INTEGRAL constraints on primordial black holes and particle dark matter

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The International Gamma-Ray Astrophysics Laboratory (INTEGRAL) satellite has yielded unprecedented measurements of the soft gamma-ray spectrum of our Galaxy. Here we use those measurements to set constraints on dark matter (DM) that decays or annihilates into photons with energies $E \approx 0.02 - 2$ MeV. First, we revisit the constraints on decaying and annihilating particle DM. For DM decaying to two photons, we find that previous limits were overstated by roughly an order of magnitude. Our new, conservative analysis finds that the DM lifetime must satisfy $\tau \gtrsim 10^{27} s \times (m_\chi/\text{GeV})^{-1}$ for DM masses $m_\chi = 0.054 - 3.6$ MeV. For MeV-scale DM that annihilates into photons INTEGRAL sets the strongest constraints to date, whereas for annihilations to electron-positron pairs, INTEGRAL only improves upon current limits when assuming $p$-waveannihilation. Second, we target ultralight primordial black holes (PBHs) through their Hawking radiation. This makes them appear as decaying DM with a photon spectrum peaking at $E \approx 5/(8\pi GM_{PBH})$, for a PBH of mass $M_{PBH}$. We use the INTEGRAL data to demonstrate that PBHs with masses less than $2 \times 10^{17}$ g cannot comprise all of the DM, setting the tightest bound to date on ultralight PBHs.

I. INTRODUCTION

Dark matter (DM) is omnipresent in the universe, from sub-Galactic scales to galaxy clusters. Despite its abundance, the nature of DM remains mysterious, as it has evaded all non-gravitational direct and indirect probes thus far.1-3. Given the enormous range in masses and interaction strengths of possible DM candidates, it is imperative to find new ways to probe different parts of their parameter space.

A powerful window into the nature of particle DM comes from its possible decay or annihilation into Standard Model (SM) particles. In particular, gamma-rays produced in DM interactions can be detected in our telescopes. Here we will use the data from the SPI spectrometer on-board the International Gamma-ray Astrophysics Laboratory (INTEGRAL) satellite, covering the $E \sim 0.02 - 2$ MeV energy band. By requiring that the DM emission does not exceed the Galactic diffuse flux measured by INTEGRAL,4-5, we will set conservative bounds on various DM interactions, including revisiting some the constraints from Ref. 6. In that work, limits were obtained using the Galactic-center gamma-ray spectrum from INTEGRAL 4. That spectrum, however, only corresponds to the emission correlated with a fiducial template – a combination of dust and CO maps – and thus may not include photons from DM interactions, as the latter have a different spatial distribution. Here, instead, we use the full emission profile from Ref. 5, which does not assume any spatial morphology. By taking conservative assumptions, we find limits on the DM lifetime that are weaker by a factor of $\sim 3 - 10$ than found in Ref. 6. For DM annihilating to electron-positron pairs our limits are broadly similar to Ref. 6, and we derive new limits on DM annihilating to photons.

We also search for gamma-ray emission from ultralight primordial black holes (PBHs). PBHs, formed from SM plasma that collapsed due to its own gravity in the very early universe, are a possible solution to the DM puzzle 7-13. The fraction $f_{PBH}$ of DM in the form of PBHs is constrained to be below unity for PBH masses $M_{PBH} \gtrsim 10^{23}$ g ($\approx 5 \times 10^{-11} M_\odot$) via various observations, such as gravitational lensing 14-24, stellar dynamics 25-31, gravitational waves 32-40, and the cosmic microwave background (CMB) 41-44. The situation is different for lower-mass PBHs, as their gravitational signatures are not strong enough to cause a measurable effect in existing data. Instead, a promising avenue consists of searching for the radiation from ultralight PBHs as they Hawking evaporate 45-49. Previous works have searched for Hawking-evaporating PBHs through electron-positron pairs 50-57, extra-Galactic gamma rays 58-60, and the CMB 61-63. These studies have ruled out PBHs as the entirety of DM for $M_{PBH} \lesssim 10^{17}$ g. Here we search for gamma rays from PBHs in the DM halo around the Milky-Way (MW), which would appear as a modified black-body spectrum in the INTEGRAL data. We are able to rule out PBHs as the sole component of DM for $M_{PBH} \lesssim 2 \times 10^{17}$ g, setting the strongest bound to date on the mass of ultralight PBH DM.

This paper is structured as follows. We begin in Sec. II by reviewing the gamma-ray emission from different DM models. We introduce the INTEGRAL data in Sec. III and use it in Sec. IV to find our constraints. We conclude in Sec. V.
II. EMISSION FROM DIFFERENT DM MODELS

Assuming a DM candidate of mass $M_{DM}$, the differential gamma-ray flux produced by its decay or annihilation (denoted by $\alpha = 1$ and 2, respectively) is

$$\frac{d\Phi}{dE} = \frac{1}{2\alpha^{-1}4\pi} \left( \frac{\rho_\odot}{M_{DM}} \right) J_{D/A} \frac{dN}{\Delta\Omega} \frac{dEdt}{}$$  \hspace{1cm} (1)

where $r_\odot = 8.1$ kpc and $\rho_\odot = 0.016 M_\odot$ pc$^{-3}$ ($= 0.61$ GeV cm$^{-3}$) are the Galacto-centric distance of the Sun and the local DM density, respectively [65] (where we note that this last quantity can vary by nearly a factor of two given current analyses, and our results can be simply re-scaled by that factor). This formula can be neatly divided into a component that depends on the spatial distribution of DM, the $J_{D/A}$ factor ($D$ for decay and $A$ for annihilation), and one that depends on the photon spectrum, $dN/(dE dt)$. The former will not vary between models, so let us begin by describing it.

We will assume that the DM in the Milky-Way (MW) halo follows a Navarro-Frenk-White (NFW) profile [65], as both MeV-scale particle DM and ultralight PBHs behave as cold DM. We take a scale radius $r_h = 17$ kpc for the MW halo [66]. The differential $J_{D/A}$ factor, integrating along the line of sight, is

$$\frac{dJ_{D/A}}{d\Omega} (\hat{n}) = \int_0^\infty ds \left( \frac{\rho(s, \hat{n})}{\rho_\odot} \right)^\alpha.$$  \hspace{1cm} (2)

The details of the DM profile are not critical for evaporating PBHs or decaying DM, whereas they have a bigger impact for annihilating DM, although our results can be rescaled to other DM profiles.

The $J_{D/A}$ factor is calculated by integrating Eq. (2) over the patch of the sky considered, with an angular extension $\Delta\Omega$. The observed flux over an energy band spanning the range $(E_1, E_2)$ is

$$\Phi = \int_{E_1}^{E_2} \frac{d\Phi}{dE} dE,$$  \hspace{1cm} (3)

with units of cm$^{-2}$s$^{-1}$sr$^{-1}$. This is the quantity we will compare with INTEGRAL observations of our Galaxy.

A. Particle Dark Matter

We now turn to describe the emission spectrum in each of our models, beginning with the simpler cases of decaying and annihilating particle DM with mass $m_\chi$.

We first study DM decaying into two photons of energy $E$, where the emission spectrum from a DM particle with lifetime $\tau$ is

$$\frac{dN}{dt dE} = \frac{2}{\tau} \delta_D \left( E - \frac{m_\chi}{2} \right).$$  \hspace{1cm} (4)

Another possible channel would consist of DM decaying to electron-positron pairs plus final-state radiation (FSR). In this case, however, the CMB can set stronger constraints than Galactic observations [67], so we do not consider it here.

For annihilating DM, we will study the case of DM annihilating to an electron-positron pair plus FSR, for which [6]

$$\frac{dN}{dt dE} = \left( \frac{\rho_\odot}{m_\chi} \right) \frac{2\alpha_{EM} \langle \sigma v \rangle}{\pi E} \left( 1 - \nu^2 \right)^{3/2} \left\{ \delta(1 - \nu^2) + \left[ 1 - \lambda + \frac{\lambda^2}{2} - \nu^2 \left( \frac{3}{2} - \lambda \right) + \frac{\nu^4}{2} \right] \log \left( \frac{\gamma_+}{\gamma_-} \right) \right\},$$  \hspace{1cm} (5)

where $\nu = m_\gamma/m_\chi$, $\lambda = E/m_\chi$, $\delta^2 = (1 - \lambda)(1 - \lambda -
\[\nu^2\text{, and } \gamma_\pm = 1 - \lambda \pm \delta.\] We will also constrain DM annihilation to two photons,

\[\frac{dN}{dtdE} = 2 \langle \sigma v \rangle_{\gamma\gamma} \left( \frac{\rho_\chi}{m_\chi} \right) \delta_D (E - m_\chi), \tag{6}\]

where \(\langle \sigma v \rangle\) denote the thermally averaged annihilation cross-sections. We show, in Fig. 1, the Galactic flux profile in the 0.2 – 0.6 MeV band, for DM annihilating to two photons, with \(m_\chi = 0.5\) MeV and \(\langle \sigma v \rangle_{\gamma\gamma} = 2 \times 10^{-31} \text{ cm}^3 \text{ s}^{-1}\).

### B. Ultralight PBHs

Black holes (BHs), with mass \(M_{\text{BH}}\), evaporate over time, emitting particles roughly as a black-body with temperature \(T_{\text{BH}}\).

\[T_{\text{BH}} = \frac{1}{8\pi GM_{\text{BH}}}. \tag{7}\]

For reference, \(M_{\text{BH}} = 10^{17}\) g corresponds to a BH temperature \(T_{\text{BH}} \approx 0.1\) MeV, and thus the Hawking emission from these BHs will predominantly consist of neutrinos and photons. We will focus on the latter, given the well-measured diffuse gamma-ray emission from the MW by INTEGRAL.

The spectrum of particles emitted from an evaporating BH does not exactly follow a black-body distribution. In particular, the photon spectrum is given by \(\tag{6}\)

\[\frac{dN}{dtdE} = \frac{1}{2\pi} \frac{\Gamma(E, M_{\text{BH}})}{e^{E/T_{\text{BH}}} + 1} , \tag{8}\]

where \(\Gamma(E, M_{\text{BH}}) = E^2 \sigma(E, M_{\text{BH}})/\pi\) is the gray-body factor, which accounts for the departure from pure black-body emission, and \(\sigma(E, M_{\text{BH}})\) is the absorption cross-section for spin-1 particles (such as photons). At high energies, this cross-section approaches the geometric limit, \(\sigma(E \gg T_{\text{BH}}, M_{\text{BH}}) \approx 27\pi G^2 M_{\text{BH}}^2\). Nonetheless, for \(E \lesssim T_{\text{BH}}\) this cross-section is significantly lower, reducing the overall amount of BH emission. For spin-1 particles, this increases the energy peak to \(E \approx 5T_{\text{BH}}\). In this work we will focus on Schwarzschild BHs (as the emission is slightly different for spinning or charged BHs \([70, 71]\)), and we use the public code BlackHawk \([72]\) to compute the Hawking emission.

We show the flux for PBH DM with \(M_{\text{PBH}} = 2 \times 10^{17}\) g in the 0.2 – 0.6 MeV band—where it peaks—in Fig. 1. The Galactic emission from annihilating DM is more concentrated towards the Galactic center, as opposed to that from PBHs (or generic decaying DM).

### III. INTEGRAL DATA

In order to constrain the emission from different DM models, we will use data from the SPI instrument on the INTEGRAL satellite, which roughly covers the 0.02 – 8 MeV energy band \([73]\). In particular, we will employ the measurements of diffuse Galactic emission from Ref. \([5]\), where point sources are simultaneously subtracted. The coded-mask system of SPI is, in principle, only sensitive to differences in flux, and thus cannot observe the isotropic extra-Galactic background \([5]\). Nonetheless, some unknown amount of background radiation can appear as part of the INTEGRAL measurements, and this uncertainty dominates the error budget (and it is expected to be behind the \(\sim 30\%\) increase in flux with respect to earlier INTEGRAL data \([4, 74]\)).

In Refs. \([4, 5]\) the INTEGRAL data is reduced in two different ways. The first way finds the spectrum of the Galactic inner radian, with a relatively fine energy resolution. While this dataset might be optimal for constraining DM, especially for decays or annihilations to a photon line, the Galactic emission in this analysis is assumed to follow the morphology of a pre-determined map \([4, 5]\), given by a combination of dust, CO, and inverse-Compton emission, and not that due to DM. Therefore, a DM signal may be hidden behind the projection onto these maps, as they are not guaranteed to account for every photon.

The second is the profile of diffuse emission as a function of Galactic angle. This is the dataset that we will use, as it does not assume any emission morphology, and thus can be used to set conservative bounds. On the one hand, the energy bands in this analysis are wider, which makes it harder to detect lines originating from DM. On the other hand, the data at angles beyond the Galactic inner radian provides more constraining power, as astrophysical backgrounds can be more concentrated than the signal for decaying DM.

The INTEGRAL measurements are divided into five energy bands, with cuts at \(E = 0.027, 0.049, 0.1, 0.2, 0.6\) and 1.8 MeV. We show the data in the fourth band (\(E = 0.2 – 0.6\) MeV) in Fig. 1, corresponding to the peak of emission for PBHs with \(M_{\text{PBH}} = 2 \times 10^{17}\) g, and for DM annihilating to photons with \(m_\chi = 0.5\) MeV. The latitude profiles are integrated over longitudes \(|l| < 23.1\) deg., whereas the longitude profiles are integrated over \(|b| < 6.5\) deg. (except the highest-energy bin, which has \(|l| < 60\) deg. and \(|b| < 8.2\) deg.). By comparing with the emission from PBH DM, we see in Fig. 1 that the constraints will be driven by intermediate latitudes, as opposed to the case of annihilating DM, which peaks closer to the Galactic center. Additionally, note that the data-point at \(b = 20 – 30\) deg. is below the expected emission from PBHs, given our chosen mass, so PBHs with this mass will be excluded. Likewise, the emission from annihilating DM with \(\langle \sigma v \rangle_{\gamma\gamma} = 2 \times 10^{-31}\) cm\(^3\) s\(^{-1}\) is above the INTEGRAL data point at \(b = 6 – 9\) deg.

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1 https://blackhawk.hepforge.org/
IV. RESULTS

We will now present conservative constraints on the DM models by requiring that their emission is below the maximum allowed by the INTEGRAL data. We note that the INTEGRAL error budget is not Poissonian, but is dominated by the fitting procedure, which simultaneously removes point sources and an isotropic extra-Galactic background. Likewise, errors between different energy bins are likely correlated. Therefore, we will take the limits stated in Ref. [6] to be 68% C.L. intervals, since multiplying the error-bars by a factor of two, as was done in Ref. [6], does not guarantee obtaining the flux at 95% C.L. We will obtain our limits by requiring that the emission from each DM candidate is smaller than the 68% C.L. upper limit from INTEGRAL.

![Graph showing limits on DM annihilation]

**FIG. 2**: Constraints on the lifetime of decaying DM, \( \tau \), assuming decay to two photons, as a function of its mass \( m_\chi \). The orange and blue shaded regions are constrained by X-ray and gamma-ray data from COMPTEL [6], and NuSTAR [75]. Our conservative re-analysis of INTEGRAL data yields the 68% C.L. constraints shaded in black, to be compared with the previous result from Ref. [6] as the dashed gray line. The kinks in our limit (as well as those presented in Fig. 4) reflect the energy binning in the INTEGRAL data.

A. Particle Dark Matter

We begin by revisiting the INTEGRAL constraints on decaying and annihilating particle DM from Ref. [6]. We show our constraint for decaying DM on Fig. 2 along with the previous result from Ref. [6]. Our robust analysis weakens the INTEGRAL constraints by nearly an order of magnitude. That is partially because not every photon is included in the data used in Ref. [6], as well as due to the loss of energy resolution (which would significantly help in this case). Moreover, we do not include extra-Galactic photons from decaying DM, as those are not accounted for in the INTEGRAL/SPI data set that we use, which narrows the mass range that can be constrained. We can probe DM masses \( m_\chi \in [0.054 - 3.6] \) MeV, over which our constraint, in Fig. 2, can be approximated by \( \tau \gtrsim 10^{27} s (m_\chi / \text{MeV})^{-1} \). Even when accounting for the weakening of the INTEGRAL limits, these are still three orders of magnitude stronger than those obtained from the CMB [67].

![Graph showing limits on DM annihilation]

**FIG. 3**: Limits for annihilation of DM to electron-positron pairs plus FSR from INTEGRAL (68% C.L., in black), compared to the limits from CMB s- (purple solid) and p-wave (blue and green, dashed) [76]. The CMB results are re-scaled by a factor of \((v_\chi/v_0)^2\) for p-wave annihilation, assuming two values of kinetic decoupling \( x_{kd} = T_{kd}/m_\chi \) for the DM. We also show the value of the thermal-relic (for s-wave annihilation) cross-section that would produce the correct DM abundance as a brown dotted line, and the limits from positron flux with Voyager 1 in red [77] (assuming their B diffusion model). We show the previous result from Ref. [6] in long-dashed grey, which is in good agreement to our approach, and note that there are additional constraints from COMPTEL gamma-ray data, which improve upon INTEGRAL at high masses.

We now study the case of annihilating dark matter. Following Ref. [6], we find constraints on DM annihilating to electron-positron pairs, plus FSR, with the spectrum given by Eq. (6). Our Galactic limits from INTEGRAL are shown in Fig. 3 along with the cross-section required to obtain the correct DM abundance as a thermal relic [78]. Our result is comparable to that of Ref. [6], as the loss of energy resolution is not very significant for the broad spectrum of this annihilation channel. Only for DM masses above \( m_\chi \gtrsim 30 \) MeV is the thermal-relic line below our INTEGRAL constraints.

In order to compare with CMB limits, we multiply the thermally averaged annihilation cross-section by a factor of \((v_\chi/v_0)^2\), where \( v_0 = 220 \) km s\(^{-1}\) is the DM velocity in the MW halo and \( \beta = \{0, 2\} \) for s- and p-wave annihilation, respectively. For the INTEGRAL result we simply take \( v_\chi = v_0 \) (although p-wave J factors can change by
$\sim 10\%$ \cite{79}, and for the CMB we take \cite{6}

$$v_\chi = \sqrt{\frac{3T_\chi}{m_\chi}} \approx 15.4 \text{ km s}^{-1} \left(\frac{m_\chi}{\text{MeV}}\right)^{-1} \left(\frac{x_{kd}}{10^{-4}}\right)^{-1/2}. \quad (9)$$

where $x_{kd} = T_{kd}/m_\chi$. We assume that the DM cools adiabatically after it kinetically decouples from the SM, which occurs at a temperature $T_{kd}$, and we have used Planck values for the cosmological parameters \cite{80}. Then, we can rescale the s-wave CMB limits, from Ref. \cite{79}, to p-wave for different values of $x_{kd}$, which we show in Fig. 3. For s-wave the CMB limits are stronger than INTEGRAL at all masses, and well below the thermal-relic line. For p-wave, on the other hand, INTEGRAL provides a robust result, which improves over the CMB limits for values of $x_{kd} \lesssim 10^{-4}$. We note, in passing, that the CMB constraints can be tightened for DM that forms bound states and self-annihilates \cite{81}.

Finally, we show the limits for DM annihilating to two photons in Fig. 4. In this case the INTEGRAL data provides stronger constraints than the CMB \cite{67} and NuSTAR observations \cite{75}. All these constraints are significantly smaller than the thermal-relic cross-section, and thus do not allow for a thermal relic within this mass range annihilating exclusively to two photons.

![Constraints on the thermally averaged cross-section of DM annihilating to two photons, $\langle \sigma v \rangle_{\gamma\gamma}$, as a function of its mass, $m_\chi$, for our INTEGRAL reanalysis (68% C.L., in black), compared to the CMB s-wave limits \cite{67} (in purple), as well as the current best limits from NuSTAR \cite{75} (in blue).](image)

**FIG. 4** : Constraints on the thermally averaged cross-section of DM annihilating to two photons, $\langle \sigma v \rangle_{\gamma\gamma}$, as a function of its mass, $m_\chi$, for our INTEGRAL reanalysis (68% C.L., in black), compared to the CMB s-wave limits \cite{67} (in purple), as well as the current best limits from NuSTAR \cite{75} (in blue).

### V. CONCLUSIONS

We have presented constraints on decaying, annihilating, and PBH DM using INTEGRAL measurements of Galactic gamma-ray emission. We followed a conservative approach, where we use the total measured flux at different Galactic coordinates to set constraints, without assuming any form for the astrophysical contribution.

For decaying DM, we have revisited the constraints from Ref. \cite{6}, which we find to be overstated by a factor of $\sim 3 - 10$. Our updated constraints, in Fig. 3, are still the strongest for decaying DM masses $m_\chi \in [0.054 - 3.6]$ MeV. We find similar results to Ref. \cite{6} for DM annihilating to two photons, as well as the current best limits from NuSTAR \cite{75} (in blue).

We show our limits in Fig. 3 where we see that INTEGRAL can rule out PBHs composing the entirety of the DM for masses up to $M_{\text{PBH}} = 2 \times 10^{17}$ g, providing the strongest constraint to date. Our result improves upon that obtained through the flux of electron-positron pairs in the Galaxy, which would then annihilate and emit a line at 511 keV \cite{55,57}. Additionally, our constraint is tighter than CMB limits \cite{61}, as well as those from Voyager-1 measurements \cite{50}. We also obtain stronger constraints using the Galactic gamma-ray emission from PBHs, as opposed to the extra-Galactic component \cite{59}. Doubling the size of the INTEGRAL error-bars (as an approximation to 95% C.L. constraints), we find that $M_{\text{PBH}} = 1.6 \times 10^{17}$ g is the minimum mass allowed, only 20% weaker than our 68% C.L. result. We note that, in principle, one could model the astrophysical emission from the Galaxy and subtract it, in order to obtain stronger limits, albeit these would be less robust.

As an example, we have found limits using the Galactic-center INTEGRAL spectrum as done for particle DM in Ref. \cite{6}. We use the data from Ref. \cite{4}, which has fine energy resolution (although we remind the reader that this data does not capture every photon, and thus cannot be used to definitively rule out PBHs). These limits extend further than our robust result, showing that a joint analysis of decaying/annihilating DM, plus other astrophysical sources, would be optimal for obtaining constraints.

Our results set the strongest lower bound on the PBH mass that is allowed to constitute the entirety of the DM, at $M_{\text{PBH}} = 2 \times 10^{17}$ g. Recent work has cast doubt on PBH constraints due to femtolensing \cite{82}, and capture onto stars \cite{83}. Thus, there is a large gap between our result and the next constraint, at $M_{\text{PBH}} = 10^{23}$ g, from Subaru microlensing data \cite{19,24}, where PBHs are currently allowed to make up all the DM. Many ideas have been proposed in order to constrain PBHs in this and higher-mass windows \cite{82,92}. Additionally, we note that our constraints would be tighter for highly spinning PBHs. We find, for instance, that for nearly extremal PBHs (with dimensionless spin parameter $a^* = 0.9999$) INTEGRAL rules out masses up to $M_{\text{PBH}} = 10^{18}$ g.
FIG. 5 : Different constraints on the fraction $f_{\text{PBH}}$ of DM that is composed of PBHs. The limit from detection of positrons with Voyager 1 is shown in red [50] (propagation model B without background), from the CMB in purple [61] (varying all parameters), from extra-Galactic gamma-ray emission in green [50] (assuming no AGN background), and from the flux of the 511 keV line in the MW in blue [50] (assuming an isothermal DM profile with 1.5 kpc positron annihilation region). Our 68% C.L. constraint, from the Galactic gamma-ray flux measured by INTEGRAL (assuming an isothermal DM profile with 1.5 kpc positron annihilation region). Our 68% C.L. constraint, from the CMB in purple [61] (varying all parameters), from extra-Galactic gamma-ray emission in green [50] (assuming no AGN background), and from the flux of the 511 keV line in the MW in blue [50] (assuming an isothermal DM profile with 1.5 kpc positron annihilation region). Our 68% C.L. constraint, from the Galactic gamma-ray flux measured by INTEGRAL (assuming $\rho_0 = 0.6$ GeV cm$^{-3}$), is shown as the black shaded region. We additionally show, in dotted gray, the result that would be obtained with an optimistic analysis of the INTEGRAL data. For reference, there are currently no robust constraints to the right of the plot until $M_{\text{PBH}} = 10^{22}$ gr [19, 24, 82, 83].

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