Constraints on the velocity-dependent dark matter annihilation cross section from Fermi-LAT observations of dwarf galaxies (Postprint)

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Date: 2016-08-30T00:00:00+00:00

Abstract

The gamma-ray observation of dwarf spheroidal satellites (dSphs) is an ideal approach for probing the dark matter (DM) annihilation signature. The latest Fermi-LAT dSph searches have set stringent constraints on the velocity independent annihilation cross section in the small DM mass range, which gives very strong constraints on the scenario to explain the the AMS-02 positron excess by DM annihilation. However, the dSph constraints would change in the velocity dependent annihilation scenarios, because the velocity dispersion in the dSphs varies from that in the Milky Way. In this work, we use a likelihood map method to set constraints on the velocity dependent annihilation cross section from the Fermi-LAT observation of six dSphs. We consider three typical forms of the annihilation cross section, i.e. p-wave annihilation, Sommerfeld enhancement, and Breit-Wigner resonance. For the p-wave annihilation and Sommerfeld-enhancement, the dSph limits would become much weaker and stronger compared with those for the velocity independent annihilation, respectively. For the Breit-Wigner annihilation, the dSph limits would vary depending on the model parameters. We show that the scenario to explain the AMS-02 positron excess by DM annihilation is still viable in the velocity dependent cases

Full Text

Preamble

Constraint on the velocity dependent dark matter annihilation cross section from Fermi-LAT observations of dwarf galaxies

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The -ray observation of dwarf spheroidal satellites (dSph's) provides an ideal approach for probing dark matter (DM) annihilation signatures. The latest Fermi-LAT dSph searches have set stringent constraints on the velocity-independent annihilation cross section in the small DM mass range, which yields very strong constraints on scenarios explaining the AMS-02 positron excess through DM annihilation. However, dSph constraints would change in velocity-dependent annihilation scenarios because the velocity dispersion in dSph' s differs from that in the Milky Way. In this work, we employ a likelihood map method to set constraints on velocity-dependent annihilation cross sections from Fermi-LAT observations of six dSph' s. We consider three typical forms of the annihilation cross section: p-wave annihilation, Sommerfeld enhancement, and Breit-Wigner resonance. For p-wave annihilation and Sommerfeld enhancement, the dSph limits become much weaker and stronger, respectively, compared with those for velocity-independent annihilation. For Breit-Wigner annihilation, the dSph limits vary depending on model parameters. We demonstrate that the scenario explaining the AMS-02 positron excess through DM annihilation remains viable in velocity-dependent cases.

Introduction

Numerous astrophysical and cosmological observations have shown that the Universe is composed of approximately 4.8% baryons, 25.8% cold dark matter (DM), and 69.3% dark energy [?]. A popular candidate for cold DM is the weakly interacting massive particle (WIMP) [?, ?, ?]. In the thermal freeze-out scenario, the current abundance of WIMPs can explain the observed DM relic density [?]. Today, WIMP annihilations can directly produce rays, or indirectly produce them through cascade decay, final state radiation, and inverse Compton scattering processes. These rays should be dominantly generated in regions with high DM densities and can be captured by terrestrial and satellite experiments, such as the space-borne -ray detector Fermi Large Area Telescope (Fermi-LAT) [?].

Many studies have investigated -ray emission from DM annihilations in various astrophysical sources, including the galactic halo [?, ?, ?, ?, ?, ?, ?], galaxy clusters [?], and galactic DM substructures [?, ?, ?]. Among these sources, nearby dwarf spheroidal satellites (dSph' s) are ideal for probing DM annihilation -ray signatures due to their high DM densities and lack of conventional astrophysical -ray sources [?, ?]. As no significant -ray excess has been found in Fermi-LAT dSph observations, stringent upper limits on the DM annihilation cross section have been established in the literature [?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?].[1]

For ordinary DM s-wave annihilation processes that are independent of DM relative velocity, the observed DM relic density can be achieved with a thermally averaged cross section of approximately $10^{-26}\,\mathrm{cm}^3\mathrm{s}^{-1}$. However, the s-wave annihilation cross section has been stringently constrained by Fermi-LAT -ray searches from dSph' s and should be smaller than this "canonical" value for DM masses above ~ 10 GeV for annihilations to $b\bar{b}$ or $\tau^+\tau^-$ [?]. Generally, the annihilation cross section can be expanded in a form that depends on the DM relative velocity. For example, in the nonrelativistic limit, $\langle \sigma v \rangle = a + b\langle v^2 \rangle + \mathcal{O}(v^4)$. Only when the s-wave annihilation is dominant is $\langle \sigma v \rangle$ a constant. If p-wave annihilation is not negligible, $\langle \sigma v \rangle$ is suppressed at small DM velocities. In this case, the annihilation cross sections in dSph' s would be smaller than those in the local halo or early Universe due to the small DM velocity dispersion of $\sim (10)\,\mathrm{km\ s}^{-1}$ in dSph' s [?]. Consequently, constraints on velocity-suppressed DM annihilations from dSph -ray searches are much weaker.

An interesting hint of a DM signature comes from cosmic-ray electron/positron observations. If the anomalous electrons and positrons observed by PAMELA [?] and AMS-02 [?] are produced by DM annihilation, the local DM annihilation cross section in the Galaxy should be of order $10^{-23}\,\mathrm{cm}^3\mathrm{s}^{-1}$, approximately 2-3 orders of magnitude larger than the canonical value in the early Universe. This discrepancy can be explained in velocity-dependent annihilation scenarios. For example, the exchange of a new light boson between two initial heavy DM particles may confer an additional factor of $1/v$ or $1/v^2$ to the annihilation cross section. This effect, known as Sommerfeld enhancement [?], can simultaneously explain the anomalous cosmic-ray electrons/positrons observed by PAMELA and the DM relic density [?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?]. In this scenario, dSph searches would set strong constraints on the annihilation cross section due to the small velocities in dSph' s [?, ?, ?] (for other cosmological limits, see e.g., [?, ?, ?]). Another important velocity-dependent scenario is the "Breit-Wigner" mechanism [?, ?, ?, ?], where DM particles annihilate via a pole near twice the DM mass. Depending on model parameters, the annihilation cross section can also be significantly enhanced at lower velocities.

In this work, we study constraints on velocity-dependent DM annihilation cross sections from Fermi-LAT dSph observations. A simple approach requires that the DM signature not exceed the observed -ray flux upper limit. However, constraints derived without spectral information would be very conservative. In Ref. [?], the authors proposed a convenient and flexible likelihood map method to derive limits from Fermi-LAT dSph observations for any given shape of the initial DM-induced -ray spectrum. We adopt a similar method to construct likelihood maps for six dSph' s with large J-factors. We can then easily obtain the total likelihood via these maps and set constraints on the DM annihilation cross section.

This paper is organized as follows. In Sec. II, we provide a detailed description of the likelihood map method. In Sec. III, we consider three typical forms of velocity-dependent DM annihilations and use the likelihood map method to set constraints. Section IV presents our summary.

II. Fermi-LAT Data Analysis

A maximum likelihood method has been developed for -ray source analysis to account for limited photon statistics and the dependence of Fermi-LAT performance on incident photon angle and energy. For each dSph, we divide Fermi-LAT observational data into several energy bins. In the likelihood calculation, the -ray flux from DM annihilation in each bin is assumed to be constant. This "energy-flux-likelihood" cube forms the likelihood map for a given dSph. Through this likelihood map, the likelihood for any -ray spectrum shape can be easily obtained across the entire energy range.

The expected -ray signature flux from dSph DM annihilation can be expressed as

$$\phi(E) = \frac{\langle \sigma v \rangle}{8\pi m_{\mathrm{DM}}^2} \frac{dN_\gamma}{dE_\gamma} \times J,$$

where $\langle \sigma v \rangle$ is the thermally averaged annihilation cross section, m_{DM} is the DM mass, dN_γ/dE_γ is the differential -ray spectrum per DM pair annihilation, and the J-factor is the line-of-sight integration of the DM distribution, i.e., $J = \int \rho^2(l)\, dl\, d\Omega$. Note that dN_γ should be a sum of photons from all possible DM annihilation final states according to the DM model. Here we only consider the -ray contribution from a specific annihilation channel using PPPC [**?**, **?**]. We define a variable $C_i = \int_{E_i}^{E_{i+1}} \frac{dN_\gamma}{dE_\gamma}\, dE_\gamma$ in each energy bin, where i is the energy bin index.

The J-factor can be derived from observed line-of-sight stellar velocities using the Jeans equation [**?**, **?**, **?**]. Numerous works [**?**, **?**] have indicated that the J-factor is not sensitive to the specific DM density profile. For instance, the J-factor of Draco for a Navarro-Frenk-White profile is similar to that for a Burkert profile. We adopt the J-factor values and their uncertainties from Table I of Ref. [**?**], which are based on results from Refs. [**?**, **?**, **?**, **?**, **?**].

For a given set of m_{DM}, $\langle \sigma v \rangle$, and J-factor inputs, the combined likelihood across all energy bins for the jth dSph is estimated as

$$L_j = \prod_i \int_{-\infty}^{\infty} L_i(\phi_i | \ln(10) J_{\mathrm{obs},j}) \frac{1}{\sqrt{2\pi}\sigma_j} e^{-[\log_{10}(J_j) - \log_{10}(J_{\mathrm{obs},j})]^2 / 2\sigma_j^2}\, d\log_{10}(J_j),$$

where i denotes the ith energy bin, ϕ_i is the DM signature flux, $J_{\mathrm{obs},j}$ is the calculated J-factor with an error of σ_j. For a given $\langle \sigma v \rangle$ and m_{DM}, J_j is chosen to maximize L_j. We then obtain a "cross section-likelihood" table for the jth dSph. The combined likelihood of all dSph's can be calculated as $L_{\mathrm{total}} = \prod_j L_j$. Through this combined cross section-likelihood table, we can set 95% confidence level (C.L.) upper limits on energy flux and find the value of $\langle \sigma v \rangle$ by requiring that the corresponding log-likelihood has decreased by 2.71/2 from its maximum [**?**, **?**].

In Ref. [**?**], the authors combined the likelihood of all selected dSph' s in the ith energy bin and then constructed the combined likelihood map across the entire energy range. Consequently, dSph uncertainties were repeatedly included in each energy bin, and correlations between different energy bins were not accounted for. Contrary to that approach, we first combine the likelihood of all energy bins L_i for the jth dSph and then construct a total likelihood. For example, we show the likelihood maps of Draco and Segue 1 in Fig. 1 [Figure 1: see original paper]. The grid scan of the likelihood map is performed in eight logarithmic energy bins in the range of 0.5-500 GeV and 300 logarithmic bins in the range of 10^{-30}-$10^{-1}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{GeV}^{-1}$. The color bar denotes the value of $-2\Delta\log L$ for given m_{DM} and signature flux.

The sensitivity of a combined dSph analysis is dominantly determined by dSph' s with large J-factors. In this analysis, we consider six dSph' s: Draco, Segue 1, Coma Berenices, Willman 1, Ursa Major II, and Ursa Minor, because the sensitivity of a combined dSph analysis is dominated by such objects with large J-factors [**?**]. The mean values and uncertainties of the J-factors for these six dSph' s are listed in Table I [TABLE:I].

Our work is based on the latest published SCIENCE TOOLS version v10r0p5. We employ six-year Fermi-LAT data recorded from 2008 August 04 to 2014 May 05 with Pass8 photon data selection in the analysis. Events from the Pass8 SOURCE class in the energy band between 500 MeV and 500 GeV are adopted. To reduce -ray contamination from the Earth limb, events with zenith angles larger than 100° are rejected, and the recommended filter cut (DATA_QUAL > 0, LAT_CONFIG == 1) is applied. Each dSph is treated as a point source. We create a $10^{\circ}\times10^{\circ}$ square region of interest around each dSph center, divided into 0.1° pixels and eight logarithmic energy bins from 500 MeV to 500 GeV. We use the galactic -ray diffuse model `gll_iem_v06.fit` and the isotropic extragalactic -ray diffuse spectrum `iso_P8R2_SOURCE_V6_v06.txt` as diffuse backgrounds. The third LAT source catalog (3FGL) [**?**] is used to handle point -ray sources. In the analysis, we perform a global fit over the entire energy range and then fix all parameters except the normalization of the two diffuse backgrounds in each energy bin. The instrument response functions P8R2_SOURCE_V6 are set corresponding to the above LAT data selection.

III. Limits on Velocity Dependent Annihilation Cross Sections

Previous works have assumed the DM annihilation cross section to be velocity independent. The primary goal of this work is to explore -ray observation limits from dSph' s on velocity-dependent annihilation cross sections. We consider the DM annihilation cross section in several typical velocity-dependent forms, such as those in p-wave annihilation, Breit-Wigner, and Sommerfeld scenarios.

The thermally averaged annihilation cross section in the nonrelativistic limit can be calculated as

$$\langle \sigma v_{\rm rel} \rangle = \int f(\vec{v}_1) f(\vec{v}_2) (\sigma v_{\rm rel})\, d^3\vec{v}_1\, d^3\vec{v}_2 = \int_0^\infty (\sigma v_{\rm rel}) f(v_{\rm rel})\, dv_{\rm rel},$$

where $f(\vec{v})$ is the DM velocity distribution, assumed to be Maxwell-Boltzmann form, $v_{\rm rel} = |\vec{v}_1 - \vec{v}_2|$ is the relative velocity of two initial DM particles, and v_p is the most probable velocity. The relation between v_p and the line-of-sight velocity dispersion v_0 can be approximated by $v_p \approx \sqrt{2} v_0$. The velocity dispersions of the six dSph’ s considered in this work are listed in Table II [TABLE:II].

Note that the DM velocity distribution is assumed to be an isotropic Maxwell-Boltzmann distribution in Eq. (4). For a given DM density profile and isotropic velocity distribution, the most probable velocity and one-dimensional DM velocity dispersion can be calculated from the Jeans equation [**?**]. In principle, a precise DM velocity distribution can be derived from N-body simulations. Many analyses based on high-resolution DM-only simulations have shown that DM velocity distributions of Milky Way-like halos are anisotropic and deviate from the standard Maxwell-Boltzmann distribution [**?**, **?**, **?**, **?**]. In recent years, more realistic DM velocity distributions have been extracted from simulations including baryonic effects during galaxy formation [**?**, **?**, **?**, **?**]. These studies also confirm that the DM velocity distribution is not a standard Maxwell-Boltzmann distribution. Further studies are required to determine precise DM velocity distributions of the Galaxy and dSph’ s. Here we adopt the standard Maxwell-Boltzmann distribution as an approximation.

Unlike the velocity-independent case where $\langle \sigma v \rangle$ has a universal value, in velocity-dependent scenarios the annihilation cross section may have different values in each dSph. Thus, the strategy for setting constraints on the DM annihilation cross section is model-dependent. For example, if we can expand $\langle \sigma v \rangle = a + bv^2$, we obtain constraints on the two constants a and b in each dSph. More severe constraints on a and b can be obtained by combining constraints from several dSph’ s. Furthermore, constraints on the local DM annihilation cross section can be obtained by taking the velocity dispersion in the Milky Way. In the following, we present our constraints on $\langle \sigma v \rangle$ for three typical velocity-dependent forms. The results have been translated to the local $\langle \sigma v \rangle$ in the Solar system.

Note that the dSph J-factor is also determined by the density profile, which is derived by fitting to the observed velocity distribution of luminous matter. Therefore, the velocity-dependent factor in the dSph DM annihilation cross section is correlated with the J-factor (see e.g., [**?**, **?**]). A detailed analysis of this correlation is complex and will be left for future study.

A. p-wave annihilation

In the WIMP scenario, the DM annihilation cross section can be generically expanded in $v_{\rm rel}^2$ in the nonrelativistic limit. We parameterize the annihilation cross section as

$$\sigma v_{\rm rel} = a + b v_{\rm rel}^2,$$

where a is the dominant contribution from the s-wave annihilation process and b is the contribution from the p-wave annihilation process. Higher-order contributions depending on $v_{\rm rel}^{2n}$ with $n > 1$ are neglected here.

For a given ratio of a/b, dSph -ray constraints on parameters a and b can be obtained through the likelihood map method described above. To compare with results from other DM detection experiments, these limits can be translated into limits on the DM annihilation cross section in other astrophysical sources. For example, we can derive limits on the local annihilation cross section with a velocity dispersion of $270\,{\rm km\ s^{-1}}$. In Fig. 2 [Figure 2: see original paper], we show these limits for several different values of a/b for six DM annihilation channels. Note that the cases $a = 0$ and $b = 0$ denote pure p-wave and s-wave annihilation, respectively. Our limits for the s-wave annihilation process are in good agreement with those given by the Fermi-LAT Collaboration [**?**]. For a pure p-wave annihilation process, the constraints can be weakened by 3 orders of magnitude.

B. Breit-Wigner scenario

In the Breit-Wigner scenario, initial DM particles annihilate via a pole that lies near twice the DM mass [**?**, **?**, **?**, **?**]. The mass of the resonance particle M can be parameterized by

$$M = 2m_\chi \sqrt{1+\delta},$$

where m_χ is the DM mass and δ is a parameter satisfying $|\delta| \ll 1$. A typical form of the DM annihilation cross section in the Breit-Wigner scenario can be written as

$$\sigma v_{\rm rel} = \frac{a}{(v_{\rm rel}^2 + \delta)^2 + \gamma^2 (1+\delta)^2},$$

where a is an undetermined parameter in the theoretical model and γ is defined as $\gamma = \Gamma/M$, with Γ being the resonance decay width.

For given γ and δ, we can set constraints on a from Fermi-LAT dSph searches. The limits on the local DM annihilation cross section for three sets of δ and γ are shown in Fig. 3 [Figure 3: see original paper]. For comparison, we also show the parameter regions [**?**] that explain the anomalous cosmic-ray electrons and positrons observed by AMS-02. For $\delta > 0$, the annihilation cross section at lower velocities in dSph’ s is always larger than that at larger velocities in the local Galaxy. Thus, dSph searches set very stringent limits on the parameter regions explaining the electron and positron excess. However, the annihilation cross section would be maximal at a velocity of $v \sim \sqrt{-\delta}$ for $\delta < 0$ and could be smaller at lower velocities in the range of $v < \sqrt{-\delta}$. This means the limits from dSph searches can be weakened if dSph DM annihilations occur below the pole, which is the case for the $\delta < 0$ limits shown in Fig. 3.

C. Sommerfeld scenario

In this subsection, we consider velocity-dependent annihilation cross sections scaled by a factor of $1/v$ or $1/v^2$, which can be obtained in the Sommerfeld scenario [?, ?, ?, ?, ?, ?, ?, ?, ?, ?, ?]. In this scenario, long-range attractive interactions between two initial heavy DM particles via exchange of light bosons ϕ can significantly enhance the annihilation cross section at low velocities. This can be expressed as

$$\sigma v_{\mathrm{rel}} \sim (\sigma v_{\mathrm{rel}})_0 \frac{\pi \alpha_\chi / v}{1 - e^{-\pi \alpha_\chi / v}},$$

where $(\sigma v_{\mathrm{rel}})_0$ is the annihilation cross section in the early Universe, α_χ is the interaction coefficient, and a is a constant. Moreover, in some special parameter regions, two incoming DM particles behave like a bound state, and the annihilation cross section would be "resonantly" enhanced at low velocities as

$$\sigma v_{\mathrm{rel}} \sim (\sigma v_{\mathrm{rel}})_0 \frac{\pi^2 \alpha_\chi m_\phi}{6 m_\chi v^2}.$$

In general, the Sommerfeld enhancement factor depends on several parameters (m_χ, m_ϕ, and α_χ) and can be obtained by solving the Schrödinger equation with an attractive potential. We do not discuss this enhancement factor in a particular model. Instead, we consider two typical annihilation cross section forms that capture the key features:

$$\sigma v_{\mathrm{rel}} = \frac{(\sigma v_{\mathrm{rel}})_0}{v_{\mathrm{rel}}},$$

and

$$\sigma v_{\mathrm{rel}} = \frac{(\sigma v_{\mathrm{rel}})_0}{v_{\mathrm{rel}}^2}.$$

The limits on the local DM annihilation cross section with the form of Eq. (12) for two annihilation channels 4μ and 4τ are shown in Fig. 4 [Figure 4: see original paper]. For comparison, we also provide limits for velocity-independent annihilation. Generally, four-body annihilation final states induce weaker limits because of softer initial -ray spectra. However, since DM annihilation cross sections are enhanced at low velocities in this scenario, dSph observations set much stricter limits than those from galactic observations.

IV. Conclusion and Discussions

In this work, we study limits on velocity-dependent DM annihilation cross sections from Fermi-LAT dSph -ray observations based on the latest Pass8 data. We construct likelihood maps in the energy range of 0.5–500 GeV for six nearby luminous dSph' s with large J-factors. We can then easily obtain the total likelihood and derive limits on the DM annihilation cross section for an arbitrary initial -ray spectrum.

In our analysis, we consider three typical velocity-dependent annihilation cross section forms. Since DM particles in different astrophysical sources often have different velocity dispersions, the annihilation rates may change dramatically. For DM annihilation with non-negligible p-wave contribution, the cross section can be parameterized as $a + bv^2$ and is suppressed in dSph' s due to their low velocity dispersions. For pure p-wave annihilation, the limits can be weakened by about 3 orders of magnitude compared with s-wave annihilation. For annihilation cross sections scaled by factors of $1/v$ or $1/v^2$, which can be obtained in the Sommerfeld scenario, dSph constraints become stronger. For other more complex velocity-dependent forms, the behavior of constraints depends on model parameters. As an example in the Breit-Wigner scenario with particular parameter sets, dSph constraints may be weaker or stronger than those for velocity-independent annihilation.

In some cases, limits on the local DM annihilation cross section from Fermi-LAT dSph observations can be relaxed. An important implication is the DM explanation of the cosmic-ray positron/electron excess observed by AMS-02. Contrary to the velocity-independent annihilation scenario, where the DM explanation has almost been excluded by Fermi-LAT data, DM annihilation in velocity-dependent scenarios may remain viable for explaining the positron/electron excess.

Acknowledgments

This work is supported by the National Natural Science Foundation of China under Grants Nos. 11475189, 11475191, 11135009, 11175147, the 973 Program of China under Grant No. 2013CB837000, and by the Strategic Priority Research Program "The Emergence of Cosmological Structures" of the Chinese Academy of Sciences under Grant No. XDB09000000. We are grateful to Q. Yuan, X.-Y. Huang, Z.-W. Li, S.-J. Lin and Q.-F. Xiang for helpful discussions.

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[1] DSph constraints on the lifetime of decaying DM can be found in Ref. [**?**, **?**].

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