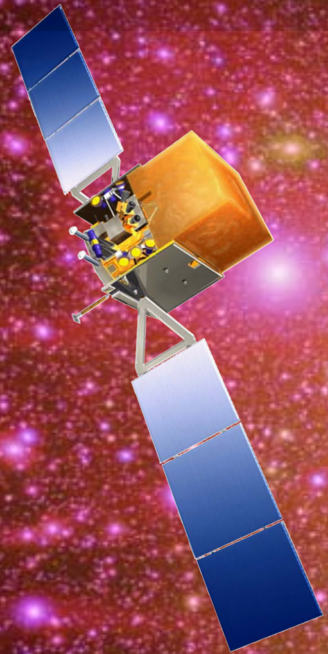
The electron/positron puzzle in the Fermi and PAMELA era



Aldo Morselli

INFN Roma Tor Vergata

May 18 2010

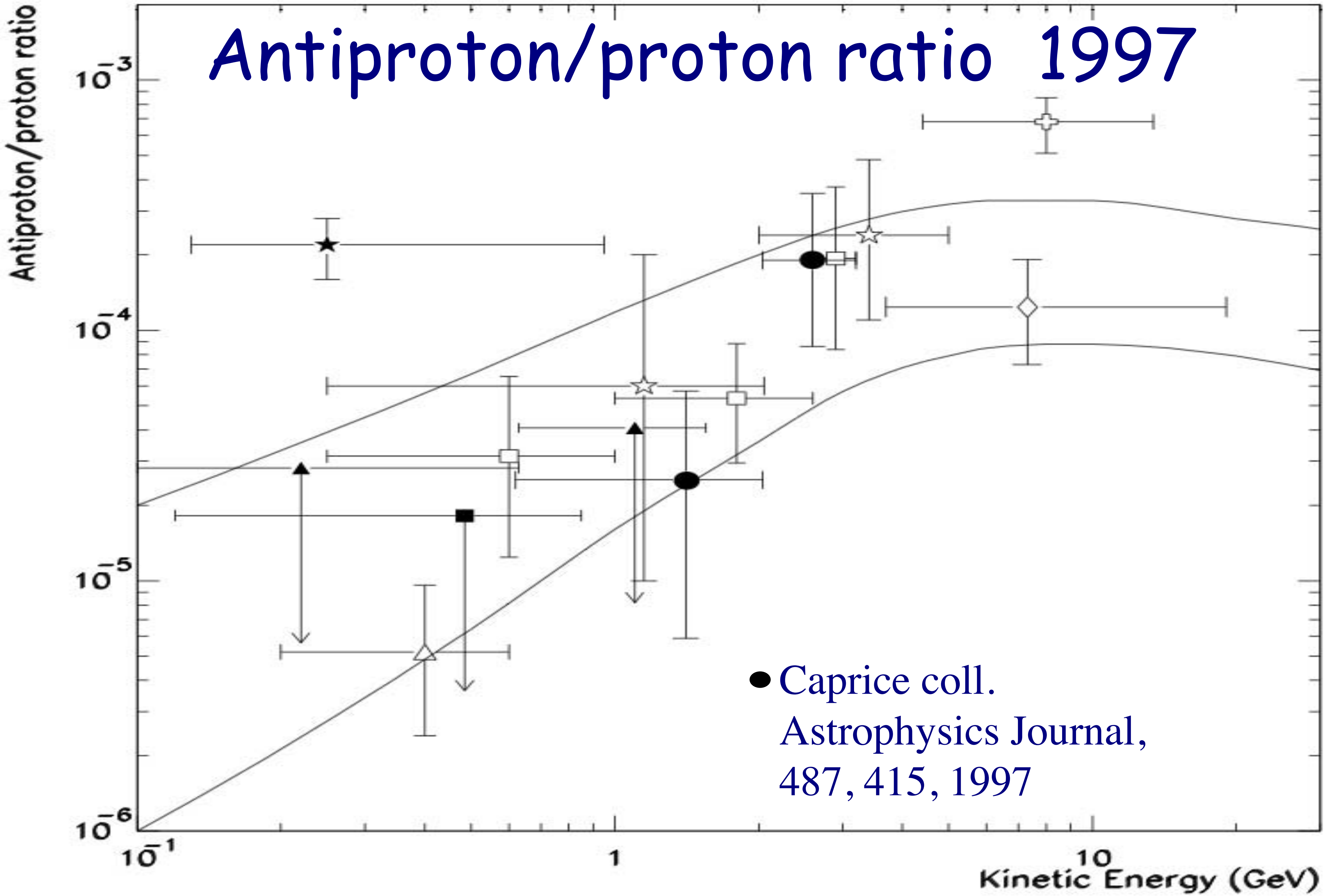
GGI Conference The Dark Matter connection: Theory & Experiment

Neutralino WIMPs

Assume χ present in the galactic halo

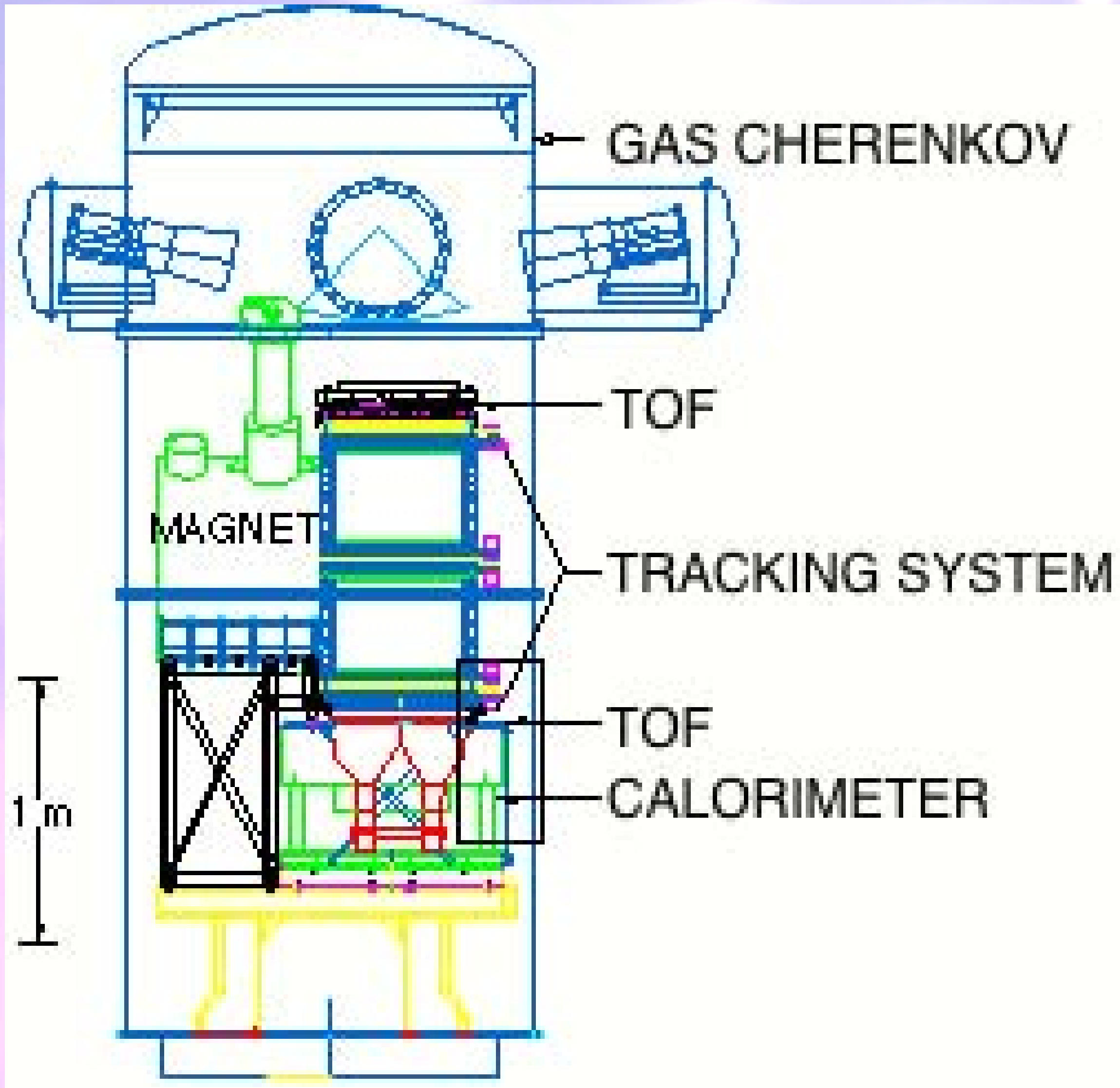
- χ is its own antiparticle **=>** can annihilate in galactic halo producing gamma-rays, antiprotons, positrons….
- Antimatter not produced in large quantities through standard processes (secondary production through p + p **-->** anti p + X)
- So, any extra contribution from exotic sources ($\chi\,\chi$ annihilation) is an interesting signature
- ie: $\chi\,\chi$ --> anti p + X
- Produced from (e. g.) $\chi\,\chi$ **-->** q / g / gauge boson / Higgs boson and subsequent decay and/ or hadronisation.

Antiproton/proton ratio 1997

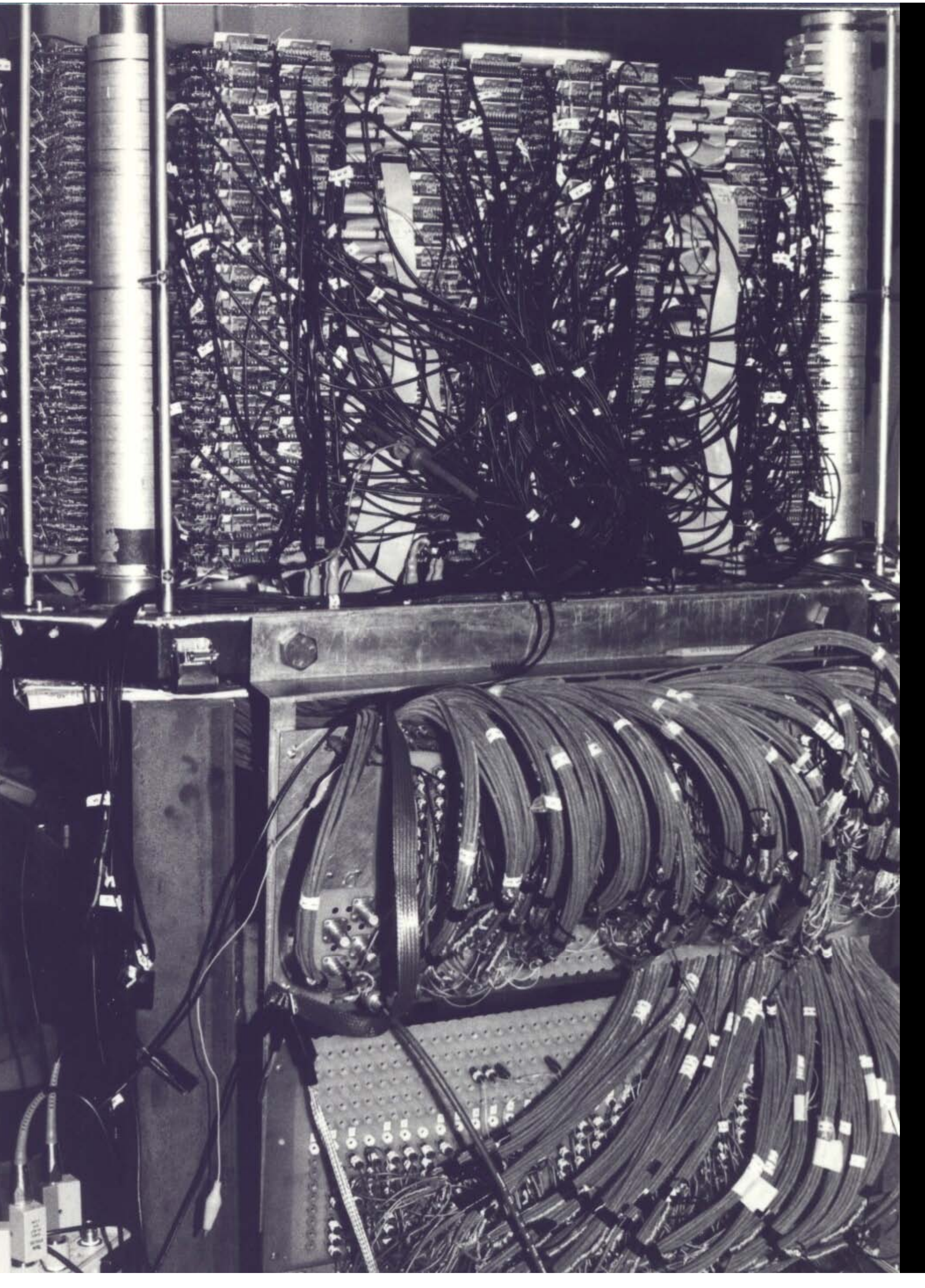


- Caprice coll. Astrophysics Journal, 487, 415, 1997

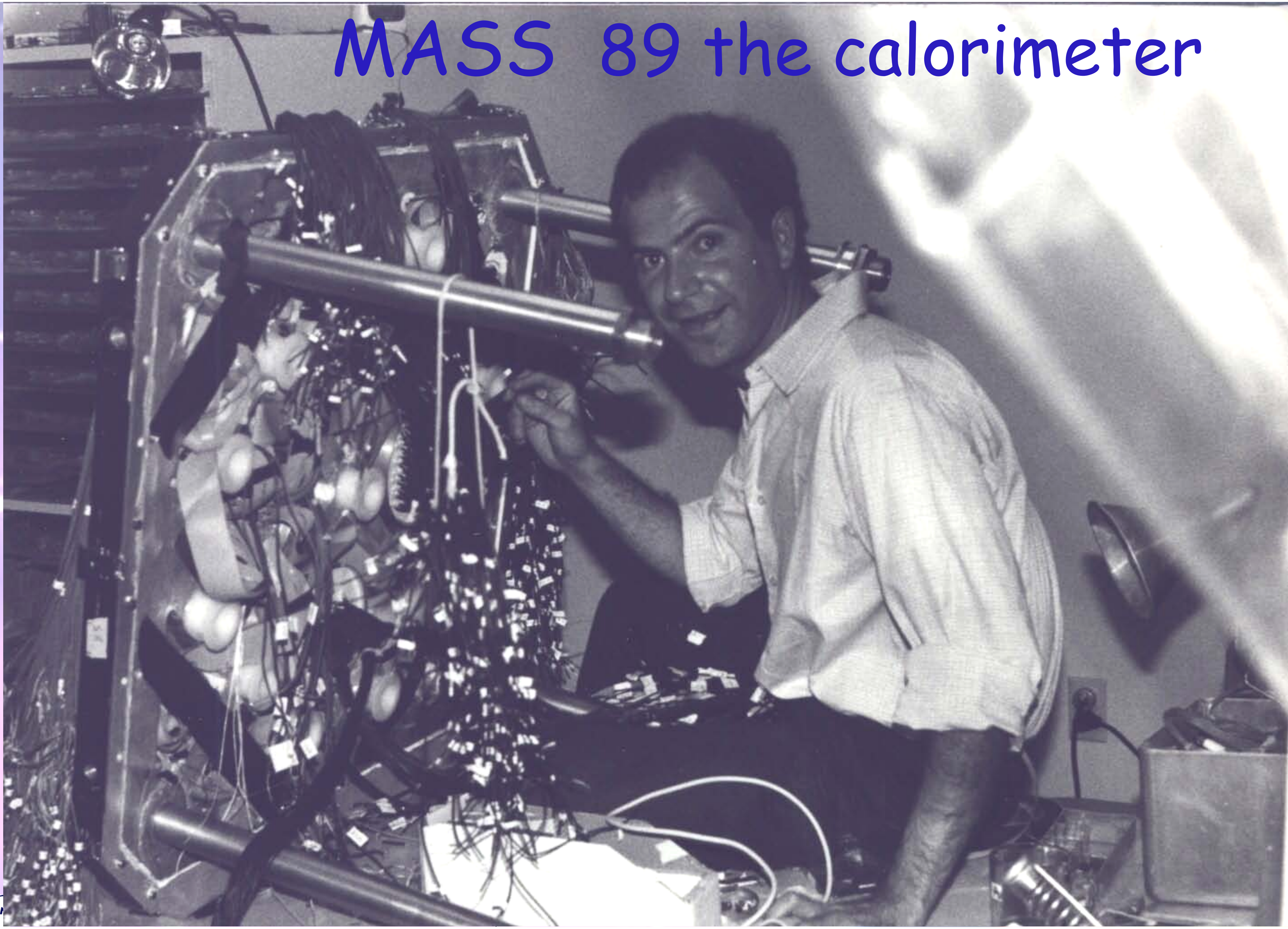
MASS Matter Antimatter Space Spectrometer



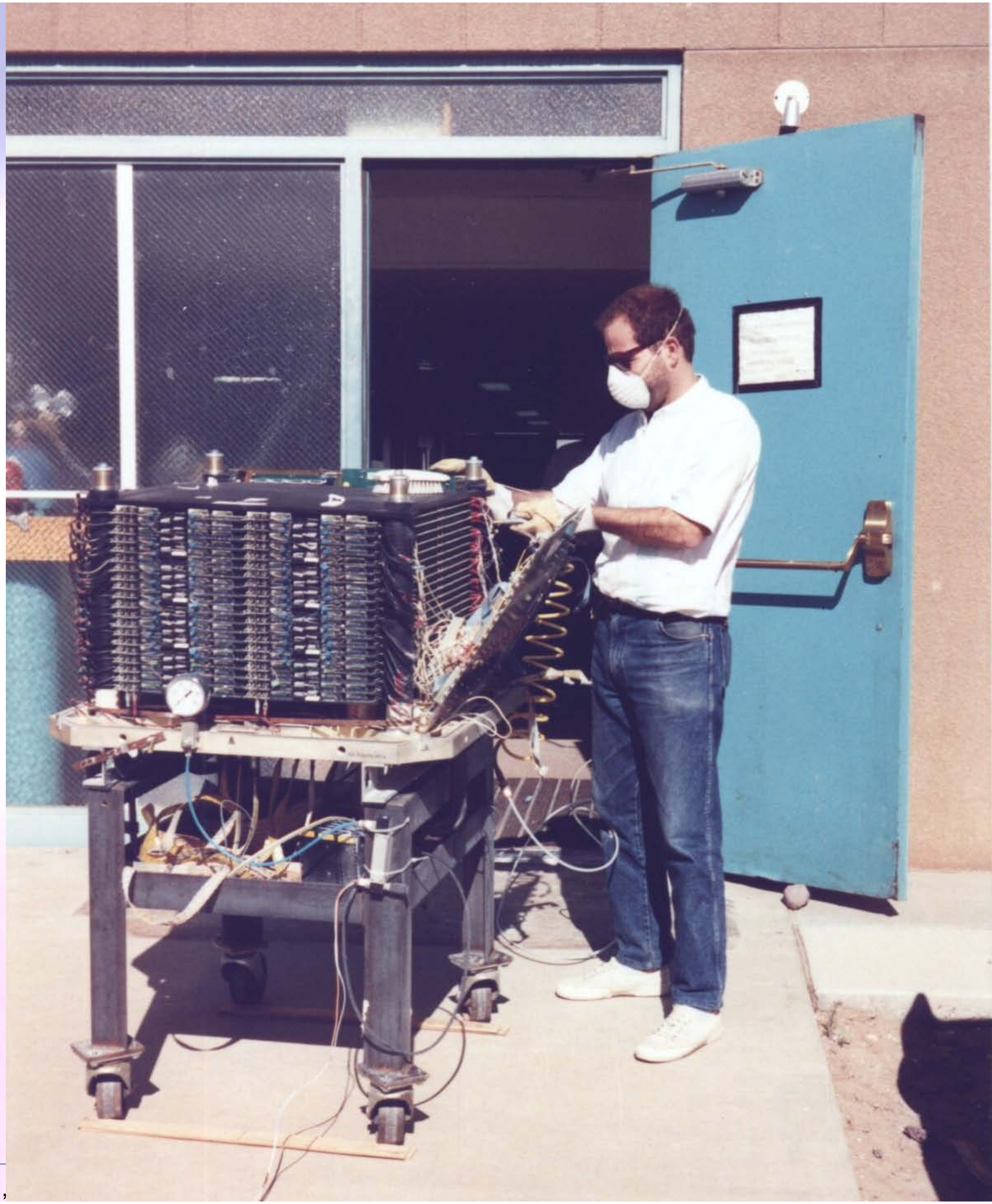
the MASS89 Calorimeter



MASS 89 the calorimeter



MASS 89 the calorimeter



from Las Cruces to Prince Albert


HOLD

MASS 89 flight


MASS 89 flight


MASS 89

PAMELA

Payload for **A**ntimatter **M**atter **E**xploration and **L**ight Nuclei **A**strophysics

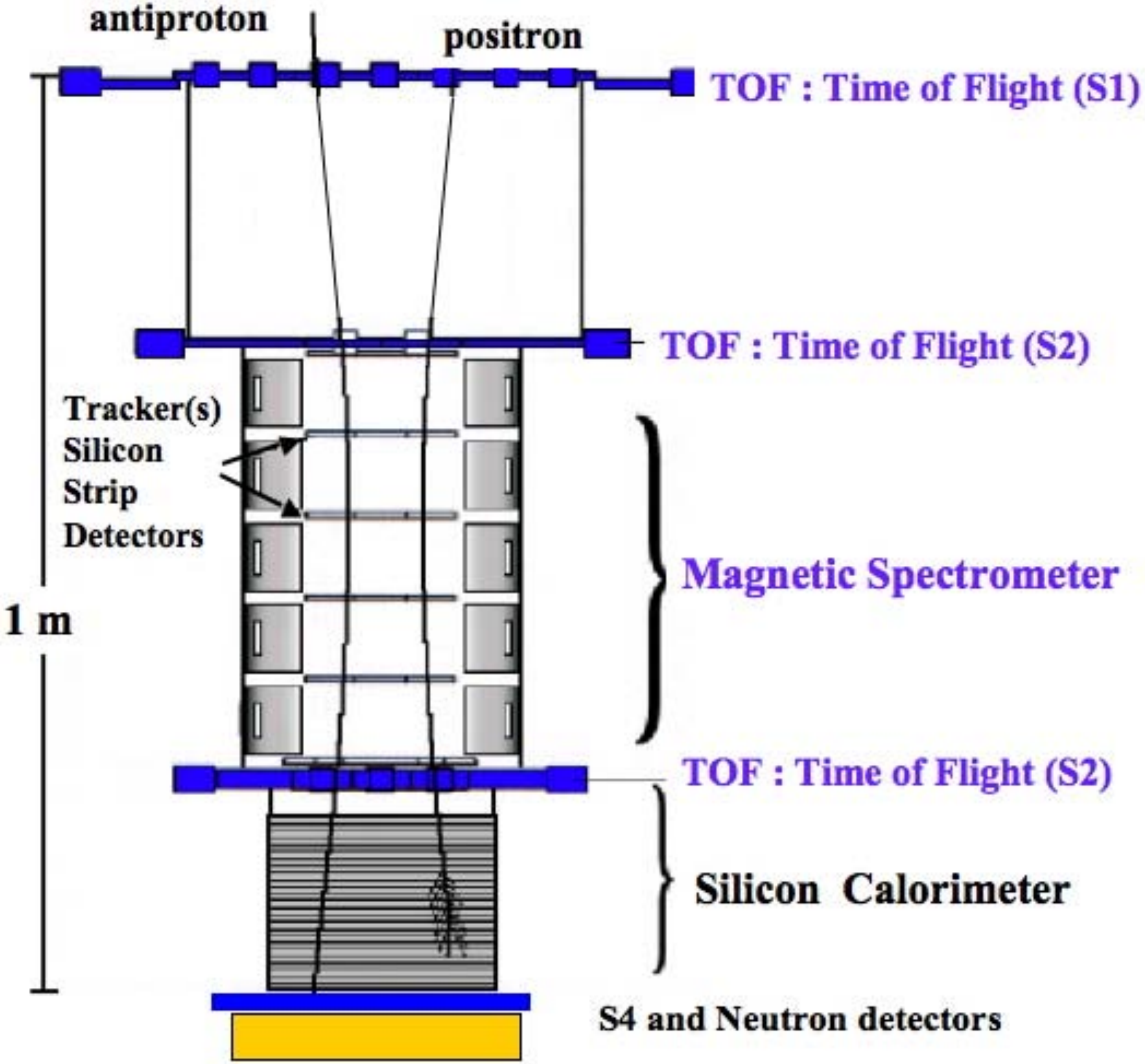
In orbit on June 15, 2006, on board of the DK1 satellite by a Soyuz rocket from the Bajkonour launch site.

First switch-on on June 21 2006

From July 11 Pamela is in continuous data taking mode

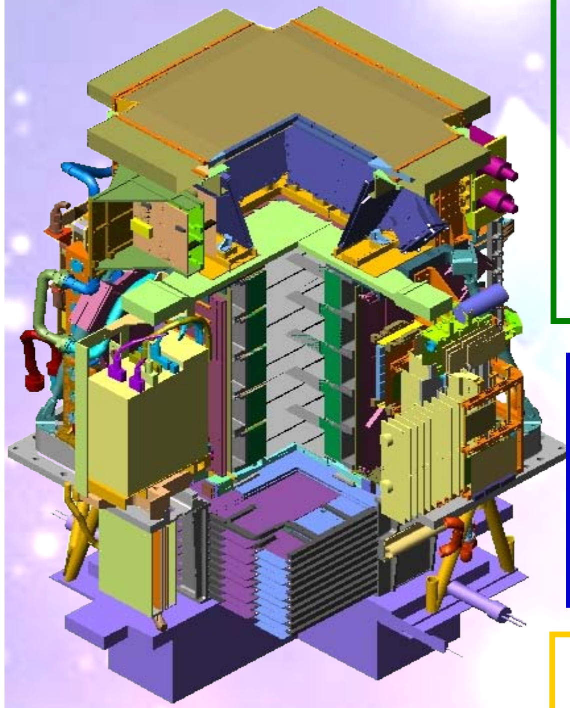
Pamela

Separating p from e^-



PAMELA detectors

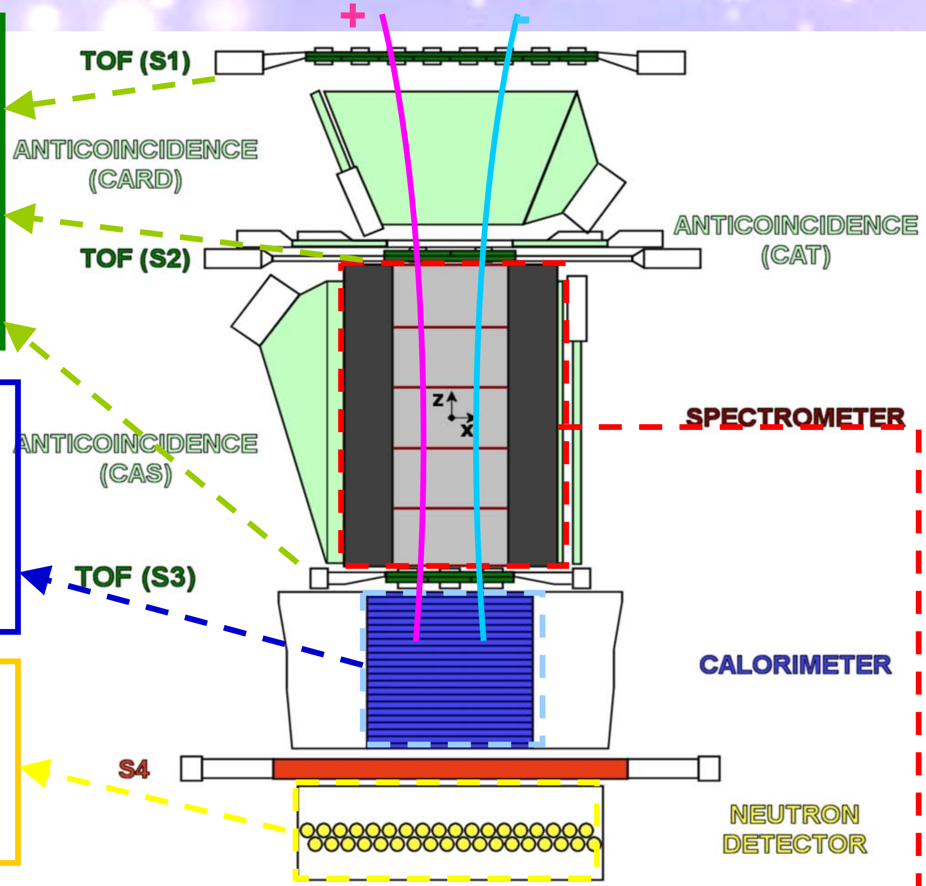
Main requirements → high-sensitivity antiparticle identification and precise momentum measure



Time-Of-Flight
plastic scintillators + PMT:
- Trigger
- Albedo rejection;
- Mass identification up to 1 GeV;
- Charge identification from dE/dX.

Electromagnetic calorimeter
W/Si sampling (16.3 X0, 0.6 λI)
- Discrimination e+ / p, anti-p / e^- (shower topology)
- Direct E measurement for e^-

Neutron detector
plastic scintillators + PMT:
- High-energy e/h discrimination



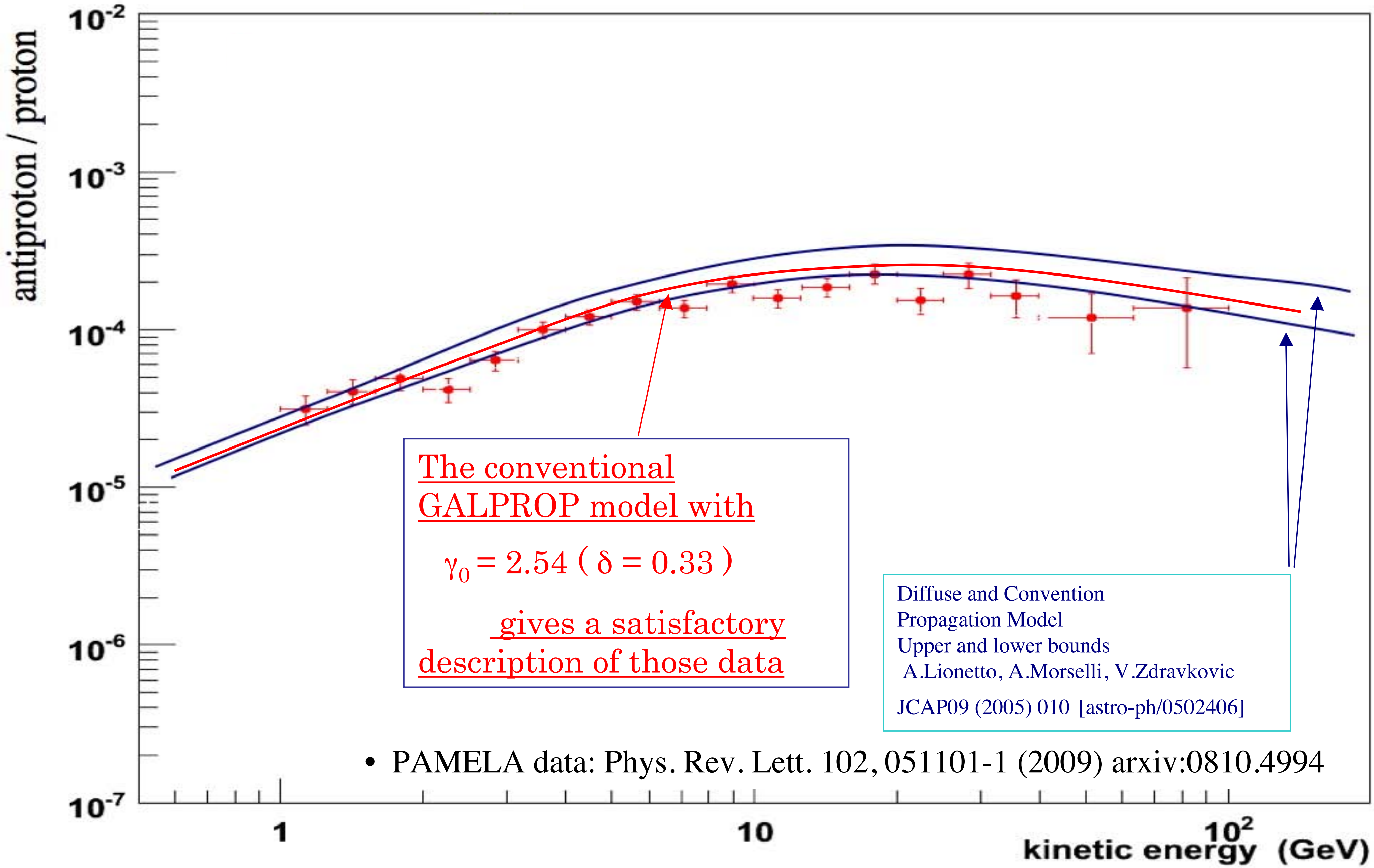
GF: 21.5 cm^2 sr
Mass: 470 kg
Size: 130x70x70 cm^3
Power Budget: 360W

Spectrometer
microstrip silicon tracking system + permanent magnet
It provides:
- *Magnetic rigidity* → R = pc/Ze
- *Charge sign*
- *Charge value from dE/dx*

- ~ 4 years from PAMELA launch

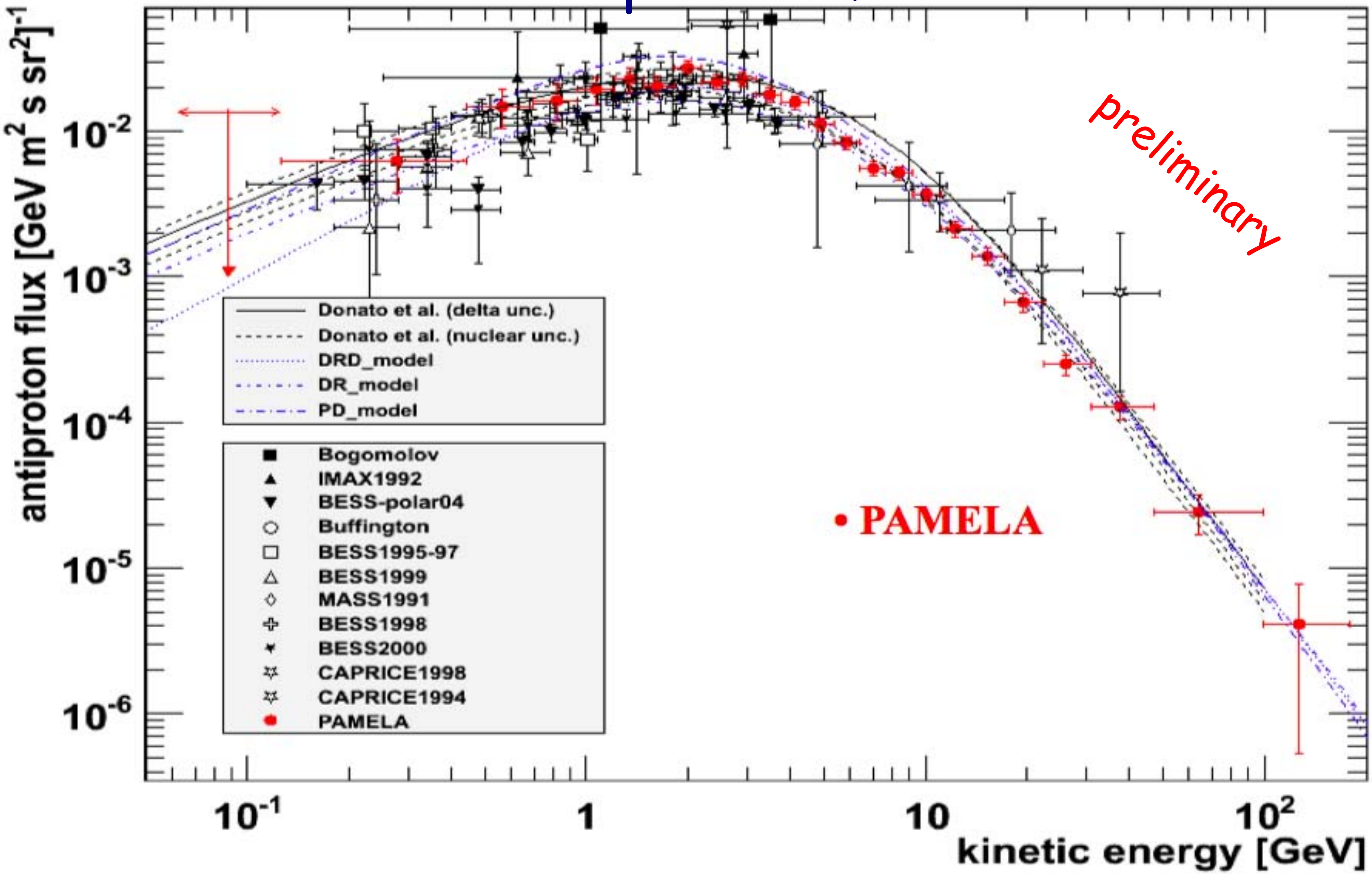
- Launched in orbit on June 15, 2006, on board of the DK1 satellite by a Soyuz rocket from the Bajkonour cosmodrom.

Antiproton-Proton Ratio

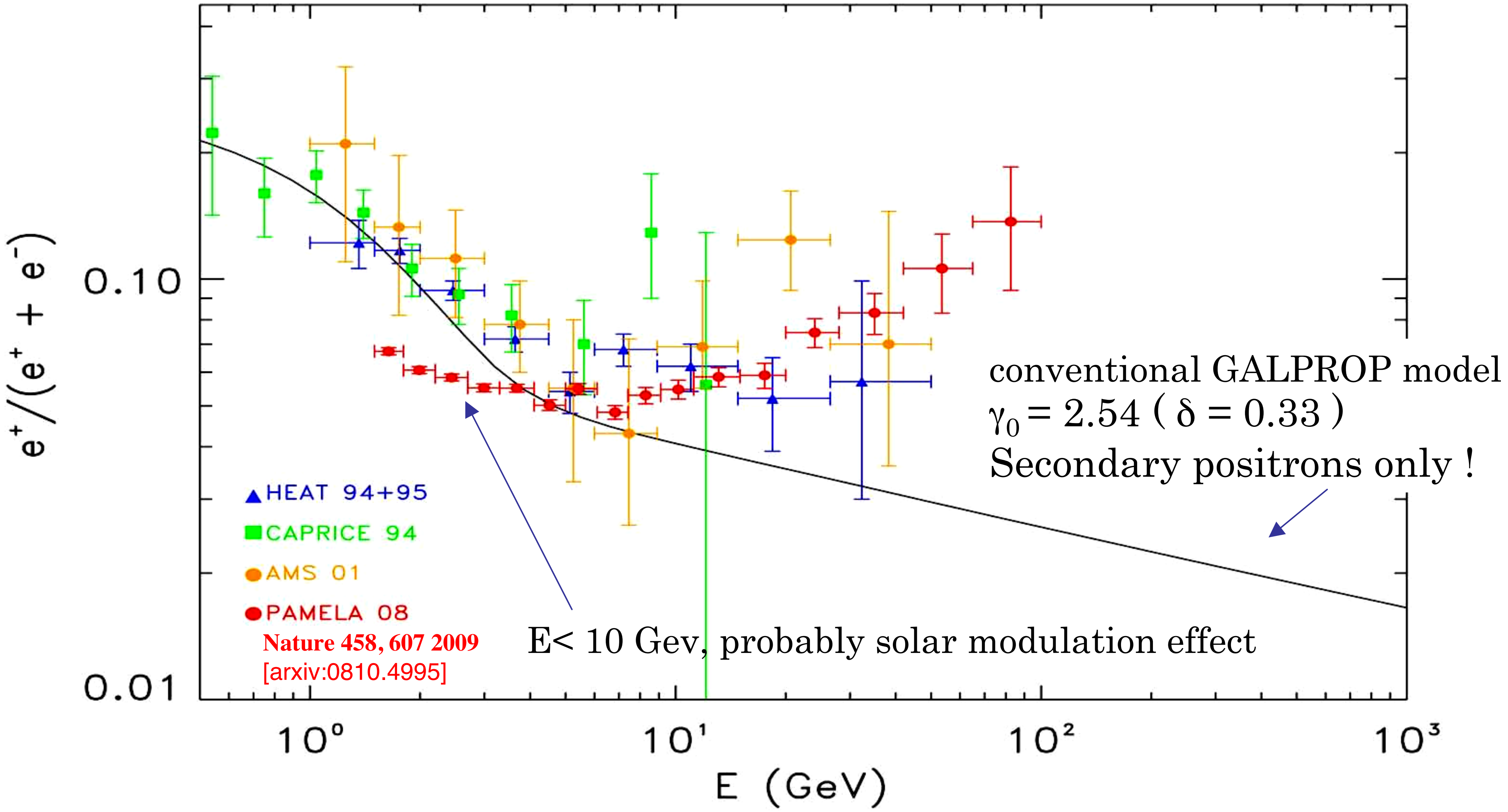


- PAMELA data: Phys. Rev. Lett. 102, 051101-1 (2009) arxiv:0810.4994

Antiproton flux



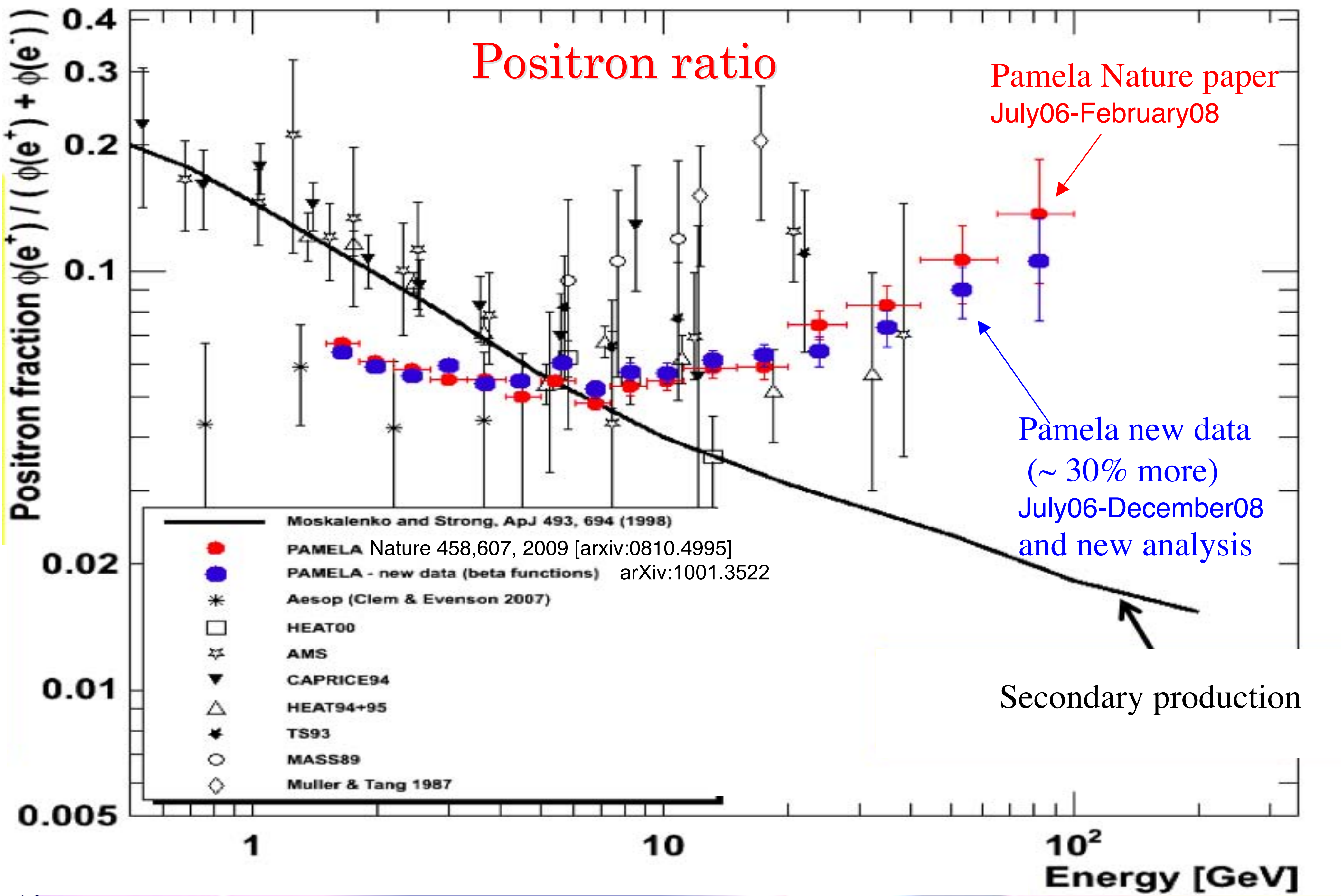
Positron ratio



$e^+/(e^+ + e^-) \propto E^{-\gamma p + \gamma_0 - \delta}$

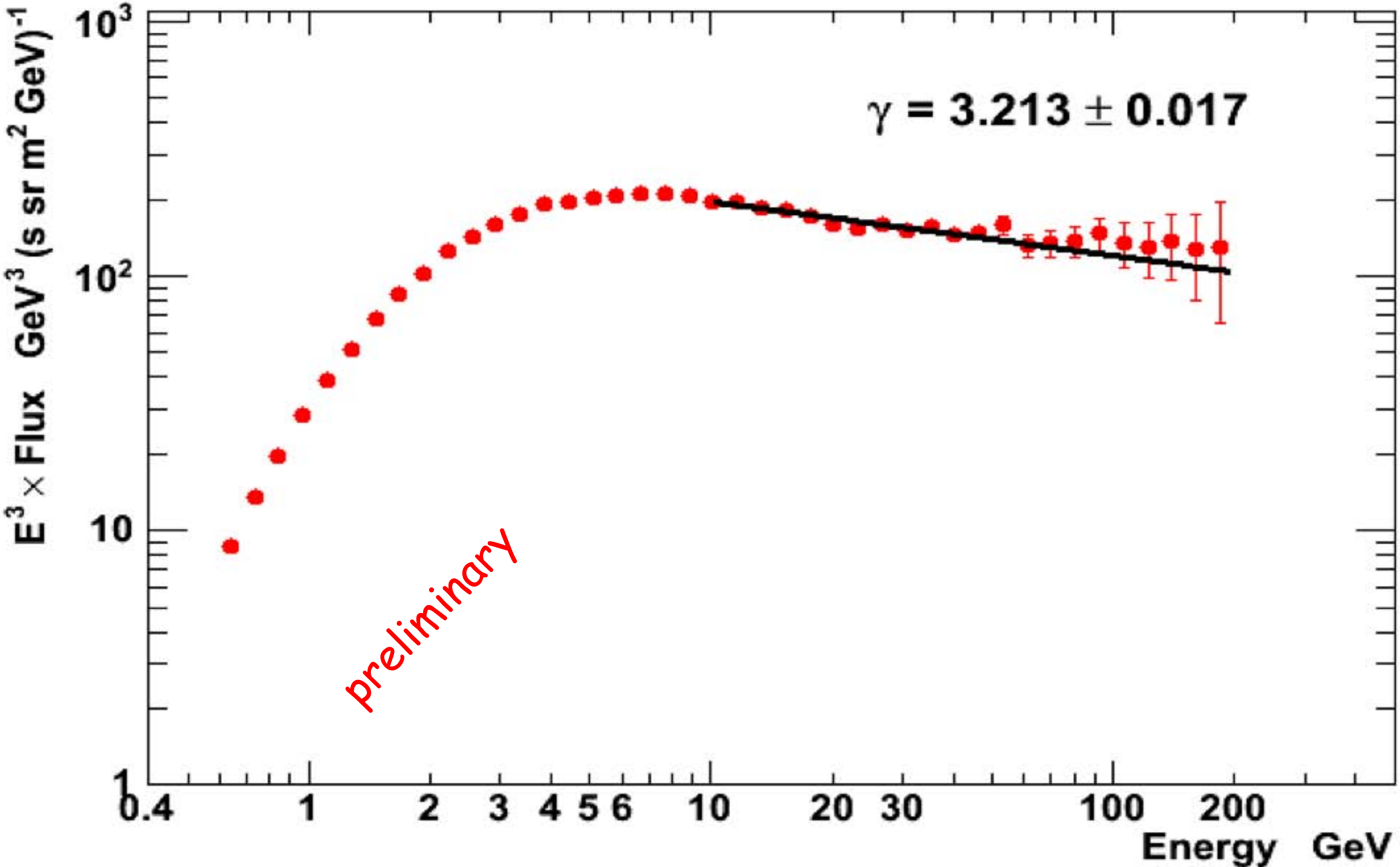
γp: proton source power-index

It improves only adopting very soft electron spectra (high γ_0)

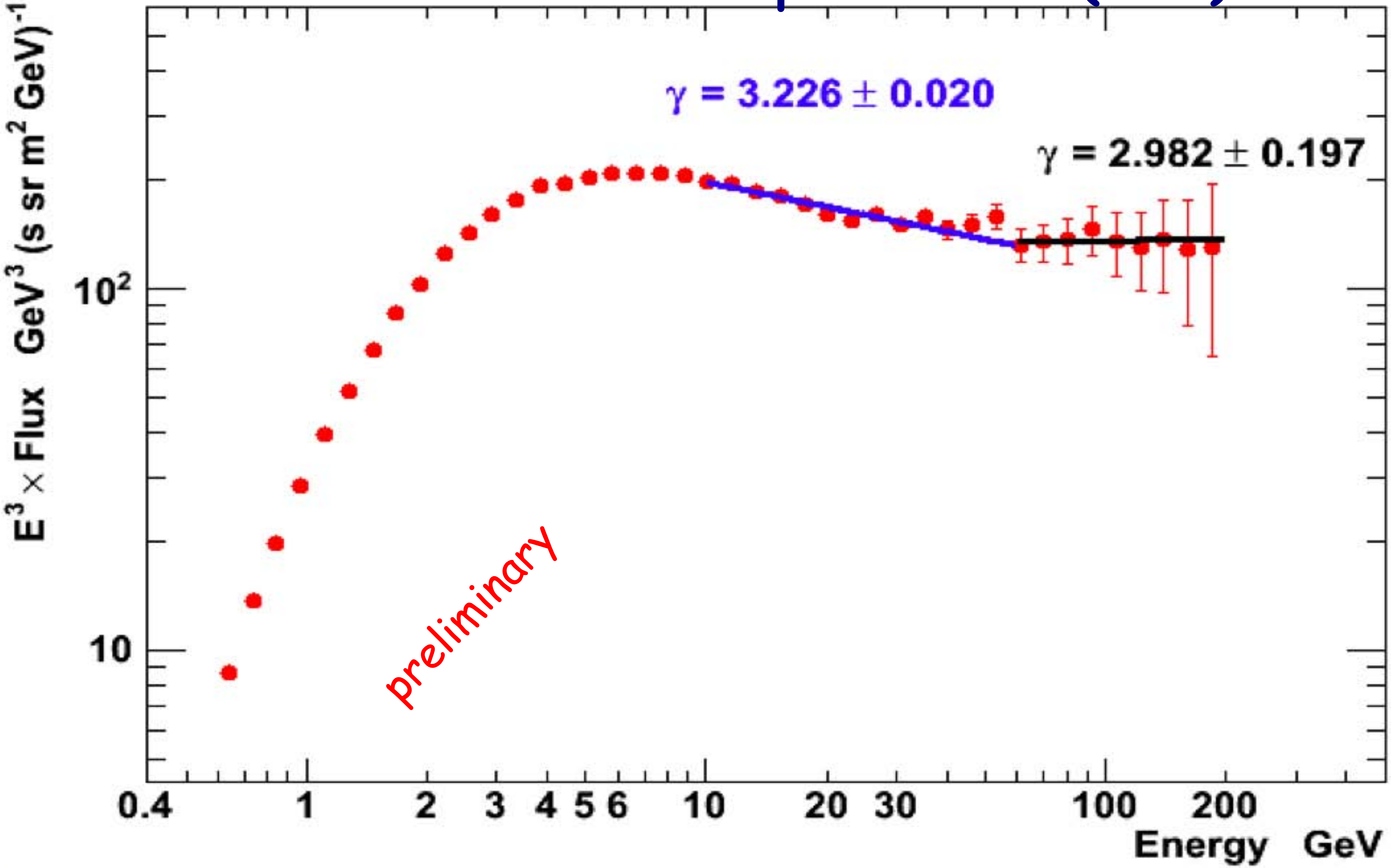


Positron ratio
Pamela Nature paper
July06-February08
Pamela new data
(~ 30% more)
July06-December08
and new analysis
Secondary production
Positron fraction φ(e+) / (φ(e+) + φ(e-))
0.4
0.3
0.2
0.1
0.02
0.01
0.005
1
10
10^2
Energy [GeV]
Moskalenko and Strong, ApJ 493, 694 (1998)
PAMELA Nature 458,607, 2009 [arxiv:0810.4995]
PAMELA - new data (beta functions) arXiv:1001.3522
Aesop (Clem & Evenson 2007)
HEAT00
AMS
CAPRICE94
HEAT94+95
TS93
MASS89
Muller & Tang 1987

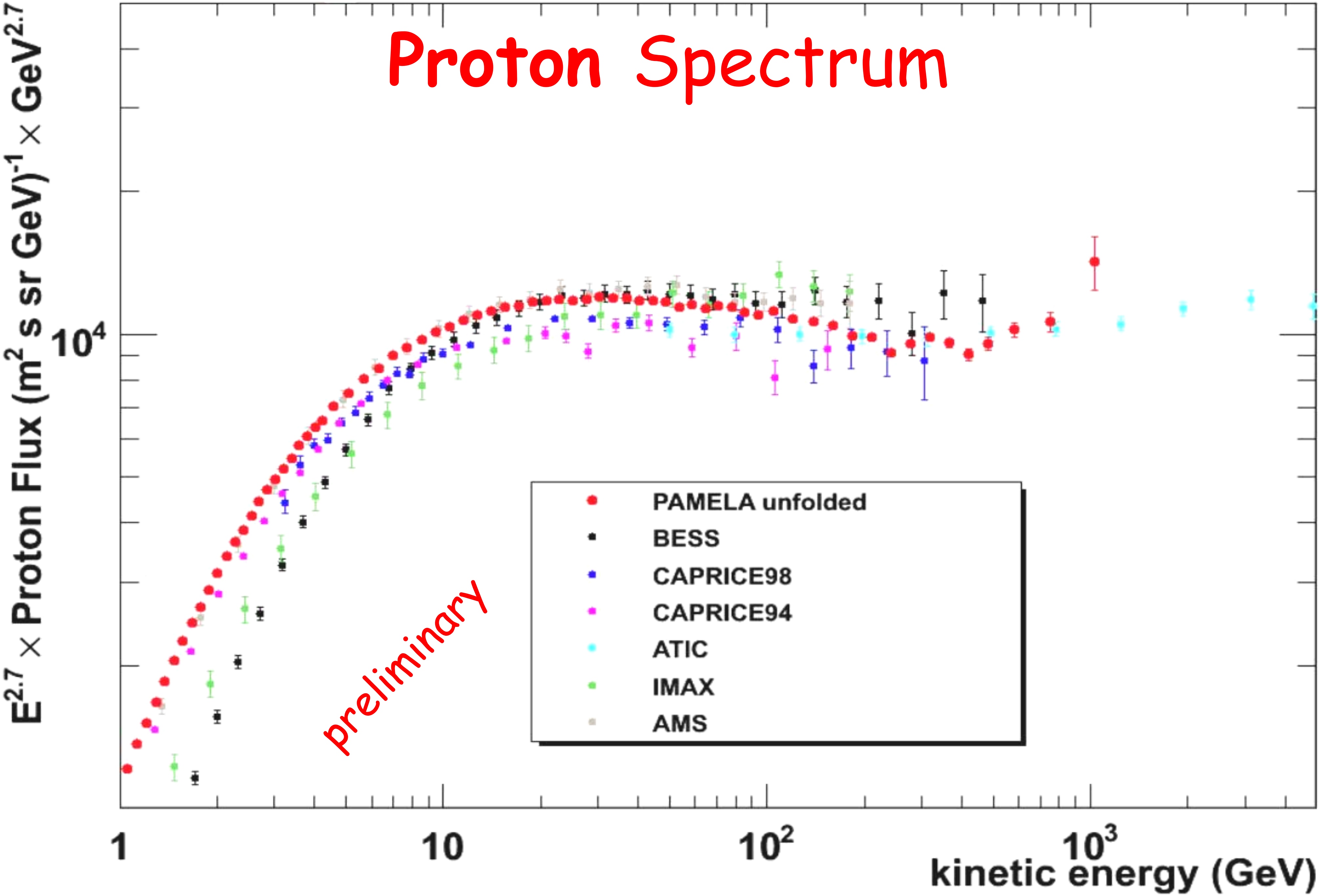
Pamela Electron Spectrum (e^-)



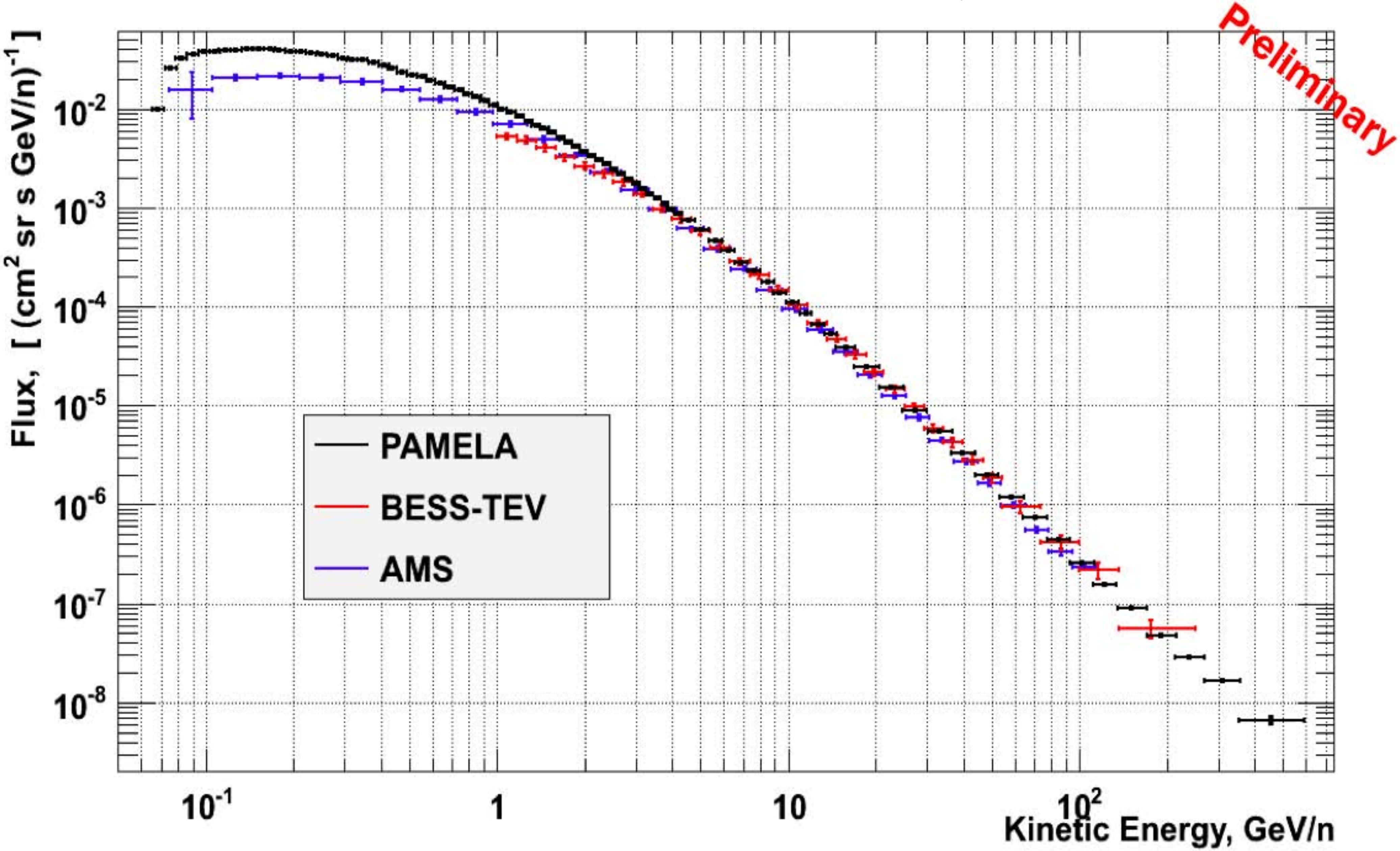
Pamela Electron Spectrum (e^-)

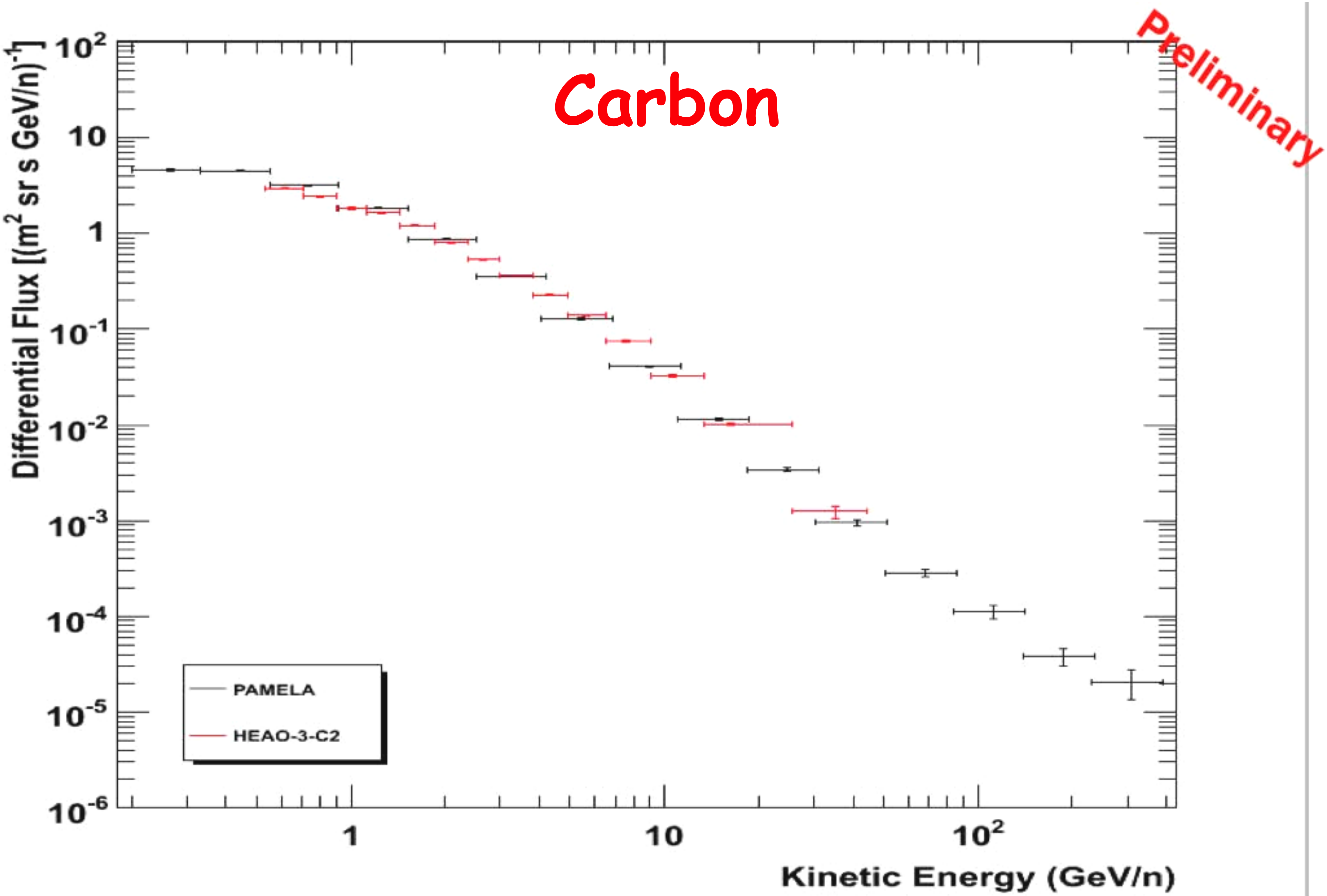


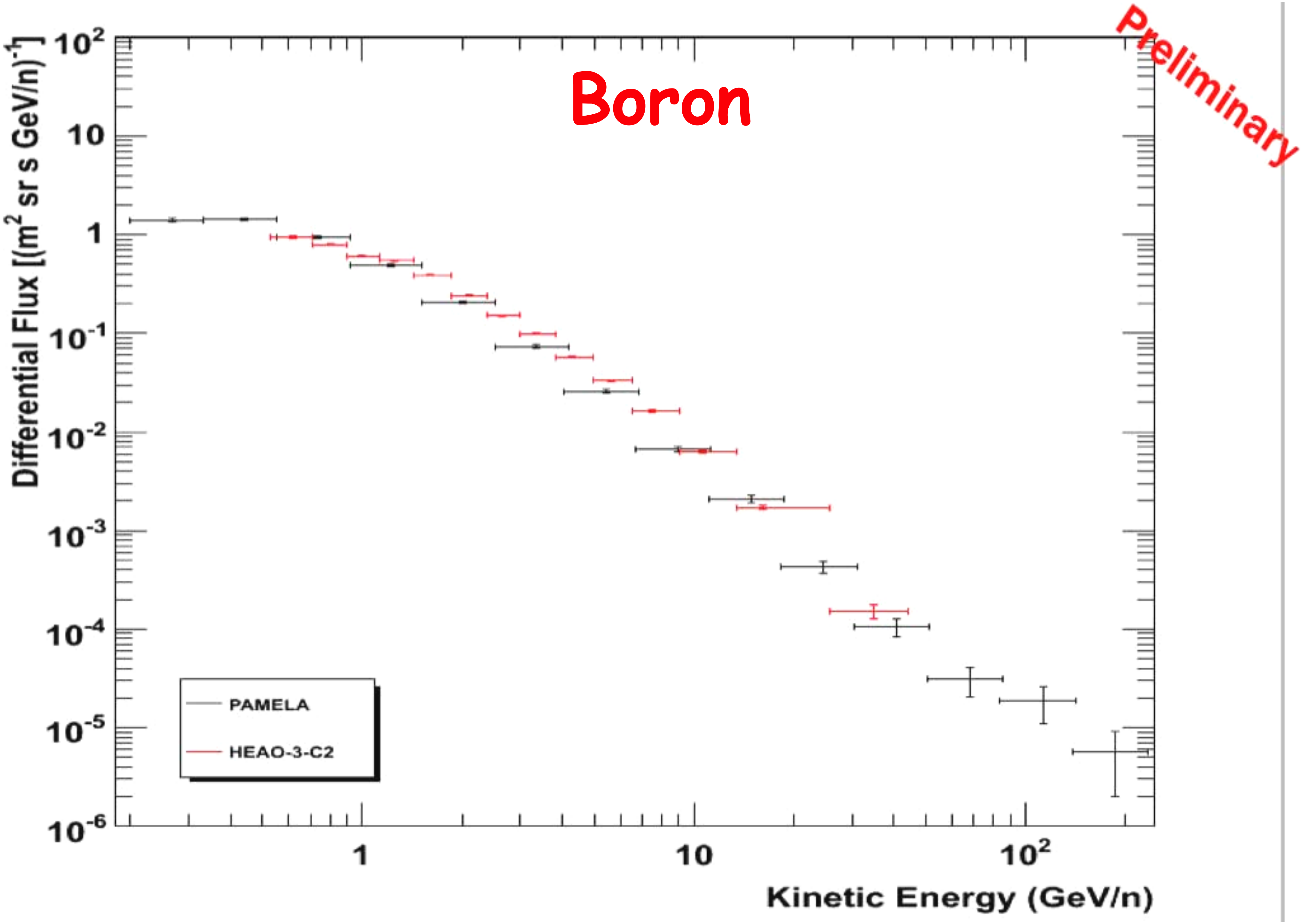
Proton Spectrum



PAMELA Helium

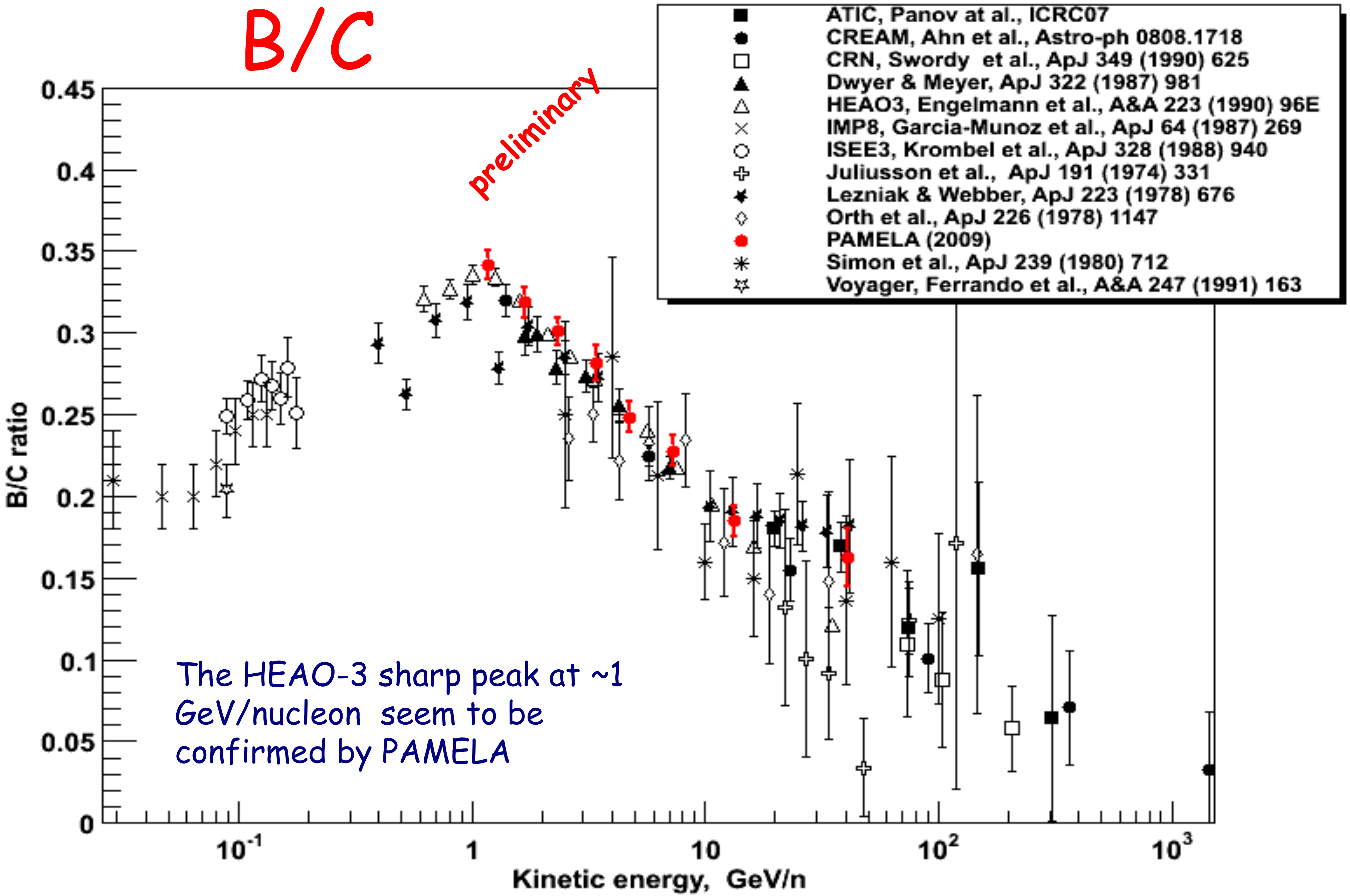


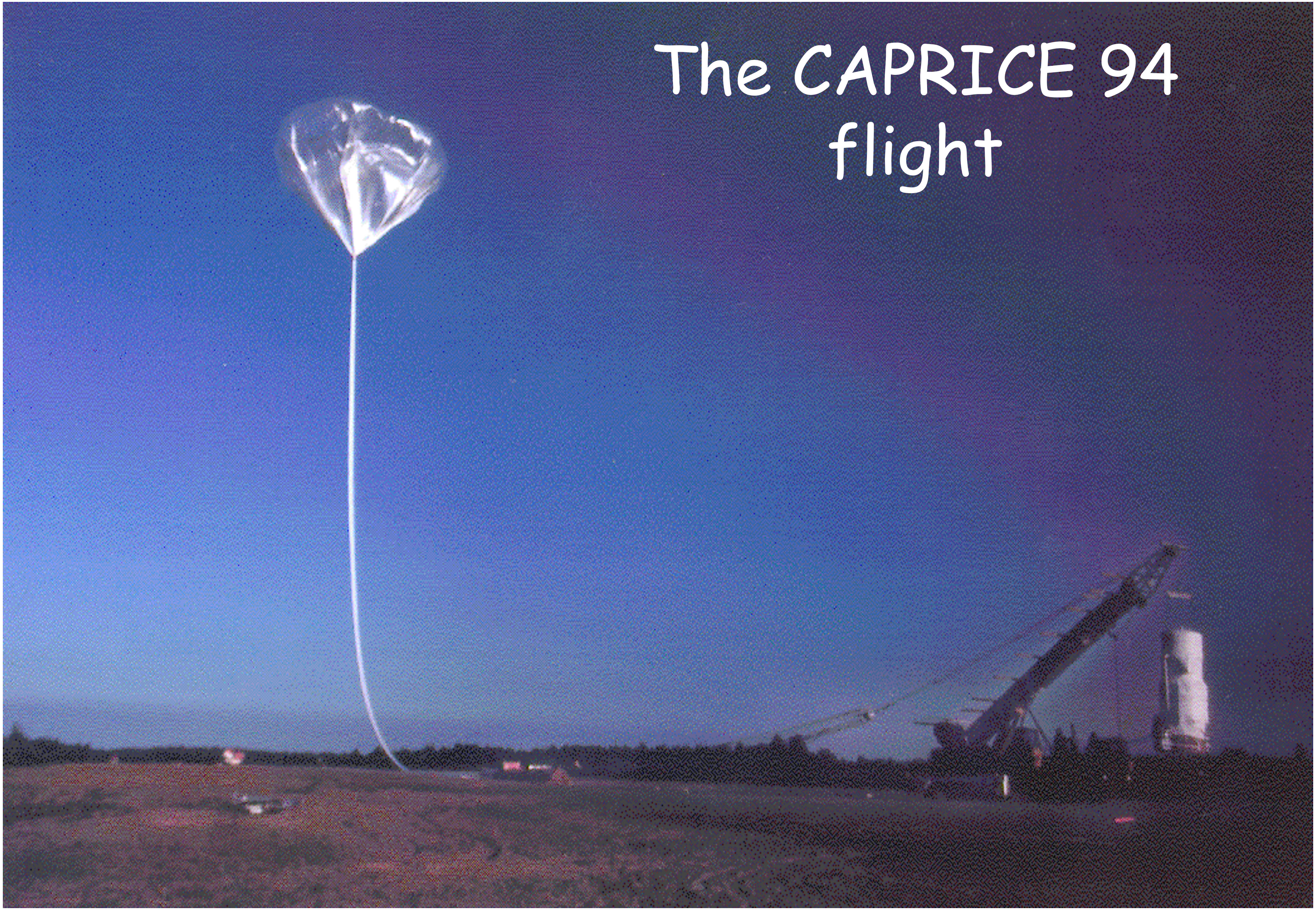

Preliminary
Carbon
Differential Flux [(m² sr s GeV/n)⁻¹]
10²
10
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
1
10
10²
Kinetic Energy (GeV/n)
PAMELA
HEAO-3-C2



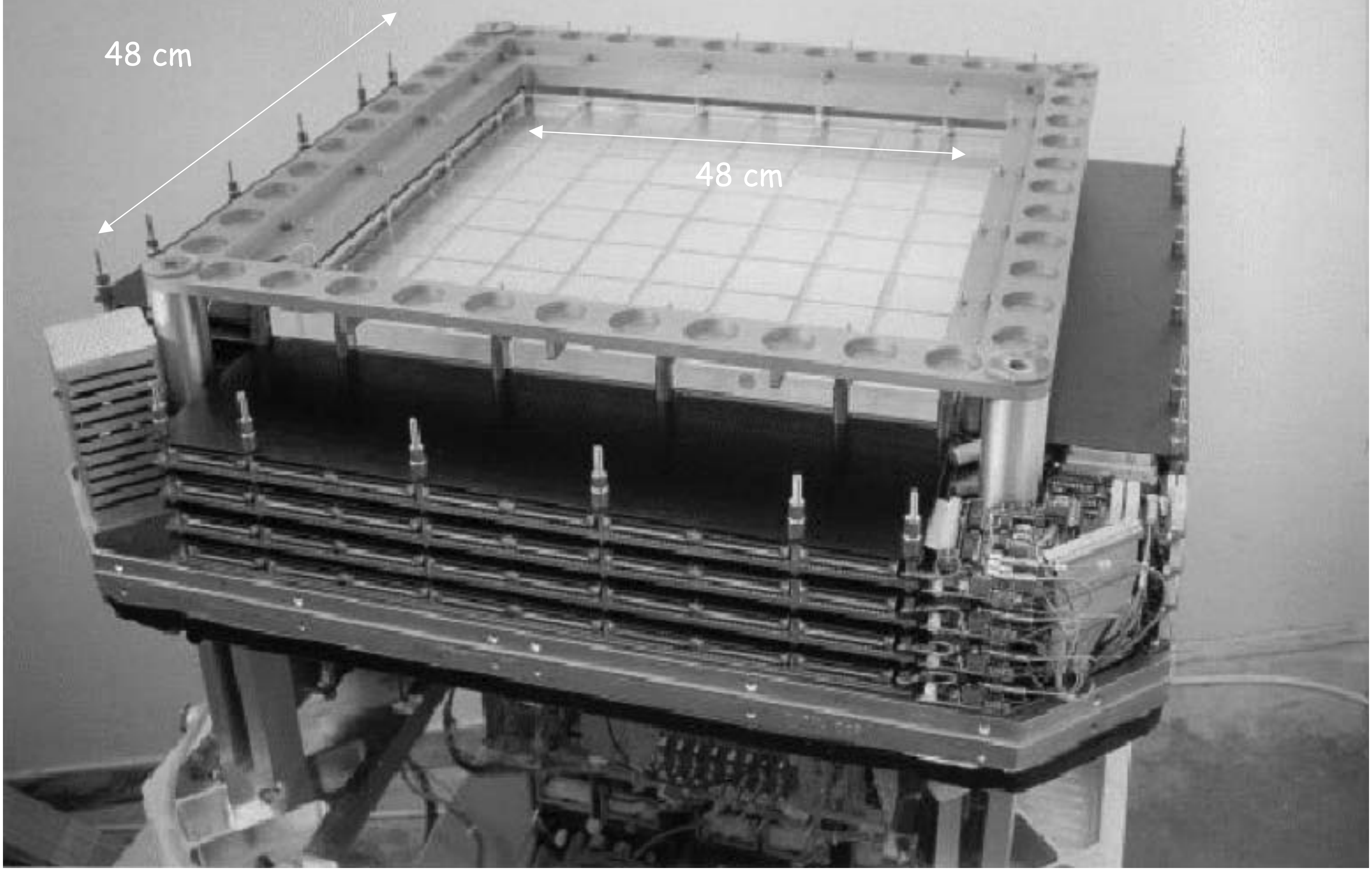
Boron
Preliminary
Differential Flux [(m^2 sr s GeV/n)^-1]
10^2
10
1
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
1
10
10^2
Kinetic Energy (GeV/n)
PAMELA
HEAO-3-C2

B/C

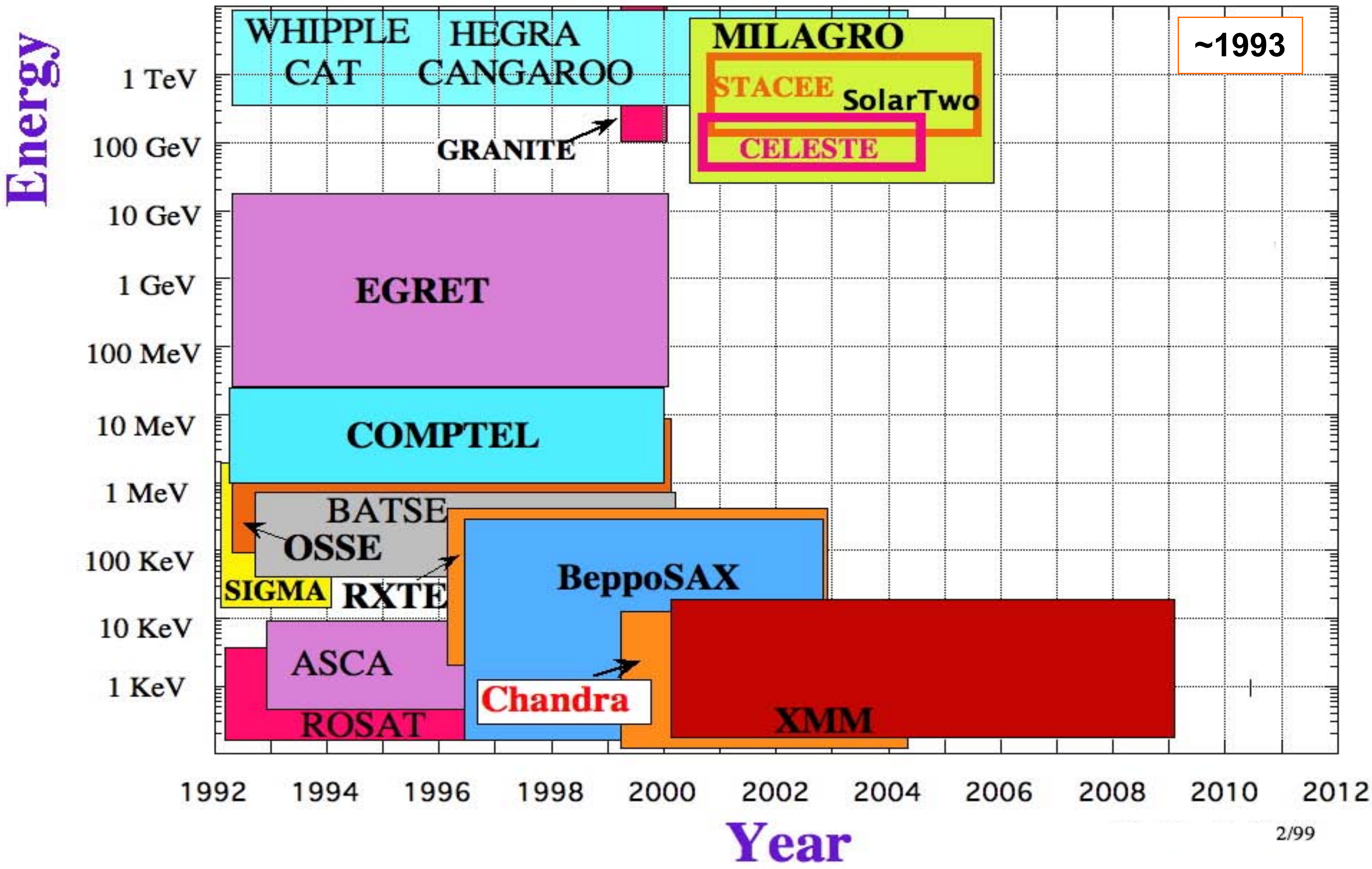

preliminary
B/C ratio
Kinetic energy, GeV/n
ATIC, Panov at al., ICRC07
CREAM, Ahn et al., Astro-ph 0808.1718
CRN, Swordy et al., ApJ 349 (1990) 625
Dwyer & Meyer, ApJ 322 (1987) 981
HEAO3, Engelmann et al., A&A 223 (1990) 96E
IMP8, Garcia-Munoz et al., ApJ 64 (1987) 269
ISEE3, Krombel et al., ApJ 328 (1988) 940
Juliusson et al., ApJ 191 (1974) 331
Lezniak & Webber, ApJ 223 (1978) 676
Orth et al., ApJ 226 (1978) 1147
PAMELA (2009)
Simon et al., ApJ 239 (1980) 712
Voyager, Ferrando et al., A&A 247 (1991) 163
The HEAO-3 sharp peak at ~1 GeV/nucleon seem to be confirmed by PAMELA


The CAPRICE 94
flight

The TS93 and CAPRICE silicon-tungsten imaging calorimeter.



High Energy Gamma Experiments Experiments



Nuclear Instruments and Methods in Physics Research A 354 (1995) 547–552

ELSEVIER

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

The GILDA mission: a new technique for a gamma-ray telescope in the energy range 20 MeV–100 GeV

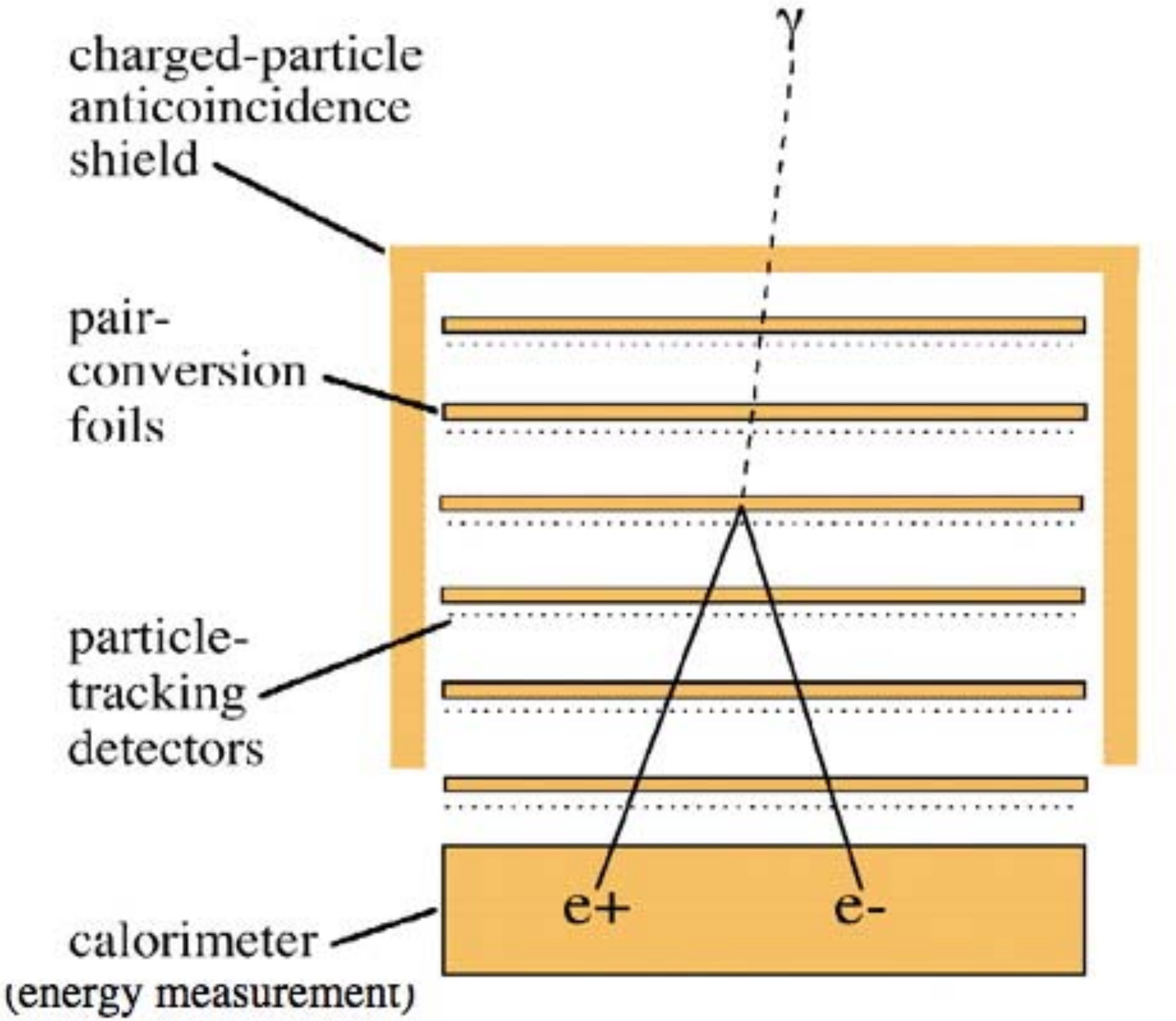
G. Barbiellini [a], M. Boezio [a], M. Casolino [b], M. Candusso [b], M.P. De Pascale [b], A. Morselli [b,*], P. Picozza [b], M. Ricci [d], R. Sparvoli [b], P. Spillantini [c], A. Vacchi [a]

[a] *Dept. of Physics, Univ. of Trieste and INFN, Italy*
[b] *Dept. of Physics, II Univ. of Rome "Tor Vergata" and INFN, Italy*
[c] *Dept. of Physics, Univ. of Firenze and INFN, Italy*
[d] *INFN Laboratori Nazionali di Frascati, Italy*
* Corresponding author
Received 5 August 1994

Abstract

In this article a new technique for the realization of a high energy gamma-ray telescope is presented, based on the adoption of silicon strip detectors and lead scintillating fibers. The simulated performances of such an instrument (GILDA) are significatively better than those of EGRET, the last successful experiment of a high energy gamma-ray telescope, launched on the CGRO satellite, though having less volume and weight.

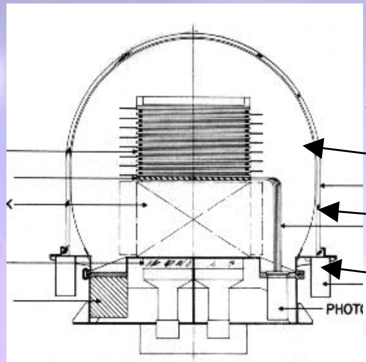
Elements of a pair-conversion telescope



- photons materialize into matter-antimatter pairs:

  E_γ --> $m_{e^+}c^2 + m_{e^-}c^2$

- electron and positron carry information about the direction, energy and polarization of the γ-ray



SAS-2
11/1972-7/1973

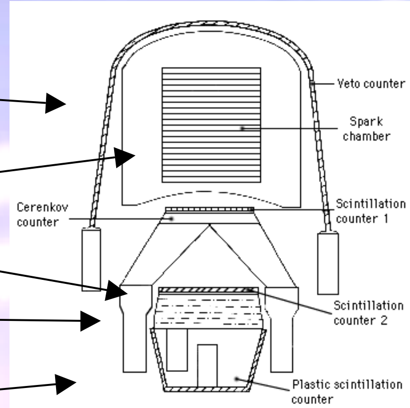
Anti-Coincidence Dome

Spark Chamber

Trigger Telescope

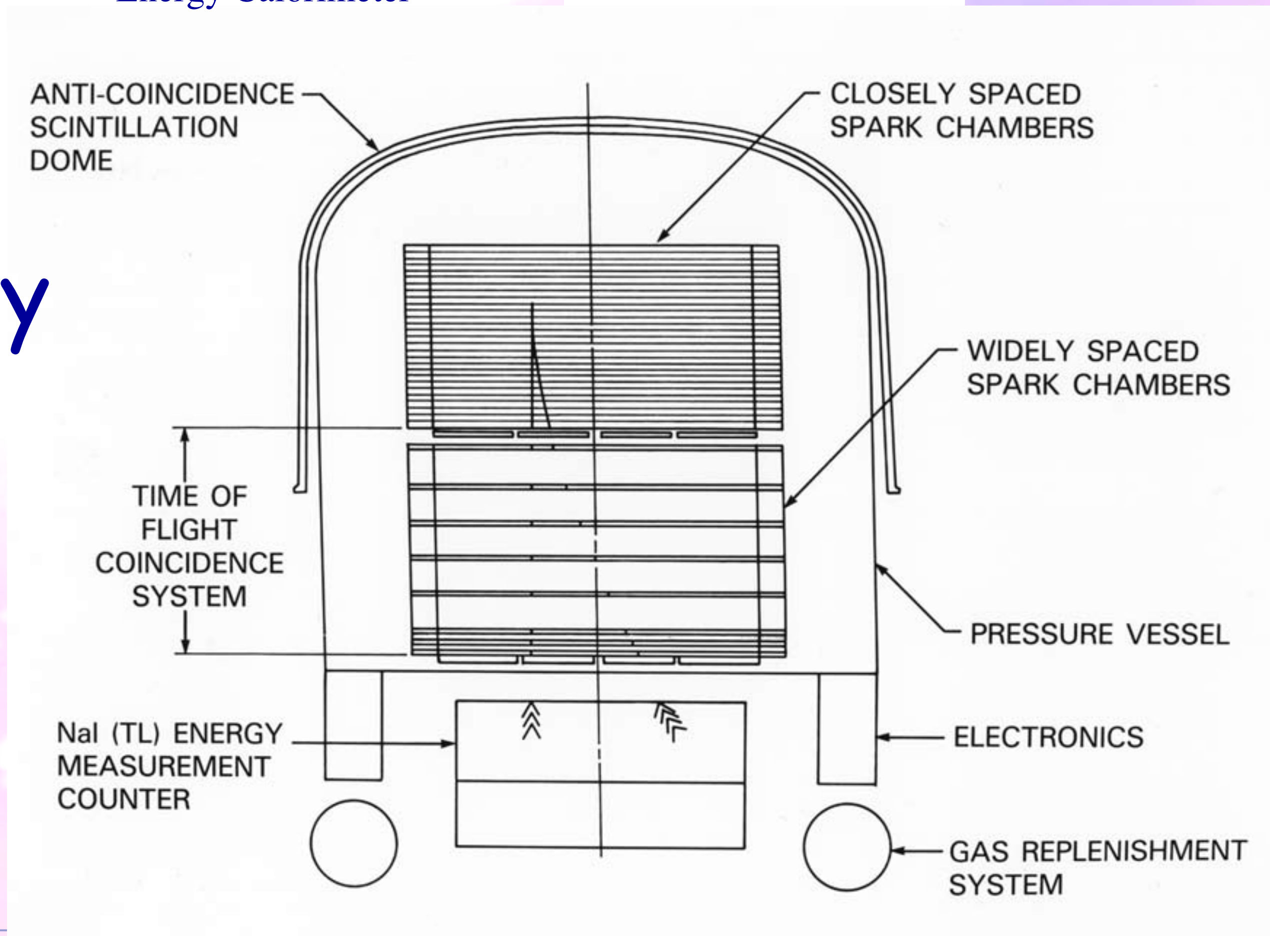
Cerenkov Counter

Energy Calorimeter

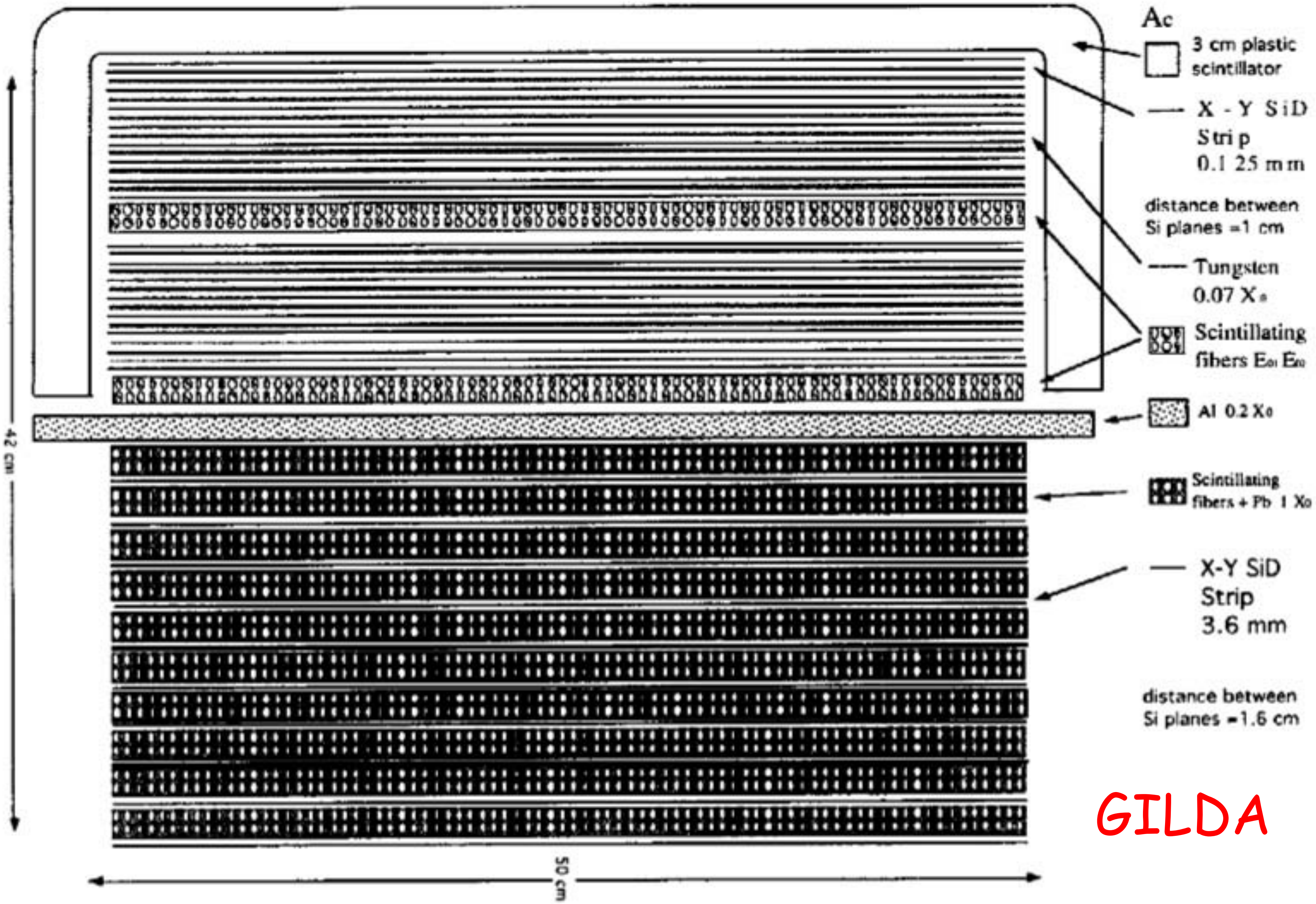


Cos-B
8/1975-4/1982

The gamma-ray missions



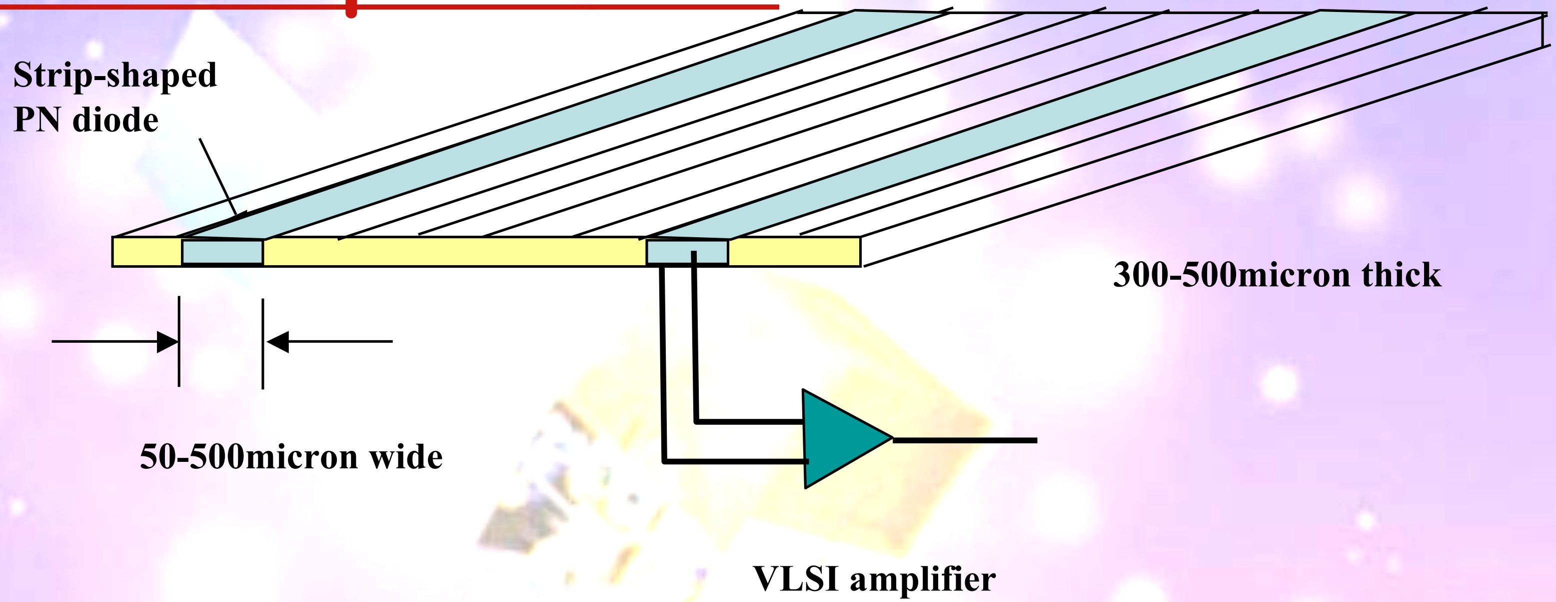
EGRET
4/1991-1999


Ac
3 cm plastic scintillator
X - Y SiD Strip 0.125 mm
distance between Si planes =1 cm
Tungsten 0.07 X0
Scintillating fibers
Al 0.2 X0
Scintillating fibers + Pb 1 X0
X-Y SiD Strip 3.6 mm
distance between Si planes =1.6 cm
42 cm
50 cm

GILDA

New Detector Technology

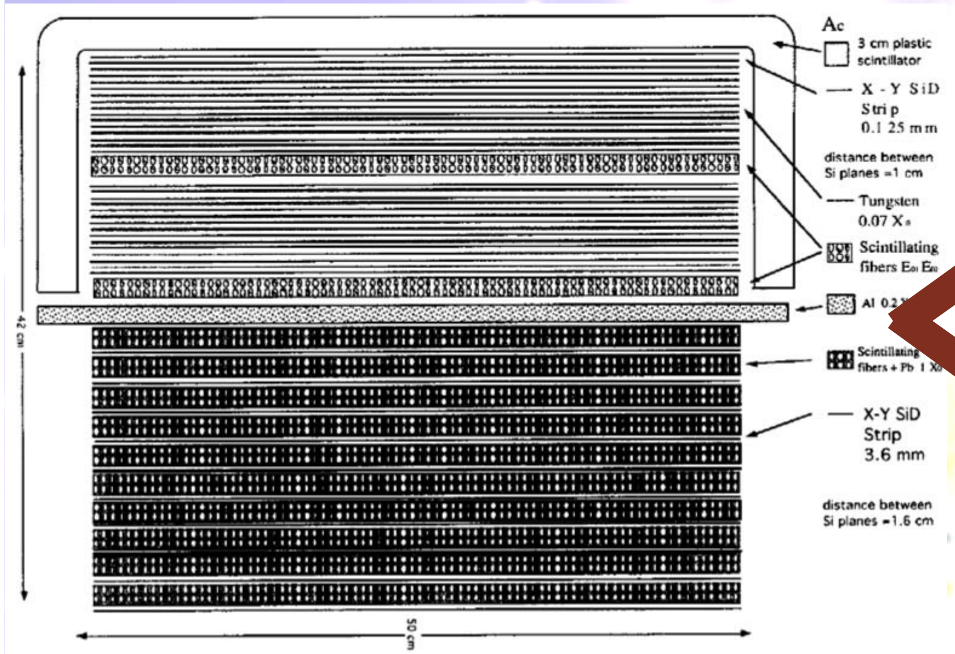
- Silicon strip detector



Stable particle tracker that allows micron-level tracking of gamma-rays

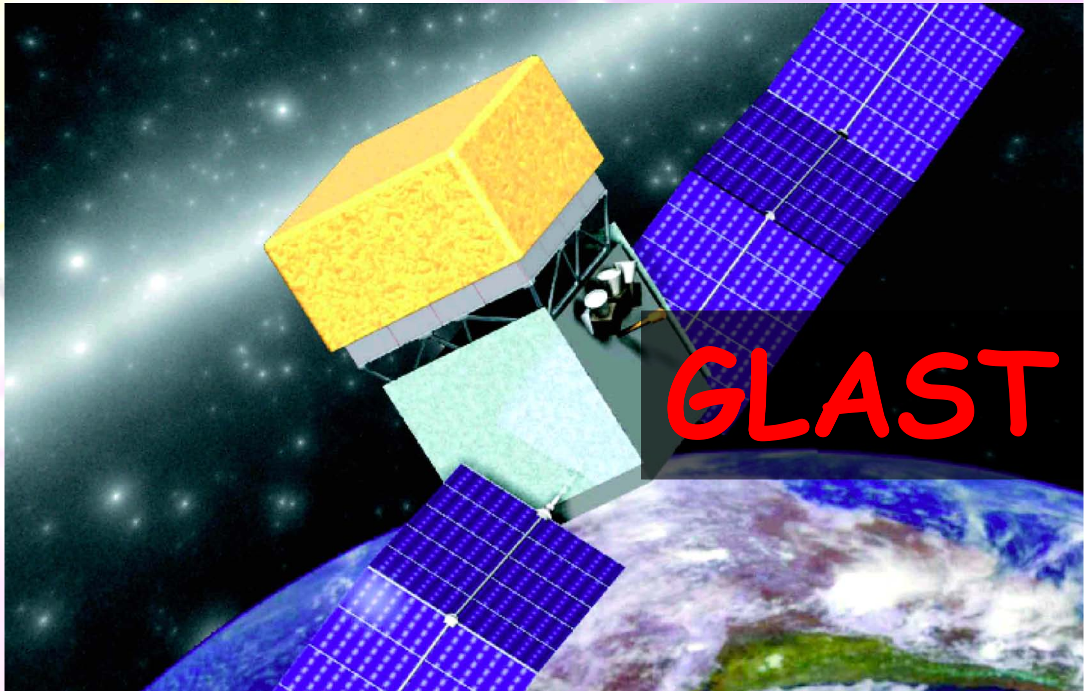
Well known technology in Particle Physics experiments.
Used by our collaboration in balloon experiments (MASS, TS93, CAPRICE), on MIR Space Station (SilEye) and on satellite (NINA)

GILDA



Ac
3 cm plastic scintillator
X - Y SiD Strip 0.1 25 mm
distance between Si planes =1 cm
Tungsten 0.07 X₀
Scintillating fibers
Al
Scintillating fibers + Pb
X-Y SiD Strip 3.6 mm
distance between Si planes =1.6 cm
42 cm
50 cm

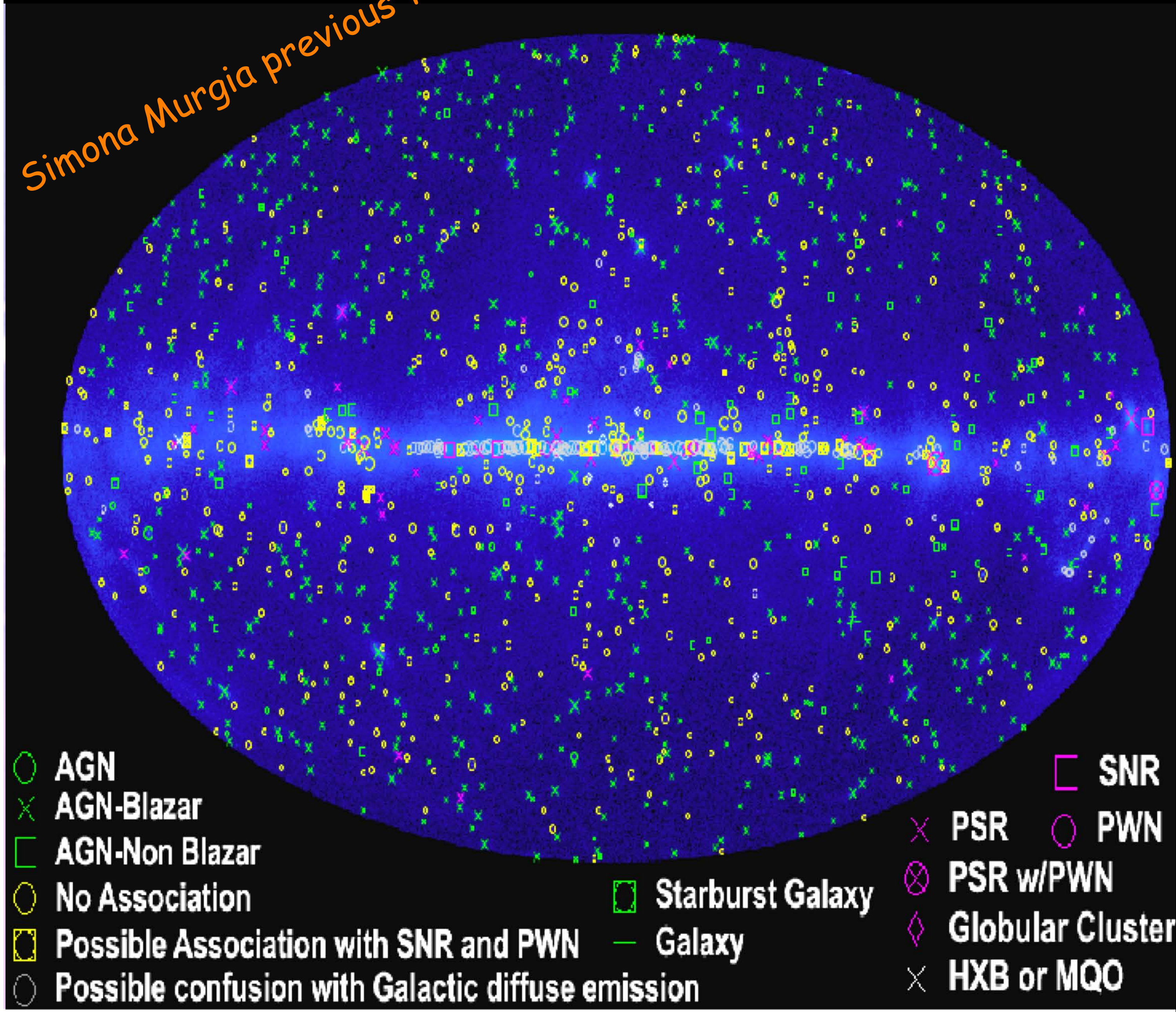
agile
Astro-rivelatore Gamma
a Immagini Leggero
INAF
INFN



GLAST

Fermi launch 11 June 2008

First Fermi LAT Catalogs



1451 sources

Fermi Large Area Telescope First Source Catalog arXiv:1002.2280, 2010 ApJS accepted. (1FGL)contains **1451** sources detected and characterized in the 100 MeV to 100 GeV, first 11 months data.

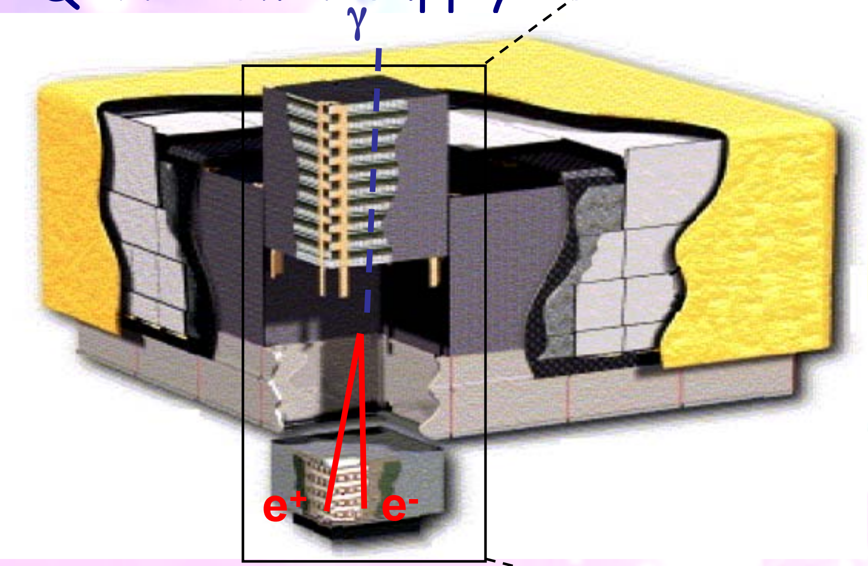
The First Catalog of Active Galactic Nuclei Detected by the Fermi Large Area Telescope arXiv: 1002.0150, includes **671** gamma-ray sources at high Galactic latitudes (|b| > 10 deg), with TS> 25 and associated statistically with AGNs.

The First Fermi Large Area Telescope Catalog of Gamma-ray Pulsars 2010ApJS..187..460A . Contains **46** high-confidence pulsed detections using the first six months of data

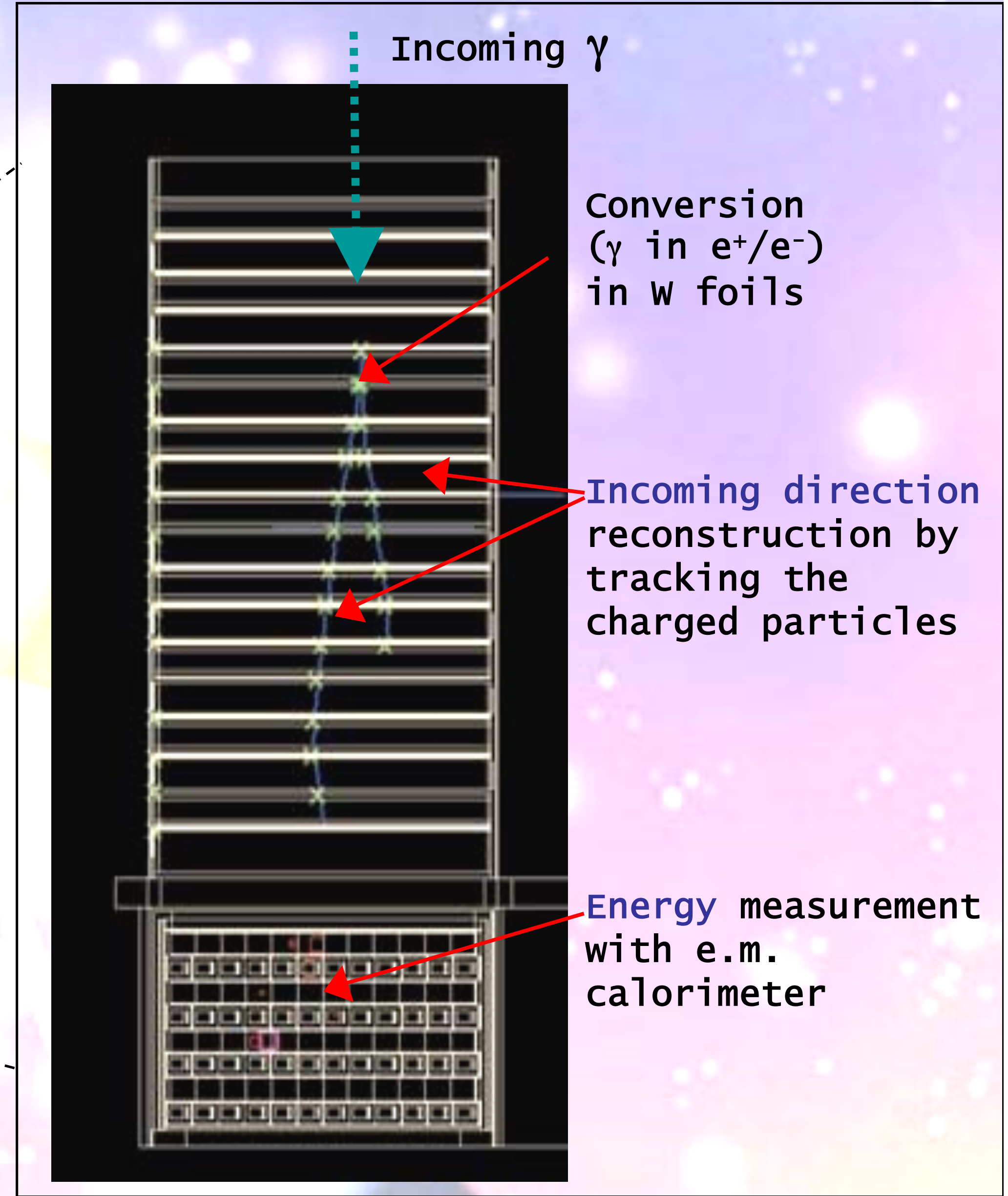
How Fermi LAT detects gamma rays

4 x 4 array of identical towers with:

- Precision Si-strip tracker (TKR)
  - With W converter foils
- Hodoscopic CsI calorimeter (CAL)
- DAQ and Power supply box



An anticoincidence detector around the telescope distinguishes gamma-rays from charged particles



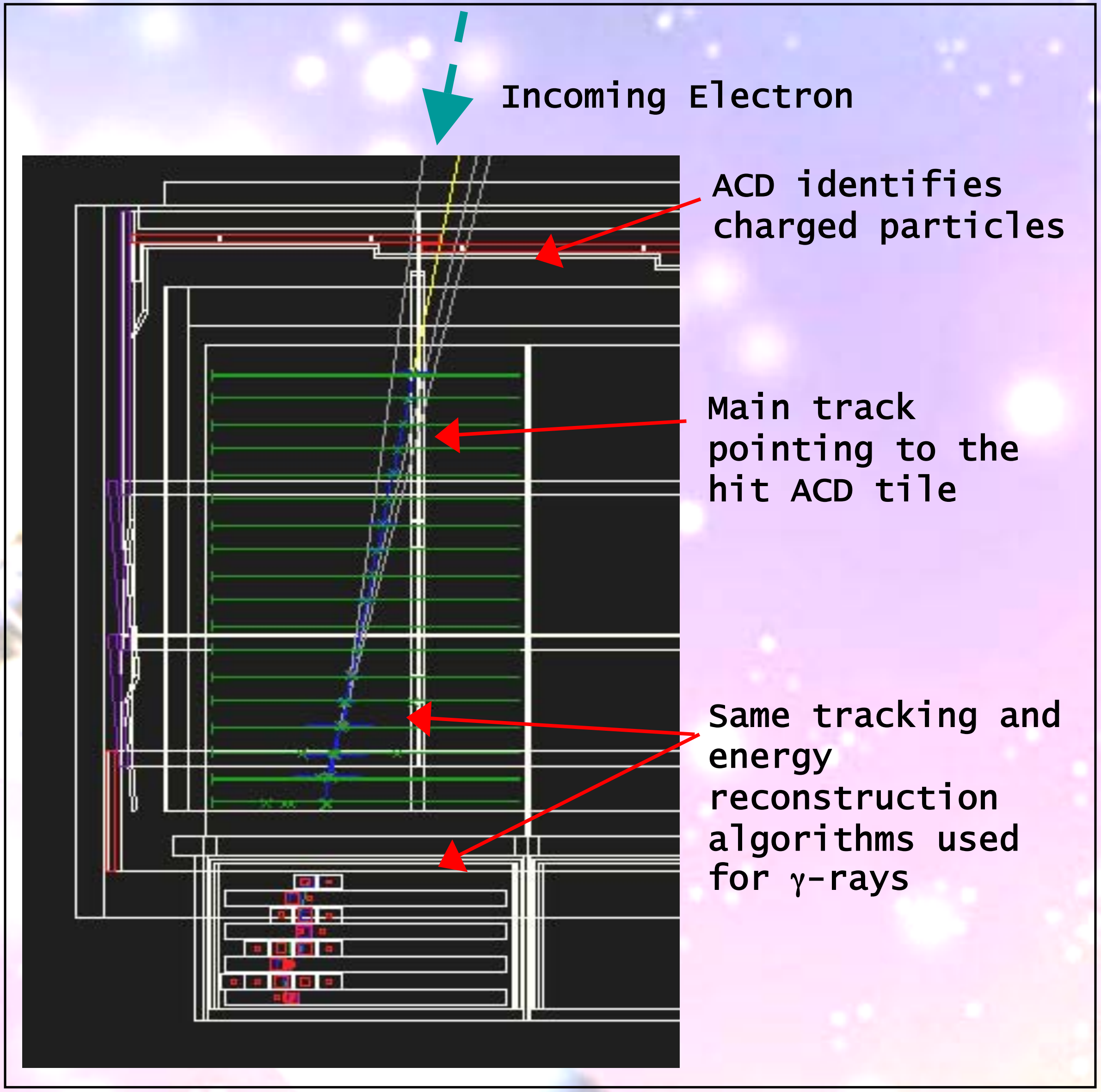
How Fermi LAT detects electrons

Trigger and downlink

- LAT triggers on (almost) every particle that crosses the LAT
  - ~ 2.2 kHz trigger rate
- On board processing removes many charged particles events
  - But keeps events with more that 20 GeV of deposited energy in the CAL
  - ~ 400 Hz downlink rate
- Only ~1 Hz are good γ-rays

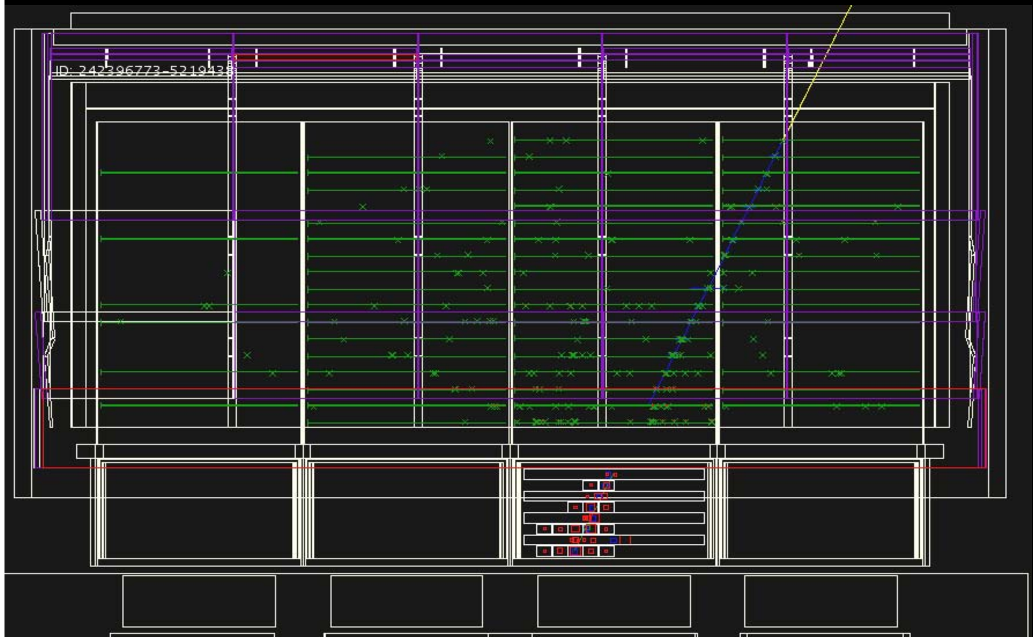
Electron identification

- The challenge is identifying the good electrons among the proton background
  - Rejection power of 10^3 - 10^4 required
  - Can not separate electrons from positrons

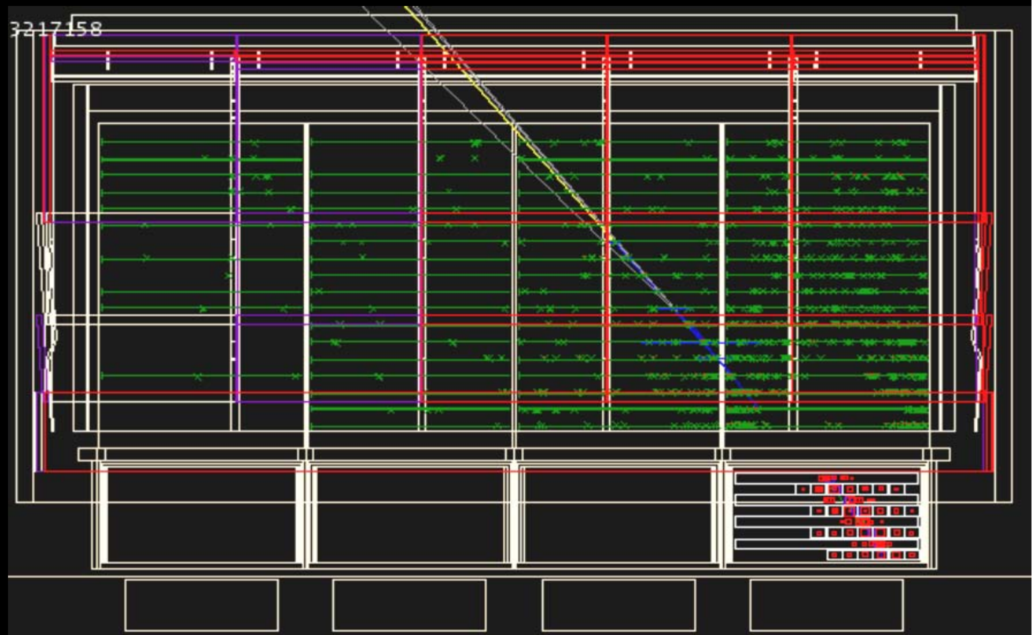


Event topology

A candidate electron (recon energy 844 GeV)



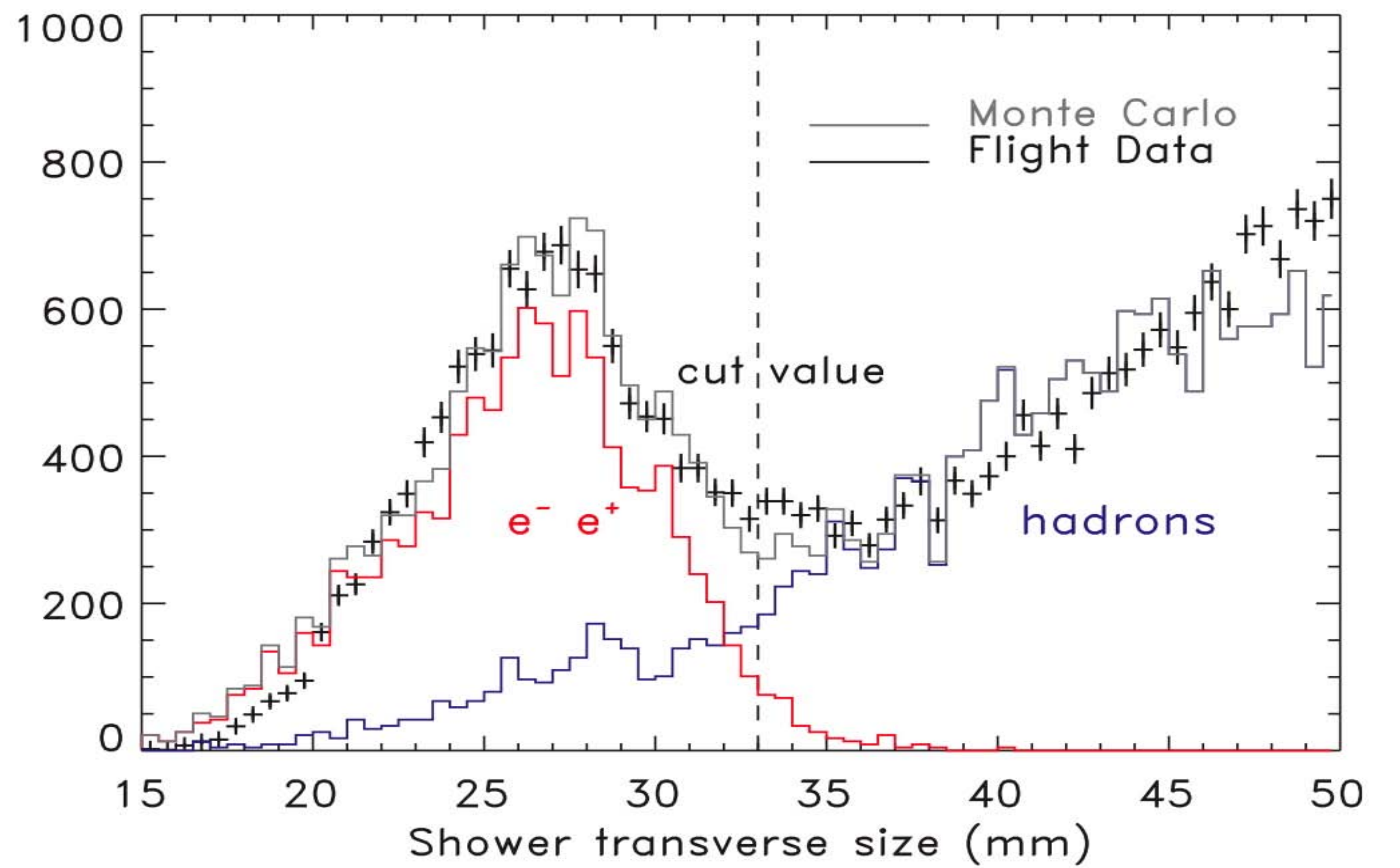
A candidate hadron (raw energy > 800 GeV)



- TKR: clean main track with extra-clusters very close to the track
- CAL: clean EM shower profile, not fully contained
- ACD: few hits in conjunction with the track

- TKR: small number of extra clusters around main track
- CAL: large and asymmetric shower profile
- ACD: large energy deposit per tile

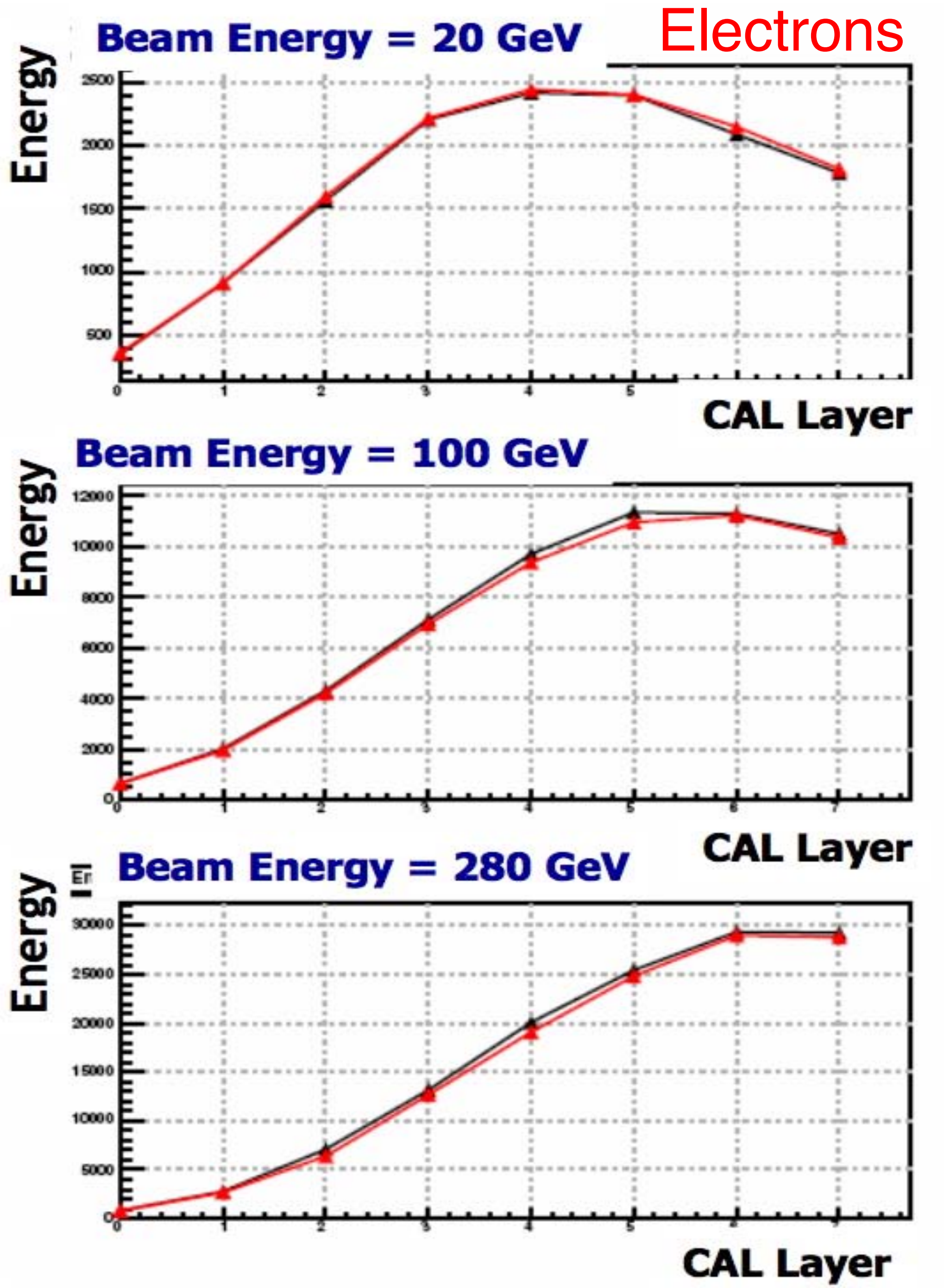
Distribution of the transverse sizes of the showers (above 150 GeV) in the calorimeter



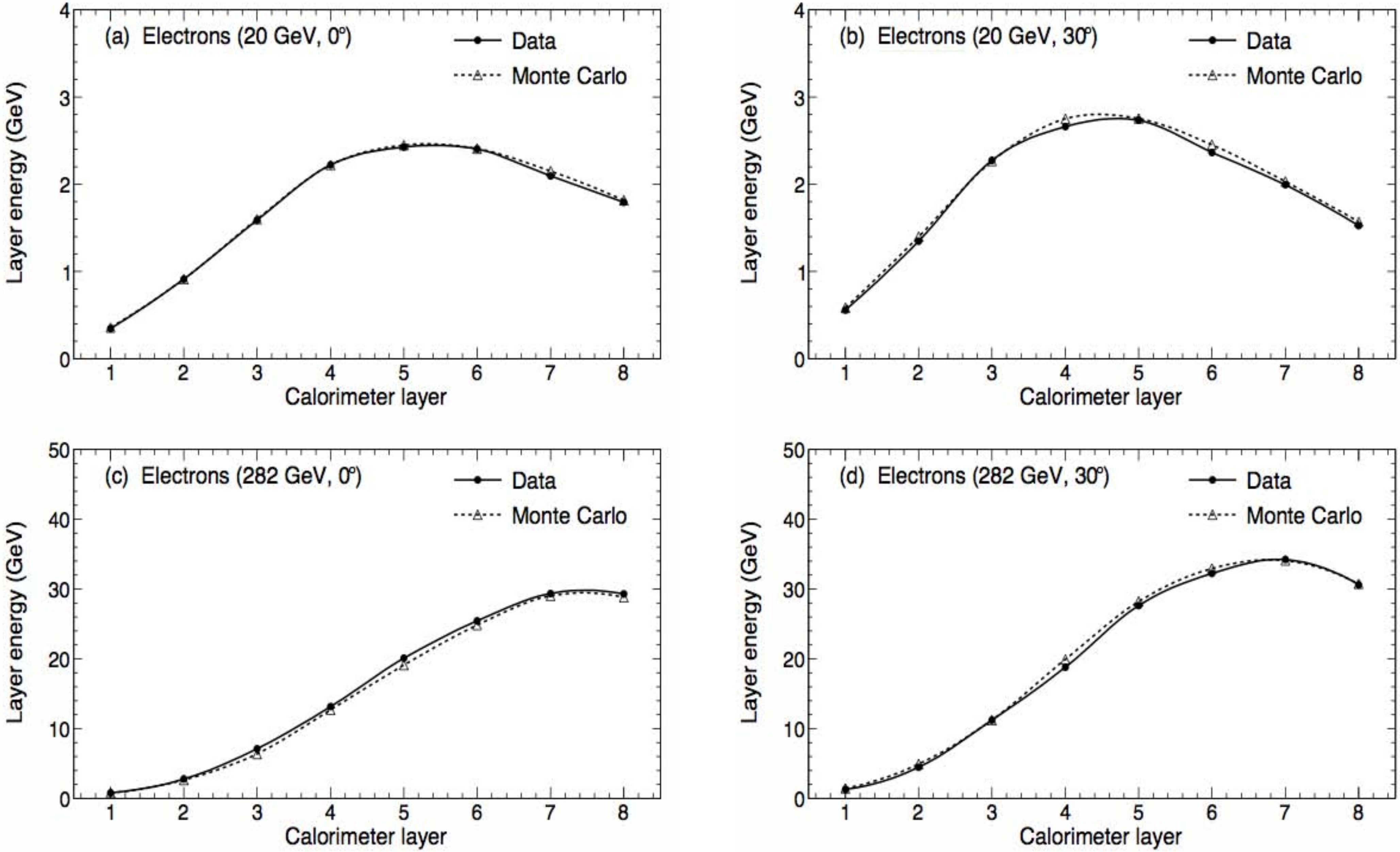
Energy reconstruction

Reconstruction of the most probable value for the event energy:
- based on calibration of the response of each of 1536 calorimeter crystals
- energy reconstruction is optimized for each event
-calorimeter imaging capability is heavily used for fitting shower profile -
-tested at CERN beams up to 280 GeV with the LAT Calibration Unit

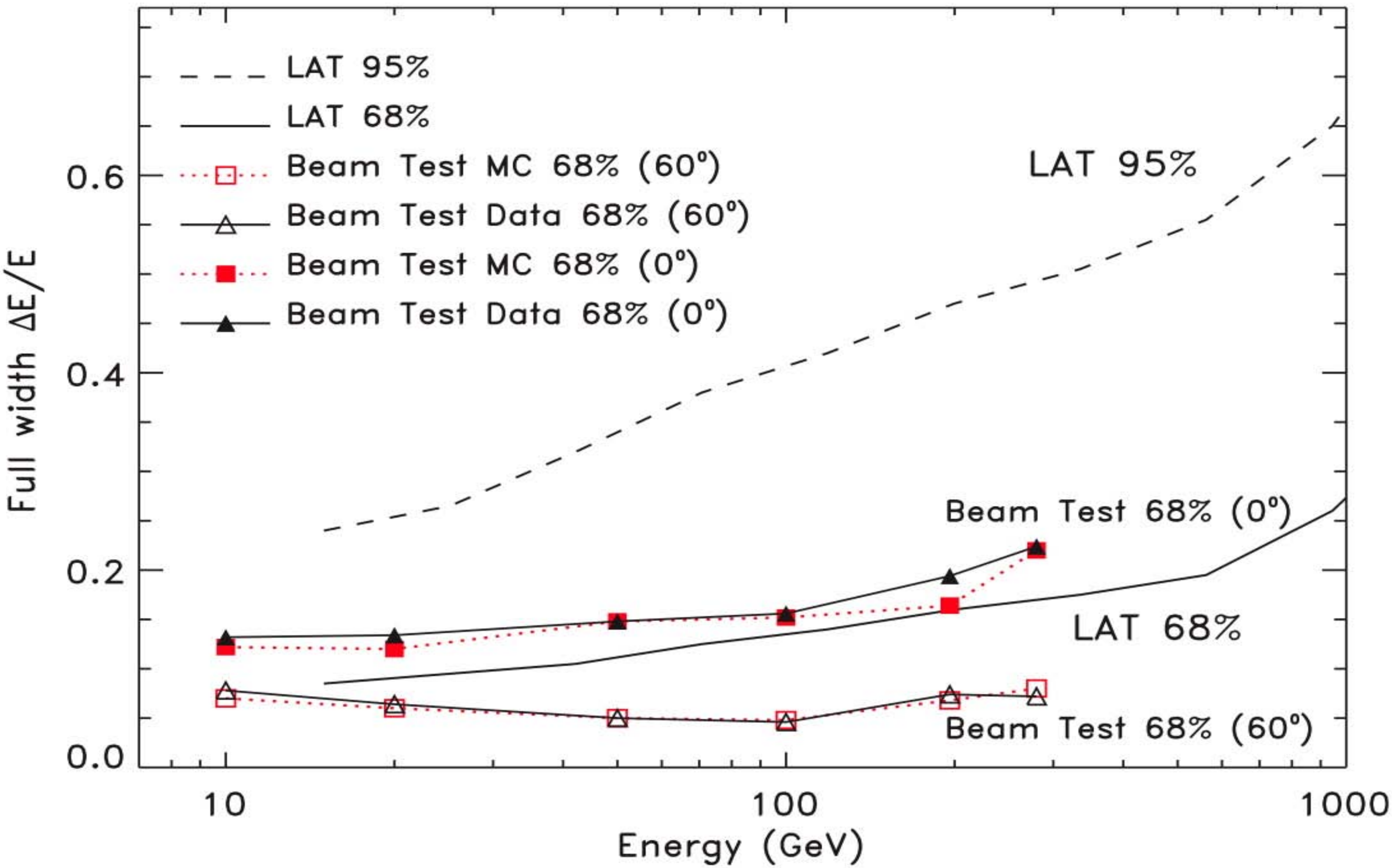
Very good agreement between shower profile in beam test data (red) and Monte Carlo (black)



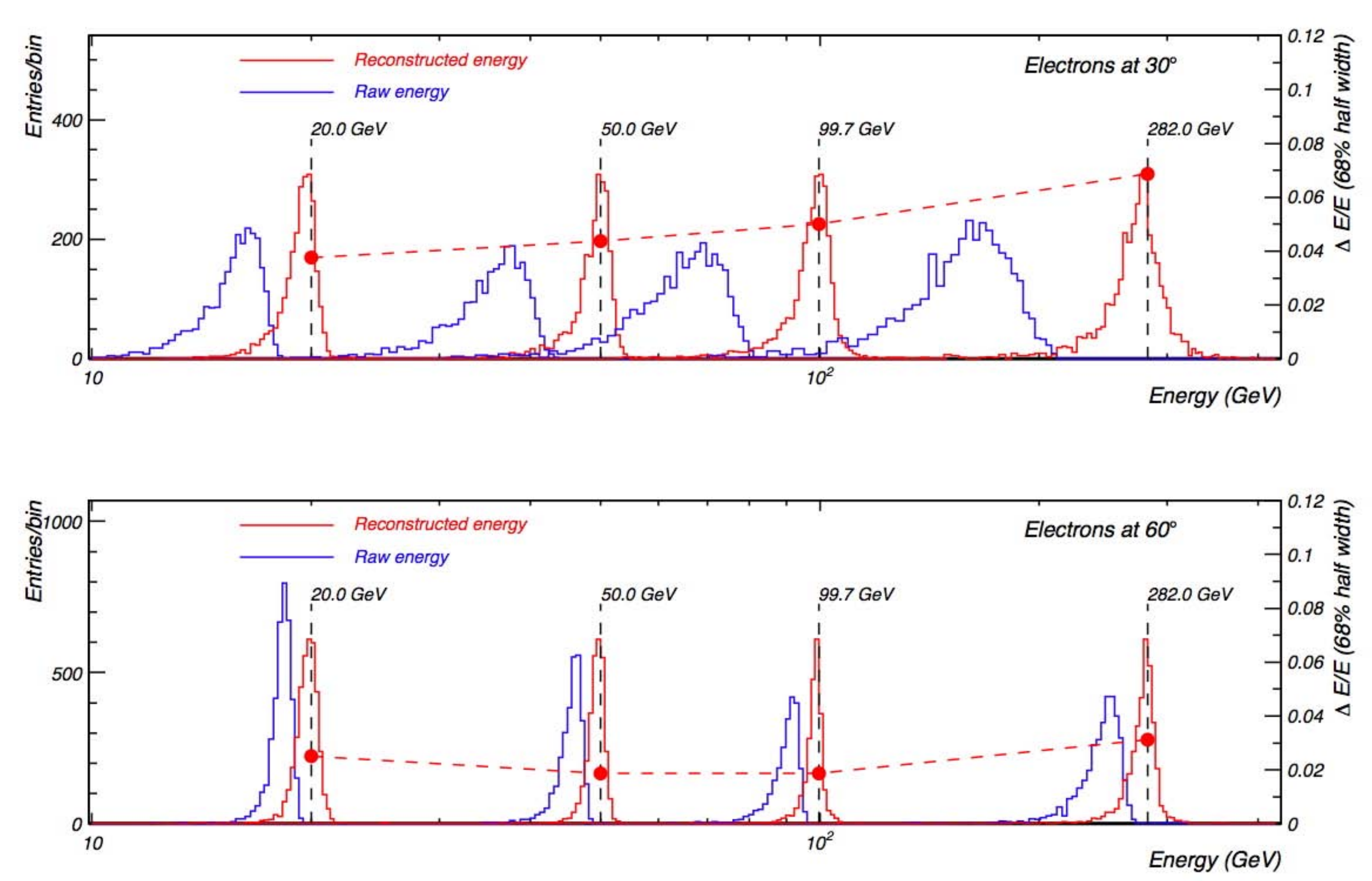
Energy reconstruction



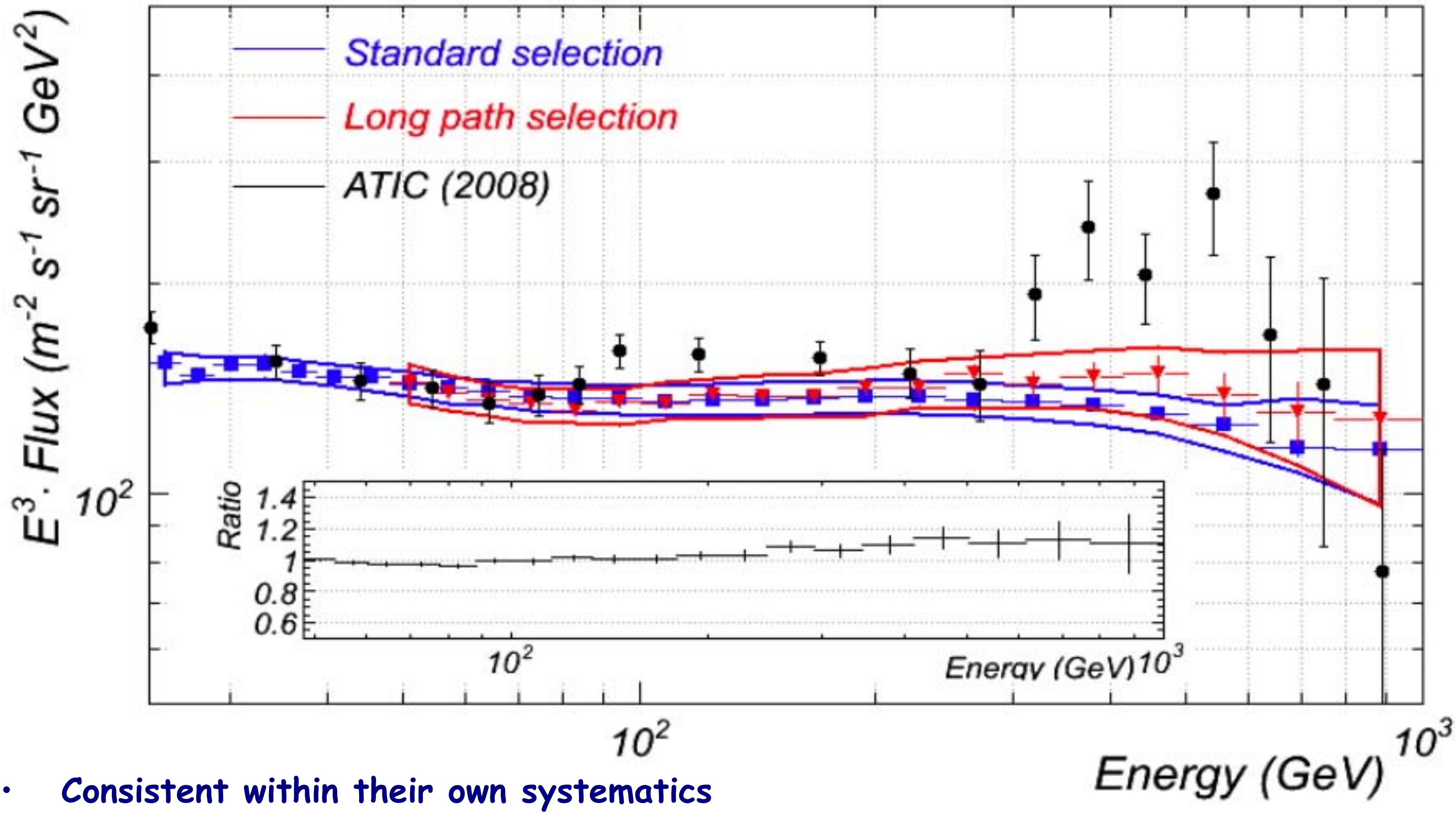
Fermi LAT Energy resolution for electrons



Energy Resolution Validation with Beam Test data

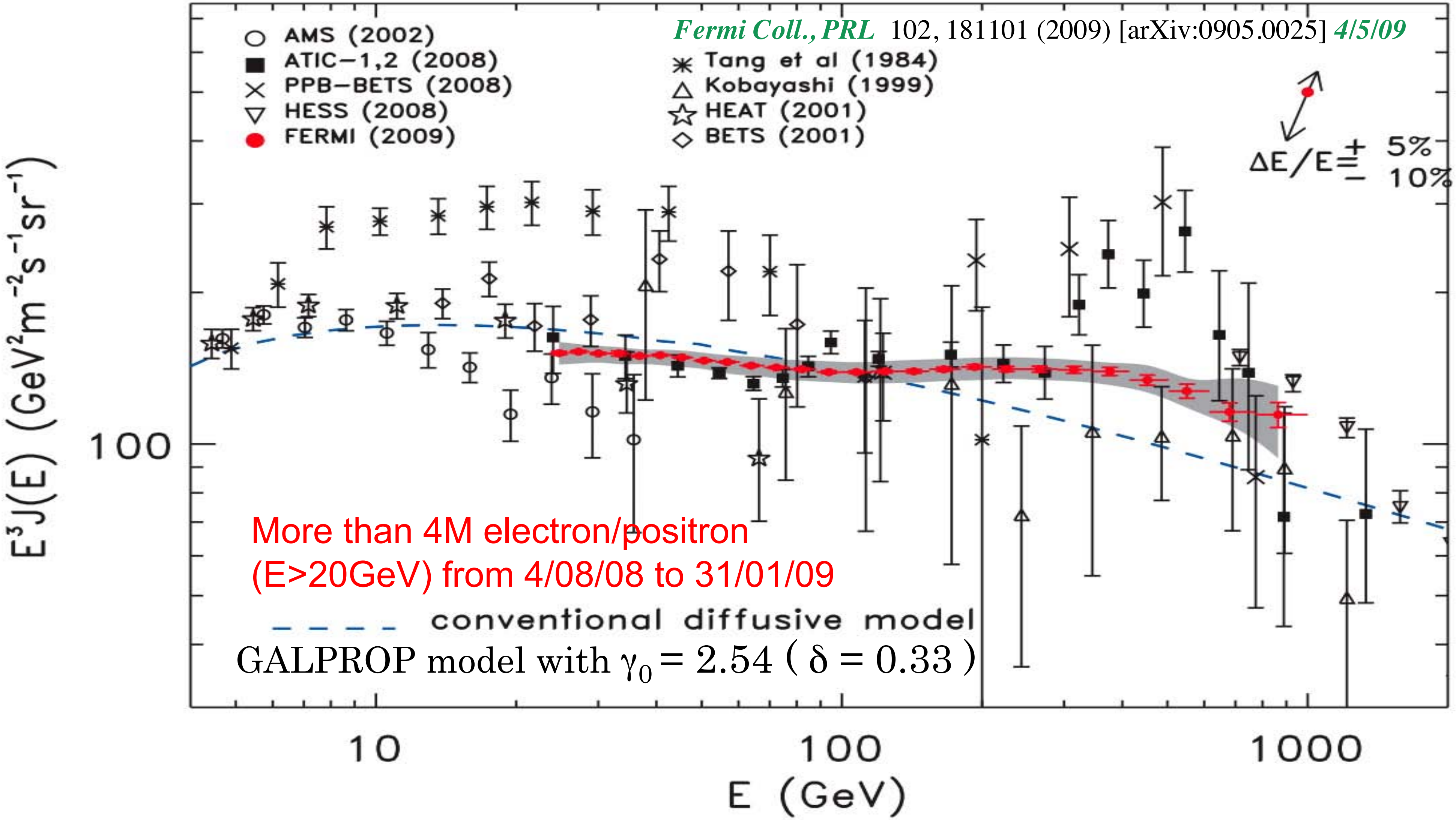


Comparison of standard and high-X0 spectra



- **Consistent within their own systematics**

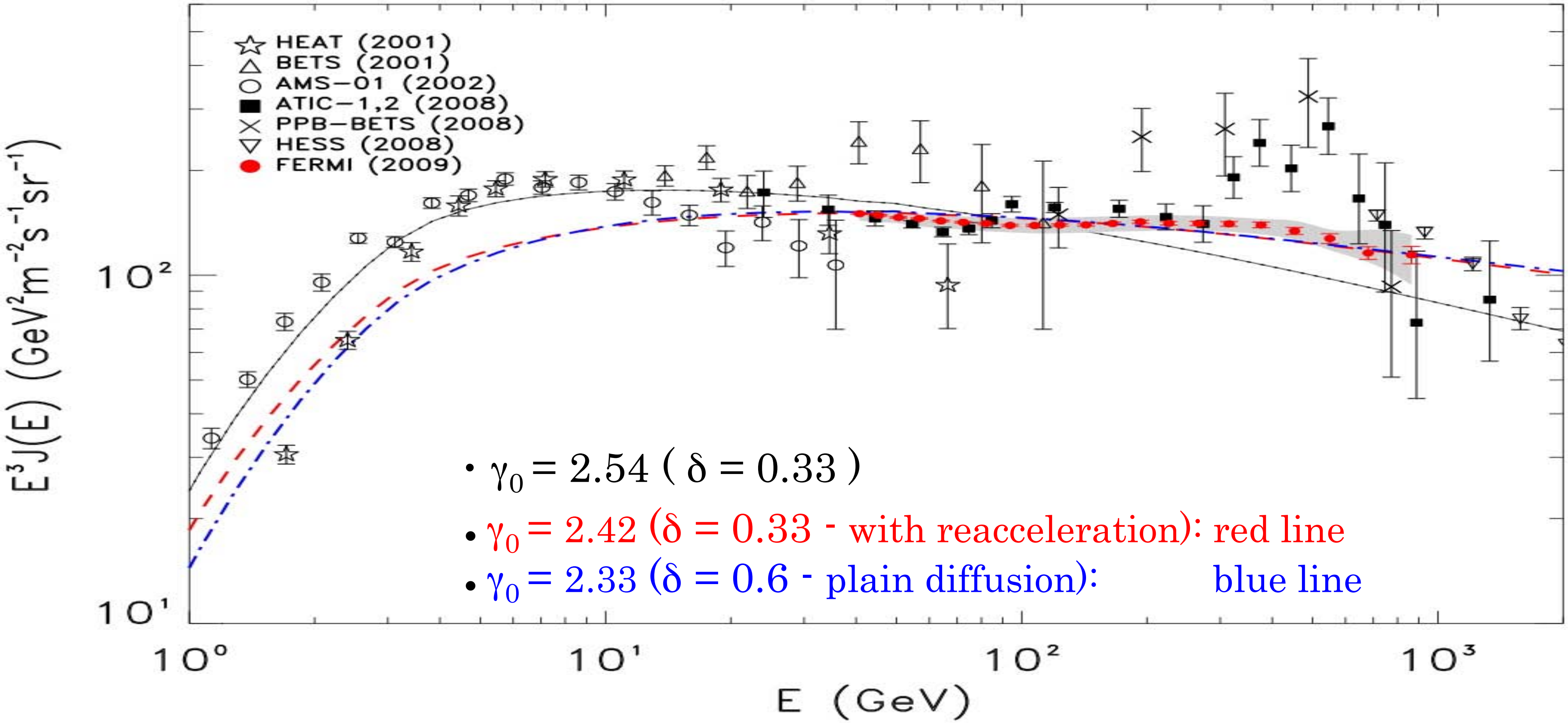
Fermi-LAT CRE data vs the conventional *pre-Fermi* model



Although the feature @~600 GeV measured by ATIC is not confirmed

Some changes are still needed respect to the *pre-Fermi conventional model*

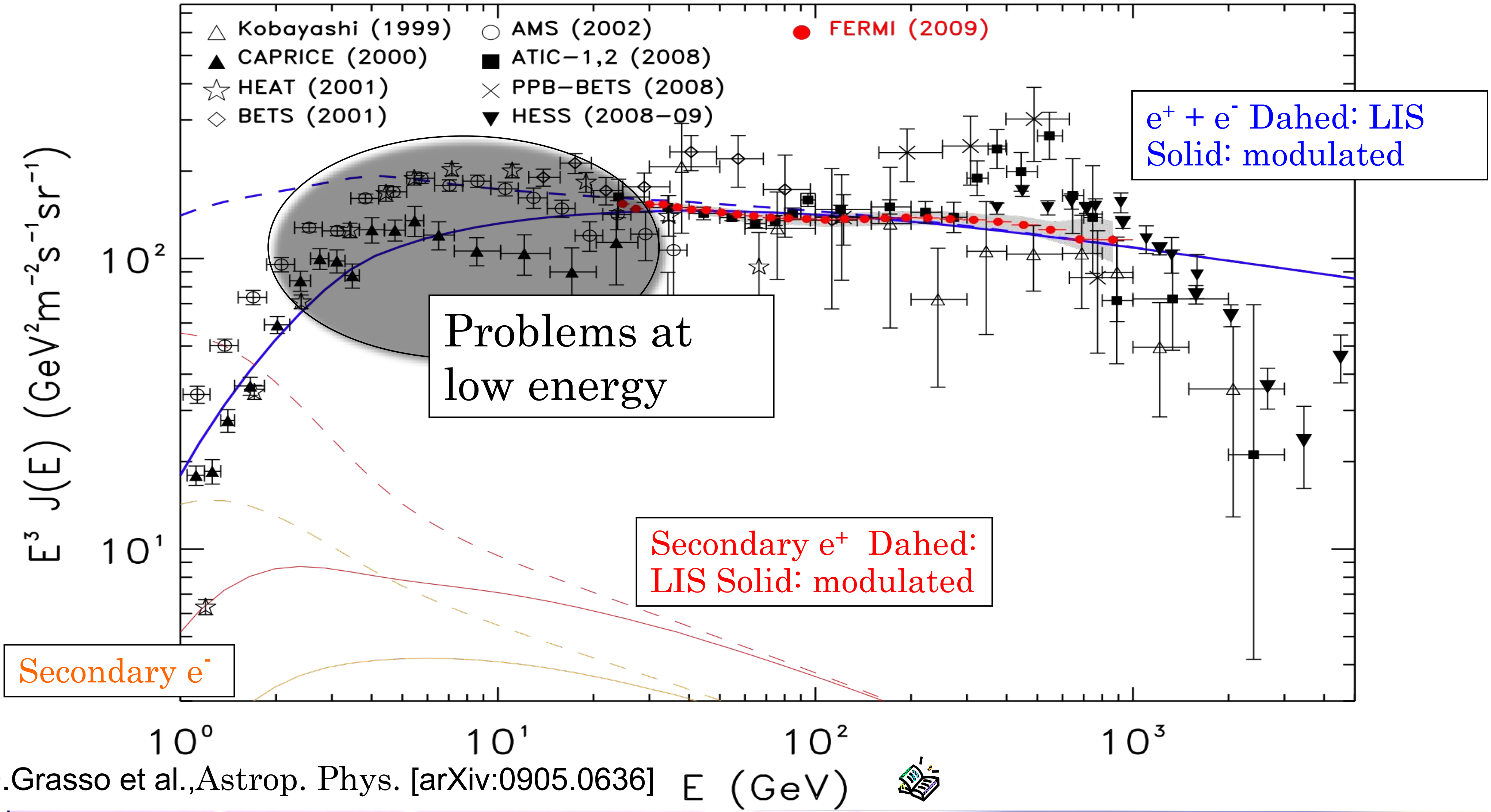
Cosmic Ray Electron propagation models



Model #	D_0 (cm^2s^{-1})	δ	z_h (kpc)	γ_0	N_{e^-} $(m^{-2}s^{-1}sr^{-1}GeV^{-1})$	γ_0^p
0	3.6×10^{28}	0.33	4	2.54	1.3×10^{-4}	2.42
1	3.6×10^{28}	0.33	4	2.42	1.3×10^{-4}	2.42
2	1.3×10^{28}	0.60	4	2.33	1.3×10^{-4}	2.1

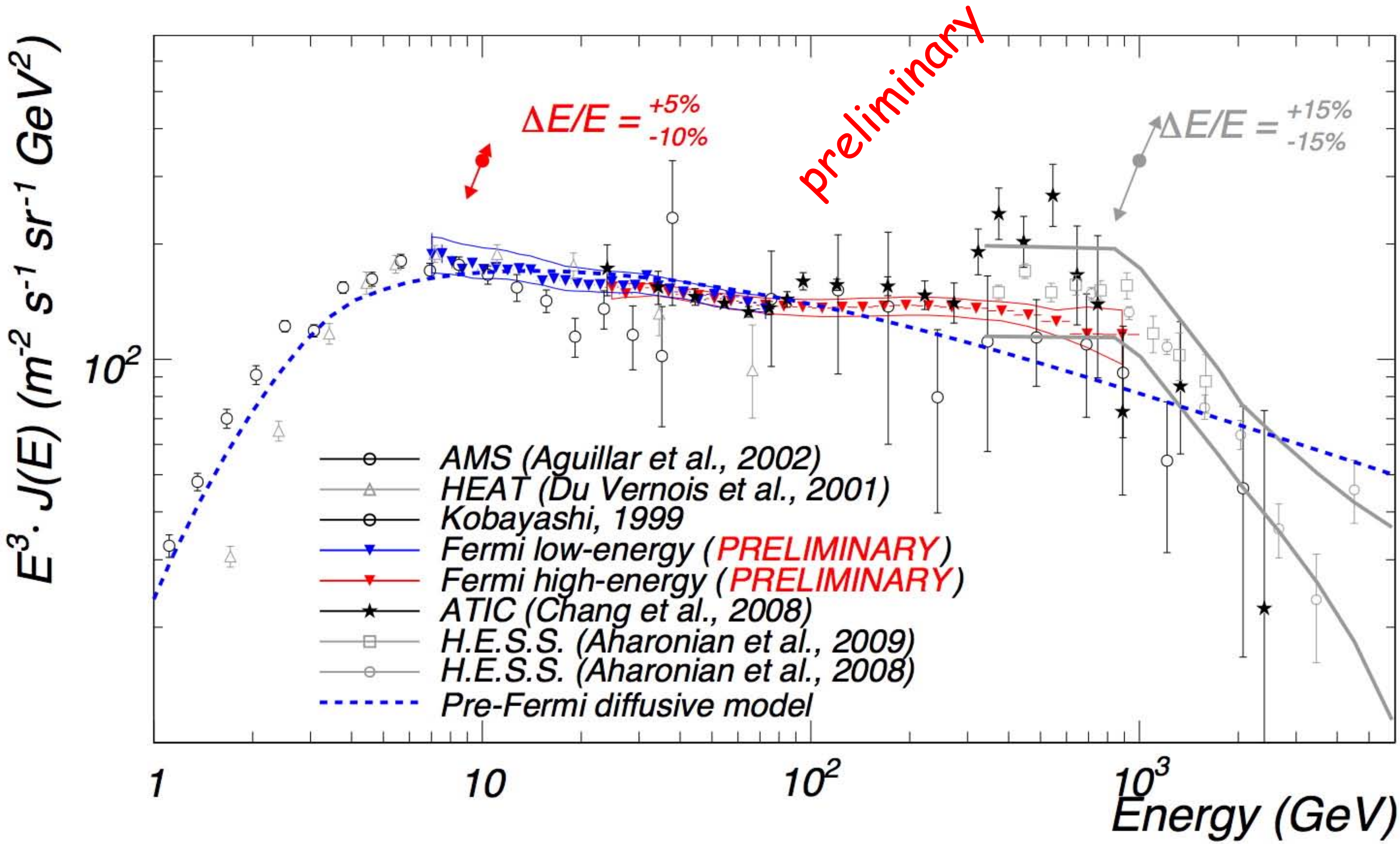
Models 0 and 1 account for CR re-acceleration in the ISM, while 2 is a plain-diffusion model. All models assume γ_0 = 1.6 below 4 GeV.

"Conventional" model with injection spectrum 1.60/2.42 (break at 4 GeV)



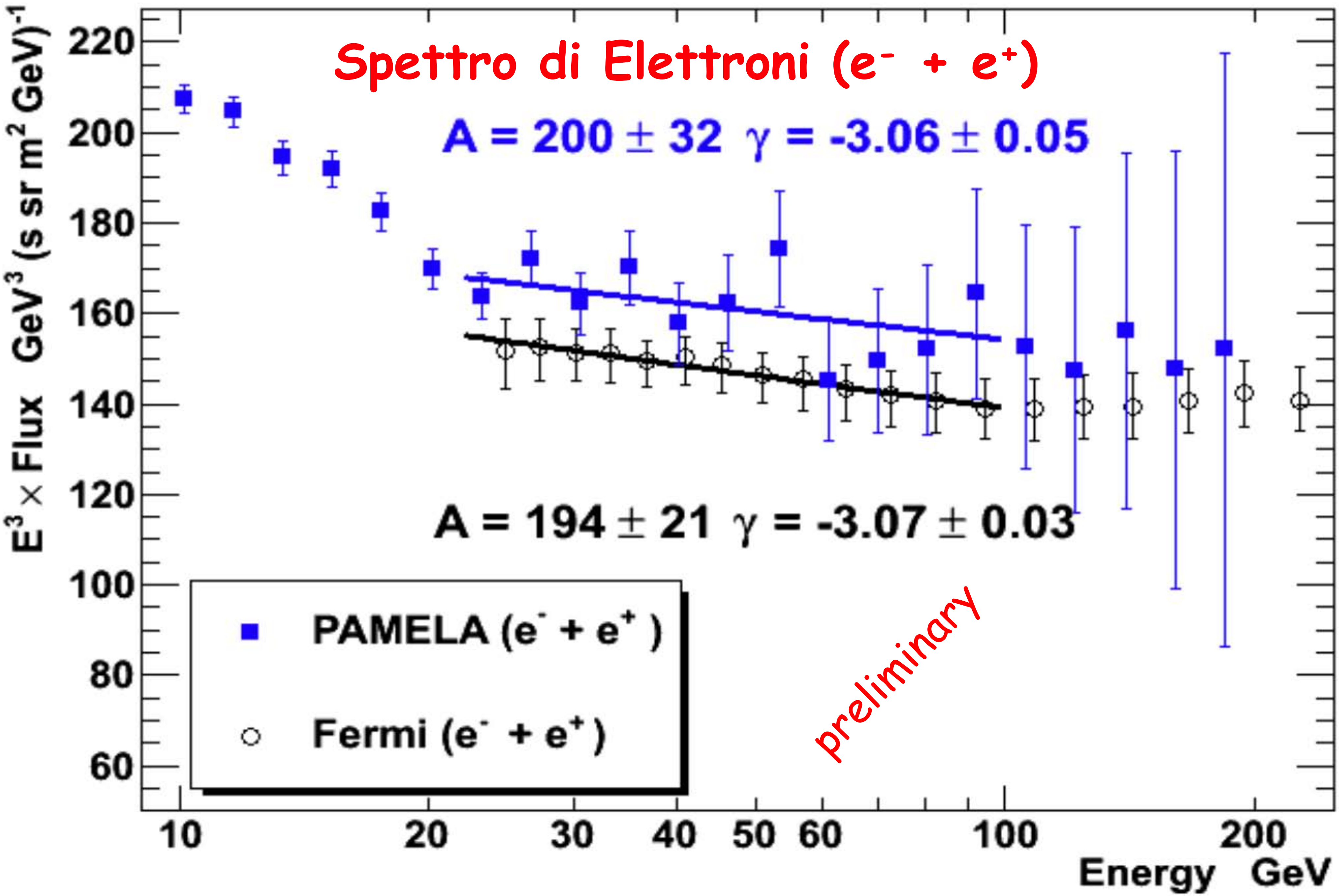
D.Grasso et al.,Astrop. Phys. [arXiv:0905.0636]

new : Fermi Electron + Positron spectrum (end 2009)



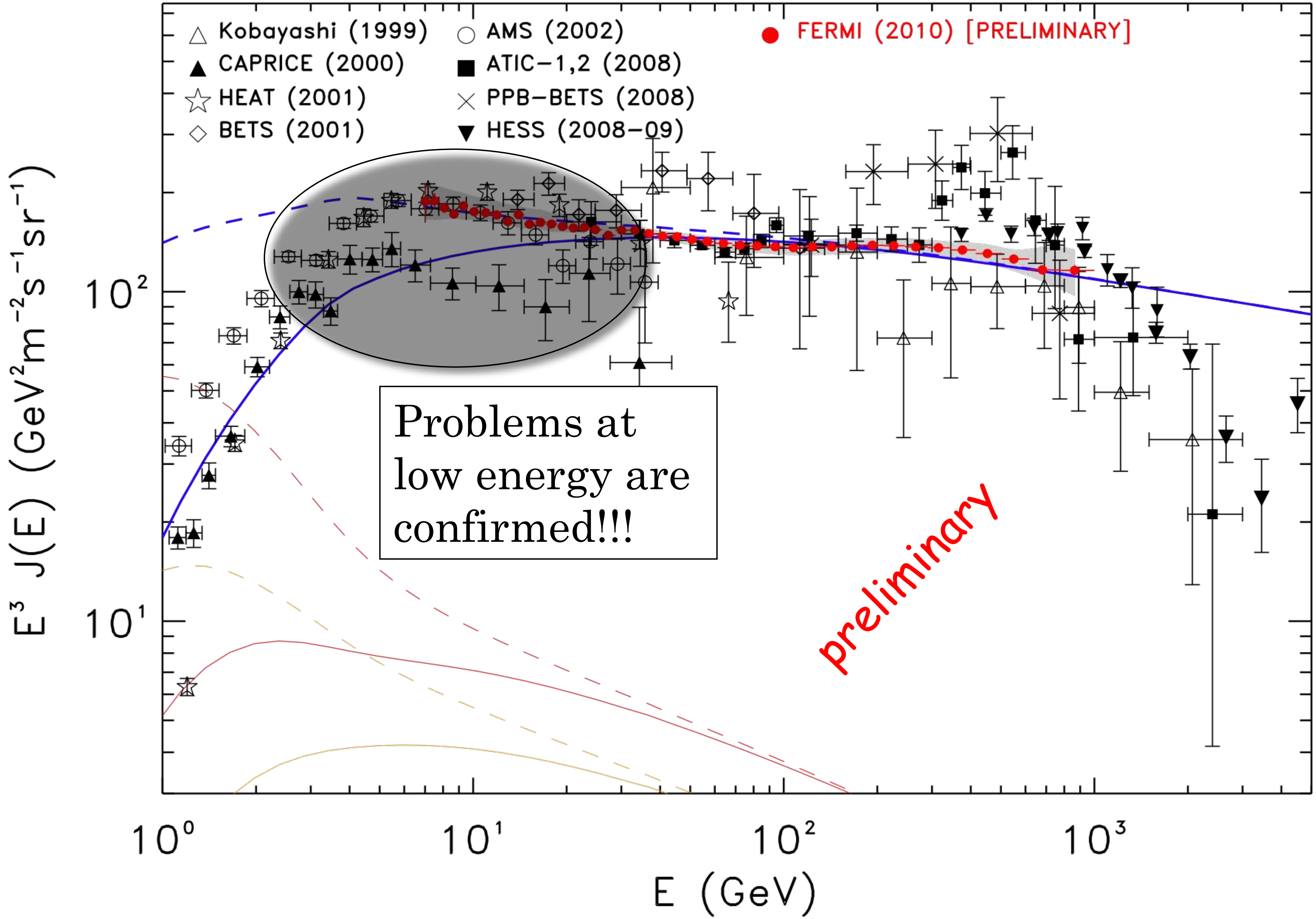
Extended Energy Range (7 GeV – 1 TeV) One year statistics (8M evts)

Fermi LAT Coll. in preparation

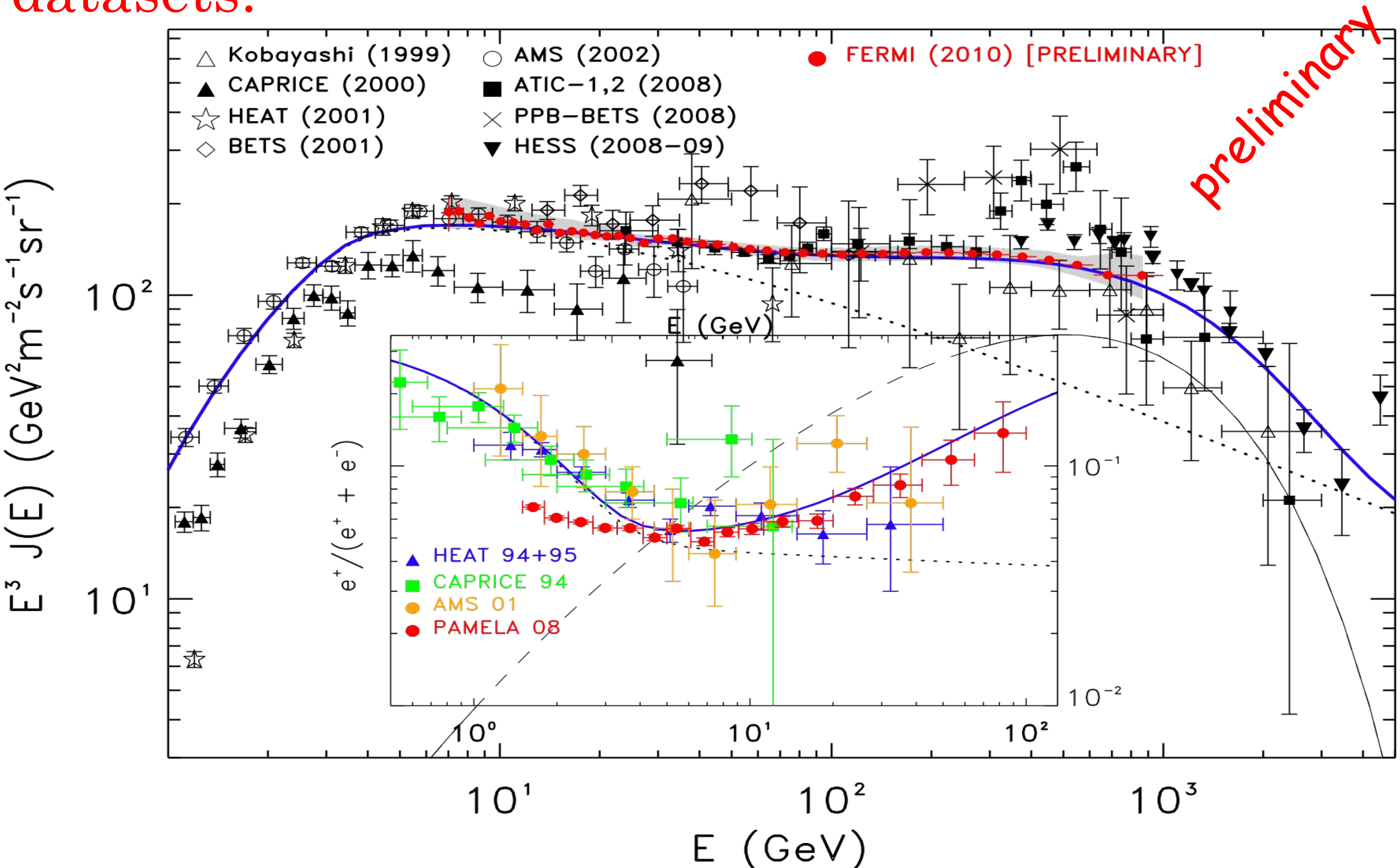


Spettro di Elettroni (e⁻ + e⁺)
A = 200 ± 32 γ = -3.06 ± 0.05
A = 194 ± 21 γ = -3.07 ± 0.03
PAMELA (e⁻ + e⁺)
Fermi (e⁻ + e⁺)
preliminary
E³ × Flux GeV³ (s sr m² GeV)⁻¹
Energy GeV

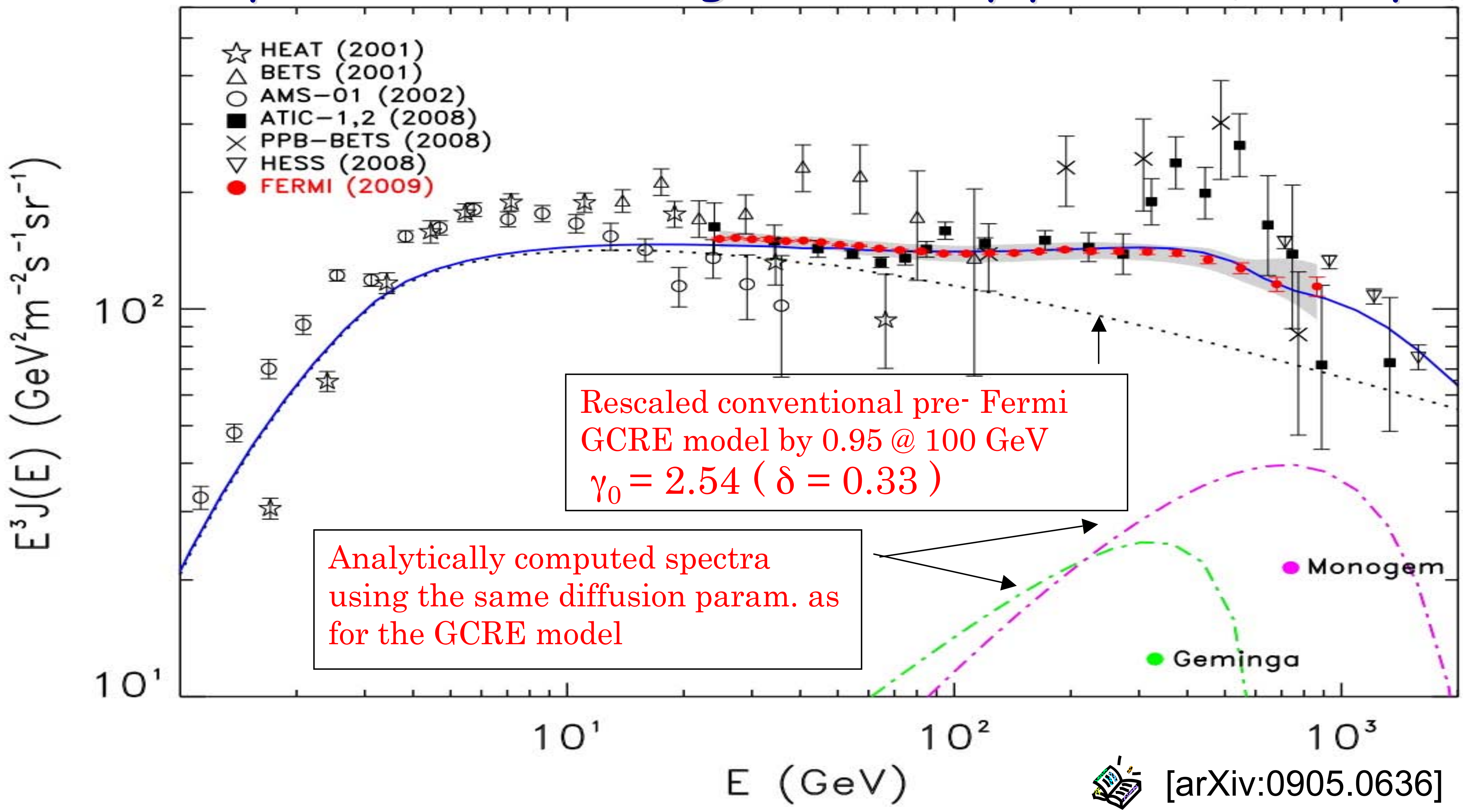
New Fermi-LAT data at low energy



An extra-component with injection index = 1.5 and an exponential cutoff at 1 TeV gives a good fit of all datasets!



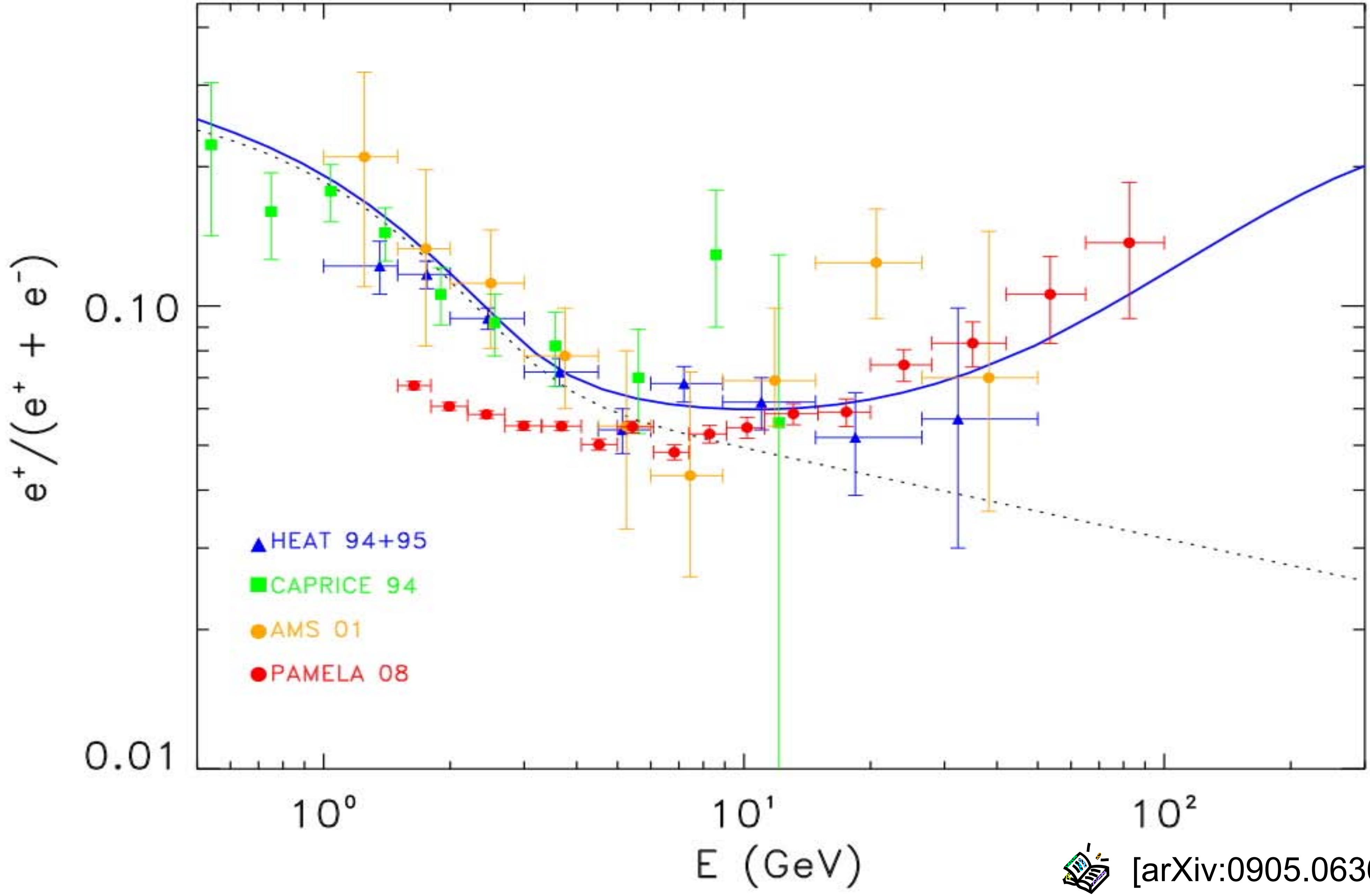
The CRE spectrum accounting for nearby pulsars (d < 1 kpc)



[arXiv:0905.0636]

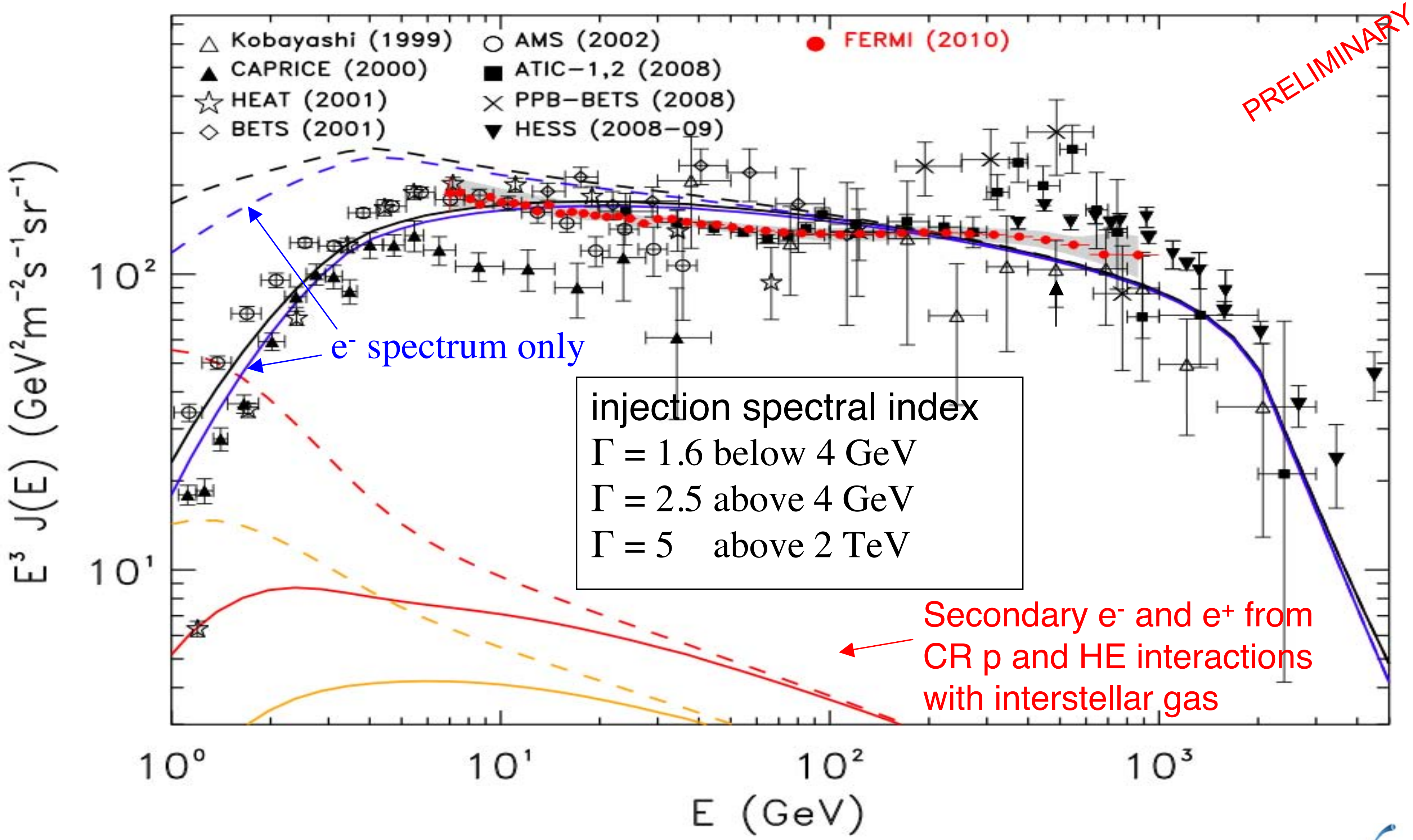
This particular model assumes: 40% $e^{\pm}$ conversion efficiency for each pulsar
- pulsar spectral index $\Gamma = 1.7$ $E_{cut} = 1$ TeV . Delay = 60 kyr

the positron ratio accounting for nearby pulsars (d < 1 kpc)



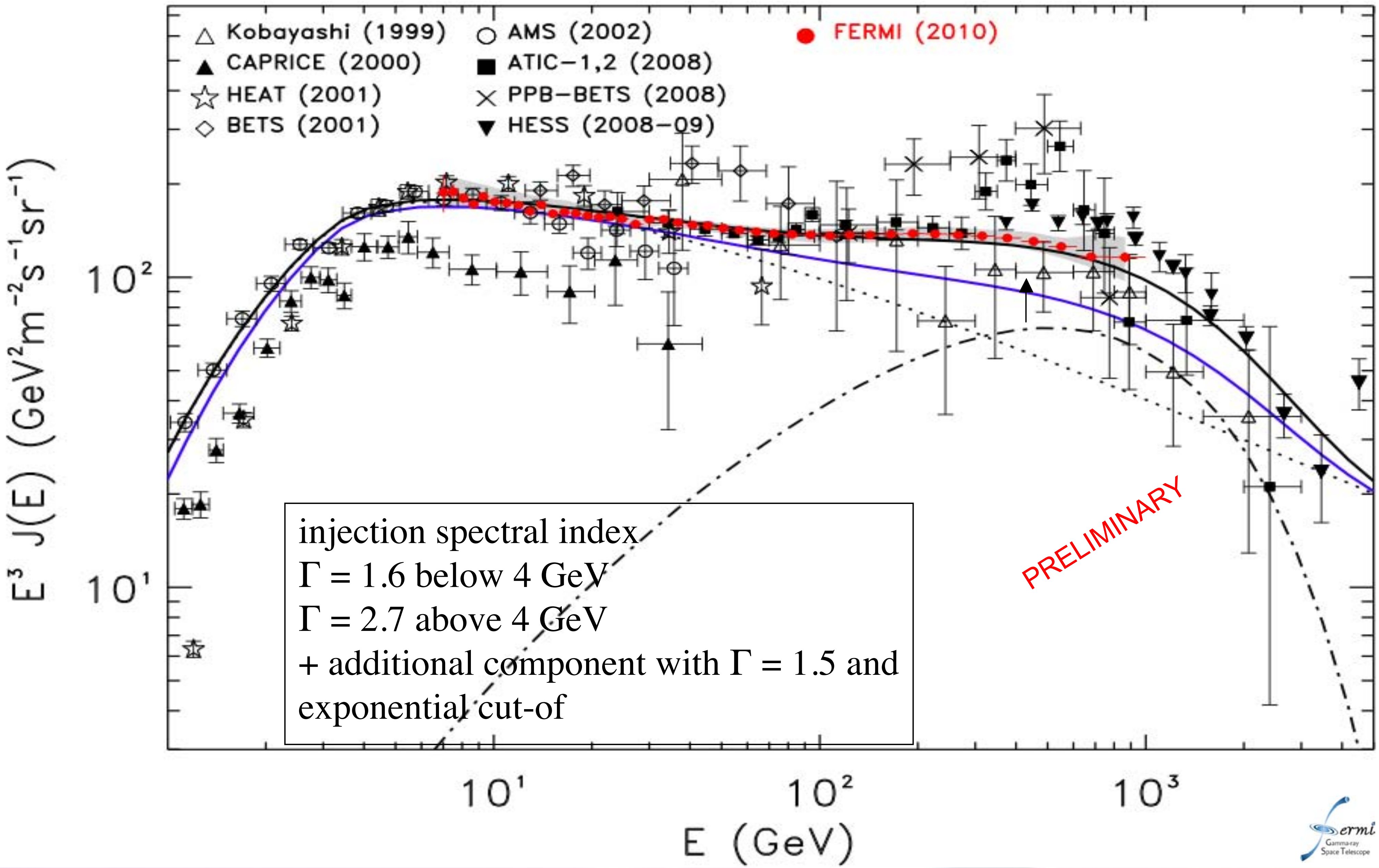
[arXiv:0905.0636]

Electron spectrum and a conventional GALPROP model



The solar modulation was treated using the force-field approximation with Φ = 550 MV

Electron spectrum and a conventional GALPROP model +...



Pulsars

1. On purely energetic grounds they work (relatively large efficiency)

2. On the basis of the spectrum, it is not clear
   1. The spectra of PWN show relatively flat spectra of pairs at Low energies but we do not understand what it is
   2. The general spectra (acceleration at the termination shock) are too steep

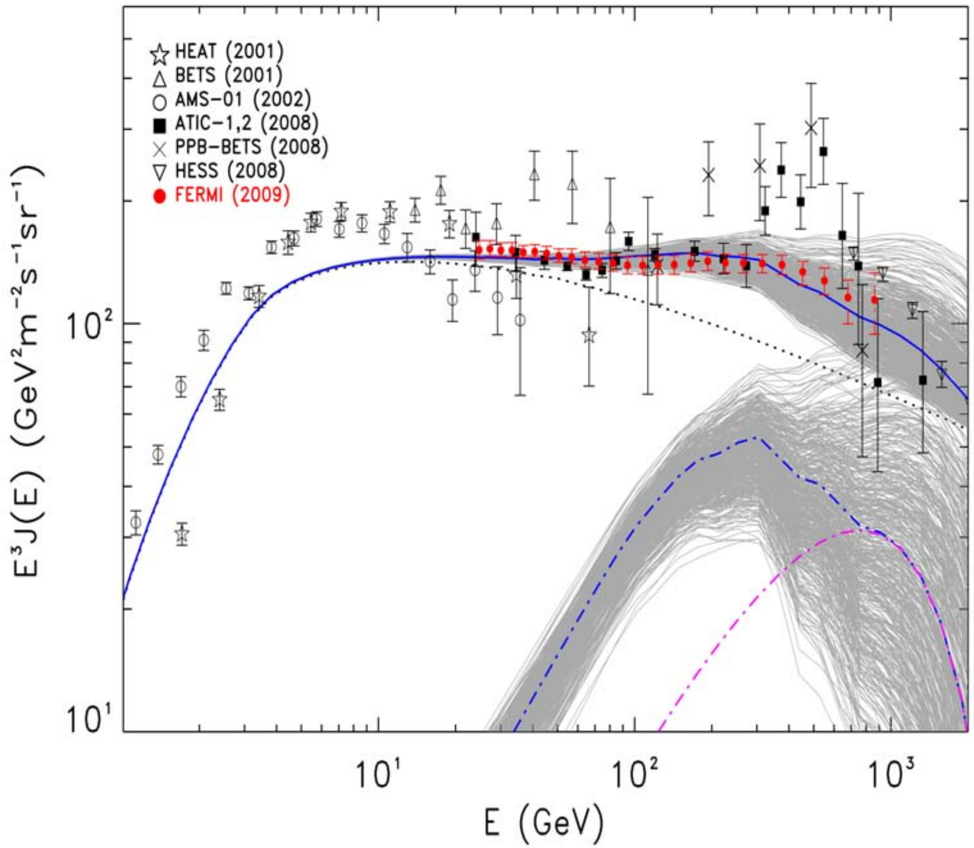
The biggest problem is that of escape of particles from the pulsar
   1. Even if acceleration works, pairs have to survive losses
   2. And in order to escape they have to cross other two shocks

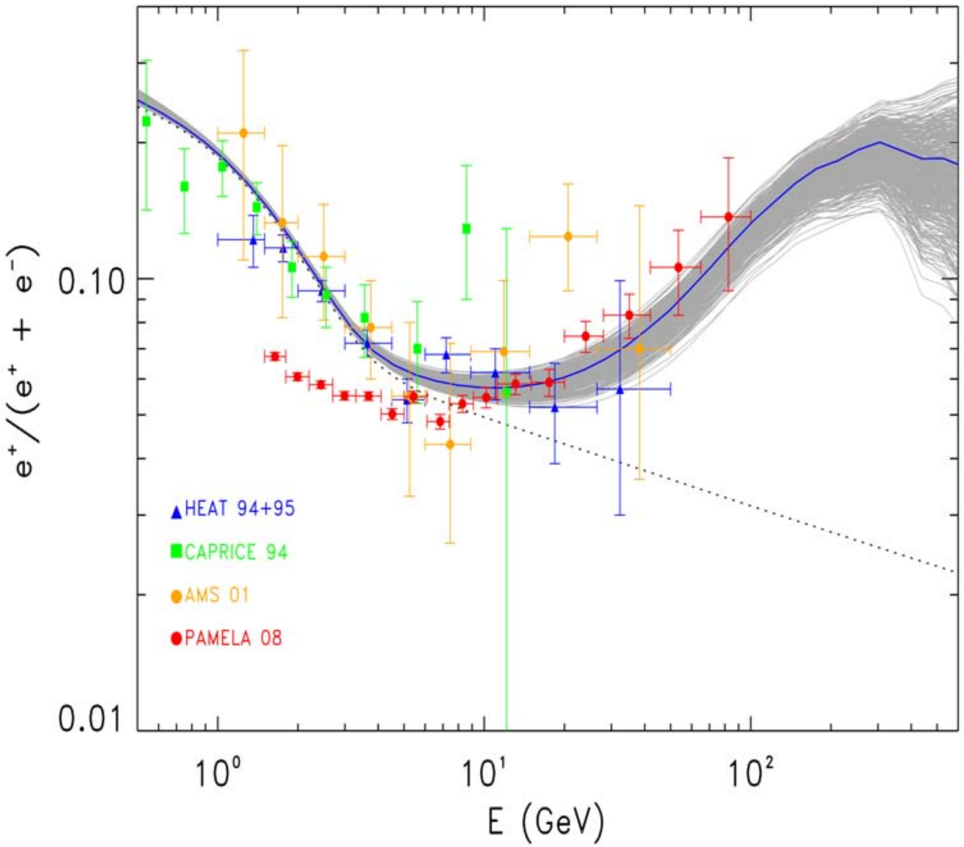
Extensive discussion two week ago @ GGI (Serpico, Blasi ..)

New Fermi data on pulsars will help to constrain the pulsar models

What if we randomly vary the pulsar parameters relevant for e+e- production?

(*injection spectrum, e+e- production efficiency, PWN "trapping" time*)

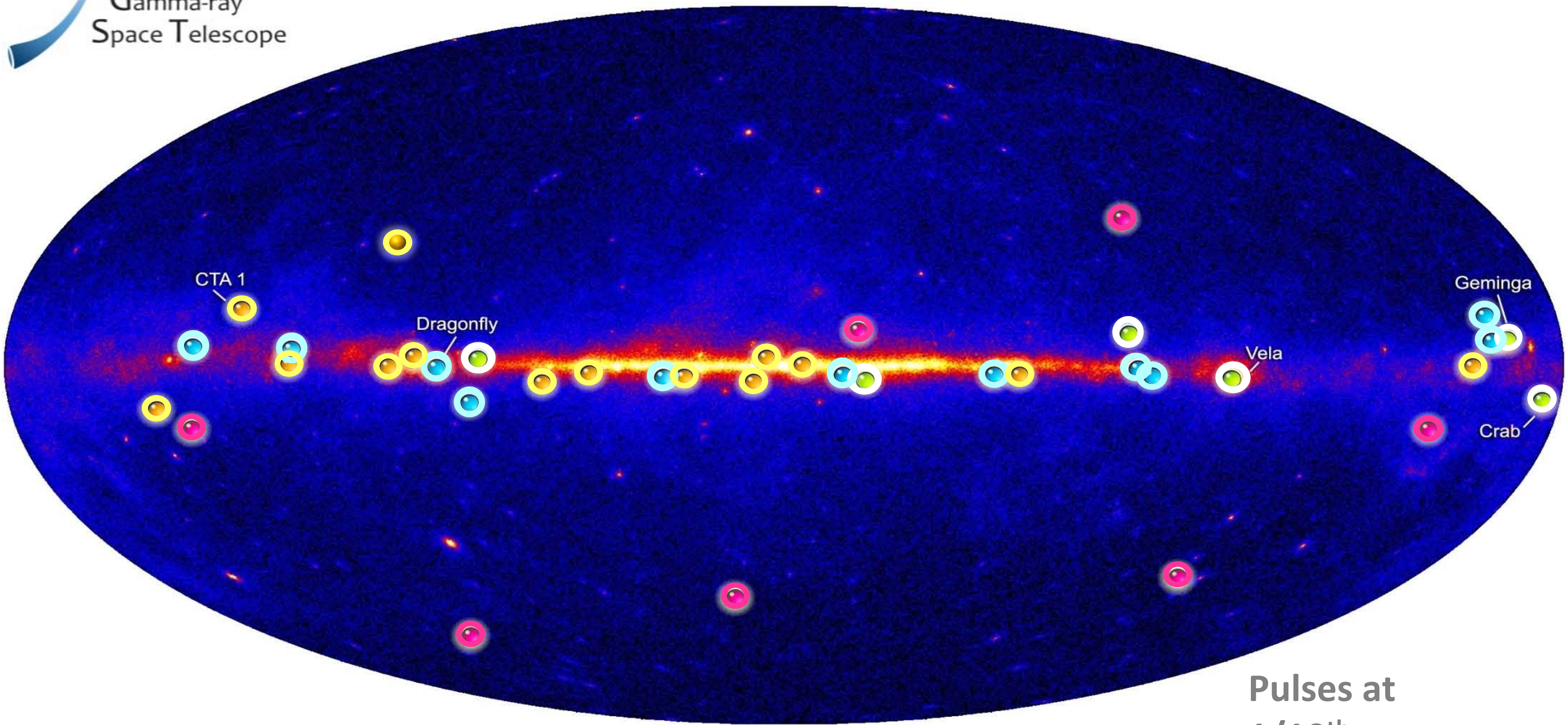




Under reasonable assumptions, electron/positron emission from pulsars offers a viable interpretation of Fermi CRE data which is also consistent with the HESS and Pamela results.

[arXiv:0905.0636]

16 Gamma-Ray Pulsars Through Blind Frequency Searches
Science 325 (5942), 840-844
A Population of Gamma-Ray Millisecond Pulsars Seen with Fermi
Science 325 (5942), 848-852 (14 August 2009)

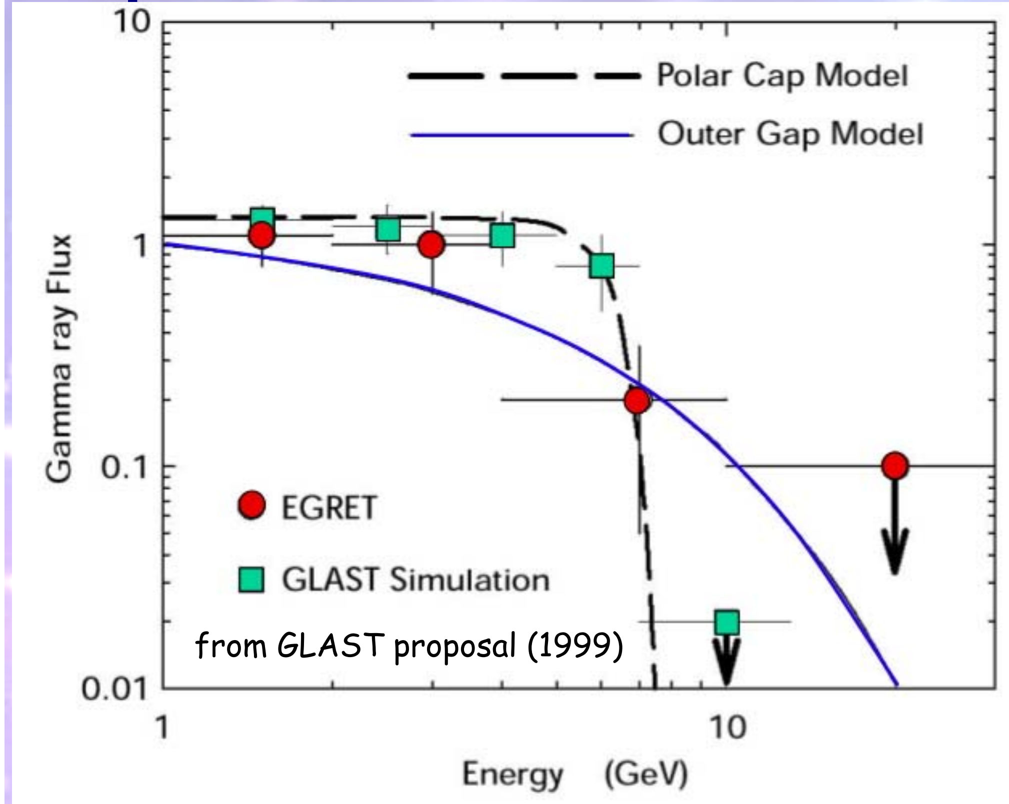


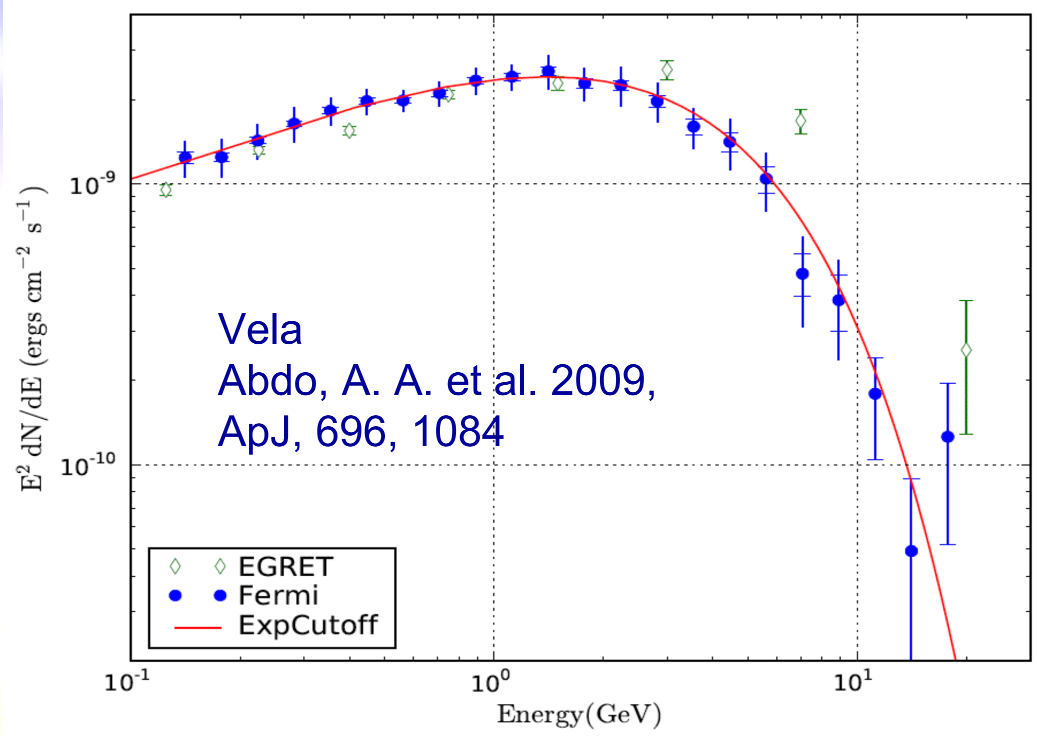
Pulses at $1/10^{th}$ true rate

The Pulsing γ-ray Sky

- New pulsars discovered in a blind search
- Millisecond radio pulsars
- Young radio pulsars
- Pulsars seen by Compton Observatory EGRET instrument

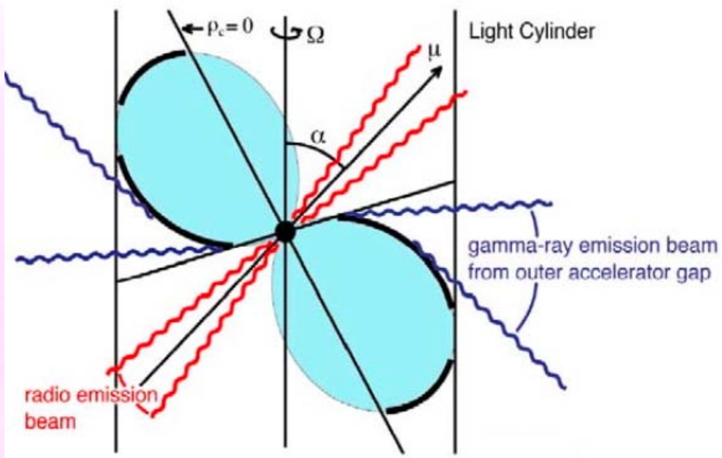
Spectral measurements and emission models

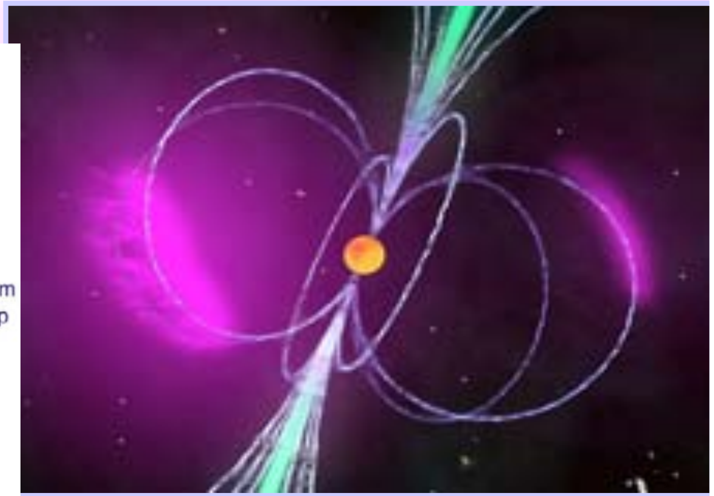




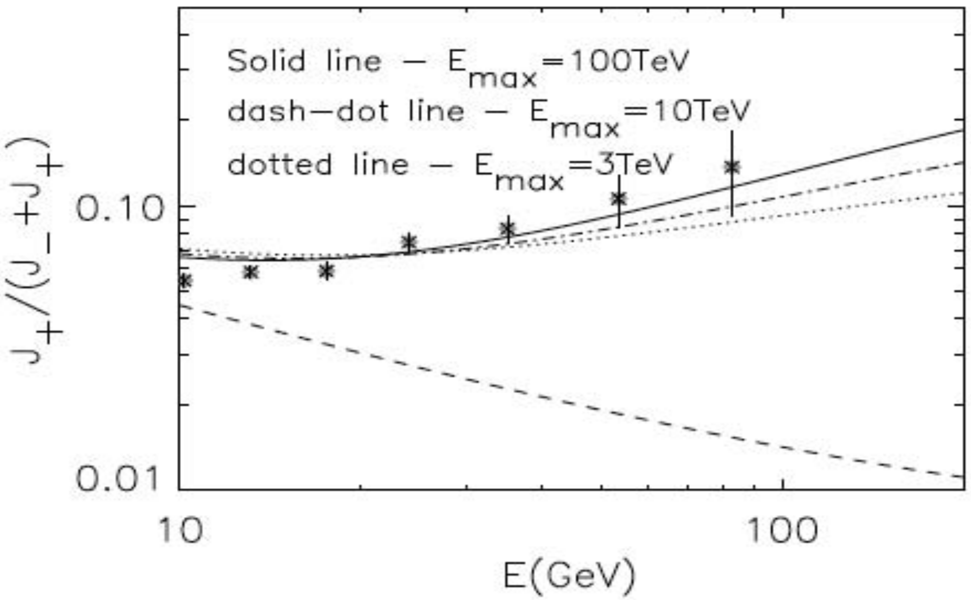
Evidence of γ-ray emission in the outer magnetopshere due to absence of super-exponential cutoff

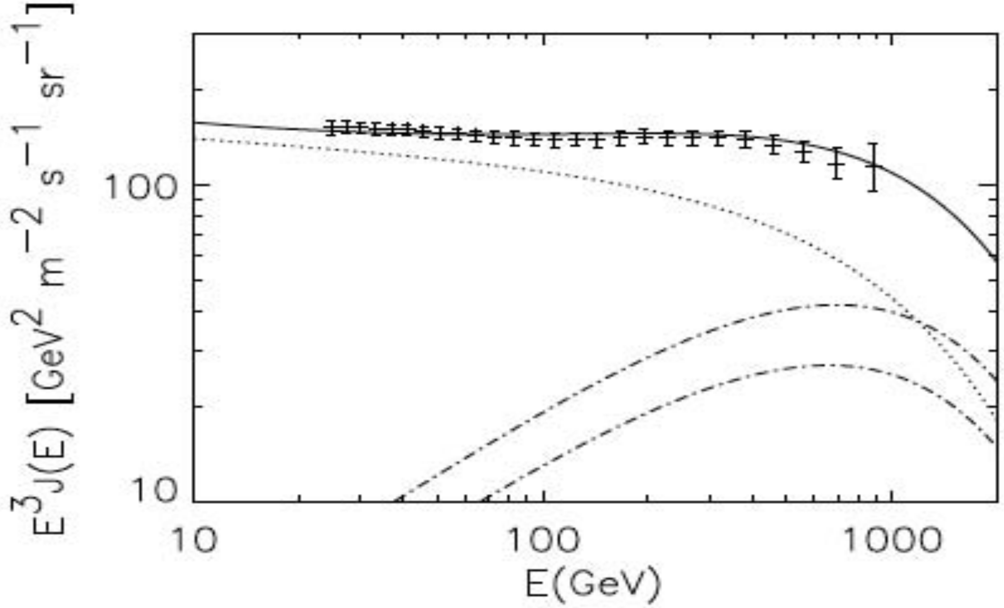
- Radio and γ-ray fan beams separated
- γ-ray only PSRs





other Astrophysical solution



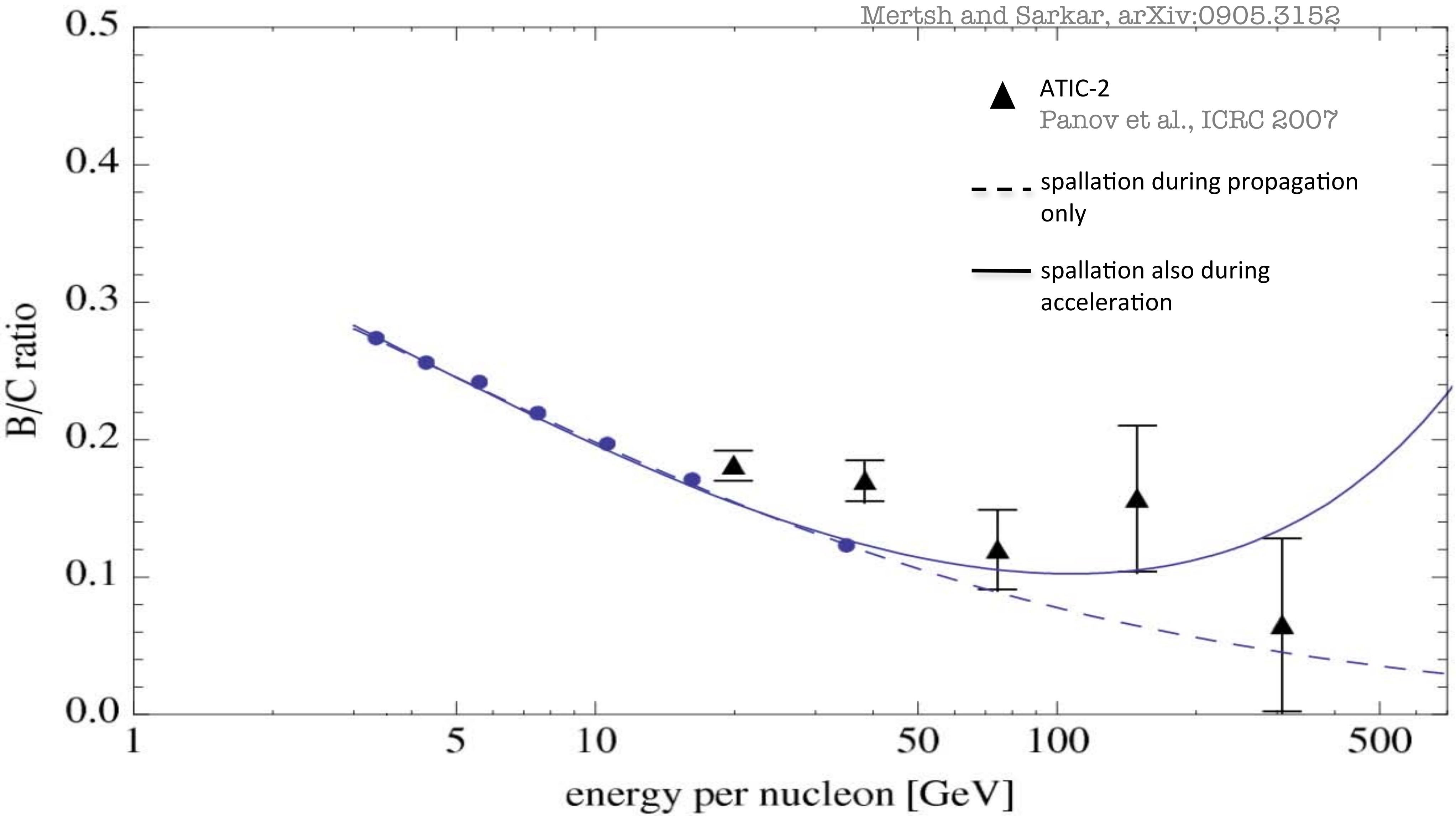


- Positrons created as secondary products of hadronic interactions inside the sources
- Secondary production takes place in the same region where cosmic rays are being accelerated

-> Therefore secondary positron have a very flat spectrum, which is responsible, after propagation in the Galaxy, for the observed positron excess

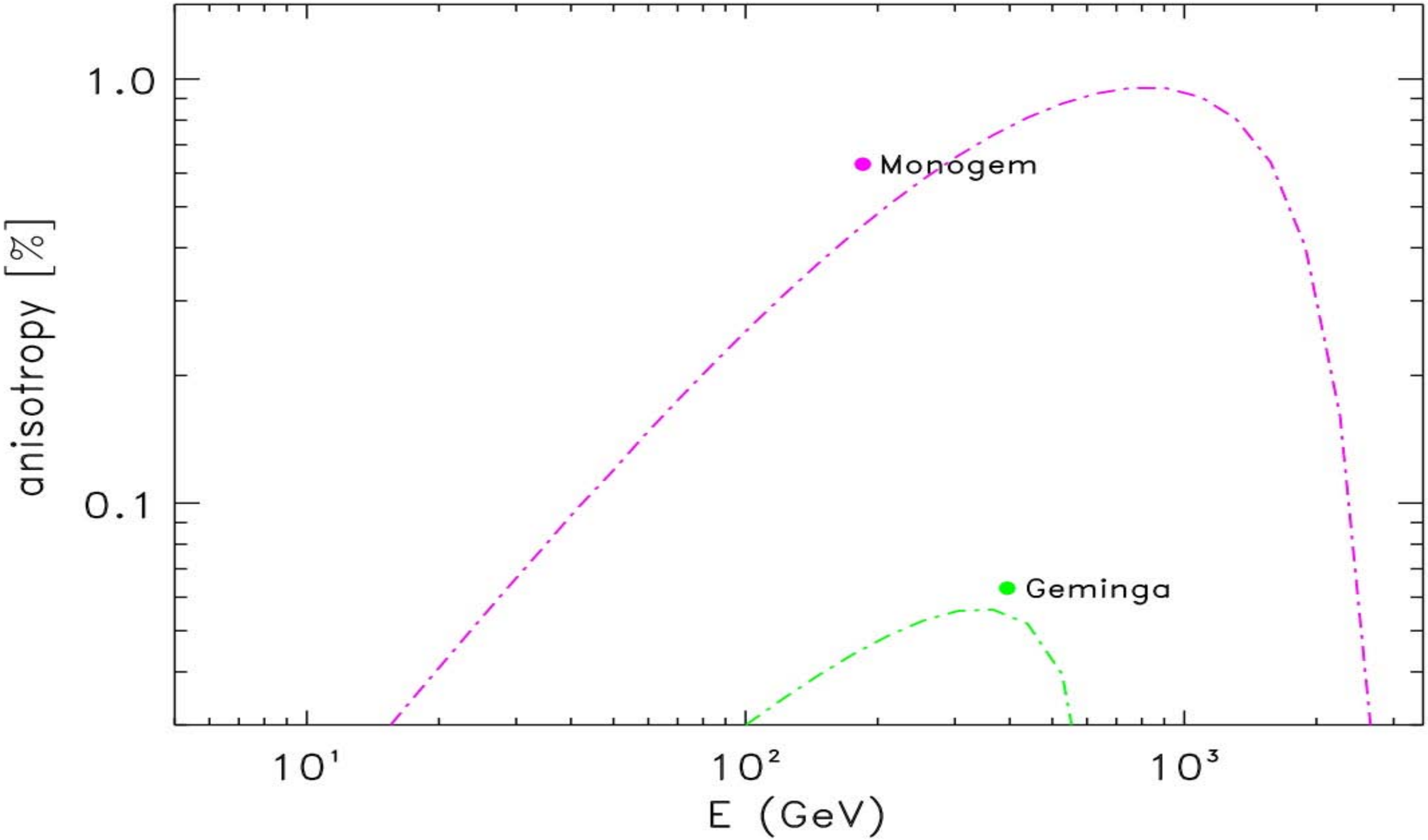
Blasi, arXiv:0903.2794

Boron-to-Carbon Ratio

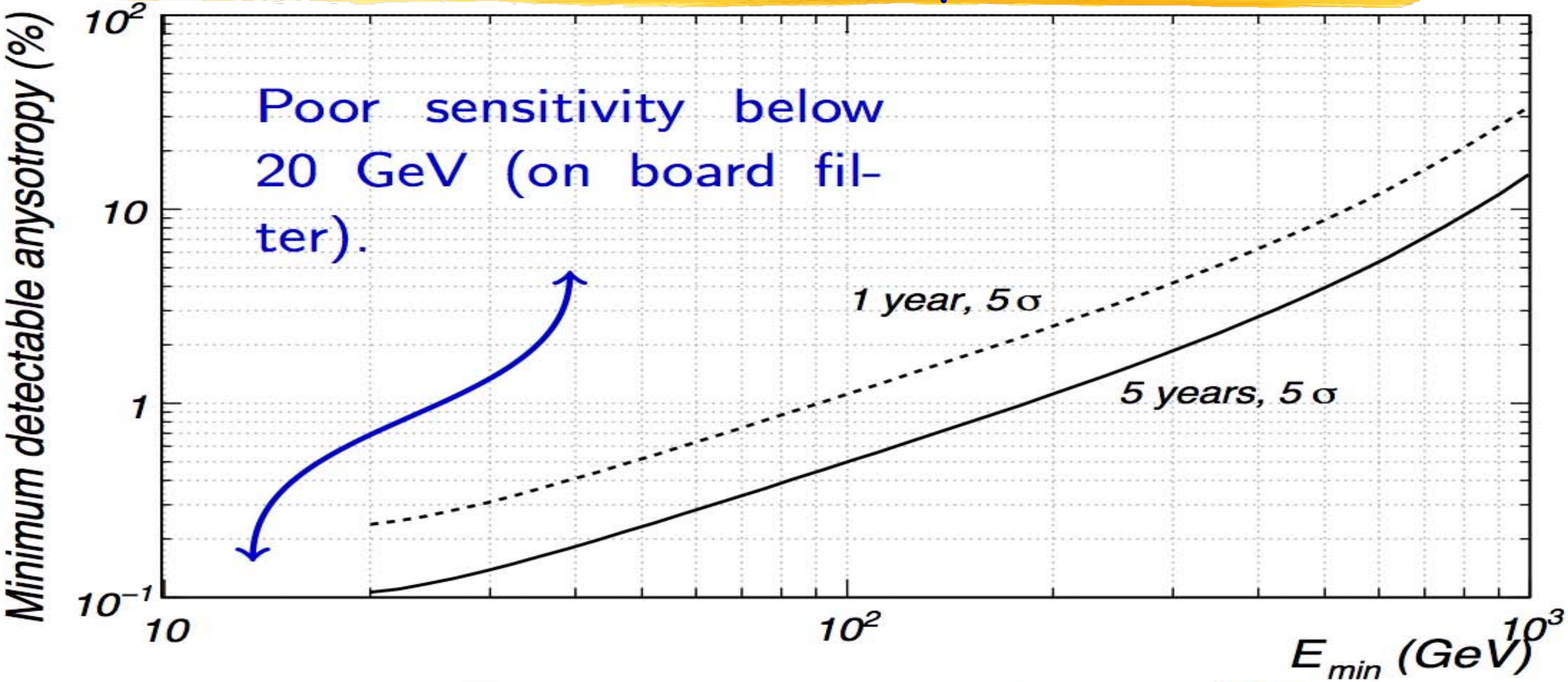


A rise would rule out the DM and pulsar explanation of the PAMELA positron excess.

electron + positron expected anisotropy in the directions of Monogem and Geminga

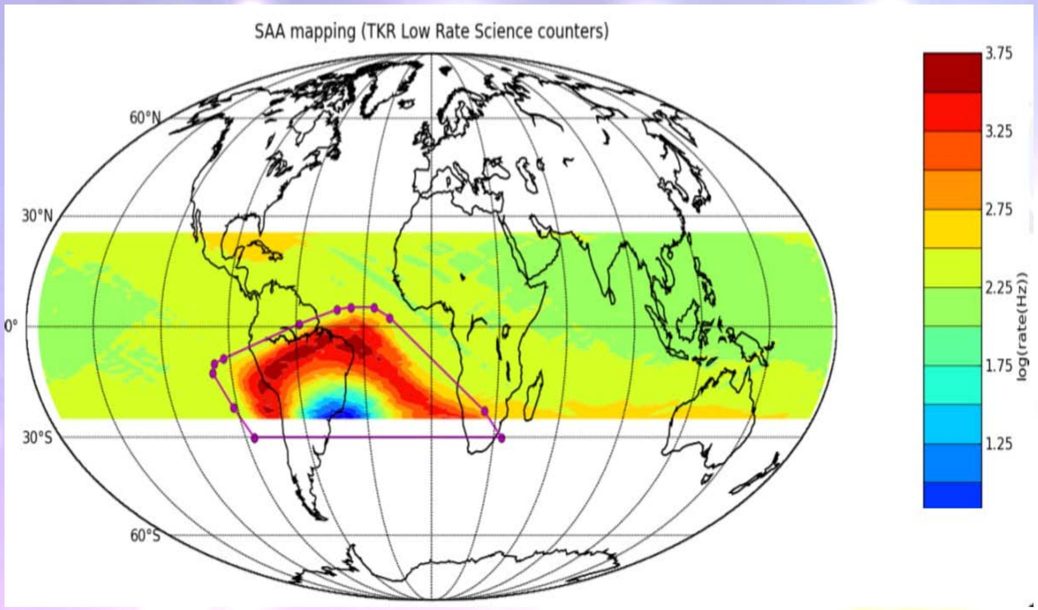


Measurement of anisotropies: statistics



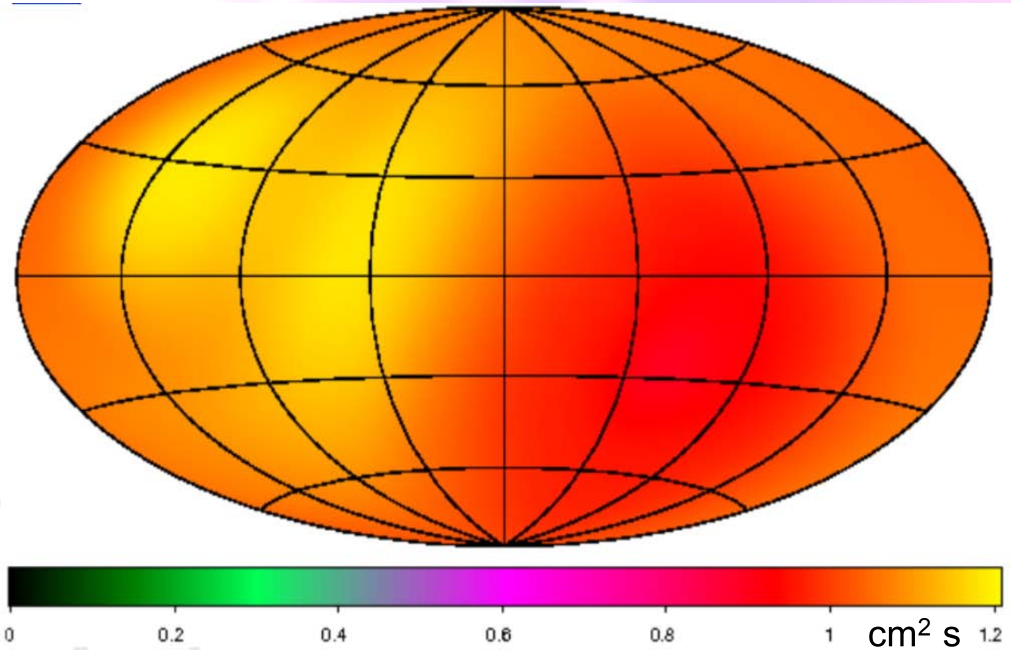
- Statistical limit for the integral anisotropy set by $\delta = \frac{\sqrt{2}N_\sigma}{\sqrt{N_{events}}}$
- The plot includes all the instrument effects:
- Energy-dependent effective geometry factor;
- Instrumental dead time and duty cycle, On board filter.
- Room for improvements with a better event selection!

Measurements of anisotropies: systematics



Terrestrial coordinates (South Atlantic Anomaly clearly visible). Fermi does not take science data within the SAA polygon.

Exposure map
For gammas, after three months of mission (used for the bright source list).
It will not be very different for the electrons and for longer time periods.



- ≈ 25% disuniformity in the exposure map induced by the SAA.

Measuring a 0.1% anisotropy requires a knowledge of the exposure map at the ≈ 0.1% level.

New Data is Forthcoming

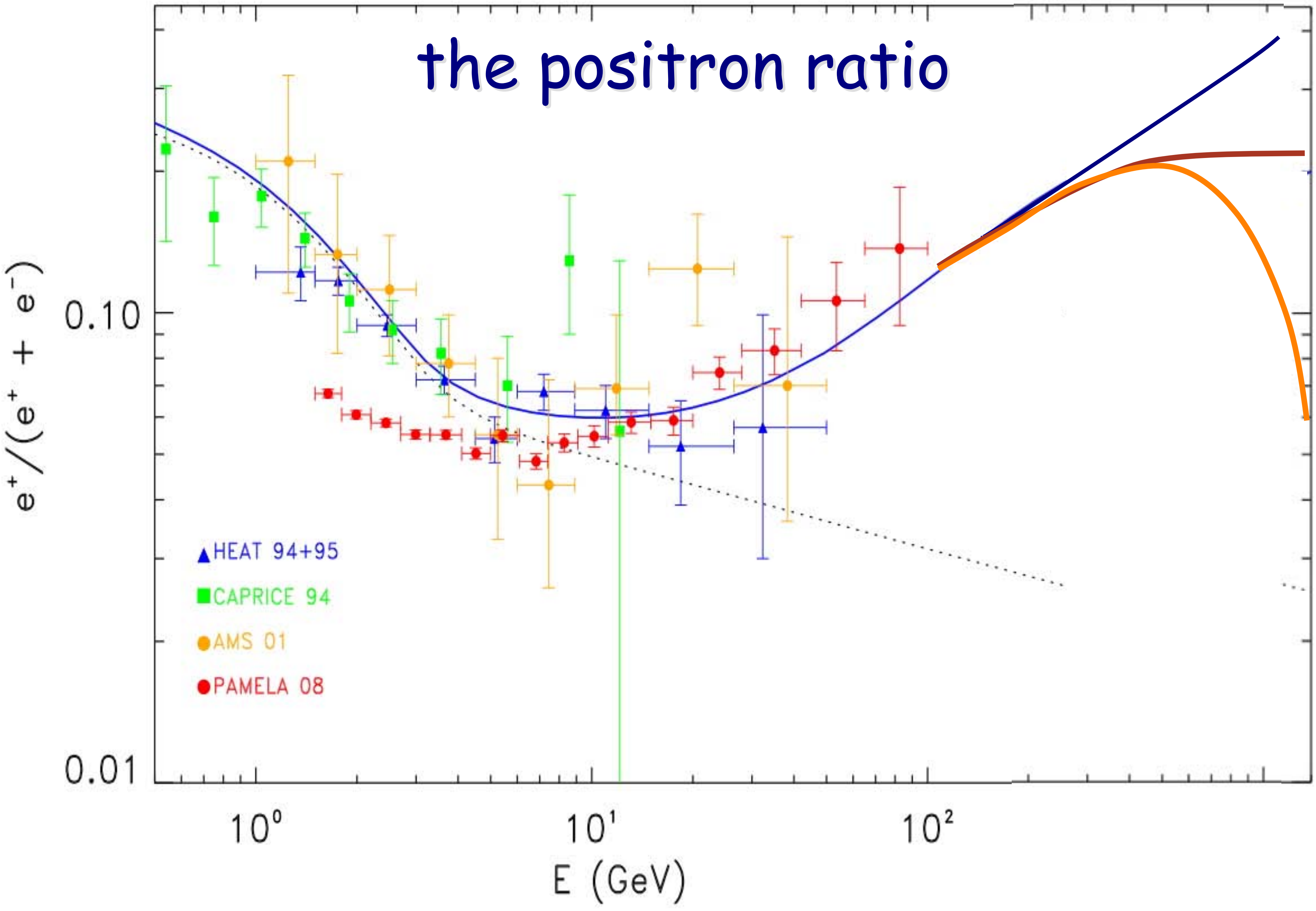
Electron Spectrum:

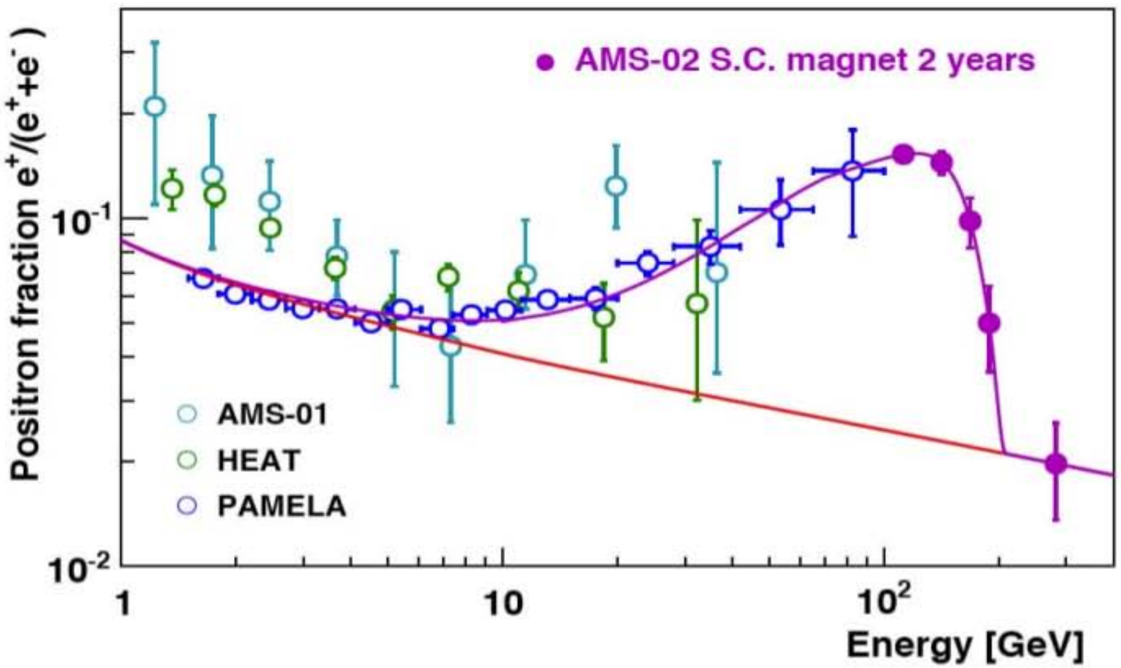
- **PAMELA & FERMI (GLAST)** (taking data in space);
- **ATIC-4** (had successful balloon flight,under analysis);
- **CREST** (new balloon payload under development);
- **AMS-02** (launch date TBD);
- **CALET** (proposed for ISS);
- **ECAL** (proposed balloon experiment).

Comparison of High-Energy Electron Missions

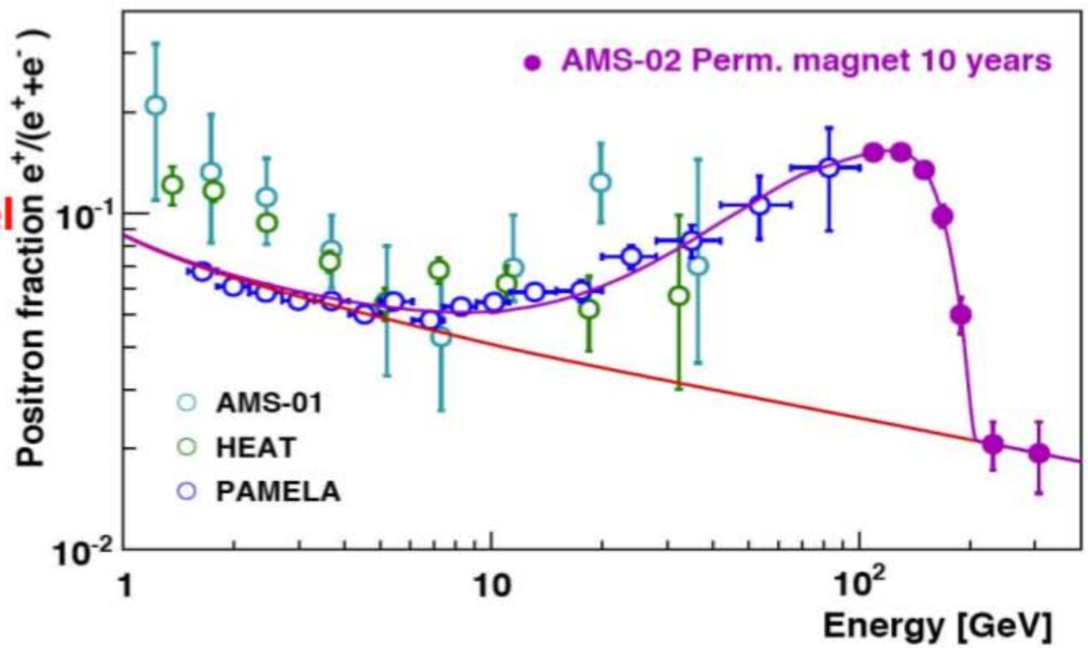
Mission	Upper Energy (TeV)	Collecting Power (m^2sr)	Calorimeter Thickness (X_0)	Energy Resolution (%)
CALET	20	0.75	30.8	< 3 (over 100 GeV)
PAMELA	0.25 (spectrometer) 2 (calorimeter)	0.0022 0.04	16.3	5.5 (300 GeV) 12 (300 GeV) 16 (1TeV)
GLAST	0.7	2.1 (100 GeV) 0.7 (700 GeV)	8.3	6 (100 GeV) 16 (700 GeV)
AMS-02	0.66 (spectrometer) 1 (calorimeter)	0.5 0.06 (100 GeV) < 0.04 (1 TeV)	16.0	< 3 (over 100 GeV)

Positron / Electron Separation: **PAMELA & AMS-02**


the positron ratio
e+/(e+ + e-)
0.10
0.01
HEAT 94+95
CAPRICE 94
AMS 01
PAMELA 08
10^0
10^1
10^2
E (GeV)



AMS sensitivity esponse to a 200 GeV Dark Matter candidate in the e+e- channel



Conclusion:

The Electron+positron spectrum (CRE) measured by Fermi-LAT is significantly harder than previously thought on the basis of previous data

Adopting the presence of an extra e^+ primary component with ~ 1.5 spectral index and E_{cut} ~ 1 TeV allow to consistently interpret Fermi-LAT CRE data (improving the fit), HESS and PAMELA

Such extra-component can be originated if the secondary production takes place in the same region where cosmic rays are being accelerated (to be tested with future B/C measurements)

- or by pulsars for a reasonable choice of relevant parameters (to be tested with future Fermi pulsars measurements)
- or by annihilating dark matter for model with $M_{DM} \approx 1$ TeV

- Improved analysis and complementary observations

(CRE **anisotropy**, spectrum and angular distribution of diffuse γ, DM sources search in γ) are required to possibly discriminate the right scenario.

Announcement for SciNeGHE 2010

8th Workshop on Science with the New Generation High Energy Gamma-ray Experiments

Gamma-ray astrophysics
in the multimessenger context

see you there !!!

TRIESTE, 8-10 September 2010