# EFFECT OF BINARIES ON DARK MATTER ESTIMATES IN DWARF GALAXIES

Caveats to Dwarf Galaxy Indirect Detection Limits

LAURA J. CHANG PRINCETON UNIVERSITY Small Galaxies, Cosmic Questions July 31, 2019

#### IN COLLABORATION WITH: LINA NECIB (CALTECH)

### THERMAL WIMP DARK MATTER (DM)











L. Pieri et al. [0908.0195]

# INDIRECT DETECTION BENCHMARK: DWARF GALAXIES

- Low astrophysical backgrounds (dust/gas) compared to other indirect detection targets
  - $\rightarrow$  some of the most stringent and robust constraints



Fermi-LAT collaboration and DES collaboration [1611.03184]

$\begin{array}{c c c c c c c c c c c c c c c c c c c $	(1)	(2)	(3)	(4)	(5)	(6)	(7)	
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	Name	l, b	Distance	$r_{1/2}$	$M_V$	$\log_{10}(J_{\text{meas}})$	$\log_{10}(J_{\text{pred}})$	
Kinematically Confirmed Galaxies           Boötes I <sup>*</sup> 358.08, 69.62         66         189         -6.3         18.2 $\pm 0.4$ 18.5           Boötes II         353.09, 68.87         42         46         -2.7          18.9           Boötes III         35.41, 75.35         47          -5.8          18.8           Canes Venatici II*         113.17, 98.2         218         441         -6.6         17.4 $\pm 0.3$ 17.4           Carnes Venatici II*         113.38, 82.70         160         52         -4.9         17.9 $\pm 0.1$ 18.1           Coma Berenices*         241.89, 83.61         44         60         -4.1         19.0 $\pm 0.4$ 18.3           Draco II         98.29, 42.88         24         16         -2.9          19.3           Fornax*         237.10, -65.65         147         594         -13.4         17.8 $\pm 0.1$ 17.8           Hercules*         28.73, 36.87         132         187         -6.6         16.9 $\pm 0.7$ 17.9           Hydra II         295.62, 30.46         134         66         -4.8          17.8           Leo I         225.99, 49.9		$(\deg, \deg)$	$(\mathrm{kpc})$	(pc)	(mag)	$\log_{10}({ m GeV^2cm^{-5}})$	$\log_{10}({ m GeV^2cm^{-5}})$	
				Kiner	natically	Confirmed Galaxies		
Bootes II         353.60, 68.87         42         46         -2.7          18.9           Boötes II         35.41, 75.35         47          -5.8          18.8           Canes Venatici I         74.31, 79.82         218         441         -8.6         17.4 $\pm$ 0.3         17.4           Canes Venatici I         113.58, 82.70         160         52         -4.9         17.6 $\pm$ 0.4         17.7           Carina*         260.11, -22.22         105         205         -9.1         17.9 $\pm$ 0.1         18.1           Coma Berenices*         241.89, 83.61         44         60         -4.1         19.0 $\pm$ 0.4         18.8           Draco*         86.37, 34.72         76         184         -8.8         18.8 $\pm$ 0.1         17.8           Draco         19.829, 42.88         24         16         -2.9          19.3           Formax*         237.10, -65.65         147         75.4         -13.4         17.8 $\pm$ 0.1         17.8           Hercules*         28.73, 36.87         132         187         -6.6         16.9 $\pm$ 0.7         17.9           Horologium I         271.38, 54.74         87         52.1         17.8         1	Boötes I*	358.08, 69.62	66	189	-6.3	$18.2 \pm 0.4$	18.5	
Boötes III         35.41, 75.35         47          5.8          18.8           Canes Venatici II         74.31, 79.82         218         441         -8.6         17.4 $\pm$ 0.3         17.4           Carnes Venatici II*         113.58, 82.70         160         52         -4.9         17.6 $\pm$ 0.4         17.7           Carnes Venatici II*         113.58, 82.70         160         52         -4.9         17.6 $\pm$ 0.4         17.7           Carnes Venatici II*         113.85, 82.70         160         205         -9.1         17.9 $\pm$ 0.1         18.1           Cornes Venatici II*         20.222         105         205         -9.1         17.9 $\pm$ 0.1         18.8           Draco II         98.29, 42.88         24         16         -2.9          19.3           Formax*         237.10, -65.65         147         594         -13.4         17.8 $\pm$ 0.1         17.8           Horologium I         271.38, -54.74         87         61         -3.5          18.2         Hydra II         205.62, 30.46         134         66         -4.8          17.8         12.0         17.4         12.0         17.4           Leo I         225.	Boötes II	353.69, 68.87	42	46	-2.7		18.9	
	Boötes III	35.41, 75.35	47		-5.8		18.8	
	Canes Venatici I	74.31, 79.82	218	441	-8.6	$17.4 \pm 0.3$	17.4	
$ \begin{array}{cccc} {\rm Carina}^{*} & 260.11, -22.22 & 105 & 205 & -9.1 & 17.9 \pm 0.1 & 18.1 \\ {\rm Coma Berenices}^{*} & 241.89, 83.61 & 44 & 60 & -4.1 & 19.0 \pm 0.4 & 18.8 \\ {\rm Draco}^{*} & 86.37, 34.72 & 76 & 184 & -8.8 & 18.8 \pm 0.1 & 18.3 \\ {\rm Draco}^{*} & 28.63, 73.4.72 & 76 & 184 & -8.8 & 18.8 \pm 0.1 & 17.8 \\ {\rm Draco}^{*} & 28.73, 36.87 & 132 & 187 & -6.6 & 16.9 \pm 0.7 & 17.9 \\ {\rm Horologium} I & 271.38, -54.74 & 87 & 61 & -3.5 & \dots & 18.2 \\ {\rm Hydra} II & 295.62, 30.46 & 134 & 66 & -4.8 & \dots & 17.8 \\ {\rm Leo} I & 225.99, 49.11 & 254 & 223 & -12.0 & 17.8 \pm 0.2 & 17.3 \\ {\rm Leo} I & 225.09, 49.11 & 254 & 223 & -12.0 & 17.8 \pm 0.2 & 17.4 \\ {\rm Leo} IV^{*} & 265.44, 56.51 & 154 & 147 & -5.8 & 16.3 \pm 1.4 & 17.7 \\ {\rm Leo} IV^{*} & 265.44, 56.51 & 154 & 147 & -5.8 & 16.3 \pm 1.4 & 17.7 \\ {\rm Leo} IV^{*} & 266.46, 58.54 & 178 & 95 & -5.2 & 16.4 \pm 0.9 & 17.6 \\ {\rm Pisces} II & 79.21, -47.11 & 182 & 45 & -5.0 & \dots & 17.6 \\ {\rm Pisces} II & 79.21, -47.11 & 182 & 45 & -5.0 & \dots & 17.6 \\ {\rm Seculpto}^{*} & 287.53, -83.16 & 86 & 233 & -11.1 & 18.5 \pm 0.1 & 18.2 \\ {\rm Segue} 1^{*} & 220.48, 50.43 & 23 & 21 & -1.5 & 19.4 \pm 0.3 & 19.4 \\ {\rm Sextans}^{*} & 243.50, 42.27 & 86 & 561 & -9.3 & 17.5 \pm 0.2 & 18.2 \\ {\rm Triangulum} II & 140.90, -23.82 & 30 & 30 & -1.8 & \dots & 19.1 \\ {\rm Tucan} II & 328.04, -52.35 & 58 & 120 & -3.9 & \dots & 18.6 \\ {\rm Ursa} Major I^{*} & 152.46, 37.44 & 32 & 91 & -4.2 & 19.4 \pm 0.4 & 19.1 \\ {\rm Ursa} Minor^{*} & 10.49.7 44.80 & 76 & 120 & -88 & 18.9 \pm 0.2 & 18.3 \\ {\rm Willman} 1^{*} & 158.58, 56.78 & 38 & 19 & -2.7 & \dots & 18.9 \\ {\rm Horologium} II & 249.78, -51.65 & 331 & 156 & -7.4 & \dots & 17.6 \\ {\rm Eridanus} II & 249.78, -51.65 & 331 & 156 & -7.4 & \dots & 17.6 \\ {\rm Eridanus} II & 249.78, -51.65 & 331 & 156 & -7.4 & \dots & 17.9 \\ {\rm Grus} II & 351.14, -51.94 & 53 & 93 & -3.9 & \dots & 18.7 \\ {\rm Horologium} II & 262.48, -54.14 & 78 & 33 & -2.6 & \dots & 18.3 \\ {\rm Horologium} II & 262.48, -54.14 & 78 & 33 & -2.6 & \dots & 18.7 \\ {\rm Horologium} II & 262.48, -54.14 & 78 & 33 & -2.6 & \dots & 18.7 \\ {\rm Horologium} II & 257.29 & -40.64 & 126 & 44 & -3.7 & \dots & 17.9 \\ {$	Canes Venatici II*	113.58, 82.70	160	52	-4.9	$17.6 \pm 0.4$	17.7	
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	Carina*	260.11, -22.22	105	205	-9.1	$17.9 \pm 0.1$	18.1	
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	Coma Berenices <sup>*</sup>	241.89, 83.61	44	60	-4.1	$19.0 \pm 0.4$	18.8	
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	Draco*	86.37, 34.72	76	184	-8.8	$18.8 \pm 0.1$	18.3	
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	Draco II	98.29, 42.88	24	16	-2.9		19.3	
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	Fornax*	237.1065.65	147	594	-13.4	$17.8 \pm 0.1$	17.8	
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	Hercules*	28.73, 36.87	132	187	-6.6	$16.9 \pm 0.7$	17.9	
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	Horologium I	271.38, -54.74	87	61	-3.5		18.2	
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	Hydra II	$295.62.\ 30.46$	134	66	-4.8		17.8	
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	Leo I	225.99, 49.11	254	223	-12.0	$17.8 \pm 0.2$	17.3	
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	Leo II*	220.17, 67.23	233	164	-9.8	$18.0 \pm 0.2$	17.4	
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	Leo $IV^*$	265.44, 56.51	154	147	-5.8	$16.3 \pm 1.4$	17.7	
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	Leo $V$	261.86, 58.54	178	95	-5.2	$16.4 \pm 0.9$	17.6	
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	Pisces II	79.21, -47.11	182	45	-5.0		17.6	
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	Reticulum II	266.30, -49.74	32	35	-3.6	$18.9 \pm 0.6$	19.1	
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	Sculptor*	287.53, -83.16	86	233	-11.1	$18.5 \pm 0.1$	18.2	
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	Segue 1*	220.48, 50.43	23	21	-1.5	$19.4 \pm 0.3$	19.4	
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	Sextans*	243.50, 42.27	86	561	-9.3	$17.5 \pm 0.2$	18.2	
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	Triangulum II	140.90, -23.82	30	30	-1.8		19.1	
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	Tucana II	328.0452.35	58	120	-3.9		18.6	
Ursa Major II*       152.46, 37.44       32       91       -4.2       19.4 $\pm$ 0.4       19.1         Ursa Minor*       104.97, 44.80       76       120       -8.8       18.9 $\pm$ 0.2       18.3         Willman 1*       158.58, 56.78       38       19       -2.7        18.9         Likely Galaxies         Columba I       231.62, -28.88       182       101       -4.5        17.6         Eridanus II       249.78, -51.65       331       156       -7.4        17.1         Grus I       338.68, -58.25       120       60       -3.4        17.9         Grus II       351.14, -51.94       53       93       -3.9        18.7         Horologium II       262.48, -54.14       78       33       -2.6        18.3         Indus II       354.00, -37.40       214       181       -4.3        17.4         Pegasus III       69.85, -41.81       205       57       -4.1        17.5         Phoenix II       323.69, -59.74       96       33       -3.7        18.1         Pictor I       257.29, -40.64	Ursa Major I	159.43, 54.41	97	143	-5.5	$17.9 \pm 0.5$	18.1	
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	Ursa Major II*	152.46, 37.44	32	91	-4.2	$19.4 \pm 0.4$	19.1	
Willman 1*       158.58, 56.78       38       19       -2.7        18.9         Columba I       231.62, -28.88       182       101       -4.5        17.6         Eridanus II       249.78, -51.65       331       156       -7.4        17.1         Grus I       338.68, -58.25       120       60       -3.4        17.9         Grus II       351.14, -51.94       53       93       -3.9        18.7         Horologium II       262.48, -54.14       78       33       -2.6        18.3         Indus II       354.00, -37.40       214       181       -4.3        17.4         Pegasus III       69.85, -41.81       205       57       -4.1        17.5         Phoenix II       323.69, -59.74       96       33       -3.7        18.1         Pictor I       257.29, -40.64       126       44       -3.7        18.2         Sagittarius II       18.94, -22.90       67       34       -5.2        18.2         Sagittarius II       18.94, -5.29       48       128       -3.5        18.7 <td>Ursa Minor*</td> <td>104.97, 44.80</td> <td>76</td> <td>120</td> <td>-8.8</td> <td><math>18.9 \pm 0.2</math></td> <td>18.3</td>	Ursa Minor*	104.97, 44.80	76	120	-8.8	$18.9 \pm 0.2$	18.3	
$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$	Willman 1*	158.58, 56.78	38	19	-2.7		18.9	
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$		100100, 00110	Likely Galaxies					
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	Columba I	231.62, -28.88	182	101	-4.5	••••	17.6	
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	Eridanus II	249.78, -51.65	331	156	-7.4		17.1	
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	Grus I	338.68, -58.25	120	60	-3.4		17.9	
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	Grus II	351.14, -51.94	53	93	-3.9		18.7	
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	Horologium II	262.48, -54.14	78	33	-2.6		18.3	
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	Indus II	354.00, -37.40	214	181	-4.3		17.4	
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	Pegasus III	69.85, -41.81	205	57	-4.1		17.5	
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	Phoenix II	323.69, -59.74	96	33	-3.7		18.1	
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	Pictor I	257.29, -40.64	126	44	-3.7		17.9	
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	Reticulum III	273.88, -45.65	92	64	-3.3		18.2	
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	Sagittarius II	18.94, -22.90	67	34	-5.2		18.4	
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	Tucana III	315.38, -56.18	25	44	-2.4		19.3	
$\begin{tabular}{ c c c c c c c c c c c c c c c c c c c$	Tucana IV	313.29, -55.29	48	128	-3.5		18.7	
Cetus II156.47, -78.533017 $0.0$ 19.1Eridanus III274.95, -59.609612-2.418.1Kim 2347.16, -42.0710512-1.518.1Tucana V316.31, -51.895516-1.618.6		-		Ambiguous Systems				
Eridanus III $274.95, -59.60$ 9612 $-2.4$ 18.1Kim 2 $347.16, -42.07$ 10512 $-1.5$ 18.1Tucana V $316.31, -51.89$ 5516 $-1.6$ 18.6	Cetus II	156.47, -78.53	30	17	0.0		19.1	
Kim 2 $347.16, -42.07$ $105$ $12$ $-1.5$ $18.1$ Tucana V $316.31, -51.89$ $55$ $16$ $-1.6$ $18.6$	Eridanus III	274.95, -59.60	96	12	-2.4		18.1	
Tucana V 316.31, -51.89 55 16 -1.6 18.6	Kim 2	347.16, -42.07	105	12	-1.5		18.1	
	Tucana V	316.31, -51.89	55	16	-1.6		18.6	

Fermi-LAT collaboration and DES collaboration [1611.03184]

#### • Constraints rely on accurate J-factors

(1)	(2)	(3)	(4)	(5)	(6)	(7)	
Name	$\hat{l},\hat{b}$	Distance	$r_{1/2}$	$\dot{M}_V$	$\log_{10}(\hat{J}_{\text{meas}})$	$\log_{10}(J_{\text{pred}})$	
	$(\deg, \deg)$	$(\mathrm{kpc})$	(pc)	(mag)	$\log_{10}({\rm GeV^2cm^{-5}})$	$\log_{10}({\rm GeV}^2{\rm cm}^{-5})$	
			- Kinematically Confirmed Galaxies —				
Boötes I*	358.08, 69.62	66	189	-6.3	$18.2 \pm 0.4$	18.5	
Boötes II	353.69, 68.87	42	46	-2.7		18.9	
Boötes III	35.41, 75.35	47		-5.8		18.8	
Canes Venatici I	74.31, 79.82	218	441	-8.6	$17.4 \pm 0.3$	17.4	
Canes Venatici II*	113.58, 82.70	160	52	-4.9	$17.6 \pm 0.4$	17.7	
Carina*	260.11, -22.22	105	205	-9.1	$17.9 \pm 0.1$	18.1	
Coma Berenices*	241 89 83 61	44	60	-4.1	$19.0 \pm 0.4$	18.8	
Draco*	86.37. 34.72	76	184	-8.8	$18.8 \pm 0.1$	18.3	
Draco II	98 29 42 88	24	16	-2.9	10.0 ± 0.1	19.3	
Fornax*	$237\ 10\ -65\ 65$	147	594	-134	$17.8 \pm 0.1$	17.8	
Hercules*	28 73 36 87	132	187	-6.6	$16.9 \pm 0.7$	17.9	
Horologium I	271 38 -54 74	87	61	-3.5	10.5 ± 0.1	18.2	
Hydra II	205 62 30 46	13/	66	-0.0		17.8	
Leo I	225.02, 30.40 225.09, 49.11	254	223	-12.0	$17.8 \pm 0.2$	17.3	
Leo II*	220.33, 43.11 220.17, 67.23	204	164	_0.8	$11.0 \pm 0.2$ $18.0 \pm 0.2$	17.0	
Leo IV*	265 44 56 51	154	1/7	-5.8	$16.0 \pm 0.2$ $16.3 \pm 1.4$	17.4	
Leo V	261.86 58 54	178	05	-5.0 5.2	$10.5 \pm 1.4$ $16.4 \pm 0.0$	17.6	
Discos II	201.00, 50.54 70.91 47.11	182	95 45	-5.2	$10.4 \pm 0.9$	17.0	
Roticulum II	266 20 40 74	32	25	-5.0	$18.0 \pm 0.6$	10.1	
Sculptor*	200.50, -49.14 287.52, 82.16	32 86	- <u>-</u>	-5.0	$18.5 \pm 0.0$ 18.5 ± 0.1	18.0	
Scuptor Secure 1*	201.00, -00.10	00	200 01	-11.1	$10.3 \pm 0.1$ 10.4 \perp 0.2	10.2	
Segue 1 <sup>*</sup>	220.40, 50.43	23	21 E61	-1.0	$19.4 \pm 0.3$ $175 \pm 0.2$	19.4	
Sextans <sup>*</sup>	243.30, 42.27	80	201	-9.3	$17.5 \pm 0.2$	18.2	
Triangulum II	140.90, -23.82	30	30	-1.8		19.1	
Iucana II Uuca Maian I	328.04, -52.35	58	120	-3.9		18.0	
Ursa Major I	159.43, 54.41	97	143	-5.5	$17.9 \pm 0.5$	18.1	
Ursa Major II <sup>**</sup>	152.46, 37.44	32	91	-4.2	$19.4 \pm 0.4$	19.1	
Ursa Minor <sup>*</sup>	104.97, 44.80	76	120	-8.8	$18.9 \pm 0.2$	18.3	
Willman 1 <sup>≁</sup>	158.58, 56.78	38	19	-2.7 Liko	 In Colorios	18.9	
Columba I	221 62 -28 88	182	101	— Like	Ty Galaxies —	17.6	
Eridonus II	231.02, -20.00 240.78, 51.65	221	156	-4.5		17.0	
Crus I	249.70, -51.05	120	60	-1.4		17.1	
Crus II	350.00, -50.25 351.14, 51.04	52	00	-3.4		18.7	
Horologium II	262 48 54 14	55 78	22	-3.9		18.2	
Induc II	202.40, -34.14 354.00 $37.40$	10 914	181	-2.0		10.5	
Dogogue III	60.85 41.81	214	57	-4.5		17.4	
Dhooniy II	393 60 50 74	205 06	22	-4.1 27		18 1	
Dictor I	223.09, -39.14 257.20 40.64	126	33 44	-3.7		17.0	
Roticulum III	201.29, -40.04	020	64	-0.7 2.2		18.9	
Socittoring II	410.00, -40.00 18 04 00 00	94 67	24			10.2	
Saginarius II Tugana III	10.94, -22.90 215 28 56 19	07 25	54 44	-0.2		10.4	
Tucana III	313.30, -30.18 212.20 FF 20	20 49	44 100	-2.4 2 F		19.3	
Tucana TV	515.29, -55.29	48	128 -3.5 18.7 ——— Ambiguous Systems ————				
Cetus II	156 47 -78 53	30	17	0.0		19.1	
Eridanus III	274 95 -50 60	96	19	_2 4		18 1	
Kim 9	214.00, -09.00 347.16 -49.07	105	12	_1 5		18 1	
Tucana V	316 31 -51 80	55	16	-1.0		18.6	
	510.51, -51.89	00	10	-1.0	•••	10.0	

Fermi-LAT collaboration and DES collaboration [1611.03184]

#### • Constraints rely on accurate J-factors

(1) Name	(2)	(3) Distance	(4)	(5) $M_{\rm W}$	(6)	(7)
Ivanie	(deg. deg)	(kpc)	(pc)	(mag)	$\log_{10}(\text{GeV}^2 \text{ cm}^{-5})$	$\log_{10}(\text{GeV}^2 \text{ cm}^{-5})$
	(408, 408)	("P°)	(P°)	(11108)	Carfana d Calaria	10810(00000000)
Detter I*	250 00 60 62	66	Kinei 180		18.9   0.4	10 5
Bootes I <sup>*</sup>	338.08, 09.02	42	189	-0.3	$18.2 \pm 0.4$	18.0
Bootes II	25 41 75 25	42	40	-2.1		10.9
Canos Vonatici I	55.41, 75.55 74.31, 70.82	218		-5.6	$17.4 \pm 0.3$	10.0 17.4
Canos Vonatici II*	113 58 89 70	160	52	-0.0	$17.4 \pm 0.5$ $17.6 \pm 0.4$	17.4
Carina*	260 11 -22 22	105	205	_0.1	$17.0 \pm 0.4$ $17.9 \pm 0.1$	18.1
Coma Berenices*	200.11, -22.22	105	200	-3.1	$17.5 \pm 0.1$ $19.0 \pm 0.4$	18.8
Draco*	86 37 34 72	76	18/	-8.8	$13.0 \pm 0.4$ $18.8 \pm 0.1$	18.3
Draco II	08 20 /2 88	24	16	2.0	$10.0 \pm 0.1$	10.3
Fornax <sup>*</sup>	$237\ 10\ -65\ 65$	$\frac{24}{147}$	594	-2.5	$17.8 \pm 0.1$	17.8
Horcules*	237.10, -03.03	139	187	-6.6	$16.9 \pm 0.1$	17.0
Horologium I	271 38 -54 74	87	61	-3.5	$10.5 \pm 0.1$	18.2
Hydra II	205 62 30 46	13/	66	-3.5		17.8
Leo I	235.02, 30.40	254	223	-4.0	$17.8 \pm 0.2$	17.3
Leo II*	220.33, 45.11 220.17, 67.23	234	164	-12.0	$11.0 \pm 0.2$ $18.0 \pm 0.2$	17.4
Leo IV*	220.11, 01.25 265.44, 56.51	255 154	1/1	-5.8	$16.0 \pm 0.2$ $16.3 \pm 1.4$	17.4
Leo V	261 86 58 54	178	95	-5.2	$16.5 \pm 1.4$ $16.4 \pm 0.9$	17.6
Pisces II	70.201.00, 50.54 70.21, -47.11	182	45	-5.0	$10.4 \pm 0.5$	17.6
Reticulum II	266 30 -49 74	32	35	-3.6	$18.9 \pm 0.6$	19.1
Sculptor*	287 53 -83 16	86	233	-11.1	$18.5 \pm 0.0$ $18.5 \pm 0.1$	18.2
Segue 1*	201.00, -00.10	23	200	-15	$10.5 \pm 0.1$ $19.4 \pm 0.3$	19.2
Sextane*	243 50 42 27	20 86	561	-0.3	$17.4 \pm 0.3$ $17.5 \pm 0.2$	18.2
Triangulum II	140.90 -23.82	30	30	-3.5	$11.5 \pm 0.2$	10.2
Tucana II	328.04 - 52.35	58	120	-3.9		18.6
Ursa Major I	159 43 54 41	97	143	-5.5	$17.9 \pm 0.5$	18.1
Ursa Major II*	152.46, 37.44	32	91	-4.2	$19.4 \pm 0.4$	19.1
Ursa Minor*	104.97, 44.80	76	120	-8.8	$18.9 \pm 0.2$	18.3
Willman 1*	158.58, 56.78	38	19	-2.7	1010 1 012	18.9
	100.000, 00.00		20	— Like	ly Galaxies ———	10.0
Columba I	231.6228.88	182	101	-4.5		17.6
Eridanus II	249.7851.65	331	156	-7.4		17.1
Grus I	338.68, -58.25	120	60	-3.4		17.9
Grus II	351.14, -51.94	53	93	-3.9		18.7
Horologium II	262.48, -54.14	78	33	-2.6		18.3
Indus II	354.00, -37.40	214	181	-4.3		17.4
Pegasus III	69.85, -41.81	205	57	-4.1		17.5
Phoenix II	323.69, -59.74	96	33	-3.7		18.1
Pictor I	257.29, -40.64	126	44	-3.7		17.9
Reticulum III	273.88, -45.65	92	64	-3.3		18.2
Sagittarius II	18.94, -22.90	67	34	-5.2		18.4
Tucana III	315.38, -56.18	25	44	-2.4		19.3
Tucana IV	313.29, -55.29	48	128	-3.5		18.7
			— Ambiguous Systems —			
Cetus II	156.47, -78.53	30	17	0.0		19.1
Eridanus III	274.95, -59.60	96	12	-2.4		18.1
Kim 2	347.16, -42.07	105	12	-1.5		18.1
Tucana $V$	316.31, -51.89	55	16	-1.6		18.6

#### Use with caution:

#### "Galaxies for which Published Kinematics May Not Reliably Translate to Masses"

J. D. Slmon [1901.05465]

Fermi-LAT collaboration and DES collaboration [1611.03184]

#### • Constraints rely on accurate J-factors



Fermi-LAT collaboration and DES collaboration [1611.03184]

- Important assumptions:
  - Equilibrium
    - K. El-Badry et al. [1610.04232]

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#### Spherical Jeans equation

3d radial velocity dispersion, stellar density profile



Halo mass (DM density profile)

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In practice, observe line-of-sight projected quantities

Line-of-sight projected velocity dispersion, stellar density profile

 $M - \beta (\rho - \beta)$  degeneracy

J.I. Read and P. Steger [1701.04833]





The question

In the cleanest scenario, what is the effect of binaries on dwarf galaxy J-factors?

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Run through pipeline to get J-factors for Gaia Challenge

Gaia Challenge <u>http://astrowiki.ph.surrey.ac.uk/dokuwiki</u>

M. G. Walker and J. Peñarrubia [1108.2404]

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 $\rightarrow$  Repeat analysis with injected binary motions

# **STEP 1: LIGHT PROFILE FIT**



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# **STEP 2: VELOCITY DISPERSION FIT**

- Use Step 1 to constrain light profile parameters: float over middle 95% posterior parameter ranges from light profile fit
- Optimistically assume velocity error of 0.2 km/s
- Extract posterior distributions for DM parameters



3000 tracers

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## **INJECTING BINARIES**



M. E. Spencer et al. [1811.06597]

As a starting point: Model and code for modeling binary motion from Spencer+ 2018 (If you have a favorite binary model we should try, please let us know!)

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# EFFECT OF UNMODELED BINARIES ON J-FACTORS



# EFFECT OF UNMODELED BINARIES ON J-FACTORS

	10 /	3000 tracers	500	tracers
	19.3	Prelim	inary	Preliminary
$2  \mathrm{cm}^{-51}$	19.2			
	<u>6</u> 19.1	In n		
	0100 19.0	• Ev	en more statistics? (Co	omputationally expensive)
	18.9	• Inj	ecting binary motion of	only in certain regions
	0	f <sub>binary</sub> • Mic	her systematics?	inary
/tracers	$f_{\rm binary}$	$\log_{10} \left( M(< R_{1/2}) / M_{\odot} \right)$	$\log_{10} \left( M(<\!\!R_{\rm max})/M_{\odot} \right)$	$\int \log_{10} \left( J/(\text{GeV}^2 \text{ cm}^{-5}) \right)$
3000	0	$7.32^{+0.02}_{-0.02}$	$9.14^{+0.25}_{-0.26}$	$19.07^{+0.07}_{-0.05}$
3000	1	$7.38^{+0.17}_{-0.19}$	$9.19^{+0.23}_{-0.20}$	$19.16^{+0.09}_{-0.06}$
500	0	$7.25^{+0.04}_{-0.05}$	$8.81^{+0.18}_{-0.17}$	$18.99^{+0.19}_{-0.10}$
500	1	$7.30^{+0.04}_{-0.04}$	$8.76^{+0.21}_{-0.18}$	$19.06^{+0.16}_{-0.10}$

# **CONCLUSIONS & EXTENSIONS**

- In very simple examples on mock data, the presence of unmodeled binaries can bias estimates of dwarf galaxy J-factors ⇒ bias dark matter constraints derived
- Effect of binaries becomes more drastic with increased statistics
  - With more stars measured and more accurate measurements, will this become a more measurable effect? J. D. Simon et al. [1903.04743]
  - With future multi-epoch binary measurements, could exclude confirmed binaries from analysis
- Statistical uncertainties in dwarf galaxy dark matter constraints need to be better understood and characterized
- Other important systematics: tidal disruption, deviations from equilibrium, nonsphericity, ...



# **BACKUP SLIDES**



Figure 6. Upper limits on flux (*left*) and cross section (*right*) versus J-factor. The points represent J-factors for each target estimated either from spectroscopy (filled circles with error bars) or from the scaling relation discussed in Section 4 (filled circles). The green and yellow shaded regions are the 68% and 95% containment regions for the blank-sky expectations, respectively. For comparison, the three solid lines show the median expected upper limits for DM annihilation with the given cross section. No significant deviation from the background-only expectation is observed.



Spherical Jeans equation



In practice, observe line-of-sight projected quantities

$$\sigma_p^2(R) = \frac{2}{\Sigma(R)} \int_R^\infty \left( 1 - \beta_{\text{ani}}(r) \frac{R^2}{r^2} \right) \nu(r) \bar{\nu}_r^2(r) \frac{r \,\mathrm{d}r}{\sqrt{r^2 - R^2}}$$

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projected velocity dispersion

Spherical Jeans equation



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projected 2d stellar density ("light profile")

### FIDUCIAL SETUP

- Nested Plummer light profile  $\nu(r) = \sum_{i=1}^{N_p} \frac{3M_i}{4\pi a_i^3} \times \left(1 + \frac{r^2}{a_i^2}\right)^{-5/2} \xleftarrow{\text{Abel transform}} \Sigma(R) = \sum_{i=1}^{N_p} \frac{M_i a_i^2}{\pi (a_i^2 + R^2)^2}$
- Broken power law DM profile: analytic formula for enclosed DM mass

$$\rho(r) = \qquad \rho_0 \left(\frac{r}{r_0}\right)^{-\gamma_0} \qquad r < r_0$$

$$\rho(r) = \qquad \rho_0 \left(\frac{r}{r_j}\right)^{-\gamma_{j+1}} \prod_{n=1}^j \left(\frac{r_n}{r_{n-1}}\right)^{-\gamma_n} \qquad r_j < r < r_{j+1}$$

DM profile can span cusped ↔ cored

- Gaia challenge spherical mocks:
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Analytic formulas for 2d/3d stellar density and enclosed DM mass profiles

 $\rightarrow$  more computationally tractable

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### **STEP 2: VELOCITY DISPERSION FIT**



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