Fermi Gamma-ray Space Telescope

New results on high energy cosmic ray electrons observed with Fermi LAT and their implications on the models of pulsars

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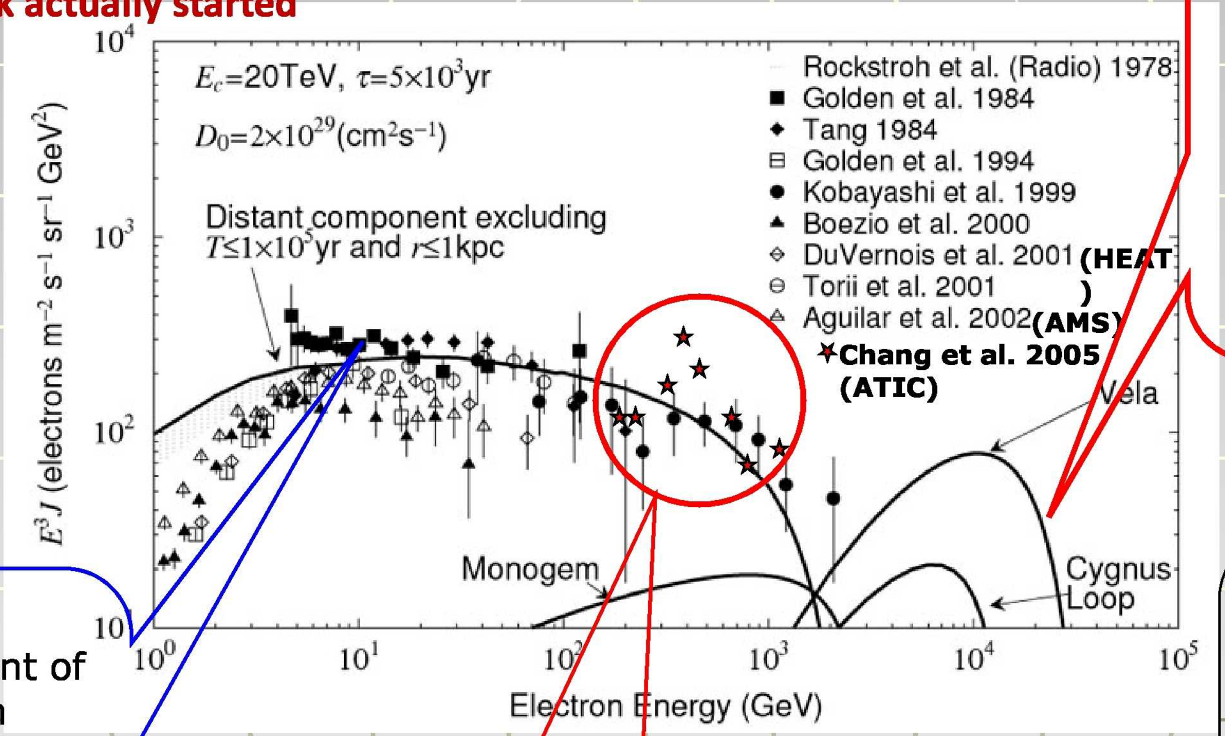
What can be learned from high energy cosmic ray electrons?

From our presentation in 2006 GLAST Collaboration meeting when this work actually started

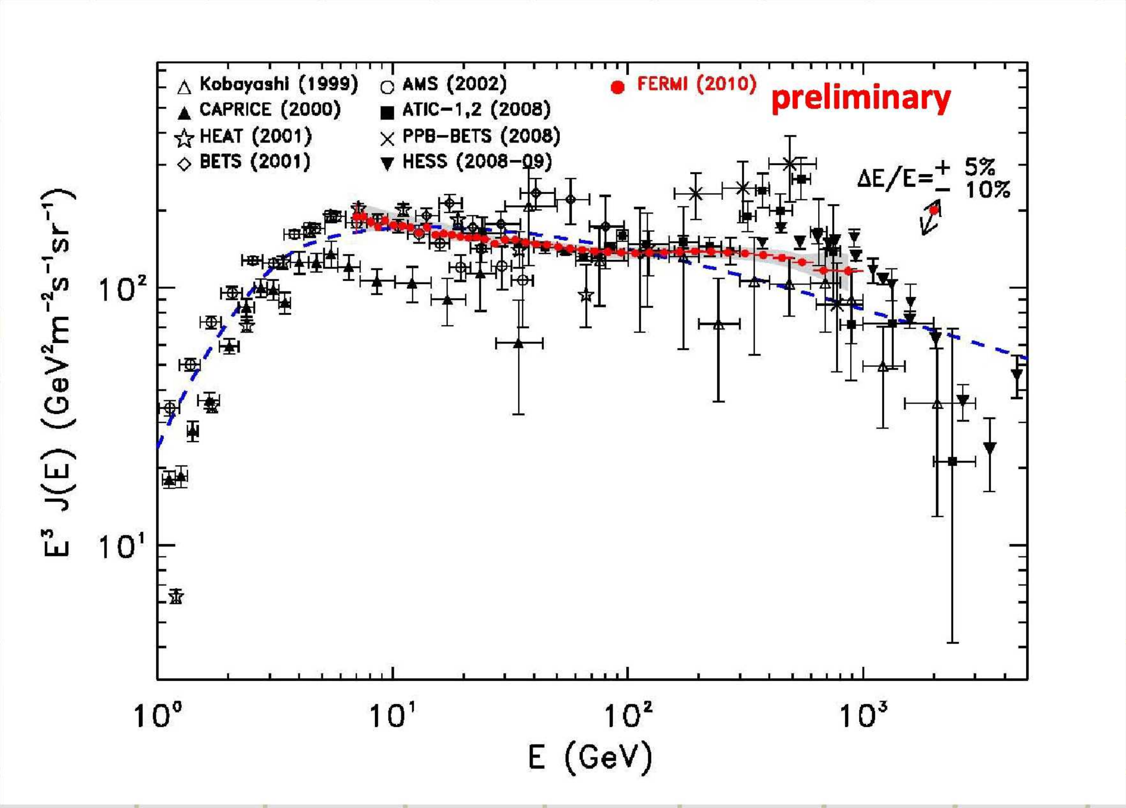


Search for the signature of nearby HE electrons sources (believed to be SNR) in the electron spectrum above ~ TeV

Precise measurement of electron spectrum above 10 GeV (calibration of IC gamma ray flux model, GALPROP)

Search for Dark Matter Signatures (KKDM) – above ~100 GeV

Search for anisotropy in HE electron flux : nearby sources, streaming of local magnetic fields?



Fermi LAT electron + positron spectrum from 7 GeV to 1 TeV, taken in the first 12 months of operation. Total statistics 7.95 M events

First publication: PRL 102, 181101, 2009 reported the spectrum from 20 GeV to 1 TeV, taken in the first 6 months of operation. Total statistics 4.7M events

Fermi Gamma-ray Space Telescope

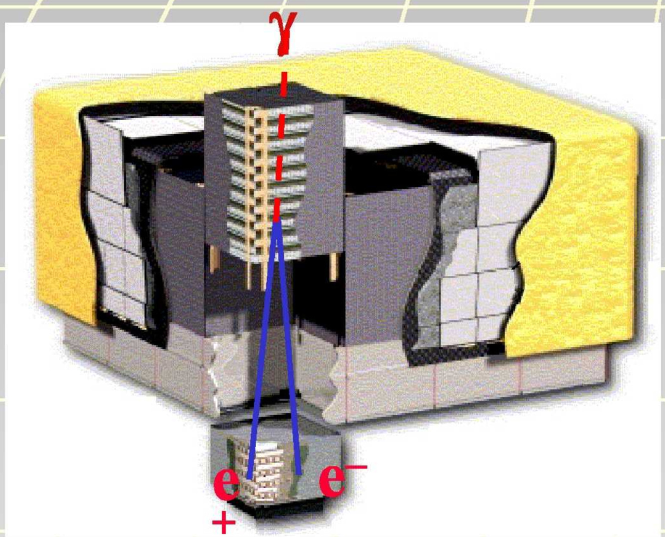
Two instruments onboard Fermi:

- ✓ 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 ($\sim 3^0$ 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

Launched on June 11, 2008 and demonstrates excellent performance so far

Fermi LAT as a detector of high energy cosmic ray electrons



• The LAT is composed of a 4x4 array of identical towers. Each tower has a Tracker and a Calorimeter module. Entire LAT is covered by segmented Anti-Coincidence Detector (ACD).

• Although the LAT was designed to detect photons, it was recognized early in its design that the LAT is a capable detector of high energy electrons too

• The electron data analysis is based on that developed for photons. The main challenge is to identify and separate electrons from all other charged species, mainly CR protons (for gamma-ray analysis this is provided by the Anti-Coincidence System)

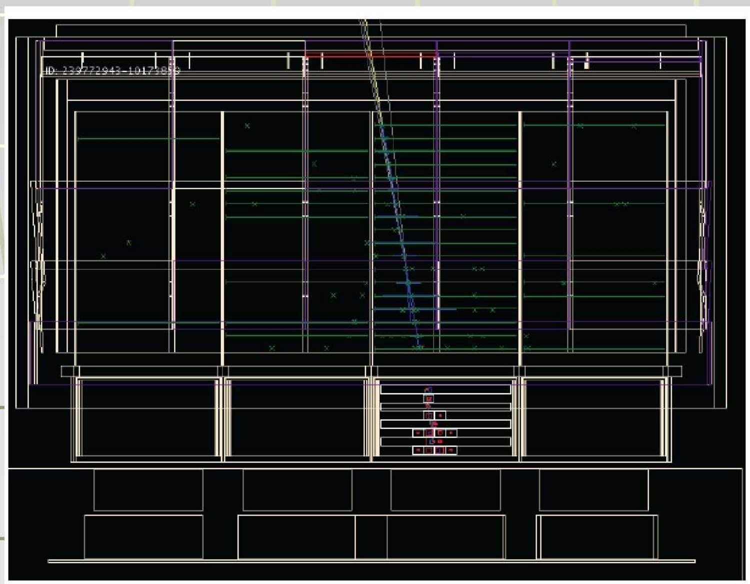
• The hadron rejection power must be 10^3 – 10^4 increasing with energy

Electron Event Selection

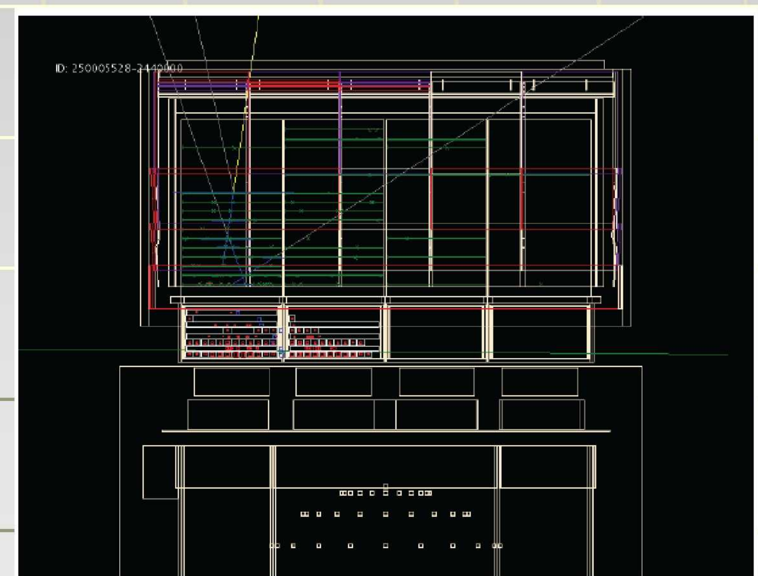
- All the LAT subsystems – tracker, calorimeter and ACD contribute to the event selection

- Event selection is based on the difference between electromagnetic and hadronic event topologies in the instrument

Flight event display



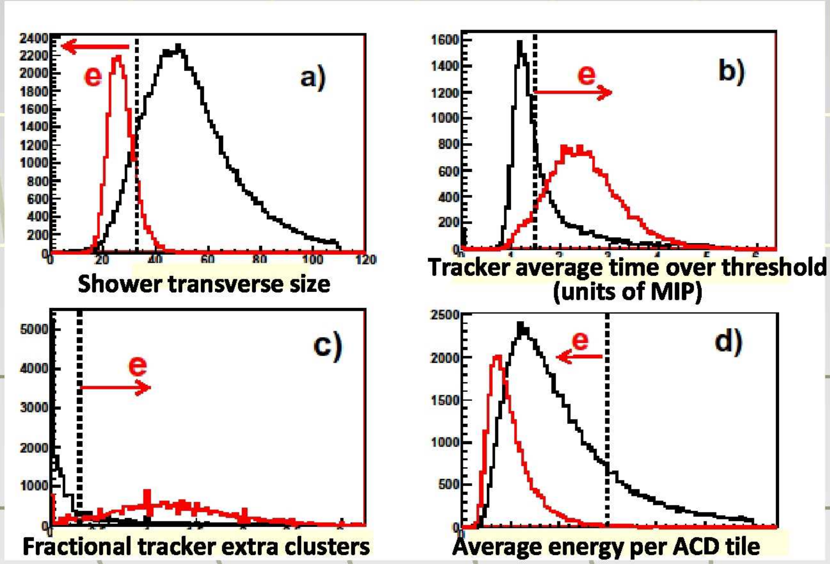
Electron candidate, 844 GeV



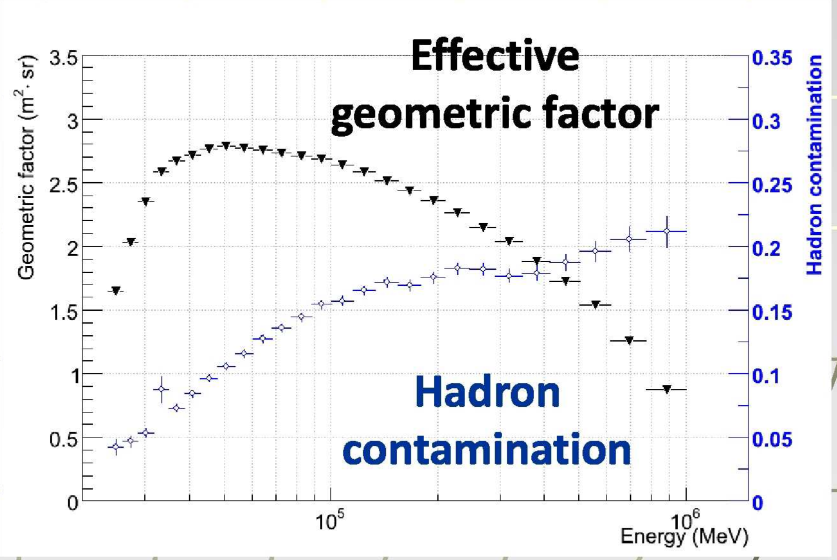
Background event, 765 GeV

Electron event selection (cont.)

- Electron event selection is a complicated, highly-optimized process that utilizes numerous physical variables from all 3 LAT subsystems, as well as combined variables calculated with the Classification Tree method
- Most of the selections are energy dependent or scaled with the energy
- The most powerful separators between electromagnetic and hadronic events are the lateral distributions of the shower image

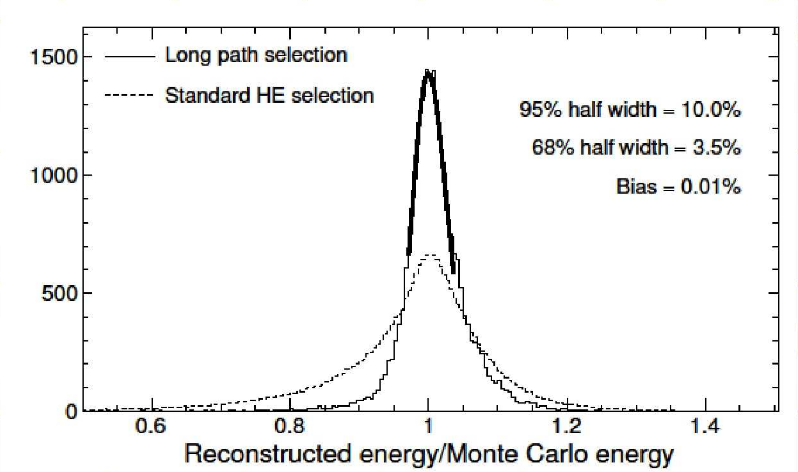


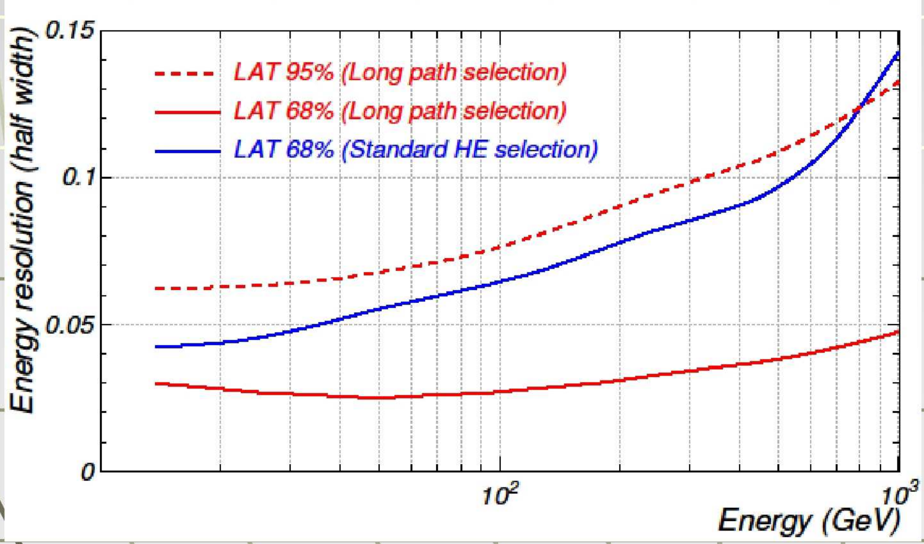
Histograms of selected variable distributions for the electron (red) and proton (black) events

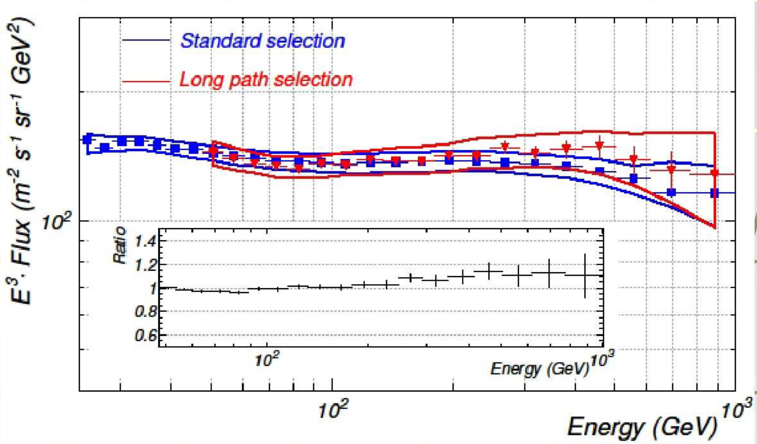


Event energy reconstruction

- Based on the algorithms developed for the LAT photon analysis
- Extended to 1 TeV for the electron analysis
- Validated in extensive beam tests (SLAC, CERN, GSI)
- Cross-checked with subset of events with long paths in the calorimeter, providing best energy resolution (better than 5% up to 1 TeV)





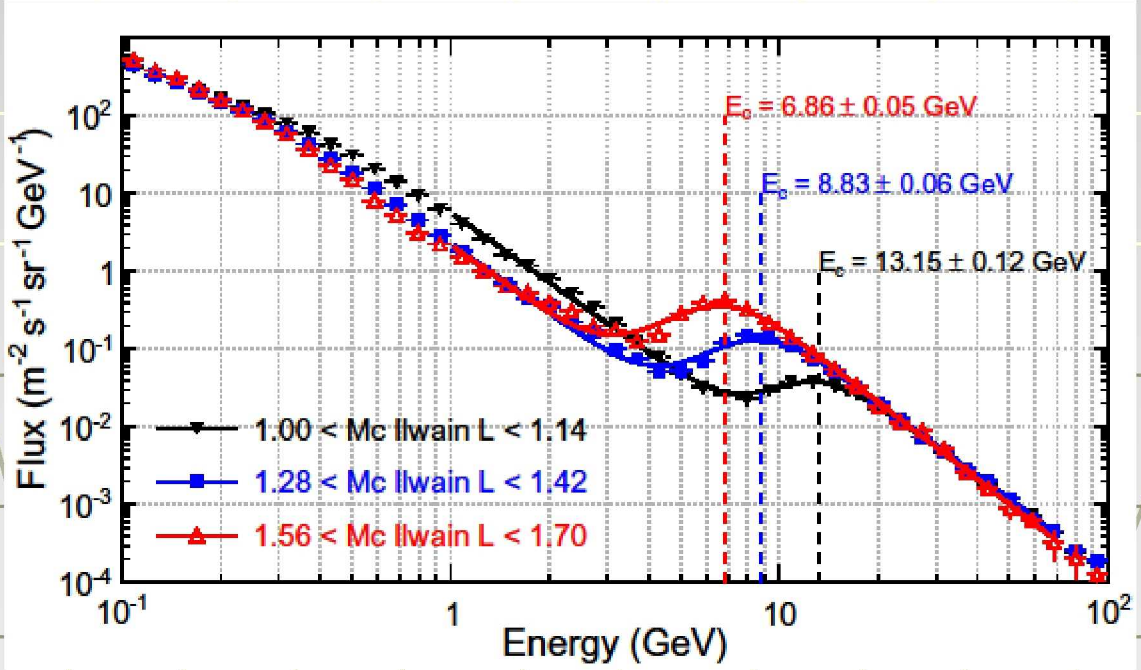


Spectrum cross check with long path events

Spectrum extension down to 7 GeV (new in respect to the PRL paper)

- Lowering the spectrum from 20 GeV to 7 GeV (lowest geomagnetic cutoff energy accessible to the Fermi satellite) requires considering the shielding effect of the geomagnetic field

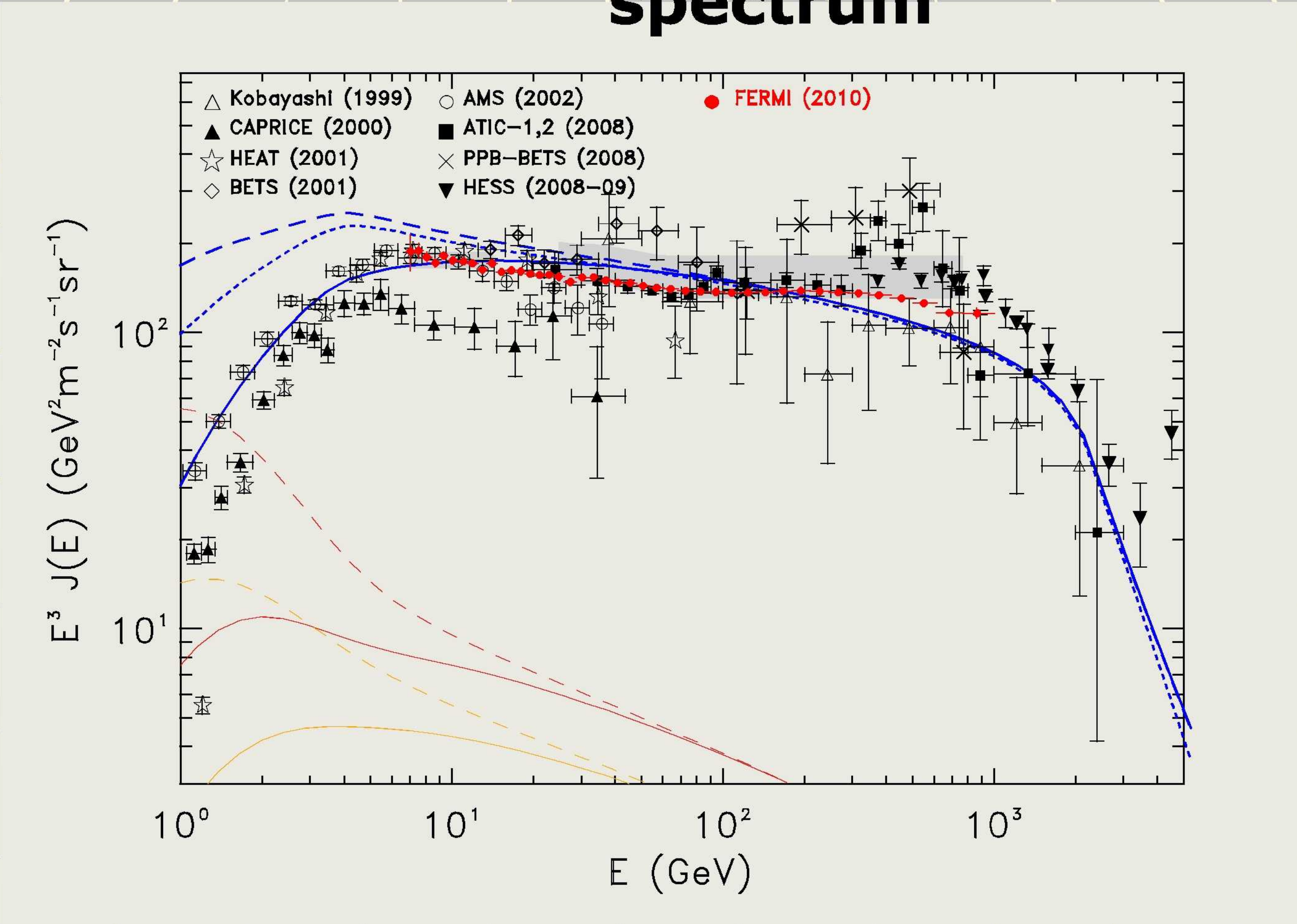
- The lowest energy of primary electrons that can be measured is strongly dependent on the satellite geomagnetic position and decreases with increasing geomagnetic latitude



Systematic uncertainties

- Very high event counting statistics makes our result dominated by systematic uncertainties.
- Main contributor to the systematic uncertainty is imperfect knowledge of the LAT response, mainly the effective geometric factor (5-20% increasing with energy)
- Another contributor comes from subtraction of residual hadron contamination (< 5%)
- Uncertainty in absolute energy scale is +5-10%

Attempt to fit with broken injection spectrum



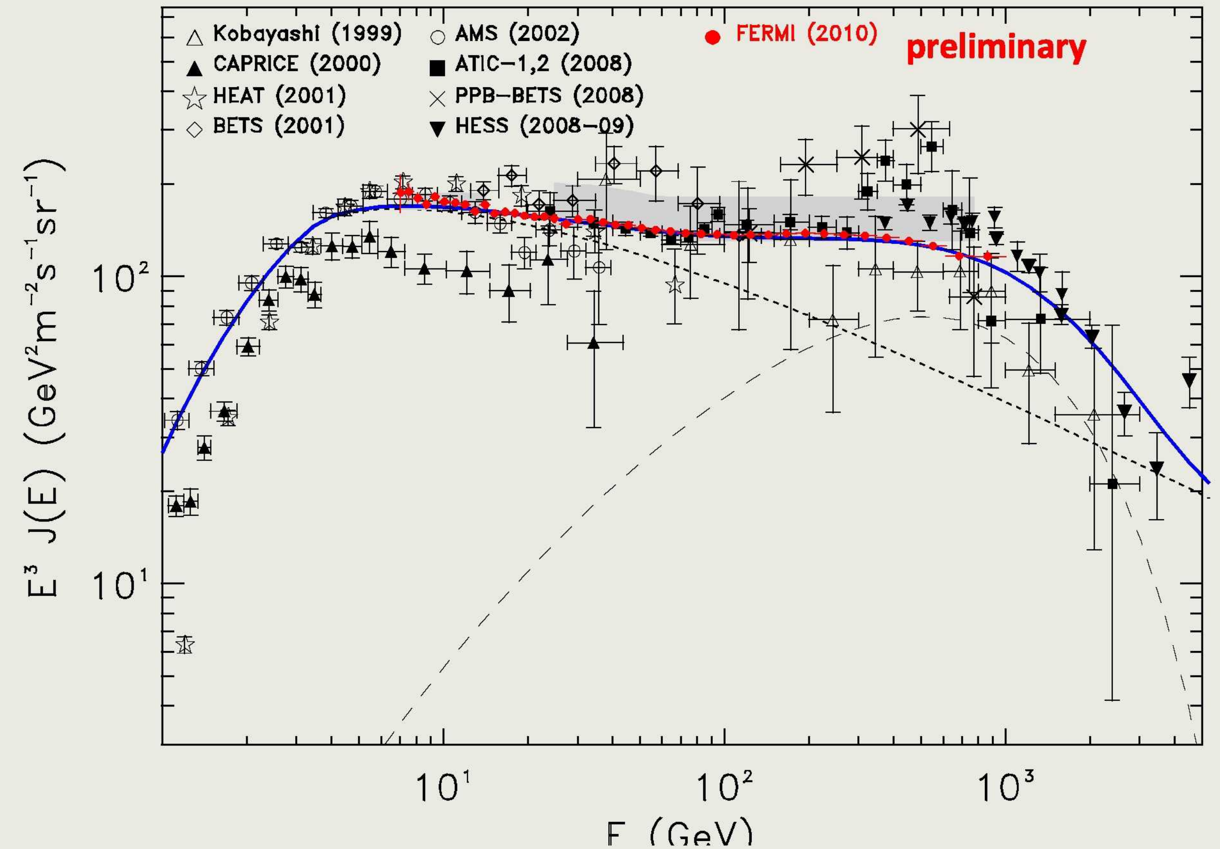
Fermi LAT spectrum fitted by a GALPROP-computed spectrum (blue line) with an injection spectral index Γ=1.6/2.5 below/above 4 GeV and a steepening to Γ=4 above 2 TeV, and modulated in a force-field approximation with Φ=450 MV

IMPLICATIONS –SOME POSSIBILITIES

1. Modify conventional diffusive model
2. Add local source
3. Pulsars as potential sources
4. PAMELA results and the need for two primary source classes

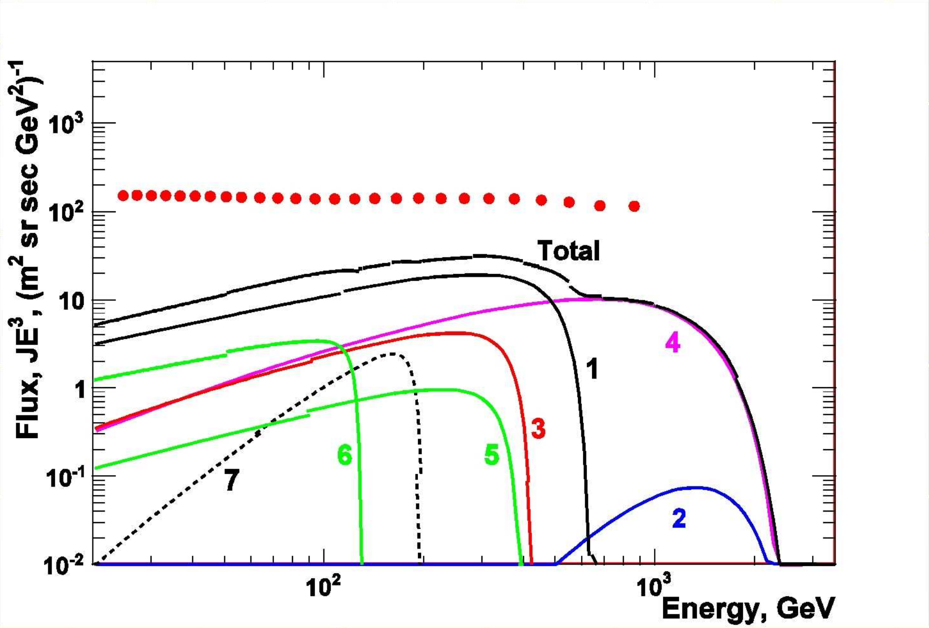
Main message: use the HE electron spectrum to constrain the source model(s)

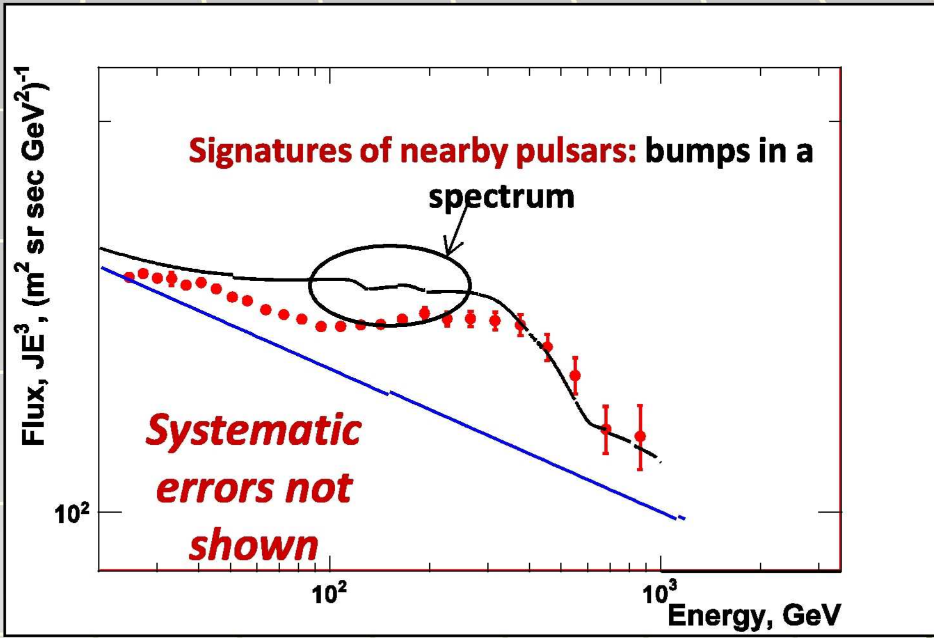
Fit with additional source



The $e^{-}+e^{+}$ spectrum computed with the GALPROP (blue line) with injection spectrum $\Gamma=1.6/2.7$ below/above 4 GeV and an additional component with an injection spectrum $\Gamma=1.5$ and exponential cutoff

Nearby pulsars can reveal themselves in $e^+ e^-$ spectrum: Contribution from selected Fermi pulsars





Contribution to the local electron flux from the most prominent Fermi pulsars. **Red points – Fermi LAT data**

1 – Geminga, 2 – J1732-31, 3 – J1057-5226

4 – J2021+4026, 5 – J0357+32, 6 – J1836+5925

7 – J2043+2740

Solid black line – total contribution from pulsars

Total electron flux (black line): sum of single power law (blue line) and contribution from local pulsars

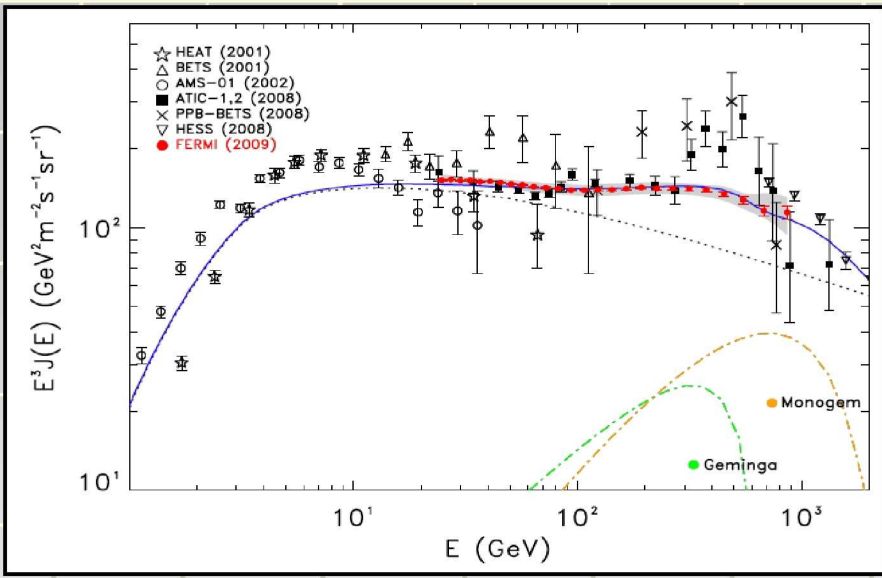
Calculations according to Gendelev, Profumo and Dormody

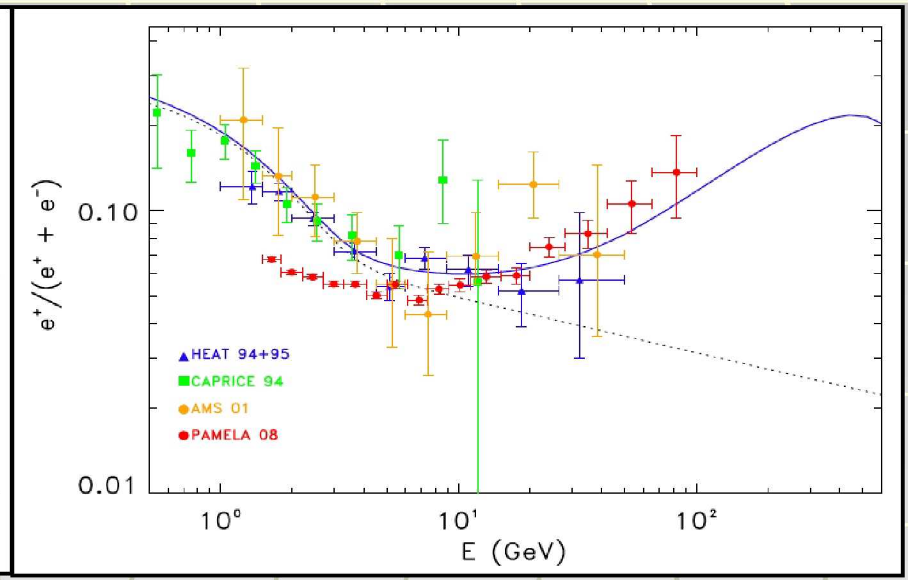
arXiv:1001.4540

- Spectral features of the Fermi LAT electron spectrum are consistent with presence of nearby source(s).
- Fermi LAT has recently found numerous gamma-ray pulsars, with several of them within 1-2 kpc, that make this explanation viable.
- Fermi LAT electron spectrum can be explained without introducing different mechanisms of electron production in the sources or different type of sources.
- Search for small irregularities in electron spectrum contributes to the understanding of their origin: astrophysical or exotic (see e.g. Malyshev, Chollis and Gelfand, PRD D80, 063005, 2009)

Now – PAMELA result on the positron fraction.

Example of fit to both Fermi and Pamela data with Monogem and Geminga pulsars





It is assumed that additional sources (here Monogem and Geminga) provide equal amount of **e^+ and e^-**

Question: why are the **e^+ e^-** sources not seen at lower energy, where the positron fraction agrees with their pure secondary origin?

Two mechanisms of primary electron production are needed

- General idea is that the "nearby" source(s) produces ~equal amount of e^+ and e^-, causing the positron fraction to increase
  - Is this nearby source unique ? Unlikely

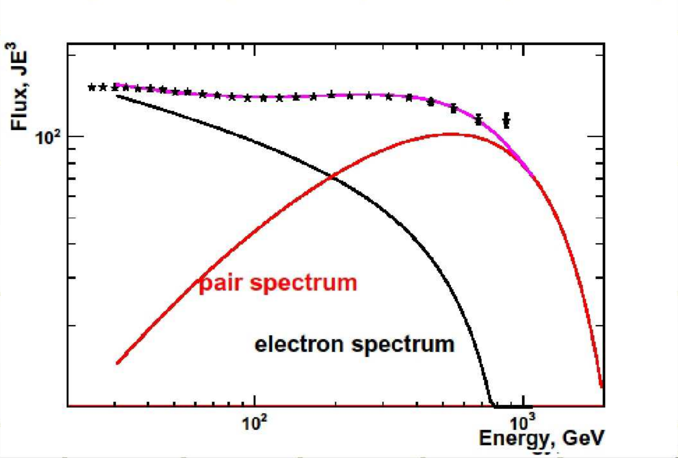
- Possible interpretation of the Pamela result could be if the total flux comprises a larger flux with softer index of "primary" negative electrons (e.g. directly accelerated in SNR shock), and smaller flux of $e^+ + e^-$ with harder index which starts showing up at higher energy, causing positron ratio to increase

$$F_{e^-} = \quad + \quad + \quad {}^{rs} \quad +$$

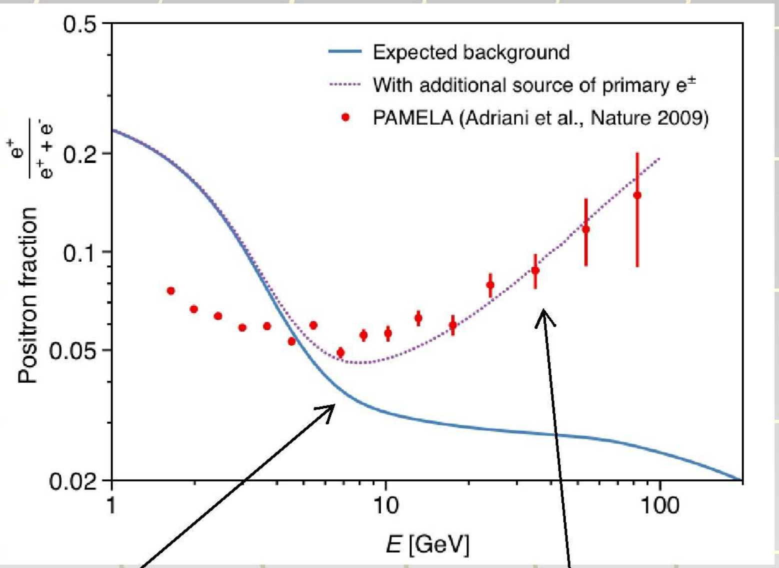
$$F_{e^+} = \quad + \quad {}^{rs} \quad +$$

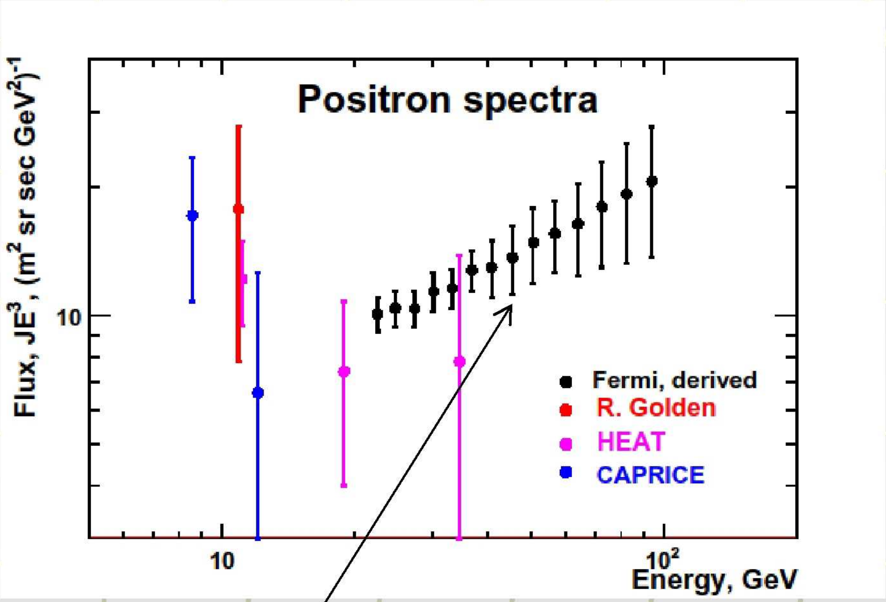
SOFT

HARD



Positron spectra





Soft spectrum of secondary positrons

Hard spectrum of e^+ and e^- Can be only positrons?

Spectral index for positron spectrum (derived from Fermi's $e^+ + e^-$ and PAMELA's positron fraction) $\Gamma \approx 2.4$

Origin of hard spectrum of pairs

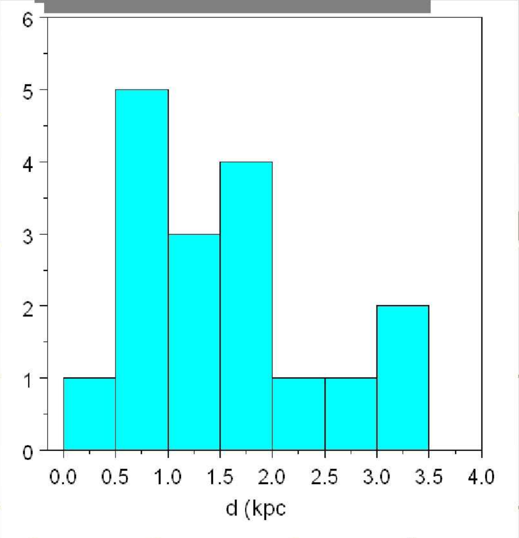
What could be the origin of the $e^+ + e^-$ hard spectrum?

There are several models, including acceleration of "secondary" e^+ and e^- in the CR acceleration regions (Blasi), consideration of Klein-Nishina suppression of energy losses near the points of origin (Aharonian & Atoyan 1991, Stawarz et al. 2009), enhanced $e^+ + e^-$ acceleration in polar cap (Biermann et al. 2009)

Multiple cascading in pulsar magnetosphere can provide needed acceleration of $e^+ + e^-$

Even more promising sources of high energy pairs could be milisecond pulsars (MSP) due to their high rotation frequency and low surface magnetic field (low energy losses)

New MSPs in LAT sources

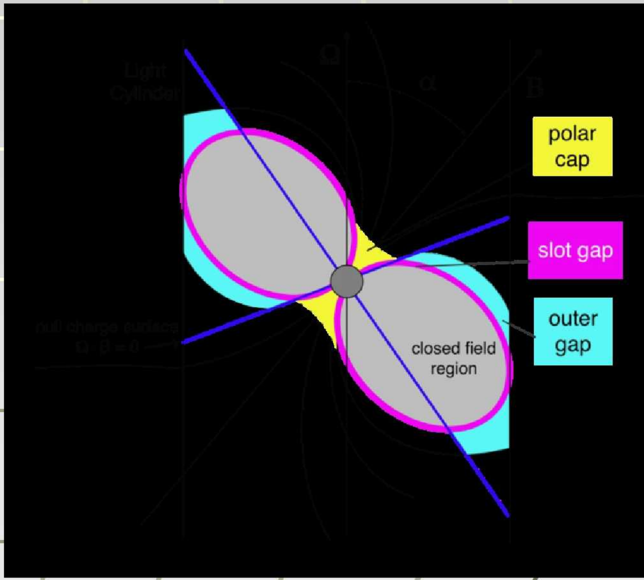


From A. Harding, HEAD2010

From Alice Harding's talk at HEAD-2010:

- Can start constraining pulsar parameters using CR data
- Impulsive injection of from pulsar wind nebulae (PWNe) of young pulsars will produce soft ($\Gamma > 2$) spectrum
- Steady injection by mature and MSPs (without PWNe) will produce harder ($\Gamma \sim 1.5 - 2$) spectrum

Gamma-ray pulsations from MSPs – narrow gaps required – screening by pair cascades! MSPs must have high pair multiplicity.

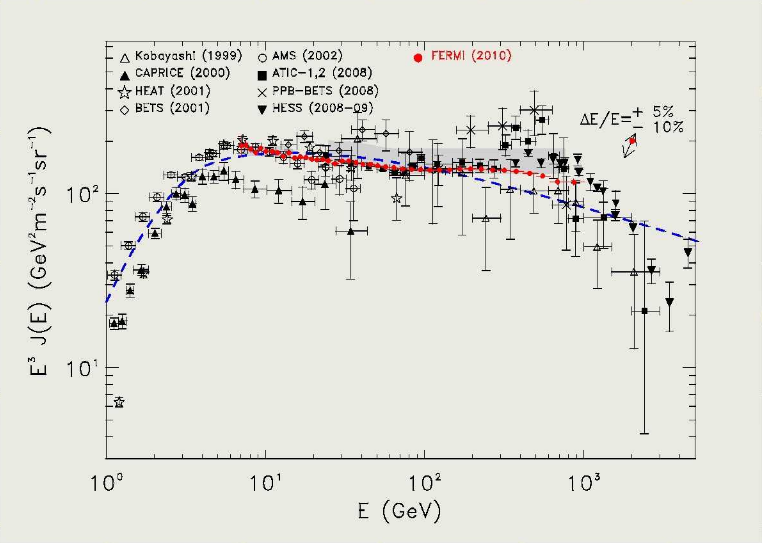


New MSPs (18 so far) discovered in Fermi LAT unidentified sources – many more nearby MSPs

SUMMARY OF OBSERVATIONS

- Real breakthrough during last 1-1.5 years in cosmic ray electrons: ATIC, HESS, Pamela, and finally Fermi-LAT. New quality data have made it possible to start quantitative modeling.

- With the new data more puzzles than before; need "multi-messenger" campaign: electrons, positrons, gammas, X-ray, radio, neutrino…



- We may be coming close to the first direct detection of cosmic ray sources

- Now we can discuss not only the origin of CR electrons, but also constraints of pulsar models based on these results.

- It is viable that we are dealing with at least two distinct mechanisms of "primary" electron (both signs) production. One produces softer spectrum of negative electrons, and the other produces a harder spectrum of both e^++e^- . Exotic (e.g. DM) origin is not ruled out.

- More accurate measurements are on the way from Fermi, PAMELA and HESS. Critical new results on the positron fraction are expected from the AMS. Results from Fermi-LAT on high energy electrons anisotropy are coming soon

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%
E³J(E) (GeV²m⁻²s⁻¹sr⁻¹)
100
diffusive model based on pre-Fermi data
10
100
1000
E (GeV)