A new method to constrain the dark matter annihilation cross section by taking the cross correlation of γ-ray diffuse maps and galaxies is proposed. As a result, the statistical power of constraining the annihilation cross section is proportional to the galaxy mass and the inverse square of the distance to the galaxy. Therefore, for analyses using dwarf galaxies, the measurement of the distance to the dwarf galaxies is crucial for stringent constraints. However, measuring the distance to galaxies is, in general observationally expensive, particularly for faint or diffuse galaxies. Under the situation of stacking N galaxies, we show that the distance to the individual galaxy measurement is not required, but the overall distance distribution is sufficient for the cross section constraints. Further, based on real Large Area Telescope (LAT) data, we show that the effect of covariance between two galaxies located closely, typically comparable with the point spread function size of the Fermi-LAT, is negligibly small. We can independently stack the likelihood for the N galaxies, which dramatically reduces the computation costs. By using actual datasets of the LAT γ-ray sky and ∼800 faint objects discovered by Hyper Suprime-Cam, we find that the upper limit on the annihilation cross-section scales with 1/N. Therefore, it can be one of the most powerful and robust probe of the annihilation signal to stack more than 10^5 galaxies readily available with the Legacy Survey of Space and Time.

I. INTRODUCTION

In the last several decades, revealing the nature of dark matter (DM) has been a major challenge in modern cosmology and particle physics. As one of the most theoretical-motivated candidates for the DM of dominant fraction, weakly interacting massive particles (WIMPs) have been considered [1] and probed via different approaches by colliders, underground experiments and astronomical observations [e.g. 2, 3]. In the context of astrophysics, researchers often focus on probing signals from the self-annihilation or decay of WIMPs. In the early universe, WIMPs are considered to be produced in thermal equilibrium with standard model (SM) particles. As these interact with each other, WIMPs can annihilate into SM particles, particularly heavy SM particles, such as \( b \bar{b} \) and \( W^+W^- \) [4, 5]. As assumed that WIMPs are of DM abundance in the Universe, WIMP were reported to have an annihilation cross-section of \( \sim 2 \times 10^{-26} \text{cm}^3/\text{s} \) in the DM mass range while trying to elucidate the DM abundance, which is known as the thermal relic cross-section [6]. As a result of the annihilation process, γ rays can be produced directly or in secondary cascades that more massive states decay into more stable ones, particularly photons, electrons, positrons and neutrinos. Therefore probing these particles induced by DM annihilation gives clues to specify DM properties.

The Fermi Large Area Telescope (LAT) has revealed the γ-ray sky over more than a recent decade in the energy range from 20 MeV to 1 TeV. In the fourth γ-ray source catalog by the Fermi collaboration [7], the most detailed galactic diffuse emission was reported and point-source catalog containing about 5,000 objects with above 4σ detection level have been resolved. In addition, more than 3,700 sources have been found to have identified or associated counterparts of pulsars, supernova remnants and blazars. These results allow us to probe the DM annihilation signal from the galactic centre and halo [8-]
As another interesting component of the observed emission, there is residual emission obtained by subtracting the resolved point-source and galactic diffuse emission from observational data. It is interpreted as γ rays from unresolved extragalactic sources and is accordingly named as unresolved γ-ray background (UGRB), which has been studied to probe the annihilation signal by combining several low-redshift object catalogs for galaxies, galaxy groups and galaxy clusters [13–20]. The galactic and extragalactic targets have numerous γ-ray sources of astronomical origins. For robustness of the search for very faint signals, it is imperative to avoid contamination of γ-ray photons from astronomical sources in target objects. The search for γ-ray emission from Milky Way dwarf spheroidals (dSphs) is a robust DM probe [21–24] because Milky Way dSphs are expected to have quiescent star-formation activities; thus, they have less γ-ray emission from a star-formation region, pulsar and supernova remnant. Using 27 dSphs in our galaxy, [20] have an upper limit of the DM annihilation cross-section as $\sim 3 \times 10^{-27}$ cm$^3$/s at a 10 GeV DM mass with 95% C.L., which was much smaller than the thermal relic cross-section.

In our previous work [27], a low-surface-brightness galaxy (LSBG), which has less than $\sim 23$ mag/arcmin$^2$ mean surface brightness, has been proposed as a new target to probe the DM annihilation signal in UGRB. LSBGs are known to be highly dominated by DM [28, 29] and have more massive halos than Milky Way dSphs, $\sim 10^9 M_\odot$. Further, they have less star-formation activities and γ-ray emission from pulsars and supernova remnants than ordinary galaxies or galaxy clusters [20]. However, owing to their faint fluxes, it is more difficult to measure their redshifts than ordinary galaxies. Therefore, in our previous work, we used an LSBG catalog constructed by [31] using the Hyper Suprime-Cam (HSC) data. Although this catalog contained ~800 objects, we could only use eight LSBGs with precisely measured redshift because of the unknown redshifts of other objects.

In this study, we propose a method to access a large number of objects without knowing their redshifts for probing the DM annihilation signal. We focus on the redshift distribution of an entire catalog instead of the redshifts of individual objects. For measuring the redshift distribution, we apply the redshift clustering method [32–34]. To validate the proposed method, we demonstrate the redshift clustering method and a composite likelihood analysis for probing the DM annihilation signal using full samples of the HSC-LSBG catalog and the UGRB emission constructed from γ-ray observation data by the Fermi-LAT. To reduce the computational cost, in the likelihood analysis we assume that all γ-ray components for the LSBGs are independent; however, in fact neighboring objects correlate because their mean angular separation is smaller than the point spread function (PSF) of the Fermi-LAT in an energy level lower than a few GeV. Therefore, we verify our assumption by estimating covariance on the model parameters of neighboring objects. We also discuss the power of stacking numerous objects in the likelihood analysis. Because LSBGs are potentially abundant in the local universe, some extremely deep galaxy surveys by next-generation telescopes such as the Legacy Survey of Space and Time (LSST), are planned in the future; a significant number of LSBGs will be discovered. Then LSBGs can be the most desirable target for the indirect search of the DM annihilation signal.

This paper is organized as follows. In Section II we visit the method of γ-ray emission modeling for target objects and the redshift clustering method. In Section III we demonstrate the proposed approach using HSC-LSBGs and Fermi-LAT data. We present a scaling relation of constraint on the DM annihilation with $N_{\gamma}$ objects in Section IV. Finally, we conclude this study in Section V.

II. THEORETICAL FRAMEWORK

In this section, we present our approach to constrain the DM annihilation cross-section using cross-correlation between diffuse γ-ray background and the massive nearby objects expected to be highly DM dense regions, such as dSphs, faint galaxies and normal galaxies, without individual distance measurement. For the analysis feasibility, we require an overall probabilistic distribution of the objects along the line of sight.

Here, we assume that all objects are statistically independent, which dramatically simplifies the stacking likelihood analysis. In Subsection IV A we evaluate the validity of this assumption.

A. γ-ray flux modeling for DM annihilation

Through the DM annihilation process, γ-ray photons are generated directly or in the cascade process in which various final states (e.g. $b\bar{b}$, $W^+W^-$ and $\mu^+\mu^-$) decay into more stable particles. The γ-ray flux $\frac{d\Phi_{\text{ann}}}{dE}$ produced by DM annihilation can be modeled as follows,

$$\frac{d\Phi_{\text{ann}}}{dE} = J \times \frac{\langle \sigma v \rangle}{8\pi m_\chi^2} \sum_i B_{ri} \frac{dN_i}{dE}, \quad (1)$$

where $m_\chi$ is the DM mass and $\langle \sigma v \rangle$ is the average DM annihilation probability. $B_{ri}$ and $\frac{dN_i}{dE}$ are the branching ratio and γ-ray energy spectrum of γ-ray photon in the $i$–th annihilation channel, respectively. In the analysis, we consider $b\bar{b}$ as a representative annihilation channel and obtain $dN_{b\bar{b}}/dE$ by DMFIT [33] included in the LAT.

\footnote{https://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/gammanc_dif.dat}
science tool, \texttt{fermipy}. \( J \) is the so-called J-factor, which is characterized by DM halo properties as follows,

\begin{equation}
J = [1 + b_{sh}(M_{\text{halo}})] \int_s ds' \int_{\Omega} d\Omega' \rho_{\text{DM}}^2(s', \Omega'),
\end{equation}

where \( s', \Omega' \) and \( M_{\text{halo}} \) are the line-of-sight vector, solid angle and halo mass of target objects, respectively. The annihilation signal may increase if we have clumpy substructures within a halo instead of the smooth halo. This can be effectively modeled as a boost factor, \( b_{sh} \) \cite{39}. For clarity, we set \( b_{sh} = 1 \) for all mass-scale halos throughout this paper. The DM density profile is assumed to follow the Navarro-Frenk-White (NFW) profile \cite{37}.

\begin{equation}
\rho_{\text{DM}}(r) \propto \frac{1}{cr/r_{\text{vir}} [(cr/r_{\text{vir}}) + 1]^2},
\end{equation}

where \( c(M_{\text{halo}}) \) is the concentration parameter. The concentration parameter primarily depends on the halo mass and we compute it using the fitting formula to model the scaling relation of \( c(M) \) with halo mass, calibrated using the high-resolution N-body simulations \cite{38}. We convert the halo mass to the concentration by using \textsc{COLOSSUS} \cite{39}.

The full description of J-factor estimation can be found in \cite{27}. A brief summary is as follows. We first convert the observed magnitude into the absolute magnitude. The V-band apparent magnitude can be converted from the gri system as \( V = g - 0.59(g - r) - 0.01 \) \cite{10}. Now, the situation is that we do not have the distance to individual galaxies but an overall distribution. However, we can formally write the distance of each galaxy as a random draw from the distribution: \( d \in dN/dz(z) \). For the particular realization of the random draw of the distance with the binding condition of \( \langle d \rangle = dN/dz \), the absolute magnitude can be computed; thus, the halo mass can be derived by assuming the relations of mass-to-light ratio \cite{41} and stellar to halo mass ratio \cite{12}.

Given that we have the overall \( dN/dz \) distribution, with measurement errors, we can simulate the effect of neglecting distance to individual galaxies. Figure 2 shows the distribution of the total J-factor after stacking \( N_{\text{st}} \) galaxies. For this plot, we use the HSC-Y1 LSBG sample, where no distance is available. The \( N_{\text{st}} \) LSBGs are randomly selected from the parent sample 500 times. The scatter in the figure correspond to the 95\% ranges due to the sample variance.

### B. Measurement of the redshift distribution of photometric samples

In this subsection, we describe a method to estimate the \( dN/dz \) distribution from spatial clustering, so called the clustering redshift method. The application of the method to the data is shown in Subsection III C.

Given two galaxy samples in an overlapped region. Even if the galaxies in the two galaxy samples are statistically different, they both correlate with the underlying DM distribution. In the case where one galaxy sample has known redshifts and the other has unknown redshifts, taking the cross-correlation between the two galaxy samples gives a statistical estimate of the redshift distribution of the galaxies with unknown redshifts. We denote the galaxy samples with known and unknown redshifts as ‘spectroscopic sample’ and ‘photometric sample’, respectively. The angular cross-correlation function can be factorized as follows \cite{32}.

\begin{equation}
w(\theta) = \int_0^{\infty} dz \frac{dN_p}{dz} \frac{dN_s}{dz} b_p(z) b_s(z) w_{\text{DM}}(z, \theta),
\end{equation}

where subscripts ‘\( s \)’ and ‘\( p \)’ represent spectroscopic and photometric samples, respectively. \( dN/\Delta z \) represents the redshift distribution normalized to unity, \( b(z) \) is a linear bias, and \( w_{\text{DM}}(z, \theta) \) is the angular DM correlation function. Notably, the mass of the employed DM model is high enough not to affect the DM clustering pattern itself. We define an integrated cross-correlation \( \bar{w} \) with a weighting function \( W(\theta) \) as follows

\begin{equation}
\bar{w} = \int_{\theta_{\text{min}}}^{\theta_{\text{max}}} d\theta \left( W(\theta) w(\theta) \right),
\end{equation}

where the weight \( W \) is introduced so that the signal to noise ratio of \( \bar{w} \) can be optimised. Following \cite{33}, we empirically adopt \( W = \theta^{-1} \). In practical measurement, we divide the spectroscopic sample into narrow redshift bins so that \( dN/\Delta z \) can be approximated by the narrow top-hat function; \( dN/\Delta z = 1/\Delta z \) if \( z_1 < z < z_{i+1} \). Now we rewrite Equation 5 at \( z = z_i \) as follows

\begin{equation}
\bar{w}(z_i) \approx \frac{dN_p}{dz}(z_i) b_p(z_i) b_s(z_i) \tilde{w}_{\text{DM}}(z_i),
\end{equation}

where \( \tilde{w}_{\text{DM}}(z) \) can be defined similarly as Equation 5 by replacing \( w(\theta) \) with \( w_{\text{DM}}(z, \theta) \). This is fully predictable from the standard cold DM theory including the non-linear matter clustering evolution. Otherwise, \( w(\theta) \) can be treated as a constant if the range of the redshift over which we are going to estimate is small enough. A better estimation might be to replace \( w(\theta) \) with the square of the linear growth factor, \( D^2(z) \). Before concluding to directly connect measurement to the \( dN_p/\Delta z \), we need to address the bias functions. The bias of the spectroscopic sample \( b_s \) can be measured using the sample auto-correlation. The redshift evolution of the photometric sample \( b_p \) is fully degenerated with the \( dN_p/\Delta z \) and cannot be further decomposed. In this study, we assume the redshift evolution of the bias can be negligible as the redshift range is small \( 0 < z < 0.15 \).

### III. RESULT

To validate the proposed method, we applied it to the LSBG samples \cite{34} observed with the HSC survey. The 781 LSBG samples in \( \sim 200 \text{ deg}^2 \) of the HSC region do
not have individual distance measure, but we have the spec-z samples from NASA Sloan Atlas (NSA) on an almost fully overlapped sky area. Using γ-ray background sky constructed from the Fermi-LAT data, we demonstrated the composite likelihood analysis for probing the DM annihilation signal with all HSC-LSBGs using given individual redshift by random draw from measured $dN/dz$.

A. Data

1. HSC-LSBG catalog

HSC is a wide-field camera, attached to the prime focus of the Subaru telescope, covering $\sim1.5\degree$ diameter field of view with 0.17 arcsec pixel scale. The HSC Subaru Strategic Program survey consists of three layers, wide, deep and ultradeep layers; the wide layer has five broad photometric bands $g,r,i,z$ and $y$. As described in a report of the second data release of the survey by [44, 45], the wide layer has a depth of 24.5–26.6 in the 5 filters for $5\sigma$ point-source detection. In the final data release, the survey will cover 1400 deg$^2$ sky in a depth of $i \sim 26$ mag.

Since the HSC pipeline, hscpipe, is not optimized for detecting and measuring diffuse objects, HSC images are reduced first by the hscpipe and then SExtractor is used for detection and measurements. [31] processed an HSC dataset with three broad bands ($g,r$ and $i$) on a patch-by-patch basis over $\sim$200 deg$^2$ and produced a catalog comprising 781 LSB objects, which have a mean surface brightness in $g$-band $> 24.3$mag/arcsec$^2$. Briefly, the following processes have been executed: (i) bright sources and associated diffuse lights are subtracted from images to avoid contamination to LSB objects detection; (ii) after the Gaussian smoothing with full depth at half maximum of $1''$, sources with the half-light radius $r_{1/2}$ satisfying $2.5'' < r_{1/2} < 20''$ are extracted; (iii) the sources are selected by applying reasonable color cuts to remove optical artifacts and distant galaxies; (iv) by modeling the surface brightness profiles of LSBG candidates, astronomical false positive are removed; (v) by visual inspection, false candidates such as point-sources with diffuse background lights are removed and then 781 LSBGs are finally left.

To minimize a possible contamination of astrophysical γ-ray photons, it might be useful to restrict our analysis to quiescent galaxies, because such galaxies do not have ongoing star-formation activities and therefore unlikely contain high-energy astrophysical sources such as supernova remnants and AGNs, at least compared to star-forming blue galaxies. We divide the sample into red and blue LSBGs, where red is defined by $g - i > 0.64$ and blue $g - i < 0.64$, which include 450 and 331 objects, respectively. This color selection roughly corresponds to the galaxy age of 1 Gyr for a $0.4 \times$ solar metallicity galaxy [31]. For a random catalog corresponding to the LSBG catalog, we employ the random catalog of the HSC photometric data, and randomly resample it such that the number density is roughly 10 times larger than the LSBG density. We also apply the bright star mask to the random catalog.

2. NSA sample

For measuring the $dN/dz$ distribution, we need reference spec-z samples in the overlapped region in both sky-coverage and redshift range. Since the LSBGs are likely detected in the nearby universe, we need a low-redshift spec-z sample. The NSA sample$^2$ is a spec-z sample obtained from the spec-z campaign of the Sloan Digital Sky Survey with the Galaxy Evolution Explorer data for the energy spectrum of the ultraviolet wavelength and includes objects up to $z = 0.15$. Since the uniformity of the NSA sample is not guaranteed, we attempt to mitigate the non-uniformity as follows. First, we remove the sample from both HSC and NSA in the bright star masked regions. We checked that, after removing the masked regions, the local number density of NSA galaxies smoothed with each HSC patch has a uniform distribution in most areas of the HSC regions we are working on, except for the low-density region in the VIMOS-VLT Deep Survey (Dec. >1). We generate random catalog including about 10 times more objects than that of the NASA galaxies. In addition, we removed the edge regions in the HSC survey footprint for safety, because the exact survey window near the boundaries is difficult to define.

3. Fermi-LAT data

For γ-ray data to probe the DM annihilation signal, we analyze Fermi-LAT Pass 8 data obtained from 2008-08-04 to 2016-08-02, which is the latest version of the entire mission dataset based on the updated reconstruction algorithms [47]. In this subsection, we describe how we reduce the raw γ-ray photon count to the scientifically usable maps where the contributions from point sources and galactic foreground emissions are removed. As recommended by the Fermi collaboration, [48] we select the photon event class P8R3 SOURCE, as the photon count data, which is the most suitable class for the point-source analysis. In addition, we apply the following selections, DATA_QUAL$>0$, LAT_CONFIG==1 and P8R3_SOURCE_V2, as the corresponding filter expression and the instrument response function for the event class, respectively. We use the photon count in the energy range from 500 MeV

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$^2$[https://data.sdss.org/sas/dr13/sdss/atlas/v1/nsa_v1_0_1.fits](https://data.sdss.org/sas/dr13/sdss/atlas/v1/nsa_v1_0_1.fits)

$^3$[https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_Data_Exploration/Data_preparation.html](https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_Data_Exploration/Data_preparation.html)
to 500 GeV with 24 logarithmically spaced energy bins and 0.1° spatial grid size. In all energy bins, the width of each bin is considered to be larger than the energy dispersion, and we require intervals of each spatial bin to be smaller than the LAT PSF at all considered energy ranges. The lower energy scale is determined to balance two opposing effects. If we lower the energy scale, photons around bright sources likely leak due to the broadening of PSF, but if we increase the scale, the number of photons available decreases. For the upper limit, we consider that the LAT performance decreases in an energy regime higher than 500 GeV.

For the composite analysis described in Subsection III B we select 29 patches whose centers are located in the HSC regions with the separation of at least 3° from each other and individual patches having $10^3 \times 10^3$ sky coverage. Moreover, to avoid contaminating the γ-ray photons produced by the Earth’s atmosphere interaction with high energy cosmic rays, we exclude the photon data with zenith angles greater than 180°. In the LAT data analysis, we use fermipy (v1.0.1) [49], which is an open-source software package based on the Fermi Science Tools (v2.0.8) [50].

4. UGRB construction and putative flux

To obtain the likelihood profile for the UGRB flux at the position of each LSBG for the composite likelihood analysis, following [21], we revisit the procedure to construct the background and estimate the profile at the LSBG position.

First, for constructing a UGRB, we perform maximum likelihood analysis in each patch to optimize the normalization and spectral parameters of flux models for all sources without our LSBGs in the patch, including the galactic diffuse emission, isotropic emission and detected sources by Fermi-LAT. To derive the flux models of all sources above, for the galactic and isotropic emission models, we adopt the standard (gll_iem_v07.fits) and the isotropic emission template (iso_P8R3_SOURCE_V2_v01.txt) respectively. The isotropic template represents isotropic contributions from undetected extragalactic sources and residual cosmic ray emission. We also derive resolved point-source models from the 4FGL catalog [7]. Notably, we confirm the nonexistence of any additional point source of test statistics (TS) larger than 25 in our patches.

After the UGRB construction by subtracting the model emissions from the observed flux, we estimate the background flux in each energy bin at the LSBG position to assess a putative flux of our LSBG. According to the prescription described in the 2FGL catalog, the Bayesian method [51] should be applied for the likelihood analysis of very faint sources [51]. To measure the UGRB flux at the position of each object energy bin-by-bin, we assume a power-law model with normalisation parameter $\alpha_{i,j}, d\Phi/dE = \alpha_{i,j}(E/1\text{GeV})^{-2}$, as the $i$–th LSBG flux model in the $j$–th energy bin. Here we define TS as $TS = -2\Delta \log \mathcal{L}$ and $\Delta \log \mathcal{L}$ is given as follows:

$$\Delta \log \mathcal{L} = \log \mathcal{L}(D, \Theta|\alpha_{i,j} = 0) - \log \mathcal{L}(D, \Theta|\alpha_{i,j}^{\text{max}})$$

where $D$ and $\Theta$ are the LAT data and the nuisance parameters of flux models for all γ-ray sources except for our LSBGs, which is fixed by the maximum likelihood runs when constructing the UGRB field; $\alpha_{i,j}^{\text{max}}$ is a value when $\log \mathcal{L}(D, \Theta|\alpha_{i,j})$ is the maximum value and $\alpha_{i,j} = 0$ means no target source. We confirm that TS values at all LSBG locations in the UGRB are less than 1 in most energy bins, which shows validity of adopting the Bayesian method following the way in [21]. In Subsection III B we perform a composite likelihood analysis with all HSC-LSBGS based on the Bayesian method using the flux likelihood of each LSBG in Equation 7 as priors.

B. Composite analysis

As described in Subsection III A 4 because of the very low γ-ray emission signal for our LSBGs, we apply the Bayesian method for the likelihood analysis, which is performed following the same approach of our previous work [27]. In the computation of the 95% C.L. the upper limits of the DM annihilation cross-section, we employ the Bayesian method for the analysis of faint objects. Since all likelihood values obtained at each object are assumed to be independent of each other, the composite likelihood $\mathcal{L}_{\text{st}}$ for the full sample of targets can be expressed as follows:

$$\log \mathcal{L}_{\text{st}}(\alpha | \langle \sigma v \rangle, J) = \sum_{i,j} \log \mathcal{L}_{i,j}^{\text{ann}}(\alpha_{i,j}|\{(\langle \sigma v \rangle, J_i)\})$$

where $J_i$ is the $J$-factor of the $i$-th target and the index $j$ runs over all energy bins. $\mathcal{L}_{i,j}^{\text{ann}}$ is the log-likelihood value for the $i$-th LSBG, which is obtained from the delta-likelihood in Equation 7 by substituting a normalization parameter which corresponds to the flux amplitude of $d\Phi_{\text{ann}}/dE(\langle \sigma v \rangle, J_i)|_{E = E_j}$ to $\alpha_{i,j}^{\text{max}}$.

Now we calculate the $J$-factor for each object to evaluate the model flux described in Subsection II A. For the simplicity of Equation 2 we need to consider the relationship between the PSF of the LAT instrument and the angular size of objects. The PSF (68% containment angles) decreases from $\sim 1.5°$ to $\sim 0.1°$ as γ-ray energy increases from 500 MeV to 500 GeV. The angular size of LSBG is smaller than a few 10 arcsec, hence smaller than the PSF in all energy bands. Therefore, we can consider them as point-like sources in the likelihood procedures. Then, the integration of $\rho_{\text{DM}}$ over the target...
volume in Equation 2 is reduced to:

$$\int ds \int d\Omega \rho^2_{\text{DM}}(s, \Omega) \to \int dV \rho^2_{\text{DM}}(r)/d_A^2,$$

(9)

where $d_A$ is the angular diameter distance to the object, which is given by assignment of distance randomly drawn followed the measured $dN/dz$ distribution. Then, Equation 9 is straightforwardly calculated; finally, we can write Equation 2

$$J = (1 + b_{\text{sh}}) \frac{M_{\text{halo}}}{d_A^2} \frac{\Delta \rho_{c,z} c^3}{9} \times$$

$$\left[1 - \frac{1}{(1 + c)^3}\right] \left[\log(1 + c) - \frac{c}{1 + c}\right]^{-2}.$$ (10)

Since our targets are regarded as point sources, our assumption is correct if the angular separations between objects are larger than the LAT PSF over all considered energy ranges; otherwise, it is incorrect because their mean surface number density is about 4 per deg$^2$. We will further discuss the parameter correlation between neighboring objects in Subsection IV A. In our procedure, we assume that the LSBG flux is positive definite, which implies that the data are well-described by a $\chi^2$ distribution rather than $\chi^2$. As such, the 95% C.L. upper limits on the cross section $\langle \sigma v \rangle_{\text{UL}}$ are given when the $\Delta \log L_{\text{th}}(\alpha_{i,j} | \langle \sigma v \rangle, J) \sim -3.8/2$.

C. $dN/dz$ measurement

In this Subsection, according to the method described in Subsection II B, we measure the $dN/dz$ distribution of the HSC-LSBG sample. We divide the reference redshift sample into five equally separated bins from $z = 0$ to 0.15. Then we take the cross correlation between the sample in each bin and the entire LSBG sample. The angular cross correlation is computed by the estimator [52] in angular bins of $0.1^\circ < \theta < 1.0^\circ$, logarithmically uniformly sampled,

$$w(z_i, \theta_j) = \frac{D_p D_{s,i} - D_p R_{s,i} - R_p D_{s,i} + R_p R_{s,i}}{R_p R_{s,i}},$$

(11)

where DD or DR represent the normalized number of pairs separated within the $j$-th angular bin between data and data or data and random, respectively. Subscripts $p, s, i$ and $r$ represent the photometric sample and reference sample in the $i$-th redshift bin, respectively. We omit the argument of $\theta_j$ on the right hand side where no confusion arises. For the spec-z samples, we apply the weight developed by [53] for a rigorous optimal variance with the galaxy power spectrum,

$$w_{\text{FKP}}(r) = \frac{1}{1 + n(r)P_0}$$

(12)

where $P_0 = 1000h^{-3}\text{Mpc}^3$ is the amplitude of the power spectrum at the scale where the variance is optimal and $n(r)$ is the comoving number density of samples at the position.

To evaluate statistical uncertainties for $\langle \sigma v \rangle_{\text{UL}}$ we use the Jackknife subsampling method [54]. We divide the HSC-LSBG and NSA samples into 100 subregions where individual regions have independent $\sim 2$ deg$^2$ sky coverage. The covariance matrix $C_{ij}$ is defined by

$$C_{ij} = \frac{M - 1}{M} \sum_{k=1}^{M} [w_k(z, \theta_i) - \bar{w}(z, \theta_i)] [w_k(z, \theta_j) - \bar{w}(z, \theta_j)],$$

(13)

where $w_k(z, \theta_i)$ is the angular correlation measurement for the $k$-th Jackknife sub-sample and $M$ is the number of the Jackknife sub-samples, $M = 100$. $\bar{w}$ is the averaged correlation function over all jackknife sub-samples,

$$\bar{w}(z, \theta_i) = \frac{1}{M} \sum_{k=1}^{M} w_k(z, \theta_i).$$

(14)

When converting $\bar{w}(z_i)$ to $dN_{\text{p}}/dz$ in Equation 6 we assume that the linear bias of the spec-z samples is unity. Figure 1 represents the $dN/dz$ distribution measurement. The errors are measured using the Jackknife resampling implemented in the treecorr [55].

D. Evaluation of statistical uncertainty

To evaluate statistical uncertainties for $\langle \sigma v \rangle_{\text{UL}}$ in the composite analysis, we consider uncertainties of halo mass and concentration parameter as well as the $dN/dz$ measurement error on 500 Monte Carlo simulations. First, for the halo mass, we evaluate its uncertainty as $\Delta \log M_{\text{halo}} = 0.8$ at 1-$\sigma$ Gaussian error by computing the scatter of stellar-to-halo-mass conversion. In addition, we adopt a concentration parameter error of $\Delta \log c$.

![FIG. 1. The $dN/dz$ of blue (blue colored) and red (red colored) HSC-LSBGs. Note that error bars present 2-$\sigma$ level of an uncertainty by considering error estimation of the Jackknife subsampling for the angular cross-correlation of HSC-LSBGs with NSA samples.](image-url)
of 0.1 at 1-σ Gaussian error [56]. Accordingly, the total uncertainty for halo properties results in J-factor uncertainties of ~0.9 dex at 1-σ error. Moreover, we randomly assign the distance to galaxies according to this distribution; therefore, the negative values of the probability are strictly prohibited. Thus, in our analysis, the amplitude in each redshift bin is considered a free parameter, and we provide the confidence intervals based on the posterior distribution. Given that the measurement gives the likelihood of the form of the Gaussian, 

\[ P(\alpha_i | D) \propto \exp[-(\alpha_i - \hat{\alpha}_i)^2 / 2\sigma_i^2] \]

where the variables are measurement. Then the stepwise prior, \( P(\alpha_i) = 0 \) for \( \alpha_i < 0 \) and 1 otherwise is applied. Further, we compute the maximum \( \alpha_i \) and 95 percentiles from the posterior distribution \( P(\alpha_i | D) P(\alpha_i) \). We finally apply linear interpolation between each center of redshift bin to the posterior distribution. We take a conservative limit of the minimum redshift of the sample corresponding to 25 Mpc, which is the minimum distance among the HSC-LSBG samples with precisely measured distance.

In Figure 2 we show the total J-factor values as a function of the number of stacked objects, \( N_{st} \). In the order of square, cross and circle symbols, the error-bars plot the total values including \( dN/dz \) measurement uncertainty, halo property and both, respectively. For comparison with relevant works for probing constraint on the DM annihilation cross-section, we display \( \langle \sigma v \rangle_{UL} \) with 95% C.L. for DM mass of 1 TeV in the right axis, which corresponds to the J-factor value on the left axis. Note that when converting J-factor to \( \langle \sigma v \rangle_{UL} \), we apply a mean flux of our UGRB sky. The upper limit is affected by both the fluctuation and target’s J-factor value, however we find that, even in the lower energy regime, the scatter by the fluctuation is smaller (\(~0.4 \text{ dex at 2-σ level}\) than the total halo property and \( dN/dz \) measurement uncertainty.

**IV. DISCUSSION**

A. Correlation between neighbors

We performed the composite likelihood analysis in Subsection III B assuming that the likelihood functions of individual objects are independent of each other. Such correlations are expected when the number density of the sample is high because the PSF of Fermi-LAT is \(~1^\circ \). In this Subsection, we demonstrate that the correlation between data at different points can be negligible.

In the HSC-Fermi sky coverage, we select 10 independent patches with the size of 10 \times 10 \text{ deg}^2. From each patch, we randomly select 60 pairs of points with separations of 0.5° to 3°. To evaluate the correlation between the putative flux amplitudes of the paired objects, we perform the joint likelihood analysis for the pairs, which simultaneously optimizes the fluxes of the paired objects.

**Figure 2.** Total J-factor values of HSC-LSBG summed over \( N_{st} \) samples taken randomly from 781 samples. The error bar with filled square includes \( dN/dz \) measurement uncertainty, cross symbol includes halo property uncertainty and circle symbol includes both. Each error bar shows 95% confidence region based on 500 Monte Carlo simulations. The right axis shows \( \langle \sigma v \rangle_{UL} \) for DM mass of 1 TeV with 95% C.L. corresponding to J-factor value in the left axis.

The putative flux of an object is parameterized as

\[
\frac{d\Phi}{dE} = \alpha \left( \frac{E}{1000 \text{[MeV]}} \right)^{-2}.
\]

Figure 2 shows the absolute value of the correlation between two amplitude parameters as the function of the separation. The error-bars are computed from the 60 independent pairs that reflects the fluctuations of the residual gamma-ray flux. The cross-covariance is normalized by the diagonal terms, i.e., \( \rho_{ij} \equiv \text{cov}(\alpha_i, \alpha_j) / \sigma_i \sigma_j \). Although we expect strong correlation on scales smaller than 1 deg. because of the PSF size of Fermi-LAT, the correlation at the smallest separation, which corresponds to the HSC-LSBG mean separation, the correlation is less than 0.1 at 1-σ level. We note that all the cross correlation is negative at all scales, which is the consequence of the conservation of the total flux. For further validation, we perform a composite likelihood analysis in which we obtain the likelihood profiles for putative fluxes of all samples within a single LAT data patch simultaneously. Figure 2 compares the \( \langle \sigma v \rangle_{UL} \) constraints with this simultaneous approach ('simultaneous' case) with the one obtained based on the assumption that all objects are independent of each other ('independent' case). We emphasize that the 'independent' case provides a weaker constraint on \( \langle \sigma v \rangle_{UL} \) than the 'simultaneous' case. This is because the total flux conservation is imposed, which results in the larger putative flux amplitude in the 'independent' case than 'simultaneous' case. Note that in this calculation, we set all objects’ J-factor to \( 10^{14.5} \text{ GeV}^2/\text{cm}^5 \) and choose a specific \( dN/dz \), therefore, the amplitudes of \( \langle \sigma v \rangle_{UL} \) in Figure 2 do not correspond to the ones in Figure 2.

We conclude that the correlation between neighboring points is less than 10%, on scales 0.5 deg. and even if
The off-diagonal value of covariance matrix between two amplitude parameters for each paired objects as a function of separation angles. The error bars represent 1-σ errors of the off-diagonals with 60 pairs in each angular bin.

The difference between $\sigma$ in the composite analysis with all LSBGs in the simultaneous approach (solid line) and the one with assumption of flux likelihood profiles of all LSBGs being independent of each other (dotted line) as a function of DM mass. (Bottom) The ratio of the upper limits in the two cases.

In this Subsection, we discuss a scaling relation of the statistical power on $\langle \sigma v \rangle_{UL}$ as a function of the number of stacking, under the low background photon limit. We will show that $\langle \sigma v \rangle_{UL}$ becomes more stringent proportional to the $N_{st}$ at high mass limit but scales as $\sqrt{N_{st}}$ at low mass ranges. We will also show that this scaling relation converges to $N_{st}$ whatever the DM mass if the $N_{st}$ is sufficiently large.

First, we revisit a Poisson likelihood for a single LSBG in the UGRB. The likelihood function for model parameters is given by the Poisson distribution,

$$\mathcal{L} = \prod_i \frac{\lambda_i^{n_i} e^{-\lambda_i}}{n_i!},$$

where the index $i$ runs over all energy bins and pixels and $n_i$ is the observed photon counts; $\lambda_i$ is expected photon counts for model fluxes, which is decomposed into the Galactic foreground, isotropic background and resolved point-source model fluxes as well as the flux by the DM annihilation for the single LSBG. A UGRB sky is derived from the modeling of all the $\gamma$-ray sources except for the LSBG flux as described in Section [III.A]. Therefore, fixing the model parameters $\Theta$ of the background sky, $\lambda_i$ depends only on the single parameter, $\langle \sigma v \rangle$. We denote $\lambda_i = \lambda_{i}^{\text{others}}(\Theta) + \lambda_{i}^{T}(\langle \sigma v \rangle)$, where $\lambda_{i}^{\text{others}}$ is the total model flux of all sources without LSBG and $\lambda_{i}^{T}$ is the model flux of LSBG. For simplicity, we consider that all LSBGs have the same J-factor, which means that their model fluxes are equal. In addition, we consider the fact that, in energy regimes higher than $\sim 30$ GeV, the LAT hardly detects photons. Given that there is no photon count ($n_i = 0$) in such energy regimes and in all pixels, we expect $\lambda_{i}^{\text{others}}(\mu) = 0$ and then log $\mathcal{L} = -\sum_i \lambda_i^{T}(\langle \sigma v \rangle)$.

Consequently, we obtain the composite likelihood with $N_{st}$ objects using Equation [8]

$$\Delta \log \mathcal{L}_{st} = -N_{st} \sum_i \lambda_i^{T}(\langle \sigma v \rangle),$$

where $N_{st}$ is the number of objects in the composite analysis. Therefore, in our criteria the upper limit is proportional to $1/N_{st}$ because of $\lambda_i^{T}(\langle \sigma v \rangle) \propto \langle \sigma v \rangle$.

In Figure [5] we show the ratio of $\langle \sigma v \rangle_{UL}$ with $N_{st}$ objects to the one with a single object for DM mass of 10 GeV, 100 GeV and 1 TeV. With $N_{st}$ larger than $\sim 30$, the upper limits scale with the inverse of $N_{st}$ for all mass ranges. For DM mass of 100 GeV and 1 TeV, this scaling relation is seen, even in smaller $N_{st}$. This behavior is reasonable, considering the photon-count statistics in a high energy regime. The annihilation process with more massive DM particles can produce higher energy photons, thus probing the DM annihilation for more massive DM is affected by photon-count statistics in high energy regimes.

### V. SUMMARY

In this study, we proposed to take a cross correlation between $\gamma$-ray sky and potential $\gamma$-ray sources with unknown redshifts for probing the DM annihilation signal. The most important point is that we do not need to measure the individual distance to the $\gamma$-ray sources but the overall redshift distribution is sufficient to constrain the DM annihilation cross section. By applying the redshift clustering method, we obtained a redshift distribution of total samples instead of redshifts of individual objects and then we randomly assigned the distance to
we performed a composite likelihood analysis in which we obtained the likelihood profiles for putative fluxes of all samples in each LAT patch simultaneously. By comparing $\langle \sigma v \rangle_{UL}$, we found that the constraints differs at most factor of 2. Moreover, if we take the data independently, the constraints become more conservative due to the relaxation of the total flux conservation condition. This means that even if we ignore the correlation among the data, particularly due to the reduction of the computational cost, we do not need to worry about the artificial constraint.

Finally, we found the scaling relation of $\langle \sigma v \rangle_{UL}$ with the number of objects $N_{st}$ in the composite likelihood analysis. Under an assumption of no observed photon, we found that $\langle \sigma v \rangle_{UL}$ is proportional to $1/N_{st}$ analytically. In addition, using the HSC-LSBGs, we computed the scaling for DM mass of 10 GeV, 100 GeV and 1 TeV and showed that for all DM masses the upper limit scales with $1/N_{st}$ using $N_{st} \gtrsim 30$. This is the significant effect which is the consequence of the Poisson statistics and is different from the Gaussian statistics in which the scaling obeys $1/\sqrt{N_{st}}$.

In future imaging surveys with next-generation telescopes such as the LSST, a huge amount of LSBGs will be detected because of wider sky coverage and better sensitivity. For example, LSST has a sky coverage of $\sim 20,000 \text{deg}^2$ and reaches the depth of $\sim 27.5 \text{mag/arcsec}^2$ in $i$ band and consequently has the potential to discover $\mathcal{O}(10^5)$ objects. Although, as the reference samples, we need spec-z or high-precision photo-z samples located in the local universe covering such a wide sky, it is expected to decrease uncertainties for estimate of $\langle \sigma v \rangle_{UL}$ due to $dN/dz$ measurement and halo properties. Moreover, by increasing statistics, we can realize a more detailed $dN/dz$ measurement, particularly a redshift range corresponding to distance of less than 25 Mpc which is the minimum distance adopted for conservative J-factor estimate in our likelihood procedure. This will give a more stringent constraint on the cross-section beyond simple scaling with $1/N_{st}$.

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