PHYSICAL REVIEW D **109,** 063024 (2024)

# Legacy analysis of dark matter annihilation from the Milky Way dwarf spheroidal galaxies with 14 years of *Fermi*-LAT data

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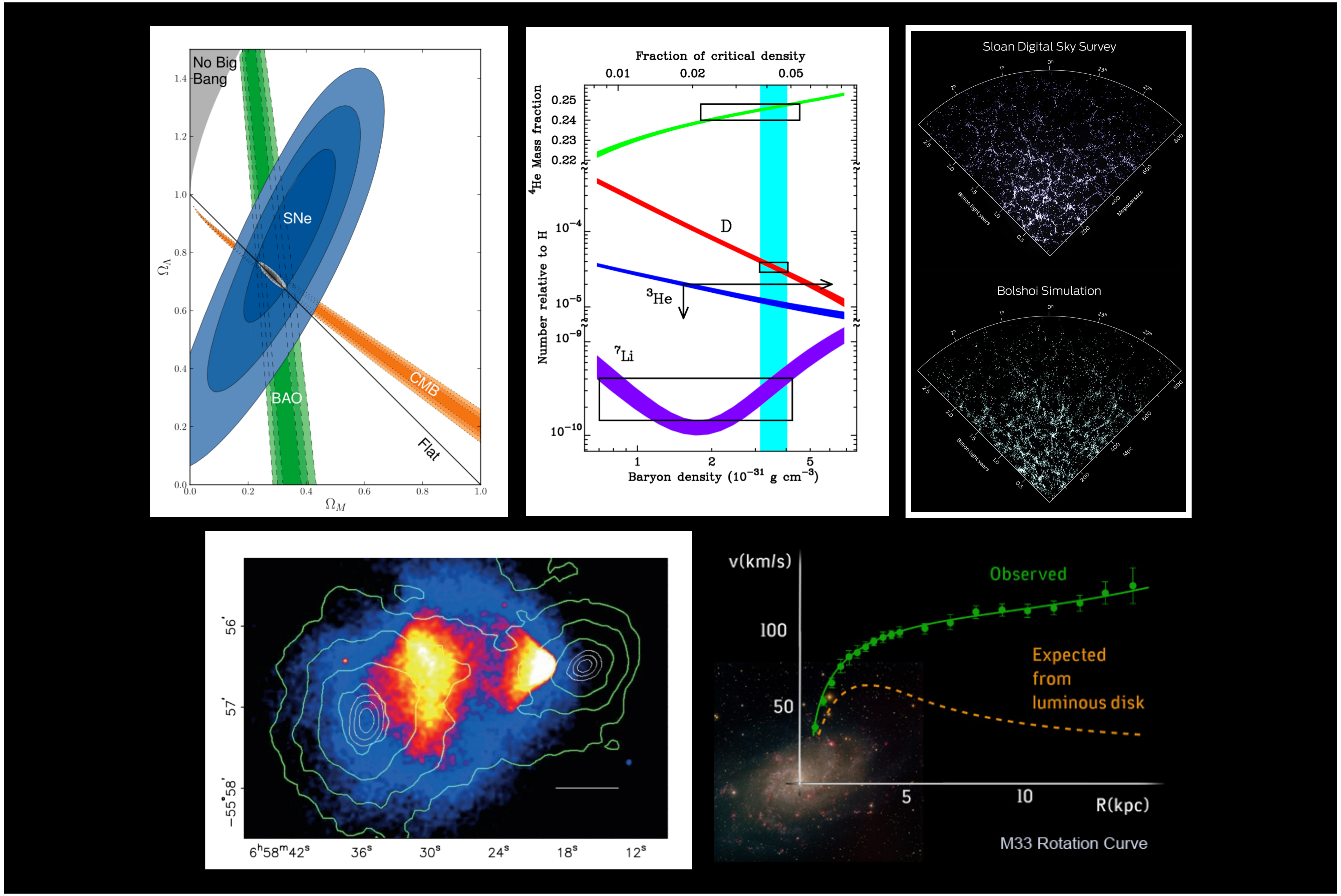
**Fermi GI Program – Cycle 15 (151038)**

*on behalf of the Fermi-LAT Collaboration*

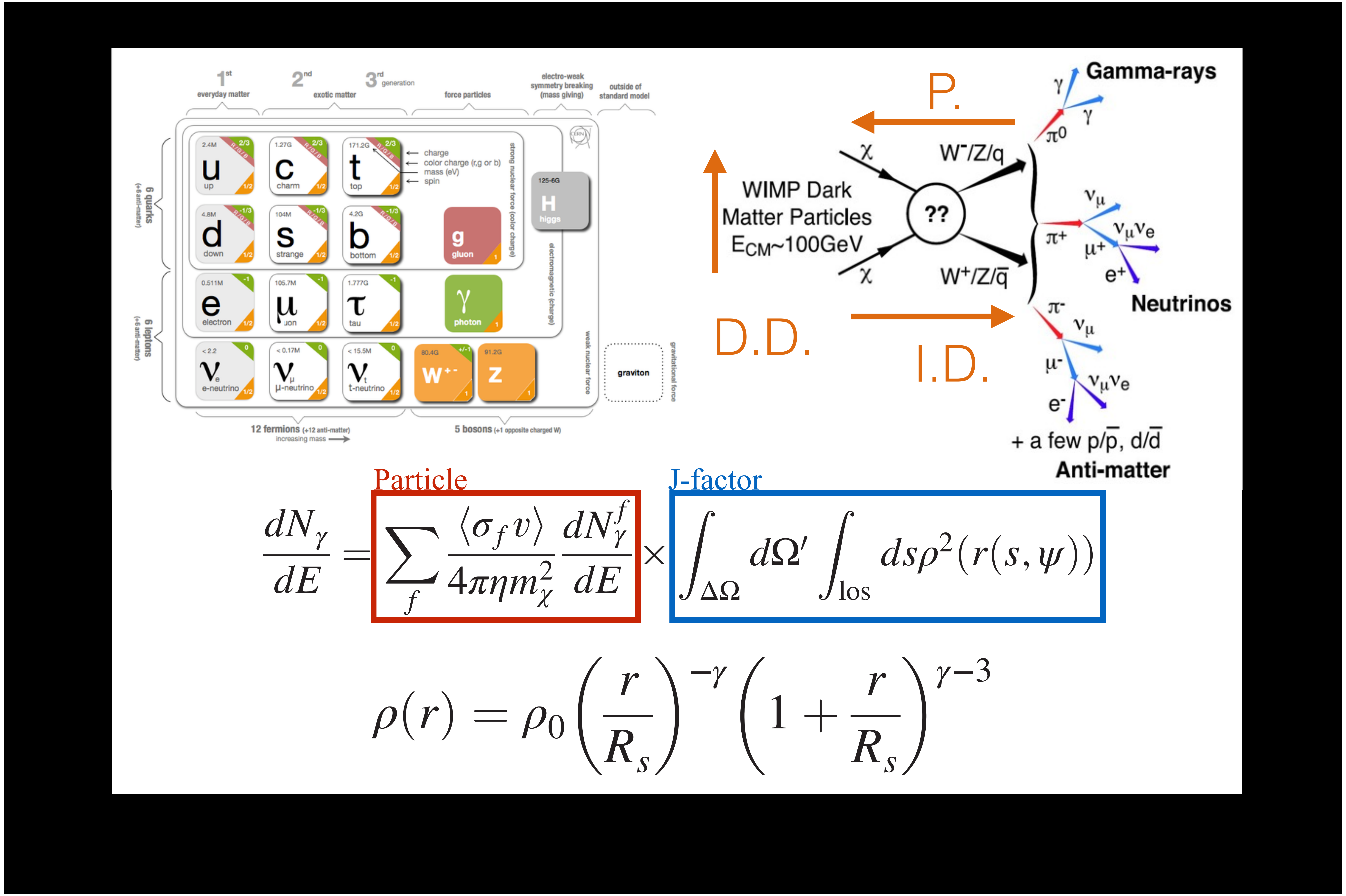
Before e.g. Abdo+10, Ackermann+11, Ackermann+14, Albert+17..

# The Dark Matter Paradigm




- Evidence for DM is found at all cosmological scales.
- Matter-energy density of the Universe:
  - Baryons: 4%
  - Dark Matter: 26%
  - Dark Energy: 70%

# Detecting Dark Matter




- Historically, DM has been thought to likely be a particle.
- Discovering DM will require complementarity between different search methods and targets.

# WHERE TO SEARCH FOR DARK MATTER?

Potential targets are numerous (see right, also dark subhalos, normal galaxies M31, galaxy groups, etc.)

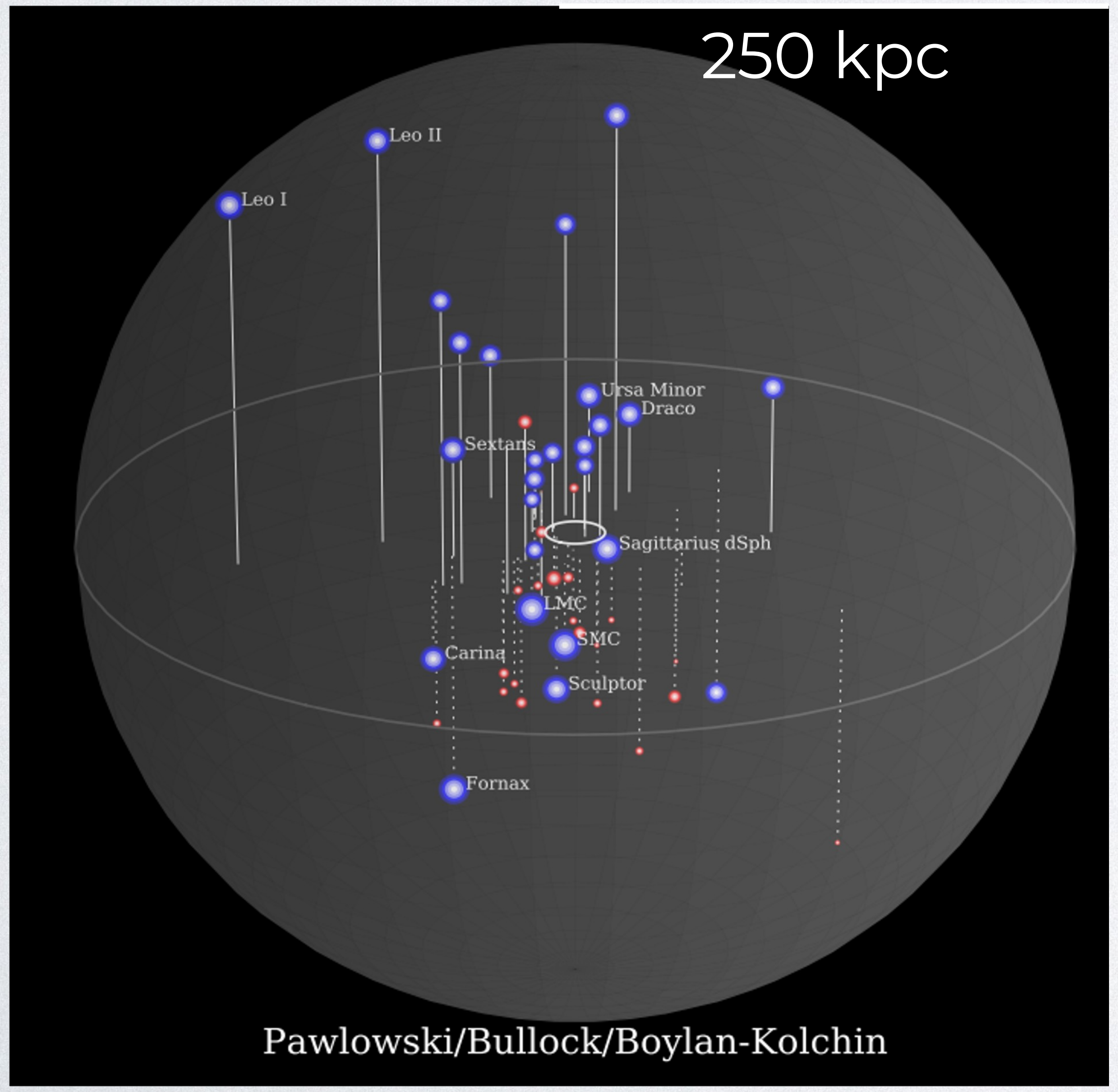
Tradeoffs of DM content, distance, background, etc…

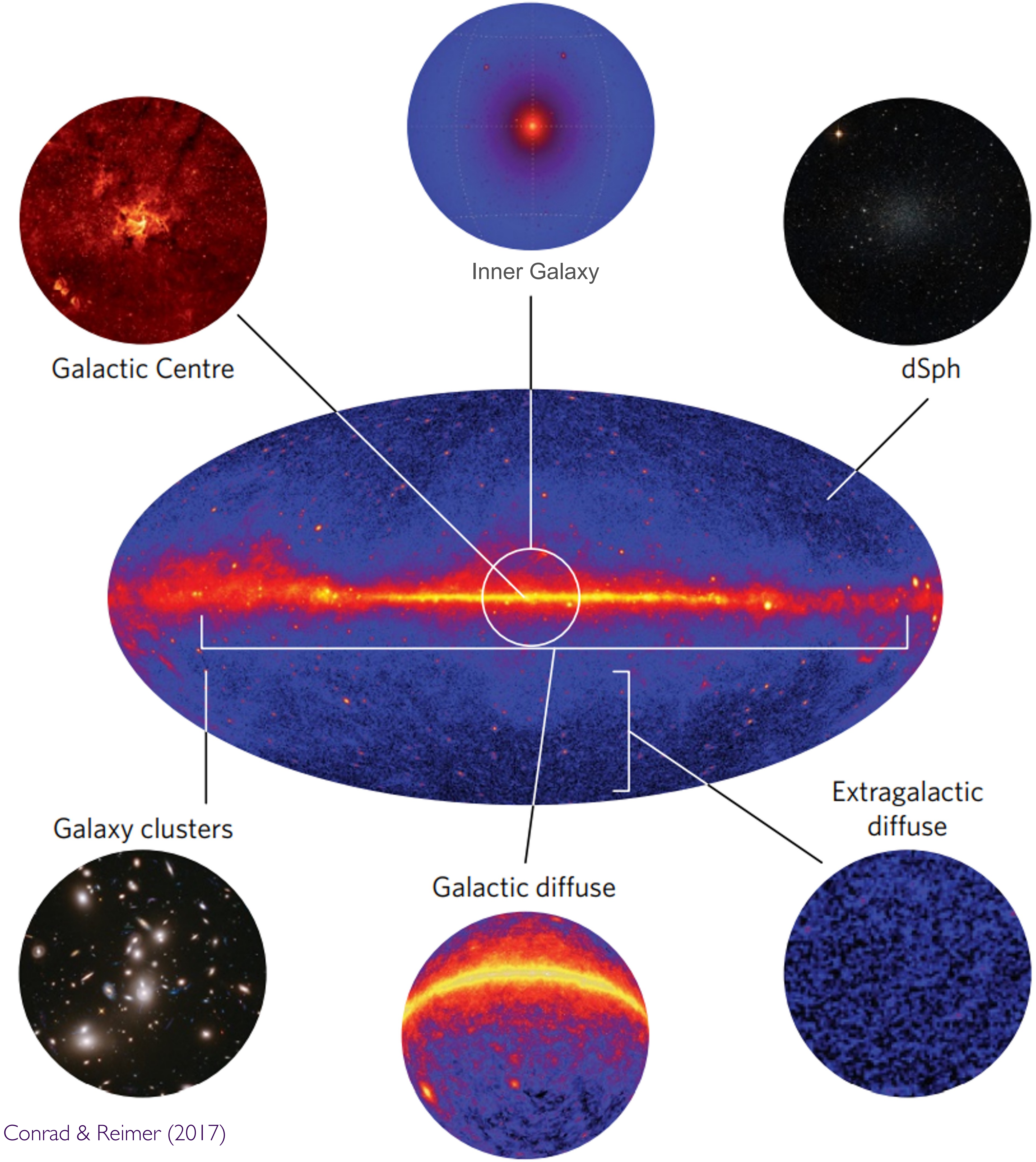
Milky Way dSphs

Nearby, w/in ~ a few hundred kpc

Low astrophysical backgrounds

High dark matter concentration




Conrad & Reimer (2017)

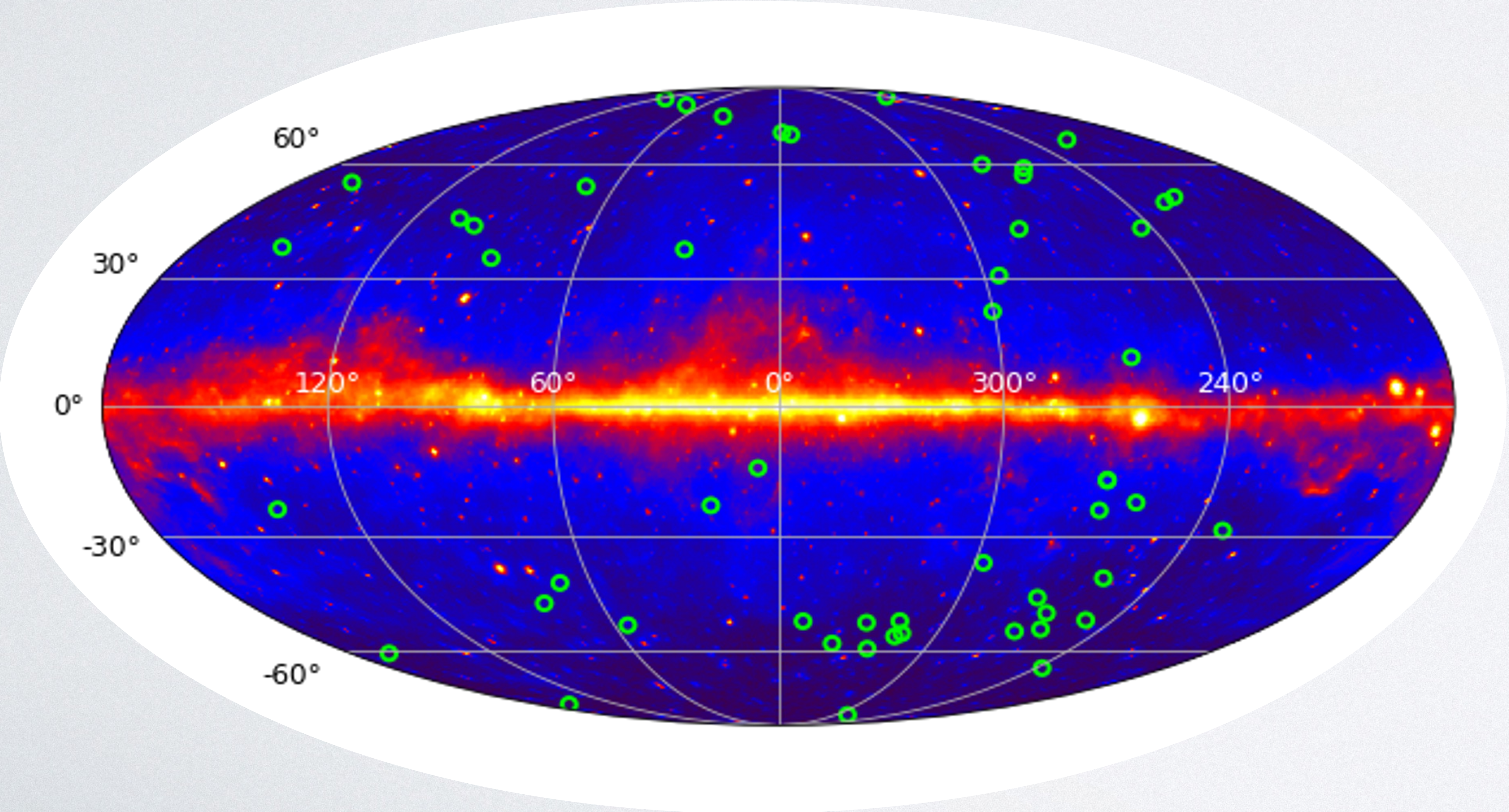
# DSPH SAMPLE SUMMARY

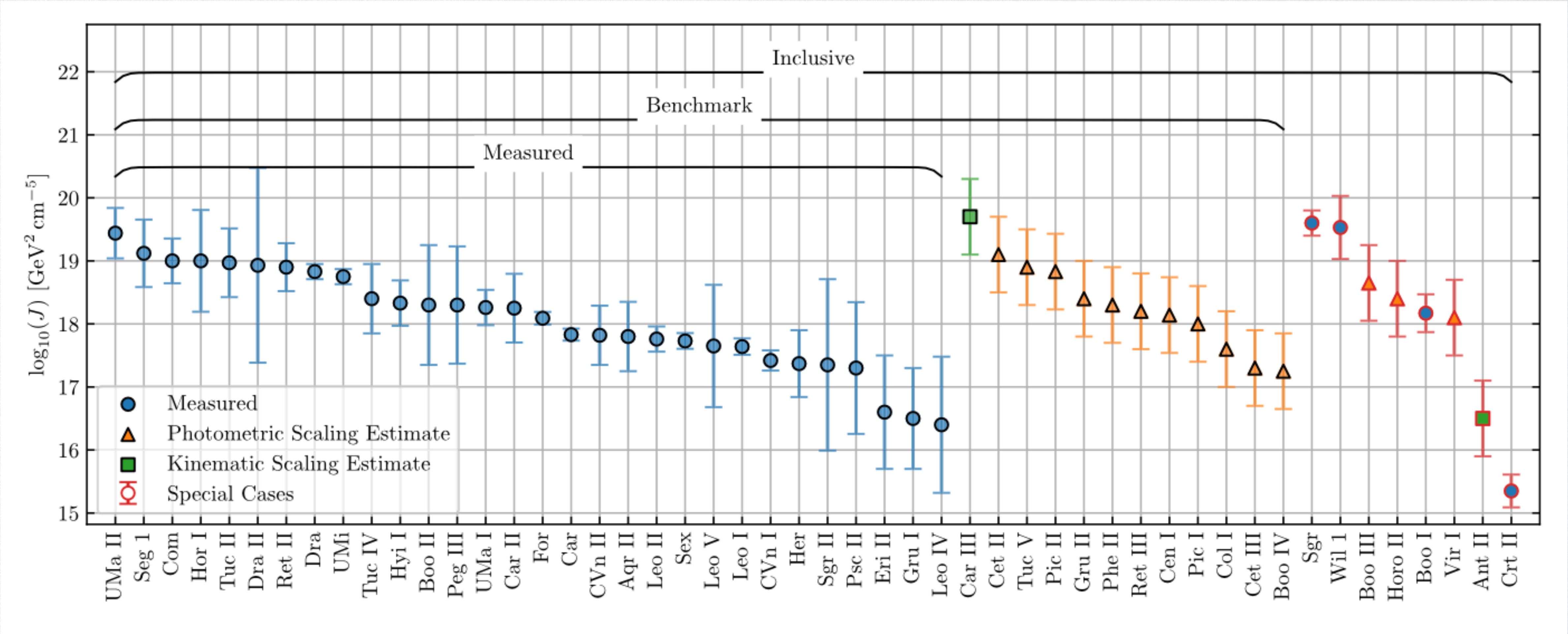
Census of known dSphs collected in Drlica-Wagner+2020 (includes 57 confirmed or possible dSphs)
Discovered in a variety of optical surveys, e.g. DES, PanSTARRs, other DECam surverys, Gaia, etc (~75 % sky coverage)

Sample subsets:

1. Inclusive: All dSphs, including special* cases (50)
2. **Benchmark**: Confirmed and Candidate (42); Excluding Special cases
3. Measured: dSphs with measured J-factors (30); Excluding Special cases

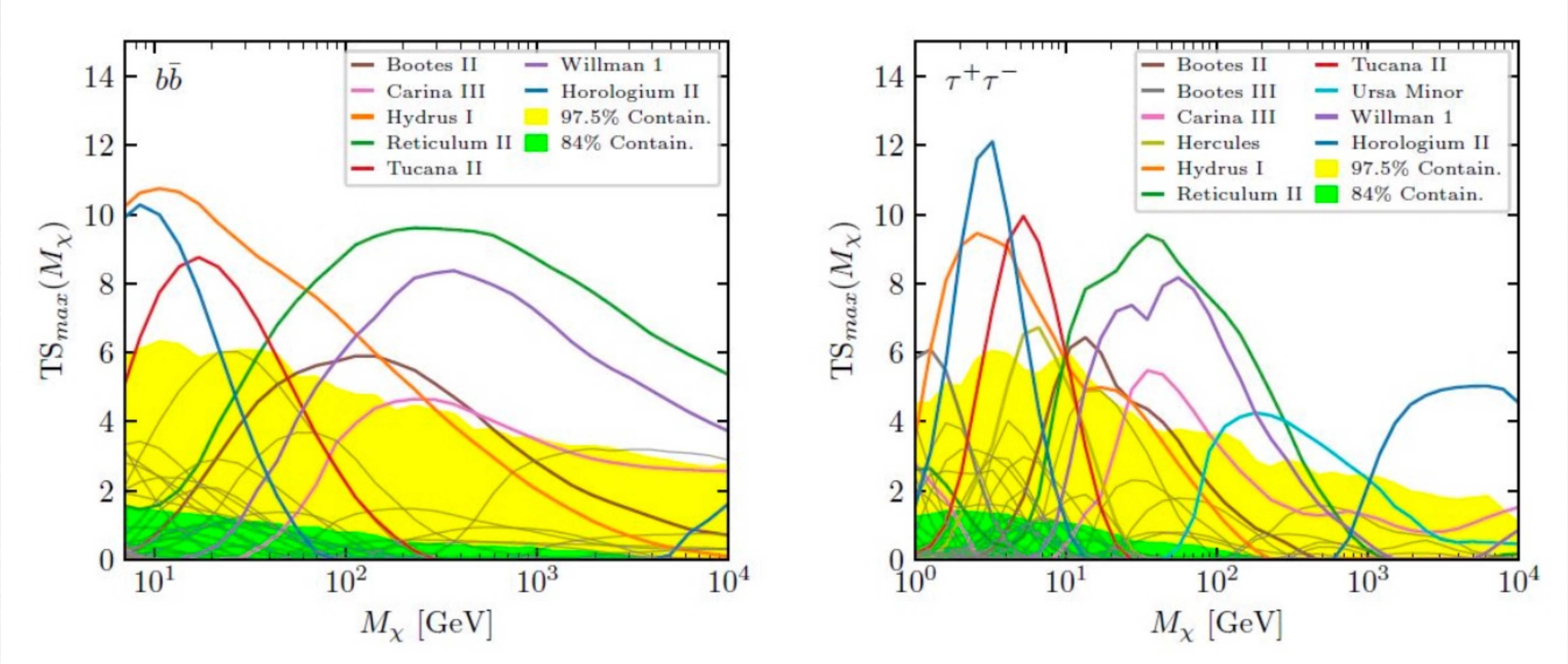
*Special cases are the tidally disrupted systems and those near unresolved blazars or blazar candidates



# INDIVIDUAL TARGETS

- 7 with local significance >2σ

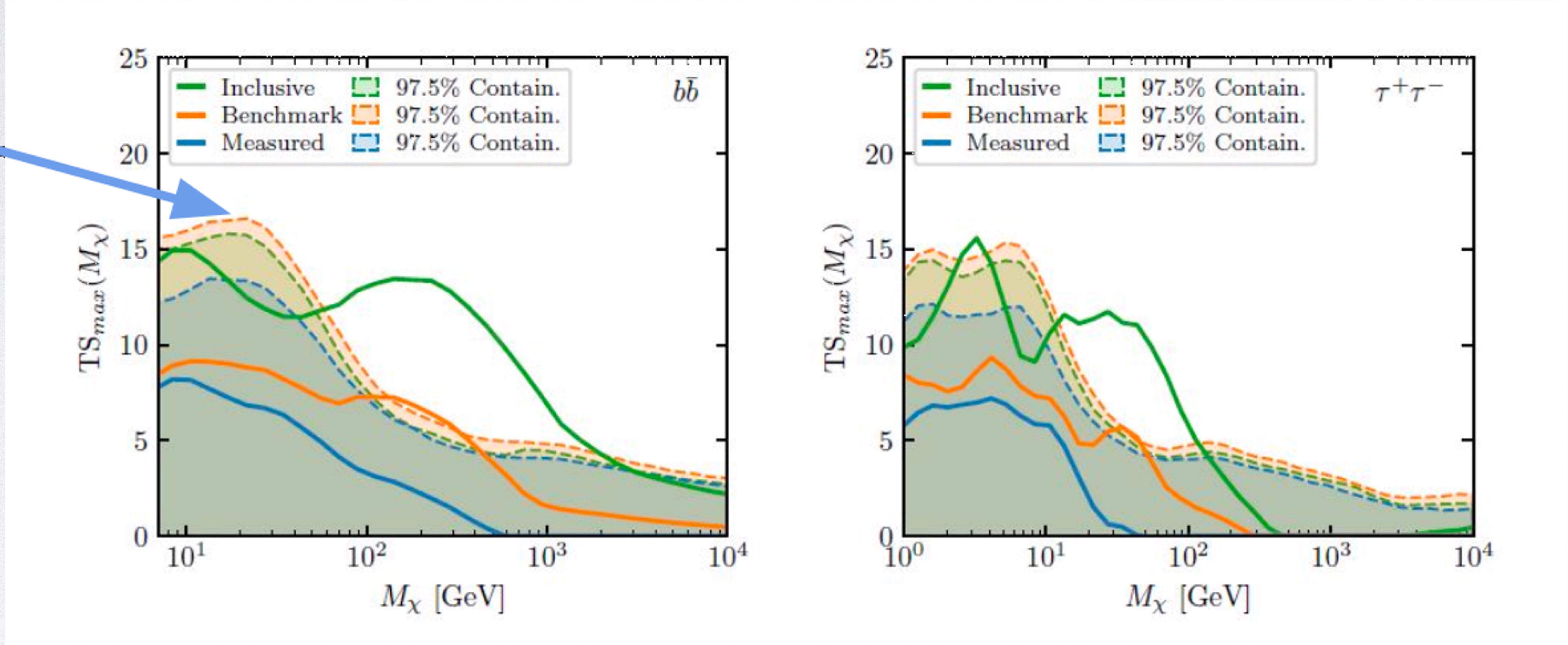



- Some of these dSphs observed at marginal local significance in past studies, e.g.:
- Ret II (DiMauro+2021, Albert+2017, Geringer-Sameth+2015, Hooper & Linden (2015)) Tucana II, Willman 1, Horologium II, Bootes I (Di Mauro+2021)

# STACKING ANALYSIS

~2σ

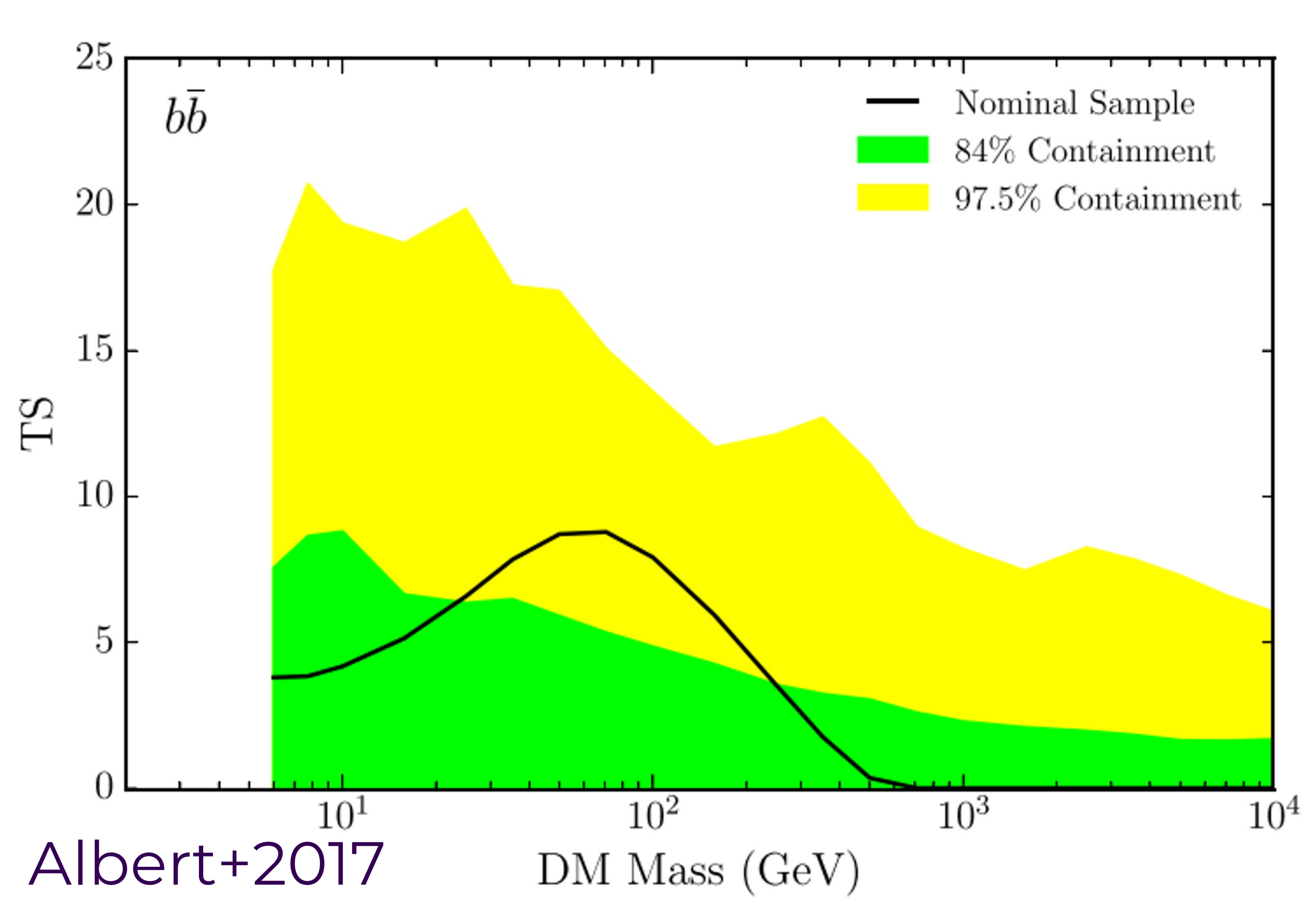
Shaded bands from the blank-field analysis




- 2σ (local) benchmark sample, reduces to <0.5 global significance

# COMBINED DSPH ANALYSIS - PREVIOUS RESULTS

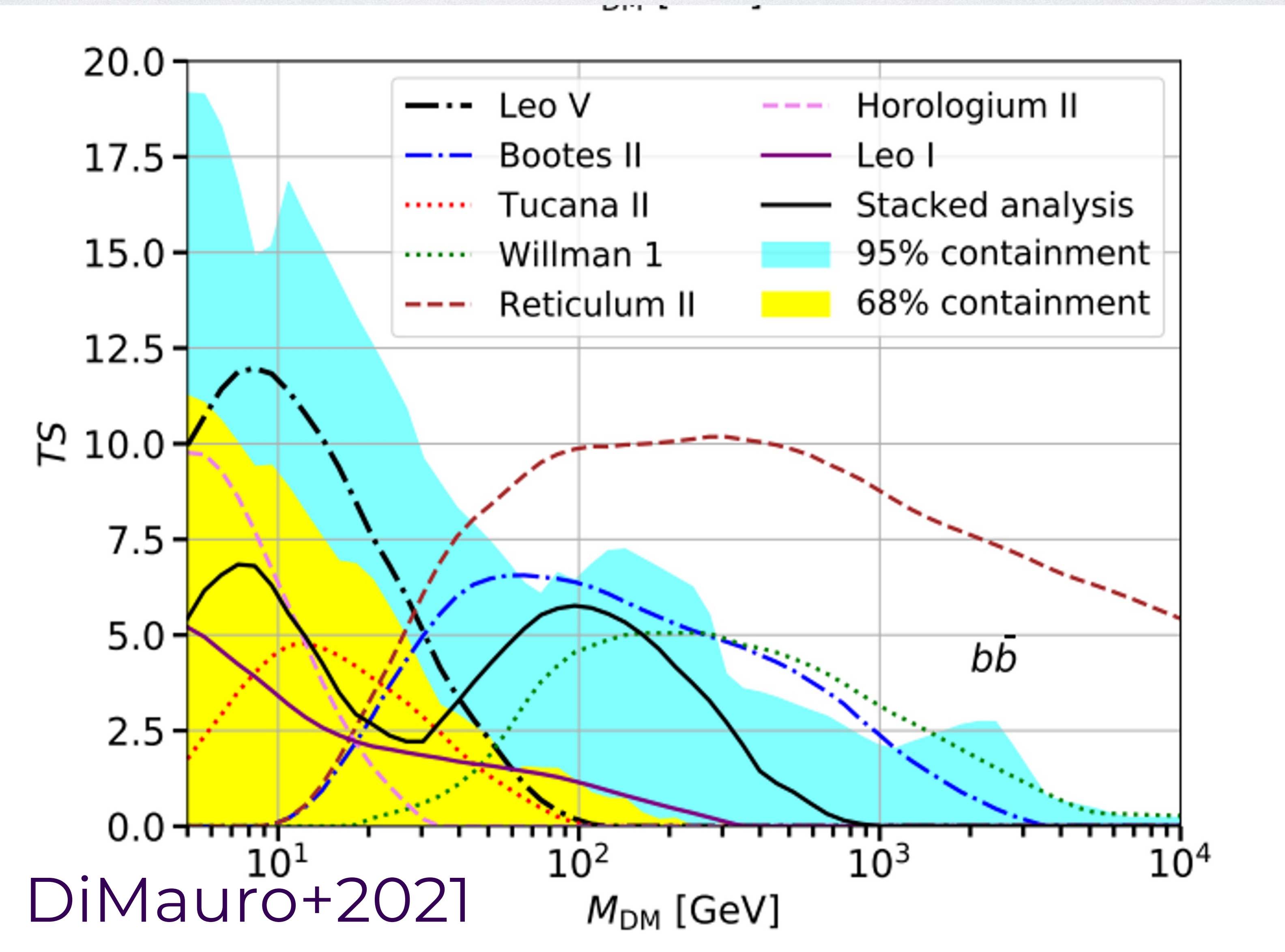
## 6 years




Albert+2017

$<2\sigma$

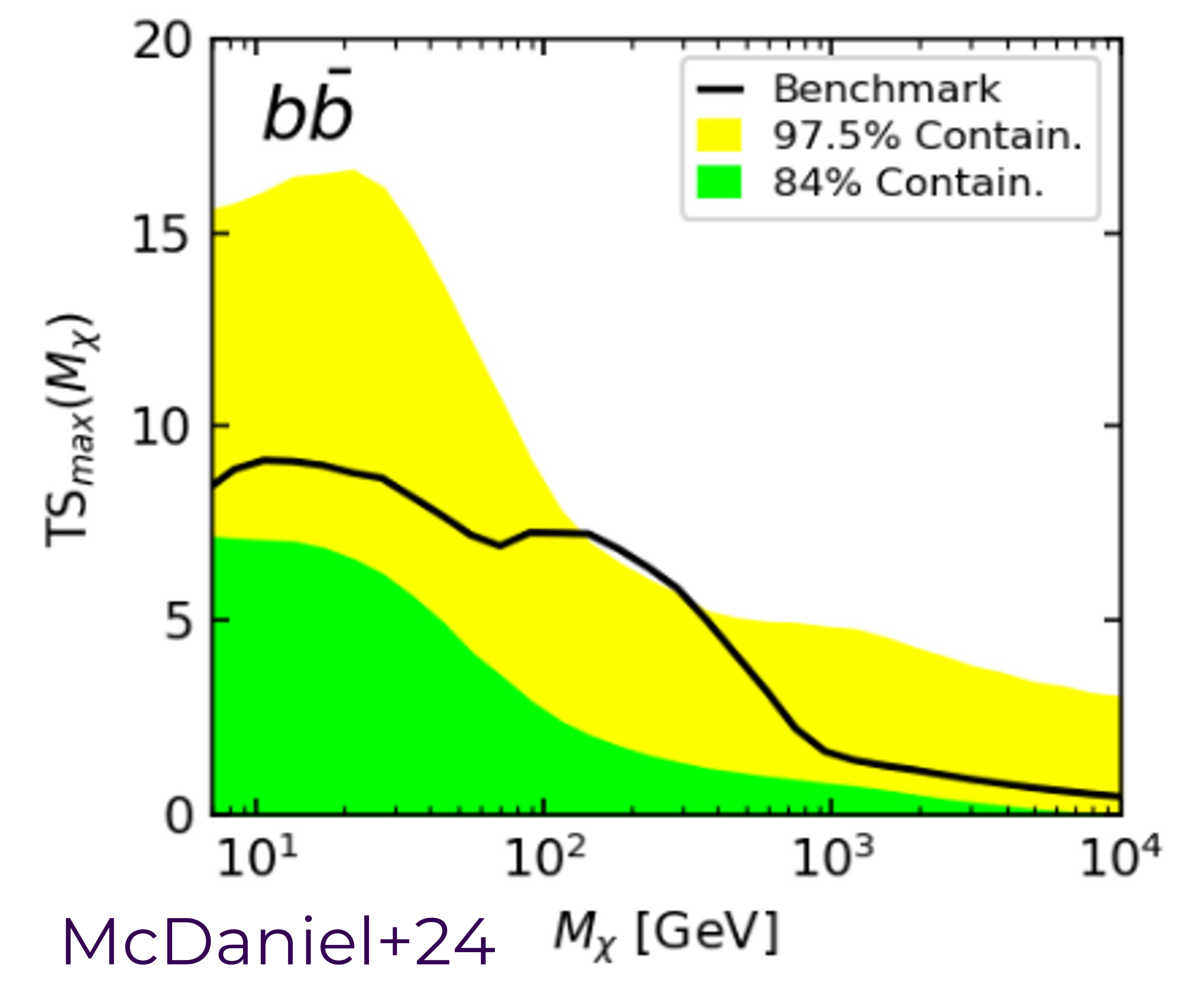
## 11 years




DiMauro+2021

$\lesssim 2\sigma$

## 14 years

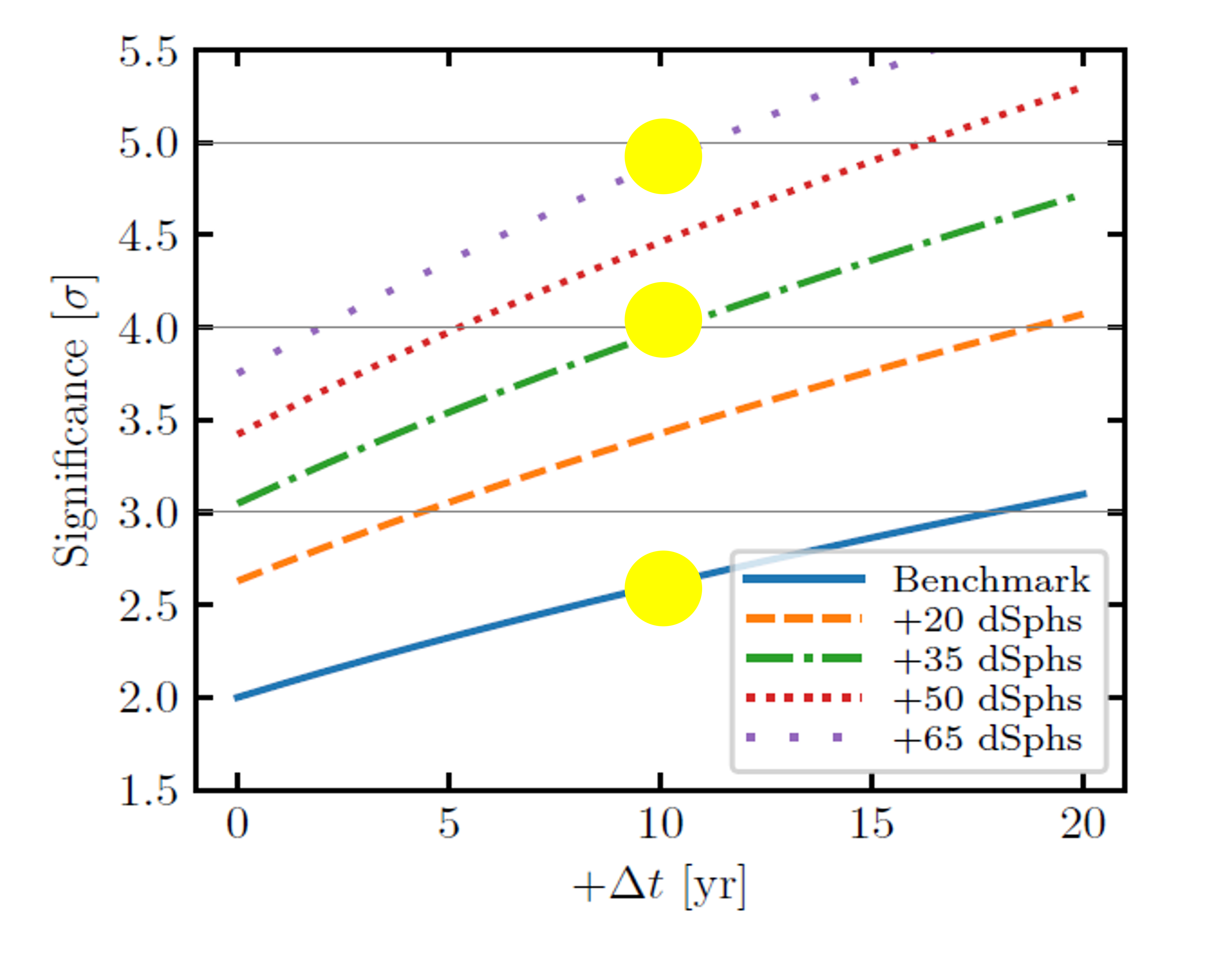



McDaniel+24

$\gtrsim 2\sigma$

# SENSITIVITY PROJECTIONS

## Additional Fermi exposure



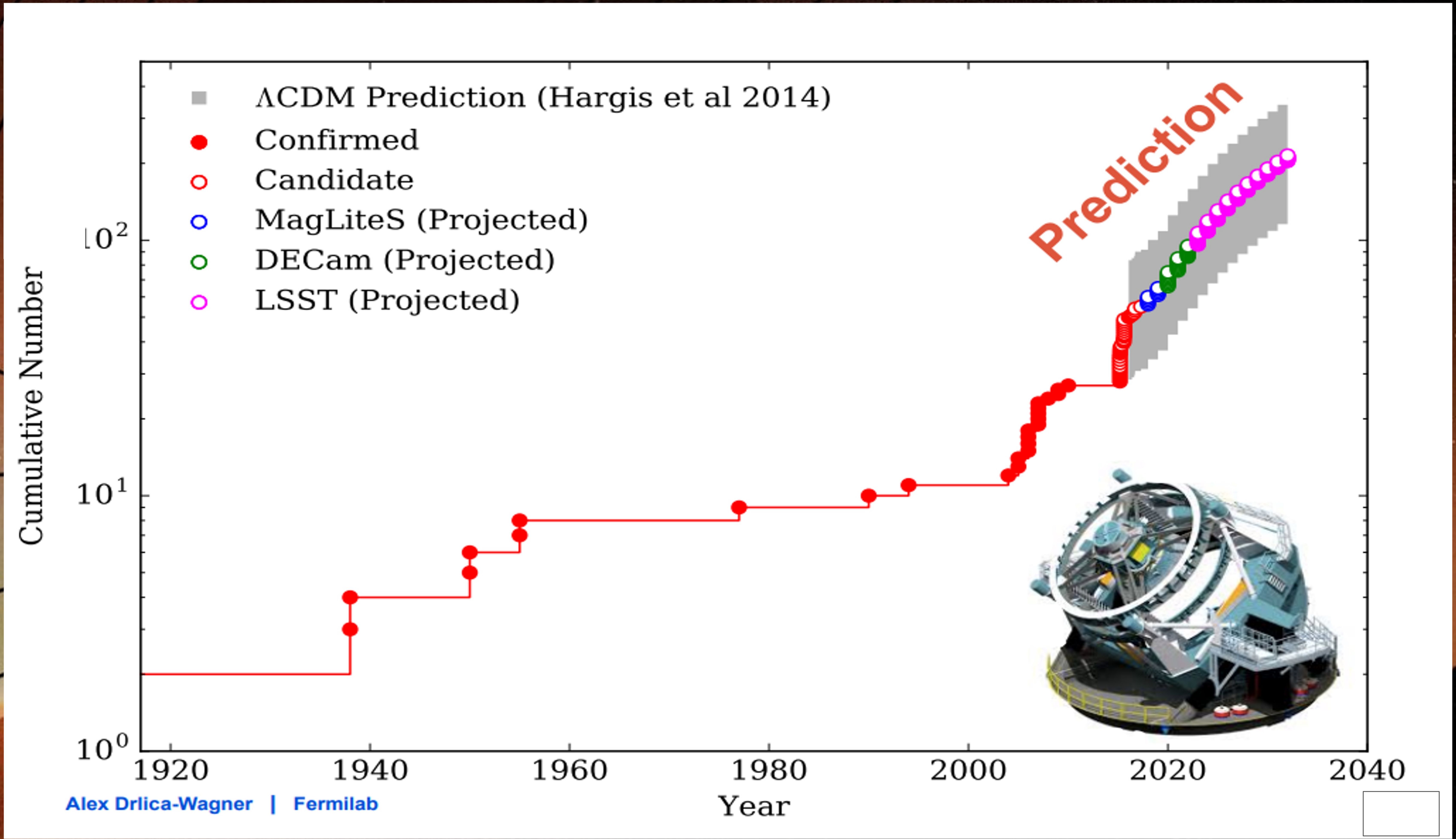

Fermi-LAT dSph sensitivity improves with greater exposure, larger sample size

Sensitivity projections were studied in depth in Charles+2016 for future dSph DM searches

Sensitivity improves with exposure time as $\sigma \sim \text{sqrt}(t)$

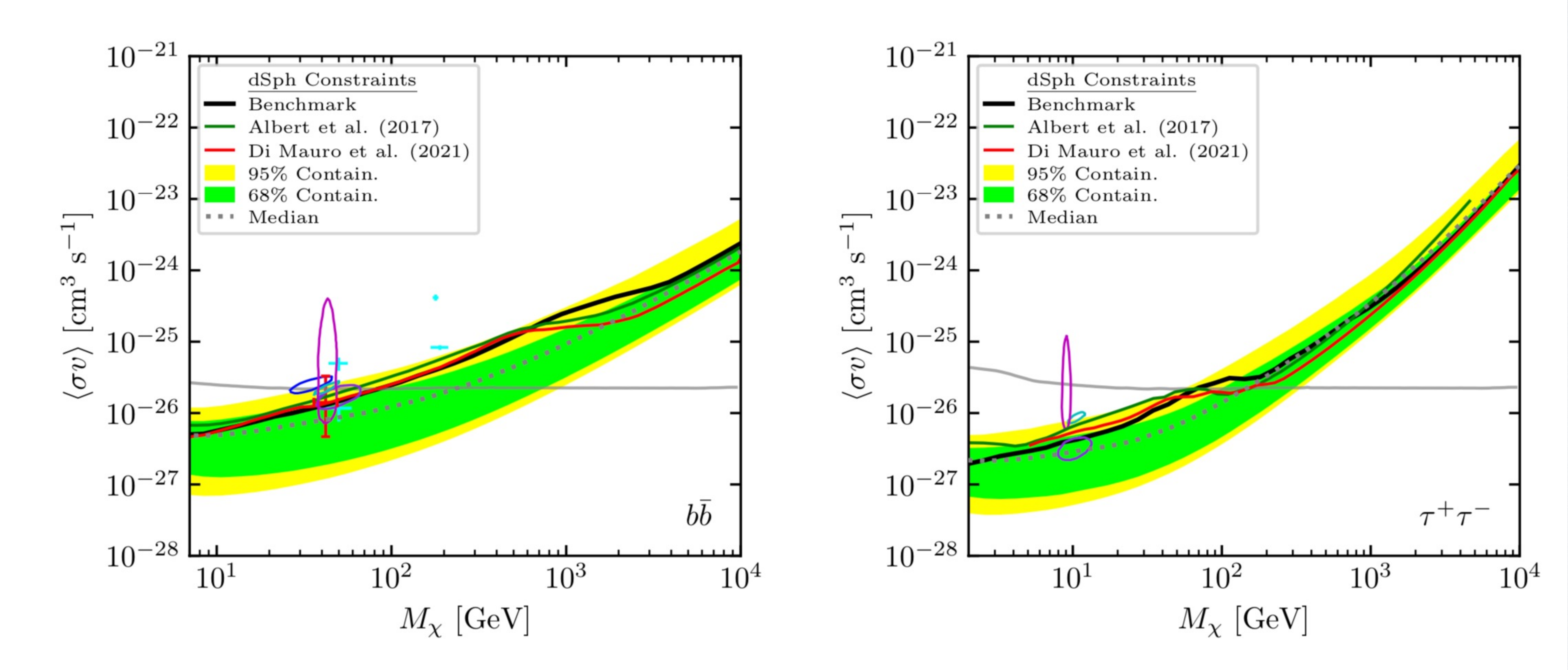
# DISCOVERY POTENTIAL

The Rubin telescope may provide ~100-200 new dSphs



# KEEP FERMI FLYING

# UPPER LIMITS



# SUMMARY

- No definitive DM signal yet, but tantalizing low-$\sigma$ signal in the latest study of MW dwarf galaxies (McDaniel+2024)
- The addition of 35 new dSphs and 10 more years of data could bring this signal above $4\sigma$ (if real)

# EXTRA: SIGNIFICANCE

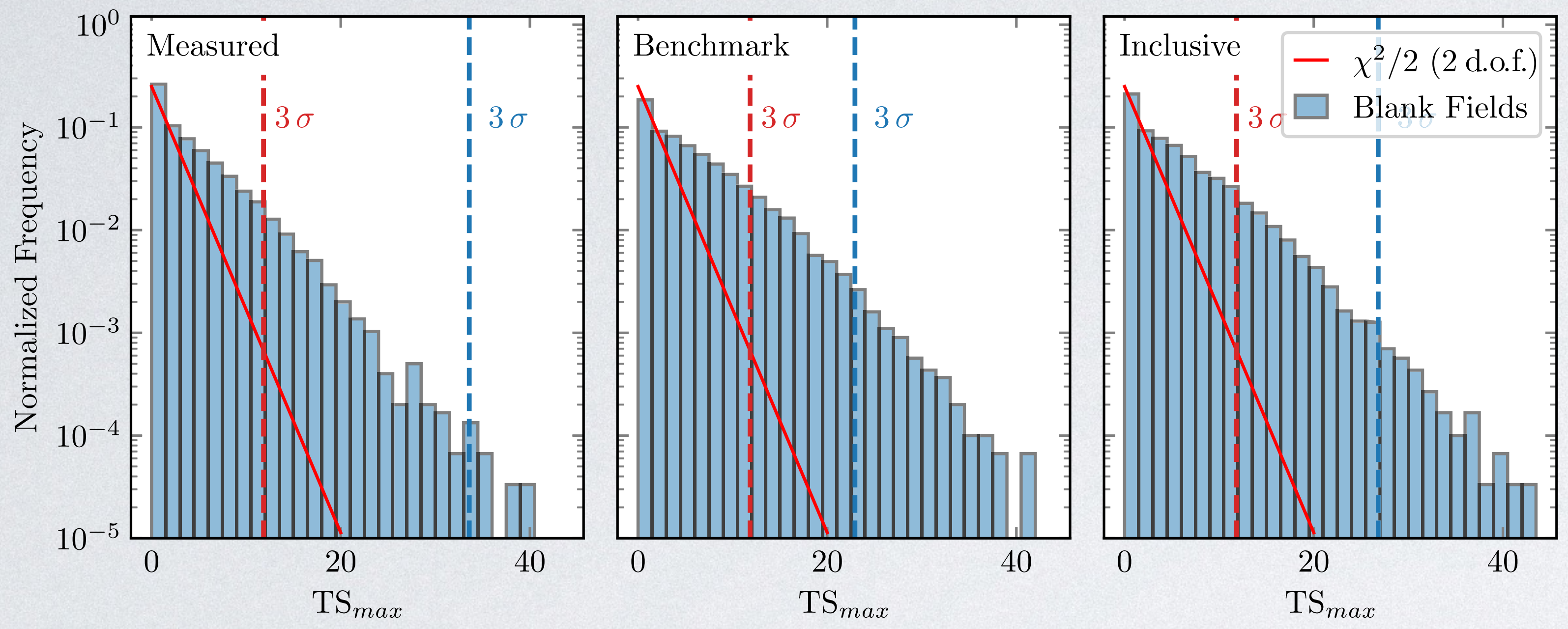



FIG. 2. TS distribution for combined blank fields corresponding to each of our subsamples. For reference, we show the distribution of $\chi^2/2$ with two degrees of freedom, as well as vertical lines comparing the TS value corresponding to $3\sigma$ for the Chernoff's theorem approach (red dashed) vs the empirical method used in this analysis (blue dashed) for a given subsample.

- Analyzed 1000 blank fields
- Sets of combined blank fields can then be obtained by randomly selecting (without replacement) from the pool of 1000 a set of analyzed fields equal to the size of the sample under consideration.
- The likelihoods are then added together to calculate the TS value for the combined blank fields.
- This process is then repeated for 10,000 iterations to construct a sample of combined blank fields.

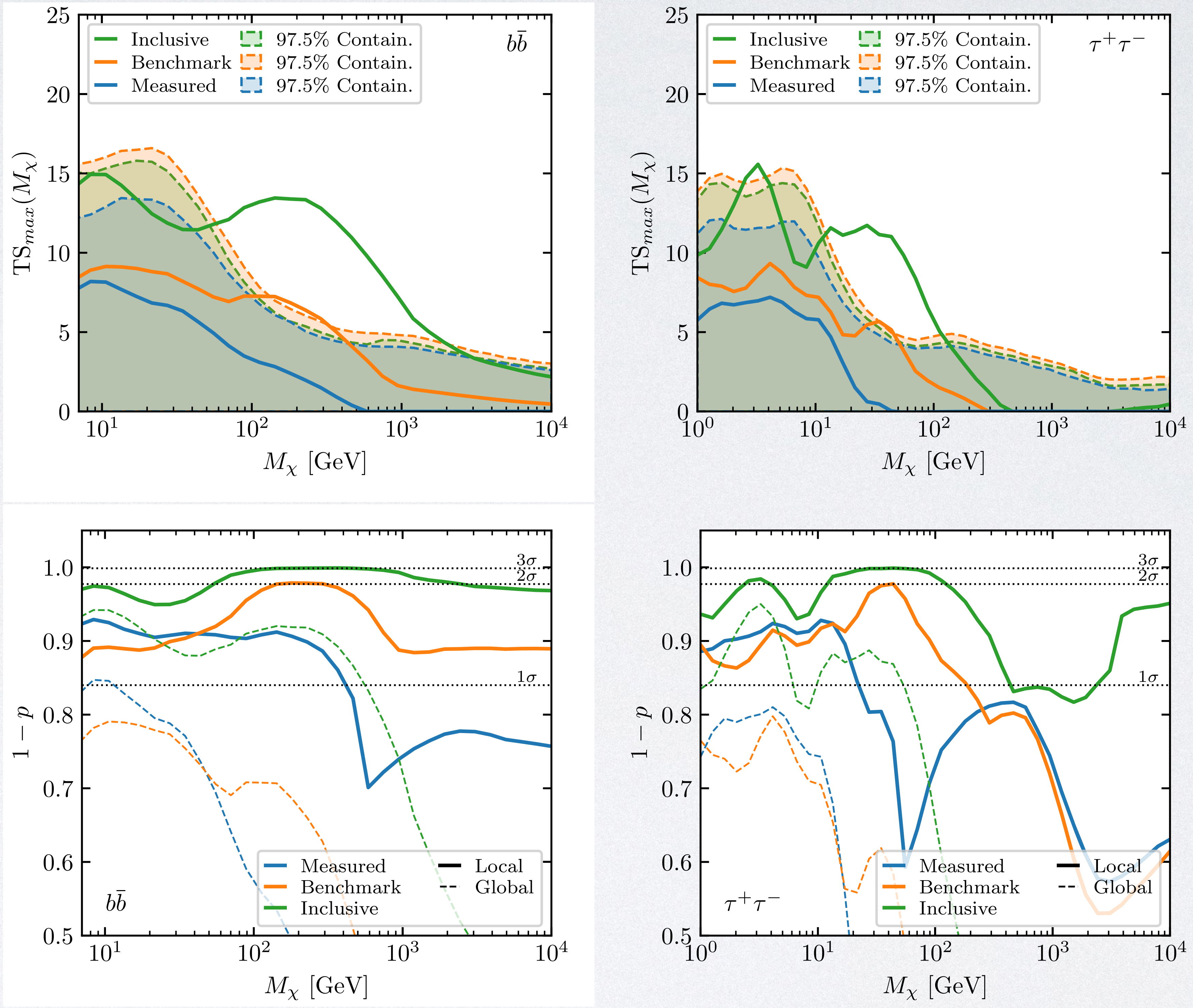



FIG. 5. Top: maximum TS as a function of $M_\chi$ over all cross section values for each dSph sample; shaded regions are the 97.5% containment region for the combined blank fields. Bottom: $1-p$ for each sample with respect to the combined blank fields. Solid lines show the local values ($1-p_{\mathrm{local}}$) while dashed lines show the global values ($1-p_{\mathrm{global}}$). Horizontal dotted lines indicate the 1, 2, and $3\sigma$ levels.

- Each mass has a corresponding TS distribution from the blank skies.
- From this a p-value can be calculated.
- The p-value is interpretated as a significance level assuming a one-sided standard distribution.
- Note that this is the peak TS at a given mass value, and for a specific annihilation channel, and thus it gives the local significance.
- The global significance is obtained by comparing the peak TS to the global distribution, shown in Figure 2.

# SENSITIVITY PROJECTIONS

Predictions about the number and $J$ factor distribution of undiscovered dSphs are very uncertain. In particular, the faint end of the dwarf galaxy luminosity function, the structural properties (and DM distributions) of the smallest satellites, and the radial distribution of subhalos that would host dSphs are not well known.

The SDSS survey covered roughly 1/3 of the sky and discovered 15 ultra-faint dSphs; DES, PanSTARRS, and in particular LSST, will cover complementary regions of the sky to significantly great depth. Combining the distribution of optical luminosities of known dSphs with $N$-body DM simulations and the expanded depth and sky coverage of the new surveys, we can anticipate 25–40 total dSphs to be discovered by DES, and possibly hundreds by LSST [185,186], however many of these dSphs would be more distant and have correspondingly smaller $J$ factors. Even so, LSST is still likely to contribute many dSphs with $J$ factors above $10^{19}$ GeV$^{-2}$ cm$^{-5}$, and is also likely to contribute at least some dSphs with larger $J$ factors than any discovered by DES [187].

In practice, the distribution of $J$ factors for the DES dSphs has been similar to previously discovered dSphs, in spite of the greater depth of the DES survey. This could reflect that the dwarf galaxy luminosity function continues below the faintest objects discovered by SDSS, or it could simply be that the DES survey region has an excess of dSphs, because of the influence of the nearby Magellanic clouds.

| | [deg] | [deg] | [kpc] | [pc] | [mag] | [km $s^{-1}$] | [$\log_{10}$GeV$^2$ cm$^{-5}$] | [M/K/P] | [C/P] |
|---|---|---|---|---|---|---|---|---|---|
| dSphs with Measured $J$-factors | | | | | | | | | |
| Aquarius II | 338.48 | -9.33 | 108.0 | 125 | -4.4 | 4.7[a] | $17.80 \pm 0.55$[a] | M | C |
| Boötes II | 209.51 | 12.86 | 42.0 | 39 | -2.94 | 2.9[a] | $18.30 \pm 0.95$[a] | M | C |
| Canes Venatici I | 202.01 | 33.55 | 218.0 | 338 | -8.8 | 7.6 | $17.42 \pm 0.16$ | M | C |
| Canes Venatici II | 194.29 | 34.32 | 160.0 | 55 | -5.17 | 4.7 | $17.82 \pm 0.47$ | M | C |
| Carina | 100.41 | -50.96 | 105.0 | 248 | -9.43 | 6.4 | $17.83 \pm 0.10$ | M | C |
| Carina II | 114.11 | -58.0 | 36.0 | 77 | -4.5 | 3.4 | $18.25 \pm 0.55$ | M | C |
| Coma Berenices | 186.75 | 23.91 | 44.0 | 57 | -4.38 | 4.7 | $19.00 \pm 0.35$ | M | C |
| Draco | 260.07 | 57.92 | 76.0 | 180 | -8.71 | 9.1 | $18.83 \pm 0.12$ | M | C |
| Draco II | 238.17 | 64.58 | 22.0 | 17 | -0.8 | 3.4 | $18.93 \pm 1.54$ | M | P |
| Eridanus II | 56.09 | -43.53 | 380.0 | 158 | -7.21 | 7.1 | $16.60 \pm 0.90$ | M | C |
| Fornax | 39.96 | -34.5 | 147.0 | 707 | -13.46 | 10.6 | $18.09 \pm 0.10$ | M | C |
| Grus I | 344.18 | -50.18 | 120.0 | 21 | -3.47 | 4.5 | $16.50 \pm 0.80$ | M | P |
| Hercules | 247.77 | 12.79 | 132.0 | 120 | -5.83 | 3.9 | $17.37 \pm 0.53$ | M | C |
| Horologium I | 43.88 | -54.12 | 79.0 | 31 | -3.55 | 5.9 | $19.00 \pm 0.81$ | M | C |
| Hydrus I | 37.39 | -79.31 | 28.0 | 53 | -4.71 | 2.7[b] | $18.33 \pm 0.36$[b] | M | C |
| Leo I | 152.11 | 12.31 | 254.0 | 226 | -11.78 | 9.0 | $17.64 \pm 0.13$ | M | C |
| Leo II | 168.36 | 22.15 | 233.0 | 165 | -9.74 | 7.4 | $17.76 \pm 0.20$ | M | C |
| Leo IV | 173.24 | -0.55 | 154.0 | 104 | -4.99 | 3.4 | $16.40 \pm 1.08$ | M | C |
| Leo V | 172.79 | 2.22 | 178.0 | 39 | -4.4 | 4.9 | $17.65 \pm 0.97$ | M | C |
| Pegasus III | 336.1 | 5.41 | 215.0 | 42 | -3.4 | 7.9 | $18.30 \pm 0.93$ | M | C |
| Pisces II | 344.63 | 5.95 | 182.0 | 48 | -4.22 | 4.8 | $17.30 \pm 1.04$ | M | C |
| Reticulum II | 53.92 | -54.05 | 30.0 | 31 | -3.88 | 3.4 | $18.90 \pm 0.38$ | M | C |
| Sagittarius II | 298.16 | -22.07 | 69.0 | 32 | -5.2 | 2.7[c] | $17.35 \pm 1.36$[d] | M | P |
| Segue 1 | 151.75 | 16.08 | 23.0 | 20 | -1.3 | 3.1 | $19.12 \pm 0.53$ | M | C |
| Sextans | 153.26 | -1.61 | 86.0 | 345 | -8.72 | 7.1 | $17.73 \pm 0.12$ | M | C |
| Tucana II | 342.98 | -58.57 | 58.0 | 165 | -3.8 | 7.3 | $18.97 \pm 0.54$ | M | C |
| Tucana IV | 0.73 | -60.85 | 48.0 | 128 | -3.5 | 4.3[e] | $18.40 \pm 0.55$[e] | M | C |
| Ursa Major I | 158.77 | 51.95 | 97.0 | 151 | -5.12 | 7.3 | $18.26 \pm 0.28$ | M | C |
| Ursa Major II | 132.87 | 63.13 | 32.0 | 85 | -4.25 | 7.2 | $19.44 \pm 0.40$ | M | C |
| Ursa Minor | 227.24 | 67.22 | 76.0 | 272 | -9.03 | 9.3 | $18.75 \pm 0.12$ | M | C |