Highlights of AMS results and implications for cosmic-ray modelling

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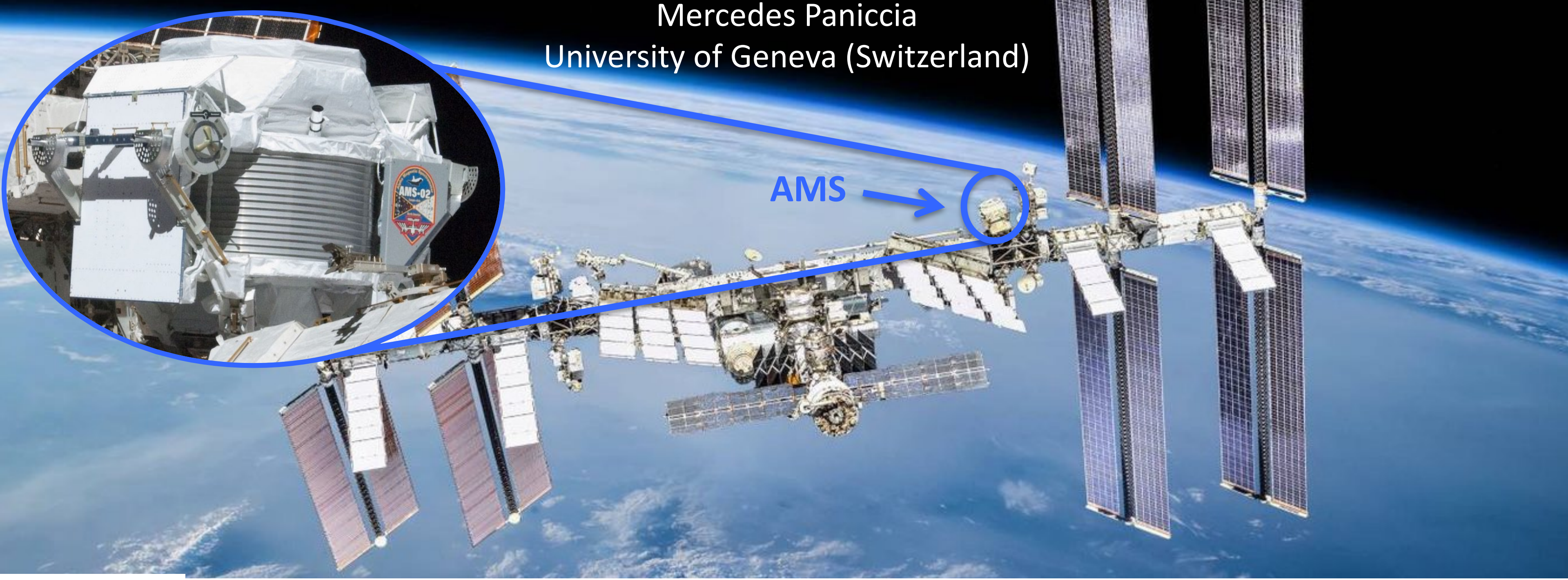
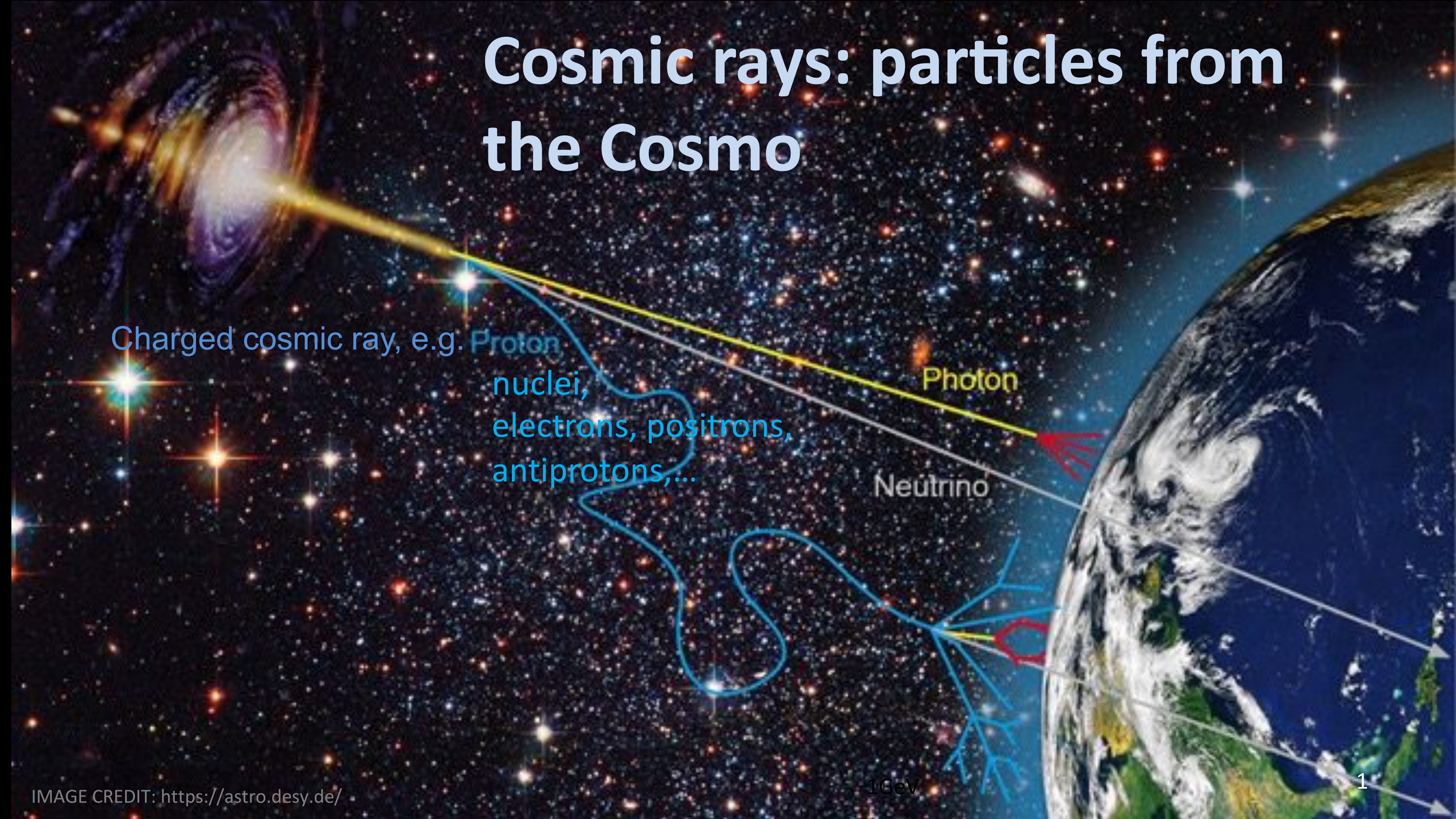


UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES
Département de physique nucléaire et corpusculaire

High-Energy Physics Summer School, Biricik Bilim
August 29, 2026

Cosmic rays: particles from the Cosmo



Charged cosmic ray, e.g. Proton

nuclei,
electrons, positrons,
antiprotons,…

IMAGE CREDIT: https://astro.desy.de/

Observables: energy spectra

Particles' Flux : intensity per unit surface, solid angle, time, and energy
[m² sr s eV]$^{-1}$

Number of particles

$$\phi(E) = \frac{N}{A \;\; \varepsilon \, T \, \Delta E}$$

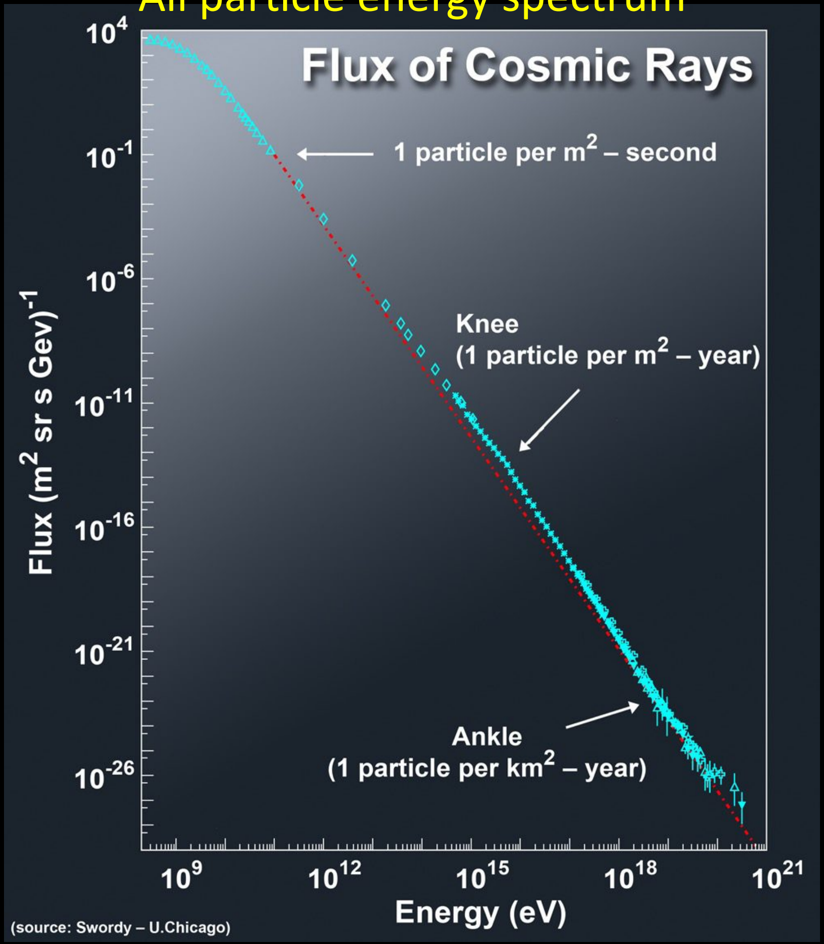
Detector geometrical acceptance: Surface and aperture in solid angle (field of view)
[m² sr]

detector efficiency

Esposure time [s]

Energy bin [eV]

All particle energy spectrum



Observables: rigidity spectra

Particles'Flux : intensity per unit surface, solid angle, time, and rigidity $[m^2\ sr\ s\ V]^{-1}$

Number of particles

$$\phi(R) = \frac{N}{A\ \varepsilon\ T\ \Delta R}$$

Detector geometrical acceptance: Surface and aperture in solid angle (field of view) $[m^2\ sr]$

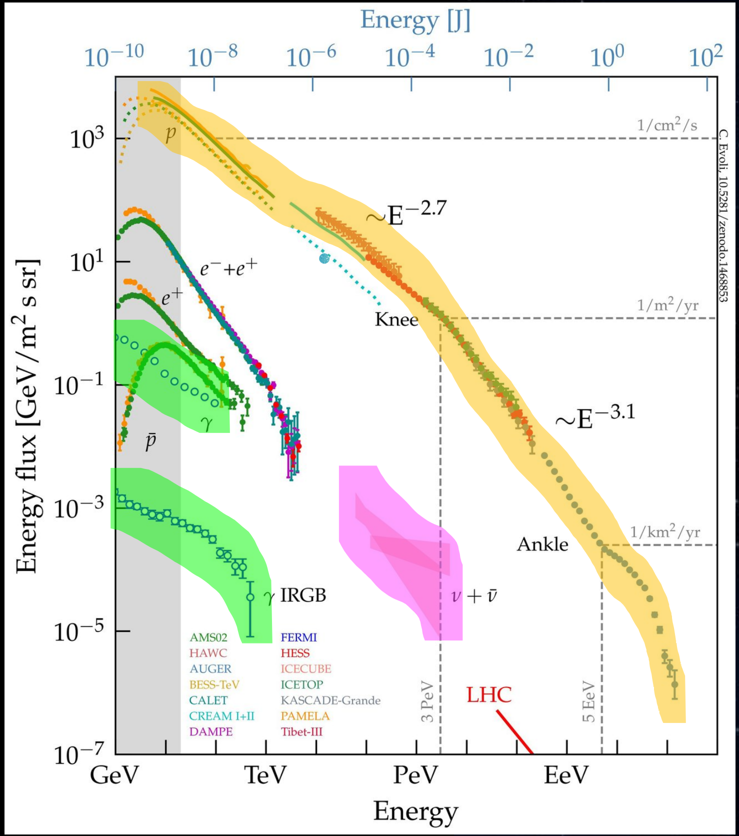
detector efficiency

Esposure time [s]

Rigidity bin [V]

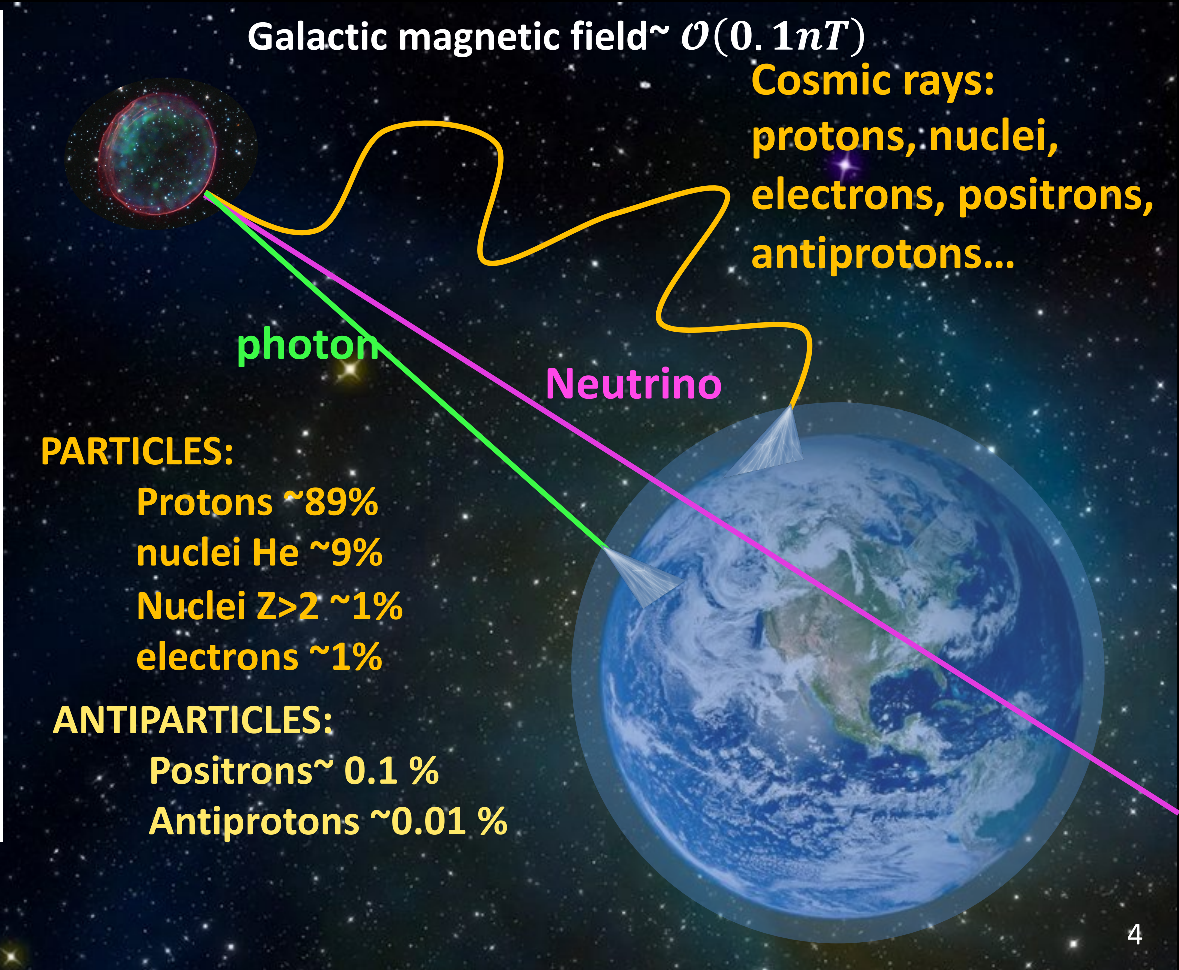
In Magnetic Spectrometers CR spectra are measured as function of Rigidity R=p/Z (momentum/charge)

Charged particles make most of the cosmic particles



Evoli https://zenodo.org/record/2360277#.X1ZFK9ZS_GI

Galactic magnetic field~ $\mathcal{O}(0.1nT)$



Cosmic rays: protons, nuclei, electrons, positrons, antiprotons…

PARTICLES:

- **Protons ~89%**
- **nuclei He ~9%**
- **Nuclei Z>2 ~1%**
- **electrons ~1%**

ANTIPARTICLES:

- **Positrons~ 0.1 %**
- **Antiprotons ~0.01 %**

Origin of elements

Protons and Helium nuclei and maybe traces of lithium nuclei formed at the time of Big Bang.

Heavier elements are synthesized in stars

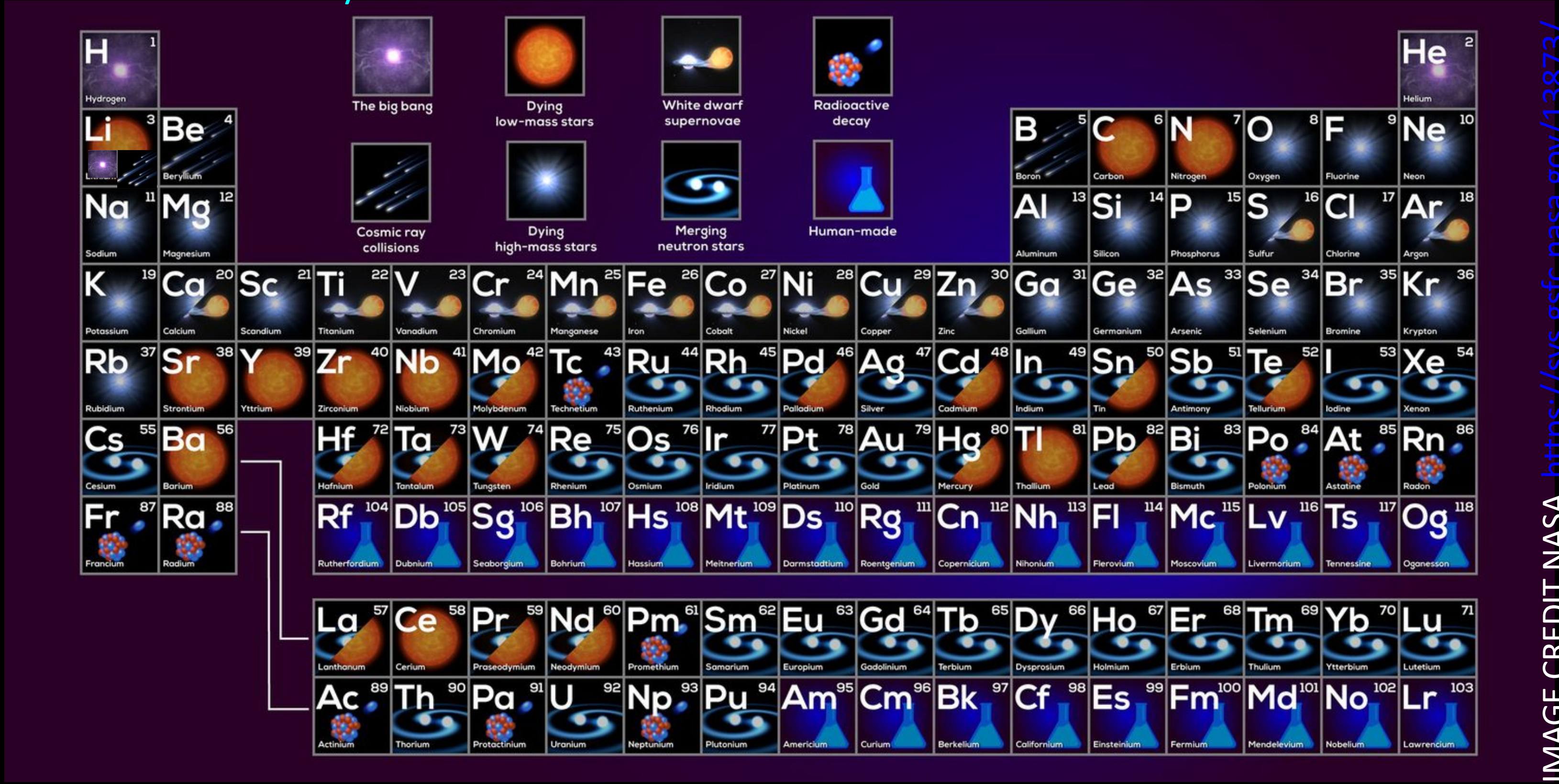
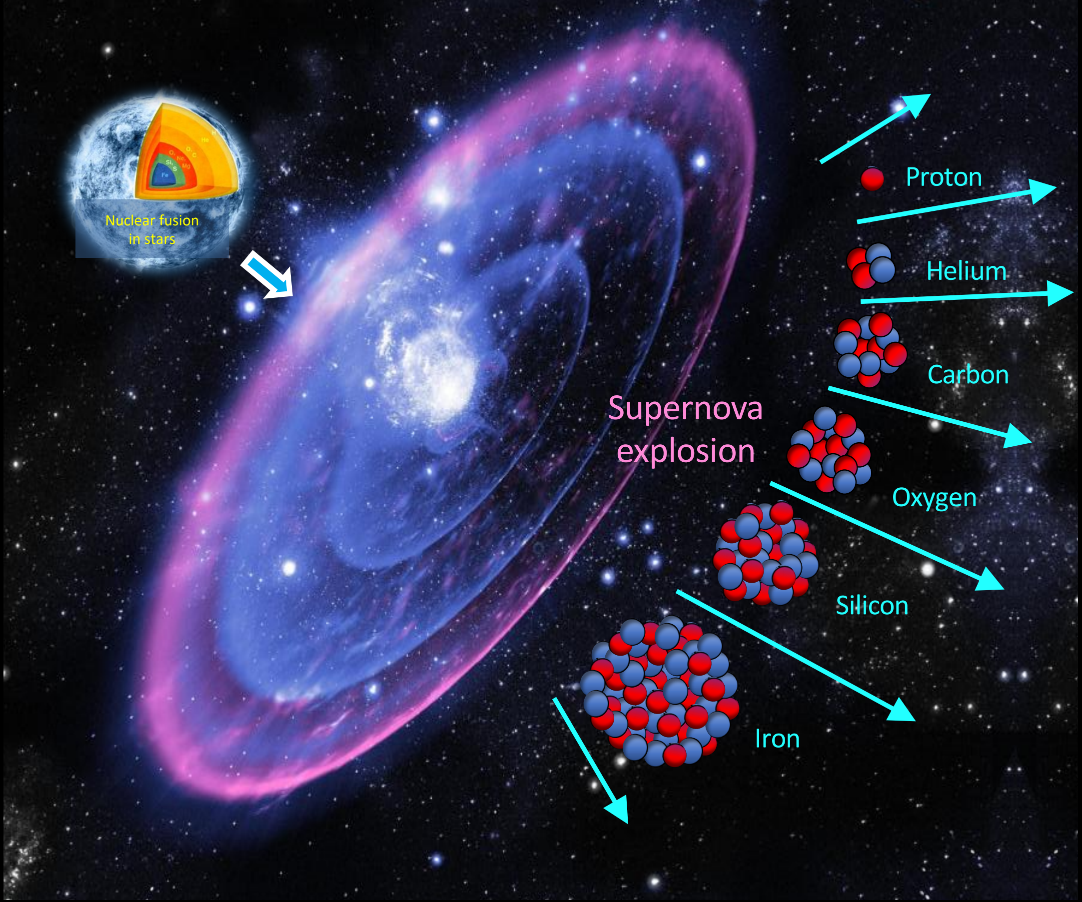


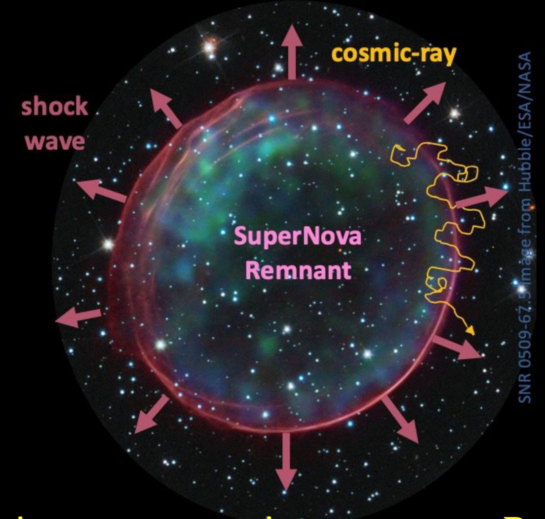
IMAGE CREDIT NASA https://svs.gsfc.nasa.gov/13873/

Primary cosmic rays



Primary cosmic ray nuclei H, He, C, O, Ne, Mg, Si..., Fe are synthesized in stars during their lifetime.

They are thought to be accelerated by diffusing through shock waves as those generated in supernovae explosions.



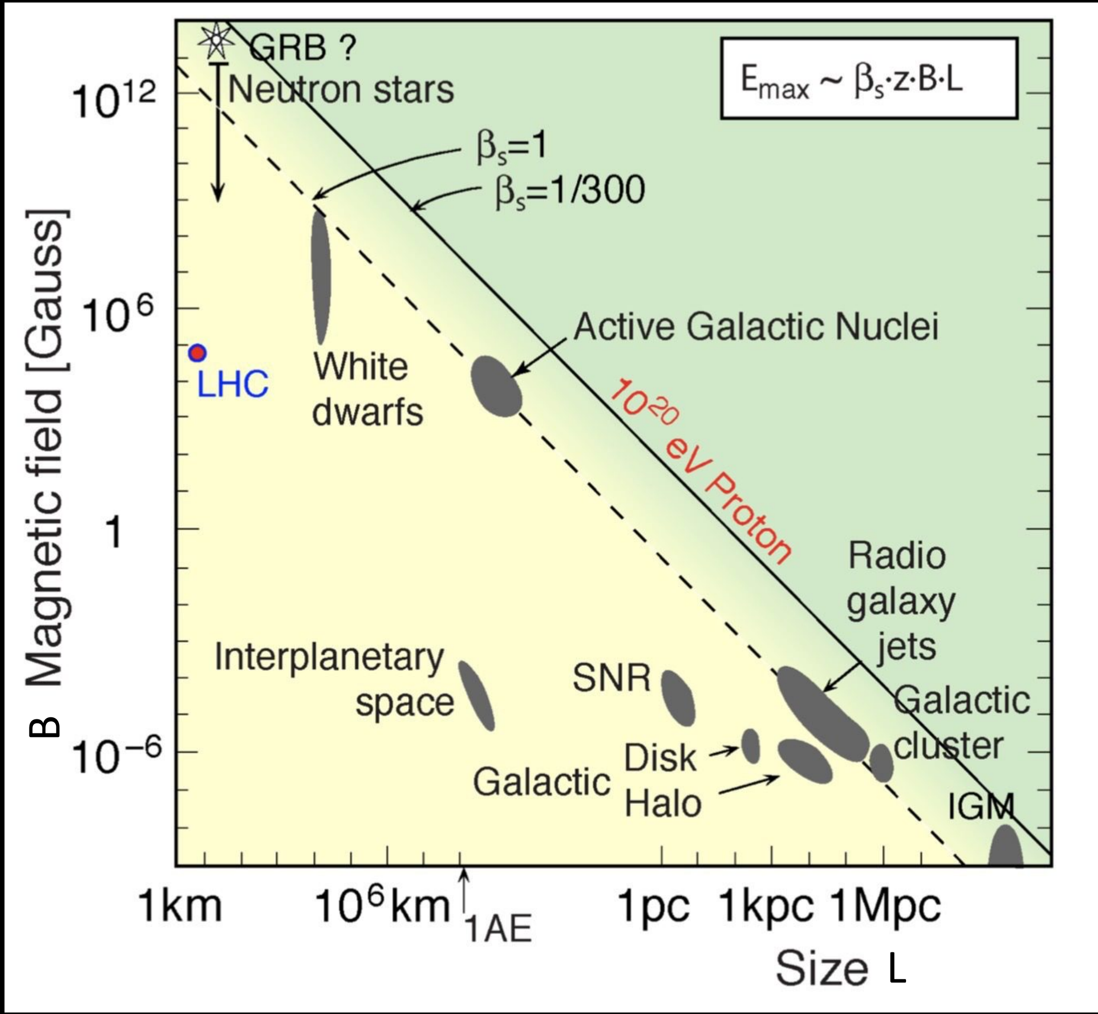
Diffusive shock acceleration produces power-law spectra $R^{-\gamma}$

Cosmic accelerators: the Hillas criterion

The Larmor radius for relativistic particles of charge Ze and energy E is given roughly as
$r_L \propto E/(ZeB)$

Thus, the energy to which a particle can be accelerated is constrained by the magnetic field B and the size L of the system, as per the Hillas criterion. This leads to the expression for
$E_{max} \sim \beta_s Z B L$

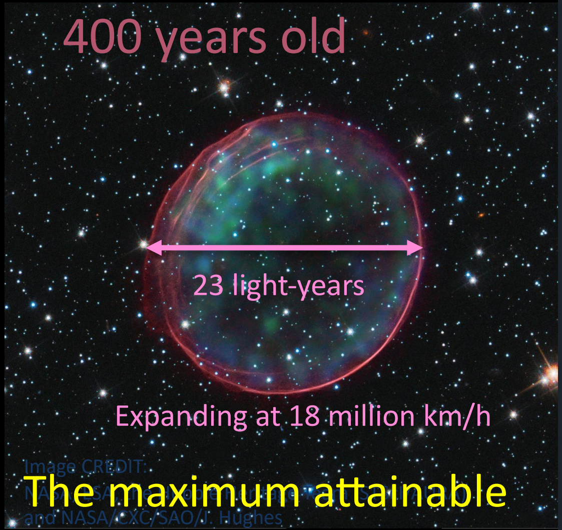
where β_s is the velocity of the accelerated particles



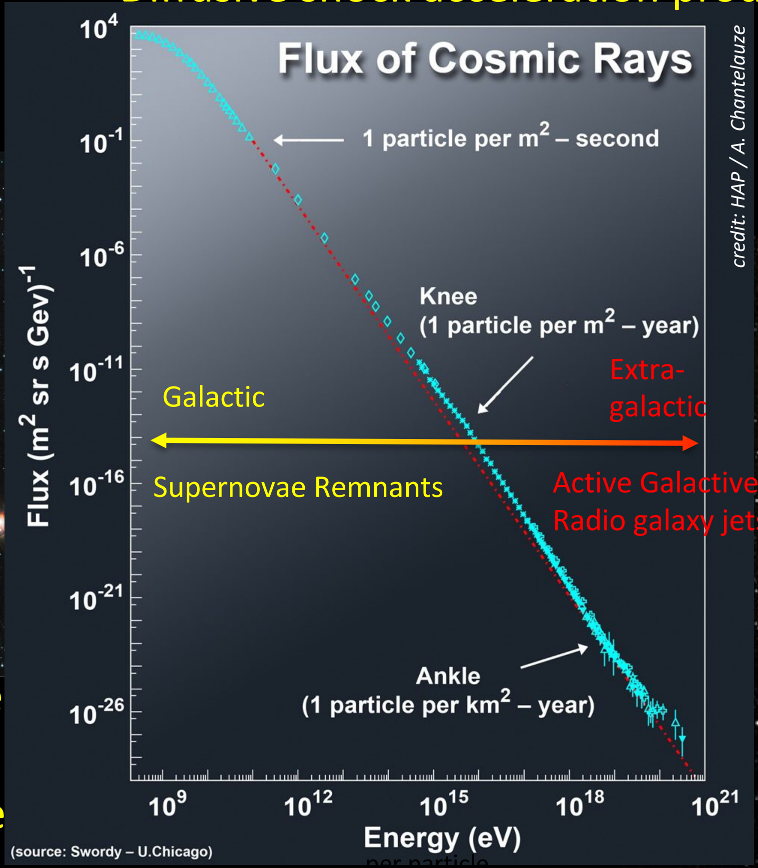
Cosmic Accelerators

Diffusive shock acceleration produce power-law spectra $R^{-\gamma}$

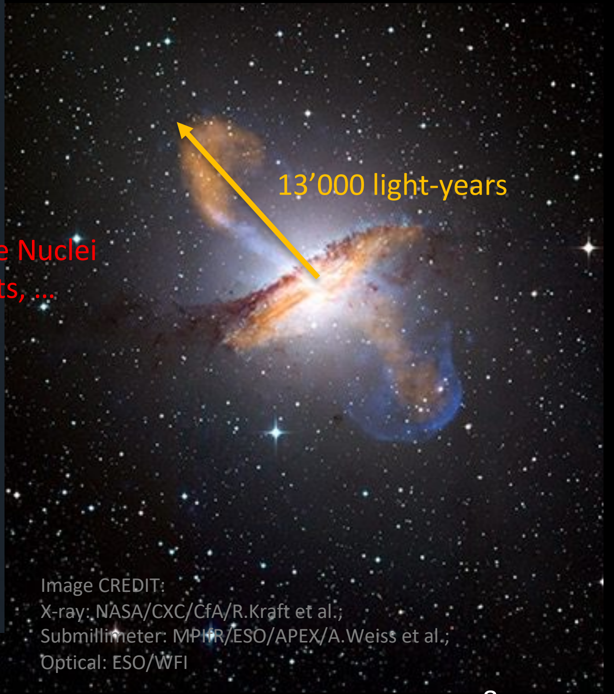
Supernova Remnant
SNR 0509-67.5



The maximum attainable energy depends on the size and magnetic field of the accelerator, for Supernovae
$E_{MAX} \sim Z \cdot 4.5 \times 10^{15}$ eV



Active Galactic Nucleus
Centaurus A



Cosmic-ray propagation in the Galaxy

Cosmic rays propagate by diffusing on the irregularities of the galactic magnetic field.

Cosmic-ray propagation is described in terms of a diffusion coefficient D which depends on the particle's rigidity as :

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

the parameter δ describes the turbulences of the galactic magnetic field

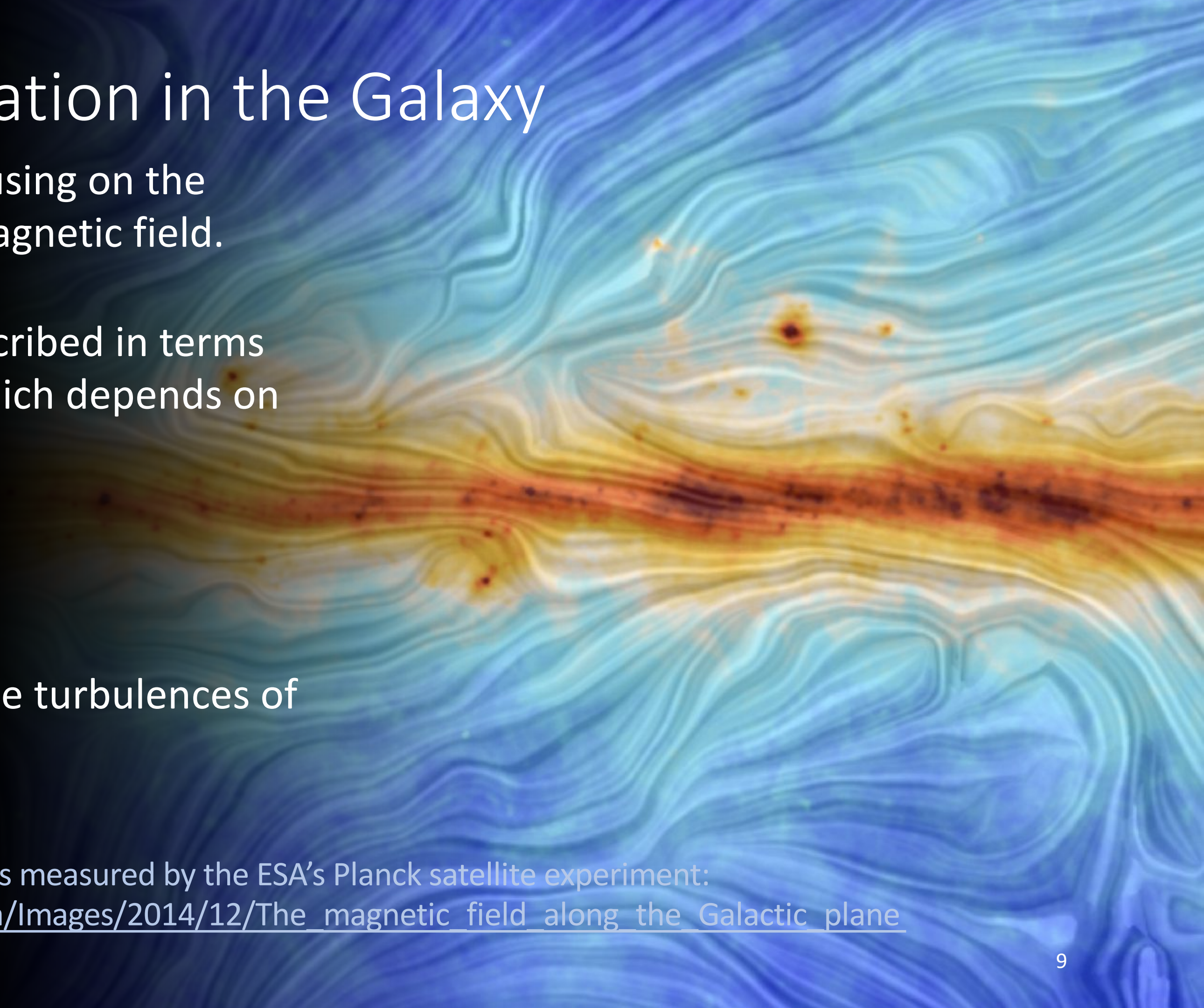
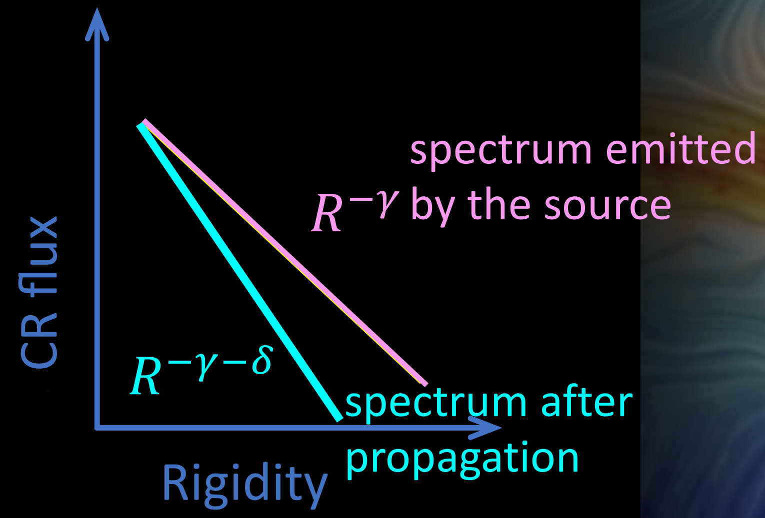


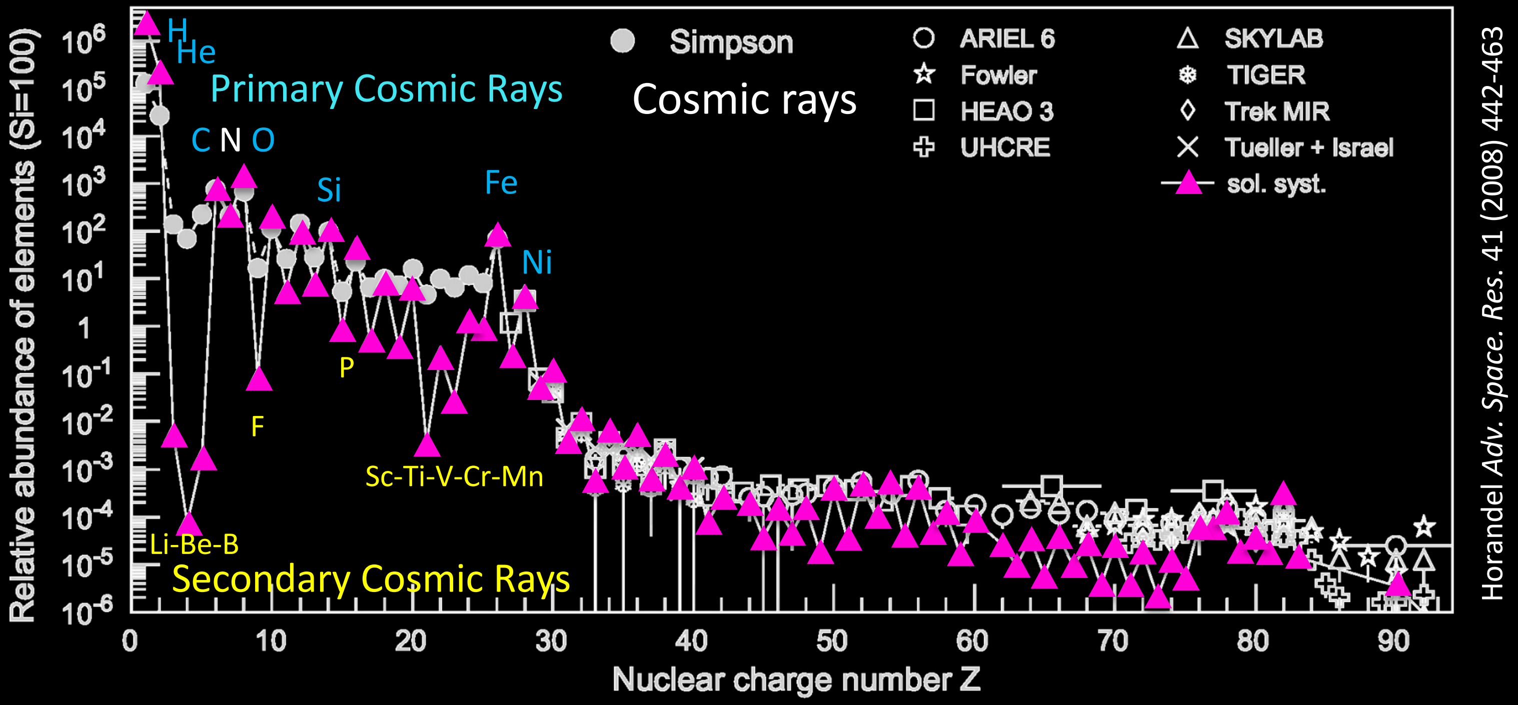
Image of the galactic magnetic field as measured by the ESA's Planck satellite experiment: https://www.esa.int/ESA_Multimedia/Images/2014/12/The_magnetic_field_along_the_Galactic_plane

Cosmic-ray propagation in the Galaxy

Due to propagation effect
CR spectra become steeper
$R^{-\gamma-\delta}$

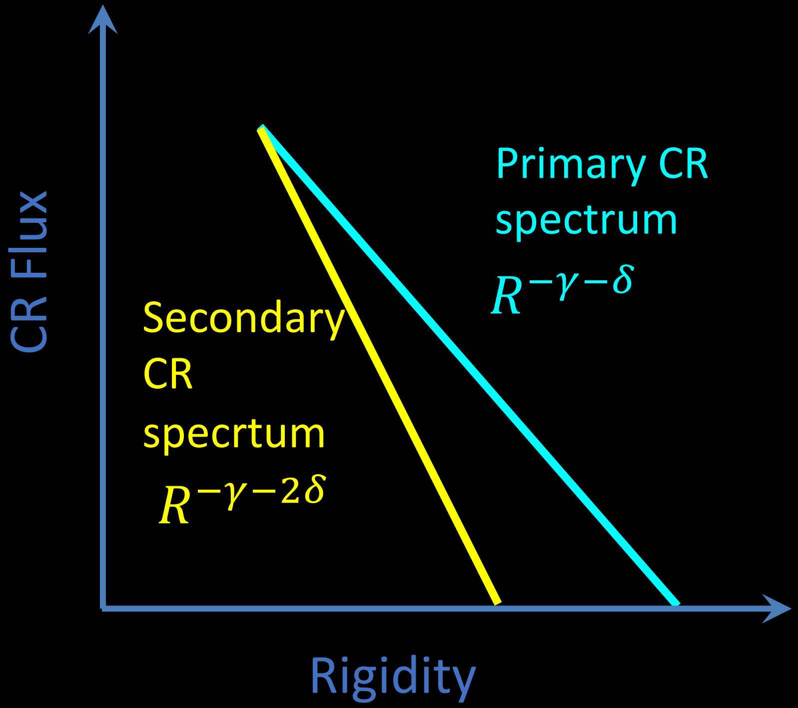


Elemental abundance in cosmic-rays and stars



Lithium, Beryllium, Boron, fluorine, and phosphorus as well as elements in the sub-Fe group, are much more abundant in cosmic rays than in the solar system: they are not direct products of cosmic-ray sources, they are produced by spallation of primary cosmic-rays with the interstellar medium

Secondary cosmic rays as probes of the CR propagation mechanism

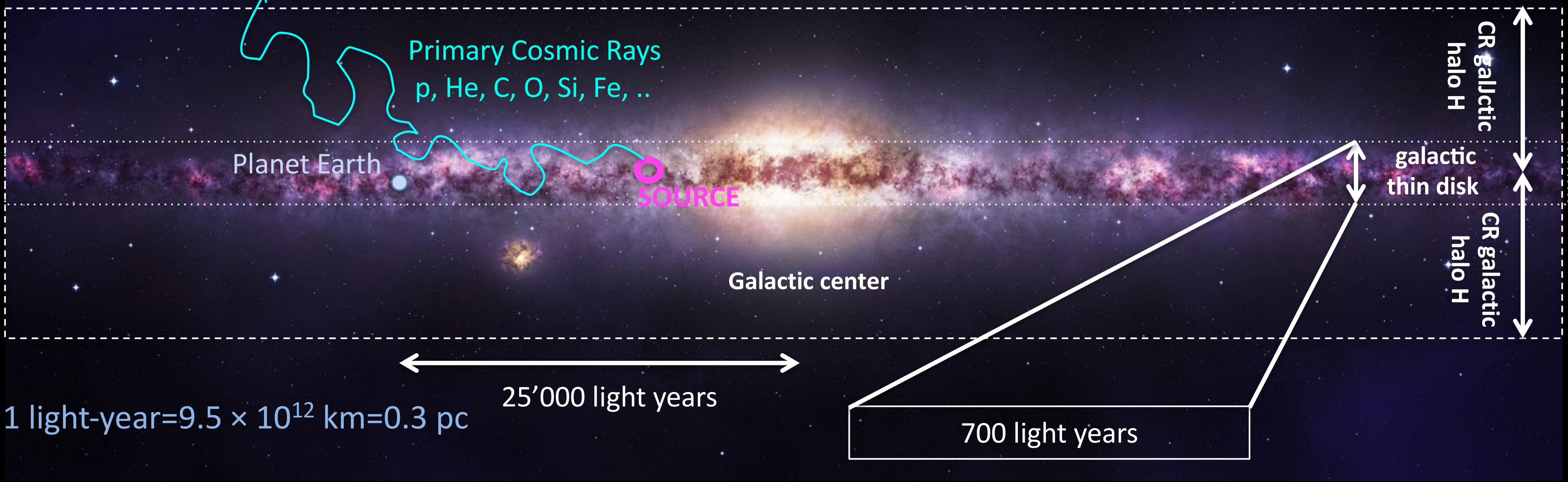


The flux ratio of secondary to primary (mother /daughter) $\propto R^{-\delta}$ measure the rigidity dependence of the diffusion coefficient

Galactic Cosmic-Ray propagation

Cosmic-ray sources resides mostly in the galactic thin disk.

After escaping from their sources cosmic rays propagate from the disk to the galactic halo until escaping through the galaxy boundary



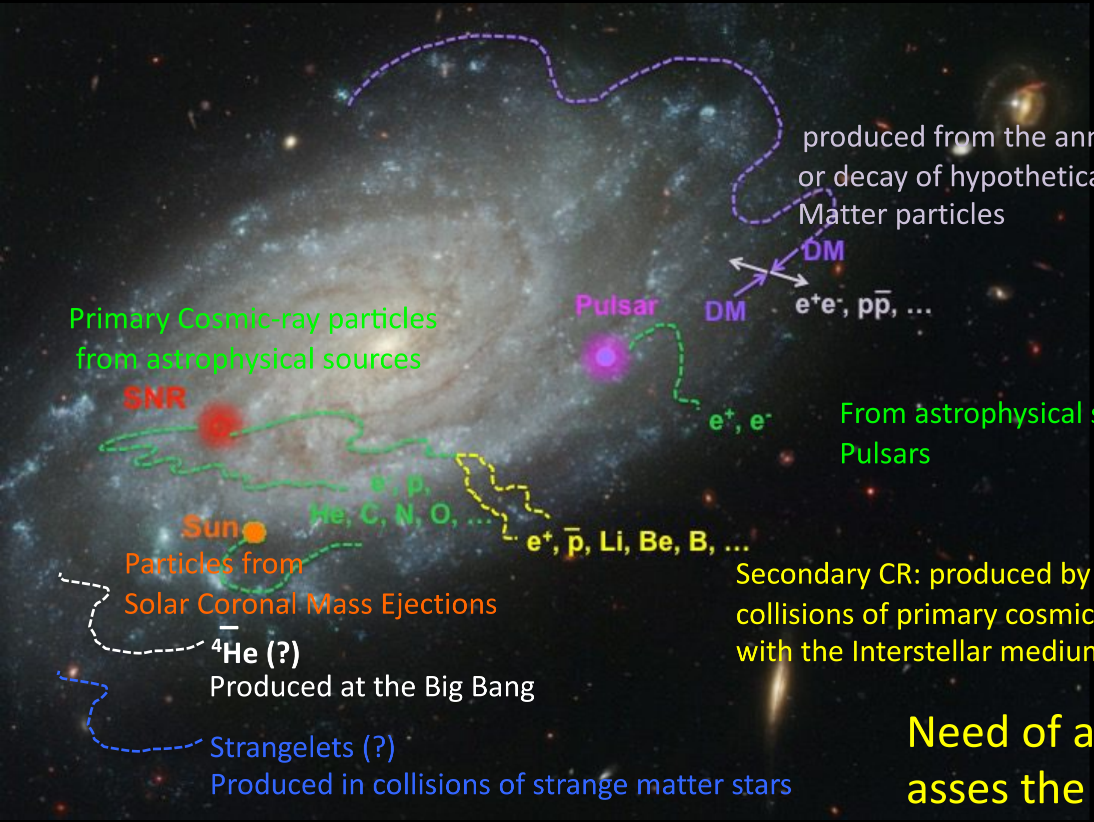
The cosmic-ray galactic halo H measures the half-height of the galactic volume filled by cosmic rays, known also as cosmic-ray diffusive halo.

Cosmic-ray propagation and secondary cosmic rays

In their journey through interstellar space CRs undergo energy losses, convection in the galactic wind, re-acceleration, and can also destroy themselves by fragmentation in collisions with gas and dust in the interstellar medium, or by annihilation, or decay if they are unstable.

Diffusion models based on different assumptions predict a Secondary/Primary ratio asymptotically proportional to **H**/D(R)

Searching for Dark Matter, Antimatter, and strange form of matter in cosmic ray spectra



Signals from DM annihilation or decay may appear in the spectra of rare secondaries as positrons, antiprotons, antideuterons.

Residual primordial antinuclei might still be present today

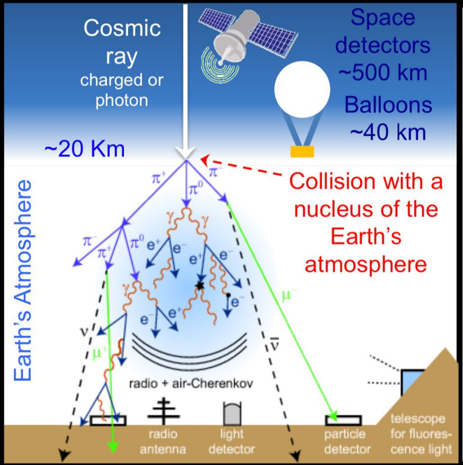
Strange form of matter may produce isotopes with low mass/charge ~0.1

Need of a comprehensive CR model to asses the background from ordinary CRs

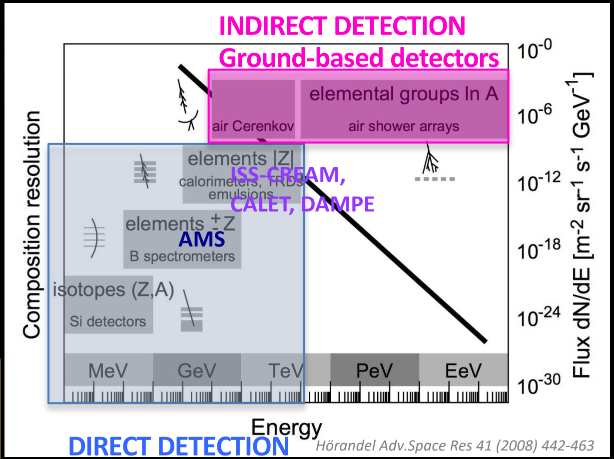
Cosmic-ray detection: space & balloons vs ground-based detectors

CR energy spectrum extends from 100 MeV to ~10^{20} eV
Steeply falling:
flux decreases by 30 orders of magnitude from GeV to 10^{20} eV

Charged cosmic rays have mass. They are absorbed by the 100 km of Earth's atmosphere (10 m of water)

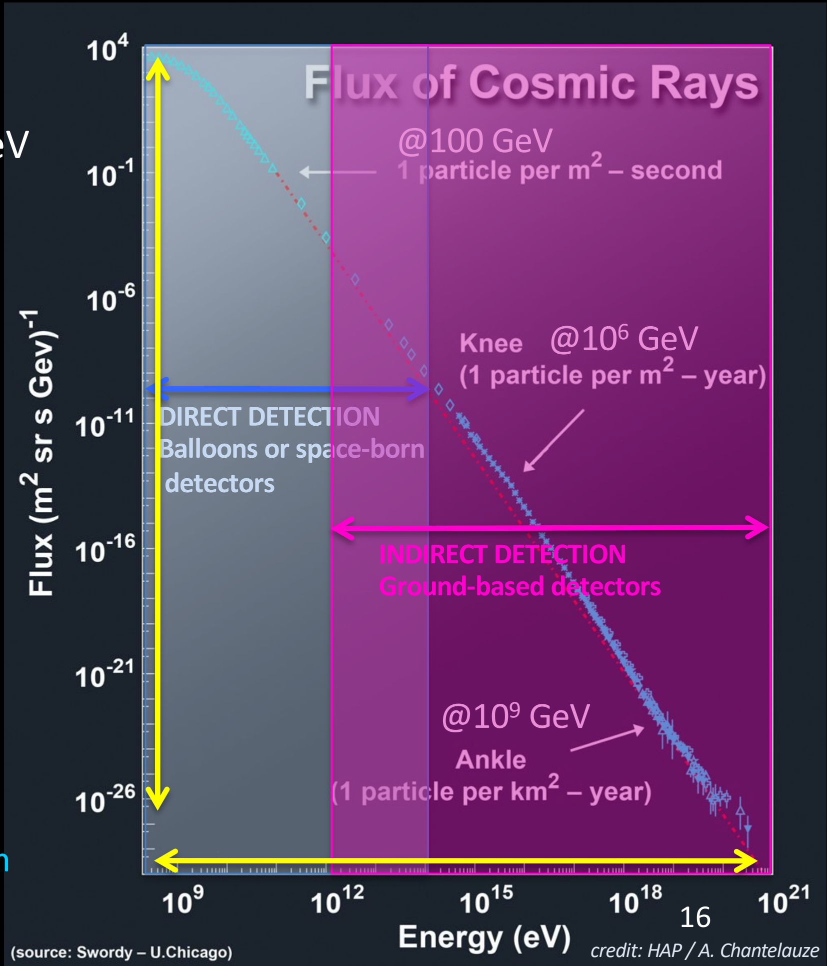


Ground-based detectors



DIRECT DETECTION
Balloons or space-born detectors

To measure their charge (including sign) and momentum requires a magnetic spectrometer in space

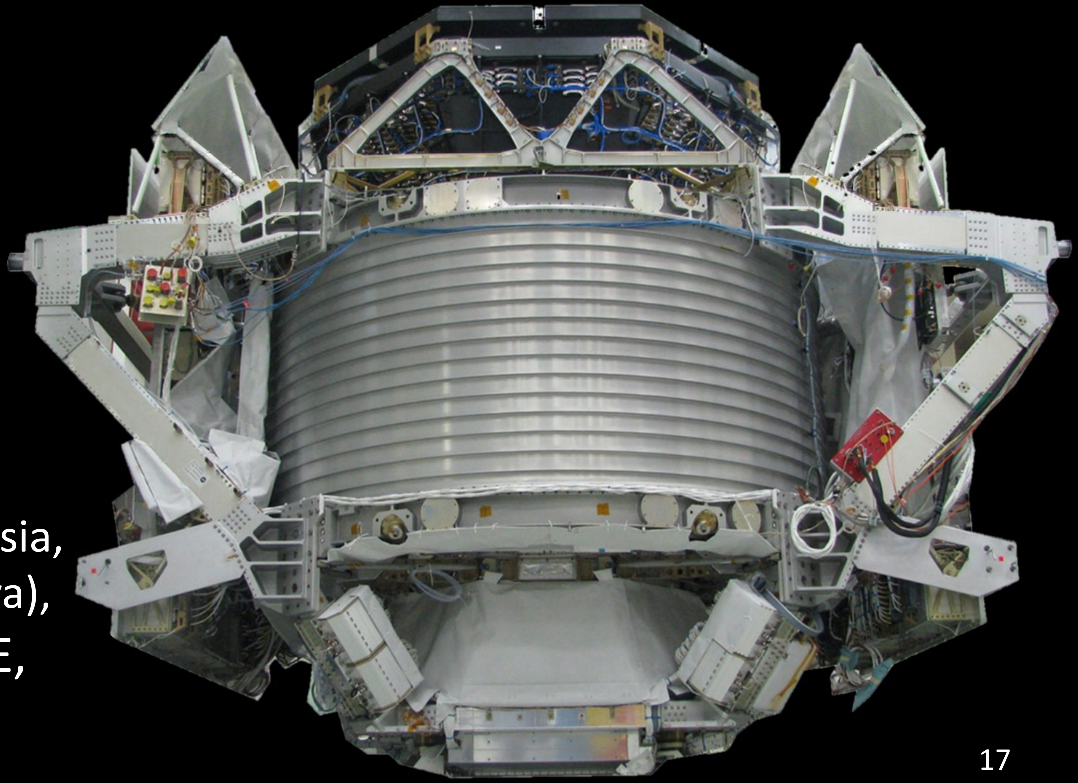


The AMS-02 detector

https://ams02.space/

AMS is a space version of a precision detector used at accelerators designed to meassure spectra of chaged cosmic-ray particles, antiparticles, and nuclei

AMS factsheet:
300,000 electronic channels
650 processors
power consumption: 2.4 kW
dimensions: 5m x 4m x 3m
weight: 7.5 tons

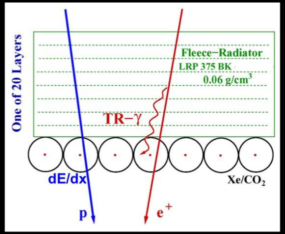


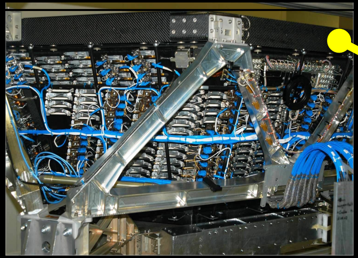
AMS was constructed in Europe and Asia, assembled and tested at CERN (Geneva), with strong support from MIT, DOE, and NASA.

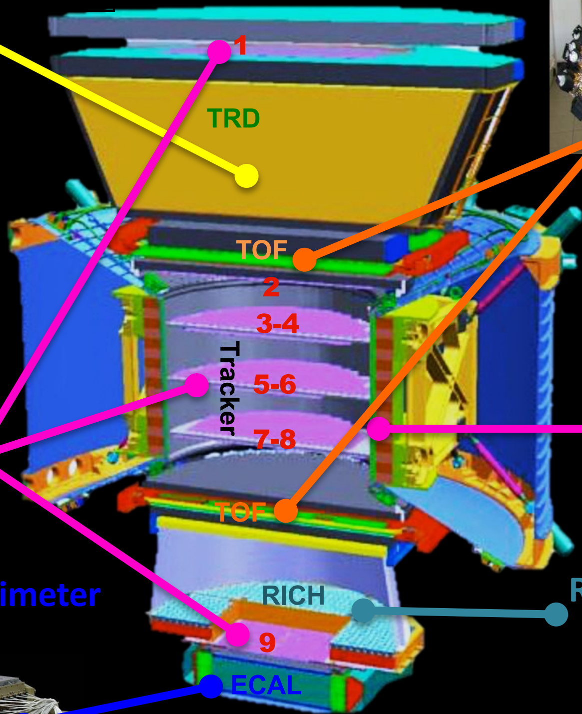
AMS-02: A TeV precision magnetic spectrometer

Transition Radiation Detector

Identifies e^+, e^-

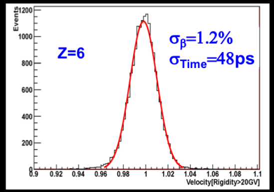






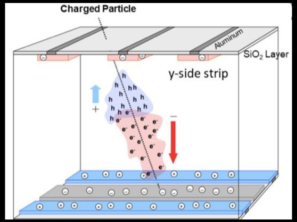
Time Of Flight

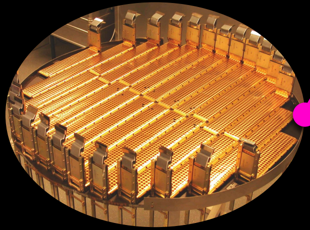
Z, β



Silicon Tracker

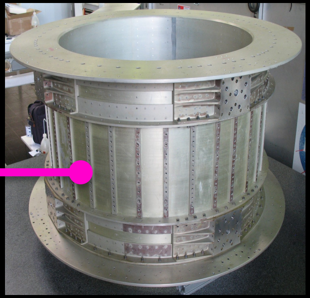
Z, Rigidity=p/Ze

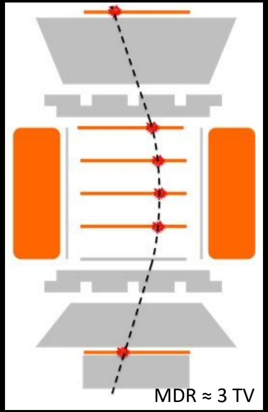




Magnet

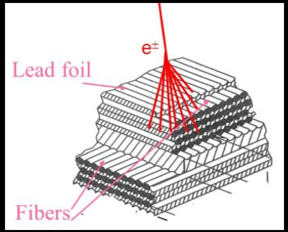
±Z





Electromagnetic Calorimeter

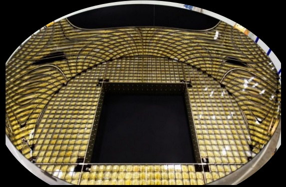
Energy of e^+, e^-

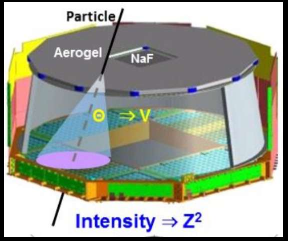


Ring Imaging Cherenkov

Z, β

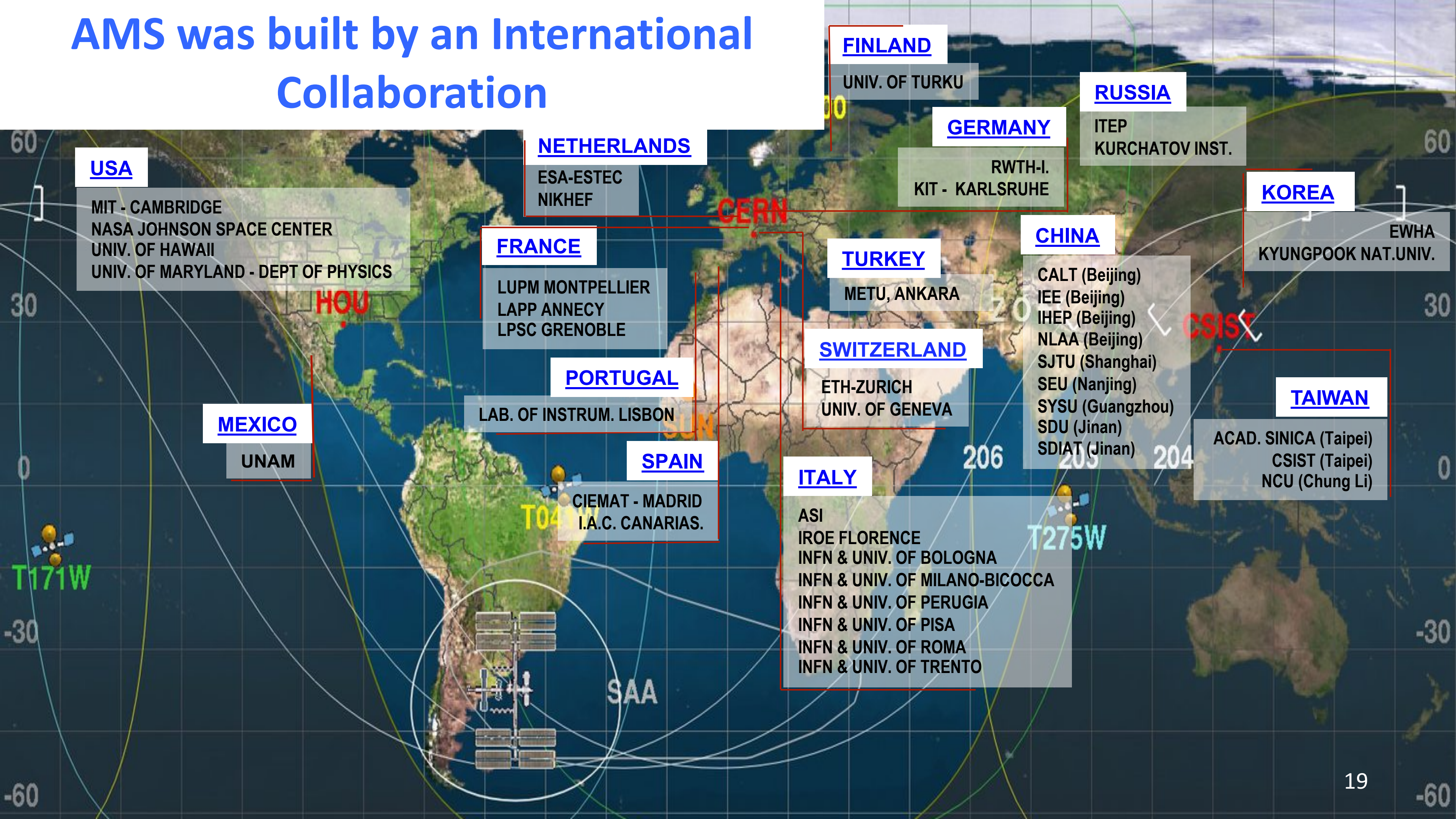
Isotopic composition





Charge Z and Energy are measured independently in several subdetectors

AMS was built by an International Collaboration



AMS Launch May 2011
Space Shuttle Endeavour
Mission STS-134

AMS installed on the ISS

Near Earth Orbit:

altitude 400 Km

inclination 52°

period 92 min

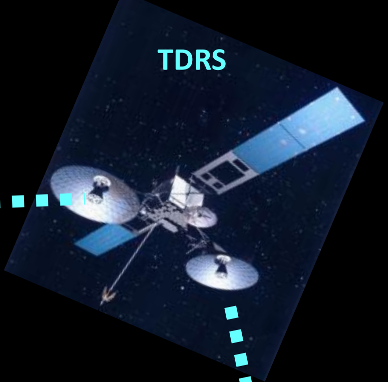
AMS mission duration: entire ISS lifetime~2030

AMS-02 webpage: https://ams02.space

AMS Operations

Flight

International Space Station



Ground


AMS
Payload Operations & Control Center
at CERN, Geneva


White Sands Ground Terminal,
New Mexico

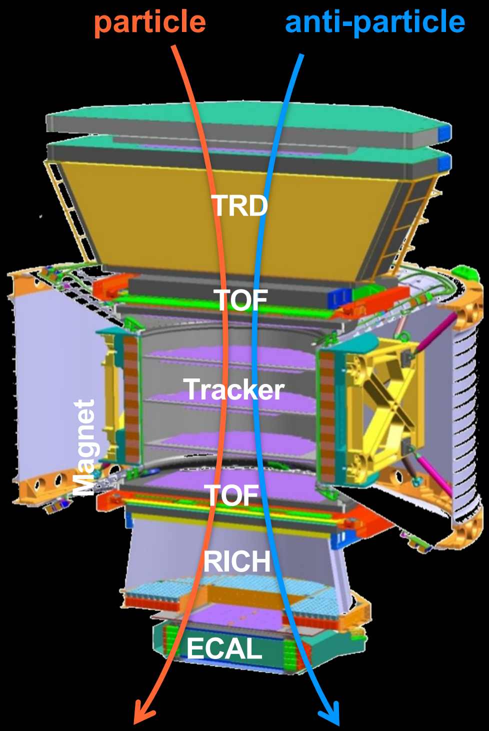
In 15 years of operation AMS collected ~270 billion cosmic-ray events

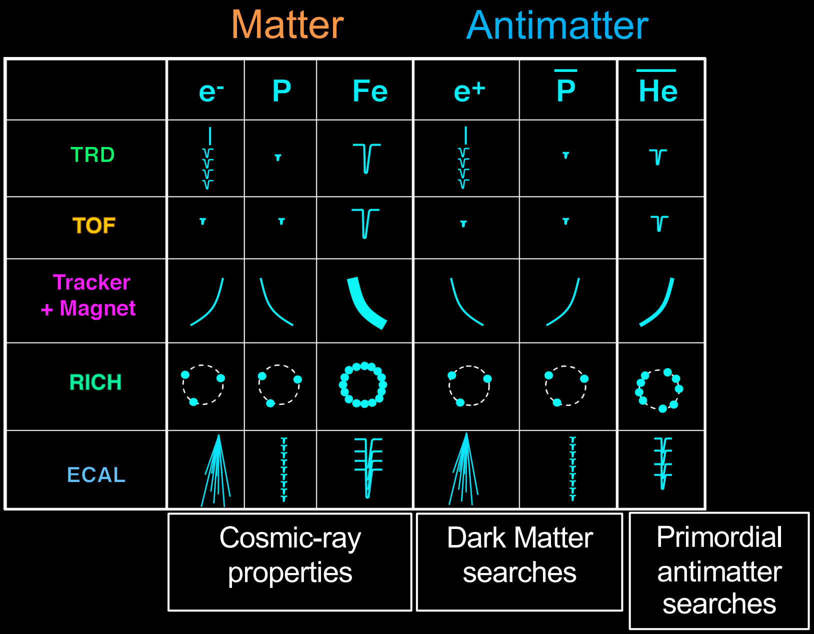
AMS provides precision, long-duration measurements of charged cosmic rays

With high accuracy, AMS measures:

- Charge (Z) and charge sign
- Rigidity (R=P/Z, GV)
- Velocity (β=v/c)
- Energy (E, GeV)
- Mass $M = \frac{R \cdot Z}{\beta\gamma}$
- Flux (Nevents/(s sr m^2 GeV))

for all the charged cosmic rays, e+, e−, p, and $\bar{p}$, and nuclei up to at least Nickel

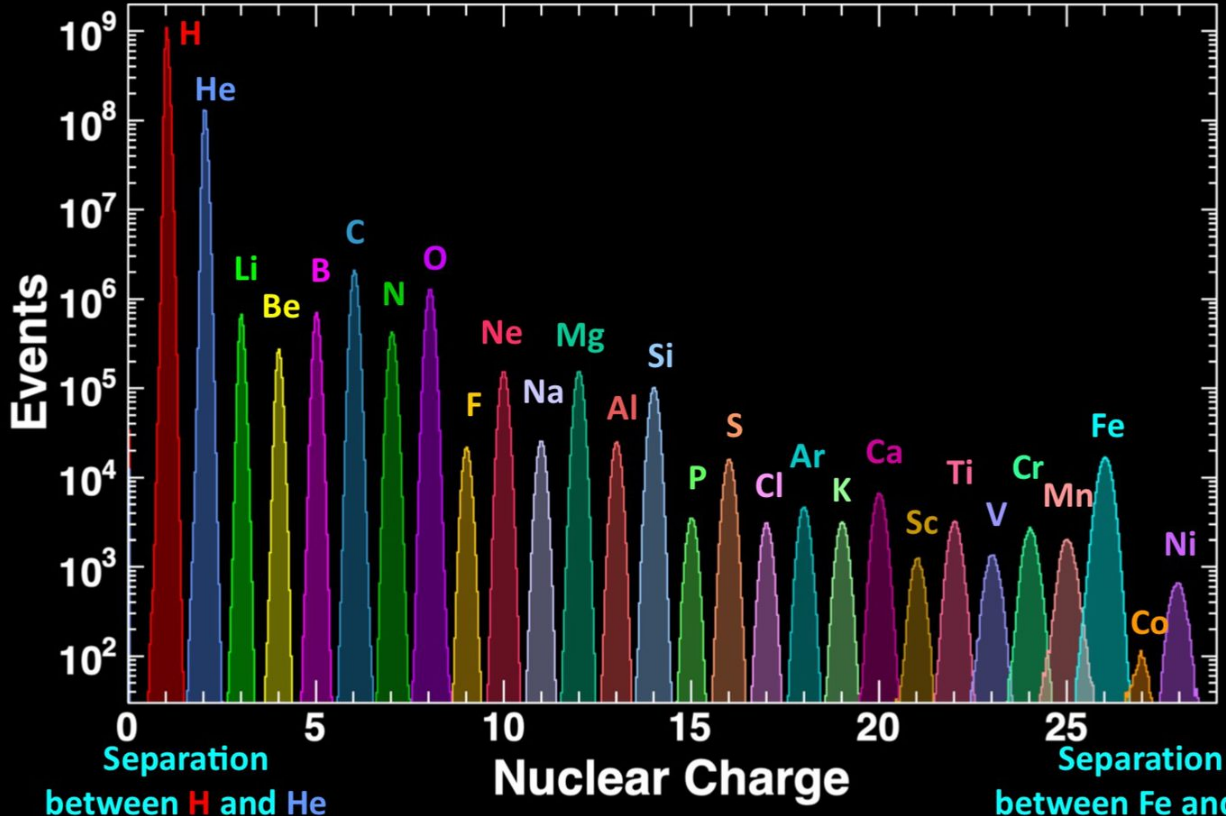




Thanks to its large acceptance and long-duration mission, AMS is also studying time evolution of cosmic-ray fluxes for e+, e−, p, and $\bar{p}$, and nuclei.

In this talk I will focus on nuclei and isotope flux measurements with AMS

Cosmic Nuclei identification with AMS



Separation between H and He is better than 1 in 10^9

Separation between Fe and Co is better than 1 in 10^2

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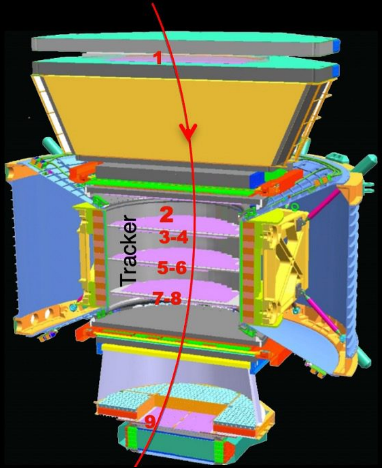
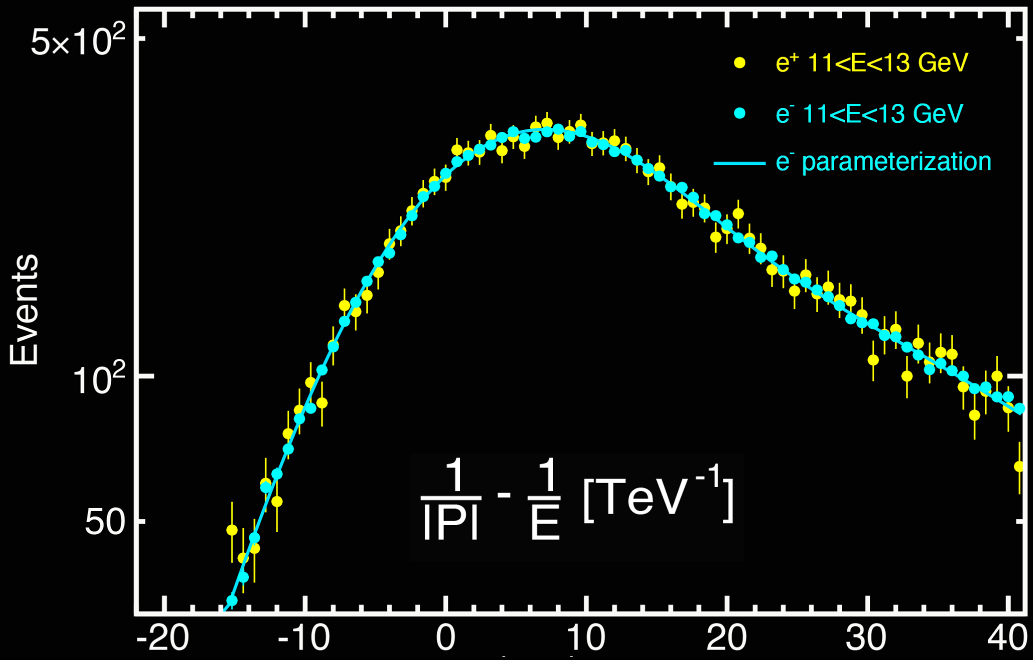
In-flight determination of the absolute Rigidity scale

Crucial for the accuracy of flux measurements at the highest energies

Nucl. Instrum. Methods Phys. Res., Sect. A 869, 10 (2017)

Rigidity scale shift and its uncertainty are evaluated from 4 independent measurements **Pe^+, Ee^+, Pe^-, Ee^-** in 72 energy bins from 2 to 300 GeV.





A shift in the central tracker planes of 0.5 microns is sufficient to create a momentum shift of 10% at 1 TV and bias flux measurements.

Rigidity scale is determined with an accuracy of 3% at 1 TV.

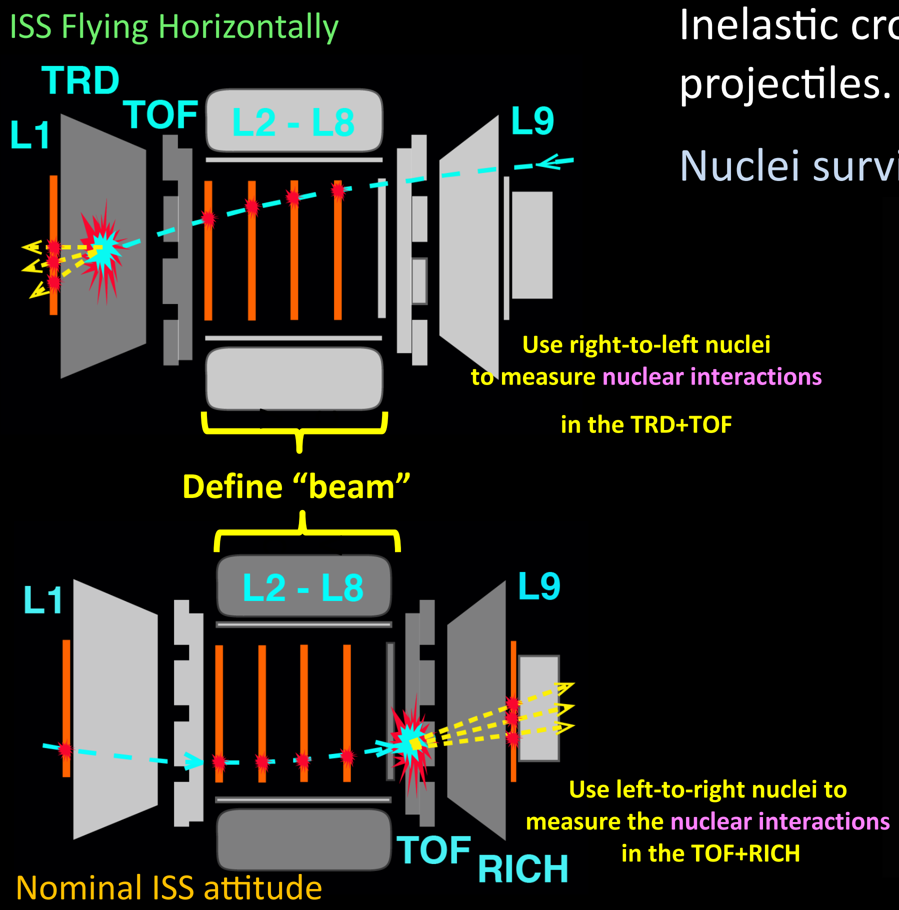
Nuclear cross-sections measurements with AMS-02

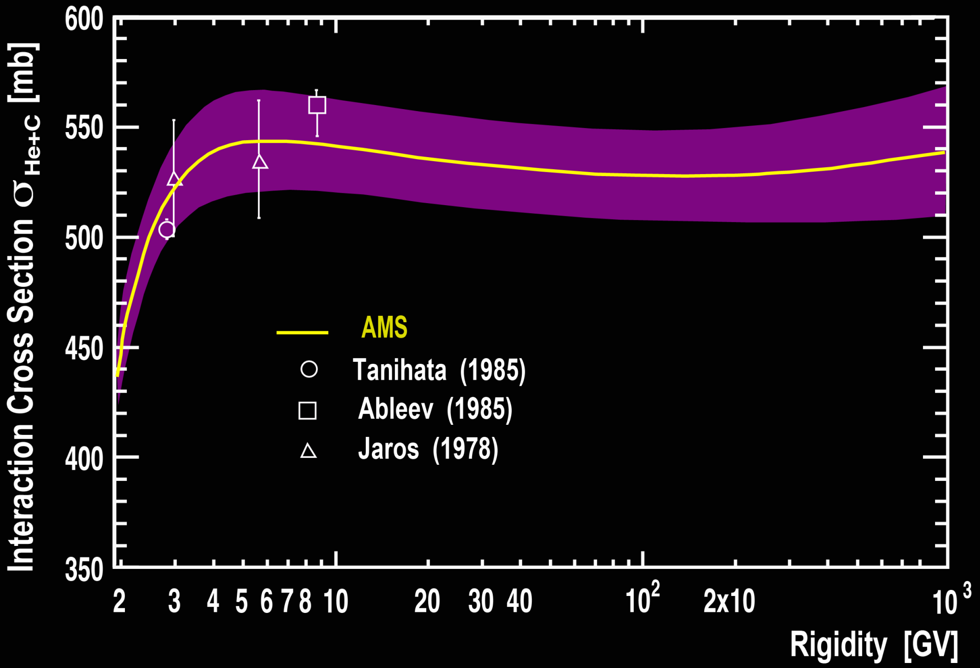
Crucial to accurately measure nuclei fluxes.

Nucl. Phys. A 996 121712 (2020)

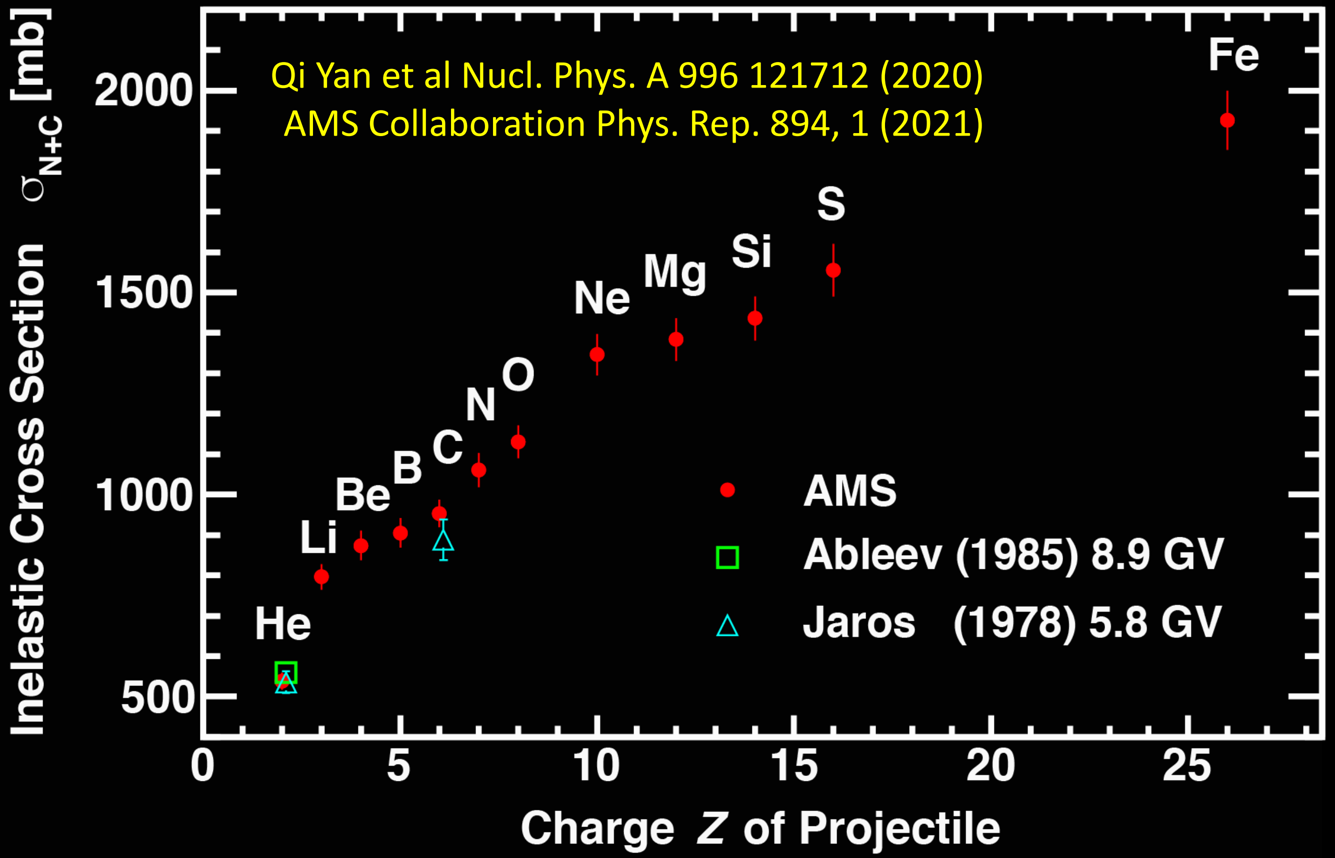
Inelastic cross sections data available only for few target and projectiles. No measurement available beyond 10 GV.

Nuclei survival probabilities measured with in-flight AMS data





AMS measured nuclear inelastic cross-sections which were not available from accelerator experiments



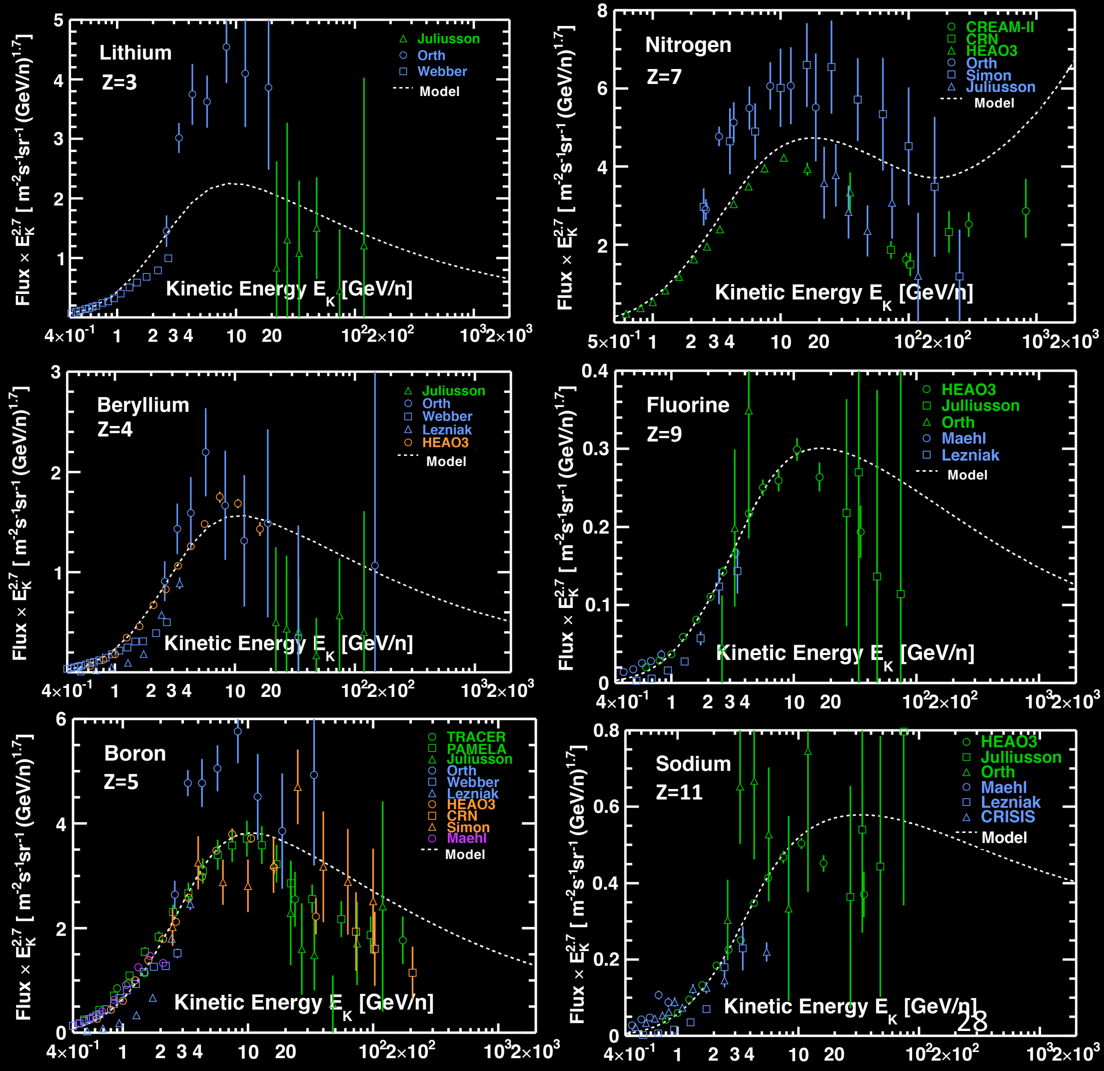
Cosmic Ray nuclei spectra in the GeV-TeV range before AMS

1912: Discovery of Cosmic Rays

In the past 100 years, measurements of charged cosmic rays by balloons and satellites have typically had 30% to 50% accuracy.

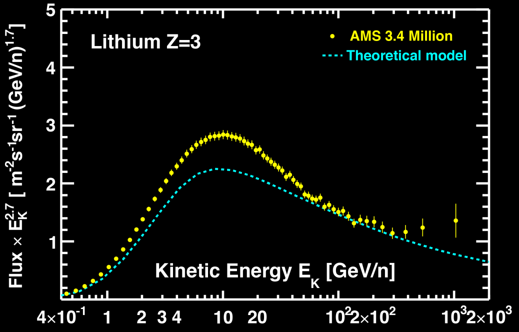
Theoretical models assumed universal energy spectrum $E^{-2.7}$ up to the PeV as for the all-particle spectrum.

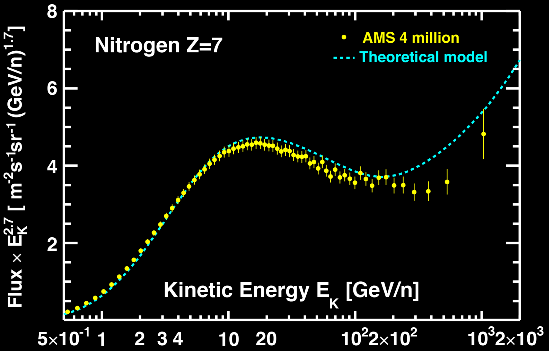
Cosmic-ray spectra are displayed multiplied by $E^{2.7}$.

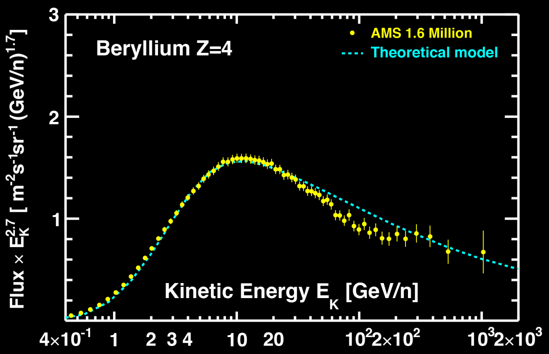


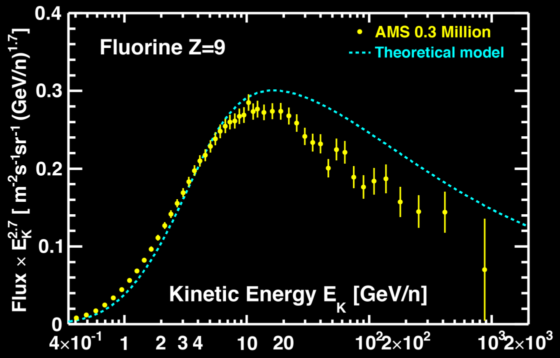
AMS is providing measurements of cosmic ray spectra with ~1% accuracy

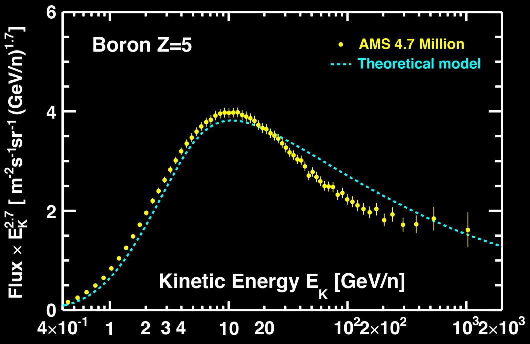
The improvement in accuracy is providing new insights about the cosmos.

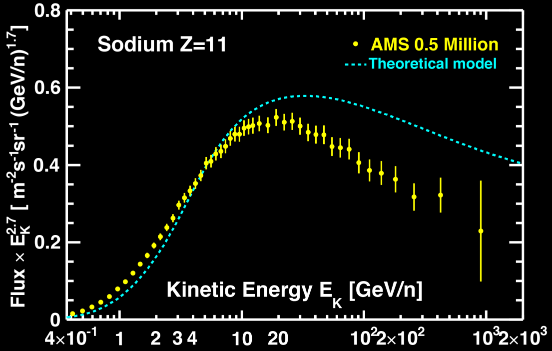




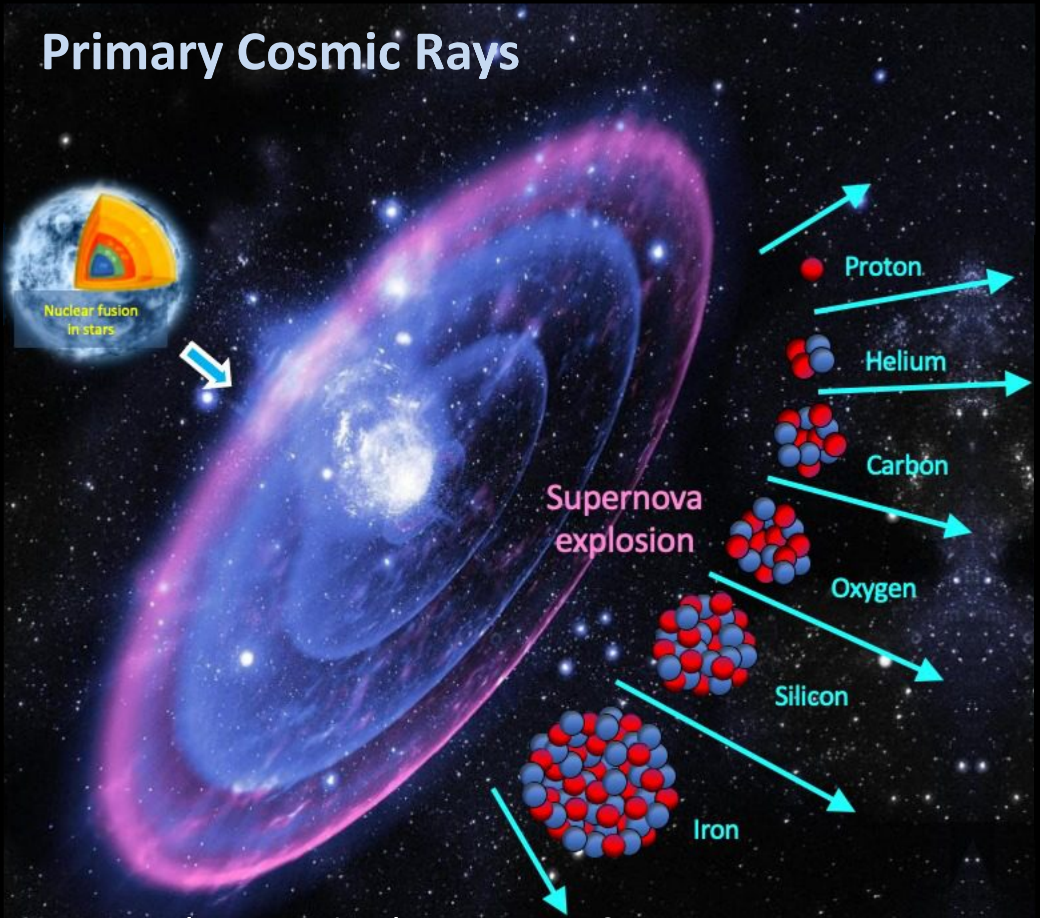




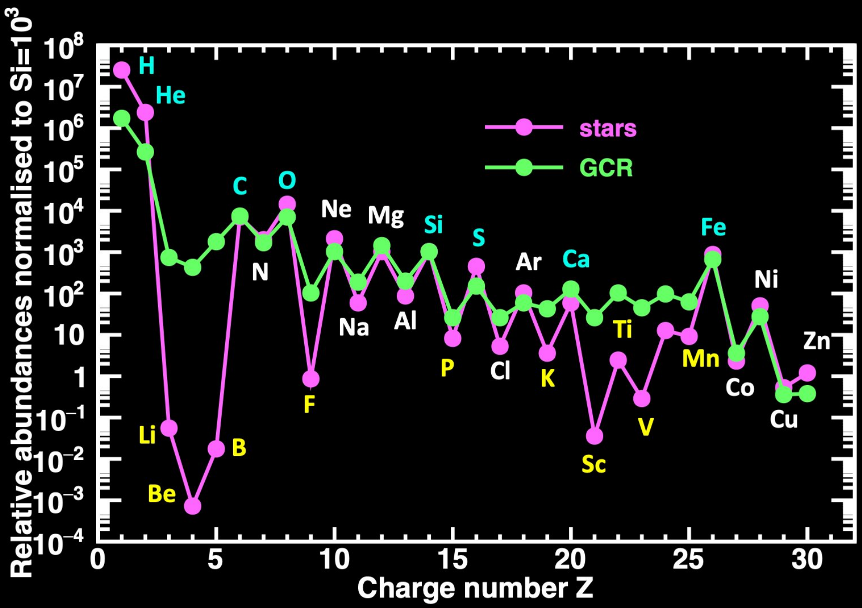




Primary Cosmic Rays



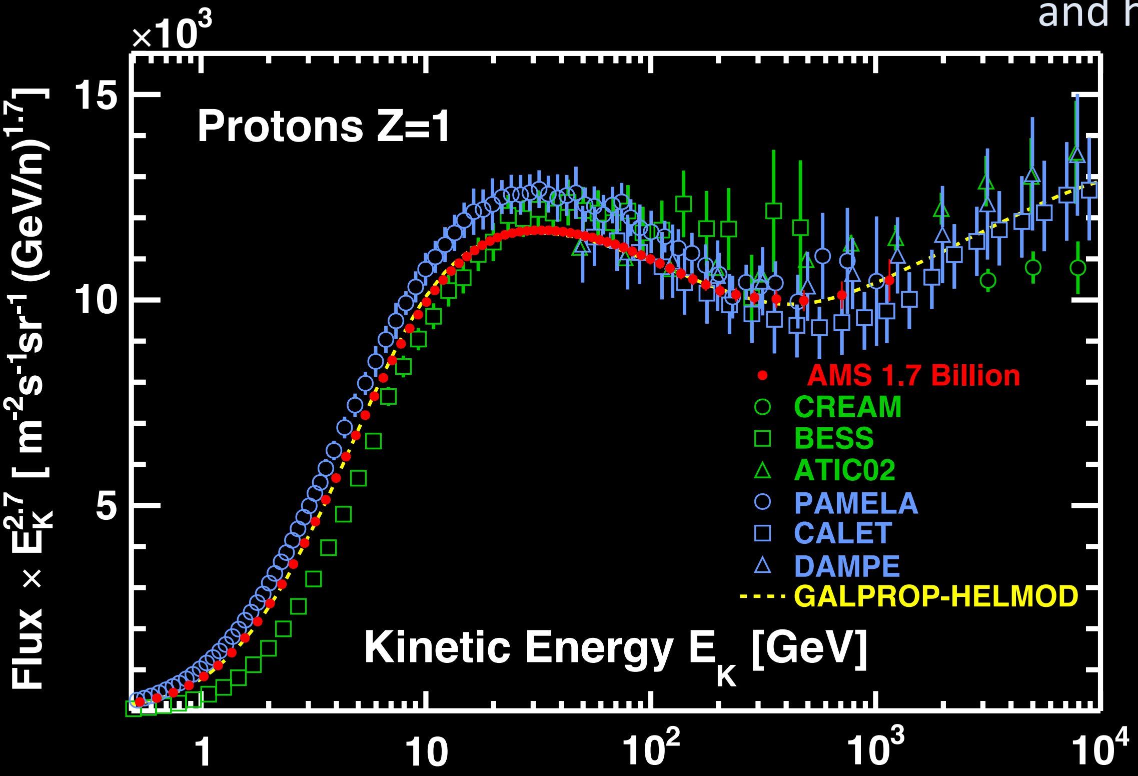
Primary elements,
protons, He, C, O, Si, S, Ca,..., Fe nuclei



Energy (or Rigidity) spectra of primary cosmic rays give information on their sources and acceleration mechanism.

Light primary cosmic-ray nuclei : H (protons)

The proton spectrum deviates from a simple power law and hardens above 200 GV



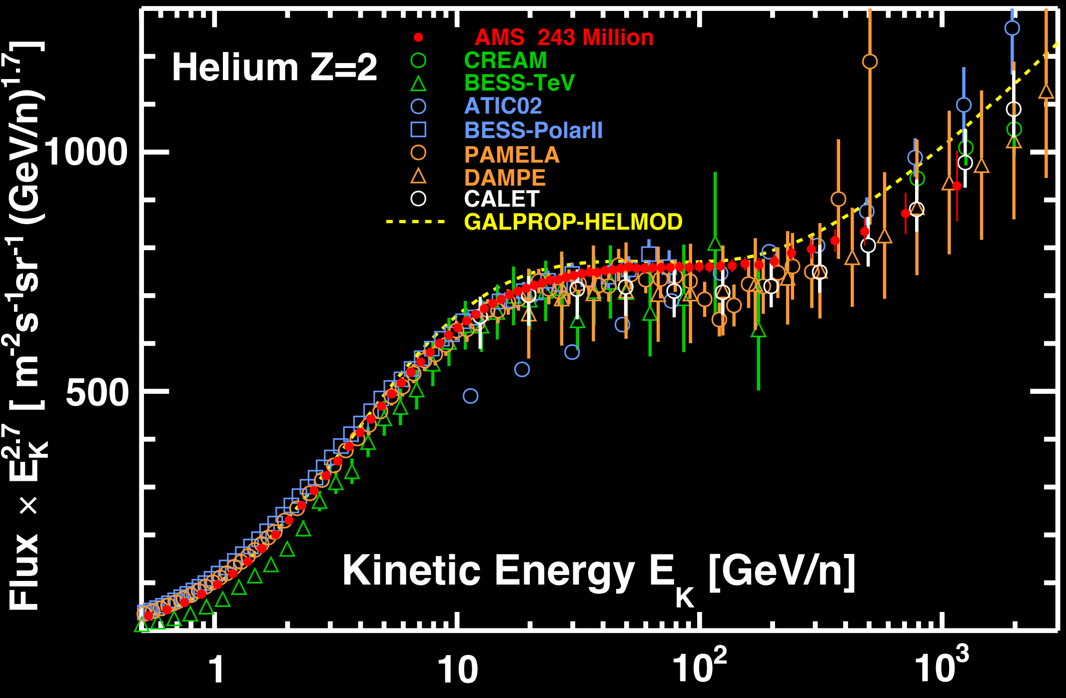
AMS confirmed early observations from CREAM and PAMELA.

The high precision of the AMS measurement allows accurate studies of the shape of the proton spectrum.

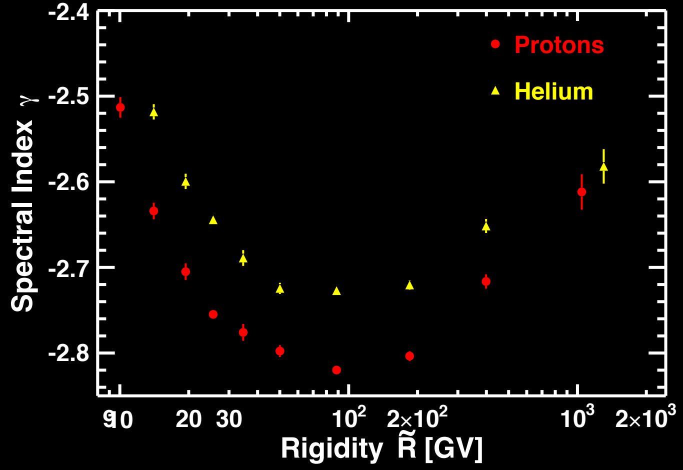
AMS provides the most accurate p measurement in the energy range 1 GeV to 1.8 TeV

Light primary cosmic-ray nuclei : Helium

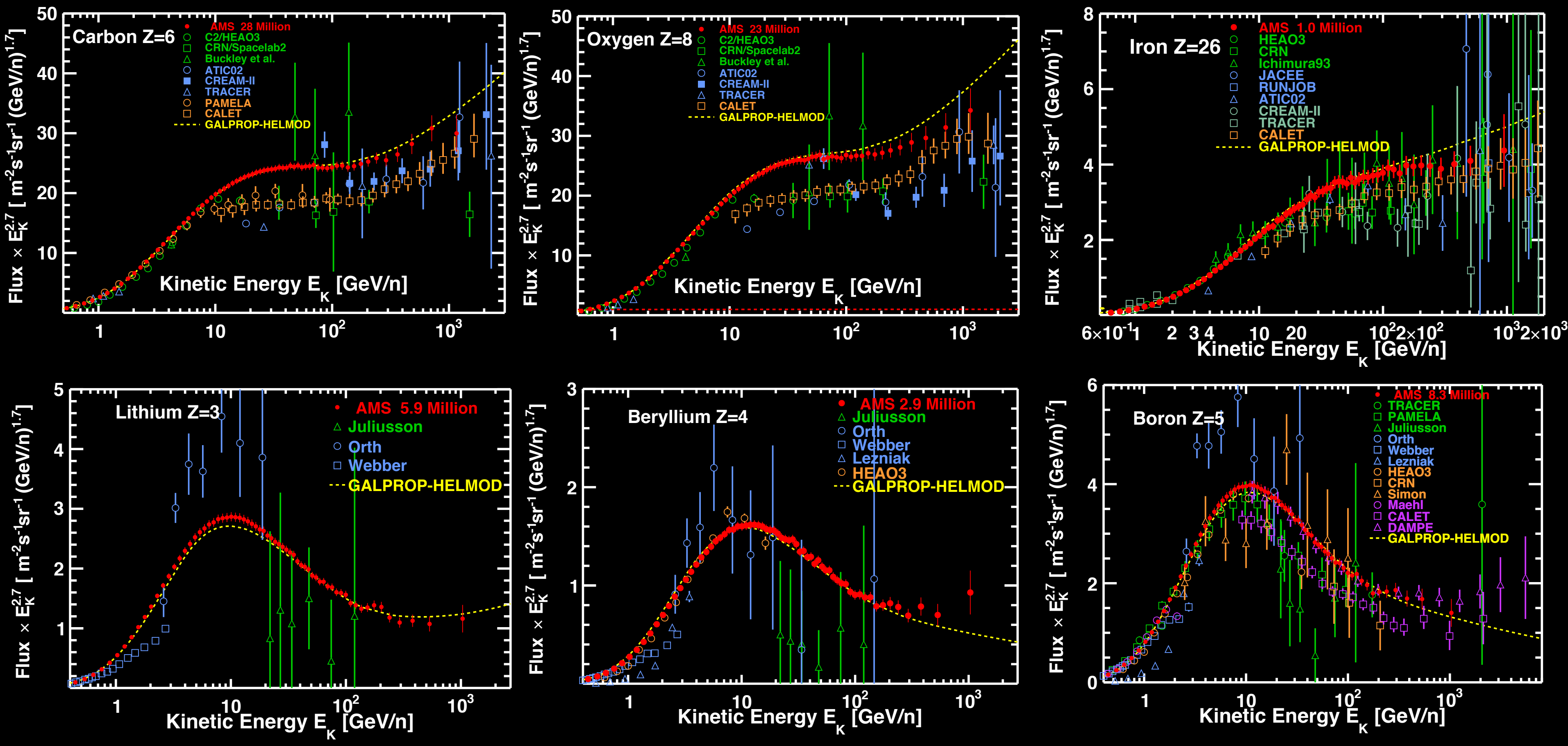
AMS confirms with high accuracy earlier observations from CREAM and PAMELA:
the helium nuclei spectrum deviates from a simple power law and hardens above 200 GV



Precise characterization of the spectral shape:

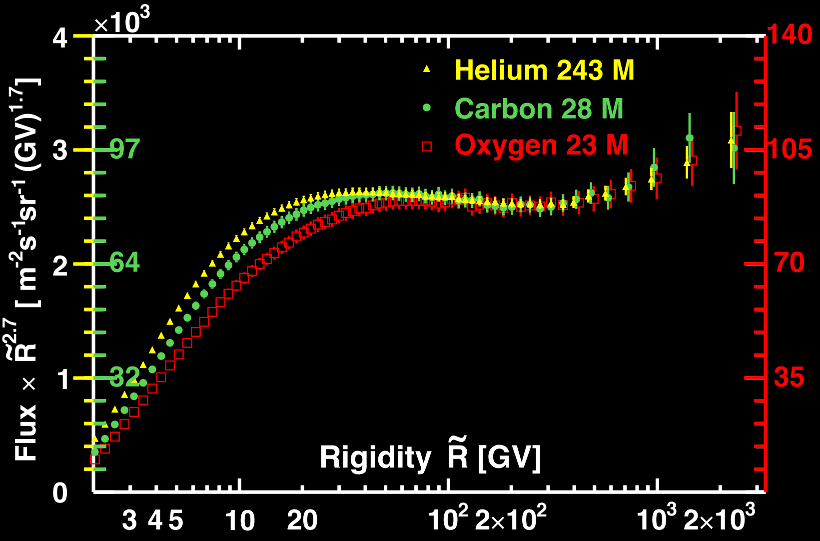


Latest AMS CR nuclei measurements

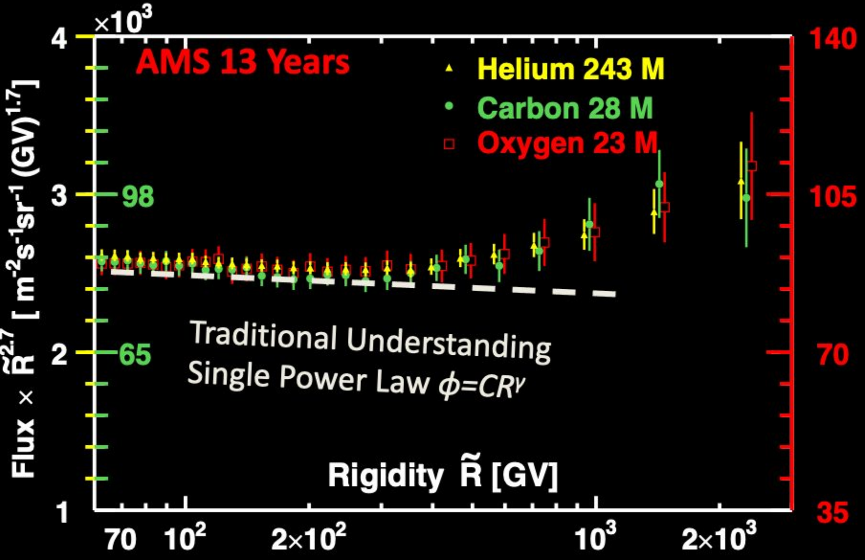


Light primary cosmic-ray nuclei: Helium, Carbon and Oxygen

AMS observed for the first time that above 60 GV He ,C and O have identical rigidity dependence



Above 200 GV He, C, and O spectra all deviate from a single power law in. an identical way

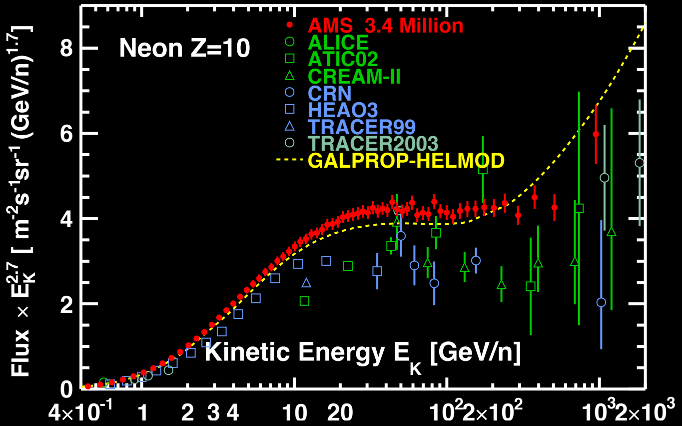


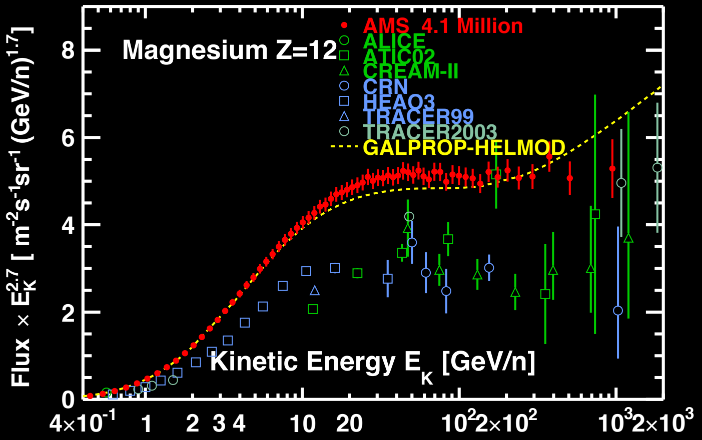
Which is the origin of the spectral hardening above 200 GV?

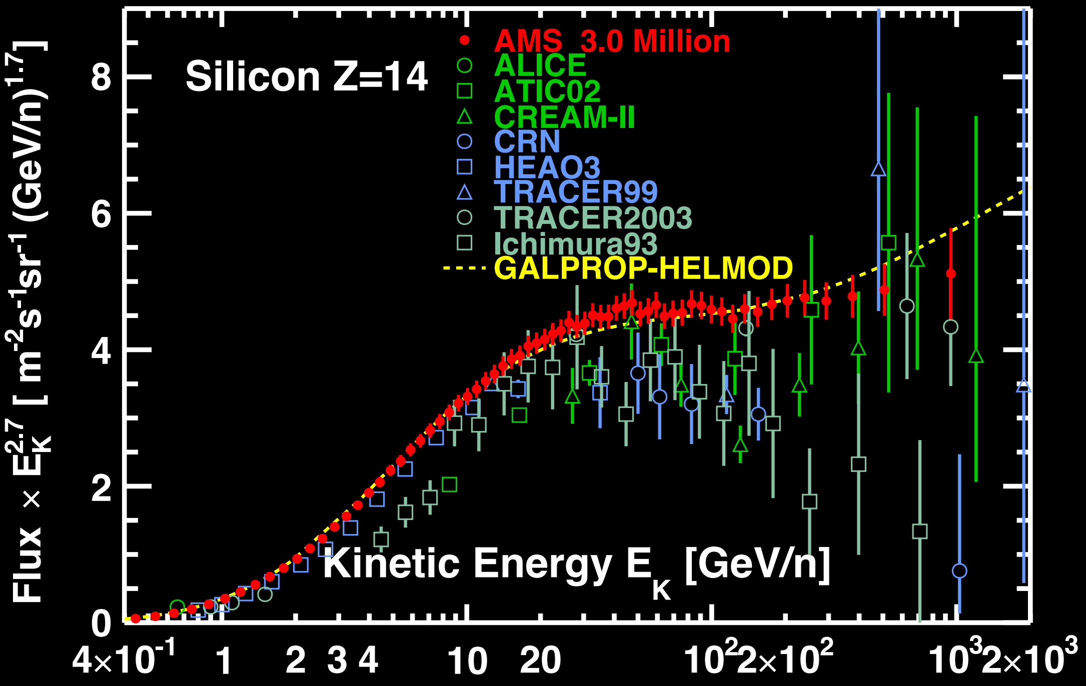
Is the spectral hardening universal ?

AMS Ne, Mg, and Si Nuclei Flux Measurements:

AMS results are different from previous measurement both in magnitude and the energy dependence. They are also different from the Cosmic Ray Theory predictions.

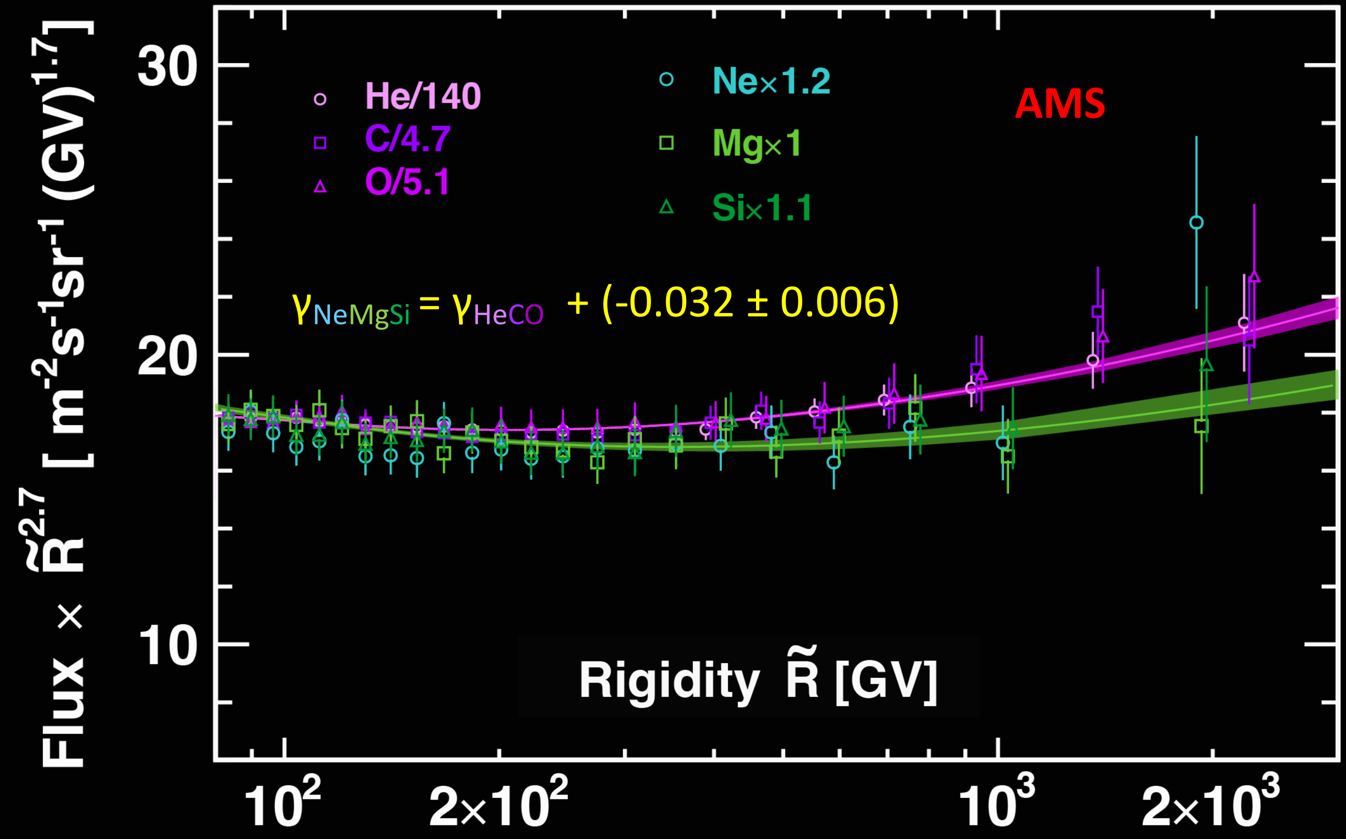






Heavy vs Light Primary Cosmic Rays: Ne-Mg-Si-S vs He- C-O

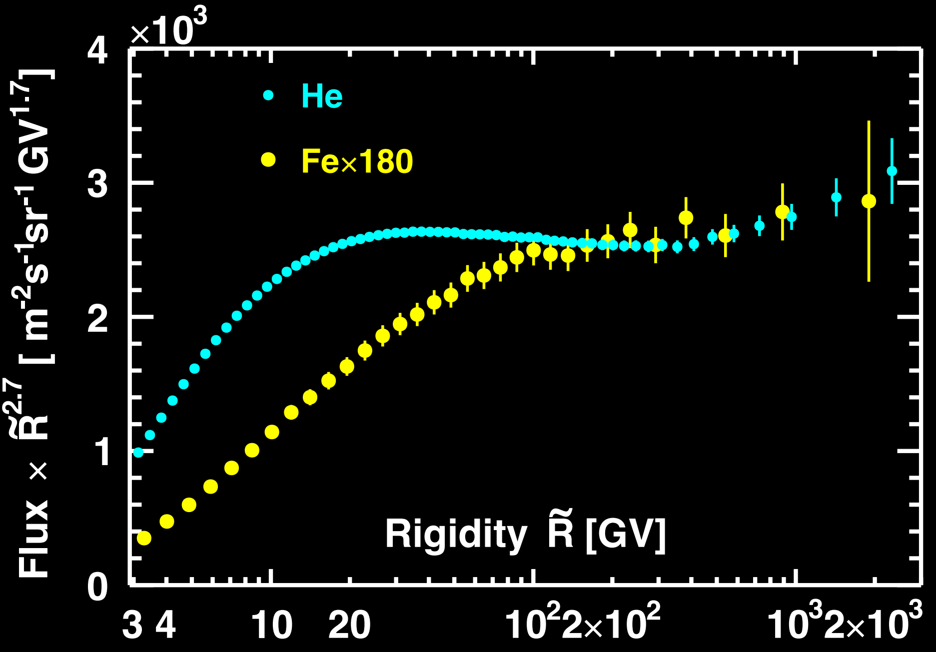
Ne, Mg, Si have distinctly (significance exceeds **5σ**) different rigidity behavior from He, C, O.

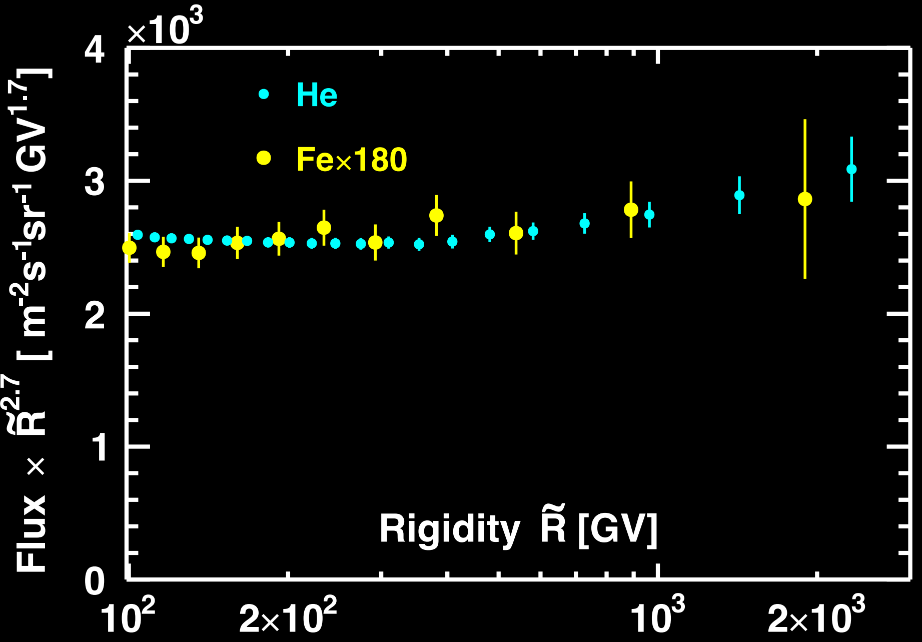


Unexpected result:
primary cosmic rays have at least two classes of rigidity dependence

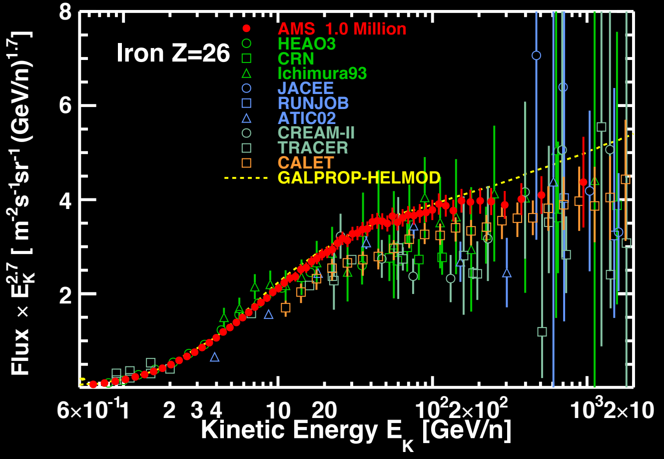
Very Heavy Primary cosmic rays: Iron nuclei flux

Iron belongs to the class of light primary cosmic rays He-C-O

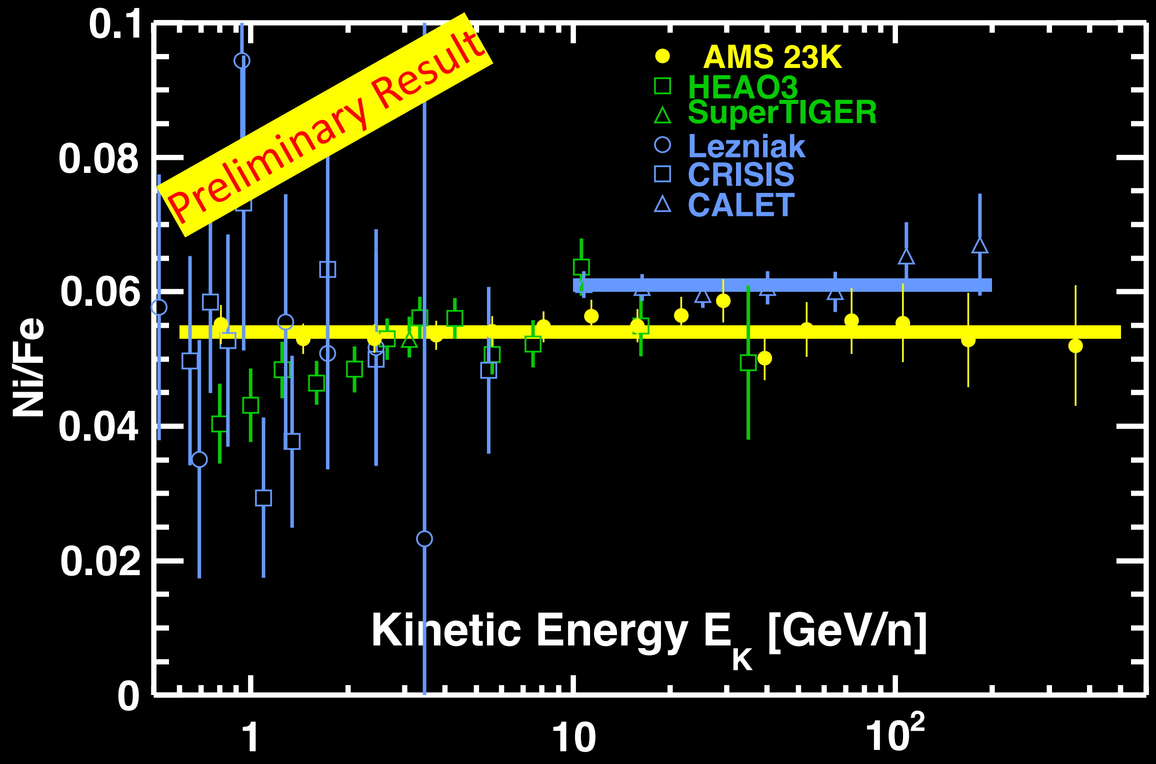


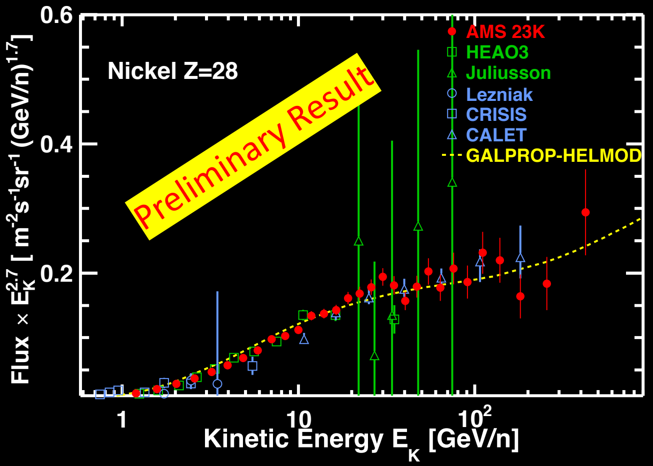


Very Heavy Primary cosmic rays: Iron and Nickel nuclei flux



Nickel and Iron belongs to the class of light primary cosmic rays He-C-O

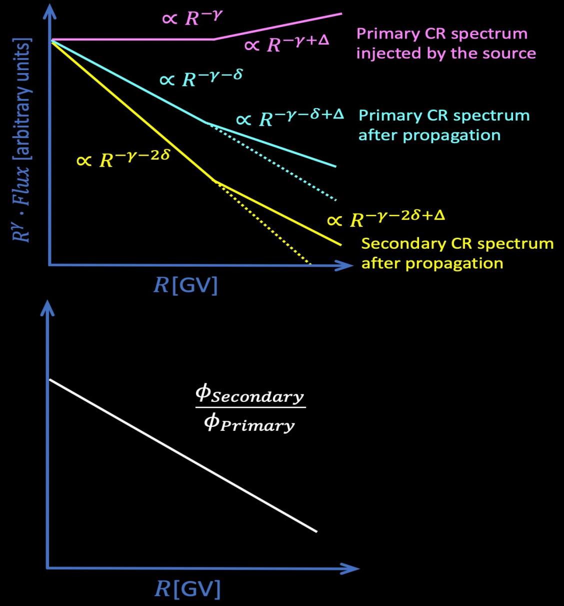




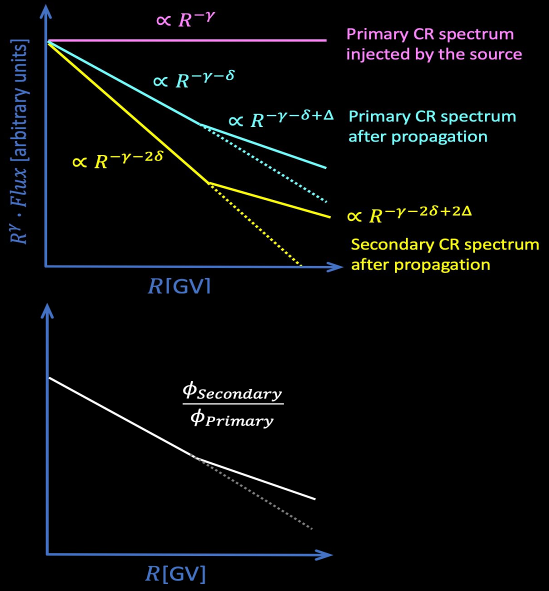
Secondary Cosmic Rays and origin of primary CR spectral hardening

Interpretations of the spectral hardening fall in three categories:

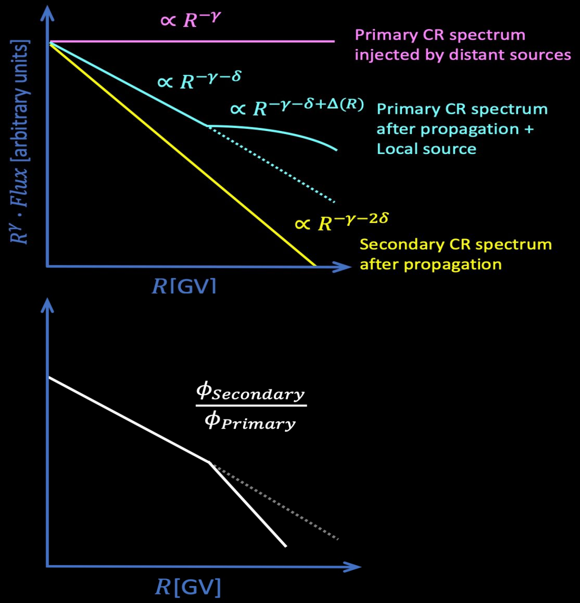
Spectral break at injection



Propagation effect



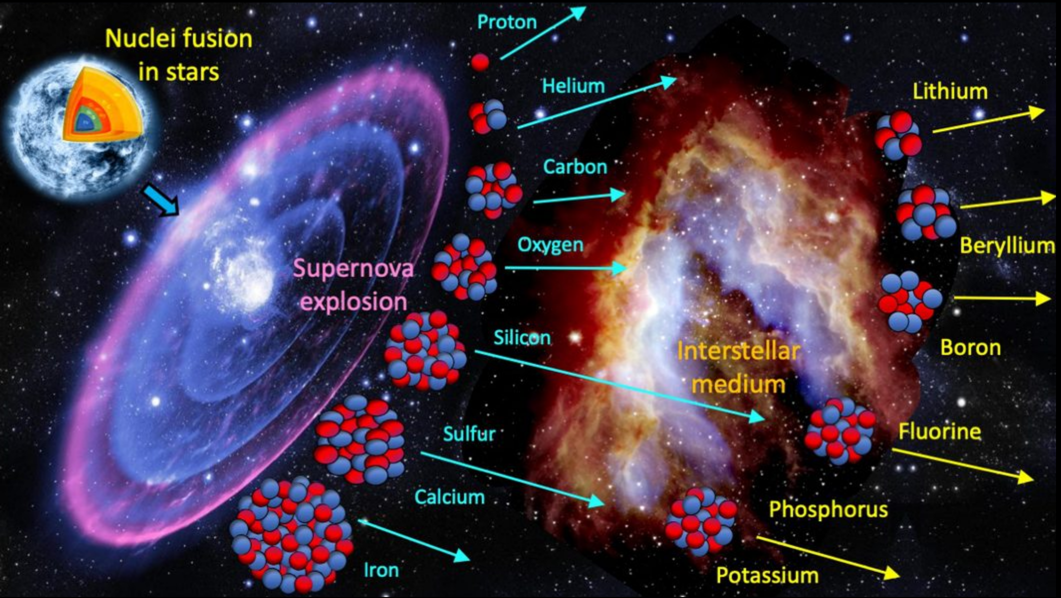
Local source

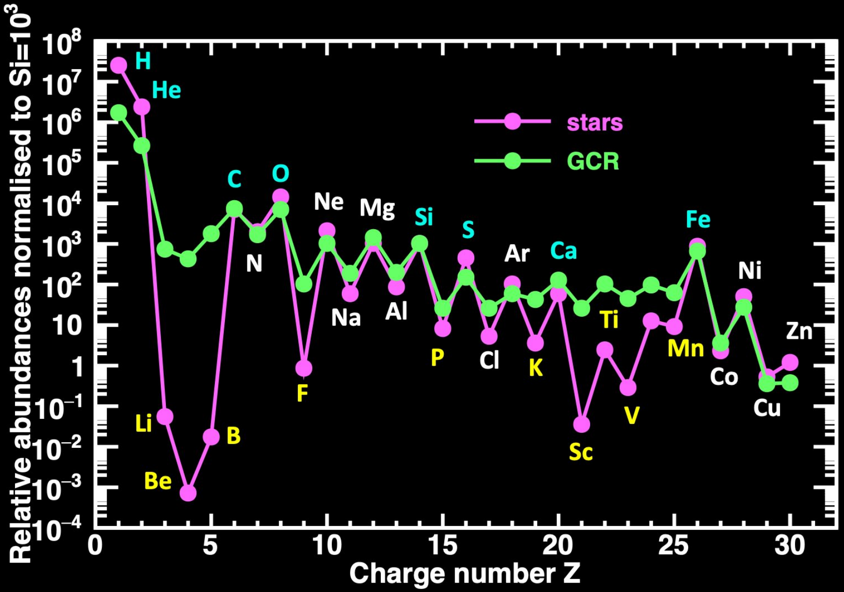


Precision measurements of the individual spectra of primary and secondary CR and their ratios can ascertain the origin of the spectral hardening.

Secondary Cosmic Rays

Secondary cosmic rays Li, Be, B, F, sub-Fe nuclei are produced by collisions of primary cosmic rays, C, O, Ne, Mg, Si, S, Ca, … , Fe, with the interstellar medium





C, O, … + ISM → Li + X
C, O, … + ISM → Be + X
C, O, … + ISM → B + X

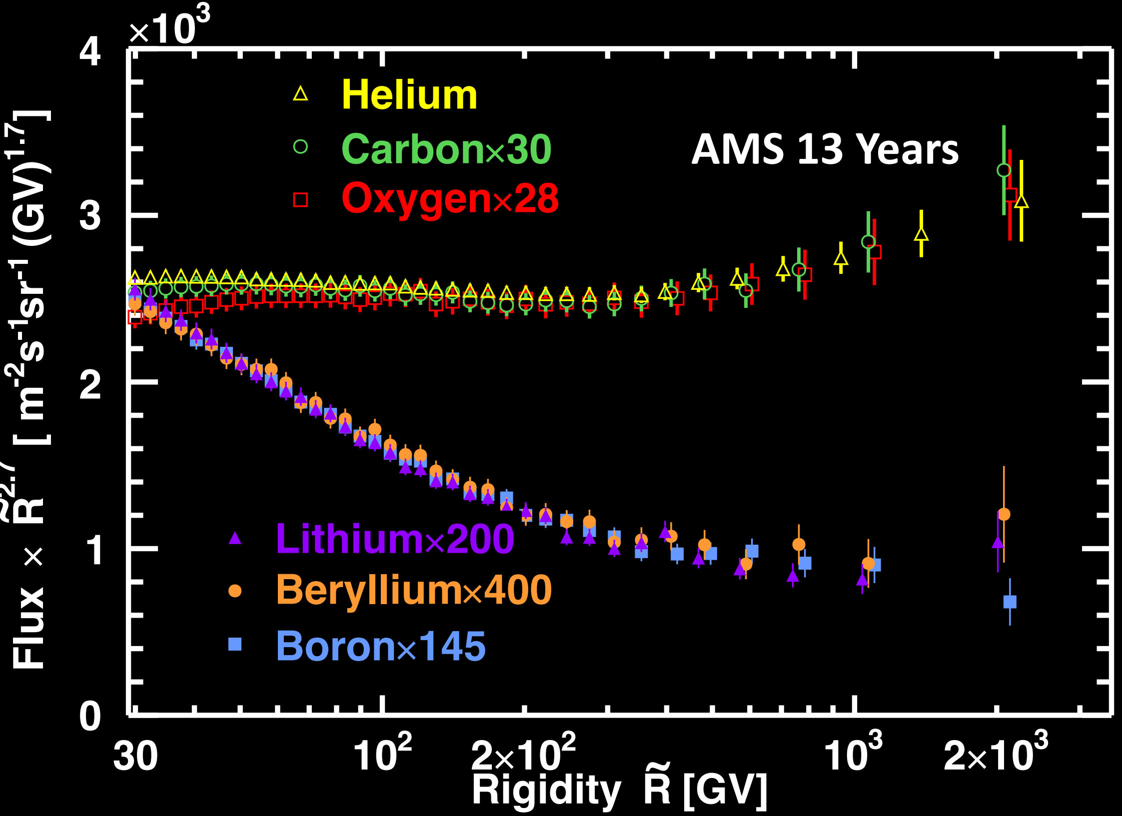
Ne, Mg, Si, … + ISM → F + X
S, Ca, … + ISM → P + X
Ca, … + ISM → K + X

Fe, … + ISM → Sc + X
Fe, … + ISM → V + X
Fe, … + ISM → Mn + X

Rigidity (or energy) spectra of secondary cosmic rays give information on cosmic-ray propagation

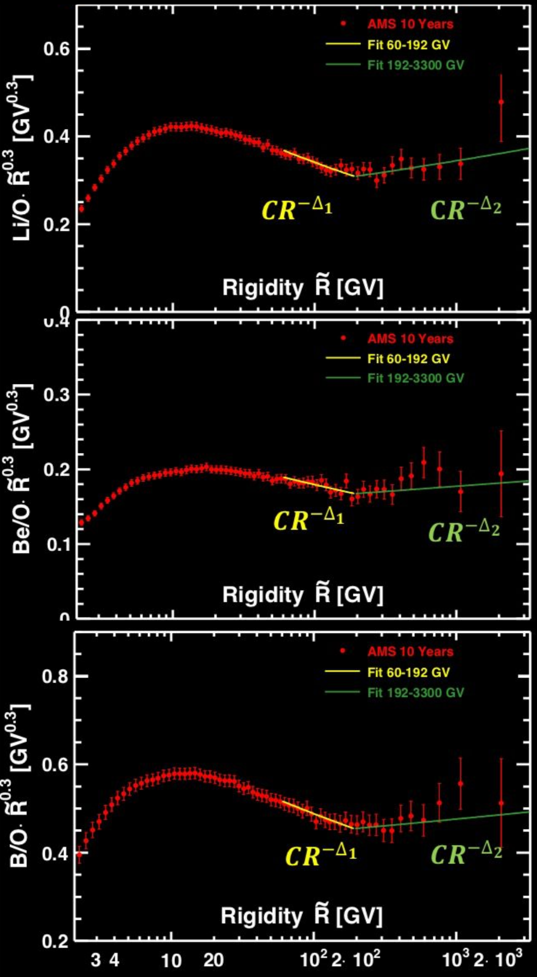
Light Secondary Cosmic Rays Li, Be and B fluxes

Above 30 GV, Li, Be and B have identical spectral shape



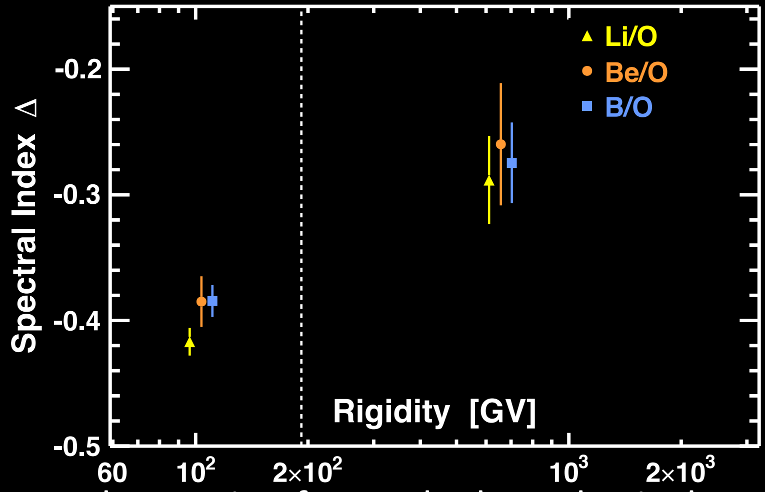
Secondaries and primaries have distinctly different spectral shapes

Light Secondary (Li, Be, B) to Primary (O) flux ratios



Above 192 GV all three secondary-to-primary flux ratios hardens

Average hardening $\Delta = \Delta_2 - \Delta_1 = 0.12 \pm 0.02$, significance: 6σ

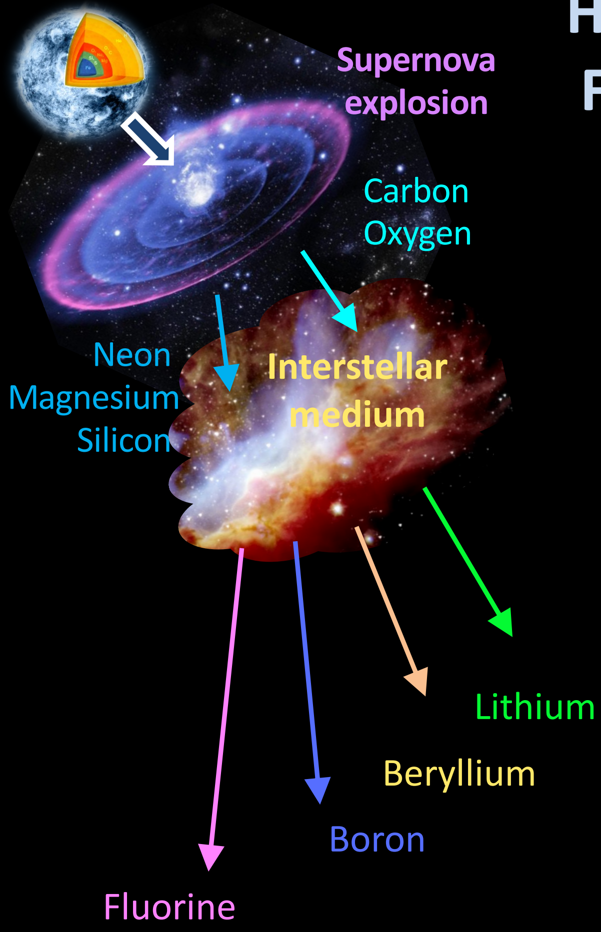


This new observation favors the hypothesis that **the observed spectral hardening** is due to a **propagation effect**.

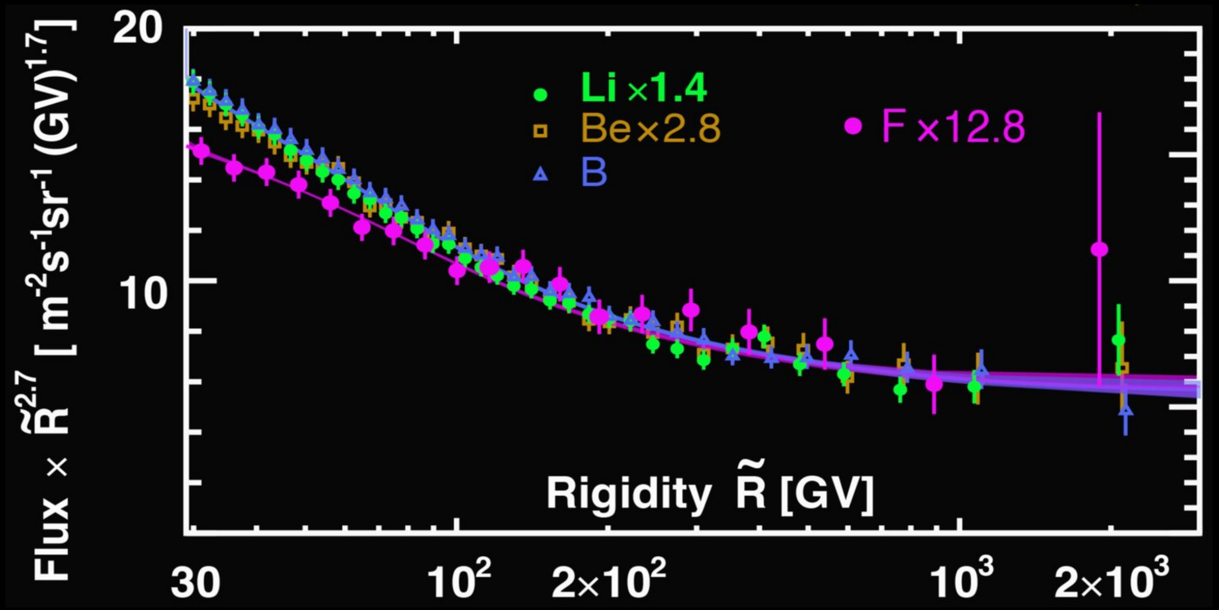
LATER Confirmed by DAMPE and CALET

What about heavier secondary-to-primary ratios?

Heavy vs Ligth Secondary cosmic rays: Fluorine vs Boron



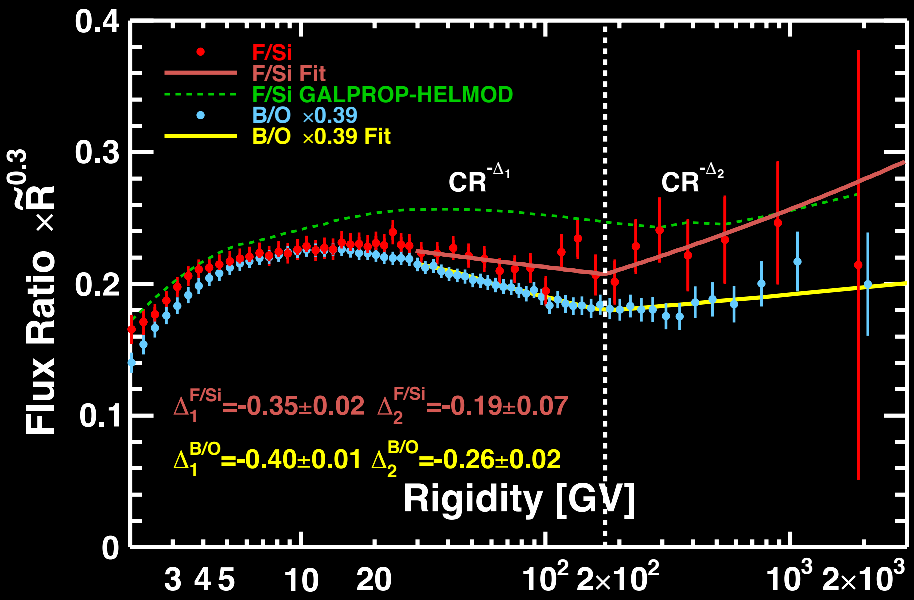
AMS found that secondary cosmic rays also have two classes of rigidity dependence

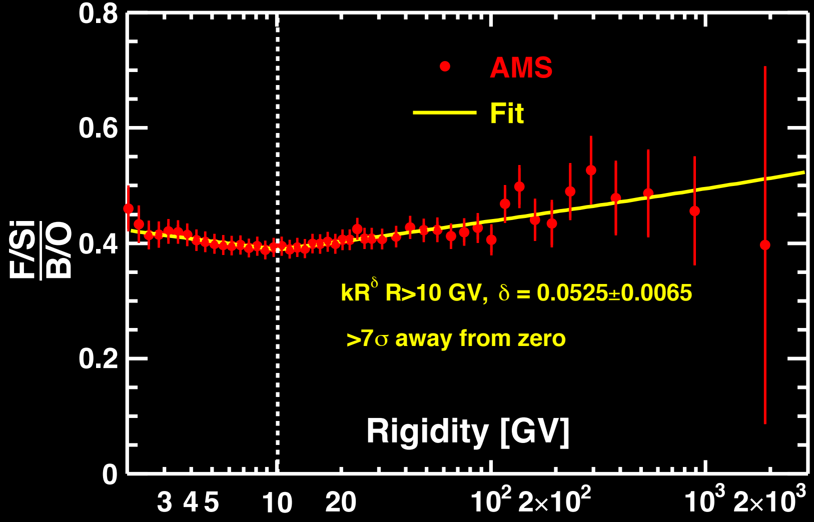


Propagation properties of heavy nuclei: light vs heavy secondary-to-primary

Traditionally the light secondary-to-primary ratio B/O (or B/C) is used to describe the propagation properties of all cosmic rays.

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



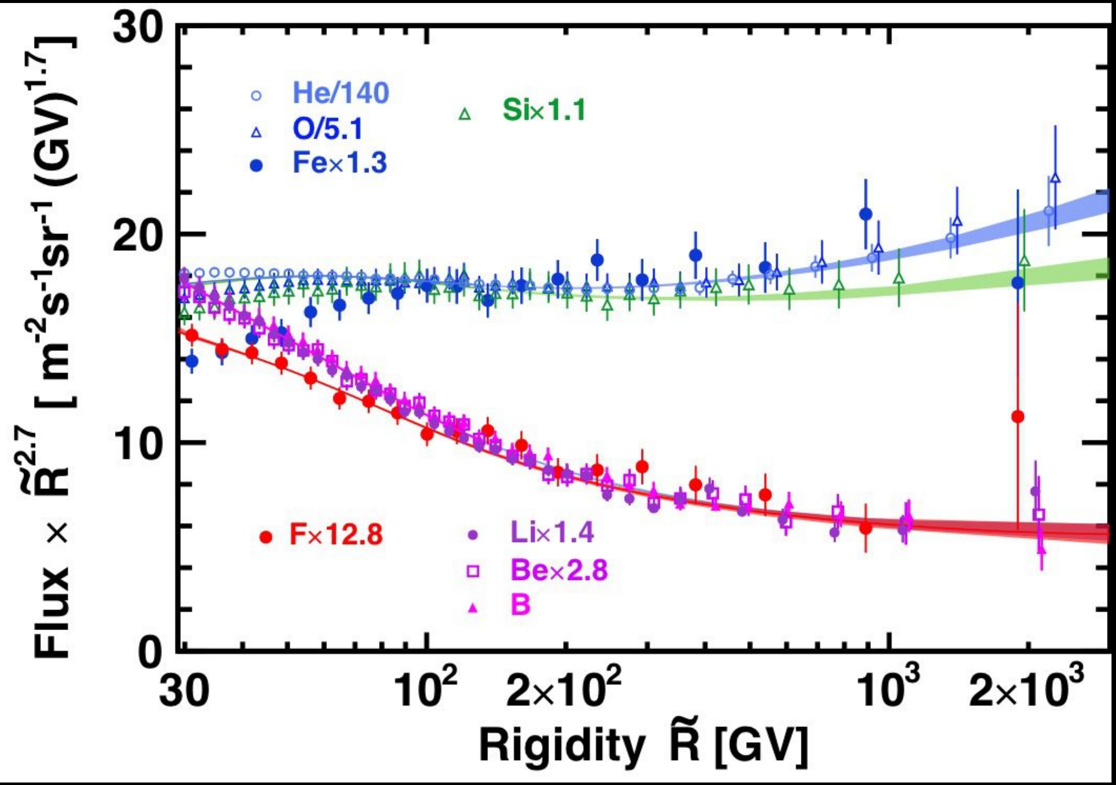


The propagation properties of heavy cosmic rays are different from those of light CRs.

Or Primary Fluorine component? Or different distribution of light and heavy CR sources?

Can be tested by future AMS measurements of heavier secondary-to-primary ratios as Sc/Fe and Vn/Fe .

Four classes of primary and secondary cosmic-ray nuclei



He, oxygen, silicon, and iron are pure primary produced in stars; they group in two classes of rigidity dependencies:

Primary I: He, O, Fe

and

Primary II: Si, Ne,Mg

Be, Li, B, and F are pure secondaries produced by collisions of heavier cosmic-ray nuclei with the interstellar medium; they group in other two distinct classes of rigidity dependence:

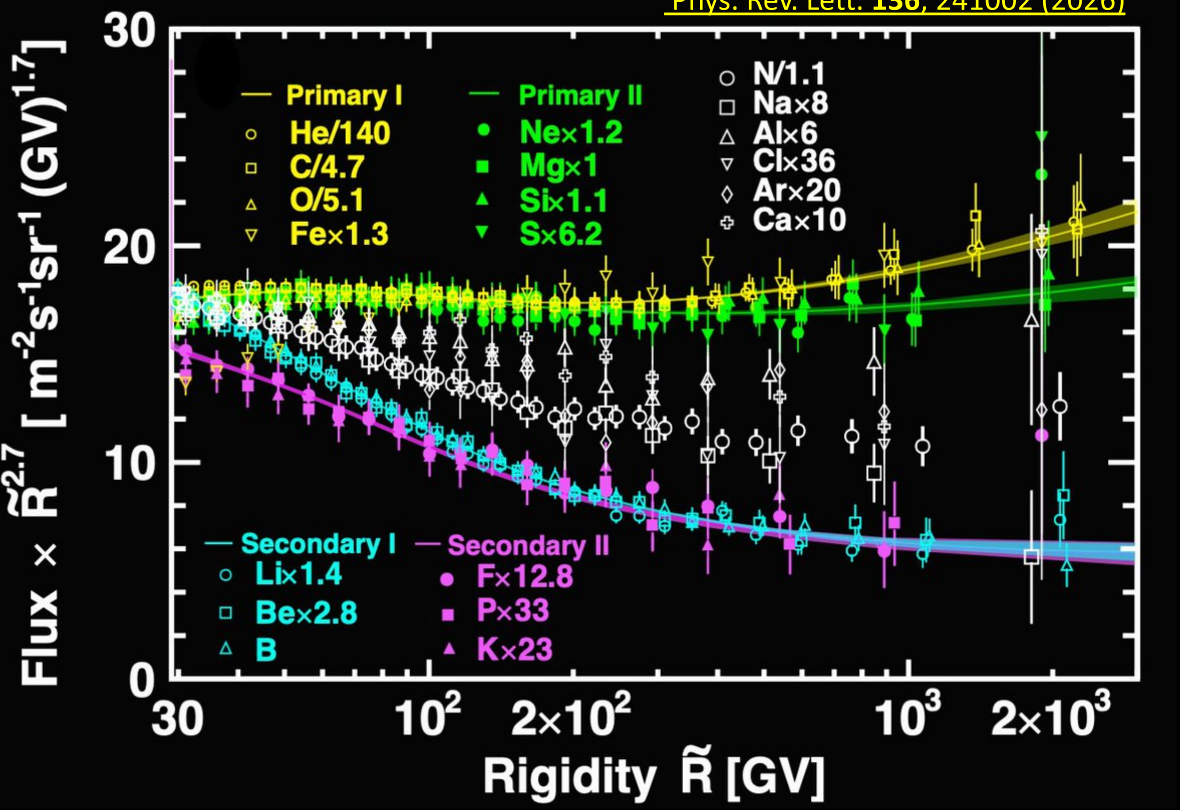
Secondary I: Li, Be, B

and

Secondary II: fluorine

Four classes of primary and secondary cosmic-ray nuclei

Phys. Rev. Lett. **136**, 241002 (2026)



C is dominantly primary
it belongs to the same class as He, O, Fe

Ne,Mg are dominantly primaries
they belong to the same class as Si

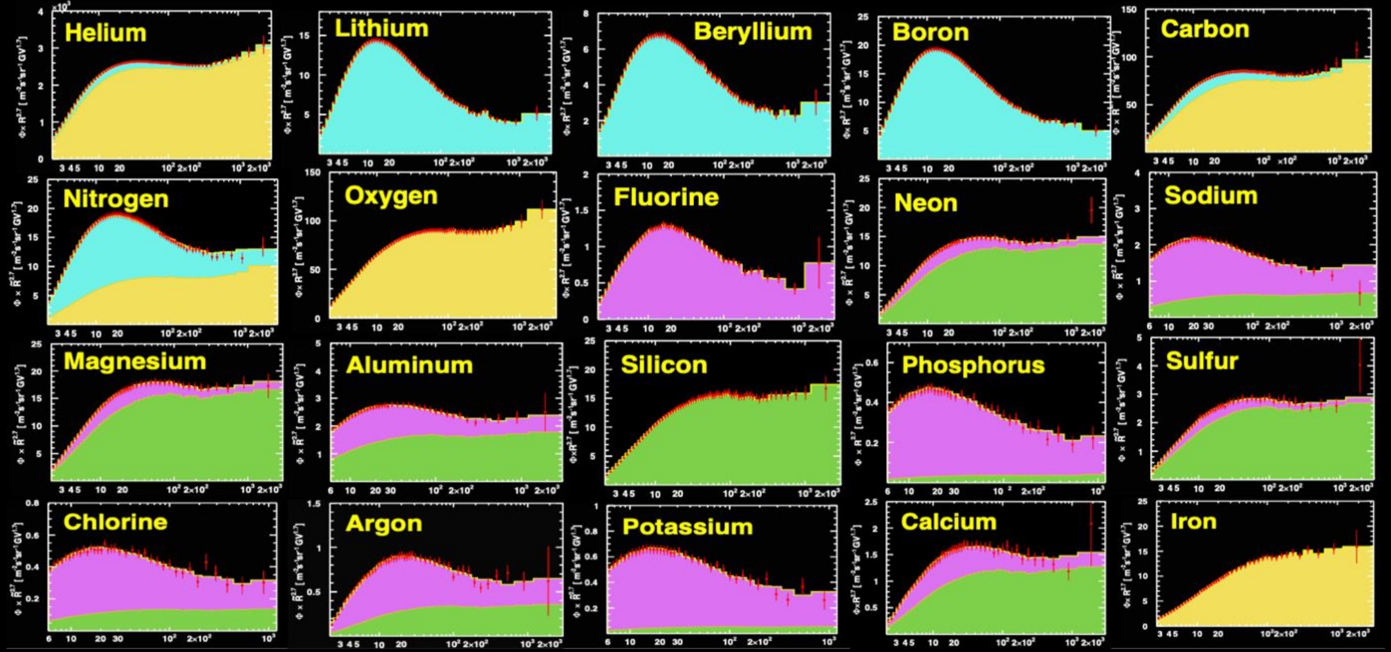
Other nuclei are a mixture of
a primary and a secondary
component.

P and K are dominantly secondaries
they belong to the same class as F

Four classes of primary and secondary cosmic-ray nuclei

The spectral shape of nuclei of mixed origin can be described by the sum of a primary component and a secondary component proportional respectively to the oxygen and boron spectra for nuclei lighter that oxygen, and to the silicon and fluorine spectra for heavy nuclei from neon to calcium

Phys. Rev. Lett. **136**, 241002 (2026)

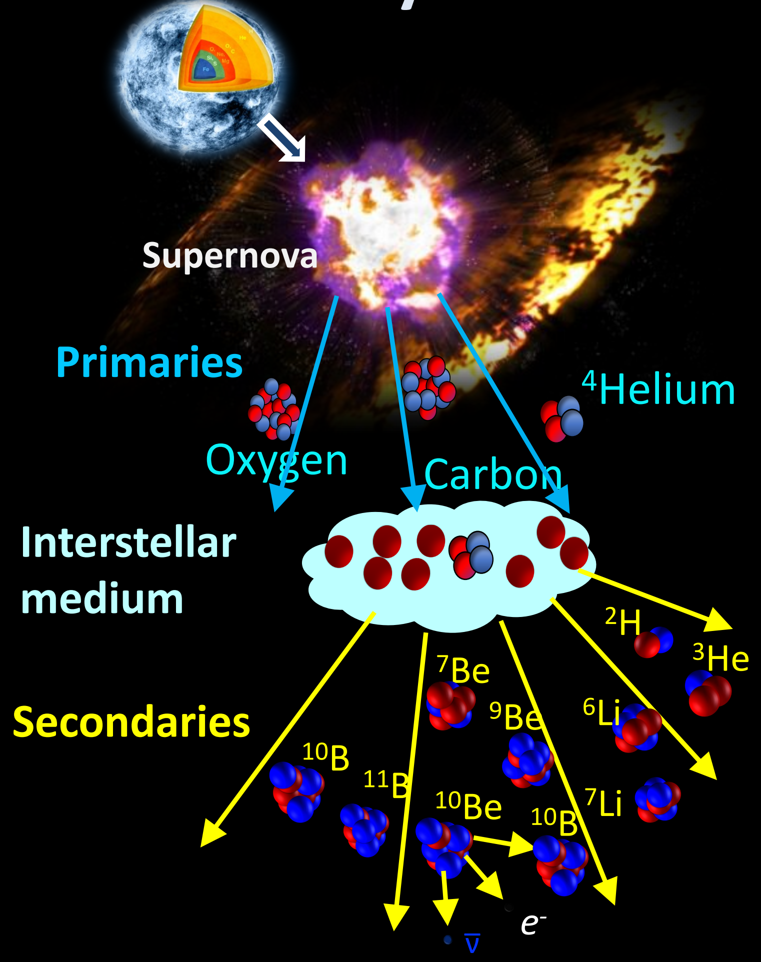


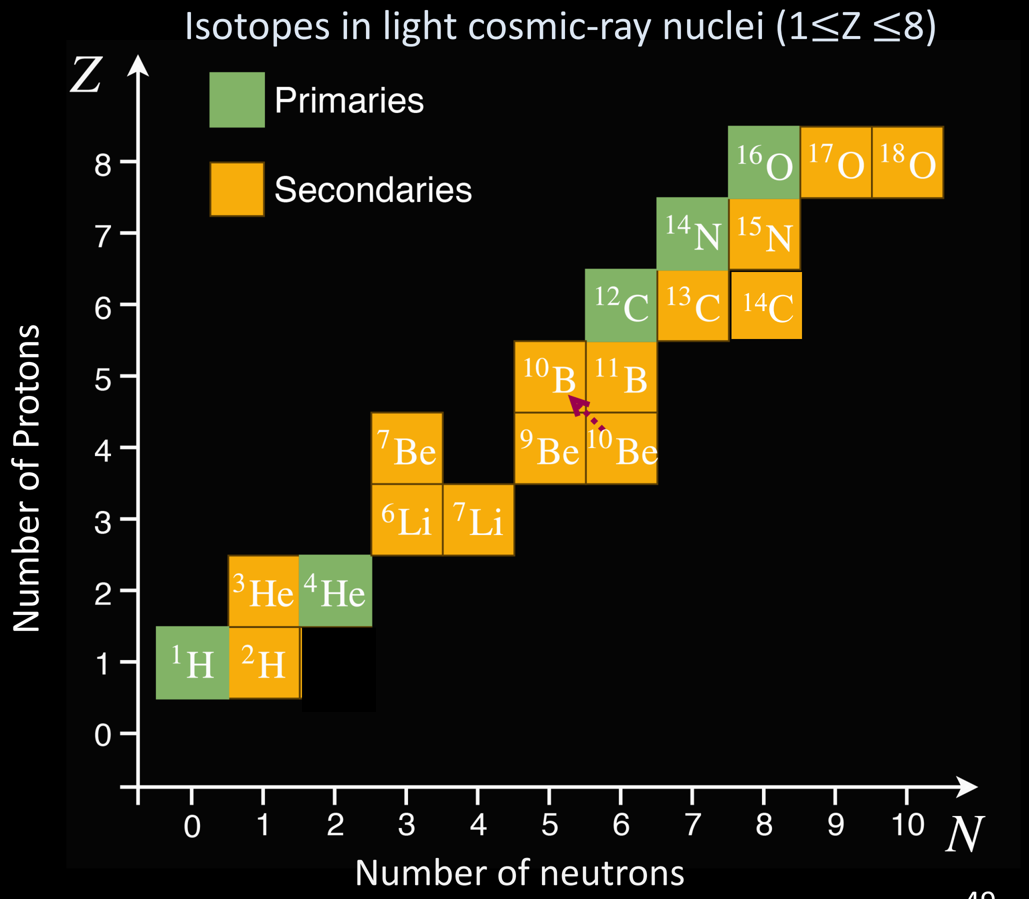
Source abundances

The fraction of the primary component measures the relative amount produced at sources of C/O, N/O, Ne/Si, Na/Si, Mg/Si, Al/Si, S/Si, Cl/Si, Ar/Si, K/Si, and Ca/Si at the source independently of cosmic ray propagation.

Abundance Ratio	AMS	HEAO	ULYSSES	Voyager-1	ACE-CRIS
Φ_C/Φ_O	0.840 ± 0.025	0.807 ± 0.015	$0.850^{+0.066}_{-0.064}$	0.800 ± 0.029	0.760 ± 0.029
Φ_N/Φ_O	0.091 ± 0.002	0.048 ± 0.012	0.065 ± 0.006	0.072 ± 0.004	0.053 ± 0.037
Φ_{Ne}/Φ_{Si}	0.823 ± 0.025	0.580 ± 0.030	0.580 ± 0.061	0.581 ± 0.004	0.511 ± 0.058
Φ_{Na}/Φ_{Si}	0.039 ± 0.003	0.0323 ± 0.0097	$0.0324^{+0.0130}_{-0.0077}$	0.040 ± 0.003	0.0372 ± 0.0256
Φ_{Mg}/Φ_{Si}	0.996 ± 0.029	1.038 ± 0.028	1.080 ± 0.040	1.110 ± 0.011	1.111 ± 0.033
Φ_{Al}/Φ_{Si}	0.108 ± 0.004	0.0778 ± 0.012	$0.0778^{+0.0130}_{-0.0100}$	0.0966 ± 0.0083	0.104 ± 0.019
Φ_P/Φ_{Si}	0.003 ± 0.001	0.008 ± 0.003	$0.0033^{+0.0033}_{-0.0027}$	0.007 ± 0.002	
Φ_S/Φ_{Si}	0.161 ± 0.005	0.131 ± 0.009	0.131 ± 0.002	0.131 ± 0.002	0.129 ± 0.019
Φ_{Cl}/Φ_{Si}	0.010 ± 0.002		0.001 ± 0.001	0.003 ± 0.002	
Φ_{Ar}/Φ_{Si}	0.022 ± 0.002	0.022 ± 0.006	0.022 ± 0.012	0.021 ± 0.003	0.019 ± 0.020
Φ_K/Φ_{Si}	0.005 ± 0.002	0.004 ± 0.003	$0.003^{+0.002}_{-0.003}$	0.003 ± 0.001	
Φ_{Ca}/Φ_{Si}	0.077 ± 0.003	0.060 ± 0.009	0.065 ± 0.012	0.065 ± 0.004	0.081 ± 0.035

Cosmic-ray nuclei are mixtures of two or more isotopes





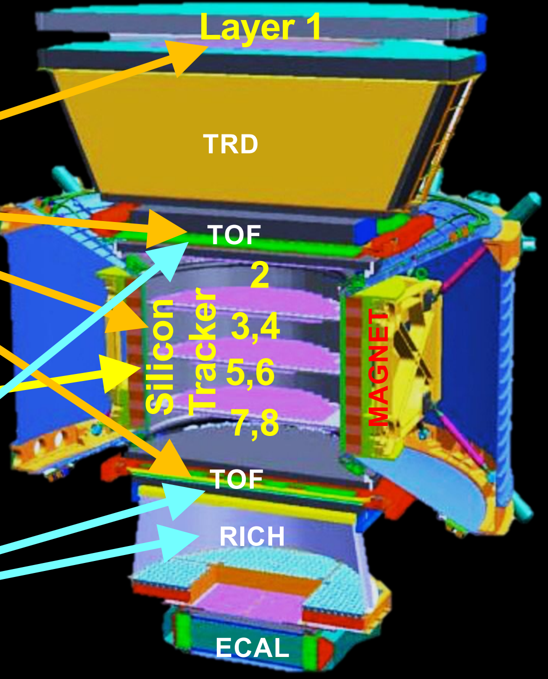
Measurement of CR nuclei isotopic composition with AMS

Nuclei mass $M = \frac{R \cdot Z}{\beta\gamma}$

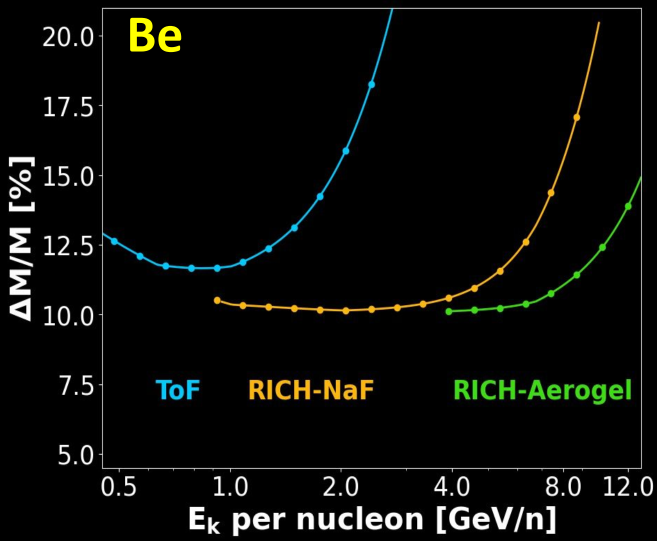
Charge Z from Silicon Tracker and TOF

Rigidity R from Silicon Tracker

Velocity β from TOF or RICH

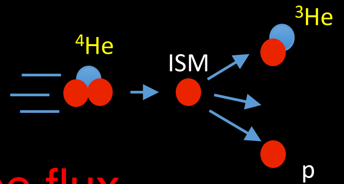


The best velocity measurement among those from TOF, RICH- NaF and RICH-Aerogel is chosen to optimize mass resolution

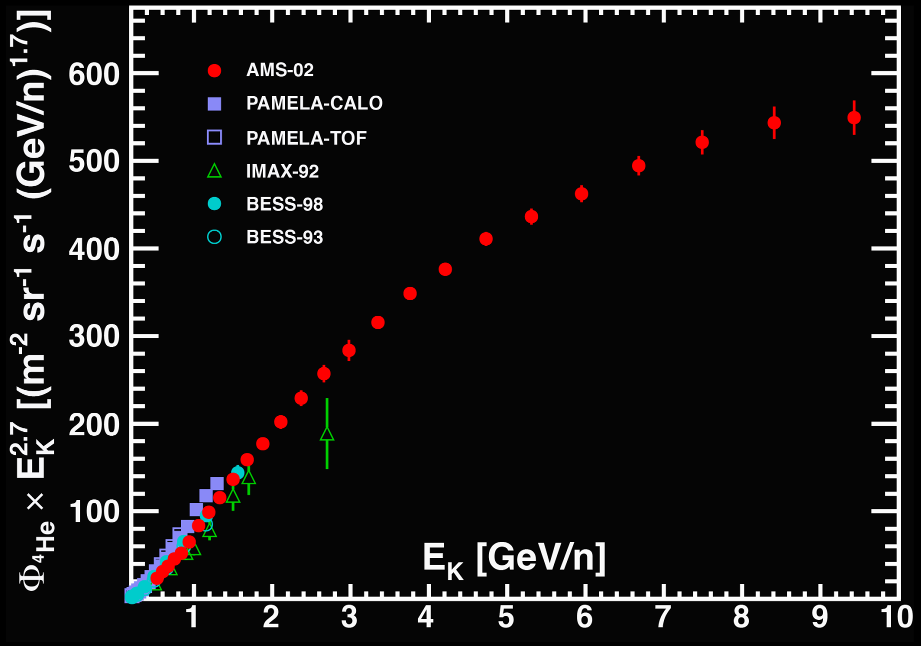


The isotopic composition is extracted from mass template fits of mass distributions in bins of E_k/n

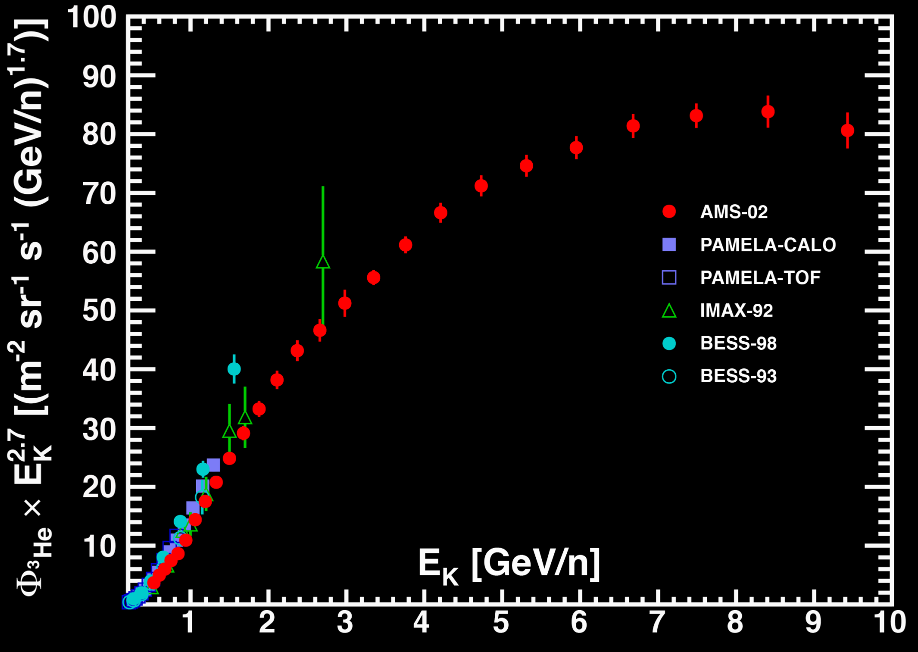
Measurement of isotopic composition of light nuclei:
Z=+2 Helium



AMS ^{4}He isotope flux



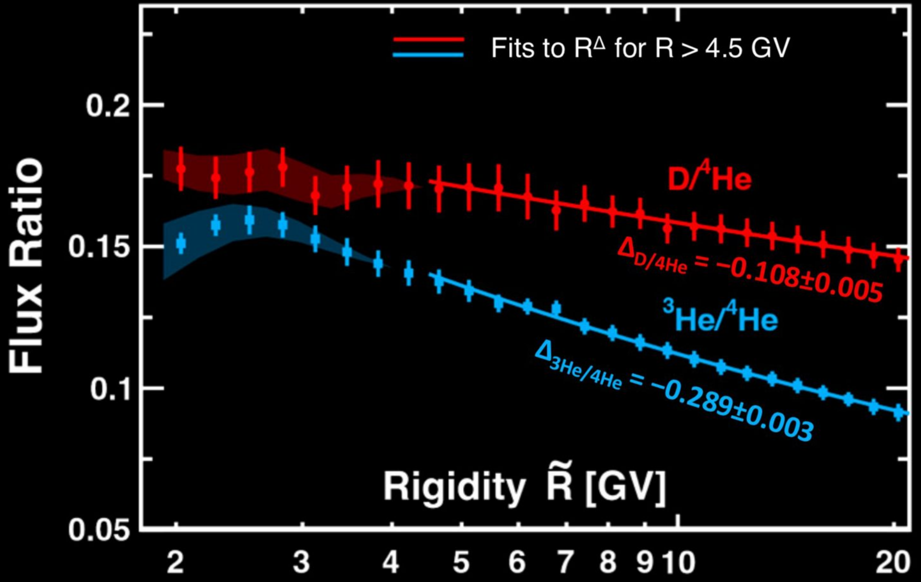
AMS ^{3}He isotope flux



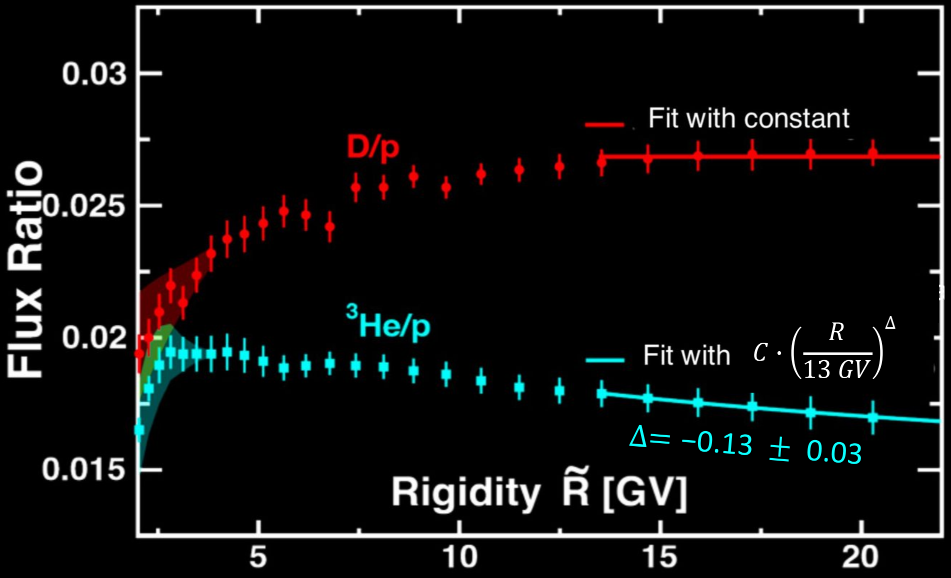
AMS result on Deuterons

Phys. Rev. Lett. 132, 261001 (2024)

D and ^{3}He are both considered to be secondary cosmic rays with ^{4}He as main progenitor
D/^{4}He and ^{3}He/^{4}He flux ratios are different



Protons are primaries
D and p have both charge Z=1
D/p is constant above 13 GV

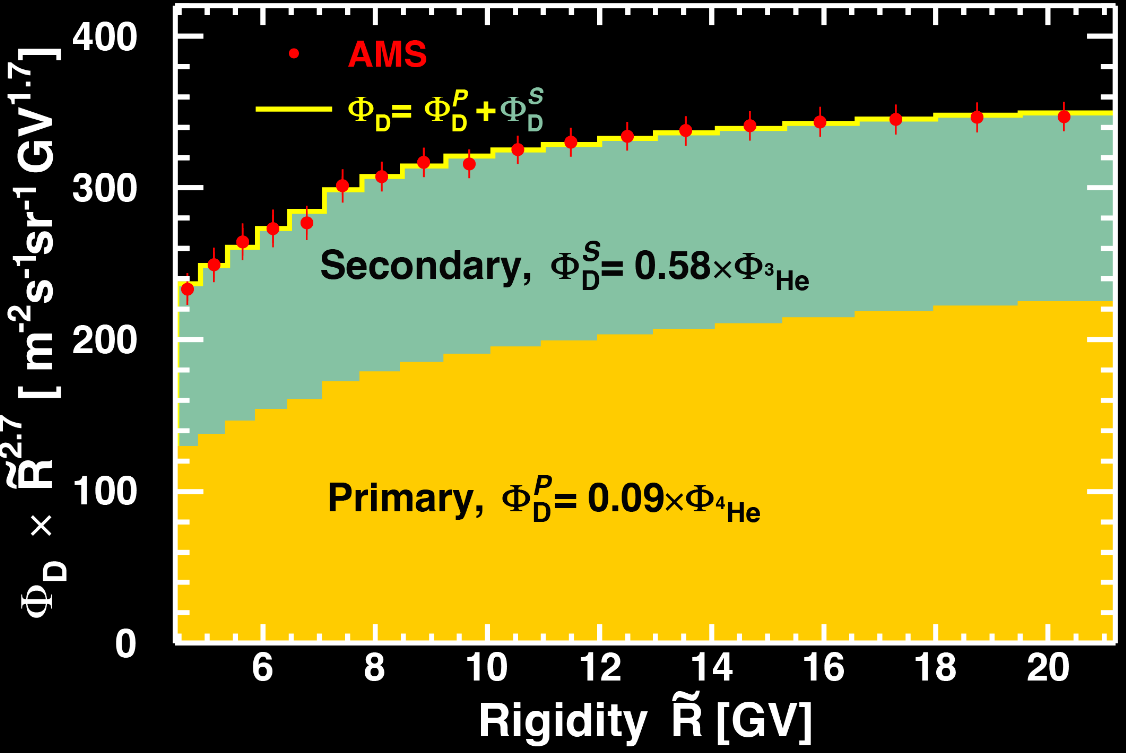


Is this suggesting a primary component in deuterons?

AMS result on Deuterons

Phys. Rev. Lett. 132, 261001 (2024)

Above 4.5 GV, the deuteron flux Φ_D is well described by the sum of a primary component $\Phi_D^P \propto \Phi_{^4He}$ and a secondary component $\Phi_D^S \propto \Phi_{^3He}$



Which is the origin of the primary-like component of deuterons?

Lithium isotopes (Z=+3)

Cosmic lithium contains two isotopes 6Li and 7Li

Both produced by spallation of heavier cosmic-ray nuclei with the interstellar medium

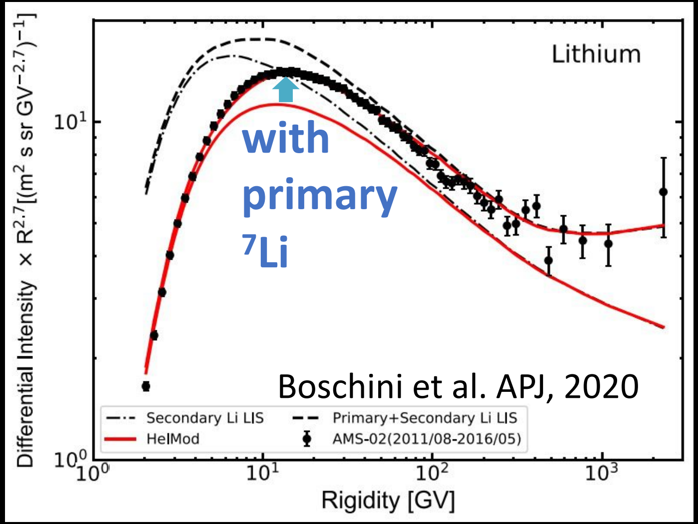
^{7}Li might have a primary component from Big Bang nucleosynthesis or low-mass stars

Cosmic-ray model calculations of Li nuclei flux undershoot AMS measurement:

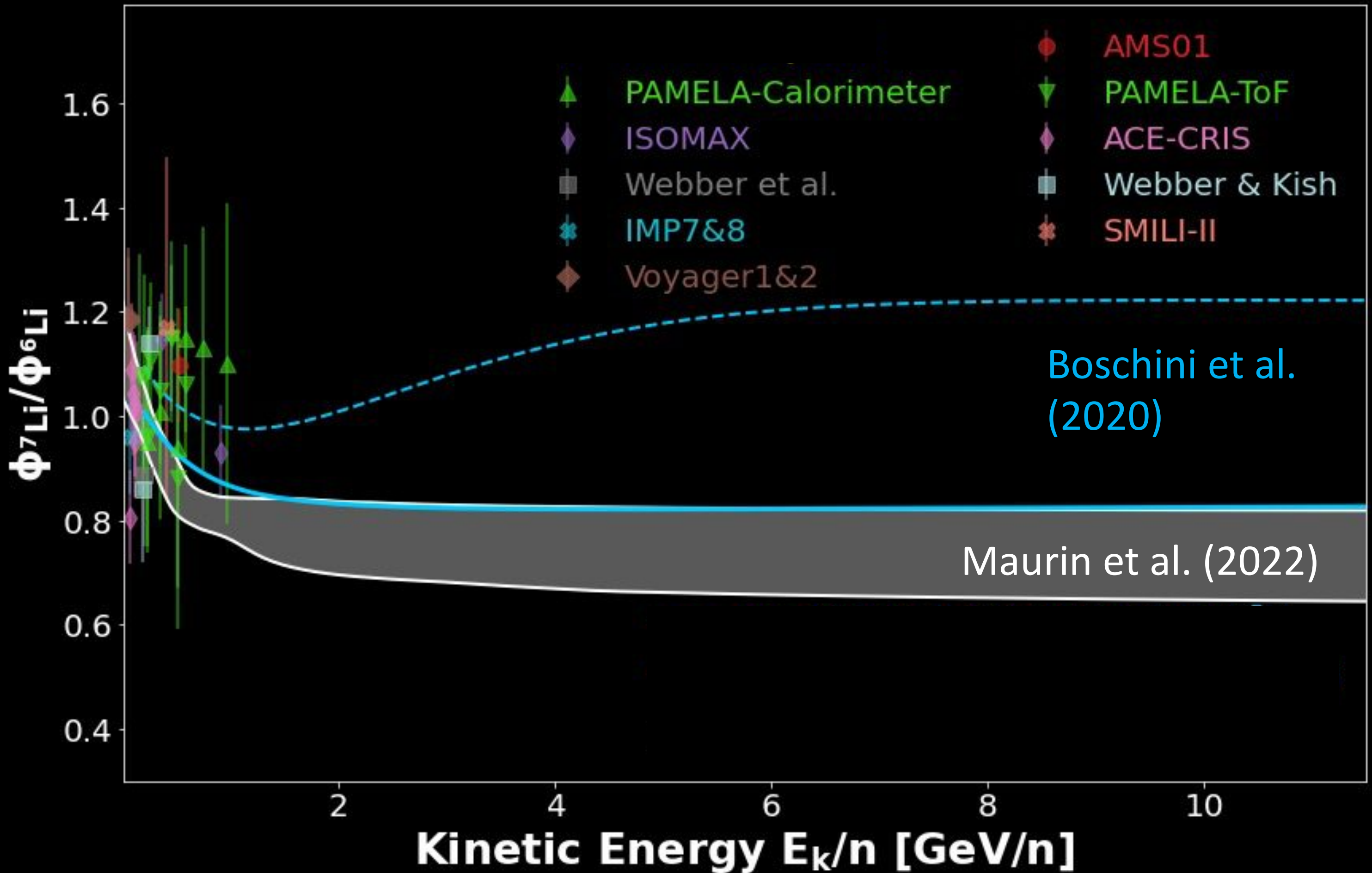
Hint of a primary lithium ^{7}Li component
(Boschini et al 2020)

OR

uncertainties in lithium production cross-sections?
(Weinrich 2020, P. De La Torre Luque 2021, Korsmeier & Cuoco 2021, Maurin 2022)



Testing the Origin of Lithium Isotopes



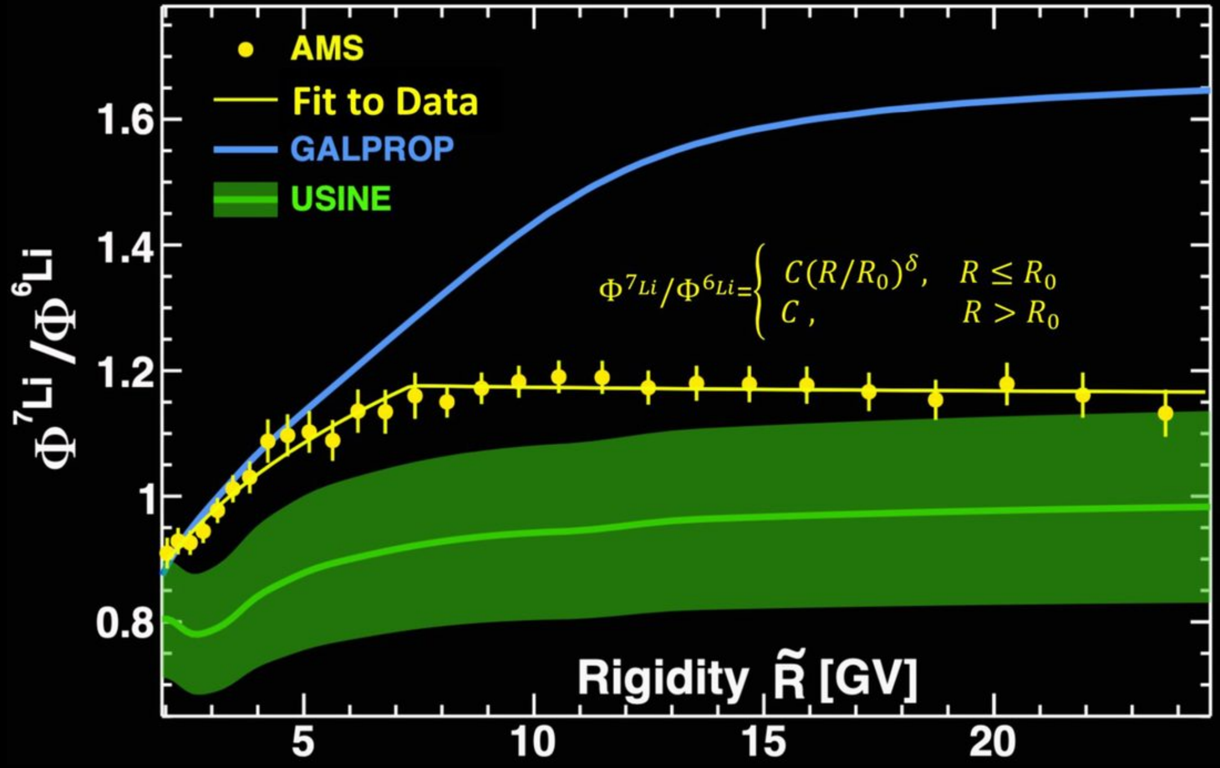
Including Primary ^{7}Li

only secondary Li

model uncertainty from Li production cross section

Testing the origin of Lithium isotopes

Phys. Rev. Lett. 134, 201001 (2025)



Model assuming a primary component in the ^{7}Li flux

Model assuming secondary origin of ^{6}Li and ^{7}Li

AMS observation exclude a sizeable primary component in ^{7}Li

Isotopic composition of light nuclei: Z=+4 Beryllium

Secondary cosmic-ray nuclei include several radioactive isotopes with a decay lifetime comparable with the cosmic rays residence time in the Galaxy, such as ^{10}Be which decays to ^{10}B.

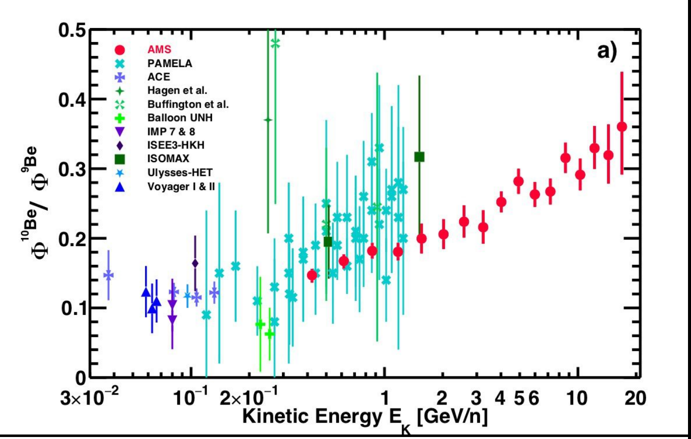
The fraction of survived radioactive isotopes at Earth measures the CR diffusive galactic halo size H

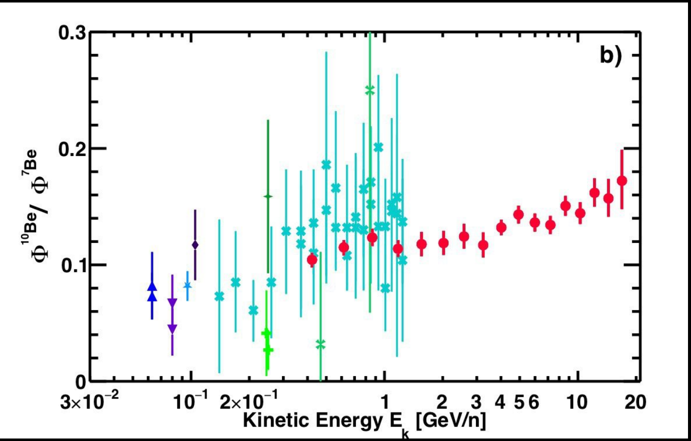
H can be obtained :

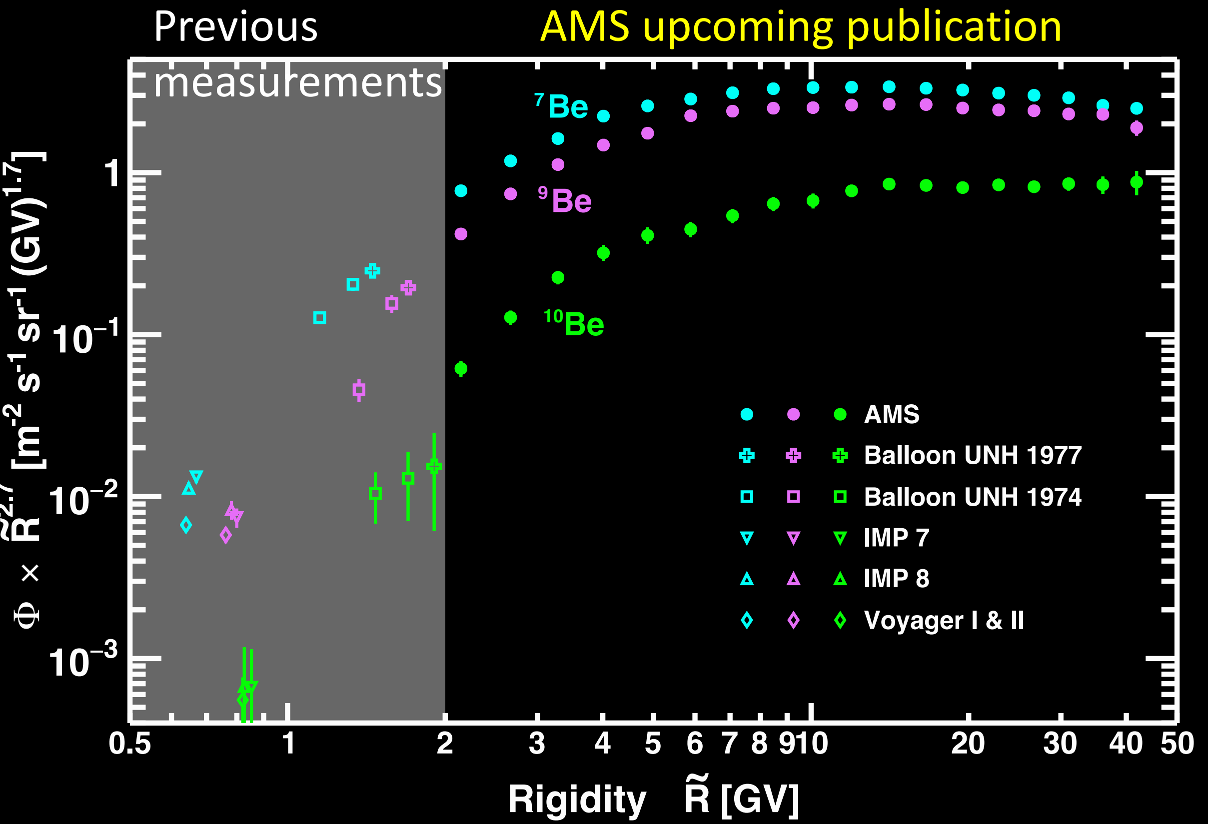
indirectly from mother-to-daughter ratio Be/B → larger uncertainty on galactic halo size

Or more directly from the unstable-to-stable secondaries ratios $^{10}Be/^{9}Be$ or $^{10}Be/^{7}Be$ -> difficult to measure

Results on Beryllium isotopes



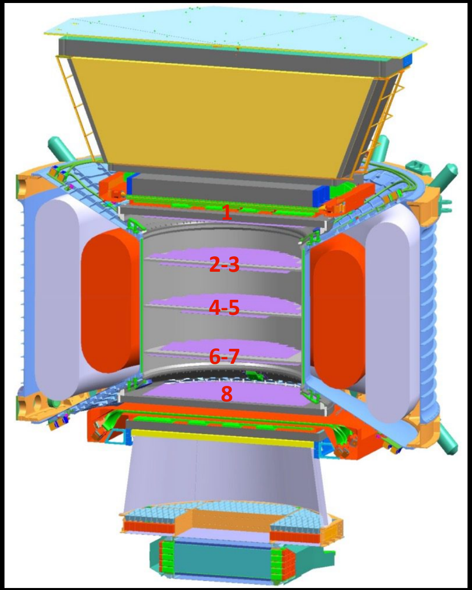




An upgrade of AMS to reach its original acceptance

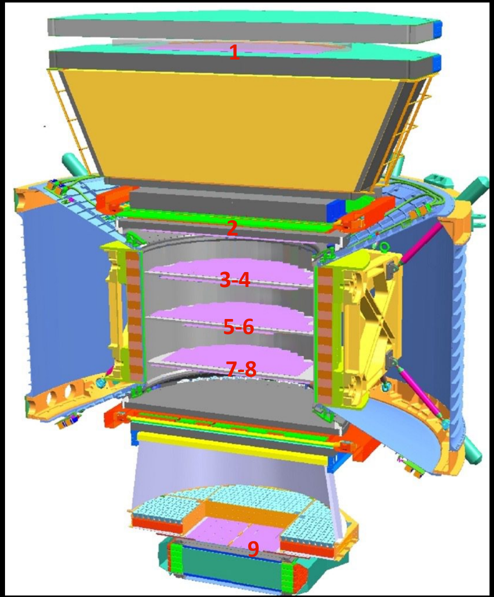
AMS as approved

Superconducting Magnet
8 layers of Silicon,
Large Acceptance



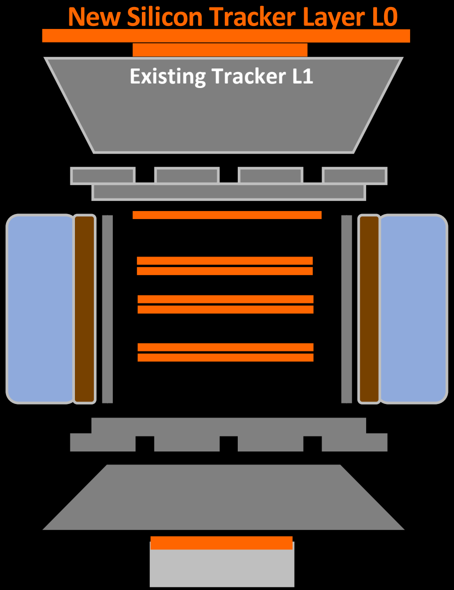
AMS on ISS today
due to termination of the Shuttle

Permanent Magnet,
9 layers of Silicon
(to maintain the resolution),
1/3 of the acceptance



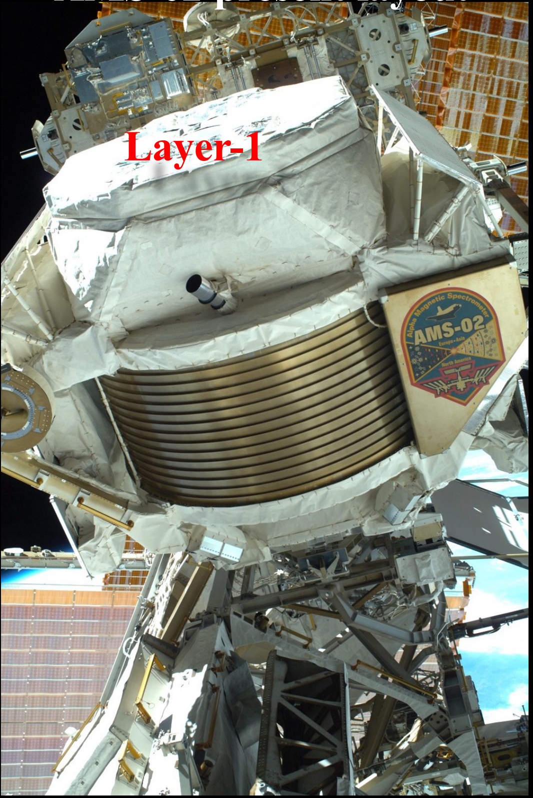
AMS on ISS to 2030

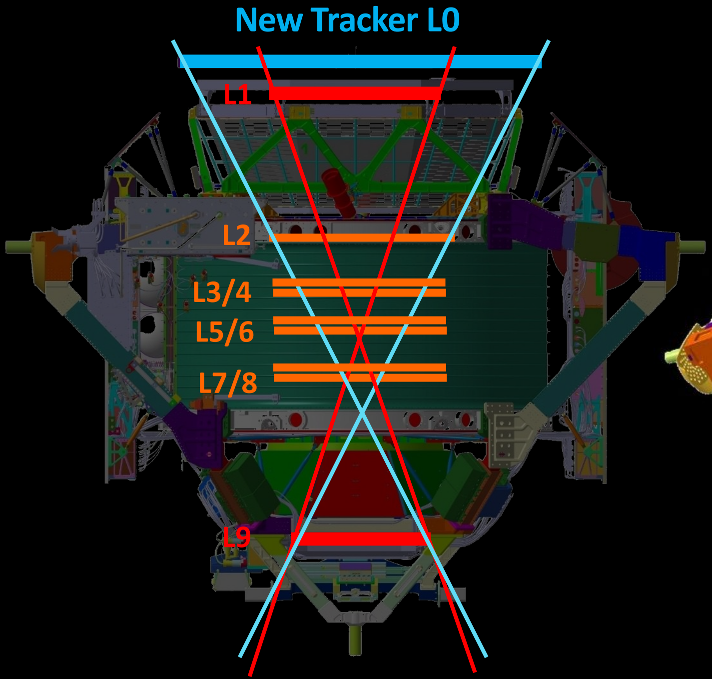
Permanent Magnet,
10 layers of Silicon
to upgrade to
full acceptance



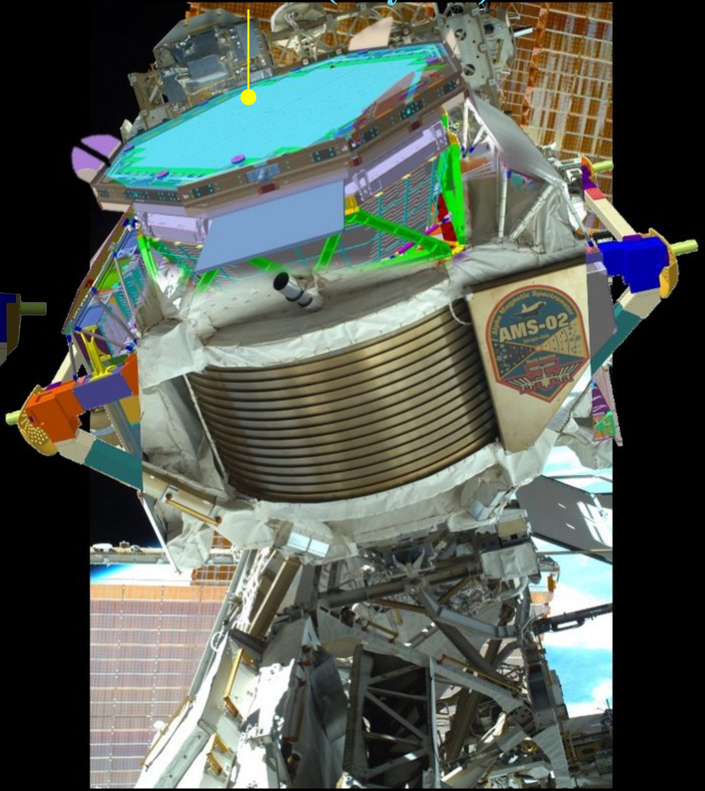
AMS Upgrade

AMS-02 present layout





With new Tracker (Layer-0)

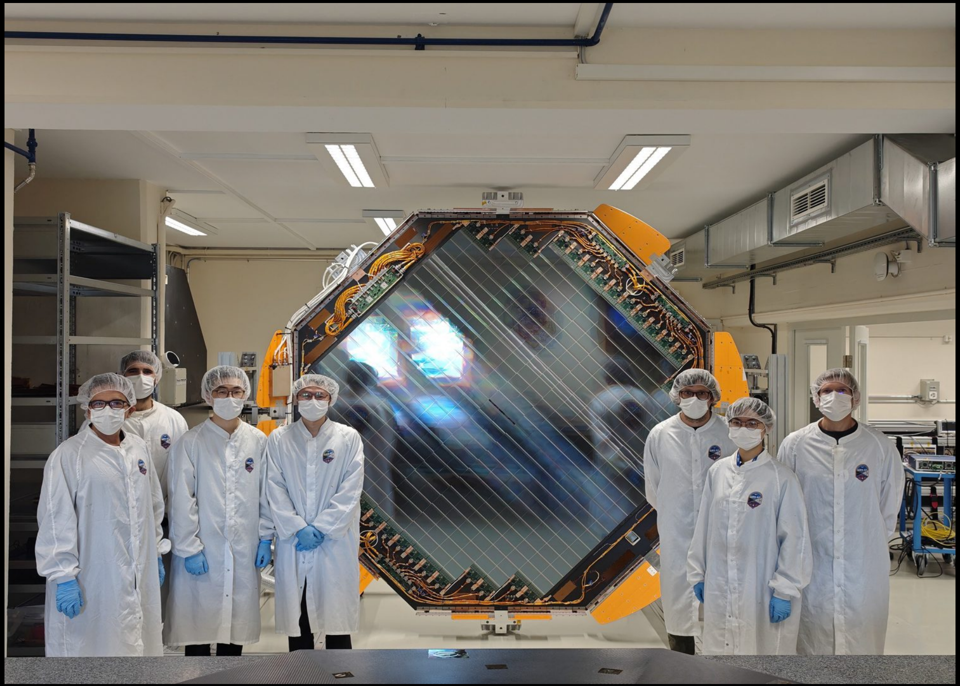


AMS Upgrade

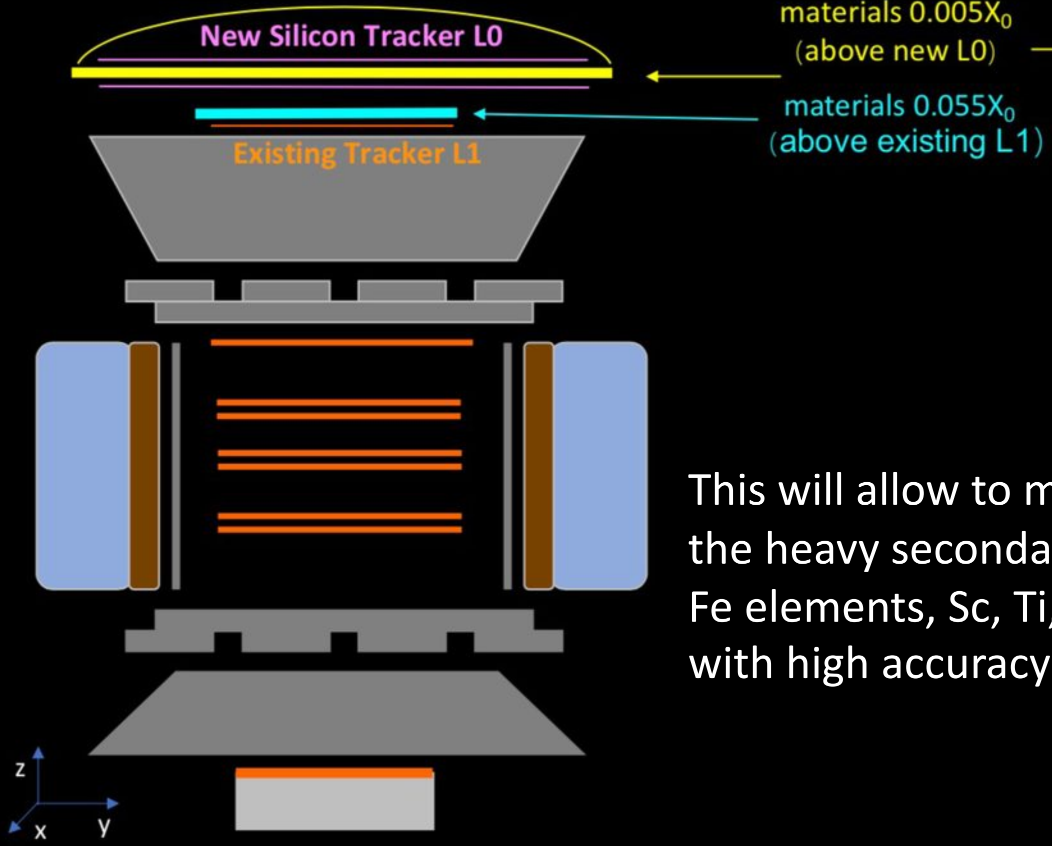
AMS L0 integration at CERN May-Sep. 2025

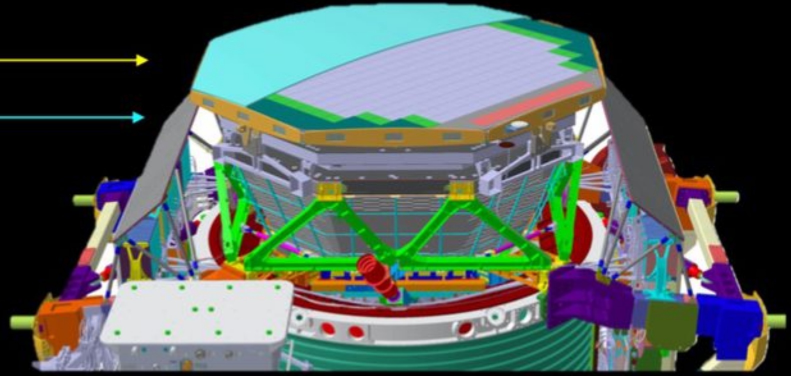
Functional tests

Silicon sensors fully integrated on plane

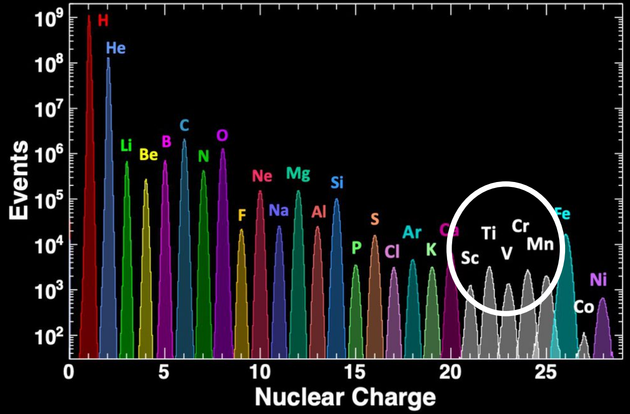


AMS Upgrade with Minimal Materials Above Layer-0: large reduction of the backgrounds





This will allow to measure the heavy secondary sub-Fe elements, Sc, Ti, V,… with high accuracy

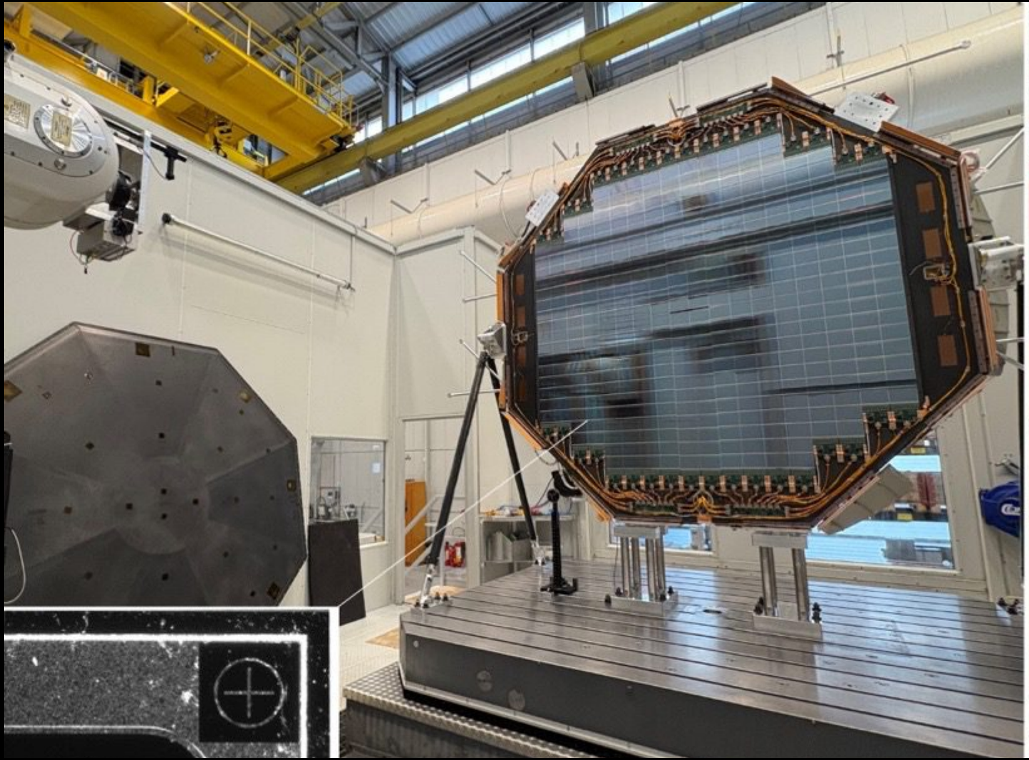


AMS Upgrade

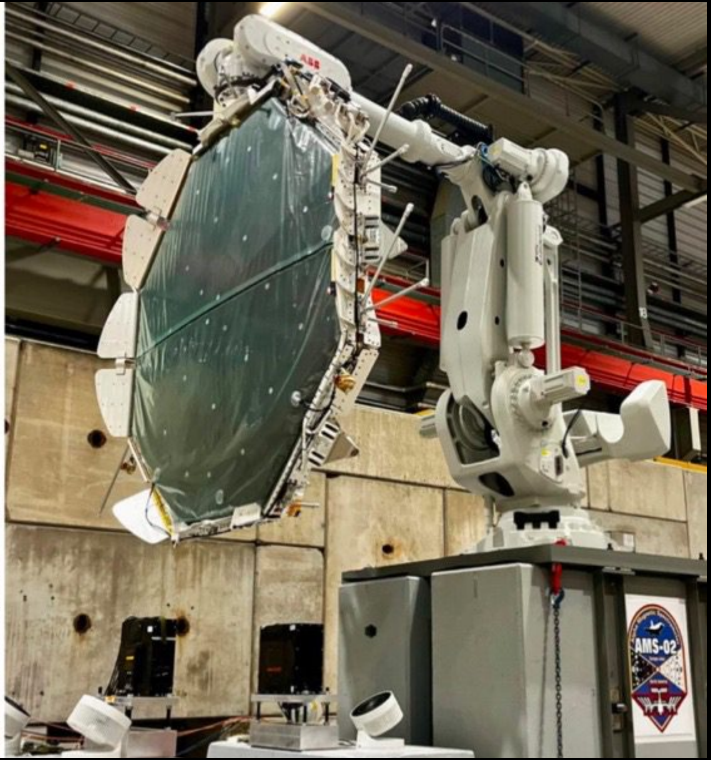
AMS L0 with temporary installation of cupola for safe transport to metrology facility Sep 2025.

AMS Upgrade

L0 at the CERN metrology measurement facility in October 2025



Performance tests at CERN SPS proton beam July 2026



Summary

Since its installation on the ISS, AMS has recorded more than 260 billion cosmic rays.

The accuracy of the AMS data is revealing new features in the GeV-TeV spectra of many different types of cosmic ray species.

The AMS data suggests a propagation origin of spectral break in primary CR He-C-O
Still to be understood are:

- the different spectral shape of Ne-Mg-Si primary group
- the difference secondary-to-primary ratios between light and heavy nuclei Li-Be-B/O vs F/Si

Recent results: Phosphorus to Ca nuclei and determination of relative source abundances

Upcoming: Be isotopes and determination of CR diffusive halo.

AMS will continue to collect and analyze data for the lifetime of the Space Station 2030.
An upgrade to reach the design acceptance (x3 current acceptance) is planned for 2027
By 2030 AMS will provide a complete inventory of CR nuclei up to Nickel.
Not shown: results on positrons, antiprotons, solar modulation see https://ams02.space/

AMS Publications

1) Phys. Rev. Lett. 110, 141102 (2013)	Editors' Suggestion. Viewpoint in *Physics*. Highlight of 2013. Ten-Year Editors' Suggestion retrospective
2) Phys. Rev. Lett. 113, 121101 (2014)	Editors' Suggestion
3) Phys. Rev. Lett. 113, 121102 (2014)	Editors' Suggestion. Featured in *Physics*.
4) Phys. Rev. Lett. 113, 221102 (2014)	
5) Phys. Rev. Lett. 114, 171103 (2015)	Editors' Suggestion
6) Phys. Rev. Lett. 115, 211101 (2015)	Editors' Suggestion
7) Phys. Rev. Lett. 117, 091103 (2016)	
8) Phys. Rev. Lett. 117, 231102 (2016)	Editors' Suggestion
9) Phys. Rev. Lett. 119, 251101 (2017)	
10) Phys. Rev. Lett. 120, 021101 (2018)	Editors' Suggestion. Featured in *Physics*.
11) Phys. Rev. Lett. 121, 051101 (2018)	
12) Phys. Rev. Lett. 121, 051102 (2018)	Editors' Suggestion
13) Phys. Rev. Lett. 121, 051103 (2018)	
14) Phys. Rev. Lett. 122, 041102 (2019)	Editor's Suggestion
15) Phys. Rev. Lett, 122, 101101 (2019)	
16) Phys. Rev. Lett. 123, 181102 (2019)	Editors' Suggestion
17) Phys. Rev. Lett. 124, 211102 (2020)	Editors' Suggestion. Featured in *Physics*.
18) Physics Reports 894, 1 (2021)	
19) Phys. Rev. Lett. 126, 041104 (2021)	Featured in *Physics*.
20) Phys. Rev. Lett. 126, 081102 (2021)	Editors' Suggestion
21) Phys. Rev. Lett. 127, 021101 (2021)	
22) Phys. Rev. Lett. 127, 271102 (2021)	
23) Phys. Rev. Lett. 128, 231102 (2022)	
24) Phys. Rev. Lett. 130, 161001 (2023)	Editors' Suggestion. Viewpoint in *Physics*.
25) Phys. Rev. Lett. 130, 211002 (2023)	Featured on *Phys.org*
26) Phys. Rev. Lett. 131, 151002 (2023)	APS Press Announcement
27) Phys. Rev. Lett. 132, 261001 (2024)	Editors' Suggestion. Featured in *Physics*.
28) Phys. Rev. Lett. 134, 051002 (2025)	Editors' Suggestion. Viewpoint in *Physics*. APS Press Announcement
29) Phys. Rev. Lett. 134, 051001 (2025)	APS Press Announcement
30) Phys. Rev. Lett. 134, 201001 (2025)	Editors' Suggestion. Featured in *Physics*. APS Press Announcement
31) Phys. Rev. Lett. **136**, 241002 (2026)	