2043-2

Summary School on Particle Physics in the LHC Era

15 - 26 June 2009

Astroparticle Physics I

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Cosmic Ray Physics: Introduction

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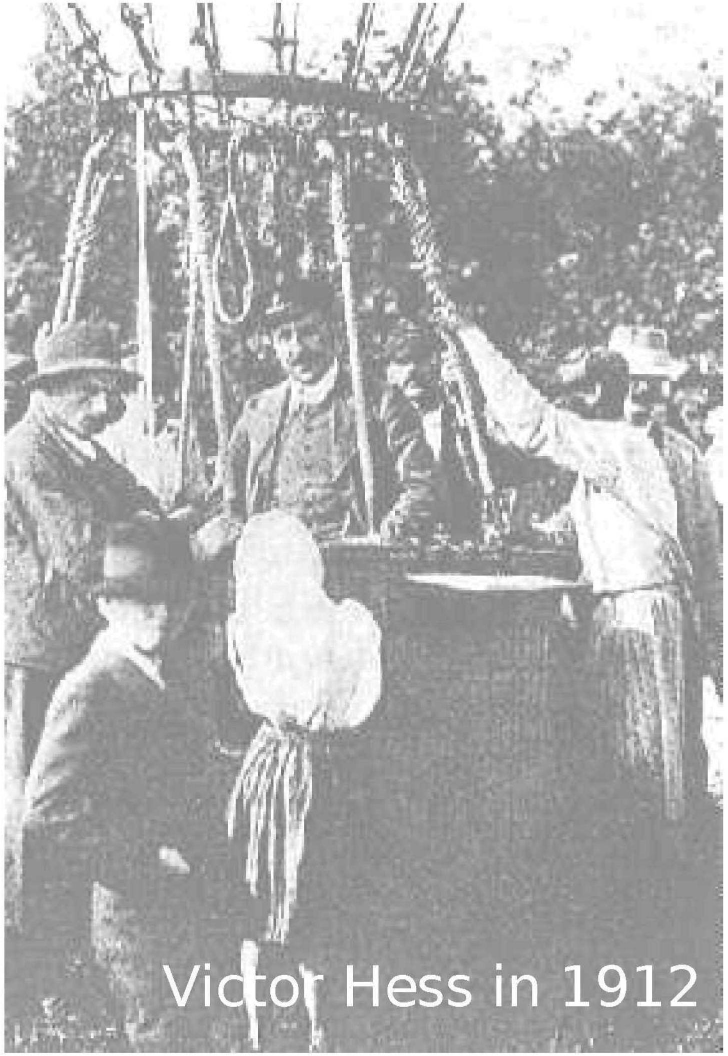


The discovery of cosmic rays in 1912 when Victor Hess proved that the ionization increases with altitude. He was awarded the Nobel prize in 1934. Up to 1950's physics of cosmic rays was essentially particle and nuclear physics. Accelerators took over after that and physics of cosmic rays is a part of astrophysics today.

Currently cosmic ray physics deals with

-- cosmic ray acceleration: where are the majority of the cosmic rays accelerated? How can one accelerate particles of energy exceeding 10^{11} GeV at astrophysical objects? Are there other ways to produce such high energy particles? Can we identify the sources of cosmic rays and how ?

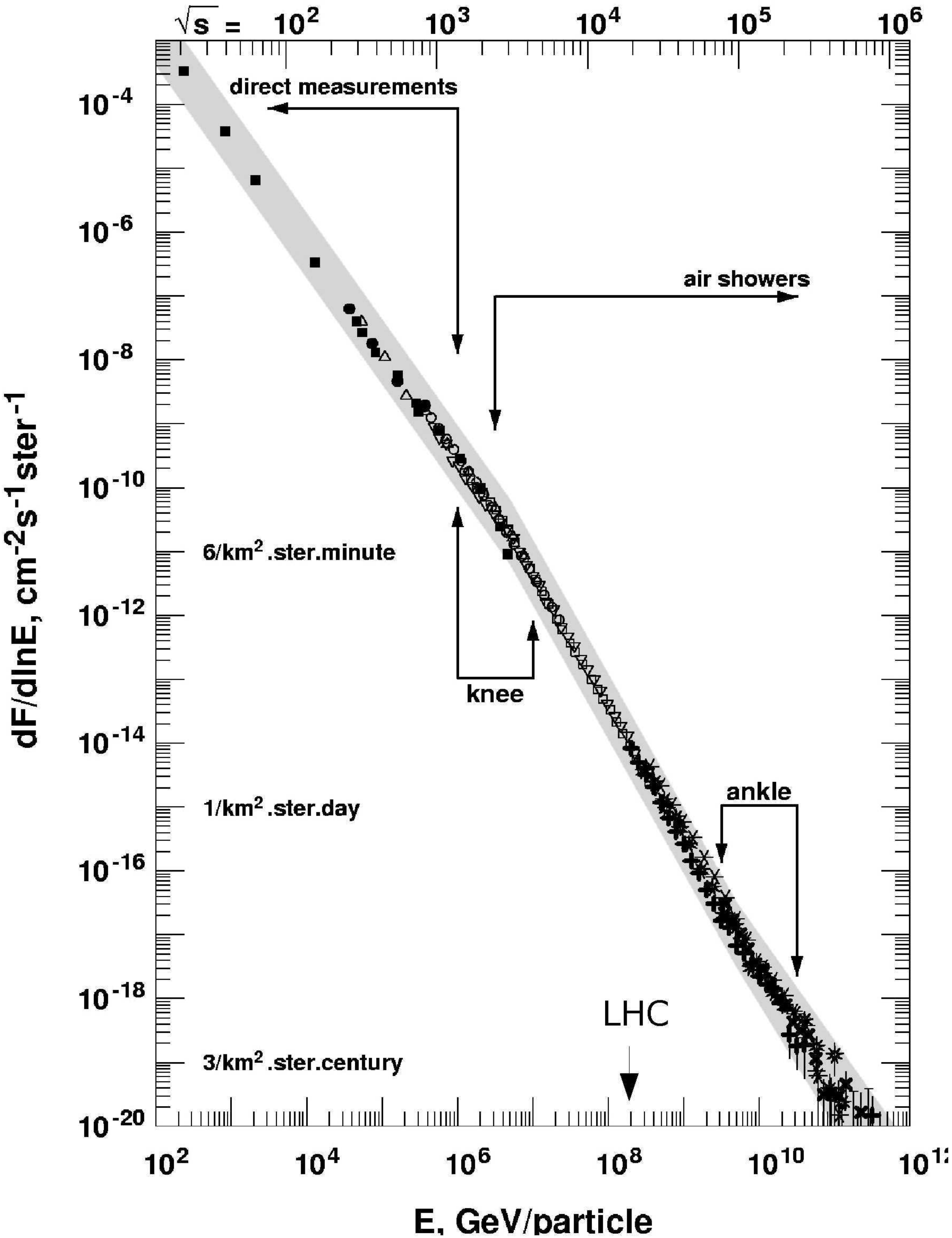
-- cosmic ray propagation in the Galaxy and the Universe: how is the cosmic ray composition affected by the propagation? Is the cosmic rays energy spectrum altered during the propagation ? Is cosmic ray astronomy possible?

-- cosmic ray detection, of course – the experimental side of cosmic ray research.

Because of the advance of the detection techniques for cosmic rays of the highest energy (above 10^9 GeV, 10^{18} eV) we have now interest in the nucleus-nucleus interactions at such energy that can not be studied in any other way.

We will give today a general introduction to cosmic ray physics that points at the main topics and will discuss briefly on of the most exciting *arguments* of recent years – the spectra of cosmic rays electrons and positrons.

The three next lectures I will give will concentrate on the highest energy cosmic rays – this is a very appropriate topic in the LHC year. Cosmic ray physicists need very much the LHC data in their attempts to improve the extensions of the hadronic interaction models used for data analysis to very high energy



Cosmic ray energy spectrum

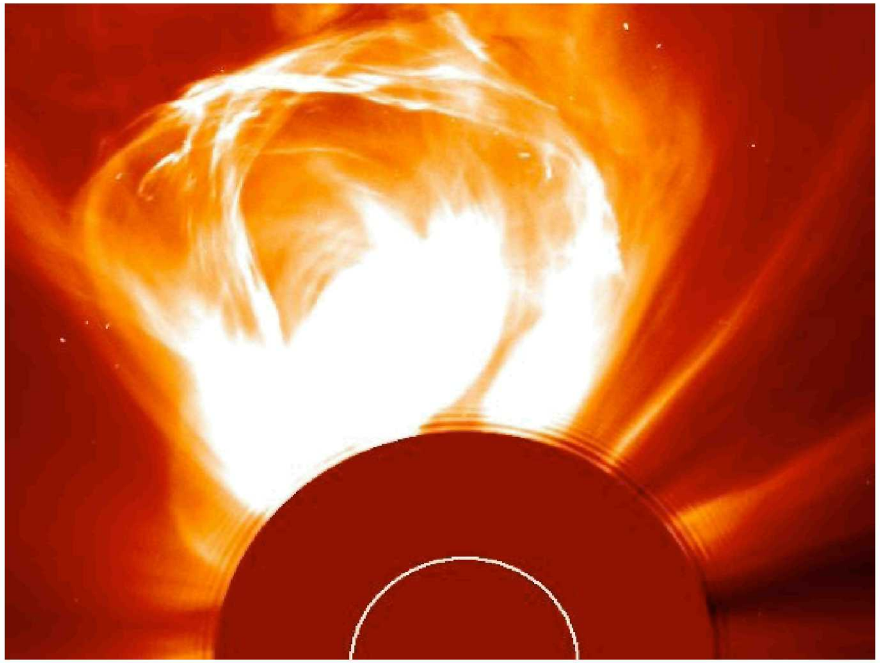
A smooth power law spectrum with a few features

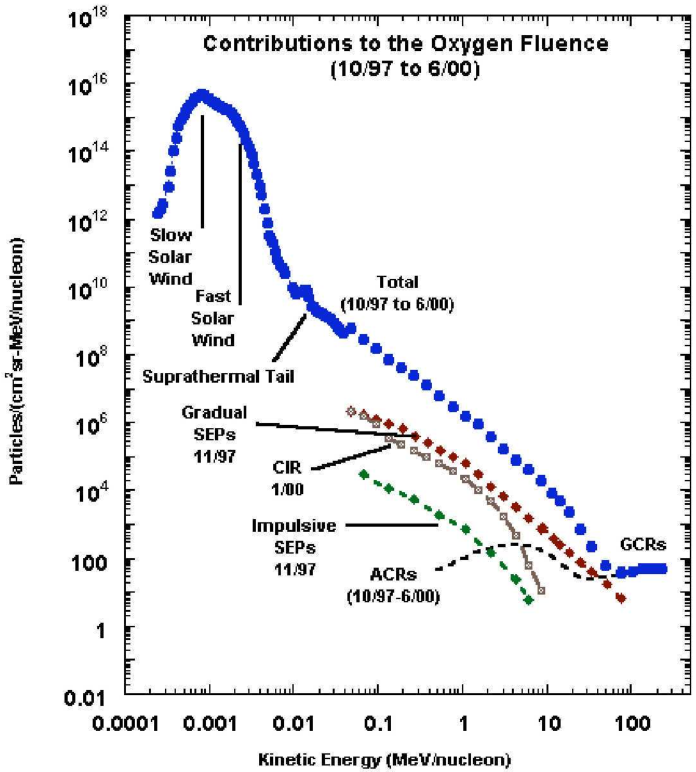
-- change of the slope at about 3.10^6 GeV from 2.7 to 3.0?

-- another change of slope from 3.0 to 2.6? at about 10^{10} GeV

-- the end of the cosmic ray spectrum. What is it due to – maximum energy of the cosmic ray acceleration, or to propagation effects.

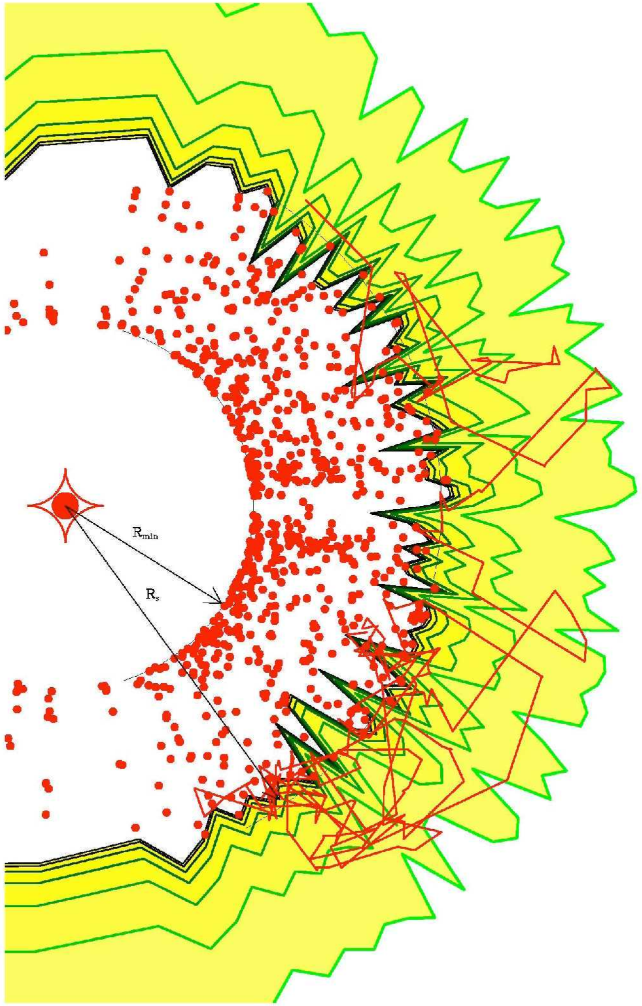
The only particle acceleration processes observed are those on the Sun. The picture below is of a coronal mass ejection on 9th of March 2000. Such events accelerate cosmic rays to energies of several GeV on a smooth spectrum.





Courtesy R.W. Mewaldt

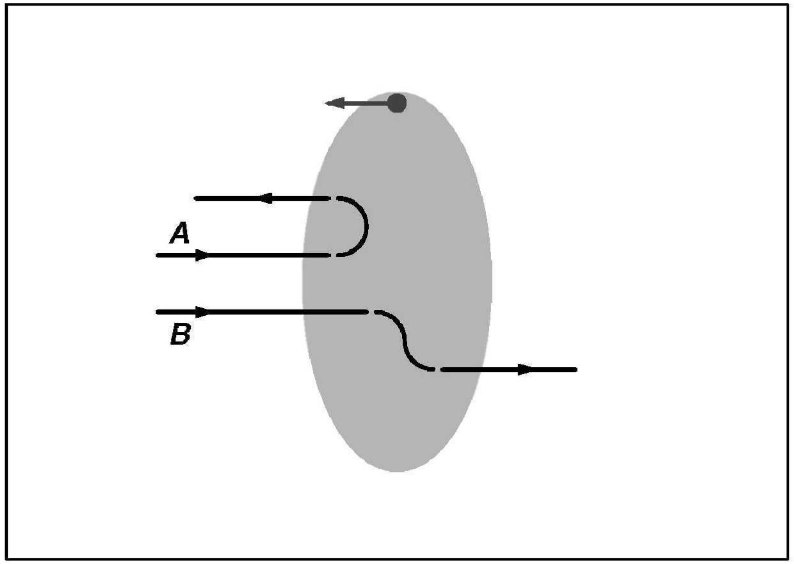
Cosmic Ray Acceleration



Ginzburg&Syrovatskii have identified supernova remnants (SNR) as possible sites of cosmic ray acceleration. If only 5% of the kinetic energy of the SNR is converted to cosmic rays this would supply all cosmic rays in the Galaxy.

The acceleration proceeds at the shock formed by the expanding SNR envelope. Most productive time is 1000 to 10000 years after the explosion. Shock compression ratios above 4 lead to flat power law spectra. Modern calculations obtain more complicated spectra that are power laws in small energy ranges.

The maximum acceleration energy is between 100 and 5,000 TeV in different estimates. It could be higher when the remnant expands in highly magnetized pre-supernova wind. Heavier nuclei reach Z times the maximum energy.



Fermi's model: cosmic ray acceleration in magnetic clouds.

particle moves on track 1 in direction opposite to the cloud motion. In the cloud system

$$E_0^* = \gamma_{cl}(E_0 + \beta_{cl} p_0)$$

The particle scatters elastically and eventually leaves the cloud. At the time of the exit

$$E_1 = \gamma_{cl}(E_0^* + \beta_{cl} p_0^*) = E_0 \times \gamma_{cl}^2 (1 + \beta_{cl})^2$$

The relative energy gain is

$$\frac{\Delta E}{E} = \frac{E_1 - E_0}{E_0} = \gamma_{cl}^2 (1 + \beta_{cl})^2 - 1 \equiv \xi$$

After n encounters of magnetic clouds under the same conditions the particle energy is

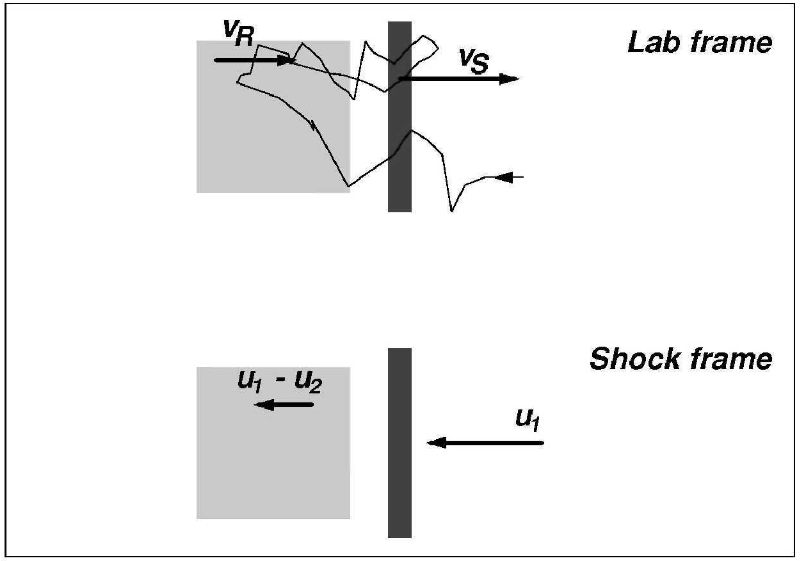
$$E_n = E_0 (1 + \xi)^n$$

The process leads to a power law spectrum.

$$N(> E_n) = N_0 \sum_n^{\infty} (1 - P_{esc})^m \propto A \left(\frac{E_n}{E_0}\right)^{-\gamma},$$

$$\gamma \simeq P_{esc}/\xi.$$

The energy gain per unit time depends on the frequency of encounters. The acceleration is slow.



Since 1970's the basic stochastic acceleration model is that in astrophysical shocks. Particles gain energy when crossing the shock in either direction. The energy gain by crossing is 4/3 β_S, i.e. it is more effective than Fermi's acceleration scenario.

The shock acceleration model gives predictions for the power law index of the accelerated particles. The escape probability $P_{esc} = \frac{\rho_{CR} u_2}{c\rho_{CR}/4} = \frac{4u_2}{c}$ leads to

$$\gamma = \frac{P_{esc}}{\xi} = \frac{4u_2}{c} \times \frac{3c}{4(u_1 - u_2)} = \frac{3}{u_1/u_2 - 1} \sim 1$$

The maximum acceleration energy is about 10^5 GeV

$$E_{max} = \frac{u_1}{c} ZeB(u_1 t) = \frac{u_1}{c} ZeBr_S$$

unless it is restricted by energy loss, which is the case for electrons that have strong synchrotron energy loss at the shock.

Casualties per attack in Iraq,
Neil Johnson et al., APS News, * Nov 2006

The Mother (Nature) of All Wars?

Modern Wars, Global Terrorism, and Complexity Science

by Neil F. Johnson

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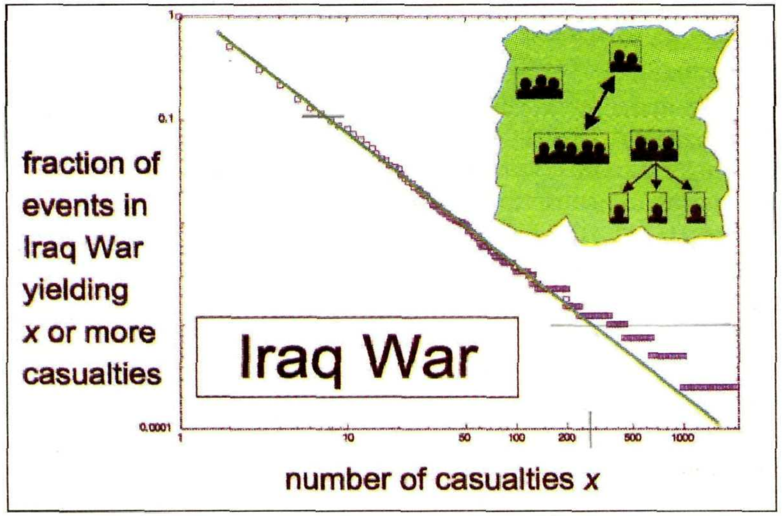

Log-log plot of the fraction of all events in the Iraq War with x or more casualties, versus x. Squares are actual war data. The line is produced by the physics-based analytic model (see inset). All modern wars, including terrorism, show power-law like behavior with exponents in the vicinity of 2.5. The analytic model considers insurgent armies as an ecology of attack units, which undergo frequent coalescence and fragmentation. The number of dark shadows is proportional to the number of casualties which each attack unit can typically inflict in a conflict event. Full details are given in e-print "Universal patterns underlying ongoing wars and terrorism," by Neil F. Johnson, Mike Spagat, Jorge A. Restrepo, Oscar Becerra, Juan Camilo Bohorquez, Nicolas Suarez, Elvira Maria Restrepo, Roberto Zarama, which is available at http://xxx.lanl.gov/abs/physics/0605035

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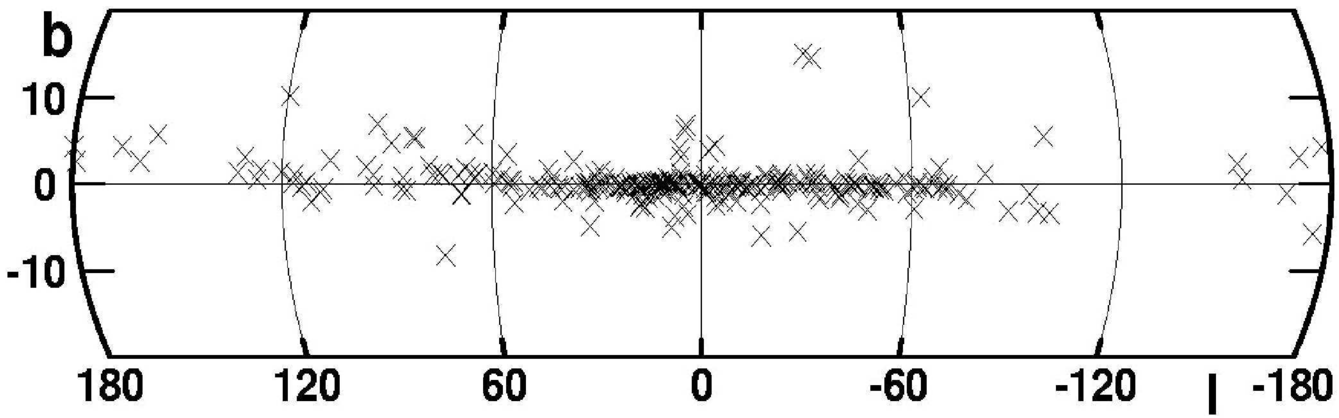
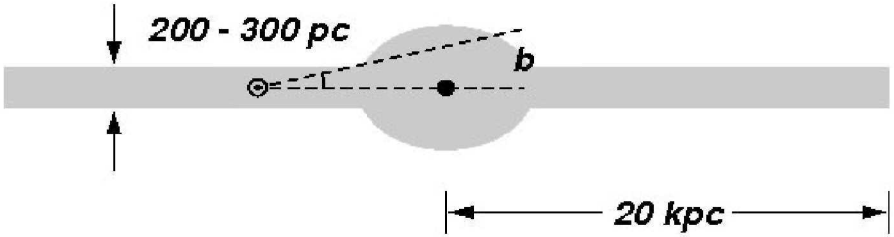
Power law distributions seem to be achieved in all stochastic processes.

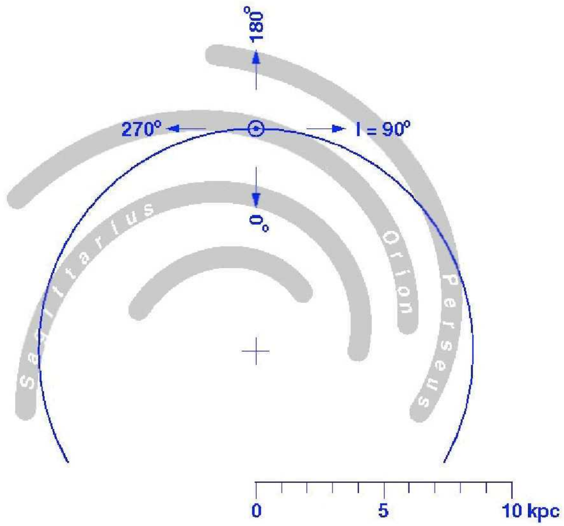
Power law index of the casualties is $\gamma = 1.5$.

Distribution of supernova remnants in the Galaxy
(from the D.A. Green's catalog)



Cosmic Ray propagation in the Galaxy





The Solar system is 8.5 kpc away from the galactic center. One *pc* is 3.10^{18} cm, so we are at a distance of $2.55\ 10^{17}$ km and the light from it reaches us after 2,800 years. One pc is the distance at which 1 AU ($149.6\ 10^{6}$ km) is seen at an angle 1 arcsec.

Galactic latitude *b* is the angle at which an object is above the galactic plane.

Cosmic rays propagation is a function of five processes:

1) Cosmic ray diffusion. Diffusion coefficient $K = c\beta\lambda/3$

2) Cosmic ray convection (convection velocity)

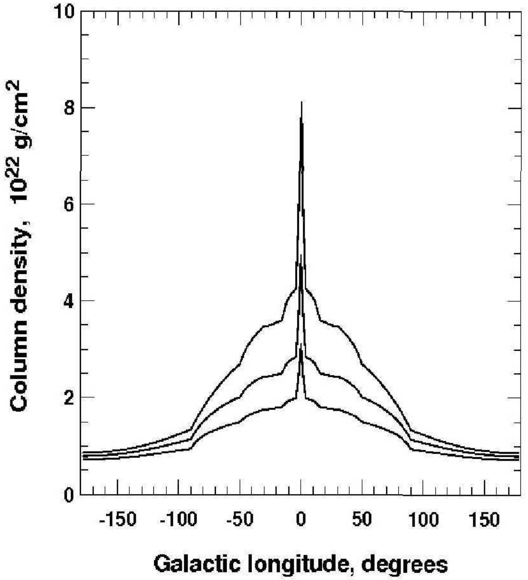
3) Rate of change of particle energy dE/dt. Could be negative (energy loss) or positive (reacceleration) term

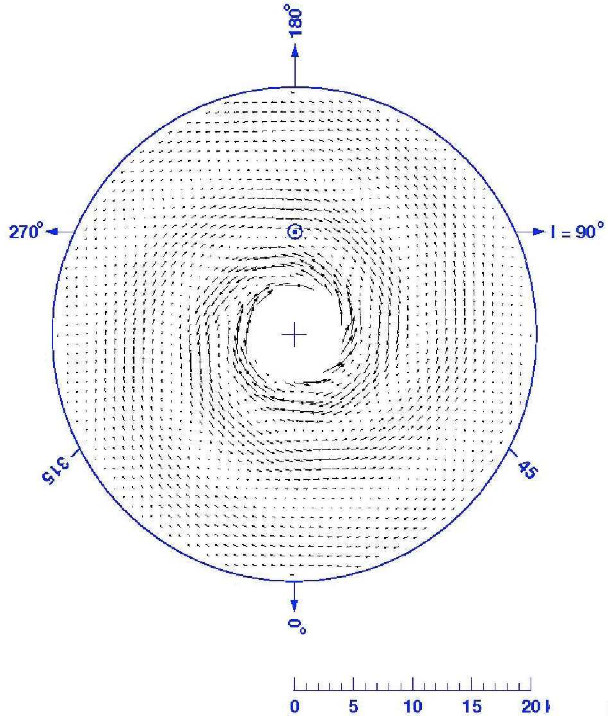
4) Particle loss term due to interactions and decays. Could be expressed as a function of particle velocity, interaction length and target density for interactions, and by lifetime in case of decay.

$$P_j = v\rho/\lambda_j + 1/\gamma_j \tau_j$$

5) Particle gain term (from all interactions and decays)

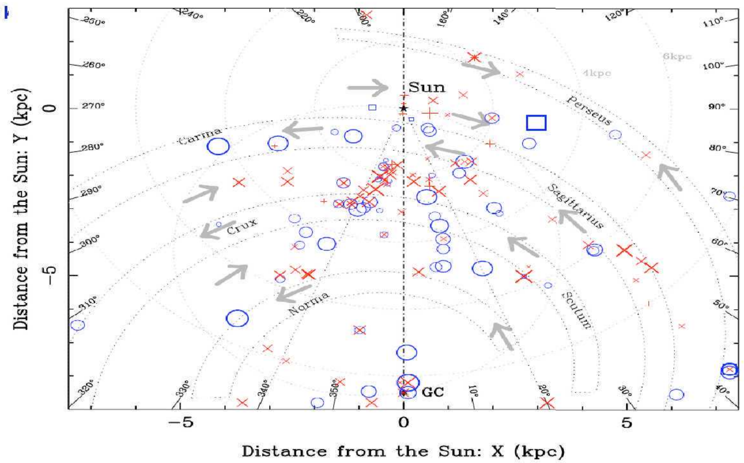
The importance of these processes depends on astrophysical parameters such as the galactic magnetic field and matter density. The cosmic ray composition and energy spectra of different types of nuclei (*primary and secondary*) are changed during propagation.





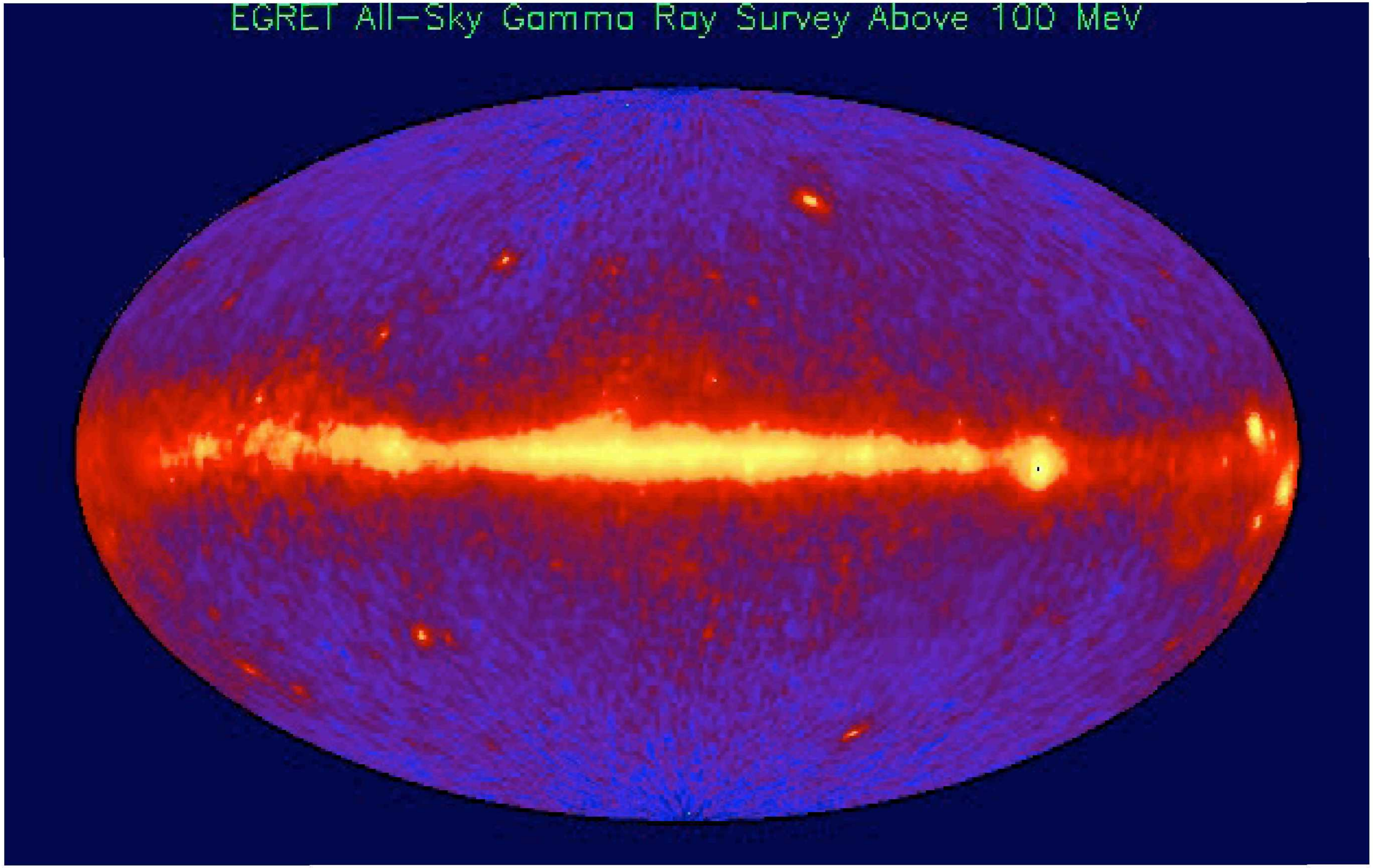
Local regular field is 1-2 μGauss and the total field maybe a factor of 3 higher.

Courtesy of J.L. Han

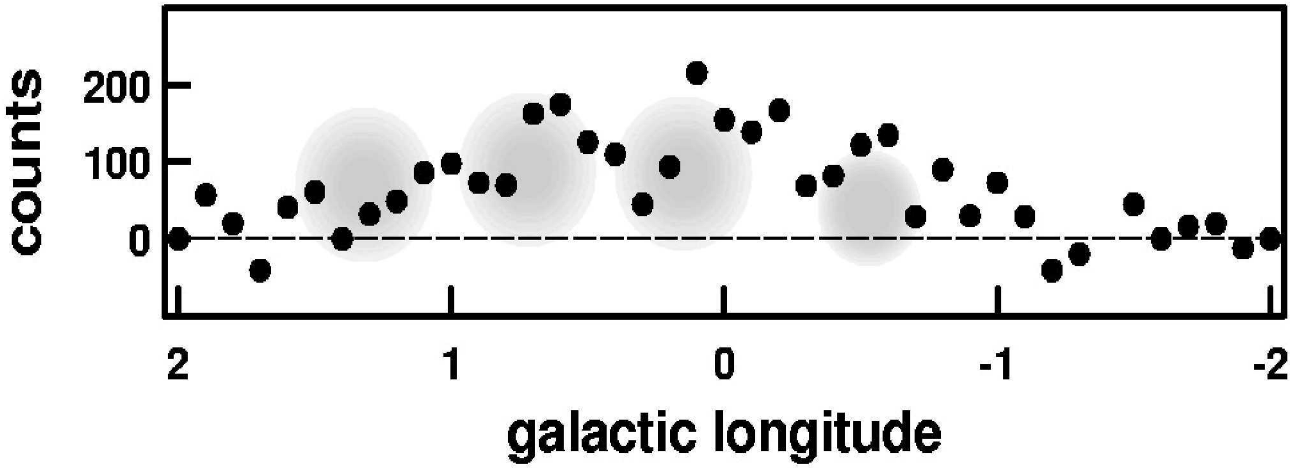


In addition to stars and planets the matter is in the forms of atomic Hydrogen (HI) and molecular hydrogen (H_2). Only 10% of the matter is in the form of He and heavier nuclei.

The propagation of cosmic rays in the Galaxy is studied by the production of gamma rays in different regions.



The galactic ridge: observation and interpretation by HESS.



TeV gamma rays prroduced in dense molecular clouds near the center of our Galaxy, not exactly at the supernova remnant where the cosmic rays are accelerated. The accelerated cosmic rays have not yet diffused far enough to reach the cloud at longitude more than 1 degree.

Detection of cosmic rays

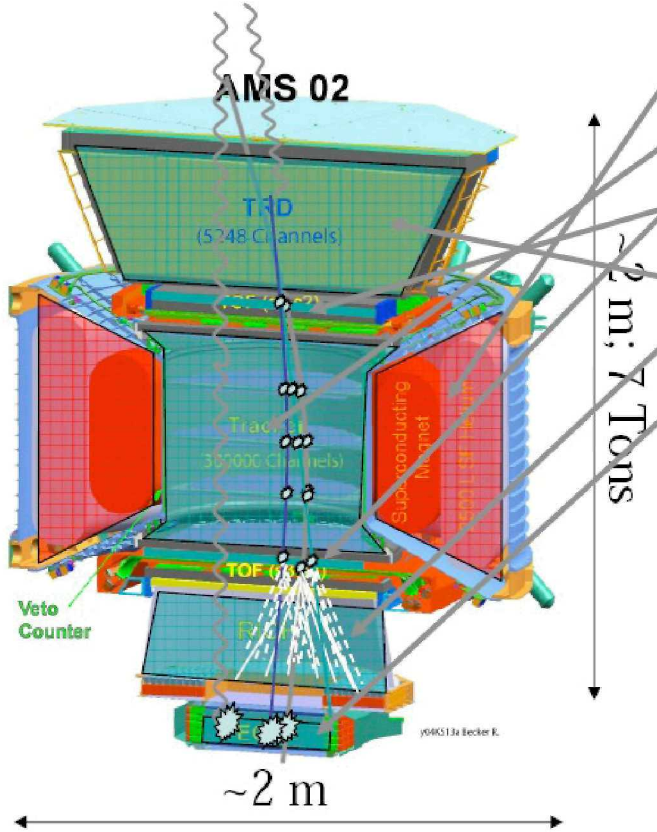
Lowest energy cosmic rays (energy below 1 GeV) can not reach the atmosphere as they are turned out by the geomagnetic field. They can only be studied by satellite detectors away fro the Earth.

The minimum energy of cosmic rays that penetrate to the atmosphere depends on the geomagnetic latitude. GeV cosmic rays penetrate close to the magnetic poles. The geomagnetic cutoff is about 40 GeV at the geomagnetic equator.

The balloon and satellite detectors study cosmic rays of energy up to 100 TeV. At higher energy the cosmic ray flux is too low to be studied well by 1 sq.m. detectors.

High energy detectors are either magnetic spectrometers or emulsion calorimiters. Thee best hope for the near feature is the AMS 2 detector to be launched to ISS.

The AMS experiment

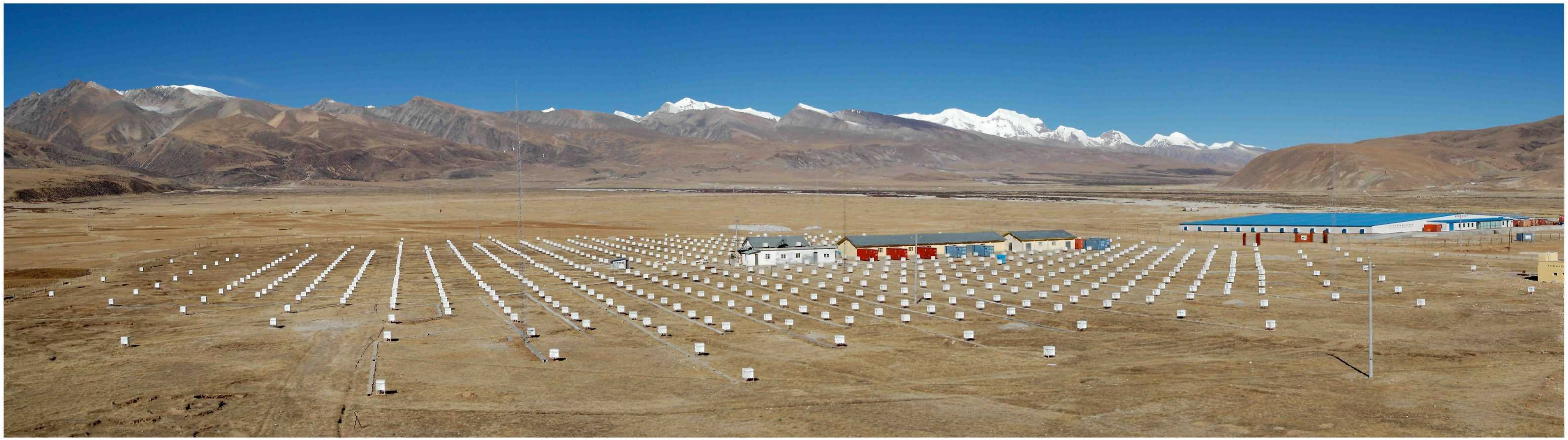


Geometrical acceptance: 0.45 m^2sr

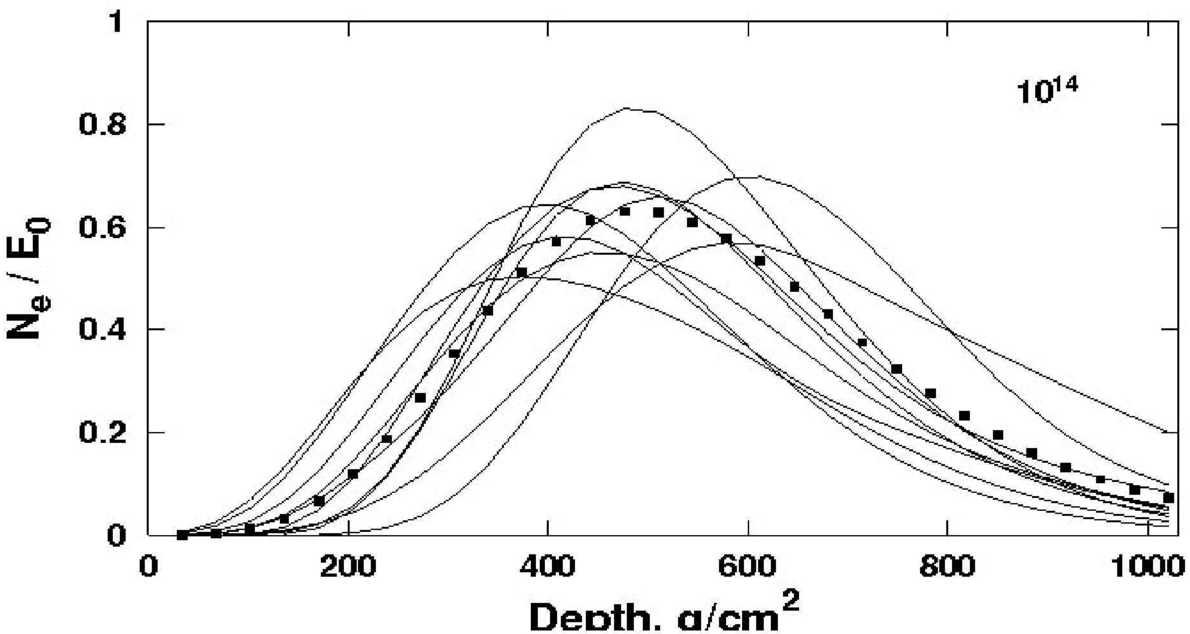
- **Superconducting magnet** (BL^2= 0.85 Tm^2)
- **Silicon Tracker** (rigidity, charge)
- **Scintillator system (TOF)** (β, dE/dx, trigger)
- **Transition Radiation Detector** (e/p)
- **Ring Imaging Cherenkov** (β, charge)
- **Electromagnetic Calorimeter**(energy, e/p)
- **Anticoincidence counters, star-tracker, GPS**
- **Also gamma rays in conversion or ECAL**

Minimum amount of material crossed: 0.4 X_o up to ECAL

At higher energy the cosmic rays are observed by the detection of the showers that they initiate in the atmosphere (extensive air showers, EAS). The extensive air shower arrays consist of particle detectors set on certain distance from each other that simultaneously trigger. The detection method was first used by Pierre Auger and collaborators in the 1930's who estimated the highest shower energy to a million GeV.



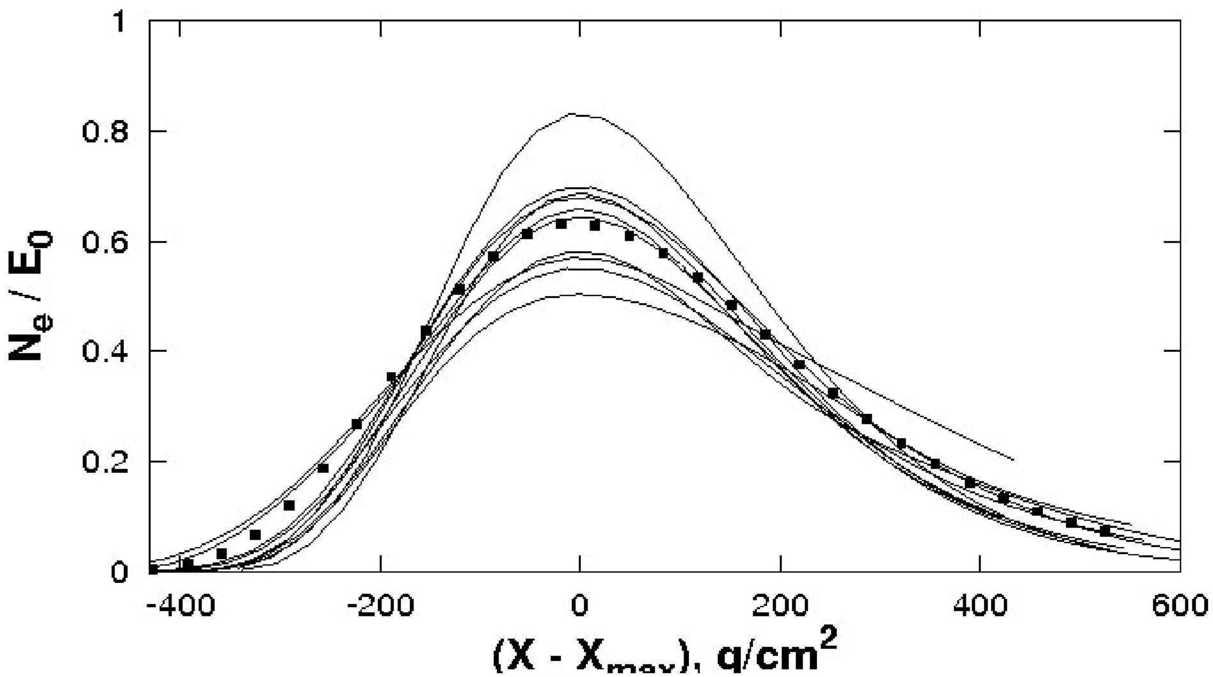
Tibet III array in Tibet, China – the highest altitude array 4,300 m.a.s.l.
Showers have less fluctuations close to shower maximum.



Individual shower profiles of 10 showers and their average.

Showers are aligned at maximum - first interaction depth taken out.

Fluctuations are minimal at shower maximum despite the visual impression.



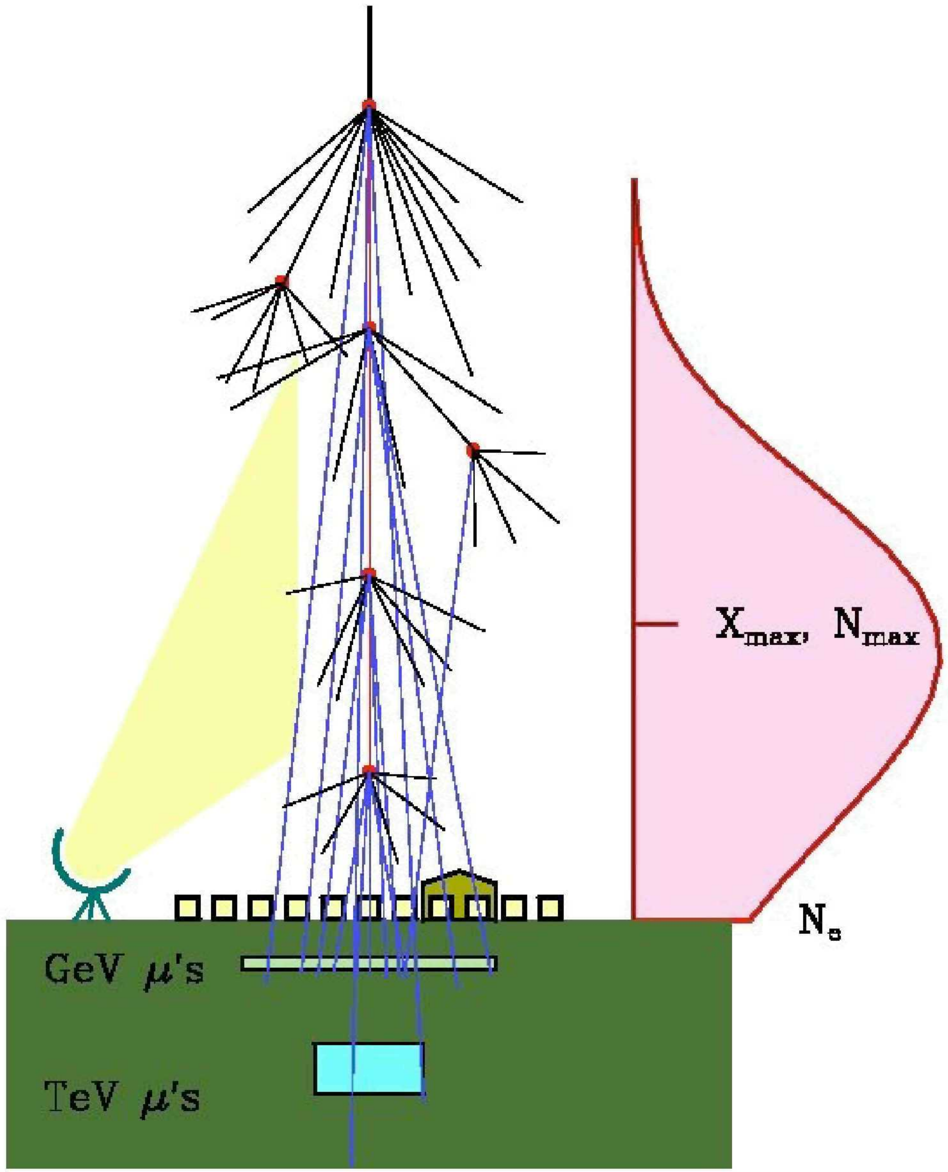
Air shower detection

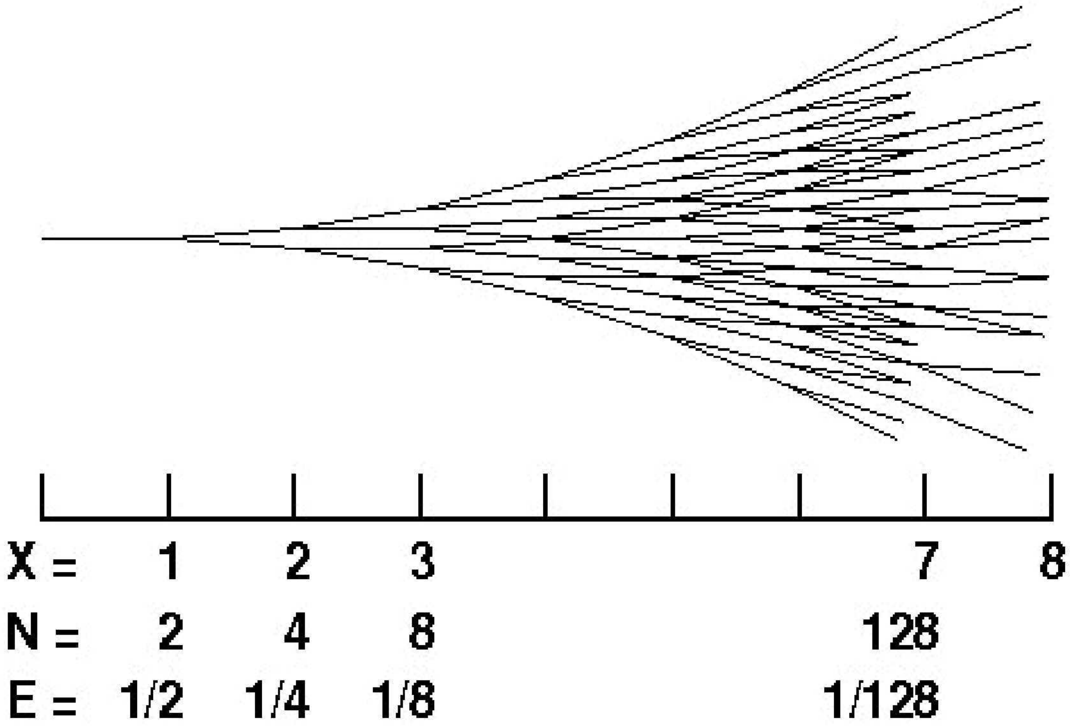
Three main methods:

1) air shower arrays

2) Cherenkov light detectors

3) fluorescent light detectors





There is only one type of particles in Heitler's cascade. They have fixed interaction length. Every time when these particles interact they generate two particles that share their energy. This way the number of particles increases and their energy declines. Energy conservation.

$N = 2^n$, $E = 1/2^n$, where n is # of interactions

$X_{max} = \lambda \log_2(E_0/E_c)$ particles of energy lower than E_c do not interact.

Jim Matthews extended the Heitler toy model to hadronic showers to calculate the number of GeV muons in the shower.

$$\ln N_\mu = \ln N_\pi = n_c 2\langle m\rangle/3 = \beta \ln(E_0/\varepsilon_\pi)$$

$$N_\mu = (E_0/\varepsilon_\pi)^\beta \qquad \beta = \ln(\frac{2}{3}\langle m\rangle)/\ln\langle m\rangle = 0.85$$

reflects the 2/3 fraction of charged pions.

When the shower is initiated by a heavy nucleus one can replace the primary energy by E/A and the number of muons increases.

$$N_\mu^A = A[(E_0/A)/\varepsilon_\pi]^\beta = A^{1-\beta} N_\mu^p$$

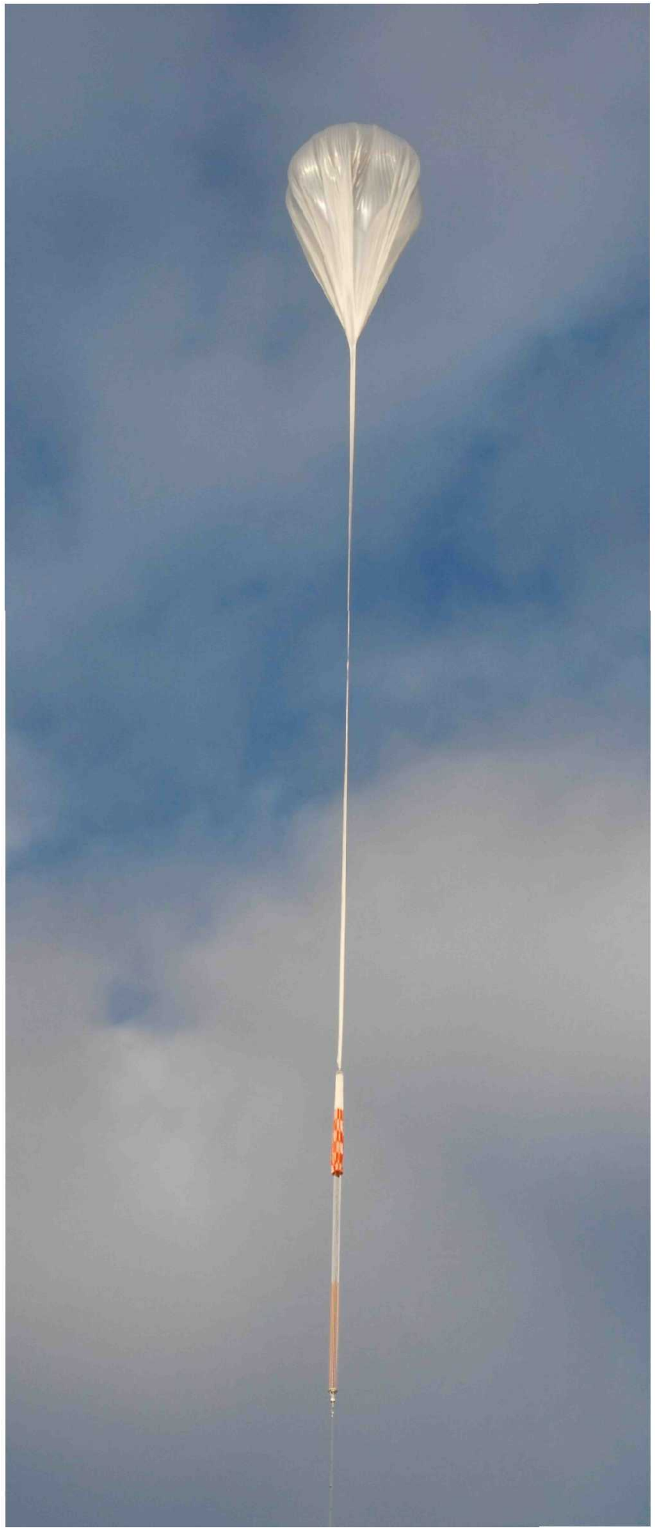
p	1.00
He	1.23
O	1.52
Fe	1.83 , which is correct in order of magnitude.

Dark matter or what?

One of the highest 10 ranking articles in *Nature* in 2008 was the publication of the electron spectrum measured by the Advanced Thin Ionization Calorimeter (ATIC). The Collaboration reported on an excess of cosmic ray electrons of energy between 300 and 800 GeV.

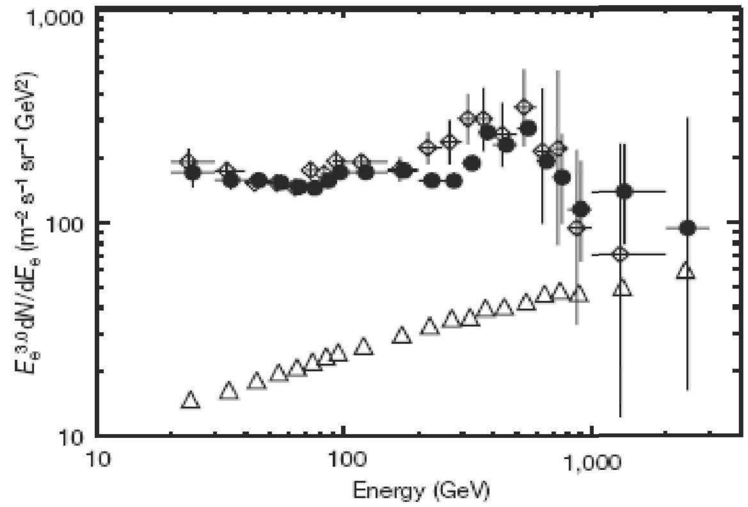
The immediate reaction according to the opinion articles in the same issue of *Nature* were that the excess particles mark the first indirect detection of dark matter.

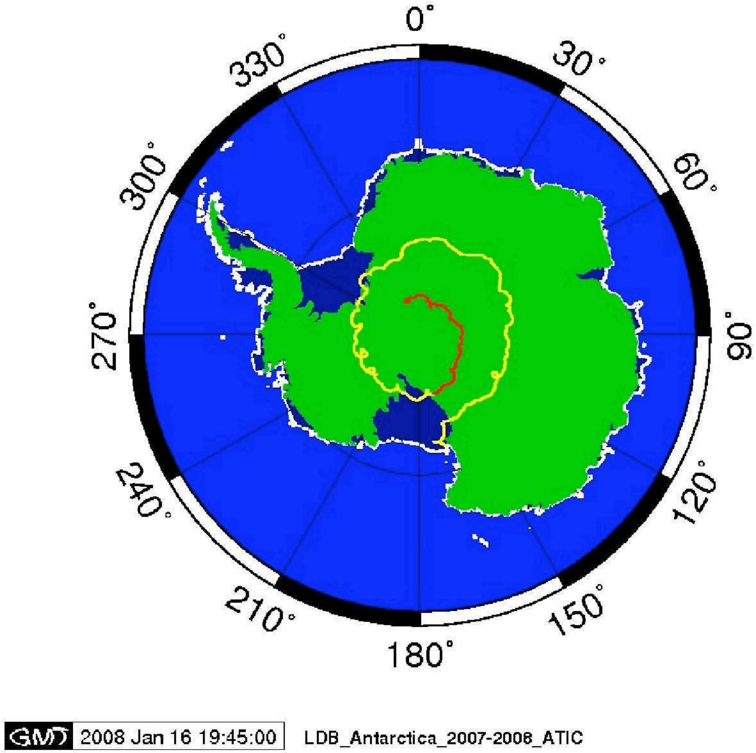
ATIC consists of a deep fully active calorimeter of depth 18 radiation lengths in 8 layers arranged in orthogonal pairs that measures the particle energy. A silicon matrix detector on top of it measures the particle charge and three layers of scintillator hodoscopes embedded in 30 cm of graphite determine the particle trajectory.



Data was presented from two ATIC flights in Antarctica.

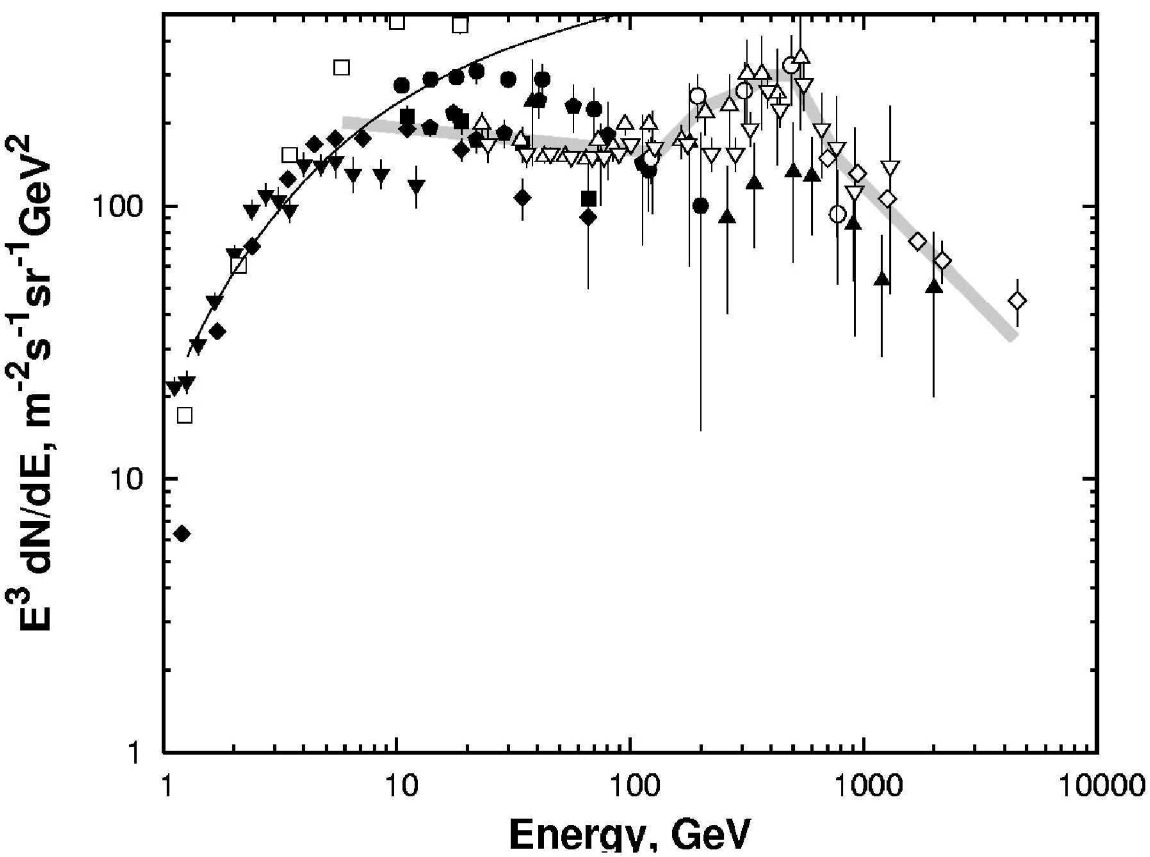
Proton misidentification is shown with empty triangles.

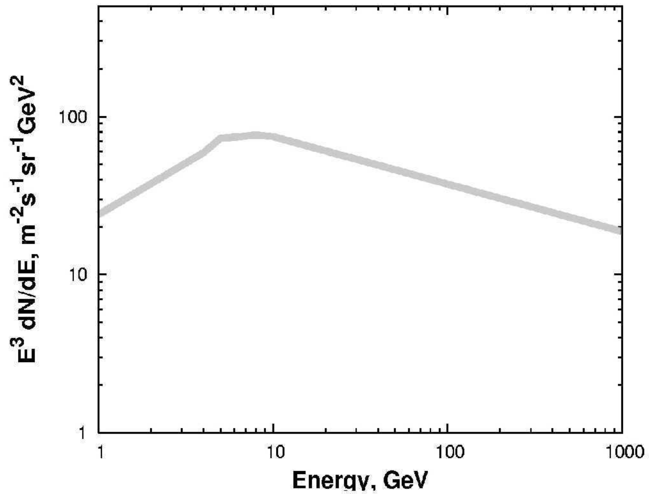




Balloon flight pattern of ATIC 2.

The ratio of cosmic ray electrons to protons is roughly 1/100 and decreases with energy, because of the large energy loss of electrons on synchrotron radiation in the galactic magnetic field and in inverse Compton collisions. The slope of the spectrum changes between 5 and 10 GeV.





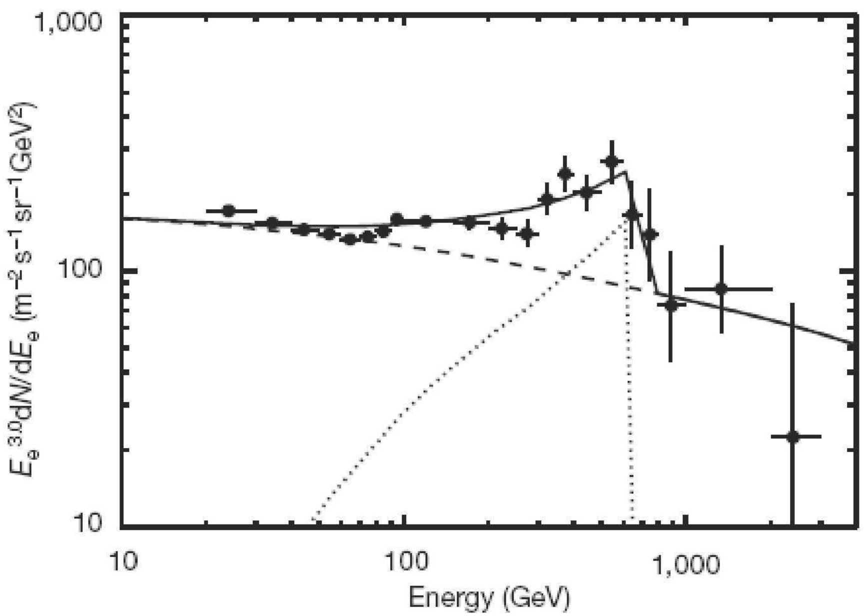
ATIC data compared to other experiments. Note BETTS that has lower normalization and HESS at the highest energy.

There are two possible explanation, the ATIC paper notes:

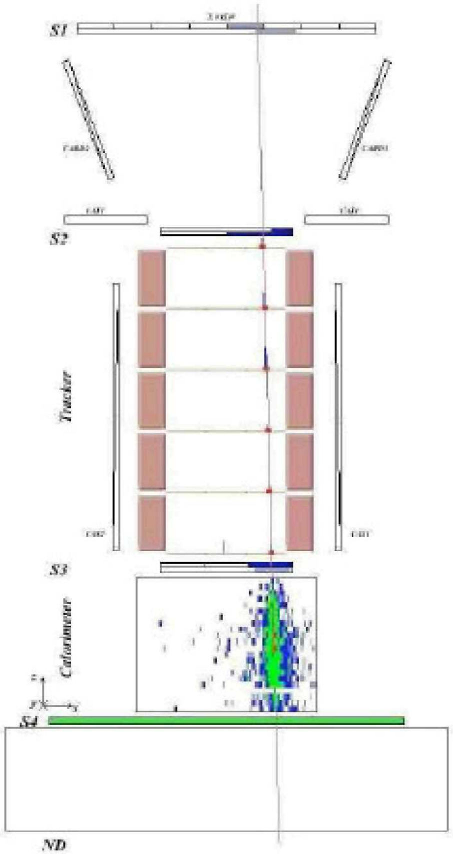
1) A nearby source of electrons, not further away than 1 Kpc. Otherwise the 500 GeV electrons would have lost energy. Possible acceleration sites are supernova remnants, pulsar wind nebulae and microquasars, sites where from TeV gamma rays are observed. Sources like that should have a sharp cutoff above 800 GeV.

2) The alternative explanation is annihilation of dark matter particles. Many WIMP or KK particles annihilate into electron positron pairs.

Annihilation of Kaluza-Klein dark matter particles of mass 620 GeV/c. Fits the spectrum well but requires high density and cross section. Calculation done with GALPROP by the ATIC collaboration.

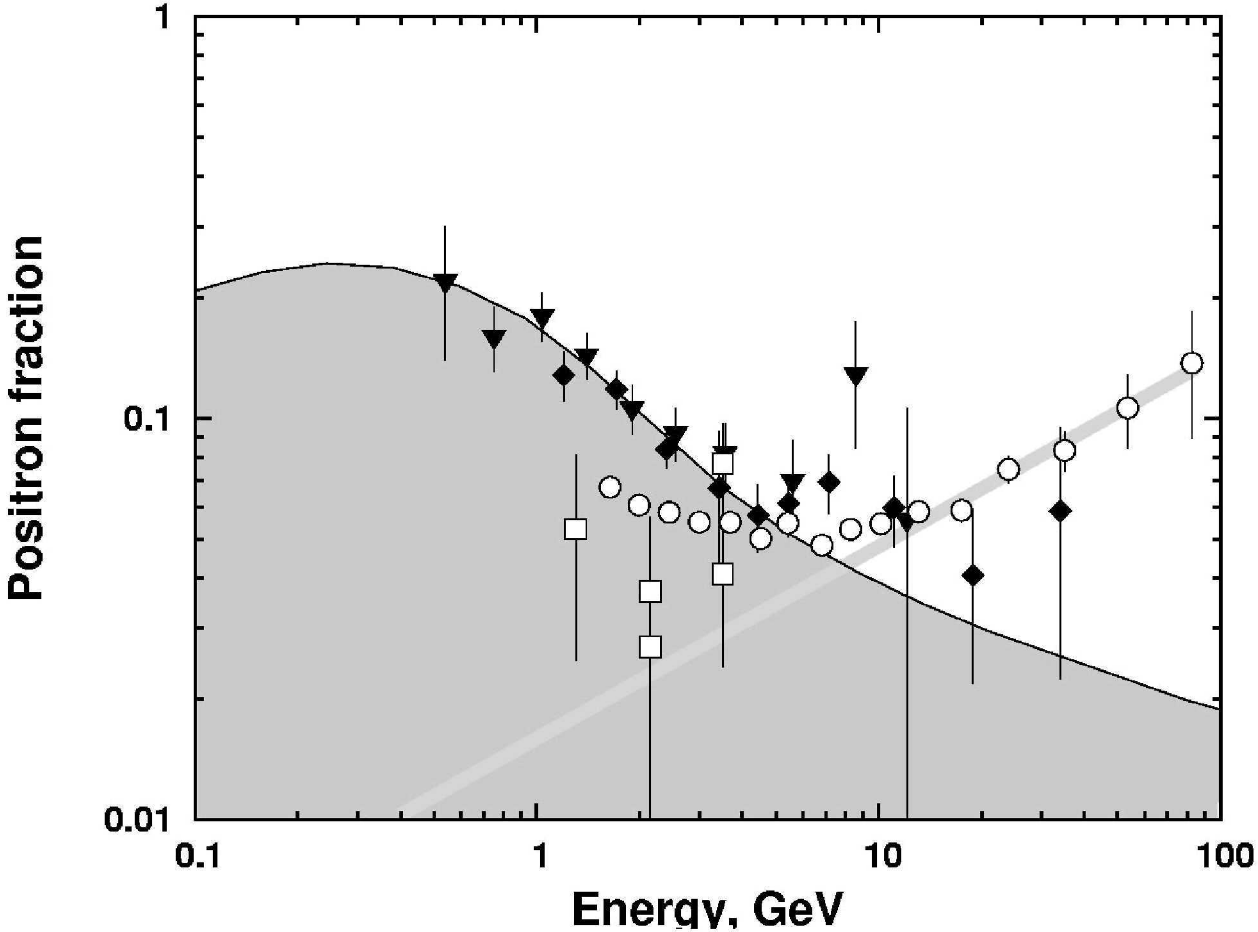


At the end of its presentation the ATIC collaboration expressed its hope that the PAMELA satellite experiment is measuring antiprotons and the positron/electron ratio and it will clarify the situation about the electron excess. Dark matter models predict electron/positron pairs and the situation will become more obvious when the positrons are measured too. This requires a magnetic spectrometer.

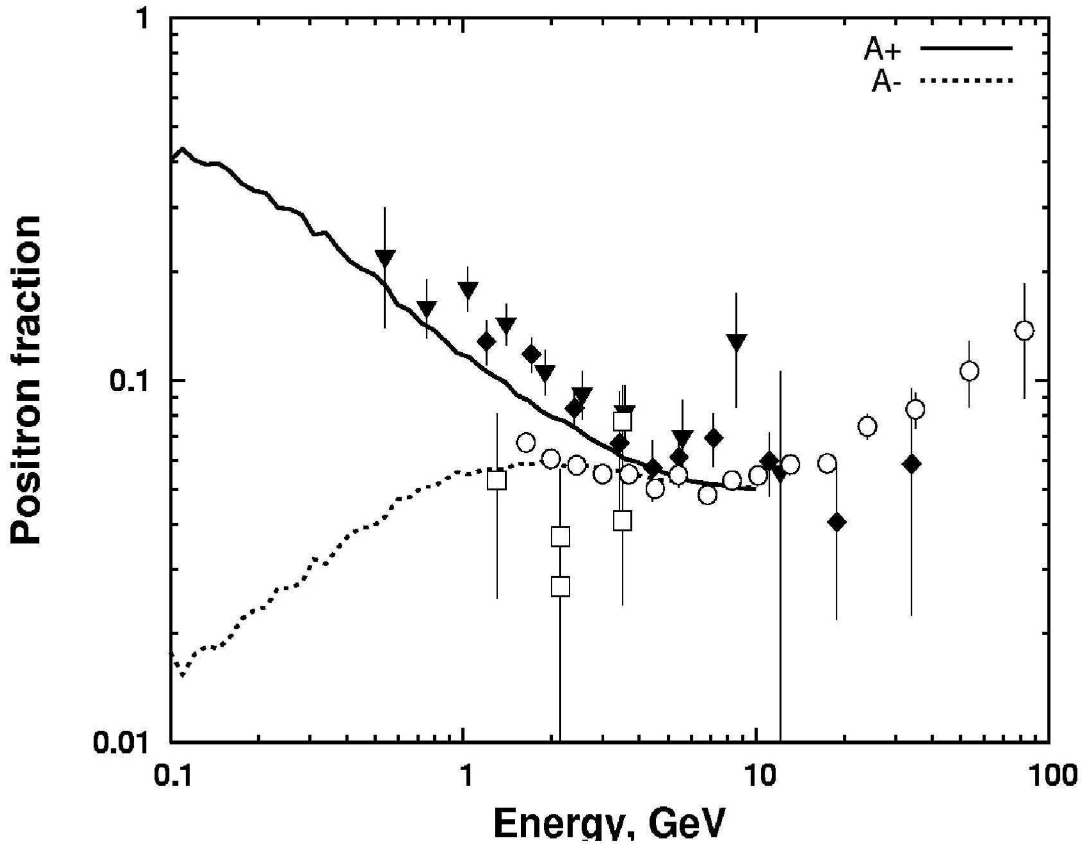


Pamela has been flying on an almost polar orbit since 2006. It consists of

-- deep magnetic calorimeter with high radiation length/proton interaction length ratio
-- time of flight system
-- anticoincidence system
-- electromagnetic imaging calorimeter
-- shower tail scintilator
-- neutron detector

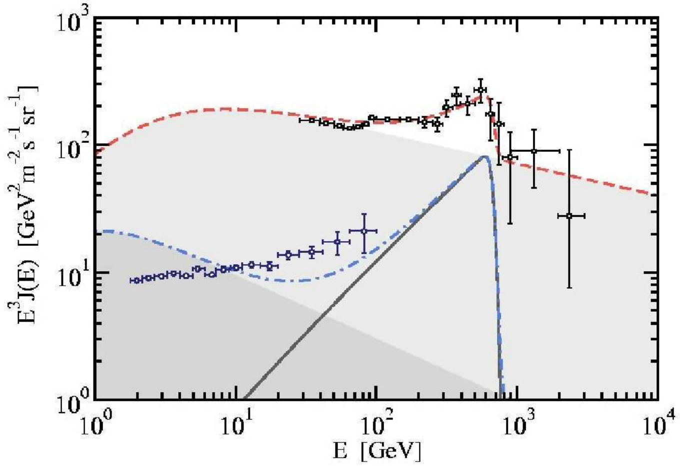


Pamela data on the positron/electron ratio [$e^+/(e^-+e^+)$] are shown with open circles. The first question is "Do they know what they are doing? Why are the positron fluxes below 5 GeV so much lower than other data?"



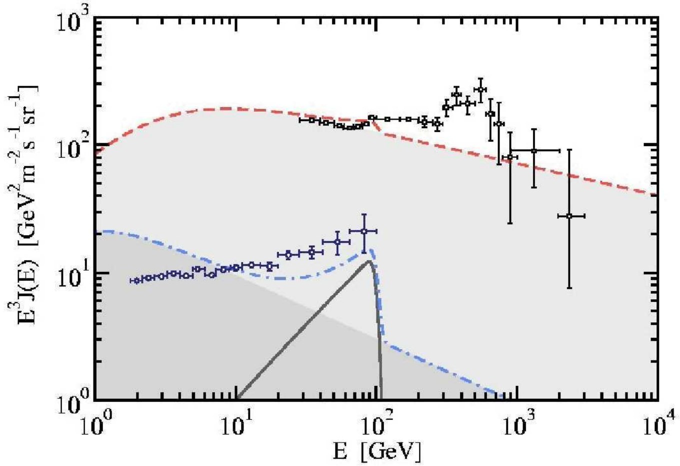
The answer is simple: the polarity of the Sun has changed before Pamela took data to A^- and the negative polarity changed the positron to electron ratio. The calculation above *(thanks to Chunsheng Pei)* shows the difference between the two polarities using a model for pair production by R.J. Protheroe.

Now the important question: **Why is the positron/electron ratio increasing?** Here is the answer of Gogoladze et al. who discuss neutralino dark matter.



A neutralino mass of about 700 GeV is needed for annihilation if one wants to explain both ATIC and Pamela. This scenario needs a boost factor.

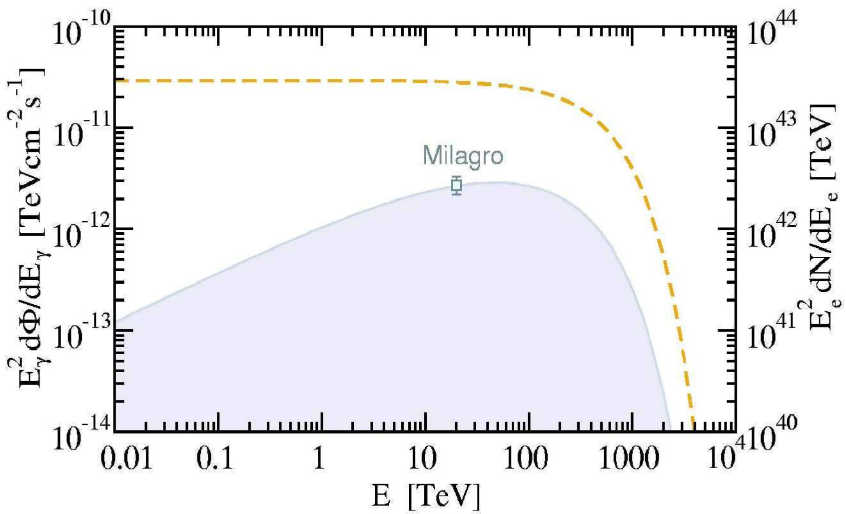
In addition one can use long lived (10^{20} sec) unstable neutrino decays with mass about 2 TeV.

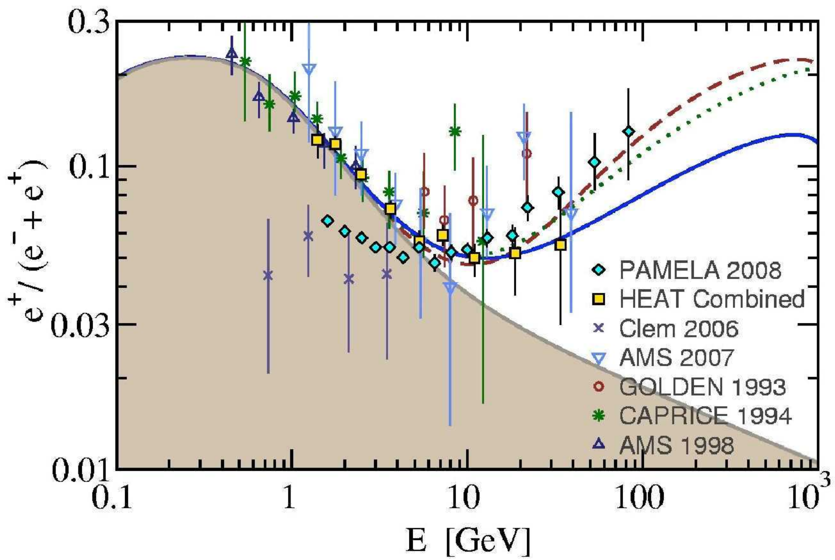


If ATIC is wrong and only Pamela needs explanation all masses come down. 300 GeV decaying neutralino can do the job. This would make sparticles much more accessible at the LHC because of the lower mass.

More conventional(???) explanation by Yuksel et al.

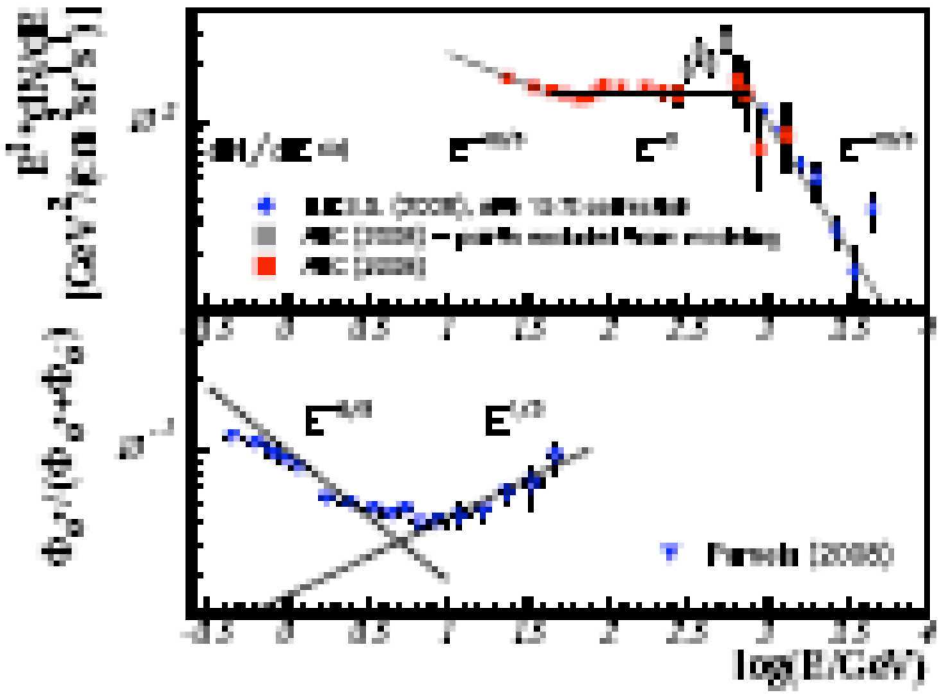
Nearby source



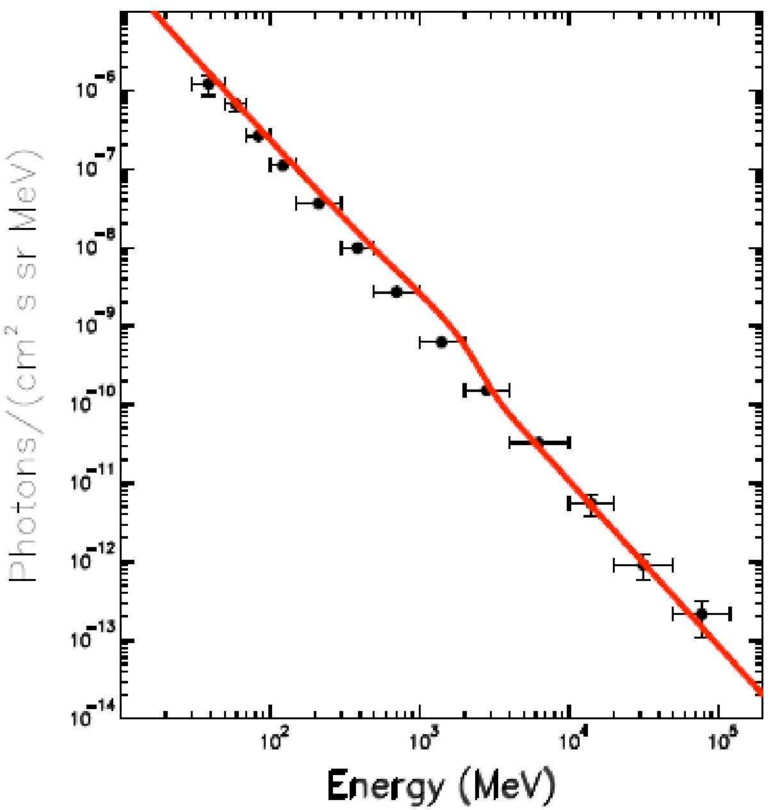


The positron excess is related to the observation of 20 TeV gamma rays from the region of Geminga by Milagro. Geminga is nearby (~200 pc) pulsar wind nebula (PWN) where high energy e^+e^- pairs are accelerated by the pulsar. The signal of Milagro is not point like source – it has 3^o diameter. The pairs produce gamma rays through inverse Compton scattering on MBR and also account for the positron excess of Pamela. Geminga is an old (3.10^5 yrs) source which must have been more active earlier. Diffusion time from 200 pc is reasonable for the excess particles. The age of the pulsar, its luminosity, distance and size of PWN are the parameters of the model.

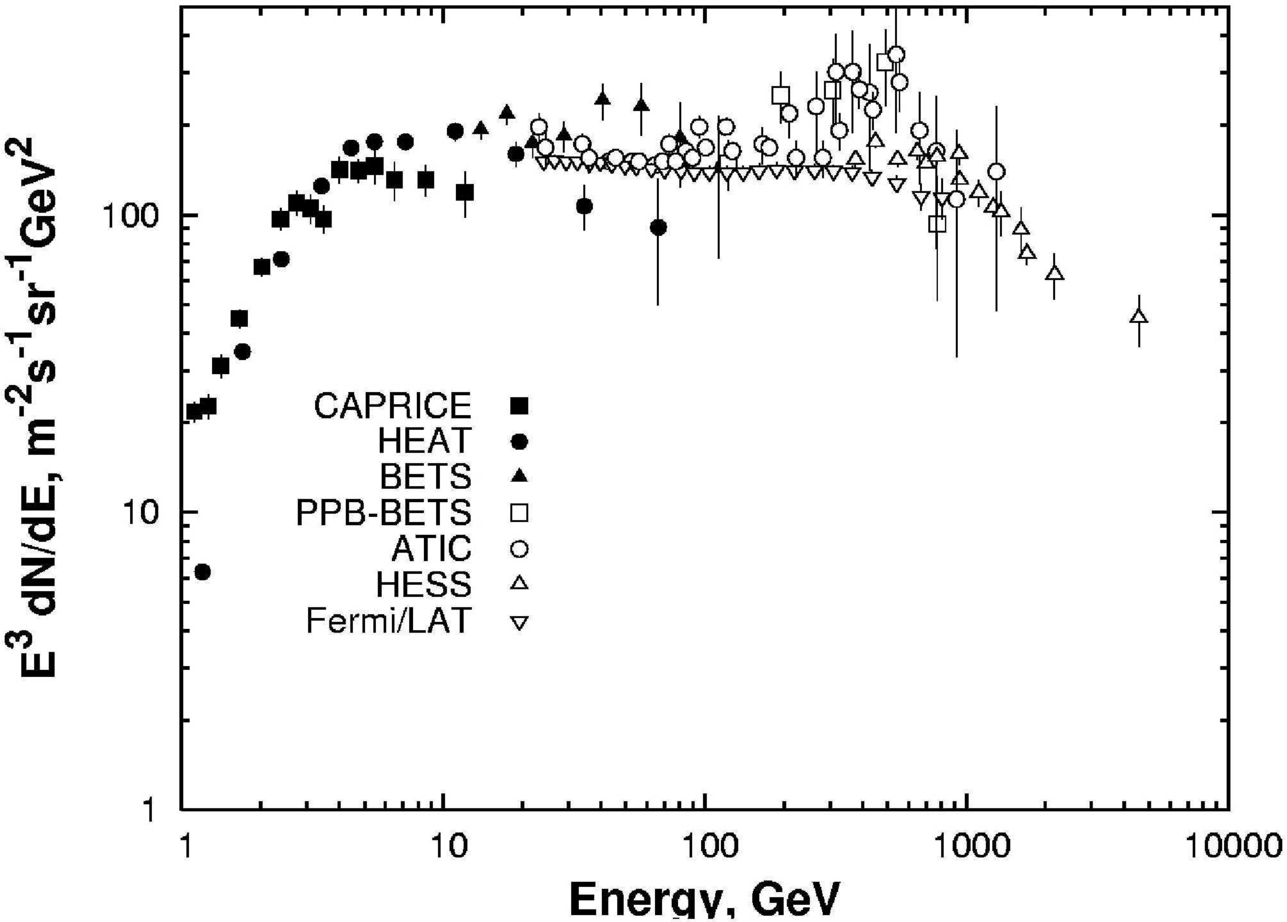
Still more conventional explanation by Biermann et al: in a small fraction of the SNR sphere (after Wolf Rayet and Red Super Giant stars explosions), at the `polar cap' all particles are accelerated in parallel shocks at a slightly flatter spectrum. Since the acceleration at the polar cap is slower there is a higher chance for electron/positron pair production that explain the Pamela results. In the case of ATIC the E^{-3} spectrum is extended to about 1,000 GeV.



The observations of ATIC and Pamela generated many different arguments that are very interesting not only for the interpretation of these results but also for understanding of previous (and future) results in cosmic ray physics. Dado&Dar, for example, developed an argument that an electron excess such as the ATIC one would create a GeV bump in the gamma ray background radiation detected by EGRET instrument on the Compton GRO.



The bump would come from inverse Compton scattering of MBR and IR/optical photons by the excess electrons. This would happen, however, if the gamma ray background were all created in our Galaxy and not in the extragalactic space as the EGRET group claimed.



E3 dN/dE, m-2s-1sr-1GeV2
Energy, GeV
CAPRICE
HEAT
BETS
PPB-BETS
ATIC
HESS
Fermi/LAT
1
10
100
1000
10000