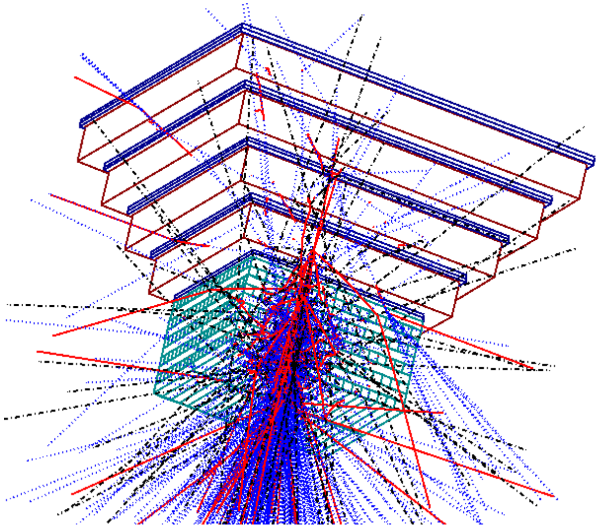


The Three Flights of ATIC

Summary of Results

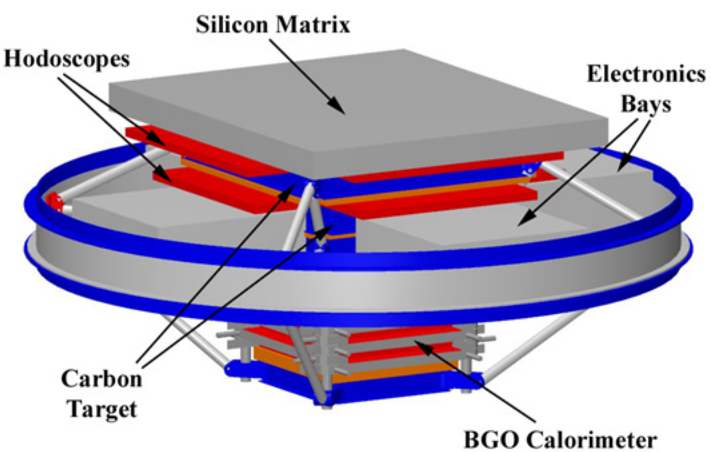
TeV Particle Astrophysics

Stockholm, Sweden

August, 2011

John P. Wefel
Department of Physics and Astronomy
Louisiana State University
Baton Rouge, LA 70803 USA

For the ATIC Collaboration



The ATIC Collaboration

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5. Southern University, Baton Rouge, LA, USA
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7. Purple Mountain Observatory, Chinese Academy of Sciences, China

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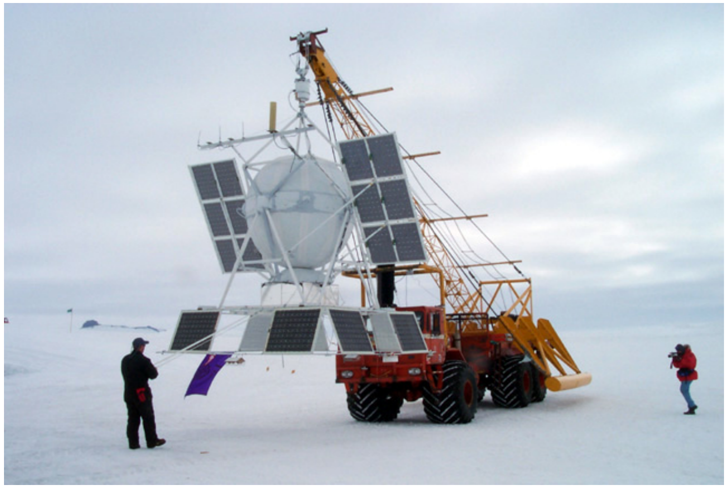

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NASA

Russian Foundation for Basic Research

National Natural Science Foundation of China

Outline of the Presentation

Introduction & History

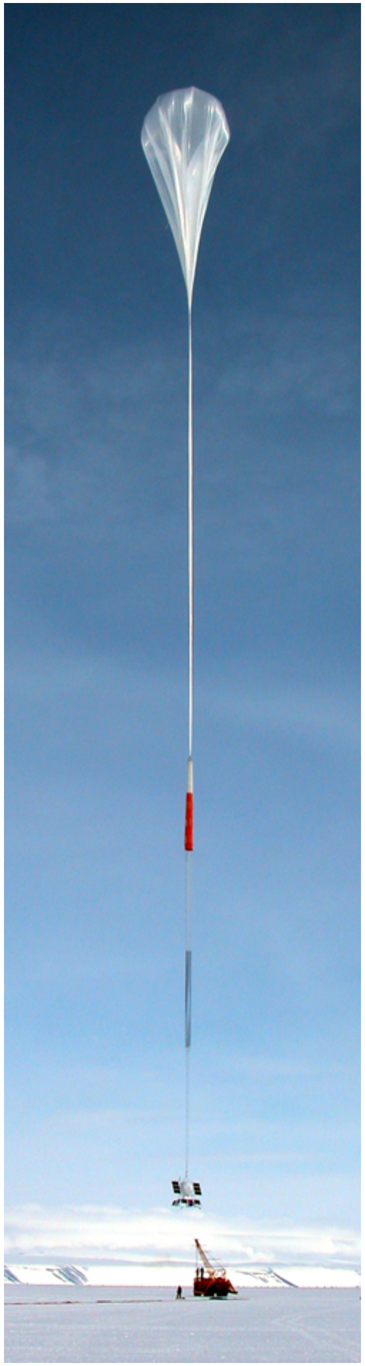
The ATIC Instrument and Flights
(ATIC-1 and ATIC-2)

Hydrogen and Helium Spectra

Hi-Z Primary and Secondary Nuclei

Very High Energy Electrons

Conclusions



Programmatic Evolution – Charged Cosmic Rays

Emulsion Chambers JACEE, RUNJOB, MUBEE

ATIC

Advanced C.R. Composition Experiment for Space Station
ACCESS Mission Investigation

Supporting Balloon Programs

- TRACER
- ATIC
- CREAM
- TIGER

OASIS Concept Study

CALET on ISS

COMPTON GRO

INTEGRAL

XMM

SWIFT

AGILE

FERMI*

*Fermi, a Gamma-ray mission, contains a high energy particle mode for data on Charged Cosmic Rays

Magnetic Spectrometers

Balloon Born Magnet Facility
BBMF - NMSU

ASTROMAG
Mission Concept

Supporting Balloon Programs

- WIZARD
- IMAX
- HEAT
- p-BAR
- SMILI
- ISOMAX
- BESS

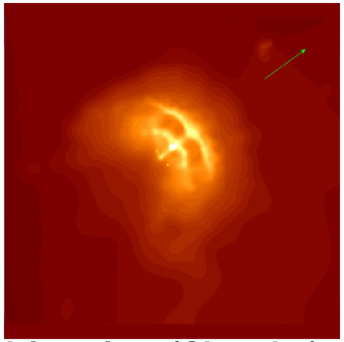
PAMELA

AMS-02

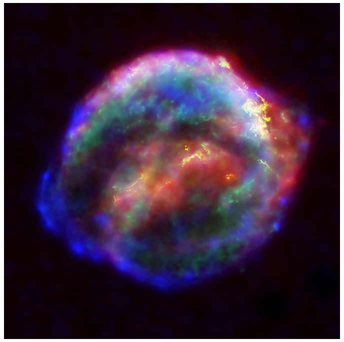
A New “ERA” in Particle Astrophysics!

Outline of the Presentation

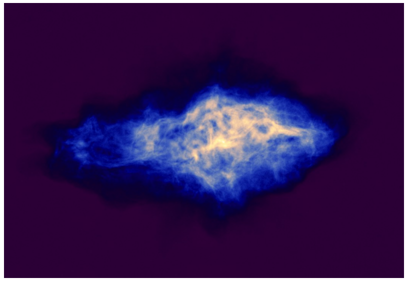
- Introduction & History
- The ATIC Instrument and Flights
- Hydrogen and Helium Spectra
- Hi-Z Primary and Secondary Nuclei
- Very High Energy Electrons
- Comparisons and Conclusions



Vela pulsar (Chandra)



Kepler's SNR



SNR 3C 58 (NRAO)

Science Questions for ATIC

Cosmic Ray Accelerators: How, What, Where, How many?

Are there nearby (local) sources?

Are there signatures of new or exotic physics at very high energy?

"Connecting Quarks to the Cosmos: Eleven Science Questions for the New Century"

What is Dark Matter?

How Do Cosmic Accelerators Work and What Are They Accelerating?

How Were the Elements from Iron to Uranium Made?

How to address these questions?

Need an instrument to measure:

⇒ Element type, Particle energy, and the Number of each element and energy

Measure before the cosmic rays break-up in the atmosphere

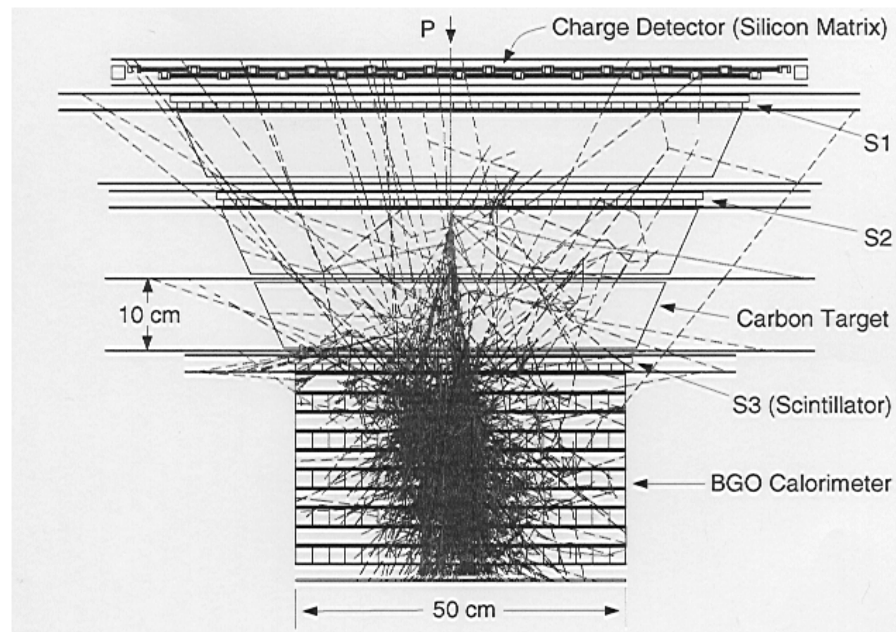
⇒ In space (expensive) or at least at very high altitude (balloon)

Need to measure for as long as possible

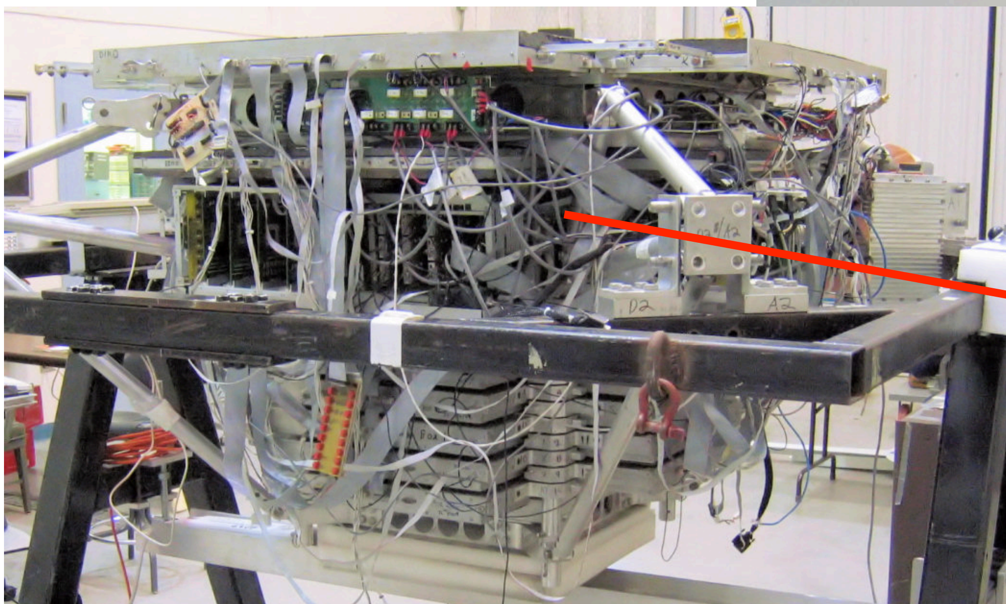
⇒ Use a long duration balloon to get 15 to 30 days of exposure

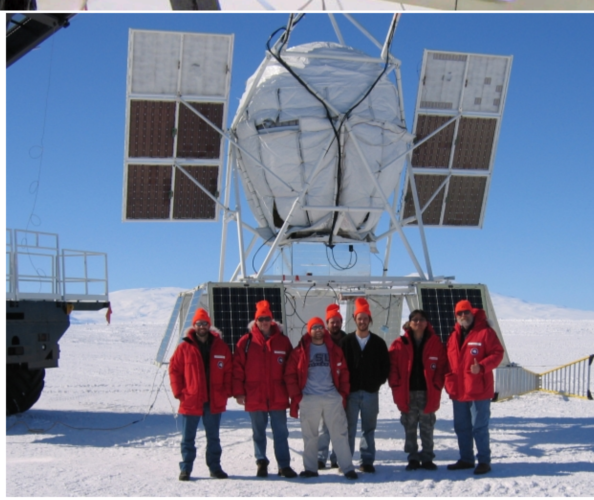
Principle of "Ionization Calorimetry"

- ⇒ **Cosmic ray enters from top**
- ⇒ **Nuclear interaction in target section**
- ⇒ **'BGO Calorimeter' fosters a cascade (or shower) of many sub-particles**
- ⇒ **How this "cloud" of sub-particles develops depends upon the initial cosmic ray energy.**

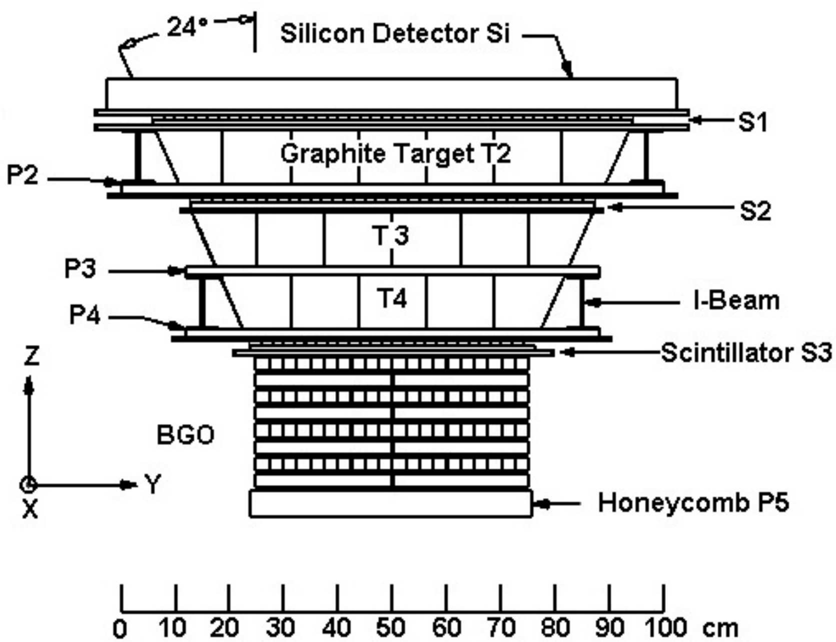


ATIC was constructed as a balloon payload





ATIC Instrument Details



- **Si-Matrix:** 4480 pixels each 2 cm x 1.5 cm mounted on offset ladders; 0.95 m x 1.05 m area; 16 bit ADC; CR-1 ASIC's; sparsified readout.
- **Scintillators:** 3 x-y layers; 2 cm x 1 cm cross section; Bicron BC-408; Hamamatsu R5611 pmts both ends; two gain ranges; ACE ASIC. S1 – 336 channels; S2 – 280 channels; S3 – 192 channels; First level trigger: S1-S3
- **Calorimeter:** 8 layers (10 for ATIC-4); 2.5 cm x 2.5 cm x 25 cm BGO crystals, 40 per layer, each crystal viewed by R5611 pmt; three gain ranges; ACE ASIC; 960 channels (1200 for ATIC-4).

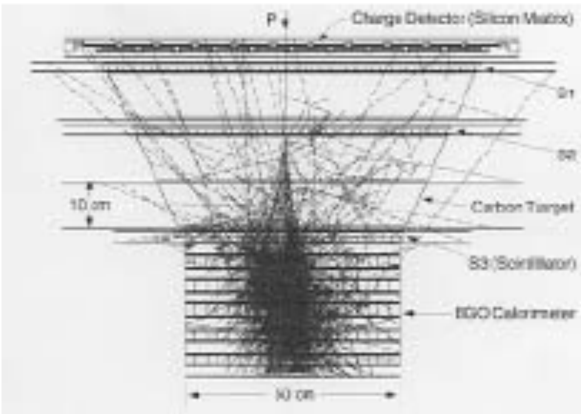
Data System: All data recorded on-board; 70 Gbyte disk (150 Gbyte for ATIC-3); LOS data rate – 330 kbps; TDRSS data rate – 4 kbps (6+ kbps for ATIC-4); Underflight capability (not used).

Housekeeping: Temperature, Pressure, Voltage, Current, Rates, Software Status, Disk status

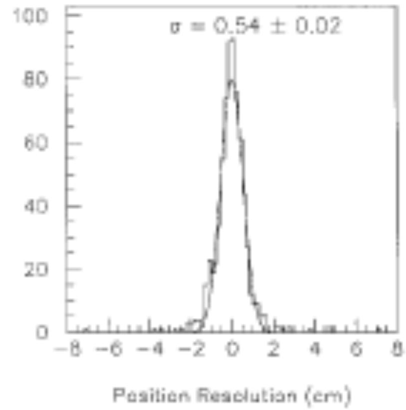
Command Capability: Power on / off; Trigger type; Thresholds; Pre-scaler; Housekeeping frequency; LOS data rate, Reboot nodes; High Volt settings; Data collection on / off

Geometry Factors: S1-S3: 0.42 m^2sr; S1-S3-BGO 6: 0.24 m^2sr; S1-S3-BGO 8: 0.21 m^2sr

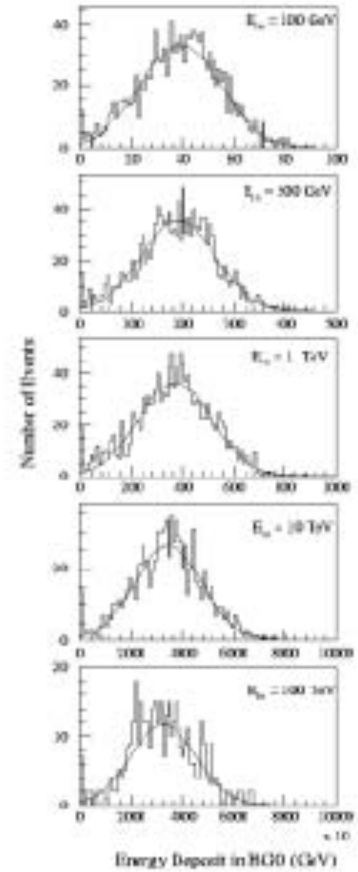
ATIC has been extensively simulated



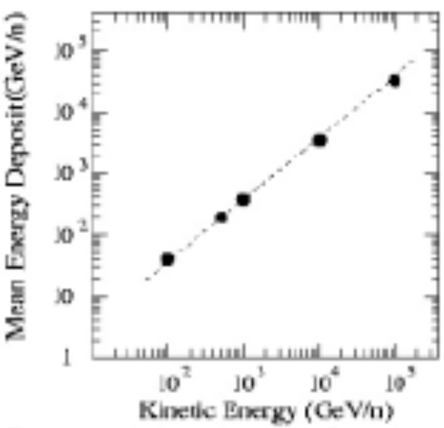
An example of a proton shower in the McMurdo flight configuration

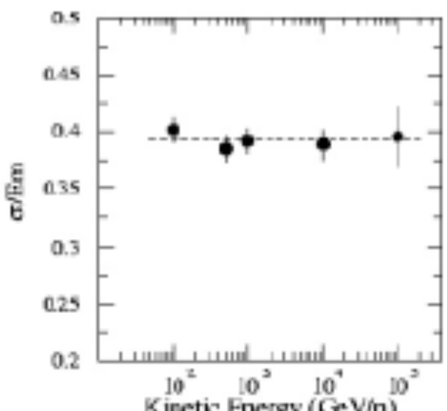


Trajectory resolution in S1 calculated from the BGO shower profile for 1 TeV protons.

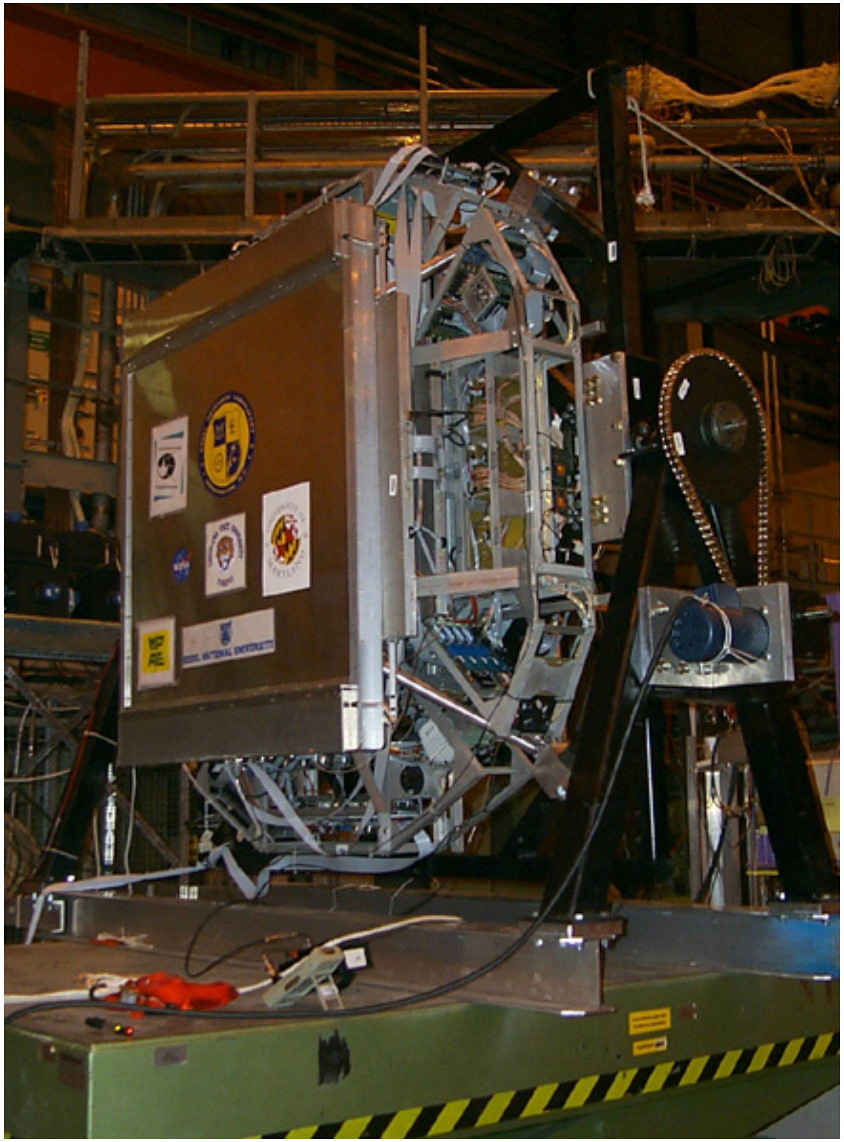


Energy deposition in 20 cm depth BGO calorimeter for 10^2, $5x10^2$, 10^3, 10^4, and 10^5 GeV protons.

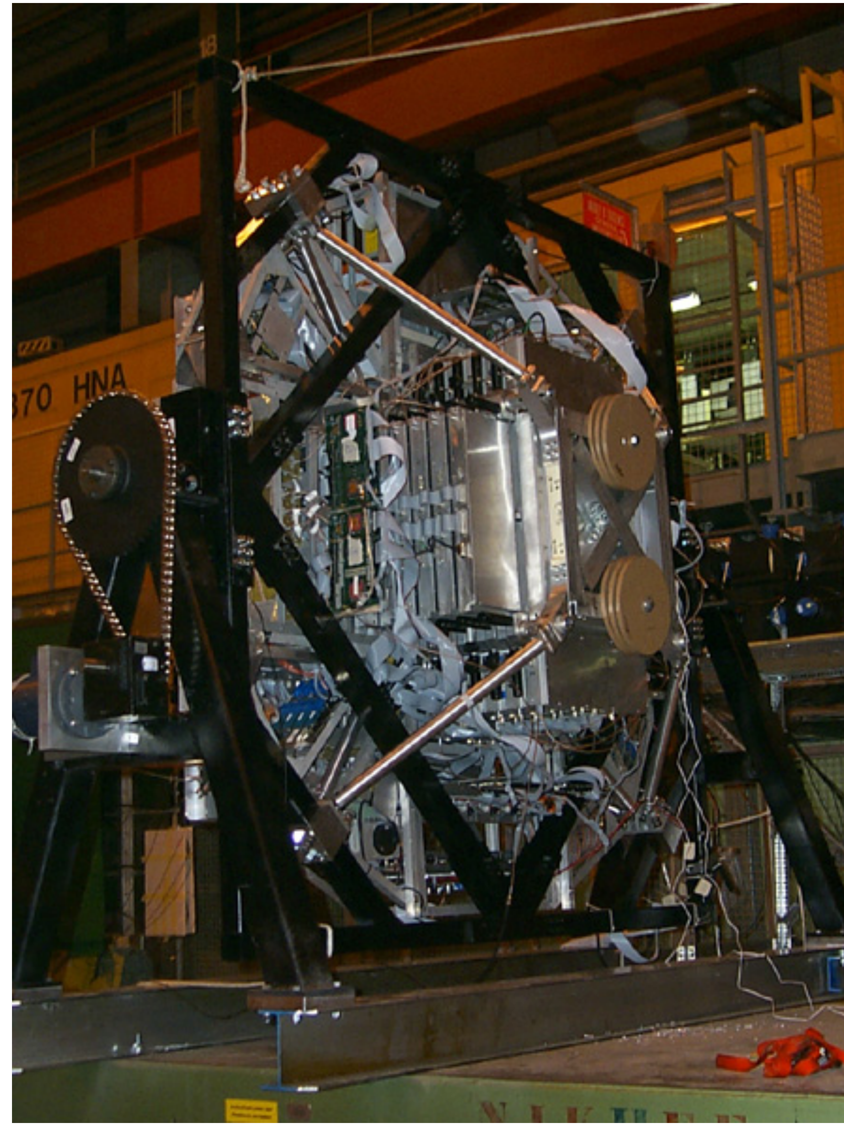




Energy dependence of the proton mean energy deposit and the energy resolution.



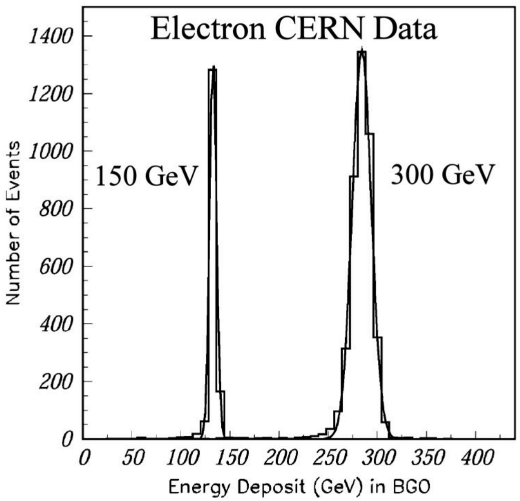
Front and Side

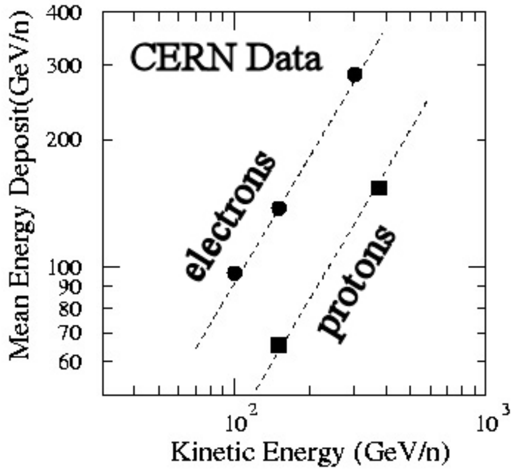


Side and Back

ATIC at CERN

The ATIC Instrument was calibrated at CERN



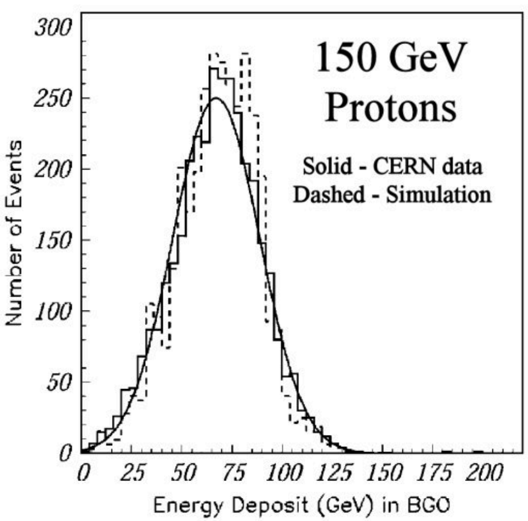


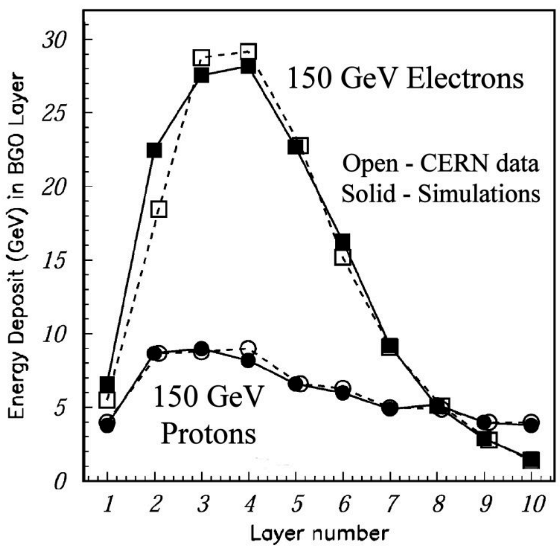
Determine instrument response.

Investigate energy resolution.

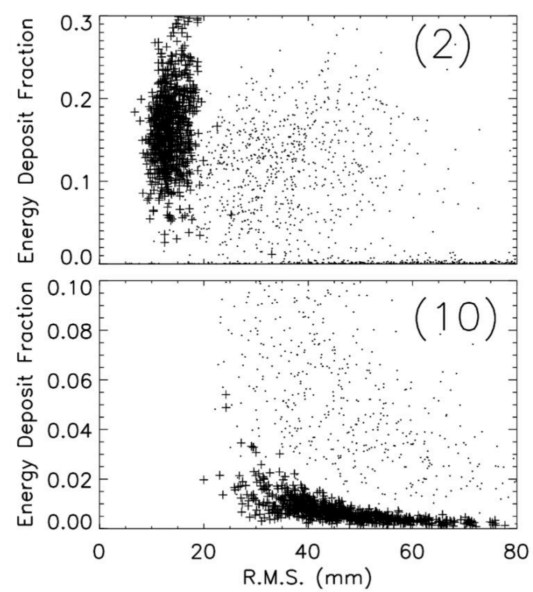
Check accuracy of simulations to allow extrapolation to higher energy.

Use 150 GeV electrons and 375 GeV protons to validate electron analysis and evaluate the proton contamination (i.e. 1 in 5000).

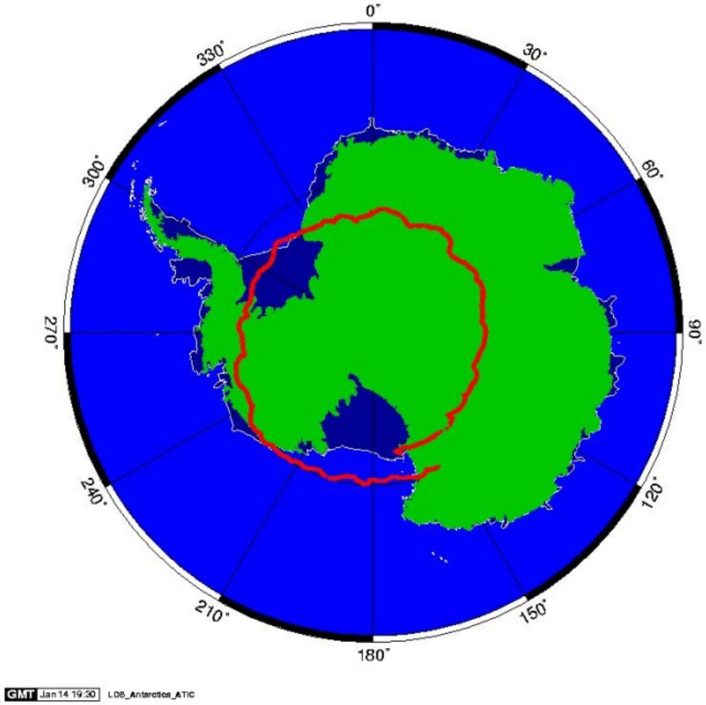




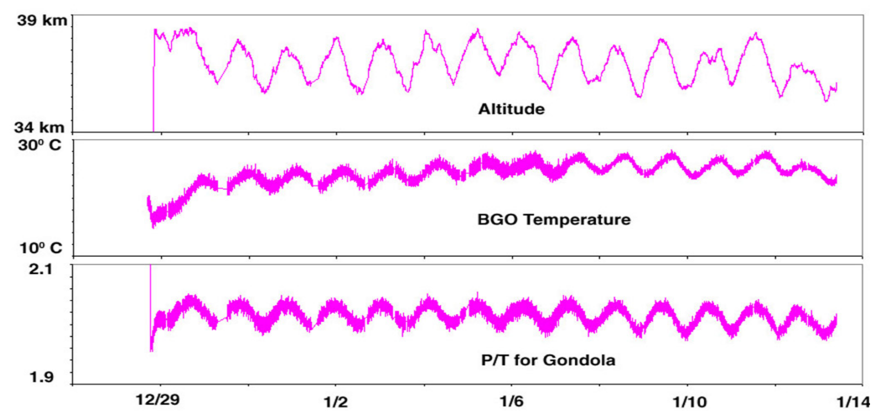
Simulations



ATIC-1 Test Flight from McMurdo - 2000

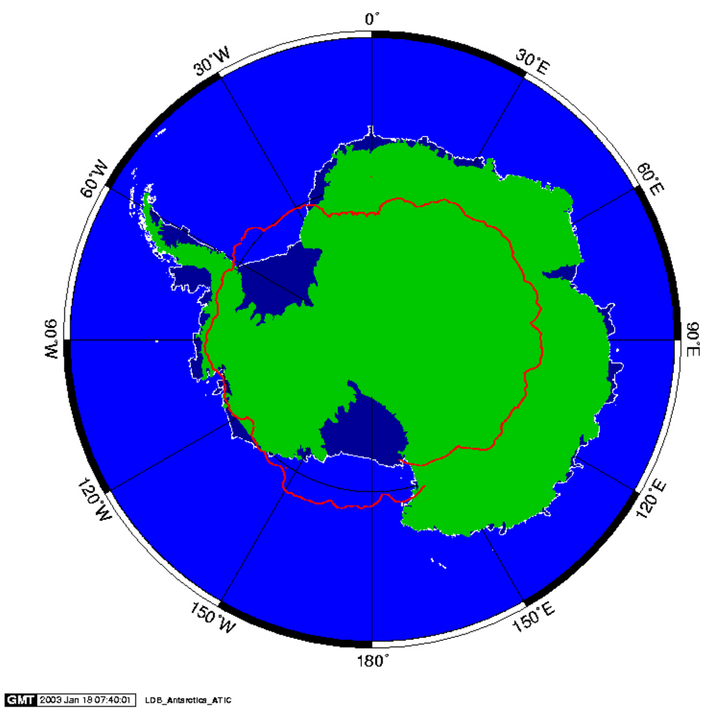


- 43.5 Gbytes Recorded Data
- 26,100,000 Cosmic Ray triggers
- 1,300,000 Calibration records
- 742,000 Housekeeping records
- 18,300 Rate records
- Low Energy Trigger > 10 GeV for protons
- >70% Live-time
- >90% of channels operating nominally
- Internal pressure (~8 psi) held constant
- Internal Temperature: 20 – 30 C
- Altitude: 37 ± 1.5 km

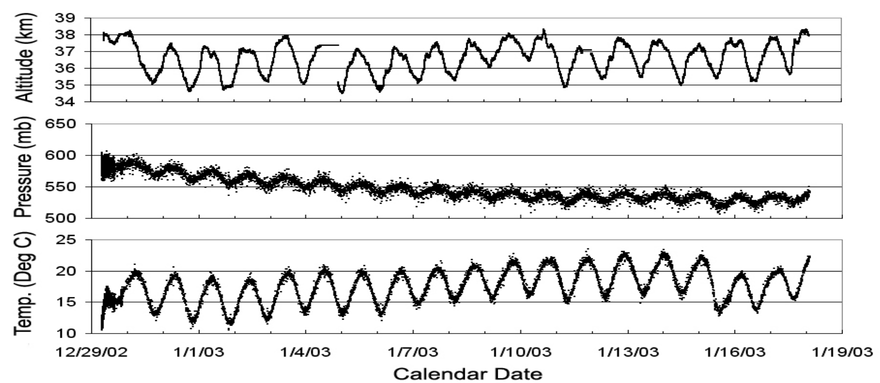


- Launch: 12/28/00 04:25 UTC
- Begin Science: 12/29/00 03:54 UTC
- End Science: 01/12/01 20:33 UTC
- Termination: 01/13/01 03:56 UTC
- Recovery: 01/23/01; 01/25/01

ATIC-2 Science Flight from McMurdo - 2002

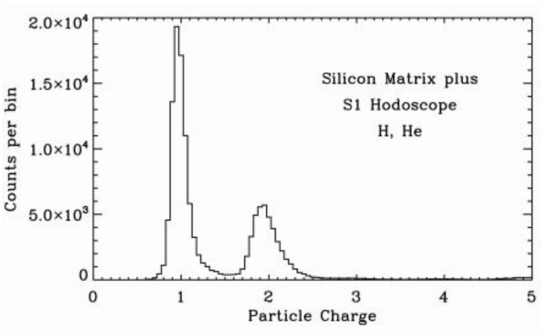


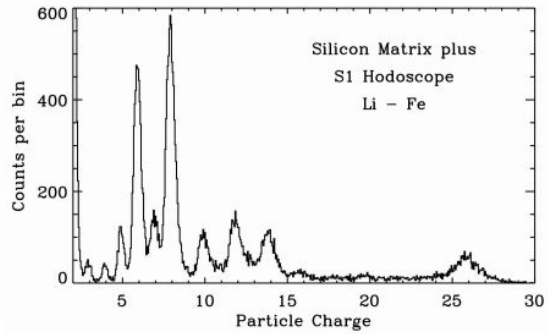
- 65 Gbytes Recorded Data
- 16,900,000 Cosmic Ray triggers
- 1,600,000 Calibration records
- 184,000 Housekeeping records
- 26,000 Rate records
- High Energy Trigger > 75 GeV for protons
- >96% Live-time
- >90% of channels operating nominally
- Internal pressure (~8 psi) decreased slightly (~0.7 psi) for 1st 10 days then held constant
- Internal Temperature: 12 – 22 C
- Altitude: 36.5 ± 1.5 km

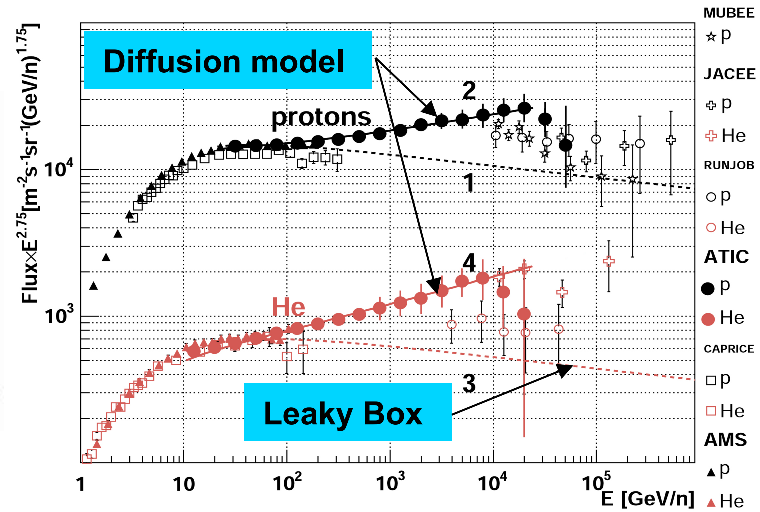


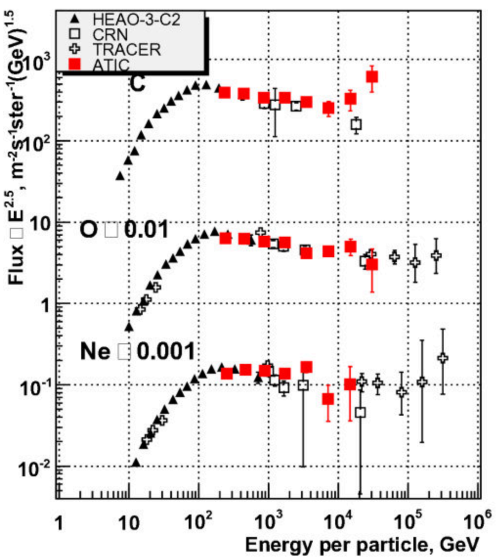
- Launch: 12/29/02 04:59 UTC
- Begin Science: 12/30/02 05:40 UTC
- End Science: 01/18/03 01:32 UTC
- Termination: 01/18/03 02:01 UTC
- Recovery: 01/28/03; 01/30/03

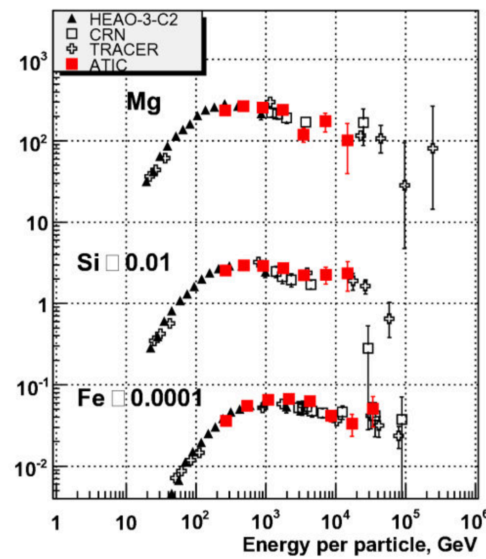
Summary of ATIC-2 Results



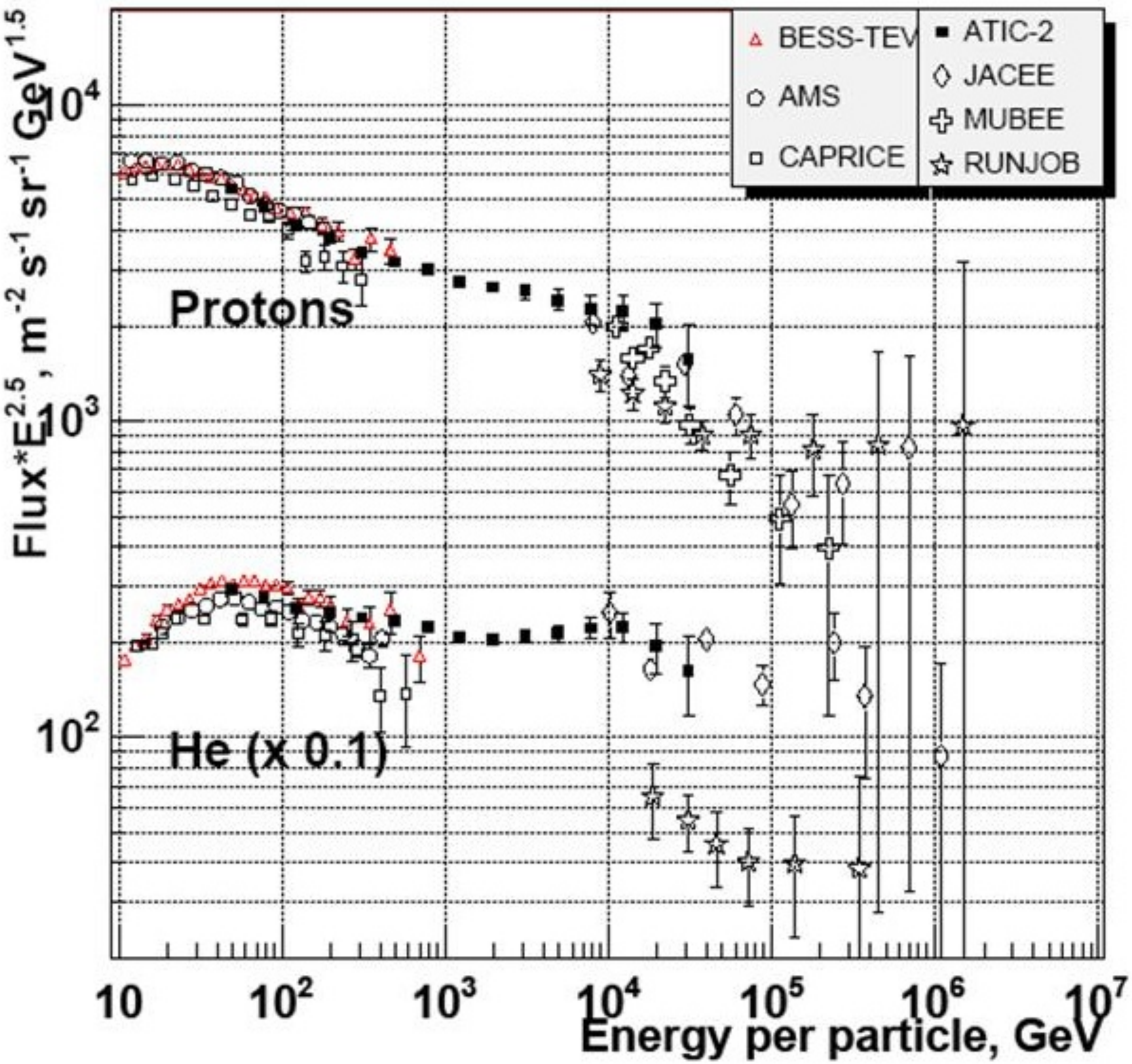






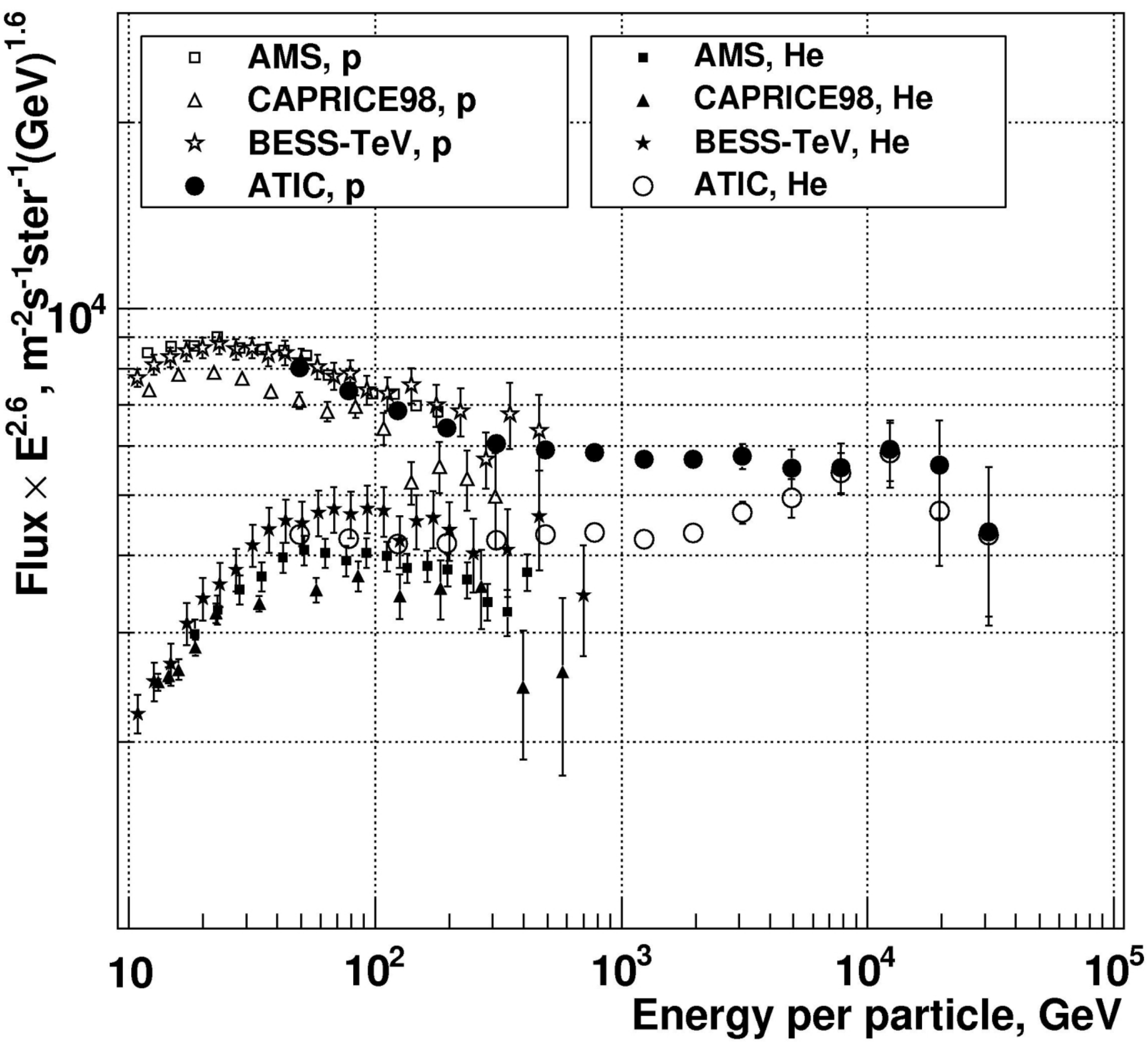


- Very good charge resolution
- Energy spectrum of H, He close to 100 TeV
- Energy spectrum of major GCR heavy ions
- Variations in energy spectra may indicate GCR are from a combination of sources



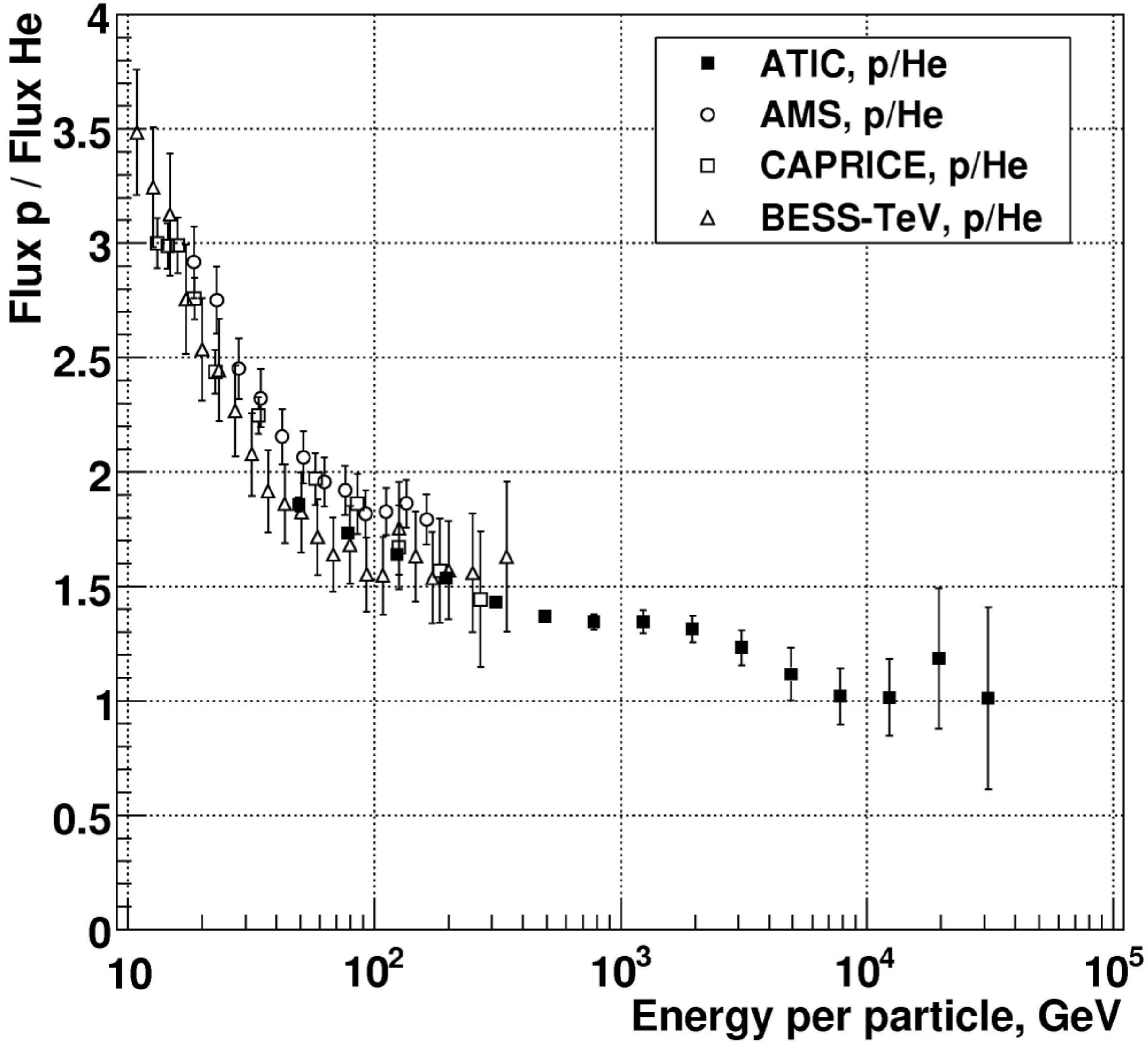
ATIC is consistent with JACEE proton and Helium results and is consistent with RUNJOB and MUBEE proton results.

ATIC is inconsistent with RUNJOB Helium spectrum.

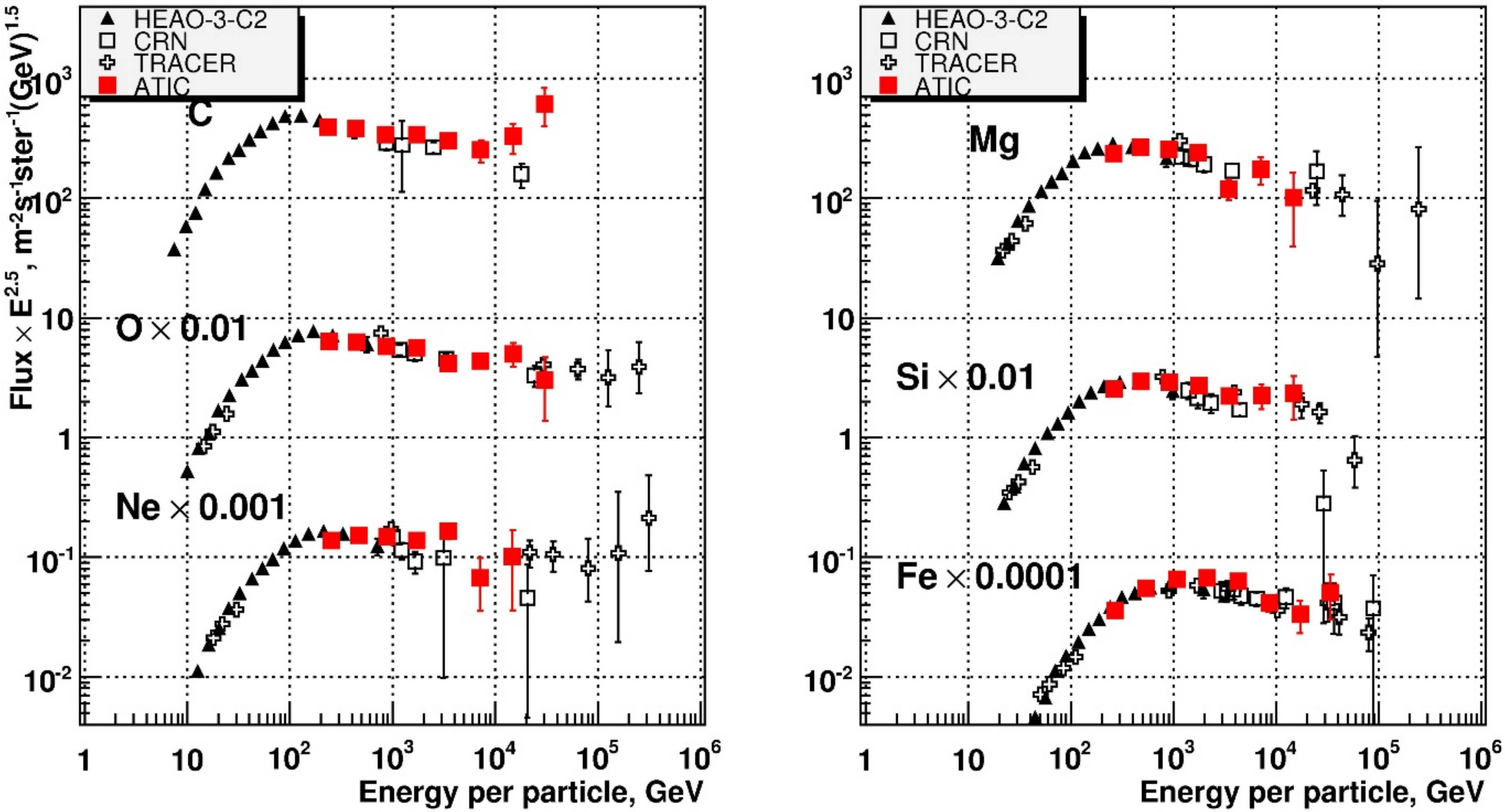


The spectra of H and He are different, confirming the early result from JACEE

The spectra show 'curvature,' i.e. are not power laws but change slope/ shape with increasing energy

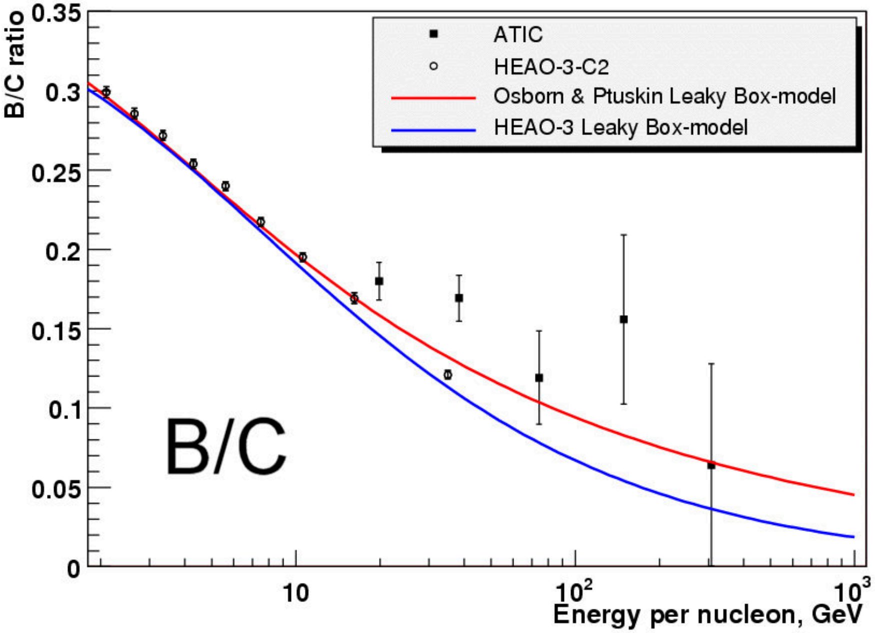


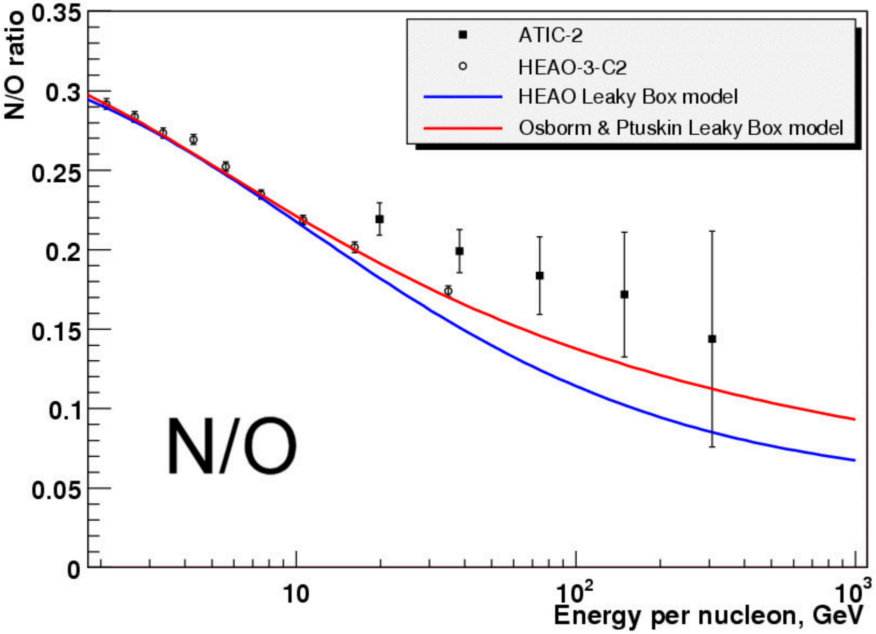
The Helium flux becomes equal to the Hydrogen flux at about 10 TeV per particle total energy.



There is general agreement with previous experiments on the Hi-Z energy spectra, but with a trend to flatten at the highest energies sampled.

Secondary GCR, such as B & N, are produced from primaries (C, O) during propagation





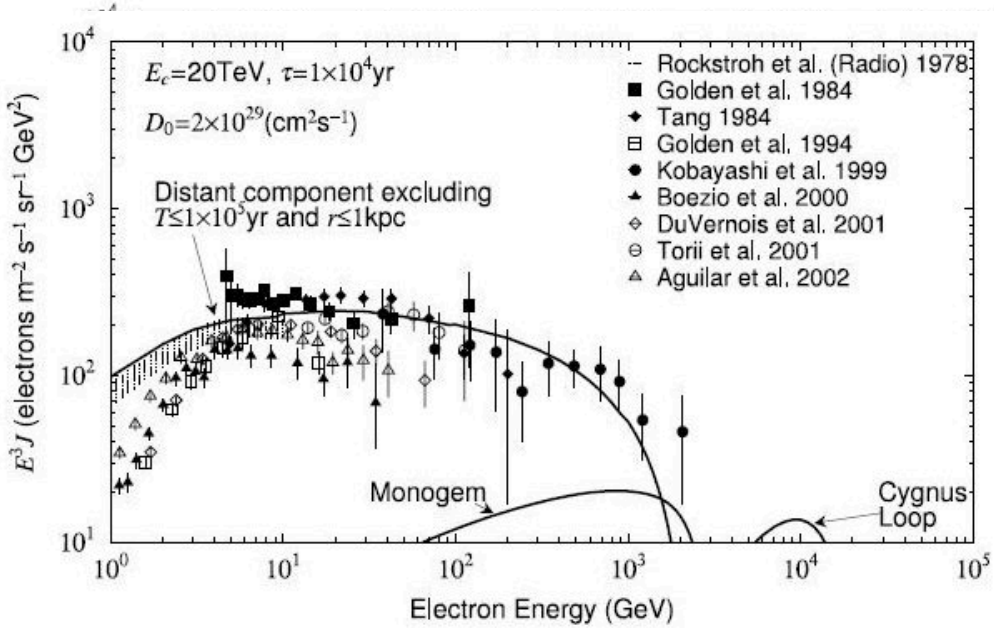
Both ratios appear to favor the diffusion propagation model, but the uncertainties are still too large for a conclusion.

Electrons can provide additional information about the GCR source

- High energy electrons have a high energy loss rate $\propto E^2$
  - Lifetime of ~10^5 years for >1 TeV electrons
- Transport of GCR through interstellar space is a diffusive process
  - Implies that source of electrons is < 1 kpc away

$$(R \approx 600 / \sqrt{E[TeV]}\ pc)$$

- Electrons <u>are</u> accelerated in SNR
- Only a handful of potential sources meet the lifetime & distance criteria
- Kobayashi et al (2004) calculations show possible structure in electron spectrum at high energy



What are the cuts?

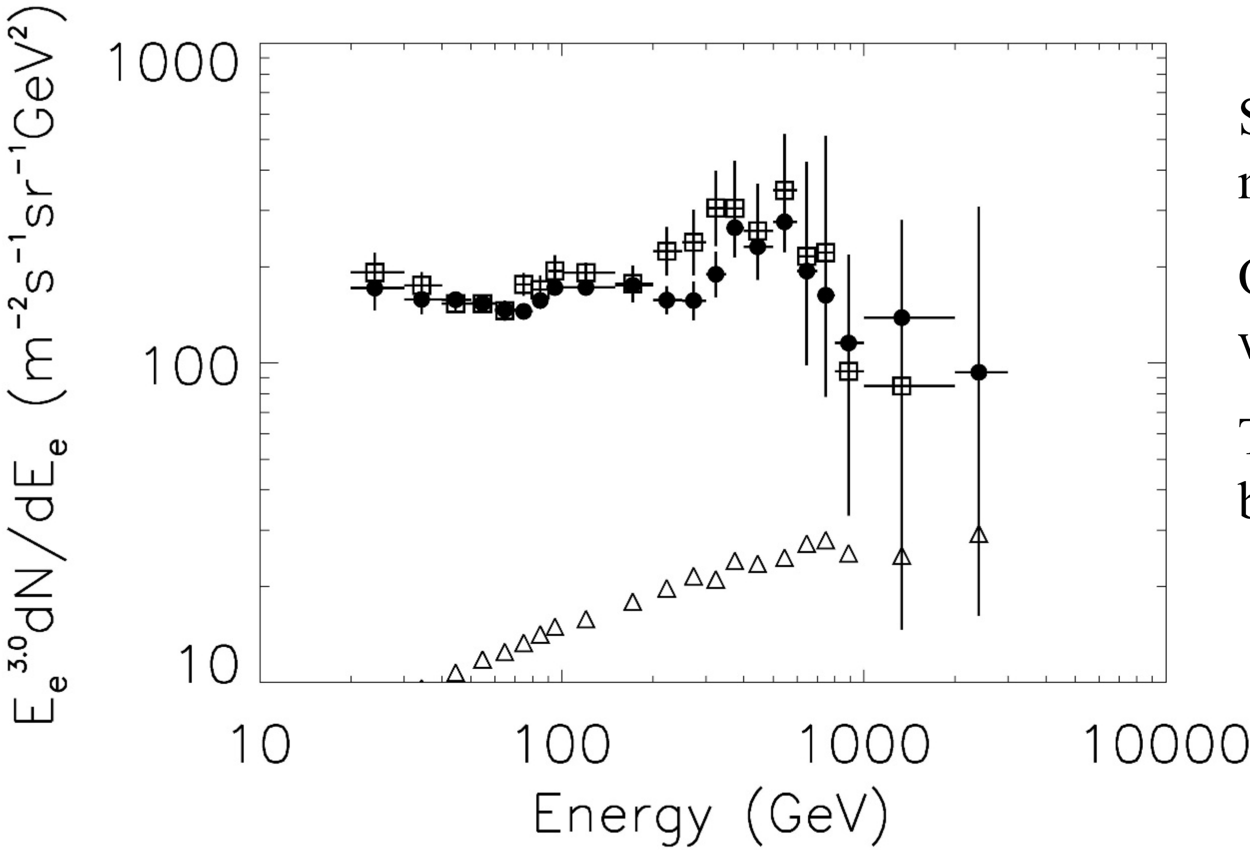
- RMS shower width in each BGO layer

$$\langle r.m.s. \rangle^2 = \sum_{i=1}^{n} E_i (X_i - X_C)^2 / \sum_{i=1}^{n} E_i$$

- Weighted fraction of energy deposited in each BGO layer in the calorimeter

$$F_j = \langle r.m.s. \rangle^2 \left[E_j / \sum_{i=1}^{n} E_i \right]$$

Results from ATIC – 1 and ATIC – 2



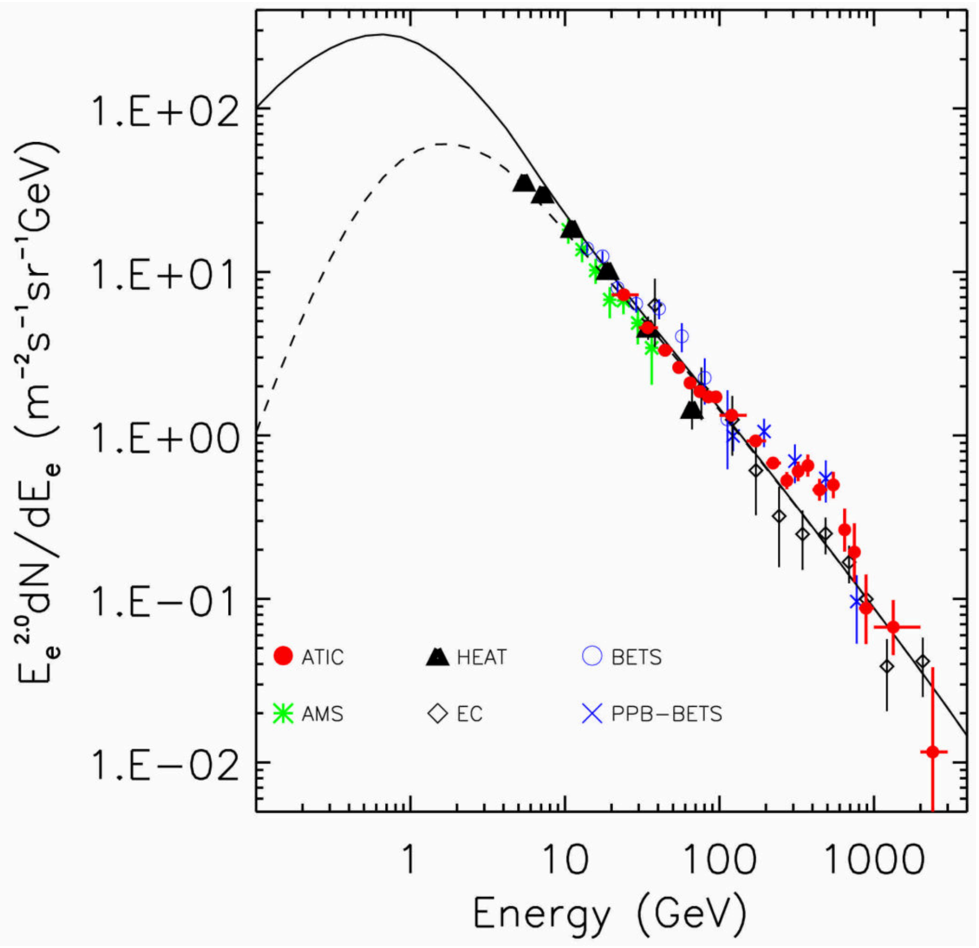
Solid = ATIC-2 with 2.5 m2-sr-days

Open square = ATIC-1 with 0.6 m2-sr-days

Triangles = combined background

The ATIC electron results exhibits a feature/excess

- Curves are from GALPROP diffusion propagation simulation code
  - Solid curve is local interstellar space
  - Dashed curve is with solar modulation (500 MV)
- “Excess” at about 300 – 600 GeV
- Also seen by recent PPB-BETS Flight



The Extended ATIC Flight Program – ATIC-3 and ATIC-4

Increase the calorimeter depth by 25%

This was possible with the new launch vehicle which could support, on the snow, a larger launch weight.

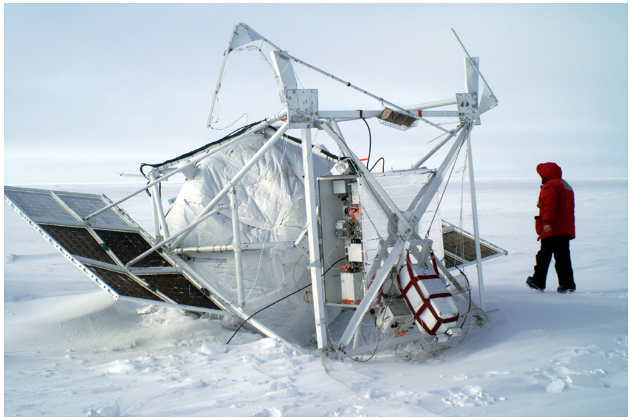
In order to

Investigate the difference between the ATIC-1 and ATIC-2 spectra of H and He

Previous datasets analyzed via different trigger modes suggested a trigger efficiency effect in the data.

Confirm the previous ATIC-1 and -2 results on the electron spectrum

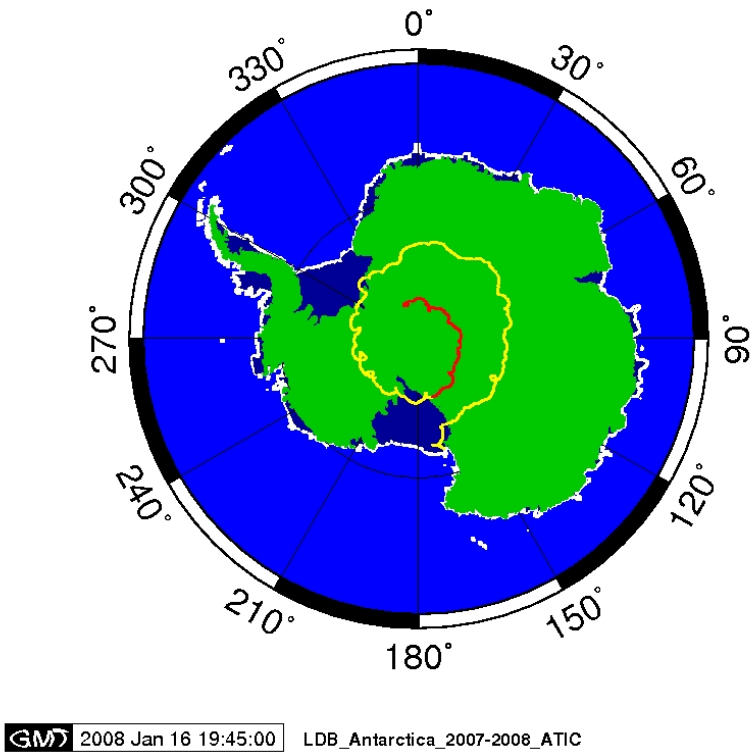
The ATIC-3 attempt ended in disaster!



- ATIC-3 was launched Dec. 19, 2005
- Balloon failure occurred almost immediately after launch
- Reached only 75,000 feet before starting down
- Had to quickly terminate as ATIC was headed out to sea
- Landed only 6 miles from edge of ice shelf

- The instrument was fully recovered instrument and refurbished in preparation for the 4th and final flight of ATIC in 2007.

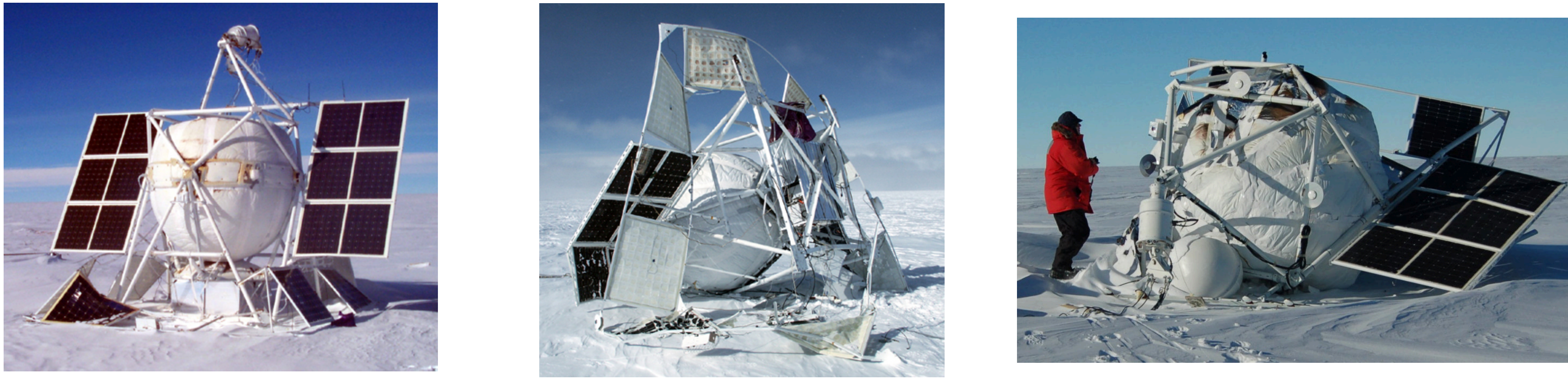
ATIC-4 Science Flight from McMurdo – 2007



- Launch: 12/26/07 13:47 UTC
- Begin Science: 12/27/07 14:00 UTC
- End Science: 01/11/08 02:00 UTC
- Termination: 01/15/08 00:30 UTC
- Recovery: 2/1/08 from South Pole

- Obtained about **14 ½ days** of science data collection
- Lost pressure within gondola on 1/11/08
- The cause of this pressure loss is still a mystery

Recovery expeditions to the plateau

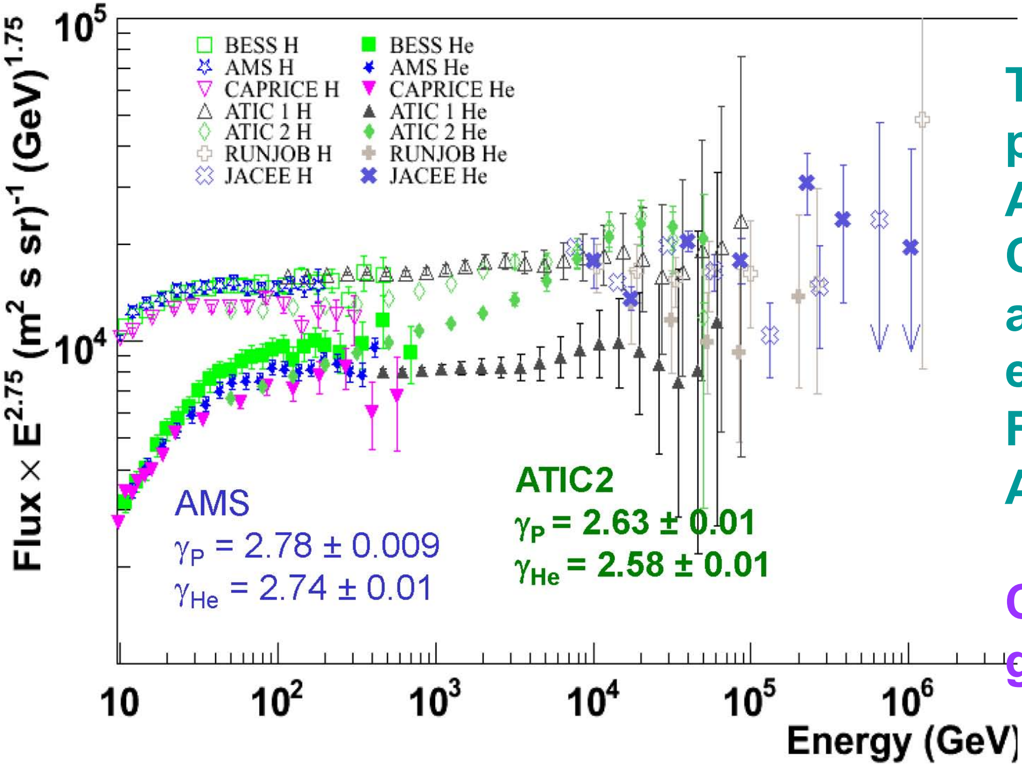


The good ATIC-1 landing (left) and the not so good landings of ATIC-2 (middle) and ATIC-4 (right)

ATIC is designed to be disassembled in the field and recovered with Twin Otters. Two recovery flights are necessary to return all the ATIC components. Pictures show recovery flight of ATIC-4

ATIC-1 vs ATIC-2: A mystery

During the ATIC-2 flight, most of the data was taken with one trigger, but there were shorter periods of data taking with different operating conditions for the scintillators. Comparisons of these files showed differences, but with low statistical significance. Nevertheless, the evidence “suggested” a possible trigger inefficiency (energy dependent) within the small datasets.



This would lead to the preliminary spectra from ATIC-1 being too soft. Combined with other trigger and performance problems encountered in the ATIC-1 Test Flight, this might explain the ATIC1 vs 2 discrepancy.

Checking this was a prime goal of ATIC-3,4

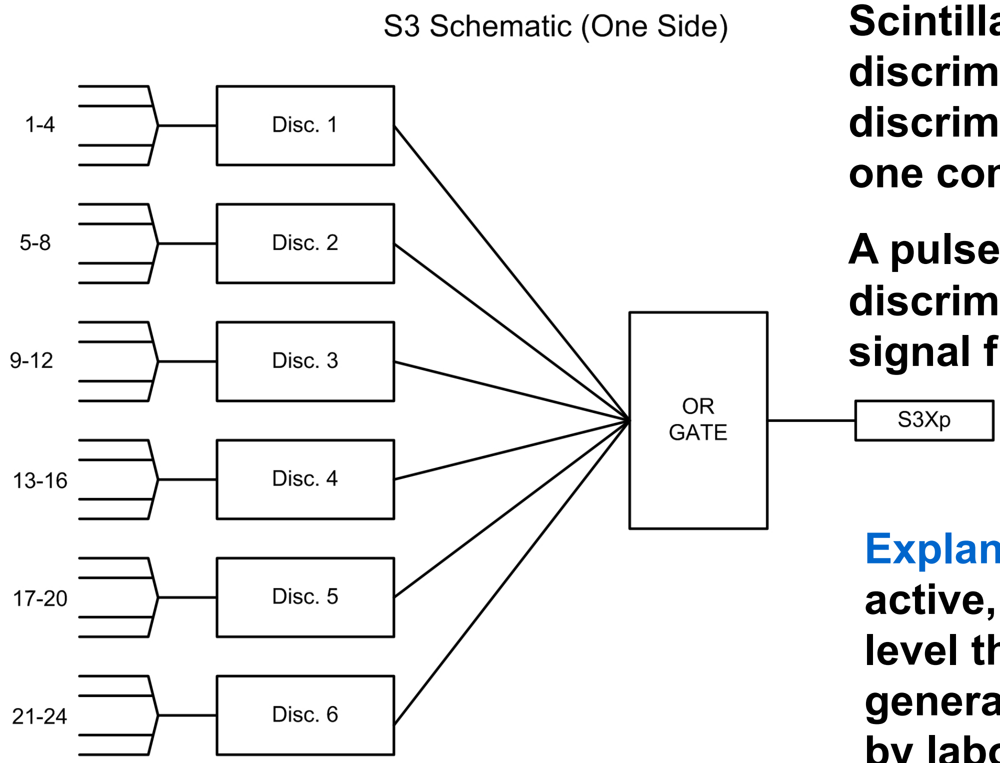
ATIC-1 vs ATIC-2: A mystery (continued)

The ATIC-4 flight confirmed that there was a probable "trigger inefficiency".

The highest energy and highest charge events were not as numerous as in ATIC-2. A high multiplicity of backscatter occurs as the incident particle Energy increases and/or the Charge of the nucleus increases. (If backscatter is the cause, it would suggest an energy dependent efficiency, reducing the number of events at high energy and steepening the energy deposited spectra.) This finding suggested that it was a trigger effect.

After the ATIC-4 flight, we re-assembled the instrument on the bench and investigated possible effects in detail in the lab ….. and were able to simulate the behavior seen in flight.

Trigger Inefficiency Problem in ATIC-1



Scintillator strips are 'ganged' into a discriminator in groups of four and six discriminators feed an OR gate to form one component of the trigger.

A pulse from any one of the six discriminators fires the OR gate, but a signal from all six did not fire the OR.

Explanation: When all six Disc. are active, they pull the power down to a level that does not allow the OR to generate an output pulse. Confirmed by laboratory testing.

Implication: Only high backscatter multiplicity events are affected, but backscatter multiplicity increases with energy and with charge. Thus, greatest inefficiency at highest energies and for heaviest nuclei. Confirmed by ATIC-4 data, but unknown during ATIC-1 preliminary analysis. Therefore, reported ATIC-1 spectra are too soft.

ATIC-1 vs ATIC-2: A mystery "Resolved"

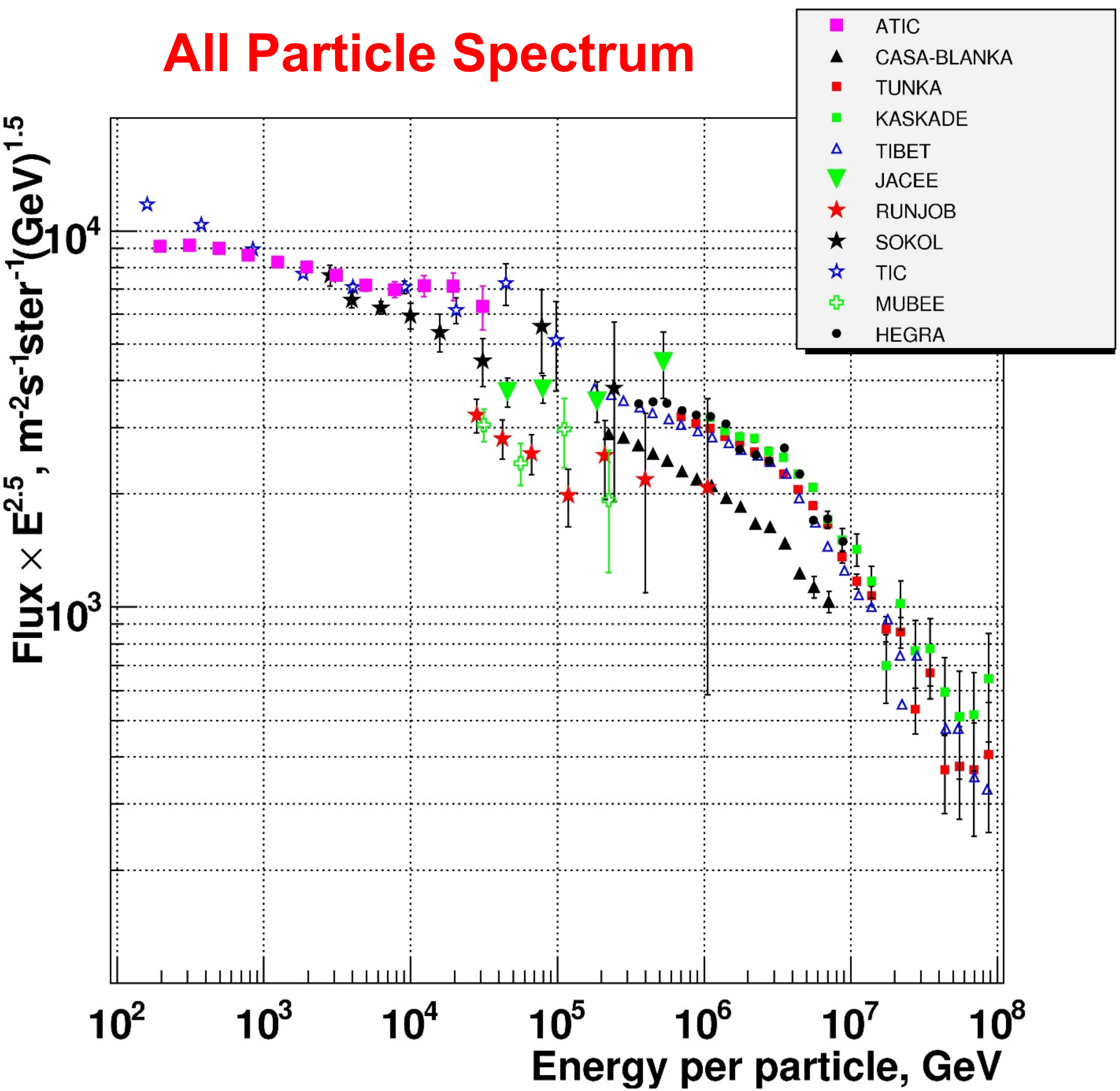
Result: The ATIC-2 data were correct due to a different hodoscope and trigger configuration, but ATIC-1 was not, leading to an inferred spectrum for H and He that was too steep.

Thus, we must withdraw the preliminary ATIC-1 spectra which were presented at COSPAR-04 and published as a conference proceedings paper.
(Adv. Sp. Res., 37, 1950-1954, 2006)

The effect of this trigger inefficiency is minimal for the electron observations which are at lower energy / lower multiplicity.

ATIC then undertook a Final Analysis of the Spectra

All Particle Spectrum

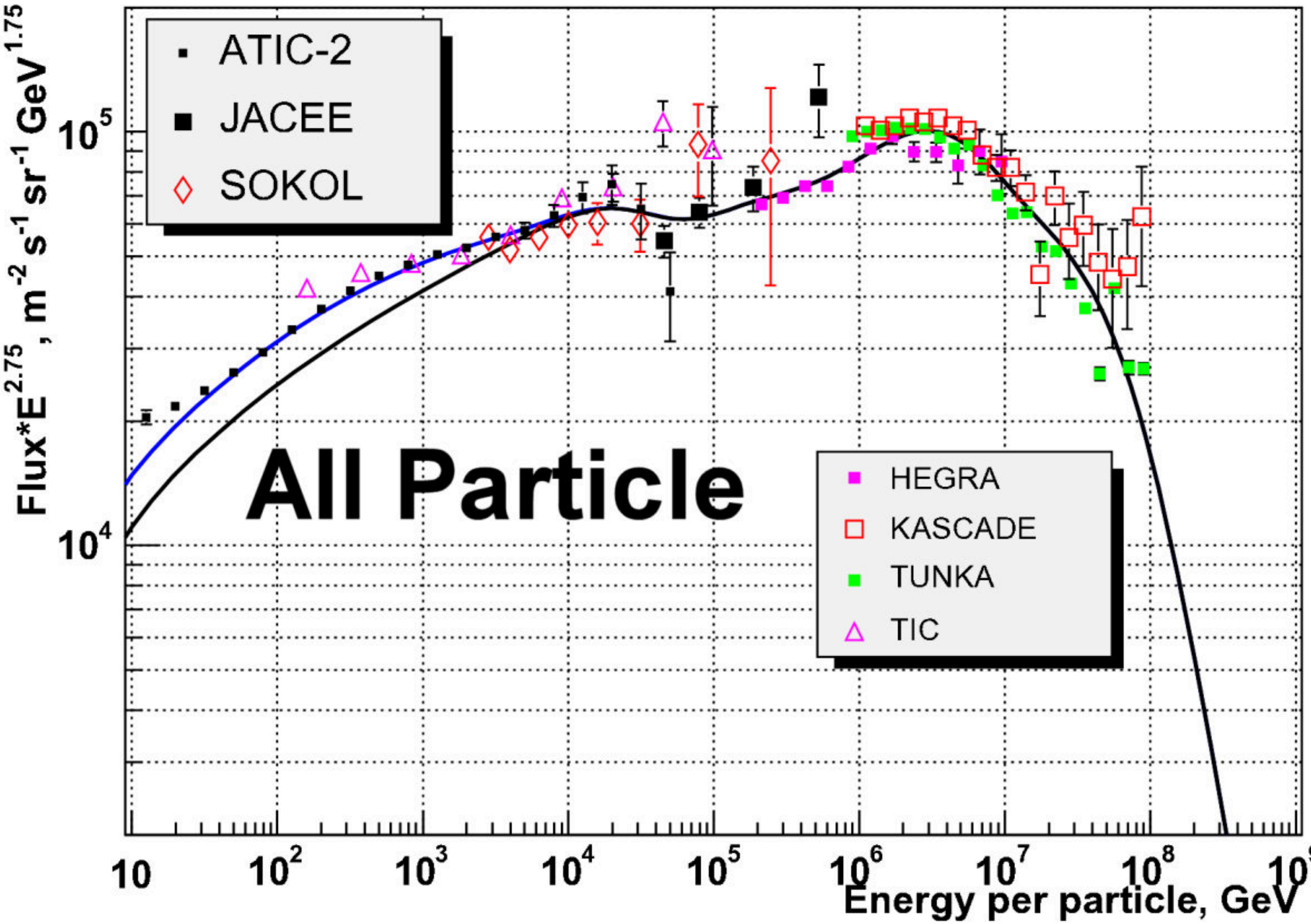


A Three Component Model

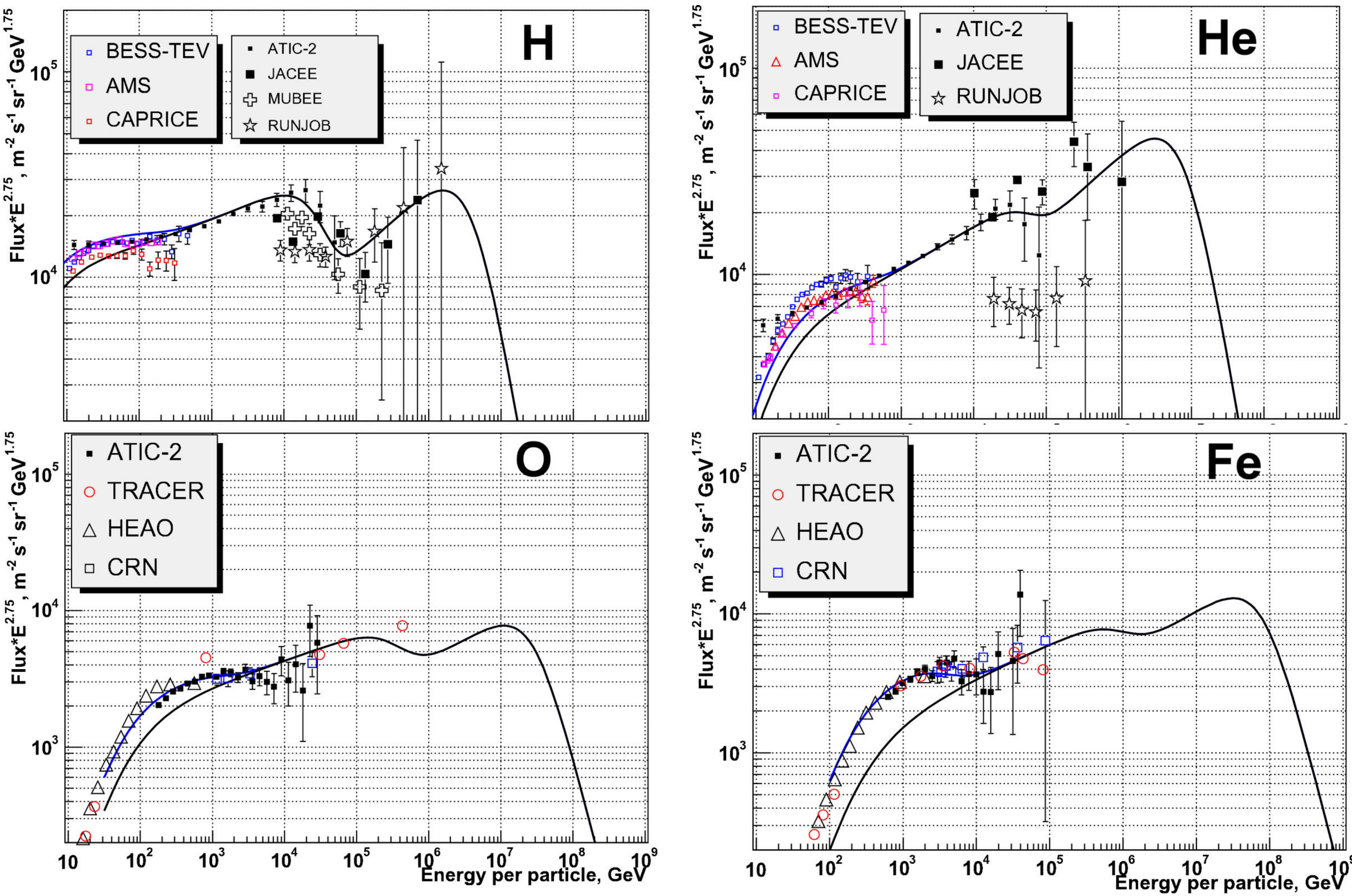
(Zatsepin and Sokalskaya, Astronomy & Astrophysics, 2006)

- Supernovae (Naked) -- < 5 x10^4 GV
  - Explodes into surrounding Interstellar Medium (ISM)
  - About 8-15 Solar masses
- Supernovae (Wind) -- < 4 x 10^6 GV
  - Explodes into a shell of matter created by its preceding stellar evolution before encountering the ISM
  - > 15 Solar Masses, e.g. Wolf-Rayet stars
- Novae -- < 200 GV
  - Needed to fit data below 300 GeV.

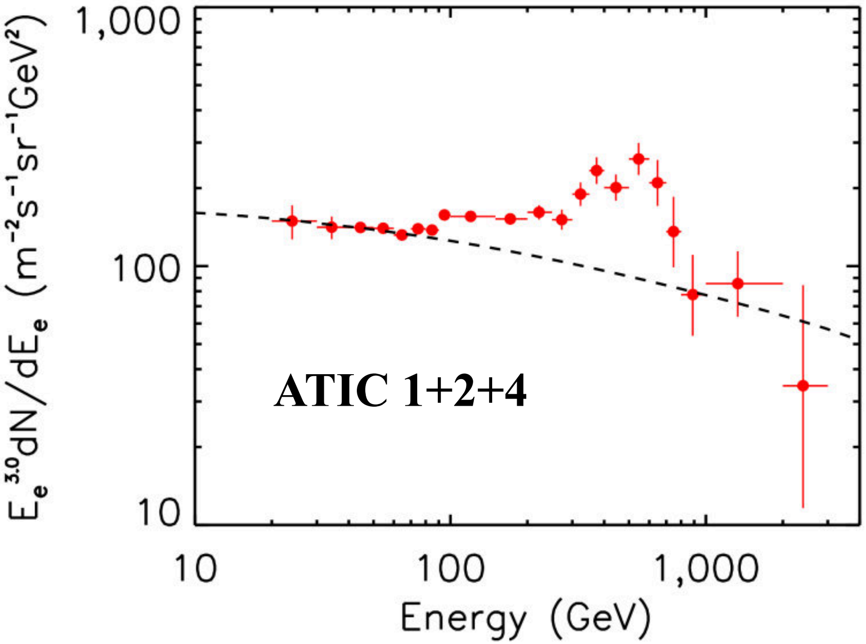
Three Component Model – All Particles

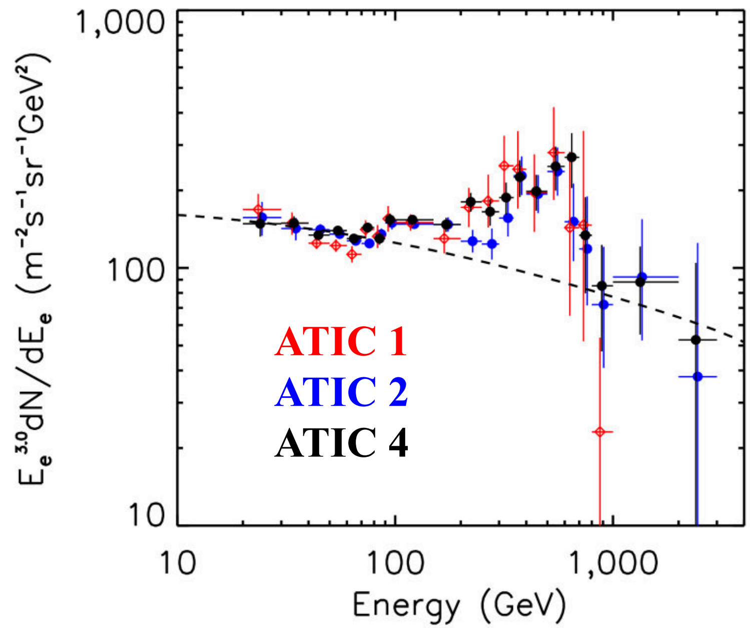


Three Component Model – Selected Elements



All three ATIC flights are consistent



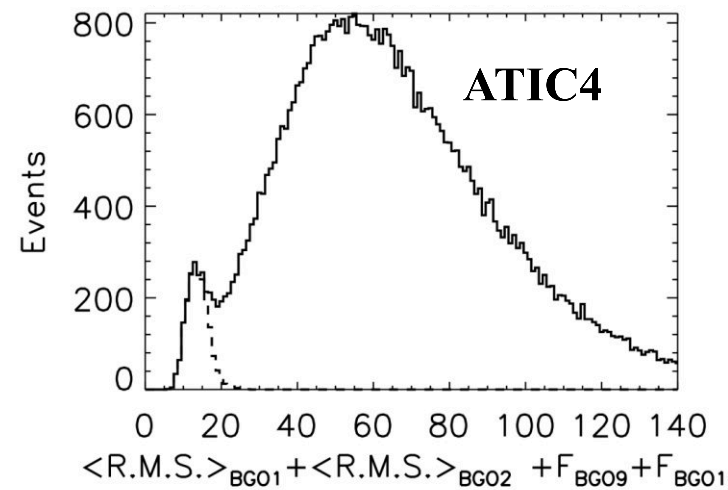


"Source on/source off" significance of bump for ATIC1+2 is about 3.8 sigma

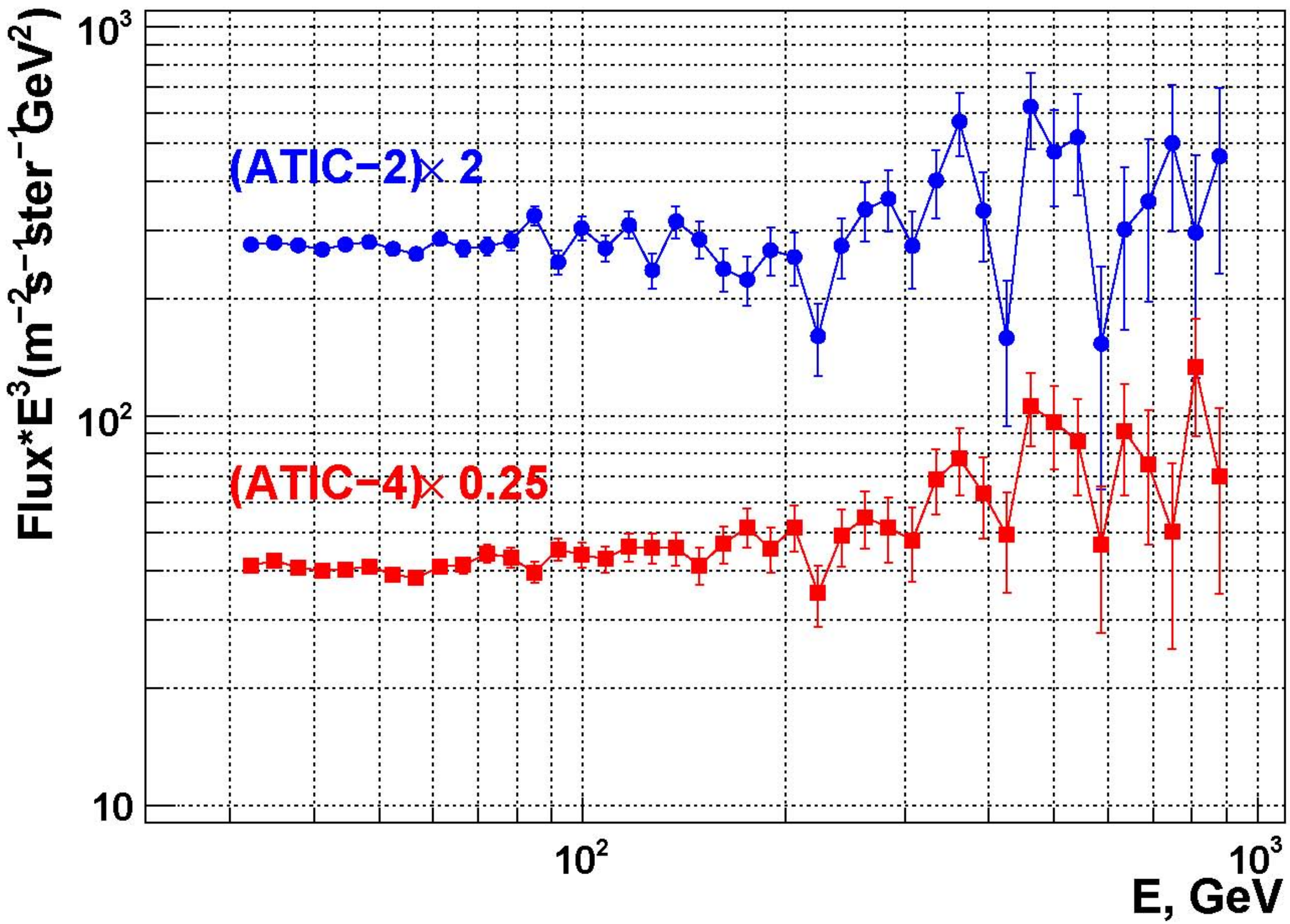
ATIC-4 with 10 BGO layers has improved e , p separation.

"Bump" is seen in all three flights.

Significance for ATIC1+2+4 is 5.1 sigma



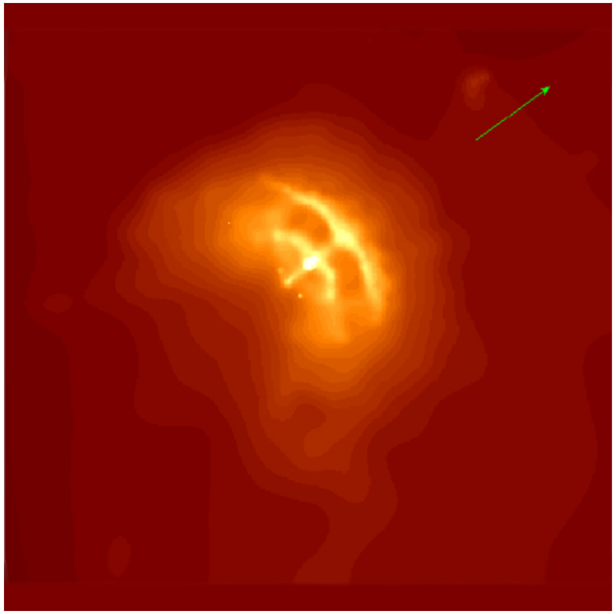
Possible 'Fine Structure' in the ATIC Electron Spectrum



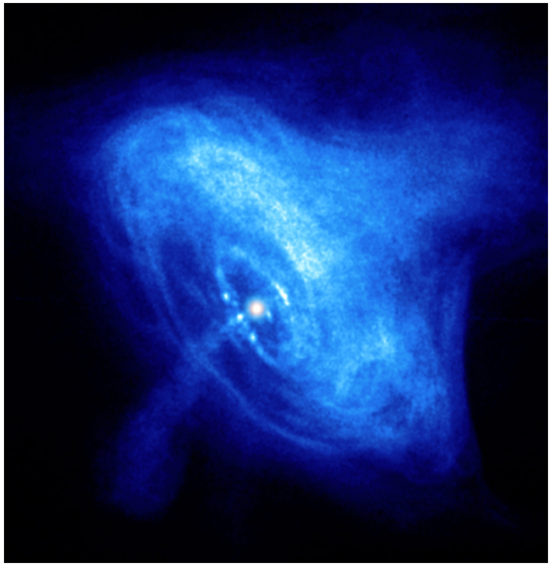
Spectrum of electrons at the top of the apparatus without subtraction of the proton background and without atmospheric correction as measured in the ATIC-2 and ATIC-4 experiments. Bin width is 0.035 of a decade in energy.

Pulsar Wind Nebulae and Magnetospheres are a favored explanation for the excess electrons

High Energy Particles are accelerated in Pulsar magnetospheres near the neutron star and give rise to X-ray and gamma ray radiation.



Cab Pulsar: in X-rays (right) from Chandra and in X-ray plus optical (top) from Chandra and Hubble



Vela Pulsar showing arcs (bows) of X-ray emission from interactions with the nebula of high energy particles accelerated near the central neutron star. Note the jets (arrows) from the central pulsar in the same direction as the motion of the pulsar through the supernova remnant (Chandra).

Summary

-- The ATIC experiment has traveled to Antarctica four times over the last seven years: Three successful flights for a total of about 48 days above 99% of the Earth's atmosphere

-- ATIC results indicate that the origin of GCR is more complex than previously expected:

Proton and Helium spectra are different (confirming early JACEE finding and refuting RUNJOB results)

Proton and Helium spectra are not pure power laws but show curvature / evolution over this VHE energy region (consistent with multi-source type models).

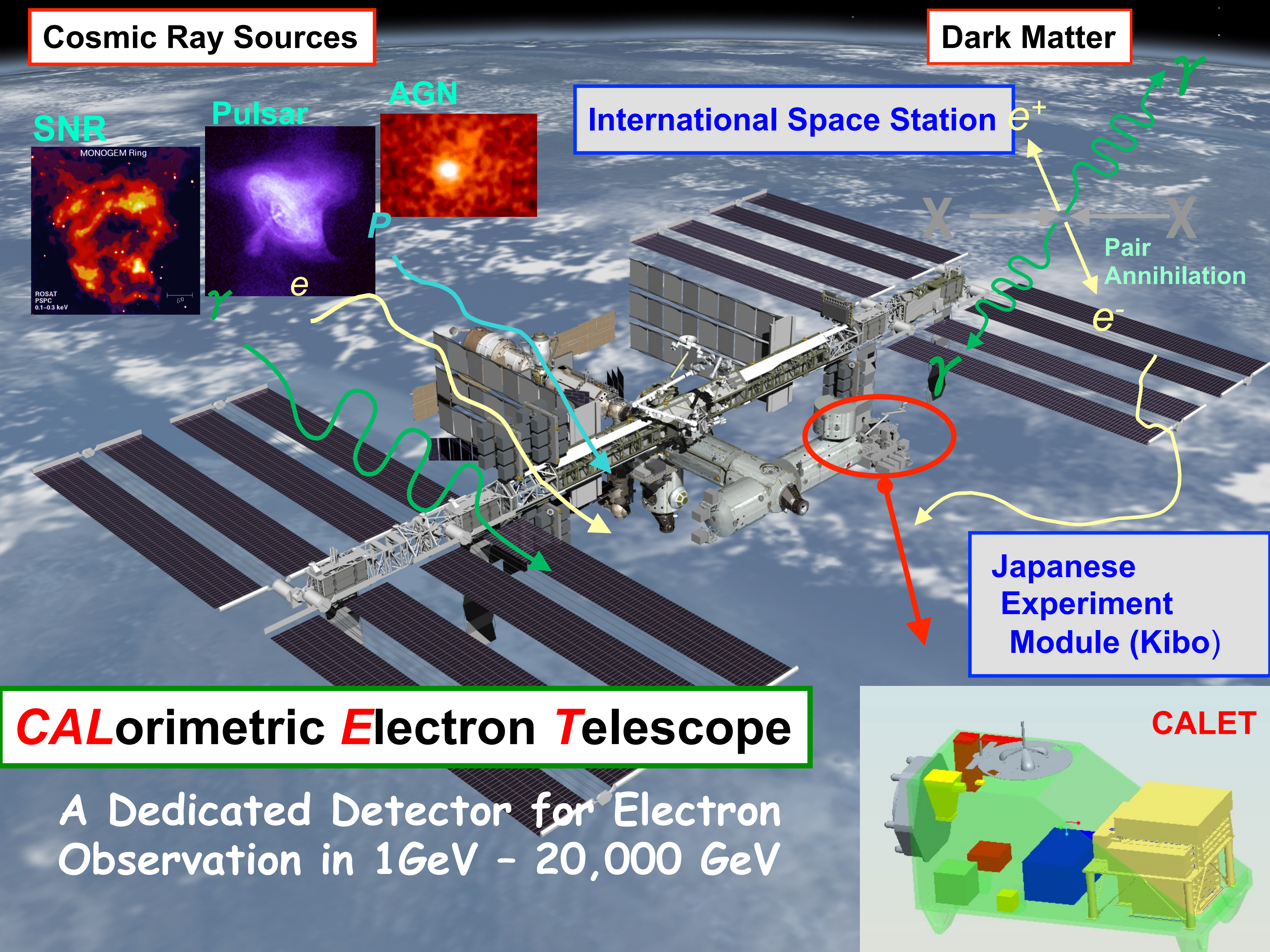
Hi-Z spectra are consistent with previous data but also have a possible curvature (uncertainty is still too large for definitive conclusions.)

Summary (continued)

- The electrons exhibit a "bump" (or excess) between 300 and 800 GeV
  - Not an instrument or background effect
  - The ATIC 4 flight, with improved background suppression, confirms the excess (as do other experiments).
  - The "source-on/source-off" significance of the excess with all three flights is now about 5 sigma
  - A 'Nearby' source for these 'electrons' is required.

- The source of this excess is difficult to explain
  - The feature is probably too low in energy and too narrow in energy to be a signature for a standard SNR source of GCR electrons
  - Micro-quasars probably can not generate electrons with high enough energy
  - Nearby pulsars (wind nebulae and magnetospheres) could be the source but they would need to be unusually efficient in generating e^+e^- pairs with the needed steep energy spectrum
  - Possible 'fine structure' in ATIC energy spectrum would favor multiple source models
  - Annihilation of an exotic dark matter particle might explain the excess positrons seen by PAMELA, the ATIC excess, and the WMAP microwave "haze", but new physics is needed for this.

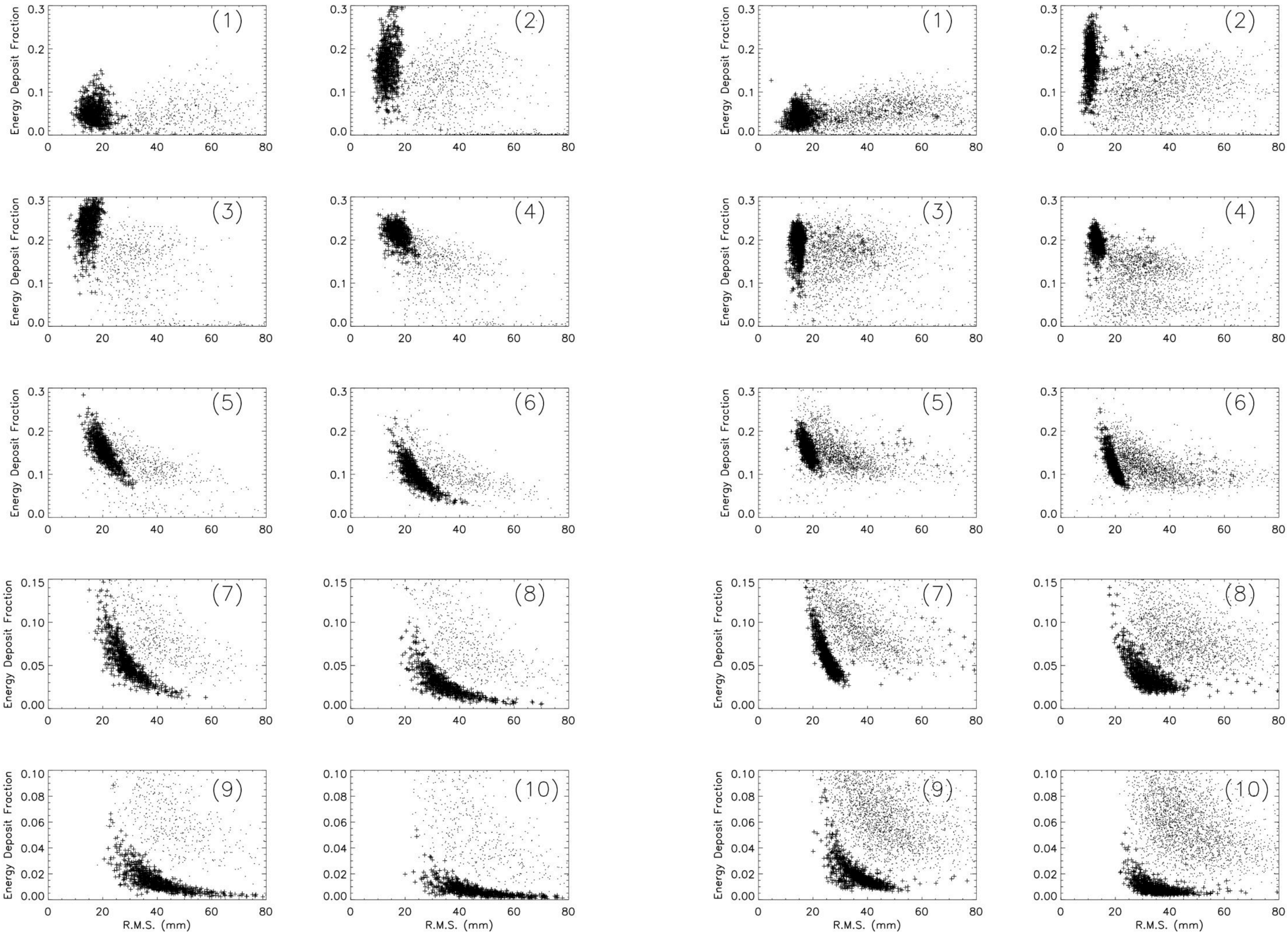
- New and continuing experiments should provide further information over the next several years
  - e.g. CALET, AMS-02, CREST, PEBS and, perhaps, the LHC.


Cosmic Ray Sources
Dark Matter
International Space Station
SNR
MONOGEM Ring
ROSAT
PSPC
0.1–0.3 keV
Pulsar
AGN
P
e
γ
e+
γ
X
X
Pair
Annihilation
e-
γ
Japanese
Experiment
Module (Kibo)
CALorimetric Electron Telescope
A Dedicated Detector for Electron
Observation in 1GeV – 20,000 GeV
CALET

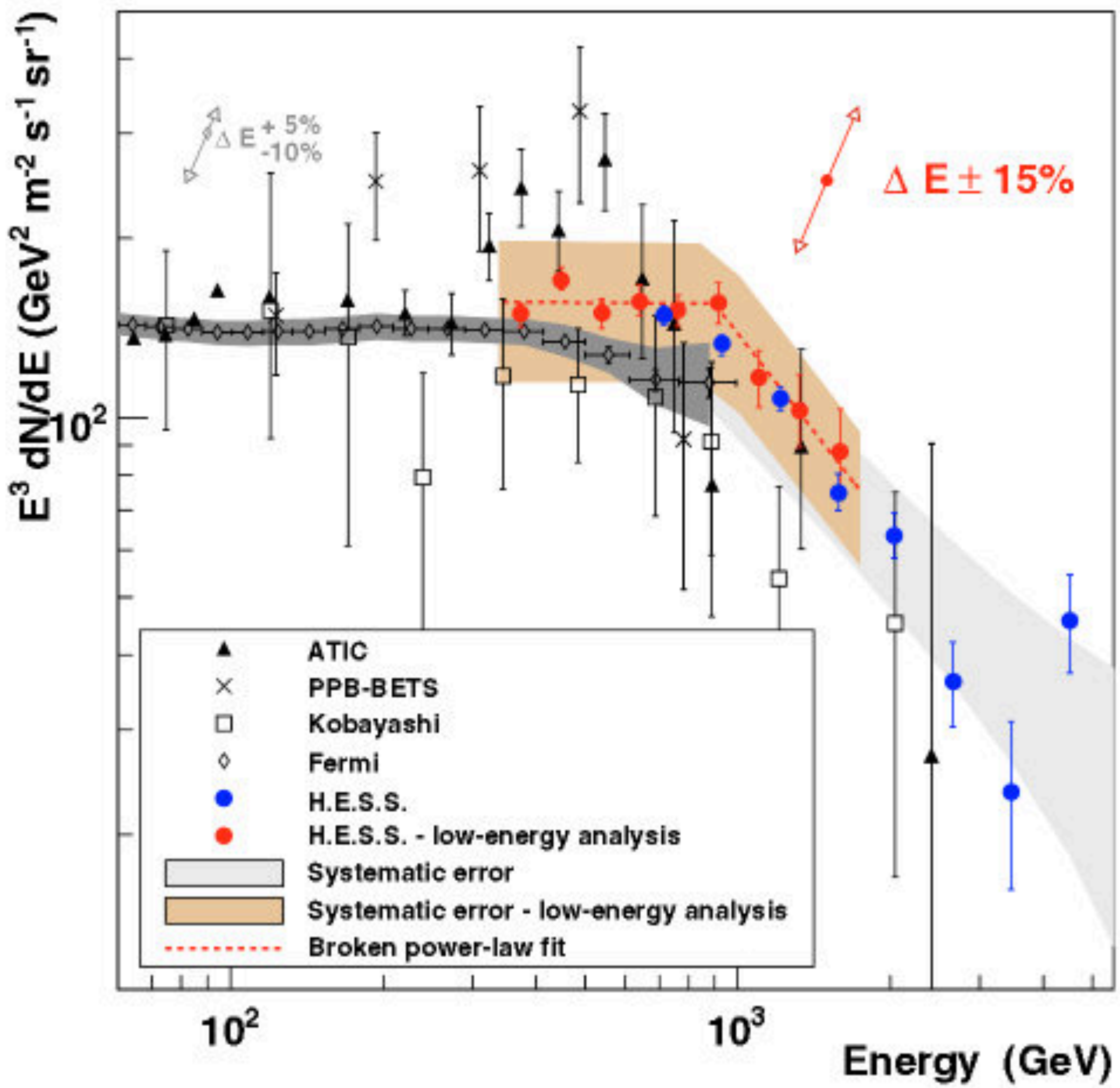
Simulation

CERN e and p

Data



ATIC, PPB-BETS, HESS and Fermi Results



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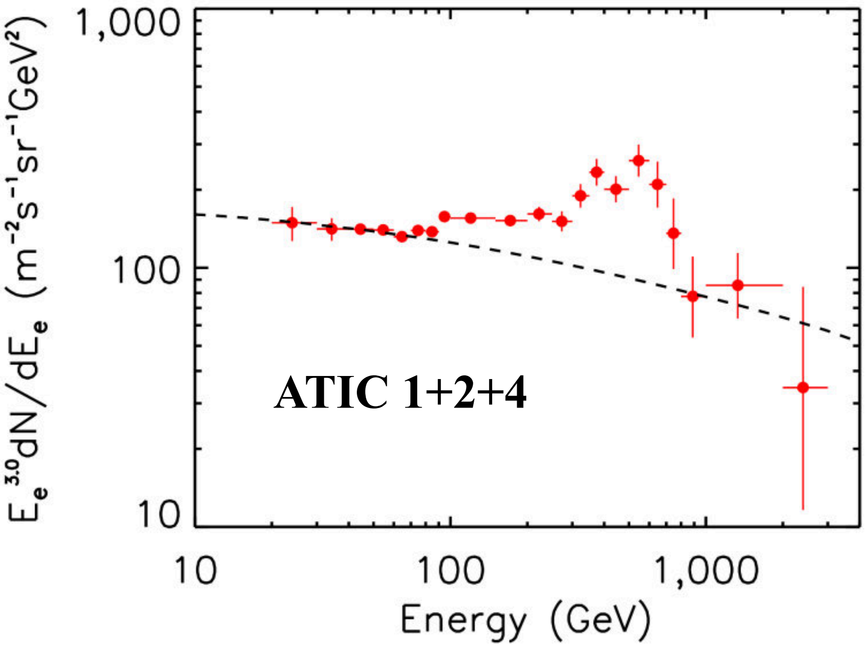

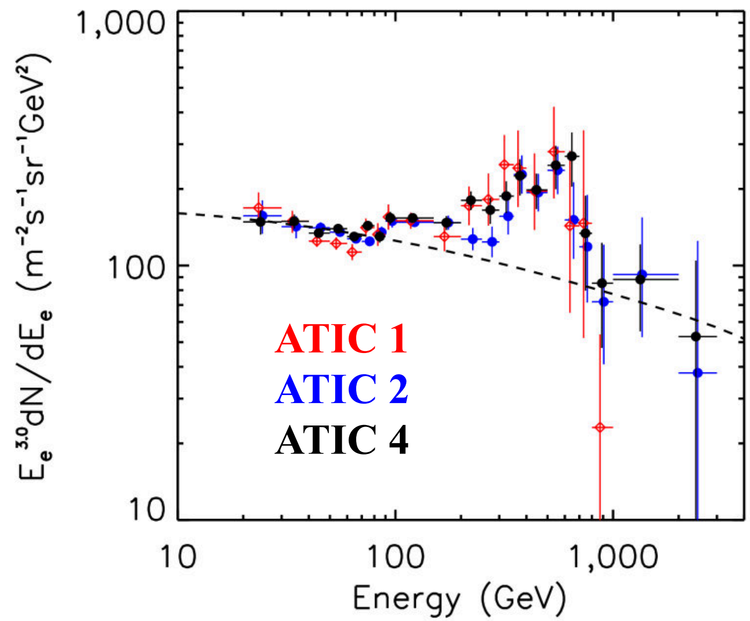

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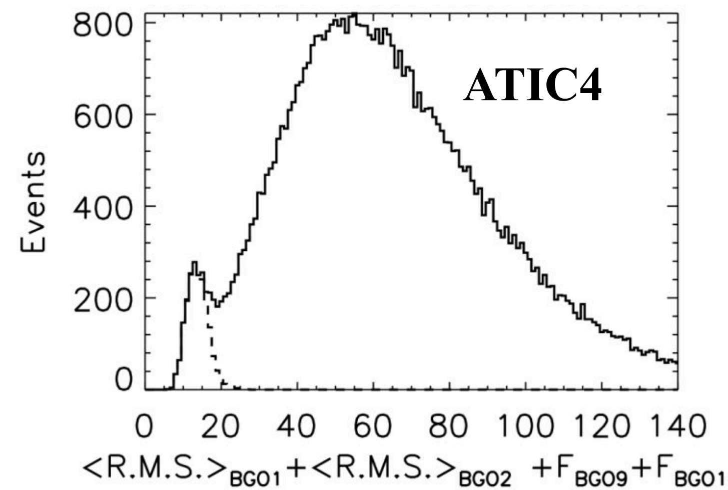

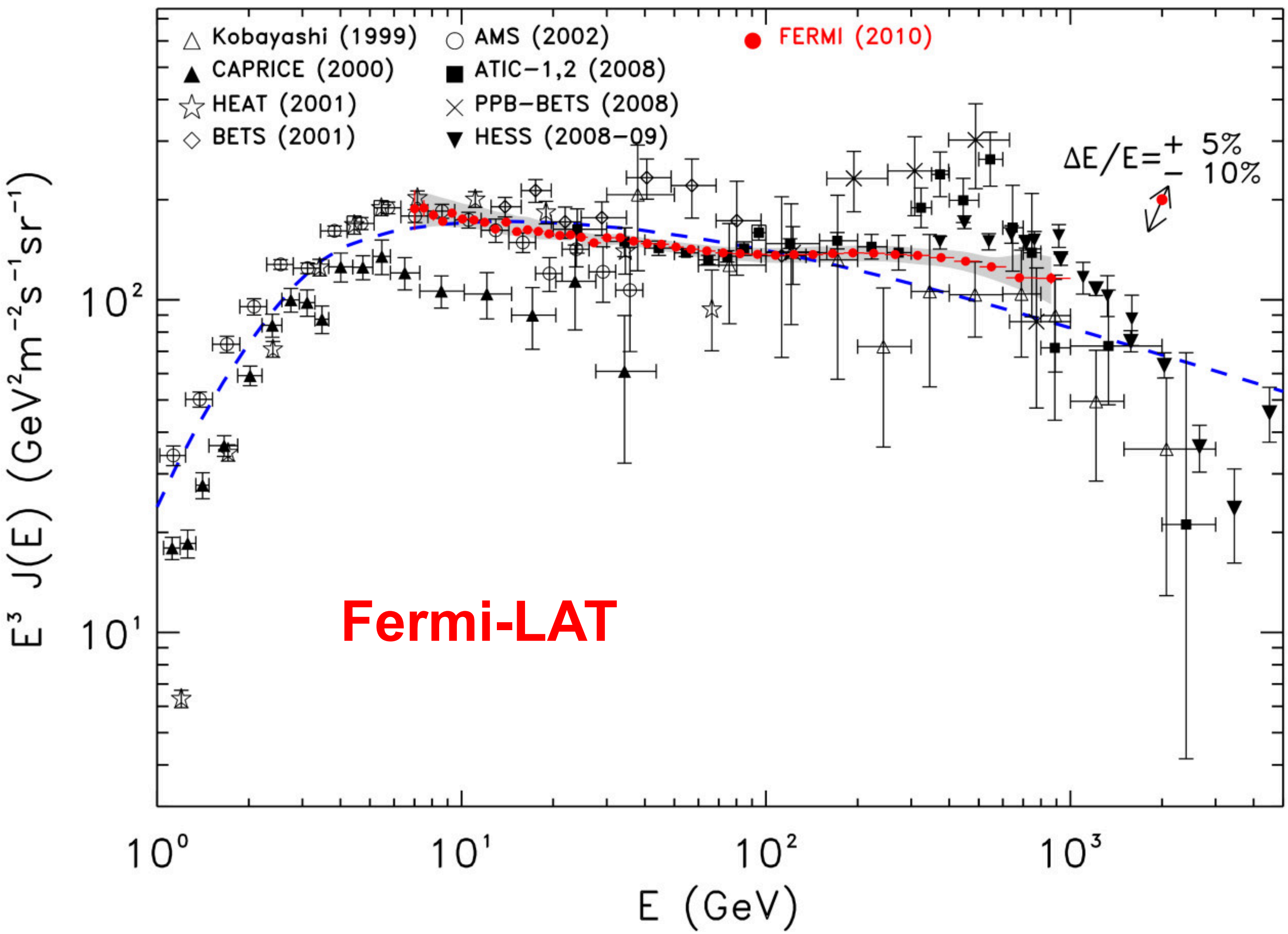

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FIG. 21: Cosmic ray electron spectrum as measured by Fermi LAT for one year of observations - shown by filled circles, along with other recent high energy results. The LE spectrum is used to extend the HE analysis at low energy. Systematic errors are shown by the grey band. The range of the spectrum rigid shift implied by a shift of the absolute energy is shown by the arrow in the upper right corner. Dashed line shows the model based on pre-Fermi results [32]. Data from other experiments are: Kobayashi [33], CAPRICE [34], HEAT [35], BETS [36], AMS [19], ATIC [7], PPB-BETS [8], H.E.S.S. [9, 10]. Note that the AMS and CAPRICE data are for e^- only.

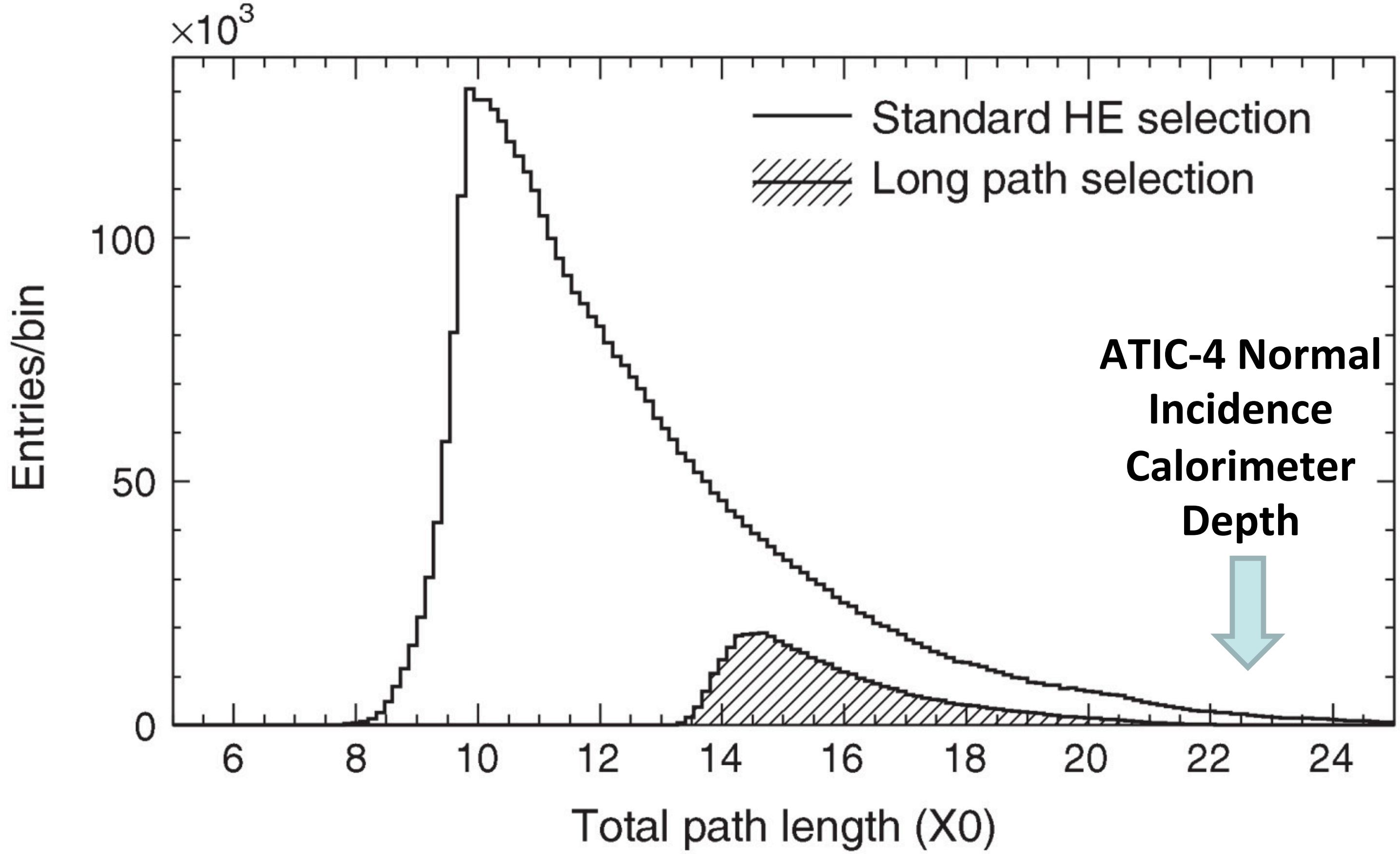

FIG. 15. Distribution of the amount of material traversed by the candidate electrons passing the long-path selection, compared with that for the entire data sample used in the standard analysis (the sharp edge at $\sim 10\ X_0$ in the latter reflects the total thickness of the instrument on-axis). Note the difference in the number of events.

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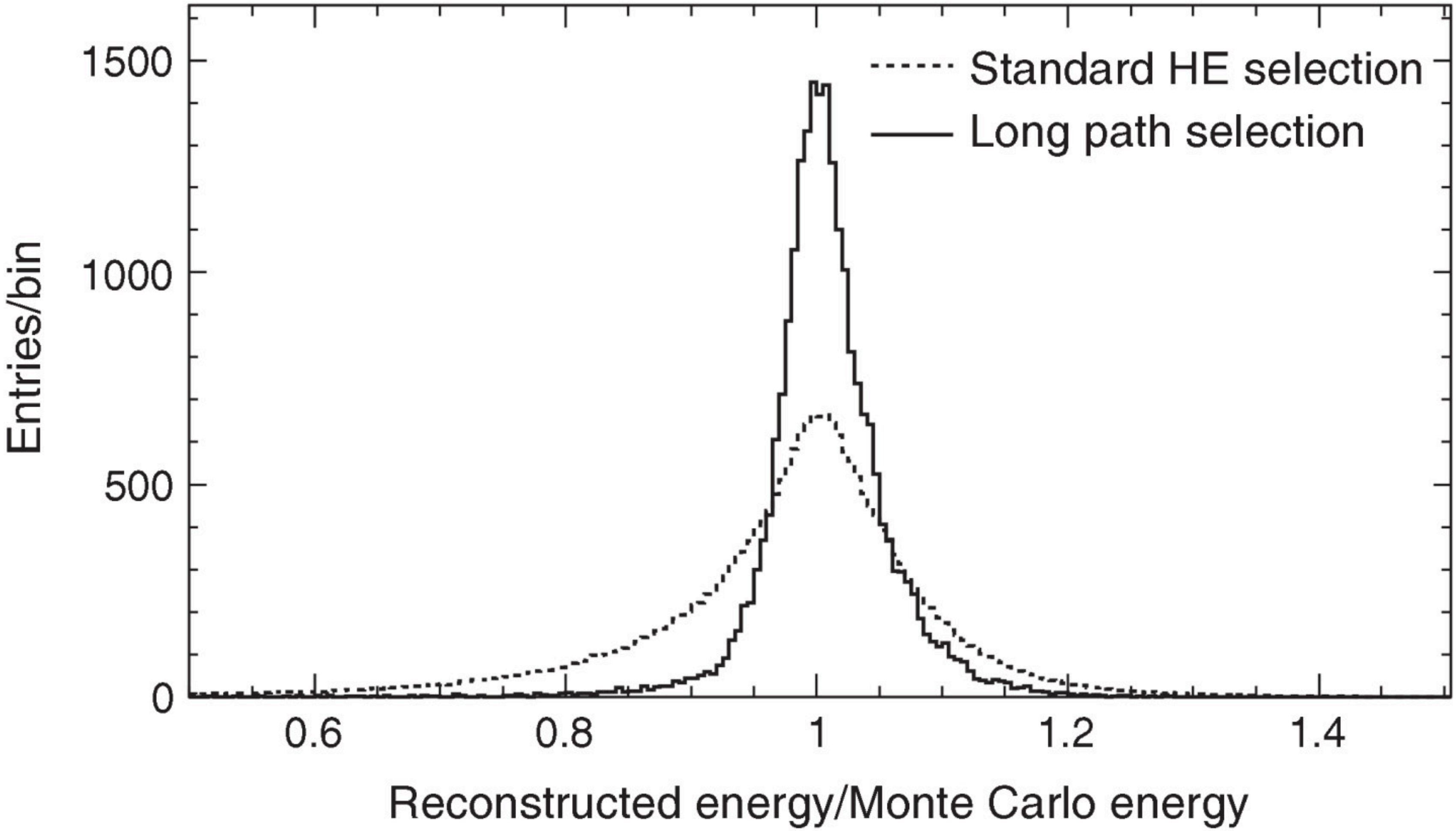


FIG. 16. Energy dispersion distribution in the energy range 242–458 GeV for the long-path selection (solid line) and the standard HE analysis (dashed line).

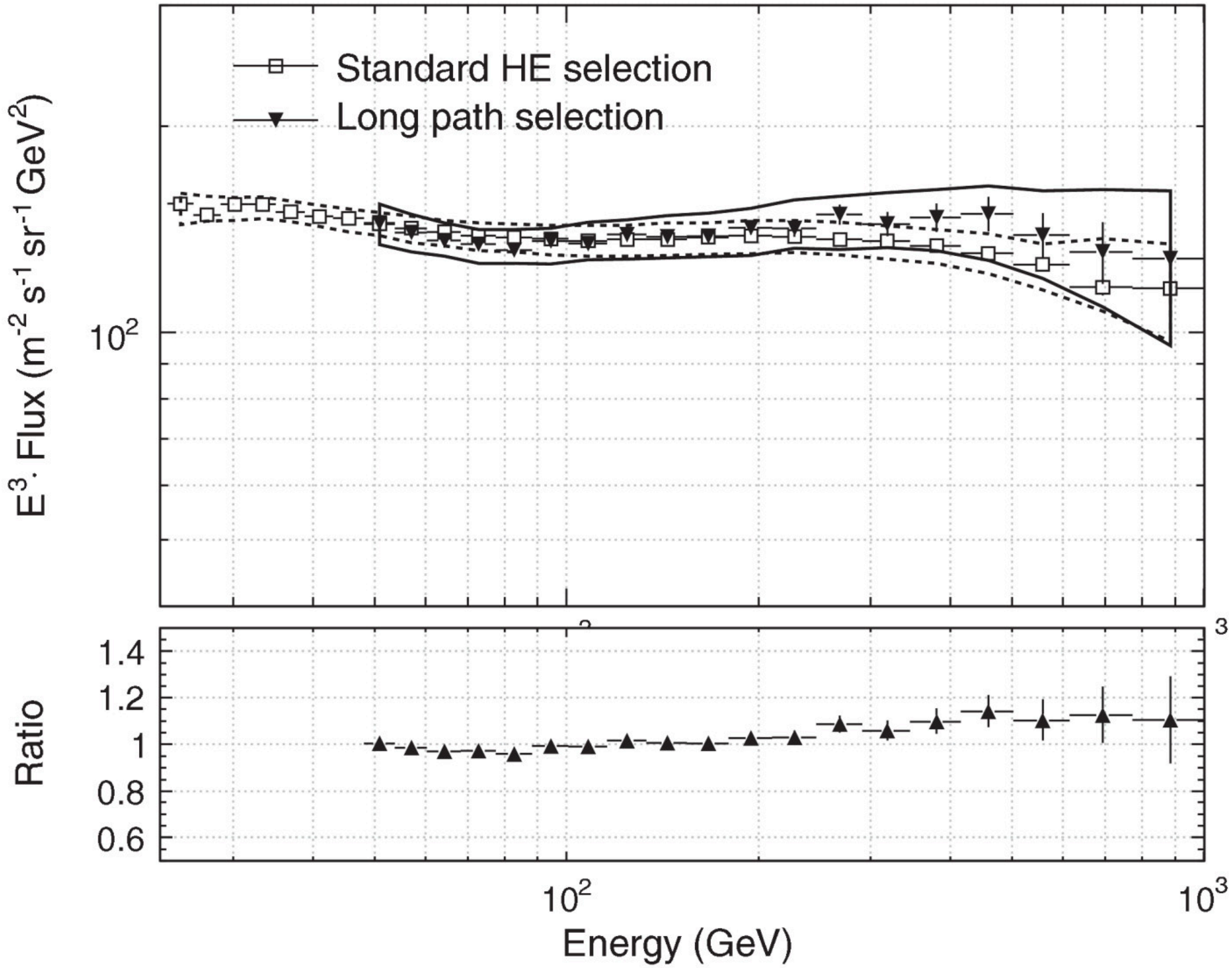
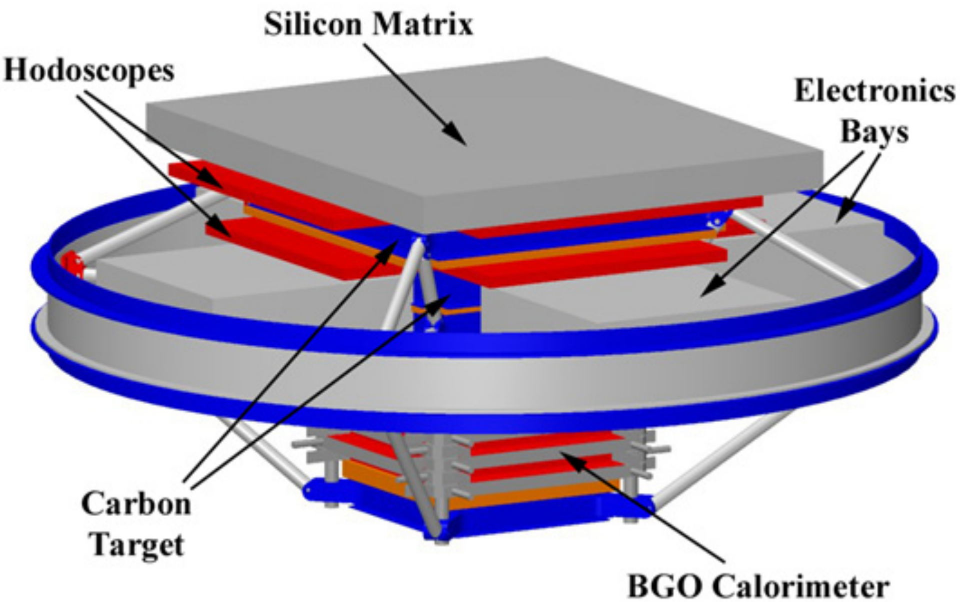


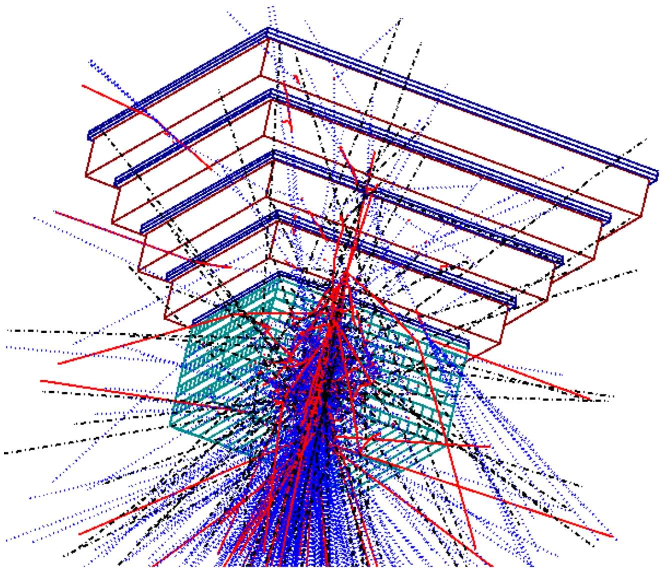
FIG. 19. Comparison of the spectra obtained with the long-path selection and the standard HE selection. The continuous lines represent the systematic uncertainties for the long-path analysis and the dashed lines for the standard analysis. The bottom panel shows the ratio of the two spectra.

ATIC Instrument



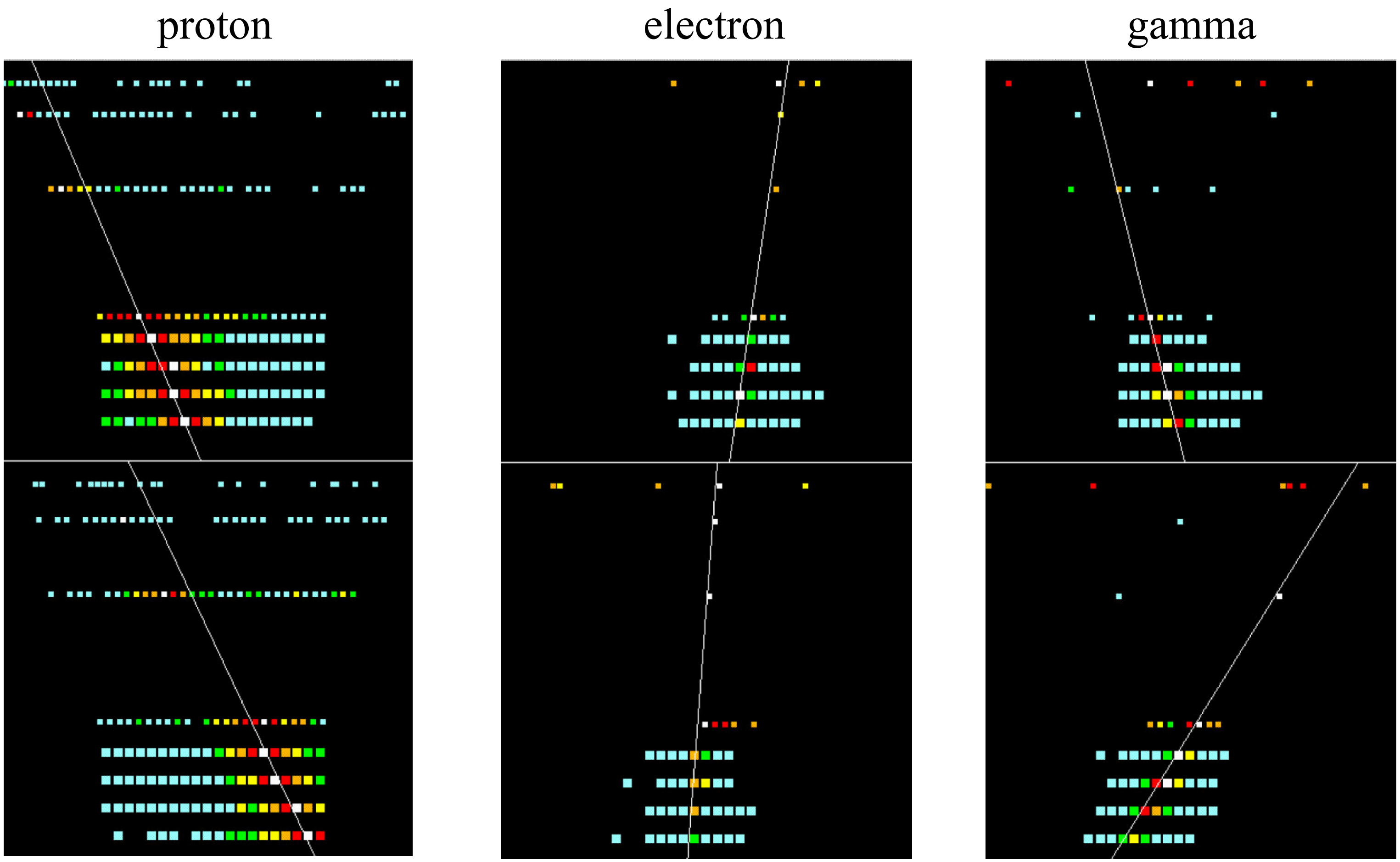
Antarctic Flights:

- 12/28/00 - 1/13/01
- 12/29/02 – 1/18-03
- 12/27/07 – 1/15/08

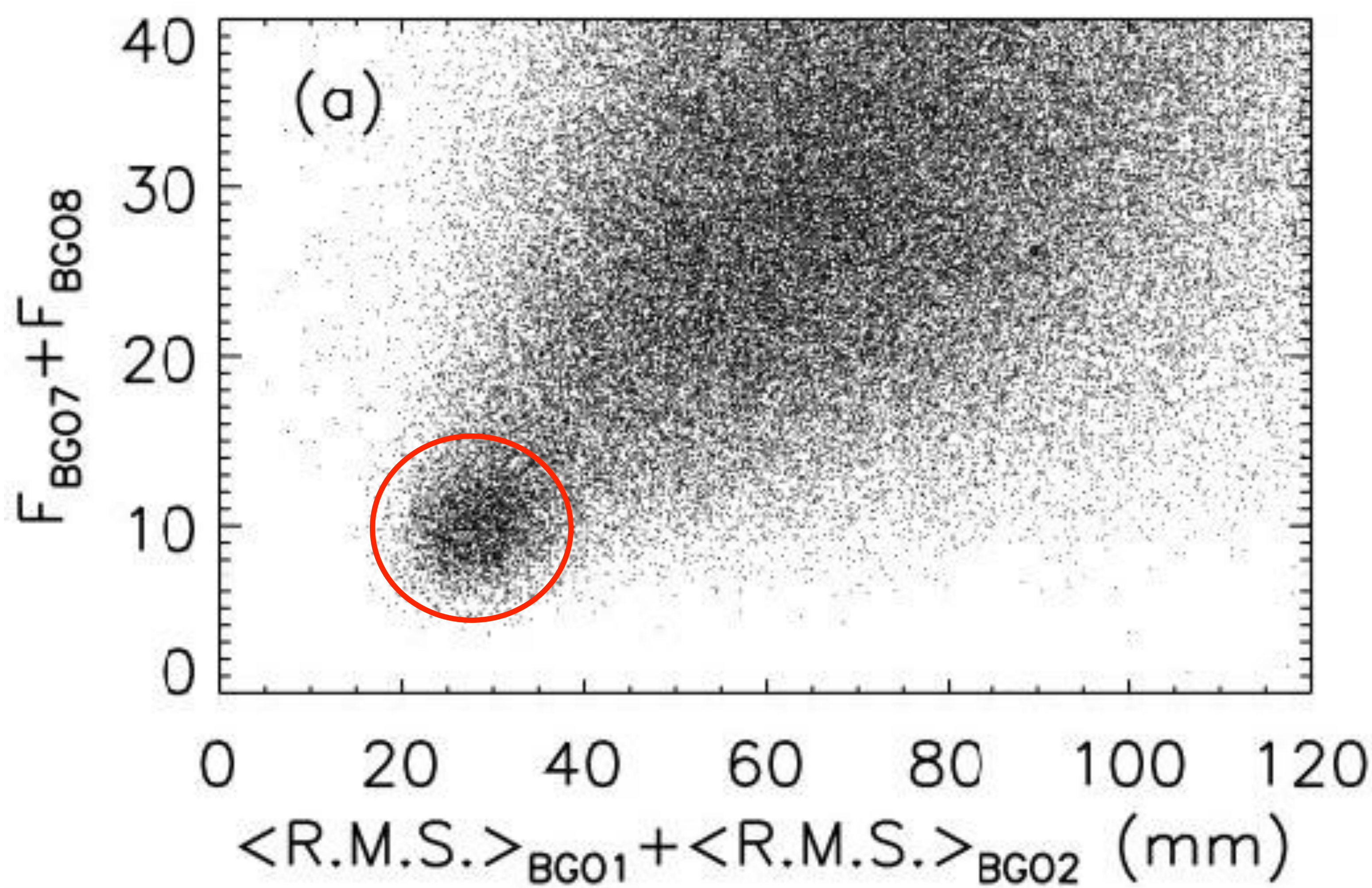


Typical (p,e,γ) shower images from ATIC flight data

- 3 events, energy deposit in BGO is about 250 GeV
- Electron and gamma-ray showers are narrower than the proton shower
- Gamma-ray shower: No hits in the top detectors around the shower axis



Cross Plot of Cuts



Flight Preparations