Abstract

The low-energy electronic recoil spectrum in XENON1T provides an intriguing hint for potential new physics. At the same time, observations of horizontal branch stars favor the existence of a small amount of extra cooling compared to the one expected from the Standard Model particle content. In this note, we argue that a hidden photon with a mass of \( \sim 2.8 \) keV and a kinetic mixing of \( \sim 10^{-15} \) allows for a good fit to both of these excesses. In this scenario, the signal detected in XENON1T is due to the absorption of hidden photon dark matter particles, whereas the anomalous cooling of horizontal branch stars arises from resonant production of hidden photons in the stellar interior.
1 Introduction

There are two environments known for their abundant production of light and very weakly coupled bosons: The early Universe [1–5] and stellar interiors [6–15]. If produced in sufficient amounts in the early Universe, light bosons may constitute the entirety of the observed dark matter [1–5]. In turn, the production of these particles in a stellar interior leads to an additional energy loss that accelerates the cooling of the star [6–15]. Both effects make these particles amenable to experimental and observational tests. Intriguingly, experiments and observations of both systems have shown (small) excesses: XENON1T has recently reported a surplus of events in $\sim\text{few} \times \text{keV}$ electron recoils [16,17], and observations of horizontal branch (HB) stars favor the existence of an extra cooling mechanism [18–20]. While both of these could have other explanations such as a tritium component in XENON1T [16] or an insufficient understanding of the stellar physics (as well as the statistical significance not being very large), it is nevertheless interesting to speculate.

In this brief note, we argue that hidden photons (also known as dark photons or paraphotons) that kinetically mix with the Standard Model photon may provide a simultaneous explanation for both of these observations: a single hidden photon with mass in the $m_X \sim 2–3\text{keV}$ range and a kinetic mixing $\epsilon \sim 10^{-15}$ connects the hidden photon dark matter interpretation of XENON1T [16,17,21] to the cooling excesses in HB stars [20].

Another kind of light bosonic dark matter that has been suggested as the potential cause for the possible XENON1T excess are axion-like particles, which were considered in the original experimental analysis [16] and have been discussed in more detail in [24]. However, axion-like particle dark matter is less well suited for simultaneously explaining the XENON1T excess and the stellar cooling anomaly for the best fit region provided in [25]. The reason to favor the hidden photon explanation is that in the relevant region for the XENON1T signal, around (2–3) keV, the production of hidden photons in HB stars is enhanced by a plasma resonance [11–15] (see below for a more detailed discussion). These stellar systems are therefore more sensitive to hidden photons than to axion-like particles in this mass range.

Furthermore and as is highlighted in [24], axion-like particles with an electron coupling $g_{ae} = (5–7) \times 10^{-14}$, as required to explain the XENON1T signal, need to have extremely suppressed couplings to photons to accommodate constraints from X-ray searches (see [26,27] and references therein). In contrast and as pointed out in this note, the most minimal hidden photon dark matter models easily evade these constraints while accounting for the XENON1T excess.

2 Hidden photons

Hidden photons [28,30] (cf., e.g. [31] for a review and further references) arise in a simple extension of the Standard Model (SM) by a $U(1)$ vector boson under which no SM particle

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1 Prior to the XENON1T result, it was suggested that relatively strongly interacting but suitably light dark matter particles could cause a peak-like electron recoil signal [22]. It has also been proposed that the XENON1T signal could be caused by a mildly relativistic dark matter component [23].

2 For axion-like particles with a negligible coupling to photons, the electron coupling that fits the XENON1T result is outside of the $2\sigma$ region preferred by the stellar cooling anomalies. Note nevertheless that in addition to HB stars, the fit in [25] includes additional data on white dwarfs and RGB stars, so a somewhat weaker fit to HB-only data may be acceptable. The agreement is also improved if axion-like particles constitute only a sub-dominant component of dark matter [24].
carries charge. Below the electroweak scale, such an extension is described by the Lagrangian
\[
\mathcal{L} = -\frac{1}{4} (F^{\mu\nu})^2 - \frac{1}{4} (X^{\mu\nu})^2 - \frac{1}{2} \epsilon F^{\mu\nu} X_{\mu\nu} - \frac{1}{2} m_X^2 (X^\mu)^2 - j^\mu A_\mu. \tag{2.1}
\]
In this equation, the photon (hidden photon) field \( A^\mu (X^\mu) \) has field strength \( F^{\mu\nu} (X^{\mu\nu}) \). An explicit mass term for the hidden photon has been included, which can be generated in a gauge-invariant way through a Higgs or Stückelberg mechanism. The current \( j^\mu \) summarizes all the interactions between the SM particles and the ordinary photon. Any interaction between the hidden photon and the SM takes place via the kinetic mixing term \([29]\).

Applying a suitable field redefinition \( A^\mu \rightarrow A^\mu - \epsilon X^\mu \), the kinetic mixing term can be traded for a direct interaction of the hidden photon with the electrically charged SM particles \( j^\mu A_\mu \rightarrow j^\mu (A^\mu - \epsilon X^\mu) \). In particular, in this basis the interaction with electrons is explicit and has a strength \( \epsilon e \), where \( e \) is the electromagnetic charge. For the purposes of the detection in an experiment such as XENON1T, this interaction is similar to the one of a scalar or pseudoscalar axion-like particle with SM electrons via a Yukawa interaction. However, for the production in stars the situation is slightly more involved, as is discussed below.

For the present purposes, we are interested in hidden photons in the keV mass range with very small kinetic mixings of the order of \( \epsilon \sim 10^{-15} \). Constructing ultraviolet models of hidden photons that can accommodate these values is an interesting but nontrivial task. One possibility would be to look at string-theoretic constructions \([32–50]\), some of which feature the possibility of tiny kinetic mixing values (cf, e.g. \([32,34,35,38–41,44]\)), and small masses (see \([39–41,44,47]\) for some examples). That said, a concrete model which features both a suitable mass and mixing is yet to be identified. In the context of field theory, twin Higgs models can feature similarly minuscule kinetic mixing parameters \([51]\).

**Hidden Photon Dark Matter**

Massive hidden photons with a sufficiently small kinetic mixing constitute excellent dark matter candidates due to their feeble interactions with SM particles \([4,5]\). For masses in the keV range or below, as is of interest here, thermal production would result in dark matter that is too warm to agree with observations of large-scale structures \([52–56]\). Furthermore, dark photons with a kinetic mixing \( \epsilon \sim 10^{-15} \) interact too weakly with the visible sector for the observed abundance of dark matter to be produced through thermal processes \([57]\).

Therefore, a suitable abundance of hidden photons as dark matter has to be produced in a non-thermal way. There exist a variety of non-thermal production mechanisms for hidden photon dark matter, some of which can successfully generate a cosmological population of \((2 – 3)\) keV hidden photons.

Conceptually, one of the simplest ones is the misalignment mechanism \([1–3]\) adapted to the case of hidden photons \([4,5]\). In this setup, the field is assumed to be spatially homogeneous and is initially displaced from the minimum of its potential. At late times, when the Hubble expansion rate \( H \) is smaller than \( m_X \), the field oscillates around the minimum of the potential and the energy density contained in the oscillations dilutes with the volume, as befits dark matter. At early times, when \( H \) is much larger than \( m_X \), vectors and scalars behave differently. While a scalar field is essentially frozen in this limit, a minimally coupled vector dilutes with expansion. Reproducing the observed dark matter density then usually requires unfeasibly large initial field values \([5,58]\). This can be remedied by adding a direct coupling of the hidden photon
to the curvature scalar of the form $\frac{1}{6} \kappa R (X^\mu)^2$, where $\kappa$ is an $O(1)$ coupling constant (see [5,58] for more details). With such a coupling, the observed dark matter density can be generated for masses in the keV-range. For example, choosing some benchmark values for the field at the beginning\(^3\) of inflation, the observed density $\Omega_c h^2 = 0.12$ is reproduced for

$$m_X = 2.8 \text{ keV}, \quad |X_0| = 10^{16} \text{ GeV}, \quad \kappa \simeq 0.7, \quad (2.2)$$

$$m_X = 2.8 \text{ keV}, \quad |X_0| = M_P \sim 2 \times 10^{18} \text{ GeV}, \quad \kappa \simeq 0.6.$$  

It has also been suggested that misalignment production could be realized by invoking a non-standard gauge kinetic function [59] or a direct coupling to the inflaton [60], but these options probably run into severe isocurvature problems [61].

Hidden photons can also be directly produced from inflationary fluctuations [58,62–64], quite independently of any initial condition. In the minimal scenario [62], the yield only depends on the hidden photon mass and the scale of inflation\(^4\). For our benchmark value, this means

$$m_X = 2.8 \text{ keV}, \quad H_I \sim 7 \times 10^{11} \text{ GeV}.$$  

(2.3)

Including a coupling to $R$ as above, allows viable HP dark matter in a wider range of inflationary Hubble scales [58],

$$m_X = 2.8 \text{ keV}, \quad H_I \sim 3 \times 10^{12} \text{ GeV} - 10^{14} \text{ GeV}, \quad \kappa \sim 0.6 - 0.8. \quad (2.4)$$

A differentiating signature of this production mechanism is the presence of very large inhomogeneities in the dark matter distribution at small scales [58,62]. This may offer the possibility to test this production hypothesis in the time-dependence of the signal detected at XENON1T.

Finally, a non-thermal dark matter population can also be produced if the hidden photon is coupled to a dark sector (pseudo)scalar. The hidden photon can then be produced from a resonant decay involving an axion condensate [65,66], a dark Higgs [67], the inflaton [68], or a network of cosmic strings [69]. All these mechanisms allow for the production of hidden photon dark matter in the keV range with reasonable choices of parameters.

A pertinent question regarding viable bosonic dark matter models in the keV range is whether such particles are sufficiently long-lived. As pointed out in [24], the cosmological stability of keV axion-like particles, which are prone to decay into a pair of photons, is a not a guaranteed fact. While the lifetimes are typically larger than the age of the Universe, stringent limits on the flux of X-rays from decaying axion-like dark matter exist [26,27]. This means that a non-trivial suppression of the generic axionic coupling to photons is necessary in order to make axion-like particle dark matter compatible with the XENON1T signal [24].

The situation of keV hidden photons is far less problematic. There are two possible decays to SM particles. The first one is the decay into three photons, which occurs with a rate [57]

$$\Gamma_{X \rightarrow 3\gamma} = \frac{17\alpha^4 e^2}{11664000\pi^3} \frac{m_X^3}{m_\gamma^3} \simeq 1.4 \times 10^{-29} \text{ Gyr}^{-1} \left( \frac{m_X}{2.8 \text{ keV}} \right)^3 \left( \frac{\epsilon}{10^{-15}} \right)^2,$$  

(2.5)

\(^3\)Here, beginning of inflation means the time at which the largest currently observable scales left the horizon, which for high scale inflation with $H_I \sim 10^{13} \text{ GeV}$ happened about 60 e-folds before the end of inflation.

\(^4\)For scenarios in which reheating is significantly delayed, the dark matter yield can also depend on the reheating temperature [63].
and is completely negligible in the mass range of interest. As a matter of fact, the dominant hidden photon decay in the mass range below $\sim 10$ keV is the one into neutrinos [70]. For our benchmark value of $m_X$, the rate is a factor of $\sim 10$ larger than the one into photons,

$$\Gamma_{X \rightarrow \nu \bar{\nu}} = \frac{\alpha^2}{8 \cos^4 \theta_W} \frac{m_X^5}{m_Z^4} \simeq 1.8 \times 10^{-28} \text{Gyr}^{-1} \left( \frac{m_X}{2.8 \text{keV}} \right)^5 \left( \frac{\epsilon}{10^{-15}} \right)^2.$$  

(2.6)

This rate does not conflict with any known constraints.

3 Signal in XENON1T

As reviewed above, hidden photons interact with electrons in the same way as photons, except that the strength of the coupling is suppressed by a factor of $\epsilon$. In an ambient dark matter background of hidden photons, these particles can be absorbed by xenon atoms just like photons, leading to an ionization signal in detectors like XENON1T [21, 57, 71, 72] (see Refs. [73–76] for earlier searches for this signal). Due to the predicted very high abundance of such low mass dark matter particles in the solar neighborhood, $n_X \sim 10^5/\text{cm}^3 (2.8 \text{keV}/m_X)^5$, very small couplings are sufficient to produce a detectable signal.

The rate of dark photon dark matter absorption in a direct detection experiment per unit time and detector mass is given by [16, 72]

$$R = \epsilon^2 \frac{\rho_{\text{DM}}}{m_X} \frac{\sigma_\gamma}{m_N},$$  

(3.1)

where $\rho_{\text{DM}} = 0.3 \text{GeV/cm}^3$ is the local DM density and $m_N$ is the target nucleus mass, while $\sigma_\gamma$ denotes the photoelectric cross section for the absorption of an ordinary photon by the target atoms. The resulting mono-energetic signal needs to be convoluted with the detector resolution $\sigma$, which varies between about 20% at $E = 2 \text{keV}$ and 6% at $E = 30 \text{keV}$ [17], leading to

$$\frac{dR}{dE} = \frac{R}{\sqrt{2\pi}\sigma} e^{-(E-m_X)^2/(2\sigma^2)} \alpha(E),$$  

(3.2)

where $\alpha(E)$ denotes the signal efficiency.

We use the data from [16], binning the signal and background predictions in 29 equidistant bins between 1 keV and 30 keV in order to compare the result to data using a $\chi^2$ test statistic. For the background model $B_0$ we obtain $\chi_B^2 = 47.6$ (29 d.o.f.), corresponding to a $p$-value of 1.6%. The best-fit signal hypothesis is found to be $m_X = 2.8 \text{keV}$ and $\epsilon = 8.6 \times 10^{-16}$, giving $\chi_{S+B}^2 = 36.6$ (27 d.o.f.) and a $p$-value of 10.3% [6]. We find the global significance of this signal to be of the order of 2$\sigma$, somewhat smaller than the value mentioned in [17], which is obtained with an unbinned profile likelihood analysis. The likely reason for this difference is that the bin width that we use is large compared to the detector resolution. We show the background model and best-fit signal prediction in Figure 1.

We also calculate the region excluded at 90% C.L. in $m_X$-$\epsilon$ parameter space by identifying all points with $\chi^2(m_X, \epsilon) > \chi_B^2 + 2.99$. This approach leads to good agreement with the

5 As a side comment, we note that in this mass range the number density is nevertheless small enough such that typical occupation numbers are less than one and the DM is more particle- than wave-like.

6 When including a background contribution from a possible tritium contamination in the detector, the best-fit point shifts to $m_X = 2.7 \text{keV}$ and $\epsilon = 6.3 \times 10^{-16}$, while the significance of the signal decreases below 2$\sigma$. We also note that there is no significant evidence for any excess at higher energies in the spectrum.
exclusion limit published by the XENON1T collaboration \[16\]. We furthermore define $\Delta \chi^2 = \chi^2(m_X, \epsilon) - \chi^2_{S+B}$ to identify the preferred parameter region around the best-fit point.\footnote{Note that, since we use a different test statistic for the exclusion limit and for the preferred parameter region, the allowed parameter region at 95\% C.L. lies fully below the 90\% C.L. exclusion bound.} At 68\% (95\%) C.L. we find $m_X \in [2.3 \text{ keV}, 3.2 \text{ keV}]$ ($m_X \in [2.0 \text{ keV}, 3.8 \text{ keV}]$).

### 4 Energy loss in stars

The core of a star, with typical temperatures of a few keV, a significant density and a large volume, constitutes an ideal source of very light bosons \[6–15, 25, 28\]. In particular, hidden photons \[11–15\] can be produced through the couplings induced by the kinetic mixing introduced in Eq. (2.1). Once produced, these particles typically leave the star unimpeded due to their large mean free path.

One may expect the production of hidden photons via their coupling to electrons $\epsilon j^\mu X_{\mu} \sim ee\bar{E}\gamma^\mu EX_{\mu}$ (here $E$ denotes the electron field) to be very similar to the one of axion-like particles via a Yukawa interaction $\sim g_{ae}\bar{E}\gamma^5 E$. In the stellar interior, however, plasma effects play an important role and make the physics of hidden photons comparably richer than the one of axion-like particles. In the dense medium, the photon acquires an effective mass term $\frac{1}{2} \omega^2 P_A^2$ due to its interaction $j^\mu A_{\mu}$. Taking the hidden photon into account, the interaction shifts to $j^\mu (A_{\mu} - \epsilon X_{\mu})$. This sources an additional non-diagonal term in the mass matrix for the photon–hidden photon system. While this suppresses the production of hidden photons with a vacuum mass $m_X \ll \omega_p$, resonant conversions of transverse modes are possible when $m_X \sim \omega_p$. In this situation, the effective mixing angle can be significantly enhanced with respect to its vacuum value $\epsilon$. This leads to an enhanced production of hidden photons, making the system sensitive to even very small values of $\epsilon$, as long as $m_X$ lies in the vicinity of the stellar plasma mass.

A large number of very different stellar objects like the Sun \[11,12,15,25,72\], white dwarfs (WD) \[20,77\], red giants (RGB) \[72,78\], horizontal branch stars (HB) \[18,20,72\], blue and red giants \[79,81\] and even neutron stars \[82\] have been used to constrain the parameters of light bosons. In several of these objects, signs of anomalous cooling have been observed \[19,82,84\].
and interpreted as a possible hint for the existence of light bosonic particles.

The observable that is most sensitive to hidden photons in the keV range is the so-called $R$-parameter, which describes the ratio of the number of HB and upper RGB stars in globular clusters. The anomalously small value of $R$ can be explained by resonant production of hidden photons from transverse modes in HB stars. Because of the resonant nature of the process and the higher core temperatures of RG stars, the cooling of members of the RGB are hardly affected by the presence of a keV hidden photon.

To our knowledge, a dedicated analysis interpreting the cooling anomalies in terms of a hidden photon with a mass in the keV range, as motivated by the XENON1T signal, has not been performed yet. The most recent limits and hints applying to hidden photons, which are shown in Figure 2, have been derived by translating the results of a detailed analysis of the additional cooling by emission of axion-like particles produced by the Primakoff effect [19, 20]. While this serves as a good estimate of the hidden photon parameters that are required to explain the HB anomaly, it is not sufficient to enable a combined statistical analysis of the XENON1T signal and stellar cooling via hidden photon emission.

Importantly, the sudden rise of both the hint and the exclusion limit at $\sim 2.6$ keV (see Figure 2 and reference [72]) arises because this is the typical plasma frequency at the core of HB stars. For hidden photons with mass larger than this value, there is no spherical shell inside the star in which resonant production occurs and hence no significant additional cooling happens. However, given an ensemble of HB stars, this sudden drop in the hidden photon-driven cooling will happen for slightly different values of $m_X$ for each individual star. The core plasma frequency of 2.6 keV is only an average and there will in general be a spread of values in the population of HB stars in globular clusters.

5 Conclusions and potential tests

As can be seen from Figure 2, the best fit region for the hidden photon dark matter fit of the XENON1T data [16] and that of an interpretation of extra cooling in horizontal branch stars in terms of hidden photon emission [20] have an intriguing overlap. This allows for a combined explanation of both of these effects with a single hidden photon with a kinetic mixing to the Standard Model photon.

Having a simple explanation of these hints allows us also to speculate on potential complementary tests of this hypothesis. One possibility may be the time-dependence of the event rate in XENON1T (this was already investigated in [16] but the results were not conclusive). As the signal is due to the absorption of dark matter particles, the kinetic energy of them does not play a crucial role. Therefore, for a locally homogeneous dark matter distribution one expects a constant rate of events $\gamma$. This is similar to the case expected for the interpretation of axion-like particles being produced in the Sun considered by the XENON1T collaboration which is also constant up to a small annual modulation from the varying distance between Earth and Sun along the Earth’s orbit [16]. However, if hidden photons are produced from inflationary fluctuations, strong inhomogeneities are expected $\delta\gamma$. On small scales, this could lead to objects (similar to axion mini-clusters $\delta\gamma$) with densities about $10^4 - 10^5$ times higher than the average local density and a size of $\sim$ few $\times$ 100 km. Such substructures would cross the $\delta\gamma$ This is in contrast to the case of a scattering of WIMPs for which a signal strongly depends on the velocity of the DM particle, leading to potential annual modulations $\delta\gamma$. 

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Figure 2: Region in the hidden photon parameter space hinted at from the XENON1T result (blue regions showing 1σ and 2σ contours with the orange dot as the best-fit point) compared to the regions suggested from stellar cooling (for the corresponding constraint see also [15]). The light gray and magenta areas correspond to the constraints from RGB and HB stars, respectively, while the darker magenta region would allow for an explanation of the anomalous cooling of HB stars. To give a rough impression of the uncertainties in the stellar cooling, we also show a stellar cooling hint region obtained from the stellar limits calculated in [72] scaled to give a small extra energy loss as dashed lines.

detector with crossing times of the order of seconds and an encounter rate of several tens per year. This could perhaps be seen as a clustering of events on short time-scales, although this would probably require much larger amounts of data and probably even a larger detector such as [88–91].

On the other hand, having a relatively narrow preferred mass range for the hidden photon from the XENON1T result, also suggests doing an improved analysis of the horizontal branch hint in the resonance region. As mentioned above, this region is quite sensitive to the parameters of the stars in question. Therefore, considering the more realistic case of a distribution of horizontal branch stars and the values of their important parameters such as, e.g., the temperature, instead of taking typical values could yield extra information on the viability of the proposed interpretation.

Given this intriguing situation, it is exciting that the next generation of dark matter experiments can conclusively shed light on the excess in XENON1T and thereby provide a test of the stellar cooling hint in horizontal branch stars.
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