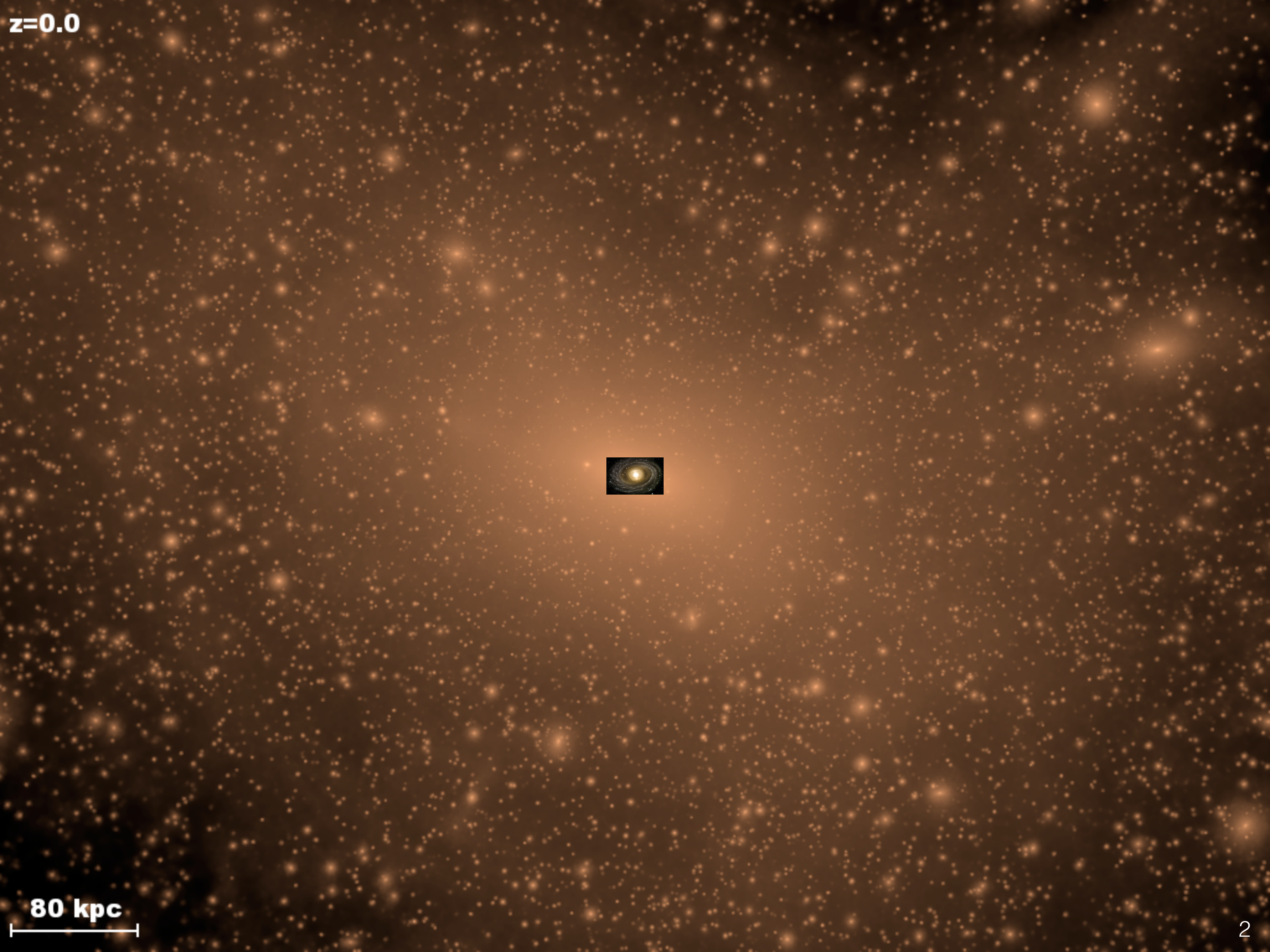
The Search for Milky Way Satellite Galaxies from Optical to Gamma-rays

Keith Bechtol

for the DES and *Fermi*-LAT Collaborations

IPA 4 May 2015

THE UNIVERSITY of WISCONSIN MADISON


z=0.0
80 kpc


z=0.0
80 kpc

z=0.0

Dwarf spheroidal galaxies (dSphs)

- ☑ Dark matter content constrained by stellar kinematics
- ☑ High mass-to-light ratio
- ☑ Close
- ☑ Astrophysically “clean”
- ☑ Ability to combine targets in a joint likelihood analysis

80 kpc

Formalism

Gamma-ray flux

$$\phi_s(\Delta\Omega) = \underbrace{\frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_{\rm DM}^2}\int_{E_{\rm min}}^{E_{\rm max}}\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}\mathrm{d}E_\gamma}_{\text{particle physics}}$$

$$\boxed{\times \underbrace{\int_{\Delta\Omega}\int_{\rm l.o.s.}\rho_{\rm DM}^2(\boldsymbol{r})\mathrm{d}l\mathrm{d}\Omega'}_{\text{J-factor}}}$$

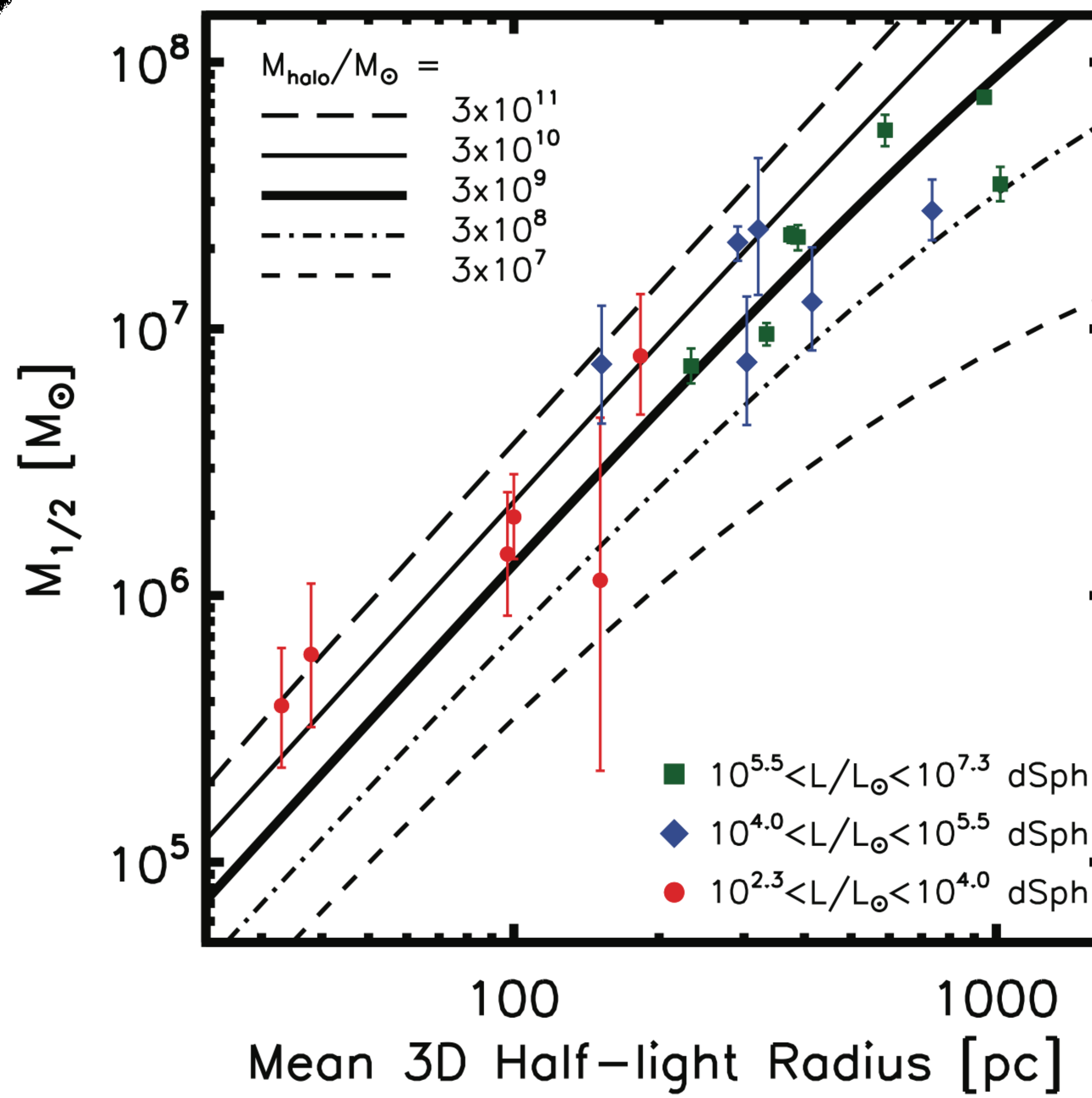
Assumed DM density profile

(e.g., NFW)

$$\rho_{\rm DM}(r) = \frac{\rho_0 r_s^3}{r(r_s+r)^2}$$

Observables

Distance, half-light radius, and enclosed mass (velocity dispersion)

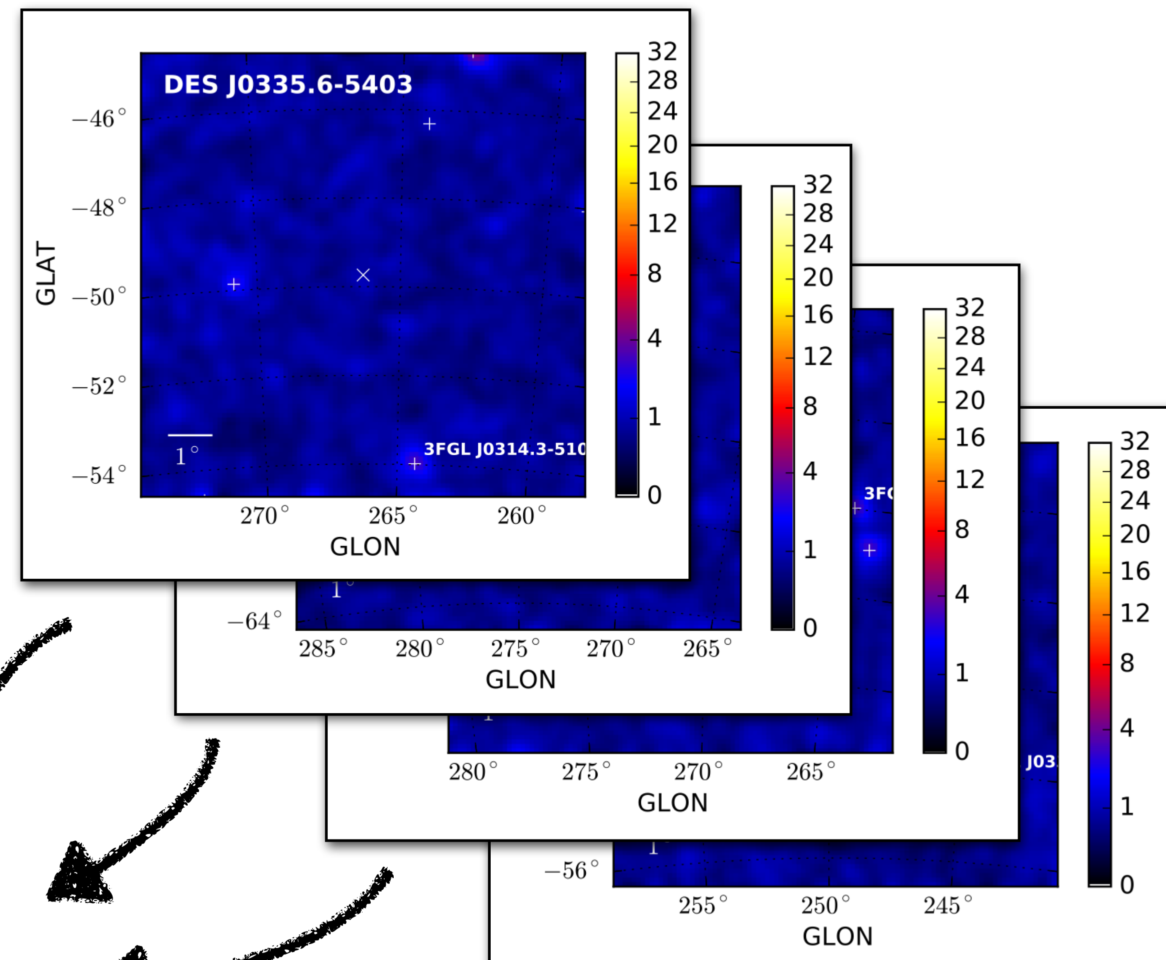


Wolf et al. 2010

Formalism

Likelihood for individual target

$$\tilde{\mathcal{L}}_i(\boldsymbol{\mu}, \boldsymbol{\theta}_i = \{\boldsymbol{\alpha}_i, J_i\} \,|\, \mathcal{D}_i) = \mathcal{L}_i(\boldsymbol{\mu}, \boldsymbol{\theta}_i \,|\, \mathcal{D}_i)\,\mathcal{L}_J(J_i \,|\, J_{\rm obs,i}, \sigma_i)$$



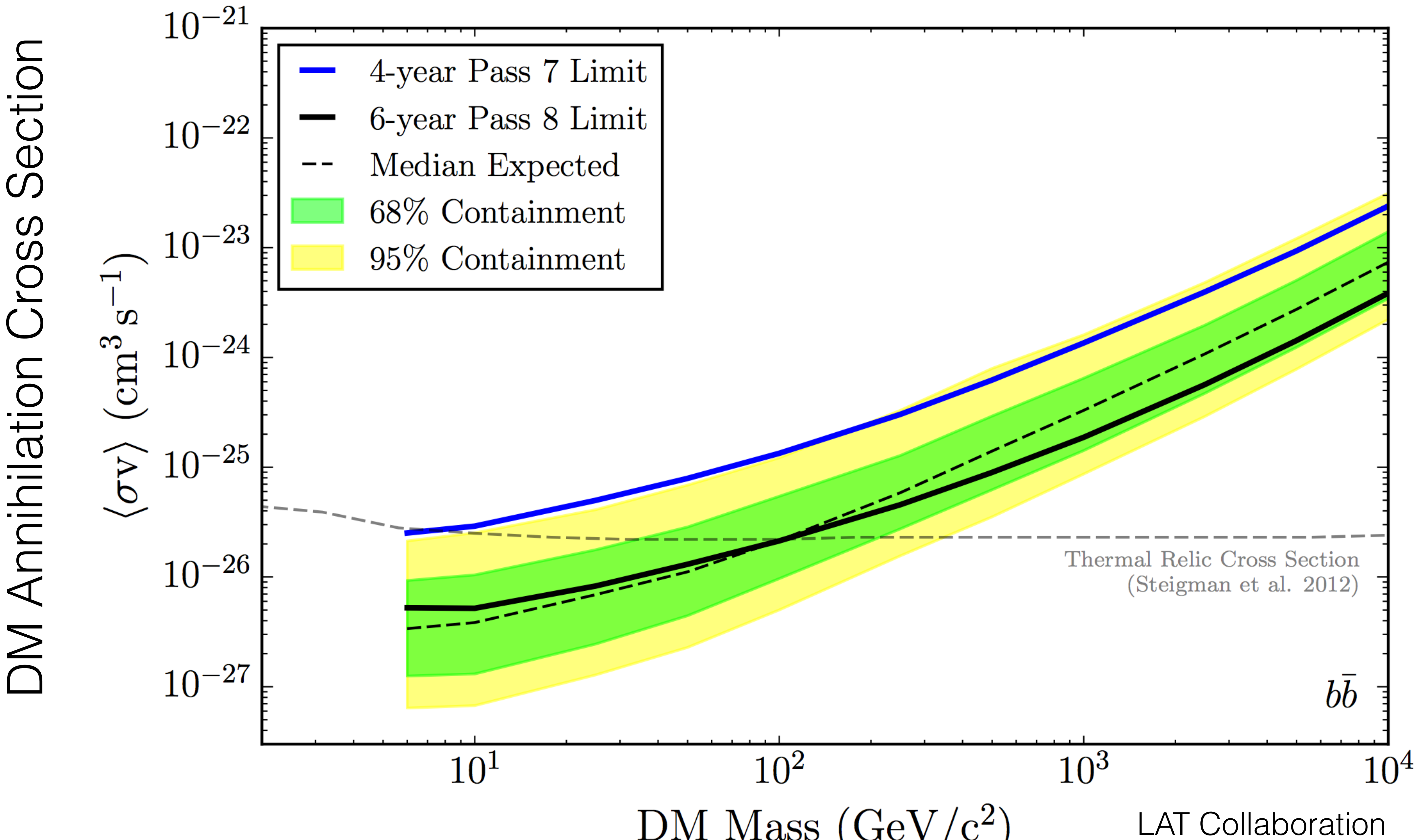
Joint likelihood

$$\mathcal{L}_i(\boldsymbol{\mu}, \boldsymbol{\theta}_i \,|\, \mathcal{D}_i) = \prod_j \mathcal{L}_i(\boldsymbol{\mu}, \boldsymbol{\theta}_i \,|\, \mathcal{D}_{i,j})$$

Limits for 15 Confirmed dSphs

15 dSphs, 6 yrs of *Fermi*-LAT data, Pass 8, 500 MeV to 500 GeV

Only 20 to 30% overlap of events with 4-year Pass 7 analysis (~statistically independent)



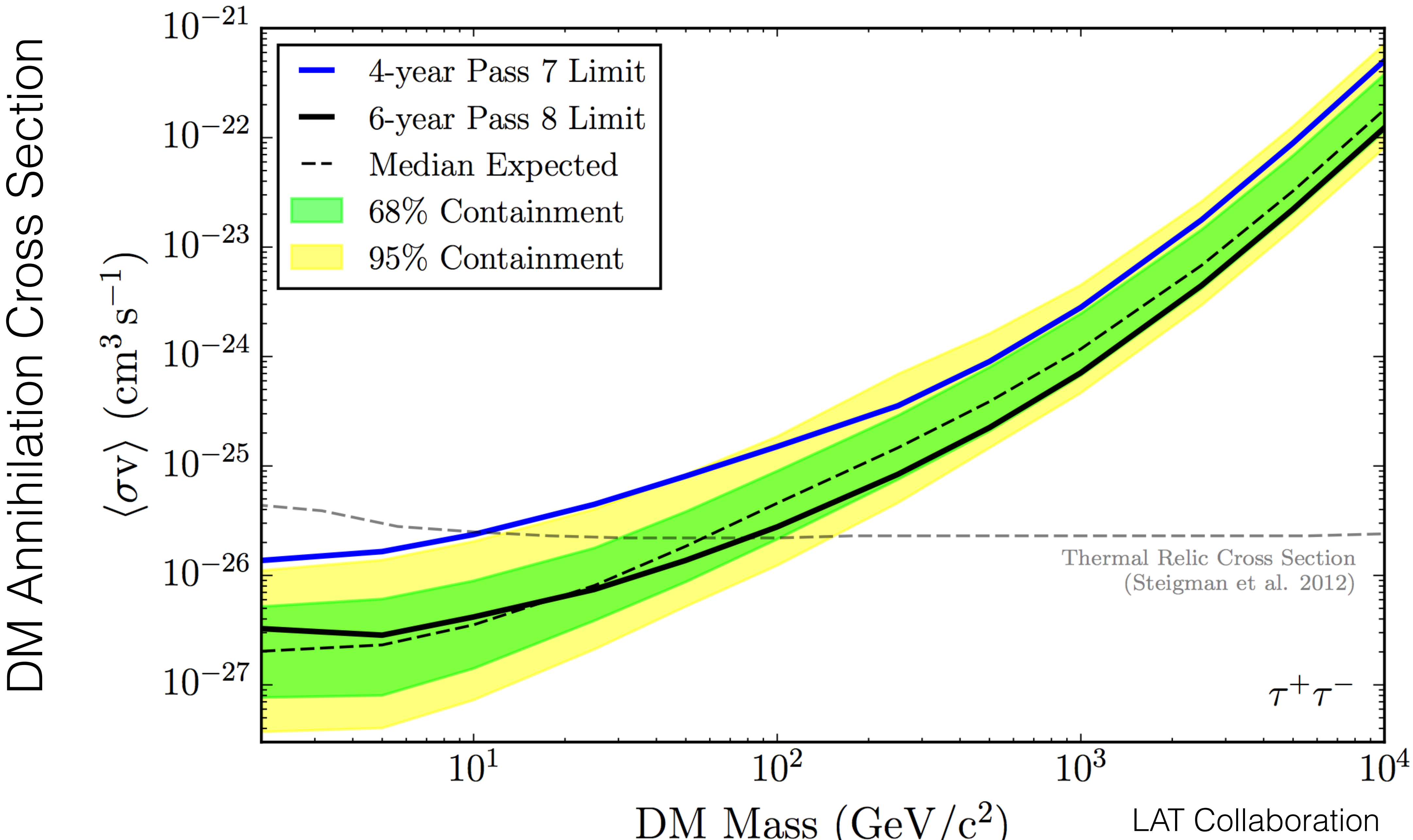
Thermal Relic Cross Section

LAT Collaboration
arXiv:1503.02641

Limits for 15 Confirmed dSphs

15 dSphs, 6 yrs of *Fermi*-LAT data, Pass 8, 500 MeV to 500 GeV

Only 20 to 30% overlap of events with 4-year Pass 7 analysis (~statistically independent)



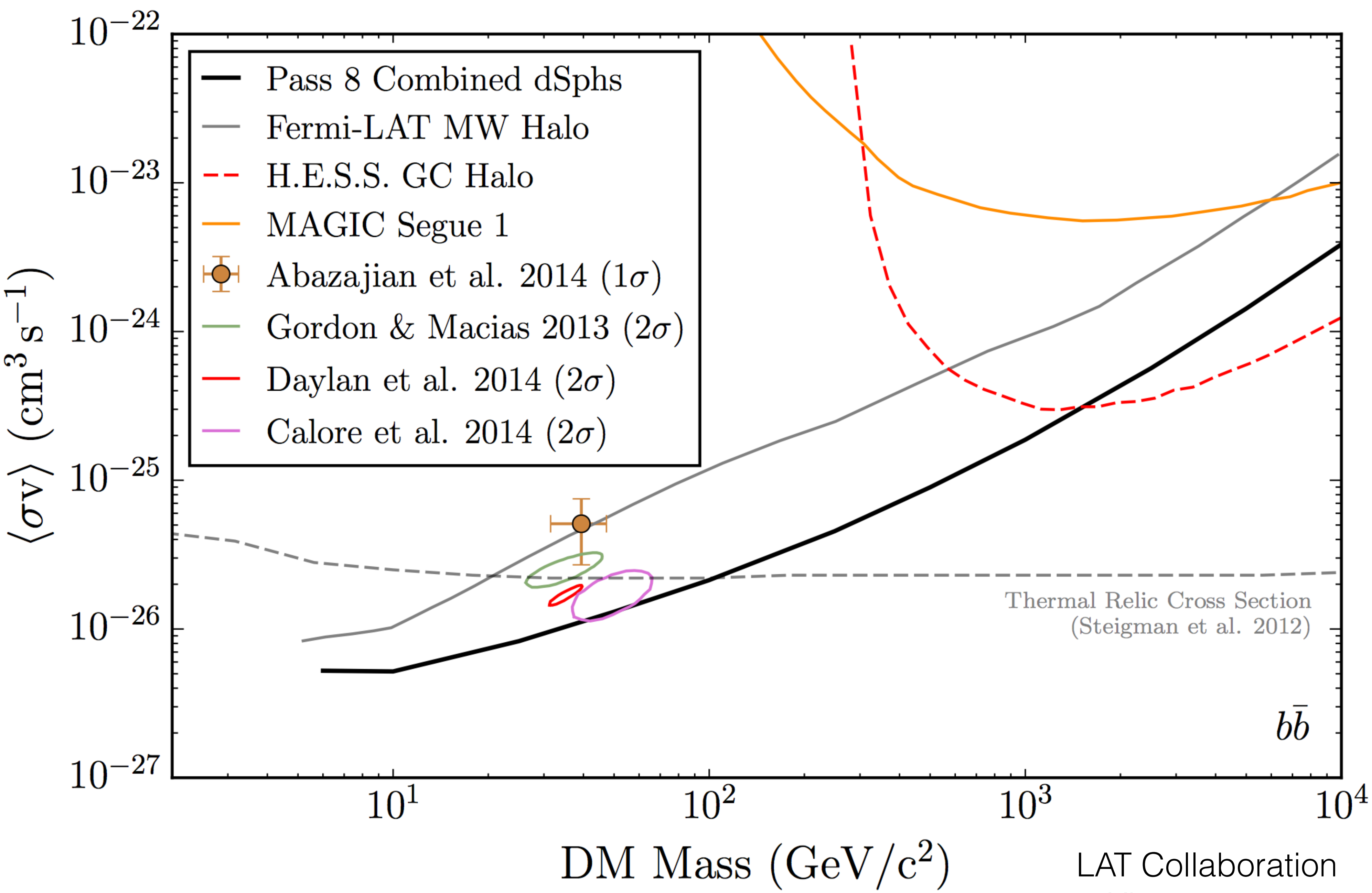
Thermal Relic Cross Section

LAT Collaboration
arXiv:1503.02641

Limits for 15 Confirmed dSphs

dSphs represent complementary targets to the Galactic Center

GC J-factor ~100 times larger, but complex conventional non-thermal emission



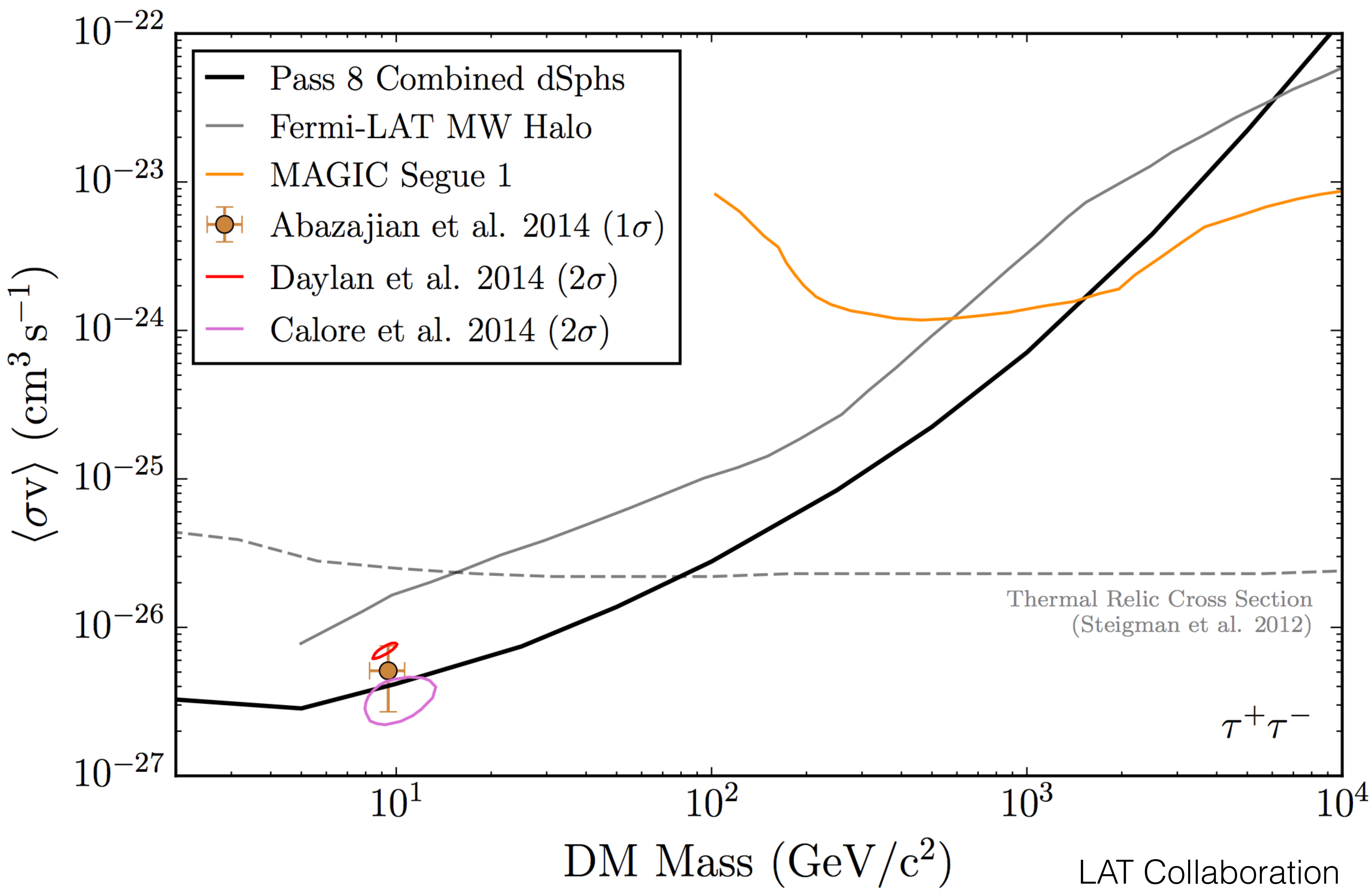
LAT Collaboration
arXiv:1503.02641

Systematic uncertainty in J-factor of GC could shift contours

Limits for 15 Confirmed dSphs

dSphs represent complementary targets to the Galactic Center

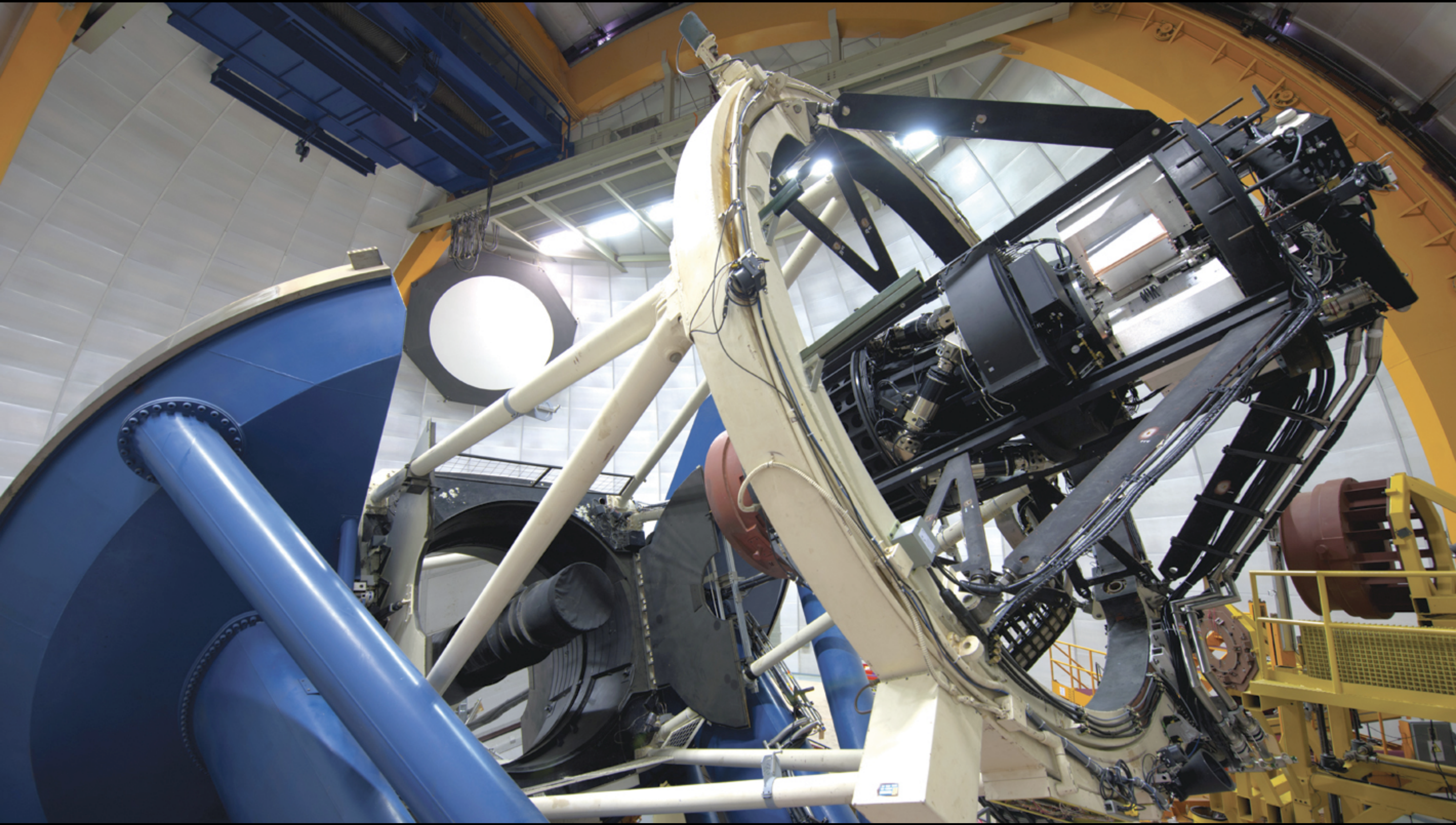
GC J-factor ~100 times larger, but complex conventional non-thermal emission



Systematic uncertainty in J-factor of GC could shift contours

LAT Collaboration arXiv:1503.02641

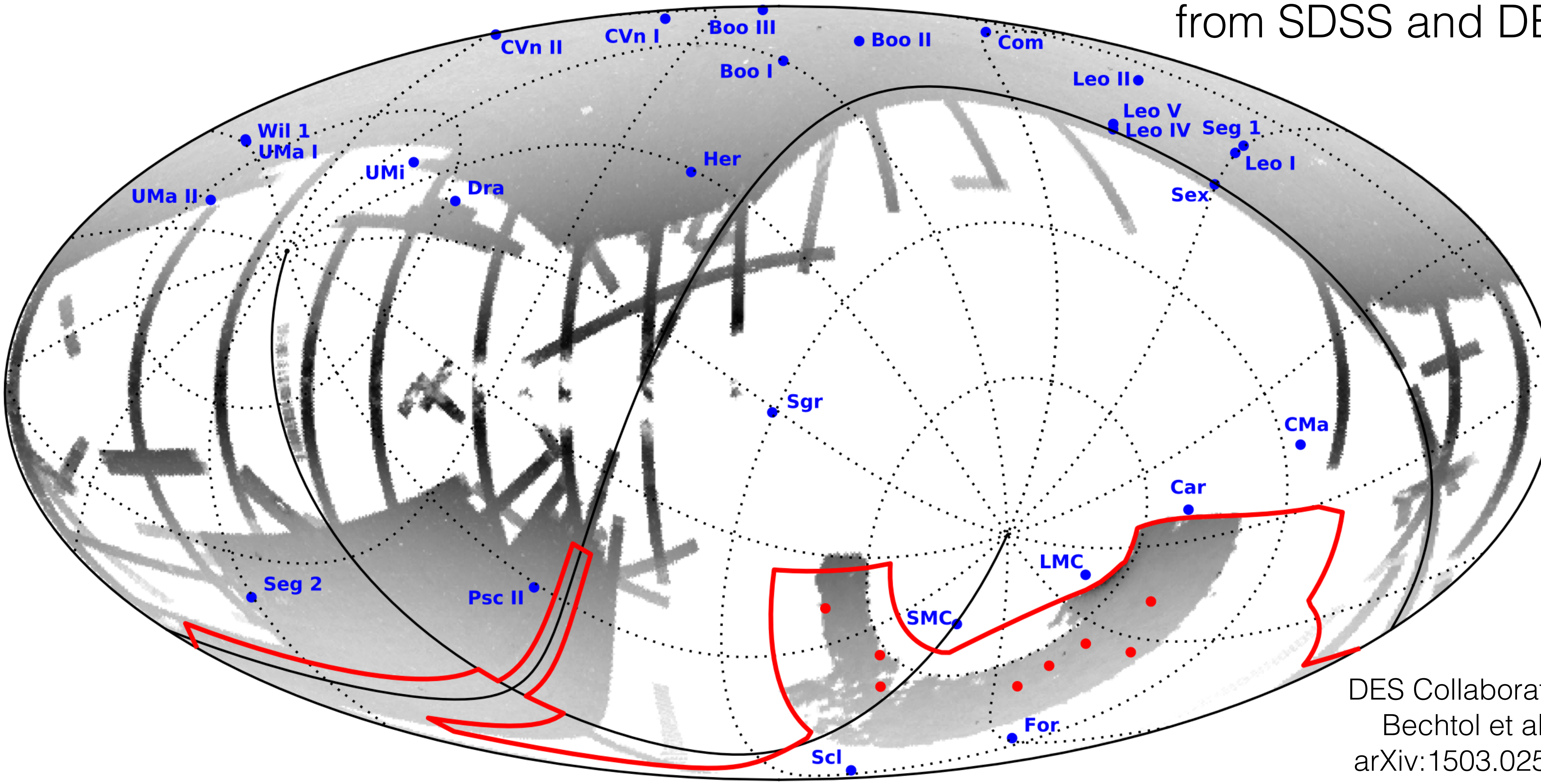
Dark Energy Camera



Blanco 4 m Telescope, CTIO

Milky Way Companions Found in First-year DES Data

Stellar density field from SDSS and DES

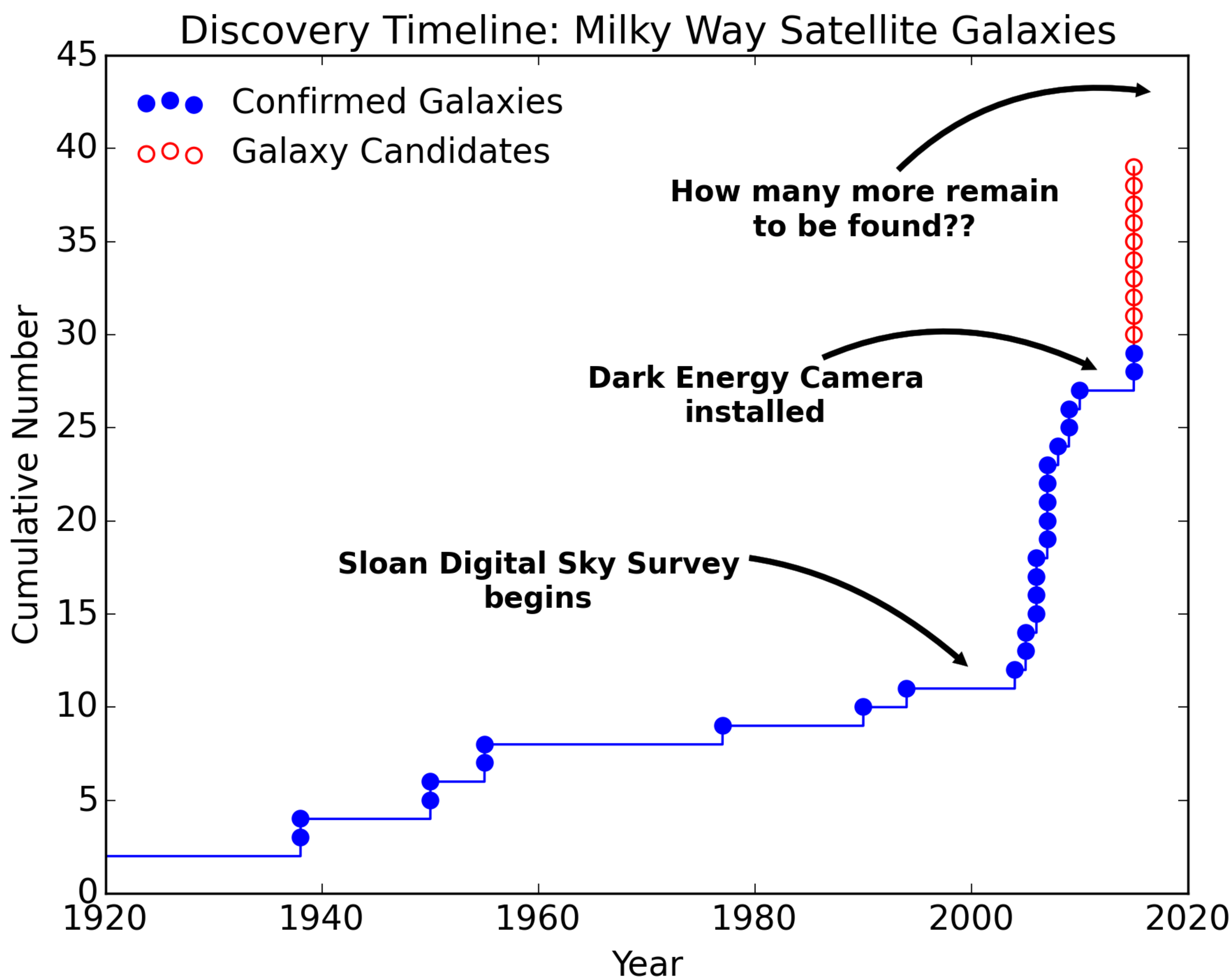


DES Collaboration
Bechtol et al.
arXiv:1503.02584

DES footprint in Galactic coordinates

Y1A1 dataset includes ~1600 deg^2 in SPT field, ~200 deg^2 in Stripe 82 field

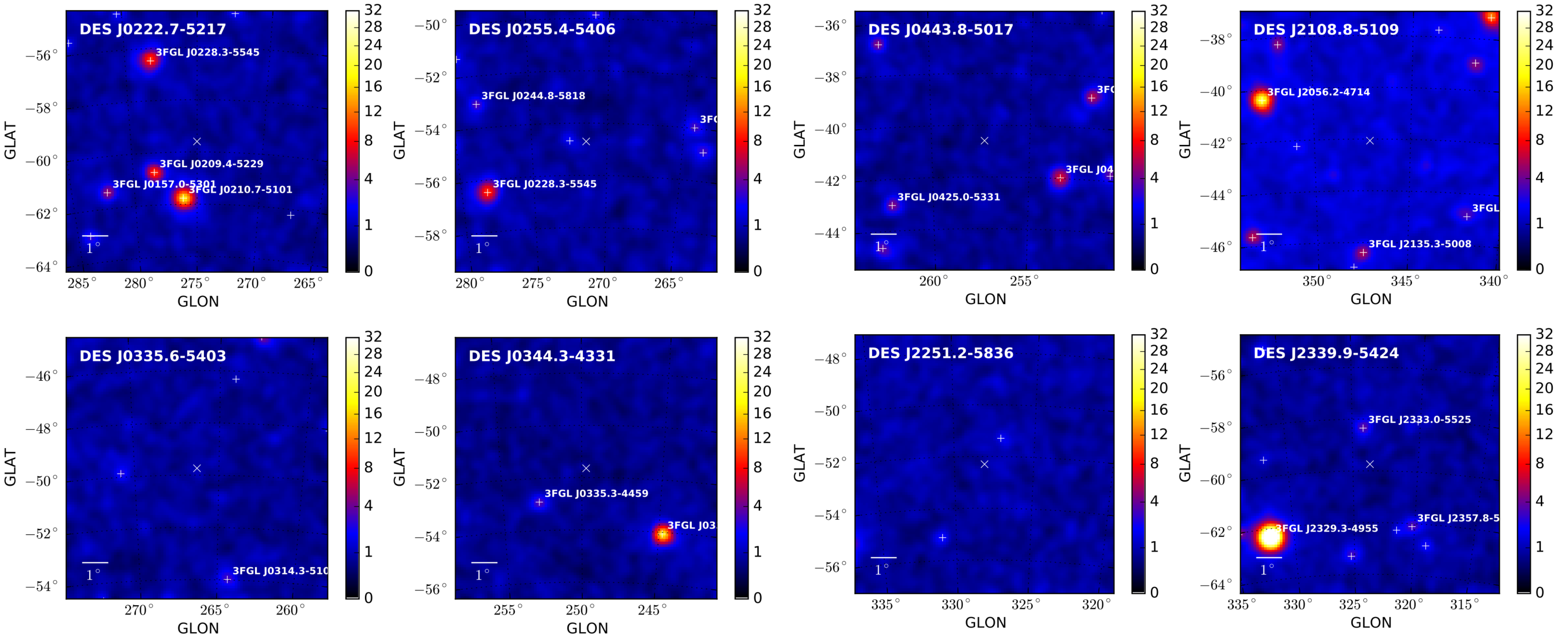
A Recent Flurry of Discoveries



Limits for 8 DES Candidates

Take advantage of existing LAT analysis pipeline with new targets

Counts maps > 1 GeV, 10 deg x 10 deg

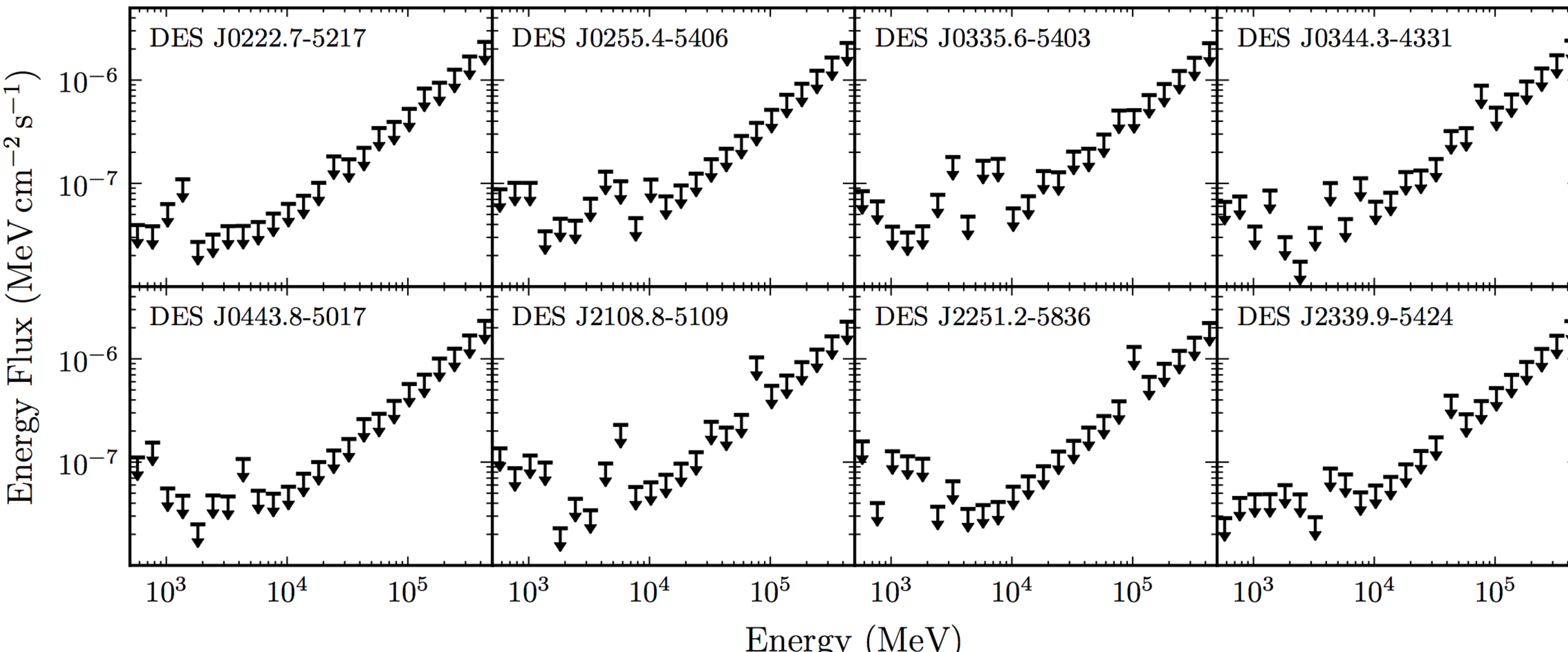


LAT & DES Collaborations
Drlica-Wagner et al.
arXiv:1503.02632

Limits for 8 DES Candidates

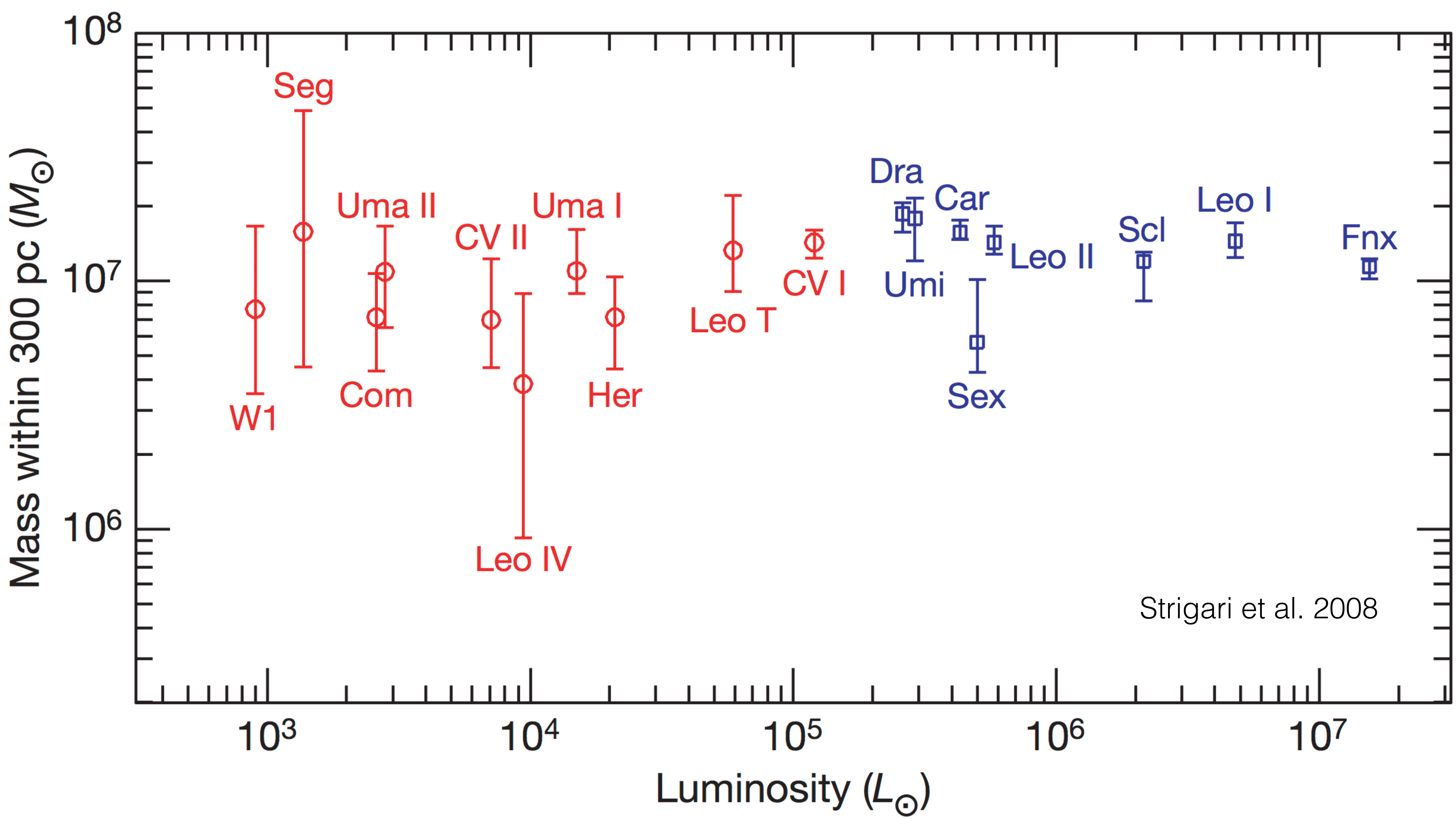
Take advantage of existing LAT analysis pipeline with new targets

Model-independent flux upper limits



LAT & DES Collaborations
Drlica-Wagner et al.
arXiv:1503.02632

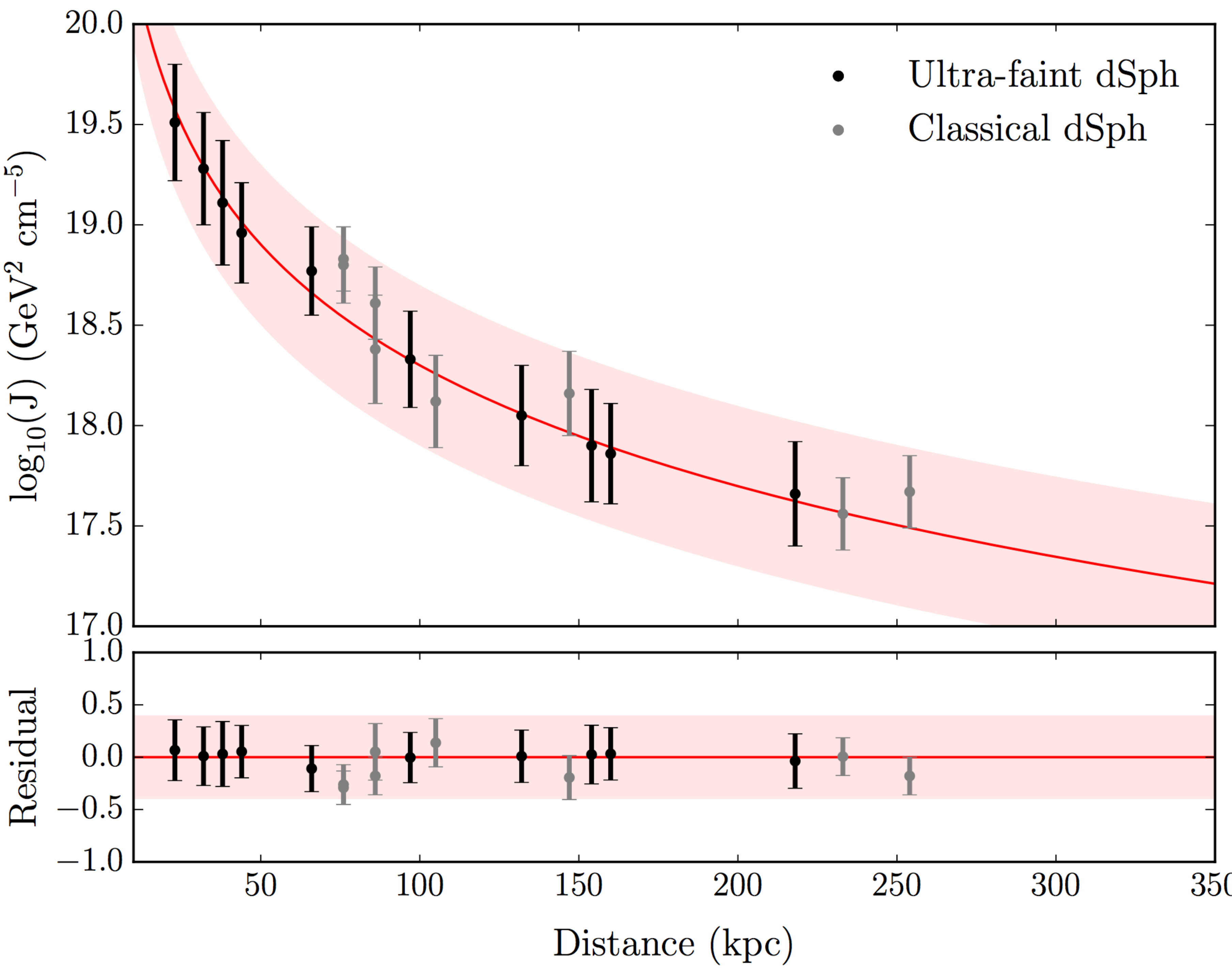
A Common mass scale for Milky Way Satellite Galaxies



With notable exceptions, e.g., Segue 2, see Kirby et al. 2013

J-factor Distance Scaling

If most Milky Way dSphs are hosted by similar DM halos, DM annihilation flux is mainly determined by heliocentric distance



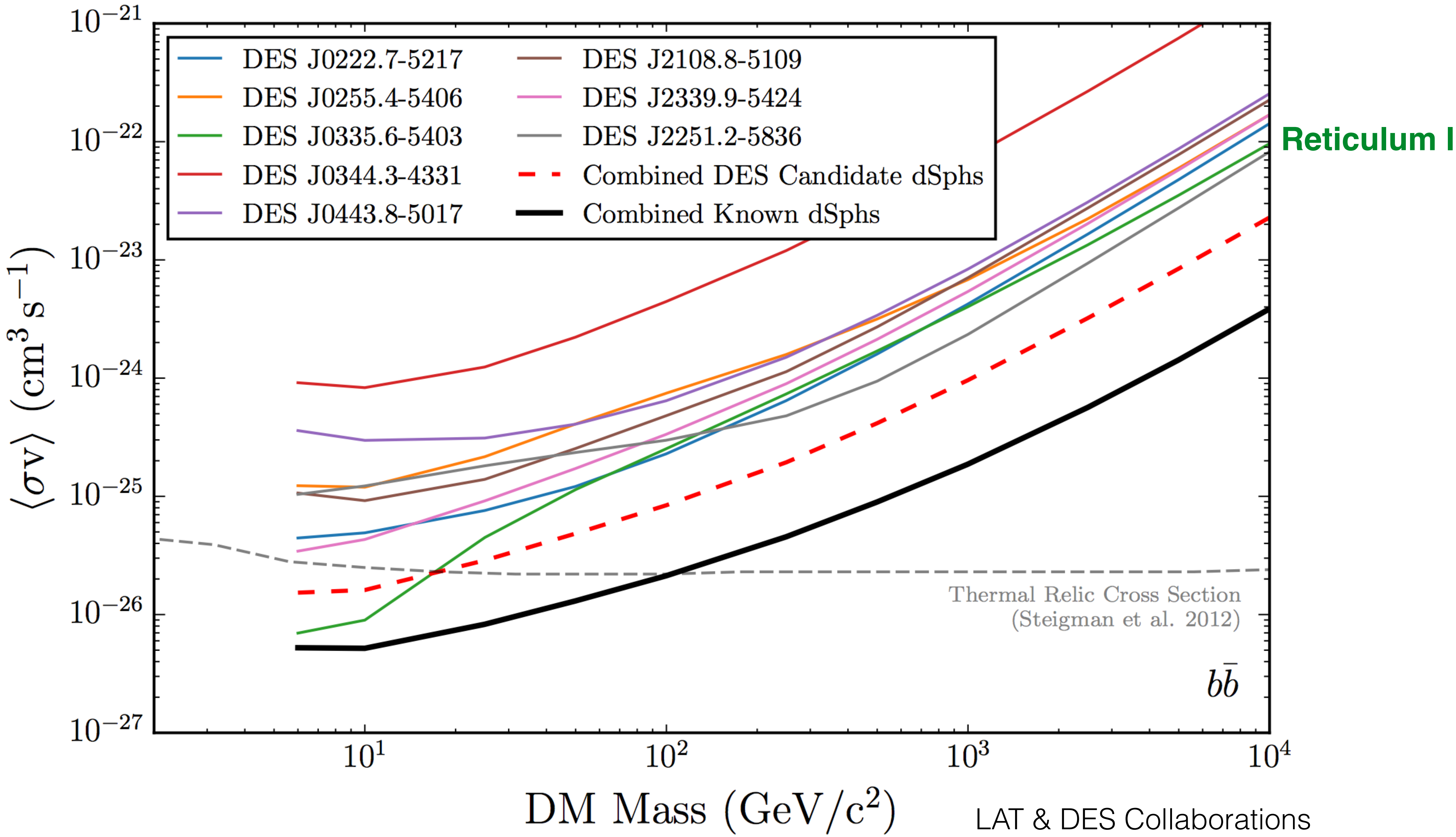
J-factors for known dSphs from Martinez et al. and LAT Collaboration arXiv:1309.2641, arXiv:1503.0264

(Distance)$^{-2}$ scaling with 0.4 dex scatter

LAT & DES Collaborations
Drlica-Wagner et al.
arXiv:1503.02632

Limits for 8 DES Candidates

J-factor estimates from distance scaling

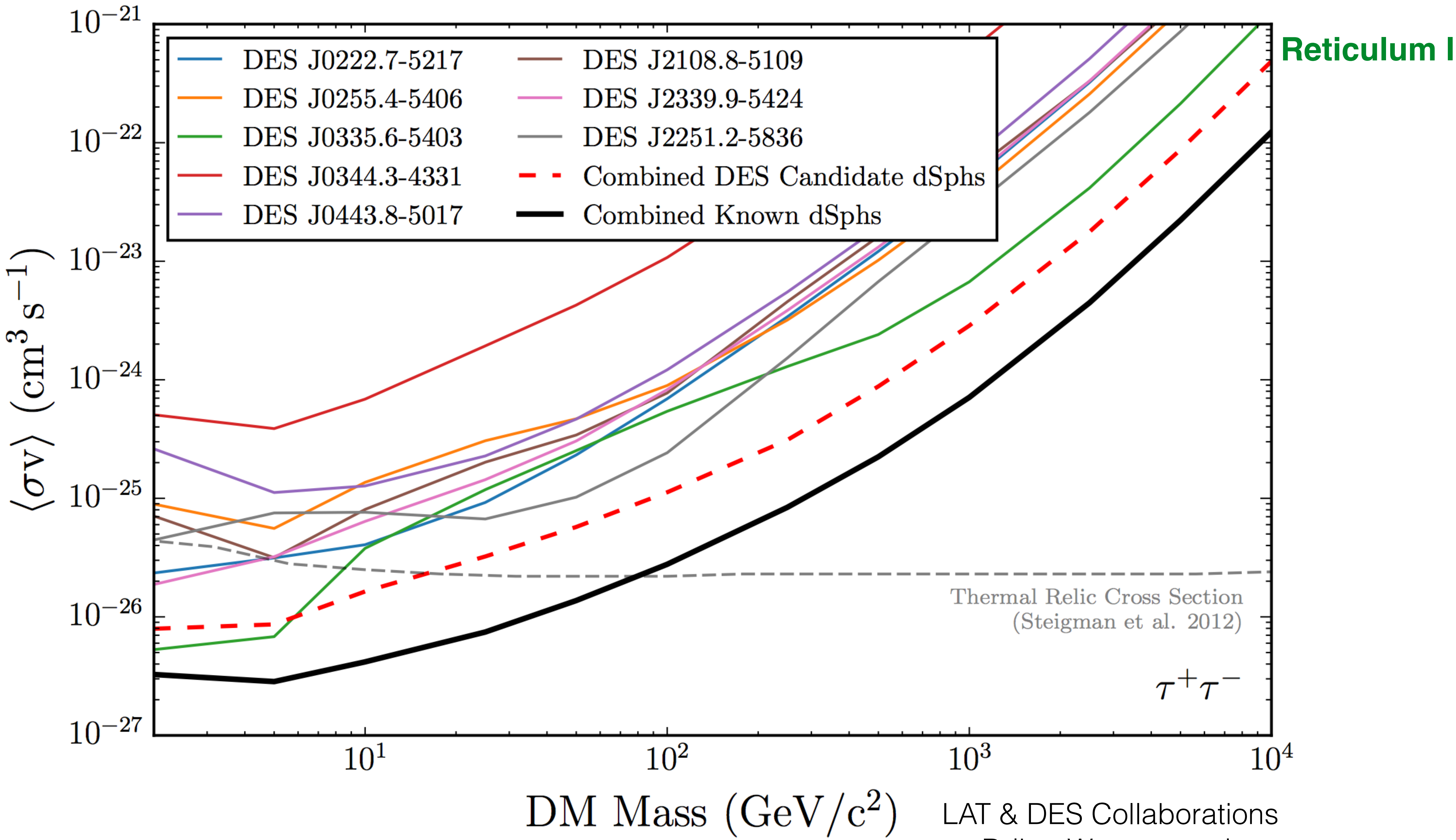


J-factor estimate for **Reticulum II**
Log(J) = 19.3 ± 0.4 (GeV^2 cm^{-5} sr)

LAT & DES Collaborations
Drlica-Wagner et al.
arXiv:1503.02632

Limits for 8 DES Candidates

J-factor estimates from distance scaling



LAT & DES Collaborations
Drlica-Wagner et al.
arXiv:1503.02632

J-factor estimate for **Reticulum II**
Log(J) = 19.3 ± 0.4 (GeV^2 cm^{-5} sr)

Gamma-ray Emission towards Reticulum II

Most significant gamma-ray excess for any dSph (or candidate) found at gamma-ray energies between 2 to 10 GeV in the direction of Reticulum II

Interpretation of significance depends on adopted trials factor

	Local Significance	Post-trials for DM mass and annihilation channel	Global Significance
Fermi-DES	2.4 σ	1.5 σ	0.26 σ
Geringer-Sameth et al.	2.8 σ	2.3 σ	Analysis focused on Reticulum II
Hooper & Linden	3.2 σ	No trials, use best-fit from Galactic Center	Depends on J-factor relative to other dSphs

Also, possible blazar PMN J0335−5046 located ~0.1 deg away

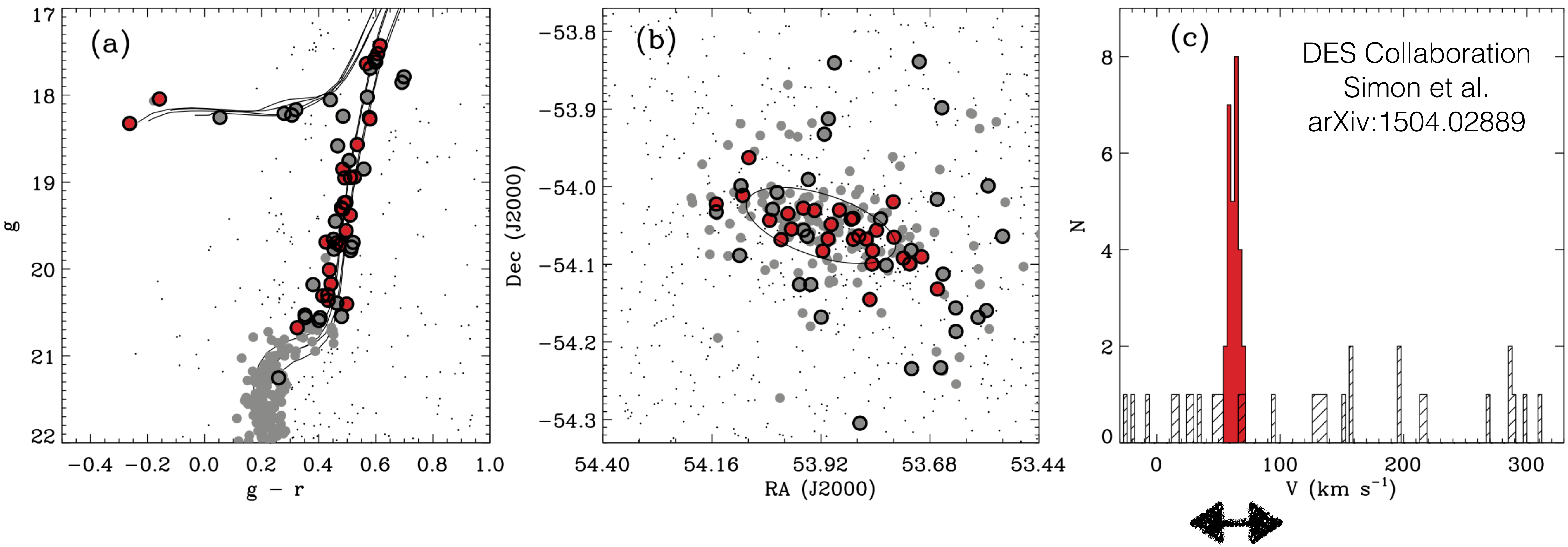
LAT & DES Collaborations
Drlica-Wagner et al.
arXiv:1503.02632

Geringer-Sameth et al.
arXiv:1503.02320

Hooper & Linden
arXiv:1503.06209

Spectroscopy of Reticulum II

Dynamical and chemical confirmation of nearest candidate from DES as a DM dominated dSph



Velocity dispersion (3.3 ± 0.7 km s^{-1}) indicates mass-to-light ratio of 470 ± 210 M_{Sol} / L_{Sol} within the half-light radius (55 pc)

Good agreement with independent analysis by Walker et al. arXiv:1504.03060

J-factor Comparison (0.5 deg)

Martinez et al. + LAT analysis

arXiv:1309.2641, arXiv:1503.0264

dSph	Log J
Segue 1	19.5 ± 0.29
Ursa Major II	19.3 ± 0.28
Coma Berenices	19.0 ± 0.25

Simon et al. analysis

arXiv:1504.02889

dSph	Log J
Reticulum II	**18.9 ± 0.6**

All in units of $GeV^2\ cm^{-5}\ sr$

Geringer-Sameth et al. analysis

arXiv:1408.0002

dSph	Log J
Ursa Major II	19.42
Segue 1	19.36
Coma Berenices	19.02

Bonnivard et al. analysis

arXiv:1504.02048, arXiv:1504.03309

dSph	Log J
Ursa Major II	19.9
Coma Berenices	19.6
Reticulum II	**19.5**
Willman 1	19.5

±0.4 dex systematic uncertainty from triaxiality

Status of 2015 Milky Way Companions

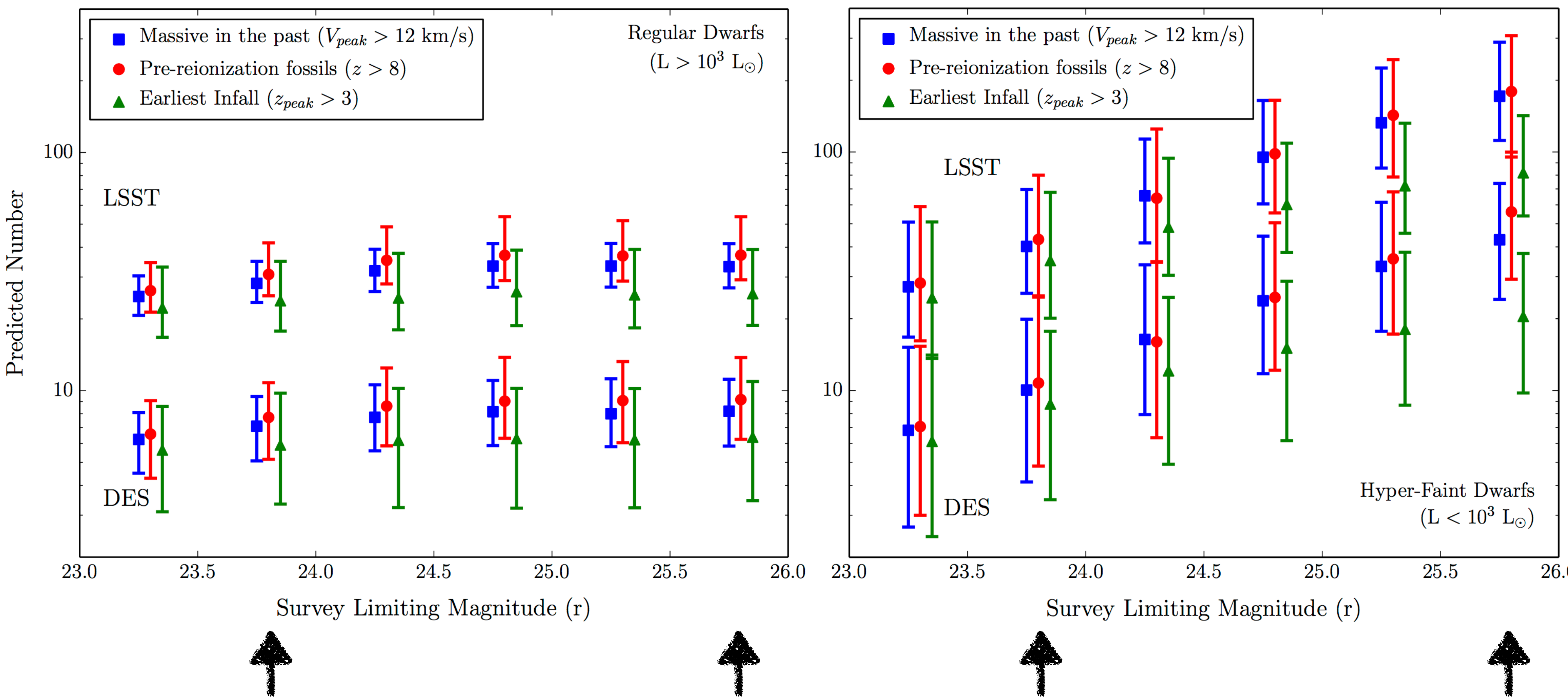
Object	Classification	Photometry	arXiv References
Reticulum II	**dSph**	DECam (DES)	1503.02079, 1503.02584, 1504.02889, 1504.03060, 1504.07916
Horologium	**dSph**	DECam (DES)	1503.02079, 1503.02584, 1504.07916
Kim 2 / Indus I / DES J2108.8–5109	Globular cluster?	DECam (Stromlo Milky Way Satellite Survey + DES)	1502.03952, 1503.02079, 1503.02584
Eridanus II	dSph?	DECam (DES)	1503.02079, 1503.02584
Tucana II	dSph?	DECam (DES)	1503.02079, 1503.02584
Pictor / DES J0443.8 –5017	?	DECam (DES)	1503.02079, 1503.02584
Phoenix II / DESJ2339.9–5424	?	DECam (DES)	1503.02079, 1503.02584
Eridanus III / DESJ0222.7–5217	?	DECam (DES)	1503.02079, 1503.02584
Grus	?	DECam (DES)	1503.02079
Hydra II	dSph?	DECam (SMASH)	1503.06216
Pegasus III	dSph?	SDSS + DECam	1503.08268
Laevens 2 / Triangulum II	?	PanSTARRS + Large Binocular Camera	1503.05554

30 kpc away, also interesting target for DM searches, see Hooper & Linden arXiv:1503.06209

Thinking Further Ahead

Tens to hundreds of additional dSphs expected

Second year of DES completed in Feb 2015, increases coverage to >4000 deg²



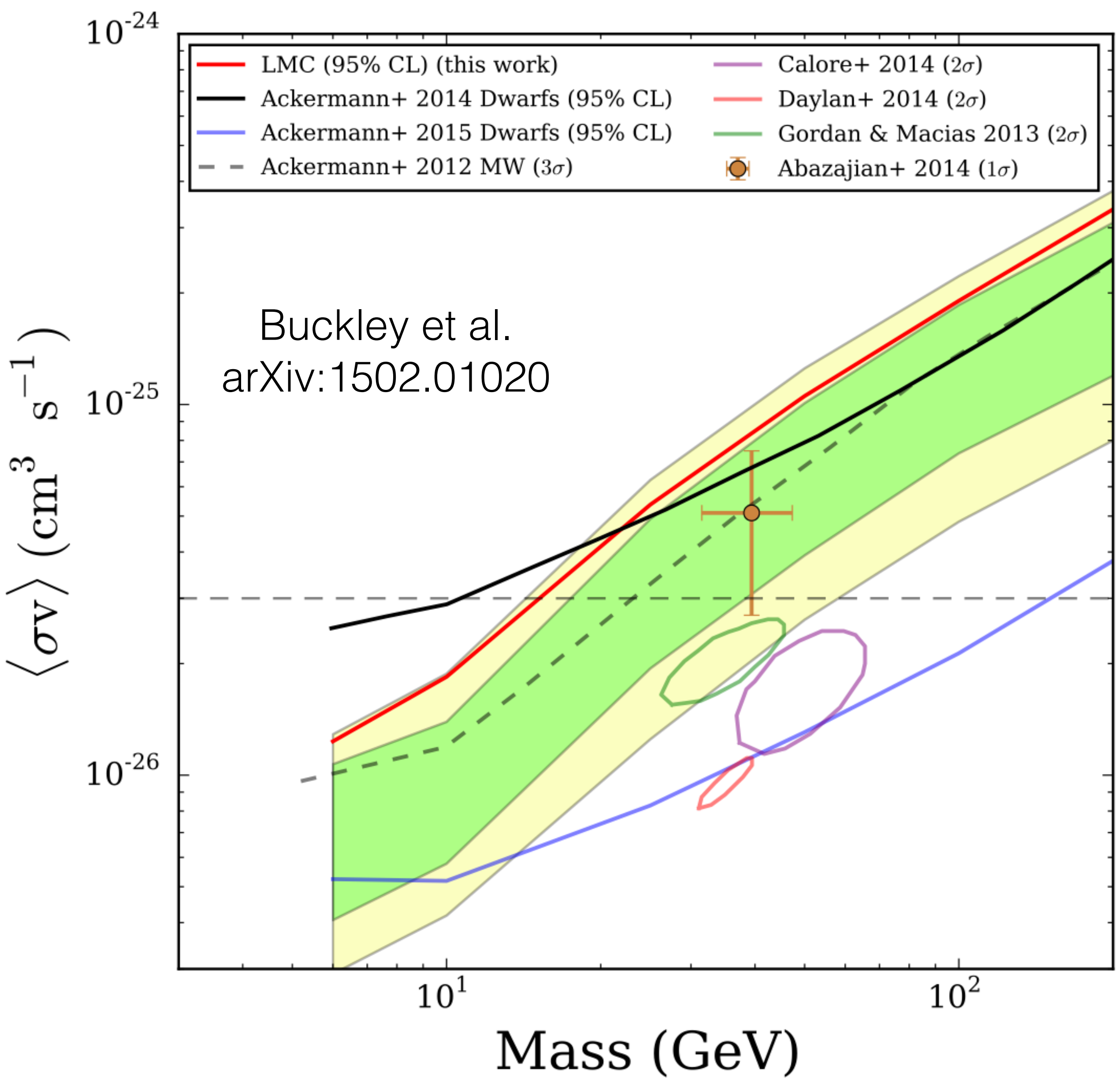
DES LSST DES LSST

Hargis et al. 2014
arXiv:1407.4470

Large Magellanic Cloud and Smith Cloud

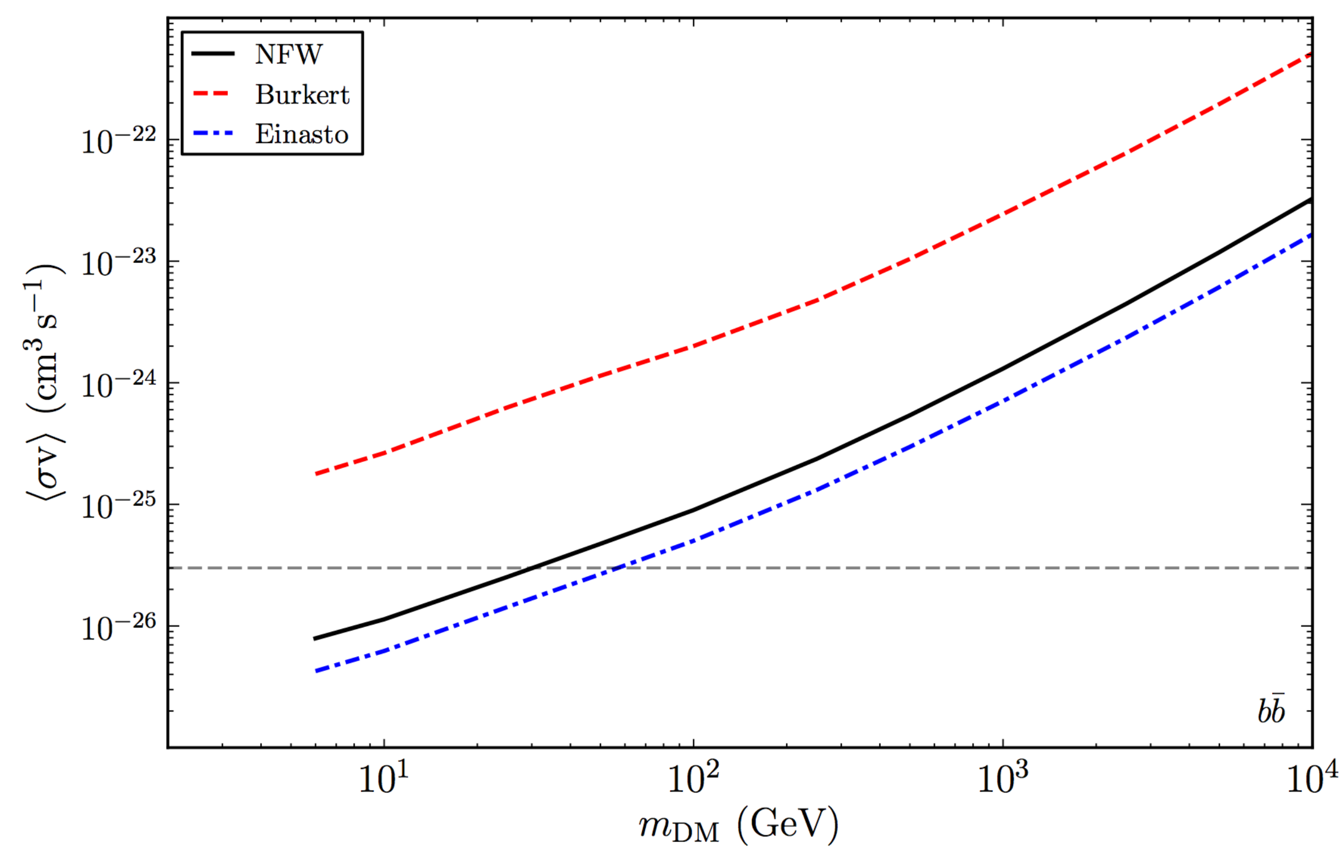
Large Magellanic Cloud

Conservative J-factor estimates in range from 9.4×10^{19} to 2.8×10^{20} (GeV^2 cm^{-5} sr)



Smith High-velocity Cloud

J-factor estimates range from 4.2×10^{18} to 1.8×10^{20} (GeV^2 cm^{-5} sr)



Drlica-Wagner et al.
arXiv:1405.1030

Conclusions

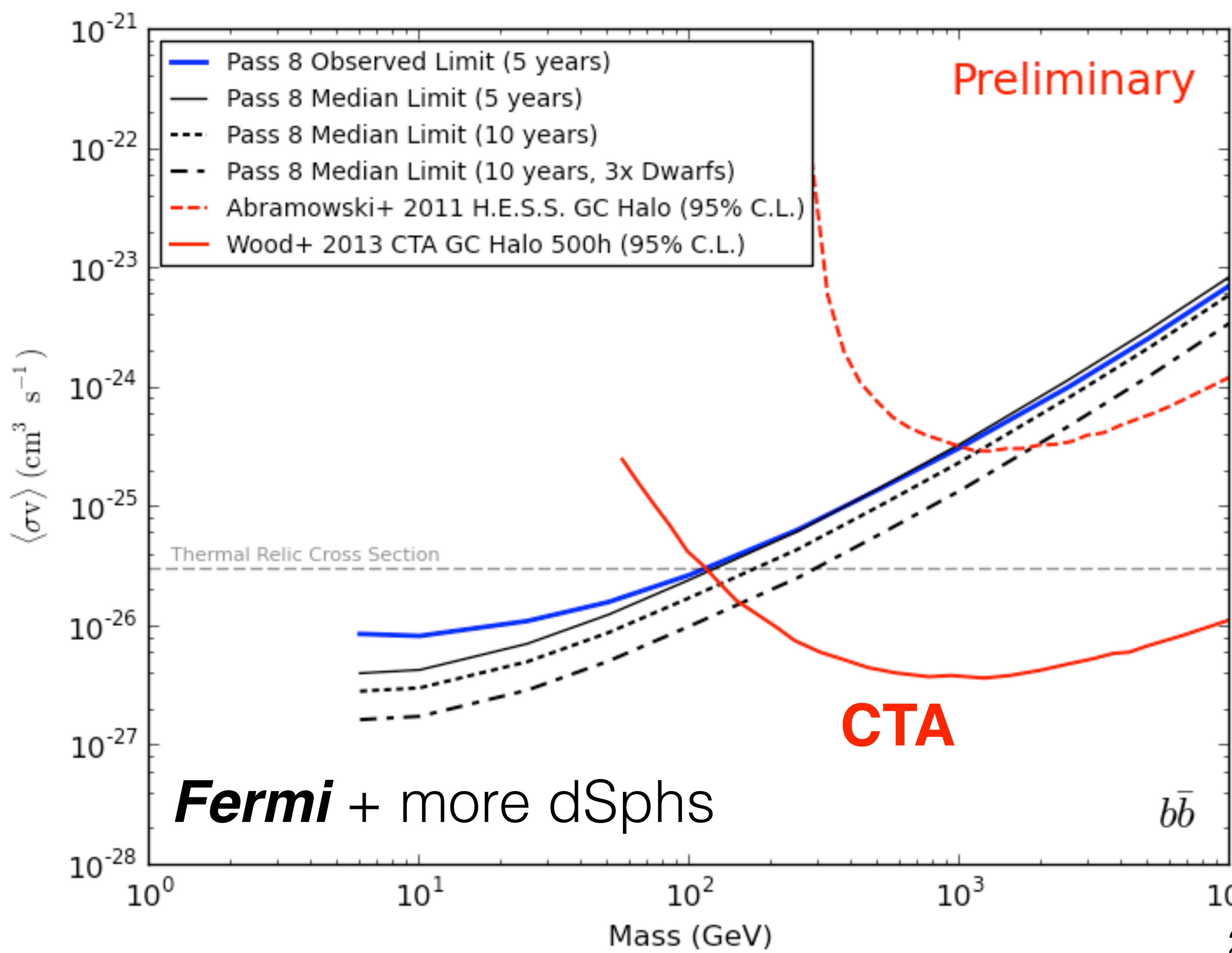
☑ **Confirmed dSphs already provide robust DM constraints**

Upper limits below the canonical thermal relic cross section for DM of mass < 100 GeV annihilating via quark and tau-lepton channels

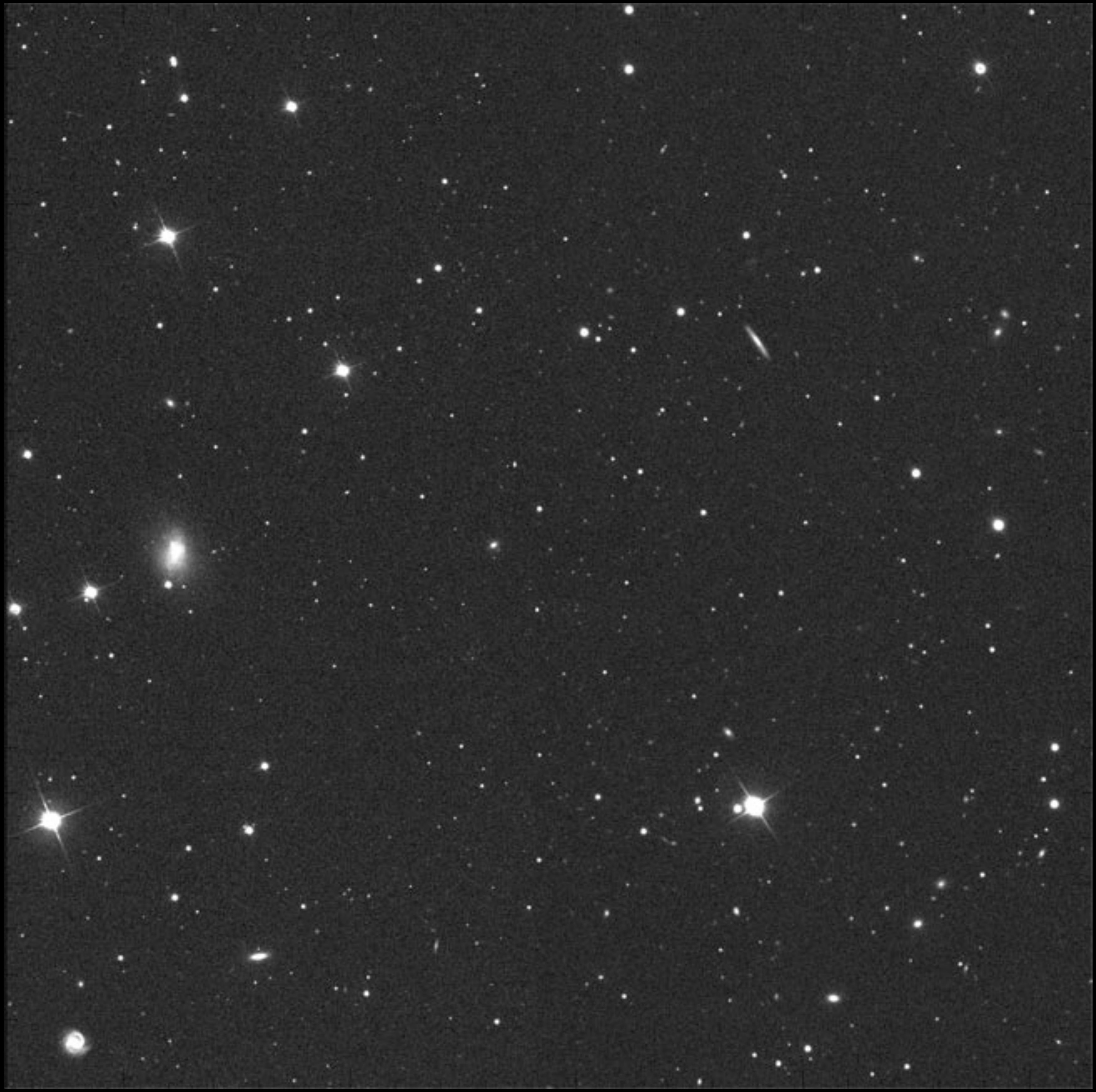
☑ **More targets can quickly translate to more sensitive searches**

Projected sensitivity in 5 to 10 yrs expressed as an upper limit…

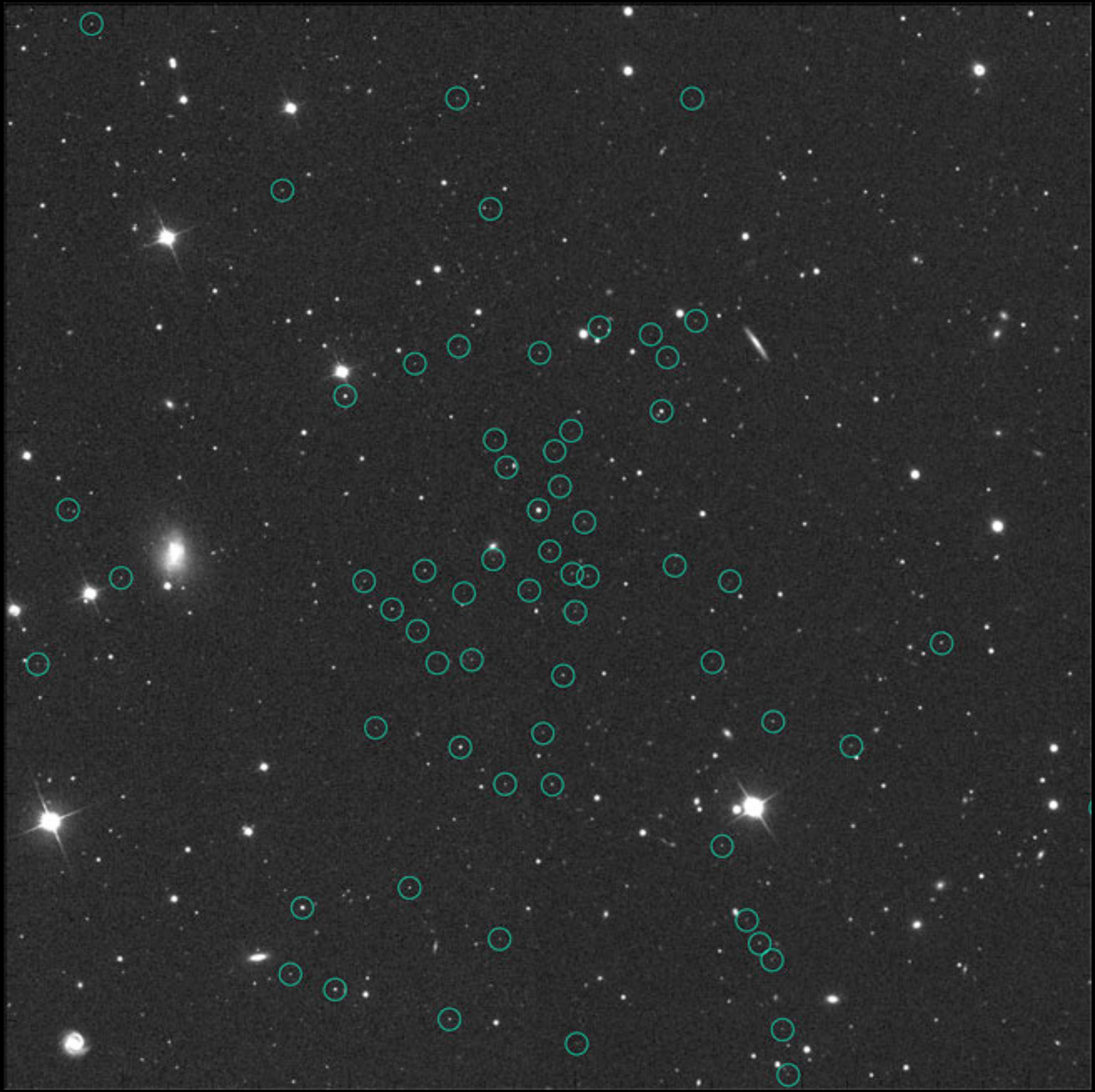
dSphs also have excellent discovery potential



Extras

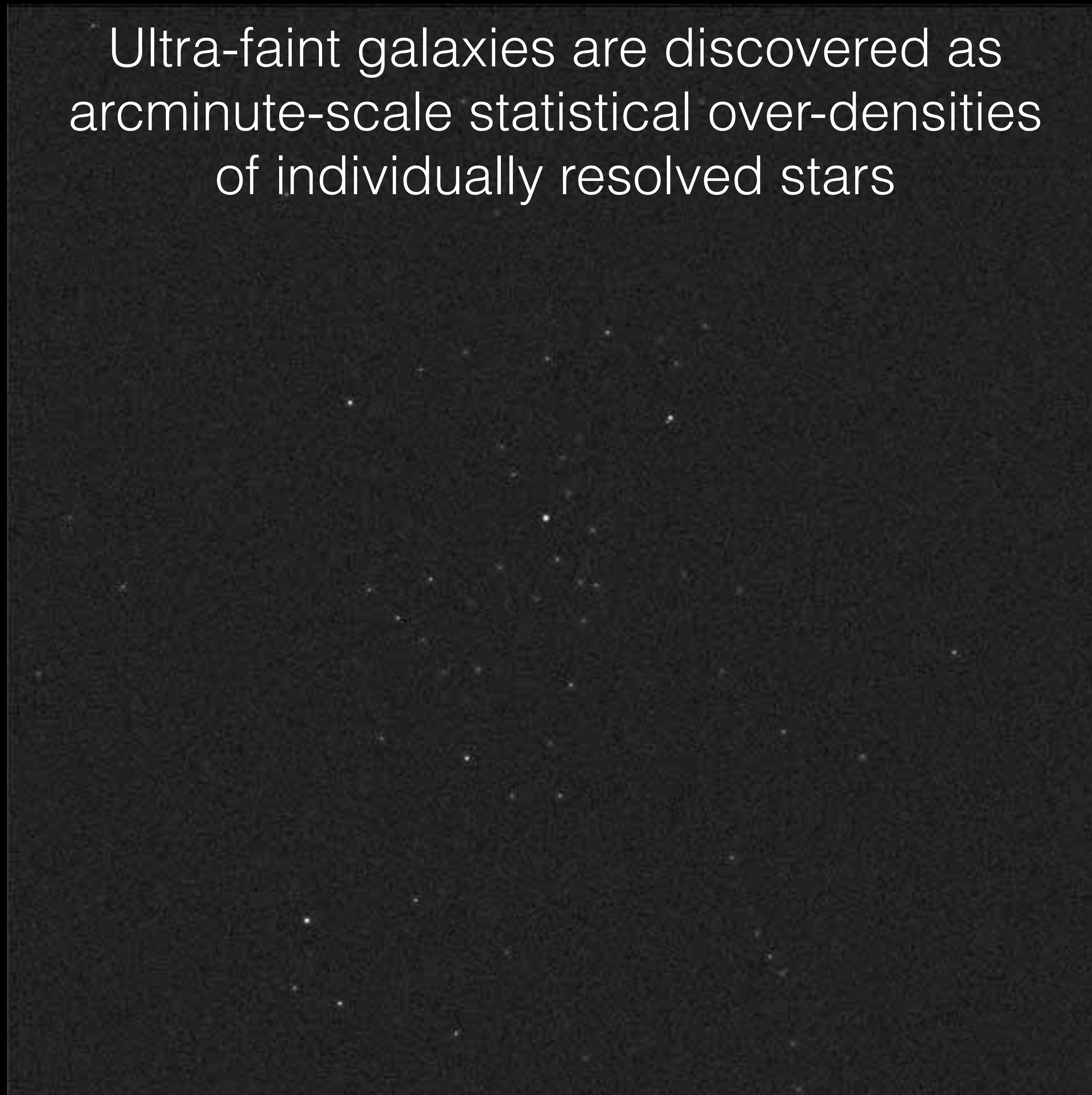


Segue 1
Credit: Marla Geha



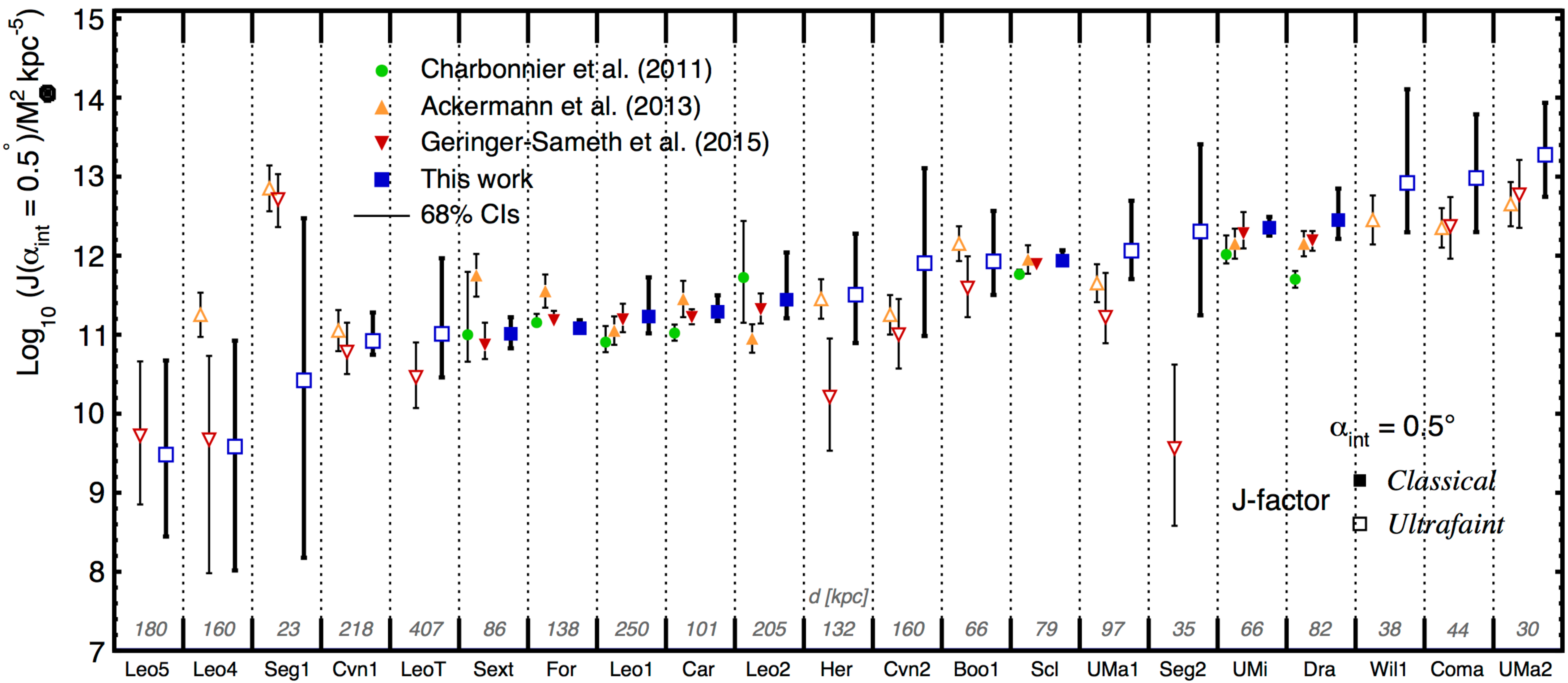
Segue 1
Credit: Marla Geha

Ultra-faint galaxies are discovered as arcminute-scale statistical over-densities of individually resolved stars



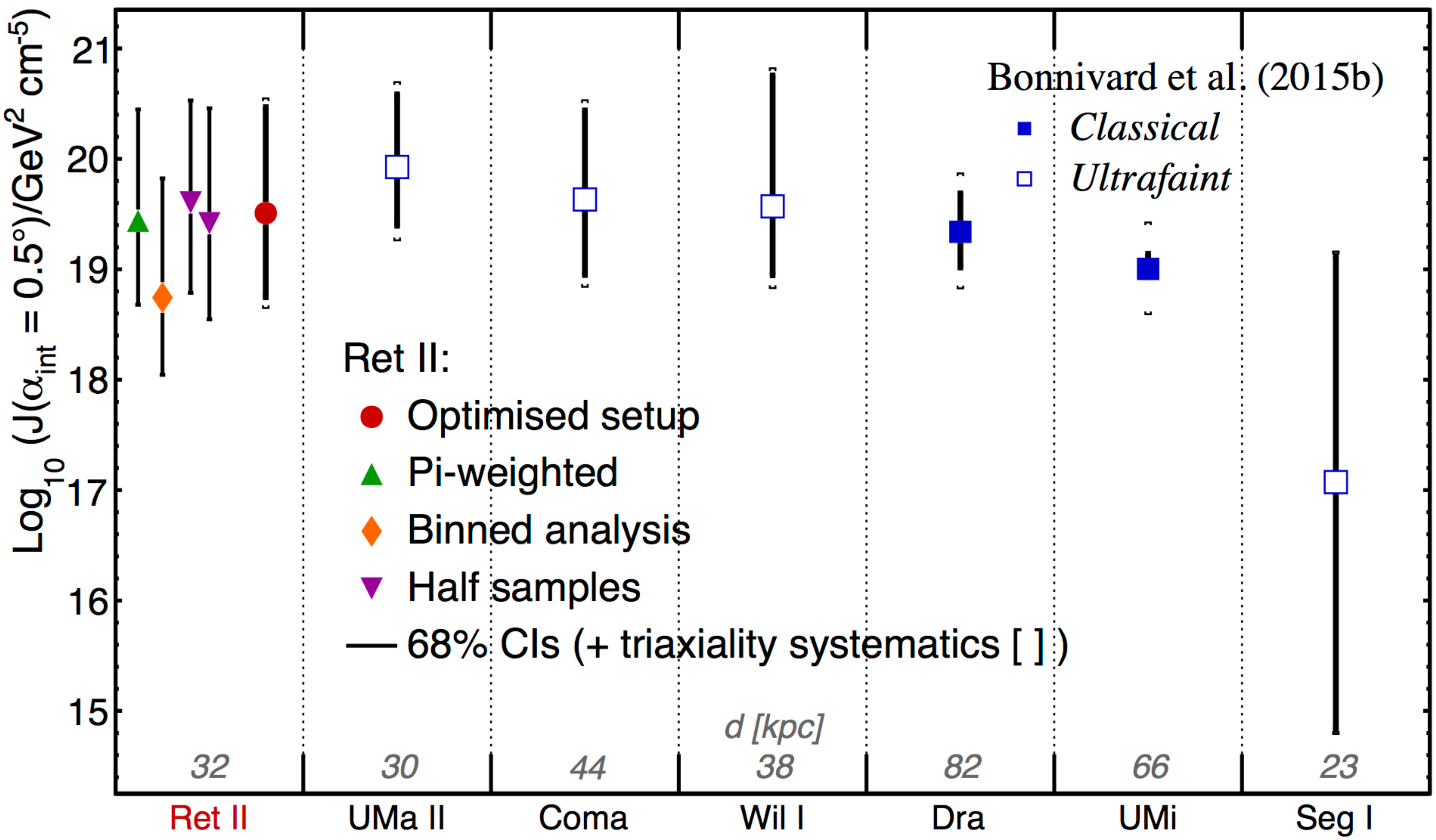
Segue 1
Credit: Marla Geha

J-factor Comparison (0.5 deg)



Bonnivard et al.
arXiv:1504.02048

J-factor Comparison (0.5 deg)



Bonnivard et al.
arXiv:1504.03309

Thinking Further Ahead

Tens to hundreds of additional dSphs expected

Second year of DES completed in Feb 2015, increases coverage to >4000 deg^2

TABLE 1
PREDICTED NUMBER OF DWARF GALAXIES FOR LSST AND DES

	DES ($\pm$ 10/90)	LSST ($\pm$ 10/90)
$L > 10^3 L_\odot$, $r_{lim} = 23.8$		
Massive in the past	7^{+2}_{-2}	28^{+6}_{-5}
Pre-reionization Fossils	7^{+3}_{-2}	30^{+11}_{-5}
Earliest Infall	5^{+4}_{-2}	23^{+11}_{-6}
$L < 10^3 L_\odot$, $r_{lim} = 23.8$		
Massive in the past	10^{+9}_{-6}	40^{+29}_{-15}
Pre-reionization Fossils	10^{+14}_{-6}	43^{+36}_{-19}
Earliest Infall	8^{+9}_{-5}	35^{+32}_{-15}
$L > 10^3 L_\odot$, $r_{lim} = 25.8$		
Massive in the past	8^{+3}_{-3}	33^{+8}_{-6}
Pre-reionization Fossils	9^{+4}_{-3}	37^{+16}_{-8}
Earliest Infall	6^{+4}_{-3}	25^{+14}_{-7}
$L < 10^3 L_\odot$, $r_{lim} = 25.8$		
Massive in the past	42^{+31}_{-18}	171^{+117}_{-60}
Pre-reionization Fossils	56^{+43}_{-27}	179^{+128}_{-84}
Earliest Infall	20^{+17}_{-11}	81^{+60}_{-28}

+ PanSTARRS, SkyMapper, etc.

Hargis et al. 2014
arXiv:1407.4470

See also He et al. 2015
arXiv:1309.4780