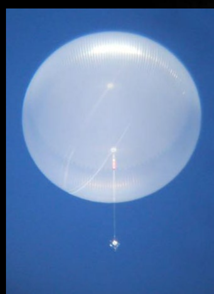
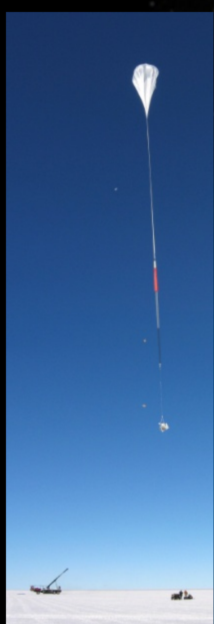
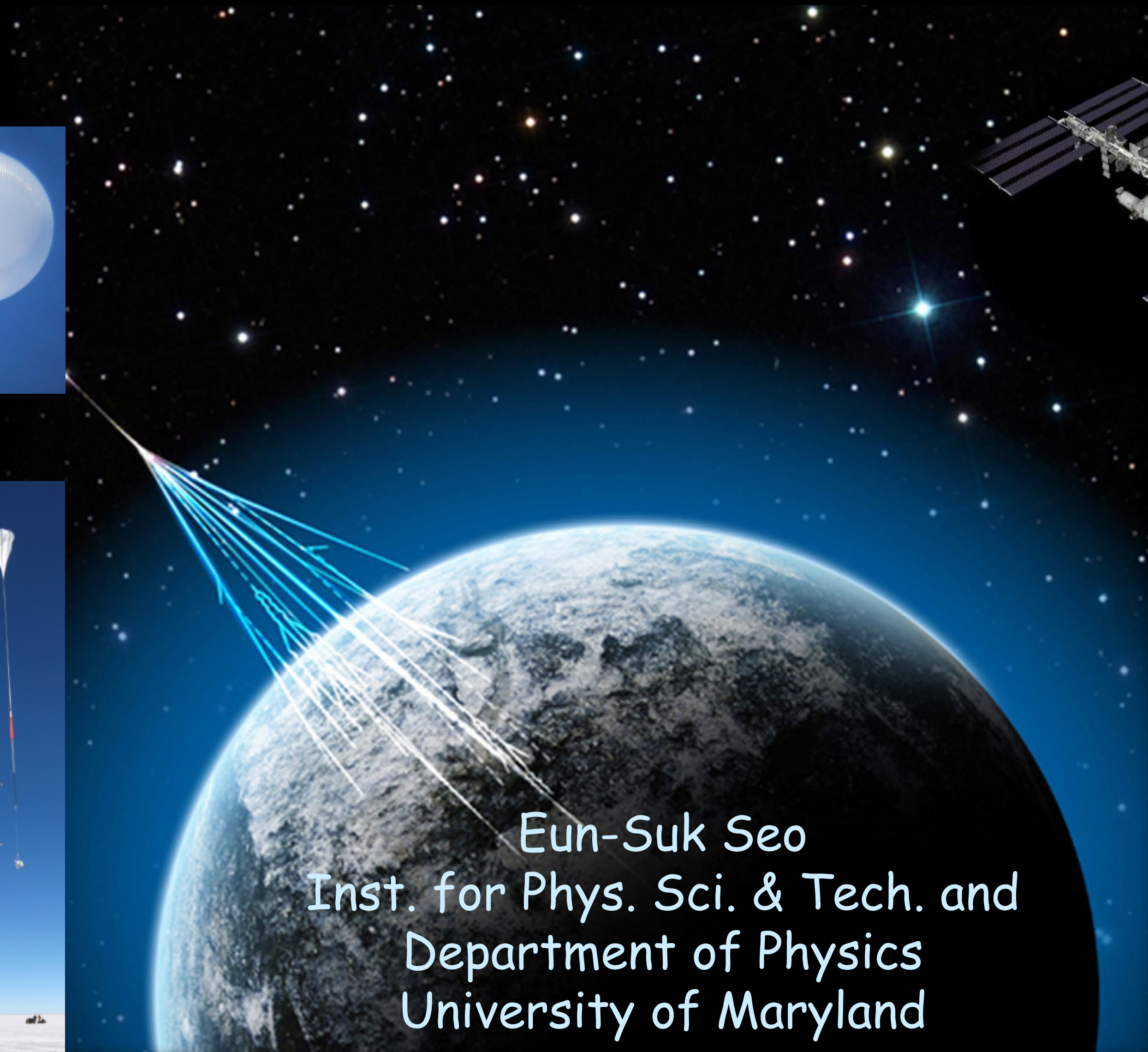
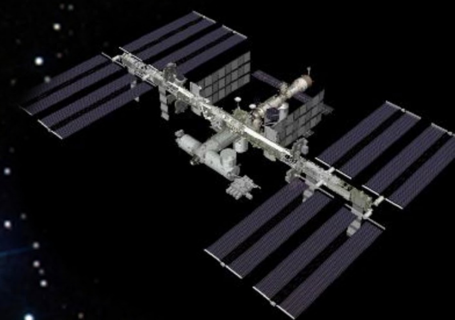
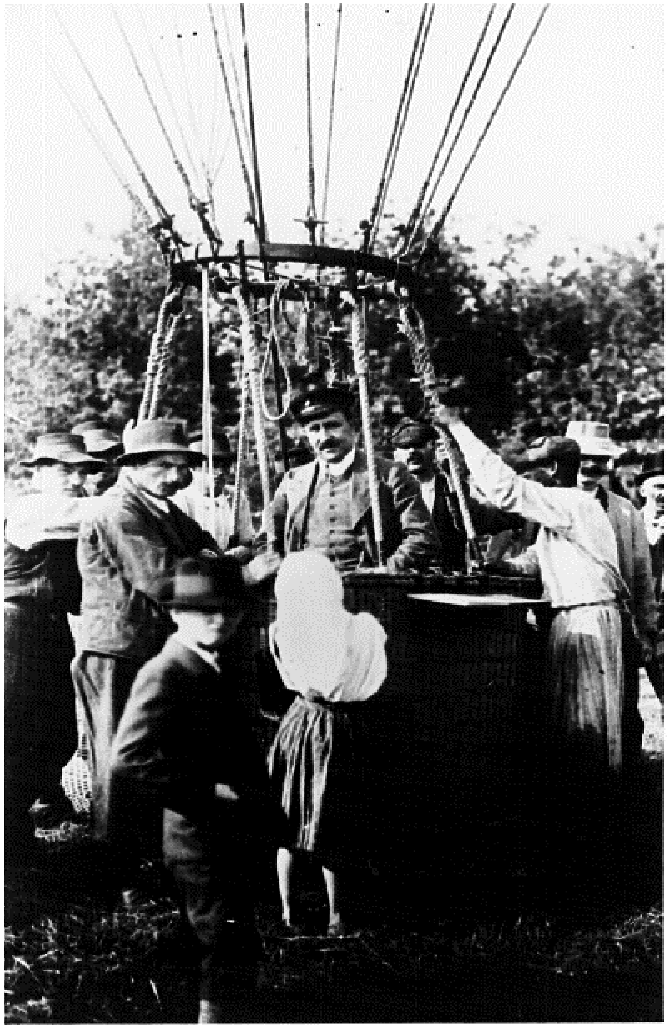
Workshop on Applications of Cosmic-ray Measurements, Atlanta, GA, October 4-6, 2019

Origin of Cosmic Rays

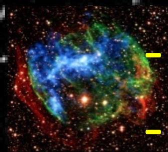

Eun-Suk Seo
Inst. for Phys. Sci. & Tech. and
Department of Physics
University of Maryland

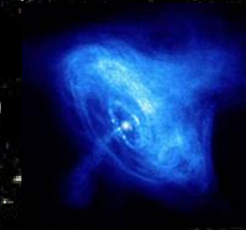
Discovery of Cosmic Rays



- 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)
  - …….
- "Direct Measurements of Cosmic Rays Using Balloon Borne Experiments," E. S. Seo, Invited Review Paper for Topical Issue on Cosmic Rays, Astropart. Phys., **39/40**, *76-87*, 2012.

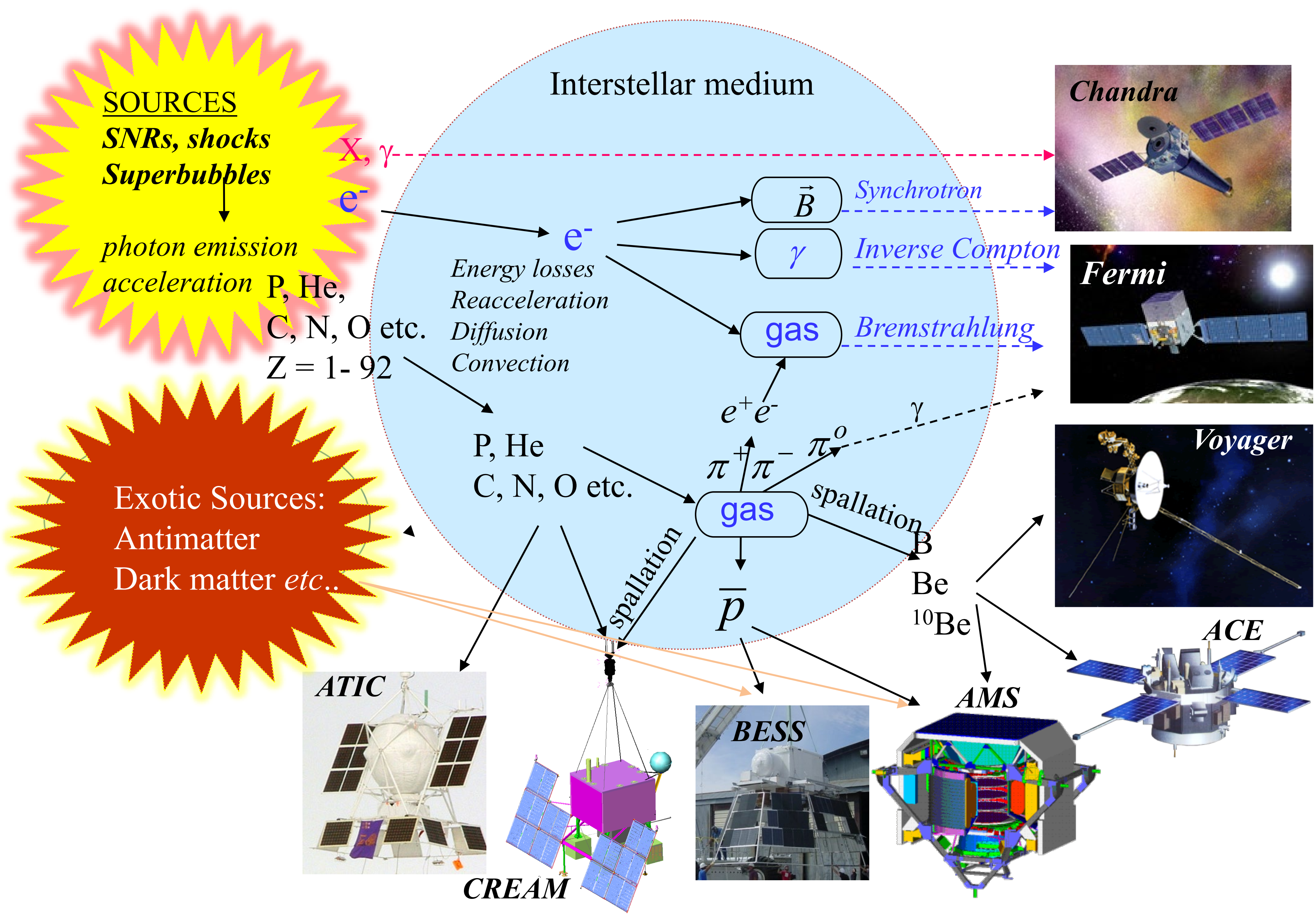
Cosmic Rays: Why care?





- Highest-energy particles known to mankind
- Made in some of the most extreme environments of the Universe
- Energy density is comparable to thermal energies, magnetic fields

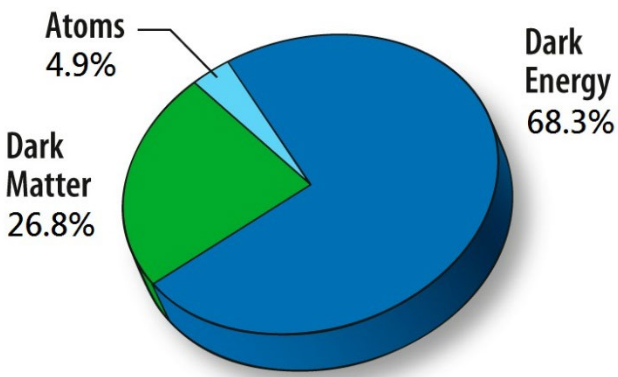
They influence
- evolution and shape of galaxies
- state of interstellar medium
- interstellar chemistry
- evolution of species on Earth
- and even the weather …

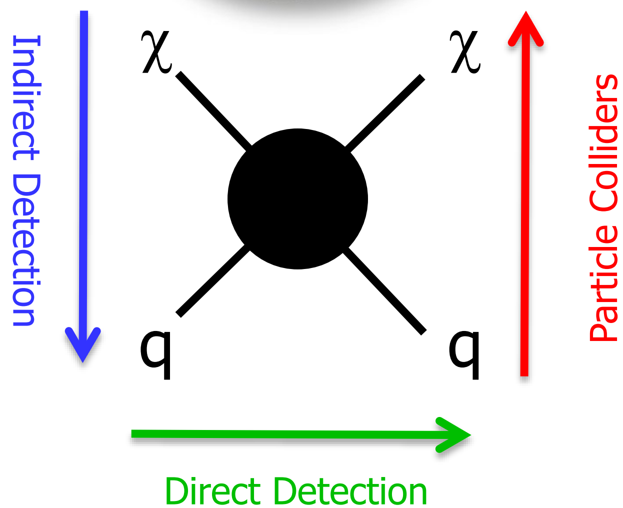


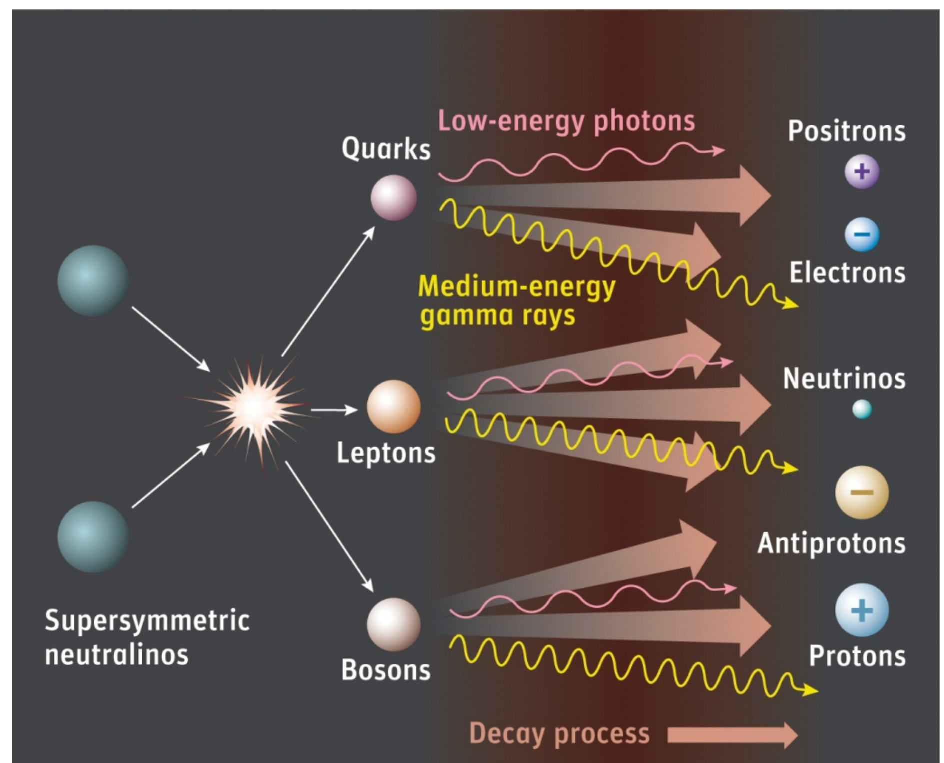
SOURCES
SNRs, shocks
Superbubbles
photon emission
acceleration
X, γ
e-
P, He,
C, N, O etc.
Z = 1- 92
Interstellar medium
e-
Energy losses
Reacceleration
Diffusion
Convection
B
γ
gas
Synchrotron
Inverse Compton
Bremstrahlung
e+e-
γ
π+ π− π0
P, He
C, N, O etc.
gas
spallation
spallation
B
Be
10Be
p
Exotic Sources:
Antimatter
Dark matter etc..
Chandra
Fermi
Voyager
ACE
AMS
BESS
ATIC
CREAM

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

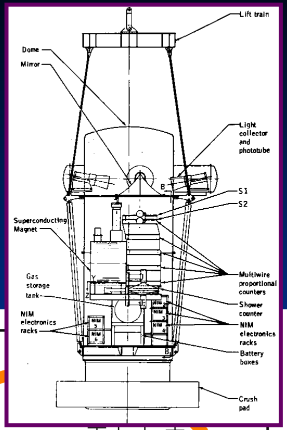
- Weakly Interacting Massive Particles (WIMPS) could comprise dark matter.
- This can be tested by direct search for various annihilating products of WIMP’s in the Galactic halo.

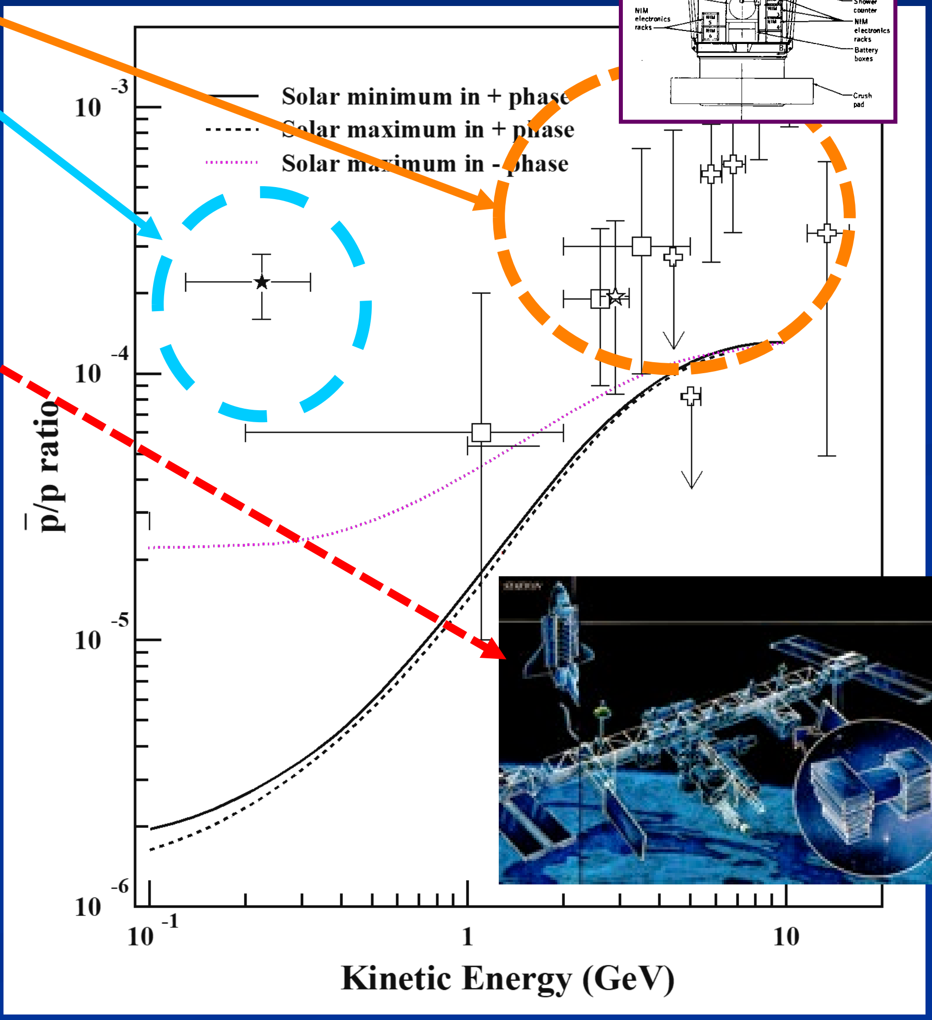






Search for Antimatter & Dark Matter Novel Cosmic Origin





<u>1979:</u> <u>first observation of antiprotons</u>

(Golden et al,1979 , Bogomolov et al.1979)

1981: Anomalous excess (Buffington et al.)

1987: <u>LEAP</u>, PBAR

1988: *ASTROMAG proposal*

1989: <u>MASS</u>

1991: *ASTROMAG shelved*

1992: IMAX

1993: <u>BESS</u>, TS93

1994: CAPRICE, HEAT

1995: AMS proposal

1998: <u>AMS-01</u> (Discovery STS-91)

2000/2: Heat-pbar

2004: <u>BESS-Polar I</u>

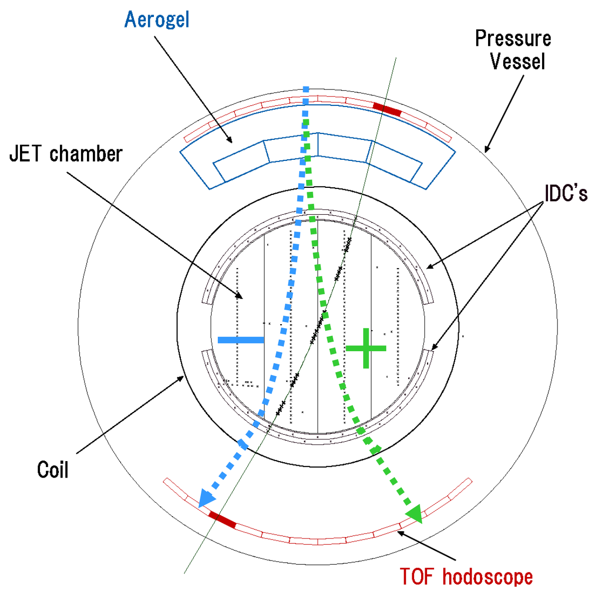
2006-present PAMELA (Polar-orbit)

2007: <u>BESS-Polar II</u>

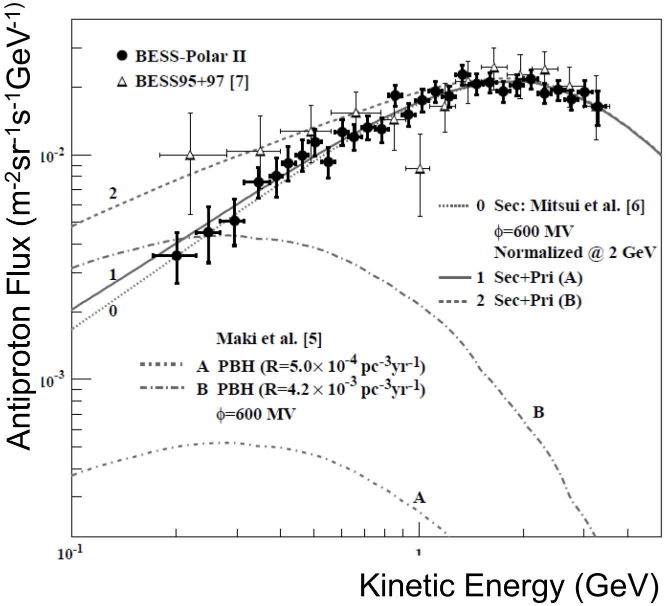
2011-present: <u>AMS-02</u> (Endeavour STS -134)

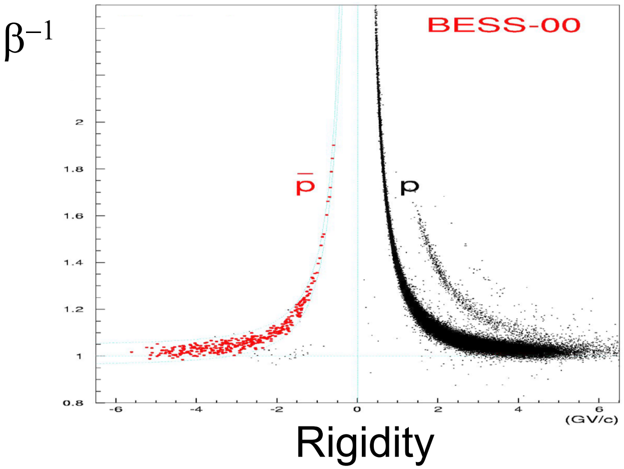
BESS-Polar II

Balloon–borne Experiment with a Superconducting Spectrometer



Abe et al. PRL, 108, 051102, 2012

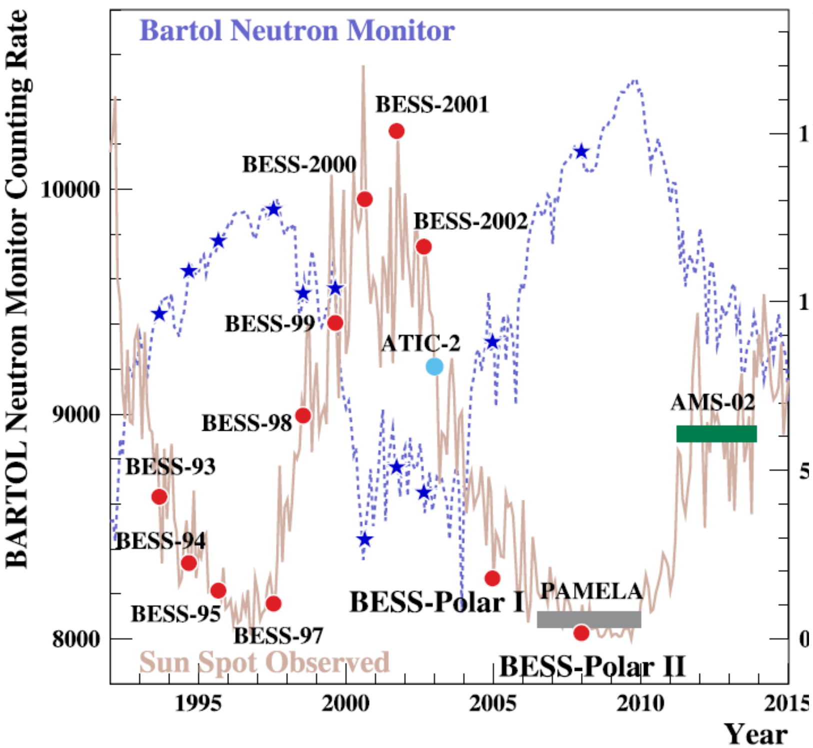


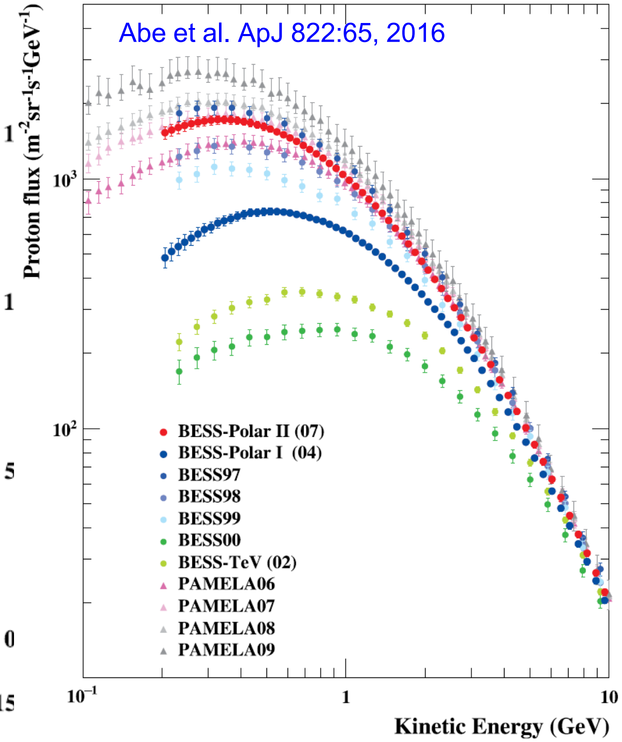


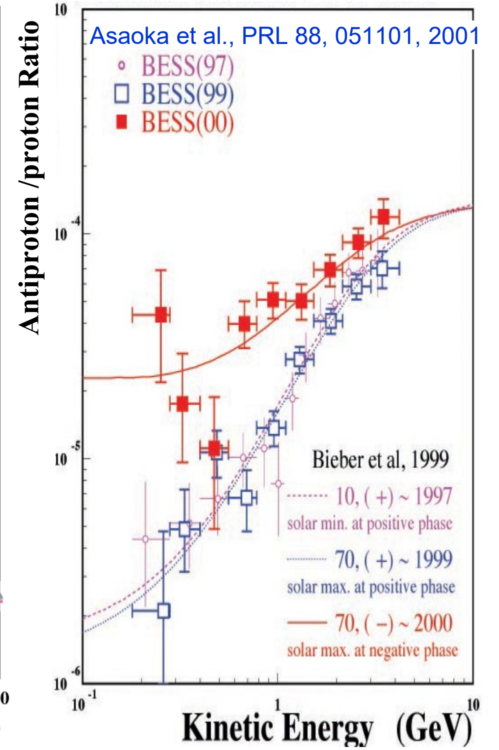
- Original BESS instrument was flown nine times between 1993 and 2002.
- New BESS-Polar instrument flew from Antarctica in 2004 and 2007
  - Polar-I: 8.5 days observation
  - Polar-II 24.5 day observation, 4700 M events

  7886 antiprotons detected: **no evidence of primary antiprotons from evaporation of primordial black holes.**

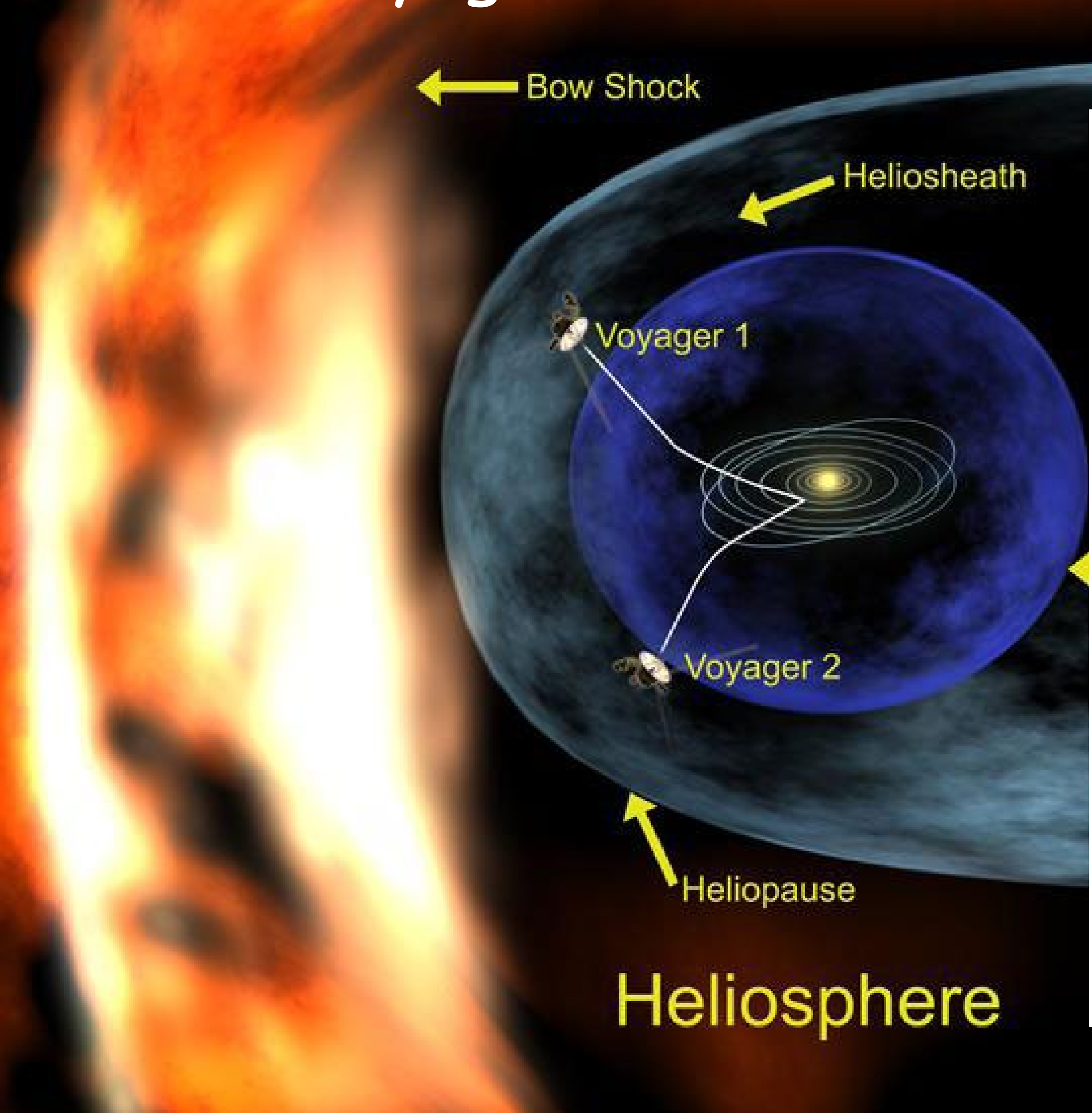
Charge Sign Dependent Solar Modulation

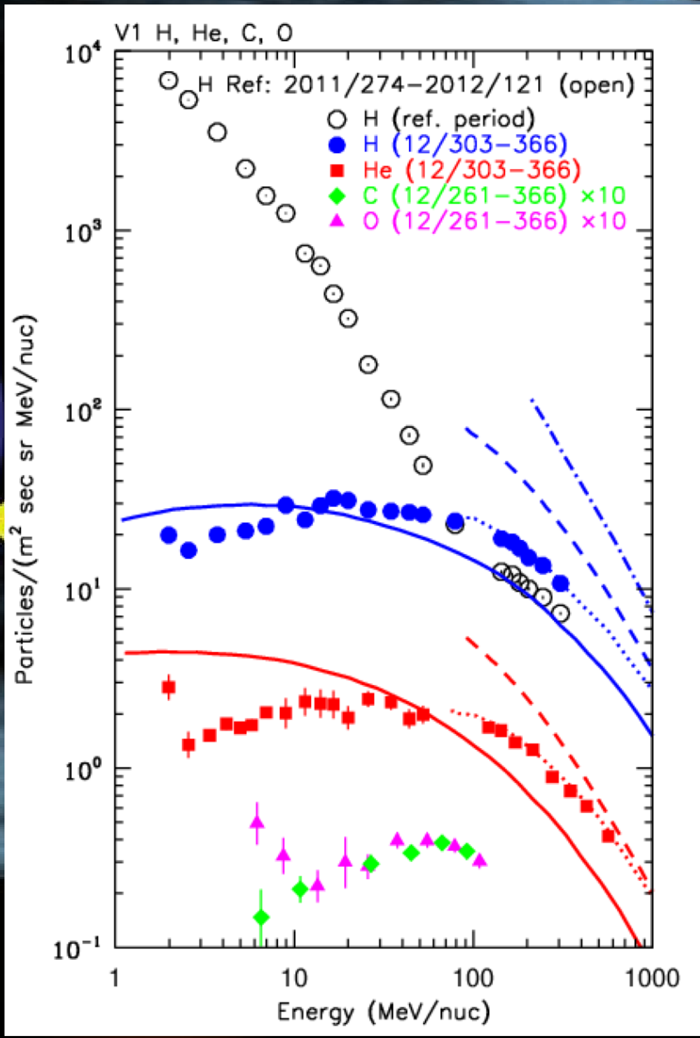






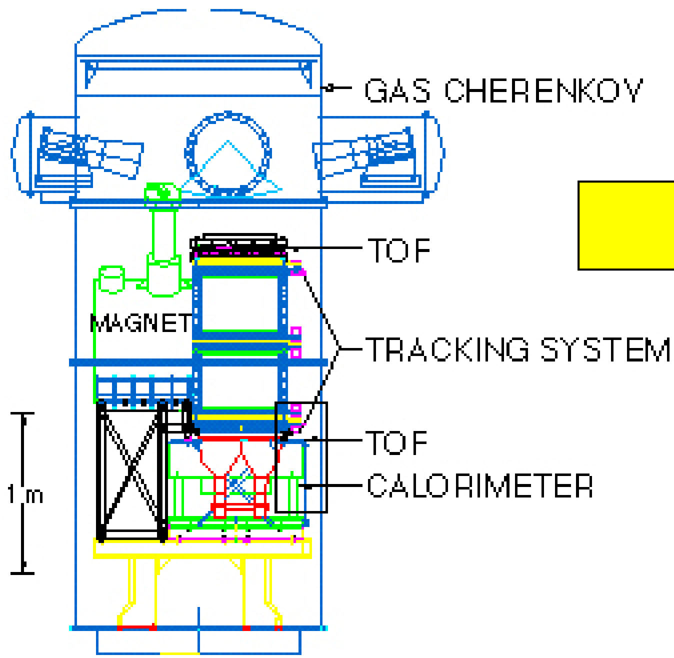
Voyager 1 in Interstellar Space

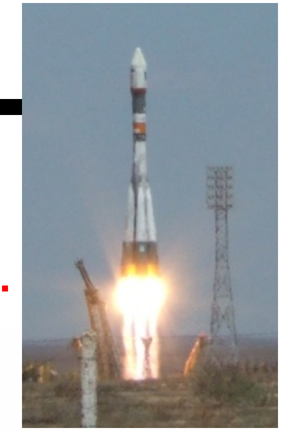


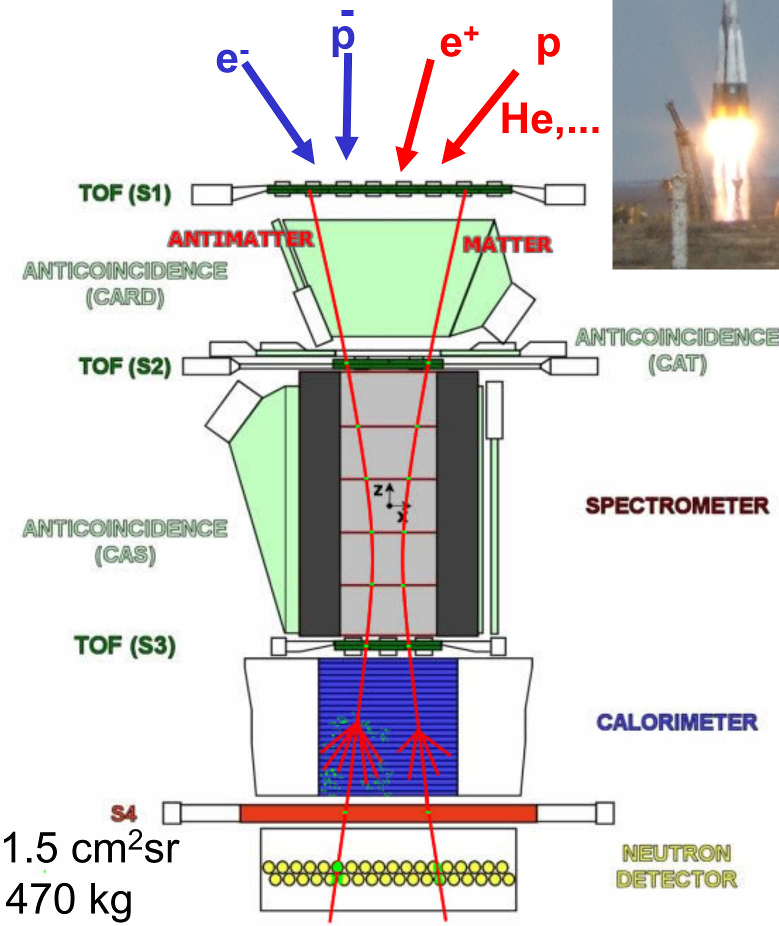


Stone et al., Science 2013

From MASS to PAMELA



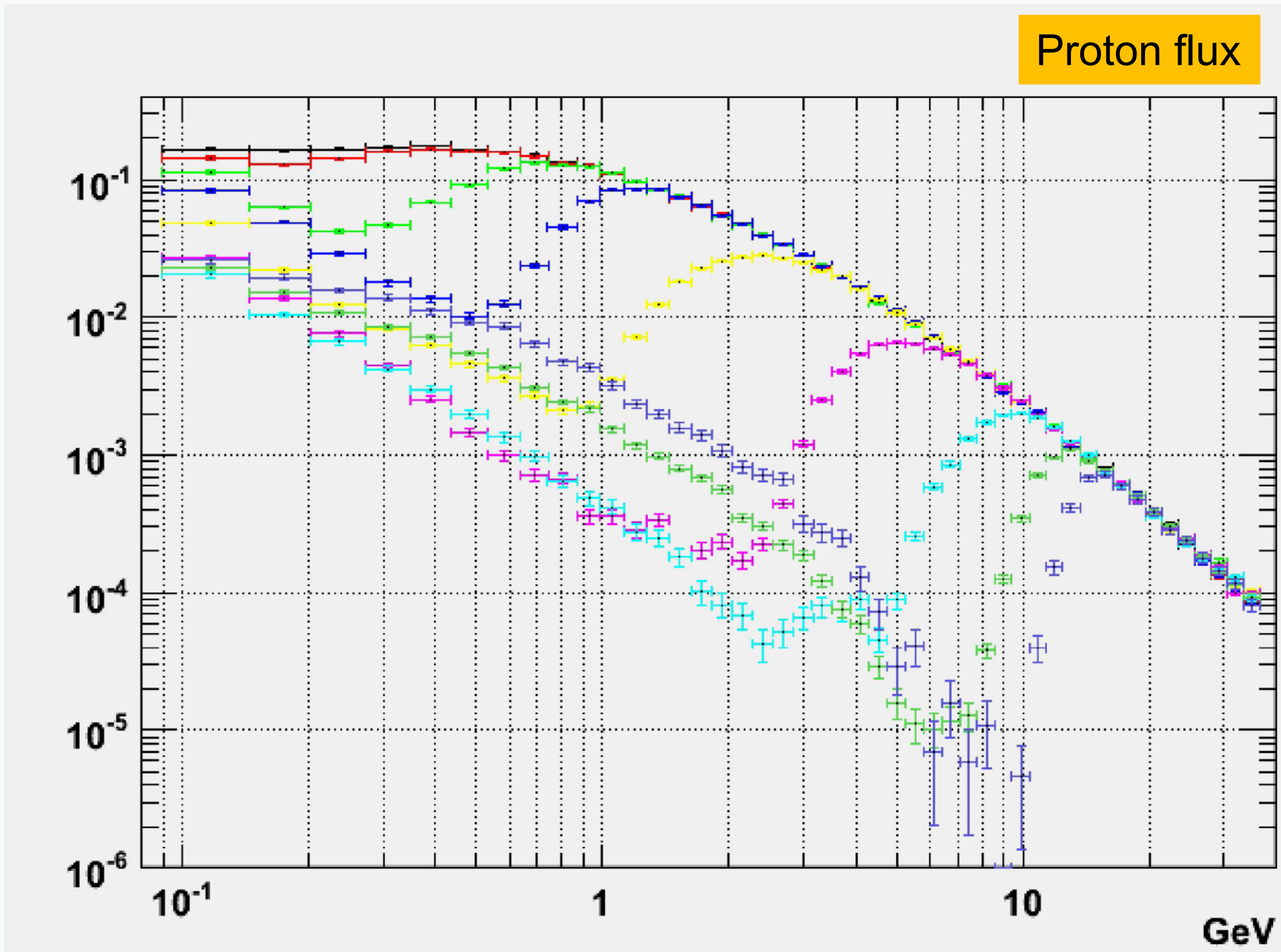




Matter Antimatter Superconducting Spectrometer (MASS)
1989 balloon flight in Canada

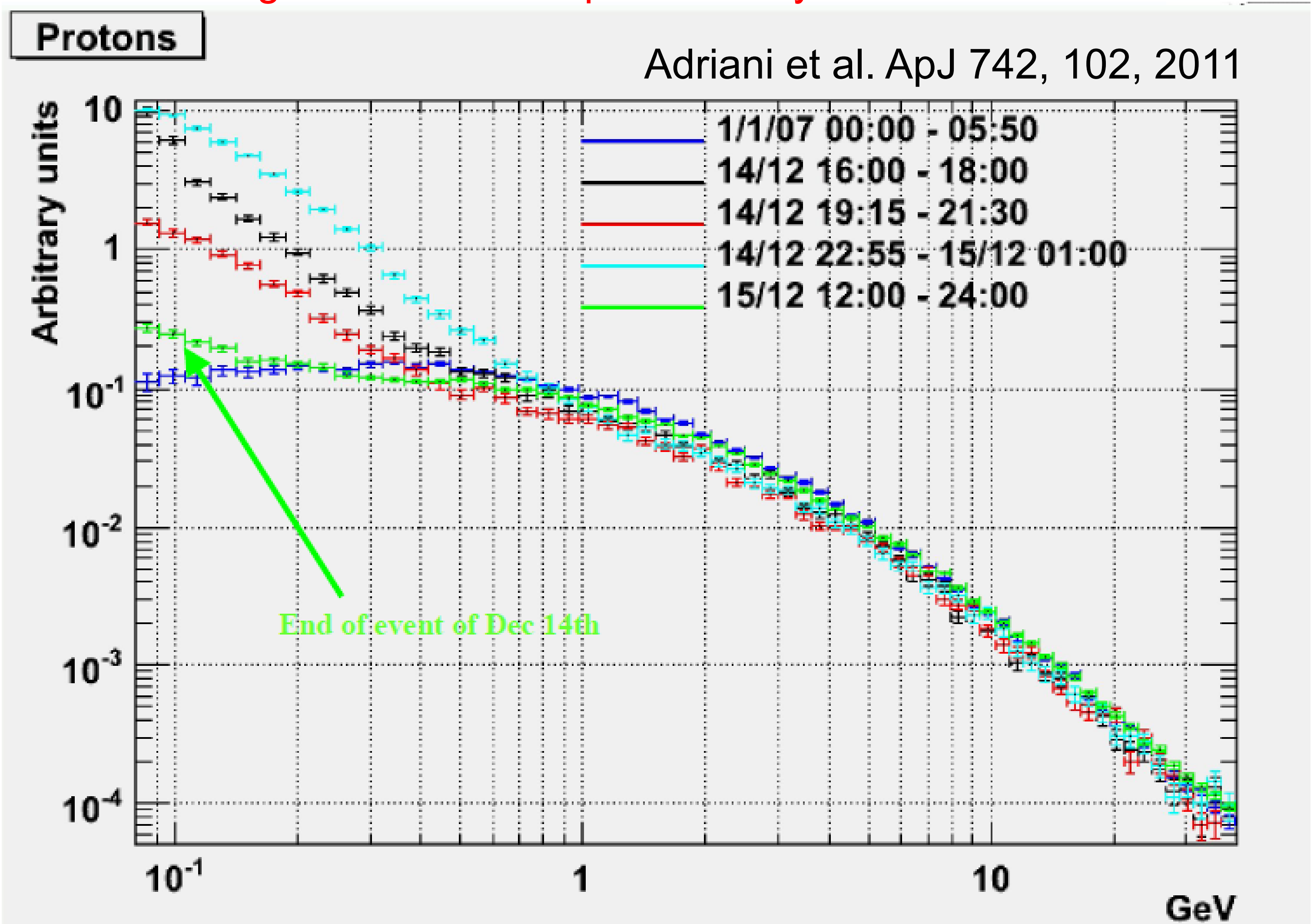
GF ~21.5 cm^2sr
Mass: 470 kg
Size: 130x70x70 cm^3
Payload for Anti-Matter Exploration and Light-nuclei Astrophysics (PAMELA)
Satellite Launch 6/15/06
Operation termination in 2016

Pamela under various geomagnetic conditions



SEP from Dec. 14, 2006 CME

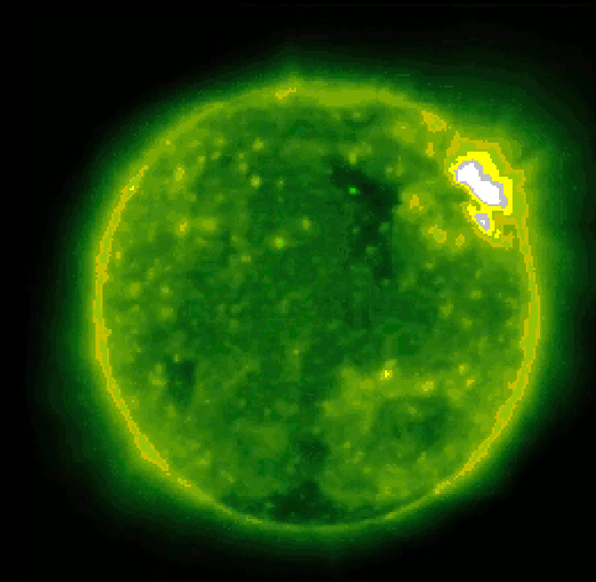
Change in flux and shape on a very short time scale



Solar Physics with the Alpha Magnetic Spectrometer

Dec 21st, 2012

00 hour : 05 min



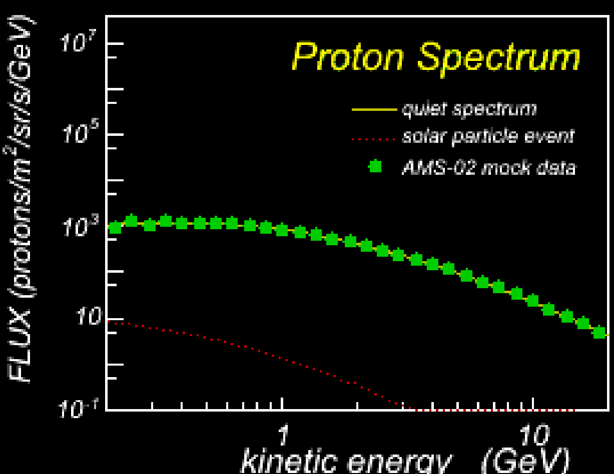
Spectacular phenomena are connected with solar activity

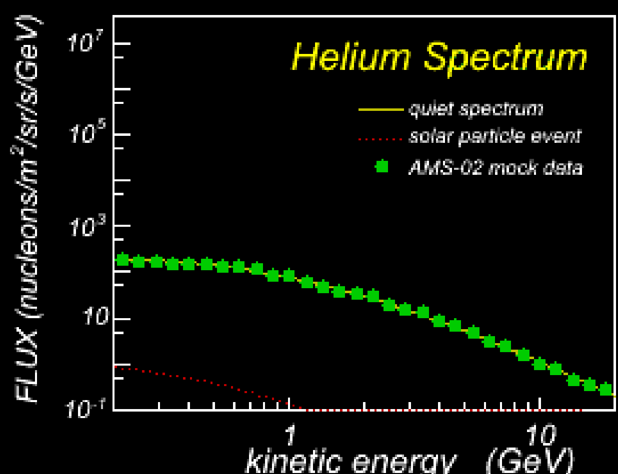
- *several solar events are expected during the lifetime of the AMS mission*
- *AMS has the capability to detect rapid variations of the cosmic ray flux*
- *case study: hypotetical flare of december 21st, 2012 (from Mayan prophecy)*

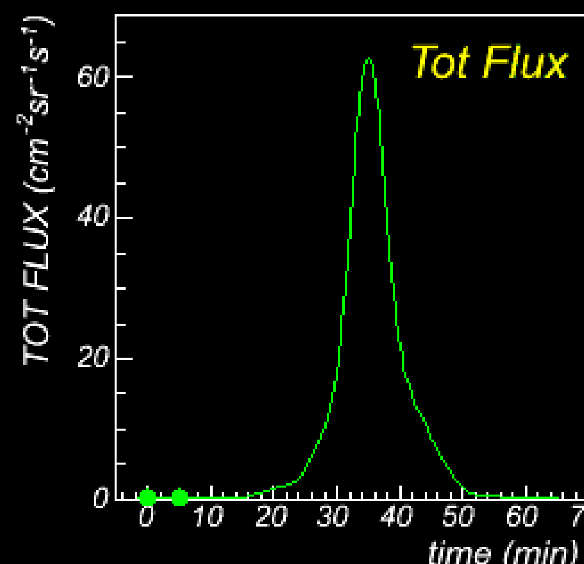
AMS-02 Projected Measurements

→ proton and helium energy spectra in 0.2 - 20 GeV

→ 5 min time intervals





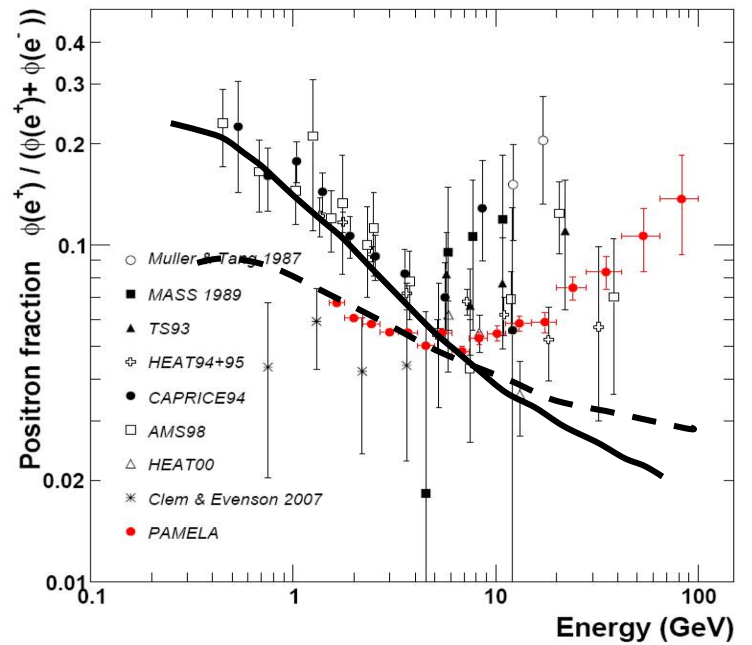


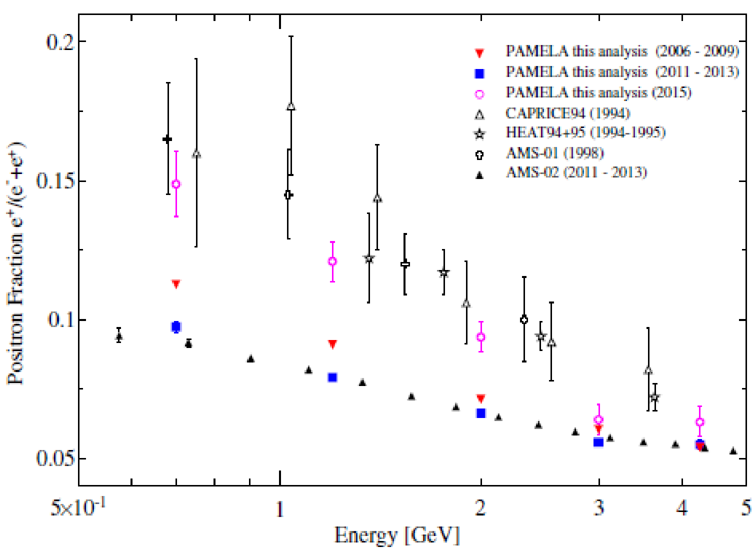
Nicola Tomassetti | Perugia University & INFN | 24-January-2011 (Gregorian) | Baktun-12 Katun-19 Tun-18 Uinal-1 Kin-3 (Mayan)

PAMELA Payload for Anti-Matter Exploration and Light-nuclei Astrophysics

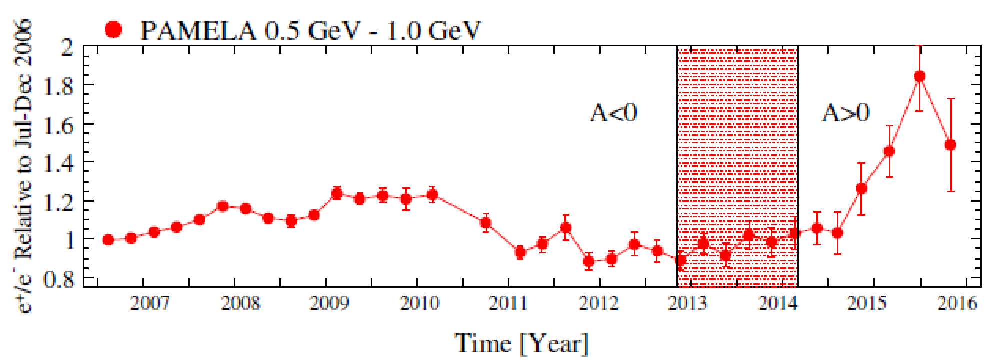
"High energy data deviate significantly from predictions of secondary production models (curves), and may constitute the evidence of dark matter particle annihilations, or the first observation of positron production from near-by pulsars."

Adriani et al., Nature, 458, 607-609 (2009)





Adriani et al. PRL 116, 241105, 2016

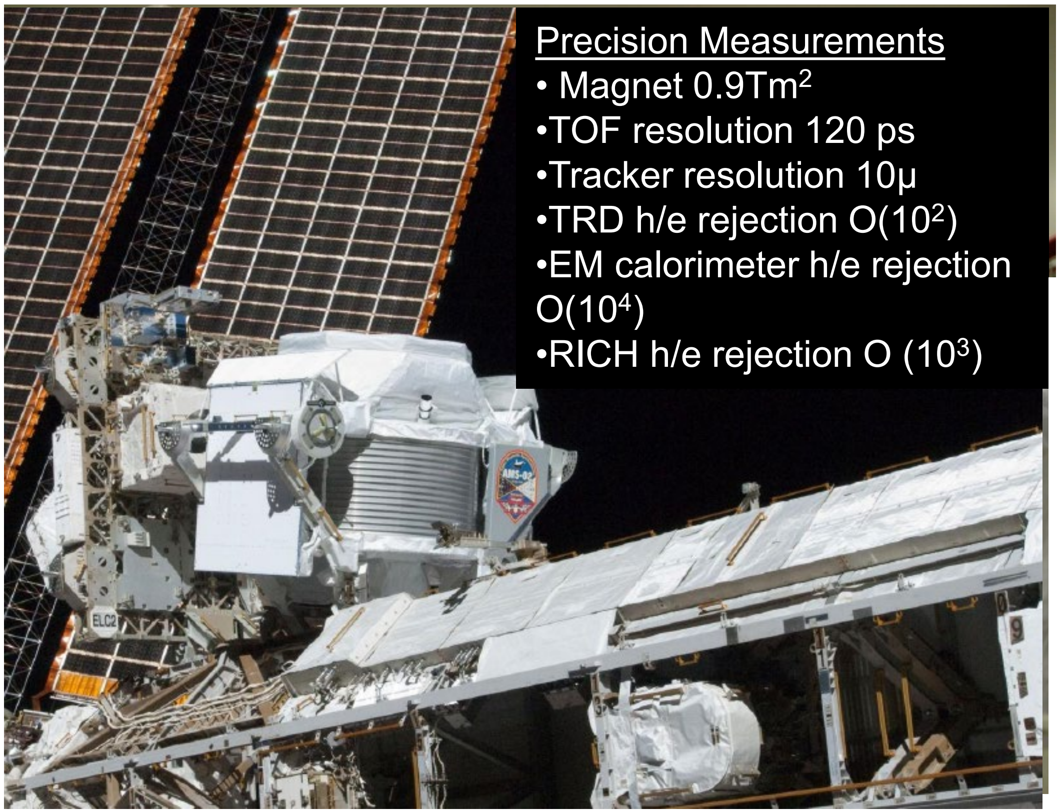


AMS

Alpha Magnet Spectrometer

Launch for ISS on May 16, 2011

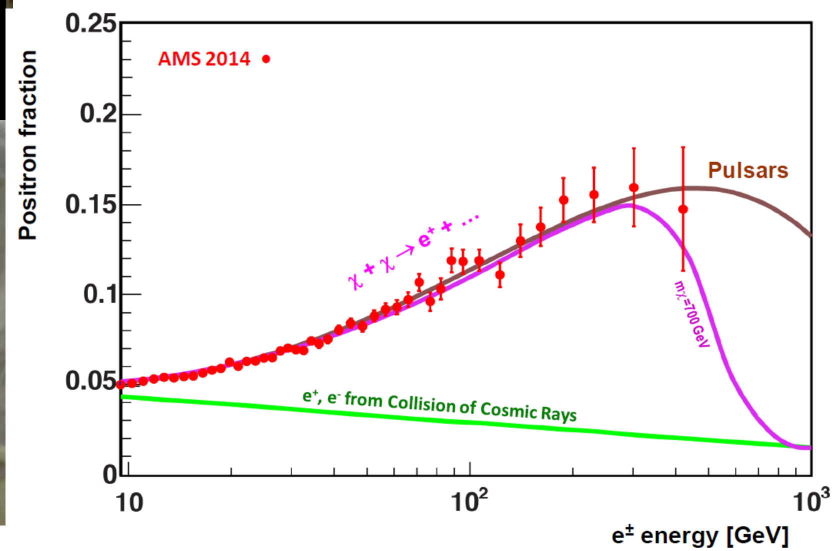
- Search for dark matter by measuring positrons, antiprotons, antideuterons and γ-rays with a single instrument
- Search for antimatter on the level of < 10^{-9}



Precision Measurements
- Magnet 0.9Tm^2
- TOF resolution 120 ps
- Tracker resolution 10μ
- TRD h/e rejection O(10^2)
- EM calorimeter h/e rejection O(10^4)
- RICH h/e rejection O (10^3)

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

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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AMS Space Experiment Sees Hints of Dark Matter Particles

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

SCIENTIFIC AMERICAN™

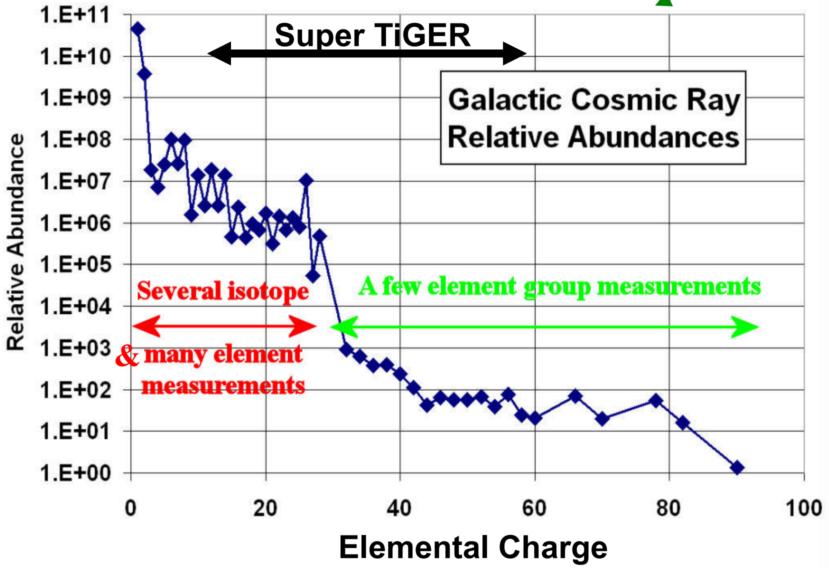
Permanent Address: http://www.scientificamerican.com/podcast/episode/dark-matter-looks-wimpy/
Space » 60-Second Space

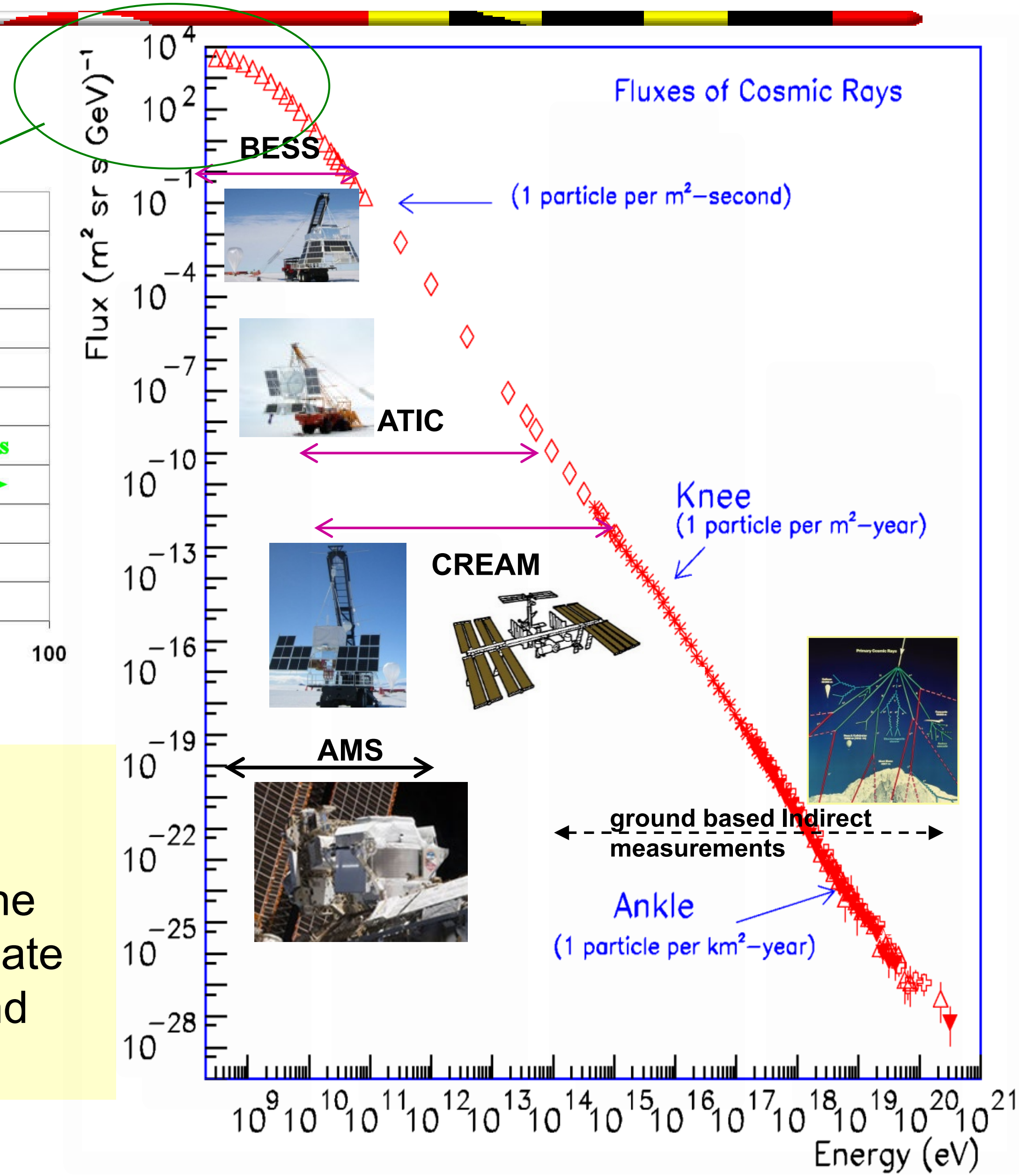
Dark Matter Looks WIMPy

Data from the International Space Station-based Alpha Magnetic Spectro
consists of the invisible particles called weakly interacting massive particl

"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.

How do cosmic accelerators work?



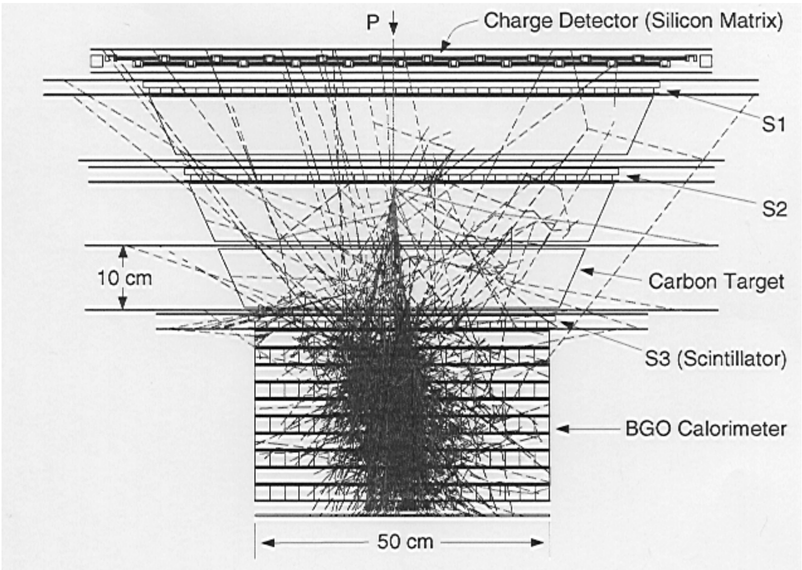


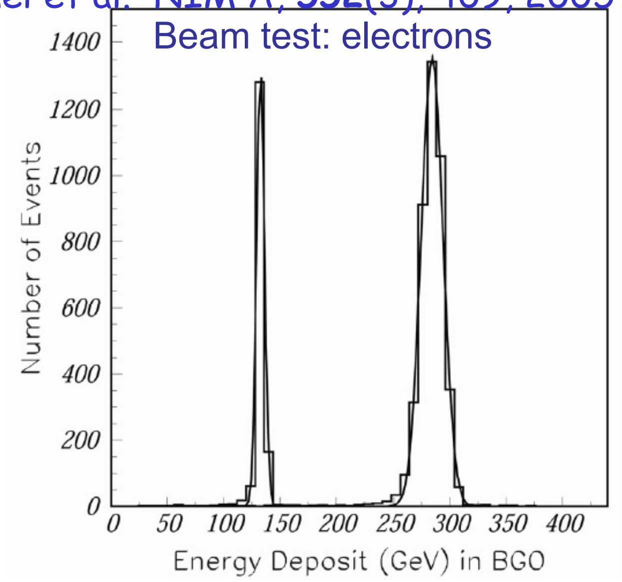
Mission Goal

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

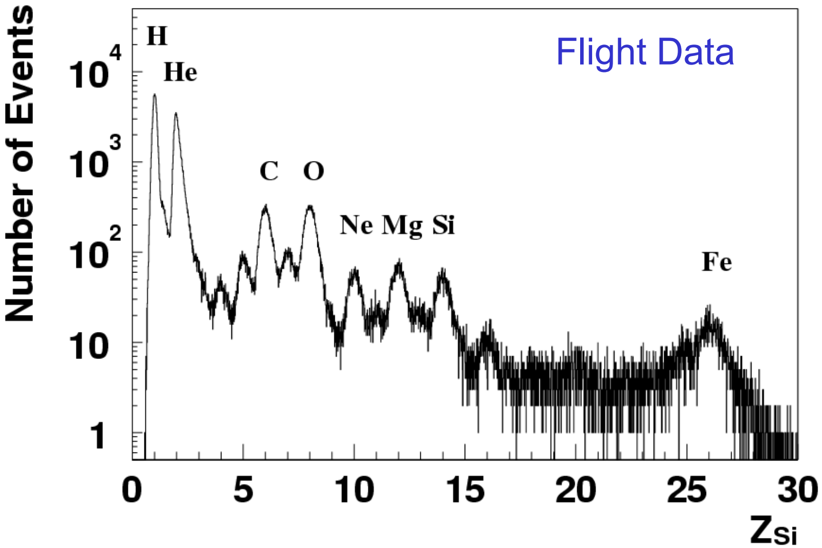
ATIC Advanced Thin Ionization Calorimeter

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



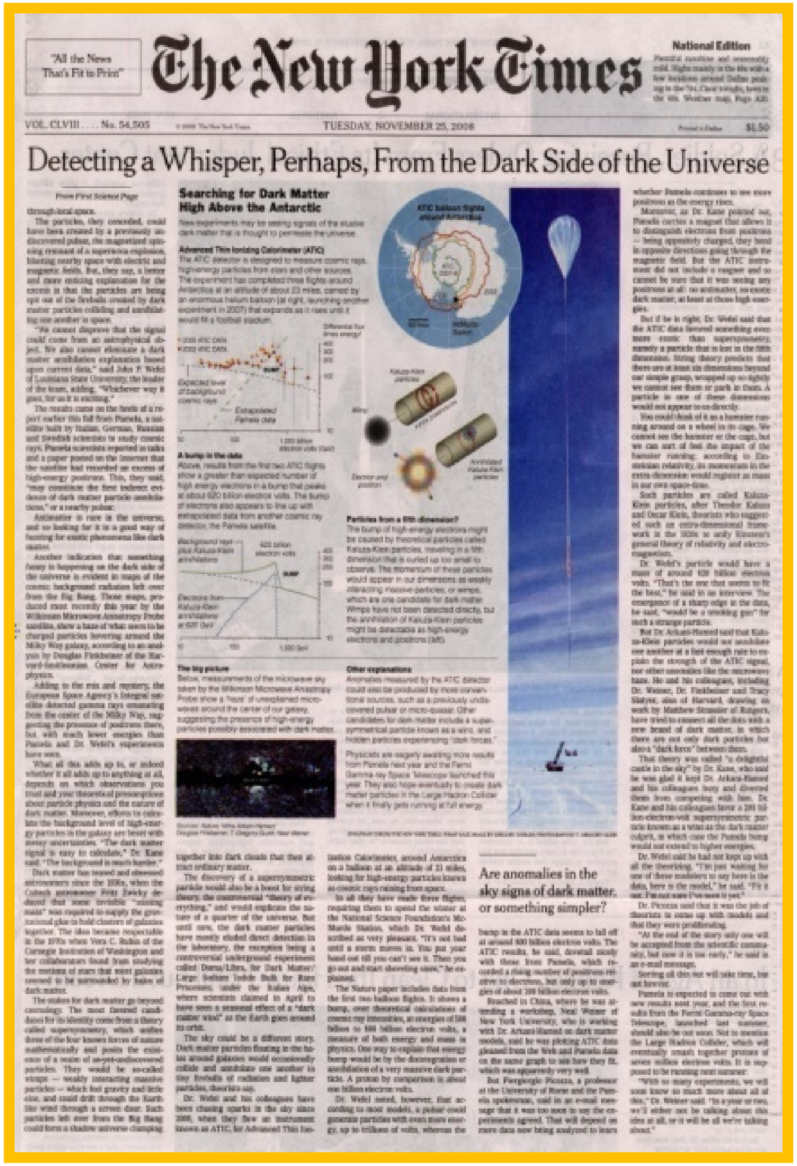


- Beam measurements for 150 GeV electrons show 91% containment of incident energy, with a resolution of 2% at 150 GeV
- Proton containment ~38%



ATIC discovers mysterious excess of high energy electrons

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



nature International weekly journal of science

Cited > 200 times in ~ 9 mo

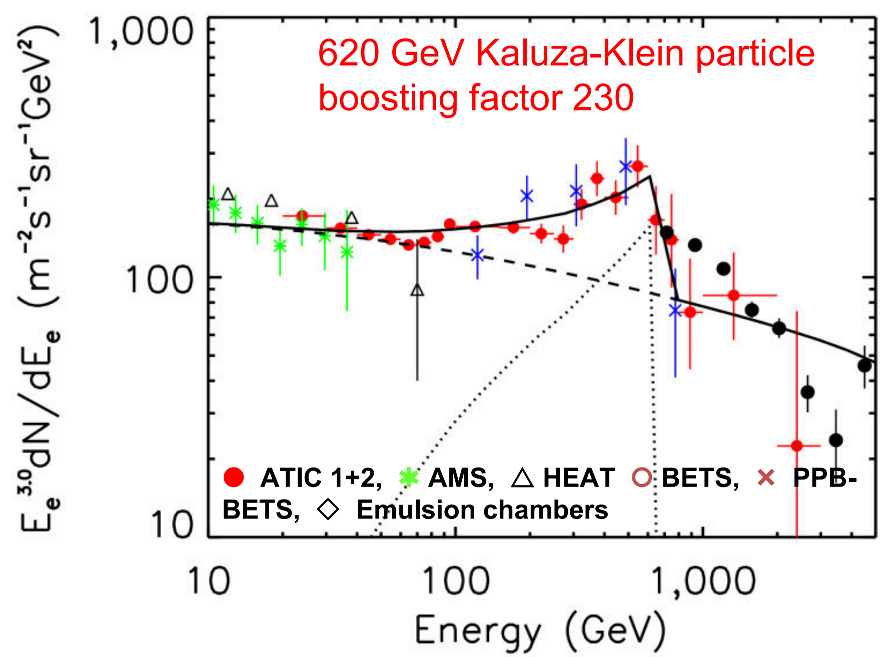
Letter

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

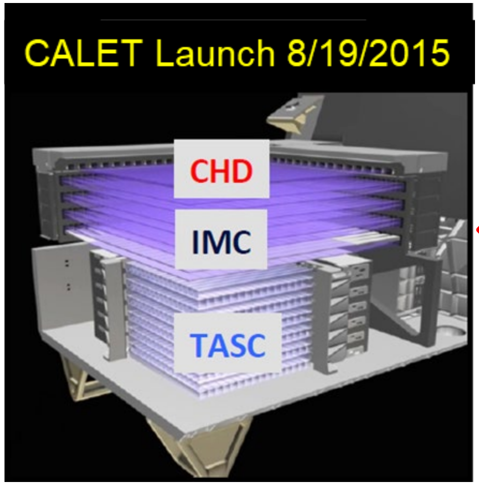
An excess of cosmic ray electrons at energies of 300–800 GeV

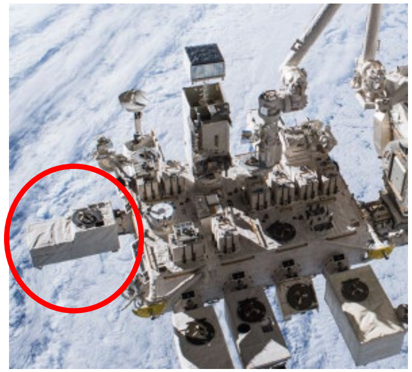
J. Chang[1,2], J. H. Adams[3], H. S. Ahn[4], G. L. Bashindzhagyan[5], M. Christl[3], O. Ganel[4], T. G. Guzik[6], J. Isbert[6], K. C. Kim[4], E. N. Kuznetsov[5], M. I. Panasyuk[5], A. D. Panov[5], W. K. H. Schmidt[2], E. S. Seo[4], N. V. Sokolskaya[5], J. W. Watts[3], J. P. Wefel[6], J. Wu[4] & V. I. Zatsepin[5]

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

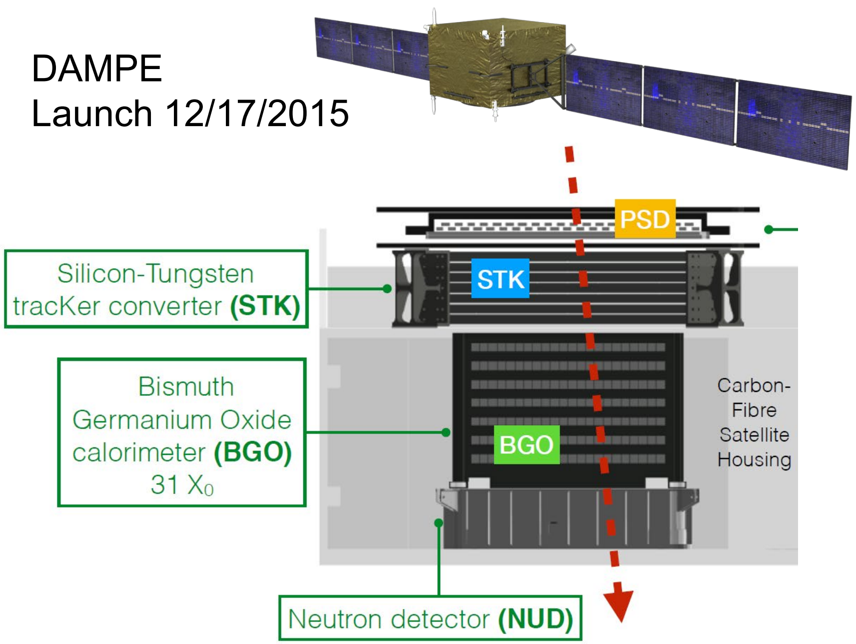


Other CAL based missions: DAMPE and CALET

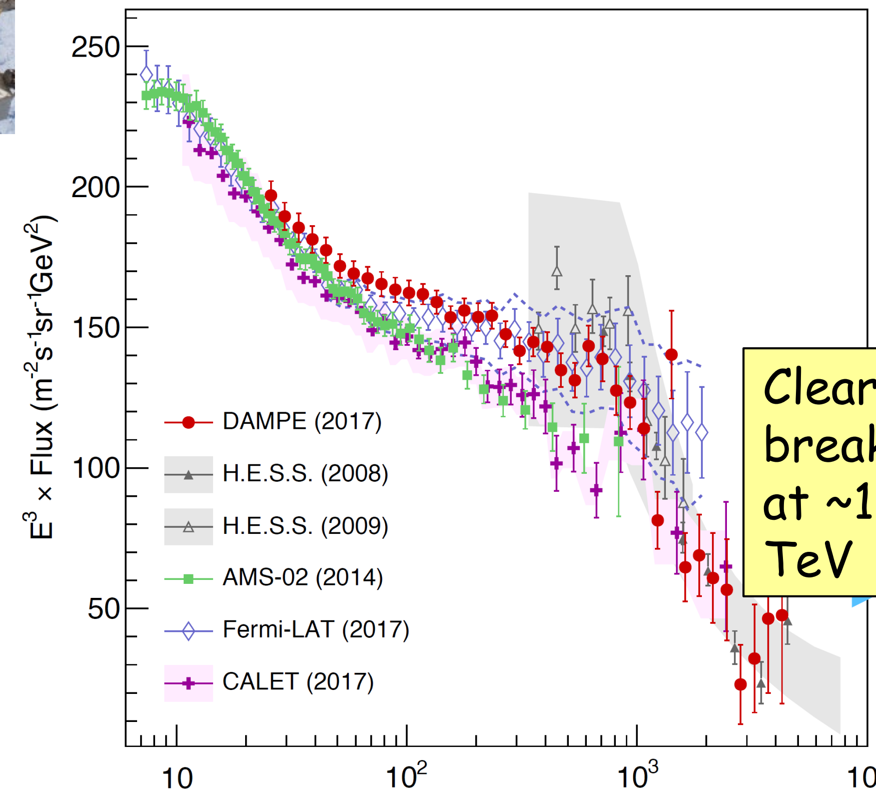




DAMPE
Launch 12/17/2015



CALET: PRL 119 (2017) 181101, 3 November 2017
DAMPE: Nature 552 (2017) 63, 7 December 2017



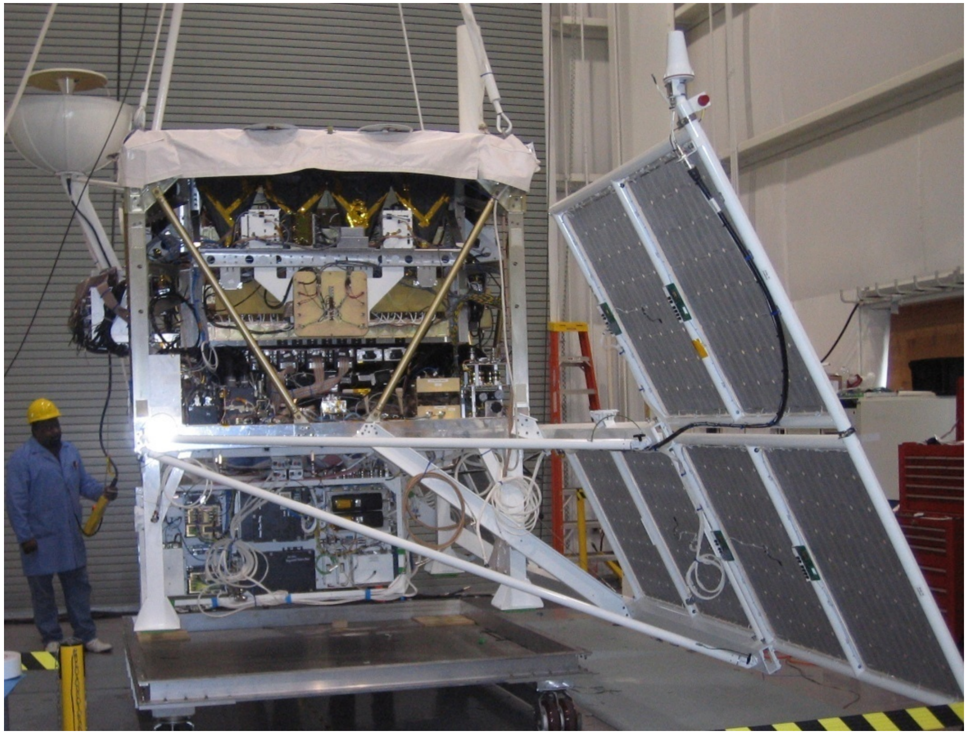
Clear break at ~1 TeV

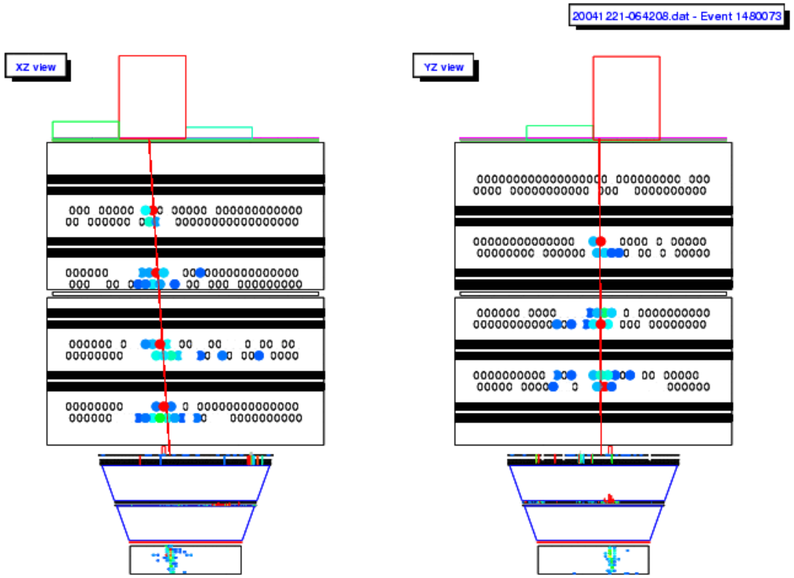
CREAM Cosmic Ray Energetics And Mass

Seo et al. Adv. in Space Res., **33** (10), *1777*, 2004; Ahn et al., NIM A, **579**, 1034, 2007

- 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

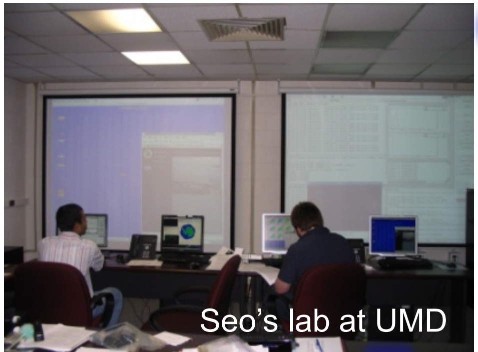
- The CREAM instrument has had seven successful Long Duration Balloon (LDB) flights and have **accumulated 191 days** of data.
  - This longest known exposure for a single balloon project verifies the instrument design and reliability.



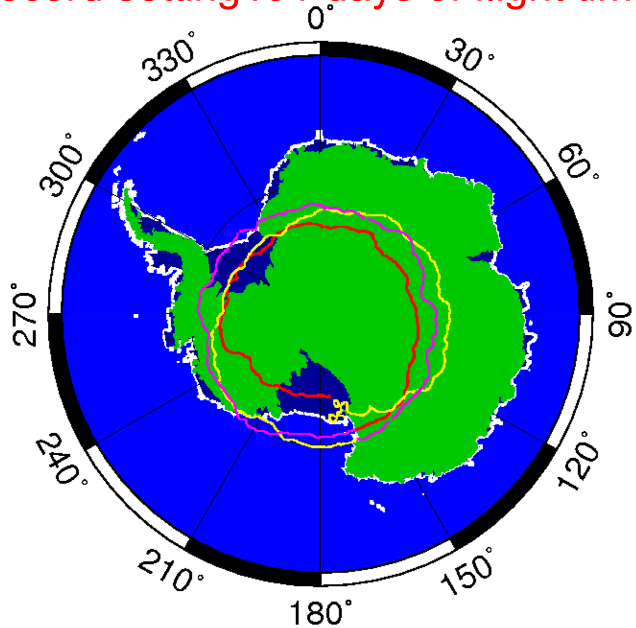


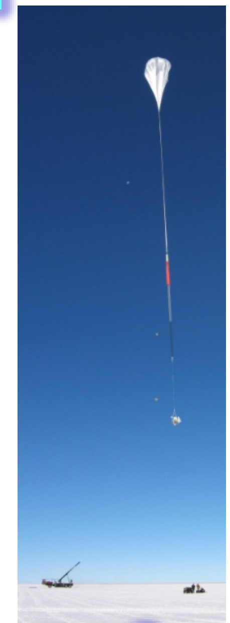
CREAM Cosmic Ray Energetics And Mass

Seo et al. Adv. in Space Res., **33** (10), *1777*, 2004; Ahn et al., NIM A, **579**, 1034, 2007

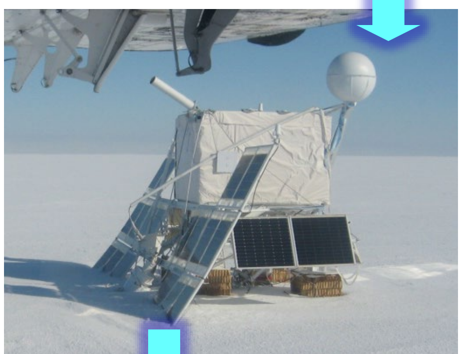


Record setting191 days of flight time





- Seven successful balloon flights and have accumulated 191 days of data.
- The instruments are for the most part **built in-house by students** and young scientists.



Instruments are fully recovered, refurbished & reflown.

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)

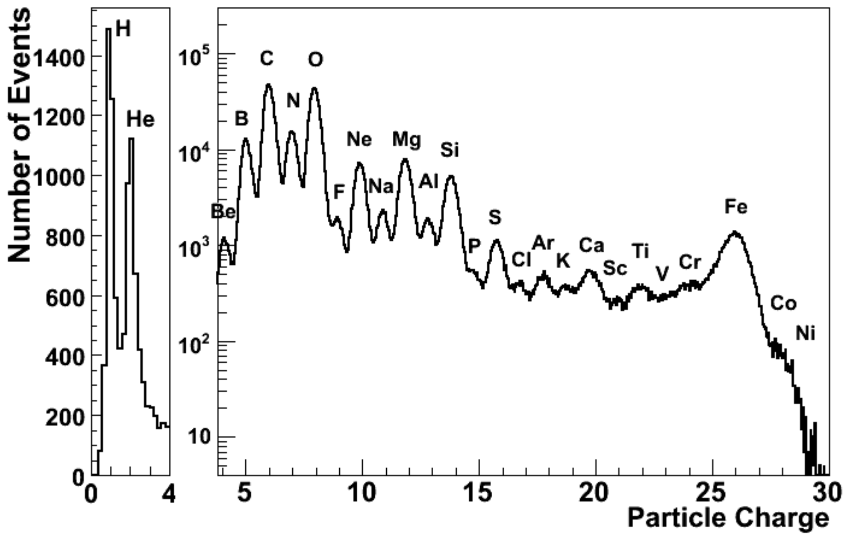
Dozens of students at the University of Maryland have toiled in the physics lab, some soldering metal parts, some debugging software and some simply slicing black pieces of paper into perfectly sized triangles.

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.

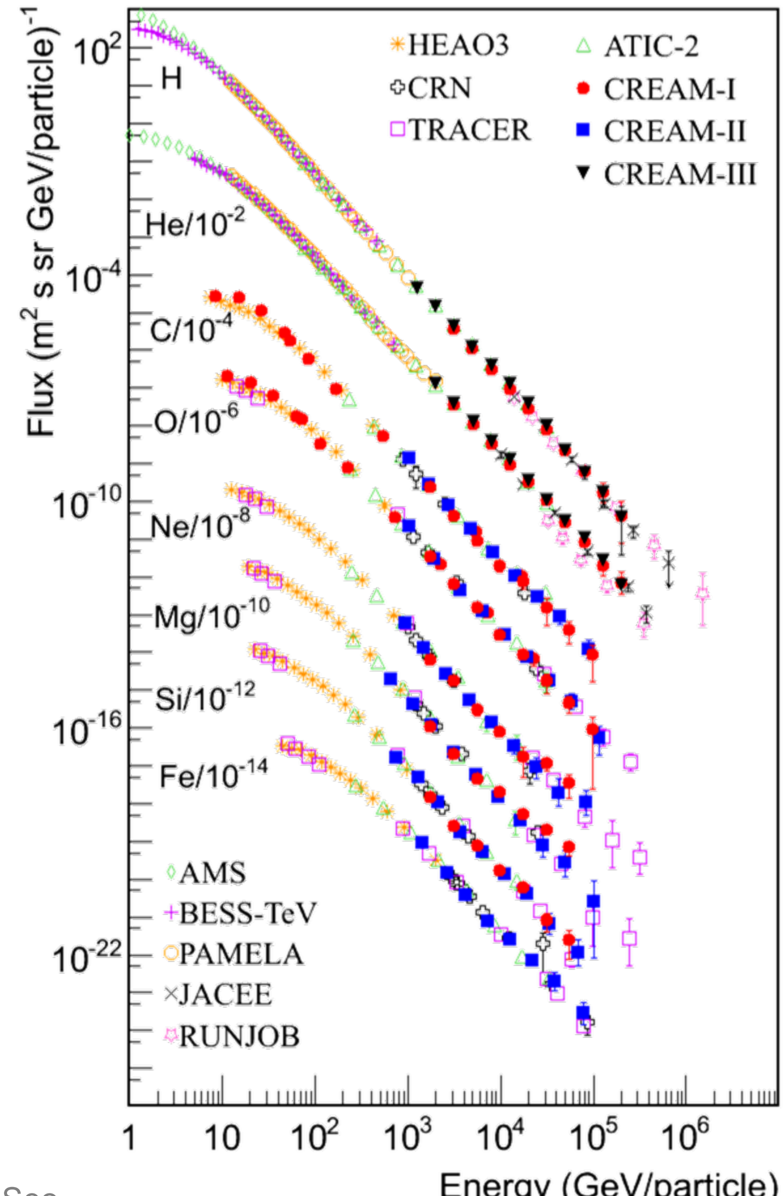
Elemental Spectra over 4 decades in energy

Yoon et al. ApJ **728**, *122*, 2011; Ahn et al., ApJ **715**, *1400*, 2010; Ahn et al. ApJ **707**, *593*, 2009

Excellent charge resolution from SCD

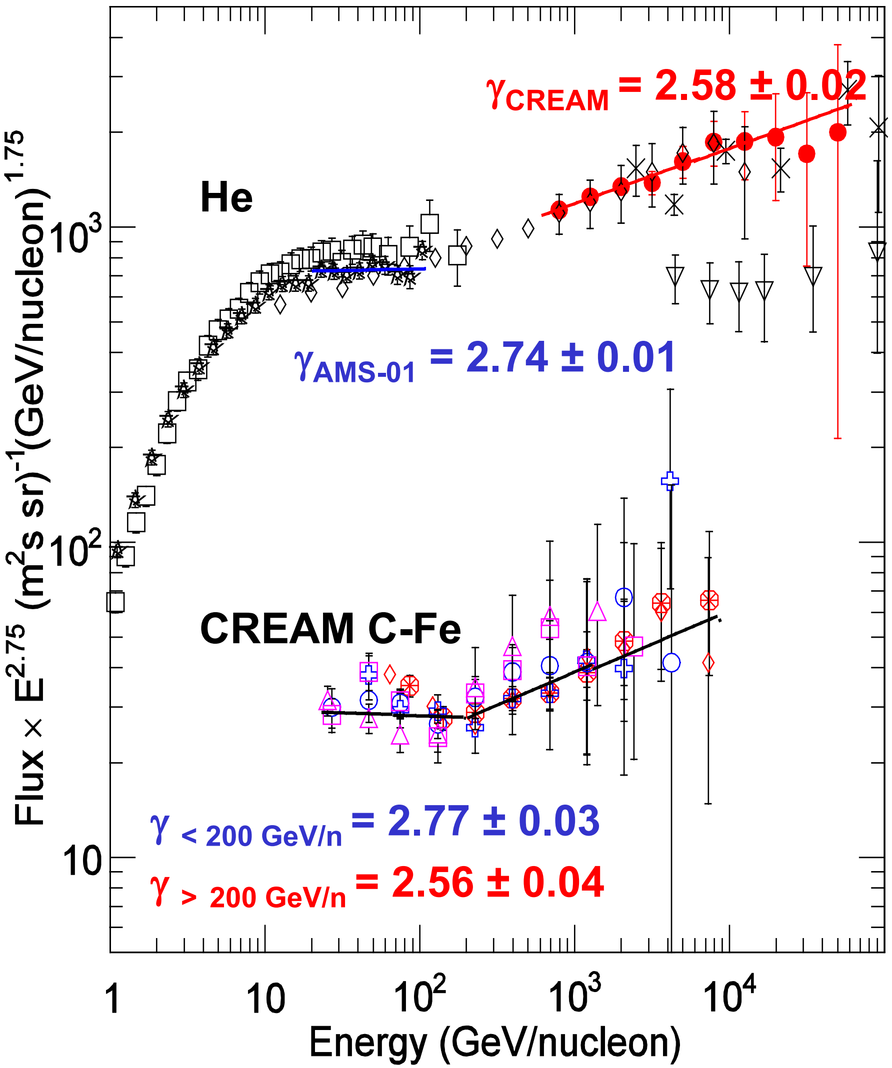


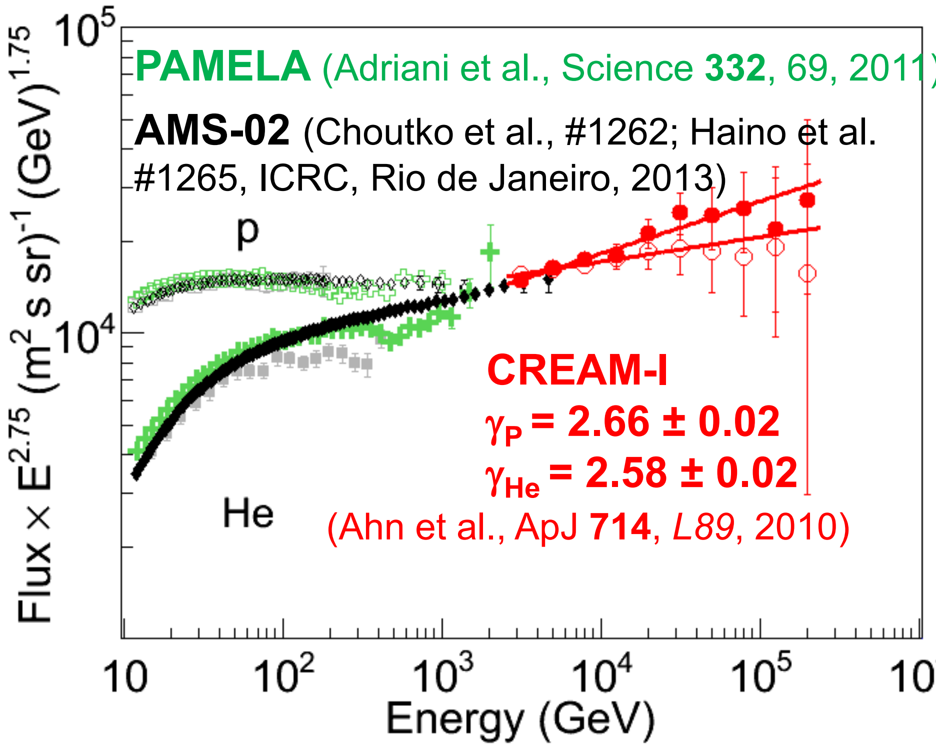
Distribution of cosmic-ray charge measured with the SCD. The individual elements are clearly identified with excellent charge resolution. The relative abundance in this plot has no physical significance.



Unexpected results challenge the standard paradigm

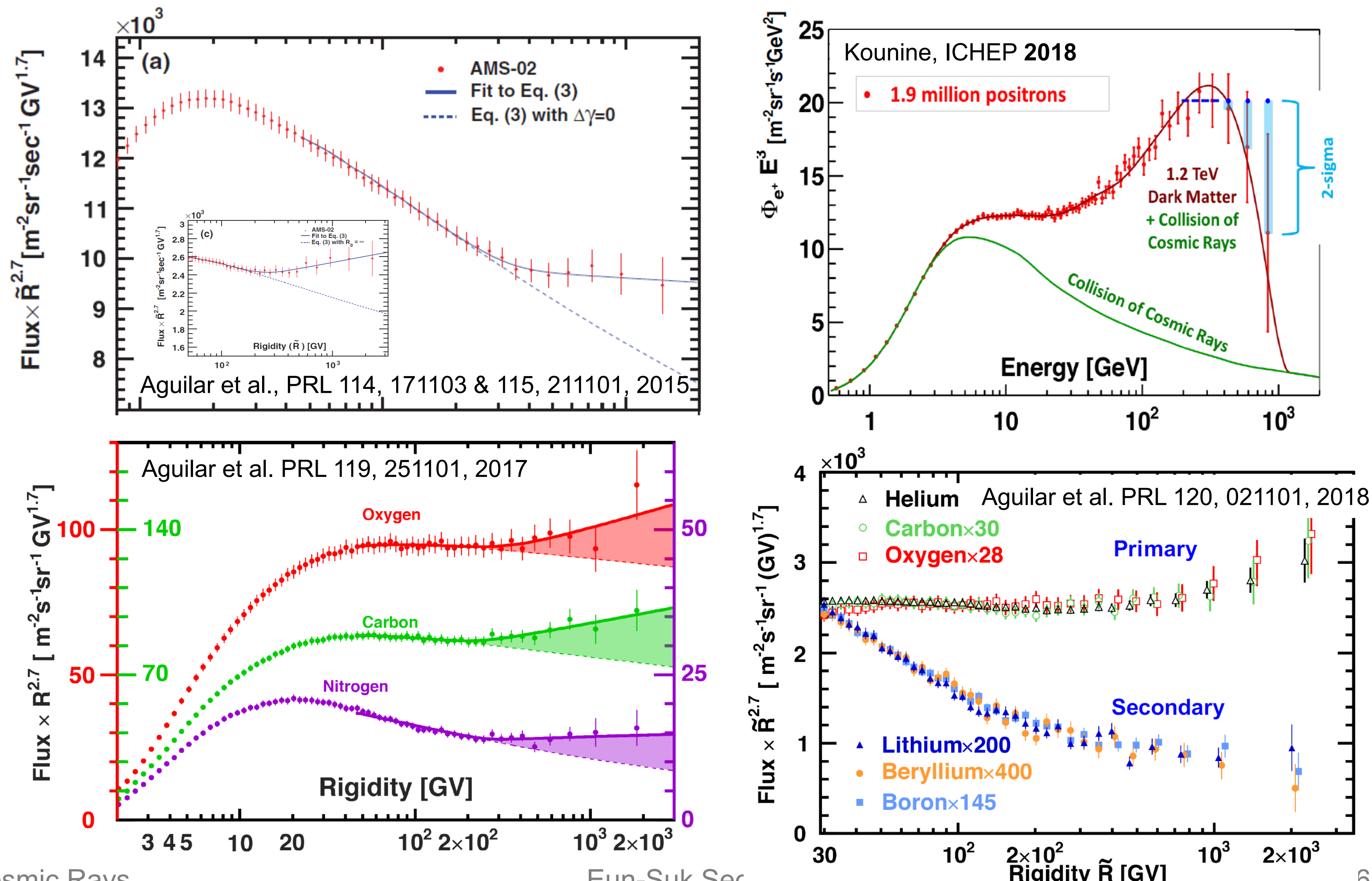
Yoon et al. ApJ **728**, *122*, 2011; Ahn et al. ApJ 714, L89, 2010





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."

Spectral Hardening Confirmed



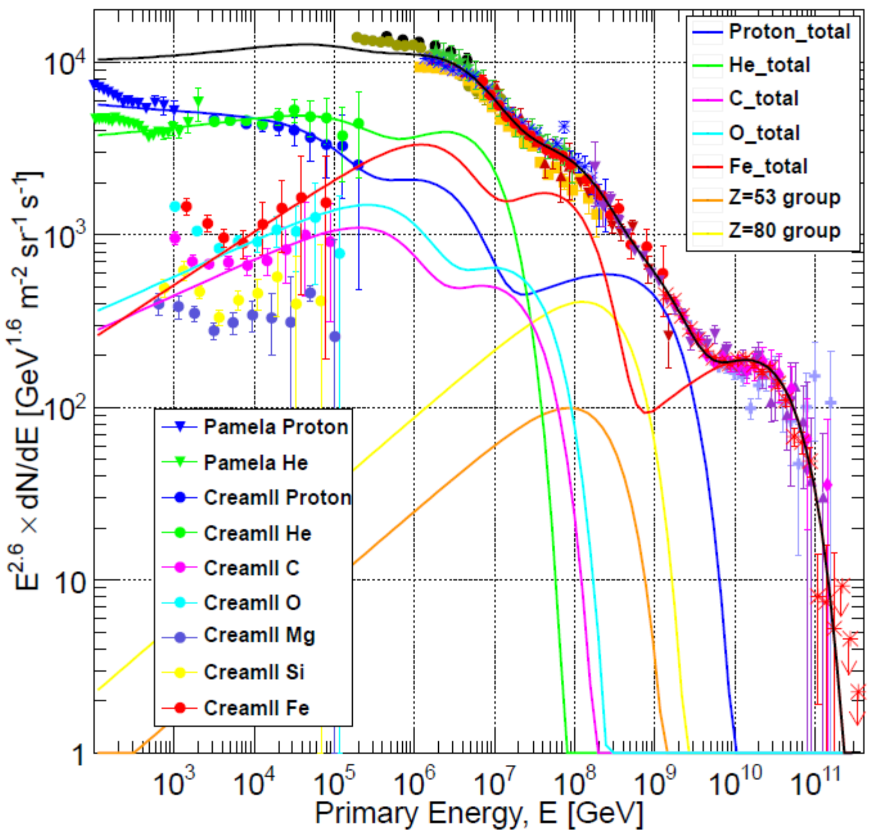
CREAM solves the puzzle with the knee and beyond

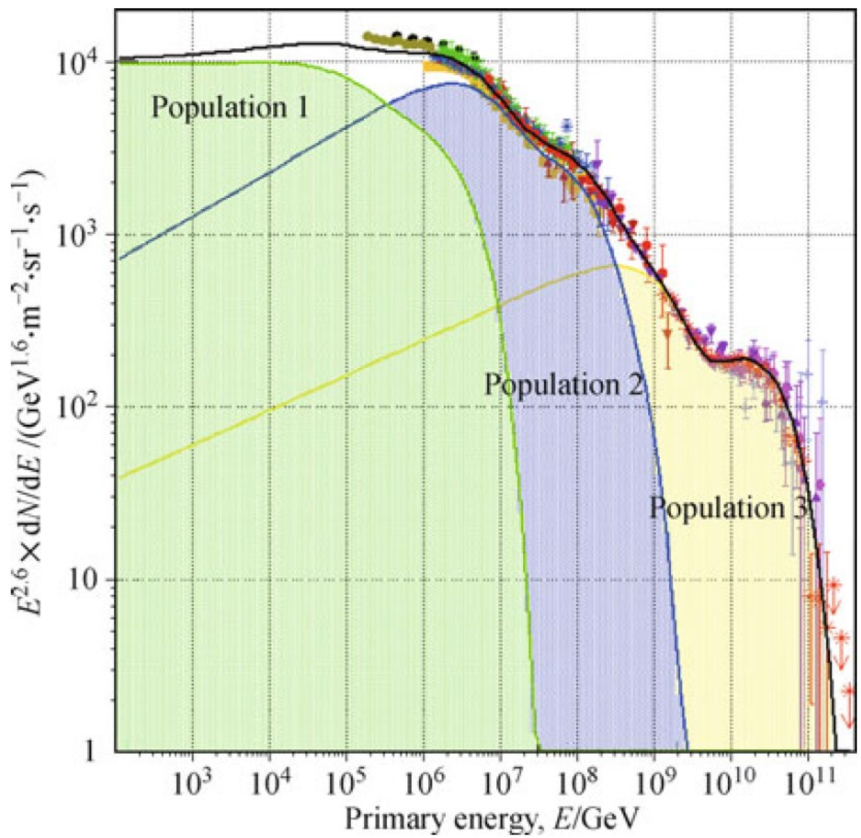
T. K. Gaisser, T. Stanev and S. Tilav, Front. Phys. 8(6), 748, 2013

S. Tilav's presentation, TeVPA, Irvine, CA , 2013

Acceleration limit:

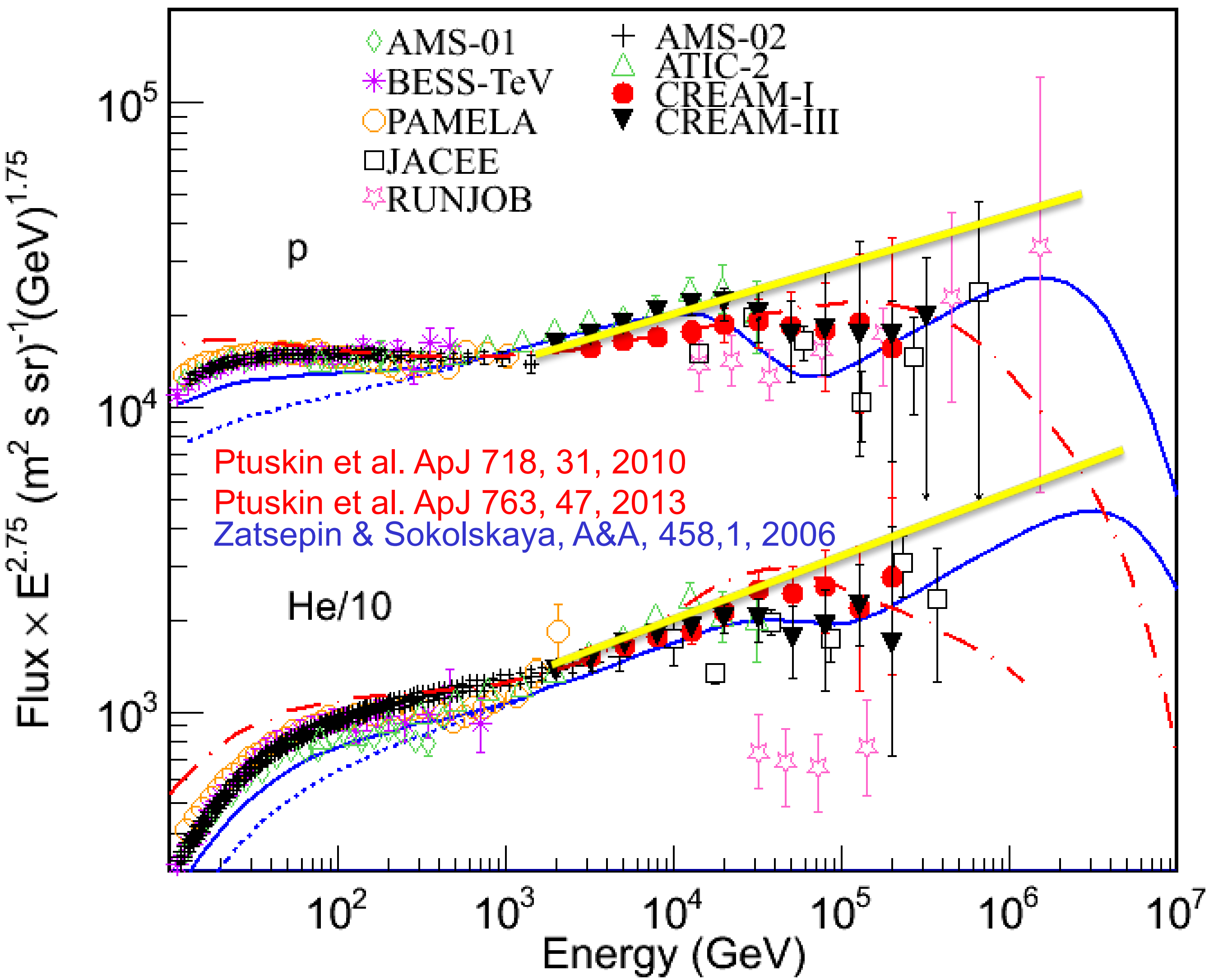
E_{max_z} = Ze x R = Z x E_{max_p}, *where rigidity R = Pc/Ze*





Need to extend measurements to higher energies

Yoon et al. (CREAM Collaboration) ApJ 839:5, 2017

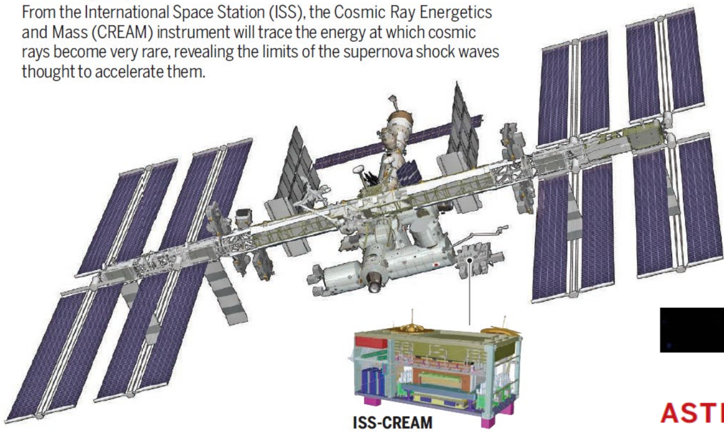


ISS-CREAM: CREAM for the ISS

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.



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

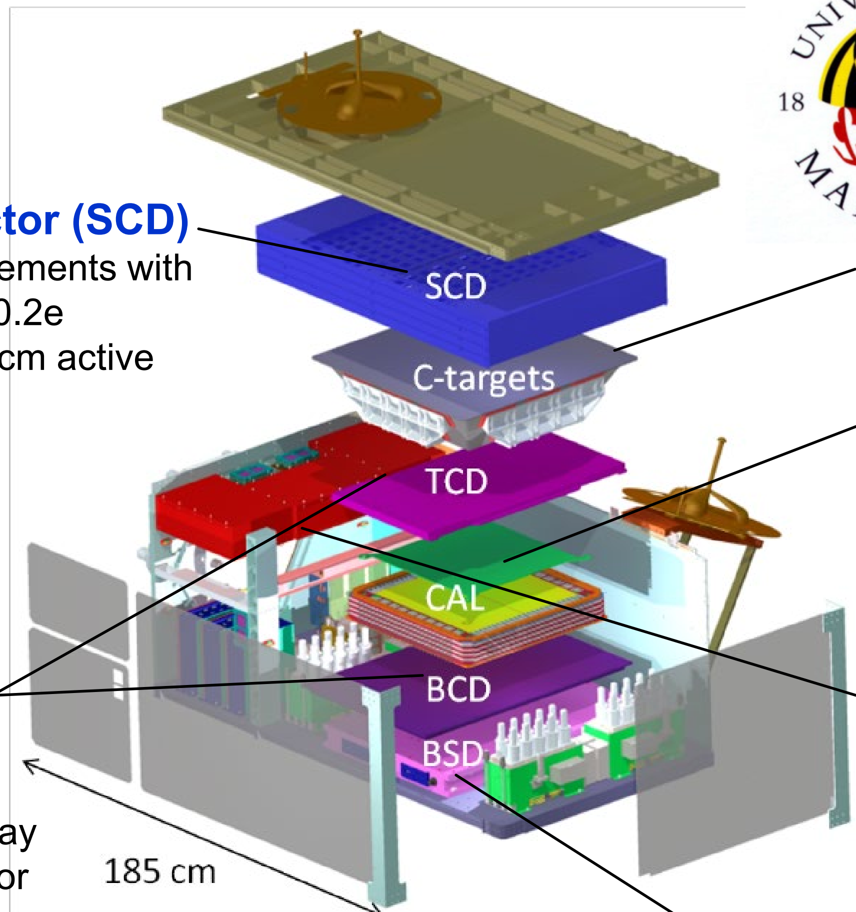
By **Eric Hand**

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,

Cosmic Rays

ISS-CREAM Instrument

Seo et al. Adv. in Space Res., **53**/10, *1451*, 2014; Smith et al. PoS(ICRC2017)199, 2017



Silicon Charge Detector (SCD)

- Precise charge measurements with charge resolution of ~ 0.2e
- 4 layers of 79 cm x 79 cm active area (2.12 cm^2 pixels)

Top/Bottom Counting Detector (T/BCD)

- Plastic scintillator instrumented with an array of 20 x 20 photodiodes for e/p separation
- Low energy trigger

Carbon Targets

- Induces hadronic interactions

Calorimeter

- 20 layers of alternating tungsten plates and scintillating fibers
- Determines energy
- Provides tracking and high energy trigger

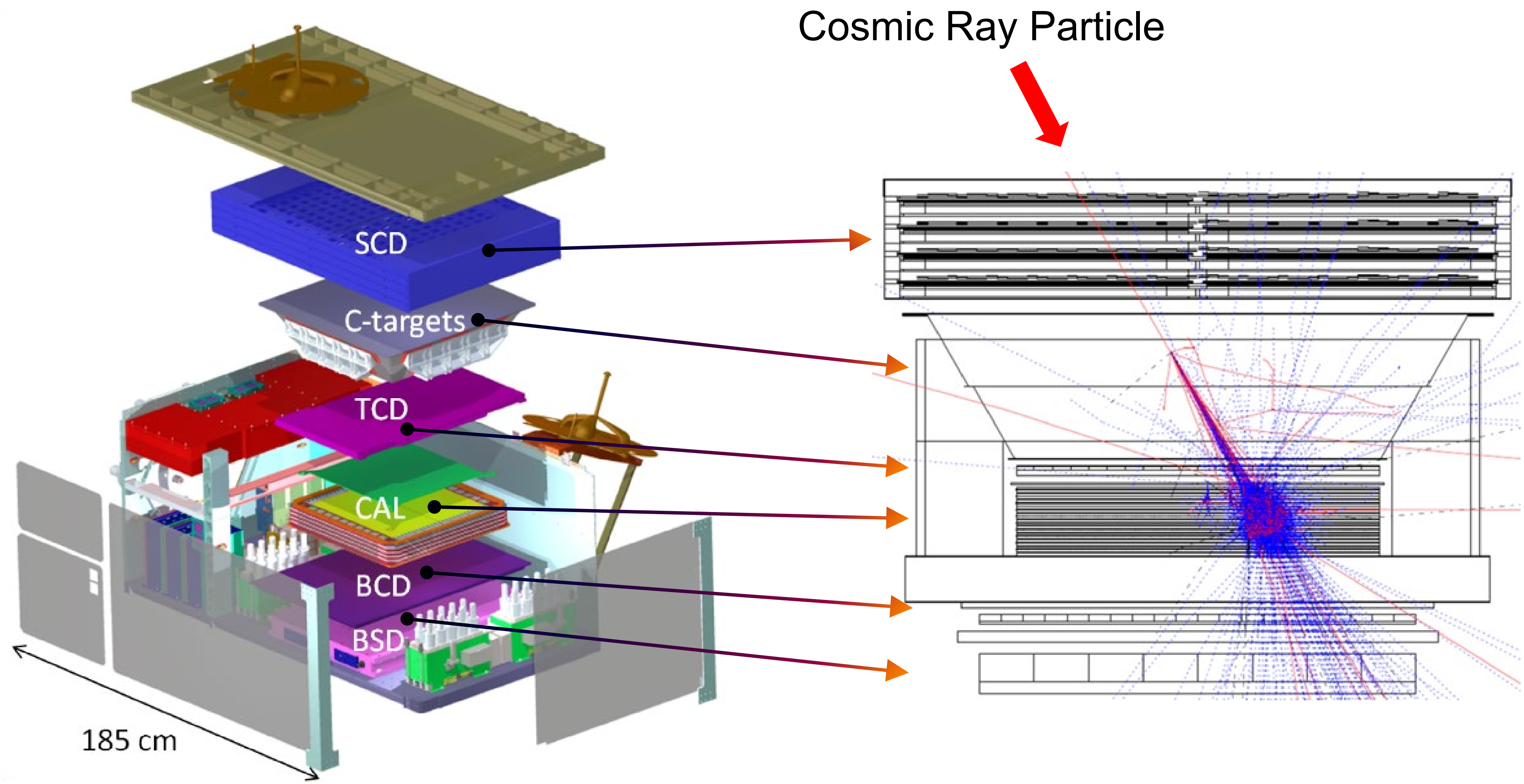
SFCs and common electronics inc. Trigger, CMD, HSK, Power

Boronated Scintillator Detector (BSD)

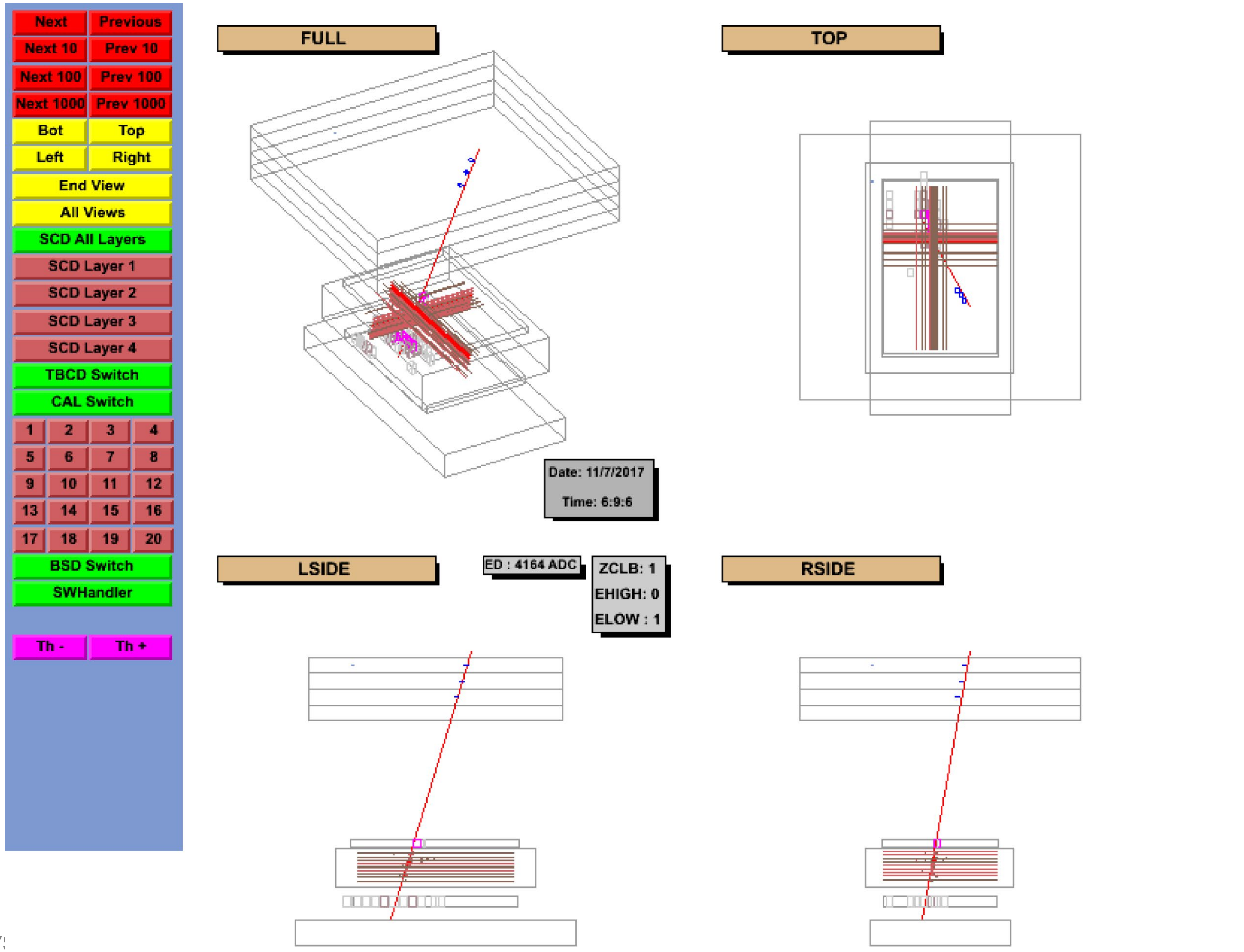
- Additional e/p separation by detection of thermal neutrons

Cosmic Ray Event Simulation

Seo et al. Adv. in Space Res., **53**/10, *1451*, 2014; Wu et al. PoS(ICRC2019)154, 2019.

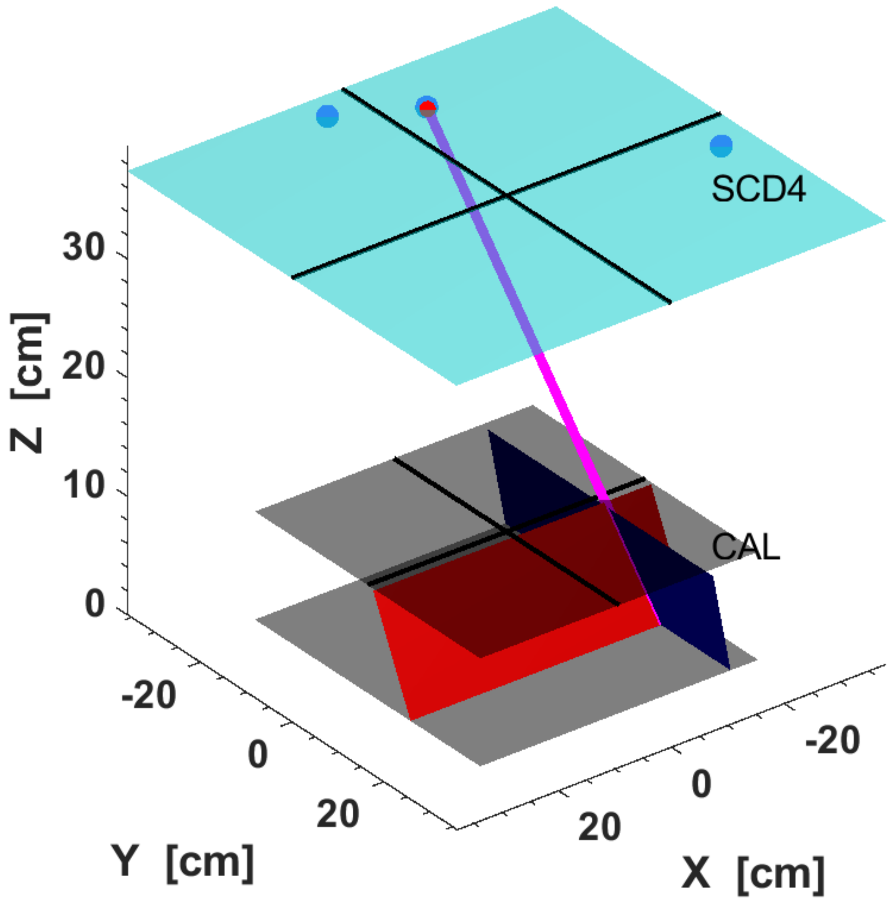


Flight data: Cosmic Ray Detection

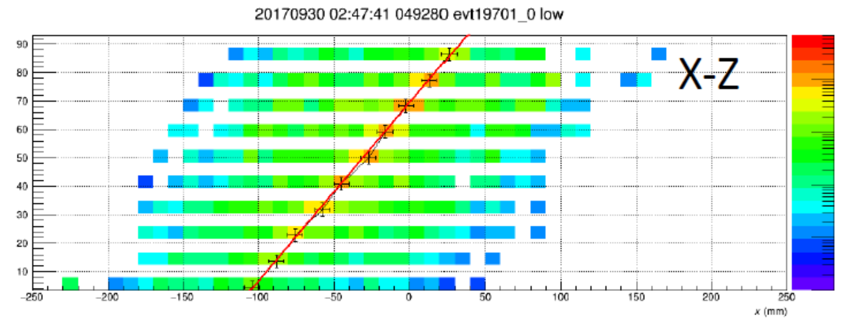


Examples of high energy events

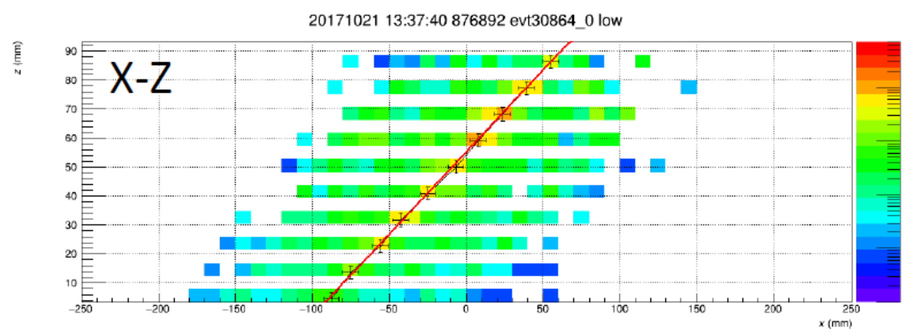
Lundquist et al. PoS(ICRC2019)099, 2019



E = 1.88 PeV

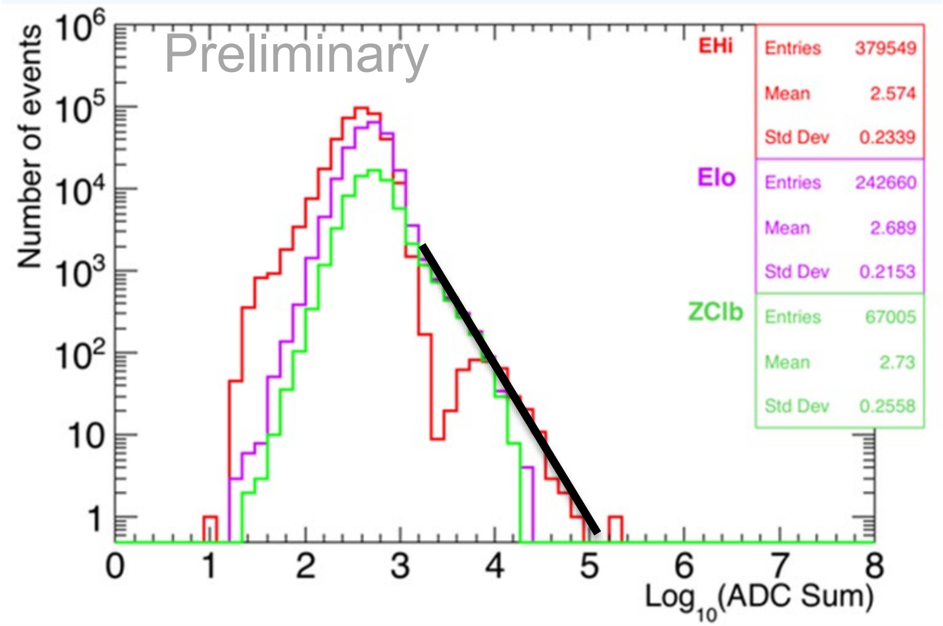


E = 748 TeV



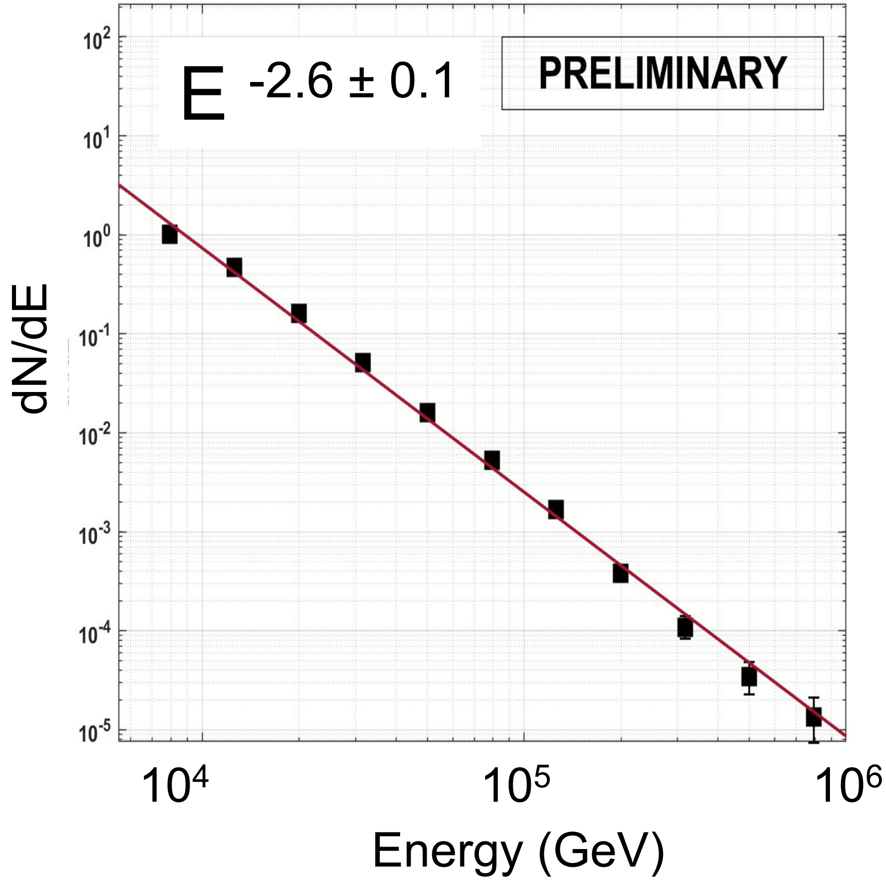
CAL provides energy measurements

Cosmic ray all particle counts



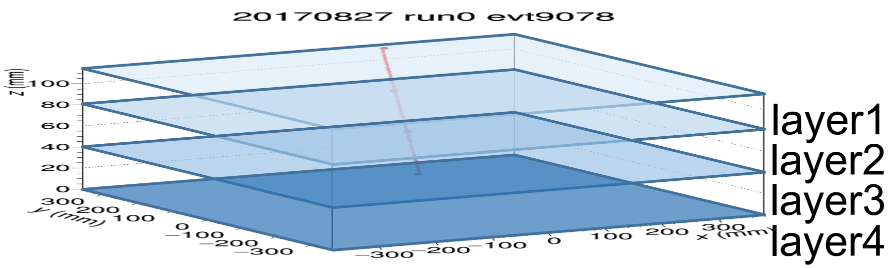
Kim et al. PoS(ICRC2019)087, 2019

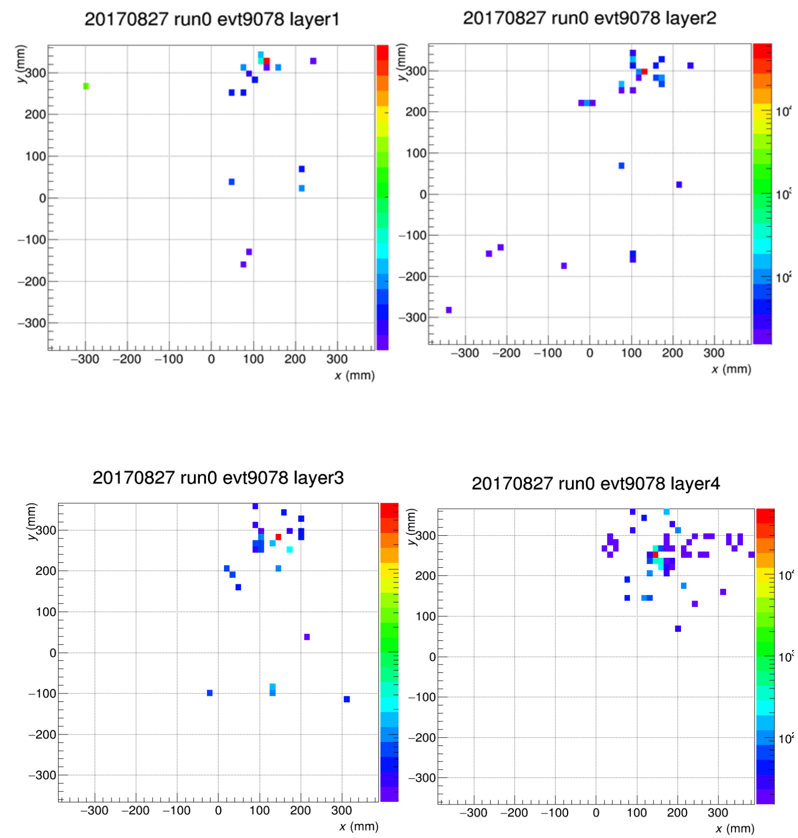
Lundquist et al. PoS(ICRC2019)099, 2019

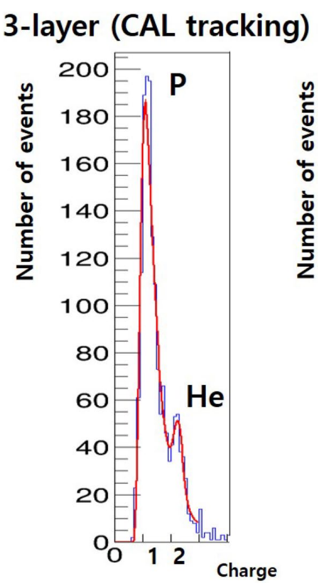


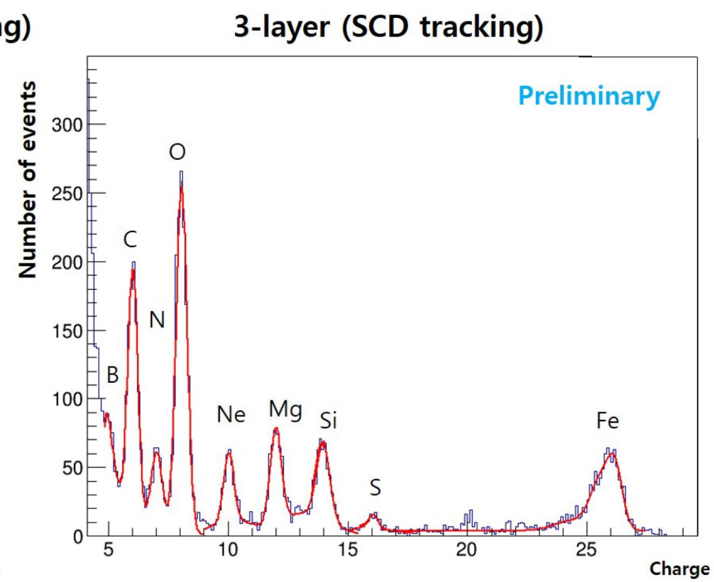
SCD provides particle charge identification

Choi et al. PoS(ICRC2019)048, 2019; Takeish et al. PoS(ICRC2019)140, 2019









The individual elements are clearly identified. The relative abundance in this plot has no physical significance, because needed corrections for interactions and propagations have not been applied to these data.


To Unveil Mysteries of the Universe
Voyager
AMS
DAMPE
ISS-CREAM
CALET
Pamela