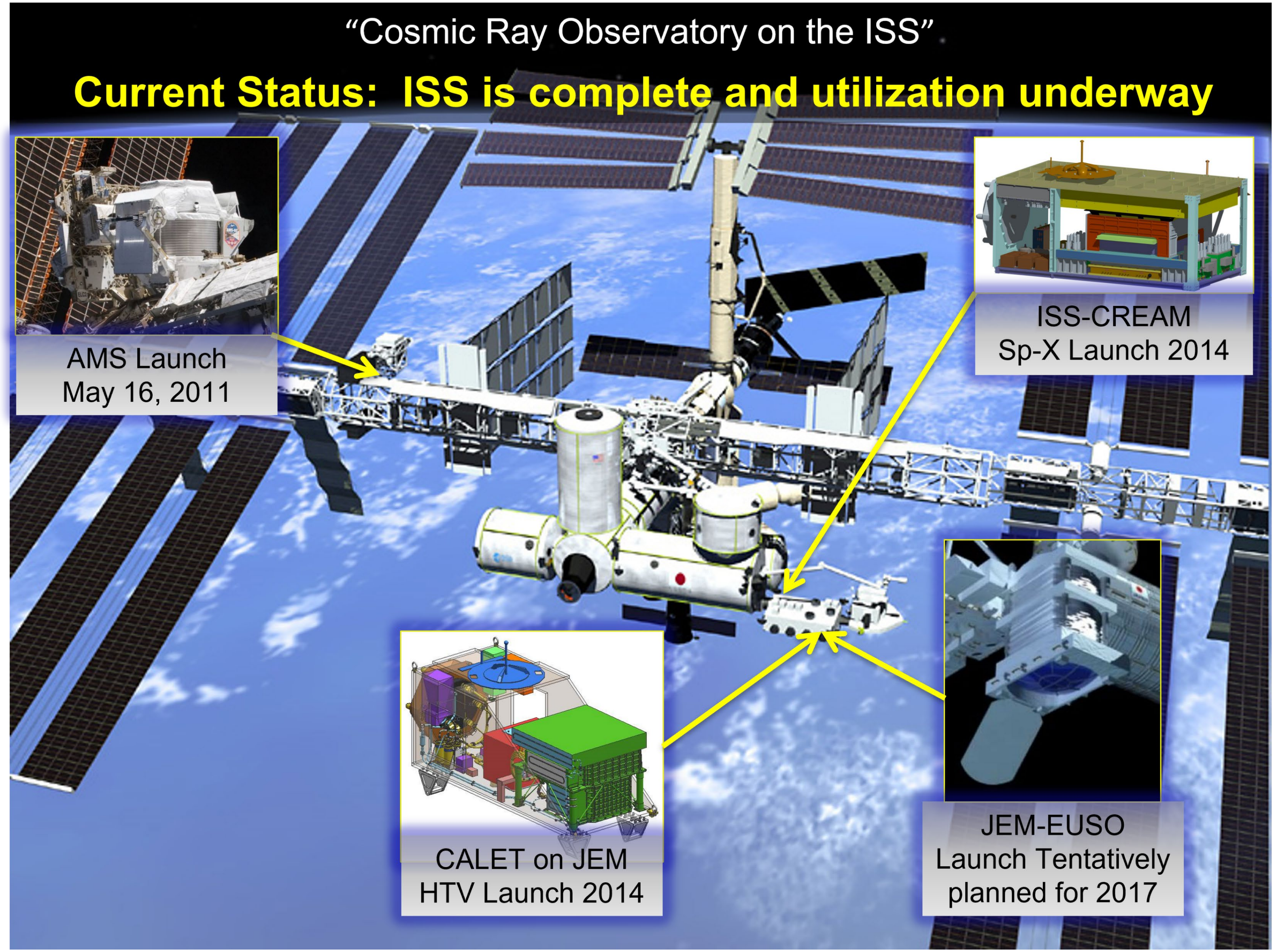
The 6th Cosmic Ray Anisotropy Workshop, Loyola University, Chicago, May 16-19, 2023

Recent Progress in Direct Measurements of Cosmic Rays

Eun-Suk Seo
Department of Physics and
Inst. for Phys. Sci. & Tech.
University of Maryland

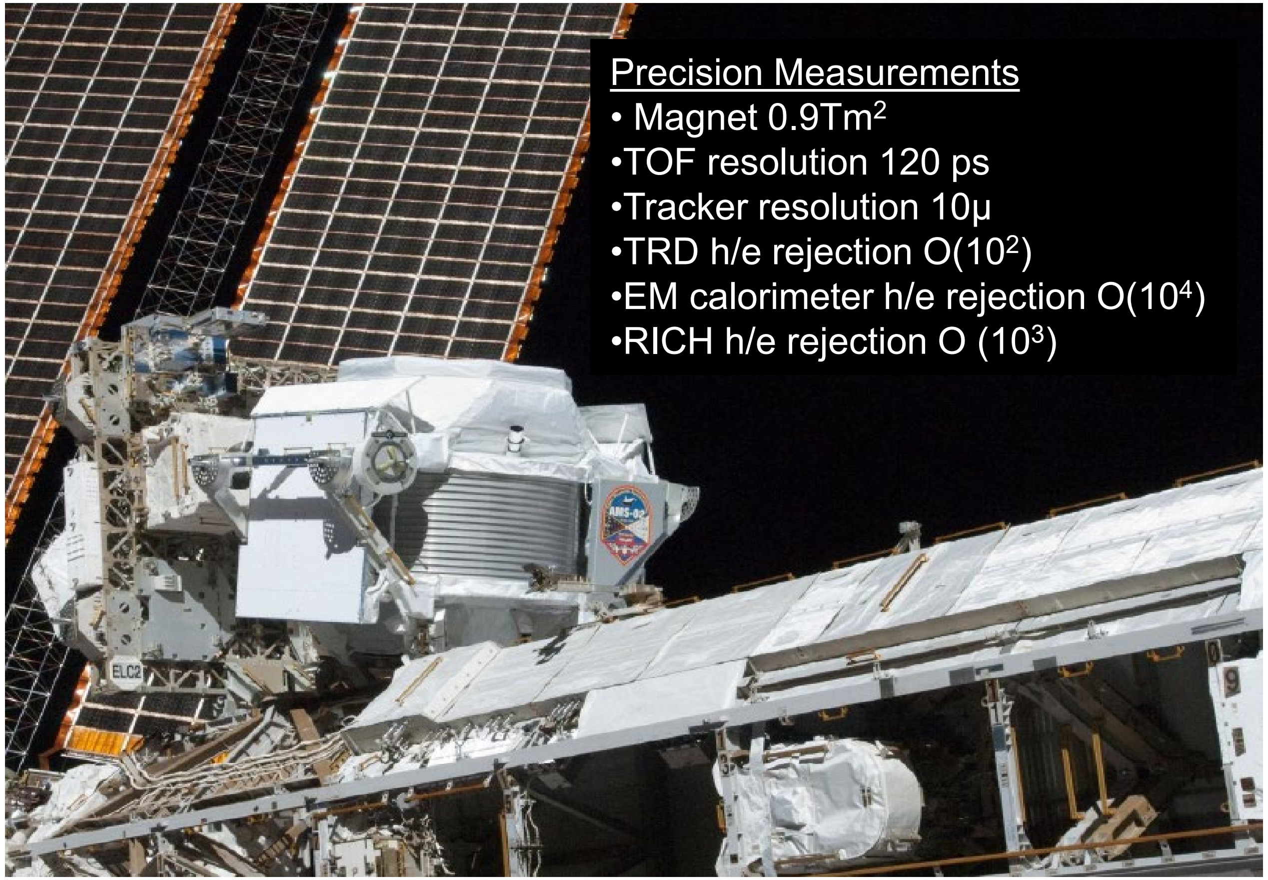
What I presented at the 2013 CRA Workshop



AMS Alpha Magnet Spectrometer

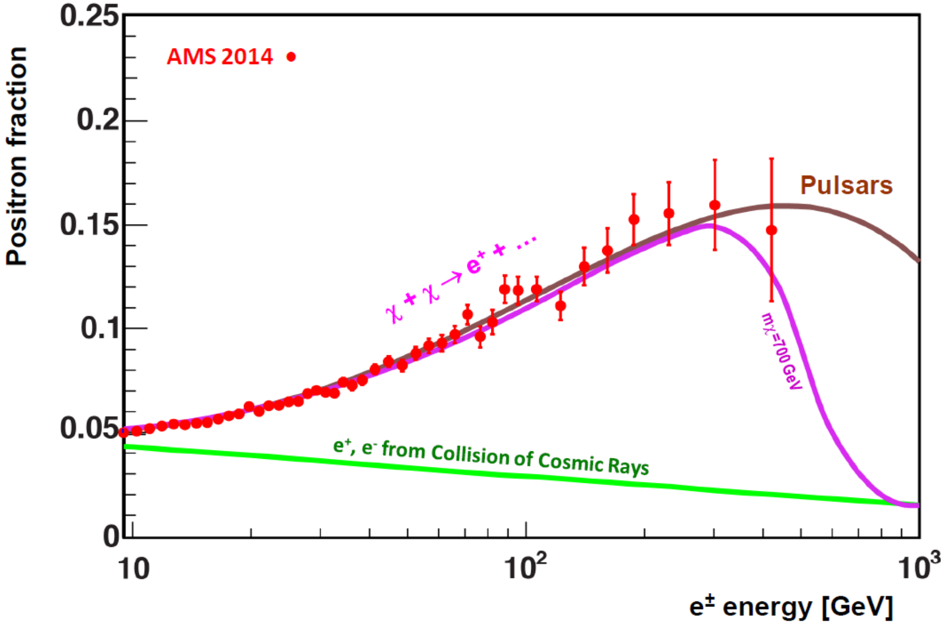
Launch for ISS on May 16, 2011

- Search for dark matter by measuring positrons, antiprotons, antideuterons and γ-rays with a single instrument
- Search for antimatter on the level of < 10^{-9}



High Statistics Measurement of the Positron Fraction in Primary Cosmic Rays of 0.5–500 GeV with the Alpha Magnetic Spectrometer on the ISS

Accado et al., PRL 113, 121101, 2014



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Latest measurements from the AMS experiment unveil new territories in the flux of cosmic rays

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Latest measurements from the AMS experiment unveil new territories in the flux of cosmic rays

The excess positrons in the flux could be an indicator of dark matter particles annihilating into pairs of electrons and positrons.

By CERN, Geneva, Switzerland | Published: Friday, September 19, 2014

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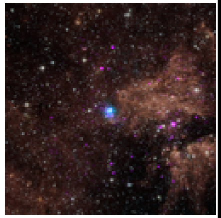


Pulse of a dead star powers intense gamma rays

NBC NEWS HOME TOP VIDEOS MORE

AMS Space Experiment Sees Hints of Dark Matter Particles

Scientists behind the $2 billion Alpha Magnetic Spectrometer experiment are reporting new data pointing toward the potential

"With AMS and with the LHC to restart in the near future ***at energies never reached before, we are living in very exciting times*** *for particle physics as both instruments are pushing boundaries of physics,"* said CERN Director-General Rolf Heuer.

SCIENTIFIC AMERICAN™

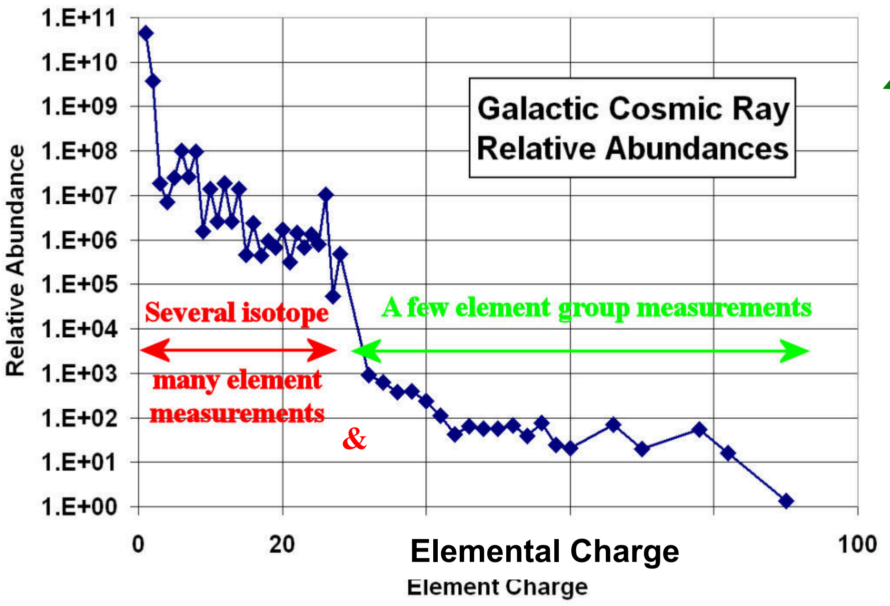
Permanent Address: http://www.scientificamerican.com/podcast/episode/dark-matter-looks-wimpy/
Space » 60-Second Space

Dark Matter Looks WIMPy

Data from the International Space Station-based Alpha Magnetic Spectrometer experiment supports the idea that dark matter consists of the invisible particles called weakly interacting massive particles, or WIMPs. Clara Moskowitz reports

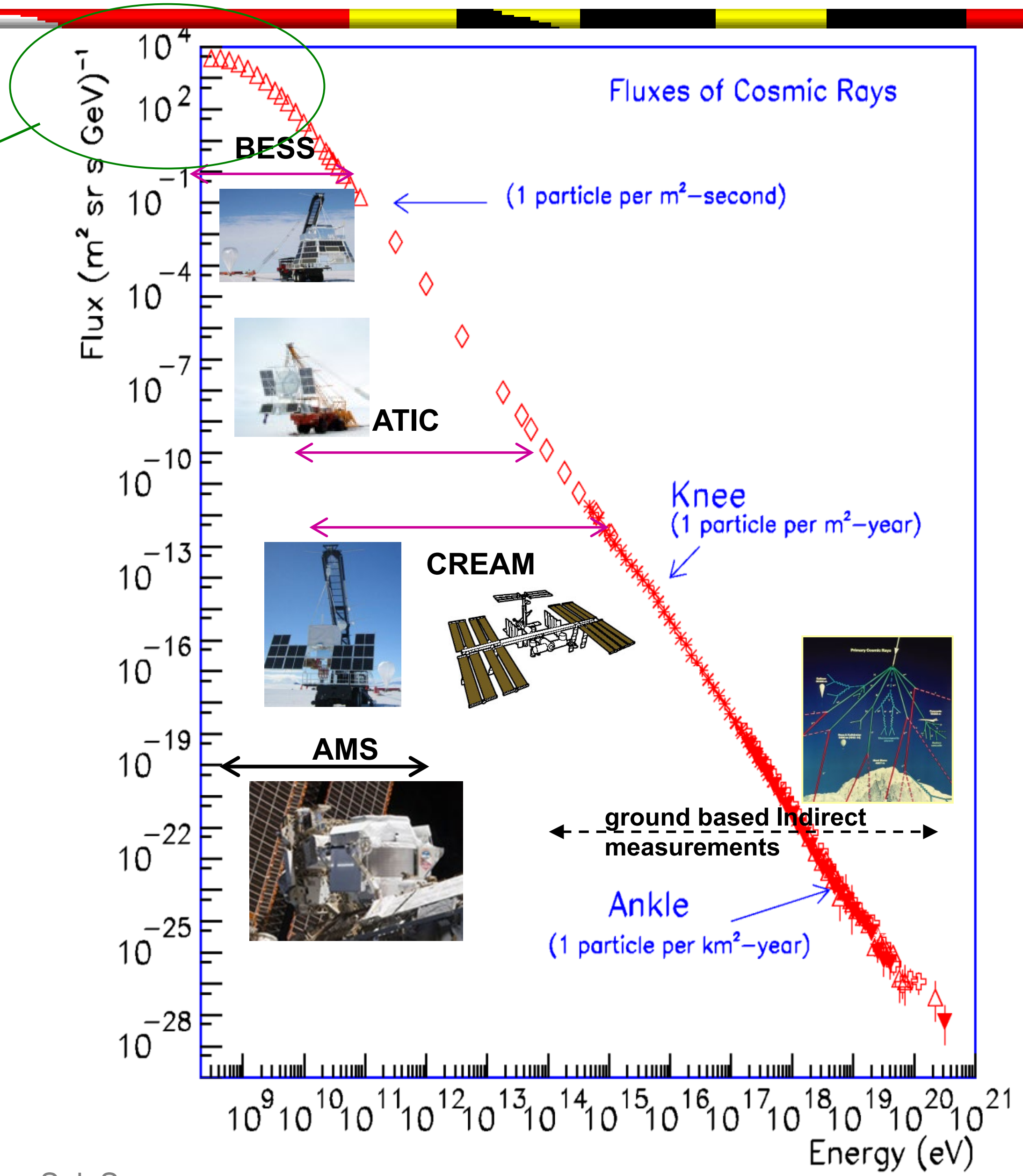
Sep 24, 2014 | By Clara Moskowitz |

How do cosmic accelerators work?



Mission Goal

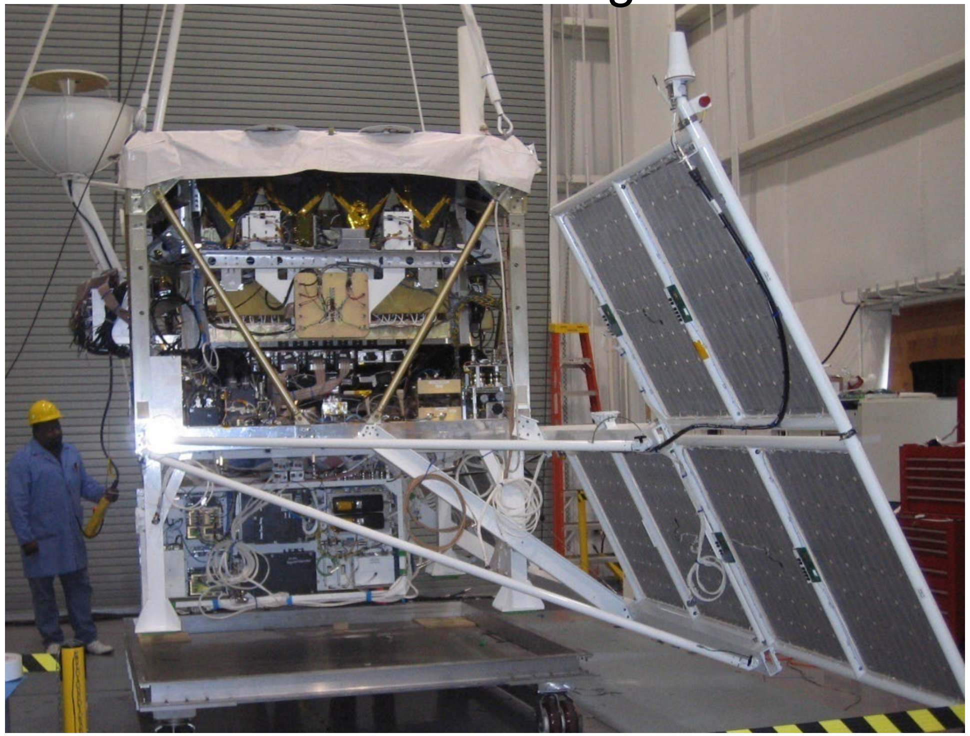
Extend the energy reach of direct measurements of cosmic rays to the highest energy possible to investigate cosmic ray origins, acceleration and propagation.



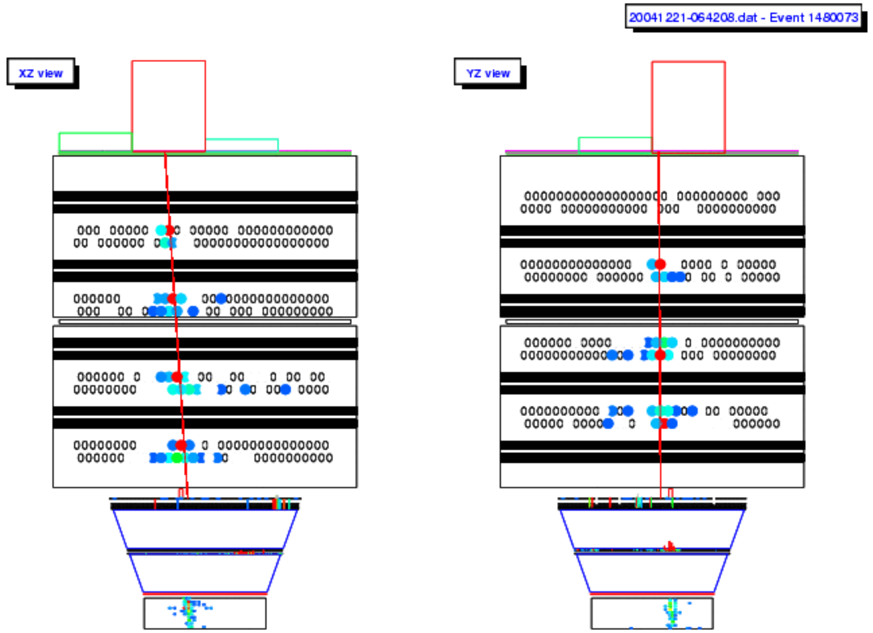
CREAM Cosmic Ray Energetics And Mass

Seo et al. Adv. in Space Res., **33** (10), *1777*, 2004

- Transition Radiation Detector (TRD) **and** Tungsten Scintillating Fiber Calorimeter
  - In-flight cross-calibration of energy scales
- Complementary Charge Measurements
  - Timing-Based Charge Detector
  - Cherenkov Counter
  - Pixelated Silicon Charge Detector

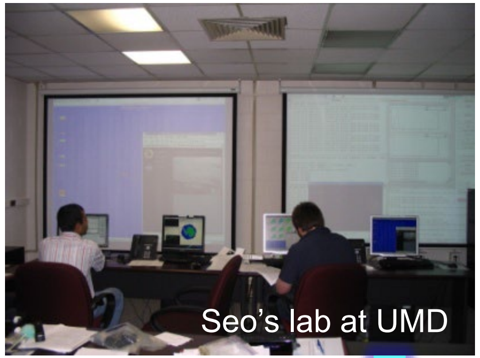


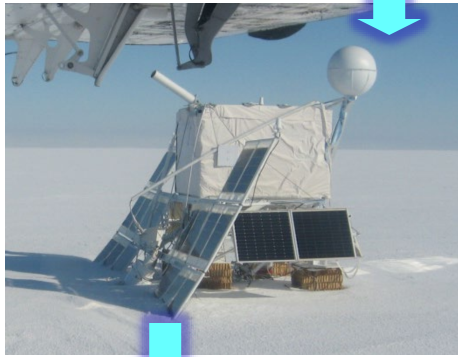
- The CREAM instrument had seven successful Long Duration Balloon (LDB) flights over Antarctica and **accumulated 191 days** of data.
  - This longest known exposure for a single balloon project verifies the instrument design and reliability.



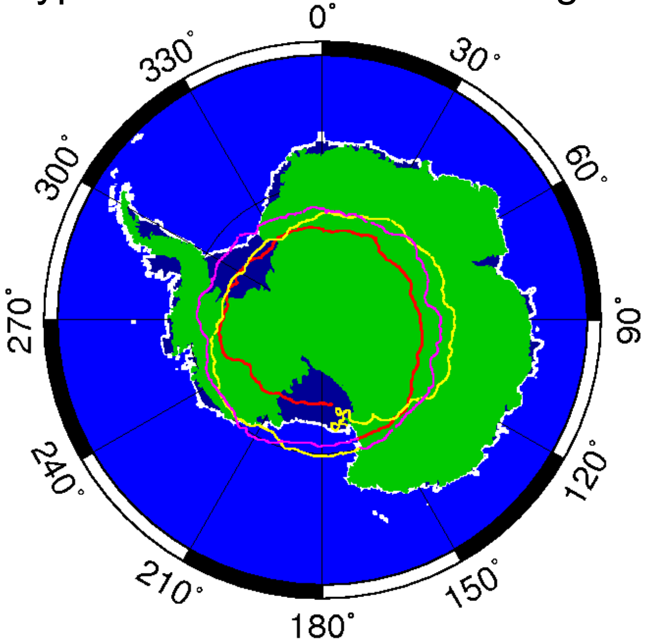
Balloon Flights in Antarctica Offer Hands-On Experience

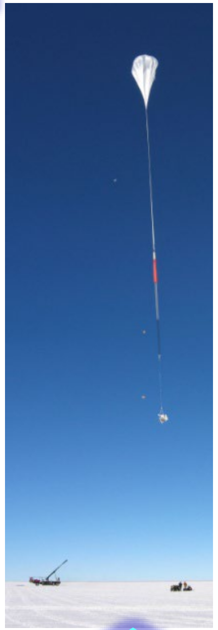
CREAM has trained >100 students





Typical duration: ~1 month/flight



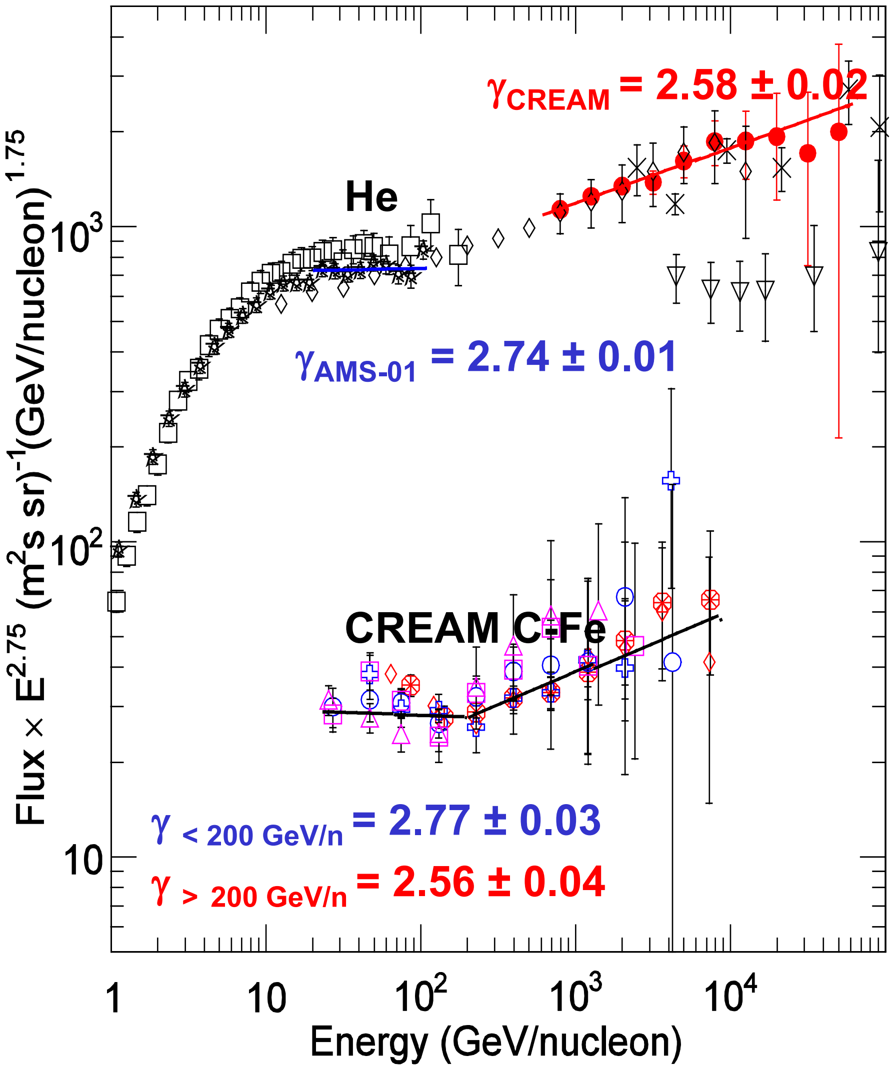


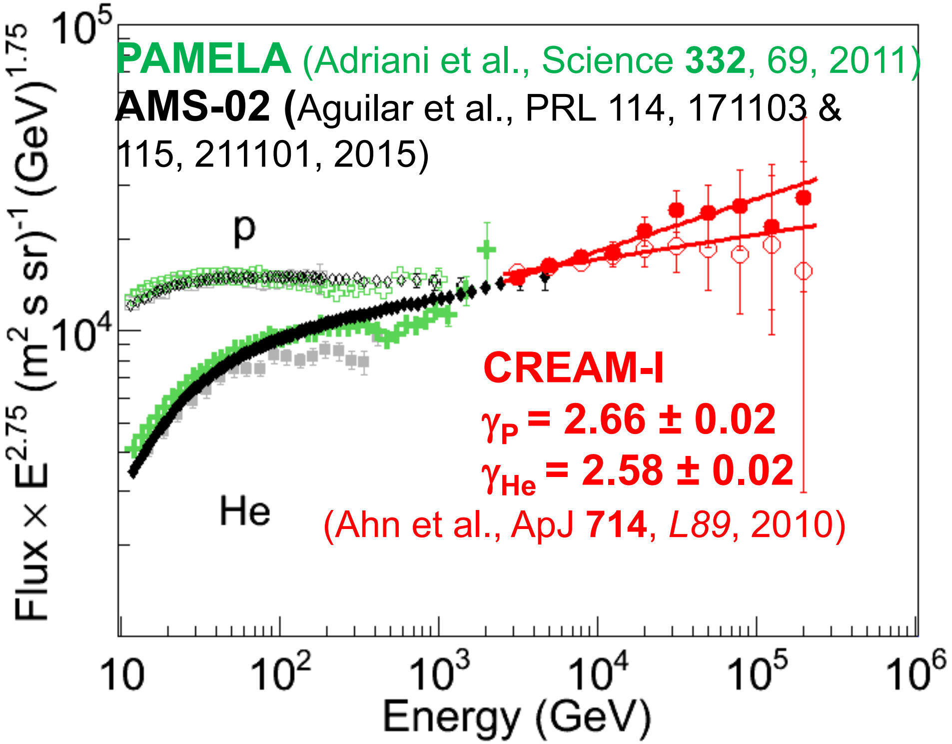
The instruments are for the most part **built in-house by students** and young scientists, many of them currently working in the on-campus laboratory.

Instruments are fully recovered, refurbished & reflown.

Discrepant hardening

Yoon et al. ApJ **728**, *122*, 2011; Ahn et al. ApJ 714, L89, 2010



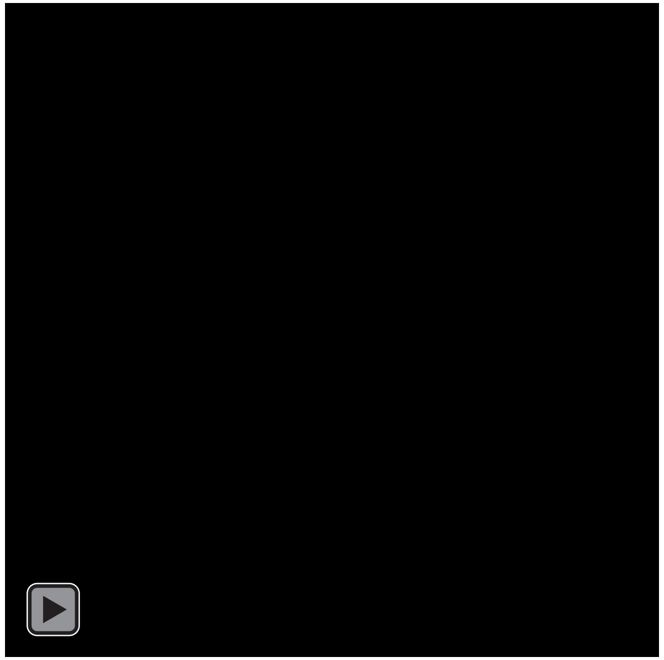


It provides important constraints on cosmic ray acceleration and propagation models, and it must be accounted for in explanations of the e^+e^- anomaly and cosmic ray "knee."

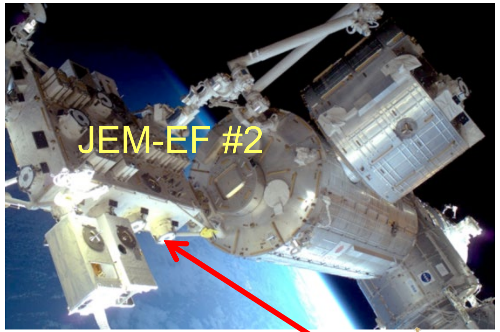
ISS-CREAM: CREAM for the ISS

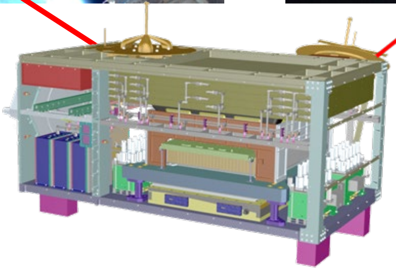
E. S. Seo et al, Advances in Space Research, **53**/10, *1451*, 2014

SpaceX-12 Launch on 8/14/2017



ISS-CREAM installed on the ISS 8/22/17



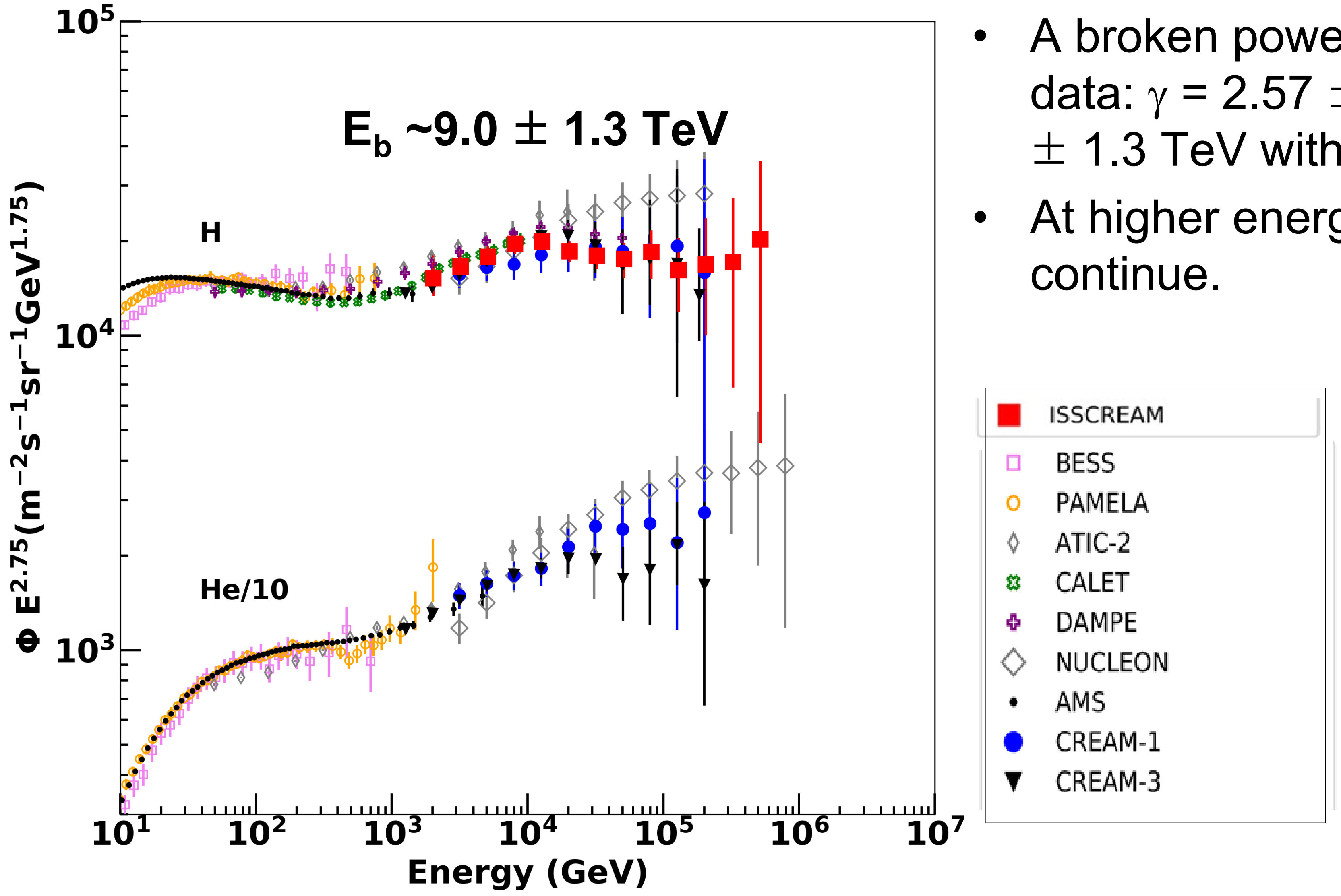


Mass: ~1258 kg
Power: ~ 415 W
Data rate: ~500 kbps

- Building on the success of the balloon flights, the payload was transformed for accommodation on the ISS (NASA's share of JEM-EF).
  - Measure cosmic ray energy spectra from 10^{12} to $>10^{15}$ eV with individual element precision over the range from protons to iron
  - Search for spectral features from nearby/young sources, acceleration effects, or propagation history.
  - Probe cosmic ray origin, acceleration and propagation.

ISS-CREAM Proton Spectrum (2.5 – 655 TeV)

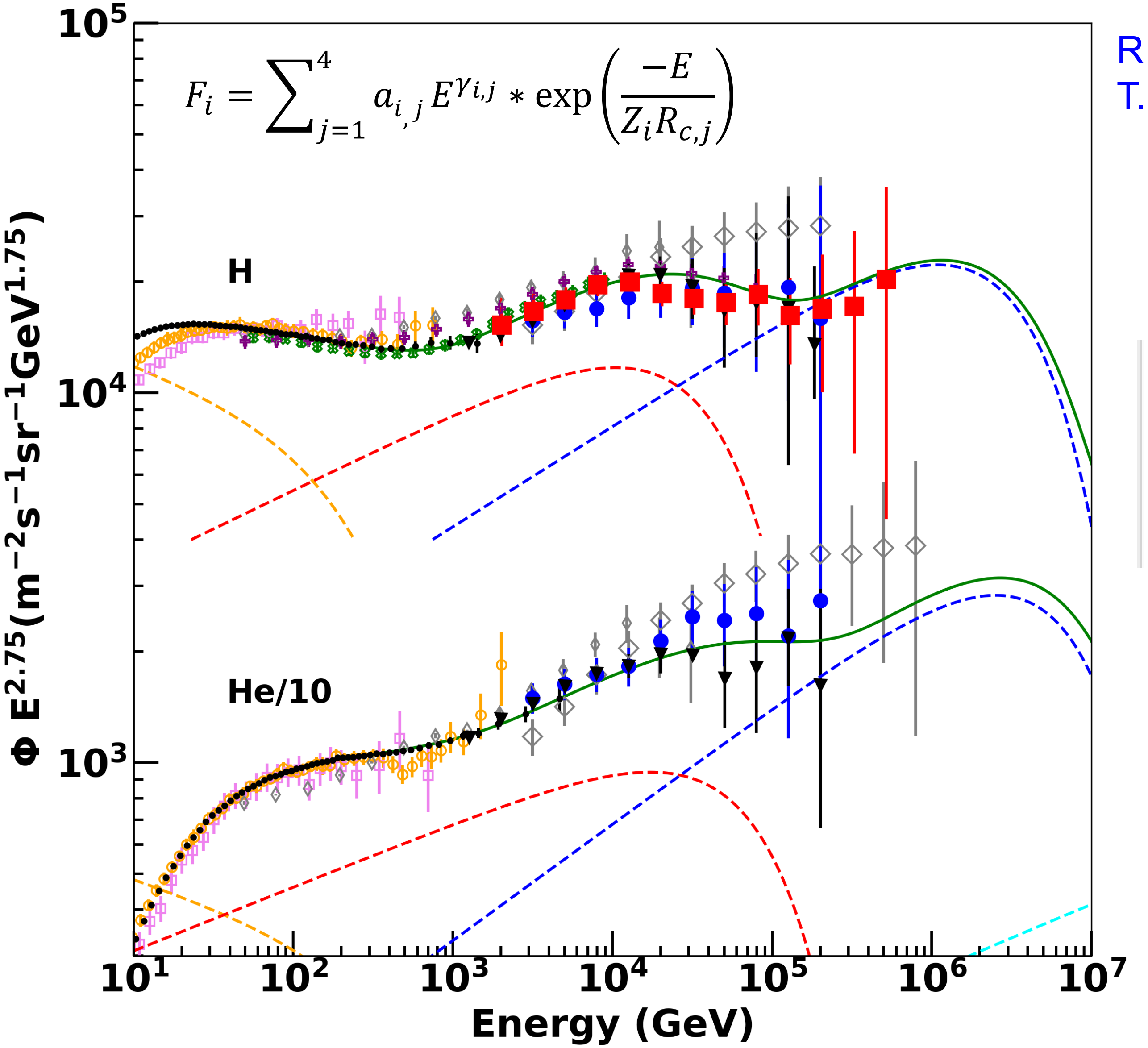
G. H. Choi et al. ISS-CREAM Collaboration, ApJ 940, 107, 2022



- A broken power law fit to 1.6 – 164 TeV data: γ = 2.57 ± 0.03 and a break at ~9.0 ± 1.3 TeV with $\Delta\gamma$ = 0.25.
- At higher energies, the softening does not continue.
- The deviation from a single power law near 10 TeV is consistent with the softening reported by CREAM-I &III, DAMPE, and NUCLEON, but ISS-CREAM extends measurements to higher energies than prior measurements.

Transition between different types of sources?

E. S. Seo for the ISS-CREAM Collaboration, PoS(ICRC2021)095



R. Scrandis, D.P. Bowman & E.S. Seo, ASR, 70 (9), 2703, 2022.
T. Gaisser, T. Stanev & S. Tilav, Frontiers of Phys. 8 (2013) 248.

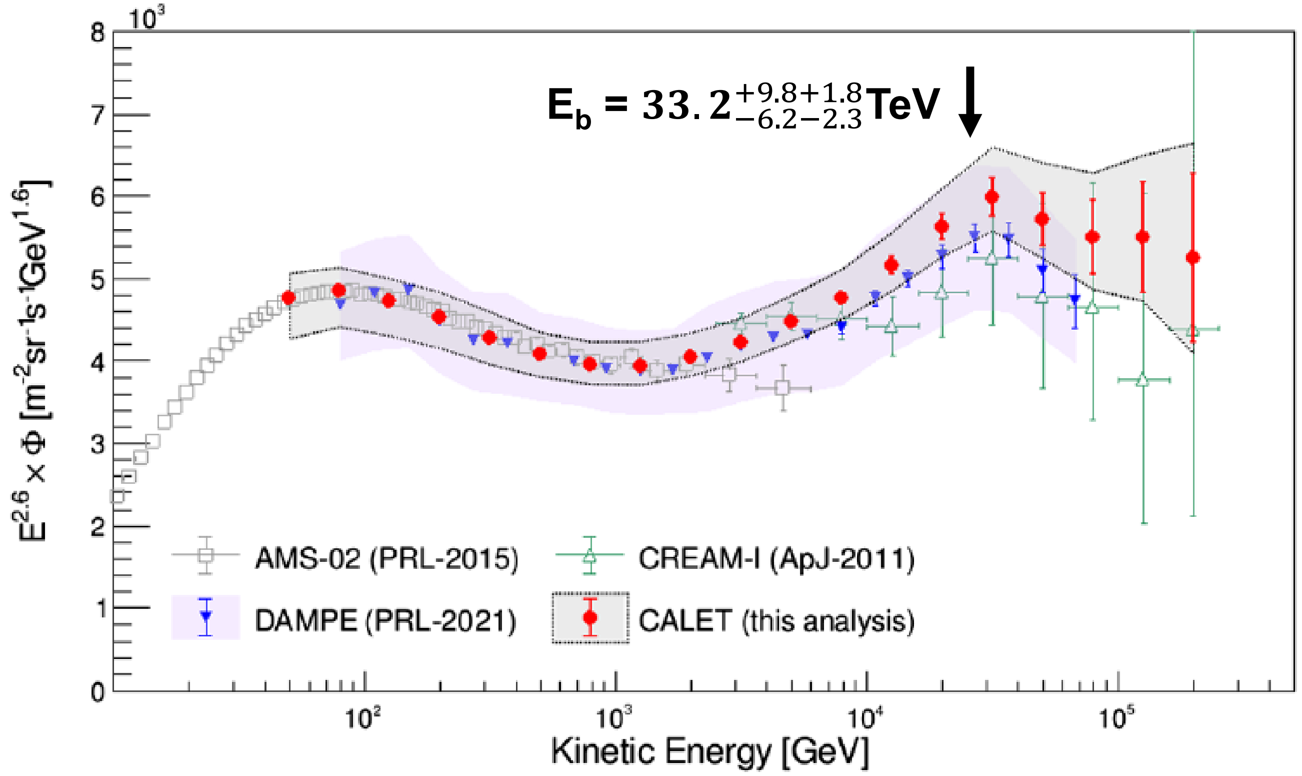
Acceleration limit:
$E_{max\_z} = Z \times E_{max\_p}$,

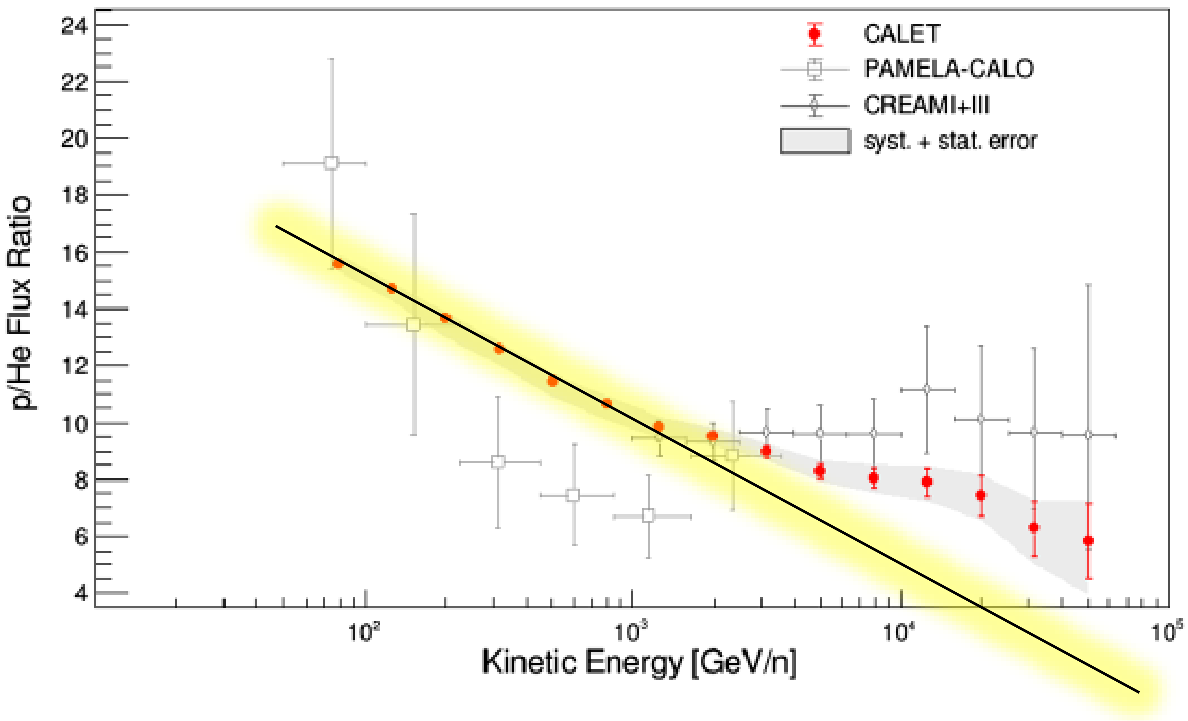
Pop 0	E_{max_p} = 400 GV
Pop 1	E_{max_p} = 50 TV
Pop 2	E_{max_p} = 4 PV
Pop 3	E_{max_p} = 500 PV

- The spectral hardening at ~ 200 GV and softening ~ 10 TeV could indicate a transition between different types of sources.

CALET Helium (40 GeV – 250 TeV) & p/He ratio

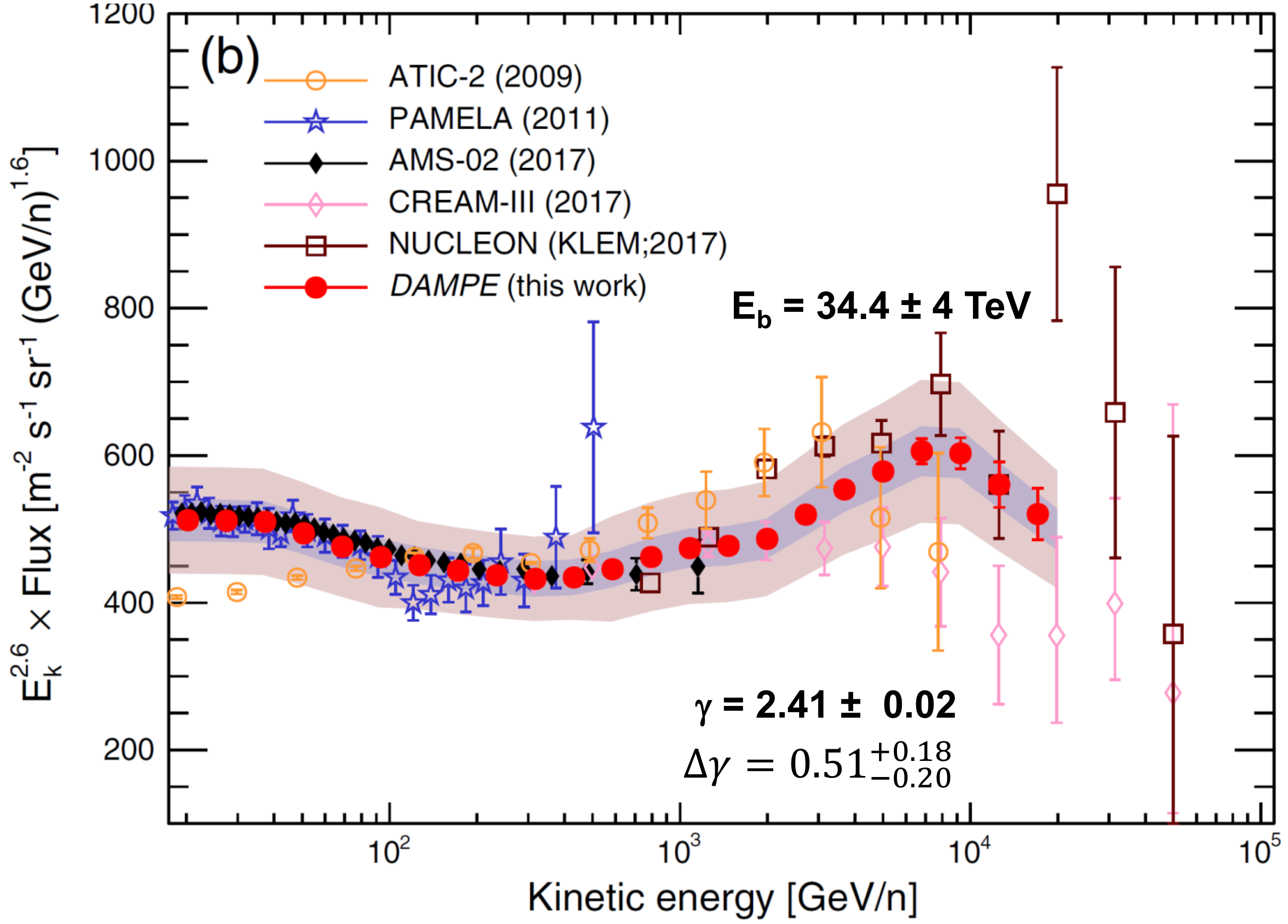
Adriani et al. PRL 130, 171002, 2023





DAMPE Helium Spectrum (70 GeV – 80 TeV)

Alemanno et al. PRL 126, 201102, 2021; Margherita Di Santo for the DAMPE Collaboration PoS(ICRC2021)114



of the softening structure with a Smoothly Broken Power-Law
3PL) in the energy range [6.8 TeV - 80 TeV].

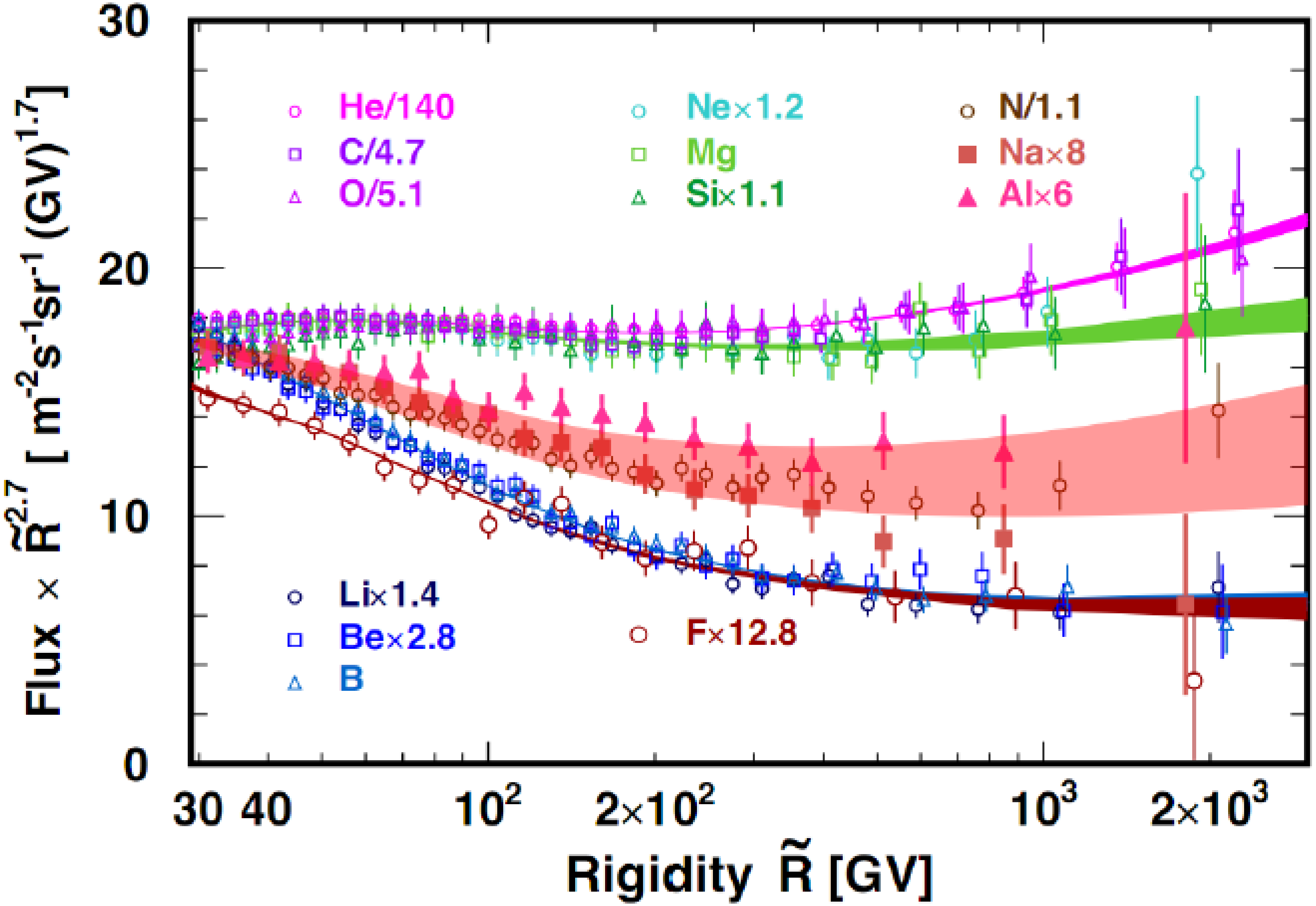
$$\Phi(E) = \Phi_0 \left(\frac{E}{\mathrm{TeV}}\right)^{\gamma} \left[1 + \left(\frac{E}{E_b}\right)^{s}\right]^{\Delta\gamma/\omega}$$

$$E_b = 34.4^{+6.7}_{-9.8}\ \mathrm{TeV}$$
$$\gamma = 2.41^{+0.02}_{-0.02}$$
$$\Delta\gamma = -0.51^{+0.18}_{-0.20}$$
$$s = 5.0\ (fixed)$$

Significance of the softening: $\sim 4.3\,\sigma$

Groups of CR nuclei ($2 \leq Z \leq 14$)

Aguilar et al. (AMS collaboration), PRL 127, 021101, 2021



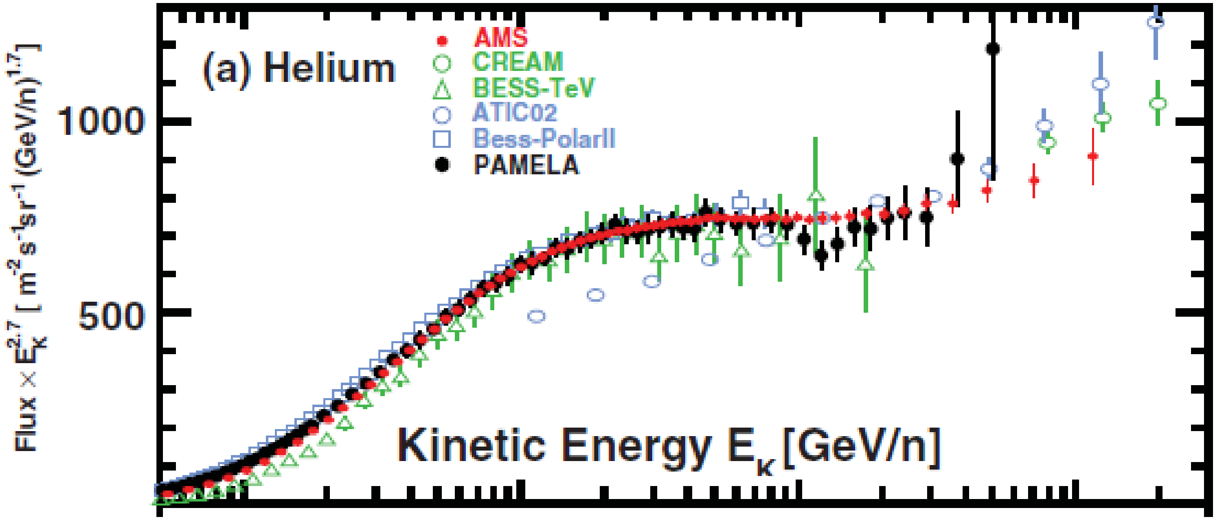
Primary — He-C-O, Ne-Mg-Si

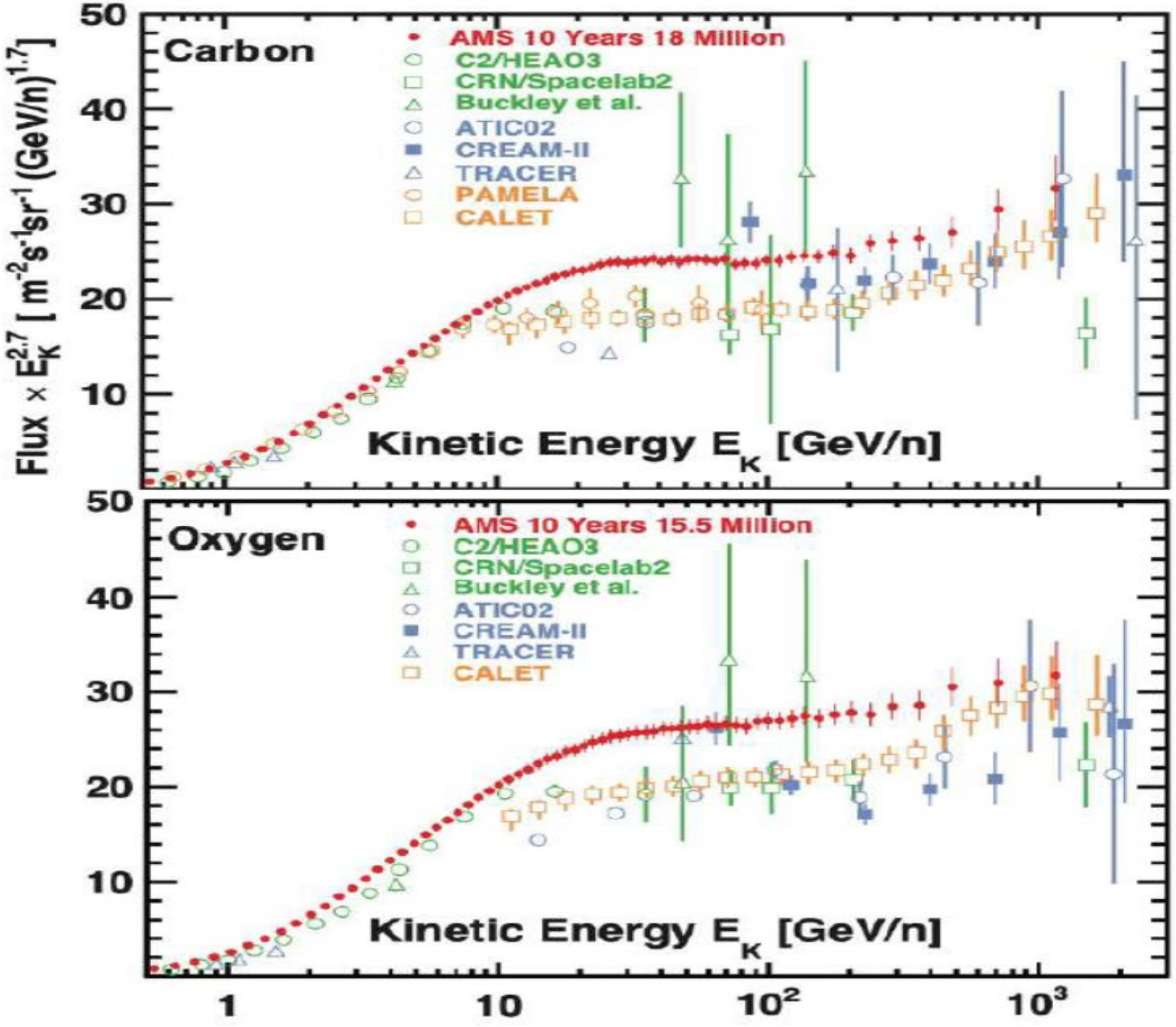
Primary + Secondary — N-Na-Al

Secondary — Li-Be-B, F

Helium, Carbon, and Oxygen (~ 2 GV – 3 TV)

Aguilar et al., PRL 119, 251101 (2017); Gast for the AMS Collaboration PoS(ICRC2021)121

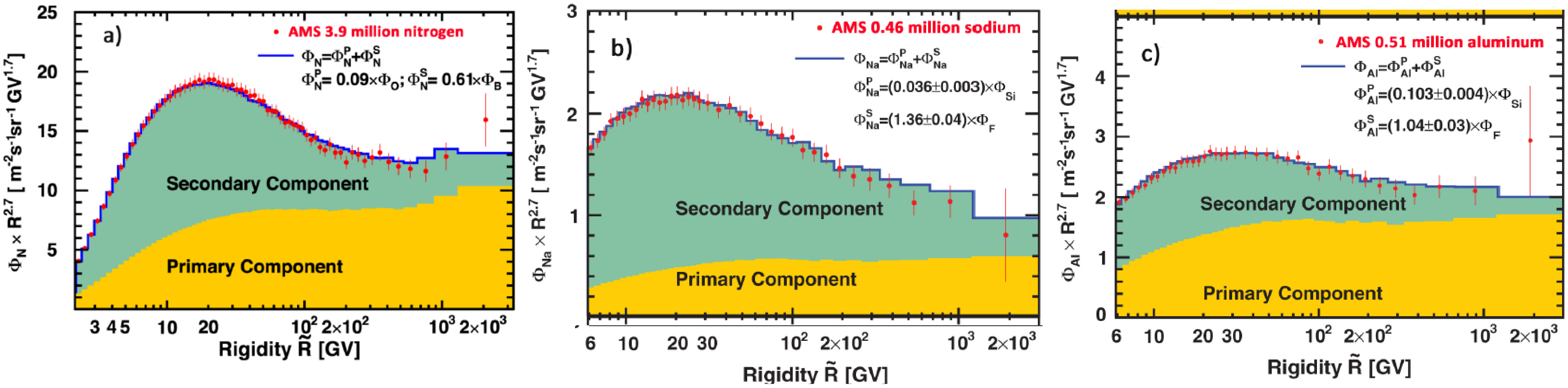




- He, C, and O spectra show identical rigidity dependence above 60 GV.
  - He/O = 27.6 ± 0.6
  - C/O = 0.91 ± 0.02
- The spectra progressively harden above 200 GV.

Nitrogen, Sodium and Aluminum

Aguilar et al., PRL 127, 021101, 2021; Cheng Zhang et al. PoS(ICRC2021)106; Zhen Liu et al. PoS(ICRC2021)110

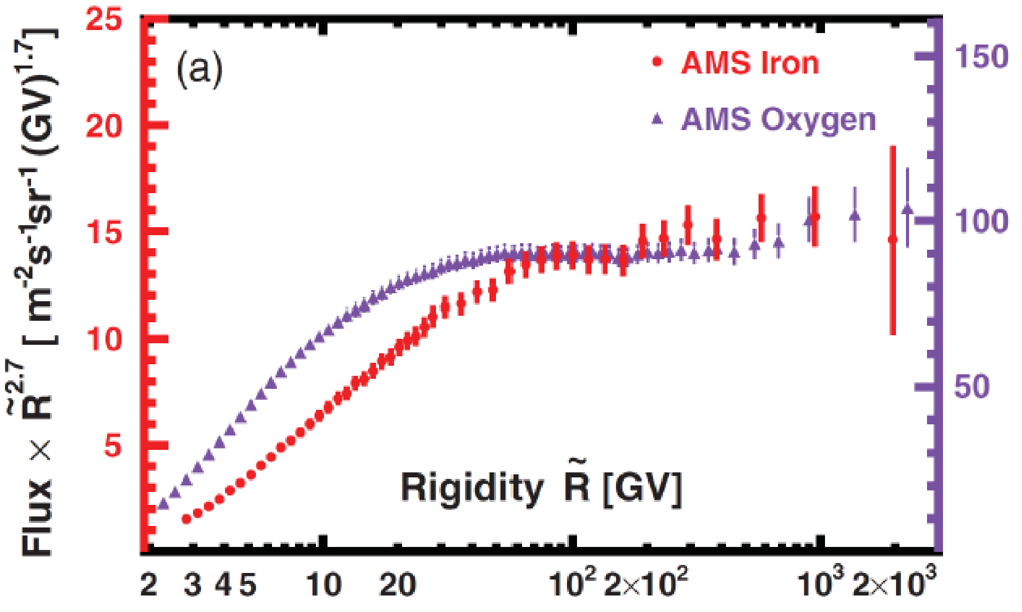


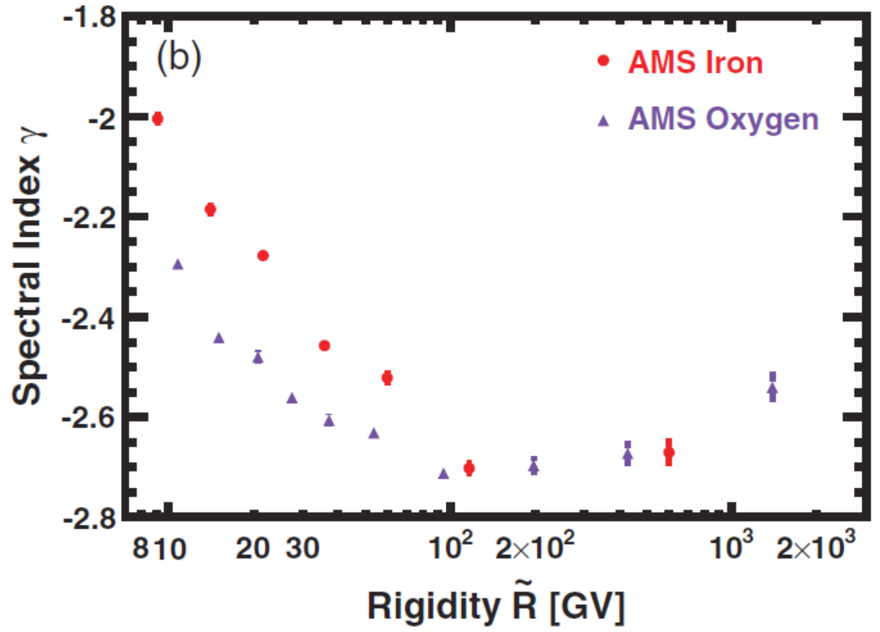
- Na and Al, together with N, belong to a distinct cosmic ray group and are the combinations of primary and secondary cosmic rays.
- The fraction of the primary component increases with rigidity for the N, Na, and Al fluxes and becomes dominant at the highest rigidities.
  - The abundance ratios Na/Si = 0.036 ±0.003 and Al/Si = 0.103 ± 0.004 at the source independent of cosmic ray propagation.

Iron (2.65 GV to 3 TV)

Yao Chen for the AMS Collaboration PoS(ICRC2021)129; M. Aguilar et al., PRL 126, 041104 (2021)

Based on 8.5 years of data (2011-2019)



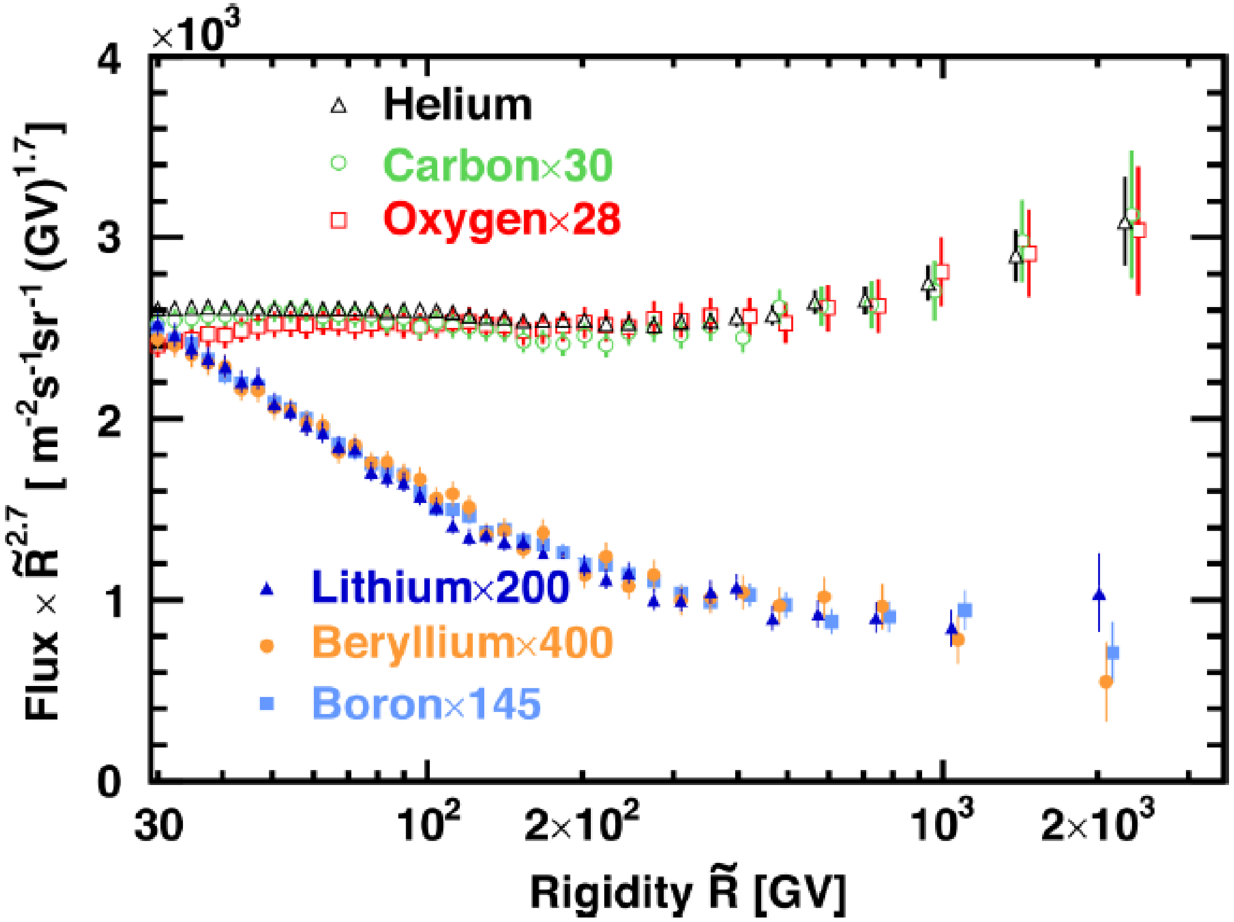


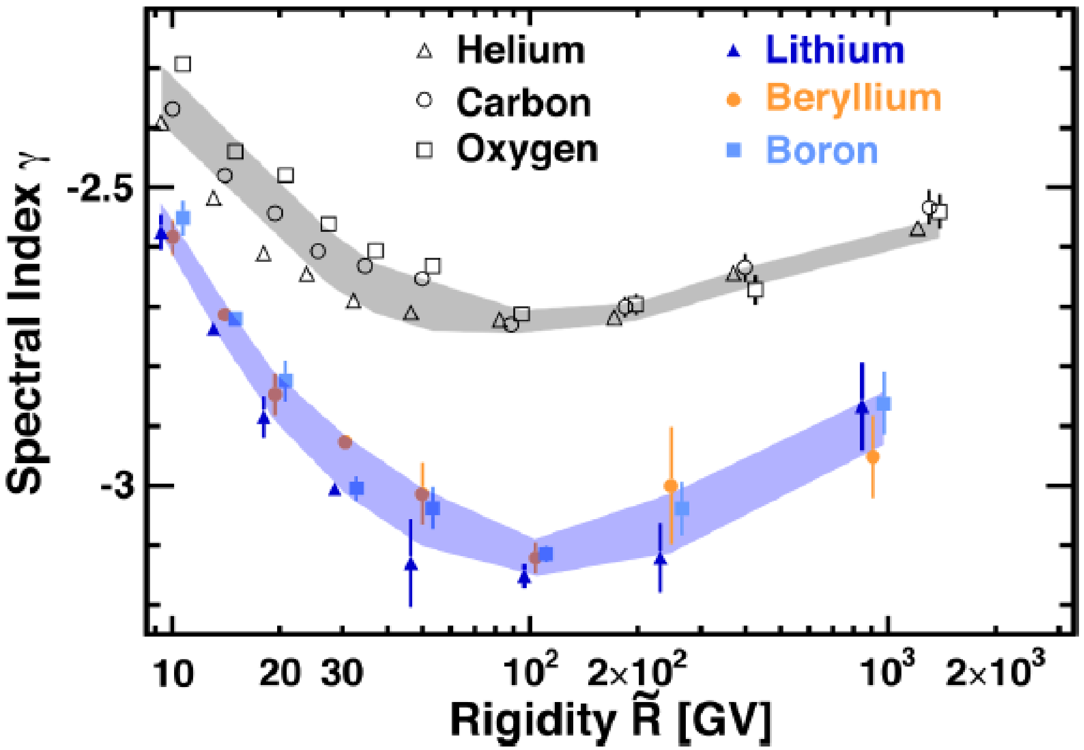
- Fe rigidity spectrum is identical to the primary cosmic ray He, C, and O spectra above 80.5 GV.
  - Fe/O = 0.155 ± 0.006
- Fe belong to the same class of primary cosmic rays as He, C, and O, which is different from the Ne, Mg, and Si class.
- The same hardening above ~200 GV.

Note CALET reported Fe (10 GeV/n - 2 TeV/n) with a single power law (γ = 2.60 ± 0.03) Adriani et al. PRl 126, 241101 (2021)

Light nuclei: Lithium, Beryllium, Boron vs He, C, O

Henning Gast for AMS



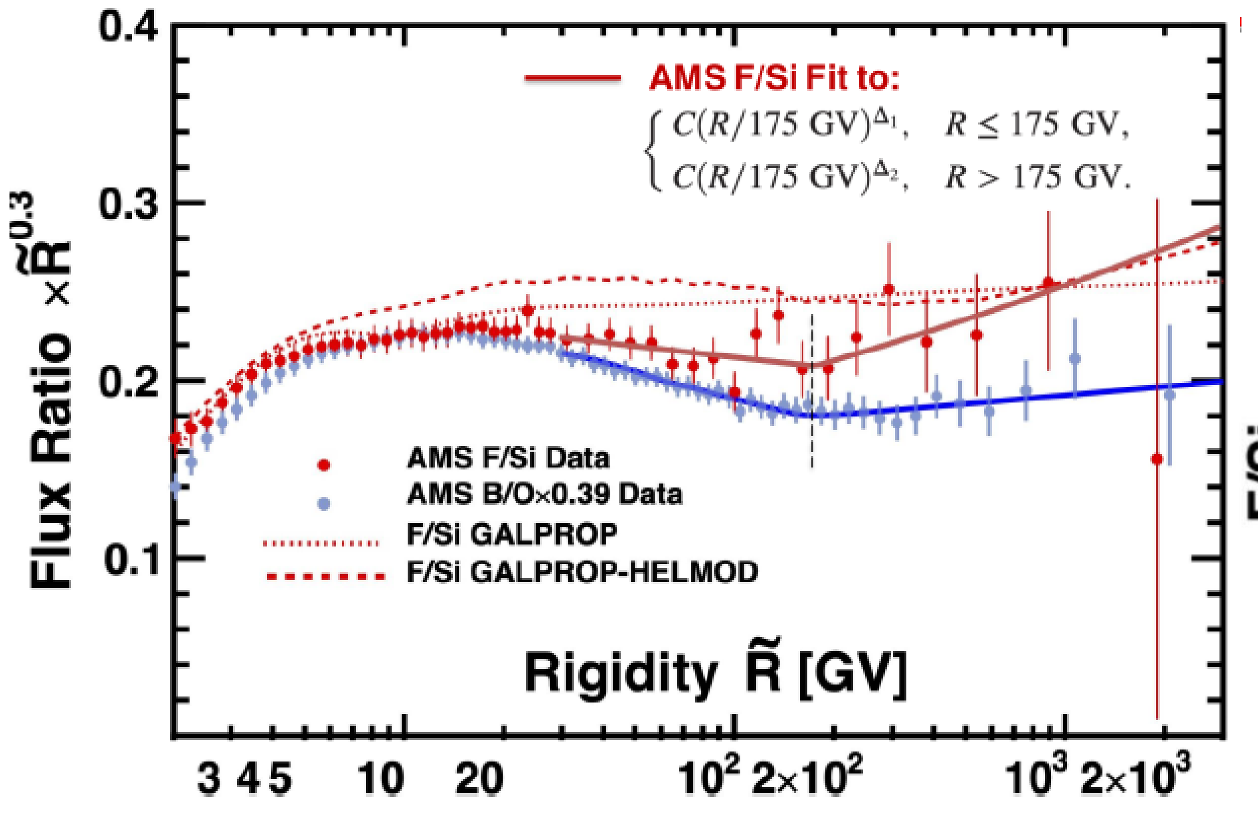


Above ~200 GV, the light secondaries Li, Be, B harden more than the primaries He, C, O.

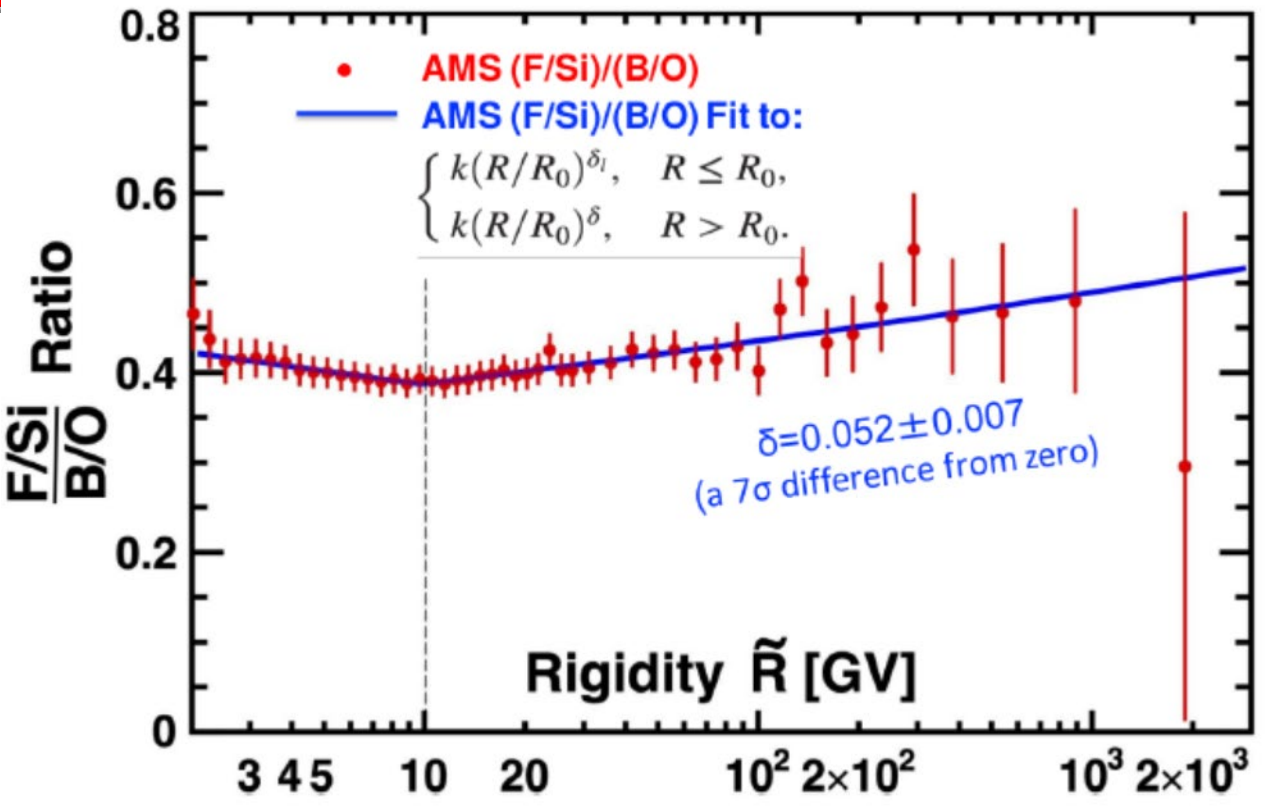
Average hardening of secondary/primary ratios: $\Delta_{[192-3300]\,\mathrm{GV}} - \Delta_{[60.3-192]\,\mathrm{GV}} = 0.140 \pm 0.025$

Heavy secondary: Flourine

Qi Yan
for AMS



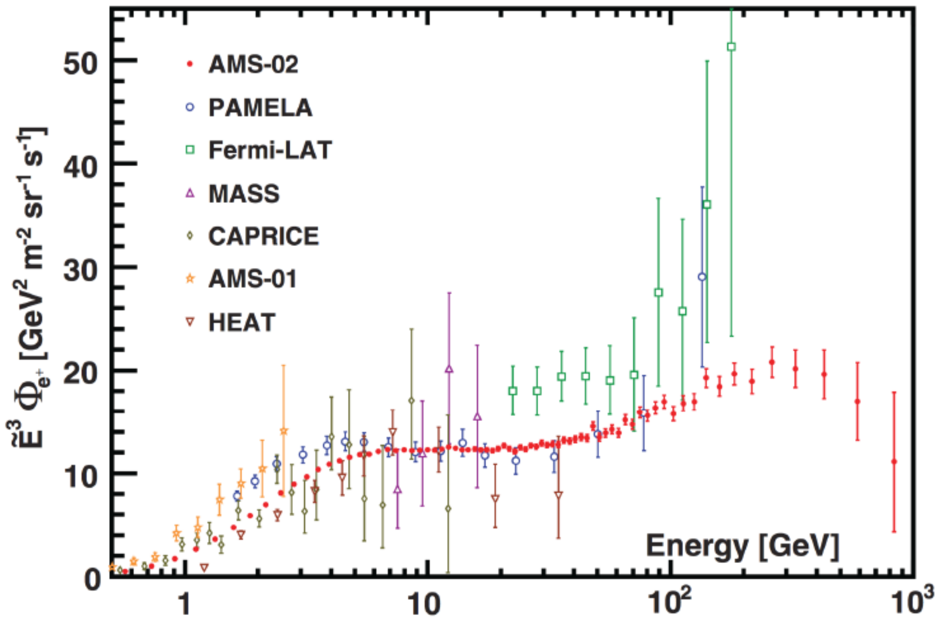
Above 175 GV, the F/Si ratio exhibits a hardening ($\Delta_2^{F/Si} - \Delta_1^{F/Si}$) = 0.15±0.07, compatible with the AMS result on the hardening of the lighter secondary/primary flux ratios.

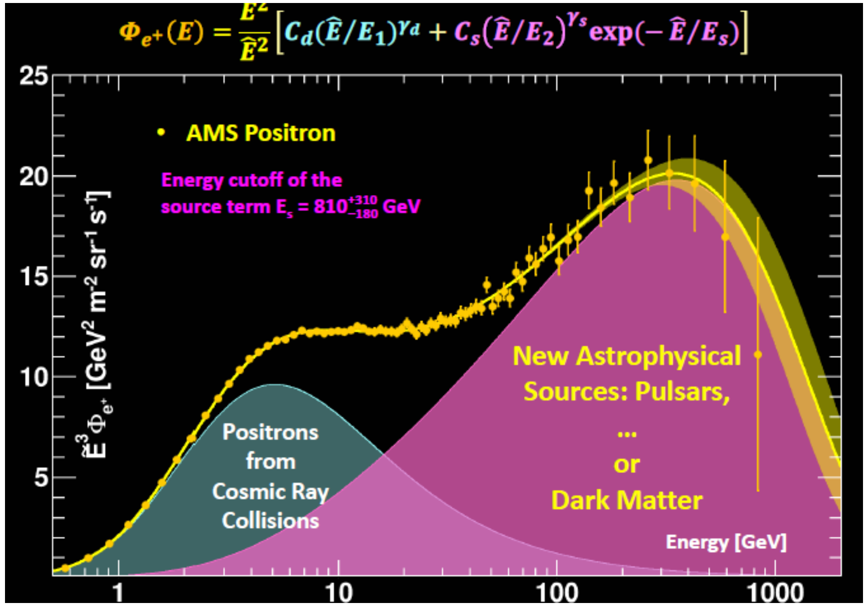


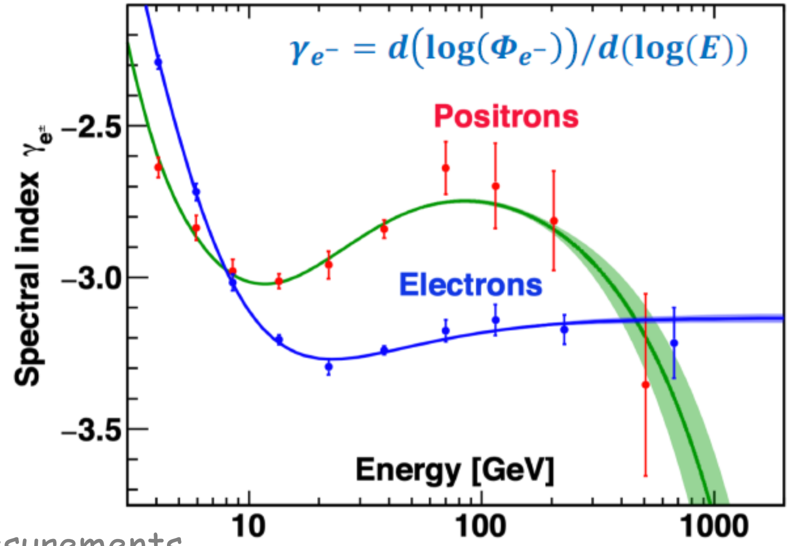
Above 10 GeV, the (F/Si) / (B/O) ratio can be described by a single power law with δ=0.052±0.007, revealing that the propagation properties of heavy cosmic rays, from F to Si, are different from those of light cosmic rays, from He to O.

Positrons and Electrons

Aguilar et al., Phys. Rev. Lett., 122, 101101, 2019; Z. Weng et al., PoS(ICRC2021)122D; Krasnopevtsev et al., PoS(ICRC2021)111

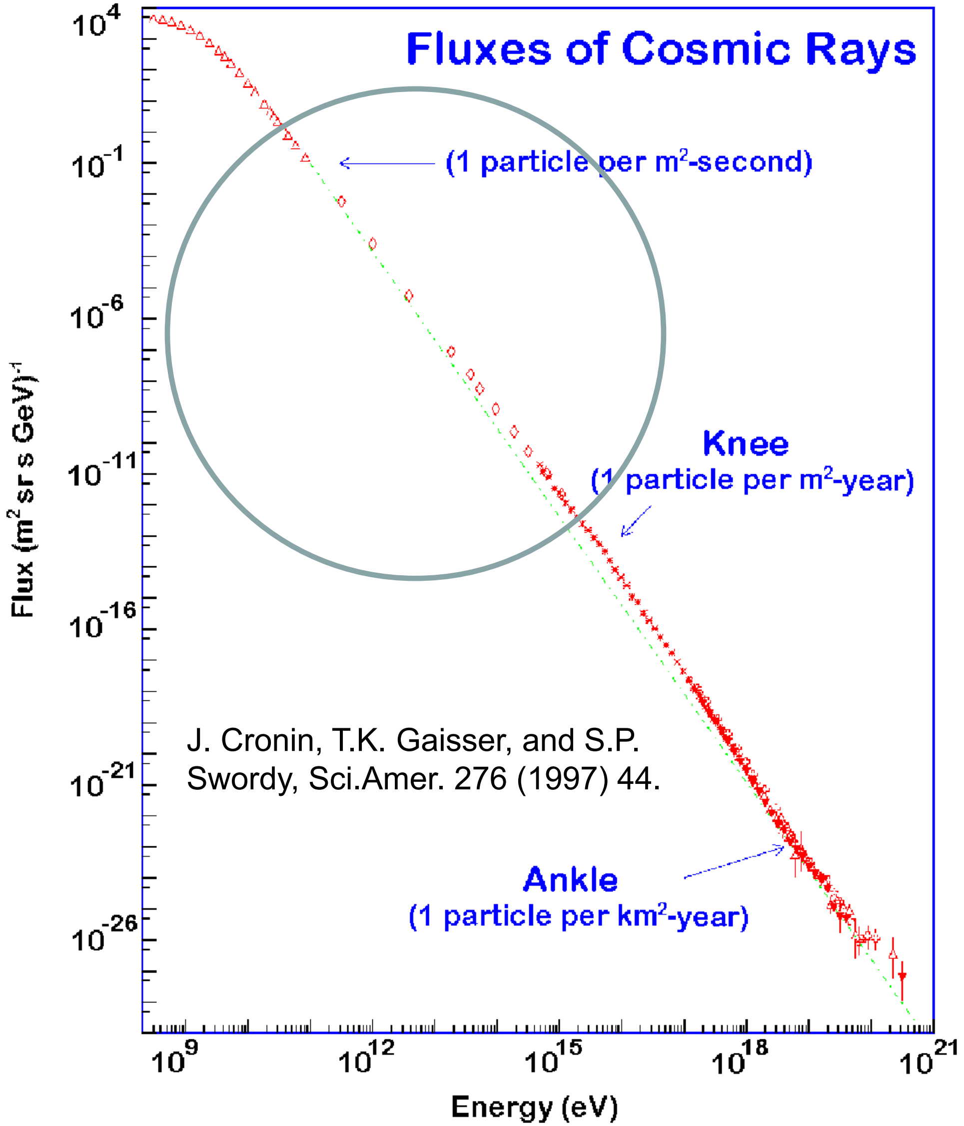


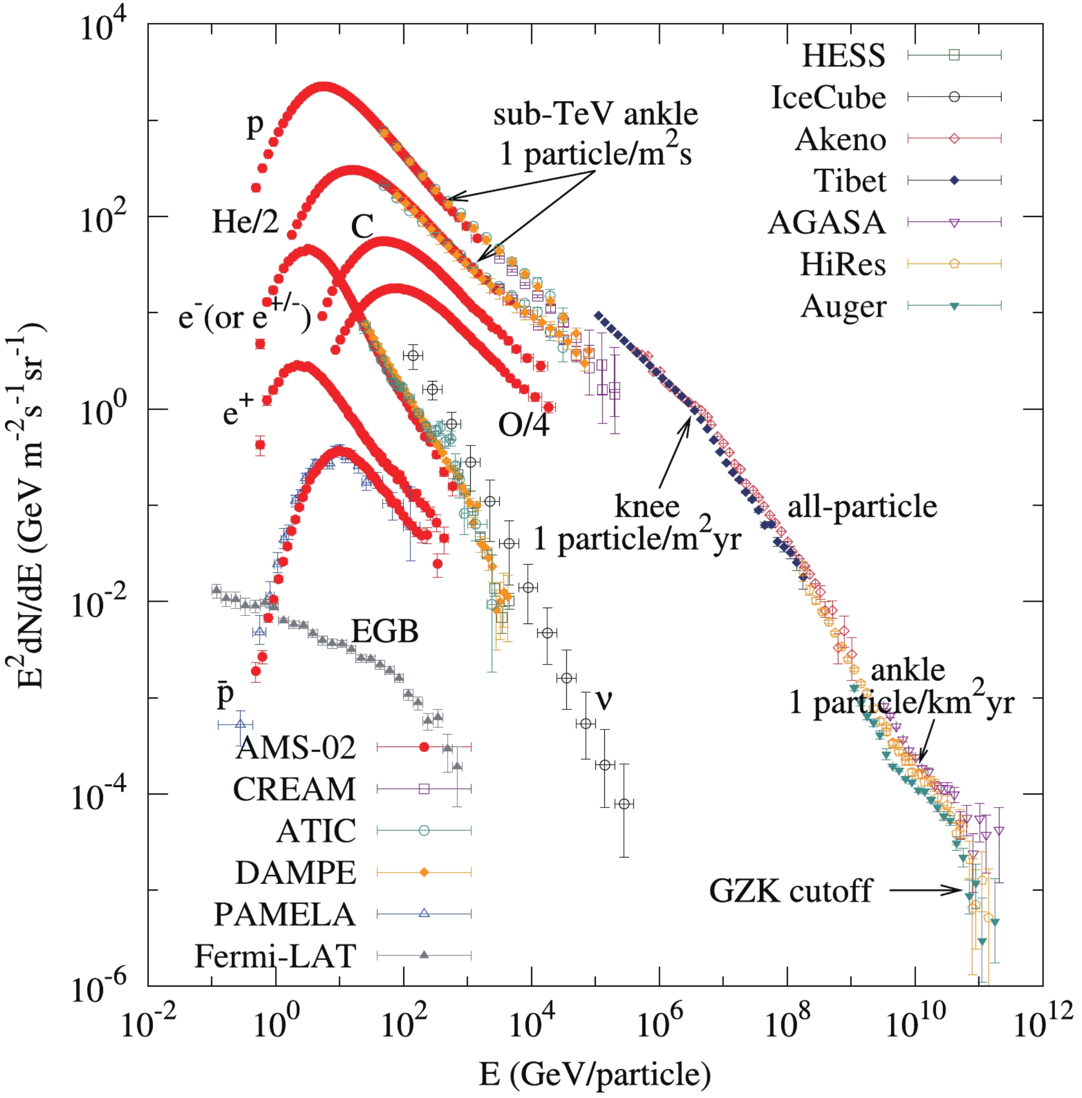




- An excess in positron spectrum > 25 GeV with a peak at ~284 GeV
- The positron flux is well described with a sum of a diffuse term and an additional source with an exponential cutoff at 810 GeV
- The electron spectrum does not show such a cutoff.
- Electron spectrum hardening > 42 GeV

Recent experiments fill the data gap





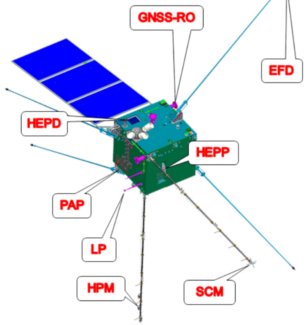
S. Liu et al., Ch. Phys. 46/3 (2022) 030004

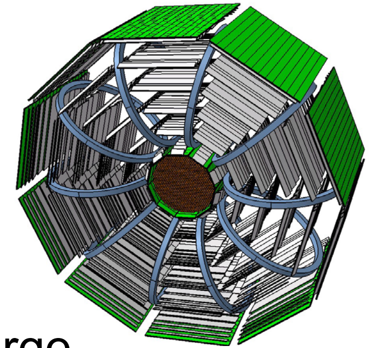
Summary

- Significant advances in CR measurements have been made in recent years
  - ✓ An excess in positron spectrum.
  - ✓ Spectral hardening above ~200 GV.
  - ✓ Spectral softening at ~10 TeV/n.
  - ✓ Harder He spectrum than the proton spectrum.
  - ✓ Different groups of cosmic rays
- These results contradict the traditional view that a simple power law can represent CR without deviations below the “knee”, and they should be incorporated in a “standard” model for CR origin/propagation/acceleration.
- Many open questions remain:
  - What is the origin of the excess positrons above 25 GeV?
  - What is the origin of the hardening in the CR nuclei above ~200 GV?
  - What is the origin of a bump like structure (softening) at ~10 TeV/n?

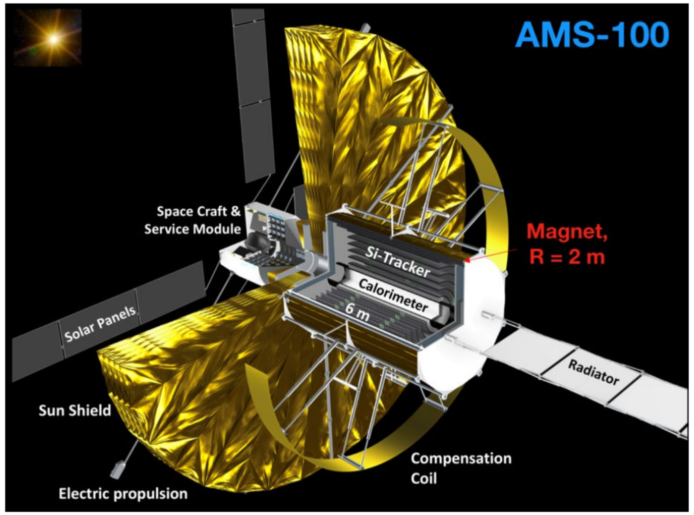
Future Outlook

China Seismo-Electromagnetic Satellite (CSES-2)
3 - ~100 MeV e, p, light nuclei





Antimatter Large Acceptance Detector In Orbit (ALADInO)
10 m^{2}sr
MDR 20 TV



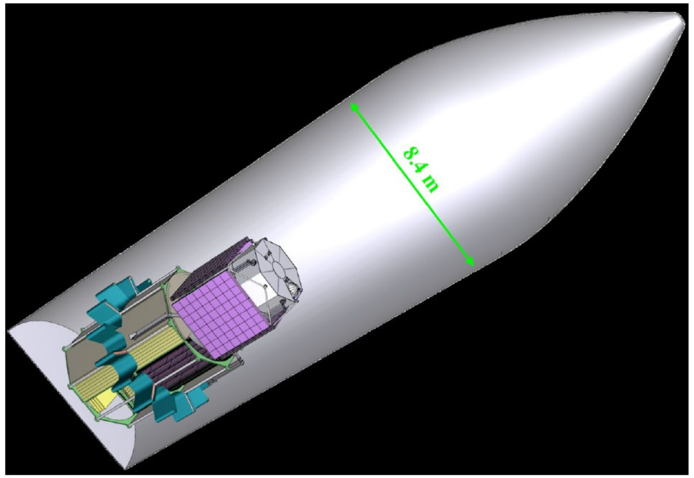
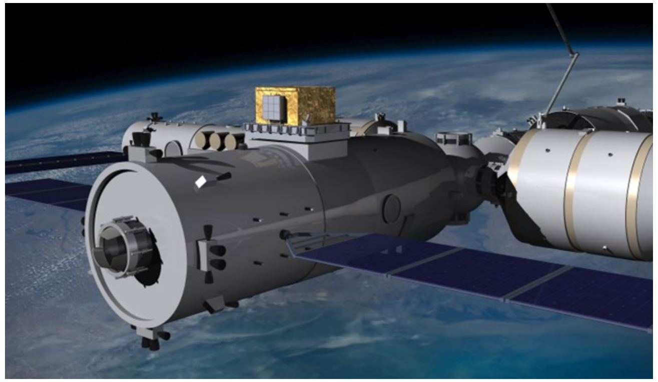
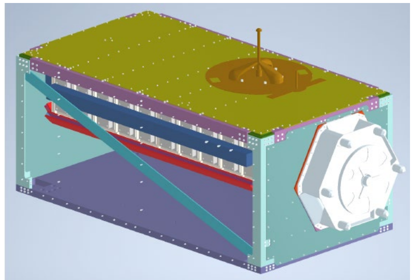


Figure 2: AMS-100 launch configuration in an SLS-Block 2 fairing. The compensation coil, the sunshield, the solar cells, and the electric propulsion system are folded up. The service module is located at the top for structural reasons.

The High Energy cosmic-Radiation Detection (HERD) facility ~ 2027





Trans-Iron Galactic Element Recorder for the International Space Station (TIGERISS)
5B - 82Pb

General Antiparticle Spectrometer (GAPS)
dbar < 0.25 GeV/n