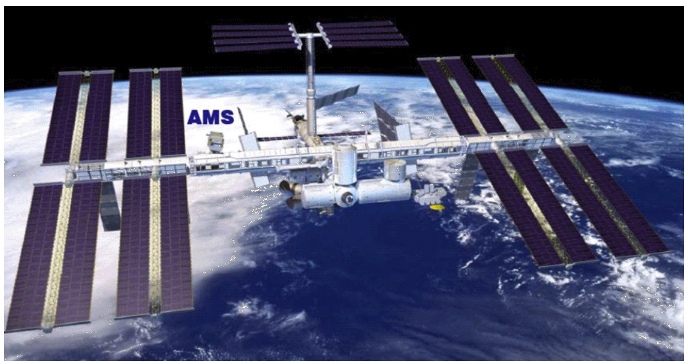
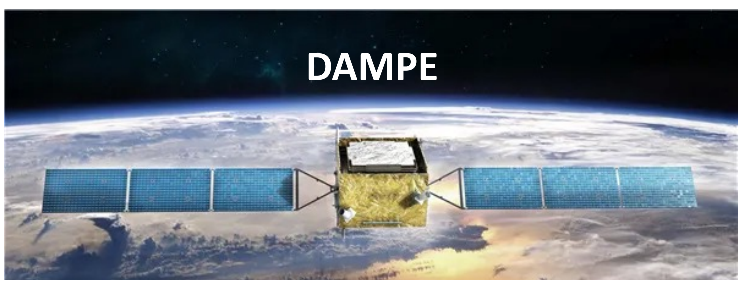
EPFL Physics and Applied Physics master programs - A.Y. 2024-2025

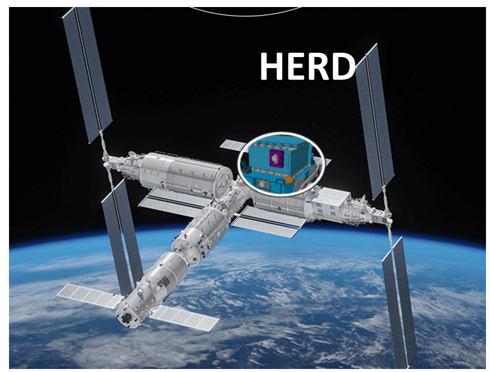
Introduction to astroparticle physics

Part 2 – Lesson 3 – May 9, 2025

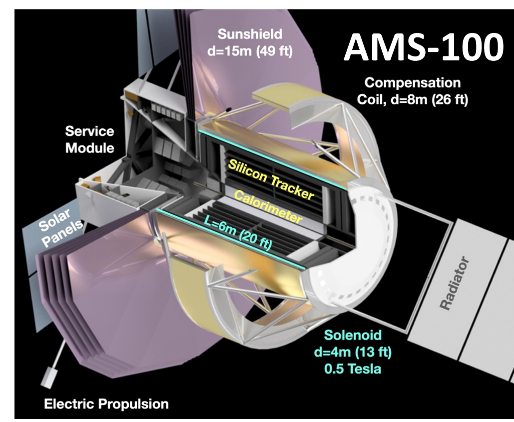
Present







Near future



Far future

Chiara Perrina

E-mail: Chiara.Perrina@epfl.ch

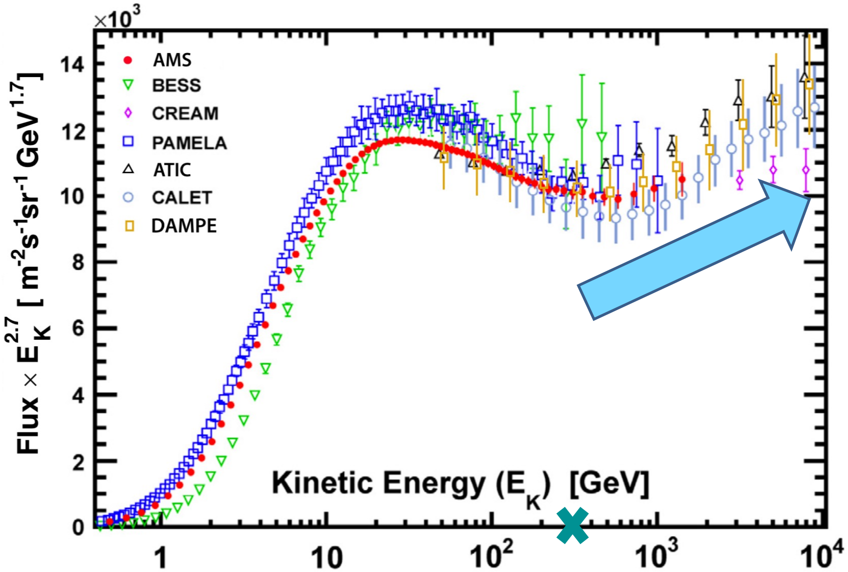
Learning outcomes and goals

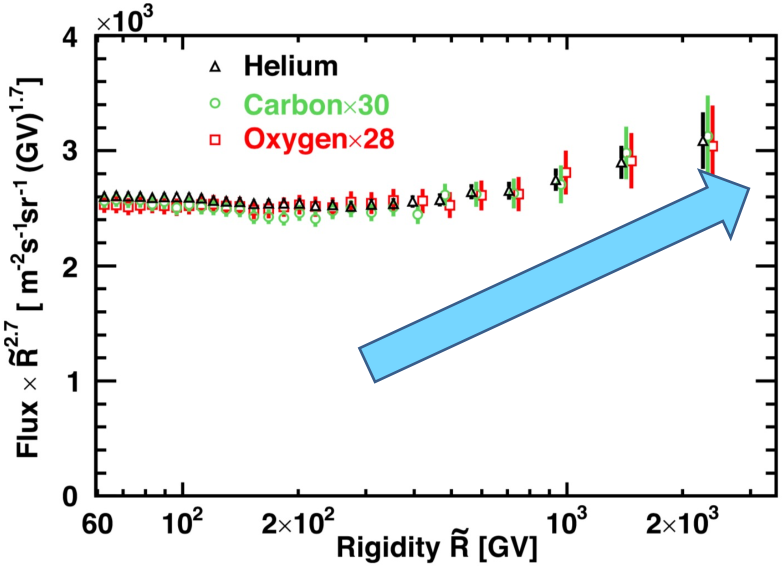
- Describe the cosmic ray (CR) energy spectrum and composition. Discuss CR origin, acceleration and propagation.
- Explain the relationship between charged CRs, gamma-rays and neutrinos.
- Discuss the detection principles and measured quantities (mass, charge, momentum, energy, rigidity, direction, …) of astroparticle physics experiments.
- Interpret the main results of selected experiments
- Assess / Evaluate the state of the art of astroparticle physics

Light Primaries: p, He, C, O

AMS Report

Protons, one billion proton events collected by AMS





The proton flux does not follow a single power law: **above 200 GV hardens**.

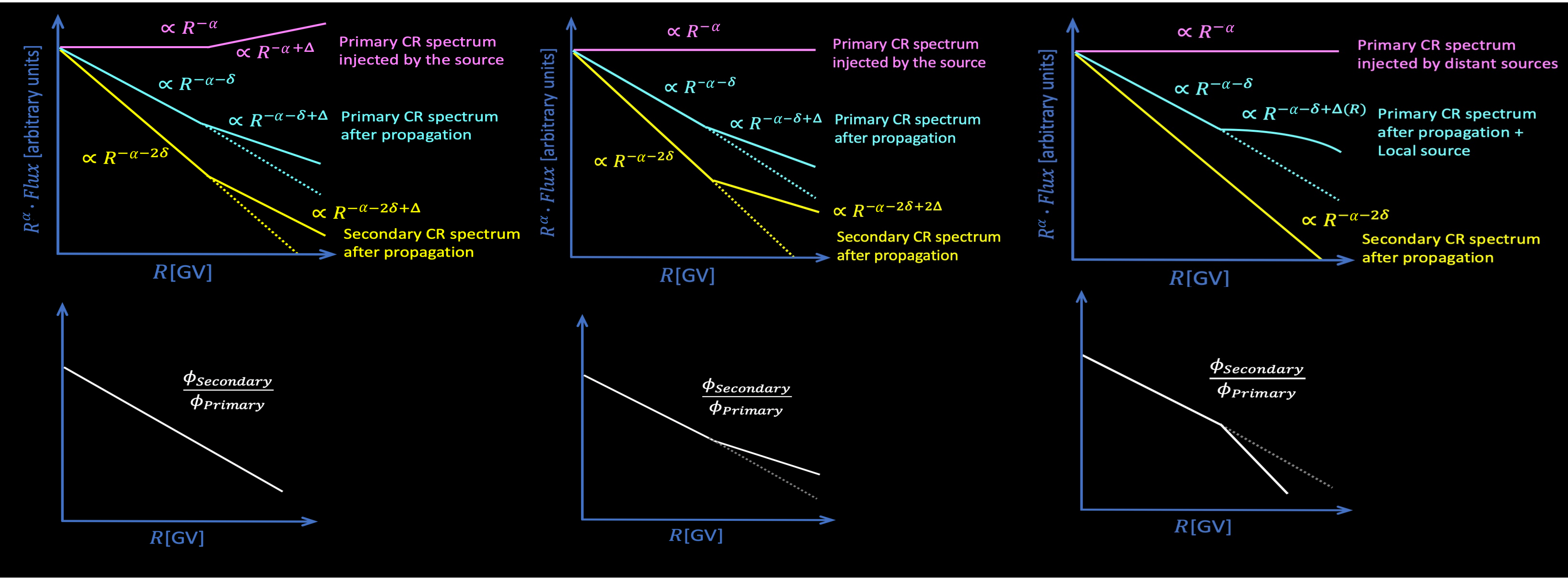
Above 60 GV, the primary cosmic rays have identical rigidity dependence. Also the spectra of He, C, and O **above 200 GV harden**.

Which is the origin of the spectral hardening?

Which is the origin of the spectral hardening?

Interpretations of the spectral hardening fall in three categories:

Spectral break at source | **Propagation effect** | **Local source**



δ describes the energy-dependence of the diffusion

$D \propto \lambda\beta$

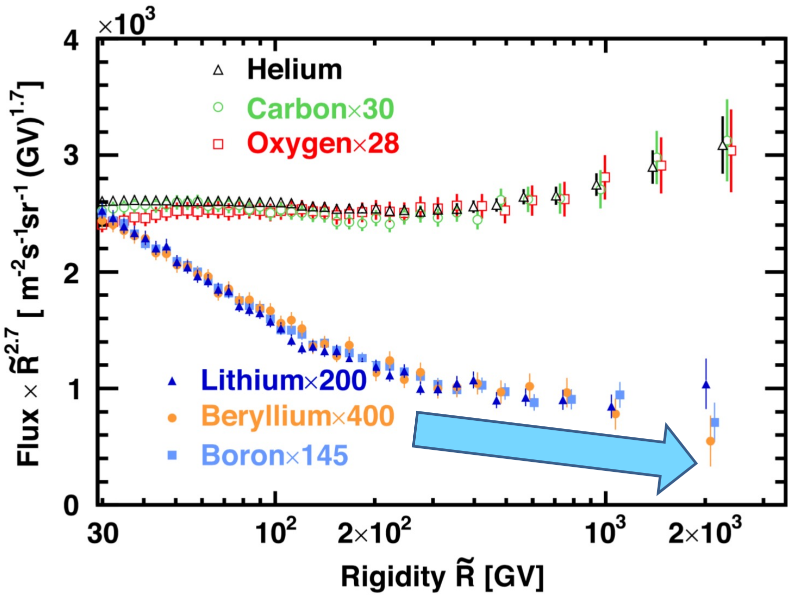
$D(E) \propto E^{\delta}$

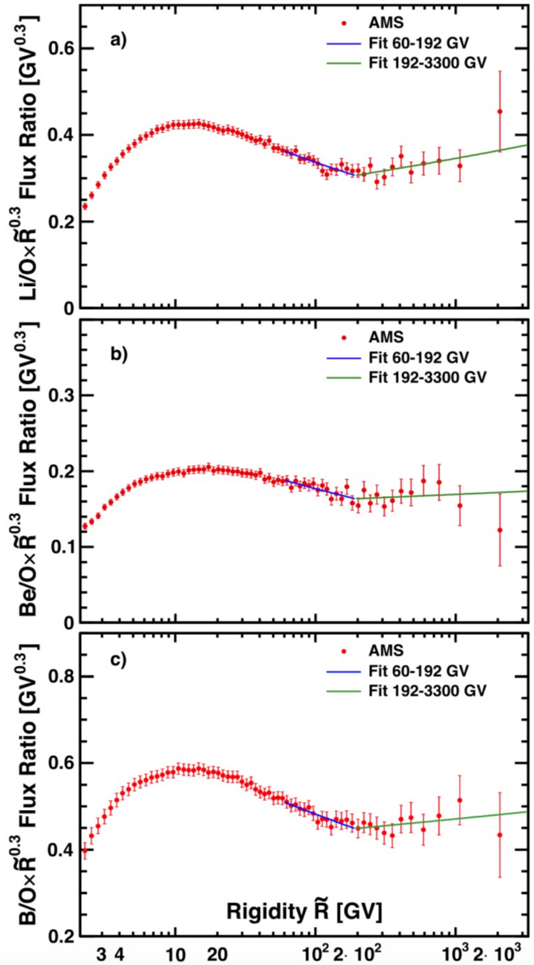
$\lambda \propto E^{\delta}$

Thanks to the measurement of the individual primary and secondary CR spectra and of their ratios we can understand the origin of the spectral hardening.

Light Primary and Secondary Cosmic Rays

AMS Report





Secondary cosmic rays Li, Be, and B have their own **identical** rigidity dependence.

Primaries and Secondaries have distinctly **different** spectral shapes: both harden above 200 GV and secondaries harden more than primaries.

Above 192 GV the secondary-to-primary flux ratios **harden**.

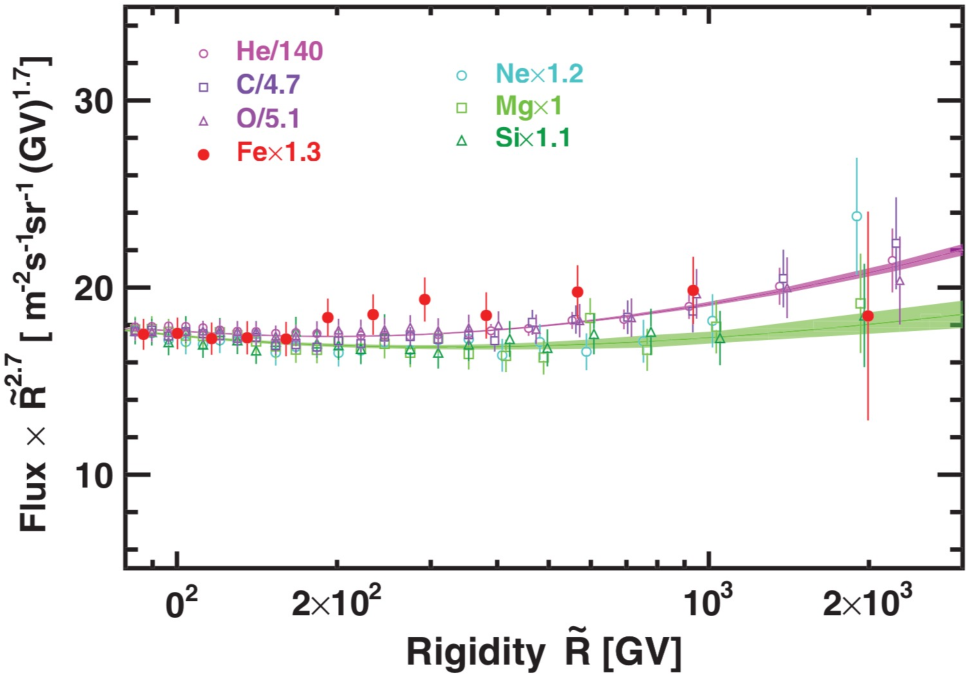
→ This observation favours the hypothesis that the observed spectral **hardening** is due to a **propagation effect**.

What about nuclei heavier than Oxygen?

Is the spectral hardening universal?

Light, Heavy and Very heavy Primary Cosmic Rays

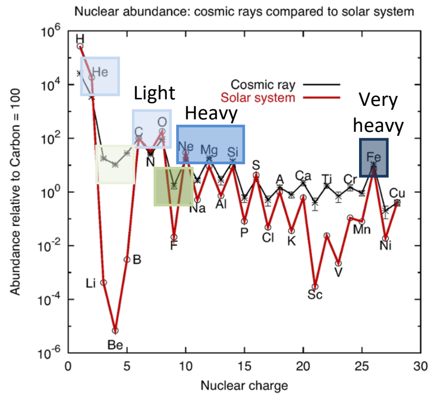
AMS Iron



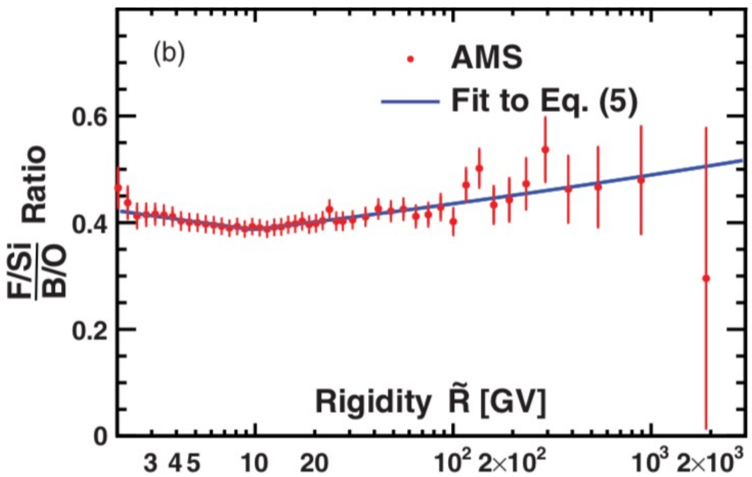
Primary cosmic rays have at least **two classes**.

Heavy primaries (Ne, Mg, Si) have their own identical rigidity behavior but different from the one of light primaries (He, C, O).

Unexpected result: Iron (Fe) belongs to the class of light primary cosmic rays.

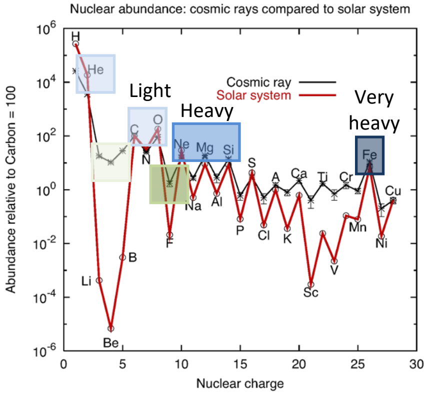


Heavy secondary/heavy primary to Light secondary/light primary Ratio



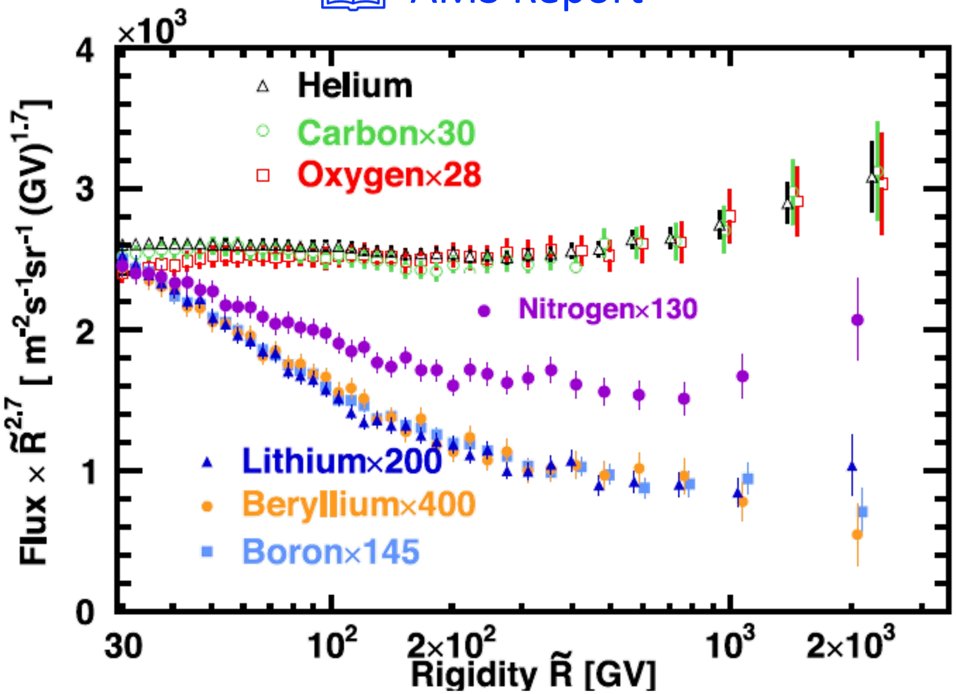
The heavy secondary-to-primary ratio F/Si and the light secondary-to-primary ratio B/O **have a different rigidity dependence**.

→ **Heavy and light cosmic rays have different propagation properties.**



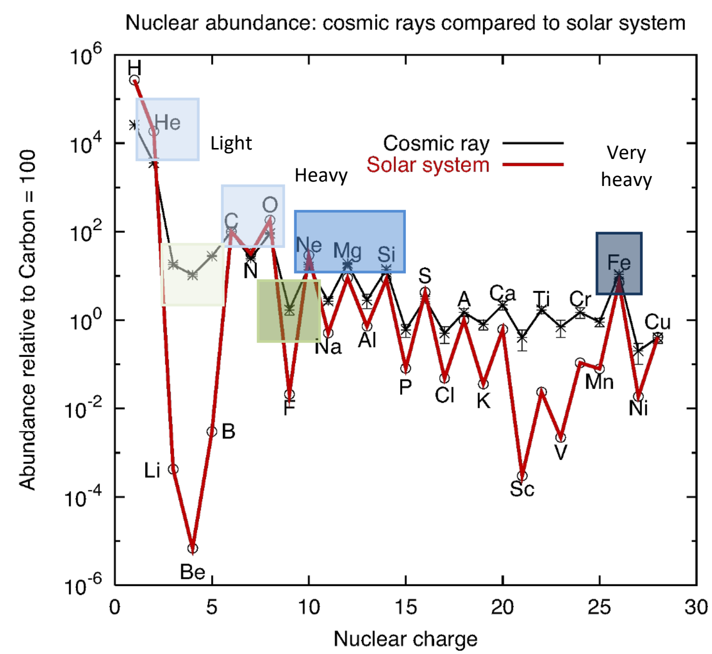
Nitrogen

AMS Report



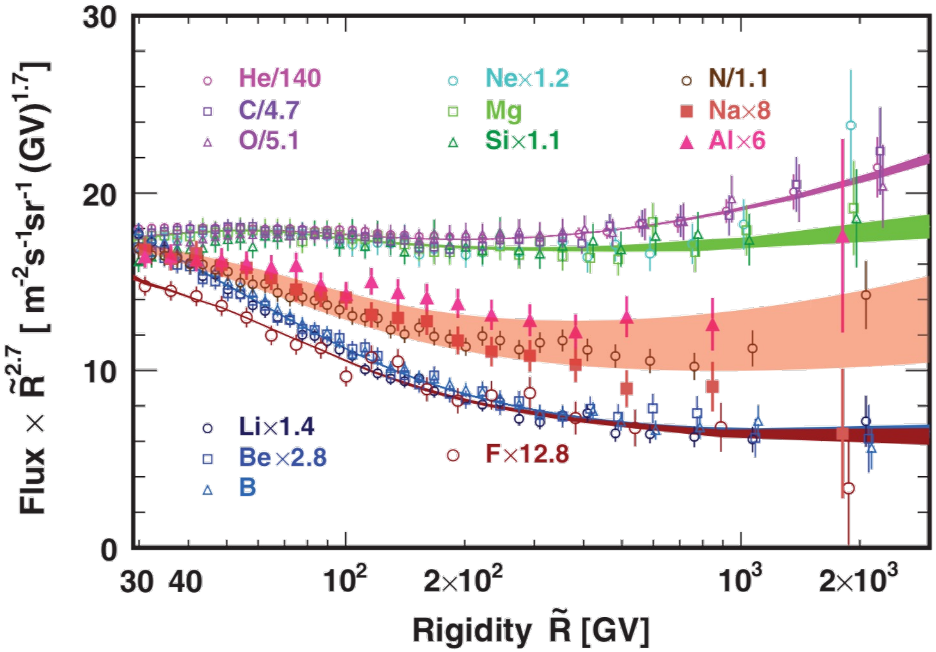
We know that Nitrogen nuclei are produced both in astrophysical sources, mostly via the C-N-O cycle, and by the collisions of heavier nuclei with the interstellar medium.

→ the nitrogen flux is observed to contain both primary and secondary components.



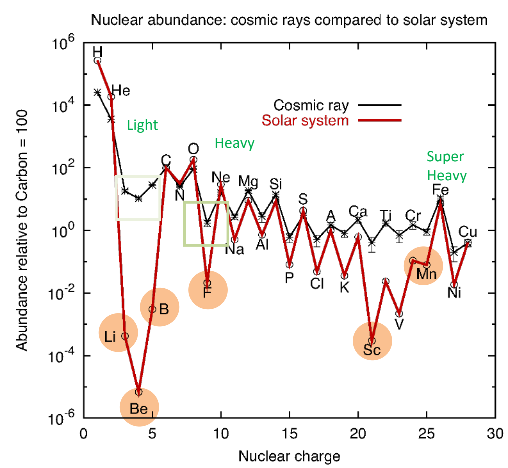
Summary: Primary and Secondary Cosmic Nuclei

AMS N Na Al



There are **classes with** their own identical rigidity behavior:

- light primaries (He, C, O)
- heavy primaries (Ne, Mg, Si)
- N, Na, Al contain both primary and secondary components
- light secondaries (Li, Be, B, F)
- heavy secondaries (F)



Question

Would the measurement of the secondary-to-secondary flux ratio be interesting?

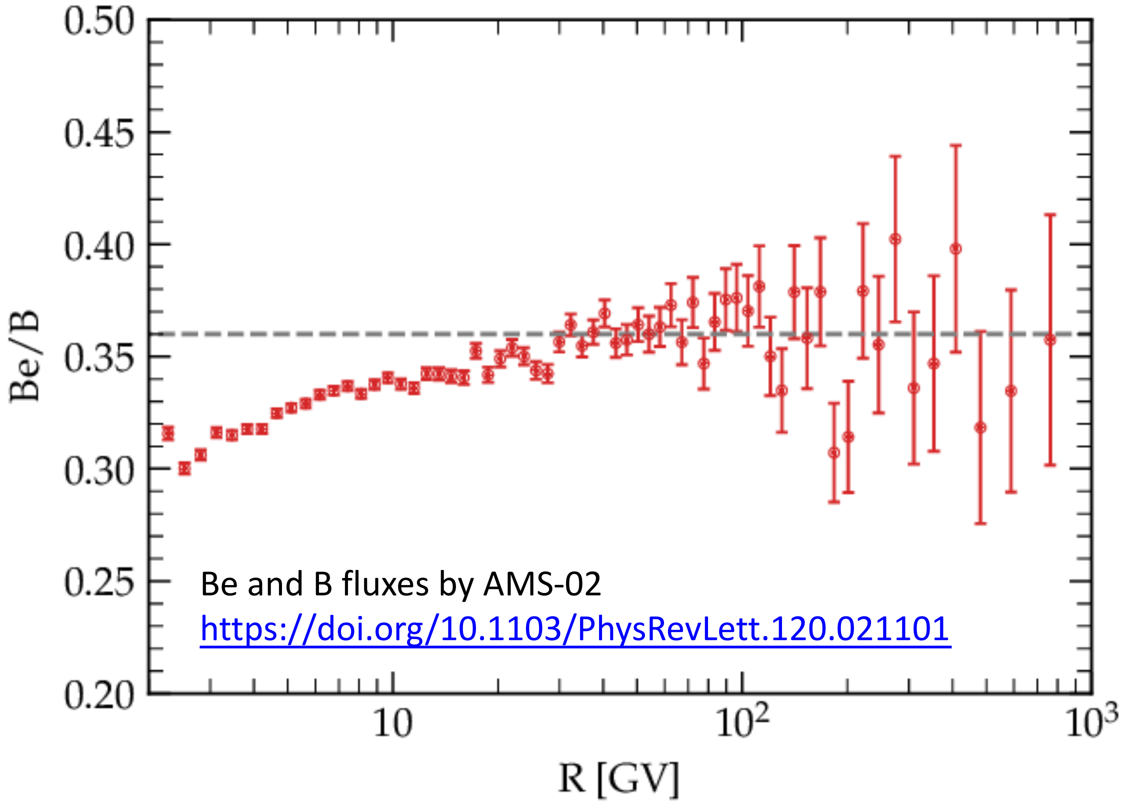
- For example, Be/B?

Question

Would the measurement of the secondary-to-secondary flux ratio be interesting?

- For example, Be/B?

https://doi.org/10.48550/arXiv.2309.00298

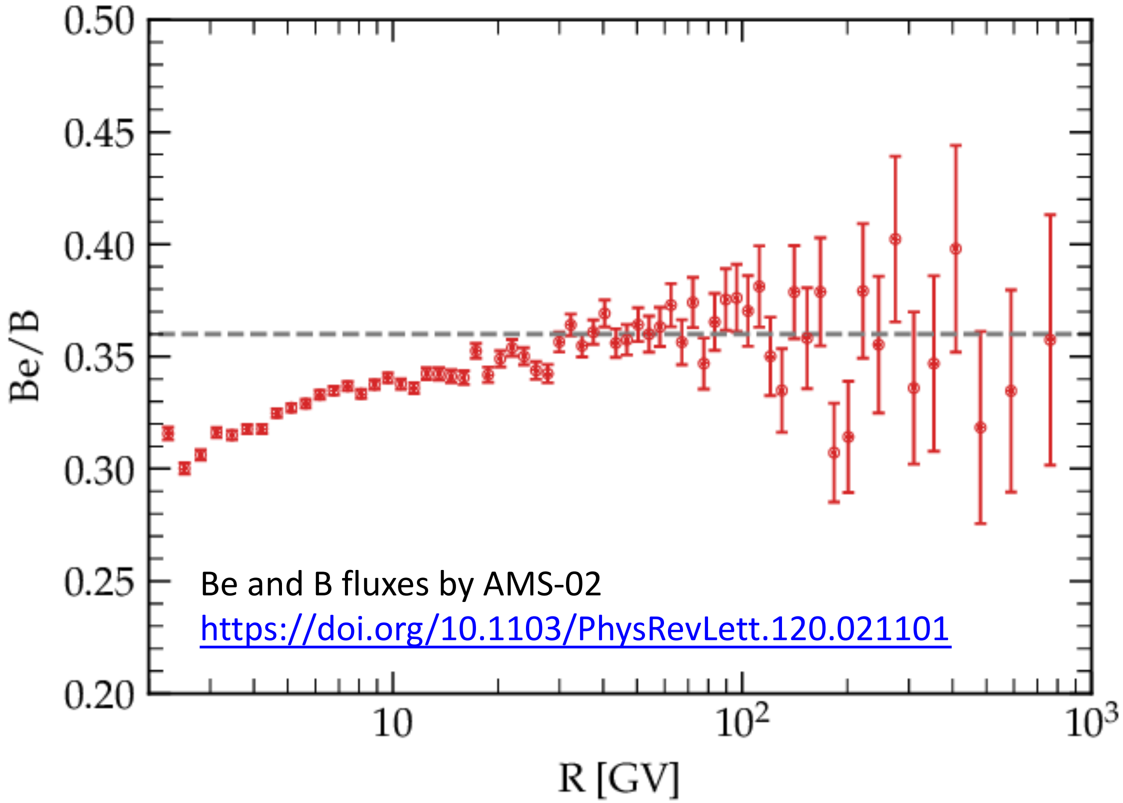


Question

Would the measurement of the secondary-to-secondary flux ratio be interesting?

- For example, Be/B?

https://doi.org/10.48550/arXiv.2309.00298



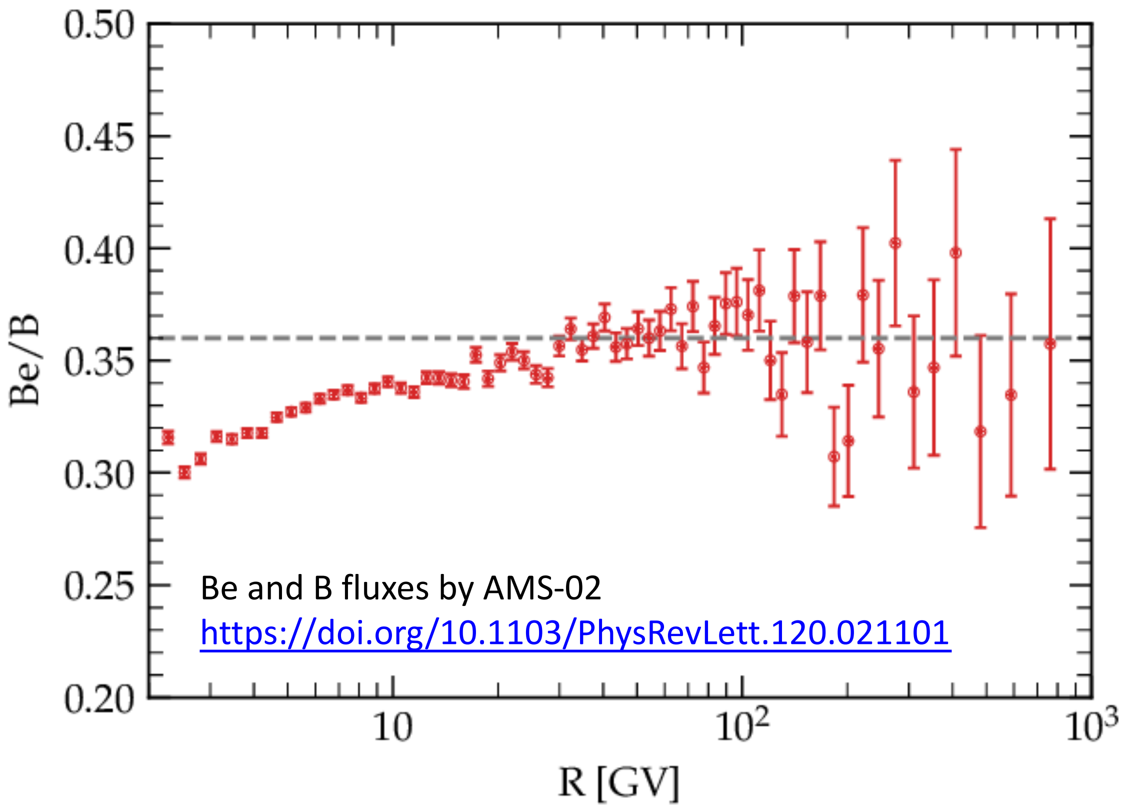
The dotted line shows the case without decay for ^{10}Be.

Question

Would the measurement of the secondary-to-secondary flux ratio be interesting?

- For example, Be/B?

https://doi.org/10.48550/arXiv.2309.00298



The dotted line shows the case without decay for ^{10}Be.

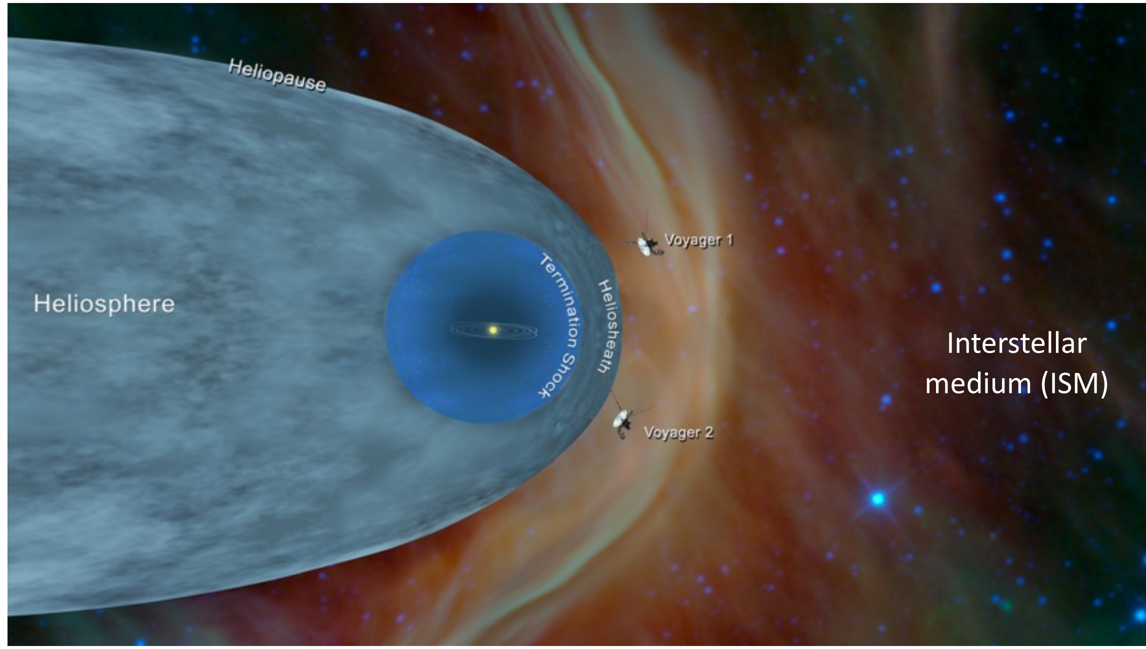
The Be/B ratio is influenced by the decay of ^{10}Be, affecting both the numerator and the denominator.
This measurement suggests that at rigidities $\lesssim$ 30 GV, the CR residence time in the Galaxy (age) is larger than the decay timescale.

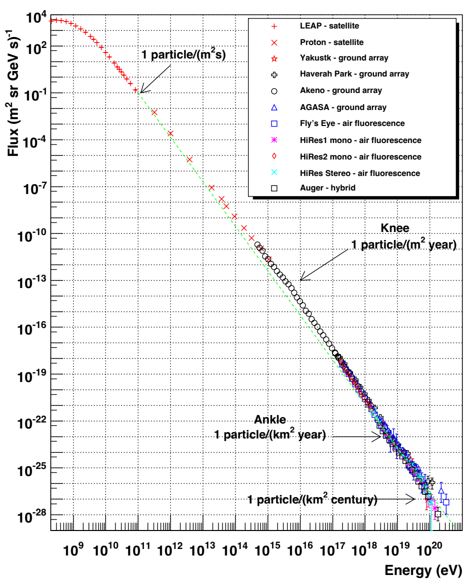
Solar Modulation of cosmic-ray spectra

https://www.nasa.gov/mission_pages/sunearth/science/Heliosphere.html

The Sun ejects a stream of electrically charged gas (electrons, protons, helium, …) called **solar wind**. It travels at an average speed ranging from 300 km/s to 700 km/s until it reaches the **termination shock**.

At this point, the speed of the solar wind drops abruptly as it begins to feel the effects of **interstellar wind**.





$E < 10$ GeV : charged CRs are affected by the **modulation** due to the solar wind

The solar wind, creates a bubble, called «heliosphere», that extends far past the orbits of the planets.

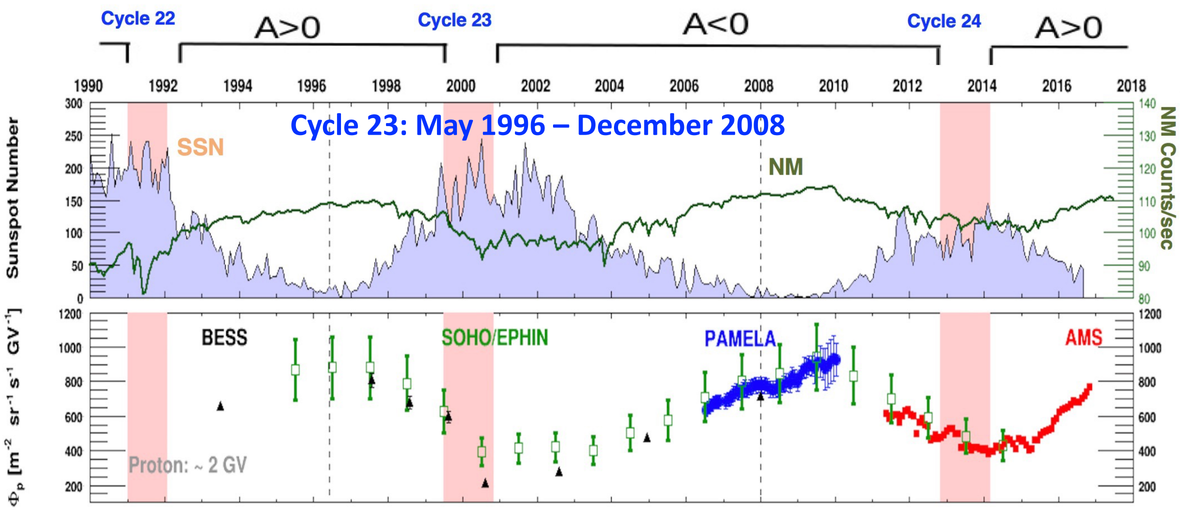
The heliosphere screens the atmosphere from low energy cosmic rays.

Solar cycle and in-time modulation of CRs

The solar wind generates a **magnetic field** which has a cycle, called «**solar cycle**».

Every ~11 years, the Sun's magnetic field completely flips.
The solar cycle affects the activity on the surface of the Sun, such as **sunspots (SSN)** which are caused by Sun's magnetic fields.

PRL 127, 271102 (2021)



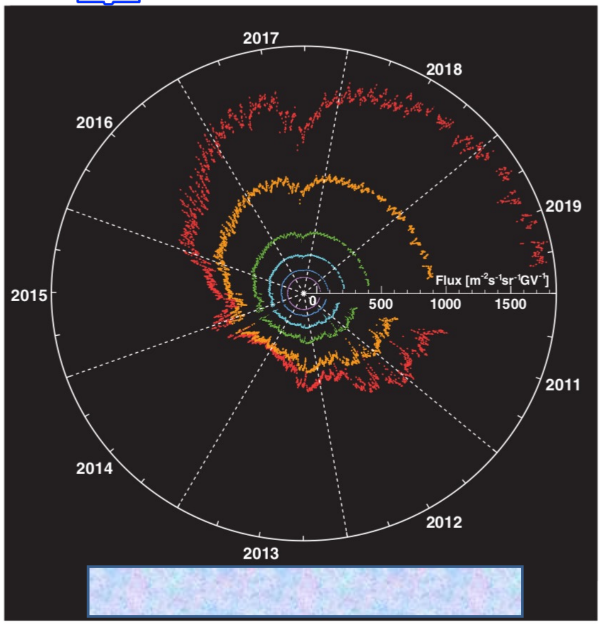


FIG. 1. The daily AMS proton fluxes for six typical rigidity bins from 1.00 to 10.10 GV measured from May 20, 2011 to October 29, 2019 which includes a major portion of solar cycle 24 (from December 2008 to December 2019). The AMS data cover the ascending phase, the maximum, and descending phase to the minimum of solar cycle 24. Days with SEPs are removed for the two lowest rigidity bins. The gaps in the fluxes are due to detector studies and upgrades. The error bars are invisible. As

Space radiation measurements are crucial to model radiation hazards for human travel in space.

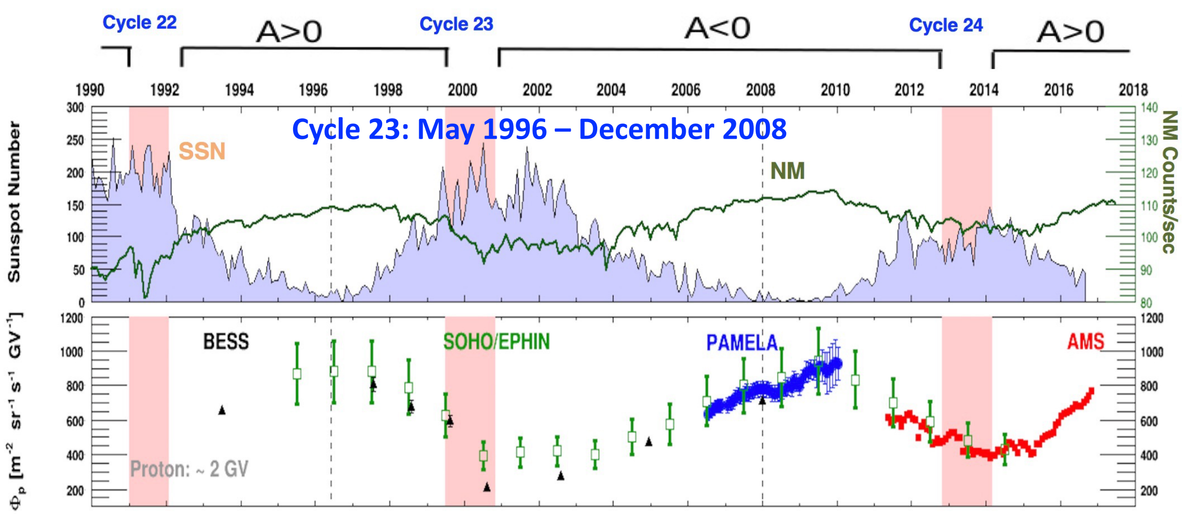
SEP: solar energetic particles

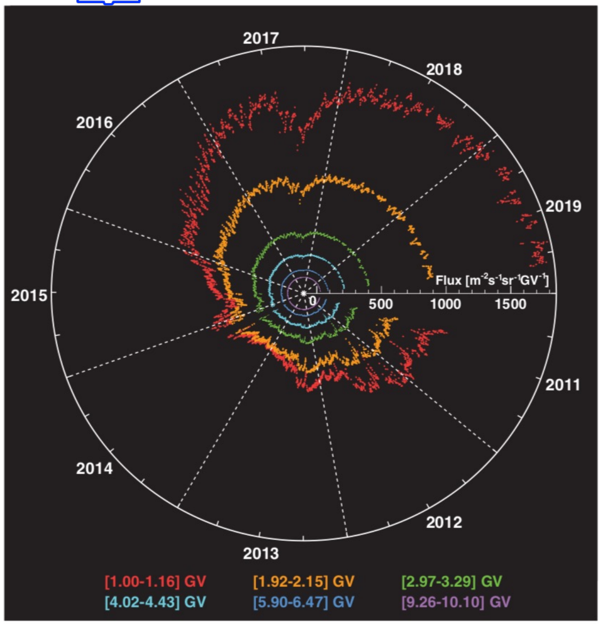
Solar cycle and in-time modulation of CRs

The solar wind generates a **magnetic field** which has a cycle, called «**solar cycle**».

Every ~11 years, the Sun's magnetic field completely flips.
The solar cycle affects the activity on the surface of the Sun, such as **sunspots (SSN)** which are caused by Sun's magnetic fields.

PRL 127, 271102 (2021)





Space radiation measurements are crucial to model radiation hazards for human travel in space.

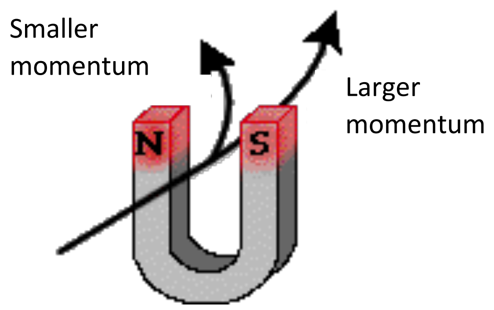
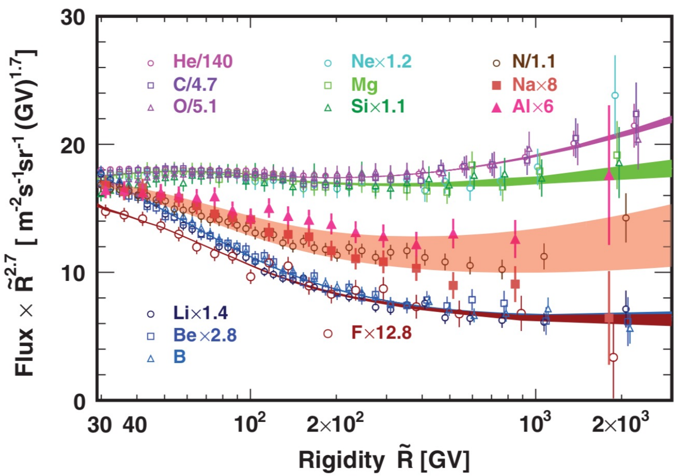


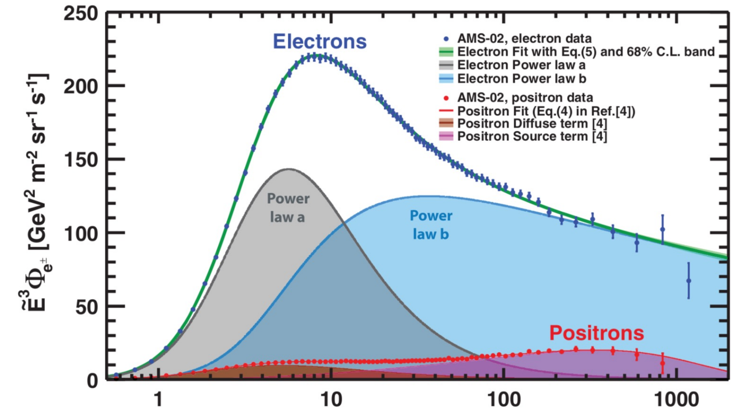
FIG. 1. The daily AMS proton fluxes for six typical rigidity bins from 1.00 to 10.10 GV measured from May 20, 2011 to October 29, 2019 which includes a major portion of solar cycle 24 (from December 2008 to December 2019). The AMS data cover the ascending phase, the maximum, and descending phase to the minimum of solar cycle 24. Days with SEPs are removed for the two lowest rigidity bins. The gaps in the fluxes are due to detector studies and upgrades. The error bars are invisible. As seen, the proton fluxes exhibit large variations with time, and the relative magnitude of these variations decreases with increasing rigidity.

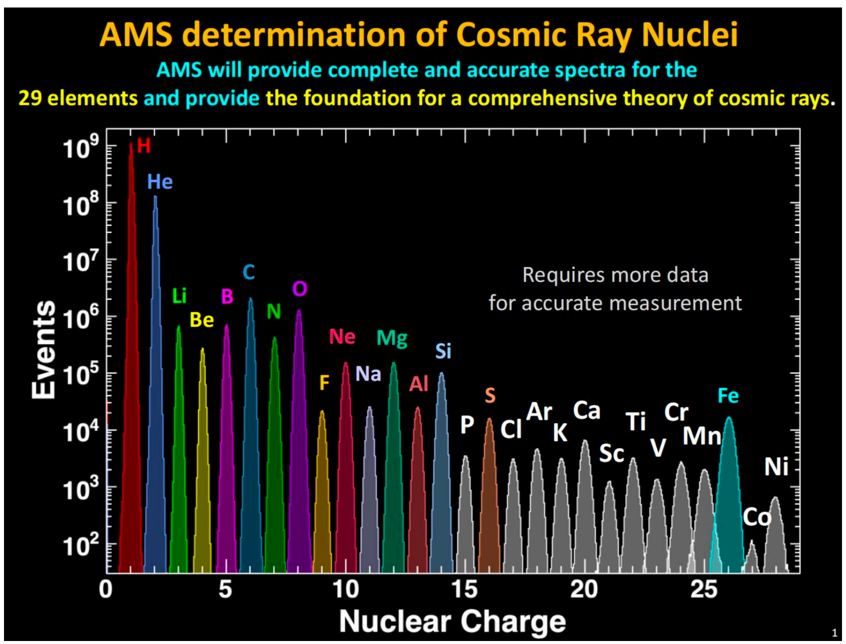
AMS future measurements

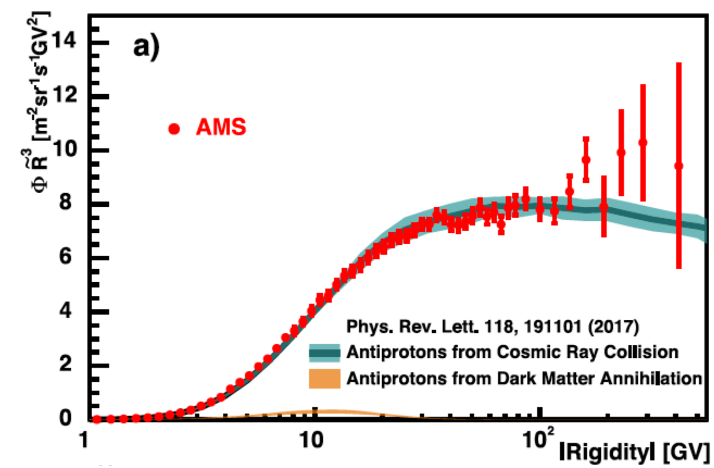
AMS N Na Al



Is there a universality of the spectrum hardening?





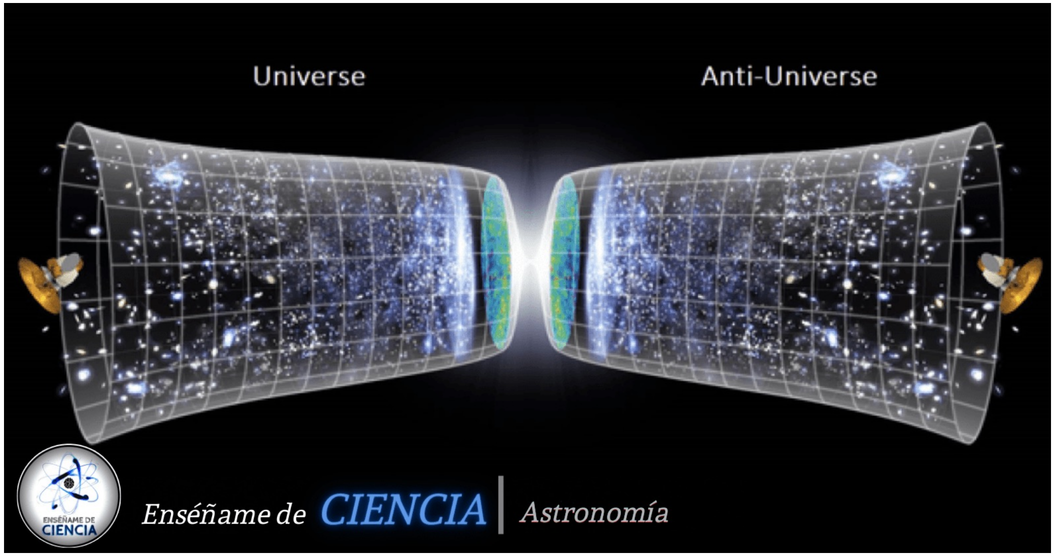


What is the origin of the observed anti-matter (positrons and antiprotons)?

https://ams02.space/physics/research-group-unveils-properties-cosmic-ray-sulfur-and-composition-other-primary-cosmic

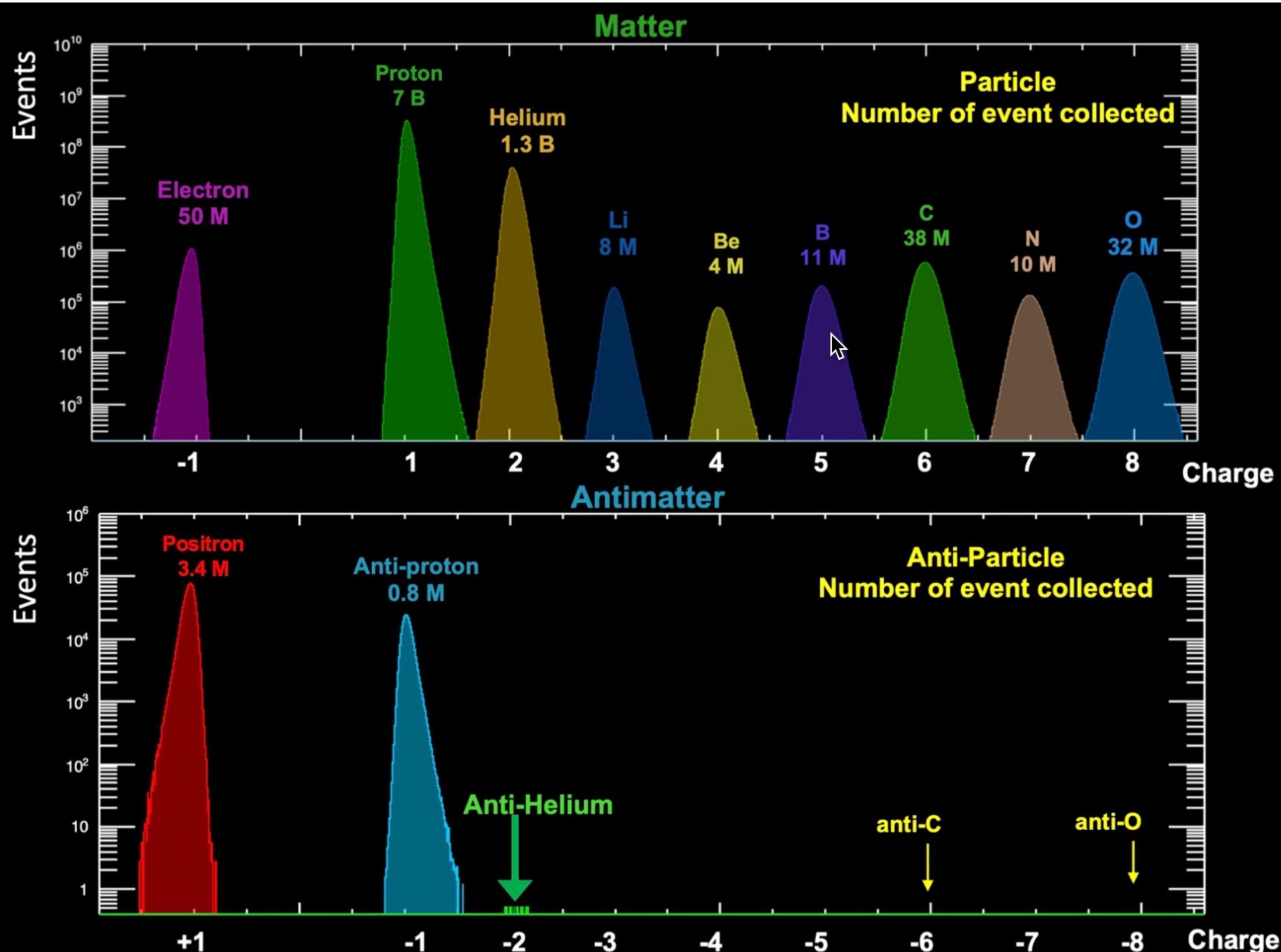
Fundamental question: Existence of Heavy Antimatter

The Big Bang origin of the Universe requires **matter and antimatter** **equally abundant** at the very hot beginning.



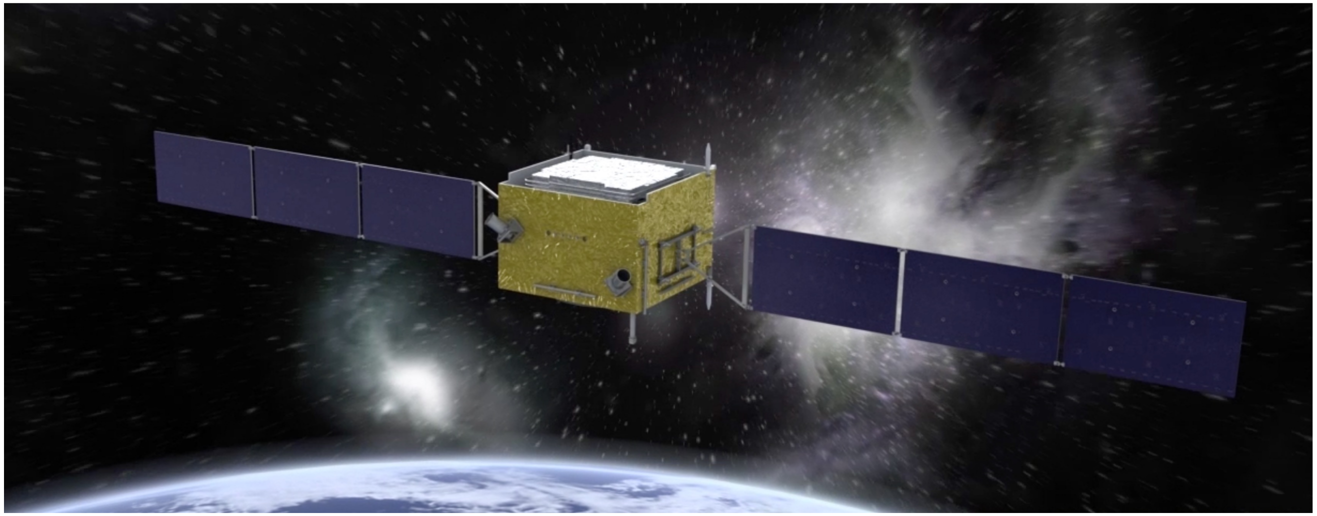
Heavy antimatter has never been found.
Where are $\overline{He}$, $\overline{C}$, $\overline{O}$?

AMS-02 measurements of matter and antimatter



V. Choutko
COSPAR 2022
Athens

DAMPE (2015 - now)



http://dpnc.unige.ch/dampe/

Launch video: https://youtu.be/Iyy_A4cQzgE

DArk **M**atter **P**article **E**xplorer goals:

- Study of cosmic ray spectra (electrons + positrons, protons and heavier nuclei)
- Gamma-ray astronomy
- Search for signatures of annihilation/decay products of **dark matter** in the electrons + positrons and gamma-ray energy spectra (indirect DM search)
  - E.g., annihilation : $\chi + \bar{\chi} \rightarrow e^{+} + e^{-}$
- Exotica and "unexpected" , e.g., electromagnetic counterpart of Gravitational waves

3 years (planned), still running (9.5 years)

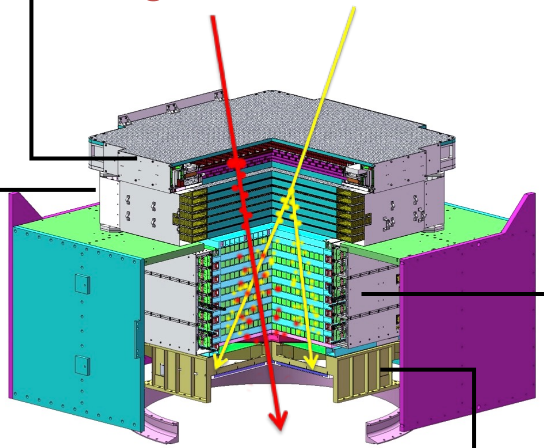
DAMPE: a calorimetric space-borne experiment

Needed: particle identification and energy and direction measurements.

1.45 tons
1.2 m × 1.2 m × 1 m

PSD: Plastic Scintillator Detector
- Charged/neutral particle identification
- Charge measurement (|Z|)

STK: Silicon-Tungsten tracKer-converter
- Track reconstruction (6x+6y)
- Photon conversion ($\gamma \rightarrow e^+ e^-$)
- Charge measurement (|Z|)



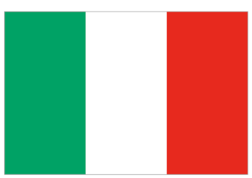
BGO: Bismuth Germanium Oxide calorimeter
- Energy measurement
- Electron/proton separation

NUD: NeUtron Detector
- Delayed neutrons coming from the hadronic interactions → electron/proton separation

The DAMPE Collaboration

- **China**
  - Purple Mountain Observatory, CAS, Nanjing
  - University of Science and Technology of China, Hefei
  - Institute of High Energy Physics, CAS, Beijing
  - Institute of Modern Physics, CAS, Lanzhou
  - National Space Science Center, CAS, Beijing

- **Switzerland**
  - University of Geneva
  - EPFL

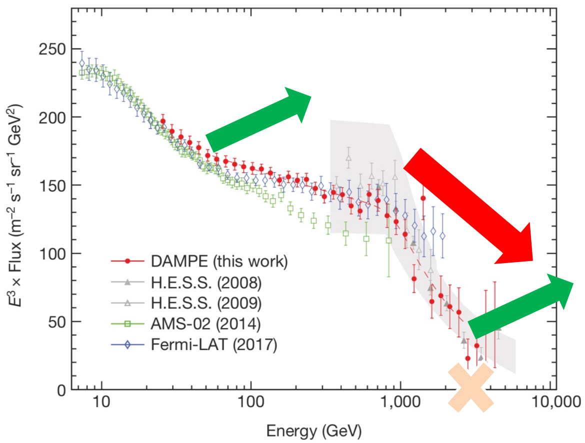


- **Italy**
  - INFN Perugia and University of Perugia
  - INFN Bari and University of Bari
  - INFN Lecce and University of Salento

DAMPE principal results

DAMPE CRE

25 GeV – 4.6 TeV

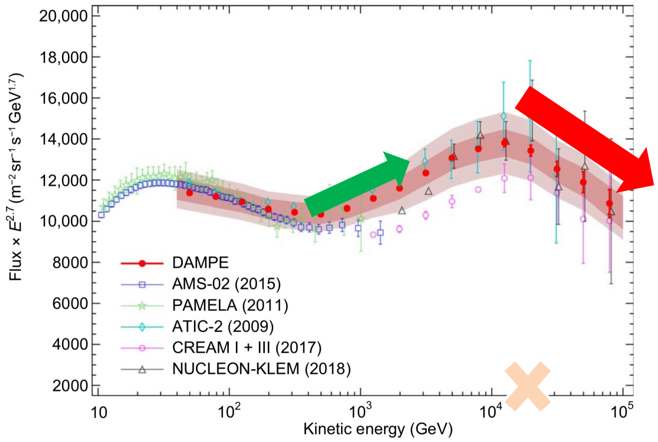


3 TeV

- A **spectral break at 0.9 TeV**, with the spectral index changing from 3.1 to 3.9 confirms the previous evidence found by the ground-based indirect measurement of the H.E.S.S. Collaboration.

DAMPE protons

40 GeV – 100 TeV

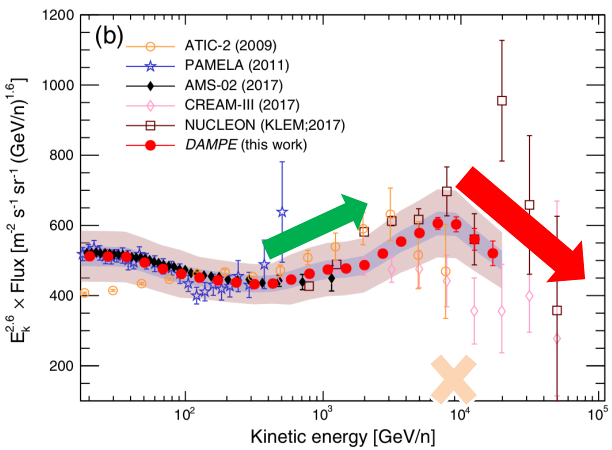


13.6 TeV

- Reveals a **softening at 13.6 TeV**, with the spectral index changing from 2.60 to 2.85.

DAMPE Helium

70 GeV – 80 TeV



8.5 TeV/n

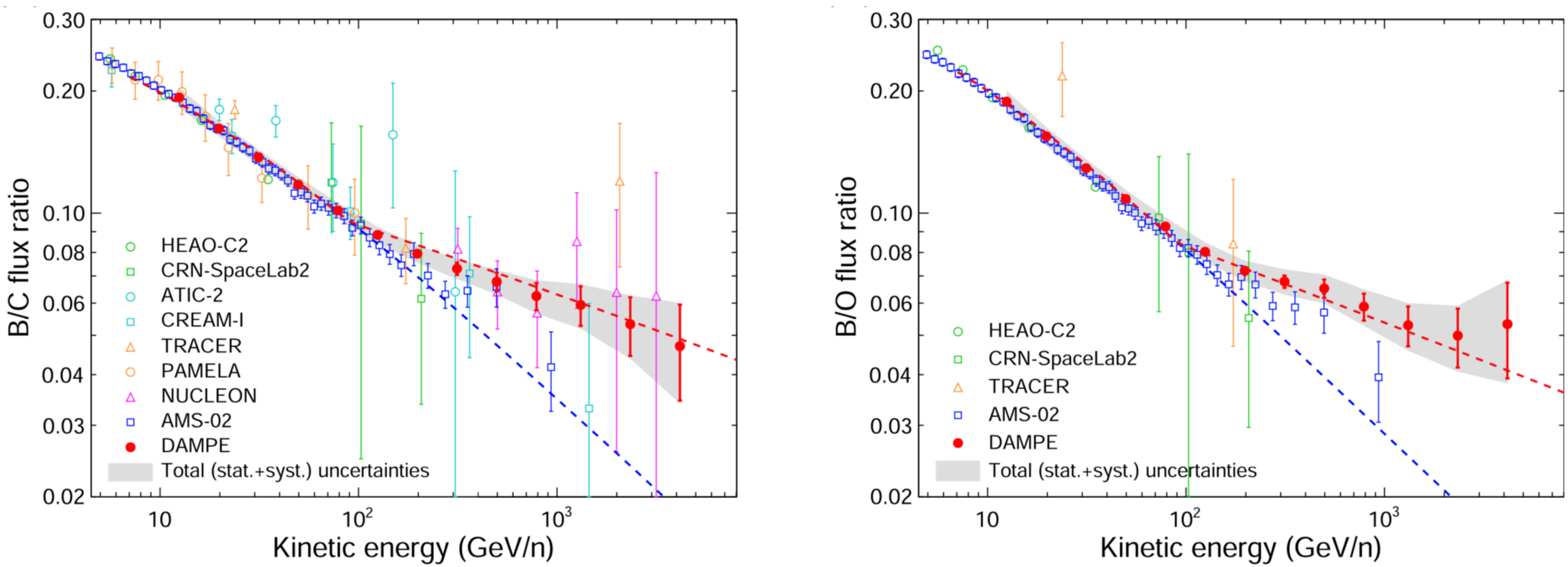
- A **softening at about 34 TeV (8.5 TeV/n)** Suggesting a Z-dependent softening energy (**14 TeV for Z = 1**)

The inner shaded band shows the systematic uncertainties due to the analysis procedure, and the outer band shows the **total systematic** uncertainties including also those from the hadronic models.

B/C and B/O flux ratios (10 GeV/n – 5.6 TeV/n)

- Several independent analyses are ongoing for $_3$Li, Be, B, C, N, O, Ne, Mg, Si and $_{26}$Fe.

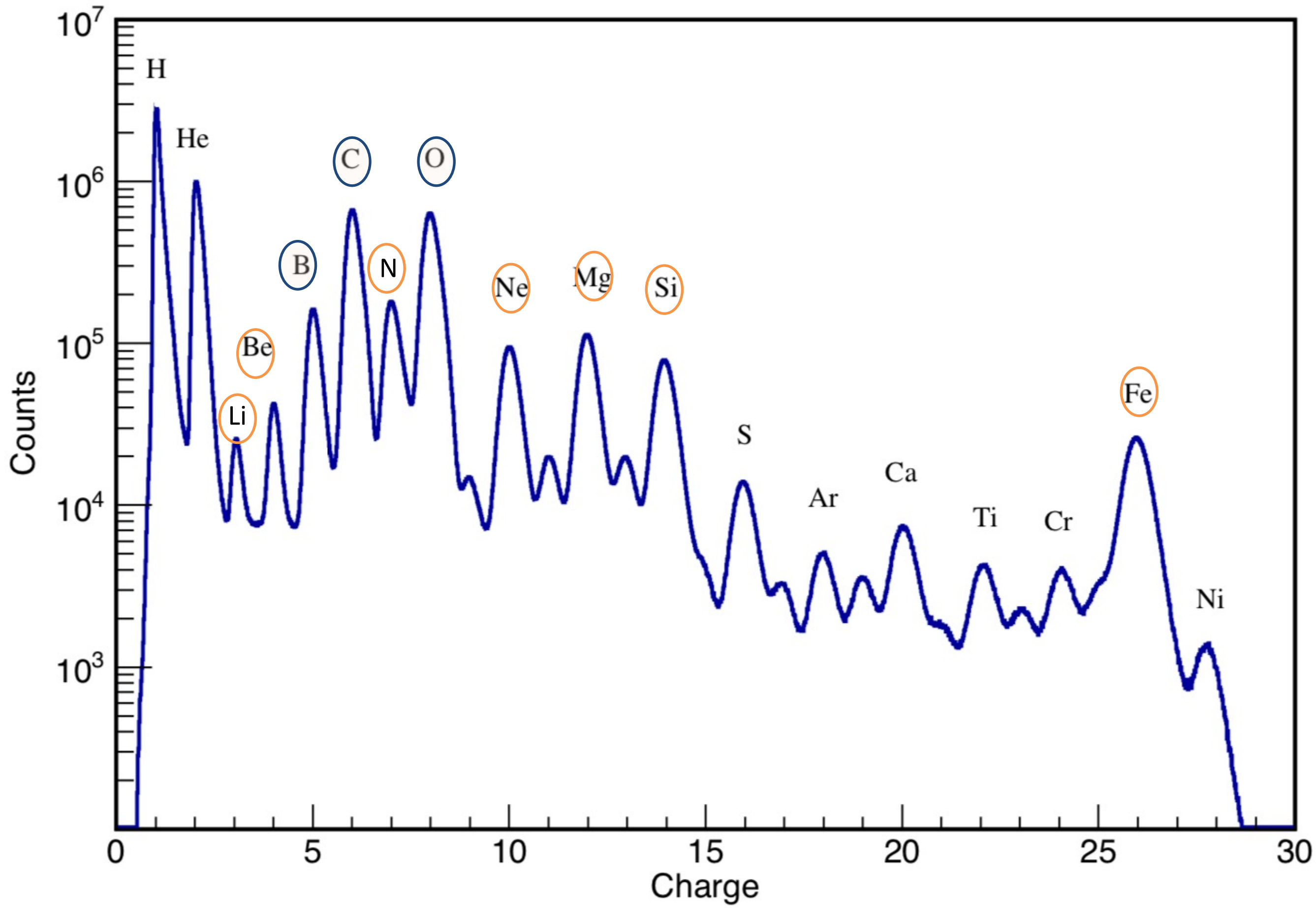
DAMPE Collaboration, Science Bulletin 67 (2022) 2162–2166



The energy dependence of both the B/C and B/O ratios is in agreement with AMS-02 measurements: they can be well fitted by a broken power-law model, suggesting the existence in both flux ratios of a spectral **hardening at about 100 GeV/n**.

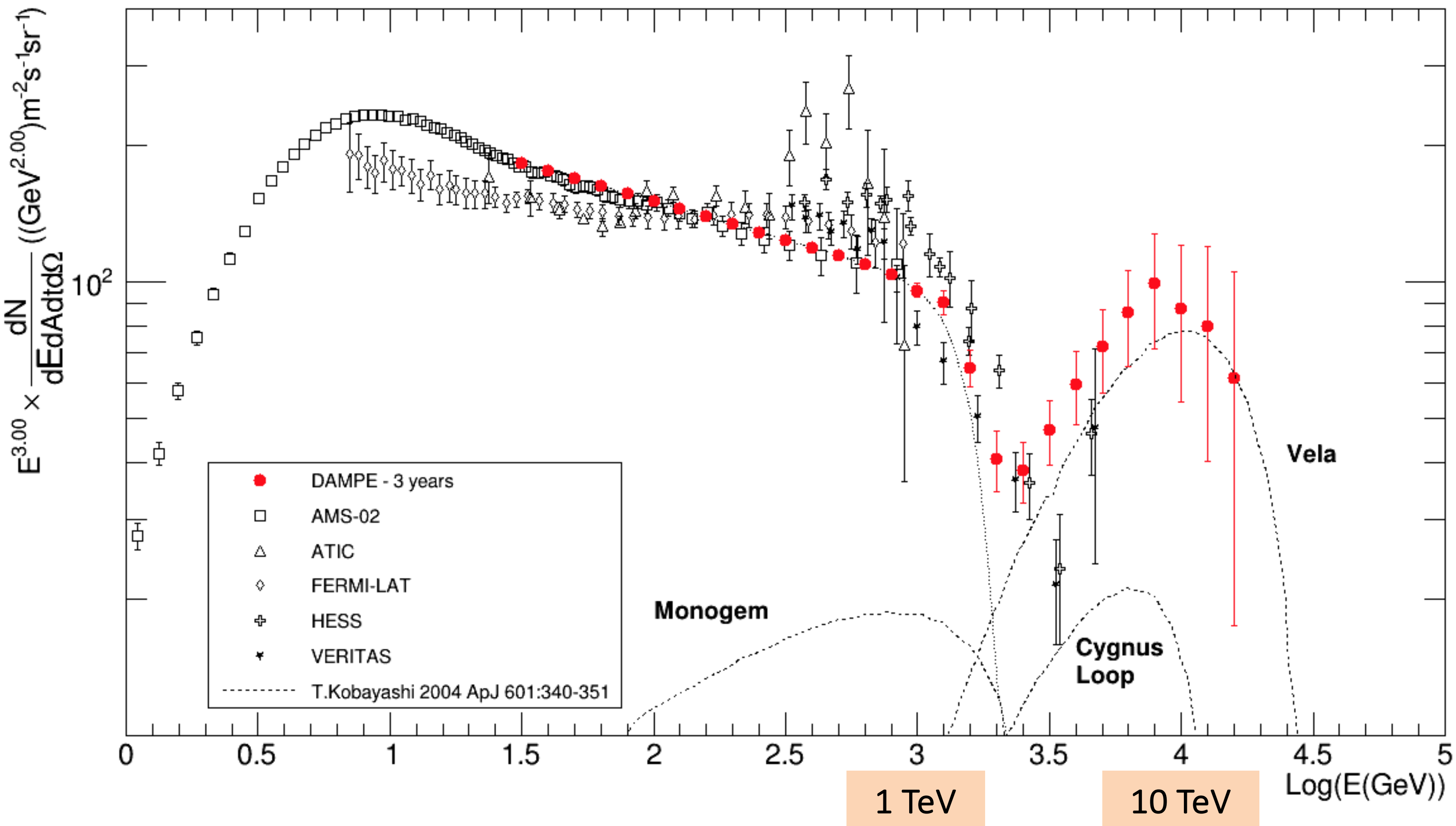
DAMPE future measurements: nuclei analysis

Analysis of Li, Be, B, C, N, O, Ne, Mg, Si



DAMPE future measurements: CRE up to few tens TeV

CRE ($e^+ + e^-$) flux at higher energies



Cosmic-Ray Database

1. The CRDB at LPSC/IN2P3/CNRS, online since 2013, is fully described in Maurin et al. (2014, 2020)

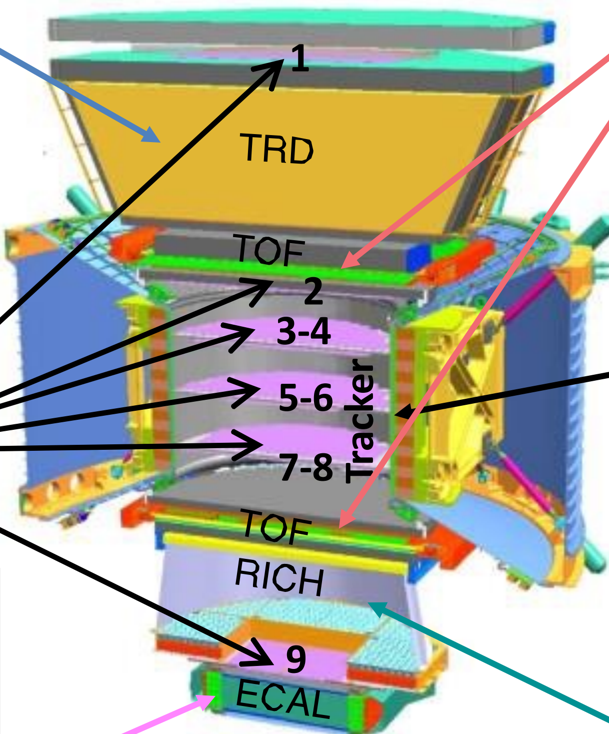
2. The CRDB © SSDC is developed at the Space Science Data Center, a facility of the Italian Space Agency (ASI).

AMS: a **TeV** precision **spectrometer** in space

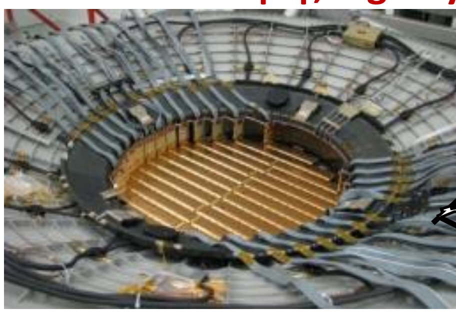
Transition Radiation Detector (TRD): Discriminate e⁺, e⁻ (TR) out of p and anti-p (no TR), |Z|

Time Of Flight (TOF): |Z|, speed

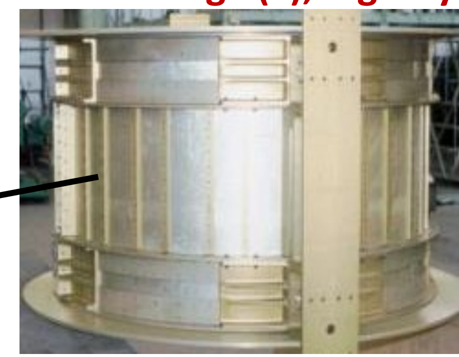
Z and E
are measured independently by several subdetectors



Silicon Tracker: |Z|, Rigidity = *p/Ze*



Magnet (0.14 T): Identify the sign of the charge (Z), Rigidity

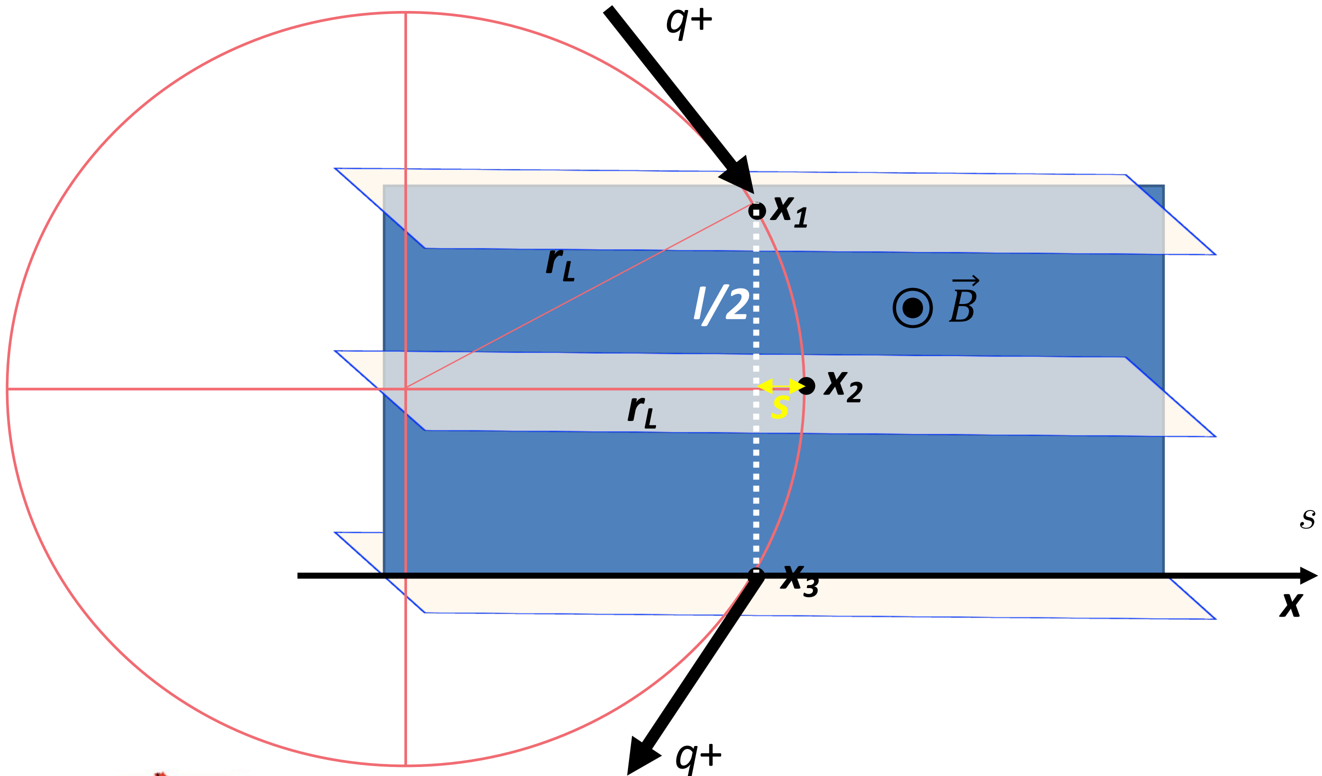


Electromagnetic Calorimeter (ECAL): *Energy* of e⁺, e⁻

Ring Imaging Cherenkov (RICH): |Z|, speed

7.5 tons
5 m × 4 m × 3 m

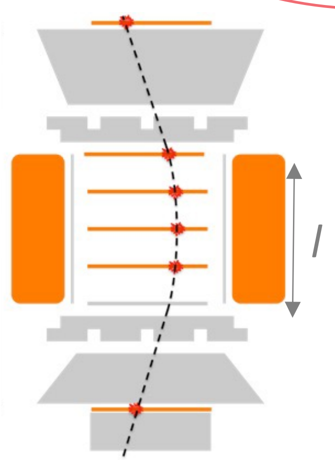
AMS Rigidity measurement: the sagitta method



$$r_{\mathrm{L}} - s = \sqrt{r_{\mathrm{L}}^2 - \left(\frac{l}{2}\right)^2}$$

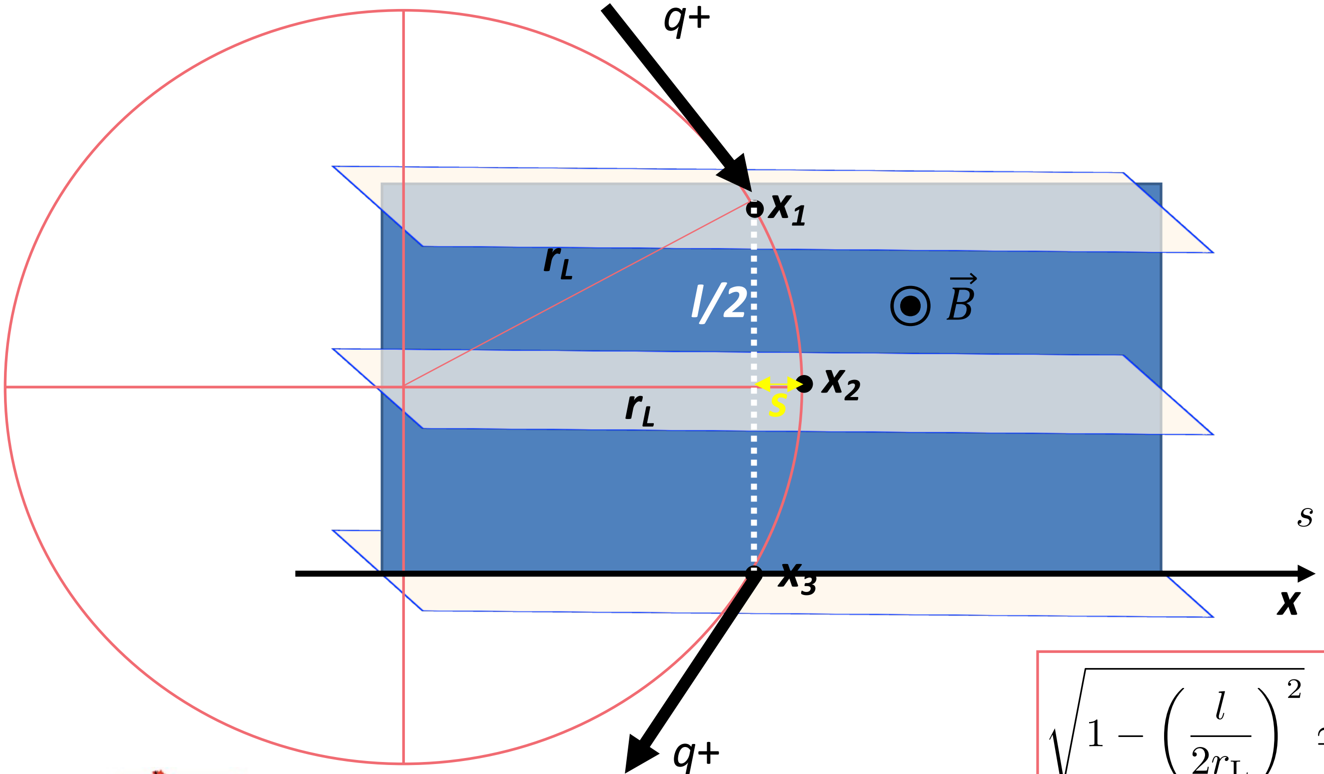
$$s = r_{\mathrm{L}} - \sqrt{r_{\mathrm{L}}^2\left[1 - \left(\frac{l}{2r_{\mathrm{L}}}\right)^2\right]}$$

$$s = r_{\mathrm{L}}\left[1 - \sqrt{1 - \left(\frac{l}{2r_{\mathrm{L}}}\right)^2}\right]$$



l is the total path length in the magnetic field

AMS Rigidity measurement: the sagitta method

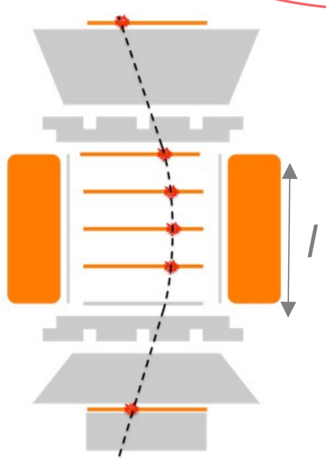


$$r_L - s = \sqrt{r_L^2 - \left(\frac{l}{2}\right)^2}$$

$$s = r_L - \sqrt{r_L^2 \left[1 - \left(\frac{l}{2r_L}\right)^2\right]}$$

$$s = r_L \left[1 - \sqrt{1 - \left(\frac{l}{2r_L}\right)^2}\right]$$

$$\sqrt{1 - \left(\frac{l}{2r_L}\right)^2} \simeq 1 - \frac{1}{2}\left(\frac{l}{2r_L}\right)^2 = 1 - \frac{l^2}{8r_L^2}$$

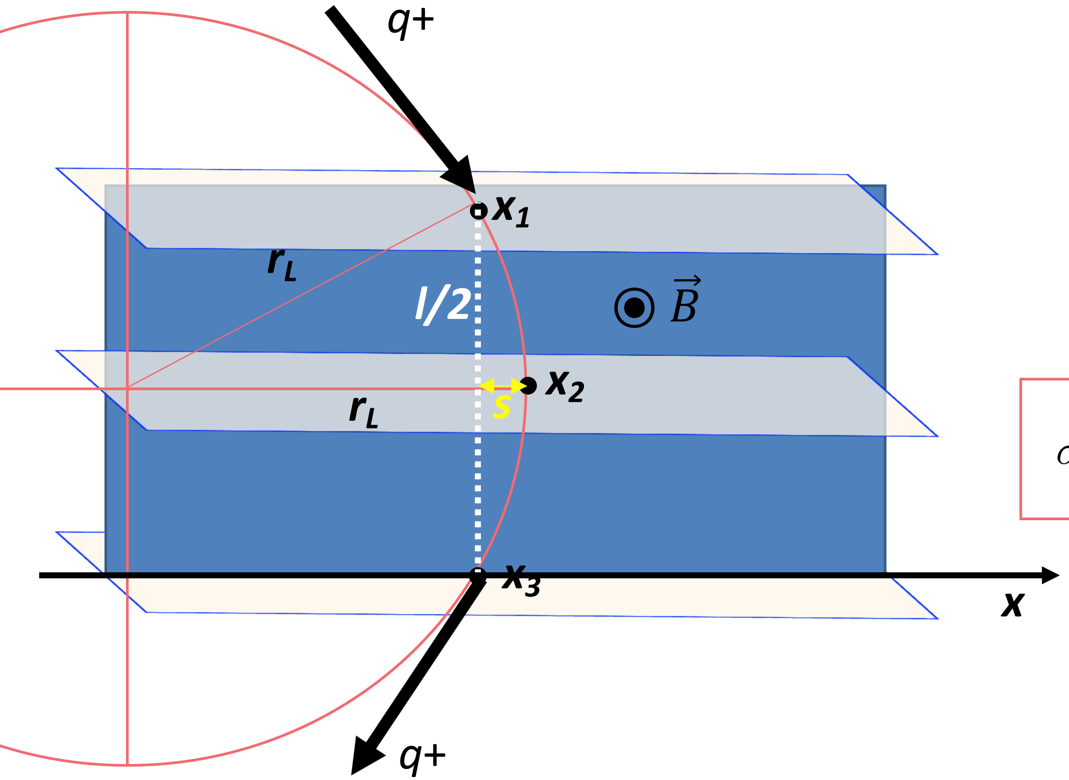


l is the total path length in the magnetic field

$$s = r_L \left(1 - 1 + \frac{l^2}{8r_L^2}\right)$$

$$s = \frac{l^2}{8r_L}$$

Rigidity relative error



$$s = \frac{l^2}{8 r_L}$$

$$R = B\, r_L = \frac{B\, l^2}{8\, s}$$

$$\sigma(R) = \left|\frac{\partial R}{\partial s}\right| \sigma(s) = \frac{B\, l^2}{8\, s^2}\sigma(s) = \frac{8\, R^2}{B\, l^2}\sigma(s)$$

$$\frac{\sigma(R)}{R} = \frac{8\, R}{B\, l^2}\sigma(s)$$

$$s = x_2 - \frac{x_1 + x_3}{2}$$

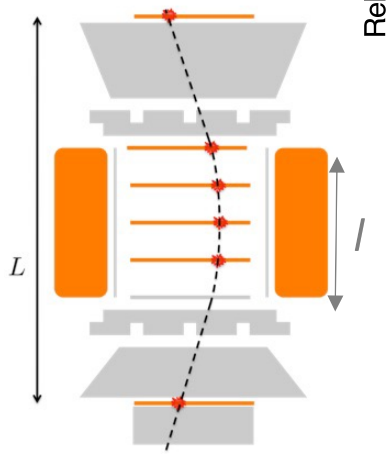
$$\sigma(s) = \sqrt{\left(\frac{\partial s}{\partial x_1}\right)^2 \sigma(x_1)^2 + \left(\frac{\partial s}{\partial x_2}\right)^2 \sigma(x_2)^2 + \left(\frac{\partial s}{\partial x_3}\right)^2 \sigma(x_3)^2}$$

$$\sigma(s) = \sqrt{\left(1 + \frac{1}{4} + \frac{1}{4}\right)}\sigma(x) = \sqrt{\frac{3}{2}}\sigma(x)$$

$$\frac{\sigma(R)}{R} = \frac{8\, R}{B\, l^2}\sqrt{\frac{3}{2}}\sigma(x)$$

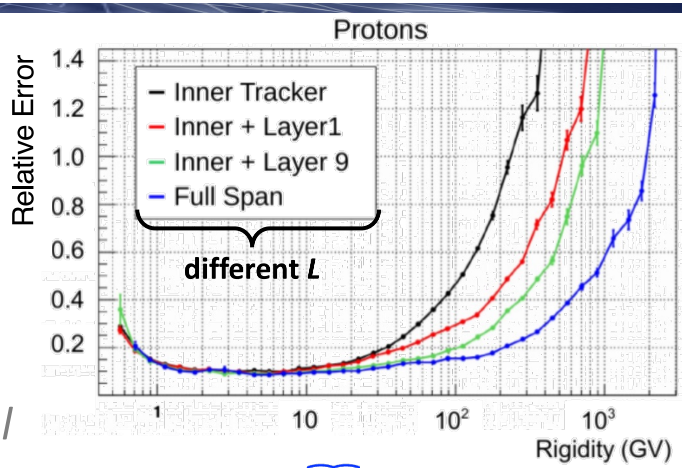
AMS Rigidity relative error

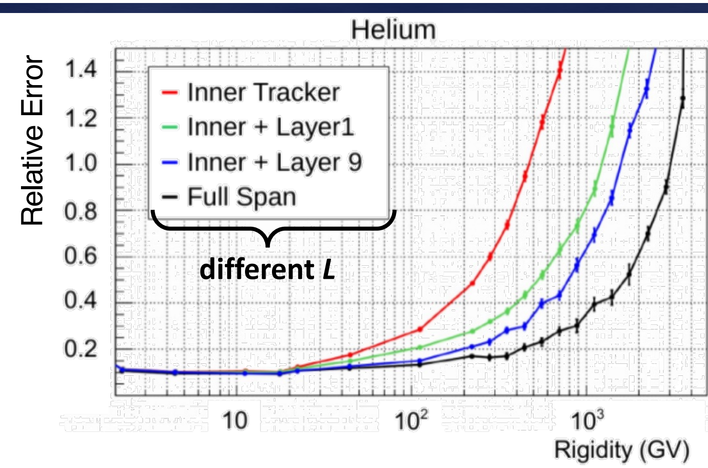
$$\frac{\sigma(R)}{R} = \frac{8\,R}{B\,l^2}\sqrt{\frac{3}{2}}\sigma(x)$$



$$\frac{\sigma(R)}{R} \propto \frac{R}{BlL}\sigma(x)$$

- *l* is the total path length immersed in the magnetic field.
- *L* is the distance between the first and last position measurement (different *L* → different «spans»)

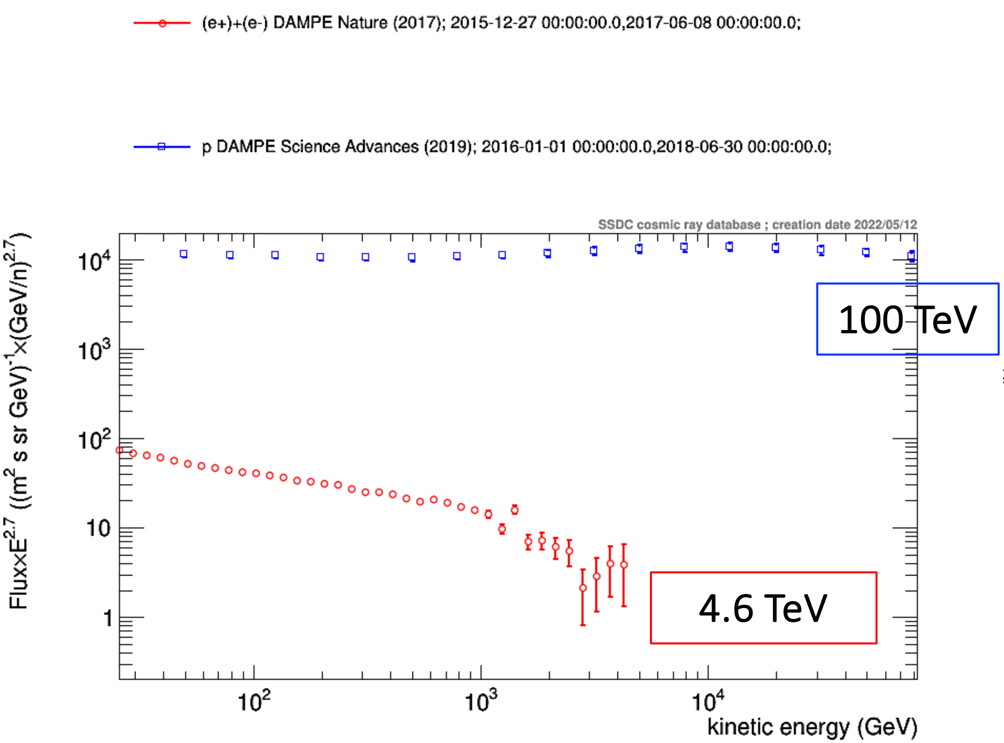


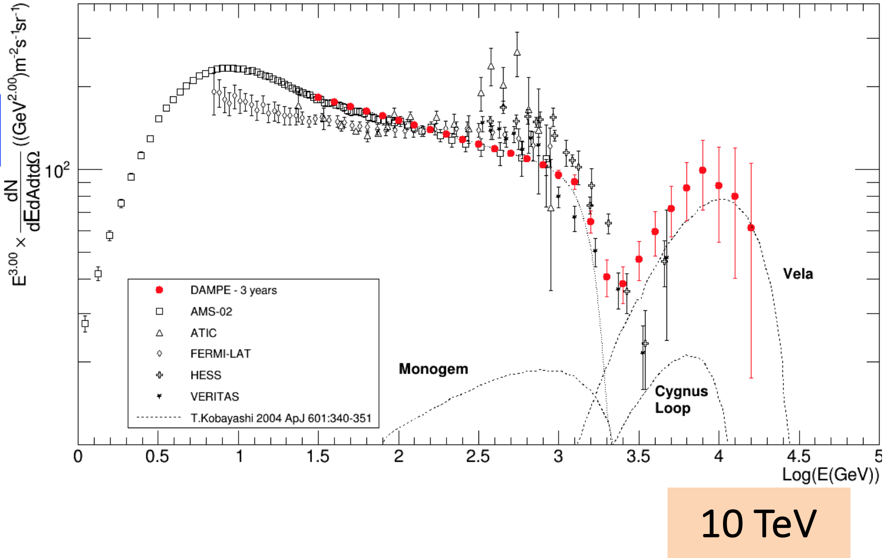


[AMS-02 Track reconstruction and rigidity measurement]

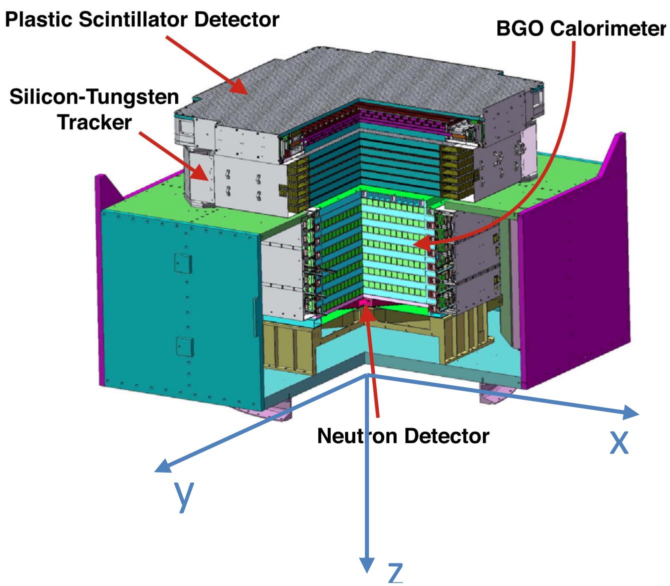
- **DEFINITION: The maximum detectable rigidity (MDR) is the rigidity value for which the relative error is 100%.**
- The spatial resolution σ(*x*) is 10.7 μm for protons and 6.5 μm for helium.
  - ➢ **The maximum detectable rigidity (MDR) is 2.0 TV for protons, 3.2 TV for helium.**
- The degradation of *σ(R)/R* at high energies is because the bending of the particle's trajectory by the magnetic field is smaller, therefore the curvature radius is measured with less precision.
- For low rigidities (< 20 GV) *σ(R)/R* is 0.1.
- The degradation of *σ(R)/R* at very low rigidities (< 1 GV) is related to the multiple Coulomb scattering.

DAMPE spectra

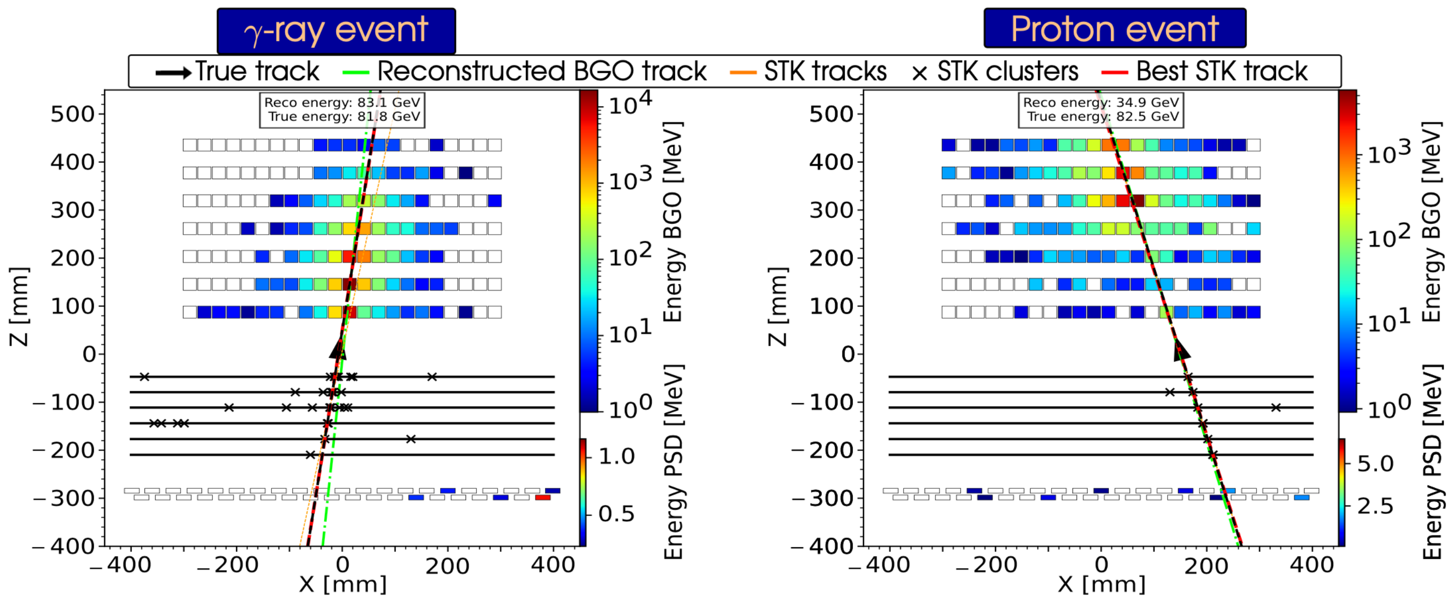




Energy measurement in DAMPE



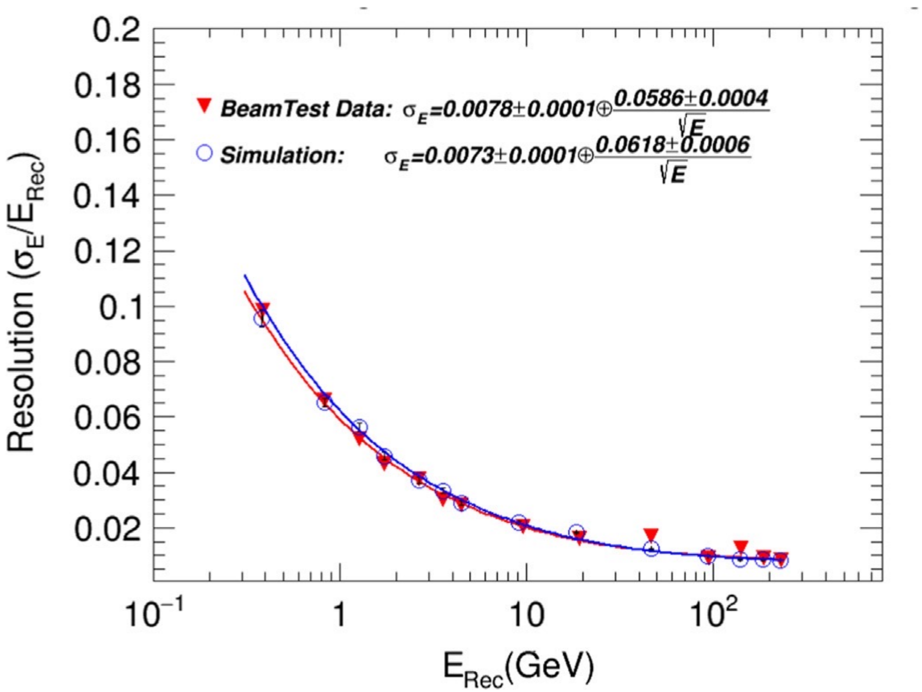
- Made of 14 layers of 22 BGO (bismuth germanium oxide) crystal bars each (size of a bar: 2.5 cm × 2.5 cm × 60 cm) → **calorimeter depth = 31 radiation length** = 31 X_0 Verify.
- Each crystal end is coupled to a photomultiplier tube (PMT)
- Adjacent layers are arranged perpendicularly to reconstruct the shower topology in the calorimeter.
- **We select only «well-contained» showers: i.e., showers with the maximum before the 10th layer.**



Event display by Parzival Nussbaum (PDM 2024)

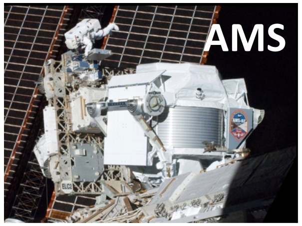
Calorimeter energy resolution

Z. Zhang et al., NIM A 836 (2016) 98–104

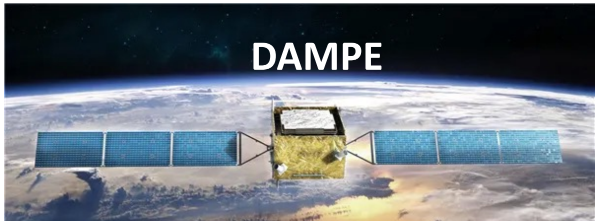


- In **calorimeters** $\sigma(E)/E \propto 1/\mathrm{sqrt}(E)$: **energy resolution improves with energy**
- In **magnetic spectrometers** $\sigma(R)/R \propto R$: the **rigidity resolution deteriorates <u>linearly</u> with rigidity**

Differences between a magnetic spectrometer and a calorimeter



$$\frac{\sigma(R)}{R} \propto \frac{R}{BlL}\sigma(x)$$



Charge measurement
(sign + absolute value)

$\sigma(R)/R \propto R$
the rigidity resolution deteriorates with rigidity

There is a MDR:
Maximum Detectable Rigidity

Solution: stronger magnetic (B) field and larger detector (L)

Only absolute value of the charge

$\sigma(E)/E \propto 1/\mathrm{sqrt}(E)$
energy resolution improves with energy

There is not energy limit in principle but at high energies becomes difficult to contain the shower

Solution: deeper calorimeter

Lesson 3 -- Bibliography

- **Introduction to Particle and Astroparticle Physics**

  Alessandro De Angelis and Mário Pimenta

  Springer (Second Edition, 2018)

  Chapter 10: Messengers from the High-Energy Universe

  https://link.springer.com/book/10.1007%2F978-3-319-78181-5
- **The Review of Particle Physics**

  R.L. Workman et al. (Particle Data Group)

  Prog. Theor. Exp. Phys. 2022, 083C01 (2022) and 2023 update

  https://pdg.lbl.gov

  https://pdg.lbl.gov/2023/reviews/contents_sports.html

  https://pdg.lbl.gov/2022/reviews/rpp2022-rev-cosmic-rays.pdf
- **AMS Publications**

  https://ams02.space/publications
- **Probes of Multimessenger Astrophysics**

  Maurizio Spurio

  Springer (Second Edition)

  Chapter 7.7

  https://link.springer.com/book/10.1007%2F978-3-319-96854-4

AMS Publications

https://ams02.space/publications

In this lecture:

1. **AMS electrons**: Towards Understanding the Origin of Cosmic-Ray Electrons
   Phys. Rev. Lett. 122, 101101 (2019)

2. **AMS positrons**: Towards Understanding the Origin of Cosmic-Ray Positrons
   Phys. Rev. Lett. 122, 041102 (2019)

3. **AMS Iron**: Properties of Iron Primary Cosmic Rays: Results from the Alpha Magnetic Spectrometer
   Phys. Rev. Lett. 126, 041104 (2021)

4. **AMS report**: The Alpha Magnetic Spectrometer (AMS) on the International Space Station: Part II - Results from the First Seven Years
   Phys. Rep. 894, 1 (2021)

5. **AMS fluorine**: Properties of Heavy Secondary Fluorine Cosmic Rays: Results from the Alpha Magnetic Spectrometer
   Phys. Rev. Lett. 126, 081102 (2021)

6. **AMS N Na Al:** Properties of a New Group of Cosmic Nuclei: Results from the Alpha Magnetic Spectrometer on Sodium, Aluminum, and Nitrogen
   Phys. Rev. Lett. 127, 021101 (2021)

DAMPE Publications

https://ams02.space/publications

In this lecture:

1. **DAMPE CRE**: DAMPE Collaboration, Nature volume 552, 63–66 (2017)

2. **DAMPE protons positrons**: DAMPE Collaboration, Science Adv. 5 (9) eaax3793 (2019)

3. **DAMPE Helium:** DAMPE Collaboration, PHYSICAL REVIEW LETTERS 126, 201102 (2021)

4. **AMS report**: The Alpha Magnetic Spectrometer (AMS) on the International Space Station: Part II - Results from the First Seven Years
   Phys. Rep. 894, 1 (2021)

5. **AMS fluorine**: Properties of Heavy Secondary Fluorine Cosmic Rays: Results from the Alpha Magnetic Spectrometer
   Phys. Rev. Lett. 126, 081102 (2021)

6. **AMS N Na Al:** Properties of a New Group of Cosmic Nuclei: Results from the Alpha Magnetic Spectrometer on Sodium, Aluminum, and Nitrogen
   Phys. Rev. Lett. 127, 021101 (2021)