Measurements of Cosmic Ray Electrons with the ATIC Balloon Experiment

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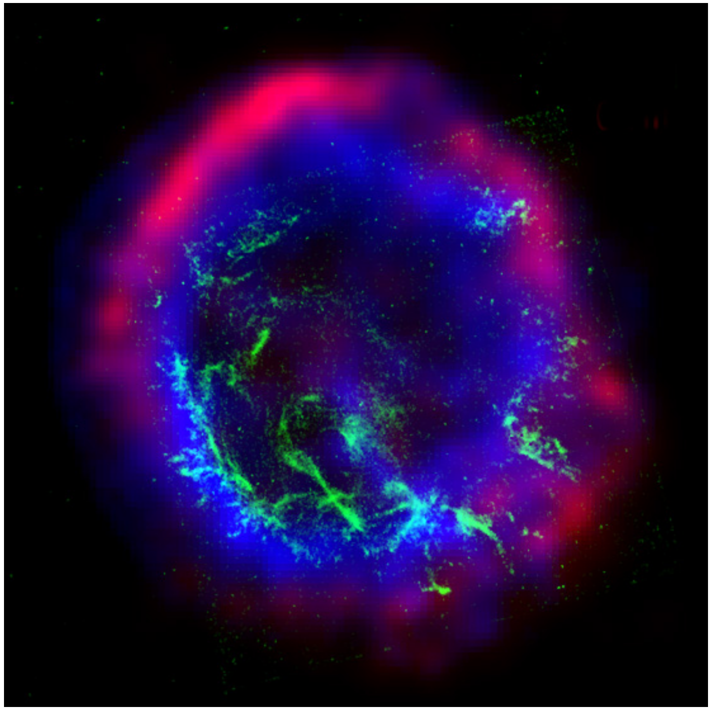
Cosmic Ray Research:
Determines Composition and Energy of Cosmic Rays to understand the "Cosmic Accelerator". Method: Measure Cosmic ray composition and spectrum and propagate back to source composition

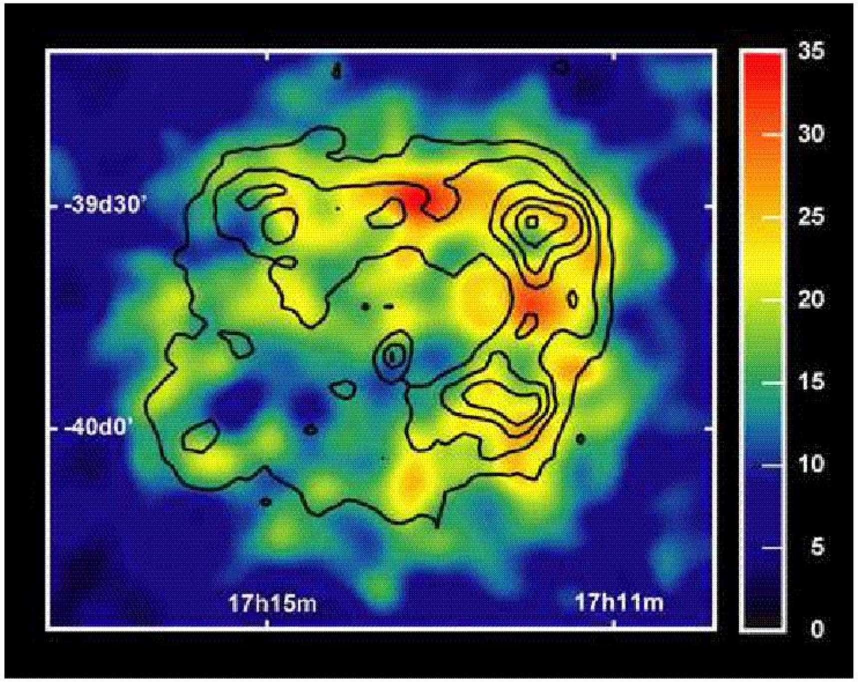
Potential Source candidates: Super Novas, Super Nova Remnants, Pulsars, Microquasars, Dark matter decay?, ...

Color-composite image of E0102-72.3:
Radio from ATCA; X-ray from Chandra and Visible from HST.



HESS image of RX J1713.7-3946

TeV gamma rays



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

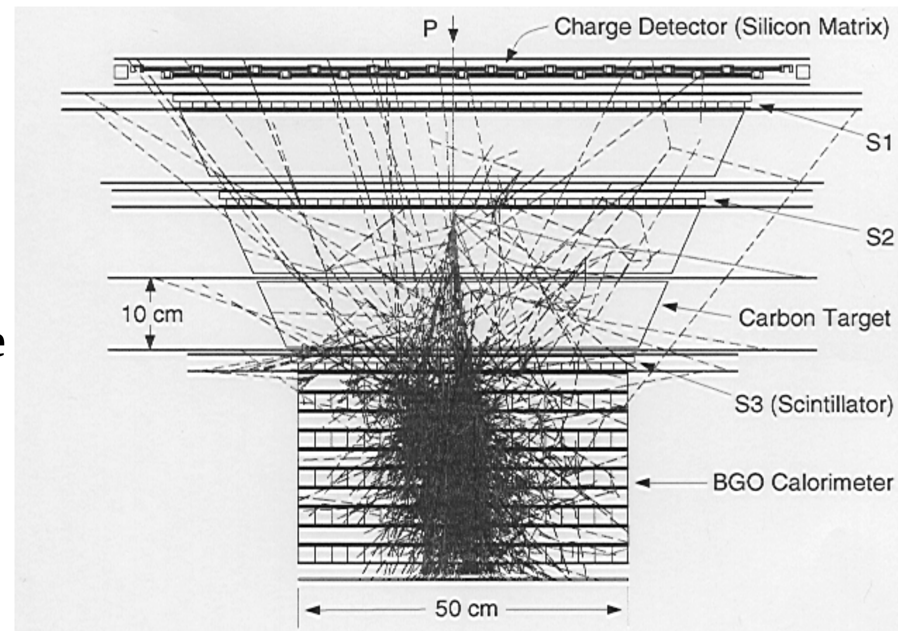
Principle of "Ionization Calorimetry"

⇒ **Cosmic ray enters from top**

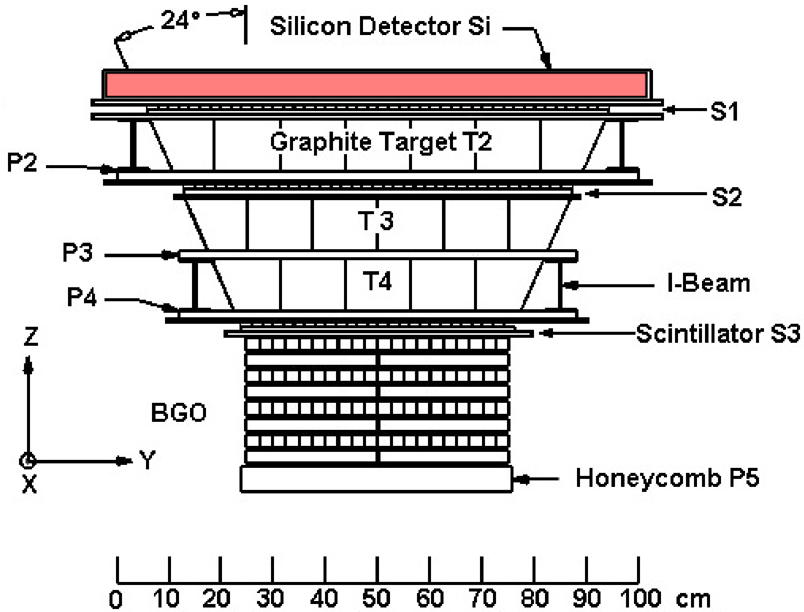
⇒ **Nuclear interaction in target section**

⇒ **'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.**

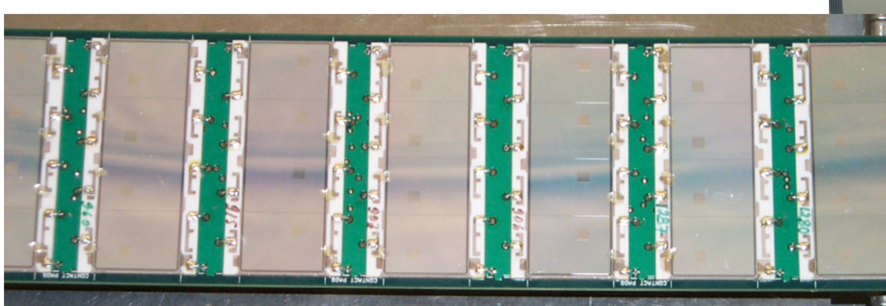


What element (Z) is it?

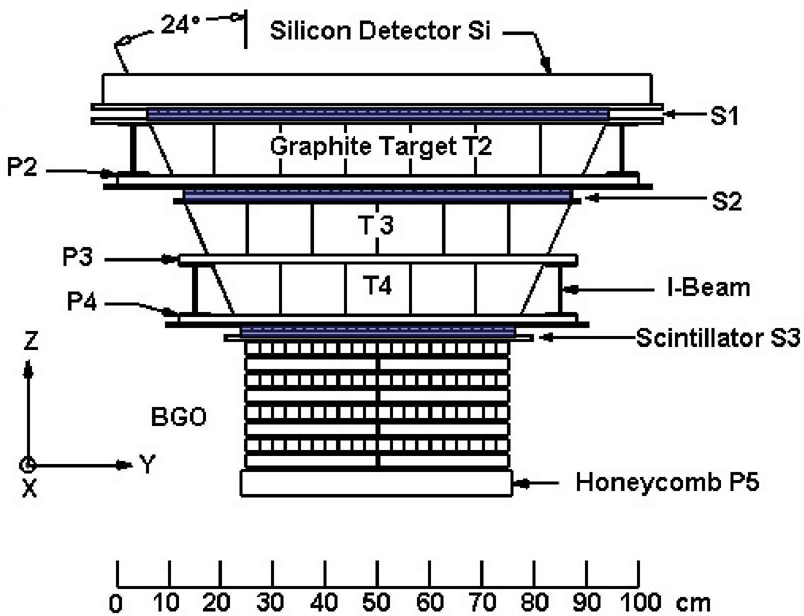


Top Silicon-Matrix detector provides a precise measurement of the cosmic ray charge (or element number).

2280 Si pixels 1.4x1.9 cm^2, each read out by a 16 bit ADC covering from Z=1 to Z=28

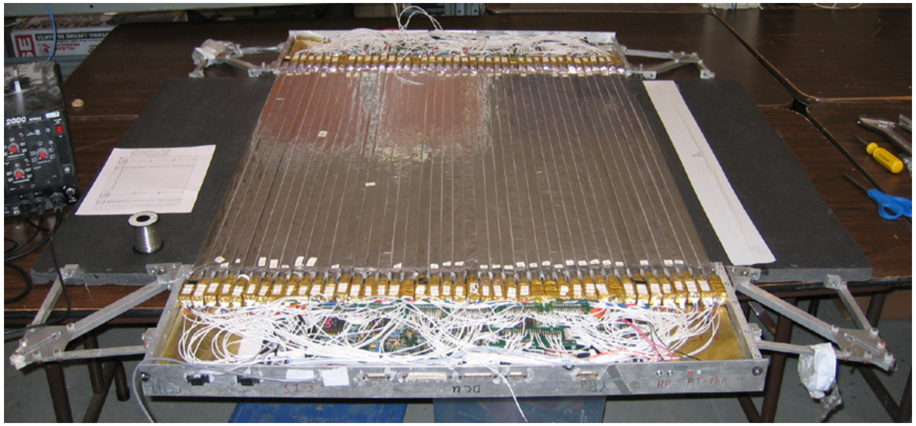


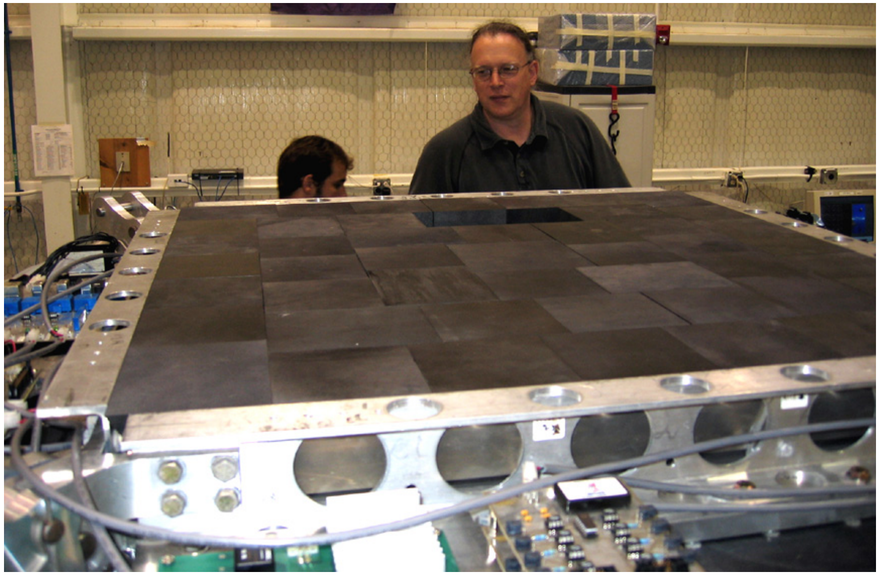
Counting the Cosmic Rays



The "hodoscope" detectors provide the "trigger" and particle track. 3 XY plastic scintillator layers, 1cm thick 2cm wide, read out by photomultipliers and digitized into 2 ranges covering Z=1 to Z=28.

The graphite target section, 3 x 10.16 cm thick enhances cosmic ray nuclear interactions.





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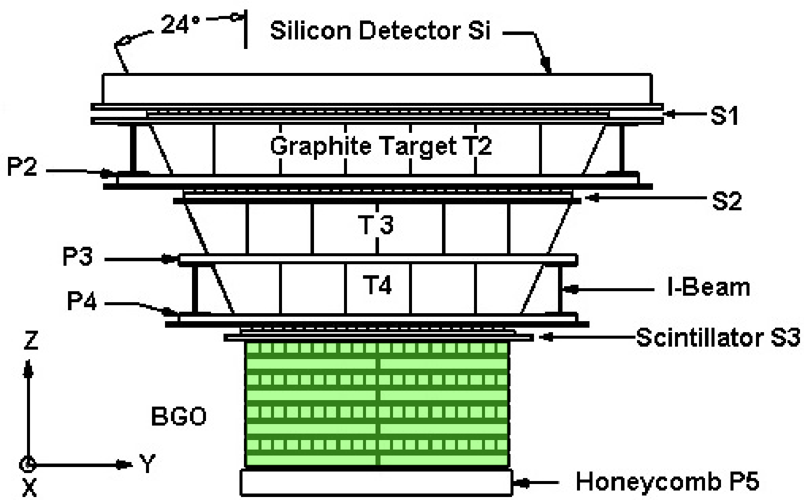
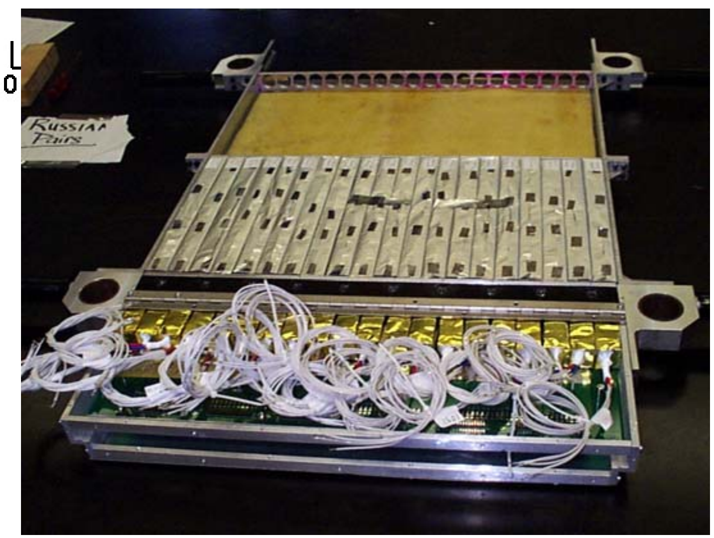
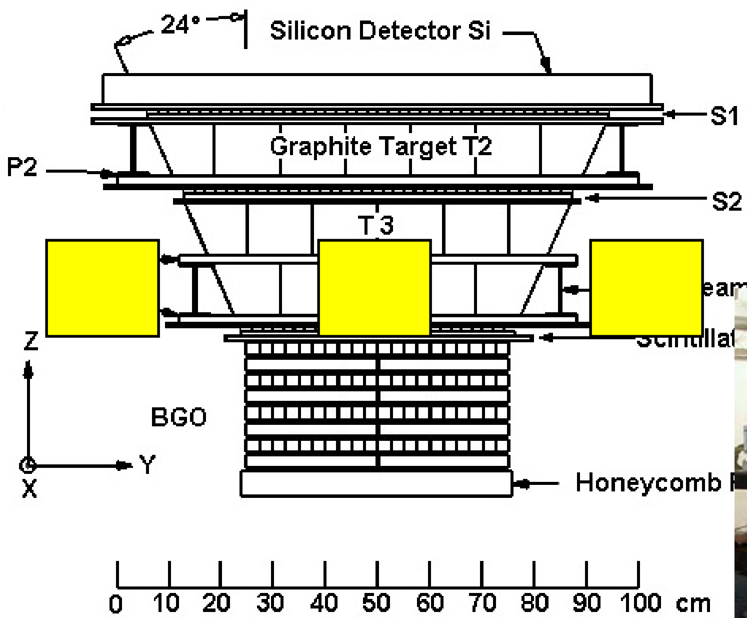
Cosmic ray energy measurement

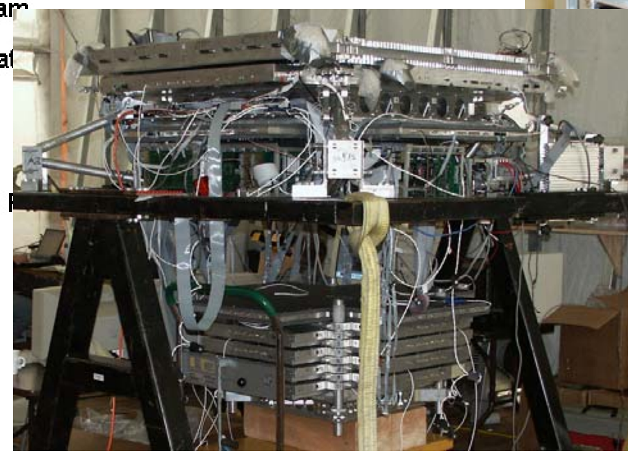


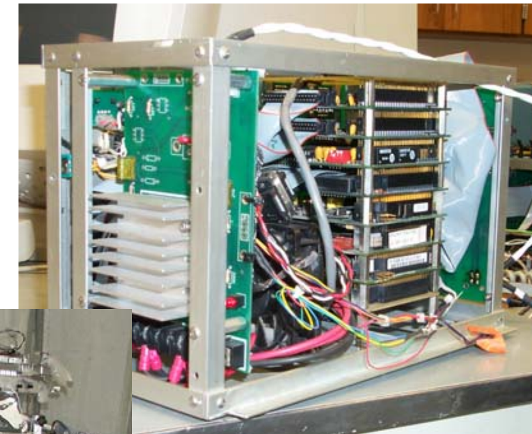
ATIC's Calorimeter is composed of 320 (ATIC 1&2), 400 (ATIC 4) Bismuth Germanate (BGO) crystals arranged in 4 (5) XY layers. Depth: 18.1 X0 (22.6 X0), read out by photomultiliers in 3 ADC ranges each, covering from 6.5 MeV (¼ MIP) to 13 TeV energy deposit in a single crystal.



The brains of the system.

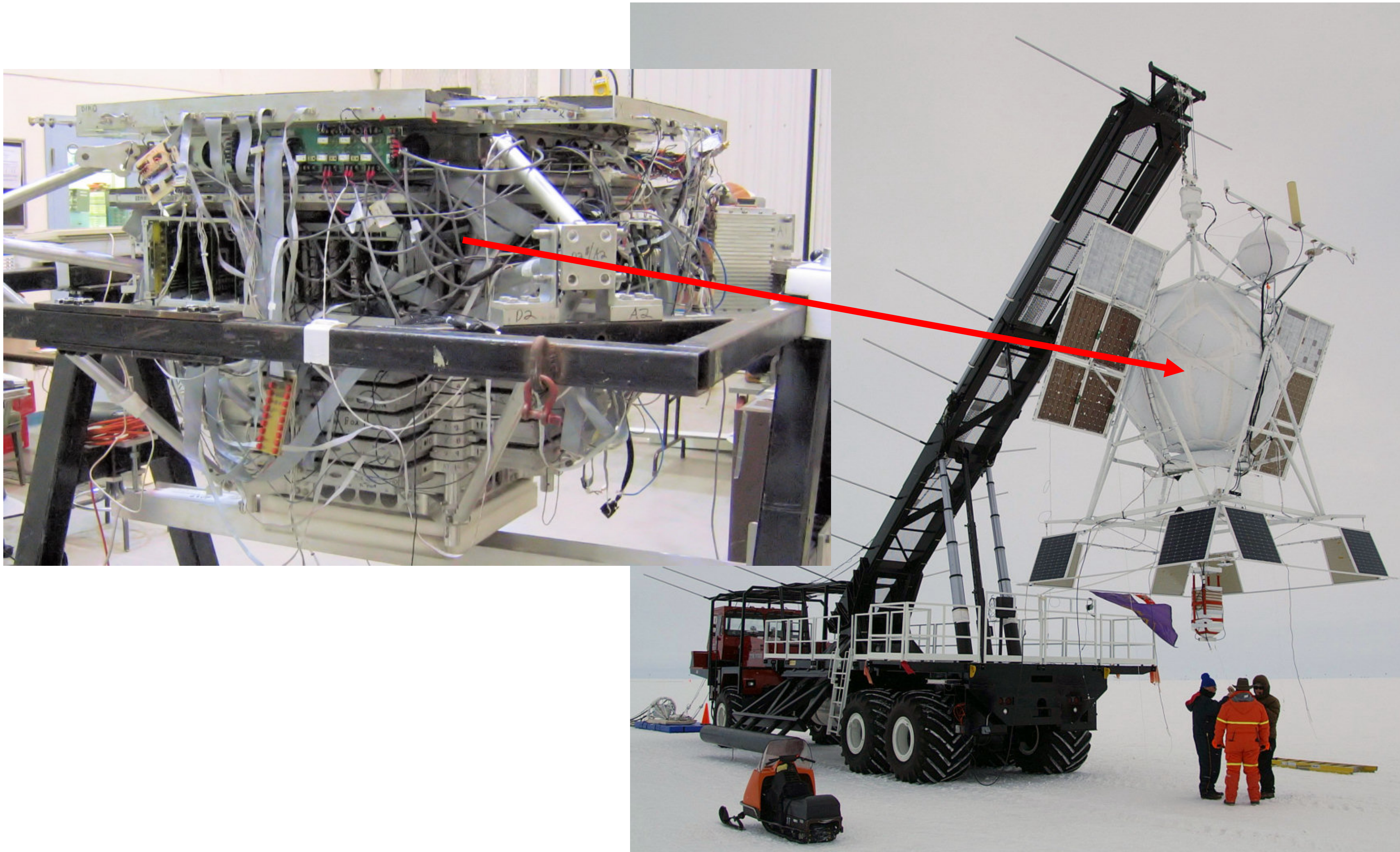






The data system hardware and software make the experiment a true robot. This system must automatically determine if a cosmic ray entered the instrument, readout out only the relevant detectors, store the data on-board, communicate to the ground the experiment status and health, plus repair failures when possible.

ATIC was constructed as a balloon payload



The current Antarctic LDB facility became operational in 2005

Assembly of ATIC at Willy

Assemble / test detector stack and mount in lower support structure

Install Kevlar pressure vessel shells

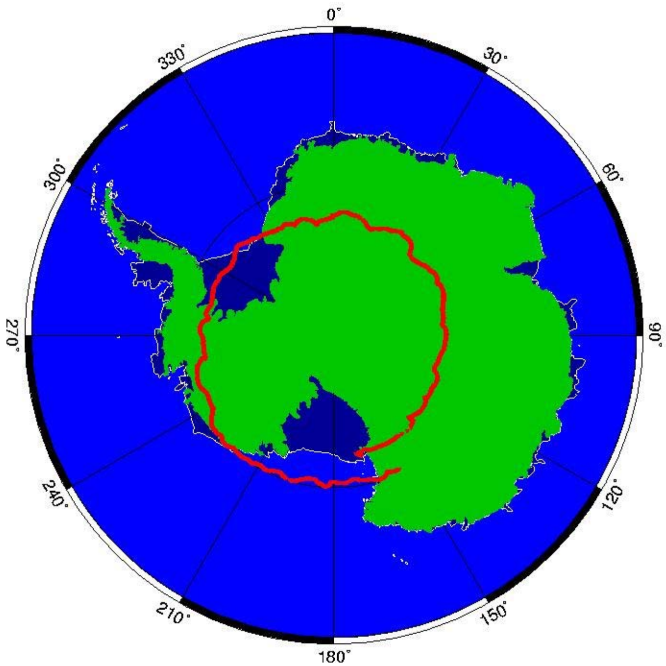
Attach the upper support structure

Attach the thermal protection insulation

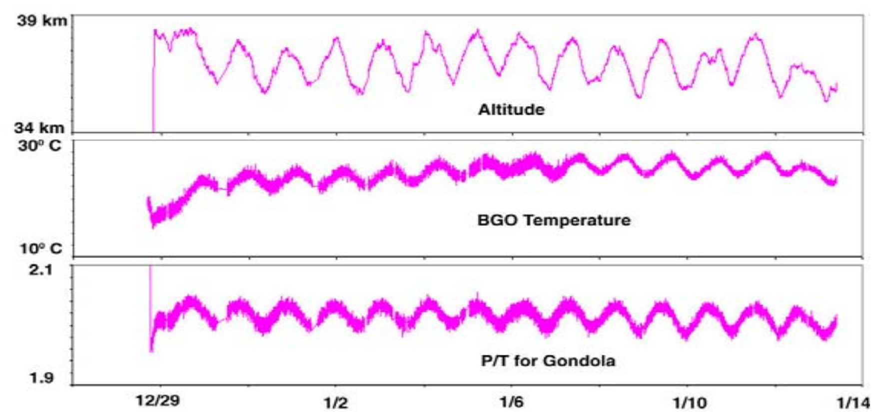
Solar arrays provide power & the payload is rolled out the hanger door

ATIC is transported to the launch pad

ATIC-1 Test Flight from McMurdo - 2000

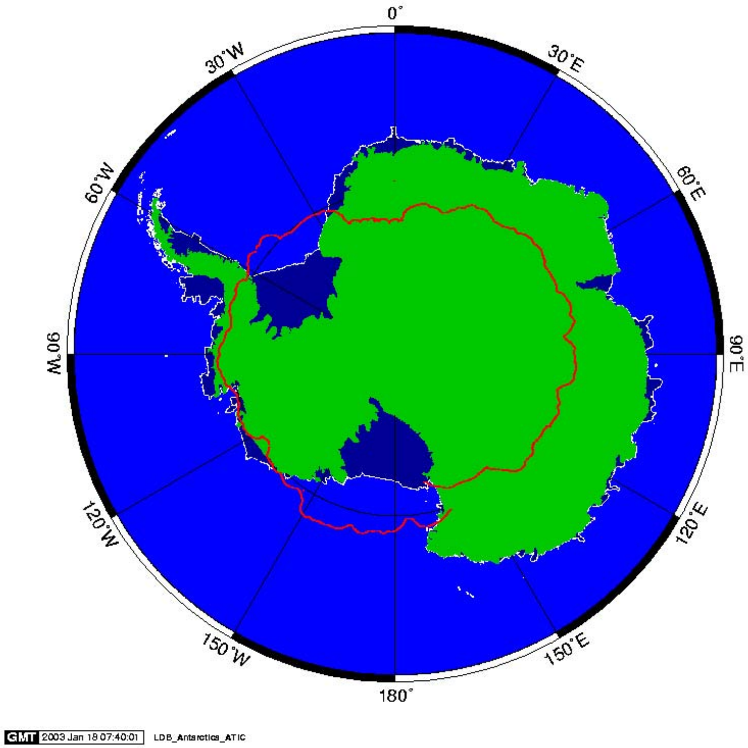


- 43.5 Gbytes Recorded Data
- 26,100,000 Cosmic Ray triggers
- 1,300,000 Calibration records
- 742,000 Housekeeping records
- 18,300 Rate records
- Low Energy Trigger > 10 GeV for protons
- >70% Live-time
- >90% of channels operating nominally
- Internal pressure (~8 psi) held constant
- Internal Temperature: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



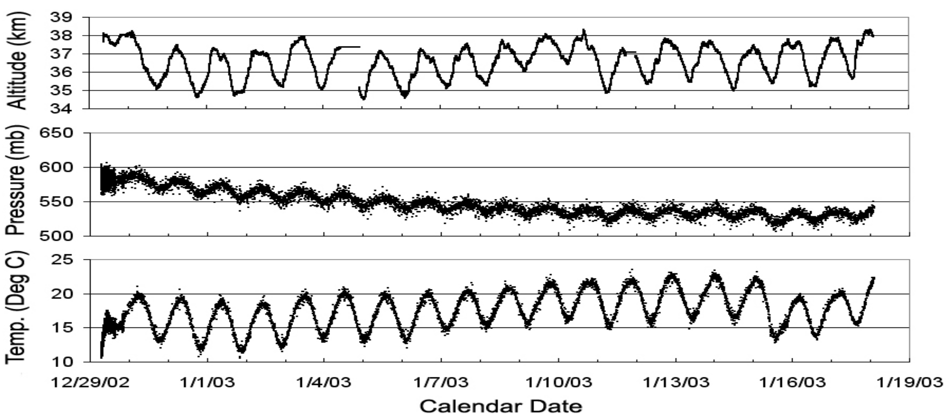
Launch:	12/28/00 04:25 UTC
Begin Science:	12/29/00 03:54 UTC
End Science:	01/12/01 20:33 UTC
Termination:	01/13/01 03:56 UTC
Recovery:	01/23/01; 01/25/01

ATIC-2 Science Flight from McMurdo - 2002



- 65 Gbytes Recorded Data
- 16,900,000 Cosmic Ray events
- High Energy Trigger > 75 GeV for protons
- >96% Live-time
- 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



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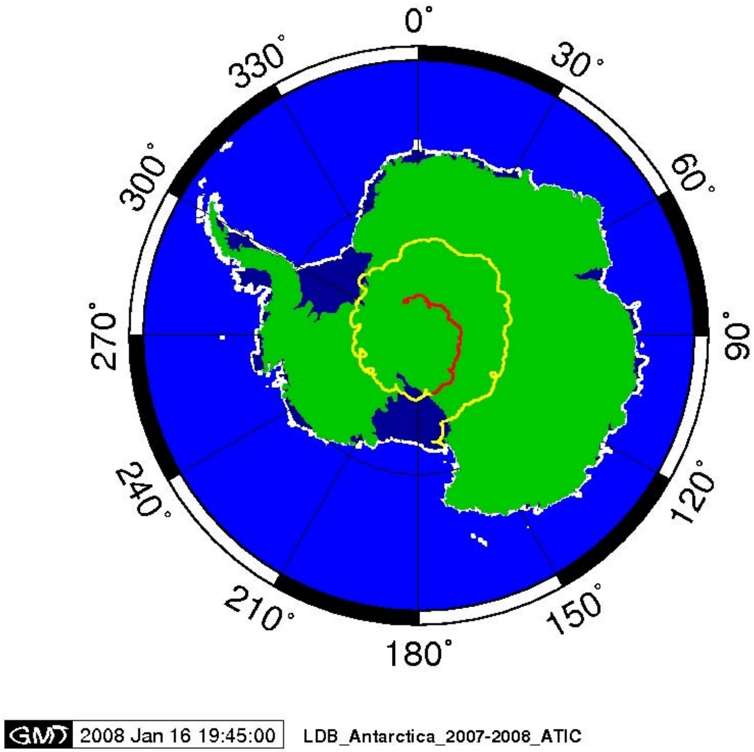
The ATIC-3 attempt ended in disaster!

- 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 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**

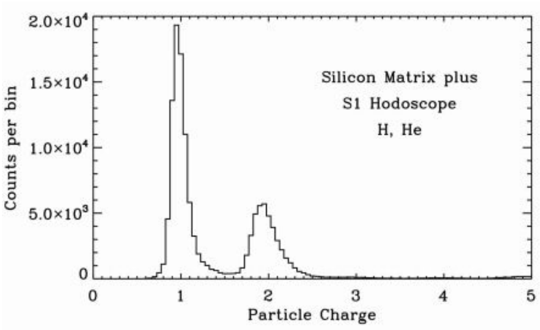
- Obtained about 14 ½ days of science data collection
- Lost pressure within gondola on 1/11/08
  - No catastrophic loss of payload
  - Found ~25 cm of vessel seam open
  - Still under investigation

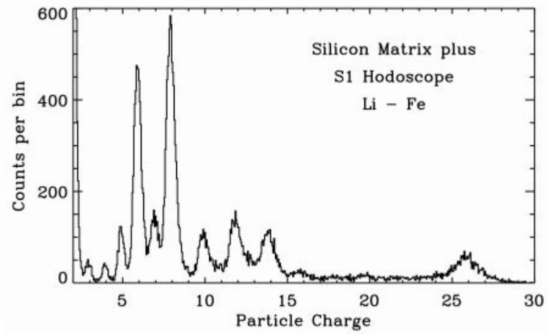
Recovery expeditions to the plateau

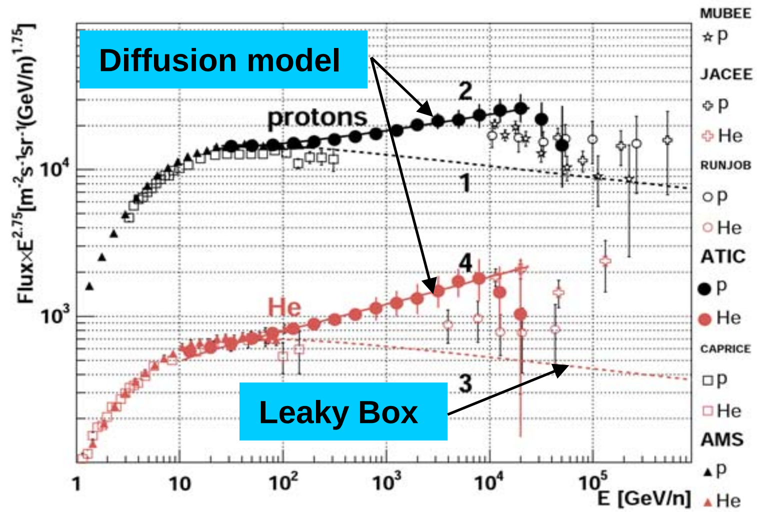
The good ATIC-1 landing (left) and the not so good landings of ATIC-2 (middle) and ATIC-4 (right)

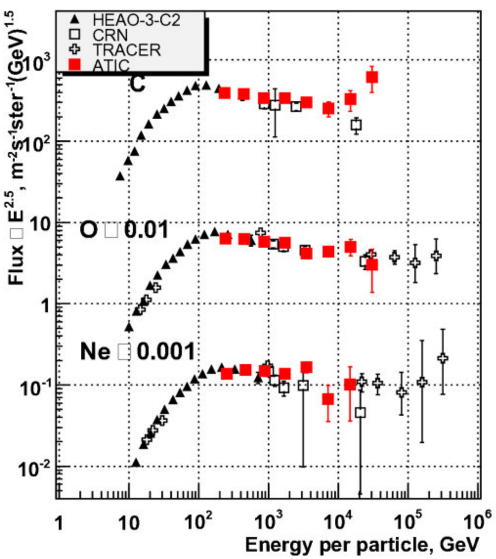
ATIC is designed to be disassembled in the field and recovered with Twin Otters. Two recovery flights are necessary to return all the ATIC components. Pictures show recovery flight of ATIC-4

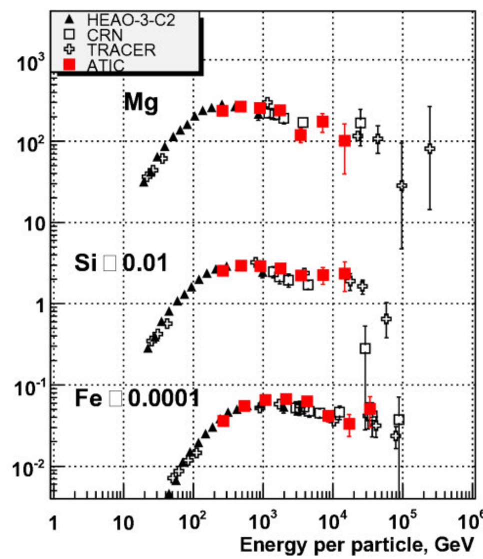
Preliminary ATIC-2 Results









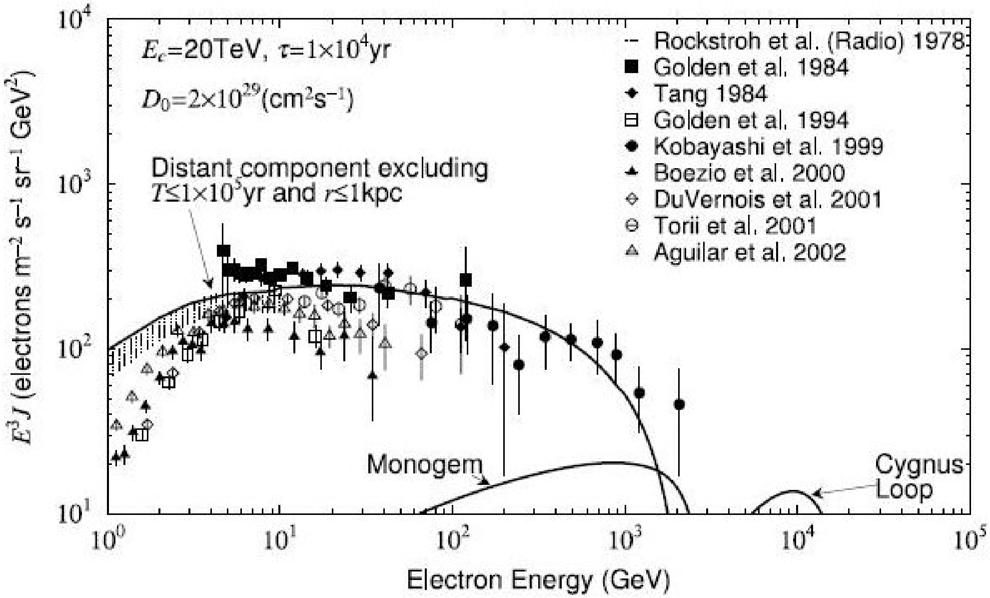


- Very good charge resolution
- Energy spectrum of H, He close to 100 TeV
- Energy spectrum of major GCR heavy ions
- Variations in energy spectra may indicate GCR are from a combination of sources

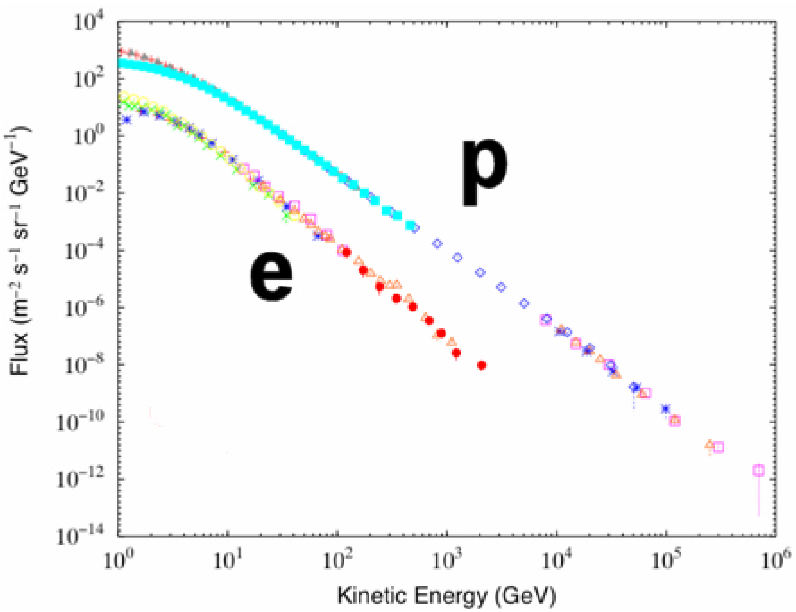
Electrons can provide additional information about the GCR source

- High energy electrons have a high energy loss rate $\propto E^2$
  - Lifetime of ~10^5 years for >1 TeV electrons $(T \approx 2.5 \times 10^5 \times E[TeV]^{-1}\ years)$
- 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 structure in electron spectrum at high energy



Observing GCR electrons can be a difficult process



- Electrons must be identified in a "sea" of protons
- At 10 GeV electrons are ~1% of protons
- Spectrum of electrons is steeper than protons

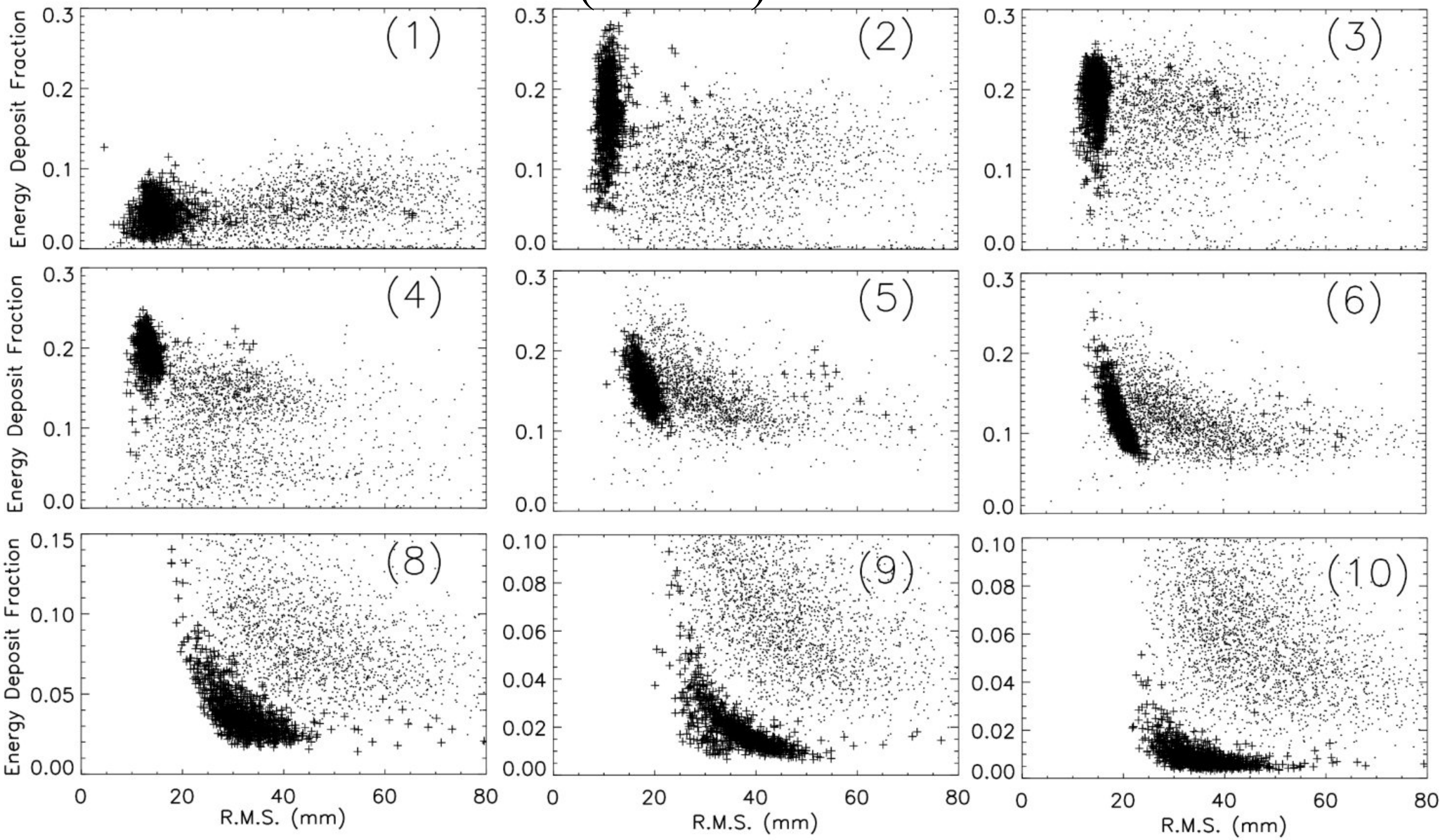
- For balloon payloads there are also secondary electron and gamma ray backgrounds caused by interaction of GCR with the residual atmosphere.
- Need a high proton rejection factor and minimize the secondary backgrounds.

How are electrons measured?

- Silicon matrix identifies charge
- Calorimeter measures energy, resolution= $\pm$2%, Important for identifying spectral features
- Key issue: Separating protons and electrons
  - Use interactions in the target
    - 78% of electrons and 53% of protons interact
  - Energy deposited in the calorimeter helps:
    - Electrons 85%; Protons 35% $\Rightarrow E_p = 2.4XE_e$
    - Reduces proton flux by X0.23
  - Combined reduction is X0.15, then
  - Examine shower longitudinal and transverse profile

Simulated e,p shower development by calorimeter layer to develop the technique

Plot fraction of energy deposited in layer versus shower lateral width (R.M.S.) distribution



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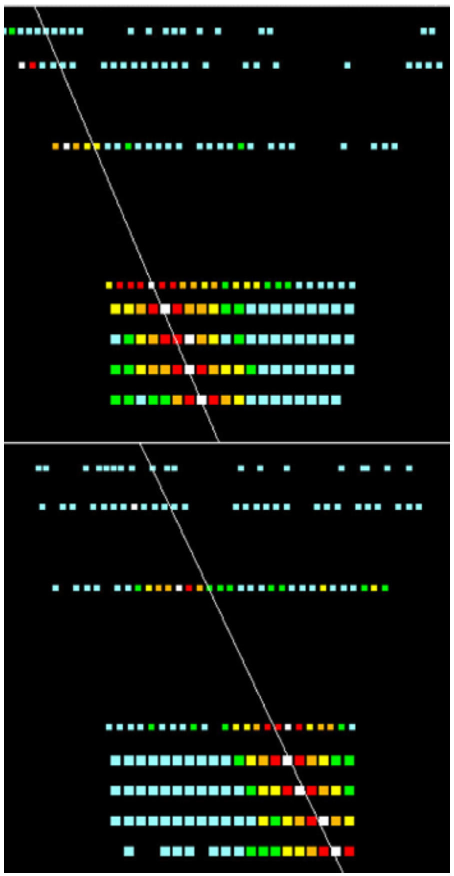
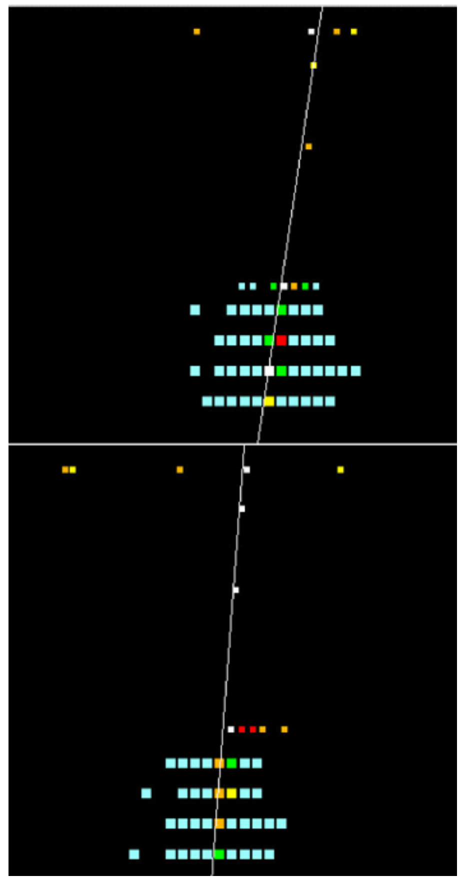
(p,e,γ) shower image from ATIC flight data

- 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

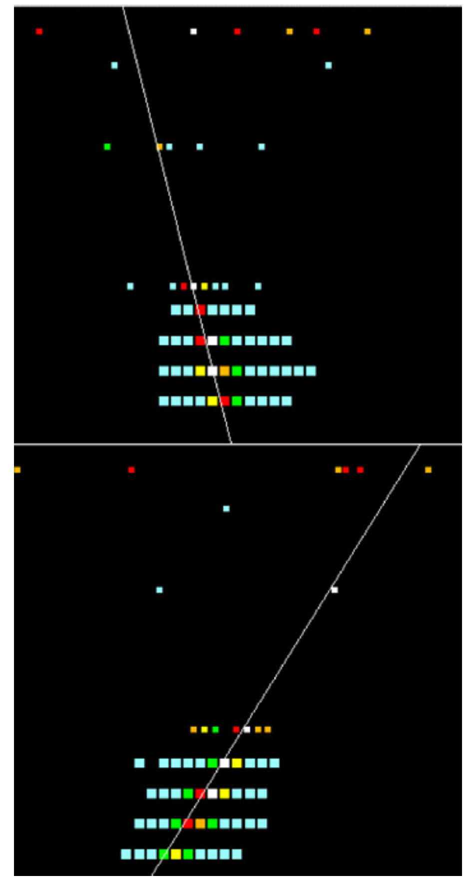
proton



electron



gamma



Parameters for Shower analysis

- RMS shower width in each BGO layer

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

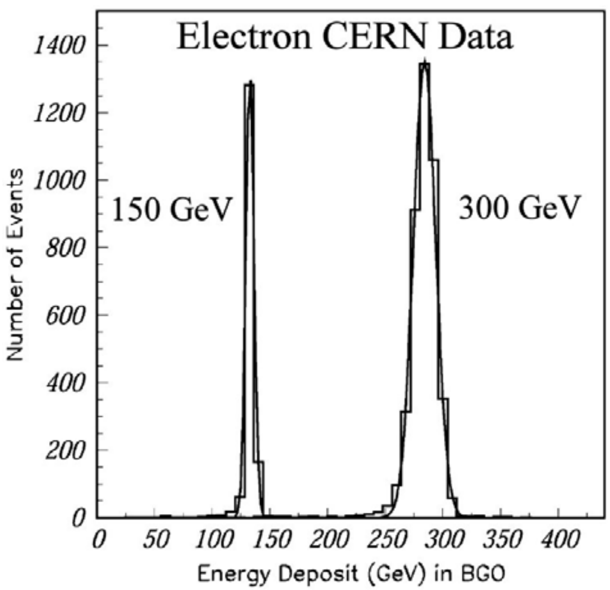
- Weighted fraction of energy deposited in each BGO layer in the calorimeter

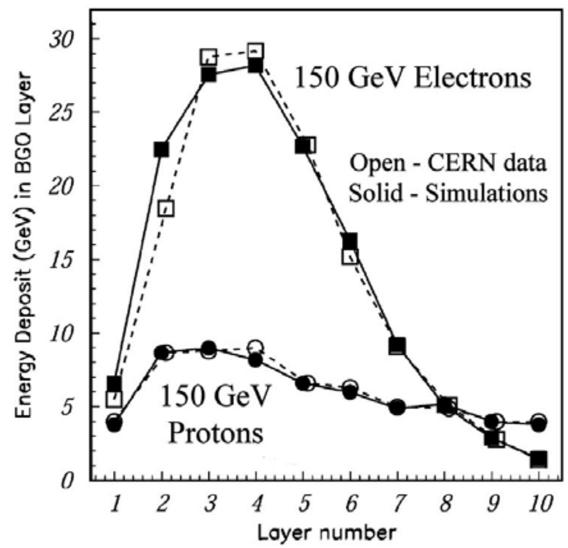
$$F_j = \langle r.m.s.\rangle^2 \left[E_j / \sum_{i=1}^{n} E_i \right]$$

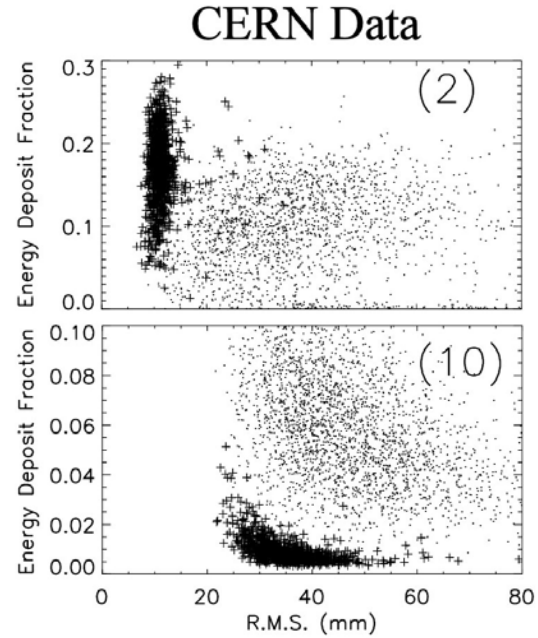
Instrument calibrations at CERN used to verify the Instrument performance and validate Simulations

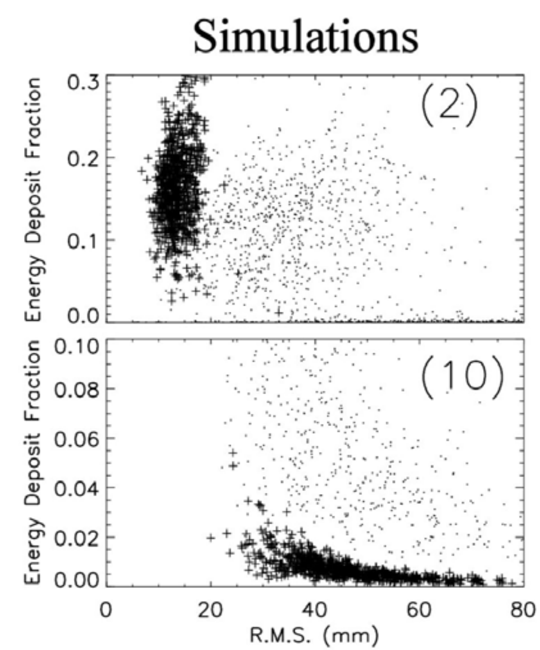
- Used CERN instrument calibration with 150 GeV electrons and 375 GeV protons to validate electron analysis and evaluate the proton contamination.

- CERN data also used to investigate instrument response, energy resolution & check simulations









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The method to select electron events:

1. Rebuild the shower image, get the shower axis, and get the charge from the Si-matrix detector:

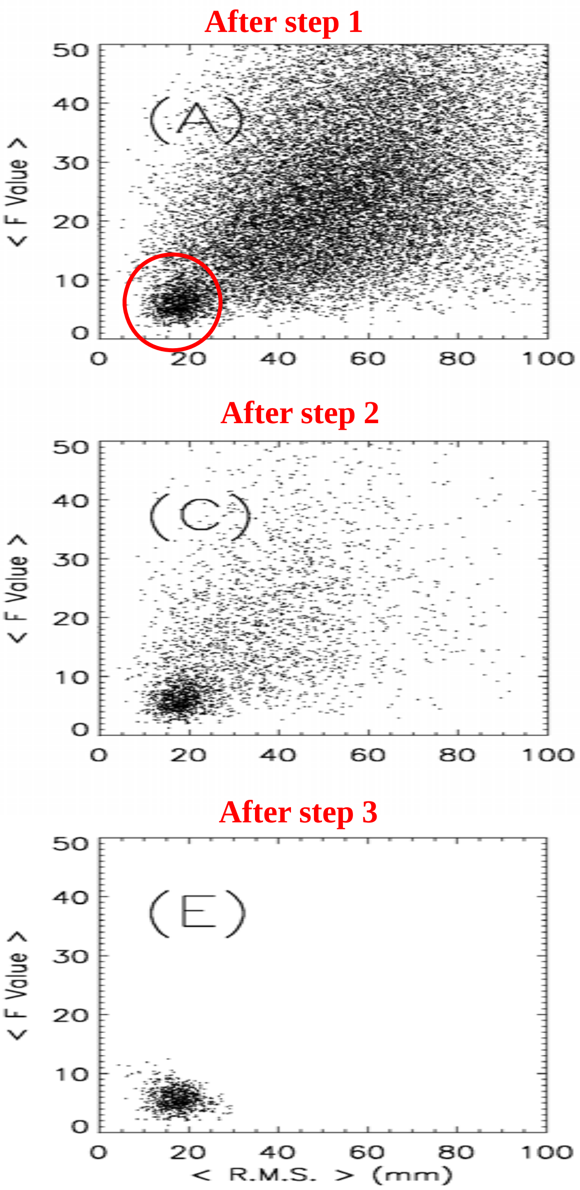
$0.8<Z<1.6$, $E>50GeV$, $\chi^2<1.5$, good geometry

2. Shower axis analysis

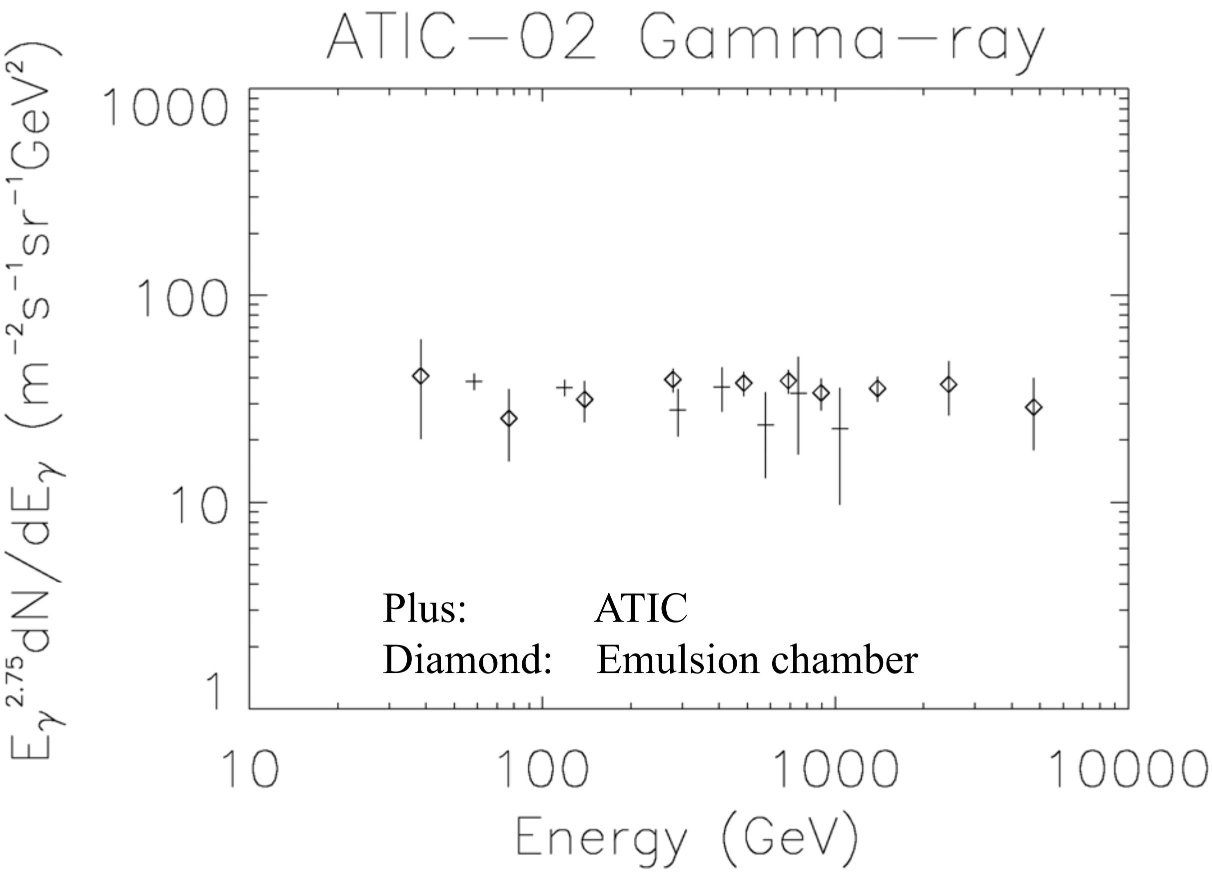
Reject Protons which have their first interaction point in carbon

3. Shower width analysis:

Cut F values for BGO1, BGO2 and BGO7, BGO8



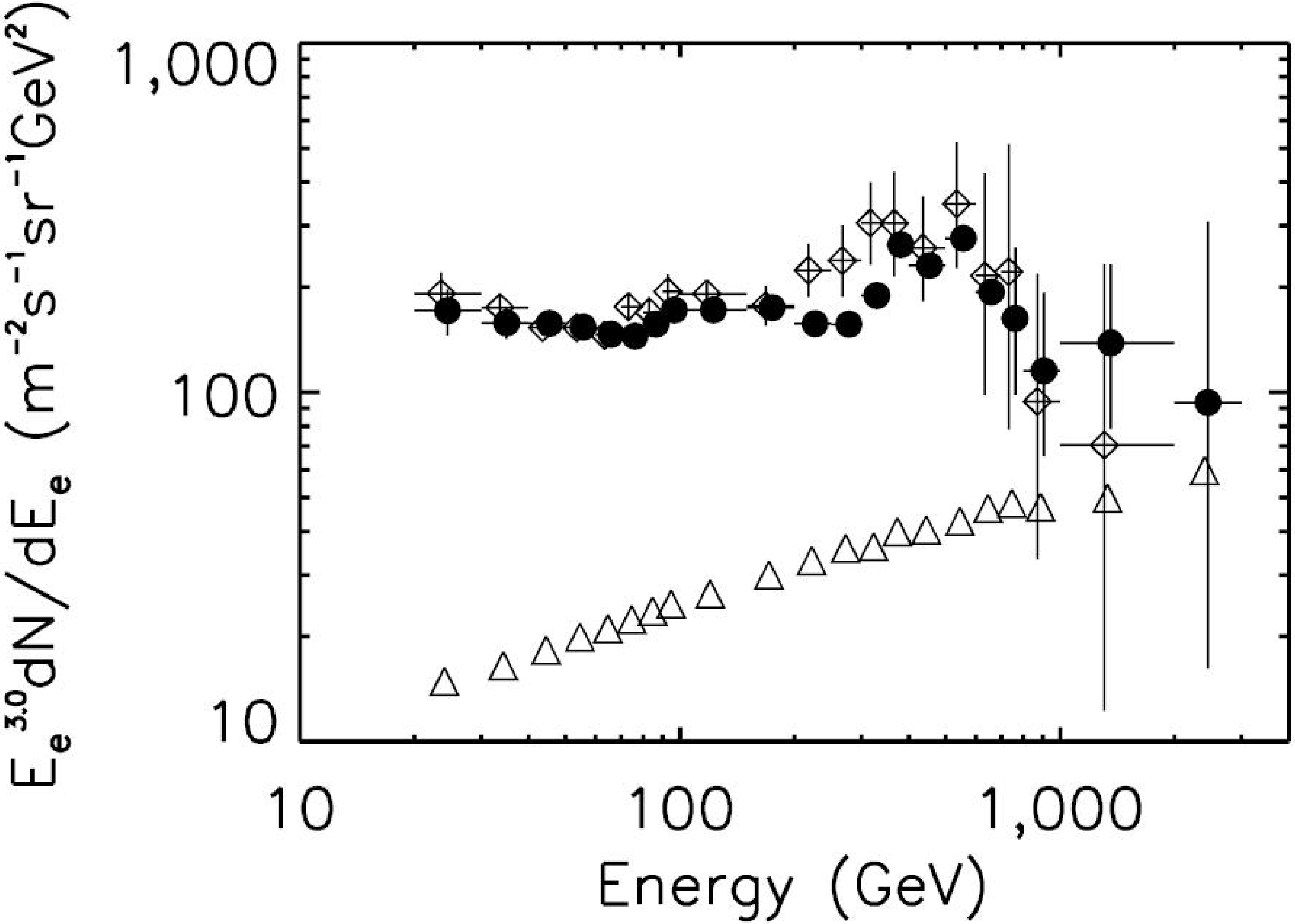
Atmospheric Gamma-rays:
Test of the electron selection method



Reject all but 1 in 5000 protons

Retain 85% of all electrons

Results



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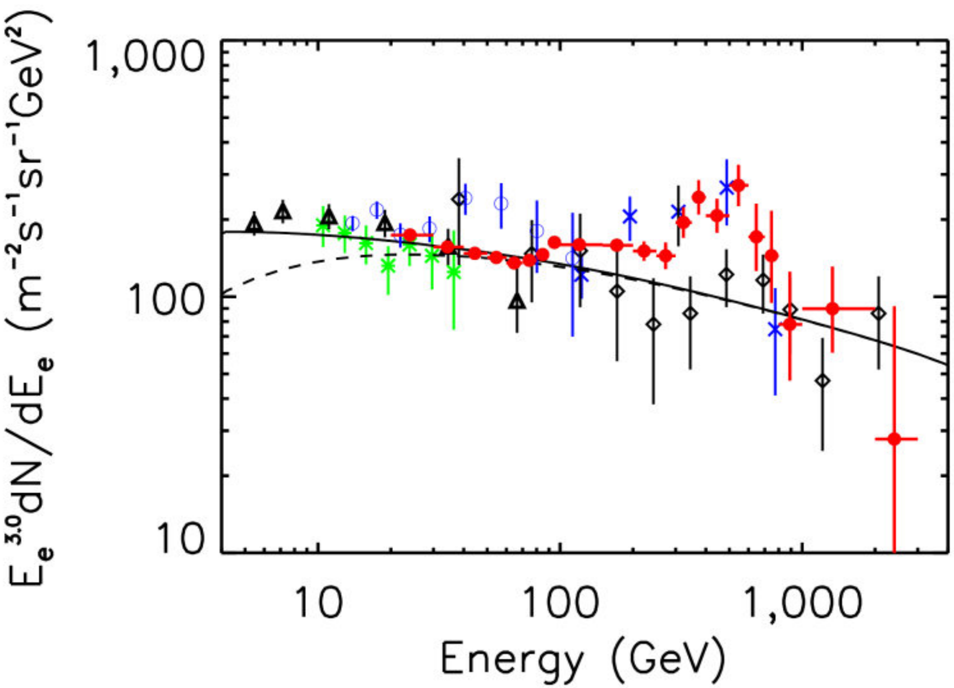
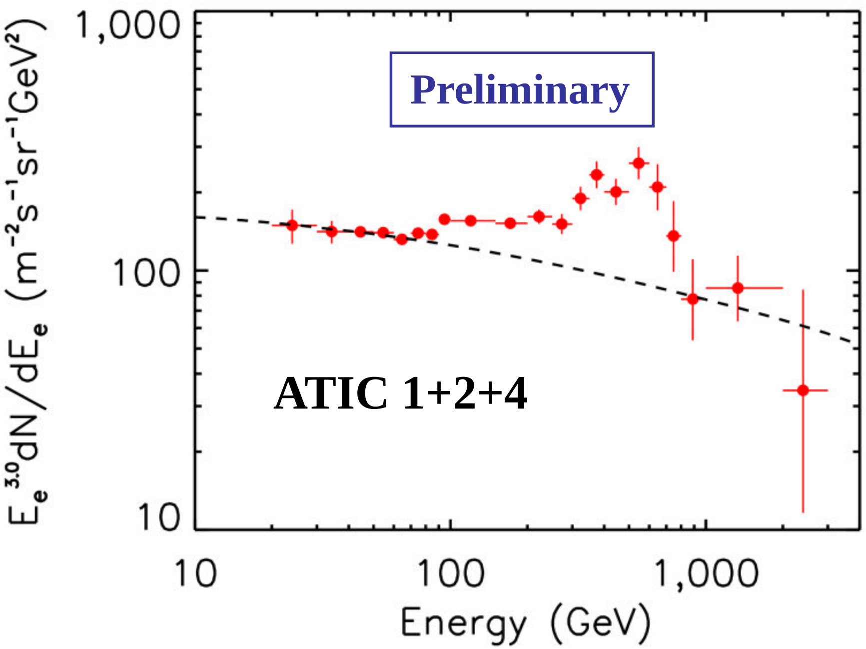
The ATIC electron results exhibits a "feature"

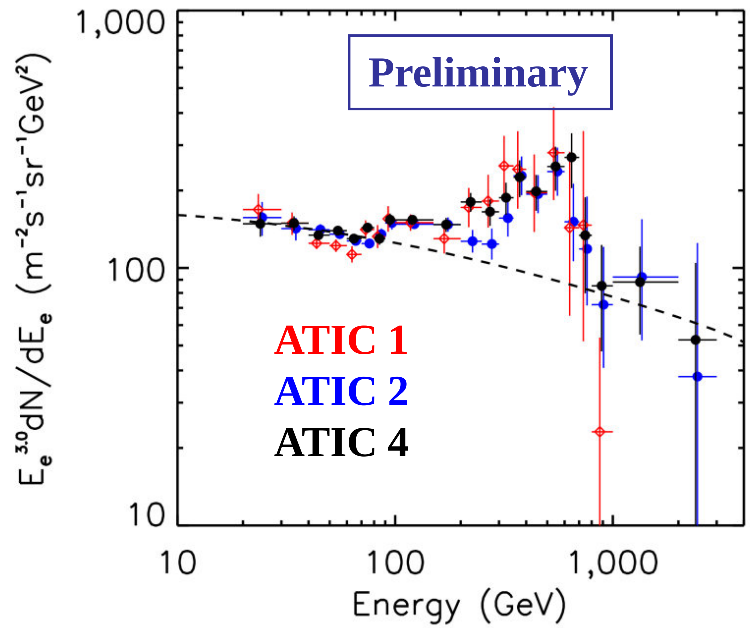
- Sum of data from both ATIC 1 and ATIC 2 flights
- Curves are from GALPROP diffusion propagation simulation
  - Solid curve is local interstellar space
  - Dashed curve is with solar modulation
- Spectral index is -3.23 for below ~ 100 GeV
- "Feature" at about 300 – 800 GeV
- Significance is about 3.8 sigma
- Also seen by PPB-BETS
- Emulsion chamber data is currently being re-analyzed



● ATIC 1+2, ✱ Alpha Magnetic Spectrometer, △ HEAT magnetic spectrometer, ○ BETS, × PPB-BETS, ◇ Emulsion chambers

All three ATIC flights are consistent



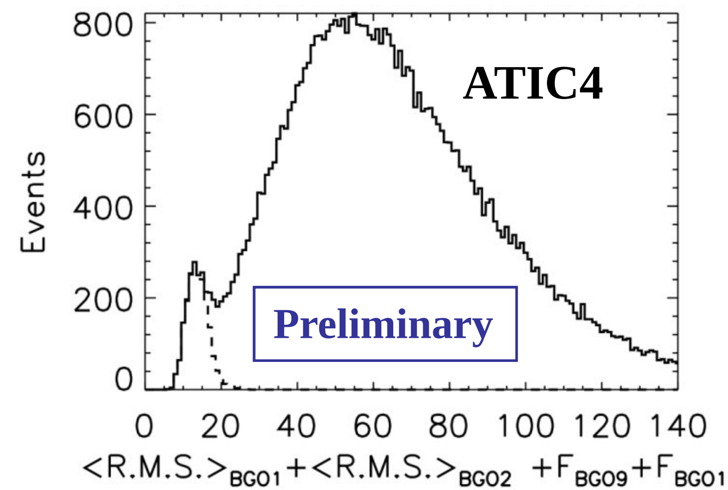


“Source on/source off” significance of bump for ATIC1+2 is about 3.8 sigma

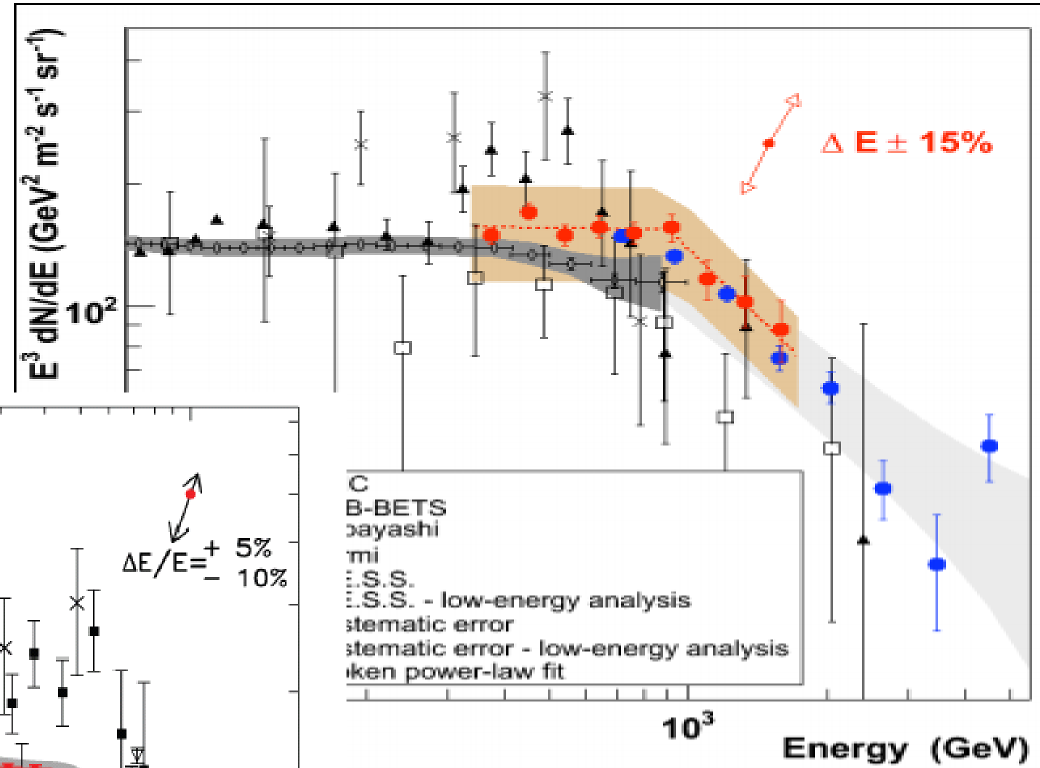
ATIC-4 with 10 BGO layers has improved e , p separation. **(~4x lower background)**

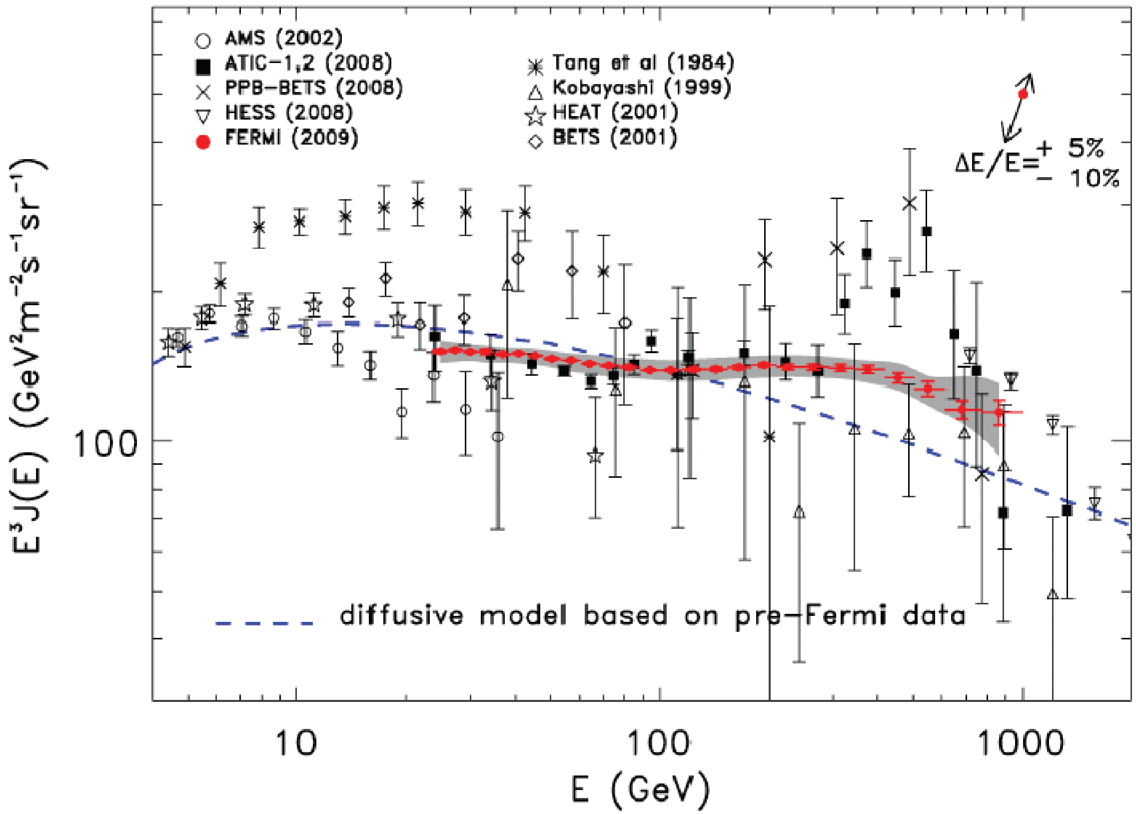
“Bump” is seen in all three flights.

Significance for ATIC1+2+4 is 5.1 sigma



Additional measurements have been published





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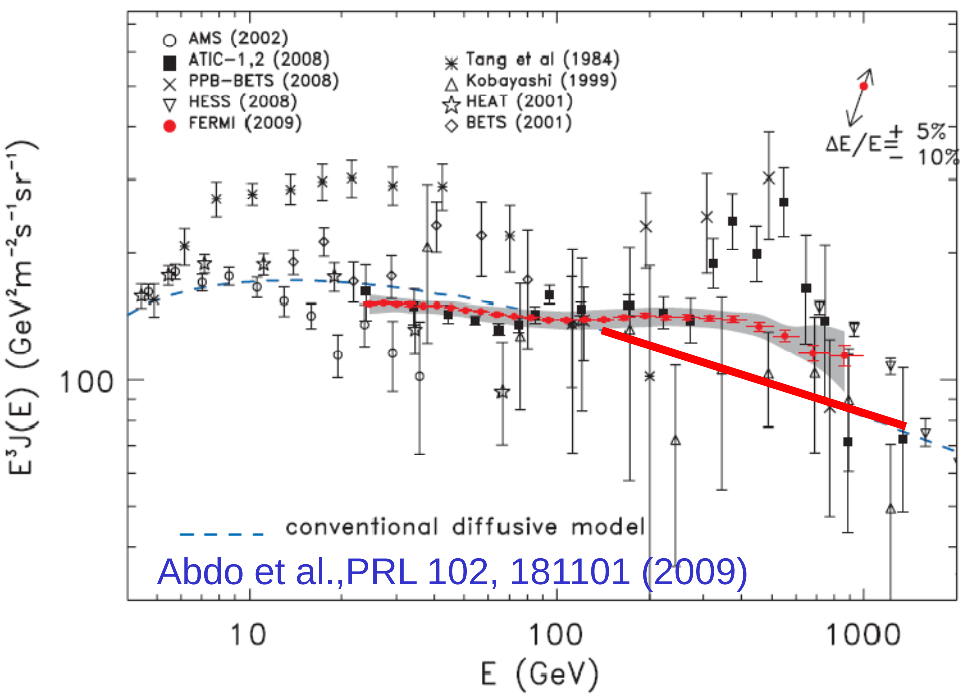
ATIC vs. Fermi - ATIC and Fermi ?

- ATIC BGO calorimeter
  - 18.1 – 22.6 Xo
  - fully contains the electron shower
  - energy resolution of ~2 %

- Fermi CsI calorimeter
  - **Thinner**, 8.6 Xo
  - showers are not fully contained
  - distribution of the reconstructed energy is asymmetric with a longer tail toward lower energies
  - **Poorer energy resolution** ~20%

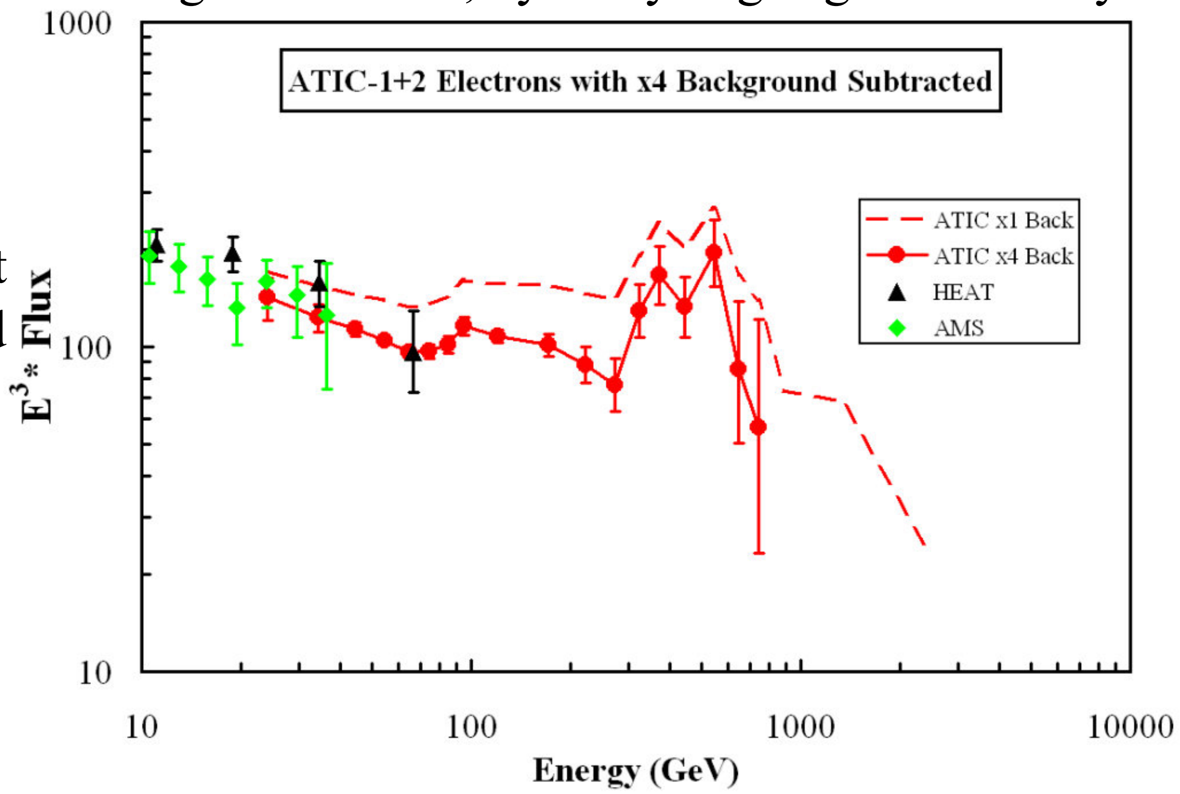
<u>Analysis method</u> comparison

- ATIC analysis uses quantities measured during flight (e.g. atmospheric secondary gammas) to set selection cuts and determine background rates.
- In Fermi much of the electron identification and background rejection is based on simulations only. Classification tree is trained by simulations



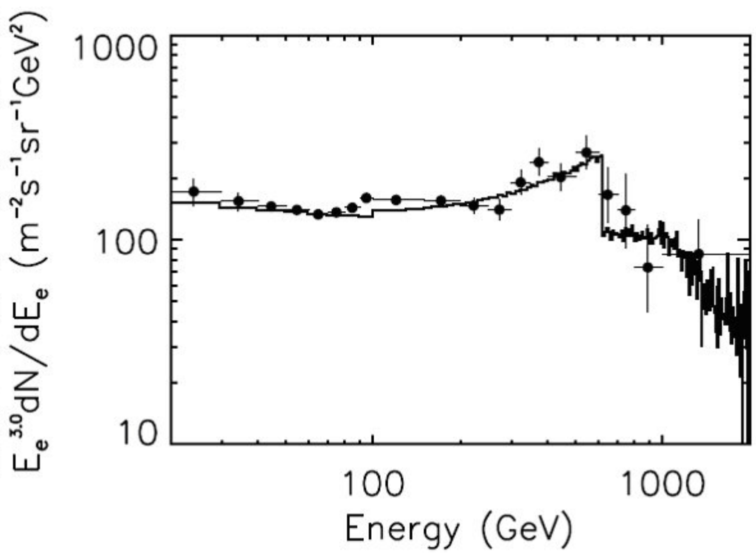
The effect of background subtraction

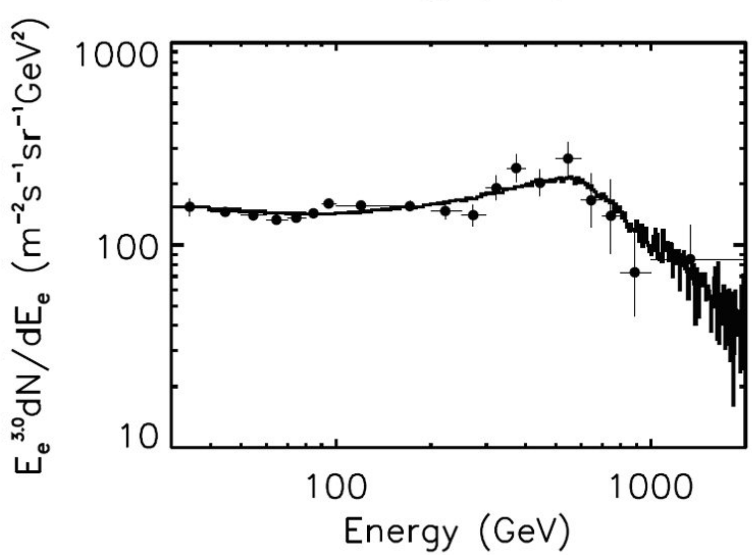
- Background includes secondary e^- as well as misidentified protons and secondary gamma rays.
- Secondary e-, γ from well established calculations (e.g. Nishimura et al., 1980)
- Proton contamination was studied using CERN data, by analyzing flight secondary γ and from simulations.
- Assume proton background is 4 times higher than estimated
- Electron spectrum is lower but still consistent with HEAT and AMS.
- Spectrum for energies < 250 GeV is steeper.
- Feature at 300 GeV to 800 GeV is still present but larger error bars at high energy edge.



The effect of the energy resolution on the feature

- The ATIC 22 X_o BGO calorimeter essentially fully contains the electron shower and provides an energy resolution of a few %.
- A spectrum with an index of -3.1 up to 1 TeV followed by a softer spectrum of index -4.5
- Add a power law spectrum component with an index of -1.5 and a cutoff at 620 GeV
- Reduce energy resolution to 15%. Features are broadened, peak value is decreased and spectrum appears to have an index of ~-2.9
- Reduce energy resolution to 25%. Features are almost "flattened" and spectrum appears to have an index of ~-3.0

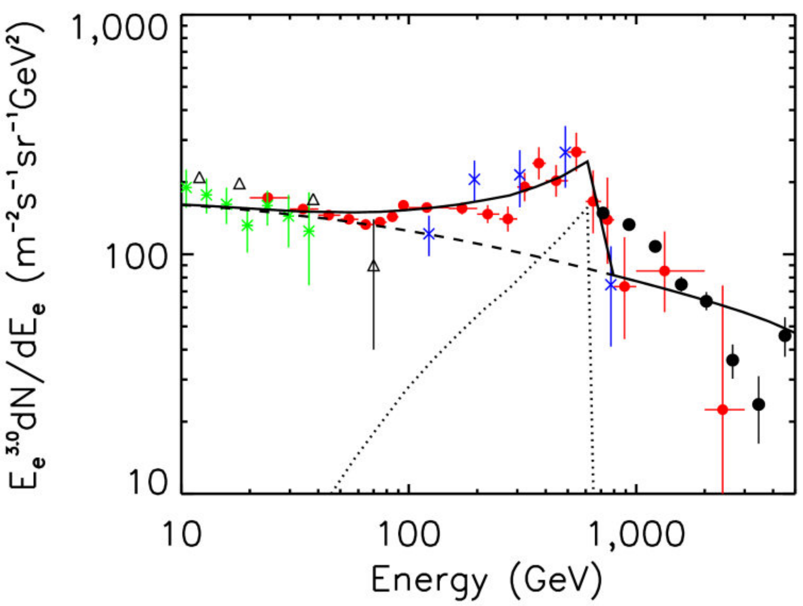




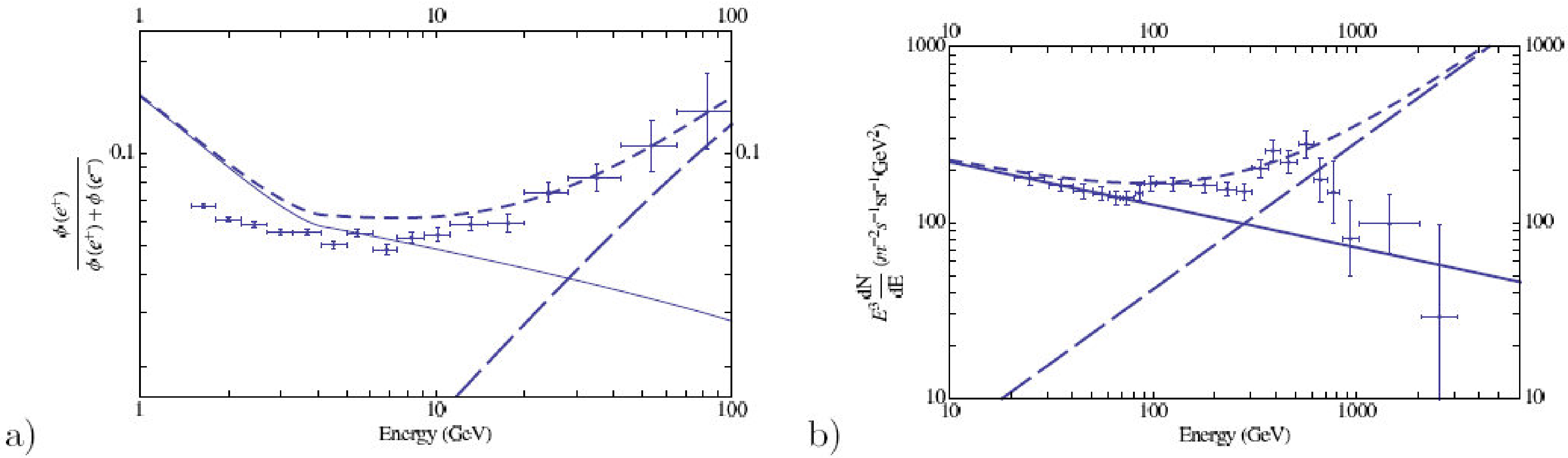
Most exotic explanation is “Dark Matter”

- Neutralinos and Kaluza-Klein particles can annihilate to produce e^+,e^- pairs, but mass and branching ratio cross sections are not well defined
- Use the KK particle generator built into GALPROP to test the parameter space
  - Use isothermal dark matter halo model of 4 kpc scale height, local DM density of 0.43 GeV/cm^3 and a KK mass of 620 GeV
- Need an annihilation cross section rate of 1 x 10^{-23} cm^3/s

- Sharp upper energy cutoff is due to direct annihilation to e^+e^-
  - Delta function source spectrum
- Annihilation rate is about a factor of 230 larger than what is calculated for a thermal relic DM particle
  - Similar factor needed to explain the HEAT positron excess at 30 GeV
- Such large “boost” factors are the subject of much debate



There might be a connection between the PAMELA and ATIC measurements

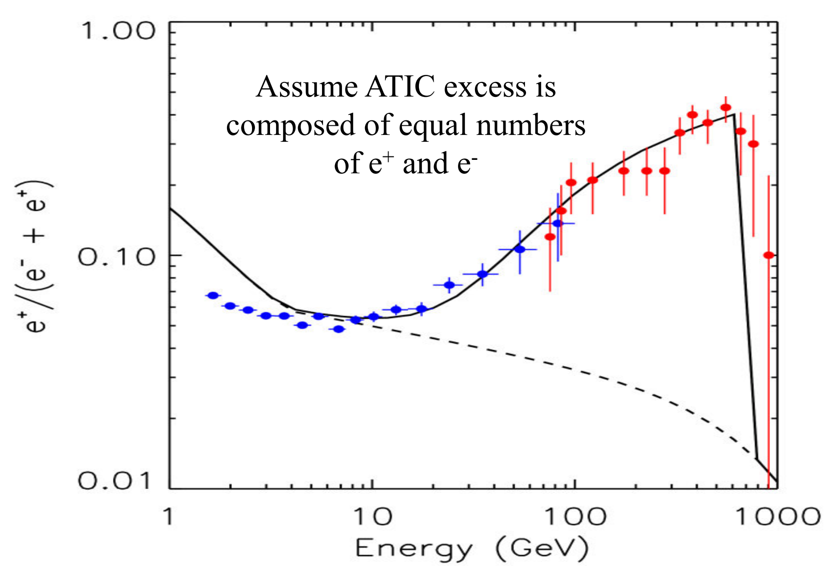


Simple argument from Cholis et al. (arXiv: 0811.3641v1), 2008

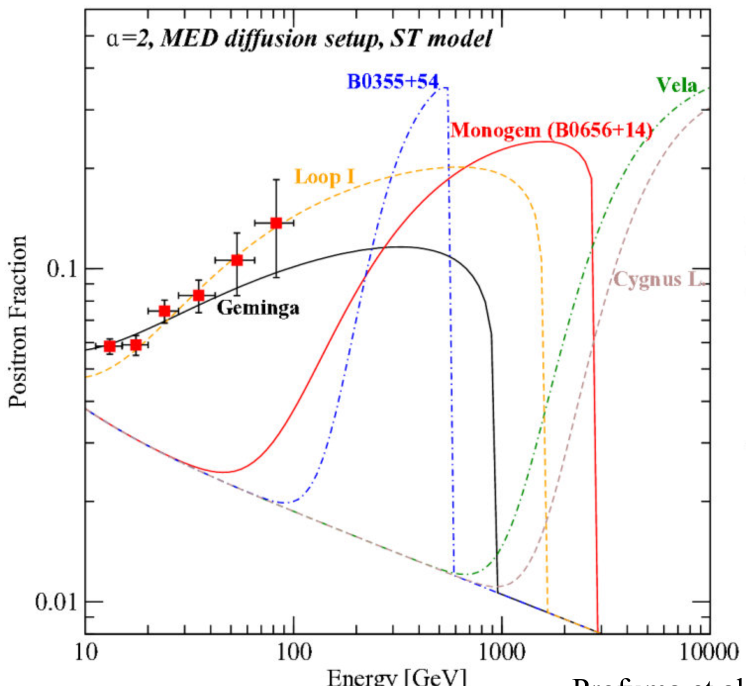
Fit power law component to > 10 GeV PAMELA positive fraction (a)

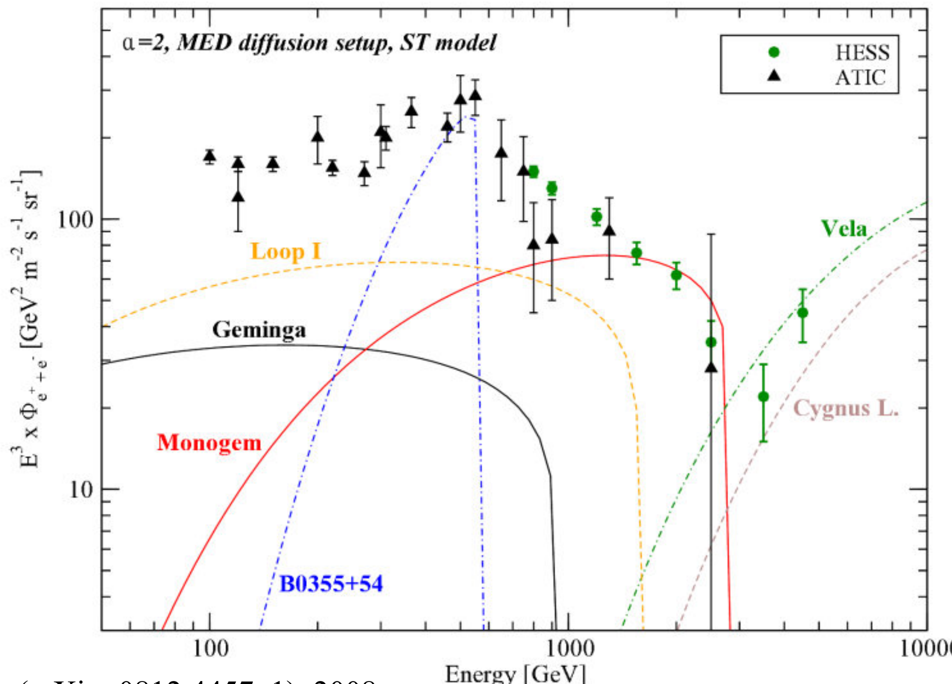
Assume this component is composed of equal numbers of e^+ and e^- and extrapolate to ATIC energy range (b)

Not bad fit to observed ATIC electron flux rise



Can e$^+$e$^-$ accelerated by pulsars explain the data?





Profuma et al. (arXiv: 0812.4457v1), 2008

TABLE II: Data for a few selected nearby pulsars and SNR's. $E_{\rm out}$ is the energy output in $e^\pm$ pairs in units of 10^{48} erg. The energy output for the SNR Loop I and Cygnus Loop are not estimated within the ST model, but via estimates of the total SNR output. The $f_{e^\pm}$ column indicates the $e^\pm$ output fraction used to compute the fluxes shown in fig. 3 and 4 within the ST model.

Name	Distance [kpc]	Age [yr]	$\dot{E}$ [ergs/s]	$E_{\rm out}$ [ST]	$E_{\rm out}$ [CCY]	$E_{\rm out}$ [HR]	$E_{\rm out}$ [ZC]	$f_{e^\pm}$	g
Geminga [J0633+1746]	0.16	3.42×10^5	3.2×10^{34}	0.360	0.344	0.013	0.053	0.005	0.70
Monogem [B0656+14]	0.29	1.11×10^5	3.8×10^{34}	0.084	0.456	0.004	0.372	0.015	0.14
Vela [B0833-45]	0.29	1.13×10^4	6.9×10^{36}	0.044	0.133	0.133	0.005	0.020	0.70
B0355+54	1.10	5.64×10^5	4.5×10^{34}	1.366	0.677	0.022	0.121	0.2	0.61
Loop I [SNR]	0.17	2×10^5		*0.3*				0.006	
Cygnus Loop [SNR]	0.44	2×10^4		*0.03*				0.01	

Conclusions (1)

- The ATIC data are determined with high energy resolution and high background rejection, relying mostly on direct measurements and a minimum simulations.

- The FERMI data points are determined with very high statistics but lower energy resolution. Background subtraction is done by relying on simulations to train a classification tree.

- The HESS measurements are done from the ground measuring the Cherenkov light from air showers. Hadron electron separation and backgound subtraction relies completely on simulations.

- The ATIC, FERMI, PAMELA, AMS and HEAT data agree below 100 GeV and show a spectral index of ~E^-3.2.

- Both ATIC and FERMI show excess electrons at high energies with reference to the E^-3.2 spectral index.

- Both the ATIC and FERMI excesses are in agreement when the broadening due to the lower energy resolution in FERMI is taken into account.

Conclusions (2)

The ATIC, PAMELA and FERMI results can probably be explained by astrophysical sources (i.e. pulsars,…) or from dark matter annihilation or a combination thereof.

Consequences of the ATIC – FERMI discussion:

- Increased requirements on MC simulation accuracy

- Comparison of model calculations with measured spectra need to take quality of data points into account (i.e. energy resolution,….)

- More critical parameters should be measured in instruments

- Future instruments should be designed for high resolution and high statistics