The Electron Injection Spectrum Determined By Anomalous Excesses in Cosmic Ray, Microwave, and Gamma Ray Data

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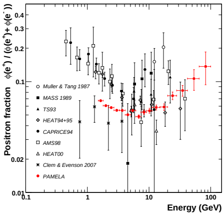
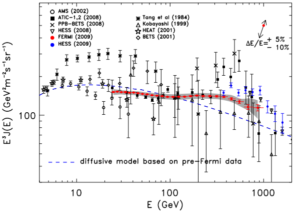
Based on Lin, Finkbeiner, and Dobler
Phys. Rev. D 82, 023518 (2010) or 1004.0989

"Anomalies" in data $\rightarrow$ new source of GeV-TeV $e^{\pm}$?

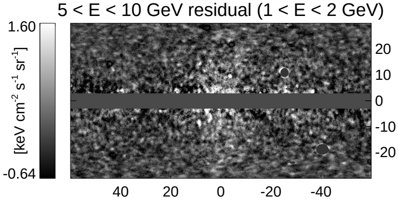
PAMELA e^+ fraction



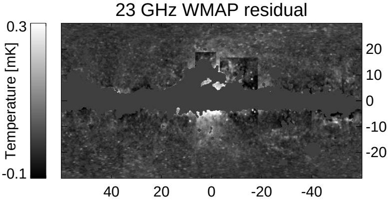
Fermi cosmic ray ($e^{\pm}$)



Fermi gamma ray "haze"



WMAP "haze"



Explanations of data

Would like a consistent framework including new effects/sources without violating other CR signals (protons, antiprotons)

Astrophysics that we don't understand yet

1. Propagation, new effects in sources of CRs

Poorly-understood new source injecting $e^{\pm}$

1. Annihilation of TeV-scale dark matter - Need boost factors, $\bar{p}$ problems
2. Decay of TeV-scale dark matter - $\tau \sim 10^{26} s$
3. An astrophysical source such as pulsars - Morphology problems

Procedure

astrophysics or particle physics model

$\Downarrow$

spectrum of particles produced by the source (e.g. Pythia)

$\Downarrow$

propagation (e.g. GALPROP)

$\Downarrow$

comparison with data

Procedure

astrophysics or particle physics model

$\Uparrow$?

spectrum of particles produced by the source (e.g. Pythia)

$\Uparrow$

propagation (e.g. GALPROP)

$\Uparrow$

comparison with data

Outline

Fit data to “backgrounds” plus new source:

$$Q(E,\vec{x}) \sim n_s(\vec{x}) \times \tau_s^{-1} \times \frac{dN}{dE}(E) \quad (1)$$

Fit for the injected spectrum $Q(E,\vec{x}_0)$ of $e^{\pm}$ which can best explain the “anomalous” signals for:

1. Annihilating Dark Matter
2. Decaying Dark Matter
3. Pulsars
4. Modification to “standard” electron injection
5. Combinations of the above

without assuming a particle physics, pulsar, or SN model, except the spatial dependence. We use GALPROP.

New sources:

Include these source terms in $Q(E, \vec{x})$:

$$\begin{aligned}
\text{annihilation:} \quad & \frac{dN}{dE}\,\langle\sigma v\rangle_0\; BF\,\frac{\langle\rho_\chi^2\rangle}{m_\chi^2}\,\frac{f_E}{2} && \to Q(E,\vec{x}_0)\left(\frac{\rho_\chi(\vec{x})}{\rho_\chi(\vec{x}_0)}\right)^2 \\
\text{decay:} \quad & \frac{dN}{dE}\,\tau_\chi^{-1}\,\frac{\langle\rho_\chi\rangle}{m_\chi}\,f_E && \to Q(E,\vec{x}_0)\left(\frac{\rho_\chi(\vec{x})}{\rho_\chi(\vec{x}_0)}\right) \\
\text{pulsars:} \quad & \frac{dN}{dE}\,\tau_p^{-1}\,\langle n_p\rangle && \to Q(E,\vec{x}_0)\left(\frac{n_p(\vec{x})}{n_p(\vec{x}_0)}\right) \\
\text{SNe } (e^- \text{ only}): \quad & \frac{dN}{dE}\,\tau_s^{-1}\langle n_s\rangle && \to Q(E,\vec{x}_0)\left(\frac{n_s(\vec{x})}{n_s(\vec{x}_0)}\right)
\end{aligned}$$

New sources:

Include these source terms in $Q(E,\vec{x})$:

$$\text{annihilation:}\quad \frac{dN}{dE}\,\langle\sigma v\rangle_0\;BF\,\frac{\langle\rho_\chi^2\rangle}{m_\chi^2}\,\frac{f_E}{2}\quad\rightarrow Q(E,\vec{x}_0)\left(\frac{\rho_\chi(\vec{x})}{\rho_\chi(\vec{x}_0)}\right)^2$$

$$\text{decay:}\quad \frac{dN}{dE}\,\tau_\chi^{-1}\,\frac{\langle\rho_\chi\rangle}{m_\chi}\,f_E\quad\rightarrow Q(E,\vec{x}_0)\left(\frac{\rho_\chi(\vec{x})}{\rho_\chi(\vec{x}_0)}\right)$$

$$\text{pulsars:}\quad \frac{dN}{dE}\,\tau_p^{-1}\,\langle n_p\rangle\quad\rightarrow Q(E,\vec{x}_0)\left(\frac{n_p(\vec{x})}{n_p(\vec{x}_0)}\right)$$

$$\text{SNe }(e^-\text{ only}):\quad \frac{dN}{dE}\,\tau_s^{-1}\langle n_s\rangle\quad\rightarrow Q(E,\vec{x}_0)\left(\frac{n_s(\vec{x})}{n_s(\vec{x}_0)}\right)$$

- No prompt photons for DM annihilation, DM decay
- Ignore low-energy gamma rays from pulsars
- "Standard" spatial profiles: e.g., Einasto $\alpha = 0.12, 0.17, 0.22$

Everything Else

Primary e^-: broken power law with varying index
Secondary $e^\pm$: very sensitive to propagation parameters

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Primary e^-: broken power law with varying index
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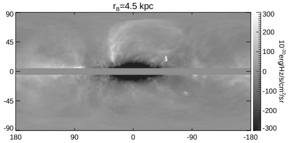
Starlight model: we use the GALPROP default.
Magnetic field model: we use $r_B = 4.5, 6.5$, and 8.5kpc .

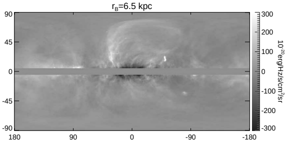
$$|B| = B_0 \exp\left(-\frac{r - r_\odot}{r_B}\right) \exp\left(-\frac{z}{z_B}\right)$$

$r_B = 8.5\text{kpc}$ is actually the best: Haslam 408 MHz minus GALPROP

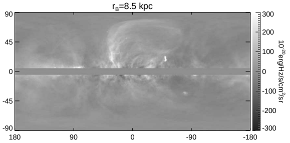
$r_B = 4.5\text{kpc},\ B_0 = 33\mu G$



$r_B = 6.5\text{kpc},\ B_0 = 18\mu G$



$r_B = 8.5\text{kpc},\ B_0 = 14\mu G$



Method

1. Separate $Q(E, \vec{x}_0)$ spectrum into energy bins between 5-5000 GeV
2. Treat each bin as a delta-function injection (LINEAR problem)
3. Signals are obtained by taking a linear combination of signals from each delta function
   $\rightarrow$ Coefficients $\mathbf{x}$, $x_i = Q(E_i, \vec{x}_0)$
4. Matrix $\mathbf{A}$ maps $\mathbf{x}$ to predicted signals,
   A_{ij} is the contribution to data point i for energy bin j
5. Fit to data minus background, $\mathbf{b}$
6. Minimize

$$\chi^2 = (\mathbf{A} \cdot \mathbf{x} - \mathbf{b})^{\mathbf{T}} \mathbf{C}^{-\mathbf{1}} (\mathbf{A} \cdot \mathbf{x} - \mathbf{b})$$

   using a non-negative fit.

Summary of fit

Linear fit parameters:

- $Q(E, \vec{x}_0)$ of new source in 17 log-spaced bins from 5-5000 GeV
- N_{ICS}: normalization of background IC
- N_s, N_p, ΔI_{wmap}

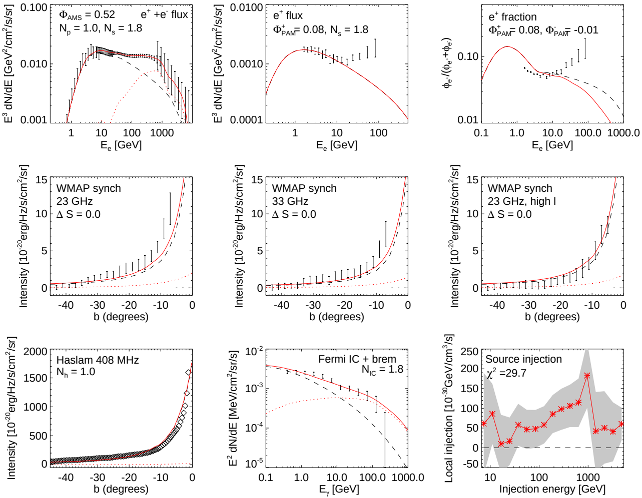
Nonlinear fit parameters:

- $r_B = 4.5, 6.5,$ and 8.5kpc
- γ_e, $\Phi_{AMS}, \Phi^+_{PAM}, \Phi^-_{PAM}$, $\alpha = 0.12, 0.17, 0.22$

350 data points:

- $e^+ + e^-$ flux: AMS, Fermi, HESS
- e^+ flux: PAMELA $\times$ $e^+ + e^-$
- pion-subtracted Fermi gamma rays
- WMAP synchrotron at 23, 33, and 41 GHz
- Haslam 408 MHz

Source Modification Best Fit Spectrum

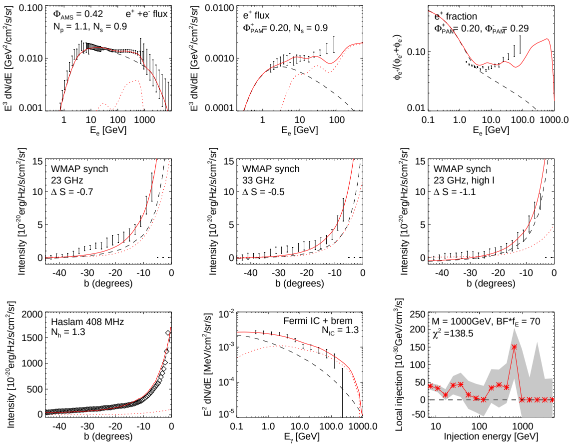


$\gamma_e = 2.65$

$r_B = 8.5\text{kpc}$

PAMELA data above 10 GeV and WMAP haze data NOT included in fit.

Annihilation Best Fit Spectrum



Einasto $\alpha = 0.22$

$\gamma_e = 2.5$

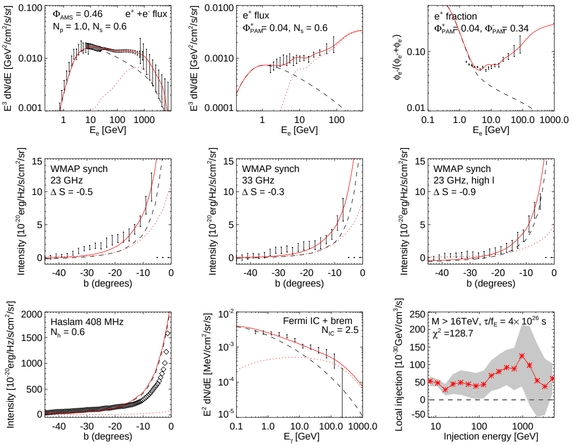
$r_B = 8.5\text{kpc}$

$m_\chi \approx 1$ TeV

$BF \times f_E(e^+ + e^-) \sim 70$

- Fit is equally good for $r_B = 4.5, 6.5\text{kpc}$
- Normalization factors $N \sim 1$

Decay Best Fit Spectrum

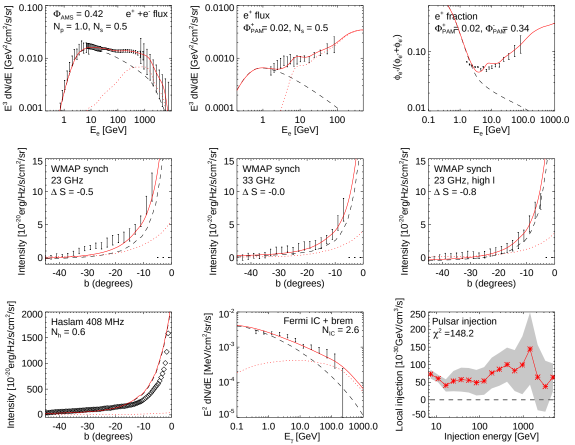


Einasto $\alpha = 0.12$
$\gamma_e = 2.6$
$r_B = 4.5$kpc

$m_\chi \gtrsim 16$ TeV
$\tau_\chi / f_E(e^+ + e^-) \sim 4 \times 10^{26}$ s

- $r_B = 4.5$kpc needed to produce WMAP haze
- Some normalization factors $N \sim 2 - 3$
- Many low energy $e^\pm$ injected

Pulsar Best Fit Spectrum



$\gamma_e = 2.6$

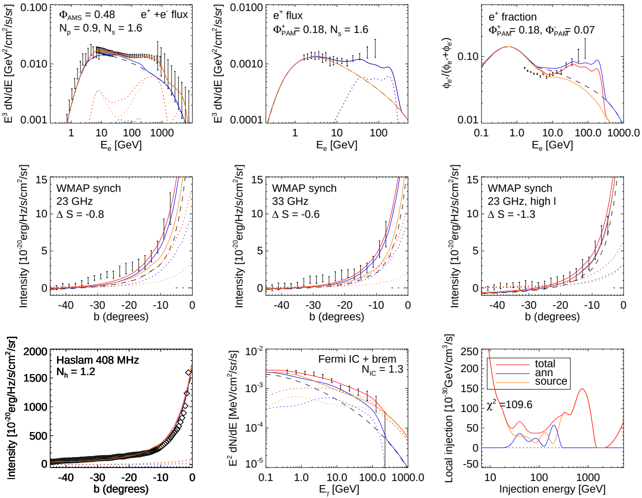
$r_B = 4.5\text{kpc}$

- $r_B = 4.5\text{kpc}$ needed to produce WMAP haze
- Some normalization factors $N \sim 2-3$
- Many low energy $e^\pm$ injected

Comments

- Fit spectrum of $e^{\pm}$ for DM Annihilation, DM Decay, Pulsars, ... to explain CR, gamma ray and microwave excesses all at once
- DM Annihilation
  $\rightarrow m_\chi \sim 1\text{TeV}, BF \times Br \sim 80$
  $\rightarrow$ self-consistent model in GALPROP with $r_B = 8.5\text{kpc}$
- DM Decay and Pulsars
  $\rightarrow$ high magnetic fields, radiation fields needed to fit haze
- Spectra qualitatively the same despite large range of background model freedom
- Source + DM Annihilation and Pulsar + DM Annihilation do well, but too much freedom

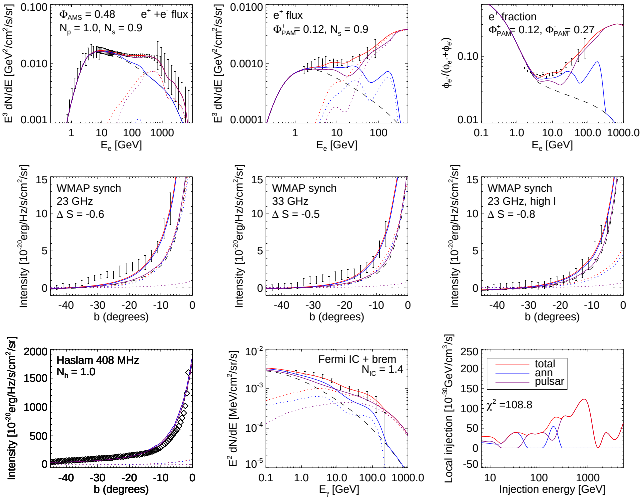
Annihilation + Source Mod Best Fit Spectrum



Einasto $\alpha = 0.17$,
$\gamma_e = 2.55$
$r_B = 8.5$kpc

- LARGE error bars, not shown
- $m_\chi \sim 300$GeV, $BF \times f_E(e^+ + e^-) \sim 10$

Annihilation + Pulsars Best Fit Spectrum



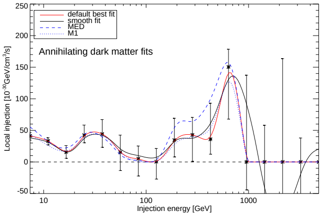
Einasto $\alpha = 0.17$,

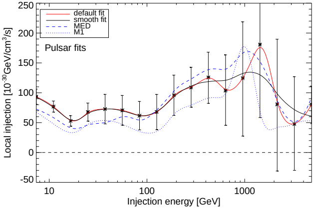
$\gamma_e = 2.65$

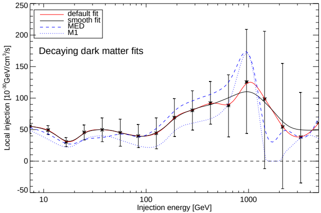
$r_B = 8.5$kpc

- LARGE error bars, not shown
- $m_\chi \sim 300\text{GeV}$, $BF \times f_E(e^+ + e^-) \sim 10$

Propagation







	K_0	δ	L
Default	0.097	0.43	4
M1	0.0765	0.46	15
MED	0.0112	0.70	4

Table: K_0 in kpc^2/Myr, L in kpc.

Injected primary electrons

$$\frac{dN}{dE} \propto \begin{cases} (E/4\text{GeV})^{1.6} & E < 4\text{GeV} \\ (E/4\text{GeV})^{\gamma_e} & 4\text{GeV} < E < 2200\text{GeV} \\ (E/2200\text{GeV})^{3.3} & E > 2200\text{GeV} \end{cases} \tag{2}$$

We use γ_e= 2.45, 2.50, 2.55, 2.60, 2.65, 2.70

Spatial distribution:

$$n_e(\vec{x}) \propto \left(\frac{r}{r_\odot}\right)^\alpha \exp\left(-\beta\frac{r}{r_\odot} - \frac{|z|}{.2\text{kpc}}\right)\Theta(r_{max} - r) \tag{3}$$

where r is distance to the center of galaxy projected on the galactic plane. The parameters are $\alpha = 2.35$, $\beta = 5.56283$, and $r_{max} = 15$kpc .
Normalization fixed using Haslam 408 MHz signal.

Spectrum for different r_B, γ_e

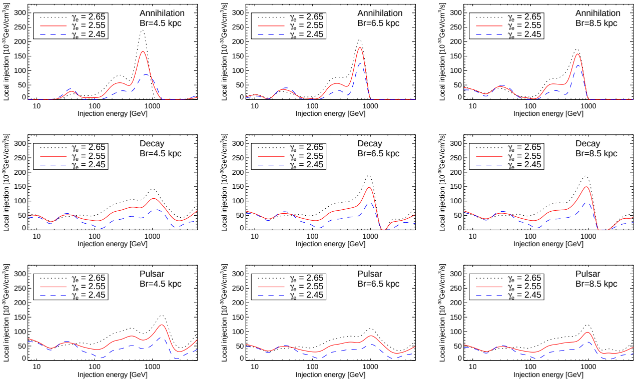
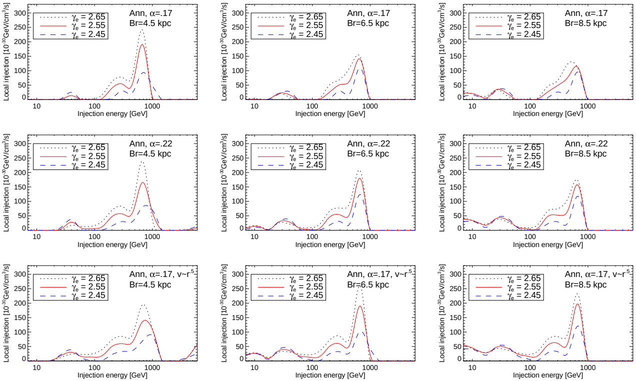


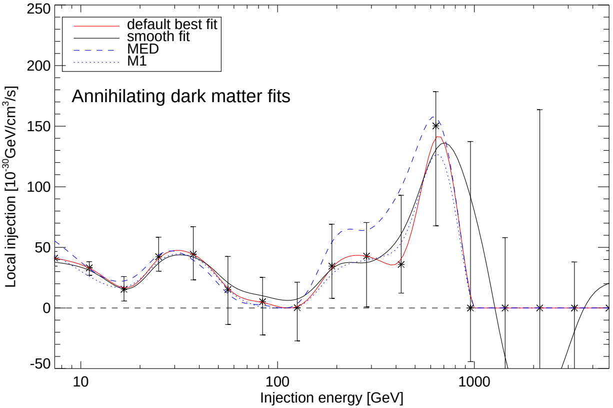
Figure: All fit results for the three scenarios, over a 3×3 grid in background electron injection index ($\gamma_e = 2.45, 2.55, 2.65$) and scale for the magnetic field $B_r = 4.5, 6.5$, and 8.5 kpc. These spectra were obtained from non-negative fits; the interpolated local injection density is plotted. Despite a wide range of assumptions about the background model, the results remain the same, qualitatively, for each scenario.

Spectrum for different α, γ_e



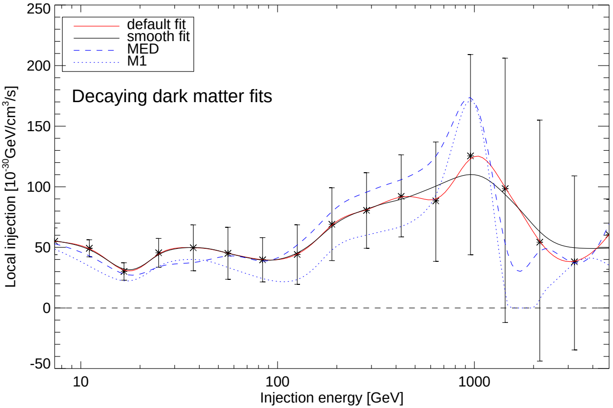
Results: DM Annihilation

- $m_\chi \sim 1\text{TeV}, BF * Br \sim 80$
- Einasto $\alpha = 0.22,\ \gamma_e = 2.5,\ B_r = 8.5\text{kpc}$



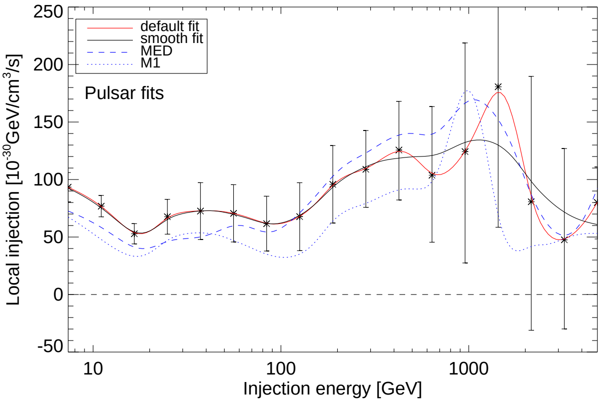
Results: DM Decay

- $m_\chi \gtrsim 3\text{TeV}, \tau/Br \sim 2 \times 10^{26} s$
- Einasto $\alpha = 0.12$, $\gamma_e = 2.6$, $B_r = 4.5\text{kpc}$



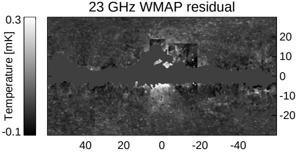
Results: Pulsar

- $\gamma_e = 2.6$, $B_r = 4.5$kpc

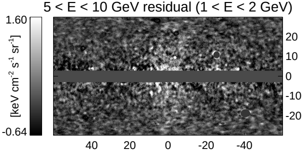


Haze morphology

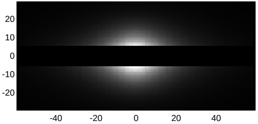
WMAP haze



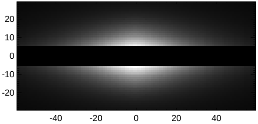
Fermi gamma ray haze



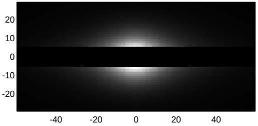
DM Ann 23 GHz, $r_B = 4.5$kpc



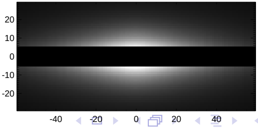
Pulsar 23 GHz, $r_B = 4.5$kpc



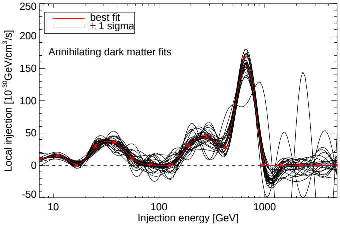
DM Ann 23 GHz, $r_B = 6.5$kpc

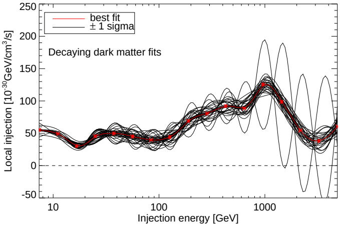


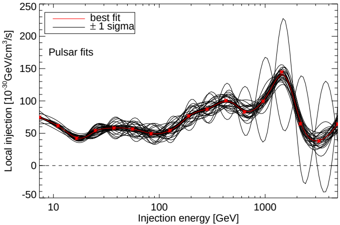
Pulsar 23 GHz, $r_B = 6.5$kpc



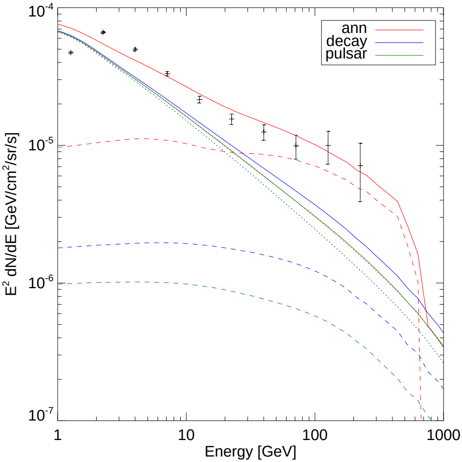
Error Bars


best fit
± 1 sigma
Annihilating dark matter fits
Local injection [10^-30 GeV/cm^3/s]
250
200
150
100
50
0
-50
10
100
1000
Injection energy [GeV]


best fit
± 1 sigma
Decaying dark matter fits
Local injection [10^-30 GeV/cm^3/s]
250
200
150
100
50
0
-50
10
100
1000
Injection energy [GeV]


best fit
± 1 sigma
Pulsar fits
Local injection [10^-30 GeV/cm^3/s]
250
200
150
100
50
0
-50
10
100
1000
Injection energy [GeV]

Gamma rays near Galaxy center



Solar Modulation

Low-energy (below $\sim 1 - 10$GeV) CR data affected by solar physics.
Solar modulation correction:

$$\frac{J_{\odot}(E)}{E^2 - m_e^2} = \frac{J_{LIS}(E+\Phi)}{(E+\Phi)^2 - m_e^2}$$

Conversion of PAMELA positron **fraction** to a positron **flux**

$$J_{PAM}(e^+) = \left(\frac{\phi(e^+)}{\phi(e^-)+\phi(e^+)}\right)_{PAM} \times \hat{S}_{\Phi^-_{PAM}} \left(\hat{S}^{-1}_{\Phi_{AMS}}\left[J_{AMS}(e^+ + e^-)\right]\right)$$

Parameters: $\Phi_{AMS}, \Phi^-_{PAM}, \Phi^+_{PAM}$ - allow two different PAMELA parameters to allow for charge sign dependence of modulation affects.

Dark matter parameters

Annihilation:

$$\int E \frac{dN}{dE} dE = m_\chi \tag{4}$$

Therefore, integrating the local injection multiplied by energy gives

$$\int E\ Q(E, \vec{x}_0) dE = \ \langle \sigma v \rangle_0 \times BF \times \frac{(\rho_0)^2}{m_\chi} \times \frac{Br(e^+ e^-)}{2}. \tag{5}$$

Decay:

$$\int E \frac{dN}{dE} = m_\chi \tag{6}$$

Again, we integrate the local injection multiplied by energy, giving

$$\int E\ Q(E, \vec{x}_0) dE = \ \tau_\chi^{-1} \times \rho_0 \times \frac{Br(e^+ e^-)}{2}. \tag{7}$$

Some standard spectra