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The cosmic-ray positron excess from a local Dark Matter over-density

Andi Hektor [a,b,*], Martti Raidal [a,c], Alessandro Strumia [a,d], Elmo Tempel [a,e]

[a] National Institute of Chemical Physics and Biophysics, Ravala 10, 10143 Tallinn, Estonia
[b] Helsinki Institute of Physics, P.O. Box 64, FI-00014, Helsinki, Finland
[c] Institute of Physics, University of Tartu, Estonia
[d] Dipartimento di Fisica dell'Università di Pisa and INFN, Italy
[e] Tartu Observatory, Observatooriumi 1, 61602 Toravere, Estonia

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ABSTRACT

We show that the cosmic-ray positron excess measured by PAMELA and AMS could be induced by Dark Matter annihilations in a local over-density. In such a context leptophilic DM is not needed and good fits to positron data, in agreement with antiproton and gamma-ray measurements, are obtained for DM annihilations to WW, hh, ZZ, $t\bar{t}$, $b\bar{b}$, $q\bar{q}$ channels. The classic Dark Matter candidates, such as the pure supersymmetric Wino with standard thermal annihilation cross-section, can fit the positron excess, without invoking any additional assumption on Dark Matter properties.

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1. Introduction

The new AMS02 measurement [1,2] of the cosmic-ray positron energy spectrum up to 350 GeV confirms with better precision the earlier claim by PAMELA [3] and FERMI [4] of a rising positron/electron fraction. Such a spectral feature demands either non-conventional models of the astrophysical background [5] or new sources, such as pulsars [6–11] or annihilations of weakly interacting Dark Matter (DM).

DM can explain the positron excess compatibly with the absence of a similar excess in the antiproton flux provided that the DM of the main Milky Way halo annihilates predominantly into the Standard Model (SM) leptons with a cross-section 2–3 orders of magnitude larger than the annihilation cross-section predicted by the hypothesis that DM is a thermal relic [12–14]. Such a large cross-section today may result from a Sommerfeld enhancement [12], maybe mediated by new hypothetical GeV scale vectors [13]. However, this scenario is severely constrained by the absence of associated gamma-rays from the galactic center, from dwarf galaxies and in the diffuse background [15–20]. Additional constraints arise from observations of the cosmic microwave background (CMB) [18,21–23]. Such constraints challenge various aspects of current DM theories — DM origin as a thermal relic, early cosmology, simulations of the Milky Way DM halo density profile, as well as particle physics models of the DM.

Furthermore, even DM annihilations into leptons are challenged, because the final state $e^\pm$ loose almost all of their energy through inverse Compton scattering on galactic star-light and CMB, producing a secondary flux of energetic photons. Such Inverse Compton photons can be compatible with gamma-ray observations provided that DM in the Milky Way has a cored (such as an isothermal) density profile [24–31].

The non-observation of such Inverse Compton photons favours the possibility that the positron excess is local, rather than present in all the Milky Way.

In this Letter we propose a solution to the positron anomaly that does not require additional *ad hoc* assumptions on DM properties. The idea is that the positron anomaly is a local effect arising from DM annihilations in a local DM over-density. DM density fluctuations, that are not gravitationally bound, are predicted to occur and disappear continuously everywhere in our Galaxy by the cold DM paradigm. The measured positron excess could then originate from such a local over-density even with the standard thermal annihilation cross-section.

This implies observable energy spectra of $e^\pm$, $\bar{p}$, γ different from the standard case where DM annihilates in all the Galaxy. Our most important result is that DM annihilations into the usual theoretically favoured channels,

$$WW,\ ZZ,\ hh,\ q\bar{q},\ b\bar{b},\ t\bar{t},\ \ldots,$$

can now reproduce the energy spectrum of the positron excess, while purely leptonic channels become disfavoured. This is because positron energy losses can now be neglected, such that a more shallow energy spectrum at production is needed to fit the positron excess. This result implies that the conventional WIMP

* Corresponding author.

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DM models are preferred by data without invoking additional assumptions. We will show that constraints from $\bar{p}$ and γ are satisfied.

Various past articles considered the possibility of interpreting the positron excess in terms of enhanced DM matter annihilations from a variety of different kinds of nearby DM sub-structures, such as clumped sub-haloes [32], black holes [34], dark stars [33], a dark disk [35]. A local DM over-density is one more possibility, that presents many similarities and one main phenomenological difference: the other sources are mildly or strongly localised, thereby predicting a gamma-ray DM signal coming from their position. Localised γ sources have been strongly constrained by the recent Fermi LAT measurements [20]. In our proposal, an over-density fluctuation surrounds the solar system predicting no localised γ excess.

Additional information that may discriminate between DM models is provided by DM direct detection experiments. If the local DM over-density exists today around us, the DM coupling to nuclei must be suppressed. This favours, for example, pure Wino DM or Minimal Dark Matter scenarios, where DM couples to matter only via a W-boson loop. If, instead, the DM over-density has already disappeared, and today we observe a remnant position excess trapped by the Galactic magnetic fields, typical WIMP DM models are viable candidates.

2. The local DM over-density

N-body simulations of cold DM structure formation predict a wide spectrum of density and velocity fluctuations in any DM halo such as our Galaxy [36]. Only a very small fraction of the density fluctuations develop high enough over-density, a few hundred times over the local average, to become gravitationally bound subhalos. A fluctuation with density ρ and radius R is gravitationally bound provided that the escape velocity from it is smaller than the typical local DM velocity dispersion,

$$v_{\rm esc} = \sqrt{\frac{8\pi}{3} G_N R^2 \rho} \ll 10^{-3}, \tag{1}$$

i.e. for $\rho/\rho_0 \gg 200 \times (\text{kpc}/R)^2$, where $\rho_0 = 0.4\ \text{GeV/cm}^3$ is the average DM density around the Sun. Those dense fluctuations collapse gravitationally and develop cuspy NFW or Einasto like profile similarly to the main halo. However, the vast majority of fluctuations just occur and disappear continuously without affecting large scale structure formation. Those over-density regions have shallow profiles, such as Gaussians, since they are not gravitationally bound.

In this work we assume that there exists, or there existed not long time ago, a local DM over-density with a radius of few hundred pc. Such an assumption is in agreement with the determination of local DM density at the distance of Sun. The latter is measured by the movement of stars in a cylinder of radius 1 kpc extending ± 4 kpc in both directions around the Galactic disk. A local over-density with radius $R = 100$ pc forms just 1/6000 of this volume, not affecting the average result. In fact, several over- and under-density fluctuations are expected to occur in such a big volume. Furthermore, a moderate local over-density is compatible with solar system gravitational measurements that imply a local DM density smaller than $\rho/\rho_0 < 15\,000$ [37].

3. Explaining the positron excess

We now try to interpret the measured positron excess as due to DM annihilations in a local DM over-density. As a result, we obtain the size and density of such a fluctuation from the AMS and PAMELA data. This will allow us to later predict the associated gamma-ray and antiproton fluxes.

In our exploration we follow the model independent approach introduced in [12,38]. We allow DM to annihilate into all possible two-body SM final states with the standard thermal relic cross-section $\langle \sigma v \rangle \approx 3 \cdot 10^{-26}\ \text{cm}^2$. The energy spectra of the various stable SM particles $(e^+, \bar{p}, \gamma, \nu, \ldots)$ are computed with PYTHIA8.

To compute the diffusion effects we assume the MIN/MED/MAX diffusion models of [39], as described in [38]. The number densities $f(\vec{x}, t, E)$ of e^+ and their fluxes $\Phi_{e^+} = cf/4\pi$ are well approximated by neglecting the energy loss term in the time-independent diffusion equation, that becomes simply

$$-K(E)\nabla^2 f = Q\,\frac{dN_{e^+}}{dE} = \frac{1}{2}\frac{\rho^2}{M^2}\langle \sigma v \rangle \frac{dN_{e^+}}{dE}, \tag{2}$$

where $K(E)$ is approximatively given by the Larmor radius in the local turbulent Milky Way magnetic field. Analyses of cosmic-ray data suggest $K(E) = K_0(E/\text{GeV})^\delta$ with $\delta = 0.85$–0.46 and $K_0 = (0.016$–$0.0765)\ \text{kpc}^2/\text{Myr}$ [39].

Assuming, for simplicity, that we live at the center of a spherical excess with constant local density ρ and radius R, and neglecting DM annihilations outside it, the solution is

$$\Phi_{e^+} = \frac{3\Gamma}{32\pi^2 K(E) R}\frac{dN_{e^+}}{dE}, \tag{3}$$

where Γ is the total DM annihilation rate in the local over-density:

$$\Gamma = \int dV\, Q = \frac{4\pi R^3}{3}\langle \sigma v \rangle \frac{1}{2}\frac{\rho^2}{M^2}. \tag{4}$$

The shape and location of the local excess only affect the overall numerical factor in Eq. (3), leaving unaffected the main feature: *The positron energy spectrum at detection is given by the positron energy spectrum at production over the diffusion factor $K(E)$.*

The boost factor B that enhances the positron DM flux with respect to the standard scenario can be expressed as

$$B = B_{\rm part} \times B_{\rm local}, \tag{5}$$

where $B_{\rm local} \propto \rho^2$ is the boost induced by the local DM over-density that we are considering, and $B_{\rm part}$ is a possible extra boost due to particle physics, not needed in our context, but that could be anyhow present. For example, DM with SM weak interactions and heavier than $M_{\rm DM} > M_W/\alpha_2 \approx$ few TeV has an annihilation cross-section enhanced at low velocity by the electroweak SM Sommerfeld effect, thereby producing $B_{\rm part} > 1$.

In Fig. 1 we plot the best fit spectra of the positron fraction from the DM annihilations to WW, hh and $b\bar{b}$ channels as functions of positron energy. We assumed a spherical local over-density with radius $R = 500$ pc. The χ^2 of the fits for the various annihilation channels as function of the DM mass are presented in Fig. 2. The required over-densities are also presented in the figures.

The main result from Figs. 1, 2 is that only DM annihilations to channels like WW, ZZ, gg, hh, $b\bar{b}$, $t\bar{t}$ give good fits to data while leptonic channels give very poor $(e^+e^-, \mu^+\mu^-)$ or poor $(\tau^+\tau^-)$ fits.

The reason for this result is that in our scenario the positron anomaly is a local phenomenon so that positron energy losses can be neglected. Therefore, the measured rise of the positron fraction is reproduced by injecting a shallow initial positron spectrum dN_{e^+}/dE into the Galactic environment. This is exactly opposite to the scenario in which the positron excess arises from DM annihilations in the main Galactic halo thanks to a large particle physics boost factor $B_{\rm part} \gg 1$. In the latter case the positron energy loss effects are significant and the injected spectrum must be hard to fit data [24]. This is the reason why only leptonic channels are able

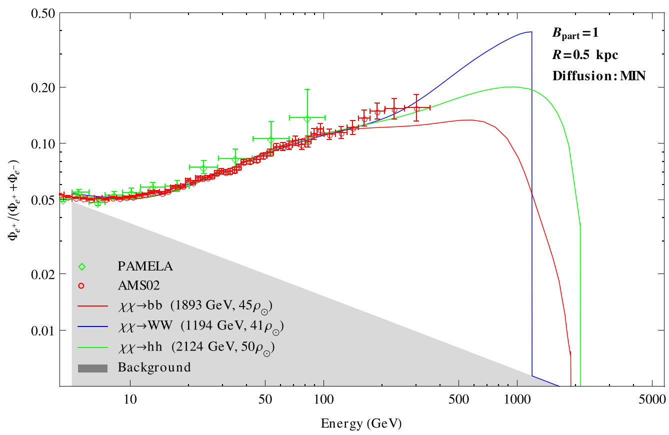

Fig. 1. Best fits of the positron fraction from DM annihilations to WW, hh, $\bar{b}b$ for parameters indicated in the figure. Over-densities are indicated as ρ_{loc} and given relative to the average density ρ_0.

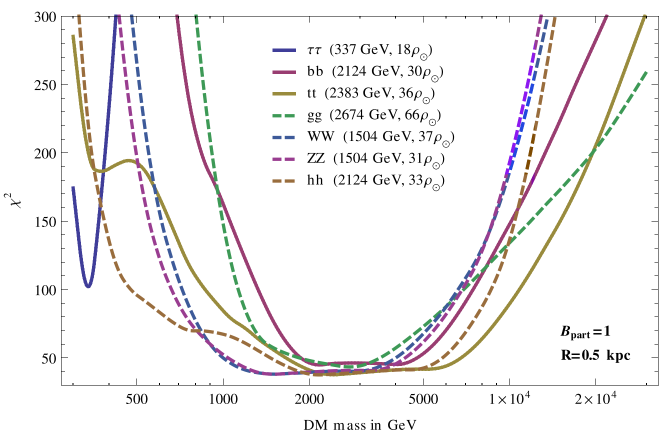

Fig. 2. Fit to the positron fraction: χ^2 as function of the DM mass for different DM annihilation channels.

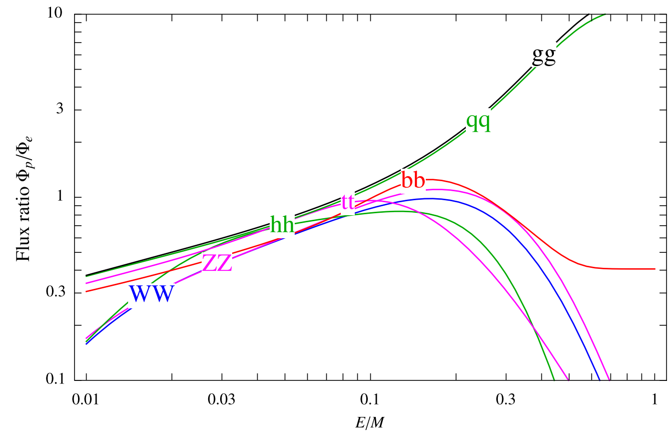

Fig. 3. Predicted $\Phi_{\bar{p}}/\Phi_{e^+}$ for various SM annihilation channels into W^+W^-, ZZ, hh, $t\bar{t}$, $b\bar{b}$, $q\bar{q}$, gg for $M \sim 1$ TeV.

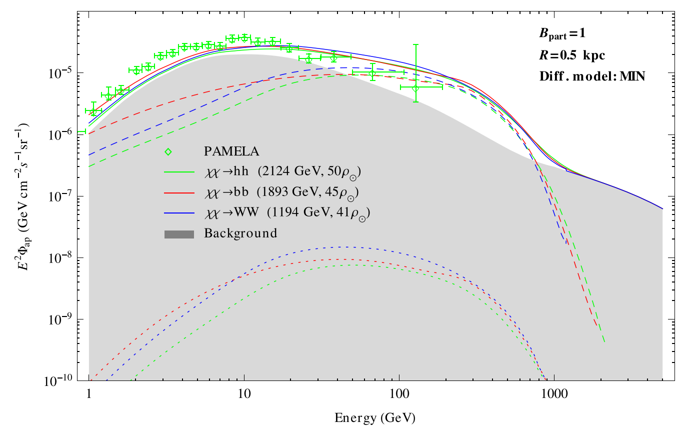

Fig. 4. Predicted $\bar{p}$ fluxes from the local DM over-density (long-dashed) and from the main halo (short-dashed) for the parameters that in Fig. 1 provide the best fits to the e^+ excess. We also show the estimated astrophysical $\bar{p}$ background.

to provide good fits in that case [24]. Therefore, particle physics models that are able to fit the data are completely different in the two cases.

AMS data prefer DM with masses 1–5 TeV. As seen in Fig. 1, the high energy behaviour of different annihilation channels are different. Measurements of the positron fraction at higher energy will provide more informations on the properties of DM.

Notice also that the required DM over-densities for the best fit channels are of order 40–50: smaller than the over-density that would form gravitationally bound sub-haloes. According to the simulations in [36] such over-density has a probability of about 10^{-9}.

In presence of a particle boost factor B_{part} of order 10, the needed over-density gets reduced down to $\rho \sim 5\rho_0$, and the probability of such over-density increases up to 10^{-5}. We thereby assume that only one such over-density is present.

With even larger boost factors the probability increases, but (as we will see) the γ fluxes start to be dominated by the galactic component, such that the strong bounds that plague the standard scenario appear again.

Based on this scenario, one expects a directional asymmetry of the positron signal, at the level or smaller than the asymmetry produced by nearby pulsars or DM sub-haloes [10], and thereby compatible with existing data. Given that we do not know the location of the local DM excess relative to us, such asymmetry cannot be precisely predicted.

Furthermore, the positron excess should also be visible as a small bump in the $e^+ + e^-$ cosmic-ray energy spectrum. The experimental situation is at the moment unclear: the recent measurement from AMS [2] contradicts earlier measurements from ATIC and FERMI, that contained two different hints of bumps. Thereby we cannot derive any safe conclusion from present data.

4. Implications for antiprotons

Fixing the local DM over-density and the DM parameters as in Figs. 1, 2, we are able to *predict* the antiproton fluxes from the local over-density due to DM annihilations.

In the relevant energy range $\bar{p}$ and e^+ diffuse in the same way, because they have the same electric charge (up to the sign), because they are both ultra-relativistic, and because we can neglect positron energy losses and $\bar{p}$ interactions. The $\bar{p}$ flux is then given by Eq. (3), just inserting the appropriate prompt energy spectrum. The prediction is:

$$\frac{\Phi_{\bar{p}}}{\Phi_{e^+}} = \frac{dN_{\bar{p}}/dE}{dN_{e^+}/dE}. \tag{6}$$

All non-leptonic SM annihilation channels predict that this ratio is ≈ 0.5 at the relevant value of $E/M \approx 0.1$, see Fig. 3.

This implies a predicted $\bar{p}$ DM flux at the level of the flux observed by PAMELA, as presented in Fig. 4.

The grey area in Fig. 4 is the antiproton astrophysical background, as estimated in [40]. Given that the astrophysical $\bar{p}$ back-

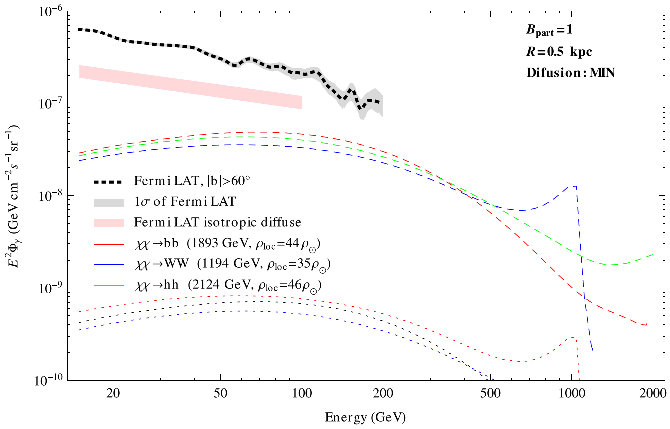

Fig. 5. Predicted gamma-ray fluxes from the local over-density (long-dashed) and the main halo (short-dashed) for the same parameters as in Fig. 1. The bands show γ-measurements: (gray) gamma-ray flux from the polar regions ($|b| > 60°$) measured by Fermi LAT and (pink) the isotropic component of gamma-ray sky estimated by the Fermi LAT Collaboration. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this Letter.)

ground is believed to have a $\sim 30\%$ uncertainty [41], there is some tension with the PAMELA data at higher energy. We find an acceptable overall global fit, even without introducing ad-hoc uncertainties in the shape of the background, and without increasing the DM mass to shift the $\bar{p}$ excess to higher energies. The issue will be soon clarified by improved AMS measurements of the $\bar{p}$ flux.

For comparison, the standard scenario without a local DM over-density predicts a $\Phi_{\bar{p}}/\Phi_{e^+}$ which is *uncertain and higher* than in Eq. (6), because energy losses from distant DM annihilations around the center of the Galaxy reduce Φ_{e^+} but not $\Phi_{\bar{p}}$, and because the amount of $\Phi_{\bar{p}}$ that reaches us depends on the unknown volume of the Galactic diffusion region. This is why, in the standard scenario, $\bar{p}$ bounds are stronger and one needs to select leptophilic DM particle physics models that avoid annihilations into $\bar{p}$.

5. Implications for gamma-rays

The γ flux is predicted as

$$\Phi_\gamma = \frac{\langle \sigma v \rangle}{4\pi} \frac{dN_\gamma}{dE} \int_{\text{l.o.s.}} ds \, \frac{1}{2} \frac{\rho^2}{M^2} = \frac{3\Gamma}{16\pi^2 R^2} \frac{dN_\gamma}{dE}, \tag{7}$$

where in the last expression we evaluated the line-of-sight integral by assuming again that we are at the center of a spherical constant over-density with radius R. The ratio between photons and positrons is predicted as

$$\frac{\Phi_\gamma}{\Phi_{e^+}} = \frac{2K}{R} \frac{dN_\gamma/dE}{dN_{e^+}/dE}. \tag{8}$$

Up to the geometry-dependent order one factor, the astrophysical factor K/R can be intuitively understood as follows. For all particles, fluxes are inversionally proportional to their speed. Photons travel at the speed of light, while e^+ diffuse in a time T for a distance R with an average velocity given by $R/T \simeq \sqrt{KT}/T \simeq K/R$.

The ratio Φ_γ/Φ_{e^+} depends on the uncertain diffusion parameter $K(E)$ and on the size of the bubble. Fig. 5 shows the predicted DM γ flux for a bubble with $R \approx 0.5$ kpc and for the MIN propagation model (notice that our result is only affected by the local value of the diffusion coefficient K, which could differ from their average galactic value).

The γ flux from local DM annihilations is a factor of few below the two measured γ fluxes plotted in Fig. 5:

1. The pink band is the diffuse isotropic gamma-ray background, as extracted from the FERMI Collaboration [42].
2. The slightly higher gray band is extracted by us from FERMI data, following a simpler procedure. We subtracted known point-like sources and reduced the Galactic gamma-ray background by restricting the observation region to high Galactic latitudes, $|b| > 60°$.

We do not show the expected astrophysical gamma-ray background because we do not know any reliable estimate of it.

We here neglected the Inverse Compton gamma-ray flux, because it is strongly reduced with respect to the standard scenario, where it is problematic, by our assumptions that the e^+ excess is just local.

Finally, we point out that, while the main features of our results have been explained with simple approximations, our numerical results have been derived from a full numerical study where we have taken into account energy losses for $e^\pm$ and other small effects. In Figs. 4 and 5 we also plotted the contributions to the gamma-ray and antiproton fluxes coming from regions of the Milky Way outside from the dominant local over-density. We see that such contribution is so small that the analysis would remain unchanged in presence of a moderate $B_{\text{part}} \sim 10$, or even larger.

6. Implications for DM direct detection

We found that the positron excess can be reproduced as due to DM annihilation with the standard thermal-relict cross-section, assuming a local DM over-density with $\rho \sim 40\rho_0/B_{\text{part}}$ (see Figs. 1, 2). Here, $B_{\text{part}} \geqslant 1$ is a boost factor of particle physics origin (e.g. Sommerfeld enhancement), that could be larger than one even if this is not needed in our scenario.

The boost of indirect DM detection signals, proportional to ρ^2, is accompanied by a smaller boost of DM direct detection signals, proportional to ρ. In order to explain the negative DM direct searches in Xenon100 [43], the DM spin-independent cross-section to nuclei must be smaller than about 10^{-45} cm^2 for $M \sim$ TeV. This happens *naturally* in various theoretically motivated DM models.

For example, if DM is a pure supersymmetric Wino (or, equivalently, a Minimal Dark Matter fermion triplet), the DM relic abundance fixes its mass to be 2.5 TeV. Such a DM candidate gives a good fit to the position excess, as seen in Fig. 1. At the same time, such particle couples to nuclei only via a W-boson loop, giving a small cross-section $\sigma_{\text{SI}} \sim 0.6 \cdot 10^{-46}$ cm^2 [44], compatible with the negative results of Xenon100.

Alternatively, in many models DM couples to SM particles only via the Higgs doublet. Such models generically predict DM annihilations into hh and may have small enough DM/nucleon cross-section σ_{SI}. In particular, scenarios in which the electroweak breaking scale is induced via the Higgs boson mixing with a singlet scalar from the dark sector [45–47] predict generically that σ_{SI} is suppressed by the small mixing angle.

If, instead, the local DM over-density fluctuation has already disappeared today, and PAMELA, AMS measure the remnant of the positron excess trapped by Galactic magnetic fields, no additional constraints on our scenario occurs from DM direct detection experiments.

7. Conclusions

We have shown that the positron excess measured by PAMELA and confirmed by AMS could be due to DM annihilations enhanced by a local DM over-density surrounding the solar system. In such a context, it is not necessary to assume leptophilic DM annihilations — on the contrary DM annihilations into the theoretically favoured channels WW, ZZ, gg, hh, $\bar{b}b$, $\bar{t}t$ can explain the data. This scenario predicts $\bar{p}$ and γ fluxes from DM annihilations at the level of present measurements. In particular, AMS can test this scenario performing and improved measurement of the $\bar{p}$ flux. In such a context, the positron excess prefers 'classical' WIMP DM candidates with suppressed coupling to nuclei, such as the pure Wino, without additional assumptions on DM properties nor invoking any exotic particle physics to boost the annihilation cross-section.

Finally, if the positron excess is not due to DM annihilations, our results imply a bound on the local DM density that is stronger than the direct bound [37] for $M \sim 1$ TeV and for a radius $R > 0.1$ pc of the local over-density, and under the assumption of a thermal DM annihilation cross-section.

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