In this thorough study, we focus on the indirect detection of dark matter (DM) through the examination of unexplained galactic and extragalactic γ-ray signatures for a low-mass DM model. For this purpose, we consider a simple Higgs-portal DM model, namely, the inert Higgs doublet model (IHDM) where the SM is extended with an additional complex SU(2)_L doublet scalar. The stability of the DM candidate in this model, i.e., the lightest neutral scalar component of the extra doublet, is ensured by imposing discrete Z_2 symmetry. The reduced-χ^2 analysis using theoretical, experimental, and observational constraints suggests that the best-fit value of DM mass in this model is ~63.5 GeV. We analyze the anomalous GeV γ-ray excess from the Galactic Center in light of the best-fit IHDM parameters. We further check the consistency of the best-fit IHDM parameters with the Fermi Large Area Telescope (Fermi-LAT) obtained limits on photon flux for 18 Milky Way dwarf spheroidal satellite galaxies (dSphs) known to be mostly dominated by DM. Also, since the γ-ray signal from DM annihilation is assumed to be embedded within the extragalactic γ-ray background (EGB), the theoretical calculations of photon flux for the best-fit parameter point in the IHDM framework are compared with the Fermi-LAT results for diffuse and isotropic EGB for different extragalactic and astrophysical background parametrizations. We show that the low-mass DM in the IHDM framework can satisfactorily account for all of the observed continuum γ-ray fluxes originating from galactic and extragalactic sources. The extensive analysis performed in this work is valid for any Higgs-portal model with DM mass comparable to that considered in this work.

Key words: dark matter – galaxies: dwarf – galaxies: halos – Galaxy: center – gamma rays: diffuse background – gamma rays: galaxies

1. INTRODUCTION

The presence of dark matter (DM) in the universe has been established thanks to various astrophysical and cosmological evidence (Begeman et al. 1991; Massey et al. 2007; Komatsu et al. 2011; Ade et al. 2014). Recent PLANCK (Ade et al. 2014) data suggest that ~26.8% of the total mass-energy content of the universe consists of cold (or non-relativistic) DM whose particle nature is yet to be resolved. The weakly interacting massive particle, commonly known as WIMP, appears to be the most promising particle candidate of cold DM in the universe.

There are various ongoing experiments for the detection of DM using both direct and indirect mechanisms. In the case of direct detection, the DM may scatter off the nucleus of a detecting material; in such direct detection experiments, researchers attempt to measure this recoil energy of the nucleus using theoretical, experimental, and observational constraints suggests that the best-fit value of DM mass in this model is ~63.5 GeV. We analyze the anomalous GeV γ-ray excess from the Galactic Center in light of the best-fit IHDM parameters. We further check the consistency of the best-fit IHDM parameters with the Fermi Large Area Telescope (Fermi-LAT) obtained limits on photon flux for 18 Milky Way dwarf spheroidal satellite galaxies (dSphs) known to be mostly dominated by DM. Also, since the γ-ray signal from DM annihilation is assumed to be embedded within the extragalactic γ-ray background (EGB), the theoretical calculations of photon flux for the best-fit parameter point in the IHDM framework are compared with the Fermi-LAT results for diffuse and isotropic EGB for different extragalactic and astrophysical background parametrizations. We show that the low-mass DM in the IHDM framework can satisfactorily account for all of the observed continuum γ-ray fluxes originating from galactic and extragalactic sources. The extensive analysis performed in this work is valid for any Higgs-portal model with DM mass comparable to that considered in this work.

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1. INTRODUCTION

The presence of dark matter (DM) in the universe has been established thanks to various astrophysical and cosmological evidence (Begeman et al. 1991; Massey et al. 2007; Komatsu et al. 2011; Ade et al. 2014). Recent PLANCK (Ade et al. 2014) data suggest that ~26.8% of the total mass-energy content of the universe consists of cold (or non-relativistic) DM whose particle nature is yet to be resolved. The weakly interacting massive particle, commonly known as WIMP, appears to be the most promising particle candidate of cold DM in the universe.

There are various ongoing experiments for the detection of DM using both direct and indirect mechanisms. In the case of direct detection, the DM may scatter off the nucleus of a detecting material; in such direct detection experiments, researchers attempt to measure this recoil energy of the nucleus as the signature of DM detection. There are various ongoing direct detection experiments around the world, such as CDMS II (Ahmed et al. 2010; Agnese et al. 2013a, 2013b), CRESST II (Angloher et al. 2012), CoGeNT (Aalseth et al. 2011), XENON 100 (Aprile et al. 2011, 2012), LUX (Akerib et al. 2014), etc., that use different detection materials, e.g., Ge, Si, Xe, etc.

Due to its pervasive nature, the DM in the universe may be trapped by very massive astrophysical objects such as the Galactic Center (GC), the solar core, etc., and may undergo multiple scattering with the dense matter present at those sites, in the process losing velocity of escape and eventually becoming trapped inside these bodies. When accumulating in large numbers, these trapped DM particles may undergo pair annihilation to produce pairs of standard model (SM) particles such as qq or ℓℓ as primary or secondary products. Gammas can be obtained as secondary products from the pair annihilation of primary pairs of SM fermions (such as hadronization of bb through π^0). Indirect DM search experiments look for these γ-rays or other SM particles from DM pair annihilation.

Satellite-borne detectors such as the Fermi Large Area Telescope (Fermi-LAT) detect γ-rays from the GC and inner galactic regions. Any anomalous GeV γ-ray excess from Fermi-LAT observations may indicate DM pair annihilation at the GC region if other known astrophysical phenomena fail to explain such excess. This excess γ-ray signal can be explained using DM models where a DM particle annihilates mainly into qq channels with a desired value for the thermally averaged annihilation cross-section similar to the canonical cross-section of typical thermal production of DM. This bump-like feature indicating γ-ray excess has also been reported by the Fermi-LAT Collaboration (Murgia 2014) for γ-rays from the GC region. An early analysis of Fermi-LAT data reveals that the γ-rays from the GC region exhibit excesses (bumps) in the energy range ~0.3–10 GeV (Hooper & Linden 2011; Hooper 2012; Hooper & Slatyer 2013; Huang et al. 2013). A recent more involved, modified analysis (Daylan et al. 2014) including more current data restricts the range of excess γ to be in the energy region of ~1–3 GeV.

Early analyses by Dan Hooper et al. (Hooper & Linden 2011) suggested that the γ-ray excesses mentioned above and the morphological features of these excesses can be satisfactorily explained by considering DM particles in the mass range of ~30–60 GeV annihilating only through the bb channel. From the latter analysis (Hooper & Slatyer 2013; Huang et al. 2013), to explain the above-mentioned γ-ray excess, the authors also gave the best-fit value of the DM mass as 61.8^{+6.9}_{-4.8} GeV.
annihilating only into the $b\bar{b}$ pair with a thermally averaged annihilation cross-section of $(\sigma v) = 3.30^{+0.69}_{-0.45} \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$. Another analysis (Hooper 2012) which considered the DM to have primarily annihilated only to $\tau\tau$, yields a DM mass in the range $\sim 7$–10 GeV with a thermally averaged annihilation cross-section $(\sigma v) = 5.6 \times 10^{-27} \text{ cm}^3 \text{ s}^{-1}$. Very recent analyses (Daylan et al. 2014; Lacroix et al. 2014), however, indicate that a DM particle with mass $\sim 31$–40 GeV and annihilating entirely into the $b\bar{b}$ channel with a thermally averaged annihilation cross-section of $(\sigma v) = (1.4$–$2.0) \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$ (normalized to a local DM density of 0.3 GeV cm$^{-3}$) would agree much better with the nature of the low-energy $\gamma$-ray spectrum (with an excess in the energy range $\sim 1$–3 GeV). These new analyses also disfavor the possibility of the previous proposition of $\sim 10$ GeV DM annihilating solely into $\tau\tau$ channels.\(^1\) There have been several attempts (Boucenna & Profumo 2011; Buckley et al. 2011a, 2011b; 2013; Logan 2011; Marshall & Primulando 2011; Zhu 2011; Hooper et al. 2012; Anchordoqui & Vleeg 2013; Modak et al. 2015; Abdallah et al. 2014; Agashe et al. 2014; Agrawal et al. 2015, 2014a; Alves et al. 2014; Balz & Li 2014; Banik & Majumdar 2015; Basak & Mondal 2015; Berlin et al. 2014a, 2014b; Boehm et al. 2014a, 2014b; Cao et al. 2015; Cerdeo et al. 2014; Chang & Ng 2014; Cheung et al. 2014; Clune et al. 2014; Detmold et al. 2014; FIELDS et al. 2014; Ghiorbani & Ghirbani 2014; Guo et al. 2015; Heikinheimo & Speithmann 2014; Huang et al. 2014; Ipek et al. 2014; Izaguirre et al. 2014; Ko et al. 2014; Martin et al. 2014; Okada & Seto 2014a, 2014b; Wang & Han 2014; Yu 2014; Arina et al. 2015; Bell et al. 2015; Borah & Dasgupta 2015; Cahill-Rowley et al. 2015; Cerdeno et al. 2015; Freytsis et al. 2015; Ghosh et al. 2015; Ko & Tang 2015) to propose DM models and study their various aspects. In more recent analyses (Agrawal et al. 2015; Calore et al. 2015a, 2015b; Murgia 2014), the GC excess has been reanalyzed considering several distinct galactic diffuse emission models; the allowed DM mass range for the generation of such GC $\gamma$-ray excess is severely relaxed. The preferred mass range for DM annihilating solely to the $b\bar{b}$ channel is derived to be 35–165 GeV (Agrawal et al. 2015). In Calore et al. (2015b), the Fermi-LAT GC GeV excess is interpreted with a DM mass allowed up to 74 GeV with the $b\bar{b}$ annihilation channel. Alternatives to annihilating DM, such as theories in which unresolved millisecond pulsars are the main origin of the observed $\gamma$-ray excess, have been discarded because the observed anomalous $\gamma$-ray emission extends far beyond the central stellar cluster.

In addition to the GC, dwarf spheroidal galaxies (dSphs) also are very rich in DM. These are faint companions of the Milky Way. The mass-to-luminosity ratio $(M/L)$ is found to be much higher than $\left[\frac{M}{L}\right]_\odot$, where $\left[\frac{M}{L}\right]_\odot$ denotes the mass-to-luminosity ratio of the Sun, indicating that these companions are rich in DM. This DM can annihilate and emit $\gamma$-rays. Using the wealth of Fermi-LAT $\gamma$-ray data, highly detailed and thorough analyses (Abdo et al. 2010a; Ackermann et al. 2011; Geringer-Sameth & Kouhiapann 2011, 2012; MAZZIOTTA et al. 2012; ACKERMANN et al. 2014) have been performed on several dSphs to constrain DM annihilation.

Apart from the Galactic cases, the observed $\gamma$-ray signal detected by Fermi-LAT from extragalactic sources may also contain the signature of DM annihilation at extragalactic sites (Stecker 1978; Gao et al. 1991; Bergstrom et al. 2001; Ullio et al. 2002; Taylor & Silk 2003; Ng et al. 2014). There may also be embedded in the signal $\gamma$-rays from possible effects other than DM annihilation. To this end, there have been attempts (Bringmann et al. 2014; Cholis et al. 2014; Sefussati et al. 2014; Tavakoli et al. 2014; Ackermann et al. 2015a; Ajello et al. 2015; Di Mauro 2015; Di Mauro & Donato 2015) to extract DM signal from the extragalactic $\gamma$-ray background (EGB) and to provide limits to the DM annihilation cross-sections for different DM masses. This requires proper modeling of the extragalactic parameters as well as proper knowledge about the other astrophysical backgrounds that contribute dominantly to the EGB signal. Based on the analyses of the new data collected by the Fermi-LAT mission, a much more detailed and clear picture of the EGB has been put forward. Information regarding astrophysical sources such as BL Lacs, millisecond pulsars, star forming galaxies, radio galaxies, etc. which may contribute to the EGB is revealed based on various observations at radio and $\gamma$ wavelengths. As Fermi-LAT collects more data, we will be able to precisely measure the EGB spectra and place stringent constraints on the DM annihilation cross-section. These constraints are contemporary with those obtained from dSphs and GC regions and may, in principle, place limits on various DM models in the future.

A number of particle physics models for DM candidates have been proposed and studied in the literature. These models include various extensions of SM (Randall & Sundrum 1999; Cheng et al. 2002; Servant & Tait 2003; Ma 2006; Duffey & van Bibber 2009), whose DM phenomenologies (Modak & Majumdar 2013; Modak 2015) are explored at length. Among these models, the Higgs-portal models such as the singlet scalar DM model (Silveira & Zee 1985; Veltman & Yndurain 1989; Burgess et al. 2001; Barger et al. 2008; Gonderinger et al. 2010), the inert Higgs doublet model (IHDM; Deshpande & Ma 1978; Lopez Honorpez & Yaguna 2011), the two Higgs doublet model (Bracco et al. 2012), the singlet vector DM model (Kanemura et al. 2010; Djourad et al. 2012; Lebedev et al. 2012), and the singlet fermionic DM model (Kim et al. 2008) could be of particular interest for the present scenario to explain the observed anomalous $\gamma$ emission by Fermi-LAT. The Higgs-portal models are interesting to study since the low-mass DM candidates of these models annihilate into quark pairs with a cross-section in the appropriate range for thermal production. A special feature of these types of models is that the DM candidates in these models exhibit resonance phenomena when their masses reach a value of approximately half of the Higgs mass while satisfying the bounds given by the PLANCK experiment ( relic density) and DM direct detection experiments.

In this work, we focus on the inert Higgs doublet model (IHDM), proposed by Deshpande and Ma (Deshpande & Ma 1978), and confront the recently observed $\gamma$-ray excesses from the GC region with the DM candidate in this model. We also explore the possibilities of the observations of $\gamma$-rays from 25 dwarf spheroidal galaxies by this IHDM DM candidate. In addition, we study the extragalactic $\gamma$-ray signals obtained by Fermi-LAT with this inert Higgs doublet DM. In the IHDM, an extra scalar doublet is added to the SM which is assumed to develop a zero vacuum expectation value after spontaneous symmetry breaking. The model has been extensively studied in...
the context of both collider and DM phenomenology (Cao et al. 2007; Hambye & Tytgat 2008; Agrawal et al. 2009; Andreas et al. 2009; Arina et al. 2009; Dolle & Su 2009; Hambye et al. 2009; Lundstrom et al. 2009; Nezri et al. 2009; Dolle et al. 2010; Lopez Honorobe & Yaguna 2010, 2011; Kanemura et al. 2011; Melfo et al. 2011; Arhrib et al. 2012; Gustafsson et al. 2012; Goudelis et al. 2013; Krawczyk et al. 2013; Swiezenska & Krawczyk 2013a, 2013b). For the DM candidate in this IHDM framework, a reduced $\chi^2$ analysis is performed considering all of the above data and constraints, and the best-fit values for the DM mass, annihilation cross-section, and other parameters of the model (various coupling constants) are determined. In the present work, we adopt those best-fit values as our benchmark and study the Fermi-LAT $\gamma$-ray flux results from both galactic (GC, dSphs) and extragalactic sources.

The paper is organized as follows. In Section 2, the theoretical framework of IHDM is briefly described. Also the theoretical, observational, and experimental constraints imposed on this model are discussed in this section. In Section 3, we confront the observed $\gamma$-ray excess from the GC in this model framework with a detailed study of the computed $\gamma$-ray spectra. We compare the calculated results with the bin-by-bin upper limits on the photon energy spectra for various Milky Way dSphs in Section 4. Section 5 contains the analysis of the EGB with calculated photon spectra in IHDM considering different extragalactic parametrizations and astrophysical non-DM backgrounds. In Section 6, we summarize our study and draw some important conclusions.

2. IHDM FRAMEWORK

The IHDM is one of the simplest extensions of the SM Higgs sector in which an additional complex scalar doublet, $\Phi$, which is odd under discrete symmetry $\mathbb{Z}_2$, is considered along with the SM Higgs doublet, $H_1$. After spontaneous symmetry breaking, while the SM Higgs obtains a vacuum expectation value (vev) $v$, the additional doublet does not acquire any vev. Thus, under $\mathbb{Z}_2$ symmetry, $\Phi \rightarrow -\Phi$ and $H \rightarrow H$ (even under $\mathbb{Z}_2$), and after symmetry breaking the two doublets $H$ and $\Phi$ can be expanded as

$$H = \begin{pmatrix} \frac{G^+}{\sqrt{2}} \\ \sqrt{2} (v + h^0 + i G^0) \end{pmatrix},$$

$$\Phi = \begin{pmatrix} \frac{H^+}{\sqrt{2}} \\ (h^0 + i A^0) \end{pmatrix}$$  (2.1)

where $G^\pm$ and $G^0$ are charged and neutral Goldstone bosons, respectively. Note that the vevs of these scalar doublet fields are $\langle H \rangle = v/\sqrt{2}$ ($v \approx 246$ GeV) and $\langle \Phi \rangle = 0$.

With the unbroken $\mathbb{Z}_2$ symmetry, the model has a CP-even neutral scalar $H^0$, a CP-odd neutral scalar $A^0$, and a pair of charged scalars $H^\pm$. Since the $\mathbb{Z}_2$ symmetry excludes the couplings of fermions with $H^0$, $A^0$, and $H^\pm$, the decay of the latter particles to fermions is thus prevented. This ensures the stability of the lightest neutral scalar ($H^0$ or $A^0$), and hence the lightest among these two can serve as a possible DM candidate. Either $H^0$ or $A^0$ is chosen as the lightest inert particle (LIP) and is the candidate of DM in the present model.

The most general tree-level scalar potential of IHDM consistent with the imposed $\mathbb{Z}_2$ symmetry can be written as

$$V_0 = \mu_s^2 |H|^4 + \mu_l^2 |\Phi|^4 + \lambda_s |H|^4 + \lambda_l |\Phi|^4$$

$$+ \lambda_s |H|^2 |\Phi|^2 + \frac{\lambda_s}{2} \left[ (H^\dagger \Phi)^2 + h.c. \right].$$  (2.2)

where $\mu_s$ and $\lambda_s$ denote various coupling parameters. The model has a set of six parameters, namely,

$$\{ M_{h^0}, M_{H^0}, M_{A^0}, M_{H^+}, \lambda_L, \lambda_S \},$$  (2.3)

where $M_{h^0}$, $M_{H^0}$, $M_{A^0}$, $M_{H^+}$ are the masses of the Higgs $h$, CP-even scalar $H^0$, pseudo-scalar $A^0$, and charged scalars $H^\pm$. $\lambda_L$ and $\lambda_S$ are in couplings given by

$$\lambda_{L} = \frac{1}{2} (\lambda_{3} + \lambda_{4} + \lambda_{5}),$$  (2.4)

$$\lambda_{S} = \frac{1}{2} (\lambda_{3} + \lambda_{4} - \lambda_{5}).$$  (2.5)

The parameters $\lambda_L$ or $\lambda_S$ denote the coupling strength for $H^0 - H^0 - h^0$ (if $H^0$ is considered to be the LIP) or $A^0 - A^0 - h^0$ (if $A^0$ is the LIP).

A detailed study of this model had been performed in Arhrib et al. (2014) where the authors made use of the various constraints available from DM experiments and other results and performed a $\chi^2$ analysis for the IHDM theory of the DM mentioned above. If we consider all of the possible experimental and theoretical constraints, such as Planck limits, direct detection constraints, unitarity, perturbativity, etc., also to be constraints from LHC, then they provide the best-fit values of the quantities $M_{h^0}^2, M_{H^0}^2, M_{A^0}^2$, and $M_{H^+}^2$, and the parameters $\lambda_L$ and $\lambda_S$ (shown in Table 1).

3. CONFRONTING $\gamma$-RAY FLUX FROM THE GALACTIC CENTER IN THIS FRAMEWORK

The differential $\gamma$-ray flux due to the annihilating DM coming from the galactic DM halo per unit solid angle can be written as (Cirelli et al. 2011)

$$\frac{d\Phi_\gamma}{d\Omega dE_\gamma} = \frac{1}{8\pi\alpha} \sum_f \frac{(\sigma_V f)}{M_{H^0, A^0, H^+}} dE_\gamma r_\od r_\od^2 J,$$  (3.1)

where $M_{H^0}$ is the mass of the DM candidate $H^0$ and $\alpha = 1$ for the present DM candidate (self-conjugated). In Equation (3.1), $r_\od$ and $r_\od$ are the distance of the solar system from the GC and the local DM halo density, respectively. The factor $J$ in Equation (3.1) gives the total DM content at the target and is given by

$$J = \int_{l.o.s.} d\varepsilon_\od \left( \frac{\rho(\varepsilon_\od)}{\bar{\rho}_\od} \right)^2,$$  (3.2)

where $\rho_\od$ and $\rho(\varepsilon_\od)$ are, respectively, the DM density in the solar region and the density at a radial distance $r$ from the GC,
where $r$ is expressed in terms of the line of sight $s$ as

$$
\begin{align*}
  r = \begin{cases} 
    \left( s^2 + r_0^2 \right)^{1/2} - 2s \rho_0 \cos \theta \sin \phi, & \text{galactic } l, \ b \text{ coordinate} \\
    \left( s^2 + r_0^2 \right)^{1/2} - 2s \rho_0 \cos \theta, & \text{galactic } r, \ \theta \text{ coordinate}.
  \end{cases}
\end{align*}
$$

and $\rho_0 \sim 0.4$ GeV cm$^{-3}$. In the above relation, the values of the parameters $r_0$ and $\gamma$ are taken to be 20 kpc and 1.26, respectively, in the present calculation following Daylan et al. (2014). We use the micrOMEGAs (Belanger et al. 2011, 2014) code to compute various DM observables in this model.

The calculated branching ratio for the channel LIP LIP $\rightarrow b\bar{b}$ is found to be 69.2%. The branching ratios for other annihilation channels in the case of the present LIP DM are also computed and are tabulated in Table 2. Since the DM mass is close to half of the SM Higgs-like ($\sim m_h/2$) particle discovered by LHC, we will have a resonance effect when obtaining the required cross-section ($2.37 \times 10^{-26}$ cm$^3$ s$^{-1}$) with $b\bar{b}$ as the dominant channel for the typical thermal production of DM. Also, the DM-nucleon scattering cross-section for the chosen benchmark point in this model is about $8.89 \times 10^{-11}$ pb (averaged value per nucleon for interaction with Xe nucleus), which is just under the present bounds for the XENON 100 and LUX experiments. This is shown in Figure 1. Future DM direct searches like XENON1T (Aprile 2013) can easily probe this point, as seen from Figure 1.

The Fermi-LAT data for the $\gamma$-ray flux from the inner $5^\circ$ surrounding the GC have been studied in Hooper (2012). The known $\gamma$-ray sources in this region can be found in (extracted from) the Fermi Second Source Catalog (2FGL; Fermi-LAT Collaboration 2012). Although the Fermi Third Source Catalog (3FGL) has recently been made available (Fermi-LAT Collaboration 2015), no analysis of the background or for $\gamma$-rays from other known processes in the ROI have been reported. Also, the interaction of cosmic rays with the gas distributed in this galactic region produces neutral pions that subsequently decay to produce enormous amounts of $\gamma$-rays. This is a viable mechanism for known disk template emission. Now, the spectral and morphological feature of the photon flux from the inner $5^\circ$ subtending the GC after subtracting the contribution from both the known sources of the Fermi Second Source Catalog and disk template emission shows a “bumpy” nature in the $\gamma$-ray energy ranging from $\sim 300$ MeV to $\sim 10$ GeV. The count drops significantly after 10 GeV of $\gamma$-ray energy.

We have computed the $\gamma$-ray spectrum from the inner $5^\circ$ subtending the GC from DM annihilation within the present framework of IHDM for DM particle. The chosen benchmark points for the parameters of the model, such as DM mass, coupling constants, etc., are given in Table 1. The flux has been computed for the generalized NFW DM halo profile. Also included in the calculations are the contributions from both point source and galactic ridge emission. The total calculated flux is then compared with the observed residual photon flux and the results are shown in Figure 2. In Figure 2, the green and blue lines represent the fluxes for point source and galactic ridge emission, respectively. The $\gamma$-ray spectrum for DM annihilation for the benchmark points mentioned above are shown with the purple line, whereas the black line is for the total $\gamma$-ray flux obtained by summing over all of the fluxes represented by the green, blue, and purple lines in Figure 2.
these calculations, we have adopted the generalized Navarro–Frenk–White (gNFW) halo profile with $\gamma = 1.26$. The total flux (black line) is then compared with the observed residual emission data. These observed data are denoted by the red points in this figure. It is clear from Figure 2 that our computation of total residual $\gamma$ emission (black line) agrees satisfactorily with the observational results.

In a recent analysis of the $\gamma$-ray flux from the GC region where the analysis is only conducted for the GC $\gamma$-rays (subtracting all possible contributions from other known astrophysical sources; Daylan et al. 2014), an excess of $\gamma$-rays in the $\gamma$ energy region of $\sim 1$–3 GeV has been reported. This excess is shown in the left panel of Figure 3 with the red points. It is suggested in the same analysis that in order to explain this anomalous $\gamma$-ray excess from the DM annihilation scenario, the DM mass should be in the range of 31–40 GeV which will annihilate purely into the $b\bar{b}$ pair. We calculated these $\gamma$-ray fluxes in our framework of inert Higgs doublet DM for a DM mass of $\sim 63.5$ GeV (adopted from Table 1 (benchmark point)) and compared our results with the analyzed data points mentioned above (red points shown in the left panel of Figure 3). In the left panel of Figure 3, the green line represents the present calculation. These calculations are performed considering the gNFW halo profile with the halo parameter $\gamma = 1.26$. Note that in the left panel of Figure 3, although the morphological feature of the spectrum from our calculation (green line) is similar in nature to that obtained from the analysis of Fermi-LAT observational data (red points) from the GC, the position of the maxima of excess $\gamma$-rays in our calculation is shifted to somewhat higher energies at $\sim 3.1$ GeV instead of being within the expected energy range of $\sim 1$–3 GeV as obtained from the Fermi-LAT data. However, the calculated position of the peak (green line) is at $\sim 2.84 \times 10^{-6}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$, which is in the same range as the observed peak (red points).

A more detailed analysis of the observed $\gamma$-ray excess reveals (Daylan et al. 2014) a further anomaly between the $\gamma$-ray spectra for the $\gamma$-rays from the galactic east–west region and from the galactic north–south region. The north–south region is designated as $|b| < |\ell|$, where $b$ and $\ell$ are the galactic latitude and longitude, respectively, and for the east–west region $|b| > |\ell|$. The two spectra are shown in the right panel of Figure 3. The red points are for the $\gamma$ spectrum from the galactic east–west region while the blue points represent the spectrum from the north–south region. As can be seen from the right panel of Figure 3, the $\gamma$ flux from the present calculation (shown by the green line in the right panel of Figure 3) agrees more satisfactorily with the “north–south” $\gamma$ emission spectrum than the “east–west” spectrum.

The systematic uncertainty for the estimate of the background model provided by Fermi-LAT is very large compared to the statistical uncertainty. Attempts (Calore et al. 2015b; Murgia 2014) have been made to quantify such systematics for the GC. We confront the flux obtained for our IHDM benchmark scenario (Table 1) using these two complementary approaches. We adopt the proposed method of Agrawal et al. (2015) for the uncertainty estimation of the $J$-factor. This involves an estimation of the halo profile uncertainty and the uncertainty in the local DM density. The density profile index, $\gamma$, is estimated to be $\gamma = 1.2 \pm 0.1$ from different galactic diffuse emission models, and $\rho_0$ is estimated to be $\rho_0 = 0.4 \pm 0.2$ GeV cm$^{-3}$ for different normalization of the halo.

We define the $J$-factor as

$$J = \frac{1}{\Delta \Omega} \int_{\Delta \Omega} J(\psi) d\Omega \equiv J \times \bar{J}_{\text{canonical}}, \quad (3.5)$$

where $\bar{J}_{\text{canonical}}$ is the central value of $\bar{J}$ and the factor $J$ signifies the deviation from the canonical halo profile due to the uncertainties of the profile. In the above equation, $\Delta \Omega$ is the region of interest (ROI) for a given analysis. The astrophysical factor $J(\psi)$ is the same as in Equation (3.2).

In Calore et al. (2015b), they provide a thorough analysis of the Fermi-LAT data in the inner galaxy region over the photon energy ranging from 300 MeV to 500 GeV, where the chosen ROI is extended to $20^\circ \times 20^\circ$ (–$20^\circ < \ell < 20^\circ$; $\sim 20^\circ < b < 20^\circ$) square region surrounding the GC. The inner galactic latitude of $2^\circ$ ($|b| < 2^\circ$) has been masked out. For the canonical halo profile with $r_s = 8.5$ kpc, $\rho_0 = 0.4$ GeV cm$^{-3}$, and $\gamma = 1.20$, the numerical value of $\bar{J}_{\text{canonical}}$ is found out to be $2.0 \times 10^{22}$ GeV$^2$ cm$^{-5}$ for the canonical halo. The uncertainty ($\Delta J \in [0.19, 3]$) in the $J$ factor is given in their analysis.

Plugging in all of the canonical parameters for the DM halo model, we compute the canonical $\gamma$-ray flux obtained from annihilation channels of $\sim 63.5$ GeV LIP DM (adopted from Table 2 (benchmark point)). The resulting plot is shown in the left panel of Figure 4 by the black line. The black line is obtained by considering only the canonical value $J \in [0.19, 3]$ of the $J$-factor. The red points denote the residual spectrum of $\gamma$-ray excess in the GC with highly correlated errors obtained from Calore et al. (2015b). We repeat the calculations by also taking the uncertainties $J \in [0.19, 3]$ in the $J$ factor. The blue and green lines in the left panel of Figure 4 denote the galactic $\gamma$-ray flux from $\sim 63.5$ GeV DM annihilation for the maximum value of the uncertainty $\Delta J_{\text{max}} \sim 3.0$ and the minimum value of the uncertainty $\Delta J_{\text{min}} \sim 0.19$, respectively. From the left panel of Figure 4, one sees that the uncertainty factor $J$ needs to be smaller than unity to provide a better fit to the data.

On the other hand, the Fermi Collaboration (Murgia 2014) has recently also studied the region surrounding the GC using different background models of galactic diffuse emission. The fit to the GC $\gamma$-ray data is observed to improve very significantly when an additional contribution similar to that from DM annihilation is added. The Fermi Collaboration has
chosen a different region (15° × 15°) surrounding the GC smaller than that chosen by Calore et al. (2015b). However, for their analysis, unlike in Calore et al. (2015b), the GC is not masked out. Based on their preliminary analysis, the Fermi Collaboration has reported four best-fit γ-ray spectra for the four distinct choices of background models for galactic diffuse emission. The nature of these four best-fit γ-ray spectra differ notably after a few GeV photon energy. The obtained γ-ray spectra are found to yield much more conservative measurements of the systematic uncertainty. Although Fermi has analyzed the data using NFW halo profiles with slope values of 1.0 and 1.2, Agrawal et al. (2015) chose a more conservative approach to the J-factor and set it to 1.2 ± 0.1. Also, the value of $\rho_0$ is chosen to be 0.4 ± 0.2 GeV cm$^{-3}$. Keeping the parameters of the J-factor fixed, in this case, one would obtain $J_{\text{canonical}} = 1.58 \times 10^{24}$ GeV cm$^{-5}$. The uncertainty in the J-factor as obtained from such parametrization is $J \in [0.14, 4.0]$ for the Fermi analysis.

We estimate the galactic γ-ray excess from the annihilation of DM as chosen in this work (benchmark point in Table 1) and confront the results with the γ-ray spectra obtained by the Fermi Collaboration. We compare the calculated spectrum with that reported by Fermi after a preliminary analysis and show it in the right panel of Figure 4. The black line in the right panel of Figure 4 denotes the photon flux obtained using the canonical parametrization of the halo profile (with $J = 1$). The blue and the green lines in the right panel of Figure 4 represent the galactic γ-ray flux calculated for the maximum uncertainty $J_{\text{max}} \sim 4.0$ and the minimum uncertainty $J_{\text{min}} \sim 0.14$, respectively. Also shown in the right panel of Figure 4 are the Fermi analysis results with their upper and lower bounds.

From the right panel of Figure 4, it appears that, unlike the previous analysis (with $-20° < \ell, b < 20°$), the uncertainty factor $J$ should be greater than unity in order to provide a better fit to the data for the considered IHDM benchmark point.

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Figure 3. Left panel: comparison of calculated γ-ray flux (green line; assuming DM annihilation) with the observed ∼1–3 GeV γ-ray excess from the GC (red data points). Right panel: same as the left panel, but here the observed data are for the galactic “north–south” region (|b| < |ℓ|; red data points) and for the galactic “east–west” region (|b| > |ℓ|; blue data points). See the text for details.

Figure 4. Left panel: comparison of calculated γ-ray flux (red points) with the observed residual γ-ray spectrum for the region in galactic coordinates |ℓ| < 20°, 2° < |b| < 20°. The black line represents the canonical J-factor while the green and blue lines are calculated with the minimum and maximum deviations of the J-factor from its canonical value. Right panel: comparison of the calculated results in the left panel with the observed γ-ray spectra (red points) obtained by studying a 15° × 15° region around GC. See the text for details.
4. CONFRONTING \(\gamma\)-RAY FLUX FROM DWARF SPHEROIDAL GALAXIES IN THIS FRAMEWORK

Some of the most promising targets in the search for DM via indirect detection (\(\gamma\)-ray) are the dwarf spheroidal galaxies (dSphs) of the Milky Way. The dSphs are considered to be promising for the study of DM phenomenology because of their proximity, low astrophysical background, and huge amount of DM content.

The satellite-based \(\gamma\)-ray experiment Fermi-LAT searched for the \(\gamma\)-ray sky in the energy range spanning from \(\sim 500\) MeV to 500 GeV (Atwood et al. 2009). In a more recent study by Ackermann et al. (2014), 4-year \(\gamma\)-ray data from Fermi-LAT for dSphs (2008 August 04–2012 August 04) with energy ranging from 500 MeV to 500 GeV have been chosen to study 25 independent Milky Way dSphs galaxies. The chosen dSphs galaxies are Bootes I, Bootes II, Bootes III, Canes Venatici I, Canes Venatici II, Canis Major, Carina, Coma Berenices, Draco, Fornax, Hercules, Leo I, Leo II, Leo IV, Leo V, Pisces II, Sagittarius, Sculptor, Segue 1, Segue 2, Sextans, Ursa Major I, Ursa Major II, Ursa Minor, and Willman 1. The galactic coordinates as well as the radial distances from the GC of these dwarf galaxies are tabulated in Table 3. From the analysis of their data, they place robust upper limits on the DM annihilation cross-section for various DM masses have been derived with 95% CL.

We calculate the \(\gamma\)-ray flux for all of the dwarf galaxies. The \(\gamma\)-ray spectrum, \(\frac{d\nu}{dE}\), can be obtained for a given DM mass. The different particle processes for the calculation of \(\frac{d\nu}{dE}\) are tabulated in Table 2. We compute \(\frac{d\nu}{dE}\) for our benchmark scenario, and using the integrated \(J\)-factor for a particular dSph, the maximum value of the velocity-averaged annihilation cross-section (\(\langle \sigma v \rangle_{\text{max}}\)) is estimated from the upper bound of the ttmkflux (LHS of Equation (3.1)) of that dSph. In this manner, the upper bounds of the annihilation cross-section are computed for all 18 dSphs considered and are tabulated in Table 3.

We now compute the \(\gamma\)-ray flux for all 18 dSphs considered using Equation (3.1). The maximum, minimum, and central values of the integrated \(J\)-factor for each dwarf galaxy, which are measured from stellar kinematics data, are tabulated in Table 3 (Ackermann et al. 2014). The integration to find the \(J\)-factor involves integration over a solid angle \(\Delta \Omega\) of \(\sim 2.4 \times 10^{-4}\) sr (the field of view of Fermi-LAT is within the angular radius of 0.5). The results are shown in the plots in Figure 5. In Figure 5, using the downward red arrows, we also show the experimentally obtained bin-by-bin upper limits of the \(\gamma\)-ray energy flux at 95% CL from each dwarf galaxy. The flux of a dSph is compared with the upper bound of the flux in each energy bin. The spread (band) of this flux, shown in green, indicates the upper and lower limits of the flux when calculated with the upper and lower limits of the integrated \(J\)-factors. The photon fluxes calculated using the central value of the \(J\)-factors are shown by the blue lines in these figures.

5. CONFRONTING THE EXTRAGALACTIC \(\gamma\)-RAY BACKGROUND IN THIS FRAMEWORK

The \(\gamma\)-rays can also be emitted from DM annihilation in extragalactic sources and such \(\gamma\)-rays can be probed for extragalactic DM and its origins (Stecker 1978; Gao et al. 1991; Bergstrom et al. 2001; Ullio et al. 2002; Taylor & Silk 2003; Ando 2005; Oda et al. 2005; Pieri et al. 2008; Ng et al. 2014). Such \(\gamma\)-rays from extragalactic sources of DM can remain hidden in the huge background of the observationally measured \(\gamma\) flux by satellite-based experiments such as the SAS-2 satellite (Fichtel et al. 1978), EGRET (Steckumar et al. 1998), and Fermi-LAT (Abdo et al. 2010b; Ackermann et al. 2015b). In order to extract information regarding the extragalactic signature of \(\gamma\)-rays from the background, one should be able to understand and subtract the galactic astrophysical components, other sources that may contribute to the background, and the backgrounds that the detector may give rise to in the process of detection. After this subtraction process, the residual \(\gamma\)-ray signal thus obtained is found to be diffuse and isotropic in nature and is known as the diffuse isotropic \(\gamma\)-ray background (DIGRB). Recently, in light of the 50-month Fermi-LAT data, an updated tight constraint on DM annihilation is given with modeling of the integrated emission of blazars with such diffuse background absorption (Ajello et al. 2015). It should also be noted that the DIGRB thus obtained has embedded in it the irreducible contributions from galactic origin as well. In this section, we estimate such DIGRB for the case of DM annihilating into \(\gamma\)-rays in the framework of the chosen IHDM DM candidate. We then compare our theoretical calculations with EGRET and Fermi-LAT results for extragalactic DIGRB.

5.1. Formalism

The number of photons which are isotropically emitted from the volume element \(dV\) over the time interval \(dt\) in the energy range \(dE\) and are collected by the detector with an effective area \(dA\) during the time interval \(dt_0\) in the redshifted energy range \(dE_0\) can be given by (Ullio et al. 2002)

\[
\frac{dN_i}{dE_0} = e^{-\gamma(z,E_0)} \left[ 1 + z \right]^3 \int dM \frac{dn}{dM} (M, z) \times \frac{dN}{dE}(E, M, z) \frac{dV}{dA} \frac{dA}{4\pi [R_0 S_i(r)]^2} dE_0 dt_0 . \tag{5.1}
\]

In the above, the volume element \(dV\) at a redshift \(z\) is given as

\[
dV = \frac{[R_0 S_i(r)]^2 R_0}{(1 + z)^5} dr d\Omega_{\text{detector}} . \tag{5.2}
\]
Table 3
Limits on the DM Annihilation Cross-section from $\gamma$-ray Flux Limits for Various Dwarf Spheroidal Galaxies for the Benchmark DM Mass of Table 1

| dSphs Name     | Longitude l (deg) | Latitude b (deg) | Distance (kpc) | $\log_{10}(\gamma_{\text{NFW}})$ (log$_{10}$(GeV$^2$ cm$^{-3}$ sr)) | $\log_{10}(\gamma_{\text{G}})$ (log$_{10}$(deg)) | Upper Limit On $\langle\sigma v\rangle$ (cm$^3$ s$^{-1}$) |
|----------------|------------------|------------------|---------------|---------------------------------|---------------------------------|---------------------------------|
| Boötes I       | 358.1            | 69.6             | 66            | 18.8 ± 0.22                     | -0.6 ± 0.3                     | 2.33 × 10$^{-24}$               |
| (Dall’Orlea 006) |                  |                  |               |                                 |                                 |                                 |
| Boötes II      | 353.7            | 68.9             | 42            | ...                            | ...                            | ...                             |
| Boötes III     | 35.4             | 75.4             | 47            | ...                            | ...                            | ...                             |
| Canis Venatici I | 74.3            | 79.8             | 218           | 17.7 ± 0.26                    | -1.3 ± 0.2                     | 9.65 × 10$^{-25}$               |
| (Simon & Geha 07) |                |                  |               |                                 |                                 |                                 |
| Canis Venatici II | 113.6        | 82.7             | 160           | 17.9 ± 0.25                    | -1.1 ± 0.4                     | 8.14 × 10$^{-25}$               |
| (Simon & Geha 07) |                |                  |               |                                 |                                 |                                 |
| Canis Major    | 240.0            | -8.0             | 7             | ...                            | ...                            | ...                             |
| (Walker et al. 09a) |            |                  |               |                                 |                                 |                                 |
| Carina         | 260.1            | -22.2            | 105           | 18.1 ± 0.23                    | -1.0 ± 0.3                     | 2.28 × 10$^{-25}$               |
| (Simon & Geha 07) |                |                  |               |                                 |                                 |                                 |
| Coma Berenices | 241.9            | 83.6             | 44            | 19.0 ± 0.25                    | -0.6 ± 0.5                     | 1.11 × 10$^{-24}$               |
| (Simon & Geha 07) |                |                  |               |                                 |                                 |                                 |
| Draco          | 86.4             | 34.7             | 76            | 18.8 ± 0.16                    | -0.6 ± 0.2                     | 3.87 × 10$^{-25}$               |
| (Munoz et al. 05) |                |                  |               |                                 |                                 |                                 |
| Fornax         | 237.1            | -65.7            | 147           | 18.2 ± 0.21                    | -0.8 ± 0.2                     | 2.53 × 10$^{-25}$               |
| (Walker et al. 09a) |            |                  |               |                                 |                                 |                                 |
| Hercules       | 28.7             | 36.9             | 132           | 18.1 ± 0.25                    | -1.1 ± 0.4                     | 9.97 × 10$^{-26}$               |
| (Simon & Geha 07) |                |                  |               |                                 |                                 |                                 |
| Leo I          | 226.0            | 49.1             | 254           | 17.7 ± 0.18                    | -1.1 ± 0.3                     | 4.37 × 10$^{-25}$               |
| (Mateo et al. 08) |                |                  |               |                                 |                                 |                                 |
| Leo II         | 220.2            | 67.2             | 233           | 17.6 ± 0.18                    | -1.1 ± 0.5                     | 3.88 × 10$^{-25}$               |
| (Koch et al. 07) |                |                  |               |                                 |                                 |                                 |
| Leo IV         | 265.4            | 56.5             | 154           | 17.9 ± 0.28                    | -1.1 ± 0.4                     | 3.72 × 10$^{-24}$               |
| (Simon & Geha 07) |                |                  |               |                                 |                                 |                                 |
| Leo V          | 261.9            | 58.5             | 178           | ...                            | ...                            | ...                             |
| Pisces II      | 79.2             | -47.1            | 182           | ...                            | ...                            | ...                             |
| Sagittarius    | 5.6              | -14.2            | 26            | ...                            | ...                            | ...                             |
| Sculptor       | 287.5            | -83.2            | 86            | 18.6 ± 0.18                    | -0.6 ± 0.3                     | 3.41 × 10$^{-24}$               |
| (Walker et al. 09a) |            |                  |               |                                 |                                 |                                 |
| Segue 1        | 220.5            | 50.4             | 23            | 19.5 ± 0.29                    | -0.4 ± 0.5                     | 1.16 × 10$^{-24}$               |
| (Simon et al. 11) |                |                  |               |                                 |                                 |                                 |
| Segue 2        | 149.4            | -38.1            | 35            | ...                            | ...                            | ...                             |
| Sextans        | 243.5            | 42.3             | 86            | 18.4 ± 0.27                    | -0.9 ± 0.2                     | 1.14 × 10$^{-25}$               |
| (Walker et al. 09a) |            |                  |               |                                 |                                 |                                 |
| Ursa Major I   | 159.4            | 54.4             | 97            | 18.3 ± 0.24                    | -1.0 ± 0.3                     | 1.64 × 10$^{-25}$               |
| (Simon & Geha 07) |                |                  |               |                                 |                                 |                                 |
| Ursa Major II  | 152.5            | 37.4             | 32            | 19.3 ± 0.28                    | -0.5 ± 0.4                     | 1.33 × 10$^{-24}$               |
| (Simon & Geha 07) |                |                  |               |                                 |                                 |                                 |
| Ursa Minor     | 105.0            | 44.8             | 76            | 18.8 ± 0.19                    | -0.5 ± 0.2                     | 6.54 × 10$^{-24}$               |
| (Munoz et al. 05) |                |                  |               |                                 |                                 |                                 |
| Willman 1      | 158.6            | 56.8             | 38            | 19.1 ± 0.31                    | -0.6 ± 0.5                     | 4.03 × 10$^{-24}$               |
| (Willman et al. 11) |            |                  |               |                                 |                                 |                                 |

where $d\Omega_{\text{detector}} = \sin \theta d\theta d\phi$ denotes the angular acceptance of the detector. In Equations (5.1) and (5.2), $S_Q(r)$ is given by the Robertson Walker metric for a homogeneous and isotropic universe

$$ds^2 = c^2 dt^2 - R^2(t) \left[ dr^2 + S_k^2(r) (d\theta^2 + \sin^2 \theta d\phi^2) \right],$$

where $S_k(r)$ signifies the spatial curvature of the universe. In Equation (5.1), $\frac{dn}{dM}(E, M, z)$ is the differential photon energy spectrum for a generic halo with mass $M$ at some redshift $z$. The term $\frac{dn}{dM}(M, z)$ is the halo mass function and is defined as the number density of bound objects with mass $M$ at redshift $z$. The term $e^{-\tau(z, E_0)}$ represents the attenuation of extragalactic $\gamma$-rays which may come from the absorption of these high-energy $\gamma$-rays in the extragalactic background light (EBL), and $\tau(z, E_0)$ is the optical depth as a function of $z$ and $E_0$. The energy and redshift dependence of this attenuation factor are shown in Figure 6. Detailed studies regarding this attenuation are given in Cirelli et al. (2011). For the ultraviolet background, we have adopted the minimal model (Franceschini et al. 2008; Domínguez et al. 2011) obtained after a recent study on blazars. Note that $d\Omega dE_0$ in Equation (5.1) is given by $d\Omega dE_0 = \frac{d\Omega}{(1 + z)} dE_0$, where $t_0$ and $E_0$ are the
time and energy, respectively, corresponding to the redshift $z = 0$. Summing over all of the above contributions, the diffuse extragalactic $\gamma$-ray flux due to DM annihilation can be written as

$$\frac{d\phi_\gamma}{dE_0} \equiv \frac{dN_\gamma}{d\Omega \, dt_0 \, dE_0} = \frac{1}{4\pi} \int dr \, R_6 \, e^{-\tau(z, E_0)} \int dM \, df \left( E_0(1 + z), M, z \right) \times \frac{dN_\gamma}{dE} \left( E_0(1 + z), M, z \right),$$

where $c$ is the speed of light in vacuum, $H_0$ is the Hubble constant at the present epoch, and $h(z)$ is written as (for a spatially flat universe ($\Omega_k = 0$))

$$h(z) = \sqrt{\Omega_M(1 + z)^3 + \Omega_\Lambda},$$

where $\Omega_M$ and $\Omega_\Lambda$ are, respectively, the matter and dark energy densities normalized to the critical density of the universe. The cosmological DM halo function $dN/dM(M, z)$ in Equation (5.4) can
be written in the form (Press & Schechter 1974)

\[
\frac{dn}{dM} = \frac{\rho_{0,m}}{M^2} \frac{f(\nu)}{d \log \nu} \frac{d \log \nu}{d \log M}, \tag{5.6}
\]

where \(\rho_{0,m}\) is the comoving background matter density. In the above, the parameter \(\nu = \delta_{sc}/\sigma(M)\) is defined as the ratio between the critical overdensity for spherical collapse \(\delta_{sc} \approx 1.686\) and \(\sigma(M)\) denotes the variance or the rms density fluctuations of the linear density field in sphere that contains the mean mass \(M\). The term \(\sigma^2(M)\) can be written in terms of the linear power spectrum \(P(k)\) of the fluctuations (Sheth & Tormen 1999) as

\[
\sigma^2(M) \equiv \int d^3k \, \tilde{W}^2(kR) \, P(k), \tag{5.7}
\]

where \(\tilde{W}(kR)\) is the Fourier transform of the top hat window function and \(R\) is the comoving length scale. For collapsed halos, the mass is found to be in the form \(M \approx (4/3)\pi R^3\rho_c(z_c)\) with \(z_c\) being the redshift where the collapse of halos occurs. The power spectrum \(P(k)\) can be parametrized as \(P(k) \propto k^{2n+2}(k)\), where \(n\) is the spectral index and \(T\) is the transfer function that incorporates the effect of the scale dependence of the primordial power spectrum generated during inflation. This transfer function depends on the nature of DM and baryon density in the universe. Thus, the transfer function can be calculated from the cosmic microwave background data. The variation of the power spectrum \(P(k)\) with wavenumber \(k\) for different redshifts is shown in the left panel of Figure 7. The right panel of Figure 7 corresponds to the plot showing the variation of variance \(\sigma\) with halo mass \(M\) for different values of redshift. The function \(f(\nu)\) in Equation (5.6), known as the multiplicity function, can be modeled in the ellipsoidal collapse model (Sheth & Tormen 1999) by

\[
\nu f(\nu) = 2.4 \left(1 + \frac{1}{\nu^2} \right)^{3/2} \exp \left( -\frac{\nu^2}{2} \right), \tag{5.8}
\]

where \(\nu' = \sqrt{a} \nu, a = 0.707, p = 0.3\) are obtained by fitting Equation (5.6) to the \(N\)-body simulation of the Virgo consortium (Jenkins et al. 1998). The value of \(A\) is determined to be 0.3222. For the choice of parameter values, \(a = 1, p = 0\), and \(A = 0.5\), Equation (5.6) reduces to the original Press–Schechter theory (Press & Schechter 1974). In \(N\)-body simulations, it is found that the estimates of higher and lower mass halos differ from those predicted by the Press–Schechter model. This problem can be handled in the Sheth–Torman

\[
\begin{align*}
\text{Figure 7.} & & \text{Left panel: variation of the linear power spectrum} & \text{of matter density perturbations with the wavenumber} & \text{for different redshifts.} \\
\text{Right panel: the variance} & & \sigma & \text{of the density perturbations is shown as a function of halo mass for different redshifts. In both plots, the values} & \text{of redshift} \\
& & \text{are} & \text{are} & \text{See the text for details.}
\end{align*}
\]

\[
\begin{align*}
\text{Figure 8.} & & \text{Left panel: fraction of mass collapsed,} & \text{in the Sheth–Torman model for different redshifts} & \text{and halo masses} M. \\
\text{Right panel: the variation of the Sheth–} & & \text{Torman halo mass function} & \text{function} & \text{with redshift} \ z & \text{and halo mass} M. \text{See the text for details.}
\end{align*}
\]
model by considering an ellipsoidal collapse model instead of a spherical one.

In the left panel of Figure 8, we show the variations in the fraction of mass collapsed, \( f(\sigma) \), in the ellipsoidal collapse model with redshift \( z \) and halo mass \( M \). Note that \( f(\sigma) \) as shown in the left panel of Figure 8 can be obtained by simple transformation of \( f(\nu) \) by plugging \( \nu = \delta_{\nu}/\sigma(\nu, M) \), and is given by
\[
 f(\sigma) = A \frac{3\chi^2}{\pi} \left[ 1 + \left( \frac{\chi}{\chi_m} \right)^2 \right]^{\frac{3}{2}} \exp \left[ -\frac{a \chi^2}{2} \right].
\]

In the right panel of Figure 8, we have shown the variations of the considered halo mass function \( dM/dn \) of the Sheth–Tormen model (Sheth & Tormen 1999) with redshift \( z \) as well as with the halo mass \( M \). All of the numerical calculations related to Figure 8 have been performed using the HMFcalc (Murray et al. 2013) code.

For the halo profile, we have chosen an NFW halo profile (Navarro et al. 1996, 1997) given by
\[
 \rho(r) = \rho_s \frac{r_s}{r} \left( 1 + \frac{r}{r_s} \right)^{-2}.
\]

Any DM halo of mass \( M_h \) enclosed at a radius \( r_h \) is
\[
 M_h = 4\pi \rho_s r_h^3 f(r_h/r_h),
\]
where \( f(x) = x^3 \ln(1 + x^{-1}) - (1 + x^{-1}) \).

Also, a halo of mass \( M \) at some redshift \( z \) can be written in terms of the mean background \( \bar{\rho}(z) \) as
\[
 M = \frac{4\pi}{3} \Delta_{\text{vir}} \bar{\rho}(z) R_{\text{vir}}^3,
\]
where \( R_{\text{vir}} \) is the virial radius defined as the radius within which the total halo mass \( M \) is contained with a mean halo density of \( \Delta_{\text{vir}} \bar{\rho}(z) \). The term \( \Delta_{\text{vir}} \) is the virial overdensity with respect to the mean matter density, which may depend on the cosmological parameters but is independent of halo mass \( M_h \). For flat cosmology, \( \Delta_{\text{vir}}(z) \) can be cast in the following form (Bryan & Norman 1998):
\[
 \Delta_{\text{vir}} \approx \left( 18\pi^2 + 82d - 39d^2 \right),
\]
with \( d = d(\nu) = \frac{\Omega_m(1 + z)^3}{(\Omega_m(1 + z)^3 + \Omega_b)} - 1 \). We choose the value of \( \Delta_{\text{vir}}(z) \).

The \( \gamma \)-ray energy spectrum \( \frac{dN_{\gamma}}{dE}(E_0(1 + z), M, z) \) (Equation (5.4)) for \( \gamma \)-rays emitted inside a halo of mass \( M \) at redshift \( z \) is written in the form
\[
 \frac{dN_{\gamma}}{dE}(E, M, z) = \frac{\langle \sigma v \rangle}{2} \frac{dN_s(E)}{dE} \int dc'_{\gamma} \mathcal{P}(c_{\gamma}) \left( \frac{c_{\gamma}}{M} \right)^2 \int d^3r \; g^2(r/a),
\]
where \( \langle \sigma v \rangle \) is the thermally averaged value of the annihilation cross-section times the relative velocity, \( \frac{dN_s(E)}{dE} \) is the differential \( \gamma \)-ray energy spectrum produced per unit annihilation of DM, and \( M_\chi \) is the mass of DM. The log-normal distribution \( \mathcal{P}(c_{\gamma}) \) of the concentration parameter \( c_{\gamma} \) around the mean value is chosen within 1\(\sigma\) deviation (Sheh & Tormen 2004) for halos with mass \( M \).

Finally, one can write
\[
 \frac{dN_{\gamma}}{dE}(E, M, z) = \frac{\langle \sigma v \rangle}{2} \frac{dN_s(E)}{dE} M^2 \Delta_{\text{vir}} \bar{\rho}(z) \times \int dc'_{\gamma} \mathcal{P}(c_{\gamma}) \left[ \frac{c_{\gamma}}{H(z)} \right] \int_0^{\infty} dx \; x^2 \; e^{-x}.
\]

In the above equation, \( r_{-2} \) is the radius between \( r_s^{(2-1)} \) and \( r_s \), where \( r_s^{(2-1)} \) is the radius at which the effective logarithmic slope is \(-2\) which follows from the relation \( d/dr (r^2 g(r)) \big|_{r=r_s^{(2-1)}} = 0 \). For the NFW profile, \( r_s^{(2-1)} = r_s \).

Hence, \( c_{\gamma} r_{-2} = R_{\text{vir}}/r \) and the form of integration \( I(x, x_{\text{max}}) \) in Equation (5.14) can be cast into the form
\[
 I_M(x_{\text{min}}, x_{\text{max}}) = \int_{x_{\text{min}}}^{x_{\text{max}}} dx \; x^2 \; e^{-x}.
\]

Plugging the above equation into Equation (5.4), the analytic form of the extragalactic \( \gamma \)-ray flux from DM annihilation can be obtained as (Ullio et al. 2002)
\[
 \frac{d\Phi_{\gamma}}{dE_0} = \frac{\langle \sigma v \rangle}{8\pi} \frac{\rho_0^2}{M_\chi^2} \times \int dz \; (1 + z)^3 \frac{\Delta_{\text{vir}}(z)}{H(z)} \times \frac{dN_s(E_0(1 + z))}{dE} e^{-\Delta_{\text{vir}}(z, E_0)}.
\]

where the expression for \( \Delta_{\text{vir}}(z) \) can be given by
\[
 \Delta_{\text{vir}}(z) = \int dM \frac{\nu(z, M) f(\nu(z, M))}{\sigma(M)} \left| \frac{d\sigma}{dM} \right| \Delta_{\text{vir}}(z, M).
\]
with
\[
\Delta_M^2(z, M) = \frac{\Delta_{\text{vir}}^2(z)}{3} \int \frac{d\ell^{eEM}}{\ell^{eEM}} P(c'_{\text{vir}}) \times \frac{\mathcal{I}_V(x_{\text{min}}, c'_{\text{vir}}(z, M), \ell^{eEM})}{\mathcal{I}_V(x_{\text{min}}, c'_{\text{vir}}(z, M), \ell^{eEM})^3} (c'_{\text{vir}}(z, M), \ell^{eEM})^3. \quad (5.18)
\]

In all of the above the concentration parameters, \(c_{\text{vir}}\) is defined as
\[
c_{\text{vir}} = \frac{R_{\text{vir}}}{r_s^{eEM}}. \quad (5.19)
\]

We have chosen two forms of concentration parameter \(c_{\text{vir}}\) following Macciò et al. (2008) and the power-law model (Neto et al. 2007; Macciò et al. 2008). For the first choice (Macciò et al.), \(c_{\text{vir}}(M, z) = k_{200} \frac{\mathcal{H}(z)}{\mathcal{H}(z)^{2/3}}\), where \(k_{200} \approx 3.9\), \(\mathcal{H}(z) = H(z)/H_0\), and \(z_M(M)\) is the effective redshift during the formation of a halo with mass \(M\). In the power-law model (second choice), however, the expression \(c_{\text{vir}}(M, z)\) is adopted as \(c_{\text{vir}}(M, z) = 6.5 \mathcal{H}(z)^{-2/3} (M/M_\odot)^{-0.1} \), \(M_8 = 3.37 \times 10^{12} h^{-1} M_\odot\). This choice of \(c_{\text{vir}}(M, z)\) provides a reasonable fit within the resolved mass range in the simulations.

The DM substructures are present within the halo and form bound objects. The mass of the smallest possible such bound object (subhalo) is denoted as \(M_{\text{min}}\). The value of this minimum subhalo mass, \(M_{\text{min}}\), is determined from the temperature at which the DM particles just start decoupling kinematically from the cosmic background.

In this work, we perform our analysis for two typical values of \(M_{\text{min}}\): \(M_{\text{min}} = 10^{-6} M_\odot\) and \(10^{-9} M_\odot\) (Bringmann 2009; Martinez et al. 2009). The boost factor for the \(\gamma\)-ray flux due to these subhalos depends inversely on \(M_{\text{min}}\); the results are shown in Figure 9.

### 5.2. Non-DM Contributions in DIGRBM

The extragalactic \(\gamma\)-ray spectrum in the energy range between \(~\) few hundred MeV and \(~\) few hundred GeV as observed by the *Fermi*-LAT telescope is found to follow almost a power-law spectrum \(\frac{dN}{dE} \propto E^{-2.41}\). There are contributions from astrophysical sources other than that from possible DM annihilation (Tavakoli et al. 2014). The possible sources that contribute to the diffuse \(\gamma\)-ray background other than the DM include BL Lacertae objects (BL Lacs), flat spectrum radio quasars (FSRQs), millisecond pulsars (MSPs), star-forming galaxies (SFGs), Fanarof–Riley (FR) radio galaxies of type I (FR I) and type II (FR II), ultra high energy cosmic rays (UHECRs), \(\gamma\)-ray bursts (GRBs), star burst galaxies (SBGs), ultra high energy protons in the inter-cluster material (UHEp ICM), gravitationally induced shock waves (IGS), etc. The spectral features of photon spectra originating from the non-DM objects (Tavakoli et al. 2014) considered in this work are concisely summarized in Table 4.

We add the contributions to the EGB from both the annihilating DM in the IHDM framework (\(\sim 63.5\) GeV DM considered in this work) and the other possible non-DM astrophysical sources. The comparison of the sum total value of the \(\gamma\)-ray flux with the observed EGB by *EGRET* and *Fermi*-LAT is shown in Figure 10. Needless to say, the four plots in Figure 10 are for different parametrizations of the concentration parameter \(c_{\text{vir}}\) and subhalo mass \(M_{\text{min}}\). As mentioned earlier, we have considered BL Lacs, FSRQs, MSPs, SBGs, FR (type I and II), UHECR, GRBs, SBGs, UHEp interacting with ICM, and IGS as contributors to EGB other than DM and their contributions to EGB are shown with different lines in Figure 10. The computed total photon spectra in the plots of Figure 10 are shown by black solid lines while the red solid line represents the minimal non-DM contribution to EGB. The black lines are found to be on top of the red lines for the Macciò et al. models.

We also note that the extragalactic \(\gamma\)-ray signal is analyzed within the DM annihilation scenario in Cholis et al. (2014). In their analysis, they constructed a model for the non-DM astrophysical contributions to the EGB and also adopted a substructure model based on numerical simulations. The authors in Cholis et al. (2014) considered the subhalo boost factor \(b_{\text{bh}}\) in their analysis using the following form (Ando & Komatsu 2013):

\[
b_{\text{bh}}(M) \approx 110 \times (\frac{M_{200}}{10^{12} M_\odot})^{0.39},
\]

where \(M_{200}\) denotes the mass enclosed within a radial region where the averaged density is 200 times more than the critical density of the universe. We have performed the calculation for the extragalactic photon flux for DM for the best-fit model parameter in IHDM based on their extragalactic modeling. The result is shown in Figure 11. In Figure 11, we only considered the contributions to EGB other than that from DM annihilation from radio galaxies, BL lacs, FSRQs, and SFGs. The sum total contribution to EGB is found to fit reasonably well with the *Fermi*-LAT data.
5.3. Galactic (Sub)Halo Contribution to DIGRB

There could be a significant contribution to the DIGRB of galactic origin along the line of sight due to the signal from extragalactic sources passing through the Milky Way galactic halo and subhalo. From numerical simulations, the main DM halo is found to host a large amount of substructures in the form of subhalos (Diemand et al. 2007; Springel et al. 2008b).

The signal from DM annihilation in galactic substructures could potentially give rise to an almost isotropic signal since this generated $\gamma$-ray flux is proportional to the less centrally concentrated number density distribution of subhalos (Springel et al. 2008a). The averaged photon intensity from DM annihilation in such a smooth Milky Way halo can be written as

$$\frac{dI_{\gamma}}{dE_{\gamma}} = \frac{(c_{\nu})}{2m_{\nu}^{2}} dN_{\nu} \int_{V_{s}} dV \frac{\rho_{\text{DM}}^{2}(s, b, \ell)}{4\pi s^2}, \quad (5.21)$$

where $s$ and $\Omega_{s}$ are the distance from the GC and the observed solid angle. In the above equation, $b$ and $\ell$ are galactic coordinates (latitude and longitude, respectively) chosen to be $30^\circ \leq |b| \leq 90^\circ$.
0 \leq \ell < 2\pi \text{ (Cholis et al. 2014). We choose } r_{\text{MW}} = 21.5 \text{ kpc}, r_{r_{\text{MW}}} = 258 \text{ kpc}, \rho_{\text{MW}} = 4.9 \times 10^{9} M_{\odot} \text{ kpc}^{-3}, M_{\text{vir, MW}} = 1.0 \times 10^{12} M_{\odot} \text{ (Klypin et al. 2002) for our calculation.}^{3}

The photon flux produced in the smooth halo component is significantly subdominant compared to that yielded in the subhalos, and hence contributes negligibly to EGB. In ΛCDM cosmology, the formation of the structures is assumed to be hierarchical. The smaller DM halos are formed first and the larger ones later. In the period of structure formation, the smaller halos are tidally disrupted after being captured by the larger host halos of galaxies and clusters, and hence the outer low-density layers are stripped in this process. Thus, the central dense cores only survive and behave as subhalos of the host halos. These substructures of DM halos enrich DM phenomenology by giving rise to substantial enhancement of the DM annihilation over the whole galaxy. The contribution to the differential γ-ray flux from subhalos can be obtained from the differential luminosity profile of each subhalo, which is given by

\[
\frac{d\mathcal{L}_{\gamma}}{dE_{\gamma}} = \frac{\langle \sigma v \rangle dN_{s}}{2m_{\text{DM}}^{2} dE_{\gamma}} \int dV_{\text{sh}} \rho_{\text{sh}}^{2}.
\] (5.22)

For an individual subhalo with mass \(M\), the photon intensity can be written as

\[
\frac{d\mathcal{I}(E_{\gamma}, s, M)}{dE_{\gamma}} = \frac{1}{4\pi^{2}} \frac{dL(E_{\gamma}, M)}{dE_{\gamma}} = \frac{1}{4\pi^{2}} \frac{b_{\text{sh}} \langle \sigma v \rangle dN_{s}}{2m_{\text{DM}}^{2} dE_{\gamma}} M^{2} G[c_{\text{cut}}(M)],
\] (5.23)

where \(r_{\text{sh}}\) denotes the scale radius of the subhalo. In the above, the factor \(b_{\text{sh}}\) determines the contribution from substructure

\[
\text{with each subhalo ("subsubhalo") and is chosen to be two (Kuhlen et al. 2008). The function } G[c_{\text{cut}}(M)], \text{ which can be obtained using the integral over the volume of each satellite and the form of subhalo concentration } c_{\text{cut}} \text{ following Ando (2009), can be given as}
\]

\[
G[c_{\text{cut}}(M)] = \frac{1}{12\pi} \left[ 1 - \frac{1}{(1 + c_{\text{cut}})^{3}} \right] \times \left[ \ln(1 + c_{\text{cut}}) - \frac{c_{\text{cut}}}{1 + c_{\text{cut}}} \right].
\] (5.25)

The total γ-ray intensity at Earth from the annihilation of DM particles in galactic subhalos can be written after integrating Equation (5.23) over the distribution of Milky Way subhalos as

\[
\frac{d\mathcal{I}_{\text{sh}}(E_{\gamma})}{dE_{\gamma}} = \int dV dM \frac{d\mathcal{I}_{\text{sh}}(M, s, \ell, b)}{dM} \frac{d\mathcal{I}(E_{\gamma}, s, M)}{dE_{\gamma}},
\] (5.26)

where \(dV dM (dn_{\text{sh}}/dM)\) is the total number of subhalos in the Milky Way. The form of the subhalo mass function, \(dn_{\text{sh}}/dM\), is chosen to be an anti-biased model following Ando (2009) for our calculations.

In order to confront observations, we are interested in the averaged intensity of the γ-rays per unit energy emitted due to DM annihilation over the whole galaxy,

\[
\frac{d\mathcal{I}_{\text{sh}}(E_{\gamma})}{dE_{\gamma}} = \frac{1}{\Omega_{e}} \frac{d\mathcal{I}_{\text{sh}}(E_{\gamma})}{dE_{\gamma}} \times \frac{1}{\Omega_{e}} \int_{V_{e}(M)} dV dM \frac{dn_{\text{sh}}(M, s, \ell, b)}{dM} \frac{d\mathcal{I}(E_{\gamma}, s, M)}{dE_{\gamma}} \times \frac{1}{4\pi^{2} m_{\text{DM}}^{2} dE_{\gamma} r_{\text{sh}}(M)^{2}} G[c_{\text{cut}}(M)],
\] (5.27)

where \(V_{e}\) is the volume beyond which satellites remain unresolved. The considered mass range of the subhalos is \(10^{-6} M_{\odot} \leq M_{h} \leq 10^{10} M_{\odot}\). Since from the luminosity \(L\) one can determine the subhalo mass \(M\), we consider the subhalo mass range in such a way that both the bright and faint subhalos are included in the calculation. Also, since luminosity is directly related to the flux sensitivity of \textit{Fermi} (\(F_{\text{sens}}\)) by the relation \(L(M) = 4\pi s_{\odot}(M) F_{\text{sens}}\), the subhalos remain unresolvable beyond a distance \(s_{\odot}(M) = \sqrt{L(M)/4\pi F_{\text{sens}}}\), where the flux sensitivity of \textit{Fermi-LAT} \(F_{\text{sens}} = 2 \times 10^{-10} \text{ cm}^{-2} \text{ s}^{-1}\).

\[
4 \text{ We choose the DM density within each subhalo of mass } M \text{ to be a truncated NFW halo profile:}
\]

\[
\rho_{\text{sh}}(r|M) = \begin{cases} \rho_{\text{NFW}}(r|M) & \text{for } r_{\text{sh}} \leq r < r_{\text{cut}}, \\ \rho_{\text{sh}}(r_{\text{cut}}) & \text{for } r_{\text{sh}} > r_{\text{cut}}, \end{cases}
\] (5.24)

where \(r_{\text{cut}}\) is the cutoff radius for this profile.

\[
5 \text{ In another model ("unbiased") for } r_{\text{sh}}(r), \text{ the subhalo distribution is assumed to follow its parent NFW halo distribution, whereas in the anti-biased model the subhalo distribution is flatter than NFW halo (Ando 2009).}
\]
(Ando 2009) and $L(M)$ is the luminosity obtained by integrating Equation (5.22) over the energy.

In Figure 12, we show the contributions to the EGB from both galactic smooth halos and subhalos. From the left panel of Figure 12, we see that the contribution to the EGB is subdominant for the annihilation of DM within galactic smooth halo. For our chosen galactic substructure model, this contribution is comparable to that from extragalactic DM halo. For the other case where the $\gamma$-ray flux from extragalactic DM annihilations have been calculated using $c_{\text{vir}}$ of the power-law model, the contributions from the galactic subhalos are fairly negligible.

6. SUMMARY AND CONCLUSION

We have chosen a simple DM model, namely, IHDM where the scalar sector of SM is extended by adding another SU(2)$_L$ doublet. The newly added doublet does not generate any vev after spontaneous symmetry breaking. The “inert” doublet is considered to be the DM candidate. The stability of DM is ensured by imposing discrete $Z_2$ symmetry. The model, in general, provides a broad range of DM mass from GeV to TeV. In this study, we only consider the lower mass range of the DM in this model. The analysis of experimental data for the DM relic density from the PLANCK experiment and the other direct detection experimental results for the case of this IHDM gives a set of best-fit values for the DM mass, annihilation cross-section, and other model parameters. We adopt this best-fit point (obtained using $\chi^2$ minimization) for the IHDM mass from such analyses. Thus, the DM mass of $\sim 63.5$ GeV is our chosen benchmark point in the present work. We study the $\gamma$-ray spectrum obtained from the annihilation of this chosen DM particle in the IHDM framework and interpret various types of continuum $\gamma$-ray fluxes with astrophysical origins measured by the Fermi-LAT satellite.

In this study, we compare our calculated $\gamma$-ray flux with the GC $\gamma$-ray excess in light of this model. For this purpose, we have employed different analyzed Fermi-LAT residual $\gamma$-ray flux data for different angular regions around the GC. The calculated low energetic photon spectra from the annihilation of the DM particle with a benchmark value of mass $\sim 63.5$ GeV in IHDM for various chosen regions surrounding the GC are found to be in the same range as reported by these studies. Although in some previous analyses it was argued that the photon spectra originating from different annihilation channels of DM particles with low masses could possibly fit the obtained data, very recent analyses have obtained the resulting best-fit masses of DM to be much more conservative (and also somewhat higher as well). We have computed the photon spectra for our benchmark scenario in the IHDM framework and have confronted with the residual photon spectra obtained for all of the above-mentioned studies. Our theoretical calculations for the photon spectra in this model have been performed after suitable parametrization of the DM halo parameters, ROI surrounding the GC, etc.

We also address the prospects of the continuum $\gamma$-ray signal which may come from DM-dominated dwarf spheroidal galaxies (dSphs) in case they originate from DM annihilation. We then compare the $\gamma$-ray flux that can be obtained from the benchmark IHDM DM with mass $\sim 63.5$ GeV. For this we choose 18 Milky Way dSphs whose $J$-factor can be estimated from measurements. The uncertainties in the measurement of the $J$-factor for different dSphs are also incorporated in our calculations. The calculated photon spectra for the IHDM benchmark point are observed to reside within the allowed limits for observed spectra of continuum $\gamma$-ray.

After addressing the issues regarding indirect DM searches with $\gamma$-ray signals from various galactic cases, we finally confront the extragalactic $\gamma$-ray signal with that from the annihilation of low-mass DM (considered in this work) in the IHDM scenario. We calculate the extragalactic $\gamma$-ray flux for different extragalactic parametrizations and compare with the observed extragalactic $\gamma$-ray background by EGRET and Fermi-LAT. For this purpose, we consider several possible classes of non-DM astrophysical sources which may yield a $\gamma$-ray signal embedded in the extragalactic background. Although there are too many uncertainties involved in modeling such astrophysical sources and other parameters for extragalactic flux calculation, we have shown that the considered low-mass DM in IHDM can generate a photon flux within the observed flux limit.

From detailed study of various galactic and extragalactic $\gamma$-ray searches probing the indirect signatures of DM in light of IHDM, we can conclude that the low-mass DM in this model framework is still a viable candidate to be probed in future $\gamma$-ray searches. Although we have performed a thorough analysis considering only a single Higgs-portal...
