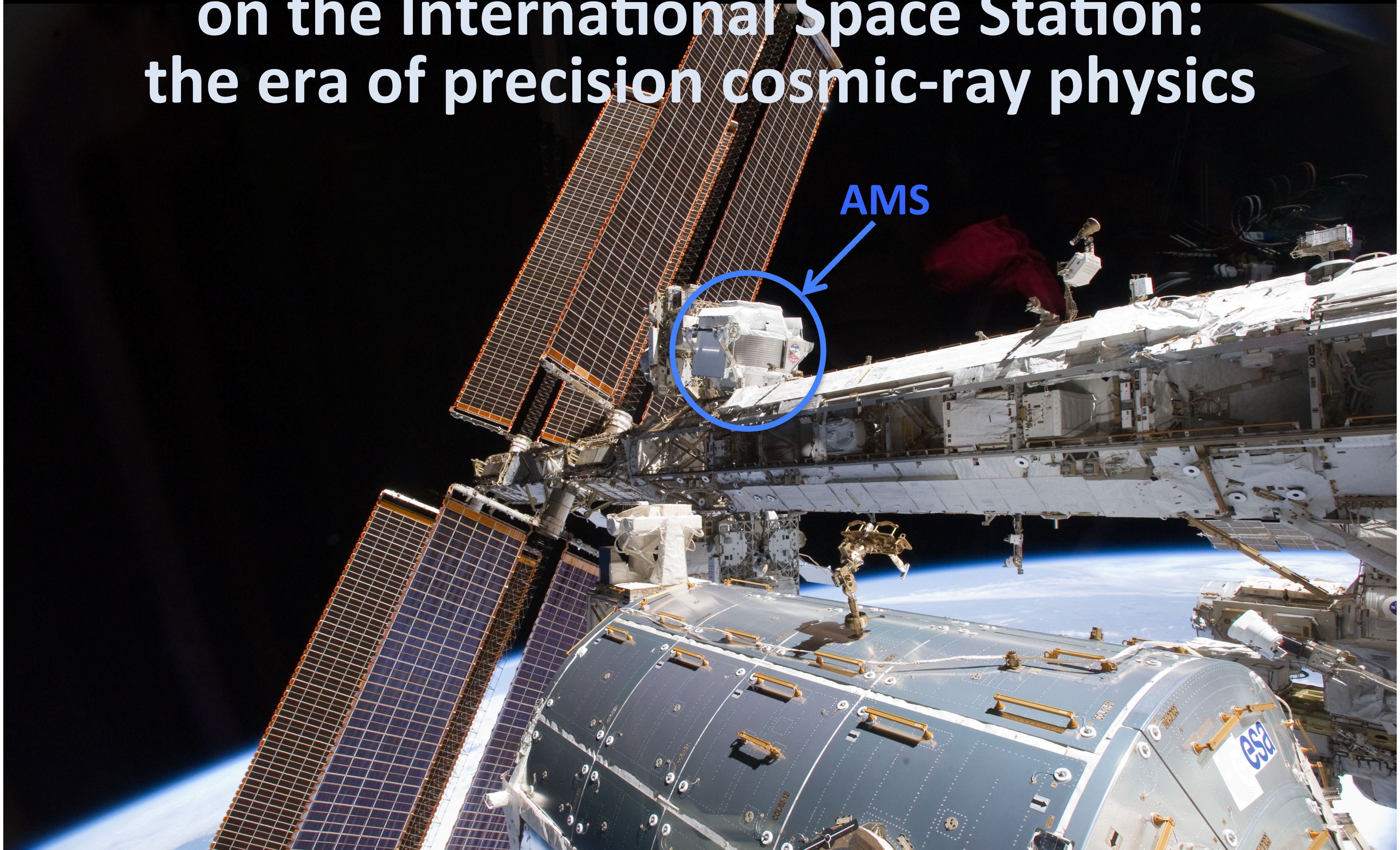
The Alpha Magnetic Spectrometer on the International Space Station: the era of precision cosmic-ray physics



Mercedes Paniccia, University of Geneva (Switzerland)
AMS Collaboration

Feb 10 2017, University College London

Outline

Cosmic Rays:
- Discovery: brief history
- Energy spectrum and composition:
  - What we know on origin, acceleration and propagation

The Alpha Magnetic Spectrometer:
- Project description
- Current results

Conclusions

Milky Way viewed from the ISS, CREDIT: NASA/Reid Weiseman

Discovery of Cosmic Rays: origin

1785 First observation of the spontaneous discharge of an electrometer

1896 Becquerel discovers radioactivity:
Spontaneous electrical discharge of electrometers due to natural radioactivity?
Many researches in UK and Germany

1899 Discharge due to highly penetrating ionizing radiation (Elster & Geitel, Wilson)

1901-1910 Several experiments to test hypothesis on the origin of such radiation:
Earth, atmosphere or outers space?

Wilson 1901: no reduction of intensity inside railway tunnel in Scotland
terrestrial origin favoured

Wulf 1909: altitude-dependent measurements on the the Tour Eiffel
reduction at 300 m too small to confirm terrestrial origin

Pacini 1910: observes intensity reduction at 3 m underwater wrt surface

Gockel 1910: no reduction with height from balloon-flight measurements up to 3000m
Purely terrestrial origin dismissed, coniates term *"kosmische Strahlung"*

1912 Hess balloon flight during solar eclipse: no essential reduction at 5300 m wrt ground
Concludes that radiation must come from the outer space

Discovery of a natural source of high-energy particles: cosmic radiation (Nobel Pize 1936)

http://timeline.web.cern.ch/timelines/cosmic-rays

Discovery of Cosmic Rays: nature

- 1911 Wilson builds the cloud chamber: sees first particle's track
- 1928 Millikan hypothezises that cosmic radiation is electromagnetic:
  coniates the term "cosmic rays"
- 1929 Geiger and Müller develop a gas-filled ionization detector
  Bothe and Kolhörster study nature of CR using a coincidence detector built connecting two Geiger-Müller counters with an electrometer:
  found cosmic rays consisted of electrically charged particles and not gamma rays
- 1932 Anderson discovers the positron studying cosmic rays with a cloud chamber
  (Nobel prize in 1936)

  Bruno Rossi coincidence experiments refute Millikan's theory that the cosmic rays consisted of gamma rays.
- 1933 Rossi demonstrated an east-west effect that showed that the majority of cosmic rays were positive (measurement also by Johnson and Alvarez&Compton)
- 1941 Schein and coll. Show that cosmic-rays are predominantly protons
- 1948 Freier and coll. detect heavy nuclei in cosmic rays
- 1962 Earl, Vogt& Mayer: first direct detection of electrons in cosmic rays

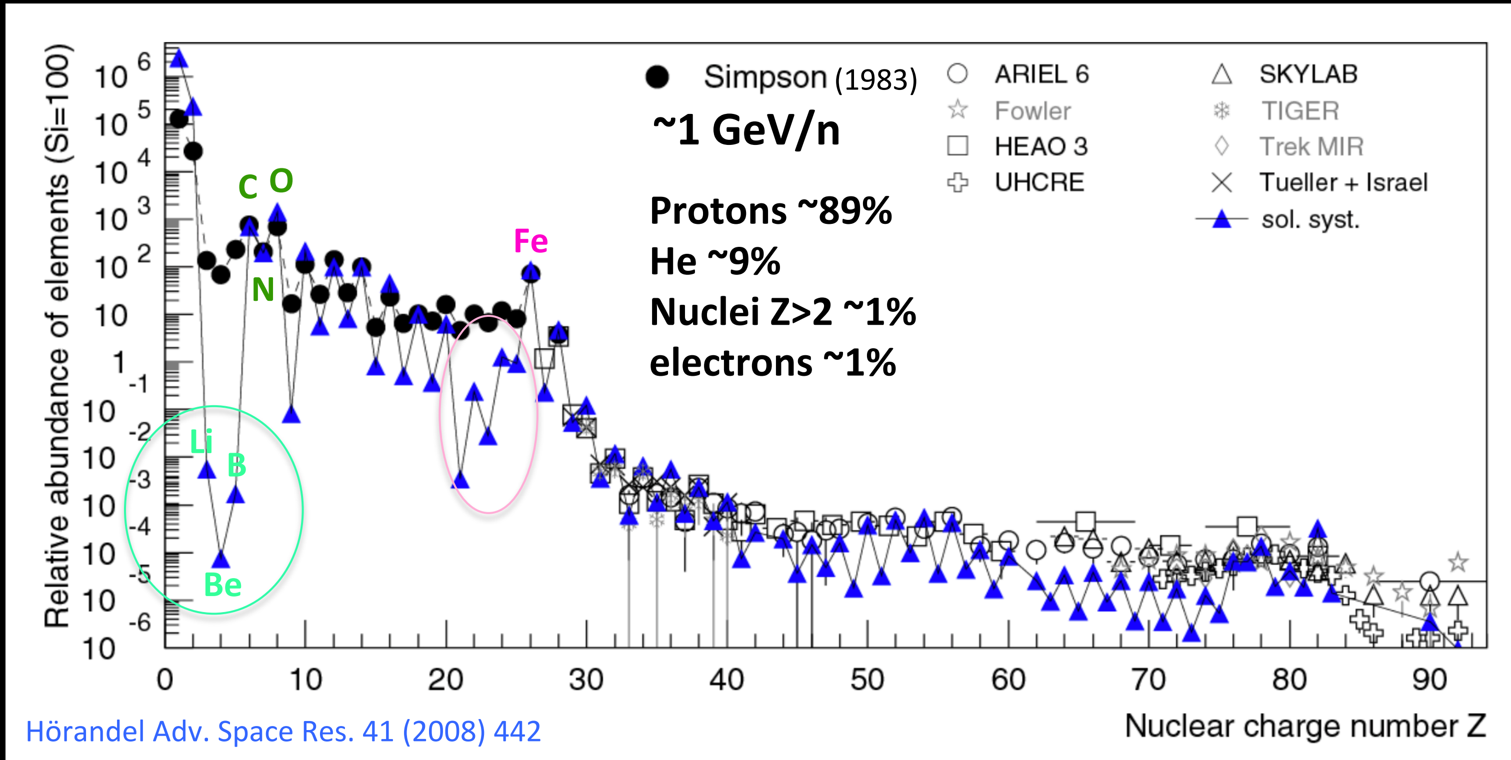
:

http://timeline.web.cern.ch/timelines/cosmic-rays

McDonald and Ptuskin, The Century of Space Science, 677–697 (2001).

Cosmic-Ray: composition and origin

Relative abundance of elements in cosmic rays at Earth compared to solar system:



Even-odd effect:

even-even nuclei more tightly bound

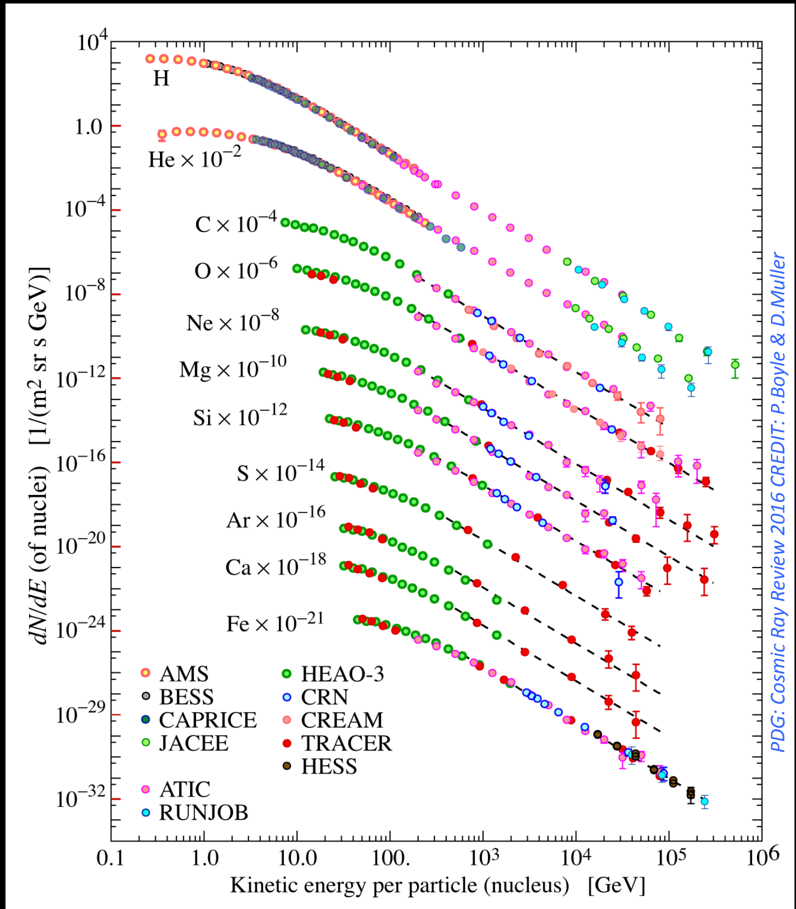
Li-Be-B and sub-Fe group overabundant in Cosmic Rays:

secondaries CR produced by spallation of primaries C-N-O and Fe respectively

Cosmic-Ray energy spectra and composition

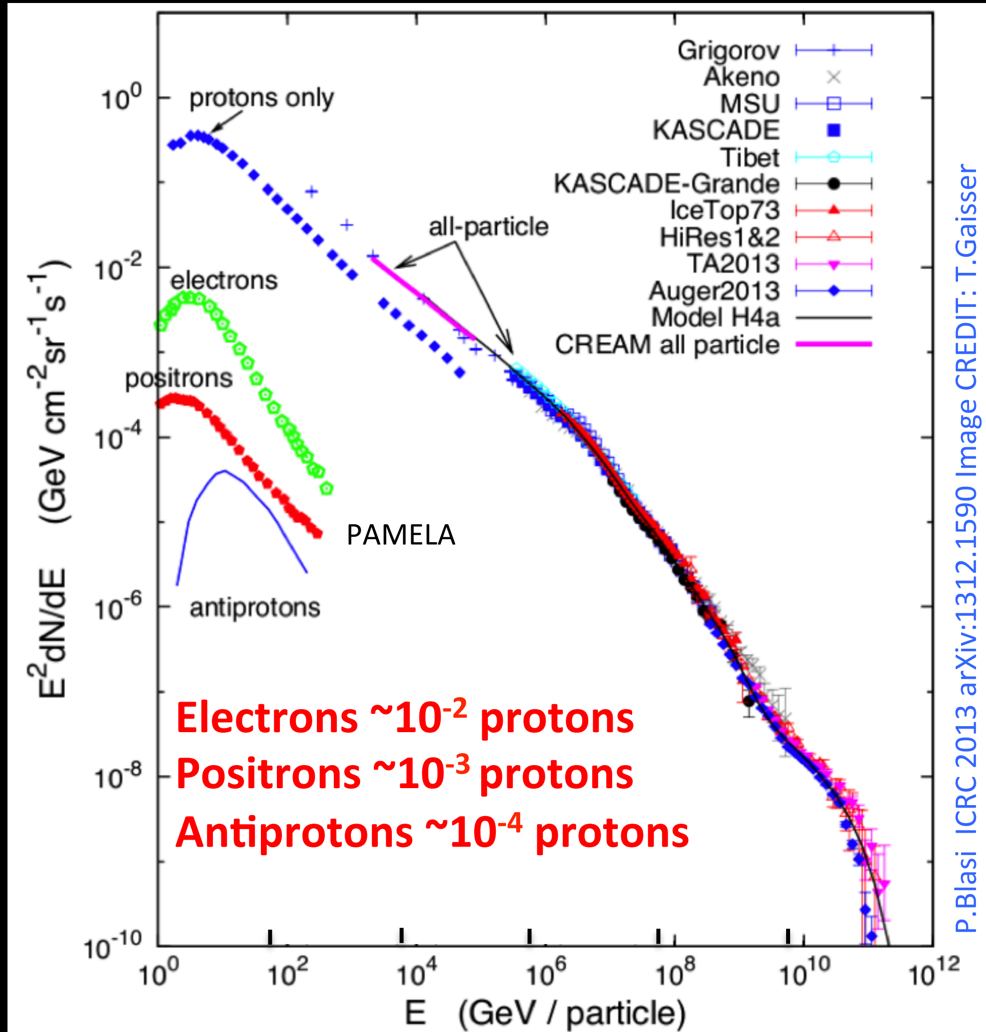
Nuclear component:

Flux



All-particle spectrum:

Flux x (Kinetic energy)^2



Kinetic energy per particle

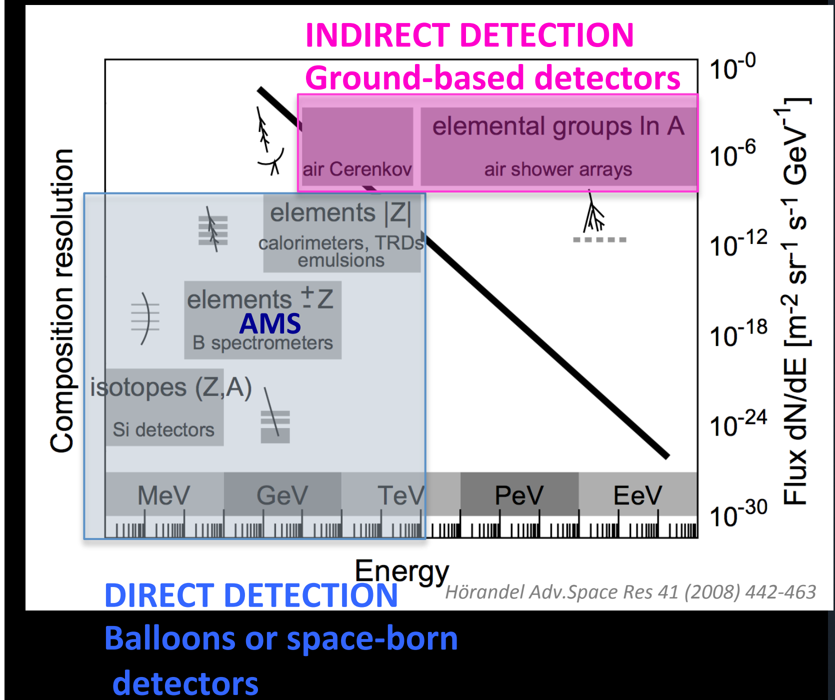
Relative abundances are not constant on full energy range

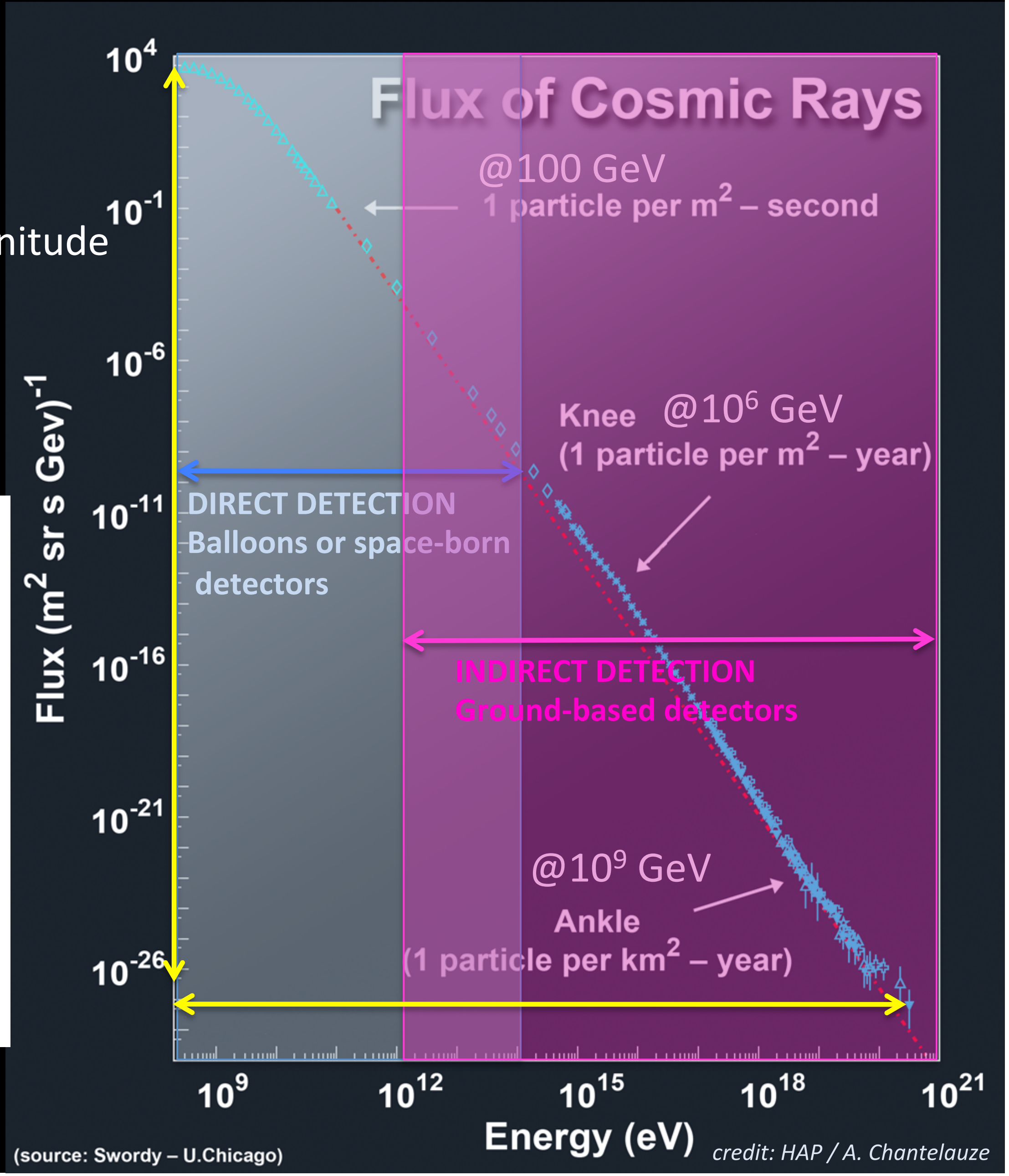
Cosmic-ray energy spectrum

Extends from 100 MeV to ~10^{20} eV

Steeply falling:
flux decreases by 30 orders of magnitude from GeV to 10^{20} eV

Detection of charged Cosmic Rays:





Cosmic-ray energy spectrum: spectral features

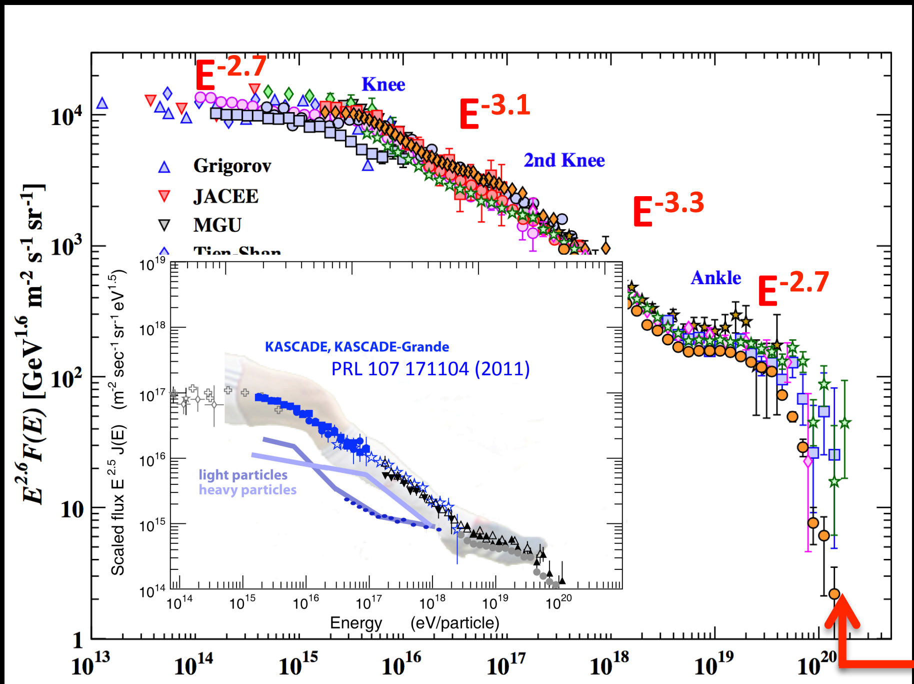
From ~10 GeV to about 10^{15} eV:

- $dN/dE = C \cdot E^{\gamma}$
- spectral index $\gamma \cong -2.7$, fairly constant
  - detailed analysis shows that γ varies

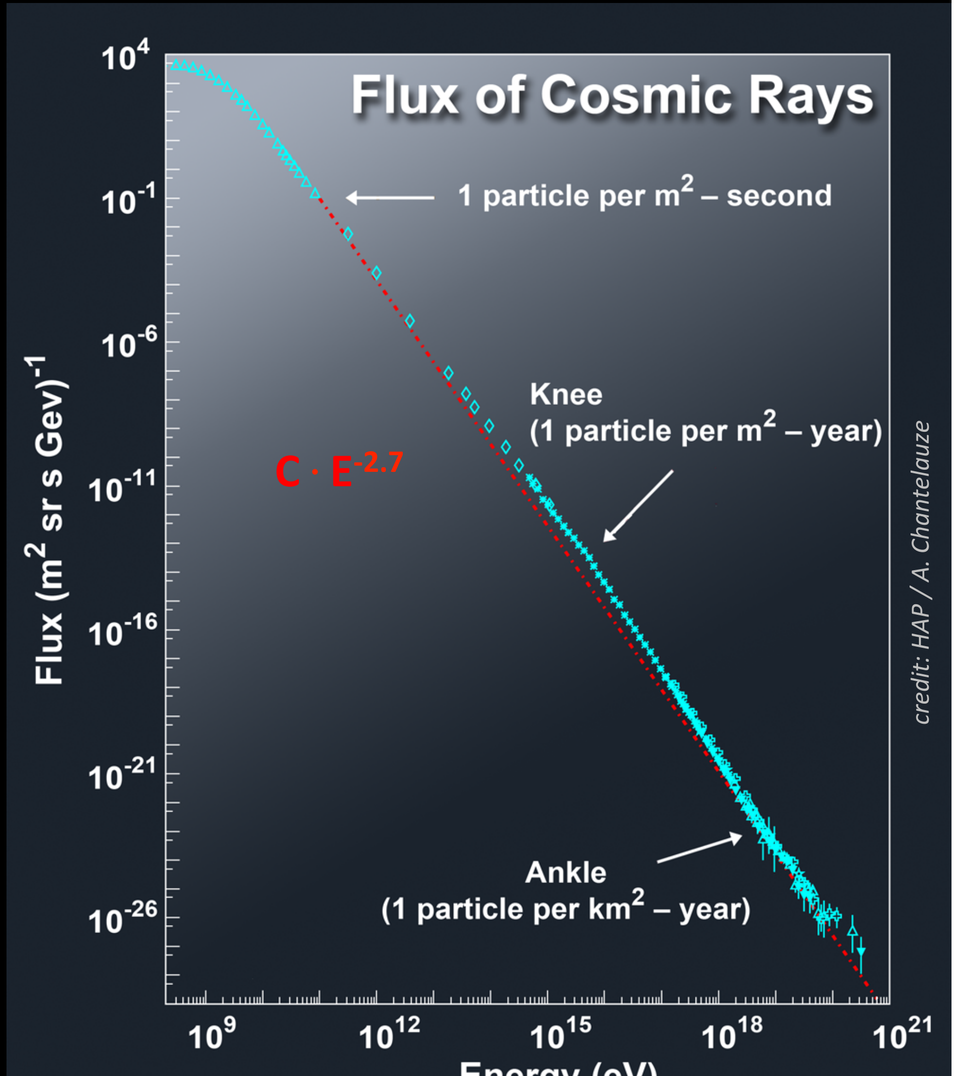
Major changes of spectral index at:

- ~4×10^{15}eV (knee),
- ~4×10^{17}eV (2^{nd} knee)
- ~$10^{18.5}$eV (ankle)

Accompanied by changes in composition



ParticleDataGroup: Cosmic Rays Review 2016



(source: Swordy – U.Chicago)

Cut-off at ~10^{20}eV

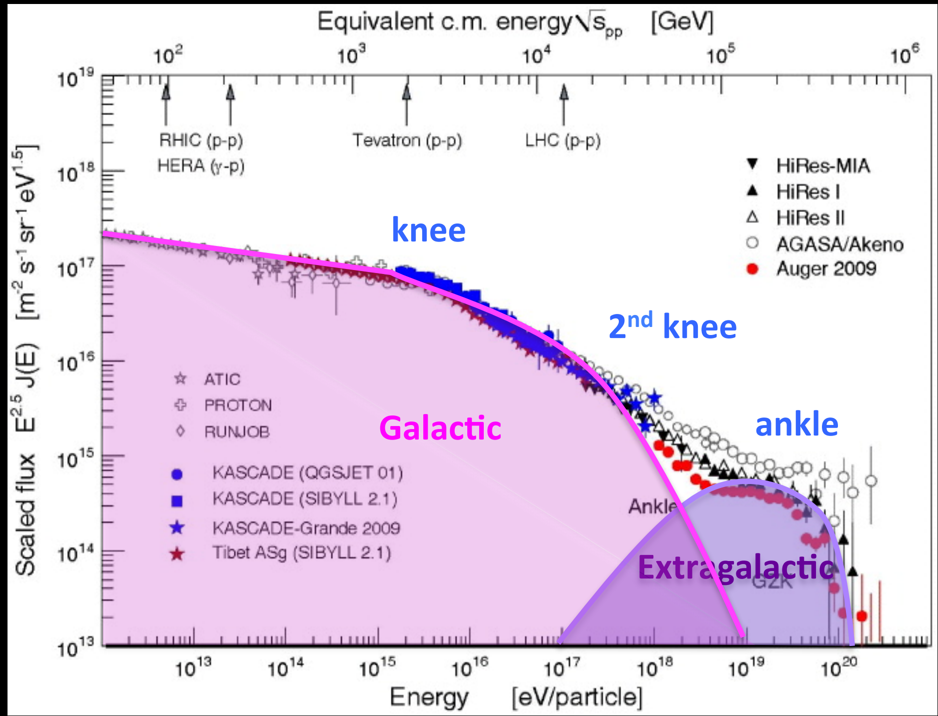
Cosmic-Ray physics:

From where they come from?

How they get accelerated to such high energies?

Which is the transport mechanism from their sources to Earth?

Are there exotic sources of CR?
Dark Matter?



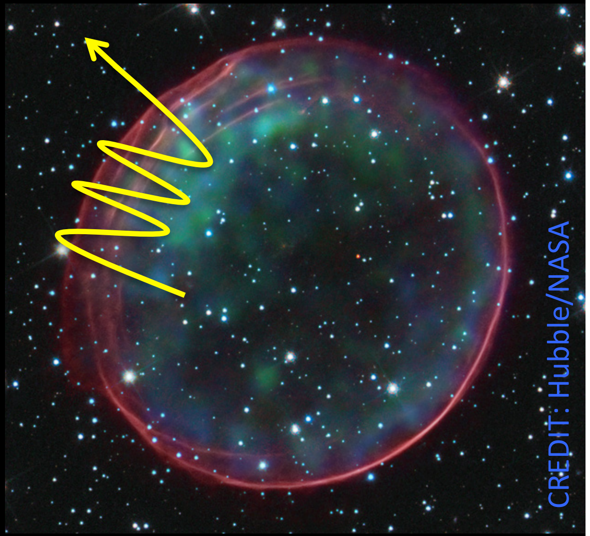
Observables:
- Spectral features
- Mass composition:
  - Individual spectra, secondary/primary ratios, Isotopes
- Arrival direction:
  - Isotropic or not isotropic?

But also multi-messenger approach: x-rays, gamma rays, neutrinos

Galactic cosmic rays acceleration and transport:

Diffusive Shock Acceleration in SuperNovae Remnants (SNR paradigm)

1st order Fermi mechanism:
Particles gain energy scattering back and forth across the shock



Maximum energy:
$E_{max} \sim Z \cdot 10^{15}$ eV

Results in universal power-law spectra E^{-2}

Spectrum at the source injected in the Inter-Stellar Medium

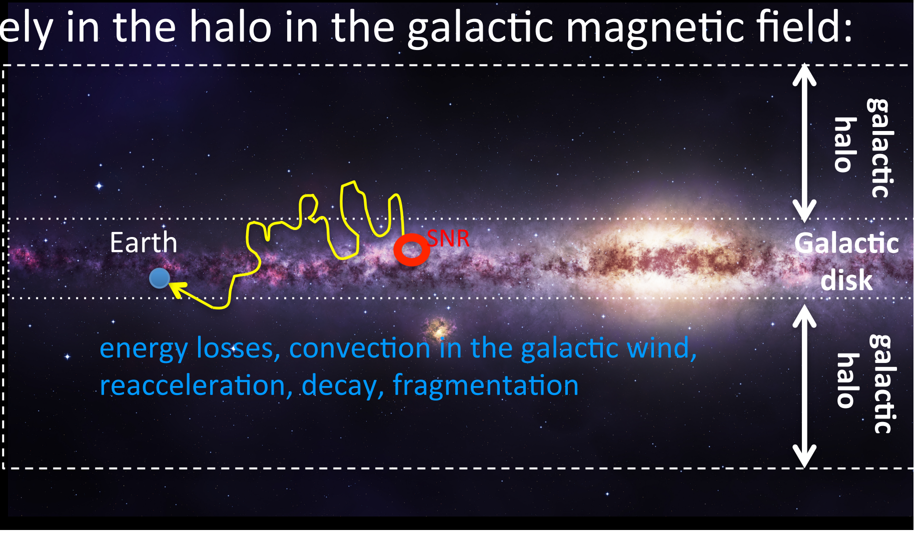
Diffusive transport in the Galaxy:

10 GeV CR galactic residence time $\sim 10^8$ yr

CR are produced in the disk and travel diffusively in the halo in the galactic magnetic field:

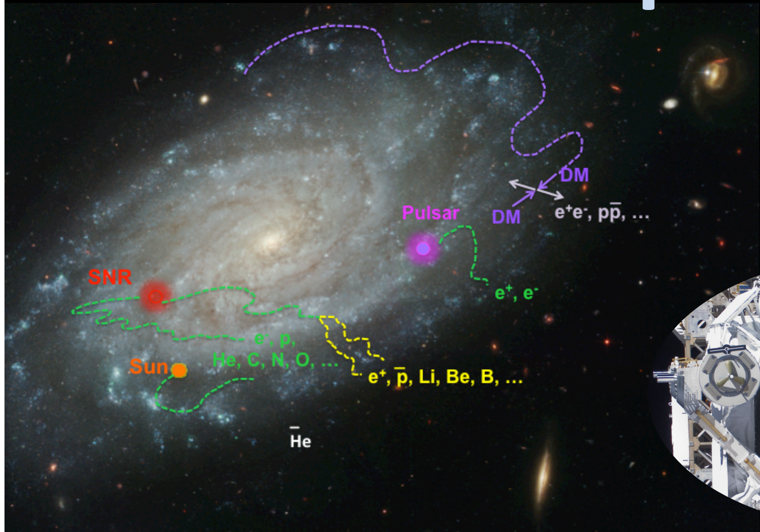
D(E) diffusion coefficient $\sim E^{\delta}$
Can be deduced from secondary/primary CR ratios (B/C)

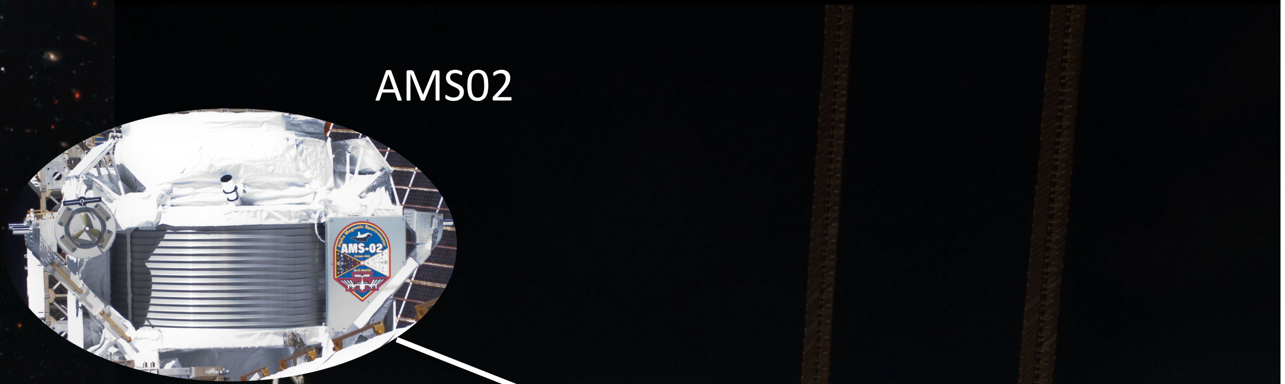
Spectrum at Earth: $\sim E^{-2-\delta}$



For a review D.Caprioli ICRC2015

Cosmic-Ray Physics at the GeV-TeV range with the Alpha Magnetic Spectrometer





Physics goals:

- **Galactic Cosmic Ray properties:**
  - **Are primary spectra at sources really universal?**
    - **measurement of primary CR spectra (electrons, protons, He, C)**
  - **Propagation through the Galaxy: diffusion coefficient, reacceleration, etc.**
    - **measurement of secondary CR fluxes and ratios to primaries (Li, B, B/C)**
- **Indirect searches for Dark Matter:**
  - **Exotic signals in rare secondary CRs (e^+, anti-p, anti-d)**
    - **measurement of positron fraction and of anisotropy of positron/electron ratio**
    - **measurement of anti-proton to proton ratio**
- **Direct detection of primordial Antimatter (anti-He)**

The AMS Experiment

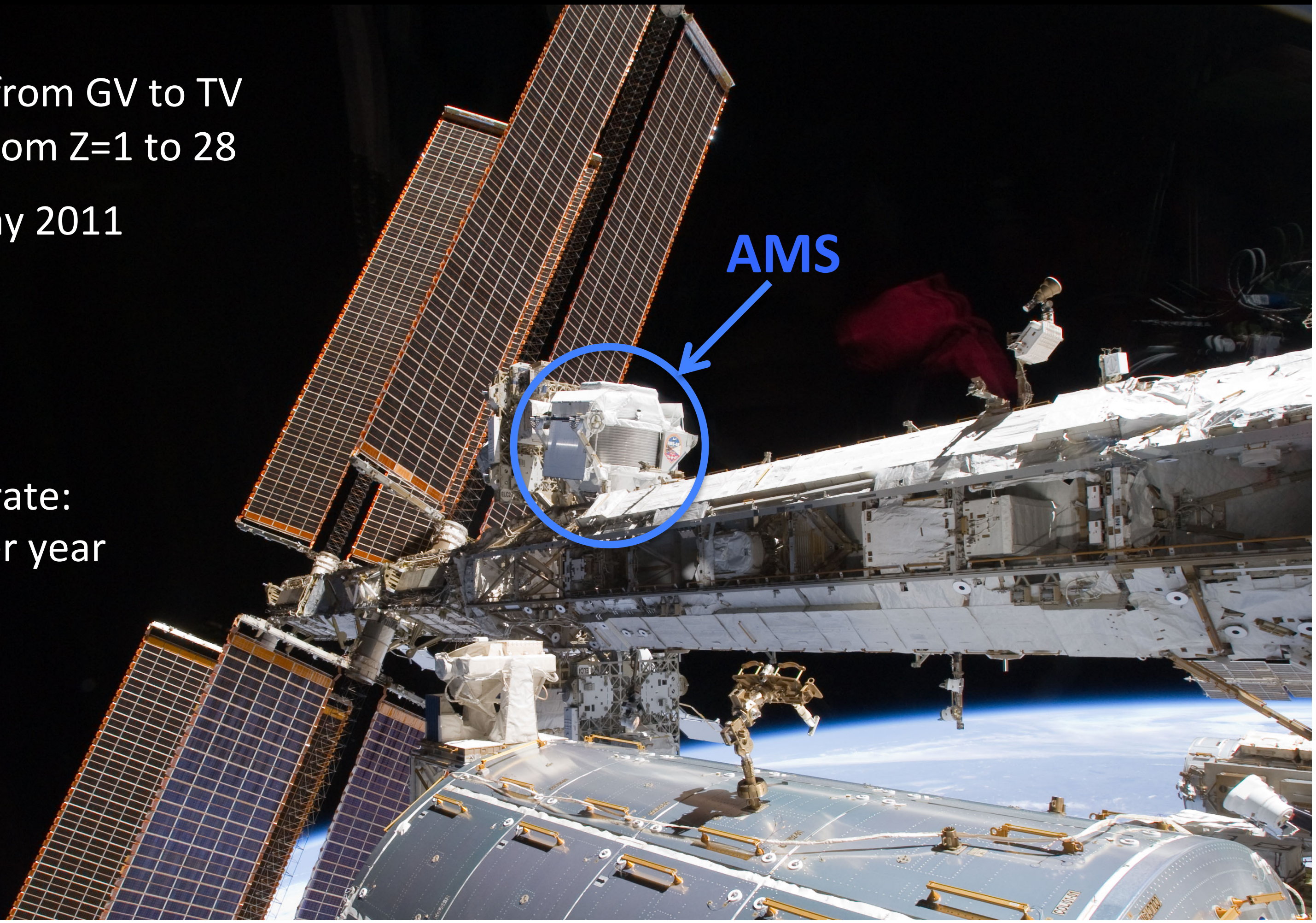
Magnetic Spectrometer:
- Rigidities (R=p/Ze) from GV to TV
- Charged particles from Z=1 to 28

Installed on ISS since May 2011

Near Earth Orbit:
- altitude 400 Km
- inclination 52°
- period 92 min

Cosmic Ray data taking rate:
- 18 billion events per year

Mission duration:
- up to 2024

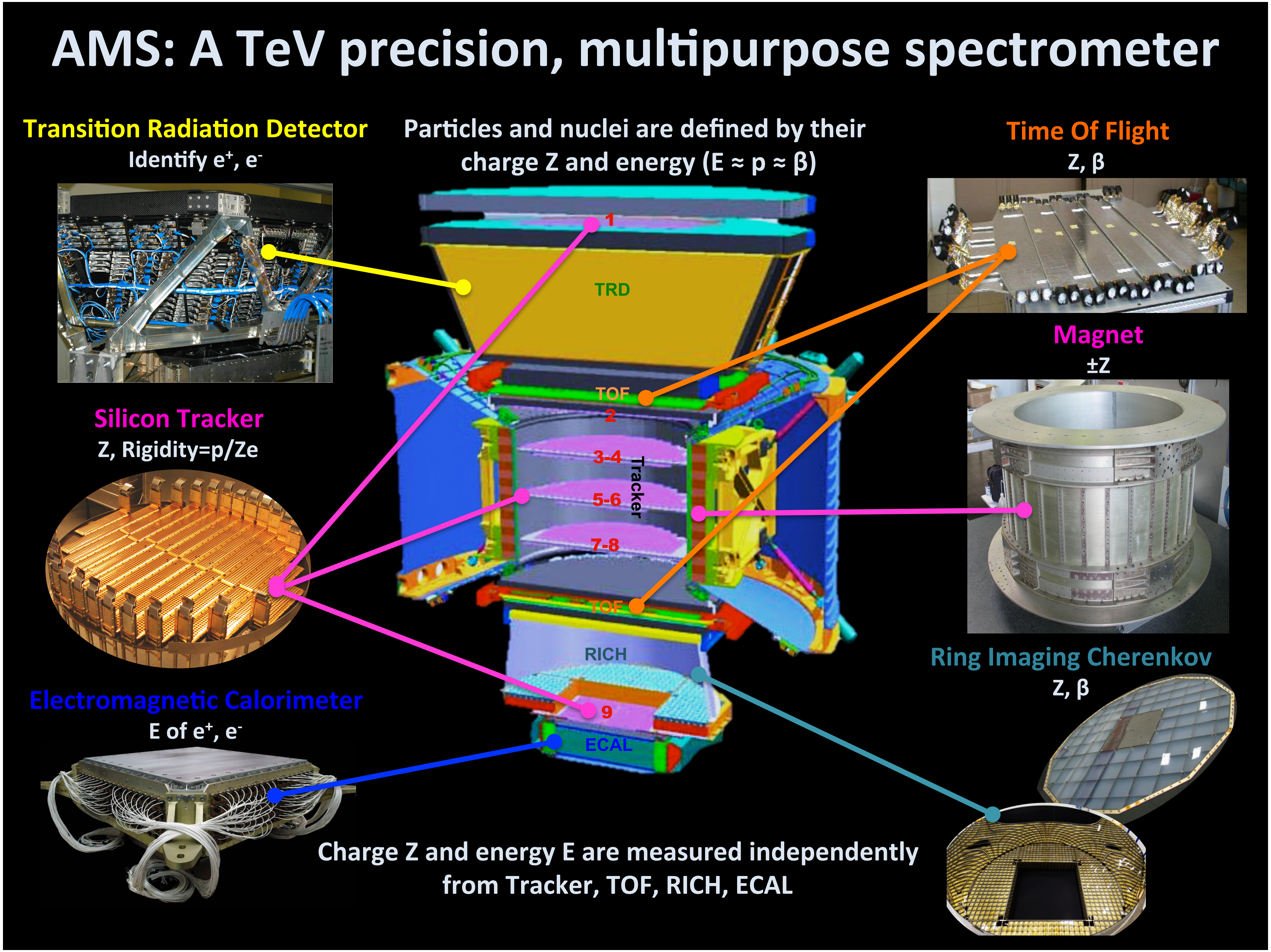


Perform complete inventory of charged Cosmic Rays from GV to few TVs :

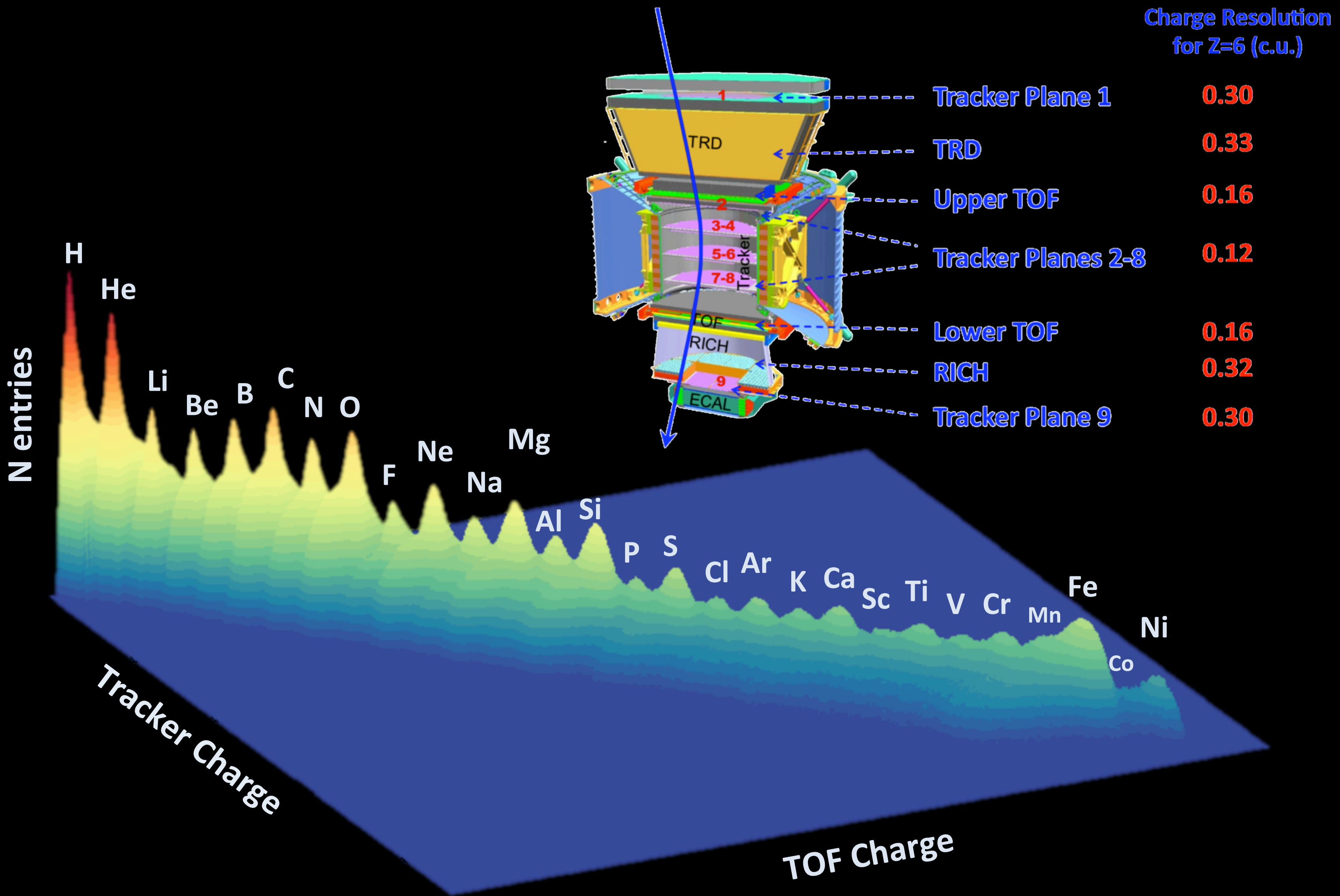
individual fluxes of e^+, e^-, protons, anti-protons and nuclei up to Ni

Isotope composition up from 0.5 GeV/n to ~10 GeV/n for light nuclei (He, Be…)

Search for anti-Helium with a sensitivity of $1/10^9$

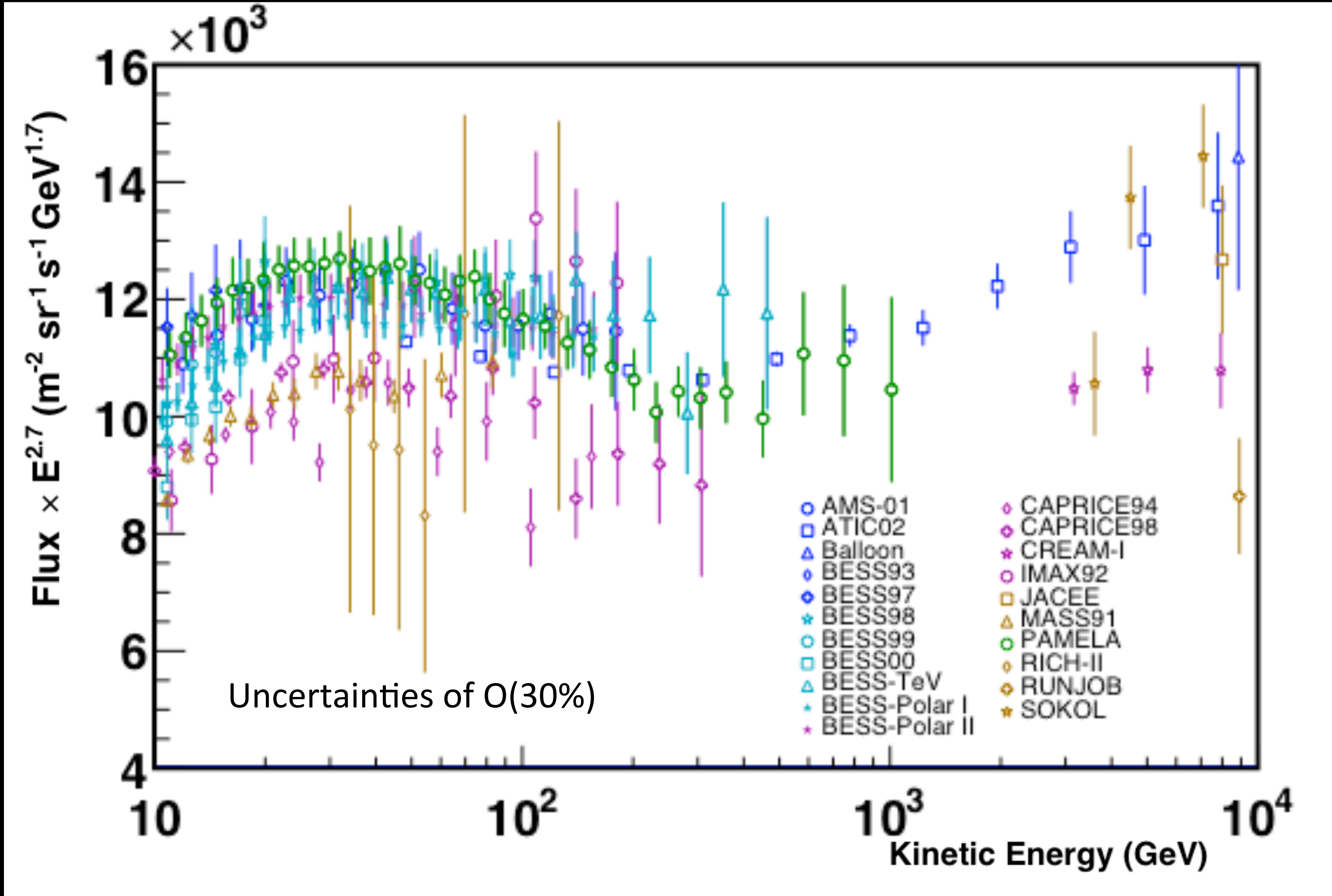

AMS: A TeV precision, multipurpose spectrometer
Transition Radiation Detector
Identify e+, e-
Particles and nuclei are defined by their charge Z and energy (E ≈ p ≈ β)
Time Of Flight
Z, β
Magnet
±Z
Silicon Tracker
Z, Rigidity=p/Ze
Ring Imaging Cherenkov
Z, β
Electromagnetic Calorimeter
E of e+, e-
1
TRD
TOF
2
3-4
5-6
7-8
Tracker
TOF
RICH
9
ECAL
Charge Z and energy E are measured independently from Tracker, TOF, RICH, ECAL

AMS Charge measurement



Measurements of the proton flux before AMS

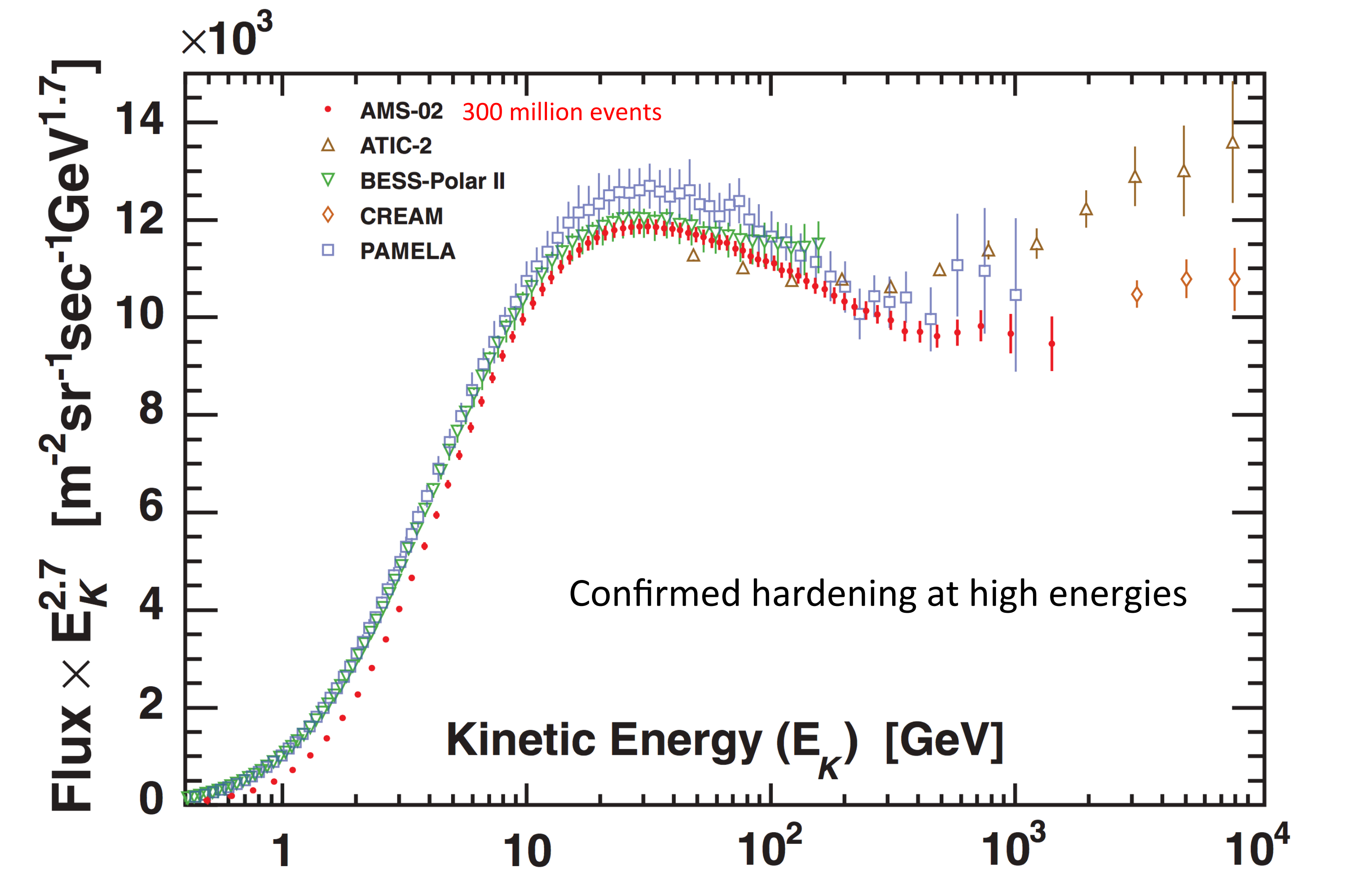
Proton Spectrum



AMS Precision Measurement of the proton flux

PRL 114, 171103 (2015)

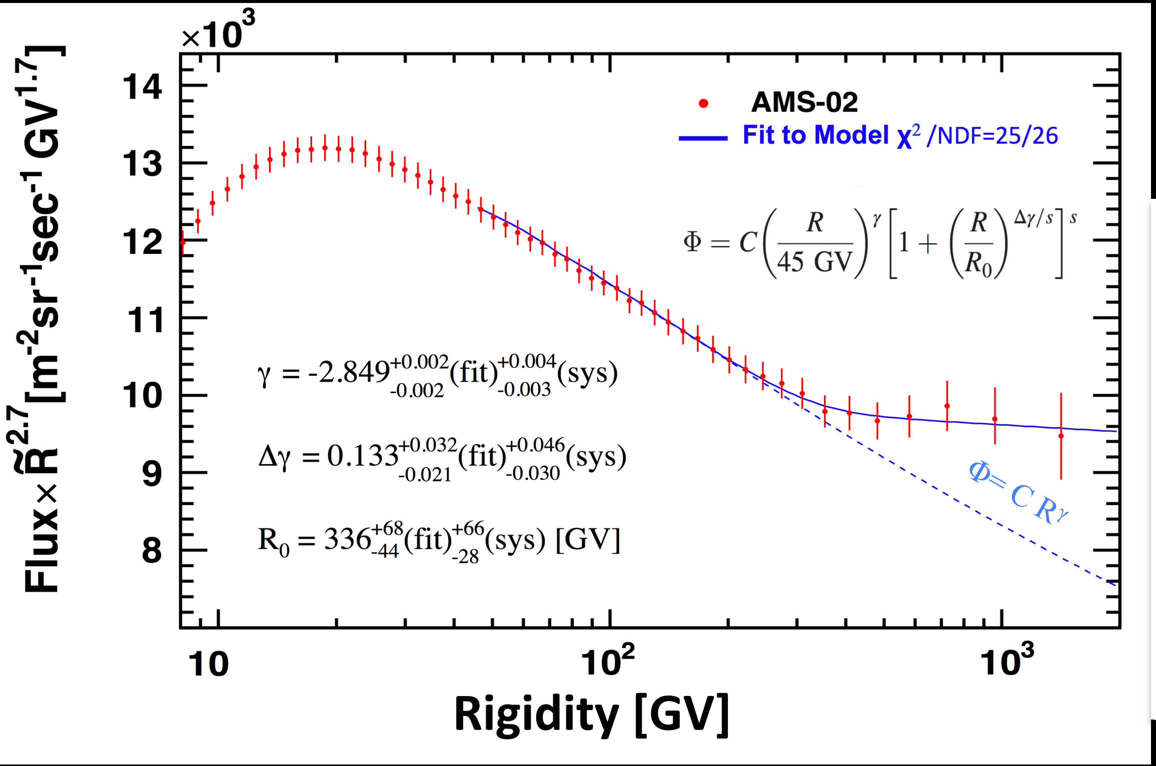
Proton Spectrum



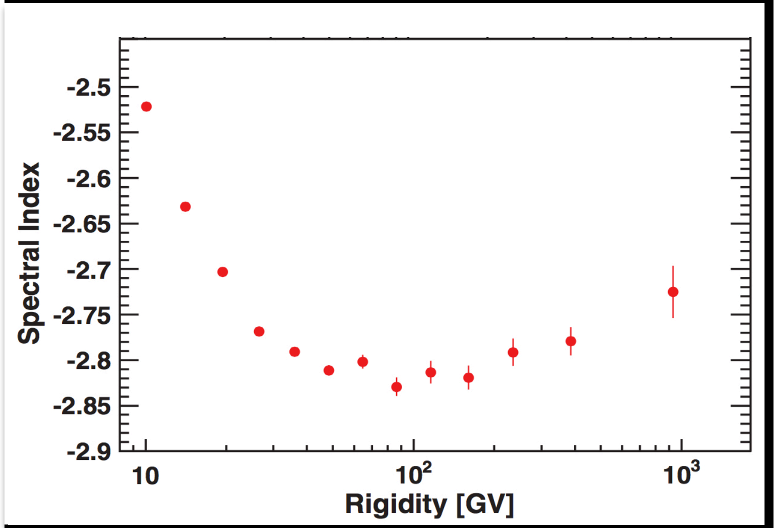
AMS Precision Measurement of the proton flux

PRL 114, 171103 (2015)

The spectrum cannot be described by a single power law

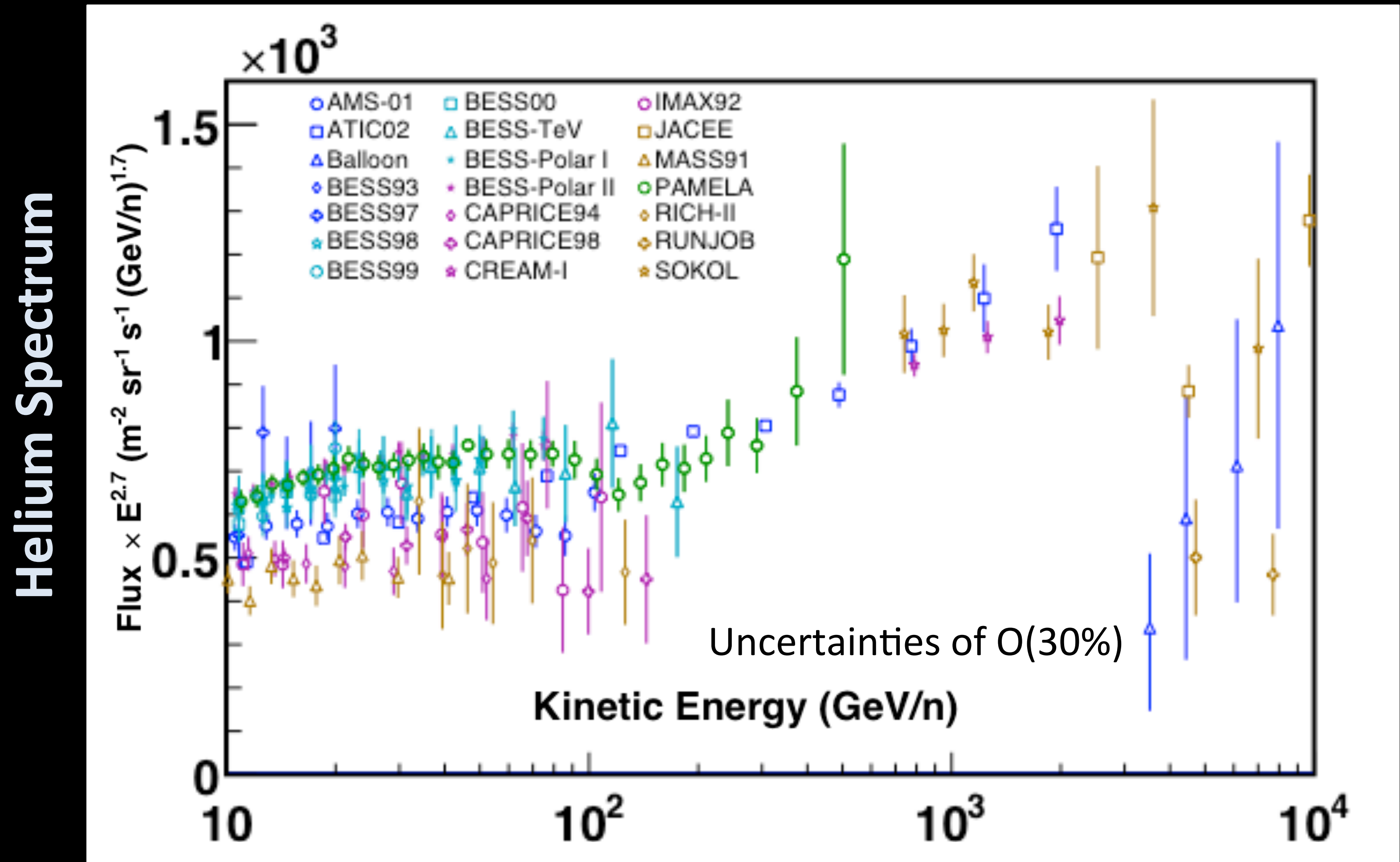


Spectral index vs Rigidity



Break around 300 GV

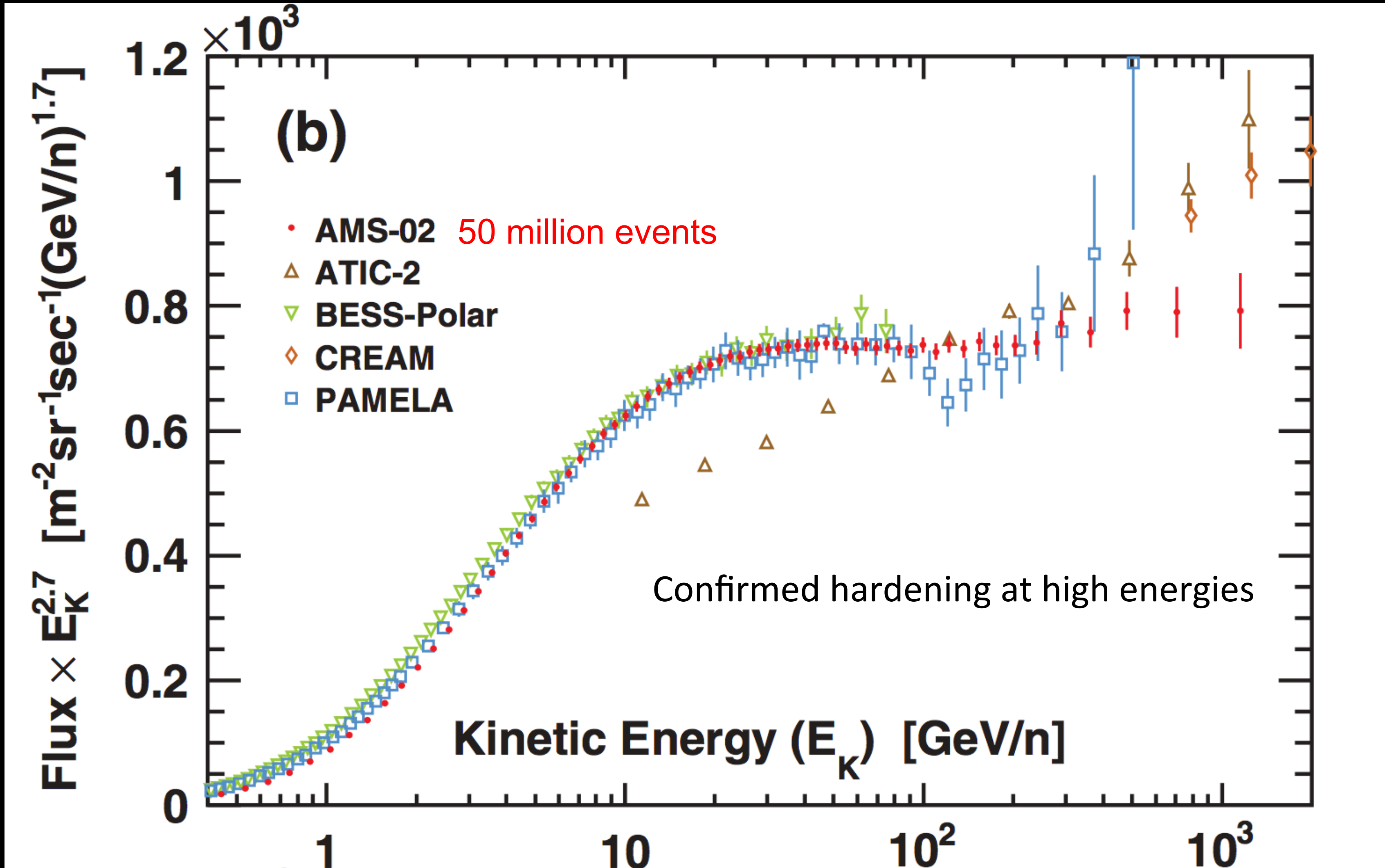
Measurements of the Helium flux before AMS



AMS Precision measurement of the Helium flux

PRL 115, 211101 (2015)

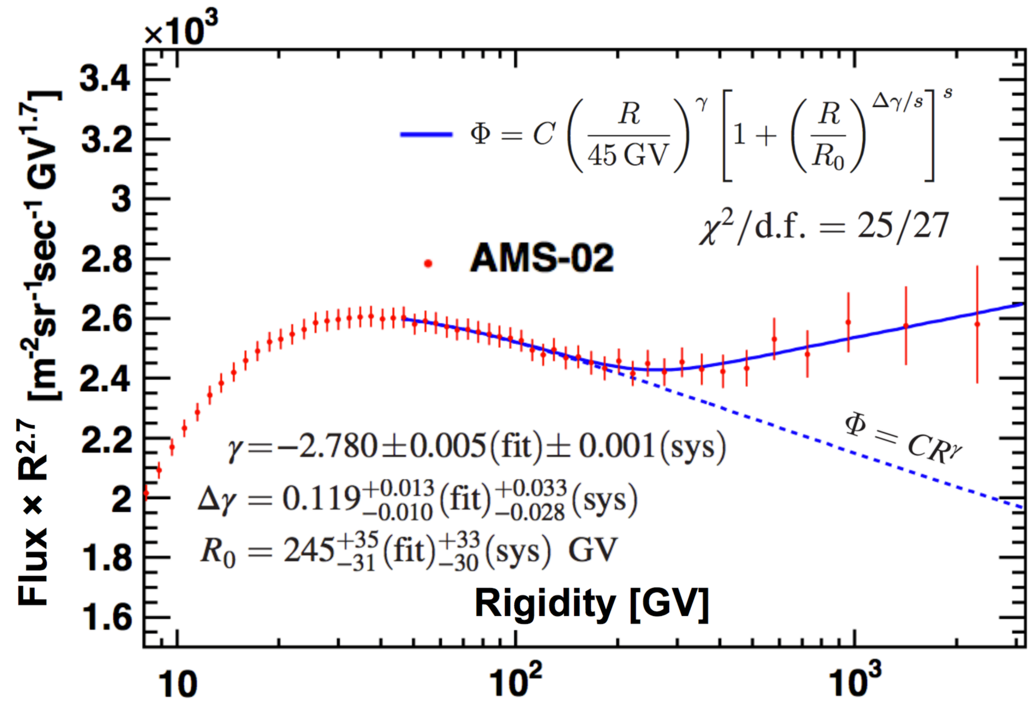
Helium Spectrum



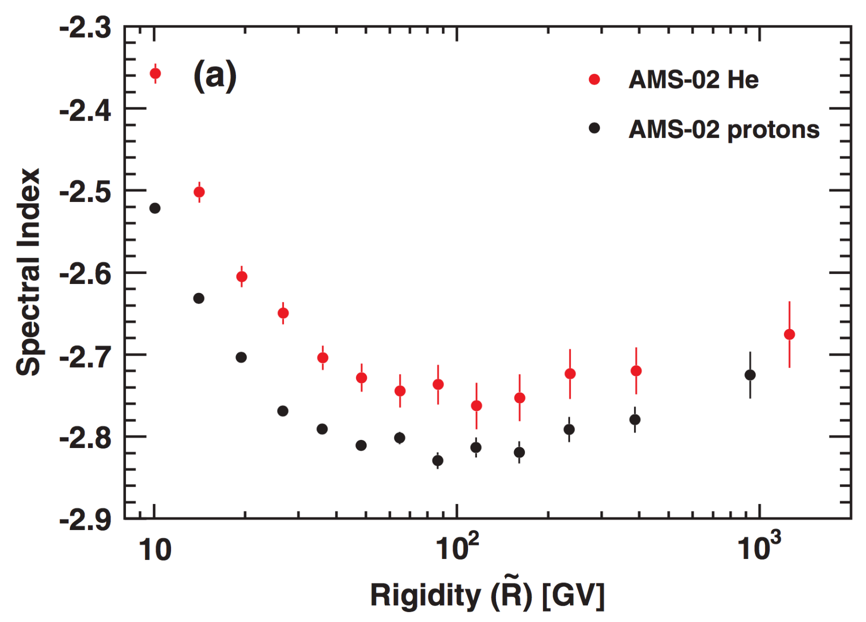
AMS Precision measurement of the Helium flux

PRL 115, 211101 (2015)

The spectrum cannot be described by a single power law



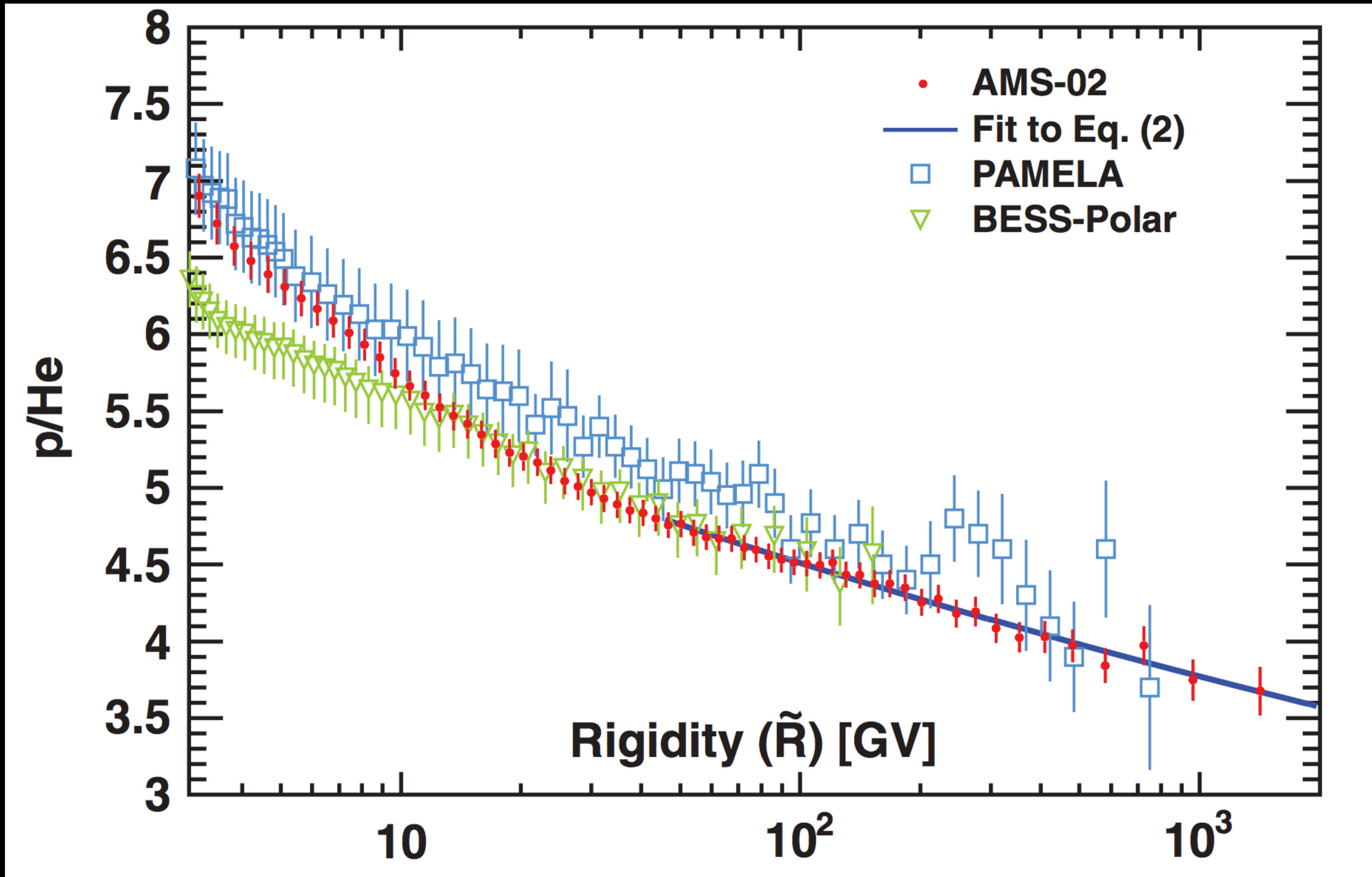
Spectral index vs Rigidity



Break around 250 GV

AMS Proton to Helium flux ratio

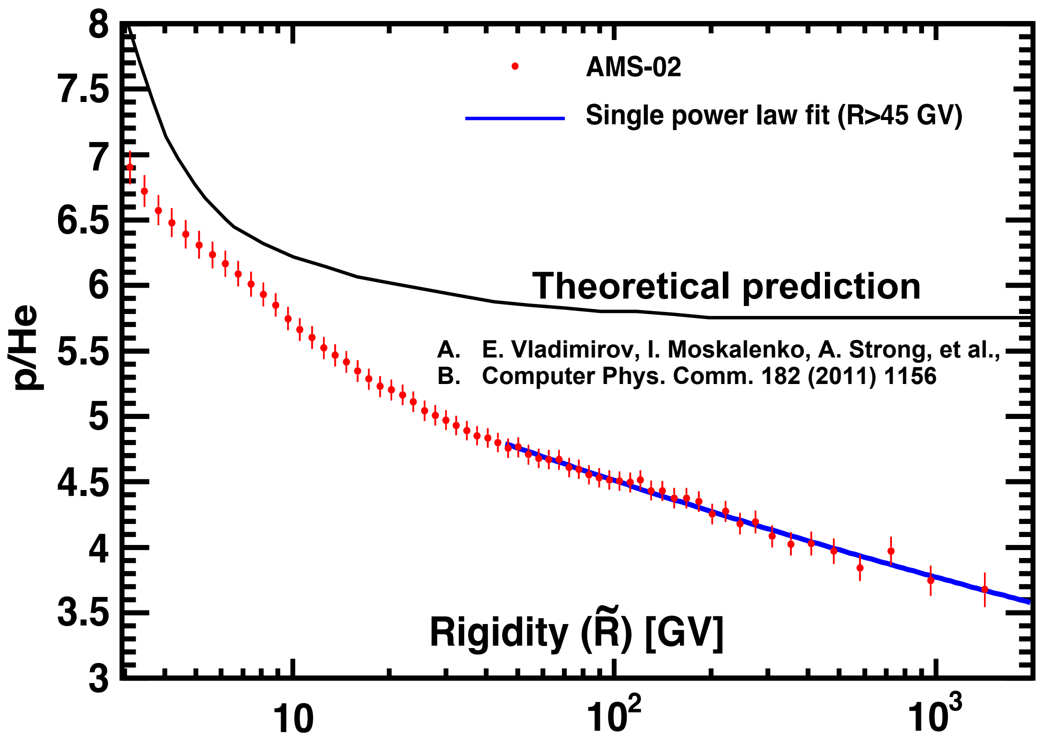
PRL 115, 211101 (2015)



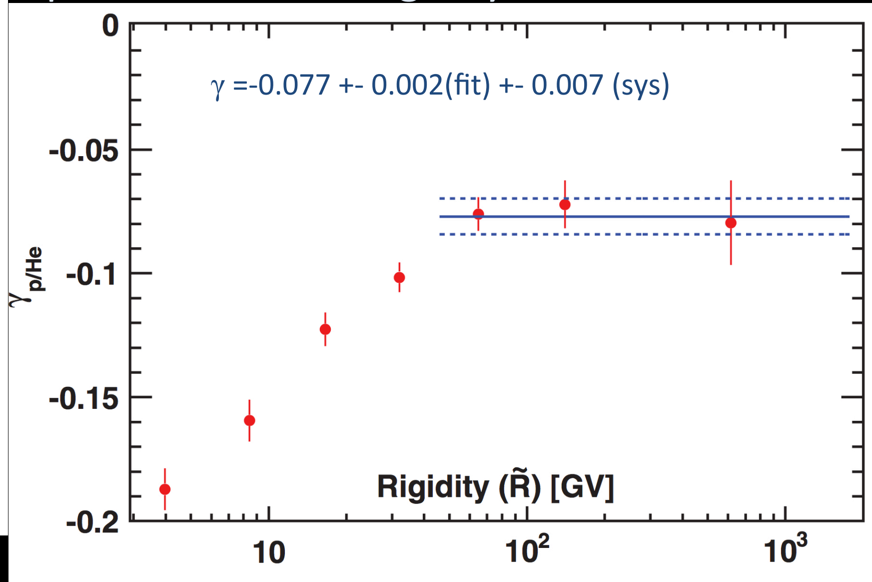
AMS Proton to Helium flux ratio

PRL 115, 211101 (2015)

Protons and helium are both "primary" cosmic rays.
If the acceleration mechanism is universal their ratio should be flat.



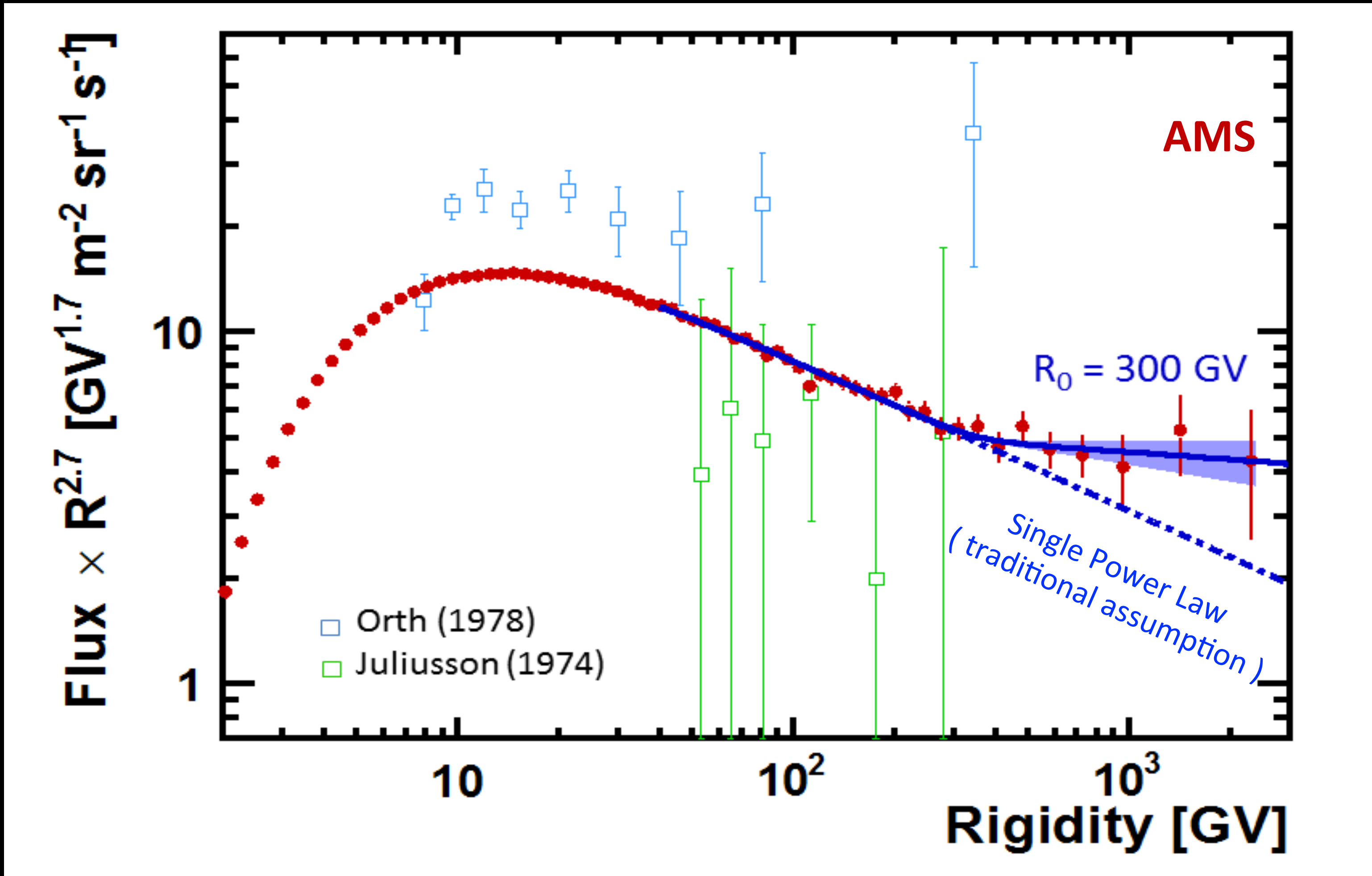
Spectral index vs Rigidity



AMS p/He ratio is not flat: He spectra harder than p.

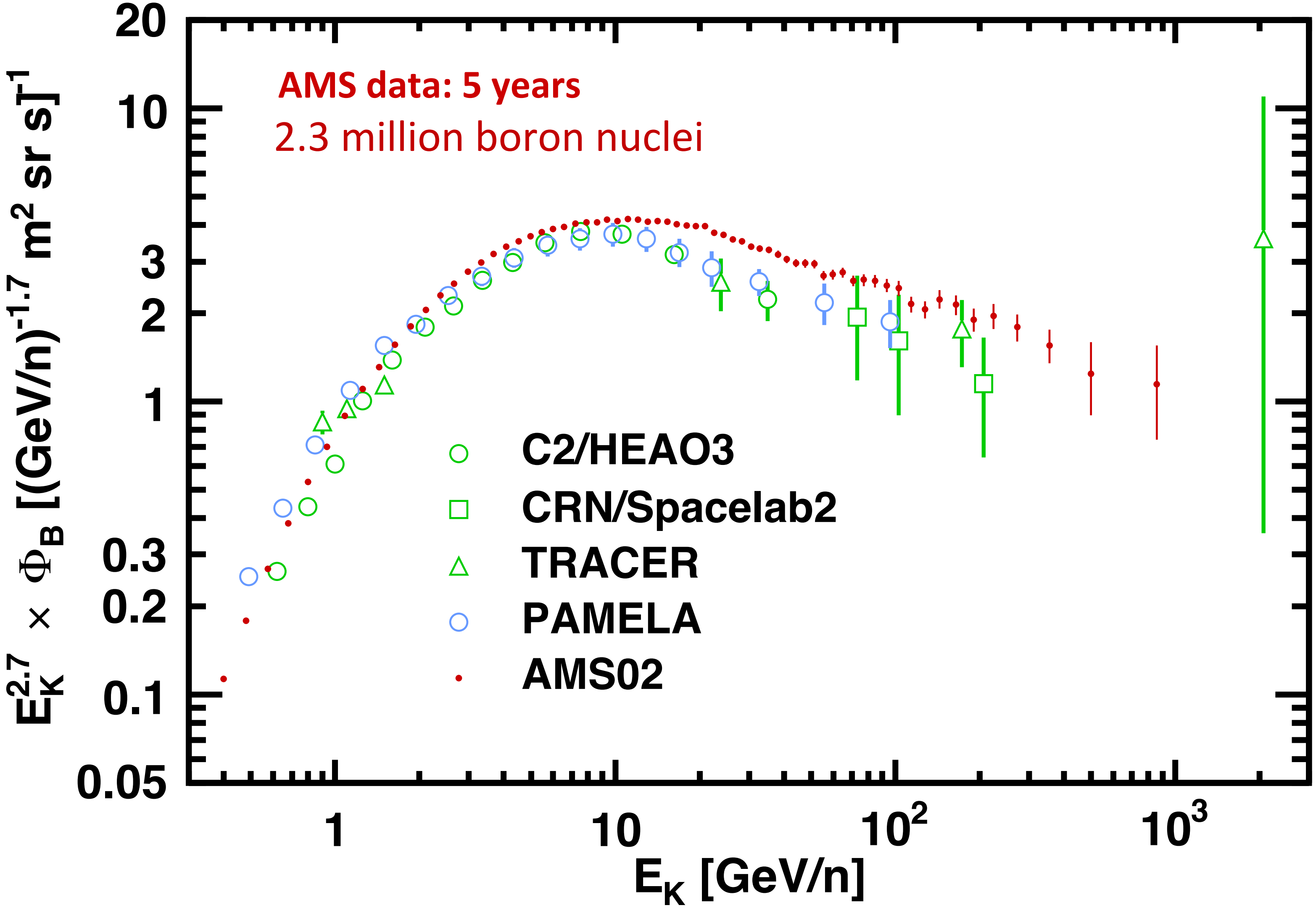
AMS measurement of Lithium flux

Up to now it was assumed that cosmic lithium is purely secondary in origin.

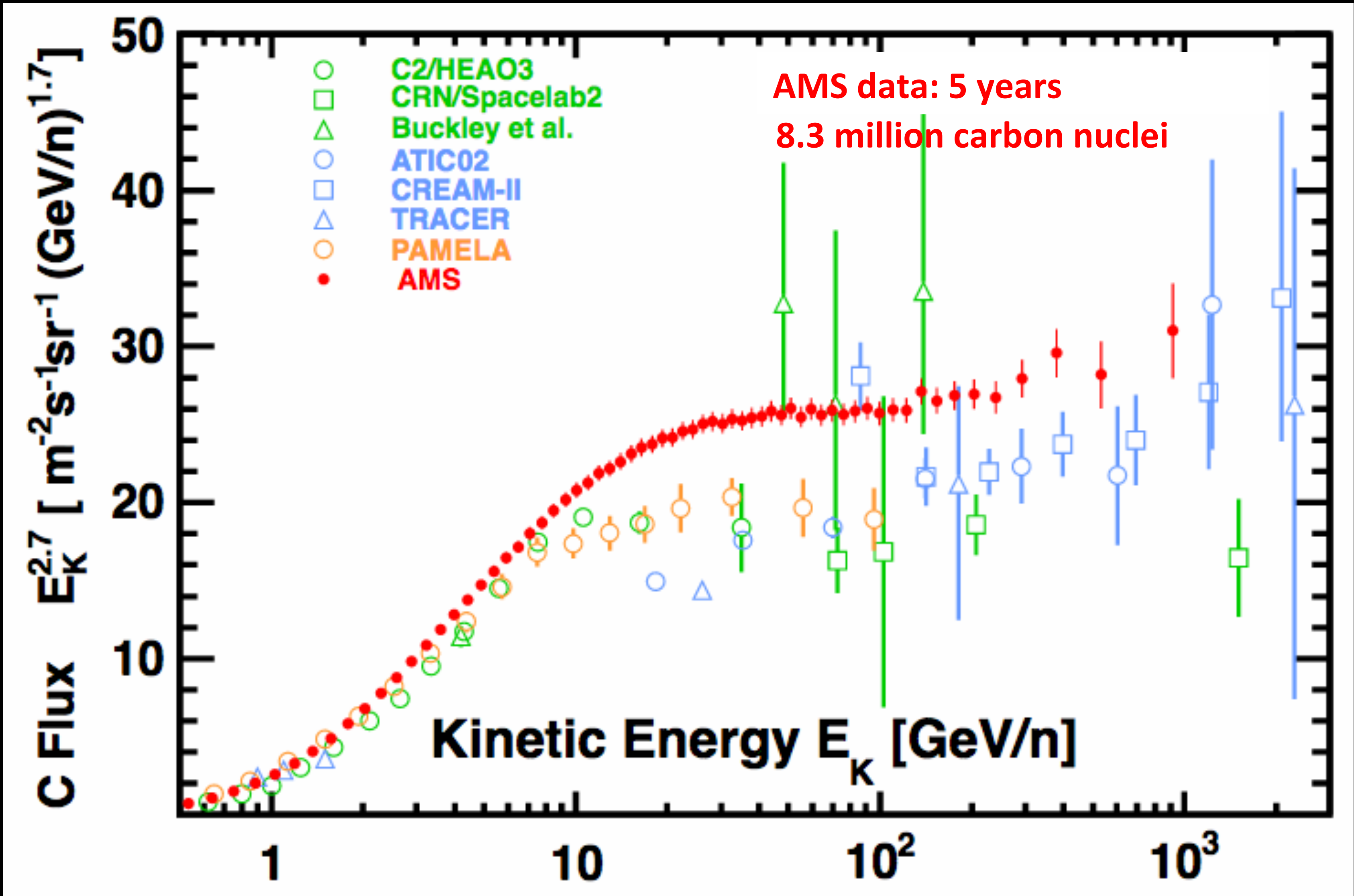


AMS data show that either cosmic lithium has also a primary origin or
the diffusion coefficient describing propagation of cosmic rays is rigidity dependent.

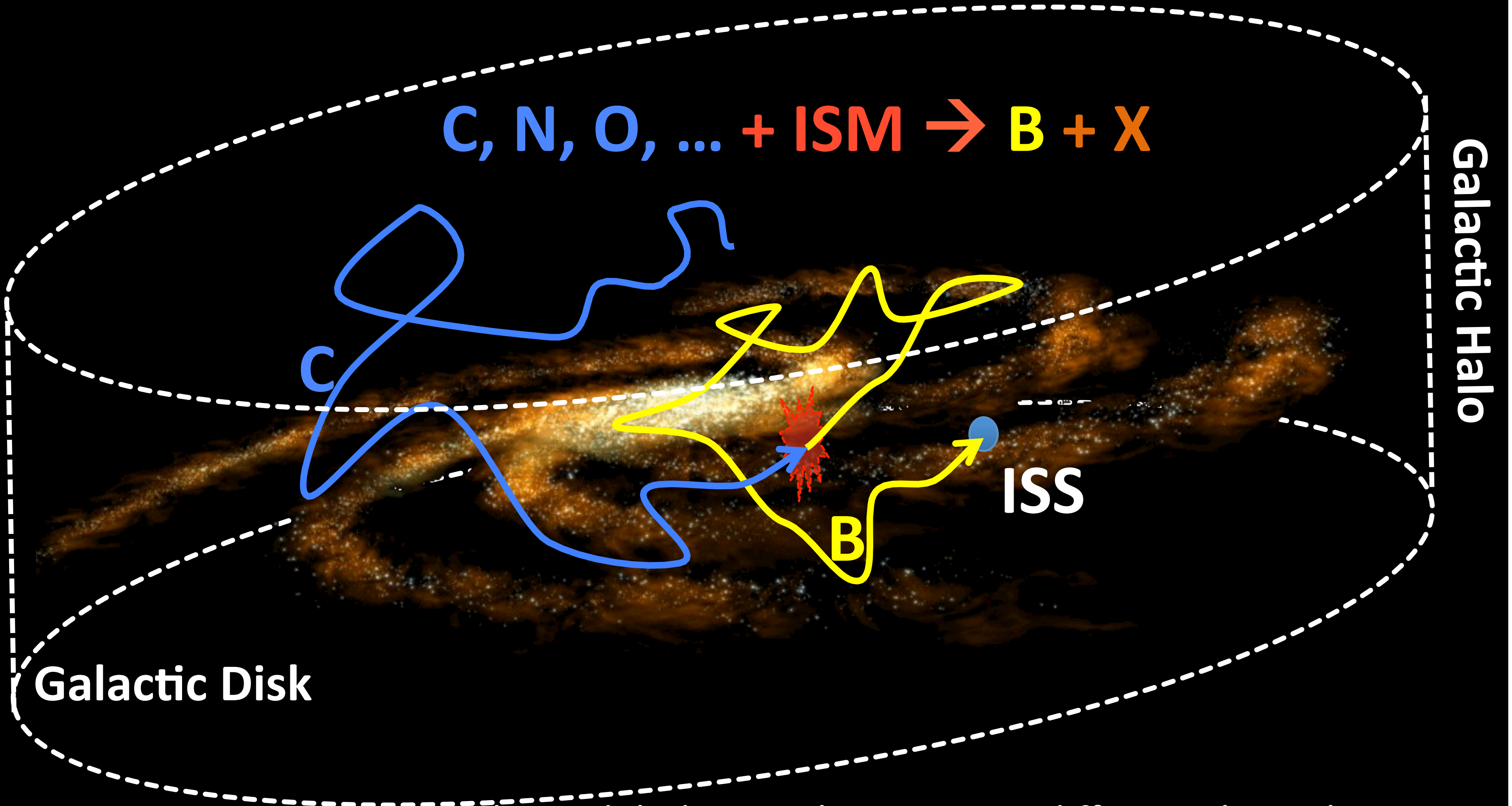
AMS measurement of Boron flux



AMS measurement of Carbon flux



Flux Ratios: Boron/Carbon and propagation



Cosmic Rays are commonly modeled as a relativistic gas diffusing through a magnetized plasma.

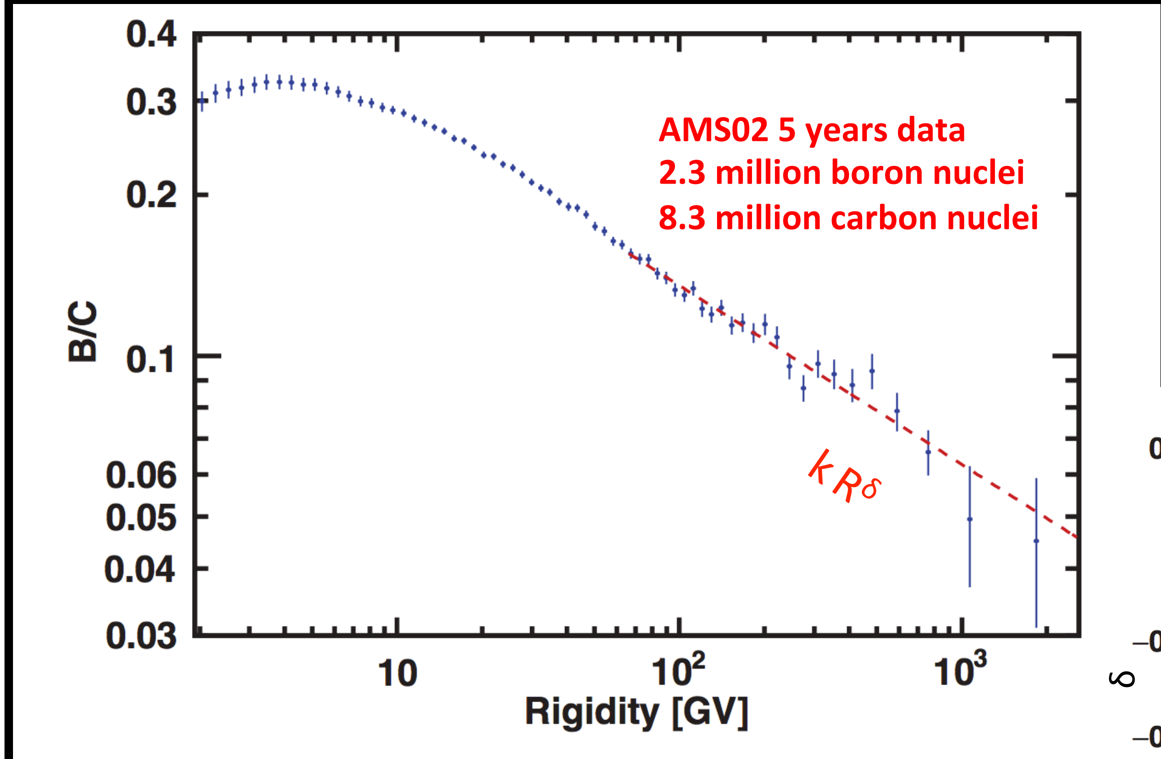
Models of the magnetized plasma predict different behavior for B/C = k R^{δ}.

With the Kolmogorov turbulence model $\delta = -1/3$ is expected,

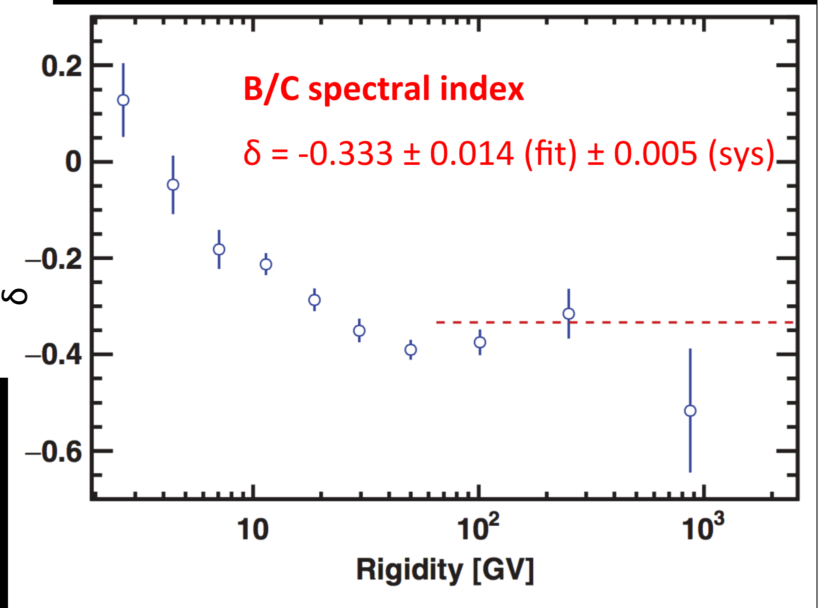
while the Kraichnan theory leads to $\delta = -1/2$.

Measurement of Boron to Carbon flux ratio

PRL 111, 231102 (2016)

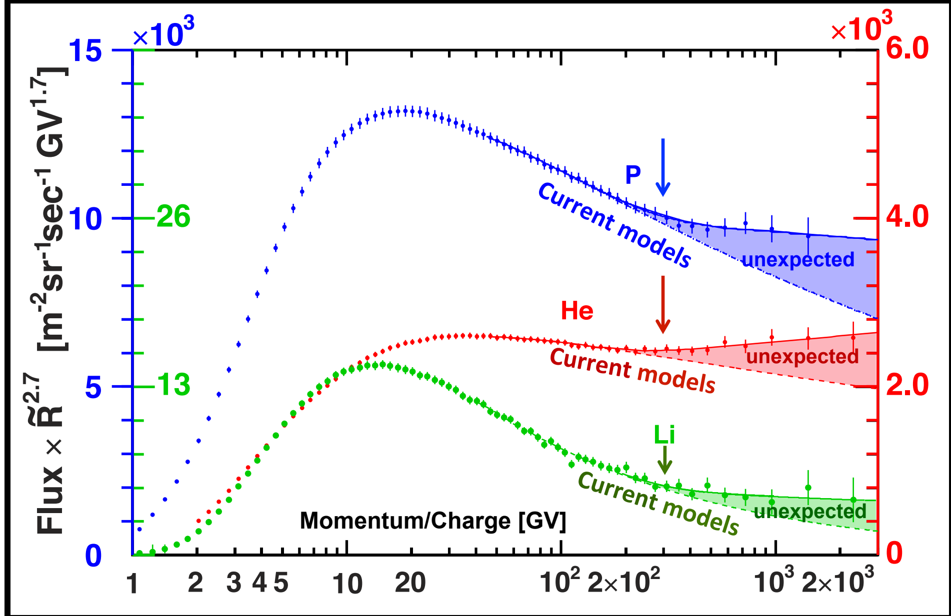


Above 65 GV B/C can be described by a single power law



AMS02 data agree with the Kolmogorov turbulence model

AMS measurement of nuclei fluxes: where we stand

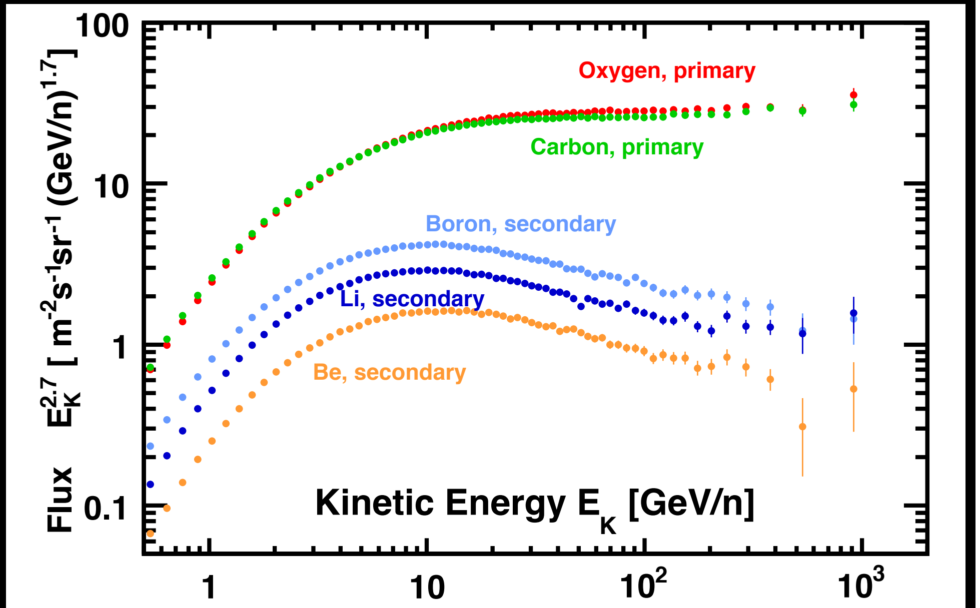


Hardening of spectra still to be understood

Several explanations proposed:

- Source origin
  - Acceleration mechanism
- Propagation effects
  - Features in the diffusion coefficient
- Local fluctuation

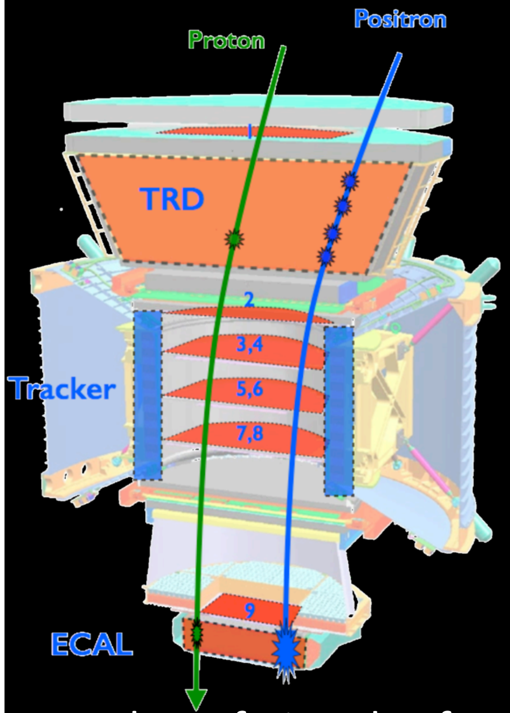
Predict different primary/secondary ratios



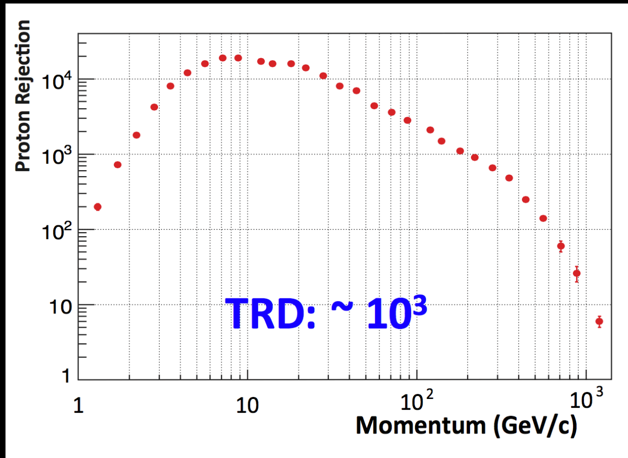
Need precise measurement of individual spectra for primary and secondary CR and their ratios

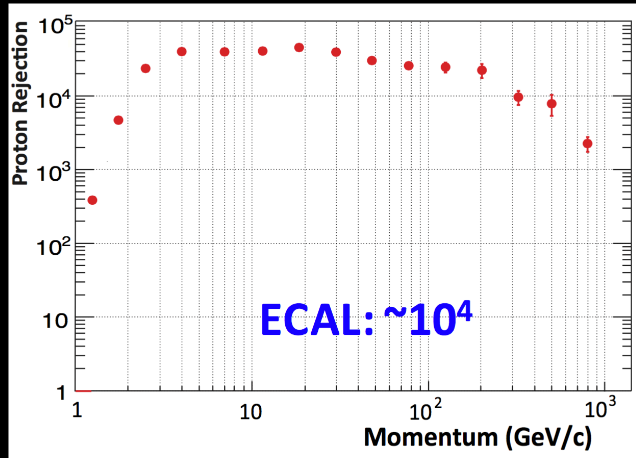
See P. Serpico ICRC 2015

AMS positron identification

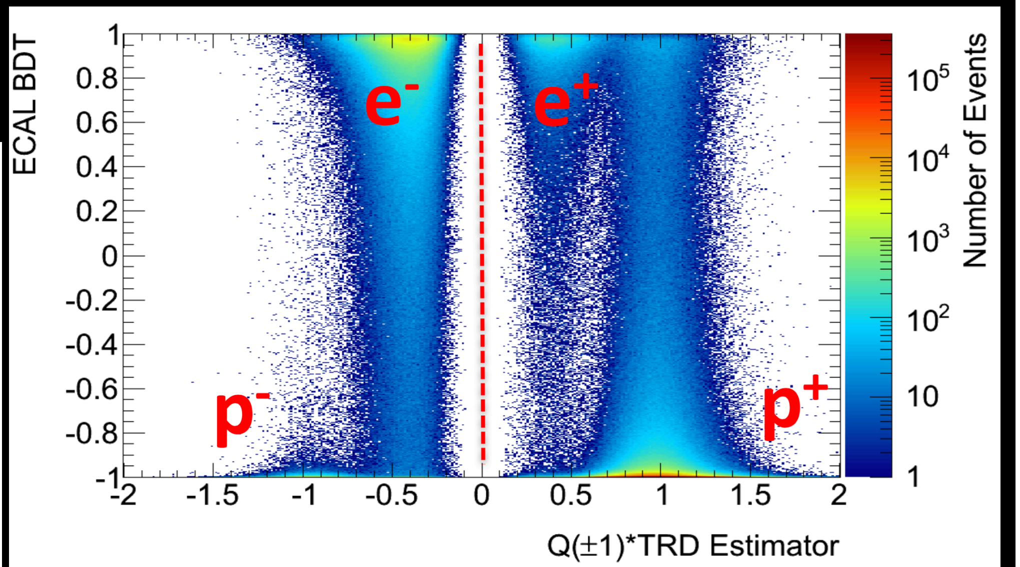


electron/proton separation power @ 90% $e^{\pm}$ selection efficiency

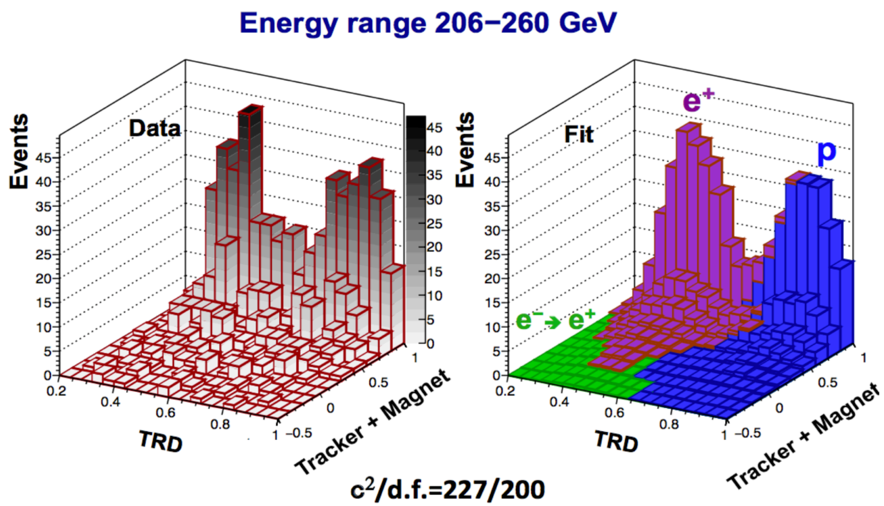




Charge 1 particle identification ECAL+TRD+Tracker:



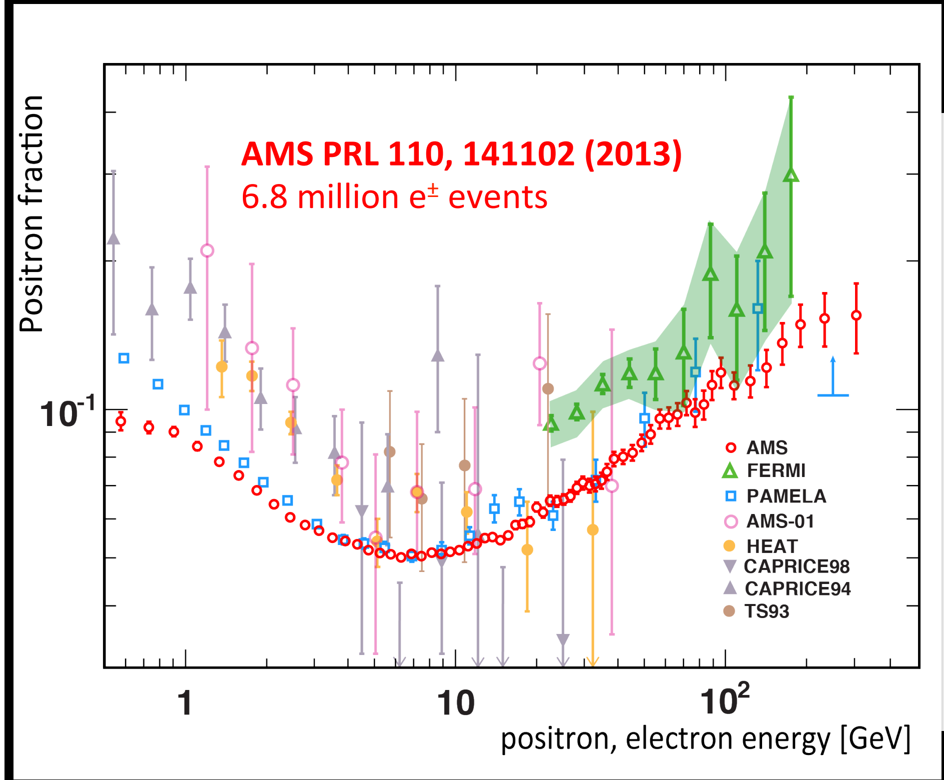
Number of e^+ and e^- from template fit

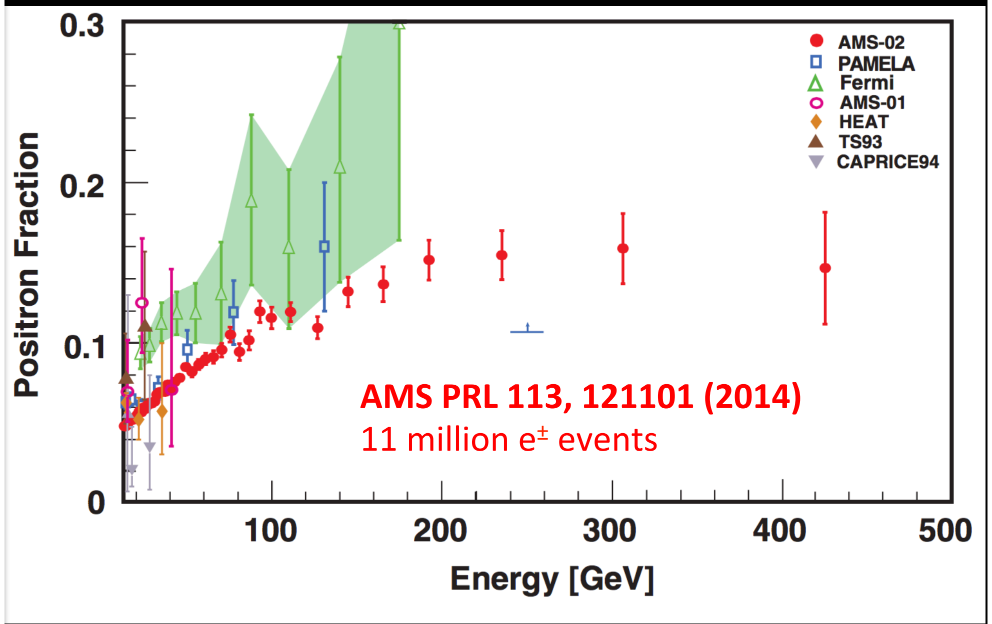


Positron fraction measurement:

PRL 110, 141102 (2013) : energy range 0.5 to 350 GeV

PRL 113, 121101 (2014) : energy range increased to 500 GeV



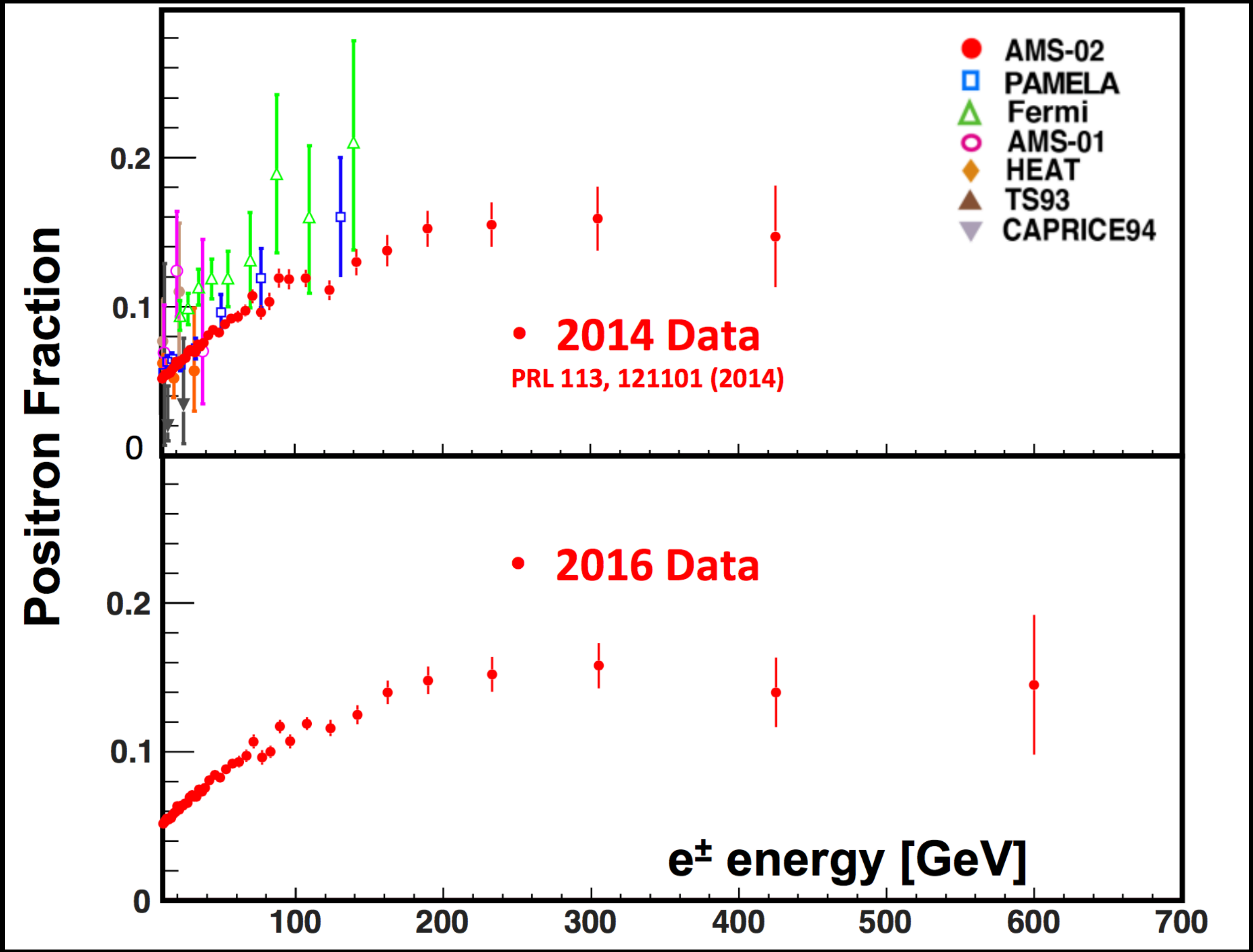


Confirm positron fraction raise for E>10GeV

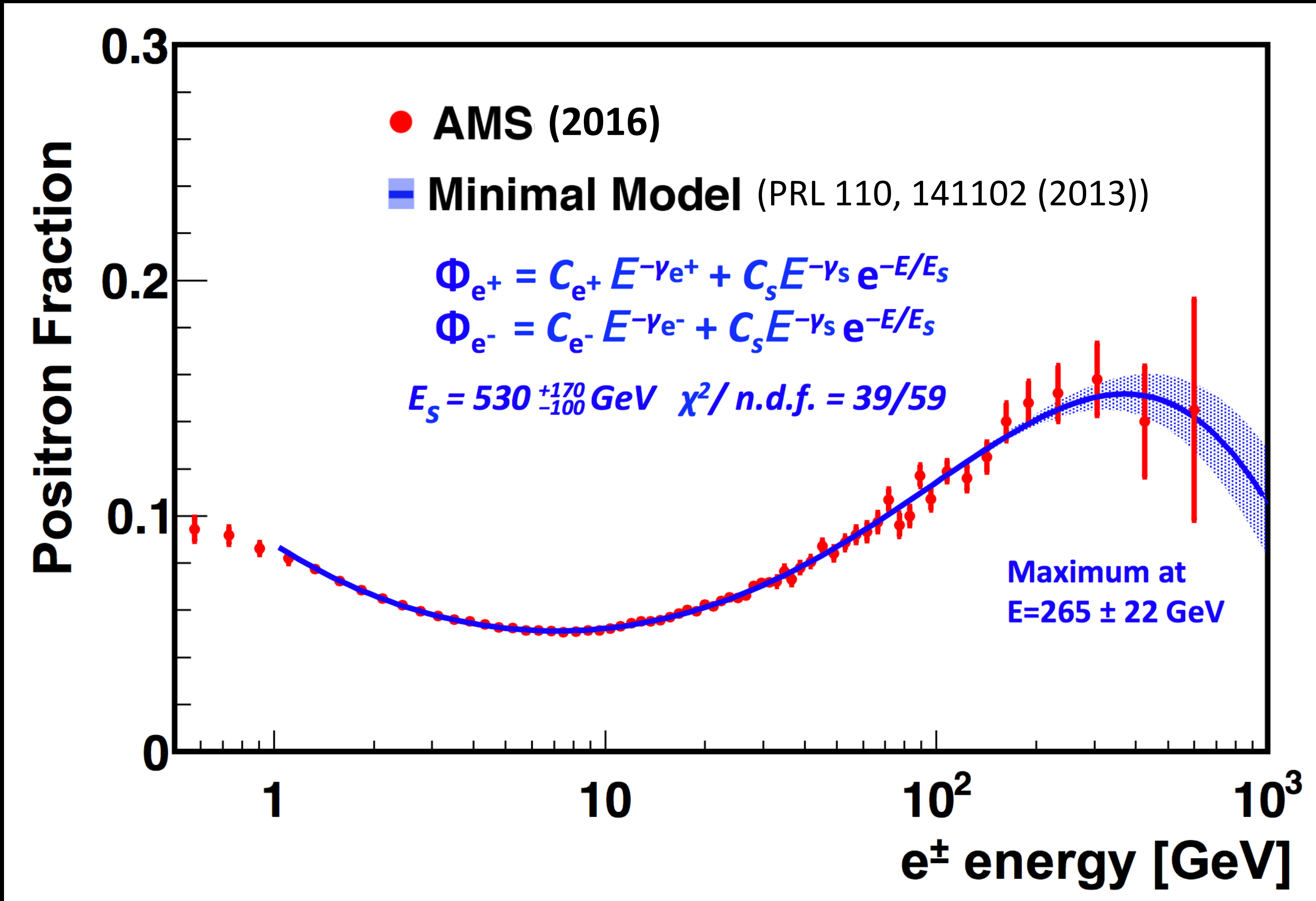
Observe flattening beyond 250 GeV

Positron fraction measurement:

PRL 110, 141102 (2013) : energy range 0.5 to 350 GeV , 6.8 million $e^{\pm}$ events
PRL 113, 121101 (2014) : energy range increased to 500 GeV , 11 million $e^{\pm}$ events
Latest result (2016): energy range increased to 700 GeV, 20 million $e^{\pm}$ events



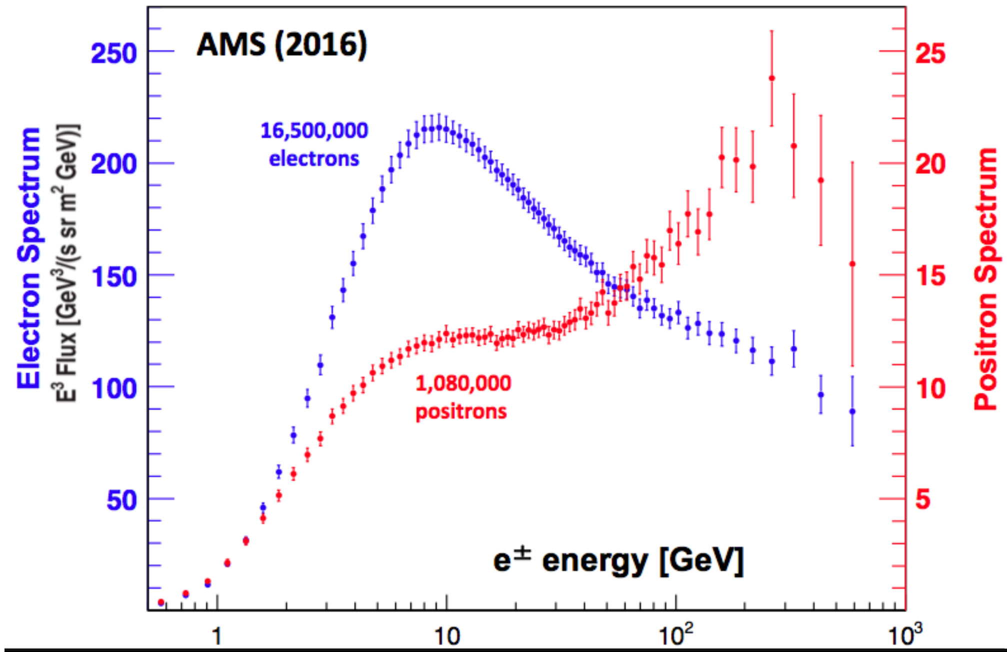
Evidence of additional source: positron fraction fit to a phenomenological model

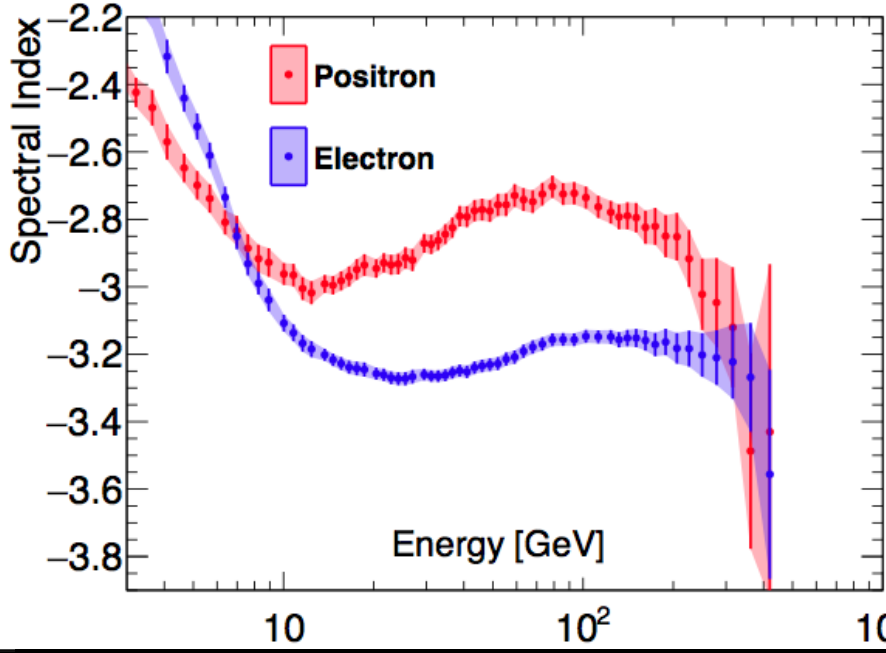


Evidence of additional source: individual positron and electron fluxes

AMS Measurement of Electron and Positron fluxes (PRL 113, 121102 (2014))

Positron fraction raise due to excess of positrons (not lack of electrons)

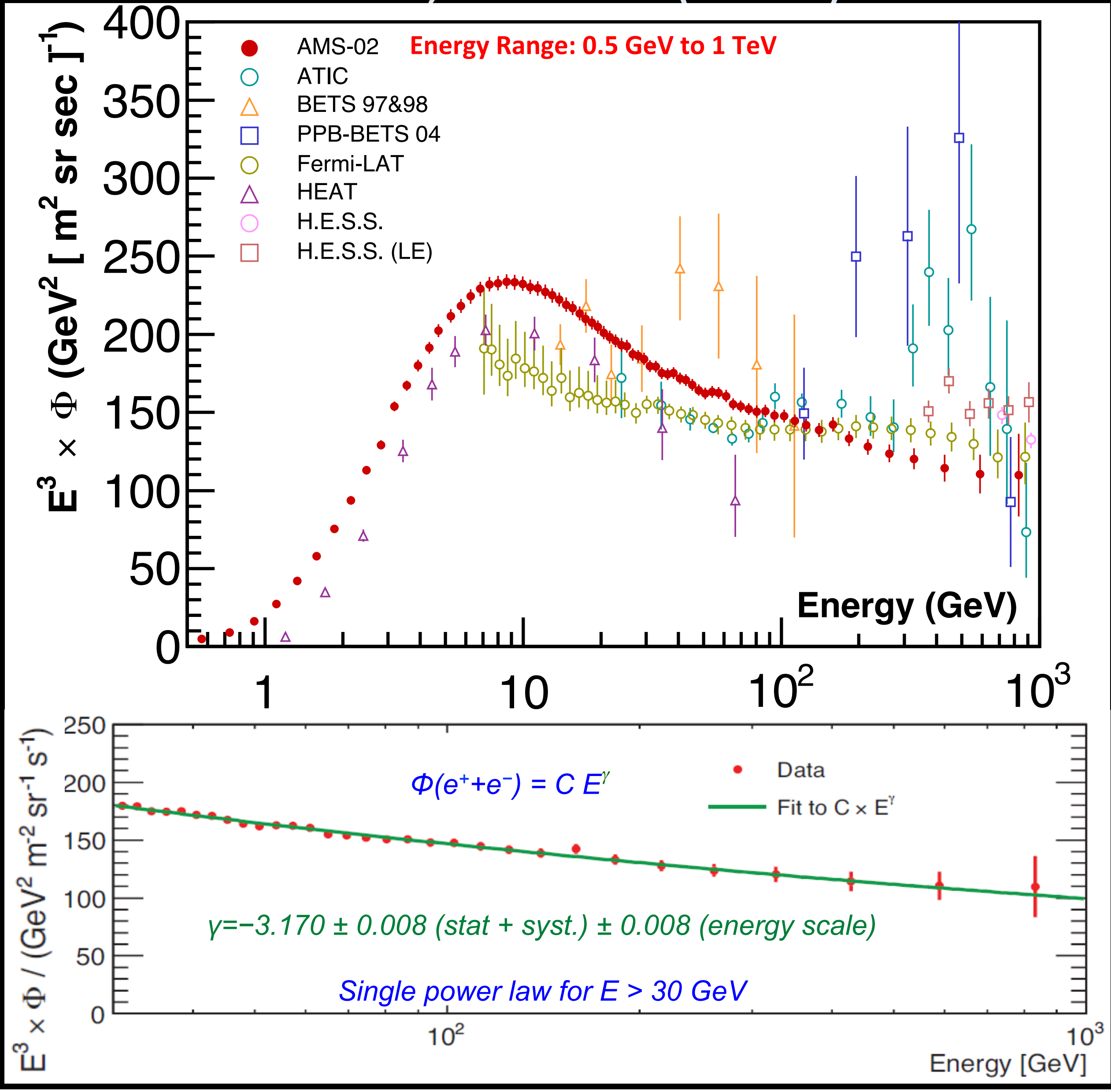




Both fluxes harden above 30 GeV : consistent with a contribution of an additional source
Positron flux harder than electron flux

The precision AMS measurement of the $(e^{+}+e^{-})$ flux

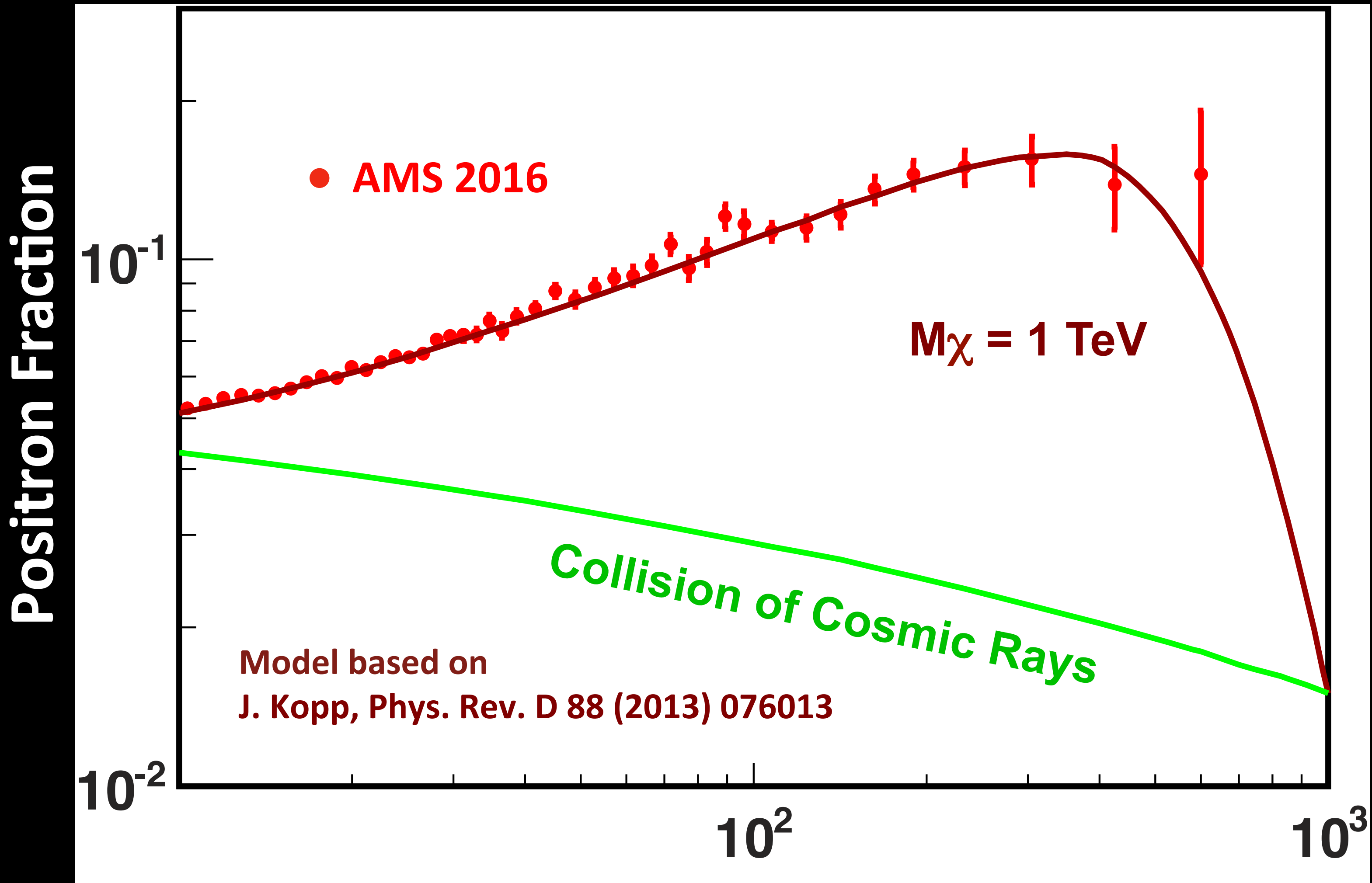
PRL 113, 221102 (2014)



Indirect search for Dark Matter

Possible enhancement of rare secondary CR spectra from $\chi + \chi \rightarrow e^+, \bar{p}, \bar{d}, \ldots$

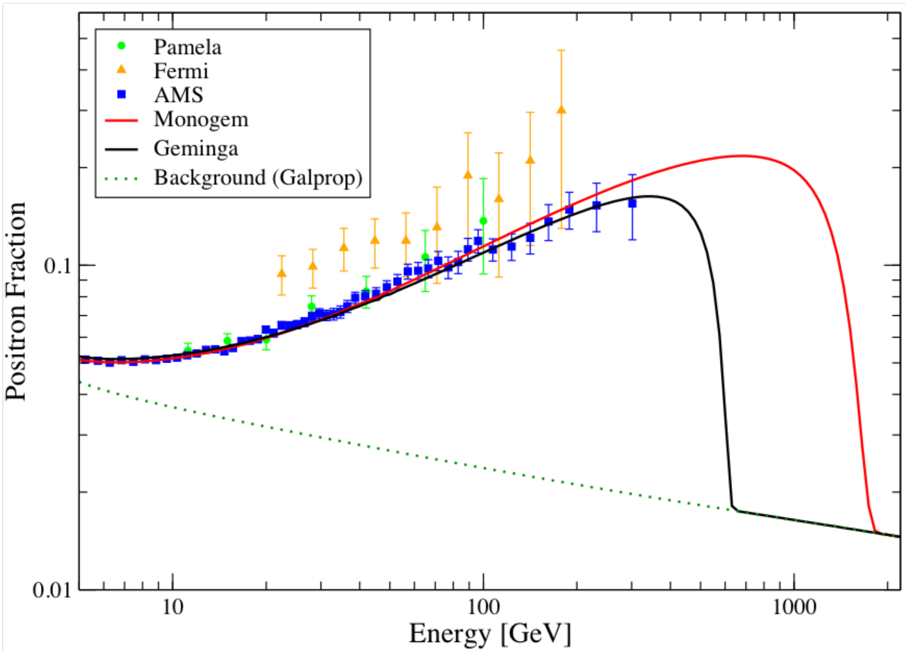
The excess of positrons is measured by the positron fraction: $e^+/(e^+ + e^-)$



However DM is not the only possible interpretation of the observed positron excess

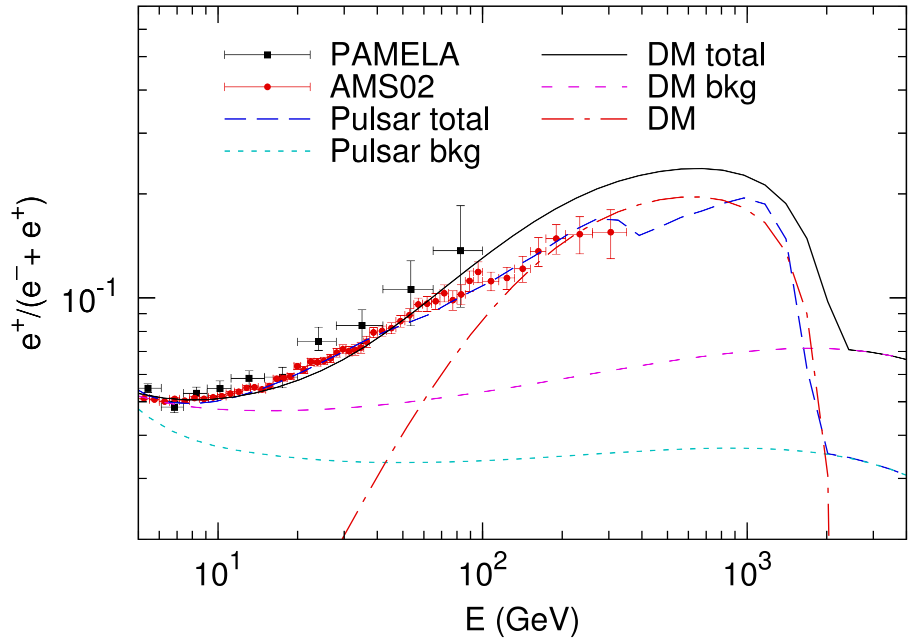
Possible interpretation of the observed positron fraction excess: astrophysical sources vs DM

Pulsar:



Tim Linden and Stefano Profumo
arXiv:1304.1791v1 [astro-ph.HE] 5 Apr 2013

Multiple Pulsars + Dark Matter:



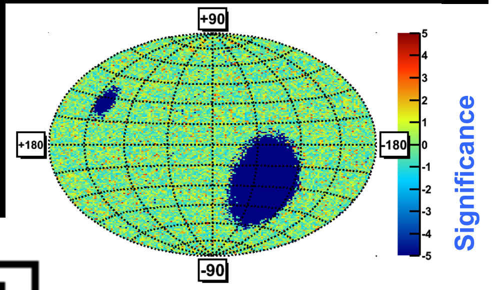
Peng-Fei Yin, Zhao-Huan Yu, Qiang Yuan and Xiao-Jun Bi
arXiv:1304.4128v1 [astro-ph.HE] 15 Apr 2013

Higher level of anisotropy in the arrival direction of e^+ and e^- is expected from Pulsars wrt DM

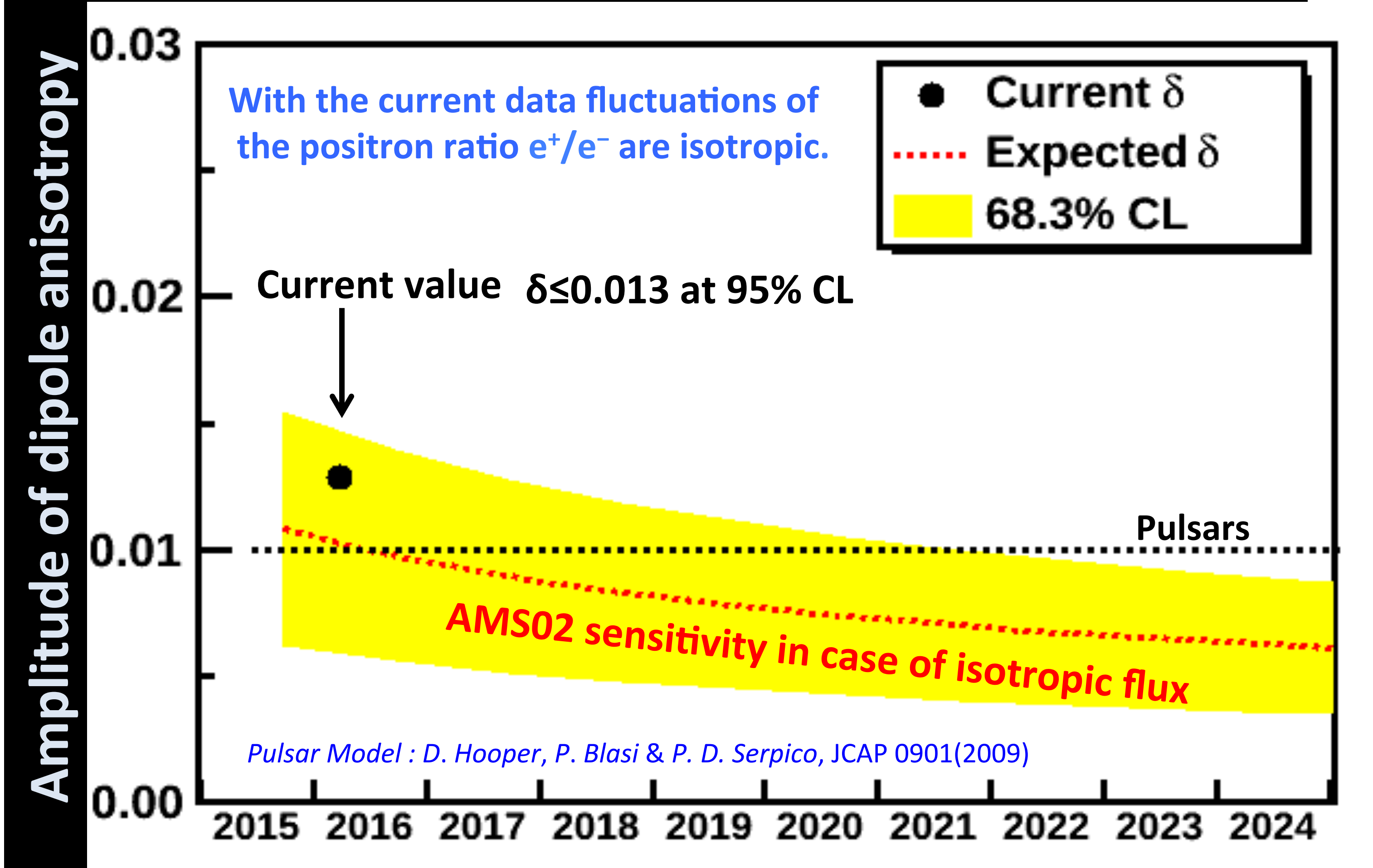
Need more data: extend at higher energies, increase precision

Anisotropy of e⁺/e⁻

Arrival directions of electrons and positrons are used to build a sky map in galactic coordinates(b,l):



Galactic coordinates (b,l)

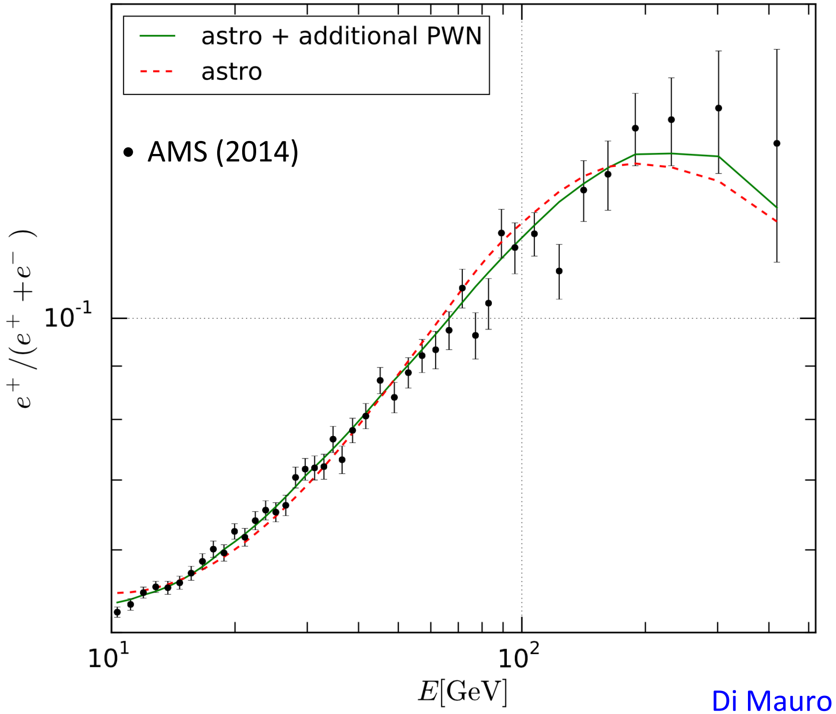


Data taking to 2024, will allow to explore anisotropies of 1%

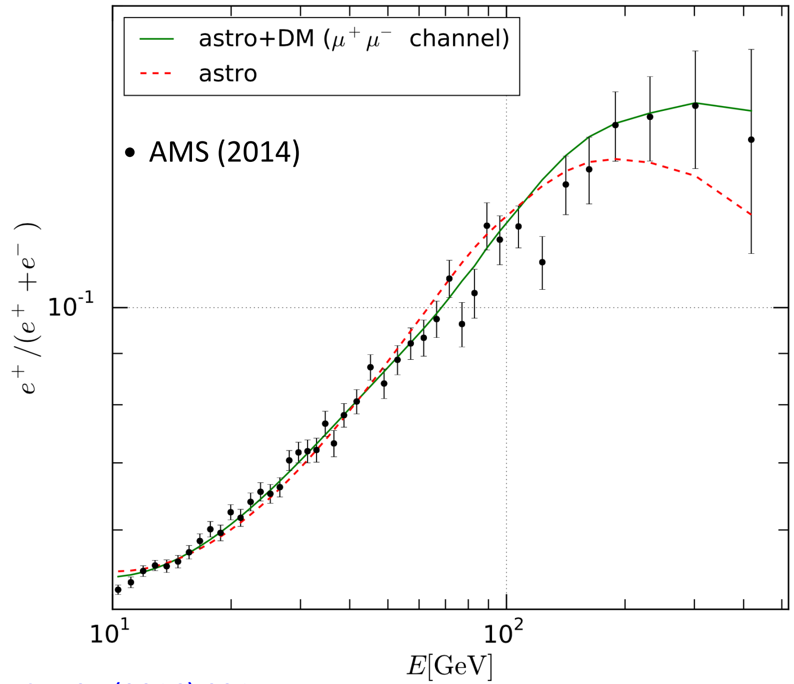
Possible interpretations of the positron excess

The measurement of positron flux, electron flux, (e+ + e-) flux and positron fraction make possible accurate comparisons with various DM models and astrophysical models

Astrophysical sources:



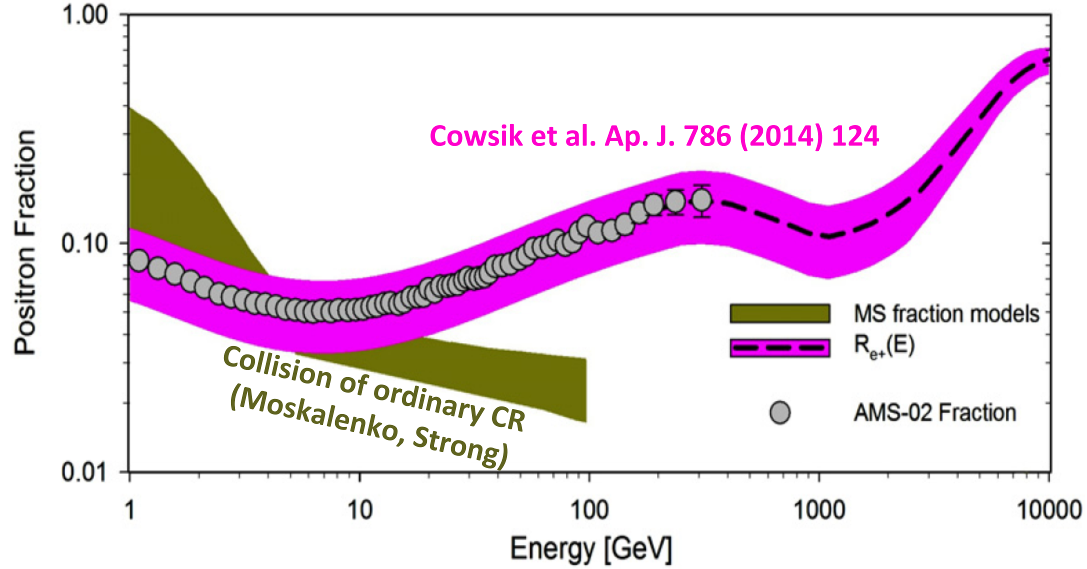
Astrophysical sources + Dark Matter:

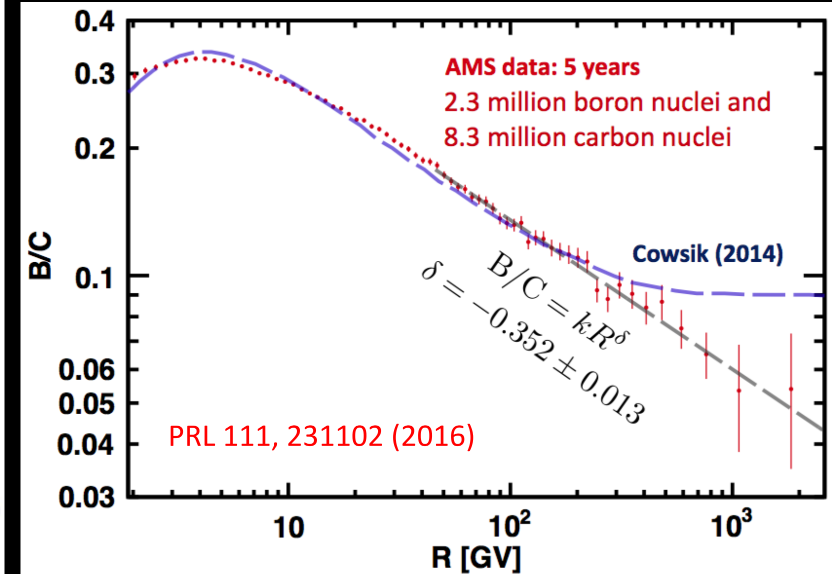


Di Mauro et al, JCAP05 (2016) 031

AMS p and He fluxes are used to estimate secondary positrons from collision of cosmic rays
Global fit of the model to the AMS e^+, e^-, $(e^+ + e^-)$ fluxes and positron fraction.

Possible explanation for the positron excess: propagation of secondaries (example of a model)



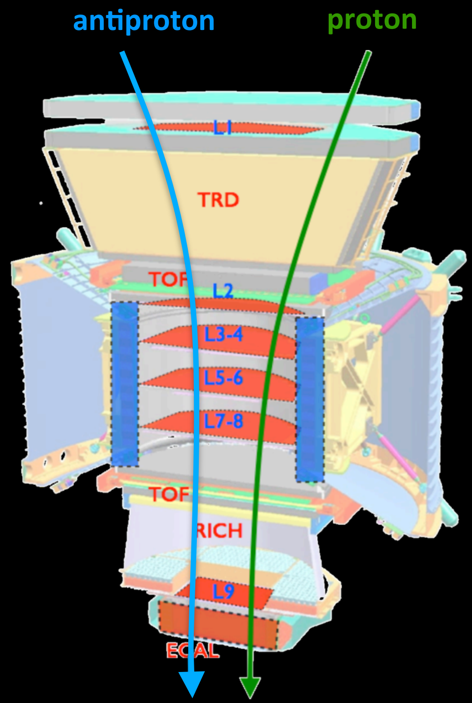


Cowsik's model predicts flattening of B/C at high rigidities (R>200 GV).

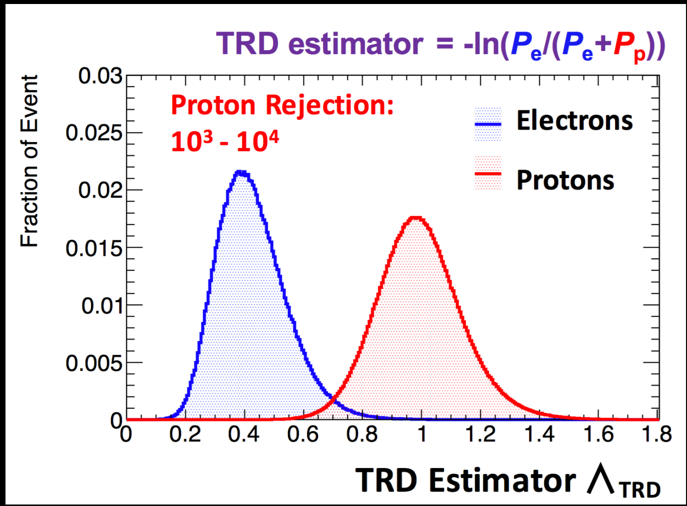
in conflict with the AMS02 B/C data

Simultaneous fit to all relevant CR species is the key to success

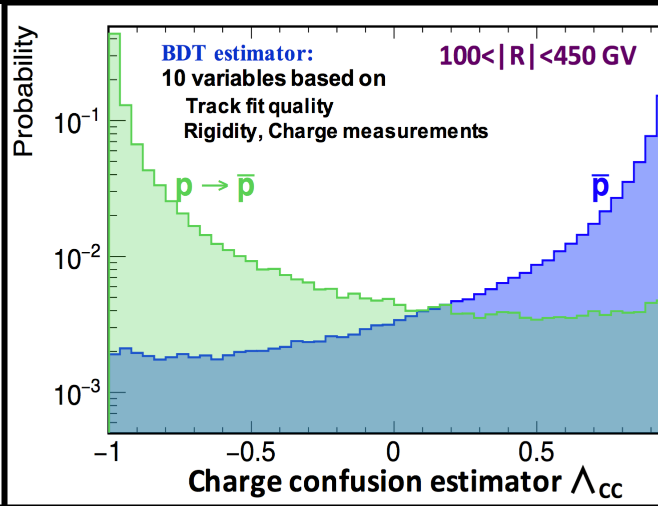
AMS antiproton identification



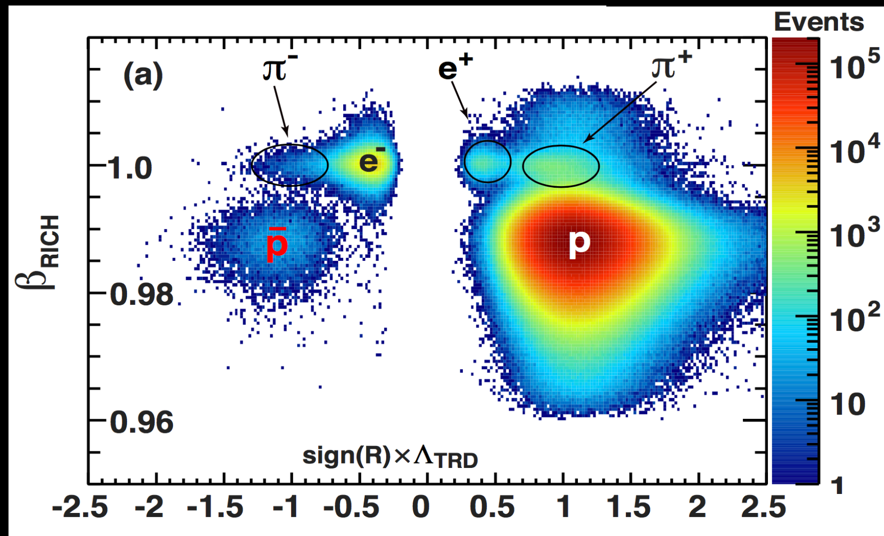
TRD to reject e⁺



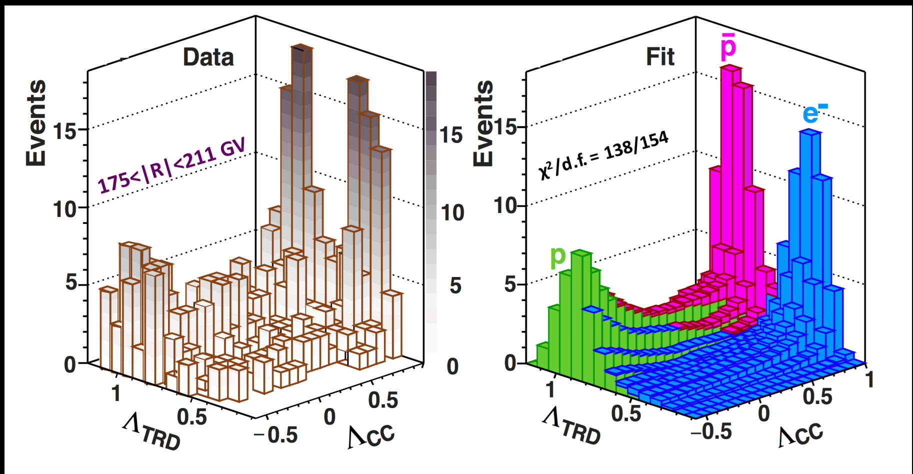
Tracker to identify charge sign:



β to separate light from heavy particles:

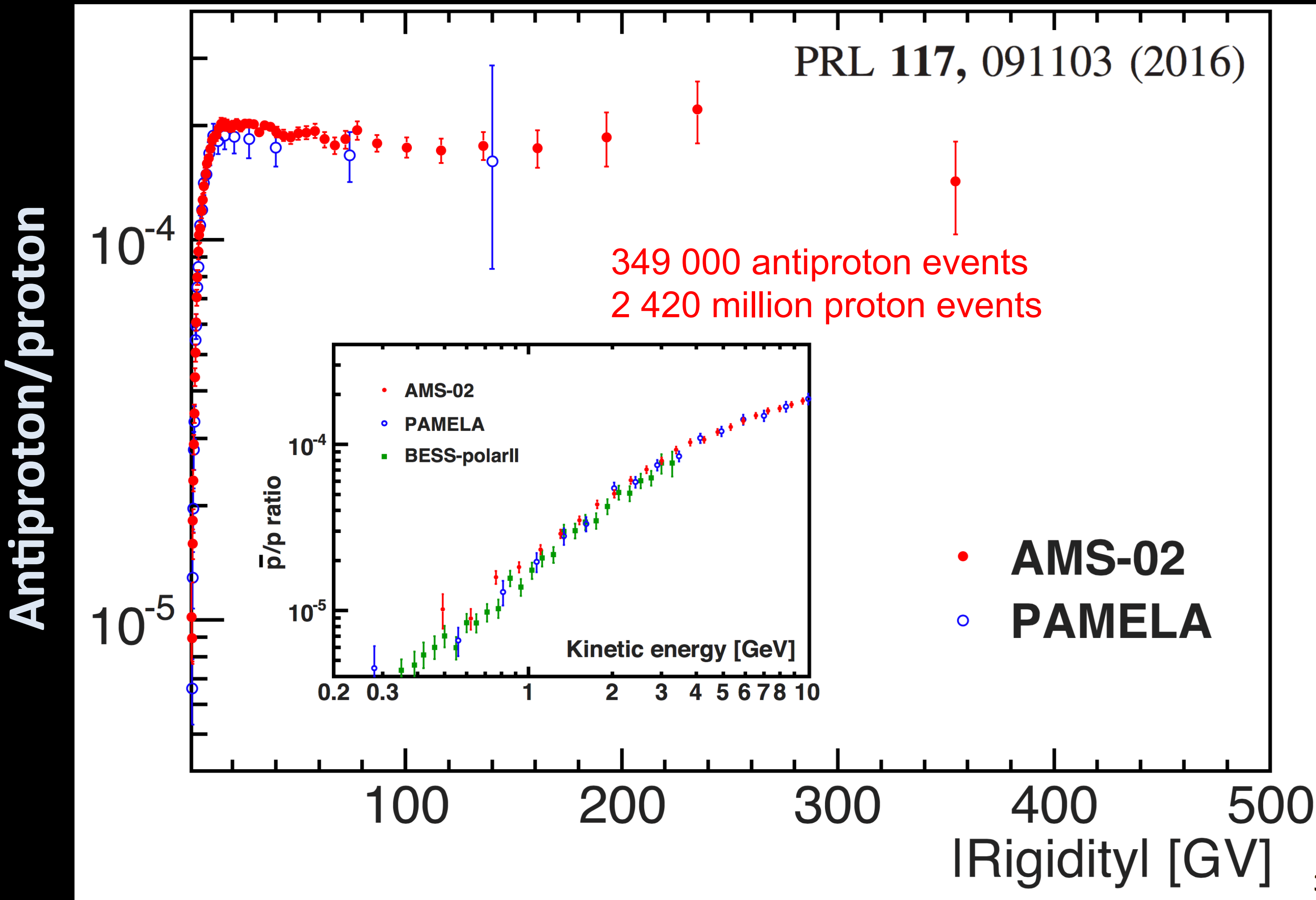


Number of antiproton from 2D template fit



Measurement of antiproton-to-proton ratio

PRL 117, 091103 (2016)

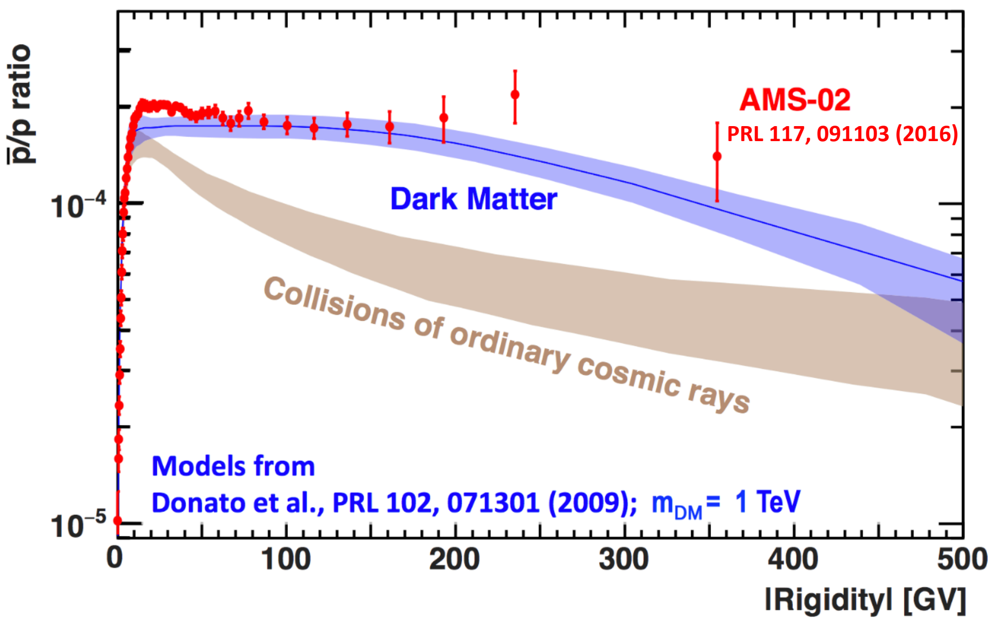


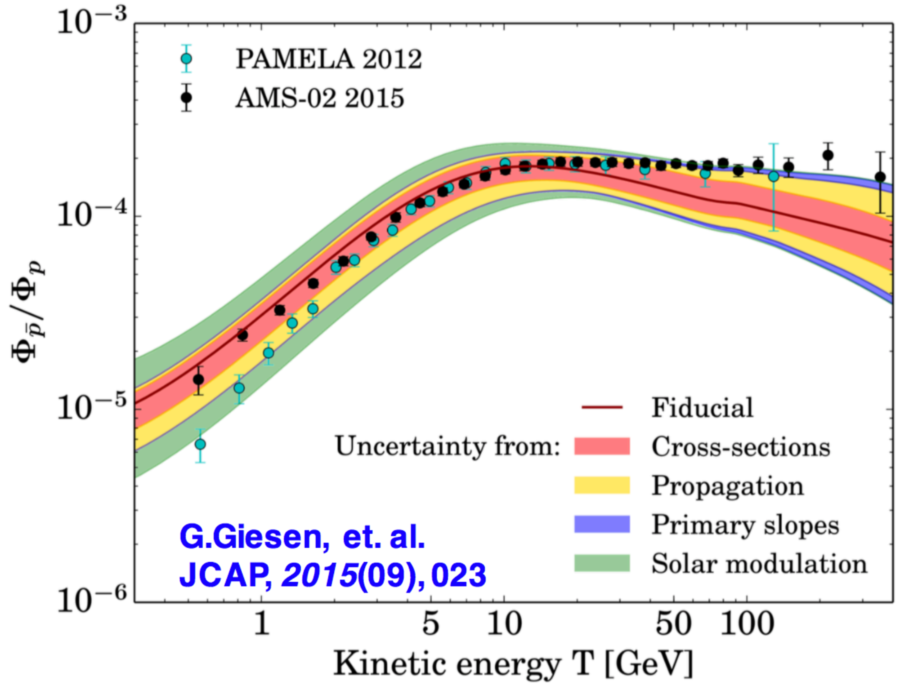
Antiproton to proton ratio is energy independent above 60 GV

Antiproton-to-proton ratio

Antiproton are assumed to be secondary CR, produced in collision of primaries with the ISM flatness of anti-p/p ratio indicates an excess of antiprotons:

Signal from Dark Matter annihilation or decay?

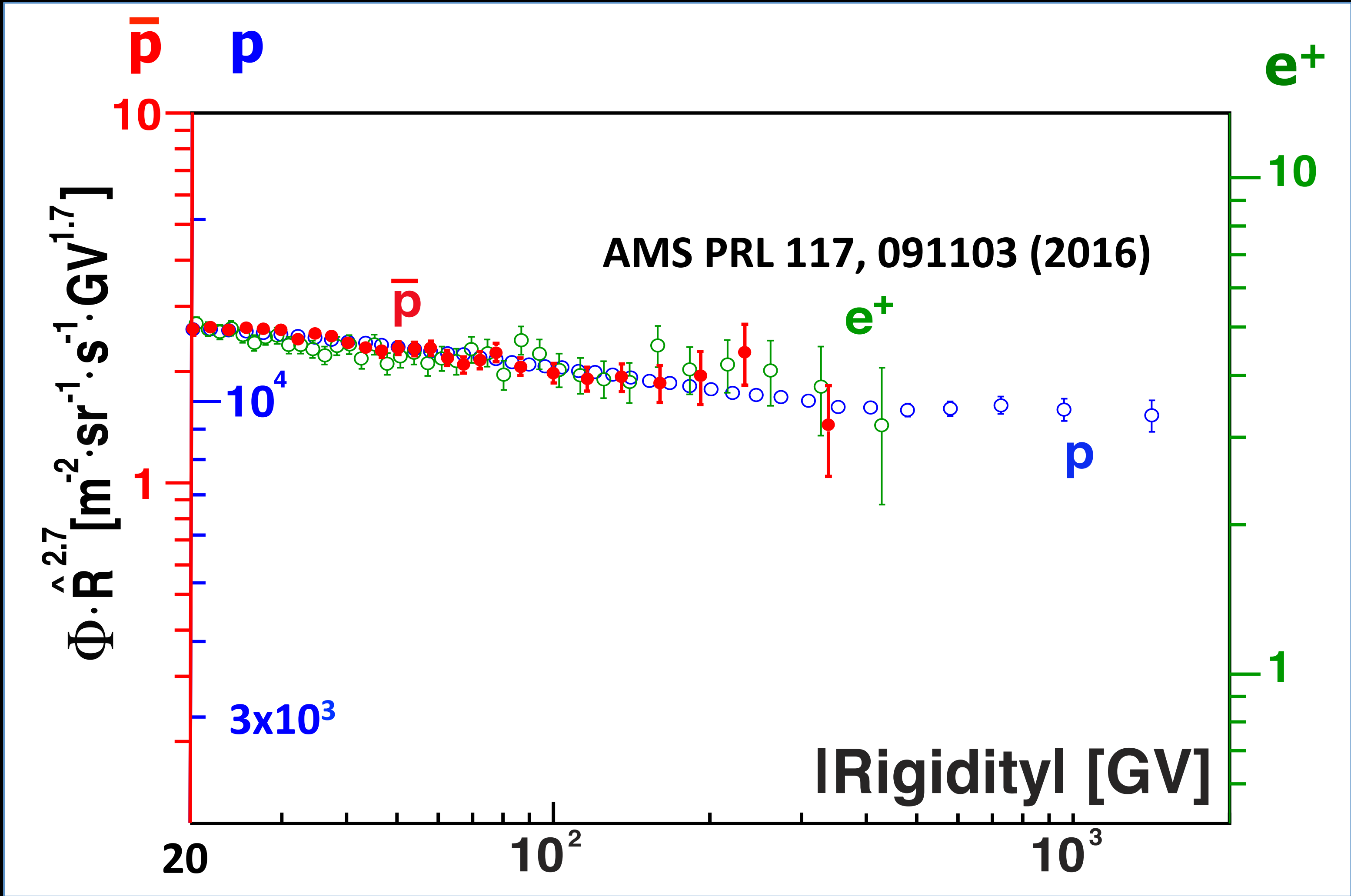




Still many uncertainties on antiproton production in the ISM:

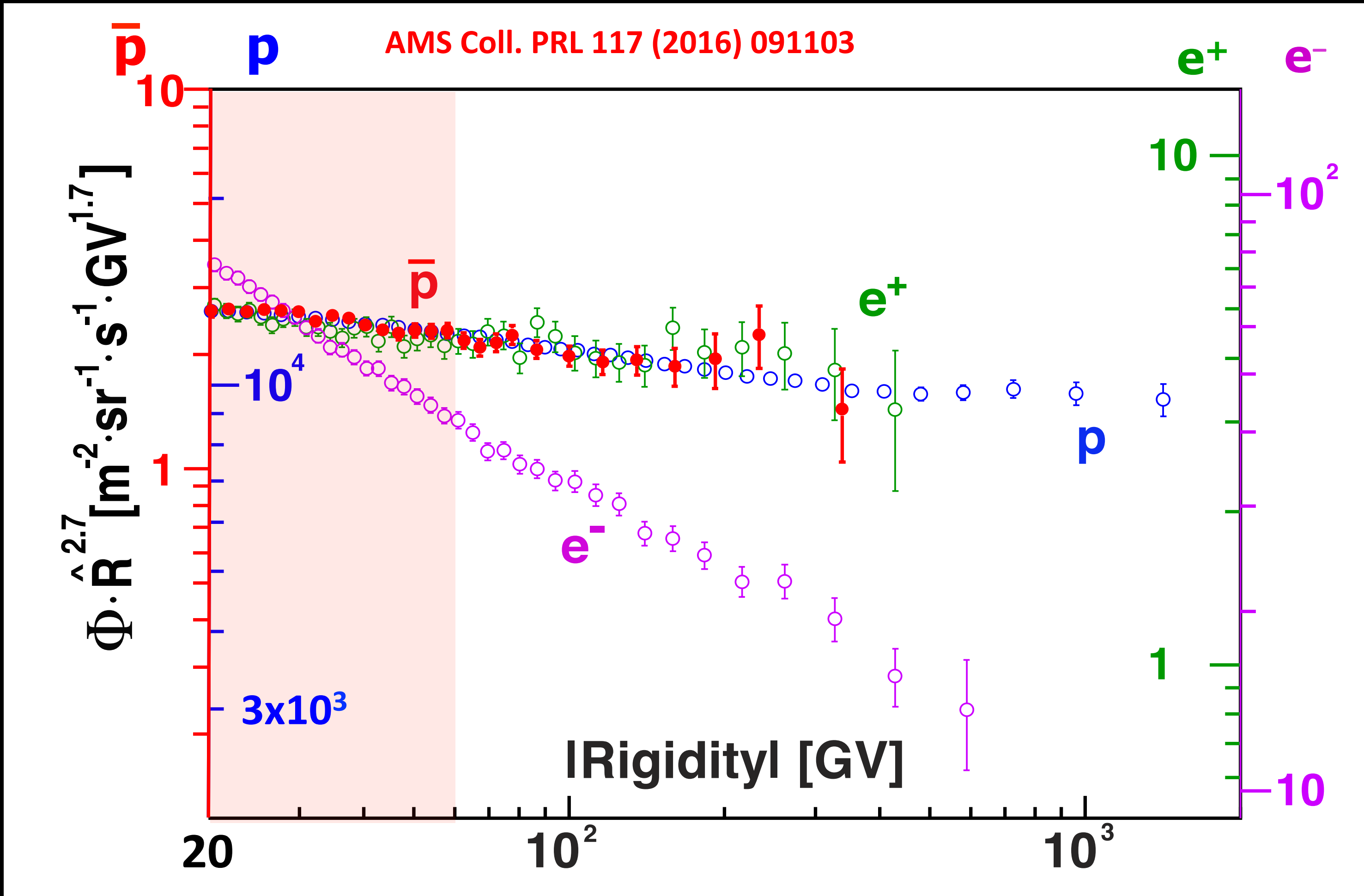
need a better understanding of primary CR spectra at sources, propagation model and cross-sections

The antiproton flux and properties of elementary particle fluxes



Unexpected Result: the Spectra of e^+, p̄, p
have identical energy dependence above 60 GeV

Unexpected Result: The Spectra of e^+, $\bar{p}$, p have identical energy dependence above 60 GeV e^- does not



As expected electrons suffer energy loss by synchrotron radiation

Why positrons behave differently? Again an hint of an additional source of e^+

Conclusions

In the past hundred years, balloons and satellites have measured charged cosmic rays with ~30% accuracy.

AMS is providing cosmic ray information with ~1% accuracy questioning the current cosmic-ray models of acceleration and propagation through the Galaxy:

- Positron and electron fluxes require an additional source of high energy e^+ and e^-
- Antiproton to proton flux ratio is flat from 60 GV to 450 GV
- Identical flux behaviour of protons, positrons and antiprotons from 60 GV to 450 GV
- Hardening of proton, Helium and Lithium nuclei fuxes at ~300 GV
- Proton to Helium flux ratio decreases with energy

Need a comprehensive model to ascertain the origin of secondary CR excess as well as of the hardening of nuclei spectra

AMS will continue to take data until 2024, to provide individual fluxes of nuclei up to Nickel, to improve measurement of rare particles at high energies