

Implications of the PAMELA and ATIC excesses on the Dark Matter properties

- 1) The data
- 2) Model-independent theory
- 3) Implications: are we finally seeing DM?

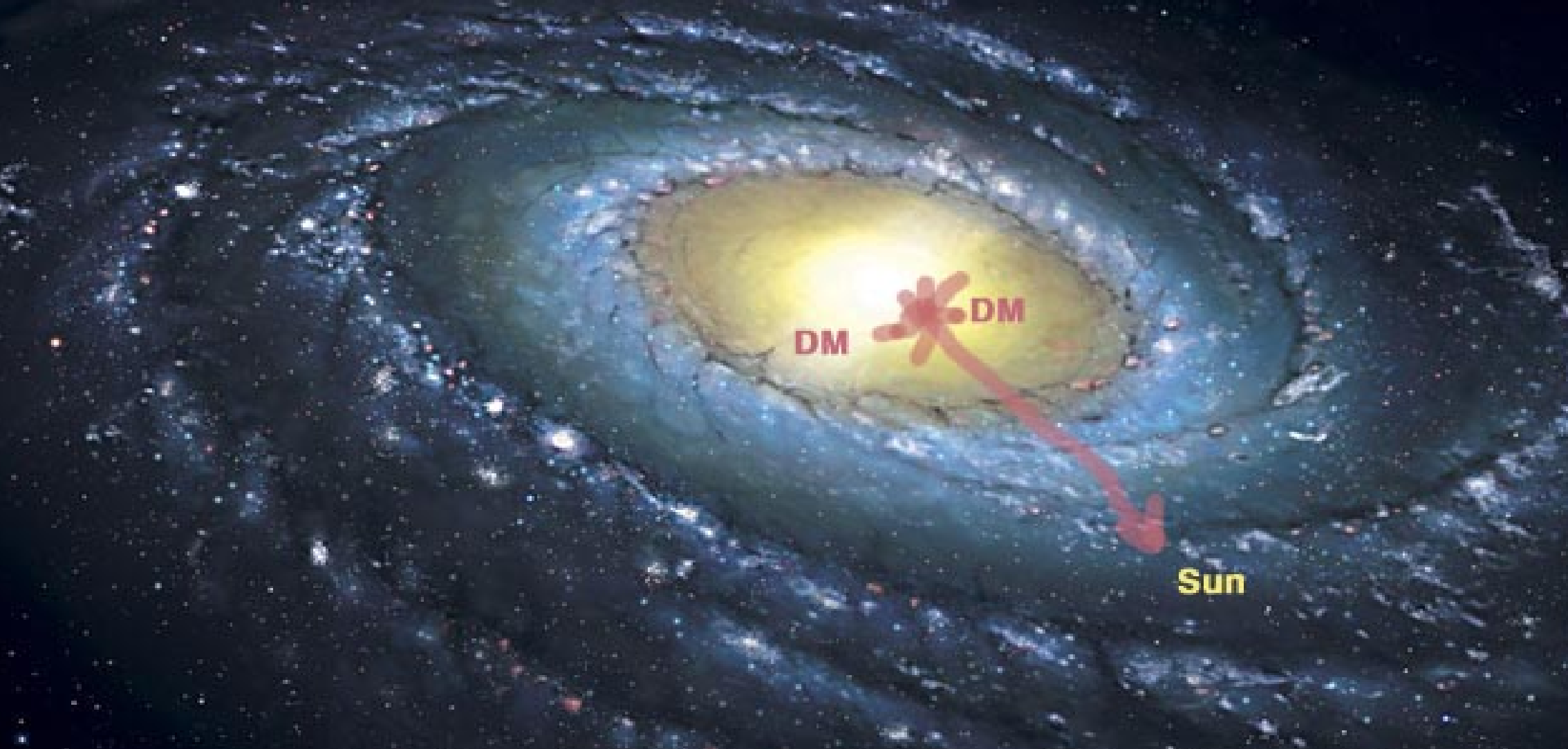
Alessandro Strumia

From [arXiv/0809.2409](https://arxiv.org/abs/0809.2409)

with M. Cirelli, M. Kadastik, M. Raidal.

www.cern.ch/astrumia/PAMELA.pdf

Indirect signals of Dark Matter



DM DM annihilations in our galaxy might give detectable γ , e^+ , \bar{p} , \bar{d} .

The galactic DM density profile

DM velocity: $\beta \approx 10^{-3}$. DM is **spherically** distributed with uncertain profile:

$$\rho(r) = \rho_{\odot} \left[\frac{r_{\odot}}{r} \right]^{\gamma} \left[\frac{1 + (r_{\odot}/r_s)^{\alpha}}{1 + (r/r_s)^{\alpha}} \right]^{(\beta-\gamma)/\alpha}$$

where $r_{\odot} = 8.5$ kpc, $\rho_{\odot} \equiv \rho(r_{\odot}) \approx 0.3 \text{ GeV/cm}^3$ and

DM halo model		α	β	γ	r_s in kpc
Isothermal	'isoT'	2	2	0	5
Navarro, Frenk, White	'NFW'	1	3	1	20
Moore	'Moore'	1	3	1.16	30

N -body simulations suggest that DM might clump in subhalos



Increase fluxes by a **boost factor** $B = 1 \leftrightarrow 100 \sim$ a few

Propagation of e^+

$\Phi_{e^+} = v_{e^+} f / 4\pi$ where $f = dN/dV dE$ obeys: $-K(E) \cdot \nabla^2 f - \frac{\partial}{\partial E}(b(E)f) = Q$.

- DM DM injection term: $Q = \frac{1}{2} \left(\frac{\rho}{m_{\text{DM}}} \right)^2 \sum_f \langle \sigma v \rangle_f \frac{dN_{e^+}^f}{dE}$.
- Diffusion coefficient: $K(E) = K_0 (E/\text{GeV})^\delta$. ($K \sim R_{\text{Larmor}} = E/eB$).
- Energy loss: $b(E) = E^2/\text{GeV}/\tau_E$ with $\tau_E = 10^{16}$ s.
- Boundary: f vanishes on a cylinder with radius $R = 20$ kpc and height $2L$.

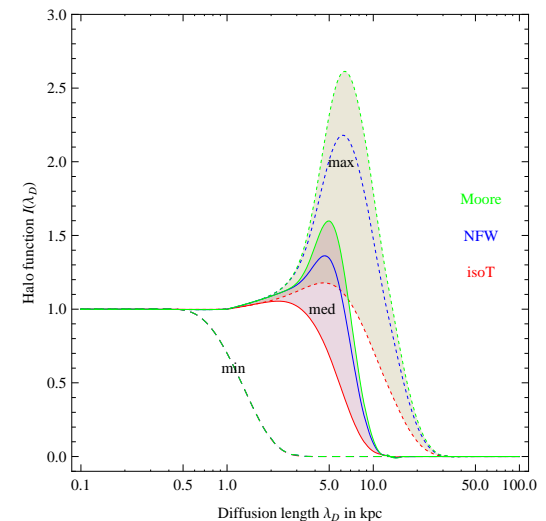
Propagation model	δ	K_0 in kpc^2/Myr	L in kpc	V_{conv} in km/s
min	0.85	0.0016	1	13.5
med	0.70	0.0112	4	12
max	0.46	0.0765	15	5

Solution: $\Phi_{e^+}(E) = B \frac{v_{e^+} \tau_E}{4\pi E^2} \int_E^{m_{\text{DM}}} dE' Q(E') \cdot I(\lambda_D(E, E'))$.

$\lambda_D(E, E')$ is the diffusion length from energy E' to E :

$$\lambda_D = \sqrt{4K_0 \tau_E \left[\frac{(E/\text{GeV})^{\delta-1} - (E'/\text{GeV})^{\delta-1}}{\delta-1} \right]}$$

We do not know if e^+ reach us from the galactic center.



1

The data

ABC of charged cosmic rays

e^\pm , p^\pm , He, B, C... Their directions are randomized by galactic magnetic fields $B \sim \mu\text{G}$. The info is in their energy spectra.

We hope to see DM annihilation products as excesses in the rarer e^+ and \bar{p} .

Experimentalists need to bring above the atmosphere (with balloons or satellites) a spectrometer and/or calorimeter, able of rejecting e^- and p .

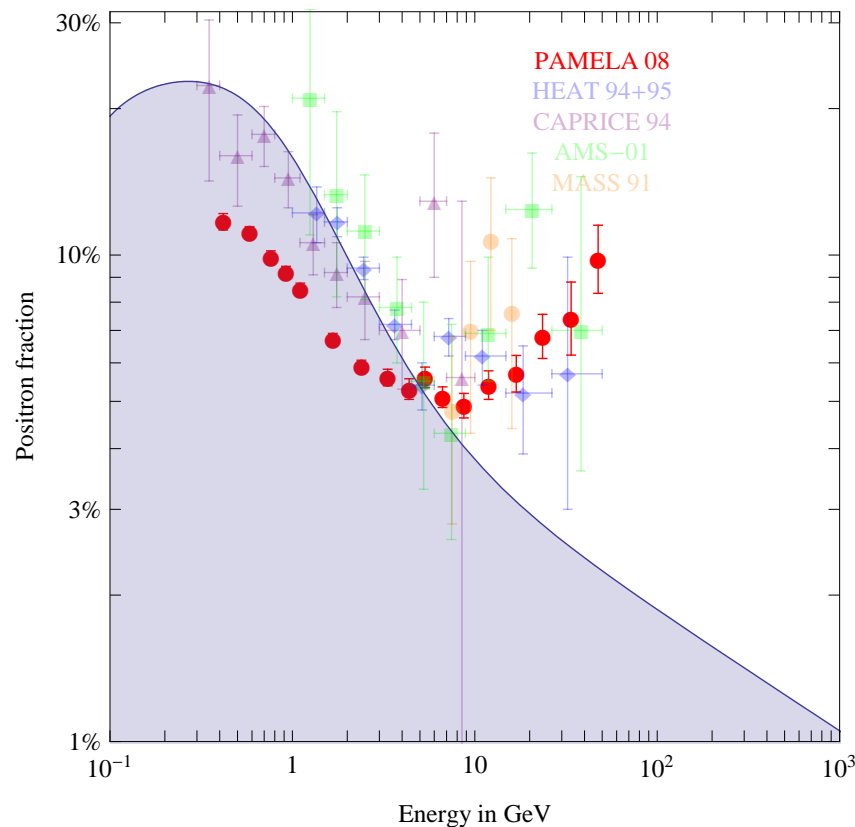
This is difficult above 100 GeV, also because CR fluxes decrease as $\sim E^{-3}$.

Energy spectra below a few GeV are \sim useless, because affected by solar activity.

$e^+ / (e^+ + e^-)$: PAMELA

PAMELA is a spectrometer + calorimeter sent to space. It can discriminate e^+ , e^- , p , \bar{p} , ... and measure their energies up to about 100 GeV. Astrophysical backgrounds should give a positron fraction that decreases with energy. This happens below 10 GeV, where the flux is reduced by the present solar polarity.

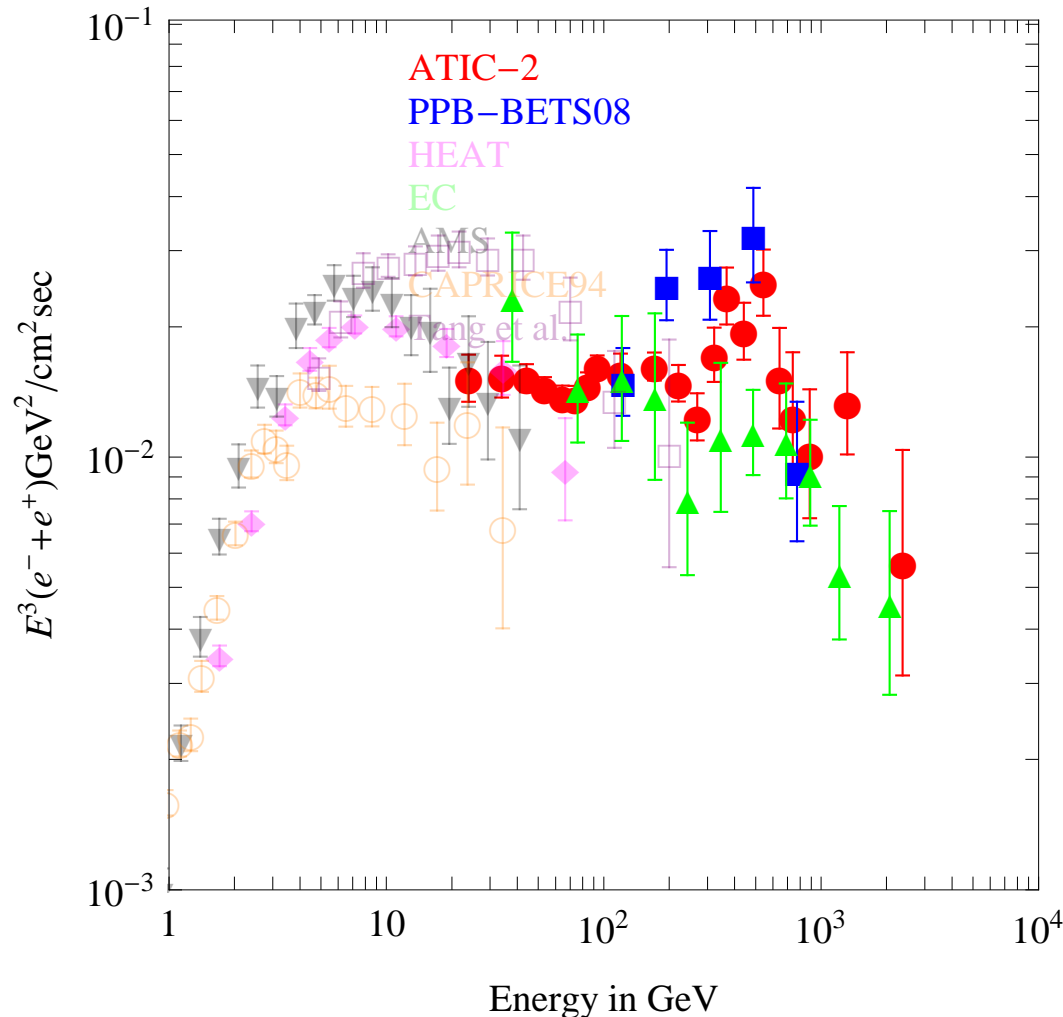
$\sim 10\sigma$ excess above 10 GeV? Data are preliminary



$e^+ + e^-$: ATIC-2 and PPB/BETS

These balloon experiments cannot discriminate e^+/e^- , but probe higher energy.

$\sim 5\sigma$ excess at 700 GeV?

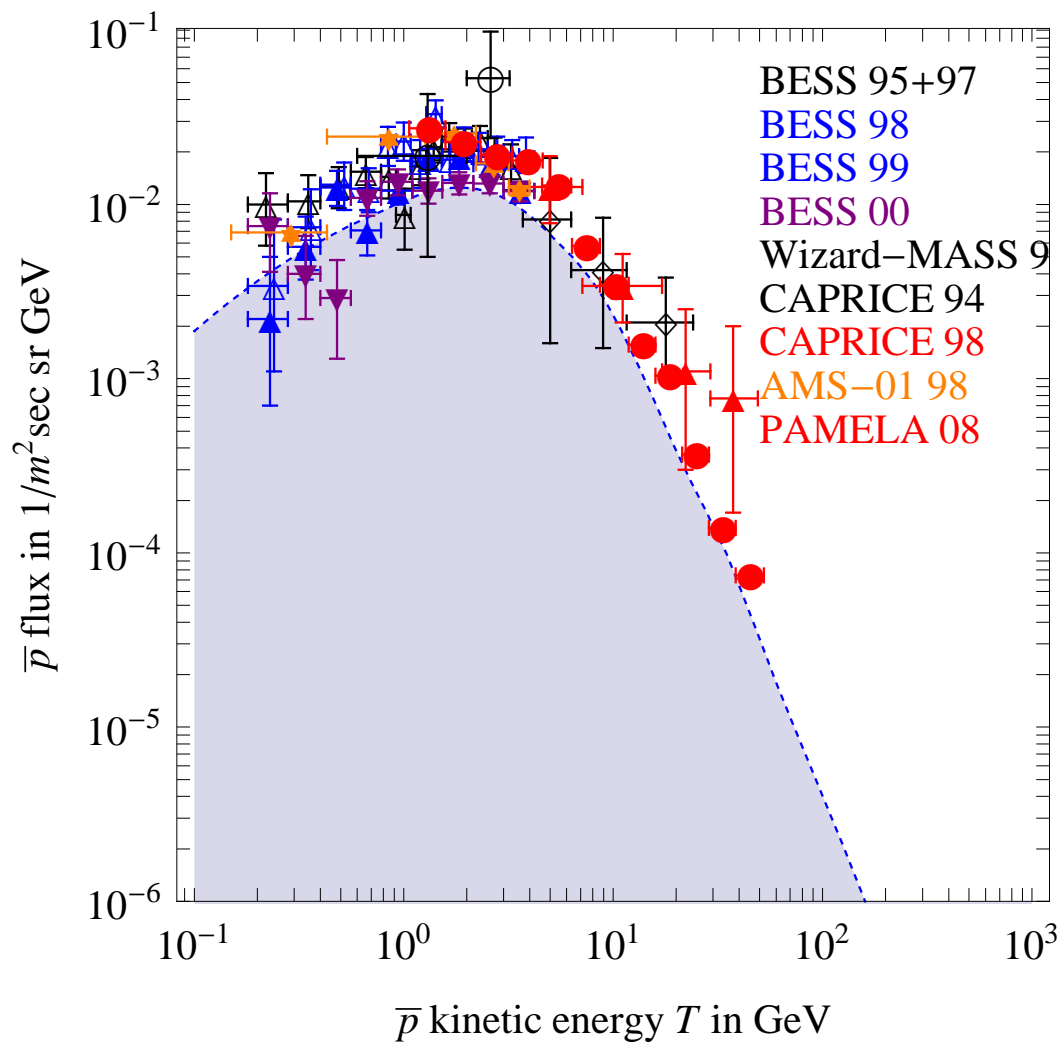


Near future: ATIC-4 and GLAST/Fermi calorimeter

ATIC-4 preliminary results:

\bar{p}/p : PAMELA

Consistent with background



Future: PAMELA, AMS

Systematics? Dark Matter? ...

Could the excesses be due to systematics?

- ATIC-2. The problem could be **discriminating** 1 e^\pm from 1000 $p \rightarrow \pi^0$: MC tested below 200 GeV. The peak is a few points. ATIC-4 enlarged the bigger calorimeter, so that a e.m. shower is contained.
- PPB-BETS. Very small. **Incompatible** with ATIC-2 and EC.
- PAMELA. Needs to find 1 e^+ among 5000 p . Calibrated below 200 GeV. Due to small size $\sim 50\%$ of the shower is lost laterally.

If the excess is due to DM:

- DM is a WIMP. (A gravitino-like particle is allowed if unstable).
- DM annihilates, so it is not there due to an asymmetry like protons
- DM is a strange WIMP...

... Just a pulsar?

A pulsar is a neutron star with a rotating intense magnetic field. The resulting electric field ionizes and accelerates e^- (and maybe iron) $\rightarrow \gamma \rightarrow e^+e^-$, that are presumably further accelerated by the pulsar wind nebula (Fermi mechanism).

- $E_{\text{pulsar}} = I\omega^2/2$, $\dot{E}_{\text{pulsar}} = -B_{\text{surface}}^2 R^2 \omega^4 / 6c^3 =$ magnetic dipole radiation.
- The guess is $\Phi_{e^-} \approx \Phi_{e^+} \propto \epsilon \cdot e^{-E/M} / E^p$ where $p \approx 2$ and M are constants.

Far galactic pulsars can fit PAMELA, but have (?) too low M to fit ATIC?

Known nearby pulsars (B0656+14, Geminga, ?) can reach a higher M , but would need an unplausibly large fraction ϵ of energy that goes into e^\pm : $\epsilon \sim 0.3$.

A young nearby pulsar easily has a high M . It can be tested searching for γ (if points towards us) and for angular anisotropies in the e^+ excess $= 3K |\vec{\nabla} n_e| / n_e$. A lower M can be given from an old pulsar as e^\pm had time to diffuse away; for the same reason it would need a huge initial intensity. Can it be tested?

2

Model-independent theory of DM indirect detection

Model-independent DM annihilations

Indirect signals depend on the DM mass M , non-relativistic σv , primary BR:

$$\text{DM DM} \rightarrow \begin{cases} W^+W^-, & ZZ, & Zh, & hh & \text{Gauge/higgs sector} \\ e^+e^-, & \mu^+\mu^-, & \tau^+\tau^- & & \text{Leptons} \\ b\bar{b}, & t\bar{t}, & q\bar{q} & & \text{quarks, } q = \{u, d, s, c\} \end{cases}$$

No γ because DM is neutral. Direct detection bounds suggest no Z .

The energy spectra of the stable final-state particles

$$e^\pm, \quad p^\mp, \quad \text{the undetectable } (\bar{\nu})_{e,\mu,\tau}, \quad \gamma$$

depend on the **polarization of primaries**.

The higher-order γ spectrum is model-dependent:

$$\gamma = (\text{Brehmstrahlung/fragmentation}) + (\text{one-loop}) + (\text{3-body})$$

The DM spin

If DM is a fundamental weakly-interacting particle, its spin can be 0, 1/2 or 1. The two-body DM DM state relevant for s -wave annihilations has zero orbital angular momentum $L = 0$. So its total angular momentum is $J = S$:

$$1 \otimes 1 = 1, \quad 2 \otimes 2 = 1_{\text{asymm}} \oplus 3_{\text{symm}}, \quad 3 \otimes 3 = 1_{\text{symm}} \oplus 3_{\text{asymm}} \oplus 5_{\text{symm}}$$

i.e. spin 0 is always allowed spin 1 only if DM is a Dirac fermion or a vector.

We impose restrictions from relativistic effective QFT

Indeed final state particles are relativistic and quantistic, and the non-relativistic nature of DM DM is a relativistically-invariant limit.

In practice: represent DM DM as a scalar field \mathcal{D} , or a vector \mathcal{D}_μ , or $\mathcal{D}_{\mu\nu}$

DM annihilations into W, Z

- The effective interactions

$$\mathcal{D}F_{\mu\nu}\epsilon_{\mu\nu\rho\sigma}F_{\rho\sigma} \quad \text{and} \quad \mathcal{D}F_{\mu\nu}^2$$

give vectors with *Transverse* polarization (with different unobservable helicity correlations), that decay in $f\bar{f}$ with $E = xM$ as:

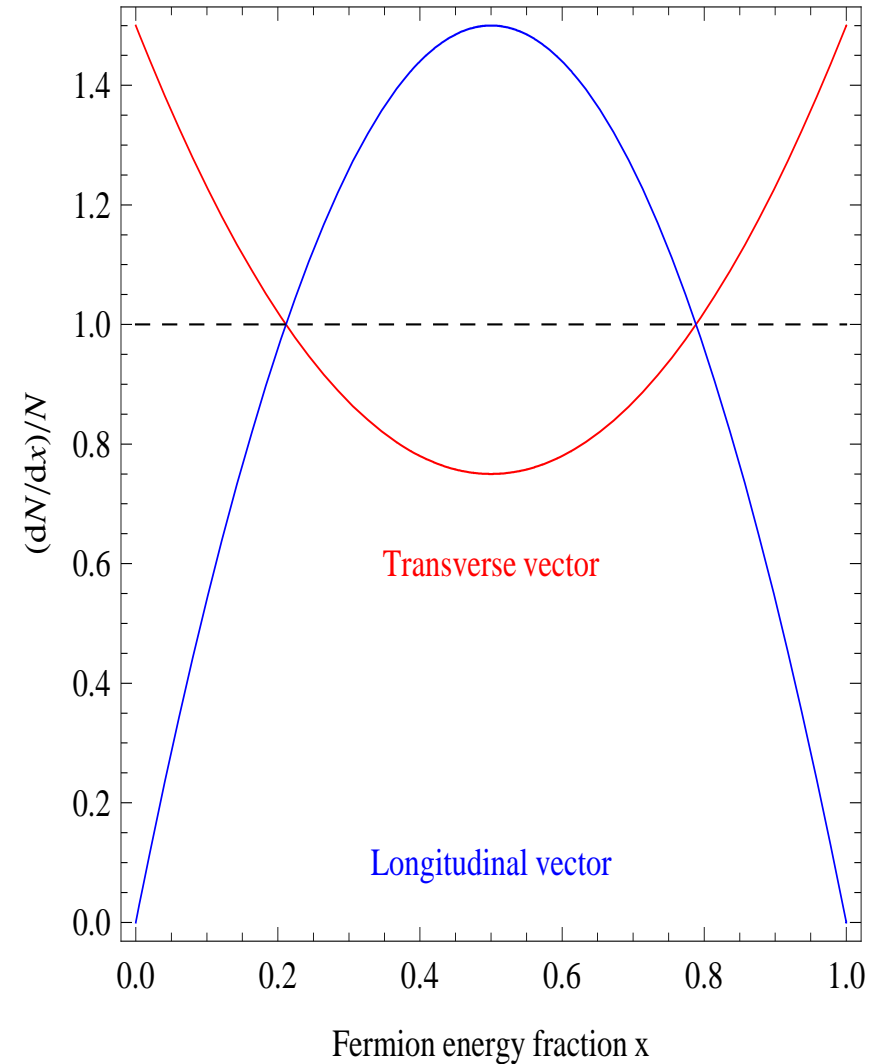
$$dN/d\cos\theta = 3(1 + \cos^2\theta)/8$$

$$dN/dx = 3(1 - 2x + 3x^2)/2,$$

- $\mathcal{D}A_\mu^2$ gives *Longitudinal* vectors (accounting for DM annihilations into Higgs Goldstones), that decay as

$$dN/d\cos\theta = 3(1 - \cos^2\theta)/4$$

$$dN/dx = 6x(1 - x).$$



DM annihilations into the higgs h

We can again focus on \mathcal{D} , so that the effective interaction $\mathcal{D}h^2$ gives DM annihilations into hH . Since they have no spin, there are no polarization issues.

We assume $m_h = 115$ GeV, so h decays mostly into $b\bar{b}$.

DM annihilations into Zh will not be considered, as they are essentially given by the average of the $Z_L Z_L$ and hh channels.

DM annihilations into fermions f

- \mathcal{D} can only couple as

$$\mathcal{D}f_L f_R + \text{h.c.} = \mathcal{D}\bar{\Psi}_f \Psi_f$$

with $\Psi_f = (f_L, \bar{f}_R)$ in Dirac notation.

It means zero helicity on average, and is typically suppressed by m_f/M .

- \mathcal{D}_μ can couple as

$$\mathcal{D}_\mu[\bar{f}_L \gamma_\mu f_L] = \mathcal{D}_\mu[\bar{\Psi}_f \gamma_\mu P_L \Psi]$$

or

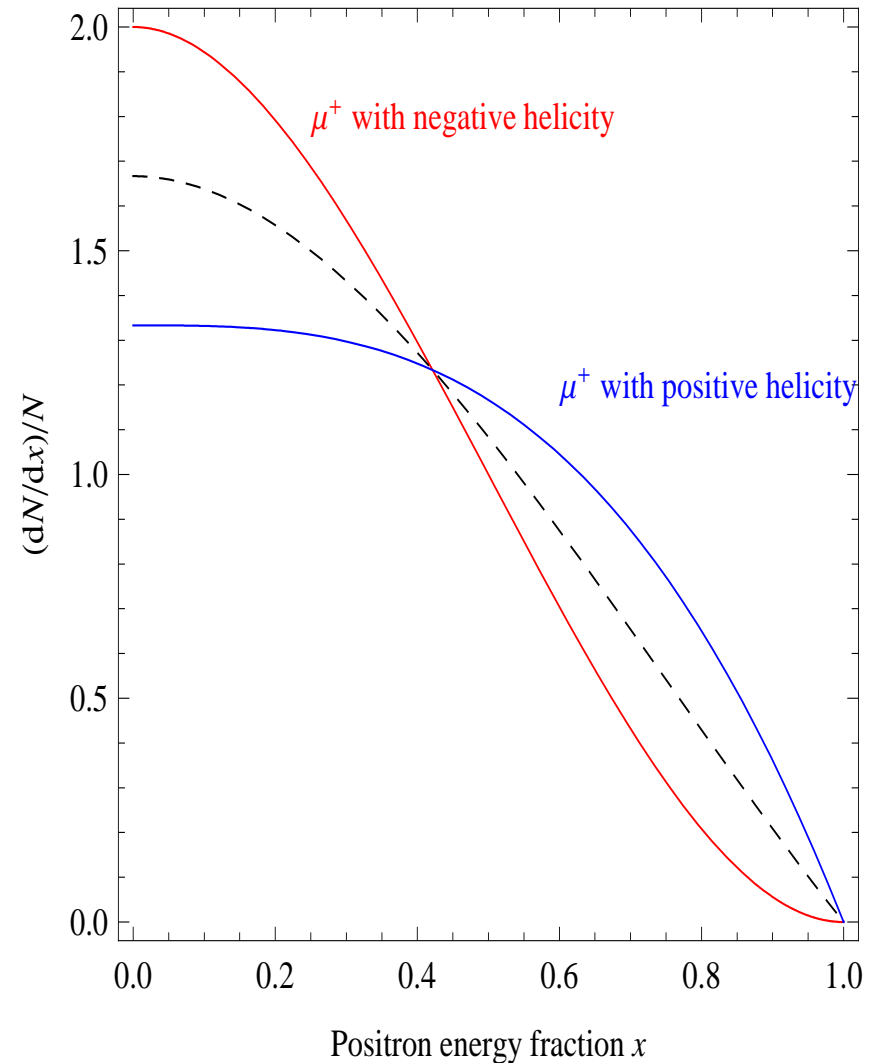
$$\mathcal{D}_\mu[\bar{f}_R \gamma_\mu f_R] = \mathcal{D}_\mu[\bar{\Psi}_f \gamma_\mu P_R \Psi]$$

i.e. fermions with *Left* or *Right* helicity.

Decays like $\mu^+ \rightarrow \bar{\nu}_\mu e^+ \nu_e$ give e^+ with

$$dN/dx|_L = 2(1-x)^2(1+2x)$$

$$dN/dx|_R = 4(1-x^3)/3$$

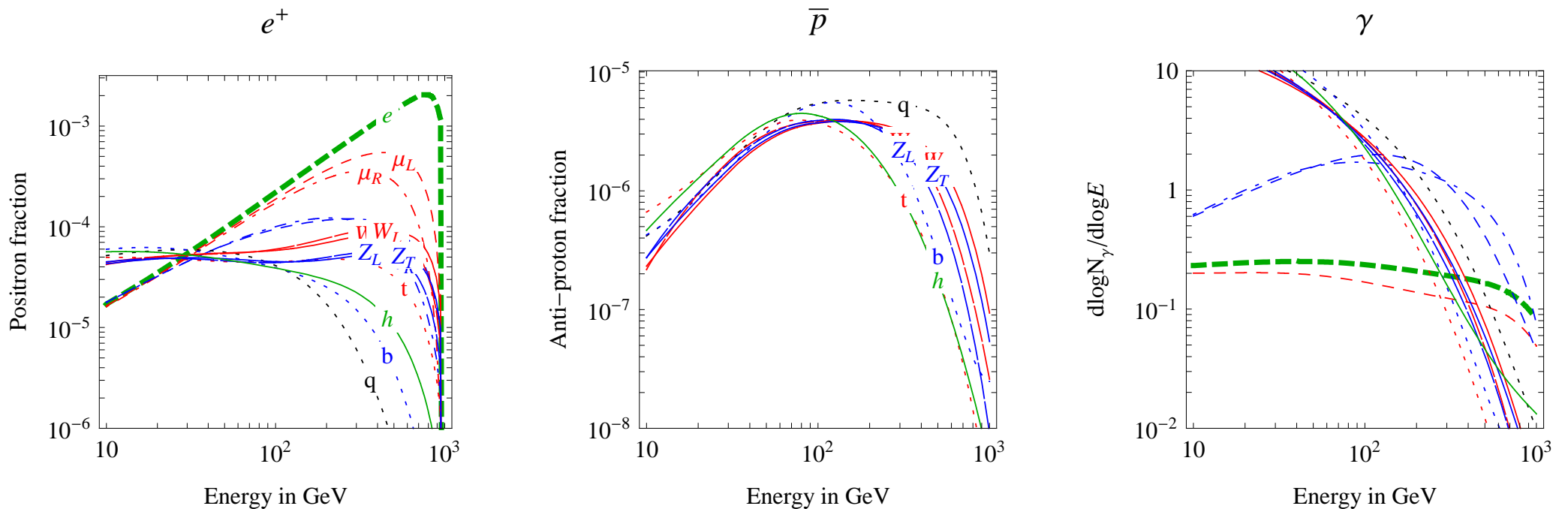


Final state spectra for $M = 1$ TeV

We consider the allowed s -wave primary annihilation channels:

$$\{e, \mu_L, \mu_R, \tau_L, \tau_R, W_L, W_T, Z_L, Z_T, h, q, b, t\},$$

computed with our Mathematica MonteCarlo + Phytia8 + (Tauola+Phytia6)



Annihilations into leptons give qualitatively different energy spectra.

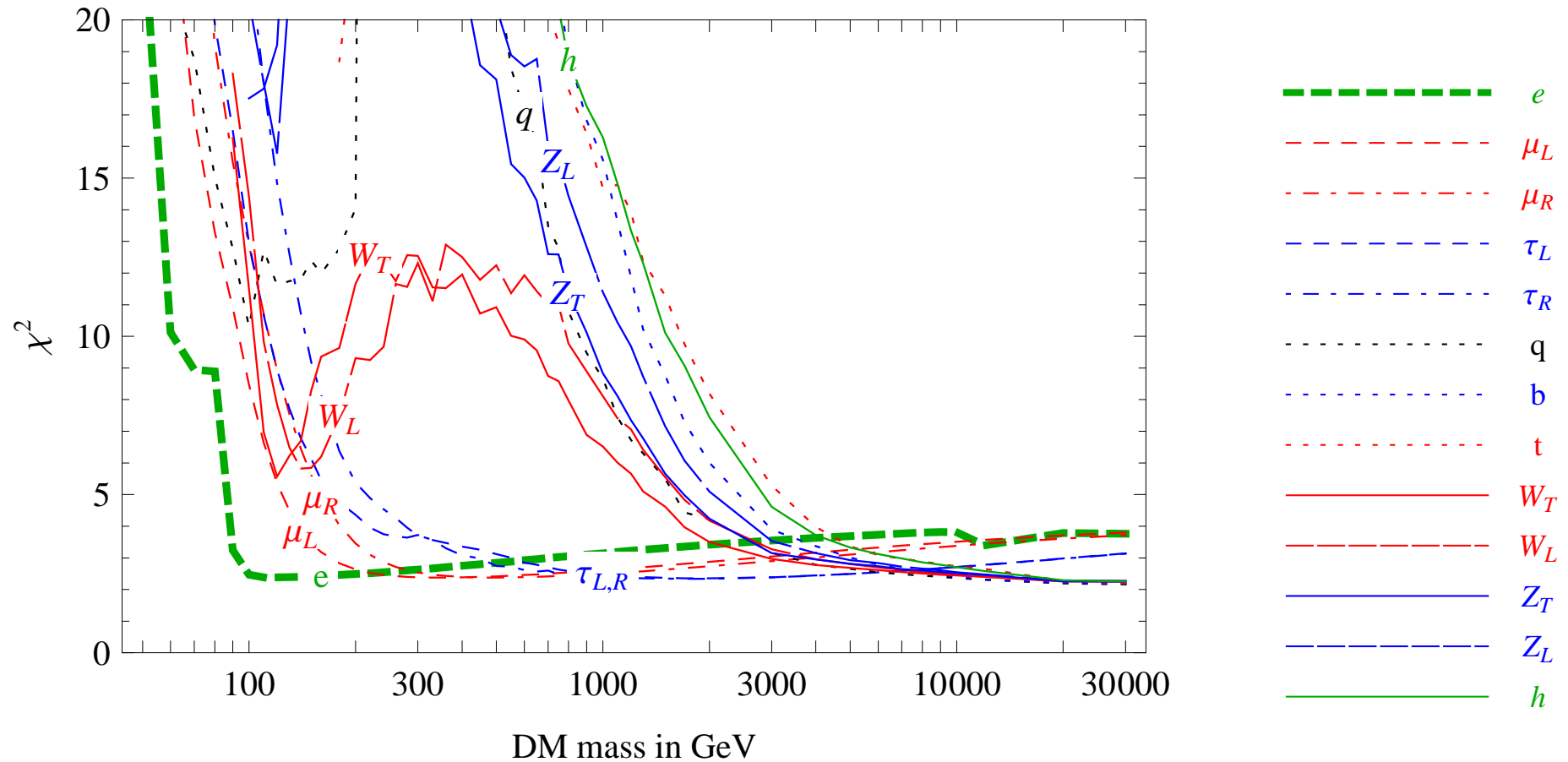
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Implications of the data

Fitting procedure

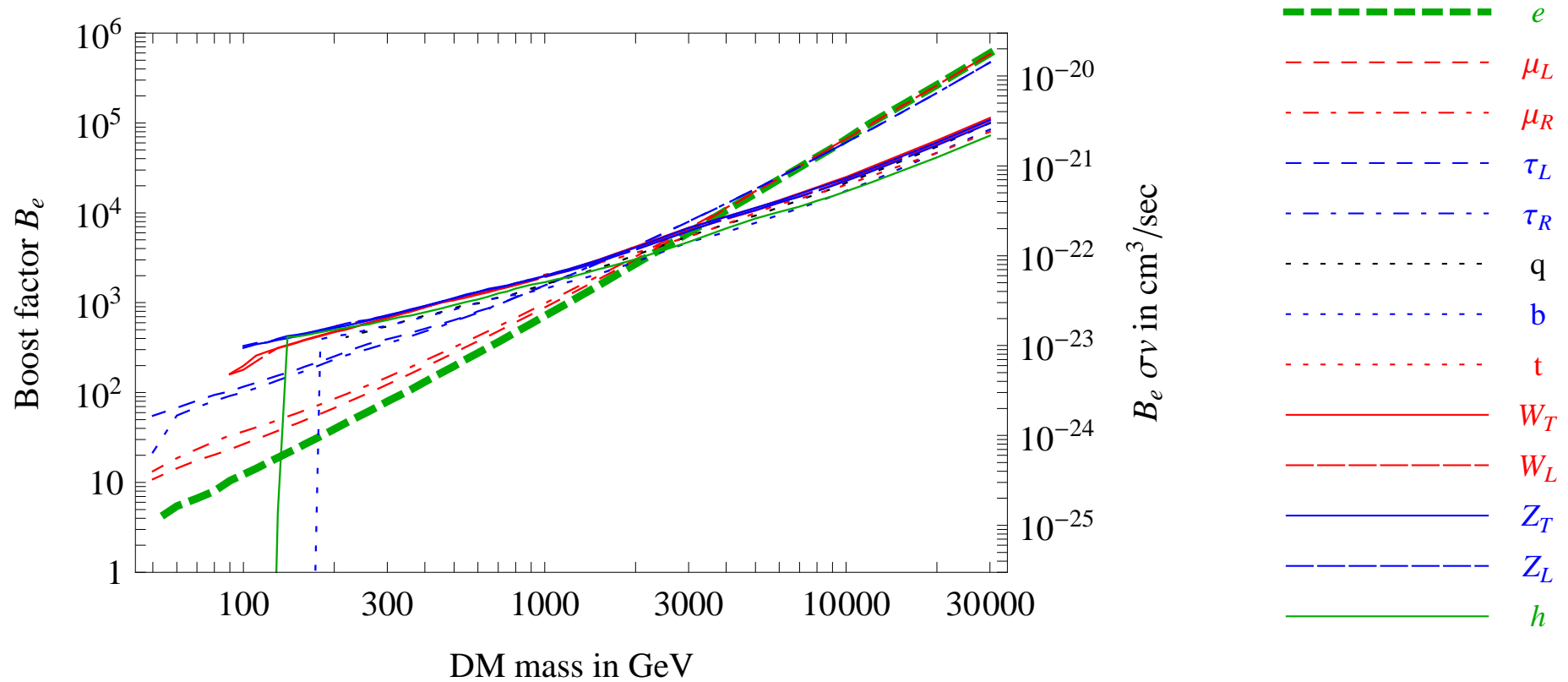
- **PAMELA** e^+ will have **systematic** uncertainties comparable to statistical.
- multiply each expected e^+ , e^- , p^+/p^- **backgrounds** times $A_i E^{p_i}$ with free A_i and $p_i = 0 \pm 0.05$, and marginalize over A_i, p_i .
- **solar modulation** as uncorrelated uncertainty below 20 GeV: $\pm 6\%$ at 10 GeV, $\pm 30\%$ at 1 GeV.
- **DM halo**: marginalize over isoT/NFW/Moore with flat prior.
- **Propagation**: marginalize over MIN/MED/MAX with flat prior. (MED is favored?).
- Statistical techniques: as reviewed in appendix B of hep-ph/0606054.

Fitting PAMELA positron data



If $M > \text{TeV}$ everything fits. At smaller M only annihilations into leptons or W .

The σv needed for PAMELA

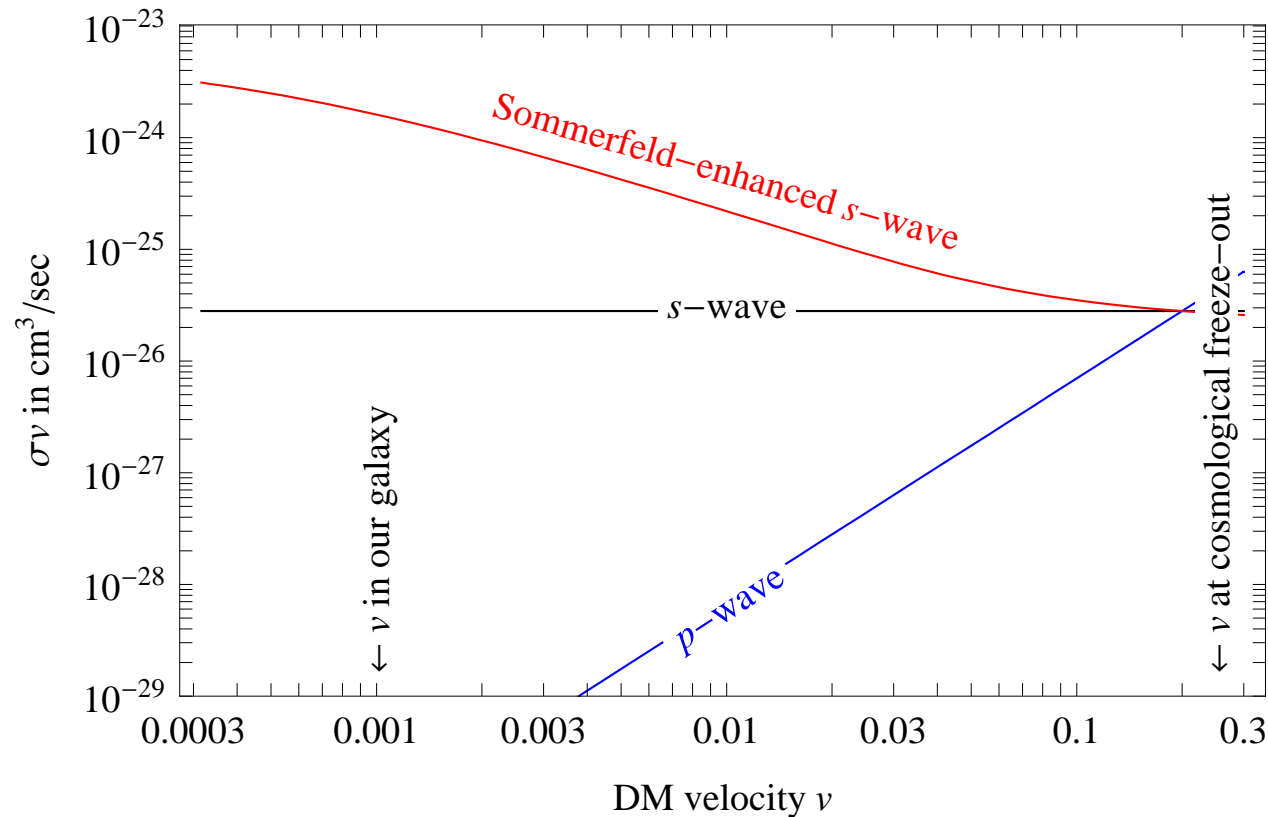


The cosmological σv

Thermal DM reproduces the cosmological DM abundance $\Omega_{\text{DM}} h^2 \approx 0.11$ for

$$\sigma v \approx 3 \times 10^{-26} \text{ cm}^3/\text{sec} \quad \text{around freeze-out, i.e. } v \sim 0.2.$$

up to co-annihilations and resonances. Possible extrapolations to $v \sim 10^{-3}$:



PAMELA needs s -wave + Sommerfeld and/or a boost factor, if DM is thermal.

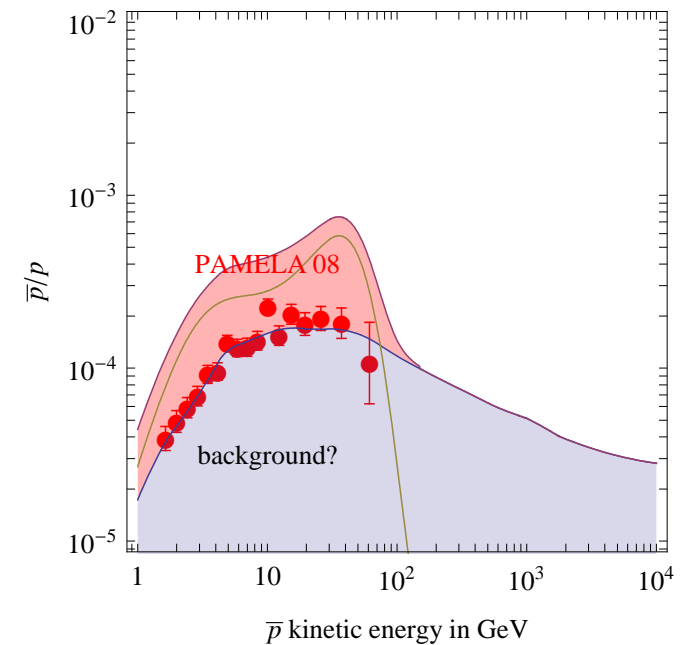
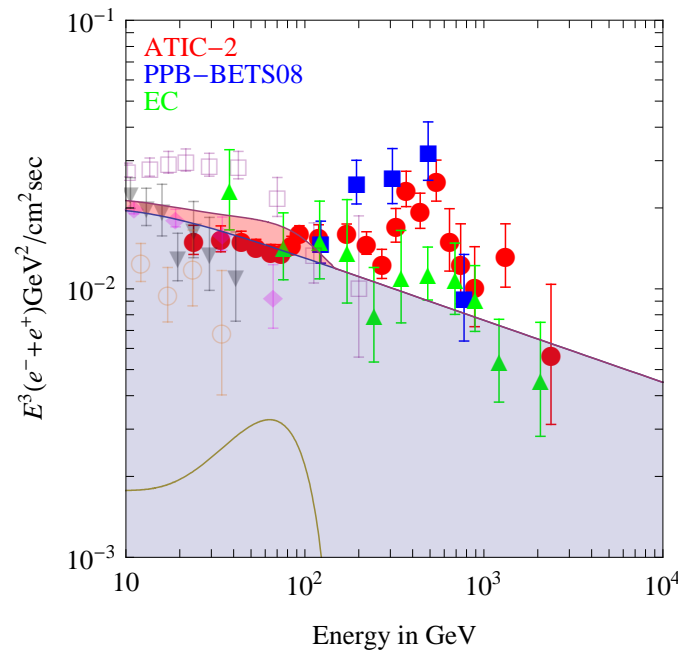
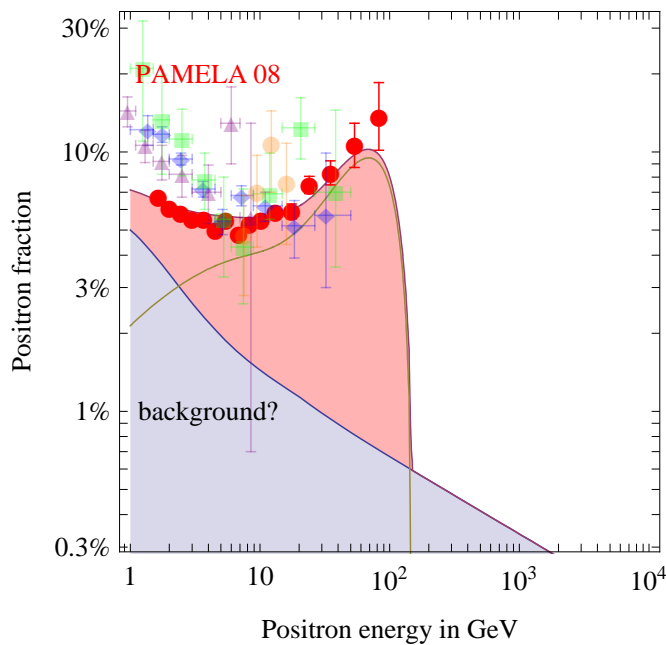
Non thermal DM

E.g. a wino that with $M \approx 100$ GeV annihilates into $W_T^+ W_T^-$ with the correct

$$\sigma v = \frac{g_2^4 (1 - M_W^2/M^2)^{3/2}}{2\pi M^2 (2 - M_W^2/M^2)^2}$$

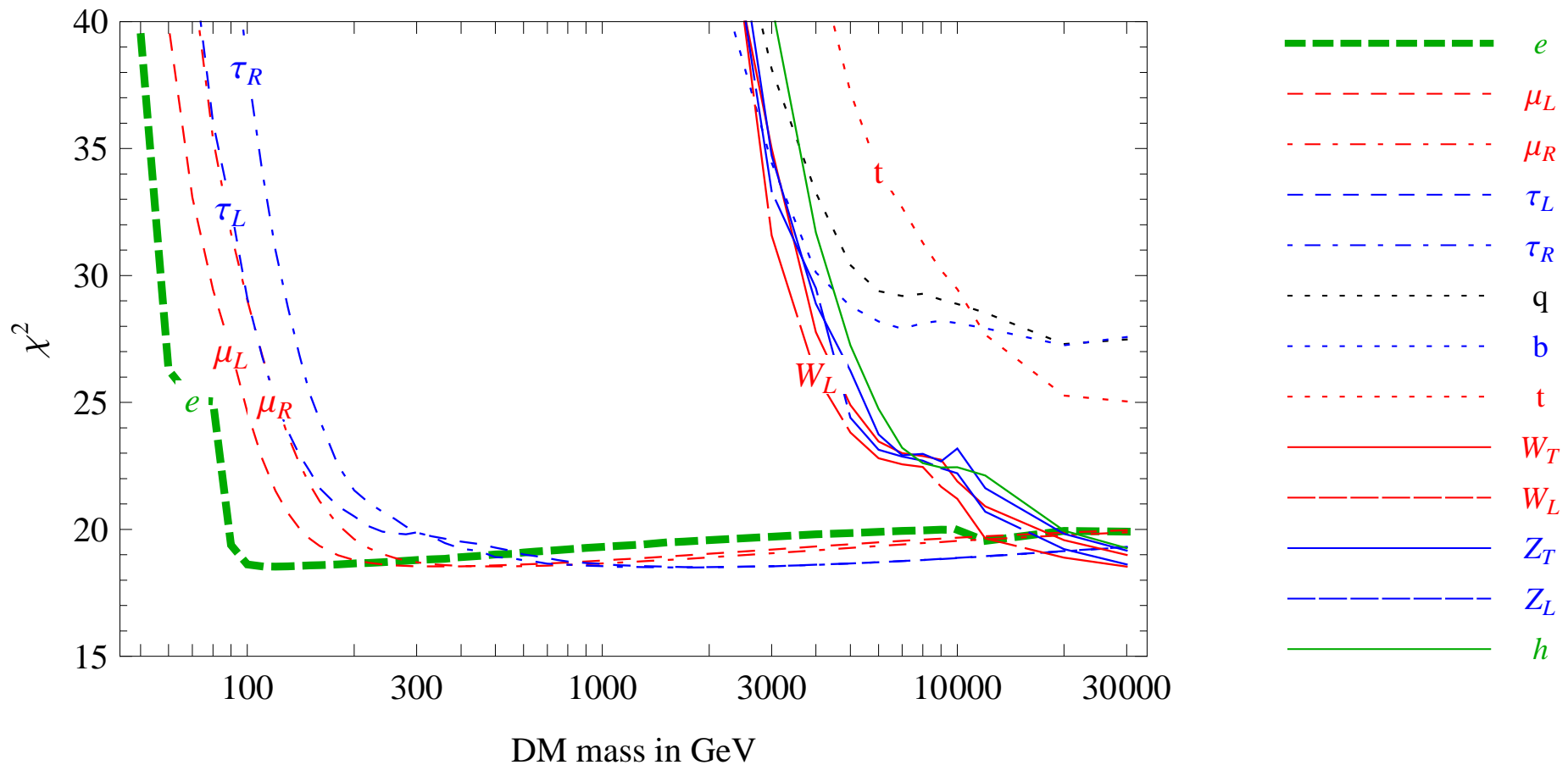
But it contradicts PAMELA \bar{p} data (unless $B_p \ll B_e$ or low L or etc...):

DM with $M = 150$ GeV that annihilates into $W^+ W^-$



Fitting PAMELA e^+ anti \bar{p} data

Assuming equal boost & propagation for e^+ and \bar{p} (otherwise everything goes):



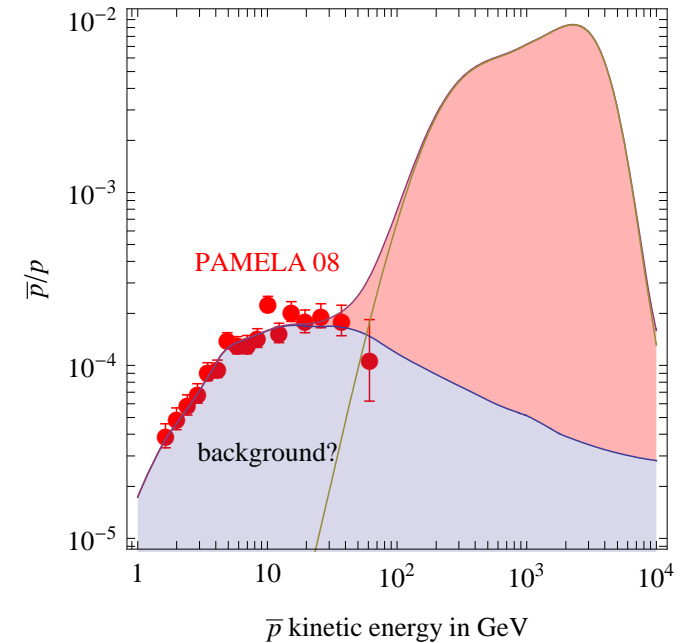
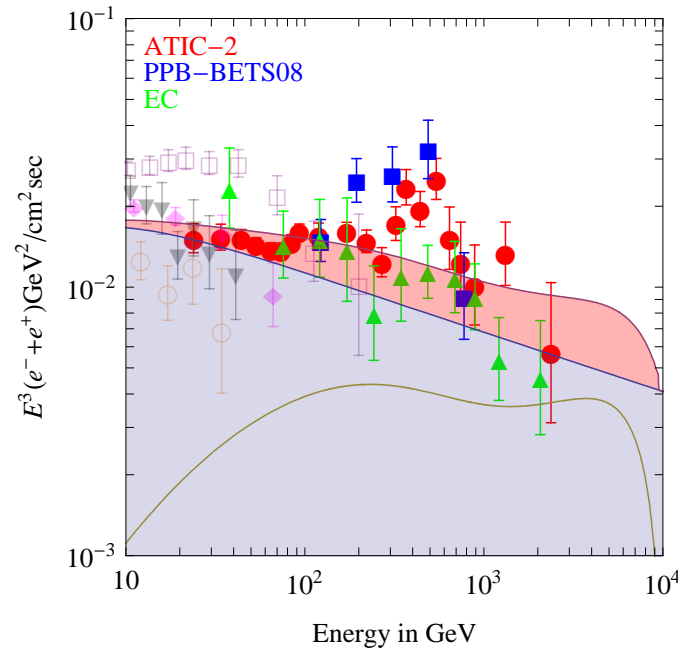
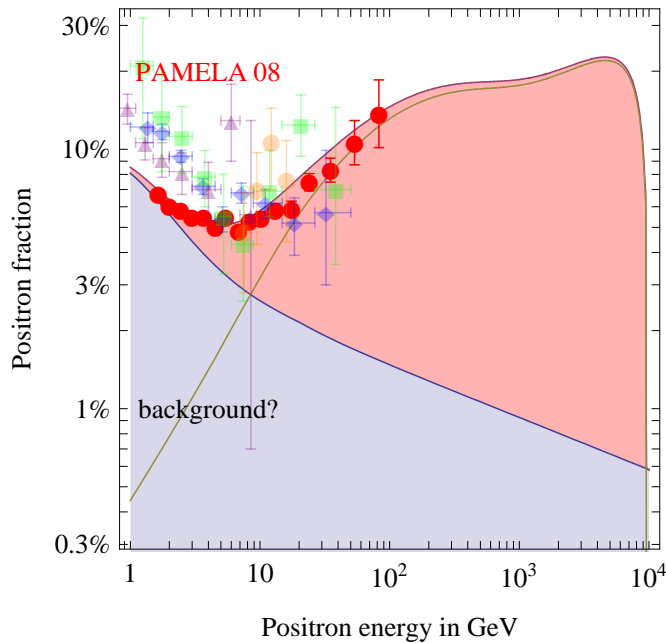
DM must annihilate into leptons or into W, Z with $M \gtrsim 10$ TeV

Indeed a W at rest gives \bar{p} with $E_p > m_p$. So a W with energy $E = M$ gives $E_p > Mm_p/M_W$, above the PAMELA threshold for $M > 10$ TeV.

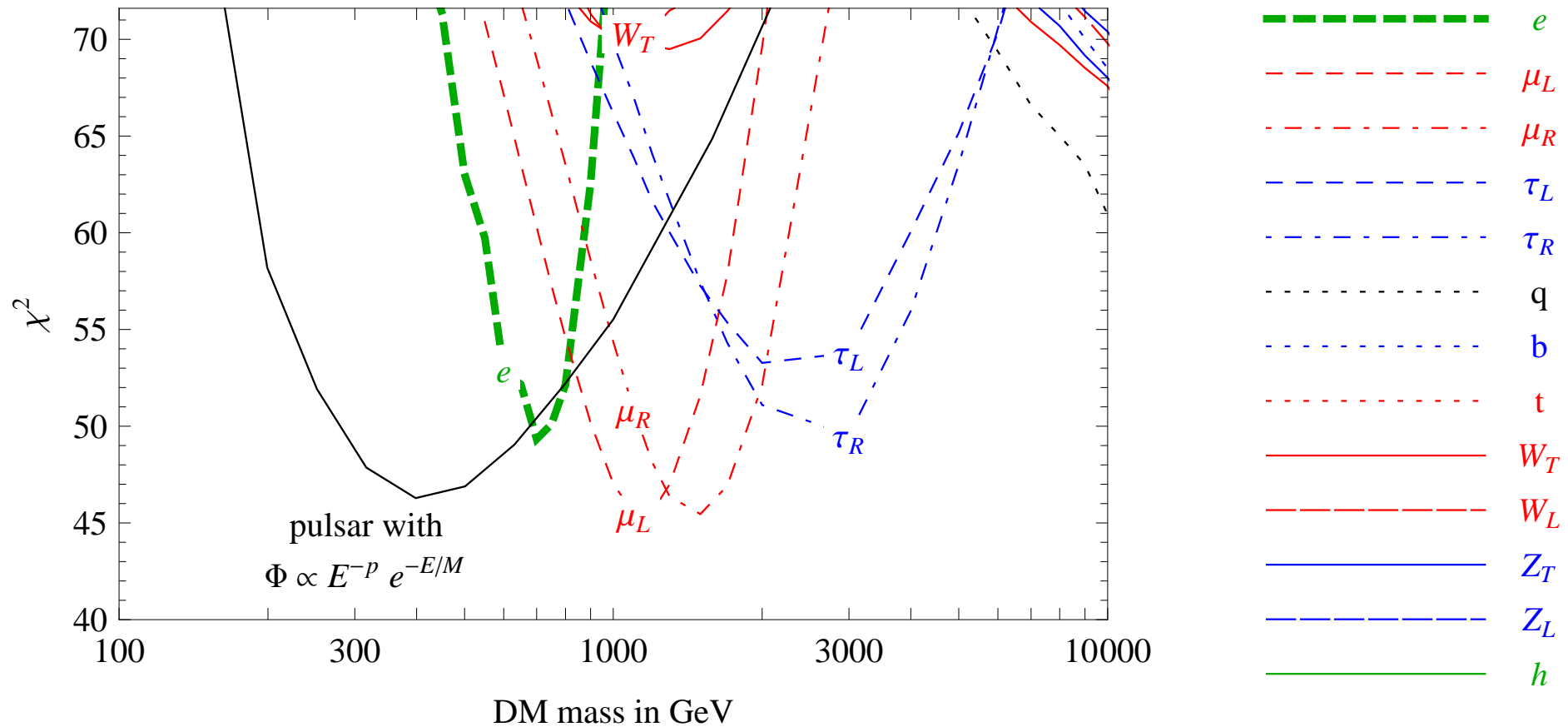
The Minimal Dark Matter 5-plet

MDM predicted: • annihilations into $W_T^+ W_T^-$; • $M = 9.6 \pm 0.2$ TeV, imposing $\Omega_{\text{DM}} h^2 \approx 0.11$; • a 10^3 Sommerfeld enhancement.

DM with $M = 10$ TeV that annihilates into $W^+ W^-$



Fitting PAMELA e^+ and balloon $e^+ + e^-$



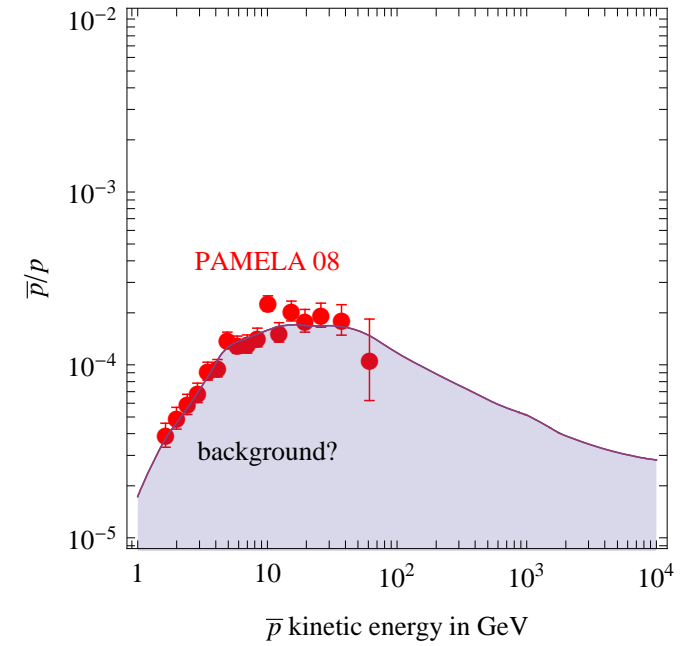
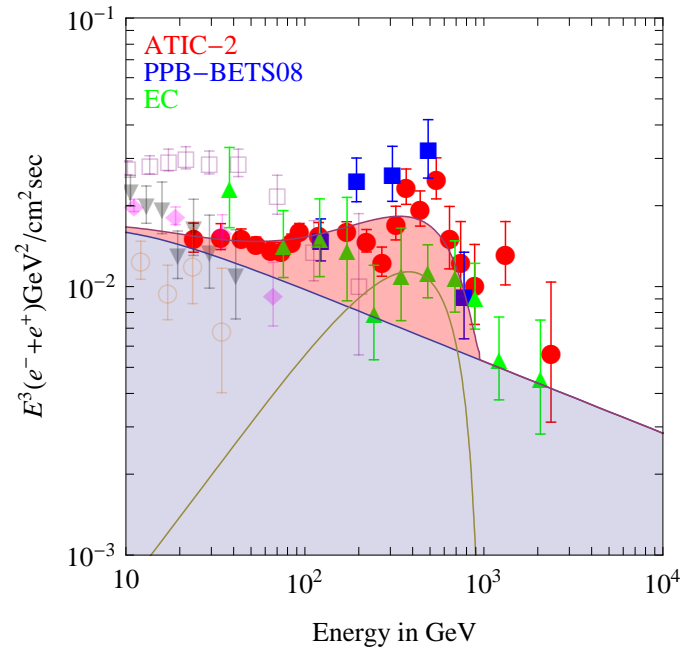
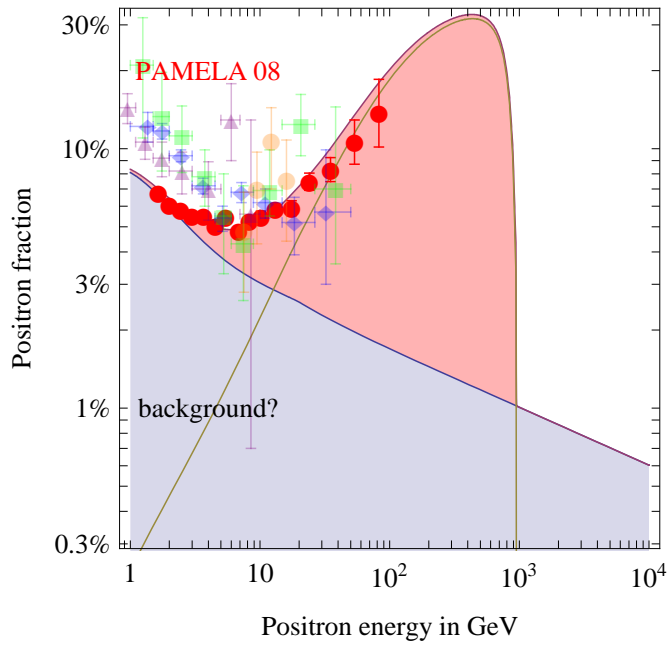
The possible excess in $e^+ + e^-$ around 700 GeV is compatible with the PAMELA excess in e^+ above 10 GeV, if DM annihilates into leptons with TeV mass.

In any case, balloons disfavor/exclude the following PAMELA interpretations:

- DM with mass $M \lesssim \text{TeV}$
- DM that annihilates in leptons with $M \gtrsim \text{TeV}$.

Dark Matter identified?

DM with $M = 1$ TeV that annihilates into $\mu^+\mu^-$



Connection with direct detection

Qualitative connection between $\sigma_{\text{ann}v} \sim 3 \cdot 10^{-23} \text{ cm}^3/\text{sec} \cdot (M/\text{TeV})^2$ and σ_{dir} :

i) if DM annihilates into quarks:

$$\sigma_{\text{dir}} \sim \frac{m_N^2}{M^2} \frac{\sigma_{\text{ann}v}}{B_e S} \sim \frac{10^{-39} \text{ cm}^2}{B_e S}$$

(possibly times m_N^2/M^2). The experimental bound is $\sigma_{\text{dir}} \gtrsim 10^{-41} \text{ cm}^2$.

ii) if DM annihilates into W, Z, h, μ, τ , the connection is model-dependent: as in i) times one or two loop factors $\sim (4\pi)^{-2}$, possibly times M^2/M_W^2 . The MDM 5plet predicts $\sigma_{\text{dir}} \sim 10^{-44} \text{ cm}^2$.

iii) if DM annihilates into and interacts with e (that in atoms reach $p \sim m_e$), the recoil energy is $\Delta E \sim vp$, above threshold in DAMA, but

$$\sigma_{\text{dir}} \sim \frac{m_e^2}{M^2} \frac{\sigma_{\text{ann}v}}{B_e S} \sim \frac{10^{-45} \text{ cm}^2}{B_e S}$$

is negligibly small.

Theoretical implications

For PAMELA only:

- The SUSY neutralino with $M \sim 100$ GeV, if it annihilates into $e^+e^-\gamma$ thanks to a fine-tuned slepton mass, and invoking a huge boost $B_e \sim 10^6$;
- Unnatural SUSY at 10 TeV with σv enhanced by Sommerfeld;
- SUSY + ad hoc stable new particles. 2-component DM: one more abundant (small σv) that decays in the other (bigger σv for PAMELA).
- a $\tilde{\nu}_R$ lighter than M_W and with a large Yukawa $\nu_R LH$ annihilates into L ;
- DM vectors or fermions suggested by wUED (would be Universal Extra Dimensions) or by LHT (Little Higgs with non-anomalous T -parity) annihilate $\sim 30\%$ into leptons, but $\sim 70\%$ into q, W .

Ad hoc new DM models

DM is charged under a new gauge group, to get the Sommerfeld enhancement.

For PAMELA and balloons. [Cirelli, Kadastik, Raidal, Strumia] proposed that DM as a Dirac fermion with $M \approx 1.5 \text{ TeV}$ and charge $q \approx 2$ under $L_\mu - L_\tau$ (suggested by $\theta_{23} \approx \pi/4$), gauged with $\alpha_V \approx 1/50$ (giving the correct thermal abundance) and mass $M_V \approx M_Z$, giving the $g_\mu - 2$ anomaly + Sommerfeld.

At 1 loop $L_\mu - L_\tau$ mixes with the photon: $\theta \sim eg_V \ln(m_\tau/m_\mu)/6\pi^2 \sim 0.005$.
Direct cross section: $\sigma_{\text{SI}} = 4\pi q^2 \alpha_V \alpha m_N^2 \theta^2 / M_V^4 \approx 10^{-42} \text{ cm}^2$

For PAMELA and balloons and DAMA and INTEGRAL. [Arkani-Hamed, Weiner et al., 3 papers] proposed that **the new vector is light** $M_V \lesssim m_N$ and couples to SM particles only via a mixing with the photon,

$$\theta \sim eg_V \ln(M_{\text{Pl}}/M_V)/6\pi^2 \sim 10^{-2 \div 3}$$

so that: • V automatically decays into light leptons e, μ, π^\pm ; • V gives a small $\delta a_\mu \sim \alpha \theta^2 (m_\mu/M_V)^2 / \pi \sim 10^{-9}$; V gives a $10^{\sim 6}$ too large elastic σ_{SI} . **If the DM gauge group is non abelian**, DM has multiple components with 100 keV ($\ll \alpha_V M_V$) mass splittings, one can instead get an **inelastic** σ_{SI} that can explain DAMA (but $M = 1 \text{ TeV}$ is too heavy?). Similarly, one can explain the INTEGRAL ex-anomaly.

Conclusions

Our analysis of **P R E L I M I N A R Y** data suggests that DM seems:

- if the balloon excess is true: a 1 TeV WIMP that annihilates into e, μ, τ ;
- if not: a 10 TeV WIMP that annihilates into W, Z, h , as predicted by MDM;
- $M \sim 100$ GeV seems disfavored/excluded by \bar{p} and/or $e^+ + e^-$ data.

This can soon be confirmed or contradicted by new experimental results:

- The e^+ fraction at higher energies continues to grow?
- Is an excess present in \bar{p} at higher energies? We expect one more data-point from PAMELA, and later AMS up to 1 TeV.
- Is the $e^+ + e^-$ balloon excess confirmed? ATIC-4 and GLAST (renamed Fermi)* with its LAT calorimeter in space already have data.

*PAMELA could similarly be renamed as Anderson, who got a Nobel prize for discovering e^+