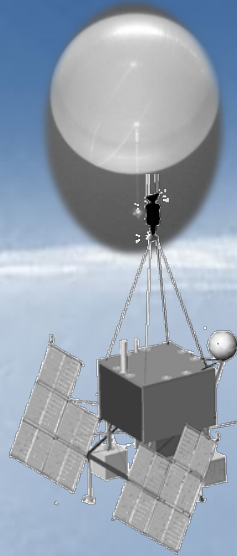
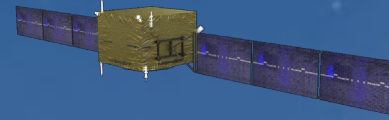
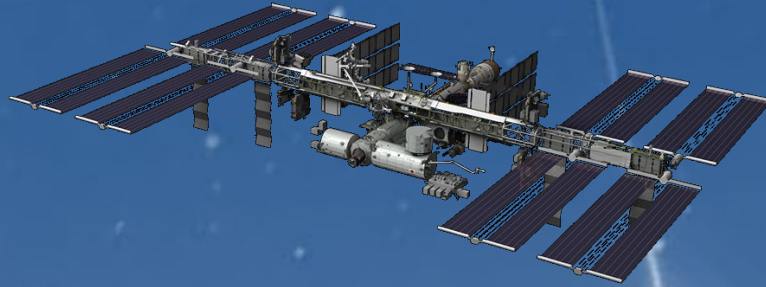
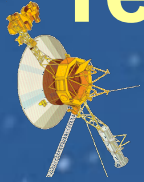
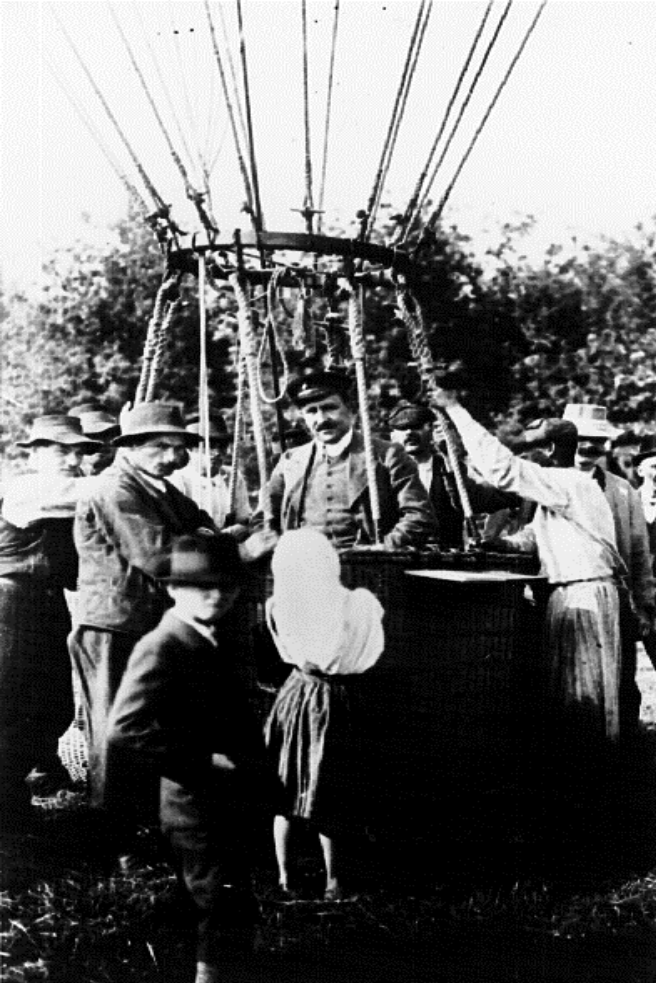


TeV cosmic ray: measurements and interpretation

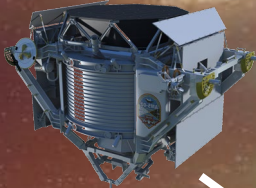


Eun-Suk Seo, Ph.D.
Professor of Physics
University of Maryland

Discovery of Cosmic Rays



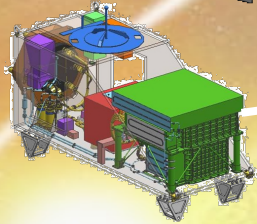
- In 1912 Victor Hess discovered cosmic rays with an electroscope onboard a balloon
 - Reached only ~ 17,000 ft but measured an increase in the ionization rate at high altitude (1936 Nobel Prize in Physics for this work)
- Discoveries of new particles in cosmic rays
 - Positrons by Anderson in 1932 (Nobel '36)
 - Muons by Neddermeyer & Anderson in 1937
 - Pions by Powell et al. in 1947 (Nobel' 50)
 - And many more.....
- Man-made particle accelerators were built to investigate the properties of newly discovered particles, marking the beginning of particle physics and nuclear physics.



AMS-02
5/16/11



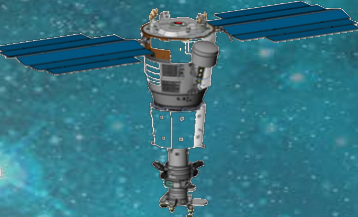
ISS-CREAM
8/14/17



CALET
8/19/15

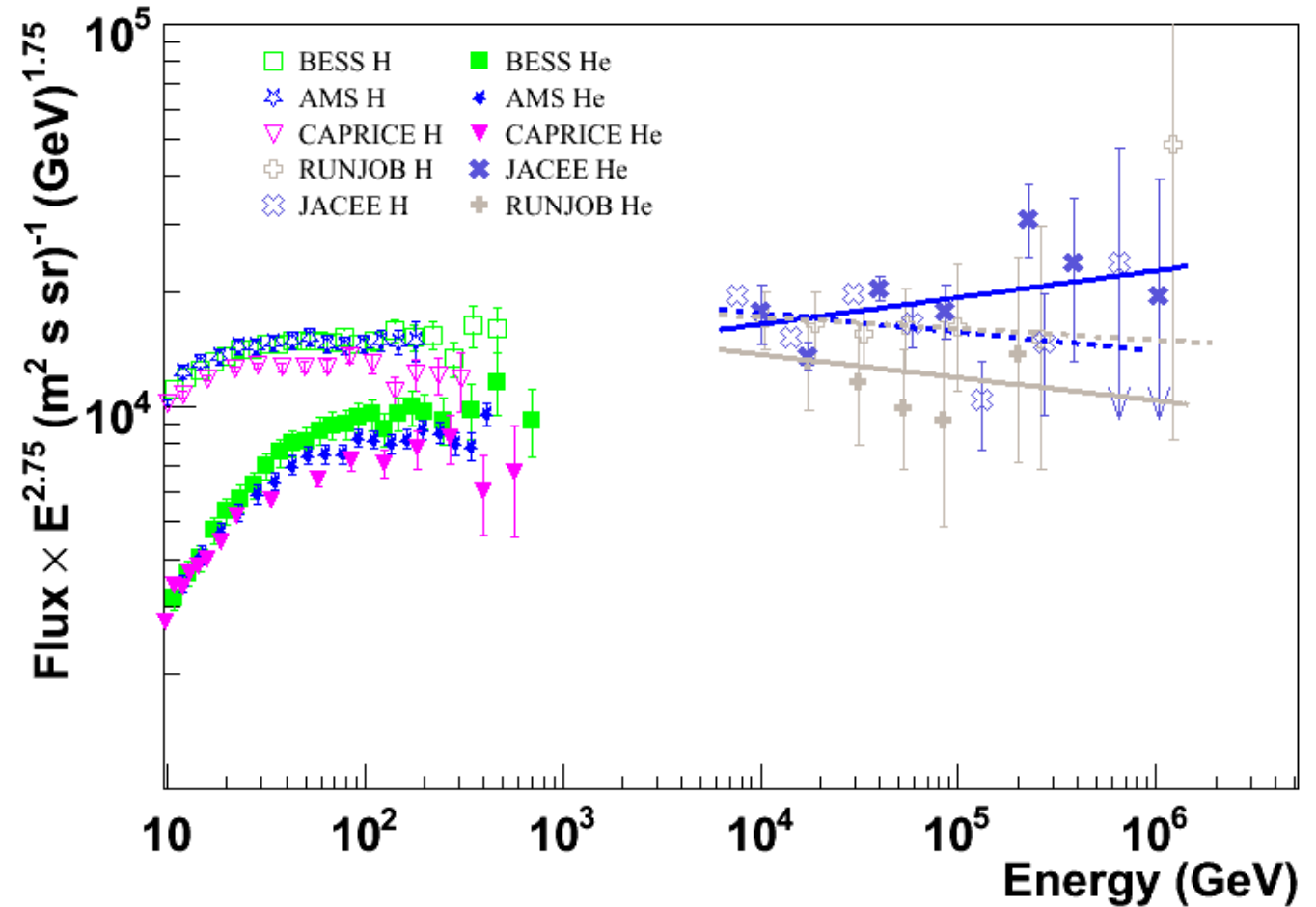
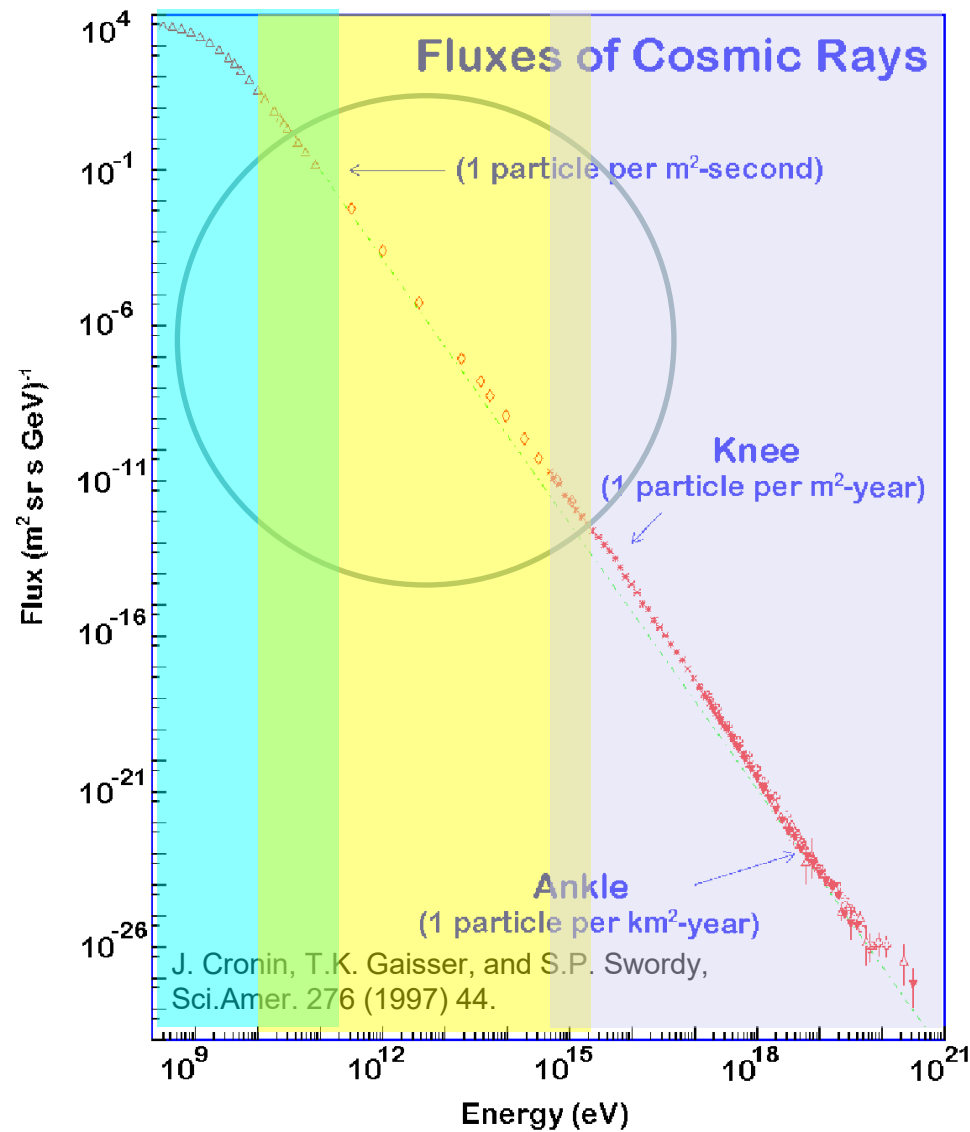


DAMPE
12/17/15

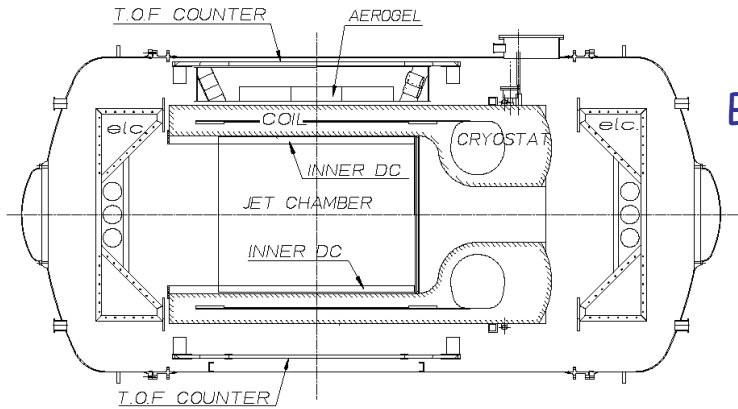


NUCLEON
12/26/14

Energy-Dependent Detection and Measurement Techniques

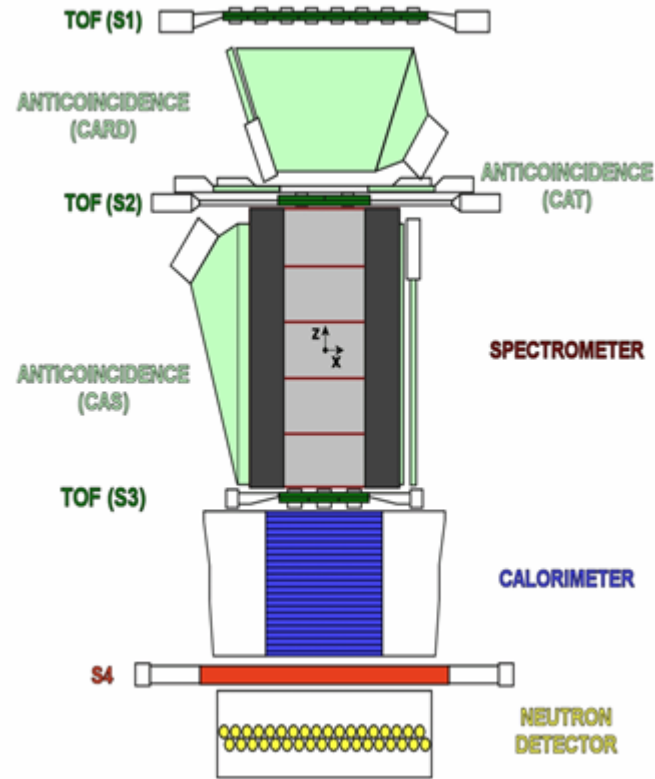


Magnet Spectrometers

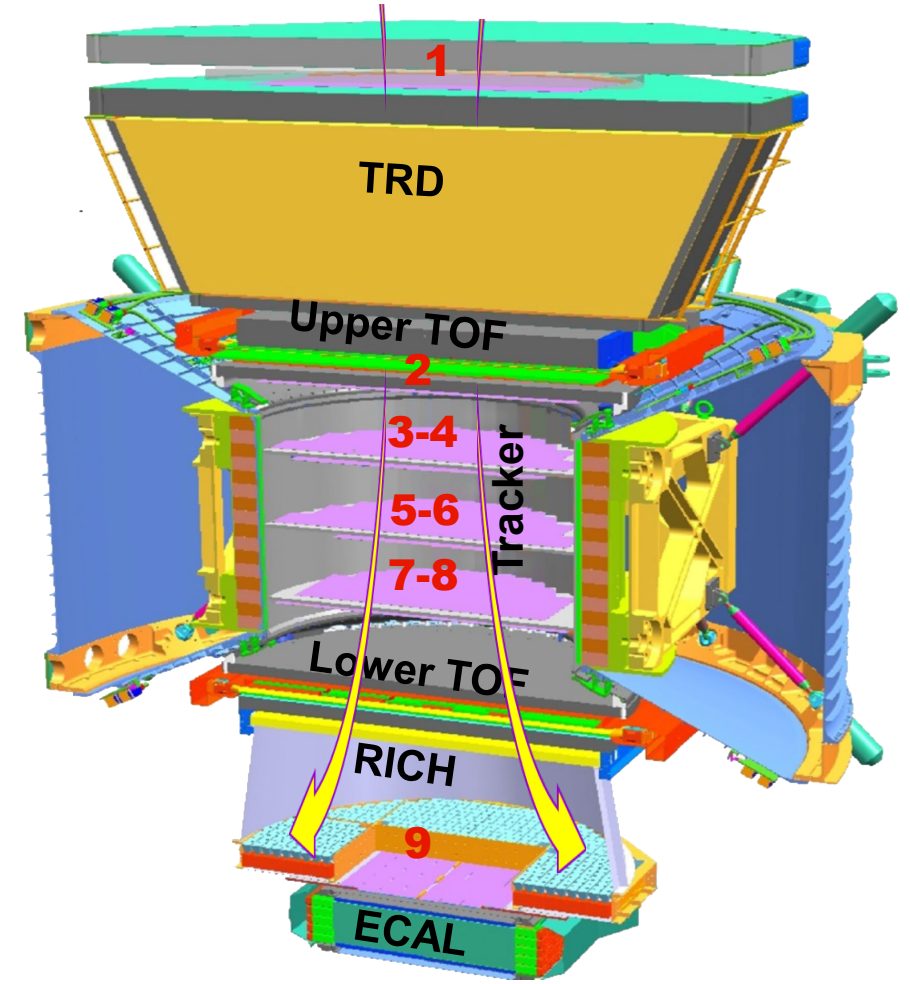


BESS

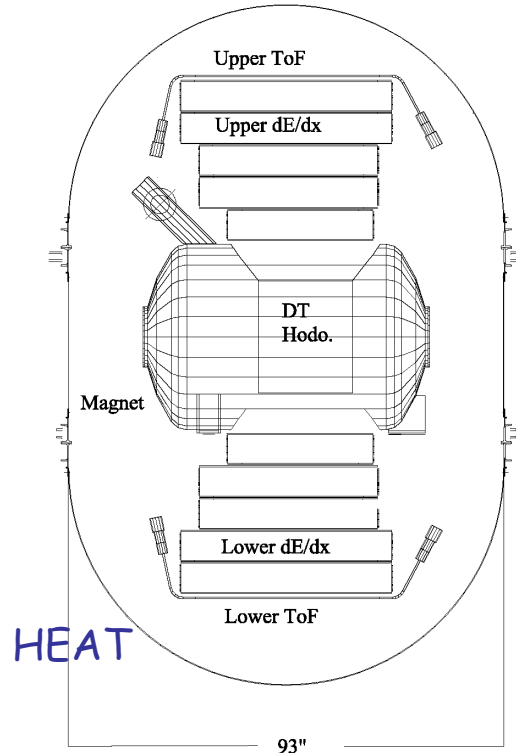
$$r = \frac{mv}{qB}$$



PAMELA

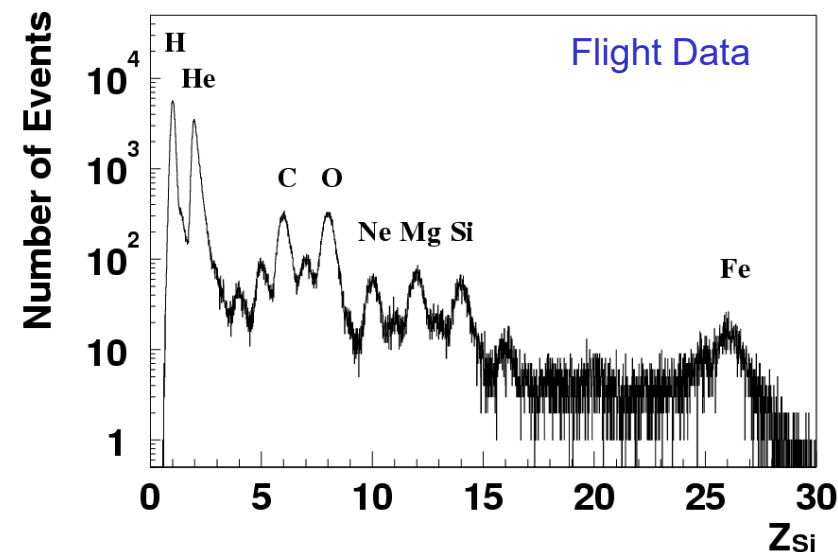
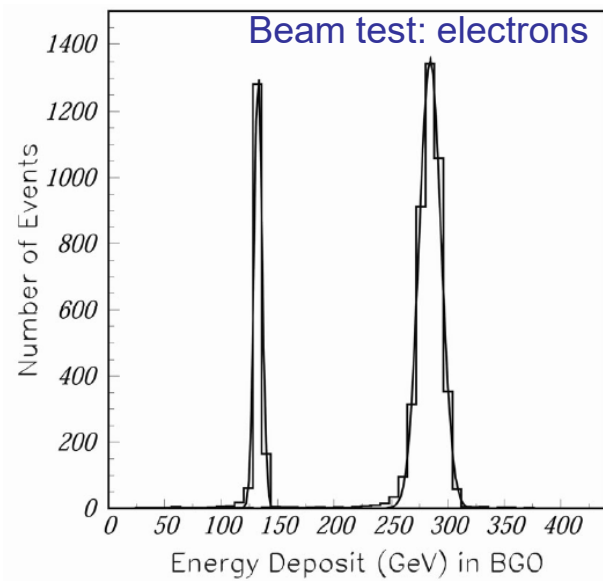
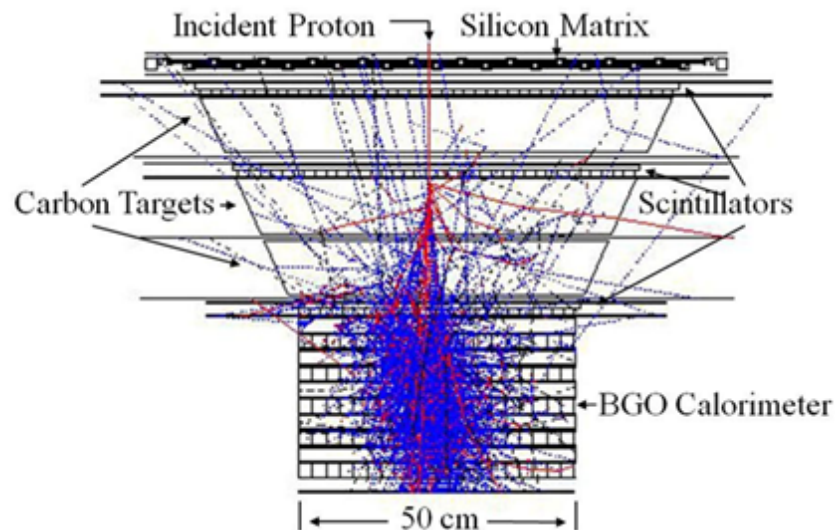


AMS



HEAT

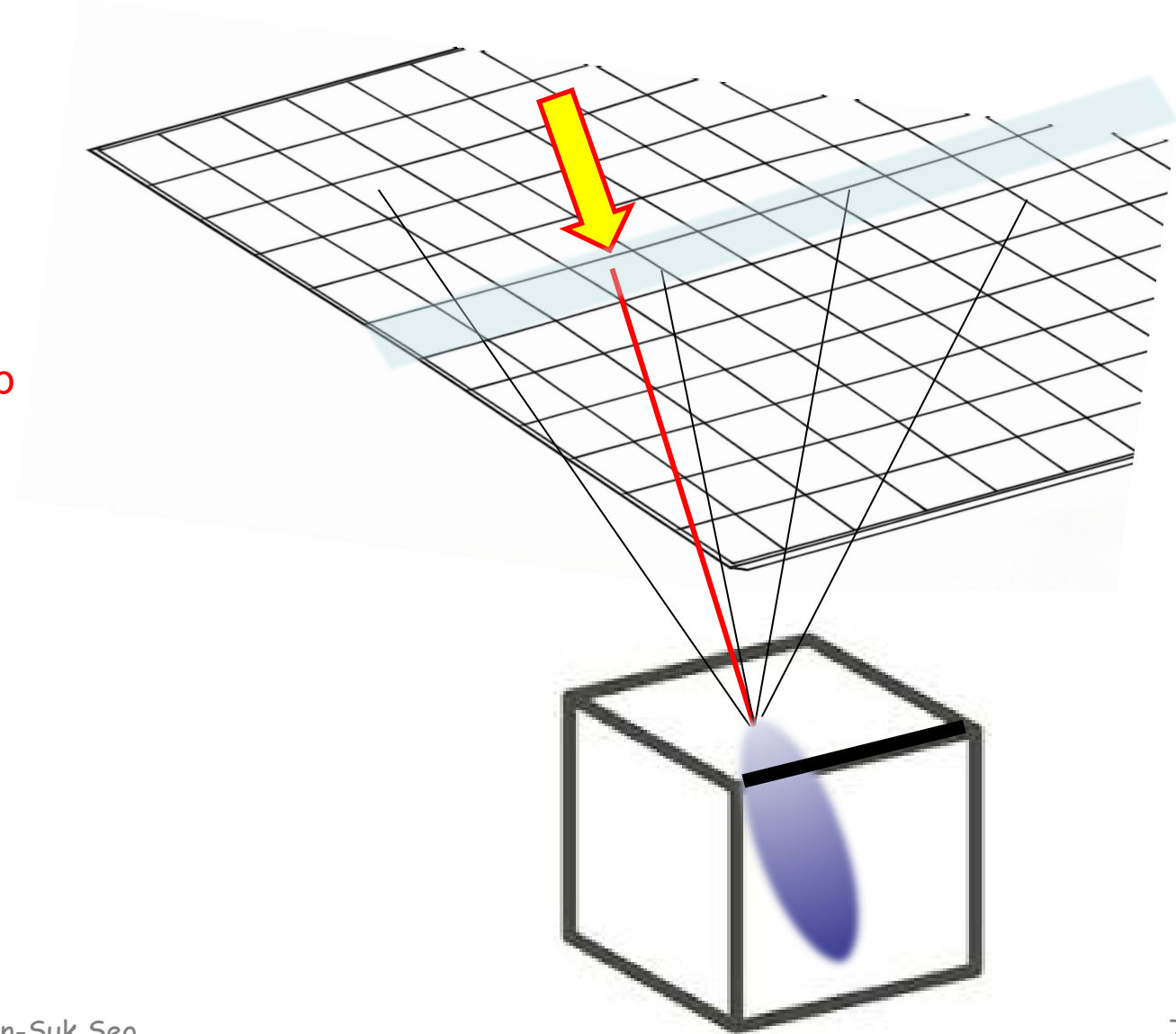
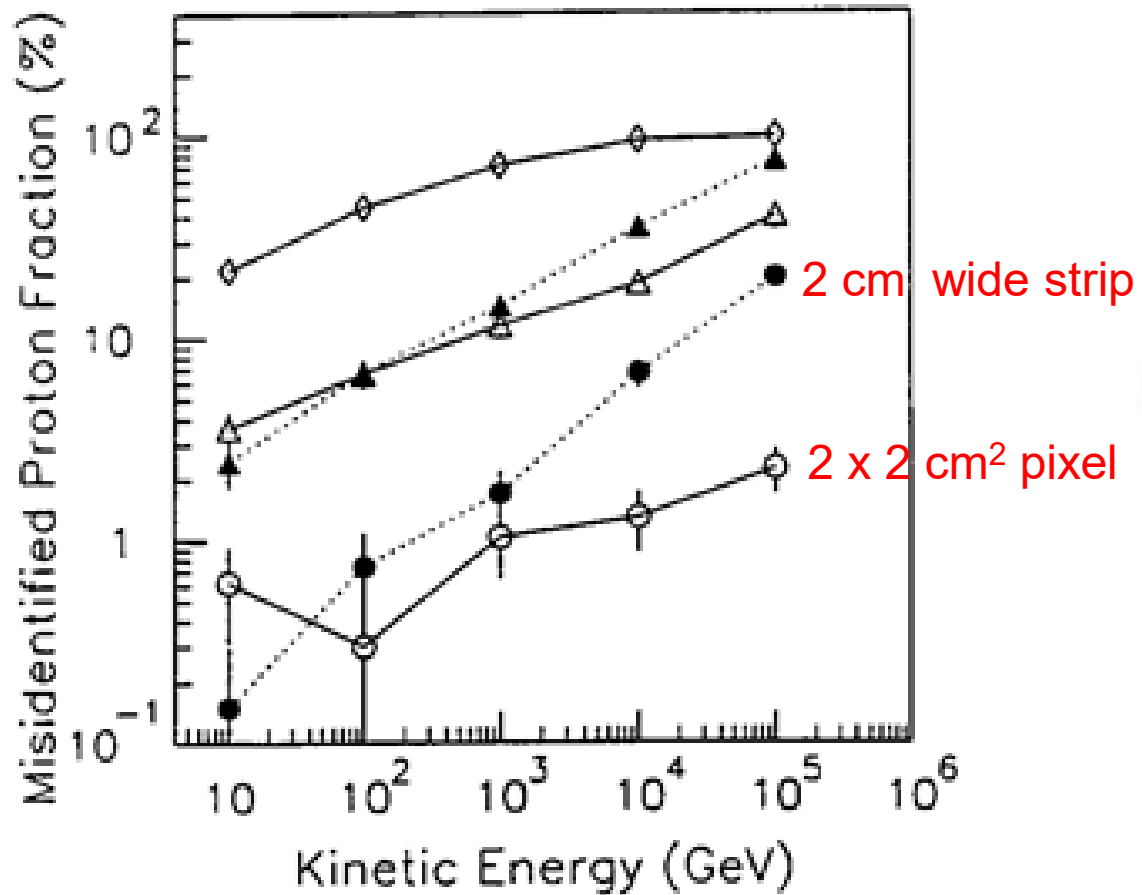
Seo et al. Adv. in Space Res., 19 (5), 711, 1997; Ganel et al. NIM A, 552(3), 409, 2005



- Beam measurements for 150 GeV electrons show 91% containment of incident energy, with a resolution of 2% at 150 GeV
- Proton containment ~38%

Backscatter Effect

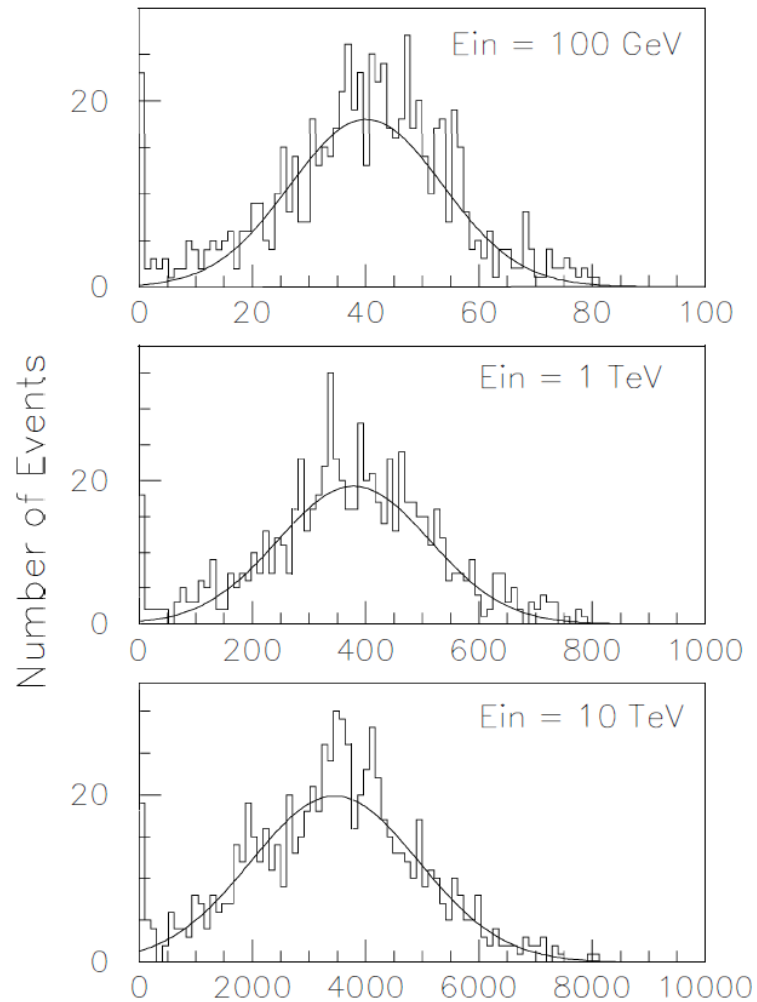
Fraction of misidentified protons



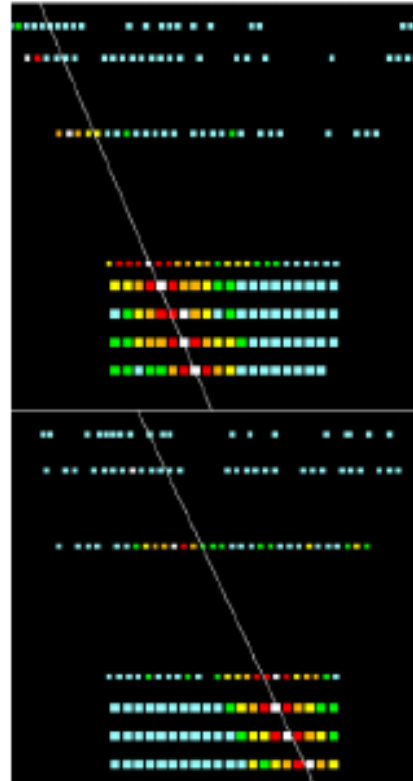
Seo et al. Proc. SPIE 2806, 134-144, 1996

Calorimeter Performance

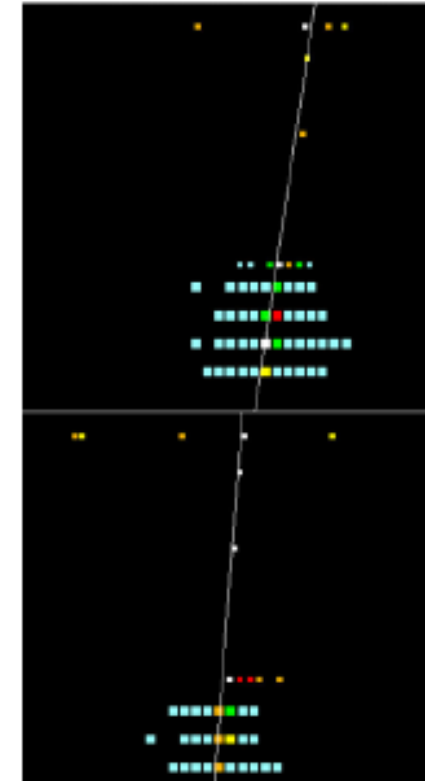
Energy deposit



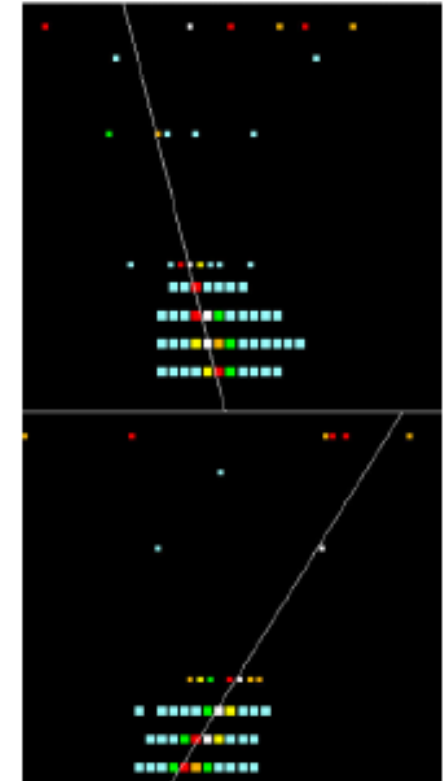
proton



electron



gamma



Reject all but 1 in 5000 protons while keeping 84% of the electrons

Surprising Electron ($e^- + e^+$) Excess

nature International weekly journal of science

Cited > 200 times in ~ 9 mo

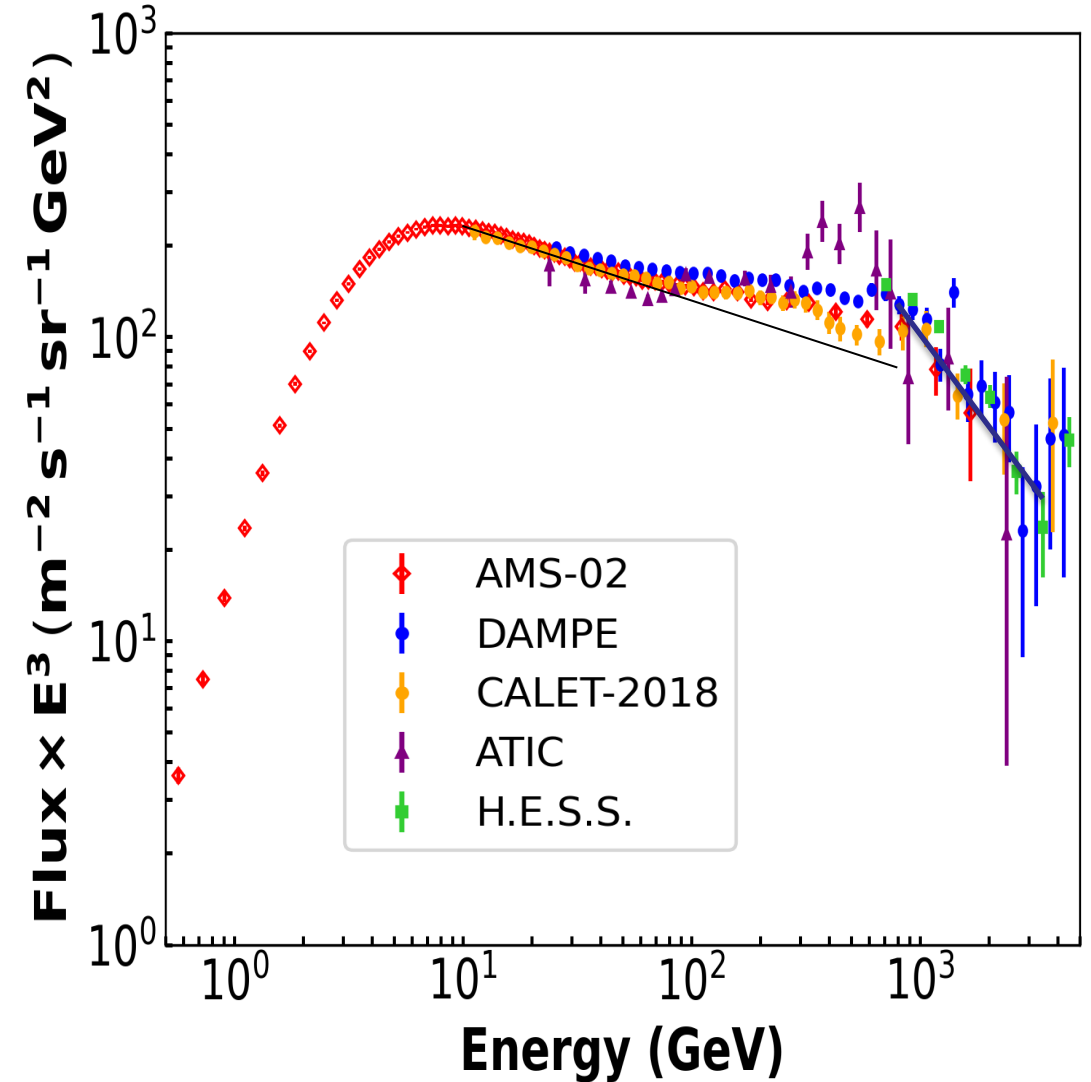
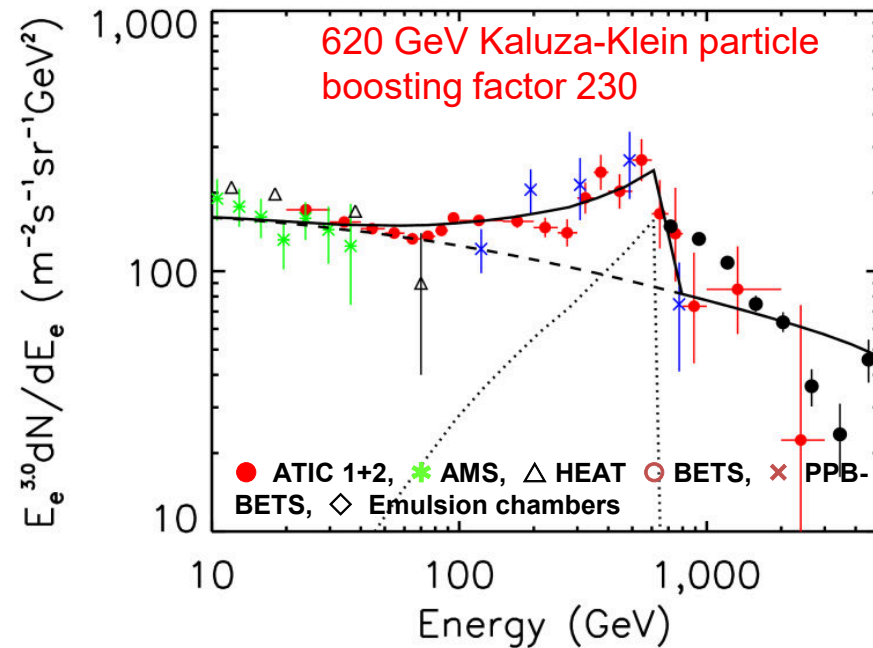
Letter

Nature **456**, 362–365 (20 November 2008) | doi:10.1038/nature07477; Received 23 May 2008; Accepted 1 October 2008

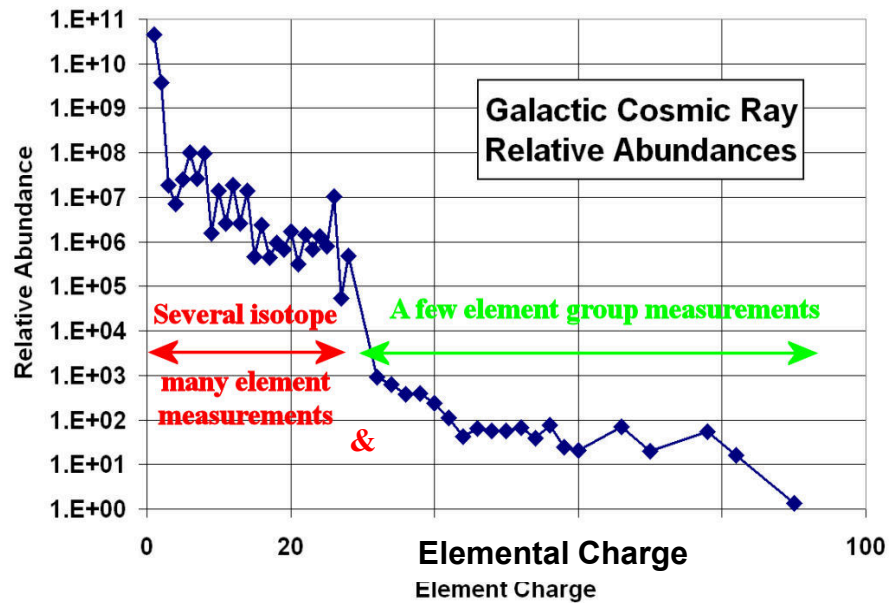
An excess of cosmic ray electrons at energies of 300–800 GeV

J. Chang^{1,2}, J. H. Adams³, H. S. Ahn⁴, G. L. Bashindzhagyan⁵, M. Christl³, O. Ganel⁴, T. G. Guzik⁶, J. Isbert⁶, K. C. Kim⁴, E. N. Kuznetsov⁵, M. I. Panasyuk⁵, A. D. Panov⁵, W. K. H. Schmidt², E. S. Seo⁴, N. V. Sokolskaya⁵, J. W. Watts³, J. P. Wefel⁶, J. Wu⁴ & V. I. Zatsepin⁵

1. Purple Mountain Observatory, CAS, 2 West Beijing Road, Nanjing 210008, China
 2. Max Planck Institute for Solar System Research, 2 Max Planck-Strasse, Katlenburg-Lindau 37191, Germany
 3. Marshall Space Flight Center, Huntsville, Alabama 35812, USA
 4. University of Maryland, Institute for Physical Science & Technology, College Park, Maryland 20742, USA
 5. Skobeltsyn Institute of Nuclear Physics, Moscow State University, Leninskie gory, GSP1, Moscow 119991, Russia
 6. Louisiana State University, Department of Physics and Astronomy, Baton Rouge, Louisiana 70803, USA

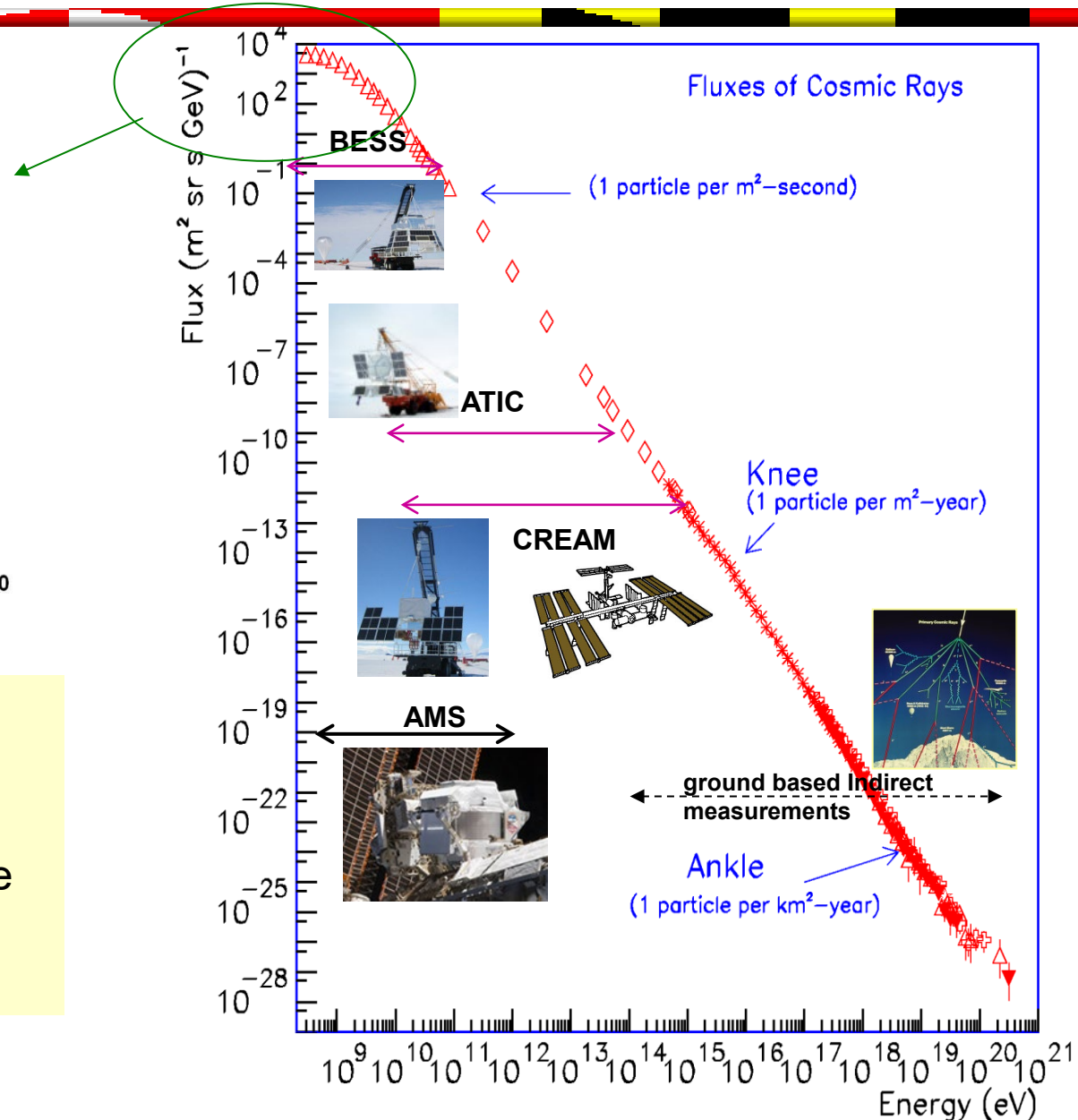


How do cosmic accelerators work?



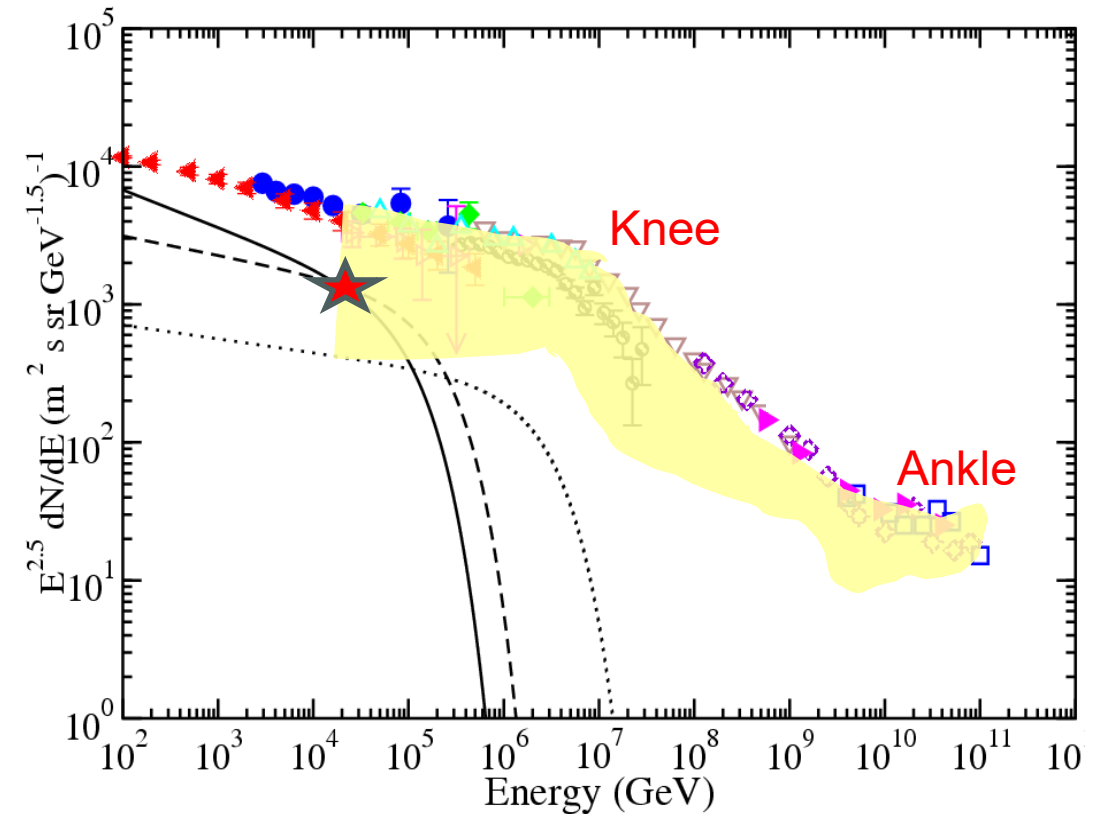
Mission Goal

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



Is the “knee” due to a limit in SNR acceleration?

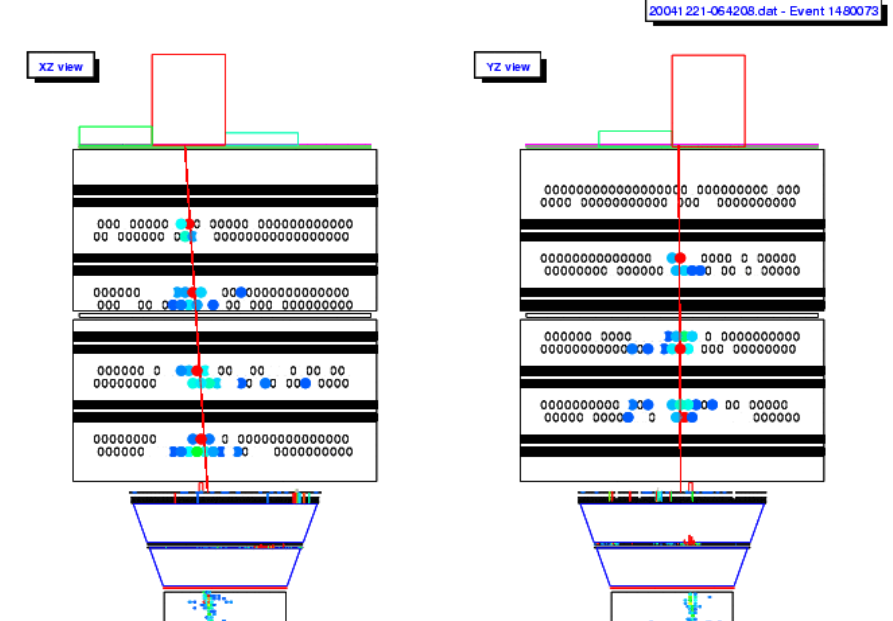
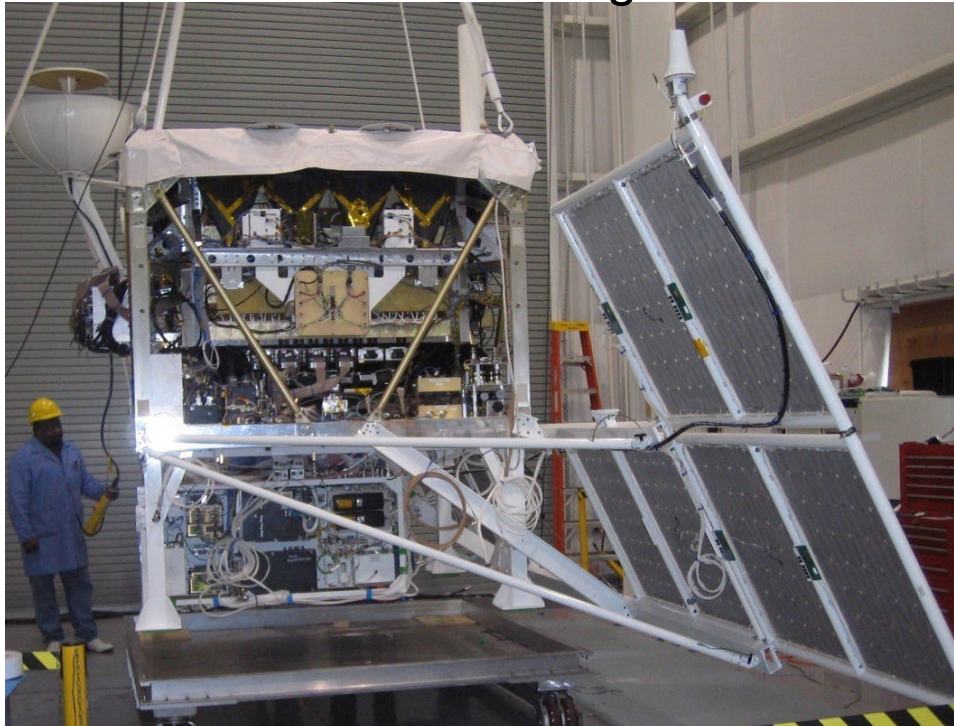
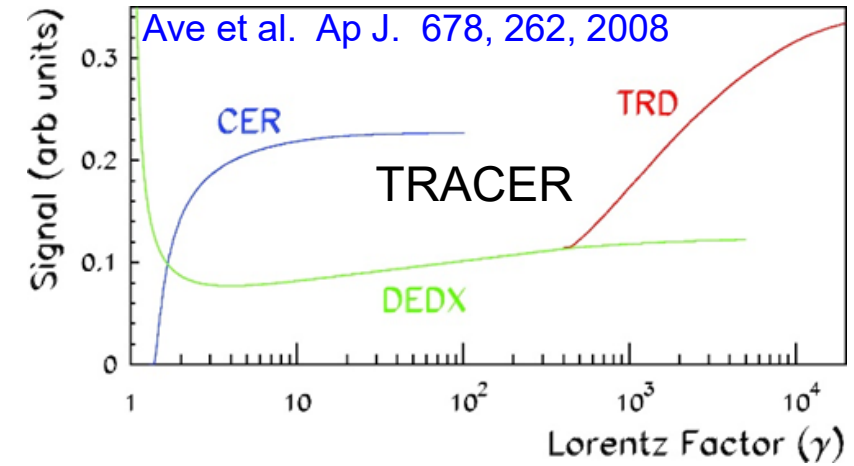
- The all particle spectrum extends several orders of magnitude beyond the highest energies thought possible for supernova shock acceleration
- And, there is a “knee” (index change) above 10^{15} eV
- Acceleration limit signature: Characteristic elemental composition change over two decades in energy below and approaching the knee
- Direct measurements of individual elemental spectra can test the supernova acceleration model

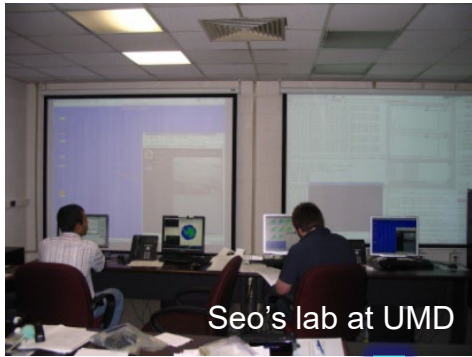


SNR acceleration limit:

$$E_{\text{max}_z} = Z \times E_{\text{max}_p},$$

- 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

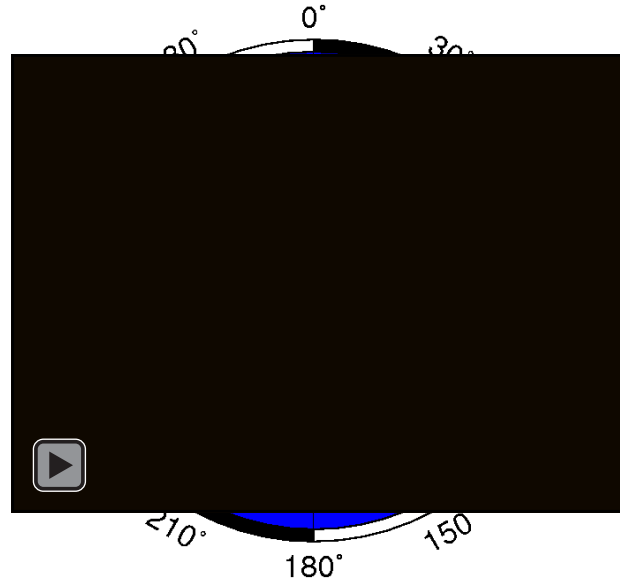




Seo's lab at UMD



Cosmic Rays



Typical duration: ~1 month/flight



Instruments are fully recovered, refurbished & reflight.



Seo's lab at UMD



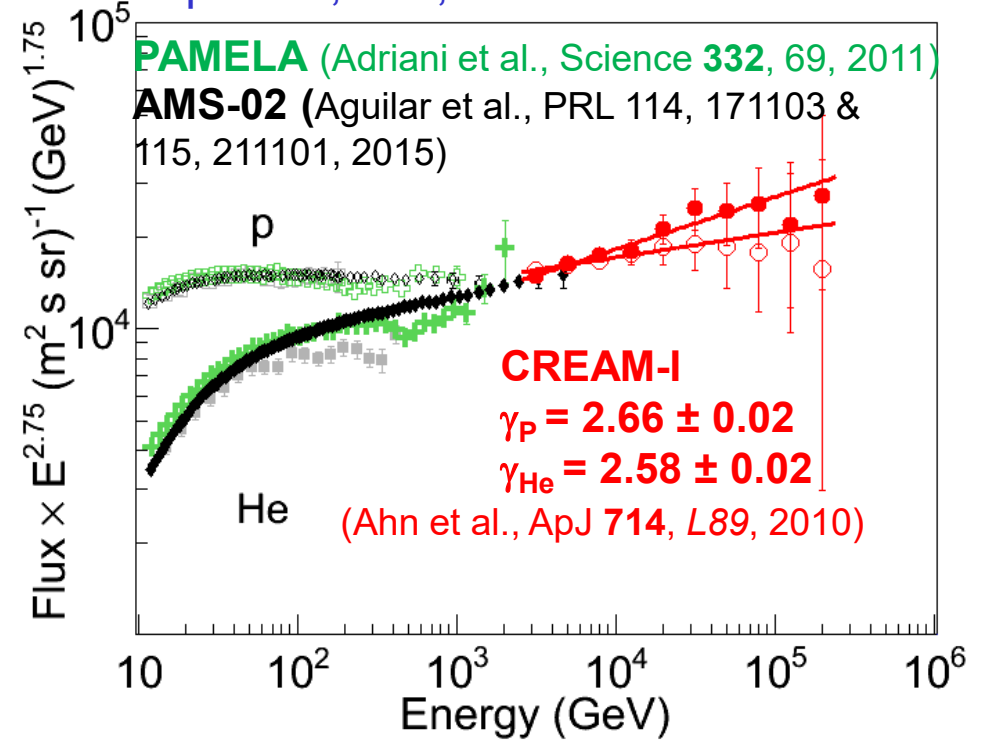
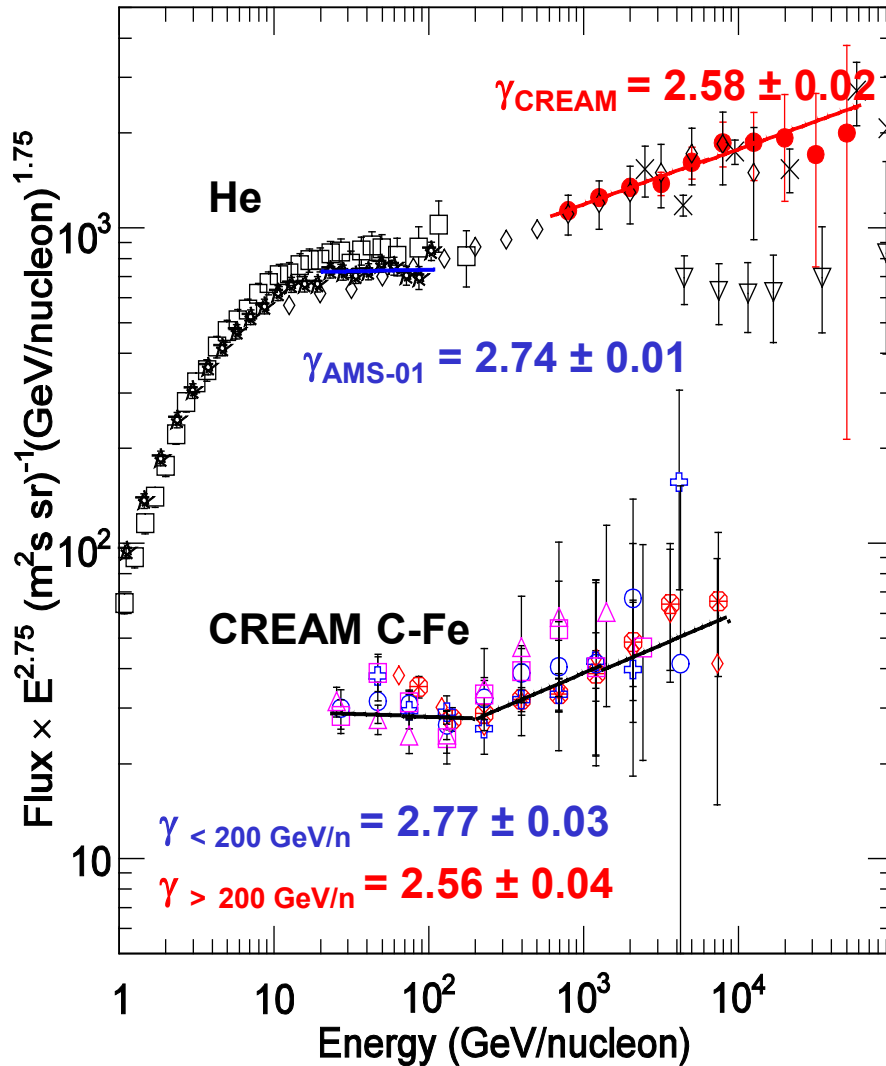
Antarctica



- 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.

Unexpected Discrepant Hardening

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



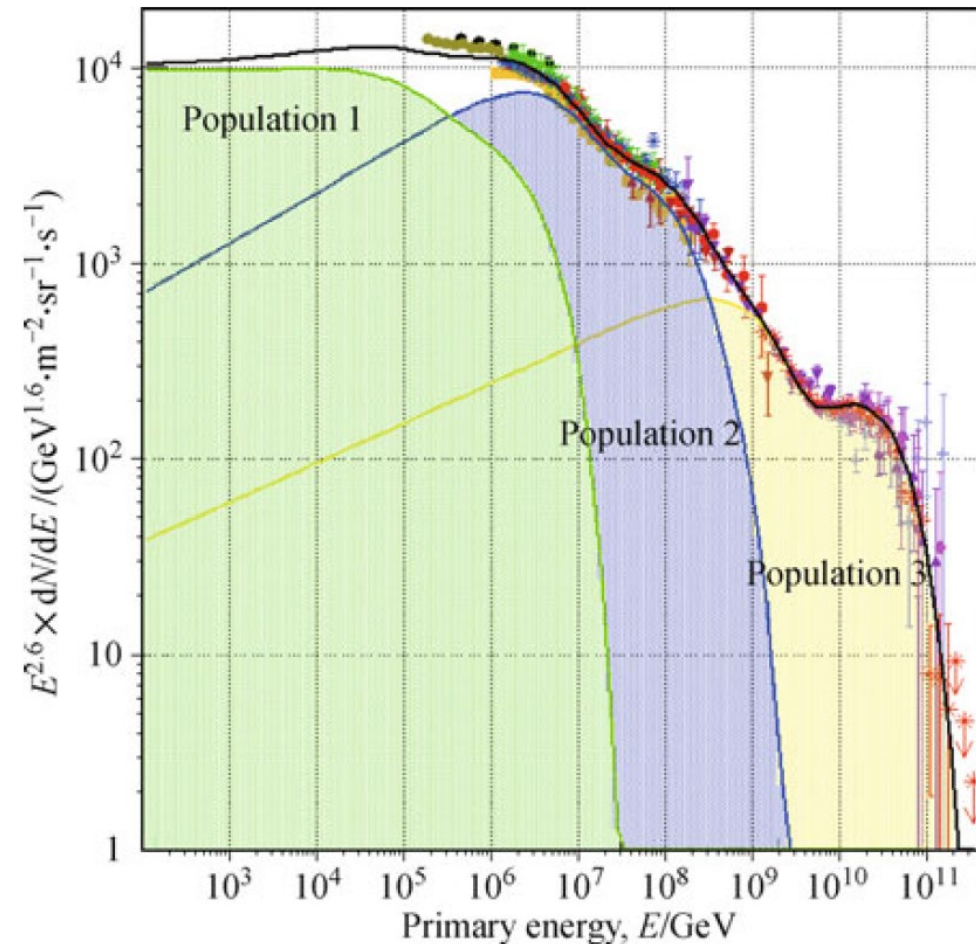
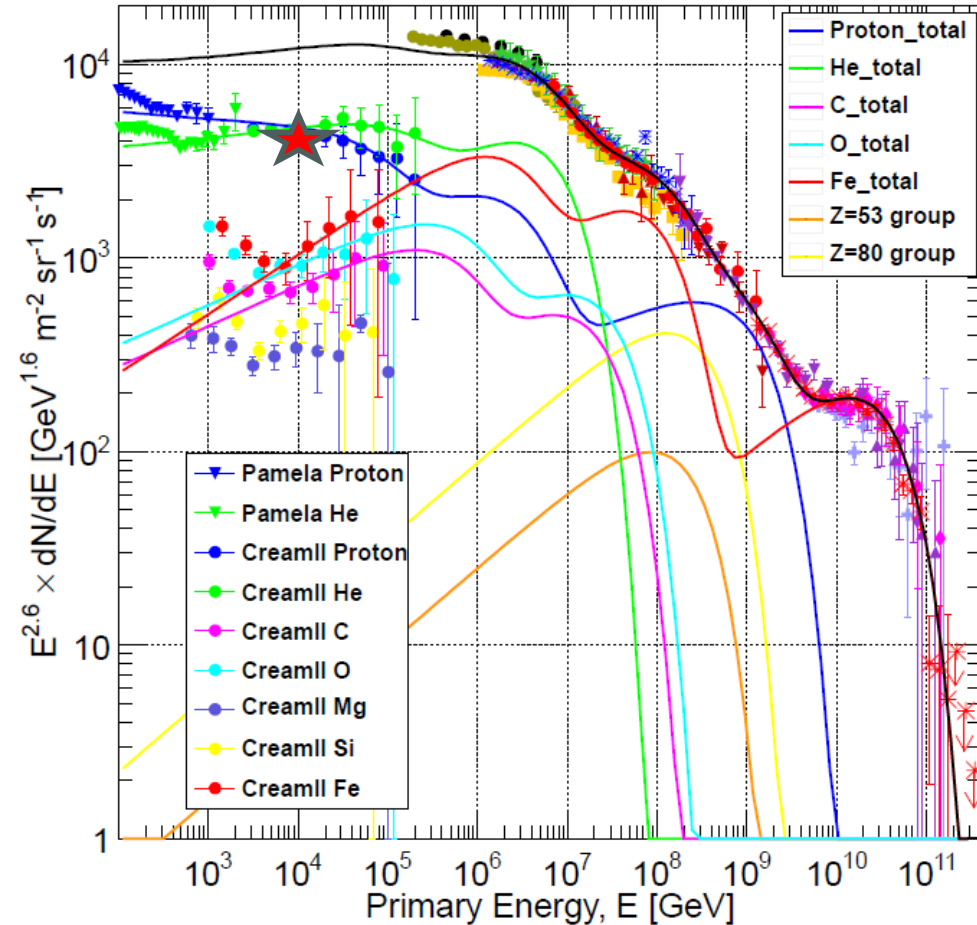
It provides important constraints on cosmic ray acceleration and propagation models, and it must be accounted for in explanations of the e^+e^- anomaly and cosmic ray “knee.”

CREAM data to explain the knee and beyond

T. K. Gaisser, T. Stanev and S. Tilav, Front. Phys. 8(6), 748, 2013

$$F_i = \sum_{j=1}^4 a_{i,j} E^{\gamma_{i,j}} * \exp\left(\frac{-E}{Z_i R_{c,j}}\right)$$

Acceleration limit: $E_{\max_z} = Z \times E_{\max_p}$,

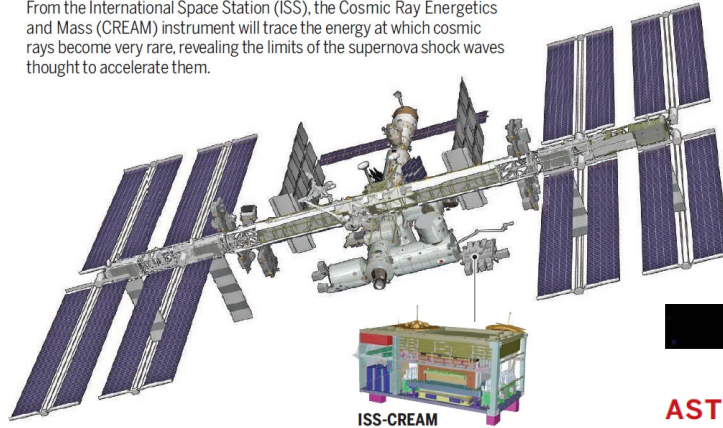


ISS-CREAM: CREAM for the ISS

SpaceX-12 Launch on 8/14/2017

Aiming high

From the International Space Station (ISS), the Cosmic Ray Energetics and Mass (CREAM) instrument will trace the energy at which cosmic rays become very rare, revealing the limits of the supernova shock waves thought to accelerate them.



ISS-CREAM



ASTROPHYSICS

Cosmic ray catcher will probe supernovae from new perch

Balloon-borne detector moves to space to trap rare, high-energy particles that carry clues to their origin

By **Eric Hand**

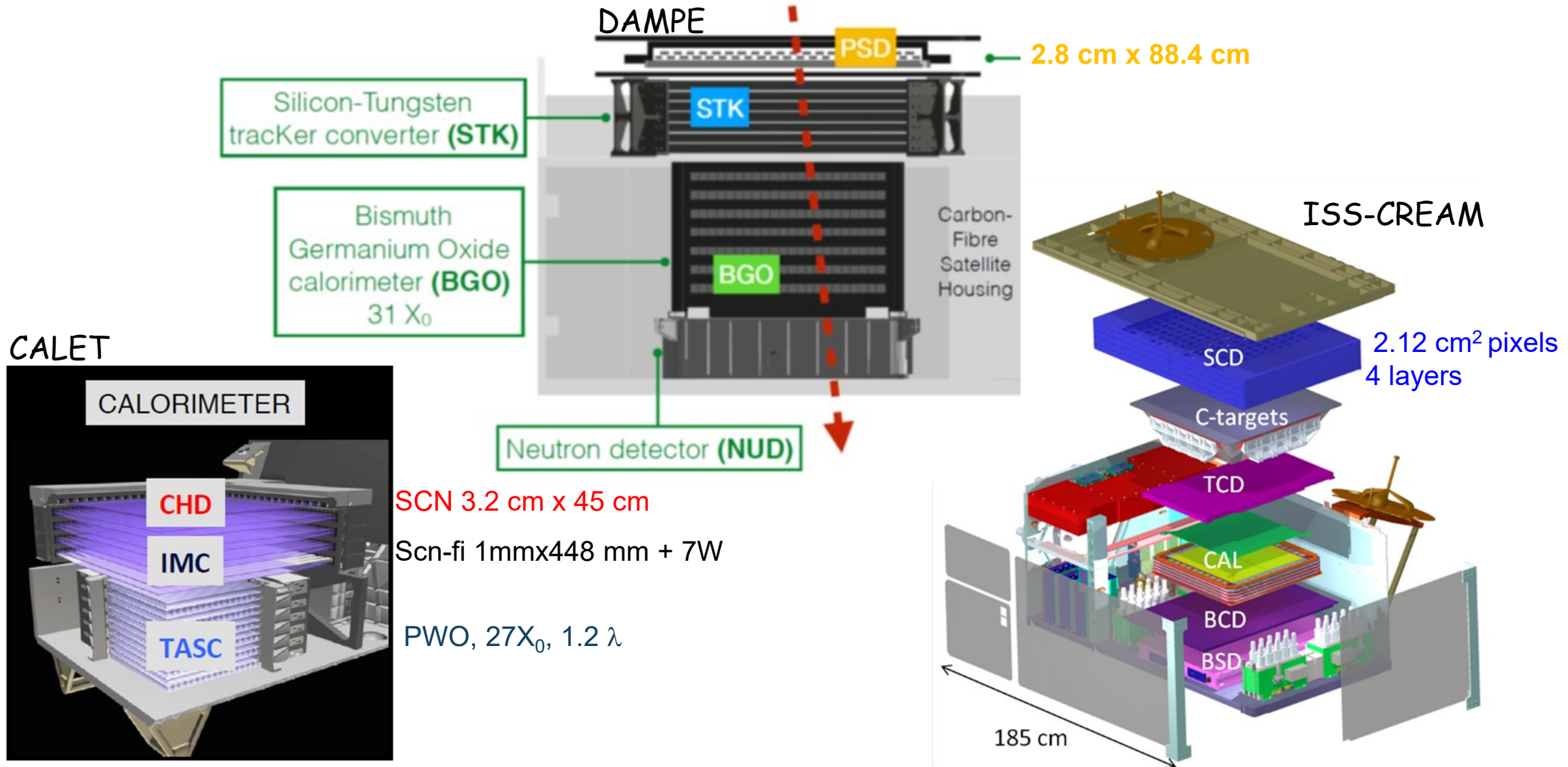
After 191 days aboard balloons sailing the stratosphere, an experiment designed to probe the galaxy's natural particle accelerators will move to higher ground: the International Space Station (ISS). The Cosmic Ray Energetics and Mass (CREAM) instrument and its successors floated above Antarctica seven times to collect high-energy cosmic

that a few smash into Earth with extraordinarily high energies—higher than today's most powerful atom smashers can generate. Their abundance drops sharply with increasing energy, following what's known as a power law distribution. In 1949, Italian-American physicist Enrico Fermi came up with a mechanism that could explain that and the cosmic rays' mind-boggling energies: supernova shock waves. In the centuries after a supernova,

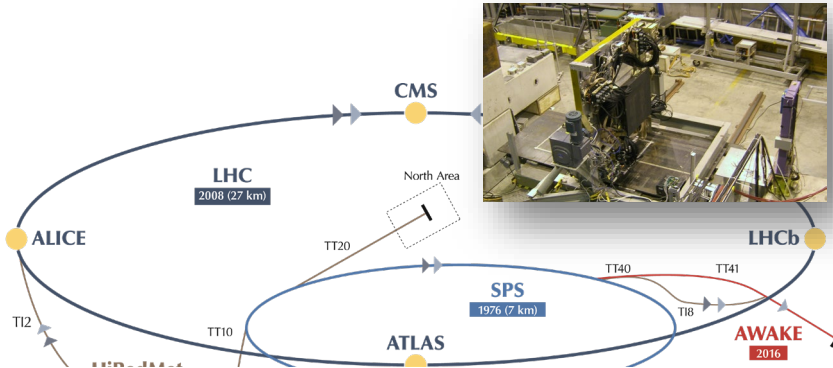
Downloaded from <http://science.sciencemag.org/> on August 11, 2017



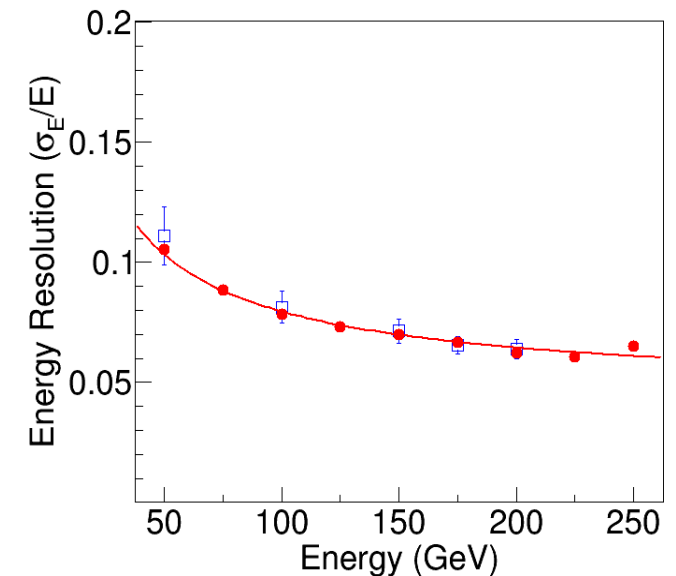
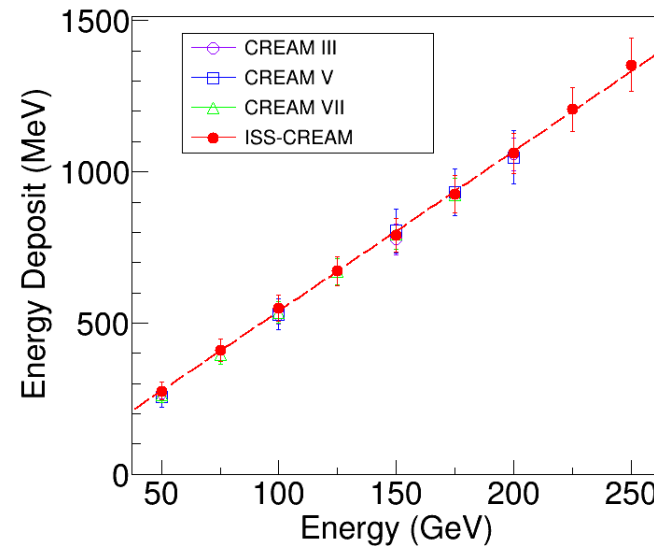
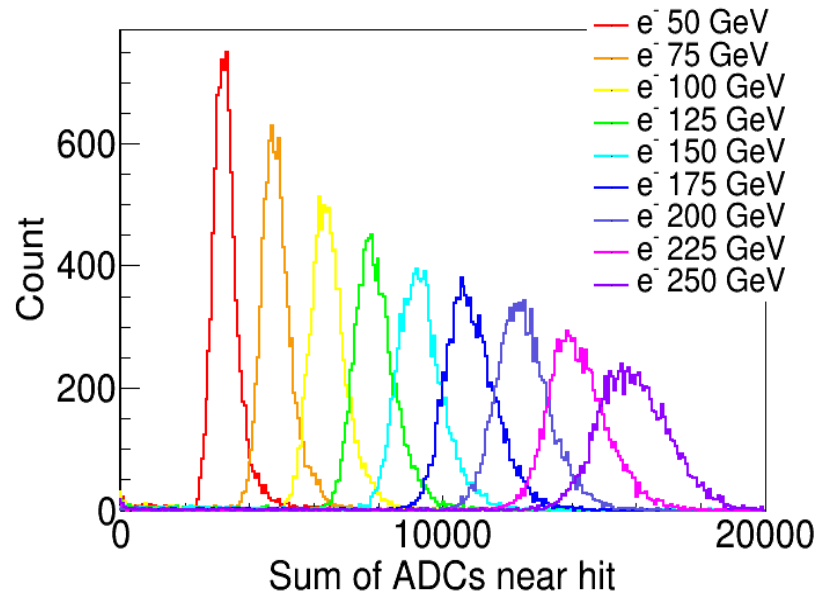
Recent calorimeter-based experiments for multi-TeV



Series of beam tests at CERN



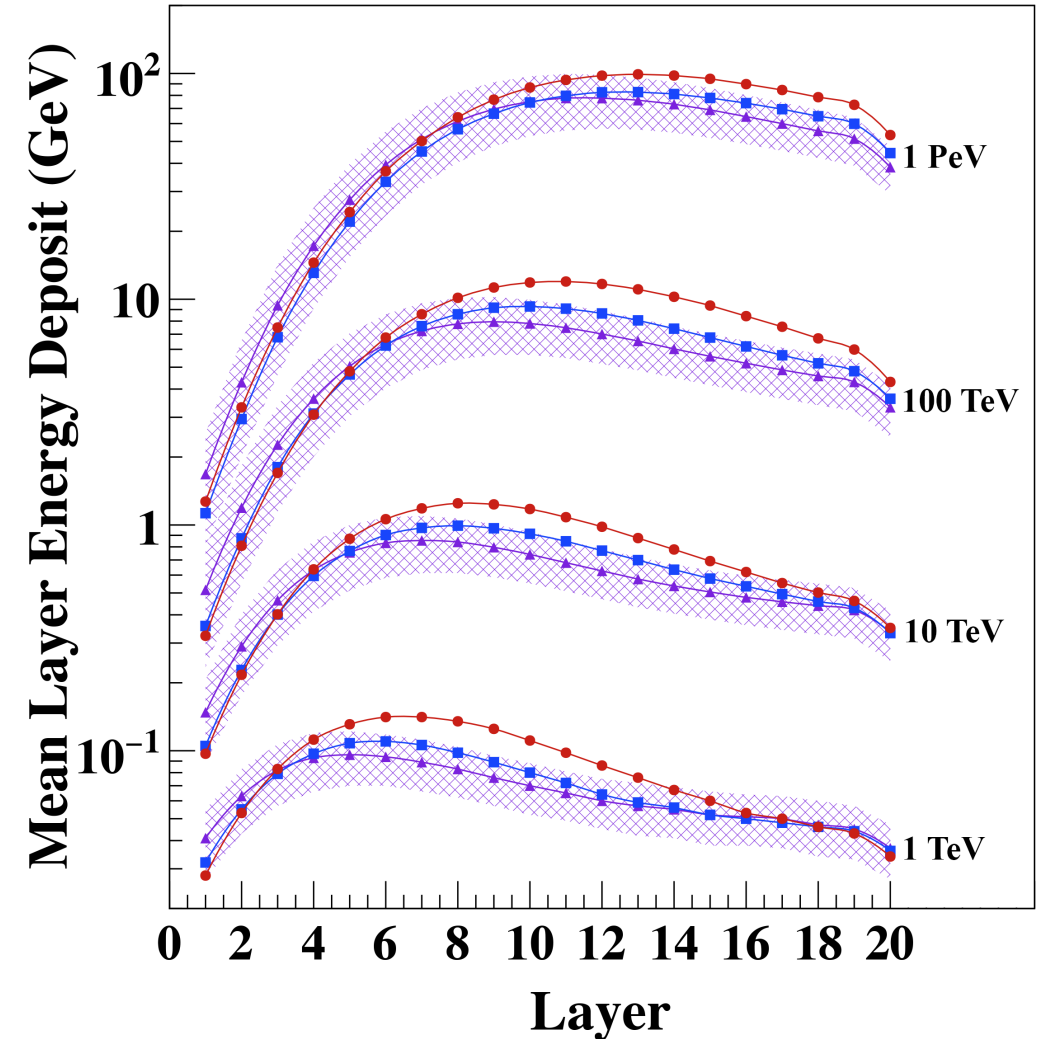
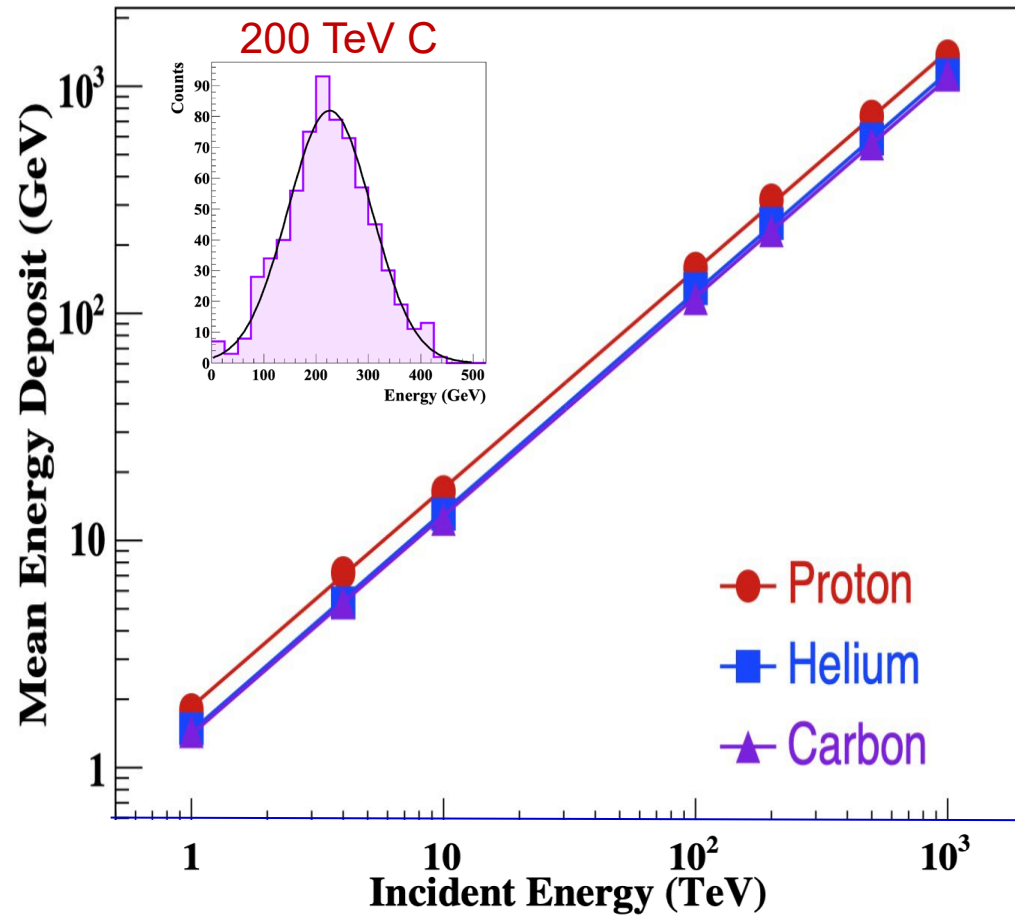
Zhang et al. ApP 130 (2021) 102583; Picot-Clemente et al., PoS(ICRC2017)247; Han et al., ICRC 2011, 6, 392; N. Park et al., NIM A, 581, 133, 2007; Ahn et al. Nucl. Phys. B (Proc. Suppl.), 150, 272, 2006; Ahn et al. CALOR 2004, 532, 2005. I. Park et al., NIM A535, 158, 2004 etc.



Monte Carlo Simulations

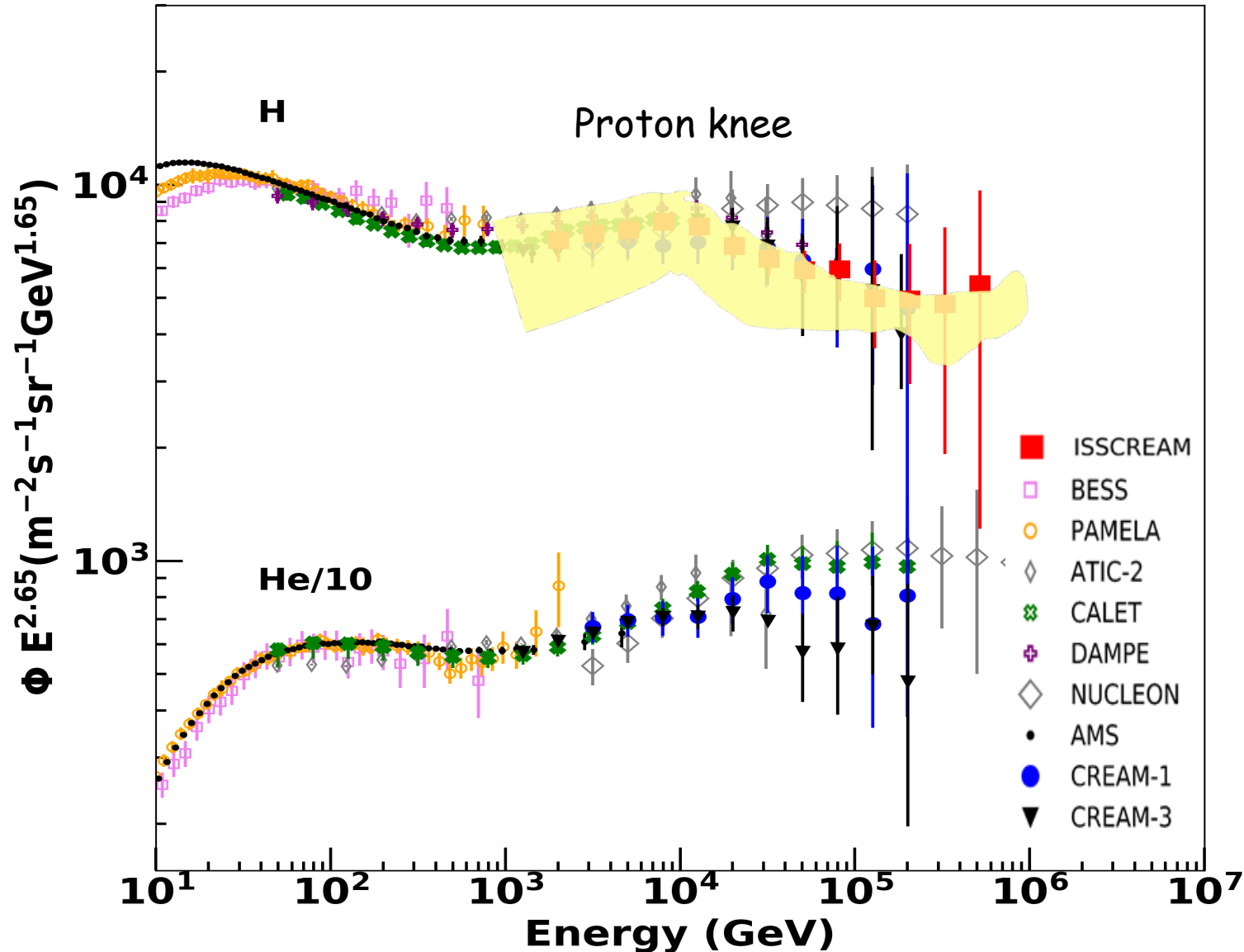
Bagga et al. (ISS-CREAM Collaboration) ASR, in press

J.Wu et al., PoS(ICRC2019)154; PoS(ICRC2021)056



ISS-CREAM Proton Spectrum (2.5 – 655 TeV)

G. H. Choi & E. S. Seo et al. (ISS-CREAM Collaboration) ApJ 940/107, 2022



- A broken power law fit to 2.5 – 164 TeV data: $\gamma = 2.57 \pm 0.03$ and a break at 9.0 ± 1.3 TeV with $\Delta\gamma = 0.25 \pm 0.05$.
- 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, NUCLEON, and CALET, but ISS-CREAM extends measurements to higher energies than those prior measurements.

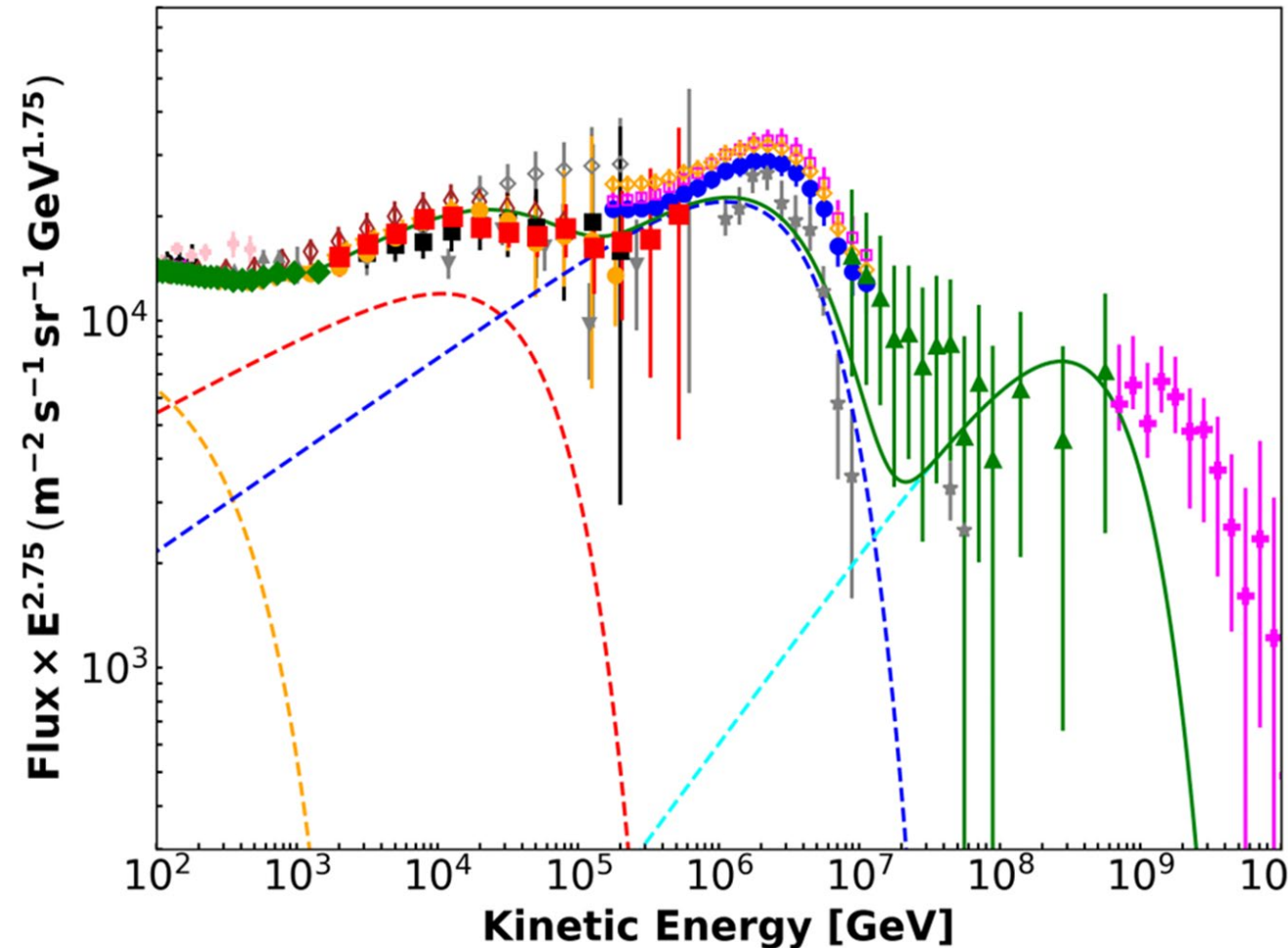
Populations of Cosmic Rays

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

$$F_i = \sum_{j=1}^4 a_{i,j} E^{\gamma_{i,j}} * \exp\left(\frac{-E}{Z_i R_{c,j}}\right)$$

Bowman, Scrandis & Seo, **ASR, 70/9, 2703, 2022**

Gaisser et al. Frontiers of Phys. 8 (2013) 248.



Acceleration limit:

$$E_{\text{max}_z} = Z \times E_{\text{max}_p},$$

--- Pop 0	$E_{\text{max}_p} = 400 \text{ GV}$
--- Pop 1	$E_{\text{max}_p} = 50 \text{ TV}$
--- Pop 2	$E_{\text{max}_p} = 4 \text{ PV}$
--- Pop 3	$E_{\text{max}_p} = 500 \text{ PV}$

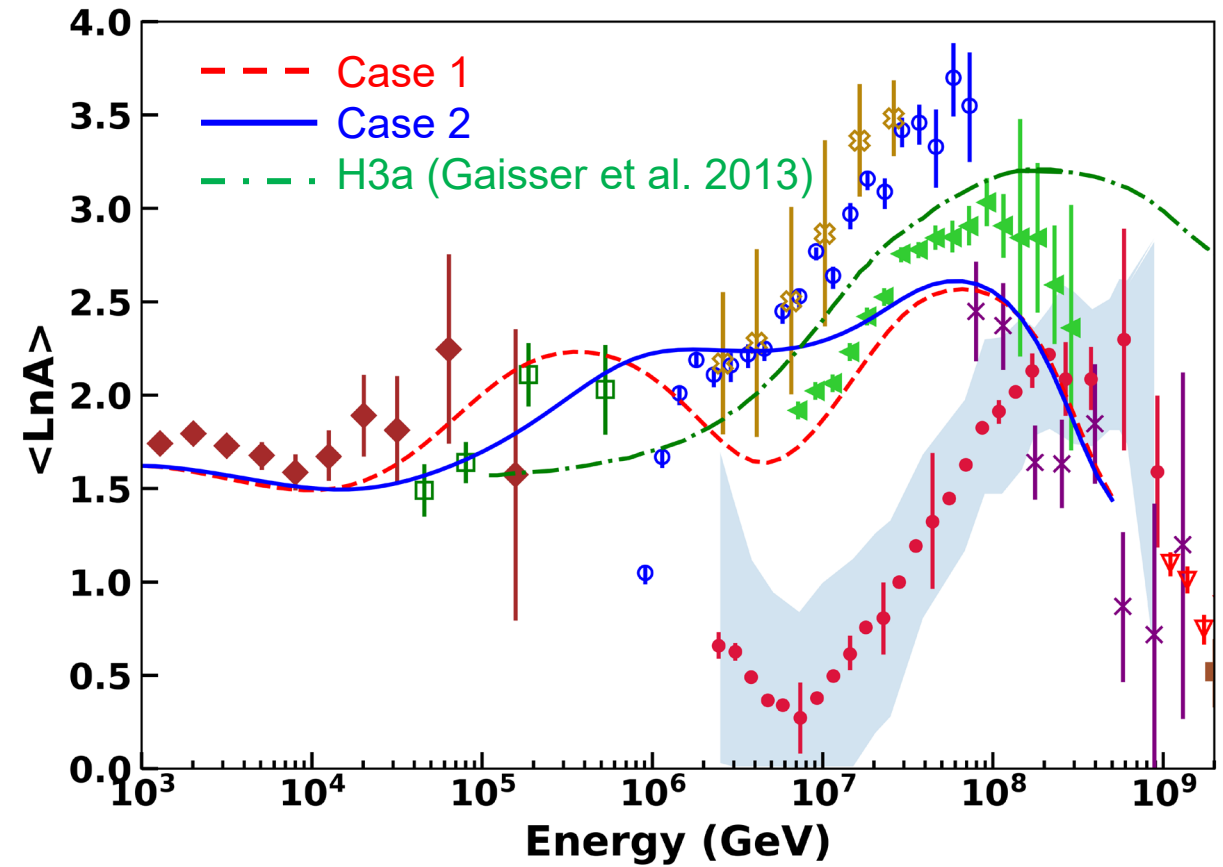
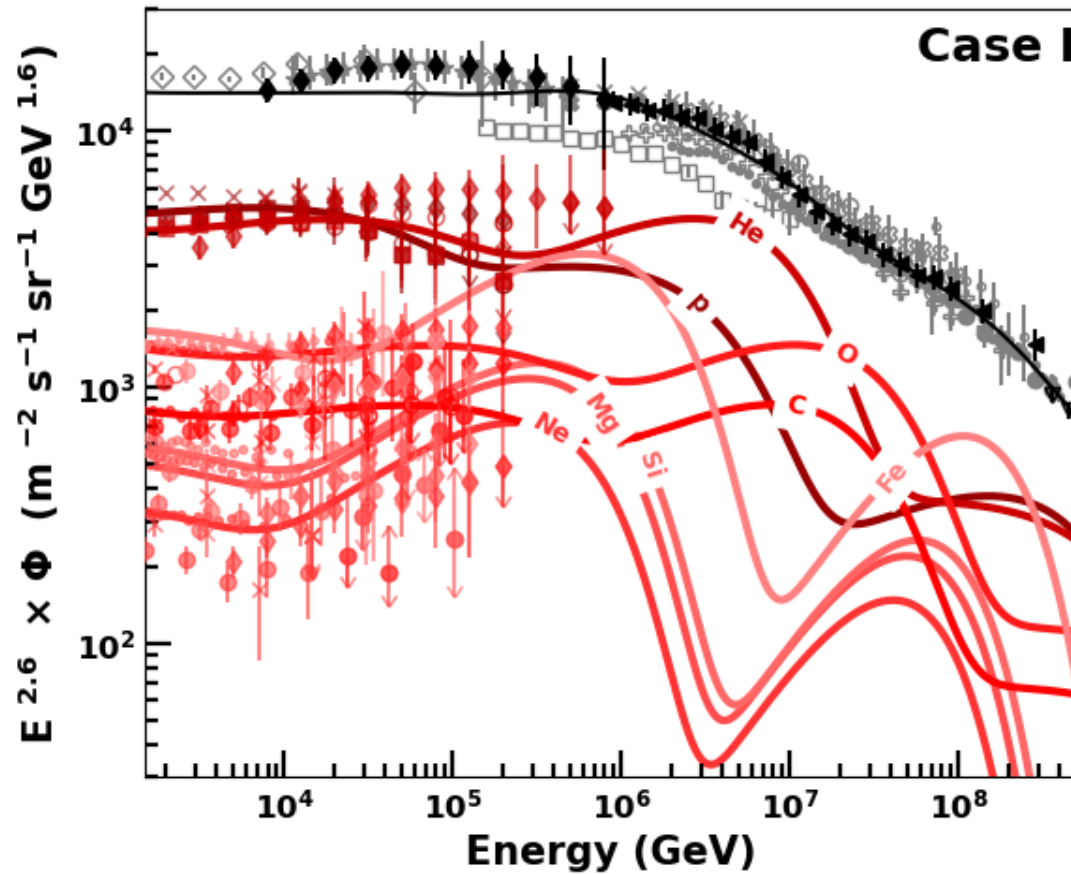
Ptuskin et al. ApJ
718,31, 2010

Allen, Biermann et al.
Astropart. Phys. 161,
102976, 2024

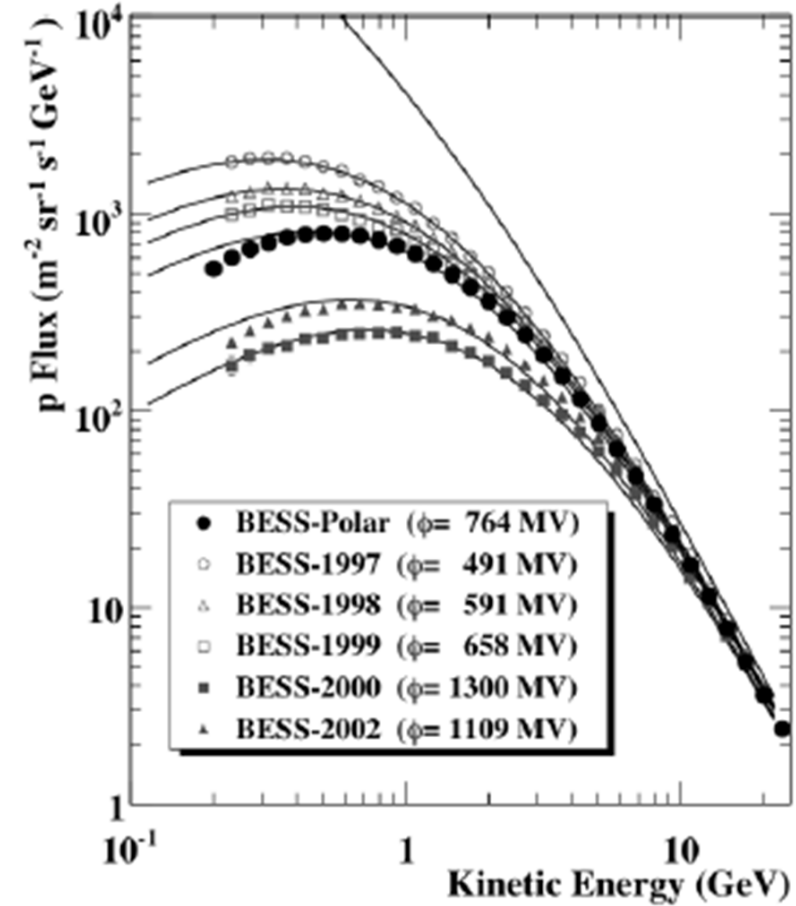
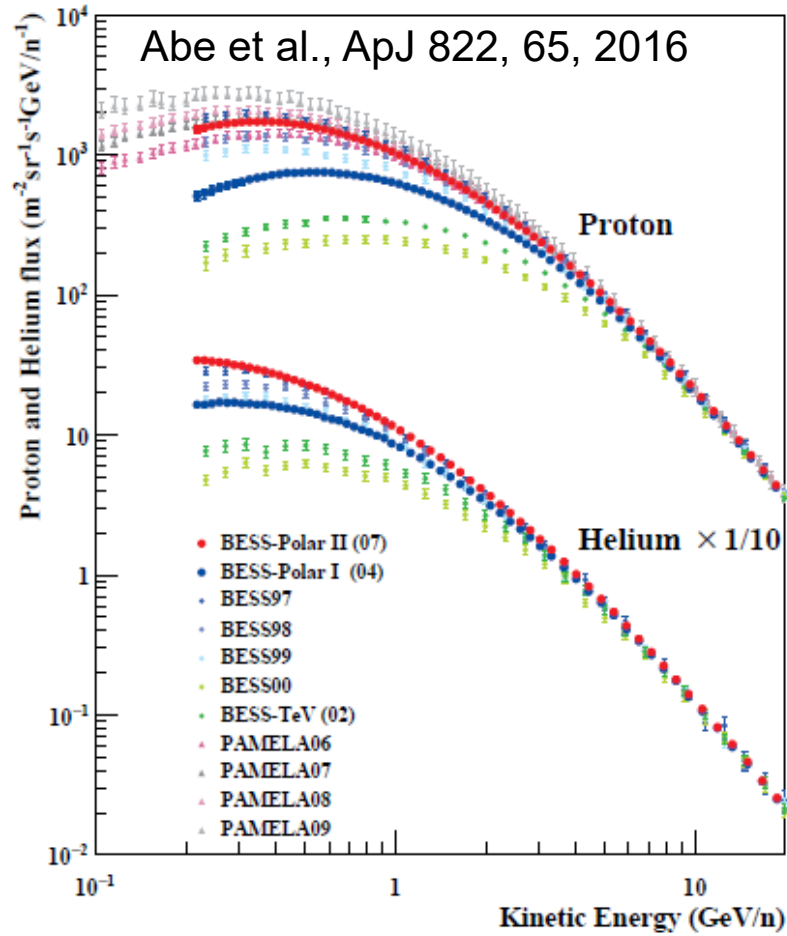
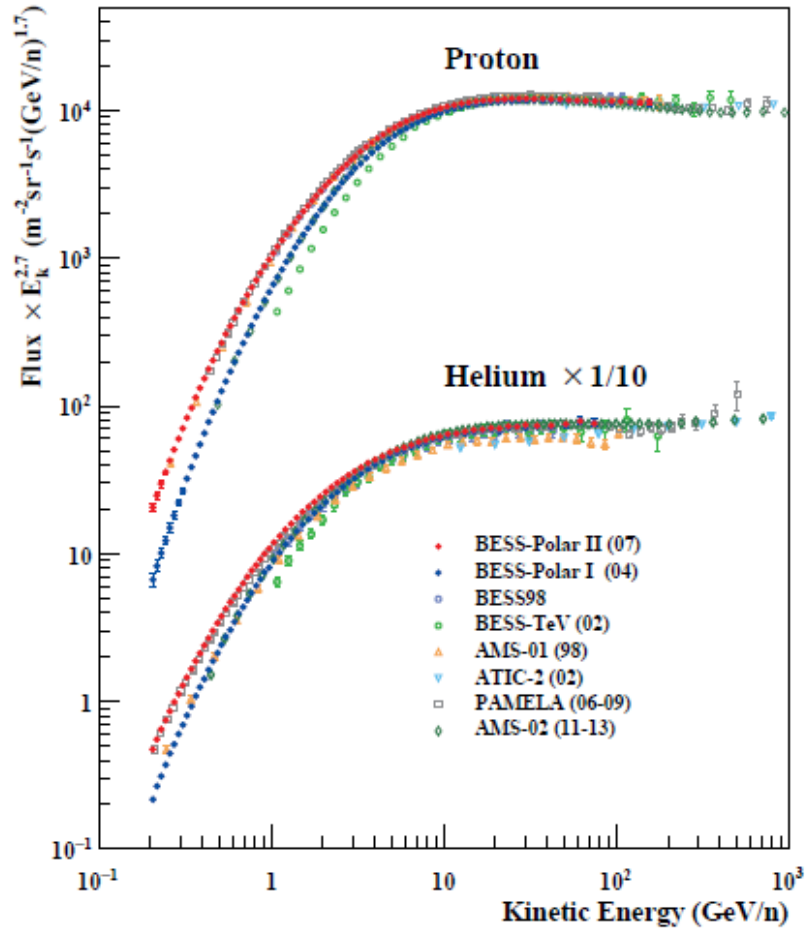
- The spectral hardening at $\sim 200 \text{ GV}$ and softening $\sim 10 \text{ TeV}$ form a “proton knee” consistent with a simple rigidity dependent acceleration limit.

Consistent with all particle spectrum and InA

Bowman, Scrandis & Seo, ASR, 70/9, 2703, 2022



Solar Modulation

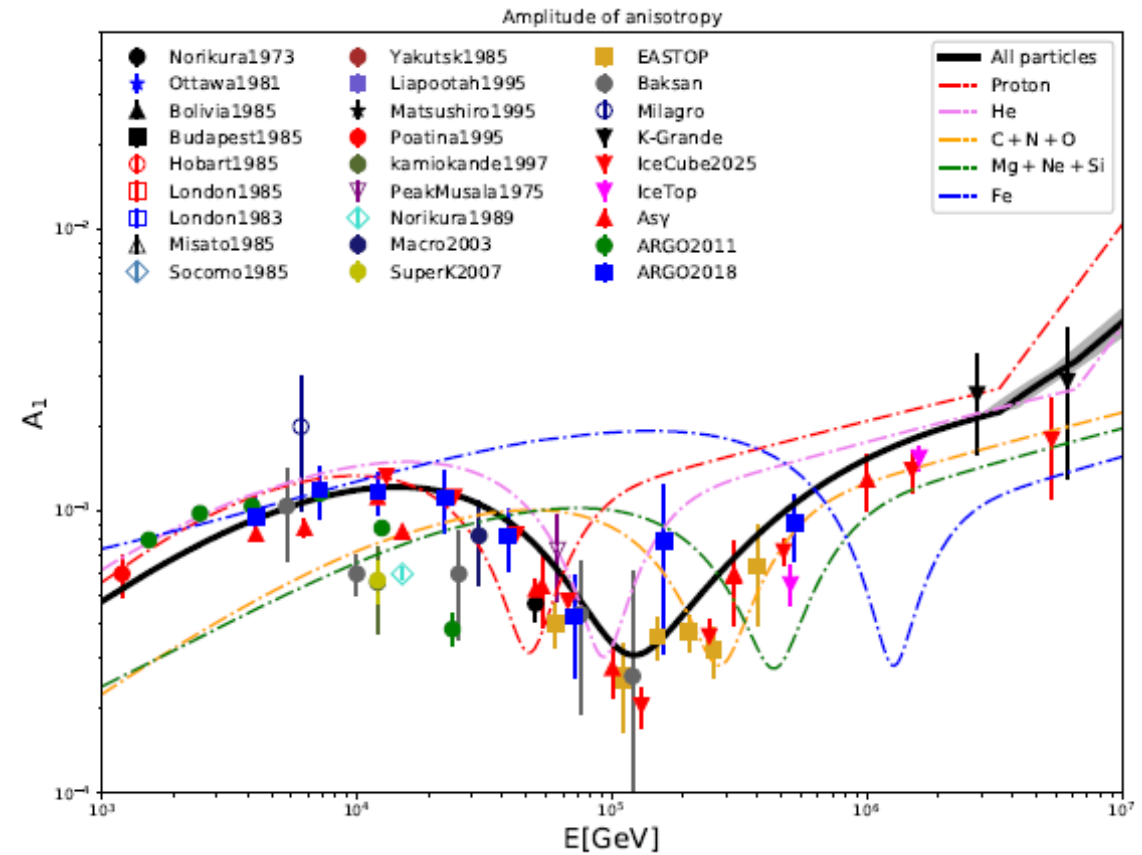
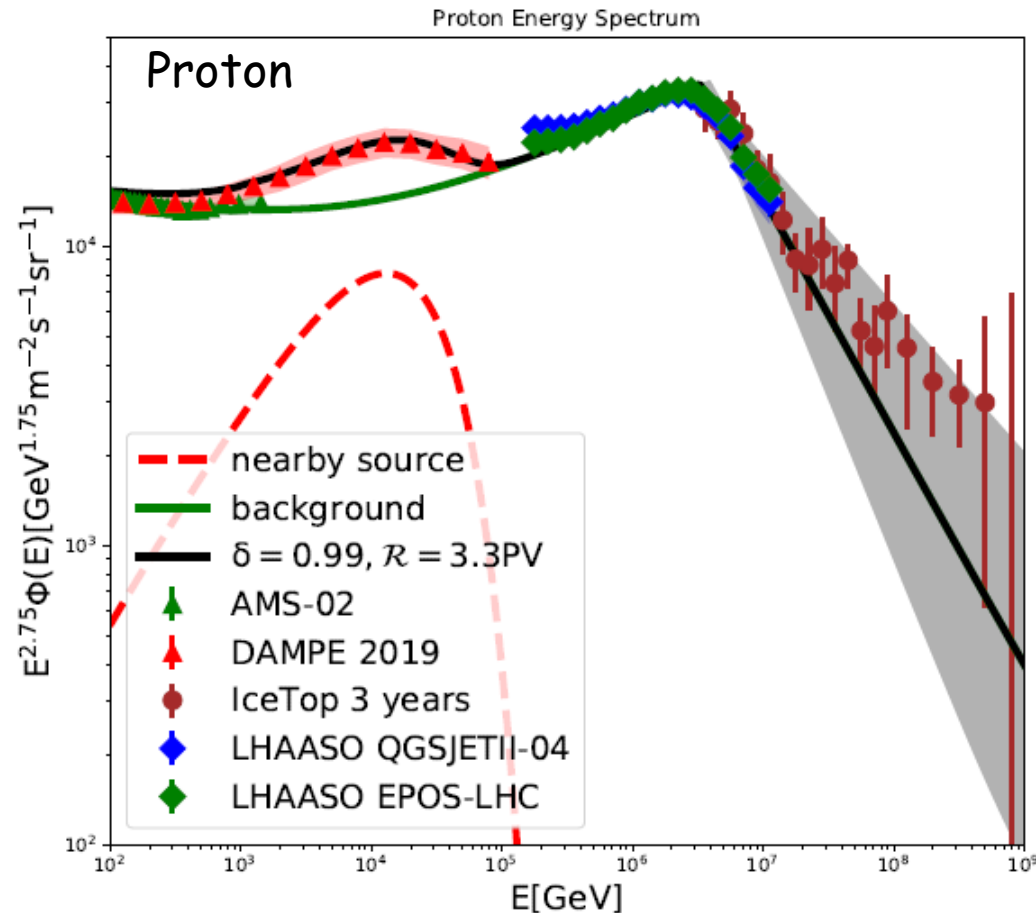


Spatial diffusion plus a nearby source

Yue et al. ApJ 998:264, 2026

$$q_{\text{local}}(\mathcal{R}) = q_{0,\text{local}} \cdot \left(\frac{\mathcal{R}}{\mathcal{R}_{br}} \right)^{-\beta} \cdot e^{-\mathcal{R}/\mathcal{R}_{c,\text{local}}}$$

$$\text{SDP model } D = \begin{cases} D_0 \beta^\varepsilon \left(\frac{\mathcal{R}}{\mathcal{R}_0} \right)^\delta, & \mathcal{R} < \mathcal{R}_{\text{knee}} \\ D_0 \beta^\varepsilon \left(\frac{\mathcal{R}}{\mathcal{R}_0} \right)^\delta \left(\frac{\mathcal{R}}{\mathcal{R}_{\text{knee}}} \right)^{\delta_{\text{knee}}}, & \mathcal{R} \geq \mathcal{R}_{\text{knee}} \end{cases}$$

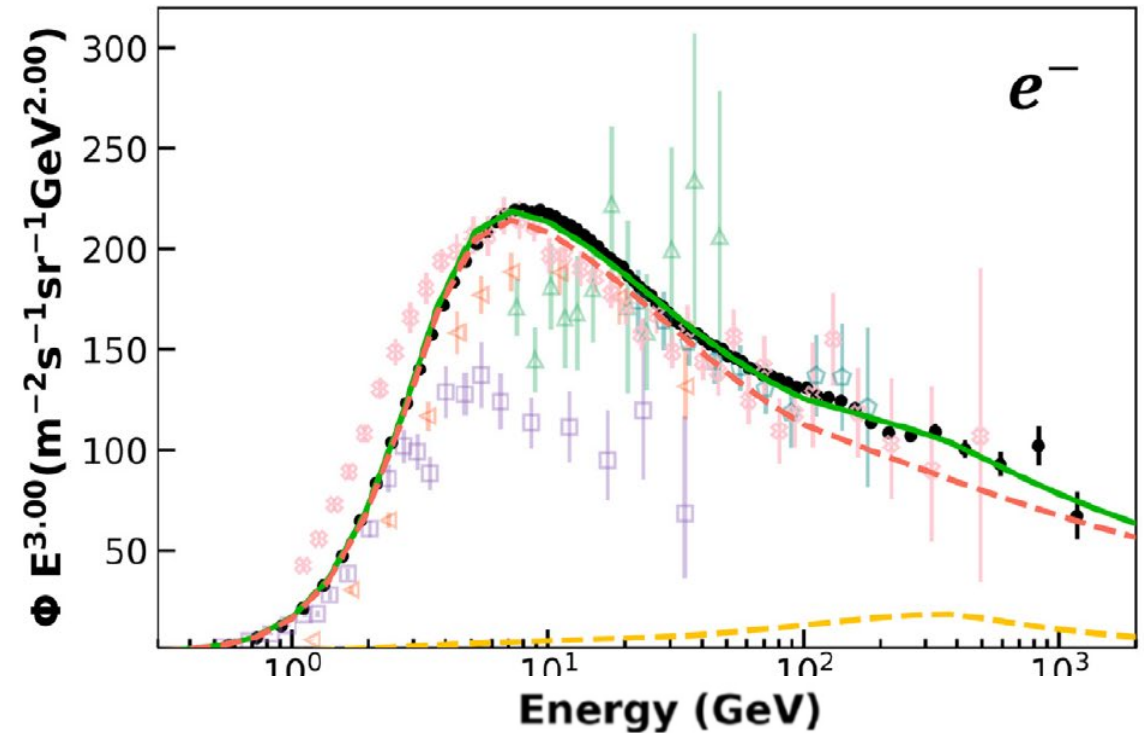
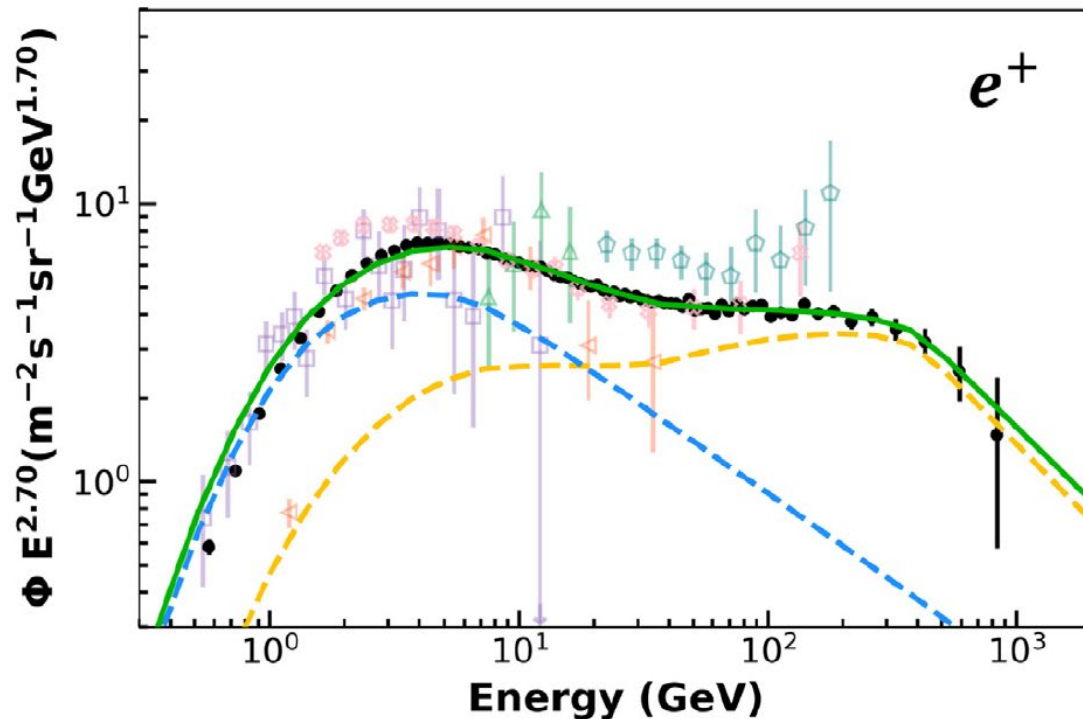


Using GALPROP

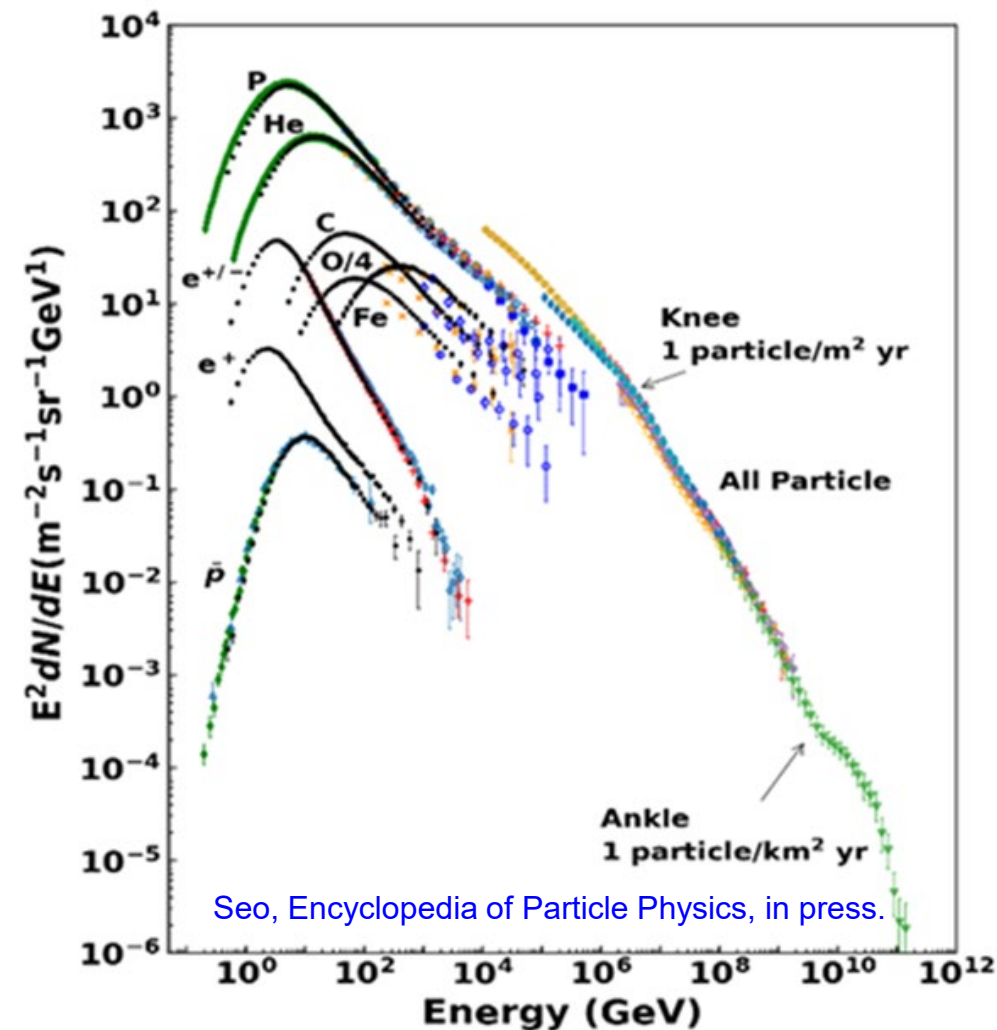
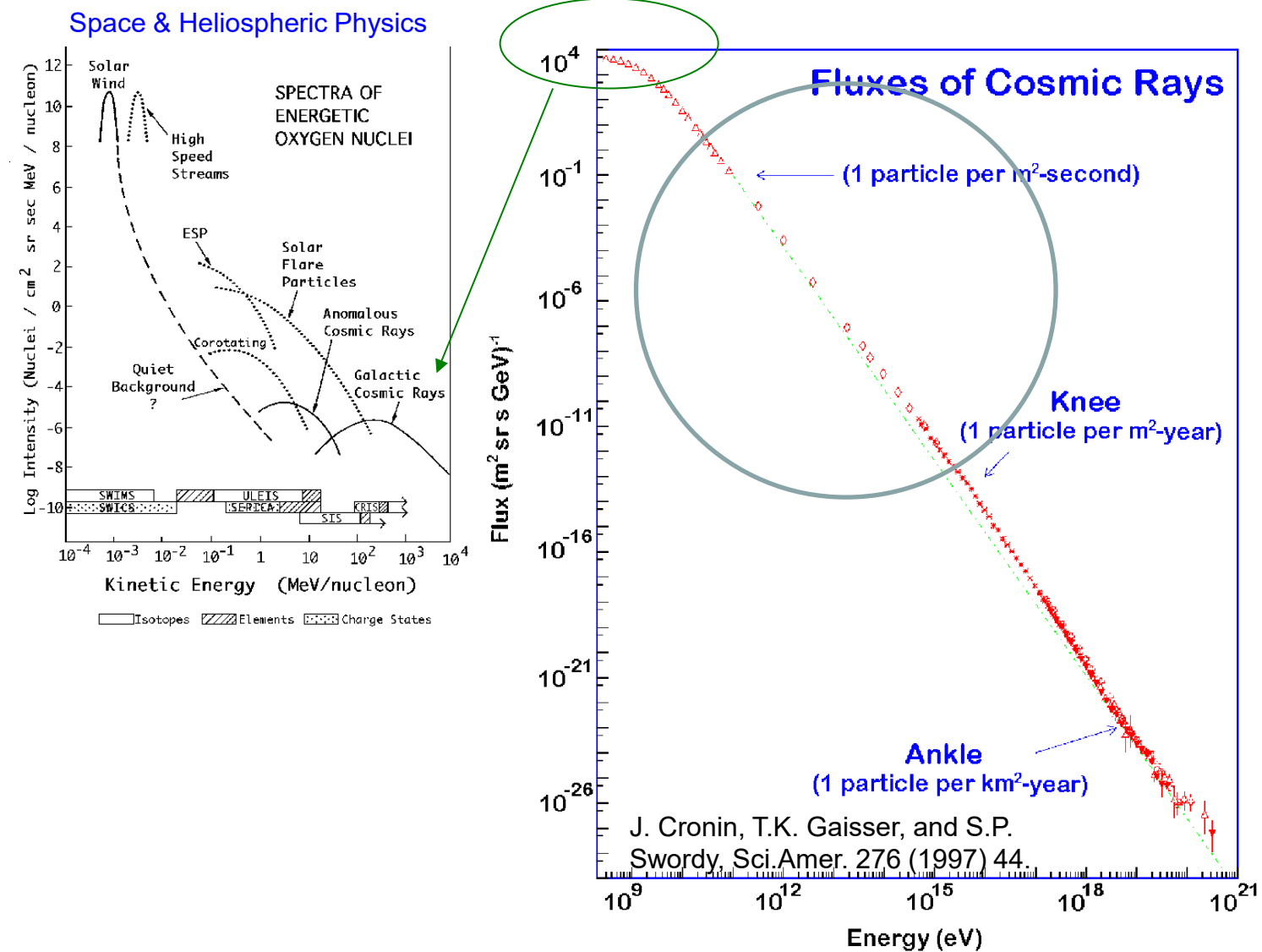
Chen, Dorris, Seo, Ptuskin, ASR, in press, 2026;
POS(ICRC2025)026, 2025.

$$\frac{\partial \psi}{\partial t} = q(\vec{r}, p) + \vec{\nabla} \cdot (D_{xx} \vec{\nabla} \psi - \vec{V} \psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi - \frac{\partial}{\partial p} \left[\dot{p} \psi - \frac{p}{3} (\vec{\nabla} \cdot \vec{V}) \psi \right] - \frac{1}{\tau_f} \psi - \frac{1}{\tau_r} \psi$$

--- charge-symmetric e^+ and e^- source



Recent experiments fill the data gap



Summary

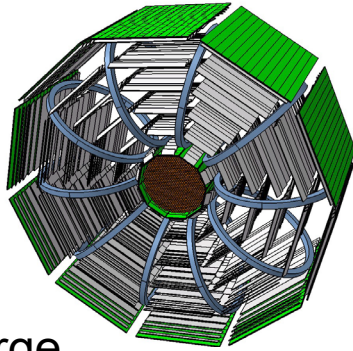
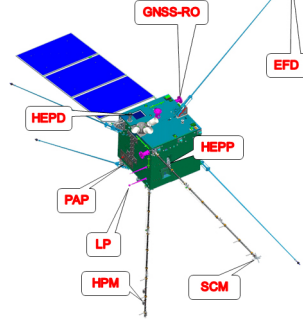


- Significant advances in CR measurements have been made in recent years.
 - ✓ An excess in positron spectrum.
 - ✓ Spectral hardening above ~ 200 GV.
 - ✓ Spectral softening at ~ 10 TeV.
 - ✓ Harder He spectrum than the proton spectrum.
- These results contradict the traditional view that a simple power law can represent CR without deviations below the “knee”, and they should be incorporated in a coherent model for CR origin/propagation.
- 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 the softening at an energy of ~ 10 TeV/n?

Future Outlook

China Seismo-Electromagnetic Satellite (CSES)

3 - ~100 MeV e, p, light nuclei



Antimatter Large
Acceptance Detector
In Orbit (ALADInO)
10 m²sr
MDR 20 TV

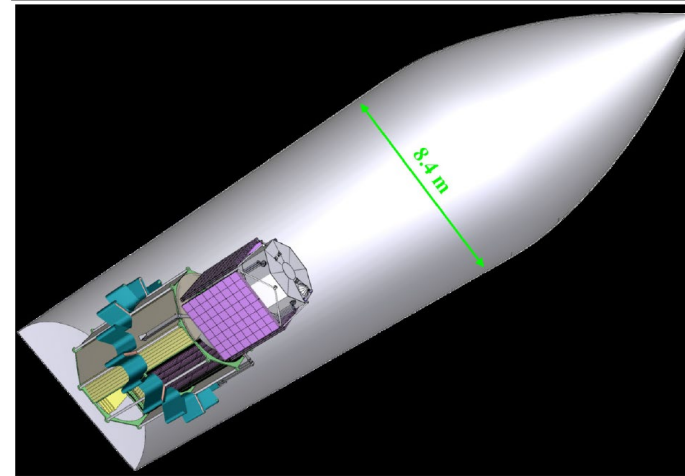
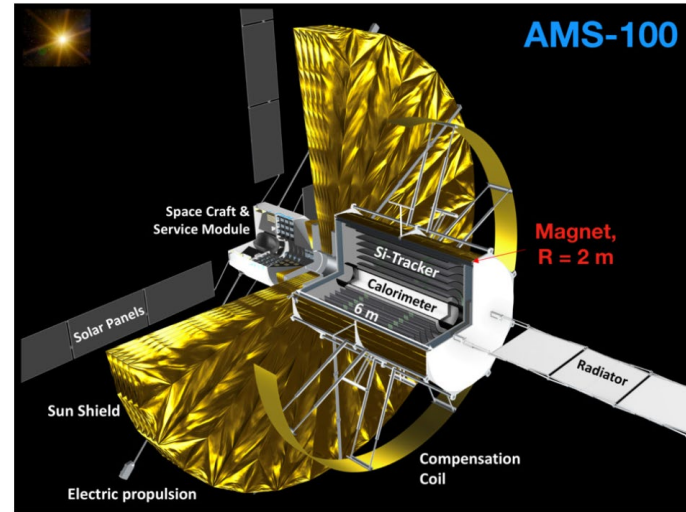
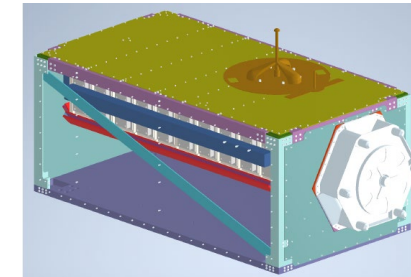
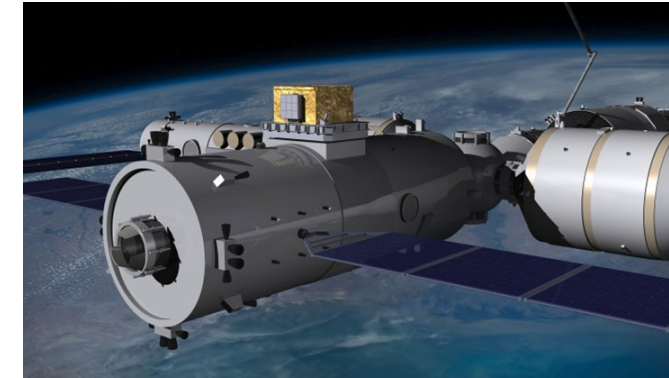


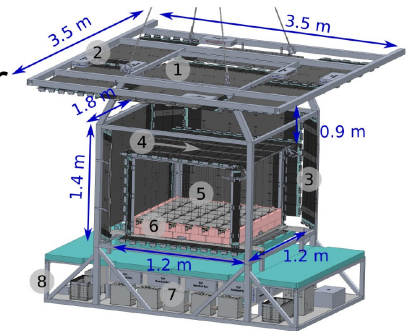
Figure 2: AMS-100 launch configuration in an SLS-Block 2 fairing. The compensation coil, the sunshield, the solar cells, and the electric propulsion system are folded up. The service module is located at the top for structural reasons.

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



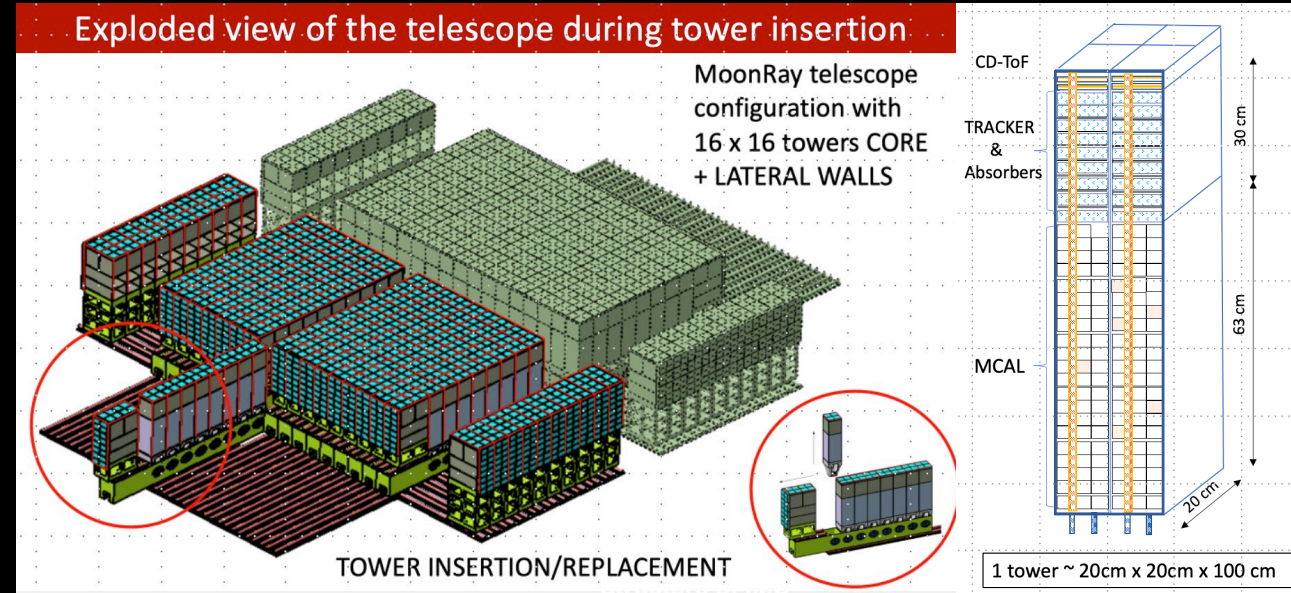
General Antiparticle
Spectrometer
(GAPS)
 $\bar{d} < 0.25 \text{ GeV}/n$

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



Lunar Calorimeter

Modular observatory at the South Pole of the Moon to study *cosmic rays* and *gamma rays* of Very High Energy ($1-10^7$ GeV).



Marrocchesi, Astropart. Phys. 152 (2023) 102879