Indications of Dark Matter from Astrophysical observations

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

Yu Gao
UW-Madison

0904.2001, V. Barger, Y. Gao, W.-Y. Keung, D. Marfatia, G. Shaughnessy **(2 body)**

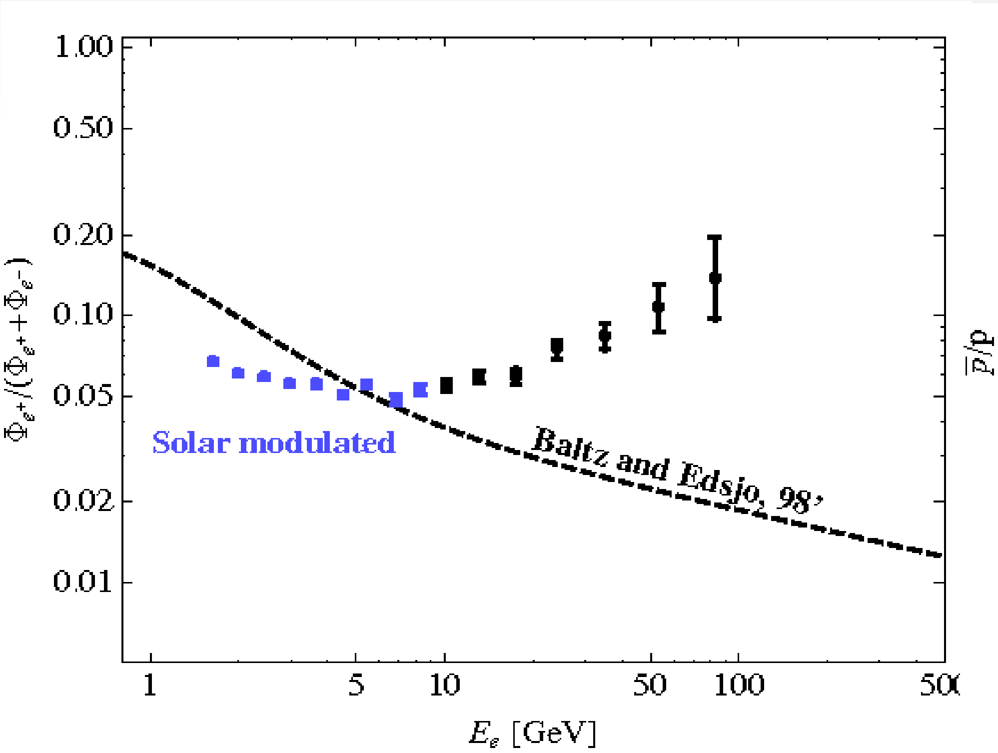
0906.3009, V. Barger, Y. Gao, W.-Y. Keung, D. Marfatia **(3 body)**

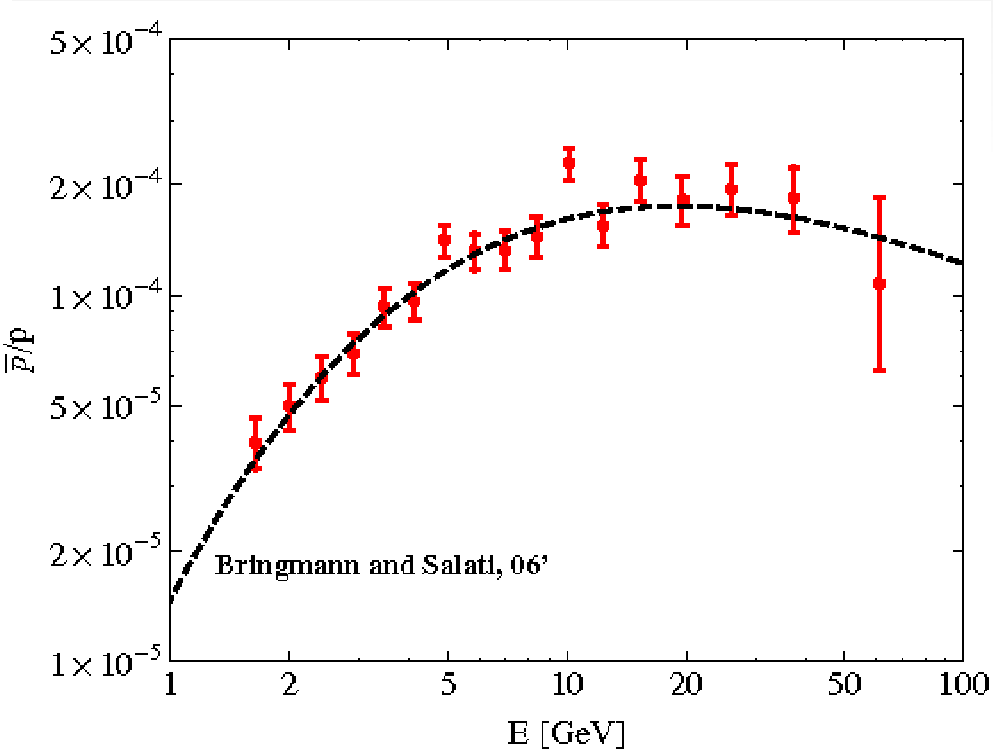
PAMELA observes e^+ excess

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

Adriani et al., (2008)

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





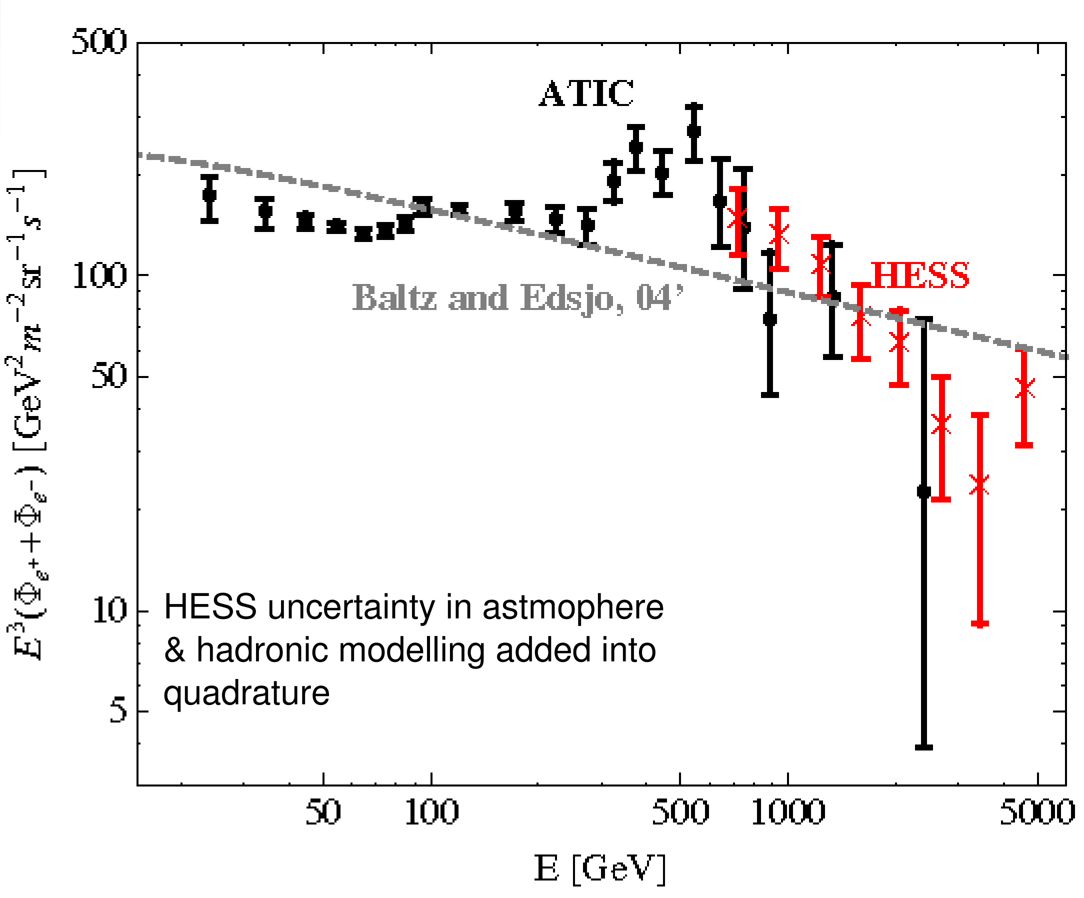
Excess in $e^+ + e^-$ spectrum

Advanced Thin Ionization Calorimeter

J. Chang et al, (2008)

High Energy Stereoscopic System

F. Aharonian et al, (2008)



HESS uncertainty in astmophere & hadronic modelling added into quadrature

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:

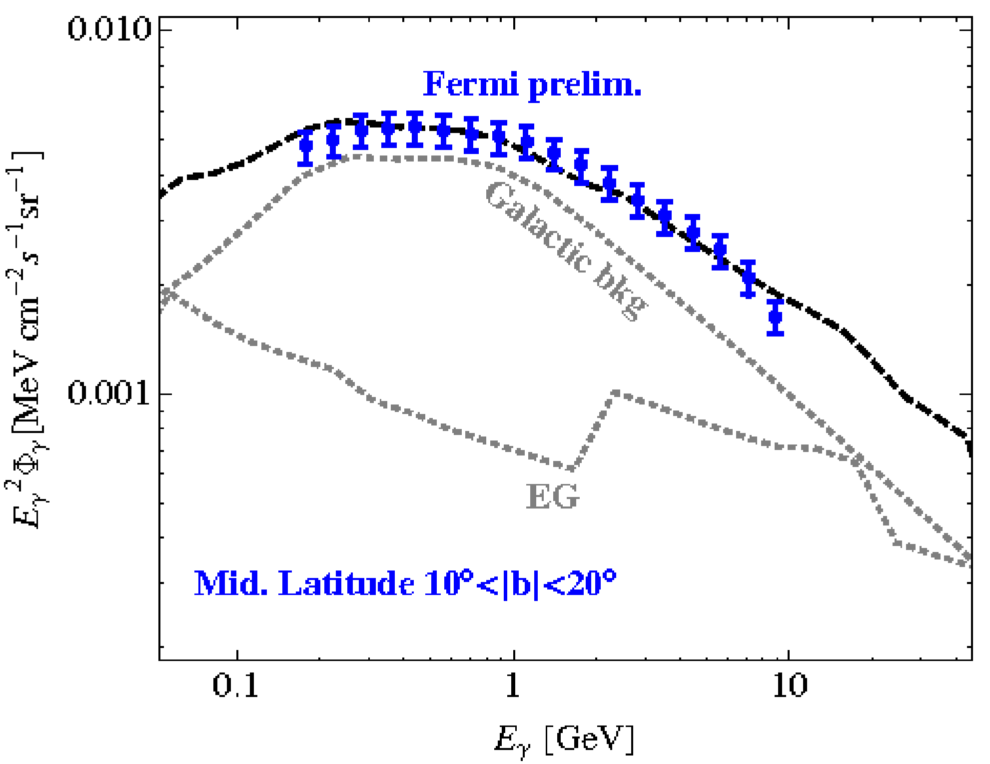
-- unexplained

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

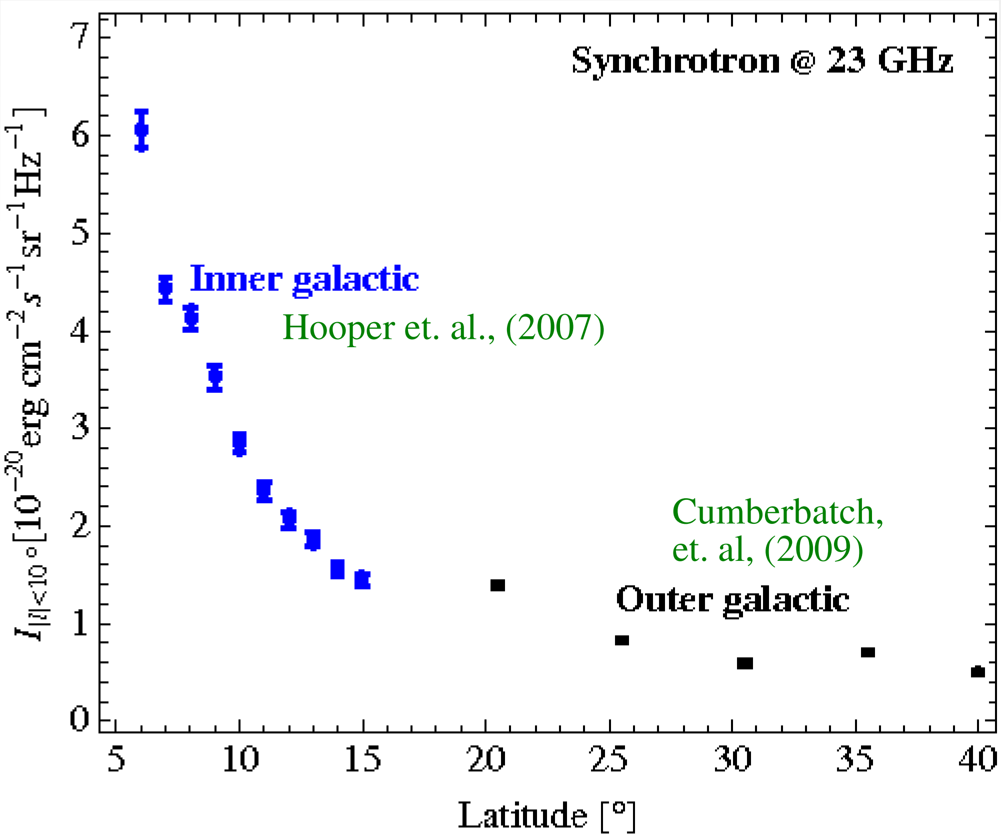
Known galactic and extragalactic sources fit data well...

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

Synchrotron excess: WMAP Haze

Residue microwave radiation in WMAP
f = 23~94 GHz

Finkbeiner (2004)



Hooper et. al., (2007)

Cumberbatch,
et. al, (2009)

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

WMAP haze as synchrotron radiation of high energy electrons

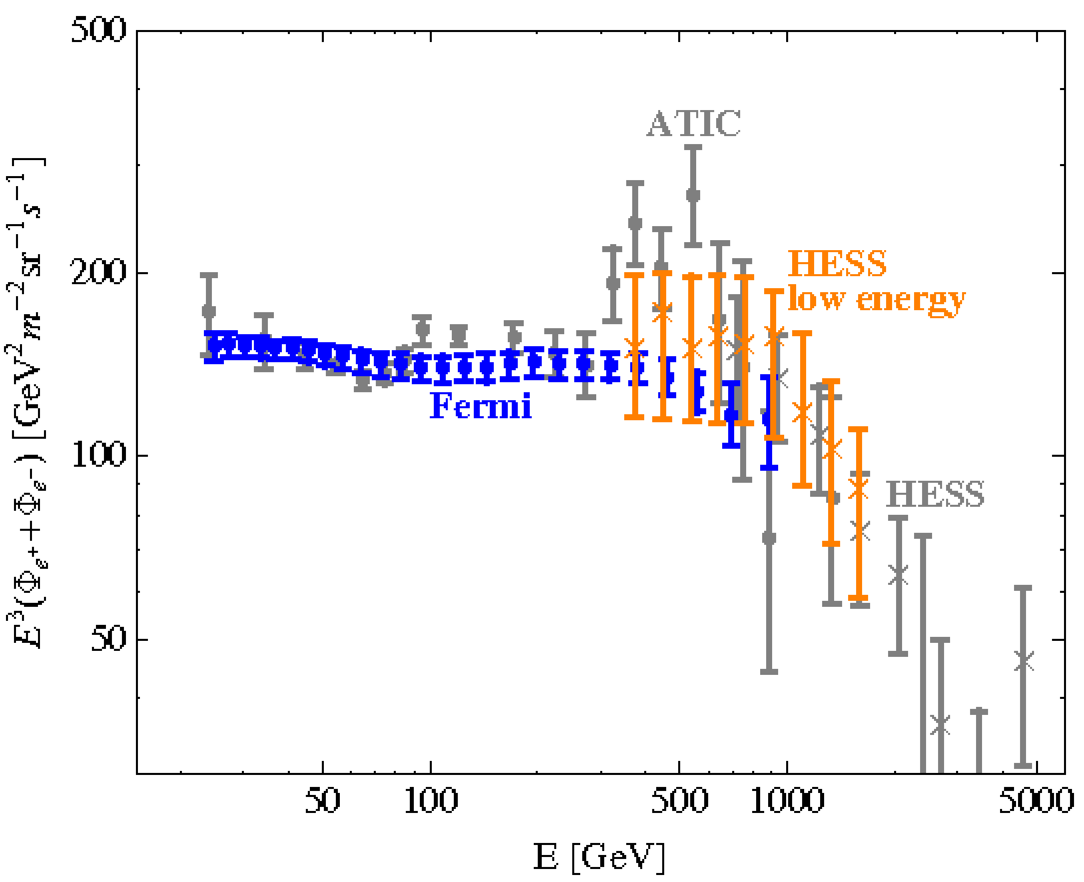
Large systematics?

Cumberbatch,
et. al, (2009)

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:

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

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

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

DM modeling

Annihilation $<v\sigma> = 3\times10^{-26}$ cm³/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

Zhang and Cheng, (2001)

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

cylindrical (r, z)

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

Direct gammas are negligible

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

$\alpha=1.5$

The GALPROP modeling

Strong, et. al. (2004)

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

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

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:

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

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.

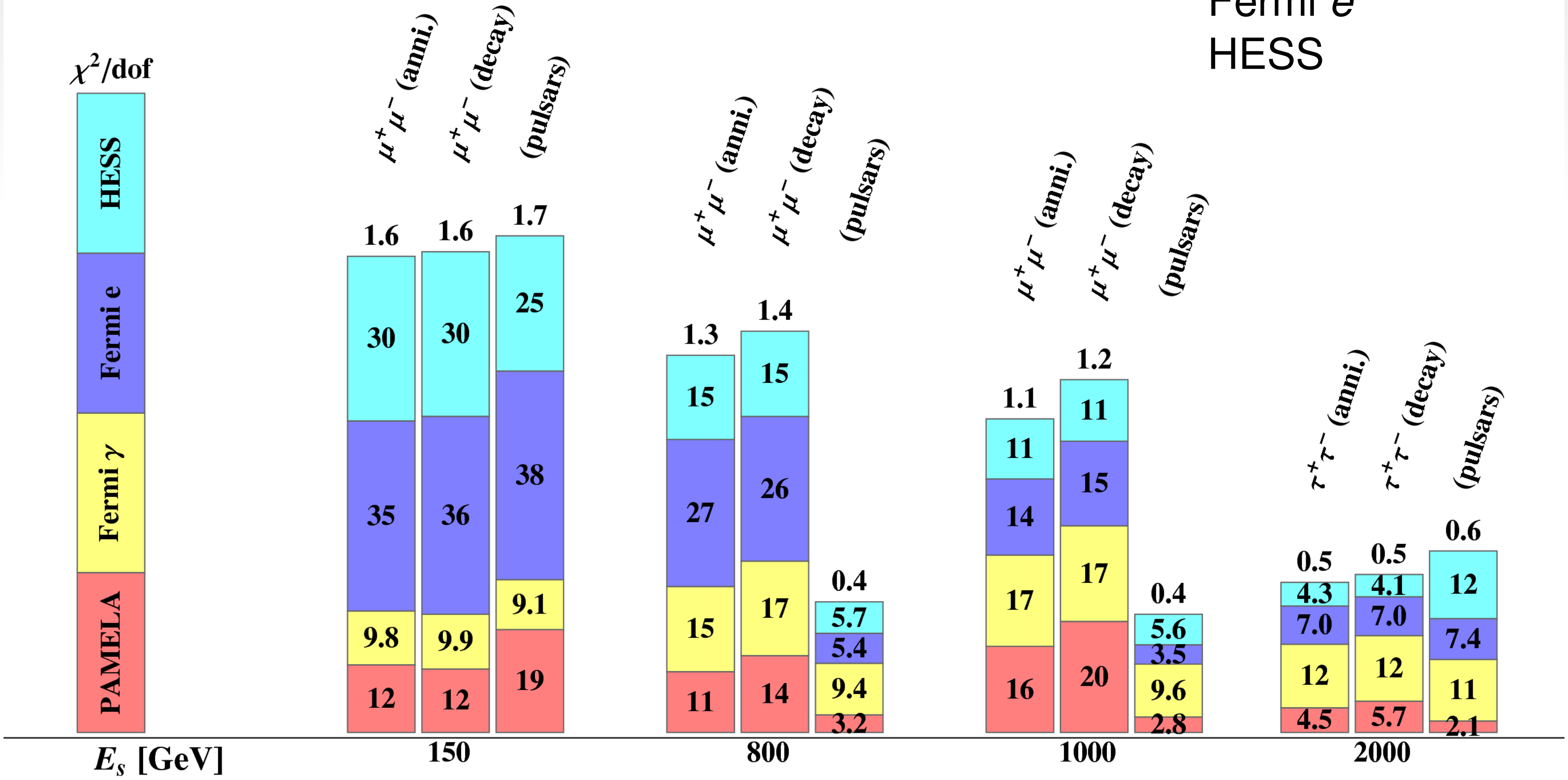
Dark matter: Two body final state

Comparing DM annihilation/decay with pulsars

- ~100 GeV dark matter okay with data; best fits near 1 TeV
  soft electron spectra preferred (mu/tau)
- Lower and steeper electron background favored
- Pulsars fit data very well

Number of data in each set:

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

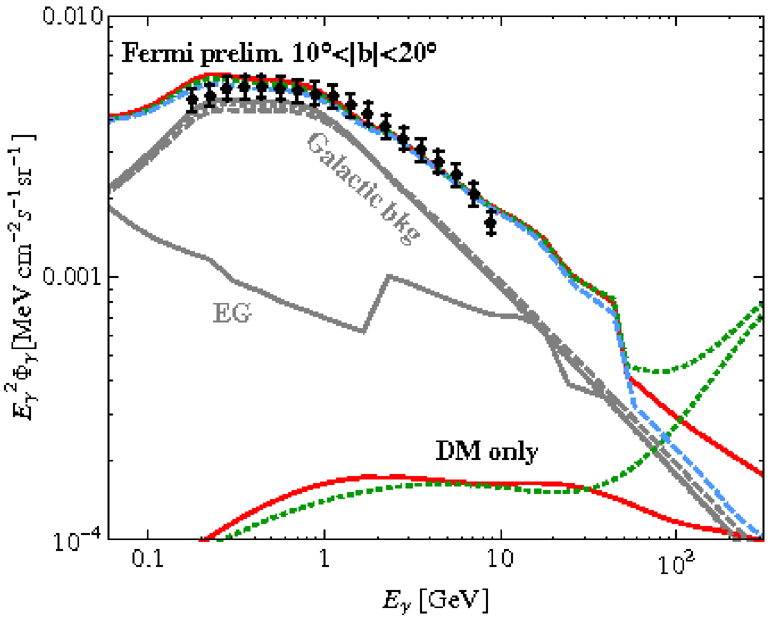


DM profile: Isothermal

Number of parameters: 8

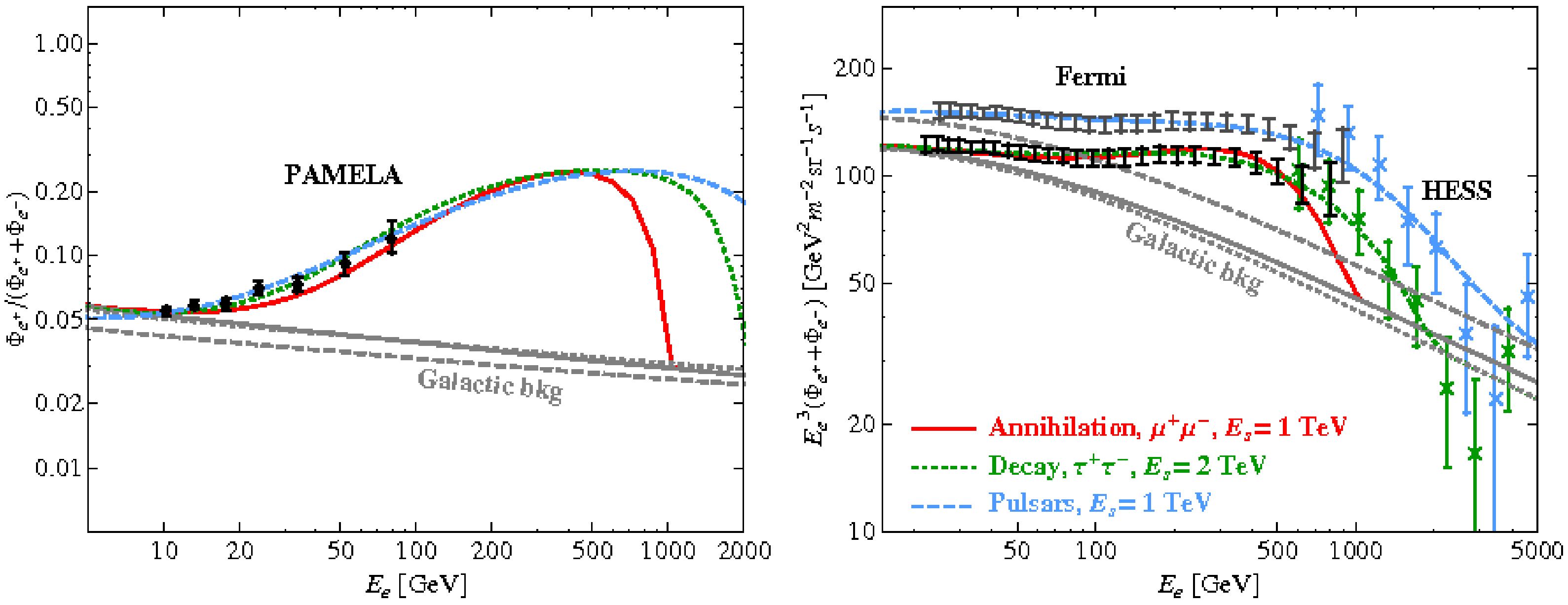
Best-fit spectra:

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



π^0 decay photons

DM prefers lower Fermi and HESS energy calibration; pulsars don't

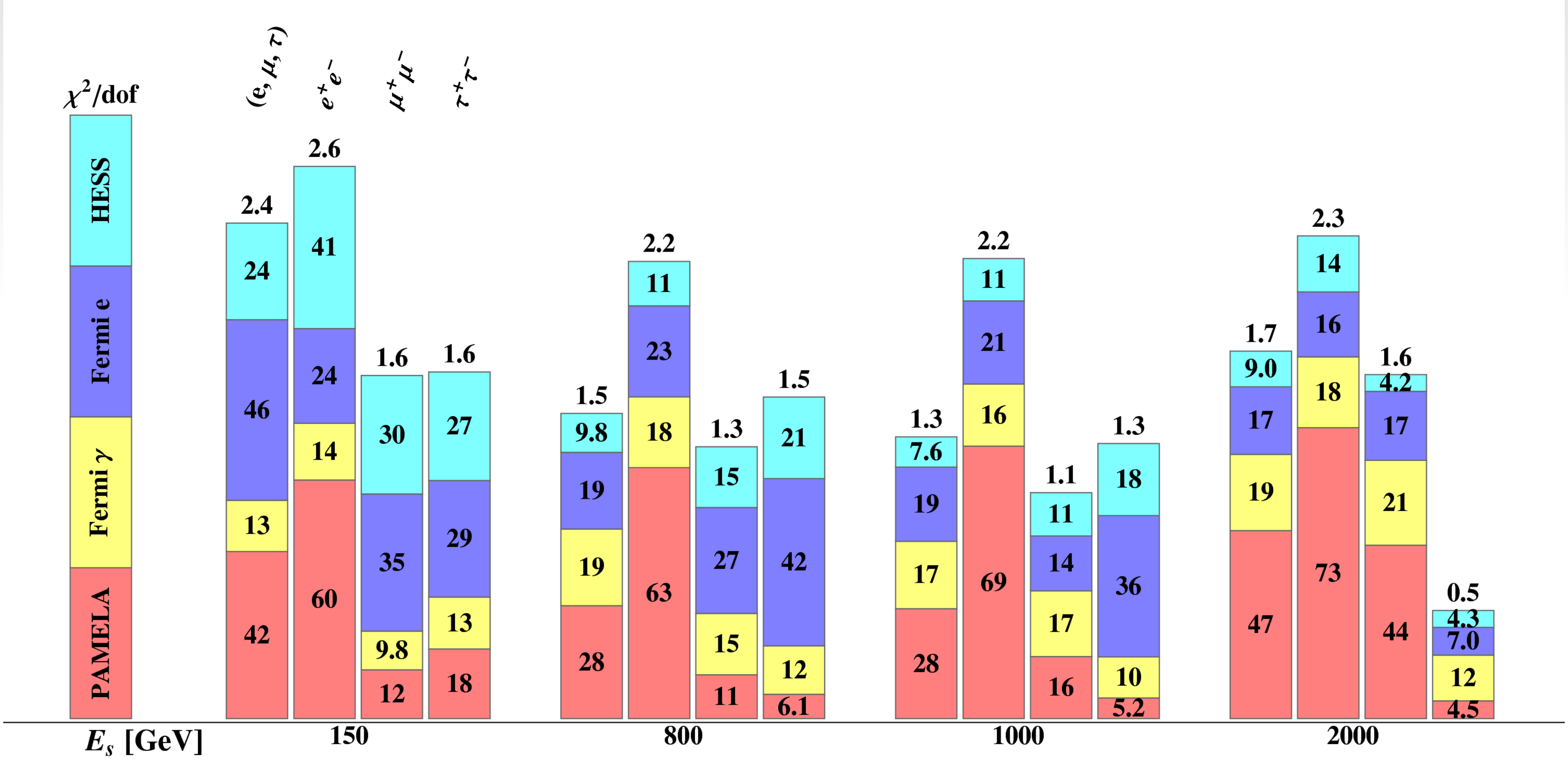


DM annihilation

Number of data in each set:

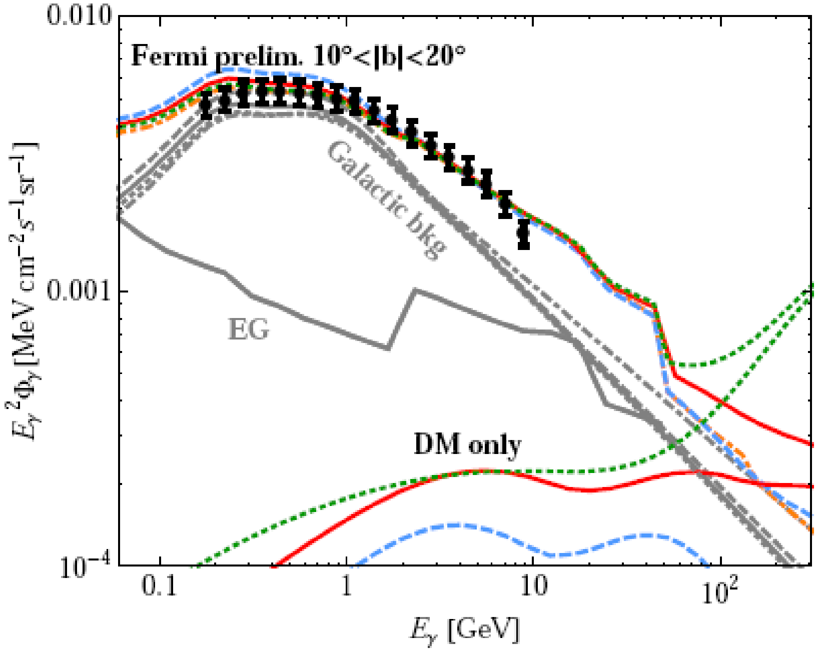
Fermi γ	18
PAMELA	7
Fermi *e*	26+1
HESS	8+1

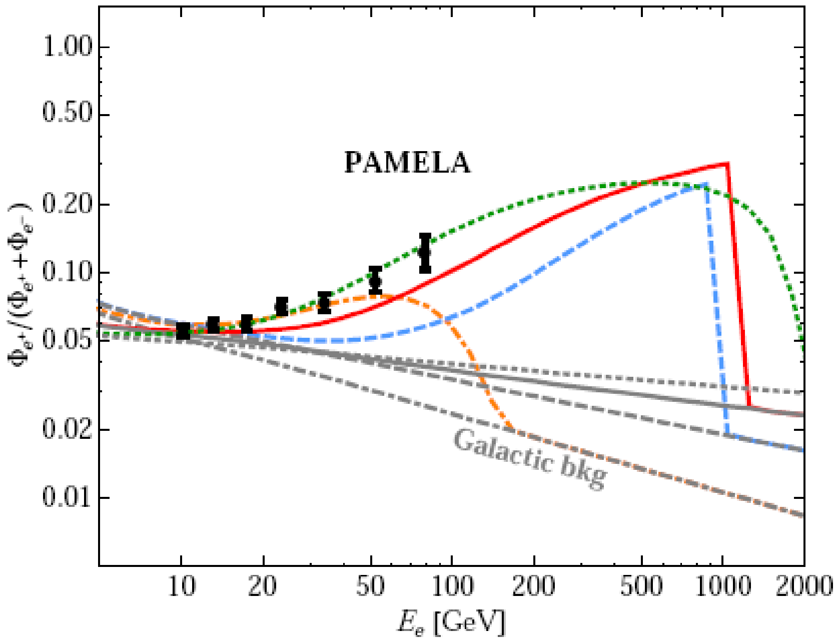
Soft positron spectrum is preferred

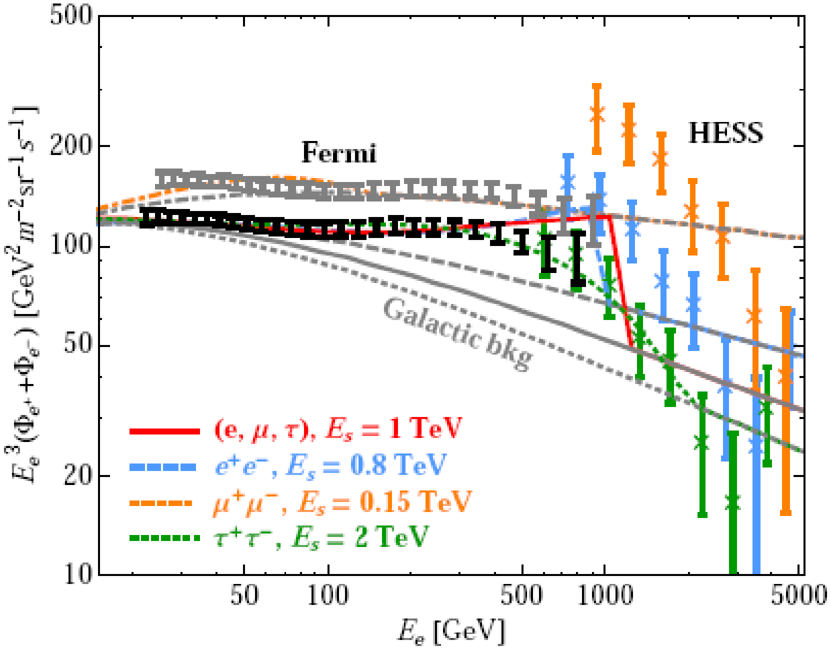


Hard electron spectrum
in trouble with PAMELA

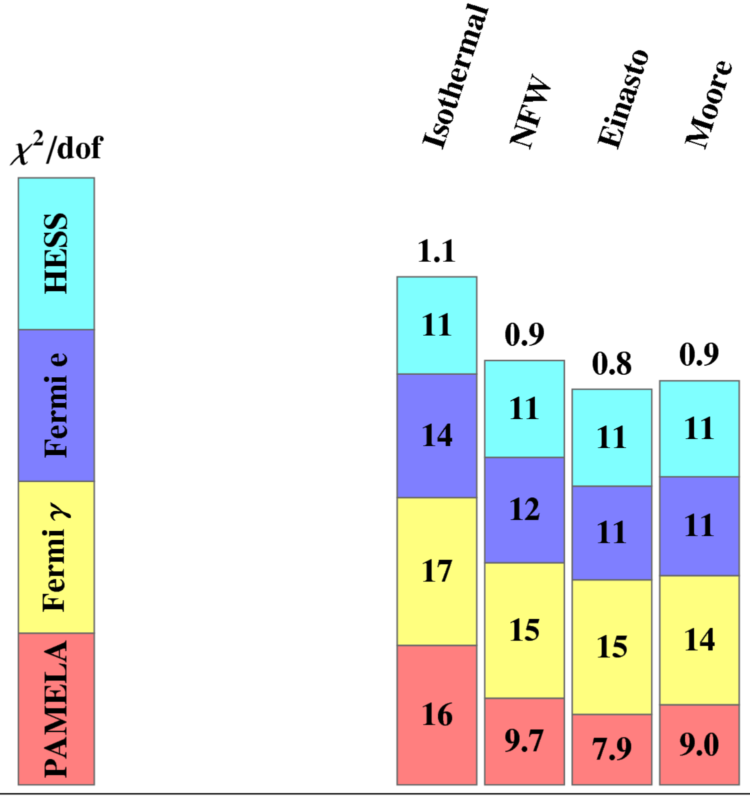
Best-fit annihilation scenarios at various DM masses



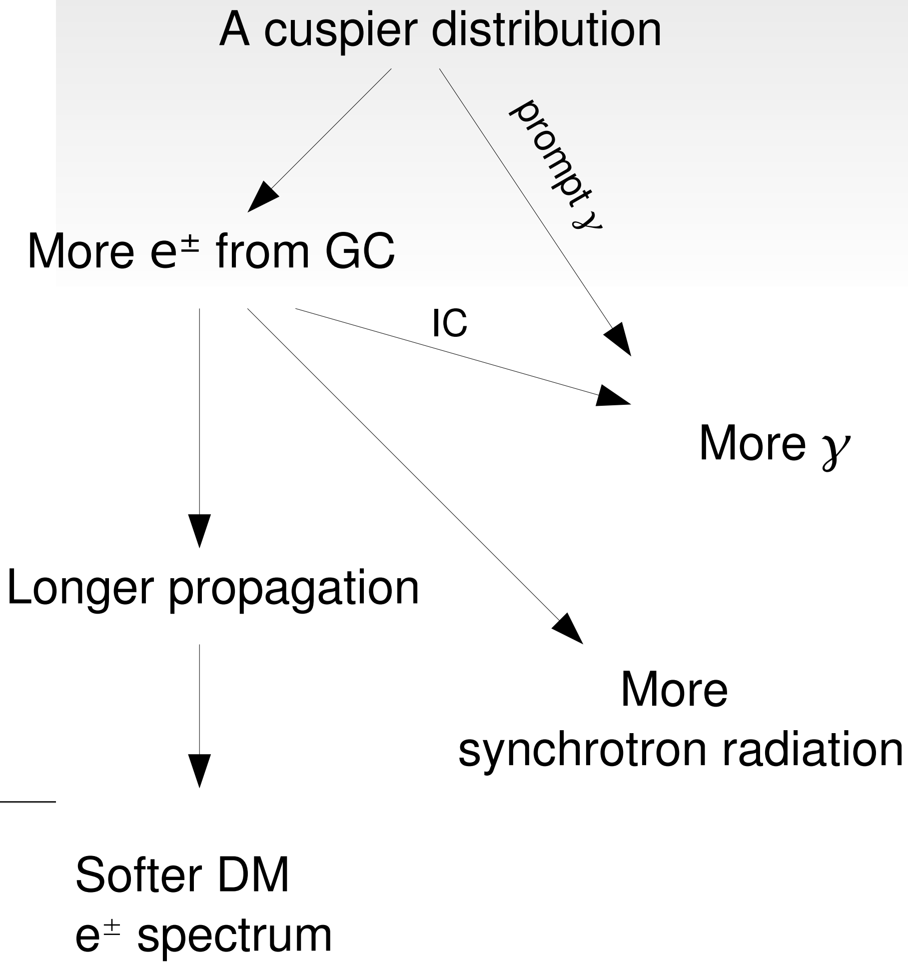




Dependence on halo profiles



Annihilation, μ±, M_{dm}=1 TeV



A cuspier distribution

prompt γ

More $e^{\pm}$ from GC

IC

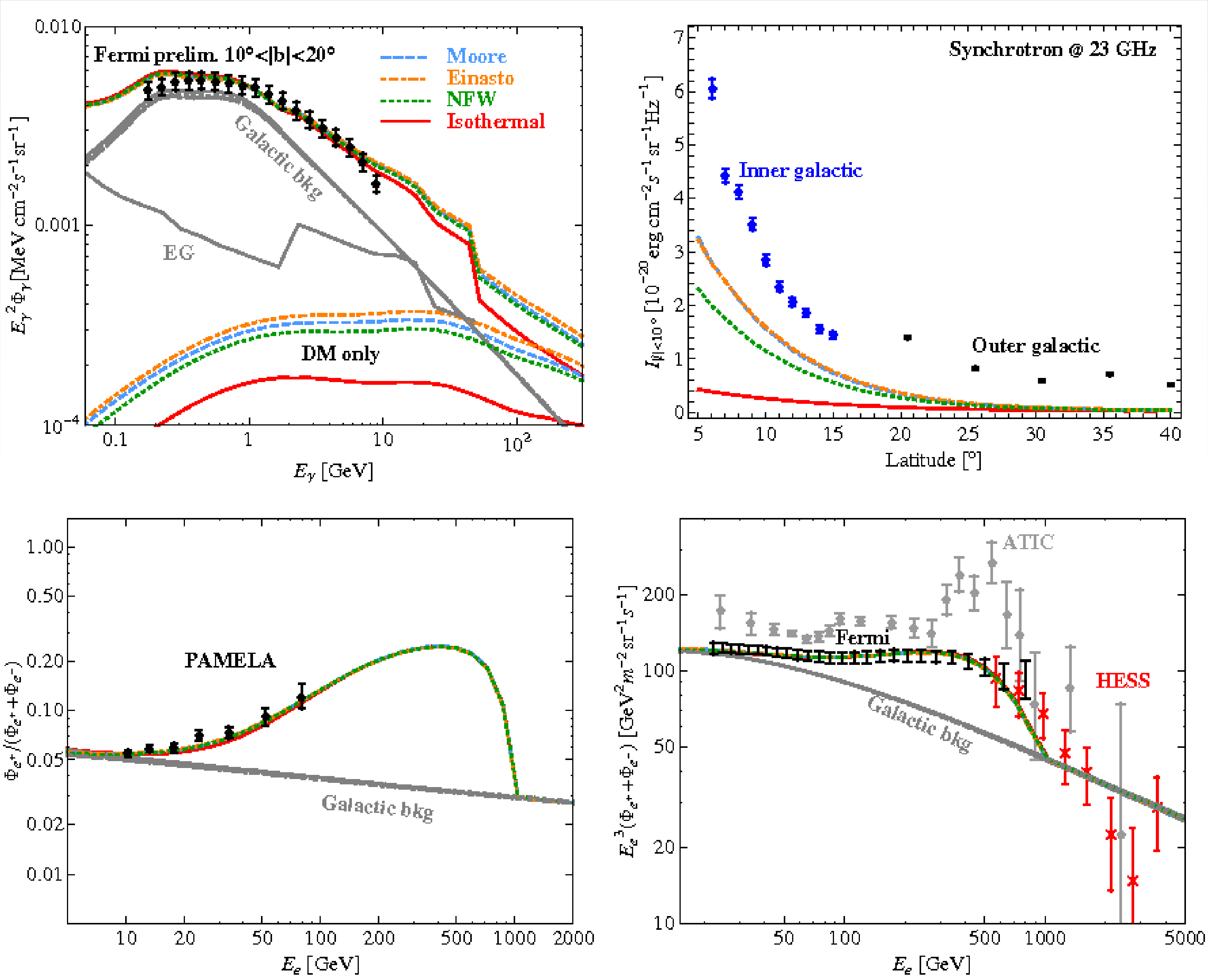
More γ

Longer propagation

More
synchrotron radiation

Softer DM
$e^{\pm}$ spectrum

Profile dependence for DM annihilation ($\mu^{\pm}$, M_{dm}=1 TeV)

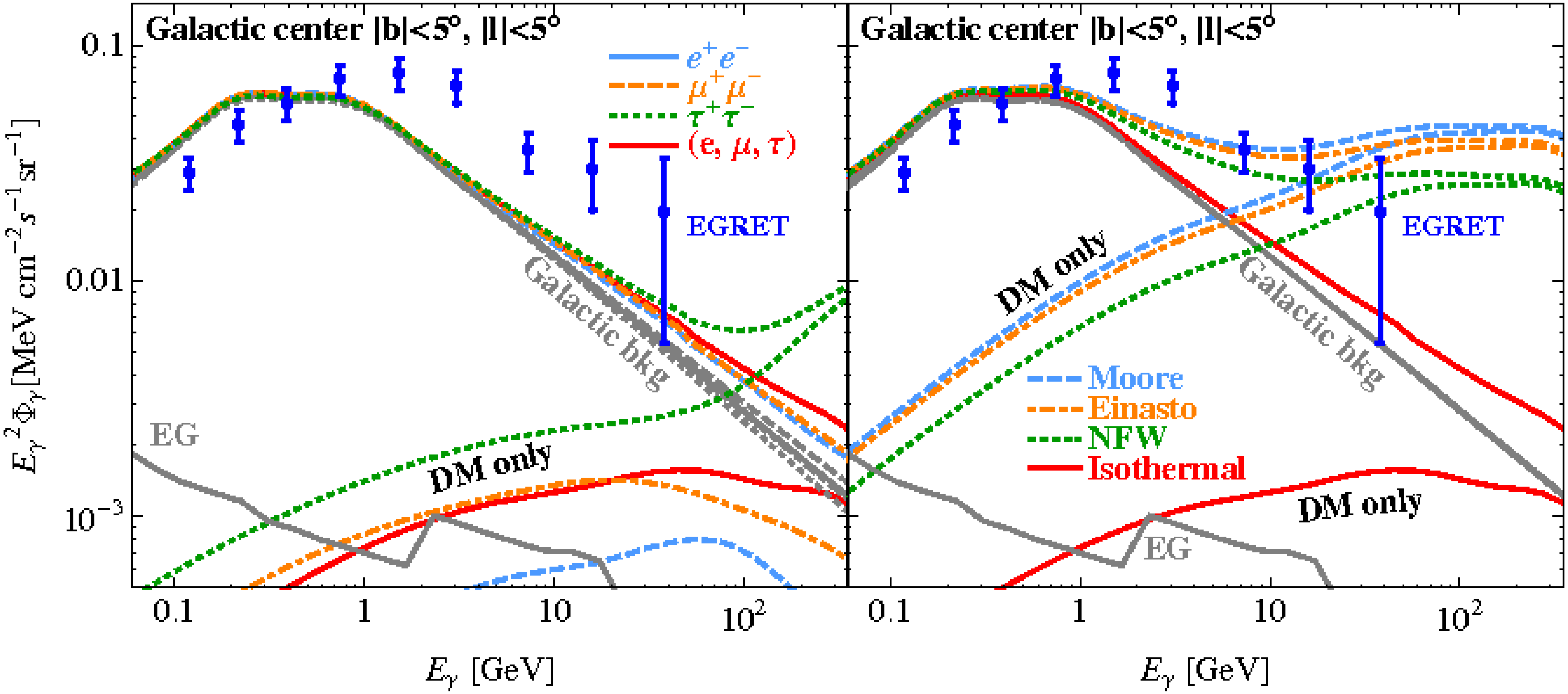


What can Fermi see near the galactic center?

- 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

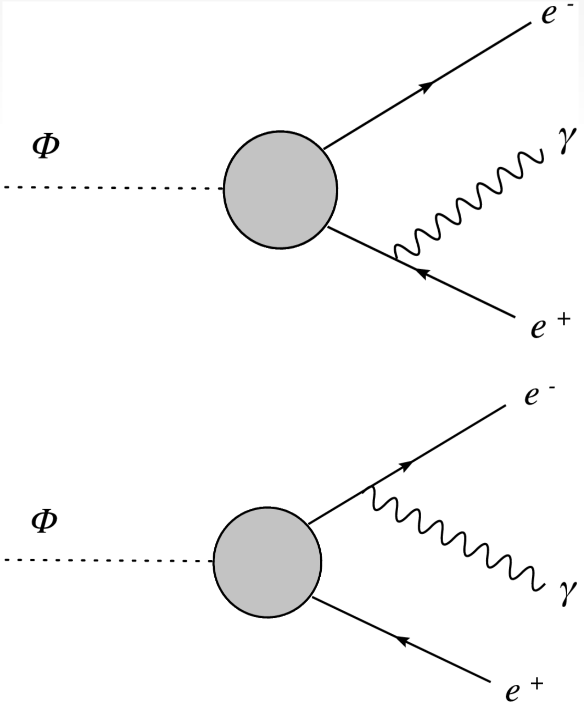


Dark matter: Generic γ signal from Three body final state

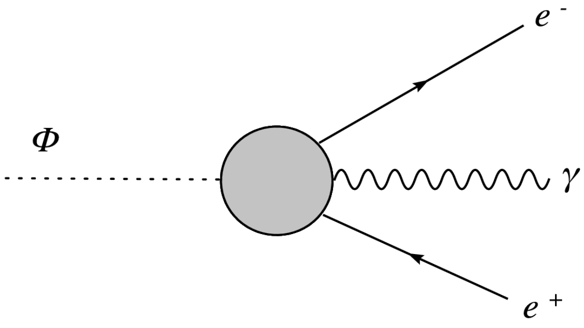
Helicity suppression: $e^+e^-\gamma$ as the leading diagrams

Non-relativistic spin-0 initial states leads to $(m_f/m_{DM})^2$ suppression if chirality-flipping couplings are absent → Two body leptonic final states suppressed

"FSR"



+ "Internal Bremsstrahlung"



Final state *photon* comes to rescue

spin 'independence'

Annihilation: Identical spin ½ or spin 0 DM particles
Decay: spin 0 particles

$$\mathcal{M} \sim \bar{u}_L(p_1)[C(p_1,p_2)\ \not{p}_2\gamma_\mu\ \not{k} + C(p_2,p_1)\ \not{k}\gamma_\mu\ \not{p}_1]v_L(p_2)\epsilon^\mu + (L \to R)$$

Effective Lagrangian for Massive intermediate states ($\Lambda/M_{DM} \to \infty$)

$$\frac{e}{\Lambda_L^3}\Phi\partial_\nu(\bar{\psi}_{eL}\gamma_\mu\psi_{eL})F^{\mu\nu} + (L \to R)$$

Prompt photon spectrum:

$$\frac{1}{\sigma_{tot}}\frac{d\sigma}{dz_\gamma} = 20(1-z_\gamma)z_\gamma^3$$

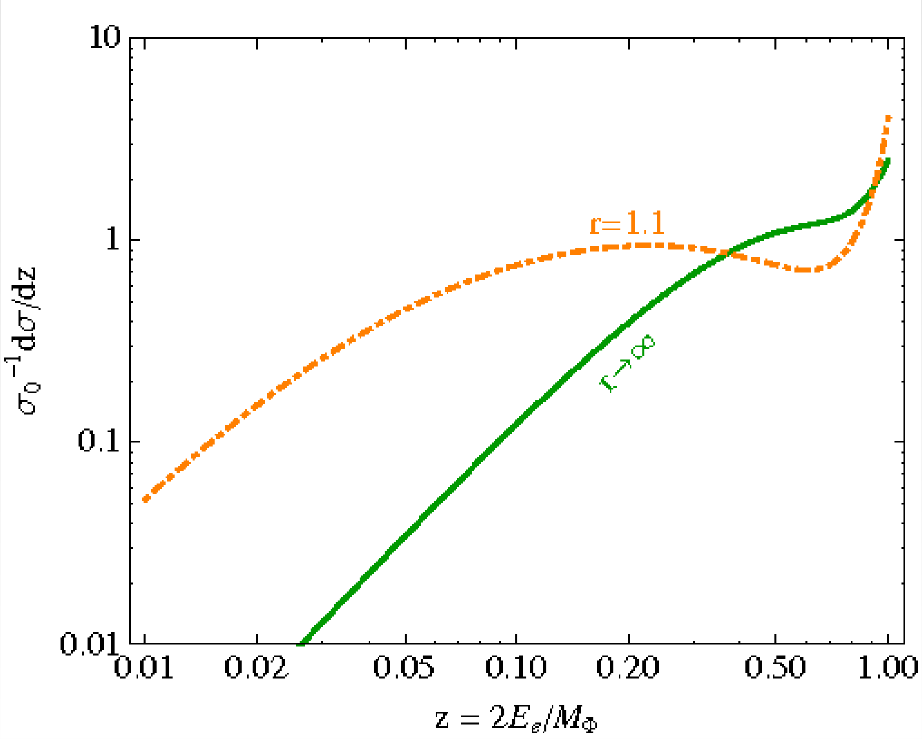
$$z_{\gamma,e} = 2E_{\gamma,e}/M_\Phi$$

$$M_\Phi = \begin{cases} 2M_{DM} & \text{for annihilation} \\ M_{DM} & \text{for decay} \end{cases}$$

Electron spectrum:

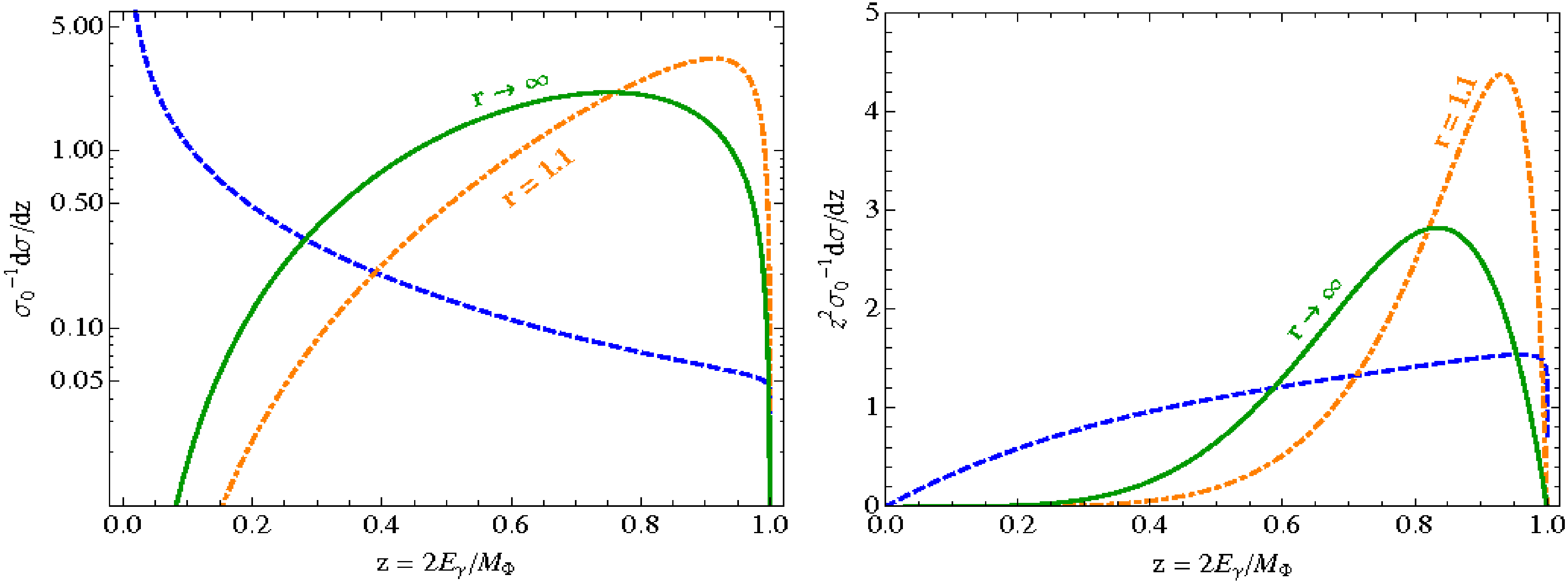
$$\frac{1}{\sigma_{tot}}\frac{d\sigma}{dz_e} = 5(3-6z_e+\frac{7}{2}{z_e}^2)z_e^2$$

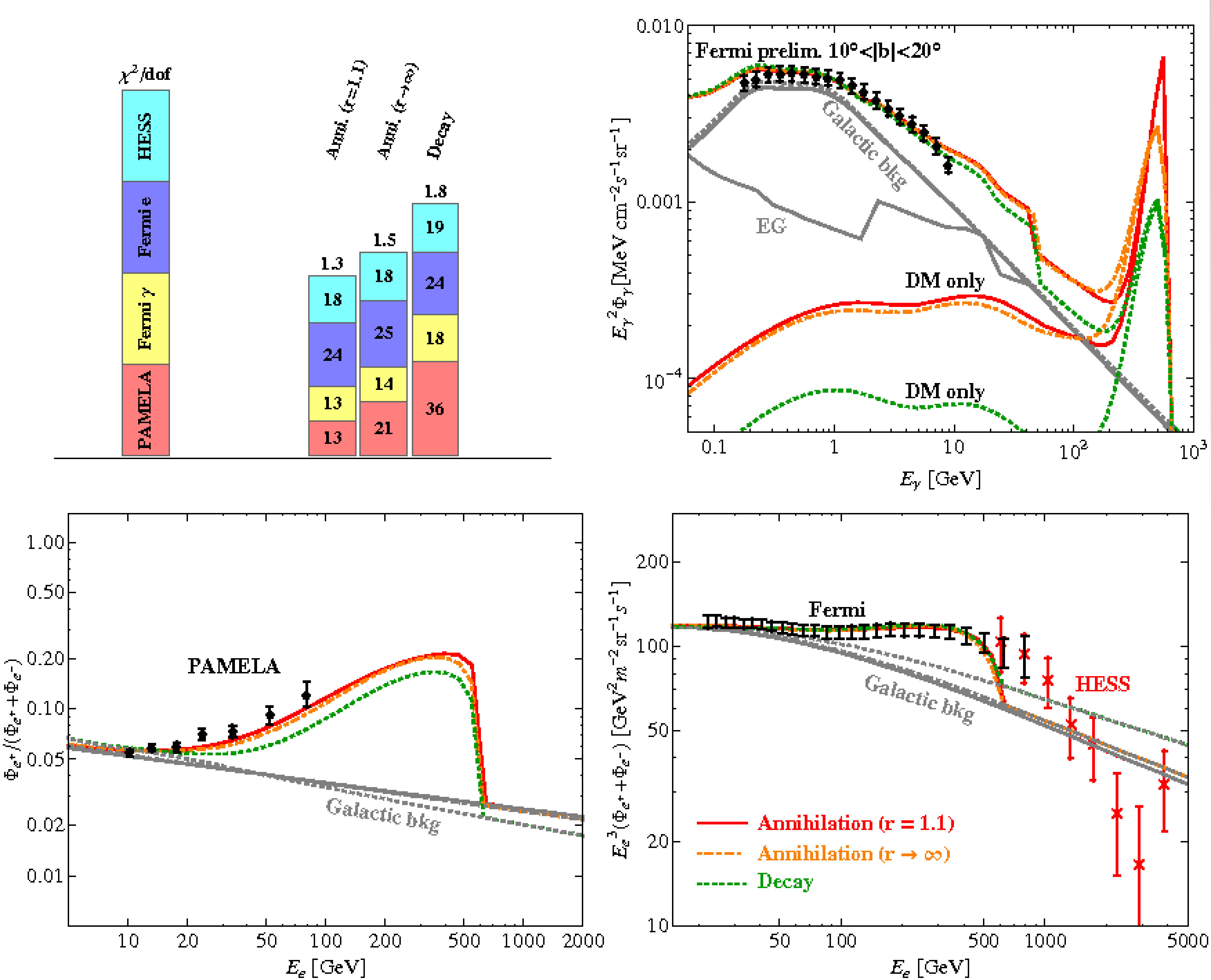
Three body electrons :
A hard spectrum peaked
at high energy



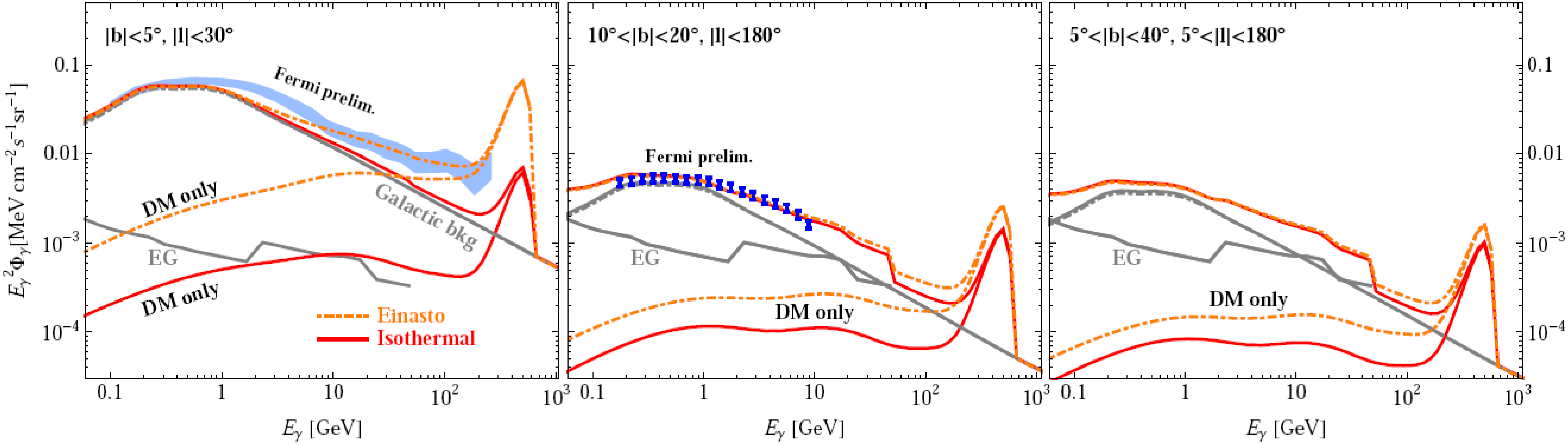
$$r = (2M_{int}/M_\Phi)^2$$

Three body prompt photons:
Peaked at the high energy, contrary to 2 body FSR




χ^2/dof
HESS
Fermi e
Fermi γ
PAMELA
Anni. (r=1.1)
Anni. (r→∞)
Decay
1.3
18
24
13
13
1.5
18
25
14
21
1.8
19
24
18
36
Fermi prelim. 10°<|b|<20°
Galactic bkg
EG
DM only
DM only
$E_\gamma^2\Phi_\gamma$ [MeV cm^{-2}s^{-1}sr^{-1}]
0.010
0.001
10^{-4}
0.1
1
10
10^2
10^3
E_γ [GeV]
PAMELA
Galactic bkg
$\Phi_{e^+}/(\Phi_{e^+}+\Phi_{e^-})$
1.00
0.50
0.20
0.10
0.05
0.02
0.01
10
20
50
100
200
500
1000
2000
E_e [GeV]
Fermi
HESS
Galactic bkg
$E_e^3(\Phi_{e^+}+\Phi_{e^-})$ [GeV^{2}m^{-2}sr^{-1}s^{-1}]
200
100
50
20
10
50
100
500
1000
5000
E_e [GeV]
Annihilation (r = 1.1)
Annihilation (r → ∞)
Decay

Annihilation, r → ∞, 600 GeV DM



P. Drell (Fermi-LAT) (2009)

summary

- Pulsar / leptophilic DM can explain Fermi LAT, PAMELA and HESS data. DM cases need lowering Fermi/HESS energy calibration
- Even with the absence of excesses at mid-latitudes huge gamma ray signal exist in the inner galactic region (with a cuspy profile)
- PAMELA + Fermi electron data disfavor hard electron injection spectra
- Gamma ray signal above 300 GeV ?

Backup slides

Density distribution: dark matter profiles

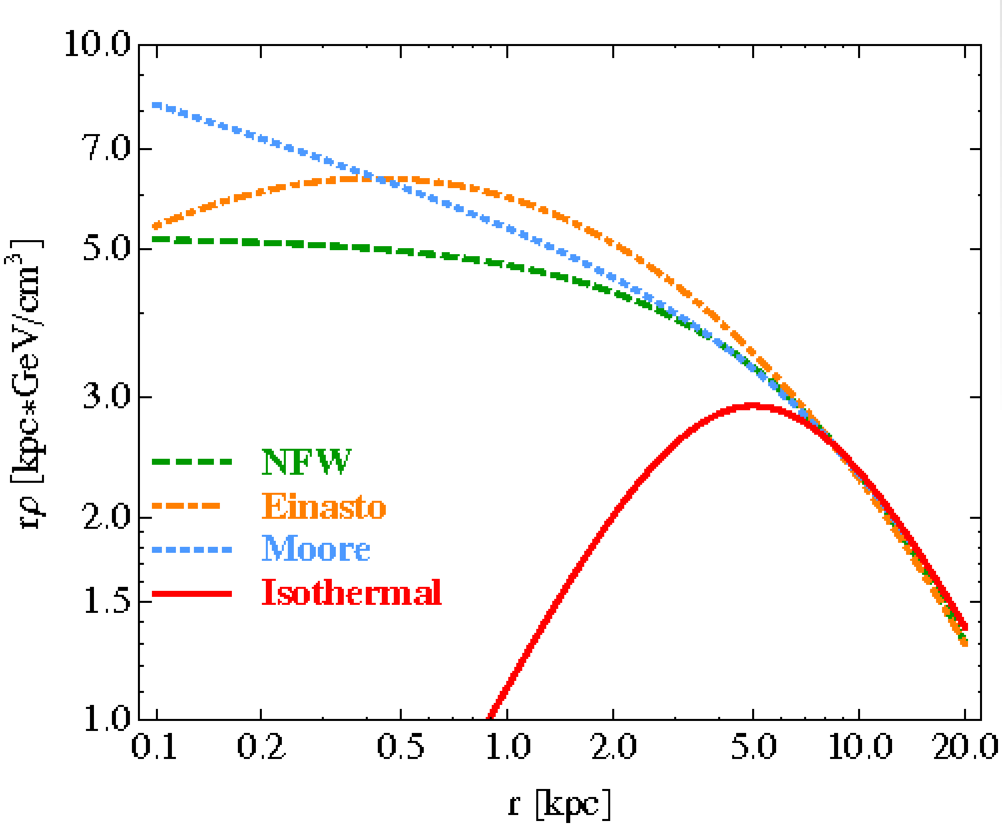
- DM density in the halo can be:

  with a 'cusp':

Moore	Diemand, et. al. (2005)
NFW	Navarro, et. al. (1995)
Einasto	Einasto, et. al. (1965)

  or non-singular:

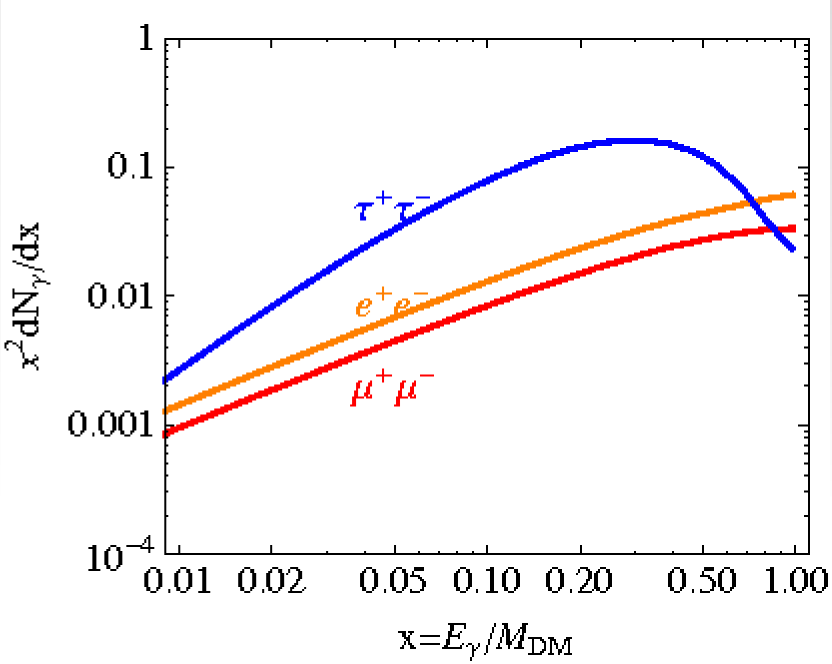
Isothermal	Bahcall and Soneira (1980)



Local DM density = 0.3 GeV/cm^3

Analysis tools

For M_{DM}=1 TeV



Photon spectrum from DMFIT

Jeltema and Profumo, (2008)

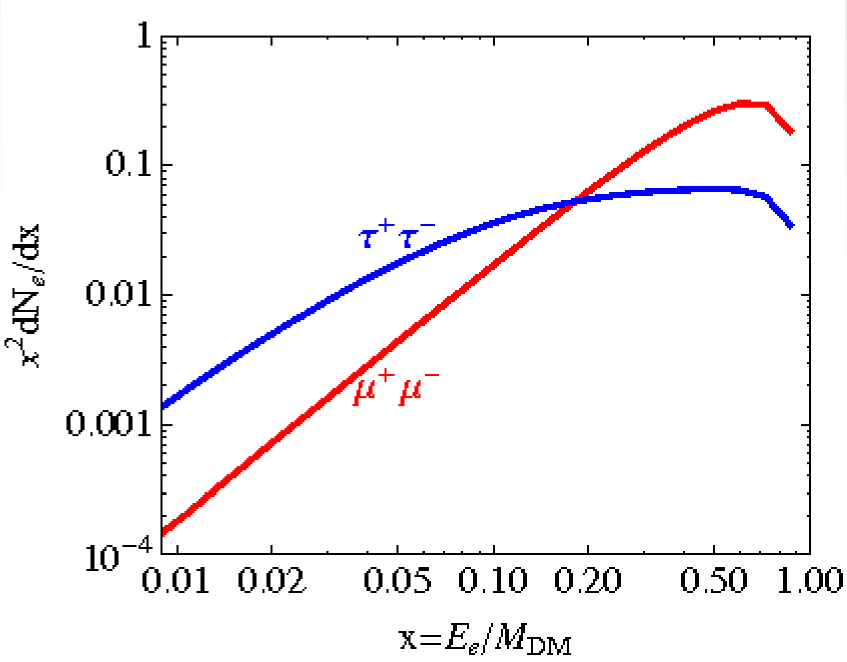
Includes final state radiation
and showering (mainly π^0) contributions

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.



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

Strong and Moskalenko, (2001)

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:

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

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

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

A diffusion parameter prior:

$D(1\text{GV}) = 3\sim5\times10^{28}\text{cm}^2/\text{s}$

to agree with cosmic ray data.

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