Constraints on mixed dark matter model of particles and primordial black holes from the Galactic 511 keV line

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Abstract. The 511 keV line was first detected in 1970’s but its origin is still unknown. It was proposed that positrons from dark matter (DM) particles in the halo of galaxy are possible sources. We consider a mixed DM model consisting of DM particles and primordial black holes (PBHs). With the existence of PBHs, the DM particles may be gravitationally bound to the PBHs and form halo around PBHs with density spikes. These density spikes can enhance the production rate of positrons from DM particles, thus they are constrained by the observations of 511 keV line. We compute the profile of the density spikes, and get the constraints on the fraction of PBHs in DM $f_{\text{PBH}}$ for light dark matter (LDM) scenario and excited dark matter (XDM) scenario respectively. For LDM with mass in the range of $1\text{MeV} \sim 3\text{MeV}$, the constraints are loose. For XDM with mass in the range of $10\text{GeV} \sim 1\text{TeV}$, the constraints have $M_{\text{PBH}}^{-2}$ slope in the relative small mass range, and roughly have $M_{\text{PBH}}^{2/5}$ slope in the relative large mass range. The most stringent constraint $f_{\text{PBH}} \lesssim 10^{-11}$ appears at the turning point which depends on the mass of XDM.
1 Introduction

In the standard model of cosmology, only 5% of the universe consisting of ordinary baryonic matter is well-known, and the rest of the universe which consists of nearly 26% dark matter (DM) and nearly 69% dark energy (DE) is barely known [1]. The puzzle of DM dates back to 1930’s [2], and the existence of DM is overwhelming with evidences from various astrophysical observations, such as rotation curves of galaxies, hot gas in clusters, gravitational lensing measurements, galaxy formation, primordial nucleosynthesis and cosmic microwave background observations [3, 4]. There are many DM candidates, including astrophysical objects such as primordial black holes (PBHs), and particles beyond the standard model of particle physics. Among the particle DM candidates, the most popular are the weakly interacting massive particles (WIMPs) and axions, since they have been proposed for some other reasons in particle physics. Other candidates include sterile neutrinos, light dark matter (LDM), self-interacting dark matter, and many others [3, 4].

The PBHs are formed from the gravitational collapse of the overdense regions in the early universe [5–7], and have attracted considerable attention and have been studied extensively ([8, 9], and references therein). Beside being candidate of DM, PBHs can also be the seeds for galaxy formation [10–13], or the sources of LIGO/VIRGO detection [14, 15]. There are a plenty of scenarios that lead to PBH formation [16, 17], and all of these require a mechanism to generate large overdensities. These overdensities are often of inflationary origin, and will collapse if they are larger than a certain threshold when reentering the horizon [18–24].

The 511 keV line was first detected at the galactic center and was identified as the result of electron-positron annihilation in 1970’s [25–27]. This line is mostly due to parapositronium annihilation of thermal or near-thermal positrons [28, 29], and the absence of continuous high-energy spectrum from positron annihilation in flight implies that the initial energy of these positrons is less than a few MeV [30], but the origin of these low-energy galactic positrons is still under debate. Several sources have been proposed to explain the low-energy galactic positrons, such as the $\beta^+$ decay of stellar nucleosynthesis products (e.g. $^{26}$Al, $^{44}$Ti and $^{56}$Ni) [31–33] and LDM [34, 35].

However, most of astrophysical sources cannot account for the observed morphology, while DM interactions have the potential to explain the observations because of the DM halo of galaxy [36]. It is possible that the low-energy galactic positrons are produced by direct annihilation of LDM (\~{}few MeV) particles into electron-positron pairs [34], or by the excited dark matter (XDM) mechanism. In the XDM mechanism, the excited states of heavy DM
are produced in collisions, and the electron-positron pairs are produced through the decay of the excited state into the ground state [37, 38]. The advantage of this mechanism is that the DM mass is relatively unconstrained, and the only requirement is that the splitting between the ground and excited states is less than a few MeV.

In principle either PBH or particle can account for the total DM abundance, but there is no evidence that one of them must account for the total abundance, and it seems that a mixed DM model consisting of both PBH and DM particle is more possible. Indeed, such a mixed DM model can lead to many interesting consequences compared with a single component DM model. Besides, even if PBHs only constitute a small fraction of the DM, they can still have significant influence as we will show. Therefore such a mixed DM model needs more studies, and it will be pretty good if we can make some constraints on such a model through some observations.

In this paper, we assume that the DM is mixed of PBHs and particles whose interactions can lead to the productions of electron-positron pairs which can explain the 511 keV line observations, i.e., the energy density of DM is given by

$$\rho_{DM} = \rho_{PBH} + \rho_\chi. \quad (1.1)$$

With the existence of PBHs, the DM particles may be gravitationally bound to the PBHs and form halo around PBHs with density spikes [39]. Since the interaction of DM particles is related to the particle density, the formation of density spikes can change the interaction and leave some imprints in the 511 keV line observations. Therefore, by analyzing the data of 511 keV line, one can get constraints on PBHs and DM particles.

This paper is organized as follows: we revisit the DM scenario which can explain the 511 keV observations in section 2 and compute the density profile of DM particle halo around PBHs in section 3, the constraints from the Galactic 511 keV line are shown in section 4, and the last section is devoted to conclusions.

## 2 511 keV line from DM particles

Firstly we revisit the scenario that the low-energy galactic positrons which lead to 511 keV line are produced from DM particles in the case that particles account for the total DM abundance. For these positrons produced from DM, its number density is closely connected to the number density of DM particles. If the positrons are produced by decay of DM particles, the rate of production is

$$\dot{n}_{e^+} = n_\chi \Gamma_d, \quad (2.1)$$

where $n_{e^+}$ and $n_\chi$ are the number densities of positrons and DM particles, respectively, and $\Gamma_d$ is the decay rate of DM particles. But if the positrons are produced from annihilation of DM particles or the decay of excited state into ground state for XDM, then the positron production rate is given by

$$\dot{n}_{e^+} = \langle \sigma v \rangle n_\chi^2, \quad (2.2)$$

where $\langle \sigma v \rangle$ is the thermally averaged cross-section for annihilations or excitations of DM particles that produce electron-positron pairs.

As the experiments show, most positron annihilations are through positronium formation [28, 40, 41], and the positronium fraction $f_p \approx 0.967$ [29]. In this channel, 1/4 of the annihilations take place in the parapositronium state yielding 2 photons with $E = 511\text{keV}$ which account for the observations, while the remaining 3/4 yield 3 photons with $E < 511\text{keV}$. 

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For these positrons which do not form positronium, they annihilate directly into 2 photons with $E = 511$ keV. Thus the total number density of 511 keV photons produced per unit time is

$$\dot{n}_\gamma = 2((1 - f_p) + f_p/4)\dot{n}_{e^+}. \quad (2.3)$$

For any particular model of the Milky Way DM halo, one can compute the intensity distribution of 511 keV signature as a function of galactic longitude $l$ and latitude $b$, by integrating the emissivity $\dot{n}_\gamma(r)$ along the line of sight (l.o.s.), which is

$$I(l, b) = \frac{1}{4\pi} \int_{\text{l.o.s.}} \dot{n}_\gamma(r) ds, \quad (2.4)$$

with

$$r = \sqrt{(s \cos b \cos l - r_\odot)^2 + s^2 \cos^2 b \sin^2 l + s^2 \sin^2 b}, \quad (2.5)$$

where $s$ denotes the distance from the solar system along the line of sight, and $r_\odot \approx 8.0$ kpc is the distance from the Sun to the Galactic center [42]. Thus the total flux of the 511 keV photons from DM is given by the integral of the intensity distribution,

$$\Phi = \int I(l, b) d\Omega. \quad (2.6)$$

Suppose the density profile of Milky Way DM halo is $\rho(r)$, the intensity distribution of 511 keV signature is

$$I(l, b) = 2(1 - 3/4f_p) \frac{1}{4\pi} \int_{\text{l.o.s.}} \frac{\rho(r)}{m_\chi} ds \quad (2.7)$$

for decaying DM, and

$$I(l, b) = 2(1 - 3/4f_p) \frac{1}{4\pi} \int_{\text{l.o.s.}} \langle \sigma v \rangle \frac{\rho^2(r)}{m_\chi^2} ds \quad (2.8)$$

for annihilating or excited DM. Noticing that the intensity distribution is $I \sim n_\chi$ for decaying DM, while that is $I \sim n_\chi^2$ for annihilating or excited DM, thus the decaying DM will lead to a more spread distribution compared with annihilating or excited DM.

Comparing the observation data of 511 keV line with the theoretical predictions, it is found that the decaying DM scenario is disfavored by data, while the annihilating or excited DM scenario is pretty plausible [43–45]. Using a model-fitting procedure to the INTEGRAL/SPI data, the best fit results are [45]

$$\langle \sigma v \rangle \sim 5 \times 10^{-25} (m_\chi/\text{GeV})^2 \text{ cm}^3\text{s}^{-1}, \quad (2.9)$$

and

$$\Phi \sim 2.1 \times 10^{-3} \text{ ph cm}^{-2}\text{s}^{-1}, \quad (2.10)$$

with the density profile of Milky Way DM halo given by the Einasto profile

$$\rho(r) = \rho_s \exp \left(-\left[\frac{2}{\alpha} \left(\frac{r}{r_s}\right)^\alpha - 1\right]\right), \quad (2.11)$$

where $r_s \approx 26$ kpc and $\alpha \approx 0.17$ come from the Via Lactea II simulation [47], and the overall density normalization $\rho_s \approx 2.5\text{TeV/cm}^3$ is computed from the local dark matter density [48].

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1The velocity dependence of this thermally averaged cross-section is neglected for simplicity, which is good approximation for MeV DM undergoing pure annihilations [34, 46] and XDM with $m_\chi \gtrsim \text{TeV}$, and more detailed study should be done for XDM with $m_\chi \lesssim \text{TeV}$ [45].
3 Particle halo around PBHs

There are many experiment constraints on the fraction of PBHs in the DM, it is possible for PBHs with mass in the range $10^{-16} \sim 10^{-12} M_\odot$ constitute all the DM, but for the steller mass PBHs, the constraints suggest that PBHs subdominant to the rest of DM [9]. The fraction of PBHs in DM is defined as

$$f_{PBH} \equiv \rho_{PBH}/\rho_{DM},$$

so the corresponding fraction of DM particles is $\rho_\chi = (1 - f_{PBH})\rho_{DM}$. In this work, we consider a particles dominating mixed DM model, i.e. $f_{PBH} \ll 1$.

Consider the PBH formation at radiation-dominated era, since we only need that PBHs are formed prior to the kinetic decoupling of DM particles from the primordial plasma, we are not assuming any specific formation mechanism of PBHs. Once the DM particles have kinetically decoupled from the primordial plasma, they could be gravitationally bound to the PBHs and form halo with density spikes.

Suppose the PBH forms at time $t_i$, we focus on a particle at position $r_i$ with velocity $v_i$. The particle would spend a fraction $2dt/\tau_{orb}$ of its period at distances between $r_i$ and $r_i + dr$, where $\tau_{orb}$ is the period of the particle’s orbital motion around the PBH and $dt$ is the time it takes for the particle to move from $r$ to $r + dr$. Given the initial density of DM particles $\rho_i(r_i)$, at later time $t > t_i$, the density of DM particle halo around PBHs $\rho_b(r)$ can be written as the relation

$$\rho_b(r)4\pi r^2 dr = \int 4\pi r_i^2 dr_i \rho_i(r_i) \int d^3 v_i f_B(v_i) \frac{2dt/dr}{\tau_{orb}} dr,$$

which follows from the Liouville equation and expresses the density conservation law in phase space integrated over the momenta by taking into account the volume transformation in momentum space, where the velocity distribution of DM particles $f_B(v_i)$ is chosen to be Maxwell-Boltzmann distribution. Therefore, we have

$$\rho_b(r) = \frac{1}{r^2} \int dr_i r_i^3 \rho_i(r_i) \int d^3 v_i f_B(v_i) \frac{2}{\tau_{orb}} \frac{dt}{dr},$$

and more details of the calculation can be found in [39, 49].

In figure 1, we show the density profile $\rho_b$ of DM particles bound to a PBH as a function of the rescaled radius $r/r_g$ (where $r_g \equiv 2G M_{PBH}$/4$\pi\rho_r$) with different values of $m_\chi$ and $M_{PBH}$. For a given $m_\chi$, the density profile for the lighter PBH constitutes an envelope to the profile for the heavier PBH, this is because the maximum rescaled radius that a PBH can gravitationally affect, i.e. $(3M_{PBH}/4\pi\rho_r)^{1/3}/r_g$ (where $\rho_r$ is the energy density of the radiation-dominated universe), is smaller for the heavier PBH. For a given $M_{PBH}$, $\rho_b$ is smaller for the lighter DM particles. This is because the initial density $\rho_i \propto \rho_{KD}$ (where $\rho_{KD}$ is the energy density of the universe when DM particles kinetically decouple from the primordial plasma), and the light particles kinetically decouple later than the heavy particles, which lead to a smaller $\rho_i$ for the lighter DM particles.

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2 Due to the symmetry of the orbit, the particle passes the same radius twice, which leads to the factor of $2$ [39].
Figure 1. The density profile $\rho_b$ of DM particles bound to a PBH with different values of $m_\chi$ and $M_{PBH}$. For a given $m_\chi$, the density profile for the lighter PBH constitutes an envelope to the profile for the heavier PBH, these profiles overlap in the small $r/r_g$ range and diverge in the large $r/r_g$ range. The horizontal dot-dashed lines denote the maximum possible density at present time of the DM particles computed from eq. (4.1).

4 Constraints from the Galactic 511 keV line

If the DM particles could annihilate, their density will decrease with time, and there will be a maximum possible density at present time which is given by [50]

$$\rho_{\text{max}} = \frac{m_\chi}{\langle \sigma v \rangle_a t_0},$$

where $t_0 \approx 4.3 \times 10^{17}$s is the age of the universe [1], and $\langle \sigma v \rangle_a$ is the thermally averaged cross-section for annihilations of DM particles. For the LDM scenario, it is obvious that $\langle \sigma v \rangle_a = \langle \sigma v \rangle \sim 5 \times 10^{-25}(m_\chi/\text{GeV})^2 \text{ cm}^3\text{s}^{-1}$, but for the XDM scenario, $\langle \sigma v \rangle$ is the thermally averaged cross-section for excitations of DM particles, thus we choose $\langle \sigma v \rangle_a \sim 3 \times 10^{-26} \text{ cm}^3\text{s}^{-1}$ which matches the observed relic density. Therefore the density profile of DM particles around PBH is

$$\rho_{\chi, PBH}(r) = \min[\rho_{\text{max}}, \rho_b(r)],$$

with critical radius $r_c$ satisfying $\rho_b(r_c/r_g) = \rho_{\text{max}}$.

For the LDM ($\sim$ few MeV) annihilating directly to electron-positron pairs, the cross-section obtained from best fit of 511 keV data is too small to give the right relic density. This will not be a problem if there are additional stronger annihilation channels into invisible particles, for example, dark gauge bosons [46] or dark neutrinos [51].
The number of positron produced in the vicinity of a PBH per unit time is

$$\Gamma_{\text{PBH}} = \Gamma_{\text{PBH}}^{(i)} + \Gamma_{\text{PBH}}^{(o)},$$

(4.3)

with

$$\Gamma_{\text{PBH}}^{(i)} = \int_{0}^{r_c} 4\pi r^2 dr \frac{\langle \sigma v \rangle}{m^2} \rho_{\text{max}}^2 = \frac{4\pi \langle \sigma v \rangle}{3m^2} \rho_{\text{max}}' c^3,$$

(4.4)

$$\Gamma_{\text{PBH}}^{(o)} = \int_{r_c}^{\infty} 4\pi r^2 dr \frac{\langle \sigma v \rangle}{m^2} \rho_{\text{o}}^2(r),$$

(4.5)

where $\Gamma_{\text{PBH}}^{(i)}$ and $\Gamma_{\text{PBH}}^{(o)}$ denote the positron production rate in the inner and outer parts (separated by $r_c$) of the halo around PBH, respectively.

Suppose the energy density of PBHs tracks the density profile of Milky Way DM halo, i.e. $\rho_{\text{PBH}}(r) = f_{\text{PBH}} \rho(r)$, the intensity distribution of 511 keV signature from the DM particles around PBHs is given by

$$I_{\text{PBH}}(l, b) = 2(1 - \frac{3}{4} f_p) \frac{1}{4\pi} \int_{f_{\text{l.o.s.}}} \Gamma_{\text{PBH}} \frac{\rho_{\text{PBH}}(r)}{M_{\text{PBH}}} ds,$$

(4.6)

and the total flux of this part is

$$\Phi_{\text{PBH}} = \int I_{\text{PBH}}(l, b) d\Omega = 2(1 - \frac{3}{4} f_p) \frac{1}{4\pi} \int_{f_{\text{l.o.s.}}} \Gamma_{\text{PBH}} \frac{\rho_{\text{PBH}}(r)}{M_{\text{PBH}}} \int d\Omega \int_{f_{\text{l.o.s.}}} \rho(r) ds,$$

(4.7)

where $\rho(r)$ is the Einasto profile given by eq. (2.11).

Since the total flux of the 511 keV photons from DM is

$$\Phi = \Phi_{\text{PBH}} + \Phi_{\chi},$$

(4.8)

where $\Phi_{\chi}$ is total flux from DM particles which are not bound to PBHs, one can get a constraint of $f_{\text{PBH}}$ from

$$\Phi_{\text{PBH}} < \Phi \sim 2.1 \times 10^{-3} \text{ ph cm}^{-2} \text{s}^{-1}.$$

(4.9)

However, comparing eq. (4.6) with eq. (2.7), we can find that the intensity distribution of 511 keV signature from DM particles around PBHs is similar to the one from decaying DM. Recalling that the decaying DM scenario is disfavored by data, which means the positrons from DM particles around PBHs must be subordinate, i.e. $\Phi_{\text{PBH}} \ll \Phi_{\chi}$, otherwise the morphology of 511 keV signature will be incompatible with the data. Therefore a more stringent constraint is given by

$$\Phi_{\text{PBH}} < \Phi_{\text{sens}} \sim 2 \times 10^{-4} \text{ ph cm}^{-2} \text{s}^{-1},$$

(4.10)

where $\Phi_{\text{sens}}$ is the sensitivity of INTEGRAL/SPI [36].

We calculate the constraints of $f_{\text{PBH}}$ from

$$f_{\text{PBH}}^{(i)} \equiv 2(1 - \frac{3}{4} f_p) \frac{1}{4\pi} \frac{\Gamma_{\text{PBH}}^{(i)}}{M_{\text{PBH}}} \int d\Omega \int_{f_{\text{l.o.s.}}} \rho(r) ds < \Phi_{\text{PBH}} < \Phi_{\text{sens}},$$

(4.11)

with different $m_\chi$ for LDM and XDM scenario, which gives

$$f_{\text{PBH}} < \Phi_{\text{sens}} \left[ \frac{2(1 - \frac{3}{4} f_p)}{4\pi} \frac{\Gamma_{\text{PBH}}^{(i)}}{M_{\text{PBH}}} \int d\Omega \int_{f_{\text{l.o.s.}}} \rho(r) ds \right]^{-1}.$$

(4.12)
For the XDM scenario, we calculate the constraint with $m_\chi = 10\text{GeV}$ and $m_\chi = 1\text{TeV}$, which are the usually used ranges of this scenario. The constraints have $M_{\text{PBH}}^{-2/5}$ slope in the relative small mass range, but roughly have $M_{\text{PBH}}^{-2}$ slope in the relative large mass range, and the turning point gives the most stringent constraint $f_{\text{PBH}} \lesssim 10^{-11}$, as shown by the green and red dot-dashed lines in figure 2. For a given $m_\chi$, $r_c/r_g$ is constant for PBHs with mass in the relatively small mass range as shown in the bottom panels of figure 1, which leads to $\Gamma_{\text{PBH}}^{(i)} \propto M_{\text{PBH}}^{3}$ and the $M_{\text{PBH}}^{-2}$ slope of the constraints.

For the LDM scenario, we calculate the constraints with $m_\chi = 10\text{MeV}$ and $m_\chi = 100\text{MeV}$. The constraints with $m_\chi \lesssim 10\text{MeV}$ are too loose and goes out of the figure’s range, this is because the light particles kinetically decouple later than the heavy particles, which leads to a smaller initial density $\rho_i$ in eq. (3.3), and therefore leads to a smaller $\rho_b$ and smaller $\Gamma_{\text{PBH}}$. Since high-energy gamma rays will be produced if the positrons are injected at even mildly relativistic energy, the positron injection energy is constrained to be $\lesssim 3\text{MeV}$, by comparing the gamma ray spectrum due to inflight annihilation with the observed diffuse Galactic gamma ray data [30], which means our obtained constraints with $m_\chi \gtrsim 3\text{MeV}$ should be abandoned. Therefore the constraints on $f_{\text{PBH}}$ in the LDM scenario are loose.

![Figure 2](image-url)

**Figure 2.** Constraints on the fraction of PBHs in DM $f_{\text{PBH}}$ from the Galactic 511 keV line with different $m_\chi$ for LDM and XDM scenario. We also show the constraints from the extragalactic gamma ray background (EG$\gamma$ [52]), galactic 511 keV line from Hawking radiation ($e^+$ [53–55]), gravitational lensing events (HSC [56], EROS [57], OGLE [58]), dynamical effects (SEGUE [59]), and cosmic microwave background (CMB [60]).

Noticing that these constraints are pretty conservative, which is not only because we use $\Phi_{\text{PBH}}^{(i)}$ instead of $\Phi_{\text{PBH}}$, but also because the morphology of 511 keV signature from observation data requires $\Phi_{\text{PBH}} \ll \Phi_\chi$. Therefore the more stringent constraint is given by $\Phi_{\text{PBH}} \ll \Phi_\chi$, which can be obtained by applying a model-fitting procedure to the observation data, and will be several orders of magnitude stronger.
Considering the velocity dependence of the thermally averaged cross-section $\langle \sigma v \rangle$, we estimate the particle velocity distribution function of the Milky Way DM halo and the spike halo around PBHs, by using Eddington’s formula \cite{61,62}. The results show the average particle velocity of the spike halo around PBHs is larger than that of the Milky Way DM halo for particles with $m_\chi \gtrsim 100\text{GeV}$, which could lead to more stringent constraints, and more details should be studied in further.

In this work, we get constraints from the data of INTEGRAL/SPI. There is study searching for the 511 keV line from galactic compact objects with the IBIS gamma ray telescope \cite{63}, which can also be used to constrain this mixed DM model. Due to the sensitivity of IBIS, current constraints from compact objects is looser than the one from INTEGRAL/SPI, but it has chance to give more stringent constraints in the future with the improvement of sensitivity.

5 Conclusions

The 511 keV line was first detected in 1970’s but its origin is still unknown. The positrons produced from the direct annihilation of LDM or the decay of the excited state into the ground state for XDM are the possible origins. Since there is no evidence that DM is composed of only one component, we consider a mixed DM model of particles and PBHs. With the existence of PBHs, the DM particles may be gravitationally bound to the PBHs and form halo around PBHs with density spikes. These density spikes can enhance the production rate of positrons from DM particles, thus they can be constrained by the observations of 511 keV line.

In this work, we compute the profile of the density spikes, and get the constraints on the fraction of PBHs in DM. For XDM with mass in the range of $10\text{GeV} \sim 1\text{TeV}$, the constraints have $M_{\text{PBH}}^{-2}$ slope in the relative small mass range, and roughly have $M_{\text{PBH}}^{2/5}$ slope in the relative large mass range. The most stringent constraint $f_{\text{PBH}} \lesssim 10^{-11}$ appears at the turning point which depends on the mass of XDM particle. For LDM with mass in the range of $1\text{MeV} \sim 3\text{MeV}$, the constraints are loose. Recalling these constraints are very conservative, we expect the more stringent constraints will be obtained with more detailed studies and the improving sensitivity of experiments.

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