Plasma dark matter, which arises in dissipative dark matter models, can give rise to large annual modulation signals from keV electron recoils. Previous work has argued that the DAMA annual modulation signal might be explained in such a scenario. Detailed predictions are difficult due to the inherent complexities involved in modelling the halo plasma interactions with Earth-bound dark matter. Here, we consider a simple phenomenological model for the dark matter velocity function relevant for direct detection experiments, and confront the resulting electron scattering rate with the new DAMA/LIBRA phase 2 data. We also consider the constraints from other experiments, including XENON100 and DarkSide-50.
1 Introduction

The DAMA collaboration have observed an annually modulating scintillation rate in an NaI target for over a decade, with properties broadly consistent with a dark matter signal [1–5]. An interpretation of the DAMA annual modulation in terms of nuclear recoils appears to be excluded by many other experiments, including XENON1T [6], DarkSide [7], PANDA [8], LUX [9], CRESST [10], CDMS [11], XMASS [12], PICO [13], etc. However the DAMA experiment is sensitive to both electron and nuclear recoils, and if the annual modulation is due to electron recoils then it is far more weakly constrained. This suggests that dark matter scattering off electrons is the more likely explanation, if the DAMA signal is indeed due to dark matter interactions.

Electron recoils with keV energy scale can arise from dark matter scattering if there are dark matter particles of mass $\sim$ MeV with kinetic energy in the keV range [14, 15]. Such particles occur in dissipative dark matter models, where the dark matter halo in the Milky Way takes the form of a dark plasma. Specifically, if dark matter consists of dark electrons and dark protons coupled together via a massless dark photon, e.g. [18], then energy equipartition implies that the dark electrons and dark protons have the same temperature and the same mean energy. The halo temperature is set by the mean particle mass, $\bar{m} \equiv \sum n_i m_i / \sum n_i$, and is estimated to be:

$$ T \approx \frac{\bar{m} v_{\text{rot}}^2}{2}. \quad (1) $$

Here, $v_{\text{rot}}$ is the asymptotic rotational velocity, which for the Milky Way galaxy is $v_{\text{rot}} \approx 220$ km/s. The above temperature relation indicates that the kinetic energy of dark electrons with a mass of order a MeV can be in the keV range provided that $\bar{m}$ is of order a few GeV or so.

In such models the kinetic mixing interaction [19, 20] is introduced to achieve consistent halo dynamics [18, 21, 22]. The dark halo is dissipative and cools, and with kinetic mixing around $\epsilon \sim 10^{-9} - 10^{-10}$ type II supernovae can be transformed into powerful dark sector heat sources. It has been argued in a number of papers, most recently in [23–25], that dissipative dark matter with heating sourced from supernovae can lead to a successful framework to understand small scale structure issues. Importantly, this picture can be tested in direct detection experiments as the kinetic mixing interaction also allows for observable dark matter scattering off ordinary particles, with the most favourable detection channels being dark electron-electron scattering, and dark proton-nuclei scattering, e.g. [26].

Kinetically mixed mirror dark matter provides a theoretically constrained dark plasma model [22, 27]. The mean halo mass is around a GeV and the temperature of the dark halo is estimated to be around $T \sim 0.5$ keV. Furthermore, the dark electron

\footnote{The DAMA experiment interpreted in terms of WIMP-electron scattering has been discussed in [16], but is however strongly constrained [17].}
is the mirror electron, a particle hypothesized to have exactly the same mass as the electron. The analysis in this paper is applicable to the mirror dark matter case, but also relevant to more generic plasma dark matter models.

Mirror dark matter, and related models, have a number of nontrivial aspects. Of particular concern for direct detection experiments is the interaction between the halo wind and captured dark matter within the Earth. The captured dark matter provides an obstacle to the halo wind, and can strongly influence halo dark matter properties (density and distribution) in the Earth’s vicinity. The effects of this ‘dark sphere of influence’ can be explored with MHD equations, and the temperature and density distributions of the halo dark matter in the Earth’s vicinity studied [15]. That investigation found that the annual modulation signal can be greatly enhanced, even a modulation amplitude near maximal (i.e. of order 1) is possible. In addition, diurnal variation is also expected to be significant, and can in fact be maximal for a detector located in the southern hemisphere [15][28][29].

The enhanced annual modulation can help reconcile the positive DAMA annual modulation signal with the results reported by XENON100 [30][31], as well as stringent constraints from the DarkSide-50 experiment [32]. Detailed predictions, though, are difficult due to the inherent complexities involved in modelling the halo plasma interactions with Earth-bound dark matter. Here, we consider a simple phenomenological model for the dark matter velocity function relevant to direct detection experiments, and confront the model with the available data. It turns out that the DAMA experiment and the DarkSide-50 experiment are the most sensitive probes of the electron scattering signal expected within this model, and in fact a self consistent picture emerges.

2 The mirror dark matter model

The mirror dark matter model assumes that dark matter arises from a hidden sector which is an exact copy of the standard model. That is, the Lagrangian describing fundamental physics is

$$\mathcal{L} = \mathcal{L}_{\text{SM}}(e, u, d, \gamma, ...) + \mathcal{L}_{\text{SM}}(e', u', d', \gamma', ...) + \mathcal{L}_{\text{mix}}.$$  \hspace{1cm} (2)

The model features an exact unbroken $Z_2$ mirror symmetry, which can be interpreted as space-time parity if the chirality of the hidden sector is flipped [27]. The mirror sector particles interact with the standard model particles via gravity and via the kinetic mixing interaction [19][20], which also leads to photon - mirror photon kinetic mixing:

$$\mathcal{L}_{\text{mix}} = \frac{\epsilon}{2} F_{\mu\nu}^{\prime} F_{\mu\nu}^{\prime}.$$  \hspace{1cm} (3)

where $F_{\mu\nu}$ [$F_{\mu\nu}^{\prime}$] is the field strength tensor of the photon [mirror photon]. The kinetic mixing interaction induces tiny ordinary electric charges for the charged mirror sector particles of $\pm \epsilon e$ for the mirror proton and mirror electron respectively.
The dark matter particles, the mirror protons and mirror electrons, constitute the inferred dark matter in the Universe in this picture, e.g. [22]. The unbroken $Z_2$ mirror symmetry implies that the masses of the mirror proton and mirror electron are exactly identical to their ordinary matter counterparts. More generally though, one can consider models with more generic hidden sectors, featuring dark electrons and dark protons coupling together via massless dark photons, e.g. [18]. In such models the dark electron and dark proton masses are independent parameters. The analysis in this paper can be applied to both mirror dark matter as well as the more generic dark sector model.

3 The electron scattering rate

Since dark electrons are electrically charged in the presence of kinetic mixing, they can scatter off ordinary electrons. As mentioned earlier, keV energy recoils are kinematically possible due to energy equipartition between the light dark electron and heavy dark nuclei halo components. Coulomb scattering of a dark electron off an electron is a spin-independent process. Approximating the target electron as free and at rest relative to the incoming dark electron of speed $v$, the cross section is

$$\frac{d\sigma}{dE_R} = \frac{\lambda}{E_R^2 v^2}$$

where $\lambda \equiv 2\pi \epsilon^2 \alpha^2/m_e$, and $E_R$ is the recoil energy of the scattered electron. Naturally, treating the target electrons as free can only be approximately valid for the loosely bound atomic electrons, i.e. those with binding energy much less than $E_R$. We define $g_T(E_R)$ as the number of electrons per target atom with atomic binding energy ($E_B$) less than $E_R$, and we approximate the electron scattering rate per target atom by replacing $\lambda \rightarrow g_T \lambda$ in Eq.(4). [For the DAMA experiment, the atom is a NaI pair.] Typically, the proportion of loosely bound electrons, i.e. with $E_B \ll E_R$ greatly outnumber those with $E_B \sim E_R$, so this approximation is expected to be reasonably accurate.

The scattering rate of a dark electron off an electron is then:

$$\frac{dR_e}{dE_R} = g_T N_T n_e' \int \frac{d\sigma}{dE_R} f(v; v_E; \theta) \mid v \mid d^3v$$

$$= g_T N_T n_e' \frac{\lambda}{E_R^2} I(v_E; \theta)$$

where

$$I(v_E; \theta) \equiv \int_{|v|>v_{\text{min}}(E_R)} \frac{f(v; v_E; \theta)}{|v|} d^3v .$$

Here, $N_T$ is the number of target atoms per kg of detector, $v_{\text{min}} = \sqrt{E_R m_e/2 \mu^2}$, where $\mu$ is the electron - dark electron reduced mass ($\mu = m_e/2$ for the mirror dark
matter case), and \( n_{e'} \) is the dark electron number density. Also, \( f(v; v_E; \theta) \) is the velocity distribution of dark electrons which arrive at the detector. The detector is in motion, due to the daily rotation of the Earth, described in terms of the angle \( \theta(t) \) to be defined shortly, and the Earth itself is in motion around the Sun, with velocity \( v_E \) of magnitude:

\[
v_E = v_\odot + \Delta v_E \cos \omega(t - t_0).
\]

Here, \( \omega = 2\pi/\text{year} \), \( v_\odot \approx v_{\text{rot}} + 12 \text{ km/s} \) (the 12 km/s correction is due to the Sun’s peculiar velocity) and \( \Delta v_E = 15 \text{ km/s} \) results from the Earth’s orbital motion. Evidently, \( v_E \) varies by \( \pm \Delta v_E \) during the year with a maximum at \( t = t_0 \simeq 153 \text{ days} \) (June 2nd).

Far from the Earth, the dark electron distribution, \( f(v; v_E) \), might possibly be approximately Maxwellian, however near the Earth it will be strongly influenced by the halo interactions with Earth-bound dark matter. The Earth-bound dark matter forms an obstacle to the halo wind, which is moving through the halo at roughly the speed of sound. It turns out that even small changes to this speed, due to the Earth’s motion around the Sun, lead to large effects for the halo dark matter density and distribution near the Earth [15]. These effects of the halo interaction with captured dark matter within the Earth thereby lead to a strongly time varying distribution at the detector’s location, \( f(v; v_E; \theta) \). Not only is it time varying, it would not be Maxwellian. On the particle level, the distribution is strongly influenced by dark electromagnetic fields induced in the halo plasma and in the Earth. The dark electron distribution can also be influenced by collisions with Earth-bound dark matter, as these interactions can effectively shield the detector from the halo wind.

A simple model arises if the dark electron distribution has a mean speed, \( \langle |v| \rangle \), which is much greater than \( v_{\text{min}} \) (for \( E_R \lesssim \text{few keV} \)). In that limit, \( I(v_E, \theta) \) becomes approximately independent of \( v_{\text{min}} \), and consequently also independent of \( E_R \). For mirror dark matter, the condition \( \langle |v| \rangle \gg v_{\text{min}} \) might be due to an effective cutoff at low velocities due to the induced dark electromagnetic fields in the Earth’s vicinity, or due to collisional shielding of the halo wind by Earth-bound dark matter. In more generic dark sector models it might easily arise if the halo temperature, Eq.\( \text{(1)} \), is high, e.g. in the multi-keV range. Independently of the details of the underlying model, we can explore the time dependence of the velocity function, \( I(v_E, \theta) \), via a Taylor series expansion,

\[
I(v_E, \theta) = I_0 + \frac{\partial I}{\partial v_E} \Delta v_E \cos \omega(t - t_0) + \frac{\partial I}{\partial \theta} (\theta - \bar{\theta}) + ... .
\]

Here, \( \theta(t) \) is the angle between the direction of the halo wind and the zenith at the detector’s location. This angle has a large daily variation as well as a small annual modulation (\( \bar{\theta} \simeq 2.17 \) is the average at Gran Sasso). See Ref. [15] for further discussion.

The net result is a rather simple phenomenological model with a time varying
electron scattering rate:

\[
\frac{dR_e}{dE_R} = g_T N_T n_e \frac{\lambda}{v_0^2 E_R^2} \left[ 1 + A_v \cos \omega (t - t_0) + A_\theta (\theta - \bar{\theta}) \right]
\]

(9)

where \(v_0^0 \equiv 1/I_0\). As discussed above, this formula assumes sufficiently low recoil energies so that \(v_{\text{min}} \ll \langle |v| \rangle \approx v_0^0\). In this energy region, the model predicts a \(dR_e/dE_R \propto 1/E_{R}^2\) behaviour for both the average rate and the annual modulation. For \(v_{\text{min}} \gtrsim v_0^0\), the scattering rate becomes suppressed, falling off much faster than \(1/E_{R}^2\).

Finally, note that the parameter \(A_\theta\) controls the diurnal variation. Published DAMA results indicate that this parameter is consistent with zero \[33\], although there is a hint of a diurnal signal at 2.3σ C.L \[14,15\]. We note that the DAMA phase 2 diurnal variation results have yet to be reported, and it will be interesting to see if stronger evidence for a daily variation emerges. For the purposes of this paper, though, we set \(A_\theta = 0\).

### 4 Implications for direct detection experiments

The electron scattering rate given in Eq. (9) is defined in terms of the remaining model parameters, \(\epsilon \sqrt{n_e'}, v_0^0, A_v\). These parameters will shortly be constrained by comparing the electron scattering rate with the data from the most relevant experiments, including the DAMA annual modulation signal.

To obtain the predicted rate for a given experiment, the detection efficiency and energy resolution will need to be modelled. This is done by convolving the rate:

\[
\frac{dR_e}{dE_{m_R}} = \int G(E_{m_R}, E_R) \frac{dR_e}{dE_R} \epsilon_F(E_R) \, dE_R.
\]

(10)

Here, \(G(E_{m_R}, E_R)\) is the resolution function taken to be a Gaussian, and \(\epsilon_F\) is the detection efficiency.

#### 4.1 DarkSide-50

We first consider constraints on the time-average electron scattering rate, and we then consider the DAMA annual modulation signal. The strongest constraint on the average rate arises from the DarkSide-50 experiment \[32\]. The limits follow from an analysis of the ionization signal for a 500 day exposure of an Argon target. The DarkSide experiment achieves a remarkably low electron recoil energy threshold of 0.1 keV. This makes it particularly sensitive to the dark matter electron scattering due to the sharply increasing rate at low energies: \(dR_e/dE_R \propto 1/E_{R}^2\).

To compare the electron scattering rate, Eq. (9), with the DarkSide data, we take into account the energy resolution using \(\sigma/E_{R} = 0.5\) \[34\], and efficiency \(\epsilon_F = 0.43\) \[7\]. The DarkSide data are given in terms of the number of extracted electrons, \(N_e\), which,
Figure 1: The DarkSide ionization spectrum (solid error bars) compared with the modelled electron recoils from dark electron interactions + background (solid curve). Also shown are the DarkSide estimated background rate (dotted error bars) and the predicted dark matter scattering rate (dashed curve). The vertical dotted line is the \( N_e = 4 \) Darkside threshold.

The low energy region of interest (\( 4 \leq N_e \leq 15 \)), is related to the recoil energy of the scattering event via \( N_e \approx 40 E_R^m / \text{keV} \). The expected rate in their experiment is then \( dR_e / dN_e = [dR_e / dE_R^m][dE_R^m / dN_e] \). A small excess above modelled backgrounds is present in the DarkSide data near their low energy threshold. If we tentatively assign this excess to electron scattering, we obtain the estimate:

\[
\epsilon \sqrt{\frac{n_{e'}}{0.2 \text{ cm}^{-3}}} \approx 1.5 \times 10^{-11} \sqrt{\frac{v_0}{50000 \text{ km/s}}}. \tag{11}
\]

The modelled rate, along with the DarkSide data, is shown in Figure 1. The figure indicates that the observed small excess near the DarkSide threshold is compatible the \( 1/E_R^2 \) scaling predicted by this model.

### 4.2 XENON100-S1

The XENON100 collaboration have searched for low energy electron recoils in the (2-6) keV region and also obtained fairly tight constraints on dark matter electron scattering rate [31]. With the \( \epsilon \sqrt{n_{e'}} \) parameter given in Eq.(11), we can compare the expected rate with the XENON100 data.

The XENON100 analysis uses the prompt photon signal (S1). At around 2 keV, the S1 signal (unlike S2) falls sharply due to detection efficiency, and other effects. To model this sharp feature, we use a low energy effective cutoff at \( E_R = 2.2 \text{ keV} \). That is, we take the detection efficiency function as \( \epsilon_F = 1 \) for \( E_R > 2.2 \text{ keV} \) and zero otherwise. For the energy resolution, the XENON100 paper indicates that it is twice worse than that of DAMA, which roughly corresponds to, \( \sigma / E_R = 1.0 / \sqrt{E_R / \text{keV}} \).
Figure 2: The XENON100 electron recoil data \[31\] compared with the (yearly average) electron recoil rate expected from dark electron interactions (solid line). The $\epsilon \sqrt{n_{e'}}$ parameter adopted [Eq. (11)] is the same as per Figure 1.

The XENON100 data are given in terms of the number of S1 photoelectrons ($N_{\text{PE}}$). The conversion between detected electron recoil energy and $N_{\text{PE}}$ is roughly, $N_{\text{PE}} = 5[E_R^m/(3 \text{ keV})]^{1.4}$, so that $N_{\text{PE}} = 3$ corresponds to $E_R^m \approx 2 \text{ keV}$. The modelled rate, along with the XENON100 S1 data, is shown in Figure 2.

The XENON100 S1 data was collected during 70 days near the expected yearly maximum on June 2\textsuperscript{nd}, so the predicted rate can be up to a factor of two larger during this period if the annual modulation is maximal. Even with such an enhancement, Figure 2 indicates that the electron scattering rate is consistent with the XENON100 S1 data (which additionally contains an uncertain unmodelled background component).

We have also examined XENON100 S2 data from \[35\]. However, the estimated rate in that experiment turns out to be more than an order of magnitude below their observed rate, and therefore does not pose any constraint on this model.

### 4.3 The DAMA annual modulation

We now consider the DAMA experiment. The DAMA collaboration have measured an annually modulated scintillation rate using an NaI target in their low energy region (1-4 keV), with phase consistent with dark matter interactions. In the dark matter model discussed here, the annual modulation is set by the parameter $A_v$ in Eq.(9). By construction, $A_v \leq 1$, with $A_v = 1$ corresponding to maximal annual modulation.

To evaluate the predicted rate we use the measured DAMA resolution of $\sigma/E_R = 0.448/\sqrt{E_R} + 0.009$ \[36\], and set the detection efficiency to unity as the DAMA collaboration give their results corrected for detection efficiency. This can only be a rough approximation, and a more sophisticated analysis should find a softening of
the annual modulation in the low energy region due to the falling efficiency below the threshold energy.

We have evaluated the predicted electron scattering rate, again fixing the $\epsilon\sqrt{n_{e'}}$ parameter by Eq.(11). The result for the maximal annual modulation case of $A_v = 1$ is shown in Figure 3. That figure indicates that the DAMA data are possibly compatible with this interpretation, given the various uncertainties involved (e.g. modelling the energy resolution and detection efficiency). Figure 3 also indicates that an approximately maximal annual modulation is implicated given the Darkside-50 constraint.

The XENON100 collaboration also searched for an annual modulation in the (2-6) keV region with the aim of testing models explaining the DAMA signal via electron scattering [30]. They obtained some interesting results, including a hint of an annual modulation with the same phase as DAMA at about the $2\sigma$ C.L. For the same parameters as per Figs.1-3, we find that this model predicts an annual modulation for the XENON100 experimental setup (S1 signal) of 1.8 cpd/tonne/keV in the (2-6) keV region. This is close to the best fit value identified in the XENON100 annual modulation analysis [30].

It appears that the annual modulation rate observed by XENON100 and DAMA are in fact consistent. The reason why the annual modulation amplitude is lower in XENON100 is easy to understand. Given the sharply rising scattering rate at low energy, $dR_e/dE_R \propto 1/E_R^2$, much of the DAMA annual modulation signal is due to recoils with actual energy below their threshold, detectable only because of their poor energy resolution. This does not happen in the XENON100 experimental setup because of the sharply falling XENON100 S1 signal efficiency near 2 keV.
5 Conclusion and Discussion

Within the mirror dark matter model the dark halo of the Milky Way is expected to take the form of a dark plasma. This plasma consists of light mirror electrons of mass \( m_e \simeq 0.511 \text{ MeV} \) and heavier mirror ions, including mirror protons, mirror helium nuclei, and possibly heavier mirror metal components. Provided that the kinetic mixing interaction exists, the mirror electrons and mirror ions in the plasma can potentially produce keV electron recoils and nuclear recoils respectively. It has been argued previously [14, 15] that mirror electron scattering off electrons might be responsible for the DAMA annual modulation signal, especially as such an electron scattering interpretation is relatively weakly constrained by other experiments. In light of the new results from DAMA [5], we have reconsidered this interpretation.

It is difficult to estimate the rate of electron recoils in a direct detection experiment due to the inherent complexities involved in modelling the halo plasma interactions with Earth-bound dark matter. Here, we consider a simple phenomenological model for the dark matter velocity function relevant for direct detection experiments. This model predicts a \( dR_e/dE_R \propto 1/E_R^2 \) behaviour for both the average scattering rate and the annual modulation. Such a recoil spectrum is roughly compatible with the annual modulation as measured in the DAMA experiment. The average rate is consistent with the results from other experiments, with the DarkSide experiment providing the most useful information. That experiment sees a small excess at low energies which can be interpreted as dark matter induced electron recoils, and in combination with DAMA, indicates that the annual modulation amplitude is near maximal. This conclusion is supported by XENON100 results as analysed here.

Although the model is phenomenological to some extent, this explanation of the DAMA signal can be conclusively tested in the near future. For example, if XENON1T shows an electron scattering rate below 0.001 cpd/kg/keV at around 2 keV, then this explanation will be excluded. If they see a rising event rate, a \( dR_e/dE_R \propto 1/E_R^2 \) behaviour is predicted, as described above. A more critical test of the model resides in the predicted sidereal daily modulation. Previous published results of DAMA [33] already contained a 2.3 \( \sigma \) hint of such a variation with the correct phase [14, 15]. Its likely that experiments at lower latitudes, including XMASS and PANDA, could have a larger diurnal variation, and we encourage these experiments to give results for this search channel. For an experiment located in the southern hemisphere, including the proposed SABRE experiment [37], the diurnal modulation can be maximal and provide an even more rigorous test of the ideas discussed here.

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