

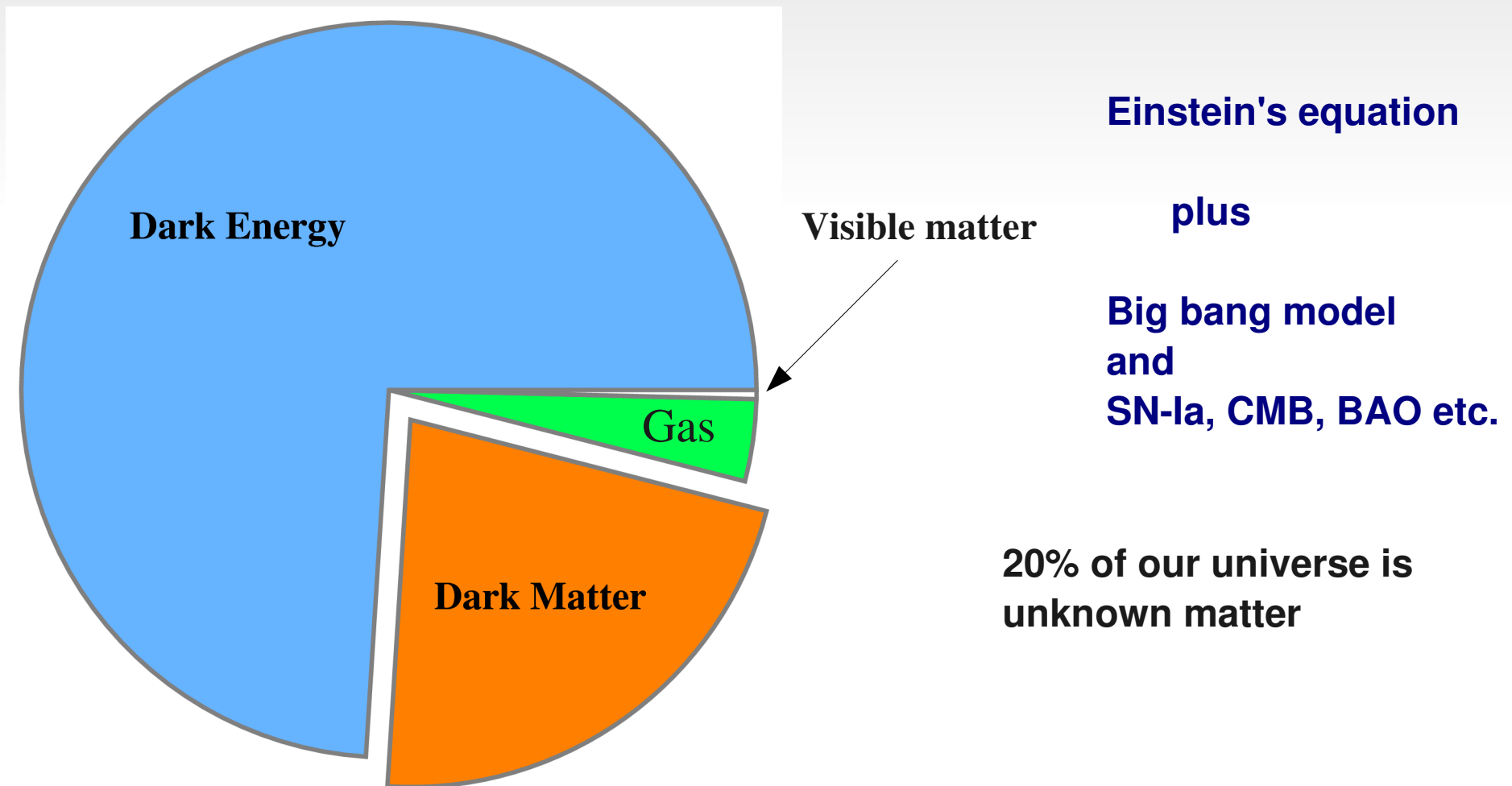
Indications of Dark Matter from Astrophysical observations

**--- Fermi LAT, PAMELA, HESS
& ATIC, WMAP Haze**

Yu Gao
UW-Madison

0904.2001, V. Barger, Y. Gao, W.-Y. Keung, D. Marfatia, G. Shaughnessy

Cosmic energy budget



DM that annihilate or decay

as source of γ , $e^\pm$, $\bar{p}/p$...

Sommerfeld enhancement,
s-channel resonance.

Dark matter source terms

$$\frac{d\phi_i}{dE_i} = \begin{cases} \frac{\text{BF}}{2} \frac{\rho^2}{M_{DM}^2} \langle v\sigma \rangle \frac{dN_i}{dE_i} & \text{DM annihilation} \\ \frac{1}{T} \frac{\rho}{M_{DM}} \frac{dN_i}{dE_i} & \text{DM decay} \end{cases}$$

$\frac{dN_i}{dE_i}$: injection spectrum of particle species i

Upper bound for hypothetical particle density:

$$\langle v\sigma \rangle_{\text{annihilation}} \sim 3 \times 10^{-26} \text{ cm}^3/\text{s}$$

Relic density $\Omega_{\text{dm}} \approx 0.20$

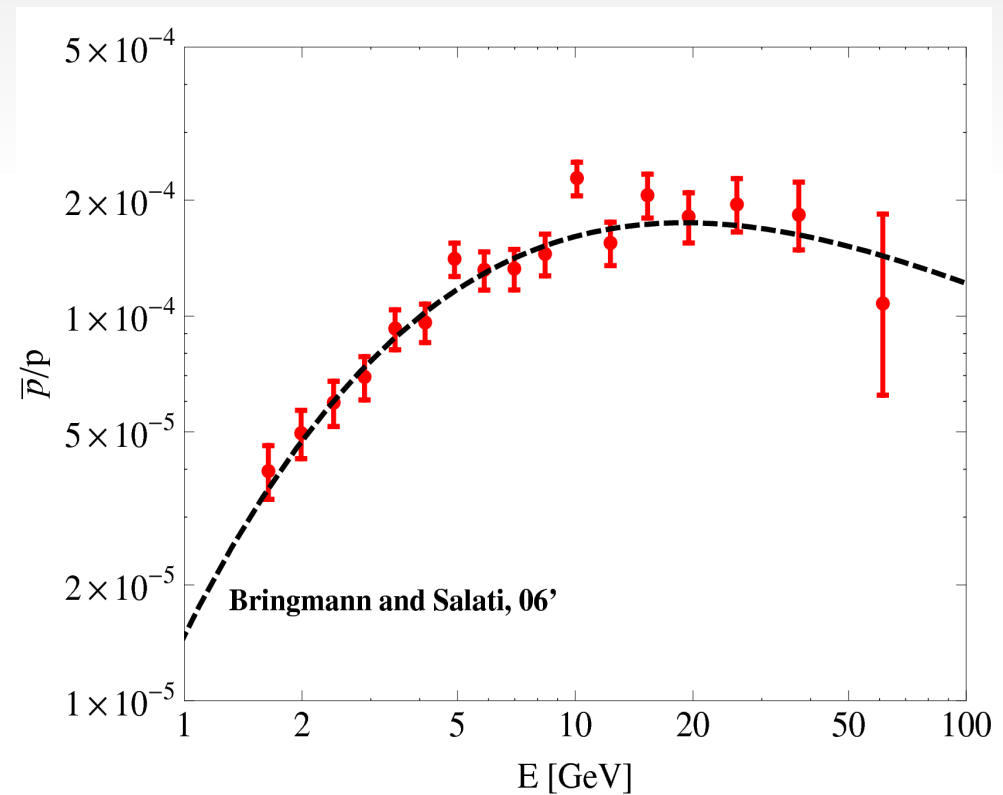
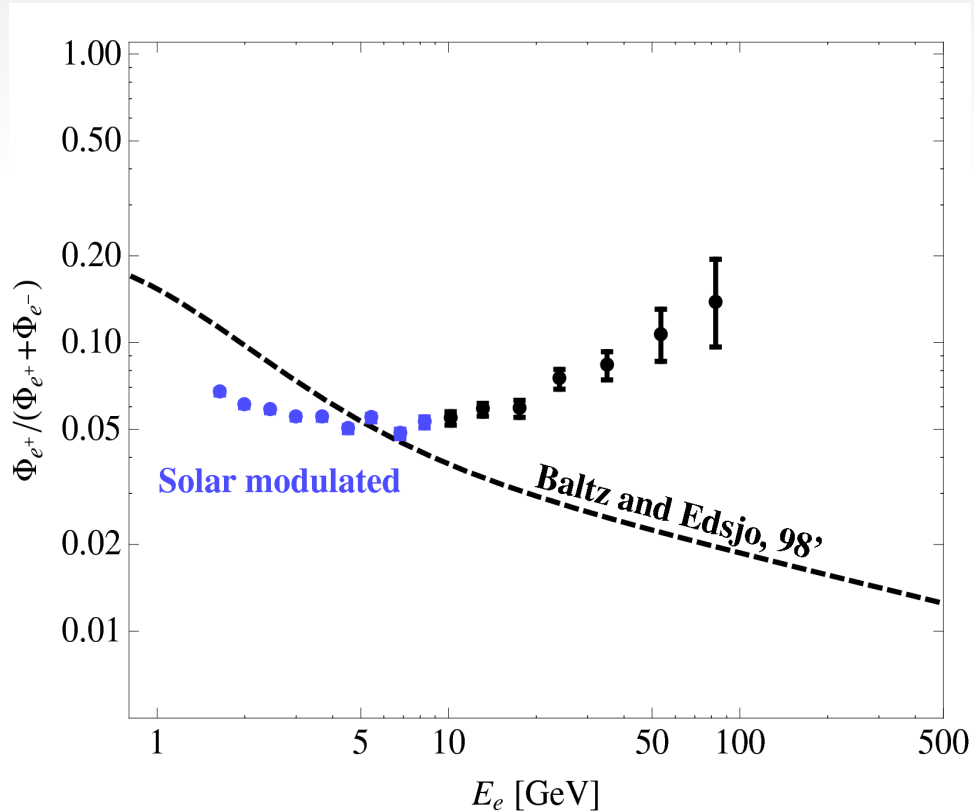
$$T_{\text{decay}} \sim 10^{26} \text{ s}$$

PAMELA observes e^+ excess

At $10 \sim 10^2$ GeV excessive positron fraction found
by the Payload for Antimatter Matter Exploration
and Light-nuclei Astrophysics

but not in $\bar{p}/p$

Adriani et al., (2008)



Excess in $e^+ + e^-$ spectrum

Advanced Thin Ionization Calorimeter

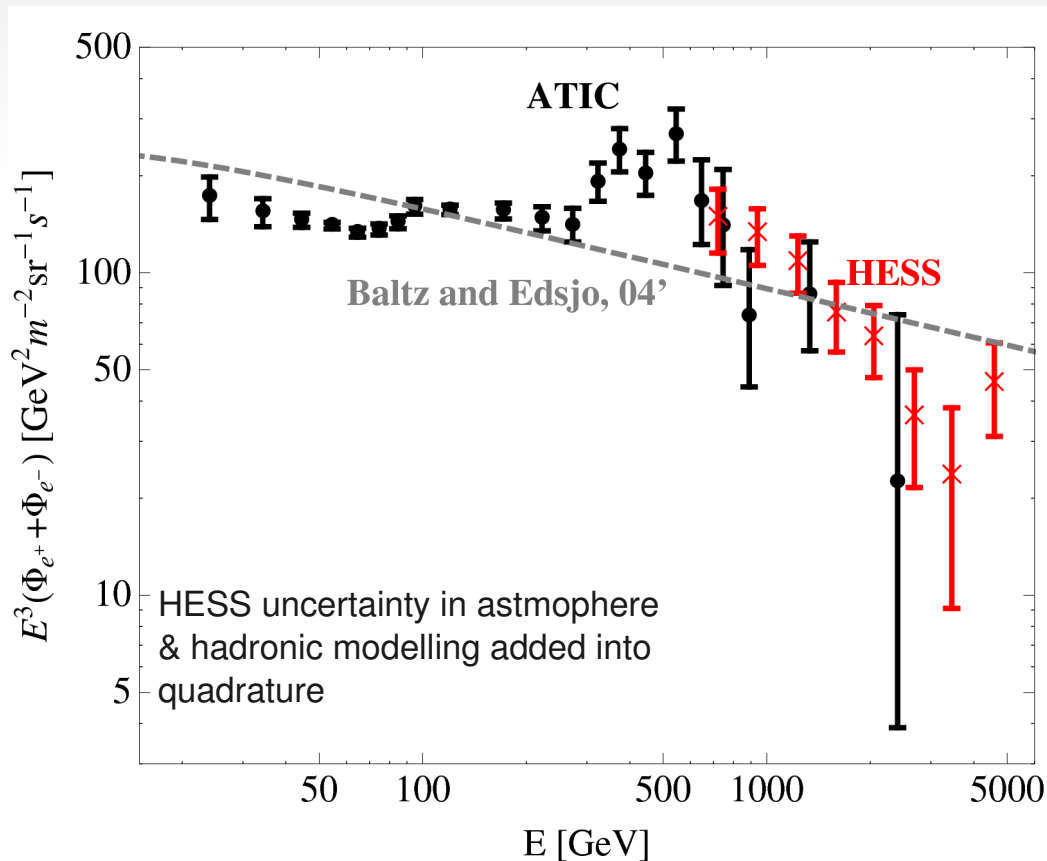
J. Chang et al, (2008)

High Energy Stereoscopic System

F. Aharonian et al, (2008)

Other experiments that observe electron excesses:

HEAT, AMS-1, PPB-BETS



ATIC 'bump' at ~600 GeV & HESS 'falling' at TeV scale:

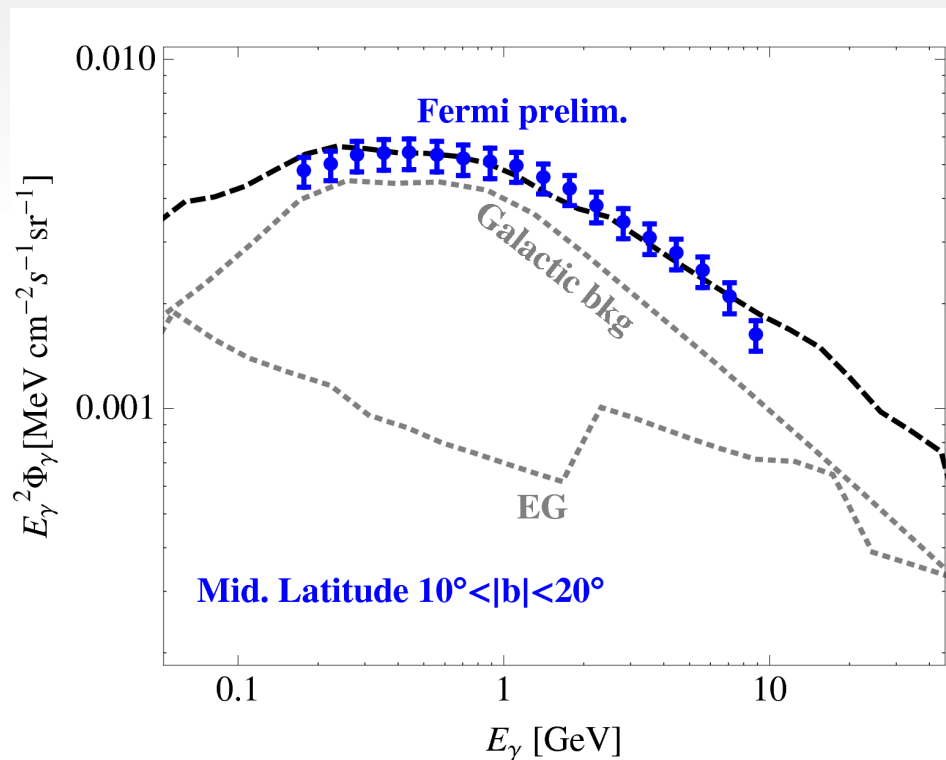
$E_{\text{threshold}} = 0.6 \sim 0.7$ for unknown sources?

ATIC observes excess in light nuclei including C, N, O and Si: Panov et al., (2006)
-- unexplained

Preliminary Fermi gamma rays

Fermi doesn't confirm the EGRET
excess in 0.1~10 GeV
diffuse gamma rays

G. Johannesson, talk at XLIVth Rencontres de Moriond
and L. Reyes, talk at SnowPAC 2009



Future Fermi data up to 300 GeV

Focus on more 'dense' areas may
increase DM signal, e.g., the GC

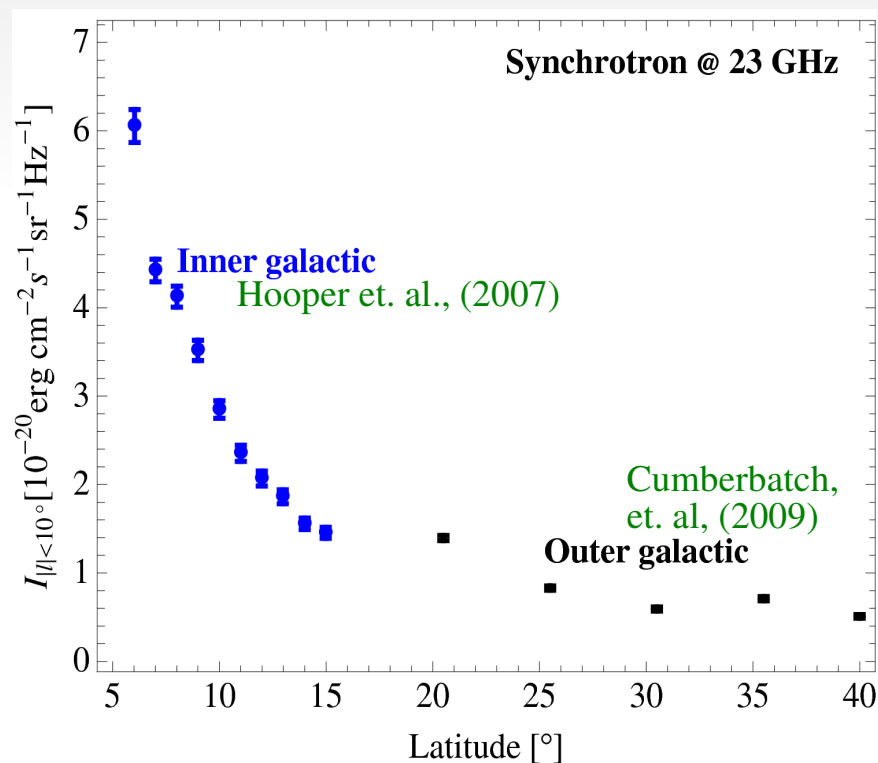
Known galactic and **extragalactic** sources fit data well...

EGRET EG spectrum analyzed by Strong, et.al. (2004)

Synchrotron excess: WMAP Haze

Residue microwave radiation in WMAP
 $f = 23\sim 94$ GeV

Finkbeiner (2004)



WMAP haze as synchrotron radiation
of high energy electrons

Large systematics?

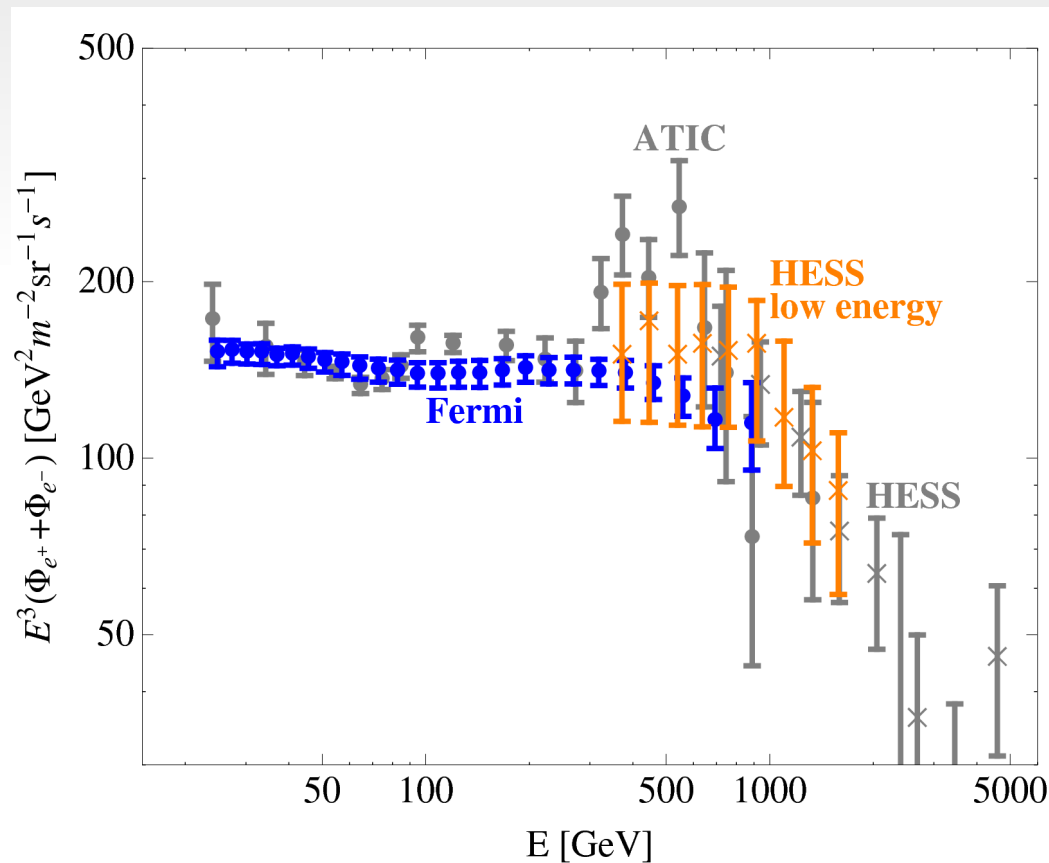
Cumberbatch,
et. al, (2009)

Flux averaged over $|l| < 10^\circ$, statistical errors only

NEW DATA: Fermi & low energy HESS electron data

Fermi/LAT Collaboration, (2009)

H.E.S.S. Collaboration, (2009)



Fermi doesn't confirm the
bump in the electron flux

Energy calibration uncertainty
Fermi : +5%, -10%
HESS: $\pm 15\%$

DM modeling

Two body annihilation or decay

$$\text{Annihilation } \langle v\sigma \rangle = 3 \times 10^{-26} \text{ cm}^3/\text{s}$$

Decay rate determined by $1/T$, $T \sim 10^{26}$ s

Leptonic final states: $e^\pm, \mu^\pm, \tau^\pm$ with equal branchings

$$600 \text{ GeV} \sim 1 \text{ TeV upper energy cut-off } E_s \equiv \begin{cases} M_{DM} & \text{Annihilating DM} \\ \frac{1}{2} M_{DM} & \text{Decaying DM} \\ E_p & \text{Pulsars} \end{cases}$$

Pulsar modeling

A continuum distribution throughout galaxy from fits to electron data

Zhang and Cheng, (2001)

$e^\pm$ injection spectra of an average pulsar
Direct gammas are negligible

$$\rho(r) = N \cdot \left(\frac{r}{r_\odot} \right)^{1.0} e^{-\frac{1.8 (r-r_\odot)}{r_\odot}} e^{-\frac{z}{0.2 \text{ kpc}}}$$

cylindrical (r, z)

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

Density distribution: dark matter profiles

- DM density in the halo can be:

with a 'cusp':

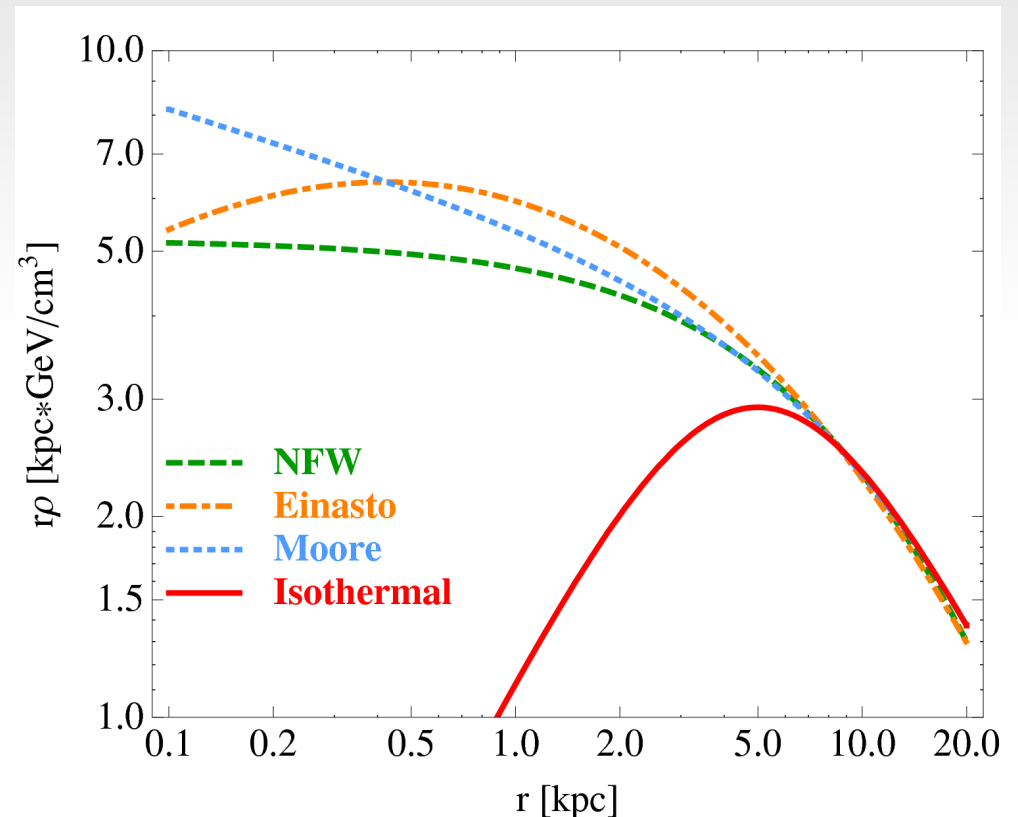
Moore Diemand, et. al. (2005)

NFW Navarro, et. al. (1995)

Einasto Einasto, et. al. (1965)

or non-singular:

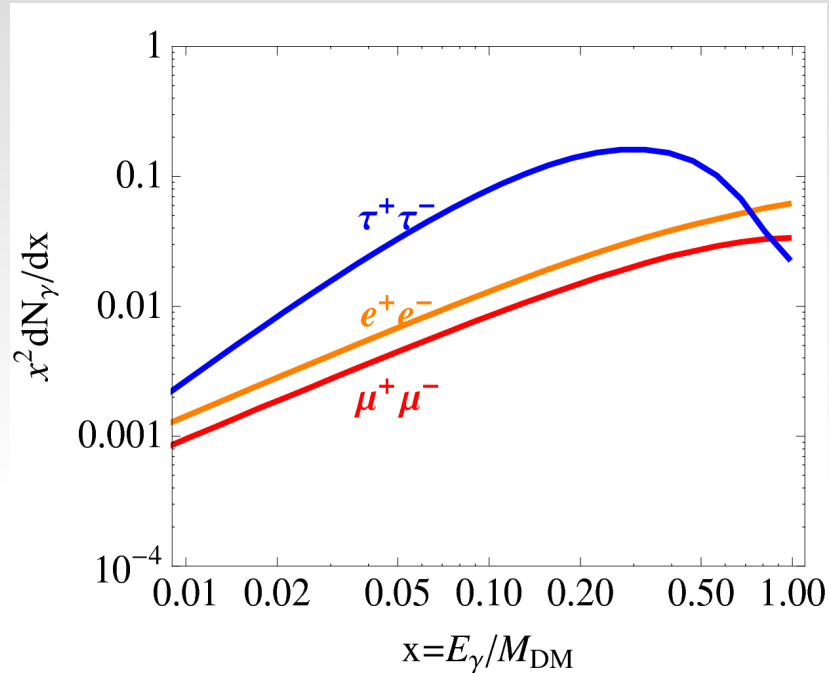
Isothermal Bahcall and Soneira (1980)



Local DM density = 0.3 GeV/cm³

Analysis tools

For $M_{\text{DM}}=1$ TeV



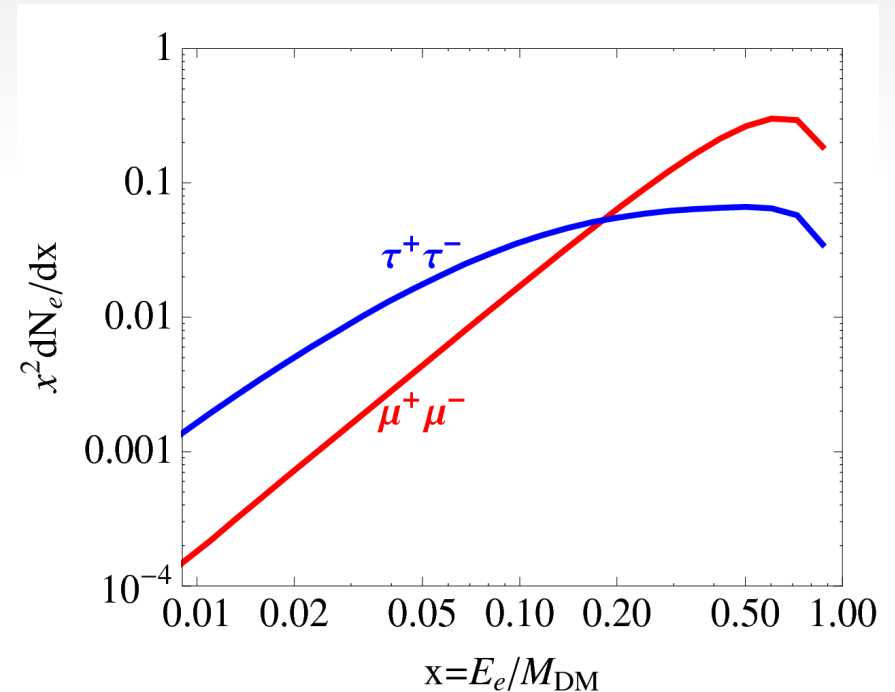
Photon spectrum from **DMFIT**
Jeltema and Profumo, (2008)

Includes final state radiation
and showering (mainly π^0) contributions

Particle propagation, galactic bkg,
IC, brems., synchrotron radiations with **GALPROP**

Belanger, et.al. (2008)

DM $e^\pm$ spectra by **MicrOMEGAs**
for $\mu^\pm$, $\tau^\pm$ final states;
line spectra for the $e^\pm$ final state.



Strong and Moskalenko, (2001)

The GALPROP modeling

Strong, et. al. (2004)

$$\frac{d\Phi}{dt} - D(E) \cdot \nabla^2 \Phi - \partial_E (D_p(E) \cdot \Phi) = Q$$

diffusion term

energy loss

source term: $Q = \frac{1}{4\pi} \frac{d\phi}{dE}$

The "conventional" 500800 model:

Primary e^- injection spectrum:

$$\phi_{e^- \text{ pri.}}(E) \propto E^{-2.54}, (4 \text{ GeV} < E < 10^3 \text{ TeV})$$

$\uparrow$
 α_{SN}

Nuclei injection spectrum:

$$\phi_{\text{nuc.}}(R) \propto R^{-2.42}, (R > 9 \text{ GV})$$

Galactic magnetic field:

$$B = B_{\odot} e^{-\frac{r-r_{\odot}}{10 \text{ kpc}}} e^{-\frac{|z|}{2 \text{ kpc}}}, B_{\odot} = 5 \mu\text{G}$$

Cylindrical diffusion zone:

$$L_{\text{max}} = 20 \text{ kpc}, z_{\text{max}} = 4 \text{ kpc}$$

Diffusion coefficient parametrization:

$$D(E) = D_0 \beta \left(\frac{R(E)}{R_0} \right)^{\delta} \text{ cm}^2 \text{ s}^{-1}$$

$\beta = v/c$

We varied the following parameters using a grid:

D_0 , E_0 , $\delta(>1/3)$, α_{SN} , $e^-_{\text{pri.}}$ norm,
 or plus BF or T_{decay} for DM annihilation
 or decay at discrete DM masses / pulsar
 cut-off energies.

Likelihood analysis

Data sets contribute independently:

$$\chi^2 = \sum_{\text{experiments}} \sum_i \frac{(f^{th}(E) - f_i^{ex}(E_i))^2}{(\Delta f_i^{ex})^2}$$

For each experiment the total (signal + galactic bkg) fitting function:

$$f = \begin{cases} \frac{\Phi_{e+}}{\Phi_{e+} + \Phi_{e-}}, & \text{for PAMELA} \\ E^3(\Phi_{e+} + \Phi_{e-}), & \text{for HESS or Fermi } e \\ E^2\Phi_{\gamma}, & \text{for Fermi } \gamma \end{cases}$$

Introduce energy calibration parameters ϵ_{HESS} , ϵ_{Fermi} for HESS and Fermi electron data:

$$(E, E^3 \frac{d\Phi}{dE}) \xrightarrow{\epsilon} (\epsilon E, \epsilon^2 (E^3 \frac{d\Phi}{dE}))$$

$$\chi'^2(\epsilon) = \sum_i \frac{(f^{th}(\epsilon E_i) - \epsilon^2 f_i)^2}{(\epsilon^2 \Delta f_i)^2} + \frac{(1 - \epsilon)^2}{(\Delta \epsilon)^2}$$

The number count
 $E \, dN/dE$ is kept invariant.

A diffusion parameter prior:

$$D(1\text{GV}) = 3 \sim 5 \times 10^{28} \text{cm}^2/\text{s}$$

to agree with cosmic ray data.

A. W. Strong, et al. (2007)

χ^2 fits to data: DM annihilation

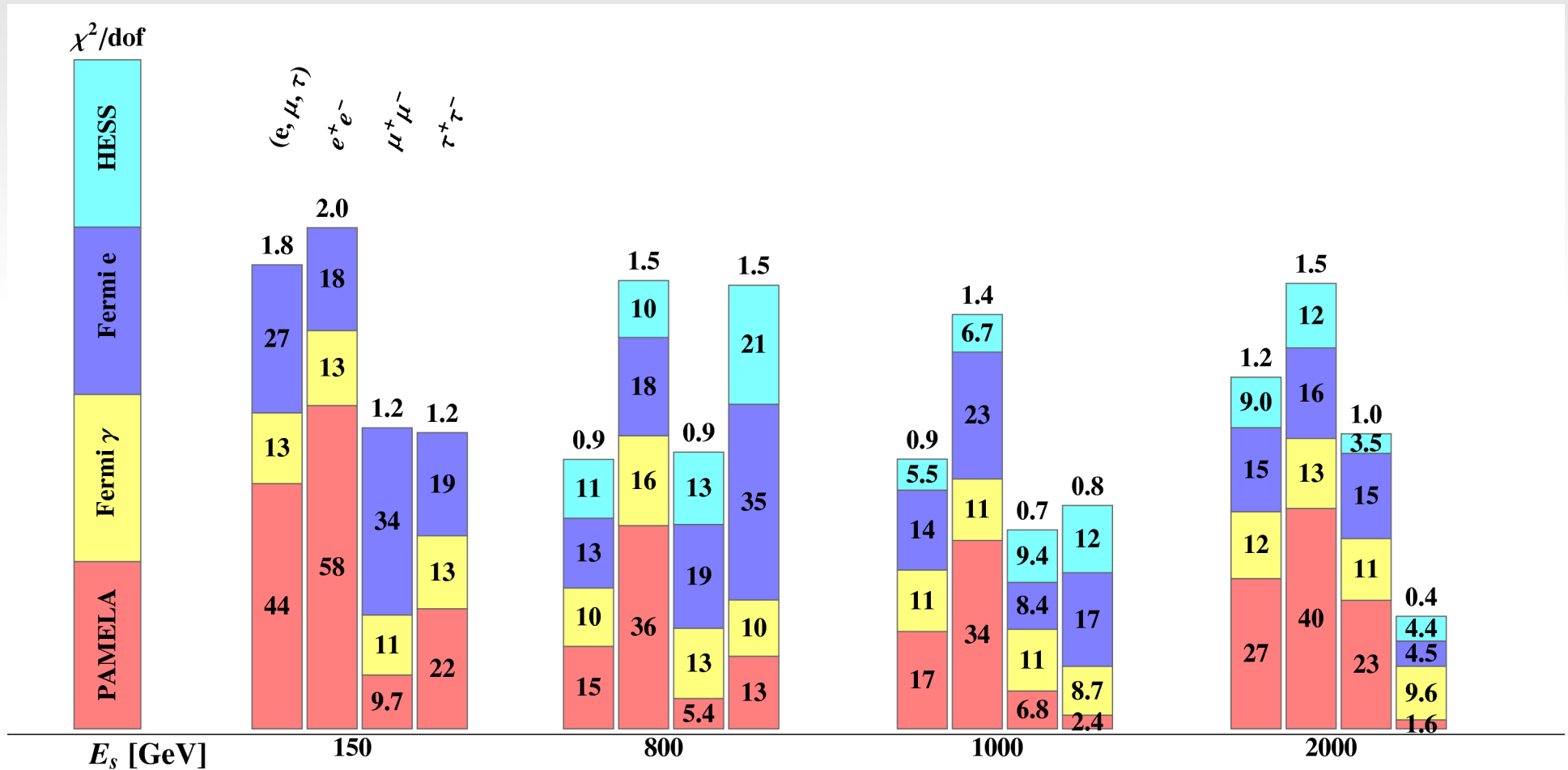
Soft positron spectrum
is preferred

DM profile: Isothermal

Number of parameters: 8

Number of data in each set:

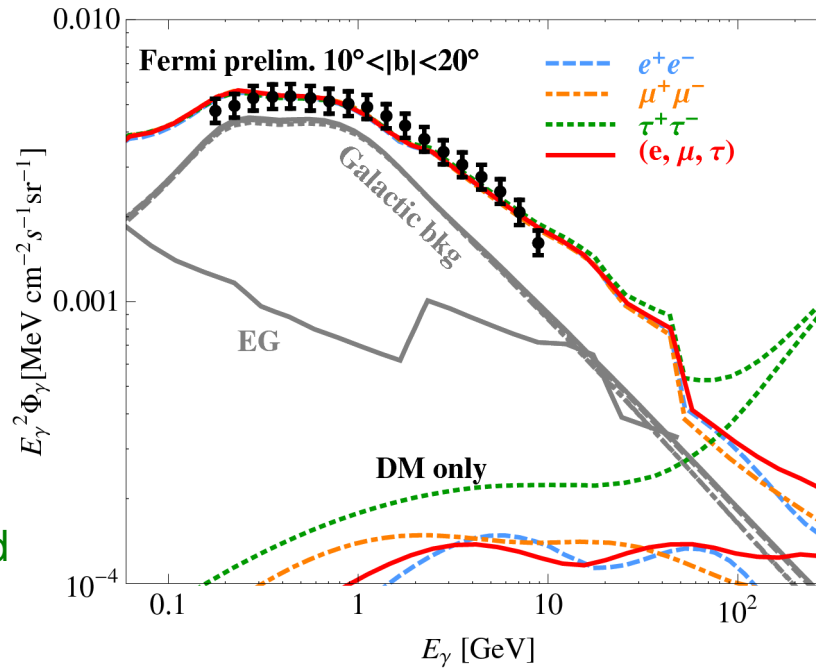
Fermi γ	18
PAMELA	7
Fermi e	26+1
HESS	8+1



Best-fit spectra: DM annihilation

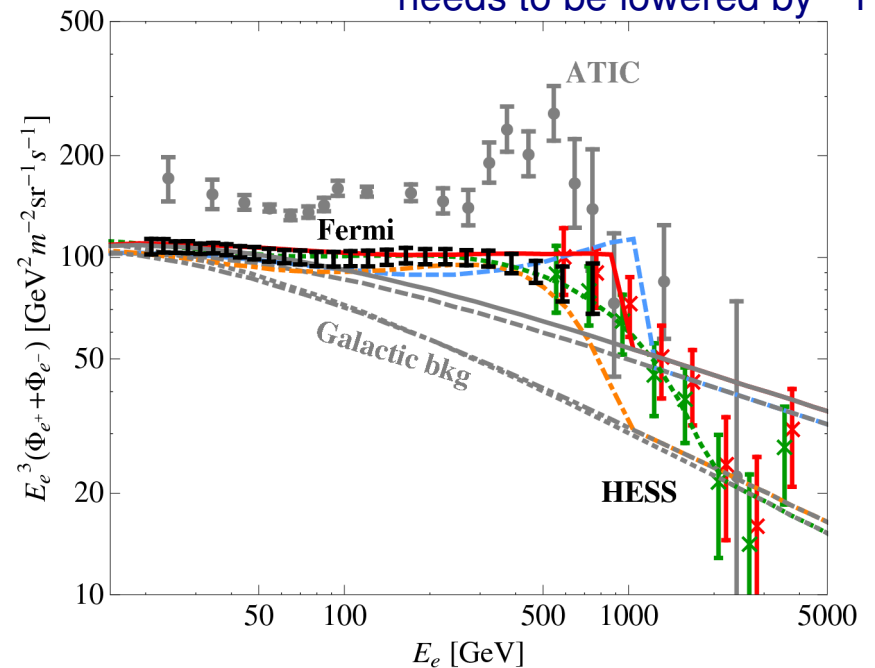
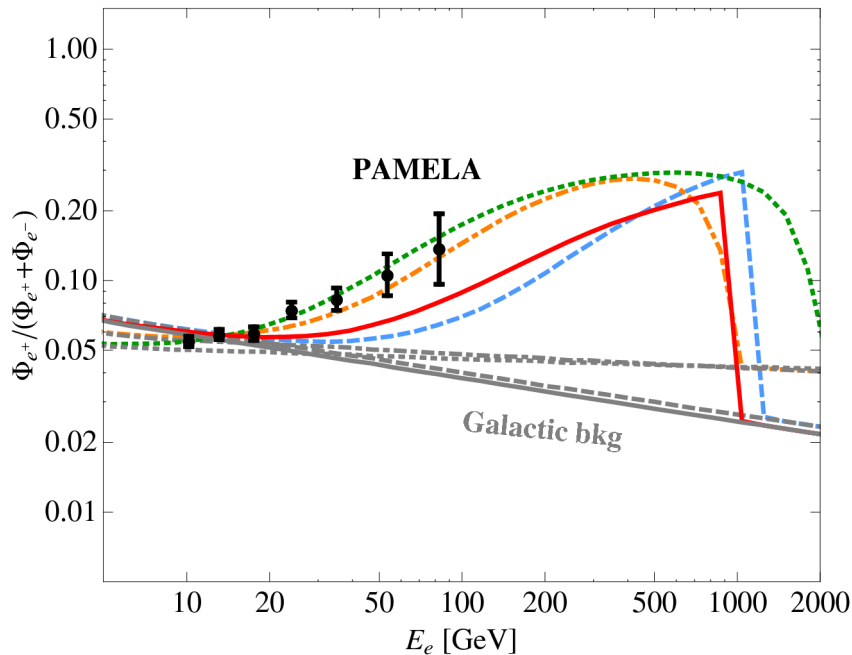
$e^\pm$ 1 TeV
 $\mu^\pm$ 1 TeV
 $\tau^\pm$ 2 TeV
 (e, μ, τ) 0.8 TeV

Hard electron spectra are constrained by new Fermi data and under-shoot positron fraction observation



π^0 decay photons

Fermi energy calibration needs to be lowered by $\sim 17\%$

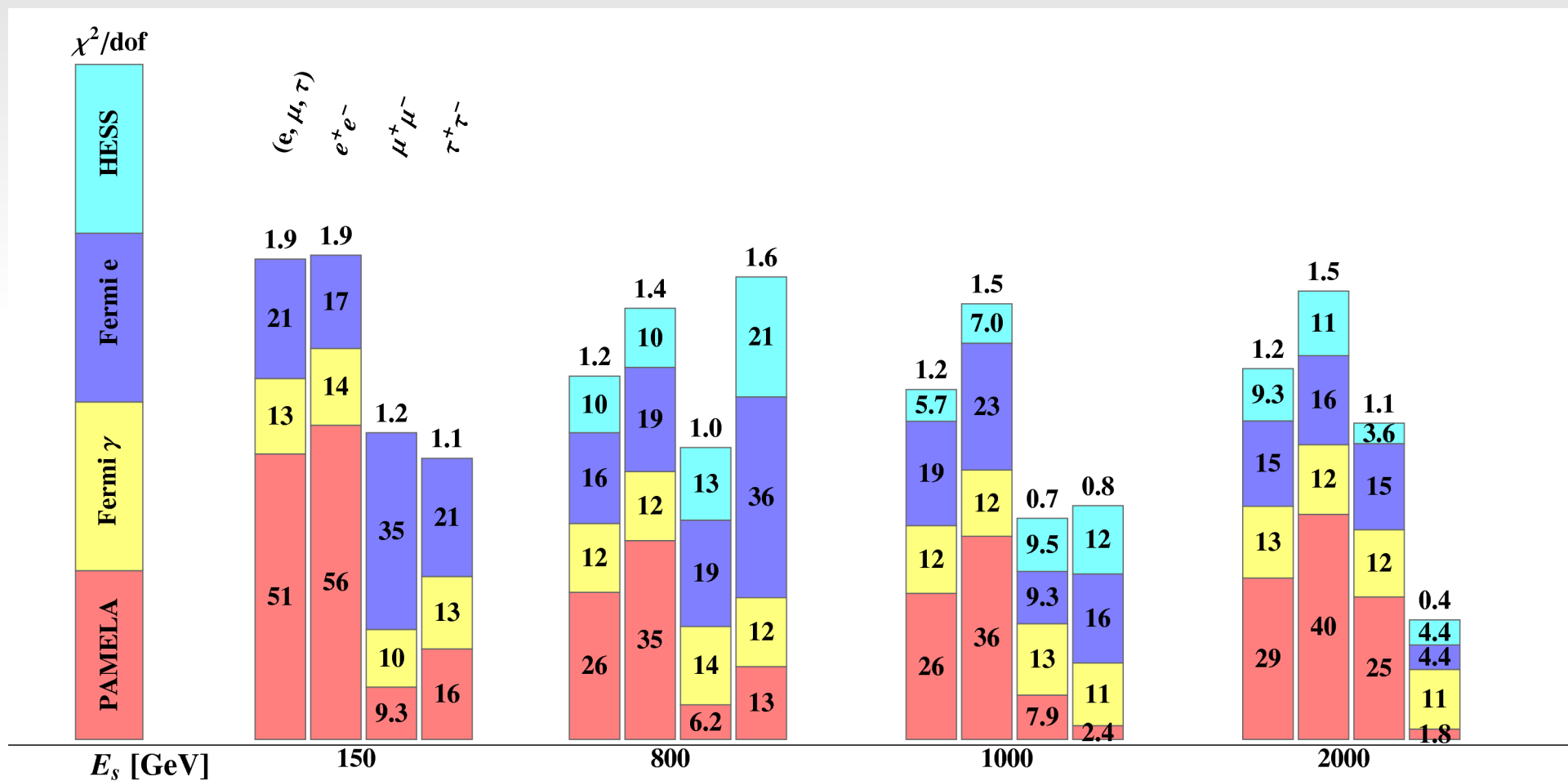


χ^2 fits to data: DM decay

Similar to the annihilation scenario

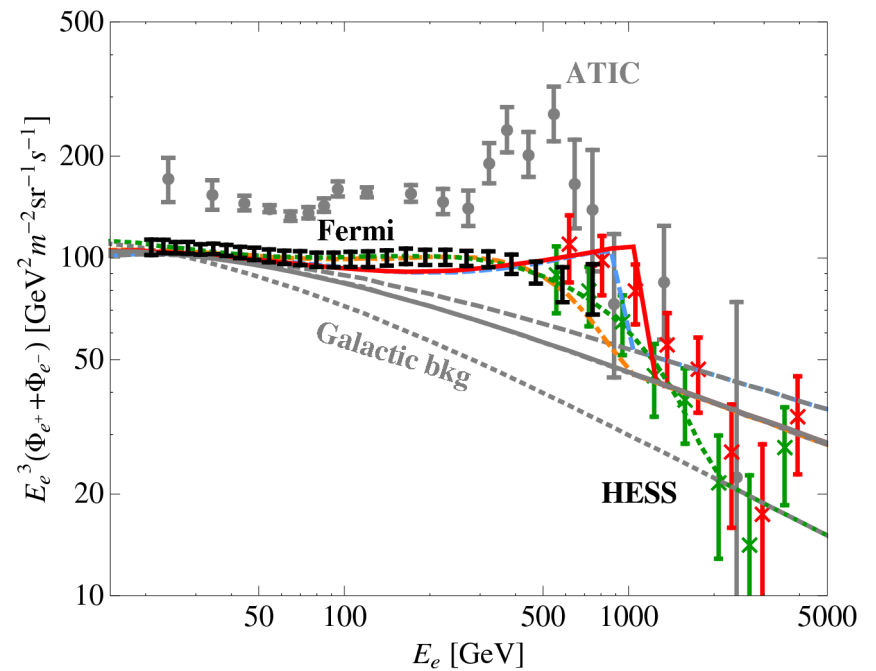
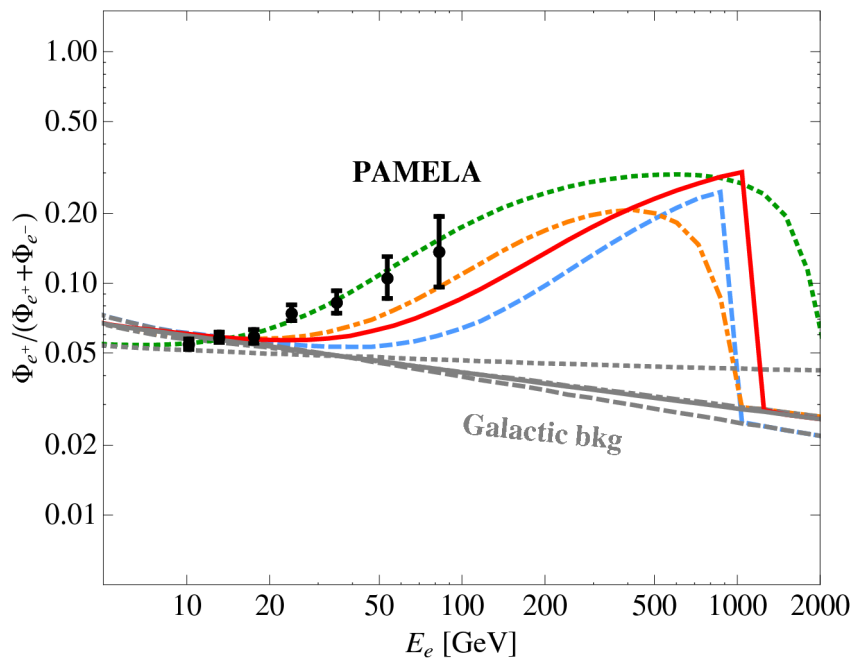
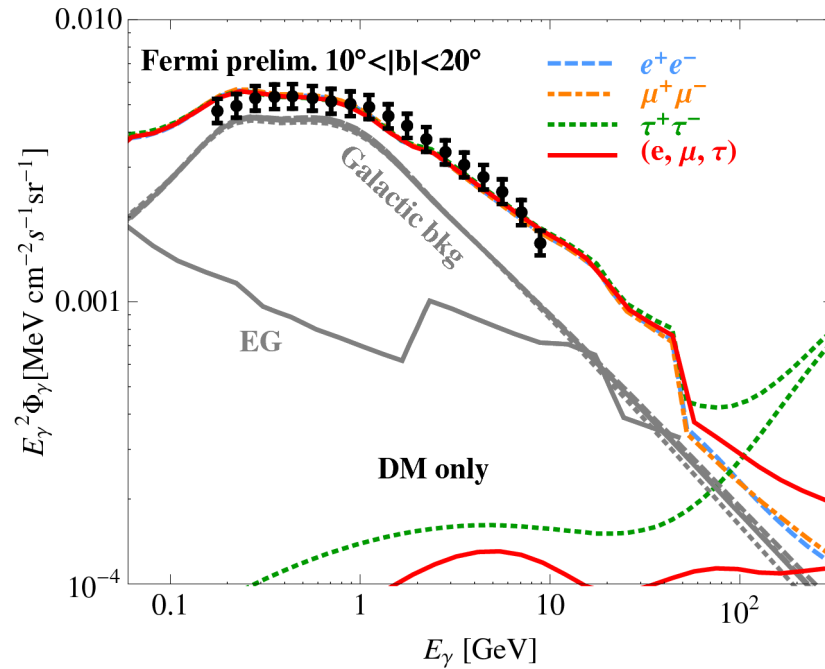
DM profile: Isothermal

Number of parameters: 8



Best-fit spectra: DM decay

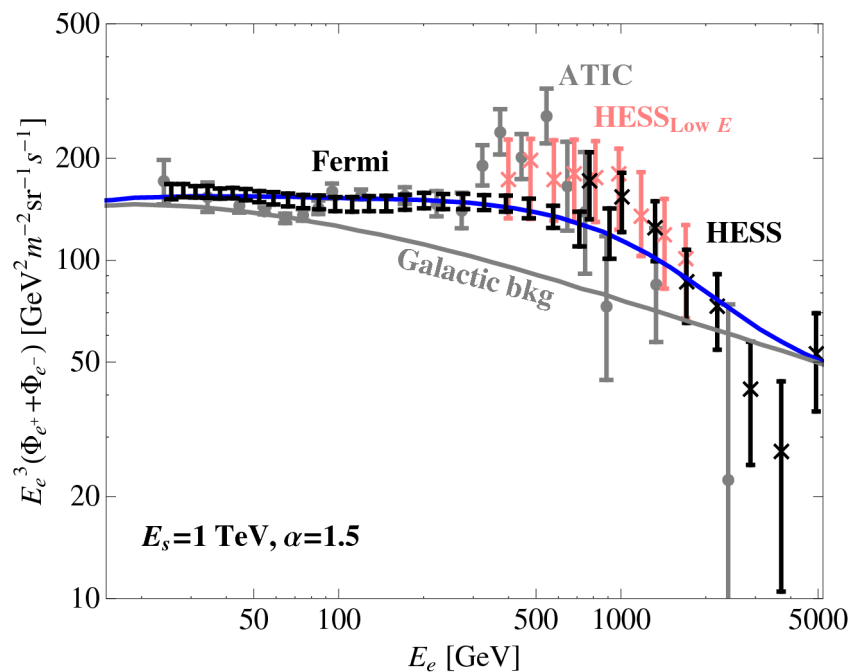
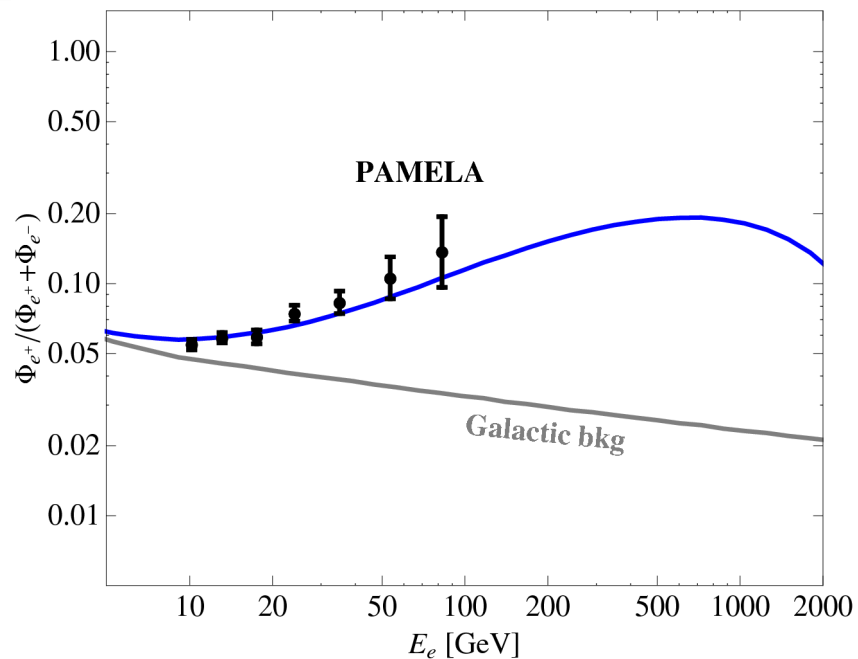
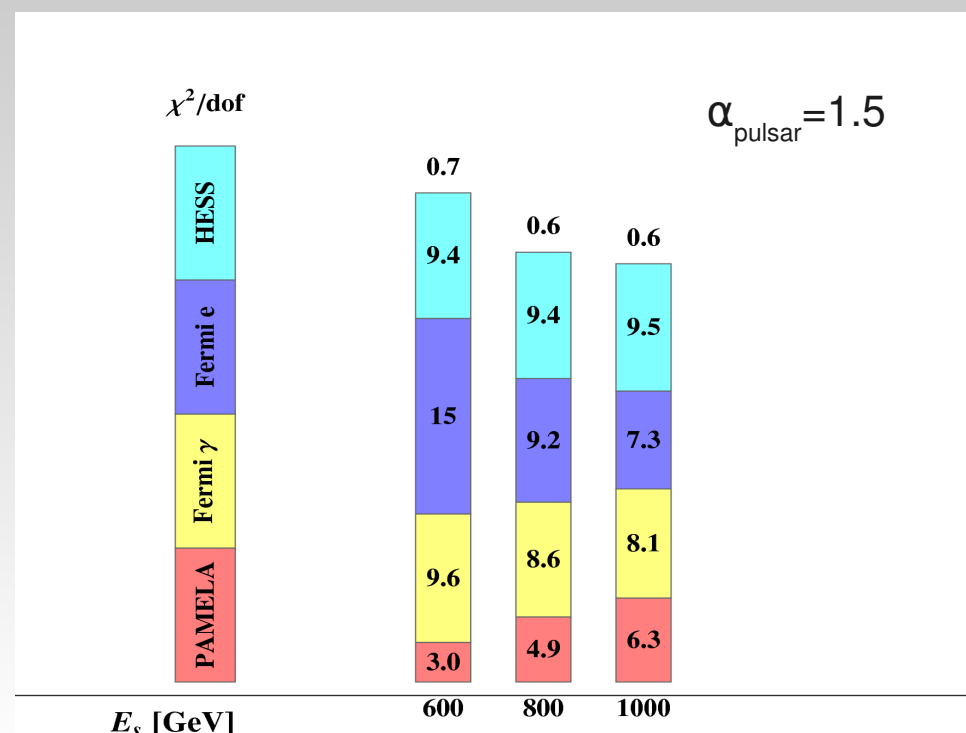
$e^\pm$ 0.8 TeV
 $\mu^\pm$ 1 TeV
 $\tau^\pm$ 2 TeV
 (e, μ, τ) 1 TeV



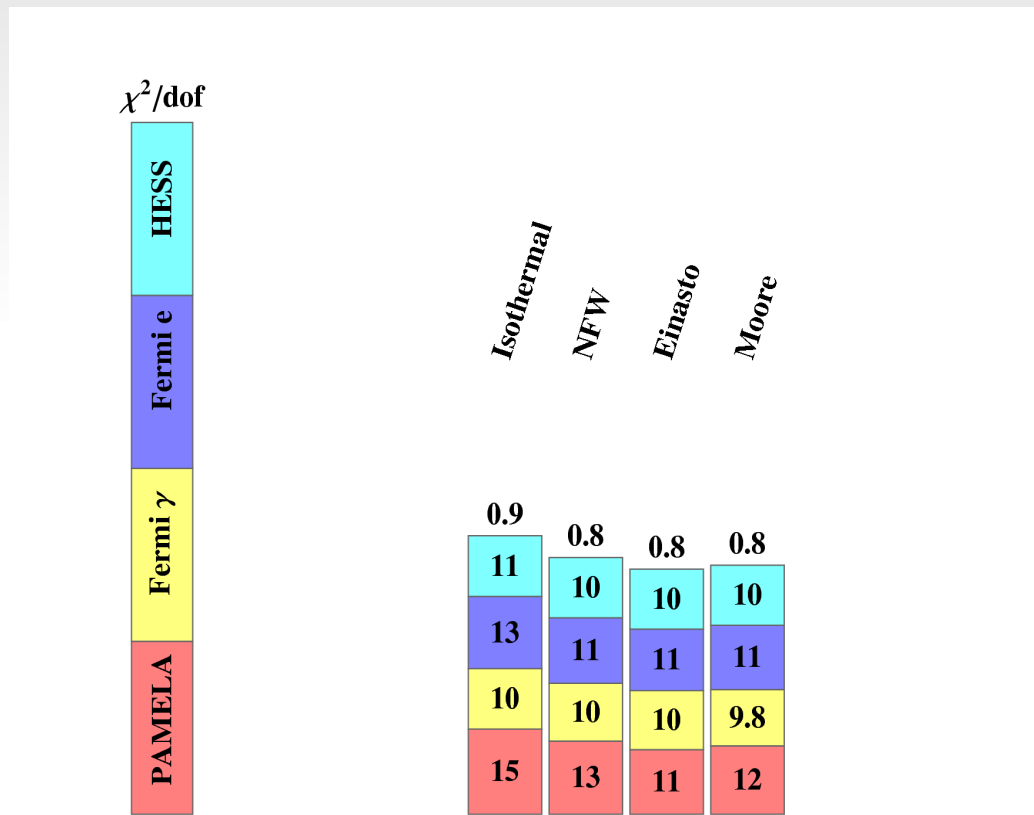
Pulsars

Fit data well without
drifting Fermi and HESS
energy calibration

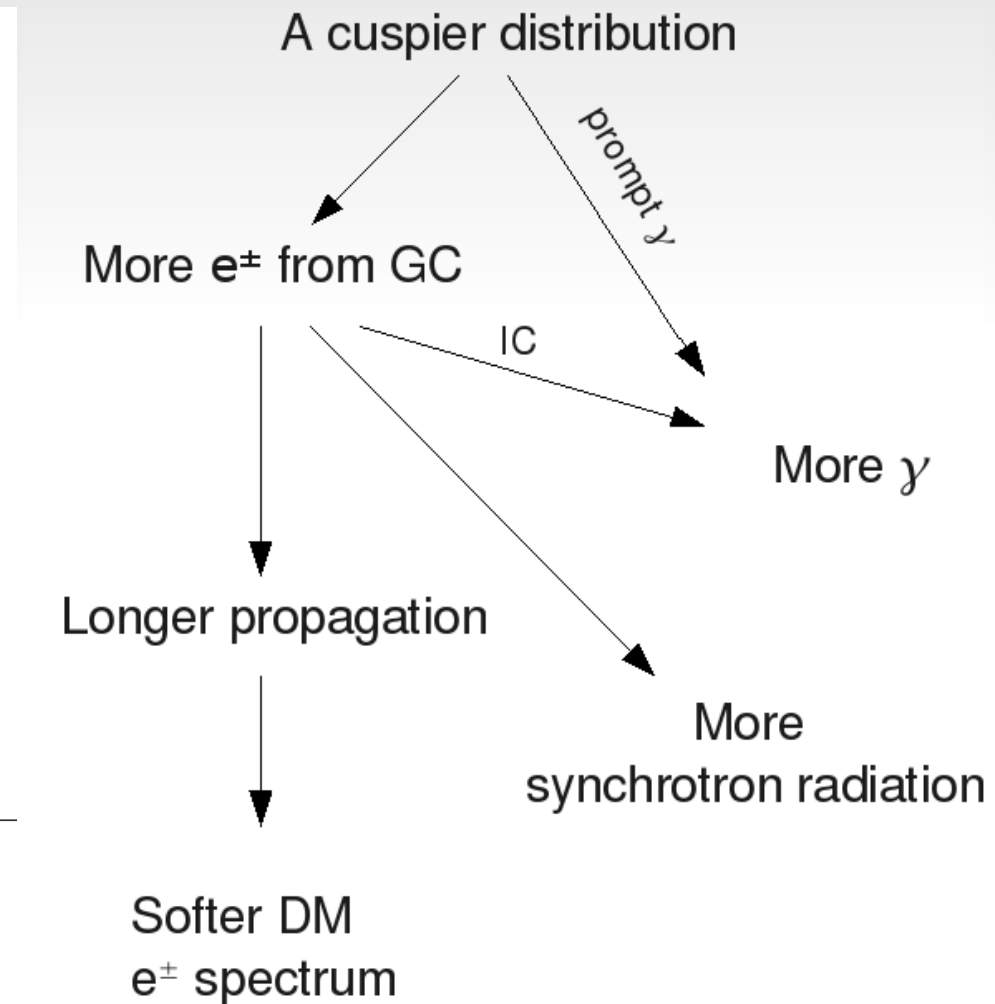
no significant photon
contribution from pulsars



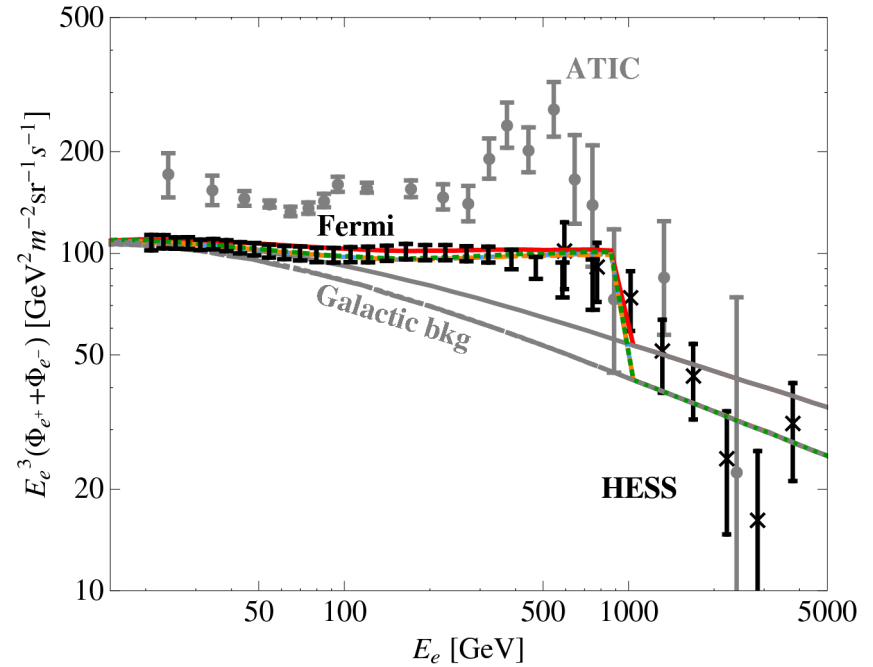
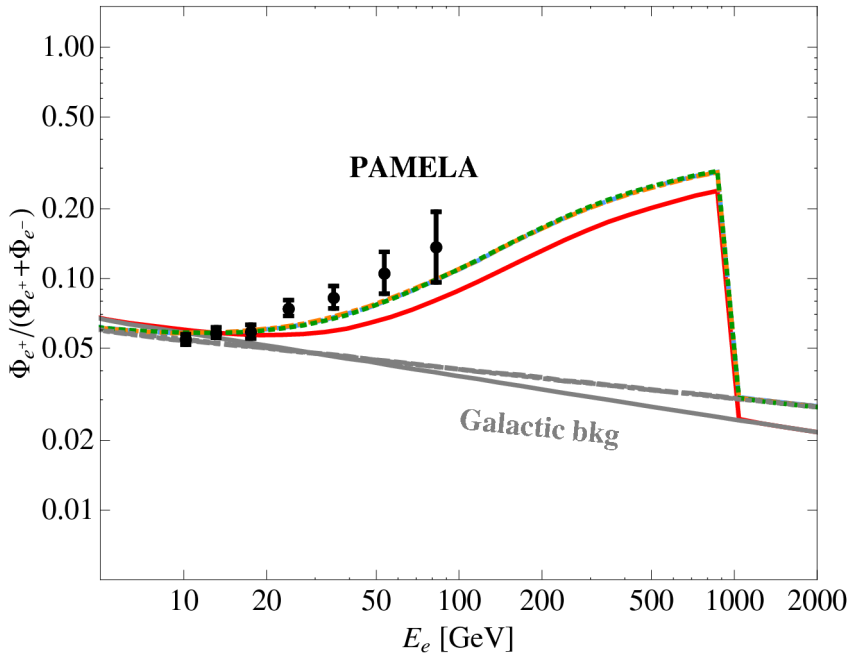
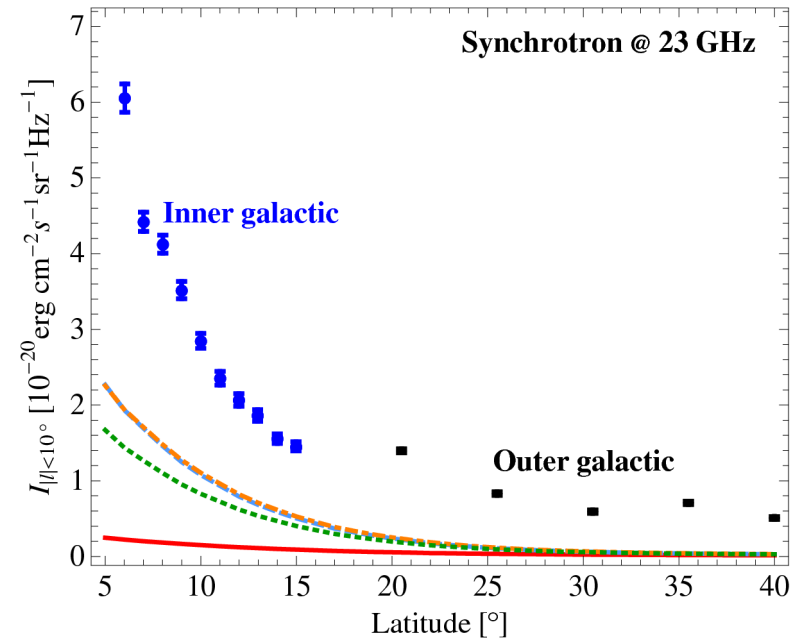
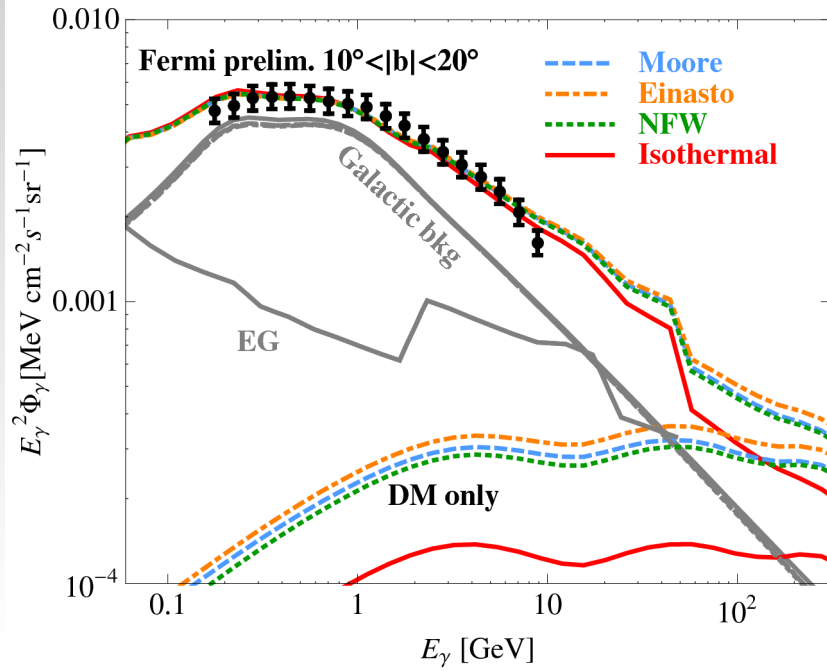
Dependence on halo profiles



Annihilation
 $M_{\text{DM}} = 0.8 \text{ TeV}$

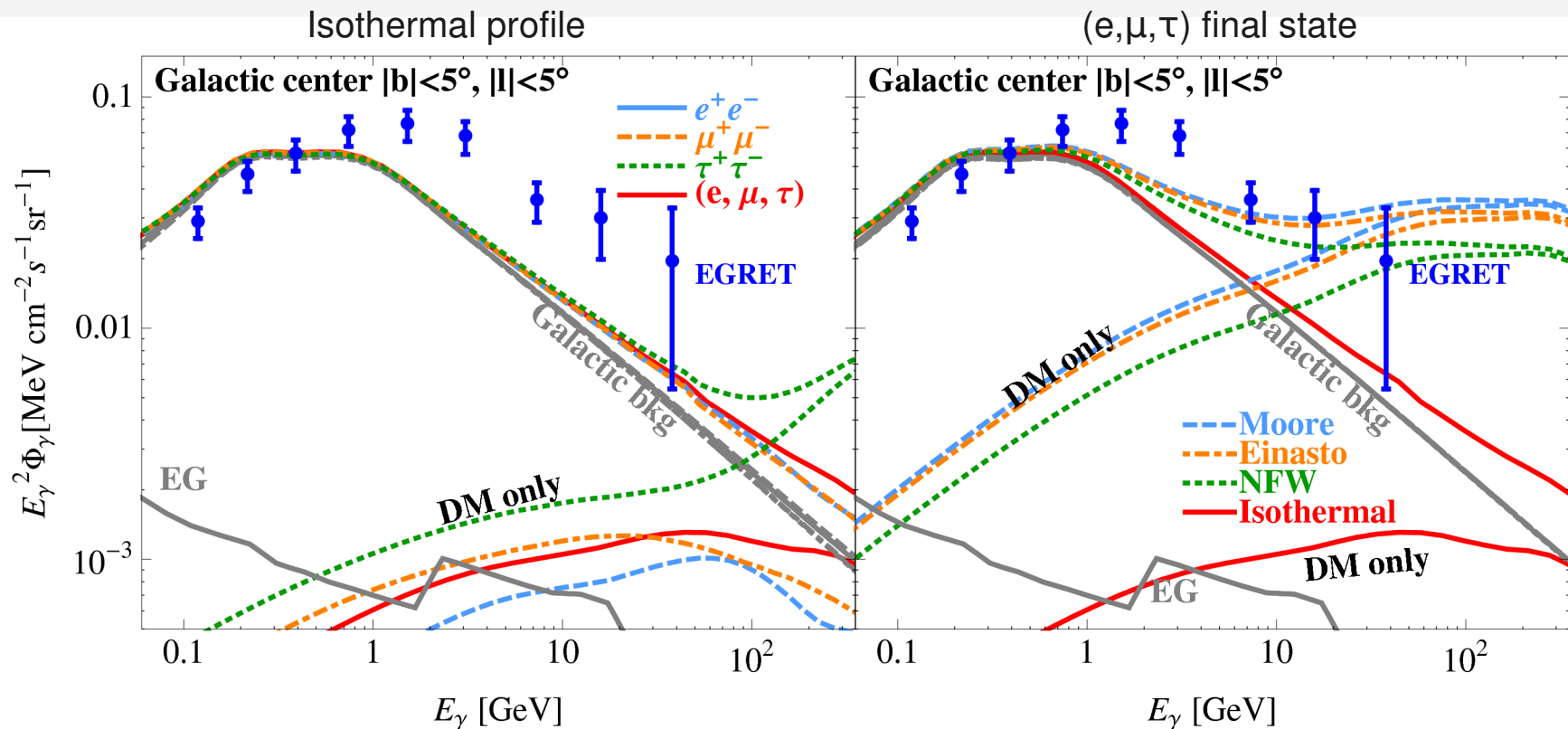


Profile dependence for DM annihilation ($M_{\text{dm}}=800$ GeV)



What can Fermi see near the galactic center?

- Zoom in to $5^\circ \times 5^\circ$ at the GC, the density cusp and the effect of ρ^2 becomes
huge gamma ray signals!



summary

- Pulsar / leptophilic DM can explain Fermi LAT, PAMELA and HESS data. DM cases needs lowering Fermi/HESS energy calibration
- Fermi gamma ray signal in the GC can exist even at the absence of excesses at mid-latitudes (profile dependent)
- PAMELA + Fermi electron data disfavor hard electron spectra
- ATIC-4 data are coming with improved π^0 rejection and a larger calorimeter.

Backups

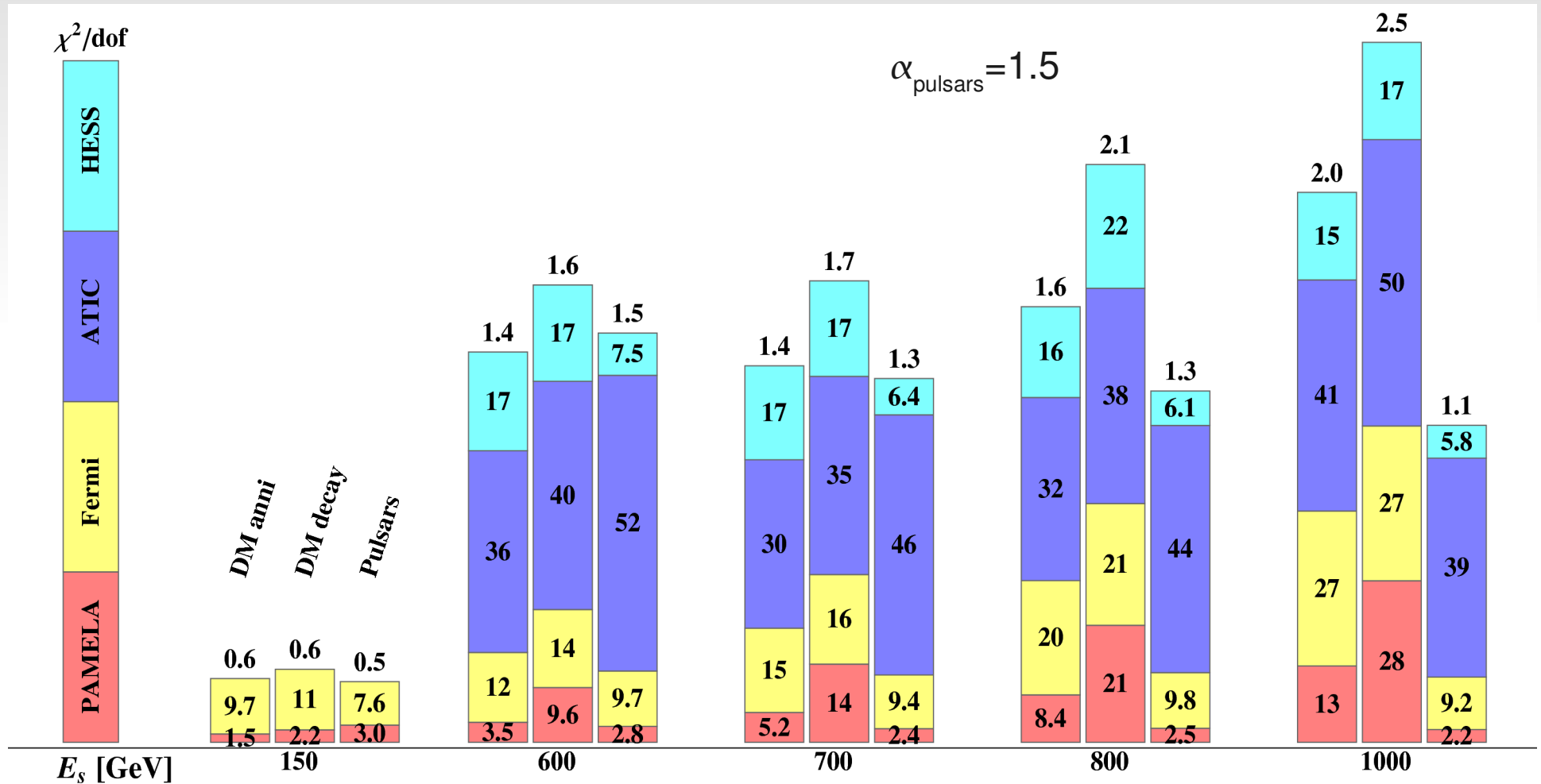
χ^2 fits to data

Number of data in each set:

Fermi	18
PAMELA	7
ATIC	21
HESS	8+1

DM profile: Isothermal

Number of parameters: 6



$$BF = 200E_s^2 + 502E_s - 40.7,$$

$$\frac{T}{10^{26} \text{ sec}} = 1.03 + \frac{0.278}{E_s} + \frac{0.0084}{E_s^2}$$

DM that annihilate or decay

as source of γ , $e^\pm$, $\bar{p}/p$...

Dark matter source terms

Annihilation:
$$\frac{d\Phi_\gamma}{dE_\gamma} = \frac{1}{2} \text{BF} \frac{\rho^2}{M_{DM}^2} \langle \sigma v \rangle \frac{dN_\gamma}{dE_\gamma}$$

Decay:
$$\frac{d\Phi_\gamma}{dE_\gamma} = \frac{1}{T} \frac{\rho}{M_{DM}} \frac{dN_\gamma}{dE_\gamma}$$

"prompt photons"
+
inverse Compton,
bremss., pion-decay, etc

Upper bound for hypothetical particle density:

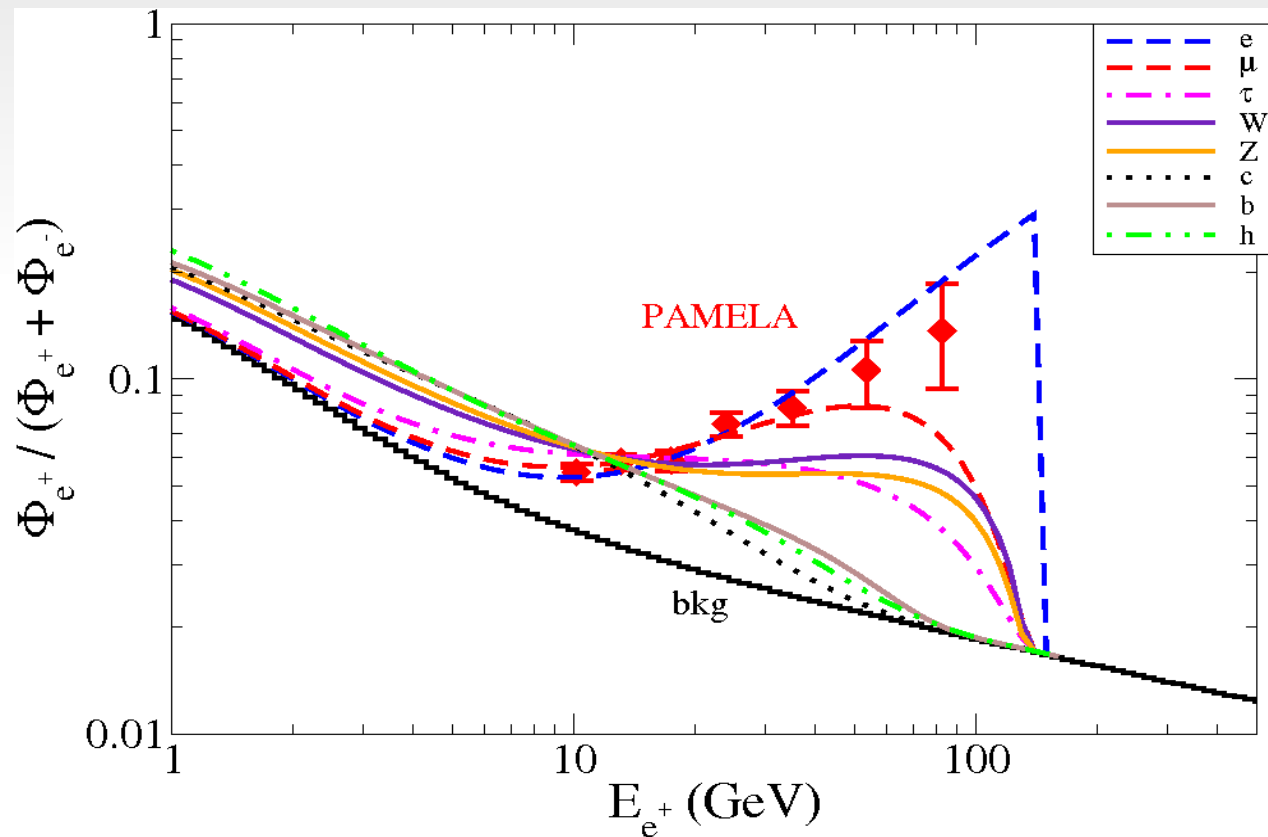
$$\text{Relic density } \Omega_{\text{dm}} \approx 0.20$$

$$\langle \mathbf{v} \sigma \rangle_{\text{annihilation}} \sim 3 \times 10^{-26} \text{ cm}^3/\text{s}$$

$$T_{\text{decay}} \sim 10^{26} \text{ s}$$

Fits to PAMELA data

A hard positron spectrum (from $e^\pm$ and $\mu^\pm$) is preferred



	B	χ^2
e^+e^-	30.7	5.63
$\mu^+\mu^-$	40.2	5.63
$\tau^+\tau^-$	73.0	32.2
W^+W^-	119.9	31.7
ZZ	155.7	42.6
hh	169.0	95.4
$c\bar{c}$	135.7	116.3
$b\bar{b}$	139.7	90.7

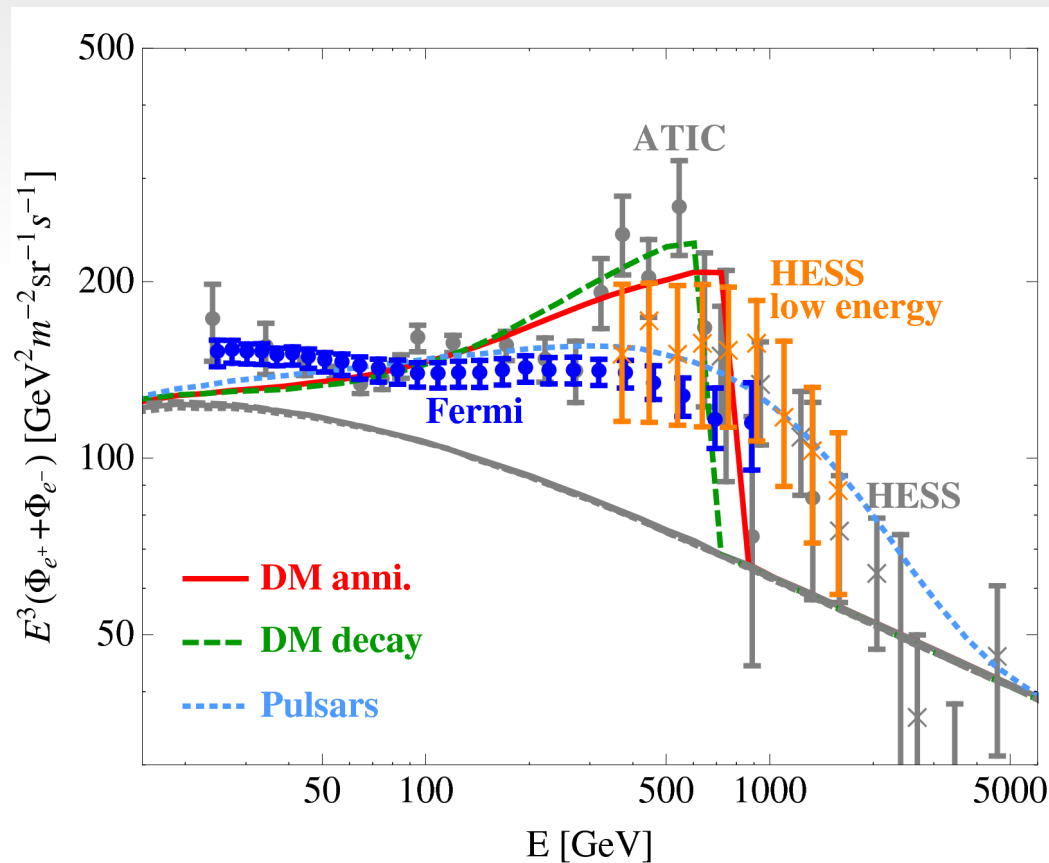
Medium propagation model
 $M_{\text{dm}} = 150 \text{ GeV}$

W,Z,h and quark final states
 are disfavored by their
 contribution to antiprotons

NEW DATA: Fermi & low energy HESS electron data

Fermi/LAT Collaboration, (2009)

H.E.S.S. Collaboration, (2009)



Fermi doesn't confirm the
bump in the electron flux

Energy calibration uncertainty
Fermi : +5%, -10%
HESS: $\pm 15\%$

Best-fit gamma, $e^+ e^-$ spectra

$M_{\text{dm}} = 700 \text{ GeV}$ for annihilation
 $= 1.2 \text{ TeV}$ for decay
 $E_p = 1 \text{ TeV}$ for pulsars

