Measurement of the cosmic ray electron spectrum with FERMI in the energy region 20 GeV – 1 TeV

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Fermi LAT Collaboration

United States (NASA and DOE)

- California State University at Sonoma
- Goddard Space Flight Center
- Naval Research Laboratory
- Ohio State University
- Stanford University (HEPL, KIPAC and SLAC)
- University of California at Santa Cruz – SCIPP
- University of Denver
- University of Washington

France

- CEA/Saclay
- IN2P3

Italy

- ASI
- INFN (Bari, Padova, Perugia, Pisa, Roma2, Trieste, Udine)
- INAF

Japan

- Hiroshima University
- Institute for Space and Astronautical Science / JAXA
- RIKEN
- Tokyo Institute of Technology

Sweden

- Royal Institute of Technology (KTH)
- Stockholm University

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122 full members

95 affiliated scientists

38 management, engineering and technical members

68 post-doctoral members

105 graduate students

Fermi Gamma-ray Space Telescope

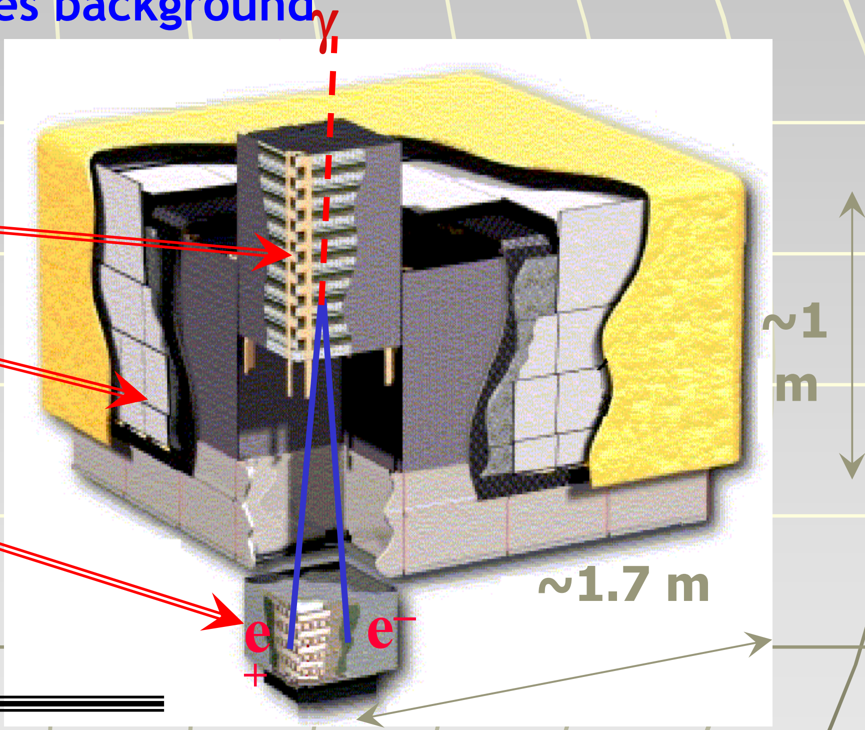
Two instruments onboard Fermi:

- ✓ **Large Area Telescope LAT**
  - main instrument, gamma-ray telescope, 20 MeV - >300 GeV energy range
  - scanning (main) mode - 20% of the sky all the time; all parts of sky for ~30 min. every 3 hours
  - ~ 2.4 sr field of view, 8000 cm^2 effective area above 1 GeV
  - good energy (5-10%) and spatial (~3^0 at 100 MeV and <0.1^0 at 1 GeV) resolution
- ✓ **GLAST Burst Monitor GBM**

5-year mission (10-year goal), 565 km circular orbit, 25.6^0 inclination

The LAT as an electron spectrometer

Pair-conversion gamma-ray telescope: 16 identical "towers" providing conversion of γ into e^+e^- pair and determination of its arrival direction (Tracker) and energy (Calorimeter). Covered by segmented AntiCoincidence Detector which rejects the charged particles background.



Silicon-strip tracker: 18 double-plane single-side (x and y) interleaved with 3.5% X_0 thick (first 12) and 18% X_0 thick (next 4) tungsten converters. Strips pitch is 228 μm

Segmented Anticoincidence Detector: 89 plastic scintillator tiles and 8 flexible scintillator ribbons.

Hodoscopic CsI Calorimeter Array of 1536 CsI(Tl) crystals in 8 layers.

Electronics System Includes flexible, robust hardware trigger and software filters.

- **LAT intrinsically is an electron spectrometer. We only needed to teach it how to distinguish electrons from hadrons**
- **expected statistics ~ 10M electrons per year for E>20 GeV**

FERMI FLIGHT DATA ANALYSIS FOR ELECTRONS

Main challenges:

- ✓ Energy reconstruction:
  - – optimized for photon energy < 300 GeV; we extended it up to 1 TeV
- ✓ Electron-hadron separation
  - \- achieved needed 10^3 - 10^4 rejection against hadrons
- ✓ Validation of Monte Carlo with the beam tests and flight data
- ✓ Assessment of systematic errors

Our strong points:

- ✓ Extensive MC simulations
- ✓ High precision 1.5 X_0 thick tracker:
  - – powerful in event topology recognition
  - – serves as a pre-shower detector
- ✓ Segmented calorimeter with imaging capability
- ✓ Segmented ACD:
  - – removes gammas and contributes to event pattern recognition
- ✓ Extensive beam tests:
  - – SLAC, DESY, GSI, CERN, GANIL
- ✓ High flight statistics:
  - – Expecting ~10 M electrons above 20 GeV a year

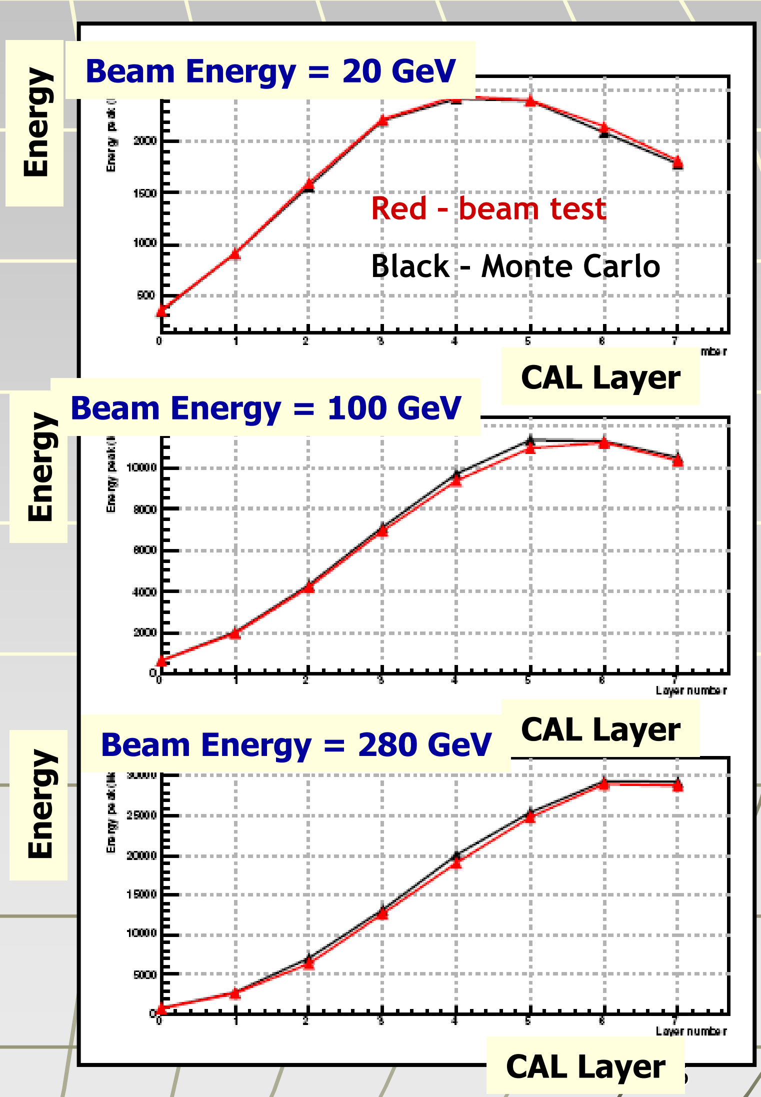
Energy reconstruction

Reconstruction of the most probable value for the event energy:

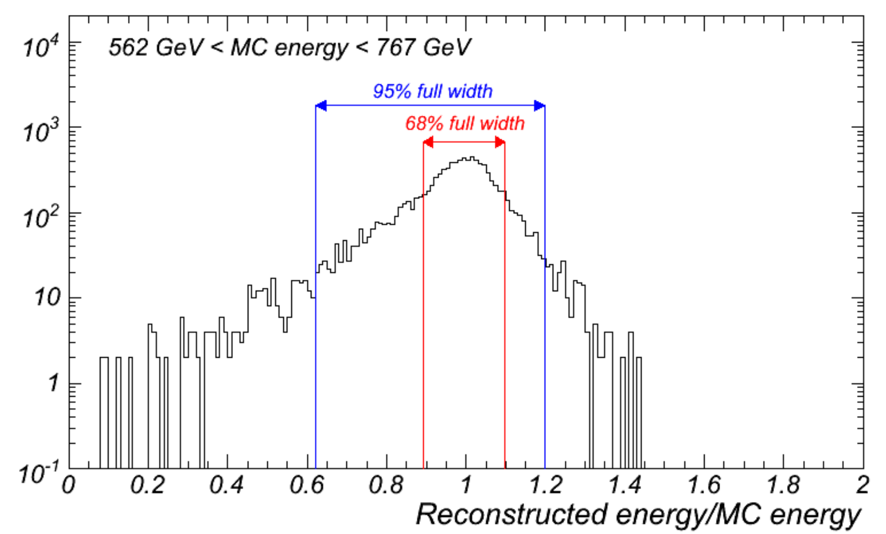
- **based on calibration of the response of each of 1536 calorimeter crystals**
- **energy reconstruction is optimized for each event**
- **calorimeter imaging capability is heavily used for fitting shower profile**
- **tested at CERN beams up to 280 GeV with the LAT Calibration Unit**

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

Beam test shower profiles for on-axis incidence: theta=0 (worst case – smallest calorimeter thickness)



Energy resolution

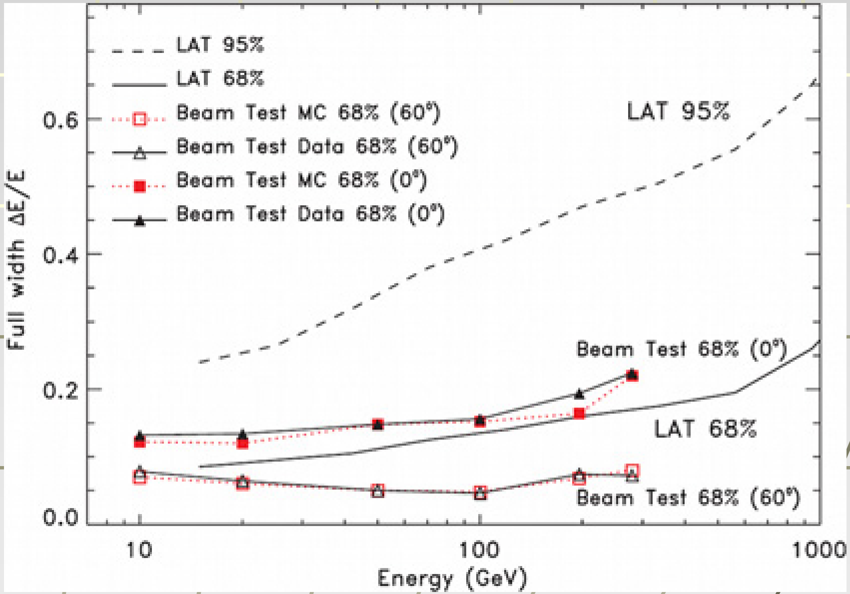


- Energy resolution defined as full width containing 68% (95%) of events
- high energy tail is exponential and drops much faster than E^{-3} spectrum

Agreement between MC and beam test within a few percent up to 280 GeV

we can be confident in MC

we have reasonable grounds to extend the energy range to 1 TeV relying on Monte Carlo simulations



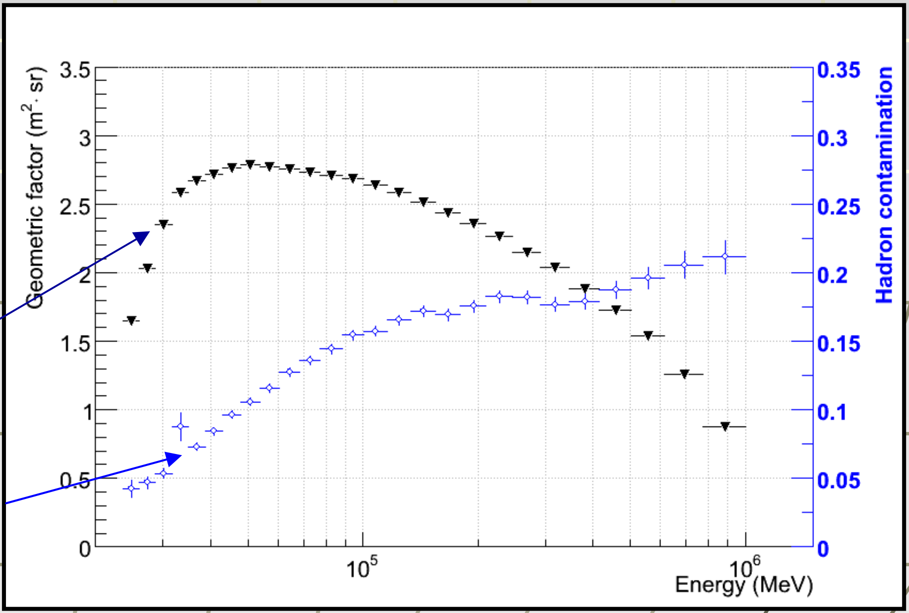
Achieved electron-hadron separation and effective geometric factor

- ✓ Candidate electrons pass on average 12.5 X_0 (Tracker and Calorimeter added together)
- ✓ Simulated residual hadron contamination (5-21% increasing with energy) is deducted from resulting flux of electron candidates
- ✓ Effective geometric factor exceeds 2.5 m^2sr for 30 GeV to 200 GeV, and decreases to ~1 m^2sr at 1 TeV
- ✓ Full power of all LAT subsystems is in use: tracker, calorimeter and ACD act together

Key issue: *good knowledge and confidence in Instrument Response Function*

Geometric Factor

Residual hadron contamination



Validation of the flight data

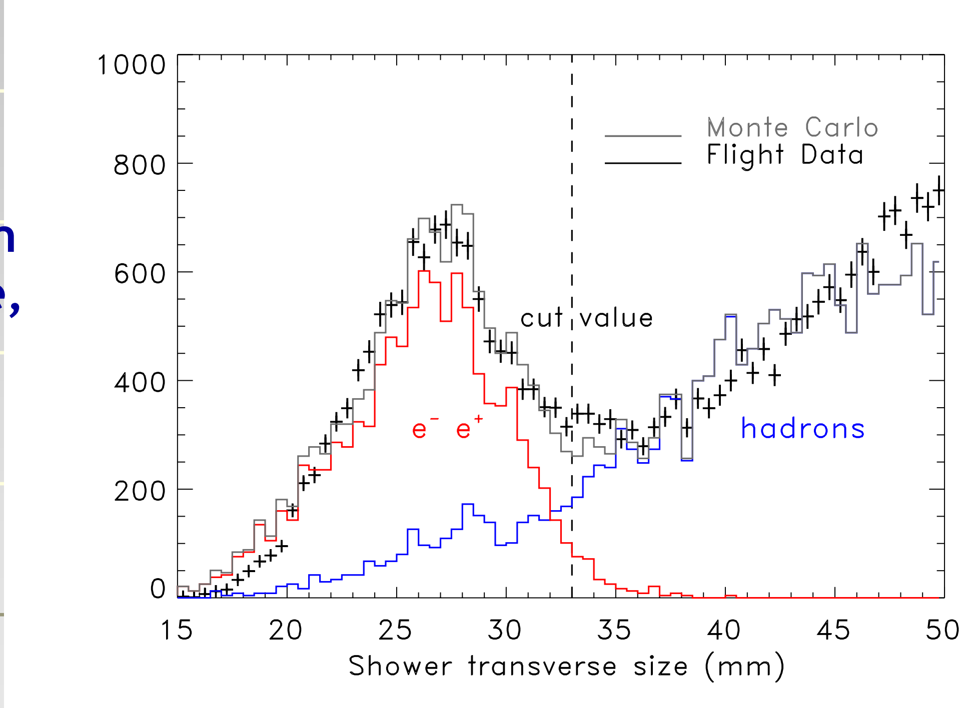
Task: compare the efficiency of all "cuts" for flight data and MC events

Approach:

- Plot from the flight data the histogram of each variable involved in the electron selections, one at a time, after applying all other cuts

- check if the flight histograms match the simulated ones, and account for the differences in systematic errors for the reconstructed spectrum

Example for the variable (shower transverse size)



Analysis variables demonstrate good agreement between the flight data and MC

Assessment of systematic errors

Contributors:

1. Uncertainty in effective geometric factor - comes from the residual discrepancy between Monte Carlo and the data. Carefully estimated for each variable used in the analysis

2. Uncertainty in determination of residual hadron contamination

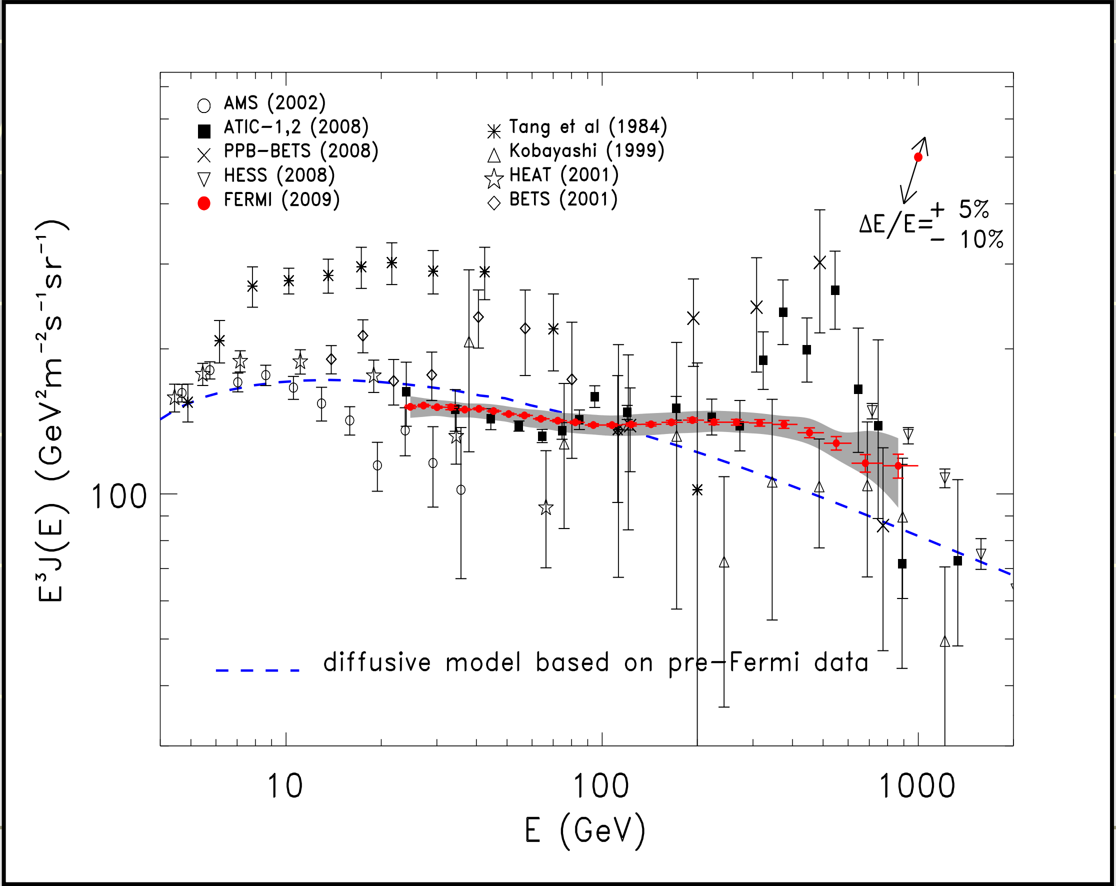
- comes mostly from the uncertainty of the primary proton flux (~ 20%)
- we validated the hadronic interaction model with the beam test data

Contributors 1 and 2 result in total systematic error in the spectrum ranging from 10% at low energy end to 25-30% at high energy end (full width)

3. **Possible bias in absolute energy determination**

- Included separately in the resulting spectrum as (+5, -10)% - estimated from MC simulations, calorimeter calibration and CERN beam test.

Fermi-LAT electron spectrum from 20 GeV to 1 TeV



Phys. Rev. Letters 102, 181101 (2009)

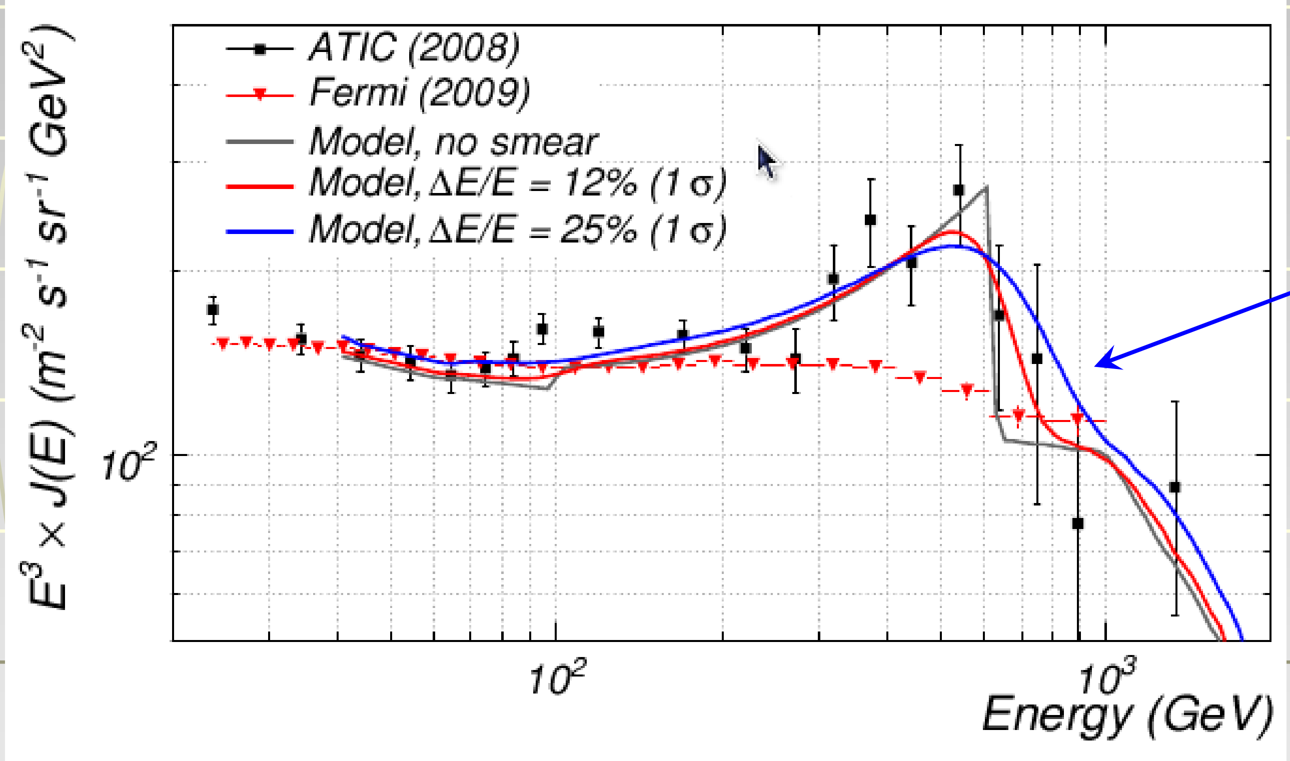
- ✓ ***Cited 38 times within a month***
- ✓ ***APS Viewpoint***

Total statistics collected for 6 months of Fermi LAT observations:

- *> 4 million electrons above 20 GeV*
- *> 400 electrons in last energy bin (770-1000 GeV)*

Final check - could we miss "ATIC-like" spectral feature?

We validated the spectrum reconstruction by several ways including simulation of the LAT response to a spectrum with an "ATIC-like" feature:



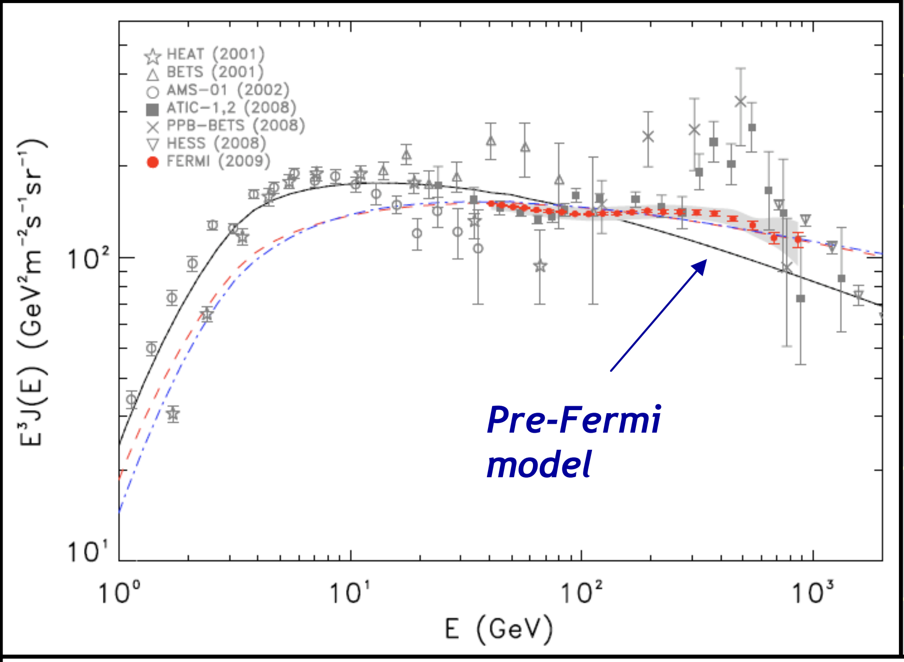
Blue line shows how Fermi-LAT would detect this feature if its energy resolution was worse by a factor of 2

This demonstrates that the Fermi LAT would have been able to reveal "ATIC-like" spectral feature with high confidence if it were there. Energy resolution is not an issue with such a wide feature

Some interpretations…

Can our result be fitted with pre-Fermi model?

Based on our interpretation paper: D.Grasso et al., astro-ph 0905. 0636 (May 4, 2009); submitted to Astroparticle Physics



Pre-Fermi model

$$J_{e^\pm} = (175.40 \pm 6.09) \left(\frac{E}{1\ \mathrm{GeV}} \right)^{-(3.045 \pm 0.008)} \mathrm{GeV}^{-1}\mathrm{m}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$

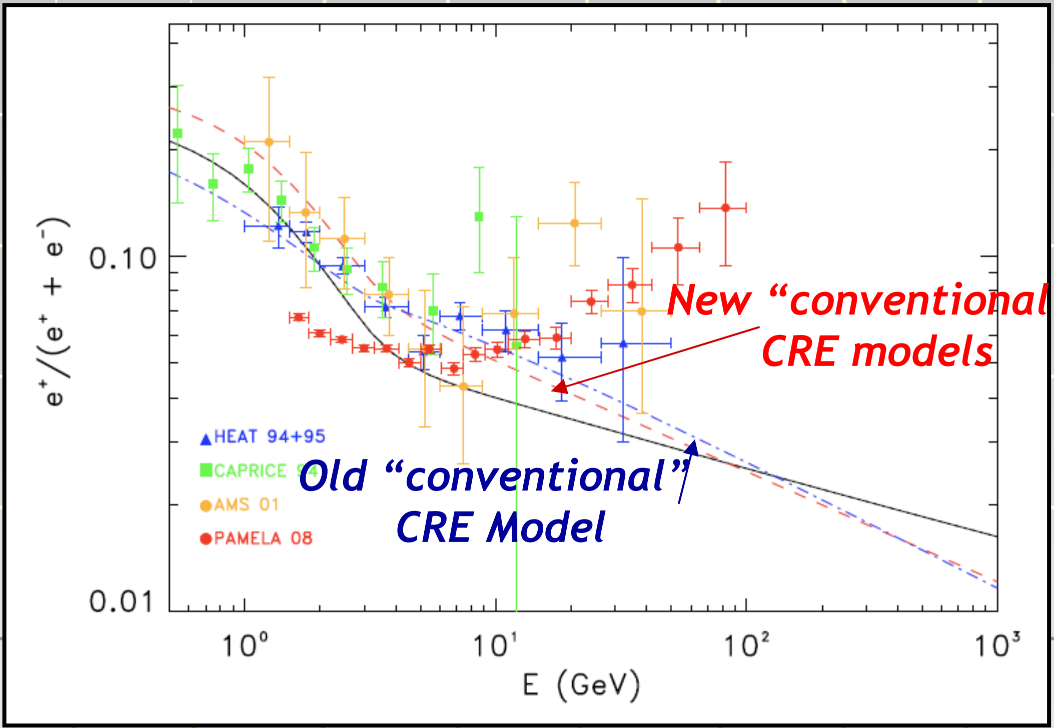
Pre-Fermi Diffuse Galactic Cosmic-Ray Source Model: electrons accelerated by continuously distributed astrophysical sources, likely SNR

Spectrum can be fitted by model with harder injection spectral index (-2.42) than in pre-Fermi model (-2.54). All that within our current uncertainties, both statistical and systematic

Remark: if we subtract the e^+ fraction of the flux, using Pamela data, the e^- spectrum becomes softer by ~0.1 and consequently requires softer injection spectrum

Now include recent Pamela result on positron fraction:

Qualitative approach: the harder primary CRE spectrum is, the steeper secondary-to-primary e+/e- ratio should be. Pamela shows the opposite



New "conventional" CRE models

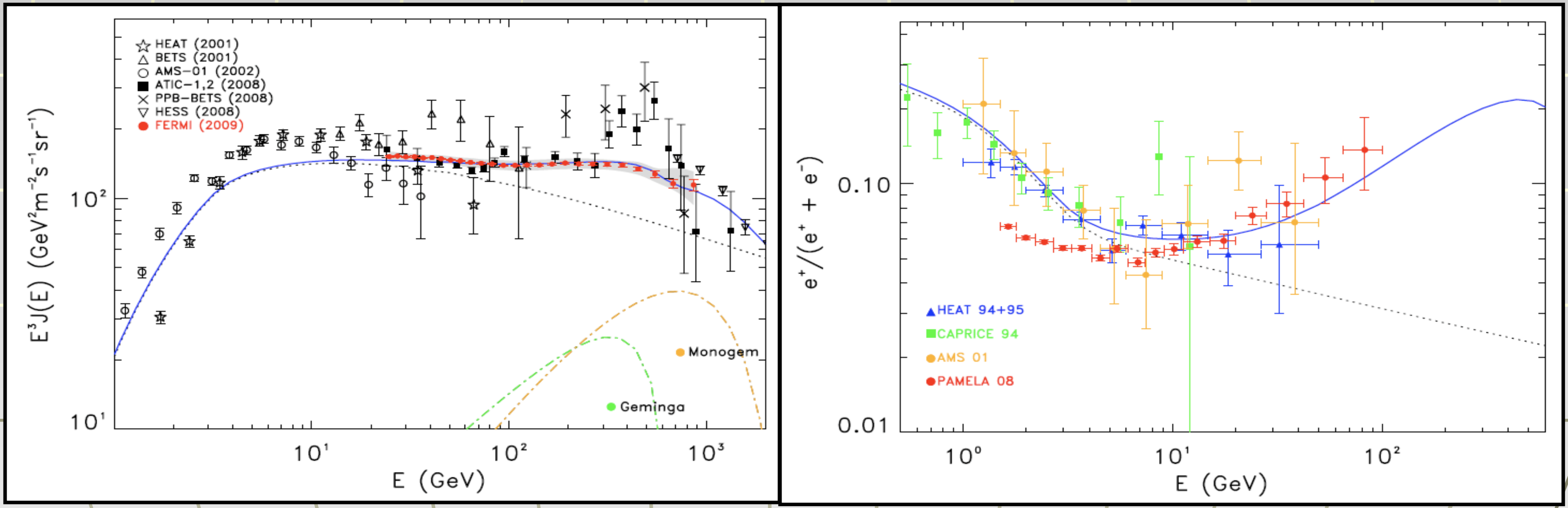
Old "conventional" CRE Model

Precise Fermi measurement of the hard *e+e-* spectrum increases the discrepancy between a purely secondary origin for positrons and the positron fraction measured by Pamela

It is becoming clear that we are dealing with at least three distinct origins of high energy electrons and positrons

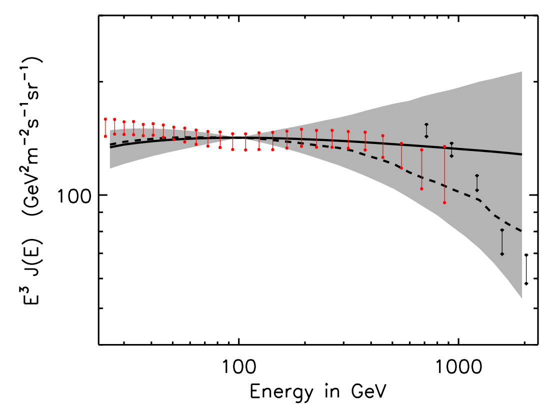
- One is uniformly distributed “distant” sources, likely SNR
- Another is unavoidable e^+e^- production in CR interactions with ISM

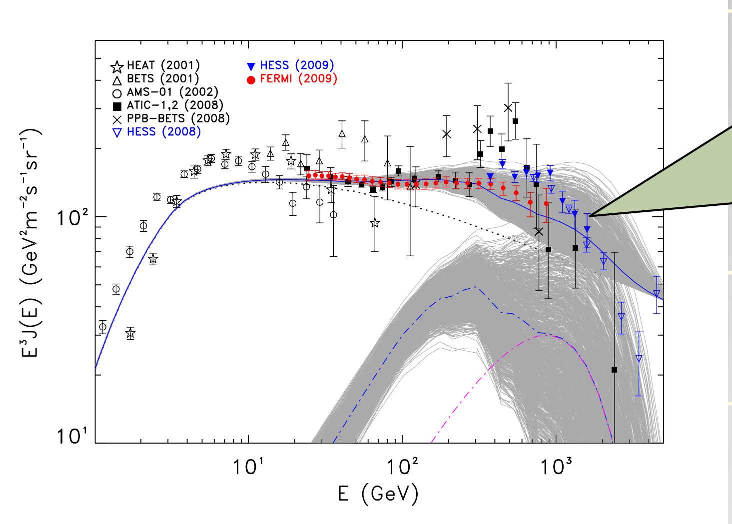
What creates positron excess at high energy? Nearby (d < 1 kpc) and Mature ($10^4 < T/yr < 10^6$) pulsars ?



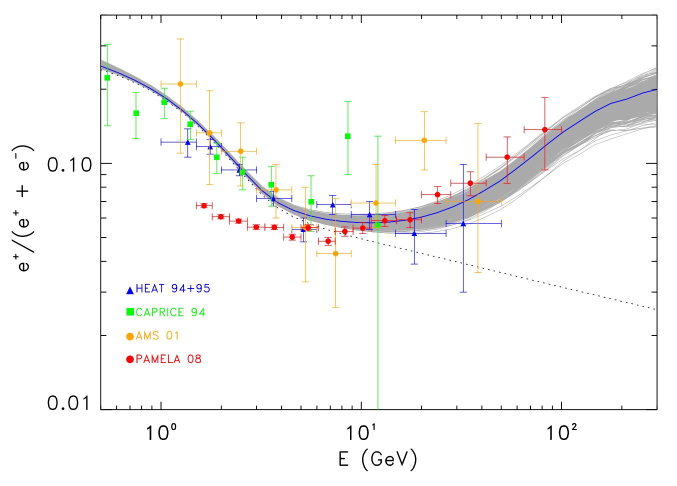
Example of fit to both Fermi and Pamela data with **Monogem and Geminga** pulsars and with a single, nominal choice for the e+/e- injection parameter - works better

What if we randomly vary the pulsar parameters, relevant for e+e- production (*injection spectrum, e+e- production efficiency, PWN “trapping” time*), and include more contributing pulsars stochastically?





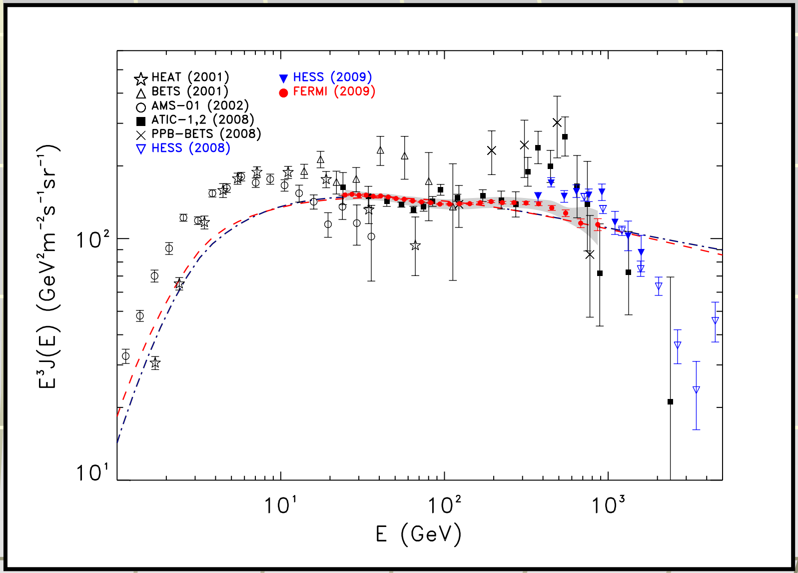
These “wings” are our next target



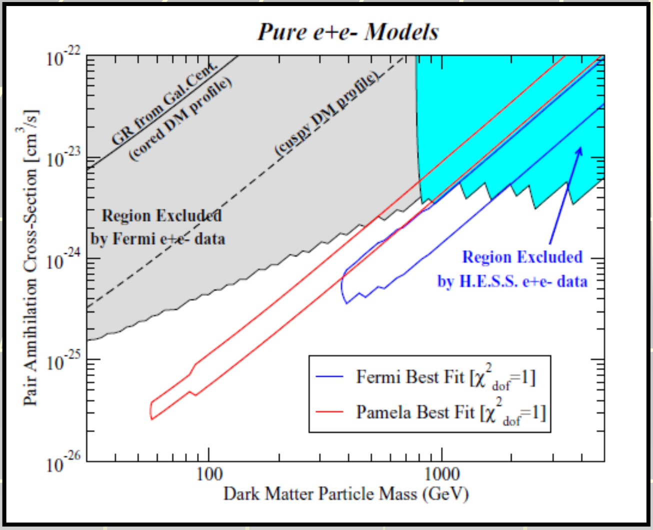
Under reasonable assumptions, electron/positron emission from pulsars offers a viable interpretation of Fermi CRE data which is also consistent with the HESS and Pamela results. Many degrees of freedom, but the assumption is plausible and realistic

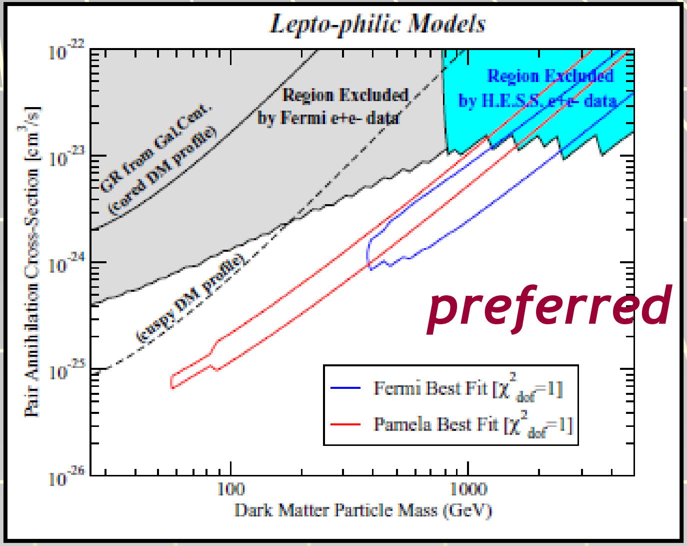
Dark matter: the impact of the new Fermi CRE data

1. *Everything said on previous slides about pulsars as sources of e^+e^- is applicable to DM. Dark matter origin of e+e- is not ruled out*
2. *If the Pamela positron excess comes from DM annihilation or decay, the Fermi CRE data set puts constraints on such interpretation (e.g. pair annihilation or decay rate for a given DM mass and diffusion setup)*
3. *Pamela and Fermi-LAT data tighten the DM constraints, favoring pure $e^{\pm}$, lepto-philic, or super-heavy DM models*

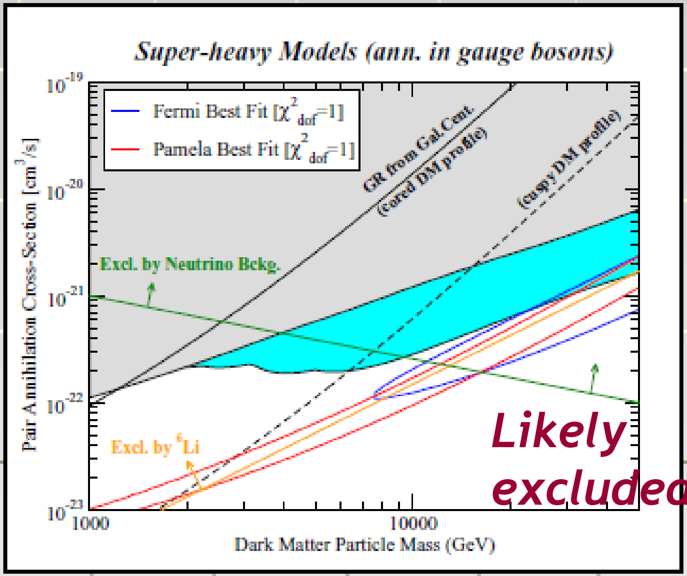


4. ***Need precise spectral shape!*** *Irregularities on the falling slope of the spectrum above ~ 1 TeV, if found, may help to determine the origin of high energy electrons, favoring nearby pulsars scenario*

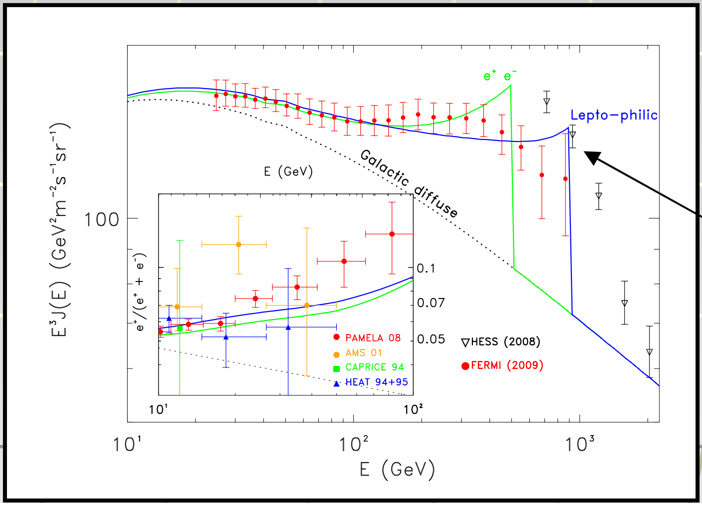




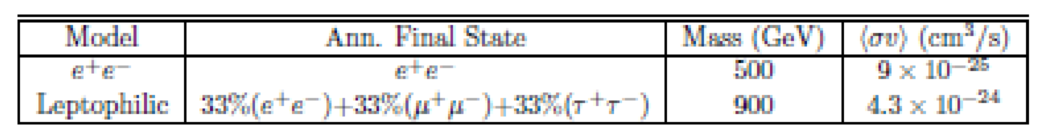
preferred



Likely excluded



Instrumental energy smearing is not included



Model	Ann. Final State	Mass (GeV)	$\langle\sigma v\rangle$ $(\mathrm{cm}^3/\mathrm{s})$
e^+e^-	e^+e^-	500	9×10^{-25}
Leptophilic	$33\%(e^+e^-)+33\%(\mu^+\mu^-)+33\%(\tau^+\tau^-)$	900	4.3×10^{-24}

Dark matter origin of CRE is not ruled out. Origin of the local source is still unclear - astrophysical or "exotic"

Future plans:

✓ Search for anisotropy in the electron flux - contributes to the understanding of the "extra" source origin

✓ Study systematic errors in energy and instrument response to determine whether or not the observed spectral structure is significant - also critical for understanding of the source origin, as well as models constrains

  ✓Work on understanding of calorimeter calibration to decrease systematic uncertainty in the absolute energy scale

✓ Expand energy range down to ~ 5 GeV (lowest possible for Fermi orbit) and up to ~ 2 TeV, in order to reveal the spectral shape above 1 TeV

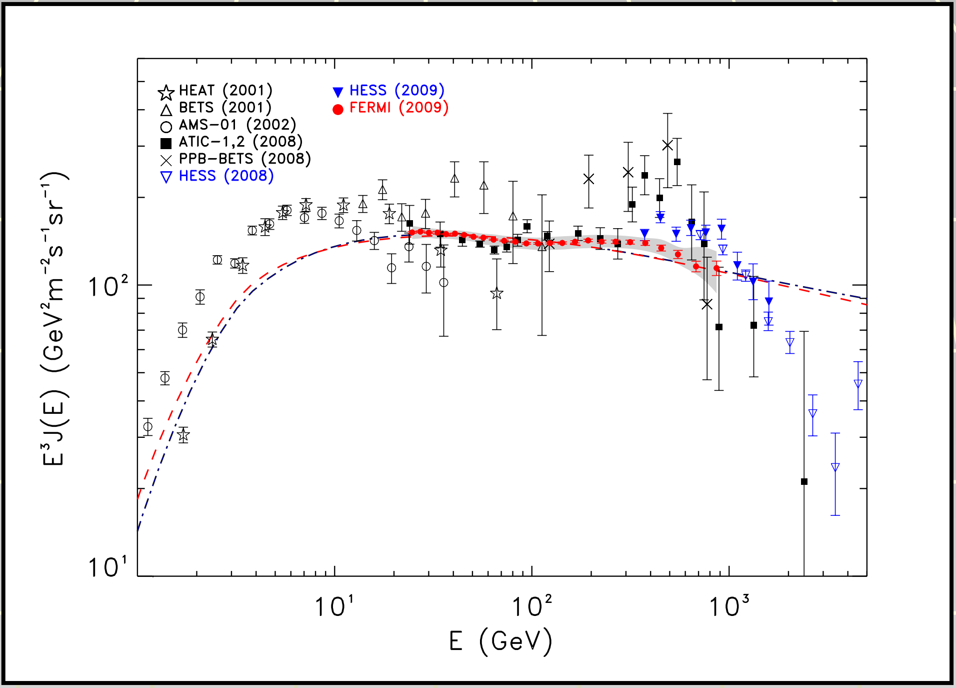
  ✓Measurement at higher energies require the use of bigger incident angles (currently theta < 70 degrees)

    ✓Thicker CsI calorimeter - up to 1.5 m of CsI at 90 degrees

    ✓Requires modified reconstruction algorithms for calorimeter and tracker

✓ Increase the statistics at high energy end. Each year Fermi-LAT will collect ~ 400 electrons above 1 TeV with the current selections if the spectral index stays unchanged

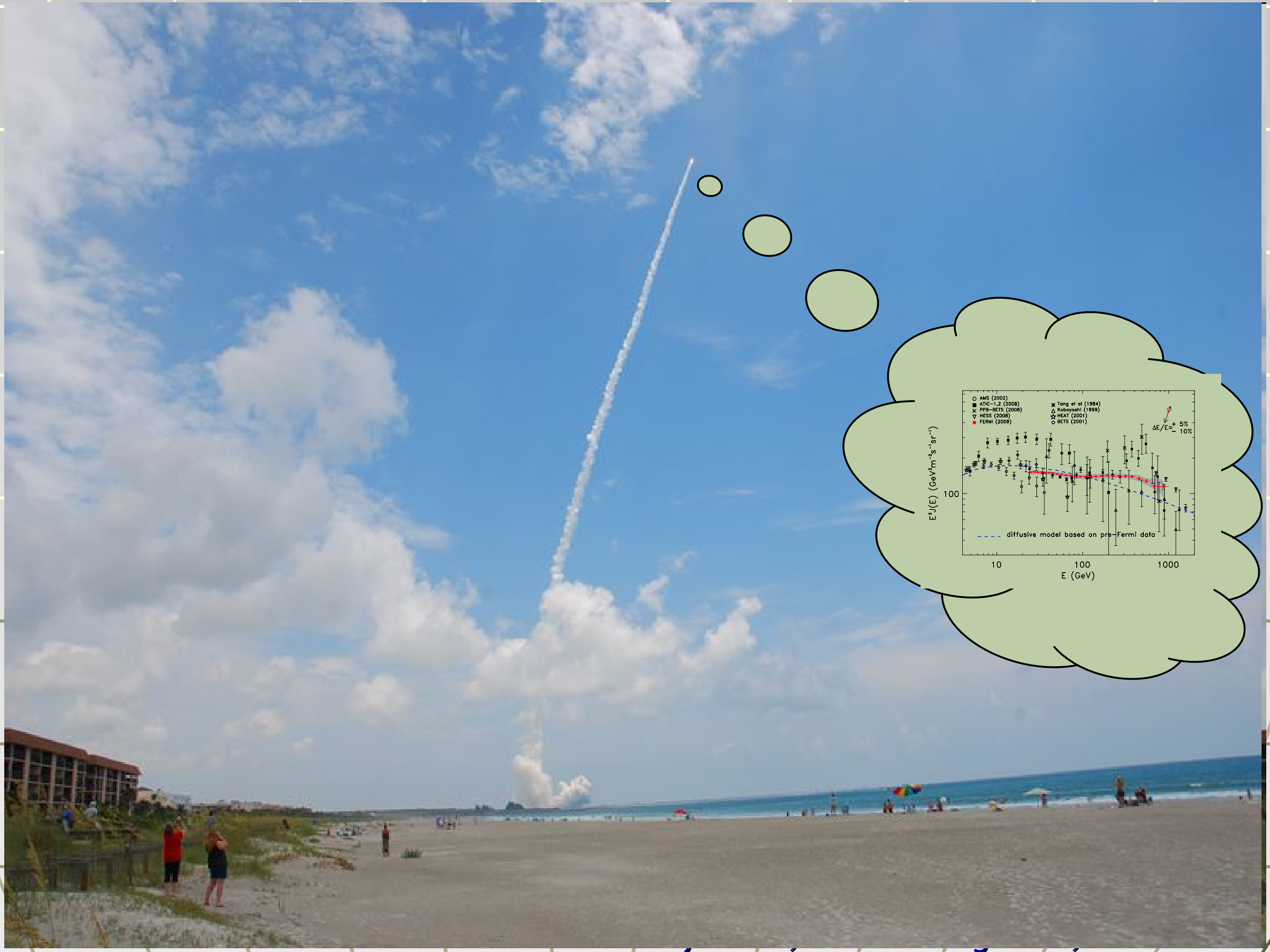
Fermi
Gamma-ray
Space Telescope



SUMMARY

- *Real breakthrough during last 1-1.5 years in cosmic ray electrons: ATIC, HESS, Pamela, and finally Fermi-LAT. New quality data are available*
- *With the new data more puzzles than was before; need "multiwavelength" campaign: electrons, positrons, gammas, X-ray, radio, neutrino…*
- *We may be coming close to the first direct detection of cosmic ray source*
- *Source nature: astrophysical or exotic - unclear. Possible that other models will be suggested*
- *More results from Fermi-LAT are coming: high energy electrons anisotropy at a level of ~ 1%, extended energy range to 5 GeV - 2 TeV*

THANK YOU !


AMS (2002)
ATIC-1,2 (2008)
PPB-BETS (2008)
HESS (2008)
FERMI (2009)
Tang et al (1984)
Kobayashi (1999)
HEAT (2001)
BETS (2001)
ΔE/E=+ 5% − 10%
$E^3J(E)$ ($GeV^2m^{-2}s^{-1}sr^{-1}$)
100
diffusive model based on pre-Fermi data
10
100
1000
E (GeV)