Sun Heated MeV-scale Dark Matter and the XENON1T Electron Recoil Excess

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The XENON1T collaboration reported an excess of the low-energy electron recoil events between 1 and 7 keV. We propose to explain such an anomaly by the MeV-scale dark matter (DM) heated by the interior of the Sun due to the same DM-electron interaction as in the detector. The kinetic energies of heated DM particles can reach a few keV, and naturally account for the excess signals detected by XENON1T. The inferred DM-electron scattering cross-section is about 0.1 pb, which is consistent with current observations. This model does not rely on any special assumptions on DM models, which serves as a general explanation of the XENON1T anomaly via DM-electron interaction. The spectrum of the Sun-heated DM is typically soft comparing to other boosted DM, so the small recoil events are expected to be abundant in this scenario. Future direct detection experiments with lower thresholds can distinguish this scenario with other boosted DM models or solar axion models.

I. INTRODUCTION

The direct detection of dark matter (DM) has reached unprecedented sensitivities. Nevertheless, no convincing signals have been detected yet (see e.g., [1, 2]). Very recently, the XENON1T collaboration reported a potential excess of electron recoils in the range of 1 – 7 keV above the known backgrounds [3]. The total number of events in such a recoil energy window is 285, while the expected background number is 232 ± 15, which suggests a significance of 3.5σ. Although the unknown backgrounds from tritium decay cannot be reliably ruled out, the estimated tritium concentration is much lower than that required to fit the data [3]. It has been postulated that the hypothetical effects from e.g., solar axions or the neutrino magnetic moment can account for the XENON1T data. However, the required model parameters are found to be in conflict with other constraints, particularly the astrophysical observations [4–8]. Alternatively, several attempts [9–13] have been proposed to explain the XENON1T data.

While the traditional weakly interacting massive particles in the Galactic halo are difficult to account for the XENON1T excess due to the very low energy deposits when scattering with electrons, one class of models with DM being boosted to relatively high velocities (∼ 0.1c) can potentially work [10, 11]. In Ref. [10] a fast DM component is simply assumed, and the possible mechanisms to produce such fast DM have been discussed, including e.g., a fast-moving subhalo, semi-annihilating DM, or nearby axion stars. A realization of the boosted DM scenario has been given in Ref. [11], where a faster DM component from the semi-annihilation of DM in the Galactic center has been proposed. The Sun could also be a site to accumulate enough DM in its interior via the DM-nucleon or DM-electron scattering. However, in this case, the required cross section is too high that the Sun would be opaque for the DM to escape [11].

Here we propose that light DM particles with MeV-scale mass heated by the high-temperature plasma inside the Sun [14] can naturally account for the XENON1T excess. Comparing with other boosted DM models (e.g., those discussed in [10, 11]), this scenario is quite clear and simple: the DM-electron scattering as seen in the detector occurs inevitably in the Sun (or any other places with the material). The temperature of the interior of the Sun is about 1.5 × 10^7 K. As long as the scattering between DM and the electrons is moderately efficient (for example, σ_e ∼ pb), the DM can be heated up to energies of ∼keV and is just consistent with the XENON1T excess. This model gives a natural explanation to boosted DM account for the XENON1T anomaly, without additional assumptions (e.g., the high-speed DM subhalos [10], and the semi-annihilation/multi-component DM [11]). In particular, the heated DM from the Sun could be a unique signal for future tests with directional direct detection experiments.
II. DARK MATTER HEATED BY THE SUN

The heated DM flux observed on the Earth can be estimated as [14]

\[
\Phi_{\text{heat}} \sim \frac{\Phi_{\text{halo}}}{4} \times \left( \frac{4\pi (\frac{R_{\text{core}}}{d})^2 \sigma_e n_e \text{core} R_{\text{core}}, \sigma_e \ll 1 \text{ pb}}{S_g \left( \frac{R_{\text{scatt}}}{d} \right)^2, \sigma_e \gg 1 \text{ pb}} \right),
\]

where \( \Phi_{\text{halo}} \) is the DM flux in the local Milky Way halo, \( R_{\text{core}} \approx 0.2R_\odot \) is the core radius of the Sun, \( n_e \text{core} \) is the electron number density inside the solar core, \( d \equiv 1.5 \times 10^{13} \text{ cm} \) is the Sun-Earth distance, \( S_g \) describes the gravitational focusing effect which enhances the scatterings, \( R_{\text{scatt}} \) is the characteristic scattering radius at which the DM-electron scattering once on average. \( \sigma_e \) is the DM-electron scattering cross section. Note that if \( \sigma_e \) is large enough, \( R_{\text{scatt}} \) reaches a maximum of \( R_\odot \), and the heated DM fluxes become weakly dependent of \( \sigma_e \). The factor \( S_g \) is estimated to be \( \mathcal{O}(10) \) according to the ratio of the escape velocity of the Sun and the halo DM velocity [14].

To properly handle the multiple scatterings, Monte Carlo simulations have been employed to calculate the energy distribution and fluxes of DM reflected by the Sun in Ref. [14], taking into account the standard solar model. In this work we adopt the results presented in Ref. [14] for our calculation.

The energy spectrum of heated DM is shown to be close to a thermal distribution, which depends on the DM mass and the scattering cross section [14]. Since most of the heated DM particles have kinetic energies lower than the threshold of XENON1T \((\sim 1 \text{ keV})\), we expect that only the high-energy tail would contribute to the XENON1T events. For a 2-body elastic scattering with the electron at rest, the maximum recoil energy is

\[
E_{\text{rmax}}^e = \frac{4E_{\text{dm}}m_em_{\text{dm}}}{(m_e + m_{\text{dm}})^2} > 1 \text{ keV},
\]

where \( m_e \) and \( m_{\text{dm}} \) are the masses of electron and DM, and \( E_{\text{dm}} \) is the kinetic energy of the DM. The energy transfer in both the scatterings inside the Sun and in the detector is the most efficient if \( m_{\text{dm}} \sim m_e \). Thus we set \( m_{\text{dm}} = m_e \) as our benchmark model in this work. Fig. 1 shows the velocity distribution of the heated DM for \( m_{\text{dm}} = 0.5 \text{ MeV} \) and \( \sigma_e = 10^{-37} \text{ cm}^2 \) [14].

III. FIT TO THE XENON1T DATA

The event rate of electron recoils in the detector is

\[
\frac{dN}{dE_r} = N_d \times \int d\frac{\sigma}{dE_r}(v_{\text{dm}}, E_r) \frac{d\Phi_{\text{heat}}}{dv_{\text{dm}}} dv_{\text{dm}},
\]

where \( N_d \simeq 4.2 \times 10^{27} \text{ ton}^{-1} \) is the number of Xe atoms for one ton mass of the detector, \( v_{\text{dm}} \) is the velocity of the DM particle, \( E_r \) is the electron recoil energy, \( d\sigma/dE_r \) is the differential scattering cross section, and \( d\Phi_{\text{heat}}/dv_{\text{dm}} \) is the flux spectrum of the heated DM component.

Following Refs. [15–17], the differential cross section for fixed DM velocity can be written as

\[
\frac{d\sigma}{dE_r}(v_{\text{dm}}, E_r) = 2m_ev_{\text{dm}}^2 \int_{q-}^{q+} a_0^2 q |F(q)|^2 K(E_r, q),
\]

where \( a_0 = 1/(am_e) \) is the Bohr radius, and the integration limits \( q_\pm = m_{\text{dm}}v_{\text{dm}} \pm \sqrt{m_{\text{dm}}^2 v_{\text{dm}}^2 - 2m_{\text{dm}}E_r} \). The DM form factor \(|F(q)|\) is assumed to be 1 for a contact interaction between heated DM and electrons. The atomic excitation factor \( K(E_r, q) \) is taken from Ref. [17], which contains the contribution from all accessible atomic energy states of Xe.

To compare with the XENON1T data, we further convolve the event rate with a Gaussian energy resolution function with a width of 0.5 keV and multiply the detection efficiency as given in Ref. [3]. The result is shown in Fig. 2. The DM-electron scattering cross section \( \sigma_e \) is found to be about \( 10^{-37} \text{ cm}^2 \). Such a value is below the upper bounds set within the same framework using past direct detection data [14].

This model gives a reasonably good description to the XENON1T excess. At the low-energy end the model slightly exceeds the data. Considering the limited energy resolution of the detector when approaching its threshold and the limited statistics, the consistency between the model and the data is acceptable. Furthermore, there could be uncertainties of the standard solar model [18], which may affect the heated spectrum of DM.

IV. CONCLUSION AND DISCUSSION

In this work we show that the electron recoil event excess detected by XENON1T [3] can be explained by MeV-scale DM particles interacting with electrons in the
Therefore the future direct detection experiments with keV cross section is about $10^{-31}$ cm$^2$. Such parameters are consistent with other constraints (e.g., [19, 20]).

Comparing with other boosted DM models [10, 11], the Sun heated DM has a softer energy spectrum which would result in quite a few low-recoil-energy events. Therefore the future direct detection experiments with lower thresholds or higher low-energy efficiencies would be able to distinguish this scenario from others. It is likely that the future XENON experiment will reduce its threshold to sub-keV energies, which can offer a critical test of this model. Furthermore, the direction sensitive direct detection experiments [21] may directly test this model, with the Sun being the main source of such heated DM.

Cosmic rays in the Milky Way could also boost DM particles to high (or even very high) energies [22, 23]. As already commented in Ref. [10], the cosmic ray electron boosted DM model seems to give conflicted results with that of neutrino experiments, since the neutrino experiments are more sensitive than the direct detection experiments for those electron boosted DM [19]. For the scenario that DM particles are boosted by cosmic ray nuclei, which then interact with electrons in the detector, the boosted DM fluxes seems to be also too low to be consistent with the existing constraints. For example, taking $\sigma_{\chi p} \sim 10^{-31}$ cm$^2$ as an illustration, the peak flux of the boosted DM is about $10^{-6}$ cm$^{-2}$ s$^{-1}$ [23, 24]. For such a DM flux, the required cross section to account for the XENON1T excess events is $\mathcal{O}(10^{-28})$ cm$^2$ [11], which exceeds significantly the current limits by neutrino experiments [19].

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FIG. 2: The spectrum of the event rate of electron recoils. The dashed orange line shows the contribution from the heated DM with $m_{\text{dm}} = 0.5$ MeV and $\sigma_e = 10^{-37}$ cm$^2$, after taking into account the energy resolution and detection efficiency. The black curve represents the background, and the red curve is the total electron distributions. Black dots are the XENON1T data [3].
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