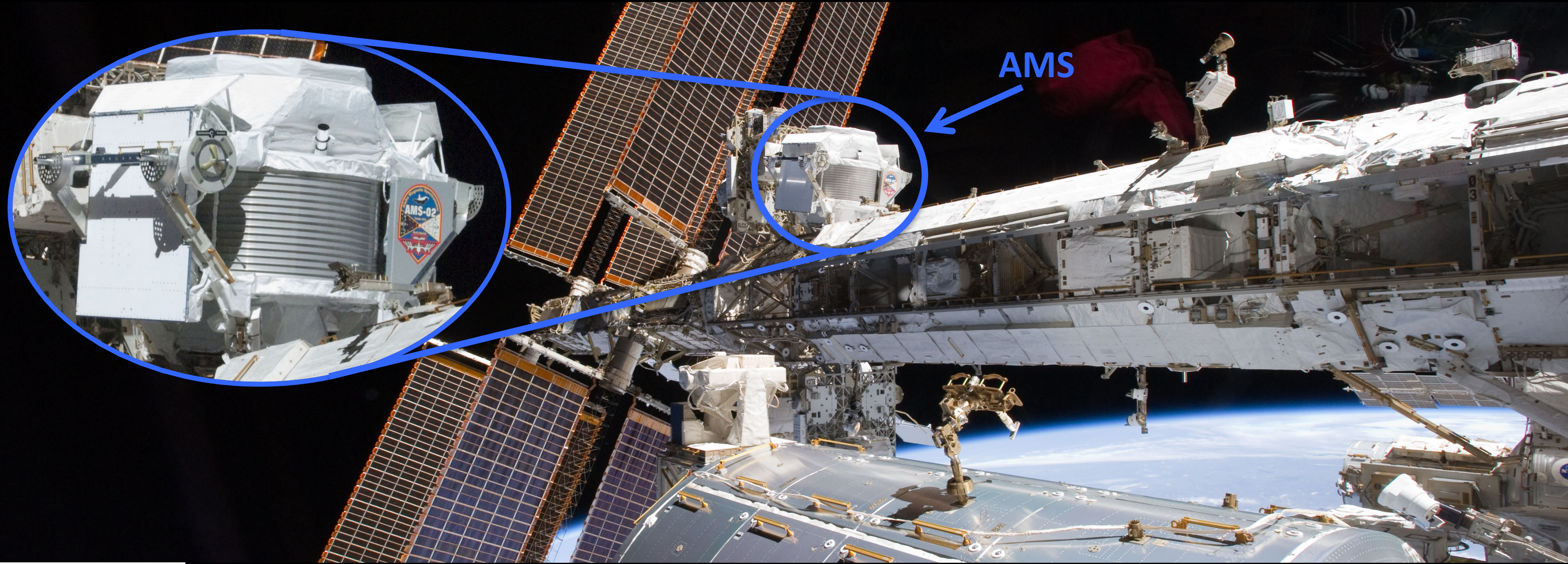
Latest Results from the Alpha Magnetic Spectrometer on the International Space Station

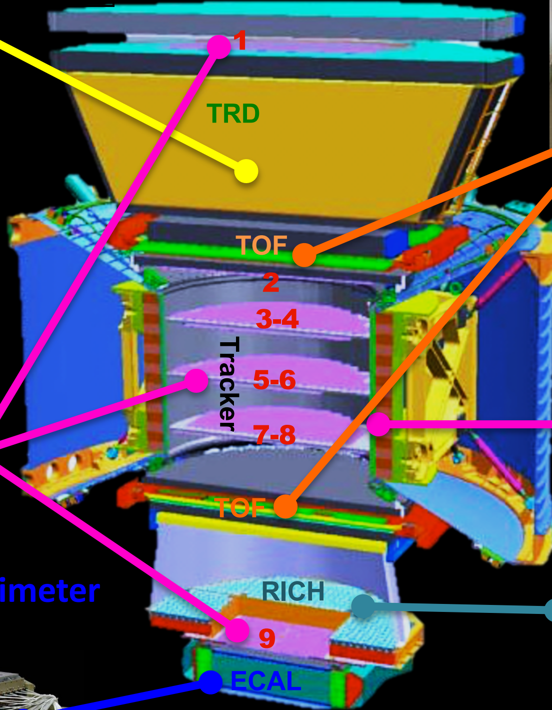


Dr. Mercedes Paniccia
University of Geneva (Switzerland)

12th January 2021
CERN EP Seminar

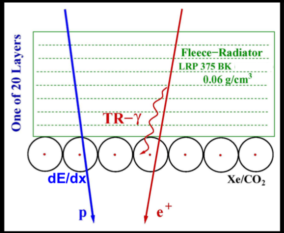
UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES
Département de physique nucléaire et corpusculaire

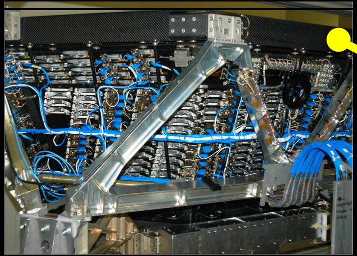
AMS-02: A TeV precision magnetic spectrometer



Transition Radiation Detector

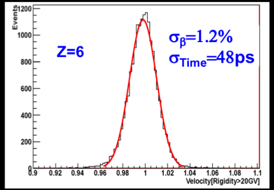
Identifies e^+, e^-





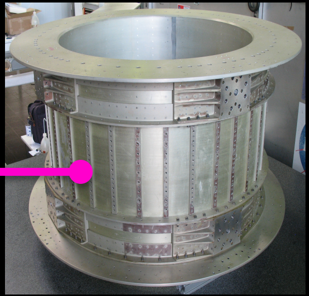
Time Of Flight

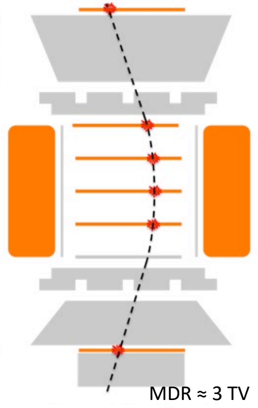
Z, β



Magnet

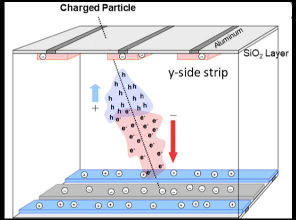
±Z

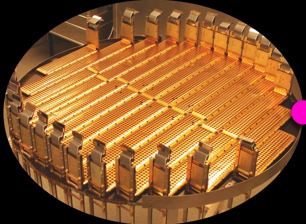




Silicon Tracker

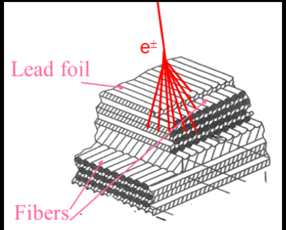
Z, Rigidity=p/Ze

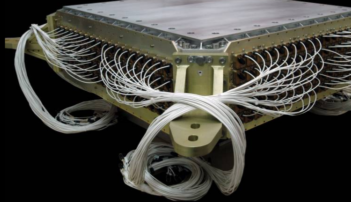




Electromagnetic Calorimeter

Energy of e^+, e^-



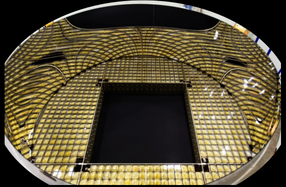


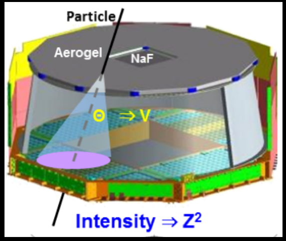
Charge Z and Energy are measured independently in several subdetectors

Ring Imaging Cherenkov

Z, β

Isotopic composition





AMS was built by an International Collaboration

USA

MIT - CAMBRIDGE
NASA JOHNSON SPACE CENTER
UNIV. OF HAWAII
UNIV. OF MARYLAND - DEPT OF PHYSICS

MEXICO

UNAM

NETHERLANDS

ESA-ESTEC
NIKHEF

FRANCE

LUPM MONTPELLIER
LAPP ANNECY
LPSC GRENOBLE

PORTUGAL

LAB. OF INSTRUM. LISBON

SPAIN

CIEMAT - MADRID
I.A.C. CANARIAS.

FINLAND

UNIV. OF TURKU

GERMANY

RWTH-I.
KIT - KARLSRUHE

TURKEY

METU, ANKARA

SWITZERLAND

ETH-ZURICH
UNIV. OF GENEVA

ITALY

ASI
IROE FLORENCE
INFN & UNIV. OF BOLOGNA
INFN & UNIV. OF MILANO-BICOCCA
INFN & UNIV. OF PERUGIA
INFN & UNIV. OF PISA
INFN & UNIV. OF ROMA
INFN & UNIV. OF TRENTO

RUSSIA

ITEP
KURCHATOV INST.

CHINA

CALT (Beijing)
IEE (Beijing)
IHEP (Beijing)
NLAA (Beijing)
SJTU (Shanghai)
SEU (Nanjing)
SYSU (Guangzhou)
SDU (Jinan)
SDIAT (Jinan)

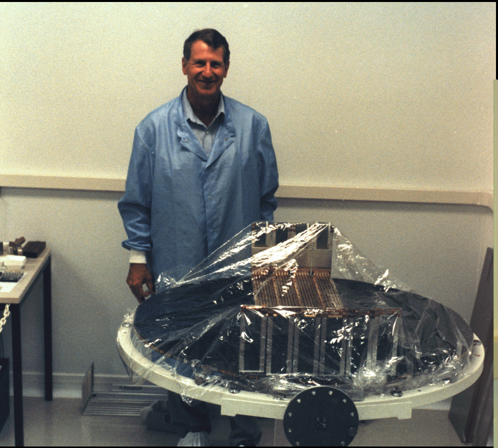
KOREA

EWHA
KYUNGPOOK NAT.UNIV.

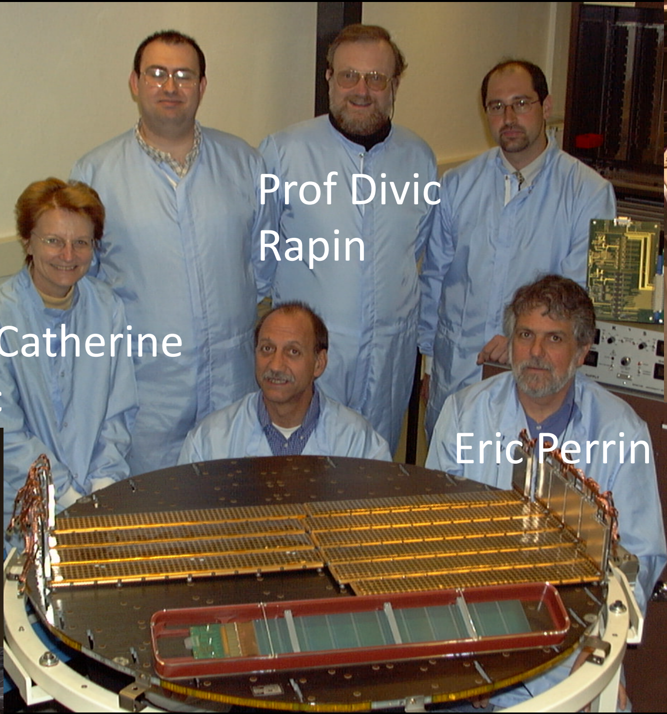
TAIWAN

ACAD. SINICA (Taipei)
CSIST (Taipei)
NCU (Chung Li)

Construction of the Silicon Tracker at University of Geneva



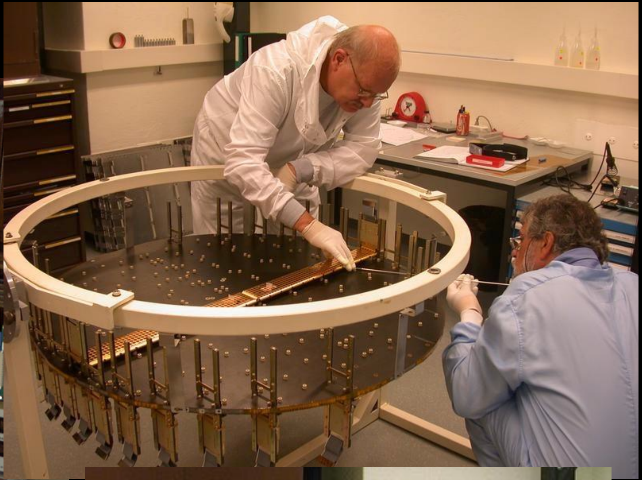
Prof Maurice Bourquin



Prof Divic Rapin

Prof Catherine Leluc

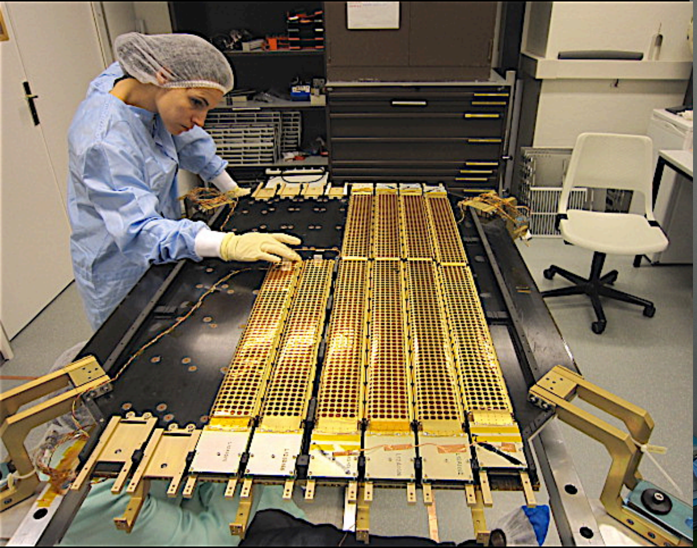
Eric Perrin



Prof Martin Pohl

Mercedes Paniccia

Construction of the Silicon Tracker at University of Geneva



Layer 9 construction, 2010

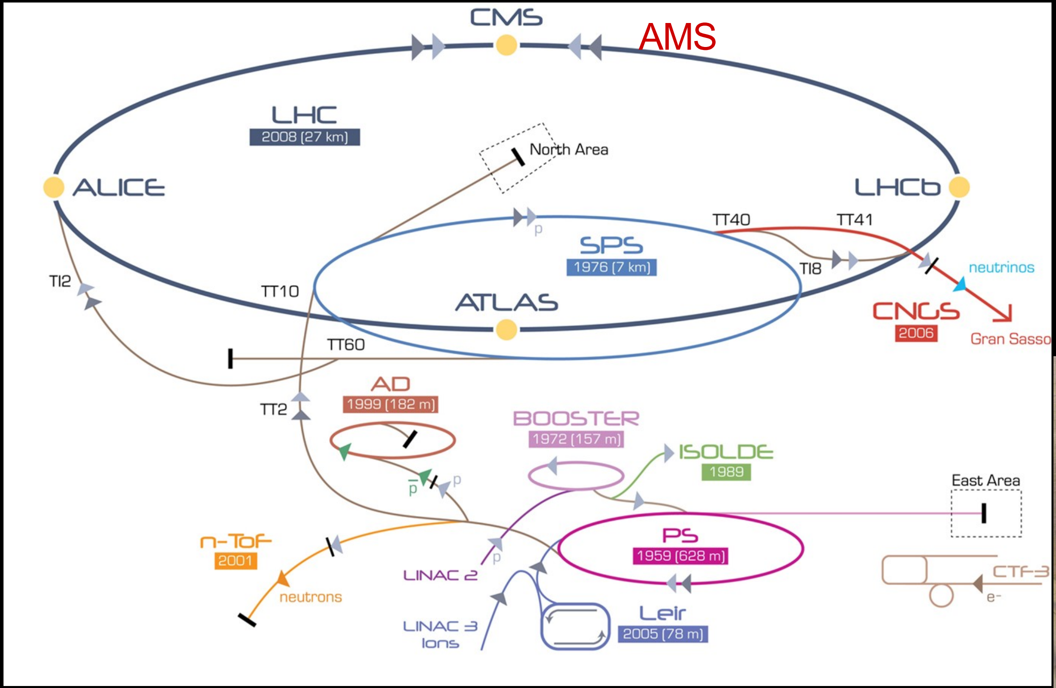
Inner Tracker assembly completed, Sep. 2007

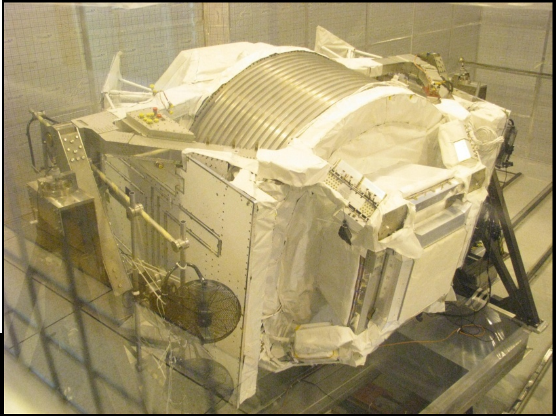
AMS detector integration at CERN

AMS has strong support from CERN

CERN provided strong support including a large team of engineers and technicians and a large clean room for assembly and test for 5 years.

AMS Calibration Tests at CERN with different beam energy and different particles





AMS Launch May 2011
Space Shuttle Endeavour
Mission STS-134

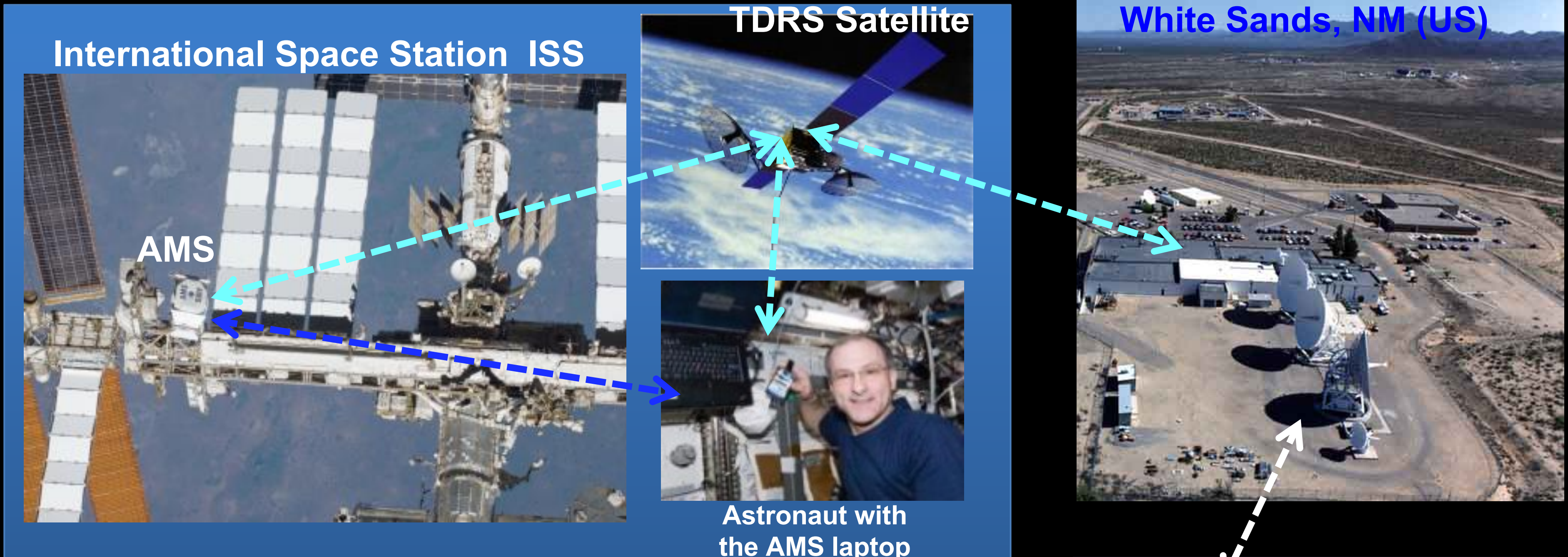
AMS mission duration:

Entire ISS lifetime (up to 2028-2030)

AMS installed on the ISS

Near Earth Orbit:

altitude 400 Km
inclination 52°
period 92 min



AMS Payload Operation and Control Center at CERN Prevessin

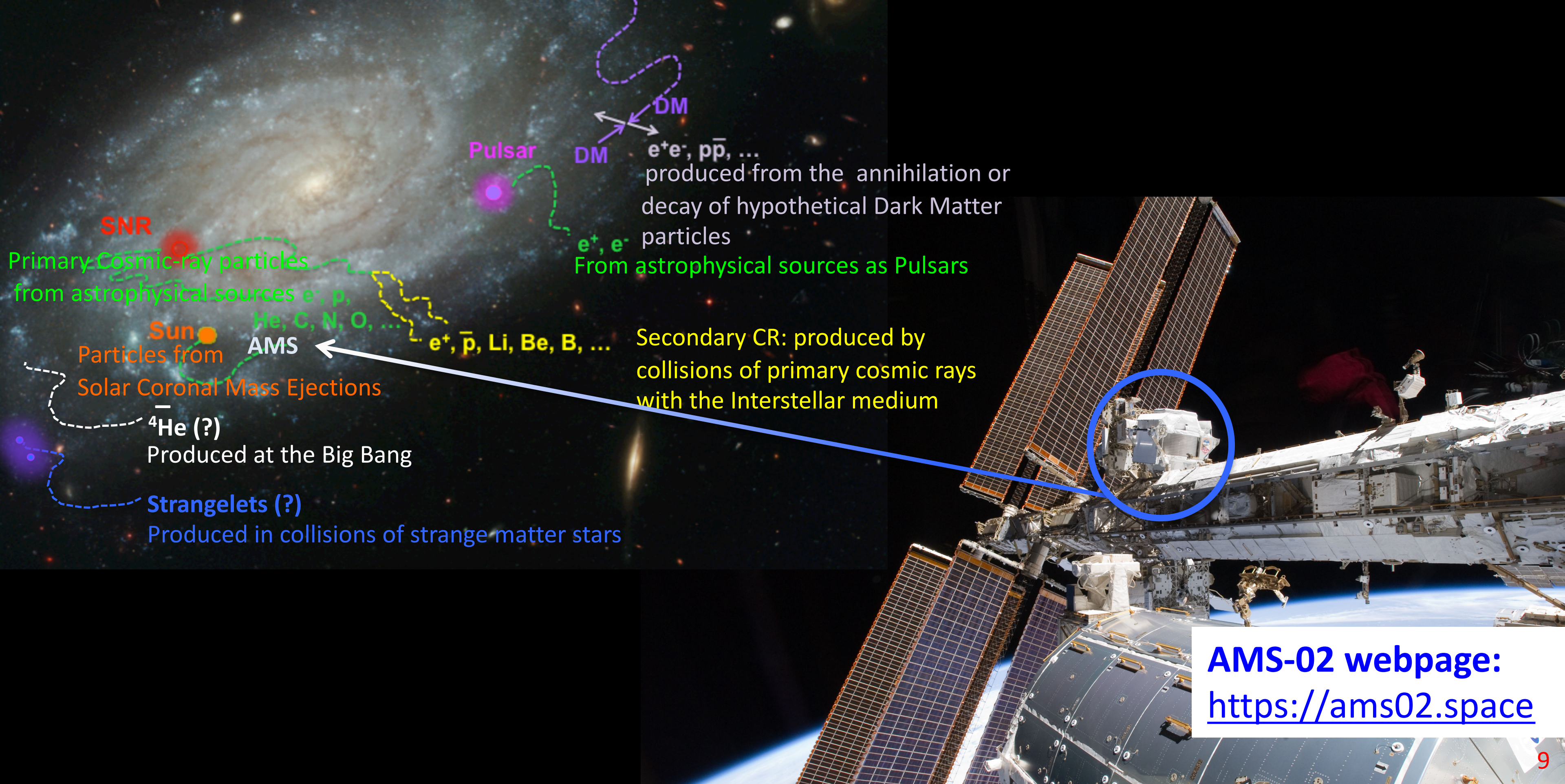
AMS Science Operation Center is also at CERN

CERN provides major computing support

So far AMS collected ~170 billion cosmic-ray events

Total expected in 2028 ~300 billion events

Charged particles of Cosmic Origin



e^+e^-, $p\bar{p}$, …
produced from the annihilation or decay of hypothetical Dark Matter particles

e^+, e^-
From astrophysical sources as Pulsars

Primary Cosmic-ray particles from astrophysical sources e^-, p, He, C, N, O, …

e^+, $\bar{p}$, Li, Be, B, …
Secondary CR: produced by collisions of primary cosmic rays with the Interstellar medium

Particles from Solar Coronal Mass Ejections

$^4\overline{He}$ (?)
Produced at the Big Bang

Strangelets (?)
Produced in collisions of strange matter stars

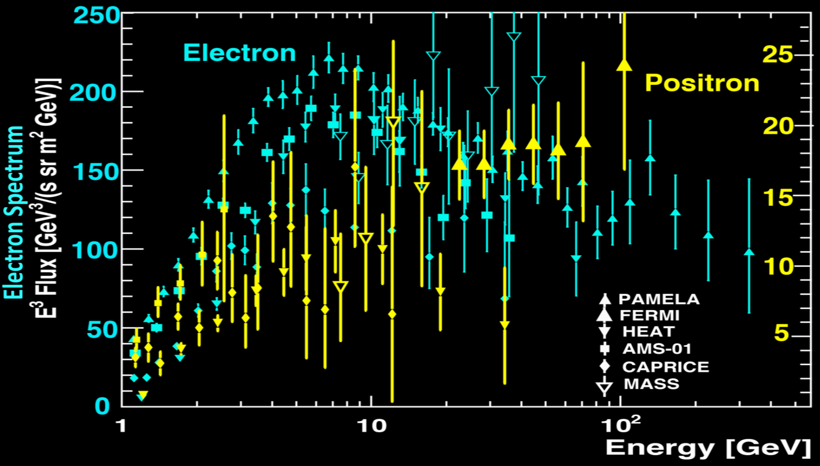
AMS-02 webpage:
https://ams02.space

AMS Publications

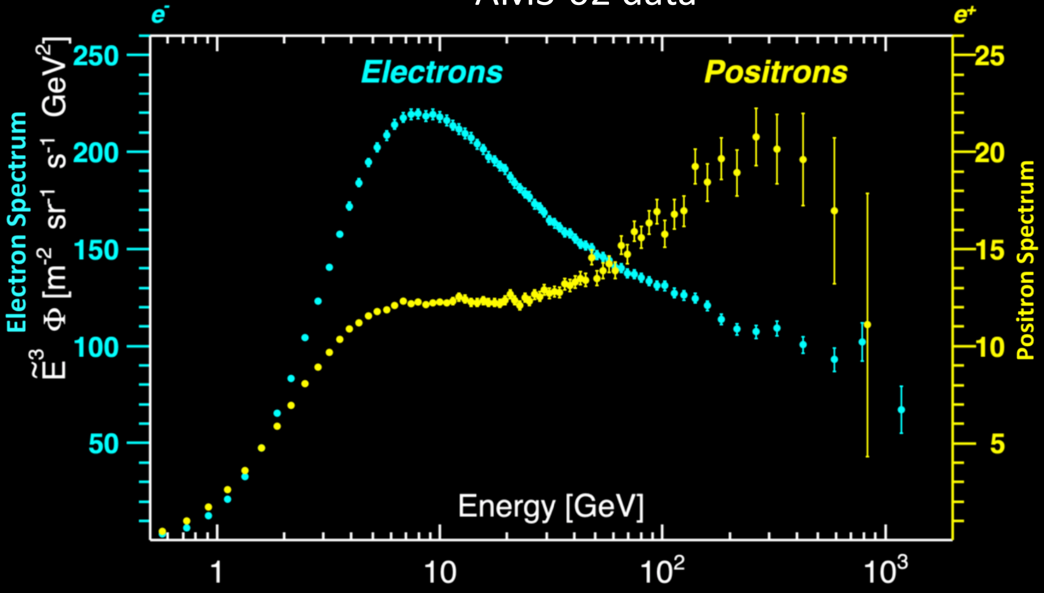
1) Phys. Rev. Lett. 110, 141102 (2013). Editors' Suggestion. Viewpoint in *Physics*.
Highlight of 2013. Ten-Year retrospective.
2) Phys. Rev. Lett. 113, 121101 (2014). Editors' Suggestion
3) Phys. Rev. Lett. 113, 121102 (2014). Editors' Suggestion
4) Phys. Rev. Lett. 113, 221102 (2014).
5) Phys. Rev. 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, "The Alpha Magnetic Spectrometer (AMS) on the International Space Station: Part II – Results from the First Seven Years"
19) Phys. Rev. Lett. *(in press).* Featured in *Physics*.
20) Phys. Rev. Lett. *(submitted).*

The Origin of Cosmic positrons and electrons

BEFORE AMS-02



AMS-02 data

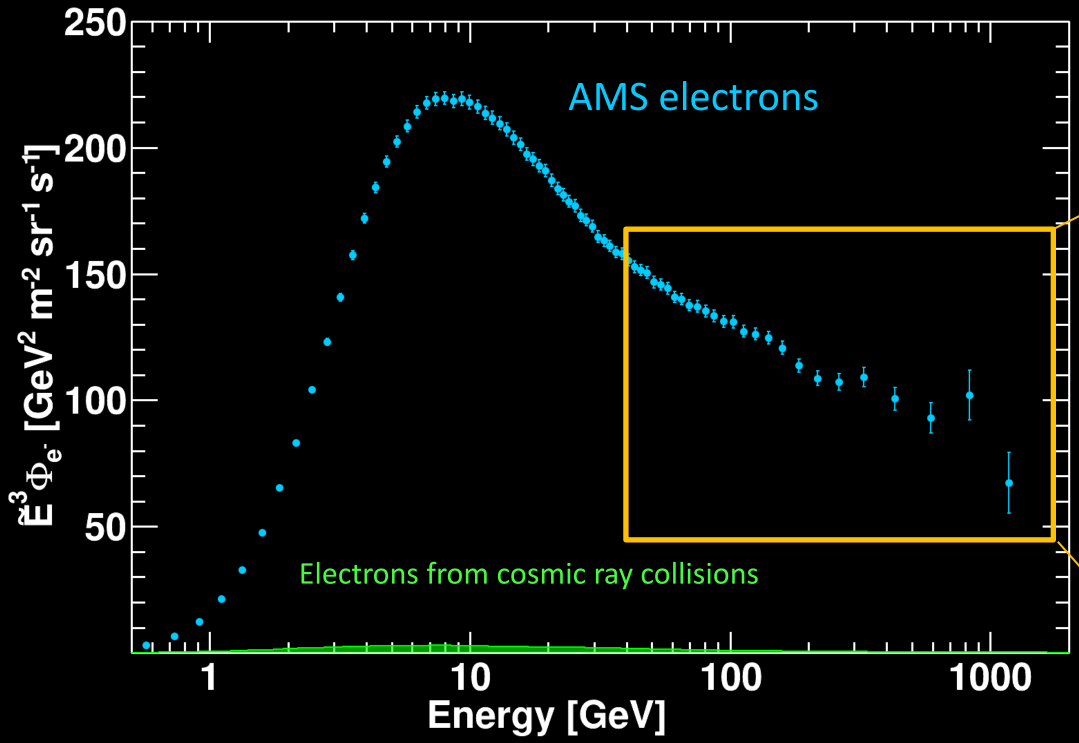


Electrons and positrons spectra have totally distinct behavior:

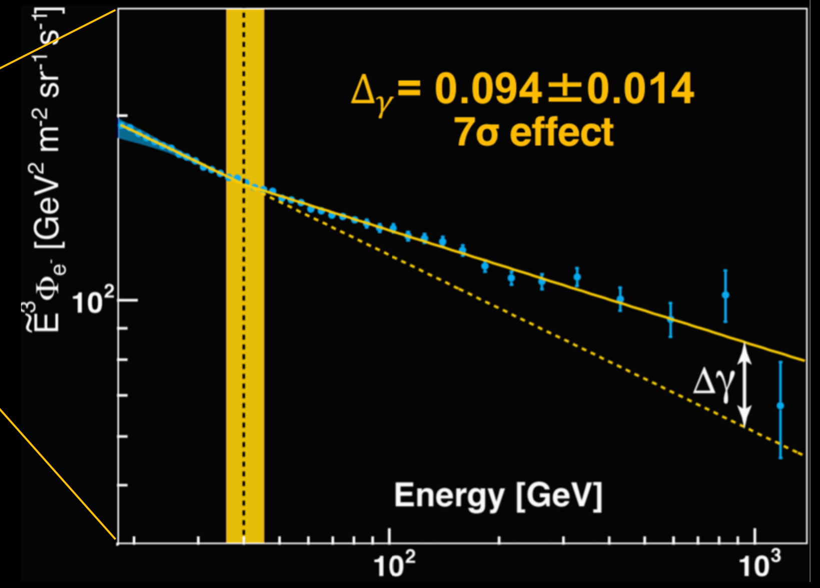
the properties of electrons and positrons cannot be studied from ($e^+ + e^-$) measurements.

Properties of Cosmic electrons

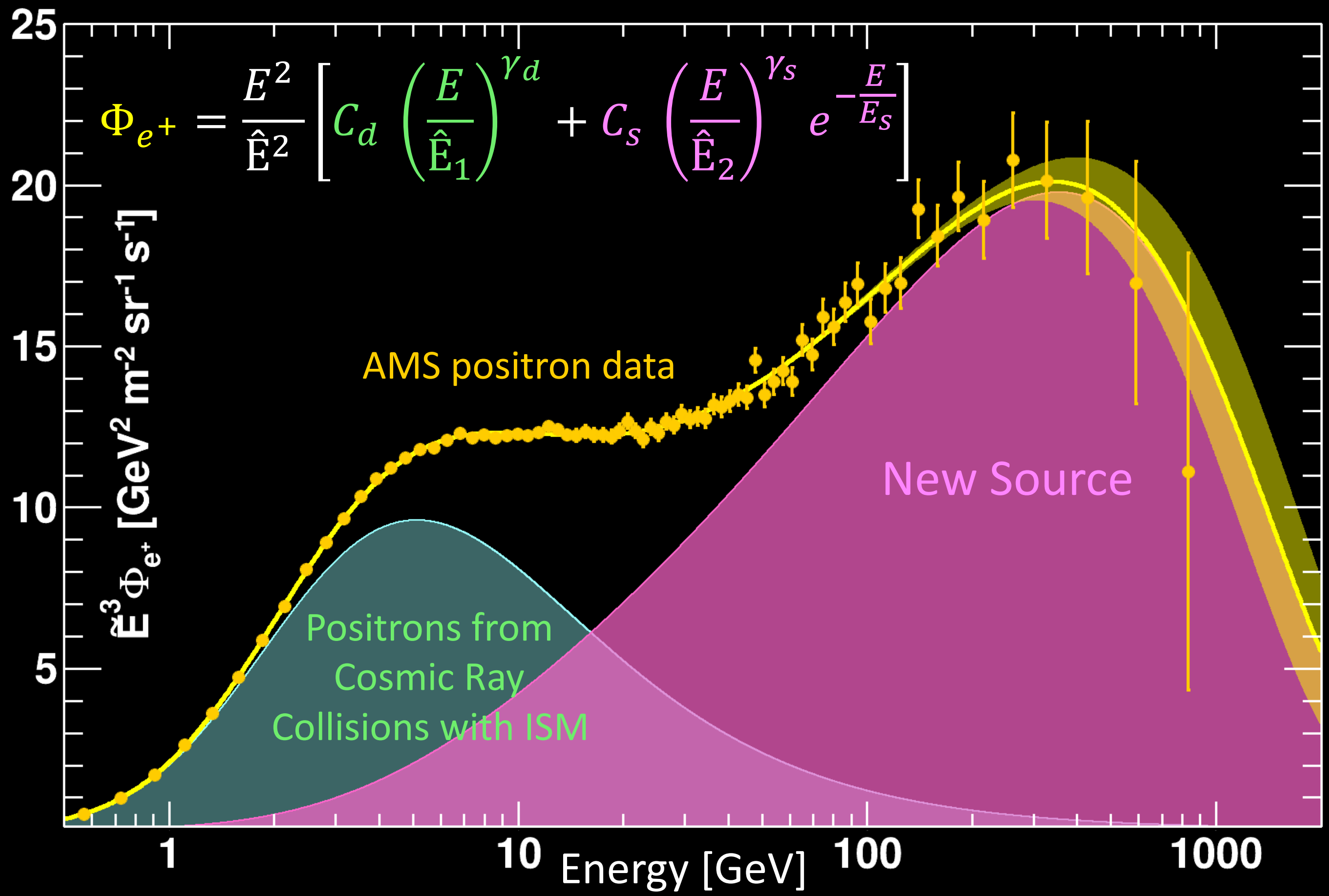
Traditionally it was assumed that the electron energy spectrum behaves like a power law $\Phi_{e^-} = C\,E^{-3}$



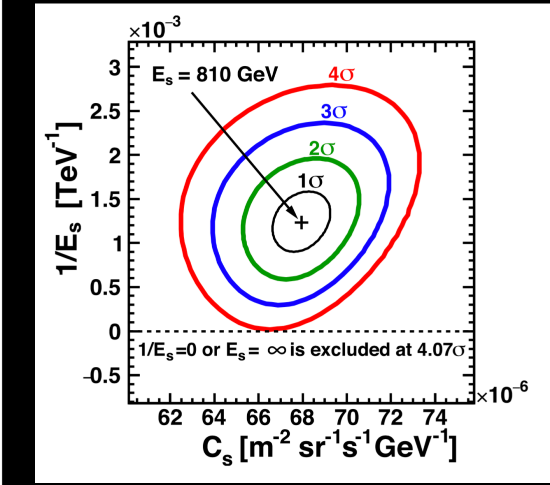
The electron spectrum exhibits a significant excess above 42 GV



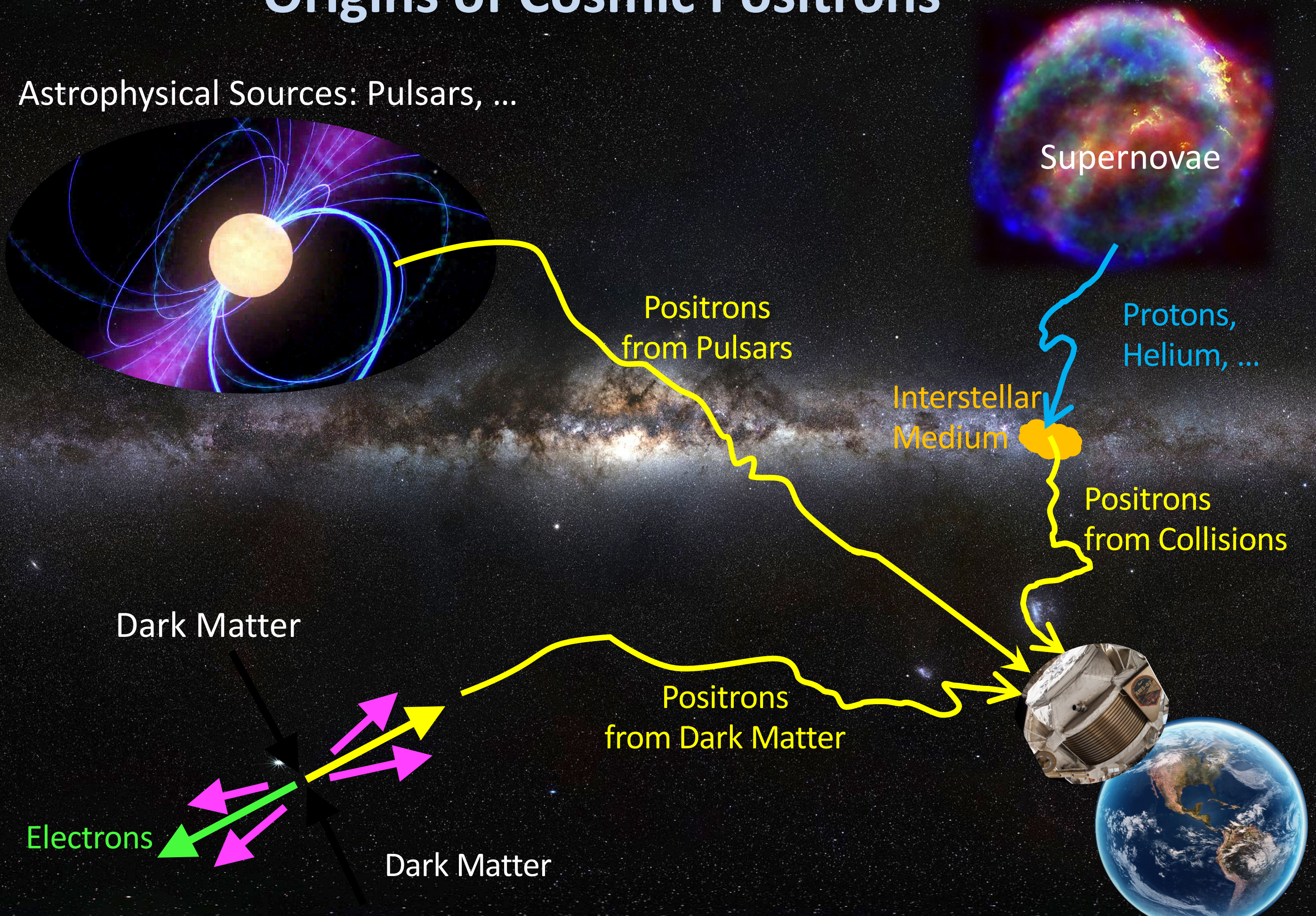
Properties of Cosmic Positrons



Source term exhibits an exponential cutoff at 810 GeV with **4σ** significance.



Origins of Cosmic Positrons



Astrophysical Sources: Pulsars, …

Supernovae

Positrons from Pulsars

Protons, Helium, …

Interstellar Medium

Positrons from Collisions

Dark Matter

Positrons from Dark Matter

Electrons

Dark Matter

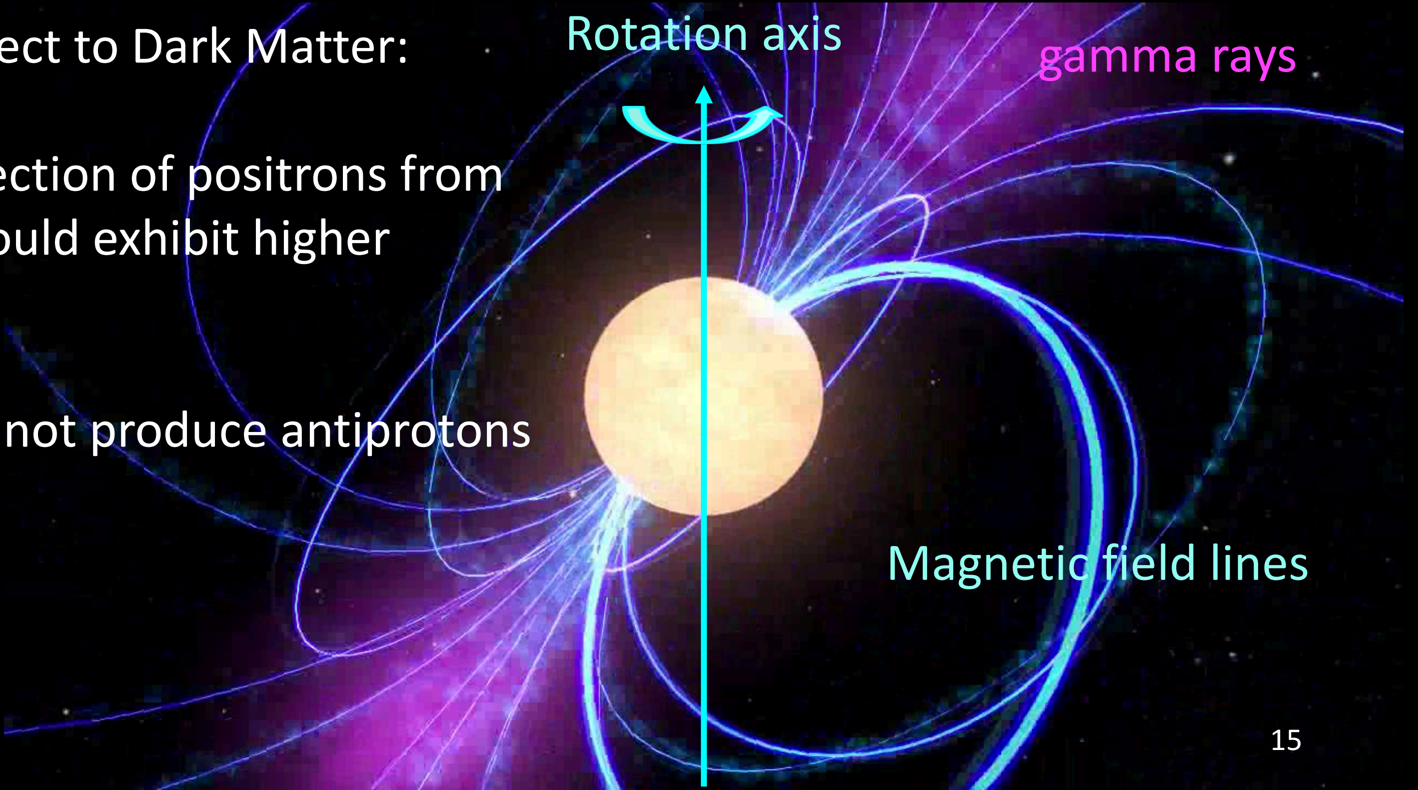
Positrons from Pulsars

Pulsars produce and accelerate positrons at high energy.

However, with respect to Dark Matter:

1. Arrival direction of positrons from Pulsars should exhibit higher anisotropy

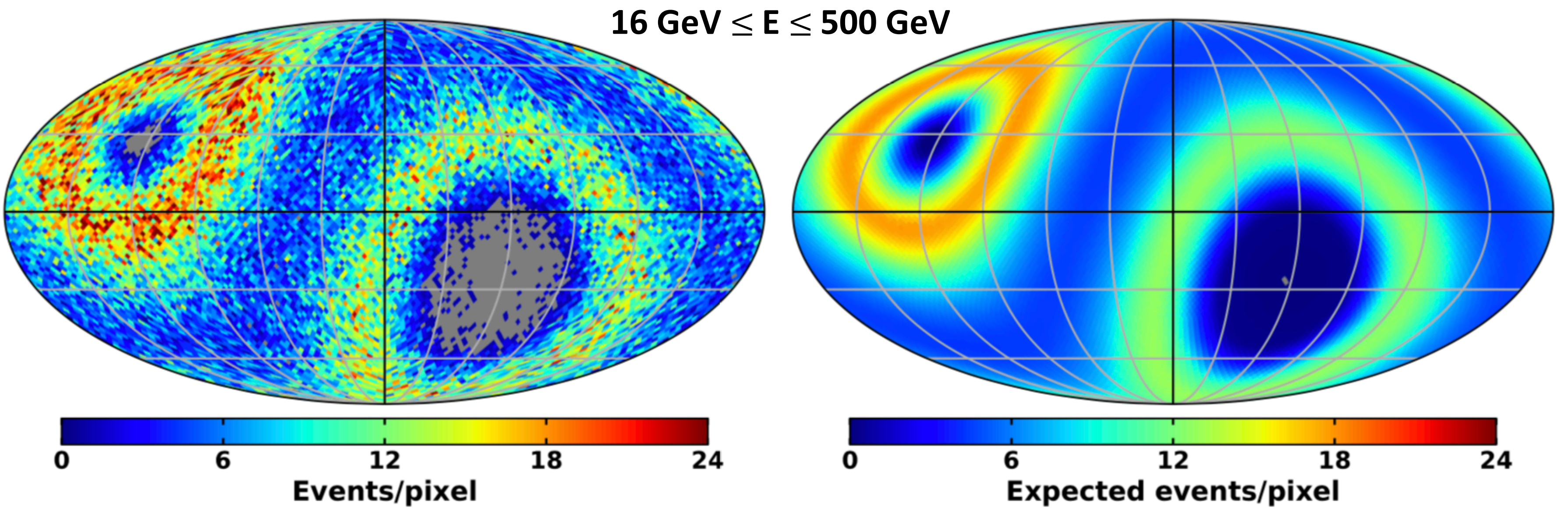
2. Pulsars do not produce antiprotons



AMS measurement of positron flux anisotropy

Sky map of positron arrival directions in galactic coordinates

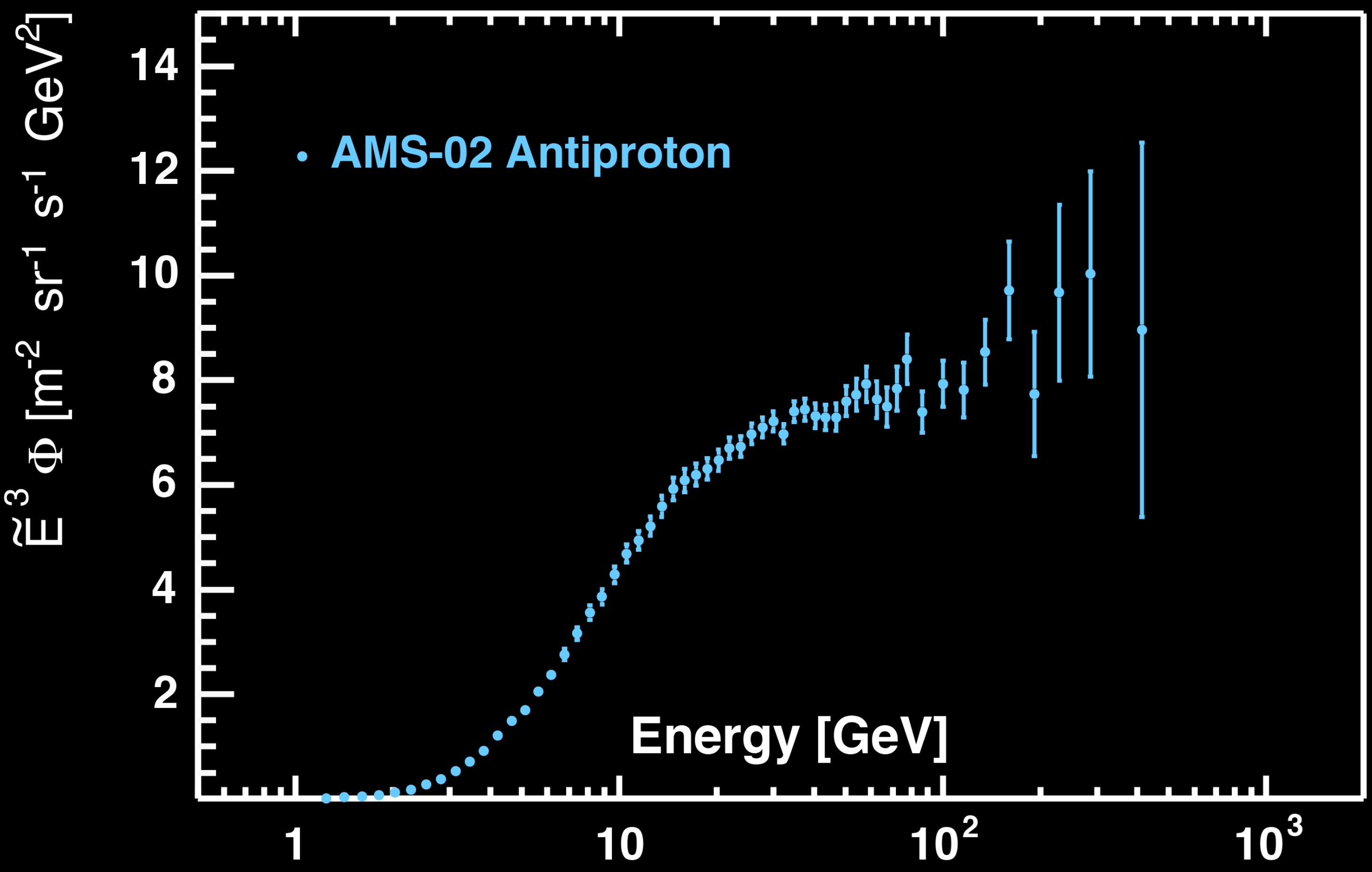
Sky map in the hypothesis of isotropic positron flux



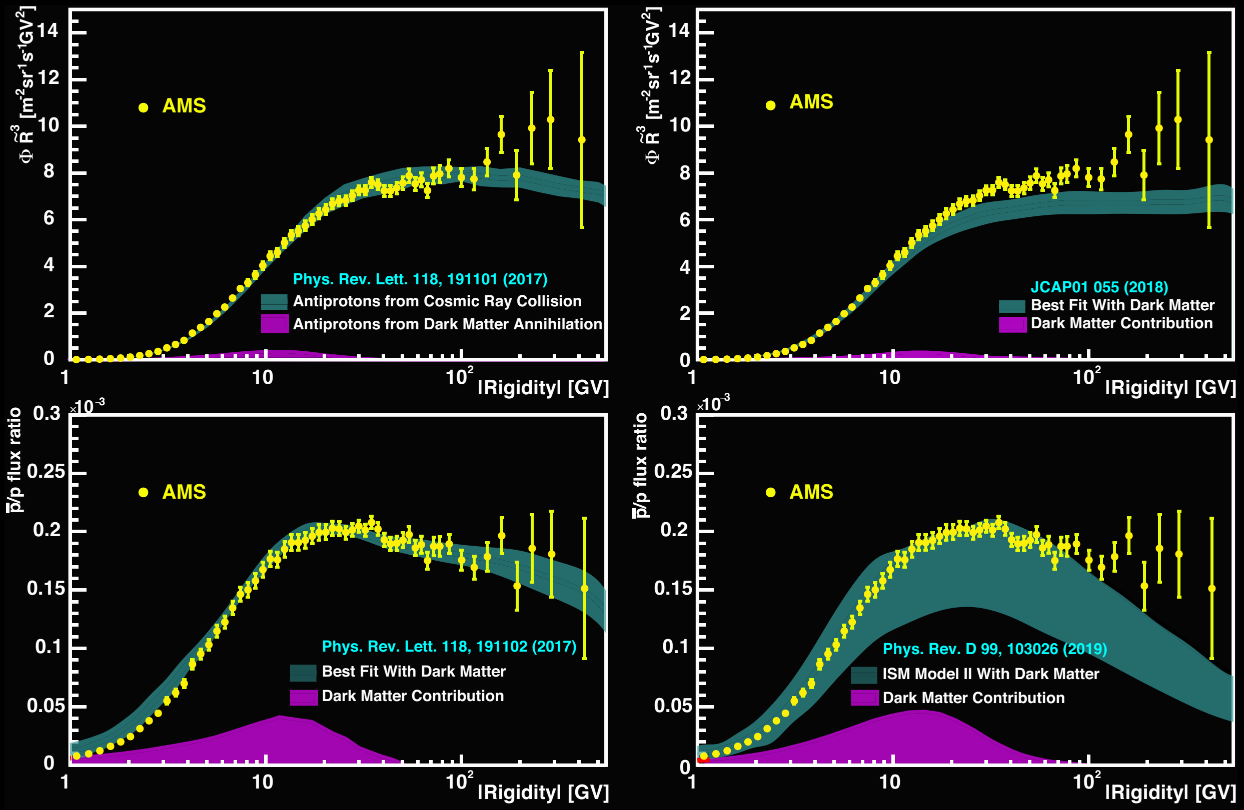
No deviation from isotropy observed

Upper limit on amplitude of the dipole anisotropy of the positron flux < 0.019 at 95% CL

Antiproton flux



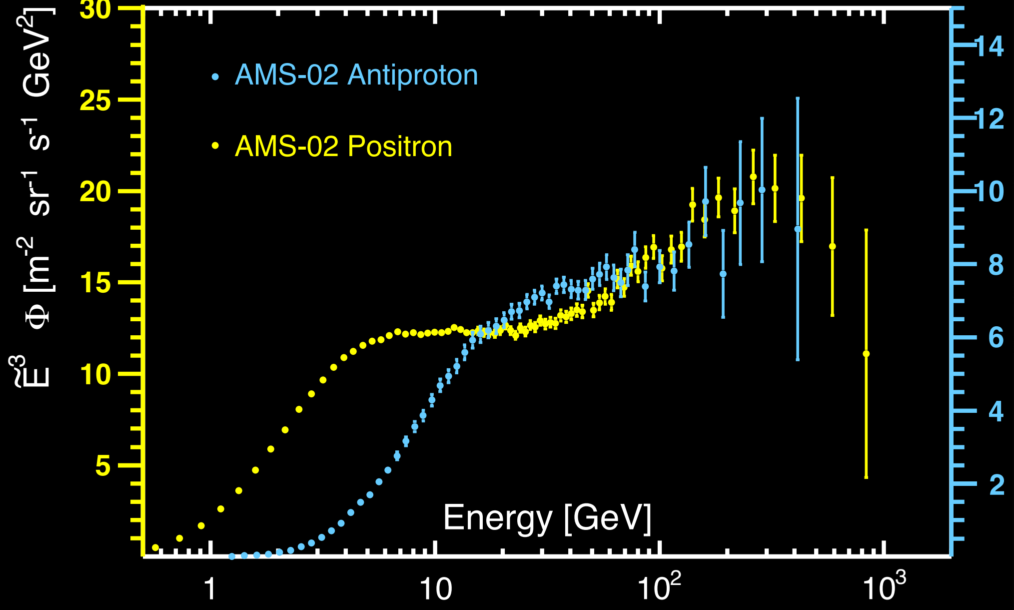
Antiproton flux

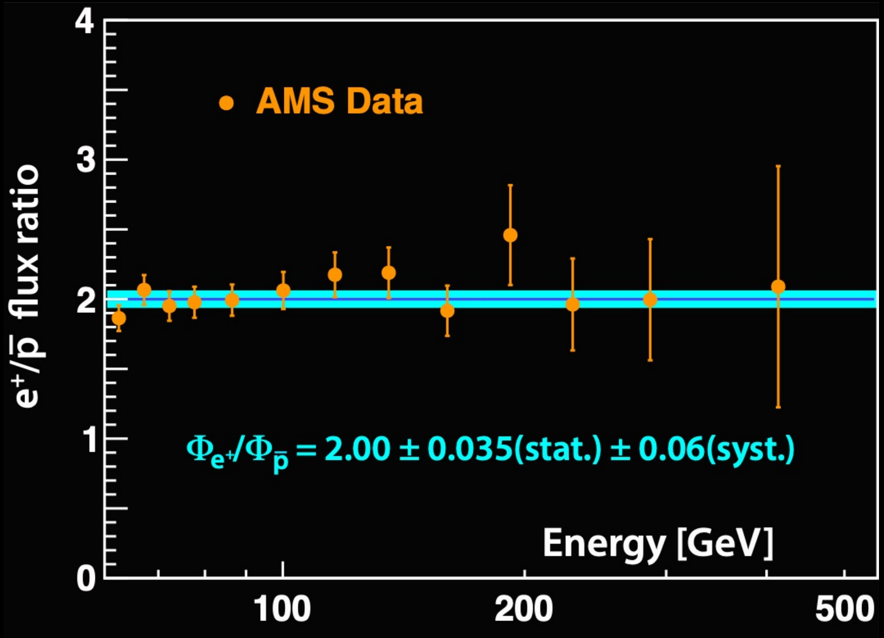


Current uncertainties on CR modelling do not allow a definitive interpretation of the AMS data

Antiprotons vs positrons

Above 60 GeV antiprotons exhibit a spectral shape similar to that of positrons

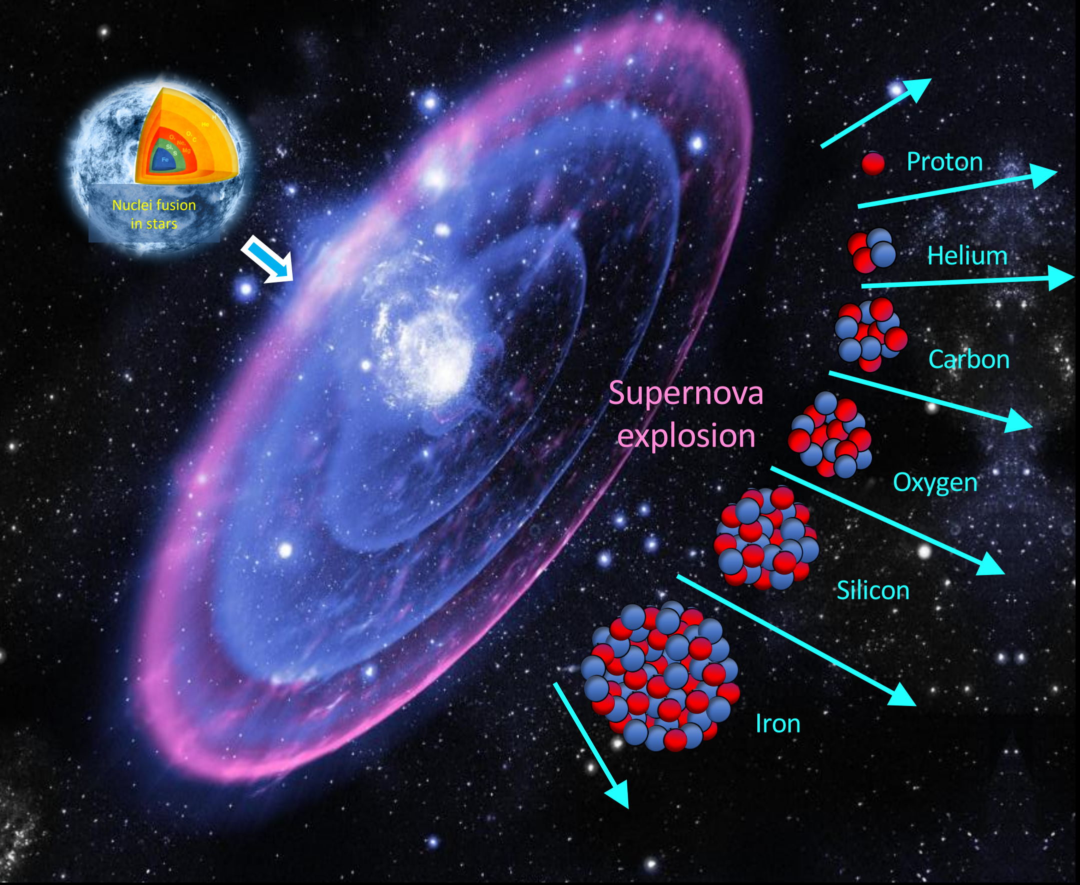




Additional source or wrong calculation of secondary production?

Can constrain cosmic-ray models with measurements of cosmic-ray nuclei

Primary Cosmic Rays

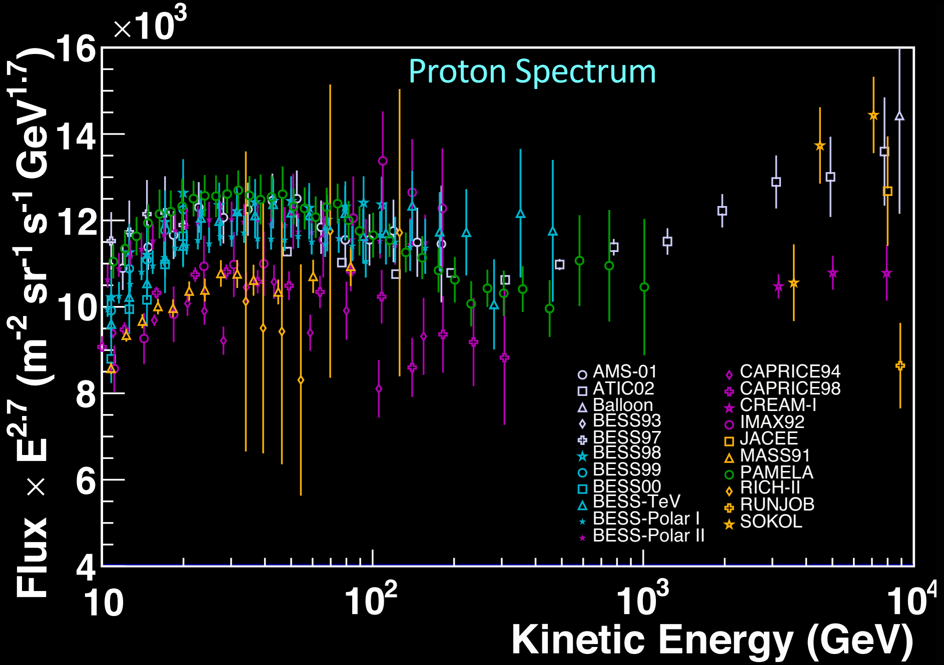


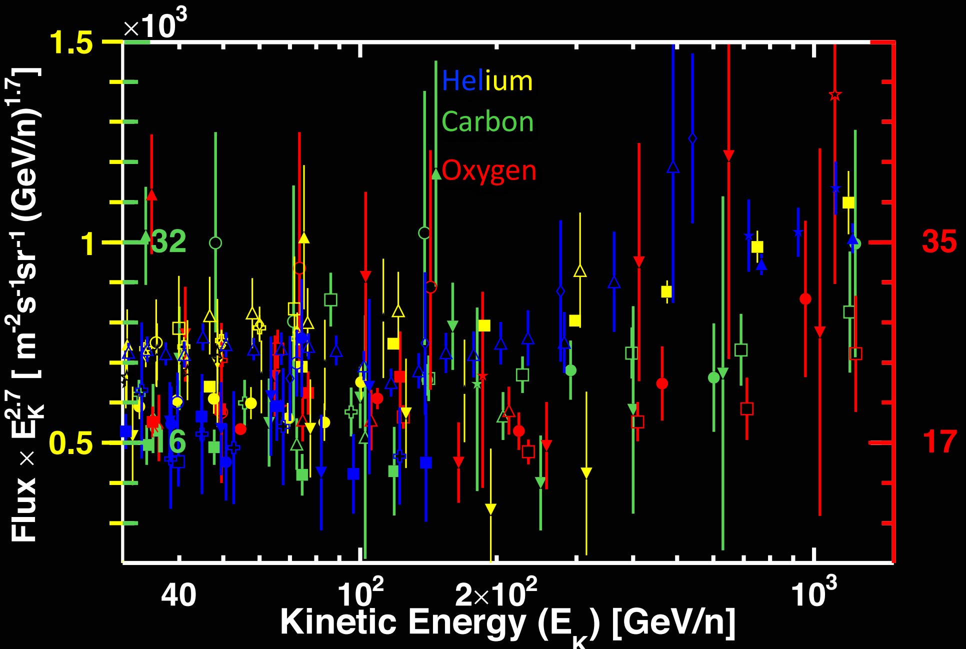
Primary elements,
protons, He, C, O, Ne, Mg, Si..., Fe nuclei
are produced
during the lifetime of stars.

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

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

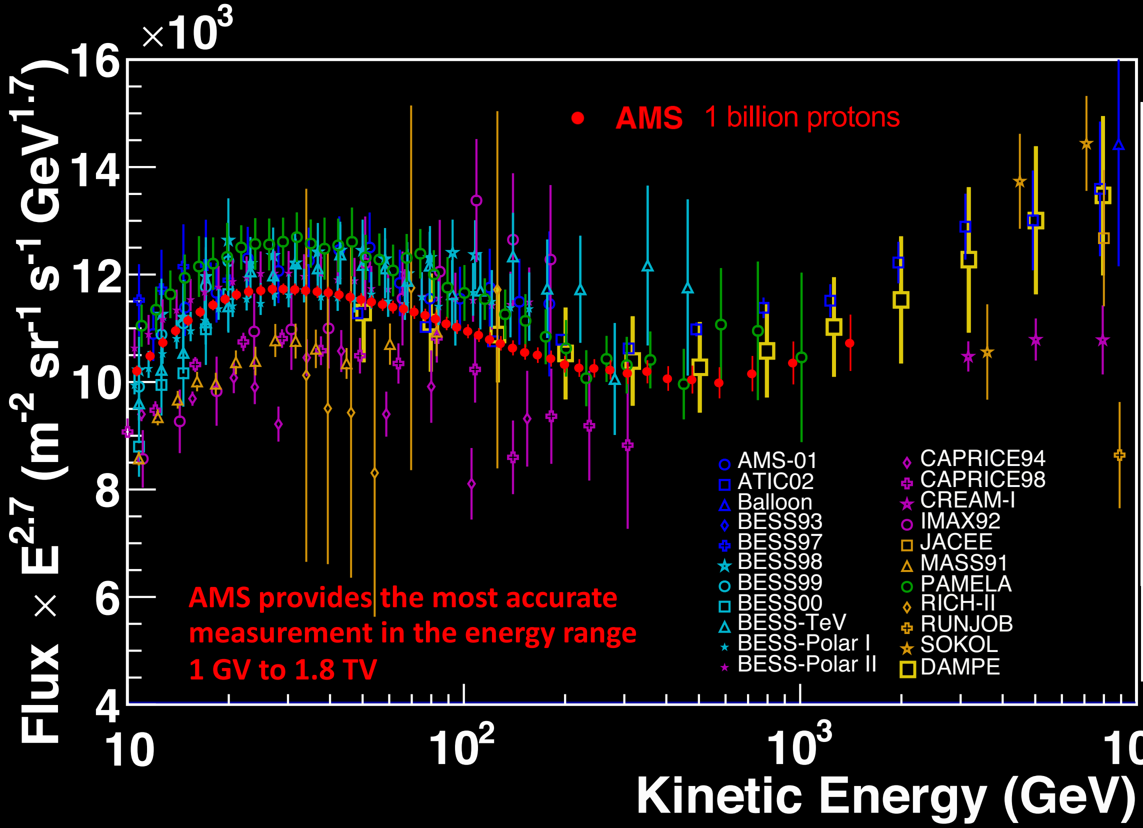
Before AMS, cosmic-ray nuclei spectra in the GeV to TeV range were assumed
to have a universal
simple power law dependence on energy (or rigidity R = p/Ze): $\Phi = CE^{-2.7}$



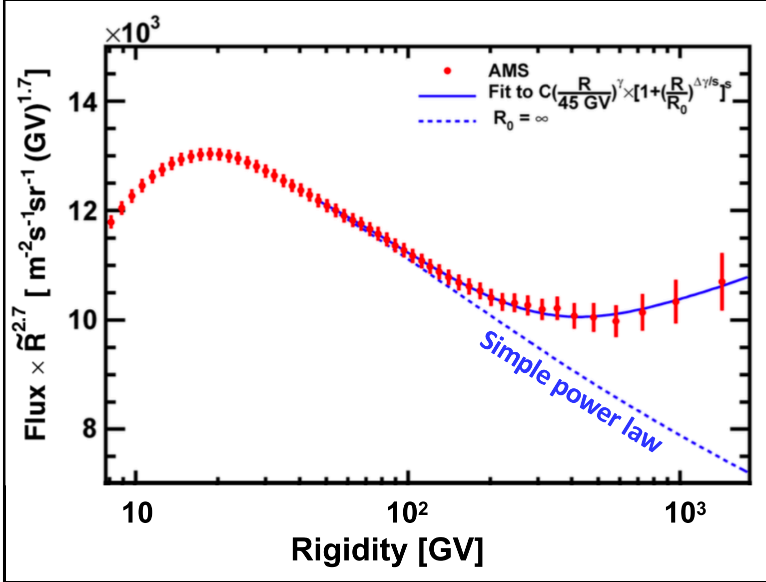


Proton flux

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



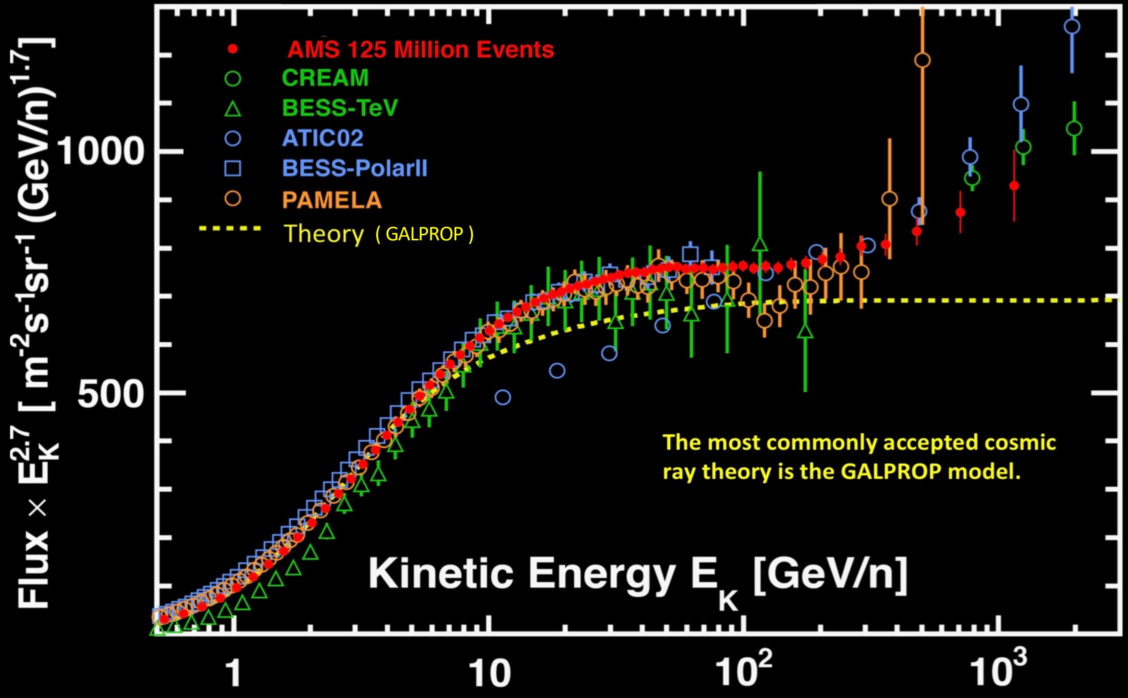
AMS provides the most accurate measurement in the energy range 1 GV to 1.8 TV



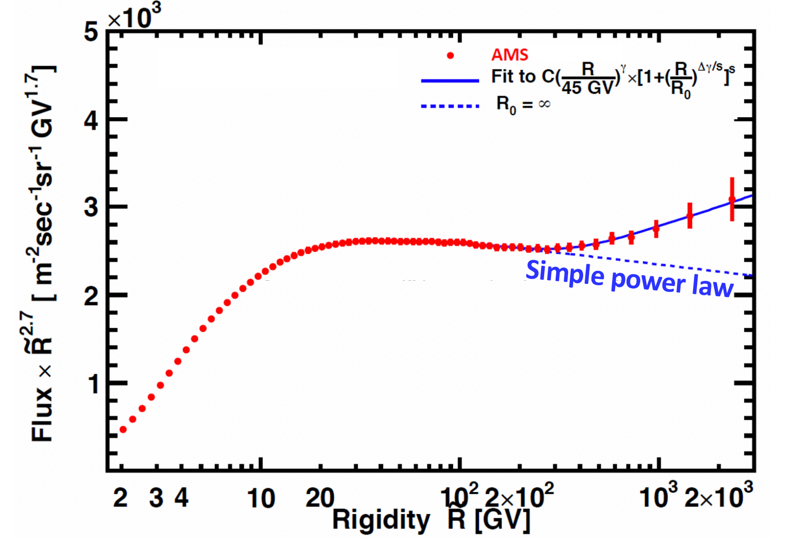
Helium nuclei flux

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

Helium (^{3}He + ^{4}He) (Z=+2)

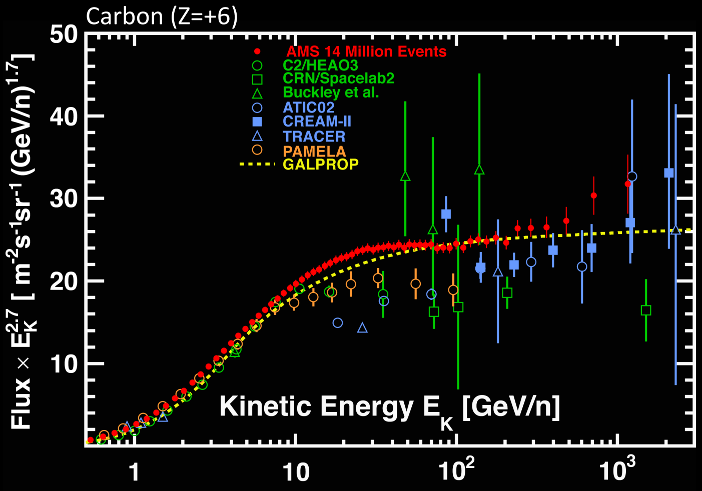


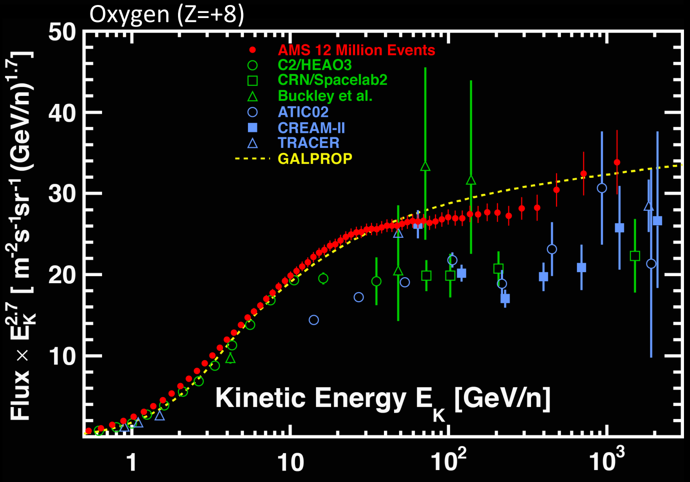
The most commonly accepted cosmic ray theory is the GALPROP model.



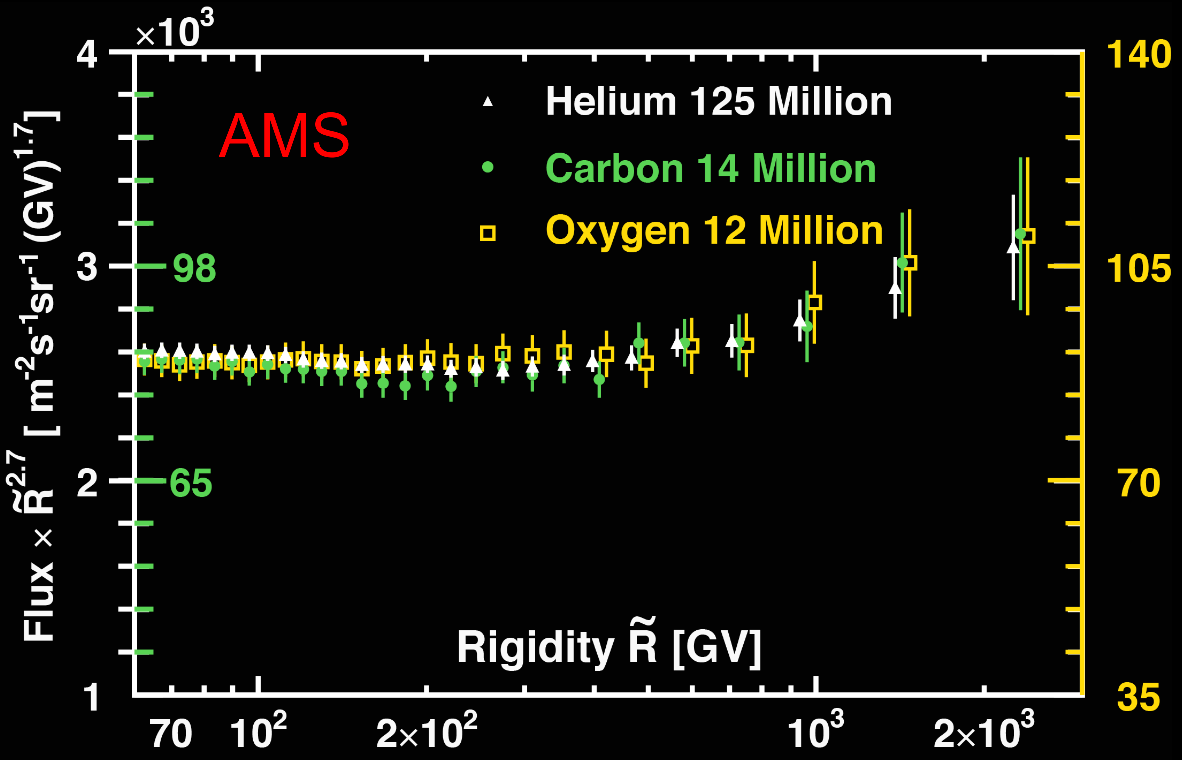
Simple power law

Carbon and Oxygen nuclei fluxes





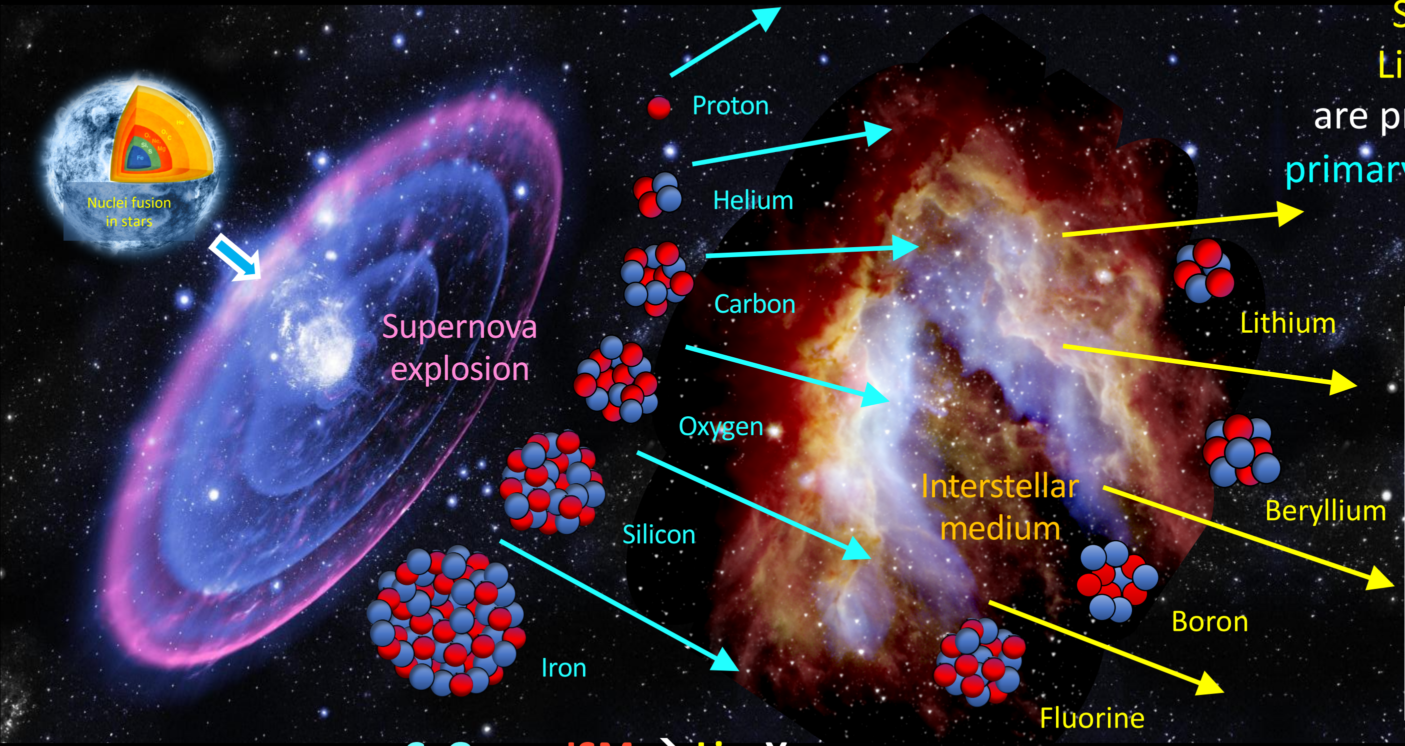
Above 60 GV He , C and O have identical rigidity dependence



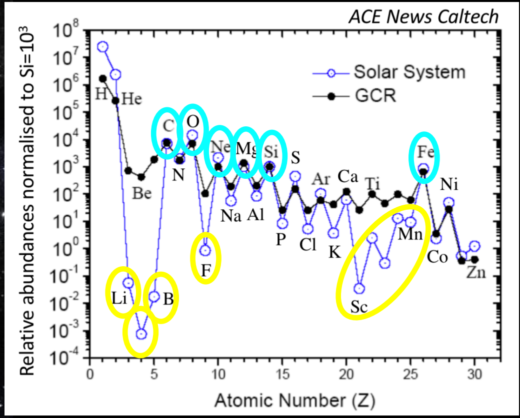
Which is the origin of the spectral hardening?

Is the spectral hardening universal ?

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


ACE News Caltech

C, O, … + ISM → Li + X

C, O, … + ISM → Be + X

C, O, … + ISM → B + X

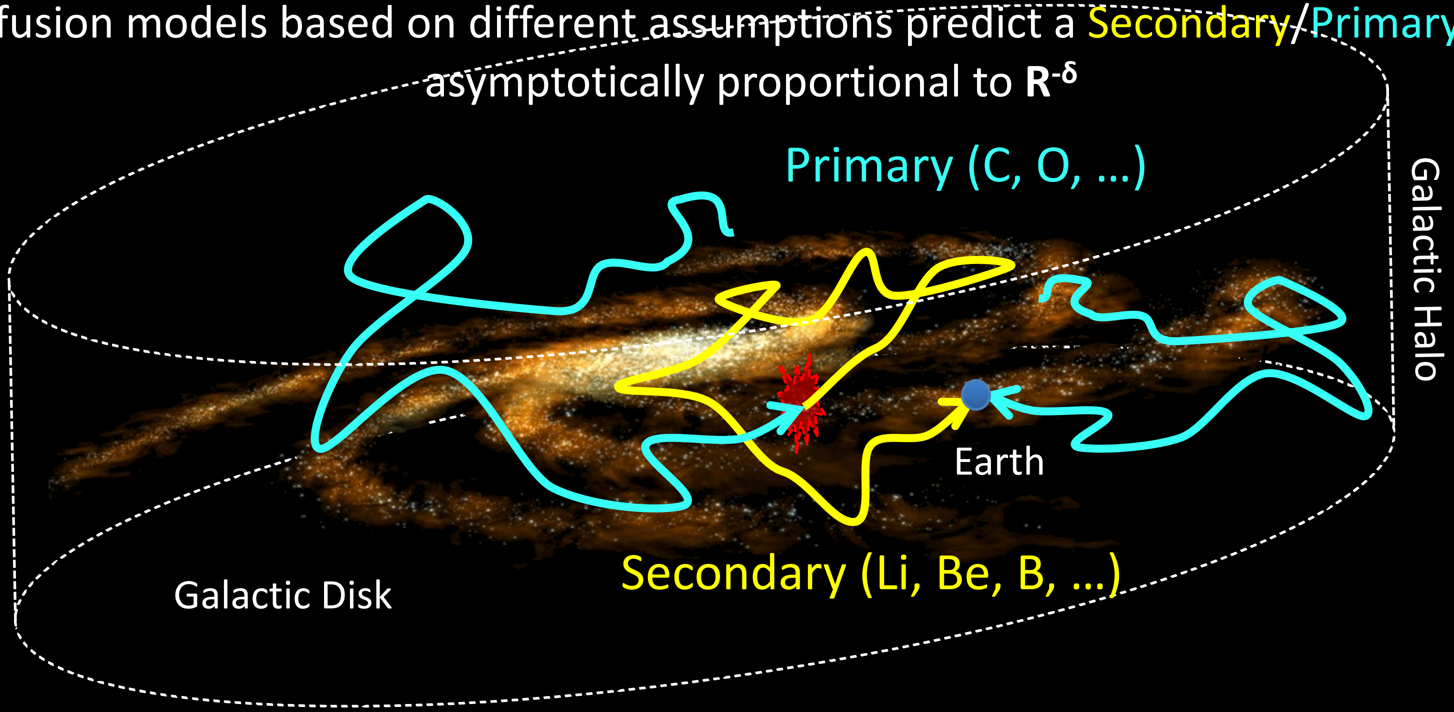
Ne, Mg, Si, … + ISM → F + X

Fe, … + ISM → Sc, … ,Mn + X

Secondary Cosmic Rays as probes of propagation processes

The motion of cosmic rays through the ISM is modeled as diffusion of charged particles in a turbulent magnetized medium.

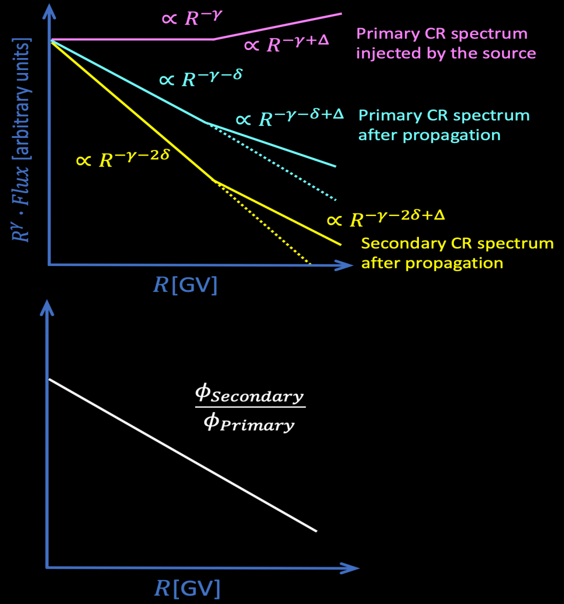
Diffusion models based on different assumptions predict a Secondary/Primary ratio asymptotically proportional to $\mathbf{R}^{-\delta}$



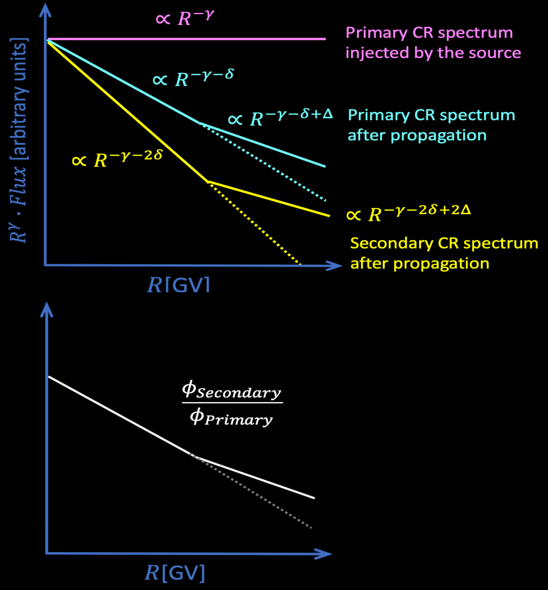
Secondary Cosmic Rays and origin of primary CR spectral hardening

Interpretations of the spectral hardening fall in three categories:

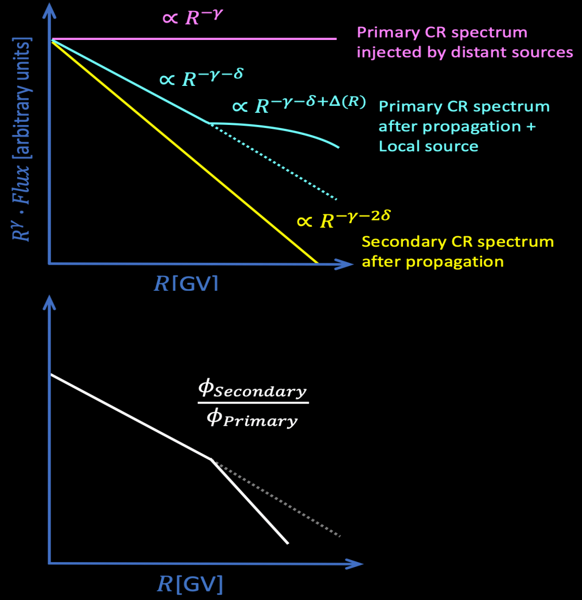
Spectral break at injection



Propagation effect

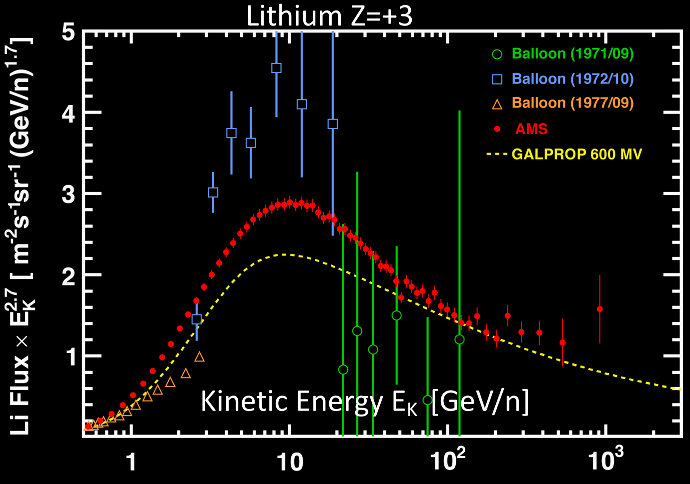


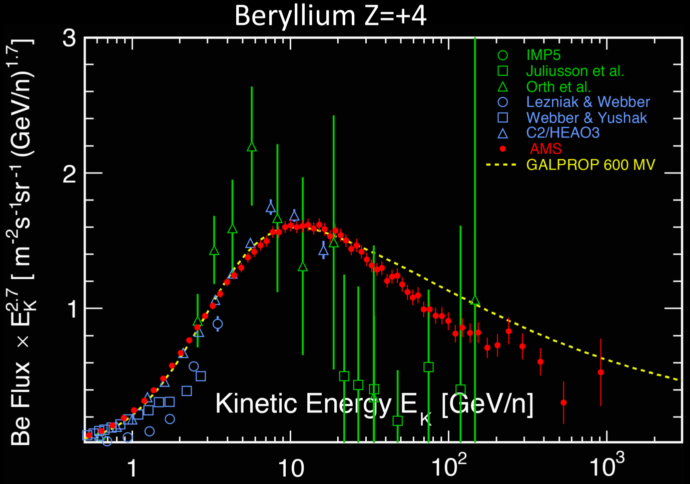
Local source

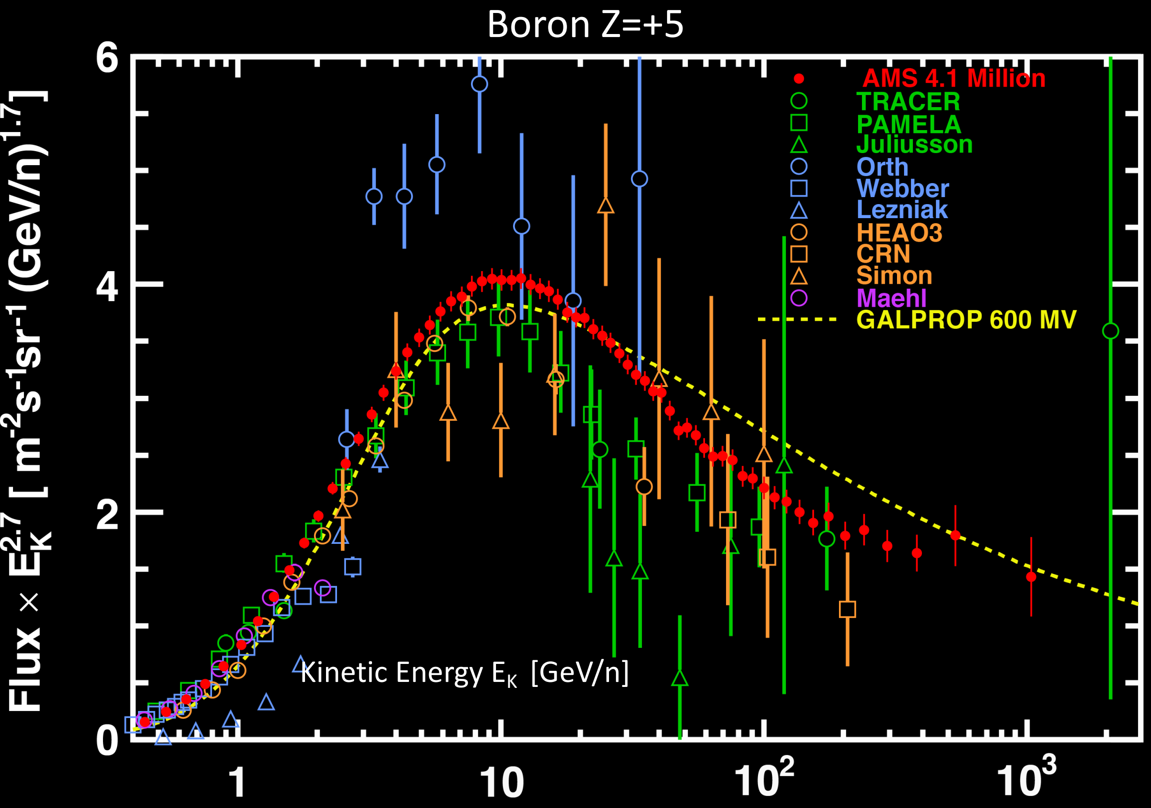


Precision measurements of the individual spectra of primary and secondary CR and their ratios can ascertain the origin of the spectral hardening.

Light Secondary Cosmic Rays Li, Be and B fluxes


Lithium Z=+3

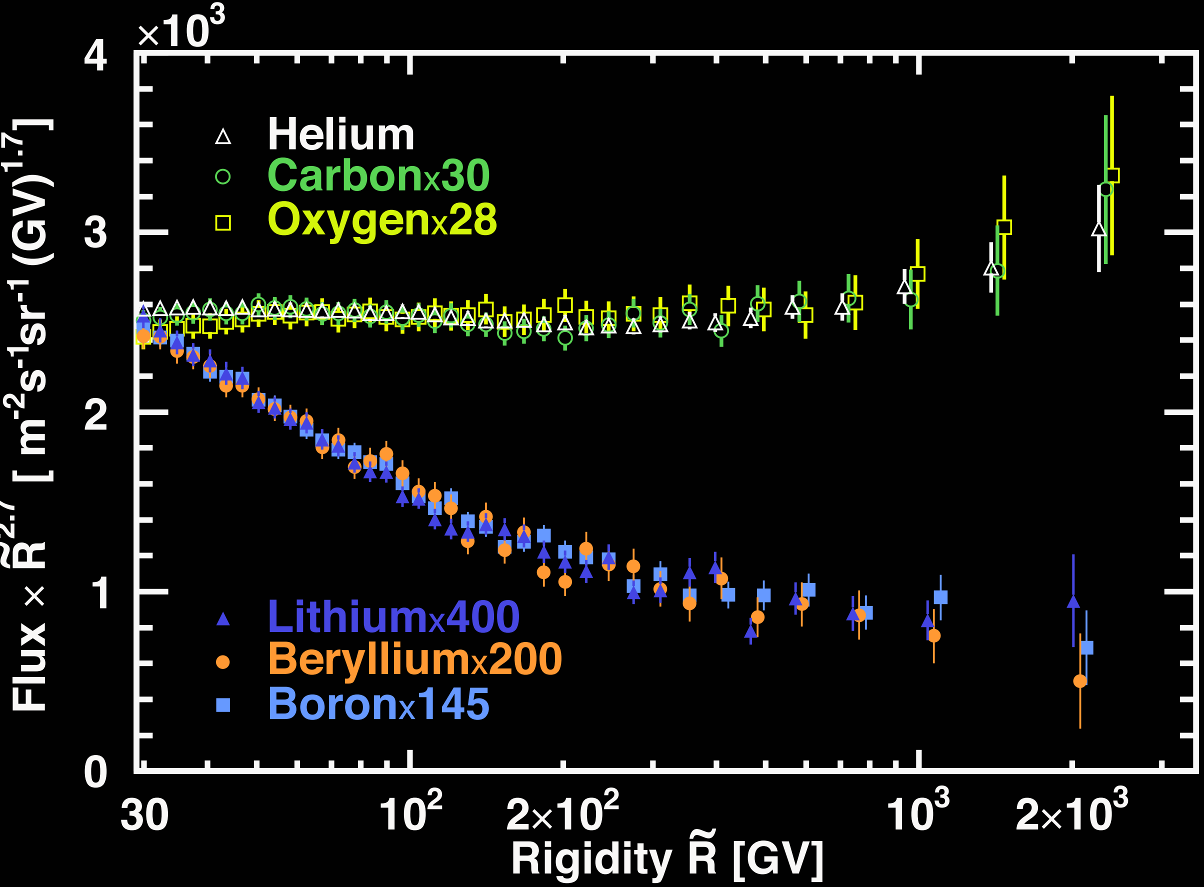

Beryllium Z=+4


Boron Z=+5

Li, Be and B also exhibit a spectral hardening at ~200 GV

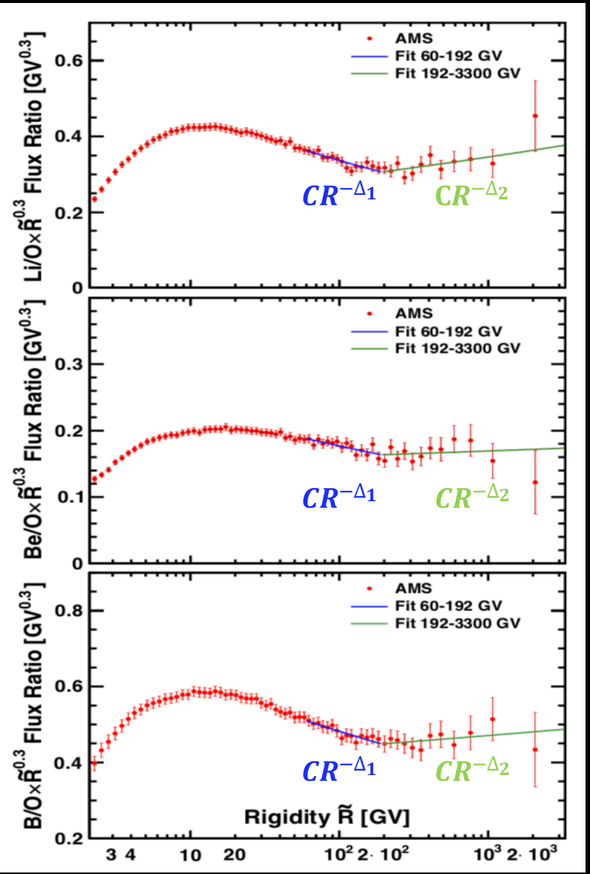
Light Secondary Cosmic Rays Li, Be and B fluxes

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



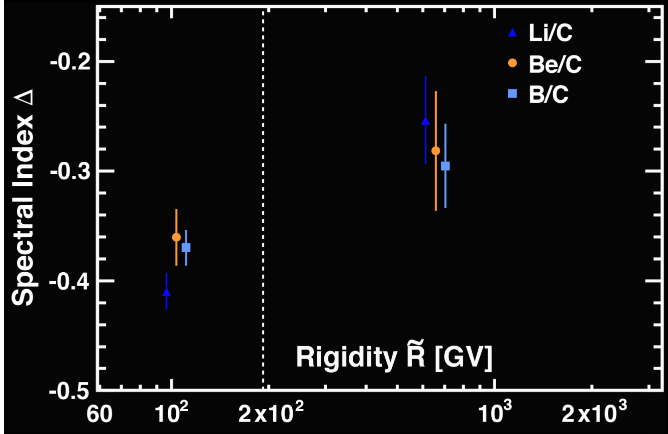
Secondaries and primaries have distinctly different spectral shapes

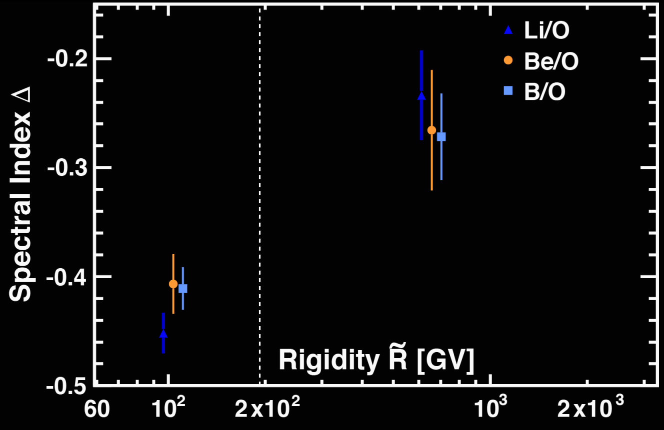
Light Secondary (Li, Be, B) to Primary (C,O) flux ratios



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

Average **hardening** $\Delta = \Delta_2 - \Delta_1$ = 0.140 ± 0.025, significance: $\mathbf{5.6\sigma}$

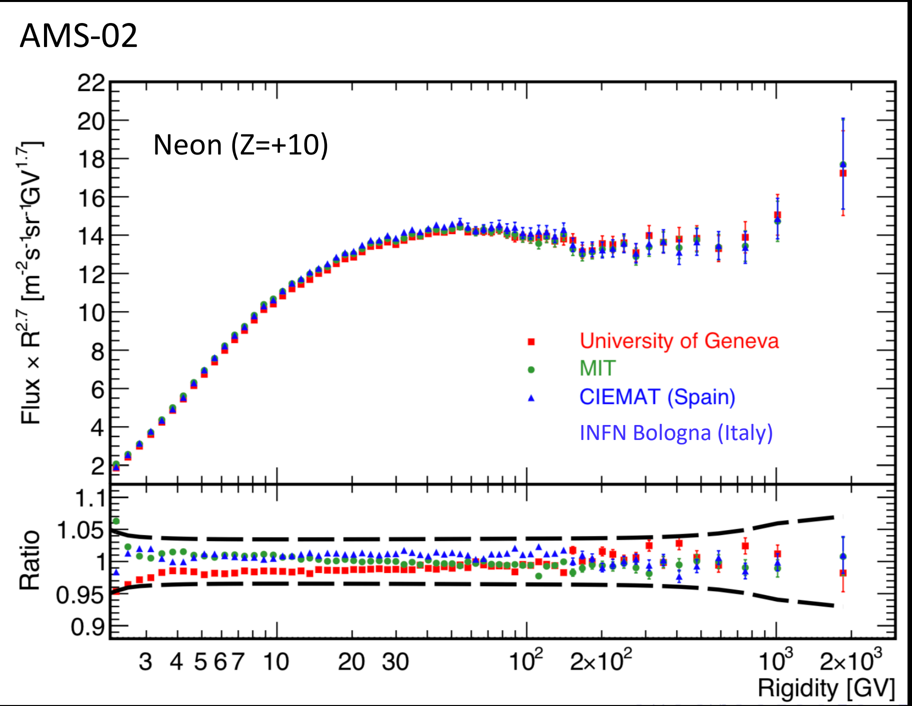




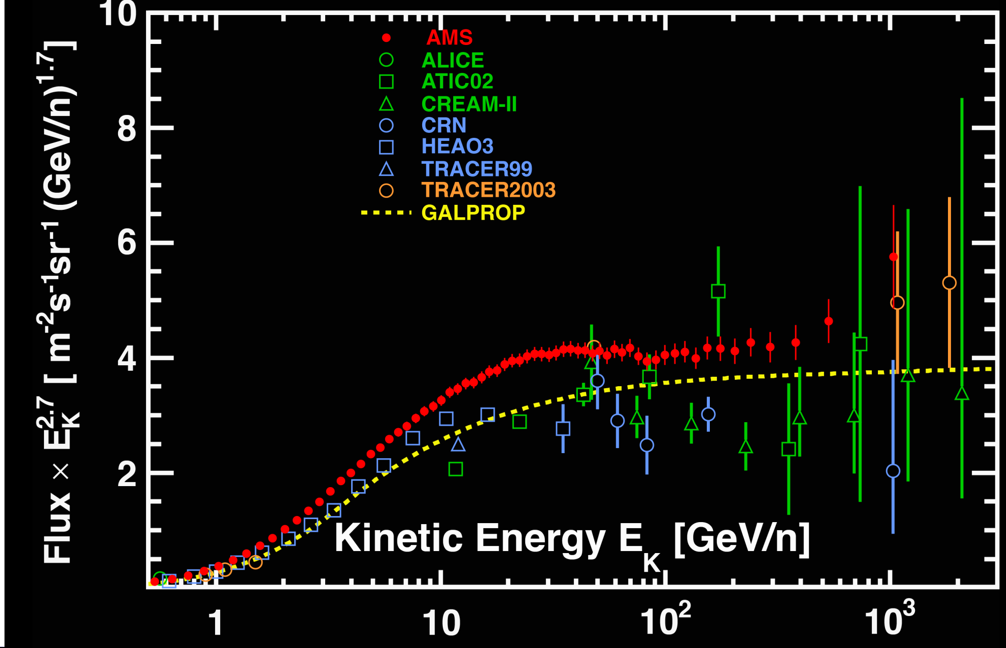
This new observation favors the hypothesis that **the observed spectral hardening** is due to a **propagation effect**.

What about nuclei heavier than Oxygen?
Is the spectral hardening universal?

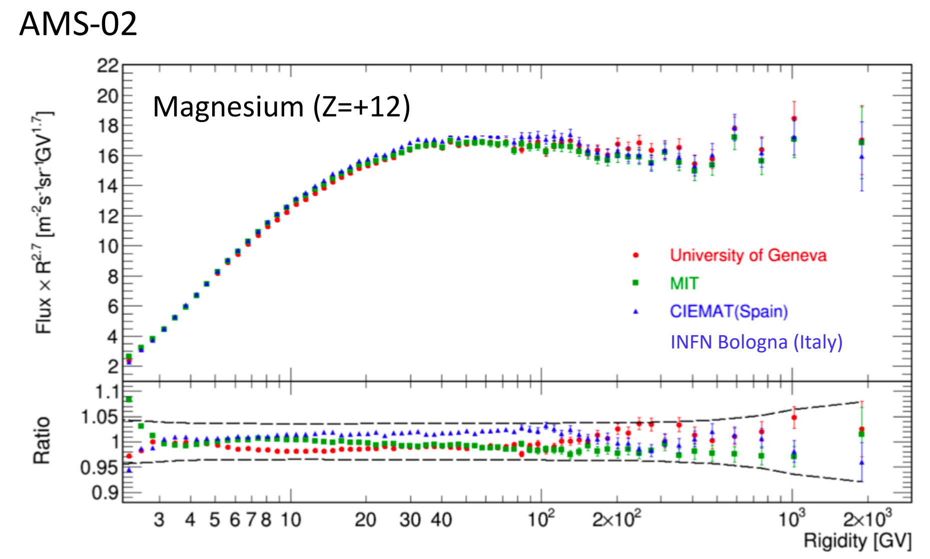
Heavy Primary Cosmic rays: Neon flux measurement

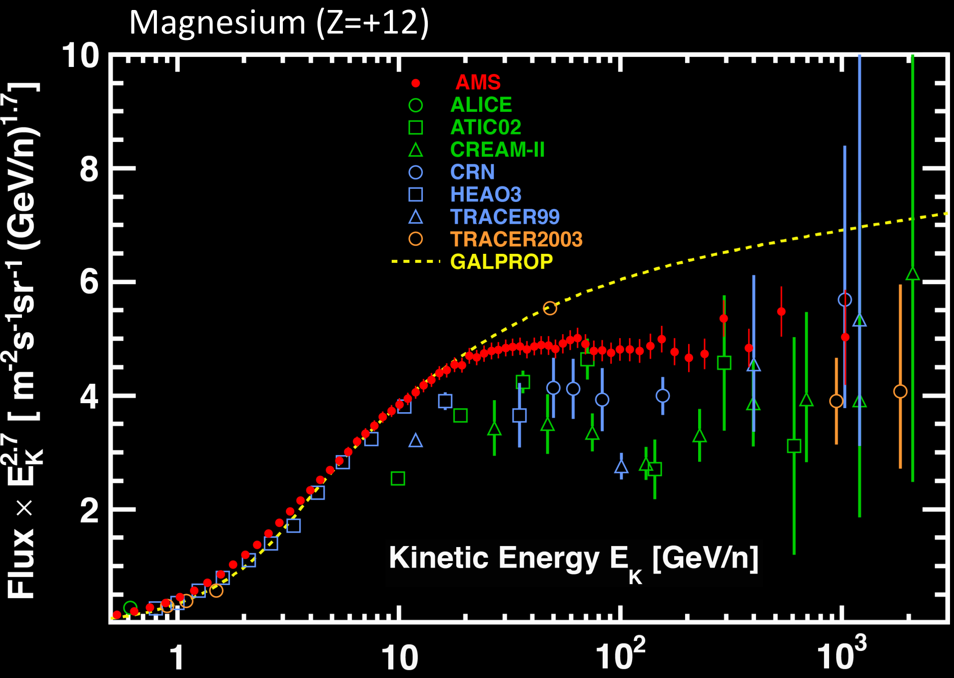


Neon (Z=+10)

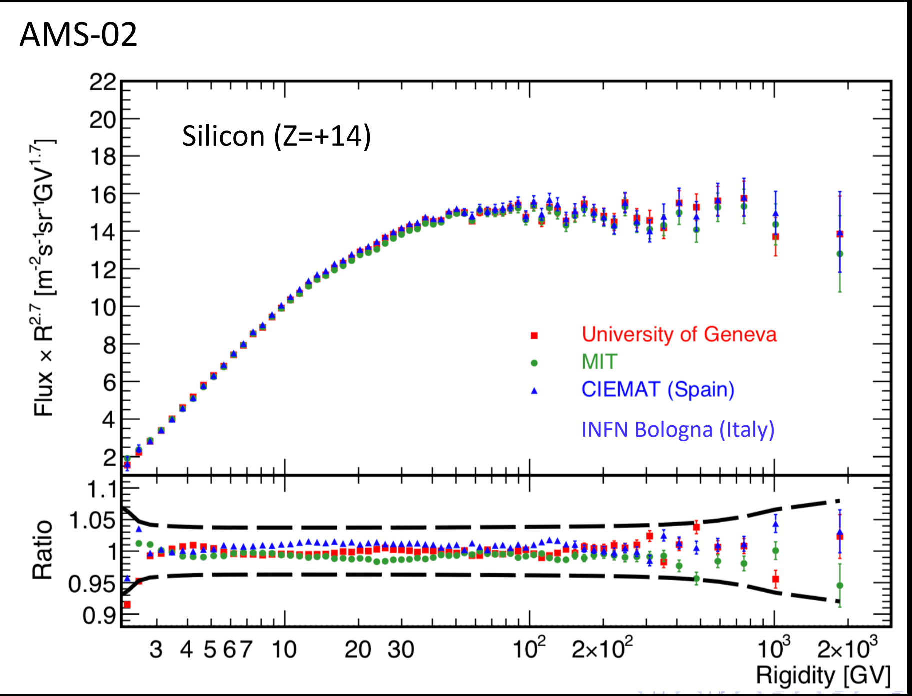


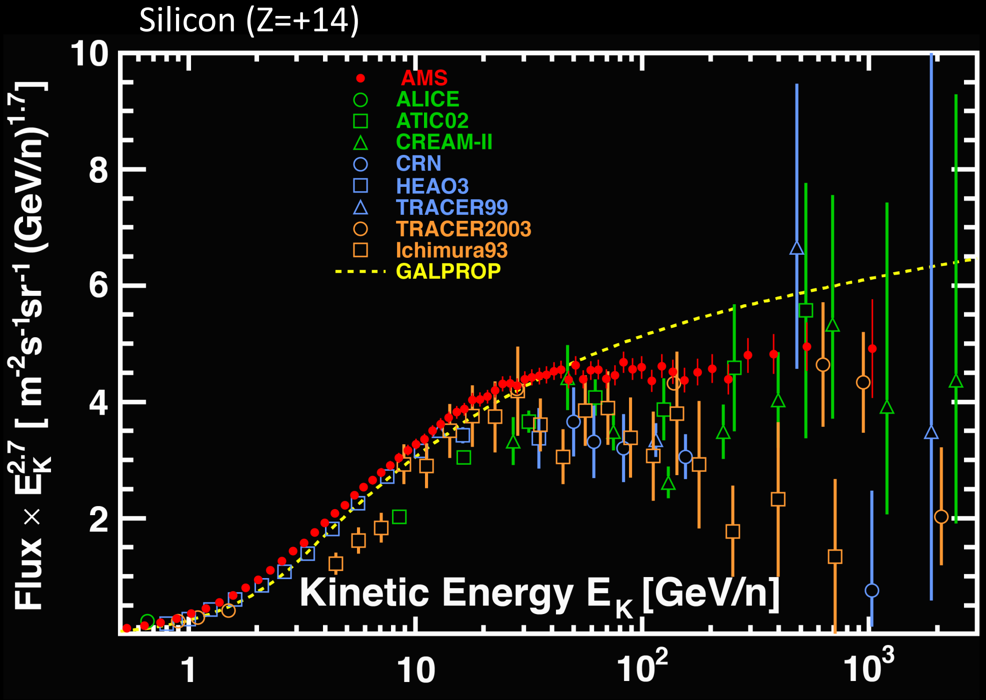
Heavy Primary Cosmic rays: Magnesium flux measurement



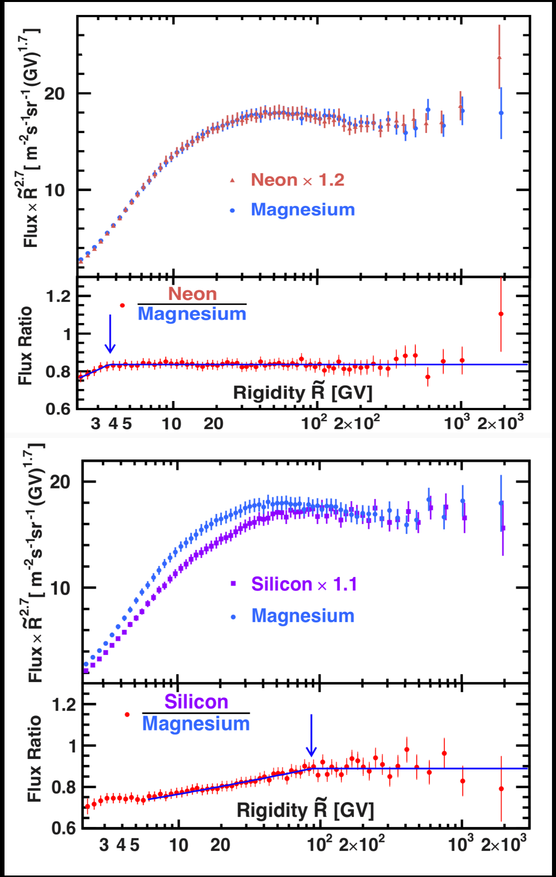


Heavy Primary Cosmic rays: Silicon flux measurement



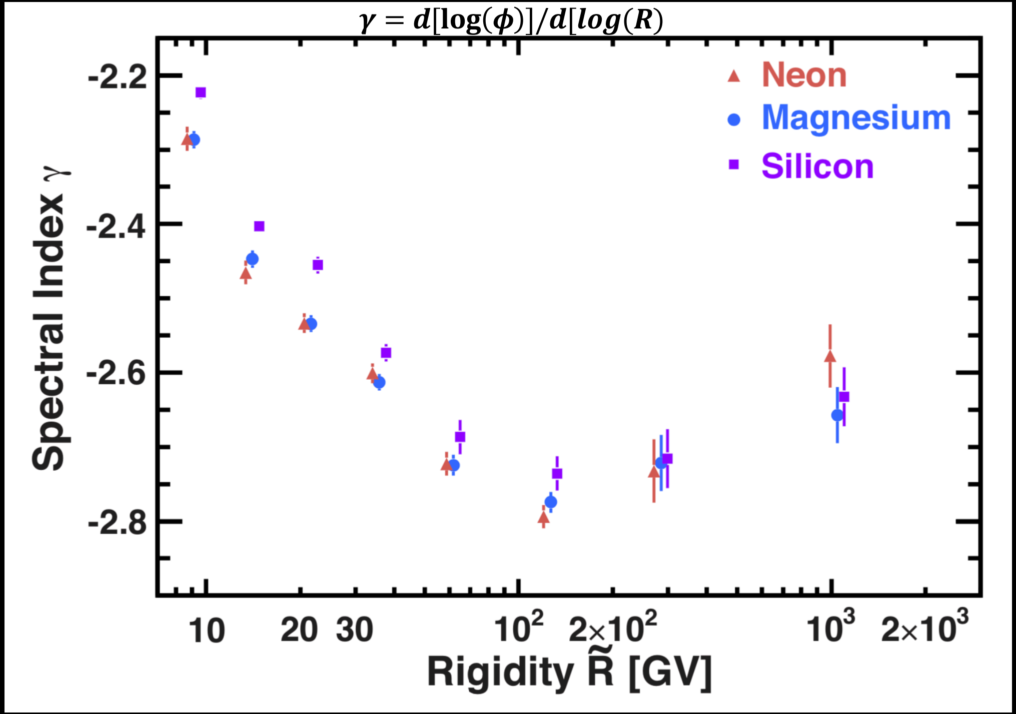


Properties of Heavy Primary Cosmic Rays: Ne, Mg and Si

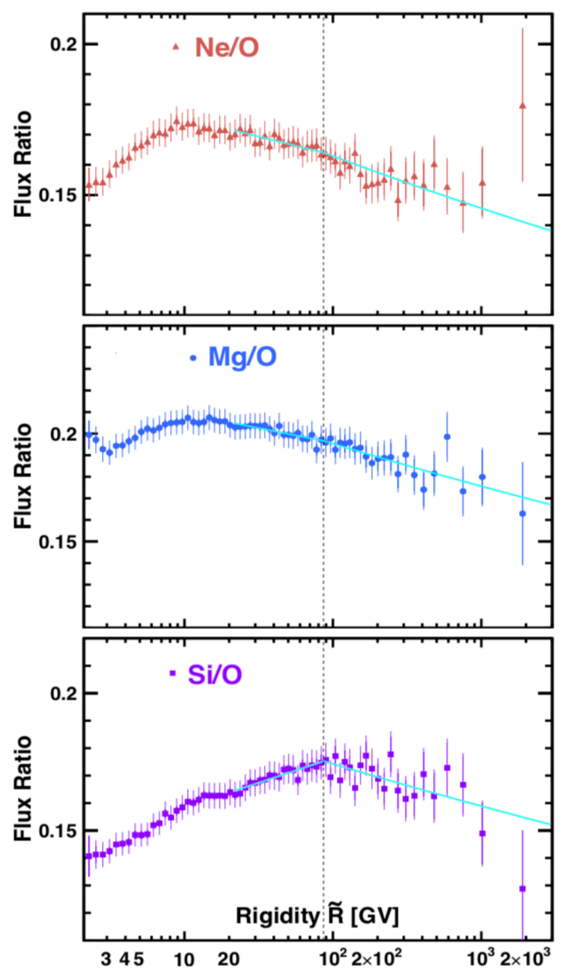


Neon and Magnesium fluxes have identical rigidity dependence above 3.5 GV.

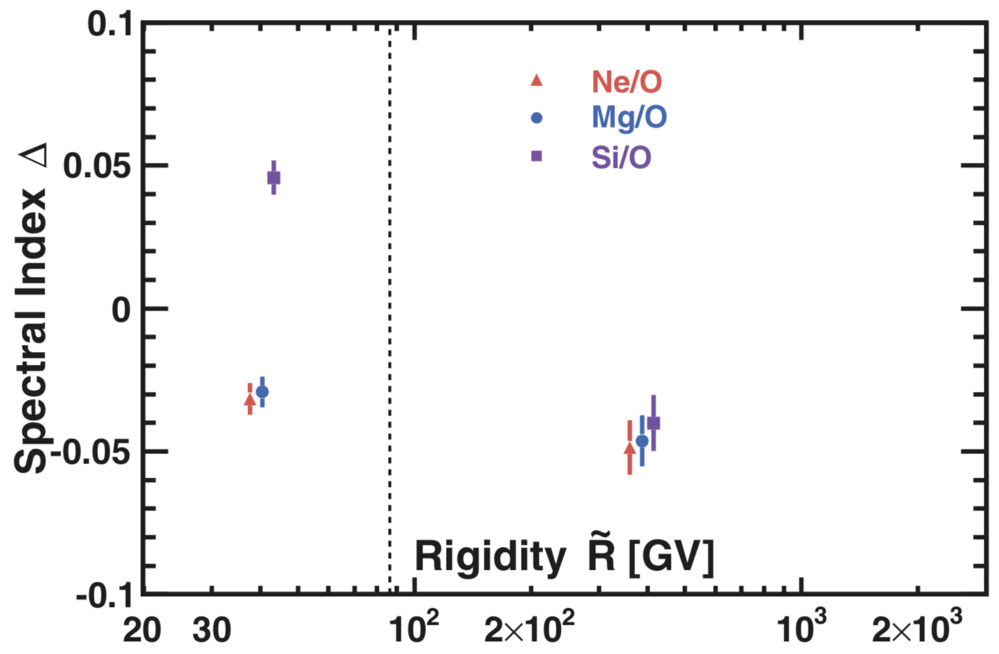
Ne, Mg and Si fluxes have identical rigidity dependence above 86.5 GV.
They all harden in an identical way above 200 GV



Heavy vs Light Primary Cosmic Rays: Ne, Mg, Si vs O



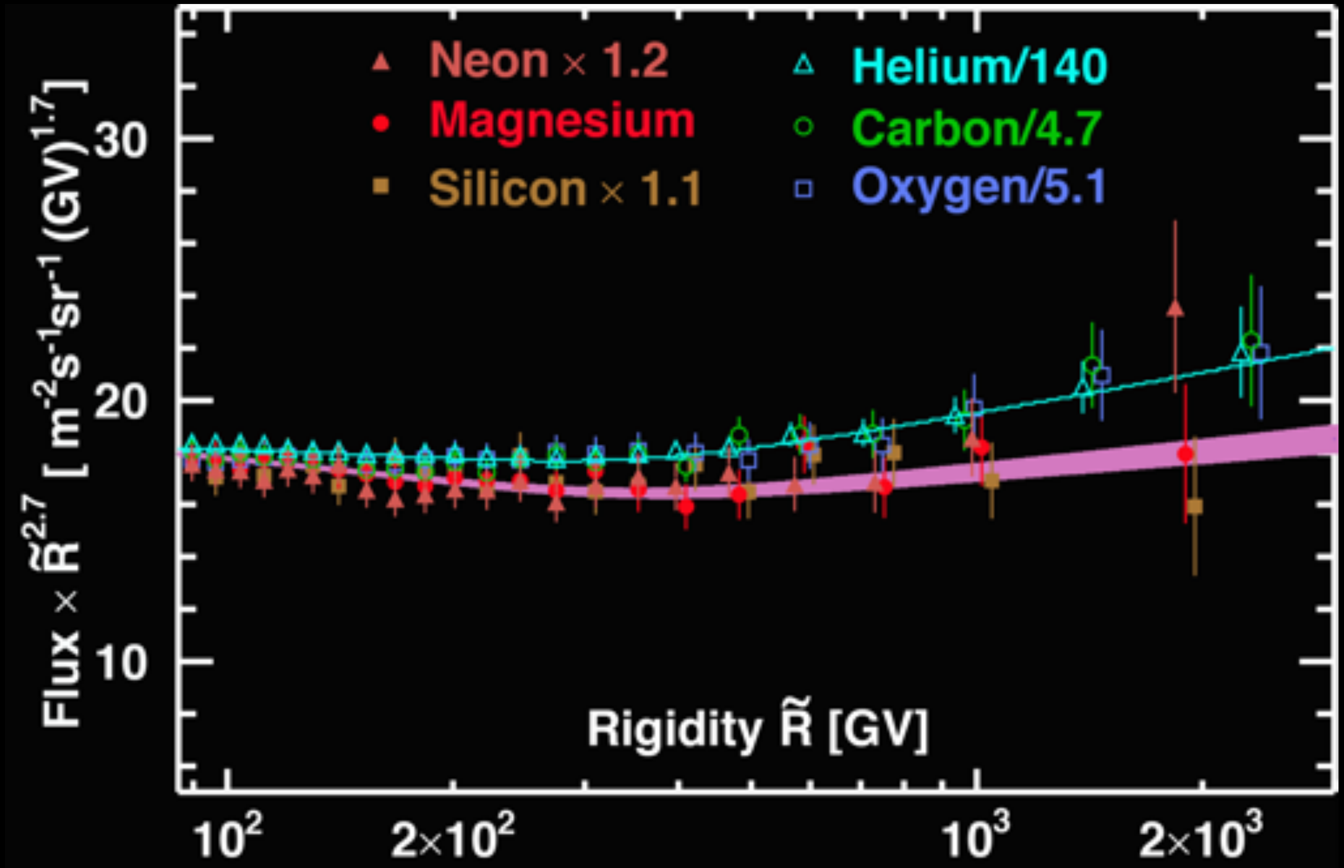
Above 86.5 GV, the three primary-to-primary flux ratios exhibit an average softening of -0.045 ± 0.008



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

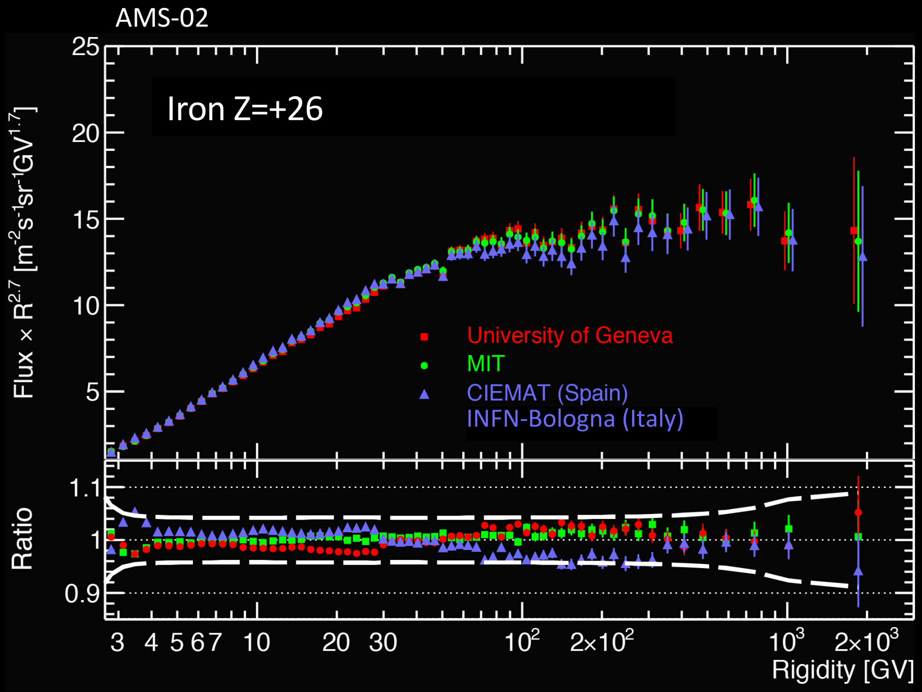
Heavy vs Light Primary Cosmic Rays: Ne, Mg, Si vs He, C, O

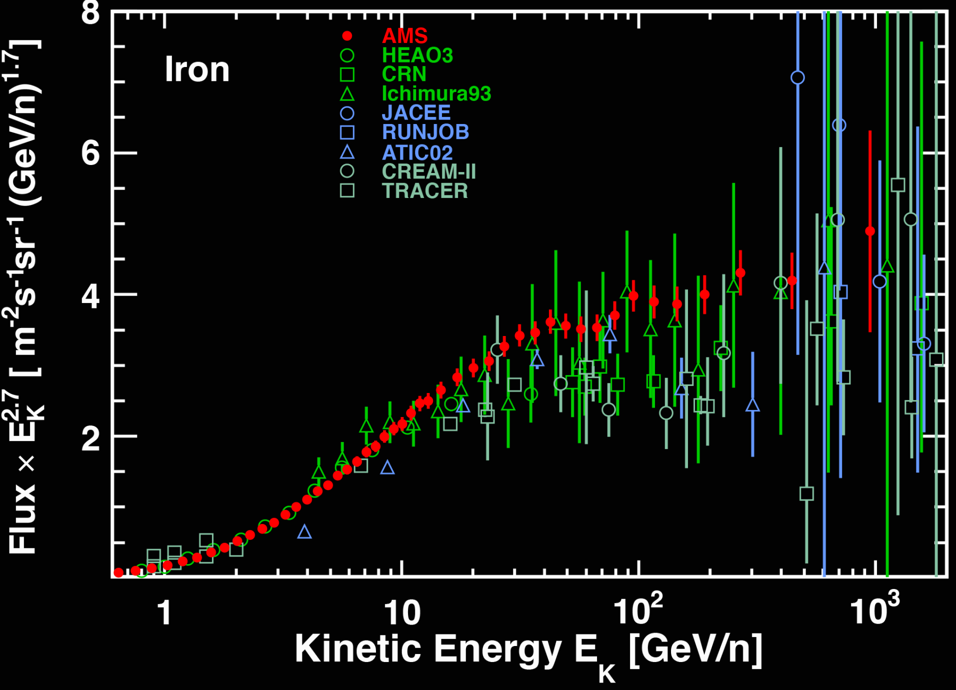
Unexpected result: primary cosmic rays have at least two classes



What about even heavier primaries?

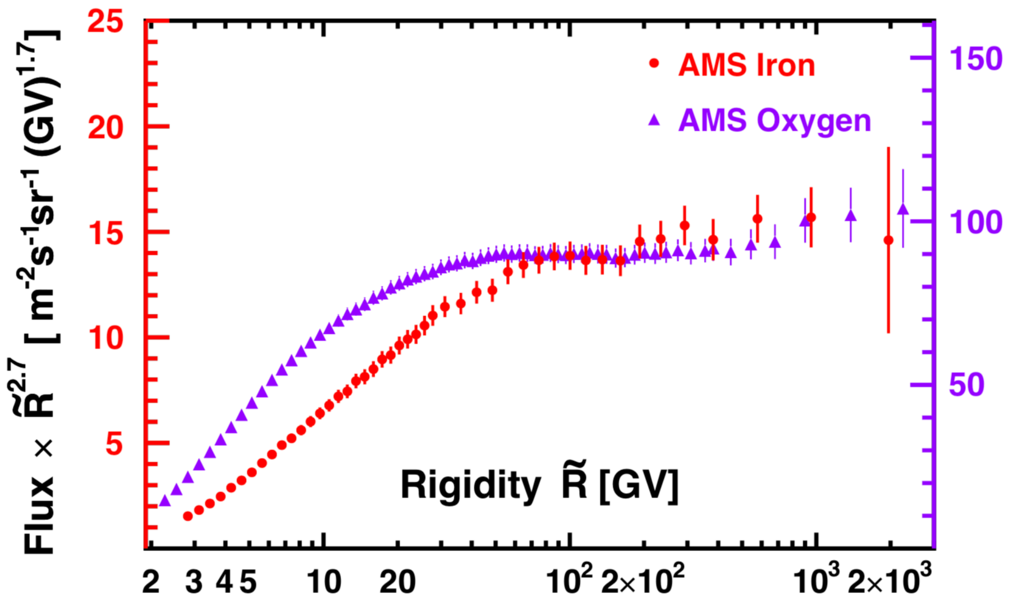
Very Heavy Primary cosmic rays: Iron nuclei flux

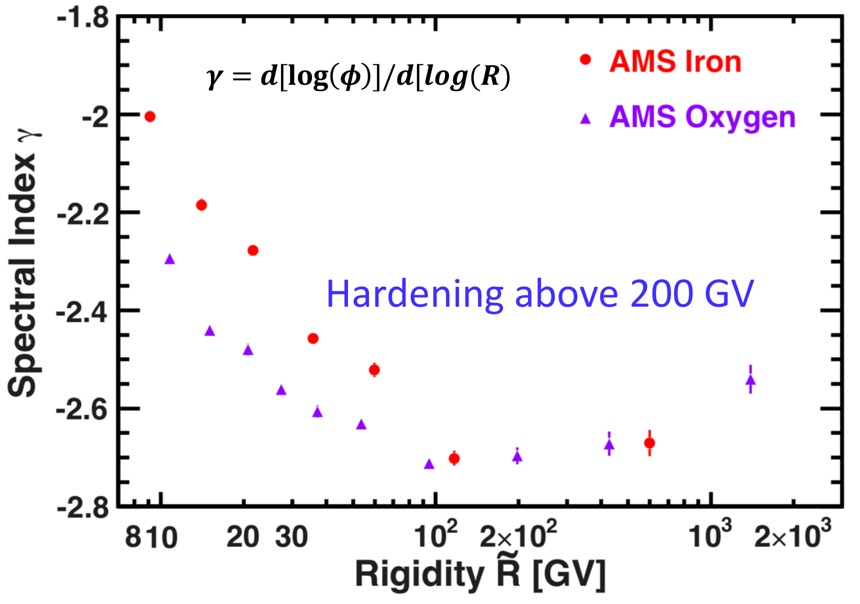




Very Heavy vs Light primary cosmic rays: Iron vs Oxygen

Iron and Oxygen fluxes have identical rigidity dependence above 80.5 GV

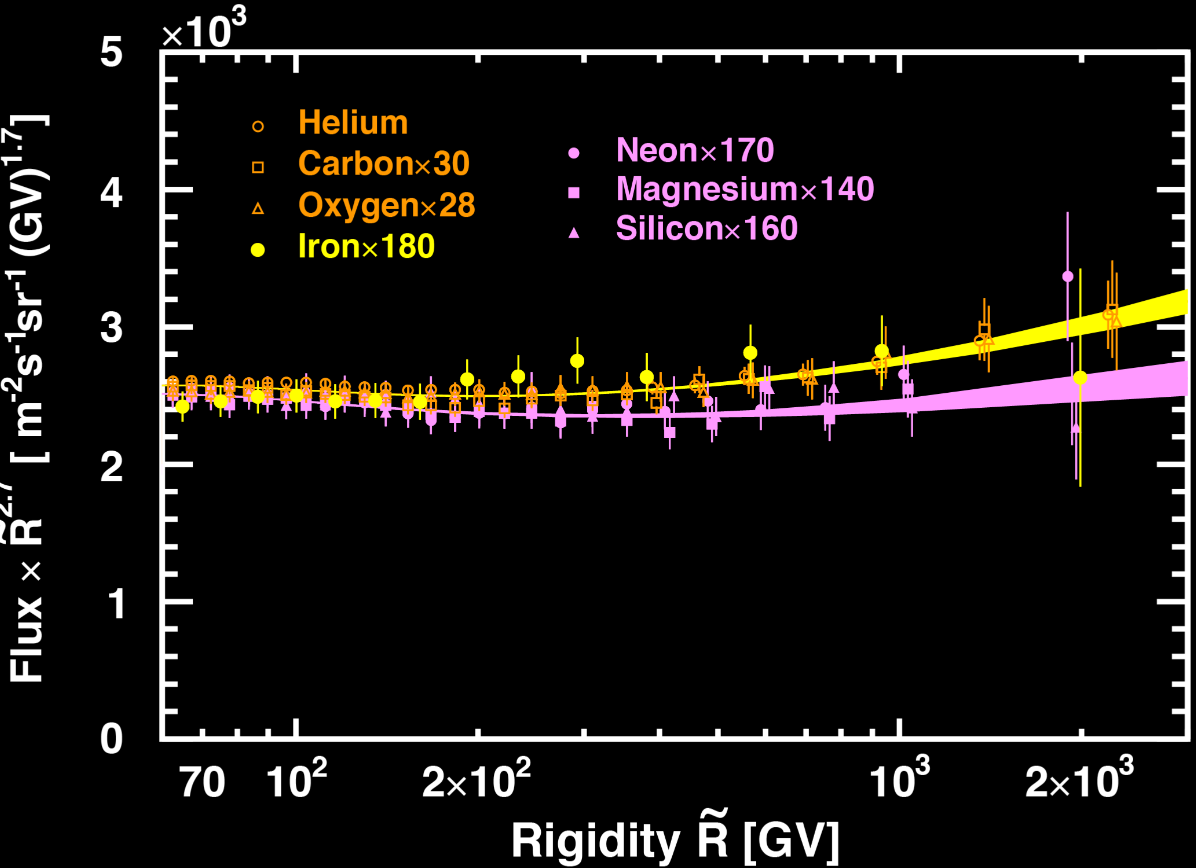




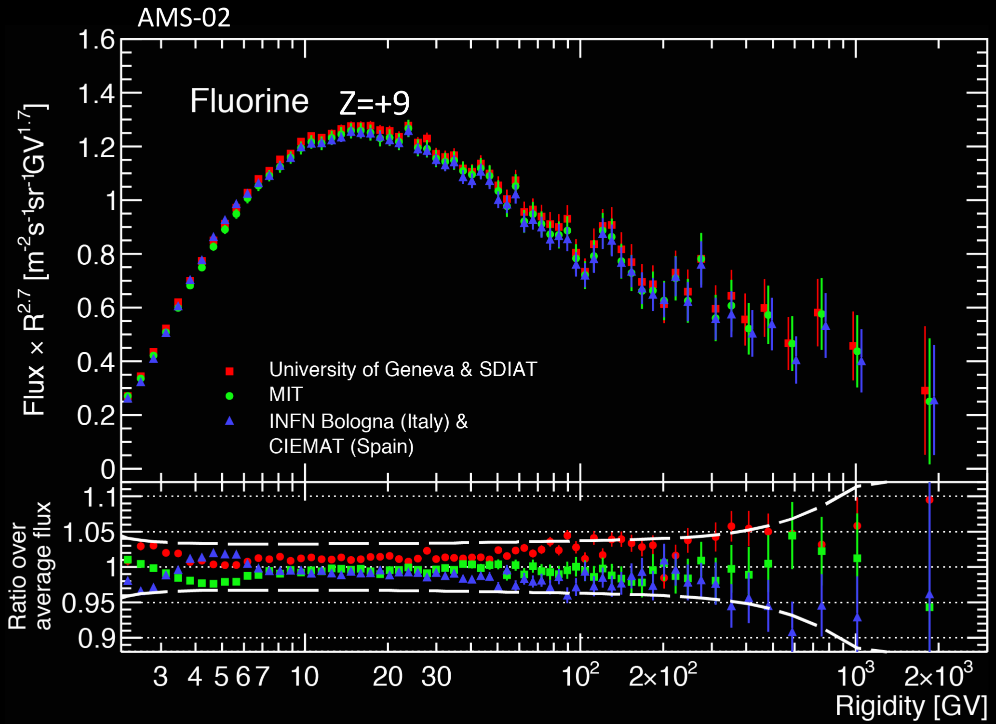
Hardening above 200 GV

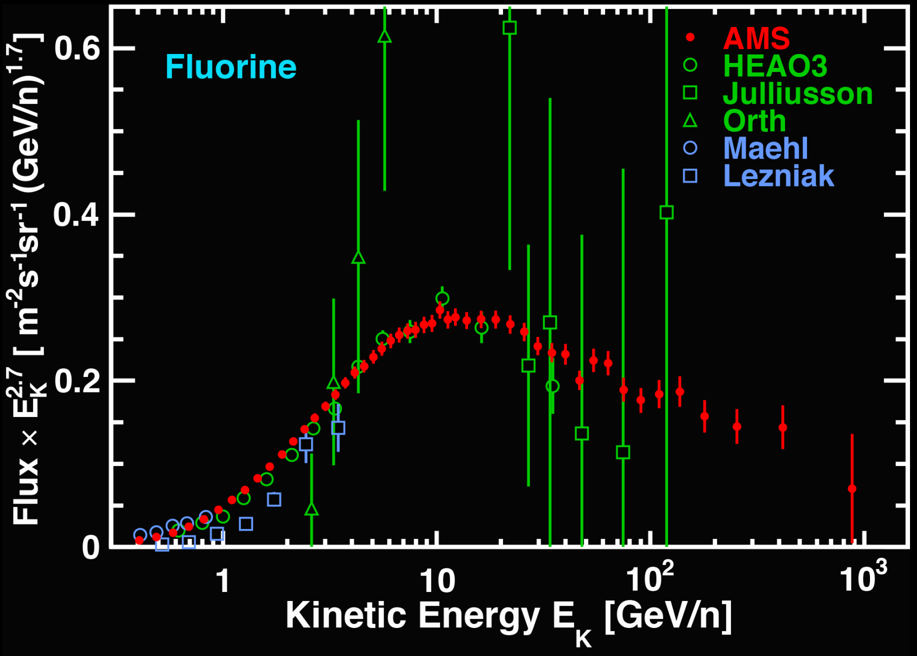
Properties of very heavy primary cosmic rays: Iron

Unexpected result: Iron belongs to the class of light primary cosmic rays, He, C and O.



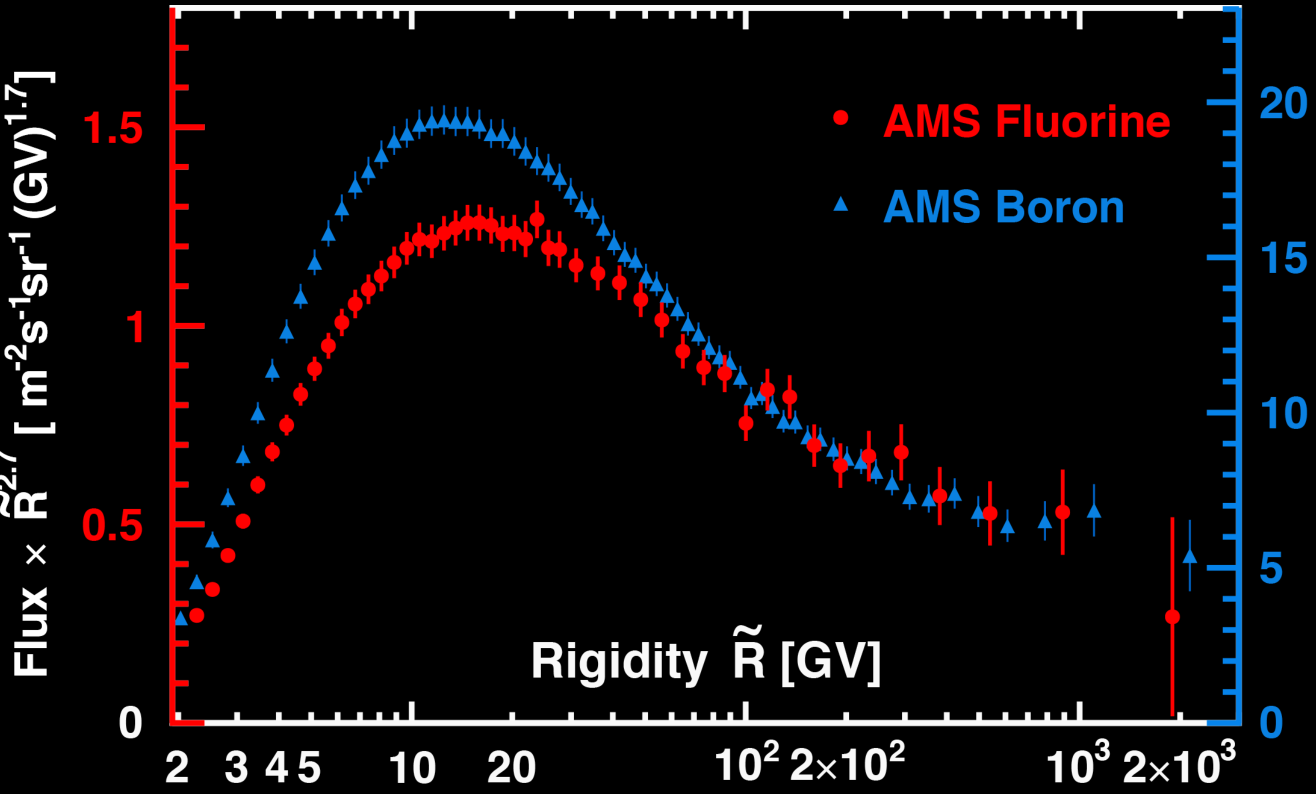
Heavy Secondary cosmic rays: Fluorine nuclei flux measurement





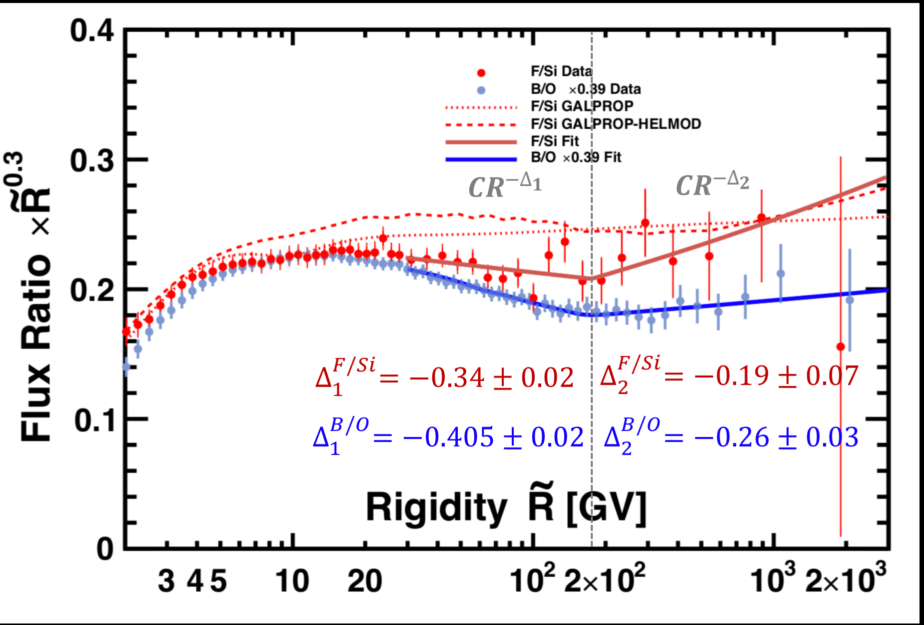
Heavy vs Ligth Secondary cosmic rays: Fluorine vs Boron

Above 175 GV the rigidity dependences of the F and B fluxes are identical



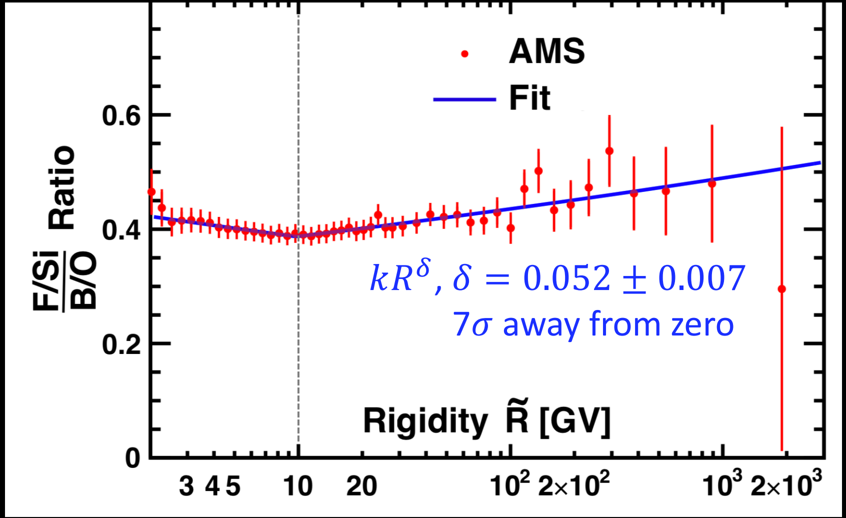
Propagation properties of heavy nuclei: light vs heavy secondary-to-primary

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



New AMS result:

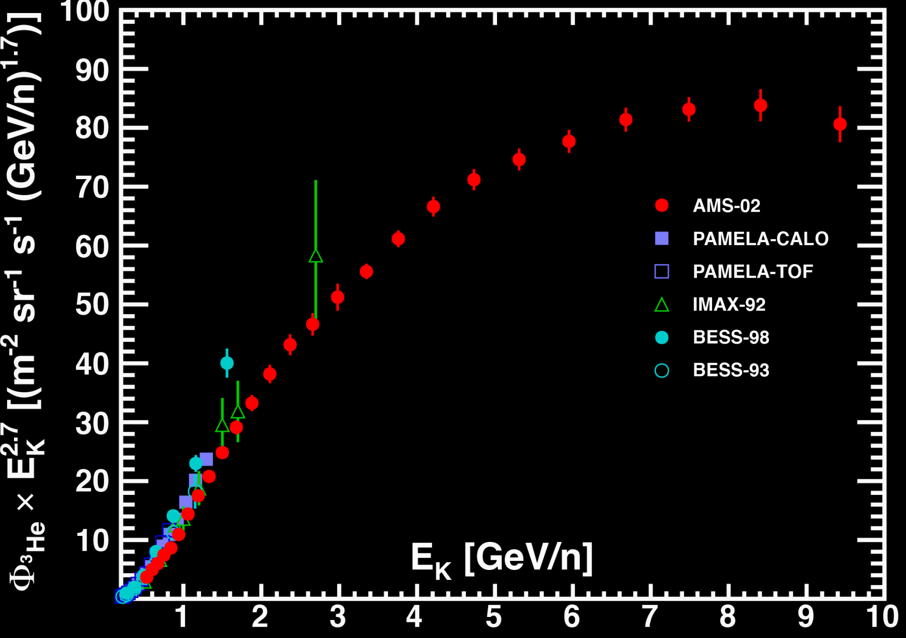
the heavy secondary-to-primary ratio F/Si has a different rigidity dependence from the lighter B/O ratio



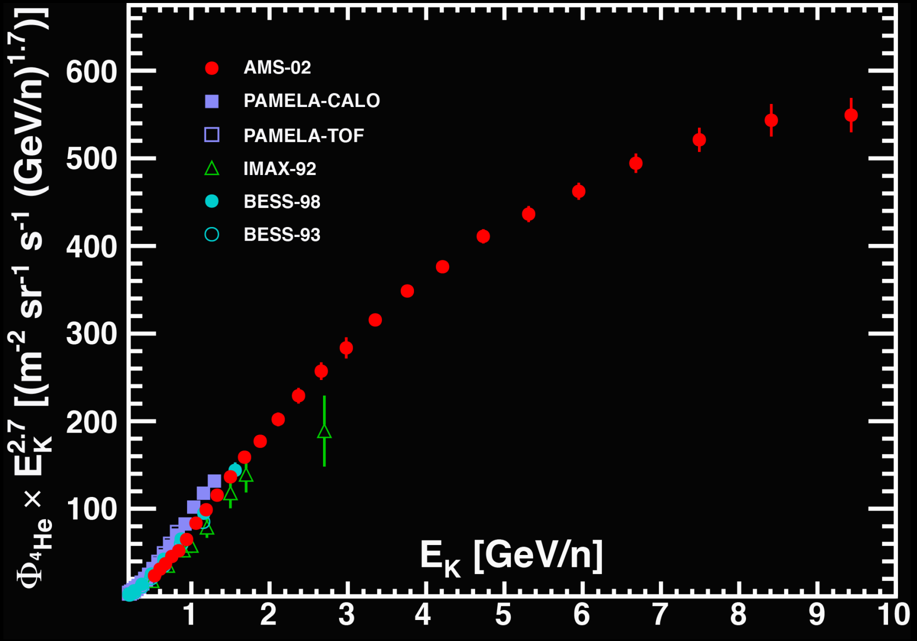
The propagation properties of heavy cosmic rays are different from those of light CRs.

Helium nuclei isotopic composition measurement

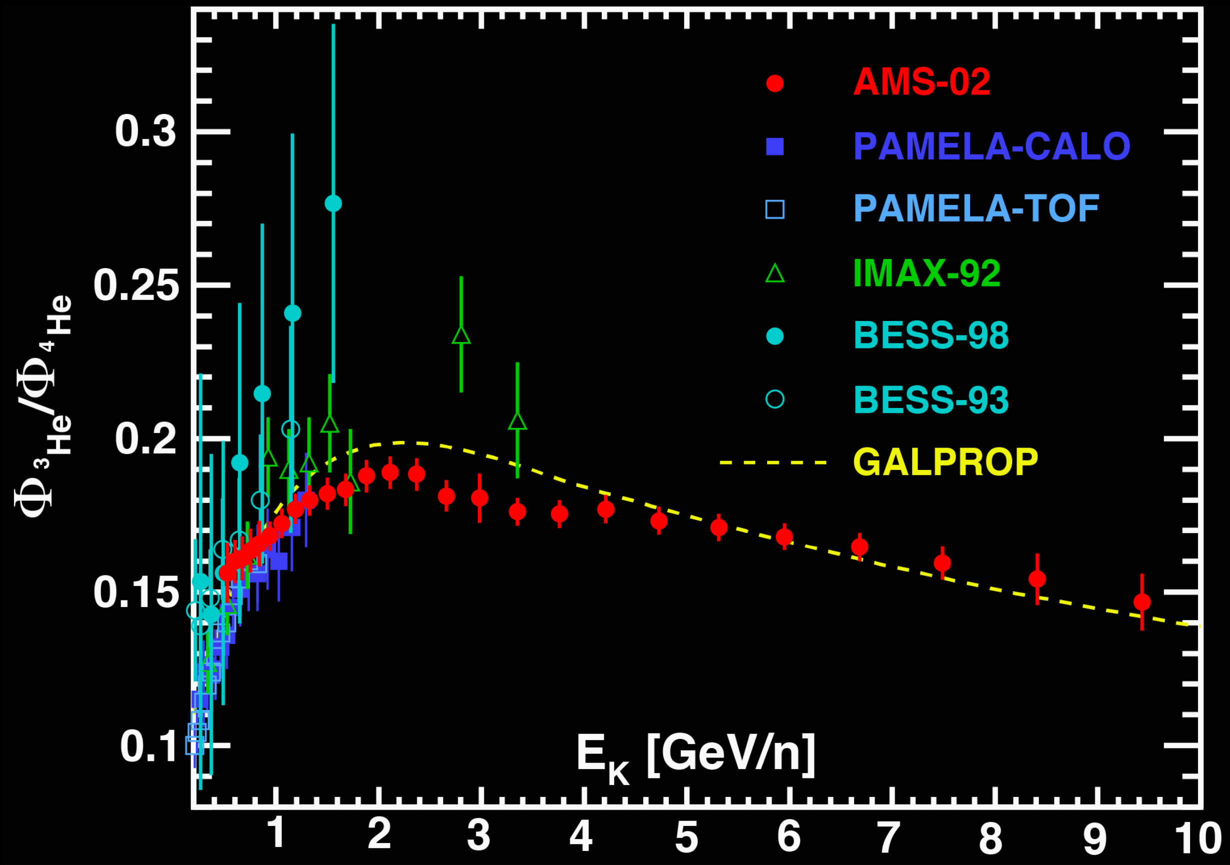
AMS ^{3}He isotope flux



AMS ^{4}He isotope flux

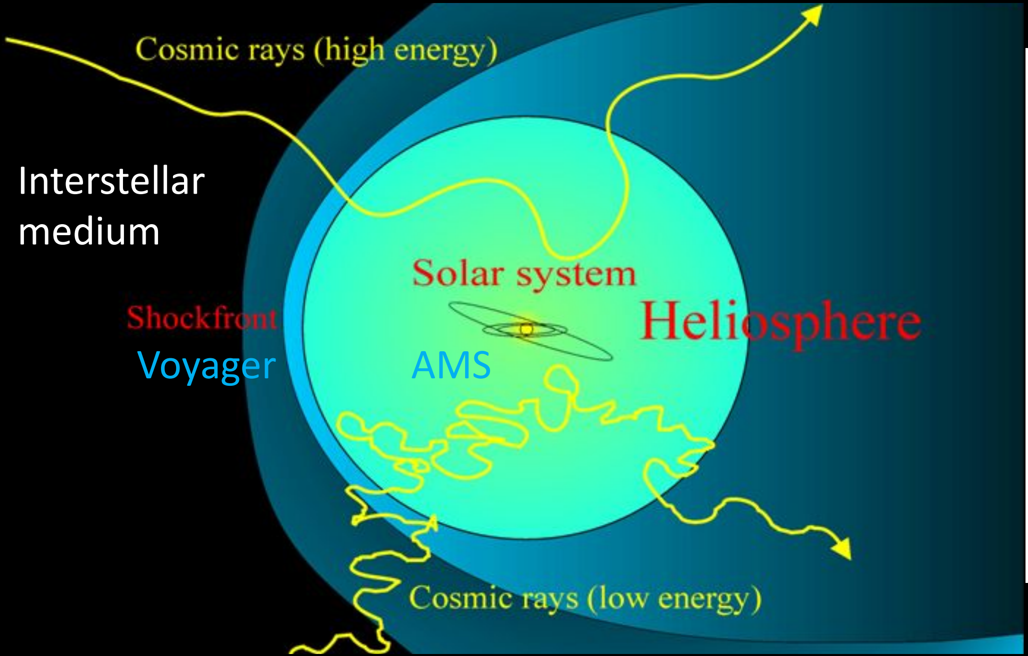


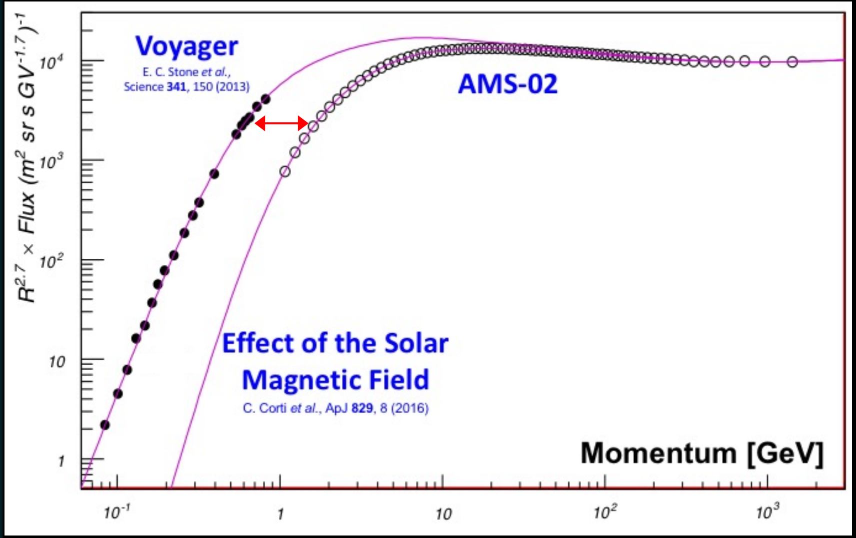
Helium isotopic composition: secondary-to primary ^{3}He/^{4}He ratio



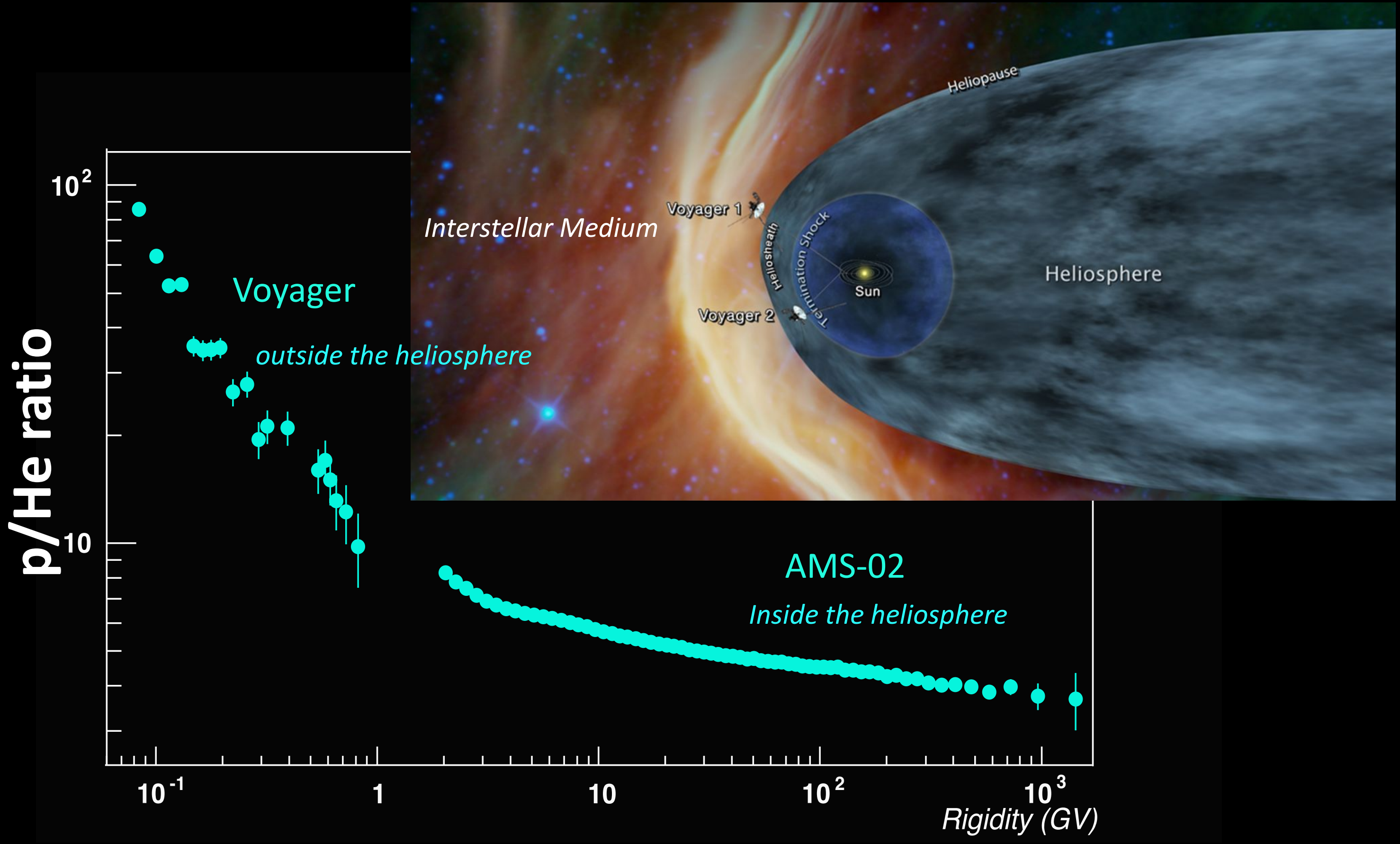
Solar Modulation of cosmic-ray spectra

Low energy cosmic rays from the interstellar medium are "screened" by the heliosphere, emanation of the Sun's magnetic field in the interstellar medium





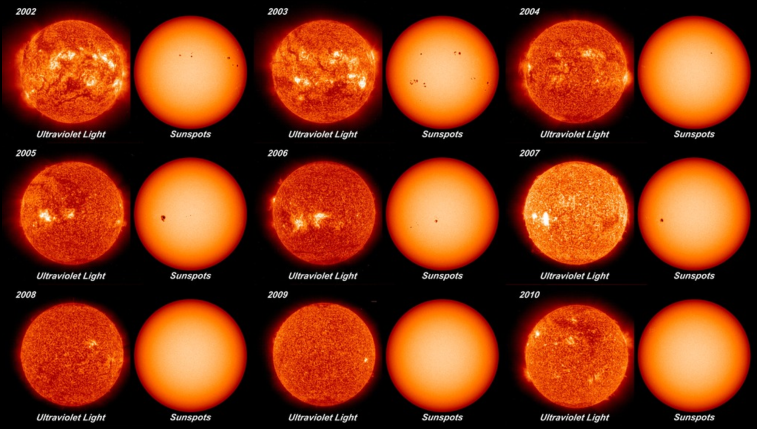
Connecting near-Earth space radiation with Deep Space

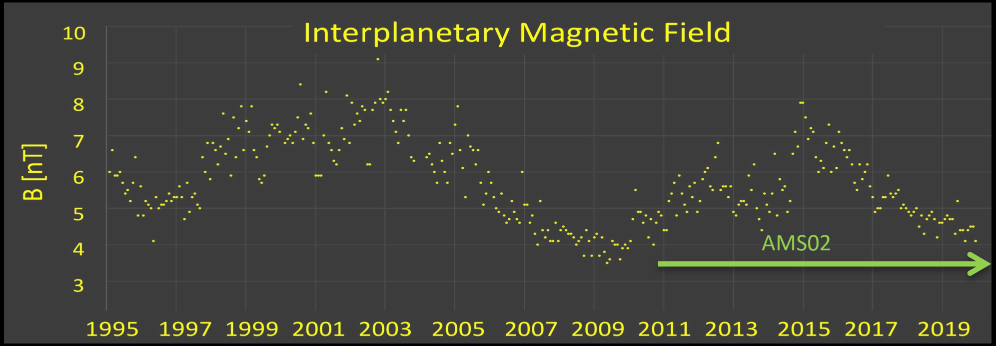


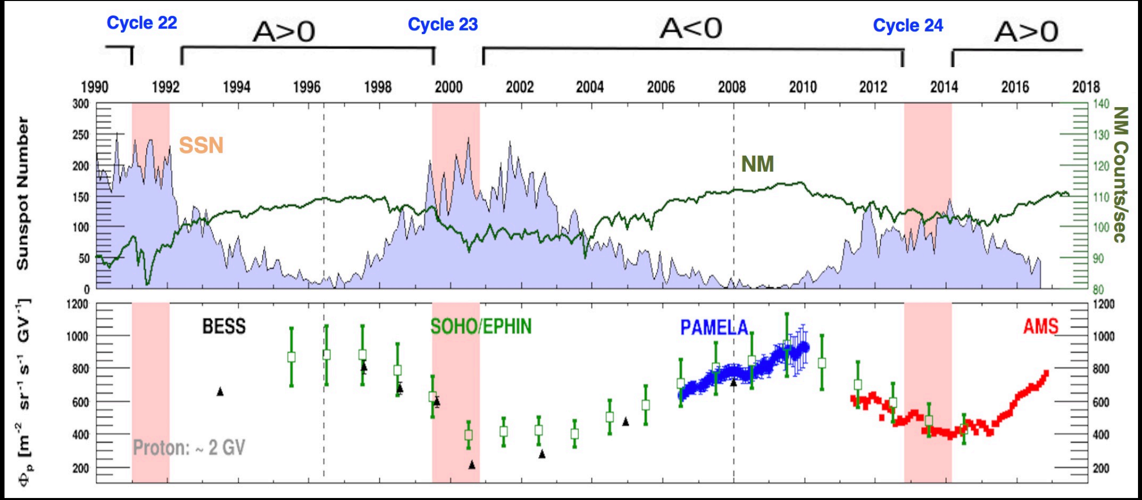
The Solar Cycle

The heliosphere changes with time following the solar cycle:

The Sun has an 11-year activity cycle shown by sunspot number (SSN)

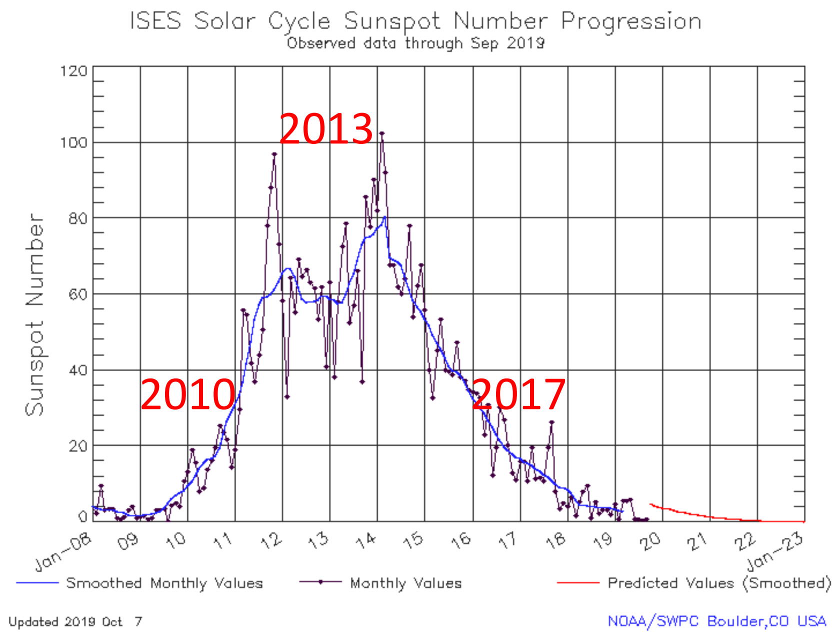


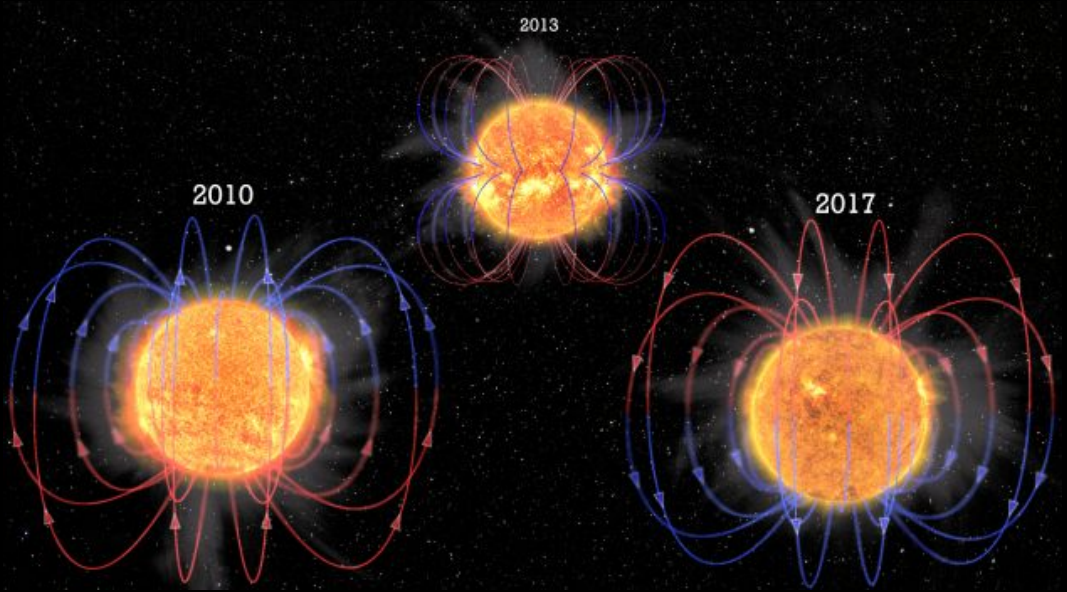




Solar Magnetic field: polarity reversal

At each solar maximum (every 11 years) the polarity of the Sun's magnetic field flips

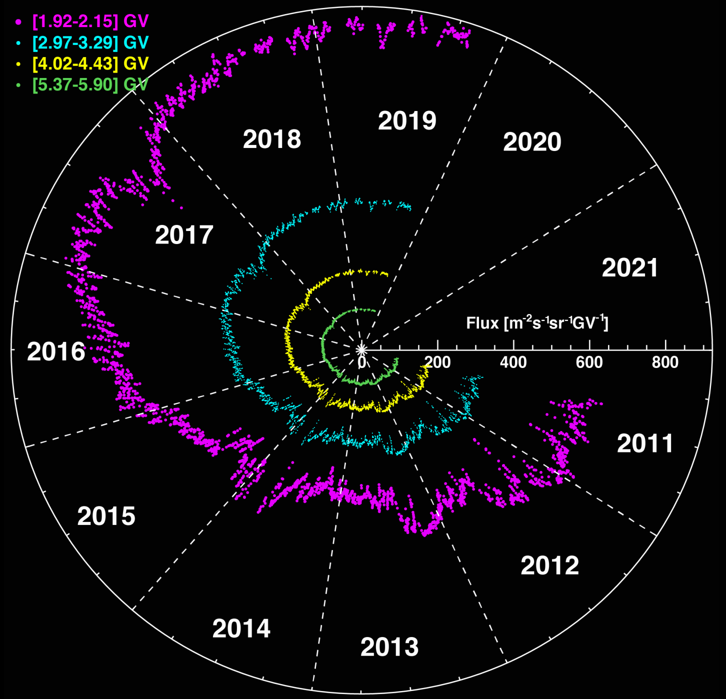




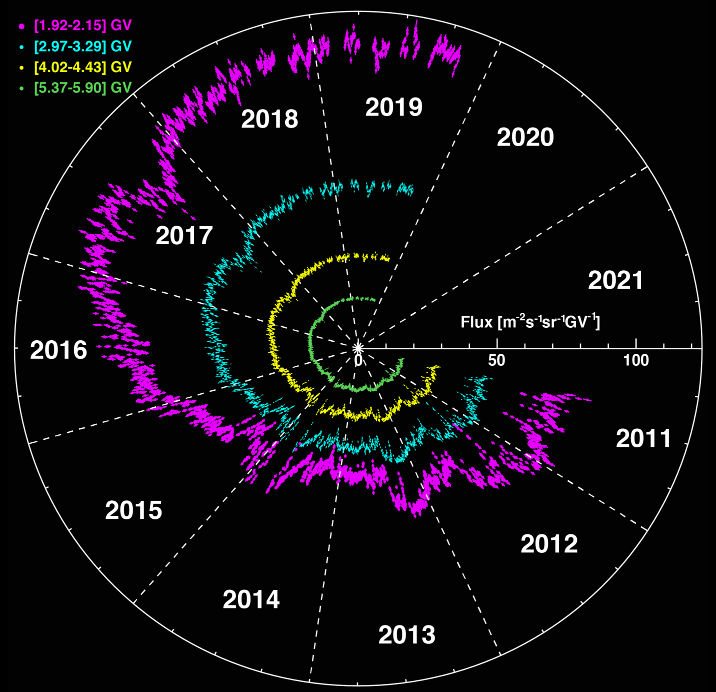
Generates charge-sign dependent effects on solar modulation of cosmic rays

Observation of Fine Time Variations in Proton and Helium Fluxes

AMS Daily Proton Fluxes



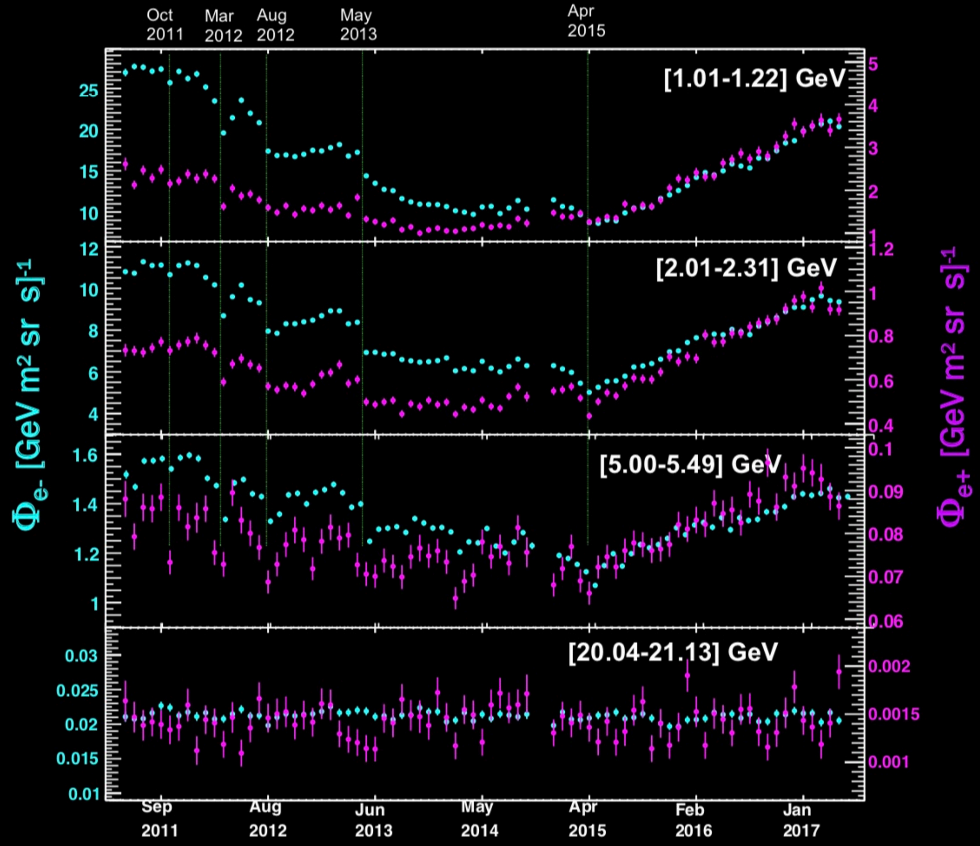
AMS Daily Helium Fluxes

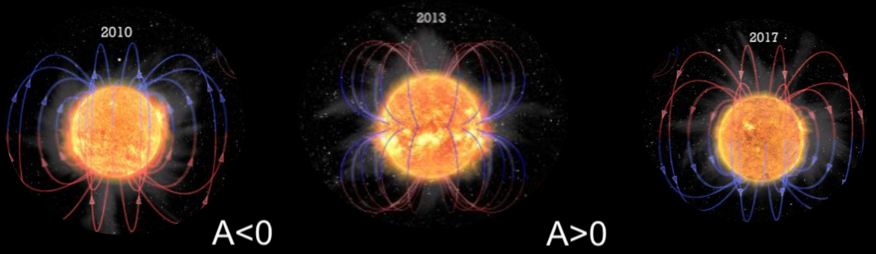


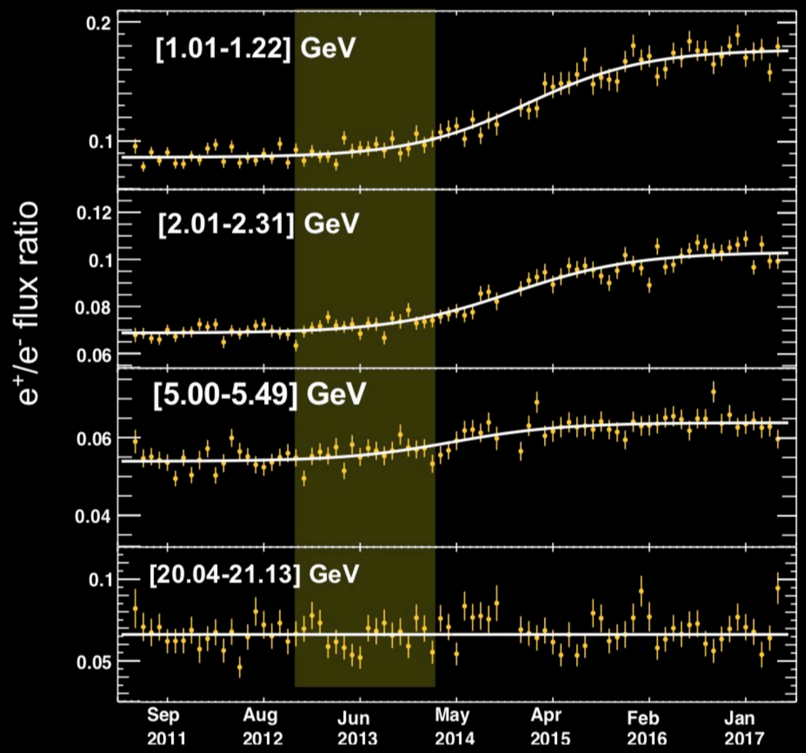
Detailed study of solar effects on cosmic rays are important to assess CR Local Interstellar Spectra

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

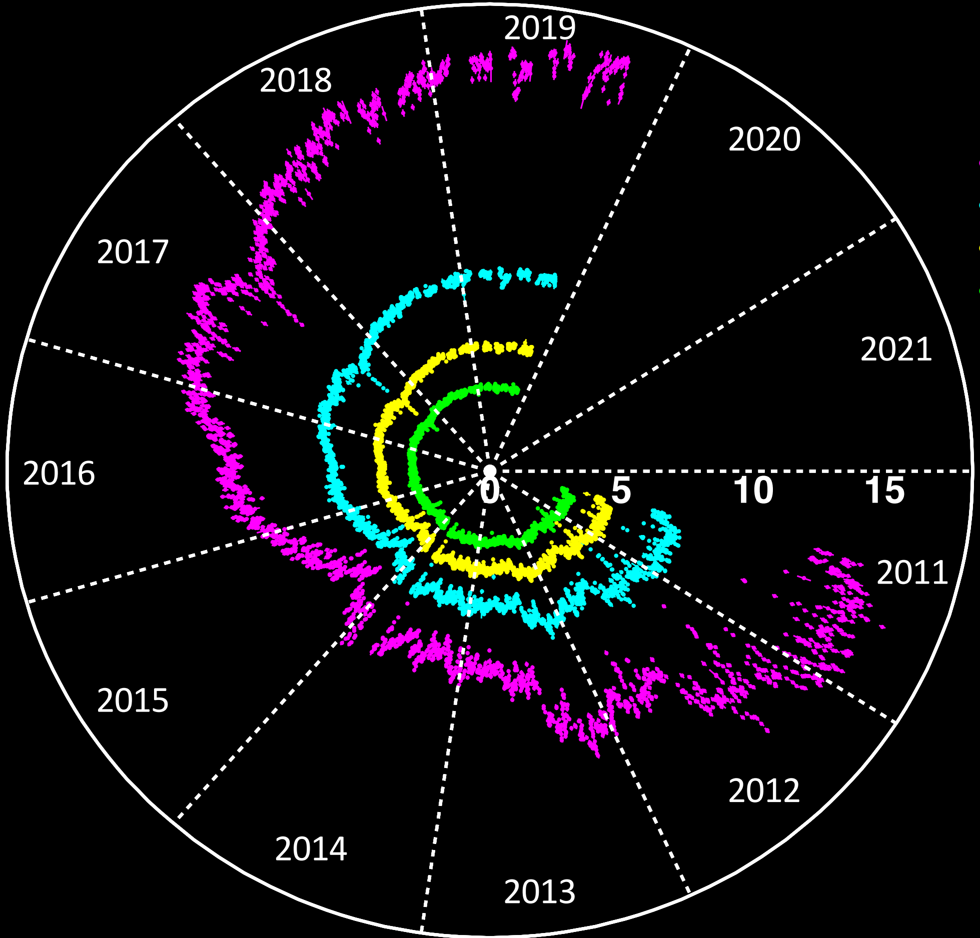
Observation of charge-sign dependent heliospheric effects: e^+ and e^- 27-day fluxes







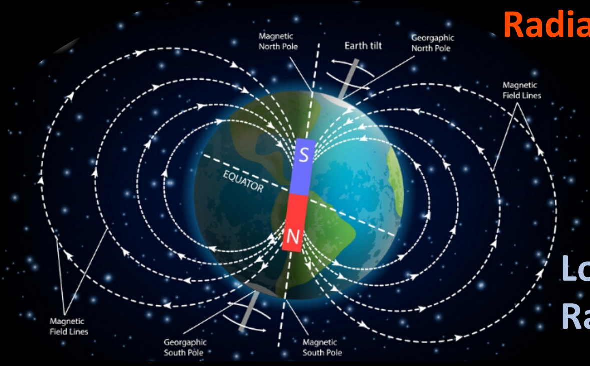
Observation of fine time variations in the electron flux

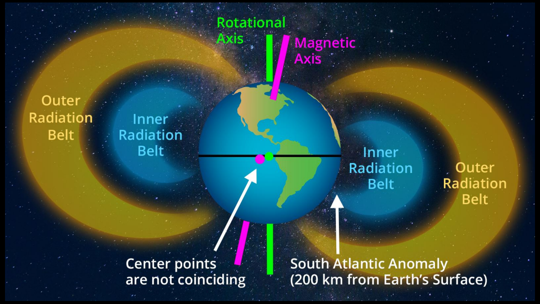


AMS Daily
Electron Fluxes

- [1.00 - 2.97] GV
- [2.97 - 4.88] GV $\phi_e \times 2$
- [4.88 - 7.09] GV $\phi_e \times 4$
- [7.09 - 10.1] GV $\phi_e \times 8$

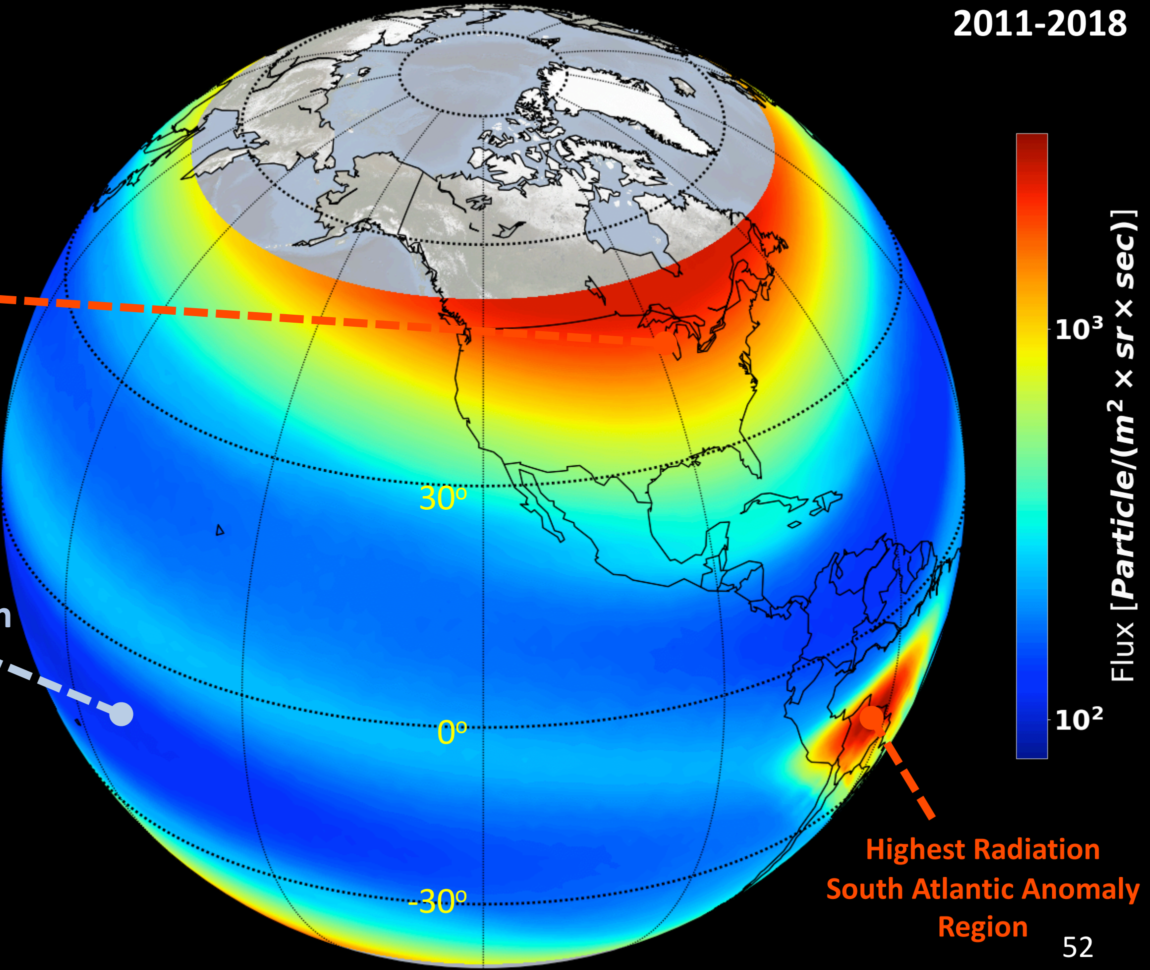
Measurement of near-Earth Radiation





AMS flux of Protons above 100 MeV

Average 2011-2018



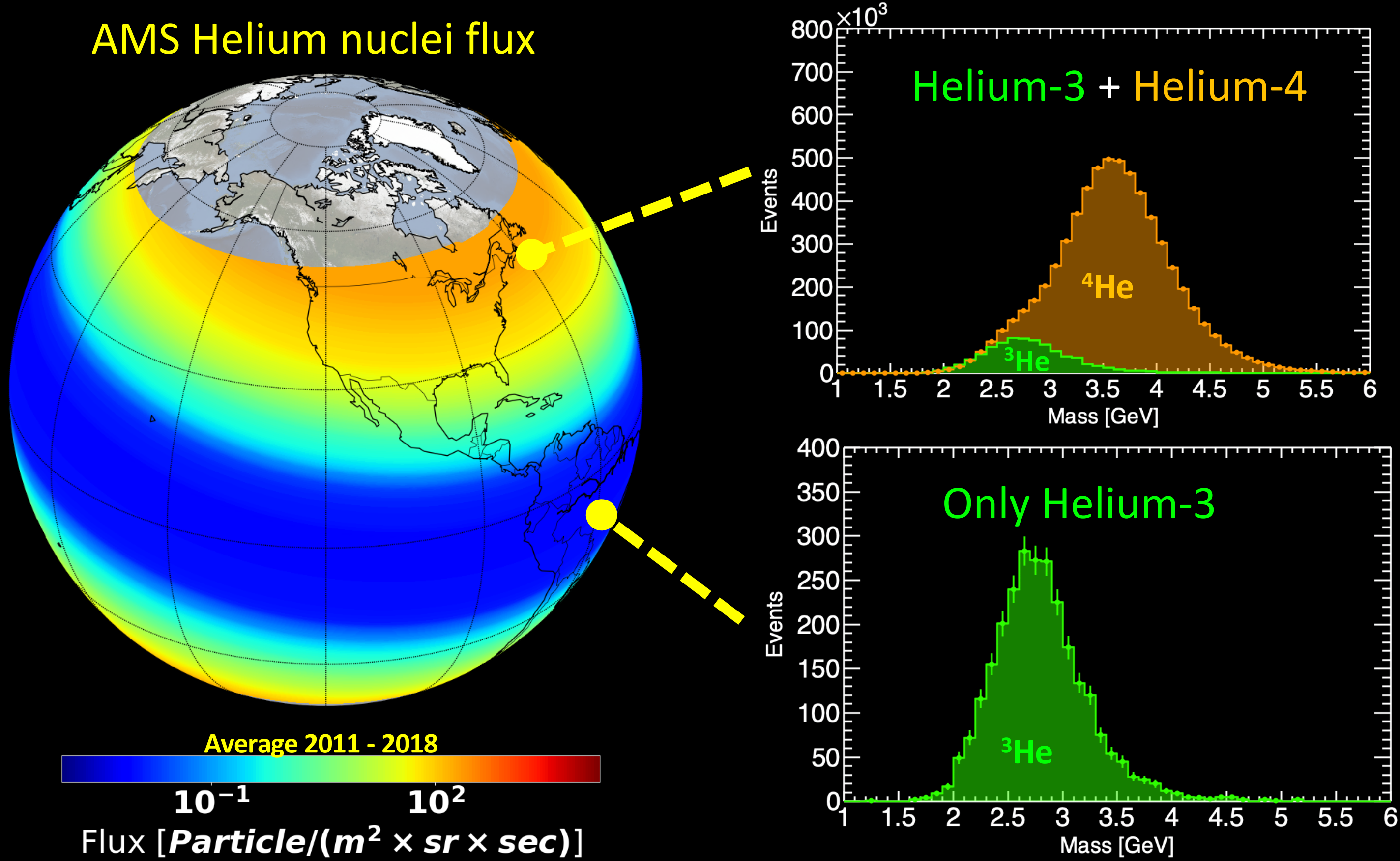
Highest Radiation

Lowest Radiation

Highest Radiation South Atlantic Anomaly Region

Measurement of near-Earth radiation

In the energy range 100 MeV to 4000 MeV over a large region, $-35° < \Theta_M < +35°$, only ^{3}He isotope exists.

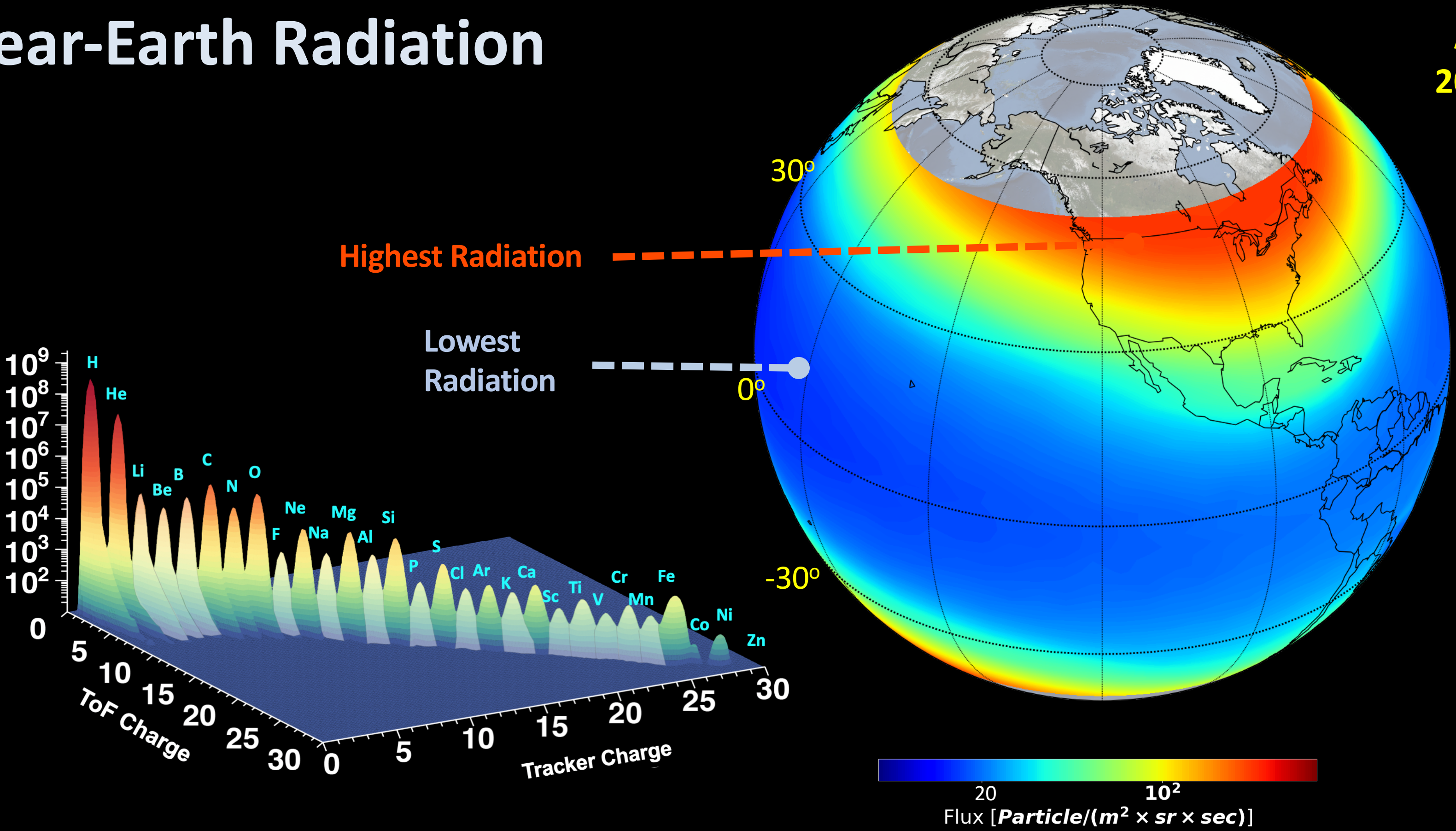


AMS Helium nuclei flux

Measurement of near-Earth Radiation

AMS Flux of Heavy Nuclei He(Z=2) to Zinc(Z=30)

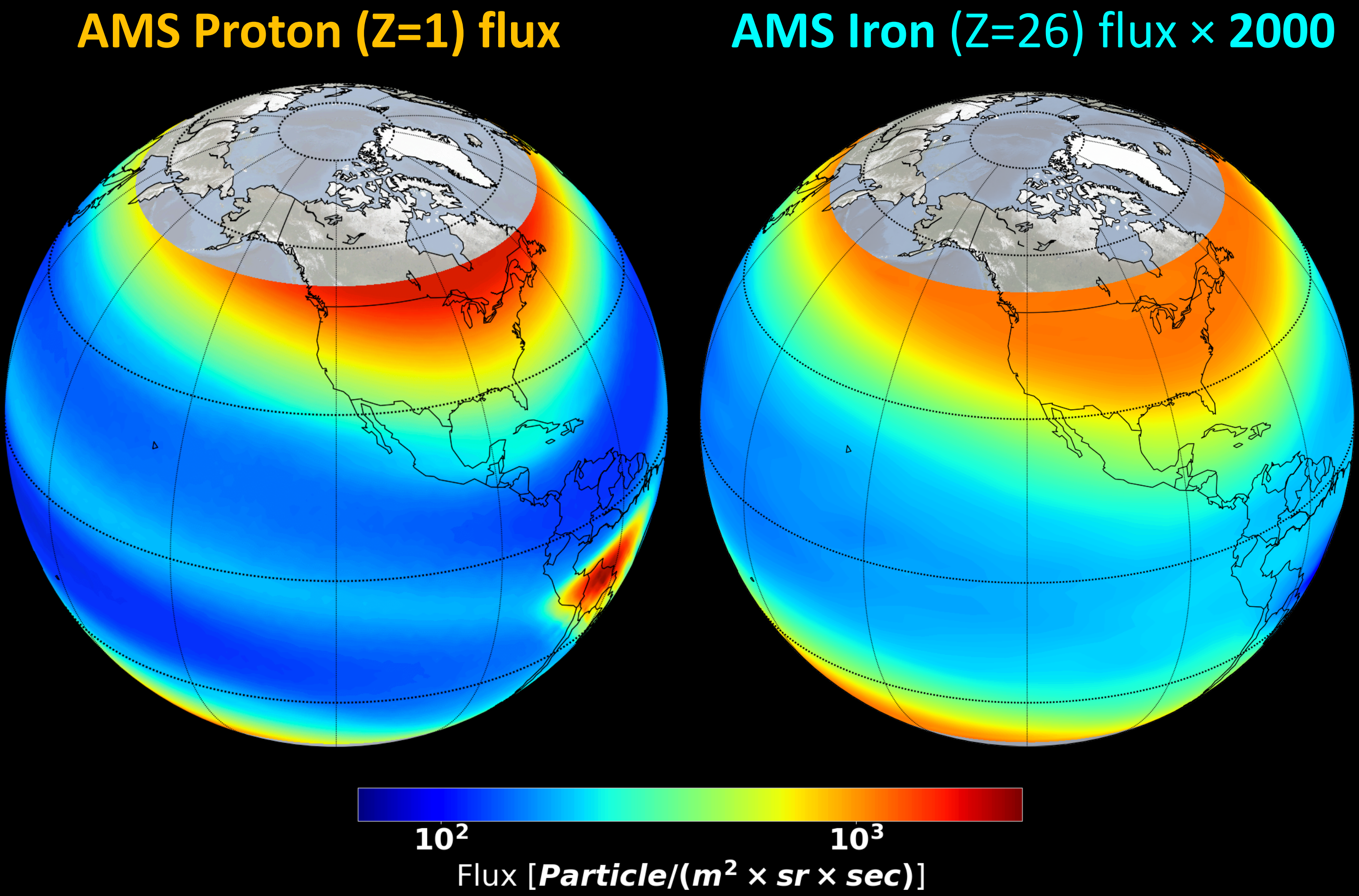
Average
2011-2018



Highest Radiation

Lowest Radiation

Measurement of near-Earth Radiation



Conclusions

In nine years on the ISS, AMS has recorded more than 170 billion cosmic rays.

The accuracy of the AMS data is revealing unexpected features in the spectra of many different types of cosmic rays requiring the development of a new comprehensive model.

AMS will continue to collect and analyze data for the lifetime of the Space Station because whenever a precision instrument such as AMS is used to explore the unknown, new and exciting discoveries can be expected.