Shining dark matter in Xenon1T

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We point out that a non-relativistic ~ 2 GeV dark matter (DM) which interacts with visible matter through higher dimensional Rayleigh operators could explain the excess of “electron recoil” events recently observed by the Xenon1T collaboration. A DM scattering event results in a few keV photon that on average carries most of the deposited energy, while the nuclear recoil energy is only a subleading correction. Since the Xenon1T detector does not discriminate between electrons and photons, such events would be interpreted as excess of the keV electrons. Indirect constraints from dark matter annihilation are avoided for light mediators of O(10 MeV) that have sizable couplings to neutrinos. One loop induced spin-independent scattering in dark matter may soon lead to a confirmation signal or already excludes regions of viable parameter space for the Rayleigh DM model, depending on what the exact values of the unknown nonperturbative nuclear matrix elements are.

Introduction. Xenon1T collaboration recently announced the results of a search for Dark Matter (DM) using electronic recoils after 0.65 tonne-years of exposure [1]. An anomalously large number of events were observed as a peak over the background at the threshold of the experimental sensitivity (using the nominal estimate by Xenon1T for tritium induced backgrounds). When interpreted as an absorption of a solar axion the excess events correspond to a 3.5σ deviation over the background only hypothesis, while the significance is somewhat reduced if interpreted as solar neutrinos scattering on electrons via nonzero neutrino magnetic moment [1], or as the absorption of bosonic dark matter/ALP on electrons [1][2]. Stellar cooling bounds are in tension with the solar axion [3][4] and neutrino magnetic moment interpretations [1][7], but not with bosonic dark matter [5]. A number of alternative explanations were also proposed: fast moving DM particles scattering on electrons [9][10], nonstandard neutrino interactions mediated by light new particles [11], hidden photon dark matter [12].

Common to all the above explanations is that they involve scattering or absorption of dark particles on electrons. In this Letter we explore a qualitatively different possibility, namely, that the anomalous events are due to electromagnetic interactions of non-relativistic dark matter with xenon nuclei. That this is a realistic possibility is somewhat surprising, for several reasons. First of all, electromagnetic interactions lead to scatterings on both nuclei and electrons. Secondly, for non-relativistic DM only the scatterings on nuclei result in large enough energy transfers, of a few keV, so that these can be observed in the Xenon1T detector. Using the relative strengths of prompt scintillation and delayed electro-luminescence signals, Xenon1T can distinguish between energy deposits in nuclear recoils or the energy deposited in photons and/or electrons (the so called “electron recoil” events). The observed excess events are unmistakably of the “electron recoil” which seems to rule out the possibility of elastic scatterings of non-relativistic DM.

The exception to this na"ive conclusion can be found if DM couples to the visible sector through the Rayleigh operator, $\phi \phi F_{\mu \nu} F^{\mu \nu}$. In this case the $2 \rightarrow 3$ scattering on a xenon nucleus $N$, $\phi N \rightarrow \phi N \gamma$, is possible, as shown in Fig. 1. The majority of the deposited energy is carried away by the photon, while the nuclear recoil energy is much smaller, cf. Fig. 2. To a very good approximation these events will therefore be indistinguishable from the pure electron recoil events.

At one-loop the Rayleigh operator also induces spin-independent $\phi N \rightarrow \phi N$ scattering [13][14], see Fig. 3, which is also constrained by Xenon1T and other direct detection experiments. As we will see, the nuclear recoil searches with direct detection experiments quite likely exclude part of the viable parameter space, although the validity of this claim depends on the value of a poorly known nonperturbative matrix element.

Rayleigh dark matter. For concreteness we assume that DM is a real scalar, $\phi$, which couples to the visible sector through dimension six Rayleigh operators

$$L_{\text{int}} = \frac{\alpha}{12\pi} \frac{1}{\Lambda^2} \left\{ C_\gamma (\phi \phi) F_{\mu \nu} F^{\mu \nu} + \bar{C}_\gamma (\phi \phi) F_{\mu \nu} F^{\mu \nu} \right\},$$

where $F_{\mu \nu}$ is the electromagnetic field strength. DM is assumed to be $Z_2$-odd and thus stable, while the SM fields are $Z_2$-even. The first operator in Eq. (1) is CP conserving, while the second is CP violating.

Despite being of relatively high dimension, the Rayleigh operators often give the most important interactions between the SM and the dark sector [15][16]. For instance, if DM couples to heavier states that are charged under the SM electroweak group, the one-loop radiative corrections would generically generate the Rayleigh operators. This possibility is reflected in the choice for the normalization of the operators in $\phi \phi$ which contain the EM loop factor, while $\Lambda$ is the apparent New Physics (NP) scale $\Lambda$ [16][17]. In the simplest case $\Lambda$ can be identified with the masses of the heavy mediators, but it does not always have to be so. In fact, we
will discuss a more general case later in this Letter. For Dirac fermion DM, the one-loop radiative corrections will generically also induce the magnetic moment of the DM, which is an operator of dimension 5. In contrast, for real scalar DM or Majorana fermion DM the operators of lowest dimension that couple DM to gauge bosons are, in fact, the Rayleigh operators.

**Signature in Xenon1T.** The direct detection signatures of Rayleigh DM are of two types: i) a purely nuclear recoil event $\varphi N \rightarrow \varphi N$ induced at one loop through two photon exchange, and ii) the $\varphi N \rightarrow \varphi N\gamma$ scattering, in which the energy is distributed between the nuclear recoil and the energy of the photon. As we pointed out above, in Xenon1T the later gives the same signature as the electron recoil events. The cross section for the $\varphi N \rightarrow \varphi N\gamma$ scattering is given by

$$\frac{d\sigma}{dE_N dE_\gamma} = \frac{1}{16} \frac{1}{(2\pi)^3} \frac{|\mathcal{M}|^2}{m_\varphi m_N v},$$

where $E_N$ is the recoil energy of the nucleus, $E_\gamma$ the photon energy, $m_\varphi$ and $m_N$ are, respectively, the masses of the DM and of the nucleus, and $v \sim 10^{-3}$ the velocity of the incoming DM. We work in the nonrelativistic limit assuming that $m_\varphi \ll m_N$, so the lab frame coincides with the center of mass frame for the scattering. The matrix element squared is given by

$$|\mathcal{M}|^2 = \left(\frac{2\sqrt{2} \alpha Z e C_\gamma}{\Lambda^2}\right)^2 \frac{1}{(Q^2)^2} \times Q^2 \left[(k \cdot p_2)^2 + (k \cdot p_4)^2 - 2m_A^2 (k \cdot q)^2\right],$$

where $Q^2 = p_1^2 - p_2^2$, and $Q^2 \equiv -q^2 = 2m_N E_{NR}$, with the four momenta as defined in Fig. 1 and $Z = 54$ is the atomic number of xenon. We simulated recoil spectra of both the nucleus and the emitted photon. They are presented in Fig. 2. Note that the differential cross section peaks toward small values of $E_{NR}$ due to the photon pole and the large mass of the nucleus, while the emitted photon tends to have the maximal energy. Here and below we set $C_\gamma = 0$. However, all our results apply also to the CP violating case, with $C_\gamma \rightarrow -C_\gamma$ replacements.

The signal rate in the Xenon1T detector is given by

$$\frac{dR}{dE_\gamma} = \rho_0 \frac{1}{m_\varphi m_A} \int_{v > v_{\text{min}}} d^3 v \frac{d\sigma}{dE_\gamma} v f_{f_\odot}(v),$$

where $v_{\text{min}} \approx \sqrt{2E_\gamma/m_\varphi}$ up to small corrections of $O(E_\gamma^2/m_N m_\varphi)$, and $\rho_0 = 0.3$ GeV/cm$^3$ is the local DM density. For the DM velocity distribution $f_{f_\odot}(v)$ we use the standard model halo type distribution, i.e., a Maxwellian velocity distribution in the galactic frame, truncated at the escape velocity $v_{\text{esc}} = 550$ km/s, and width of $\sigma = 220$ km/s (for notation, see, e.g., [20]).

We fit for the optimal Rayleigh DM signal, ignoring $E_{NR}$ contributions, using a $\chi^2$ constructed from Xenon1T measurements in the recoil energy interval up to 30 keV, with the efficiency curve and the nominal background model given in Ref. [1]. The best fit is obtained for $m_\varphi = 1.9$ GeV and $C_\gamma/\Lambda^2 = f_\varphi/(50 \text{ MeV})^2$, where $f_\varphi \equiv \Omega_\varphi/\Omega_{\text{DM}}$ is the fraction of DM relic abundance that is due to $\varphi$. The best fit point has a significance of 3.3$\sigma$ over the background only hypothesis. The comparison with Xenon1T data (depicted as black points with error bars) is given in Fig. 3, with the signal due to Rayleigh DM shown with blue dashed line, while the background prediction from Xenon1T is shown with the solid red line. Since the Rayleigh DM signal is relatively wide, the energy smearing by the detector does not lead to any visible effect, which we checked using the energy dependent Gaussian smearing as described in [21] [22] (to speed up the fit we do not use the smearing in the $\chi^2$, and it is also not used in Fig. 3). Varying the mass of DM and the effective
scale $\Lambda/\sqrt{C_\gamma}$ gives the 1σ (2σ) preferred regions, shown with dark (light) green shading in Fig. 5.

We see that the DM mass on the range $\sim 1$ to 3.5 GeV is preferred, which as expected is right on the border of the detection threshold for Xenon1T. The effective scale $\Lambda/\sqrt{C_\gamma}$ is in the range of $\mathcal{O}(50\text{ MeV})$.

As we can see, the Rayleigh DM scattering describes the observed Xenon1T excess rather well. However, the low effective NP scale $\Lambda$ that is required in the Rayleigh operator in Eq. (1) raises a question whether the described scenario is really a phenomenologically viable possibility. We next address these concerns, starting with the induced spin independent nuclear recoil scattering.

**Spin independent nuclear scattering.** As shown in Fig. 5 at one loop the Rayleigh operator generates spin-independent scattering on the nuclei, $\varphi N \to \varphi N$, through the two photon exchange diagram. This contribution is dominated by nuclear scales and is thus described by a nonperturbative matrix element. For a spin-1/2 nucleus $N$ the matrix element is defined through

$$\langle f|\langle \varphi\varphi|F_{\mu\nu}F^{\mu\nu}|i\rangle = \frac{\alpha Z^2}{4\pi}Q_0\langle f|\langle \varphi\varphi|\pi_A u_A|i\rangle, \quad (5)$$

and similarly for 0 spin nucleus, where $\pi_A u_A \to 2m_A$ in the above expression. The initial and final $|\varphi\rangle|N\rangle$ states were shortened as $|i\rangle, |f\rangle$. The prefactor $\alpha Z^2/(4\pi)$ is based on naive dimensional analysis, assuming coherent scattering of two photons on the whole charge of the nucleus. The nonperturbative parameter $Q_0$ has a dimension of GeV and is expected to be parametrically of the inverse size of the corresponding nucleus, $Q_0 = \kappa/\sqrt{r^2}$, where $\sqrt{r^2}$ is the charge radius of the nucleus. In the numerical analysis we use two values for the coherence factor, $\kappa = 0.5$ and $\kappa = 0.05$, to show the uncertainties related to this otherwise completely unknown matrix element. The perturbative two-photon exchange model gives larger estimates for $Q_0$ [13,14].

On the other hand, the Rayleigh operator mixes at one loop into dimension 5 DM-scalar-quark-current operators, leading to destructive interference in direct detection rate [14], highlighting the uncertainties surrounding the estimates of $Q_0$ nuclear matrix elements (for the potentially important contributions from two-body currents see Ref. [23]).

The $\varphi N \to \varphi N$ scattering cross section (per nucleon) is then given by

$$\sigma_0 = \frac{1}{64\pi} \left( \frac{\alpha}{12\pi} \frac{C_\gamma}{\Lambda^2} \right)^2 \left( \frac{\alpha Z^2}{2\pi} Q_0 \right)^2 \frac{1}{A^2}, \quad (6)$$

where $A$ is the atomic mass number. While the $\varphi N \to \varphi N$ scattering cross section is loop suppressed, it is still much larger than the $\varphi N \to \varphi N\gamma$ cross section, which has the phase suppression due to the extra particle in the final state, and, more importantly, also the extra suppression due to small available recoil energies (the $\varphi N \to \varphi N$ cross section is relatively enhanced by the much larger dimensionful quantity $Q_0^2$).

A number of direct detection experiments were able to probe the low mass dark matter region using nuclear recoils with low thresholds. The most important constraints for the case of Rayleigh DM are shown in Fig. 5 with blue lines denoting CRESST-III [24], gray lines CDMS-lite [25], orange lines DarkSide-50 [26], and black lines the Xenon-100 low mass dark matter search [27], where the dotted (solid) lines correspond to coherence factors $\kappa = 0.5(0.05)$. The regions below the lines are excluded for the assumed inputs. The two choices illustrate the large uncertainties that are inherently present when translating the results of direct detection searches using nuclear recoils to the bounds.
on the Wilson coefficients of the Rayleigh operators. Even though one cannot draw definitive conclusions due to the large uncertainties, it is still quite likely that for \( m_{\varphi} \gtrsim 1.8 \text{ GeV} \) the region preferred by Xenon1T anomaly is excluded by the spin-dependent nucleon scattering search by Xenon-100, as this would require a significantly suppressed nuclear nonperturbative matrix element. For lower masses, however, the region is most probably allowed since exclusions would require enhanced nonperturbative matrix elements instead.

Similarly to the spin-independent scattering on nucleons, the one-loop two photon exchange also induces scattering of DM on electrons (for collection of present experimental results see [28]). However, these cross sections are parametrically smaller, suppressed by \( m_e^2 \) and do not lead to relevant constrains on \( \Lambda/\sqrt{C_{\gamma}} \).

**Secluded DM.** The relatively low effective scale in the Rayleigh operator, \( \Lambda/\sqrt{C_{\gamma}} \sim \mathcal{O}(50 \text{ MeV}) \) can be easily realized if DM is secluded, i.e., if it does not directly couple to the visible matter but rather through a mediator. We consider a simple model where the interaction with photon is mediated through a light (pseudo)scalar \( a \) with mass \( m_a \sim \mathcal{O}(1-10 \text{ MeV}) \). The relevant interaction terms are

\[
\mathcal{L}_a \supset \mu_a \varphi \varphi a + \frac{\alpha_m}{12\pi} \frac{C_{a\gamma}}{\Lambda_{UV}} a F_{\mu\nu} F^{\mu\nu} + \frac{\alpha}{12\pi} \bar{C}_{a\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}. \tag{7}
\]

For momenta exchanges below \( m_a \), which is the case for Xenon1T anomalous events, the light scalar \( a \) can be integrated out, resulting in the CP even Rayleigh operator, \( \Lambda \sim \mathcal{O}(50 \text{ MeV}) \).

**Indirect DM constraints.** In the secluded DM model there are two types of tree level processes that give gamma ray line signals from DM annihilations to photons. The first is s channel \( \varphi \varphi \) annihilation from an exchange, \( \varphi \varphi \rightarrow a^* \rightarrow \gamma \gamma \), where \( a \) is an off-shell scalar and \( m_a \ll m_{\varphi} \). This gives a gamma ray line at \( m_a \) with the annihilation cross section

\[
\sigma_{\varphi\varphi \rightarrow 2\gamma} = \frac{\mu_a^2 C_{a\gamma}}{12\pi \Lambda_{UV}} \frac{1}{4\pi m_a^2}. \tag{10}
\]

The \( \varphi \varphi \rightarrow aa \) annihilation, where \( a \) decays to two photons, also gives in the limit \( m_a \ll m_{\varphi} \) a line-shaped gamma-ray signal but at \( m_{\varphi}/2 \). The relative width of the gamma-ray line is given by \( m_a/m_{\varphi} \) and is in our case small, \( \sim 10^{-3} \). The \( \varphi \varphi \rightarrow aa \) annihilation cross section, induced by the trilinear coupling, is

\[
\sigma_{\varphi\varphi \rightarrow 2a} = \frac{\mu_a^4}{32\pi m_a^6}. \tag{11}
\]

and is in general large, barring possible cancellations with the quartic contributions in \( \mathcal{L}_a \). If \( a \) decays predominantly to two photons this would lead to an unacceptably large signal in gamma ray flux in the sky. We thus assume that \( a \) decays predominantly to either neutrinos or other invisible states, such that \( Br(a \rightarrow \gamma \gamma) \) is below \( \mathcal{O}(10^{-7}) \), in which case the bounds from gamma ray lines are avoided.

The constraints from \( \varphi \varphi \rightarrow 2\gamma \), on the other hand, are relevant and are shown in Fig. 2 for \( f_{\varphi} = 0.2 \) (for smaller values of \( f_{\varphi} \) the indirect bounds become less important). For easier comparison with Fig. 5 we translate, using Eq. (8), the bounds to the value of effective NP scale on the Rayleigh operator, \( \Lambda/\sqrt{C_{\gamma}} \), choosing several representative values of \( m_a = \{2, 10, 30, 80\} \text{ MeV} \). The brown (black) lines show the corresponding 90\% CL limits from gamma-ray emissions in the Galaxy Center (GC) region as observed by EGRET [39] (Fermi-LAT [41]). The Fermi-LAT constraints start at about \( m_{\varphi} = 3 \text{ GeV} \) and overlap with EGRET, for given value of \( m_a \). Note that the regions below the lines are excluded for particular choices of \( m_a \). We see that the region preferred by the Xenon1T anomaly is not constrained, if the mediator is lighter than about \( m_a \sim 10 \text{ MeV} \).

Since the mediator decays invisibly the direct constraints on the production of \( a \) from colliders or in beam-dumps are significantly weakened. Interestingly, even for a pseudoscalar of a mass of a few 10's of MeV that couples exclusively to photons, the bounds are quite weak, see, e.g., Ref. [42].

**Discussion and conclusions.** We showed that the intriguing “electron recoil” excess events in Xenon1T can be interpreted in terms of nonrelativistic DM scattering off nuclei, if the scattering is induced by Rayleigh operators. Since the...
Xenon1T detector does not discriminate between electrons and photons, the observation of a keV photon created in the scattering event would be interpreted as an excess of the keV electrons. As it turns out, the energy carried away in the nuclear recoil is much smaller. In our analysis we neglected this small recoil contribution, which we believe to be an excellent approximation. It would be useful that this is checked by a detailed detector response simulation.

The Rayleigh DM model that explains the Xenon1T anomaly faces, unsurprisingly, severe constraints from indirect detection and one-loop induced spin independent scattering. We have showed that viable parameter space exists for the case of MeV scale mediators. There are several uncertainties that enter the discussion. First of all there is the issue of the nonperturbative matrix elements that enter the prediction of one-loop two-photon exchange nuclear scattering cross sections. Since these are quite uncertain, one cannot draw definite conclusions to what extent the Rayleigh DM model that explains Xenon1T is constrained. Any progress on these nuclear matrix elements, or even lattice QCD estimates of the two-photon exchange contribution for proton, would be very welcome.

Our predictions were obtained using the truncated standard halo model for DM velocity distributions. However, the signal arises from parts of the DM velocity distribution that are relatively close to the escape velocity. The predictions are thus subject to enhanced uncertainties in the DM halo velocity distributions. It would be interesting to revisit in the future these issues as well as other effects related to our setup, such as the possible effects of a light mediator propagator on the shape of the Xenon1T signal, provided that $m_\phi$ is comparable or below the typical momenta exchanges.

There are several possibilities to probe the suggested Rayleigh DM model experimentally. For instance, improving the experimental bounds on low mass dark matter searches from nuclear recoils could well lead to a positive signal, if Rayleigh DM is responsible for Xenon1T excess events. The other possibilities include searching for neutrino interactions with the MeV scale mediator, or the production of this weakly-coupled mediator in collider experiments.

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FIG. 6. The region preferred by the Xenon1T anomaly is shown with green shading, as in Fig. 5, while the brown solid lines shown constrains from gamma ray line searches from dark matter annihilation in the galactic center, due to EGRET [30] (brown) and Fermi-LAT [31] (black) data, for several values of mediator, as indicated.

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