V. FORMATO on behalf of the AMS collaboration

INFN - Sezione di Roma Tor Vergata

24/08/2021 - 20th Lomonosov conference

OBSERVATION OF FINE TIME STRUCTURES IN THE PRIMARY COSMIC RAYS LIGHT NUCLEI FLUXES

AMS-02 IN ORBIT

AMS-02 is a large-acceptance high-energy **magnetic spectrometer** capable of measure accurately particles in the **GeV-TeV** energy range.Since **2011** May 19th AMS-02 has been operating on the International Space Station (ISS). AMS recorded **>180 billion CR triggers** in ~10 years of operation.

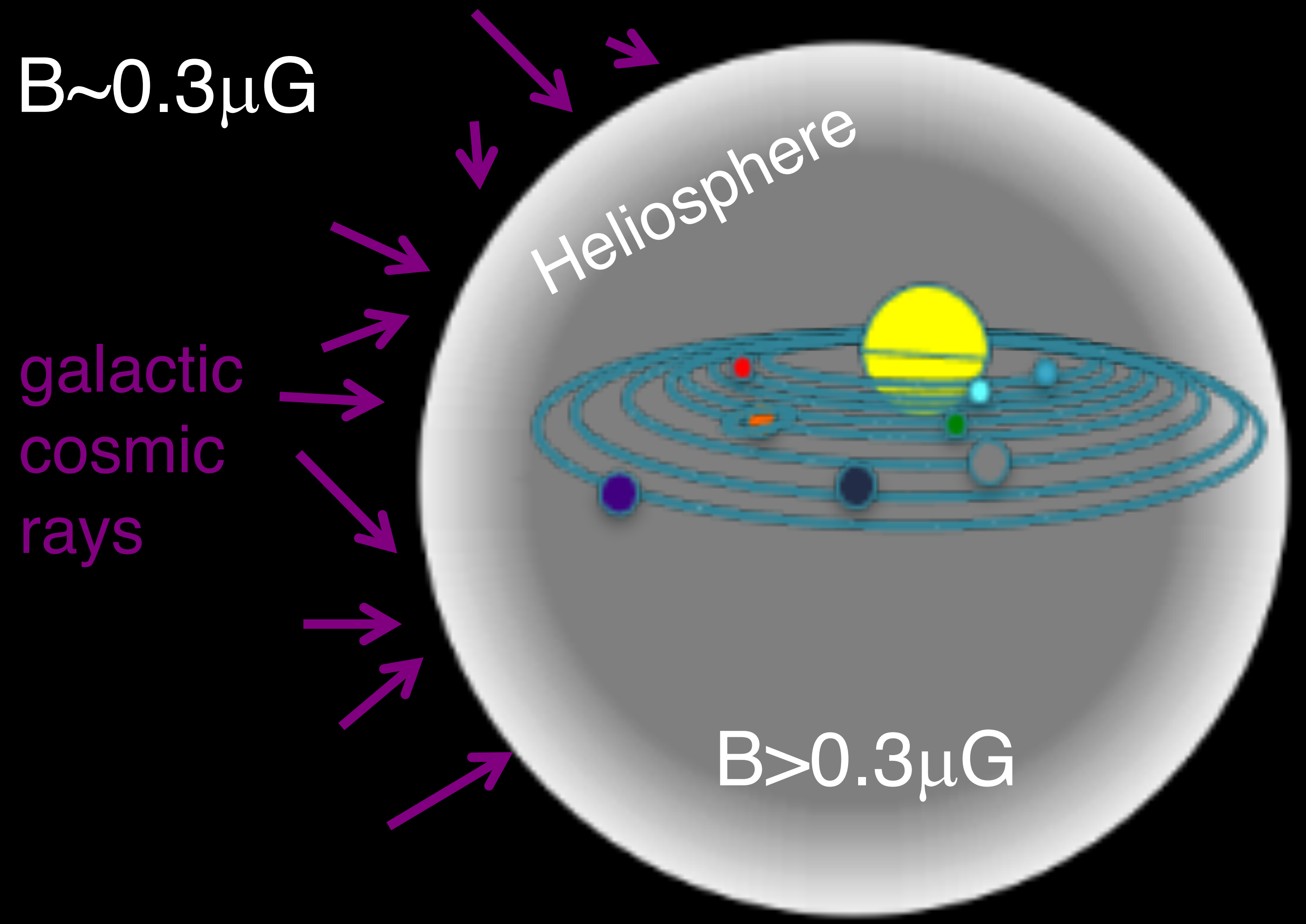
AMS is expected to take data during the whole ISS lifetime (at least 2028)

COSMIC RAYS IN THE GALAXY

(but also other stuff like) $\pi^{\pm} \rightarrow \mu^{\pm} \rightarrow e^{\pm}$

$p + p \rightarrow p + \bar{p} + ...$

COSMIC RAYS IN THE HELIOSPHERE

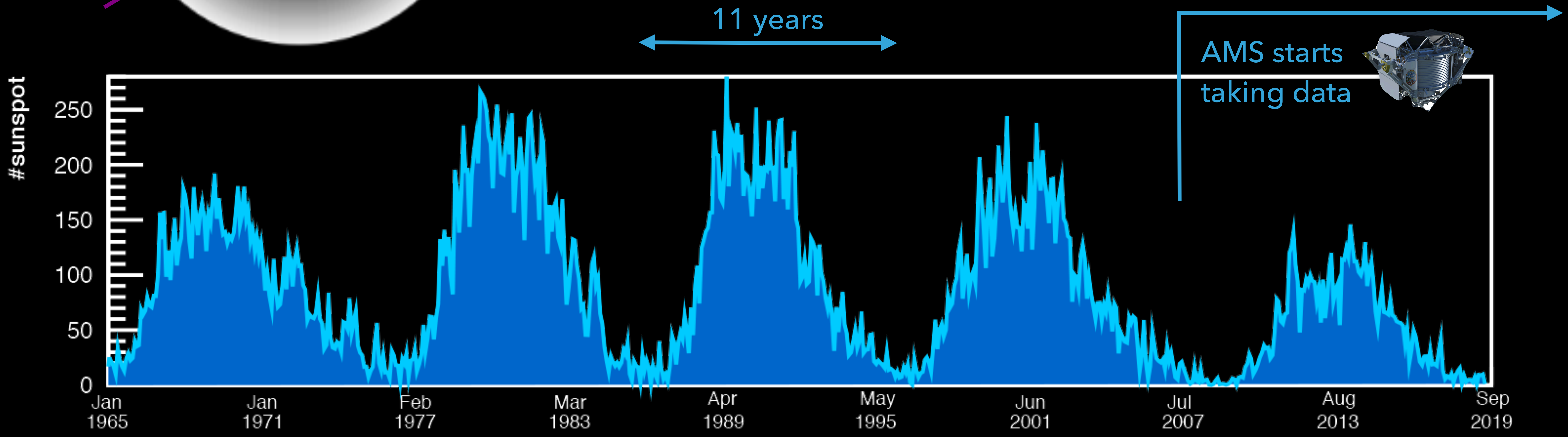


1. Large time scale effects (~years):

- change on intensity of CRs
- charge-sign dependence:
  - at maximum: diffusive motion
  - at minimum: magnetic drift + diffusive motion

2. Small time scale effects (~days)

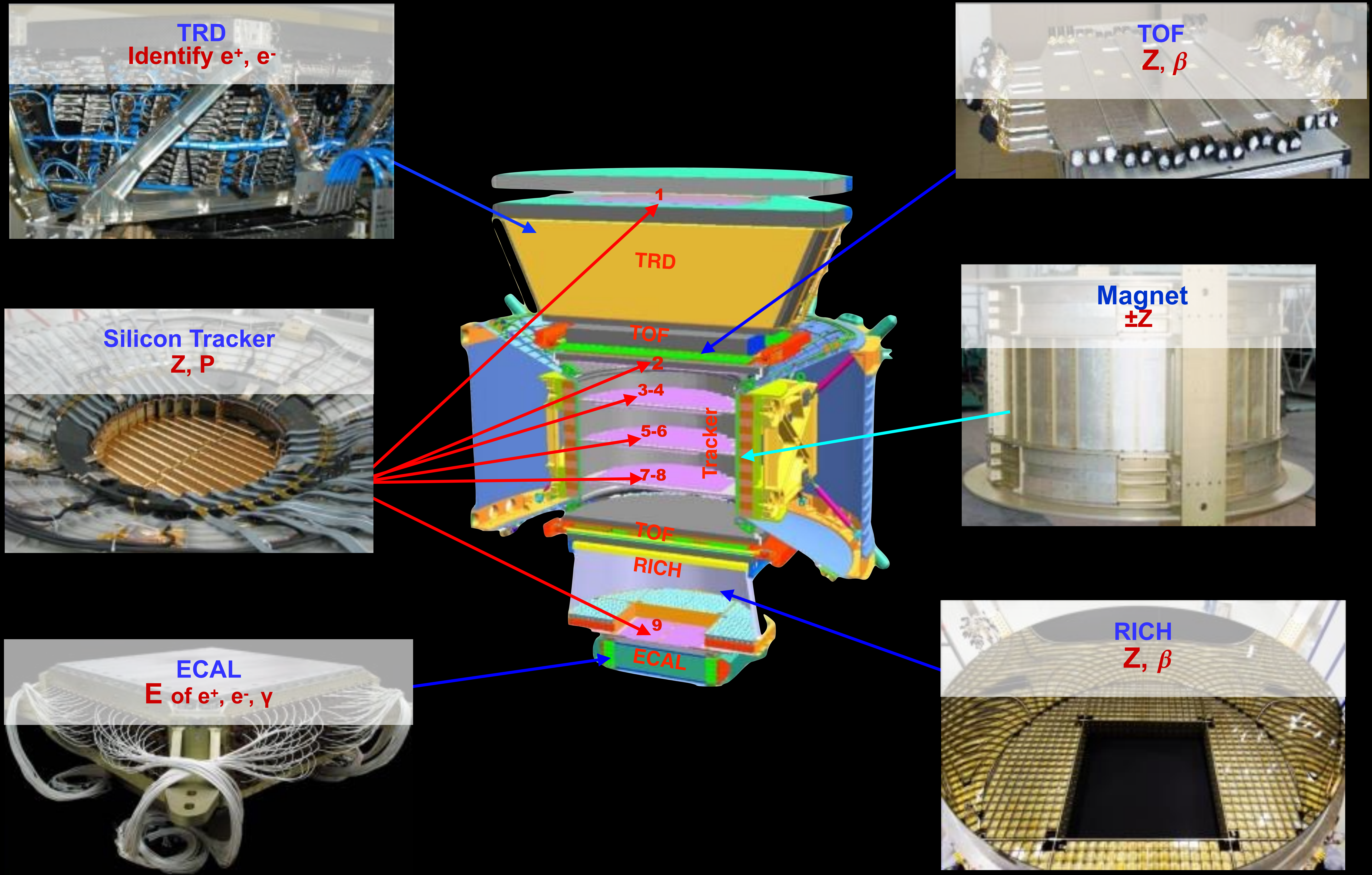
- Forbush decrease & Solar Energetic Particles (SEP)



AMS-02

Particles and nuclei are defined by their charge (**Z**) and energy (**E ~ P**)

Both quantities are measured redundantly and independently by the *Tracker, TOF, RICH* and/or *ECAL*



FLUX MEASUREMENT

In this talk we will focus about ***flux*** measurements

A ***flux*** is defined as:

$$\Phi_i = \frac{\tilde{N}_i}{A_i \, \varepsilon_i \, T_i \, \Delta R_i}$$

$\tilde{N}_i$: Number of events
(in rigidity bin i, corrected for bin-to-bin migrations)

T_i: Exposure time
Duty cycle + geomagnetic cutoff.
(s)

ΔR_i: Rigidity bin width

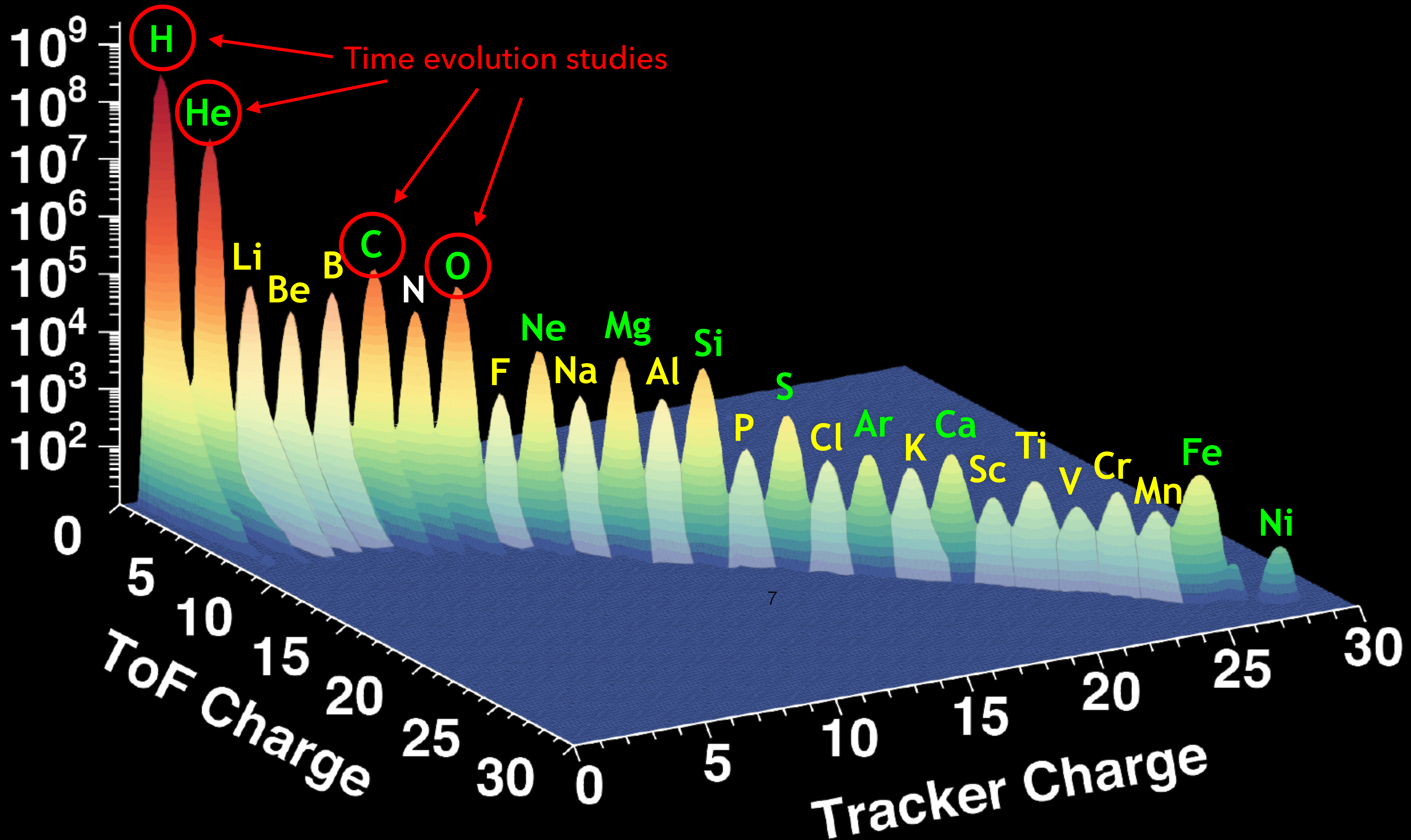
ε_i: Trigger efficiency
Estimated on flight data.

A_i: Acceptance (Effective geometrical factor)
Estimated from Montecarlo and validated on flight data.
$(\mathrm{m^2\ sr})$

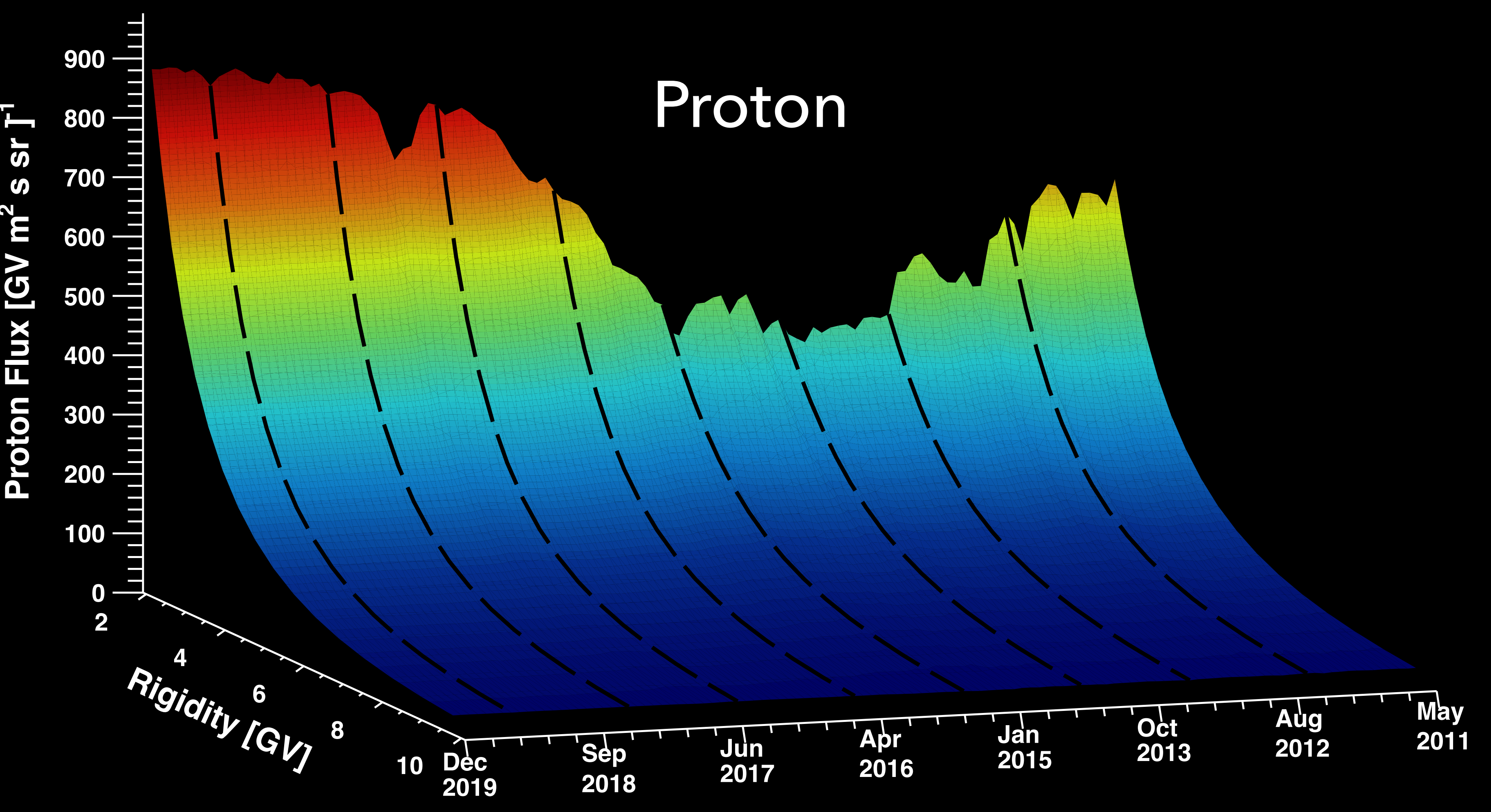
Φ_i: Differential flux
$(\mathrm{m^2\ s\ sr\ GV})^{-1}$

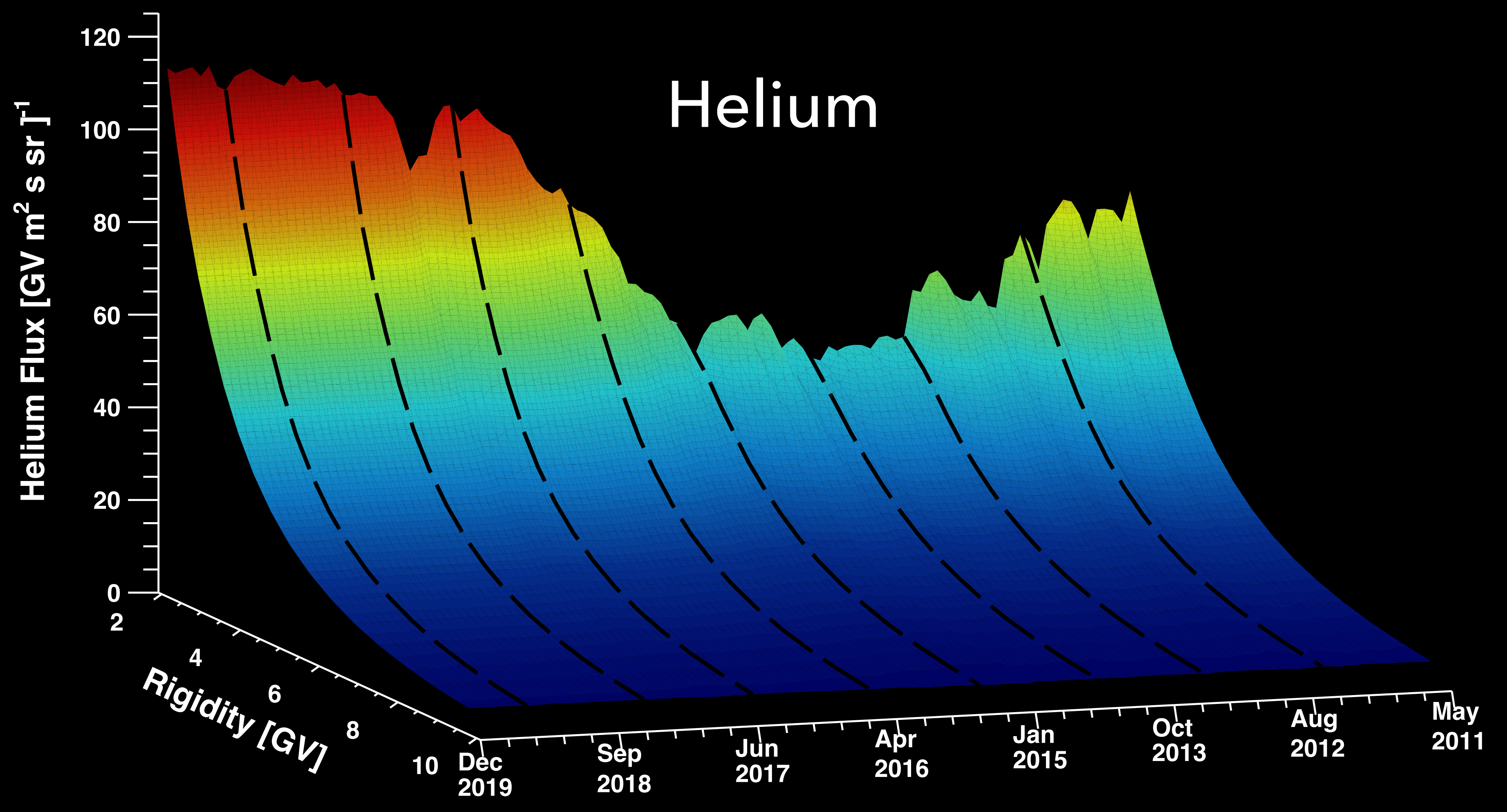
THE AMS PERIODIC TABLE

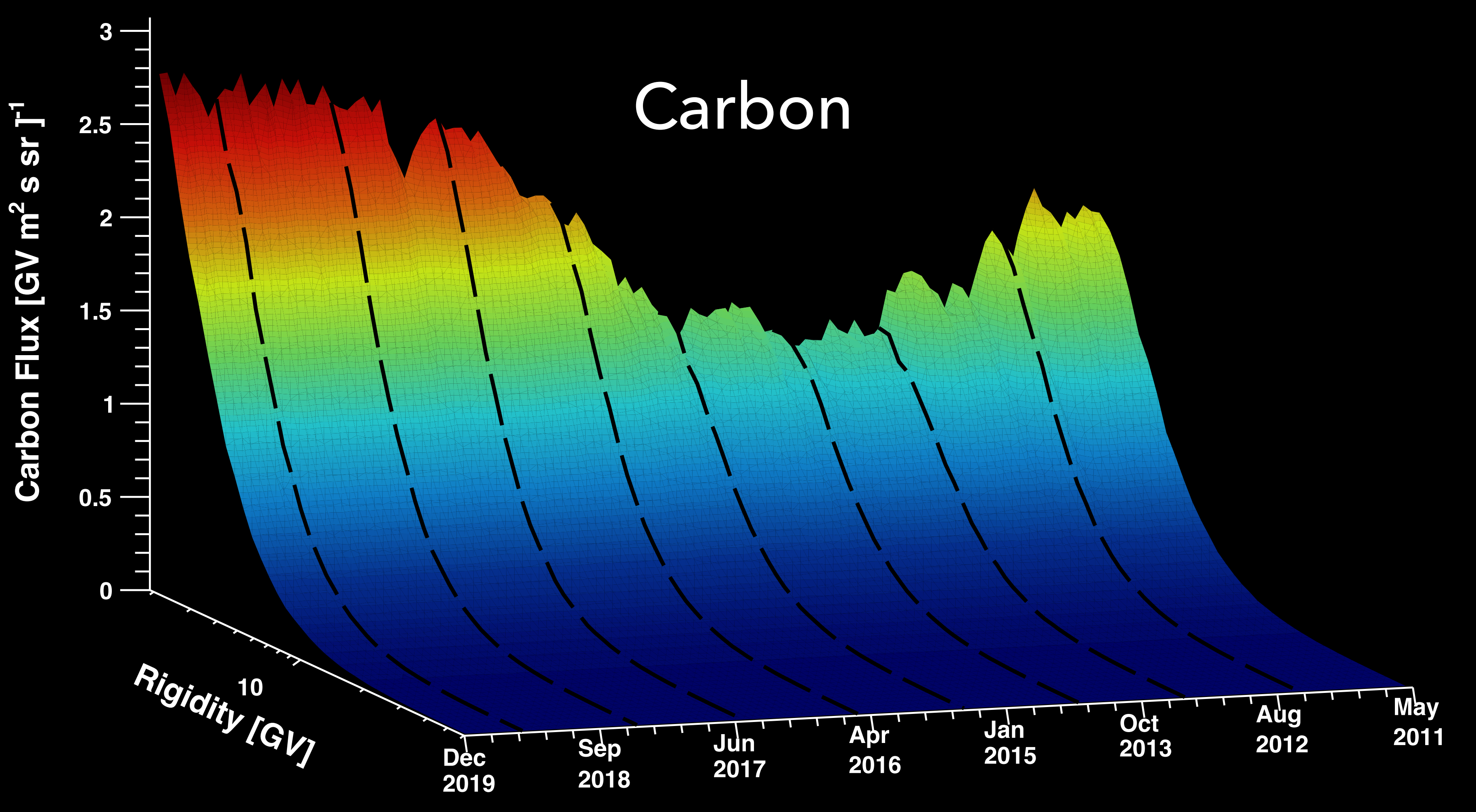
Primary
Secondary

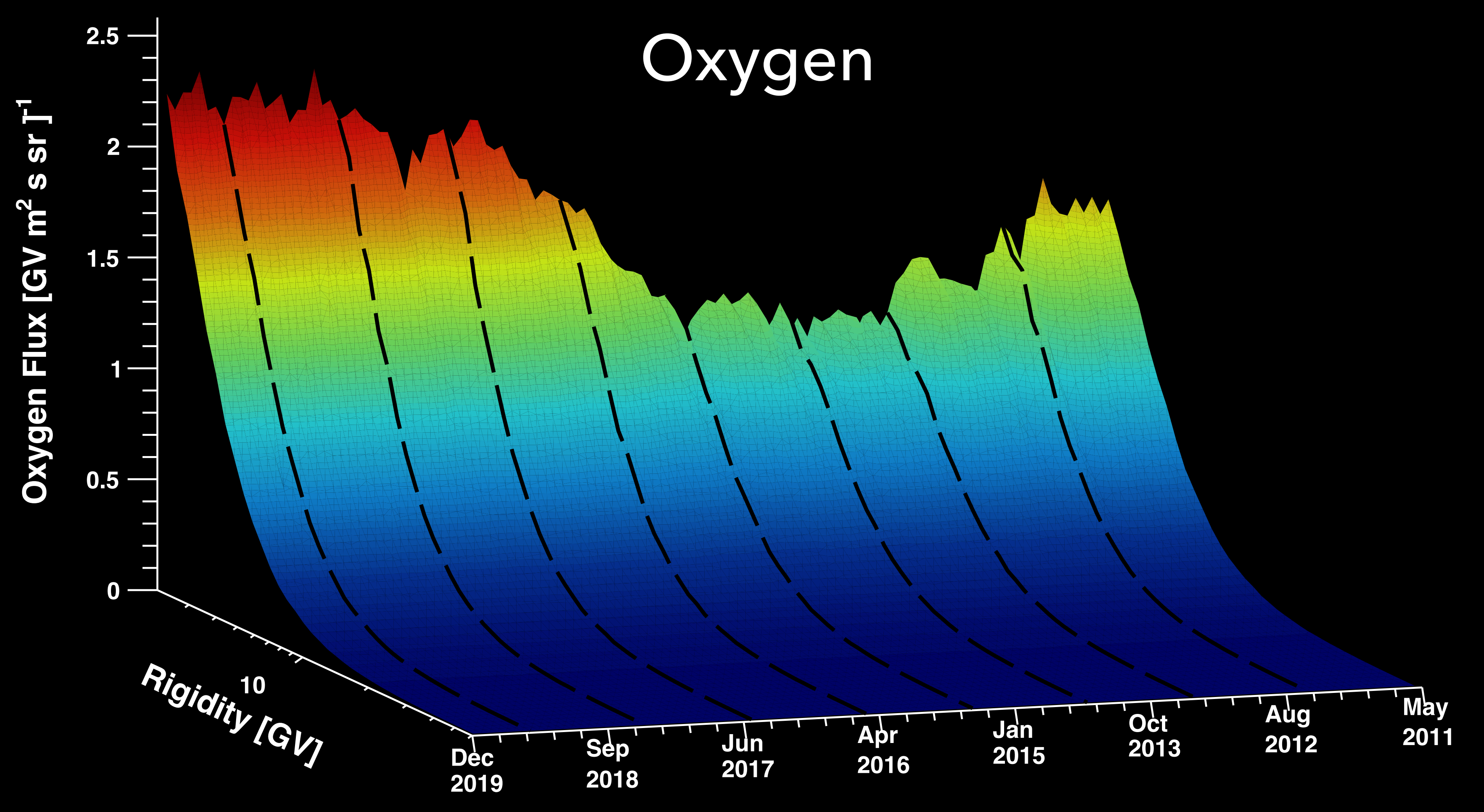


PRIMARY NUCLEI FLUXES









Proton, Helium, Carbon and Oxygen fluxes from May 2011 up to November 2019.
The time interval is 27 days (Bartels Rotation)

WHAT CAN WE LEARN?

Let's take a step back and consider how cosmic rays **travel through the heliosphere**

$$\frac{\partial f}{\partial t} = -\mathbf{V}_{\mathrm{sw}} \cdot \nabla f + \nabla \cdot (K \cdot \nabla f) + \frac{1}{3} \nabla \cdot \mathbf{V}_{\mathrm{sw}} \frac{\partial f}{\partial \ln R}$$

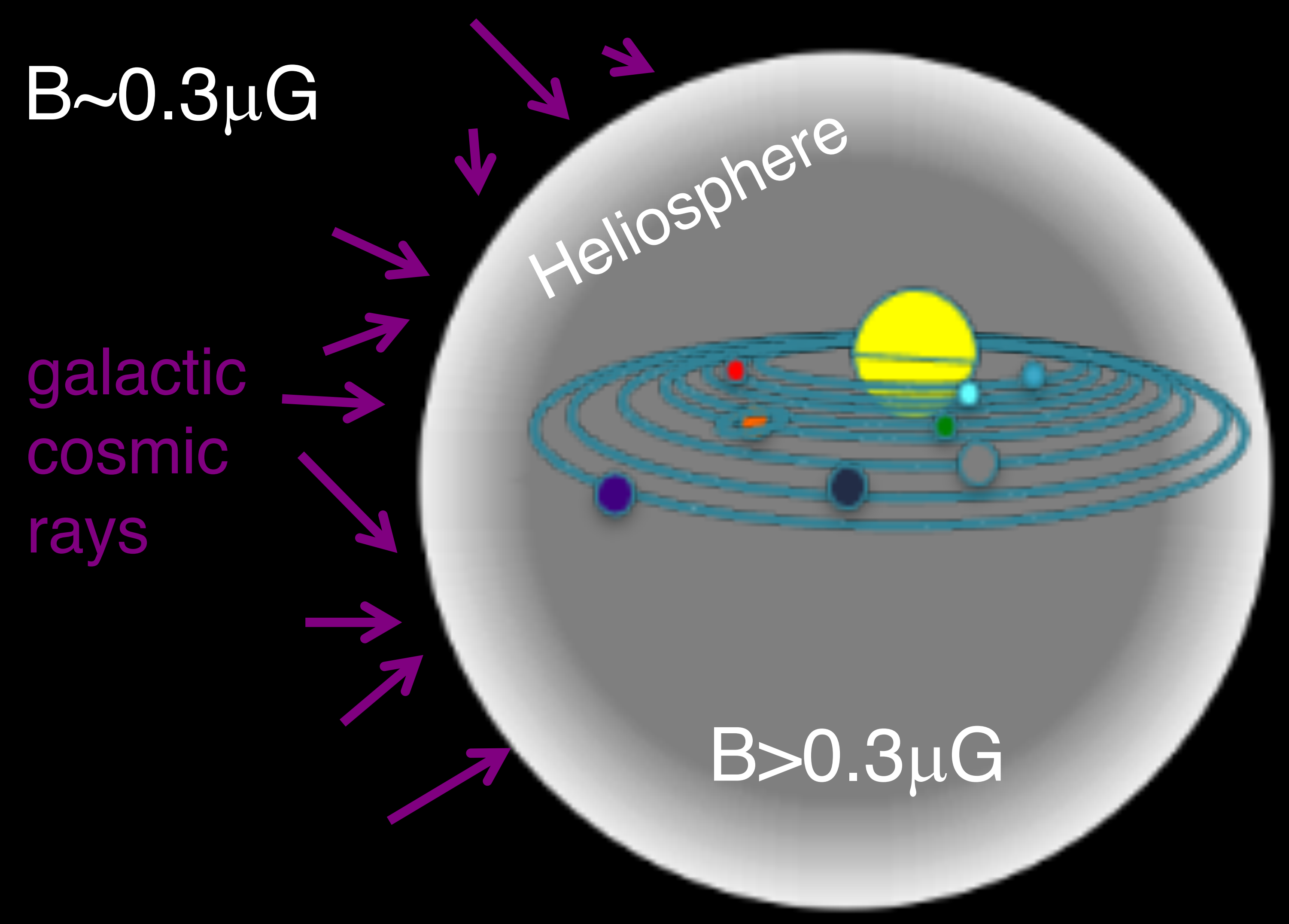
Particle phase-space density

Convection by radially outflowing solar wind

Diffusion against heliospheric magnetic field irregularities

Drift on gradients and curvatures of heliospheric magnetic field / current sheet

Adiabatic energy losses due to expanding solar wind



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$$K(\mathbf{x}, R) = \beta K_1(\mathbf{x}) K_2(R)$$

Modulation of different nuclei driven mainly by two effects:

1. Velocity dependence of the diffusion tensor:
   K_2 is assumed to be the same for all nuclei, but the velocity dependence induces changes in this term of the Parker equation for nuclei with different A/Z.
2. Difference in spectral shape:
   The adiabatic energy change term in the Parker equation depends on the spectral shape. If two nuclei have the same A/Z, but different spectral shape outside the heliosphere (LIS), the last term will be different.

By looking at flux ratios using species with similar A/Z we can probe the shape of the Local Interstellar Spectrum. In particular we can point out if the shape of the LIS is similar or significantly different in the rigidity range $R > 2$ GV, where no direct measurements outside the heliosphere are available.

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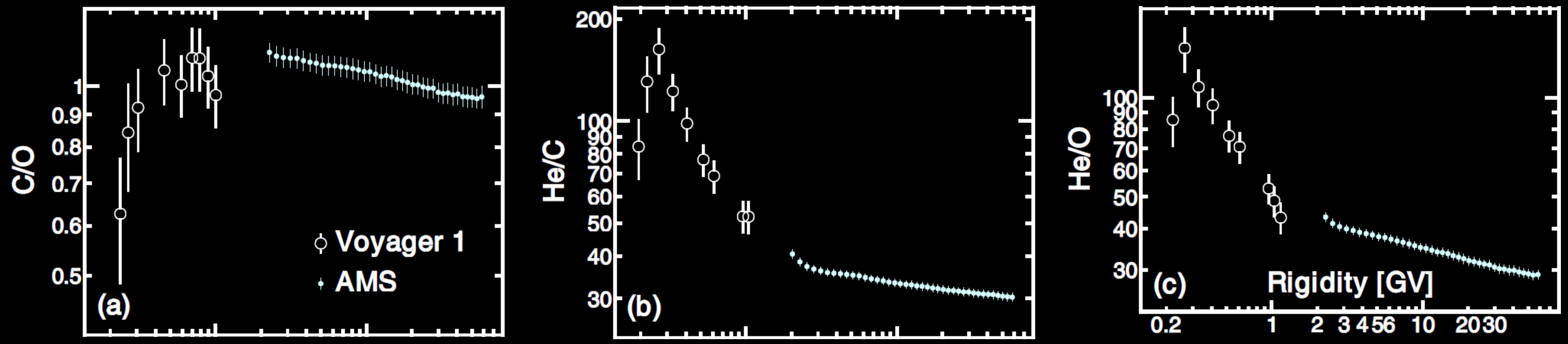
	$\Delta A/Z$ [1]
$\mathbf{C/O}$	0.01 ± 0.02
$\mathbf{He/C}$	-0.08 ± 0.03
$\mathbf{He/O}$	-0.07 ± 0.02
$\boldsymbol{p}/\mathbf{C}$	-1.02 ± 0.02
$\boldsymbol{p}/\mathbf{O}$	-1.01 ± 0.01
$\boldsymbol{p}/\mathbf{He}$	-0.94 ± 0.02

[1]: Average weighted by isotopic composition.
Based on data from CRDB: Maurin et al, 2020 (https://lpsc.in2p3.fr/crdb)

1) $\mathbf{C/O}$: same velocity, so any time dependence comes from spectral shape differences.
2) $\mathbf{He/C}$, $\mathbf{He/O}$: very similar velocities, so any time dependence comes from spectral shape differences.

Flux ratio vs time	LIS ratio
Flat	Flat
Correlated with solar activity	Increasing
Anti-correlated with solar activity	Decreasing

3) $\boldsymbol{p}/\mathbf{C}$, $\boldsymbol{p}/\mathbf{O}$: numerical model needed to disentangle between velocity and LIS difference.
4) $\boldsymbol{p}/\mathbf{He}$: from numerical model, velocity difference is the main contribution to time dependence.

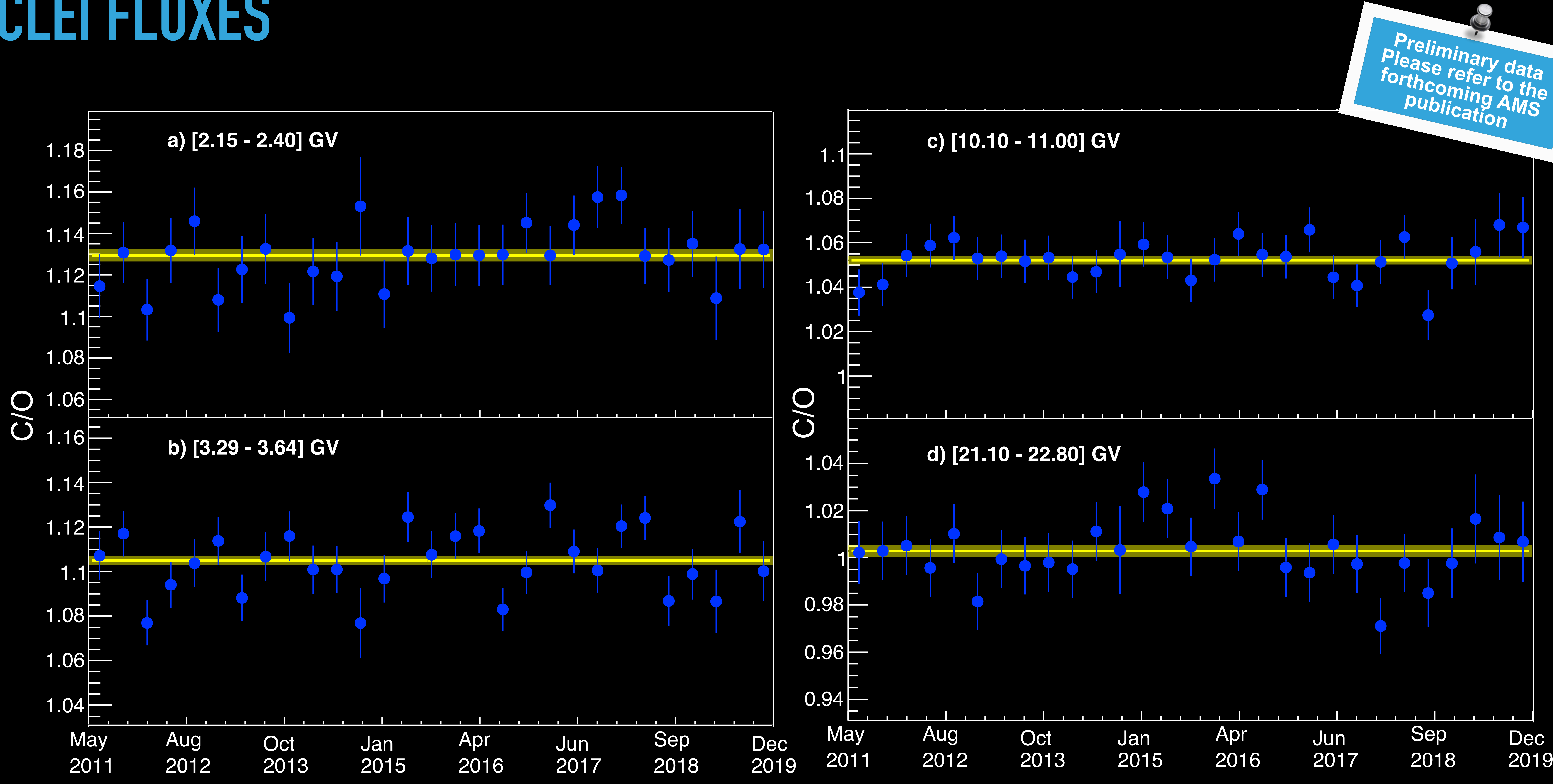


PRIMARY NUCLEI FLUXES

- proton, Helium, Carbon & Oxygen fluxes from May 2011 to Oct. 2019, in 27 days time interval (Bartels rotations)
- Rigidity ranges:
  [1 , 60] GV for p
  [1.7, 60] GV for He
  [1.9 , 60] GV for C
  [2.1 , 60] GV for O
- Similar long-term and short-term time structures
- The amplitude of these structures decreases with increasing rigidity and becomes non-observable at:
  ~ 25 GV for C & O
  ~ 50 GV for He
  while it's ***always observable for protons*** in the rigidity range analyzed.

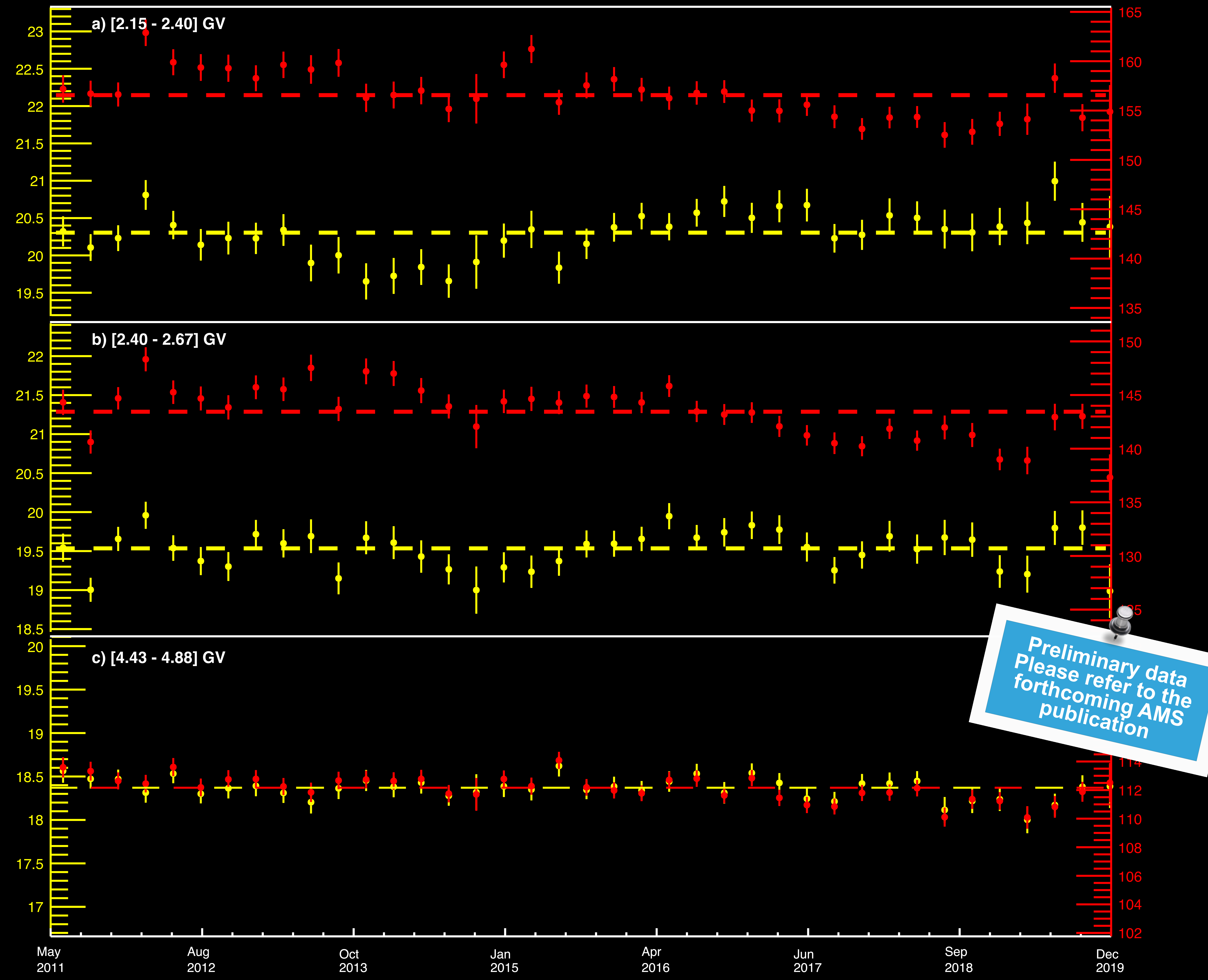
PRIMARY NUCLEI FLUXES

- 4 Bartels rotations time interval
- the first and only measurement of the time dependence of Carbon and Oxygen fluxes as a function of rigidity
- C&O have similar A/Z, hence same velocity, no time dependence difference arising from the velocity
- The C/O flux ratio is time independent in the whole rigidity range (from 2 to 60 GV)



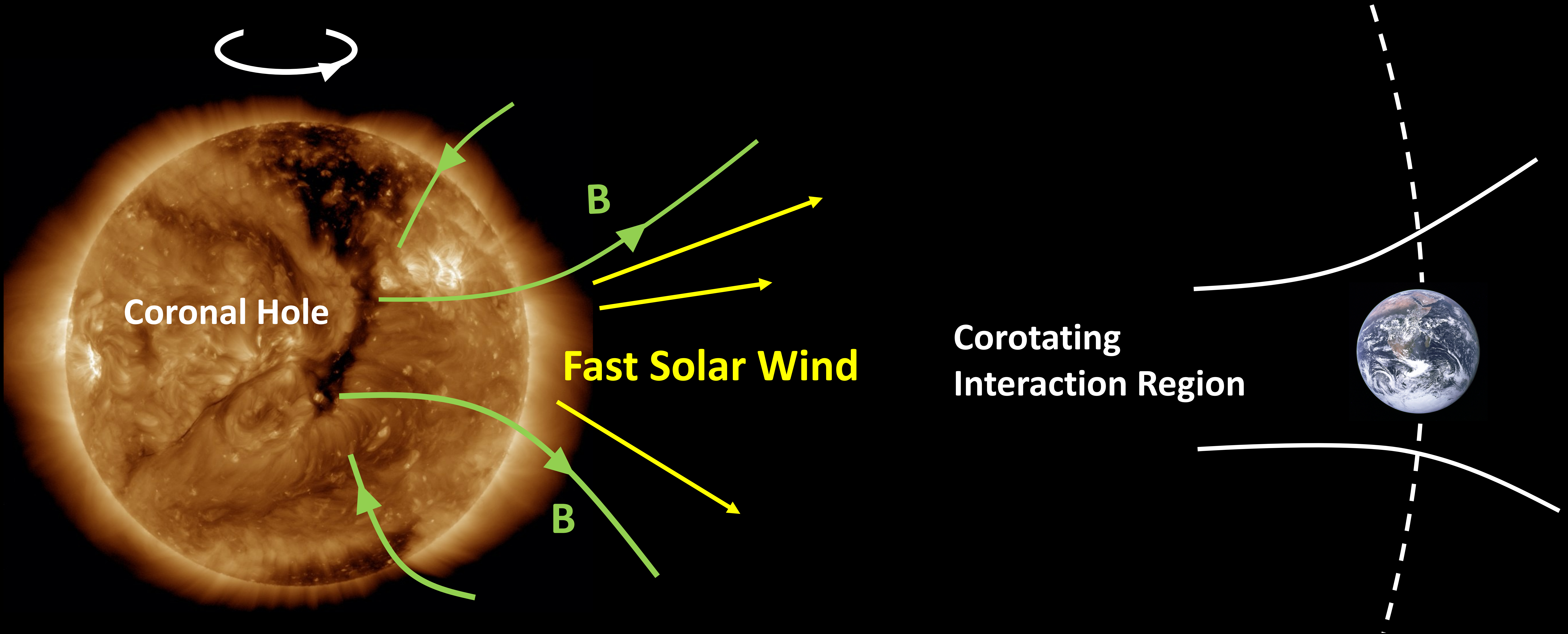
PRIMARY NUCLEI FLUXES

- 3 Bartels rotations time interval
- He/(C+O) flux ratio exhibits a time dependence up to ~2.5 GV
- He, C&O have similar A/Z, hence their LIS must have different rigidity dependence above 2 GV
- p/(C+O) flux ratio exhibits a time dependence up to ~4 GV
- p, C&O have different A/Z, hence both LIS rigidity dependence and velocity contribute to the observed time dependence of p/(C+O)



FINER STRUCTURES

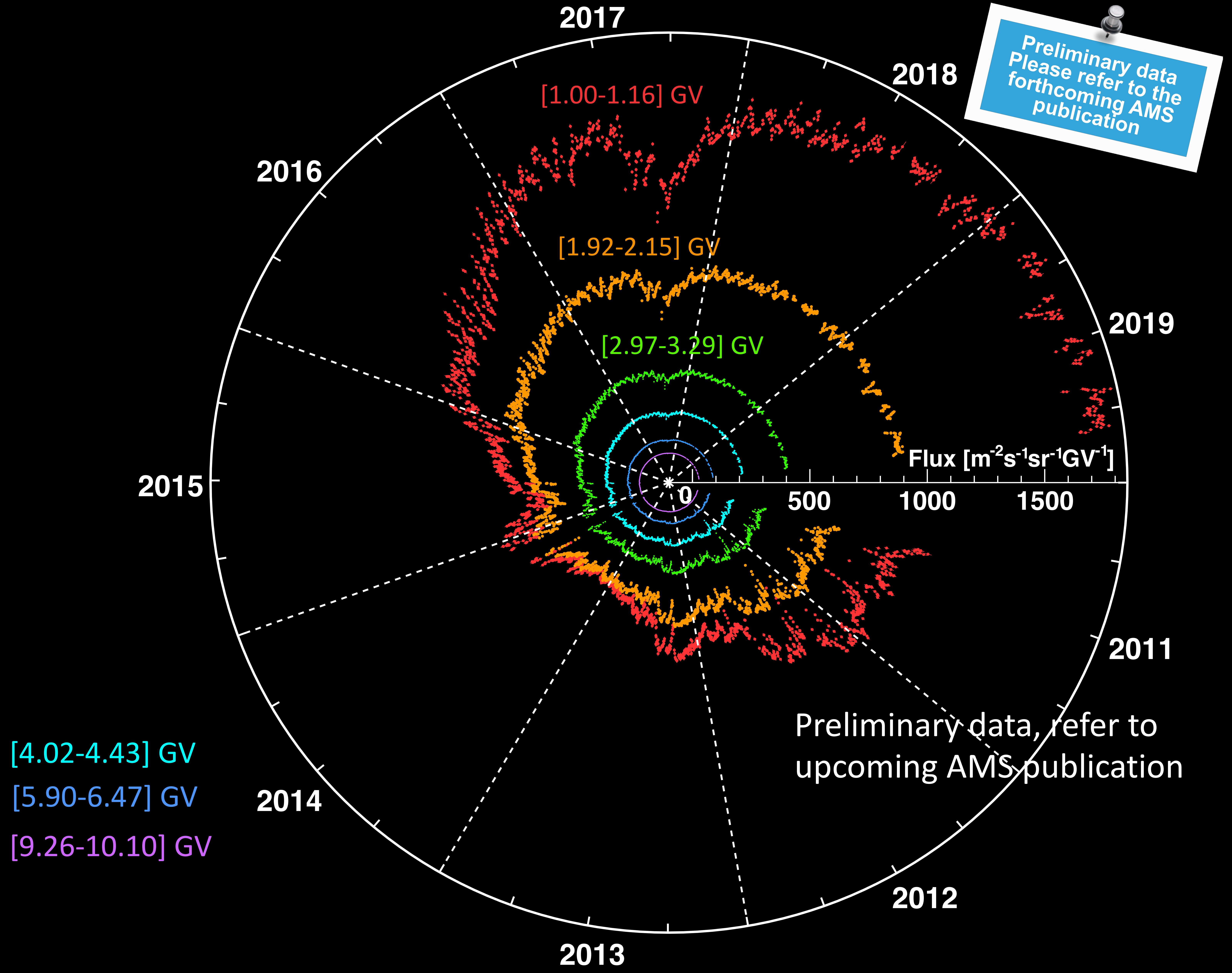
The presence of one or more coronal holes on the surface of the Sun creates recurrent variations in cosmic rays with a period of 27, 13.5, and 9 days.



DAILY FLUXES

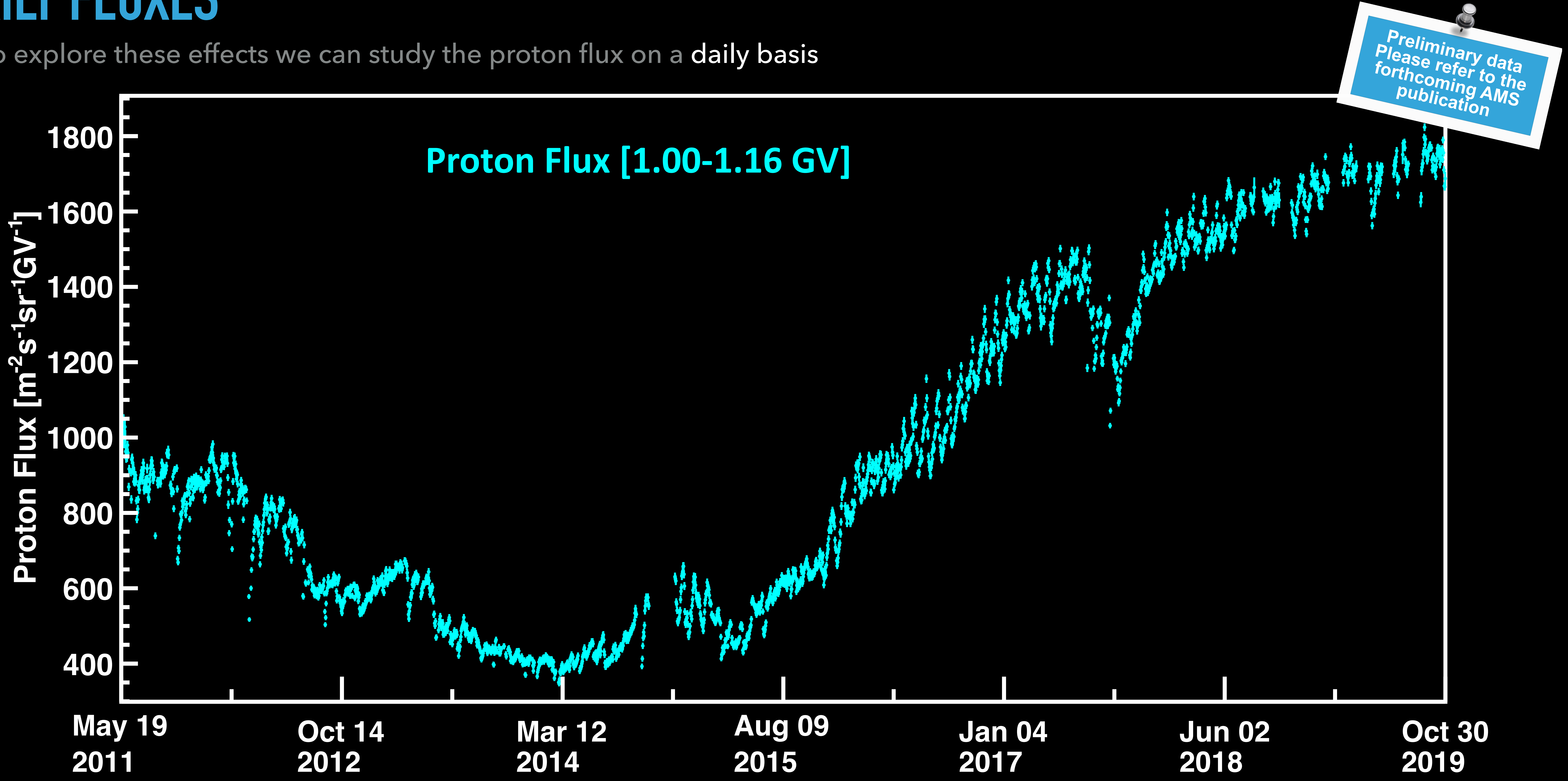
To explore these effects we can study the proton flux on a daily basis

5.5 billion protons collected from May 20, 2011 to October 29, 2019 (a total of 2824 days or 114 Bartels rotations)



DAILY FLUXES

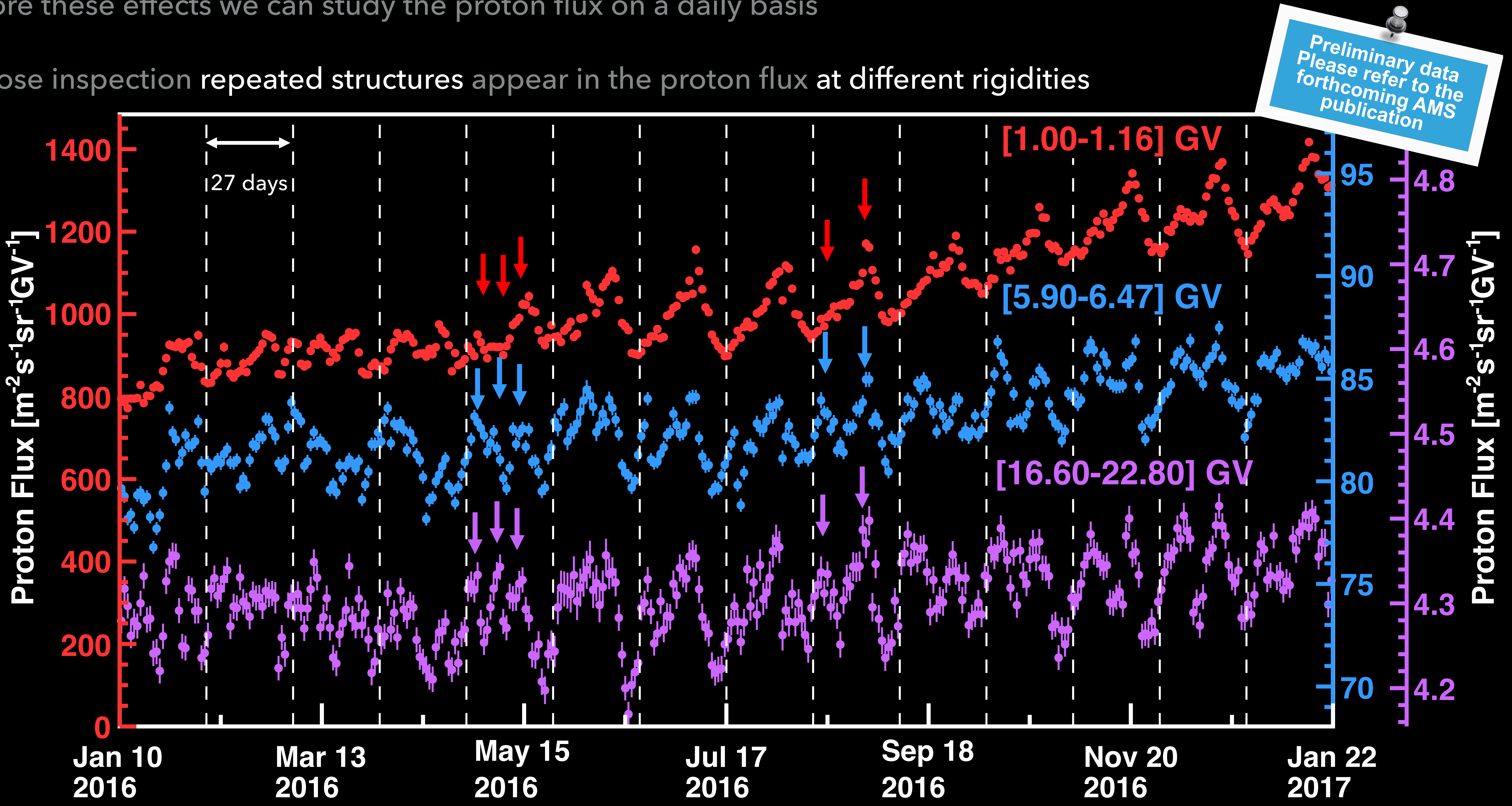
To explore these effects we can study the proton flux on a **daily basis**



DAILY FLUXES

To explore these effects we can study the proton flux on a daily basis

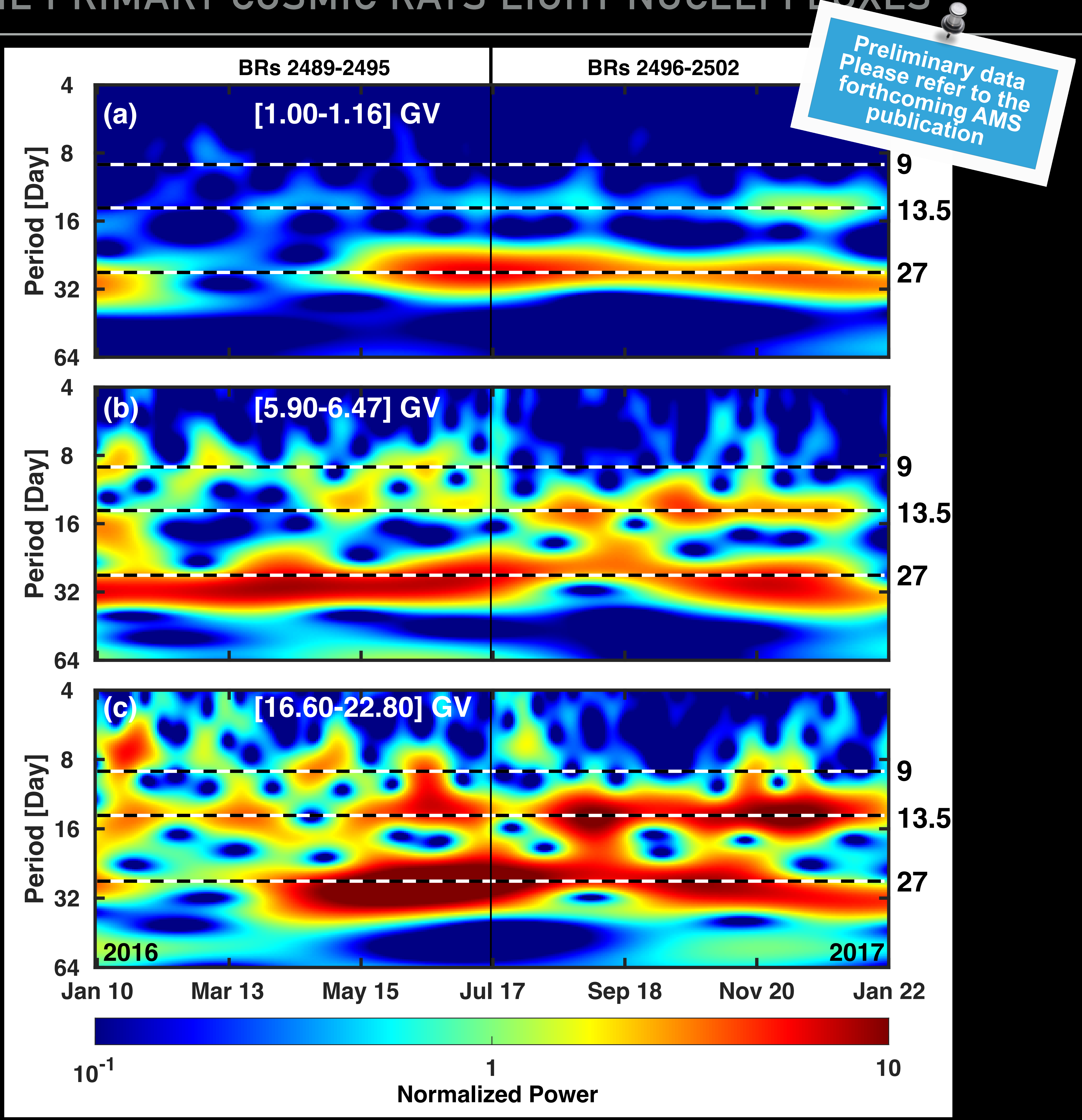
Upon close inspection **repeated structures** appear in the proton flux **at different rigidities**



WAVELET ANALYSIS

To better understand these structures we perform a **wavelet analysis** on the flux and look at the **frequency power** as a function of time.

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.



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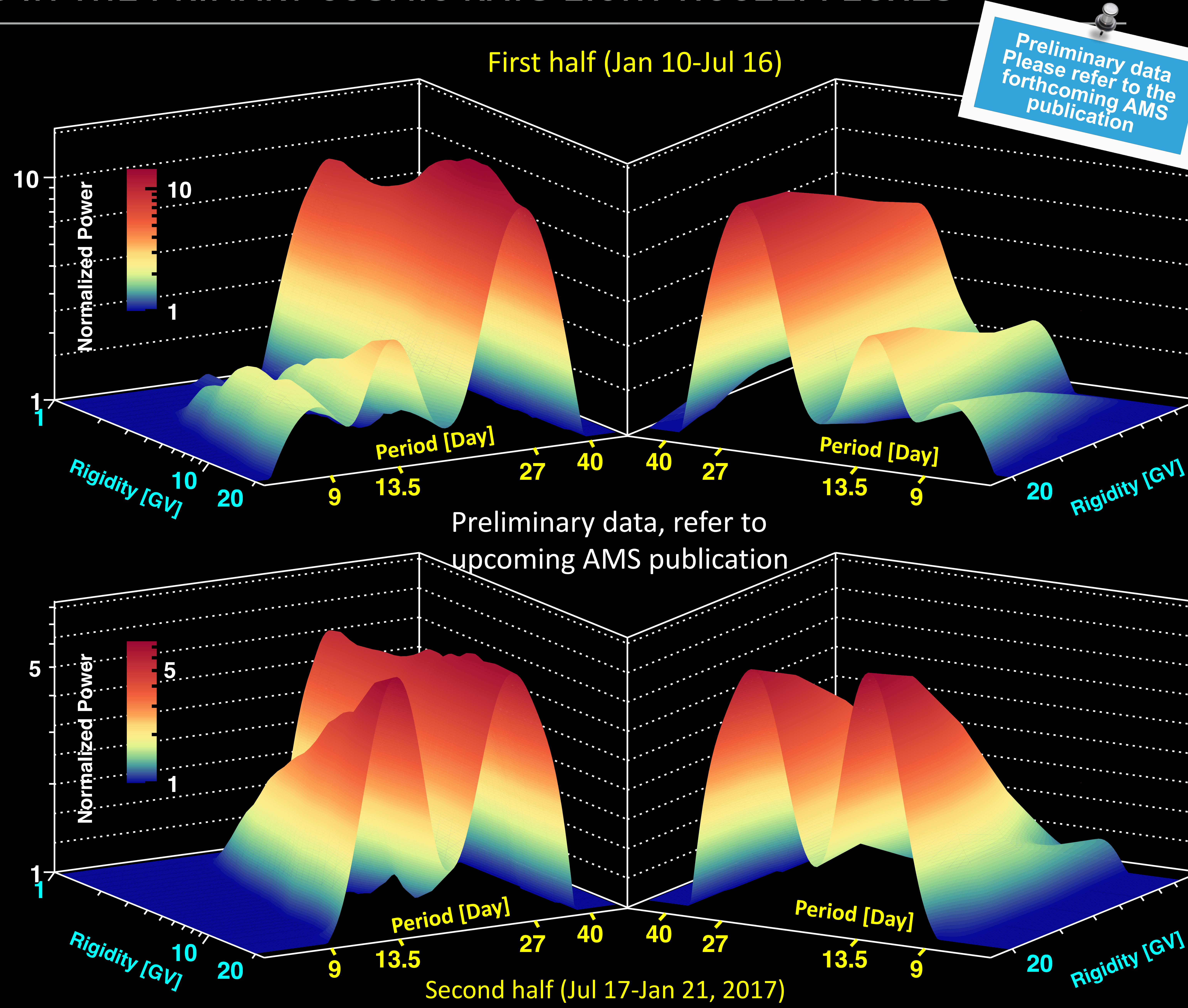
Periods of **9, 13.5, and 27 days are observed in 2016. The strength of all three periodicities change with time and rigidity.** In particular, shorter periods of 9 and 13.5 days, when present, are more visible at ~6 GV and ~20 GV compared to 1 GV.

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



CONCLUSIONS

- The precision measurement of proton, Helium, Carbon and Oxygen fluxes in Bartels rotations from May 2011 to October 2019 has been presented.
- The study of the time evolution as a function of rigidity for different nuclei species provides unique info to understand the contribution of the LIS and of the velocity dependence of CR propagation in the heliosphere.
- The first and only measurement of the time dependence of Carbon and Oxygen fluxes as a function of rigidity.
- The 4 nuclei species exhibit similar behavior in time:
    - 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 a time dependence up to ~2.5 GV, indicating that their LIS has a different rigidity dependence.
    - The p/(C+O) flux ratio also shows a time dependence up to ~4 GV. Both LIS rigidity dependence and velocity contribute to this time behavior.

- We have presented the precision measurements of the daily proton fluxes in cosmic rays from 1 GV to 100 GV between May 20, 2011 and October 29, 2019 based on 5.5×10^9 protons. The proton fluxes exhibit variations on different time scales, in days, months, and years.

- From 2014 to 2018, we observed recurrent flux variations with a period of 27 days. Shorter periods of 9 days and 13.5 days are observed in 2016.

- The strength of all three periodicities changes with both time and rigidity. In particular, the strength of 9-day and 13.5-day periodicities increases with increasing rigidities up to ~10 GV and ~20 GV respectively, and then decreases with increasing rigidity up to 100 GV.