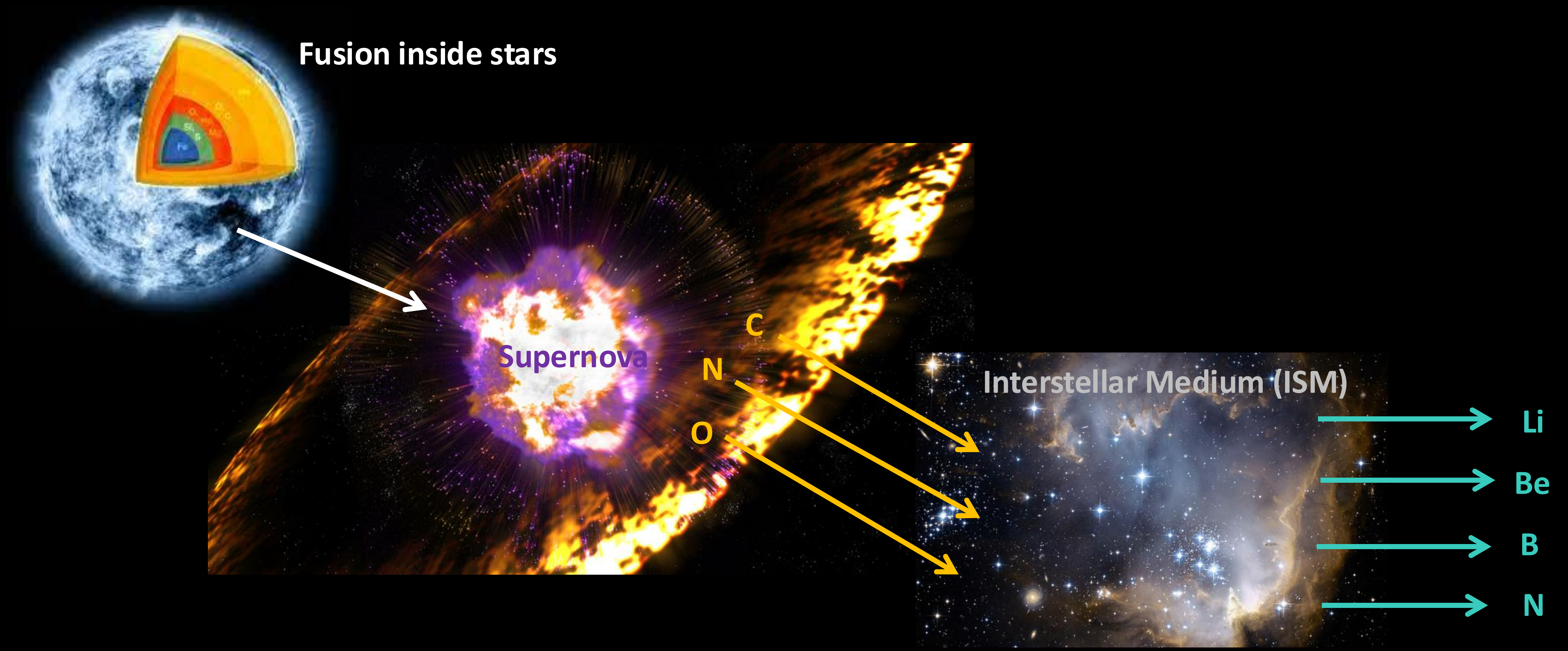
Unique Properties of Light Nuclei Time Variation up to 60 GV Measured by the Alpha Magnetic Spectrometer

Valerio Formato, INFN, Sezione di Roma Tor Vergata
on behalf of the AMS-02 Collaboration

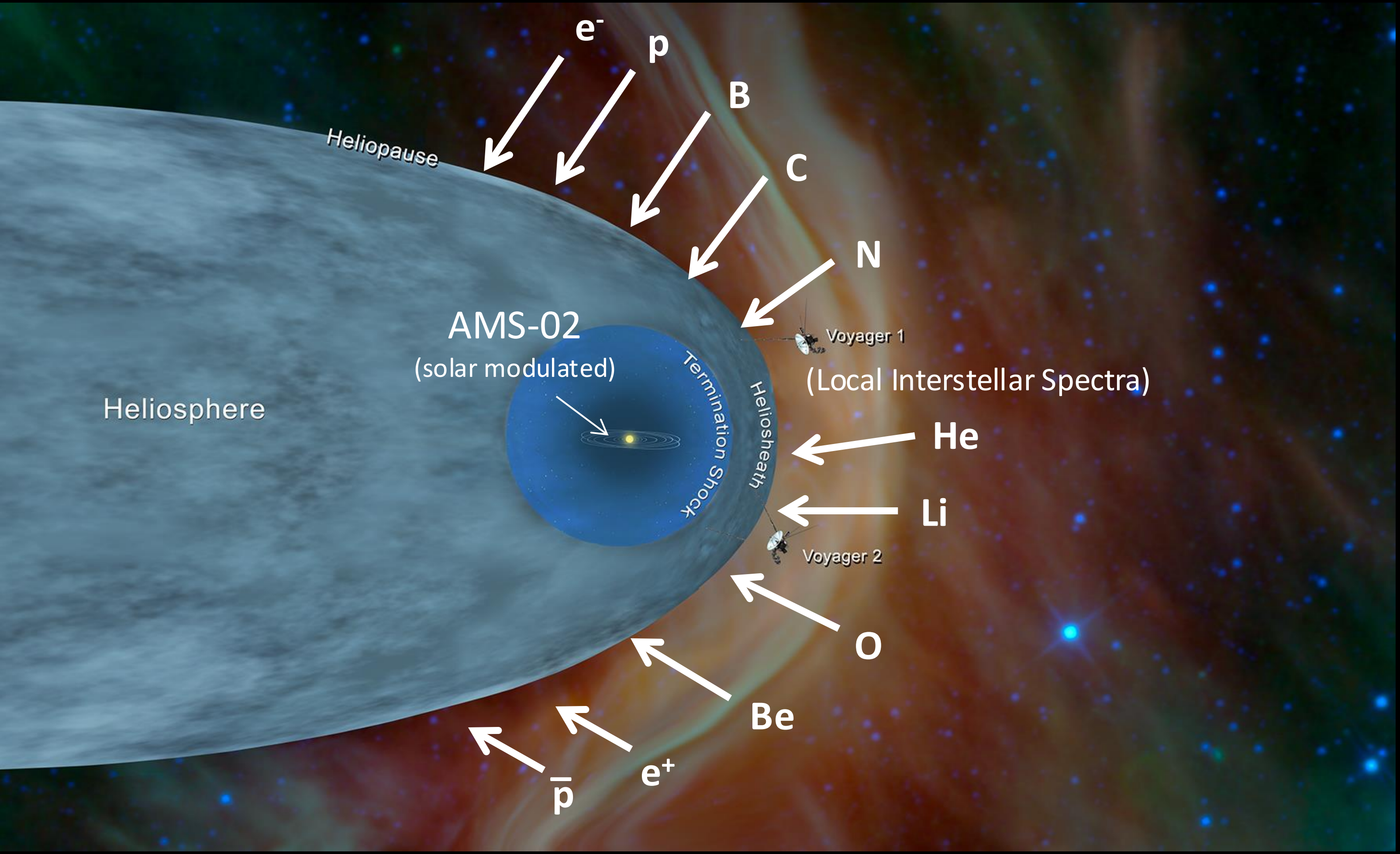
Galactic Cosmic Rays (GCRs) Propagation in the Galaxy



Primary GCRs are mostly created inside stars and accelerated in supernovae.
Secondary GCRs are mostly produced by the collisions of primaries with the **ISM**.

GCRs Propagation in the Heliosphere

GCRs entering the heliosphere are subject to diffusion, convection, adiabatic energy losses and magnetic drift.
This is commonly known as Solar Modulation.



Differences in solar modulation among different nuclei can be attributed to:

- Differences in the spectral (LIS) shape of cosmic rays entering the heliosphere.
- Differences arising from the velocity dependence of the solar modulation (for the same rigidity different species have different velocities depending on the A/Z ratio).

Measuring the effect of solar modulation on elements with **different spectral shape** (primary/secondary) and/or **different A/Z** (as ex. C, O = 2, Li ≃ 2.17) provides information of the propagation of CRs in the heliosphere.

Parker's Equation

GCRs entering the heliosphere are subject to diffusion, convection, adiabatic energy losses and magnetic drift.
This is commonly known as Solar Modulation.

$$\frac{\partial \varphi}{\partial t} = \nabla \cdot (\mathbf{k} \nabla \varphi) - (\mathbf{V} + \langle \mathbf{v}_d \rangle) \cdot \nabla \varphi + \frac{1}{3}(\nabla \cdot \mathbf{V}) \frac{\partial \varphi}{\partial \log p}$$

Similar to the galactic transport equation (in part, similar underlying physics), describes CR diffusion in the heliosphere

Magnetic diffusion on field perturbations

Convection due to solar wind

Drift due to magnetic field gradients

Adiabatic energy losses due to expanding sloar wind

Parker's Equation

GCRs entering the heliosphere are subject to diffusion, convection, adiabatic energy losses and magnetic drift.
This is commonly known as Solar Modulation.

$$\frac{\partial \varphi}{\partial t} = \nabla \cdot (\mathbf{k} \nabla \varphi) - (\mathbf{V} + \langle \mathbf{v}_d \rangle) \cdot \nabla \varphi + \frac{1}{3}(\nabla \cdot \mathbf{V}) \frac{\partial \varphi}{\partial \log p}$$

Similar to the galactic transport equation (in part, similar underlying physics), describes CR diffusion in the heliosphere

Magnetic diffusion on field perturbations

Convection due to solar wind

Drift due to magnetic field gradients

$$\langle \mathbf{v}_d \rangle = \nabla \times \left(K_d \frac{\mathbf{B}}{|\mathbf{B}|} \right)$$

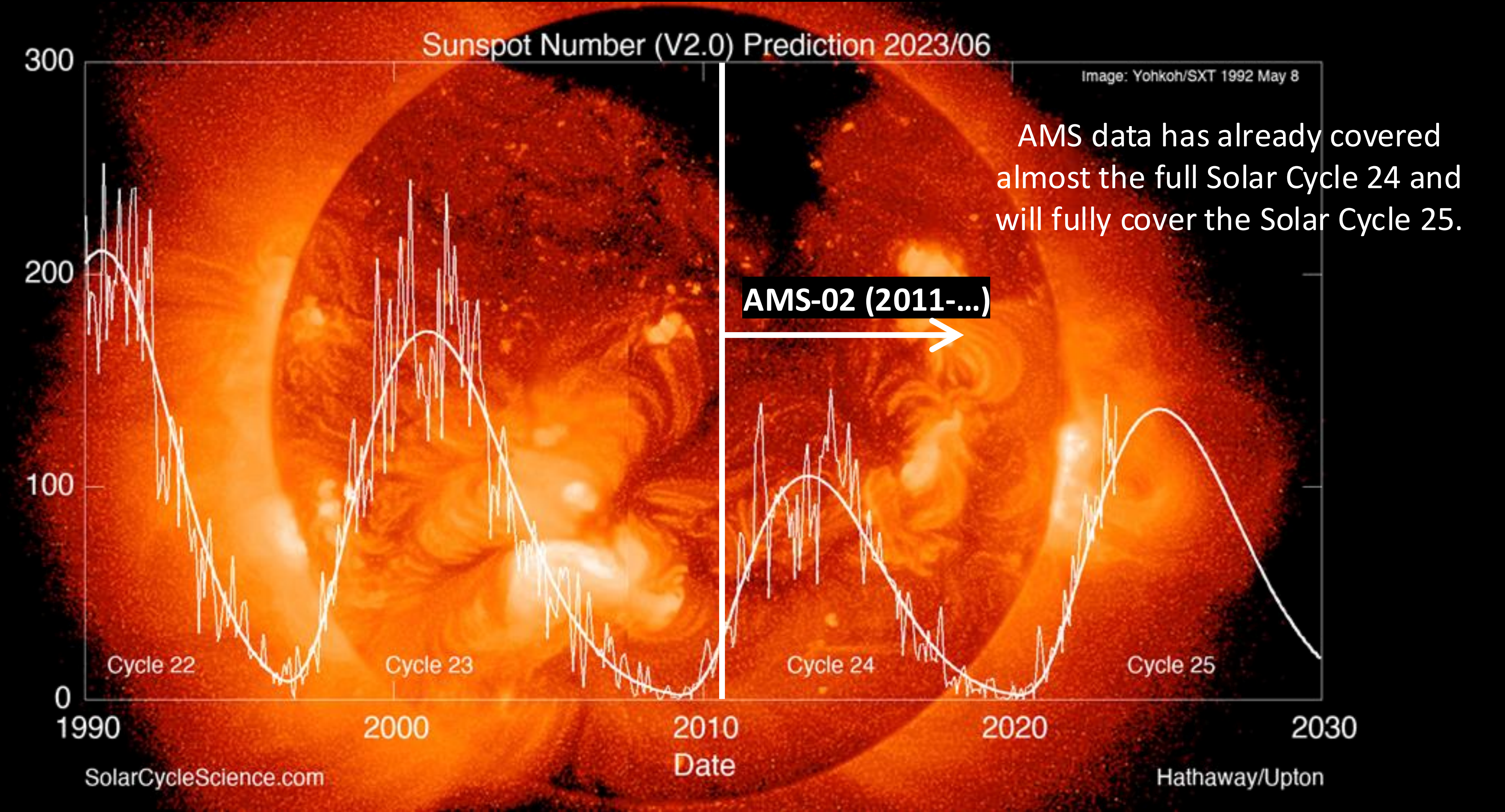
$$K_d = K_0 \frac{\beta R}{3|\mathbf{B}|}$$

Adiabatic energy losses due to expanding sloar wind

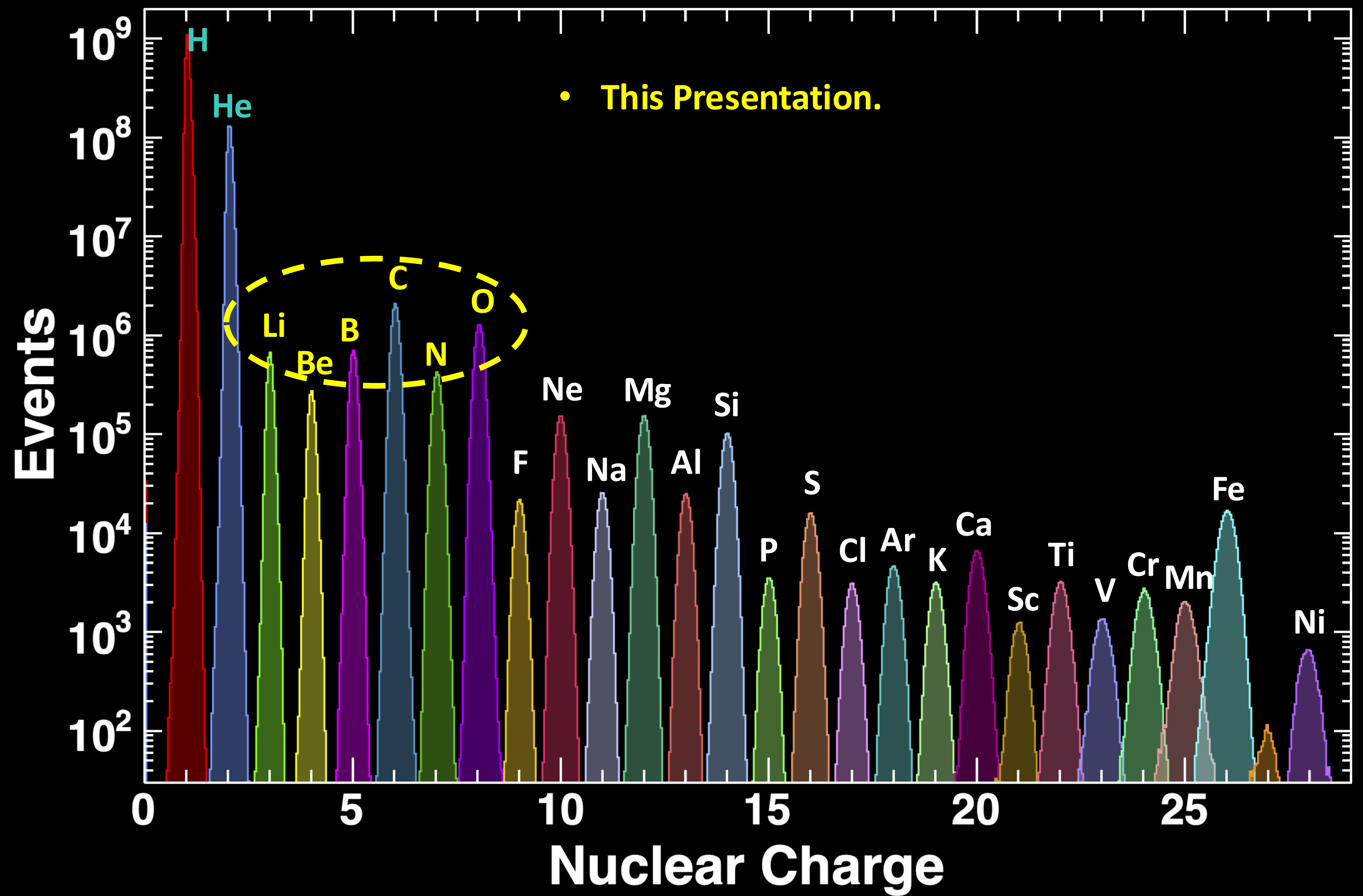
Explicit dependence on spectral shape

Solar activity and Sunspot Number

The amount of solar activity defines how the LIS is modulated in different periods.
The Sunspot Number can be used as a proxy of the solar activity.



Latest AMS results on Nuclei



AMS Nuclei Flux Measurement

The isotropic differential flux in the i-th rigidity bin (R_i; $R_i + \Delta R_i$)

Number of events after background subtraction and bin-to-bin migration correction

$$\Phi_i = \frac{N_i}{A_i \epsilon_i T_i \Delta R_i}$$

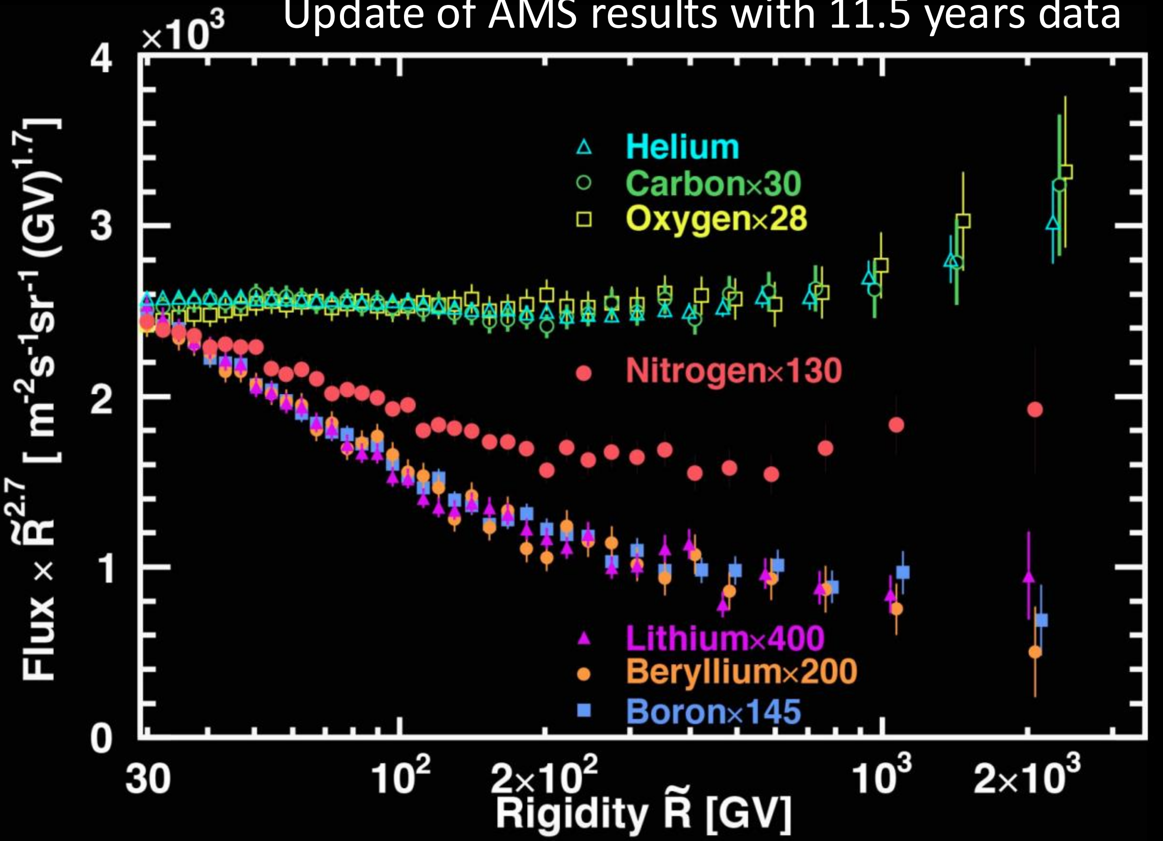
Effective acceptance

Trigger efficiency

Exposure time

Bin width

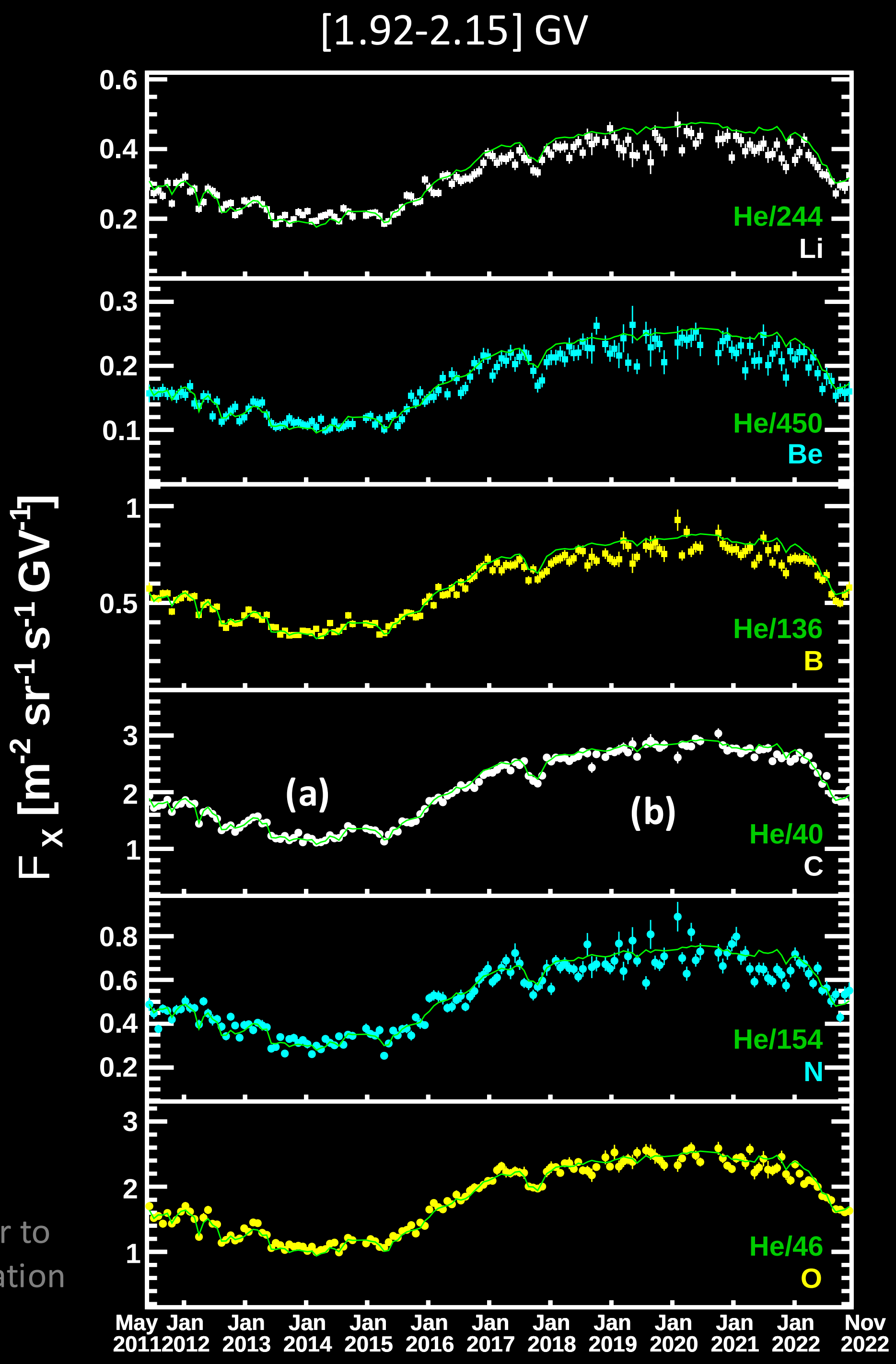
Update of AMS results with 11.5 years data



The measurement of the flux is done with accurate study of systematics errors on background evaluation, trigger efficiency, acceptance, rigidity resolution function and absolute rigidity scale.

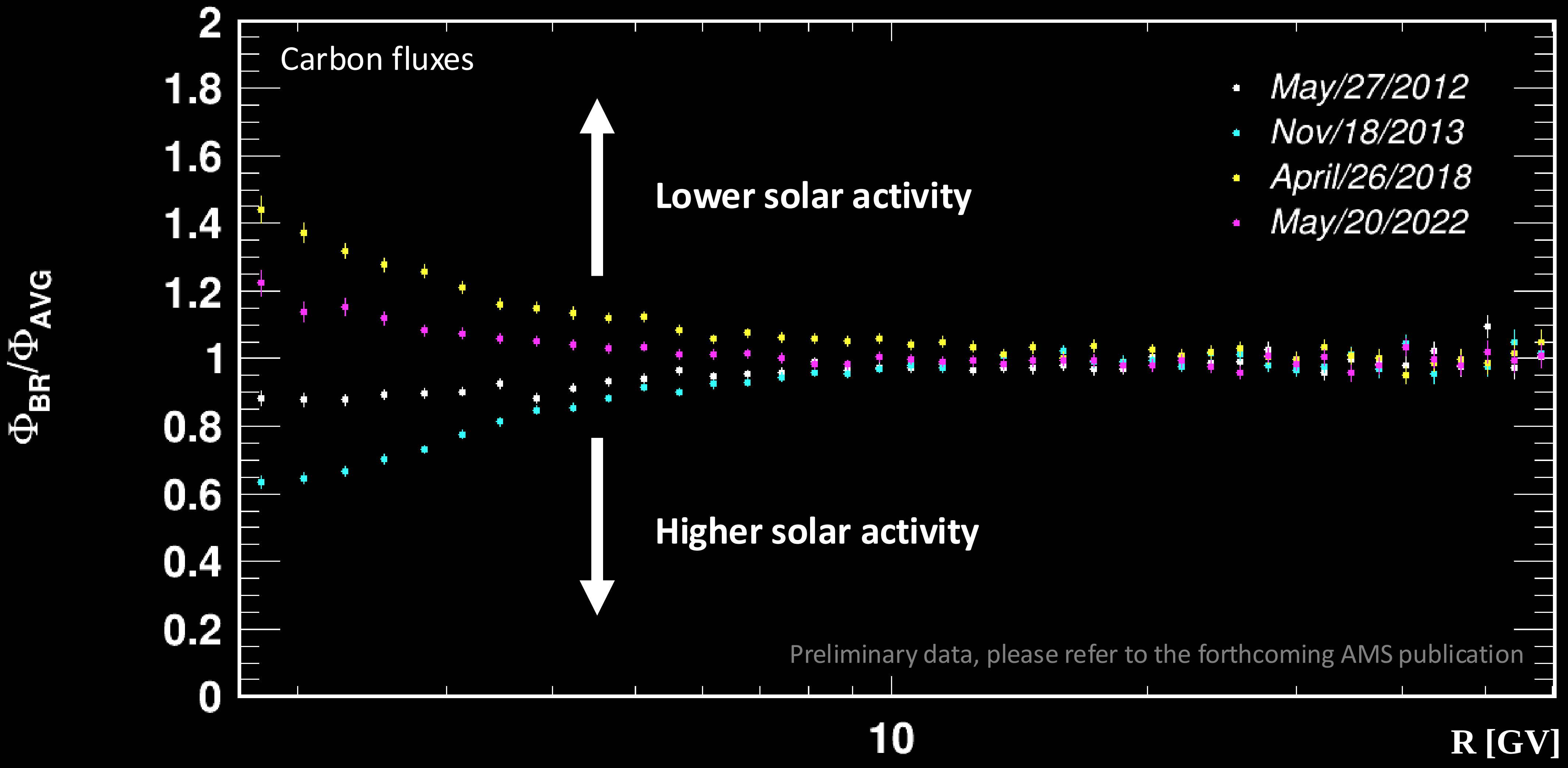
Time Variation of Cosmic Light Nuclei

- In this work we present the time evolution of light nuclei from 2 GV to 60 GV, with 5.3M Li, 2.6M Be, 7.8M B, 26.1M C, 6.6M N and 22.1M O events.
- The time range is from May 2011 to Nov 2022, for a total of 147 Bartels rotations (27 days).
- Fluxes are anti-correlated with solar activity, (a) being lower during epoch of high solar activity and (b) higher during epoch of low solar activity.
- All nuclei exhibit similar long-term and short-term time dependences.



Preliminary data, please refer to the forthcoming AMS publication

$\Phi_{BR}/\ \Phi_{AVG}$ during the Solar Cycle

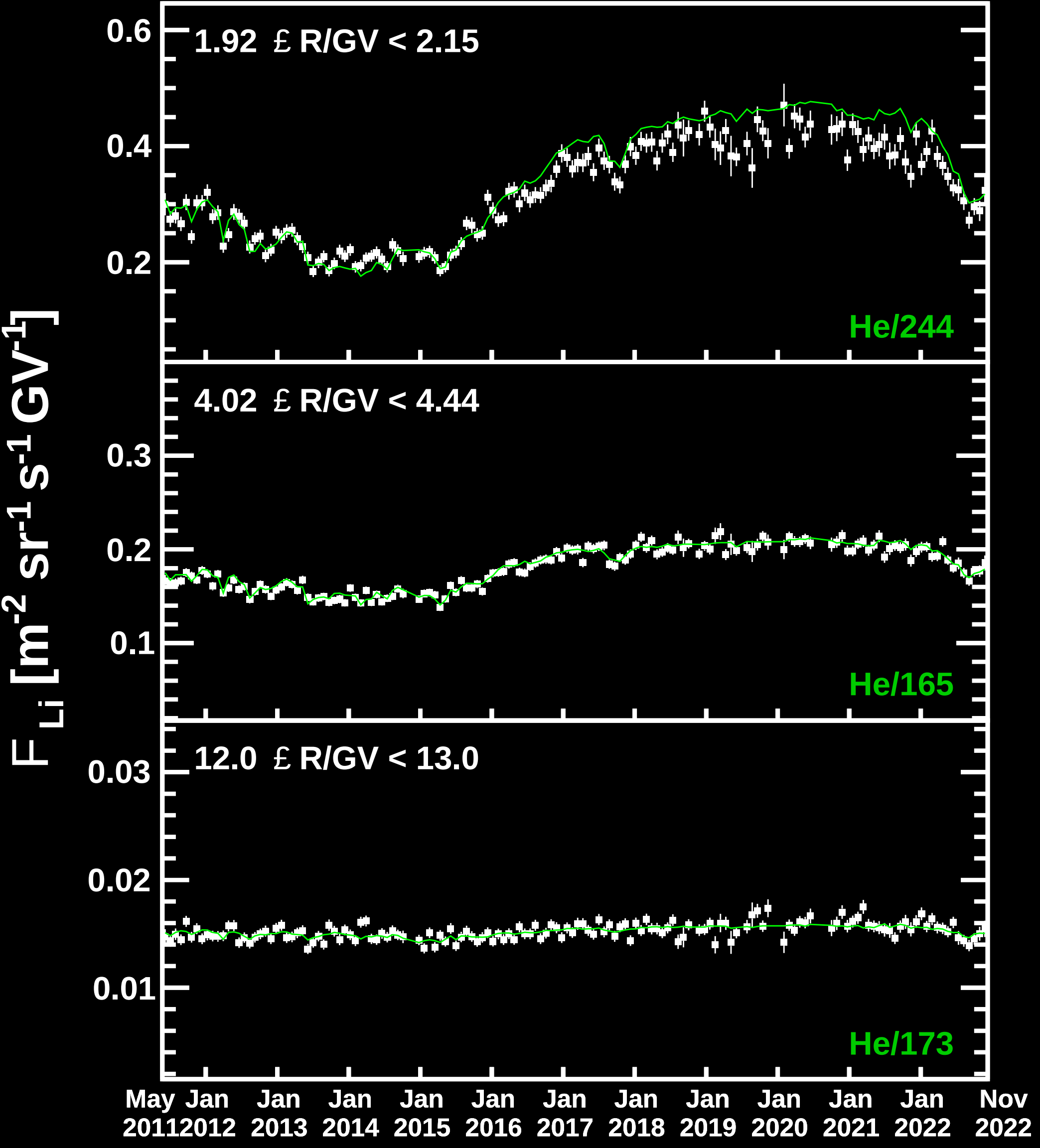


The $\Phi_{BR}/\ \Phi_{AVG}$ ratio for four Bartels rotations, shows the anti-correlation between flux and solar activity.

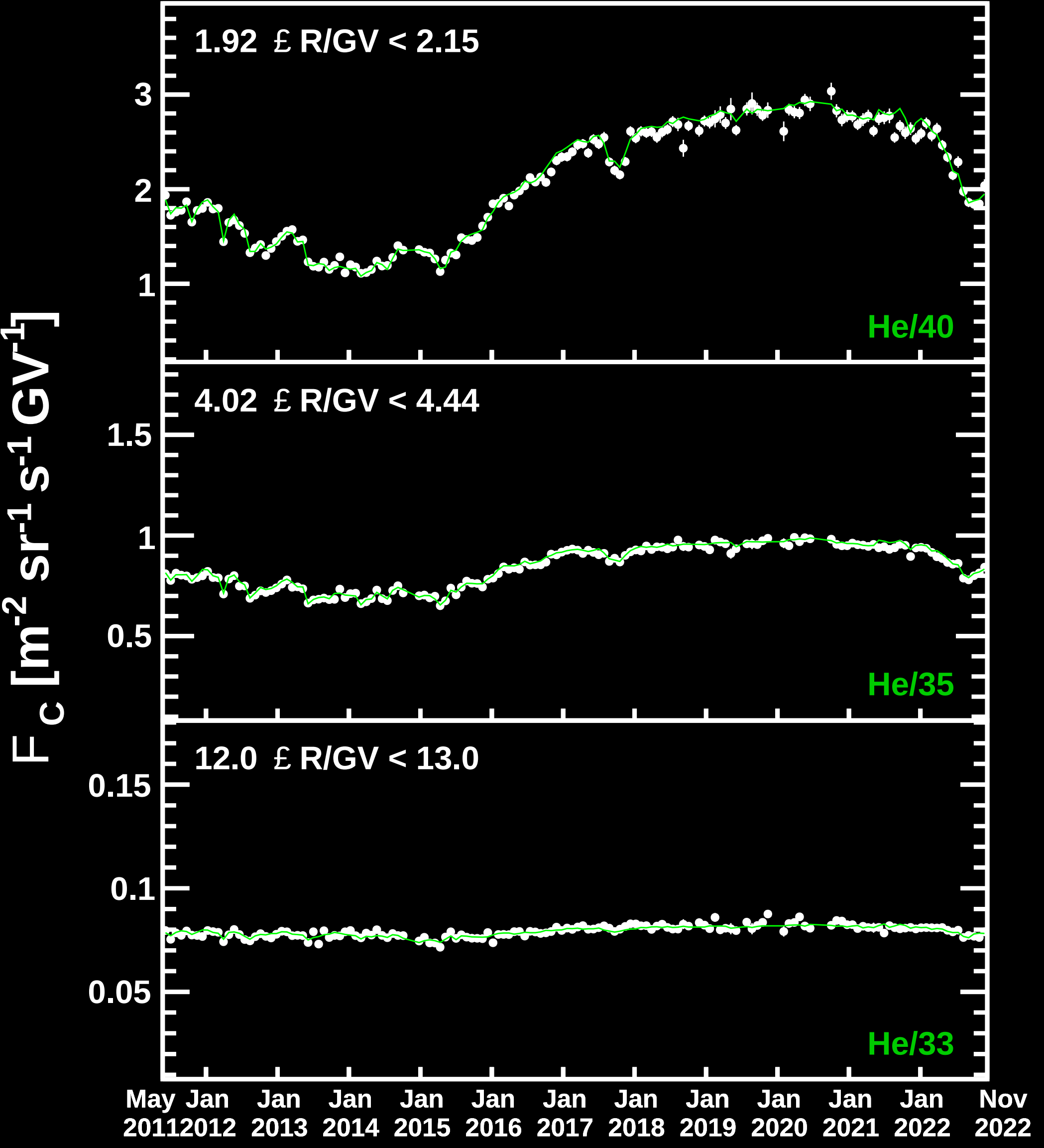
Time Variation of Cosmic Light Nuclei

Preliminary data, please refer to the forthcoming AMS publication

Lithium



Carbon



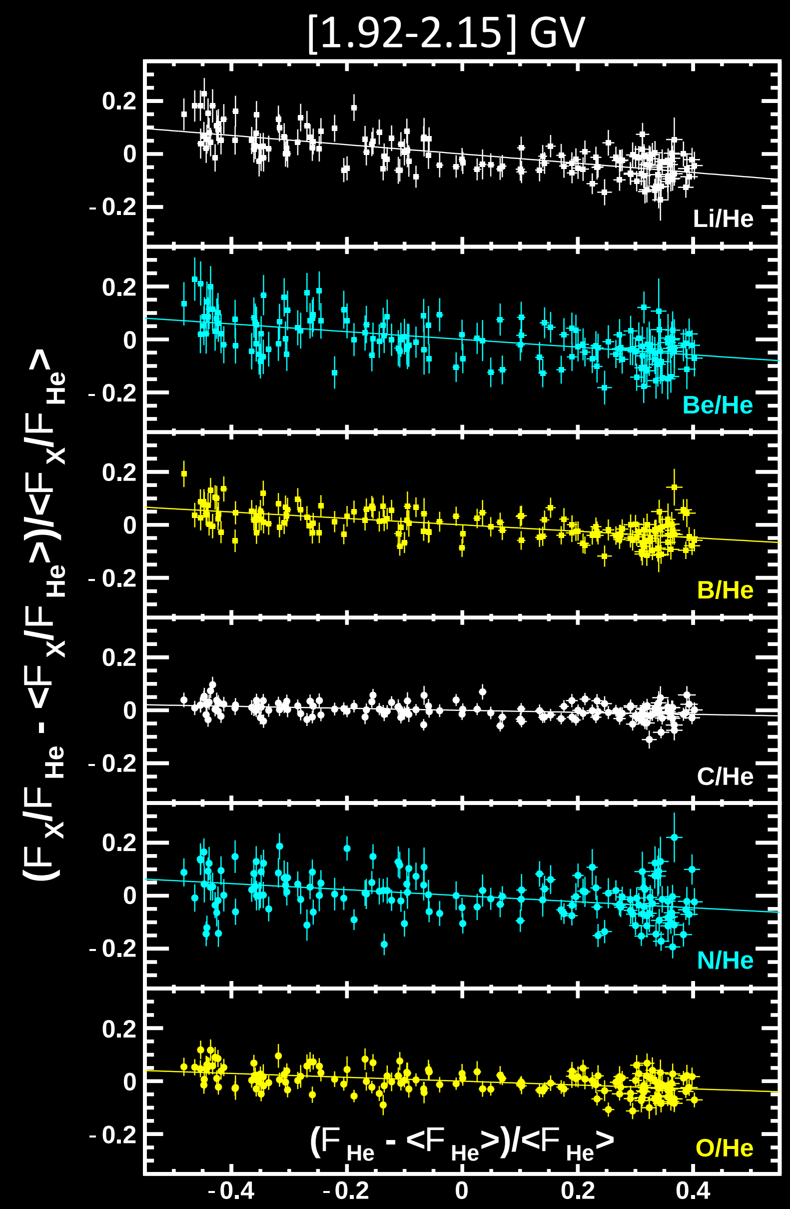
The amplitude of the time structures decreases with increasing rigidity.

Differences in solar modulation in light nuclei

To study the differences in the solar modulation of each nuclei, the relative variation of the fluxes are estimated, for the i-th rigidity bin (R_i; $R_i + \Delta R_i$), as:

$$\frac{\Phi^i_X/\Phi^i_{\rm He} - \langle \Phi^i_X/\Phi^i_{\rm He} \rangle}{\langle \Phi^i_X/\Phi^i_{\rm He} \rangle} = K^i_{X/{\rm He}} \frac{\Phi^i_{\rm He} - \langle \Phi^i_{\rm He} \rangle}{\langle \Phi^i_{\rm He} \rangle}$$

where "X" is the selected nuclei between Li and O.

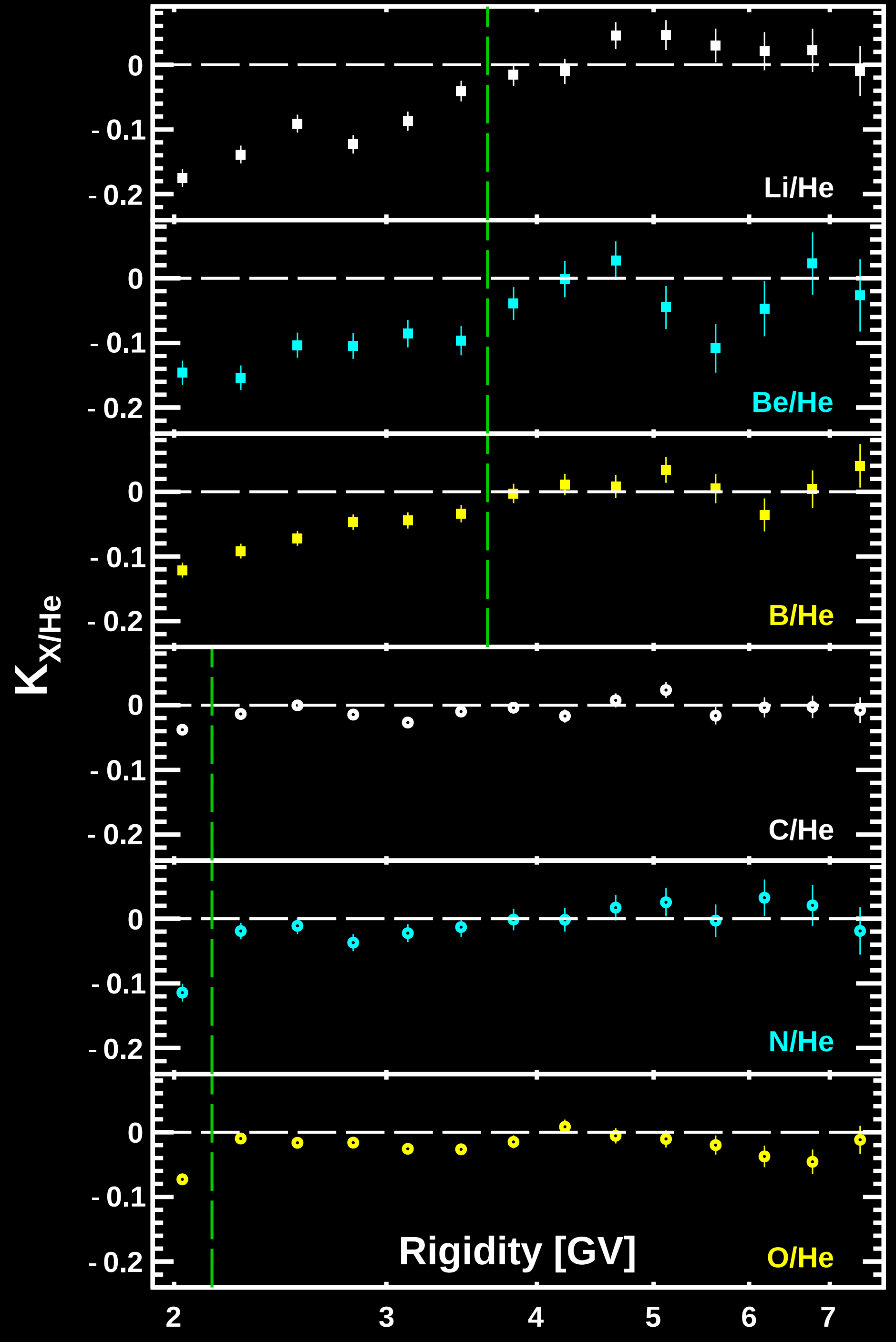


The K-parameter gives the relative solar modulation with respect to He. A K-parameter equal to zero means same modulation of He, below zero less modulated than He and above zero more modulated than He.

K-parameter as function of rigidity

$$\frac{\Phi^i_X/\Phi^i_{\mathrm{He}} - \langle \Phi^i_X/\Phi^i_{\mathrm{He}} \rangle}{\langle \Phi^i_X/\Phi^i_{\mathrm{He}} \rangle} = K^i_{X/\mathrm{He}} \frac{\Phi^i_{\mathrm{He}} - \langle \Phi^i_{\mathrm{He}} \rangle}{\langle \Phi^i_{\mathrm{He}} \rangle}$$

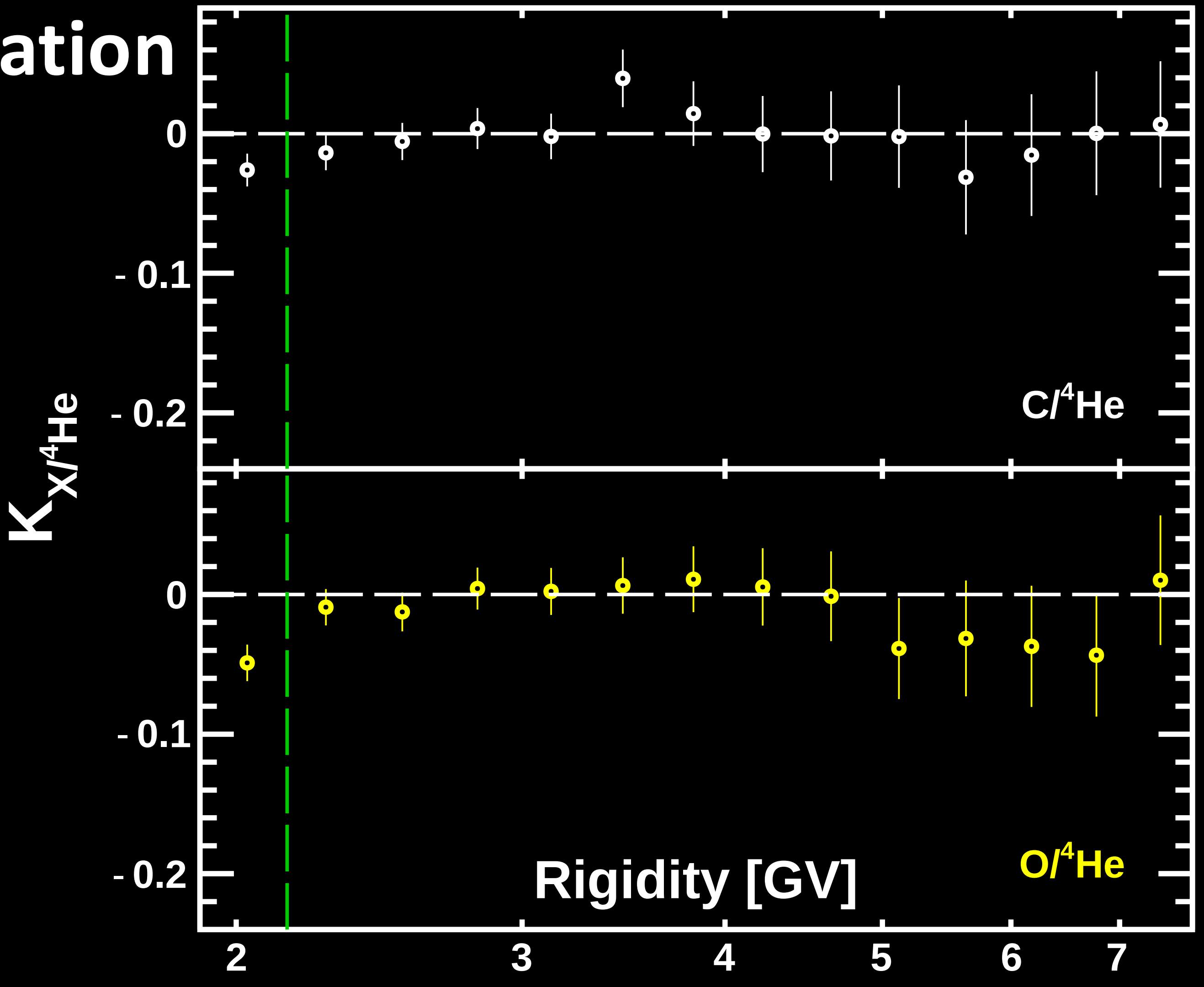
- **Li, Be and B are significantly less modulated than He up to 3.6 GV.**
- **C, N and O are significantly less modulated than He up to 2.15 GV.**



Mass-to-charge ratio (A/Z) contribution to solar modulation

For the same rigidity, nuclei with $3 \leq Z \leq 8$ have lower velocities than He, traveling for more time in the heliosphere and, therefore should exhibit more modulation than He. In contrast, we observe they are less modulated than helium.

C, and O nuclei in cosmic rays are expected to be dominated by isotopes with A/Z = 2, for the same rigidity ^{4}He, C and O should all have the same velocity, and they should have a similar solar modulation in the case of dominating velocity effect.



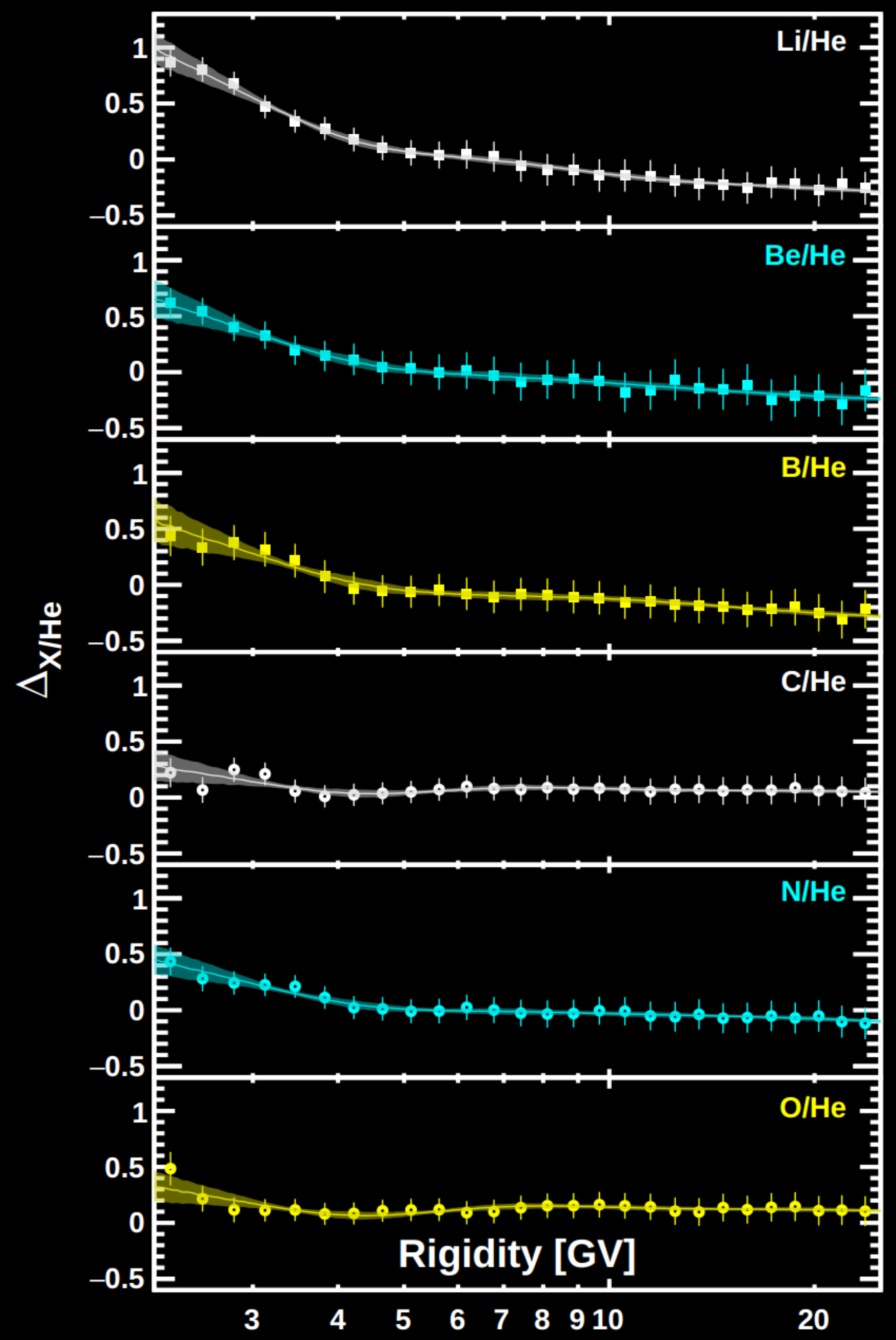
We observe that C and O are significantly less modulated than ^{4}He up to 2.15 GV, similarly of when compared with He(^{4}He+ ^{3}He). Proving in a model-independent way that the dominant effect comes from differences in the spectral shape.

Spectral Index contribution to solar modulation

To explore the spectral dependency of the solar modulation, in a model-independent way, the spectral index $\boldsymbol{\Delta_{X/He}}$ of the flux ratio has been calculated using:

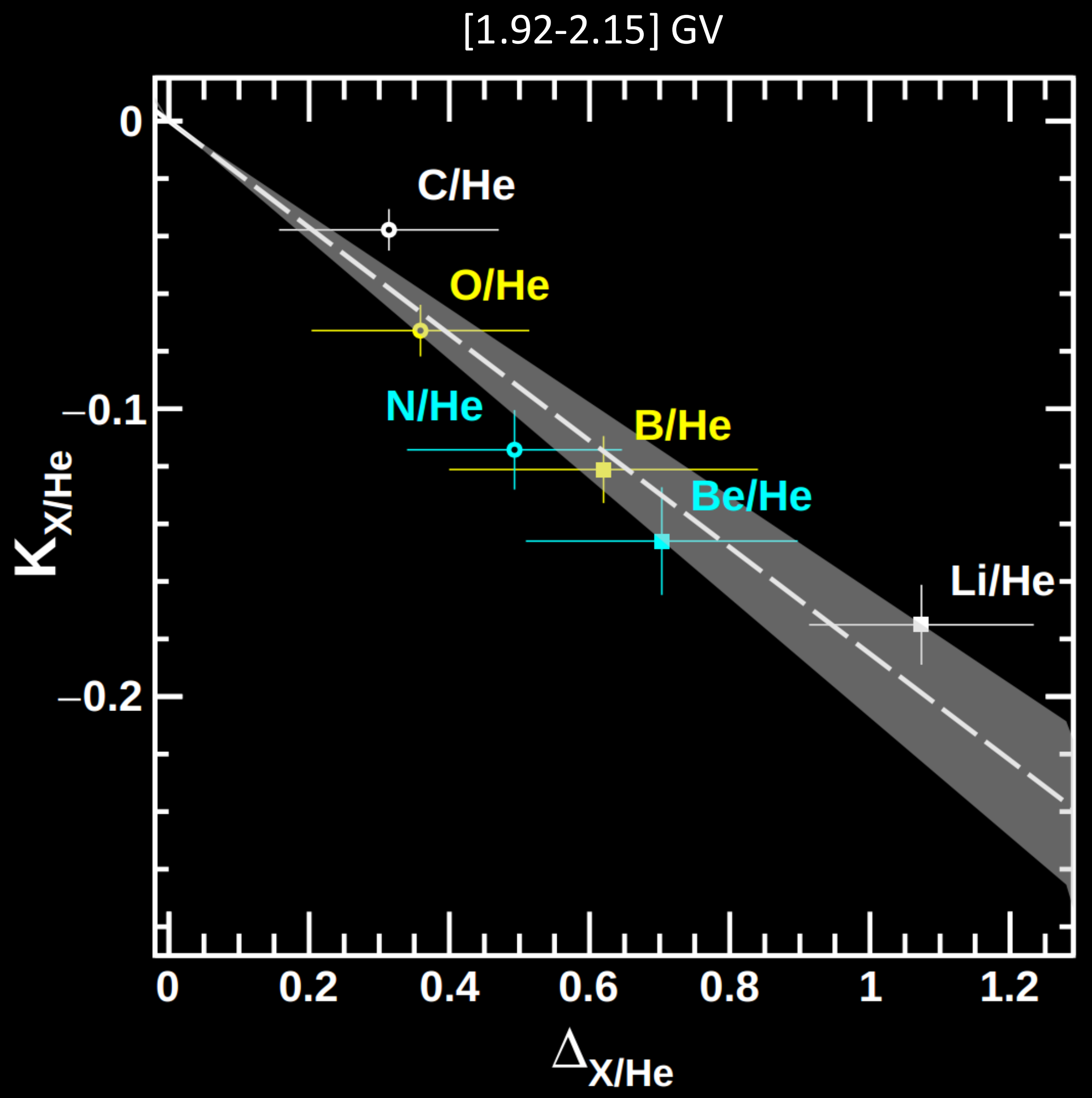
$$\Delta_{X/\mathrm{He}} = \frac{\mathrm{d}[\log \langle \Phi^i_X / \Phi^i_{\mathrm{He}} \rangle]}{\mathrm{d}[\log(R)]}$$

in consecutive ranges of three rigidity bins each. The shaded area corresponds to the spectral index derived from a fit to the average flux ratio using a spline function.



K-parameter and Spectral Index Correlation

- When comparing the $K_{X/He}$ vs the $\Delta_{X/He}$ for the first rigidity bin an anti-correlation is observed.
- Nuclei with higher $\Delta_{X/He}$ suffer less modulation.
- To test the correlation between the two parameters a fit with $K = \xi \Delta$ leads to $\xi = -0.18 \pm 0.02$.
- This is the first time this effect has been measured directly from data, independently of any model.



Conclusions

- The AMS fluxes vs time for light ions (Li to O), from May 2011 to Nov 2022, has been presented. It is the first time-dependent measurement of these fluxes between 1.92 and 60 GV. The fluxes have been determined for 147 Bartels rotations, i.e. on a 27-day basis.

- The fluxes are anti-correlated with solar activity, and the amplitude of the time structures decrease with increasing rigidity. All nuclei exhibit similar long-term and short-term time variation.

- We observe that Li, Be and B are less modulated than He up to 3.6 GV. Meanwhile, C, N and O are less modulated than He up to 2.15 GV.

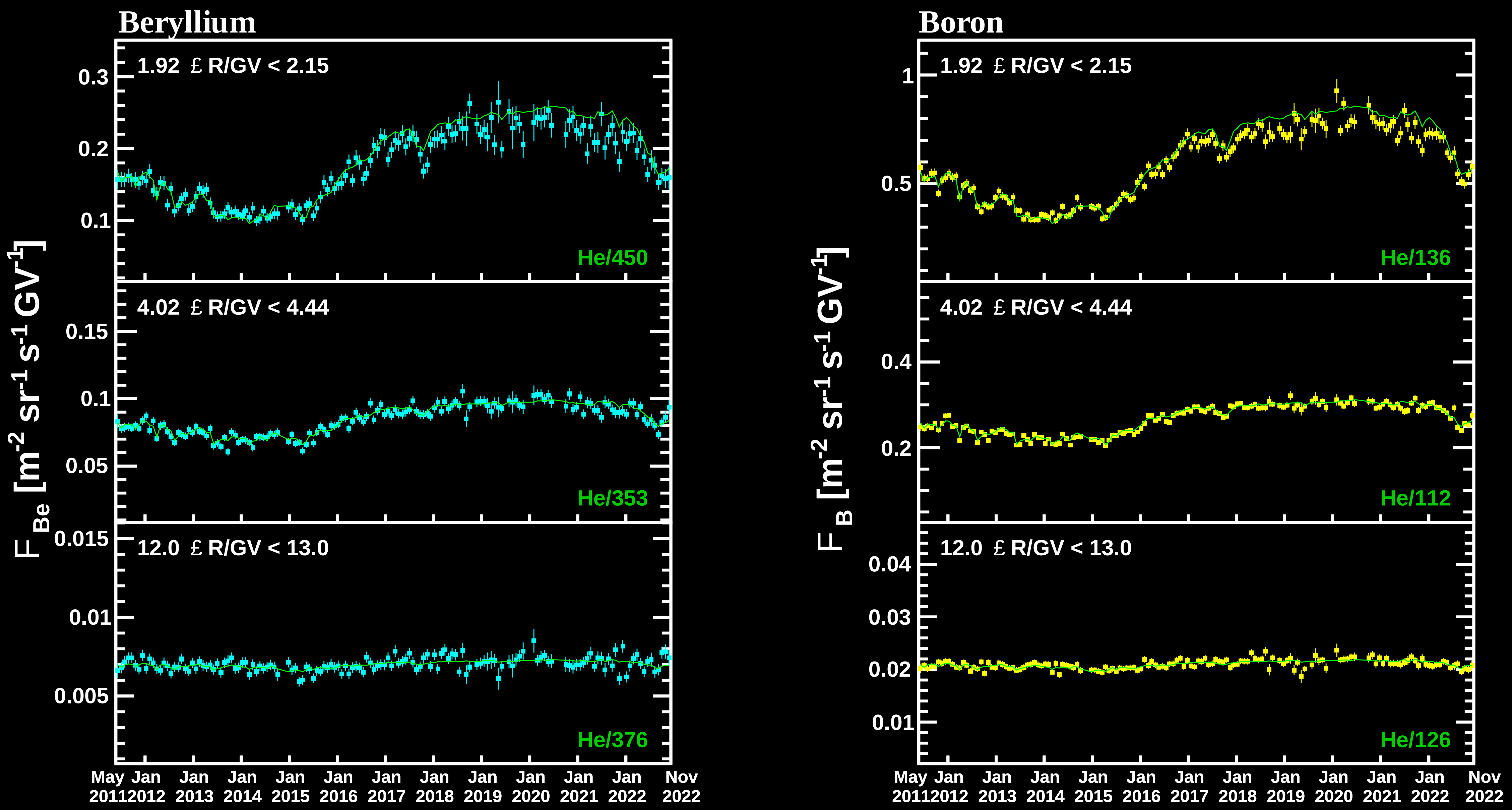
- We observe that C and O are significantly less modulated than 4He up to 2.15. Proving in a model-independent that the dominant effect comes from differences in the spectral shape.

- We observe an anti-correlation between the amount of solar modulation and the spectral index. This is the first time this effect has been measured directly from data, independently of any model.

- AMS-02 will continue operating during the full Solar Cycle 25. Its precise data will improve our understanding about the cosmic rays propagation mechanism inside the heliosphere.

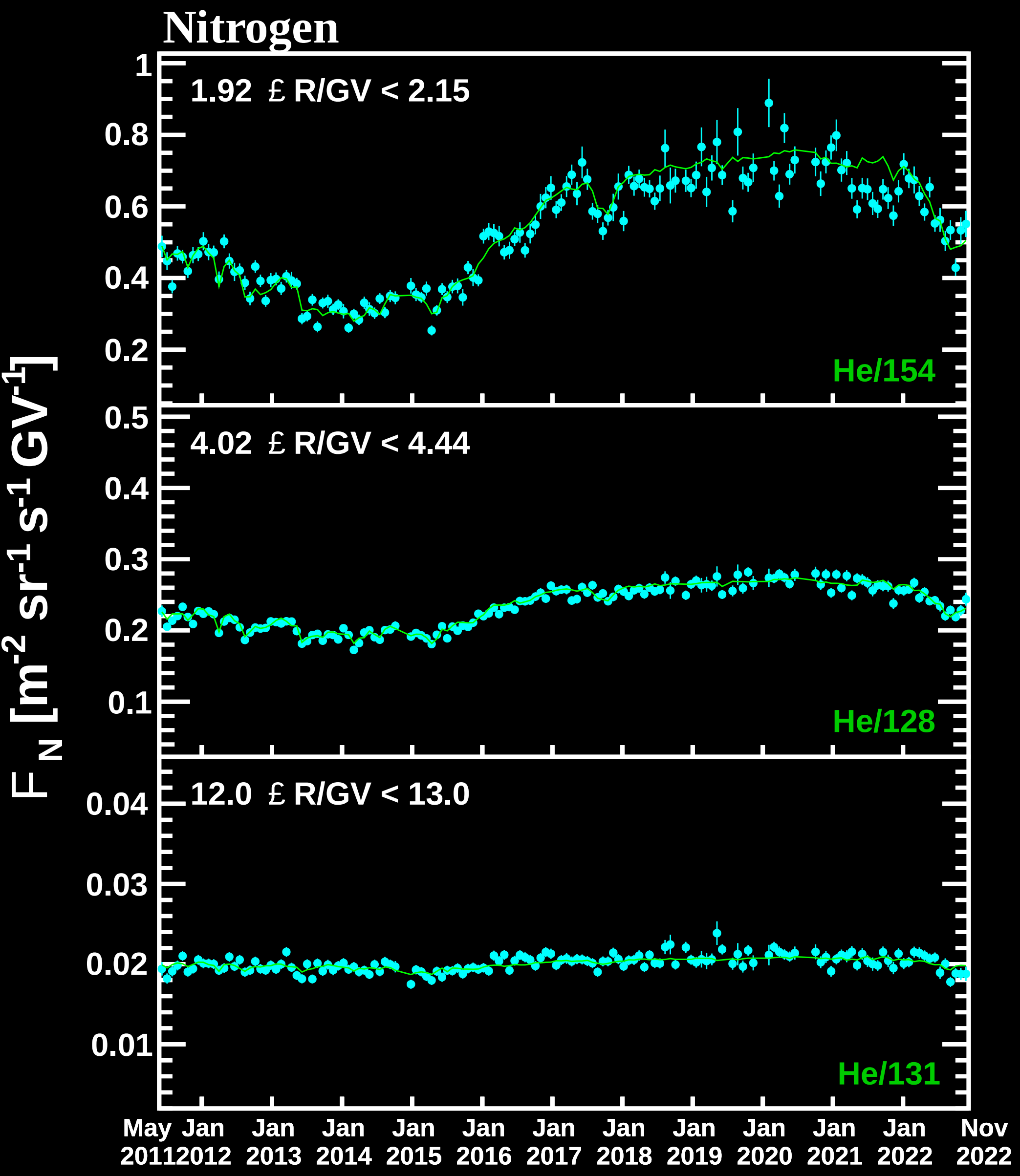
Back Up

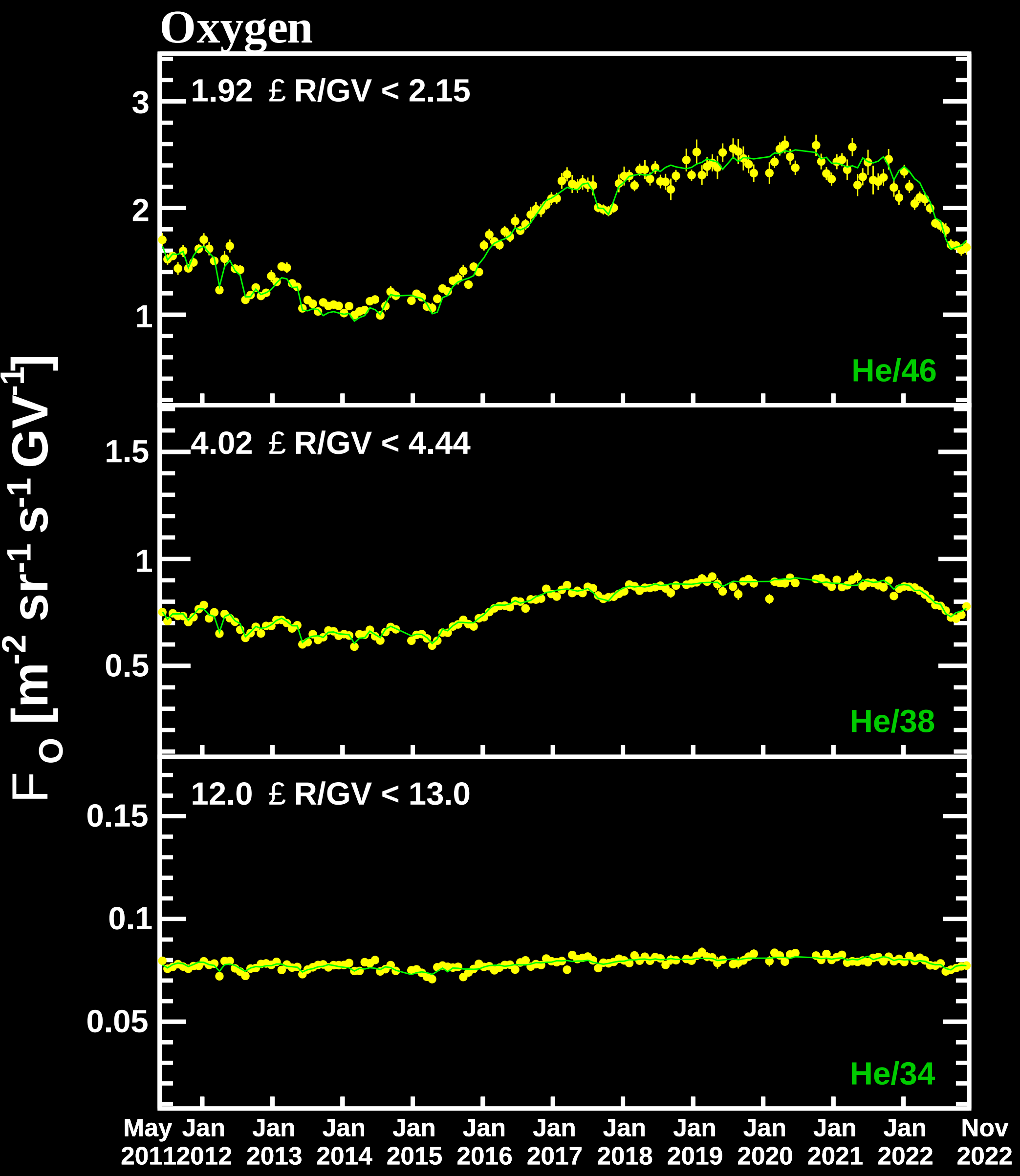
Time Variation of Cosmic Light Nuclei



The amplitude of the time structures decreases with increasing rigidity.

Time Variation of Cosmic Light Nuclei



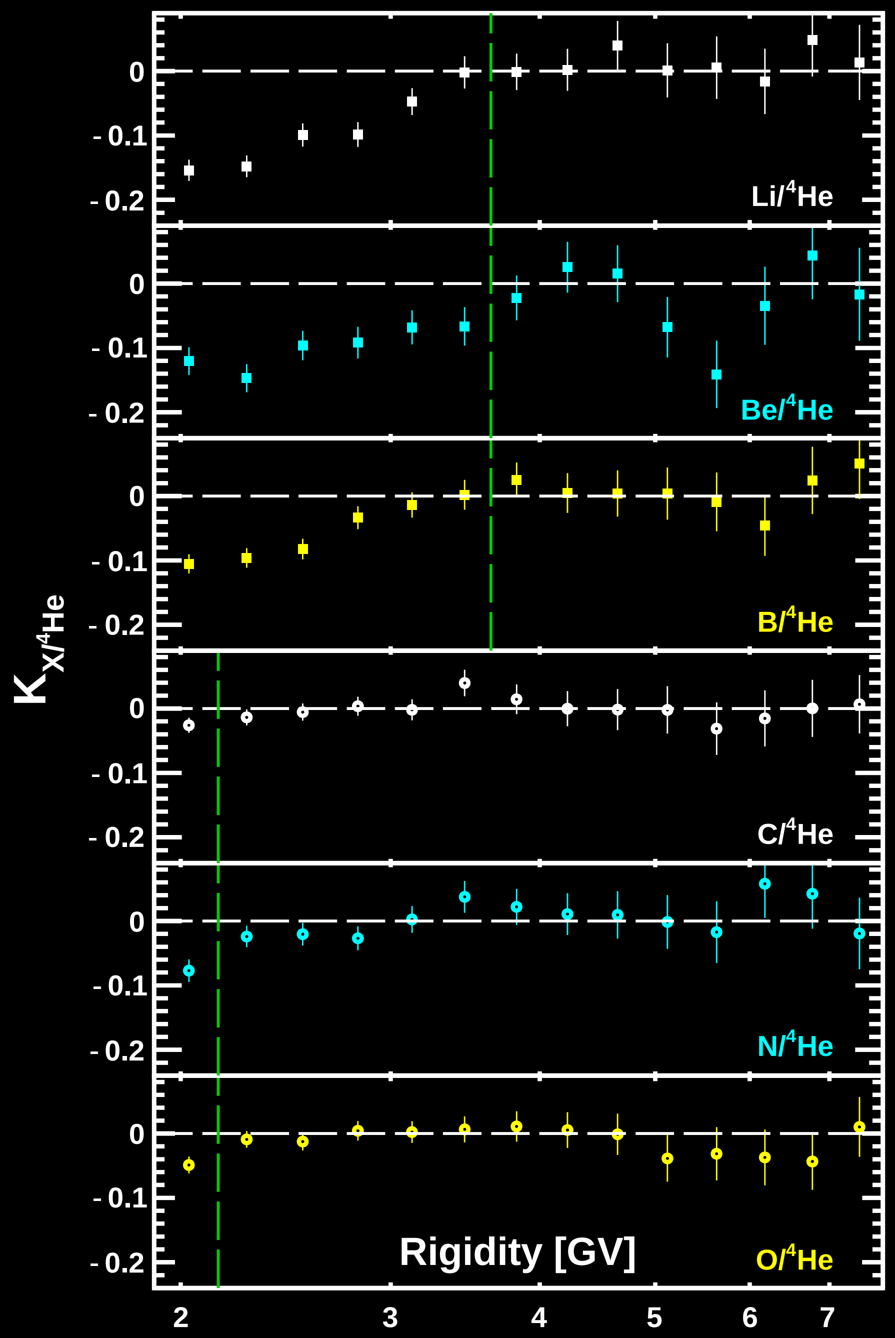


The amplitude of the time structures decreases with increasing rigidity.

Beta contribution to solar modulation

For the same rigidity, nuclei with 3 ≤ Z ≤ 8 have lower velocities than He, traveling for more time in the heliosphere and, therefore should exhibit more modulation than He.

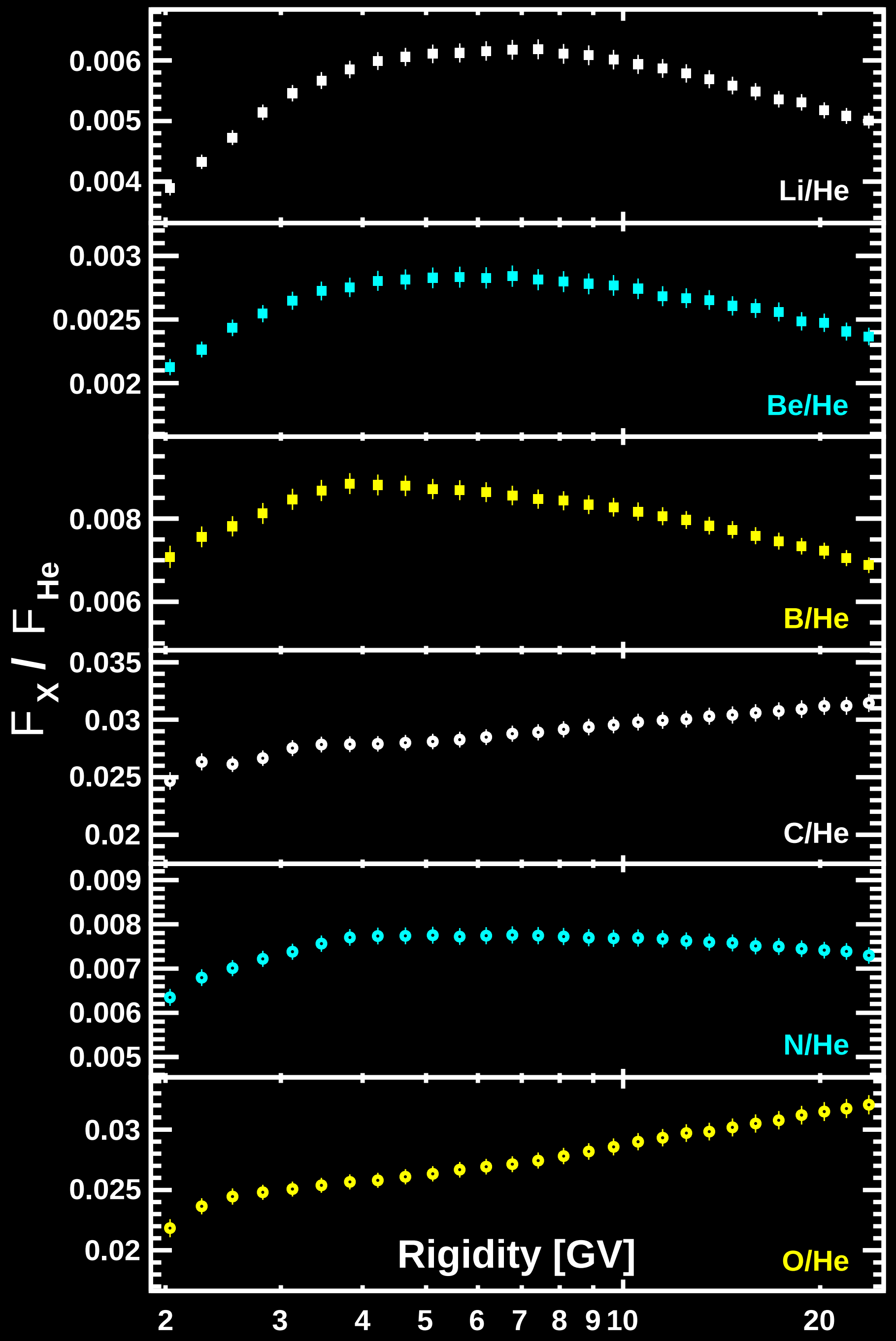
In contrast, we observe that nuclei with 3 ≤ Z ≤ 8 experience less modulation than helium, indicating that factors other than velocity have a more significant impact.



Flux Ratios over He

The Li/He, Be/He, B/He, C/He, N/He, and O/He flux ratios measured by AMS in the rigidity averaged over 11.5 years (May 2011 to November 2022) in the rigidity range from 1.92 to 25 GV.

The shaded bands show the time variation from the observed minimum to the maximum (calculation is performed with fitting).



K-parameter and Spectral Index Correlation

The solar modulation intensity **K** as a function of the spectral index **Δ** for several rigidity bins. Only K factors below 2.15 GV for C, N, and O and below 3.6 GV for Li, Be, and B are considered. A linear fit is superimposed.

There is a clear correlation between the solar modulation intensity and the spectral index.