Dark Matter interpretations of the cosmic-ray $e^{\pm}$ excesses

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Abstract

The cosmic-ray excess observed by PAMELA in the positron fraction and by FERMI and HESS in $e^- + e^+$ can be interpreted in terms of DM annihilations or decays. We summarize the main possibilities and their possible tests.

1 Introduction

Recently the PAMELA experiment [1] observed an unexpected rise with energy of the $e^+/(e^+ + e^-)$ fraction in cosmic rays, suggesting the existence of a new component. The sharp rise suggests that the new component may be visible also in the $e^- + e^+$ spectrum: although the peak hinted by previous ATIC data [2] is not confirmed, the FERMI [3] and HESS [4] observations still demonstrate a deviation from the naive power-law spectrum, indicating an excess compared to conventional background predictions of cosmic ray fluxes at the Earth. The excess could be due to a new astrophysical component, such as a nearby pulsar. We here focus on the most interesting possibility: the excess could be the first manifestation of Dark Matter, rather than a new background to Dark Matter searches.

Fig. 1 shows the PAMELA (left) and FERMI, HESS (middle) data together with a possible DM fit.

2 The e^+ PAMELA excess

As directions of charged comic rays get randomized by galactic magnetic fields, the information lies in the energy spectra. Dark Matter could manifest as an excess in the rarer positrons or anti-protons. Observations so far have been made only below 100 GeV: the experimental difficulty is bringing above the atmosphere a large enough calorimeter with a spectrometer able of discriminating the sign of the charge. Furthermore, cosmic ray fluxes roughly decrease as E^{-3}.

Observations below $\sim 10\,\mathrm{GeV}$ are affected by the solar activity and thereby provide essentially no information on the underlying particle physics.

According to standard astrophysics, the positron/electron fraction above 10 GeV should decrease with energy, while PAMELA finds the steep increase in fig. 1a, signaling a new component. As the relevant DM annihilations into pairs of SM particles are non-relativistic, given any channel the energy spectra of the final stable $e^+, \bar{p}$ can computed in a model-independent way (even taking into account the possible polarizations of the primary annihilation products [6]).

PAMELA data suggest two classes of DM interpretations for the excess: a) DM that annihilates into pairs of charged leptons, of W or of Z, with any DM mass above about 100 GeV;

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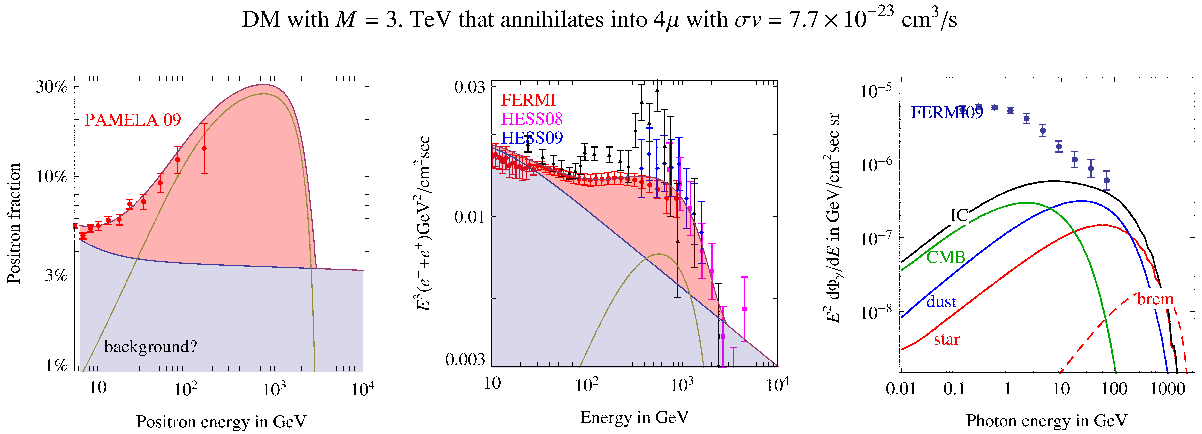

Figure 1: **Sample DM fits**. *We consider DM annihilations into $\tau^+\tau^-$ with MED diffusion [5] and the isothermal DM profile: all good fits are very similar. Left: the positron fraction compared with the PAMELA excess. Middle: the $e^+ + e^-$ flux compared with the FERMI and HESS data. Right: the DM contribution to the diffuse photon energy spectra produced by brehmastahlung (dashed red curve) and Inverse Compton (black thick line); we also separately show the 3 IC components from star-light (red), CMB (green), dust (blue).*

b) DM that annihilates into pairs of quarks or higgs, but only if DM is heavier than a few TeV, as these channels give a soft e^+ spectrum.

The result does not depend much on the unknown DM density profile in our galaxy, $\rho(r)$, nor on the typical galactic DM velocity ($v \sim 10^{-3}$ comparable to the escape velocity from the Milky Way) nor on the $e^\pm$ propagation model in the turbulent galactic magnetic fields.

The σv at $v \approx 10^{-3}$ needed to fit PAMELA grows with M and typically is a few order of magnitude larger than the value, $\sigma v = 3\ 10^{-26}\,\mathrm{cm}^3/\,\mathrm{sec}$ at $v \approx 0.2$, such that thermal DM freeze-out in standard cosmology reproduces the observed cosmological DM abundance. Non-relativistic DM annihilations should be dominated by the s-wave, such that σv stay constant, and PAMELA is not compatible with standard cosmology.

Various ways out have been proposed, such as a non-standard cosmologies. A possible particle-physics way of reconciling PAMELA with standard cosmology is s-channel DM annihilations mediated by a narrow particle with a mass very close to $2M$, such that astrophysical annihilations ($v \sim 10^{-3}$) can be more resonantly enhanced than cosmological annihilations ($v \sim 0.2$) [6, 7]. More interestingly, if DM is charged under a vector with mass m much lighter than DM, the resulting attractive long-range force between pairs of DM particles enhances their annihilation cross section: σv would grow as $1/v$ for small velocities down to $v \gtrsim m/M$, making PAMELA compatible with standard cosmology [6]. This phenomenon is fully analogous to the QED Sommerfeld enhancement of processes like $\sigma(\mu^+\mu^- \to e^+e^-)$, and analogous to the classical enhancement of the probability of hitting the sun in view of its long range attractive gravity. In the DM case, the lighter vector could be the W [8], if DM has a multi-TeV mass: in such a case DM DM $\to W^+W^-$ must be one of the main DM annihilation channels [9]. Otherwise one can add an ad-hoc light vector V, and DM DM $\to VV$ becomes one of the main channels [6]. If $m < m_p$, V can only decay into the lighter leptons e, μ and possibly into π's: this scenario nicely explains why DM could annihilate only into leptons [10].

3 The $\bar{p}$ PAMELA observations

Adding to the data-set the PAMELA [11] observation of a $\bar{p}/p$ fraction compatible with the astrophysical background restricts the range of possible DM interpretations for the e^+ excess, giving another argument in favor of lepto-philic DM. Indeed DM annihilations into e, μ, τ leptons

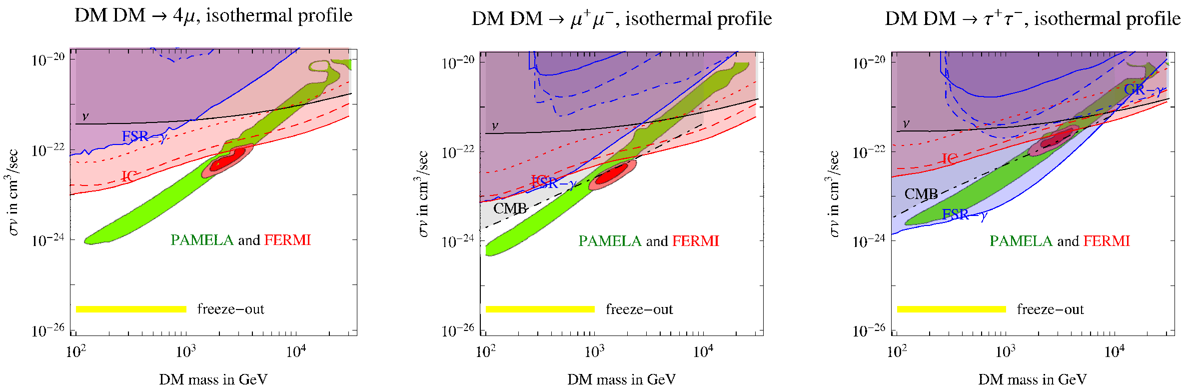

Figure 2: **Bounds on DM annihilations into leptonic channels**. *The* FERMI *bounds are denoted as FSR*γ *(continuous blue line) and IC*γ *(red curves, for* $L = 1, 2, 4\,\mathrm{kpc}$ *from upper to lower). Other bounds are described in the text; their labels appear along the corresponding lines only when these bounds are significant enough to appear within the plots. Cosmological freeze-out predicts* $\sigma v \approx 3\ 10^{-26}\,\mathrm{cm}^3/\,\mathrm{sec}$ *(lower horizontal band) and connections with the hierarchy problem suggest* $M \sim (10 \div 1000)\,\mathrm{GeV}$*. The region that can fit the* $e^\pm$ *excesses survives only if DM annihilates into e's or* μ*'s and DM has an isothermal profile. All bounds are at* 3σ*; the green bands are favored by PAMELA (at* 3σ *for 1 dof) and the red ellipses by PAMELA, FERMI and HESS (at* 3 *and* 5σ*, 2 dof, as in [***?***]).*

do not give any $\bar{p}$ excess, as leptons do not decay into protons. On the contrary all other DM channels are significantly constrained: trusting the available astrophysical models for $\bar{p}$ propagation and for the $\bar{p}$ background[1], these channels are compatible with PAMELA $\bar{p}$ data only if $M \gtrsim 10\,\mathrm{TeV}$ [6, 12]. Indeed let us consider for example the DM DM $\to W^+W^-$ channel. A W at rest produces (anti)protons with $E_p > m_p$, so a W with energy equal to the DM mass M produces protons with $E_p > m_p M/M_W$, which is above the energy range observed by PAMELA if M is heavy enough. (Final State Radiation produces some protons with lower energy).

Thereby DM leaves open the possibility that the e^+ excess is accompanied by a $\bar{p}$ excess, but only above 100 GeV. This heavy DM scenario is compatible with the Sommerfeld enhancement as due to SM electroweak effects, and it was predicted [9] (before PAMELA) by the Minimal Dark Matter theory, according to which Dark Matter is the neutral component of an electroweak fermion quintuplet (selected because automatically stable and automatically lighter than the other charged components) with mass $M \approx 9.6\,\mathrm{TeV}$ in order to reproduce the DM cosmological abundance, taking into account the built-in Sommerfeld enhancement. As this is the only theory of Dark Matter that makes univocal predictions, it can be contradicted by a single new experimental result.

4 The $e^+ + e^-$ FERMI and HESS observations

The growing excess in the positron fraction observed by PAMELA below 100 GeV could become of order unity at TeV energies, so that it is interesting to consider measurements of the $e^+ + e^-$ cosmic ray spectrum, made by calorimeters that cannot discriminate the $e^\pm$ charge. (We recall that $e^\pm$ in matter shower in an exponential way, so that calorimeters become more precise and easily reach higher energies, where spectrometers see all tracks as quasi-straight becoming less precise and eventually useless).

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[1] $\bar{p}$ backgrounds are predicted with a plausible ±20% uncertainty. The $\bar{p}$ DM excess can be suppressed if the diffusion zone is small, e.g. if it extends away from the galactic plane for only 1 kpc, as in the so-called MIN possibility.

One year ago the ATIC balloon had the best measurement, and its data showed a peak around 700 GeV. This peak was incompatible with the Minimal Dark Matter prediction and could be fitted only by annihilations of TeV-scale DM into e or μ leptons [6].

The FERMI experiment now provides the first high-statistics measurement of the $e^+ + e^-$ spectrum, which do not confirm the ATIC peak, but still indicate an $e^+ + e^-$ excess. Indeed the $e^+ + e^-$ spectrum is harder than what expected, and the data indicate two spectral features in it, suggesting that the excess appears around 100 GeV and terminates around 1 TeV. These features are clearly larger than the statistical errors and it seems unlikely that they could be due to systematic uncertainties, although only the FERMI collaboration can answer the crucial question: are these features really there? HESS observations around and above 1 TeV independently indicate the termination of the excess.

If both features are real, DM annihilations into $\tau^+\tau^-$ and $\mu^+\mu^-$ can fit the PAMELA, FERMI and HESS data [13]. Models where DM annihilates into light vectors that decay into leptons, giving rise to 4 leptons with a smooth energy spectrum, can fit all the data [13]. The Minimal Dark Matter prediction would be excluded. Models where DM is lighter than about a TeV can no longer produce the PAMELA excess, as it would terminate below 1 TeV where FERMI data show a smooth spectrum.[2] Thereby DM predicts that the PAMELA excess will continue to grow as in fig. 1.

5 γ observations

The DM DM $\to \ell^+\ell^-$ interpretations of the $e^\pm$ excess predict related excesses in γ and ν fluxes. Indeed γ's are unavoidably generated by 3 different processes:

1. *Brehmstralung* from $\ell^\pm$. This gives γ with the largest $E_\gamma \sim M$, probed by HESS. However the γ energy spectrum significantly depends on the DM annihilation mode: modes involving τ (that decay into $\pi^0 \to 2\gamma$) give the largest γ yield, while models involving neutral light vectors give the smallest γ yield.

2. *Inverse Compton*: $e^\pm$ scatterings on the galactic ambient light (CMB and star light, partially rescattered by dust) give rise to $e^\pm\gamma \to e'^\pm\gamma'$ with $E_{\gamma'} \sim E_\gamma (E_e/m_e)^2 \sim 10\,\mathrm{GeV}$, being probed by FERMI. The resulting $e^\pm$ energy loss is proportional to the energy density u_γ in γ.

3. *Synchrotron*: $e^\pm$ diffuse in the galactic magnetic fields, radiating γ at radio-frequencies, $E_\gamma \sim 10^{-6}\,\mathrm{eV}$, probed by radio-observations: DAVIES, WMAP. The resulting $e^\pm$ energy loss is proportional to the energy density $u_B = B^2/2$ in magnetic fields

As it is believed that u_γ is about one order of magnitude larger than u_B, Inverse Compton is the dominant energy loss mechanism, and it can be reliably computed as essentially all the $e^\pm$ energy goes into IC, irrespectively of the precise value of u_γ. We use the full first γ maps from FERMI, dividing the sky in many regions as detailed in [14].

In fig. 3 (from [14]) we compare the values of σv and M suggested by the $e^\pm$ excesses with the various γ and ν bounds, computed imposing that the DM γ [15] and ν [16] fluxes do not exceed the various observations by more than 3σ in any region of the sky.

We needed to consider the quasi-constant 'isothermal' DM density profile because otherwise, had we assumed the Einasto or NFW profiles favored by N-body DM simulations, the DM density around the Galactic Center would have been so large that various bounds would be violated. Interpretations of the $e^\pm$ excesses in terms of DM DM $\to \ell^+\ell^-$ annihilations are thereby excluded, if N-body simulations reliably predict the DM density profile. Even with the

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[2] Unless the unseen drop at $E \lesssim M$ of the DM contribution is compensated by a new astrophysical component that grows.

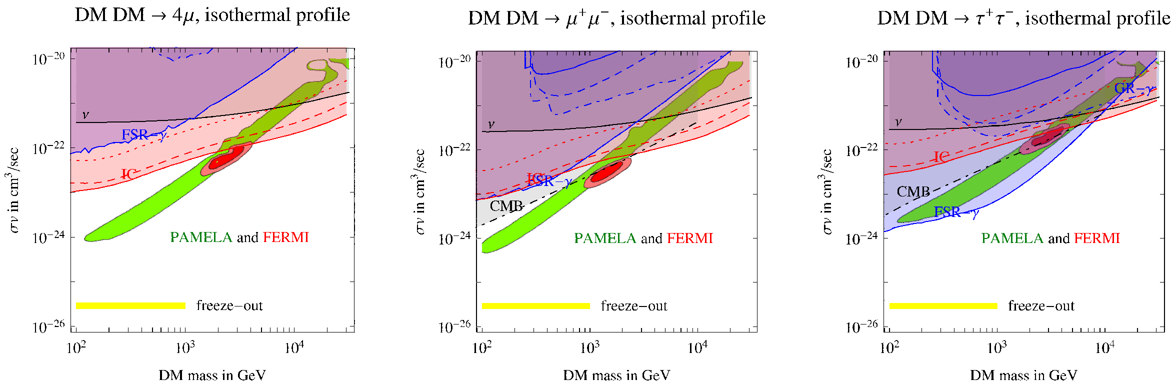

Figure 3: *We compare the region favored by PAMELA (green bands) and by PAMELA, FERMI and HESS observations (red ellipses) with* γ *observations of the Galatic Center (blue continuous line), of the Galactic Ridge (blue dot-dashed), of spherical dwarfes (blue dashed), with neutrino data, with FERMI observations in the* '$10^\circ \div 20^\circ$' *region.*

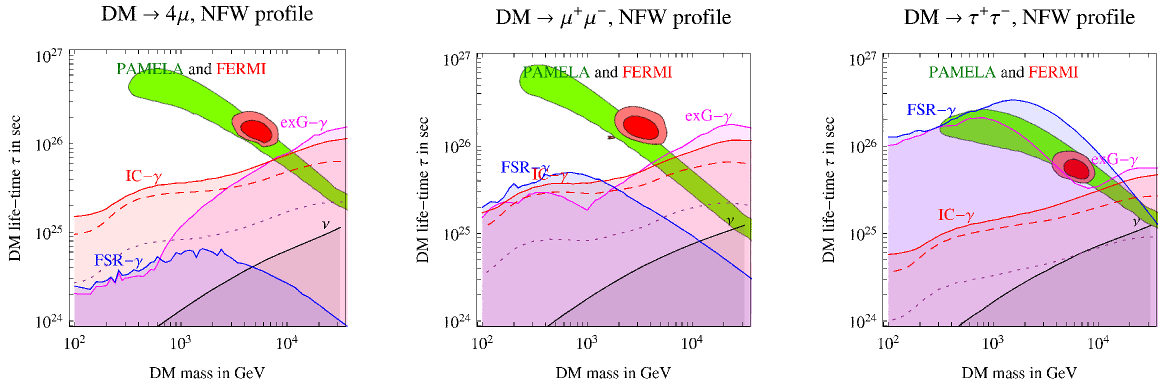

Figure 4: *As in fig. 3, here for DM decaying into* $\mu^+\mu^-$ *(middle),* $\tau^+\tau^-$ *(right),* 4μ *(left).*

'isothermal' profile, only a few DM annihilation channels satisfy all the bounds. For example, solutions in terms of DM annihilation into τ's are now excluded, because the $\tau \to \pi^0 \to \gamma$ process gives too many γ. Non-leptonic channels are excluded for the same reason.

Among all the DM annihilations into two body SM particles, only the $\mu^+\mu^-$ channel survives. Models where DM annihilates into two light vectors that decay into lepton pairs (giving rise to $4e$ or 4μ states) are less constrained: the γ FSR flux is roughly reduced by a factor $\ln(m/m_\ell)/\ln(M/m_\ell)$. Despite that, a DM density profile more constant than what suggested by N-body simulations remains again needed. If the light vectors have a long kpc-scale lifetime, the consequent smoothing of the $e^\pm, \gamma, \nu$ injection from DM annihilations is effectively equivalent to have the smoother DM density profile suggested by γ bounds [17].

Inverse Compton provides the dominant constraint for such leptonic channels that have suppressed FSR. As the energy spectrum of the $e^\pm$ excess is now strongly constrained by FERMI, HESS and PAMELA, the IC γ flux can be reliably computed to be as in fig. 1c: all DM models able of fitting the $e^\pm$ excess predict roughly the same IC flux.

Finally, various authors noticed that the DM annihilation rate, being proportional to the DM density squared, is enhanced in the early universe by the larger DM density. The resulting constraints on DM interpretations of the $e^\pm$ excesses are significant [18] ('CMB' line in our plots).

6 DM decay

The alternative interpretation of the $e^\pm$ excesses in terms of DM decays solves three difficulties faced by DM annihilations. First, the decay rate is not linked with cosmological freeze-out, so that one does not need to invent Sommerfeld or other enhancements. Second, cosmological constraints are not significant, as the DM life-time is not enhanced in the early universe. Third, the decay rate is proportional to ρ rather than to ρ^2: thereby the $e^\pm, \gamma$ injection term is less enhanced close to the Galactic Center where ρ is large. Fig. 4 shows that, as a result, the DM decay interpretation of the $e^\pm$ excesses is compatible with γ, ν bounds even for a NFW DM density profile. Again, only the $\mu^+\mu^-$, 4μ and $4e$ models provide solutions to the $e^\pm$ excesses compatibly with γ constraints.

We see that the needed DM mass and lifetime is $M \sim 3\,\text{TeV}$ and $\tau \sim 10^{26}$sec. DM decays via a GUT-suppressed dimension 6 operator naturally give the needed $\tau \sim M^4_{\rm GUT}/M^5$ [19, 20]. Furthermore, if DM is a proton-like particle, composite of chiral fermions, with an asymmetry kept in thermal equilibrium by sphalerons down to the electroweak symmetry breaking scale at $T \sim 100\,\text{GeV}$, the cosmological DM abundance is naturally obtained as $\Omega_{\rm DM}/\Omega_b \sim e^{-M/T} M/m_p$ for $M \sim$ few TeV [19]. DM might be not the only particle charged under the new strong interactions: as well known the few TeV scale independently appears in technicolor solutions to the higgs mass hierarchy puzzle, where a strong $\lambda \sim 4\pi$ coupling gives mass $M \sim 4\pi v$ to chiral fermions.

7 Conclusions

The excesses in $e^\pm$ cosmic rays measured by FERMI, PAMELA and HESS can be interpreted in terms of Dark Matter annihilations or decays into leptonic final states. The following solutions emerge:

- Annihilations or decays into $\mu^+\mu^-$, 4μ and $4e$.
- Annihilations are only allowed if the galactic DM density profile is quasi-constant, e.g. isothermal. This is disfavored by N-body simulations.
- Decays are allowed even for the NFW or Einasto profiles favored by N-body simulations.

The next step is using better FERMI data to model and subtract the astrophysical background; if this can be done precisely enough such the sensitivity to γ from DM become a factor of few stronger, even these remaining models can be tested [21].

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