Search for Dark Matter Annihilation from the Milky Way Dwarf Spheroidal Galaxies with the Fermi Large Area Telescope

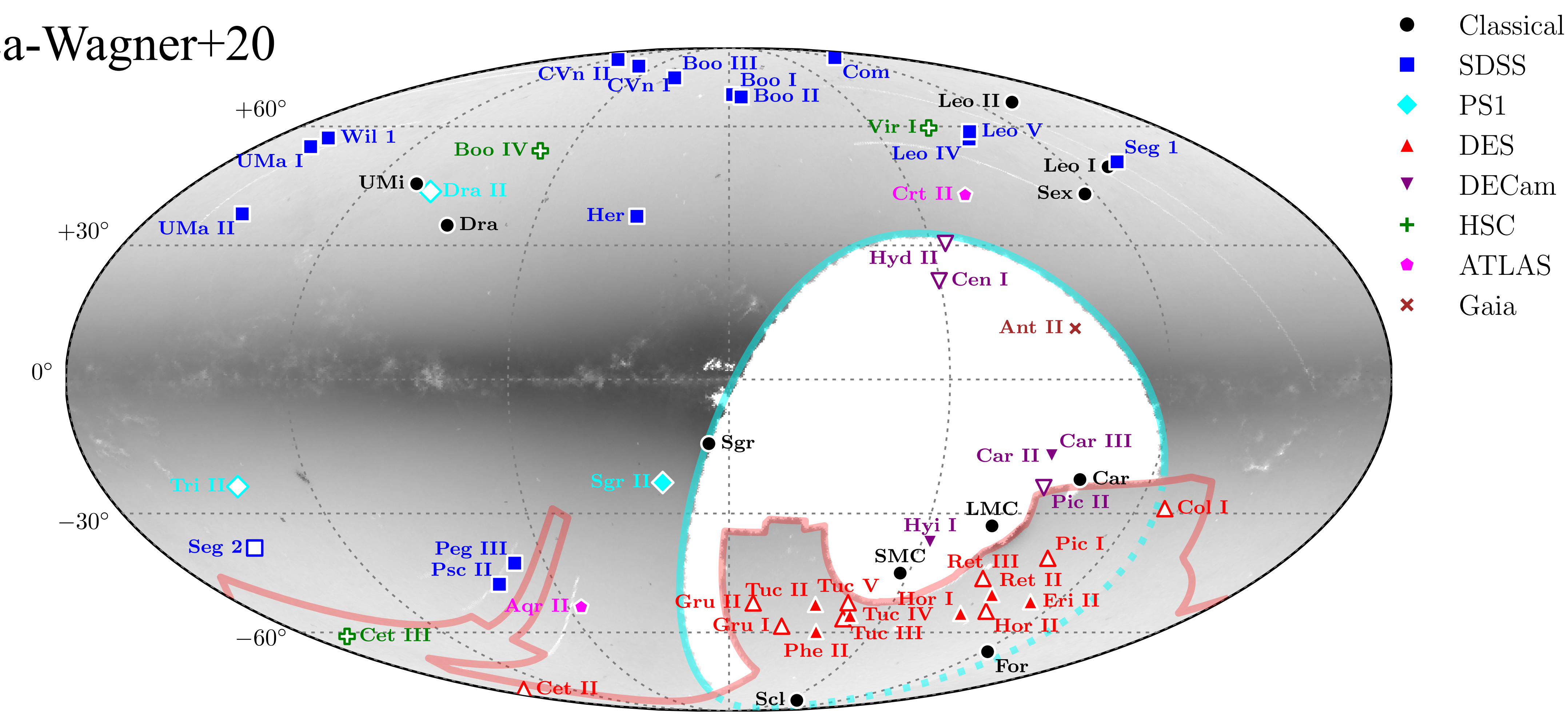
Chris Karwin, Marco Ajello, Alex McDaniel, Alex Drlica-Wagner, Miguel Sanchez-Conde, Mattia Di Mauro, and Michael Gustafsson

On behalf of the *Fermi*-LAT collaboration

9th International Fermi Symposium
April 12, 2020

Motivation

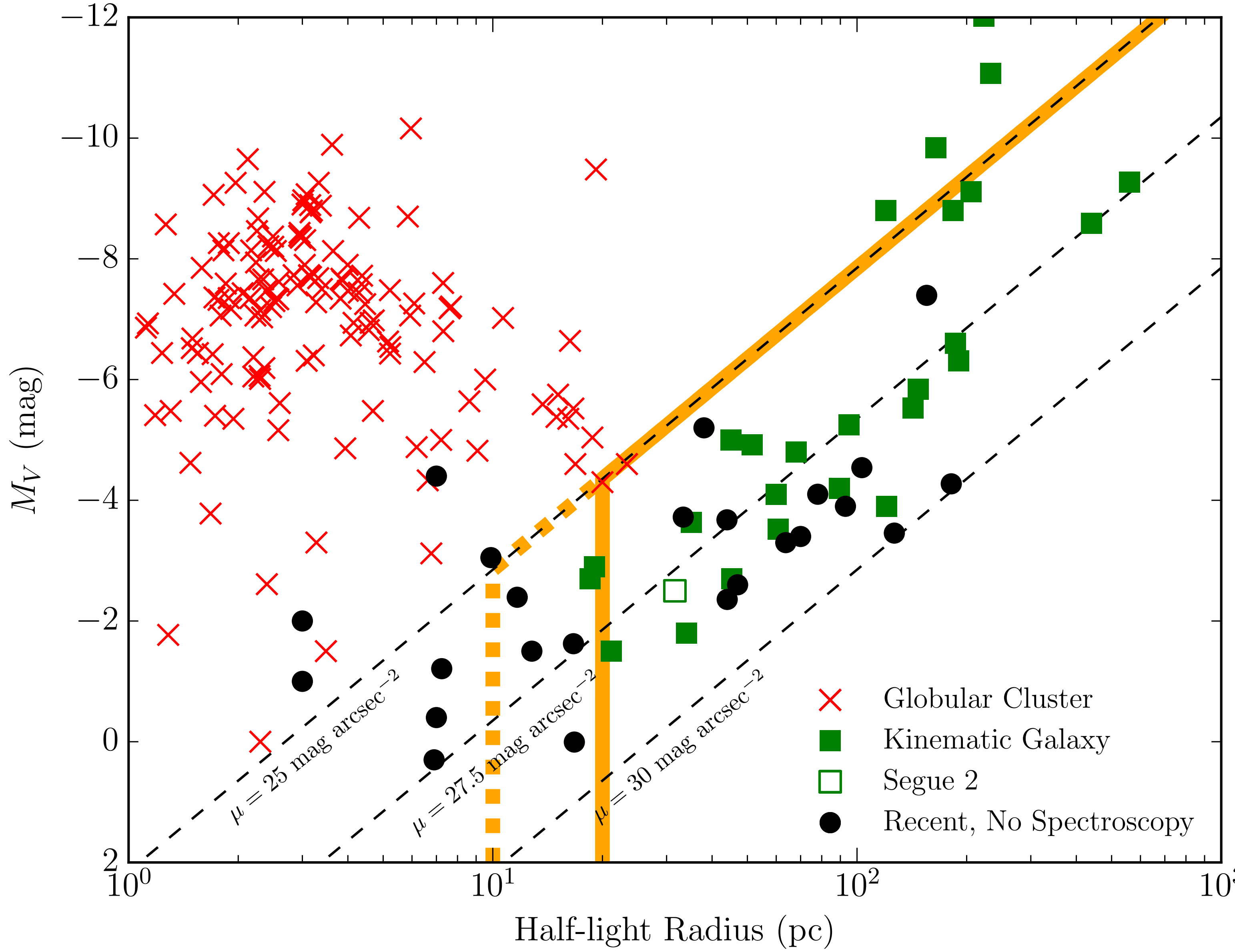
Drlica-Wagner+20



- An updated MW satellite census is now available, giving more sources and refinements/updates to the source properties.
- The accumulation of over 12 years of data and an improved LAT data set (Pass 8 R3, 4FGL DR2)
- A robust analysis pipeline
- The Vera Rubin Observatory will see first light soon, and will likely detect many new dwarfs
- **Now is an ideal time to conduct a detailed up-to-date gamma-ray analysis**

Sample

Albert+17



Sample based on Drlica-Wagner+20

- Total number of confirmed and possible dwarfs: **57**
- Kinematically confirmed sources: **39**
- Likely dwarfs based on photometric data: **18**

Sample J-Factors

kinematic scaling:

$$\frac{J(0.\!\!^\circ 5)}{\mathrm{GeV^2\,cm^{-5}}} \approx 10^{17.87} \left(\frac{\sigma_{\rm los}}{5\,\mathrm{km\,s^{-1}}}\right)^{4} \left(\frac{d}{100\ \mathrm{kpc}}\right)^{-2} \left(\frac{r_{1/2}}{100\ \mathrm{pc}}\right)^{-1}$$

photometric scaling:

$$\frac{J(0.\!\!^\circ 5)}{\mathrm{GeV^2\,cm^{-5}}} \approx 10^{18.17} \left(\frac{\mathrm{L_V}}{10^4\,\mathrm{L_\odot}}\right)^{0.23} \left(\frac{d}{100\ \mathrm{kpc}}\right)^{-2} \left(\frac{r_{1/2}}{100\ \mathrm{pc}}\right)^{-0.5}$$

Method for assigning J-factors:

1. measured J from Pace and Strigari 19
2. new calculation (with CLUMPY) using v_disp from Simon 19
3. kinematic scaling from Pace and Strigari 19
4. photometric scaling from Pace and Strigari 19

- Quantify systematic uncertainty in ULs due to uncertainty in the J-factor, i.e. from the assumption of spherical symmetry for the density profiles (Bonnivard+15), as well as the use of log uniform priors instead of informed priors based on structure formation models (Ando+20).

Sample

(1) Name	(2) RA (deg)	(3) DEC (deg)	(4) Distance (kpc)	(5) $r_{1/2}$ (pc)	(6) M_V (mag)	(7) $\log_{10}J$ ($\log_{10}$GeV^2 cm^{-5})	(8) Method
Antlia II	143.89	-36.77	132	2301	-9.03	16.50	3
Aquarius II	338.48	-9.33	108	125	-4.4	$18.27^{+0.58}_{-0.66}$	1
Boötes I	210.02	14.51	66	160	-6.02	$18.17^{+0.29}_{-0.31}$	1
Boötes II	209.51	12.86	42	39	-2.94	20.32	3
Boötes III	209.3	26.8	47	289	-5.75	18.65	4
Canes Venatici I	202.01	33.55	218	338	-8.8	$17.42^{+0.15}_{-0.17}$	1
Canes Venatici II	194.29	34.32	160	55	-5.17	$17.82^{+0.47}_{-0.47}$	1
Carina	100.41	-50.96	105	248	-9.43	$17.83^{+0.09}_{-0.1}$	1
Carina II	114.11	-58.0	36	77	-4.5	$18.25^{+0.54}_{-0.55}$	1
Carina III	114.63	-57.9	28	30	-2.4	19.70	3
Coma Berenices	186.75	23.91	44	57	-4.38	$19.0^{+0.35}_{-0.36}$	1
Crater II	177.31	-18.41	117.5	1066	-8.2	15.63	3
Draco	260.07	57.92	76	180	-8.71	$18.83^{+0.12}_{-0.12}$	1
Eridanus II	56.09	-43.53	380	158	-7.21	$17.28^{+0.31}_{-0.34}$	1
Fornax	39.96	-34.5	147	707	-13.46	$18.09^{+0.1}_{-0.1}$	1
Hercules	247.77	12.79	132	120	-5.83	$17.37^{+0.53}_{-0.53}$	1
Horologium I	43.88	-54.12	79	31	-3.55	$19.0^{+0.78}_{-0.835}$	1
Hydrus I	37.39	-79.31	28	53	-4.71	18.19	3
Leo I	152.11	12.31	254	226	-11.78	$17.64^{+0.12}_{-0.14}$	1
Leo II	168.36	22.15	233	165	-9.74	$17.76^{+0.18}_{-0.22}$	1
Leo IV	173.24	-0.55	154	104	-4.99	$16.4^{+1.15}_{-1.01}$	1
Leo V	172.79	2.22	178	39	-4.4	$17.65^{+1.03}_{-0.91}$	1
Pegasus III	336.1	5.41	215	42	-3.4	$18.3^{+0.97}_{-0.89}$	1
Phoenix II	355.0	-54.41	83	21	-3.3	18.3	4
Pisces II	344.63	5.95	182	48	-4.22	$17.3^{+1.09}_{-1.0}$	1
Reticulum II	53.92	-54.05	30	31	-3.88	$18.9^{+0.37}_{-0.39}$	1
Sagittarius[b]	283.83	-30.55	26.7	2662	-13.5	18.72	3
Sagittarius II	298.16	-22.07	69	32	-5.2	18.8	4
Sculptor	15.02	-33.72	84	223	-10.82	$18.58^{+0.05}_{-0.05}$	1
Segue I	151.75	16.08	23	20	-1.3	$19.12^{+0.58}_{-0.49}$	1
Sextans	153.26	-1.61	86	345	-8.72	$17.73^{+0.12}_{-0.13}$	1
Tucana II	342.98	-58.57	58	165	-3.8	$18.97^{+0.52}_{-0.57}$	1
Tucana IV	0.73	-60.85	48	128	-3.5	18.7	4
Ursa Major I	158.77	51.95	97	151	-5.12	$18.26^{+0.27}_{-0.29}$	1
Ursa Major II	132.87	63.13	32	85	-4.25	$19.44^{+0.39}_{-0.41}$	1
Ursa Minor	227.24	67.22	76	272	-9.03	$18.75^{+0.12}_{-0.12}$	1
Willman I[c]	162.34	51.05	38	20	-2.53	$19.53^{+0.5}_{-0.5}$	1

Note: Column descriptions: (1) source name (2) right ascension (3) declination (4) heliocentric distance (5) half-light radius (6) absolute V-band magnitude (7) benchmark J-factor used in this analysis (8) method used to determine the J-factor. The methods are as follows: (1) measured J-factors from Pace and Strigari 19 (2) new kinematic calculations using velocity dispersion measurements from Simon 19 (3) calculated with kinematic scaling relation from Pace and Strigari 19 (4) calculated with photometric scaling relation from Pace and Strigari 19. Columns 2-6 are taken from Drlica-Wagner+20. For J-factors predicted from scaling relations we assume an error of 0.6 dex. [a] Excluded due to spatial extension and complexity; [b] Source is in the Galactic plane (special case); [c] Excluded due to evidence of tidal disruption and/or non-equilibrium dynamics.

(1) Name	(2) RA (deg)	(3) DEC (deg)	(4) Distance (kpc)	(5) $r_{1/2}$ (pc)	(6) M_V (mag)	(7) $\log_{10}J$ ($\log_{10}$GeV^2 cm^{-5})	(8) Method
Bootes IV	233.69	43.73	209	277	-4.53	17.25	4
Centaurus I	189.59	-40.9	116	76	-5.55	18.14	4
Cetus II	19.47	-17.42	30	17	0.0	19.1	4
Cetus III	31.33	-4.27	251	44	-2.5	17.3	4
Columba I	82.86	-28.01	183	98	-4.2	17.6	4
Draco II[c]	238.17	64.58	22	17	-0.8	$18.93^{+1.39}_{-1.70}$	1
Grus I[c]	344.18	-50.18	120	21	-3.47	$16.88^{+1.51}_{-1.66}$	1
Grus II	331.02	-46.44	53	92	-3.9	18.4	4
Horologium II	49.11	-50.05	78	33	-2.6	18.4	4
Hydra II	185.43	-31.99	151	58	-4.6	17.88	4
Pictor I	70.95	-50.29	114	18	-3.45	18.0	4
Pictor II	101.18	-59.9	46	47	-3.2	18.83	4
Reticulum III	56.36	-60.45	92	64	-3.3	18.2	4
Segue II[d]	34.82	20.16	35	34	-1.86	19.01	4
Triangulum II	33.33	36.17	30	13	-1.6	19.33	4
Tucana III	359.15	-59.6	25	44	-2.4	19.3	4
Tucana V	354.35	-63.27	55	16	-1.6	18.9	4
Virgo I	180.04	-0.68	91	30	-0.33	18.1	4

Note: Column descriptions: (1) source name (2) right ascension (3) declination (4) heliocentric distance (5) half-light radius (6) absolute V-band magnitude (7) benchmark J-factor used in this analysis (8) method used to determine the J-factor. The methods are as follows: (1) measured J-factors from Pace and Strigari 19 (2) new kinematic calculations using velocity dispersion measurements from Simon 19 (3) calculated with kinematic scaling relation from Pace and Strigari 19 (4) calculated with photometric scaling relation from Pace and Strigari 19. Columns 2-6 are taken from Drlica-Wagner+20. For J-factors predicted from scaling relations we assume an error of 0.6 dex. [c] Contains tail in posterior ($\sigma_{\rm los}$ and J) distributions and thus have a higher level of uncertainty; [d] Excluded due to low velocity diespersion.

- We exclude LMC, SMC, Canis Major, and Sagittarius 2.
- Special cases: Willman I, Sagittarius, Bootes I, Crater II, Sculptor.
- We define 3 subsets:
  - **conservative**: all confirmed sources, excluding special cases
  - **benchmark**: all confirmed and probable sources, excluding special cases
  - **inclusive**: all confirmed and probable, including special cases.

Source Sample from Albert+17

Albert+17

Table 1
Confirmed and Candidate Dwarf Galaxies

(1) Name	(2) l, b (deg, deg)	(3) Distance (kpc)	(4) $r_{1/2}$ (pc)	(5) M_V (mag)	(6) $\log_{10}(J_{\rm meas})$ $\log_{10}(\,{\rm GeV^2\,cm^{-5}})$	(7) $\log_{10}(J_{\rm pred})$ $\log_{10}(\,{\rm GeV^2\,cm^{-5}})$	(8) Sample
Kinematically Confirmed Galaxies							
Boötes I*	358.08, 69.62	66	189	-6.3	18.2 ± 0.4	18.5	I,N,C
Boötes II	353.69, 68.87	42	46	-2.7	...	18.9	I,N,C
Boötes III	35.41, 75.35	47	...	-5.8	...	18.8	I,N
Canes Venatici I	74.31, 79.82	218	441	-8.6	17.4 ± 0.3	17.4	I,N,C
Canes Venatici II*	113.58, 82.70	160	52	-4.9	17.6 ± 0.4	17.7	I,N,C
Carina*	260.11, -22.22	105	205	-9.1	17.9 ± 0.1	18.1	I,N,C
Coma Berenices*	241.89, 83.61	44	60	-4.1	19.0 ± 0.4	18.8	I,N,C
Draco*	86.37, 34.72	76	184	-8.8	18.8 ± 0.1	18.3	I,N,C
Draco II	98.29, 42.88	24	16	-2.9	...	19.3	I,N,C
Fornax*	237.10, -65.65	147	594	-13.4	17.8 ± 0.1	17.8	I,N,C
Hercules*	28.73, 36.87	132	187	-6.6	16.9 ± 0.7	17.9	I,N,C
Horologium I	271.38, -54.74	87	61	-3.5	...	18.2	I,N,C
Hydra II	295.62, 30.46	134	66	-4.8	...	17.8	I,N,C
Leo I	225.99, 49.11	254	223	-12.0	17.8 ± 0.2	17.3	I,N,C
Leo II*	220.17, 67.23	233	164	-9.8	18.0 ± 0.2	17.4	I,N,C
Leo IV*	265.44, 56.51	154	147	-5.8	16.3 ± 1.4	17.7	I,N,C
Leo V	261.86, 58.54	178	95	-5.2	16.4 ± 0.9	17.6	I,N,C
Pisces II	79.21, -47.11	182	45	-5.0	...	17.6	I,N,C
Reticulum II	266.30, -49.74	32	35	-3.6	18.9 ± 0.6	19.1	I,N,C
Sculptor*	287.53, -83.16	86	233	-11.1	18.5 ± 0.1	18.2	I,N,C
Segue 1*	220.48, 50.43	23	21	-1.5	19.4 ± 0.3	19.4	I,N,C
Sextans*	243.50, 42.27	86	561	-9.3	17.5 ± 0.2	18.2	I,N,C
Triangulum II	140.90, -23.82	30	30	-1.8	...	19.1	I,N,C
Tucana II	328.04, -52.35	58	120	-3.9	...	18.6	I,N,C
Ursa Major I	159.43, 54.41	97	143	-5.5	17.9 ± 0.5	18.1	I,N,C
Ursa Major II*	152.46, 37.44	32	91	-4.2	19.4 ± 0.4	19.1	I,N,C
Ursa Minor*	104.97, 44.80	76	120	-8.8	18.9 ± 0.2	18.3	I,N,C
Willman 1*	158.58, 56.78	38	19	-2.7	...	18.9	I,N
Likely Galaxies							
Columba I	231.62, -28.88	182	101	-4.5	...	17.6	I,N,C
Eridanus II	249.78, -51.65	331	156	-7.4	...	17.1	I,N,C
Grus I	338.68, -58.25	120	60	-3.4	...	17.9	I,N,C
Grus II	351.14, -51.94	53	93	-3.9	...	18.7	I,N,C
Horologium II	262.48, -54.14	78	33	-2.6	...	18.3	I,N,C
Indus II	354.00, -37.40	214	181	-4.3	...	17.4	I,N,C
Pegasus III	69.85, -41.81	205	57	-4.1	...	17.5	I,N,C
Phoenix II	323.69, -59.74	96	33	-3.7	...	18.1	I,N,C
Pictor I	257.29, -40.64	126	44	-3.7	...	17.9	I,N,C
Reticulum III	273.88, -45.65	92	64	-3.3	...	18.2	I,N,C
Sagittarius II	18.94, -22.90	67	34	-5.2	...	18.4	I,N,C
Tucana III	315.38, -56.18	25	44	-2.4	...	19.3	I,N
Tucana IV	313.29, -55.29	48	128	-3.5	...	18.7	I,N,C
Ambiguous Systems							
Cetus II	156.47, -78.53	30	17	0.0	...	19.1	I
Eridanus III	274.95, -59.60	96	12	-2.4	...	18.1	I
Kim 2	347.16, -42.07	105	12	-1.5	...	18.1	I
Tucana V	316.31, -51.89	55	16	-1.6	...	18.6	I

- Ackermann+15: 15 kinematically confirmed srcs
- Albert+17: 28 kinematically confirmed srcs, 17 candidate galaxies
- Updated analysis: 37 kinematically confirmed srcs, 17 candidate galaxies

LAT Analysis

- tmin: 8/4/08 (239557417 MET)
- tmax: 12/25/20 (630600013 MET)
- 12.1 years of data
- P8R3
- 500 MeV - 800 GeV
- z < 100
- 10x10 ROI
- Include sources within 15 degrees of ROI center
- 8 energy bins per decade
- pix=0.1
- irfs=P8R3_SOURCE_V2
- 4FGL DR2
- edisp=True (disable for isodiff)
- JLA with 4 PSF classes
- New established stacking method

The points highlighted in red are the main differences with respect to the last LAT collaboration study dedicated to the dwarfs (Albert+17).

Analysis Procedure

- **Using Fermipy v0.19.0**
- **Ran on Clemson University HPC (Palmetto)**
- **Stacking code based on the codes of Vaidehi Paliya and Abhishek Desai**
- **Successfully employed for EBL, extreme blazars, star-forming galaxies, and ultra-fast outflows.**

1. Preprocessing

- Optimize ROI for each source
- Model consists of: Galactic diffuse, isotropic, point sources, and dwarf source
- Find new sources
- **Dwarfs are fit with PL spectrum**

2. Stacking

- Construct likelihood (TS) profiles for the source by iterating through DM mass and cross-section
- Only free parameters in likelihood fit are Galactic diffuse and isotropic

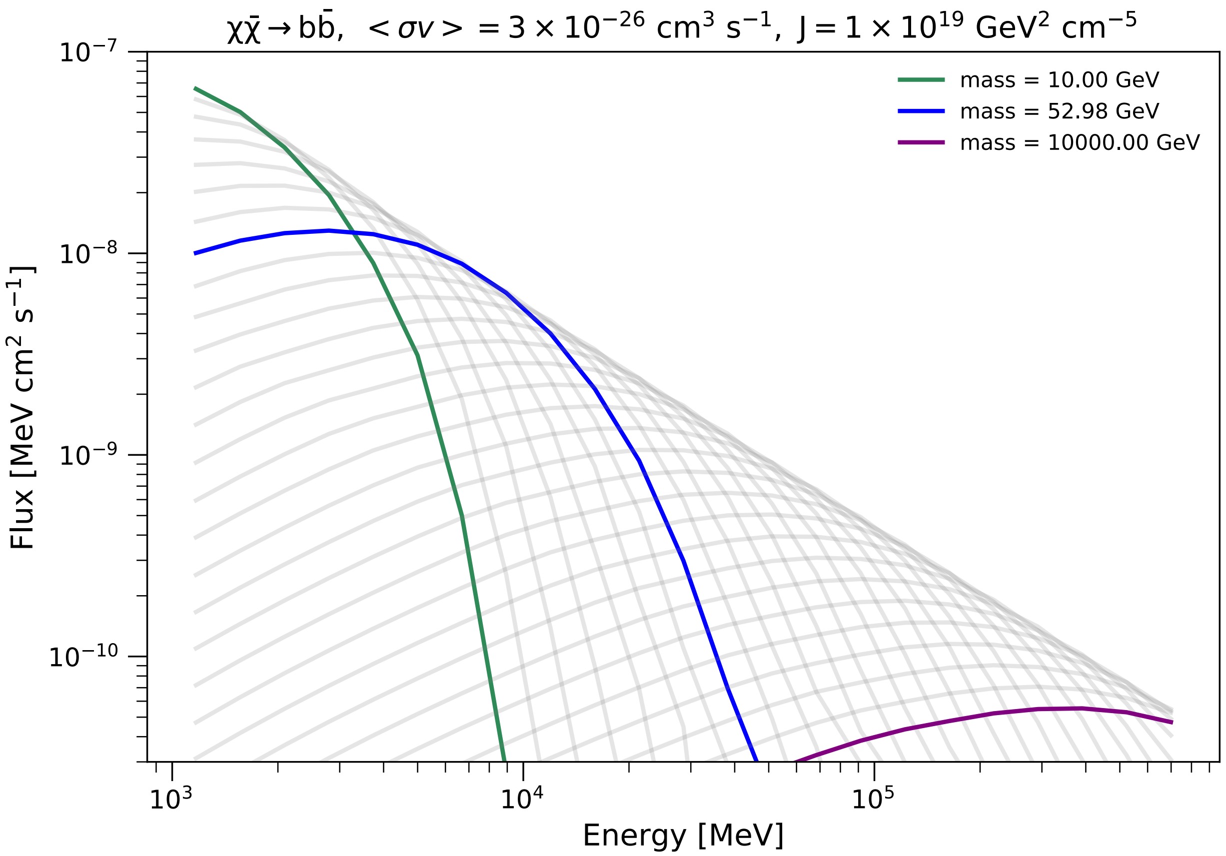
$$\mathrm{TS} = -2(\log \mathrm{L}_0 - \log L)$$

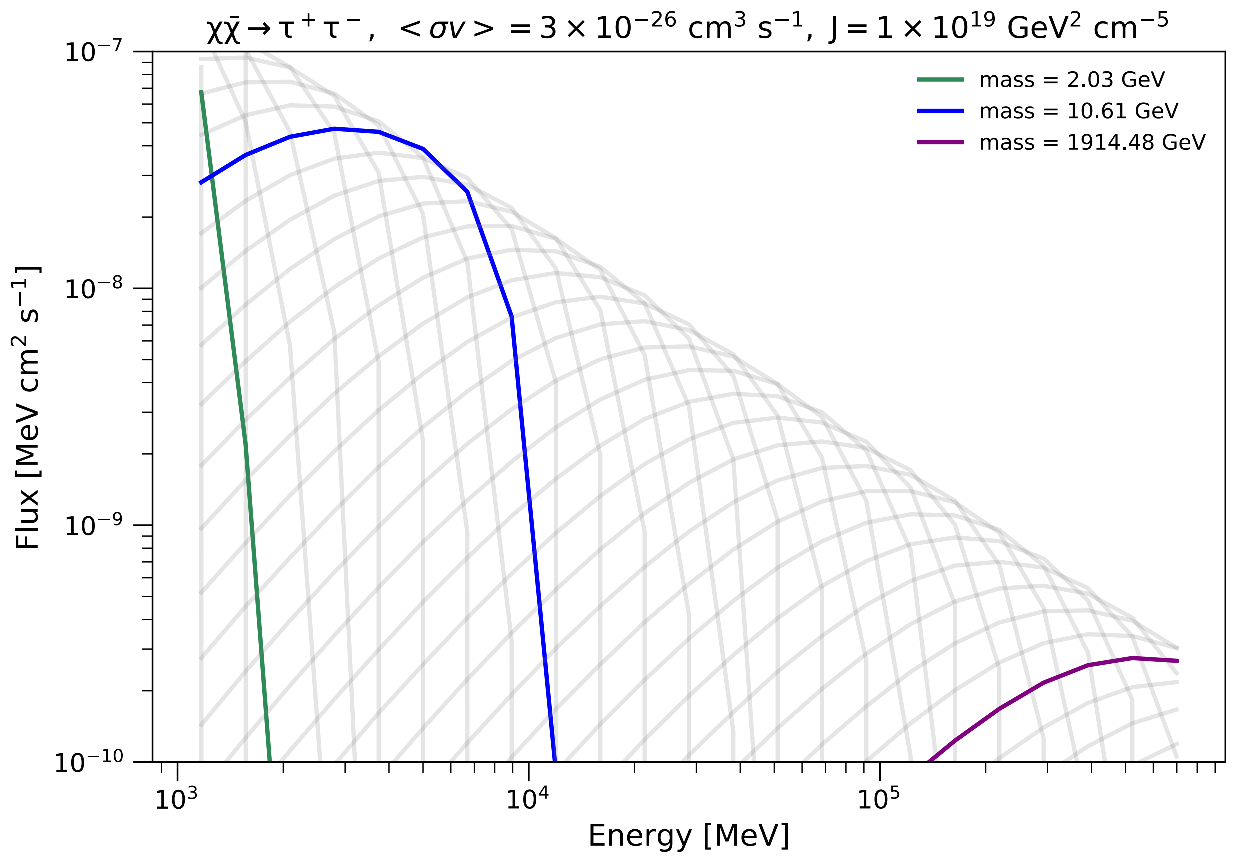
$$\log(\mathrm{L}) = \log(L_1 L_2) = \log L_1 + \log L_2 \text{ , where } L(\theta | X) = P(X | \theta)$$

Standard “Sample Cleaning”

- Cross-correlate with **4FGL, Radio Catalog (Yuan and Wang), and Crates**
- Sources that are found to be correlated are excluded from the benchmark sample, but are included in the inclusive sample.
- To account for background mis-modeling we will follow the data-driven approach in Linden 20, where we will determine the distribution of “fake” point-source fluxes from blank sky regions, and fold this result directly into the calculated ULs.
- **The same cleaning is applied to the blank sky regions.**

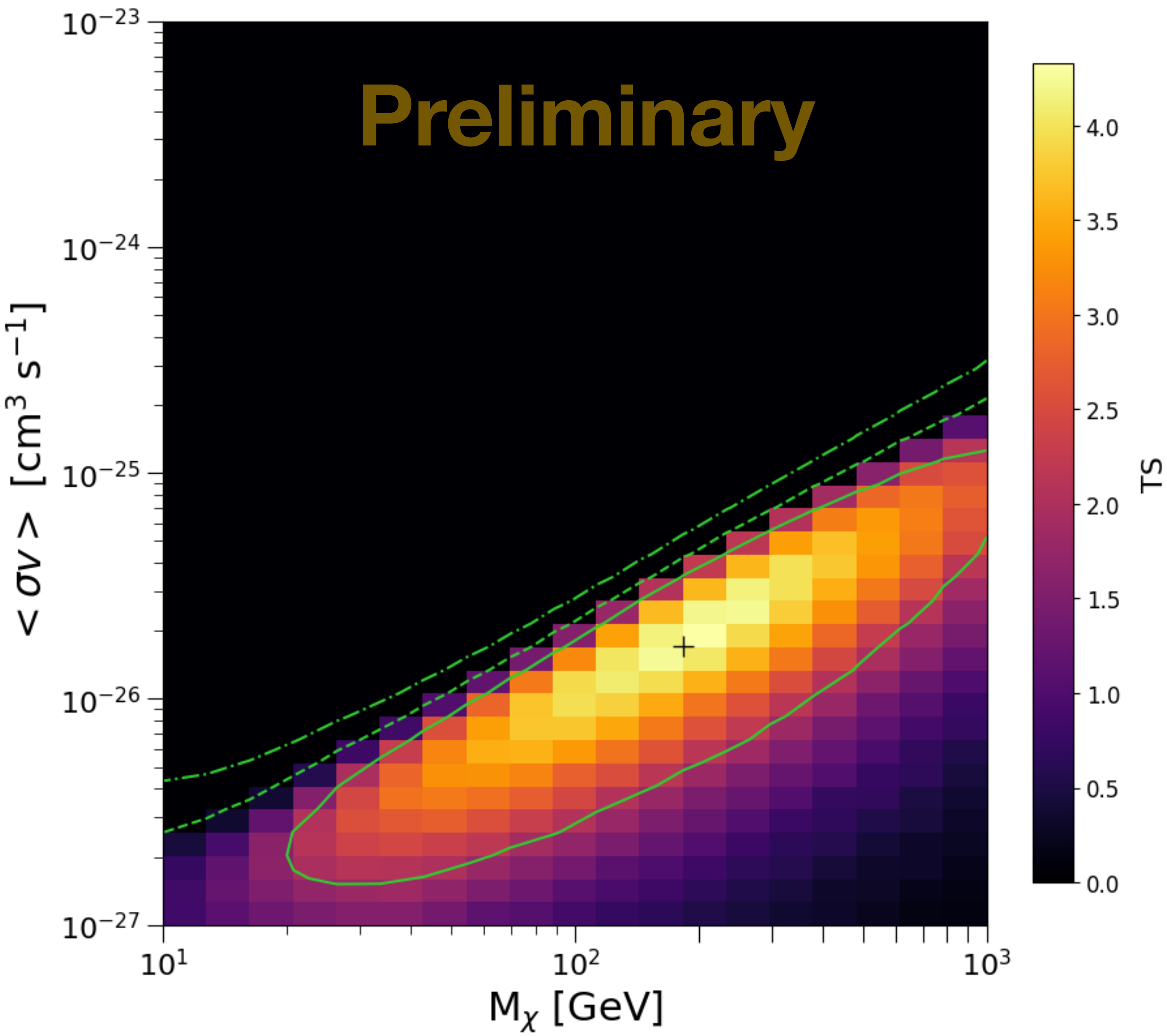
DM Spectra





- DM Spectra are calculate with DMFitFunction in Fermipy, which is based on DMFit.
- The dwarfs are modeled as point sources.

Results



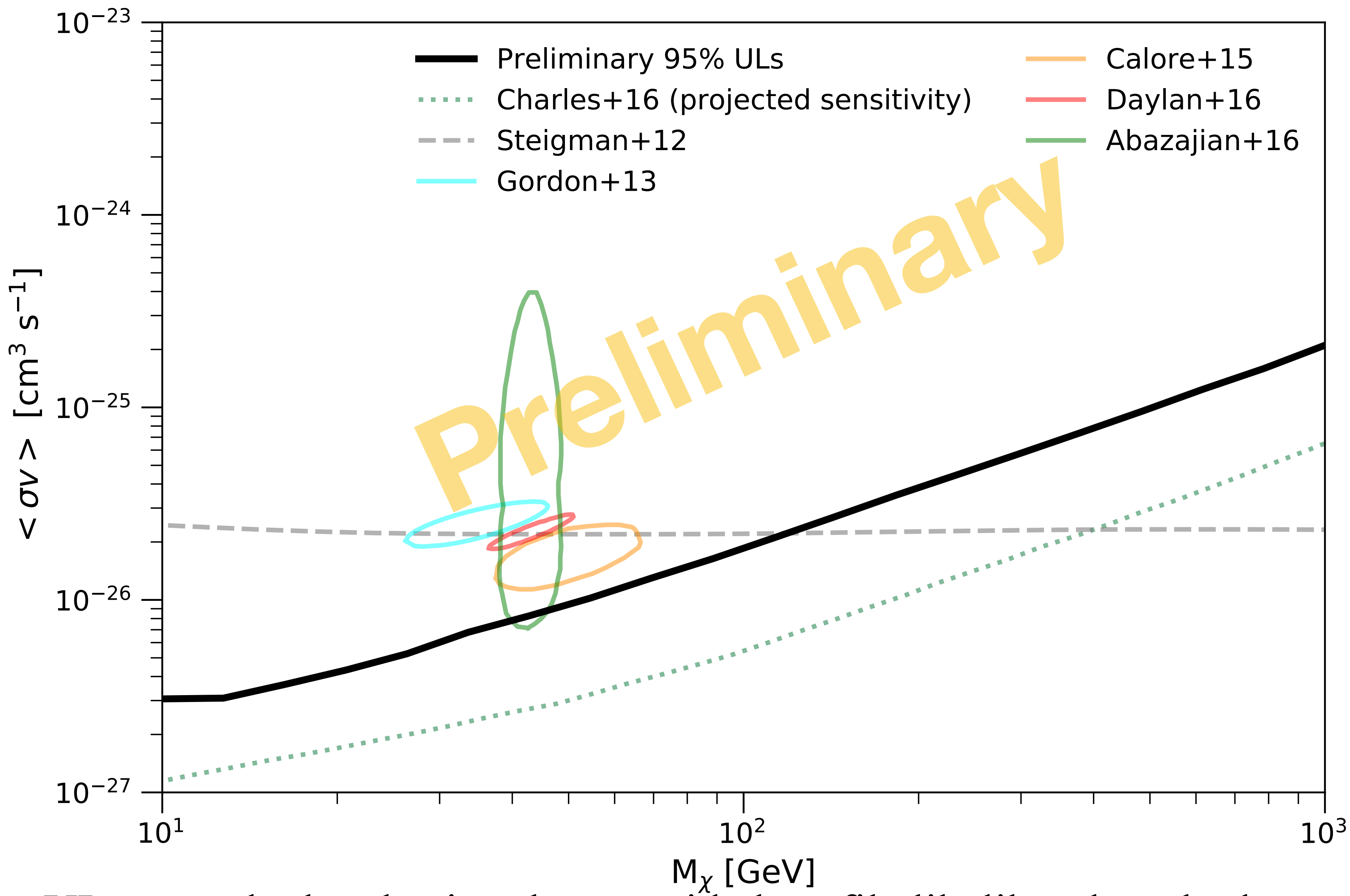
$$TS_{max} = 4.3 \ (1.6\sigma)$$

$$M_\chi = 183.3^{+432.6}_{-94.7} \text{ GeV}$$

$$< \sigma v > = 1.7^{+2.7}_{-1.3} \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$$

- Standard analysis with 41 dwarfs (nominal sample from Albert+17)
- Green contours show 68%, 90%, and 99% significance contours.
- **These results do not account for J-factor error (statistical and systematic), astrophysical mis-modeling, nor trials factor.**

Upper Limits



- ULs are calculated using the one-sided profile likelihood method: $2(\log L_{max} - \log L) = 2.71$
- Projected sensitivity for 60 dSphs and 15 years
- **These ULs do not account for J-factor error nor astrophysical mis-modeling.**
- **The ULs shown here are not for the fully updated analysis.**

Next Steps

- Update source sample and J-factors
- Run JLA and full DM scan
- Incorporate J-factor uncertainty.
- To account for background mis-modeling we will follow the data-driven approach in Linden 20, where we will determine the distribution of “fake” point-source fluxes from blank sky regions, and fold this result directly into the calculated ULs.
- Quantify systematic uncertainty in ULs due to uncertainty in the J-factor, i.e. from the assumption of spherical symmetry for the density profiles, as well as the use of log uniform priors instead of informed priors based on structure formation models.
- Make our stacking code available to the community and provide a comprehensive set of J-factors in machine-readable format via the DMSky package (part of *fermipy*).