Indications of Dark Matter from Astrophysical observations

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

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UW-Madison

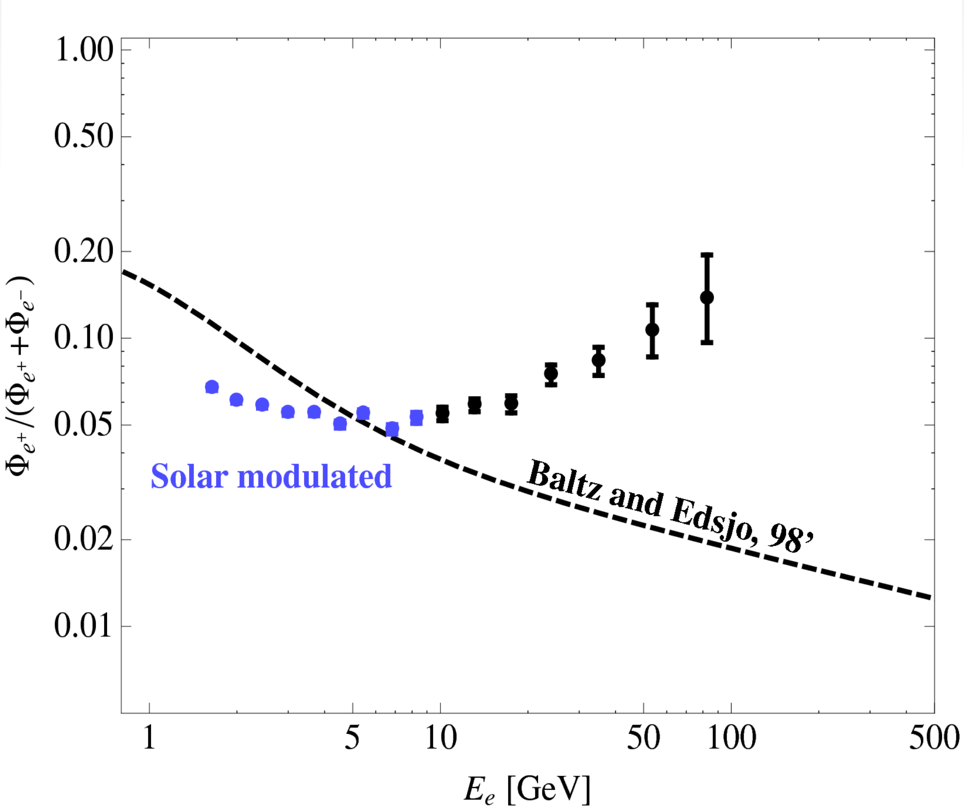
0904.2001, V. Barger, Y. Gao, W.-Y. Keung, D. Marfatia, G. Shaughnessy

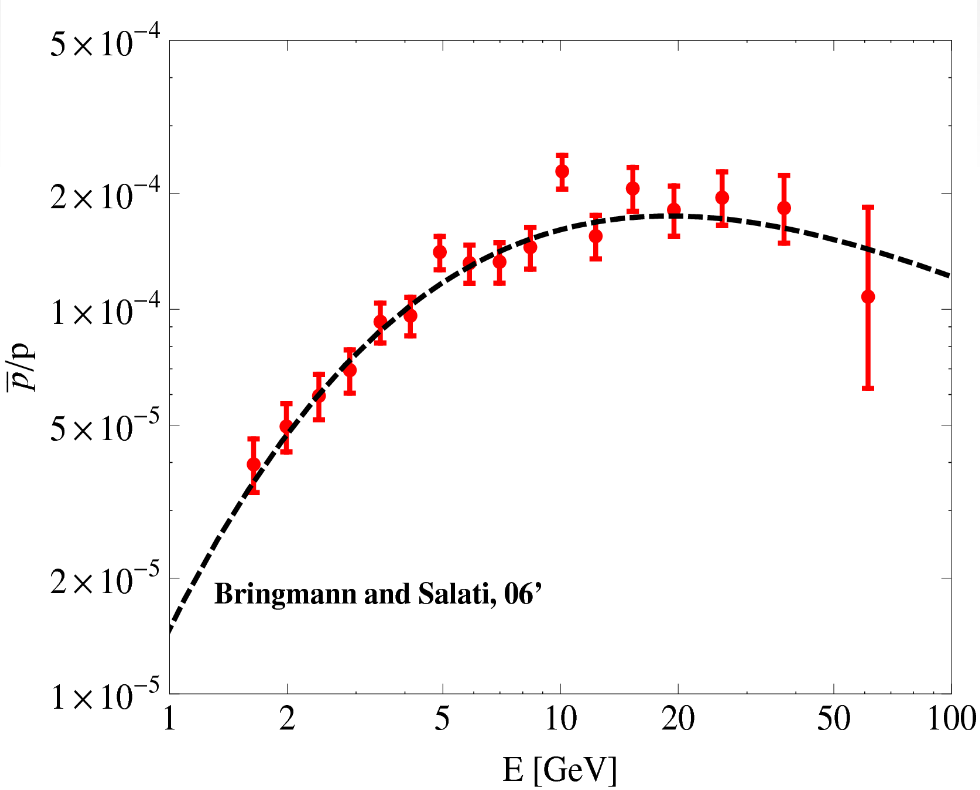
PAMELA observes e^+ excess

At 10~10² 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)





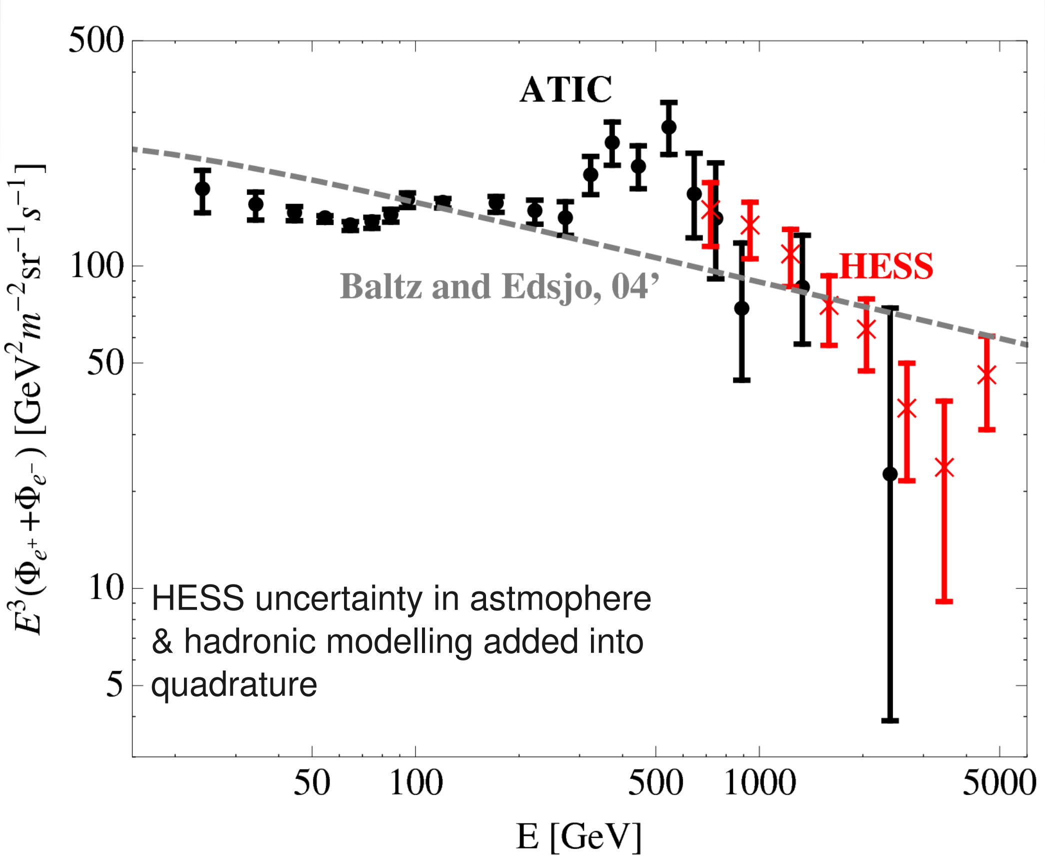
Excess in $e^+ + e^-$ spectrum

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:

$E_{threshold}$ = 0.6 ~ 0.7 for unknown sources?

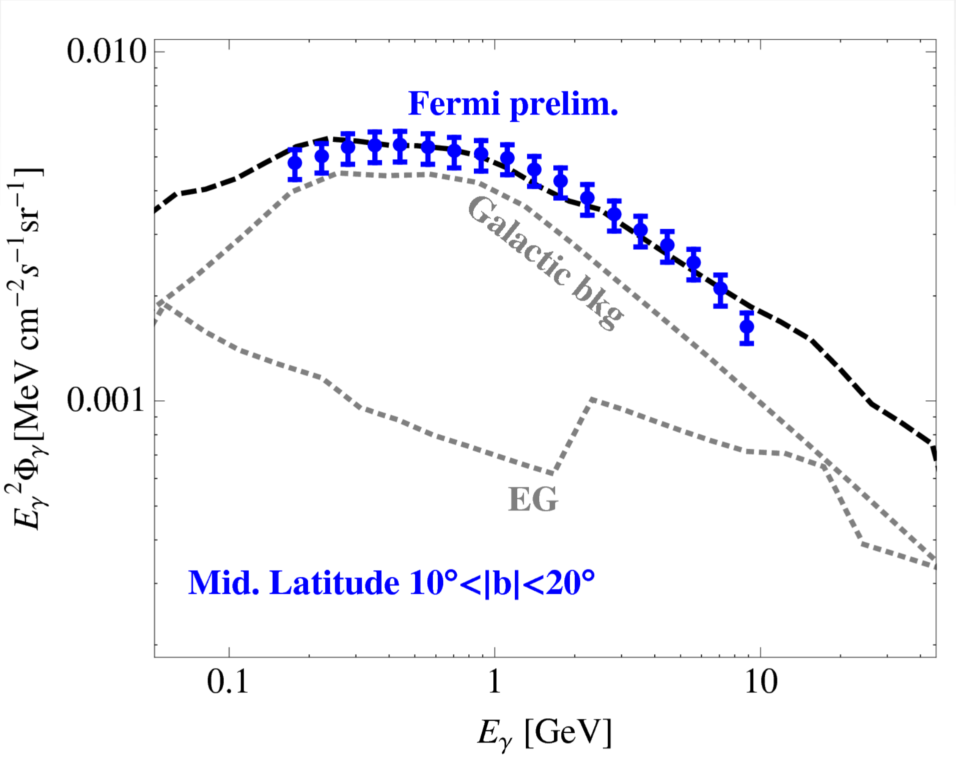
ATIC observes excess in light nuclei including C, N, O and Si:
-- unexplained

Panov et al., (2006)

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

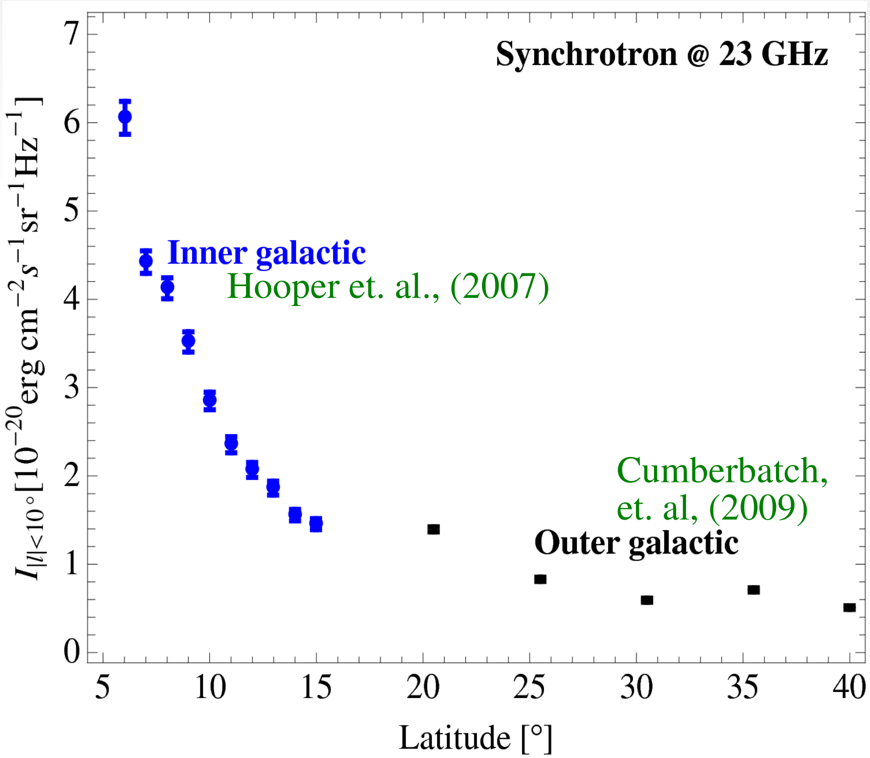
Known galactic and extragalactic sources fit data well...

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

Synchrotron excess: WMAP Haze

Residue microwave radiation in WMAP
f = 23~94 GeV

Finkbeiner (2004)



Flux averaged over $|l|<10°$, statistical errors only

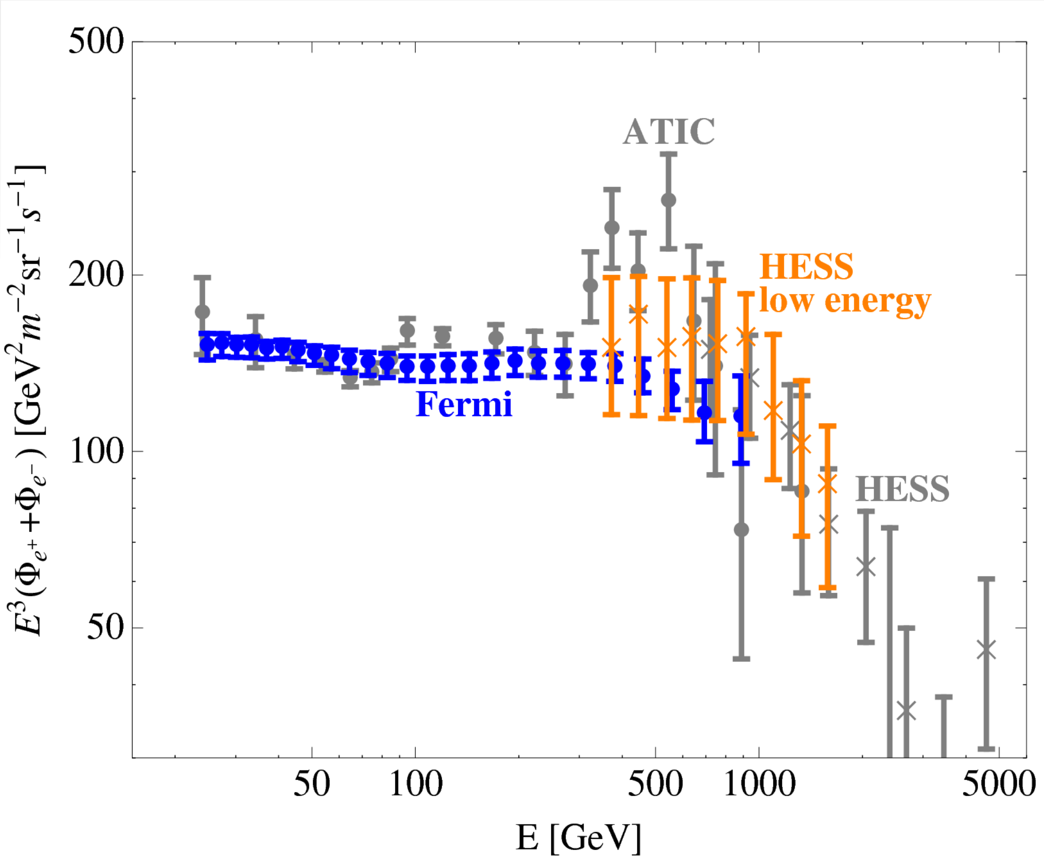
WMAP haze as synchrotron radiation of high energy electrons

Large systematics?

Cumberbatch, et. al, (2009)

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: ± 15%

DM that annihilate or decay

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

Sommerfeld enhancement,
s-channel resonance.

Dark matter source terms

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

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

Upper bound for hyperthetical particle density: $\langle v\sigma \rangle_{\text{annihilation}} \sim 3\times10^{-26}\ \text{cm}^3/\text{s}$

Relic density $\Omega_{dm} \approx 0.20$ $T_{\text{decay}} \sim 10^{26}\ \text{s}$

DM modeling

Two body annihilation or decay

Annihilation $<v\sigma> = 3\times10^{-26}$ cm^3/s

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

Leptonic final states: separate $e^\pm$, $\mu^\pm$, $\tau^\pm$ channels
or (e, μ, τ) with equal branchings

600 GeV ~ 1 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

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

cylindrical (r, z)

Zhang and Cheng, (2001)

$e^\pm$ injection spectra of an average pulsar

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

Direct gammas are negligible

Density distribution: dark matter profiles

- DM density in the halo can be:

  with a 'cusp':

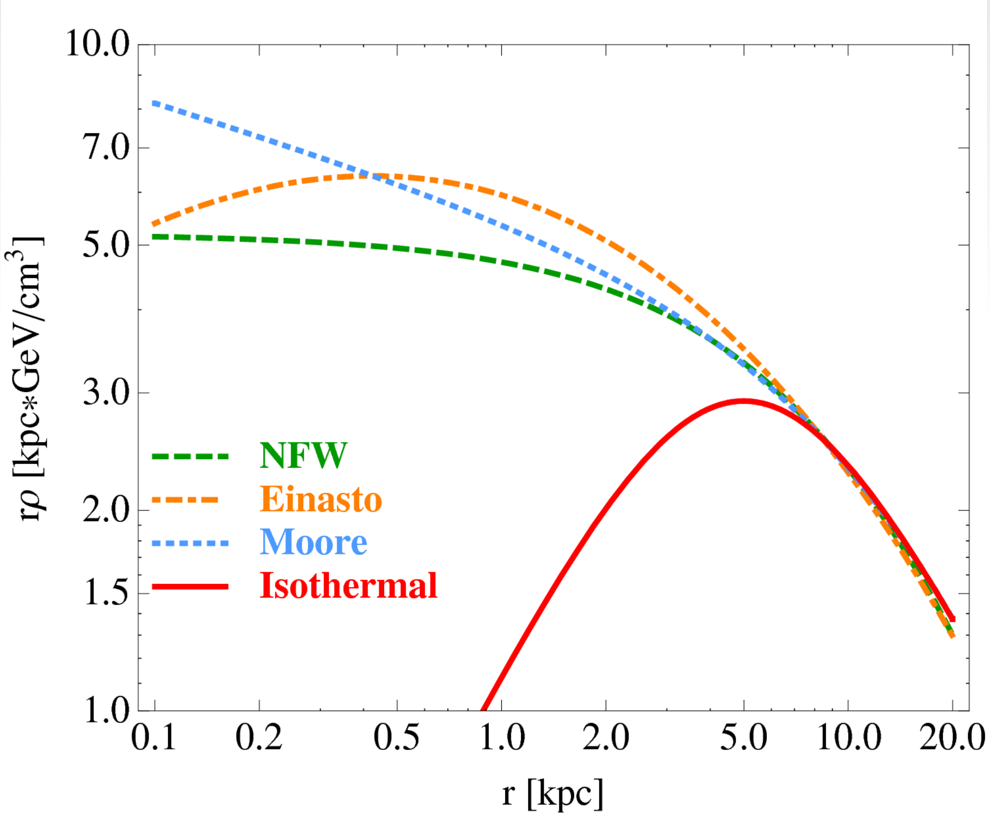
  Moore Diemand, et. al. (2005)

  NFW Navarro, et. al. (1995)

  Einasto Einasto, et. al. (1965)

  or non-singular:

  Isothermal Bahcall and Soneira (1980)

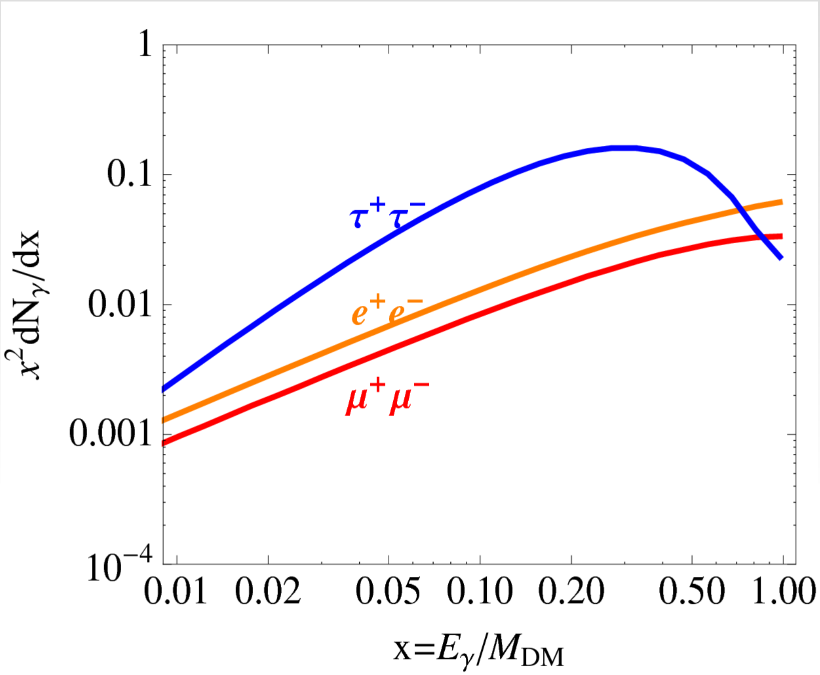


Local DM density = 0.3 GeV/cm³

Analysis tools

For M_{DM}=1 TeV

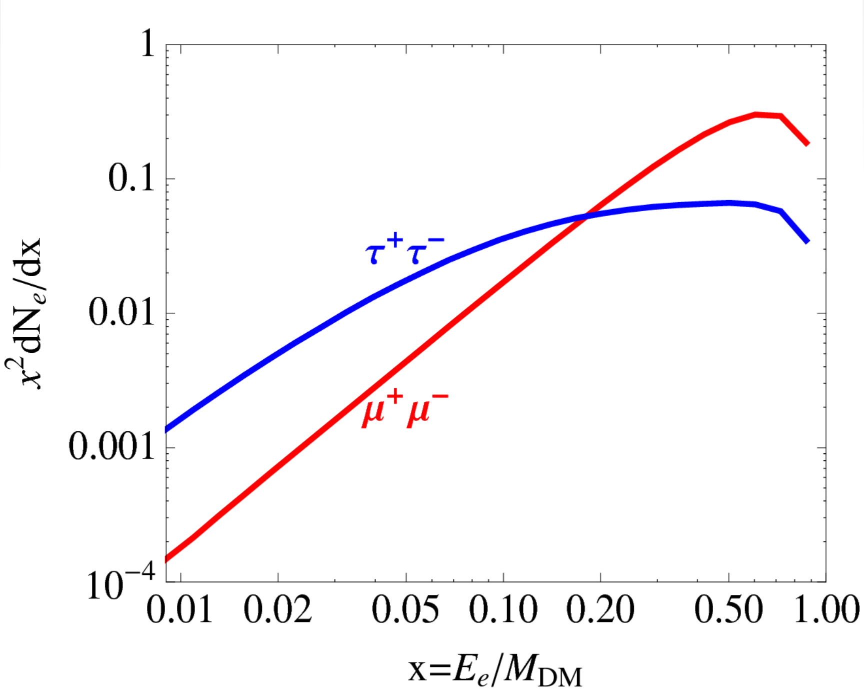
Belanger, et.al. (2008)



DM $e^\pm$ spectra by MicrOMEGAs

for $\mu^\pm$, $\tau^\pm$ final states;

line spectra for the $e^\pm$ final state.



Photon spectrum from DMFIT

Jeltema and Profumo, (2008)

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

Particle propagation, galactic bkgs,
IC, brems., synchrotron radiations with GALPROP

Strong and Moskalenko, (2001)

The GALPROP modeling

Strong, et. al. (2004)

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

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

diffusion term **energy loss:** IC, bremss., etc.

The "conventional" 500800 model:

Primary e^- injection spectrum:

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

α_{SN}

Nuclei injection spectrum:

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

Galactic magnetic field:

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

Cylindrical diffusion zone:

L_{max}=20 kpc, z_{max}=4 kpc

Diffusion coefficient parametrization:

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

$\beta = v/c$

We varied the following parameters using a grid:
D_0 , E_0 , δ(>1/3) , α_{SN} , $e^-_{pri.}$ 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:

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

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:

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

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

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

A diffusion parameter prior:

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

to agree with cosmic ray data.

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

χ^2 fits to data: DM annihilation

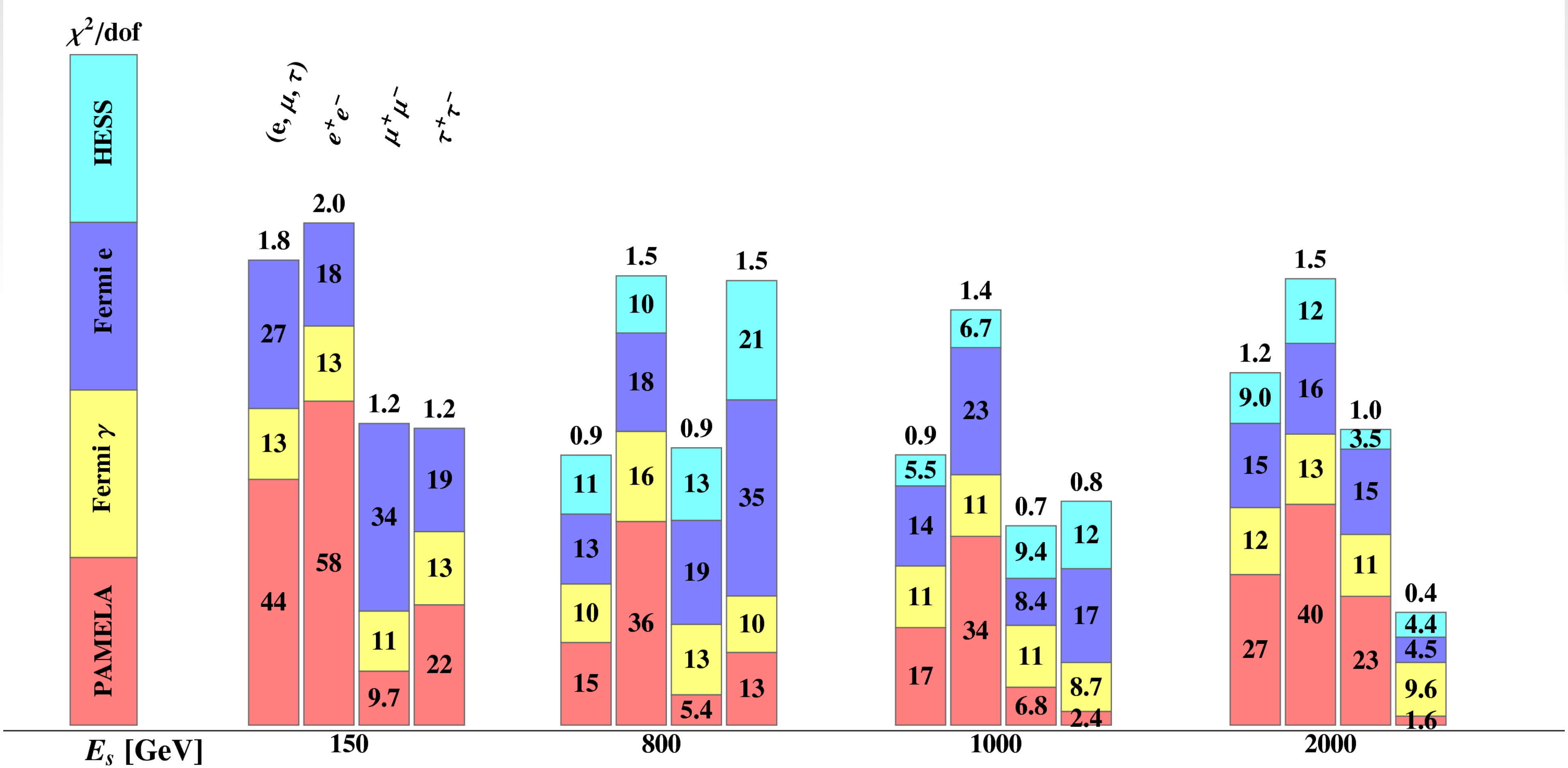
Soft positron spectrum is preferred

Number of data in each set:

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

DM profile: Isothermal

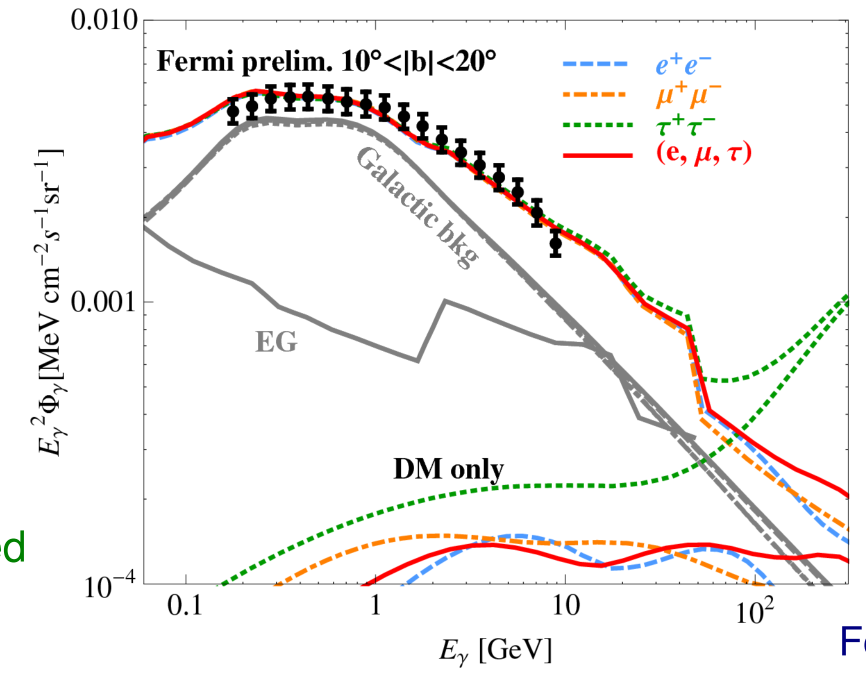
Number of parameters: 8



Hard electron spectrum in trouble with PAMELA

Best-fit spectra: DM annihilation

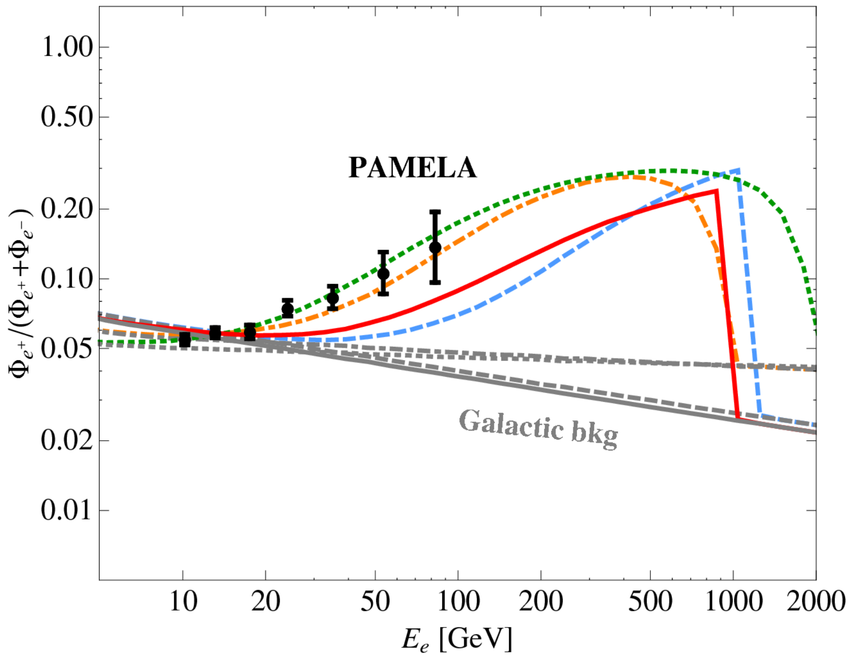
$e^{\pm}$	1 TeV
$\mu^{\pm}$	1 TeV
$\tau^{\pm}$	2 TeV
(e,μ,τ)	0.8 TeV

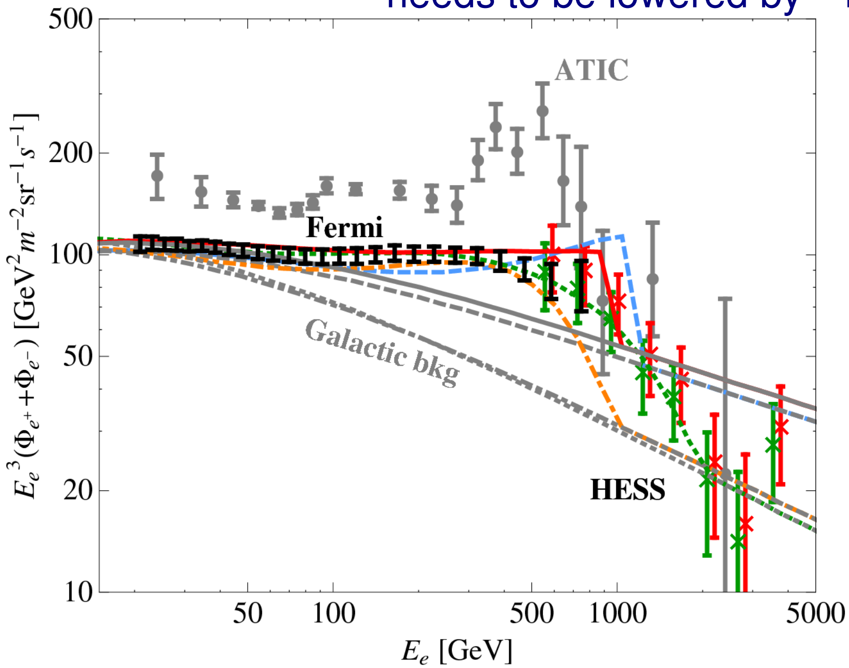


π^0 decay photons

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

Fermi energy calibration needs to be lowered by ~17%





Best-fit spectra: DM annihilation

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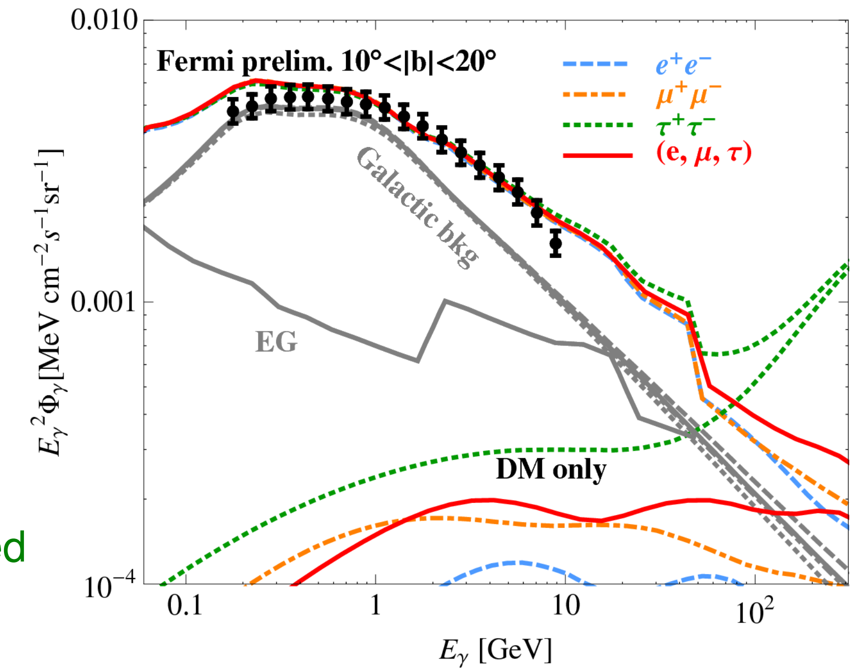
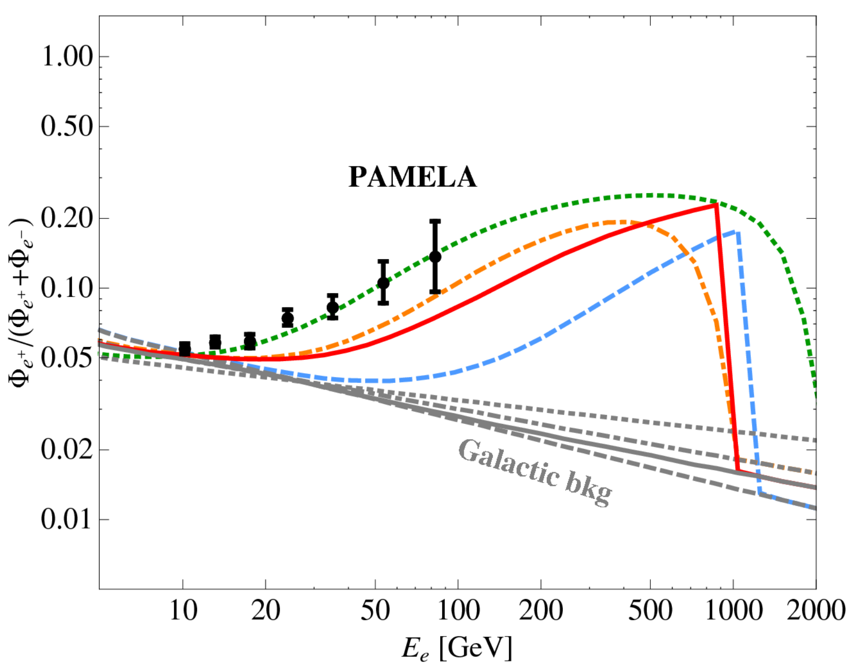
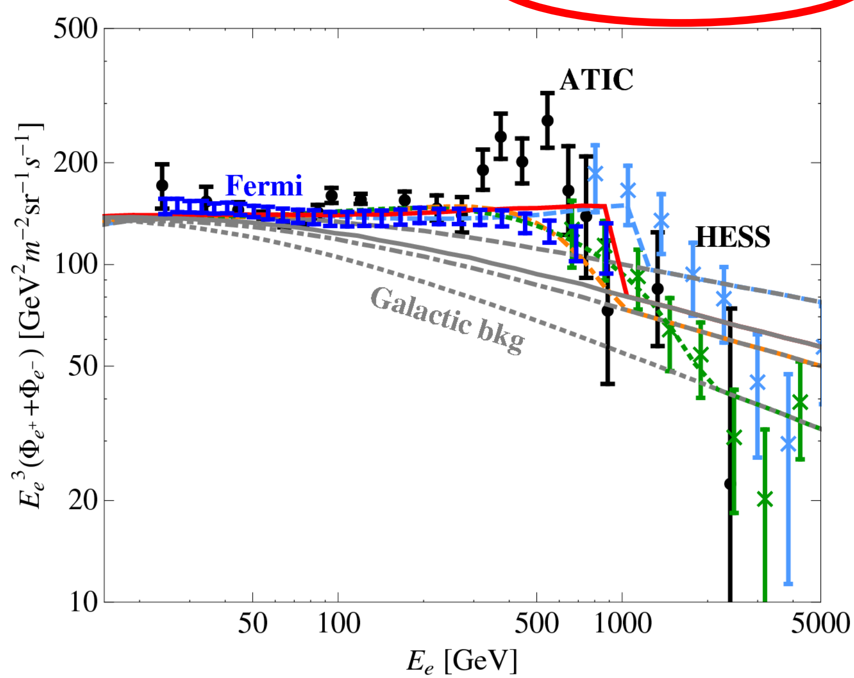


π^0 decay photons

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

Put ATIC back





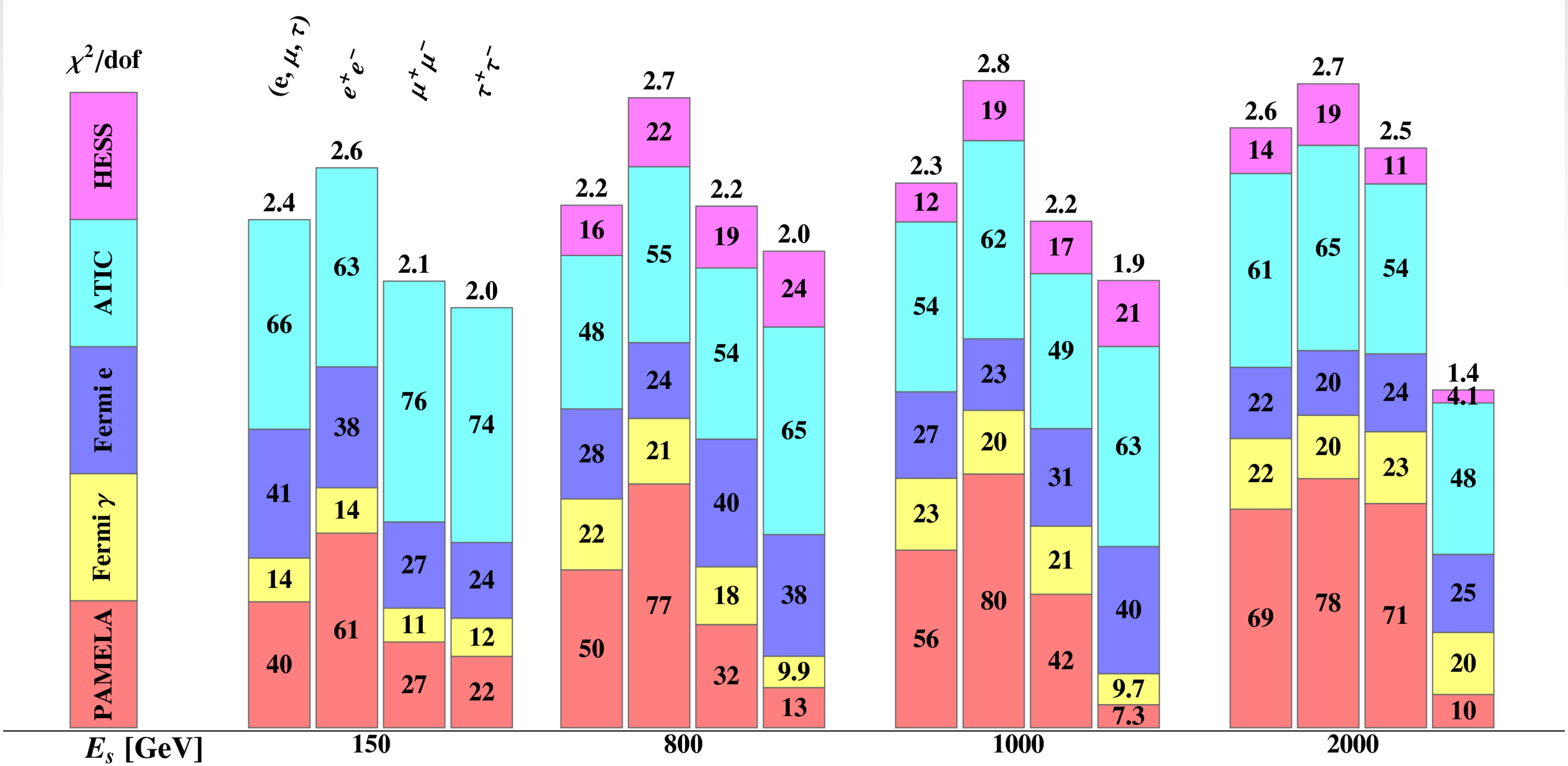
χ^2 fits to data: DM annihilation with ATIC

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
ATIC	21



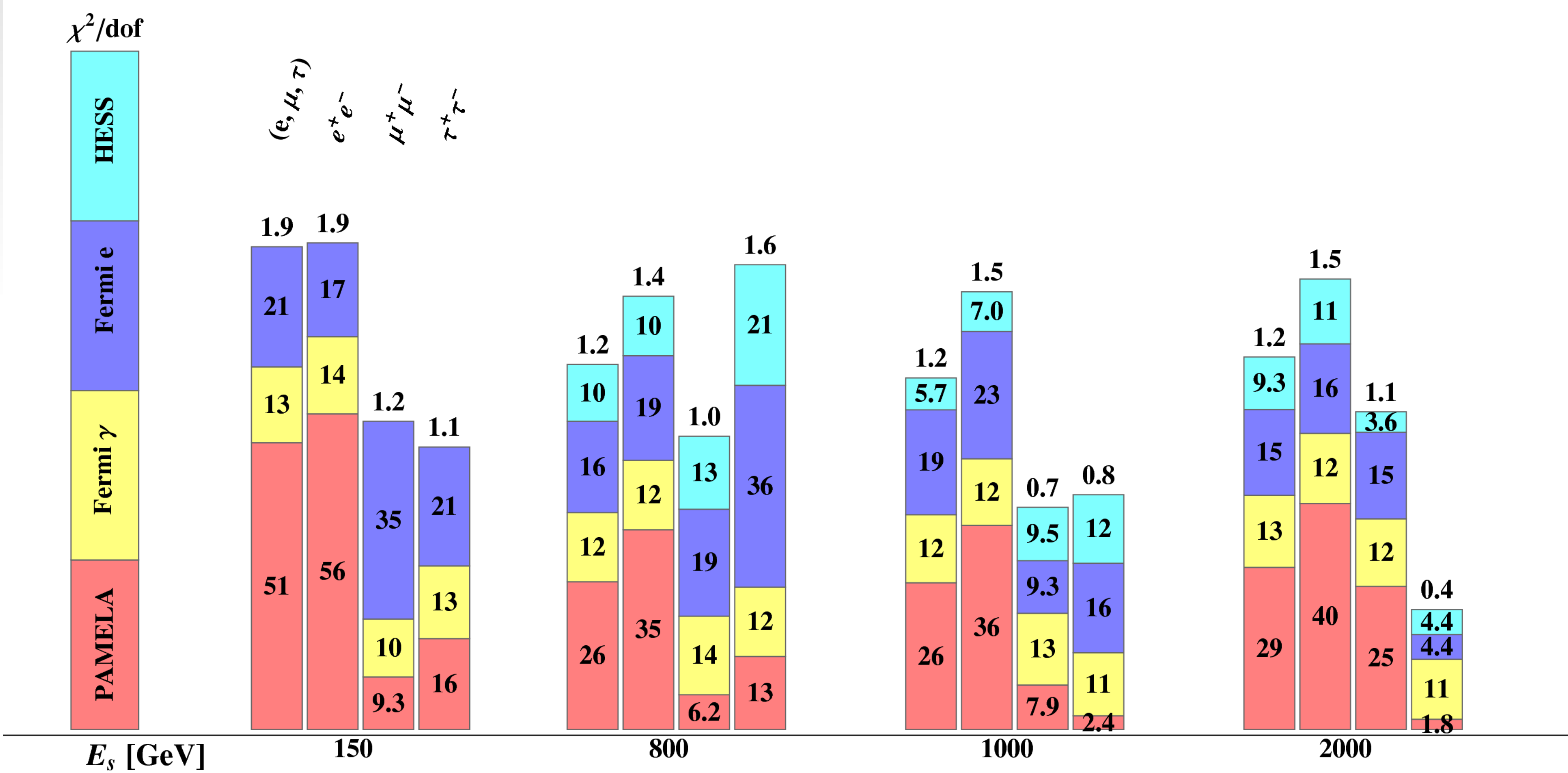
Soft positron spectrum
is still preferred

χ^2 fits to data: DM decay

Similar to the annihilation scenario

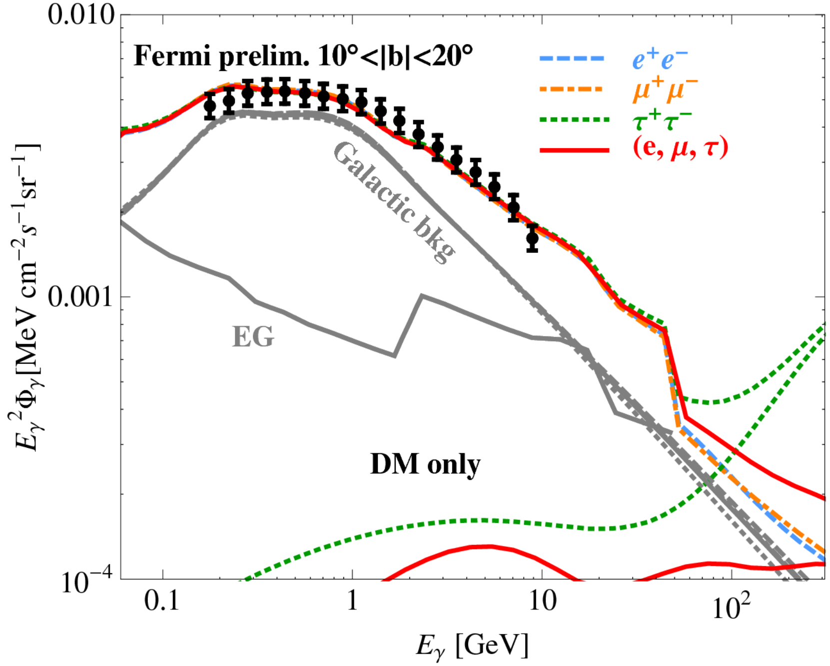
DM profile: Isothermal

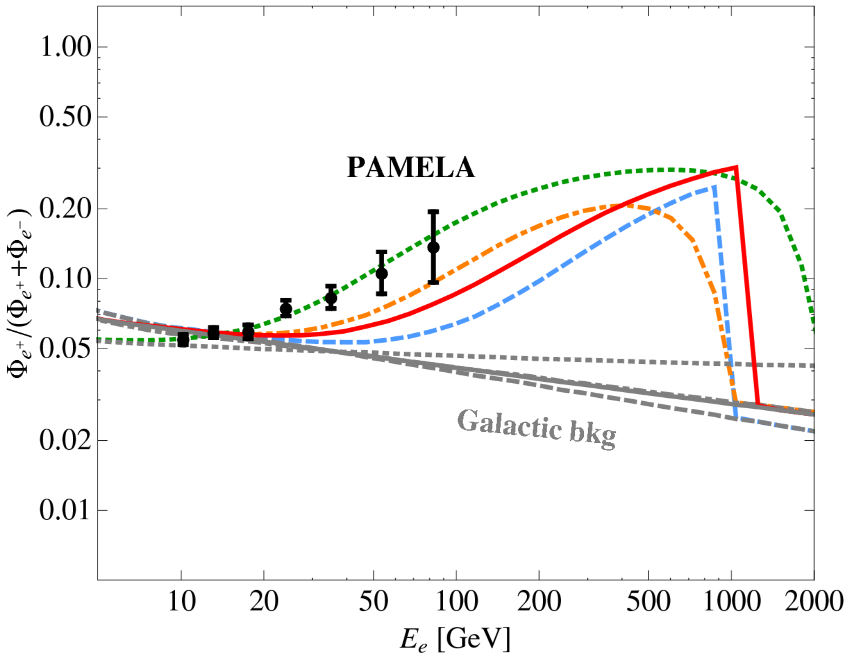
Number of parameters: 8

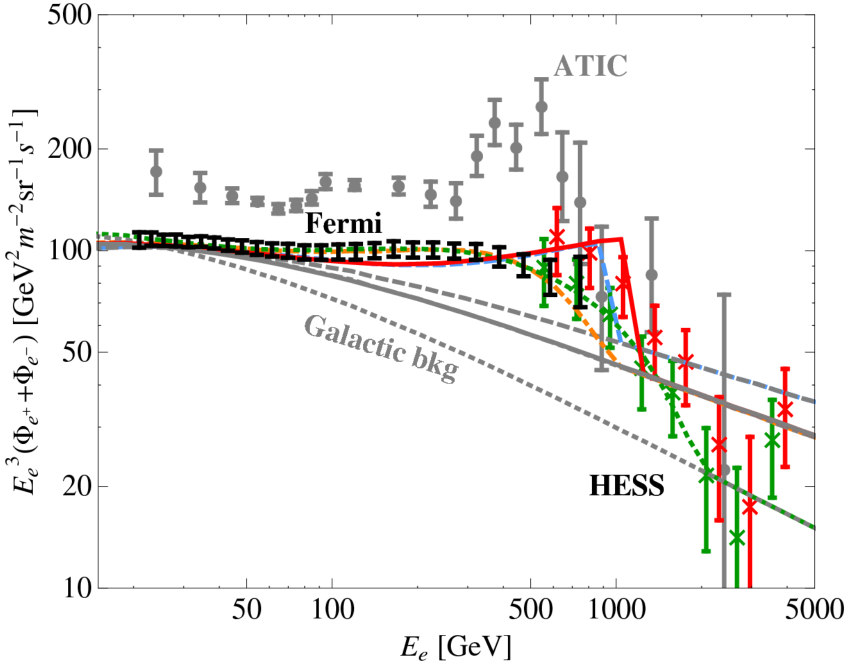


Best-fit spectra: DM decay

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



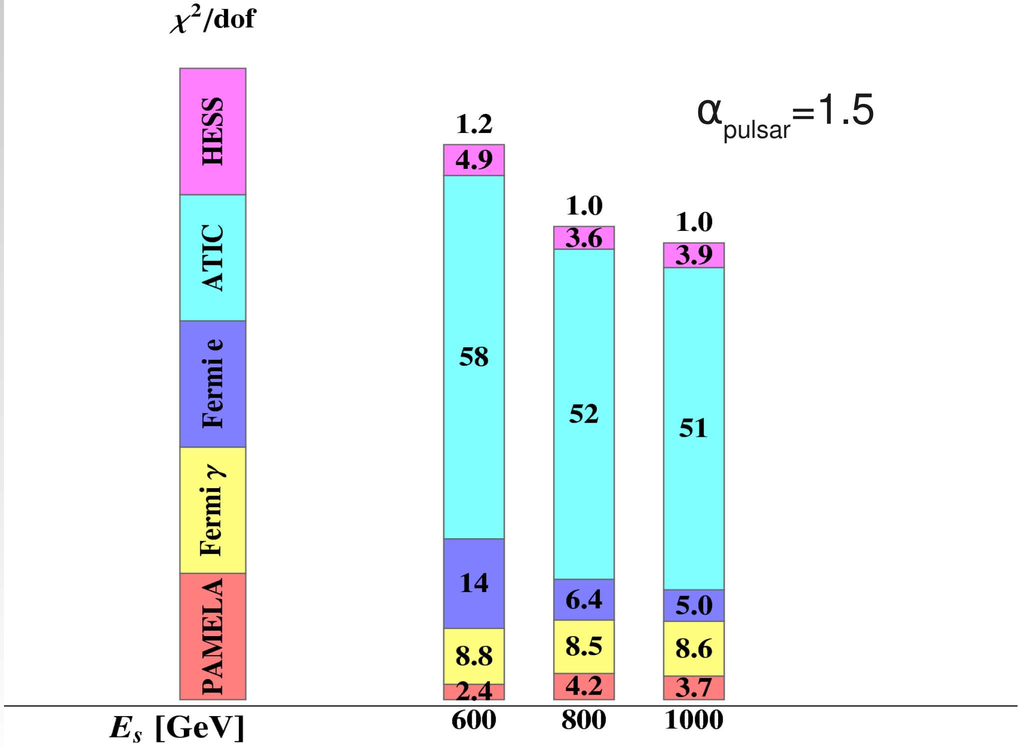


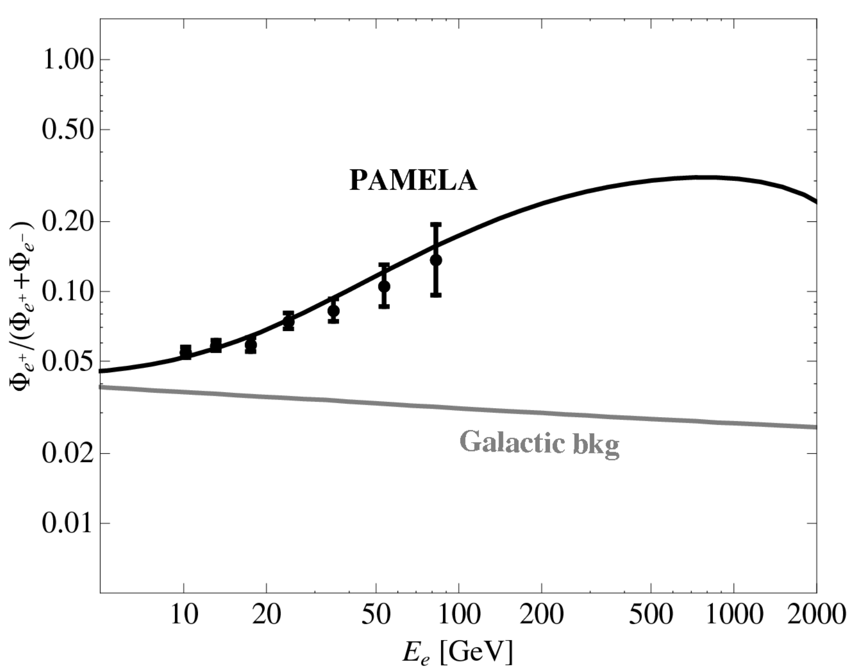


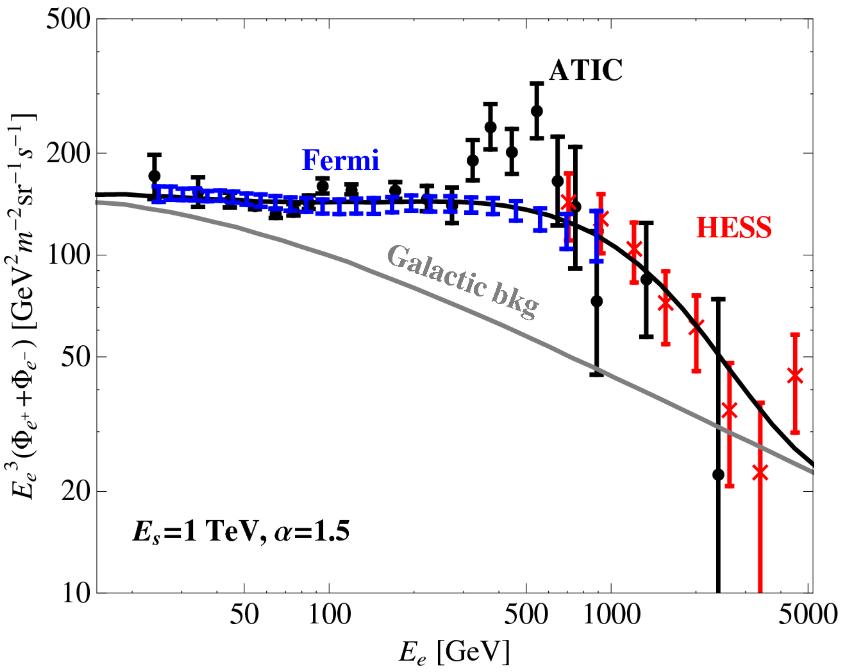
Pulsars

Fit data well without drifting Fermi and HESS energy calibration

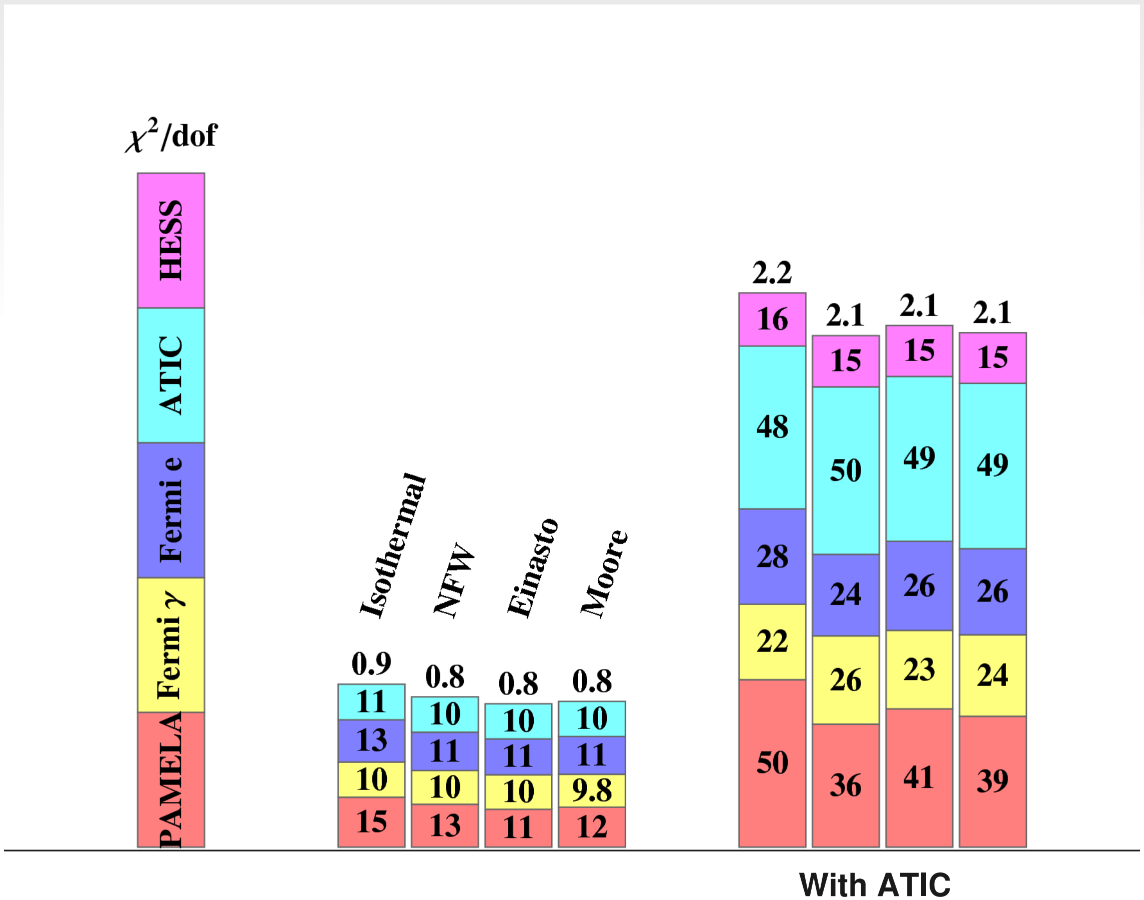
no signifcant photon contribution from pulsars



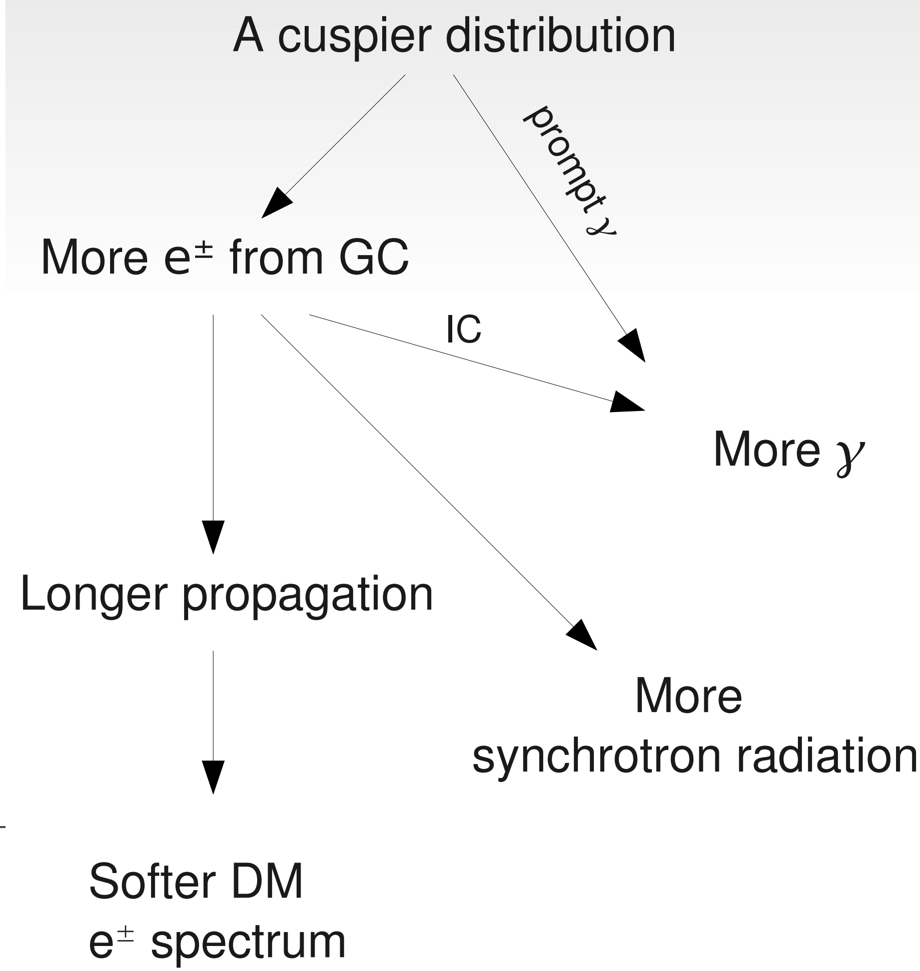




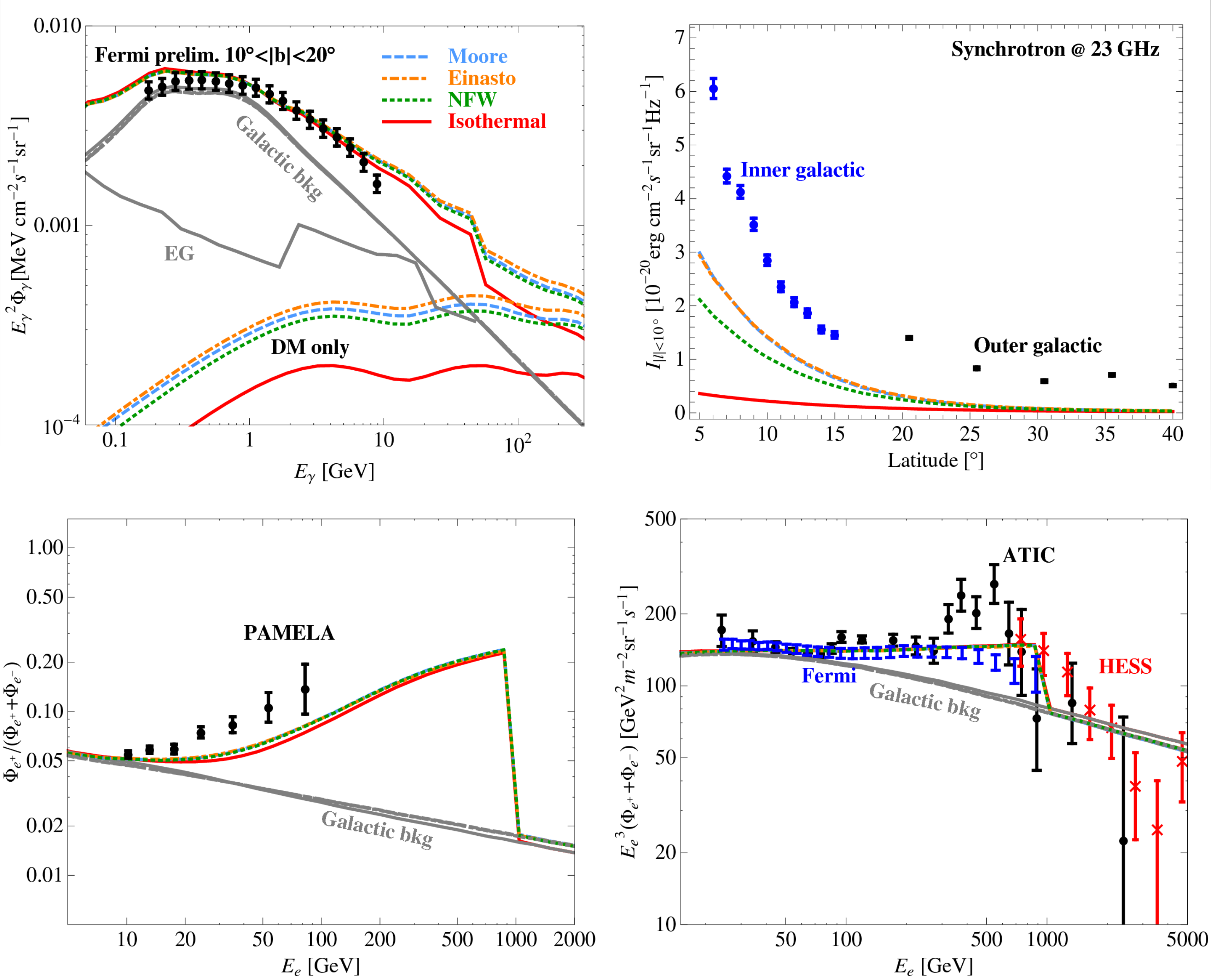
Dependence on halo profiles



Annihilation M_{DM}=0.8 TeV



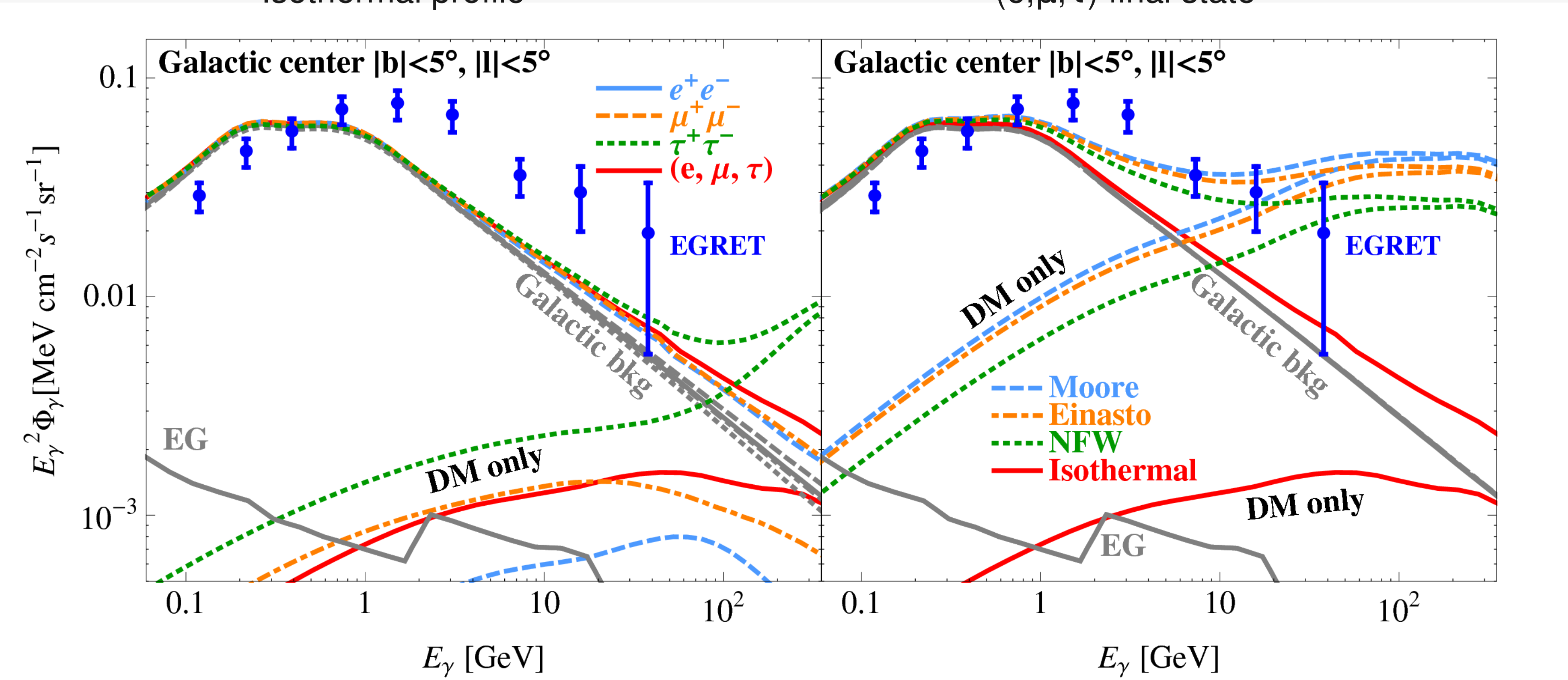
Profile dependence for DM annihilation (M_{dm}=800 GeV)



What can Fermi see near the galactic center?

- Zoom in to 5°×5° at the GC , the density cusp and the effect of ρ^2 becomes
  huge gamma ray signals!

Isothermal profile (e,μ,τ) final state



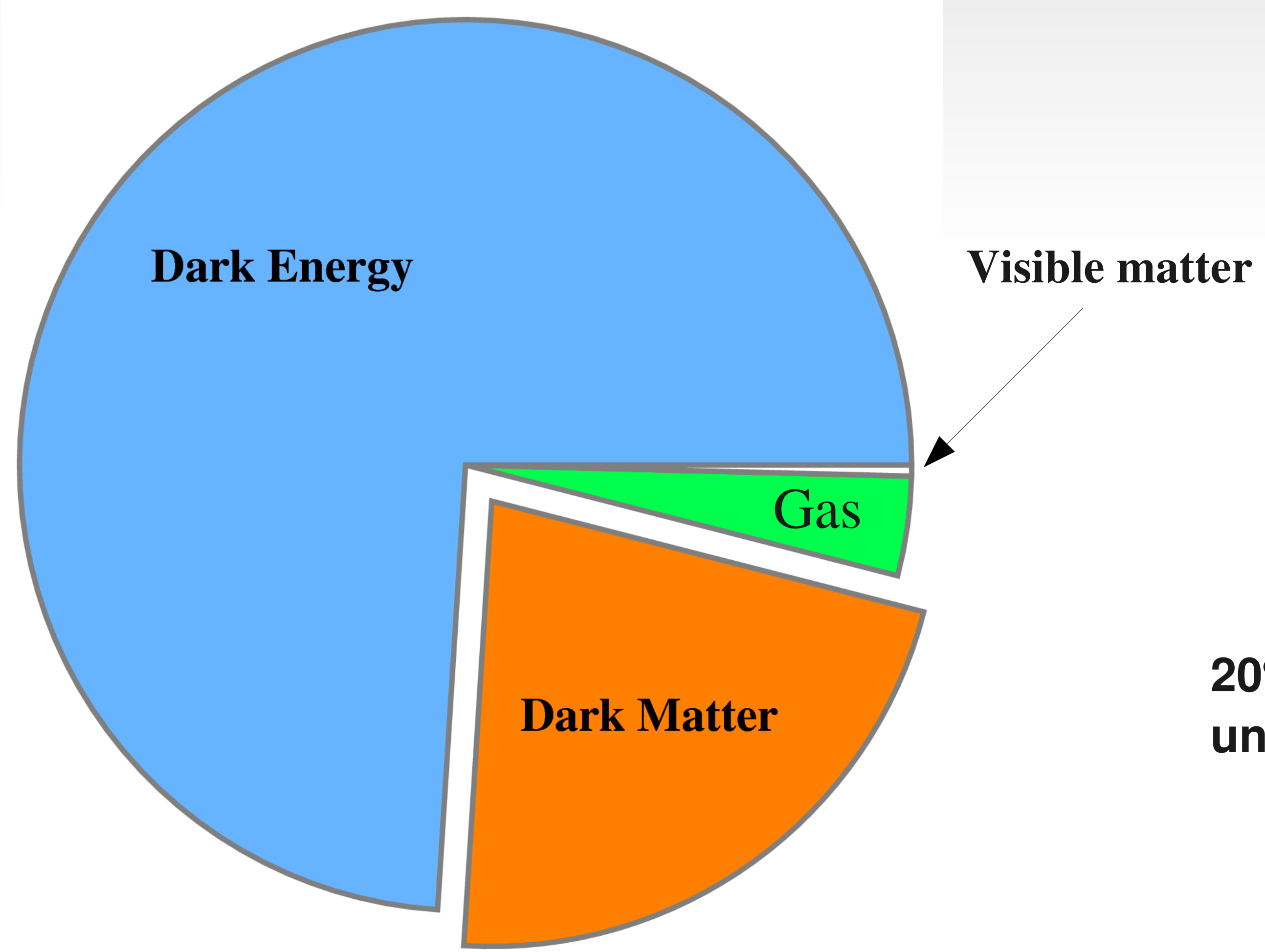
summary

- 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

Cosmic energy budget



Einstein's equation

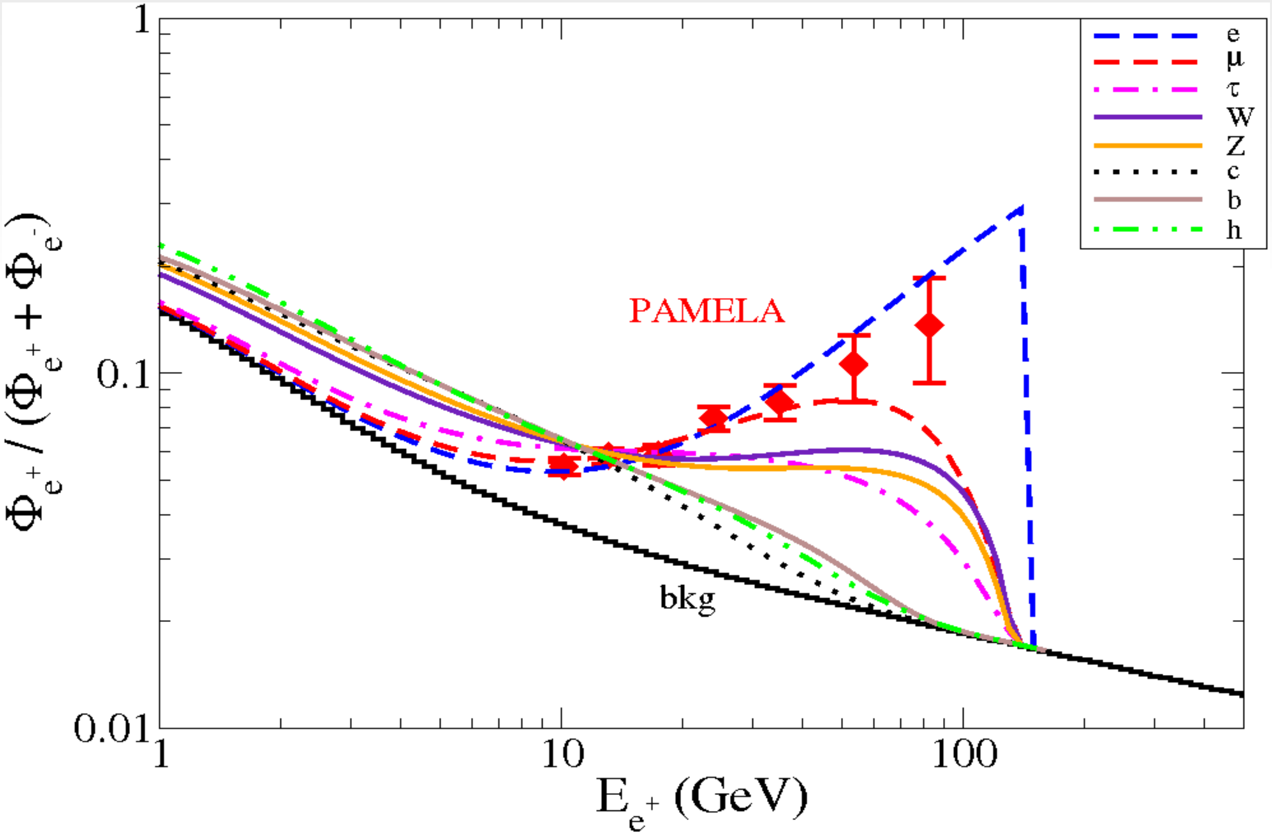
plus

Big bang model
and
SN-Ia, CMB, BAO etc.

20% of our universe is unknown matter

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_{dm}=150 GeV

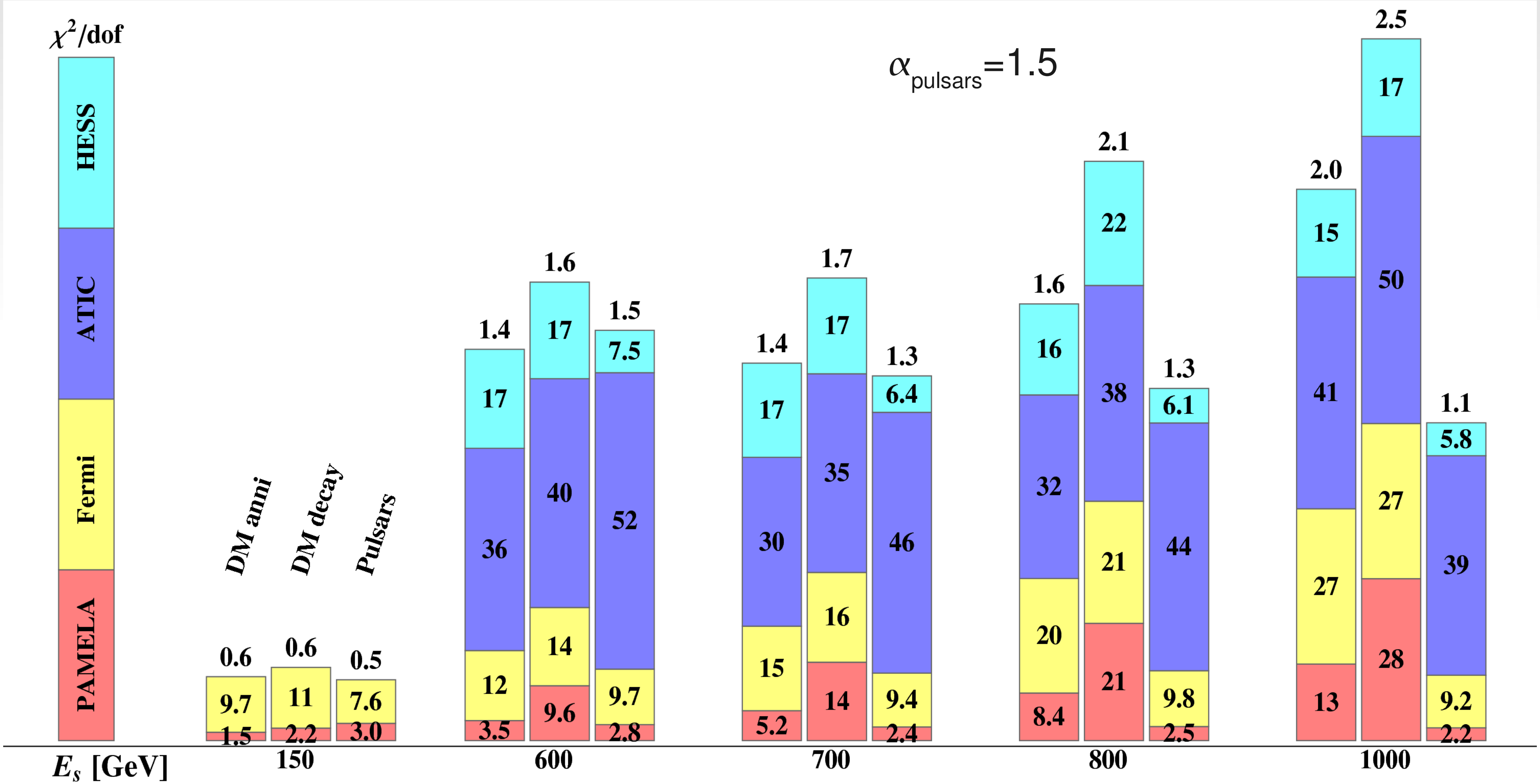
W,Z,h and quark final states are disfavored by their contribution to antiprotons

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



$$BF = 200E_s^2 + 502E_s - 40.7\,,\qquad \frac{T}{10^{26}\,\mathrm{sec}} = 1.03 + \frac{0.278}{E_s} + \frac{0.0084}{E_s^2}$$

DM that annihilate or decay

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

Dark matter source terms

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

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 hyperthetical particle density:

$\langle v\sigma\rangle_{\mathrm{annihilation}} \sim 3\times10^{-26}\ \mathrm{cm^3/s}$

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

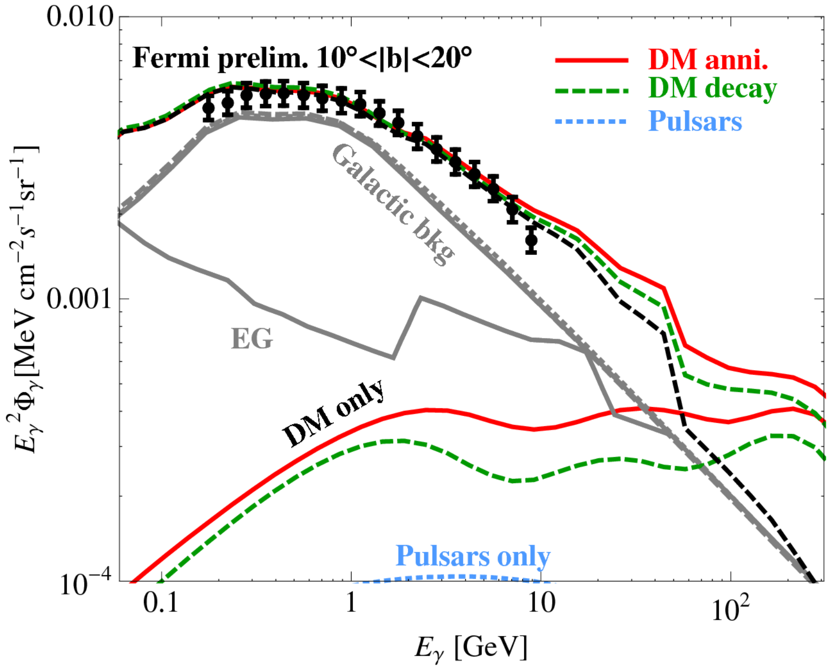
$T_{\mathrm{decay}} \sim 10^{26}\ \mathrm{s}$

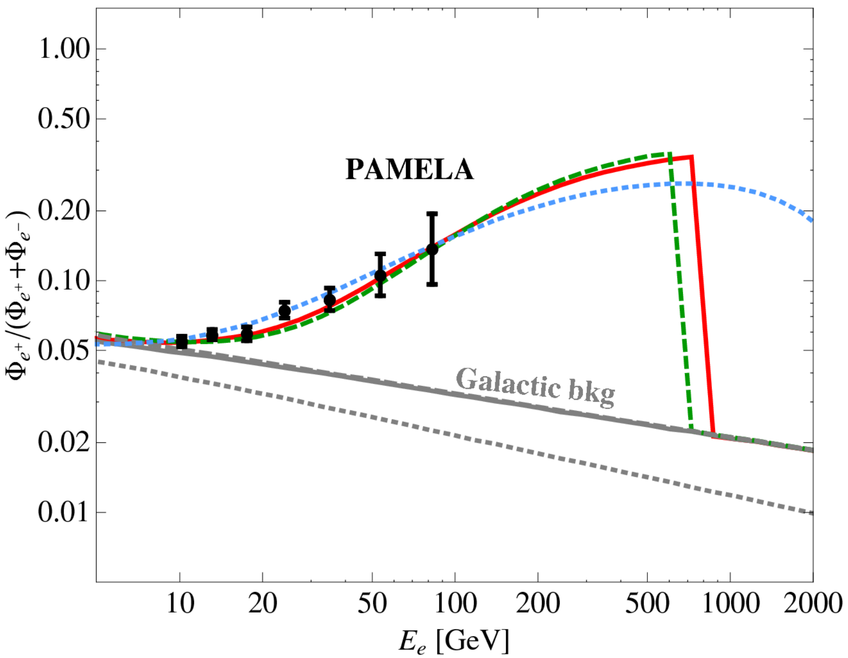
Best-fit gamma, e^+ e^- spectra

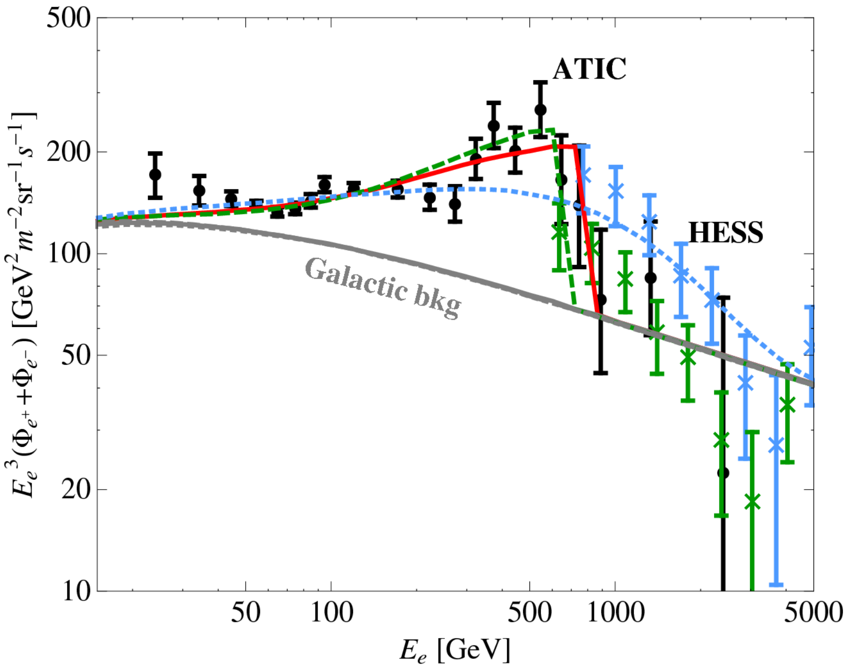
M_{dm} = 700 GeV for annihilation

= 1.2 TeV for decay

E_P = 1TeV for pulsars







NEW DATA:
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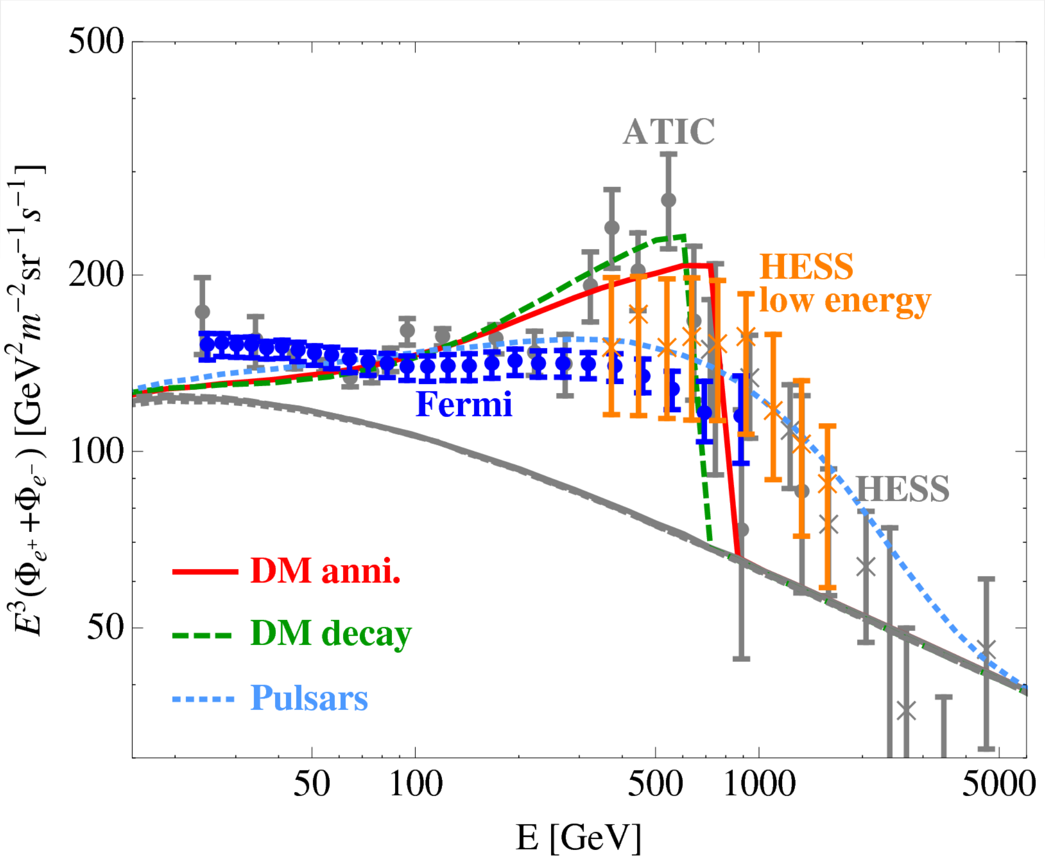
Fermi/LAT Collaboration, (2009)

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



Fermi doesn't confirm the bump in the electron flux

Energy calibration uncertainty
Fermi : +5%, -10%
HESS: ± 15%