Multiwavelength analysis of low surface brightness galaxies to study probable dark matter signature

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Low Surface Brightness (LSB) galaxies are thought to be one of the most dark matter (DM) dominated galaxies in our Universe. They have very diffuse, low surface density stellar disks that have poor star formation rates and hence appear faint in optical images. LSB galaxies are also very rich in neutral hydrogen (HI) gas which usually extends well beyond their stellar disks. Their extended HI rotation curves indicate the presence of very massive DM halos compared to normal bright galaxies and their mass to light (M/L) ratios are high, which is typical for dark matter dominated galaxies. Hence, LSB galaxies are ideal laboratories for the indirect detection of DM using observations of γ-ray emission which could possibly originate from pair-annihilation (or decay) of the weakly interacting massive particles (WIMPs) in their halos. In this paper we have searched for WIMP annihilation or decay signatures in four LSB galaxies, UGC 12632, UGC 12732, UGC 11707, UGC 3371. Here we present analysis of nearly nine years data from the Fermi Large Area Telescope (LAT). Above 100 MeV, no excess emission was detected from the LSB galaxies. We have then determined the stacked γ-ray flux using spectra expected for WIMP annihilation. With the RX-DMFIT code, we have also predicted the possible upper limits for the detection of radio emission associated with WIMP annihilation from LSB galaxies. We have compared our results with different proposed theoretical WIMP models to examine the constraints on the parameter space of the DM models. We also discuss the possibility of detecting a positive signal from LSB galaxies using the upcoming ground-based γ-ray telescope, the Cherenkov Telescope Array.

Keywords: dark matter, WIMP, Low Surface Brightness galaxy.

1. INTRODUCTION

The data from several astrophysical and cosmological observations (e.g. [1, 2]) evidently reveal that a large portion of the total mass density of our Universe (~85%) is made of non-luminous and non-baryonic matter, described as the Dark Matter (DM). Cosmological N-body simulations (e.g. [3, 4]) and theoretical predictions mainly favor the cold dark matter (CDM) model to explain the formation of the large scale structure of the Universe. Moreover, the beyond-Standard Model (SM) physics anticipates that CDM consists of some form of massive, non-baryonic and neutrally charged particles, or weakly interacting massive particles (WIMPs). In the past decade, theoretical studies have shown that WIMPS are the most promising DM candidate and their pair annihilation can lead to the production of high energy γ-rays ([5–9]). This γ-ray emission can be detected by space-based telescopes such as the Fermi Large Area Telescope (or Fermi-LAT) [7, 10–15]. The most promising candidates for WIMP detection has traditionally been dwarf spheroidal galaxies (dSphs), as they are thought to be one of the most DM dominated galaxies in our local Universe and the closest to our Galaxy [7, 16–18]. Although such studies have not yet detected γ-rays from WIMP annihilation, they have put strong constraints on the γ-ray fluxes ([7, 10–15, 19, 20]), which is important for constraining the theoretical models of DM.

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In our local Universe, low surface brightness (LSB) galaxies, like dwarf spheroidal (dSph) galaxies, would also be considered as DM dominated galaxies. But unlike dSphs, LSBs are more massive and they hardly show any signs of star formation [21]. LSB galaxies are metal-poor and their stellar disks are generally embedded in a rich extended neutral HI gas disk [22–25]. It is interesting to mention that LSB galaxies lie in the same mass range as high brightness galaxies (HSB) with a few times of lower surface brightness than HSBs but the HI mass-to-luminosity ratio of LSBs are much higher than the surface brightness counterpart of HSBs [24]. The difference between the estimated HI mass from their rotation curves and the observed baryonic mass (i.e. from gas and stars) generally indicates the presence of a large amount of DM in the halos of LSBs [26]. These galaxies satisfy the two main criteria that candidates for indirect searches of DM should satisfy i.e. (i) they should have high DM masses and (ii) should not have obvious sources of γ radiation such as star-forming regions and active galactic nuclei (AGN). The smaller LSB galaxies termed as LSB dwarfs or irregulars have very little star formation and no nuclear activity [27]. They are thus good sources to search for γ-rays from WIMP annihilation. The main differences between dwarf spheroidal (or we can say Milky Way satellite galaxies) and LSB dwarfs/irregulars are that LSB galaxies have large HI masses and are generally more massive than the satellite galaxies [27]. They are also at much larger distances. But their lack of star formation, low metallicities and overall low luminosities make them very similar to dwarf spheroidal [28]. The large mass to light ratios of LSBs may be treated as probable targets for indirect DM search. Moreover, the HI rotation curves and gas kinematics in LSB dwarfs may be used to determine the central halo density profiles in these galaxies which may help to resolve the 'cusp-core' problem in the CDM theory of galaxy formation [29, 30].

Despite of being probable targets of indirect DM searches, the γ-ray signature from LSB galaxies have been analyzed in very few cases [31, 32]. The reason why LSBs have not been widely studied in indirect DM searches may be due to the small values of their astrophysical factor (J) and their large distances from the Milky Way compared to dSphs [31, 32]. However, some LSB dwarfs are relatively close by e.g. UGC 12632. Furthermore, their fluxes can be stacked to improve the results. With this in mind, we have done a study of the Fermi-LAT data of four nearby LSB dwarfs to constrain the DM models of WIMP annihilation. Moreover, we have also used a multiwavelength approach to search the DM signal by exploring whether the DM signal can be detected at radio frequencies. This may help to improve the constraints on the DM models.

The paper is organised as follows. We first discuss the properties of the LSB galaxies (section 2) and then describe the analysis of nine years of Fermi-LAT data (section 3). In subsection 3.1 and subsection 4.2, we have estimated the upper limits of γ-ray flux from each LSB galaxy and the upper limits of the velocity-averaged pair-annihilation cross-section (i.e.<σv>) of the WIMPs for different pair-annihilation channels. We have compared our <σv> upper limits with various theoretical WIMP models. Comparisons of the <σv> upper limit from LSB galaxies, with the results obtained from Tri-II are also presented in subsection 4.2. Next, in subsection 4.3, we have performed a joint likelihood test of all four LSB galaxies. In subsection 4.4, we have tried to predict the possible diffuse radio signal from LSB galaxies with RX-DMFIT code[33] and in subsection 4.5, we have performed a comparison between three density profiles, i.e. between NFW, Burkert and Isothermal. In section 5 we have compared the flux upper limits obtained from four LSBs with the Cherenkov telescope array sensitivity curve. Finally, in the concluding section, a brief discussion of our results obtained from γ-ray data with the Fermi-LAT and the prediction from radio emission are presented.

2. SAMPLE SELECTION:

The LSB dwarf galaxies in our sample were selected based on the following criteria. (i) They should have low luminosities but large DM masses. The galaxies should not show any signs of star formation or active galactic nuclei (AGN) activity in their optical images as such processes can also give rise to γ-rays [34, 35]. (ii) They should be within 5 Mpc to 15 Mpc distances so that the astrophysical factor is not too low. Based on these constraints, we selected a sample of nearby LSB dwarf galaxies that were extremely LSB in nature from published surveys of gas-rich dwarf galaxies in the literature [30]. Table I lists the sample galaxies, their distances and their properties. The neutral hydrogen observations data obtained from the Westerbork Synthesis Radio Telescope are presented here for our 4 late-type LSB galaxies [36].

- **UGC 3371 (DDO 039)**: UGC 3371 is a Irregular galaxy (Irr). The observational study indicates that in the case of UGC 3371 there is an excellent agreement between HI velocity data and Hα rotation curve but HI rotation curve rises more steeply than Hα data. This inconsistency in observational data could come from the overcorrection in beam smearing of HI data [37] and because of this disagreement it is not possible to strongly
The study of Ref. [38] indicates that the best-fit models of UGC 3371 prefer a DM halo with a steep central cusp. The halo profile of UGC 3371 is hence consistent with CDM models.

- **UGC 11707**: UGC 11707 is a spiral galaxy with loosely bound broken arms made of individual stellar clusters. It also has a very faint central bulge (Sd). Due to the lack of data, the Hα rotation curve of UGC 11707 is poorly sampled but the inner rise in the Hα rotation curve appears as a steeper profile than HI rotation curve. This galaxy appears to have a very large amount of freedom in its model parameters from Ref. [38]. This is partly due to the relatively large error bars for the inner data points, which is a reflection of the asymmetry between the receding and approaching rotation velocities \( \lesssim 7 \text{ kpc} \). It halo profile is consistent with CDM models.

- **UGC 12632 (DDO 217)**: UGC 12632 is a weakly barred spiral galaxy (SABm). The observational data shows that it has an evenly distributed HI gas over its disk and a very high velocity bump on the blue side of the Hα rotation curve. The position velocity map indicates a narrow rise of the rotational velocity near the center and a gradual increase in the outer disk. Moreover, the observed rotational velocities of UGC 12632 are in excellent agreement with CDM halos. Thus it shows that this galaxy is consistent with CDM models.

- **UGC 12732**: UGC 12732 is a weakly barred spiral galaxy (SABm), similar to UGC 12632. Studies suggest that there is a ring of 0.5° × 0.5° in UGC 12732 with one long thin arm of very low surface brightness. It is interesting to note that Ref. [39]. have shown in their study that the Hα and HI rotation curves of UGC 12732 are in good agreement. It is also is consistent with CDM models [39].

| Name    | D (Mpc) | \( L_B \left( 10^9 L_B \right) \) | \( R_{last} \) (Kpc) | \( V_{last} \) (\( \text{km s}^{-1} \)) | \( R_d \) (Kpc) | \( M_{HI} \left( 10^9 M_\odot \right) \) | i° | \( \lambda \text{CDM} \) |
|---------|---------|-------------------------------|-----------------|-----------------|----------------|-----------------|---|----------------|
| UGC 3371 | 12.7 | 1.54 | 10.2 | 86 | 3.09 | 12.2 | 49 | Yes |
| UGC 11707 | 15.0 | 1.13 | 15.0 | 100 | 4.30 | 37.2 | 68 | Yes |
| UGC 12632 | 8.36 | 0.86 | 8.53 | 76 | 2.57 | 8.7 | 46 | Yes |
| UGC 12732 | 12.38 | 0.71 | 15.4 | 98 | 2.21 | 36.6 | 39 | Yes |

The details of Table I has been described below:

- **Column I**: Name of LSB galaxies
- **Column II**: The adopted galactocentric distance to the galaxies, based on a Hubble constant \( (H_0) = 75 \text{ km s}^{-1} \text{ Mpc}^{-1} \).
- **Column III**: B band Luminosity of LSBs.
- **Column IV**: Location of the last observed data points of LSB galaxies.
- **Column V**: Observed rotational velocity at last measured point of rotational curve.
- **Column VI**: Scale length of stellar disk.
- **Column VII**: The observed HI gas masses of LSB galaxies.
- **Column VIII**: Inclination angle.
- **Column IX**: Connection with \( \lambda \) CDM cosmology; the ‘yes’ indicates that galaxy is consistent with \( \lambda \) CDM.

### 3. FERMI-LAT OBSERVATION AND DATA ANALYSIS OF LSBS

The Fermi-LAT was launched on 2008 June 11 by a Delta II Heavy launch vehicle. The LAT on-board Fermi is a pair-conversion \( \gamma \)-ray detector capable of measuring \( \gamma \)-rays in a very wide range of energy from 20 MeV to 300 GeV. It can track the electron and positron resulting from pair conversion of an incident \( \gamma \)-ray in thin high-Z foils, and can also measure the energy deposition due to the subsequent electromagnetic shower that develops in the calorimeter. The LAT nominally operates in a scanning mode observing the whole sky every 3 hours, resulting in the overall...
coverage of the sky being fairly uniform. In our paper, we have analyzed almost 9 years of sky survey data (from 2008-05-04 to 2017-10-22) from the direction of each galaxy in our sample.

In our analysis of the γ-ray data, we have used the Fermi ScienceTools of version v10r0p5\textsuperscript{1}. This Fermi ScienceTools is processed with an improved PASS 8 instrument response function (IRF)\textsuperscript{2} and for our purpose we have used source class IRF\textsuperscript{2}, P8R2\_SOURCE\_V6\textsuperscript{3}. For each galaxy we have extracted the LAT data within a 10° of radius of interest (ROI) around each the source. In order to reduce the possible uncertainties at low energies and background contamination at high energies, we have put energy limits of 0.1 ≤ E ≤ 300 GeV on the reconstructed energy (E). In our analysis, with gtmtime we have extracted the good time interval (GTI) data from the whole dataset. In this selection, we have applied zenith-angle cut at 90° as recommended by the Fermi-LAT team. It will remove the possible contamination from the earth albedo. The Earth’s limb lies at a zenith angle of 113°, so applying the zenith cut at 90° provides protection against significant contamination from atmospheric γ-rays.

Next with gtlike\textsuperscript{4}, we have performed the binned likelihood analysis\textsuperscript{4} on the GTI dataset. Gtlike is used to fit the data to its spatial and spectral model using the maximum likelihood method. The four LSB galaxies, that we have considered for analysis, have not been detected by Fermi-LAT yet. So along with other sources from Fermi 3FGL catalog\textsuperscript{42} we have externally included them to the source model file. Furthermore, during the likelihood process, we have included the galactic diffusion emission (gll\_iem\_v06\_fits) model and the corresponding isotropic component (iso\_P8R2\_SOURCE\_V6\_v06\_txt) to the source model for eliminating the possible background photons coming from the galactic and the extragalactic components\textsuperscript{5}.

In the course of fitting, the spectral parameters of all the sources within 5° ROI and the normalizations of the two diffuse background components were left free. In the following section, we have modeled our sources with power-law

\begin{table}
\centering
\begin{tabular}{c c}
\hline
(\textbf{a})UGC 3371 & (\textbf{b})UGC 11707 \\
\hline
\end{tabular}
\end{table}

\begin{table}
\centering
\begin{tabular}{c c}
\hline
(\textbf{c})UGC 12632 & (\textbf{d})UGC 12732 \\
\hline
\end{tabular}
\end{table}

\textbf{FIG. 1:} The residual plots of all four LSB galaxies for a chosen ROI are shown here, in which, we have modeled them with power-law for spectral index, Γ = 2.

\begin{enumerate}
\item \url{https://fermi.gsfc.nasa.gov/ssc/data/analysis/software/}
\item \url{https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_LAT_IRFs/IRF_overview.html}
\item \url{https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Pass8_usage.html}
\item \url{https://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/binned_likelihood_tutorial.html}
\item \url{https://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html}
\end{enumerate}
spectra for five different spectral indices.

### 3.1. Results from the power-law modelling

In this section, we have modeled all the LSB galaxies with power-law spectra in order to constrain the \( \gamma \)-ray flux from each source. The expression of differential flux for power-law spectrum is [7]:

\[
\frac{dN}{dA dt} = N_0 \left( \frac{E}{E_0} \right)^{-\Gamma},
\]

where, \( dN \) denotes the number of photons within energy interval \( E \) to \( E + dE \) and \( dA \) is the elemental area where photons are incident with time interval, \( dt \).

In Eq. (1), the reconstructed energy \( (E) \) is varied between 100 MeV to 300 GeV and \( \Gamma \) and \( N_0 \) are the spectral index and normalisation constants respectively. We have fixed \( E_0 \) at 100 MeV [7]. During likelihood analysis, \( N_0 \) is fitted every time for each ROI separately. We have kept the \( \Gamma \) fixed at five different spectral indices, i.e. at \( \Gamma = 1, 1.8, 2, 2.2, 2.4 \) [7]. The \( \Gamma = 1 \) is considered because of its connection with DM annihilation model [43], while the other four indices are chosen to check the constraints on the standard astrophysical source spectra. For each of these above mentioned \( \Gamma \), we have repeated the binned analysis and during this process, we have also checked the best fit value of the \( N_0 \) along with the isotropic and the galactic diffuse normalization parameters.

Fig. 1(a,b,c,d) shows the residual fit for the four LSB galaxies. All of these residual plots are generated for a power-law spectrum with \( \Gamma = 2 \). In Table II, we have represented our results obtained for each LSB galaxy for \( \Gamma = 2 \). Here we have shown the best-fitted values of isotropic and the galactic diffuse normalization components along with the \( N_0 \) and its statistical error.

In the case of converge-fitting, the ideal value of two diffuse normalization components should be close to \( \sim 1 \) [7]. From Table II, we find that the best-fitted values of the galactic and isotropic component are close to 1 and it provides the confidence on our analysis mechanism. It is important to note that for each galaxy the normalization parameter, \( N_0 \) is always lower than the statistical error by an order of 2. This implies that Fermi-LAT has not detected any signal from the direction of the LSB sources.

We have then derived the upper limits of \( \gamma \)-ray flux by profile likelihood method [44, 45]. In this procedure, all the normalization parameters i.e. \( N_0 \) and galactic and isotropic components were continuously fitted with spectrum model at every step until the logarithmic difference of two likelihood function comes to 1.35 [7] which corresponds to a one-sided 95% confidence level (C.L.).

In Table III, we have displayed the flux upper limits for two different energy ranges i.e. from 100 MeV to 300 GeV and from 1 GeV to 300 GeV. From, Table III, we also find that for energy range \( > 100 \) MeV, the 95% C.L. \( \gamma \)-ray flux upper limit for \( \Gamma = 1 \) is roughly 10 times lower than the one for \( \Gamma = 2.4 \).

| LSB galaxies | Galactic foreground | Isotropic Component | \( N_0 \times 10^{-5} \) |
|--------------|-------------------|--------------------|---------------------|
| UGC 3371     | 0.9991 ± 0.0073   | 0.9875 ± 0.0171    | (6.29 ± 21.5512) × 10^{-8} |
| UGC 11707    | 0.9551 ± 0.00557  | 1.2305 ± 0.01660   | (0.1099 ± 6.058) × 10^{-7} |
| UGC 12632    | 0.9785 ± 0.0060   | 1.2902 ± 0.0135    | (0.334+5.822) × 10^{-6}   |
| UGC 12732    | 1.074 ± 0.0085    | 1.1742 ± 0.01276   | (0.12 ± 2.299) × 10^{-6}   |
TABLE III: Flux upper limits of four LSB galaxies at 95% C.L.

| LSB galaxies | Spectral Index (Γ) | E > 1 GeV | E > 100 MeV |
|--------------|-------------------|-----------|-------------|
| UGC 11707    | 1                 | 5.045 × 10⁻¹¹ | 6.0245 × 10⁻¹¹ |
|              | 1.8               | 2.8562 × 10⁻¹⁰ | 3.1542 × 10⁻¹⁰ |
|              | 2                 | 4.274 × 10⁻¹⁰ | 5.6616 × 10⁻¹⁰ |
|              | 2.2               | 6.4977 × 10⁻¹⁰ | 1.0118 × 10⁻⁹ |
|              | 2.4               | 9.2187 × 10⁻¹⁰ | 1.7838 × 10⁻⁹ |
| UGC 12732    | 1                 | 4.99 × 10⁻¹¹ | 5.4138 × 10⁻¹¹ |
|              | 1.8               | 3.2354 × 10⁻¹⁰ | 3.5258 × 10⁻¹⁰ |
|              | 2                 | 2.997 × 10⁻¹⁰ | 6.3478 × 10⁻¹⁰ |
|              | 2.2               | 3.9791 × 10⁻¹⁰ | 1.1325 × 10⁻⁹ |
|              | 2.4               | 4.9879 × 10⁻¹⁰ | 1.9791 × 10⁻⁹ |
| UGC 12632    | 1                 | 6.6677 × 10⁻¹¹ | 6.2831 × 10⁻¹¹ |
|              | 1.8               | 3.3804 × 10⁻¹⁰ | 3.8664 × 10⁻¹⁰ |
|              | 2                 | 5.3875 × 10⁻¹⁰ | 6.89877 × 10⁻¹⁰ |
|              | 2.2               | 6.6677 × 10⁻¹⁰ | 1.2223 × 10⁻⁹ |
|              | 2.4               | 7.9394 × 10⁻¹⁰ | 2.1324 × 10⁻⁹ |
| UGC 3371     | 1                 | 6.1656 × 10⁻¹¹ | 7.6915 × 10⁻¹¹ |
|              | 1.8               | 3.5542 × 10⁻¹⁰ | 4.3698 × 10⁻¹⁰ |
|              | 2                 | 6.9656 × 10⁻¹⁰ | 7.4205 × 10⁻¹⁰ |
|              | 2.2               | 8.9510 × 10⁻¹⁰ | 1.2457 × 10⁻⁹ |
|              | 2.4               | 7.8068 × 10⁻¹⁰ | 2.0570 × 10⁻⁹ |

4. A THEORETICAL FRAMEWORK TO ESTIMATE γ-RAY FLUX FROM PAIR-ANNIHILATION OF WIMPS IN CASE OF LSB GALAXIES

4.1. Dark matter density profile modelling

At given photon energy E, the expression of photon flux originated from WIMP pair annihilation of mass $m_{DM}$, within a solid angle $\Delta \Omega$ is [7, 46]:

$$\phi_{WIMP}(E, \Delta \Omega) = \Phi_{pp}(E) \times J(\Delta \Omega),$$

(2)

where, $\Phi_{pp}(E)$ and $J(\Delta \Omega)$ are referred as “particle physics factor” and “astrophysical factor” (or “J factor”), respectively.

4.1.1. Particle Physics factor

$\Phi_{pp}(E)$ is defined as the Particle physics factor. It depends on the nature of the particles generating from WIMP annihilation. The expression of $\Phi_{pp}(E)$ is [7]

$$\Phi_{pp}(E) = \frac{<\sigma v>}{8\pi m_{DM}^2} \sum_f \frac{dN_f}{dE} B_f.$$  

(3)

$\Phi_{pp}(E)$ is a function of the DM particle mass ($m_{DM}$) and the thermally averaged WIMP annihilation cross-section times the relative velocity ($<\sigma v>$). Here, $\frac{dN_f}{dE}$ and $B_f$ denote the γ-ray spectrum and branching fraction corresponding to the $f^{th}$ final state of WIMP annihilation, respectively.

In our analysis, we have not considered any effect of the Sommerfeld enhancement [7, 47, 48]. Sommerfeld enhancement may change the relative velocity of WIMP and in that case, the γ-ray flux can be enhanced by the
factor of 7 to 90 for a wide range of DM masses (i.e. for 100 GeV to 3 TeV).

### 4.1.2. Astrophysical factor

The astrophysical factor $J$ depends on the DM density distribution in the LSB galaxies and is given by the expression,

$$J(\Delta \Omega) = \int \int \rho^2(r(\lambda))d\lambda \ d\Omega$$

$$= 2\pi \int_{\theta_{\text{min}}}^{\theta_{\text{max}}} \sin\theta \int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} \rho^2(r(\lambda))d\lambda \ d\theta.$$  

(4)

where, $\rho(r)$ is the DM mass density profile of the LSB galaxies, whereas $\lambda$ and $r(\lambda)$ denote the line-of-sight and galactocentric distance of the galaxies respectively. The expression for $r(\lambda)$ is,

$$r(\lambda) = \sqrt{\lambda^2 + d^2 - 2\lambda \ d \cos\theta}.$$  

(5)

Here $d$ denotes the heliocentric distance of LSB galaxies and $\theta$ is the angle between the direction of LAT observation and the center of LSB galaxies. The minimum and maximum limits of $\lambda$ can be represented as [49]

$$\lambda_{\text{max}} = d \cos\theta + \sqrt{R_{\text{vir}}^2 - d^2 \sin^2\theta}$$

(6)

$$\lambda_{\text{min}} = d \cos\theta - \sqrt{R_{\text{vir}}^2 - d^2 \sin^2\theta}$$

(7)

where, $R_{\text{vir}}$ is the virial radius of LSB galaxies and for our calculation purpose, we have taken $\theta_{\text{min}} = 0^\circ$ and $\theta_{\text{max}} = \sin^{-1}\left(\frac{d}{\lambda}\right)$.

The estimation of the J-factor helps us to rank the LSBs without assuming any specific DM models. Furthermore, it also allows us to estimate any possible detection from LSBs for any theoretical favored DM particle models.

### 4.1.3. LSB galaxies and NFW density profile

For our analysis, we have considered the Navarro-Frenk-White (NFW) density profile [50] to model DM mass distribution of LSB galaxies. In this paper, for modeling the DM mass density of each LSB galaxies, we have used the parameters obtained by the study of their rotation curve universality (see section. 2). This may help us to describe the dark and luminous properties of these galaxies. All the parameters derived from the systematic study of galactic rotation curves are mentioned in Table I and Table IV.

The expression of the NFW density profile is [7, 50]

$$\rho(r) = \frac{\rho_s r_s^3}{r(r_s + r)^2}$$

(8)

where $\rho_s$ and $r_s$ are the characteristic density and scale radius, respectively and $r$ is the distance from the center of the LSB galaxy.

We have used the following relations to calculate the value of $\rho_s$ and $r_s$:

$$\rho_s = \rho_0 \delta_{\text{char}} [51],[52],$$  

where $\rho_0$ is the critical density of Universe,

$$H_0 = \text{Hubble constant} = 75 \text{ km s}^{-1}\text{Mpc}^{-1} = 100h \text{ km s}^{-1}\text{Mpc}^{-1} [53],$$

$$r_s = R_{\text{vir}}/c [53],$$  

where $c$ = concentration parameter [51],

$$R_{\text{vir}} = r_{200} = \text{radius at which density is 200 times of critical density} = V_{200\text{h}^{-1}} \text{kpc},$$

where, $V_{200}$ (in km s$^{-1}$) = circular velocity at $r_{200}$ [51],[53].

In Table IV, we have displayed all the necessary parameters to estimate the J-factors from Eq. 4.
TABLE IV: Different parameters to calculate J-factor for LSB galaxies for $h_0 = 0.75$

| Galaxy name | R.A. (hh mm ss) | DEC. (dd mm ss) | Distance (Mpc) | c | v (km/sec) | J from integration (GeV$^2$/cm$^5$) |
|-------------|----------------|----------------|----------------|---|------------|-------------------------------------|
| UGC 3371    | 05 56 38.6     | +75 18 58      | 12.7           | 14.55 | 69.2 | 0.67 x 10$^{16}$ |
| UGC 11707   | 21 14 31.7     | +26 44 04      | 15.0           | 14.7  | 67.1 | 0.44 x 10$^{16}$ |
| UGC 12632   | 23 29 58.7     | +40 59 25      | 8.36           | 15.6  | 51.5 | 0.73 x 10$^{16}$ |
| UGC 12732   | 23 40 39.8     | +26 14 11      | 12.38          | 14.5  | 70.45 | 0.73 x 10$^{16}$ |

4.1.4. Comparison with Toy Model

In this section, we have used the toy model proposed by Ref. [54] to cross-check our method of numerical integration to calculate J-factor for NFW density profile. In Fig. 2, we have portrayed the toy model for J-factor calculation[54]. In this figure, the vertical hatched region is for contribution from integration and the cross-hatched region is for toy model.

![Fig. 2: Sketch of the toy model for J-factor calculation[54]](image)

In Fig. 2, $d$ is the distance to the center of the galaxy from the observer and $\alpha_{\text{int}}$ is the angle for integration where $r_{\alpha_{\text{int}}} = d \sin \alpha_{\text{int}}$. In the toy model, it is assumed that at about 90% clump luminosity can be contained in scale radius, $r_s$ and it does not depend on any specific density profile. Then the simplified form of Eq.(8) can be written as,

$$\rho_{\text{approx}} = \rho_s r_s/r \text{ for } r_{\text{sat}} < r \leq r_s$$

where, $r_{\text{sat}}$ is the saturation distance. The corresponding approximate form of J-factor is:

$$J_{\text{approx}} = \frac{4\pi}{d^2} \int_0^{\min[r_{\text{int}}, r_s]} \rho_{\text{approx}}^2 r^2 \, dr$$

$$= \frac{4\pi}{d^2} \rho_s^2 r_s^2 (\min[r_{\text{int}}, r_s])$$

If $r_{\text{int}} > r_s$, the density profile falls faster than $1/r$ for $r \sim r_s$. The toy model advised us stop the integration at $r_x$ where $\rho_{\text{true}} = \frac{\rho_{\text{approx}}}{x}$, $x = 2$ and $r_x = r_s[\sqrt{2} - 1]$ [54].

$$J_{\text{approx}} = \frac{4\pi}{d^2} \rho_s^2 r_s^2 (\min[r_x, r_{\text{int}}])$$
In Table V, we have compared our estimated J-factor for all four LSB galaxies with the J-factor obtained from Toy-model calculation of Ref. [54]. Our calculated J-factor from Eq. 4, is nearly differ by the factor of 2 from Toy-model calculation. This result is consistent with approximation assumed by Ref. [54].

**TABLE V: value of J-factor in two different calculation for $h_0=0.75$**

| Galaxy name | J-factor from integration (GeV$^2$/cm$^2$) | J-factor from toy model (GeV$^2$/cm$^2$) |
|-------------|------------------------------------------|----------------------------------------|
| UGC 3371    | $0.66 \times 10^{16}$                    | $0.89 \times 10^{16}$                 |
| UGC 11707   | $0.44 \times 10^{16}$                    | $0.60 \times 10^{16}$                 |
| UGC 12632   | $0.73 \times 10^{16}$                    | $0.99 \times 10^{16}$                 |
| UGC 12732   | $0.73 \times 10^{16}$                    | $0.99 \times 10^{16}$                 |

### 4.2. Constraints on the annihilation cross-section

In this subsection, we have estimated the possible $\gamma$-ray flux from each LSB galaxy which originates from WIMP pair annihilation using the DMFit package[55, 56]. This package is used to fit the $\gamma$-ray signal from WIMP pair annihilation and moreover, with this tool, we can obtain the information on the DM mass, WIMP pair-annihilation $<\sigma v>$, possible WIMP annihilation final states. This tool is already implemented in the ScienceTools. For the $\gamma$-ray spectra originating from the WIMP pair annihilation, we have estimated the upper limits of flux in 95% C.L. from LSB galaxies (already described in subsection 3.1) and the relative thermally averaged pair-annihilation crosssection $<\sigma v>$ as a function of DM mass ($m_{\text{DM}}$) and WIMP annihilation final states ($f$).

For our paper, we have chosen five supersymmetry-theorem favored WIMP pair annihilation final states ($f$), such as, 100% $b\bar{b}$, 80% $b\bar{b} + 20% \tau^+\tau^-$, 100% $\mu^+\mu^-$ and 100% $W^+W^-$, respectively[8]. These five annihilation channels have been used in several previous studies, particularly when the neutralino is a WIMP candidate. It is true that supersymmetry theory favors neutralino as CDM candidate, but our results are generic to any WIMP models.

In this section, for obtaining the variation of flux upper limit and the corresponding $<\sigma v>$ as a function of $m_{\text{DM}}$, we have used our estimated J-factors from Table IV. In Fig. 3(a,b,c), we have shown the variation of flux upper limit in 95% C.L. of the LSB galaxies with $m_{\text{DM}}$ for three particular pair annihilation final states i.e. for 100% $b\bar{b}$, 80% $b\bar{b} + 20% \tau^+\tau^-$ and 100% $\mu^+\mu^-$ respectively, whereas in Fig. 4(a,b,c), we have shown the variation of $<\sigma v>$ upper limits in 95% C.L. for these three annihilation channels. In Figs. 3(d) and 4(d), we have displayed the variation of flux upper limit and $<\sigma v>$ of UGC 12632 for five annihilation final states i.e. for 100% $b\bar{b}$, 100% $\tau^+\tau^-$, 80% $b\bar{b} + 20% \tau^+\tau^-$, 100% $\mu^+\mu^-$ and 100% $W^+W^-$. Fig. 3(d) shows that 100% $\mu^+\mu^-$ and 100% $\tau^+\tau^-$ annihilation channels can provide the best flux upper limits; especially at higher energies with less background diffusion, these two final states can even predict abundant photon flux. From fig. 3(d), we also observe that at $m_{\text{DM}} \sim 1$ TeV, the flux upper limit for all five annihilation final states varies within a factor of 2 but for low mass WIMP, this variation is about factor of 4. We have checked that all of our LSB galaxies have showed the same signature for each annihilation channels. Hence in figs. 3(d) and 4(d), we have only shown the variation of flux upper limit and corresponding $<\sigma v>$ limits of UGC 12632 for five annihilation final states.

In Figs. 5(a,b) and Fig. 6, we have shown the $<\sigma v>$ upper limits of all LSB galaxies for $b\bar{b}$ annihilation channel. In those figures, we have compared our limits from the LSB galaxies with four different theoretical models which predict various signature of DM candidates. From Fig 4, we have observed that amongst five annihilation channels, $b\bar{b}$ produces the most stringent limits. Hence, for comparison in Figs. 5 and 6, we have only considered the $b\bar{b}$ annihilation channel. In Figs. 5(a,b) and Fig. 6, we have also compared the LAT-sensitivity obtained from LSB galaxies with newly discovered ultra faint dwarf spheroidal (dSph) galaxy, Triangulum-II (Tri-II) [19] for its two different values of velocity dispersion $\sigma$. 
FIG. 3: The flux upper limits of all the LSB galaxies for different pair annihilation final states: (a)(upper left) 100% b¯b, (b) (upper right) 80% b b + 20% τ+τ−, (c) (lower left) 100% τ+τ−, and (d) (Lower right) plot shows the variation of flux upper limits of UGC 12632 with mDM for all selected annihilation final states.

In Fig 5(a,b), we have considered two DM particle models, namely, minimal supergravity (mSUGRA) [57] and Minimal Supersymmetric Standard Model (MSSM) [58]. These models are two theoretically favored DM models but in mSUGRA, the supersymmetry breaking parameters are defined in high energy scale i.e. at the order of grand unification scale ∼ 2 × 10¹⁶ GeV while on the other hand, in MSSM, the supersymmetry breaking parameters are defined in low energy scale i.e. at electro-weak energy range. Next in Fig. 6, we have considered another two theoretically motivated DM models, one is the lightest Kaluza-Klein particle of universal extra dimensions (UED) [59–61] and the other one is anomaly mediated supersymmetry breaking (AMSB) model [62]. In AMSB model, the supersymmetry breaking parameter can define the winos or wino-like neutralino scenario. From thermal relic equilibrium scenario, at about 2 TeV mass of DM candidate, winos can explain the universal DM density but in several non-thermal production scenarios, winos can also define the universal DM density for lower mass range [7]. The Kaluza-Klein particle model holds a nearly exact relation between the DM mass and its pair annihilation cross-section and from this model, at around 700 GeV DM mass, the thermal relic abundance matches with the universal DM density [7, 60].

From Figs. 5(a,b) and Fig. 6, we can observe the comparison between the LAT sensitivity obtained for the LSB galaxies in (mDM, < σv >) plane for b¯b annihilation channel and the theoretically predicted < σv > limits from four DM models i.e. from mSUGRA, MSSM, Kaluza-Klein DM in UED and wino-like DM in AMSB. In Figs. 5(a,b), the red points are related to the WIMP thermal production mechanism which is also consistent with the 3σ WMAP constraint and blue points are related to the non-thermal WIMP production mechanism [7].
FIG. 4: The upper limit on $<\sigma v>$ of all the LSB galaxies for different pair annihilation final states: (a)(upper left) 100% $b\bar{b}$, (b) (upper right) 80% $b\bar{b}$ + 20% $\tau^+\tau^-$, (c) (lower left) 100% $\tau^+\tau^-$, and (d) (Lower right) plot shows the variation of $<\sigma v>$ upper limits of UGC 12632 with $m_{DM}$ for all selected annihilation final states.

From both Figs. 5(a,b) and 6, we can notice that none of the LSB galaxies have put any constraint on any of these above mentioned theoretical models. The LAT sensitivities obtained from these four LSB galaxies are nearly 3 orders higher than the LAT sensitivity estimated from Tri-II [19]. Hence, from Figs. 5(a,b) and 6, we could not particularly favor any selected DM theoretical model. In the following section, we will try to estimate whether the stacking analysis can improve the limits on the theoretical models.

4.3. Stacking Analysis

In this section, we have performed a joint likelihood test on these four LSB galaxies. From Figs. 5(a,b) and 6, we have observed that the individual LSB galaxies could not provide any constraint to the DM theoretical models. Hence, the joint likelihood test would be an ideal approach for this scenario because it is expected that the sensitivity of our analysis would increase after stacking. For this purpose, we have generated a joint likelihood function as a product of individual likelihood functions of LSB galaxies. This function has combined the DM annihilation $<\sigma v>$, J-factor, DM mass, Branching ratio and the $\gamma$-ray spectrum of all individual LSB galaxies.

$$\hat{L}(\mu, [\alpha_i] | \mathcal{D}) = \prod_{i=1}^{4} \hat{L}_i(\mu, \alpha_i | \mathcal{D})$$

(12)
For combined likelihood analysis, the individual likelihood function for each LSB galaxy is weighted with their respective $J$-factor. If we assume that our estimated $J$-factor gives a rough representation of WIMP annihilation signal, a joint likelihood treatment would then provide a more stringent limits than any individual LSB. The combined analysis of LSBs also has not shown any $\gamma$-ray emission resulting from the WIMP annihilation, hence, we have derived the upper limit of $\gamma$-ray flux and $<\sigma v>$ in 95% C.L. by the delta-likelihood method. In Fig. 7(a), we have therefore presented the upper limit of $<\sigma v>$ as a function of $m_{\text{DM}}$ from the combined analysis along with their individual limits for 100% $b\bar{b}$ annihilation channel.

Even though the stacking analysis has improved the $<\sigma v>$ limits obtained from LSB galaxies (by order of $\approx 2$), it is not improved enough to constraint the mSUGRA, Kaluza-Klein and AMSB models. From Figs. 7(b) we can find that the combined $<\sigma v>$ upper limits of LSB can only put a very narrow constraint on MSSM model (between $\sim 80$ GeV to $\sim 340$ GeV).
FIG. 7: (a) Comparison of the $<\sigma v>$ upper limits obtained from LSB stacking analysis with their individual limits for 100% bb pair annihilation final state. b) Predictions from MSSM models are plotted in ($m_{DM}, <\sigma v>$) plane. The upper limit on combined $<\sigma v>$ for LSB galaxies and the upper limit on $<\sigma v>$ for Tri-II with $\sigma = 4.2$ km sec$^{-1}$ are shown in the plot.

4.4. Possible radio constraint obtained from LSB galaxies

With nine years of Fermi-LAT data, LSB galaxies do not provide any strong constraint on theoretical limits of DM. Hence, in this section, we have attempted to examine the possible radio emission from LSB galaxies. The $\gamma$-ray analysis is one of the most popular ways to examine the indirect detection of DM signature [15, 63–67] but a multiwavelength approach can also provide a complementary probe of $\gamma$-ray analysis [68–70]. For dSphs, several pieces of literature point out that the constraint obtained from the radio data can be competitive with $\gamma$-ray data.

WIMP can self-annihilate to the standard model particles such as bosons, quarks, leptons and then they decay to the charged particles such as positrons, electrons etc. Secondary charged particles are generated through the various mechanisms of generation and the decay of charged pions, i.e., $\pi^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$.

These secondary charged particles in the astrophysical system can lead to a generation of multileaks energy spectrum caused by several radiation mechanisms such as synchrotron, inverse Compton (IC), bremsstrahlung and Coulomb energy loss [71–73]. At high energies, the synchrotron and the inverse Compton radiation mechanisms play a dominant role.

In order to predict the radio or the x-ray emission through DM annihilation, we need to solve the diffusion equation of the secondary electron spectrum. The transport equation is [73, 74]:

$$\frac{\partial}{\partial t} \frac{\partial n_e}{\partial E} = \nabla \left[ D(E, r) \nabla n_e \frac{\partial n_e}{\partial E} \right] + \frac{\partial}{\partial E} \left[ b(E, r) \frac{\partial n_e}{\partial E} \right] + Q(E, r)$$ \hspace{1cm} (13)

$$Q(E, r) = \frac{<\sigma v>}{2 m_\chi^2} \sum_f \frac{dN_f^e}{dE} B_f.$$ \hspace{1cm} (14)

Here, we have assumed that at high energy $e^\pm$ are in equilibrium, i.e., $n_{e^+} = n_{e^-}$, $\frac{\partial n_{e^-}}{\partial t} = 0$ in eq. 13. $Q_e(E, r)$ is the source term and $\frac{\partial n_e}{\partial E}$ is the equilibrium energy density of $e^\pm$. $b(E, r)$ is the $e^\pm$ energy loss per unit time where, $b(E, r) = b_{\text{inverse Compton}} + b_{\text{synchrotron}} + b_{\text{bremsstrahlung}} + b_{\text{Coulomb}}$ (see Ref. [73]) and $D(E, r)$ is the diffusion coefficient.

The synchrotron emission from secondary electrons is the result of ambient magnetic fields that accelerate the charged particles, causing them to emit radiation at radio wavelengths [71, 72]. The IC radiation peaks at X-ray frequencies and is the result of photons from various radiation sources such as the cosmic microwave background.
(CMB) and starlight being up-scattered by the relativistic particles [71, 72].

In this subsection, we would wish to estimate the radio signature from LSB galaxies and for such purpose, we have used a publicly available code, RX-DMFIT [33]. This code is basically an extension of DMFIT tool [55, 56] which is used for $\gamma$-ray fitting in Fermi-LAT science tools. For calculating the source term ($Q_e$) from Eq. 13, RX-DMFIT code calls for the Fortran package DarkSUSY v5.1.2. DarkSUSY determines the electron/positron injection spectrum per DM annihilation event, $\sum f \frac{dN}{dE} B_f$ which is dependent on the DM particle mass, annihilation channel, and the source energy, $E$.

RX-DMFIT includes a large range of astrophysical and particle parameters which we can customize according to our need. This code incorporates important astrophysical scenario including diffusion of charged particles, relevant radiative energy losses, and field modeling. RX-DMFIT code [33] uses two forms of diffusion coefficients and magnetic field models. For our purpose, we have assumed the Kolmogorov form of diffusion coefficient, $D(E) = D_0 E^\gamma$ where $D_0$ is the diffusion constant and the diffusion mechanism would extend to the diffusion zone, $r_h$. Like dSphs, the magnetic field strength of LSBs is very weak and their spatial extension is not well defined. Hence, we have taken the exponential form of magnetic field, i.e. $B(r) = B_0 e^{-r/rc}$, where, $r_c$ is the core radius. For LSB galaxies, we have taken $r_h = 2 \times R_{last}$, whereas $r_e = r_d$ (from Table I). We have fixed the magnetic field of LSB galaxies at $1 \mu G$ and the thermally-averaged DM annihilation cross section is fixed to the value $<\sigma v> \approx 3 \times 10^{-26}\text{cm}^3\text{s}^{-1}$. The parameters that we have used as inputs of RX-DMFIT code are mentioned in Table VI.

With RX-DMFIT code, we can predict the properties of secondary emission generated from DM annihilation due to synchrotron and inverse Compton process. In Fig. 8, we have shown the multiwavelength spectral energy distribution (SED) of four LSB galaxies for three annihilation channels at $m_{DM} = 100\text{ GeV}$. From Fig. 8, we find that even for radio and x-ray emission, $\tau^+\tau^-$ and $\mu^+\mu^-$ produce the harder spectrum than $b\bar{b}$ annihilation channel.

### TABLE VI: parameter set for RXDMFIT code

| Galaxy     | $d$ (Mpc) | $r_h$ (Kpc) | $D_0$ (cm$^2$s$^{-1}$) | $\gamma$ | $B_0$ ($\mu G$) | $r_c$ (Kpc) | $\rho_s$ (GeV/cm$^3$) | $r_s$ (kpc) |
|------------|----------|-------------|------------------------|---------|----------------|------------|----------------------|-----------|
| UGC 3371   | 13.1     | 20.4        | $3 \times 10^{28}$     | 0.3     | 1              | 3.09       | 0.5725               | 6.5151    |
| UGC 11707  | 15.4     | 30.0        | $3 \times 10^{28}$     | 0.3     | 1              | 4.30       | 0.5875               | 6.2529    |
| UGC 12632  | 8.59     | 17.06       | $3 \times 10^{28}$     | 0.3     | 1              | 2.57       | 0.6825               | 4.5223    |
| UGC 12732  | 12.72    | 30.8        | $3 \times 10^{28}$     | 0.3     | 1              | 2.21       | 0.5676               | 6.5556    |

One of the important aspects of this code is to predict the possible limits on the DM cross-section from the observed data of radio and $x$-ray emission. From the observed flux density data, it can estimate the limits on ($<\sigma v>$ vs. $m_{DM}$) plane for several annihilation channels. LSB could be an ideal place for studying the diffuse radio signals obtained from DM pair annihilation, as their low star formation rate is very low and it also minimizes the uncertain contribution of astrophysical processes. For our purpose, we have predicted the DM constraints of four LSB galaxies using the observed radio data from Very Large Array (VLA) radio telescope at the frequency ($\nu$) = 1.4 GHz. VLA is a 27 element interferometric array which produces images of the radio sky at a wide range of frequencies and resolutions. The VLA is located at an elevation of 2100 meters on the Plains of San Agustin in southwestern New Mexico. For estimating the radio-limits on $<\sigma v>$ from DM annihilation, we have taken the observed radio data from VLA and except for UGC 11707, we have only obtained the upper limits of flux density for other three LSB galaxies (Table VII).

### TABLE VII: Radio flux-limit obtained from VLA radio telescope at 1.4 GHz

| Galaxy     | Observed Flux density in mJ |
|------------|-----------------------------|
| UGC 3371   | < 1 mJ                      |
| UGC 11707  | 1.17 mJ                     |
| UGC 12632  | < 1 mJ                      |
| UGC 12732  | < 1 mJ                      |
In Fig. 9 (a), we have shown the upper limits on the annihilation cross-section of all four LSB galaxies for three annihilation channels using VLA radio data with diffusion constant $D_0 = 3 \times 10^{28} \text{ cm}^2 \text{ s}^{-1}$. From Fig. 9 (a), it is evident that $\mu^+\mu^-$ and $\tau^+\tau^-$ final states provide the strongest limit on DM cross-section. In Figs. 9 (b,c,d), we have compared the constraints on the DM particle cross-section from radio observations with the stacked and the individual limits obtained from Fermi-LAT data (sections 4.2 and 4.3) for a variety of annihilation channels. From Figs. 9 (b,c,d) we clearly see that the predicted radio constraint provides a more stringent constraint than the $\gamma$-ray data. Especially for the $\mu^+\mu^-$ annihilation channel (Fig. 9 (d)) at $m_{DM}=100$ GeV, the constraints on the DM annihilation cross-section obtained from the VLA radio data is $\approx 2$ orders more stringent than the stacked limits and $\approx 3$ orders more stringent than the individual limits obtained by Fermi-LAT in the $\gamma$-rays. These limits scale with the strength of the magnetic field. For our study, we have fixed the magnetic field of LSB galaxies at 1 $\mu$G.

From Figs. 8 and 9, we have shown that in the case of LSB galaxies, radio emission provides better limits on DM cross-section than $\gamma$-ray data observed from Fermi-LAT. Therefore, the radio limits might impose a strong limits on theoretical DM models. It is also true that except for UGC 11707, the VLA radio fluxes can only provide the upper limits to the flux densities for the other LSB galaxies. Hence, in the following section we explore a more sensitive telescope like Square Kilometre Array (SKA) for detecting the radio synchrotron signal [75] from LSB galaxies.

The proposed SKA radio telescope will be one of the most sensitive radio telescopes in the next decade and is expected to explore many important questions in astrophysics and cosmology. Such as the fundamental physics aspects of dark energy, gravitation and magnetism. The exploration of the nature of DM is one of the most important additions to its scientific themes [76].

With RX-DMFIT code, we have predicted radio flux density $S(\nu)$ for DM annihilating into a specific channel in the form of synchrotron emission. In Fig. 10, we plot the $S(\nu)$ of radiation as a function of $\nu$ for DM annihilating into $b\bar{b}$, $\mu^+\mu^-$ and $\tau^+\tau^-$ channels, using the benchmark thermally averaged cross-section value $<\sigma v> = 3 \times 10^{26} \text{ cm}^3 \text{ s}^{-1}$.
and DM mass ($M_{DM}$) 100 GeV. From Fig. 10 (a,b,c,d), we can observe that for these annihilation channels, the DM candidates seem to be detected with SKA sensitivity curve with 10-100-1000 hours of observation. The halo profile is NFW, $B_0=1 \mu G$ and the thermal averaged DM annihilation cross-section is fixed to the value to $<\sigma v> = 3 \times 10^{26} \text{cm}^3\text{s}^{-1}$.

In this section, we have tried to check whether radio emission can produce a stronger constraint on the DM cross-section and find out that it is very likely. We can expect that in future with SKA telescope, it would be possible to detect the radio emission signature results from DM annihilation.

4.5 LSB galaxies and NFW, Burkert and Pseudo Isothermal density profile

In several studies, it has been mentioned that two types of DM density profile are popularly used to fit the observational data obtained from dSphs or LSBs [77]; those are cusp-like profile (eg. NFW profile[50]) and cored profile (eg. Pseudo Isothermal profile (ISO)[78] or Burkert profile (BURK)[79, 80]). Unfortunately, with insufficient kinematics or poor information from the rotational curve, we are unable to strongly favor any particular type of DM density profile. In this work, we have used NFW density profile throughout our analysis, but several pieces of literature suggest that for LSB galaxies BURK profile can reproduce the rotational curves and for such cases, BURK profile is generally favored over NFW profile [30, 32].

According to Ref. [30], the cored density profile with constant central density can produce a better fit than NFW profile, but it does not suggest that rotational curve does not agree with CDM. It is also possible that cuspy-like
(a) UGC 3371, \( M_{DM} = 100 \text{GeV} \)

(b) UGC 11707, \( M_{DM} = 100 \text{GeV} \)

(c) UGC 12632, \( M_{DM} = 100 \text{GeV} \)

(d) UGC 12732, \( M_{DM} = 100 \text{GeV} \)

FIG. 10: Flux densities of four LSB galaxies for DM annihilating into \( b \bar{b}, \mu^+\mu^- \) and \( \tau^+\tau^- \) final states. The halo profile is NFW, \( B_0 = 1 \mu \text{G}, m_{DM} = 100 \text{GeV} \) and the thermal averaged DM annihilation cross-section is fixed to the value of \( \langle \sigma v \rangle = 3 \times 10^{-26} \text{cm}^3\text{s}^{-1} \). The SKA sensitivity limits for integration times of 10, 100 and 1000 hours are overplotted as dashed, dotted and dot-dashed black lines, respectively.

profile can also fit the rotational curve of LSBs ([32, 50, 81]).

In this section, we have compared the J-factor values obtained from NFW with ISO and BURK density profiles. From Table VIII, we can find out that NFW density profile gives the largest values of J-factor and hence, NFW can possibly produce more stringent limit on DM particle models than ISO and BURK density profile.

We have also tried to estimate the upper limits of \( \gamma \)-ray flux and annihilation \( \langle \sigma v \rangle \) of UGC 12632 for each of the density profiles. In Table IX, we have shown the values of flux upper limits and limits on \( \langle \sigma v \rangle \) for three different density profiles for 100% \( b \bar{b} \) channel. From Fig. 11(a,b), it is also clearly evident that all three density profiles have estimated nearly same order of flux upper limits but the NFW density profile has provided a comparatively more stringent \( \langle \sigma v \rangle \) upper limits than other two density profiles. Therefore, in case LSB galaxies, we have found that NFW density profile can provide the strongest limit on the theoretical models (Fig. 11(b)). Hence, this result supports our arguments for choosing NFW density profile to model the DM density of LSB galaxies.

5. THE FUTURE OF LSB GALAXIES FOR DARK MATTER SEARCHES AND THE IMPACT OF THE CTA

In the next decade, the Cherenkov Telescope Array (CTA) will be the most sensitive instrument to study the high-energy \( \gamma \)-rays. It can detect the \( \gamma \)-rays from very faint and distant sources within a very large span of energies, i.e. between 20 GeV to 300 TeV. It has a large field of view, \( \sim 8 \) degrees for medium and small-sized of telescopes. The large angular resolution of CTA is about 2 arc minutes and its energy resolution is well below \( \sim 10\% \). The
TABLE VIII: J-factor for three density profiles ($h_0 = 0.75$)

| Galaxy name | Density Profile | Astrophysical Constant ($J$)(GeV$^2$/cm$^{-4}$) |
|-------------|----------------|-----------------------------------------------|
| UGC 3371    | NFW            | 0.67 × 10$^{16}$                            |
|             | IS0            | 0.17 × 10$^{16}$                            |
|             | BURKERT        | 0.25 × 10$^{16}$                            |
| UGC 11707   | NFW            | 0.44 × 10$^{16}$                            |
|             | IS0            | 0.11 × 10$^{16}$                            |
|             | BURKERT        | 0.17 × 10$^{16}$                            |
| UGC 12632   | NFW            | 0.73 × 10$^{16}$                            |
|             | IS0            | 0.19 × 10$^{16}$                            |
|             | BURKERT        | 0.27 × 10$^{16}$                            |
| UGC 12732   | NFW            | 0.73 × 10$^{16}$                            |
|             | IS0            | 0.19 × 10$^{16}$                            |
|             | BURKERT        | 0.27 × 10$^{16}$                            |

TABLE IX: Comparison between upper limits on flux and $<\sigma v>$ for 100% b$\bar{b}$ channel for three different density profiles. (UGC 12632)

| Density Profile | m$_{DM}$ (GeV) | Flux U.L. with 95% C.L. (cm$^{-2}$ sec$^{-1}$) | $<\sigma v>$ U.L. with 95% C.L. (cm$^3$ sec$^{-1}$) |
|-----------------|----------------|-----------------------------------------------|-----------------------------------------------|
| NFW             | 10             | $6.28 \times 10^{-10}$                        | $2.41 \times 10^{-23}$                        |
|                 | 100            | $1.68 \times 10^{-10}$                        | $24.17 \times 10^{-23}$                       |
|                 | 1000           | $7.08 \times 10^{-11}$                        | $450.067 \times 10^{-23}$                     |
| BURK            | 10             | $6.27 \times 10^{-10}$                        | $4.49 \times 10^{-23}$                        |
|                 | 100            | $1.67 \times 10^{-10}$                        | $44.92 \times 10^{-23}$                       |
|                 | 1000           | $7.08 \times 10^{-11}$                        | $837.98 \times 10^{-23}$                      |
| ISO             | 10             | $6.27 \times 10^{-10}$                        | $3.03 \times 10^{-23}$                        |
|                 | 100            | $1.68 \times 10^{-10}$                        | $30.30 \times 10^{-23}$                       |
|                 | 1000           | $7.08 \times 10^{-11}$                        | $564.98 \times 10^{-23}$                      |

effective area of CTA increases with increasing energies, such as, $5 \times 10^4$ $m^2$ at 50 GeV, $10^6$ $m^2$ at 1 TeV, and $5 \times 10^6$ $m^2$ at 10 TeV. Hence, CTA is capable of producing better sensitivity than other ground-based and space-based $\gamma$-ray instruments. All of these qualities make CTA an ultimate observatory to identify the positive detection of DM annihilation.

In this section, we have compared the sensitivity of $\gamma$-ray detection of the CTA with the Fermi-LAT and have tried to predict whether it is possible for CTA to detect any $\gamma$-ray signal from LSBs. In an aspect of energy resolution, angular resolution, effective area and any other key feature, there are some differences between space-based and ground-based telescope. However, for our study, this comparison will play an important role. We have adopted the CTA differential flux sensitivities curve from Ref. [82], whereas for Fermi-LAT we have taken the sensitivity curve for 9 years of observation of point-like and high-Galactic latitude sources$^6$. The CTA sensitivity curve is estimated for the point sources with power-law modeling and also with the detection significance of 5$\sigma$ for 50 hours of observation$^7$. For Fermi-LAT instrument, that sensitivity curve is drawn with a similar approach$^7$.

In Fig. (12), we have shown the differential fluxes of all LSB galaxies and have compared the fluxes with Fermi-LAT.

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$^6$ http://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm
$^7$ http://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm
and CTA sensitivity limits. For LSB galaxies, the differential flux values are obtained from power-law modeling with spectral index = 2. With Fermi-LAT data, we have not detected any signal from LSB galaxies (section 3.1), but from Fig. 12 we can observe that between 100 GeV to 1 TeV energy range, it might be possible for CTA to detect γ-ray signal from LSBs. Hence, from Fig. 12, we can expect that in the future, CTA would an ultimate instrument for detecting any positive signal from LSB galaxies.

FIG. 11: (a) shows the γ-ray flux upper limit of UGC 12632 annihilating into 100% $b\bar{b}$ final state for three different density profiles and (b) shows comparison between the $<\sigma v>$ upper limits for three density profiles for 100% $b\bar{b}$ final state.

FIG. 12: Comparison of differential energy flux of LSB galaxies with CTA and Fermi-LAT sensitivity curves.
6. DISCUSSIONS & CONCLUSIONS

In our paper, we have analyzed nearly nine years of Fermi-LAT observed γ-ray data along the direction of four LSB galaxies and for each cases, no excess γ-ray emission is detected along the direction of LSB. We have then determined the flux upper limit for those LSB galaxies. With the γ-ray spectrum from DM annihilation (i.e. with DMFit function), we have tried to estimate the flux and \( <\sigma v> \) upper limit for several pair-annihilation final states. Our estimated result shows that for LSB galaxies, the \( <\sigma v> \) upper limit for 100\% bb annihilation does not put any constraint on any considered theoretical models and from our results we could not particularly favor any theoretical model. Even though LSB galaxies are considered as one of the probable DM dominated galaxies, their individual \( <\sigma v> \) upper limits are almost 3 orders of magnitude higher than the DM dominated dSph galaxies.

From this work, we have also shown that amongst three popular density profiles for DM distribution, the NFW profile provides the strongest limit on the \((<\sigma v>, m_{DM})\) plane. Hence, throughout our analysis, we have considered only the standard NFW density profile.

We have also performed joint likelihood on these four LSB galaxies. The joint likelihood would be an ideal approach to obtain more stringent limits from LSB galaxies because through joint likelihood we have combined individual likelihood function of each LSB galaxies. Hence, it is expected that such an approach would increase the sensitivity of our analysis. After performing the combined likelihood, we found that the stacking analysis has improved the sensitivity of LSB limits. But, it is not improved enough to constraint the mSUGRA, Kaluza-Klein and AMSB models. The combined limits of \( <\sigma v> \) only put a very narrow constraint on MSSM model.

For indirect detection of DM signature, the γ-ray analysis is assumed to be one of the most popular ways to examine the but a multiwavelength approach can also provide a complementary probe of γ-ray analysis. LSB galaxies have very low star formation rate and it also minimizes the uncertain contribution of astrophysical processes. Hence, LSB galaxies could be an ideal place for studying the diffuse radio signals obtained from DM pair annihilation.

We have considered the multiwavelength approach and attempted to predict the possible radio emission from LSB galaxies. For this purpose, we have used a publicly available code, RX-DMFIT, an extension of DMFIT tool.

We have taken the radio data observed by VLA for all four LSB galaxies and then with the help of RXDMFIT code, we have found that the predicted radio constraint provides a more stringent constraint than γ-ray data. Specially, for \( \mu^+\mu^- \) annihilation channel, constraints on the DM annihilation cross-section obtained from the VLA radio data is \( \approx 3 \) orders more stringent than the stacked limits obtained by Fermi-LAT data.

One of the interesting findings of this work is that in the case of LSB galaxies, radio analysis would take a more important role than γ-ray analysis. But from the VLA telescope, we have only obtained the upper limit of flux density (except for UGC 11707). So to comment anything precisely about the DM signal from LSB galaxies, we need to focus on a more sensitive telescope than VLA (e.g SKA) and Fermi-LAT (e.g CTA).

Hence, we have tried to find out whether in the future SKA and CTA can detect any positive DM signal from LSB galaxies. From, our study (Fig. 10 (a,b,c,d)) we have observed that the DM candidates seem to be detected with the SKA sensitivity curve with 10-100-1000 hours of observation, specially for \( \mu^+\mu^- \) and \( \tau^+\tau^- \) annihilation channels. The SKA detection threshold with 1000 hours of observation has higher chances to detect the radiation from DM annihilation. We have obtained the same findings with the CTA telescope. We have found that (Fig 11) between 100 GeV to 1 TeV energy range, it might be possible for CTA to detect γ-ray signal from LSBs.

Hence, from our work we can conclude that γ-ray data obtained Fermi-LAT could not impose any strong limits on WIMP models. But the radio emission generated from WIMP-annihilation may be able to provide a much stronger constraint. In the future, the SKA telescope might play an important role to detect a radio signal from LSB galaxies. At present, with Fermi-LAT data we are unable to examine any signal from LSB galaxies, but at high energies, (i.e. between 100 GeV to 1 TeV), CTA may possibly detect the signal from LSB galaxies.
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[1] E. Komatsu et al., Astrophys. J. Suppl. 192, 18 (2011).
[2] P. A. R. Ade et al. [Planck Collaboration], Astron. and Astrophys. 594, A13 (2016).
[3] J. Diemand et al., Nature, 454, 735 (2008).
[4] V. Springel et al., Mon. Not. R. Astron. Soc., 391, 1685 (2008).
[5] N. W. Evans, F. Ferrer and S. Sarkar, Phys. Rev. D 69, 123501 (2004).
[6] V Bonnivard et al., J. Phys. Conf. Ser. 718, 042005 (2016).
[7] A. A. Abdo et al., Astrophys. J. 712, 147 (2010).
[8] G. Jungman, M. Kamionkowski and K. Griest, Phys. Rep. 267, 195 (1996).
[9] G. Steigman and M. S. Turner, Nucl. Phys. B. 253, 375 (1985); G. Bertone, D. Hooper and J. Silk, Phys. Rept. 405, 279 (2005).
[10] A. Albert et al., Astrophys. J. 834, 110 (2017).
[11] M. Ackermann et al. [The Fermi-LAT Collaboration], Phys. Rev. Lett. 107, 241302 (2011).
[12] M. Ackermann et al. [The Fermi-LAT Collaboration], Phys. Rev. D. 89, 04200 (2014).
[13] A. Geringer-Sameth et al., Phys. Rev. D 91, 083535 (2015).
[14] D. Hooper & T. Linden, J. Cosmol. Astropart. Phys. 09, 016 (2015).
[15] M. Ackermann et al., Phys. Rev. Lett. 115, 231301 (2015).
[16] J. Diemand, B. Moore and J. Stadel, Nature (London) 433, 389 (2005).
[17] M. Kuhlen et al., J. Phys. Conf. Ser. 125, 012008 (2008).
[18] V. Springel et al., Nature (London) 435, 629 (2005).
[19] S. Biswas et al., J. Cosmol. Astropart. Phys. 11, 003 (2017).
[20] P. Bhattacharjee et al., J. Cosmol. Astropart. Phys. 08, 028 (2019).
[21] C. Impey and G. Bothun, Annu. Rev. Astron. Astrophys. 35, 267 (1997).
[22] W. J. G. de Blok, S. S. McGaugh and J. M. van den Hulst; Mon. Not. R. Astron. Soc. 283, 18 (1996).
[23] V. Burkholder, C. Impey and D. Sprayberry, Astrophys. J. 122, 2318 (2001).
[24] K. O’Neil, G. Bothun, W. V. Driel and D. M. Ragaigne, Astron. and Astrophys. 428, 823 (2004).
[25] W. Du et al., Astron. J. 149, 199 2015.
[26] W. J. G. de Blok and S. S. McGaugh, Mon. Not. R. Astron. Soc. 290, 533 (1997).
[27] M. Honey et al., Mon. Not. R. Astron. Soc. 476, 4488 (2018).
[28] S. J. Schombert, S. McGaugh and J. A. Eder, Astron. J. 121, 2420 (2001).
[29] R. K. de Naray, S. S. McGaugh and J. C. Milos, Astrophys. J., 692, 1321 (2009).
[30] F. K. van den Bosch and R. A. Swaters; Mon. Not. R. Astron. Soc. 325, 1017 (2001).
[31] V. Gammaldi et al., arxiv:1706.01843v3 (2017).
[32] S. H. Cadena et al., Proceedings of science; POS (ICRC2017) 897 (2017).
[33] A. McDaniel, T. Jeltema, S. Profumo and E. Storm, J. Cosmol. Astropart. Phys. 09, 027 (2017).
[34] A. A. Abdo et al., Astrophys. J. 715, 429 (2010).
[35] M. Ajello et al., Astrophys. J., 819, 44 (2016).
[36] R. A. Swaters et al., Astron. and Astrophys. 390, 829 (2002).
[37] R. A. Swaters et al., Astron. J., 583, 732 (2003).
[38] R. A. Swaters [PhD Thesis] Dark matter in late-type dwarf galaxies (1999).
[39] R. A. Swaters et al., Astron. and Astrophys. 493, 871 (2009).
[40] W. Cash, Astrophys. J. 228, 939 (1979).
[41] J. R. Mattox, et al, Astrophys. J. 461, 396 (1996).
[42] F. Acero, et al., Astrophys. J. Suppl. 218, 23 (2015).
[43] R. Essig, N. Sehgal, L.E. Strigari, Phys. Rev. D. 89, 023506 (2009).
[44] W. Rolke, A. Lopez, J. Conrad, Nucl. Instrum. Methods A, 551, 493 (2005).
[45] R. Barbieri, S. Ferrara and C. A. Savay, Phys. Lett. B 119, 343 (1982).
[46] E. A. Baltz et al., J. Cosmol. Astropart. Phys. 07, 13 (2008).
[47] N. Arkani-Hamed et al., Phys. Rev. D 79, 015014 (2009).
[48] J. L. Feng, M. Kaplinghat, and H. B. Yu, Phys. Rev. D 82, 083525 (2010).
[49] N. W. Evans, F. Ferrer and S. Sarkar, Phys. Rev. D 69, 123501 (2004).
[50] J. F. Navarro, C. S. Frenk, S. D. M. White, Astrophys. J. 490, 493 (1997).
[51] F.L. Lokas et al., Mon. Not. R. Astron. Soc.321, 155 (2001).
[52] A. Liddle in an introduction to Modern Cosmology, Willey (2008).
[53] F.C. van den Bosch and R.A. Swaters, Mon. Not. R. Astron. Soc. 325, 1017 (2001).
[54] A. Charbonnier et al., Mon. Not. R. Astron. Soc. 418, 1526 (2011).
[55] T. E. Jeltema and S. Profumo, J. Cosmol. Astropart. Phys. 11, 003 (2008).
[56] P. Gondolo et al., J. Cosmo Astropart. Phys. 07, 008 (2004).
[57] A. H. Chamseddine, R. Arnowitt, P. Nath, Phys. Rev. Lett. 49, 970 (1982).
[58] D. J. H. Chung et al., Phys. Rep. 407, 1 (2005).
[59] H. C. Cheng, J. L. Feng, K. T. Matchev, Phys. Rev. Lett. 89, 211301 (2002).
[60] G. Servant and T. M. P. Tait, Nucl. Phys. B 650, 391 (2003).
[61] D. Hooper and S. Profumo, Phys. Rep. 453, 29 (2007).
[62] G. F. Giudice, R. Rattazi, M. A. Luty and H. Murayama, J. High Energy Phys. 12, 027 (1998); L. Randall and R. Sundrum, Nucl. Phys. B 557, 79 (1999).
[63] M. Ackermann et al., J. Cosmol. Astropart. Phys. 5, 025 (2010).
[64] E. Charles et al., Phys. Rep. 636, 1 (2016).
[65] T. Daylan et al., Phys. of the Dark Universe 12, 1 (2016).
[66] A. Abramowski et al., Phys. Rev. D 90, 112012 (2014).
[67] A. Abramowski et al., Phys. Rev. Lett. 106, 161301 (2011).
[68] E. Storm et al., Astrophys. J. 768, 106 (2012).
[69] E. Storm et al., Astrophys. J. 839, 33 (2017).
[70] M. Regis, L. Richter and S. Colafrancesco, J. Cosmol. Astropart. Phys. 07, 025 (2017).
[71] V. L. Ginzburg and S. I. Syrovatskii, The Origin of Cosmic Rays. 1964.
[72] M. S. Longair, High Energy Astrophysics. Cambridge University Press, New York, 3 ed., 2011.
[73] S. Colafrancesco, S. Profumo and P. Ullio, Astron. and Astrophys. 455, 21 (2006).
[74] S. Colafrancesco, S. Profumo and P. Ullio, Phys. Rev. D 75, 023513 (2007).
[75] S. Colafrancesco et al., PoS AASKA 14, 100 (2015).
[76] R. Braun et al., PoS AASKA 14, 174 (2015).
[77] A. Boyarsky et al., arxiv:0911.1774v1 (2009).
[78] J. Gunn and J. R. Gott., Astrophys. J. 176, 1 (1972).
[79] A. Burkert, Astrophys. J. Lett. 447, L25 (1995).
[80] P. Salucci et al., Mon. Not. R. Astron. Soc. 420, 2034 (2012).
[81] J. F. Navarro et al., Mon. Not. R. Astron. Soc. 402, 21 (2010).
[82] G. Maier et al., Proceedings of the 35th International Cosmic Ray Conference (ICRC 2017), Bexco, Busan, Korea (2017).