Recent results from ATIC, HESS and Pamela

New Paradigms for Dark Matter

Workshop at U. C. Davis

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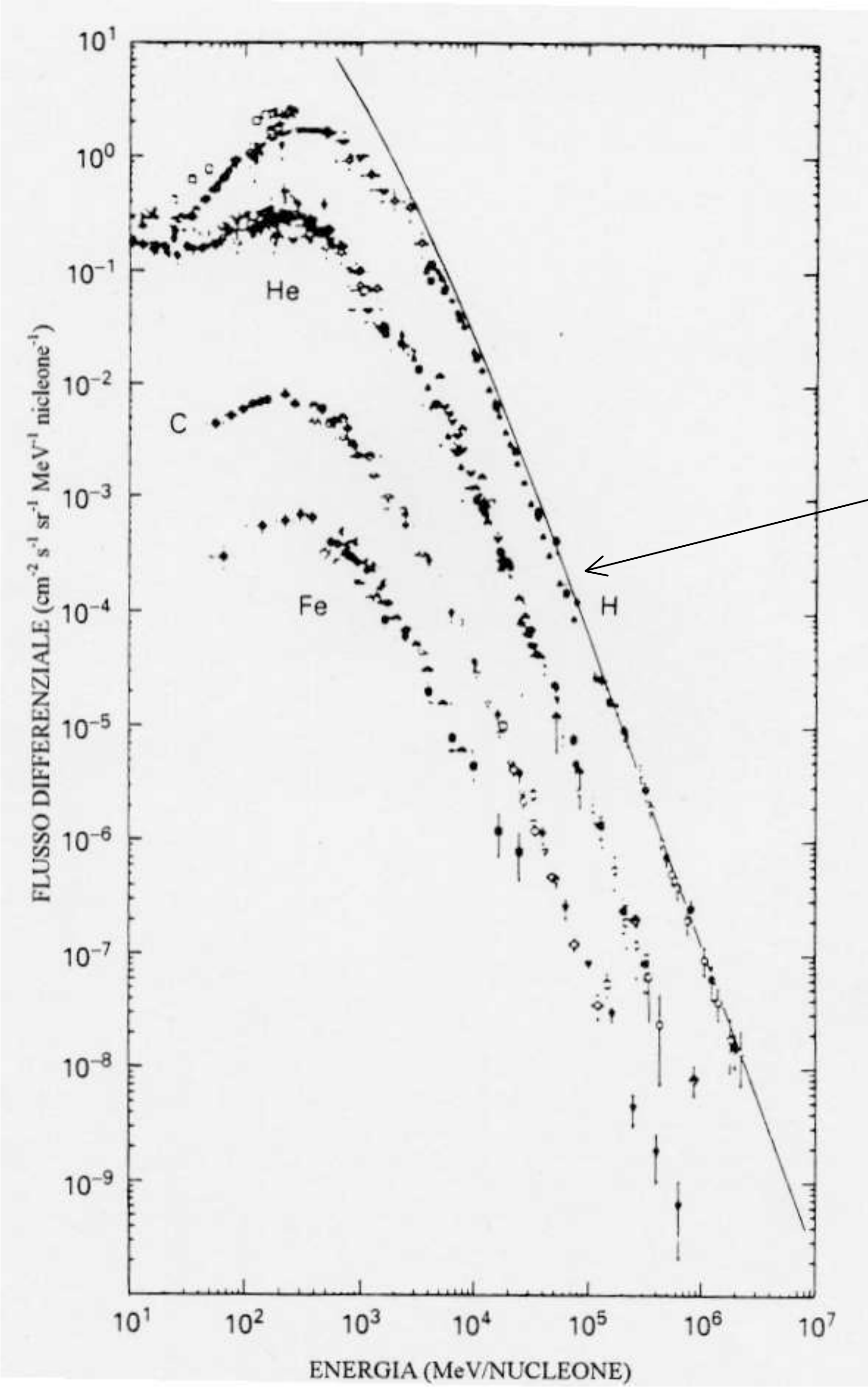
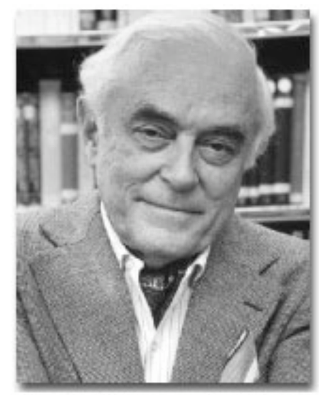
Outline

- A bit about cosmic rays
- ATIC spectrum (e- + e+)
- HESS spectrum (e- + e+)
- Pamela e+/(e- + e+)
  - An evaluation



All primary components have similar spectra

$dN/dE \propto E^{-2.7}$



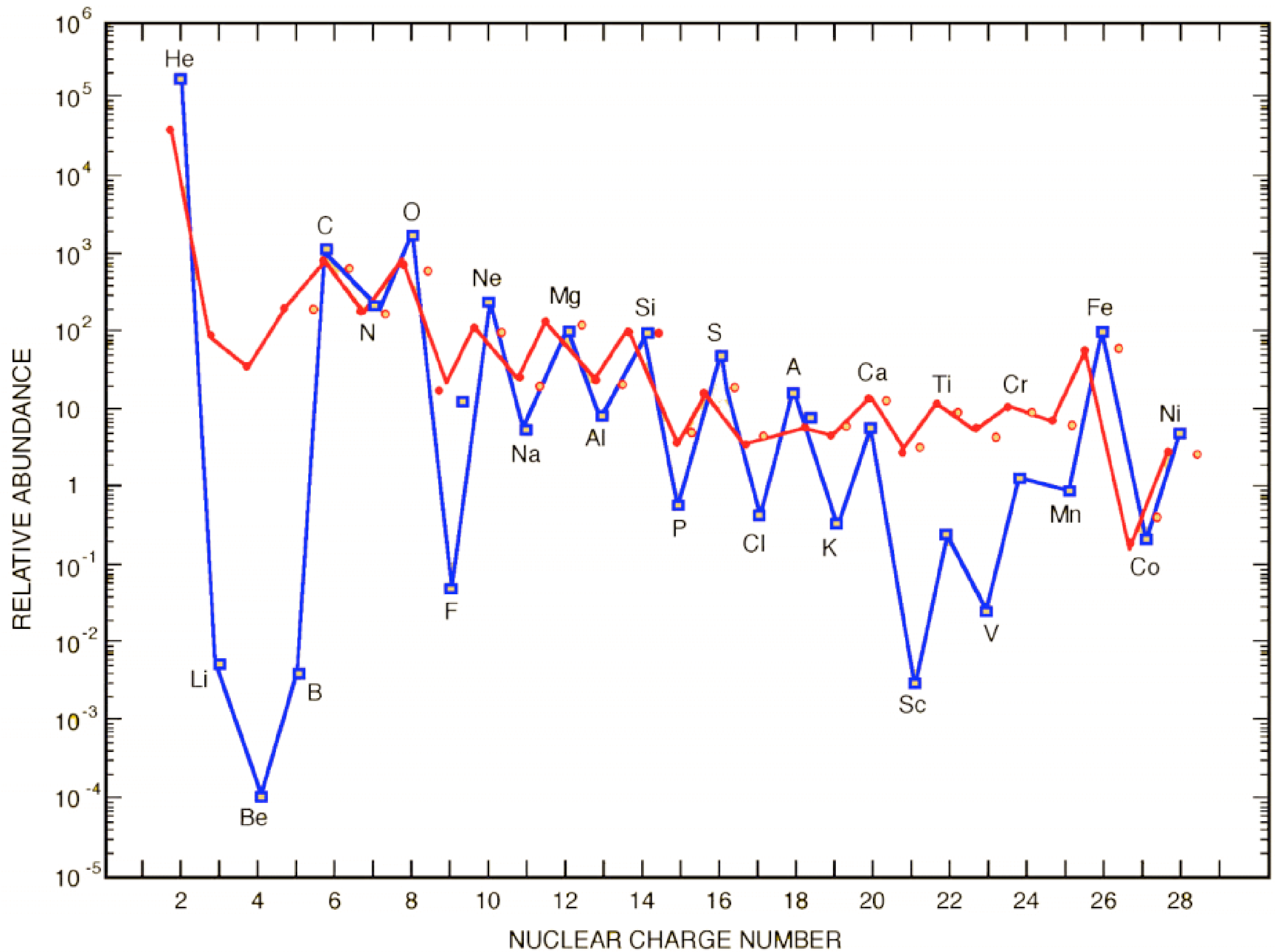
John Simpson
The U. of Chicago

Cosmic ray nuclear abundances

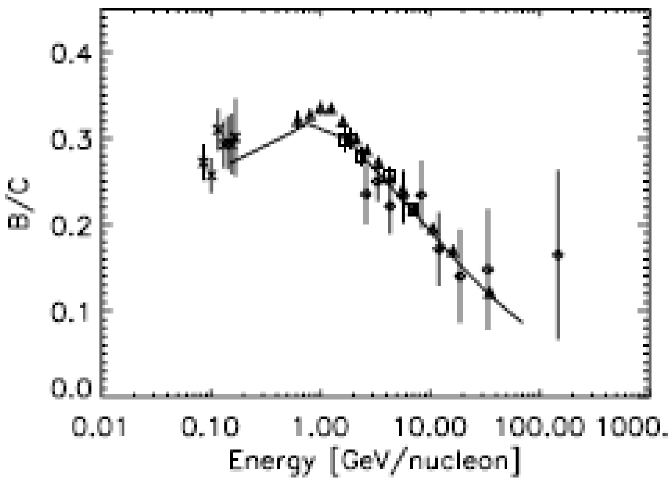
Freier, Ney, Oppenheimer: 1948, discovered **heavy nuclei** in cosmic rays

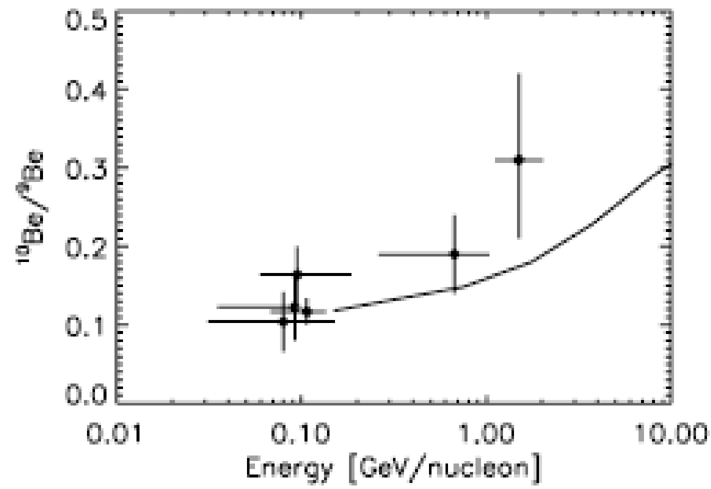
Cosmic Rays

Solar system material



Cosmic ray lifetime





Target to make Be, B from C: 5-10 g/cm^2
Decreases with energy

Fractional survival of radioactive nuclides ^{10}Be => lifetime >10^7 years

^{10}Be 1/2 life = 1.5 x 10^6 years

Time to leave the galaxy (10 kp) at c = 10^4 years,
combined with the >10^7 year actual lifetime in galaxy
=> Cosmic rays must be diffusively trapped in the galaxy
by magnetic scattering

Data summary from Büsching et al. 2005, ApJ, **619**, 314

Cosmic ray energy requirements

The local energy density of cosmic rays is
$\sim 1 eV/cm^3 = 1.6 \times 10^{-12}$ erg/cm^3

V_{galaxy} * (energy density) / lifetime => 1.3×10^{41} ergs/s

Supernova estimated to release (1-2) x 10^{51} erg
or at 1 SN per 30 years (1-2) x 10^{42} ergs/s

Stellar winds (1-2) x 10^{41}erg/s

Circumstantial evidence => Supernova, however
The acceleration process must be **~10%** efficient at converting this energy into cosmic rays!

What is the source spectrum of cosmic rays?

- Observed $dN/dE = kE^{-\alpha}$
- Diffusion out of galaxy

$$D(R,\beta) = \frac{1}{3}\lambda(R)\beta c$$

$$\lambda(R) = \lambda_0 \left[R/R_0 \right]^{\delta}$$

- Source $dN/dE = kE^{-\alpha+\delta}$

See talk by Igor Moskalenko

Observed index α is 2.7

What is δ?

Observed 0.6±0.1
Theory 1/3=0.33
(Kolomogorov turbulence)

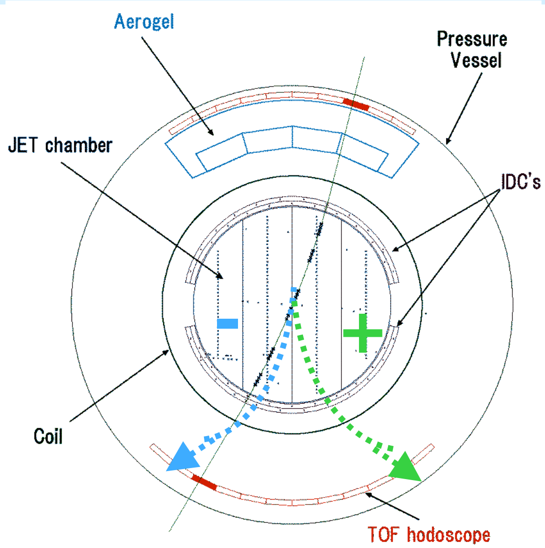
We don't know; it depends on how much 2nd order Fermi acceleration takes place in the ISM.

Source spectral index is unknown but expected by theory of shock acceleration to be between 2.1 and 2.4

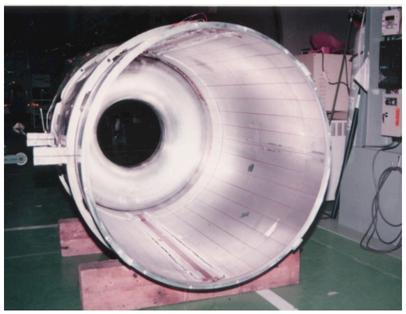
Measurement Technique

Particle identification by mass and charge

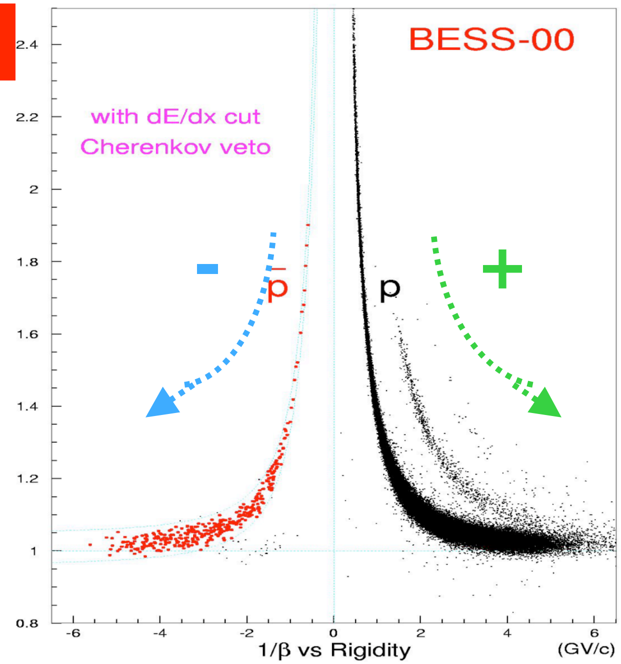
Charge-sign from deflection direction



Warm bore solenoid
B~1 Tesla +/-3%
Drift chambers
dx~150microns



β^{-1}



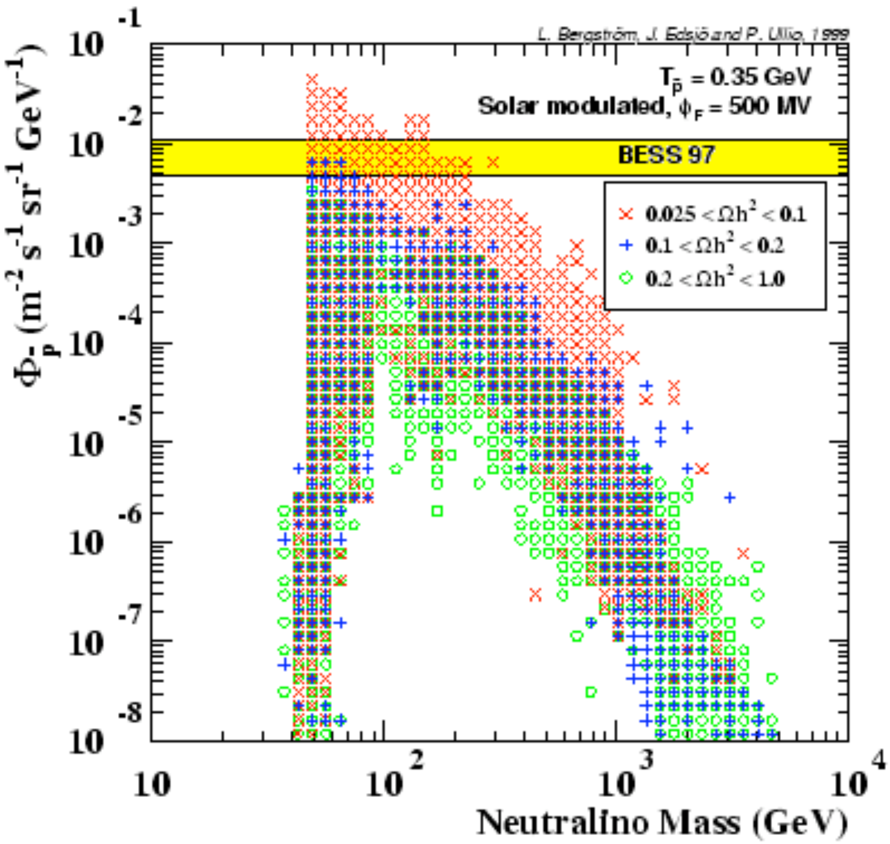
Rigidity (R = pA/Ze)

- Superconducting magnetic-rigidity spectrometer (B~1Tesla)
  - measures momentum per unit charge or rigidity (pA/Ze)
- Precision time-of-flight system: measures velocity and charge
- Silica-aerogel Cherenkov detector: background rejection

$$m = \frac{RZe}{\gamma\beta c}$$

Dark Matter Searches

BESS has limited the allowable parameter space for dark matter supersymmetric particles
Bergström, Edsjö & Ullio, ApJ 526, 215, (1999)



Disallowed models above

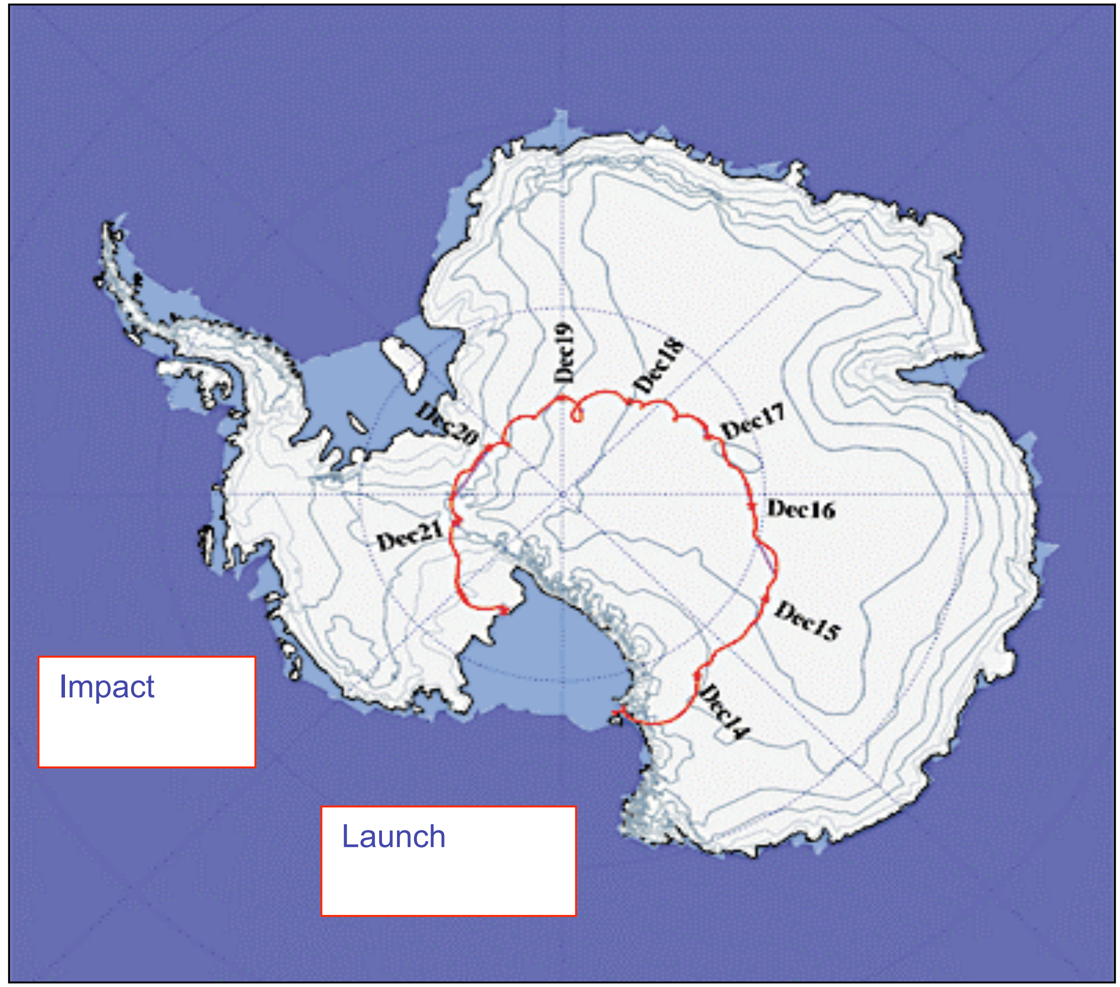
BESS '97 limit

Allowed models below

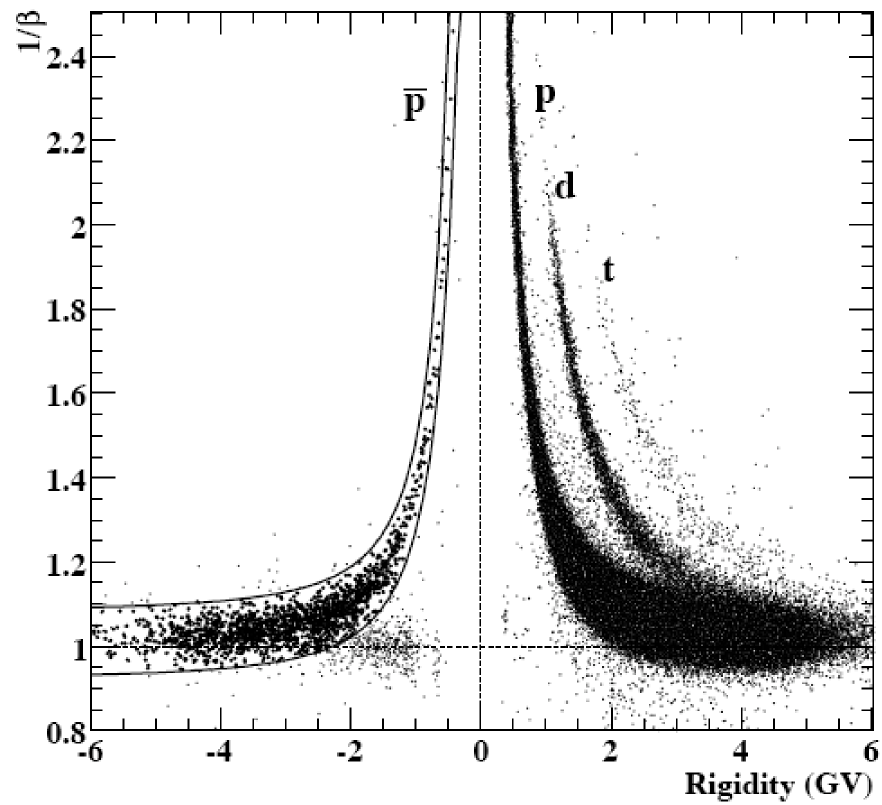
BESS limited models with $0.05 < \Omega_\chi < 0.25$
They tend to be Gaugino-like models

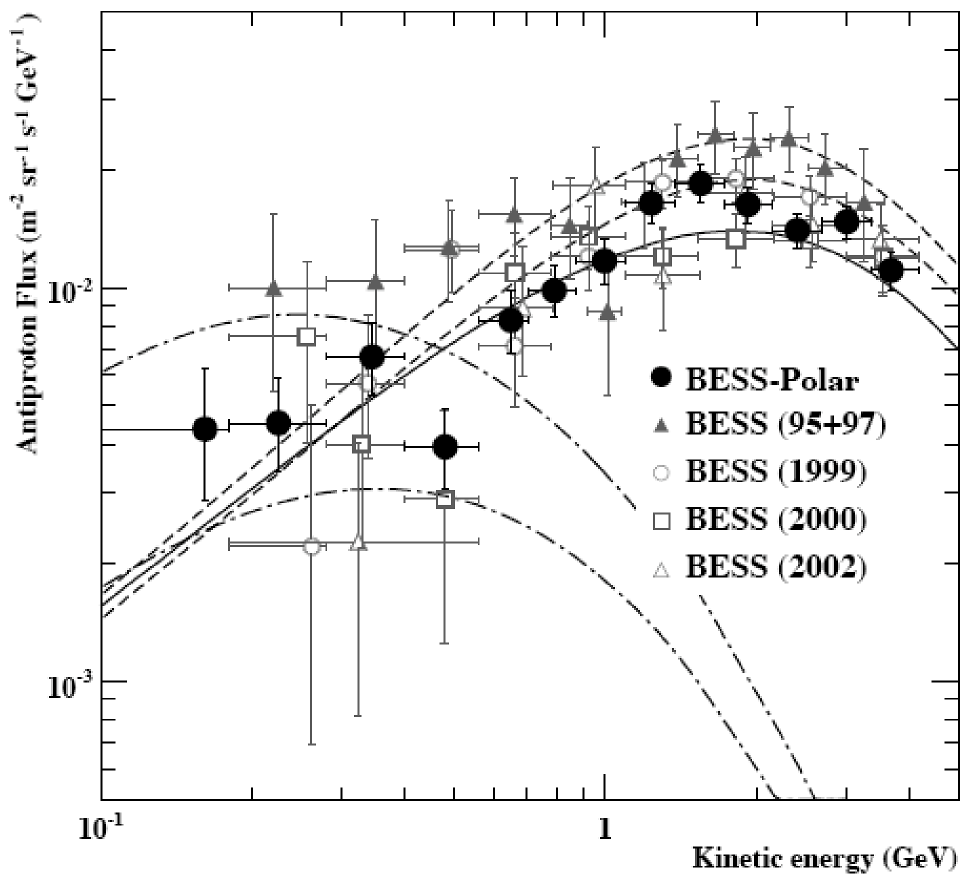
BESS in Antarctica Dec. 2004

- Flight duration
  8 days, 13 hours
- Payload mass
  1950 kg
- Power
  700 watts
- Altitude 37-39 km
  4-5 g/cm^2



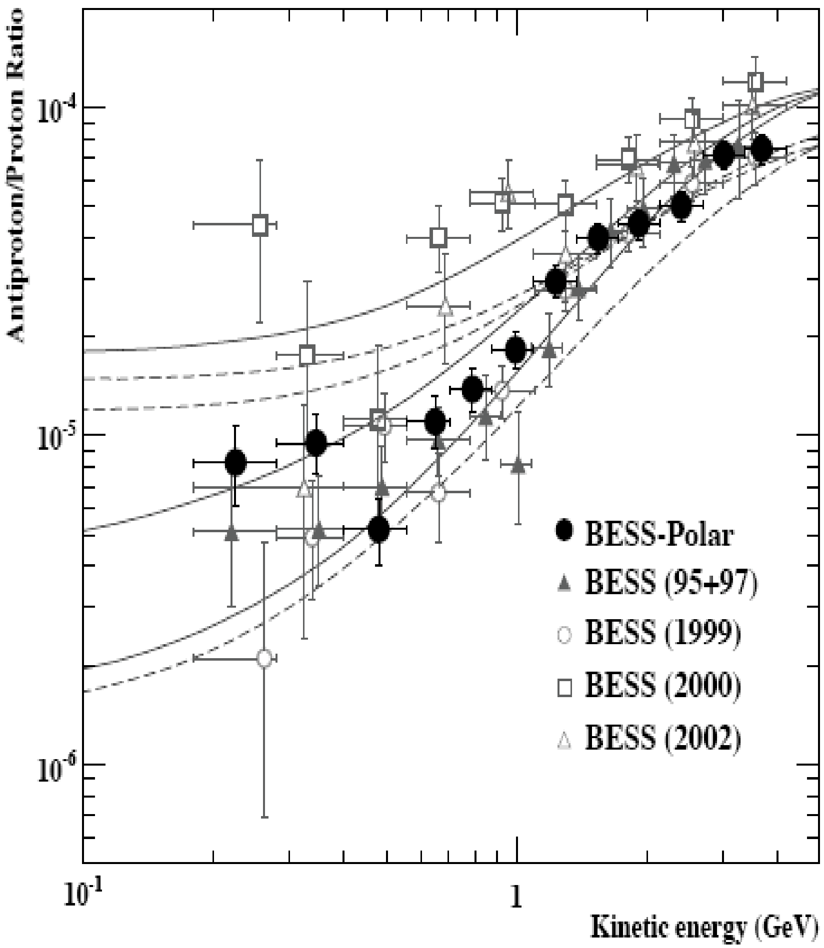
BESS Polar 2004

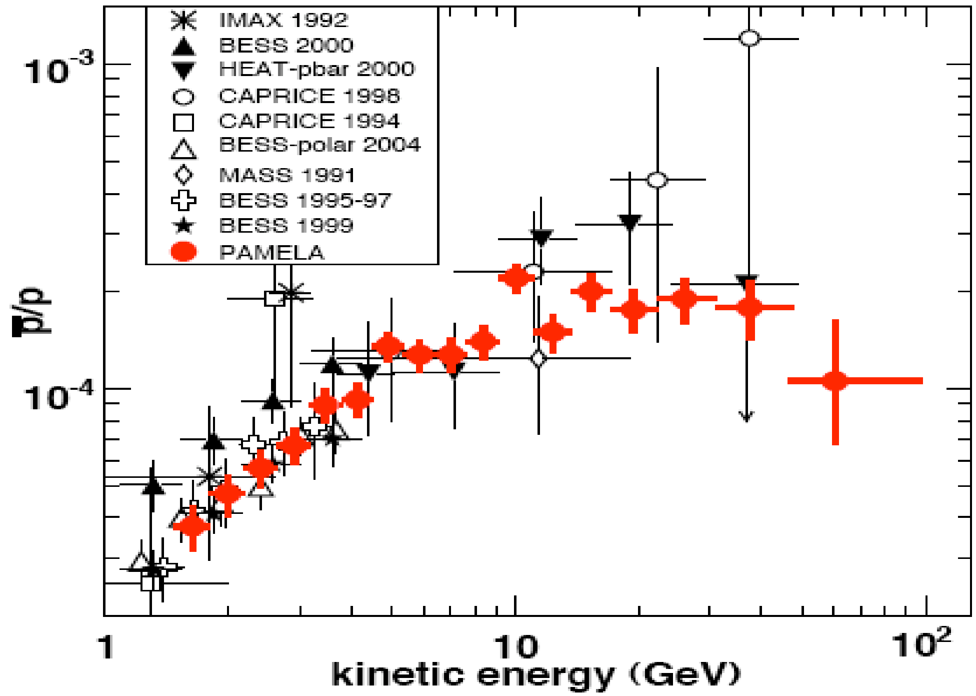




Abe et al., 2008, Nucl. Phys. B., in press, arXiv:0805.1754v1 [astro-ph]

antiproton/proton ratio

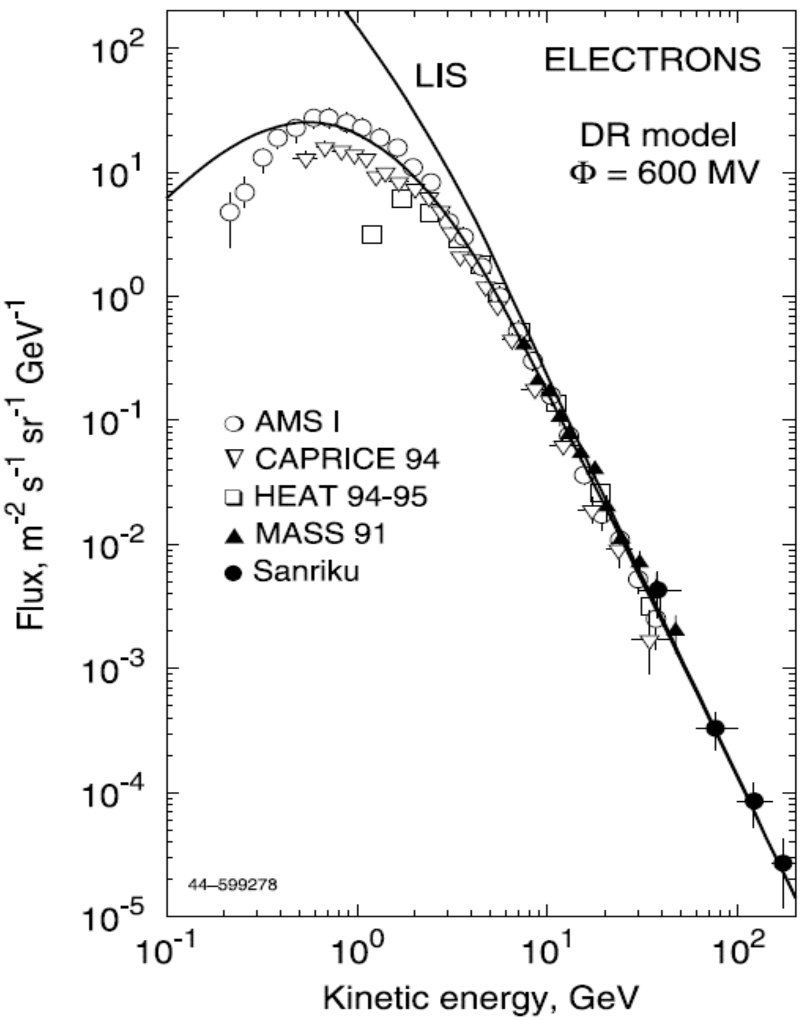


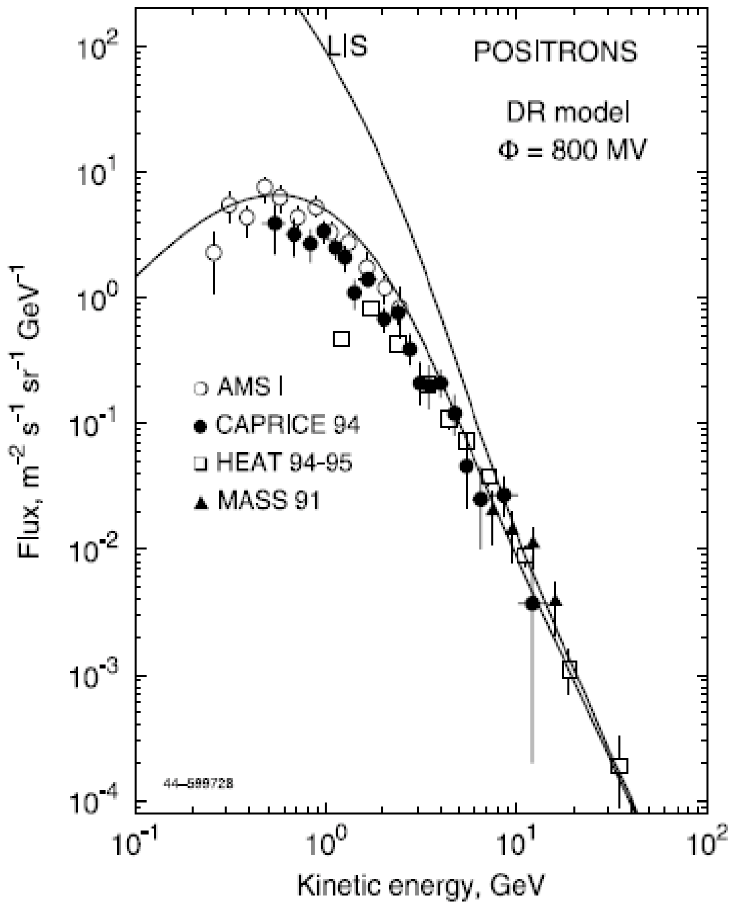


Adriani et al., 2008, Phys. Rev. Lett., submitted, arXiv:0810.4994v1 [astro-ph]
Abe et al., 2008, Nucl. Phys. B., in press, arXiv:0805.1754v1 [astro-ph]

Cosmic Ray data: e- and e+

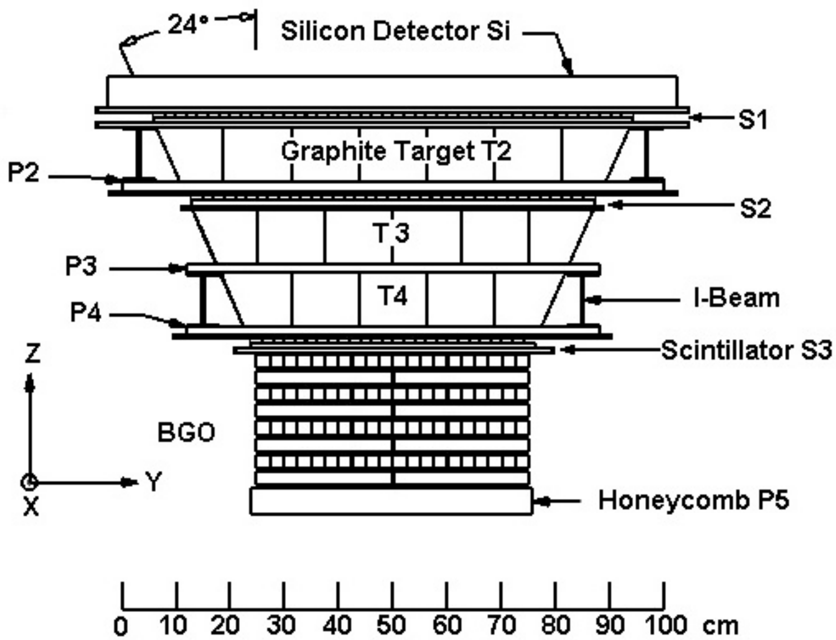
Summary by Moskalenko et al. 2002





e+/(e+ + e-) ~ e+/e- ~0.1

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-3); 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).

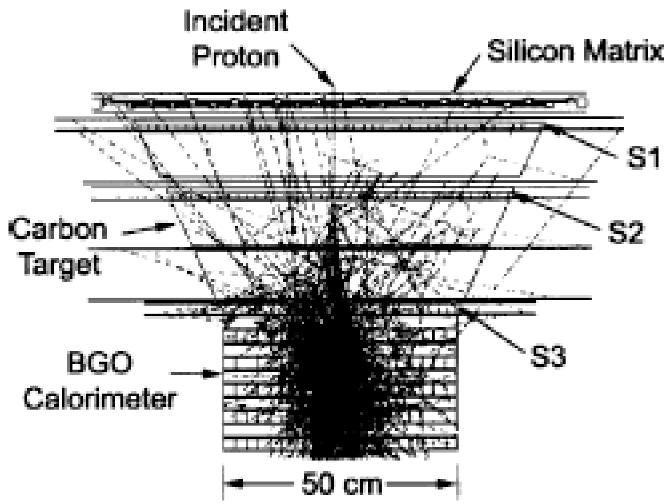
Data System: All data recorded on-board; 70 Gbyte disk (150 Gbyte for ATIC-4); LOS data rate – 330 kbps; TDRSS data rate – 4 kbps (6+ kbps for ATIC-3); Underflight capability (not used).

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

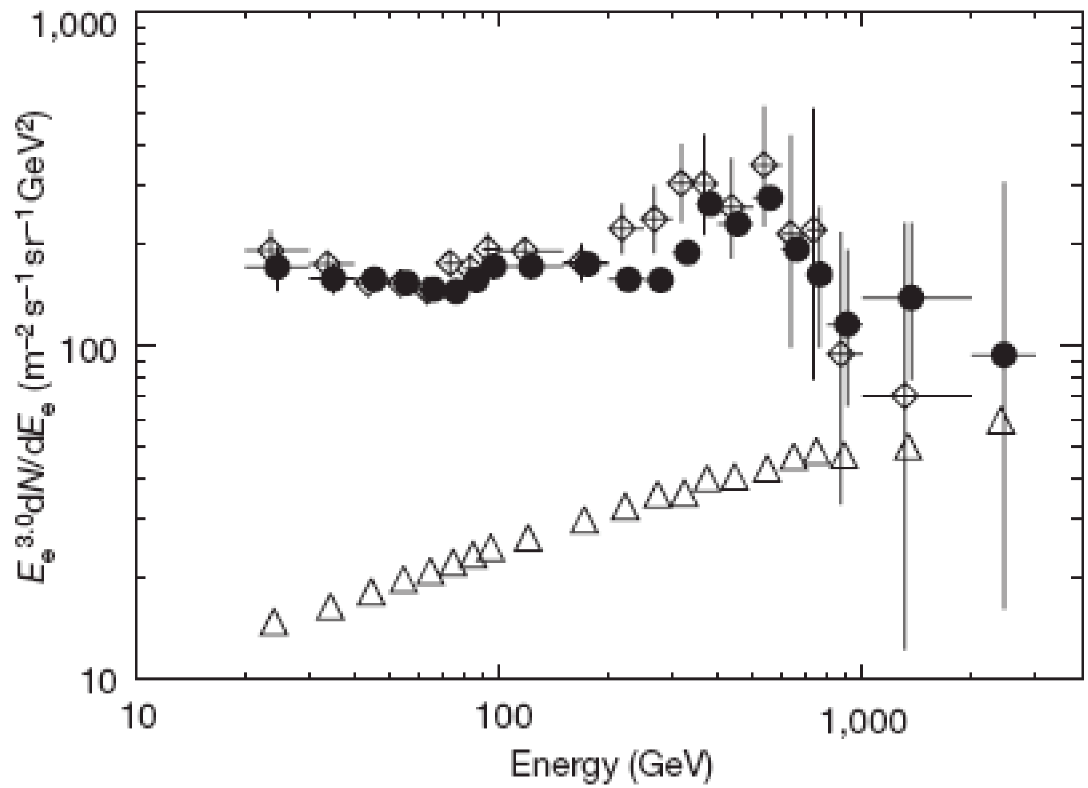
Geometry Factors: S1-S3: 0.42 m^2sr; S1-S3-BGO 6: 0.24 m^2sr; S1-S3-BGO 8: 0.21 m^2sr

ATIC electrons: 2 flights w/ estimated proton contamination



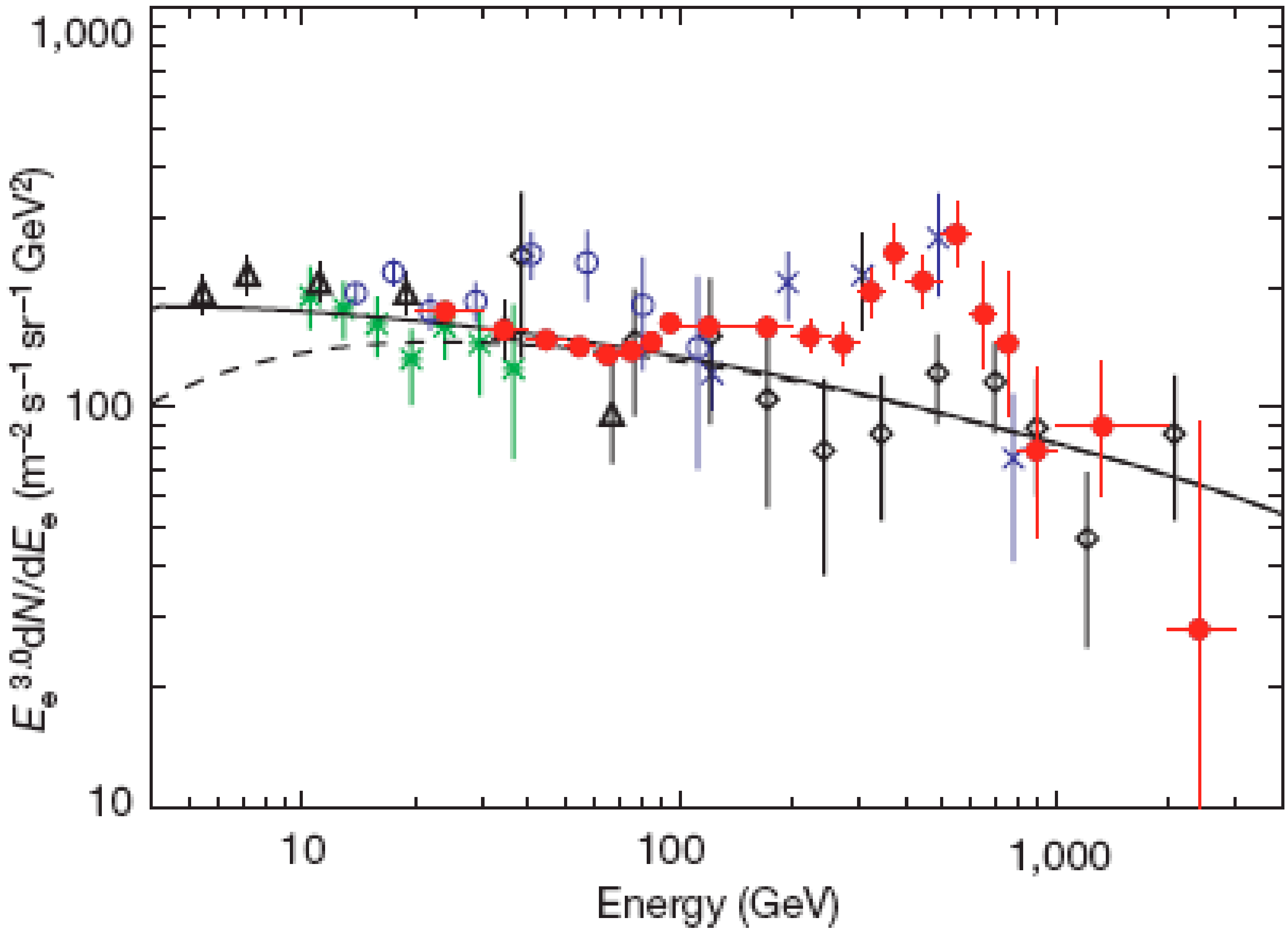
Guzik et al., 2004, Advances in Space Research, **33**, 1763

Wefel et al., 2008, Nature, **456**, p362



ATIC electrons

Wefel et al., 2008, Nature, **456**, p362



The ATIC electron results exhibits a feature

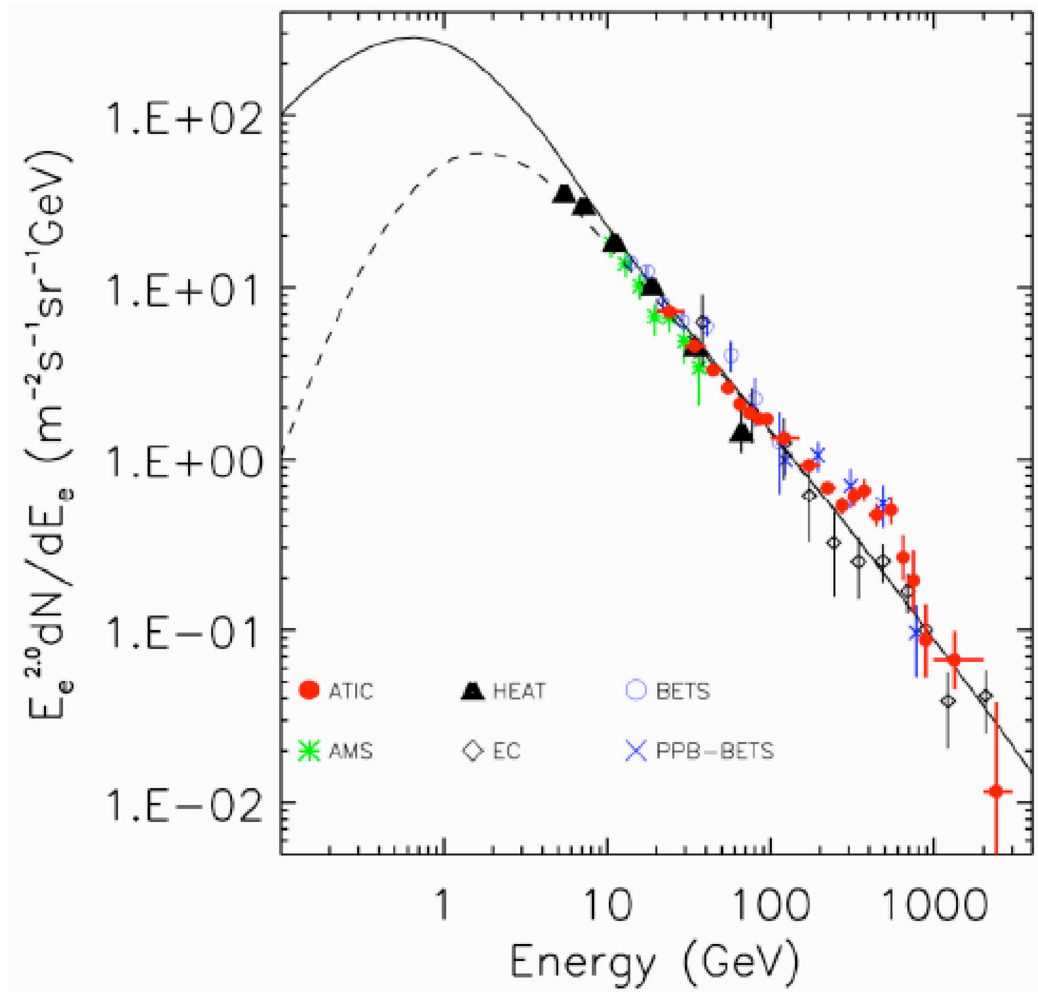
(e+ + e-)

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

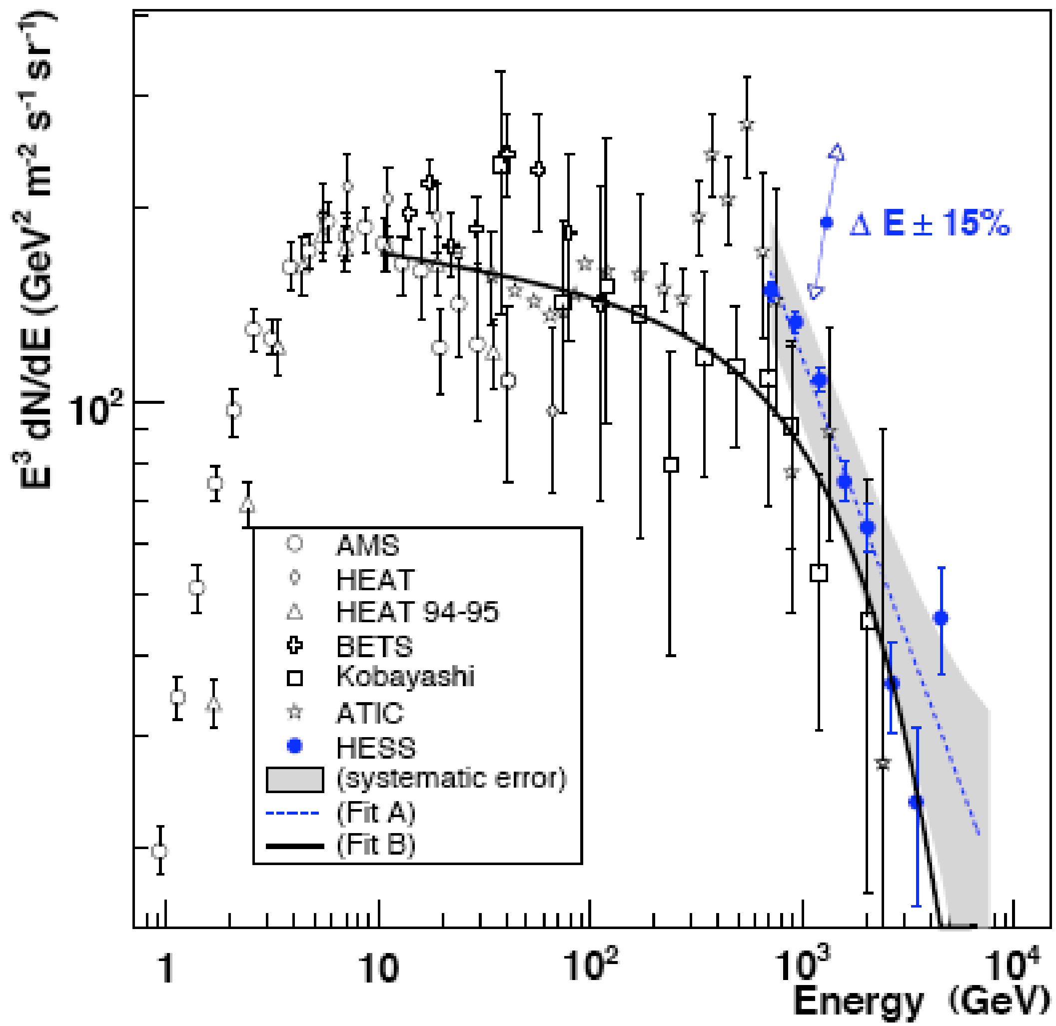


HESS electrons

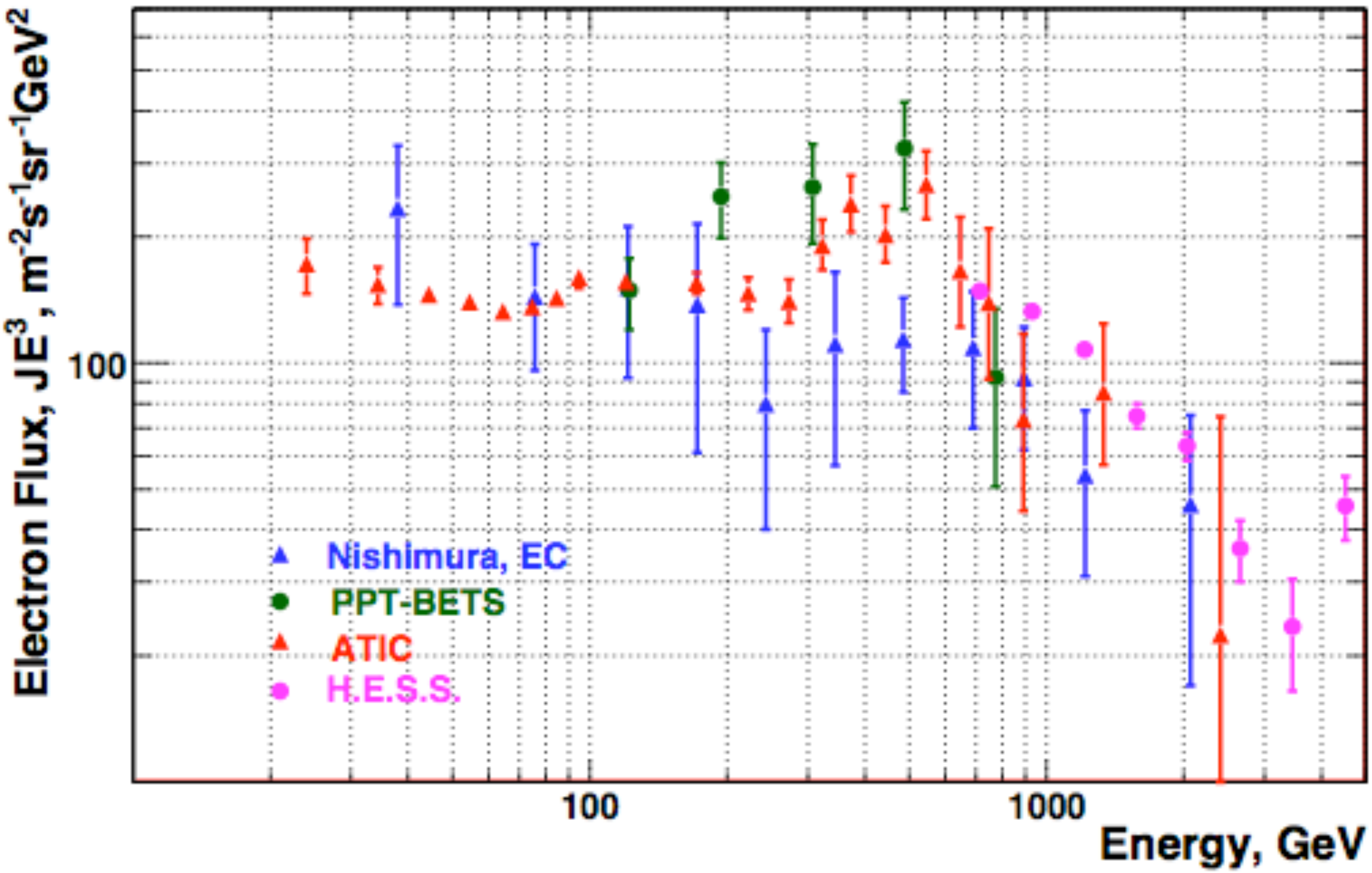
Power law fit $E^{-3.9}$

Black line:
Power law $E^{-3.05+/-0.02}$
with exponential cutoff
2.1 +/-0.3 TeV

Aharonian et al., 2008
Phys. Rev. Lett. in press
arXiv:0811.3894v1 [astro-ph]

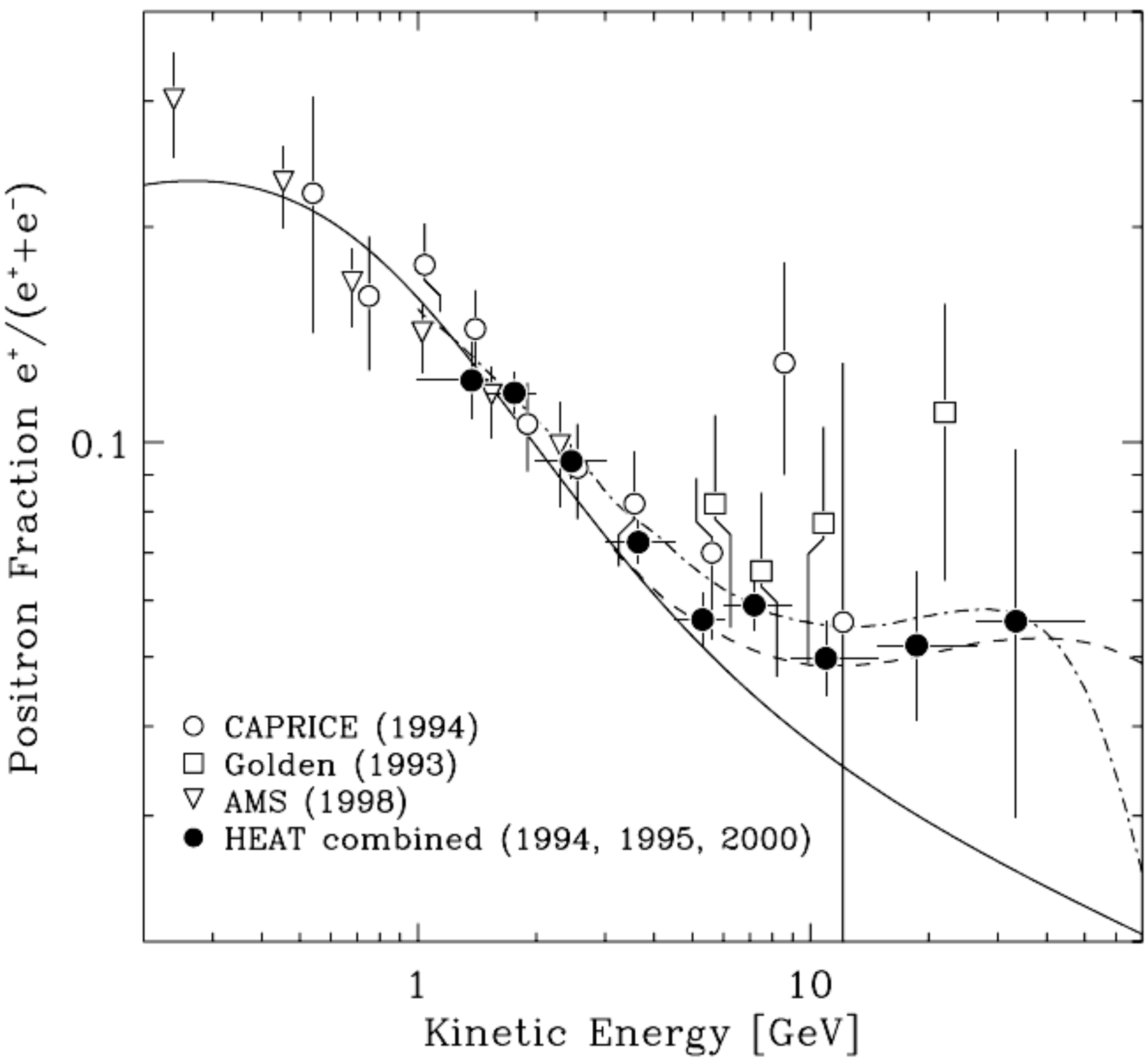


Cosmic ray electrons

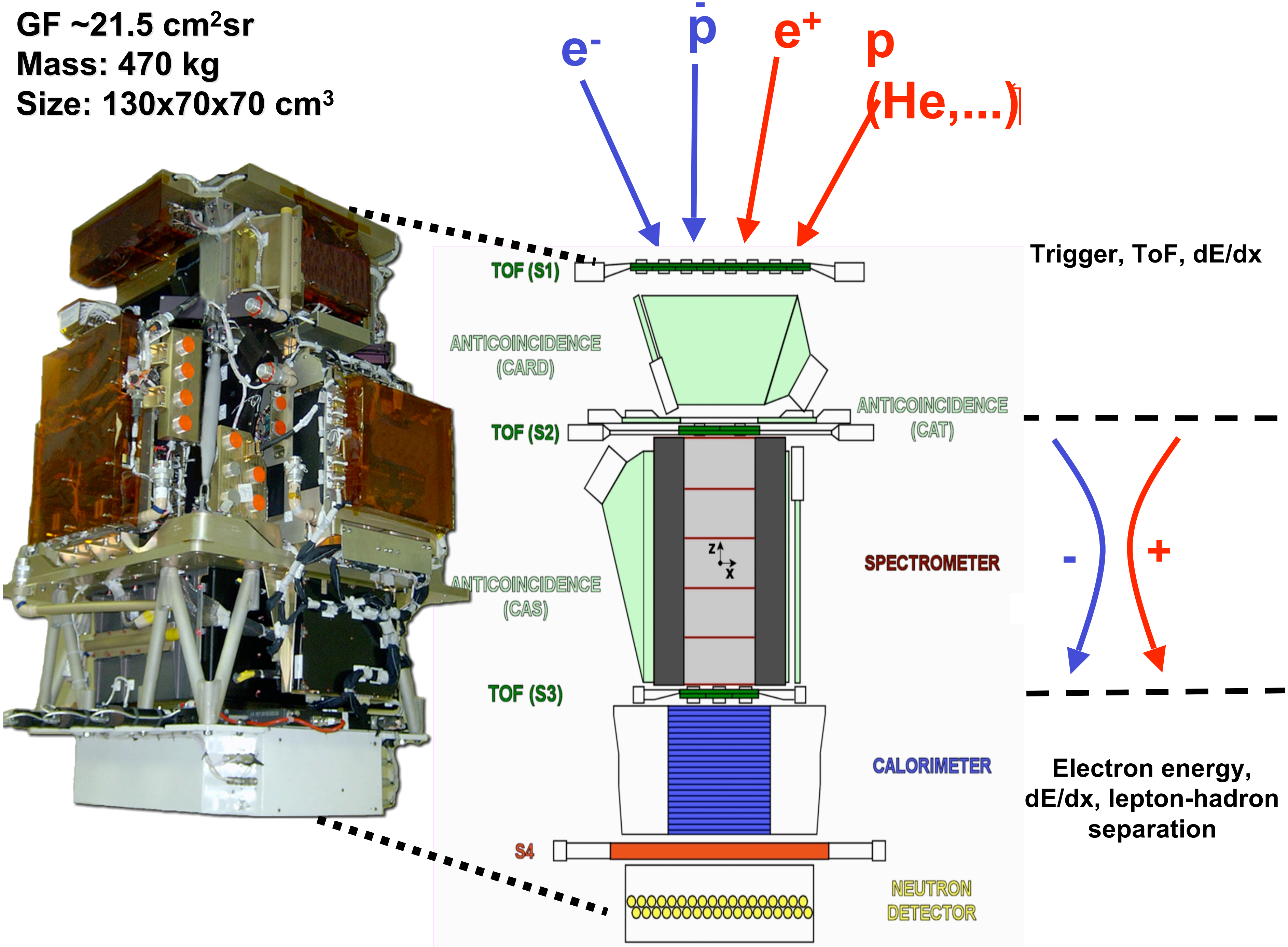


Positron Fraction

HEAT (Beatty et al., 2004, PRL, **93**, 241102)

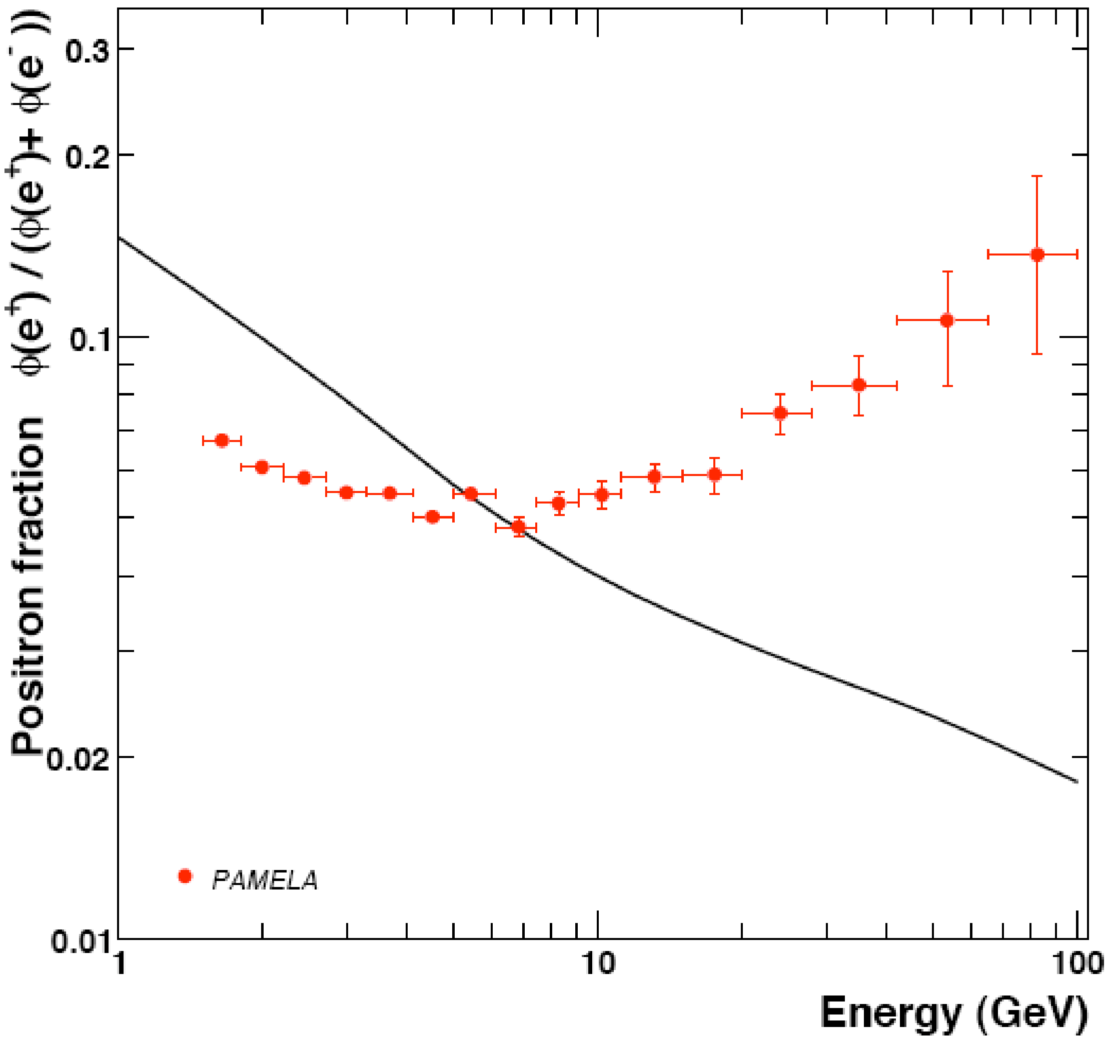


GF ~21.5 $cm^2 sr$
Mass: 470 kg
Size: 130x70x70 cm^3

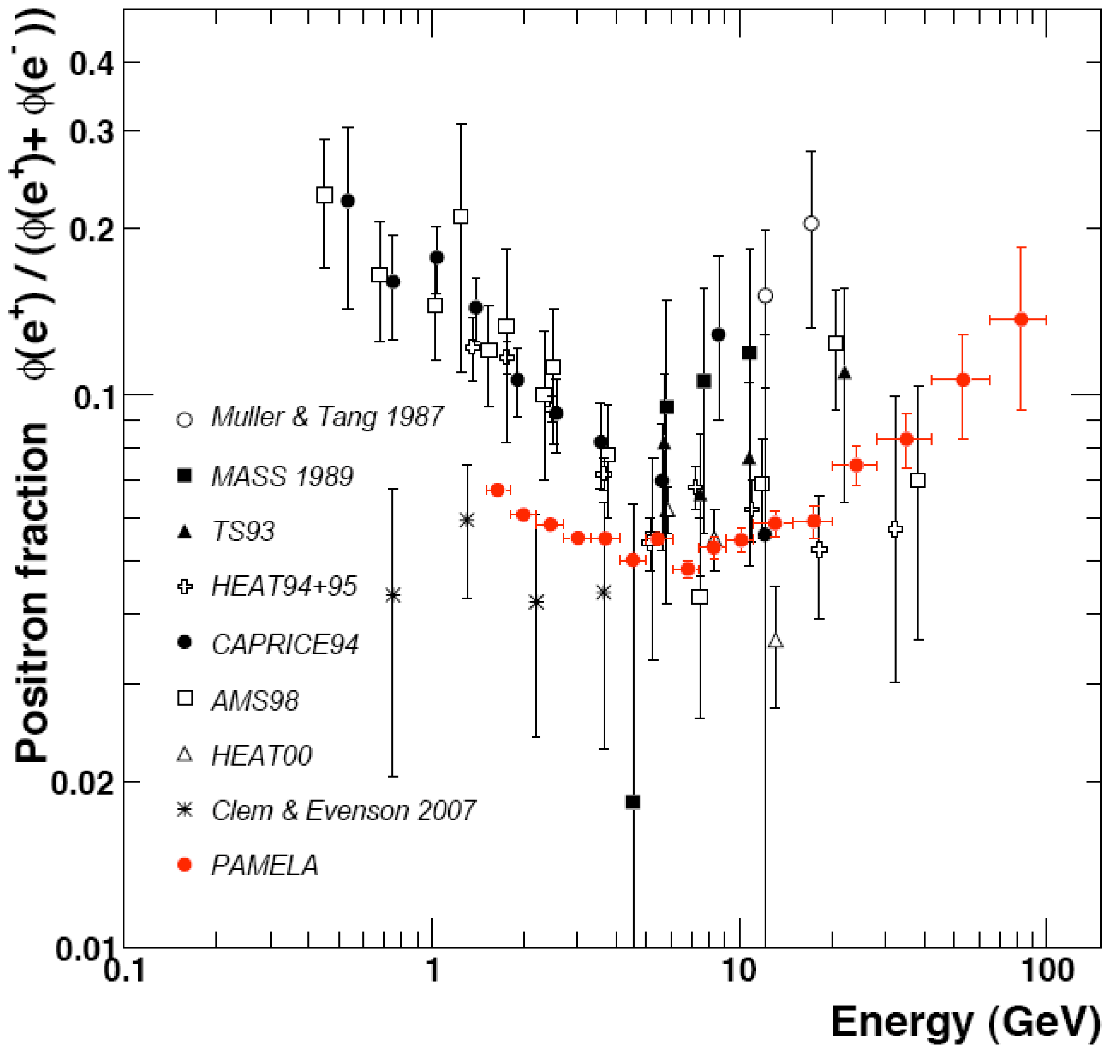


Pamela positron fraction

astro-ph
arXiv:0810.4995v1
28 Oct. 2008

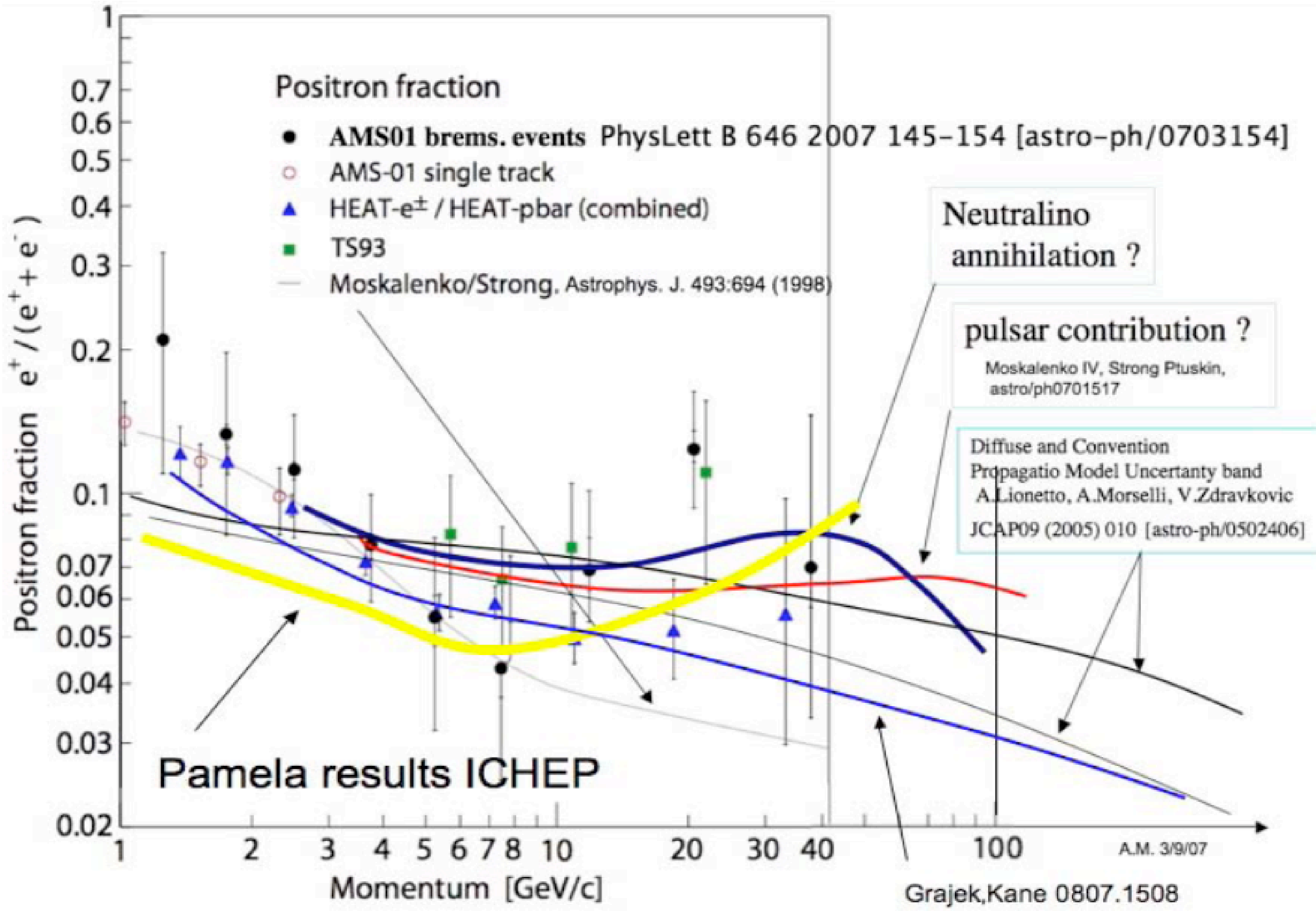


Pamela positrons

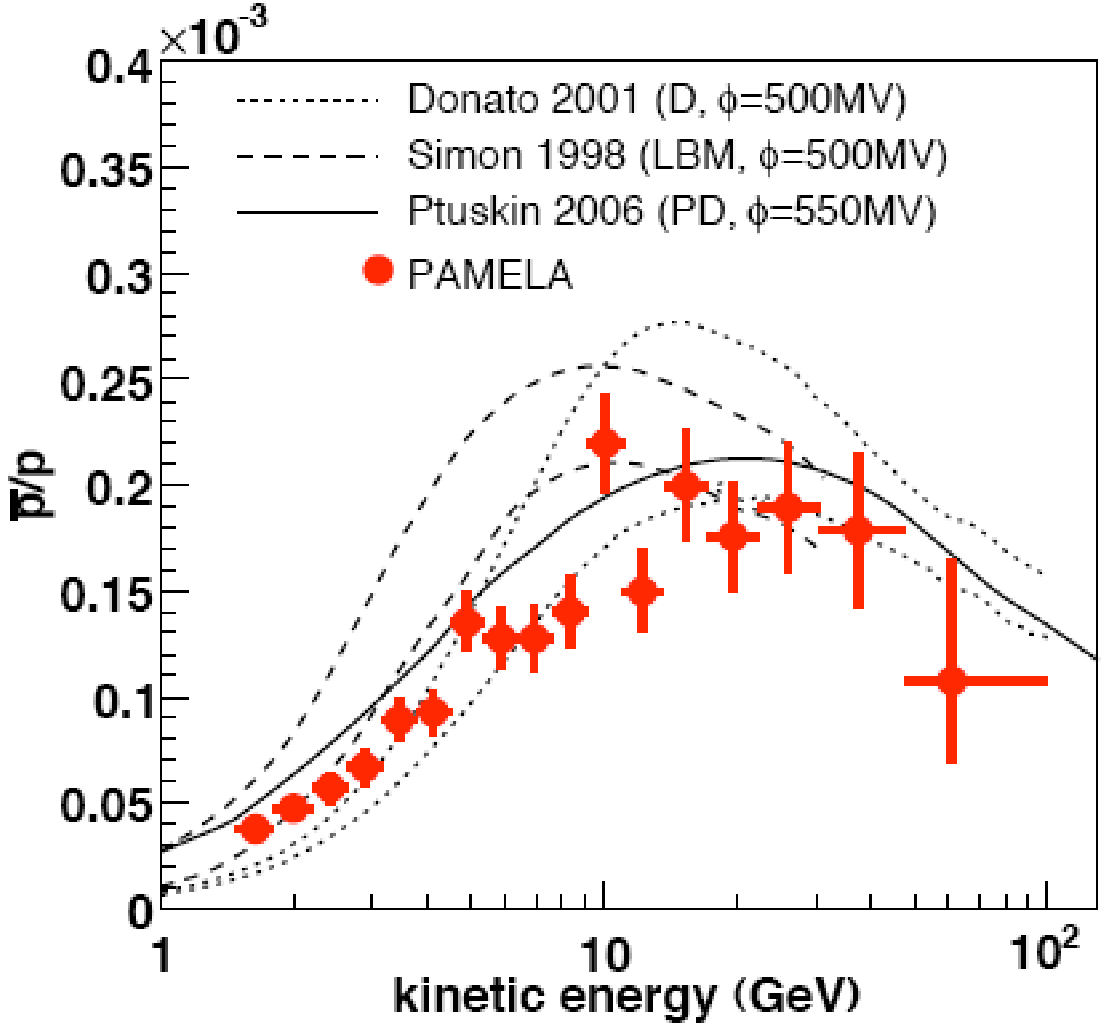


Adriani et al., 2008, submitted, Nature, arXiv:0810.4995v1 [astro-ph]

From Morselli et al. 2008 idm2008

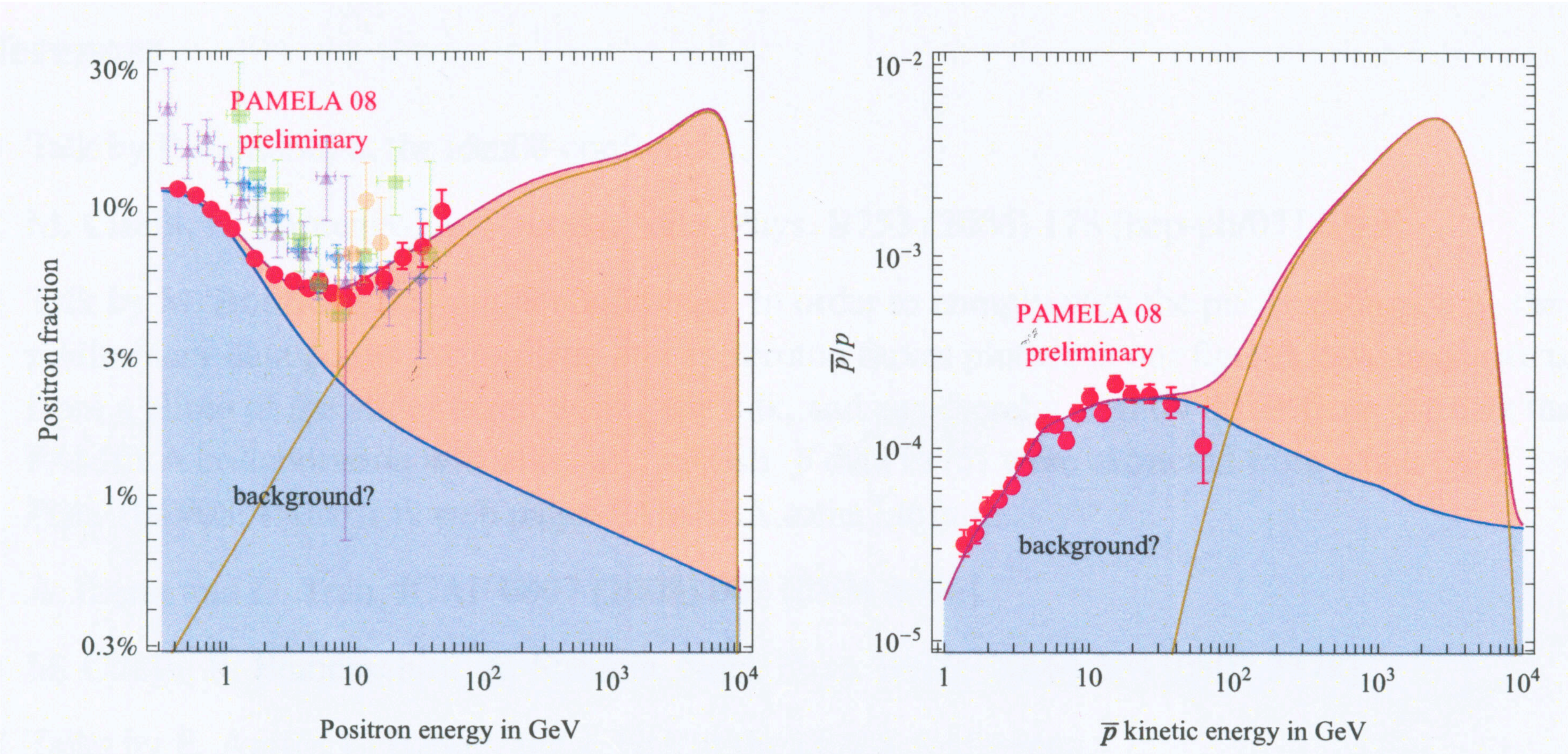


Pamela antiproton/proton ratio



Adriani et al., 2008, submitted, Phys. Rev. Lett., arXiv:0810.4994v1 [astro-ph]

Minimal Dark matter predictions and the Pamela positron excess
(Cirelli and Strumia 2008)
arXiv:0808.3867v1 astroph 28 Aug 2008



Data from photo of slide shown by Pamela team member
M. Boezio at idm2008 - identification of dark matter 2008

Cirelli and Strumia model

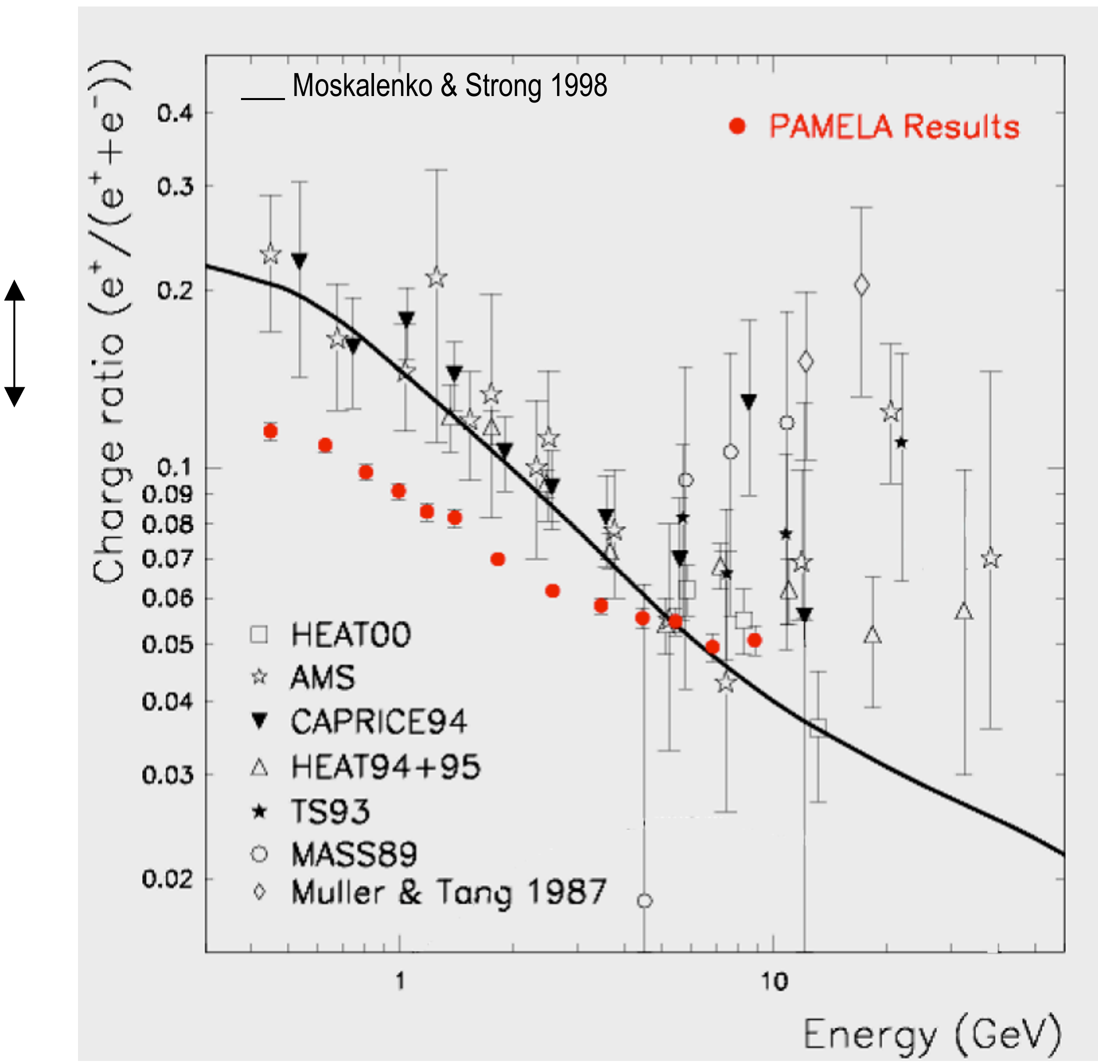
- Minimal dark matter (MDM)
  - one extra electroweak multiplet that is not already constrained by measurement
  - univocal predictions
  - M_d = 9.6 ±0.2 TeV fixed by mass of dark matter in the universe
- Flux(e+) α $E^{-(2.64\pm0.06)}$
- LAT would see hardening of the electron (e+ + e-) spectrum in the range 100-1000 GeV but no cutoff (cutoff is near 10 TeV).
- ATIC "feature" is inconsistent with this model.

arXiv:0808.3867v1 astro-ph 28 Aug 2008

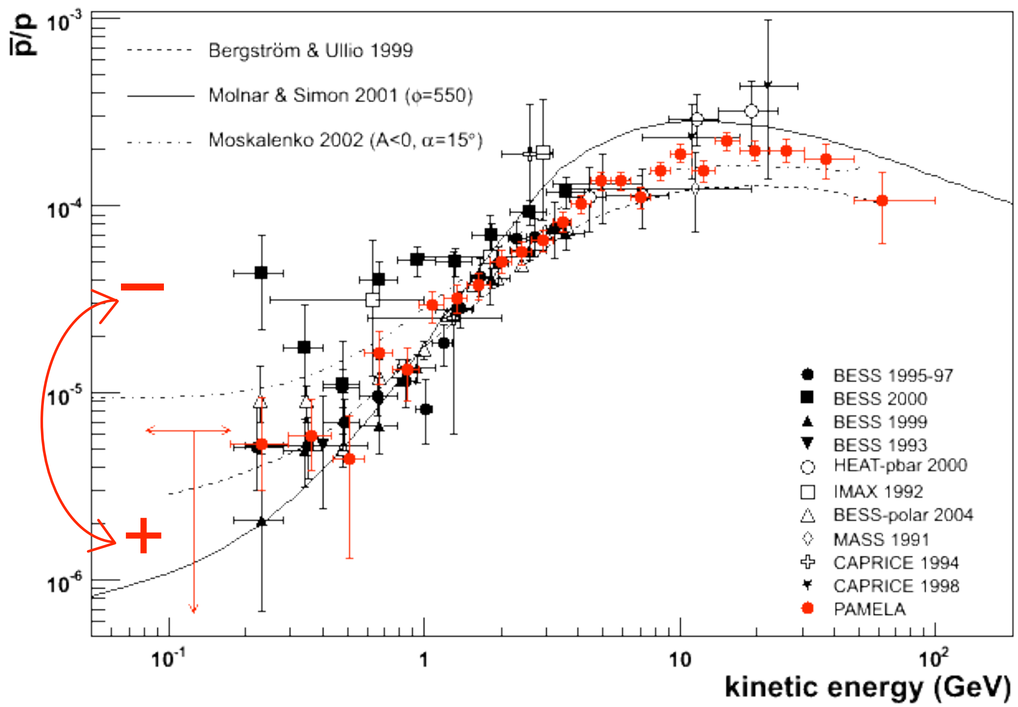
Positron charge fraction

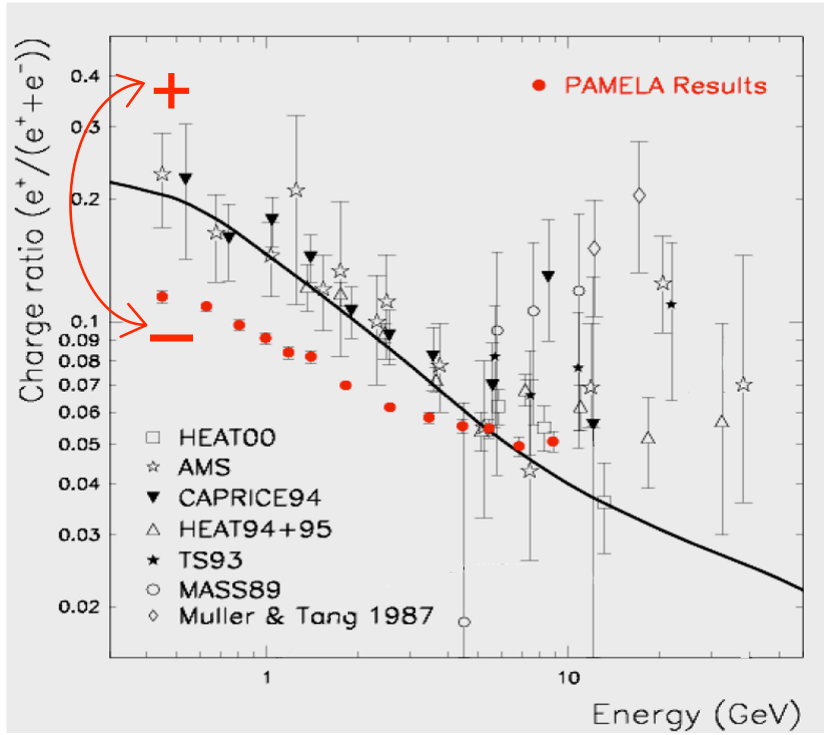
Charge sign dependent modulation effect?

statistical errors only, energy in the spectrometer



Charge dependent solar modulation

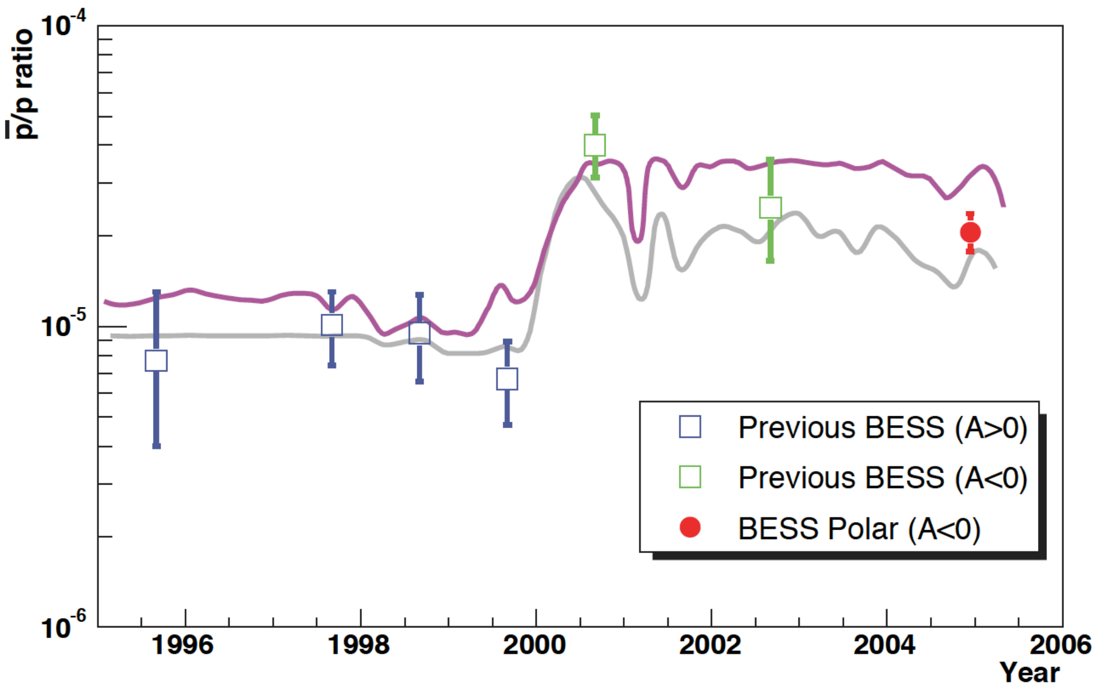




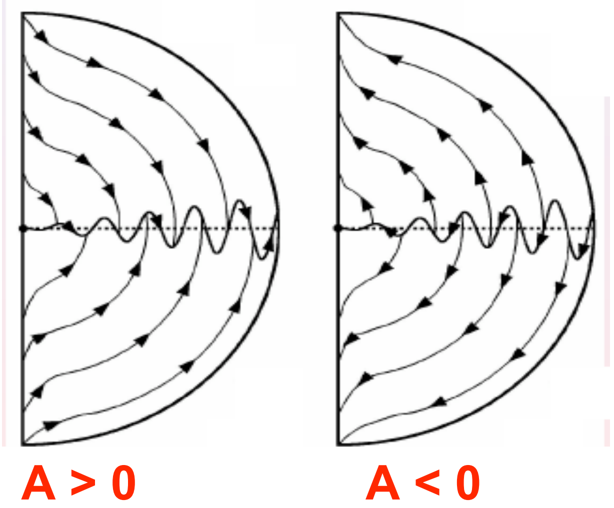
antiprotons/protons

positron fraction

Charge dependent solar modulation



Positive particles

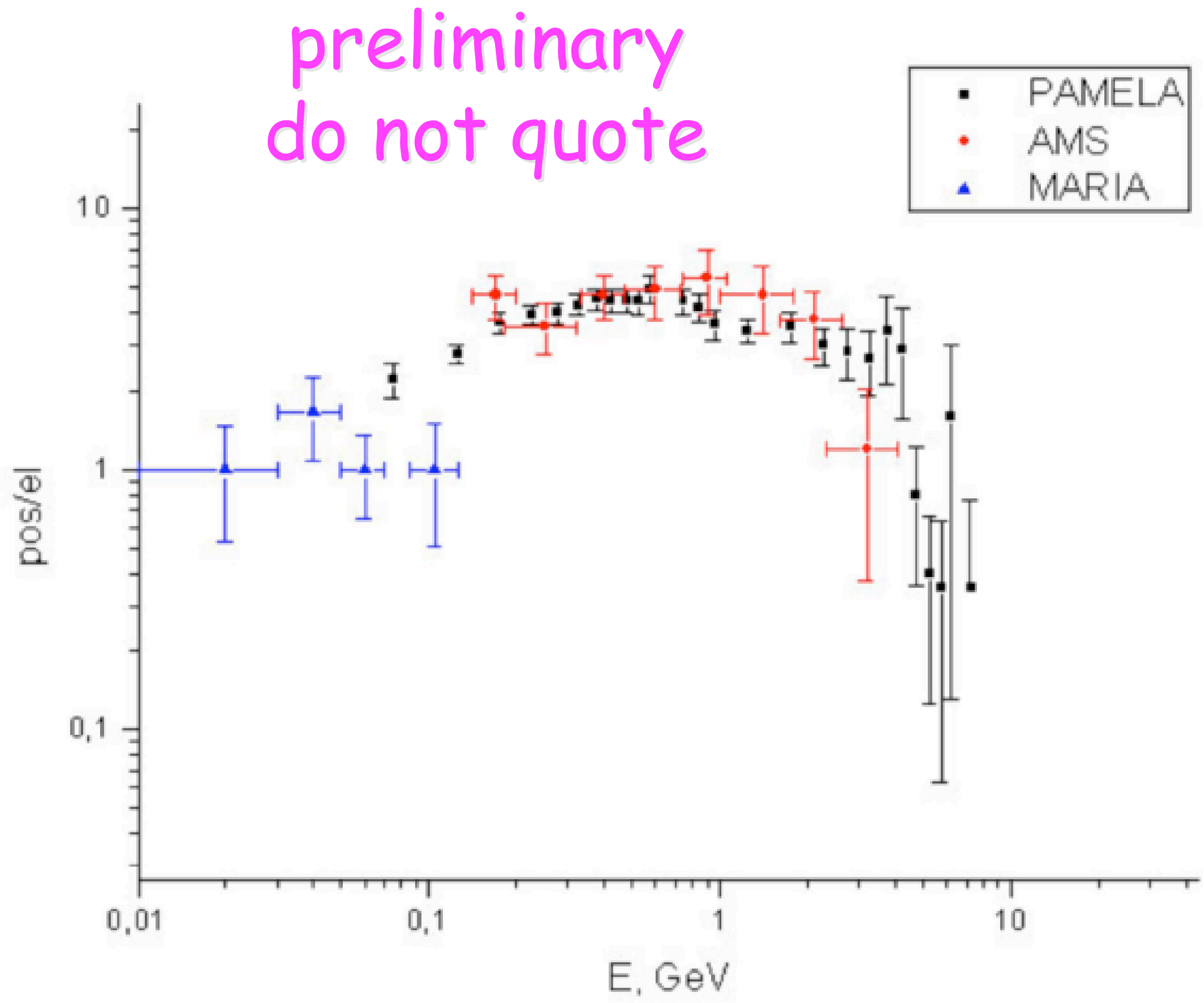


Bieber et al. PRL, 88, 4, 8 (1999) 674.

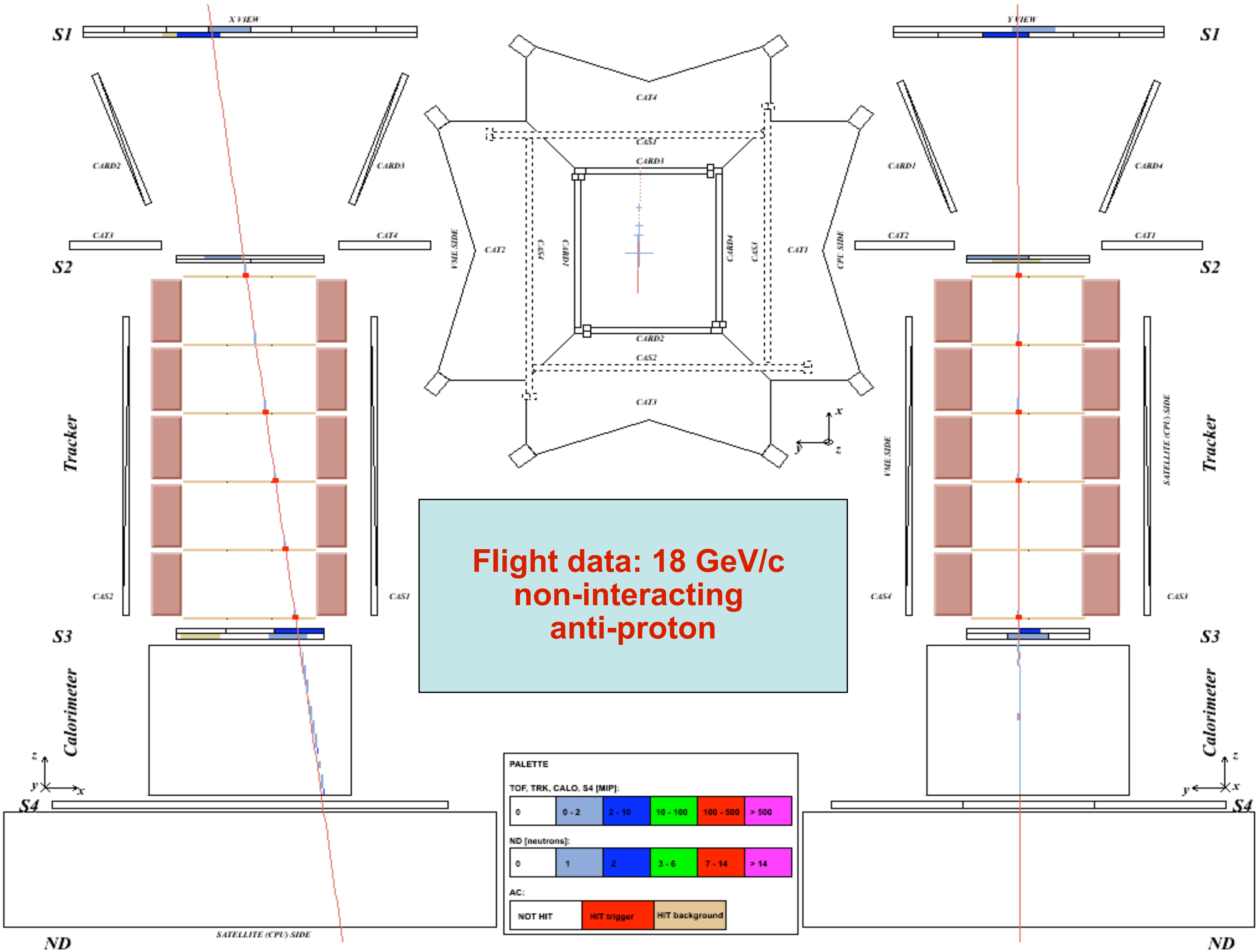
Moskalenko et al., APJ, 565 (2002) 280.

Negatively charged particles behave oppositely.

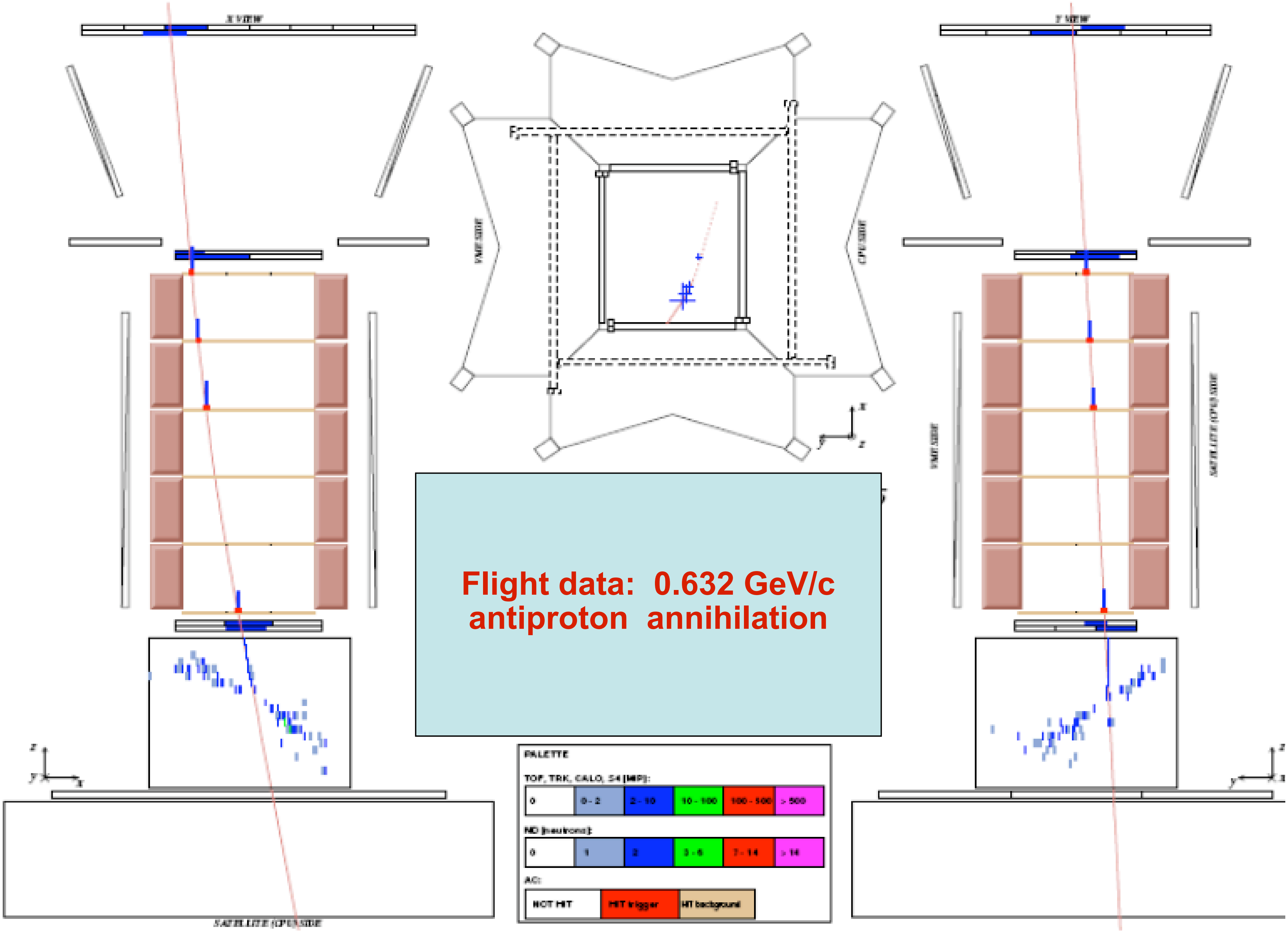
Pamela albedo e+/e- near equator

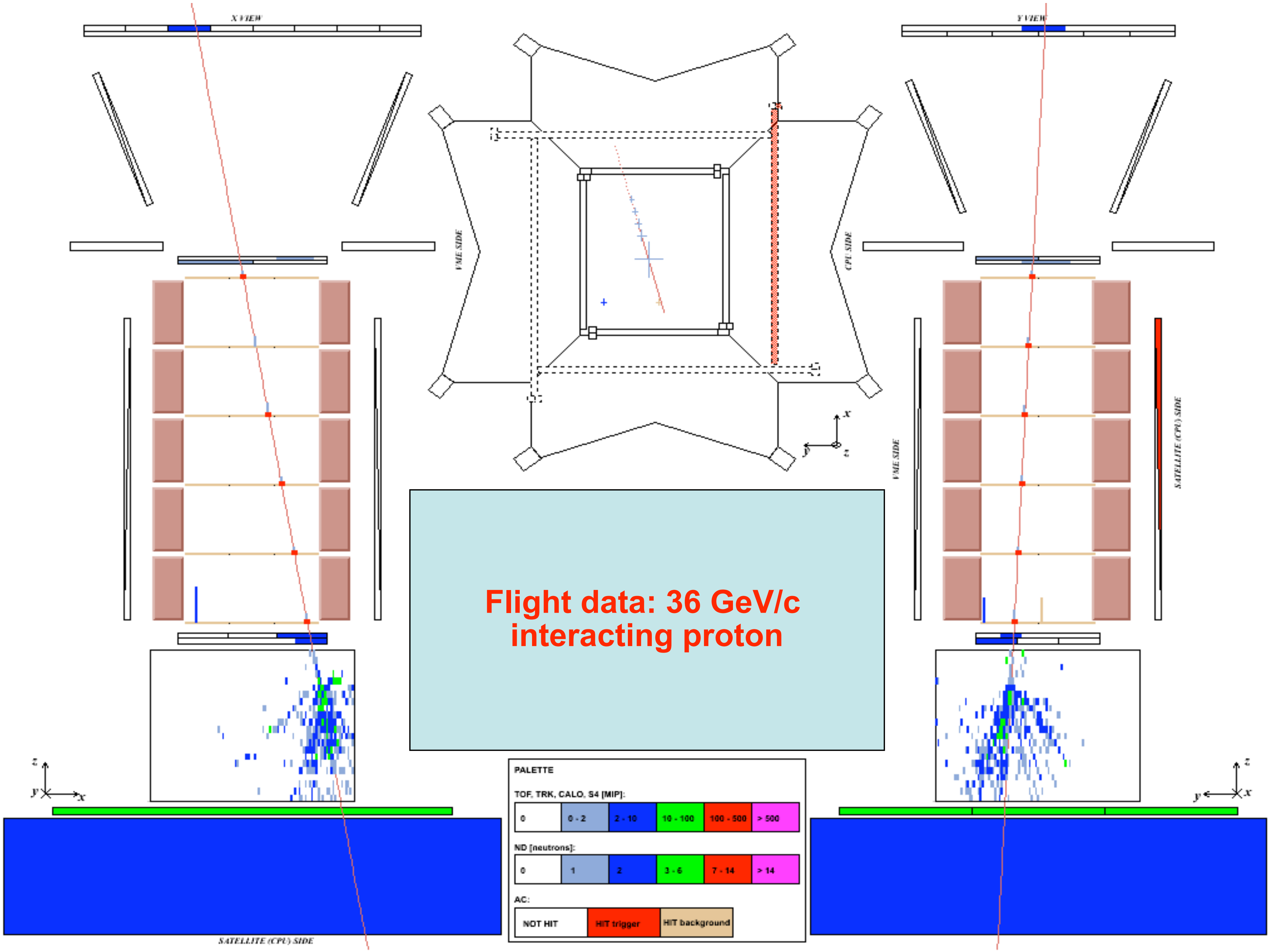


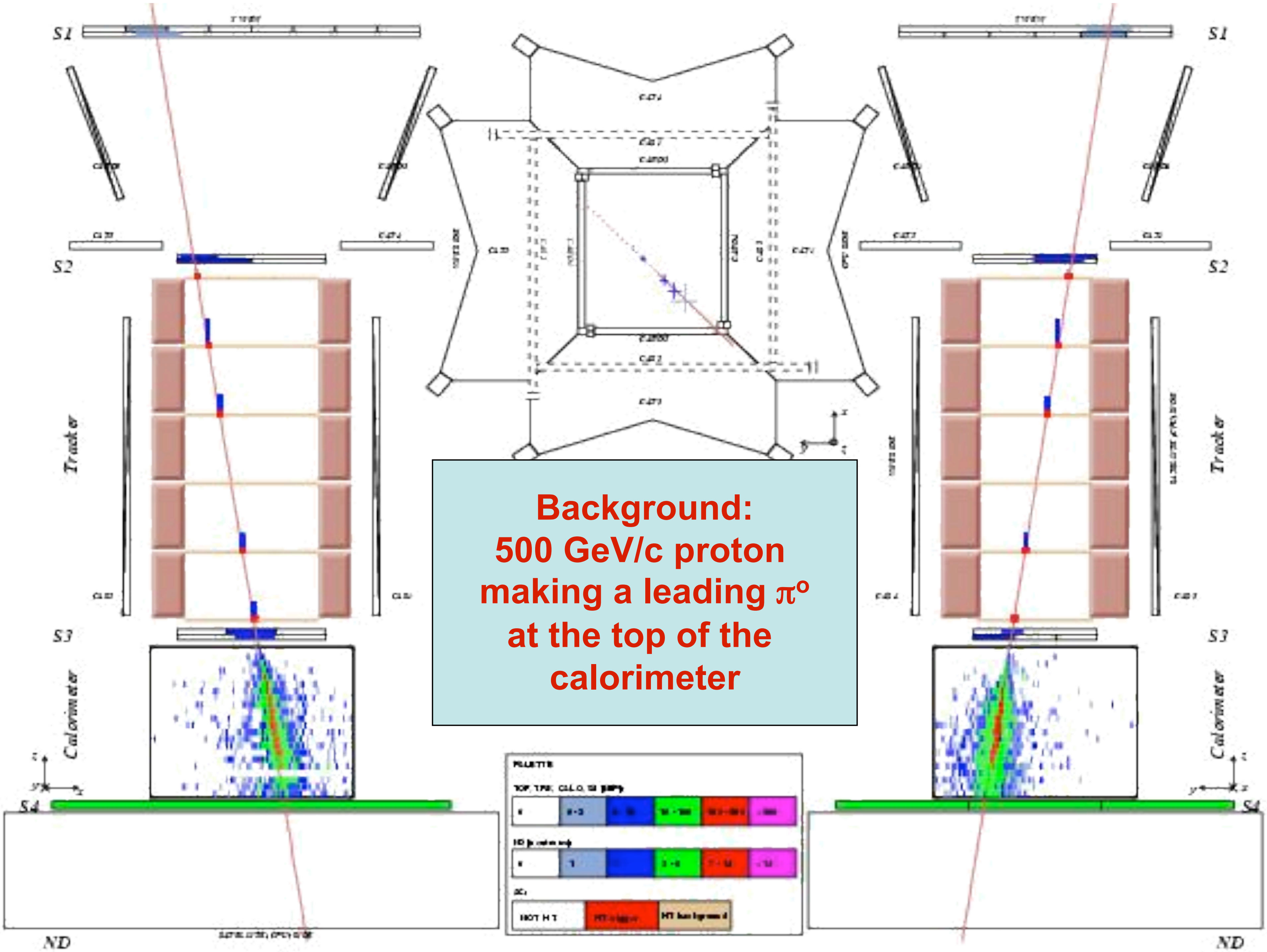
Good agreement with LAT background model



Flight data: 18 GeV/c non-interacting anti-proton


Flight data: 0.632 GeV/c
antiproton annihilation
X VIEW
Y VIEW
VME SIDE
CPU SIDE
SATELLITE (CPU) SIDE
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC:
NOT HIT
HIT trigger
HIT background


Flight data: 36 GeV/c interacting proton
X VIEW
Y VIEW
VME SIDE
CPU SIDE
SATELLITE (CPU) SIDE
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC:
NOT HIT
HIT trigger
HIT background



**Background:
500 GeV/c proton
making a leading π^o
at the top of the
calorimeter**

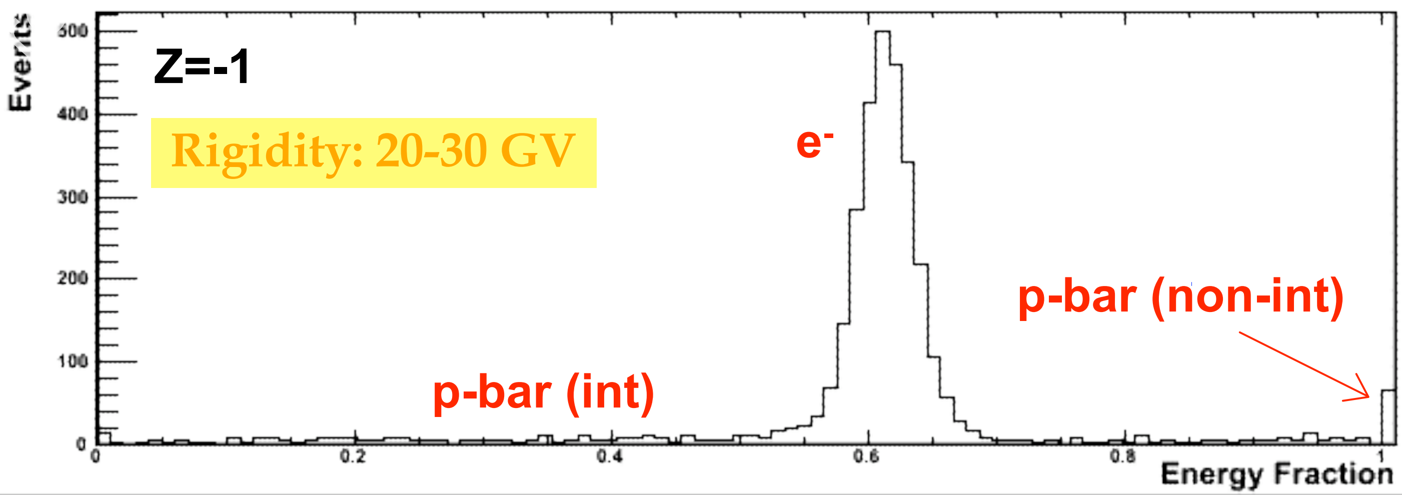
Claimed rejection 10^5

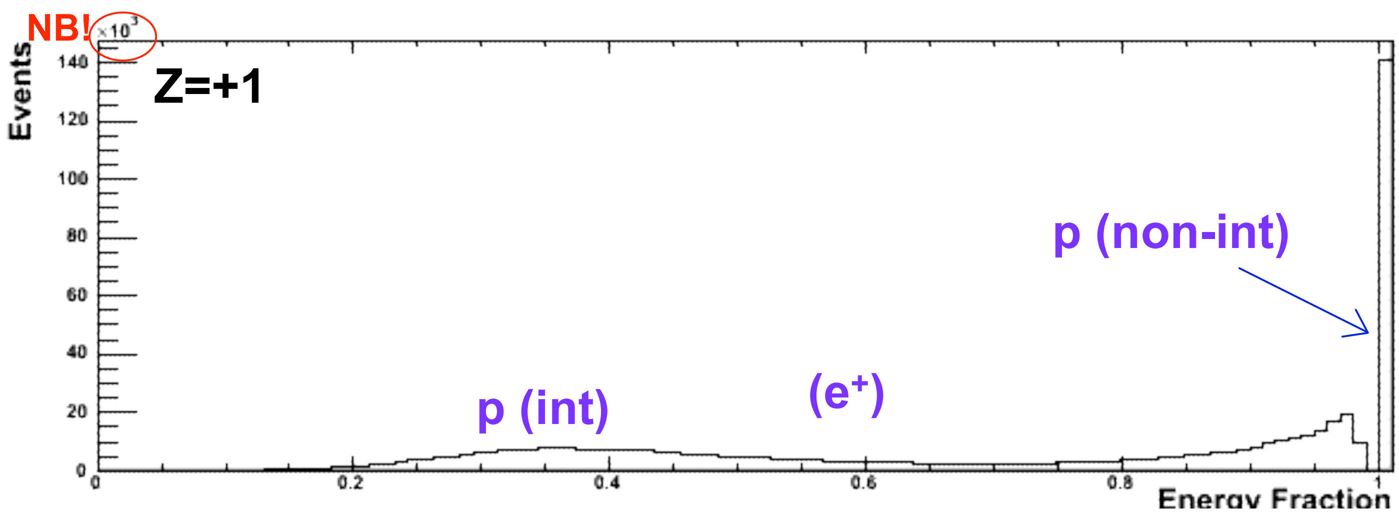
Background requirements

- proton to positron flux ratio at 200 GeV
  - 2 x 10^4
- gain 30 energy transfer
  - e+ show up factor of 3-10 lower energy
- gain 20 X_o/λ_o
  - must interact near the top of the calorimeter
- small fraction of interactions make π^o
  - 1%?
  - some make neutrons, too (1/2?)
- 30 x 20 x 100 x 2 = 120,000
  - 10^5 rejection is not implausible

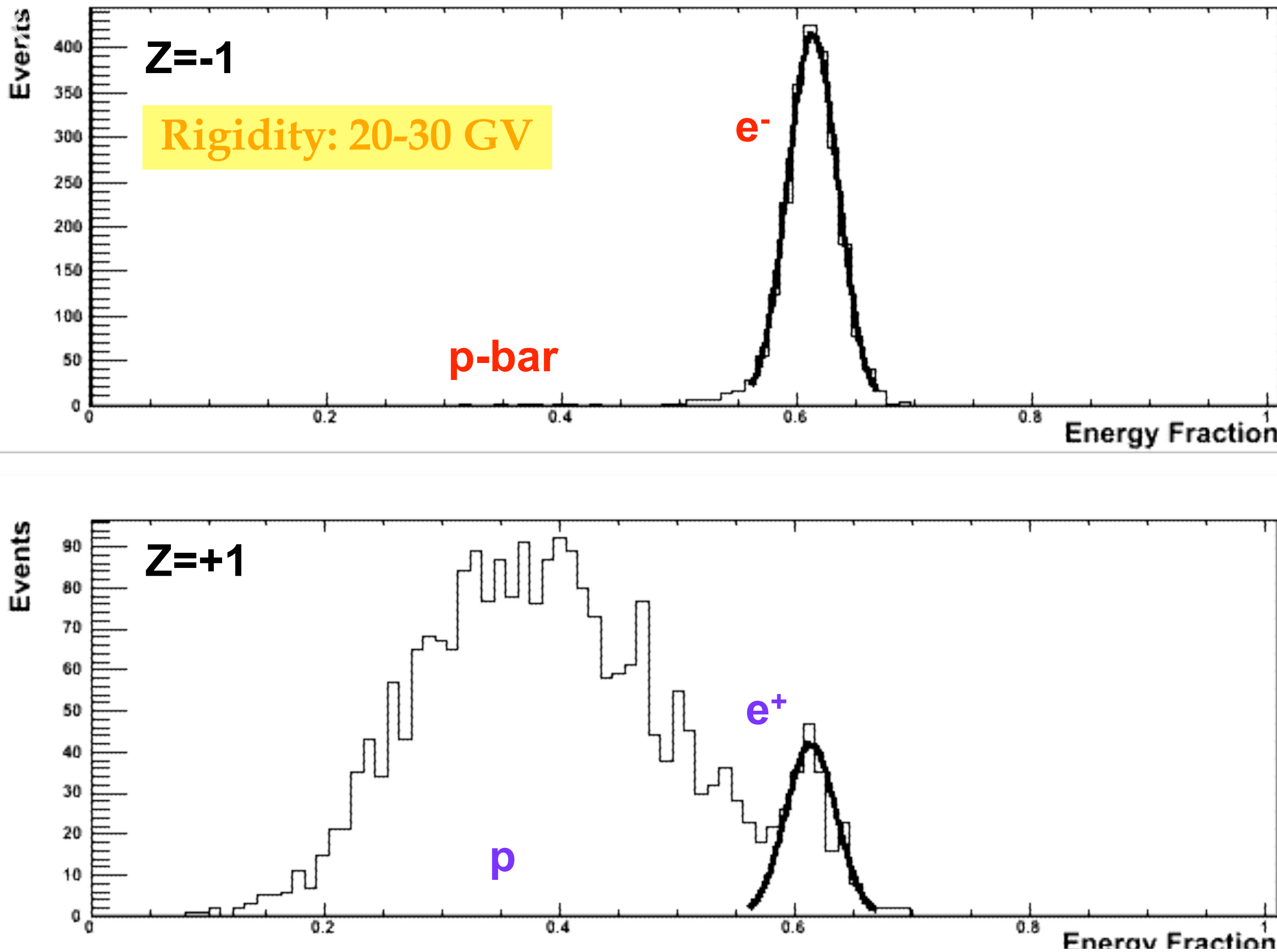
Proton background suppression

Fraction of charge released along the calorimeter track (left, hit, right)





Proton background suppression



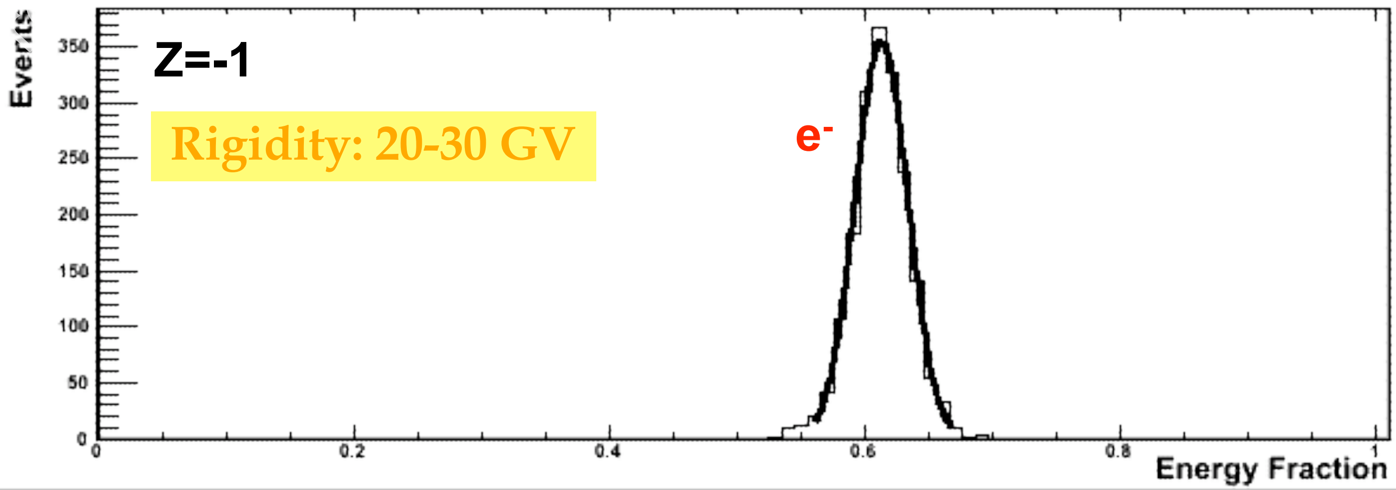
Fraction of charge released along the calorimeter track (left, hit, right)

+

Constraints on:

Energy-momentum match

Proton background suppression



Fraction of charge released along the calorimeter track (left, hit, right)

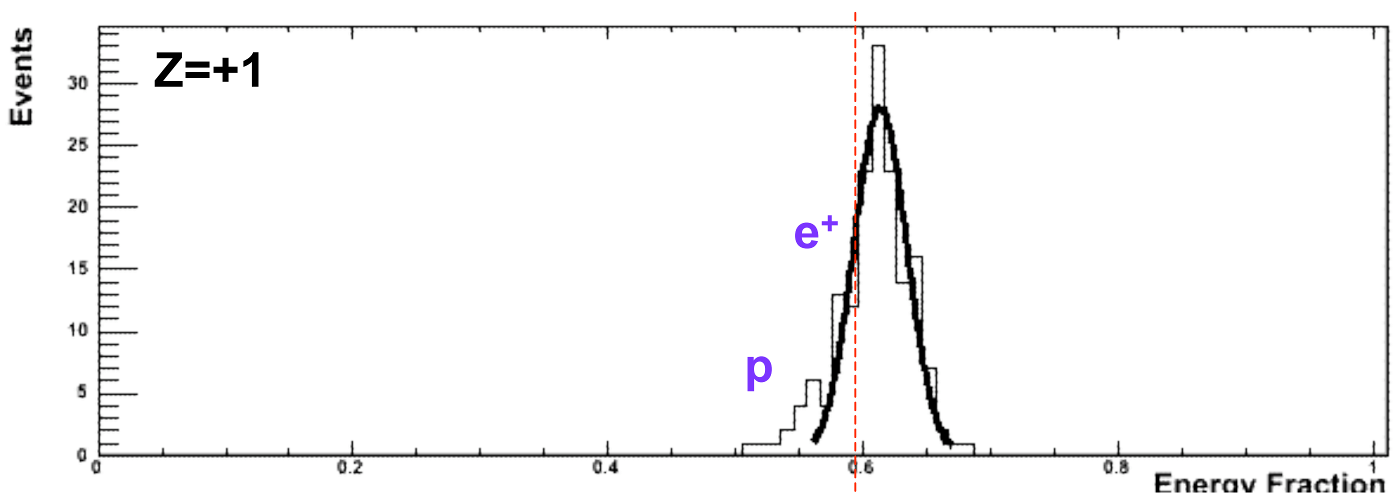
+

Constraints on:

Energy-momentum match

Shower starting-point

Longitudinal profile



Proton background evaluation

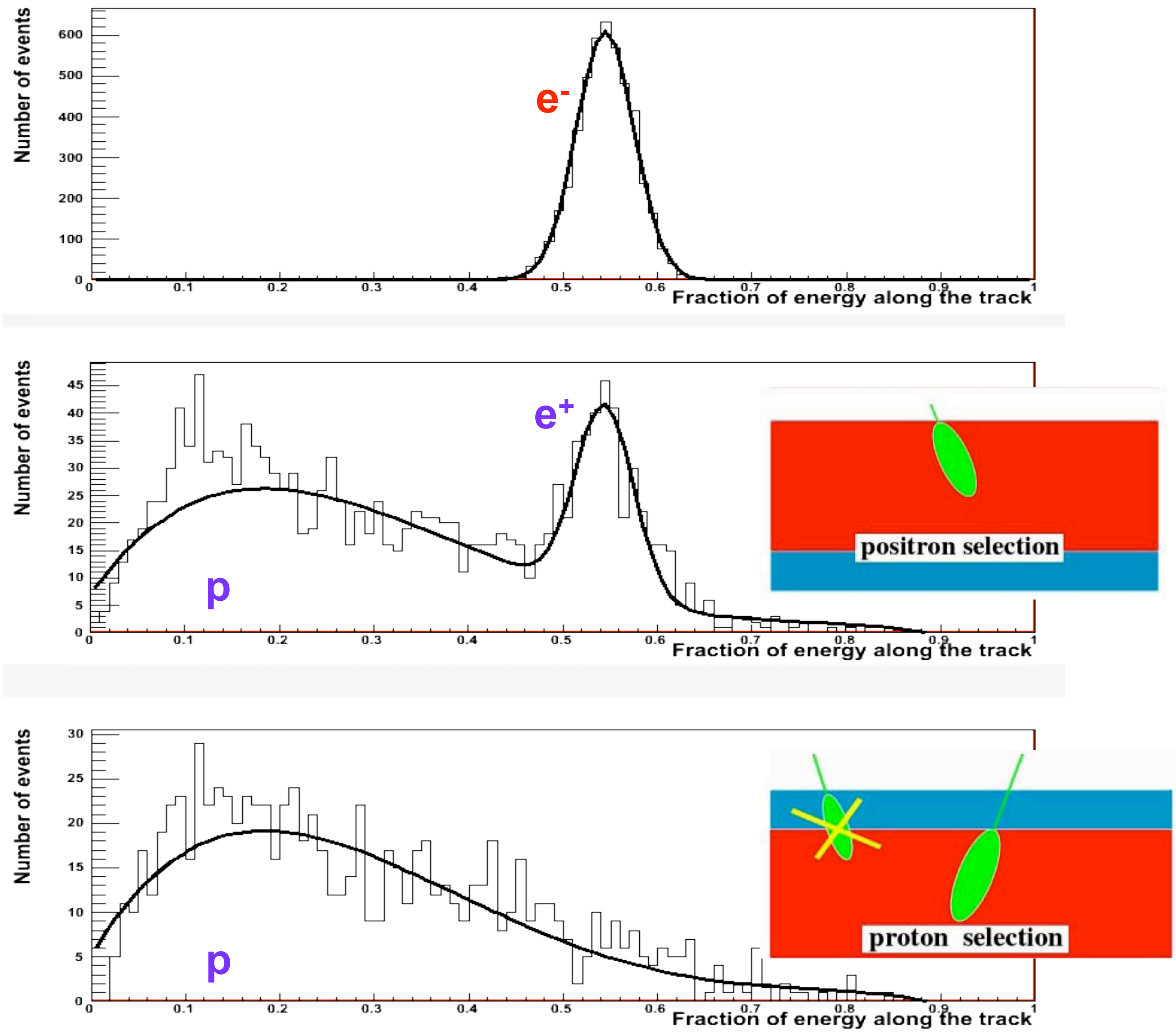
Rigidity: 6-8 GV

Fraction of charge released along the calorimeter track (left, hit, right)

+

Constraints on:

- Energy-momentum match
- Shower starting-point
- ~~Longitudinal profile~~



Explanation

- Requires source with hard spectrum (E^{-2})
- Dark matter?
  - needs corroborating evidence
  - stimulates the most interest
  - reject other explanations first
- Nearby sources
  - supernova remnants (primarily e-)
  - pulsars (e+ and e- pair making machines)
  - many, some close by &/or well connected magnetically

Kobayashi et al. 2004, ApJ, **601**, 340

TABLE 1
List of Nearby SNRs

SNR	Distance (kpc)	Age (yr)	E_{max}[a] (TeV)	Reference
SN 185	0.95	1.8×10^3	1.7×10^2	1
S147	0.80	4.6×10^3	63	2
HB 21	0.80	1.9×10^4	14	3, 4
G65.3+5.7	0.80	2.0×10^4	13	5
Cygnus Loop	0.44	2.0×10^4	13	6, 7
Vela	0.30	1.1×10^4	25	8
Monogem	0.30	8.6×10^4	2.8	9
Loop1	0.17	2.0×10^5	1.2	10
Geminga	0.4	3.4×10^5	0.67	11

[a] Maximum energy limited by the propagation of electrons in the case of the prompt release after the explosion. The delay of the release time gives the larger value.

References.—(1) Strom 1994; (2) Braun et al. 1989; (3) Tatematsu et al. 1990; (4) Leahy & Aschenbach 1996; (5) Green 1988; (6) Miyata et al. 1994; (7) Blair et al. 1999; (8) Caraveo et al. 2001; (9) Plucinsky et al. 1996; (10) Egger & Aschenbach 1995; (11) Caraveo et al. 1996.

e- + e+ electrons: Kobayashi et al. 2004

Hard (E^{-2}) spectrum expected from pulsars with e+ = e-.

Total electron spectrum from Fermi's LAT would be harder than E^{-3}.

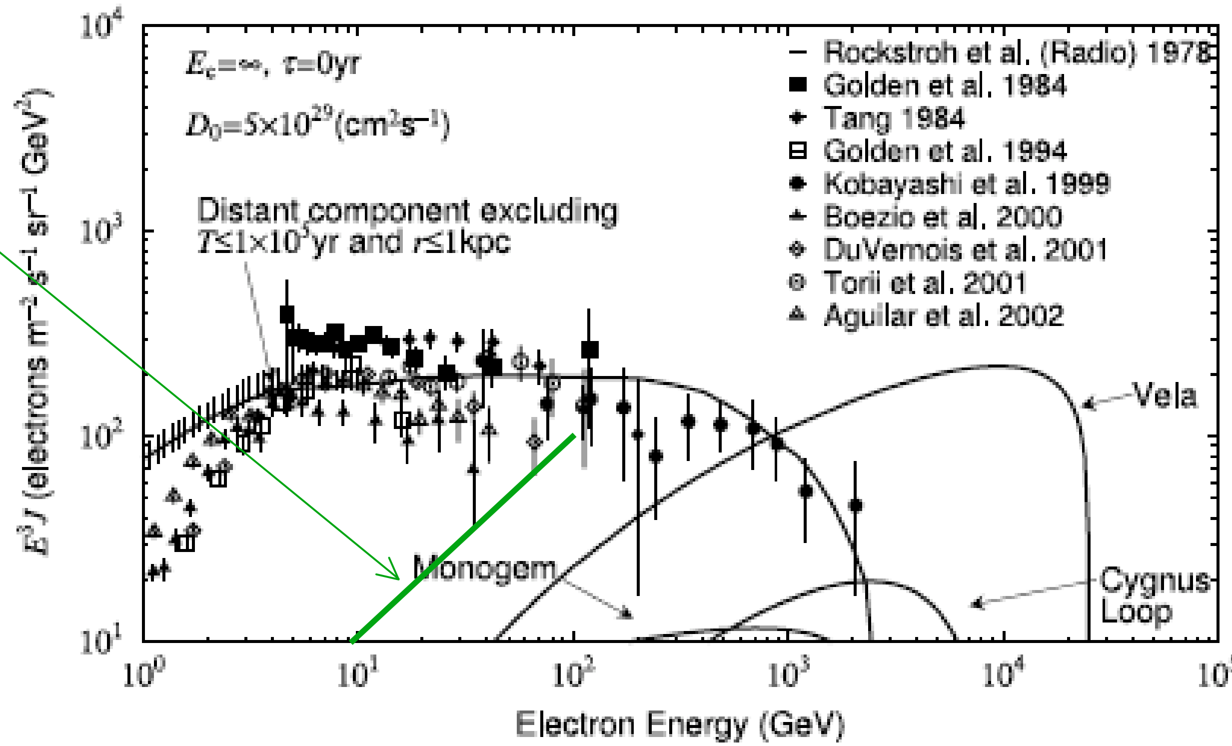


Fig. 3.—Calculated energy spectra of electrons without a cutoff of the injection spectrum for the prompt release after the explosion ($\tau = 0$), compared with presently available data. Here we took the diffusion coefficient of $D = D_0(E/\mathrm{TeV})^{0.3}$ with $D_0 = 2 \times 10^{29}$ cm^2 s^{-1} and $D_0 = 5 \times 10^{29}$ cm^2 s^{-1} in the TeV region, and $D = 2 \times 10^{28}(E/5\ \mathrm{GeV})^{0.6}$ in the GeV region as given by eq. (3). See text for details.

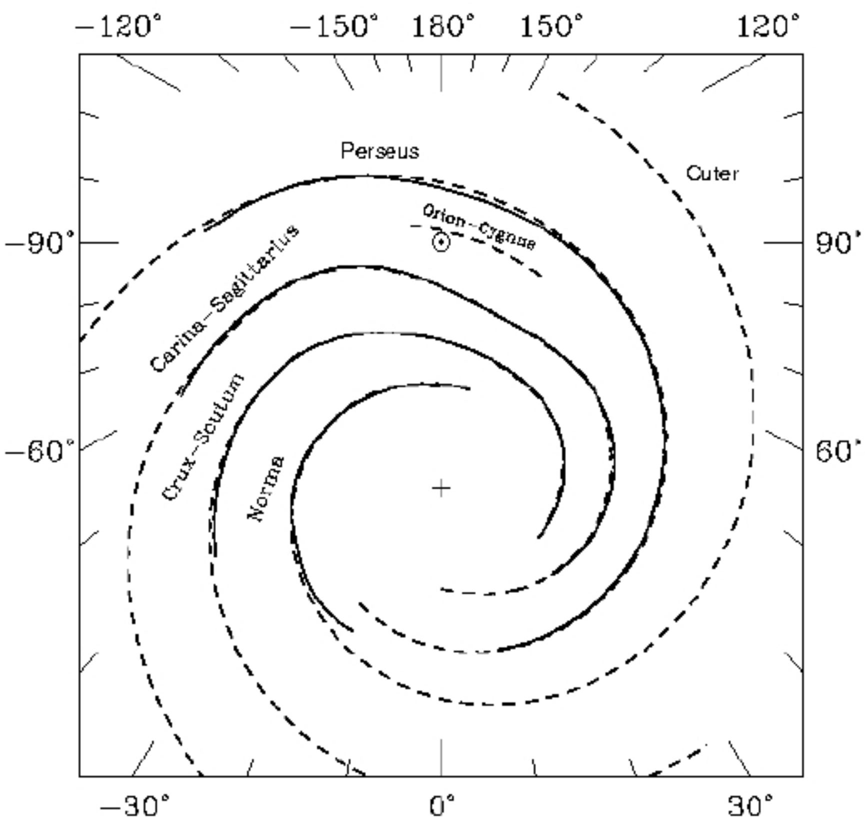
Parallax pulsars: www.astro.cornell.edu/~shami/psrvlb

Most recent pulsar parallaxes, distances, and velocities.

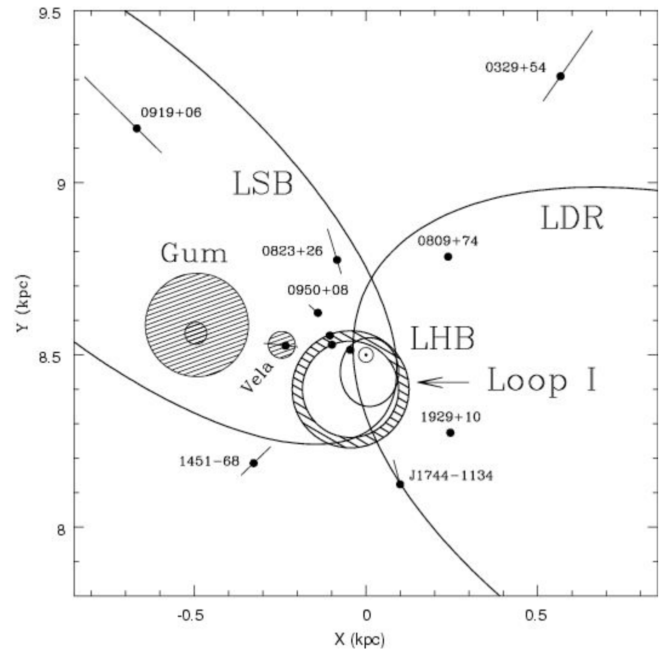
Pulsar	Parallax (mas)	Distance (kpc)	Velocity (km/s)	Reference
B0329+54	0.94 ± 0.11	1.03+0.13-0.12	95+12-11	Brisken 2001 (PhDT)
J0437-4715	7.19 ± 0.14	0.139+0.003-0.003	92.8+2.0-2.0	2001Natur.412..158V
B0809+74	2.31 ± 0.04	0.433+0.008-0.008	102+2-2	Brisken 2001 (PhDT)
B0823+26	2.8 ± 0.6	0.36+0.10-0.06	194+55-34	1986AJ.....91..974G
B0833-45	3.5 ± 0.2	0.287+0.019-0.017	61+2-2	2003ApJ...596.1137D
B0919+06	0.83 ± 0.13	1.21+0.19-0.19	505+80-80	2001ApJ...550..287C
B0950+08	3.82 ± 0.07	0.262+0.005-0.005	36.6+0.7-0.7	2000ApJ...541..959B
B1133+16	2.80 ± 0.16	0.35+0.02-0.02	631+38-35	Brisken 2001 (PhDT)
B1237+25	1.16 ± 0.08	0.85+0.06-0.06	475+34-30	Brisken 2001 (PhDT)
B1451-68	2.2 ± 0.3	0.46+0.07-0.06	90+13-13	1990Natur.343..240B
B1534+12	0.93 ± 0.13	1.08+0.16-0.14	131+20-17	1998ApJ...505..352S
J1713+0747	0.9 ± 0.3	1.1+0.5-0.3	30+20-10	1994ApJ...437L..39C
J1744-1134	2.8 ± 0.3	0.36+0.04-0.03	36+4-4	1999ApJ...523L.171T
B1855+09	1.1 ± 0.3	0.9+0.4-0.2	26+12-6	1994ApJ...428..713K
J1909-3744	1.22 ± 0.44	0.8+0.5-0.2	140+80-40	2003ApJ...599L..99J
B1929+10	3.02 ± 0.09	0.33+0.01-0.01	163+4-5	Brisken 2001 (PhDT)
B1937+21	< 0.28	> 3.5	> 8.0	1994ApJ...428..713K
B2016+28	1.03 ± 0.10	0.97+0.10-0.08	30.9+4.4-4.0	
B2020+28	0.37 ± 0.12	2.3+1.0-0.6	256+114-61	Brisken 2001 (PhDT)
B2021+51	0.50 ± 0.07	1.9+0.3-0.2	115+18-15	Brisken 2001 (PhDT)
Geminga	6.4±1.7	0.157+0.59-0.034	122	1996ApJ...461L..91C
Vela	3.4±0.7	0.294+0.076-0.050	65	2001ApJ...561..930C
J1856.5-3754	7±2	0.140±0.040	220±60	2002ApJ...571..447K

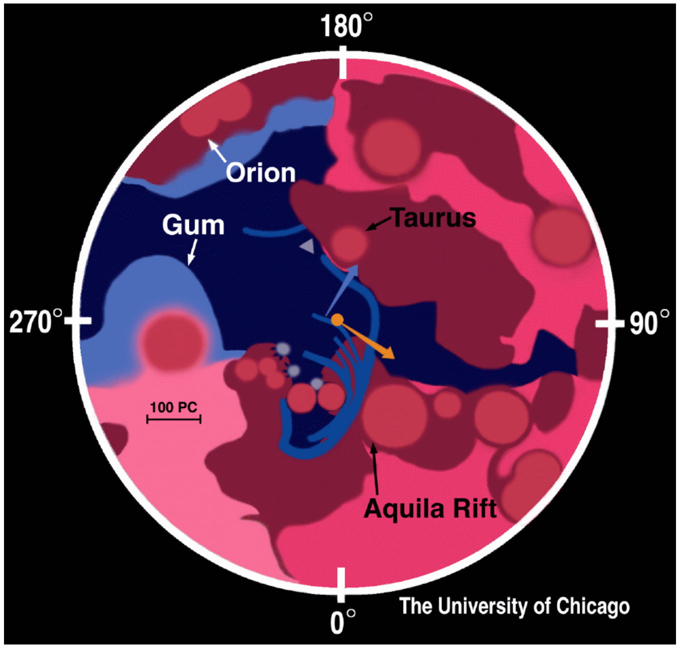
Highlighted pulsar names link to postscript plots of their parallax.
Older results, such as Salter, Lyne & Anderson (1979),Backer & Sramek (1982) and Gwinn, Taylor, Weisberg & Rawley (1986), have been replaced with current values, as available.
Shami Chatterjee (shami @ astro.cornell.edu) with input from David Kaplan
Last modified: 25 Mar 2004

Local arm: Orion-Cygnus



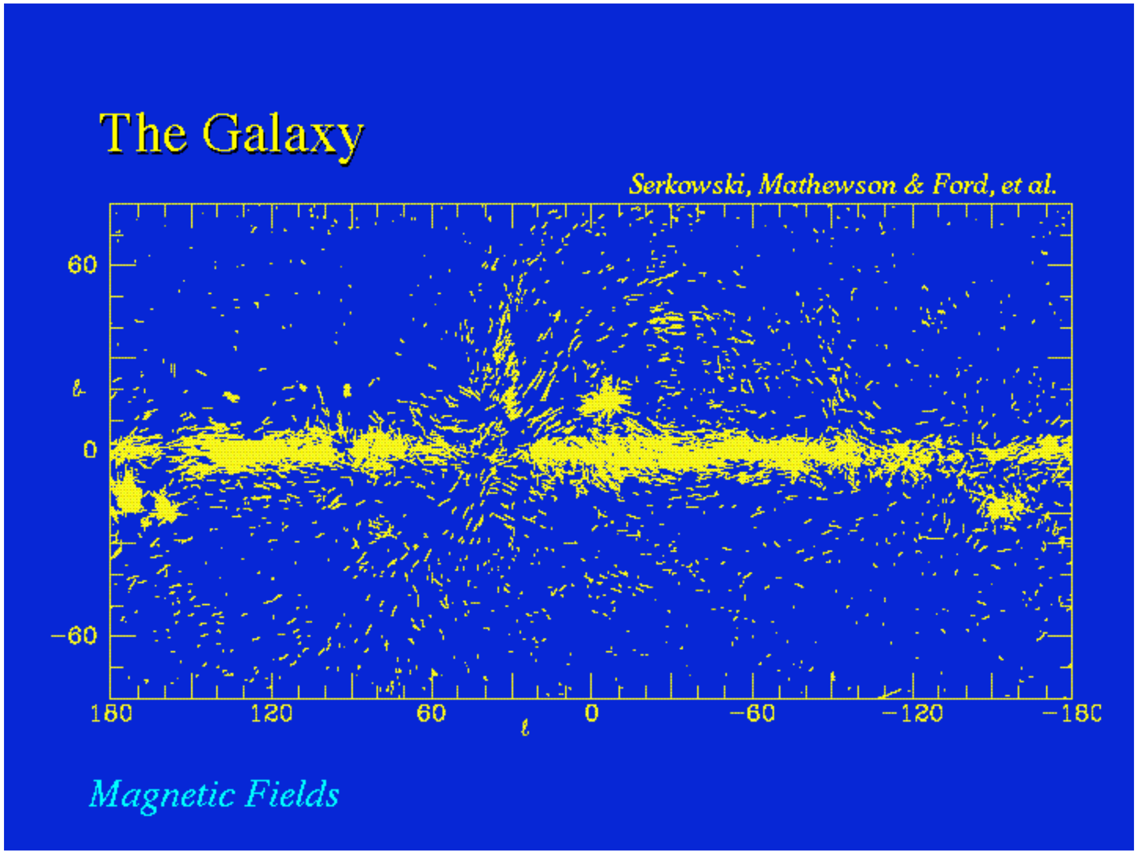
NE2001 Spiral Arms



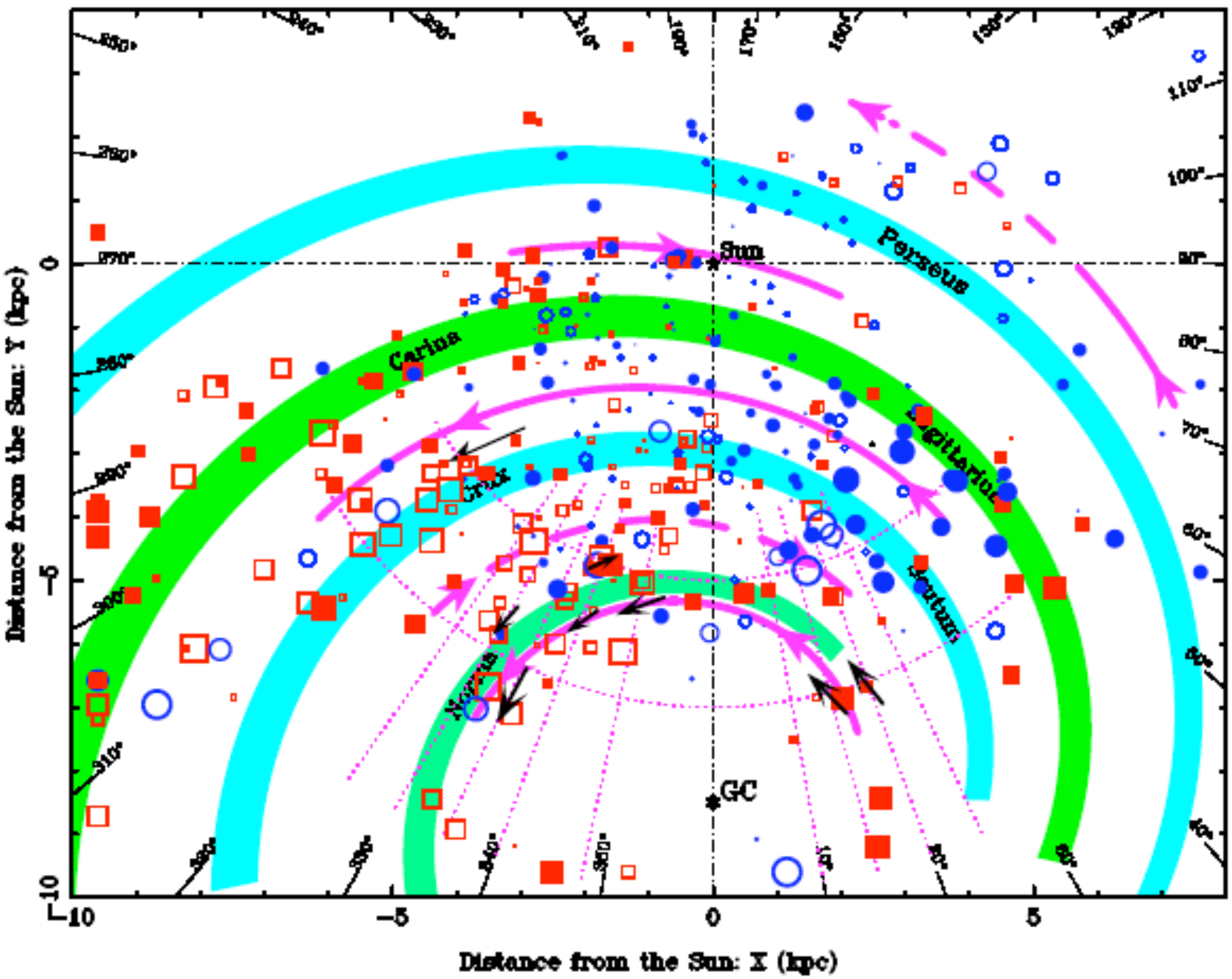


Large scale galactic magnetic fields

Is of order 5 microgauss, however, dense clouds of cold molecular gas host fields of up to several mG strength (Heiles & Crutcher, in Wielebinski & Beck 2005).

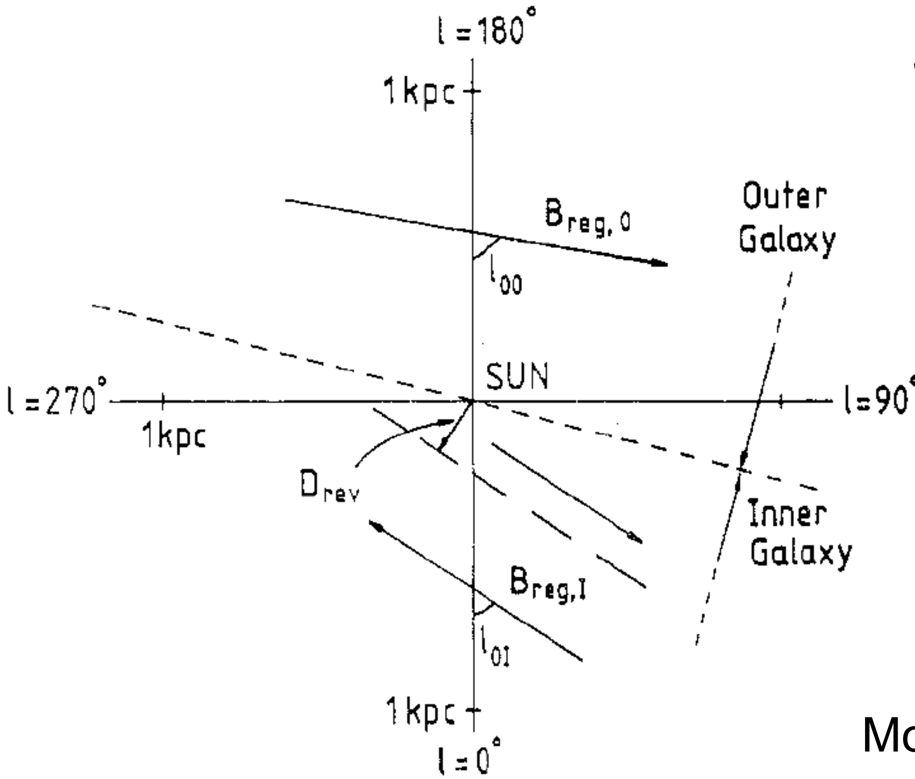


Large Scale Galactic Magnetic Field

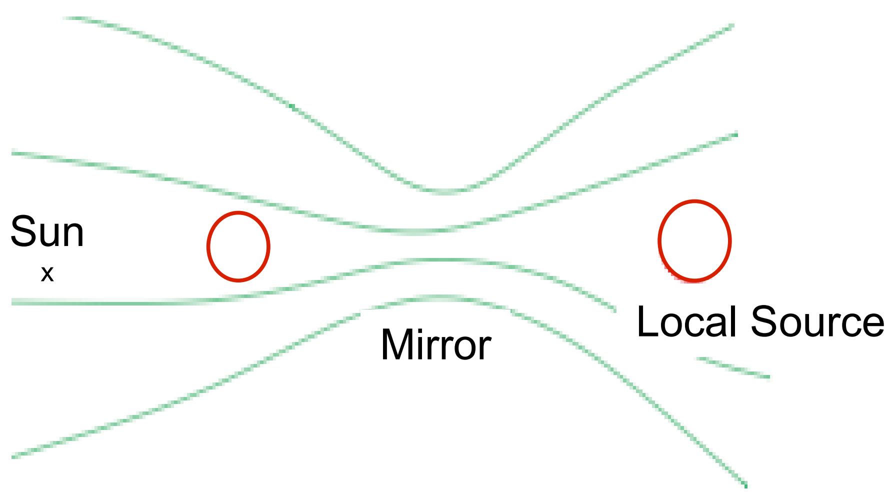


Han, astro-ph/0402170 (2004)

Local galactic magnetic fields



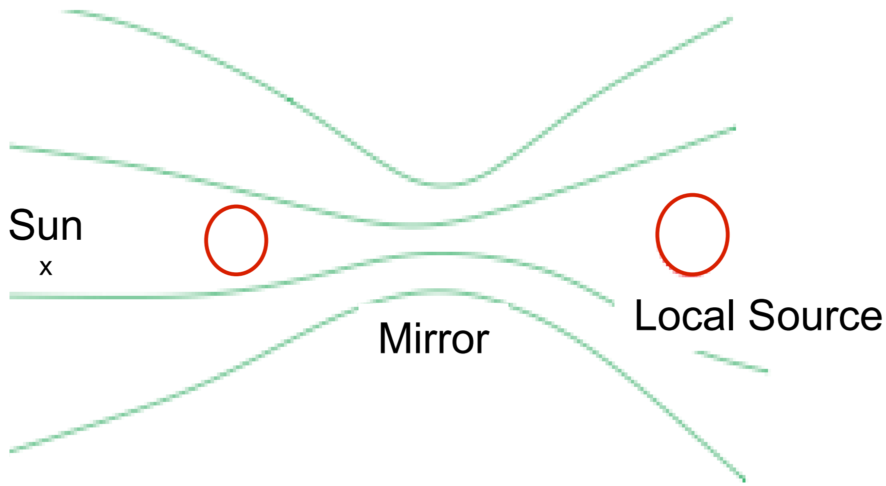
Chi and Wolfendale, 1990
J. Phys G: Nucl. Part. Phys.**16**, 1409

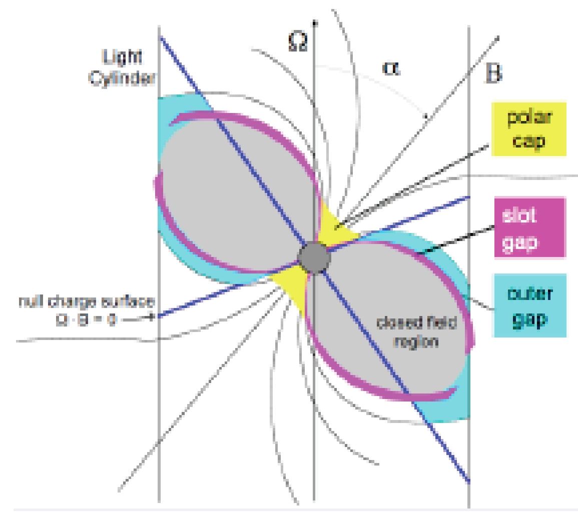


Model proposed for the Milagro "Hot Spot"
Drury and Aharonian, 2008,
Astroparticle Physics **29**, 280.

Interstellar magnetic field is of order 5 microgauss, the ordered component being about 3 microgauss and the remainder being due to fluctuations. However, dense clouds of cold molecular gas host fields of up to several mG (Heiles & Crutcher, in Wielebinski & Beck 2005).

Transport controlled by magnetic fields





Cautions

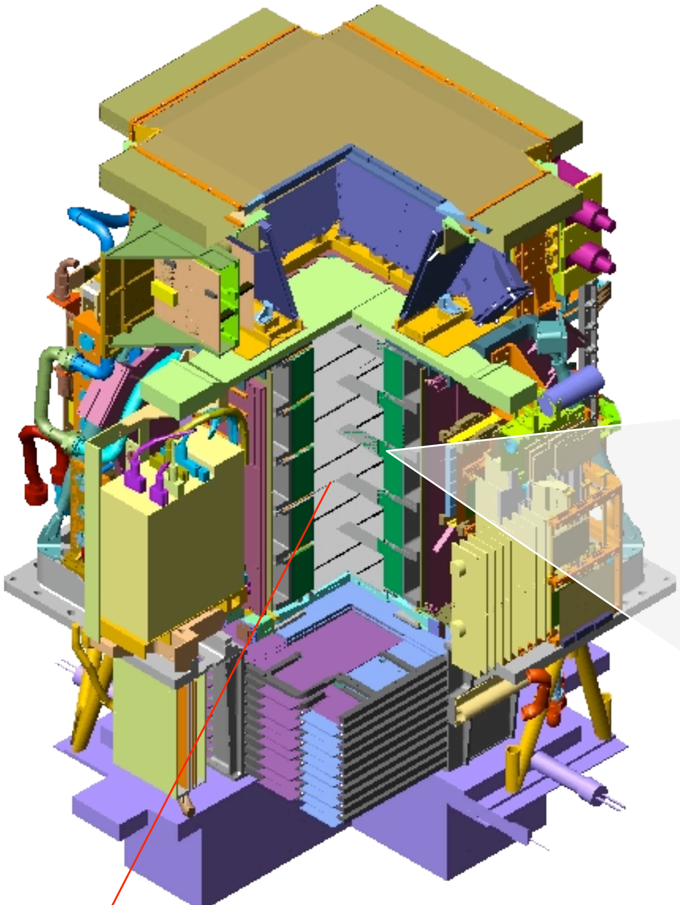
- Measuring electron spectra are difficult
  - Spectra are very steep and background rises with increasing energy
- Magnetic fields are ubiquitous
  - Push particles around
  - Separate charges
  - Acceleration is common
  - Magnetic reconnection is poorly understood
- Physics tends to be “messy”
  - Multiple explanations often work
  - Nature is more complex than simple models

Summary + Conclusions

- Results are interesting
  - Data look good to me
- Need to rule out other sources
  - How can Fermi LAT help?
    - pulsar observations and modeling
    - e+e- spectrum 10 many hundreds of GeV
- Even the magneto tails of Earth and Jupiter accelerate electrons.
- Need E-2 spectrum added to the "background" of GCR e+ and e-

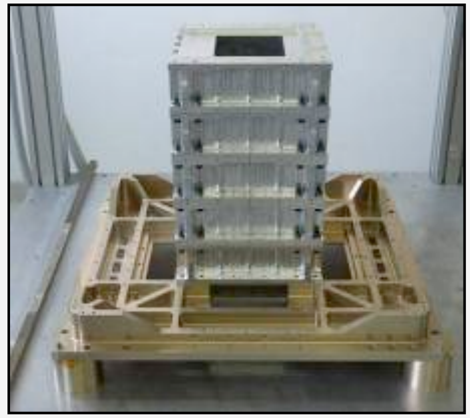
Some theoretical papers

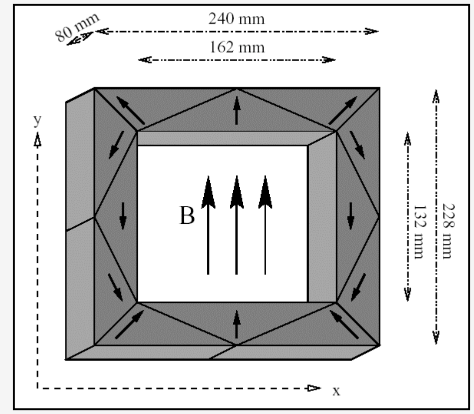
- Cholis et al., 2008, arXiv:0811.3641v1 [astro=ph]
- Hooper, Blasi and Serpico, 2008, arXiv:0810.1527v1 [astro=ph]
- Hall and Hooper, 2008, arXiv:0811.3362v1 [astro=ph]
- Cirelli and Strumia, 2008, arXiv:0808.3867v1 [astro-ph]
- Finkbiner, 2004, Ap.J., **614,** 186-193.



SPECTROMETER

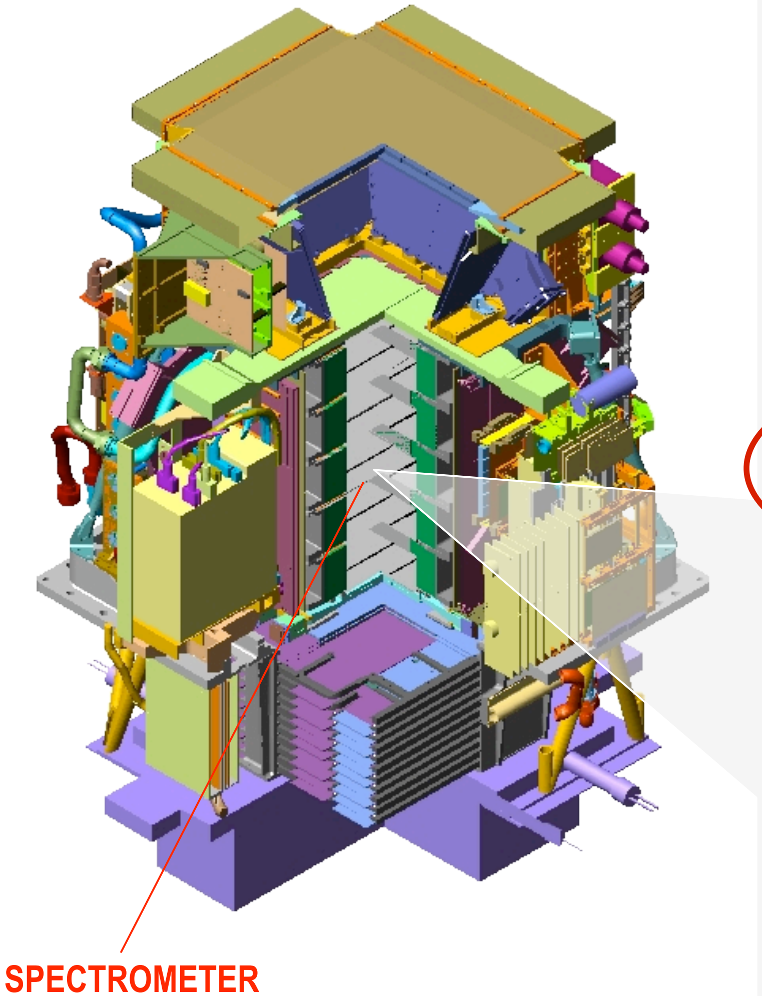
The magnet





Characteristics:

- 5 modules of permanent magnet (Nd-B-Fe alloy) in aluminum mechanics
- Cavity dimensions 162x132x445 cm^3
  → GF 21.5 cm^2sr
- Magnetic shields
- 5mm-step field-map
- B=0.43 T (average along axis), B=0.48 T (@center)



The tracking system

Main tasks:

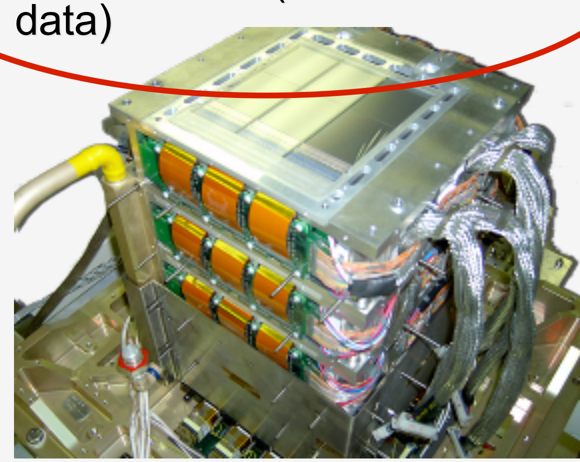
- Rigidity measurement
- Sign of electric charge
- dE/dx

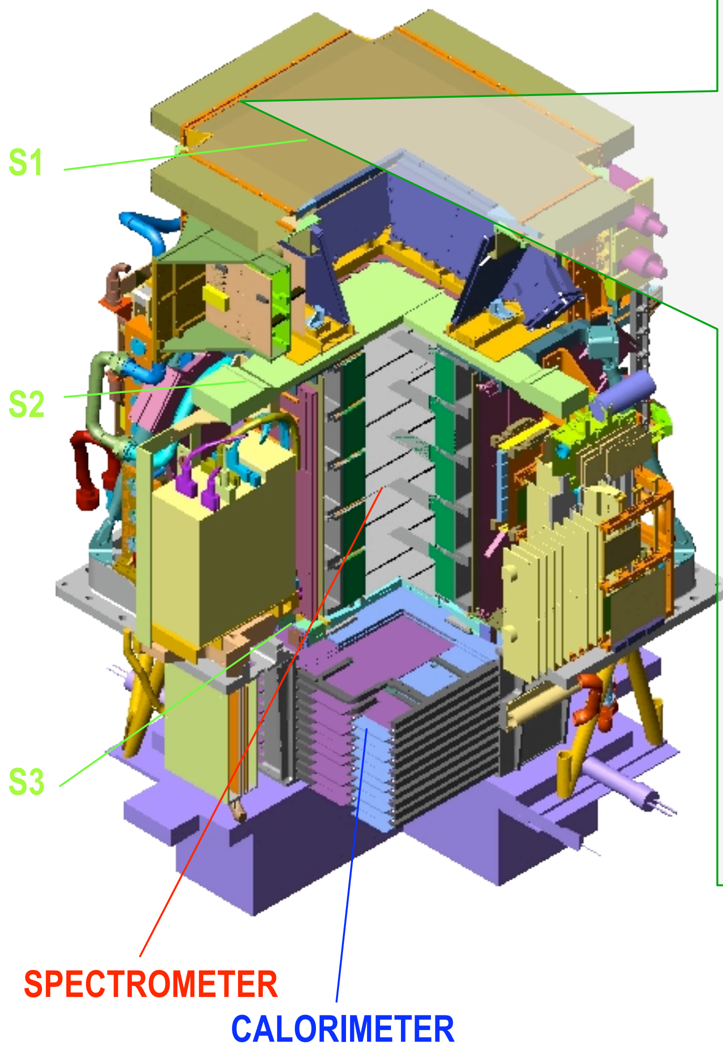
Characteristics:

- 6 planes double-side (x&y view) microstrip Si sensors
- 36864 channels
- Dynamic range 10 MIP

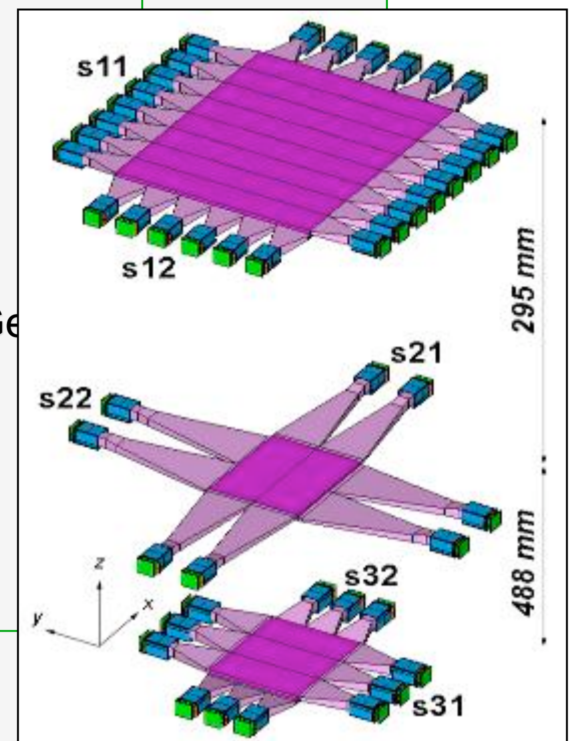
Performances:

- Spatial resolution: 3-4μm
- MDR ~1TV/c (from test beam data)





The time-of-flight system



Main tasks:

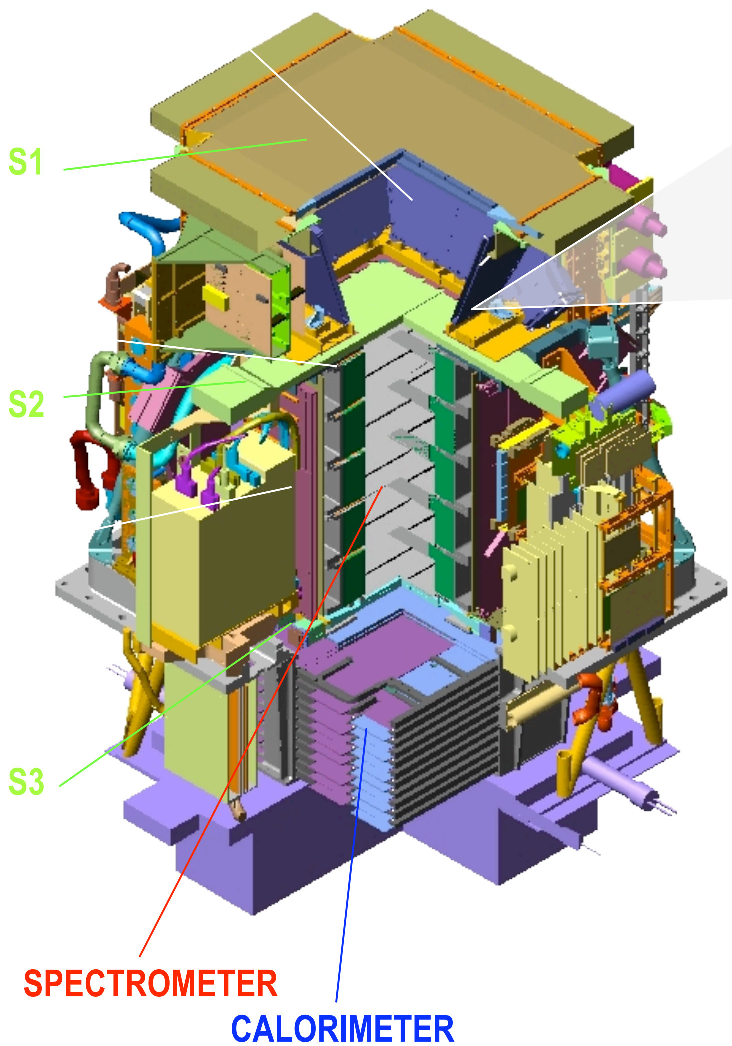
- First-level trigger
- Albedo rejection
- dE/dx
- Particle identification (<1 Ge

Characteristics:

- 3 double-layer scintillator paddles
- X/Y segmentation
- Total: 48 Channels

Performances:

- σ(paddle) ~ 110ps
- σ(TOF) ~ 330ps (for MIPs)



The anticounter shields

Main tasks:

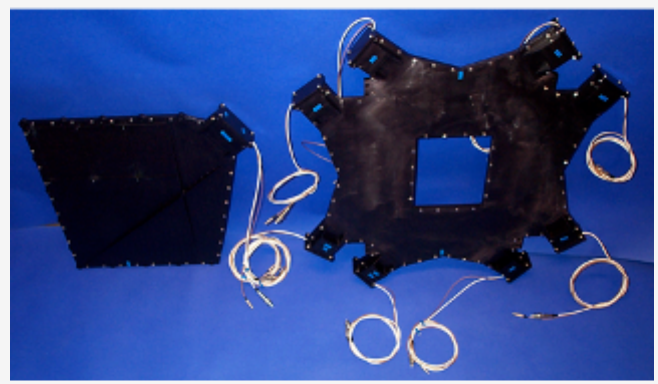
- Rejection of events with particles interacting with the apparatus (off-line and second-level trigger)

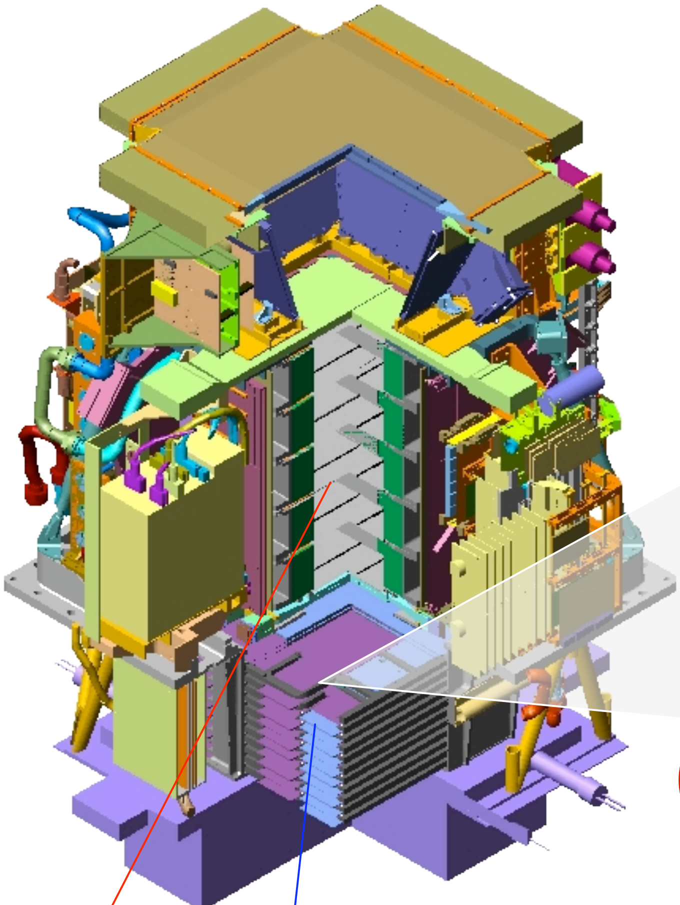
Characteristics:

- scintillator paddles 10mm thick
- 4 up (CARD), 1 top (CAT), 4 side (CAS)

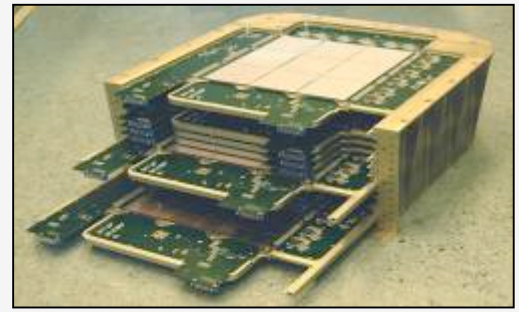
Performances:

- Efficiency > 99.9%





The electromagnetic calorimeter



Main tasks:

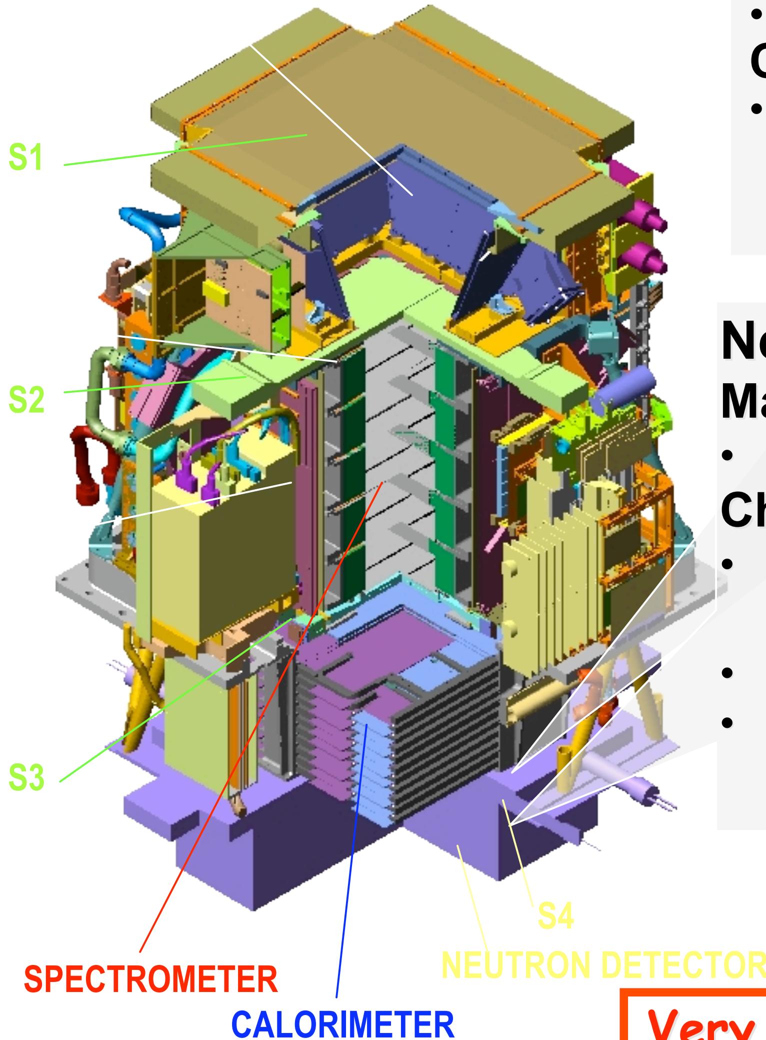
- e/h discrimination
- $e^{+/-}$ energy measurement

Characteristics:

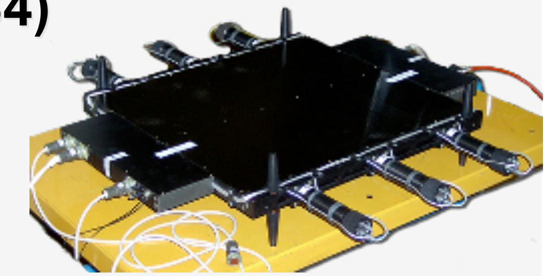
- 44 Si layers (X/Y) +22 W planes
- 16.3 X_o / 0.6 λ_0
- 4224 channels
- Dynamic range 1400 mip
- Self-trigger mode (> 300 GeV GF~600 cm^2 sr)

Performances:

- p-bar and e^+ selection efficiency ~ 90%
- p rejection factor ~ 10^5
- e^- rejection factor ~ 10^4
- Energy resolution ~5% @200GeV



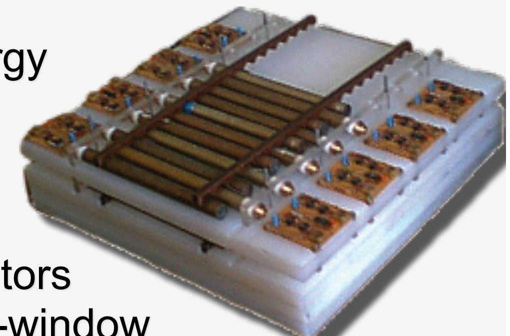
Shower-tail catcher (S4)



Main tasks:
- ND trigger

Characteristics:
- 1 scintillator paddle 10mm thick

Neutron detector



Main tasks:
- e/h discrimination @high-energy

Characteristics:
- 36 ^{3}He counters:
  ^{3}He(n,p)T → Ep=780 keV
- 9 cm thick polyetilene moderators
- n collected within 200 μs time-window

Very important to help the Calorimeter in the particle separation