Possible interpretations of the electron + positron spectrum measured by Fermi

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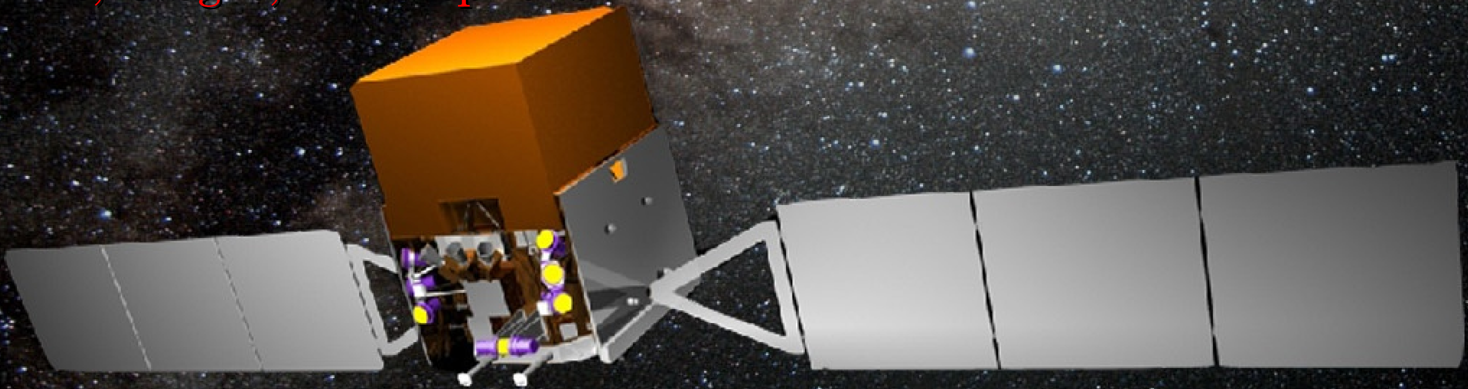
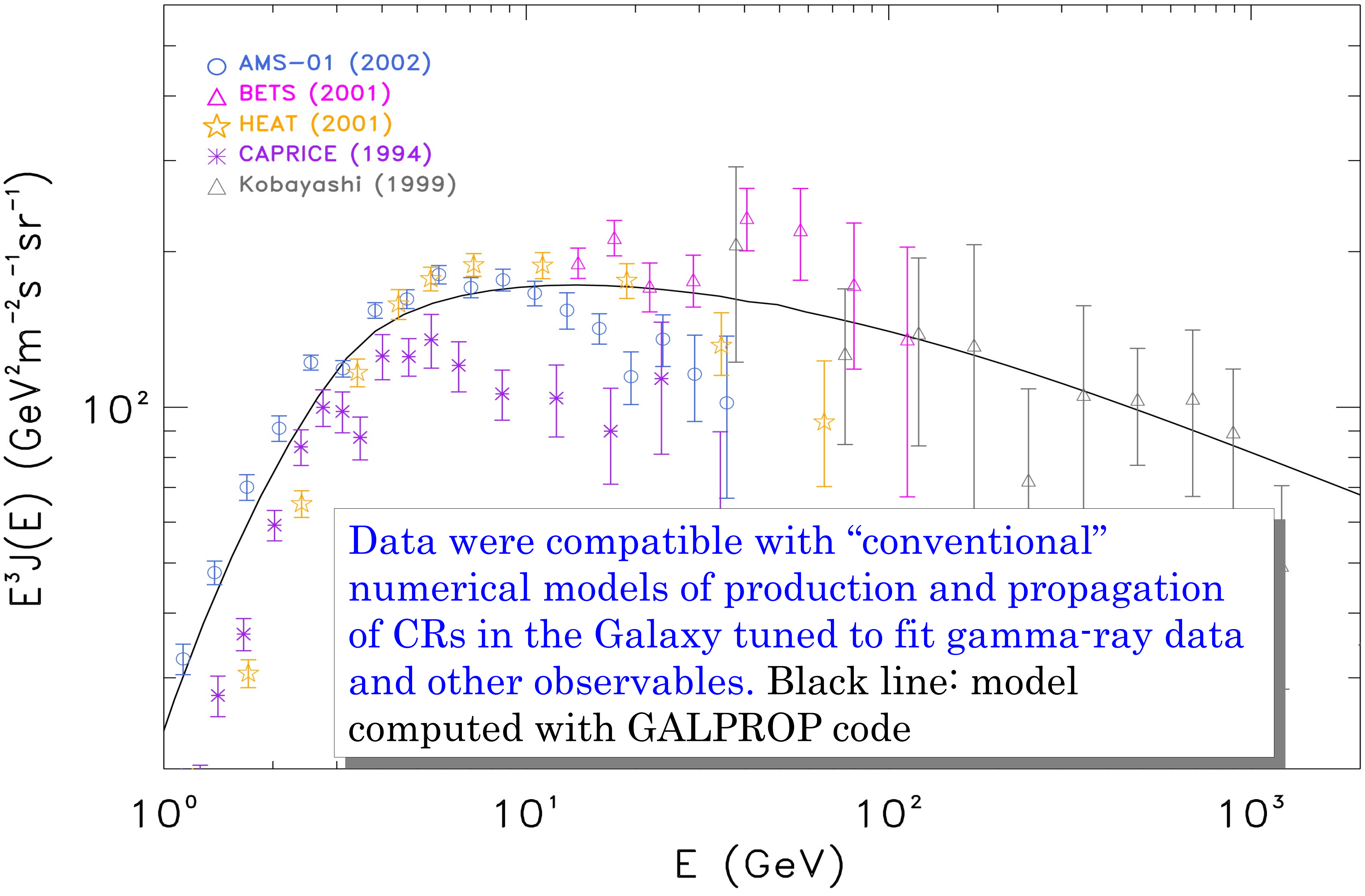


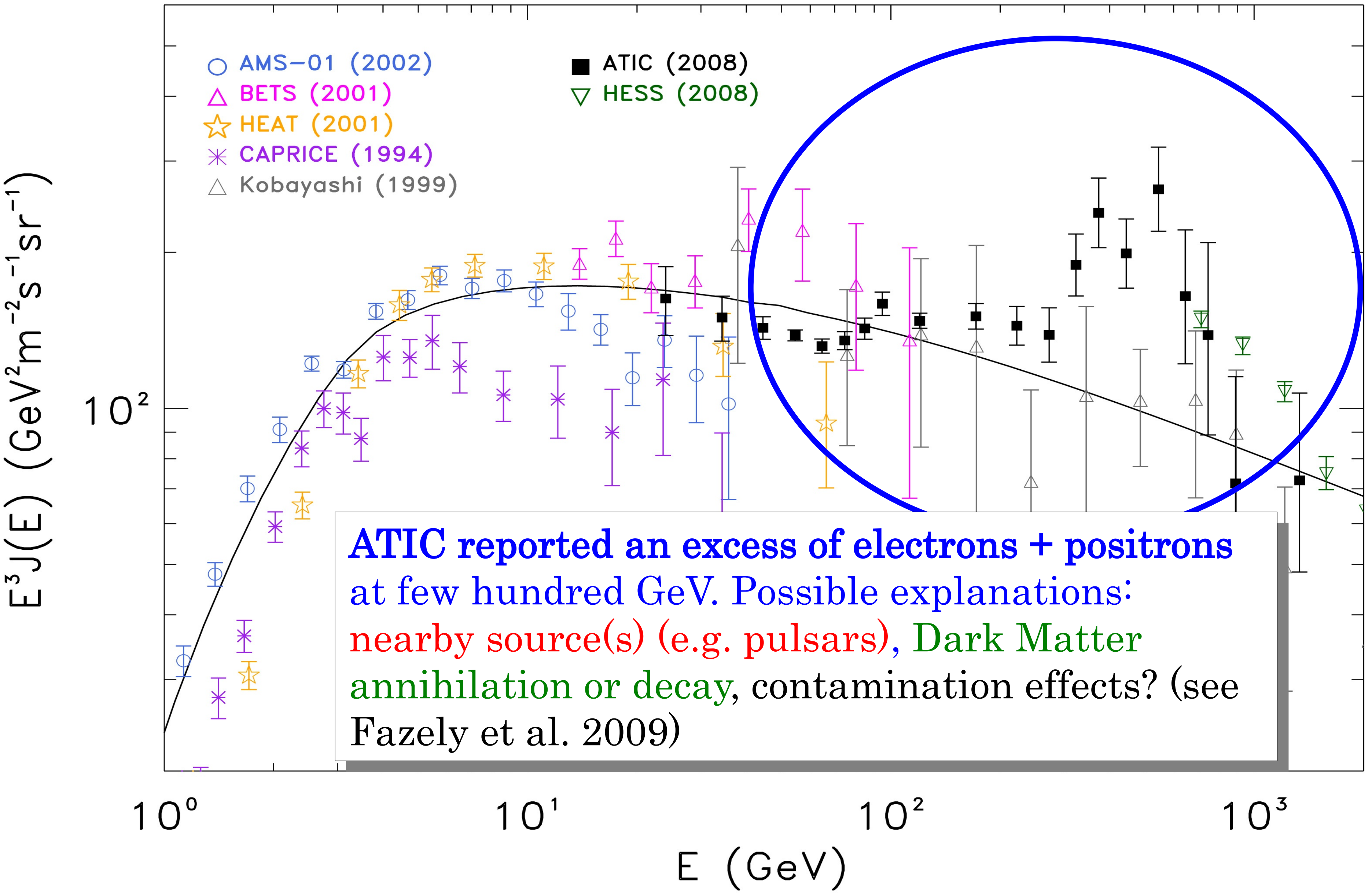
On behalf of Fermi collaboration

The situation before 2008



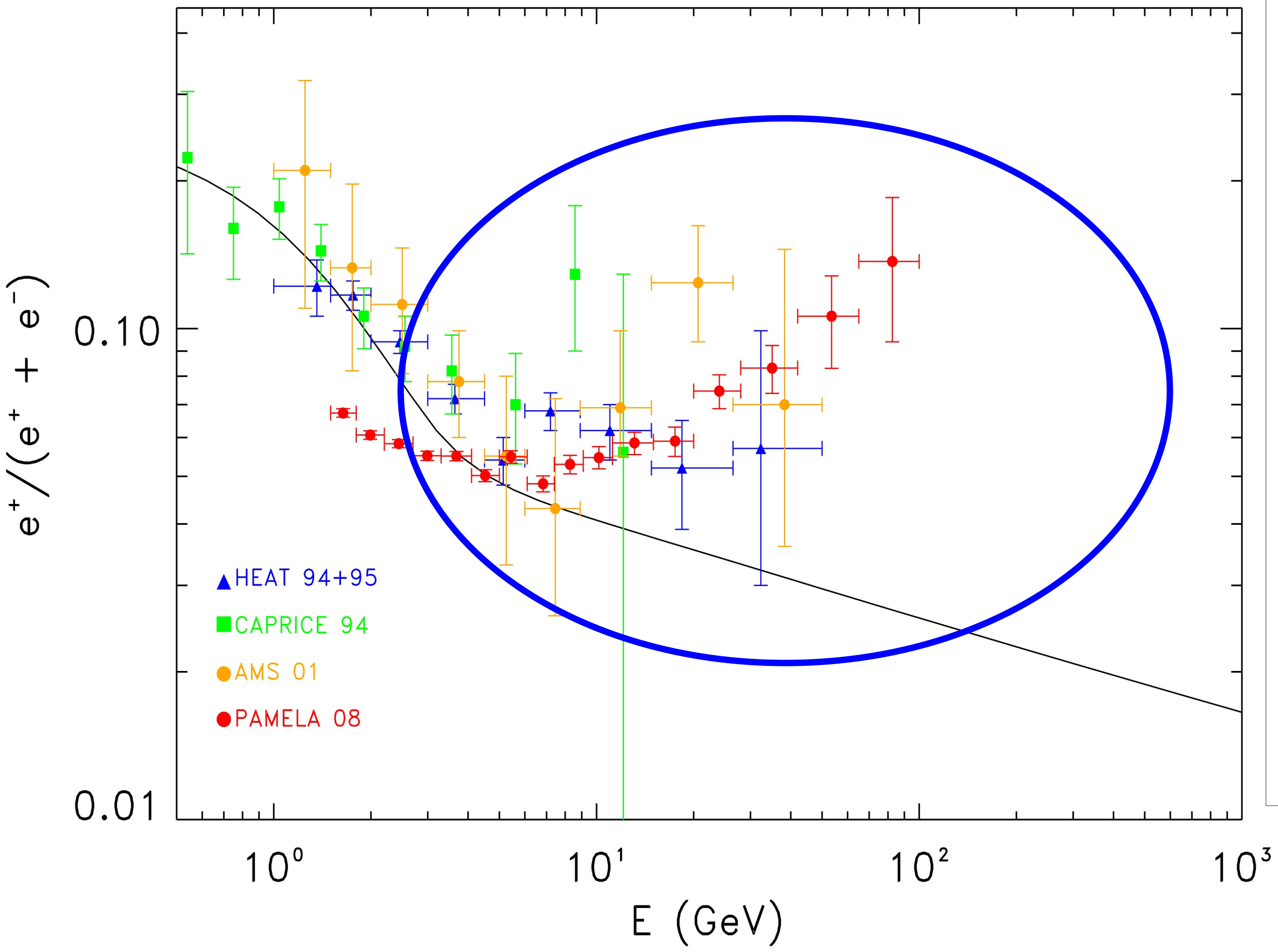
Data were compatible with “conventional” numerical models of production and propagation of CRs in the Galaxy tuned to fit gamma-ray data and other observables. Black line: model computed with GALPROP code

Results from ATIC and HESS (2008)



ATIC reported an excess of electrons + positrons at few hundred GeV. Possible explanations: nearby source(s) (e.g. pulsars), Dark Matter annihilation or decay, contamination effects? (see Fazely et al. 2009)

Results from PAMELA: the positron excess problem

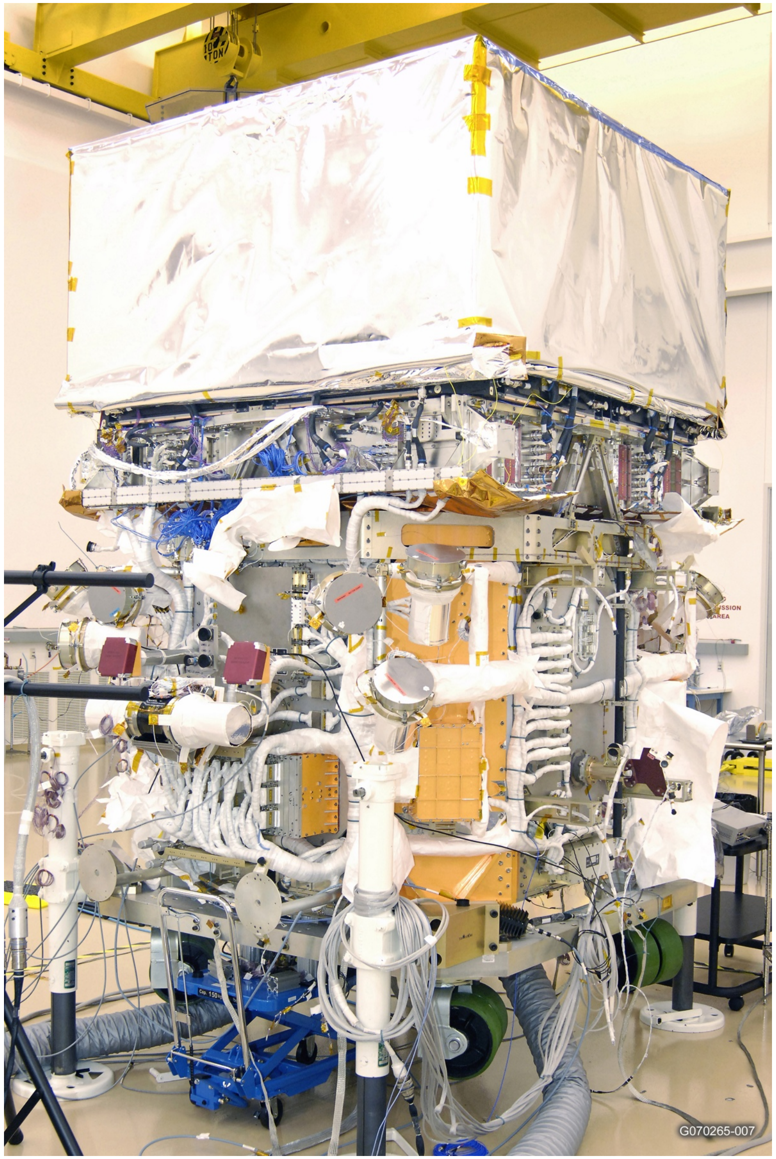


Rising positron/electron ratio measured by PAMELA is incompatible with "conventional models"

Similarly to ATIC excess, it suggests a primary unknown source of positrons

More than 50 papers in 1 year about this issue!!!

11/06/08: Fermi in orbit!



LAT (Large Area Telescope)

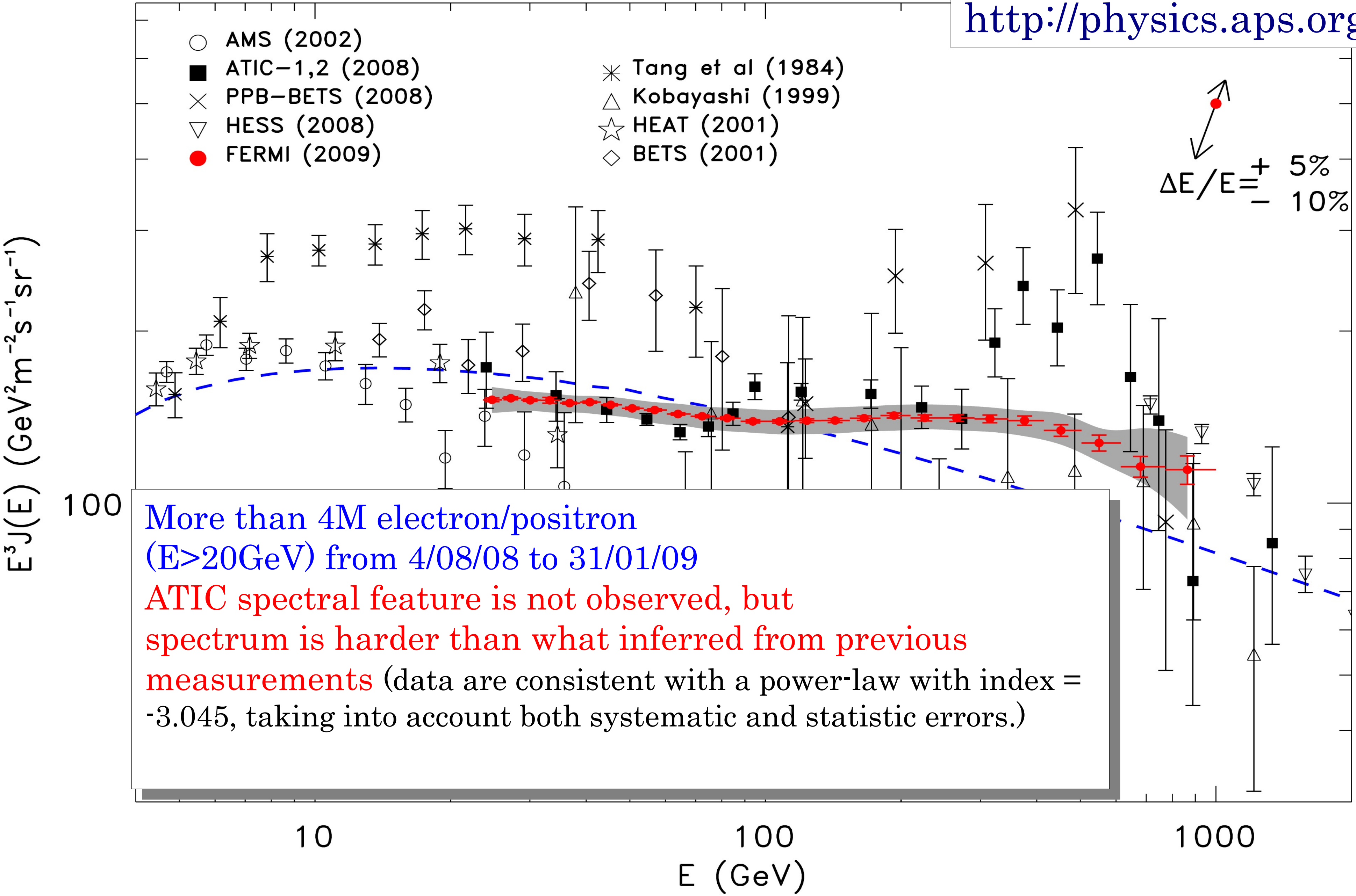
- is designed as a gamma-ray detector in the energy range from 20 MeV to 300 GeV
- can successfully operate as a high-energy electron telescope from 20 GeV to 1 TeV

Key features:

- Large collecting area
- Continuous and long observations
- No atmospheric corrections
- Rejection power greater than 10^3

And finally... Fermi data

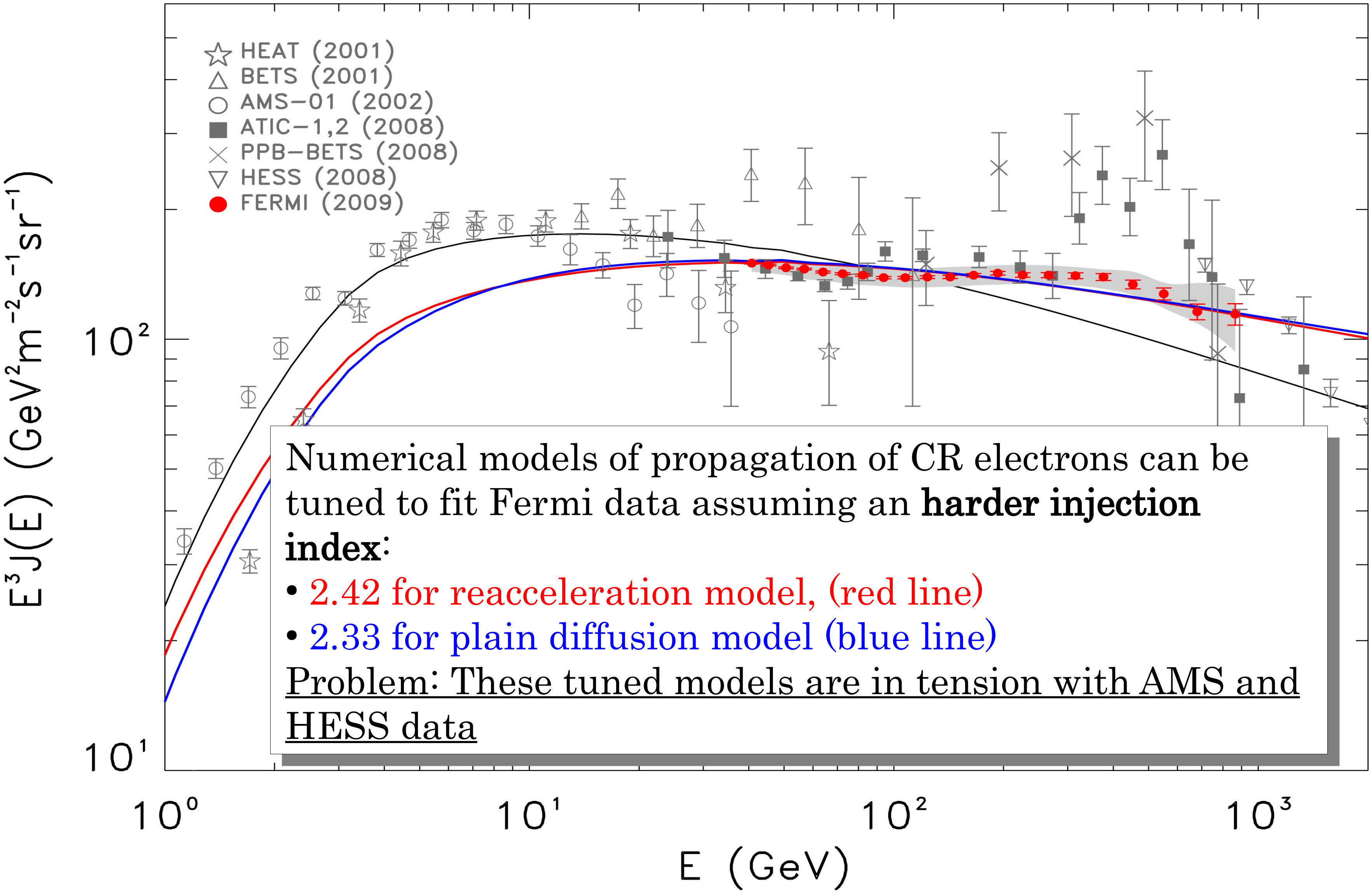
submitted to PRL on
March 19, 2009
accepted on April 21
http://physics.aps.org/



More than 4M electron/positron (E>20GeV) from 4/08/08 to 31/01/09

ATIC spectral feature is not observed, but spectrum is harder than what inferred from previous measurements (data are consistent with a power-law with index = -3.045, taking into account both systematic and statistic errors.)

A simple interpretation of Fermi spectrum...

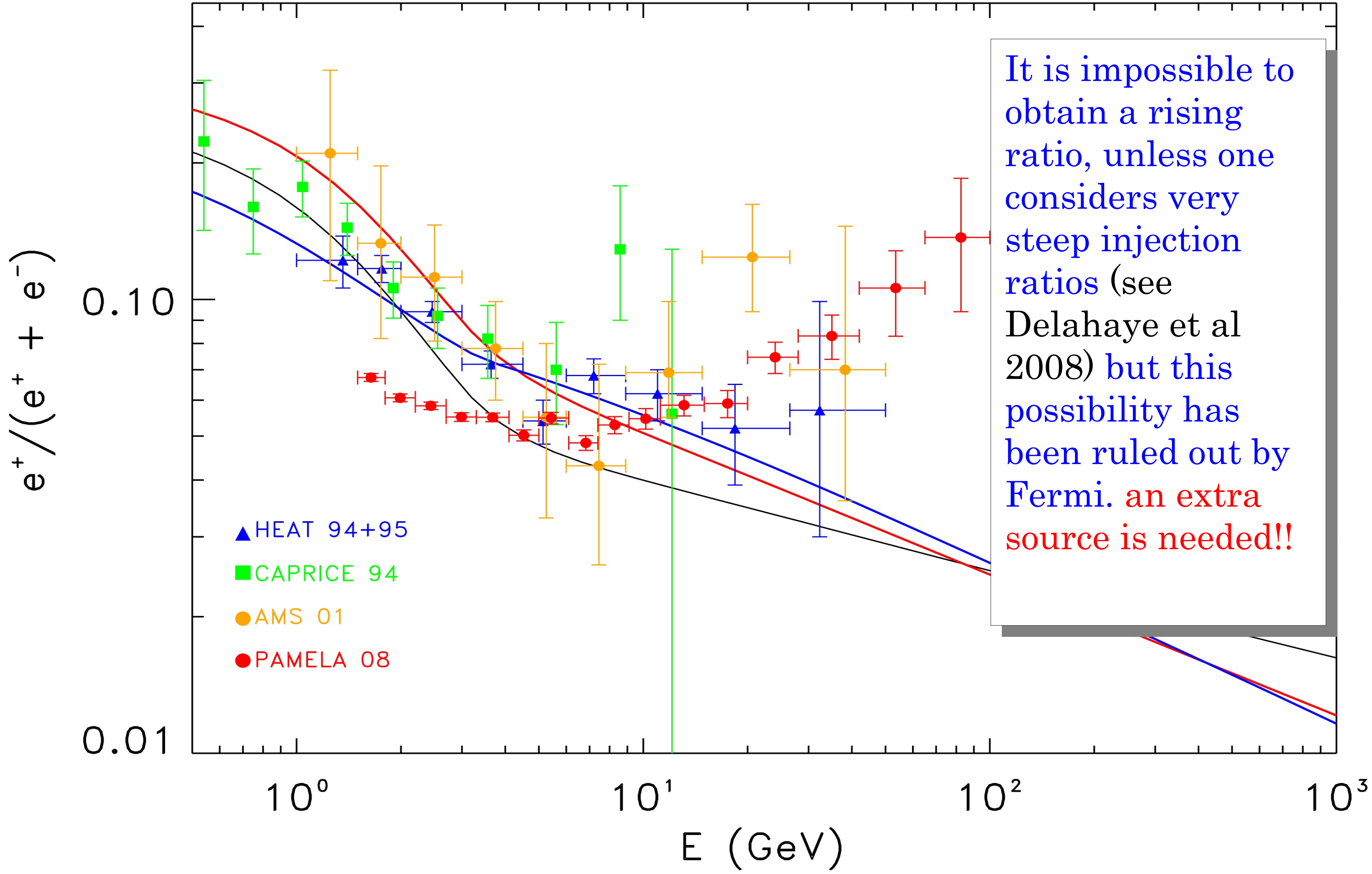


Numerical models of propagation of CR electrons can be tuned to fit Fermi data assuming an **harder injection index**:

- 2.42 for reacceleration model, (red line)
- 2.33 for plain diffusion model (blue line)

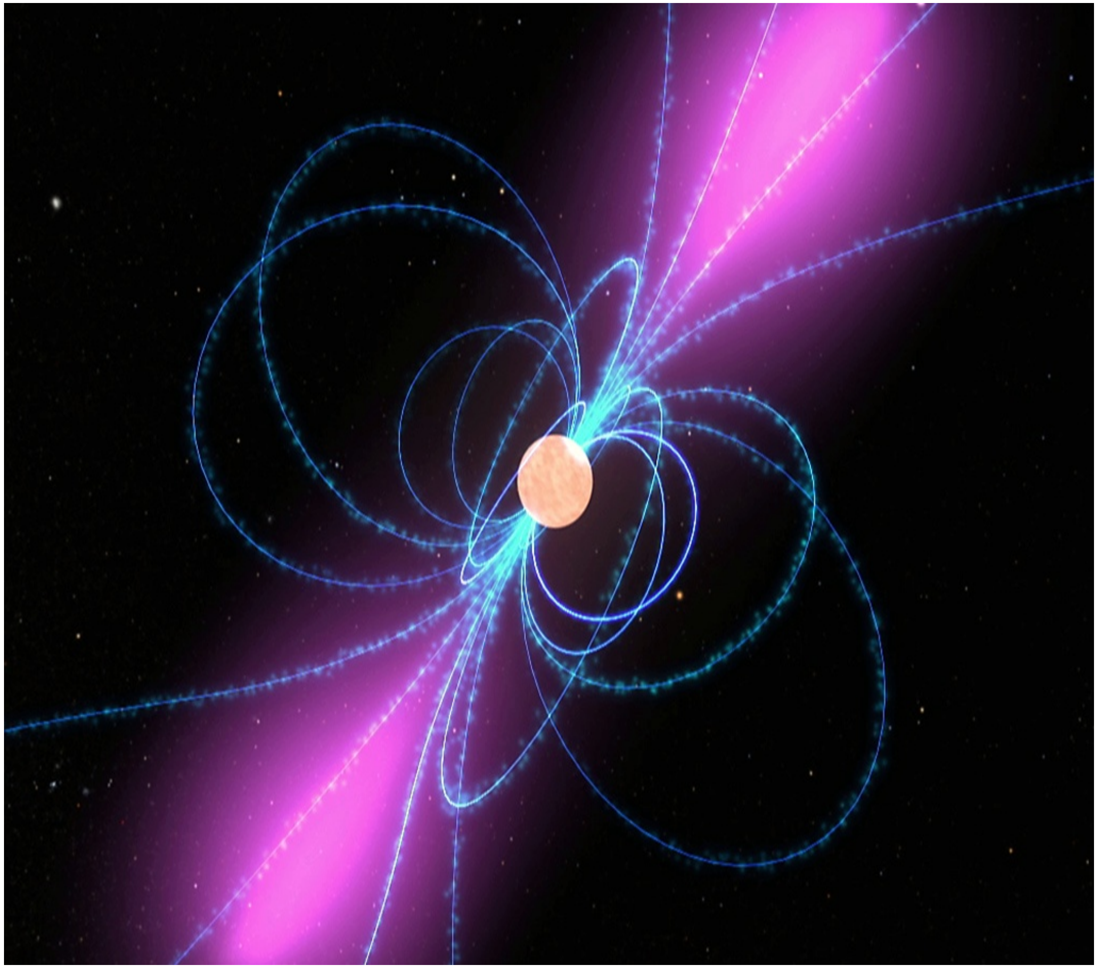
<u>Problem: These tuned models are in tension with AMS and HESS data</u>

...Doesn't work for PAMELA



It is impossible to obtain a rising ratio, unless one considers very steep injection ratios (see Delahaye et al 2008) but this possibility has been ruled out by Fermi. an extra source is needed!!

Pulsars as sources of electron-positron pairs

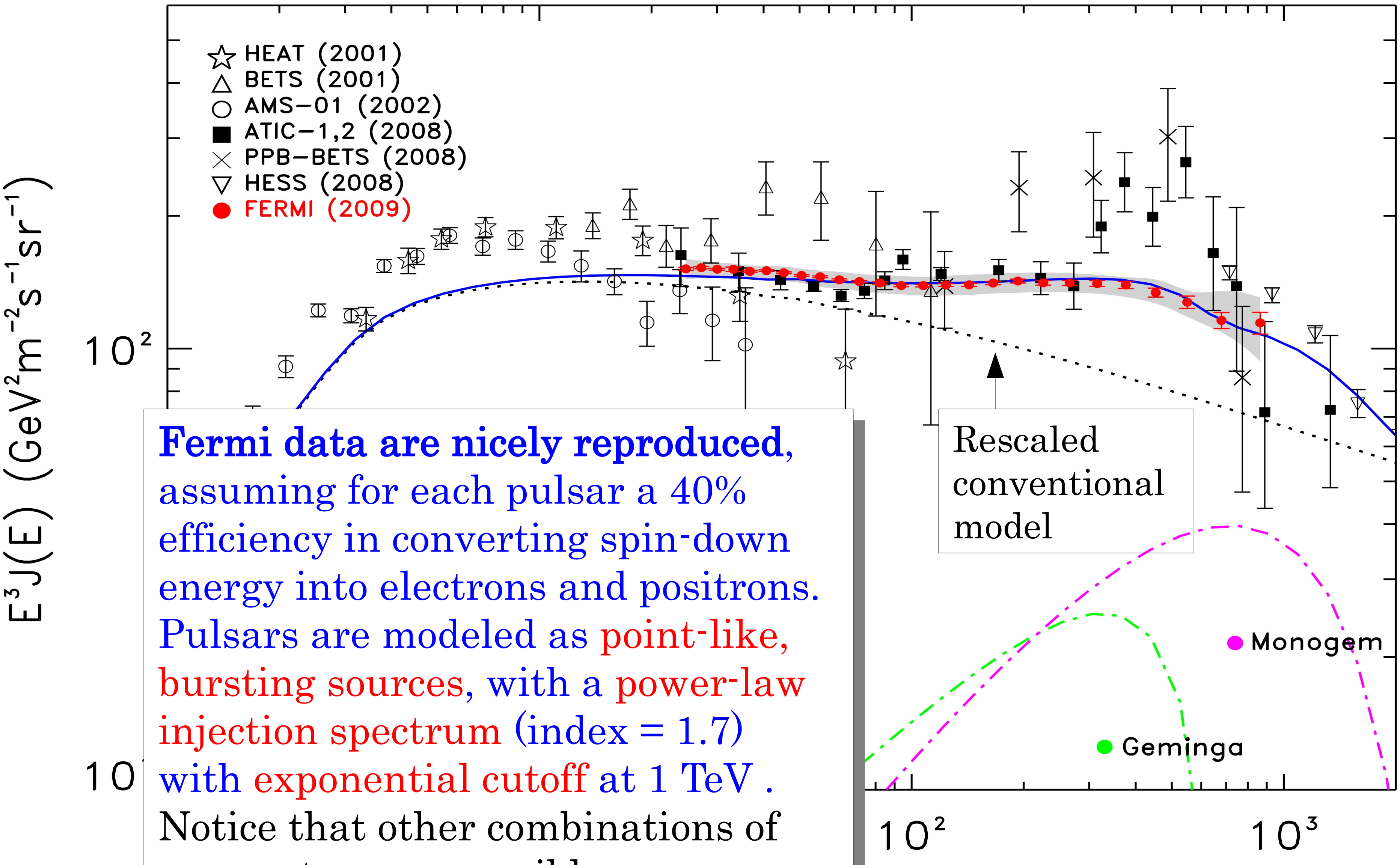


Pulsars are candidate sources of relativistic electrons and positrons (see e.g. Shen 1970, Harding & Ramaty 1987)

e^+/e^- pairs are believed to be produced in the magnetosphere and re-accelerated in the wind

To explain Fermi/Pamela excesses with respect to conventional model, the pulsars we're interested in are nearby (because of heavy energy losses) and mature (because electrons remain confined in the Pulsar Wind Nebula until it merges with ISM)

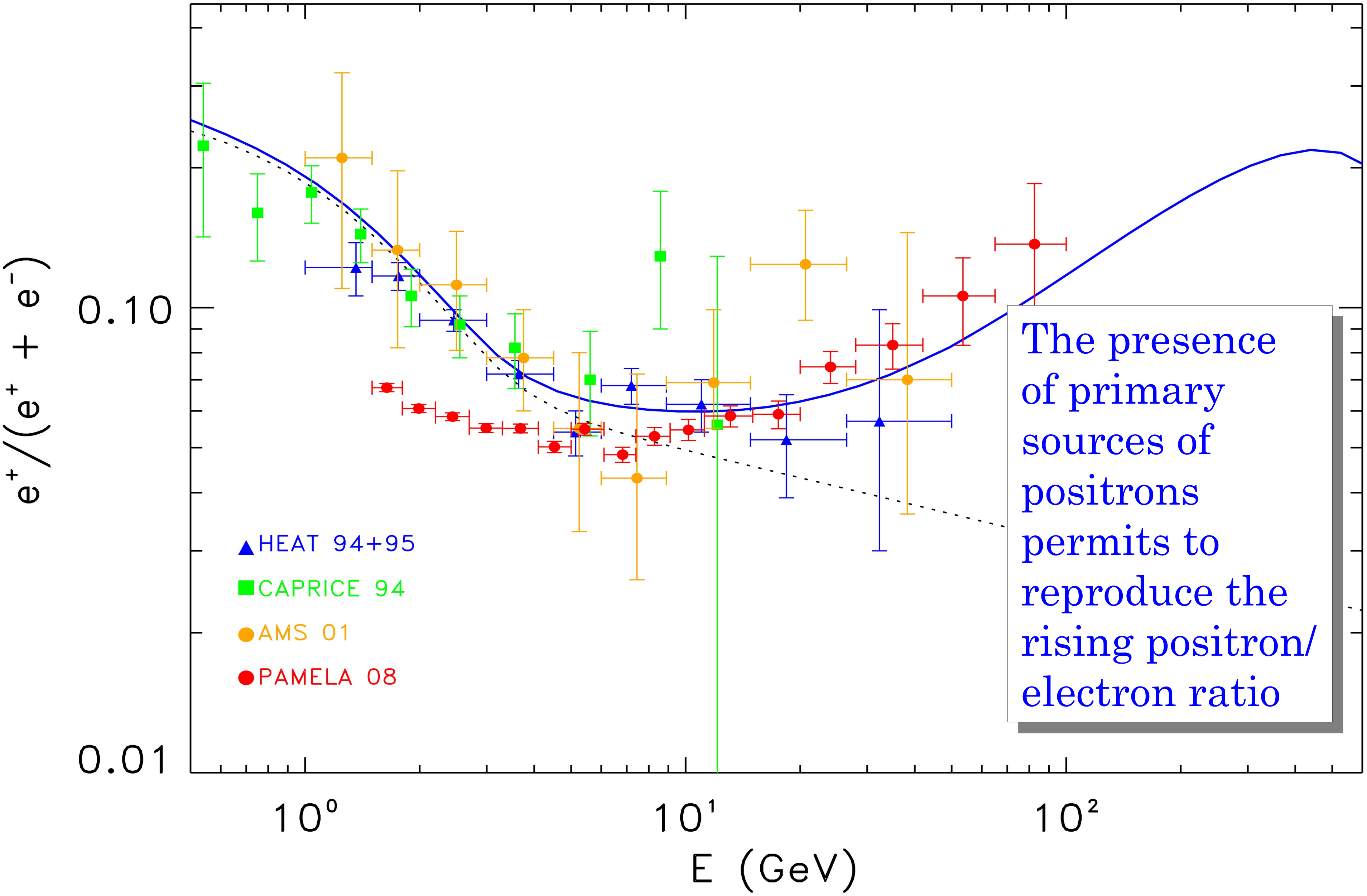
Results: adding pulsars within 1 kpc



Rescaled conventional model

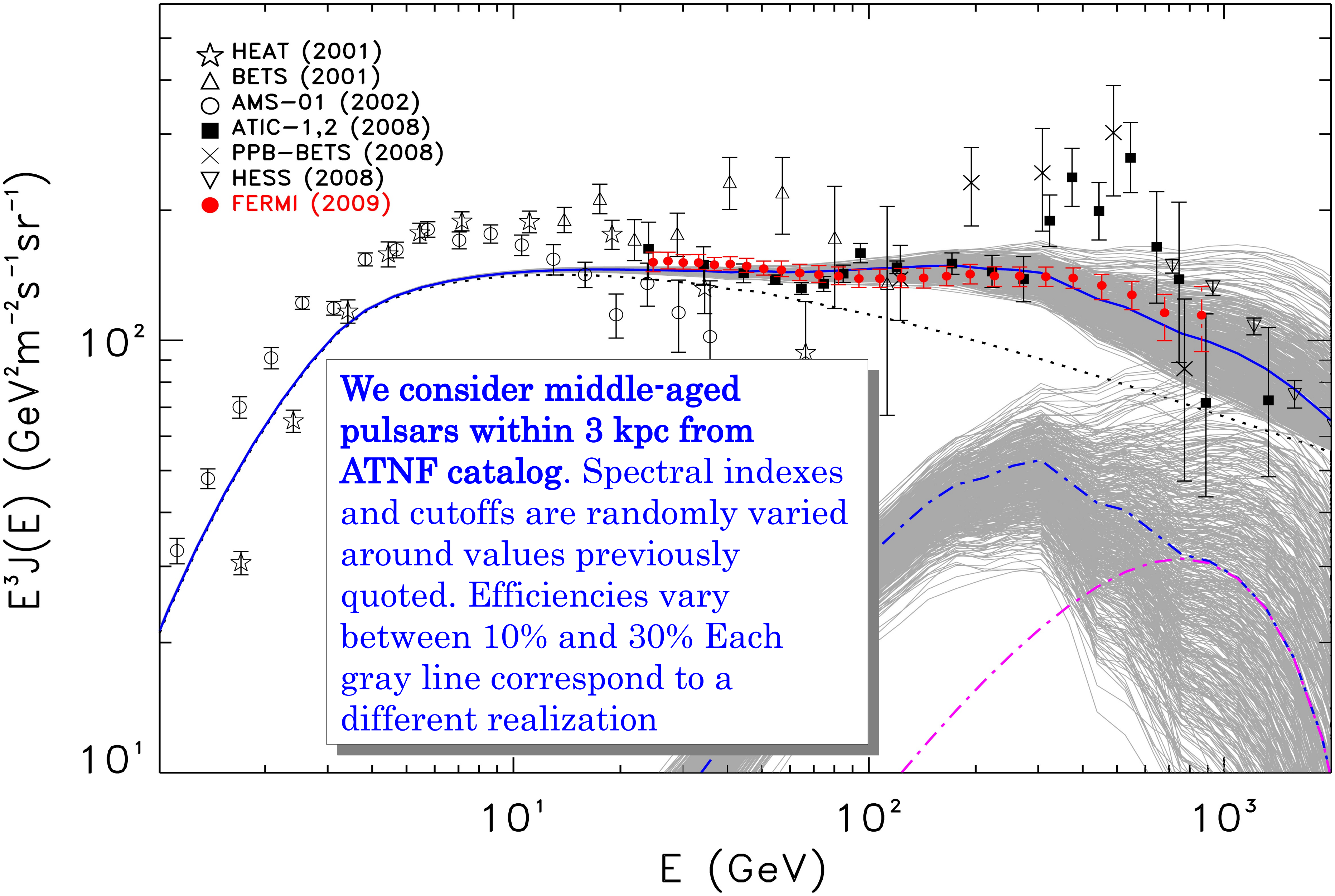
Fermi data are nicely reproduced, assuming for each pulsar a 40% efficiency in converting spin-down energy into electrons and positrons. Pulsars are modeled as point-like, bursting sources, with a power-law injection spectrum (index = 1.7) with exponential cutoff at 1 TeV . Notice that other combinations of parameters are possible

The model is compatible with PAMELA



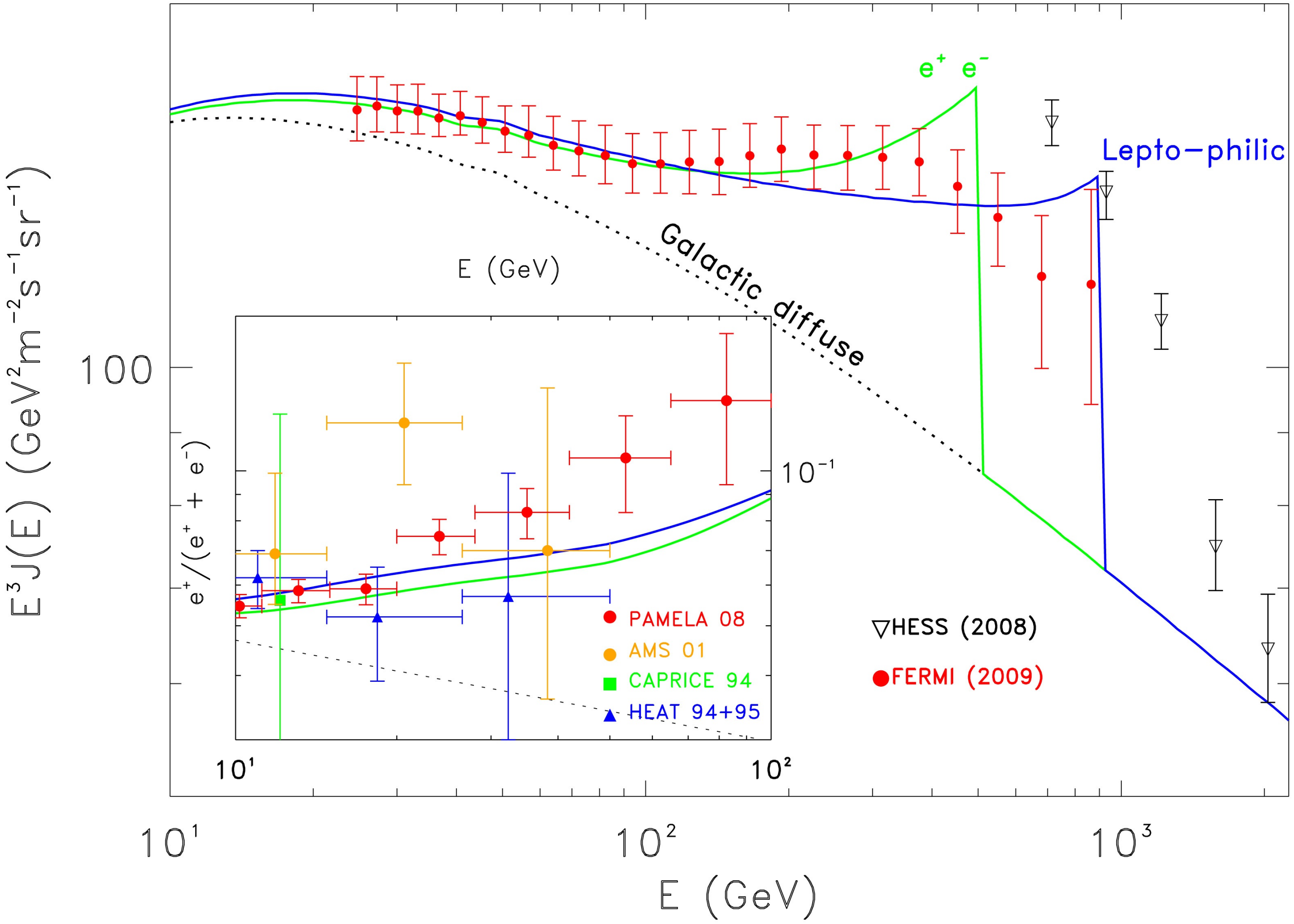
The presence of primary sources of positrons permits to reproduce the rising positron/ electron ratio

Adding all pulsars within 3 kpc



We consider middle-aged pulsars within 3 kpc from ATNF catalog. Spectral indexes and cutoffs are randomly varied around values previously quoted. Efficiencies vary between 10% and 30% Each gray line correspond to a different realization

Other possible scenarios



Green line: DM particles annihilate only into electron/positrons

Blue line: DM particles annihilate into leptons/antileptons

An interpretation based on dark matter annihilation is an open possibility

However DM interpretation seems disfavoured because:

- Antiproton measurements rule out most annihilation modes, only “leptonic” models are allowed
- Large “boost factors” are needed (from 20 to 100) compared with expected annihilation rates

How to distinguish between pulsar and DM interpretation

- A possible "smoking gun" signature for pulsar scenario may be **IC emission** in the direction of closest mature pulsars (Monogem, Geminga). Unfortunately, the expected flux is **2 order of magnitude smaller** than diffuse gamma flux measured by EGRET

- Observation of anisotropies in the electron flux may help to distinguish between pulsar and DM interpretations: **pulsar scenario implies a 1% anisotropy at 800 GeV towards Monogem!** Such anisotropy can be detected in few years of Fermi data taking

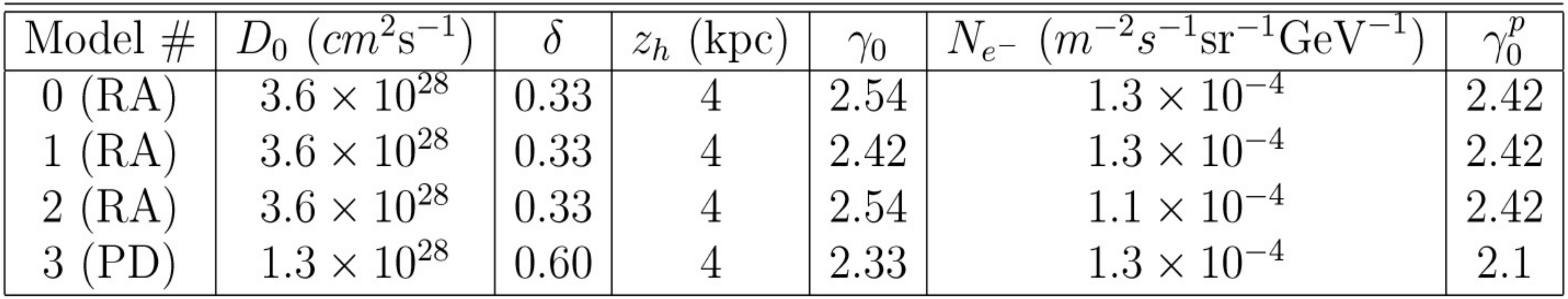
- New Fermi data on **electron spectrum at lower and higher energies** than reported so far, as well as future **diffuse gamma-ray emission measurements**, will help to clarify which is the correct interpretation

Conclusions

- The release of Fermi data changed radically our understanding of the high energy part of the electron CR spectrum
- Fermi spectrum is well fitted by a single power-law with spectral index = -3.045 if both systematic and statistic errors are accounted
- The spectrum can be reproduced tuning "conventional" diffusive models, but this interpretation isn't in accord with PAMELA positron data
- In order to simultaneously fit Fermi, HESS and PAMELA data, an extra-component is needed
- Nearby mature pulsars are natural candidates for this purpose
- The contribution of pulsars within few kpc, summed to a conventional "background", can nicely reproduce all data mentioned above
- More exotic explanations, such as Dark Matter annihilation scenarios, cannot be excluded; a study on anisotropy of the electron flux may help to distinguish between these two possible explanations

Backup slides

GALPROP models



Model #	D_0 $(cm^2\mathrm{s}^{-1})$	δ	z_h (kpc)	γ_0	N_{e^-} $(m^{-2}s^{-1}\mathrm{sr}^{-1}\mathrm{GeV}^{-1})$	γ_0^p
0 (RA)	3.6×10^{28}	0.33	4	2.54	1.3×10^{-4}	2.42
1 (RA)	3.6×10^{28}	0.33	4	2.42	1.3×10^{-4}	2.42
2 (RA)	3.6×10^{28}	0.33	4	2.54	1.1×10^{-4}	2.42
3 (PD)	1.3×10^{28}	0.60	4	2.33	1.3×10^{-4}	2.1

Pulsar model

$$\frac{\partial N_e(E,t,\vec{r})}{\partial t} - D(E)\nabla^2 N_e - \frac{\partial}{\partial E}(b(E)N_e) = Q(E,t,\vec{r})$$

Diffusion equation

$$Q(E,t,\vec{r}) = Q_0 \left(\frac{E}{1\,\mathrm{GeV}}\right)^{-\Gamma} e^{(-E/E_{\mathrm{cut}})}\ \delta(t-t_0)\ \delta(\vec{r})$$

Source term

Solution

(A-4) $$N_e(E,\ t,\ \vec{r}) = \frac{Q_0}{\pi^{3/2}\ r_{\mathrm{diff}}^3}\ (1-E/E_{max})^{\Gamma-2}\, e^{-\frac{E}{(1-E/E_{max})\ E_{\mathrm{cut}}}}\ e^{(-r/r_{\mathrm{diff}}(E))^2}$$

for $E < E_{max}$, and 0 otherwise, where the diffusion distance is given by

(A-5) $$r_{\mathrm{diff}}(E,t) \approx 2\sqrt{D(E)(t-t_0)\ \frac{1-(1-E/E_{max}(t))^{1-\delta}}{(1-\delta)E/E_{max}(t)}}$$

and

(A-6) $$E_{\mathrm{max}}(t) = \frac{1}{b_0\ (t-t_0)}$$

Pulsar parameters

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------------------------------------------------------
#     NAME                   DIST   AGE       EDOT
                             kpc)  (Yr)      (ergs/s)
------------------------------------------------------
1     J0633+1746  hh92       0.16   3.42e+05 3.2e+34   ← Geminga
2     J1856-3754  tm07       0.16   3.76e+06 3.3e+30
3     B0656+14    mlt+78     0.29   1.11e+05 3.8e+34   ← Monogem
4     J0720-3125  hmb+97     0.36   1.9e+06  4.7e+30
5     B0823+26    cls68      0.36   4.92e+06 4.5e+32

6     B1133+16    phbc68     0.36   5.04e+06 8.8e+31
7     B1929+10    lvw68      0.36   3.1e+06  3.9e+33
8     B2327-20    ll76       0.49   5.62e+06 4.1e+31
9     J1908+0734  nft95      0.58   4.08e+06 3.4e+33
10    B0906-17    mlt+78     0.63   9.5e+06  4.1e+32

11    B2045-16    tv68       0.64   2.84e+06 5.7e+31
12    J1918+1541  nft95      0.68   2.31e+06 2.0e+33
13    J0006+1834  cnt96      0.70   5.24e+06 2.5e+32
14    B0834+06    phbc68     0.72   2.97e+06 1.3e+32
15    B0450+55    dth78      0.79   2.28e+06 2.4e+33

16    B0917+63    dtws85     0.79   6.89e+06 3.7e+31
17    B2151-56    mlt+78     0.86   5.15e+06 6.4e+31
18    B0203-40    mlt+78     0.88   8.33e+06 1.9e+32
19    B1845-19    mlt+78     0.95   2.93e+06 1.1e+31
20    J0636-4549  bjd+06     0.98   9.91e+06 1.6e+31

21    B0943+10    vazs69     0.98   4.98e+06 1.0e+32
------------------------------------------------------
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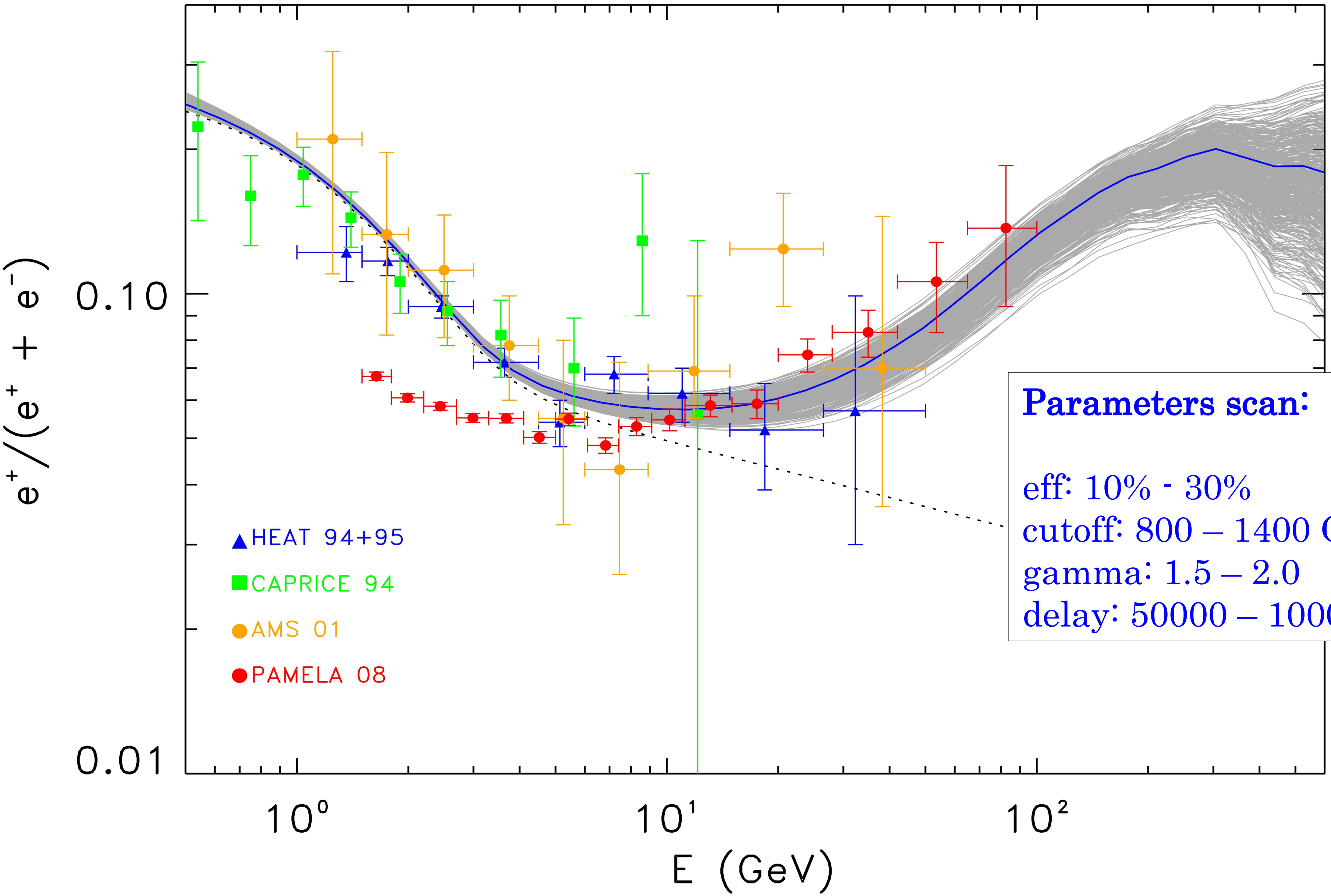
$$E_{e^\pm} \simeq \eta_{e^\pm}\;\dot{E}_{\mathrm{PSD}}\;\frac{T^2}{\tau_0}\;,$$

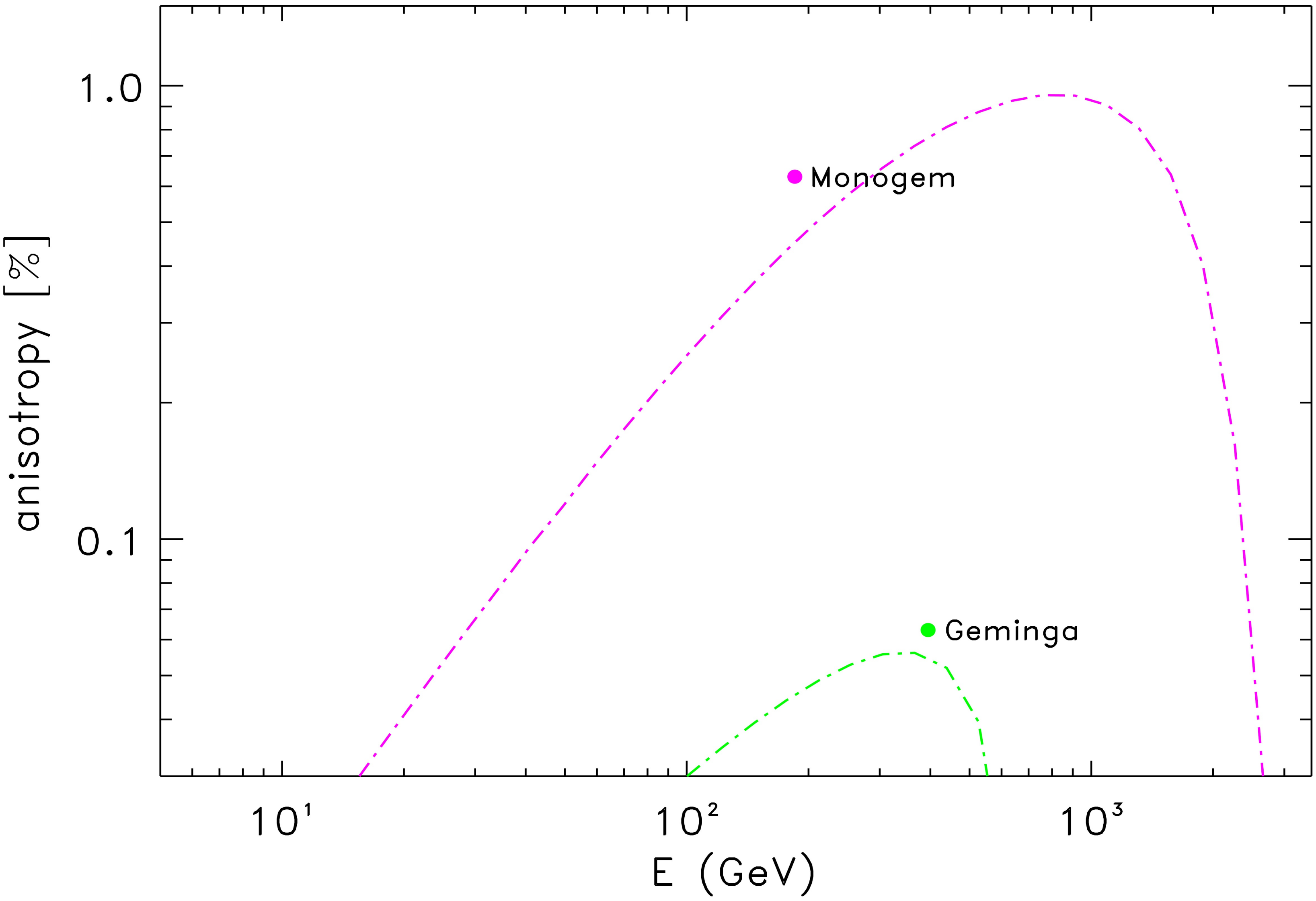
Pamela fit with all pulsars within 3 kpc



Parameters scan:

eff: 10% - 30%
cutoff: 800 – 1400 GeV
gamma: 1.5 – 2.0
delay: 50000 – 100000 y

Expected anisotropy in pulsar scenario



Dark Matter models

$$\rho_{\rm DM}(r) = \rho_{\odot}\left(\frac{r}{R_{\odot}}\right)^{-1.24}\left(\frac{R_{\odot}+R_s}{r+R_s}\right)^{1.76}$$

DM profile, from Via Lactea II N-body simulation (Diemand et al. 2008); The simulation follows the growth of a Milky Way-size system from redshift 104.3 to the present

DM models parameters

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