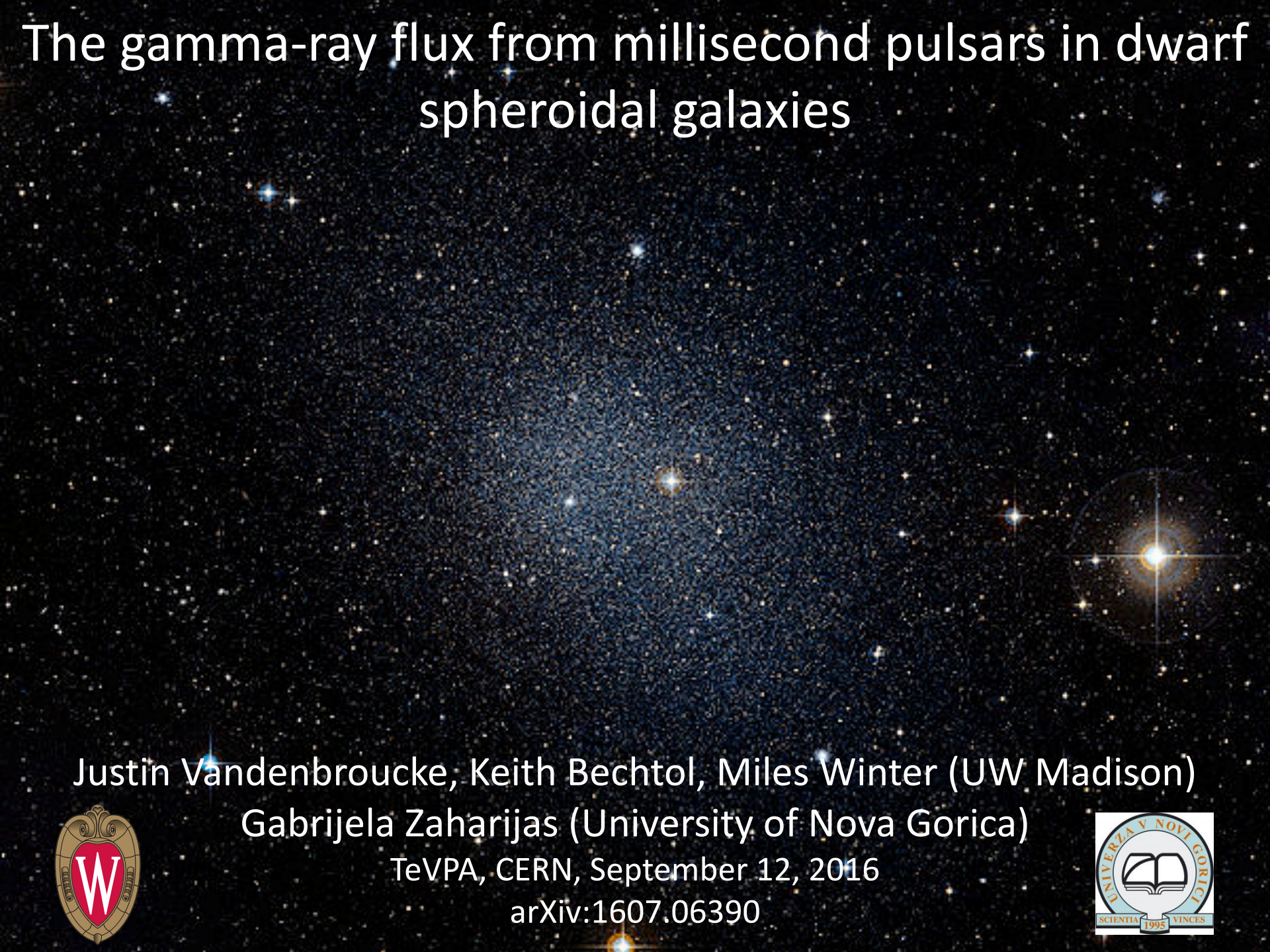
The gamma-ray flux from millisecond pulsars in dwarf spheroidal galaxies



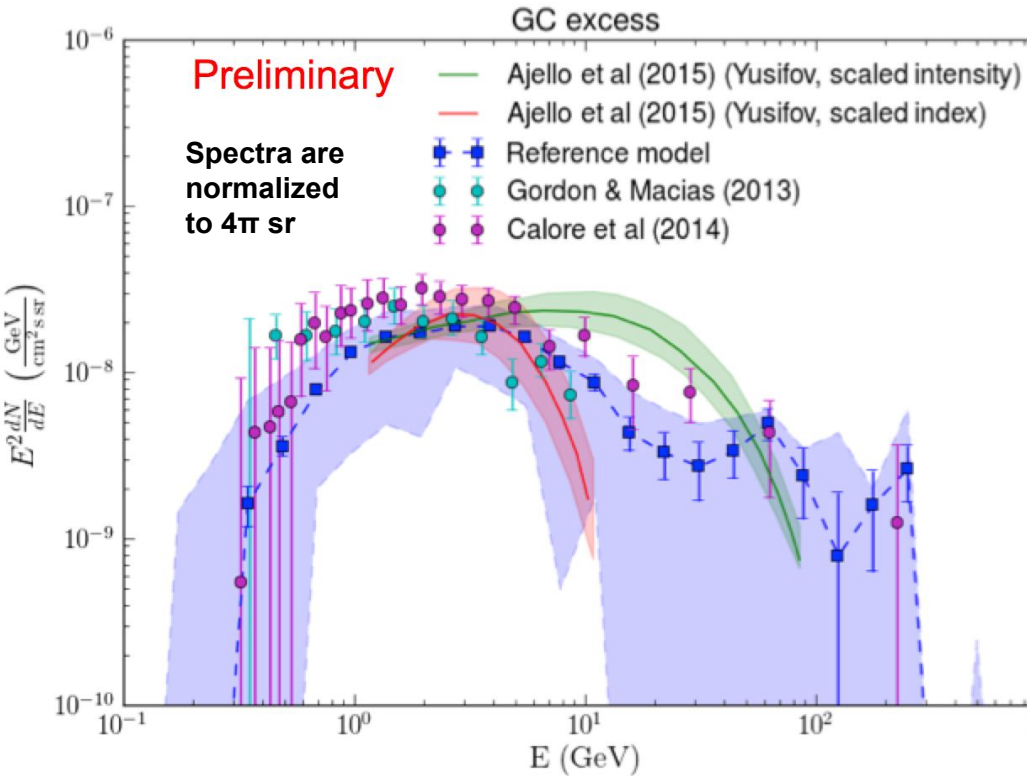
Justin Vandenbroucke, Keith Bechtol, Miles Winter (UW Madison)
Gabrijela Zaharijas (University of Nova Gorica)

TeVPA, CERN, September 12, 2016
arXiv:1607.06390

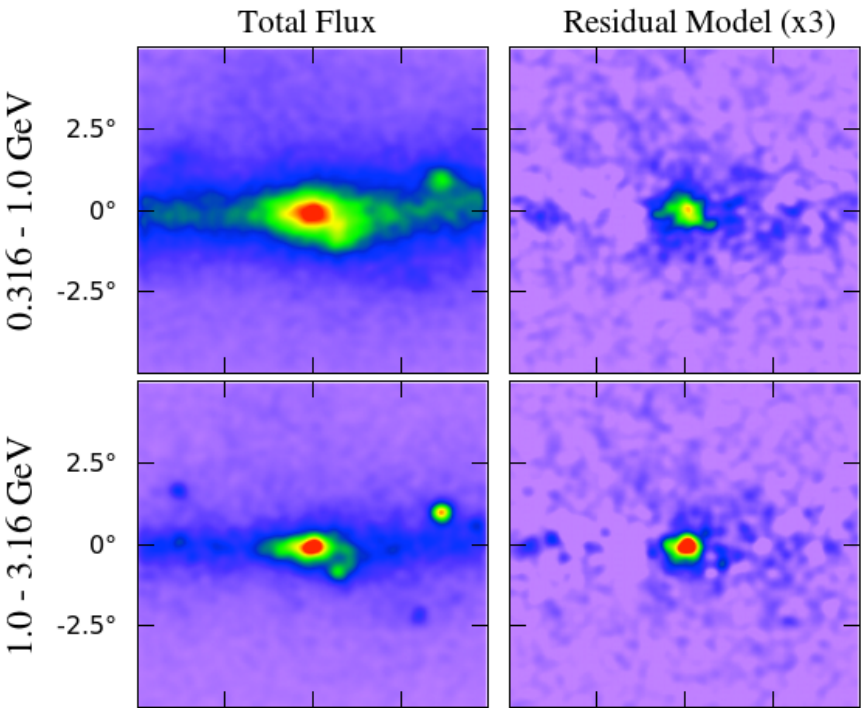
Outline

- Motivation: dark matter search (inc. testing the Galactic Center excess) with dwarf spheroidal galaxies
- If a signal is detected from dwarf galaxies, is there an astrophysical background?
- Two mechanisms of millisecond pulsar (MSP) formation
- MSP luminosity function
- Predicted number of MSPs and gamma-ray flux from individual dwarf galaxies
- Conclusion

The GeV excess from the Galactic center



A. Albert for LAT Collaboration
IAU GC Symposium 2016

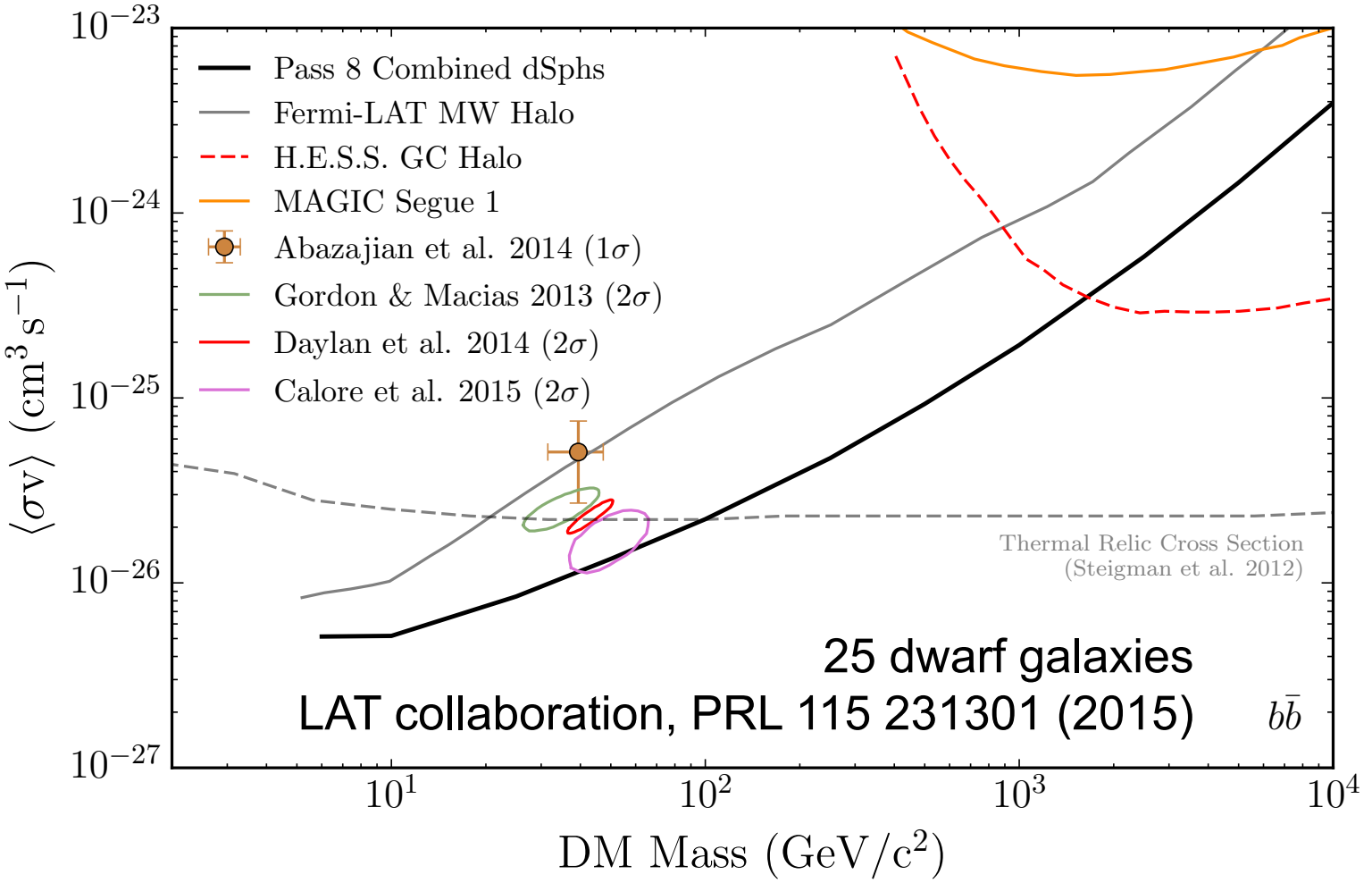


Daylan et al. 2016

Dark matter? Millisecond pulsars? Something else?

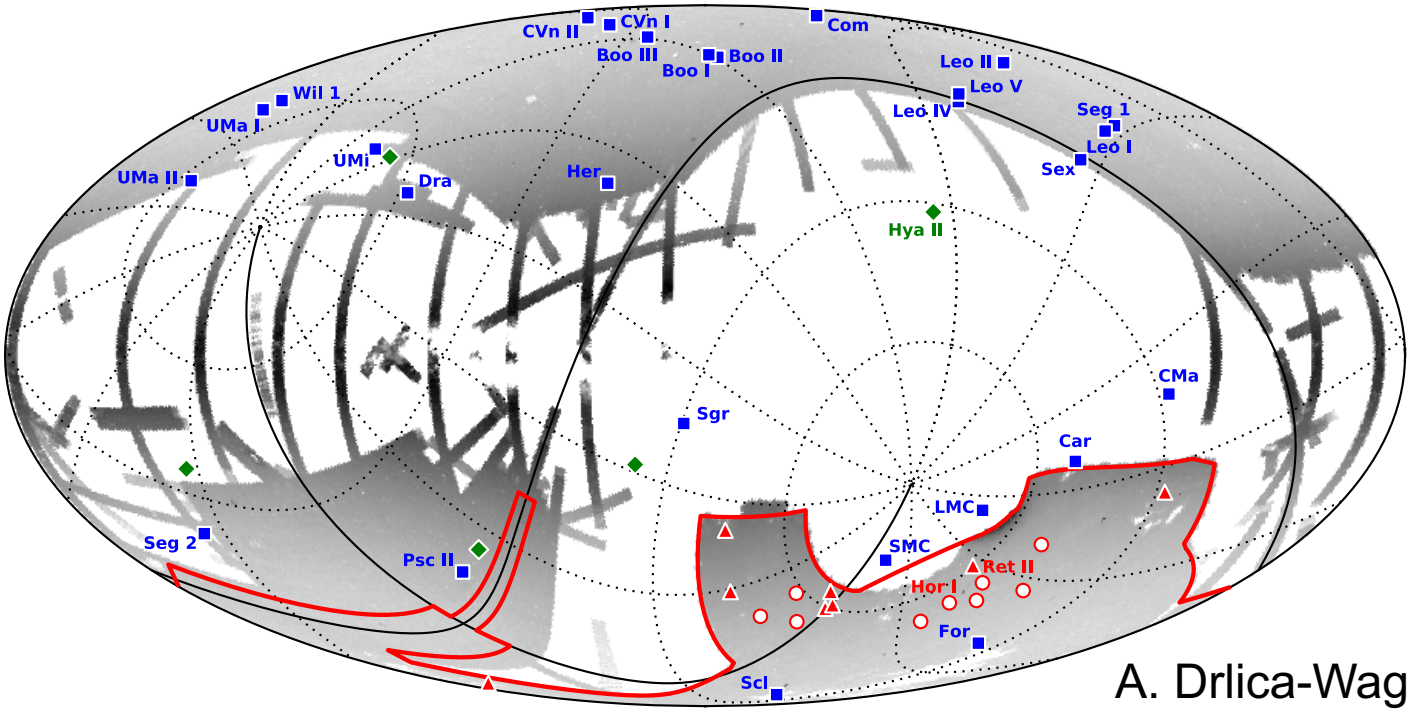
See Thursday afternoon session

Latest dark matter upper limits from dwarf galaxies



- Tension between dwarf limits and Galactic Center excess
- Will a signal soon emerge from dwarf galaxies?
- Would it be a smoking gun?

Additional dwarf galaxies continue to be discovered



A. Drlica-Wagner et al.
ApJ 813:109 (2015)

27 previously known

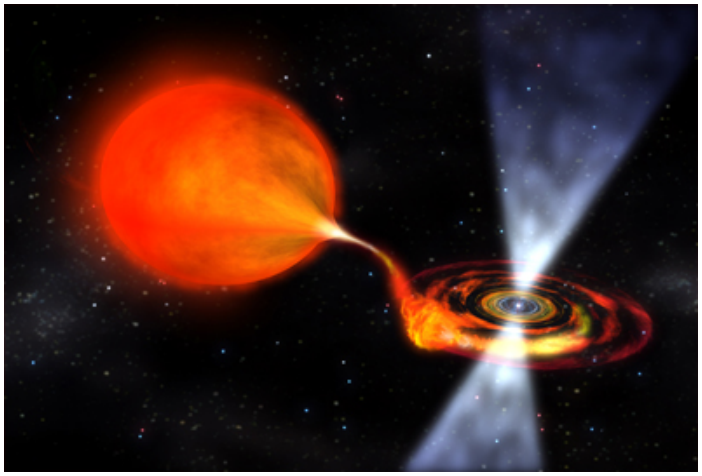
Discovered in past 2 years: 17 by DES and 5 by others

- DES much deeper than previous searches
- DES (and SkyMapper, Pan-STARRS, LSST) will continue to provide new dwarfs, potentially with excellent J factors

Astrophysical backgrounds must exist from dwarf galaxies: are they negligible?

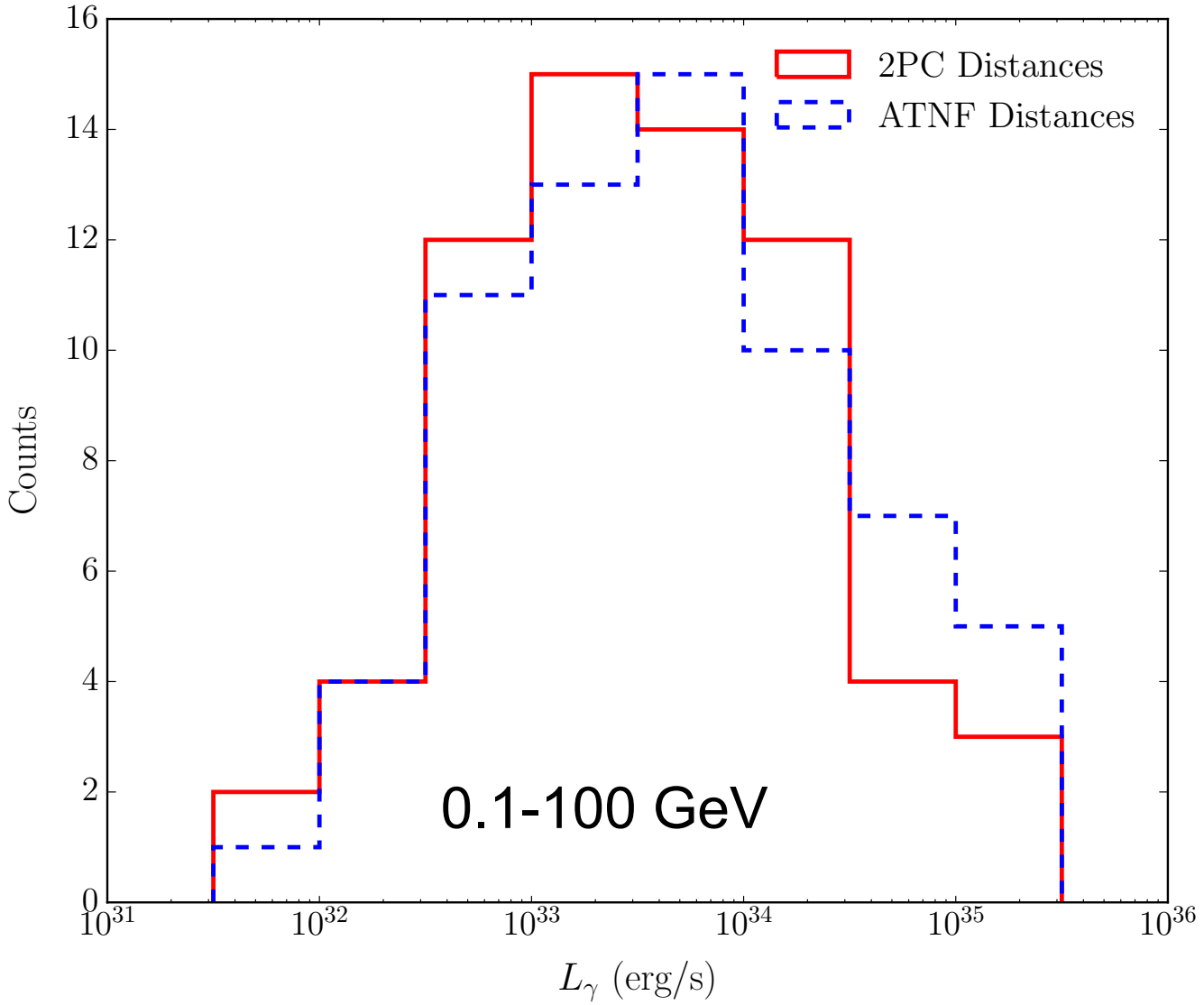
- Stacked dwarf galaxy dark matter sensitivity is comparable to the Galactic Center, and growing as more galaxies are discovered
- If a signal is seen from dwarf galaxies, is it confirmation of Galactic Center excess?
- Or will we repeat the same discussions of dark matter vs. pulsars vs. other?
- Be ready for this possibility by quantifying astrophysical backgrounds now

How do millisecond pulsars form?



- **Primordial channel**
  - Binary is formed during stellar birth, before one becomes neutron star
  - Rate proportional to stellar density
  - Dominant in low stellar densities: Milky Way disk, **dwarf galaxies**
- **Dynamical channel**
  - Existing neutron star is captured into orbit of companion
  - Rate proportional to stellar density squared
  - Dominant in high stellar densities: globular clusters, perhaps Milky Way bulge

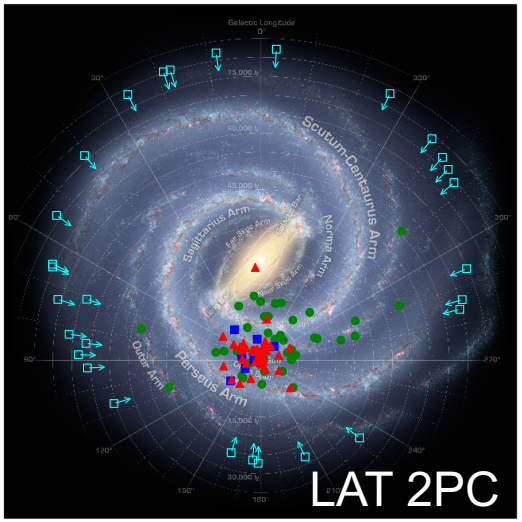
Luminosity distribution of LAT millisecond pulsars



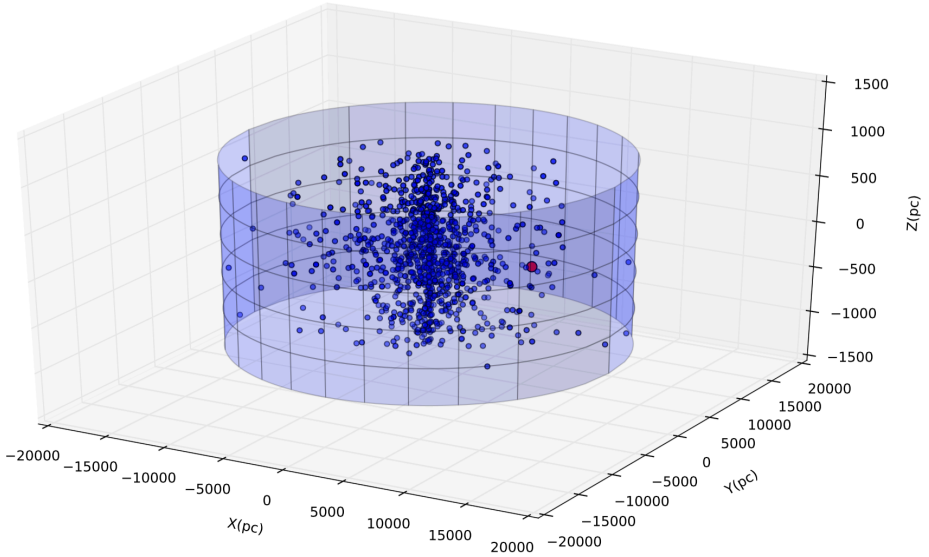
66 MSPs with distance estimates and not in globular clusters

Accounting for completeness fraction in LAT detection of Galactic millisecond pulsars

Detected MSPs are nearby:

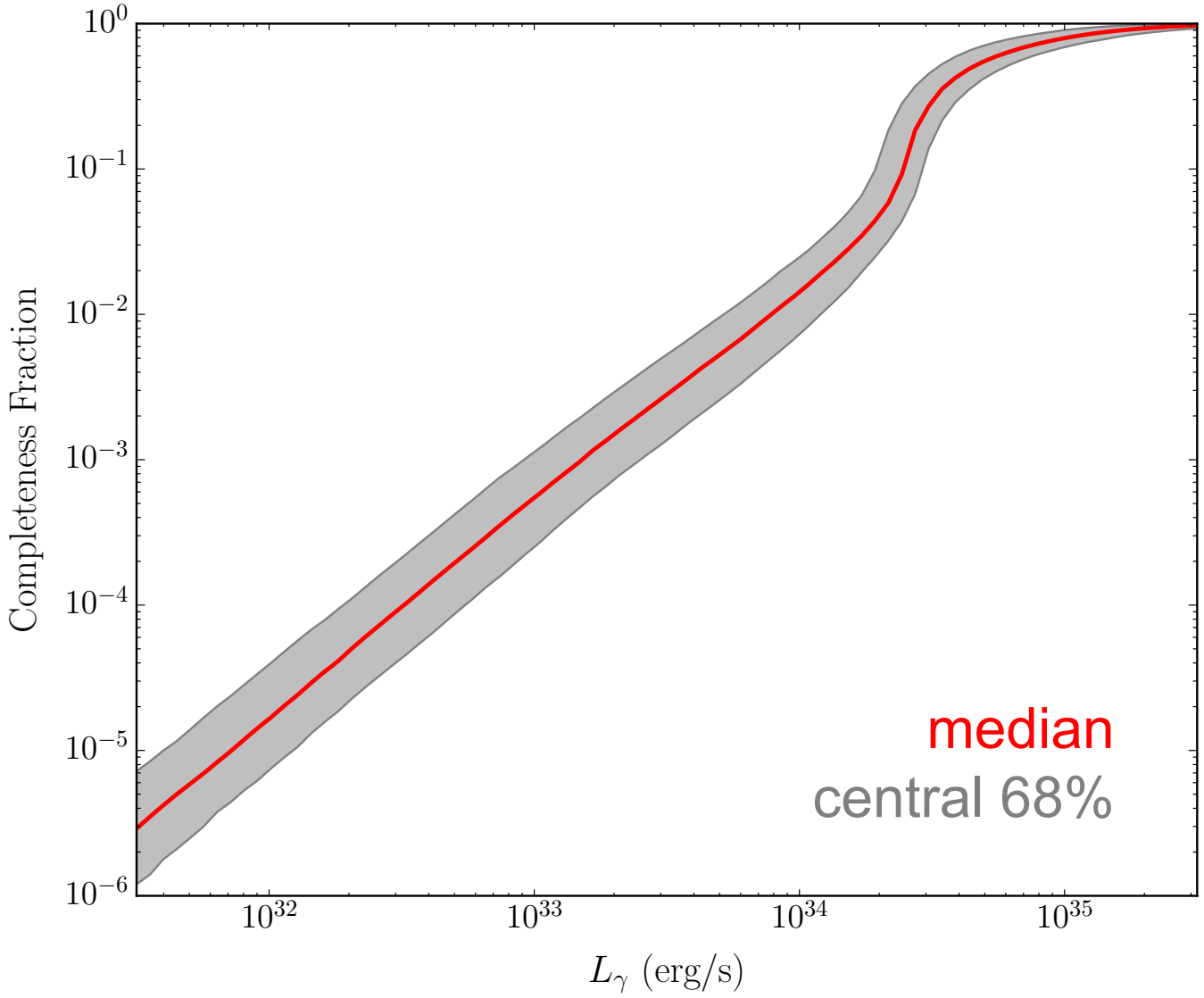


Monte Carlo of true distribution:

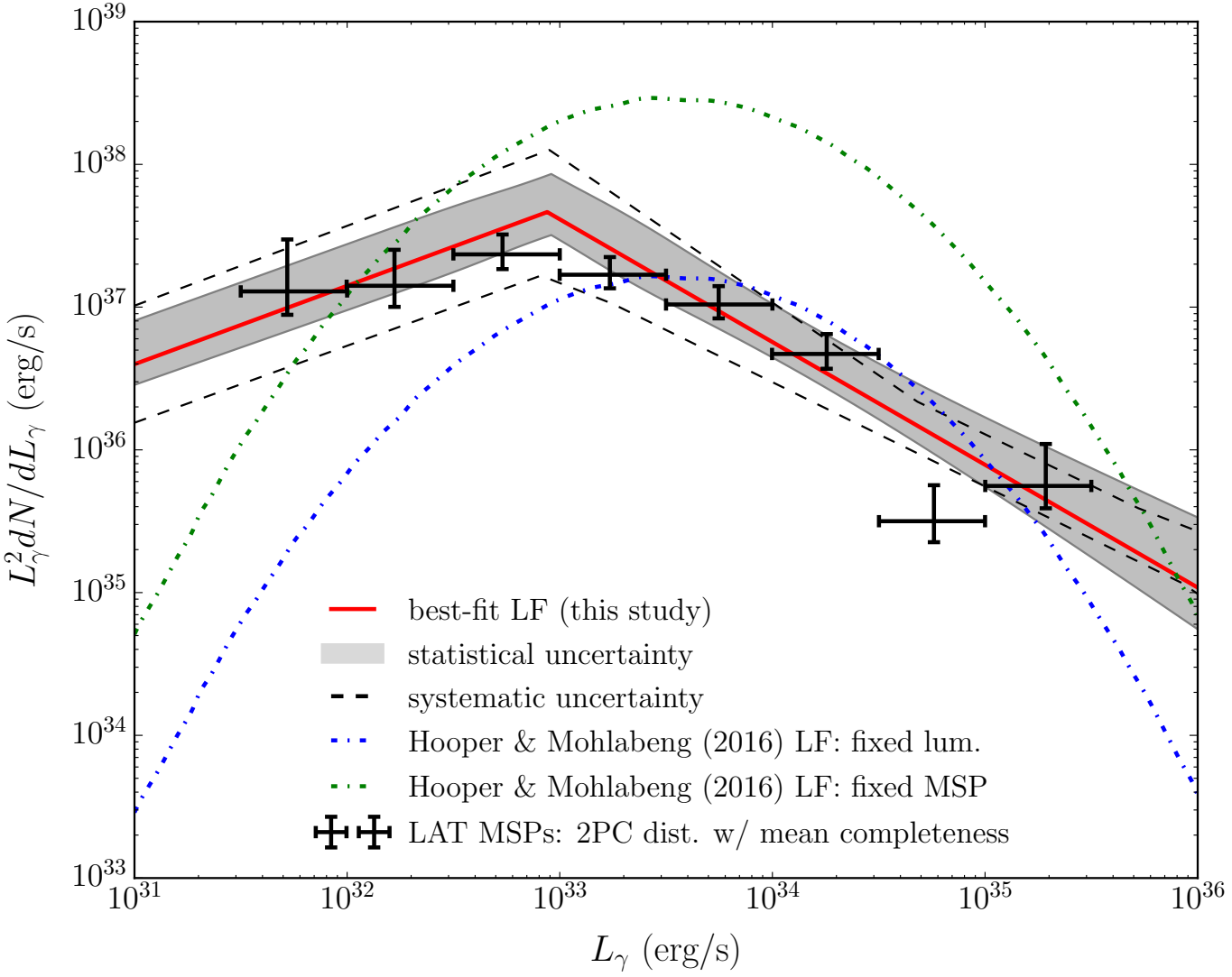


- Model density of Milky Way MSPs as exponential in R and z
- Scale height z_0 = 0.6 (+0.6, -0.3) kpc
- Scale radius R_0 = 3 (+3, -1) kpc
- Generate MSPs according to spatial model and determine which fraction would be detected by LAT
- Repeat for many spatial models according to uncertainty in (z_0, R_0)

Calculated completeness fraction for LAT millisecond pulsar detection



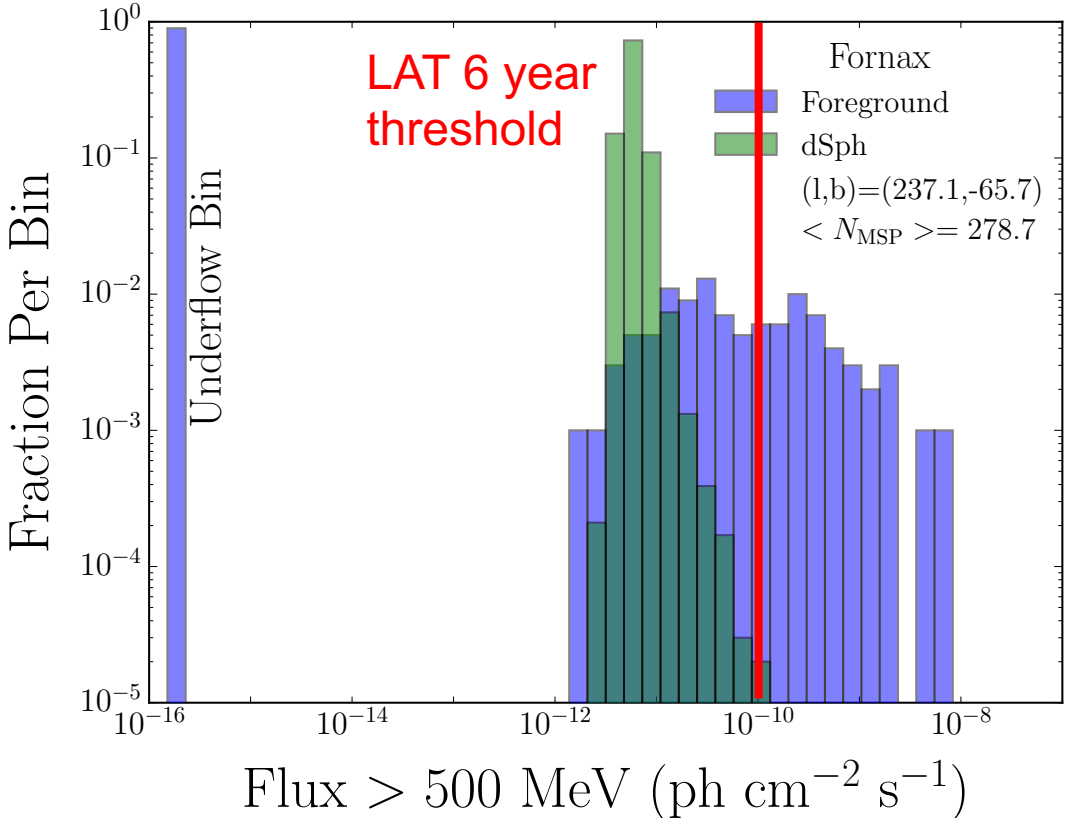
Accounting for completeness fraction to determine luminosity function for Milky Way stellar mass



What about the chance occurrence of a foreground MSP along the line of sight to a dwarf galaxy?

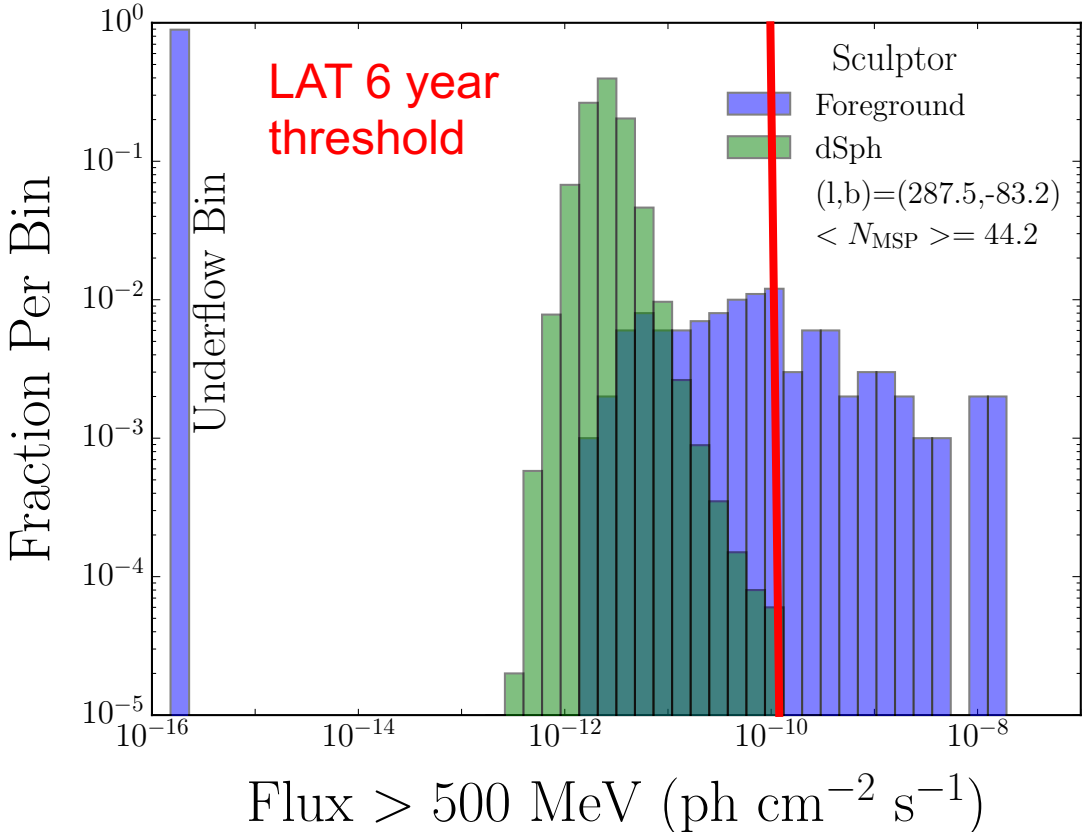
- Estimated using the same spatial distribution and Milky Way luminosity function
- Used Monte Carlo to determine probability of one MSP lying along line of sight, and if it occurs what is the PDF for its flux
- Most often there is no MSP along line of sight
- When there is one, it is typically brighter than MSP emission from dwarf

Results: Fornax



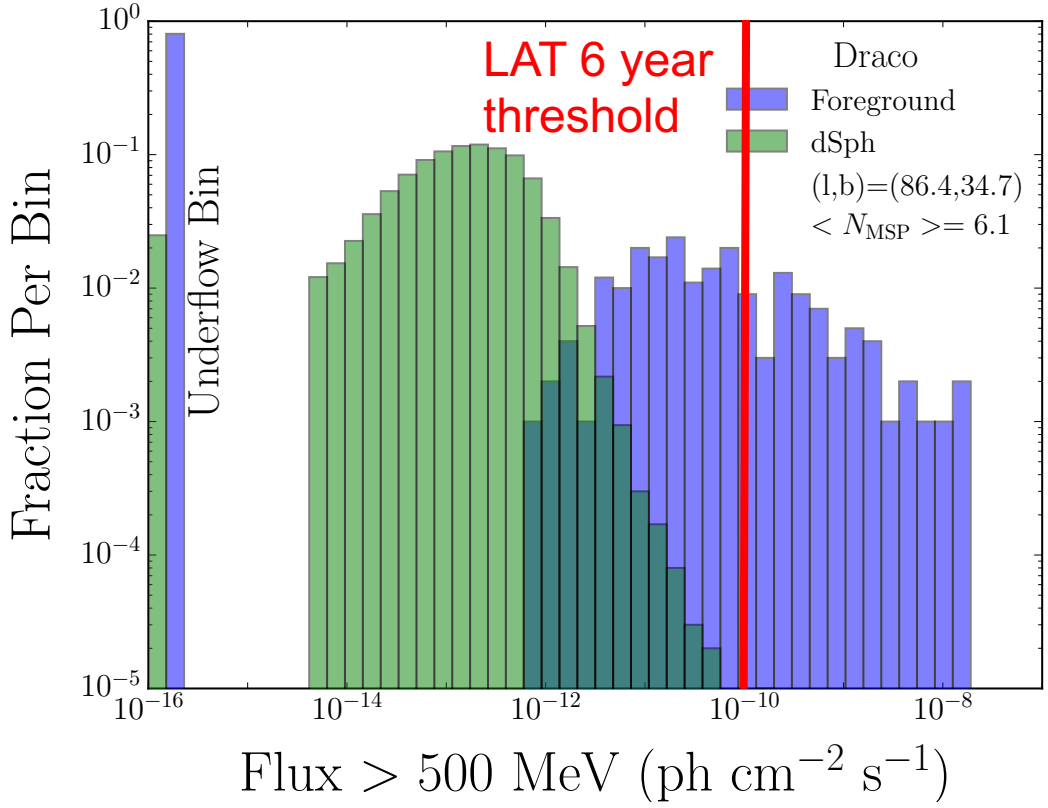
- Underflow bin: no foreground MSP
- Expect on average ~300 MSPs with luminosity above $10^{31.5}$ erg/s
- Brightest expected MSP flux among all dwarfs investigated
- Still below current LAT sensitivity and Galactic center DM model prediction
- Very small probability of a foreground source, but if there is one it is likely to be brighter than MSP signal from Fornax

Results: Sculptor



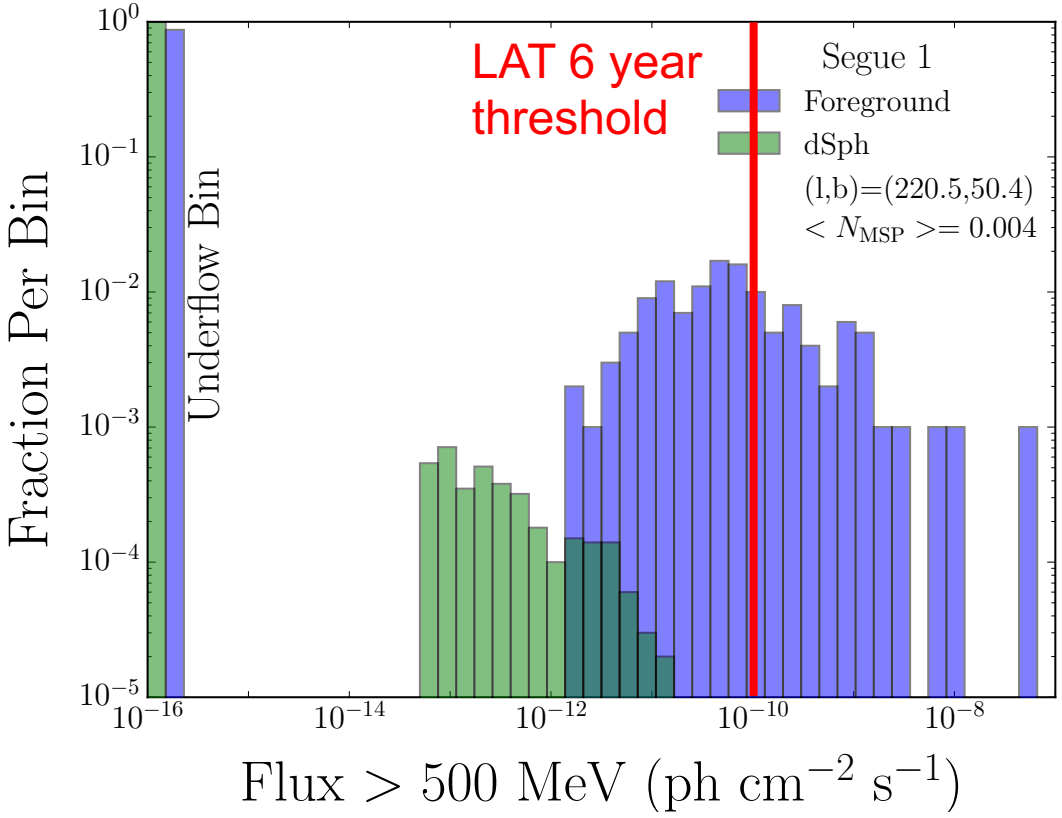
- Underflow bin: probability of there being no foreground MSP
- Expect on average ~40 MSPs with luminosity above $10^{31.5}$ erg/s in Sculptor
- Very small probability of a foreground source, but if there is one it is likely to be brighter than MSP signal from Sculptor

Results: Draco



- Underflow bin: probability of there being no foreground MSP (or MSP in dSph)
- Expect on average ~6 MSPs with luminosity above $10^{31.5}$ erg/s in Draco
- Moderate Poisson probability of zero MSPs in Draco
- Very small probability of a foreground source, but if there is one it is likely to be brighter than MSP signal from Fornax

Results: Segue 1

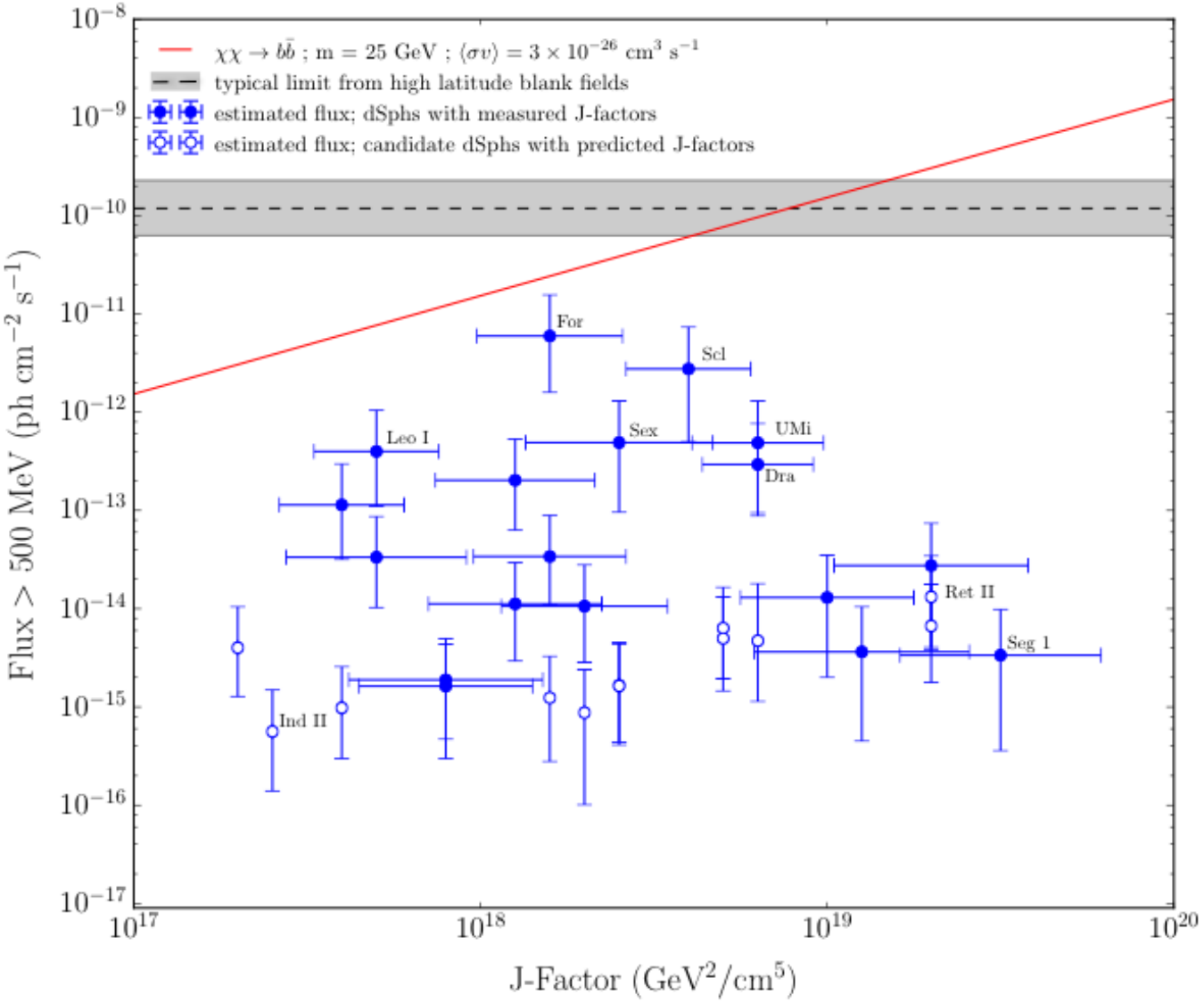


- Underflow bin: probability of there being no foreground MSP (or MSP in dSph)
- Expect on average 0.004 MSPs with luminosity above $10^{31.5}$ erg/s in Segue 1
- Most likely to have zero MSPs above 10^{31} erg/s

Calculated MSP flux for 30 individual dwarf galaxies/candidates with good stellar mass estimates

Galaxy	D(kpc)	$\log_{10}(M_*/M_\odot)$	Flux > 500 MeV (ph cm^{-2} s^{-1})						$\log_{10}\left(\mathrm{J}\left[\frac{\mathrm{GeV}^2}{\mathrm{cm}^5}\right]\right)^{\mathrm{a}}$	Ref.
			Mean	Stat.	Syst.	Pois.	Total			
Segue I	23.0	$2.53^{+0.38}_{-0.20}$	3.36	$^{+1.42}_{-0.93}$	$^{+5.16}_{-2.01}$	$^{+2.26}_{-1.29}$	$^{+6.51}_{-3.00}$	$\times10^{-15}$	19.5 ± 0.29	1,5
Tucana III	25.0	$2.90^{+0.05}_{-0.05}$	6.68	$^{+2.81}_{-1.85}$	$^{+10.2}_{-3.99}$	$^{+3.11}_{-2.04}$	$^{+11.1}_{-4.91}$	$\times10^{-15}$	19.3	4
Ursa Major II	32.0	$3.73^{+0.23}_{-0.23}$	2.75	$^{+1.16}_{-0.76}$	$^{+4.22}_{-1.65}$	$^{+0.58}_{-0.43}$	$^{+4.65}_{-2.37}$	$\times10^{-14}$	19.3 ± 0.28	2,5
Reticulum II	32.0	$3.41^{+0.30}_{-0.03}$	1.32	$^{+0.56}_{-0.37}$	$^{+2.02}_{-0.79}$	$^{+0.37}_{-0.27}$	$^{+2.13}_{-0.91}$	$\times10^{-14}$	19.3	3,6
Willman I	38.0	$3.00^{+0.39}_{-0.22}$	3.64	$^{+1.53}_{-1.01}$	$^{+5.58}_{-2.17}$	$^{+1.56}_{-1.02}$	$^{+6.82}_{-3.19}$	$\times10^{-15}$	19.1 ± 0.31	1,5
Coma Berenices	44.0	$3.68^{+0.22}_{-0.22}$	1.30	$^{+0.55}_{-0.36}$	$^{+1.99}_{-0.78}$	$^{+0.28}_{-0.21}$	$^{+2.19}_{-1.10}$	$\times10^{-14}$	19.0 ± 0.25	2,5
Tucana IV	48.0	$3.34^{+0.08}_{-0.06}$	4.99	$^{+2.10}_{-1.38}$	$^{+7.65}_{-2.98}$	$^{+1.51}_{-1.08}$	$^{+8.13}_{-3.53}$	$\times10^{-15}$	18.7	4
Grus II	53.0	$3.53^{+0.04}_{-0.05}$	6.34	$^{+2.67}_{-1.75}$	$^{+9.72}_{-3.79}$	$^{+1.61}_{-1.17}$	$^{+10.2}_{-4.40}$	$\times10^{-15}$	18.7	4
Tucana II	58.0	$3.48^{+1.01}_{-0.14}$	4.72	$^{+1.99}_{-1.31}$	$^{+7.23}_{-2.82}$	$^{+1.24}_{-0.92}$	$^{+13.3}_{-3.58}$	$\times10^{-15}$	18.8	3,6
Bootes I	66.0	$4.45^{+0.09}_{-0.06}$	3.40	$^{+1.43}_{-0.94}$	$^{+5.21}_{-2.03}$	$^{+0.36}_{-0.27}$	$^{+5.46}_{-2.30}$	$\times10^{-14}$	18.2 ± 0.22	1,5
Indus I	69.0	$2.90^{+0.22}_{-0.22}$	8.76	$^{+3.69}_{-2.43}$	$^{+13.4}_{-5.24}$	$^{+4.08}_{-2.63}$	$^{+15.2}_{-7.75}$	$\times10^{-16}$	18.3	3,6
Ursa Minor	76.0	$5.73^{+0.20}_{-0.20}$	4.88	$^{+2.06}_{-1.35}$	$^{+7.49}_{-2.92}$	$^{+0.14}_{-0.11}$	$^{+8.09}_{-3.93}$	$\times10^{-13}$	18.8 ± 0.19	2,5
Draco	76.0	$5.51^{+0.10}_{-0.10}$	2.94	$^{+1.24}_{-0.81}$	$^{+4.51}_{-1.76}$	$^{+0.10}_{-0.09}$	$^{+4.73}_{-2.06}$	$\times10^{-13}$	18.8 ± 0.16	2,5
Sculptor	86.0	$6.59^{+0.21}_{-0.21}$	2.76	$^{+1.16}_{-0.76}$	$^{+4.24}_{-1.65}$	$^{+0.03}_{-0.03}$	$^{+4.59}_{-2.26}$	$\times10^{-12}$	18.6 ± 0.18	2,5
Sextans	86.0	$5.84^{+0.20}_{-0.20}$	4.91	$^{+2.07}_{-1.36}$	$^{+7.53}_{-2.94}$	$^{+0.12}_{-0.10}$	$^{+8.14}_{-3.95}$	$\times10^{-13}$	18.4 ± 0.27	2,5
Horologium I	87.0	$3.38^{+0.25}_{-0.13}$	1.66	$^{+0.70}_{-0.46}$	$^{+2.55}_{-1.00}$	$^{+0.50}_{-0.35}$	$^{+2.86}_{-1.25}$	$\times10^{-15}$	18.4	3,6
Reticulum III	92.0	$3.30^{+0.13}_{-0.15}$	1.24	$^{+0.52}_{-0.34}$	$^{+1.90}_{-0.74}$	$^{+0.40}_{-0.27}$	$^{+2.04}_{-0.96}$	$\times10^{-15}$	18.2	4
Phoenix II	95.0	$3.45^{+0.19}_{-0.11}$	1.64	$^{+0.69}_{-0.45}$	$^{+2.52}_{-0.98}$	$^{+0.46}_{-0.32}$	$^{+2.74}_{-1.20}$	$\times10^{-15}$	18.4	3,6
Ursa Major I	97.0	$4.28^{+0.13}_{-0.13}$	1.06	$^{+0.45}_{-0.29}$	$^{+1.63}_{-0.64}$	$^{+0.13}_{-0.10}$	$^{+1.73}_{-0.78}$	$\times10^{-14}$	18.3 ± 0.24	2,5
Carina	105.0	$5.63^{+0.11}_{-0.09}$	2.03	$^{+0.86}_{-0.56}$	$^{+3.12}_{-1.22}$	$^{+0.06}_{-0.05}$	$^{+3.27}_{-1.40}$	$\times10^{-13}$	18.1 ± 0.23	1,5
Hercules	132.0	$4.57^{+0.14}_{-0.14}$	1.12	$^{+0.47}_{-0.31}$	$^{+1.72}_{-0.67}$	$^{+0.10}_{-0.08}$	$^{+1.82}_{-0.83}$	$\times10^{-14}$	18.1 ± 0.25	2,5
Fornax	147.0	$7.39^{+0.14}_{-0.14}$	5.97	$^{+2.51}_{-1.65}$	$^{+9.15}_{-3.57}$	$^{+0.03}_{-0.03}$	$^{+9.68}_{-4.38}$	$\times10^{-12}$	18.2 ± 0.21	2,5
Leo IV	154.0	$3.93^{+0.15}_{-0.15}$	1.89	$^{+0.79}_{-0.52}$	$^{+2.89}_{-1.13}$	$^{+0.32}_{-0.24}$	$^{+3.08}_{-1.42}$	$\times10^{-15}$	17.9 ± 0.28	2,5
Canes Venatici II	160.0	$3.90^{+0.20}_{-0.20}$	1.63	$^{+0.69}_{-0.45}$	$^{+2.50}_{-0.97}$	$^{+0.29}_{-0.22}$	$^{+2.71}_{-1.33}$	$\times10^{-15}$	17.9 ± 0.25	2,5
Columba I	182.0	$3.79^{+0.13}_{-0.07}$	9.78	$^{+4.12}_{-2.71}$	$^{+15.0}_{-5.85}$	$^{+1.93}_{-1.43}$	$^{+15.9}_{-6.78}$	$\times10^{-16}$	17.6	4
Indus II	214.0	$3.69^{+0.16}_{-0.14}$	5.62	$^{+2.37}_{-1.56}$	$^{+8.61}_{-3.36}$	$^{+1.21}_{-0.89}$	$^{+9.25}_{-4.22}$	$\times10^{-16}$	17.4	4
Canes Venatici I	218.0	$5.48^{+0.09}_{-0.09}$	3.34	$^{+1.41}_{-0.92}$	$^{+5.12}_{-2.00}$	$^{+0.12}_{-0.10}$	$^{+5.35}_{-2.31}$	$\times10^{-14}$	17.7 ± 0.26	2,5

Calculated MSP flux for 30 different dwarf galaxies compared to point source sensitivity and DM model

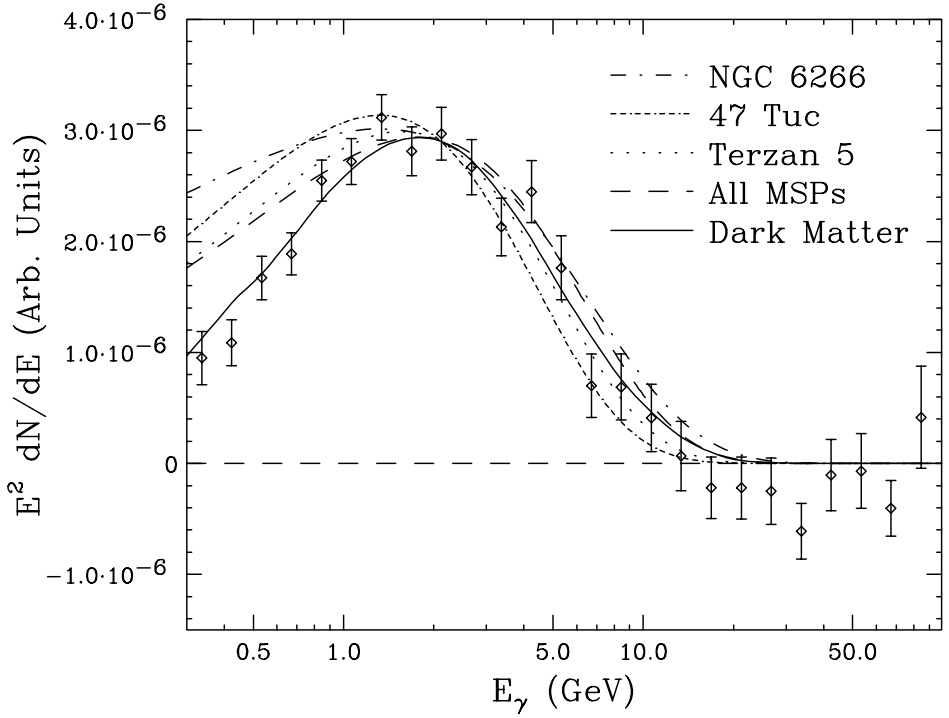


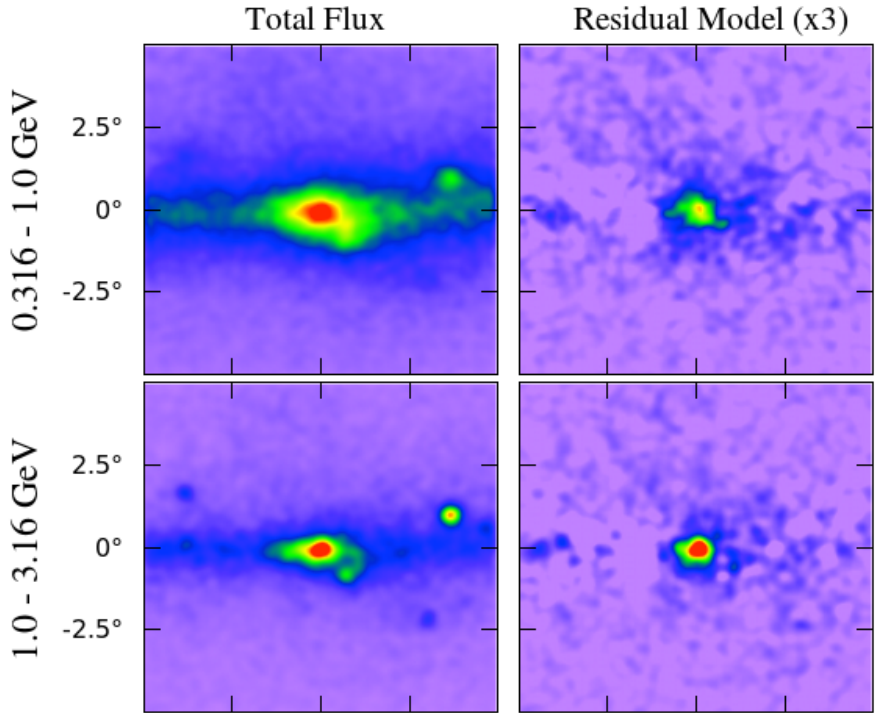
Conclusion

- Astrophysical backgrounds for dark matter signals from dwarf galaxies are said to be “negligible”
- For the first time we have systematically calculated the expected background
- The largest contribution is expected to be from millisecond pulsars
- We determined the MSP luminosity function using Milky Way MSPs and used it to calculate the expected flux from individual dwarf galaxies
- The largest expectations are an order of magnitude below current LAT sensitivity, and those from ultra-faints are even lower
- An even smaller contribution is expected from diffuse cosmic-ray interaction within each dwarf galaxy
- See arXiv:1607.06390

Additional slides

The GeV excess from the Galactic center

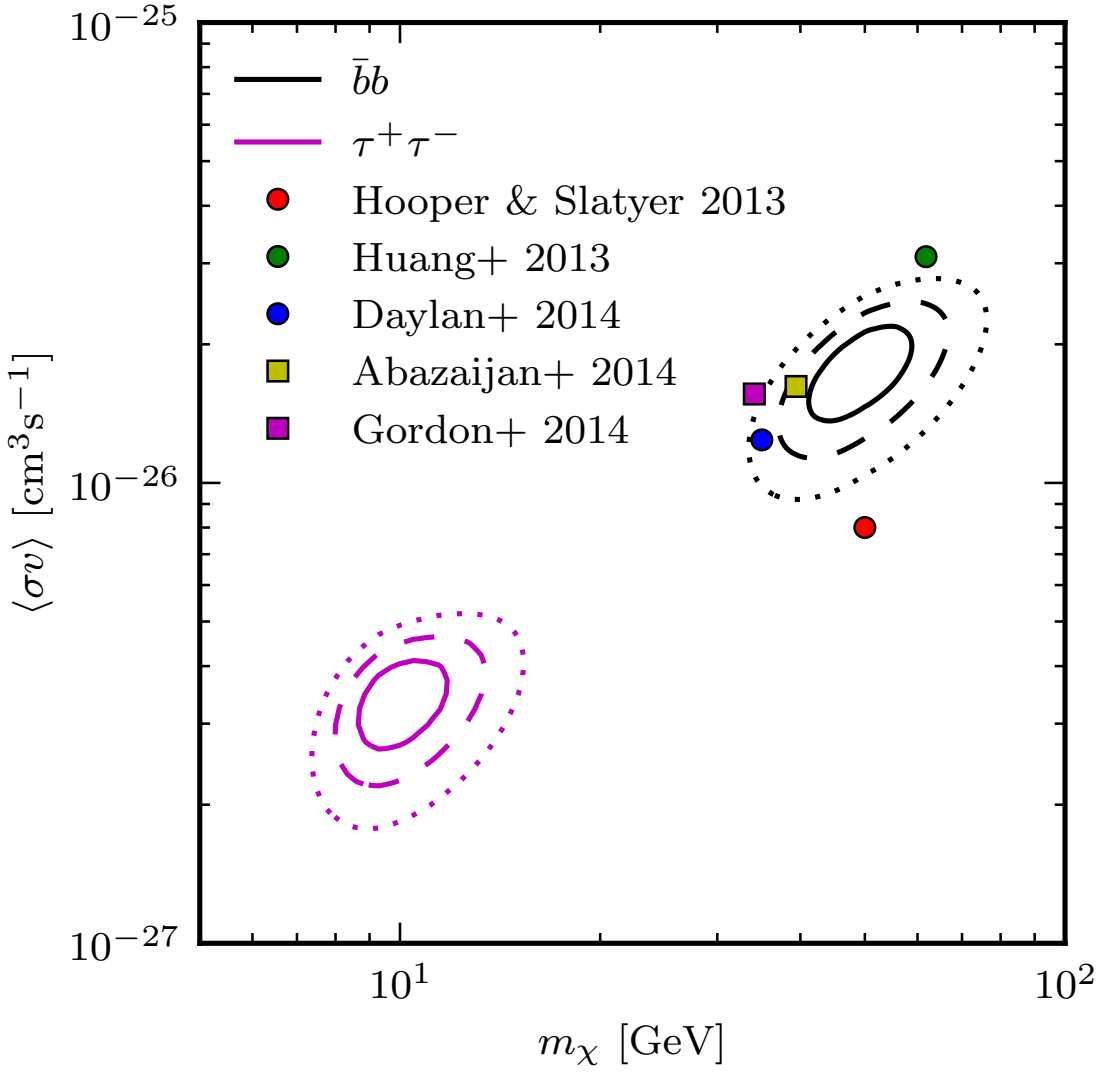




Daylan et al. 2016

Dark matter? Millisecond pulsars? Something else?

Dark matter models to explain Galactic Center excess

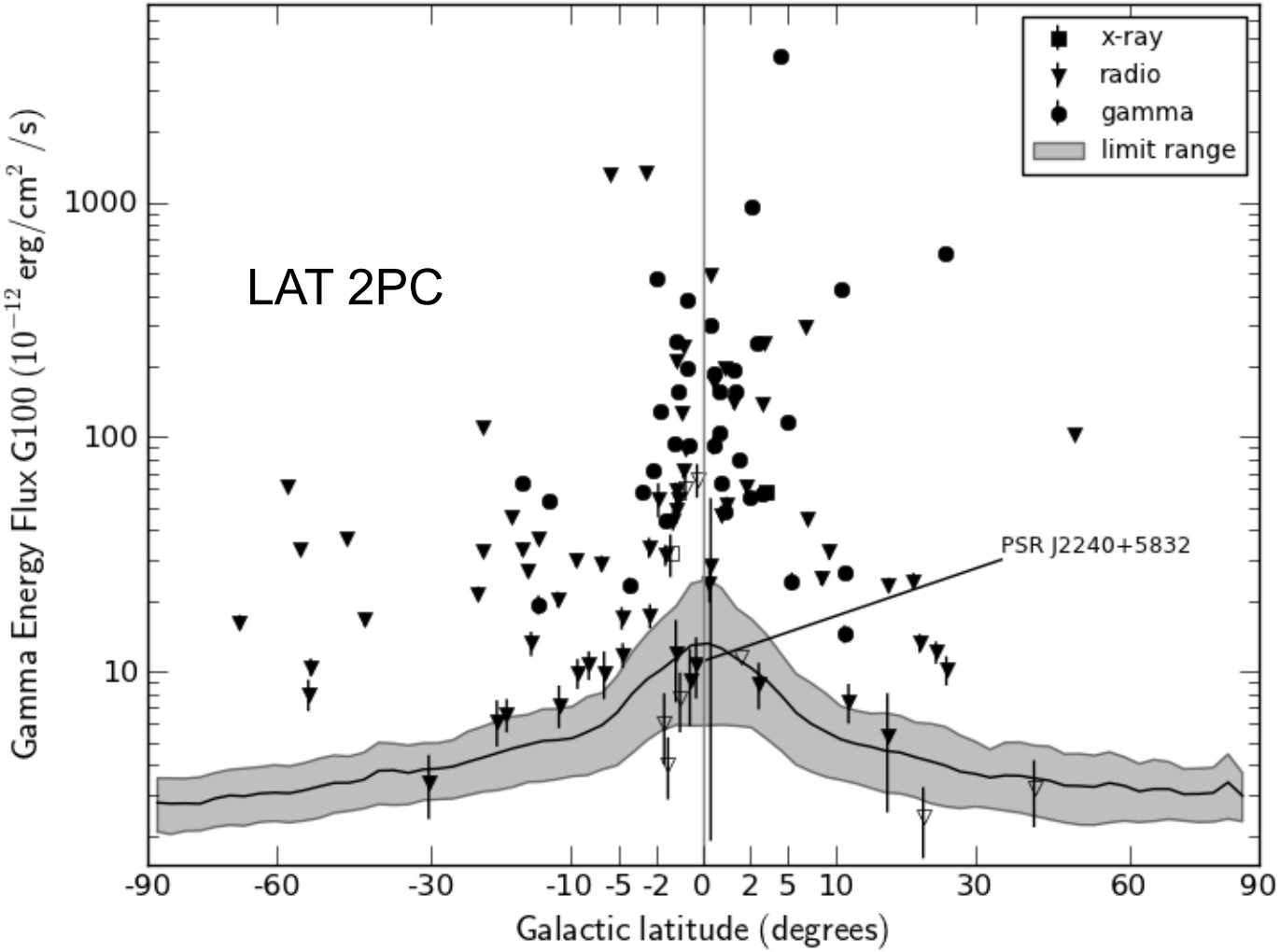


Calore, Cholis, and Weniger JCAP03 (2015) 038

Contributions to uncertainty in MSP flux from each dSph

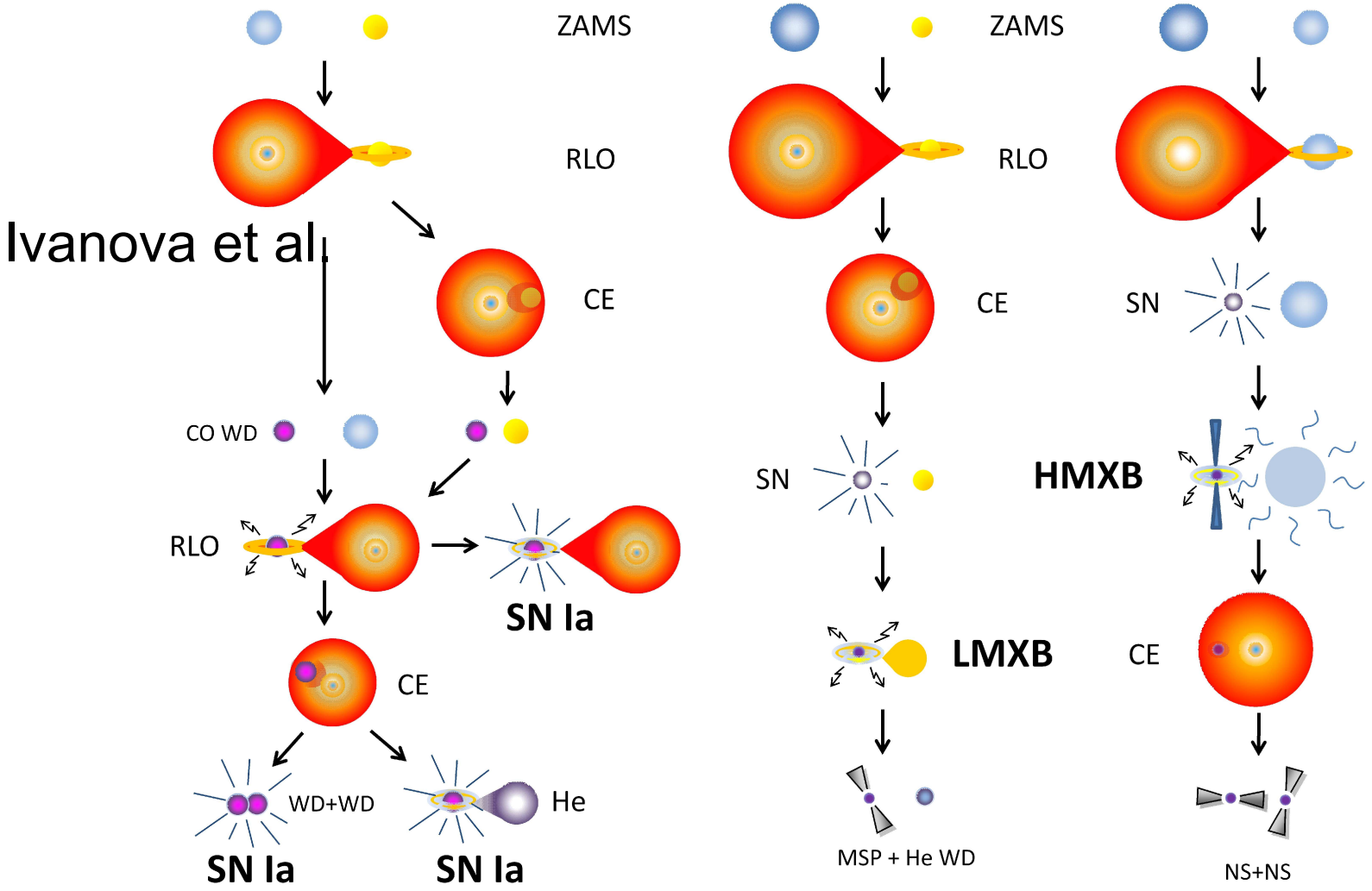
1. Statistical uncertainty in luminosity function from finite number of LAT MSPs
2. Systematic uncertainty in MSP luminosity due to distance uncertainty
3. Systematic uncertainty in incompleteness correction due to spatial model and effective LAT threshold
4. Poisson fluctuations in number of MSP per dSph
5. dSph stellar mass uncertainty

LAT MSP detection threshold



For incompleteness correction systematics, we vary the effective threshold across the limit range (10% to 90% three-year mean sensitivity)

Formation of X-ray binaries and millisecond pulsars

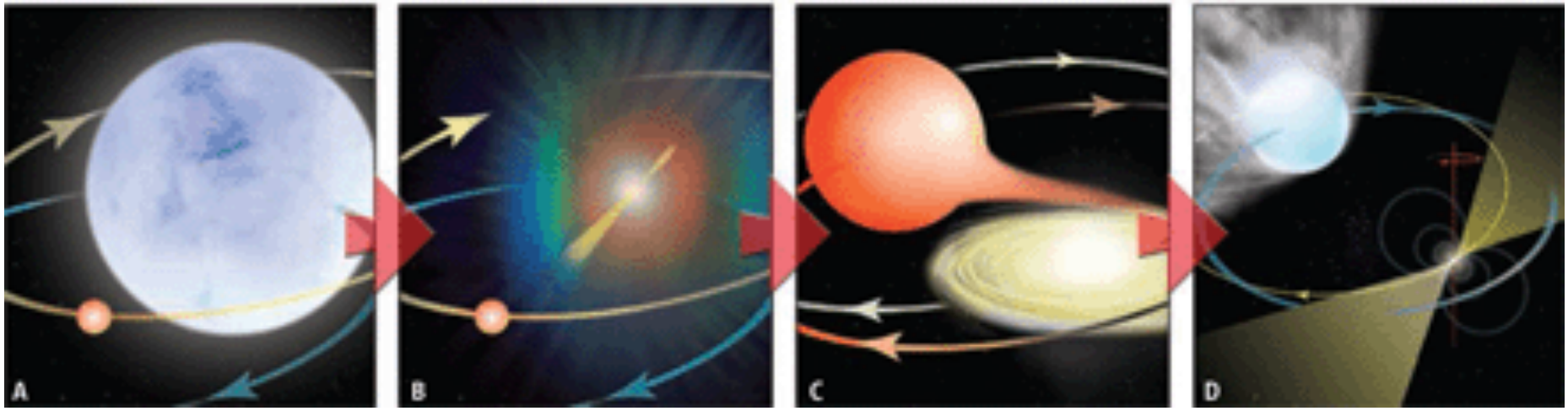


Low-mass X-ray binaries (LMXB)

- 5 detected in Sculptor with deep Chandra search
- Not detected in other dwarf galaxies
- LMXB are the predecessor phase to MSP and are shorter lived (0.1-1 Gyr)
- NS spin period in some LMXB measured to be millisecond scale (without radio pulsations)
- LMXB number is observed to scale with stellar mass among galactic disks
- When companion has donated its envelope it becomes a white dwarf and the LMXB becomes a MSP

The “missing link” pulsar: evidence for transition from LMXB to MSP

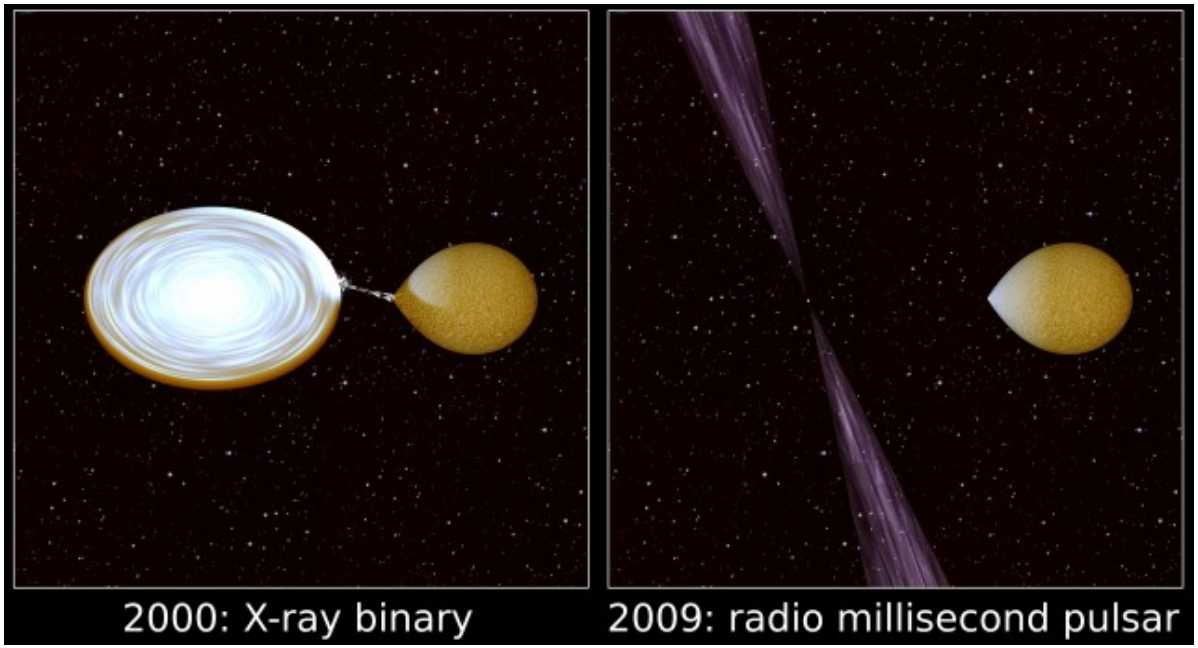
A. Archibald et al. Science 324 (2009)1411-1414



massive star and low-mass star	neutron star and low-mass star	accretion disk and low-mass star: LMXB	white dwarf and MSP

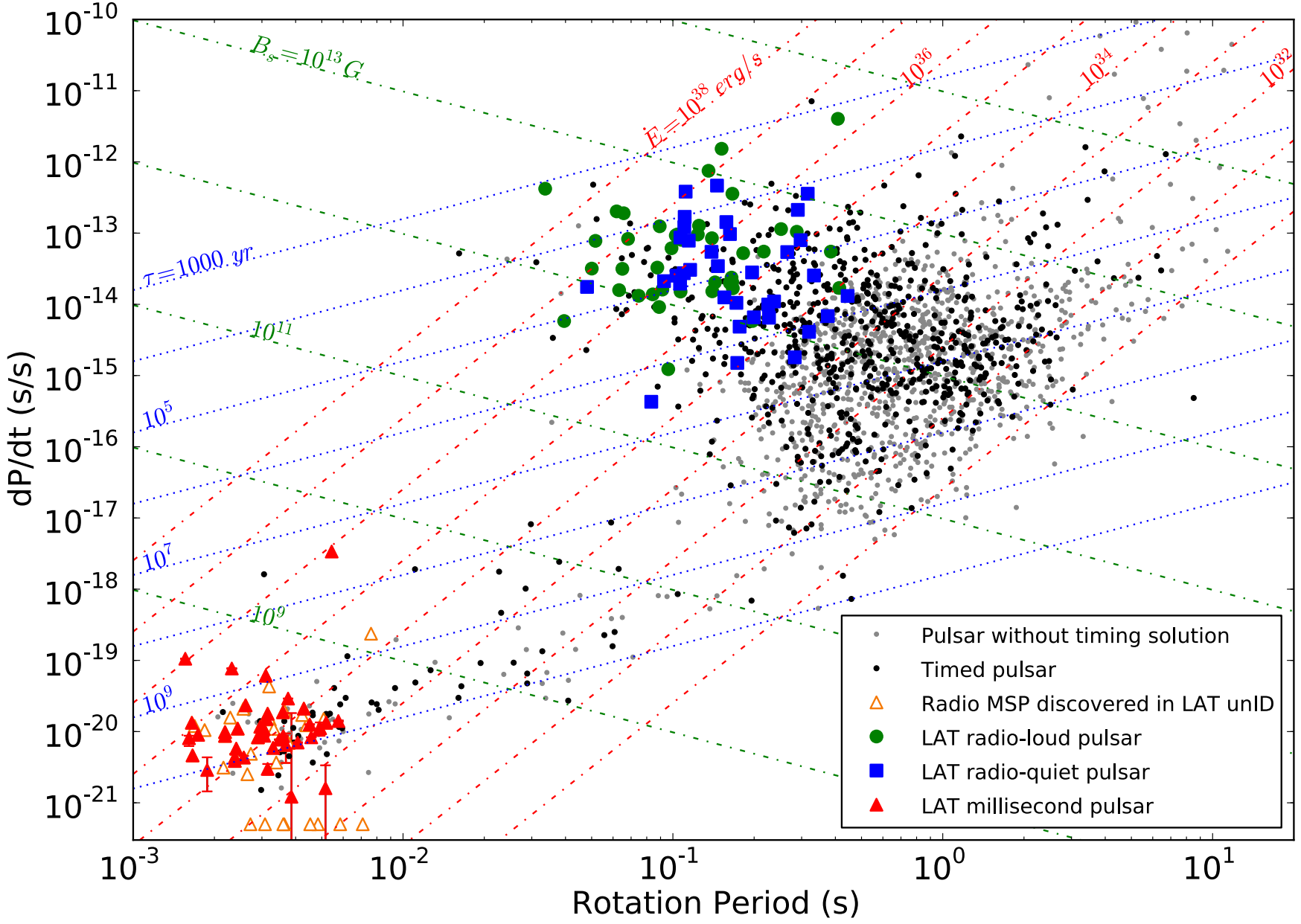
- 2000: identified as LMXB, with optically observed accretion disk
- 2009: identified as MSP, with radio pulsations and optically identified companion, no optical accretion disk

The “missing link” pulsar: evidence for transition from LMXB to MSP

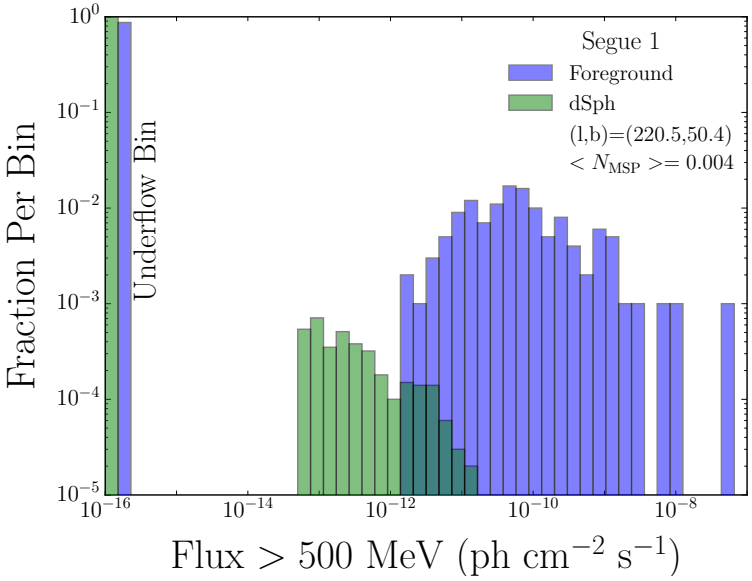


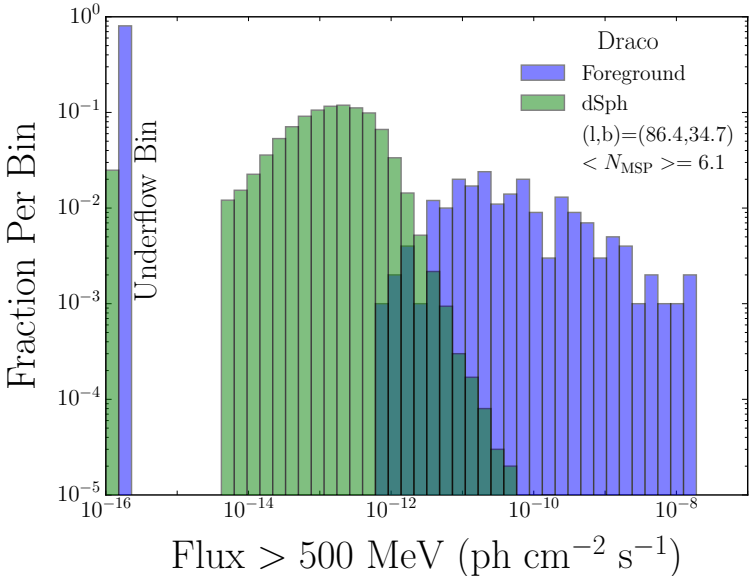
A. Archibald et al. Science 324 (2009)1411-1414

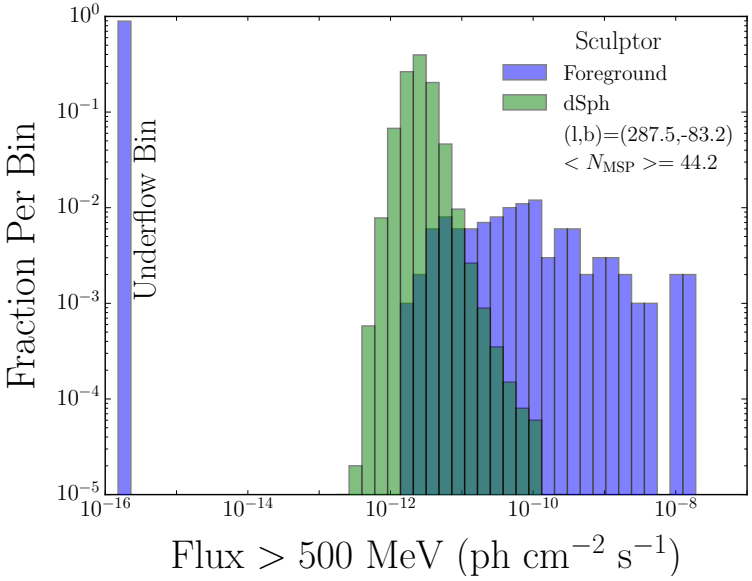
LAT second pulsar catalog (2PC)

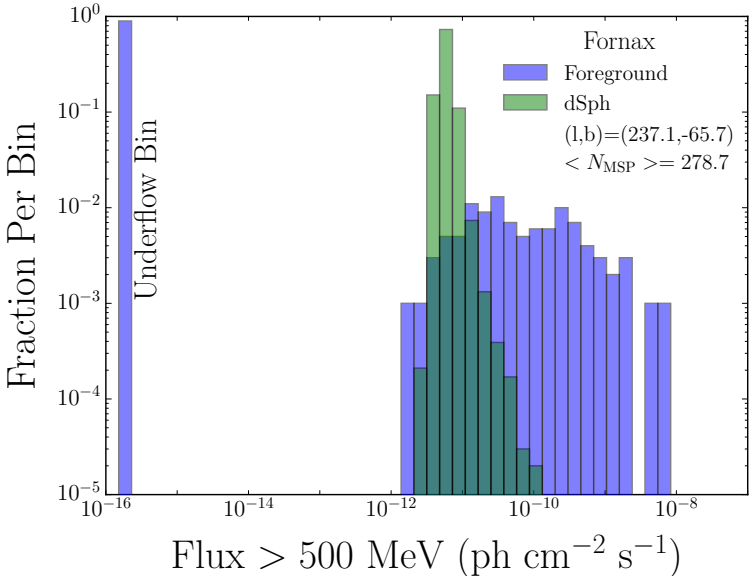


Results for four example dwarf galaxies









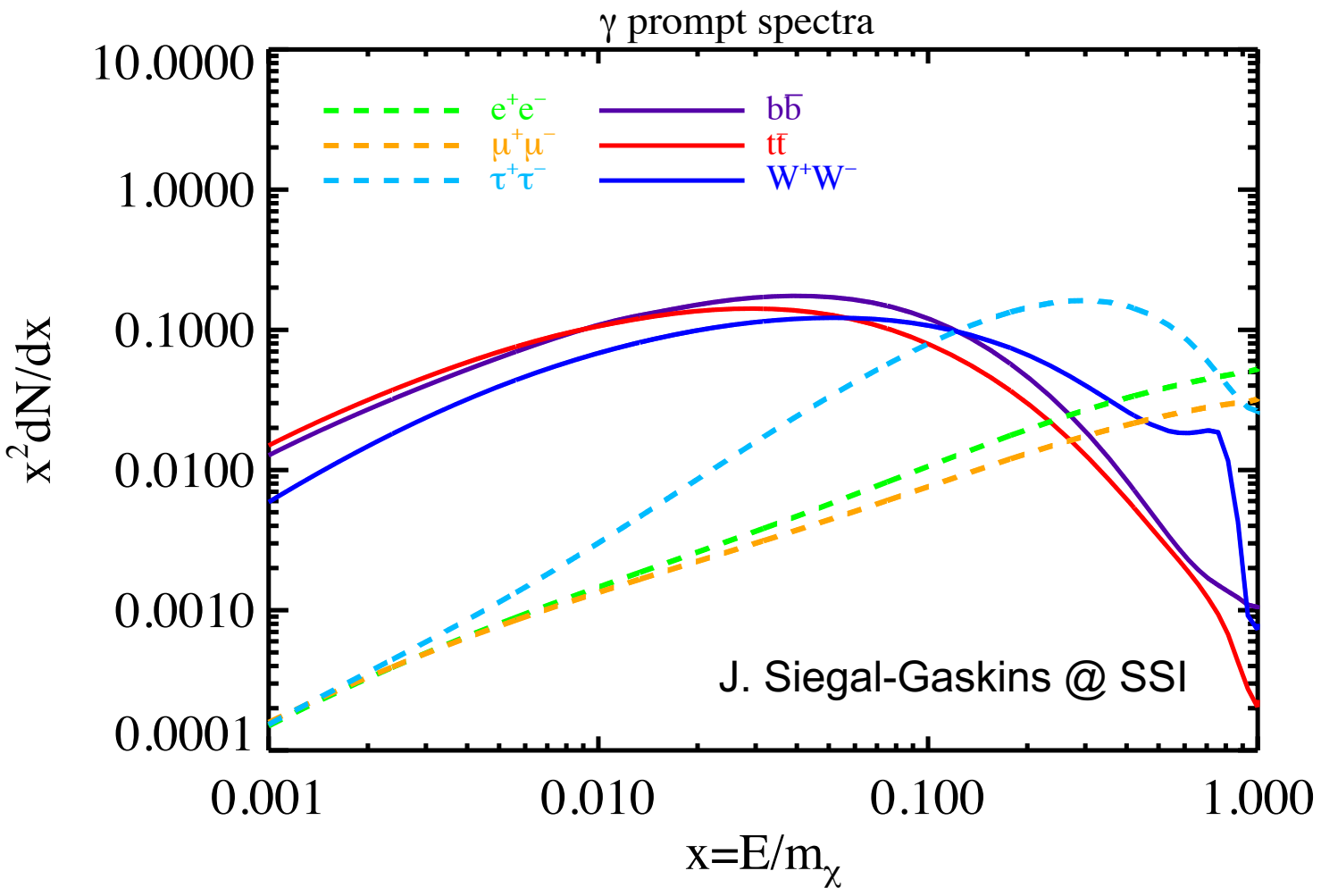
Gamma-ray background due to diffuse interaction of cosmic rays within dwarf galaxies

- Uncertain CR acceleration
- Uncertain CR confinement
- But dSph have old stellar populations (few accelerators) and low gas content (little target material)
- Scaling from SMC (SFR 0.1 solar mass per year and gamma-ray luminosity above 0.1 GeV 10^{37} erg/s) to Fornax (SFR 10^{-4} solar mass per year), expect 10^{34} erg/s Fornax gamma-ray luminosity, comparable to predicted MSP luminosity
- But Fornax has 10^{2} times lower gas mass (relative to stellar mass) than SMC
- CR confinement time in dSph likely comparable to time between acceleration events (both ~1 Myr), so not steady state

These are conservative predictions (upper limits)

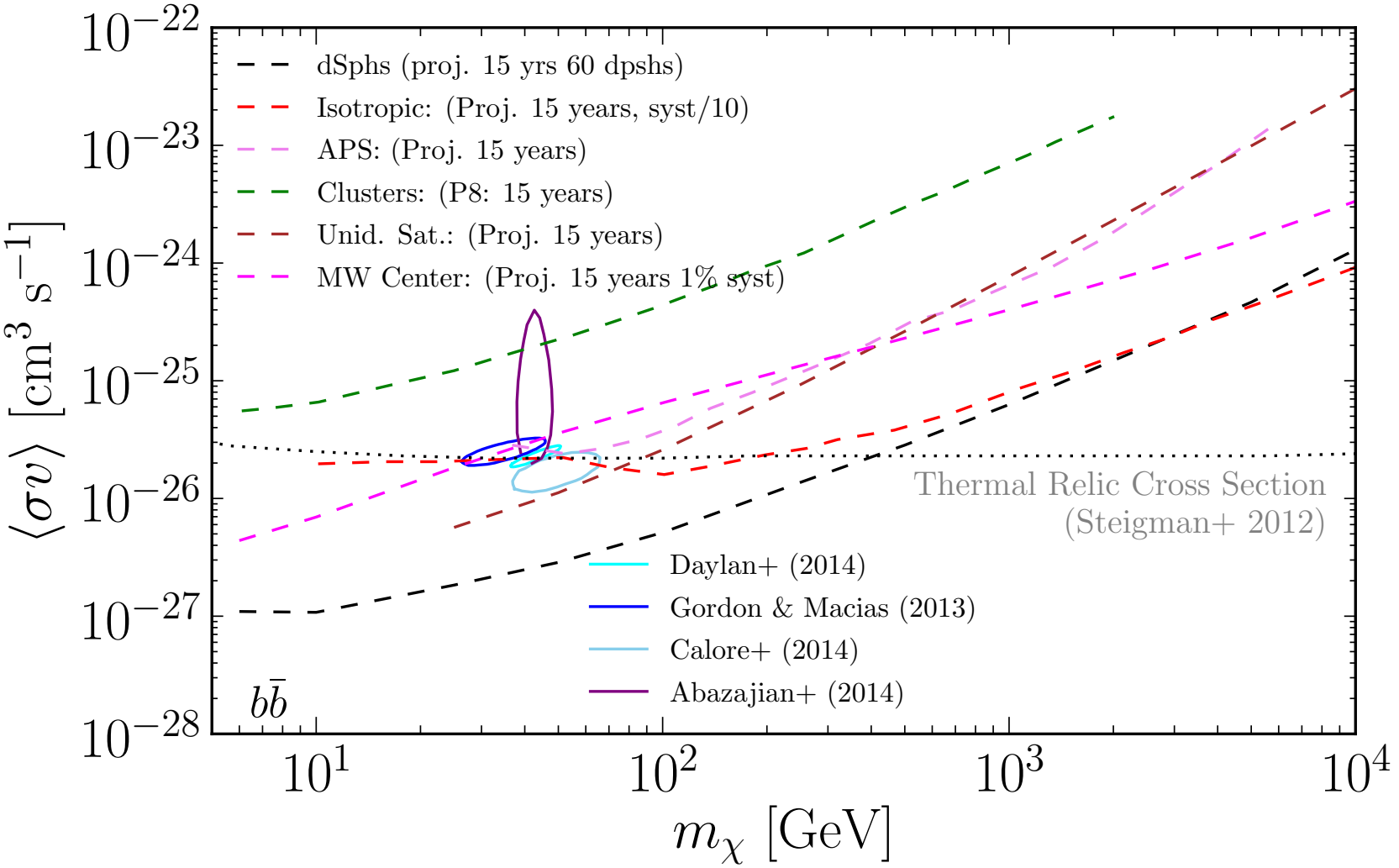
- While Milky Way star formation is still active, dSph are not: MW MSP have ~1 Gyr characteristic age, and dSph MSP likely closer to 10 Gyr
- Some MSP may have large kicks and therefore escaped the dSph or moved to its outskirts (away from the central dark matter distribution)

Gamma-ray spectrum from dark matter annihilation



Hard: e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$
Soft: $b\bar{b}$, $t\bar{t}$, W^+W^-

LAT dSph sensitivity will increase by almost an order of magnitude with 15 years of LAT data and 60 dSPphs



E. Charles et al. Phys Rep. 636 (2016) 1-46

Dwarf galaxy J factors

TABLE I. DES dSph Candidates and Estimated J-factors

Name	$(\ell,\, b)^{a}$	Distance[b]	$\log_{10}(\mathrm{Est.J})^{c}$
	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 $0.^{\circ}5$). See text for more details.

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

Fermi LAT & DES 1503.02632

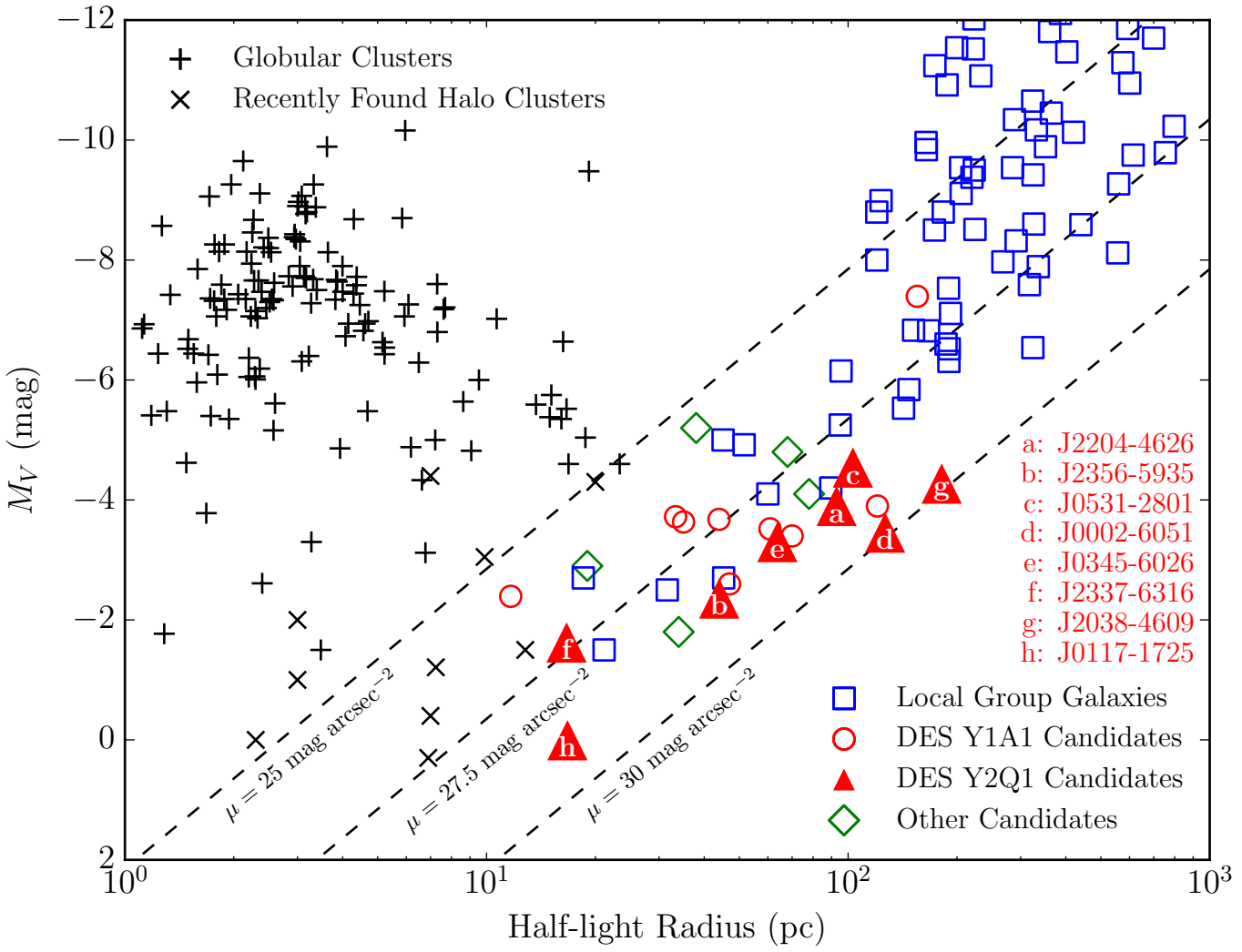
TABLE I. Properties of Milky Way dSphs.

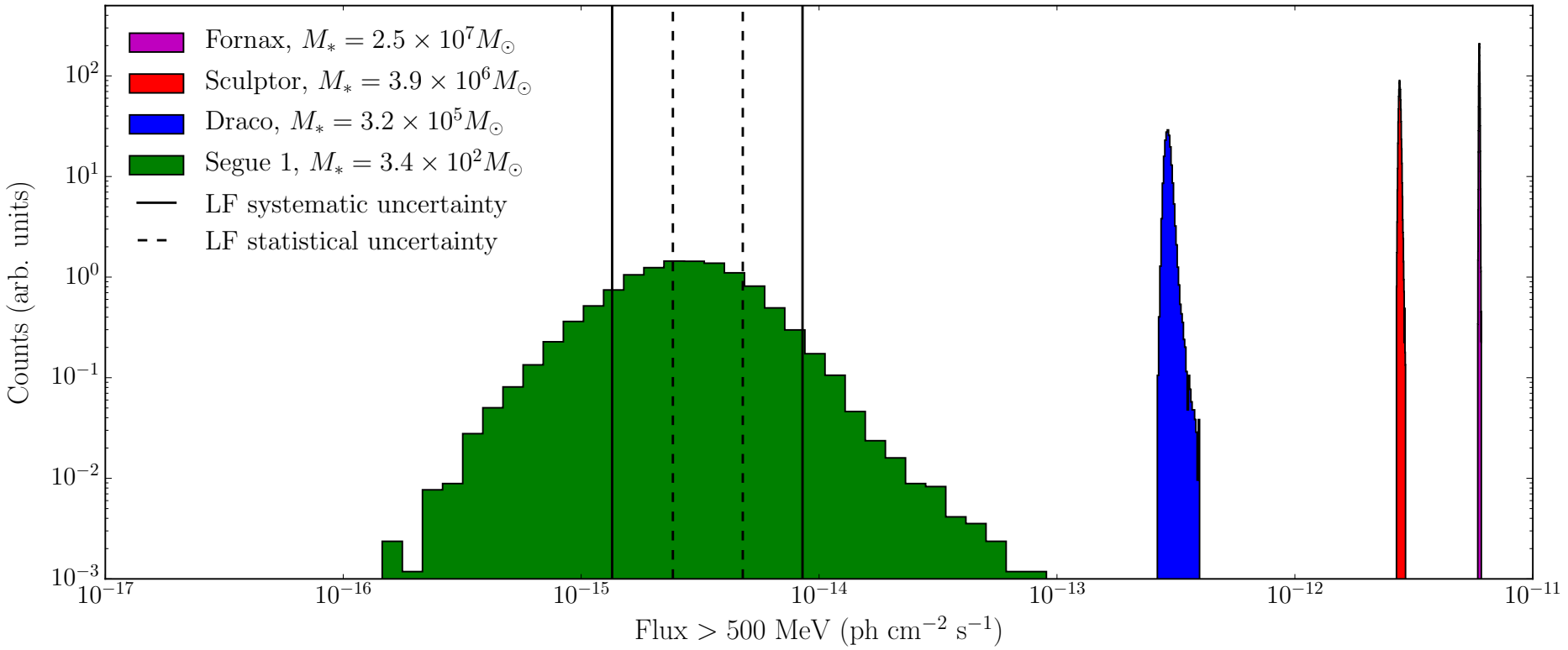
Name	ℓ^{a} (deg)	b^{a} (deg)	Distance (kpc)	$\log_{10}(J_{\mathrm{obs}})^{b}$ ($\log_{10}[\mathrm{GeV}^2\,\mathrm{cm}^{-5}]$)	Ref.
Bootes I	358.1	69.6	66	18.8 ± 0.22	[39]
Canes Venatici II	113.6	82.7	160	17.9 ± 0.25	[40]
Carina	260.1	−22.2	105	18.1 ± 0.23	[41]
Coma Berenices	241.9	83.6	44	19.0 ± 0.25	[40]
Draco	86.4	34.7	76	18.8 ± 0.16	[42]
Fornax	237.1	−65.7	147	18.2 ± 0.21	[41]
Hercules	28.7	36.9	132	18.1 ± 0.25	[40]
Leo II	220.2	67.2	233	17.6 ± 0.18	[43]
Leo IV	265.4	56.5	154	17.9 ± 0.28	[40]
Sculptor	287.5	−83.2	86	18.6 ± 0.18	[41]
Segue 1	220.5	50.4	23	19.5 ± 0.29	[44]
Sextans	243.5	42.3	86	18.4 ± 0.27	[41]
Ursa Major II	152.5	37.4	32	19.3 ± 0.28	[40]
Ursa Minor	105.0	44.8	76	18.8 ± 0.19	[42]
Willman 1	158.6	56.8	38	19.1 ± 0.31	[45]
Bootes II [c]	353.7	68.9	42	–	–
Bootes III	35.4	75.4	47	–	–
Canes Venatici I	74.3	79.8	218	17.7 ± 0.26	[40]
Canis Major	240.0	−8.0	7	–	–
Leo I	226.0	49.1	254	17.7 ± 0.18	[46]
Leo V	261.9	58.5	178	–	–
Pisces II	79.2	−47.1	182	–	–
Sagittarius	5.6	−14.2	26	–	–
Segue 2	149.4	−38.1	35	–	–
Ursa Major I	159.4	54.4	97	18.3 ± 0.24	[40]

[a] Galactic longitude and latitude.
[b] J-factors are calculated assuming an NFW density profile and integrated over a circular region with a solid angle of $\Delta\Omega \sim 2.4 \times 10^{-4}$ sr (angular radius of 0.5°).
[c] dSphs below the horizontal line are not included in the combined analysis.

Fermi LAT 1503.02641

Dwarf spheroidals vs. globular clusters



A. Drlica-Wagner et al. ApJ 813:109 (2015)

Calculated flux PDF from individual dwarf galaxies