Dark Fluxes from Accreting Black Holes and Direct Detections

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We show that accreting black hole systems could be sources for keV light dark matter flux through several different mechanisms. We discuss two types of systems: coronal thermal plasmas around supermassive black holes in active galactic nuclei (AGNs), and accretion disks of stellar-mass X-ray black hole binaries (BHBs). We explore how these black hole systems may produce keV light dark matter fluxes and find that in order to account for the XENON1T excess, the dark fluxes from the observed AGNs and BHBs sources have to exceed the Eddington limit. We also extend the black hole mass region to primordial black holes (PBHs) and discuss the possibility of contributing to keV light dark flux via superradiance or Hawking radiation of PBHs. Besides, black holes can be good accelerators to accrete and boost heavy dark matter particles. If considering collisions or dark electromagnetism, those particles could then escape and reach the benchmark speed of 0.1c at the XENON1T detector.

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I. INTRODUCTION

Dark matter direct search experiments have been very successfully developed to put constraints on the dark matter properties [1]. While the search for a few GeV dark matter is still going on without confirmed signals so far, lighter sub-GeV dark matter scenarios have received more attention in the recent years [2–11], encouraged by the cosmic ray excesses [12–14]. The galactic center dark matter has been widely considered to be the sources of the cosmic ray excesses as well as the possible explanation for the XENON1T excess [1, 15, 16]. The other sources for relativistic dark matter particles or axions are the Sun and stars, although such light dark matter models face many astrophysical constraints such as stellar cooling [17].

FIG. 1: The schematic diagram of axion flux converted from the X-rays passing through the cluster of magnetic field.

With the first detection of gravitational waves from the binary black hole mergers [18] and the Event Horizon Telescope (EHT) [19], we have new methods to probe black holes. A black hole can be a host of many processes involving the beyond the Standard Model (SM) physics [20, 21]. Particles may be accreted, pair-produced around the event horizon, and accelerated around the black hole without the coupling to SM physics. In principle, the dark particles can also be thermally produced or thermalize around the black holes, and be ejected along with...
the standard keV X-ray radiations.

One can see for example how to produce dark matter relic in the early universe through black hole evaporation in [22]. Black holes have also been discussed as the arbitrary high energy particle accelerators [23, 24]. Moreover, the disks around accreting black holes can be the places for nucleosynthesis [25]. For axions, it may be accumulated around the black hole through superradiance effects and form clouds. The accretion disk is heated through viscous dissipation of gravitational energy. For the light particles, such as dark photon or axion which may be thermally produced in the coronal thermal plasmas and accretion disks, a flux of them at keV temperature would be expected, similar to the solar source [26].

On the other hand, astrophysical black holes are known to carry a large-scale magnetic field, which is the agent to tap the spin energy of the black holes through the Blandford-Znajek process. The poloidal magnetic field of a black hole provide an environment for photon-to-axion conversion ($\gamma \rightarrow a$) [27, 28]. Besides, as being depicted in Figure 1, the cosmic magnetic field between the source and the Earth can convert part of the X-ray photons to axions at the same energy scale, which is similar to neutrino oscillations. It has been found that up to 1/3 of photons can be converted [29, 30].

The heavier MeV - GeV dark matter particles can also be accelerated to be relativistic, since the orbiting speed at the so-called Innermost Stable Circular Orbit (ISCO) is around the order of 0.1c. These kinds of keV sources are a lot less constrained comparing to the stellar sources, and provide a mechanism to accumulate dark matter density much larger than the Galactic center [31]. However, since the coupling (if any) between the dark sector and the electromagnetic fields is quite small, the radiations of the dark particles can be quite different from the radiations of the Standard Model charged particles. (For e.g. emergent dark sector in [32], there is only gravitational interaction between the dark sector and the standard model sector.) For the case of light dark matter without the dark electromagnetism (which is presumably mediated by the light dark photons), we can look back at the traditional Penrose process [33] or superradiance, where the energy can be extracted from the rotating black holes directly. The process can also be independent of the black hole accretion of standard model matters.

Moreover, black hole system provides a good mechanism to heat up the dark matter. The scattering process around the black hole can also heat up dark particles around it, in analogy to the visible process considering that black holes can be assumed to interact with the visible/dark sector equivalently. In this case, we need self-interactions in the dark sector or the couplings to the standard model to provide enough scattering. Even if there is very small interaction between the dark matter and the Standard model particles, in this self interacting dark matter case [34], accretion disk model with the viscous hydrodynamical approximation can be applied, e.g. the double-disk dark matter [35, 36].

The cross section of self interacting dark matter is bounded by $\sigma_X/m_X \lesssim 1\text{cm}^2/\text{g}$ [37]. It is however, comparable to $\sigma_T/m_p \approx 0.3\text{cm}^2/\text{g}$ for the ionized hydrogens with the Thomson scattering cross-section. We will show how the dark luminosity can be as bright as the visible luminosity if considering the radiation of dark photons.

Alternatively, one may consider a possible black hole dark star binary system which is depicted in Figure 2. If dark matter particles have enough self-interactions, it can clump together to form a star. We can see the examples of e.g. boson stars, axion stars or moduli stars [21, 38]. If such a dark star happens to be accreted by a black hole, a dark disk may form around the black hole. Similar to an X-ray binary, this object, if exists, could be a power source of dark matter flux, without necessarily being observed in the X-ray band, such that it could be quite close to our earth. Since these systems are mostly invisible, it is possible for the black hole - axion star binaries to produce the required relativistic flux of axions with the self-interactions. More detailed modeling of black hole dynamic processes is required for a similar production rate calculation around the black holes.

In the following sections, we discuss these processes in more details and relate them to the XENON1T excess explanations. Here in section II, we discuss different kinds of X-ray hosts. In section III, we argue that the same accreting black hole can also produce dark particles/axions. However, in order to explain the Xenon 1T excess in the low energy electron recoil between 2 - 4 keV, the fluxes from the known source of AGNs are too weak, but there are still possibilities for the BHBs or the primordial black holes (PBHs) inside the Milky Way galaxy. We summarize and discuss these issues more in section IV.

II. X-RAYS FROM ACCRETING BLACK HOLES

In this section, we discuss different kinds of hosts. One class is the active galactic nuclei (AGNs) of supermassive black holes which are heavier than $10^5M_\odot$. The other class is the stellar-mass black holes ($3-10^2M_\odot$) with companion stars, which are the so-called X-ray black hole binaries (BHBs). There are also possibilities for the primordial black holes (PBHs) such that the mass range can be extended to the region that is much smaller than three
A. Accretion Disks and Temperature

There are a few interesting circular orbits very close to the event horizon of the black holes. The photon sphere near a black hole is where the photons travel in circular orbits. For a Schwarzschild black hole with the event horizon located at $R_e = \frac{2GM}{c^2}$, the photon sphere is located at $3R_e$. And the innermost stable circular orbit of the massive particles is located at $3R_e$. For a rotational black hole, it has corrections due to the rotational effects [39] which can be diagnosed using BH images obtained from EHT (see e.g. [19]). In general, for a rotating and charged black hole with angular momentum $J$ and charge $Q$, the outer event horizon is $R_+ = R_e(1 + \sqrt{1 - a^2 - q^2})/2$, where $a = J/M$ and $q = Q/M$. Here when $a^2 + q^2 = 1$, $R_+ = R_e/2$ is the extremal radius. Normally $a^2 + q^2 < 1$ is required by the cosmic censorship hypothesis to avoid naked singularities.

The Hawking temperature sourced by the quantum radiation of a Schwarzschild black hole is around $T_H \simeq 6 \times 10^{-8}K\left(\frac{M_\odot}{M}\right)$ [40]. For stellar-mass black holes around 3-10$M_\odot$, one has $T_H \sim 10^{-8}K$. For super massive black holes ($\gtrsim 10^6M_\odot$), one has $T_H \lesssim 10^{-13}K$. Both are much lower than the observed temperature of the cosmic microwave background temperature 2.7K. However, some black holes are surrounded by very hot coronal thermal plasmas and accretion disks, with the inner circle located around ISCO $R_I = 3R_e$. Observationally [41, 42], astrophysical black holes radiate keV X-rays, which are well explained in theoretical models.

The widely considered accretion flow model is the so-called Shakura-Sunyaev model [43], which is used for the observed emission energies less than 10 keV. This thin disk model was also worked out by Lynden-Bell, Pringle and Rees [44], and a general relativistic treatment for the inner part of the disk can be found in Novikov and Thorne’s [45, 46]. For the purpose of order of magnitude estimation of this paper, the simple Shakura-Sunyaev disk model suffices. We use the notations $r = R/R_e$ and $m = M/M_\odot$. The local radiation energy flux from unit surface at the radius $R$ of the disk is determined by the gravitational energy release $\mathcal{E}_r = \frac{\dot{E}}{4\pi} \left(1 - \sqrt{3/r}\right)$, where $\mathcal{E}_0 = \frac{3}{16\pi} \frac{M_\odot c^2}{R_e^3}$. The luminosity is related to the accretion rate via $L = f_s \dot{M} c^2$, where $f_s \approx 0.06$ for the Schwarzschild black hole and $f_s \approx 0.4$ for the extremal Kerr black hole [47].

If considering the critical Eddington luminosity $L_s = f_e \dot{M} c^2 = f_e L_E$, the typical energy flux is around $\mathcal{E}_0 = \frac{10^{43} \text{ergs}}{\text{s}}$. Here the Eddington luminosity has been approximated as $L_E \simeq 3.2 \times 10^4 \left(\frac{M}{M_\odot}\right) L_\odot$, where $L_\odot \simeq 3.8 \times 10^{33} \text{ergs/s}$ is the solar luminosity. In the following calculation, we will simply take $f_s \simeq 0.1$ and $f_e = 1$ for the estimation [48]. The Shakura-Sunyaev disk is optically thick, which can be roughly approximated as blackbody. From the law of thermal radiation $\sigma T^4_s \mathcal{E}_s = \mathcal{E}_s$, with the Stefan-Boltzmann’s constant $\sigma = \frac{\pi^2}{30}\frac{k^4}{c^2}\hbar^3$, the local effective temperature of the disk becomes $T_r = \left(1 - \frac{3}{r^4}\right)^{1/4} T_0$, $T_0 \approx \left(\frac{10}{m}\right)^{1/4} \times 3 \text{keV}$. (1)

The typical value of $T_0$ is calculate from $T_0 \equiv \langle \mathcal{E}_0/\mathcal{E}_s \rangle^{1/4}$.

In Figure 3, we make the contour plot of temperature $T_r$ in (1) as a function of locations in the disk $r = R/R_e$ and black hole masses $m = M/M_\odot$. One can see that the peak temperature of the disk is around $T_r \simeq 1.2 \text{keV}/m^{1/4}$ at the radius $r \approx 4$. And in Table I, we list two benchmark points for the black hole source. The gravity of primordial black holes is too weak to have significant accretion, so we leave the discussion to the last section.

| Types of X-ray sources | AGNs | BHs |
|------------------------|------|-----|
| Benchmark Masses ($M_\odot$) | $\sim 10^5$ | $\sim 10^6$ |
| Eddington Luminosity $L_E$ (erg/s) | $\sim 10^{34}$ | $\sim 10^{39}$ |
| Disk Temperature $T_0$(keV) | $\sim 10^6$ | $\sim 1$ |

TABLE I: Here we list two benchmark points for the accreting black hole sources, with the Eddington luminosity and the peaked temperature in thin accreting disk in (1).

B. Luminosity and Energy Flux

With the simple model of the thin accretion disk with the temperature distribution in (1), in the X-ray black hole binaries, the temperature of the disk peaks at energies around 1 keV. The temperature of disk around the supermassive black hole peaks at around $10^{-2}$ keV. For the AGNs, more complicated models are required. From the observations of a couple of AGNs, e.g. 1H
0707-495 [49–51] and analysis, the X-ray emission comes from the corona surrounding the black hole of an AGN as well as the reflection and thermal emission of the rays from the accretion disk. It has multiple features including reflection from accretion disk from 0.5 keV to 1 keV, corona X-ray around 1-5 keV and Iron Kα emission line peaked at \( \simeq 6.8 \) keV. The number flux in the spectrum from sources [49–51] is around \( \frac{\delta N}{\delta E} \simeq 10^{-3} \) photons /\((\text{cm}^2 \cdot \text{s} \cdot \text{keV})\).

The Eddington luminosity corresponds to the balance between gravity and radiation in the spherical plasmas [52]. It leads to \( \frac{GMm}{R^2} = \frac{LE E}{4 \pi c^2 \kappa} \), where \( m \) is the test mass of a small part in the accreting matter at radius \( R \). One then obtains the Eddington luminosity
\[
LE = 4\pi GMc/\kappa E,
\]
where \( \kappa_E \equiv \sigma_i/m_i \) is the cross-section due to photon scattering per unit mass. In the high energy approximation of the accretion, the accreting matters are mostly ionized hydrogens and the mass is dominated by the proton mass \( m_p \). The opacity is provided by the Thomson scattering, and the cross-section is dominated by the radiation pressure on the electrons \( \sigma_T \).

If most of the emission is released in the keV band, one may estimate the X-ray flux from the Eddington luminosity in (2), which leads to the total energy flux
\[
\mathcal{E}_E = \frac{LE}{4\pi R^2} \simeq \left( \frac{M}{M_\odot} \right) \left( \frac{\text{kpc}}{R} \right)^2 \times 10^8 \text{keV} / (\text{cm}^2 \cdot \text{s} \cdot \text{keV}). \tag{3}
\]

The number flux can be obtained through \( \Phi_E = \mathcal{E}_E / E \), where \( E \) is the energy scale of each particle in the flux. For the super massive black hole at the kpc distance, the energy flux \( \mathcal{E}_E \) is comparable with the X-ray flux from the Sun detected at the Earth at 1 erg/\((\text{cm}^2 \cdot \text{s} \cdot \text{keV}) \simeq 10^8 \text{keV} / (\text{cm}^2 \cdot \text{s} \cdot \text{keV}) \). However, most of those active AGNs are at Gpc distances. Since their luminosities are much higher, their fluxes can be comparable to X-ray BHBs as below.

1. **AGNs in supermassive black holes.** One source of the X-ray radiations is the active galactic nucleus (AGN), which is a compact region at the center of a galaxy that has extremely high luminosity. The wide waveband from radio wave of \( O(10^{-3}) \) keV to gamma-ray of \( O(10^7) \) keV has been observed, which is powered by the accretion of matters surrounding supermassive black holes ranging from \( 10^5 M_\odot \) to \( 10^9 M_\odot \). For the supermassive black holes with typical mass \( M \sim 10^6 M_\odot \), the luminosity \( L \sim 10^{44} \) erg/s. In our Galactic center, Sgr A* and other low luminosity AGNs, the luminosity is in the order of \( 10^{-3} L_E \). For very active galaxies, the bolometric luminosities can be higher than \( 10^2 L_E \).

2. **X-Ray Black Hole Binaries (BHBs).** Accreting black holes in the Galactic scale are BHBs. The candidates include Cygnus X-1, XTE J1650-500 and GX 339-4 [53–55]. There are two kinds of X-ray spectra of the accreting black holes. In the so-called soft state, the X-ray spectrum is composed of a strong and narrow peak at a few keV and a soft power-law spectrum up to hundreds of keV. The hard state peaks below 1 keV while the Comptonized component is extended up to 100 keV. The luminosity of the soft state can be near or much higher than \( L_E \), while the hard state is usually two orders of magnitude below the Eddington luminosity \( L_E \).

### III. Dark Fluxes from Black Holes

In this section, we will discuss several mechanisms that may produce, accumulate, and accelerate dark matter particles, dark photons, or axions around the black hole. Especially for some dark particles, the creation and acceleration do not necessarily require the standard model couplings.

#### A. Different Mechanisms of the Dark Fluxes

The observations and models show that the radiations from plasmas around black holes are partly X-rays, around keV scale. The light dark matter particles/axions can be thermally produced around the visible matter and their energy is expected to be around keV, in analogy to the production in the Sun. The keV medium can produce axion/dark photon flux, as calculated in [26, 56], through a few processes. These processes include dark Higgs strahlung, oscillations from the visible photons to the dark photons, Primakoff processes \( \gamma + Ze \rightarrow Ze + a \), and ABC processes for axion production. The ABC processes stand for Atomic axio-recombination and Atomic axio-deexcitation, axio-Bremstrahlung in electron-Ion or electron-electron collisions, Compton scattering (see eg [56] for a sample of Feynman diagrams).

1. **Emission from AGNs or X-ray binaries.** The temperature of the AGNs or the disk around the X-ray binaries can be as high as keV, which is close to the temperature in the core of the Sun. However, the density of the accretion disk for AGNs with mostly ions and electrons, \( \rho_{\text{disk}} \sim 10^{-7} \) g/cm\(^3\) [57], is much smaller than the \( \rho_{\text{HB}} \sim 10^4 - 10^6 \) g/cm\(^3\) (HB stands for the stars in the horizontal branch with the solar masses), and is model-dependent. The nuclear reactions take place in the core of the Sun and the reaction rates are highly temperature dependent. Black hole accretion disks can have high temperatures generated by the high accretion rates with nuclear fusions, such that the dark particles/axion can be generated.

   Similar to the solar environment where axion is converted via \( \gamma \rightarrow a \) [17], AGN corona (or solar corona) and X-ray BHB accretion disk can have a temperature of \( \sim 10^7 \) Kelvin and produce keV dark matter. The thermal emission is a process where the collected excitations, plasmons converted to the light-dark matter of the comparable energy. The frequency of the plasmons is dominated by the medium temperature at a high-
temperature. However, since the production rate is related to the density so that the production rate from AGN has been found to be quite low [58]. Only the solar corona or BHB accretion disk may reach an enough axion flux, which is usually bounded by the visible luminosity. Considering that the luminosity of dark particles/axions from the Sun is bounded by 10% of visible luminosity [26, 56], we assume that the dark luminosity $L_D$ is comparable to the visible luminosity.

For the AGN corona, one needs to consider the alternative mechanism as shown in Figure 1. It has been proposed that the cosmic magnetic field may convert part of the X-ray photons to high energy axions [29, 30], where up to about 1/3 of photons can be converted which is similar to neutrino oscillations. Thus, we simply start from the total energy flux (3) with Eddington luminosity in (2), and make the major assumption that the total dark luminosity is characterized by the Eddington luminosity $L_D \lesssim L_E$.

Notice here that this assumption is rather ad hoc. If the dark particles are produced thermally, the couplings with the standard model particles are bounded by the stellar cooling constraints, so it is reasonable to assume the similar bounds for the black hole productions with bounded couplings. If the dark flux is not produced thermally, then Eddington luminosity can be a benchmark point for the dark luminosity, assuming that dark sector is accreted by the black holes and balanced by some self-interaction induced scatterings within the dark sector. If considering the axion fluxes converted from the X-ray photons under the cosmic magnetic field, this bound is also plausible.

2. Superradiance and Dark Radiation. One kind of interesting objects is the gravitationally bounded “atoms” with light bosons (e.g. axions) or vectors [59]. Similar to the hydrogen atoms, those light particles occupy different energy levels of the rotating black holes. Although the kinetic energy in the superradiance clouds is non-relativistic, these accumulated light particles can be accelerated through different energy extraction processes around the black hole.

Notice that in the gravitational atoms, when the Compton wavelength of dark particle is comparable to the size of a black hole, the number of dark particles can grow exponentially from extracting energy of the rotating black holes. When the attractive self-interactions become stronger than the gravitational binding energy, the clouds collapse and explosion induces an outflow [59]. If considering the decay of axion through $a \rightarrow \gamma \gamma$, it has been shown in [20, 21] that the $\mu$eV axion clouds around $10^{-5} M_\odot$ PBHs can induce fast radio bursts (FRBs), and the luminosity can be as high as $10^{40}$ erg/ms. Though the time scale of FRBs is around milliseconds, the total energy released is comparable to the energy released by the Sun in one day.

Thus, it is also interesting to consider the bursts of dark sectors with the similar mechanism. If considering the channel of $\phi \rightarrow \gamma \gamma'$, the dark photon at 3.5 keV requires $m_\phi \sim 7$keV. Considering the reduced Compton wavelength $\lambda_\phi = h/(m_\phi c)$, the dimensionless number describing the dark matter superradiance cloud is $\alpha_s \equiv R_5 \simeq 0.1 \times \left( \frac{M_{BH}}{10^{-15} M_\odot} \right) \left( \frac{m_\phi}{10^{15} \text{ keV}} \right)$. If we take the typical value of $\alpha_s$ as order of 0.1, it is interesting to see that the black holes of the masses $10^{-15} M_\odot$ have the Hawking temperature $T_{BH} \sim \text{keV}$. To see this, consider the Hawking radiation with the temperature

$$T_{BH} = \frac{\hbar}{4\pi k_B R_s} \simeq 5.3 \text{keV} \left( \frac{10^{-15} M_\odot}{M_{BH}} \right).$$

If requiring $k_B T_{BH} = 3.5 \text{keV} \approx 4 \times 10^7 K$, we obtain $M \simeq 1.5 \times 10^{-15} M_\odot$, which is in the mass region of the primordial black holes [60]. The life time for such PBHs to evaporate is around $\tau_{BH} \simeq 10^{22}$ years $(\frac{M_{BH}}{10^{-15} M_\odot})^3$, which is still much longer than the age of the universe at $10^{10}$ years. If the particles in Hawking radiation of PBHs are mainly in the dark sectors [61], the dark radiations at keV energy scale could also be one candidate source for the dark fluxes.

The Bekenstein-Hawking luminosity of a Schwarzschild black hole is given by $A_5 \sigma_s T_{BH}^4$, with the area of the horizon $A_5 = 4\pi R_5^2$. It is calculated to be $L_{BH} = \frac{\hbar}{4\pi} (\frac{c^2}{16\pi G})^2 \simeq 2 \times 10^{-25} L_\odot \left( \frac{10^{-15} M_\odot}{M_{BH}} \right)^2$. Thus, even for these $10^{-15} M_\odot$ PBHs, the luminosity of Hawking radiation $L_{BH} \sim 10^{-25} L_\odot$ is still quite small compared to the solar luminosity. Due to the small luminosity, one might not need to consider them here for XENON1T.

3. Self-interacting Dark Matter. Now we consider a different mechanism to produce an outflow of dark matter particles. The heavier non-relativistic MeV-GeV dark matter cannot be thermally produced in the plasma. They can however get boosted around the event horizon or captured/accreted by the black hole. Especially the black holes have been considered to act like particle accelerators to boost the particles to arbitrary high energy and collide [23, 24]. However, for the traditional collision-less cold dark matter, the dark matter particles can have a larger speed near the black hole, but that does not mean they can escape. If we assume the collision can happen, then some of the products may escape the near horizon region of black holes. That means that we need to consider self-interacting dark matter in order to account for a dark flux [34]. Another possibility is the charged DM model with the dark electromagnetism (mediated by the dark photon). One may be able to invoke shocks or magnetic reconnection processes to accelerate particles via the first-order Fermi acceleration mechanism. All these processes require charged dark matter particles.

At the galaxies scale, the self-interacting dark matter model is introduced to solve the problems in small scale structures [34], such as the core-cusp problem, the rotation curve’s diversity problem, the missing satellites problem, etc. The double-disc dark matter is also moti-
vated [35, 36], such that accretion disk model with viscous hydrodynamical approximation can be applied. For example in [28], the hypothetical dark photon was proposed to mediate the interactions of dark matter particles through $\mathcal{L}_{\chi\gamma'} = \bar{\chi}(i\not{D} + m_\chi)\chi - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}$. Neither of them interacts much with the standard model particles.

It is interesting to estimate the dark luminosity following the similar derivation of Eddington luminosity in (2). Assuming the dark matter particles are scattered upon the dark photons via the cross section $\sigma_{\chi\gamma'}$ due to the interaction above, we can have the dark luminosity

$$L_\chi = \frac{4\pi G M_c}{\kappa'_\chi} = L_E \frac{\kappa_E}{\kappa'_{\chi}}, \quad (5)$$

where $\kappa'_{\chi} \equiv \sigma_{\chi\gamma'}/m_\chi$. For ionized hydrogens, one has $\kappa_E = \sigma_T/m_\text{p} \sim 0.3 \text{cm}^2/\text{g}$. From numerical simulations of merging cluster galaxies [34, 37], one bound of the self-interaction cross-section of dark matter particles is $\sigma_{\chi\chi} \lesssim 1 \text{cm}^2/\text{g}$. Here the cross sections $\sigma_{\chi\chi}$ and $\sigma_{\chi\gamma'}$ are both related to the dark photon fine-structure constant $\alpha'$, which is bounded by the relic abundance [28]. Hence, it is reasonable to assume $\kappa'_{\chi} \sim \kappa_E$, and we can have the dark luminosity as bright as the Eddington luminosity $L_\chi \sim L_E$. If considering the case of the self-interacting dark matter without the dark radiation, the gravitation could be balanced by the pressure of the dark particle gas $\kappa_{\chi\chi} \equiv \sigma_{\chi\chi}/m_\chi$, then again we can reach $L_\chi \sim L_E$.

In summary, the total number flux is given by $\Phi_D \equiv \mathcal{E}_D/E_D = L_D/(4\pi R^2 E_D)$ where $E_D$ the energy of dark matter particles. Considering the bound for the dark luminosity $L_D \lesssim L_E$, the number flux is bounded by

$$\Phi_D \lesssim \left( \frac{M}{M_\odot} \right)^2 \left( \frac{\text{keV}}{E_D} \right)^2 \times 10^3/(\text{cm}^2 \cdot \text{s}). \quad (6)$$

In Figure 4, we make the contour plot of dark flux $\Phi_D$ as a function of locations in the disk $R/R_\odot$ and black hole masses $M/M_\odot$, which will be used in the estimations below. In the following, we list a few mechanisms to produce the dark matter flux.

**B. Possible Explanation for XENON1T**

Below we discuss three possible dark matter candidates that can be produced around black holes and provide possible XENON1T excess explanations. Before that, we summarize the general result on the detection. One possibility is to consider the electron recoil, and the total number of signal events is given by $N_\text{s} = \Phi_1 \times \sigma_\text{e} \times T_\text{X} C_X$. Here $C_X = Z_e n_X V_X$ and $\Phi_1$ is the incoming flux with dimension $[\text{cm}^{-2} \cdot \text{s}^{-1}]$, $\sigma_\text{e}$ is the cross section with dimension $[\text{cm}^2]$ and $T_\text{X}$ is the operation time. $C_X$ is the total number of effective electrons in the detector, which can be calculated by the product of the effective number $Z_e$ of electrons in each xenon atom that undergo recoils, the number density of Xenon atoms $n_X$ and the total fiducial volume $V_X$. On the XENON1T excess with $N_\text{s} \sim O(100)$, e.g. in [62], the required product of the number flux and cross section has been found to be of $\Phi_1 \times \sigma_\text{e} \sim O(10^{-35})/\text{s}$. In the following, we will use this relation to estimate the required flux and then the distance to the sources with (6), considering the accreting black holes as the sources.

1. **Axion/Axion Like particles (ALP).** One possible explanation of the claimed XENON1T excess is the solar axion/ALP. It requires the coupling to the electrons without/with photon coupling through the inverse Primakoff process [63], $a + Ze \rightarrow \gamma + Ze$ or inverse Compton scattering $a + e \rightarrow e + \gamma$, with the couplings in the Lagrangian

$$\mathcal{L}_a = -\frac{g_{a\gamma}}{4} a F_{\mu\nu} F^{\mu\nu} - \frac{g_{ae}}{2} m_e \psi_e \gamma^\mu \gamma_5 \psi_e. \quad (7)$$

Since the solar axion luminosity is bounded by stellar cooling, the couplings have been constrained as $g_{a\gamma} < 10^{-10} \text{GeV}^{-1}$ or $g_{ae} < 10^{-12}$ [26]. The kinetic energy of axion/ALP considered for Xenon here is 2-4 keV with the axion mass $m_a < 1 \text{eV}$. However, this explanation is in tension with astrophysical stellar cooling constraints [17], because the solar axion production is well studied.

What’s more, the couplings bounded by the stellar cooling constraints also lead to the bounded cross sections. The minimum required number flux density of the incoming axions for the XENON1T excess is around $\Phi_a \gtrsim 10^{11}/(\text{cm}^2 \cdot \text{s})$. Here instead, it is possible to consider the accreting black holes as the sources. If we consider the keV axion in the dark flux bounded by (6), with the help of Table I, one can obtain the minimum distance of the three types of black holes. It is tempting to explain the Xenon 1T axion with the black hole sources rather than the Sun, provided that the thermal plasma around the observed black hole is at keV temperature.

![FIG. 4: The contour plot of the bound of total dark flux $\Phi_D$ in (6) with the Eddington luminosity and $E_D \simeq 3.5 \text{keV}$, as a function of the distances $R/\text{kpc}$ and masses $M/M_\odot$ of black holes.](image-url)

2. **Light Dark Photon.** The dark photon production in the Sun is mostly from dark Higgstrahlung and visible
photons or resonances with real or virtual photons. And the dark photon sector is given by the Lagrangian

$$\mathcal{L}_{\gamma'} = \frac{1}{4}(F_{\mu\nu}^\gamma)^2 + \frac{\epsilon}{2} F_{\mu\nu} F^{\mu\nu} + \frac{m_{\gamma'}^2}{2} A^2.$$  (8)

The typical solar flux is $\Phi_{\gamma'} \lesssim 10^{10}/(\text{cm}^2\cdot\text{s})$ for mixing $\epsilon \sim O(10^{-14})$ [56]. It was recently pointed out in [64] that solar emission of dark photons is a soft little to fit well with the recent XENON1T excess.

However, here if we replace the Sun by other sources such as the two types of accreting black holes in our Table I, with different couplings, the flux aimed at the XENON1T excess received on Earth is $\Phi_{\gamma'} \gtrsim 10^{11}/(\text{cm}^2\cdot\text{s})$. Considering the keV dark photons in (6), one can summarize in Table II below with the minimum required distance of black hole accretion with the assumed dark luminosity $L_D \simeq 10^{38}\text{erg}/\text{s}$.

| DM Types | Axion or ALP | Dark Photons |
|-----------|--------------|--------------|
| Masse (m/keV) | $< 10^{-4}$ | $< 10^{-4}$ |
| Energy(E/keV) | $\sim 3$ | $\sim 3$ |
| Flux($\Phi/(\text{cm}^{-2}\cdot\text{s}^{-1})$) | $\sim 10^{11}$ | $\sim 10^{14}$ |
| Couplings | $g_{a\gamma} \sim 10^{-14}\text{GeV}^{-1}$ | $\epsilon \sim 10^{-14}$ |
| and $g_{\gamma e} \sim 10^{-12}$ | | |
| Distances (R/kpc) | $< 10^{-4}$ | $< 10^{-4}$ |

TABLE II: Here we list two benchmark points for the XENON1T explanations with a black hole source. We assume the dark particle luminosity of the host black hole is $L_D \sim 10^{38}\text{erg}/\text{s}$.

For the much lighter axion, the self interaction is very small [65]. If we take the cross section $\sigma_{a\gamma'} \simeq \sigma_{a\gamma}$ and usual QCD axion at $\mu\text{eV}$ scale, then $\kappa' \equiv \frac{\sigma_{a\gamma}}{\sigma_{a\gamma}}$ will be many orders of magnitude smaller than $\kappa_E$, which means that the luminosity $L_a = L_E \frac{\sigma_{a\gamma}}{\kappa'}$ can be much higher. Although the distances in Table II that bounded by the visible Eddington luminosity can be relaxed, this kind of system is usually unstable and may lead to bursts of photons or axions after a short time. This process may be an interesting source to search for axions and will be interested in further exploration.

There are also a lot of discussions on the cosmological origin of the dark photons (see e.g. [66]), similar to the dark photon dark matter model. It was found in [56] that the local dark photon dark matter with mixing angles $\epsilon \sim O(10^{-16})$ can fit well and satisfy the astrophysical constraints. Here one can find for the local 3 keV dark matter with the density $\rho_{\gamma'} \simeq 0.3\text{GeV}/\text{cm}^3$ and $10^{-3}\text{c}$, the flux can be as high as $\Phi_{\gamma'} \sim 10^{12}/(\text{cm}^2\cdot\text{s})$. The intrinsic mass $m_{\gamma'} \sim 3\text{keV}$ is built into the model [56]. In fact, if we consider the black hole sources for it, the mixing $\epsilon$ and $m_{\gamma'}$ can also be relaxed accordingly.

3. Boosted Dark Matter. The heavier boosted dark matter from MeV to GeV mass with around 0.1c can also explain the excess as in [62, 67] with a number flux of $\Phi_{\gamma} \sim 10^{-5}/(\text{cm}^2\cdot\text{s})$ in an NFW profile [68] from galactic center to produce Xenon excess considering an elastic scattering between the dark matter particle and an electron $\chi + e \rightarrow \chi + e'$. For the non-relativistic case, the transferred recoil energy is $E_R \sim 2m_e v_e(v_\chi - v_e)$, for the case of $m_\chi \gg m_e$. Considering the mass of electron as 511keV, for the XENON1T excess between 2-4 keV, a required benchmark velocity of the heavy dark matter particles is $v_\chi \sim 0.1c$, with the boost factor $\gamma_{0.1} = (1 - v_e^2/c^2)^{-1/2} \simeq 1.005$. The flux has been calculated $\Phi_\chi \simeq 10^{-6}/(\text{cm}^2\cdot\text{s}) \left(\frac{3 \times 10^{-29}\text{cm}^2}{\sigma_{e\chi}}\right)$, where $\sigma_{e\chi}$ is the required cross section and here we just use it as the benchmark flux for our dark sources [62, 67].

Black holes can be good accelerators to accrete and boost heavy dark matter particles. For the boosted dark matter to escape and reach the benchmark speed of 0.1c at the Xenon detector, we need to assume extra ingredients. One may consider the semi-annihilation dark matter $\chi' \rightarrow \chi \phi$, where $\chi'$ and $\chi$ are the heavy DM particles with the same mass, and $\phi$ is a light particle coupled to the SM sector [69]. The boost factor of the final states turns out to be $\gamma_{\chi} = 1 + \frac{m_{\chi}^2}{4v_e^2} \leq \gamma + \frac{1}{4v_e^2}$, where $\gamma$ is the boost factor of $\chi'$ in the center of mass frame. When $\gamma_{\chi} = 1$, we reach the limit $\gamma_{\chi} = 1.25$ and $v_e = 0.6c$. For the two-component DM model $\chi_A \chi_A \rightarrow \chi_B \chi_B$ studied in [62] with initial boost factor $\gamma_A$, the boost factor for $\chi_B$ is simply given by $\gamma_{\chi} = \gamma_A m_A/m_B$ [2], which can go beyond 0.6c easily. Thus, for both cases, the velocities of the produced dark matter particles $\chi_B$ can reach or go beyond the escape velocity outside ISCO. The dark accretion disk also provides a higher density environment to enhance semi-annihilation and collision rates, and the products could then escape. Alternatively, we need to consider the charged DM model with the dark electromagnetism sector, as discussed in section III.A, such that it is possible to reach a larger flux as described around the dark luminosity in eq. (5).

| DM Types | Dark Photon DM | Boosted DM |
|-----------|----------------|------------|
| Masse (m/keV) | $\sim 3$ | $\sim 10^{7} - 10^{9}$ |
| Velocity(v/c) | $\sim 10^{-3}$ | $\sim 10^{-3}$ |
| Flux($\Phi/(\text{cm}^{-2}\cdot\text{s}^{-1})$) | $\sim 10^{12}$ | $\sim 10^{10}$ |
| Parameters | $\epsilon \sim 10^{-15}$ | $\sigma_{e\chi} \sim 10^{-29}\text{cm}^2$ |
| Distances (R/kpc) | $< 10^{-4}$ | $< 10^{3} - 10^{4}$ |

TABLE III: Here we list the other two benchmark points for the XENON1T explanations with a black hole source. The parameter choices are based on [64] and [62]. We assume the dark particle luminosity is $L_D \simeq 10^{38}\text{erg}/\text{s}$.

Here we again assume that the dark luminosity is characterized by the Eddington luminosity. In Table III, we list the possible dark matter candidates, such as the dark photon dark matter and boosted dark matter with a black hole source. The parameter choices are from [64] and [62], and we assume the dark particle luminosity of the host black hole is $L_D \simeq 10^{38}\text{erg}/\text{s}$. 
IV. SUMMARY AND DISCUSSION

In this study, we propose that accreting black holes can be the natural sources to produce the keV order light dark matter and boost the heavier dark matter. We discuss several mechanisms to produce, accumulate and accelerate the dark photon, axion, even heavier dark matter around the black holes, motivated by the fast dark matter explanations of XENON1T excess. Various kinds of explanations have also been proposed in e.g. [70]-[152].

The X-ray black hole binaries with stellar masses, or AGNs in the super massive black holes can be possible hosts (see also a recent event of an intermediate mass black hole [153]). However, the fluxes observed in AGNs and BHBs are many orders of magnitude smaller than the flux required for the XENON1T excess due to the distance > 1 kpc to the Earth. At the galactic center of the Milky Way galaxy, there is a supermassive black hole of 4 × 10^6 M⊙ which powers the compact radio source Sag A* and is around 8 kpc from the Earth [154, 155], which might be a possible source for the dark matter fluxes. Although the black hole corona and disk productions of axions and dark photons require some detailed modeling of the accretion processes, the observed X-ray emissions provide benchmark points around the 1-8 keV range.

The black hole candidates such as primordial ones (e.g. the smaller “Planet 9” with 10^{-5} M⊙) with closer locations may also be the sources to boost dark matter [156, 157]. The other possible region is the micro PBHs around 10^{-15} M⊙ which can emit X-rays through thermal radiations, although the luminosity is quite small, it is plausible to assume the radiations partly belong to the dark sector. Besides, there are many bright X-ray sources in the sky that originate from accreting or spindown-driven neutron stars. Supernova remnants, Gamma ray bursts (GRB) afterglows can also produce bright X-rays although the density in the emission region is extremely low and the radiation process is synchrotron radiation. Those systems could be interesting subjects of study in the future.

The dark cosmic fluxes created around the black holes can be interesting and less explored targets for direct detections, in light of the multi-messenger detections for the black holes such as gravitational waves and EHT. The constraints are also less severe comparing to the stellar productions. Especially with the help of the multi-messenger detections, we hope the dark processes around the black holes can be understood and modeled better in the near future.

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