Dark matter models for the 511 keV galactic line predict keV electron recoils on Earth

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Abstract We propose models of Dark Matter that account for the 511 keV photon emission from the Galactic Centre, compatibly with experimental constraints and theoretical consistency, and where the relic abundance is achieved via p-wave annihilations or, in inelastic models, via co-annihilations. Due to the Dark Matter component that is inevitably upscattered by the Sun, these models generically predict keV electron recoils at detectors on Earth, and could naturally explain the excess recently reported by the XENON1T collaboration. The very small number of free parameters make these ideas testable by detectors like XENONnT and Panda-X, by accelerators like NA64 and LDMX, and by cosmological surveys like the Simons observatory and CMB-S4. As a byproduct of our study, we recast NA64 limits on invisibly decaying dark photons to other particles.

1 Introduction

Data that deviate from standard predictions are lifeblood of progress in physics. The past few decades have seen a plethora of such observational ‘anomalies’, both in cosmic rays and in underground detectors, that could have been explained by some property of particle Dark Matter (DM). None of them has been so far enough to claim the discovery of a new DM property, because of the possible alternative explanations in terms of new astrophysical sources, of underestimated systematics, etc, often flavored with a healthy dose of skepticism. An awareness has therefore emerged that the confirmation of a DM origin for some anomaly would require, as a necessary condition, that many anomalies are intimately linked together within a single model of DM.

It is the purpose of this letter to point out one such link. Not only we propose DM models that explain the observed 511 keV line from the Galactic Centre (GC) [1–3], but also we show they predict electron recoils with energies of the order of a keV, of the right intensity and spectrum to be observed by XENON1T [4,5] and to explain the excess seen in [5]. Our spirit in writing this paper is not to abandon the skepticism praised above, but rather to add an interesting –in our opinion– piece of information to the debates surrounding both datasets.

1.1 The 511 line and Dark Matter: preliminaries

Given that the origin of the bulge 511 keV line has not yet been clarified, and given that DM exists in our galaxy, it makes sense to entertain the possibility that the latter is responsible for the former. A DM origin for the positron injection in the bulge has indeed been investigated since [6]. The morphology of the signal excludes DM decays in favor of annihilations, see e.g. [7]. The 511 keV line emission in the galactic bulge could be accounted for by self-conjugate DM annihilations into an e⁺e⁻ pair with

\[
\langle \sigma v \rangle_{511} \simeq 5 \times 10^{-31} \left( \frac{M_{DM}}{3 \text{ MeV}} \right)^2 \text{ cm}^3 \text{ s}^{-1},
\]

where we have used the best fit provided in [7] for an NFW DM density profile, as an indicative benchmark. Different profile shapes and the use of new data for the line could change the precise value of \( \langle \sigma v \rangle_{511} \), which however is not crucial for the purpose of this paper.

The need for a positron injection energy smaller than 3 MeV [8] implies that, unless one relies on cascade annihilations [9], \( M_{DM} \lesssim 3 \text{ MeV} \). Since so small values of \( M_{DM} \) have been found to be in conflict with cosmological observations, a simple DM-annihilation origin of the 511 keV line

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has been claimed excluded in [10]. Recently, however, the refined analysis of [11,12] found that values of $M_{\text{DM}}$ down to $\sim 1$ MeV can be made consistent with CMB and BBN, by means of a small extra neutrino injection in the early universe, simultaneous with the electron one from the DM annihilations. We will rely on this new result in building DM models for the 511 keV line.

Equation (1) clarifies that s-wave DM annihilation cannot explain the 511 keV line, because so small cross sections imply overclosure of the universe. To be compatible with a thermal generation of the DM abundance, one therefore needs annihilation cross sections in the early universe much larger than today in the GC. This is realised for example in two simple pictures, where the DM relic abundance is set by:

- p-wave annihilations;
- coannihilations with a slightly heavier partner.

We will build explicit DM models that realise each of them in the next two paragraphs.

1.2 DM for the 511 keV line: p-wave

Using $\langle \sigma v \rangle^{(p)}_\text{relic} (M_{\text{DM}}=2 \text{ MeV}) \simeq 2.2 \times 10^{-25} v_\text{rel}^2 \text{cm}^3/\text{s}$ [13], we find

$$M_{\text{DM}}^{(p)} \simeq 2 \text{ MeV} \frac{(v_\text{rel}^{1/2}_\text{bulge})}{1.1 \times 10^{-3}},$$

where we have normalised $(v_\text{rel}^{1/2}_\text{bulge})$ to the value obtained from the velocity dispersion in the bulge $\sigma \simeq 140 \text{ km/s}$ [14], and where we have assumed that the dominant annihilation channel at freeze-out is $e^+e^-$. Note that the preferred DM mass would be the same for non-self-conjugate annihilating DM, for which both $(\sigma v)|_{511}$ and $(\sigma v)|_{\text{relic}}$ are larger by a factor of 2.

An explicit model realising this picture consists of a Majorana fermion $\chi$ as DM candidate, whose interactions with electrons are mediated by a real scalar $S$ via the low-energy Lagrangian (we use 2 component spinor notation throughout this work)

$$\mathcal{L} = y_D \chi^2 S + g_{e} e_L^c e_R^\dagger S + \text{h.c.}$$

This results in the annihilation cross section

$$\sigma e^+e^- = v_\text{rel}^2 \frac{(y_D g_e)^2}{8\pi} \frac{M_{\text{DM}}^2 (1 - m_e^2/M_{\text{DM}}^2)^2}{(m_S^2 - 4M_{\text{DM}}^2)^2 + m_S^2 \Gamma_S^2},$$

and in the cross section for DM-e elastic scattering

$$\sigma_e = \frac{(y_D g_e)^2}{\pi} \frac{\mu_{eDM}^2}{m_S^4},$$

where $m_S$ is the scalar mass, $\Gamma_S$ its width, and $\mu_{eDM} = m_e M_{\text{DM}}/(m_e + M_{\text{DM}})$. Once $\sigma v e^+ e^-$ and $M_{\text{DM}}$ are fixed by the requirements to fit the 511 keV line Eq. (1) and to reproduce the correct relic abundance Eq. (2), then only two free parameters are left, which we choose as $g_e$ and $m_S$ in Fig. 1. We find that a region capable of explaining the 511 keV line exists, delimited by perturbativity, direct detection (derived later) and collider limits (see the Supplemental Material).2

The existence of 3 degrees of freedom with masses $M_{\text{DM}}$ and $m_S$ of a few MeV is not in conflict with cosmological data, provided one posits a small injection of neutrinos in the early universe in a proportion $\sim 1:10^4$ to the electron injection, see [11,12]. This can for example be achieved with a coupling to neutrinos, $g_\nu v^2 S$, of size $g_\nu \sim 10^{-2} g_e$, and where $g_e \sim 10^{-6}$ in the region allowed by the various limits, see Fig. 1. Coupling of neutrinos and electrons of these sizes can be easily obtained in electroweak-invariant completions of the Lagrangian of Eq. (3). Since they do not present any particular model-building challenge, we defer their presentation to the Supplemental Material. The results of [11,12] indicate that agreement with cosmological data fixes that ratio up to roughly one order of magnitude, so in

1 An interesting future direction would be to refine the DM fit of the excess, by taking into account not only the radial dependence of the DM velocity dispersion (see e.g. [15,16] for old such studies), but also new data and models for the positron injection from astrophysical sources.

2 Limits from CMB [17], CR electrons [18] and CR-electron-upsattered DM [19,20] do not constrain the explanation of the 511 keV line in the models presented in this paper.
this sense we do not need a very precise tuning between the electron and neutrino couplings.

Coming to future tests of this model, direct detection experiments like XENONnT and Panda-X will play a leading role in testing the available parameter space of Fig. 1. We stress that the shape of the electron recoil spectrum is fixed over the entire parameter space, only its normalisation changes according to the DD cross section shown by the orange lines. LDMX [22] will further cut in the available parameter space, as it can probe invisibly decaying dark photon with $m_V = 15$ MeV down to $\epsilon = 10^{-6}$, corresponding to $g_e$ of the same order (see Supplemental Material). Finally, according to Ref. [12], both CMB-S4 [23] and the Simons Observatory [24] will probe $M_{DM} = 2$ MeV at 95%CL or more and regardless of the ratio of the electron and neutrino couplings, thus offering useful complementary information.

1.3 DM for the 511 keV line: coannihilations

As a model that concretely realises this idea, we add to the SM a gauge group $U(1)'$, two fermions $\xi$ and $\eta$ with charges 1 and $-1$ respectively, and a scalar $\phi$ with charge 2 that spontaneously breaks the symmetry. The most general low-energy Lagrangian that preserves charge conjugation ($\eta \leftrightarrow \xi$, $\phi \leftrightarrow \phi^*$, $V_\mu \leftrightarrow -V_\mu$) reads

$$\mathcal{L} = V(|\phi|) + \frac{\epsilon}{2} V_{\mu \nu} F^{\mu \nu} + (i g_D \chi_1^2 \overline{\sigma}_\mu \chi_1 V^{\mu} + \text{h.c.}) - \frac{m}{2} (\chi_1^2 + \chi_2^2) - \frac{y_\phi}{2} (\phi + \phi^*) (\chi_2^2 - \chi_1^2) + \text{h.c.},$$

where $\chi_1 = i(\eta - \xi)/\sqrt{2}$ and $\chi_2 = (\eta + \xi)/\sqrt{2}$ are the Majorana mass eigenstates, $F_{\mu \nu}$ is the electromagnetic field strength and we have understood all kinetic terms. The scalar mass and triple-coupling read

$$V(|\phi|) = \lambda_0 \left( |\phi|^2 - \frac{\nu_\phi^2}{2} \right) \Rightarrow m_\phi^2 = 2\lambda_0 \nu_\phi^2, \quad \lambda_{\psi^3} = 6\lambda_0 \nu_\phi,$$

where $\phi = (\varphi + \nu_\phi)/\sqrt{2}$ and $\lambda_{\psi^3}$ is defined by $\mathcal{L} \supset \lambda_{\psi^3} \psi^3 / 6$. The physical vector and fermion masses read

$$m_V = 2g_D \nu_\phi, \quad m_{1,2} = \tilde{m} \pm \frac{\epsilon}{2}, \quad \delta = 2 \sqrt{2} \nu_\phi.$$

$\chi_1$ coannihilates with $\chi_2$ via dark photon exchange. In the limit $\delta \ll m_{1,2} = M_{DM}$, one finds

$$\sigma v_{\chi_1 \chi_2 \to e^+ e^-} = 4\alpha_e e^2 \frac{g^2_D}{2} \frac{M^2_{DM} + m_e^2/2}{(m^2_{1,2} - 4M^2_{DM})^2} \sqrt{1 - \frac{m_e^2}{M^2_{DM}}},$$

where $\alpha_e$ is the fine-structure constant. For definiteness, we then assume that $\chi_2$ decays on cosmological scales, such that coannihilations cannot be responsible for a positron injection in the GC today. We will come back to this point in the end of the paragraph.

One can then explain the 511 keV line, if $m_\varphi < M_{DM}$ and $\varphi$ decays to $e\bar{e}$, via pair annihilations $\chi_1 \chi_1 \to \varphi \varphi$. The associated cross section, at first order in $y_\varphi/\lambda_{\psi^3} \ll 1$, reads ($i = 1, 2$)

$$\sigma v_{\chi_i \chi_i \to \varphi \varphi} = \frac{v^2_{\text{rel}} y^2_\varphi \lambda_{\psi^3}}{64\pi} \frac{1}{(4m^2_{\varphi} - m^2_i)^2} \sqrt{1 - \frac{m^2_i}{m^2_\varphi}}.$$

An operator $|\phi|^2 (\epsilon_L \epsilon_R^\dagger + \text{h.c.})/\Lambda_{\phi e}$ with $\Lambda_{\phi e} \sim 10^0$–$10^1 \nu_\phi$ guarantees that $\varphi$ decays to $e\bar{e}$ instantaneously on astrophysical scales, while being allowed by collider, supernovae and BBN limits [25,26]. It could originate – at the price of some tuning – from a $|\phi|^2 |H|^2$ term, or from the models discussed in the Supplemental Material. Since a $\chi_1 \chi_1$ annihilation injects two $e\bar{e}$ pairs, the cross section that best fits the 511 keV line is reduced by a factor of 2 with respect to Eq. (1). Therefore we impose

$$\sigma v_{\chi_i \chi_i \to \varphi \varphi} = \frac{1}{2} (\sigma v)|_{111} \frac{v^2_{\text{rel}}}{(v^2_{\text{rel}})^{\text{bulge}}},$$

where the left-hand side sums the $s$- and $p$-wave contributions (see e.g. [27] for the origin of the relative factors) and where we use for simplicity the $s$-wave values at $M_{DM} = 3$ MeV, $\sigma v_{111} \approx 8 \times 10^{-26} \text{cm}^3/\text{s}$ [13] and $x_{31} \approx 15$ (their dependence on $M_{DM}$ is very mild).

The model is then left with 4 free parameters, we visualise its parameter space in Fig. 2 for the benchmark values $m_\varphi = 2$ MeV and $m_V = 15$ MeV [4]. The allowed region is again delimited by perturbativity, direct detection and collider limits. Analogously to the previous model, these low values of $M_{DM}$ can be brought in agreement with BBN and CMB data by a coupling $g_v V_\mu \overline{\sigma} \nu_\phi$, with $g_v \sim 10^{-2} e\bar{e}$. We refer the reader to the Supplemental Material for a possible origin of $g_v$. Here we just point out that it induces

$^3$ This is larger than 2 MeV on the previous section because of the factor of 2 with respect to Eq. (1) that we just explained, and because the relic cross-section is twice that of self-conjugate particles, because $\chi_1, \chi_2$ cannot annihilate via $\sigma v_{\chi_1 \chi_1 \to \varphi \varphi}$. Note that, for $M_{DM} < 6$ MeV, the positron injection energy is always smaller than the needed 3 MeV thanks to the extra step in the annihilation.

$^4$ The phenomenology we discuss next is not affected by their precise values, as long as $1.5 \lesssim m_\varphi / M_{DM} \lesssim 3$, and $10 \lesssim m_V / M_{DM} \lesssim 100$, where the lower limits are potentially in conflict with BBN and the upper ones close the available parameter space. Since $\delta$ is independent of $m_\varphi, m_\varphi < 2$ MeV would not open any new allowed parameter space.
Fig. 2 The conditions to reproduce the DM abundance and the 511 keV line impose $M_{\text{DM}} \lesssim 4 \text{ MeV}$ and leave 4 free parameters, chosen here as $M_{\text{DM}}, \delta, m_\nu$, and $m_\chi$. Shaded: non-perturbative dark coupling (gray), NA64 limit [21] (blue), indicative limit from XENON1T data [5] (orange). Lines: $\sigma_\nu$ (orange), $g_\chi$ (gray), $e$ (cyan). The dashed gray line roughly delimits the region where $\chi_2$ decays into neutrinos are not enough to deplete the primordial $\chi_2$ population, and further constraints could arise. The blue triangle corresponds to the electron recoil spectrum at XENON1T shown in Fig. 3, and it explains the excess events presented in [5].

While this goes beyond the purpose of this work, it would be interesting to investigate it in combination with the 511 keV line and we plan to come back to it in future work.

2 keV electron recoils from Sun-upscattered DM

The models we proposed to explain the 511 keV line require DM with a mass of a few MeV, interacting with electrons. Such a DM is efficiently heated inside the sun, resulting in a flux of solar-reflected DM with kinetic energy ($\sim$ keV) significantly larger than the one of halo DM, thus offering new detection avenues to direct detection experiments [36]. We now show that, via this higher-energy component, both ‘$p$-wave’ and ‘coannihilations’ models for the 511 keV line automatically induce electron-recoil signals that are probed by XENON1T S2-only [4] and S1+S2 [5] data.

We outline the procedure to obtain the event rate caused by the solar-reflected DM flux and refer to the Supplemental Material for more details. In the case of our interest with relatively small $\sigma_e$, the solar-reflected DM flux $\Phi_{\text{refl}}$ is estimated as

$$\frac{d\Phi_{\text{refl}}}{dE} \approx \frac{n_\text{DM}}{(1\text{AU})^2} \int_0^{r_{\odot}} dr \frac{r_{\odot}}{r^2} v_{\odot} n_e(r) \left( \frac{d\sigma_e}{dE} \right) v_e(r),$$

where $E$ is the DM kinetic energy, $n_\text{DM}$ is the DM number density, $r_{\odot}$ is the solar radius, $v_{\odot}$ is the escape velocity, $v_D$ is the halo DM velocity, $n_\epsilon(v_\epsilon)$ is the electron number density (velocity), and $\langle \ldots \rangle$ denotes the thermal average. In this formula, we have improved the analysis of [28] by including the radial dependence of the solar parameters, taken from [37]. The recoil spectrum of the electron initially in the $(n, l)$ state of a XENON atom is given by

$$\frac{dR_{nl}}{dE_R} = \frac{N_T \sigma_e}{8\mu^2_{\text{DM}} E_R} \int dq f_{nl} |\xi(E_{\text{min}})|,$$

$$\xi(E_{\text{min}}) = \int_{E_{\text{min}}}^{E_D} dE \left( \frac{M_{\text{DM}}}{2E} \right) \frac{d\Phi_{\text{refl}}}{dE},$$

$$E_{\text{min}} = \frac{M_{\text{DM}}}{2} \left( \frac{E_{nl} + E_R - \delta}{q} + \frac{q}{2M_{\text{DM}}} \right)^2,$$

where $N_T$ is the number of target particles and $E_{nl}$ is the electron binding energy, see e.g. [38] for a detailed derivation of the above expressions. We compute the atomic form factor $f_{nl}$ following [32,39], and leave a refined treatment including relativistic effects [40,41] to future work.

In Fig. 3, we show the electron recoil spectra for two benchmark points $M_{\text{DM}} = 2 \text{ MeV}$ and $\sigma_e = 4 \times 10^{-38} \text{ cm}^2$ in the $p$-wave case and $M_{\text{DM}} = 3 \text{ MeV}, \sigma_e = 1.9 \times 10^{-38} \text{ cm}^2$ and $\delta = 3 \text{ keV}$ in the coannihilation case. The induced electron recoils peak at energies below 2 keV in the $p$-wave
case, and in the coannihilation one if $\delta \lesssim$ keV. In the former case, the position of the peak is fixed by the dark matter mass Eq. (2), and it does not appear possible to explain signal excess observed at XENON1T. On the other hand, in the latter case with larger $\delta$ the events instead peak at $E_R \sim \delta$, because the downscattering $\chi_2 \rightarrow \chi_1$ releases more energy than the initial one of $\chi_2$. In particular, the events are peaked at $E_R = 2–3$ keV in our benchmark point, which can explain the recent XENON1T anomaly. We emphasize that this result is non-trivial, because the allowed parameter region is defined by requirements and experimental limits that are completely independent of XENON1T. It is then a fortunate accident that this region is in the right ballpark for the explanation of the XENON1T anomaly.

The results of this paragraph are of course interesting beyond these anomalies, as they quantify how XENON1T tests models of light electrophilic DM. The limits shown in Figs. 1 and 2 are derived by the conservative requirement that signal plus background should not overshoot the data in [5] by more than 3$\sigma$, a more precise limit derivation is left to future work.

3 Conclusions and outlook

We have presented two models which explain the 511 keV line in the galactic bulge by annihilation of particle dark matter with a mass of order MeV. The relic abundance is set by p-wave annihilations in one model, and by coannihilations with a slightly heavier partner in the other model. We have found the novel result that these models induce electron recoils on Earth that are being tested by XENON1T, and that coannihilation models could, non-trivially, simultaneously explain the 511 keV line and the excess events recently presented by XENON1T [5]. In addition, we have demonstrated that both models are compatible with all experimental constraints, in particular with cosmological ones: to evade the conclusion of [10] that no $\mathcal{O}$(MeV) DM model could explain the 511 keV line, we have relied on an extra annihilation channel into neutrinos and on the new results of [11, 12].

Independently of the XENON1T anomaly, our proposed DM explanations of the 511 keV constitute a new physics case for experiments sensitive to keV electron recoils, like XENONnT and Panda-X [42], for accelerators like NA64 and LDMX [22], and for cosmological surveys like CMB-S4 [23] and the Simons Observatory [24]. The origin of a long-standing astrophysical mystery could be awaiting discovery in their data.

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