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Constraint on the Annihilation Cross-section with Fermi Gamma-Ray Sky and HSC Lower Surface Brightness Galaxies

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Self interacting massive particles created as a consequence of thermal production in the early Universe are one of the most theoretically motivated candidate of dark matter (DM). Those particles can emit γ rays through annihilation processes and contribute to an observed cosmic γ-ray flux, and thus measurements of extragalactic γ-ray allow us to probe the nature of DM. In particular, annihilation cross-sections for DM has been constrained by comparing the observed γ-ray flux with a model of γ-ray flux induced by DM annihilation within nearby objects like Milky Way dwarf spheroidals (dSphs). In this work, we propose that low surface brightness galaxies (LSBGs) can be used as novel tracers of DM annihilation signals because those galaxies are more massive than Milky Way dSphs, which leads to production of more luminous γ-ray flux by DM annihilation. Moreover, it is expected to be less contaminated by extragalactic γ-ray sources (e.g., blazars) compared to star forming galaxies. We find that the upper limit with a joint analysis of the eight LSBGs detected by Subaru Hyper Suprime-Cam survey data and exclude (at the 95% confidence level) the annihilation cross-section for the $b\bar{b}$ channel higher than $\sim 10^{-23}$ [cm^3/s] for DM mass of 10 GeV. However our constraint is weaker than the ones reported in recent studies using other targets, we note that in near future observations, the number of LSBGs should be a few orders of magnitude larger, and the constraint with LSBGs on the DM annihilation cross-section can become stronger than the ones from other probes.

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1. Introduction

In several decades, researchers have discovered that dark matter (DM) contributes to $\sim 25\%$ of the energy density of the Universe. On the other hand, DM have not been still identified. To reveal the nature of DM is one of the most important subjects in astrophysics. One of the best theoretically motivated candidates for a dominant fraction of DM is Weakly Interacting Massive Particles (WIMPs, e.g., [1]), which can be produced in thermal equilibrium through interactions with standard model particles in the early Universe. Thus WIMPs can have some processes that they annihilate into standard model particles.In these processes, γ rays are produced directly or in cascade processes which are caused by unstable particles produced in the annihilation. Although γ rays induced by those processes would be very rare, we can search for DM annihilation signals by measuring how the γ-ray flux is strong in direction of high density regions of the Universe.

γ-ray telescope like the Fermi Large Area Telescope (*Fermi*-LAT), which is the latest and most sensitive γ-ray telescope in the energy range of 20 MeV to 1TeV, can observed the signal. In recent studies, nearby objects like the Milky Way or dwarf spheroidal galaxies (dSphs) have been probed to research the annihilation signal indirectly (e.g., [2, 3]). They have provided the upper limit of the DM annihilation cross-section by comparing the excess flux and a model flux for DM annihilation at the Galactic center or dSphs. It is true that the Galactic center is where the most luminous annihilating DM emission is expected, however, it is difficult to execute a robust analysis due to challenges to estimate highly astronomical gamma-ray contamination from gamma-ray sources such as star-forming regions, pulsars and supernova remnants. In case of dSphs, they have less the contamination so that to date they are the most desirable objects in the indirect search and provide the strongest constraints on the DM annihilation cross-section.

In this work, we propose a novel target for the indirect search; low surface brightness galaxies (LSBG), which have very low surface brightness of $> 23\ \mathrm{mag/arcmin^2}$ in most cases. They are highly DM dominated system, more massive than dSphs and are expected to have less astronomical contamination. Moreover, angular scale of LSBGs are smaller than the point spread function (PSF) of the *Fermi*-LAT, as a result we can consider LSBGs as not γ-ray extended sources but point ones. Finally in the future observation like the Large Synoptic Survey Telescope (LSST), the number of nearby LSBGs will increase more and more, a search for the annihilation signal using LSBGs will become a powerful probe to reveal the nature of annihilating DM.

In our analysis, we use a LSBG catalog with $\sim 200\ \mathrm{deg^2}$ of the sky for Subaru Hyper Suprime-Cam (HSC) Wide survey data [4], which includes ~ 800 objects. Using eight HSC-LSBGs, We provide current constraint on the DM annihilation cross-section with DM mass of GeV order with the *Fermi*-LAT observation.

2. Data and Observed Flux

In this section, we describe eight LSBG samples and *Fermi*-LAT data and obseved γ-ray flux of the eight LSBGs briefly. At first, in our analysis, we use the LSBG catalog of the HSC-Wide survey data of S16A with g, r, i-band (see [4] for reduction of this catalog in detail). This catalog contains about 800 objects with mean surface brightness of $> 24.3\ \mathrm{mag/arcmin^2}$ with $\sim 200\ \mathrm{deg^2}$ of the sky.

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In this work, we use 8 years (2008-08-04 to 2016-08-02) of *Fermi*-LAT observations. We selecte the photon event class `P8R3 SOURCE` and set the energy range of 500 MeV to 500 GeV with 26 logarithmically spaced energy bins, and as our region of interests (ROIs), select a patch of the sky of size $10^\circ \times 10^\circ$ with centroid in each LSBG.To construct photon counts maps or corresponding residual maps, we employ spatial bins of size 0.1 deg and derive instrument response functions (IRFs) `P8R3_SOURCE_V2`. Furthermore, we reject events with zenith angles larger than 100° to avoid contamination of photons produced by interaction of cosmic rays with the Earth's atmosphere. The analysis of the LAT data was done with `fermipy` [5], which is an open-source software package based on the `Fermi Science Tools(v11r5p3)`.

In the reduction of the residual maps, we perform the maximum likelihood analysis to estimate parameters for all γ-ray sources including isotropic or Galactic sources in our ROIs. In this analysis, we apply gll_iem_v07.fits, iso_P8R3_SOURCE_V2_v01.txt and the 4FGL point source catalog [6] as the Galactic emission template, the isotropic emission template and point source emission, respectively. We note that photons counts above a few of tens of GeVs hardly contribute to the overall observed emission.

To search for the excess of γ-ray emission for our LSBGs, we follow the procedure of [7], and to compute the flux upper limits of each LSBGs, we apply a Bayesian method giving in the 2FGL catalog [8]. As a result, we obtain the flux profiles for our LSBGs. All of our samples have no significant emission at 95% confidence level (C.L.). We note that some of our ROIs overlap with each other, however, in the computation of the combined limits with a joint likelihood procedure we assume that all of our ROIs are independent. Details on the methods utilized for converting flux upper limits into constraints for the DM annihilation cross-section are given in the next section.

3. Methods and Results

In this section, we provide a brief summary of our model for γ-ray flux induced by the DM annihilation from our LSBGs and our method to constrain the DM model parameters. The γ-ray annihilation flux from each LSBG can be written as

$$\frac{d\Phi_\gamma}{dE_\gamma} = J \times \frac{\langle \sigma v \rangle}{8\pi m_\chi^2} \sum_i Br_i \frac{dN_i}{dE'_\gamma}\bigg|_{E'_\gamma=(1+z)E_\gamma}, \tag{3.1}$$

where z is the redshift of the LSBGs, $\langle \sigma v \rangle$ is the ensemble average of the annihilation cross-section and relative velocity of DM particles, E_γ, E'_γ are observed and emitted γ-ray energy, m_χ is DM mass, dN/dE_γ is the γ-ray energy spectrum and Br_i is the branching ratio in the i-th annihilation channel, respectively. The J-factor, J contains any astronomical parameters related to target objects like the halo mass or distance. Other factors in the right-hand side of Eq. (3.1) depend on particle physical propertyies of DM. In our analysis, we consider the single annihilation channel $b\bar{b}$, and the DM spectra is obtained with the `DMFIT` package provided within `fermipy`. The `DMFIT` itself provides an interpolation to DM γ-ray spectra tables extracted from `DarkSUSY`.

To obtain the halo mass of our LSBGs, first, we convert the observed g, r and i band magnitudes into V band magnitude using $V = g - 0.59(g-r) - 0.01$ and the magnitude into absolute magnitude M_V with the halo distance d using $M_V = V + 5 - 5\log_{10} d$. Second is to estimate the stellar mass

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M_{sstar} setting the mass to light mass ratio to 1. Finally, we apply the stellar to halo mass ratio [9] for the crude estimate of the total halo mass $M_{\rm halo}$ of our LSBG samples.

In Table **??**, stellar mass and halo mass of the eight LSBGs are summarized. Below we describe for the J-factor calculation. The J-factor is defined as the line of sight integral of the squared DM density profile,

$$J = [1 + b_{\rm sh}(M_{\rm halo})] \int_s ds' \int_\Omega d\Omega' \rho^2_{\rm DM}(s', \Omega') \tag{3.2}$$

where Ω, $\rho_{\rm DM}$ and $M_{\rm halo}$ are the solid angle of the target object, the DM density profile and the halo mass, respectively. The the boost factor $b_{\rm sh}(M_{\rm halo})$ takes into account the excess of the annihilation rate due to the substructure present in the halo, here we set the factor to 1 for our samples. As for the dark matter profile, we assume the NFW density profile [10] and we obtain the J factor of our LSBGs from $\sim 10^{14-16}$ [$\rm GeV^2 cm^{-5}$]

We show the 95% C.L. upper limits on $\langle \sigma v \rangle$ using each individual LSBG (dashed lines) with their respective median J-factor in Figure 1 as well as one by the joint analysis of our eight LSBGs (black solid line). The green band displays the impact on our limits due to astrophysical uncertainties in the DM model parameters. Even after stacking over the full sample of eight LSBGs, our joint constraints are weaker than the ones obtained using more traditional targets like dSphs or nearby galaxy groups and clusters of galaxies [2, 3]. We confirm our assumption for the joint analysis that our LSBGs are independent from each other goes well within $\sim$ 10% fluctuation.

In addition, we have estimated the systematic uncertainties introduced by our Galactic diffuse emission model, which are provided by using the Cosmic Rays (CR) propagation code `GALPROP` (see [11] in more detail). Using the alternative Galactic diffuse emission models we repeated our $\langle \sigma v \rangle$ upper limits calculation and find that those are affected at the few percent level for DM mass values smaller than 100 GeV, while no difference was apparent for larger dark matter masses. This is shown by the black dotted lines in Figure 1.

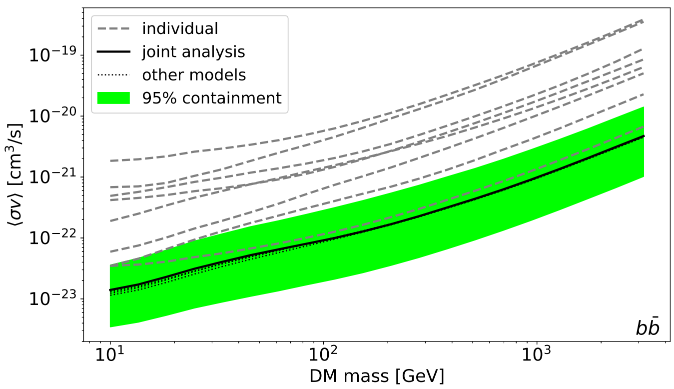

Figure 1: The 95% C.L. upper limits on the DM annihilation cross-section in the $b\bar{b}$ channel. Black solid line represents the upper limit obtained with the joint analysis assuming the median J-factor values of each LSBG, while black dotted lines show the joint 95% C.L. upper limits obtained after replacing our baseline galactic diffuse emission model by 3 different alternative models simulated with GALPROP. The green band displays containment region for our joint upper limits obtained by Monte Carlo sampling the individual J-factors.

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4. Summary

In this study, we proposed a new promising target, LSBG, to probe the DM annihilation signal using eight HSC LSBGs and the *Fermi*-LAT 8-year γ-ray observation. We found that our eight samples had no significant association with γ-ray sky in each ROI and γ-rays above 20 GeV were rarely observed in our ROIs. This fact indicates that LSBG has no significant γ-ray emission. We performed joint likelihood analysis to probe the annihilation cross-section of DM and provided upper limits on the cross-section as a function of DM masses, for example $\langle \sigma v \rangle \sim 10^{-23}$ [cm^3/s] at DM mass of 10 GeV. Although our constraint is fairly weaker than ones in recent studies using other targets like the center of Milky Way or the Milky Way dSphs, in future observations like LSST the number of LSBGs should increase in order of magnitudes and the future constraint on the cross section using LSBGs will become stronger in order of magnitudes. We should investigate a relation between the increase of the number of LSBGs and the constraint on the cross-section and develop the method to derive huge mount of LSBGs in our approach.

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