Dark Matter and Pulsar Signals for PAMELA, Fermi and ACTs

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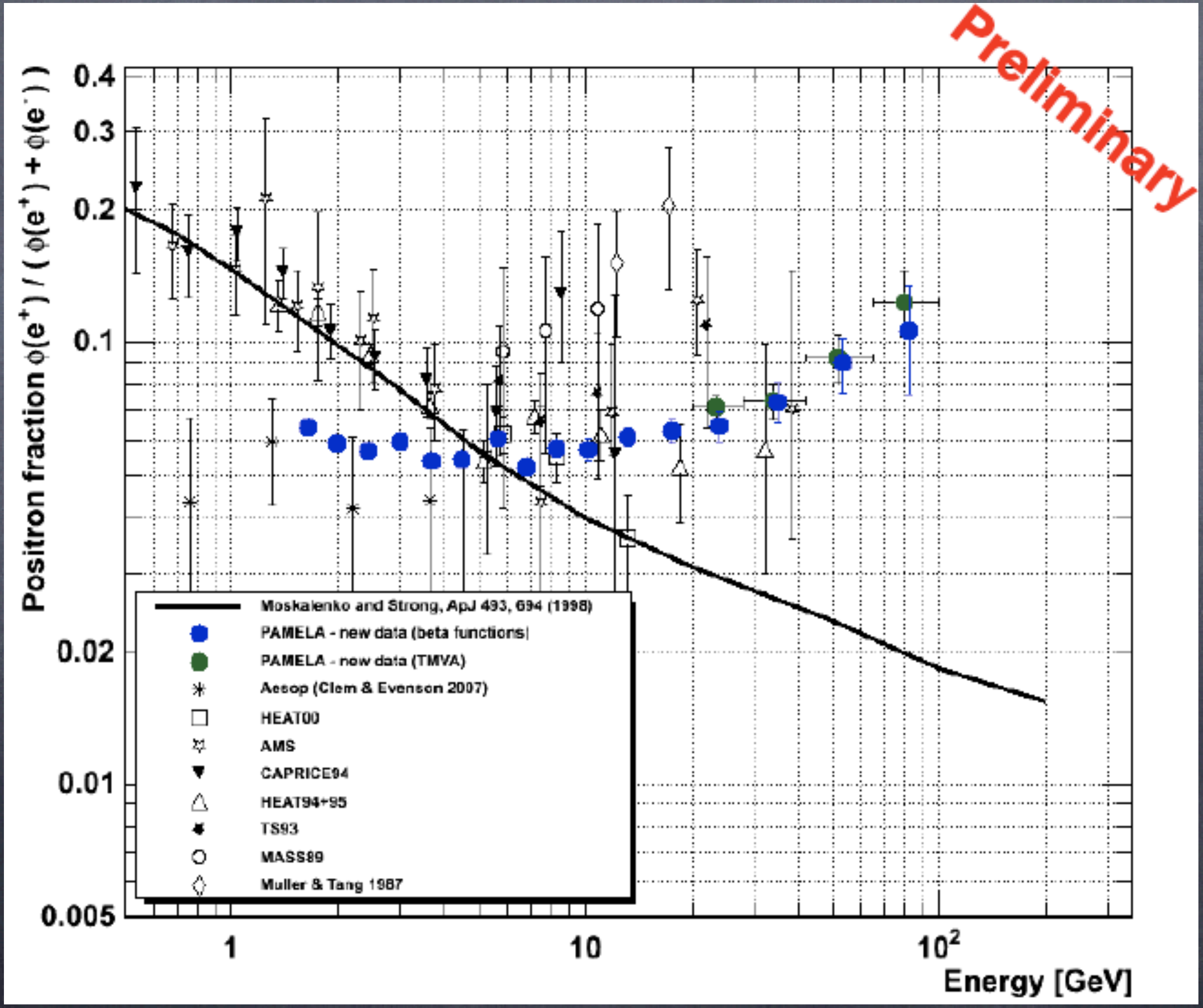
with Barger, Gao, Keung, Shaughnessy 0904.2001

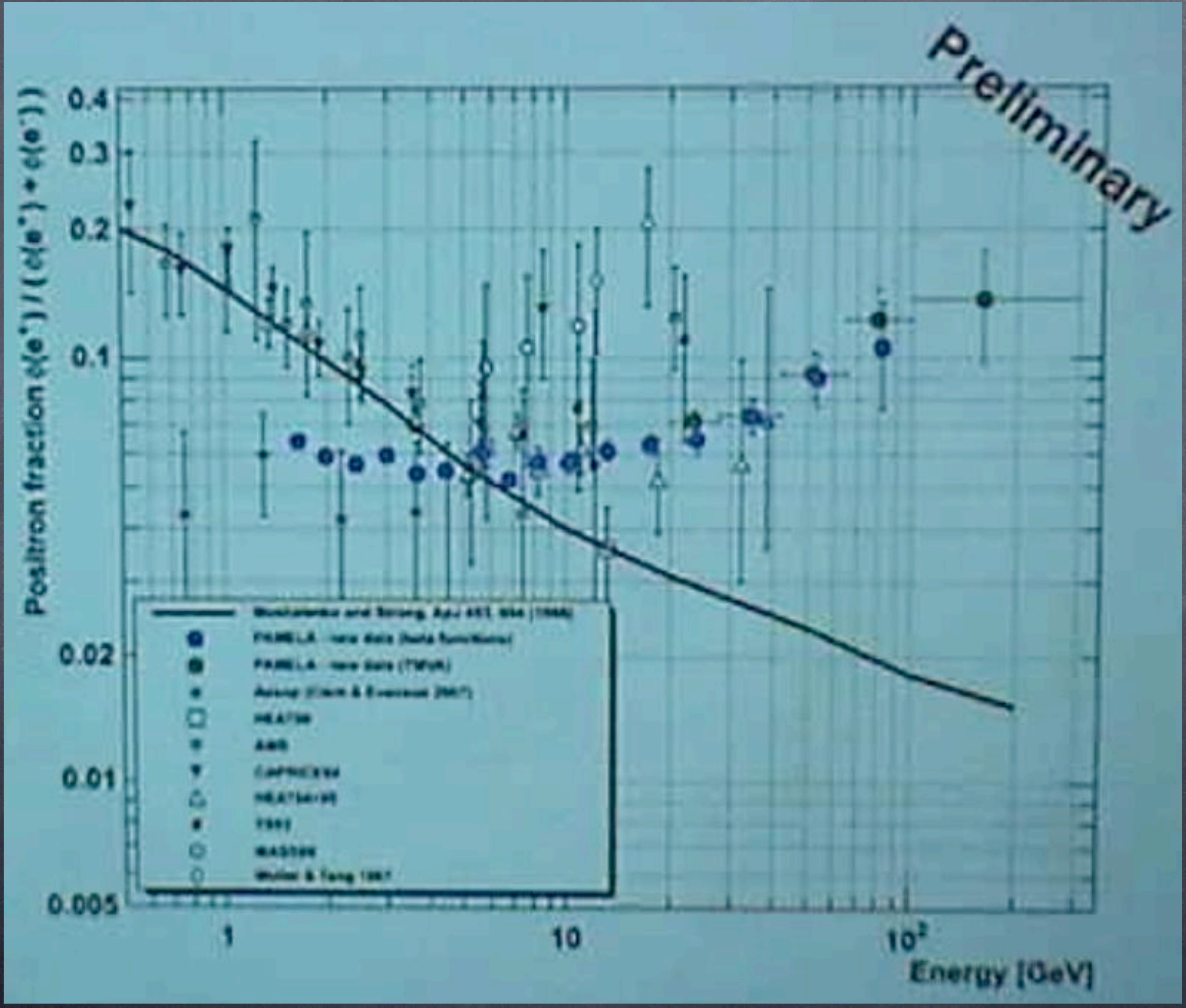
with Barger, Gao, Keung 0906.3009

A survey of recent cosmic ray data

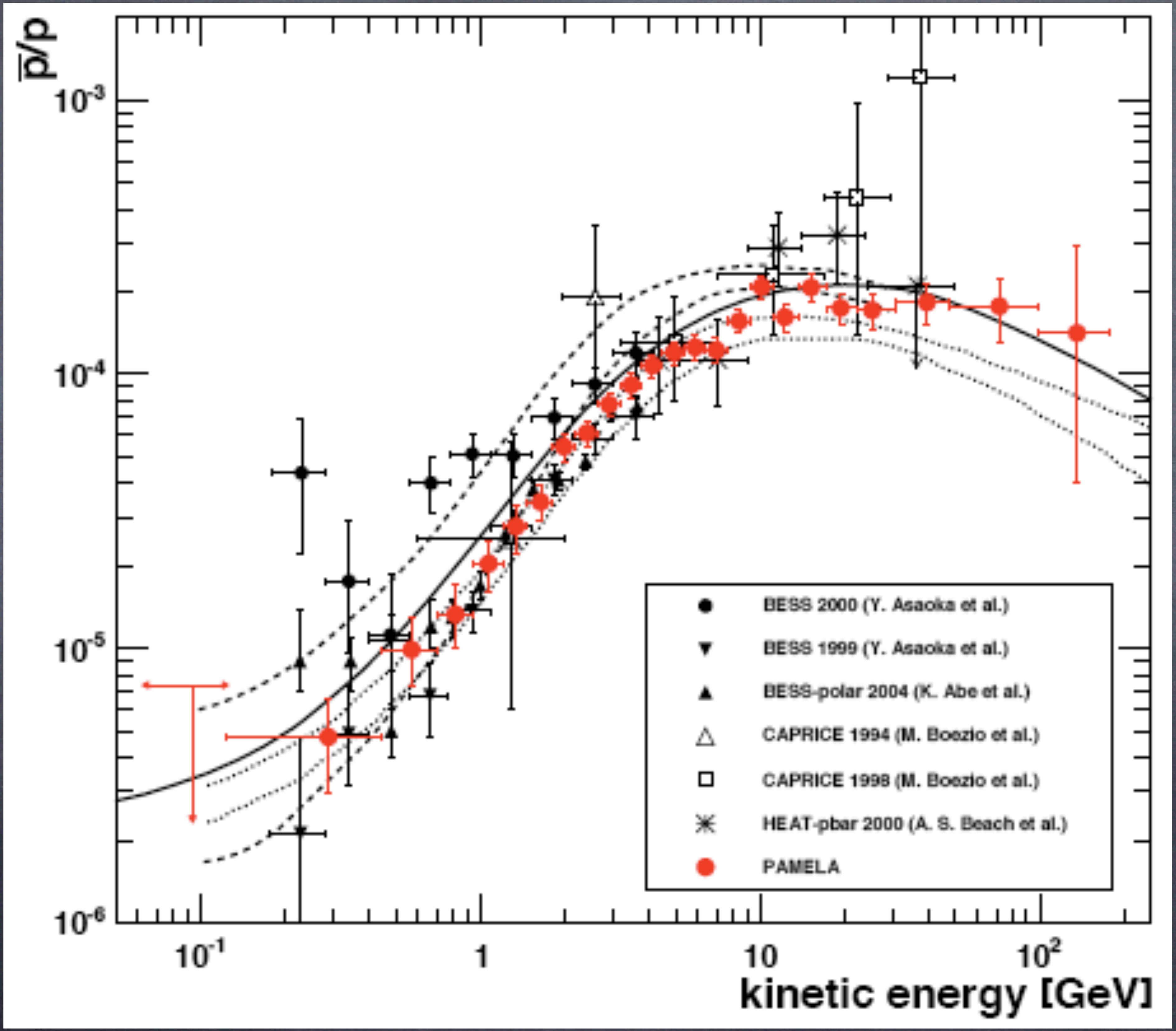
PAMELA: rising positron fraction from 10 - 100 GeV

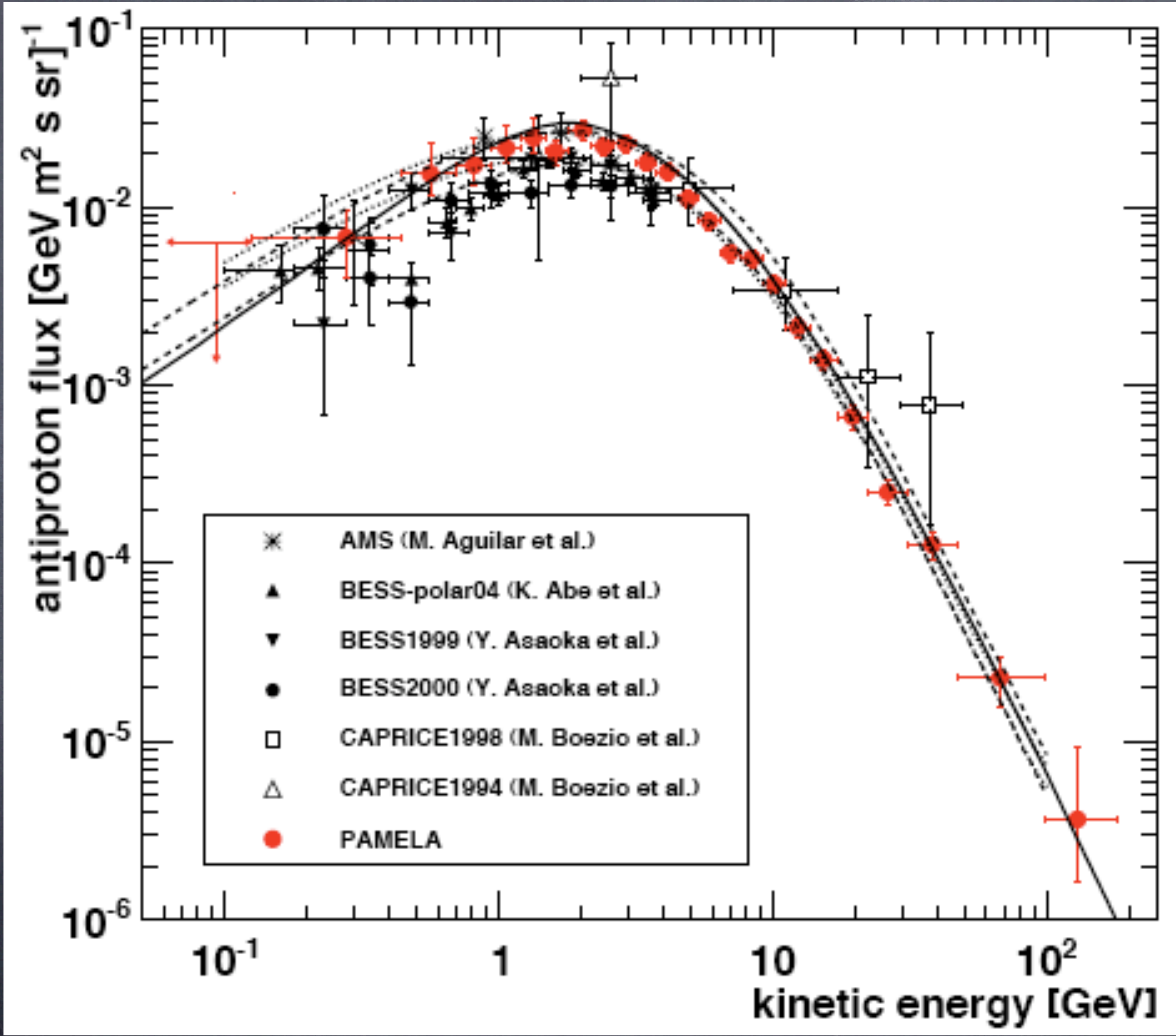


PAMELA: does the positron fraction continue rising?



PAMELA: no excess in $\bar{p}/p$ spectrum from 0.06 - 180 GeV

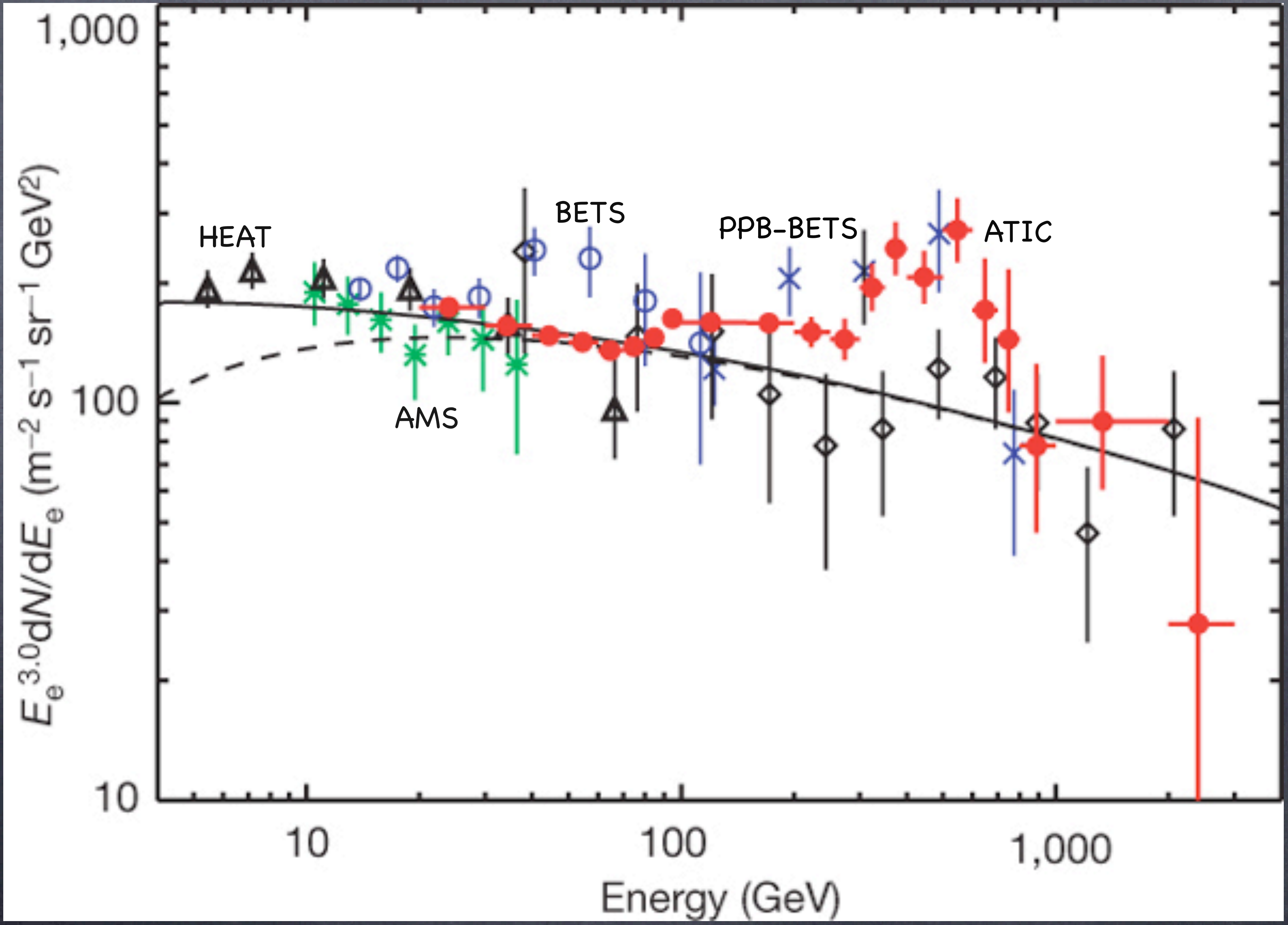


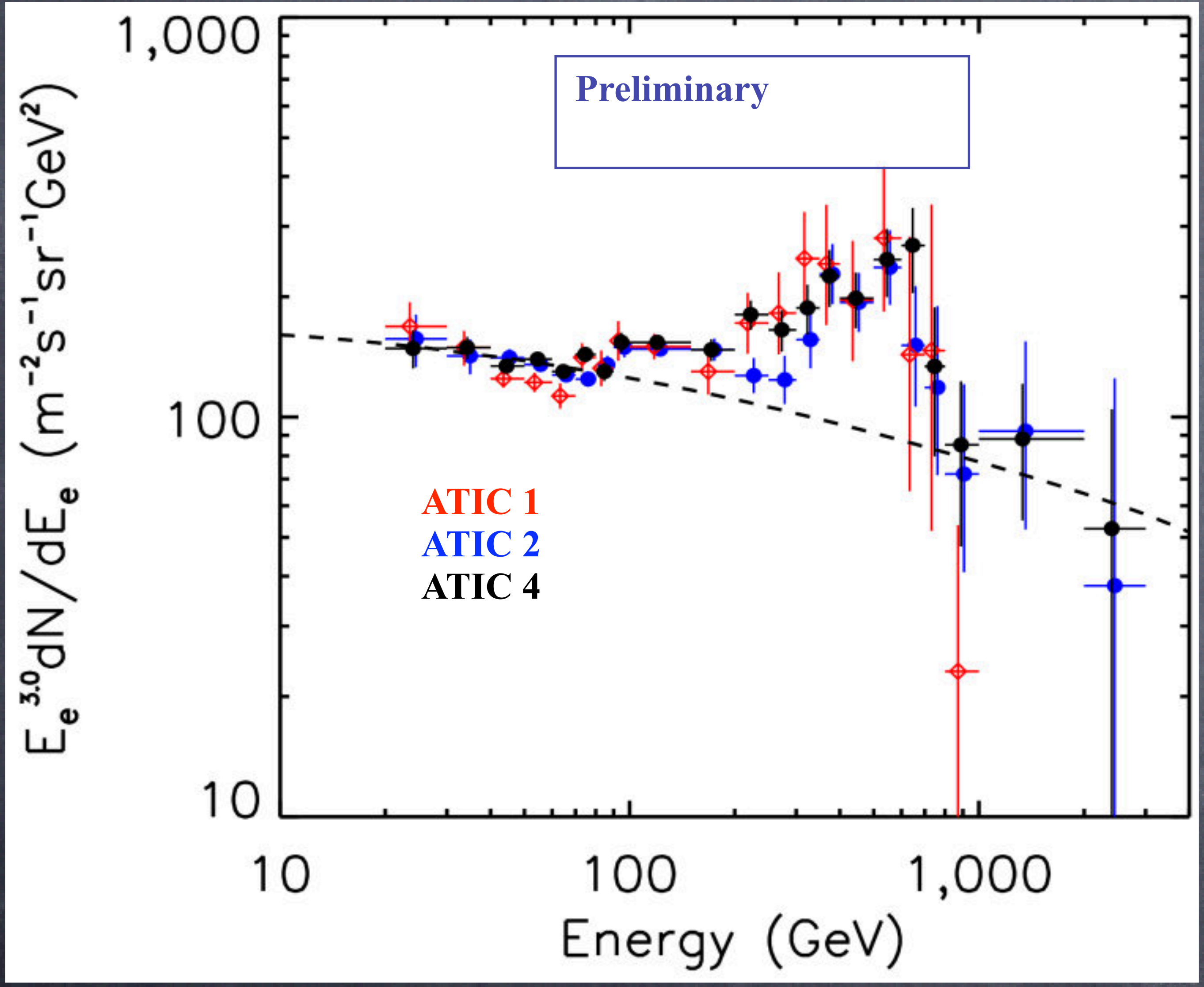


antiproton flux [GeV m^2 s sr]$^{-1}$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-1}
1
10
10^2
kinetic energy [GeV]
AMS (M. Aguilar et al.)
BESS-polar04 (K. Abe et al.)
BESS1999 (Y. Asaoka et al.)
BESS2000 (Y. Asaoka et al.)
CAPRICE1998 (M. Boezio et al.)
CAPRICE1994 (M. Boezio et al.)
PAMELA

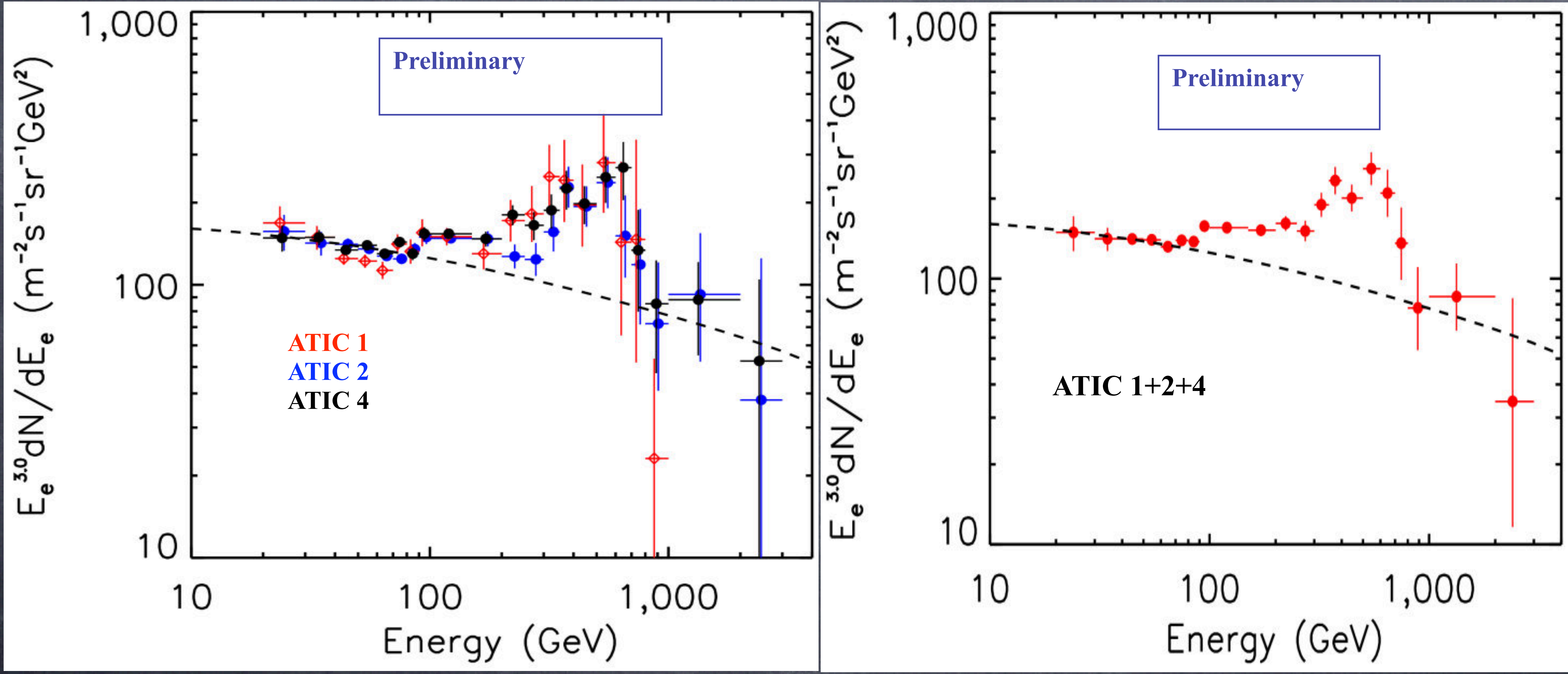
ATIC/PPB-BETS: - bump in $e^+ + e^-$ spectrum between 200 and 800 GeV

- ATIC excess is 70 events



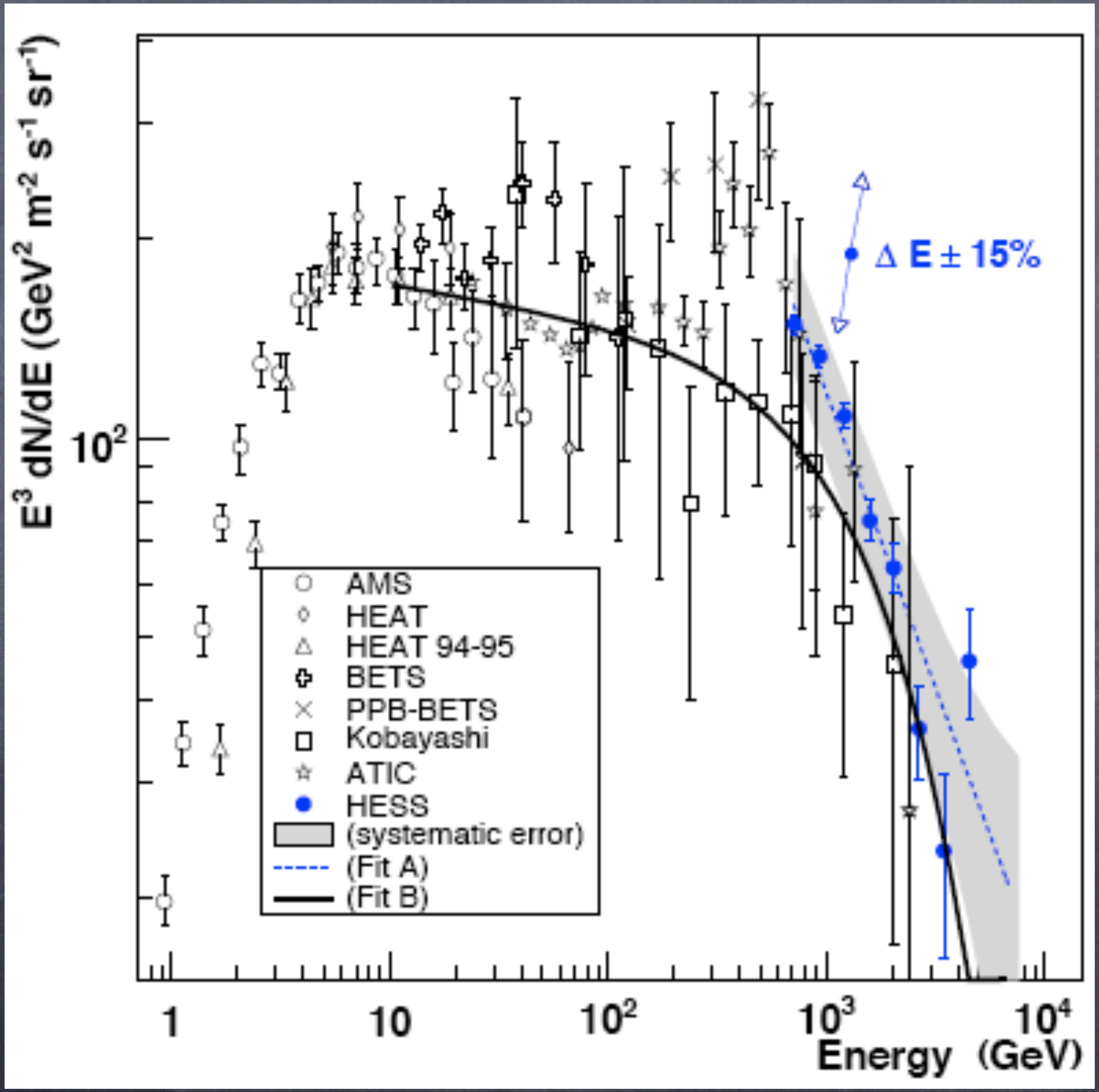


Preliminary
ATIC 1
ATIC 2
ATIC 4
$E_e^{3.0} dN/dE_e$ ($m^{-2}s^{-1}sr^{-1}GeV^2$)
Energy (GeV)
10
100
1,000



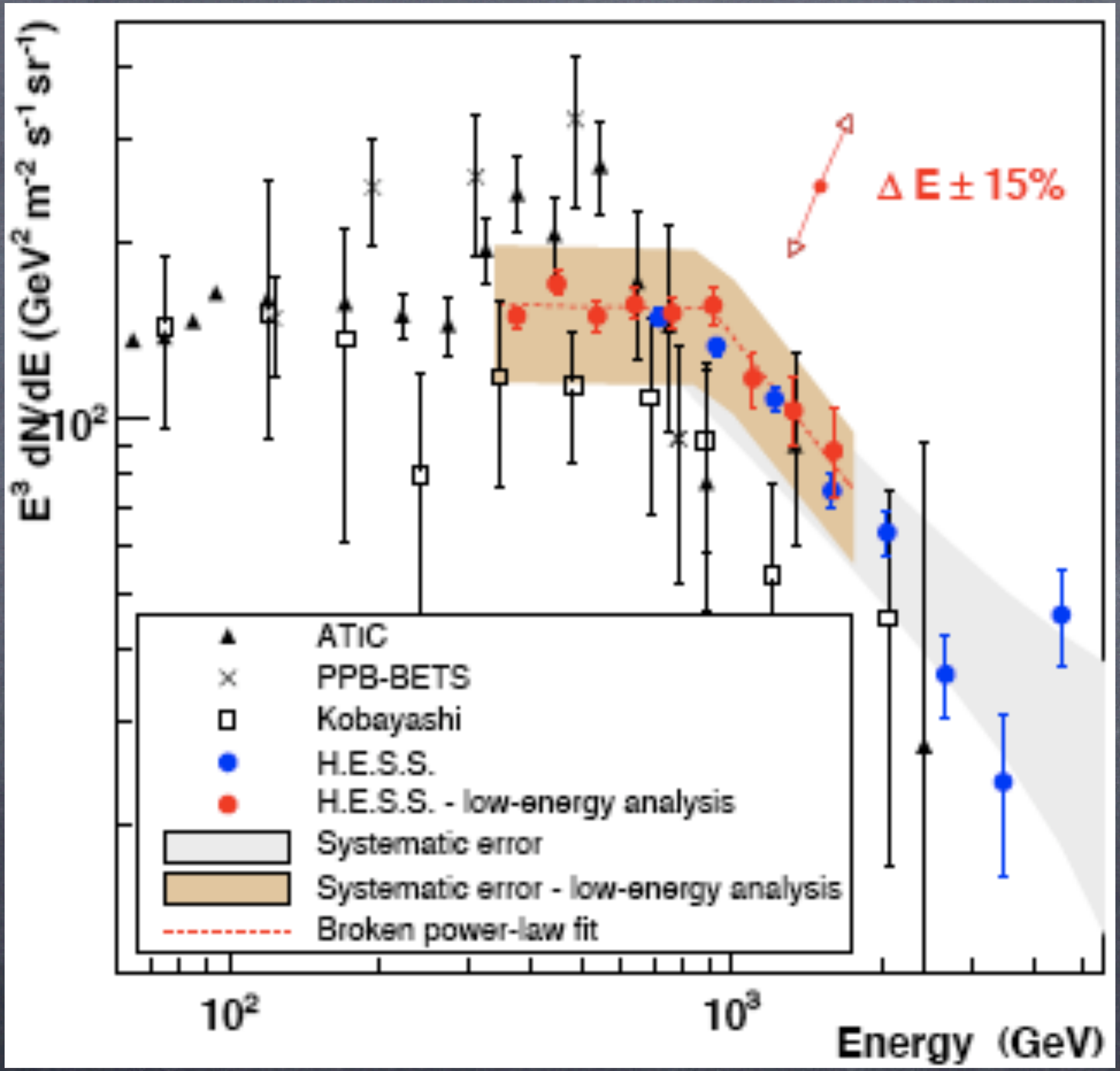
Preliminary
ATIC 1
ATIC 2
ATIC 4
$E_e^{3.0}dN/dE_e$ $(m^{-2}s^{-1}sr^{-1}GeV^2)$
Energy (GeV)
Preliminary
ATIC 1+2+4
$E_e^{3.0}dN/dE_e$ $(m^{-2}s^{-1}sr^{-1}GeV^2)$
Energy (GeV)

HESS: cutoff in $e^+ + e^-$ spectrum at about a TeV



HESS: - no bump in $e^+ + e^-$ spectrum from 340 - 1000 GeV

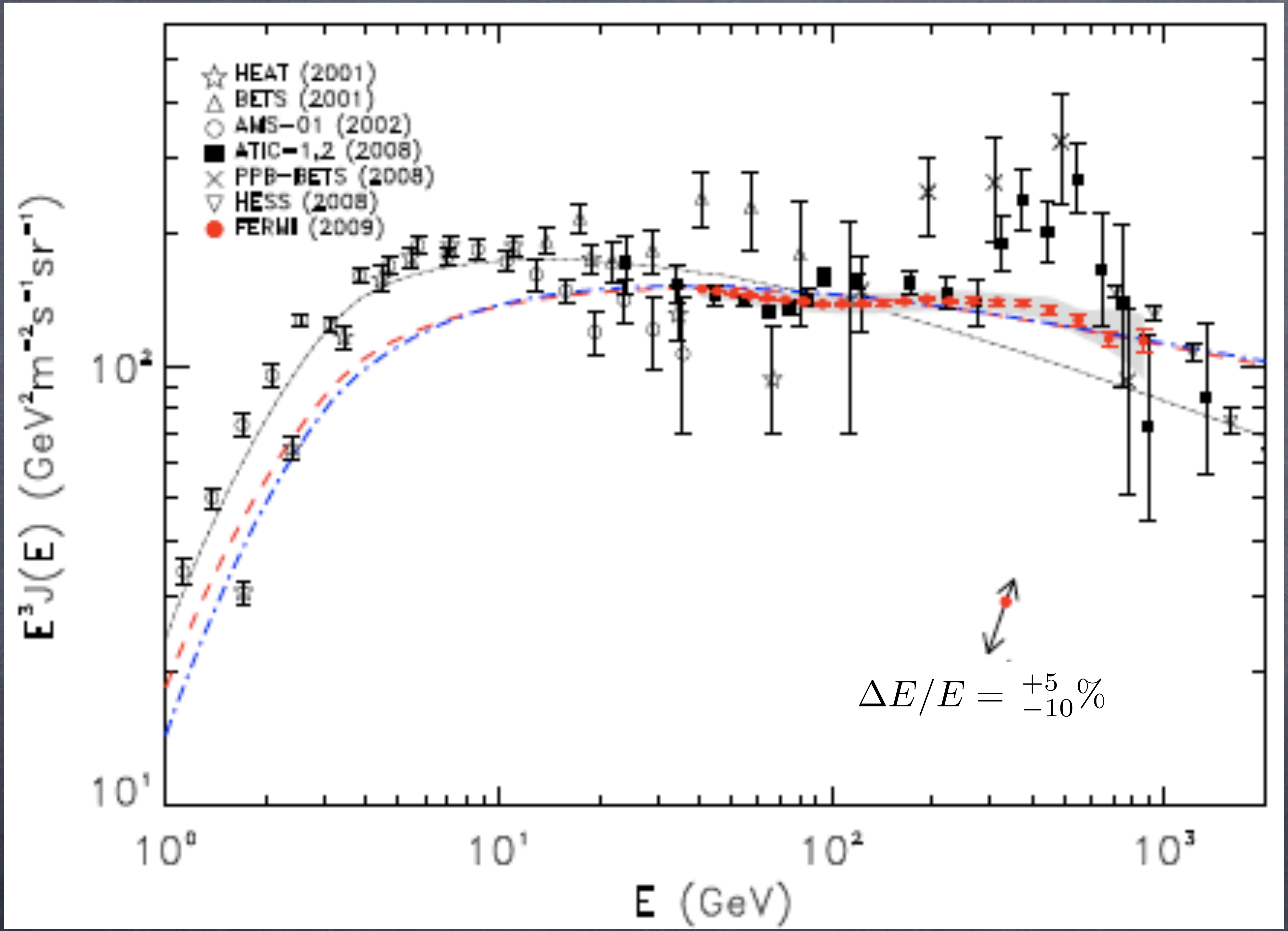
- confirms falling spectrum above 1 TeV



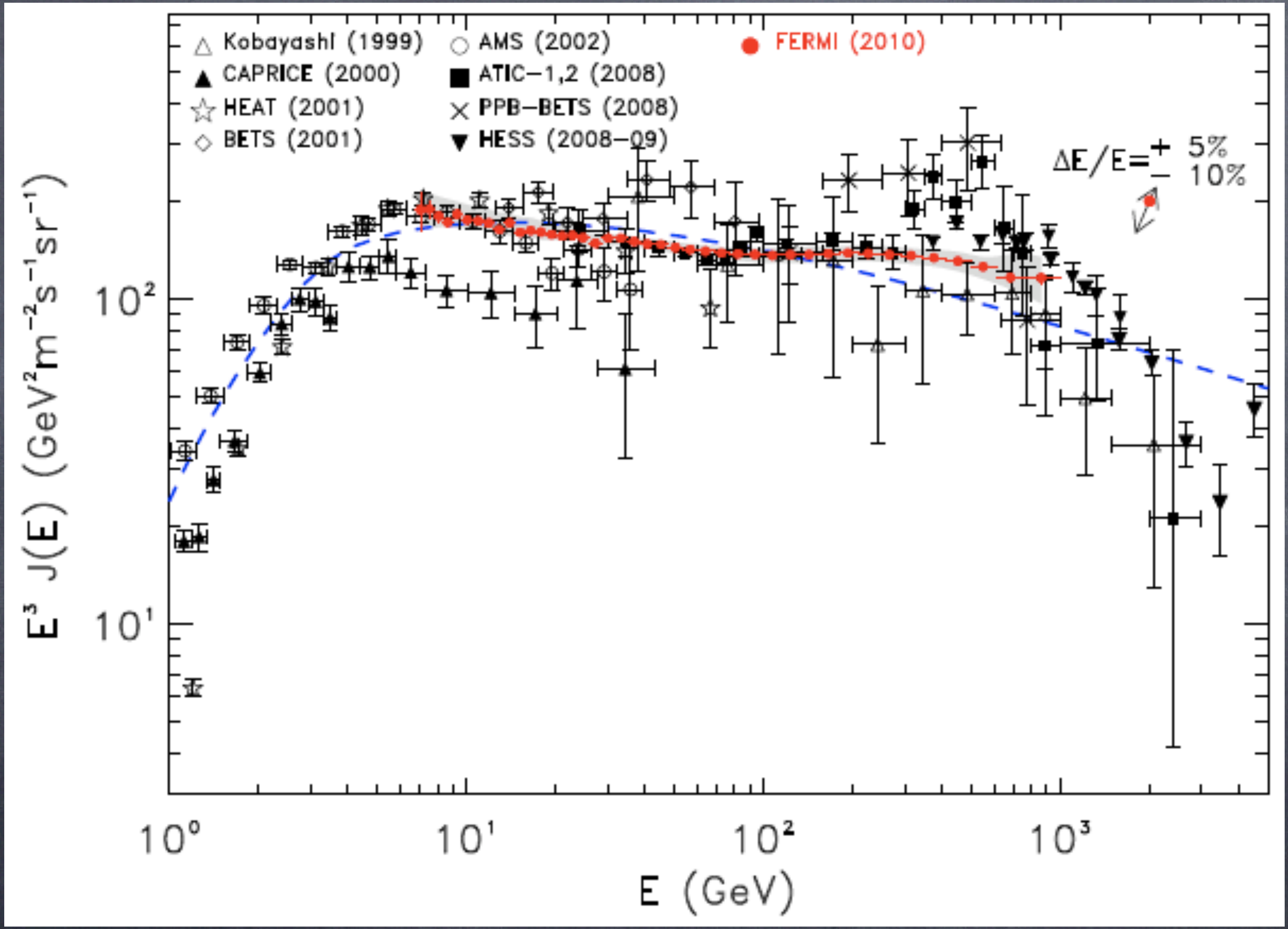
- statistically limited

Fermi: - no bump in $e^+ + e^-$ spectrum from 20 - 1000 GeV

- expected 7000 excess events to confirm ATIC

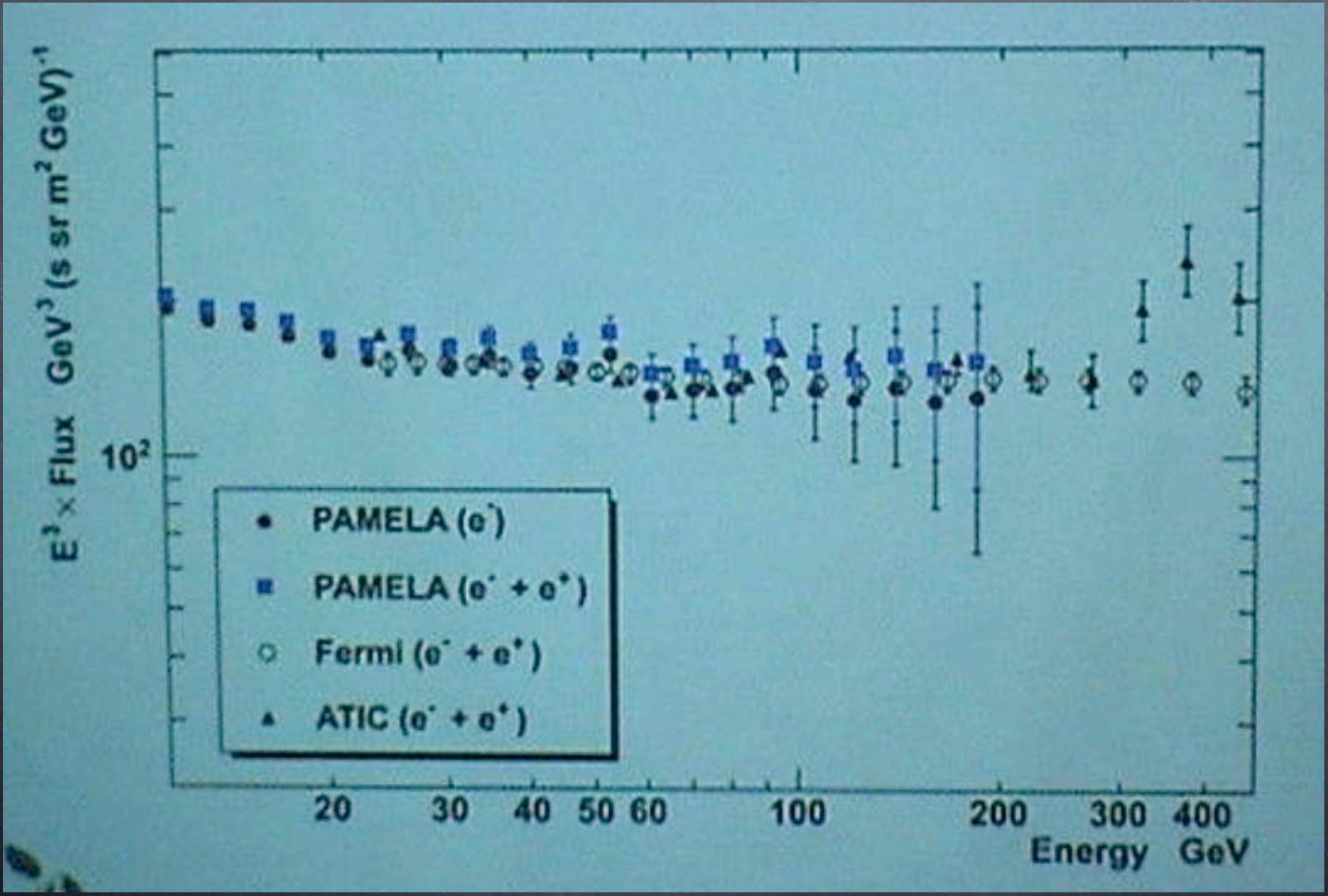


- excess from 200-1000 GeV subject to interpretation
- slight change in SN injection spectrum can reproduce data

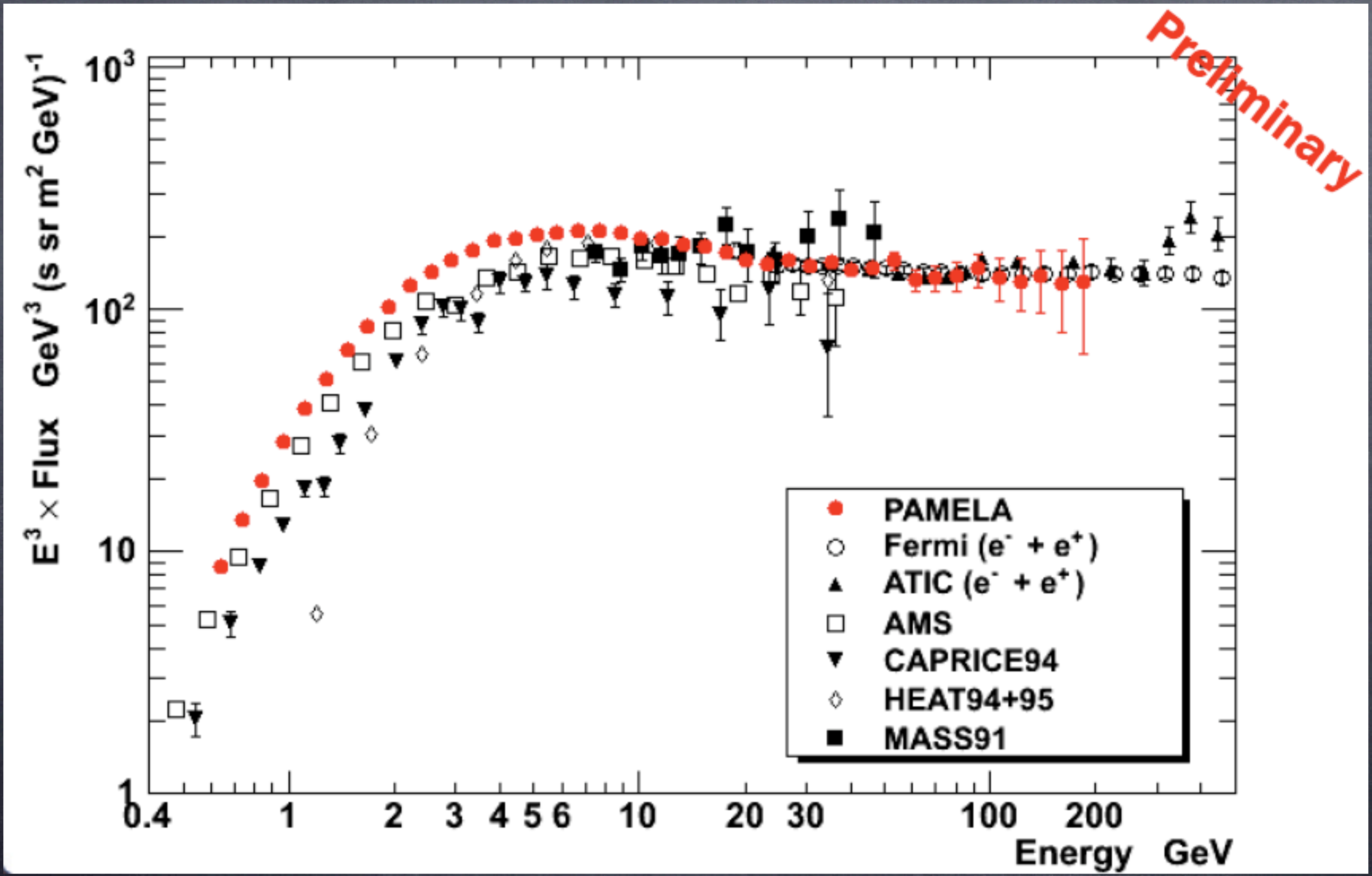


Kobayashi (1999)
CAPRICE (2000)
HEAT (2001)
BETS (2001)
AMS (2002)
ATIC−1,2 (2008)
PPB−BETS (2008)
HESS (2008−09)
FERMI (2010)
ΔE/E=+ 5% − 10%
E³ J(E) (GeV²m⁻²s⁻¹sr⁻¹)
E (GeV)

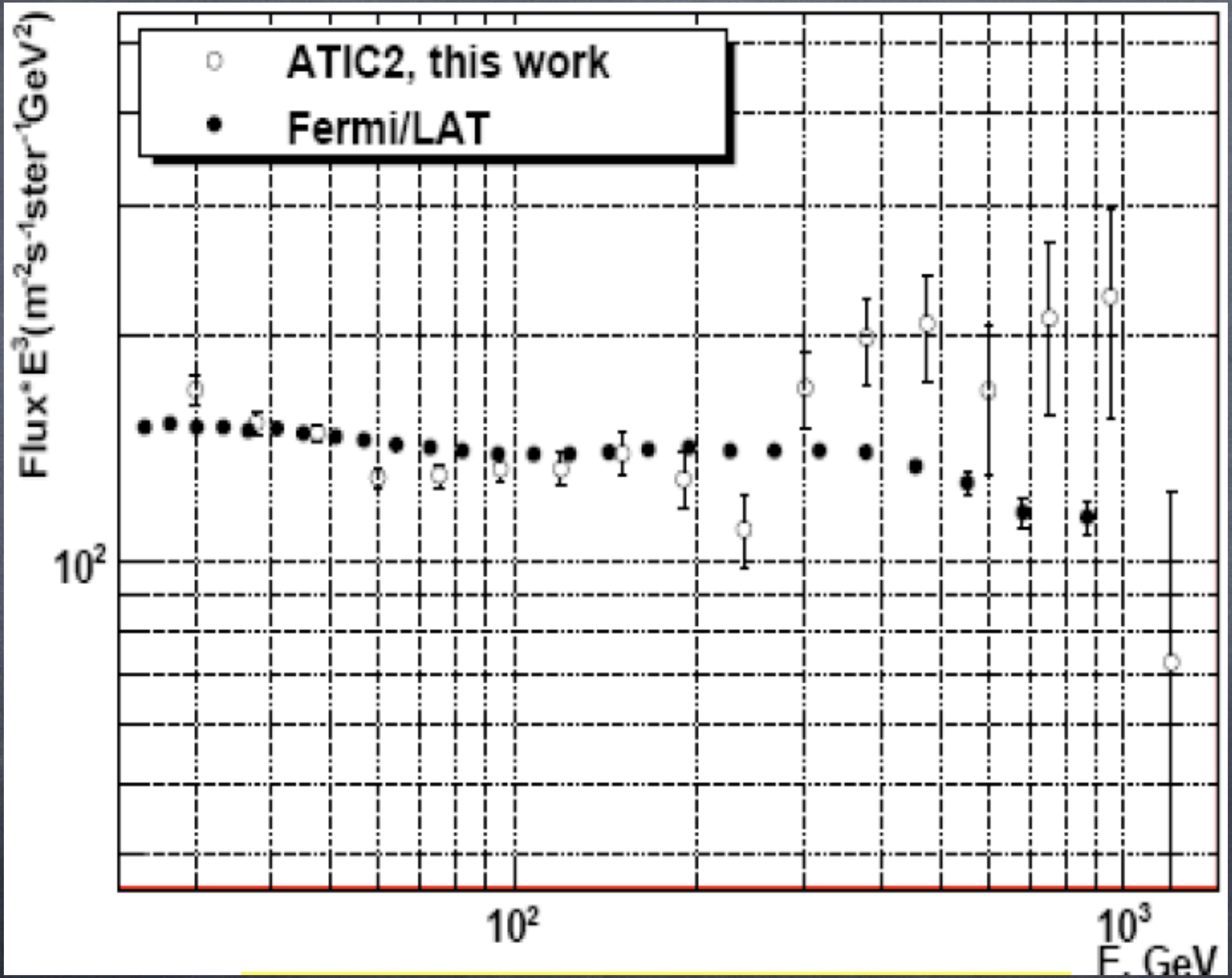
PAMELA: $e^+ + e^-$ spectrum up to 200 GeV



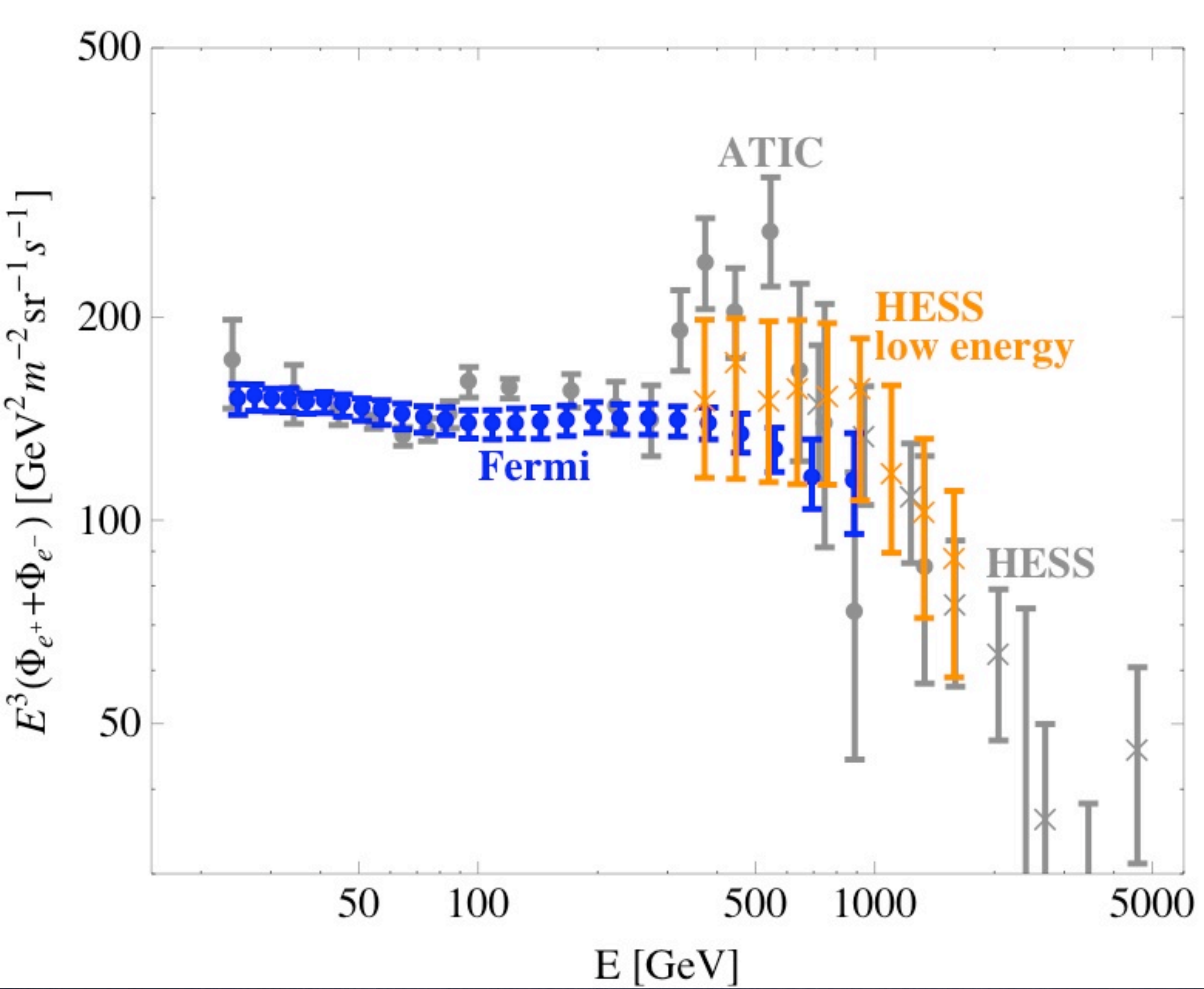
PAMELA: electron spectrum up to 200 GeV



New ATIC analysis

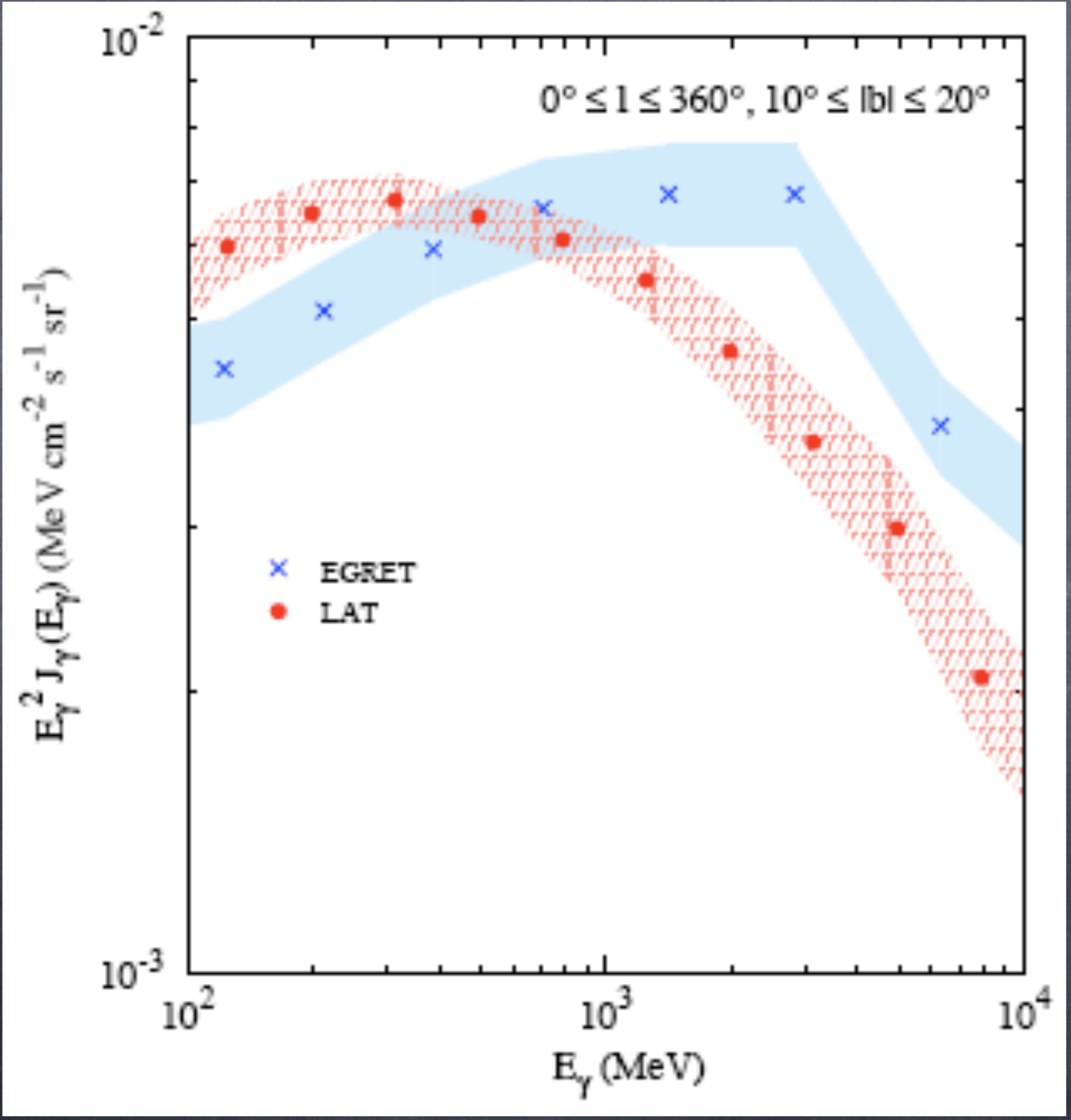


Spectrum hardens slightly at 100 GeV and softens at 1 TeV

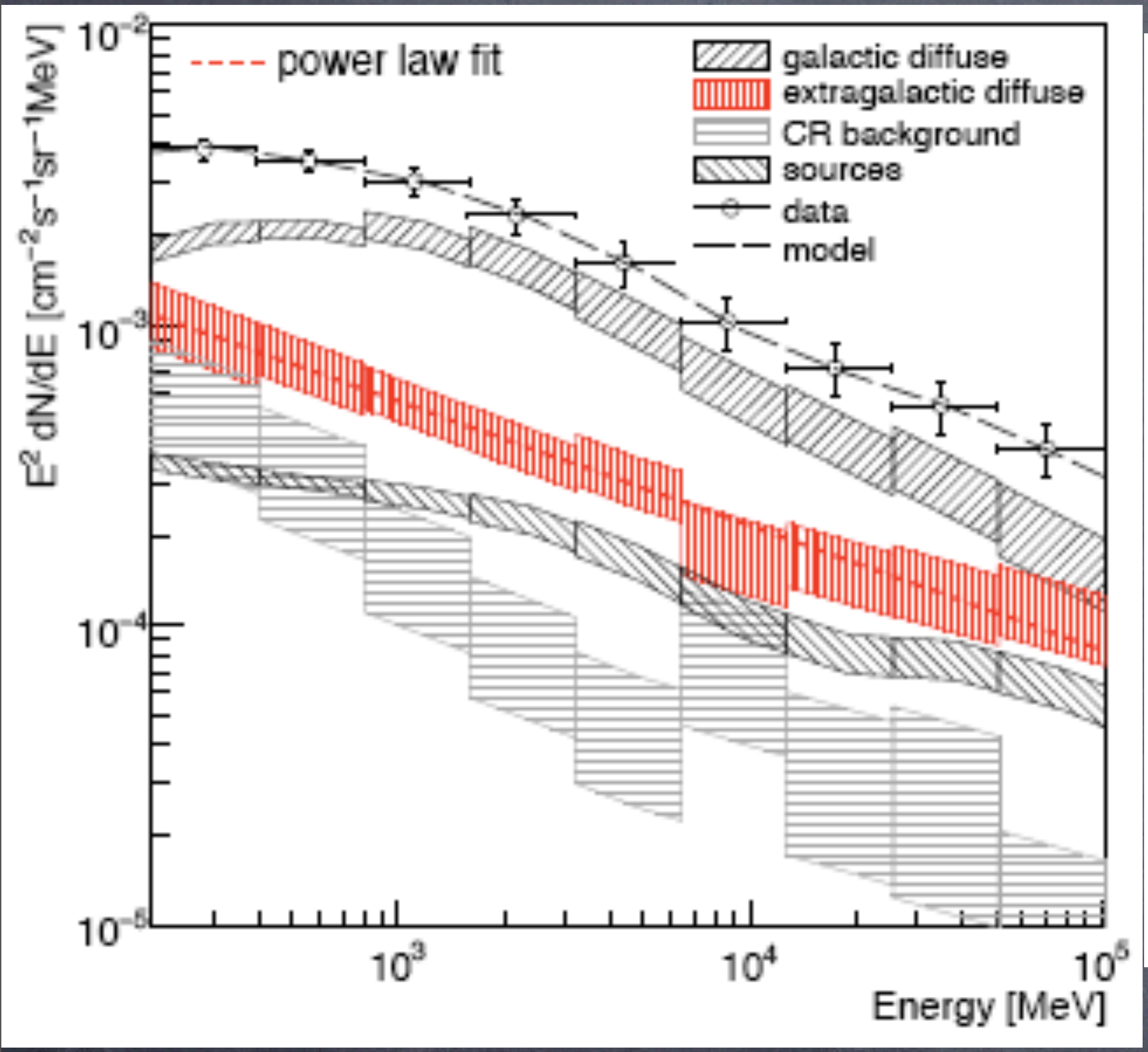


Statistical and systematic uncertainties added in quadrature for Fermi and HESS

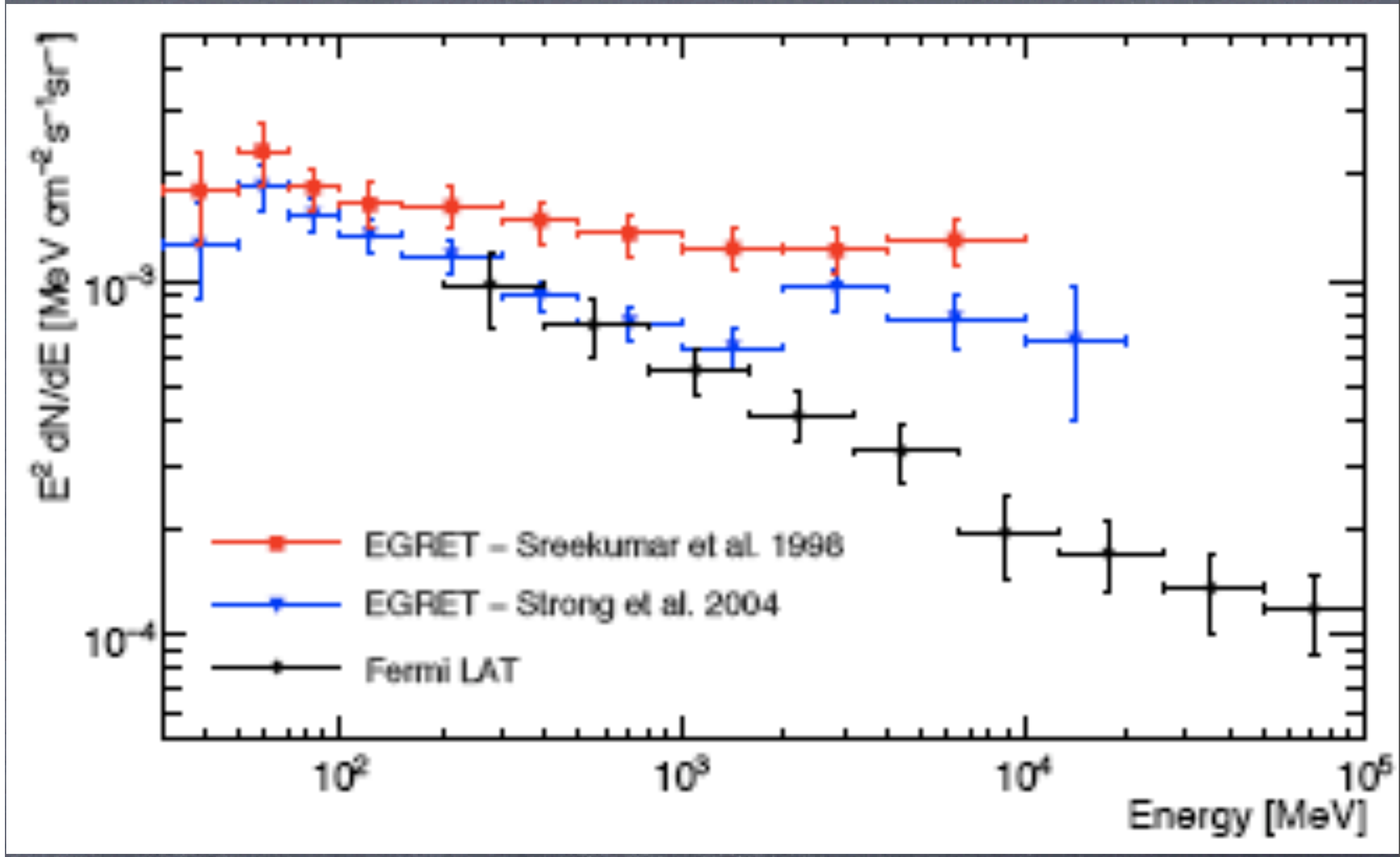
Fermi: - no excess in gamma-ray spectrum from 0.1 - 10 GeV
- contradicts EGRET data



|b|>10 degrees

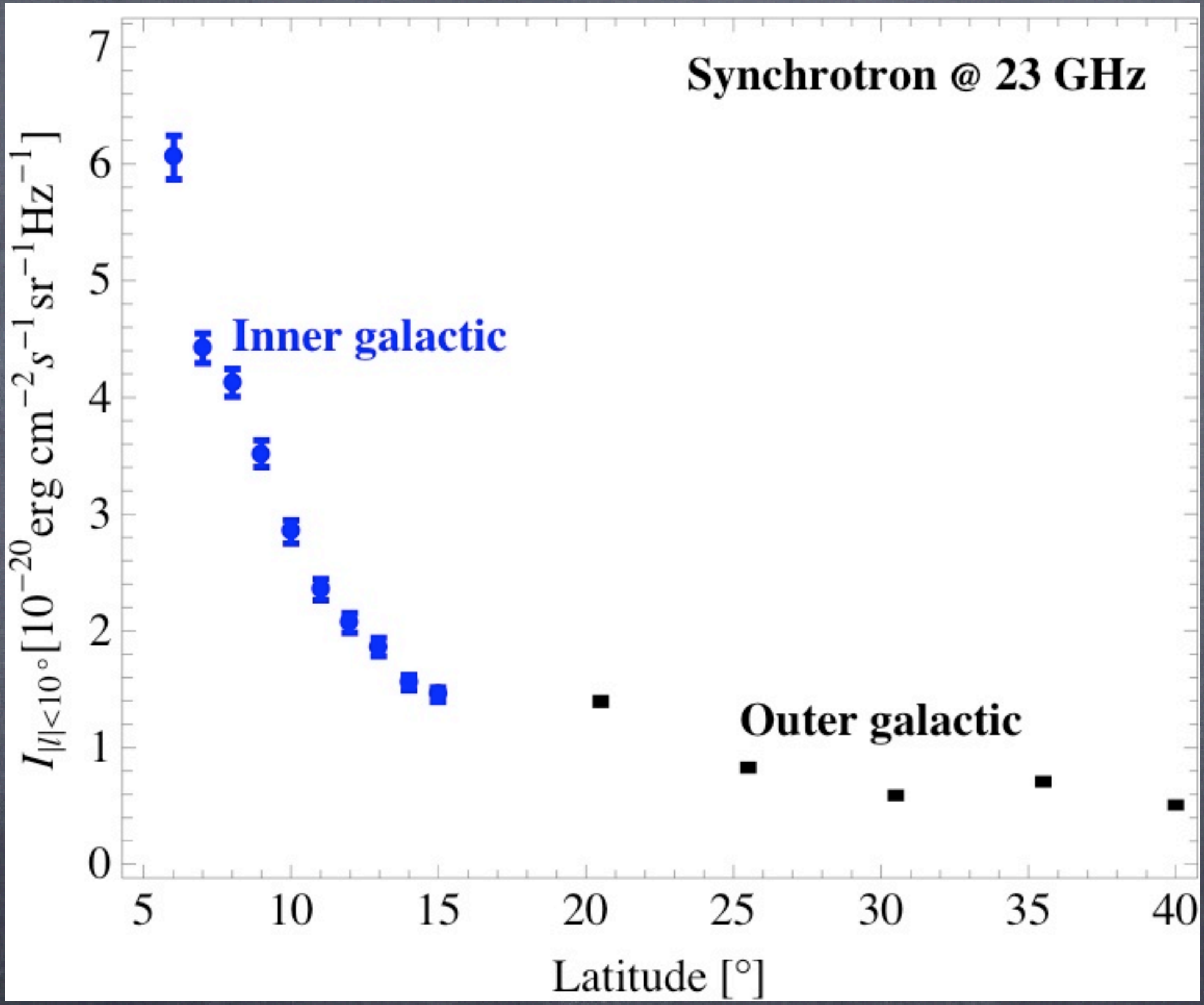


power law fit
galactic diffuse
extragalactic diffuse
CR background
sources
data
model
E^2 dN/dE [$cm^{-2}s^{-1}sr^{-1}$MeV]
Energy [MeV]



EGRET - Sreekumar et al. 1998
EGRET - Strong et al. 2004
Fermi LAT
E^2 dN/dE [MeV $cm^{-2}s^{-1}sr^{-1}$]
Energy [MeV]

WMAP Haze: residual microwave radiation between 23 - 94 GHz



Large and unknown systematic uncertainties, especially in the inner galactic region

- change in background injection spectrum can achieve agreement with Fermi electron data, but not PAM data: primary anomaly is PAM positron excess
- consider all data except ATIC
- need source that produces positrons but not antiprotons
- source must not produce a "feature" to be consistent with Fermi data
- spectrum must fall off above 1 TeV as per HESS
- possibilities are
  - dark matter annihilation
  - dark matter decay
  - pulsars

How these sources provide viable explanations:

DM annihilation/decay:

In the halo,
DM+DM --> SM particles --> decay/hadronize/shower to $e^{\pm}, \bar{p}$
or long-lived DM --> SM particles --> $e^{\pm}, \bar{p}$

$e^{\pm}, \bar{p}$ interact with the galactic magnetic field, ISRF, ISM and lose energy via
- inverse compton scattering which produces gamma rays
- synchrotron radiation in the form of radiowaves
- spallation on heavy nuclei

$e^{\pm}, \bar{p}$ eventually make it to the earth with scrambled trajectories

Gamma-rays produced as FSR, bremsstrahlung, in pion decay and IC essentially come directly to the earth

IC spectral shape will turn out to be similar for all scenarios since the $e^{\pm}$ required by data is basically fixed

Main difference in gamma-ray spectra arises from pion decay and FSR which is model-dependent and dominates IC close to the endpoint

Mature pulsars: (0.05 < T < 1 Myr)

$e^{\pm}$ are confined to the pulsar wind nebula until it merges with the ISM. Merger process is fast so that pulsars can be treated as burst-like sources of $e^{\pm}$

Contribution could be from a few local pulsars
- Geminga: d = 160 pc, T = 0.37 Myr
- Monogem: d = 290 pc, T = 0.11 Myr

but pair conversion efficiency needs to be high (30 - 40%)

Contribution could be from a large number of pulsars, distant and local, with an assumed continuum distribution and injection spectrum

$$\frac{dN_{e^{\pm}}}{dE} \propto E^{-1.5} e^{-E/E_p}$$

- absence of hadronic showers
  --> no antiprotons
  --> easily consistent with PAM antiproton data

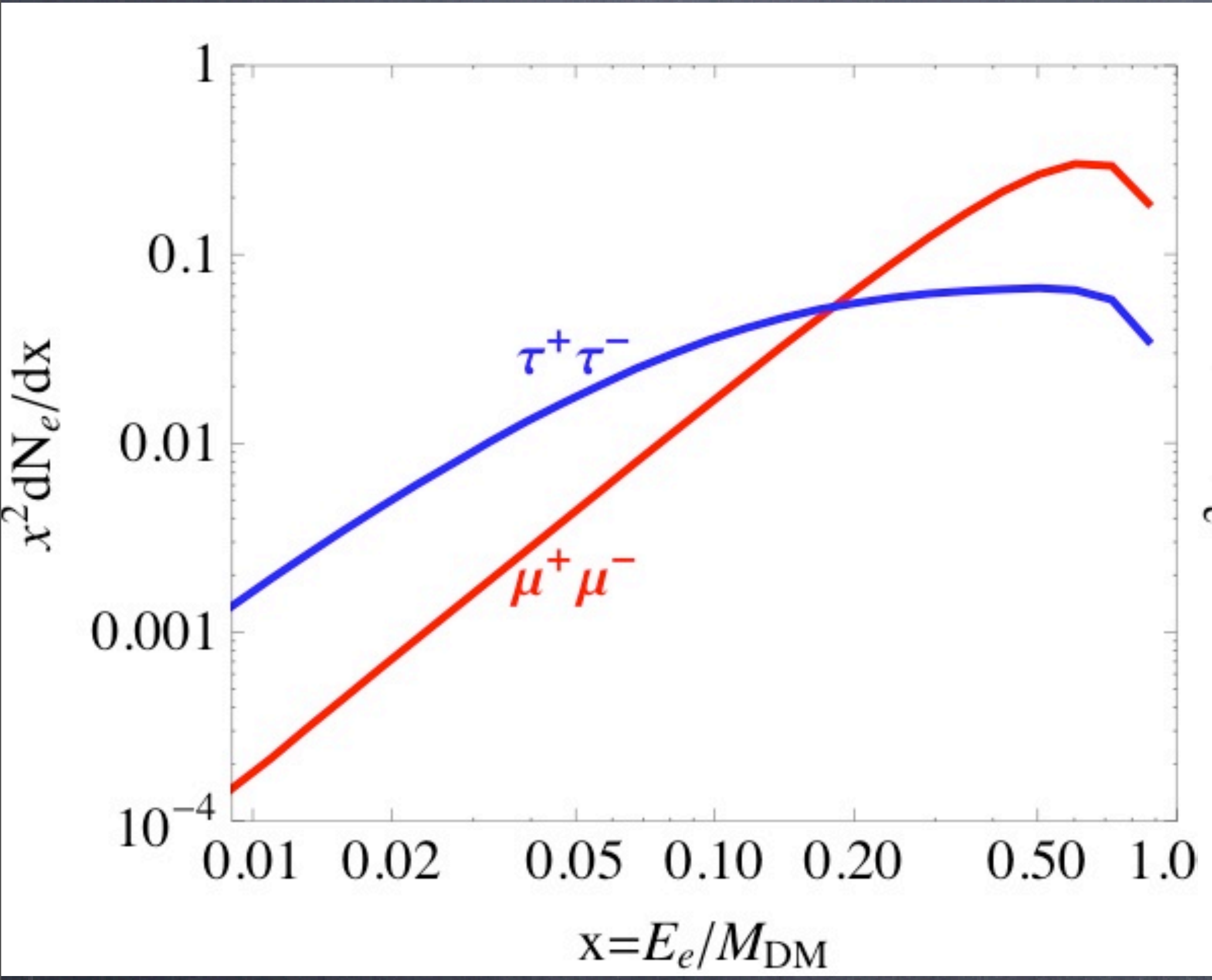
- primary gamma-ray flux is negligible compared to the diffuse flux
  --> only contribution is from IC scattering
  --> easily consistent with Fermi gamma-ray data

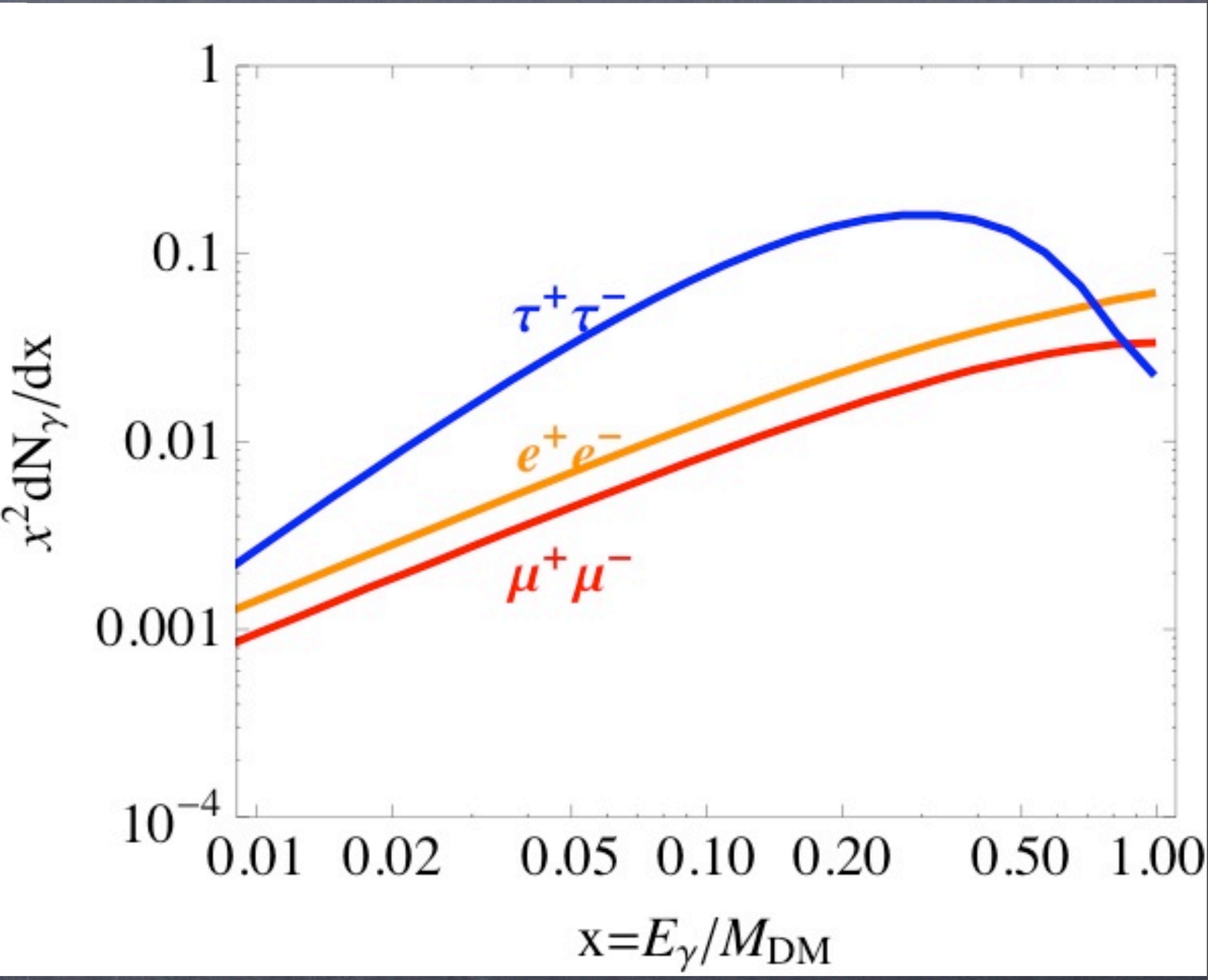
DM annihilation/decay

- Consider 2-body final states
- WW, ZZ, qq, hh are disfavored because of overproduction of antiprotons, or positron spec too flat
- Consider only $ee, \mu\mu, \tau\tau$, and to these channels with equal branching fractions
- For DM decay, effectively assuming that DM is a scalar
- Other channels, $W\ell, Z\nu, \ell\ell\nu$ possible for fermion DM decay
  - $W\tau, Z\nu, \tau\tau\nu$ give too flat positron spectra

$M_{DM} = 1\,\mathrm{TeV}$

line spectrum for ee

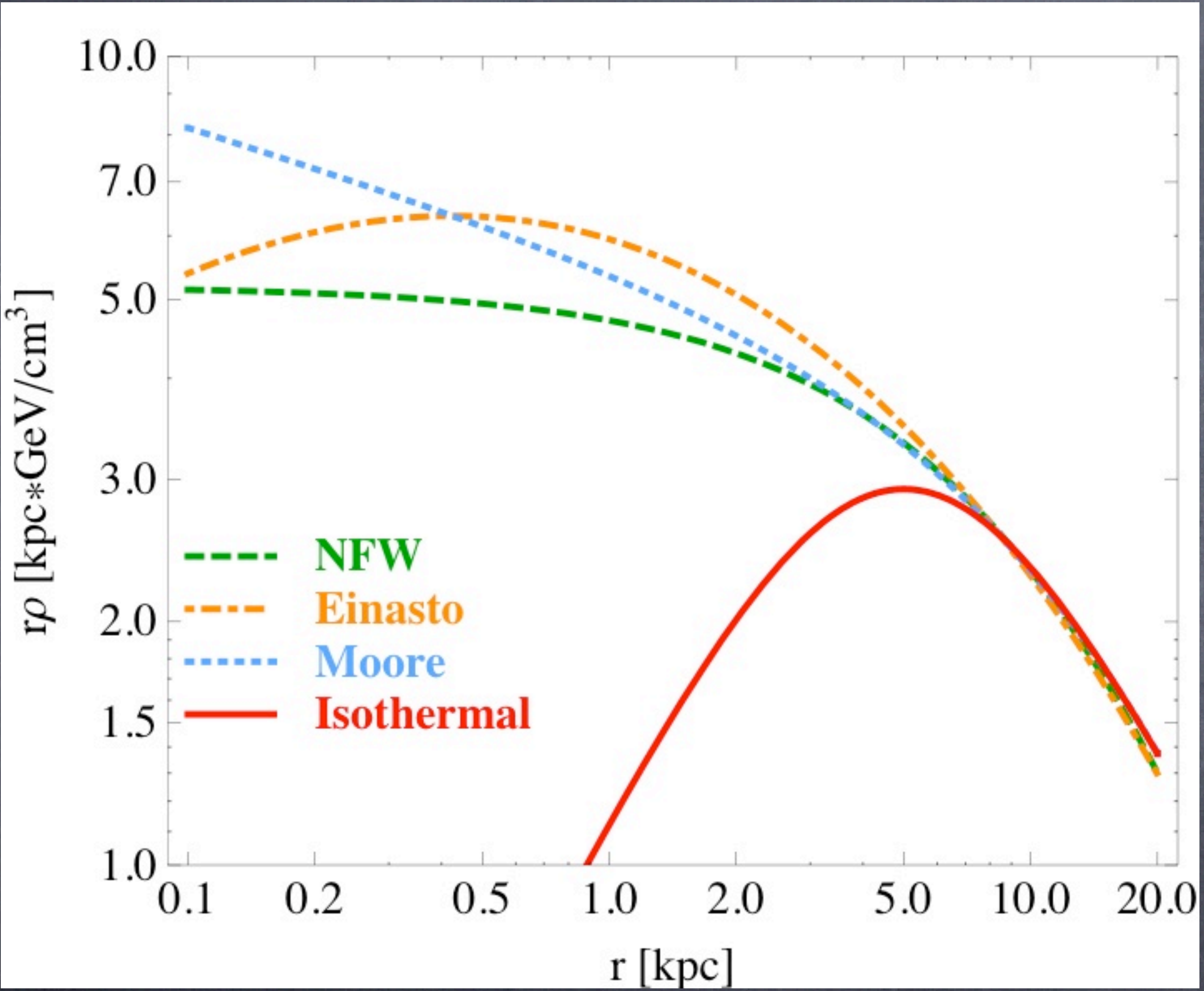


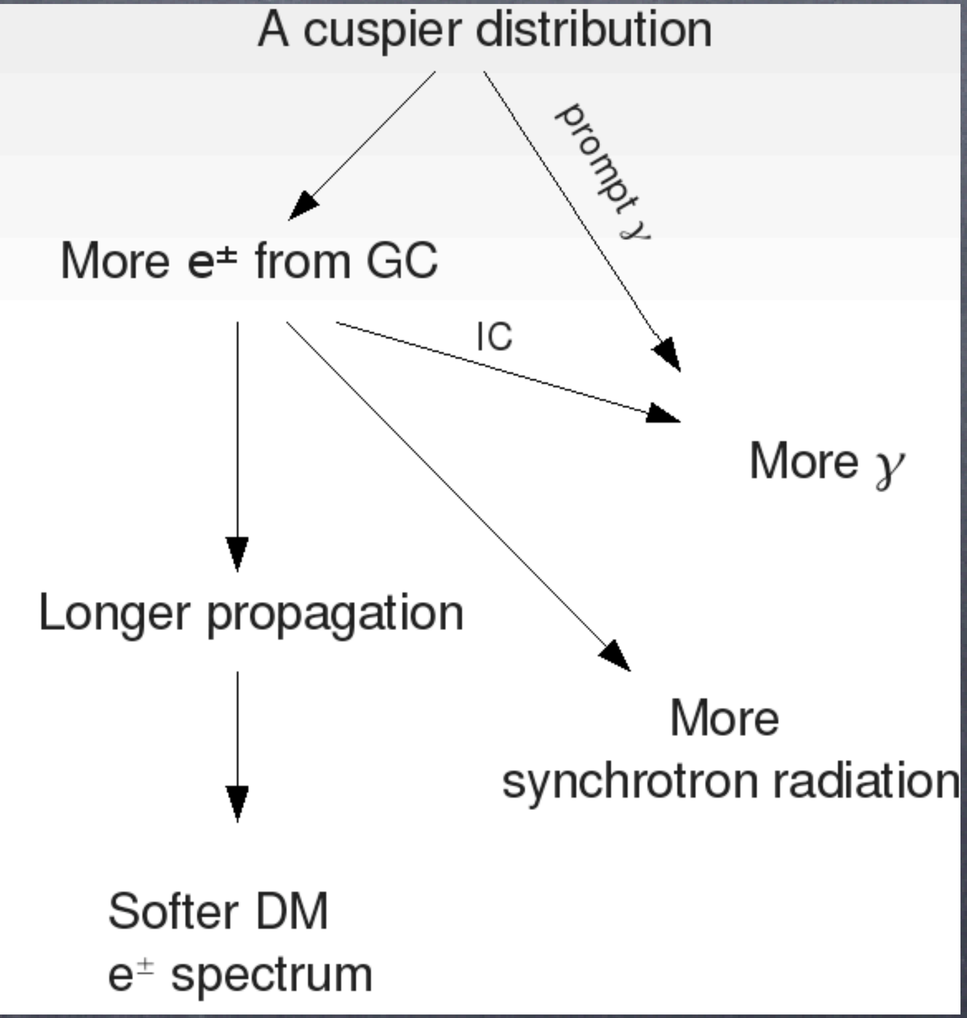


from MicrOMEGAs

from DMFIT

Dark matter halo profiles





- Source terms: $\frac{d\Phi_i}{dE_i} = \begin{cases} \frac{\mathrm{BF}}{2} \frac{\rho^2}{M_{DM}^2} \langle \sigma v \rangle \frac{dN_i}{dE_i} & \text{DM ann.} \\ \frac{1}{T} \frac{\rho}{M_{DM}} \frac{dN_i}{dE_i} & \text{DM decay} \end{cases}$

- Reference $\langle \sigma v \rangle = 3 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}$ to obtain relic density

- BF = "boost factor" from s-channel resonance, Sommerfeld effect, DM overdensities. Need large BF of order 100-10000.

- Need T of order $10^{26}\mathrm{s}$ (billion times the age of the universe)

- Typical lifetime of a TeV-scale particle that decays via a dim-6 operator suppressed by the GUT scale is

$$\mathrm{T} \sim 2 \times 10^{26} \mathrm{s} \left(\frac{\mathrm{TeV}}{\mathrm{M_{DM}}} \right)^5 \left(\frac{\mathrm{M_{GUT}}}{10^{16}\,\mathrm{GeV}} \right)^4$$

Propagation with GALPROP

Allow variations of

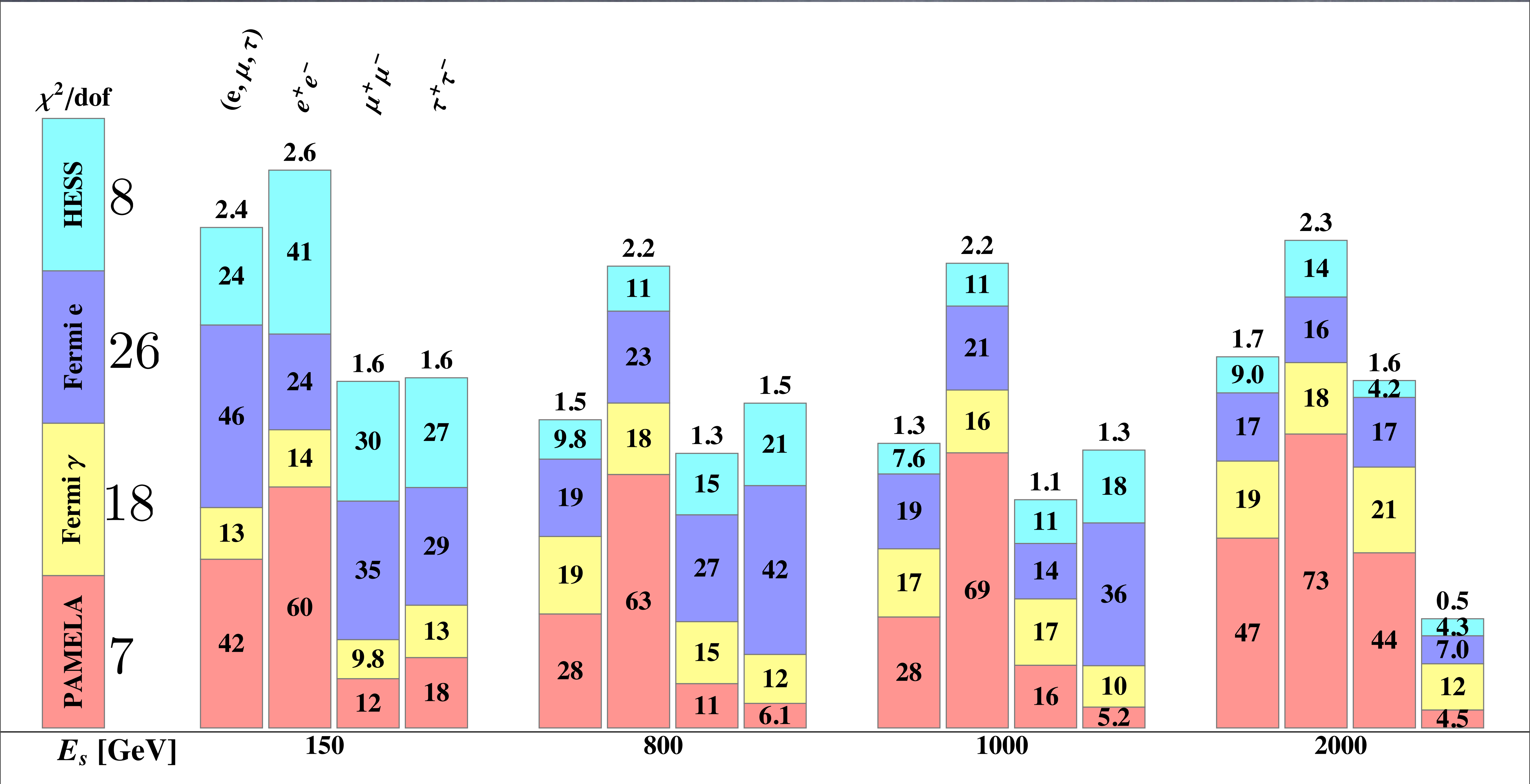
- background injection spectral index between 2.2 - 2.9
- overall normalization of the background
- 3 diffusion parameters within ranges consistent with nuclei data
- energy calibration scale for HESS and Fermi electron data

Define a generic energy scale of injected positrons:

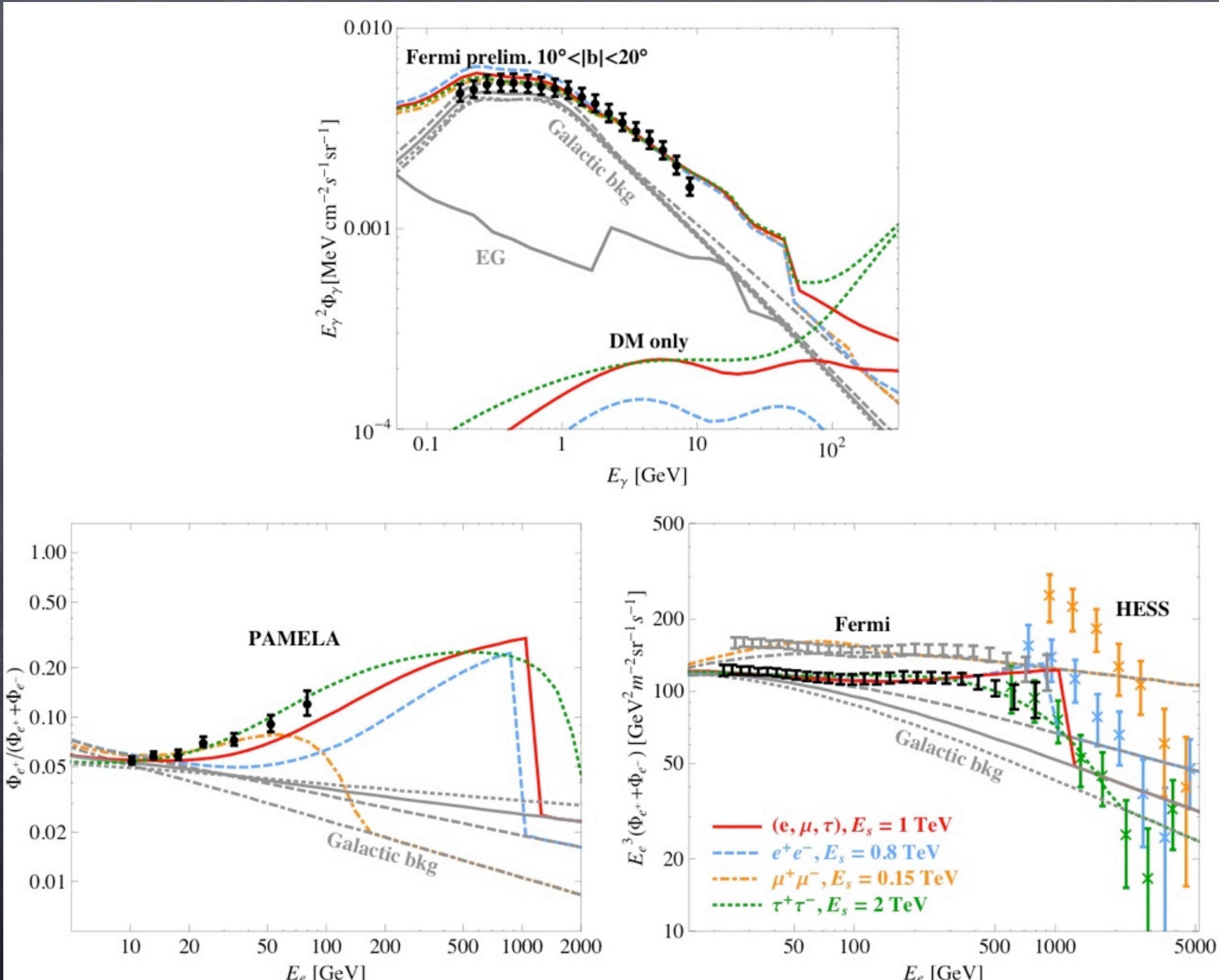
$$E_s \equiv \begin{cases} M_{DM} & \text{Annihilating DM} \\ \frac{M_{DM}}{2} & \text{Decaying DM} \\ E_p & \text{Pulsars} \end{cases}$$

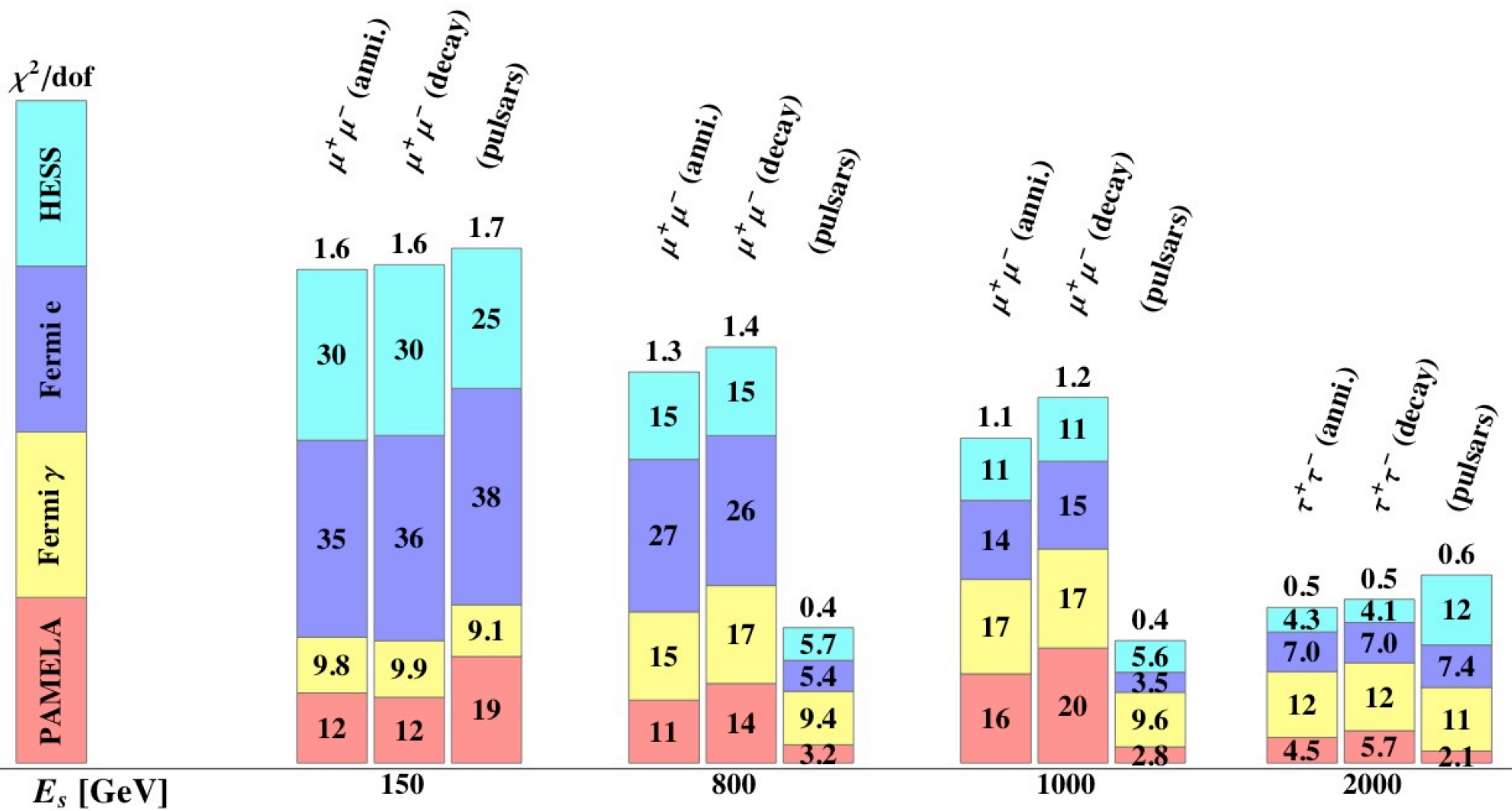
For a given E_s vary BF (for DM annihilation), T (for DM decay) and a spectrum normalization for pulsars

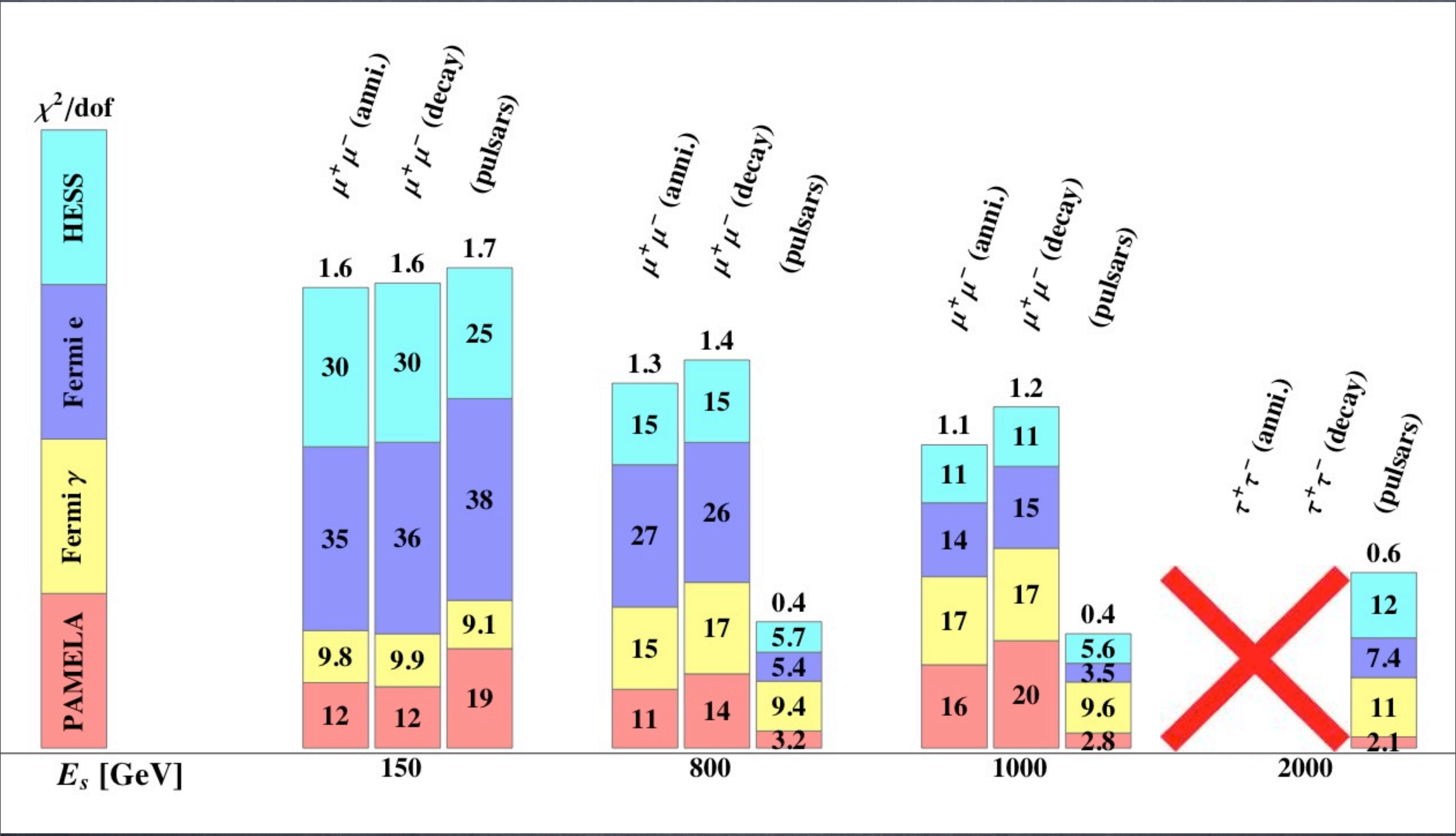
DM annihilation (isothermal profile)



- Soft spectra preferred
- 1 TeV into $\mu\mu$ works well; 2 TeV into $\tau\tau$ works best


Fermi prelim. 10°<|b|<20°
Galactic bkg
EG
DM only
$E_\gamma^{\ 2}\Phi_\gamma$ [MeV cm$^{-2}s^{-1}$sr^{-1}]
E_γ [GeV]
PAMELA
Galactic bkg
$\Phi_{e^+}/(\Phi_{e^+}+\Phi_{e^-})$
E_e [GeV]
Fermi
HESS
Galactic bkg
$(e, \mu, \tau), E_s = 1$ TeV
$e^+e^-, E_s = 0.8$ TeV
$\mu^+\mu^-, E_s = 0.15$ TeV
$\tau^+\tau^-, E_s = 2$ TeV
$E_e^{\ 3}(\Phi_{e^+}+\Phi_{e^-})$ [GeV$^2m^{-2}$sr$^{-1}s^{-1}$]
E_e [GeV]

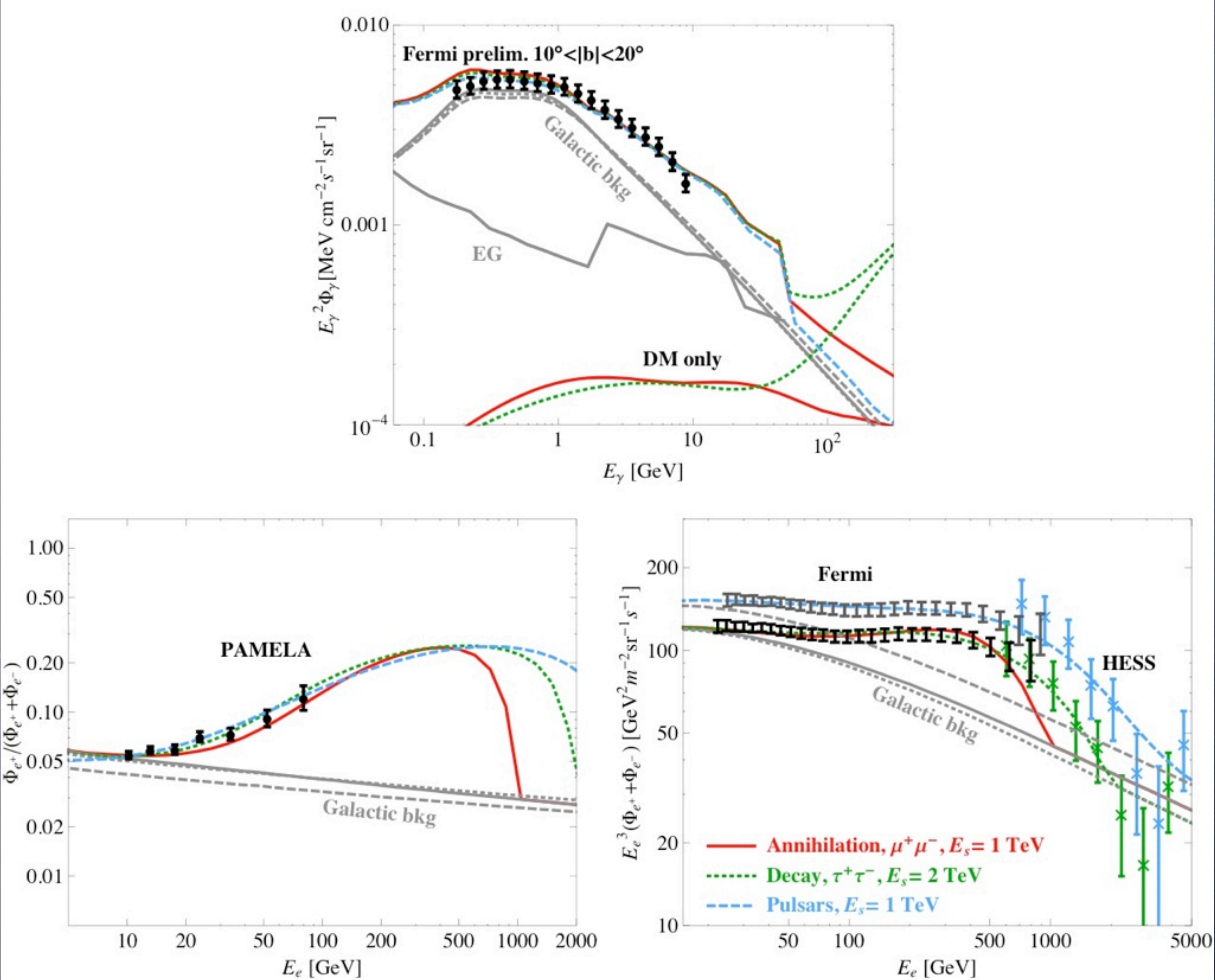

χ^2/dof
HESS
Fermi e
Fermi γ
PAMELA
$\mu^+\mu^-$ (anni.)
$\mu^+\mu^-$ (decay)
(pulsars)
$\tau^+\tau^-$ (anni.)
$\tau^+\tau^-$ (decay)
1.6
1.6
1.7
30
30
25
35
36
38
9.8
9.9
9.1
12
12
19
1.3
1.4
0.4
15
15
27
26
15
17
11
14
5.7
5.4
9.4
3.2
1.1
1.2
0.4
11
11
14
15
17
17
16
20
5.6
3.5
9.6
2.8
0.5
0.5
0.6
4.3
4.1
12
7.0
7.0
7.4
12
12
11
4.5
5.7
2.1
E_s [GeV]
150
800
1000
2000



$\tau\tau$ disfavored by preliminary all-sky Fermi gamma-ray data

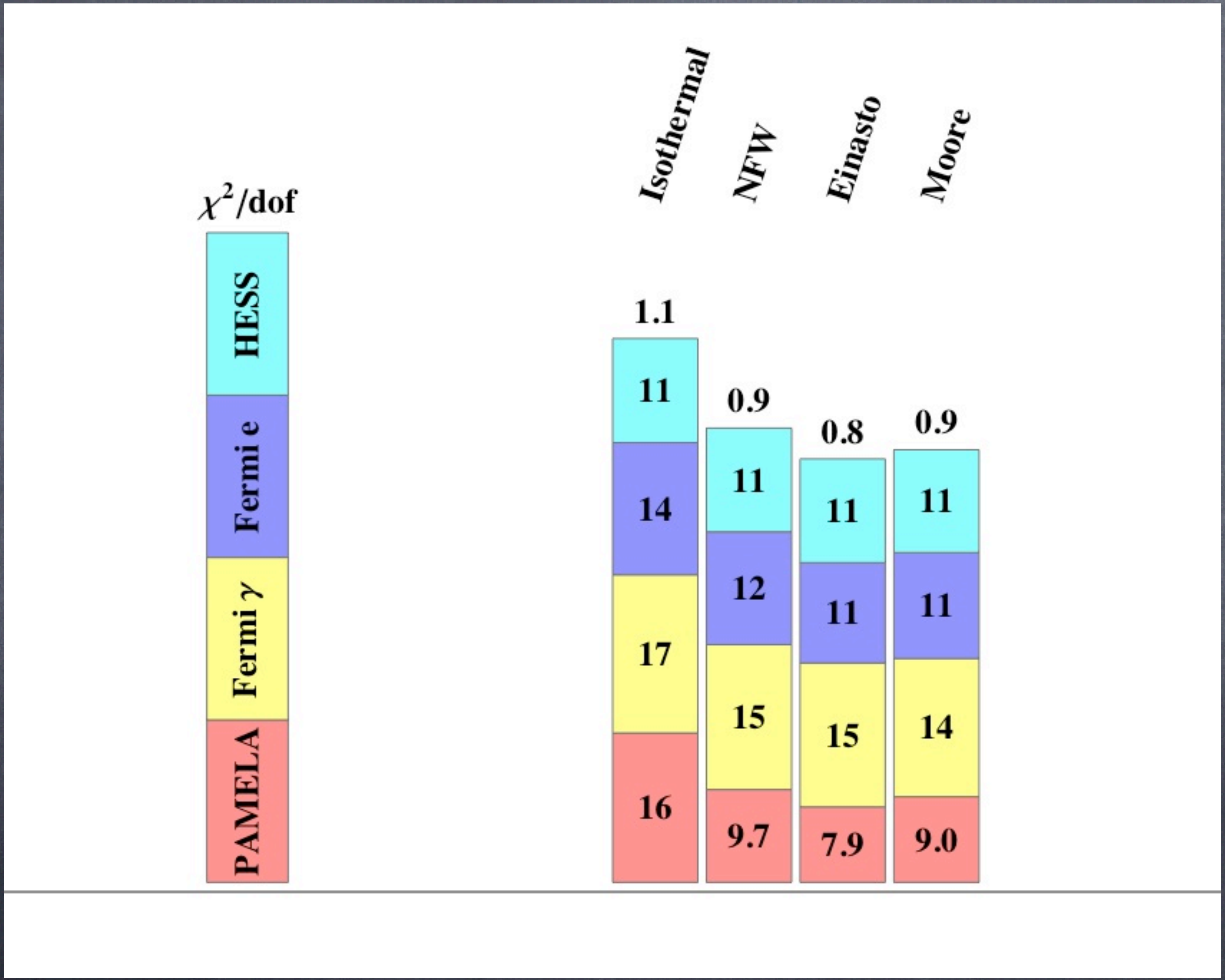
Only $\mu\mu$ allowed

See talk by Cirelli

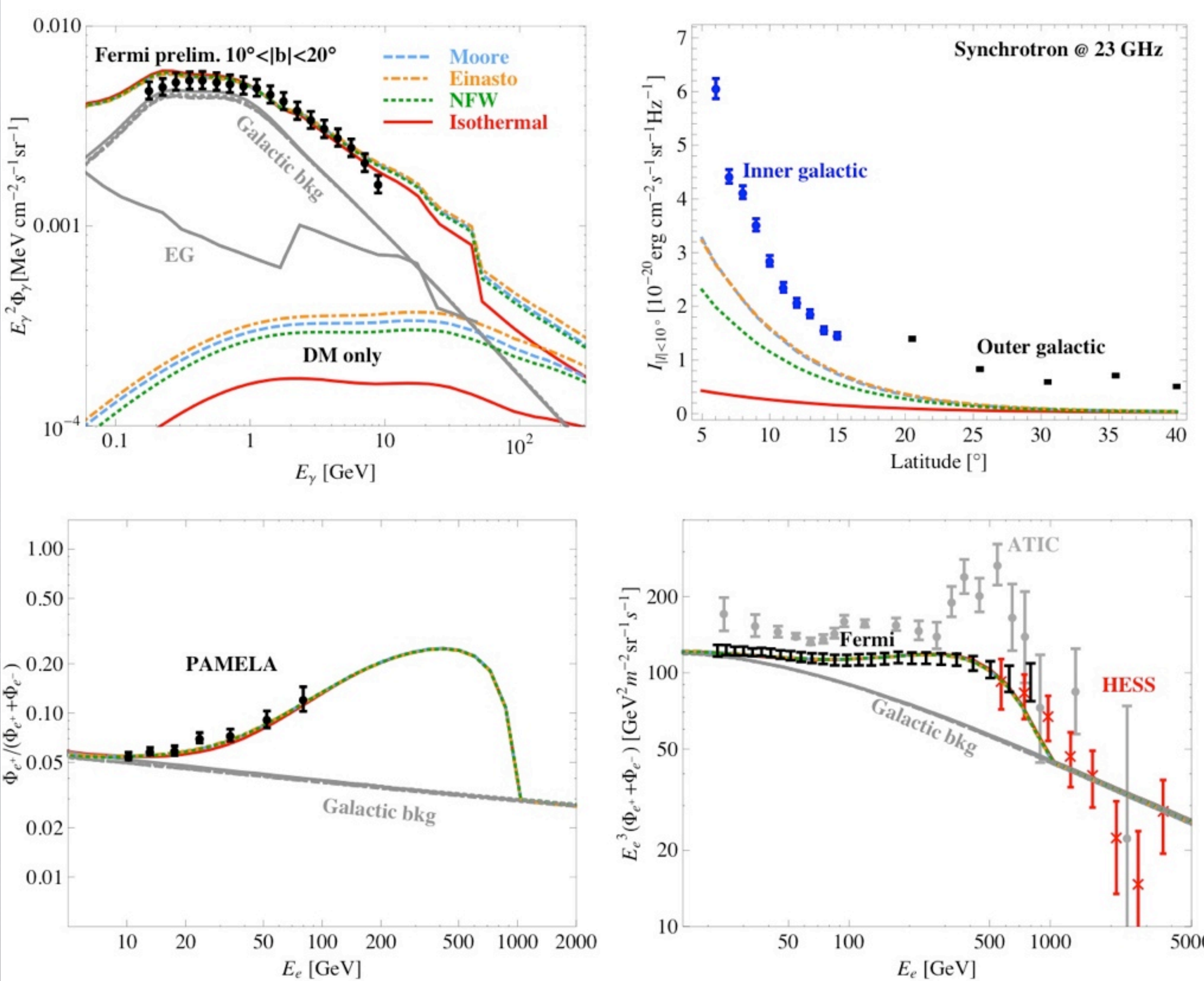

Fermi prelim. 10°<|b|<20°
Galactic bkg
EG
DM only
$E_\gamma{}^2\Phi_\gamma$ [MeV cm$^{-2}s^{-1}$sr^{-1}]
E_γ [GeV]
PAMELA
Galactic bkg
$\Phi_{e^+}/(\Phi_{e^+}+\Phi_{e^-})$
E_e [GeV]
Fermi
HESS
Galactic bkg
$E_e{}^3(\Phi_{e^+}+\Phi_{e^-})$ [GeV$^2m^{-2}$sr$^{-1}s^{-1}$]
Annihilation, $\mu^+\mu^-$, E_s= 1 TeV
Decay, $\tau^+\tau^-$, E_s= 2 TeV
Pulsars, E_s= 1 TeV
E_e [GeV]

Pre-Fermi all-sky gamma-ray map showed no halo profile preference

DM annihilation



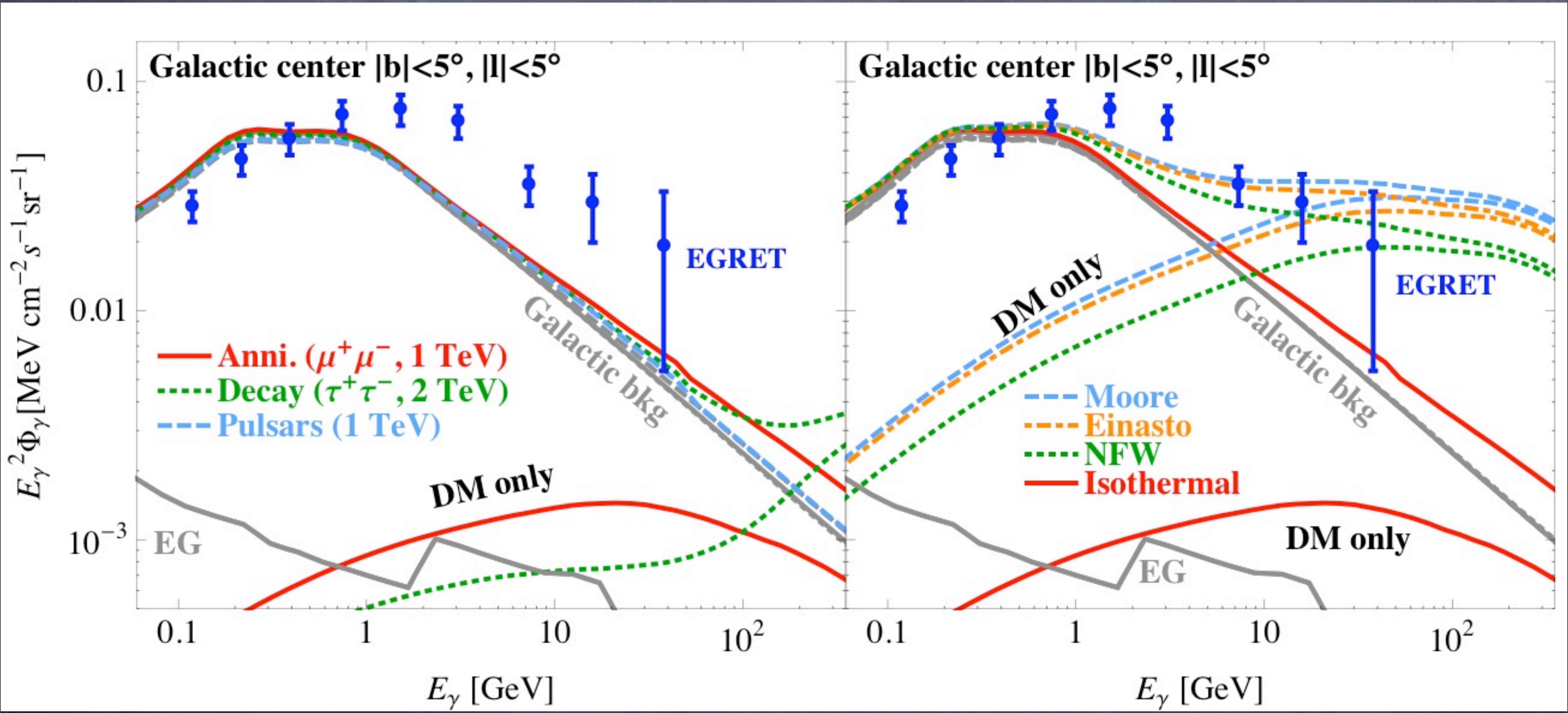
$M_{DM} = 1$ TeV into $\mu\mu$


Fermi prelim. 10°<|b|<20°
Moore
Einasto
NFW
Isothermal
Galactic bkg
EG
DM only
$E_\gamma{}^2\Phi_\gamma$ [MeV cm$^{-2}s^{-1}$sr^{-1}]
E_γ [GeV]
Synchrotron @ 23 GHz
Inner galactic
Outer galactic
$I_{|l|<10°}$ [10^{-20}erg cm$^{-2}s^{-1}$sr^{-1}Hz^{-1}]
Latitude [°]
PAMELA
Galactic bkg
$\Phi_{e^+}/(\Phi_{e^+}+\Phi_{e^-})$
E_e [GeV]
ATIC
Fermi
HESS
Galactic bkg
$E_e{}^3(\Phi_{e^+}+\Phi_{e^-})$ [GeV$^2m^{-2}$sr$^{-1}s^{-1}$]
E_e [GeV]

Gamma-ray predictions for Fermi

Isothermal profile

$M_{DM} = 1$ TeV into $\mu\mu$



Now cored profiles favored for DM annihilation

Summary

- Pulsars readily reproduce the data

- Simplest dark matter scenarios are strained

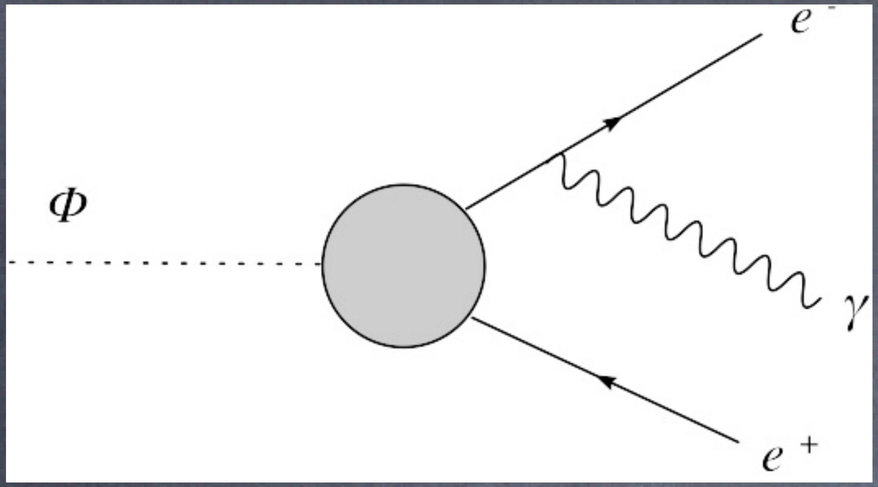
- Annihilation:
  - need a huge cross section (PAM positron data)
  - to $\mu\mu$ (PAM antiproton and Fermi gamma-ray data)
  - TeV and higher mass (HESS and Fermi electron data)
  - cored halo profiles preferred

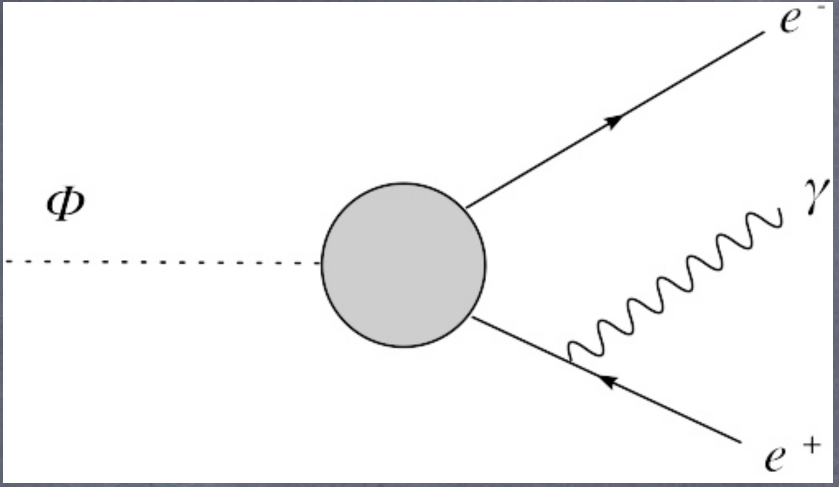
- Decay:
  - need very long lifetime
  - to $\mu\mu$
  - multi-TeV mass

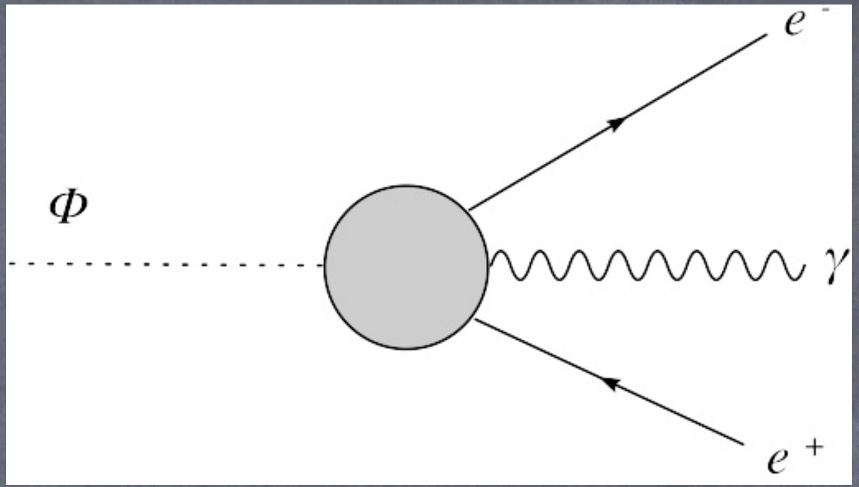
- To invoke dark matter explanations, need to go from demonstrating consistency to seeing unique signals

PS:

Generic dark matter signatures?

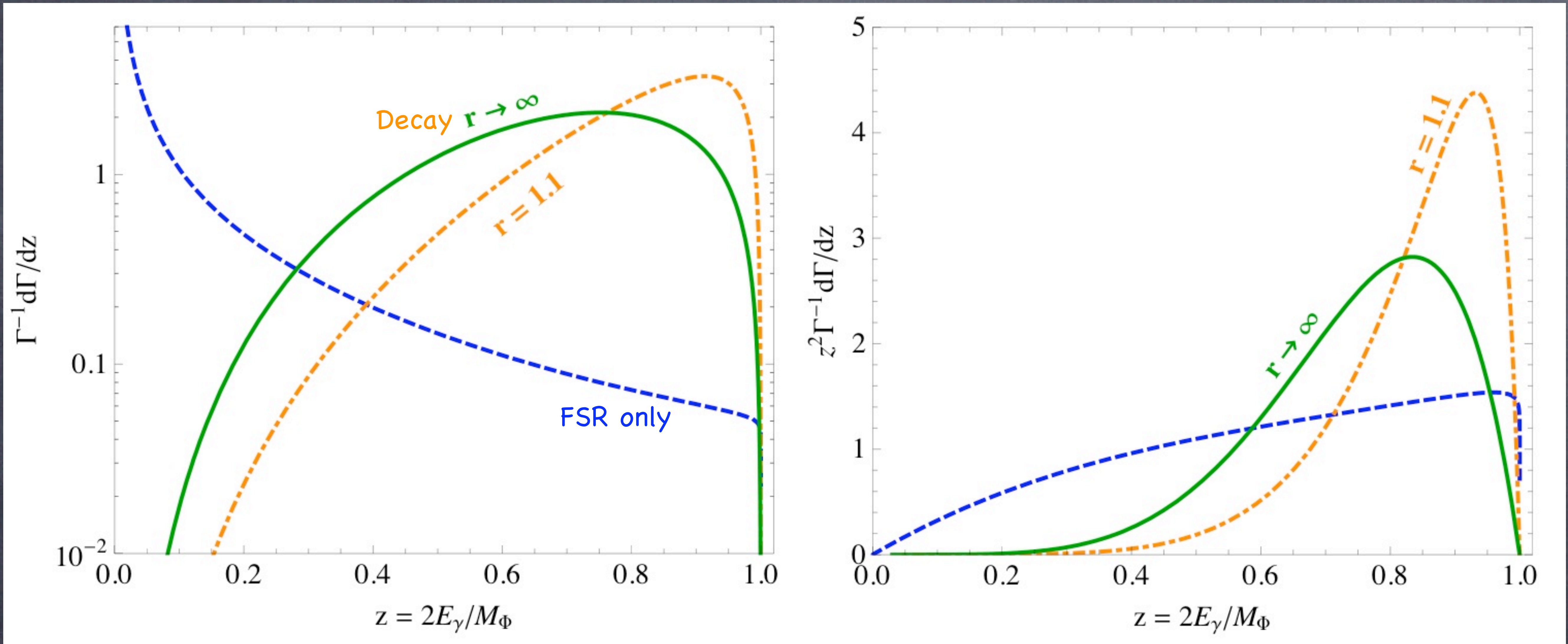






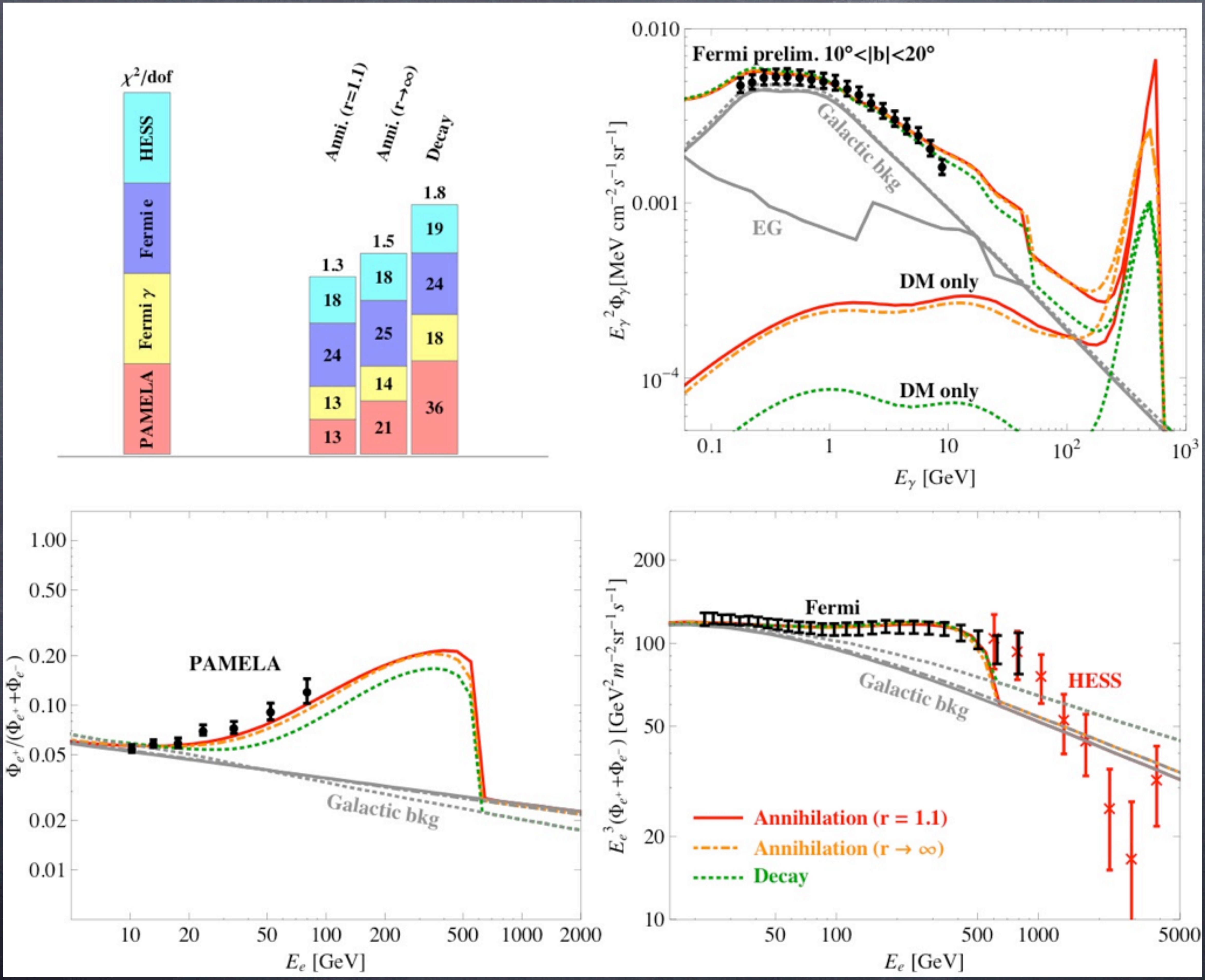
- Φ has zero total angular momentum
- helicity suppression prevents annihilation/decay to light fermion pairs
- suppression disappears if final state contains an additional photon
- Φ may be
  - annihilating Majorana fermions
  - annihilating self-conjugate scalars
  - a decaying scalar

Photon distributions

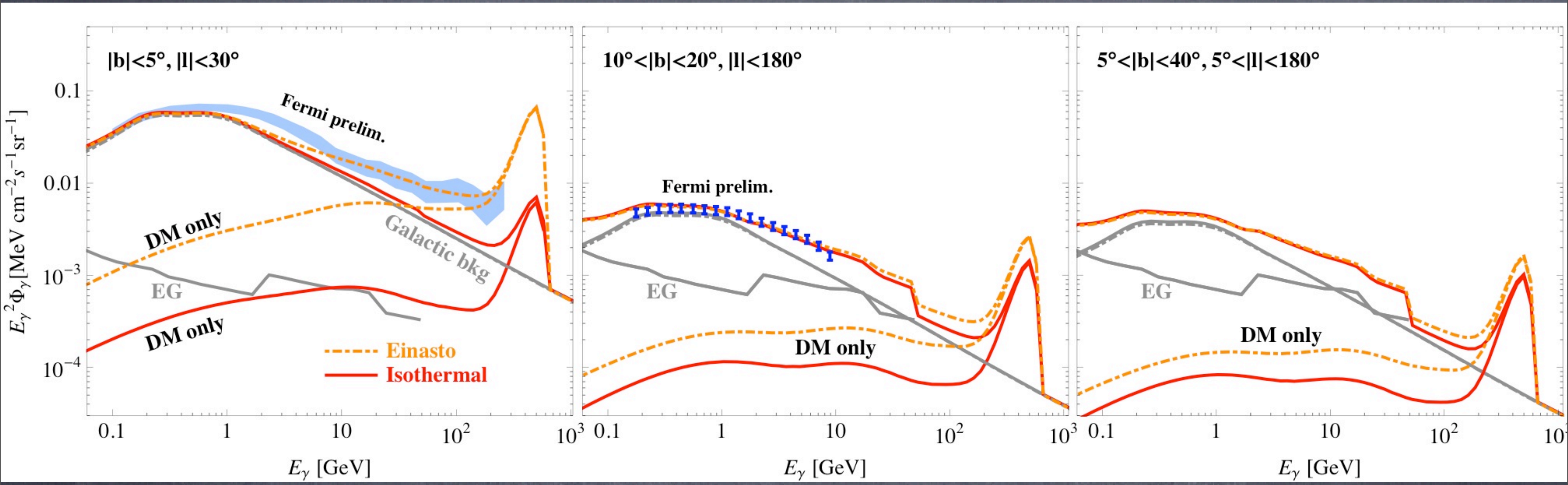


$$r = 4m_E^2/M_\Phi^2$$

$M_\Phi = 1.2$ TeV (Einasto profile)



Gamma-ray predictions for Fermi and ACTs



For electroweak bremsstrahlung, see talk by Bell