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Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

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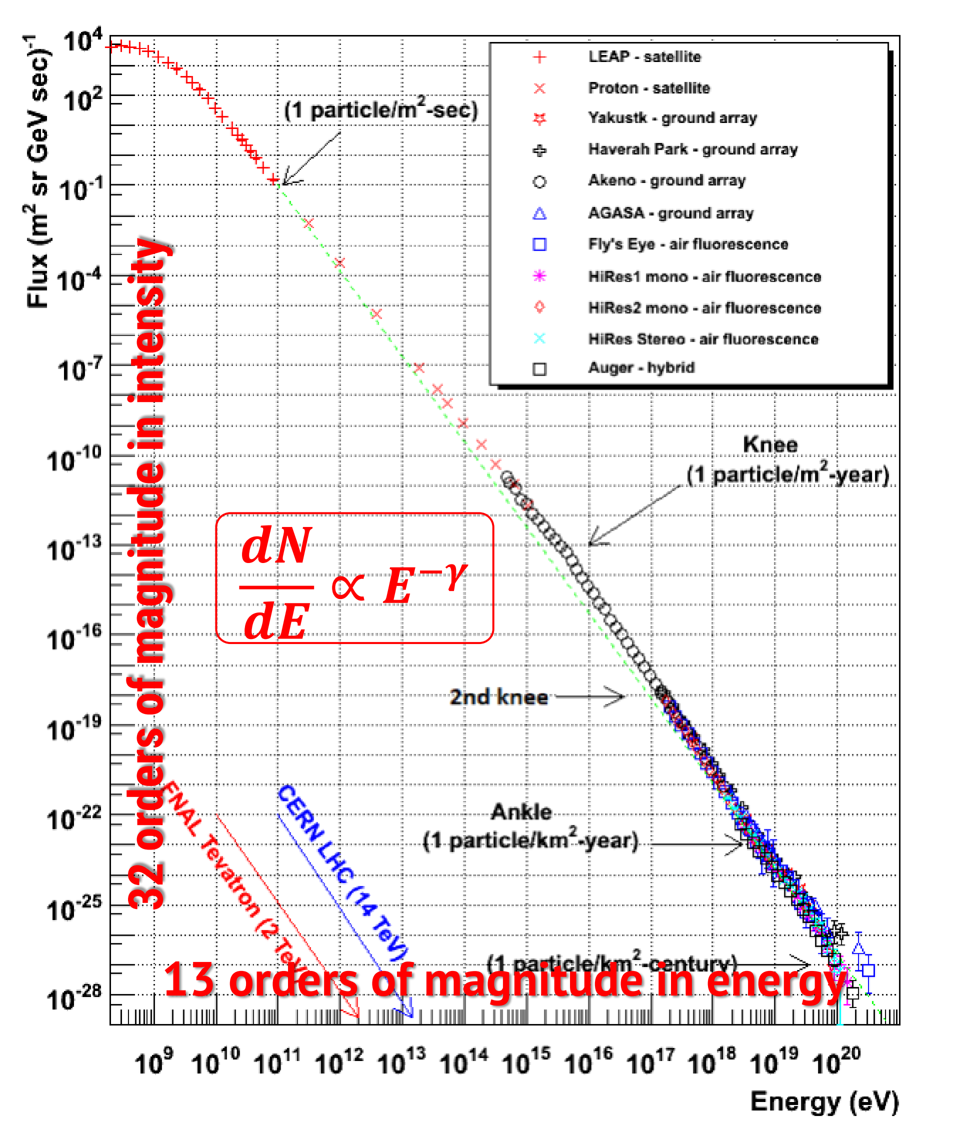
Cosmic Rays: Direct Detection

M. A. Velasco, CIEMAT, Madrid (Spain)

Red Nacional Temática de Astropartículas (RENATA) meeting

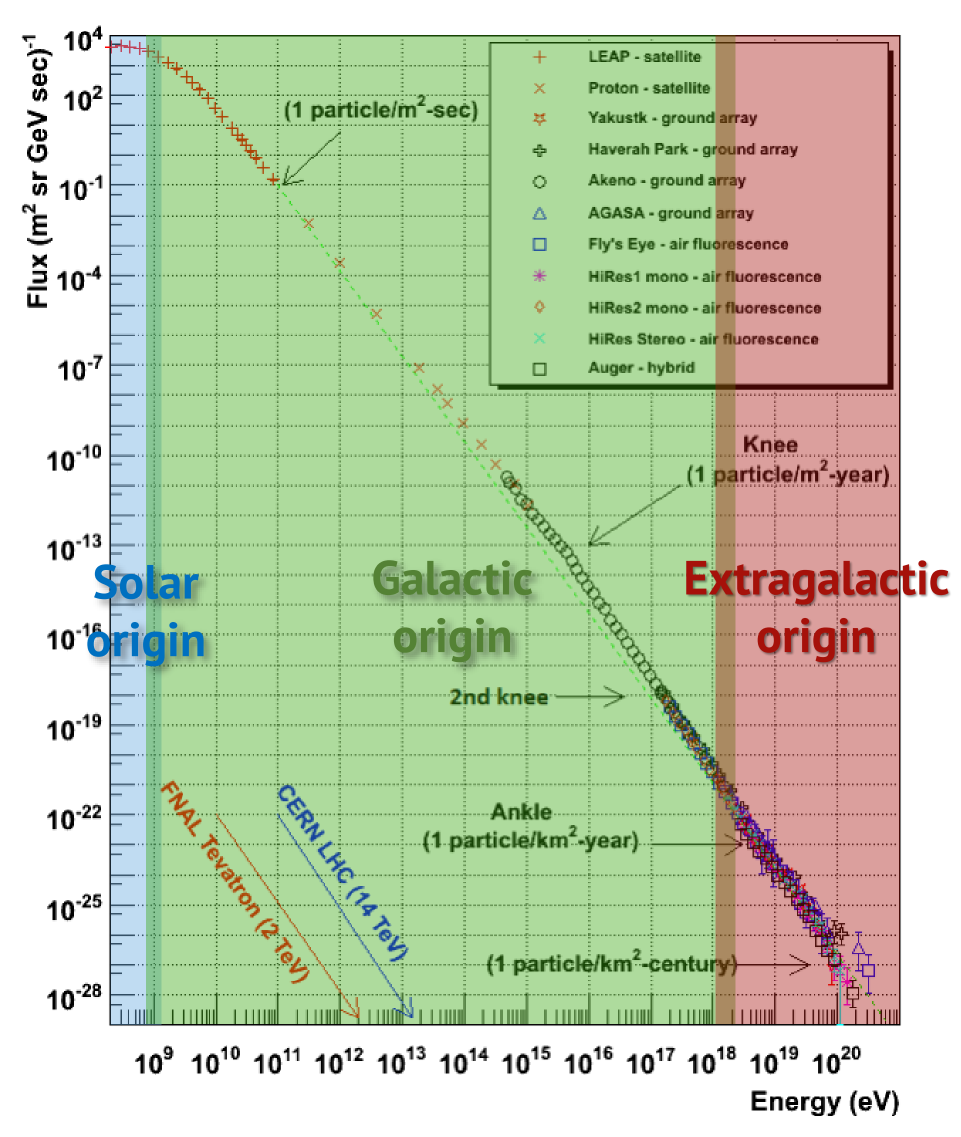
Zaragoza, September 22, 2025

Cosmic rays



- The flux of cosmic rays exhibits a wide range of variation in both energy and intensity
- Its energy dependence follows a power law with several features where the value of the spectral index changes (*knee*, *2nd knee*, *ankle*…)

Cosmic rays



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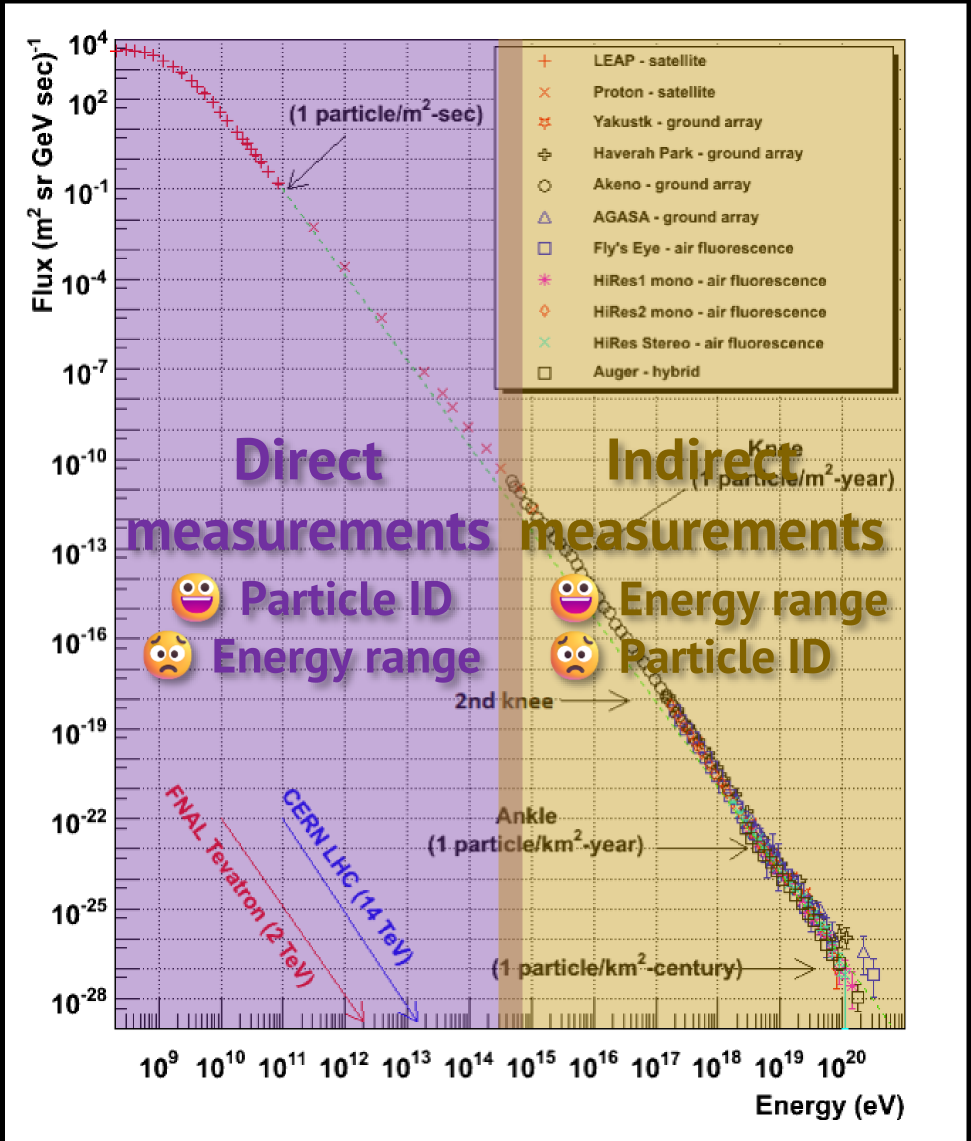
- Its energy dependence follows a **power law** with several features where the value of the **spectral index changes** (*knee*, *2nd knee*, *ankle*…)
- Sources of CRs: **solar**, **galactic** and **extragalactic**
  - Ionized nuclei (~98%)
  - Electrons (~2%)
  - Tiny amount of antimatter (e^+, $\bar{p}$)

Cosmic rays



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- Sources of CRs: **solar**, **galactic** and **extragalactic**
  - Ionized nuclei (~98%)
  - Electrons (~2%)
  - Tiny amount of antimatter ($e^{\mp}$, p)
- Two **independent** and **complementary** detection techniques: **direct** and **indirect measurements**
- Efforts to **increase** the **overlapping energy range** and establish **synergies** among **space-based** and **ground-based** detectors

AMS: a TeV precision magnetic spectrometer for direct detection of CRs from the International Space Station

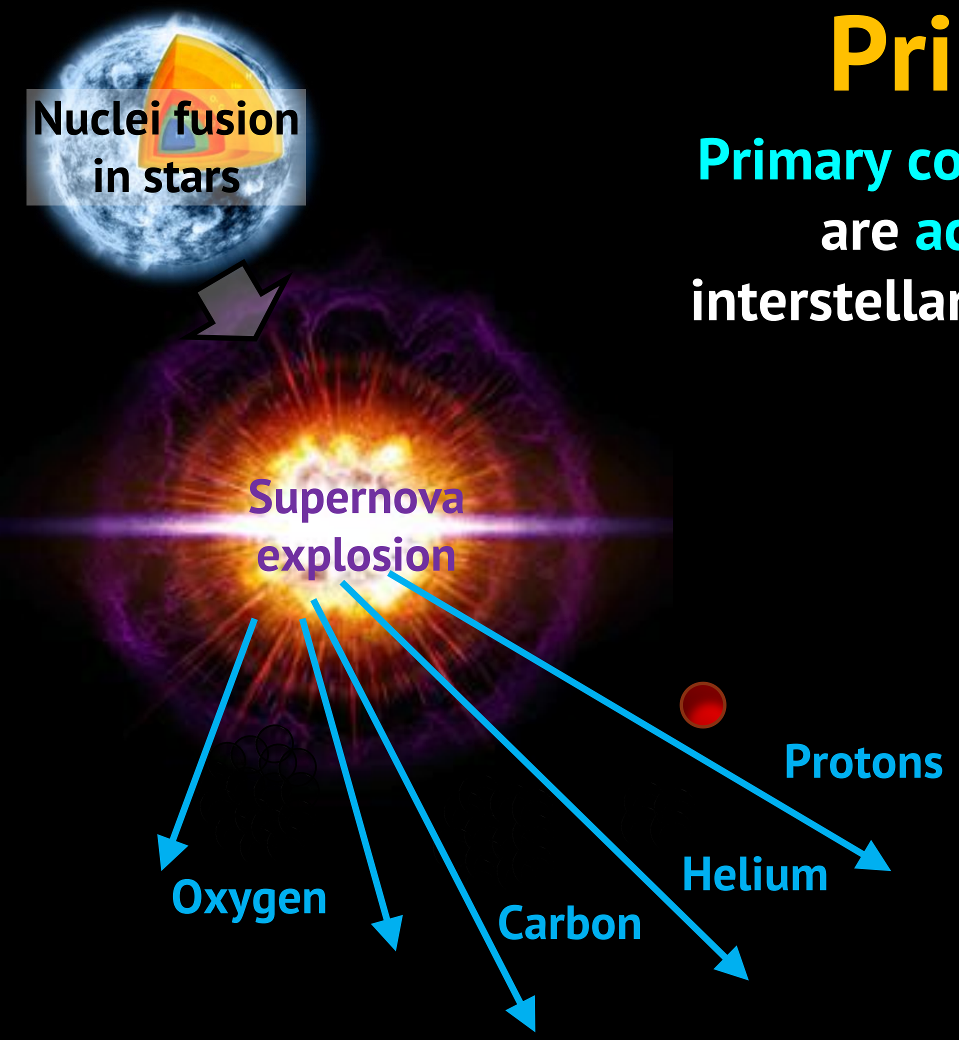
- ✓ Installed on the ISS in May 2011
- ✓ Near Earth Orbit:
  - altitude 400 km
  - inclination 52 deg
  - period 92 min
- ✓ Continuous operation through the ISS lifetime (at least 2030)
- ✓ To date, over 250 billion charged particles have been collected by AMS

AMS: 5m × 4m × 3m
7.5 tons

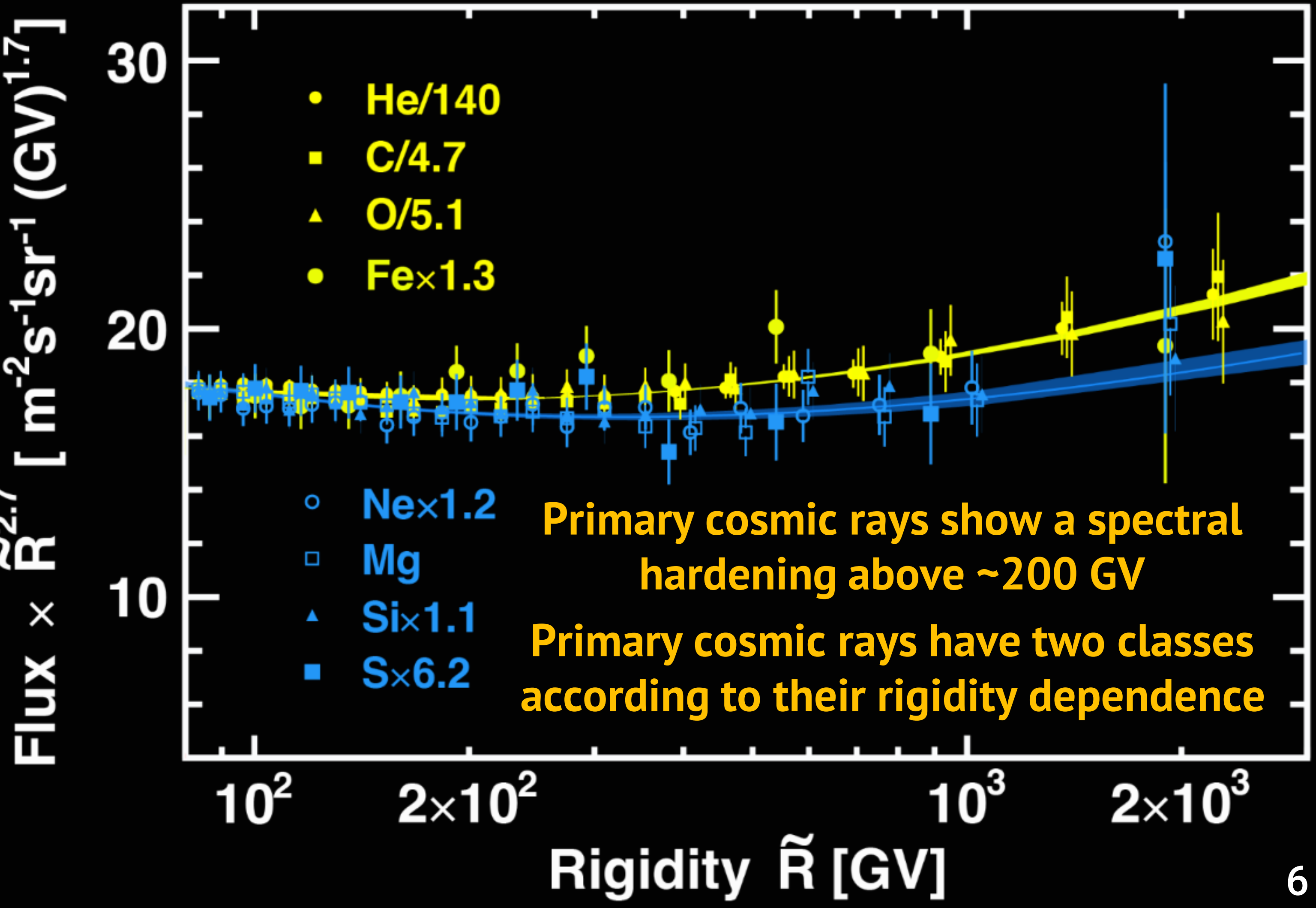
AMS provides precision, long-duration measurements of charged cosmic rays to study the Origin of the Cosmos and the physics of Dark Matter and Antimatter

Primary cosmic rays

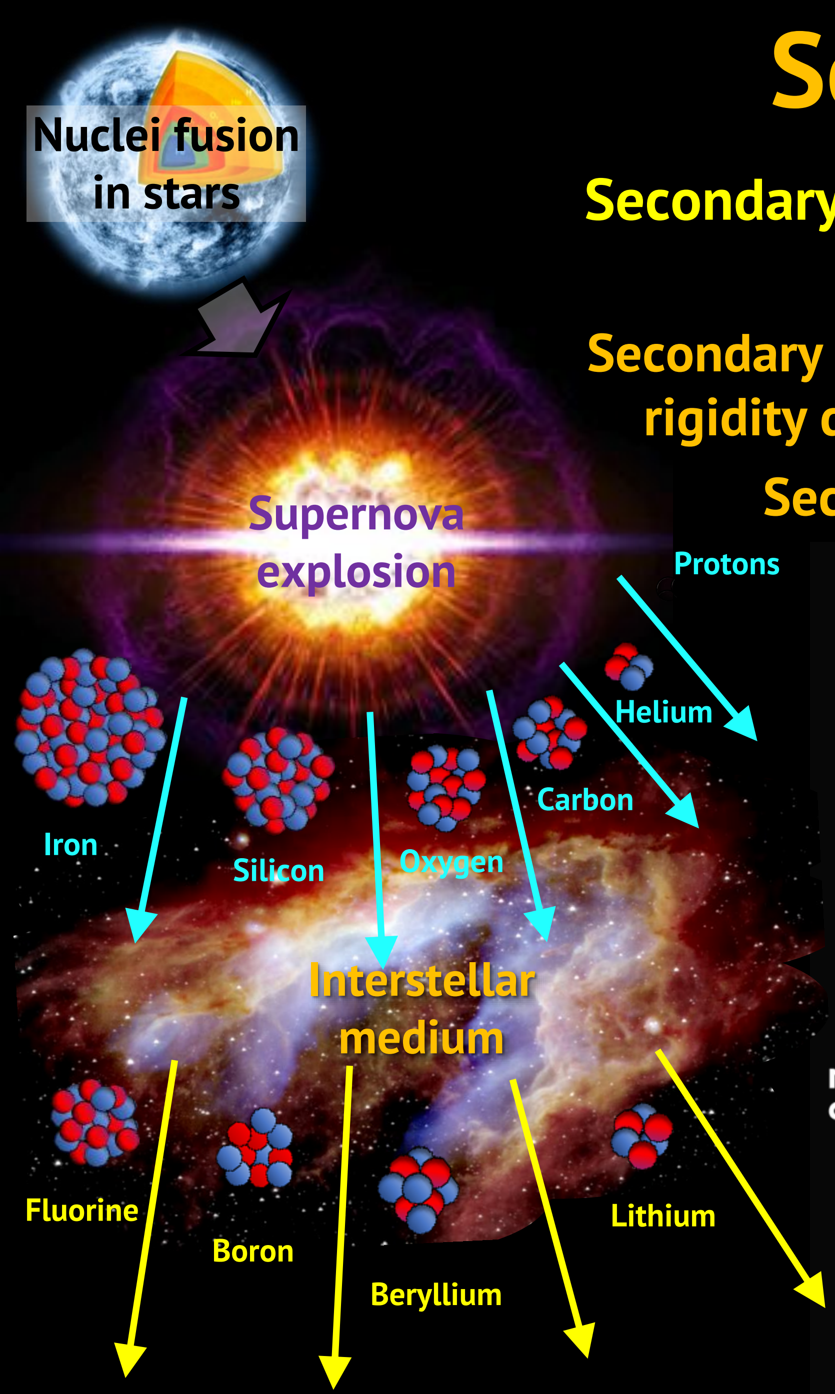
Primary cosmic rays are mostly produced during the lifetime of stars and are accelerated in supernovae shocks. They are expelled in the interstellar medium where they propagate diffusively through the Galaxy



Primary cosmic rays carry information about the injection at the sources and the propagation



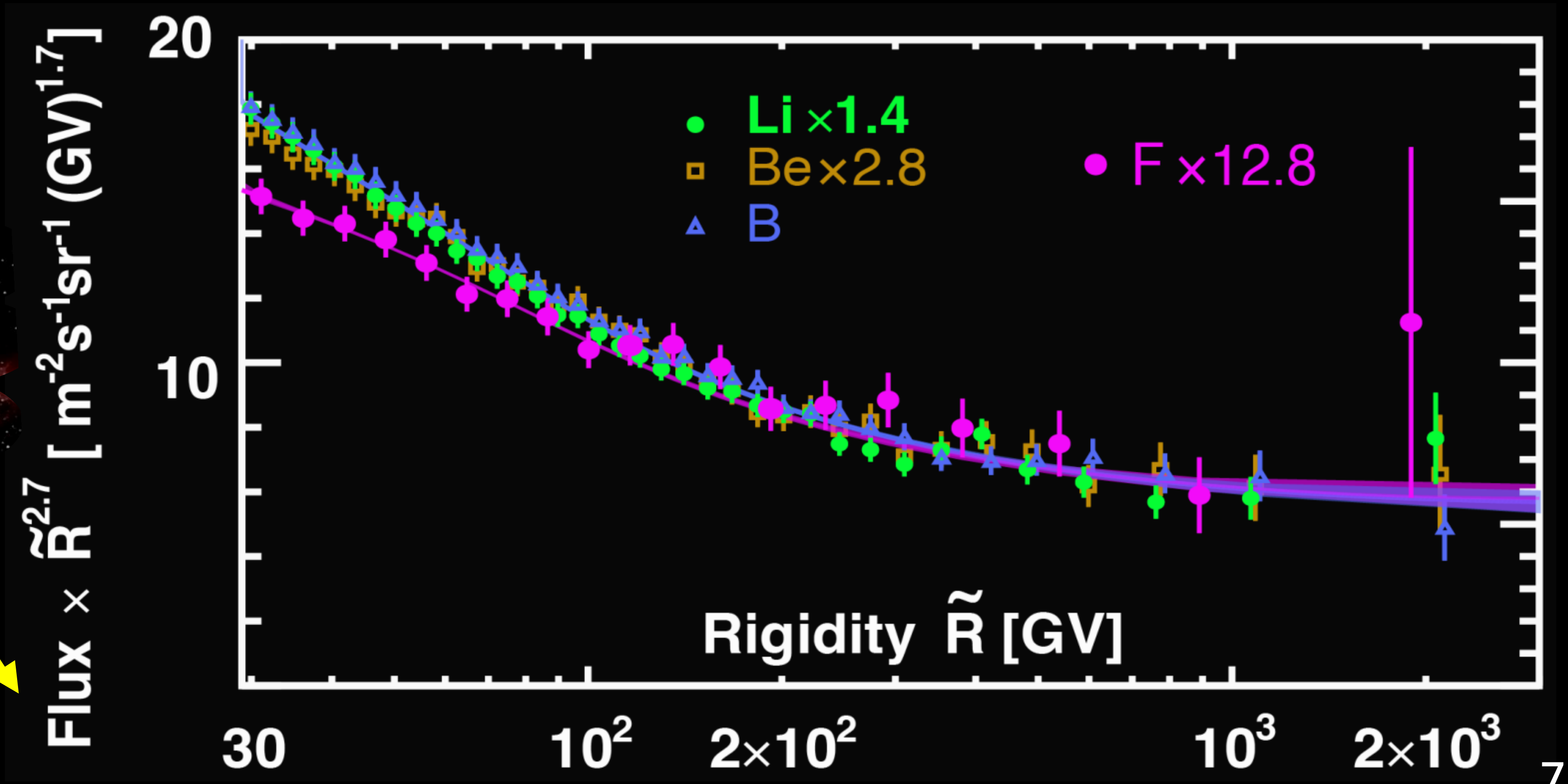
Secondary cosmic rays



Secondary cosmic rays are produced in the collisions of **primary cosmic rays** with the **interstellar medium** (**ISM**)

Secondary cosmic ray fluxes also show a spectral hardening above ~200 GV, but its rigidity dependence is distinctly different from that of the primary cosmic rays

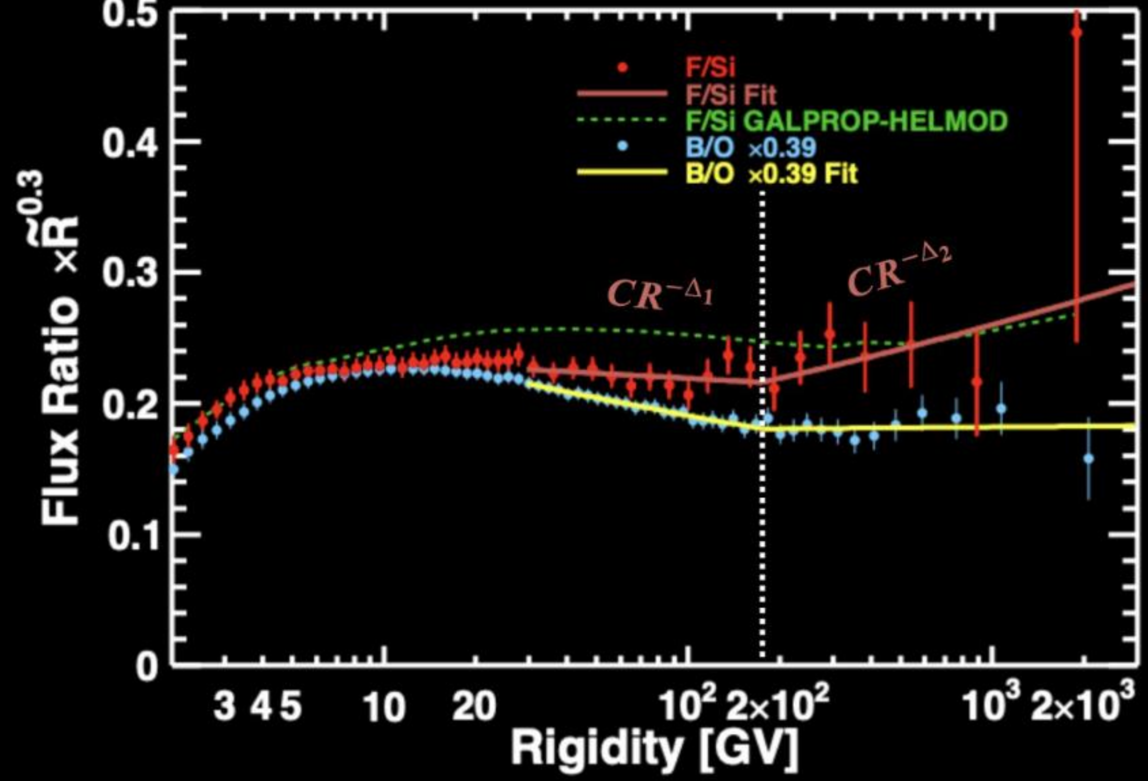
Secondary cosmic rays also have two classes of rigidity dependence

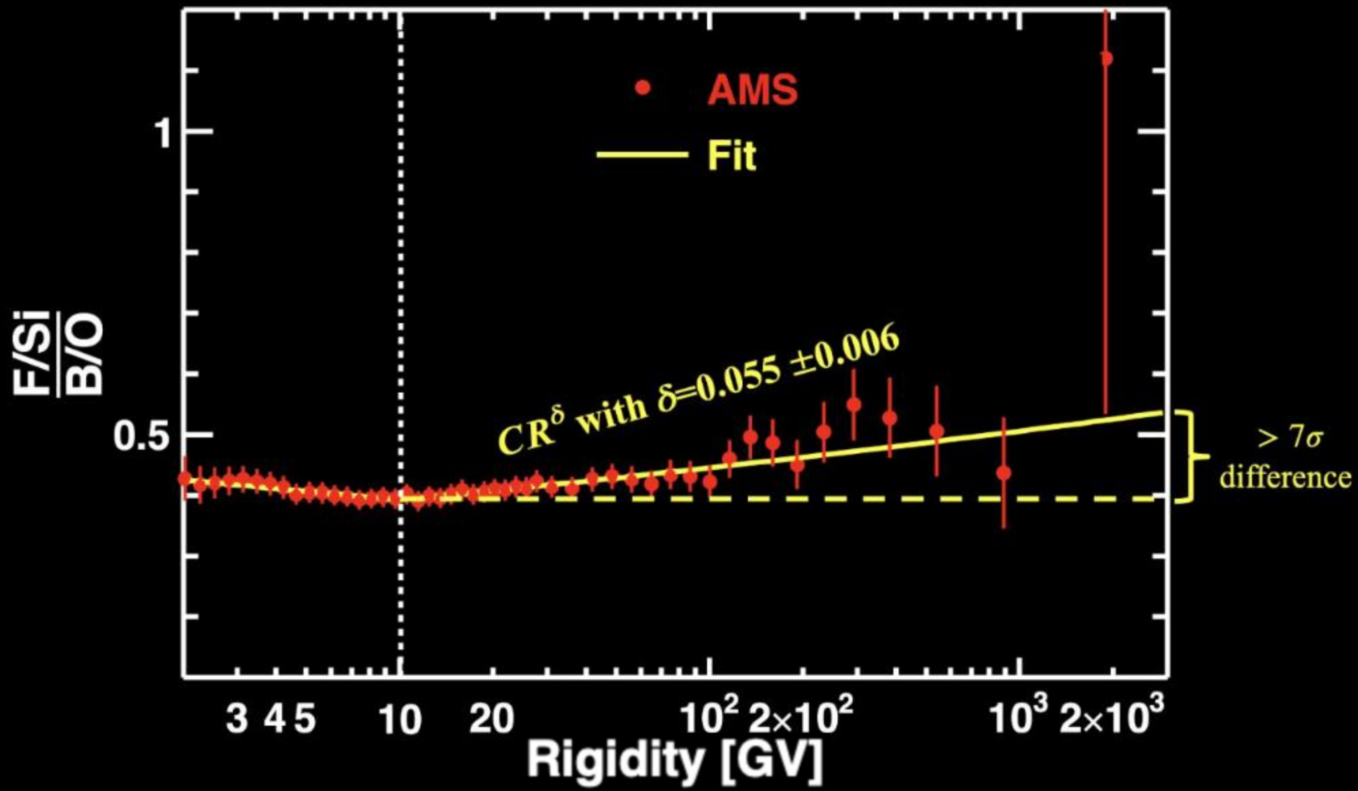


Secondary-to-primary flux ratios

The heavy secondary-to-primary ratio F/Si has a different rigidity dependence from the lighter B/O ratio

The secondary-to-primary flux ratios measured by AMS support a propagation origin of the spectral hardening of cosmic ray nuclei



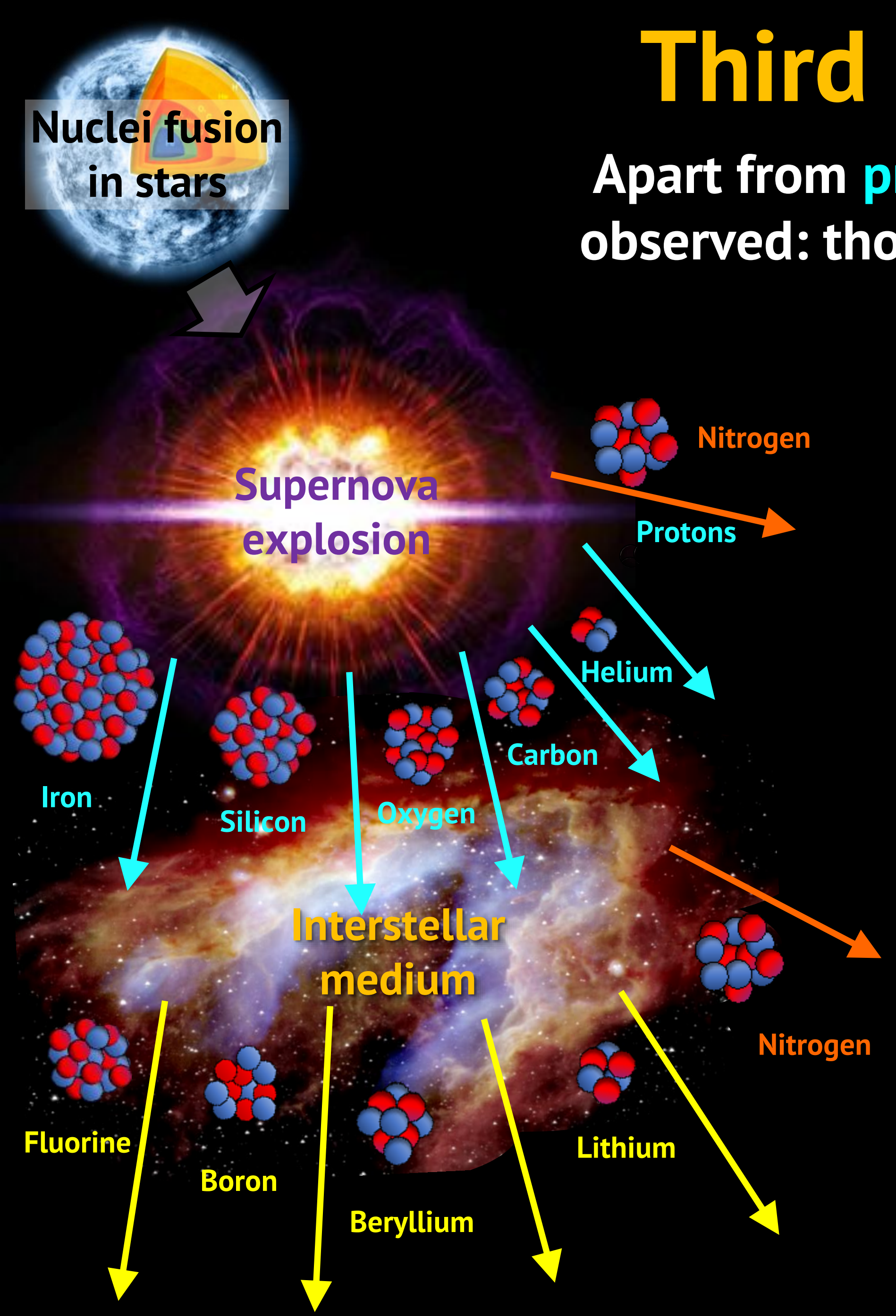


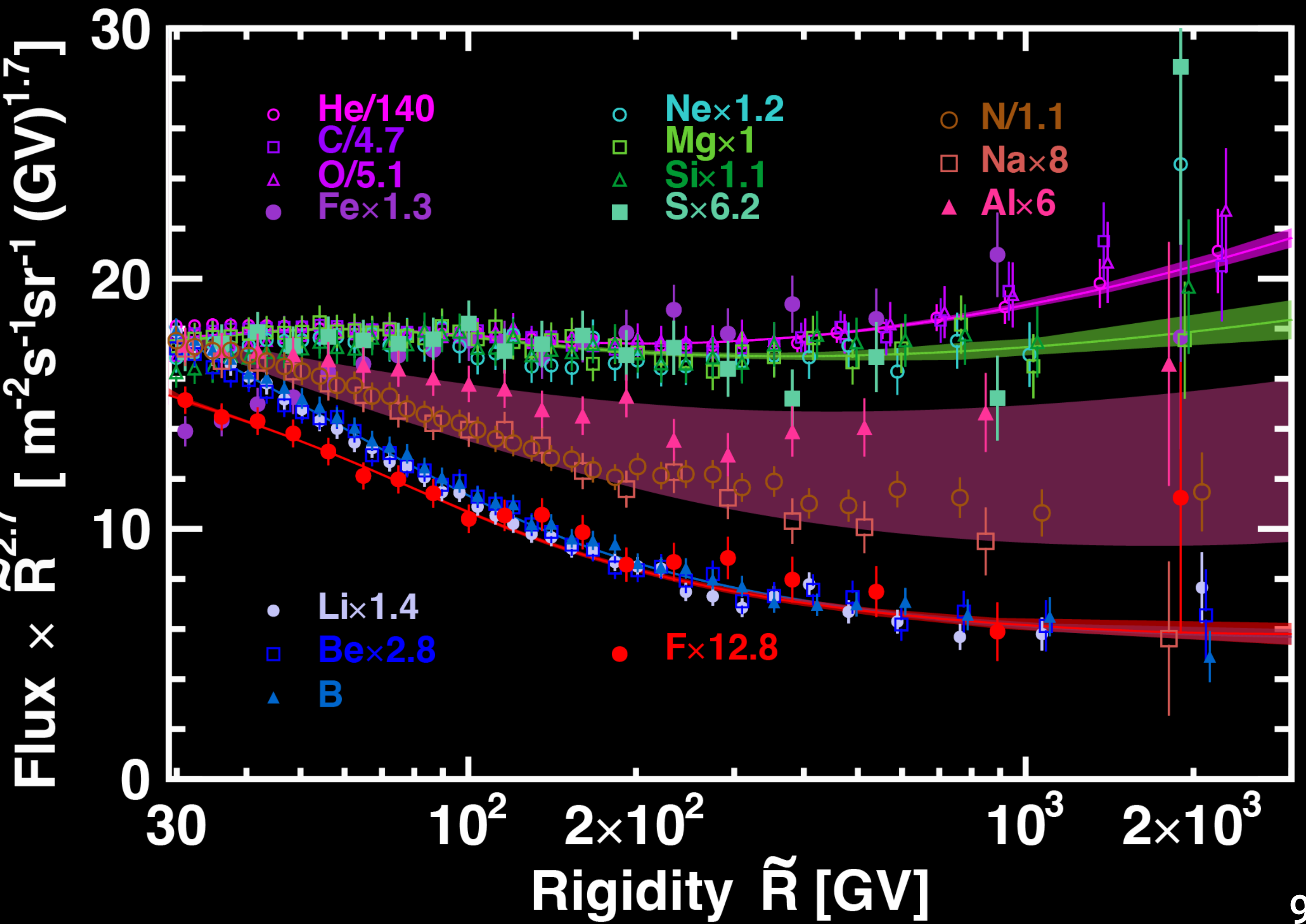
The propagation properties of heavy cosmic rays are different from those of light CRs

A precise knowledge of interaction cross-sections is fundamental to understand these effects

Third group of cosmic rays

Apart from primaries and secondaries, a third group of cosmic rays is observed: those that are the result of a combination of both: N, Na, Al



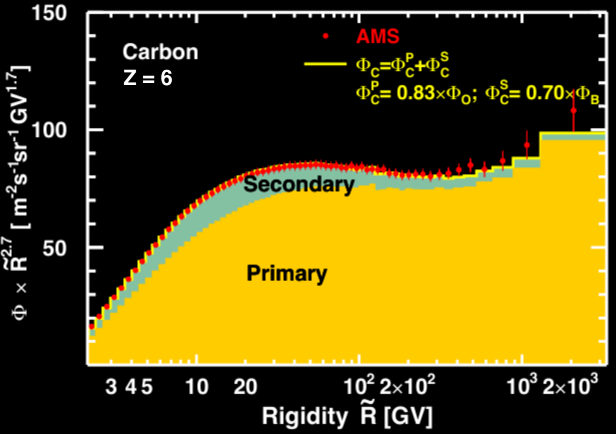


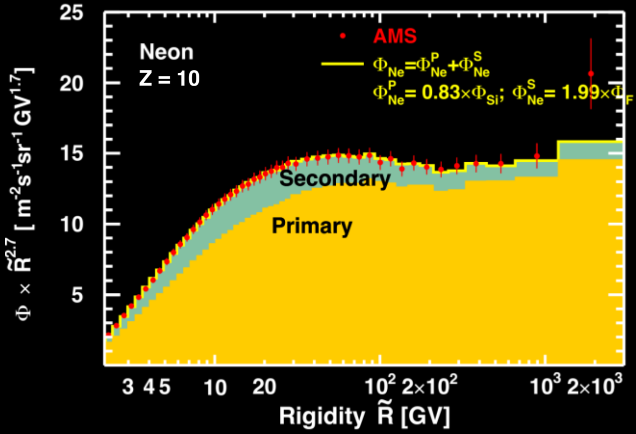
Composition of cosmic rays

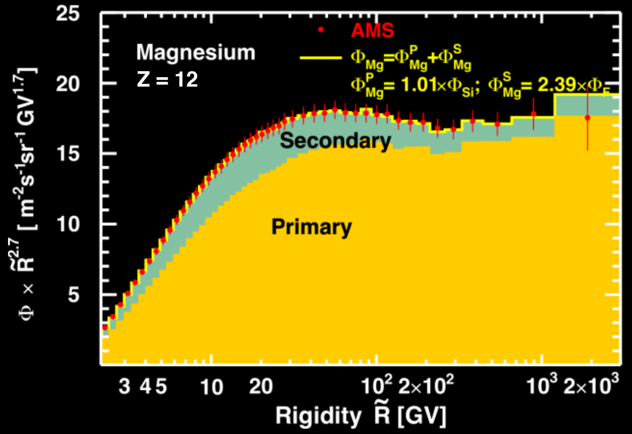
Model-independent measurements of the relative abundances at the source (before cosmic ray propagation)

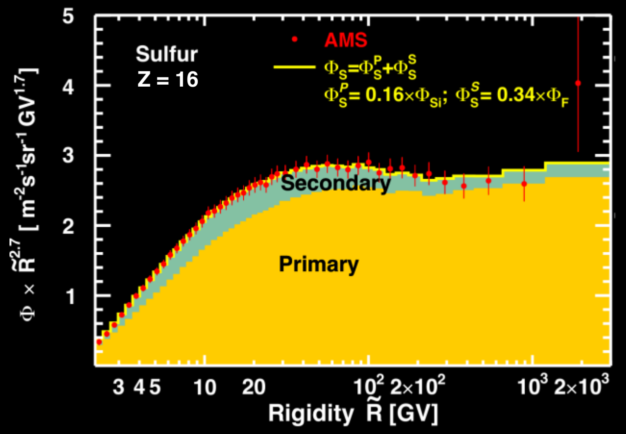
Traditional primary cosmic rays C, Ne, Mg, and S fluxes are not pure primary; they all have a significant secondary component

Even-Z nuclei are dominated by primaries

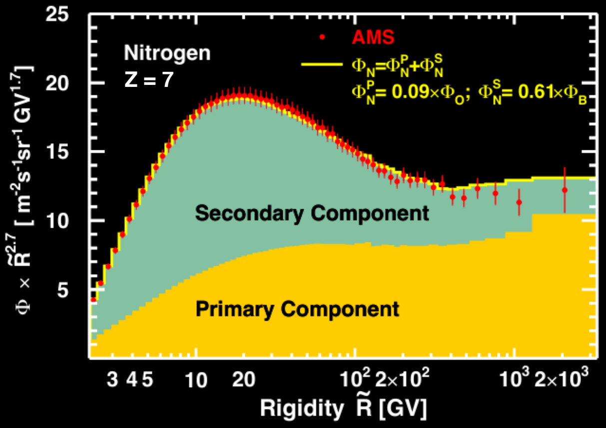


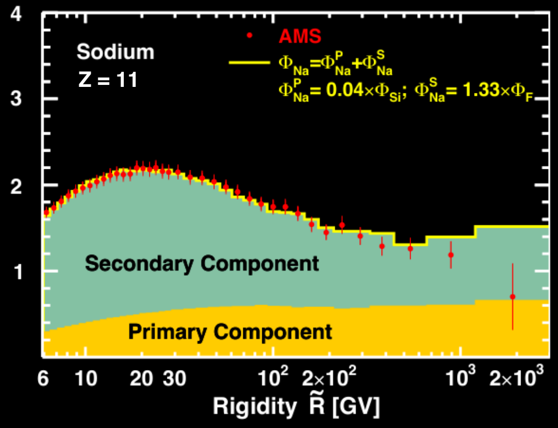


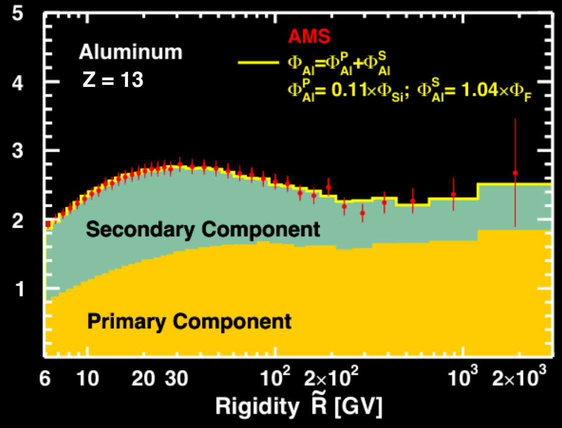




Odd-Z nuclei have more secondaries than even-Z





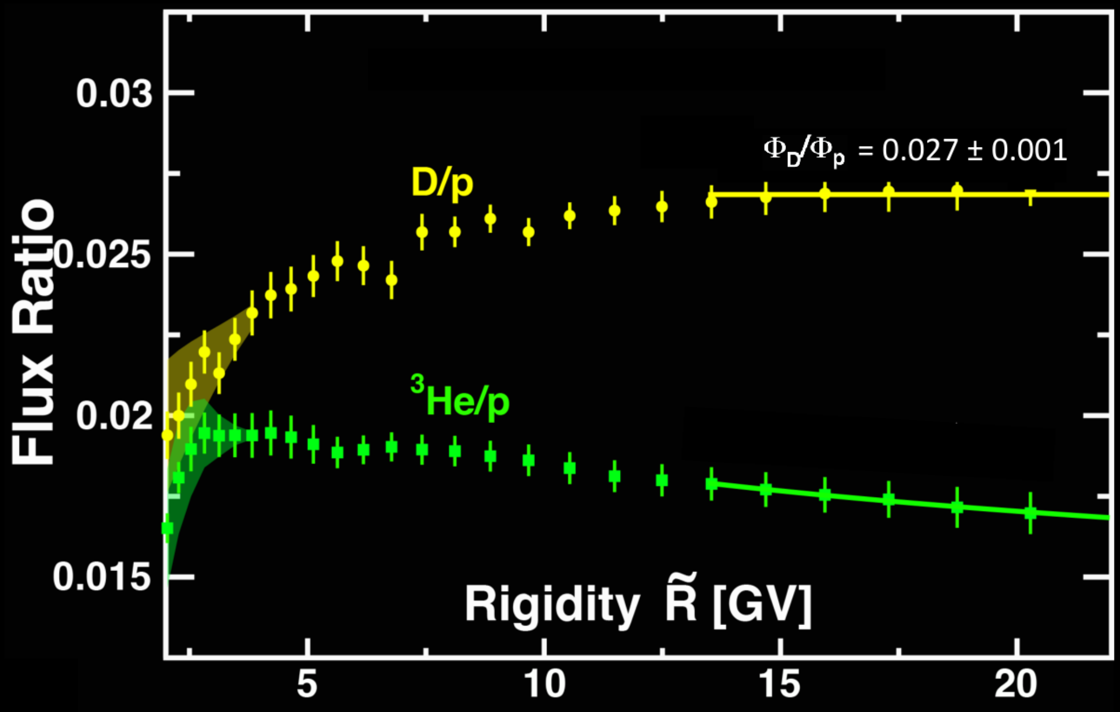


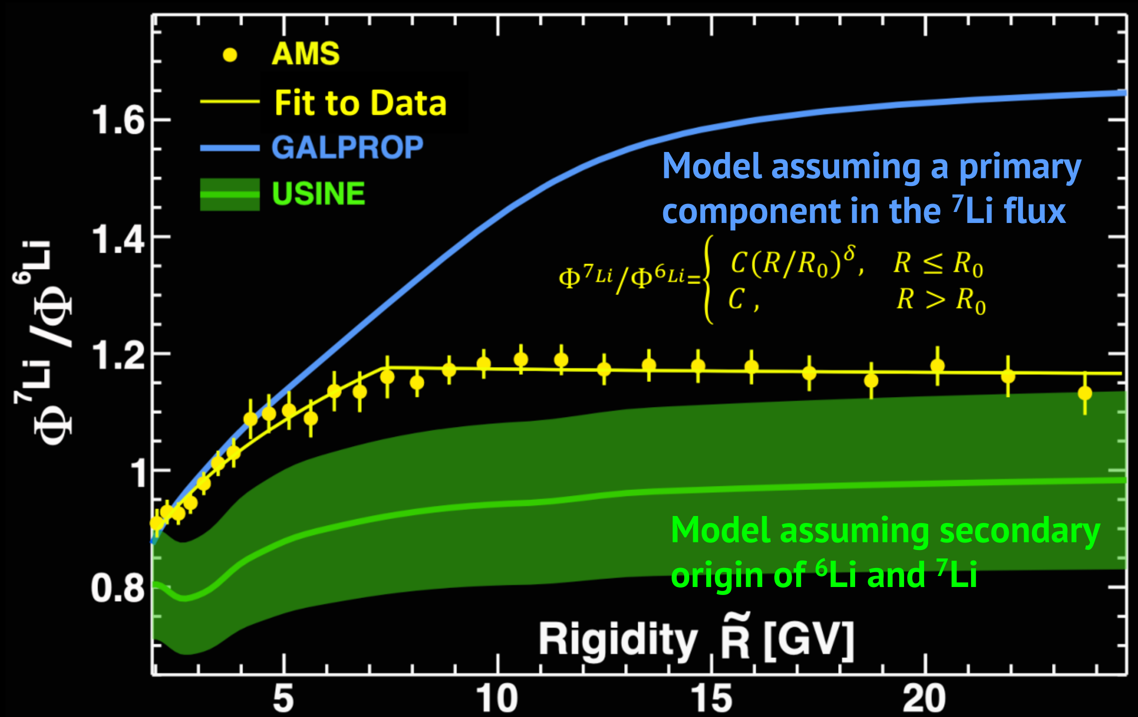
Cosmic-ray isotopes

The measurement of CR isotopes provides crucial information for modelling CR propagation in the Galaxy

D and ^{3}He are produced by the collision of primary CRs with the ISM. Contrary to the flux ratio of ^{3}He/p, D/p increases with rigidity and is constant above 13 GV. D must have an additional primary source

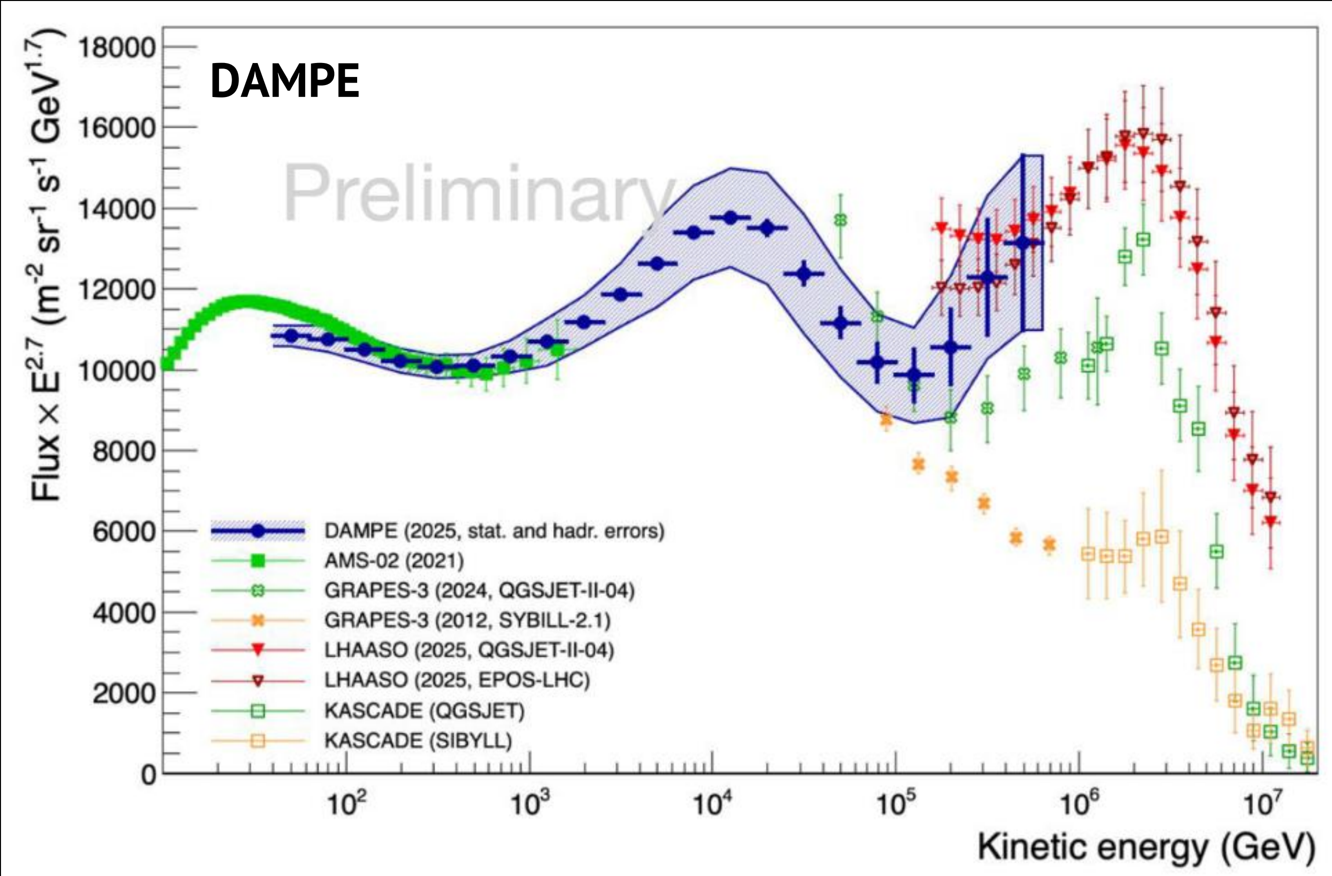
^{7}Li has 3 or more possible sources in the cosmos: BBN, stellar evolution and CR collisions in the ISM. Above ~7 GV, the rigidity dependence of ^{6}Li and ^{7}Li fluxes are identical. The AMS result excludes the existence of a sizable primary component in the ^{7}Li flux

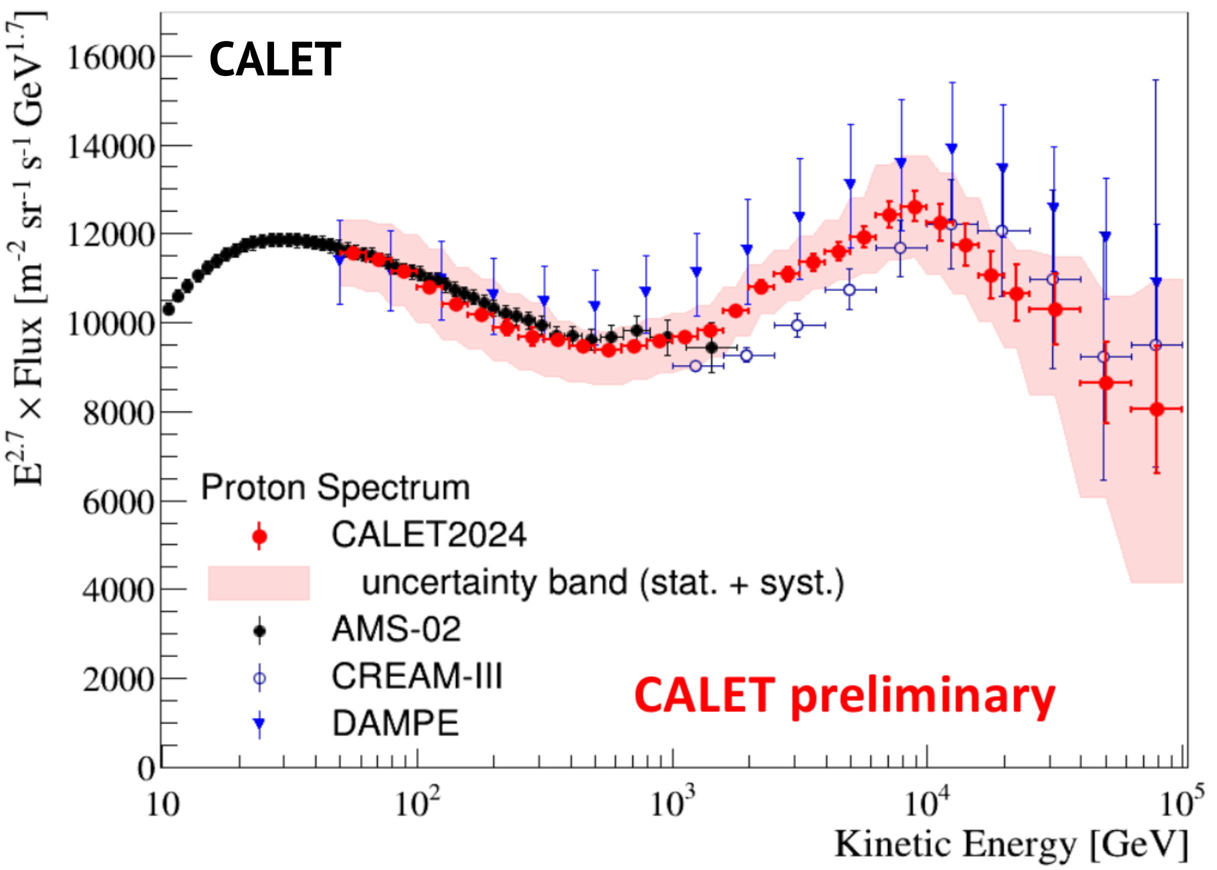




Extension to higher energies: DAMPE & CALET

The proton spectrum measured by DAMPE reveals a softening at ~14 TeV and a hint of a new hardening above 100 TeV

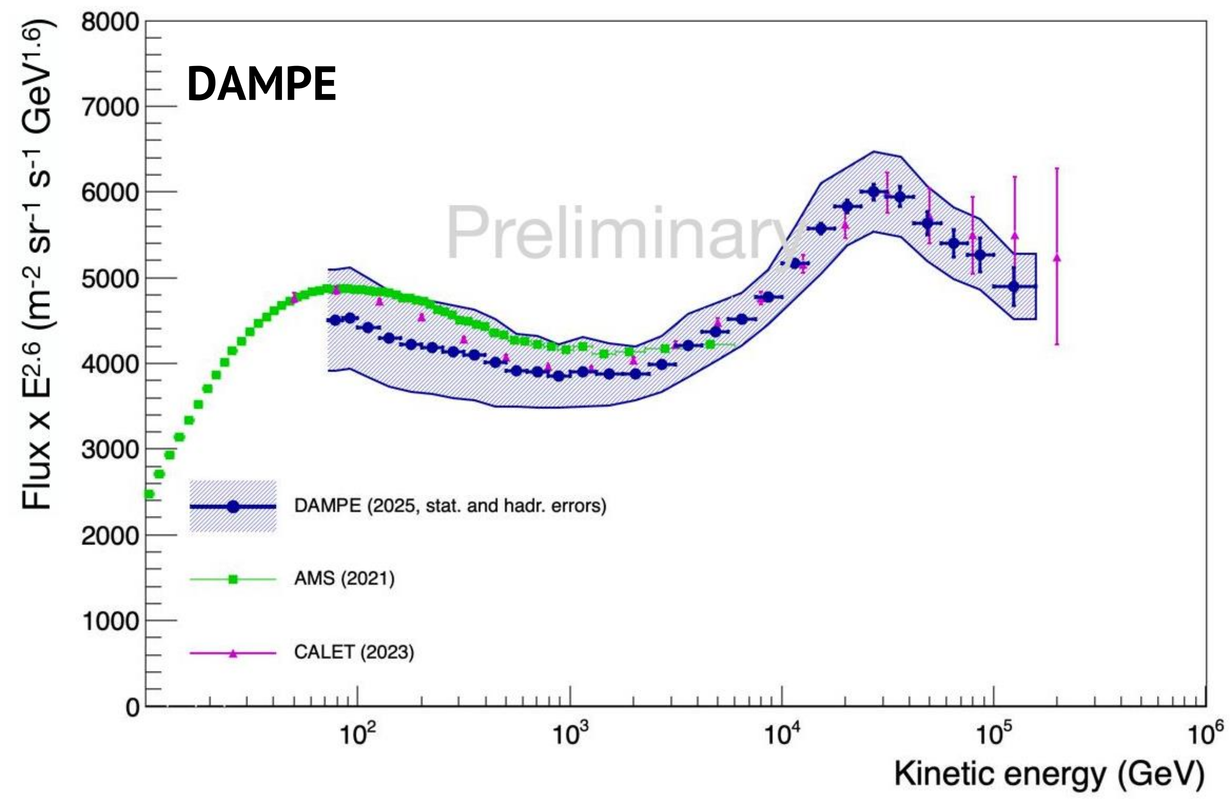


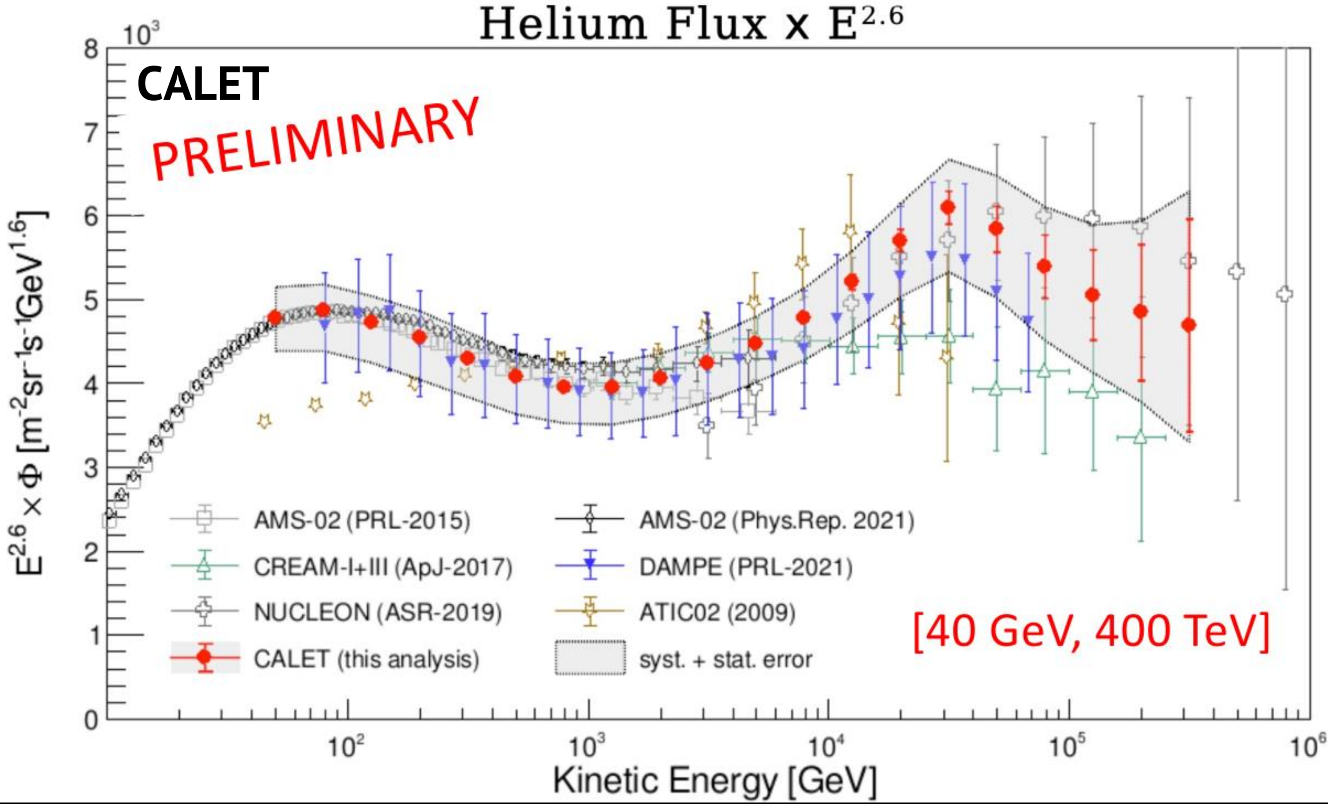


CALET proton spectrum shows a progressive hardening above a few hundred GeV consistent with AMS and a spectral softening above ~10 TeV consistent with DAMPE

Extension to higher energies: DAMPE & CALET

The helium spectrum measured by DAMPE reveals a hardening at ~TeV energies followed by a spectral softening at ~30 TeV

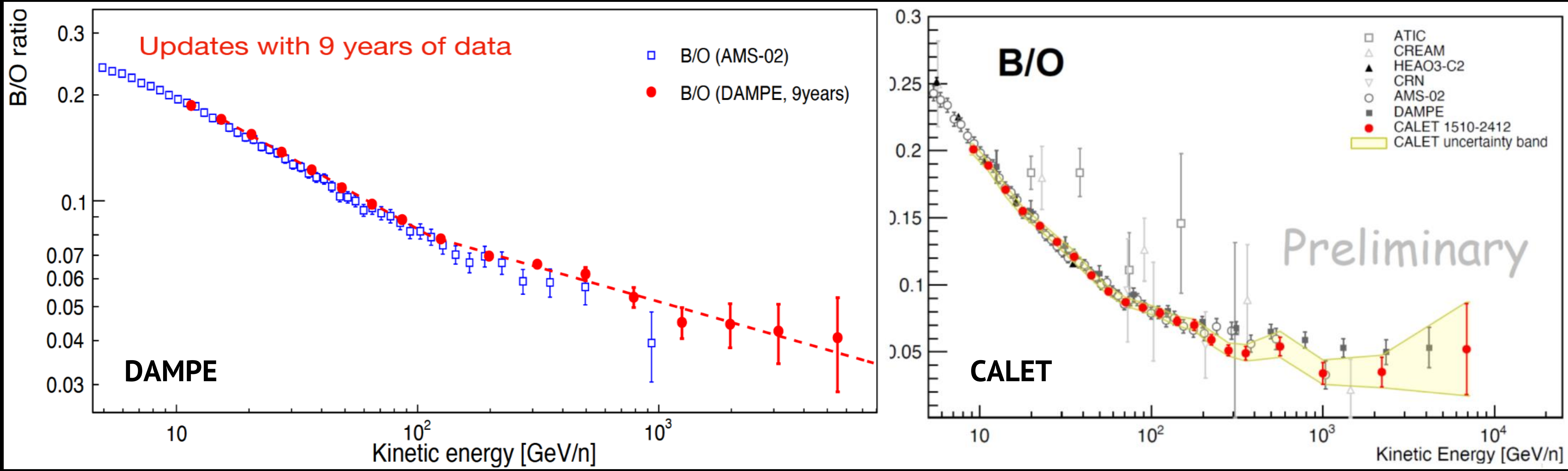




CALET helium spectrum shape confirms the presence of a hardening above a few hundred GeV and the onset of a flux softening at ~30 TeV

Extension to higher energies: DAMPE & CALET

DAMPE B/O flux ratio can be well fitted by a **broken power-law** model rather than a single power-law model



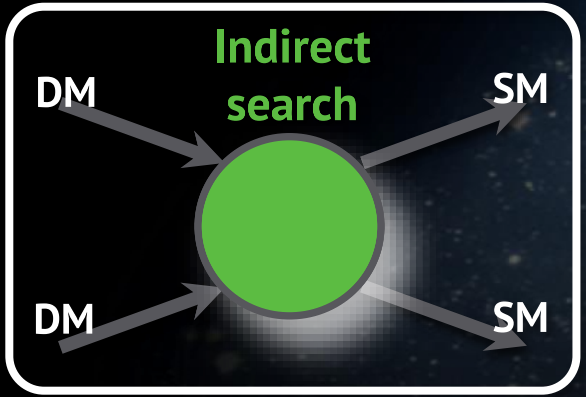
CALET reports the observation of a **flattening** on the **B/O** flux ratio and supports the result from AMS that secondary CRs exhibit a stronger hardening than primaries

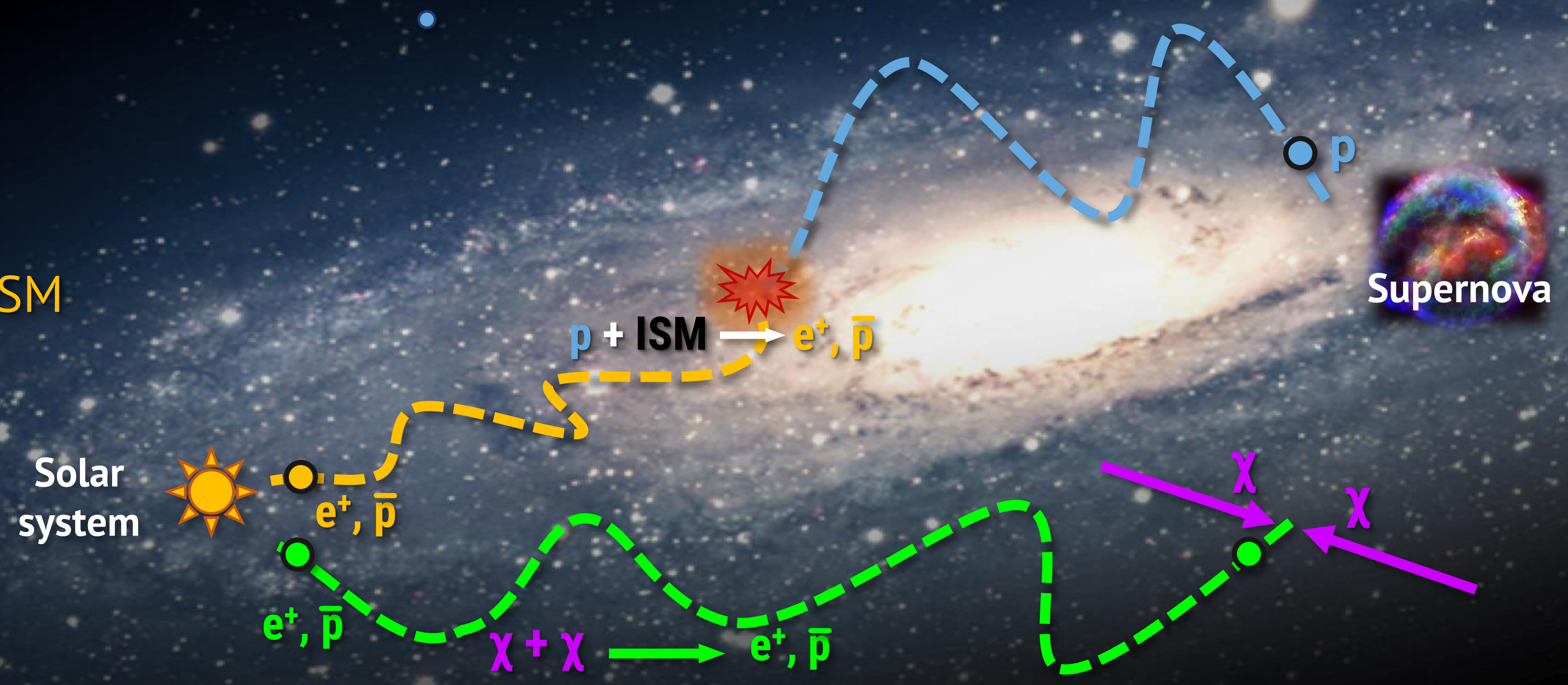
Indirect searches for dark matter

According to traditional models, galactic cosmic ray protons and electrons are considered mainly primaries while positrons and antiprotons are secondaries

Primary production
CRs produced at sources

Secondary production
Collision of primary CRs with the ISM

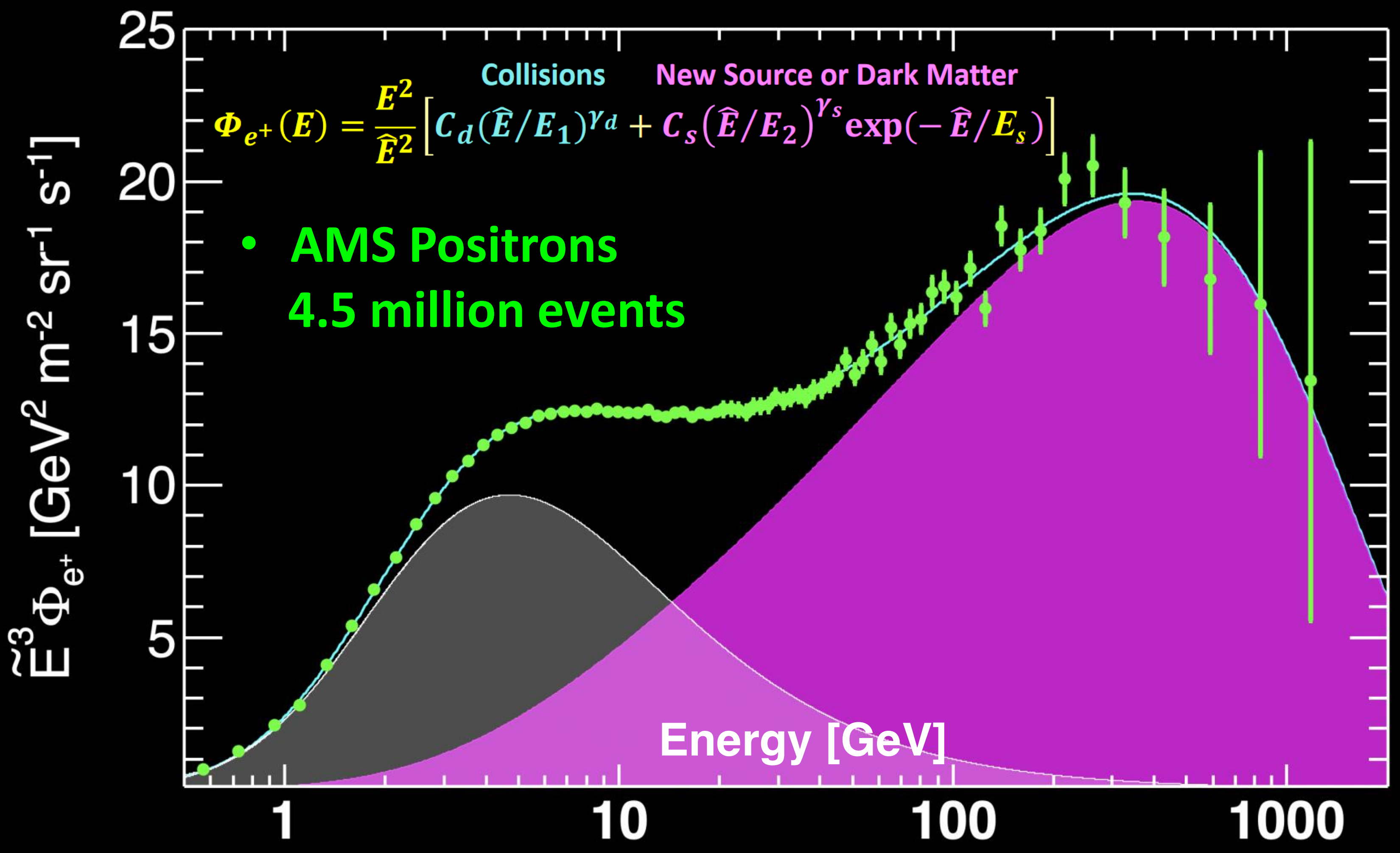




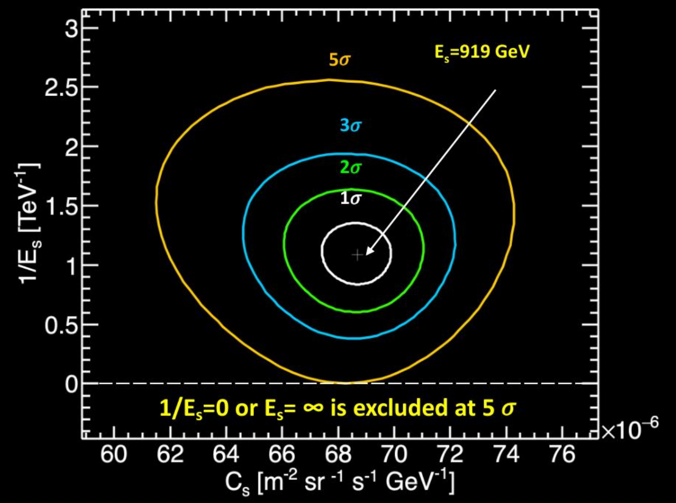
Dark Matter annihilations may produce additional contributions of antimatter particles in the CRs

Cosmic-ray positrons

The positron flux measured by AMS shows a significant excess above ~20 GeV that is not consistent with only the secondary production of positrons

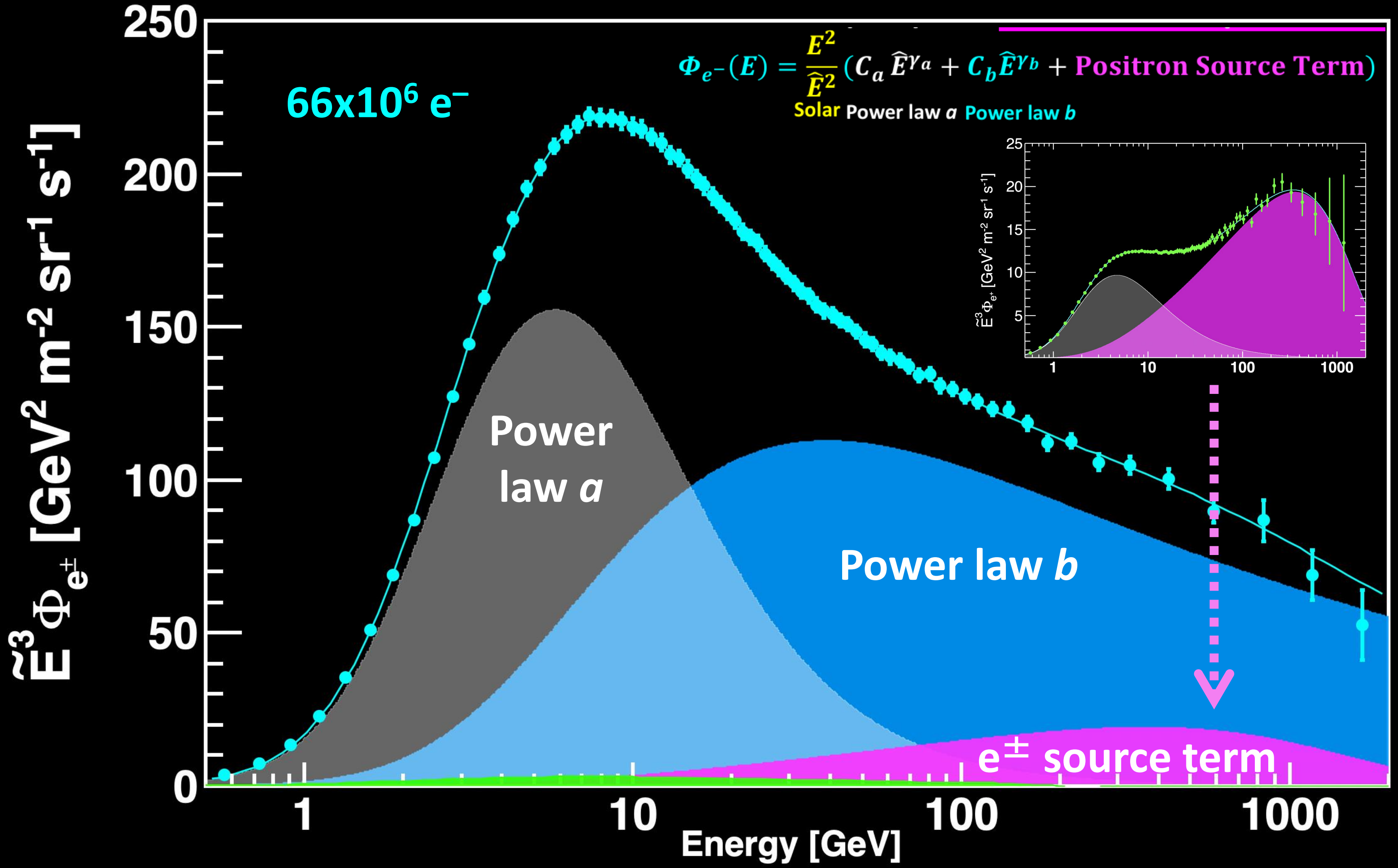


- At low energies, the positron flux is consistent with the secondary production
- At high energies, the positron flux is consistent with a source term characterized by a finite energy cutoff at ~900 GeV (5σ)



Cosmic-ray electrons

The electron flux measured by AMS can be best described by the sum of two power laws (*a*, *b*) and the contribution of a positron-like source term at the highest energies



99.1% CL

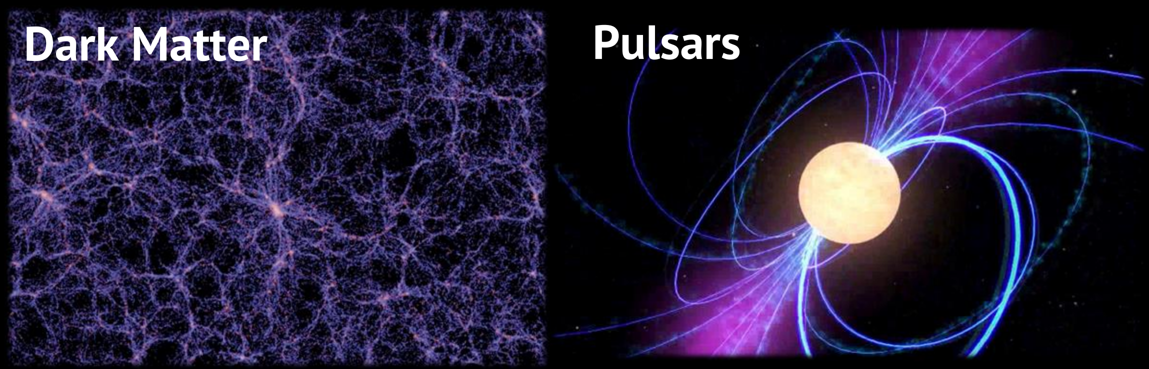
Currently, this observation is established with a statistical significance of 2.6σ

More data is needed to establish the existence of charge-symmetric positron-like source term at highest electron energies

Origin of cosmic-ray positrons

Possible explanations for the high energy positron source term are traditionally grouped into two categories:

- ❑ Dark Matter
- ❑ Astrophysical sources (pulsars)

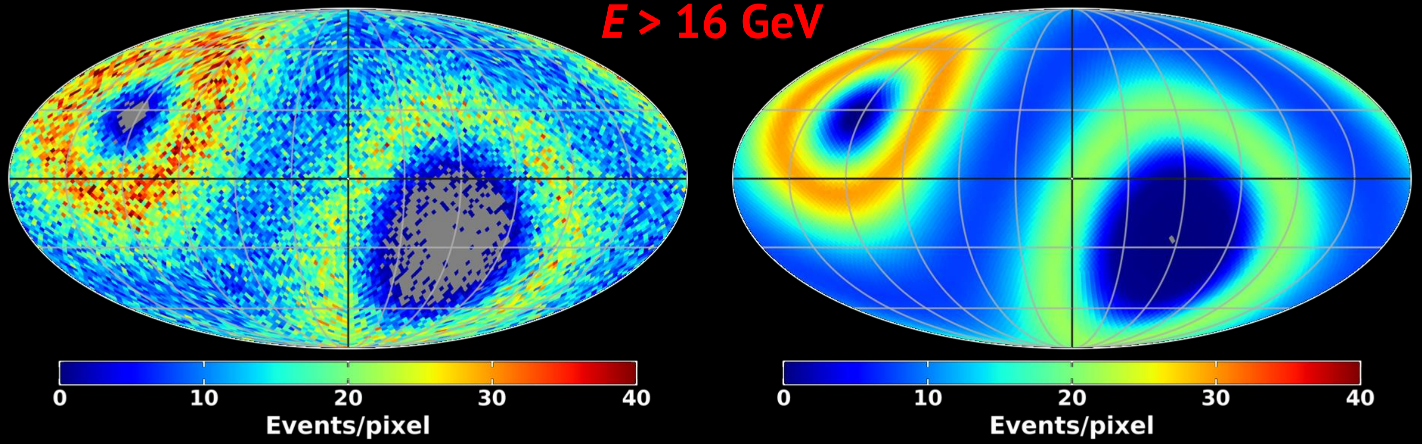


CRs arriving at Earth are highly isotropic. The existence of nearby compact sources of positrons may induce a directionality (anisotropy) that could be detected in the high energy sample

Map of measured positrons in galactic coordinates

Isotropic map

$E > 16$ GeV

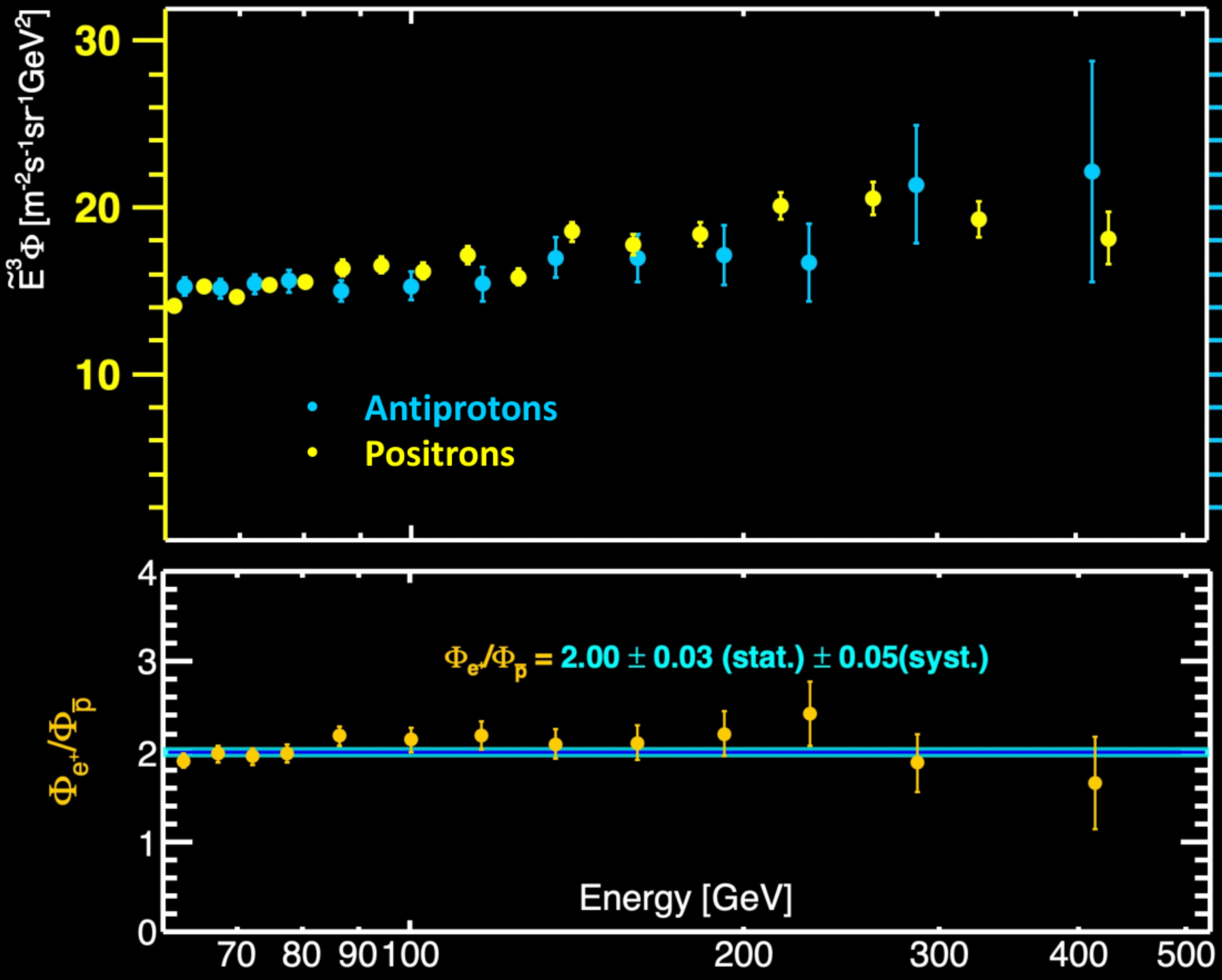


AMS results consistent with isotropy: $\delta_{e+} < 1.44\%$ (95% C.I.)

Cosmic-ray positrons and antiprotons

Above 60 GeV, the $\bar{p}$ and e+ fluxes have identical rigidity dependence

Antiprotons cannot come from pulsars



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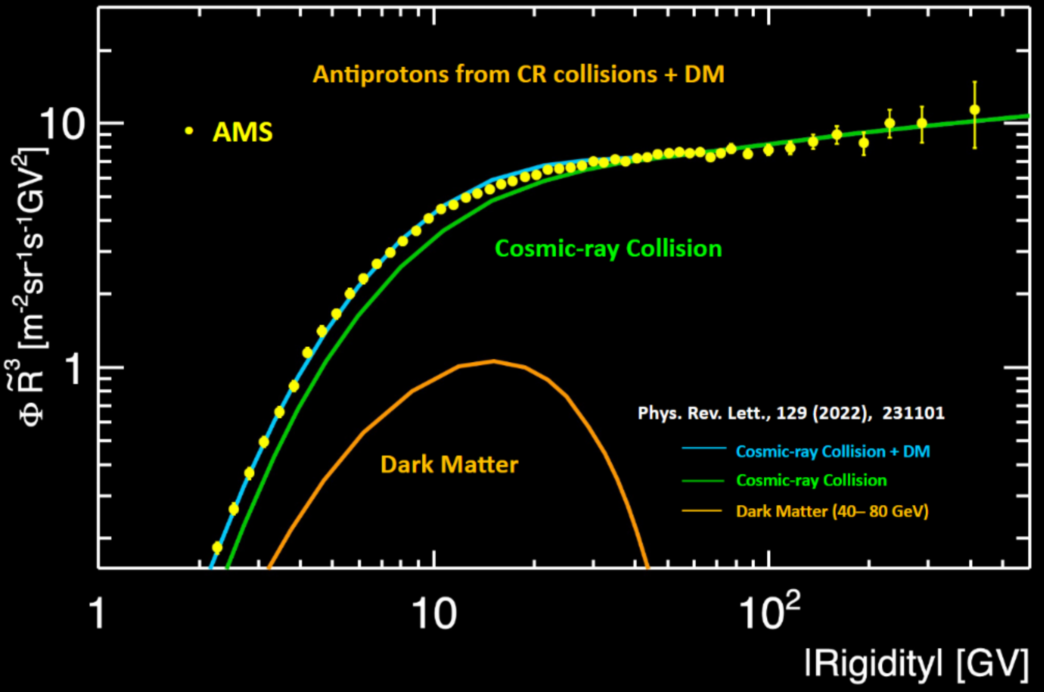
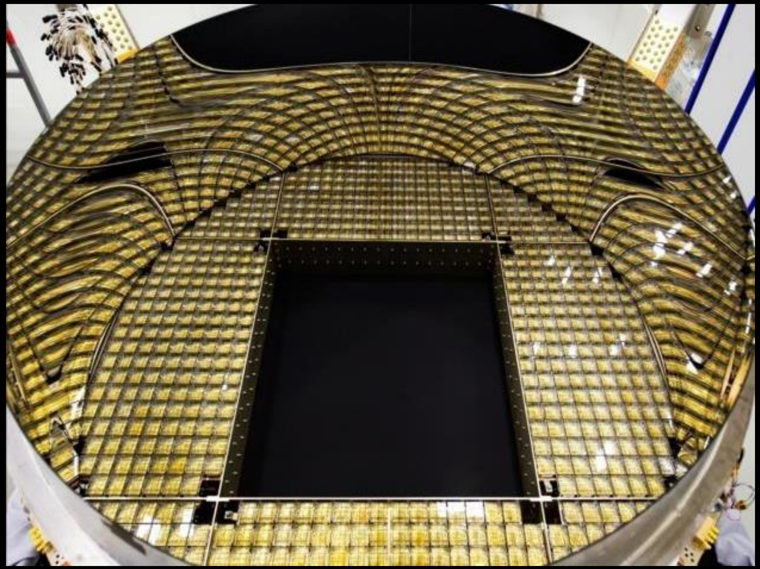


The current uncertainties of the modelling (e.g.: cross-sections) need to be further improved before a definitive theoretical interpretation of the origin of cosmic ray antiprotons is possible

Spain in AMS

AMS is an international collaboration with 250 members from 44 institutions from Europe, Asia, and America



CIEMAT and IAC made major contribution to AMS in the design and construction of the RICH detector

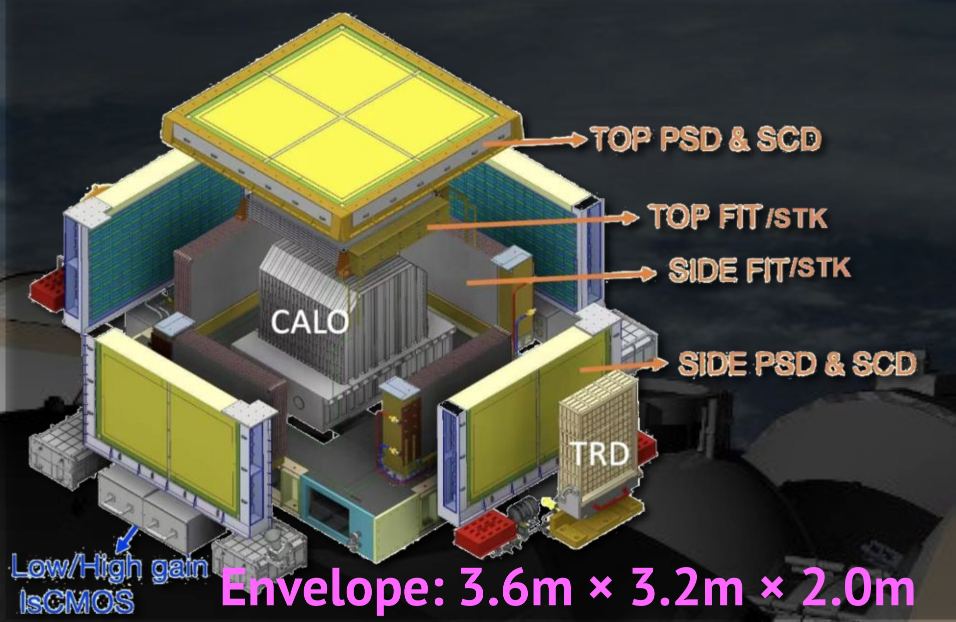
CIEMAT is responsible for the RICH operation from CERN and plays a leading role in several data analysis topics (nuclei fluxes, isotopes, anisotropies, time variation,…)

The Spanish participation in AMS has been consistently supported by the Spanish Space Program

HERD: the next generation of space-based cosmic ray detectors

HERD profits from a new concept design where particles can be accepted from the top and the sides, which provides an increase in the acceptance and energy range of current measurements by one order of magnitude

- ✓ To be installed on the China's Space Station (CSS) in 2028
- ✓ Near Earth Orbit:
  - altitude 340-450 km
  - inclination 42 deg
  - period 92 min
- ✓ Planned for a mission of about 10 years

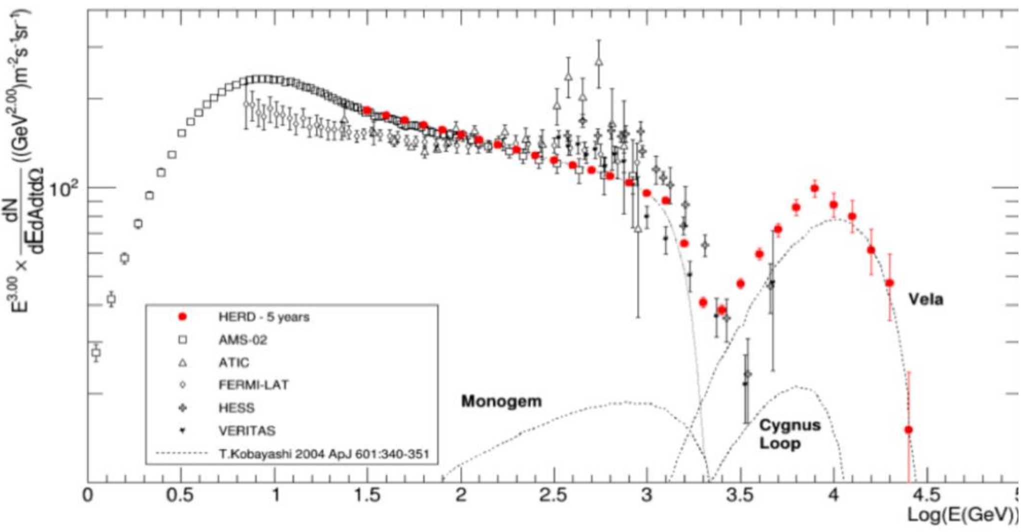


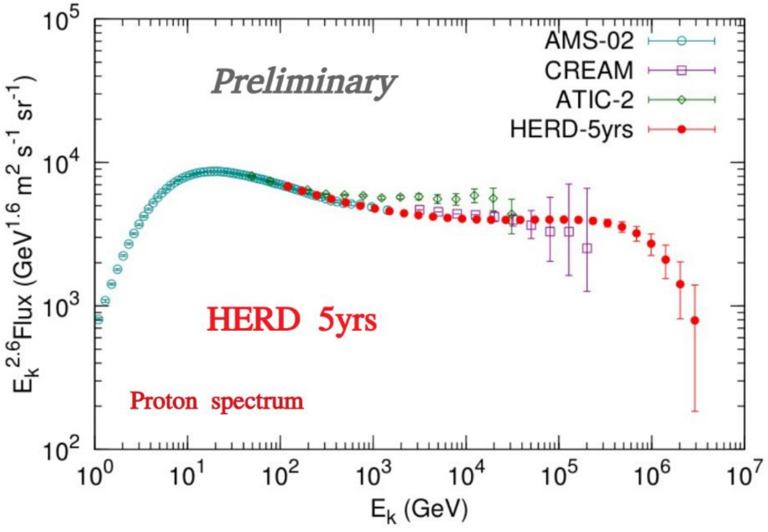
Envelope: 3.6m × 3.2m × 2.0m
4.0 tons

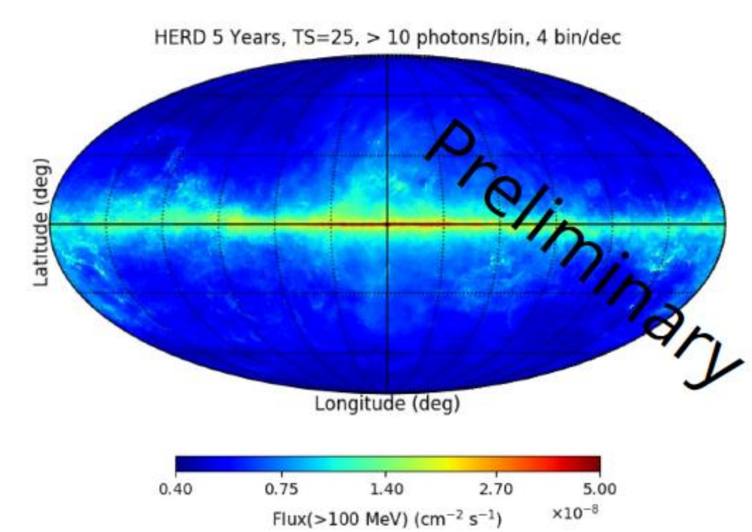
HERD features a 3D calorimeter (CALO) made of ~7500 LYSO crystals surrounded by plastic scintillators (PSD), charge detectors (SCD) and a tracker system

HERD: Scientific goals

- ❑ **Indirect search for DM** in the **all-electron spectrum** up to **few tens of TeV**
  - Detection of potential contributions from **nearby astrophysical sources**
  - Hits of **DM signals** in the structures on the all-electron spectrum
- ❑ **Spectra** and **composition** of **CRs** in an **extended energy range**, in particular, proton and helium up to the **knee** (~1 PeV)
- ❑ **Gamma-ray monitoring** and **full sky survey**







Spain in HERD

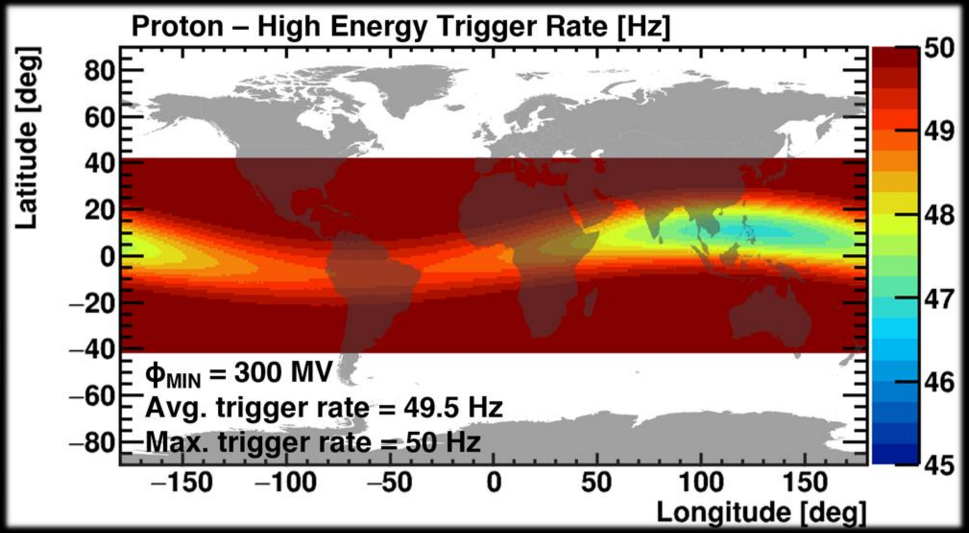
HERD is an **international collaboration** with 200 members from 28 research institutions and universities from China, Italy, Spain and Switzerland

The **Spanish institutions in HERD** (CIEMAT, ICCUB, IFAE) contributed to the development of the **readout** and **trigger electronics** of several subsystems (CALO, FIT and PSD)

After the discontinuation of the European contribution to hardware activities, the Spanish groups are involved in the assessment of **HERD's scientific capabilities** and in the future **scientific exploitation**

Spanish activities in HERD are supported by **space sub-area** within the physics area of **AEI**

Readout electronics for HERD CALO Photodiode system, as a continuation of the CIEMAT activities initiated in 2015 within the INFN Calocube project for R&D of calorimeters in space

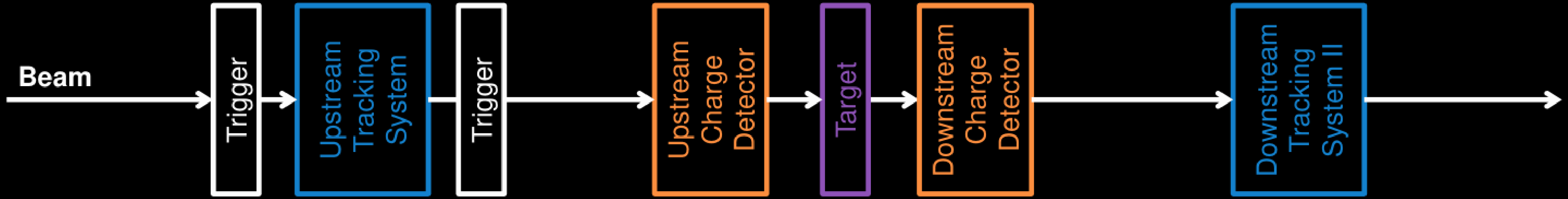


Expected proton rate map for High Energy trigger proposed for HERD

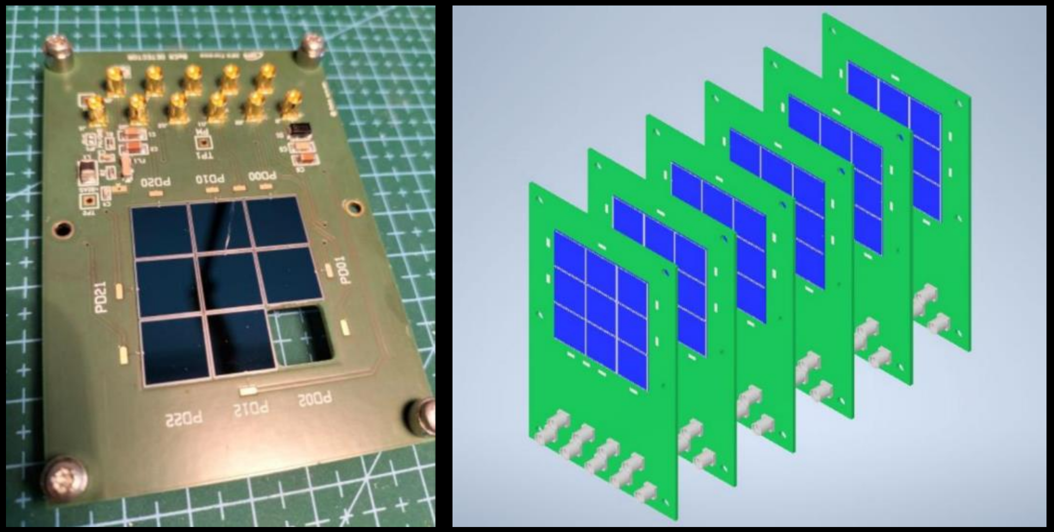
BeER: Beam-monitor with Extreme Range

BeER is a multi-purpose, high-resolution, high dynamic-range charge detector proposed as a technological spin-off of the hardware contributions initially developed for Calocube and later for HERD CALO PD

Performance of a prototype evaluated in a test beam at CERN-SPS in Nov. 2024



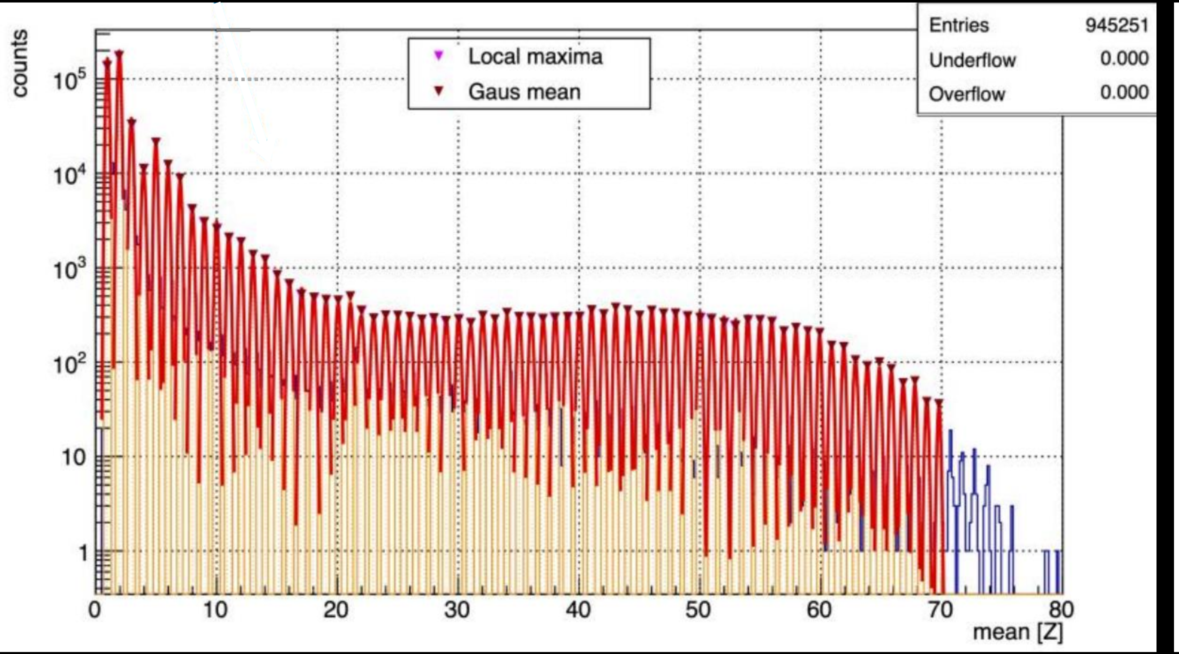
Charge detector



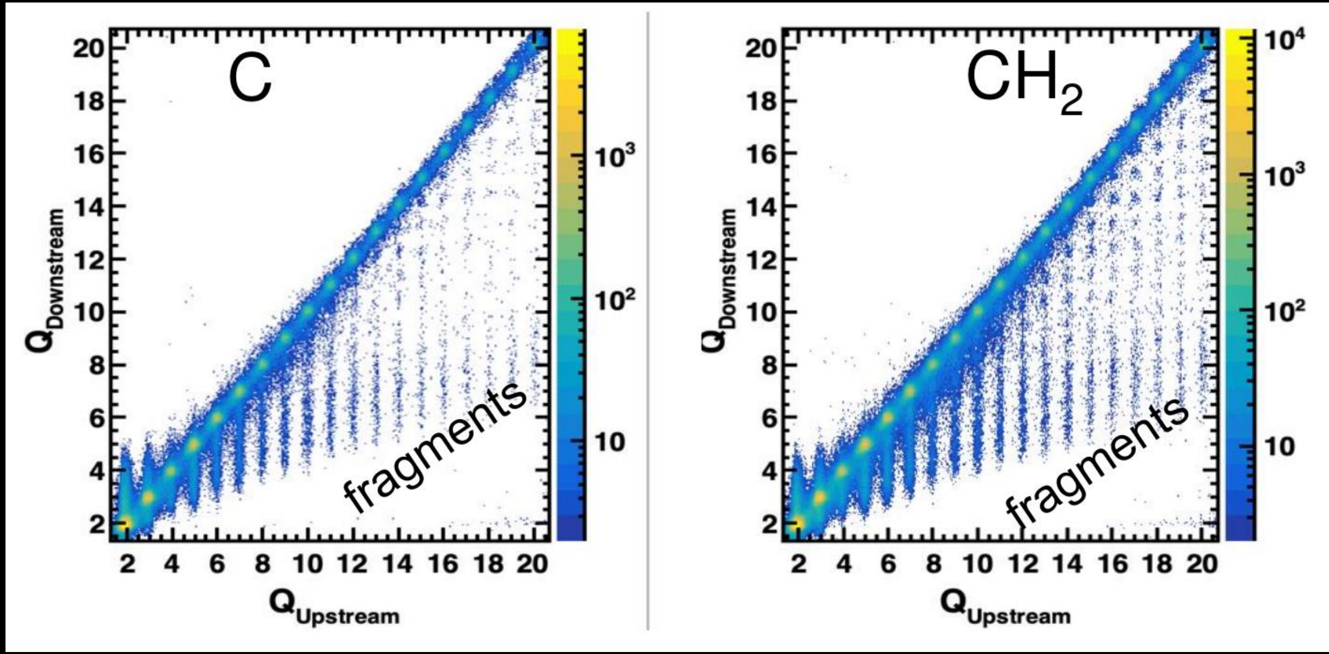
- **Geometrical configuration**: 6 layers, 3×3 PDs (9.2×9.2 mm^2)
- **Read-out electronics** developed by CIEMAT and INFN
- **Charge resolution** $\Delta Z/Z$ better than 0.3 up to Z~80

BeER: Beam-monitor with Extreme Range

Upstream Charge Identification



Downstream Charge Identification



- ❑ **BeER** can be used as a **self working detector** for heavy ion observation or added to **general purpose CR experiment**
- ❑ **BeER** also provides the opportunity for a dedicated program for **precise measurements** of **nuclei cross-section** needed to improve the understanding of **CR propagation in the Galaxy**

BeER pioneers an all-around detector that encompasses the R&D of instrumentation for CR space-based detectors and cross-section measurements needed to provide a definite interpretation of the observed features in the CR fluxes

Conclusions

In the last decades, technological and engineering advances have provided new instruments and detection techniques that allowed for an unprecedented rise in the field of the Astroparticle Physics thanks to direct measurements conducted by CR space-based detectors (AMS-02, DAMPE, CALET…)

Observations challenge the standard paradigm of CRs origin and propagation. Indirect searches for DM in CRs provide a window into Fundamental Physics

Direct measurement of CRs is now a high precision field. The scarce understanding of nuclei cross-section is limiting the interpretation of current measurements

HERD, to be installed in the CSS in 2028, will provide an increase in the acceptance and energy range of current measurements by one order of magnitude

BeER is a spin-off from HERD hardware developments that combines the R&D of instrumentation for future space-based detectors and its application for cross-section measurements in test beams

…a lot of work ahead of us!