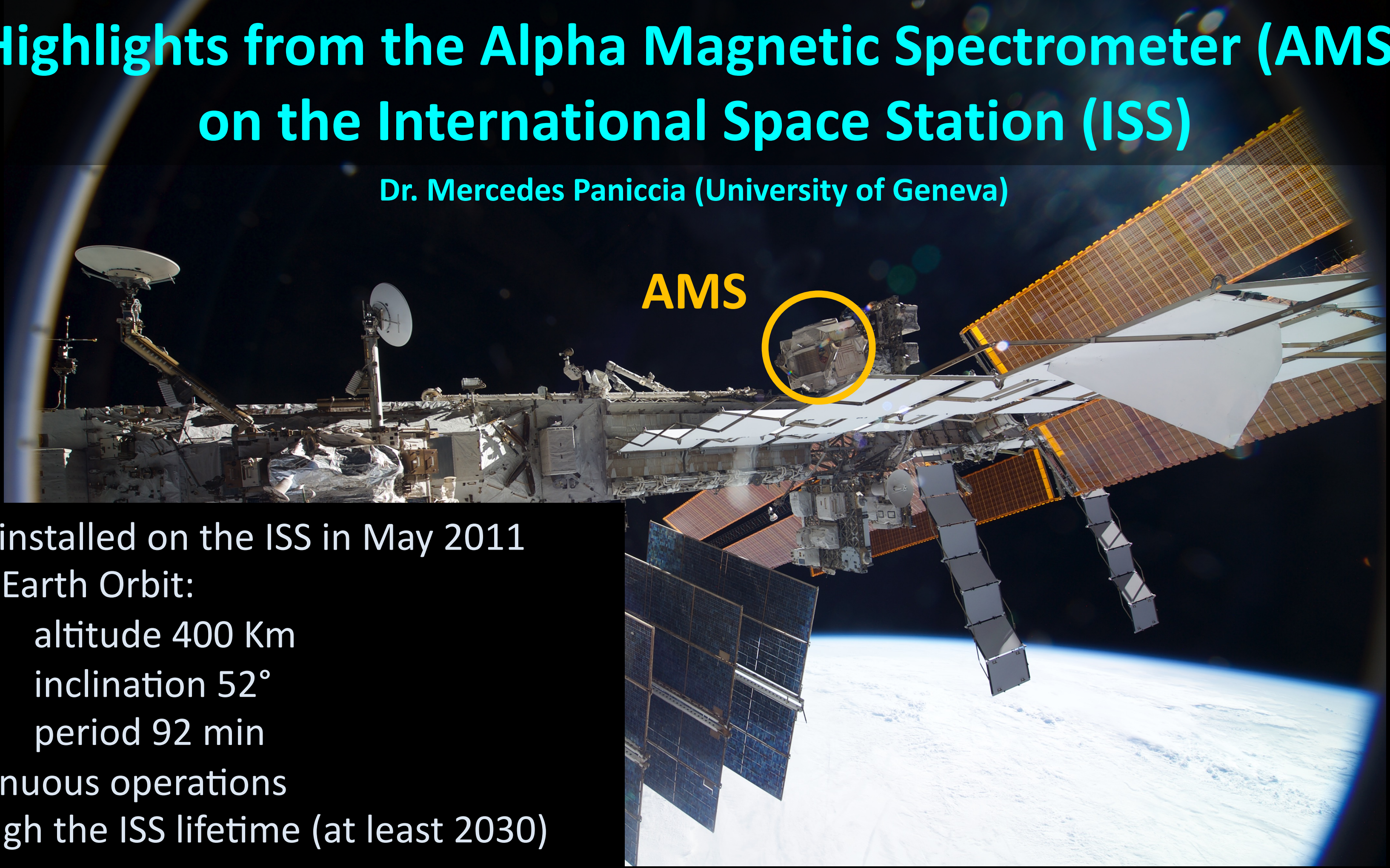
Highlights from the Alpha Magnetic Spectrometer (AMS) on the International Space Station (ISS)

Dr. Mercedes Paniccia (University of Geneva)



AMS installed on the ISS in May 2011
Near Earth Orbit:
- altitude 400 Km
- inclination 52°
- period 92 min

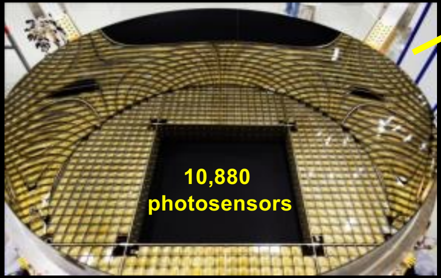
Continuous operations
through the ISS lifetime (at least 2030)

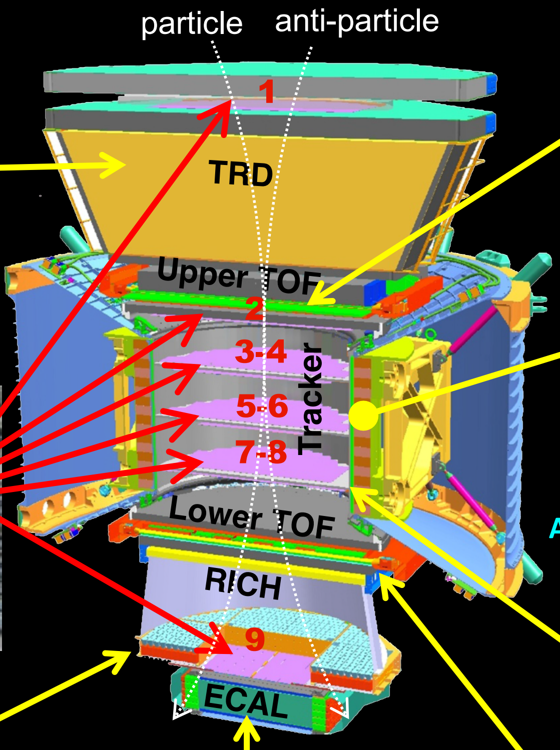
AMS is a space version of a precision detector used in accelerators

Transition Radiation Detector (TRD)
identify e^+, e^-

Silicon Tracker
measure Z, Rigidity=p/Z

Ring Imaging Cerenkov (RICH)
measure Z, velocity





Electromagnetic Calorimeter (ECAL)
measure E of e^+, e^-

Upper TOF measure Z, velocity

Magnet identify ±Z, P

Anticoincidence Counters (ACC)
reject particles from the side

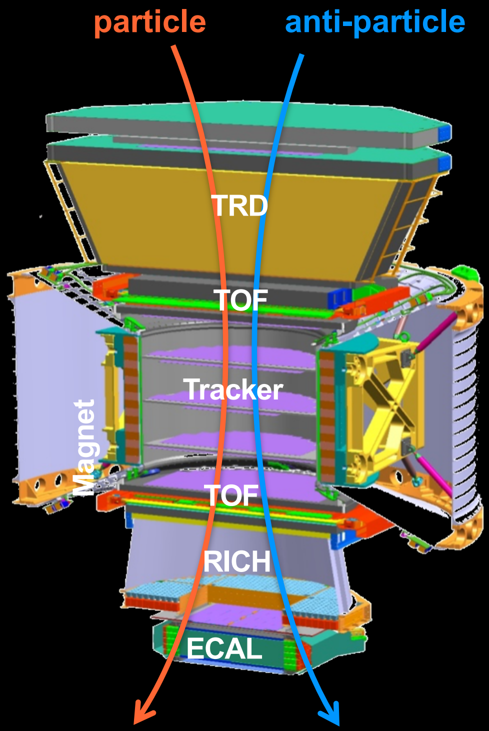
Lower TOF measure Z, E

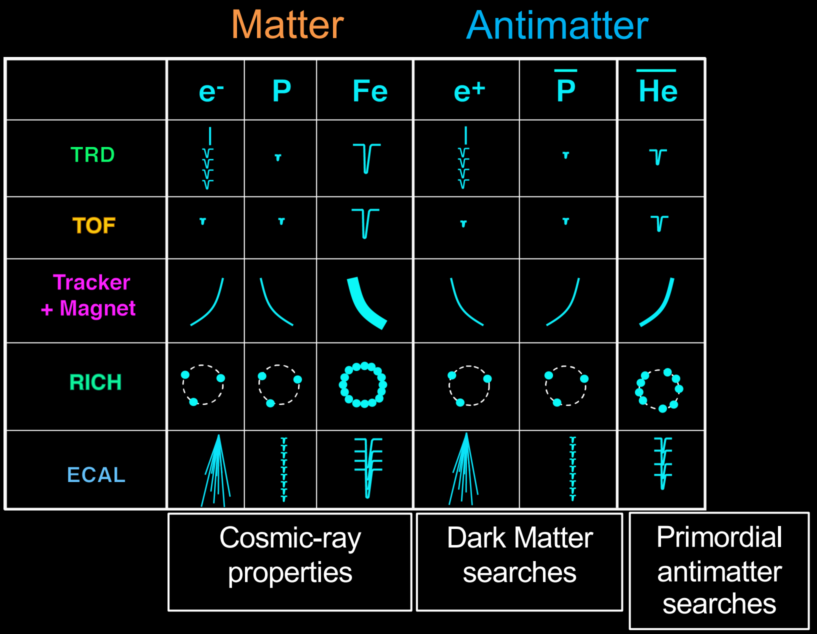
AMS provides precision, long-duration measurements of charged cosmic rays

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 the nuclei in the Periodic Table

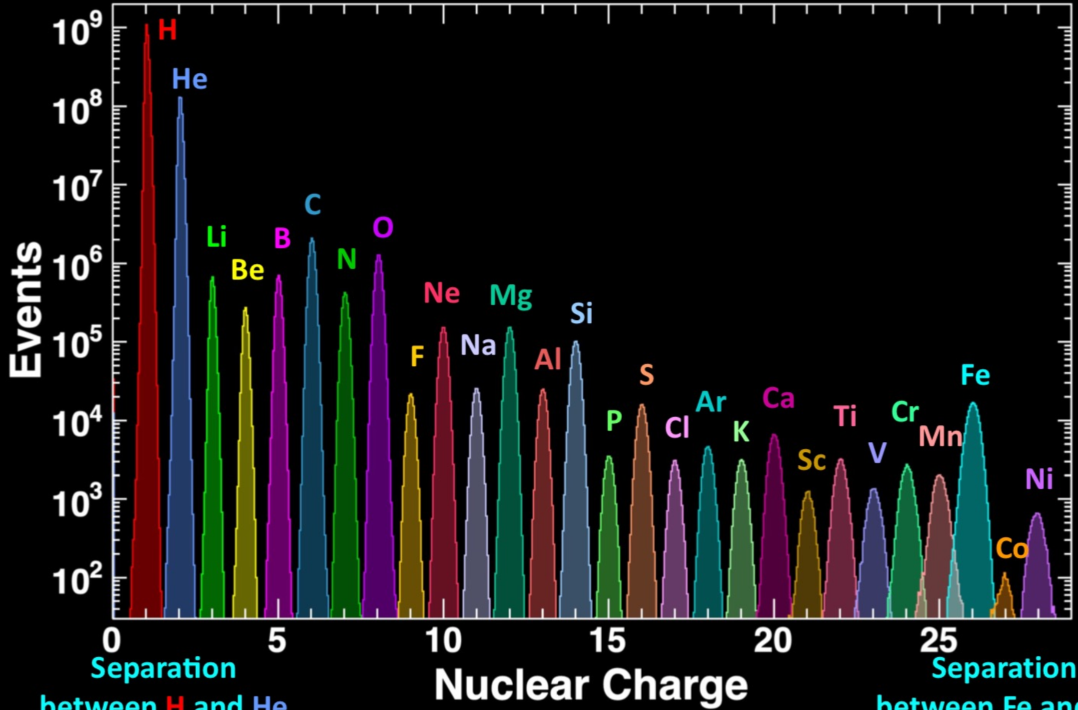




Thanks to its large acceptance and long-duration mission, AMS is also studying time evolution of cosmic-ray fluxes for e+, e−, p, and $\bar{p}$, and nuclei.

Cosmic Nuclei identification with AMS

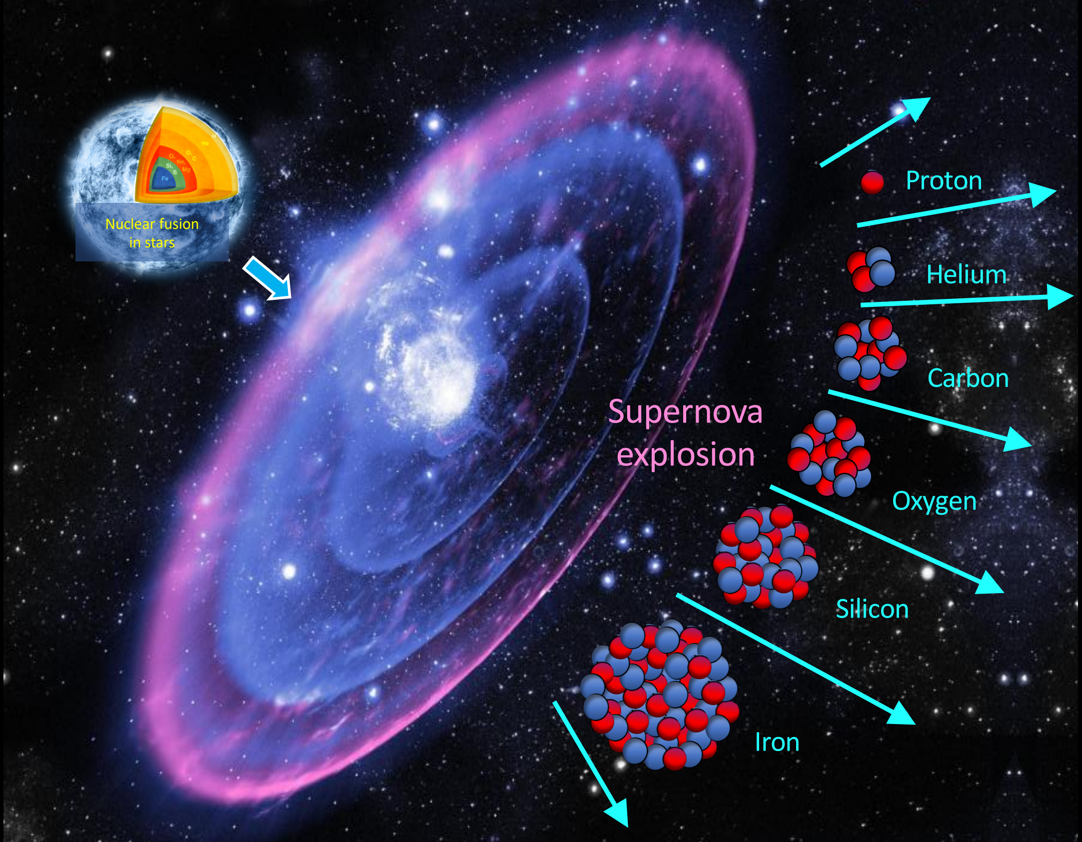
Today, with 240 billion events and improved analysis, we have precise spectroscopy of cosmic ray nuclei



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

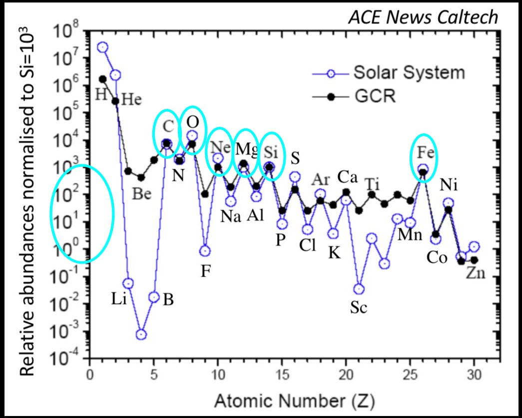
Separation between Fe and Co is better than 1 in 10^2

Primary Cosmic Rays



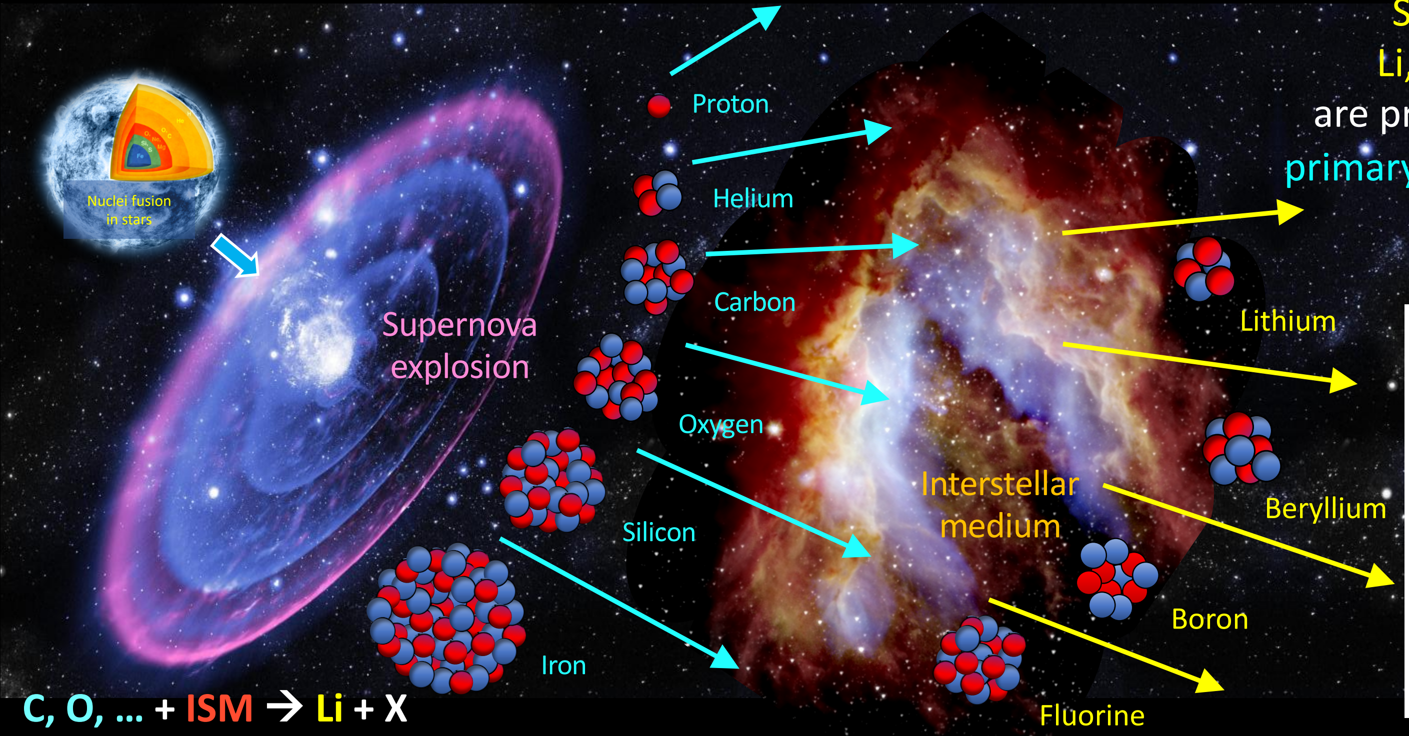
Primary elements,
protons, He, C, O, Ne, Mg, Si..., Fe nuclei
are produced
during the lifetime of stars.

They are accelerated in
supernovae explosions
and
expelled in the interstellar medium
where they propagate diffusively
through the galaxy.

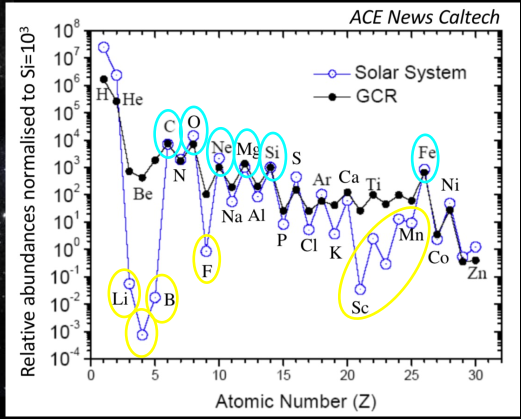


Energy (or Rigidity) spectra of primary cosmic rays give information on their sources,acceleration, and propagation mechanisms.

Secondary Cosmic Rays



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



C, O, … + ISM → Li + X

C, O, … + ISM → Be + X

C, O, … + ISM → B + X

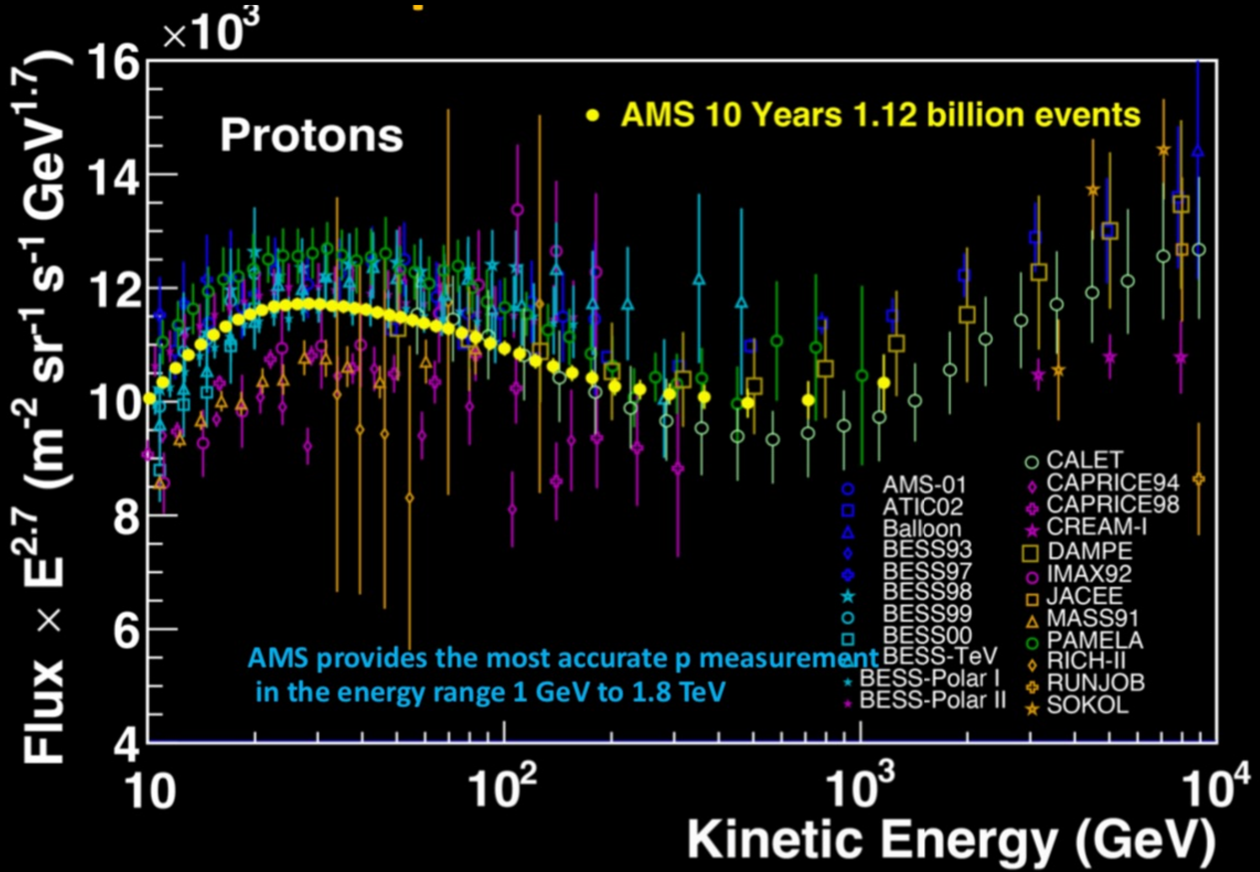
Ne, Mg, Si, … + ISM → F + X

Fe, … + ISM → Sc, … ,Mn + X

Rigidity (or energy) spectra of secondary cosmic rays compared to primary spectra give information on cosmic-ray propagation: measure of rigidity dendence of CR diffusion coefficient

Light primary cosmic-ray nuclei : H (protons)

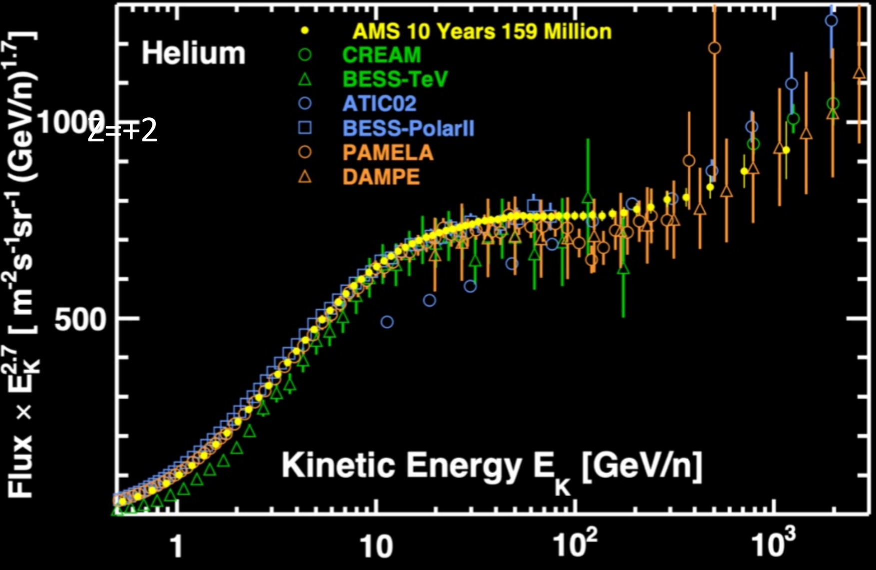
The proton spectrum deviates from a simple power law and hardens above 200 GV



Light primary cosmic-ray nuclei : Helium

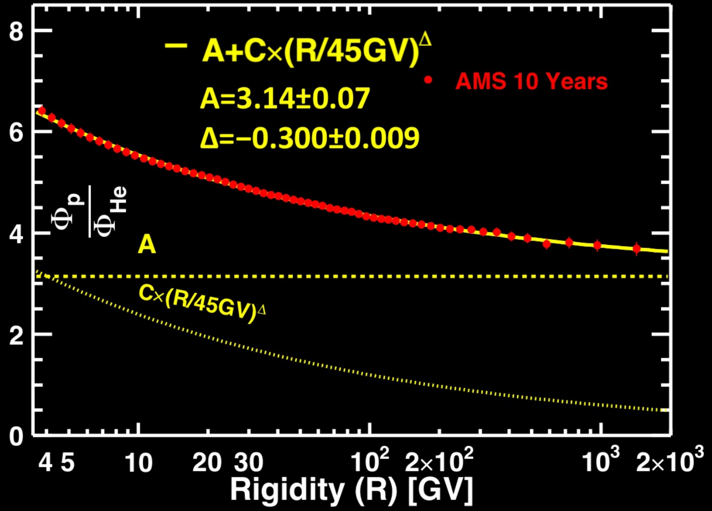
AMS Collaboration Phys. Rep. 894, 1 (2021)

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



He and protons are both primaries, but they have different spectral shapes.

Proton spectrum is described by a He-like component and an additional power law component



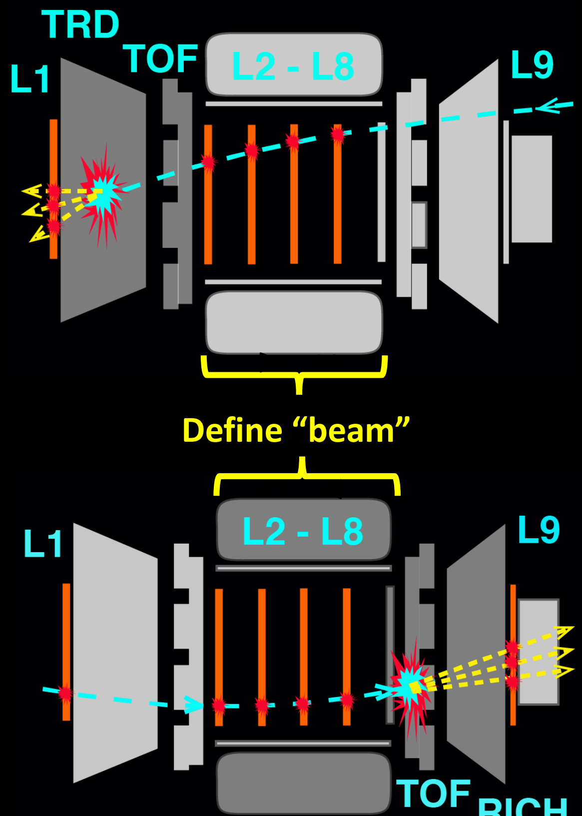
Which is the source of this additional power-law component in protons?

Nuclear cross-sections measurements with AMS-02

Crucial to accurately measure nuclei fluxes.

Qi Yan et al, Nucl. Phys. A 996 121712 (2020)

ISS Flying Horizontally

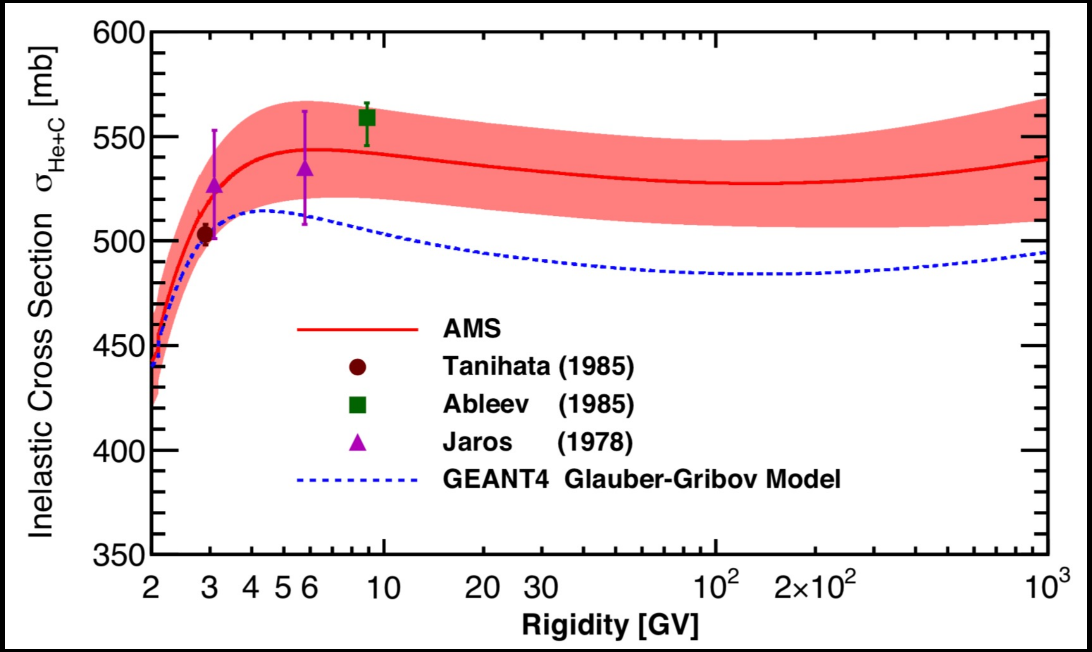


Nominal ISS attitude

Inelastic cross sections data available only for few target and projectiles.

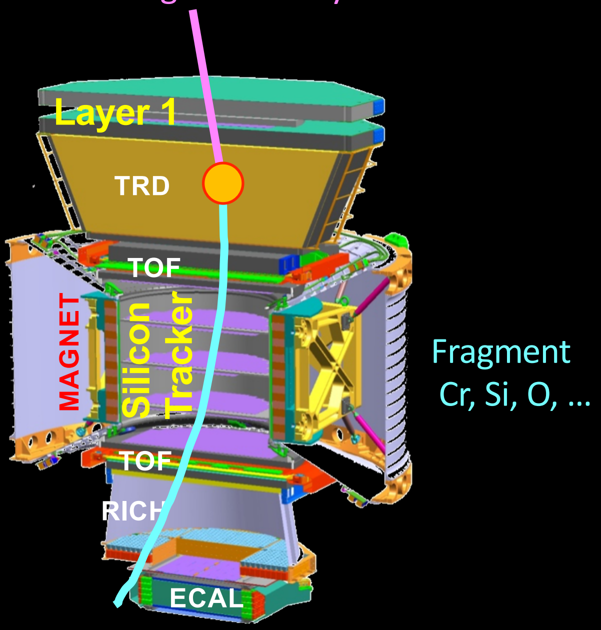
No measurement available beyond 10 GV.

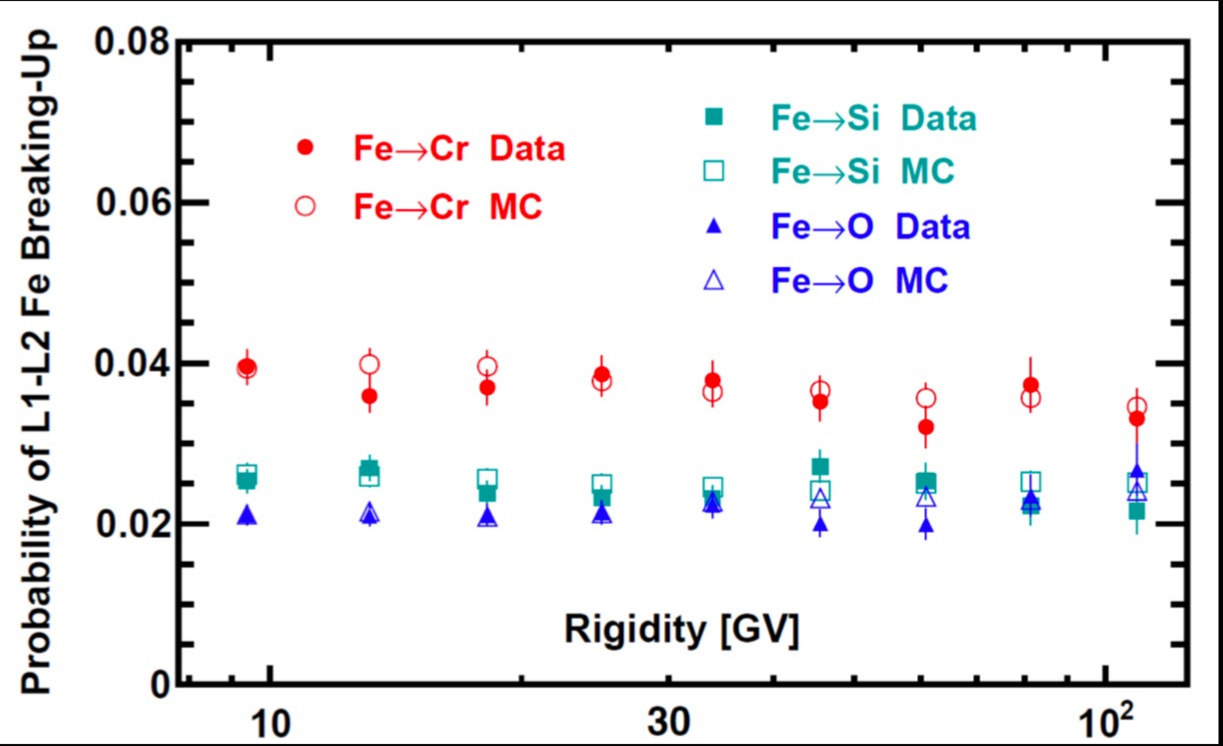
Nuclei survival probabilities measured with in-flight AMS data



Nuclear cross-sections measurements with AMS-02

Nuclei breaking-up probability measured channel by channel with in-flight AMS data:

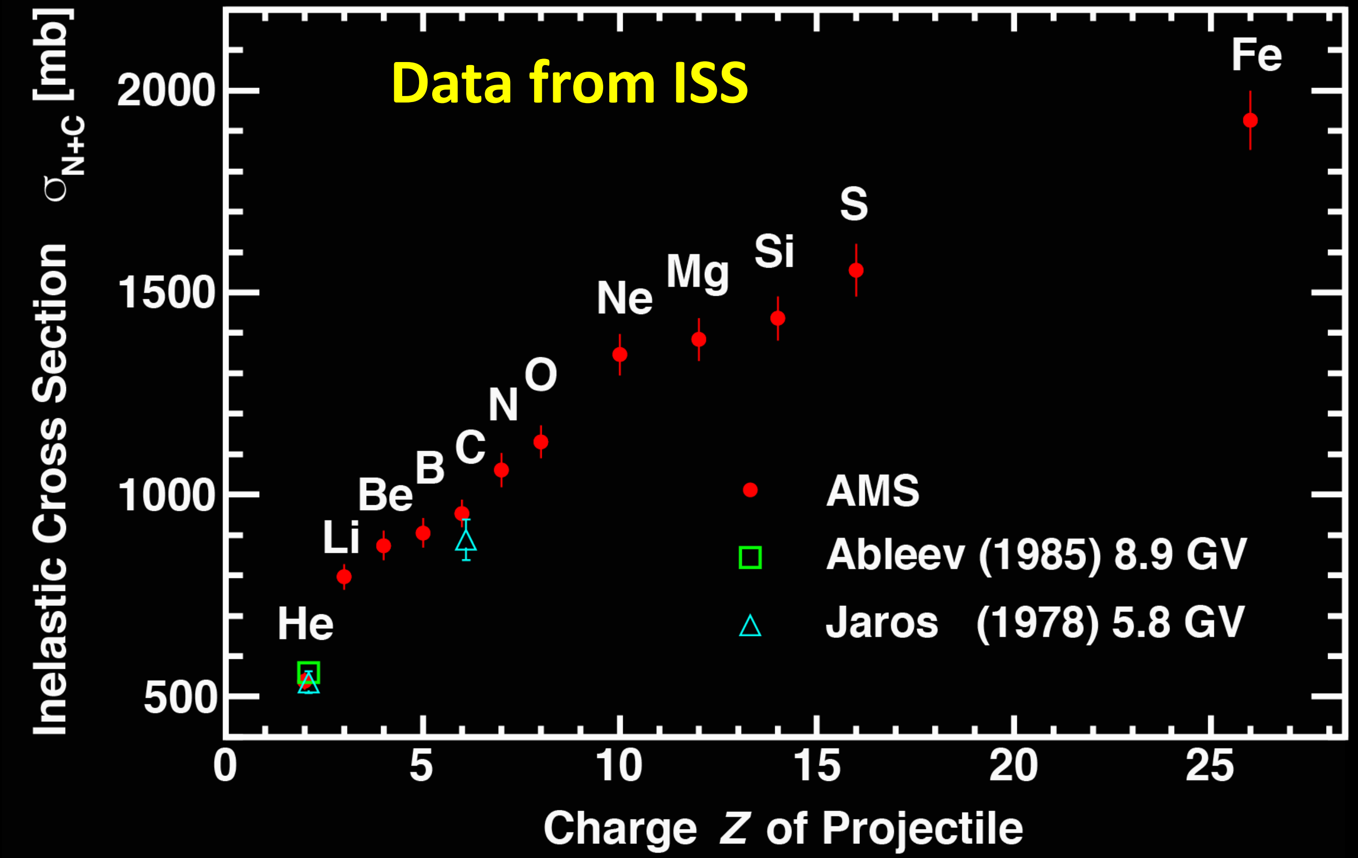




Qi Yan et al Nucl. Phys. A 996 121712 (2020)
AMS Collaboration Phys. Rep. 894, 1 (2021)

AMS measured nuclear inelastic cross-sections

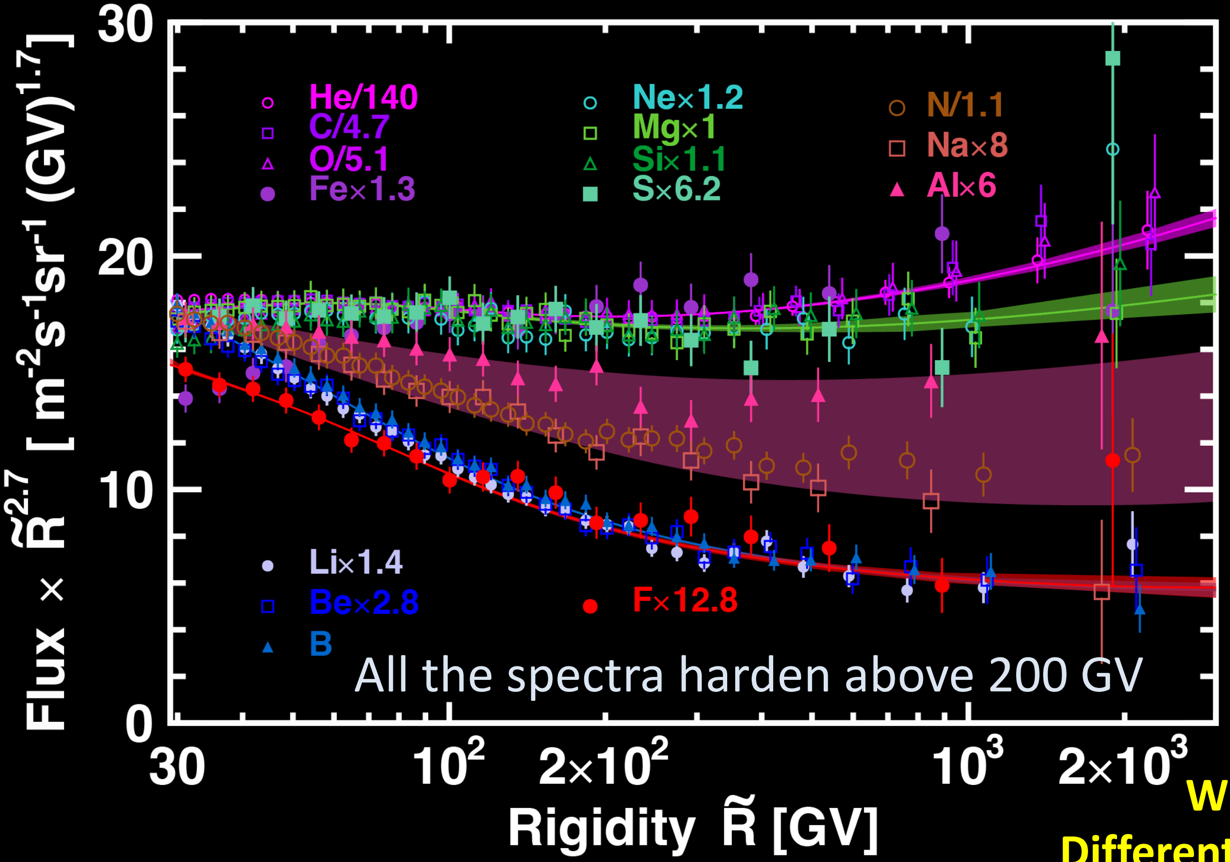
Qi Yan et al Nucl. Phys. A 996 121712 (2020)
AMS Collaboration Phys. Rep. 894, 1 (2021)



Latest AMS results on nuclei

Phys. Rev. Lett. **130**, 211002 (2023)

Primaries and secondaries group each in two classes of rigidity dependence



Primaries group in two classes:

He, C, O, and Fe

Ne, Mg, Si, and S

Secondaries are different from primaries. And they also group in two classes: **Li, Be, B** and **F**

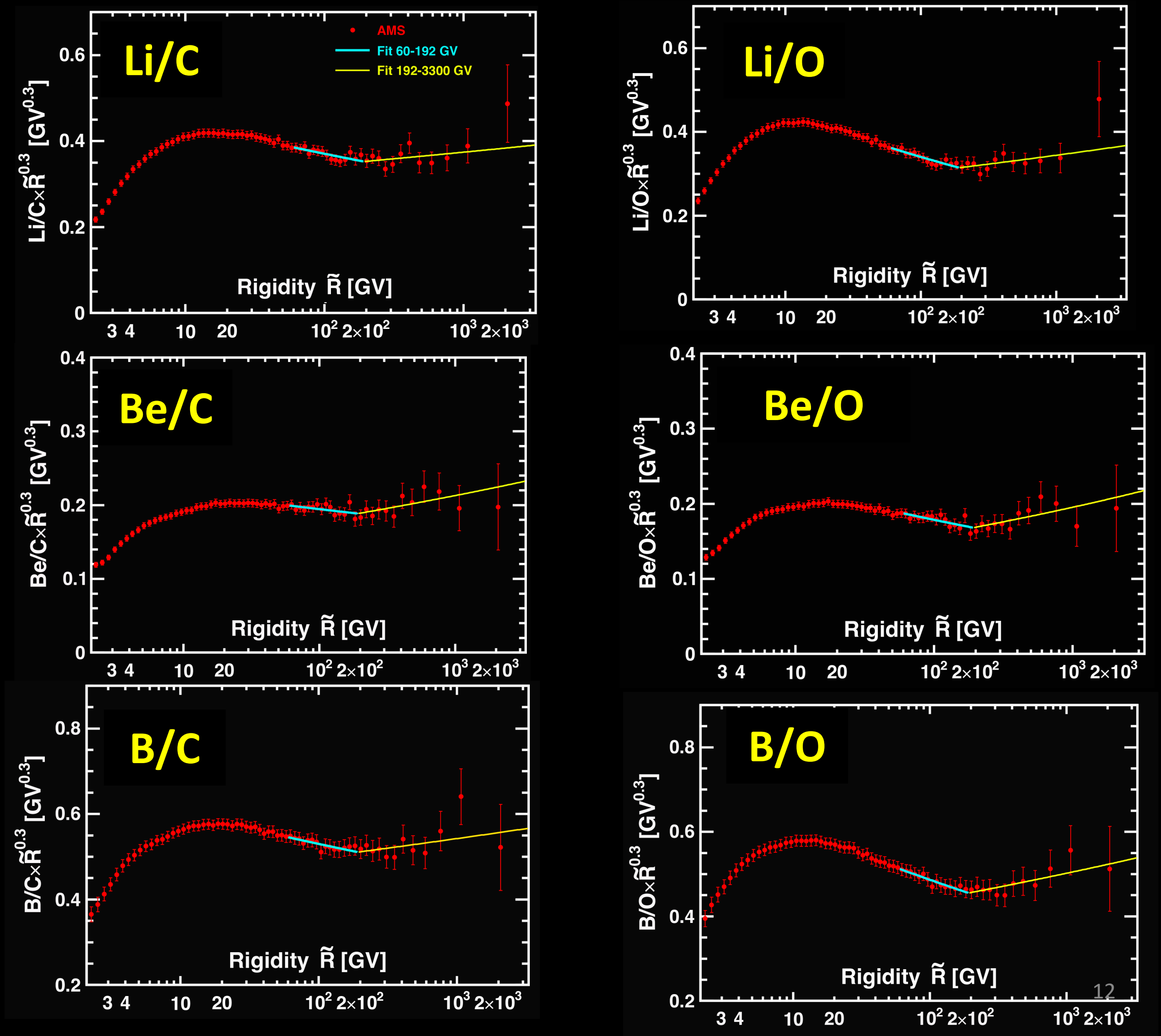
What is all this suggesting?

Different origin of the different classes?

Also secondary cosmic-ray spectra Li, Be nad B, harden above 200 GV but they harden more (about twice) than their primary progenitors

Secondary/Primary = *CR* $^{\Delta}$

AMS found
***Δ* is not a constant**



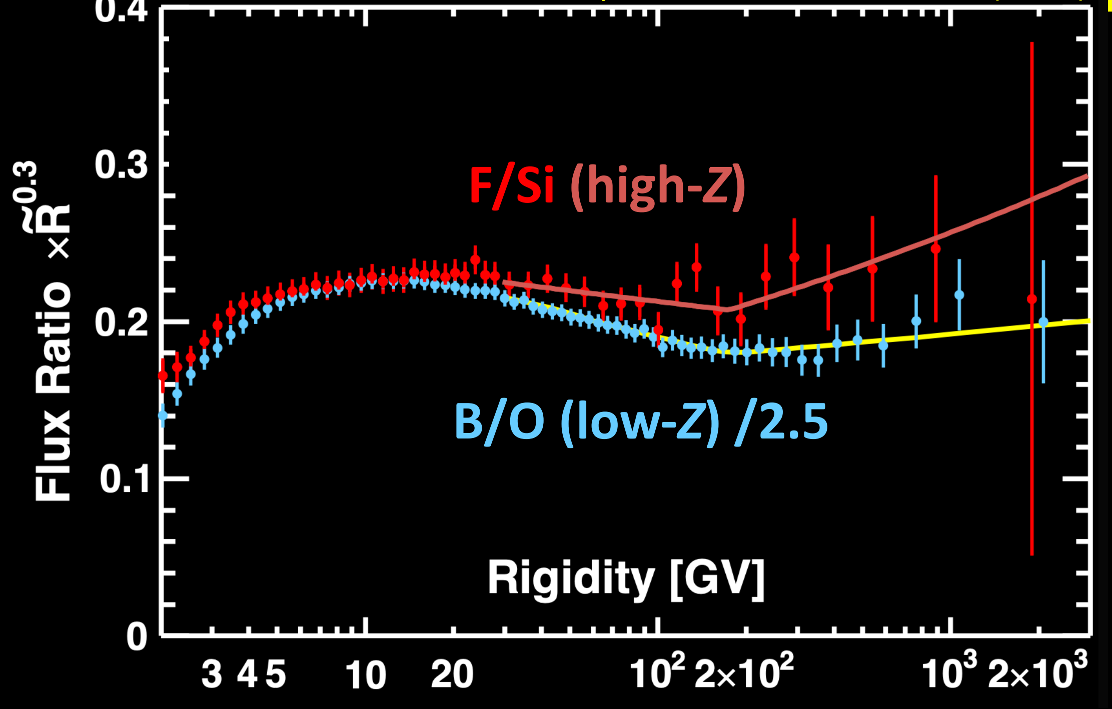
AMS collaboration Phys. Rev. Lett. **120**, 021101 (2018)

AMS result on Fluorine spectrum

Phys. Rev. Lett. **126**, 081102 (2021)

The heavy secondary-to-primary ratio F/Si differs significantly from light secondary-to-primary ratios , B/O, B/C, Li/O, etc..

AMS Collaboration. Phys. Rev. Lett. 126, 081102 (2021)

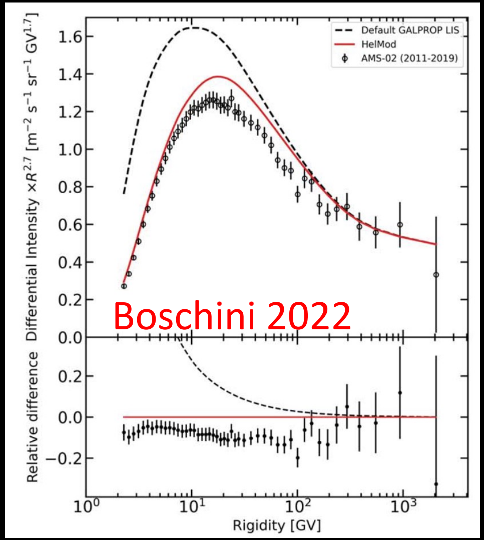


What is this suggesting?

Different propagation properties between light and heavy?

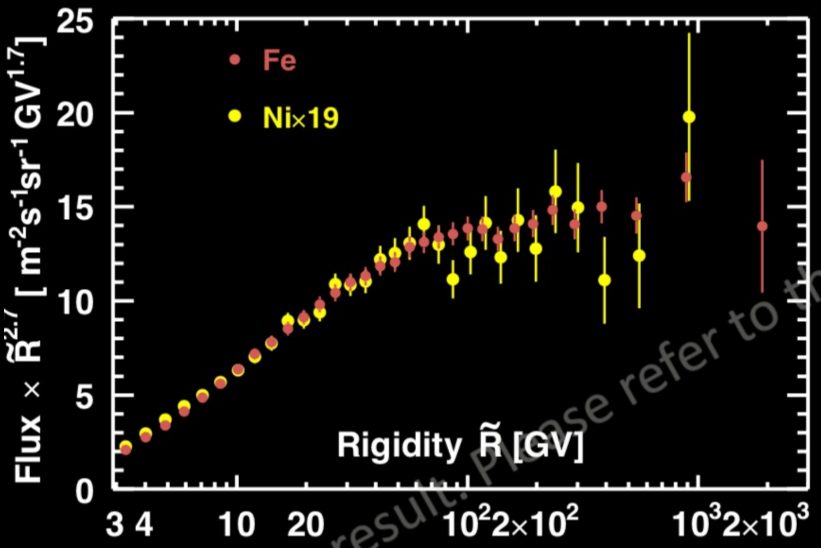
(see Ferronato-Bueno et al A&A, 688, A17 (2024))

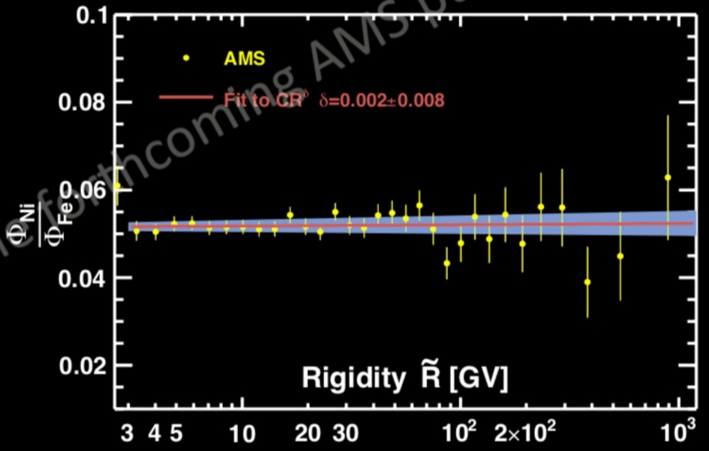
or primary component in fluorine?



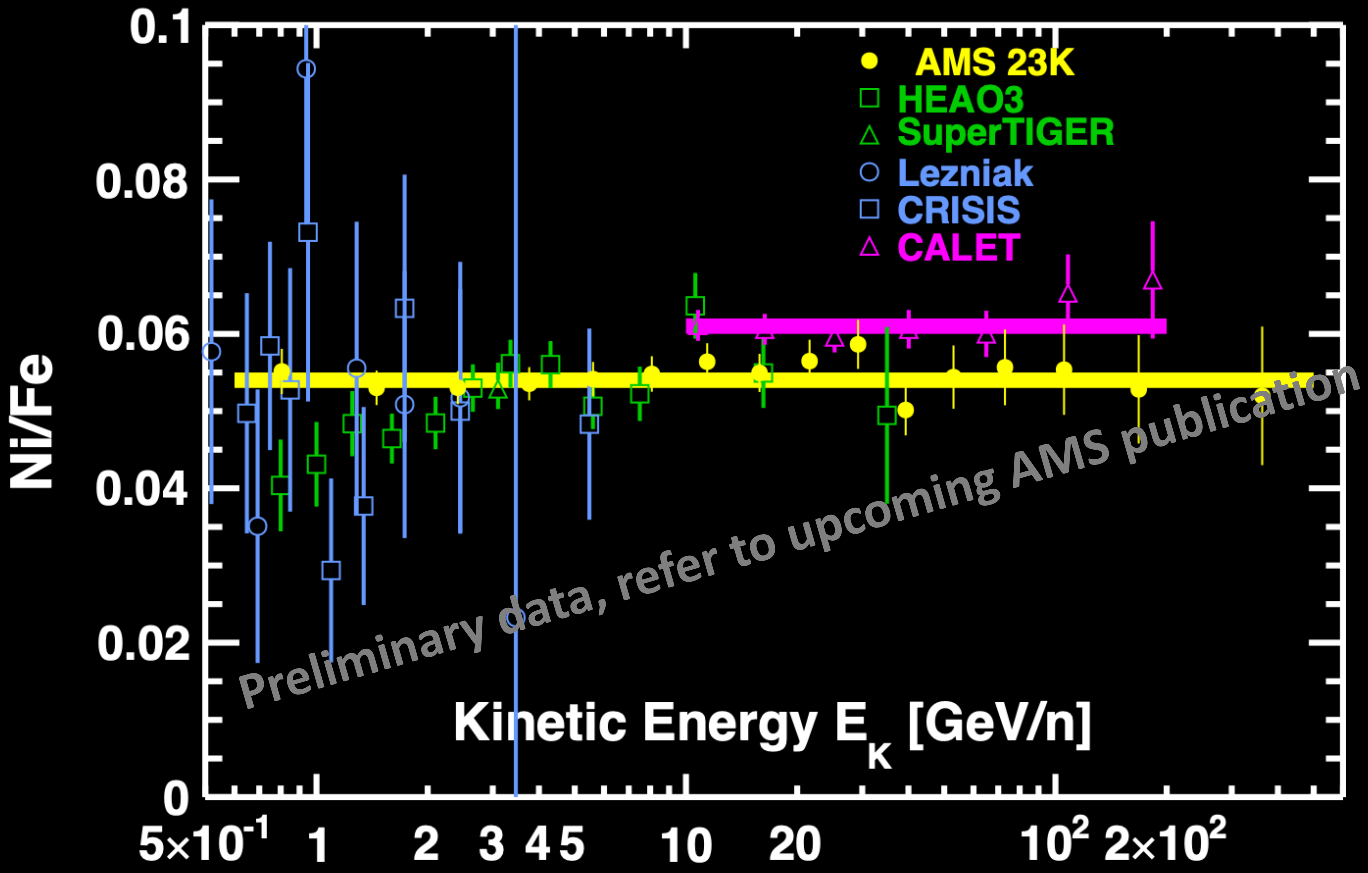
Latest results on very heavy primary cosmic rays: Nickel nuclei

AMS Nickel flux: rigidity dependence is similar to Fe

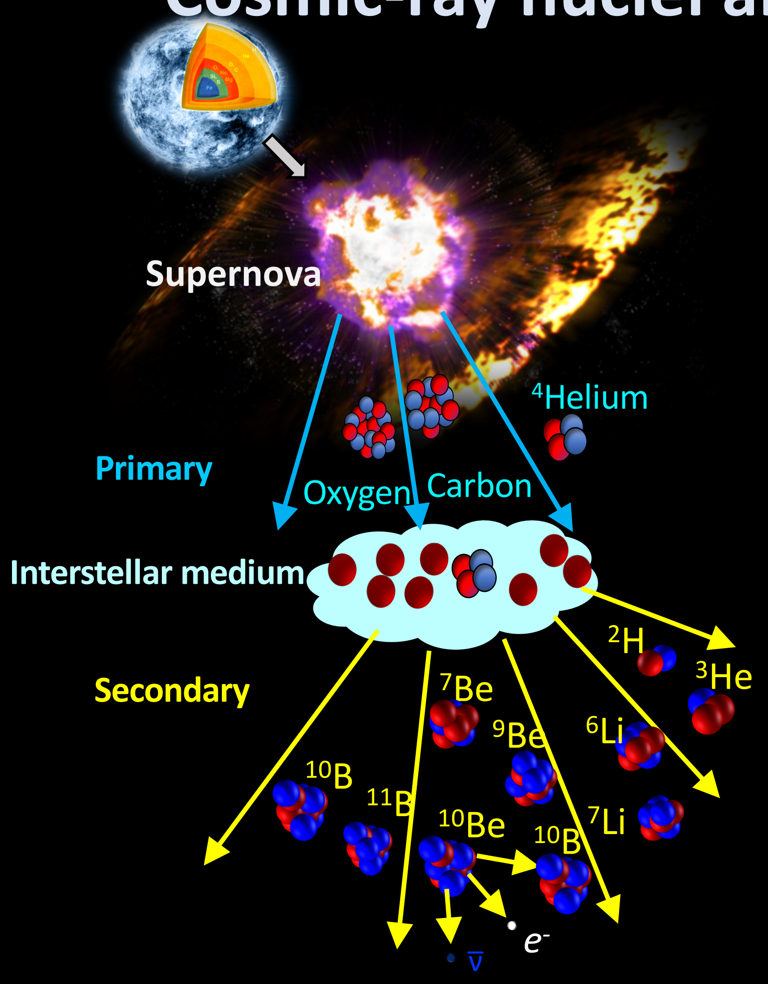




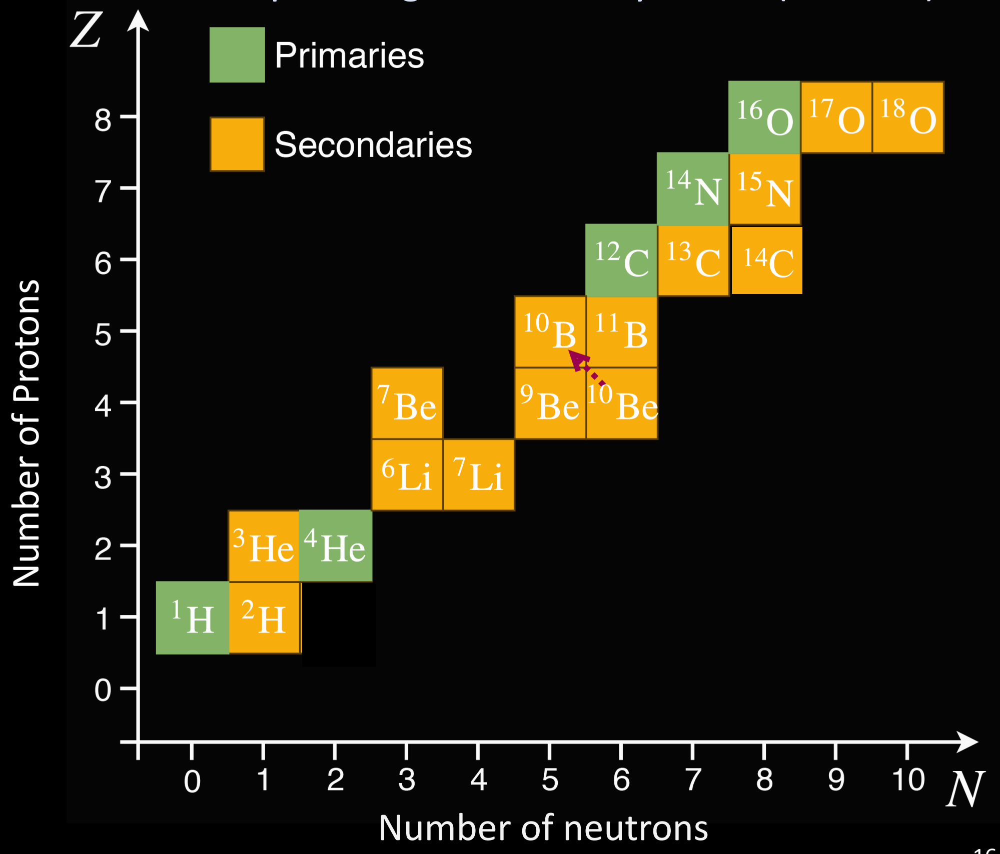
AMS Ni/Fe Flux Ratio



Cosmic-ray nuclei are mixtures of two or more isotopes



Isotopes in light cosmic-ray nuclei (1≤Z ≤8)



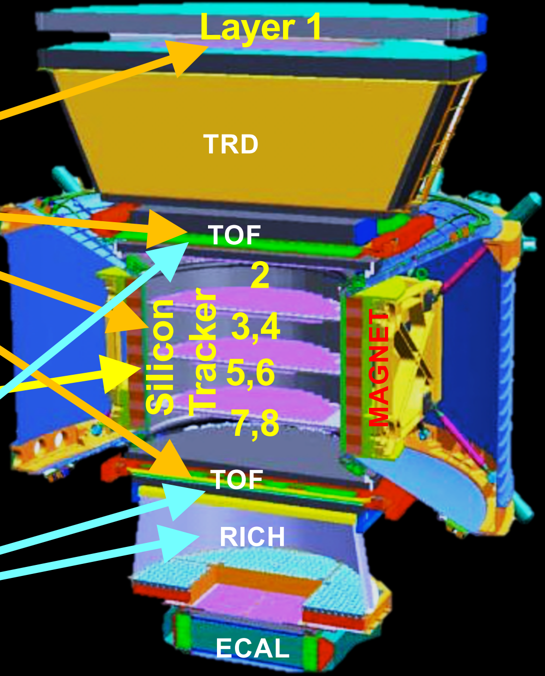
Measurement of CR nuclei isotopic composition with AMS

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

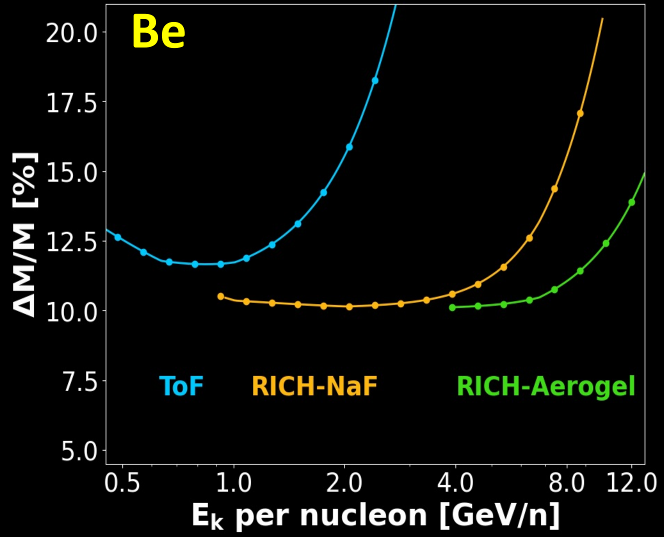
Charge Z from Silicon Tracker and TOF

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

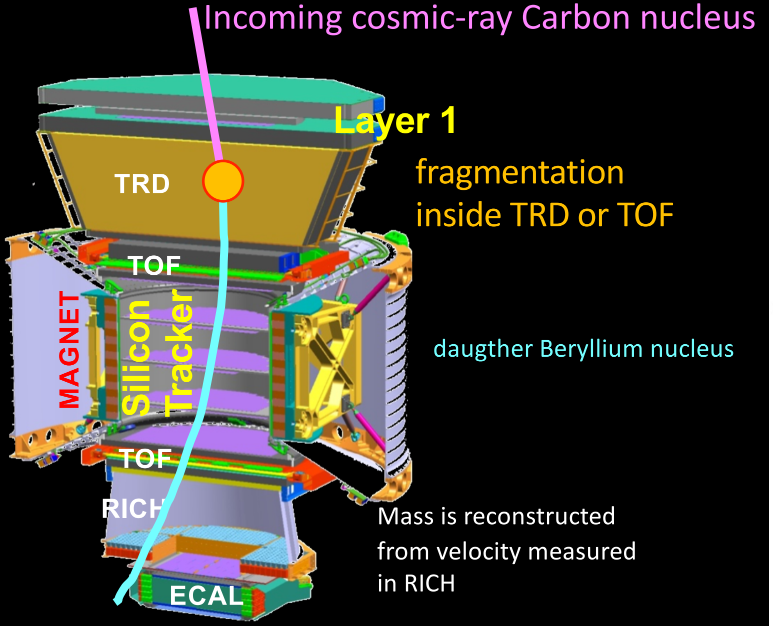


The isotopic composition is extracted from mass template fits of mass distributions in bins of E_k/n

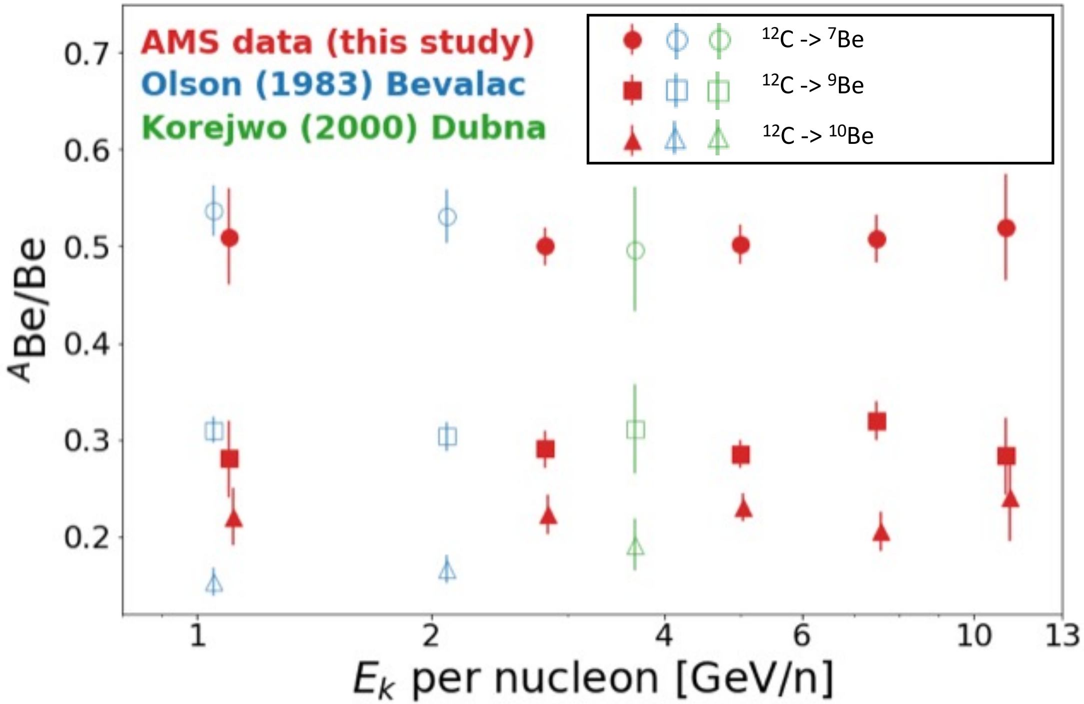
Measurement of cosmic-ray nuclei isotopic composition with AMS

Extensive checks of mass templates definition, simulation of detector response and nuclear fragmentation cross-sections are done

Example: check of fragmentation background simulation for Be isotopes



Jiahui Wei (PhD thesis), Univ. Genève, 2021 - Sc. 5582 - 2021/08/24
https://doi.org/10.13097/archive-ouverte/unige:155018

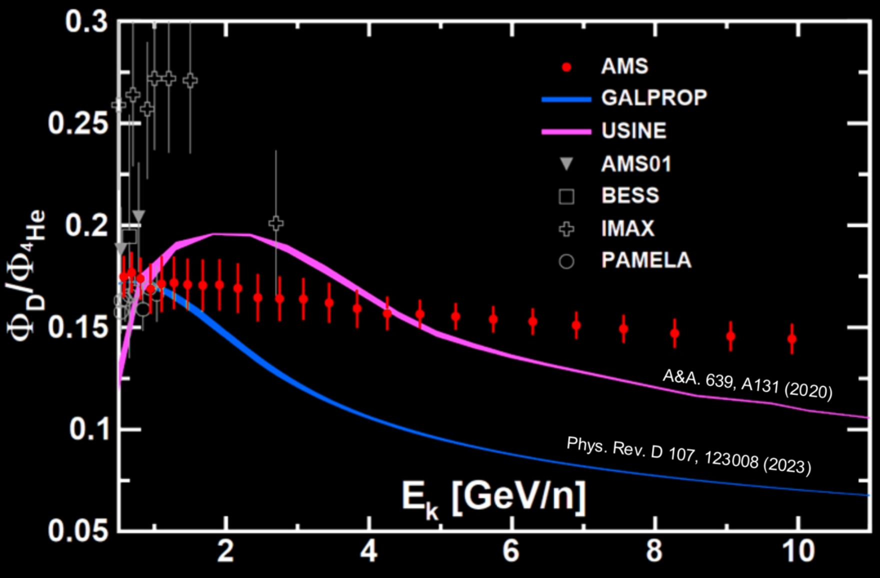


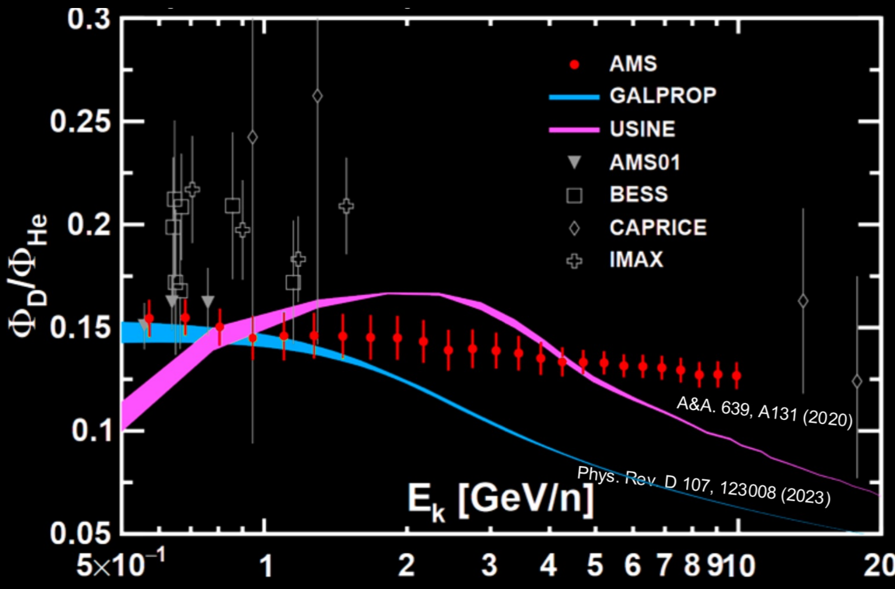
AMS result on Deuterons

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

D are considered to be secondary cosmic rays originating mainly from fragmentation of 4He

Model calculations do not reproduce D/^{4}He and D/He flux ratios



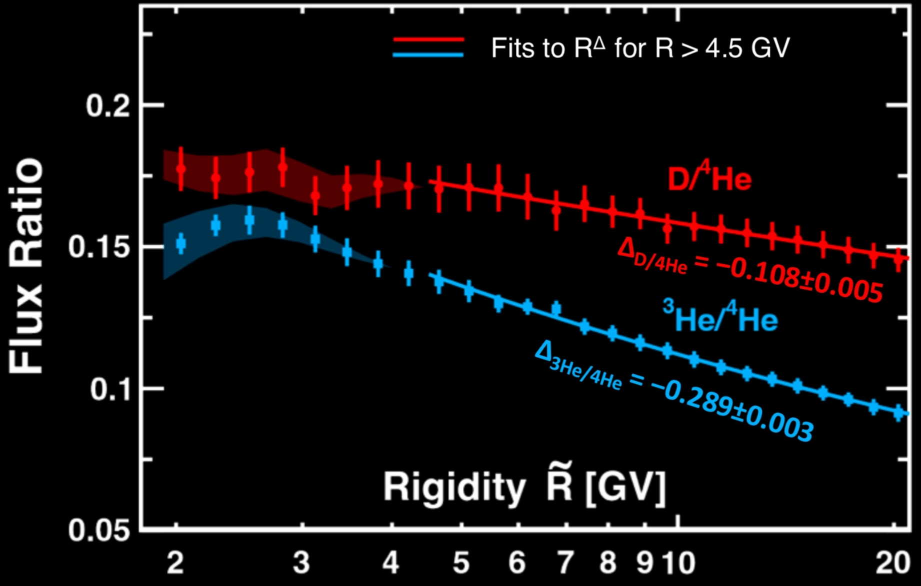


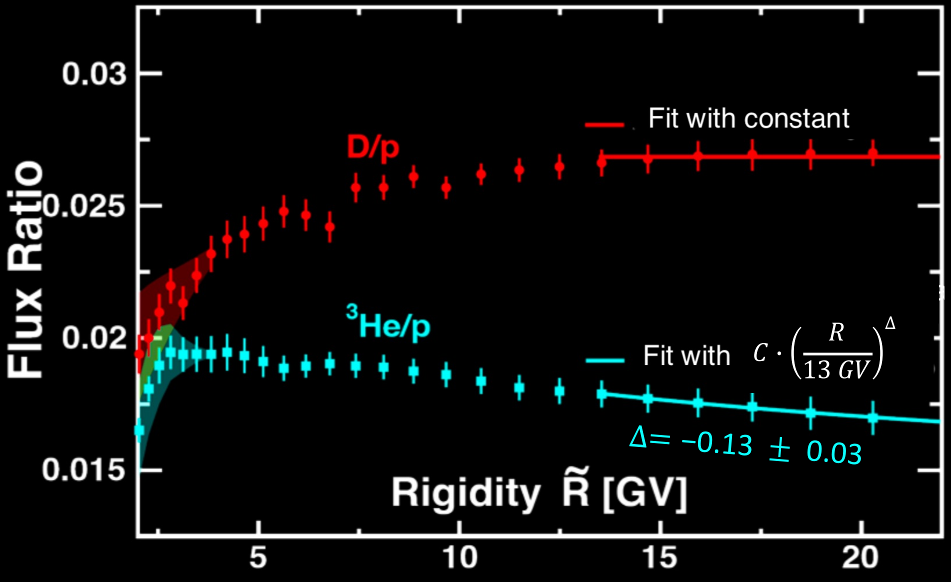
AMS result on Deuterons

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



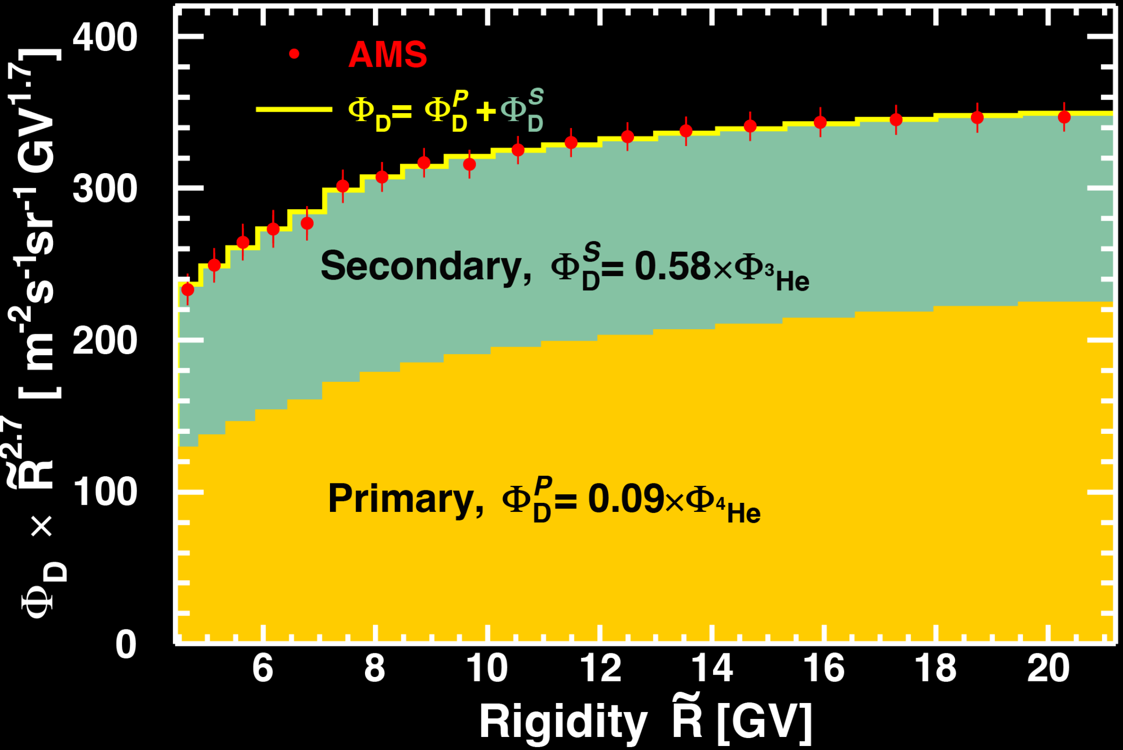


Is this suggesting a primary component of deuterons?

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

AMS result on Deuterons

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

Cosmic lithium contains two isotopes 6Li and 7Li

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

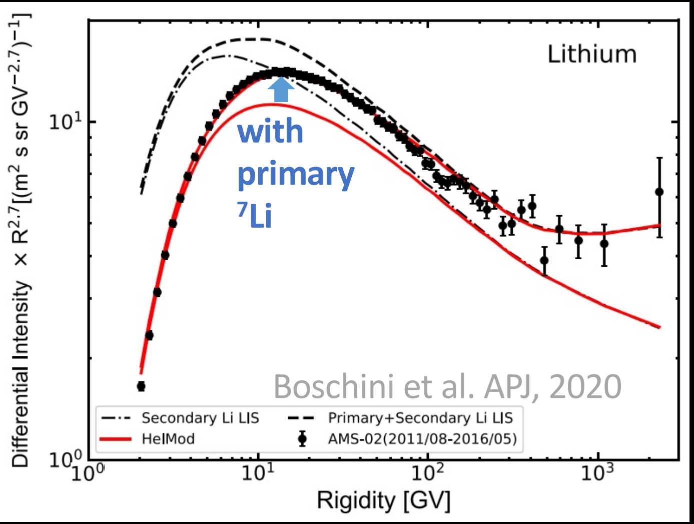
^{7}Li might have a primary component from Big Bang nucleosynthesis or low-mass stars

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

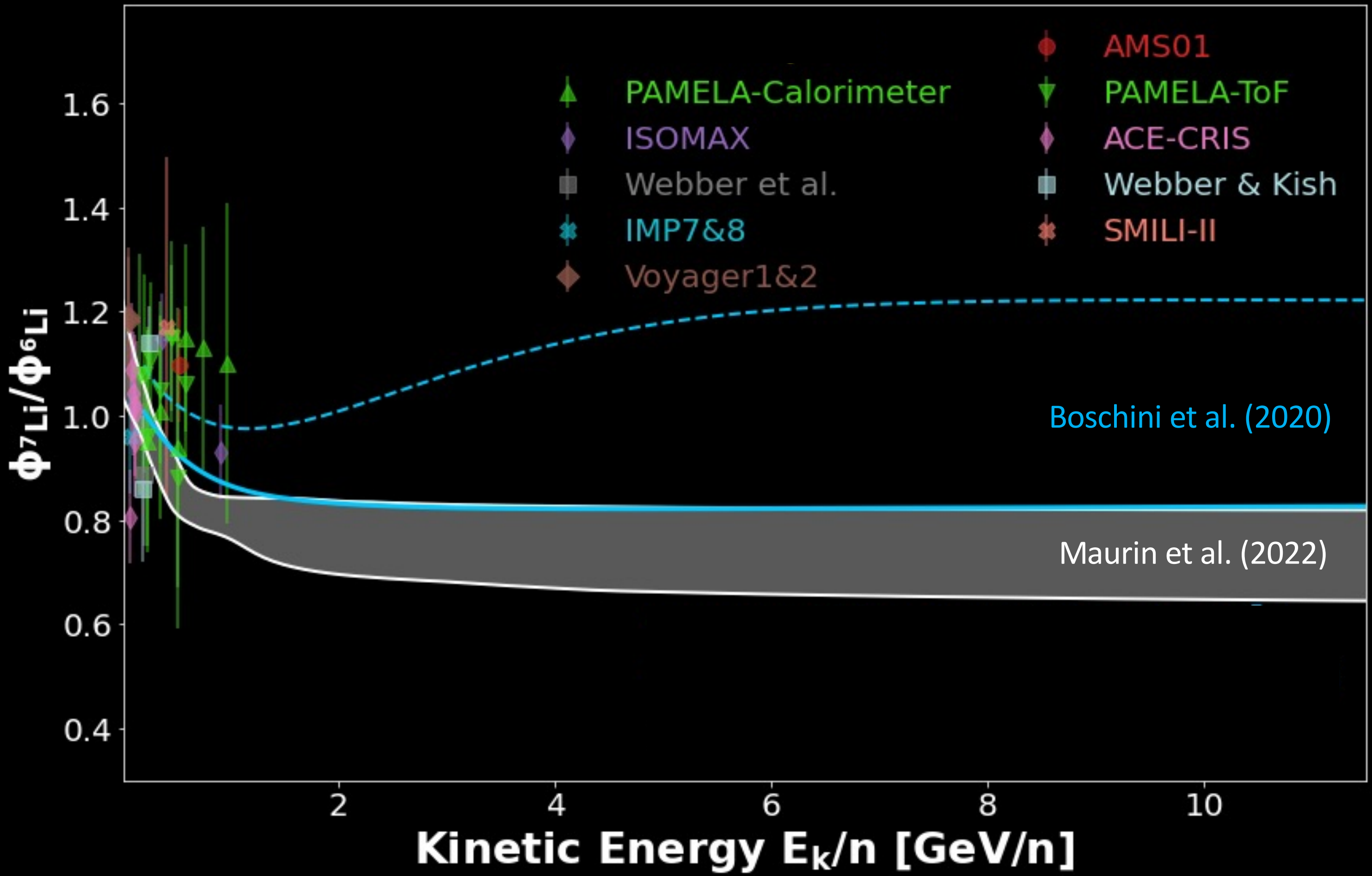
Hint of a primary lithium ^{7}Li component
(Boschini et al 2020)

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 ^7Li

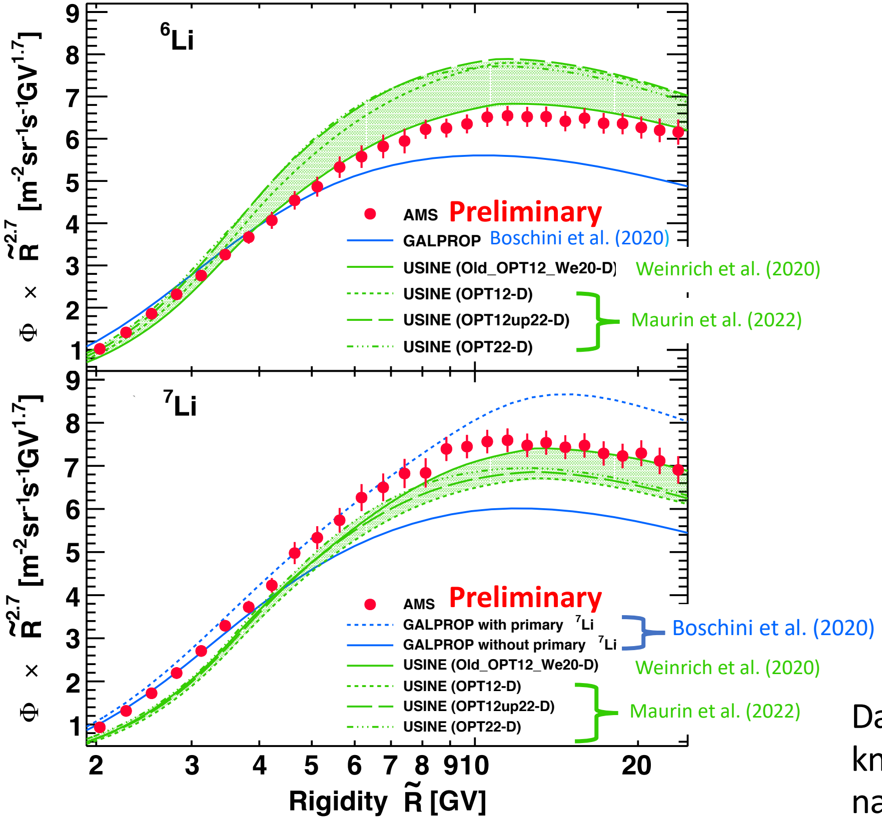
only secondary Li

model uncertainty from Li production cross section

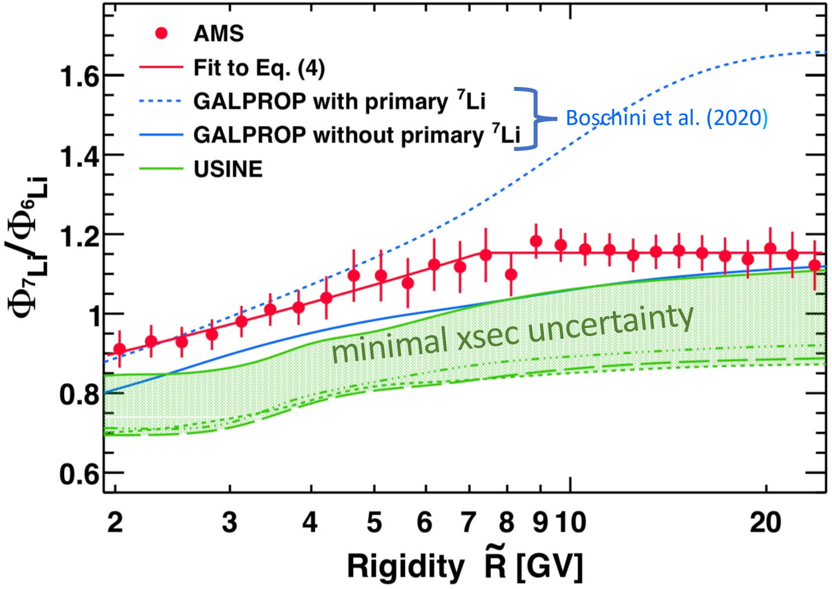
Testing the origin of Lithium Isotope Fluxes

Comparison with model calculations

Preliminary data, please refer to upcoming AMS publication



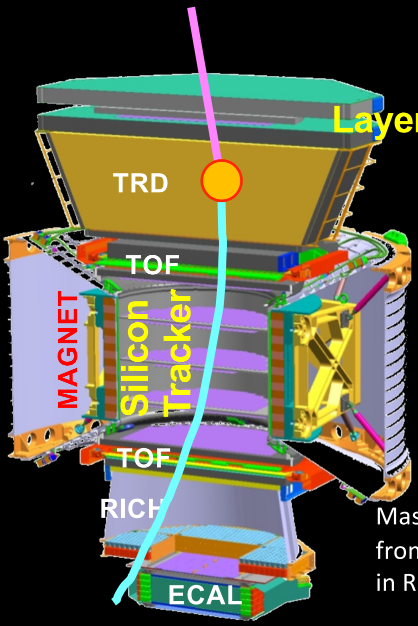
No evidence of primary ^{7}Li



Data and (USINE) model calculations can be reconciled by a better knowledge of fragmentation branching ratios to 6Li and 7Li: naively -8% rescaling of 6Li flux and +8% rescaling of 7Li flux

Measuring isotope branching ratios with AMS

Incoming cosmic-ray Carbon nucleus

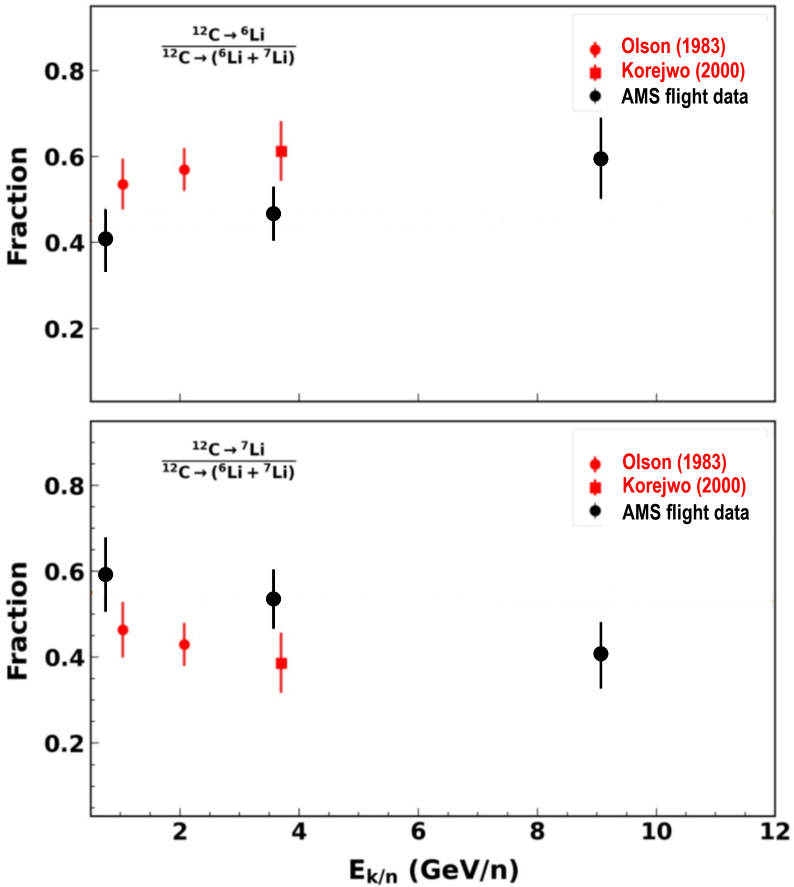


fragmentation inside TRD or TOF

Lithium daughter nucleus

Mass is reconstructed from velocity measured in RICH

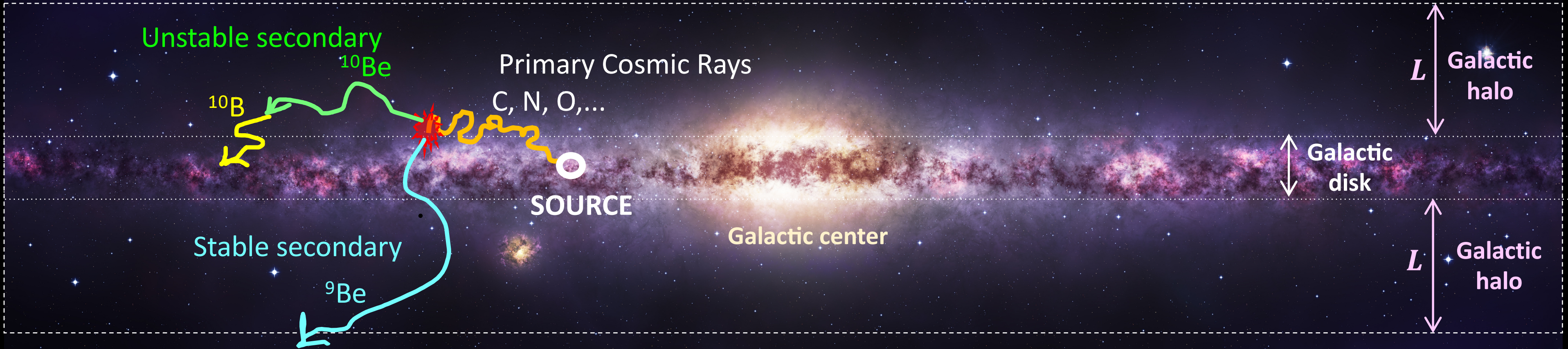
Manbing Li PhD thesis Univ. Genève, 2024 - Sc. 5842 - 2024/06/25
https://doi.org/10.13097/archive-ouverte/unige:180626



Measuring cosmic-ray propagtion volume with radioactive clocks

Secondary cosmic-ray nuclei include several radioactive isotopes with a decay lifetime comparable with the cosmic-ray residence time in the Galaxy, such as ^{10}Be, ^{26}Al, ^{36}Cl, and ^{54}Mn.

Stable secondaries as ^{9}Be propagate in the entire galactic halo, while ^{10}Be decay to ^{10}B before reaching the boundary of the Galaxy.



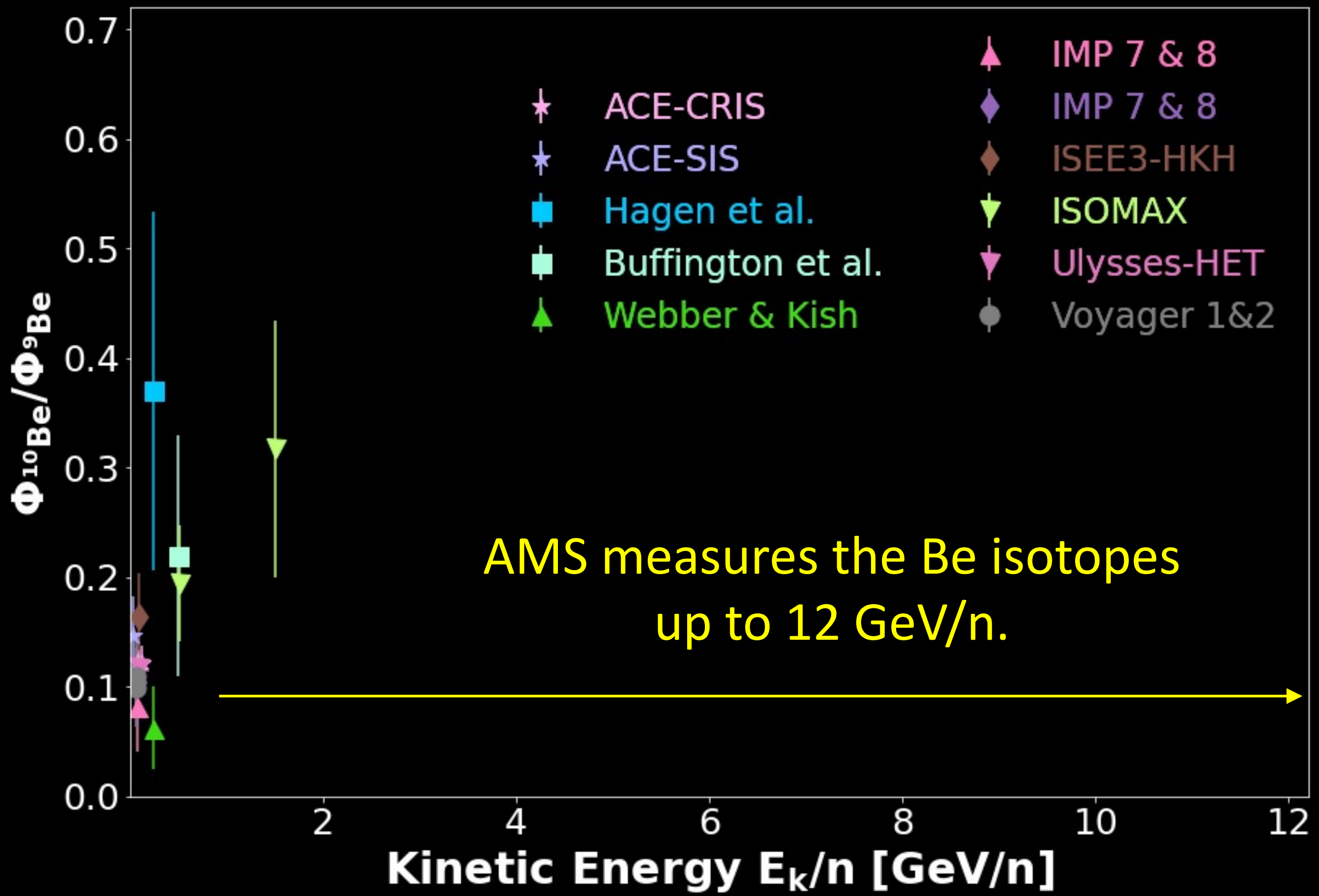
The fraction of survived radioactive isotopes at Earth measures the Galactic halo size L.

This can be obtained

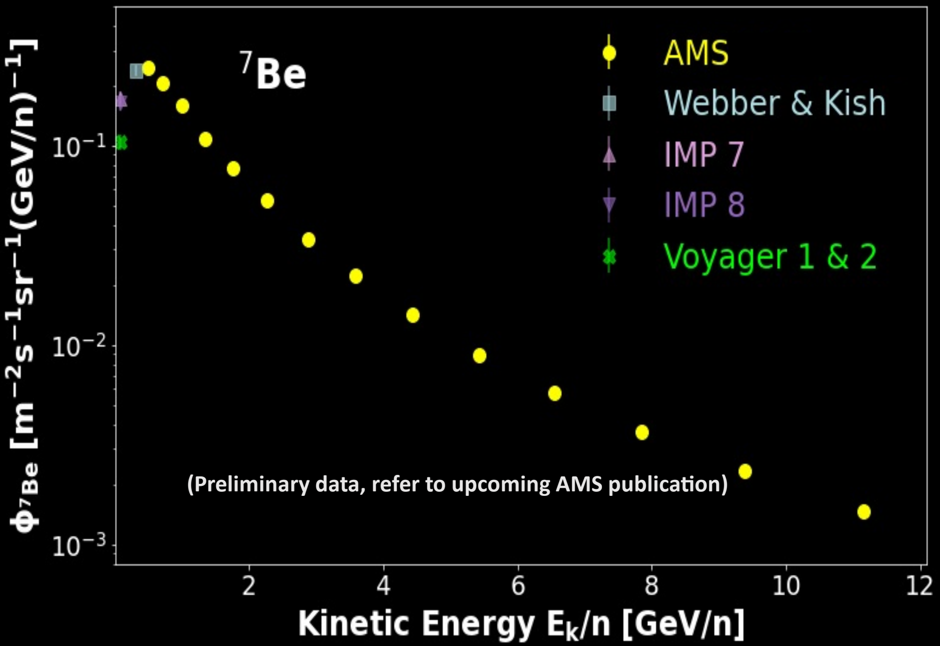
Indirectly from mother-to-daughter ratio Be/B, Al/Mg, Ar/Cl, → larger uncertainty on L due to xsec

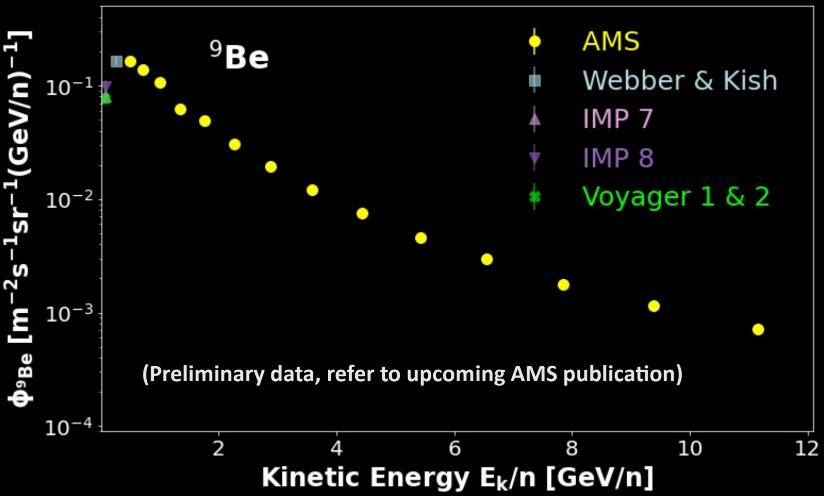
Or more directly from the unstable-to-stable secondaries ratio ^{10}Be/^{9}Be -> more difficult to measure

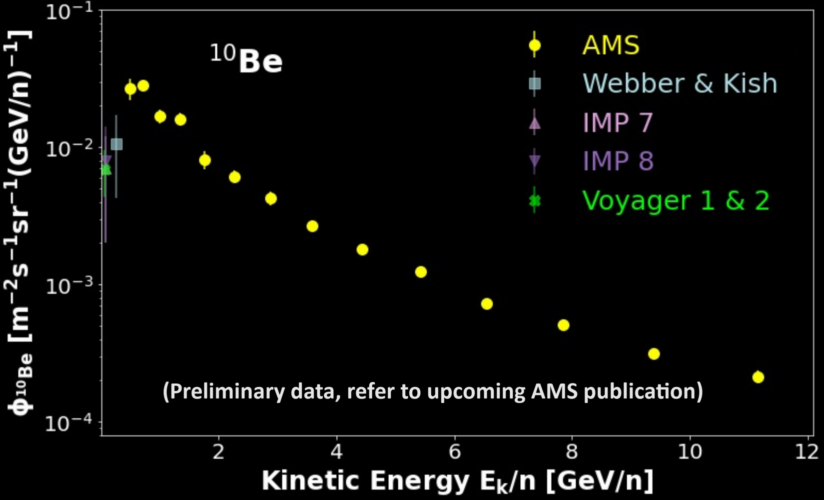
Cosmic $^{10}Be/^{9}Be$ Flux Ratio Before AMS-02



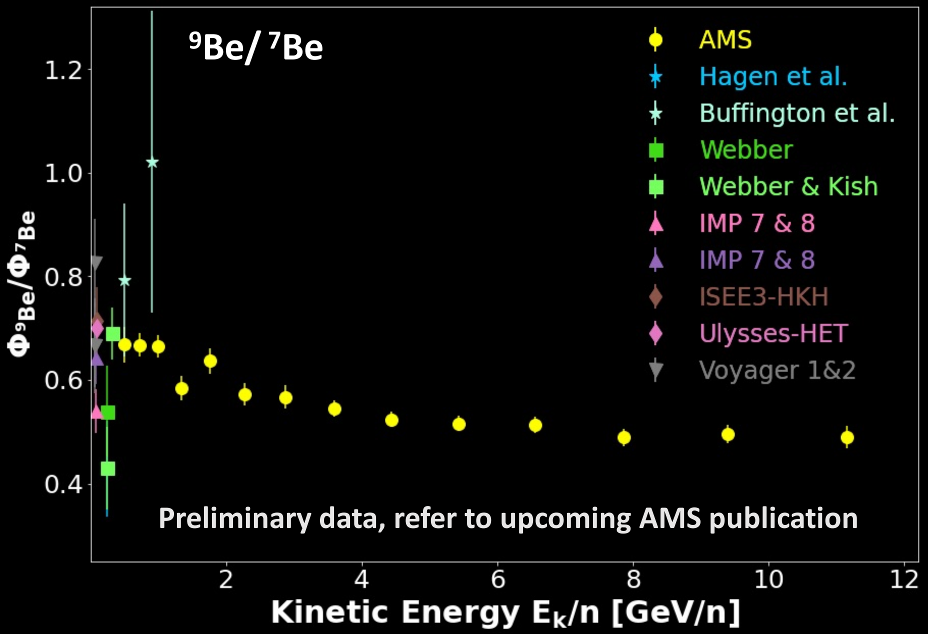
Beryllium Isotope Fluxes

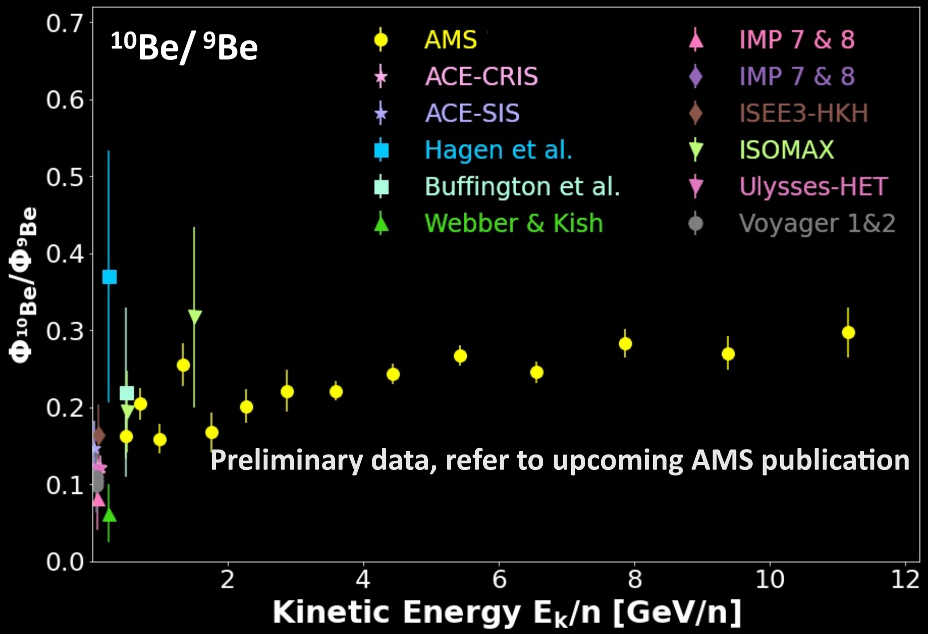




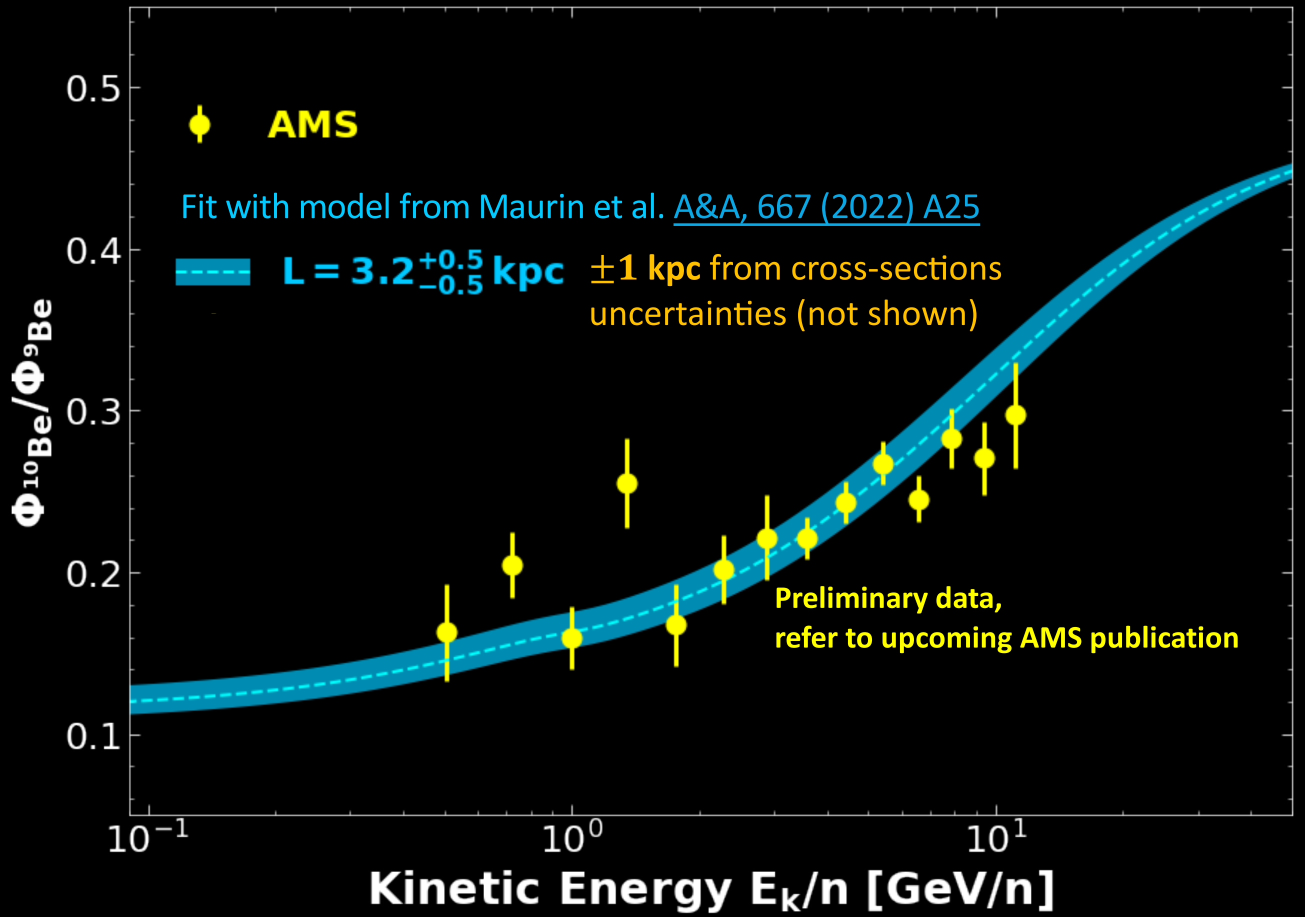


Beryllium Isotope Flux Ratios

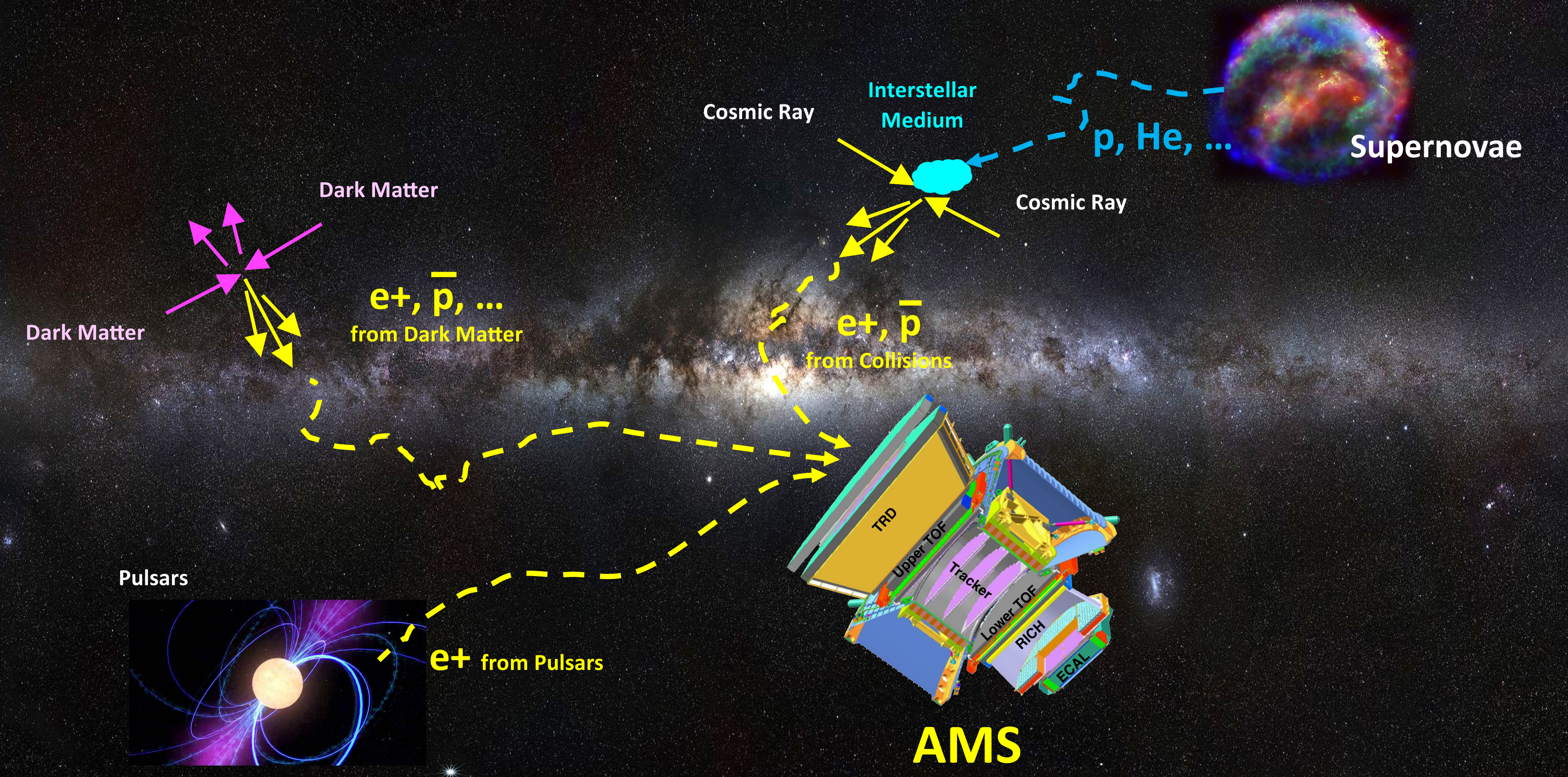




Galactic halo size L with AMS $^{10}Be/^{9}Be$ Flux Ratio



Latest Results on cosmic particles: e+, e−, and anti-protons



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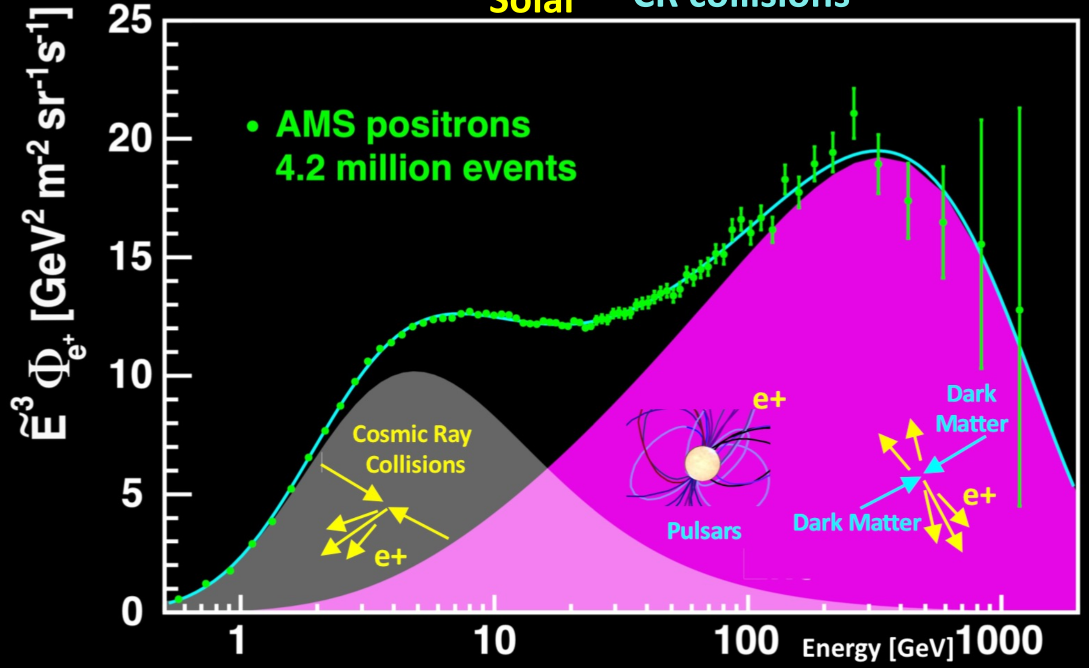
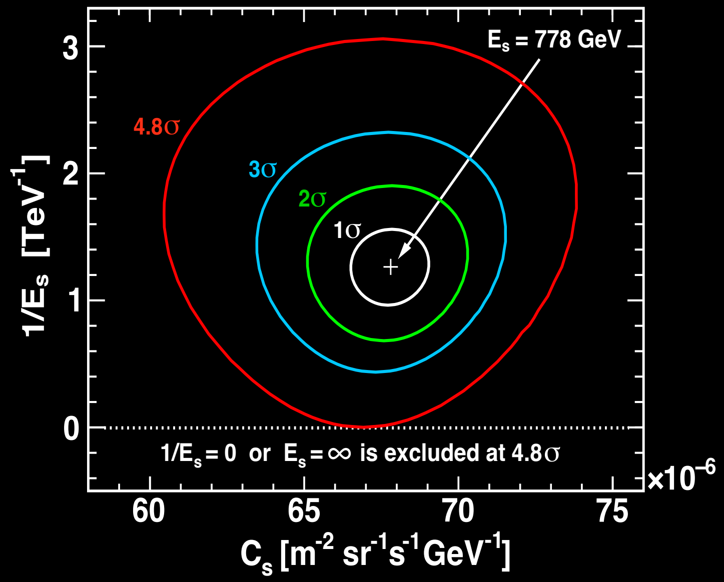
AMS positron flux measurement

Well described by the sum of low-energy part from cosmic ray collisions plus a high-energy source term from pulsars or dark matter with a cutoff energy E_S

$$\Phi_{e^+}(E) = \frac{E^2}{\hat{E}^2}\left[C_d(\hat{E}/E_1)^{\gamma_d} + C_s(\hat{E}/E_2)^{\gamma_s}\exp(-\hat{E}/E_s)\right]$$

Solar CR collisions source term





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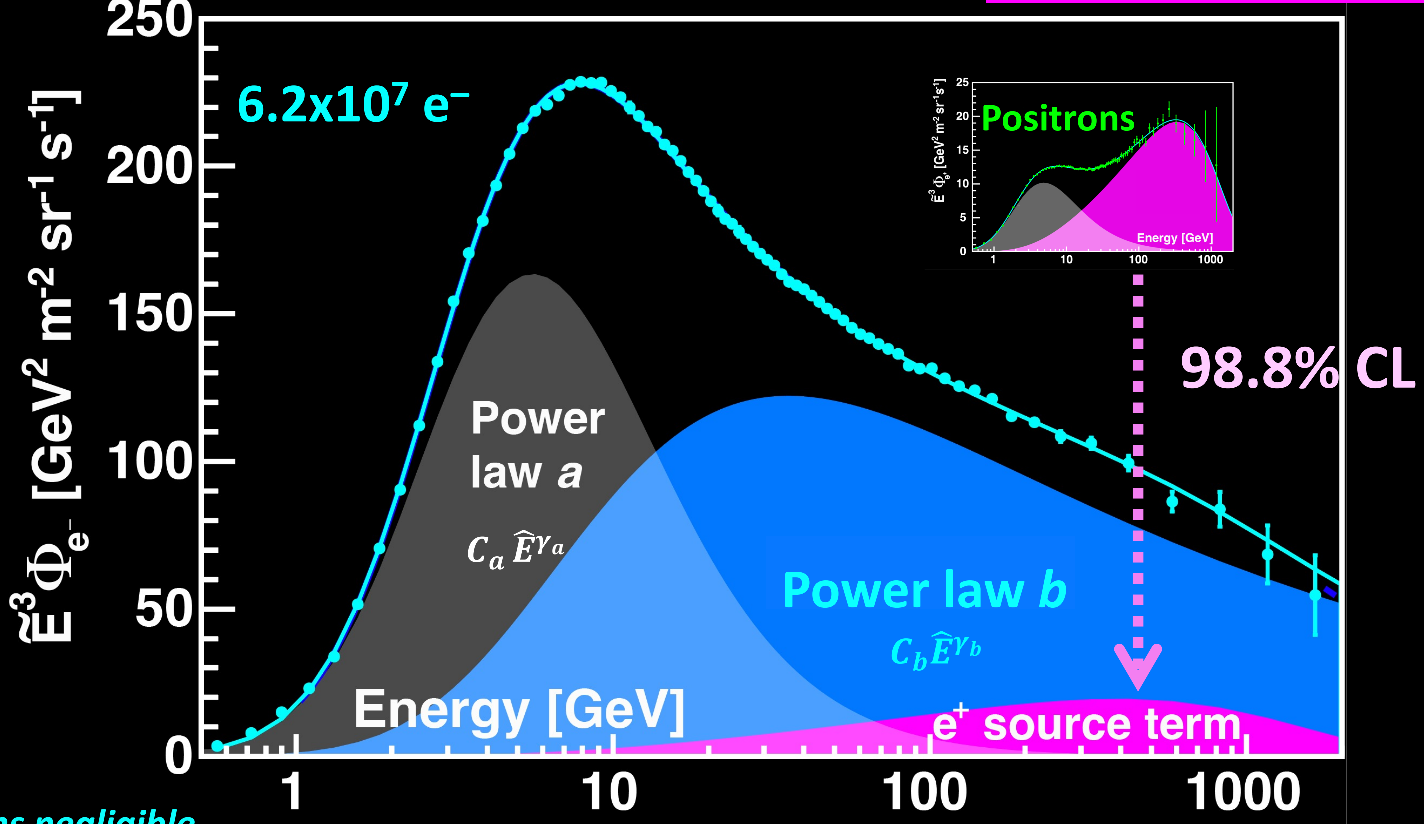
AMS Result on the electron spectrum

The spectrum fits well with two power laws (*a*, *b*) and a source term like positrons



e⁻ from collisions negligible

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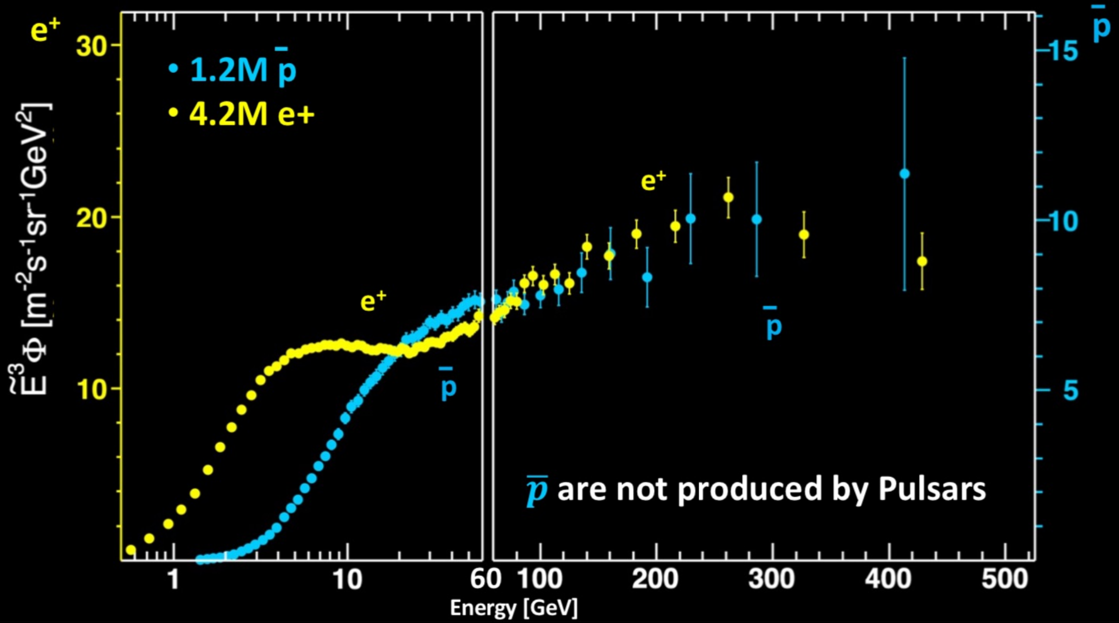
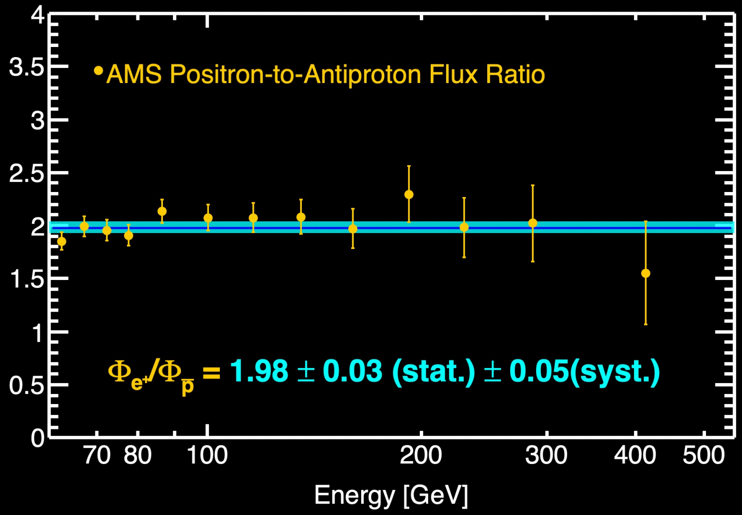
Cosmic Antiprotons and Positrons

Pulsars do not produce antiprotons

Above 60 GeV, the $\overline{p}$ and e^+ fluxes have identical energy dependence





Which is the origin of the high-energy positrons?

Why their spectrum is similar to the antiproton spectrum?

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Summary and Conclusions

In the past hundred years, measurements of charged cosmic rays by balloons and satellites have typically had ~(30-50)% accuracy.

AMS is providing cosmic ray information with ~1% accuracy.

The improvement in accuracy and energy range is providing new insights on cosmic-ray origin, acceleration and propagation mechanisms.

AMS data are arising questions to be addressed by a comprehensive model of cosmic rays:

which is the origin of the high-energy positrons ?

why positron and antiproton spectra have identical shape at high energy?

which is the origin of the high-energy deuterons?

why there are two classes of spectra in both primary and secondary cosmic-ray nuclei?

do light and heavy cosmic-ray nuclei propagate in the same way? primary component in fluorine? why Fe and Ni group with the light primaries He, C, and O?

Measurements of production cross-sections are eagerly awaited to answer these questions but also to precisely determine model parameters from current data (as the propagation halo size).

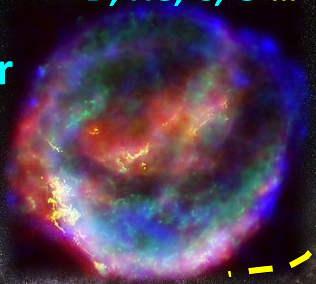
Latest AMS Results on Heavy Antimatter

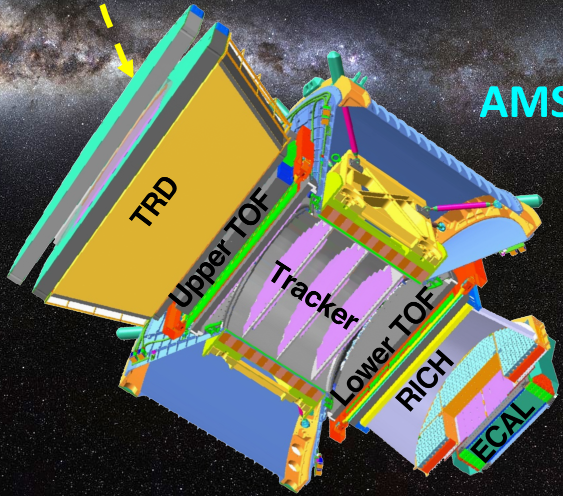
Matter is defined by its mass *M* and charge *Z*.

Antimatter has the same mass *M* but opposite charge –*Z*.

$\overline{\mathrm{D}}$, $\overline{\mathrm{He}}$, $\overline{\mathrm{C}}$, $\overline{\mathrm{O}}$ ...

Antimatter Star





AMS on ISS

AMS is a unique antimatter spectrometer in space

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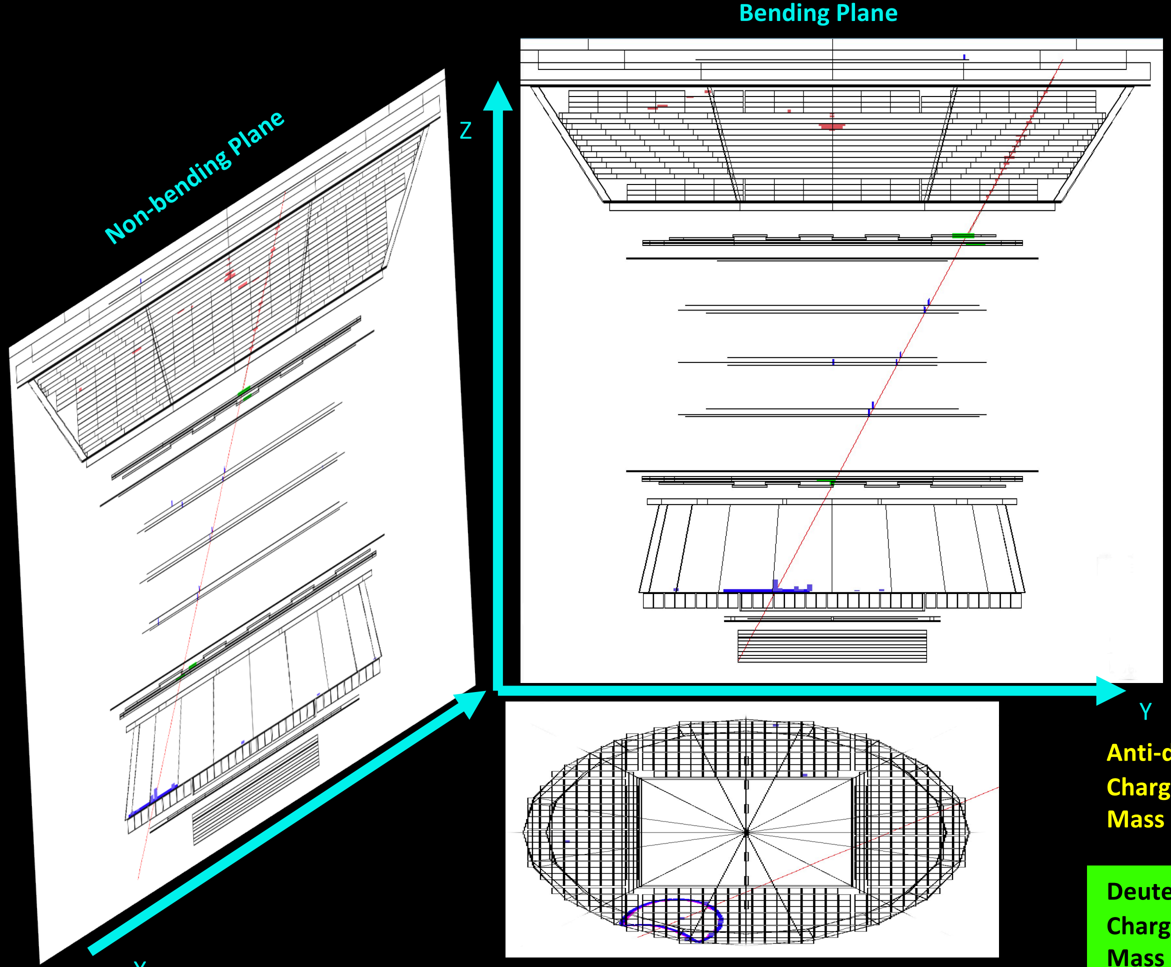
An Anti-Deuteron Candidate from ~100 million deuterons and ~10 billion protons

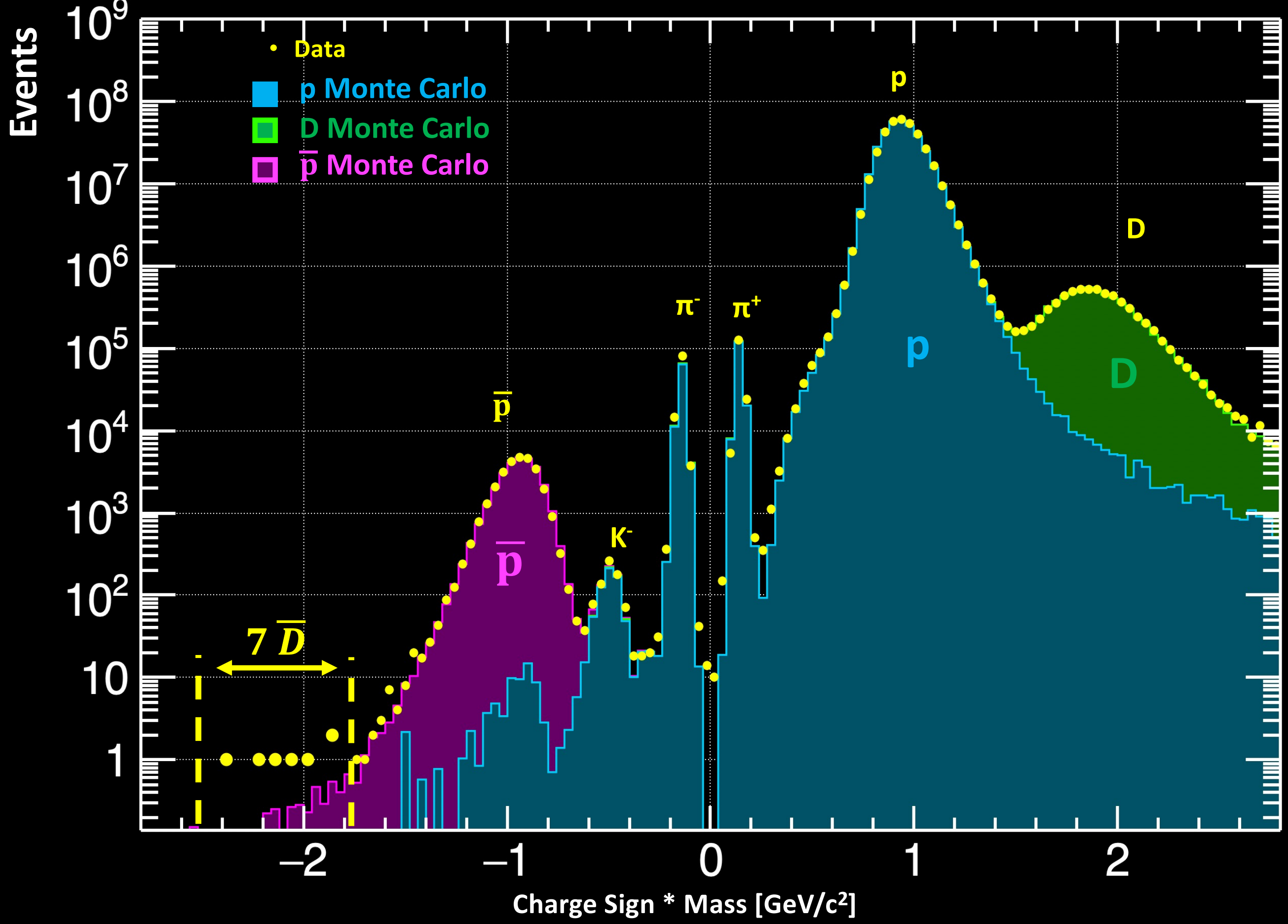


Cherenkov cone in RICH

Anti-deuteron Candidate
Charge = −1.02 ± 0.05
Mass = 1.9±0.1 *GeV/c*^{2}

Deuteron
Charge = +1
Mass = 1.88 *GeV/c*^{2}

Current Anti-Deuteron Results



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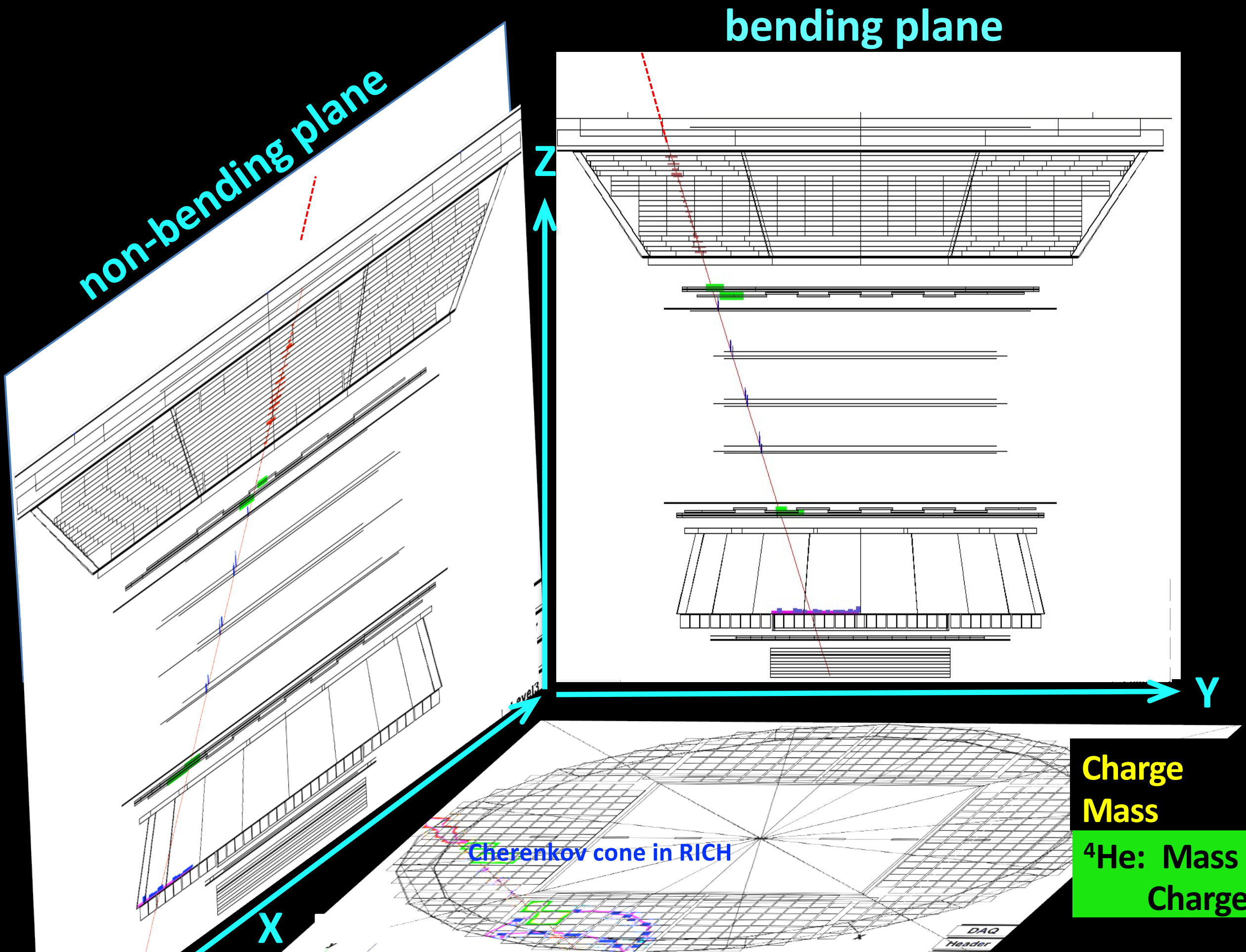
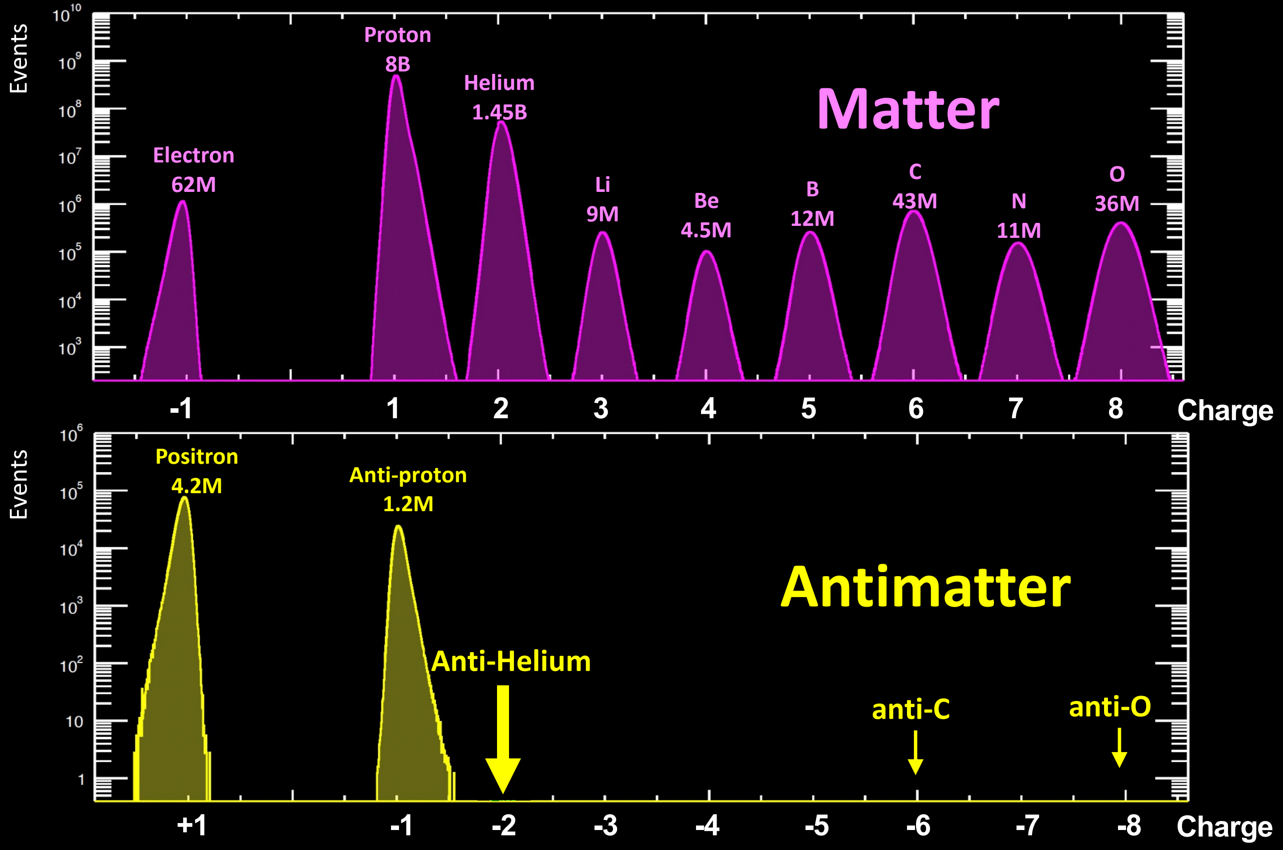
Anti-⁴Helium Event



Charge = −2.05 ± 0.05
Mass = 3.81 ± 0.29 GeV/c^2

^{4}He: Mass = 3.73 GeV/c^2
Charge = +2

Current Matter and Antimatter Statistics



By 2030, AMS will have additional measurement points in the study of antimatter: anti-deuterons, anti-helium, anti-carbon, and anti-oxygen.