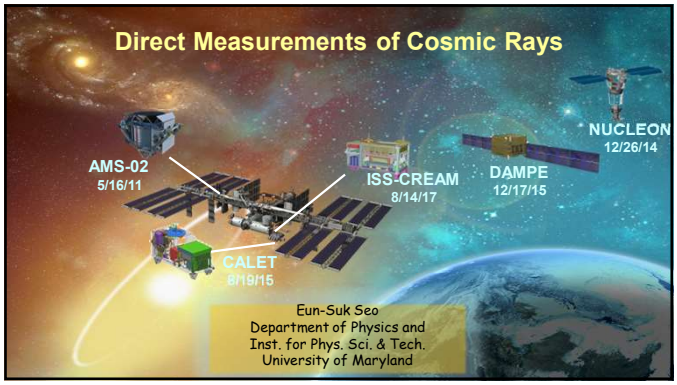


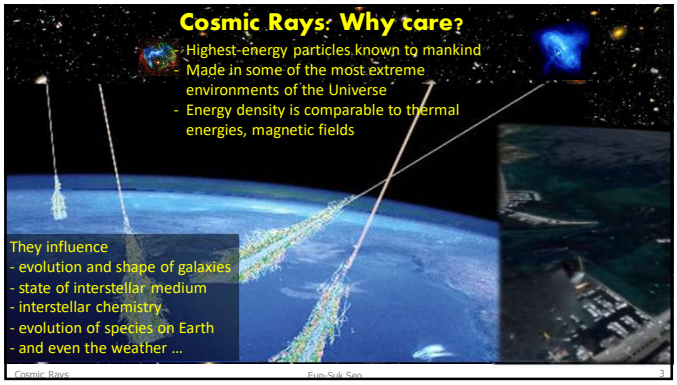

1

## 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)
  - …….
- Advances in direct measurements of cosmic rays, E.S.Seo, invited review, J.Kor. Phys. Soc., 78(10), 923-931, 2021.

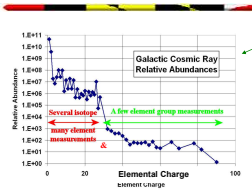
Cosmic Rays Eun-Suk Seo 2

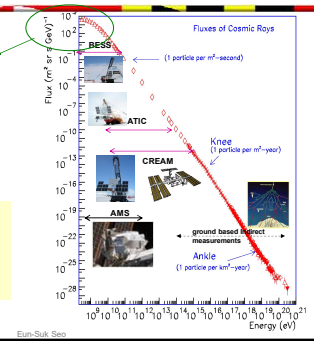
2




3

## How do cosmic accelerators work?



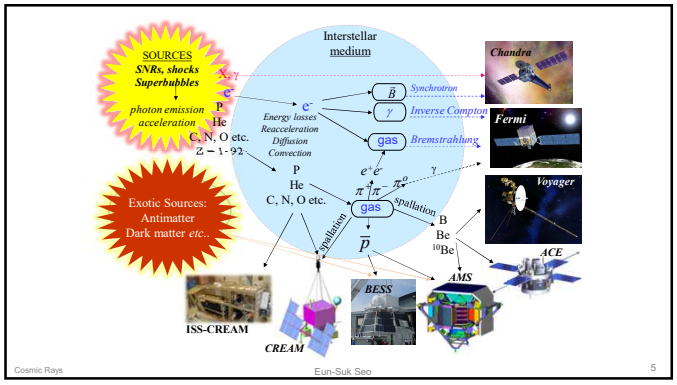




**Mission Goal**

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

Cosmic Rays Eun-Suk Seo 4

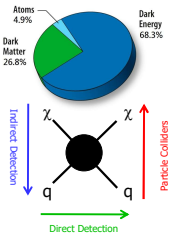
4

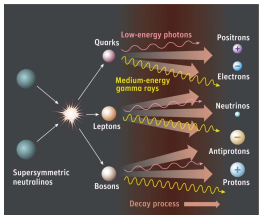



5

## We do not know what 95% of the universe is made of!

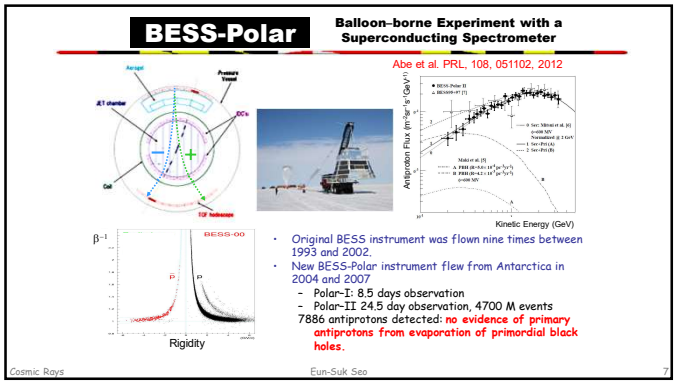
- Weakly Interacting Massive Particles (WIMPS) could comprise dark matter.
- This can be tested by direct search for various annihilating products of WIMP's in the Galactic halo.




Cosmic Rays Eun-Suk Seo 6

6


BESS-Polar
Balloon-borne Experiment with a Superconducting Spectrometer
Abe et al. PRL, 108, 051102, 2012
Kinetic Energy (GeV)
Rigidity
Original BESS instrument was flown nine times between 1993 and 2002.
New BESS-Polar instrument flew from Antarctica in 2004 and 2007
Polar-I: 8.5 days observation
Polar-II 24.5 day observation, 4700 M events
7886 antiprotons detected: no evidence of primary antiprotons from evaporation of primordial black holes.
Cosmic Rays
Eun-Suk Seo
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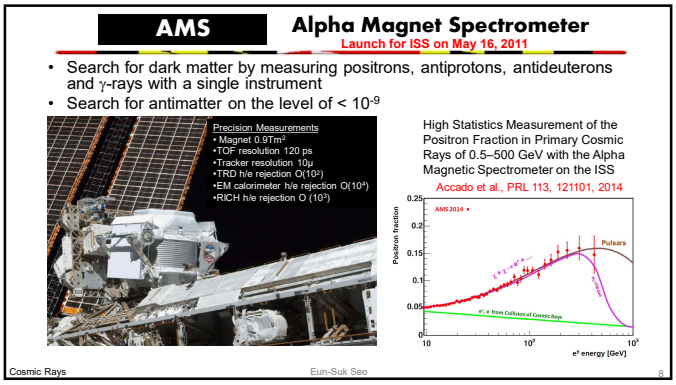
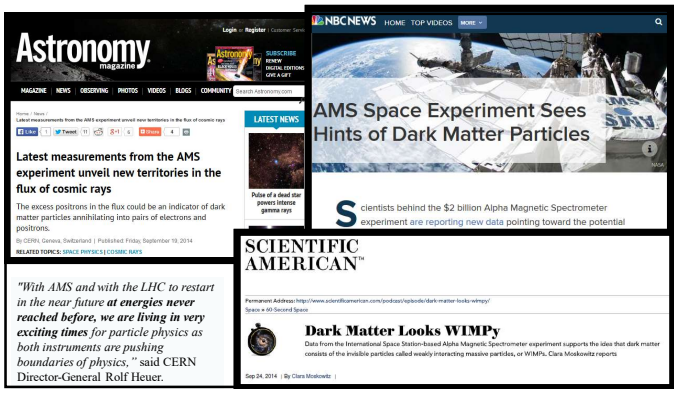
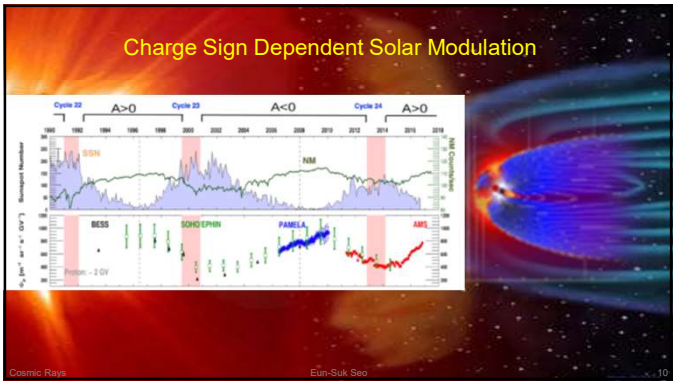
7


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
Precision Measurements
Magnet 0.9Tm²
TOF resolution 120 ps
Tracker resolution 10μ
TRD h/e rejection O(10²)
EM calorimeter h/e rejection O(10⁴)
RICH h/e rejection O (10³)
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
Positron fraction
Pulsars
Cosmic Rays
Eun-Suk Seo
8

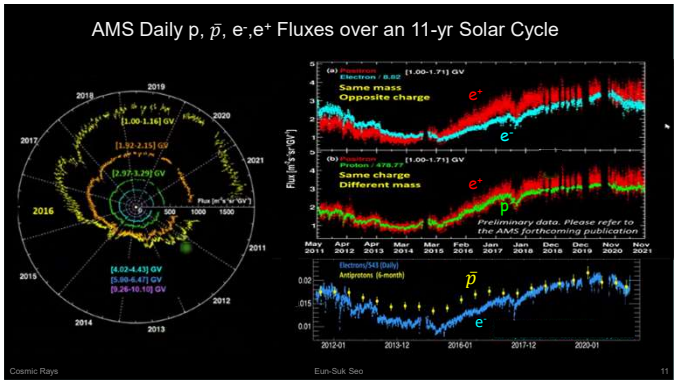
8


Astronomy magazine
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.
"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.
NBC NEWS
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
SCIENTIFIC AMERICAN
Dark Matter Looks WIMPy

9


Charge Sign Dependent Solar Modulation
Cycle 22
A>0
Cycle 23
A<0
Cycle 24
A>0
SSN
NM
BESS
SOHO EPHIN
PAMELA
AMS
Cosmic Rays
Eun-Suk Seo
10

10


AMS Daily p, p̄, e⁻,e⁺ Fluxes over an 11-yr Solar Cycle
Same mass
Opposite charge
Same charge
Different mass
Preliminary data. Please refer to the AMS forthcoming publication
Cosmic Rays
Eun-Suk Seo
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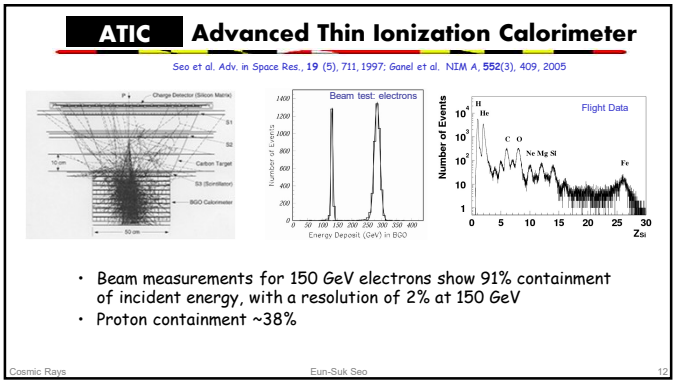
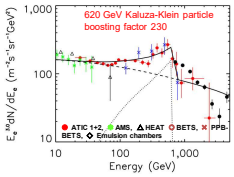

ATIC
Advanced Thin Ionization Calorimeter
Seo et al. Adv. in Space Res., 19 (5), 711, 1997; Ganel et al. NIM A, 552(3), 409, 2005
Beam test: electrons
Flight Data
Beam measurements for 150 GeV electrons show 91% containment of incident energy, with a resolution of 2% at 150 GeV
Proton containment ~38%
Cosmic Rays
Eun-Suk Seo
12

12

## ATIC discovers mysterious excess of high energy electrons

Chang et al., Nature, **456**, 362-365 (2008)




Cosmic Rays Eun-Suk Seo 13

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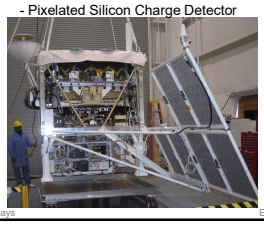
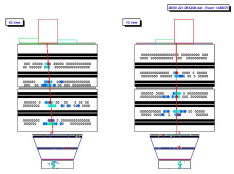
## CREAM Cosmic Ray Energetics And Mass

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.



Cosmic Rays Eun-Suk Seo 14

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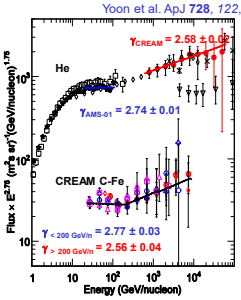
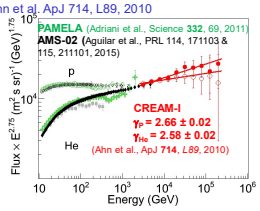
## Discrepant hardening

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."

Cosmic Rays Eun-Suk Seo 15

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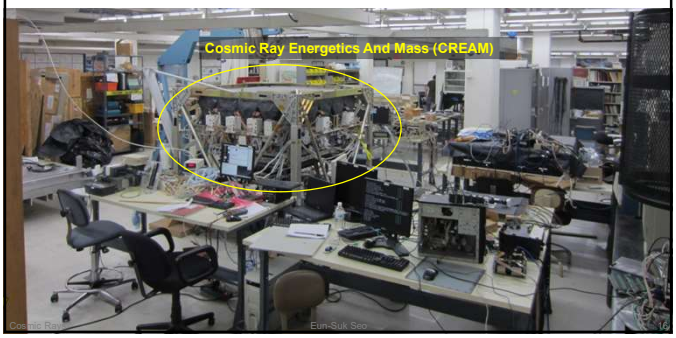
## Seo's Lab at the University of Maryland




Cosmic Rays Eun-Suk Seo 16

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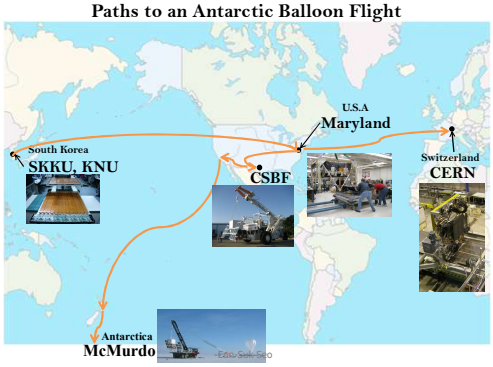
## Paths to an Antarctic Balloon Flight

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## Balloon Launch in Antarctica

Cosmic Rays Eun-Suk Seo 18

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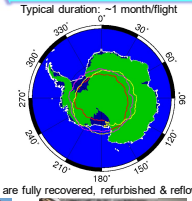
## Balloon Flights in Antarctica Offer Hands-On Experience

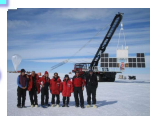
CREAM has trained >100 students

Typical duration: ~1 month/flight



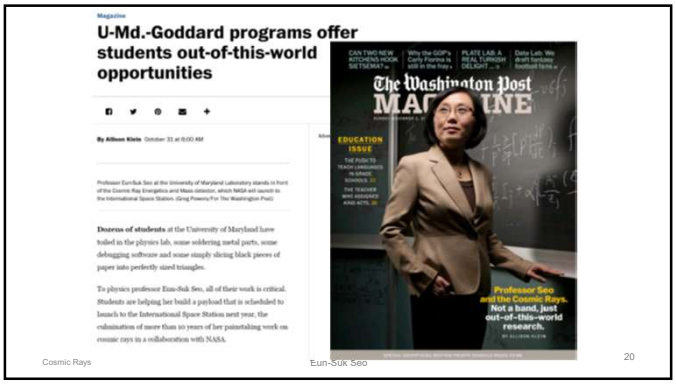
The instruments are for the most part **built in-house by students** and young scientists, many of them currently working in the on-campus laboratory.

Instruments are fully recovered, refurbished & reflown.





19



Magazine

**U-Md.-Goddard programs offer students out-of-this-world opportunities**

By Allison Klein October 31 at 6:00 AM

Professor Eun-Suk Seo at the University of Maryland laboratory stands in front of the Cosmic Ray Energetics and Mass detector, which NASA will launch to the International Space Station. (Greg Powers/For The Washington Post)

**Dozens of students** at the University of Maryland have toiled in the physics lab, some soldering metal parts, some debugging software and some simply slicing black pieces of paper into perfectly sized triangles.

To physics professor Eun-Suk Seo, all of their work is critical. Students are helping her build a payload that is scheduled to launch to the International Space Station next year, the culmination of more than 10 years of her painstaking work on cosmic rays in a collaboration with NASA.

The Washington Post MAGAZINE

EDUCATION ISSUE

Professor Seo and the Cosmic Rays. Not a band, just out-of-this-world research.



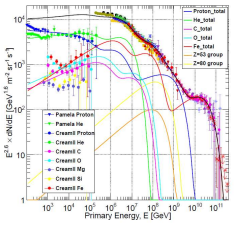
20

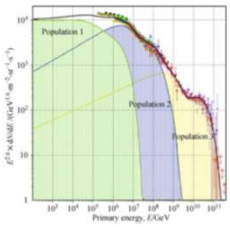
## CREAM data to explain the knee and beyond

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

Acceleration limit:

$E_{max_z} = Ze \times R = Z \times E_{max_p}$, *where rigidity R = Pc/Ze*



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## ISS-CREAM: CREAM for the ISS

SpaceX-12 Launch on 8/14/2017

Aiming high

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 ...

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 1940, 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 ...

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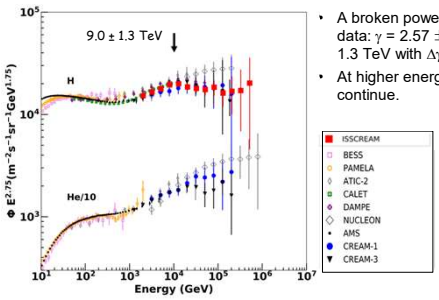
## ISS-CREAM Proton Spectrum (2.5 – 655 TeV)

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



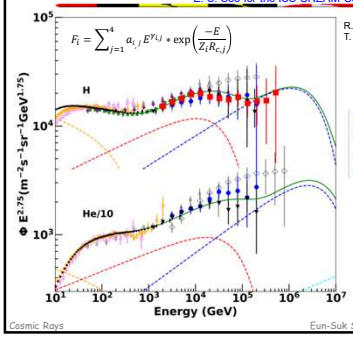

- A broken power law fit to 2.5 – 164 TeV data: $\gamma = 2.57 \pm 0.03$ and a break at $9.0 \pm 1.3$ TeV with $\Delta\gamma = 0.25 \pm 0.05$.
- At higher energies, the softening does not continue.
  - The deviation from a single power law near 10 TeV is consistent with the softening reported by CREAM-I &III, DAMPE, NUCLEON, and CALET, but ISS-CREAM extends measurements to higher energies than those prior measurements.



23

## 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.

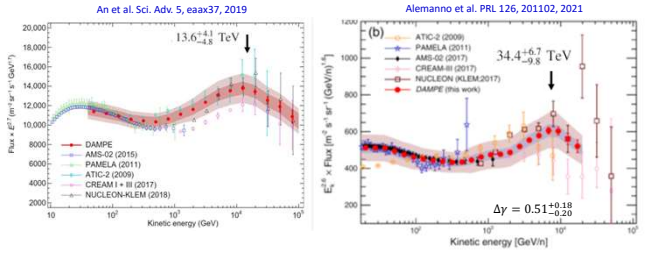


24

## DAMPE Proton (40 GeV – 100 TeV) and Helium (70 GeV – 80 TeV) Spectra

An et al. Sci. Adv. 5, eaax37, 2019

Alemanno et al. PRL 126, 201102, 2021



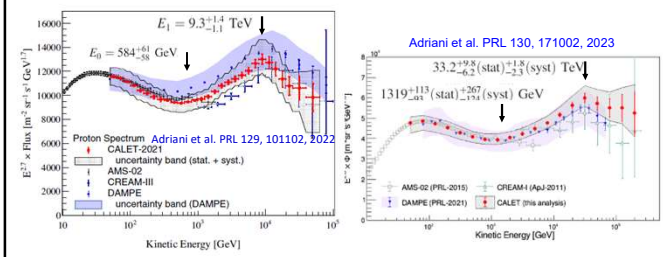



25

## CALET Proton (50 GeV – 60 TeV) Helium (40 GeV – 250 TeV) Spectra

Adriani et al. PRL 129, 101102, 2022

Adriani et al. PRL 130, 171002, 2023

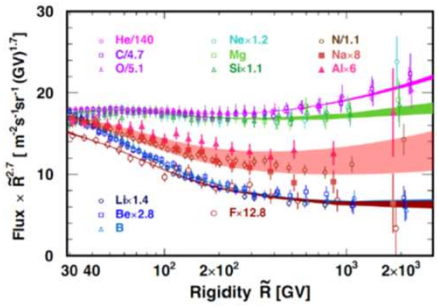





26

## Groups of CR nuclei ($2 \le Z \le 14$)

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



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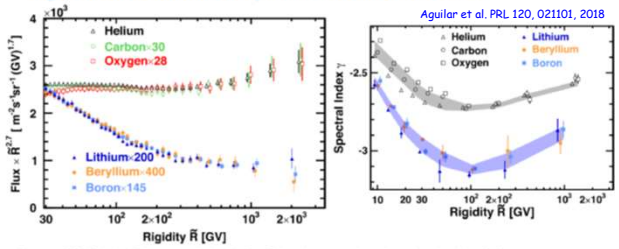
## Light nuclei: Lithium, Beryllium, Boron vs He, C, O

Aguilar et al. PRL 120, 021101, 2018




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

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



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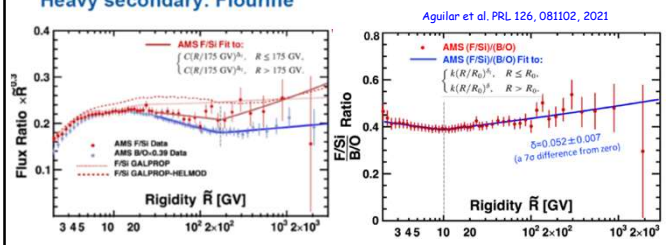
## Heavy secondary: Flourine

Aguilar et al. PRL 126, 081102, 2021




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.



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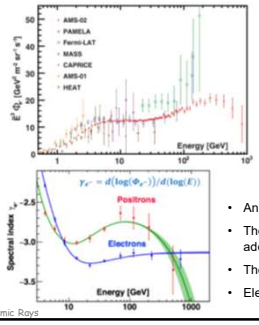
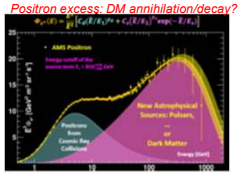
## Positrons and Electrons

Aguilar et al., Phys. Rev. Lett., 122, 041102, 2019; Aguilar et al., Phys. Rev. Lett., 122, 101101, 2019




*Positron excess: DM annihilation/decay?*




- 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



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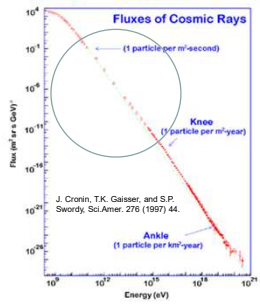
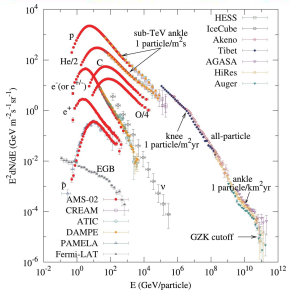
## Recent experiments fill the data gap

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## Summary

- Significant advances in CR measurements have been made in recent years.
  - ✓ An excess in positron spectrum.
  - ✓ Spectral hardening above ~200 GV.
  - ✓ Proton spectrum softening at ~10 TeV.
  - ✓ 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 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 possible softening at an energy of ~10 TeV/n?
  - What causes different classes of the primary CR spectra with different rigidity dependence?



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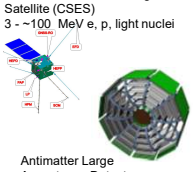
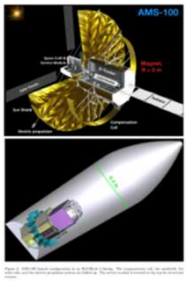
## Future Outlook

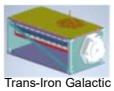
China Seismo-Electromagnetic Satellite (CSES)
3 - ~100 MeV e, p, light nuclei





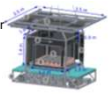

The High Energy cosmic-Radiation Detection (HERD) facility ~ 2027

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



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

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





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