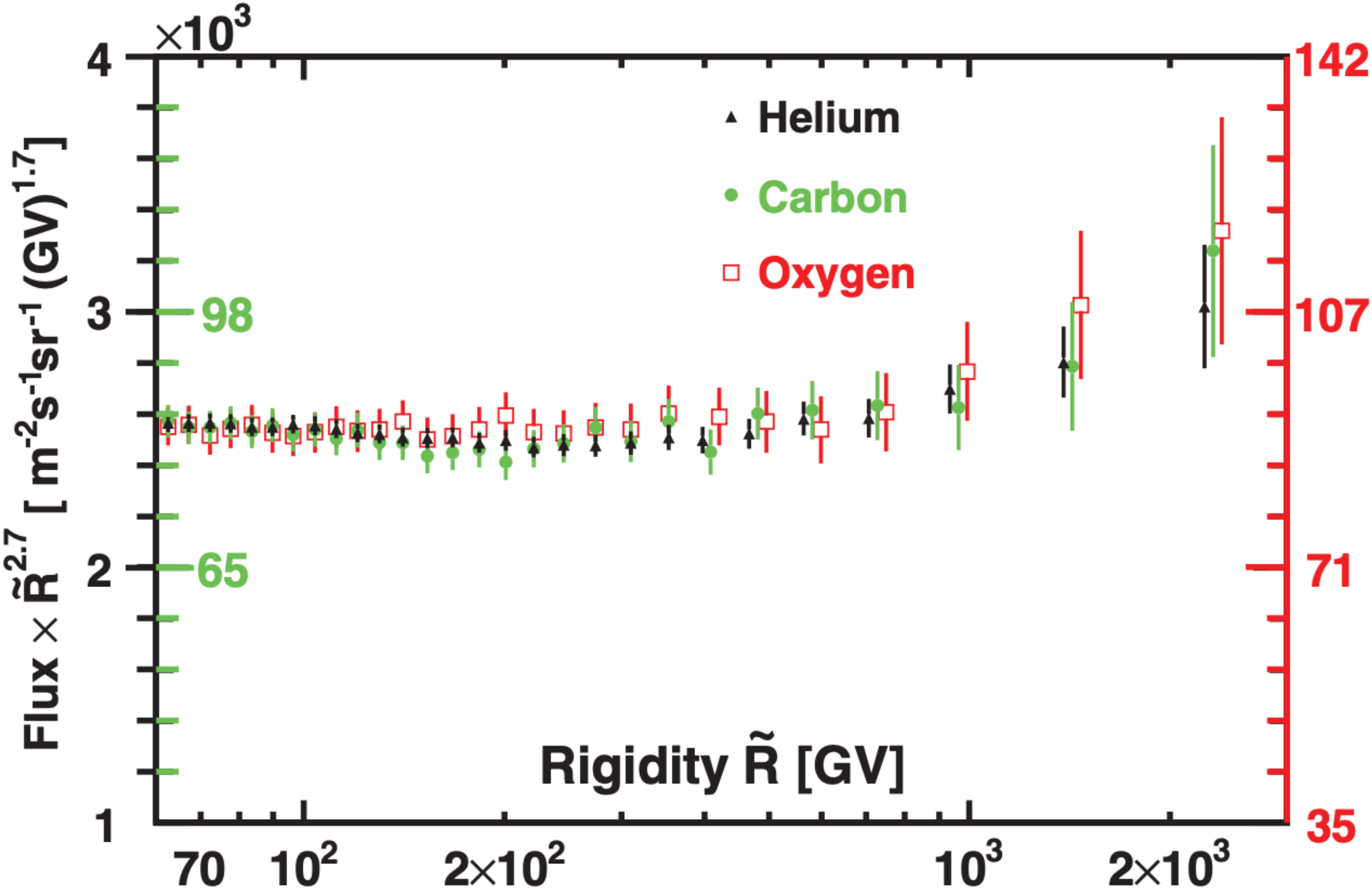
The time dependence variation on He/(C+O) due to the different LIS shape should be much smaller than the corresponding effect on p/(C+O) because the LIS He/(C+O) spectral index is at least 3 times smaller than the LIS p/(C+O) spectral index.

Still working on errors to try to understand if this behavior is really constant or not.

Also because for ^{3}He/O and ^{4}He/O the velocity term is a little bit different for the ^{3}He.



- **The fluxes of cosmic nuclei measured by AMS as a function of rigidity from Z = 2 to Z = 14 above 30 GV.**
- **Two classes of primary cosmic rays, He-C-O and Ne-Mg-Si, and two classes of secondary cosmic rays, Li-Be-B and F.**
- **N, Na and Al belong to a distinct group and are the combinations of primary and secondary cosmic rays.**



The rigidity dependence of the helium (left black axis), carbon (left green axis), and oxygen (right red axis) fluxes. For clarity, horizontal positions of the helium and oxygen data points above 400 GV are displaced with respect to the carbon. As seen, above 60 GV the three fluxes have identical rigidity dependence.