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Search for Gamma-Ray Emission from DES Dwarf Spheroidal Galaxy Candidates with Fermi-LAT Data

A. Drlica-Wagner,[1,2,*] A. Albert,[3,†] K. Bechtol,[1,4,‡] M. Wood,[3,§] L. Strigari,[5,¶] M. Sánchez-Conde,[6,7] L. Baldini,[8] R. Essig,[9] J. Cohen-Tanugi,[10] B. Anderson,[11] R. Bellazzini,[12] E. D. Bloom,[3] R. Caputo,[13] C. Cecchi,[14,15] E. Charles,[3] J. Chiang,[3] J. Conrad,[7,6,11,16] A. de Angelis,[17] S. Funk,[3] P. Fusco,[18,19] F. Gargano,[19] N. Giglietto,[18,19] F. Giordano,[18,19] S. Guiriec,[20,21] M. Gustafsson,[22] M. Kuss,[12] F. Loparco,[18,19] P. Lubrano,[14,15] N. Mirabal,[20,21] T. Mizuno,[23] A. Morselli,[24] T. Ohsugi,[23] E. Orlando,[3] M. Persic,[25,26] S. Rainò,[18,19] F. Spada,[12] D. J. Suson,[27] G. Zaharijas,[28,29] and S. Zimmer[7,6]

(The Fermi-LAT Collaboration)

T. Abbott,[30] S. Allam,[2,31] E. Balbinot,[32,33] A. H. Bauer,[34] A. Benoit-Lévy,[35] R. A. Bernstein,[36] G. M. Bernstein,[37] E. Bertin,[38] D. Brooks,[35] E. Buckley-Geer,[2] D. L. Burke,[39] A. Carnero Rosell,[40,33] F. J. Castander,[34] R. Covarrubias,[41] C. B. D'Andrea,[42] L. N. da Costa,[33,40] D. L. DePoy,[5] S. Desai,[43,44] H. T. Diehl,[2] C. E Cunha,[45] T. F. Eifler,[37,46] J. Estrada,[2] A. E. Evrard,[47] A. Fausti Neto,[33] E. Fernandez,[48] D. A. Finley,[2] B. Flaugher,[2] J. Frieman,[2,4] E. Gaztanaga,[34] D. Gerdes,[47] D. Gruen,[49,50] R. A. Gruendl,[51,41] G. Gutierrez,[2] K. Honscheid,[52,53] B. Jain,[37] D. James,[30] T. Jeltema,[13] S. Kent,[2] R. Kron,[4] K. Kuehn,[54] N. Kuropatkin,[2] O. Lahav,[35] T. S. Li,[5] E. Luque,[55,33] M. A. G. Maia,[33,40] M. Makler,[56] M. March,[37] J. Marshall,[5] P. Martini,[53,57] K. W. Merritt,[2] C. Miller,[47] R. Miquel,[48,58] J. Mohr,[43,44,49] E. Neilsen,[2] B. Nord,[2] R. Ogando,[40,33] J. Peoples,[2] D. Petravick,[41] A. Pieres,[55,33] A. A. Plazas,[59,46] A. Queiroz,[55,33] A. K. Romer,[60] A. Roodman,[45,39] E. S. Rykoff,[39] M. Sako,[37] E. Sanchez,[61] B. Santiago,[55,33] V. Scarpine,[2] M. Schubnell,[47] I. Sevilla,[61,51] R. C. Smith,[30] M. Soares-Santos,[2] F. Sobreira,[2,33] E. Suchyta,[53,52] M. E. C. Swanson,[41] G. Tarle,[47] J. Thaler,[62] D. Thomas,[42] D. Tucker,[2] A. Walker,[30] R. H. Wechsler,[63,45,39] W. Wester,[2] P. Williams,[4] B. Yanny,[2] and J. Zuntz[64]

(The DES Collaboration)

[1] *Member of Fermi-LAT and DES collaborations.*
[2] *Fermi National Accelerator Laboratory, P. O. Box 500, Batavia, IL 60510, USA*
[3] *W. W. Hansen Experimental Physics Laboratory, Kavli Institute for Particle Astrophysics and Cosmology, Department of Physics and SLAC National Accelerator Laboratory, Stanford University, Stanford, CA 94305, USA*
[4] *Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL 60637, USA*
[5] *George P. and Cynthia Woods Mitchell Institute for Fundamental Physics and Astronomy, and Department of Physics and Astronomy, Texas A&M University, College Station, TX 77843, USA*
[6] *The Oskar Klein Centre for Cosmoparticle Physics, AlbaNova, SE-106 91 Stockholm, Sweden*
[7] *Department of Physics, Stockholm University, AlbaNova, SE-106 91 Stockholm, Sweden*
[8] *Università di Pisa and Istituto Nazionale di Fisica Nucleare, Sezione di Pisa I-56127 Pisa, Italy*
[9] *C.N. Yang Institute for Theoretical Physics, State University of New York, Stony Brook, NY 11794-3840, U.S.A., USA*
[10] *Laboratoire Univers et Particules de Montpellier, Université Montpellier 2, CNRS/IN2P3, Montpellier, France*
[11] *Royal Swedish Academy of Sciences Research Fellow, funded by a grant from the K. A. Wallenberg Foundation*
[12] *Istituto Nazionale di Fisica Nucleare, Sezione di Pisa, I-56127 Pisa, Italy*
[13] *Santa Cruz Institute for Particle Physics, Department of Physics and Department of Astronomy and Astrophysics, University of California at Santa Cruz, Santa Cruz, CA 95064, USA*
[14] *Istituto Nazionale di Fisica Nucleare, Sezione di Perugia, I-06123 Perugia, Italy*
[15] *Dipartimento di Fisica, Università degli Studi di Perugia, I-06123 Perugia, Italy*
[16] *The Royal Swedish Academy of Sciences, Box 50005, SE-104 05 Stockholm, Sweden*
[17] *Dipartimento di Fisica, Università di Udine and Istituto Nazionale di Fisica Nucleare, Sezione di Trieste, Gruppo Collegato di Udine, I-33100 Udine*
[18] *Dipartimento di Fisica "M. Merlin" dell'Università e del Politecnico di Bari, I-70126 Bari, Italy*
[19] *Istituto Nazionale di Fisica Nucleare, Sezione di Bari, 70126 Bari, Italy*
[20] *NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA*
[21] *NASA Postdoctoral Program Fellow, USA*
[22] *Georg-August University Göttingen, Institute for theoretical Physics - Faculty of Physics, Friedrich-Hund-Platz 1, D-37077 Göttingen, Germany*
[23] *Hiroshima Astrophysical Science Center, Hiroshima University, Higashi-Hiroshima, Hiroshima 739-8526, Japan*
[24] *Istituto Nazionale di Fisica Nucleare, Sezione di Roma "Tor Vergata", I-00133 Roma, Italy*
[25] *Istituto Nazionale di Fisica Nucleare, Sezione di Trieste, I-34127 Trieste, Italy*
[26] *Osservatorio Astronomico di Trieste, Istituto Nazionale di Astrofisica, I-34143 Trieste, Italy*

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[27] Department of Chemistry and Physics, Purdue University Calumet, Hammond, IN 46323-2094, USA
[28] Istituto Nazionale di Fisica Nucleare, Sezione di Trieste, and Università di Trieste, I-34127 Trieste, Italy
[29] Laboratory for Astroparticle Physics, University of Nova Gorica, Vipavska 13, SI-5000 Nova Gorica, Slovenia
[30] Cerro Tololo Inter-American Observatory, National Optical Astronomy Observatory, Casilla 603, La Serena, Chile
[31] Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
[32] Department of Physics, University of Surrey, Guildford GU2 7XH, UK
[33] Laboratório Interinstitucional de e-Astronomia - LIneA, Rua Gal. José Cristino 77, Rio de Janeiro, RJ - 20921-400, Brazil
[34] Institut de Ciències de l'Espai, IEEC-CSIC, Campus UAB, Facultat de Ciències, Torre C5 par-2, 08193 Bellaterra, Barcelona, Spain
[35] Department of Physics & Astronomy, University College London, Gower Street, London, WC1E 6BT, UK
[36] Carnegie Observatories, 813 Santa Barbara St., Pasadena, CA 91101, USA
[37] Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, PA 19104, USA
[38] Institut d'Astrophysique de Paris, Univ. Pierre et Marie Curie & CNRS UMR7095, F-75014 Paris, France
[39] SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA
[40] Observatório Nacional, Rua Gal. José Cristino 77, Rio de Janeiro, RJ - 20921-400, Brazil
[41] National Center for Supercomputing Applications, 1205 West Clark St., Urbana, IL 61801, USA
[42] Institute of Cosmology & Gravitation, University of Portsmouth, Portsmouth, PO1 3FX, UK
[43] Department of Physics, Ludwig-Maximilians-Universitat, Scheinerstr. 1, 81679 Munich, Germany
[44] Excellence Cluster Universe, Boltzmannstr. 2, 85748 Garching, Germany
[45] Kavli Institute for Particle Astrophysics & Cosmology, P. O. Box 2450, Stanford University, Stanford, CA 94305, USA
[46] Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA 91109, USA
[47] Department of Physics, University of Michigan, Ann Arbor, MI 48109, USA
[48] Institut de Física d'Altes Energies, Universitat Autònoma de Barcelona, E-08193 Bellaterra, Barcelona, Spain
[49] Max Planck Institute for Extraterrestrial Physics, Giessenbachstrasse, 85748 Garching, Germany
[50] University Observatory Munich, Scheinerstrasse 1, 81679 Munich, Germany
[51] Department of Astronomy, University of Illinois,1002 W. Green Street, Urbana, IL 61801, USA
[52] Department of Physics, The Ohio State University, Columbus, OH 43210, USA
[53] Center for Cosmology and Astro-Particle Physics, The Ohio State University, Columbus, OH 43210, USA
[54] Australian Astronomical Observatory, North Ryde, NSW 2113, Australia and Argonne National Laboratory, 9700 S. Cass Avenue, Lemont IL 60639 USA
[55] Instituto de Física, UFRGS, Caixa Postal 15051, Porto Alegre, RS - 91501-970, Brazil
[56] ICRA, Centro Brasileiro de Pesquisas Físicas, Rua Dr. Xavier Sigaud 150, CEP 22290-180, Rio de Janeiro, RJ, Brazil
[57] Department of Astronomy, The Ohio State University, Columbus, OH 43210, USA
[58] Institució Catalana de Recerca i Estudis Avançats, E-08010 Barcelona (Spain)
[59] Brookhaven National Laboratory, Bldg 510, Upton, NY 11973, USA
[60] Astronomy Centre, University of Sussex, Falmer, Brighton, BN1 9QH, UK
[61] Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
[62] Department of Physics, University of Illinois, 1110 W. Green St., Urbana, IL 61801, USA
[63] Department of Physics, Stanford University, 382 Via Pueblo Mall, Stanford, CA 94305, USA
[64] Jodrell Bank Center for Astrophysics, School of Physics and Astronomy, University of Manchester, Oxford Road, Manchester, M13 9PL, UK

Due to their proximity, high dark matter content, and apparent absence of non-thermal processes, Milky Way dwarf spheroidal satellite galaxies (dSphs) are excellent targets for the indirect detection of dark matter. Recently, eight new dSph candidates were discovered using the first year of data from the Dark Energy Survey (DES). We searched for gamma-ray emission coincident with the positions of these new objects in six years of *Fermi* Large Area Telescope data. We found no significant excesses of gamma-ray emission. Under the assumption that the DES candidates are dSphs with dark matter halo properties similar to the known dSphs, we computed individual and combined limits on the velocity-averaged dark matter annihilation cross section for these new targets. If confirmed, they will constrain the annihilation cross section to lie below the thermal relic cross section for dark matter particles with masses $\lesssim 20\,\mathrm{GeV}$ annihilating via the $b\bar{b}$ or $\tau^+\tau^-$ channels.

Keywords: dark matter, Galaxy: halo, galaxies: dwarf, gamma rays: galaxies

INTRODUCTION

In the standard model of cosmology, dark matter (DM) is the dominant component of matter in the Universe [1]. Weakly interacting massive particles (WIMPs) are an attractive candidate to constitute some or all of DM [2–5]. If WIMPs are in thermal equilibrium in the early

Universe and have a velocity-averaged annihilation cross section of $\langle\sigma v\rangle \sim 2.2\times10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$, their relic abundance can account for the observed DM abundance measured today [6]. WIMPs may continue to annihilate in regions of high DM density to produce energetic Standard Model particles that can be detected as indirect signatures of DM. These indirect searches complement terrestrial searches for DM at accelerator and direct detection experiments [7].

Gamma rays are one product of WIMP annihilations [8, 9]; they may be produced directly or in a shower of secondary particles. Depending on the WIMP mass, these gamma rays could be detectable with the *Fermi* Large Area Telescope (LAT) [10].

The integrated gamma-ray flux in a specific energy range ($E_{\mathrm{min}} < E < E_{\mathrm{max}}$) and region of interest (ROI) on the sky from DM annihilation is given by

$$\phi_s(\Delta\Omega) = \underbrace{\frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_{\mathrm{DM}}^2}\int_{E_{\mathrm{min}}}^{E_{\mathrm{max}}}\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}\mathrm{d}E_\gamma}_{\text{particle physics}} \times \underbrace{\int_{\Delta\Omega}\int_{\mathrm{l.o.s.}}\rho_{\mathrm{DM}}^2(\boldsymbol{r})\mathrm{d}s\mathrm{d}\Omega}_{\text{J-factor}}, \tag{1}$$

where the first term encompasses the particle properties of the DM, while the second term (the so-called "J-factor") incorporates information about the distribution of DM along the line of sight. Specifically, m_{DM} is the DM particle mass, $\mathrm{d}N_\gamma/\mathrm{d}E_\gamma$ is the differential gamma-ray yield summed over all final states, $\Delta\Omega$ is the solid angle of the ROI, and $\rho_{\mathrm{DM}}(\boldsymbol{r})$ is the DM density.

Current N-body cosmological simulations of Milky Way-sized regions predict the existence of more than thousands of Galactic DM overdensities called subhalos [11, 12]. Luminous Milky Way dwarf spheroidal satellite galaxies (dSphs) are believed to reside in a subset of the most massive subhalos. The proximity and large DM content of dSphs make them promising targets for indirect DM searches. Several searches for gamma-ray emission from known dSphs have been performed using LAT data, none of which resulted in a positive detection [13–19].

The census of known Milky Way satellites is certainly not complete. Prior to the Sloan Digital Sky Survey (SDSS) [20], there were ten dSphs known to orbit the Milky Way (called classical dwarfs). The deep and systematic coverage of the northern celestial hemisphere by SDSS has more than doubled the number of known Milky Way satellites [21]. Additionally, SDSS data led to the discovery of a new population of "ultra-faint" satellite galaxies, which were found to be the most DM dominated objects known [22–24]. The Dark Energy Survey (DES) [25] is a southern-hemisphere optical survey expected to find new dSphs [26, 27], which would increase the sensitivity of searches for particle DM [28].

Photometric survey data can be used to identify stellar overdensities associated with satellite dwarf galaxies or globular clusters. Satellite galaxies require DM to explain their observed kinematics, while the mass of globular clusters can be accounted for by their visible matter alone. Globular clusters can be distinguished from dwarf galaxies based on spectroscopic measurements [29]. The range of stellar metallicities in globular clusters is narrower than that observed in dSph galaxies. Though globular clusters and satellite galaxies may possess similar stellar velocity dispersions, the larger spatial extent of dwarf galaxies implies that they are DM-dominated.

The first internal annual release of DES data (Y1A1)[1] covers $\sim$1,800 deg^2 in the southern hemisphere ($\sim$1,600 deg^2 not overlapping with SDSS). Recent studies of the Y1A1 data set have revealed eight new dSph candidates [30, 31].[2] Since the LAT continuously surveys the entire sky, LAT data collected over the duration of the mission can be used to search for gamma-ray emission from the DES dSph candidates.

DISCOVERY OF NEW DSPH CANDIDATES WITH DES

Current, and near-future, deep wide-field optical imaging surveys have the potential to discover many new ultra-faint Milky Way satellites [26–28]. The ensemble of PanSTARRS [32], the SkyMapper Southern Sky Survey [33], DES [25], and the Large Synoptic Survey Telescope [34] will explore large areas of the sky to unprecedented depths. Here, we focus on a set of dSph candidates recently found in first-year DES data.

Details regarding the first-year DES data set and techniques to search for ultra-faint dSphs are provided in Bechtol *et al.* [30] and Koposov *et al.* [31]. Briefly, a dSph candidate is identified as a statistically significant arcminute-scale overdensity of resolved stars consistent with an old (>10 Gyr) and metal-poor ($Z\sim0.0002$) stellar population. A variety of search techniques have been applied to the first-year DES data, including visual inspection of DES images, thresholding stellar density maps, scanning with optimized spatial filters, and automated matched-filter maximum-likelihood algorithms. The physical characteristics of dSph candidates (e.g., centroid position, distance, and spatial extension) can be inferred by fitting the spatial and color-magnitude distributions of the stars. Table I provides a summary of the eight dSph candidates reported by Bechtol *et al.* [30].

[1] http://data.darkenergysurvey.org/aux/releasenotes/DESDMrelease.html

[2] Koposov *et al.* [31] find a ninth candidate inside the DES year-one imaging footprint but outside the Y1A1 coadd catalog.

TABLE I. DES dSph Candidates and Estimated J-factors

Name	(ℓ, b)[a]	Distance[b]	$\log_{10}$(Est.J)[c]
	deg	kpc	$\log_{10}(\frac{\mathrm{GeV}^2}{\mathrm{cm}^5})$
DES J0222.7−5217	(275.0, −59.6)	95	18.3
DES J0255.4−5406	(271.4, −54.7)	87	18.4
DES J0335.6−5403	(266.3, −49.7)	32	19.3
DES J0344.3−4331	(249.8, −51.6)	330	17.3
DES J0443.8−5017	(257.3, −40.6)	126	18.1
DES J2108.8−5109	(347.2, −42.1)	69	18.3
DES J2251.2−5836	(328.0, −52.4)	58	18.8
DES J2339.9−5424	(323.7, −59.7)	95	18.4

[a] Galactic longitude and latitude.
[b] We note that typical uncertainties on the distances of dSphs are 10–15%.
[c] J-factors are calculated over a solid angle of $\Delta\Omega \sim 2.4 \times 10^{-4}$ sr (angular radius 0.°5). See text for more details.

LAT ANALYSIS

To search for gamma-ray emission from these new dSph candidates, we used six years of LAT data (2008 August 4 to 2014 August 5) passing the `P8R2_SOURCE` event class selections from 500 MeV to 500 GeV. Compared to the previous iteration of the LAT event-level analysis, `Pass 8` [35] provides significant improvements in all areas of LAT analysis; specifically the differential point-source sensitivity improves by 20–40% in `P8R2_SOURCE_V6` relative to `P7REP_SOURCE_V15`. To remove gamma rays produced by cosmic-ray interactions in the Earth's limb, we rejected events with zenith angles greater than 100°. Additionally, events from time intervals around bright gamma-ray bursts and solar flares were removed using the same method as in the 4-year catalog analysis (3FGL) [36]. To analyze the dSph candidates in Table I, we used 10° × 10° ROIs centered on each object. Data reduction was performed using *ScienceTools* version 09-34-03.[3] Figure 1 shows smoothed counts maps around each candidate for energies > 1 GeV.

We applied the search procedure presented in Ackermann *et al.* [19] to the new DES dSph candidates. Specifically, we performed a binned maximum-likelihood analysis in 24 logarithmically-spaced energy bins and 0.°1 spatial pixels. Data are additionally partitioned in one of four PSF event types, which are combined in a joint-likelihood function when performing the fit to each ROI [19].

We used a diffuse emission model based on the `Pass 7 Reprocessed` model for Galactic diffuse emission,[4] but with a small (< 10%) energy-dependent correction to account for differences in the LAT response.[5] Point-like sources within each ROI from the recent 3FGL catalog [36] were also included in the fit. The spectral parameters of these sources were fixed at their 3FGL catalog values, while their normalizations were refit over the broadband energy range. The normalizations of 3FGL sources more than 5° away from the center are fixed at

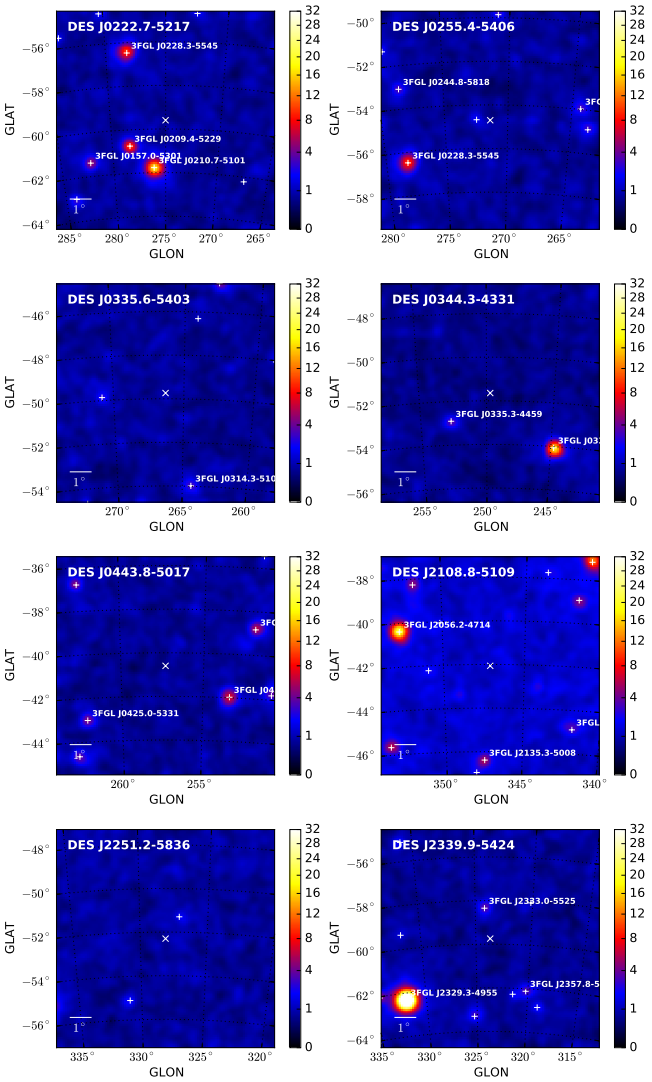

FIG. 1. LAT counts maps in 10° × 10° ROI centered at each DES dSph candidate (white '×' symbols), for $E > 1$ GeV, smoothed with a 0.°25 Gaussian kernel. All 3FGL sources in the ROI are indicated with white '+' symbols, and those with a test statistic > 100 are explicitly labeled.

[3] http://fermi.gsfc.nasa.gov/ssc/data/analysis/software/
[4] http://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html

[5] The energy dependence of the effective area and energy resolution is somewhat different in `Pass 7 Reprocessed` and `Pass 8`. Because the Galactic diffuse emission model was fit to `Pass 7 Reprocessed` data without accounting for the energy dispersion, we have rescaled the model for this analysis.

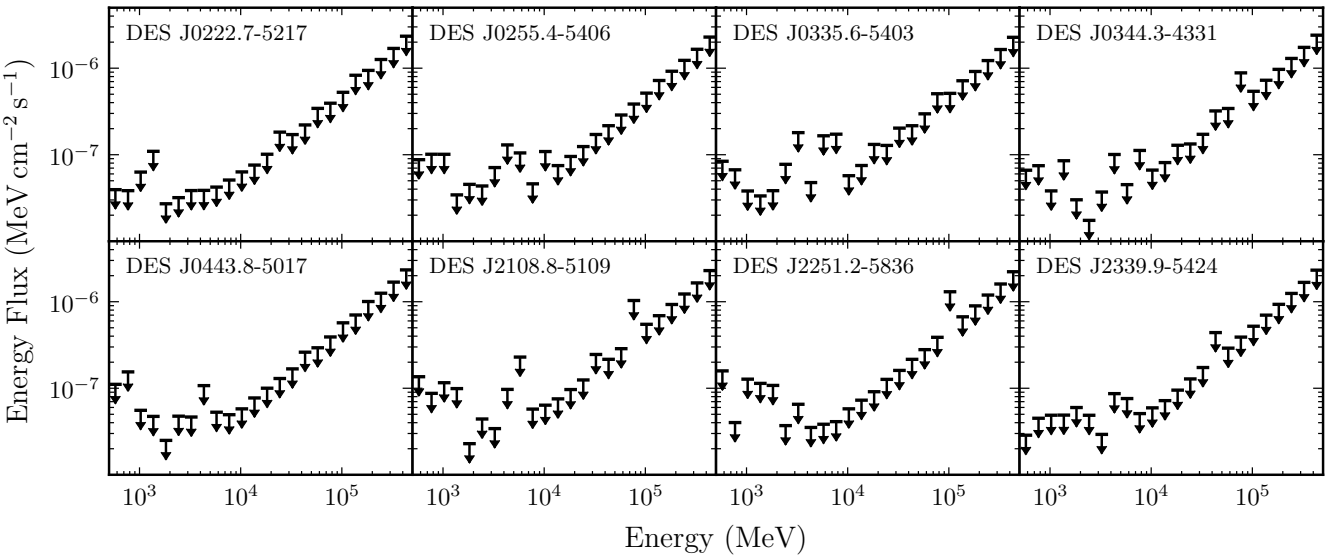

FIG. 2. Bin-by-bin integrated energy-flux upper limits at 95% confidence level for the eight DES dSph candidates modeled as point-like sources.

the catalog values.

In contrast to Ackermann *et al.* [19], we modeled the dSph candidates as point-like sources rather than spatially extended Navarro, Frenk and White (NFW) DM density profiles [37]. This choice was motivated by the current uncertainty in the spatial extension of the DM halos of these new objects. Previous studies have shown that the LAT flux limits are fairly insensitive to modeling dSph targets as point-like vs. spatially extended sources [17]. We fit for excess gamma-ray emission associated with each target in each energy bin separately to derive a set of flux constraints that are independent of the choice of spectral model. The Poisson likelihoods from each bin were combined to form global spectral likelihoods for different DM annihilation channels and masses.

No significant gamma-ray emission was observed from any of the DES dSph candidates. We show the bin-by-bin integrated energy-flux 95% confidence level upper limits for each dSph candidate in Figure 2.

By assuming a specific DM differential gamma-ray yield ($\mathrm{d}N_\gamma/\mathrm{d}E_\gamma$ for a given m_{DM} and annihilation channel), we calculated the test statistic (TS) for signal detection by comparing the likelihood values both with and without the added dSph candidate template (see Equation 6 in Ackermann *et al.* [19]). The most significant excess for any of the DM masses, annihilation channels, and targets we consider here was TS = 6.7, corresponding to a local signficance[6] of 1.5σ ($p = 0.06$) and a global significance of 0.26σ ($p = 0.40$). This coincides with DES J0335.6−5403 when considering a DM particle with $m_{\mathrm{DM}} = 25\,\mathrm{GeV}$ annihilating into $\tau^+\tau^-$.[7]

ESTIMATING J-FACTORS FOR THE DES DSPH CANDIDATES

The DM content of the DES dSph candidates cannot be determined without spectroscopic observations of their member stars. However, it is possible to derive upper limits on the DM annihilation cross section under the assumption that these candidates possess DM distributions similar to the known dSphs. Our estimates for the astrophysical J-factors of these candidates are motivated by two established relationships. First, the known dSphs have a common mass scale in their interiors, roughly 10^7 $\mathrm{M}_\odot$ within their central 300 pc [38]. Additionally, the half-light radius of a dSph and the mass within the half-light radius have a simple scaling relation [39, 40].

In the analysis that follows, we used the ten ultra-faint SDSS satellites with spectroscopically determined

[6] To convert from TS to a p-value, we use the TS distribution measured from performing our search for gamma-ray emission in 800 random blank sky fields [17, 19]. The reported p-value includes a trials factor from testing multiple dark matter masses and channels at each location. We report the significance as the inverse survival function of a normal distribution for the stated p-value (one-sided significance).

[7] We note that the radio continuum source PMN J0335−5046 is located $\sim 0\overset{\circ}{.}1$ from the center of DES J0335.6−5403. It is not a cataloged blazar, but has radio and infrared spectral characteristics consistent with blazars detected by the LAT.

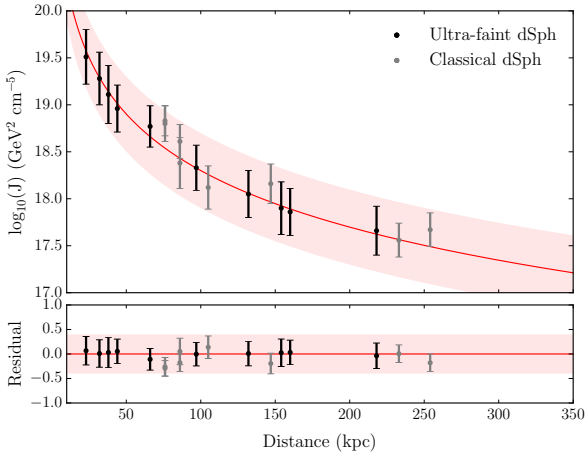

FIG. 3. J-factor distance scaling. Black points are from Table 1 in Ackermann *et al.* [17]. The red curve is our best-fit with an assumed inverse square distance relation (see text). The red band shows the ± 0.4 dex uncertainty that we adopt.

J-factors as a representative set of known dSphs.[8] Figure 3 shows the relation between the heliocentric distances and J-factors of ultra-faint and classical dSphs. As expected from their similar interior DM masses, the J-factors of the known dSphs scale approximately as the inverse square of the distance. The best-fit normalization is $\log_{10}(\mathrm{J}, d = 100\,\mathrm{kpc}) = 18.3 \pm 0.1$.[9] We note that the limited scatter in Figure 3 is primarily due to the known dSphs residing in similar DM halos [17]. Under the assumption that the new DES dSph candidates belong to the same population, we estimated their J-factors based on the distances derived from the DES photometry. Table I gives the estimated J-factors integrated over a solid-angle of $\Delta\Omega \sim 2.4 \times 10^{-4}$ sr using our simple, empirical relation.

Several caveats should be noted. None of the DES candidates have been confirmed to be gravitationally bound. It is possible that some have stellar populations characteristic of galaxies but lack substantial DM content, as is the case for Segue 2 [42], or have complicated kinematics that are difficult to interpret [43]. Kinematic measurements of the member stars are needed to unambiguously resolve these questions.

Using the J-factor estimates presented in Table I, we followed the likelihood procedure detailed in Ackermann *et al.* [19] to obtain limits on DM annihilation from these eight candidates shown in Figure 4.

We assumed a symmetric logarithmic uncertainty on the J-factor of ± 0.4 dex for each DES candidate. This value is representative of the uncertainties from ultra-faint dSphs [17, 41] and is somewhat larger than the uncertainties derived in Martinez [44]. The corresponding uncertainty band is illustrated in Figure 3. We apply the same methodology as Ackermann *et al.* [19] to account for the J-factor uncertainty by modeling it as a log normal distribution with $\mathrm{J}_{\mathrm{obs},i}$ equal to the values in Table I, and $\sigma_i = 0.4$ dex (see Equation 3 of Ackermann *et al.* [19]).

We derived individual and combined limits on the DM annihilation cross section for DM annihilation via the $b\bar{b}$ and $\tau^+\tau^-$ channels, under the assumption that each DES candidate is a dSph and has the J-factor listed in Table I. We stress that these limits may change substantially as spectroscopic data become available to more robustly constrain the DM content of the DES candidates. Given the current uncertainty regarding the nature of the dSph candidates, we do not combine limits with those from previously known dSphs (i.e., Ackermann *et al.* [19]).

DISCUSSION AND CONCLUSIONS

The discovery of eight dSph candidates in the first year of DES observations sets an optimistic tone for future dSph detections from DES and other optical surveys. DES J0335.6−5403, at a distance of ~ 32 kpc, is a particularly interesting candidate in this context, and should be considered a high-priority target for spectroscopic follow up. The location of any newly discovered dSph, including the candidates investigated in this work, will have already been regularly observed since the beginning of the *Fermi* mission. No significant gamma-ray excess was found coincident with any of the eight new DES dSph candidates considered here. If the dSph candidates have J-factors similar to our estimates, they constrain the annihilation cross section to lie below the thermal relic cross section for DM particles with masses $\lesssim 20$ GeV annihilating via the $b\bar{b}$ or $\tau^+\tau^-$ channels.

The population of nearby DM-dominated dSphs represents an independent set of targets to test possible signals of DM annihilation in other regions such as the Galactic center [45–48]. Though the expected DM signals of individual dSphs are smaller than that of the Galactic center, a joint-likelihood analysis of many dSphs can probe the DM annihilation cross section at a similar level of sensitivity. The incorporation of new dSphs in indirect searches for DM with the LAT will further enhance the sensitivity of this method.

[8] Specifically, Boötes I, Canes Venatici I, Canes Venatici II, Coma Berenices, Hercules, Leo IV, Segue 1, Ursa Major I, Ursa Major II, and Willman 1 (see Table 1 in Ackermann *et al.* [17]).

[9] We performed the same analysis using the J-factors derived by Geringer-Sameth *et al.* [41] and obtain a similar best-fit value, $\log_{10}(\mathrm{J}, d = 100\,\mathrm{kpc}) = 18.1 \pm 0.1$.

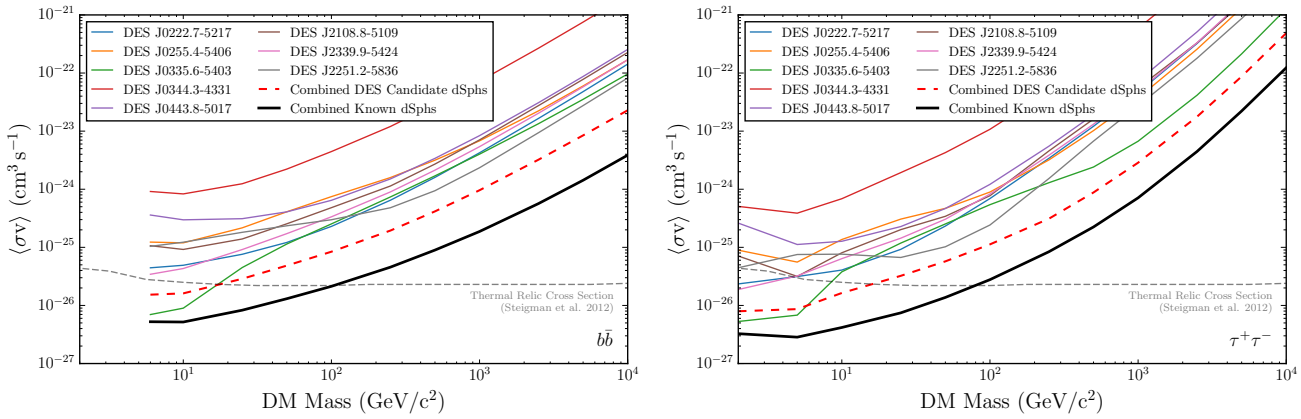

FIG. 4. Upper limits on the velocity-averaged DM annihilation cross section at 95% confidence level for DM annihilation to $b\bar{b}$ (left) and $\tau^+\tau^-$ (right). Limits for each DES candidate dSph, as well as the combined limits (dashed red line) from the eight new candidates are shown. Here we assume that each candidate is a dSph and use an estimate of the J-factor based on photometric data (see text). For reference, we show the current best limits derived from a joint analysis of fifteen previously known dSphs with known J-factors (black curve) [19].

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Facilities: Blanco, Fermi-LAT

* kadrlica@fnal.gov
† aalbert@slac.stanford.edu
‡ bechtol@kicp.uchicago.edu
§ mdwood@slac.stanford.edu
¶ strigari@physics.tamu.edu

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