# Dark Matter Subhalos in the Fermi First Source Catalog


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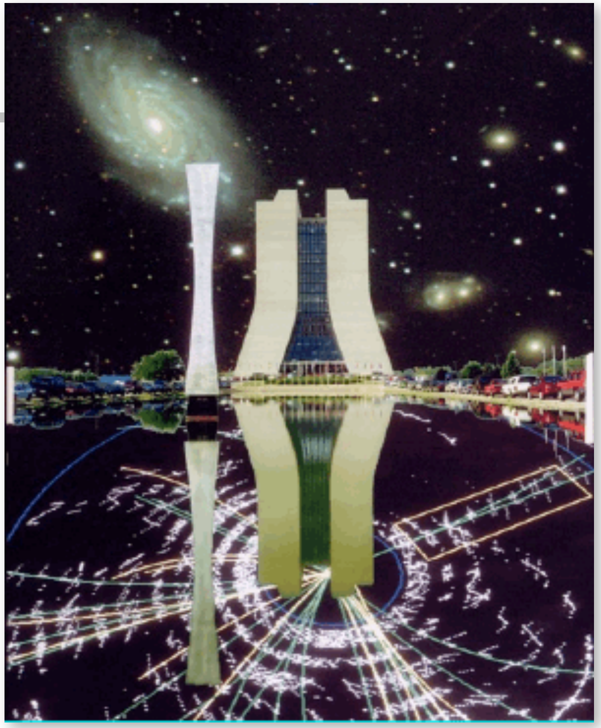
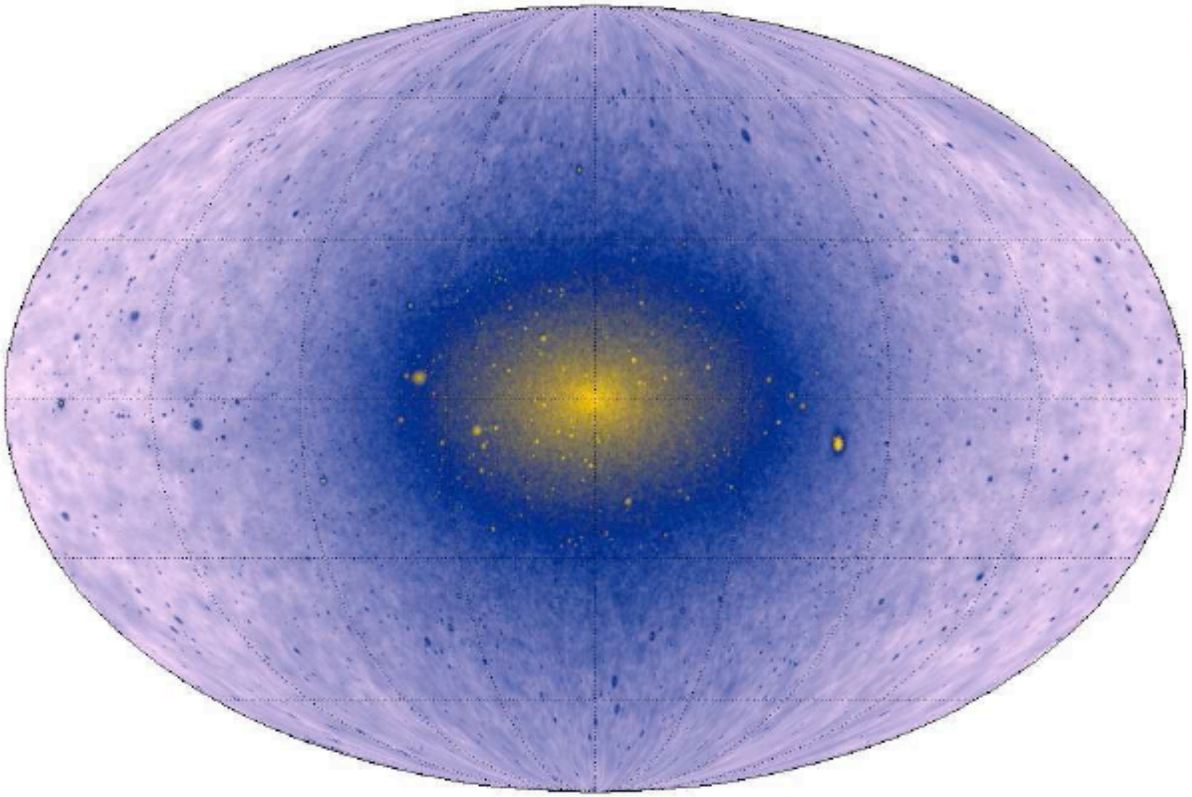


# An Essential Test:
## Searches For Gamma Rays From Dark Matter Annihilations With Fermi

- Last year, the FERMI collaboration announced their first results!
- In August, their first year data became publicly available
- Signatures of dark matter annihilation might appear clearly and quickly, or over years of exposure, or not at all, depending on the dark matter distribution, annihilation cross section, mass, and astrophysical backgrounds

# Where To Look For Dark Matter With Fermi?

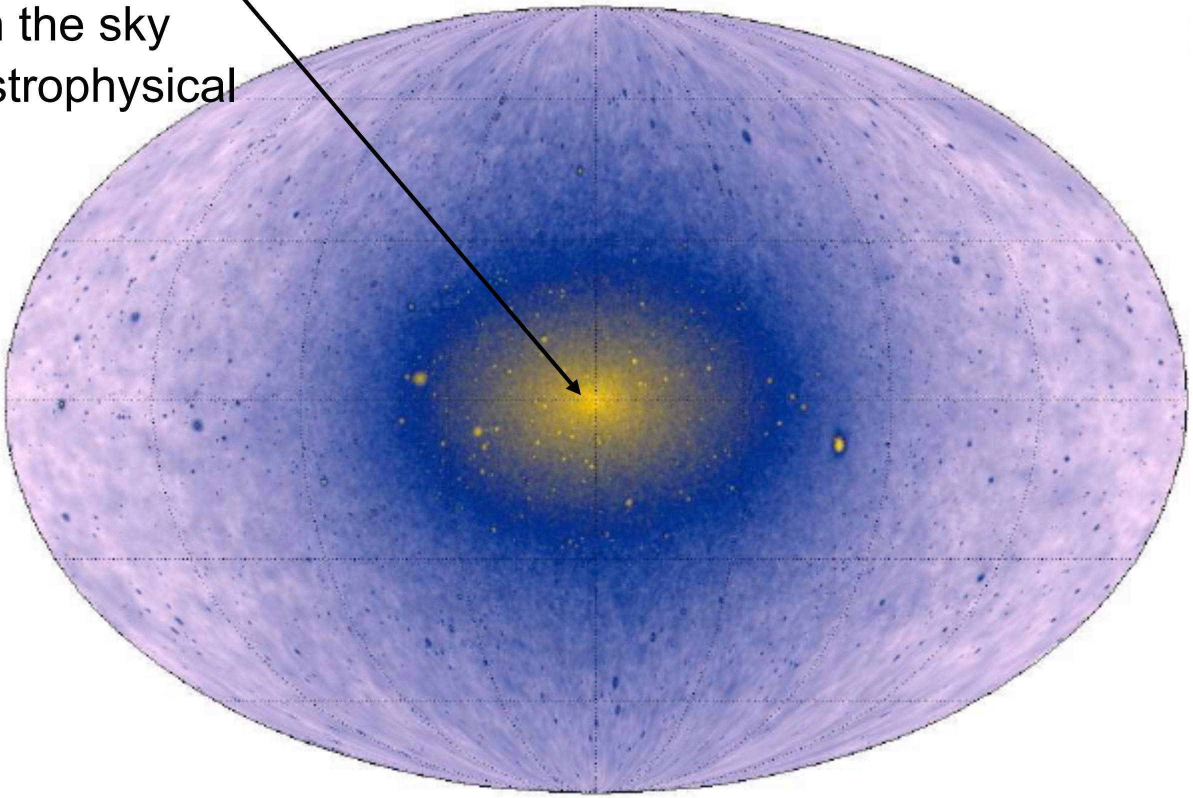


# Where To Look For Dark Matter With Fermi?

## The Galactic Center

-Brightest spot in the sky

-Considerable astrophysical backgrounds



# Where To Look For Dark Matter With Fermi?

## The Galactic Halo

-High statistics
-Requires detailed model of galactic backgrounds

## The Galactic Center

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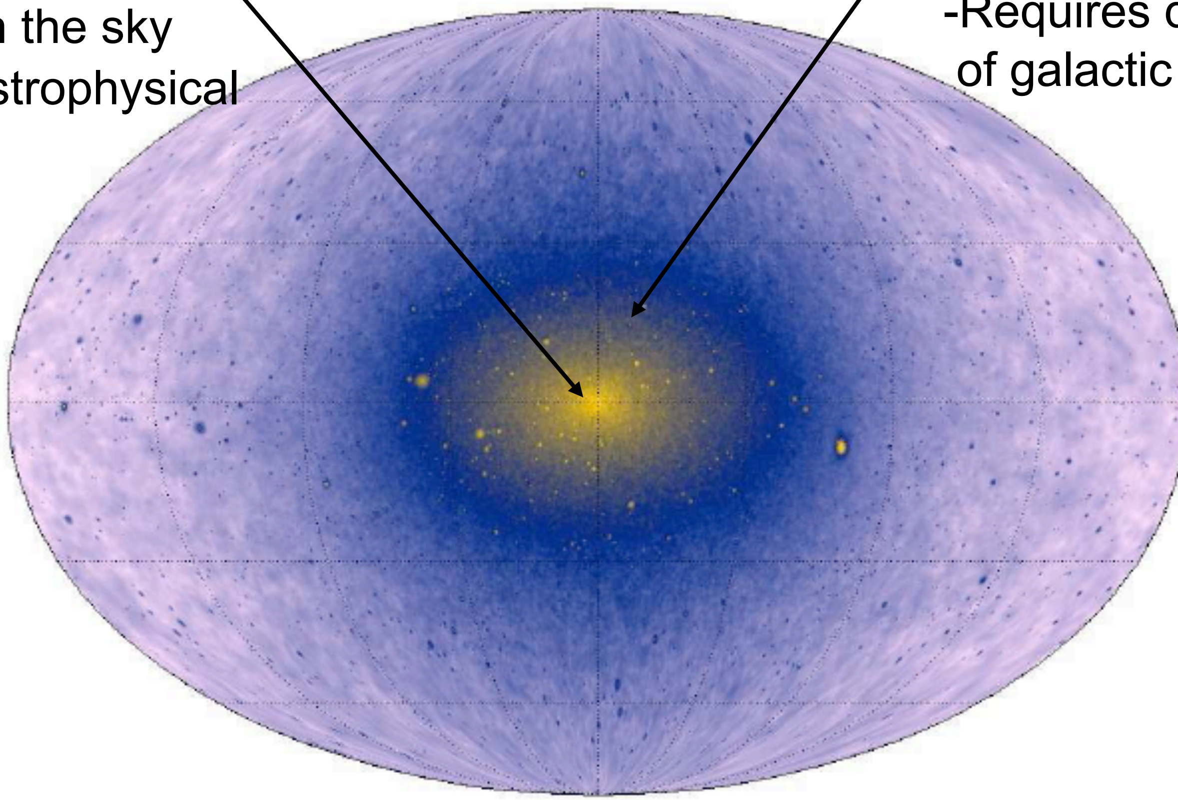

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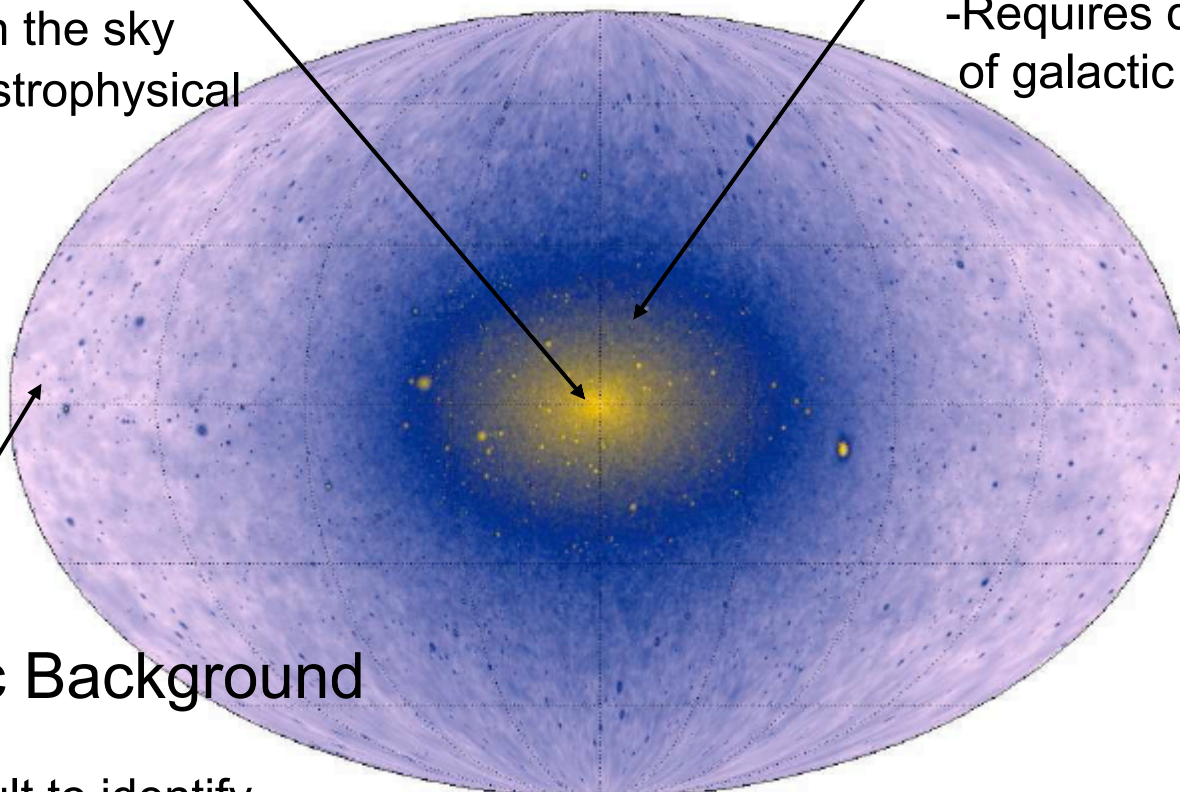

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-High statistics
-potentially difficult to identify

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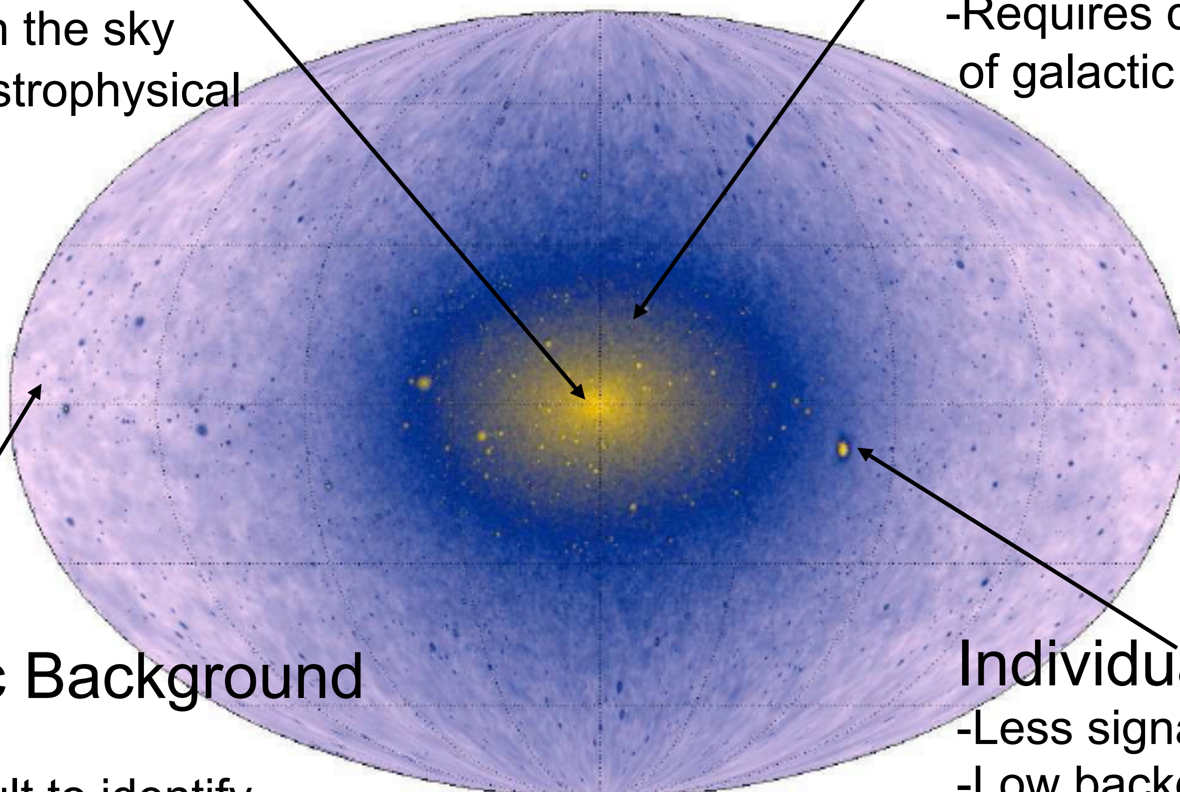


## Extragalactic Background

-High statistics
-potentially difficult to identify

## Individual Subhalos

-Less signal
-Low backgrounds

# Nearby Dark Matter Subhalos

- In the standard picture of hierarchical structure formation, dark matter formed the smallest halos first, which larger merged to eventually form galaxies and clusters
- The Milky Way is expected to contain ~$5 \times 10^{16}$ subhalos of Earth mass or greater (~30-40 per $pc^3$ in our local neighborhood)
- Simulations find ~10% of the Milky Way halo's mass is expected to be in $10^7$-$10^{10}$ solar mass subhalos
- Potentially detectable gamma ray point sources

# Nearby Dark Matter Subhalos

- The Fermi Collaboration has recently published a catalog of point sources, 368 of which are more than 10˚ away from the galactic plane and not associated with any known source in other wavelengths
- Might some number of these unidentified sources be dark matter subhalos?
- What kind of subhalos could potentially appear among these sources?

Fermi Collaboration, arXiv:1002.2280

# The Largest Dark Matter Subhalos - Dwarf Spheroidal Galaxies

- The FGST collaboration has recently placed some relatively stringent limits on dark matter from observations of a number of satellite galaxies (dwarf spheroidals) of the Milky Way
- The most stringent limits come from those dwarfs which are dense, nearby, and in low background regions of the sky

| Name | Distance (kpc) | year of discovery | $M_{1/2}/L_{1/2}$ ref. 8 | l | b | Ref. |
|---|---|---|---|---|---|---|
| Ursa Major II | 30± 5 | 2006 | $4000^{+3700}_{-2100}$ | 152.46 | 37.44 | 1,2 |
| Segue 2 | 35 | 2009 | 650 | 149.4 | -38.01 | 3 |
| Willman 1 | 38± 7 | 2004 | $770^{+930}_{-440}$ | 158.57 | 56.78 | 1 |
| Coma Berenices | 44± 4 | 2006 | $1100^{+800}_{-500}$ | 241.9 | 83.6 | 1,2 |
| Bootes II | 46 | 2007 | 18000?? | 353.69 | 68.87 | 6,7 |
| Bootes I | 62±3 | 2006 | $1700^{+1400}_{-700}$ | 358.08 | 69.62 | 6 |
| Ursa Minor | 66± 3 | 1954 | $290^{+140}_{-90}$ | 104.95 | 44.80 | 4,5 |
| Sculptor | 79± 4 | 1937 | $18^{+6}_{-5}$ | 287.15 | -83.16 | 4,5 |
| Draco | 76± 5 | 1954 | $200^{+80}_{-60}$ | 86.37 | 34.72 | 4,5,9 |
| Sextans | 86± 4 | 1990 | $120^{+40}_{-35}$ | 243.4 | 42.2 | 4,5 |
| Ursa Major I | 97±4 | 2005 | $1800^{+1300}_{-700}$ | 159.43 | 54.41 | 6 |
| Hercules | 132±12 | 2006 | $1400^{+1200}_{-700}$ | 28.73 | 36.87 | 6 |
| Fornax | 138± 8 | 1938 | $8.7^{+2.8}_{-2.3}$ | 237.1 | -65.7 | 4,5 |
| Leo IV | 160±15 | 2006 | $260^{+1000}_{-200}$ | 265.44 | 56.51 | 6 |

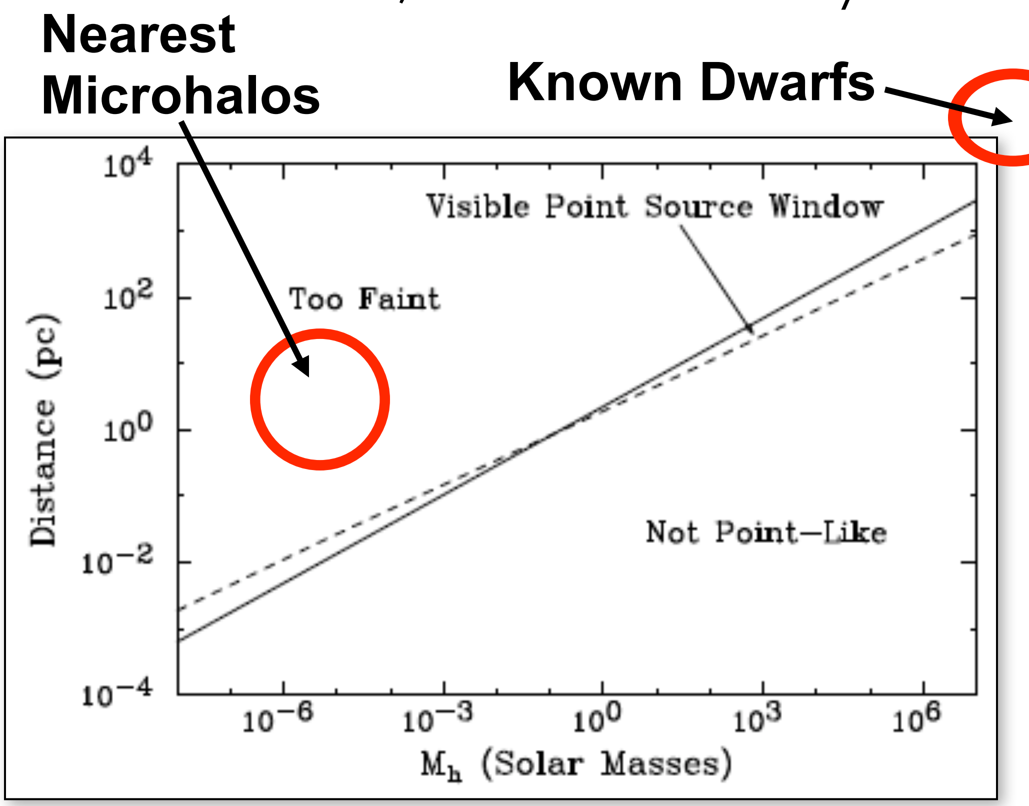
FGST Collaboration, arXiv:1001.4531

# The Smallest Dark Matter Structures- Microhalos

- The first dark matter halos to form are also the smallest
- This minimum halo mass depends on the temperature at which the dark matter decoupled from the cosmic neutrino background - for typical WIMPs, the smallest halos are $\sim 10^{-8}$ to $10^{-3}$ solar masses
- The Milky Way should be utterly swimming in microhalos

# Dark Matter Subhalos

- Neither dwarf spheroidals, nor microhalos are the most likely type of subhalos to appear within the First Fermi Source catalog
- To be detectable by FGST, a $10^{-3}$ solar mass halo would have to be within ~0.1 pc; not likely at this distance, and would likely be extended (not point-like)




M. Buckley and D. Hooper, arXiv:1004.1633

- A $10^3$ solar mass halo could be as far away as ~100 pc, and appear point-like to FGST

⇒ *Focus on ~$10^3$-$10^7$ $M_\odot$ subhalos within ~1 kpc (bonus - range where halo survival, concentrations are least uncertain!)*

# Nearby Dark Matter Subhalos

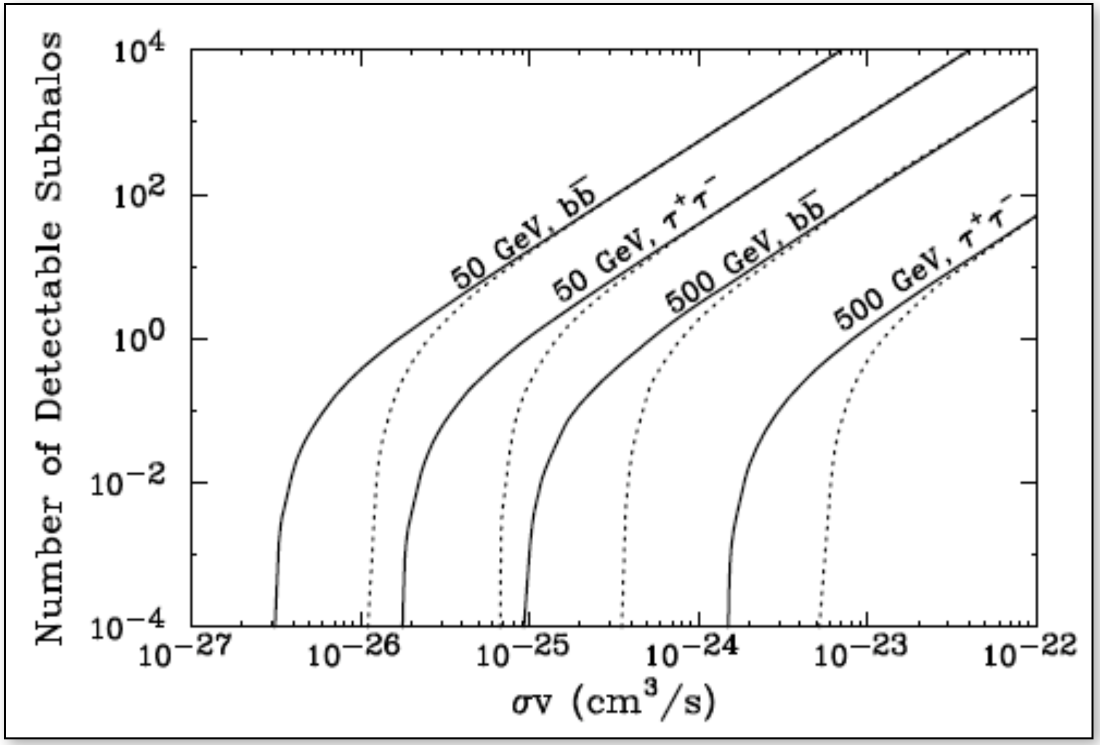
- Adopt a default halo profile motivated by Via Lactea (NFW-like, with inner slope of ~1.2)
- Tidal effects are expected to remove much of a given subhalo's mass (default assumption: outer 99% is removed)
- Adopt Bullock *et al*. mass-concentration relationship
- These represent reasonable and fairly conservative assumptions



Fermi Collaboration, arXiv:1002.2280

# Nearby Dark Matter Subhalos

- The number of subhalos detectable by FGST depends on the WIMP's mass, annihilation cross section, and annihilation channel
- A 50 GeV WIMP with a simple thermal cross section is expected to yield a few subhalos that are detectable by FGST

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- Variations in halo profile shape and mass losses assumed can alter the number of subhalos by a factor of a several in either direction
- If sub-substructure is significant the number can be larger

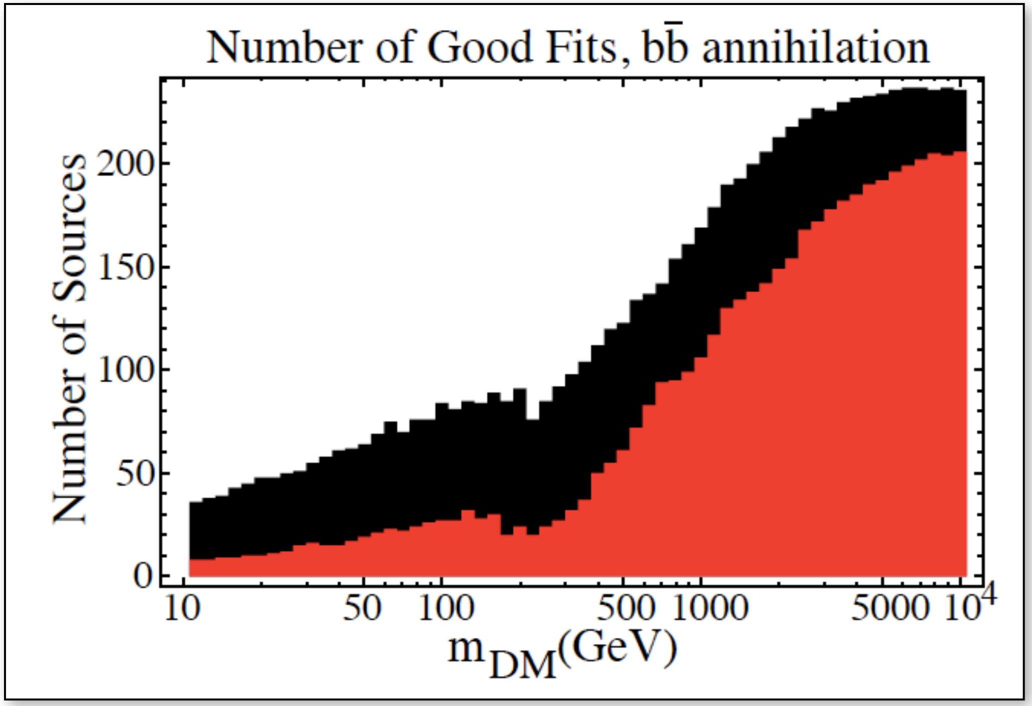
| Model/Parameters | Detectable, Point-Like Subhalos |
|---|---|
| Default ($\gamma = 1.2$, ML=99%) | 16.8 |
| $\gamma = 1.0$, ML=99% | 1.94 |
| $\gamma = 1.2$, ML=90% | 46.4 |
| $\gamma = 1.0$, ML=90% | 8.57 |
| Einasto $\alpha = 0.17$, ML=99% | 6.50 |
| Einasto $\alpha = 0.17$, ML=90% | 13.4 |
| Default w/ sub-subhalos | |
| $M_{\rm min} = 10^{-6} M_\odot$ | 40.9 |
| $M_{\rm min} = 10^{-8} M_\odot$ | 83.9 |

TABLE I: The impact of various astrophysical assumptions on the number of point-like subhalos observable by FGST. Results are shown for a 50 GeV dark matter particle that annihilates with $\sigma v = 10^{-25}$ cm$^3$/s to $b\bar{b}$. Note that halo-to-halo variation in the concentration parameter is expected to further increase the number of detectable point-like halos by a factor of $\sim$2. See text for more details.

M. Buckley and D. Hooper, arXiv:1004.1633

# Nearby Dark Matter Subhalos

- For a given mass and annihilation channel, we determine how many of the Fermi point sources provide a good fit
- A population of dark matter subhalos would be expected to generate a feature in this distribution (we determine the expected shape by Monte Carlo, see paper for more details)
- In most cases, we find that there cannot be more than 20-60 subhalos among the sources in the Fermi catalog

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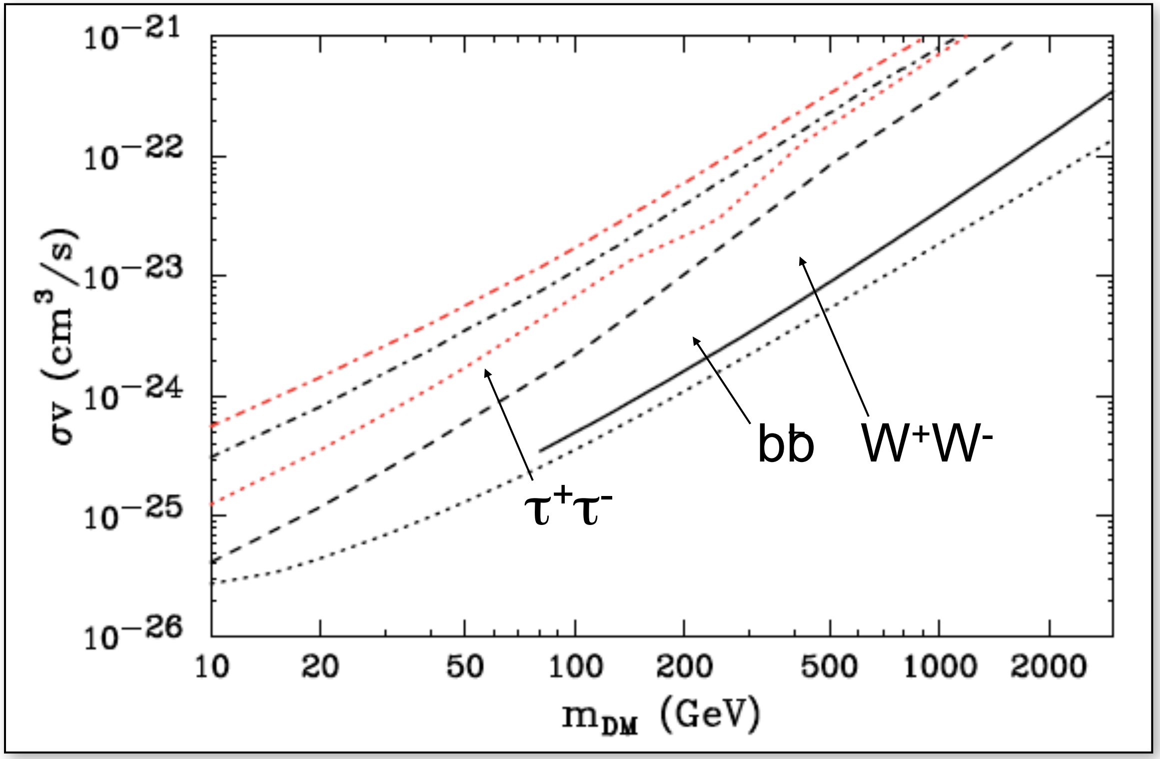
# Nearby Dark Matter Subhalos

- The upper limit on the number of subhalos can be translated into a limit on the WIMP's annihilation cross section
- For masses below ~200 GeV, the limits are comparably stringent to those derived from dwarf spheroidal and diffuse emission measurements

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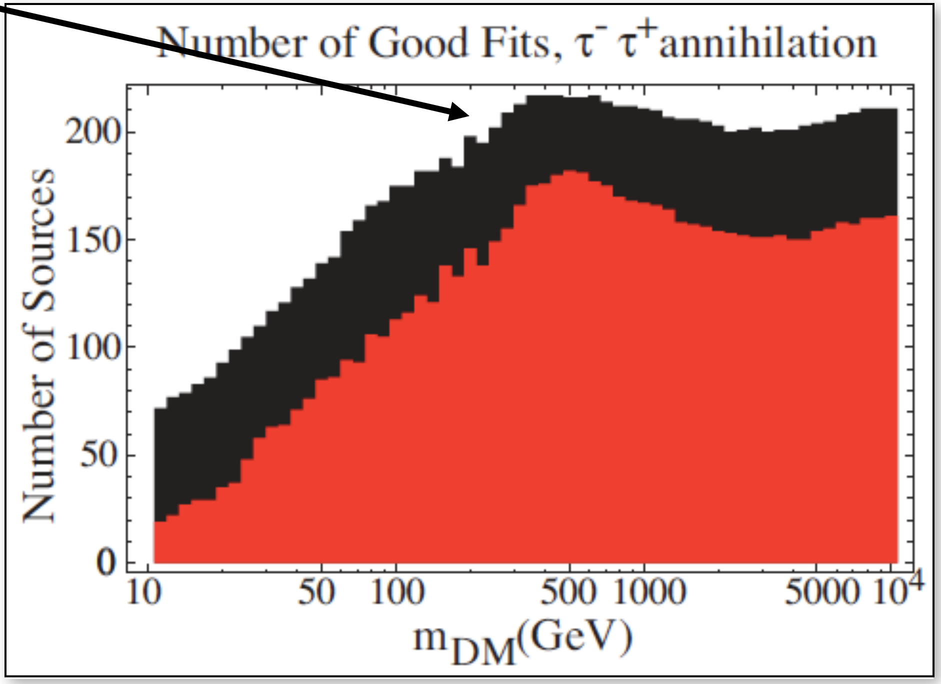
# Nearby Dark Matter Subhalos

- But what would a subhalo population within the FGST look like?
- Perhaps something like this?
- A surprising number of FGST sources can be well fit by a 500 GeV WIMP annihilating to $\tau^+\tau^-$
- Bump-like feature could be explained by ~30 subhalos within the FGST catalog
- Or could be (read "probably is") a feature of the astrophysical source population




- Corresponds to a cross section of ~$6\times10^{-23}$ cm$^3$/s, not far from that required to explain PAMELA



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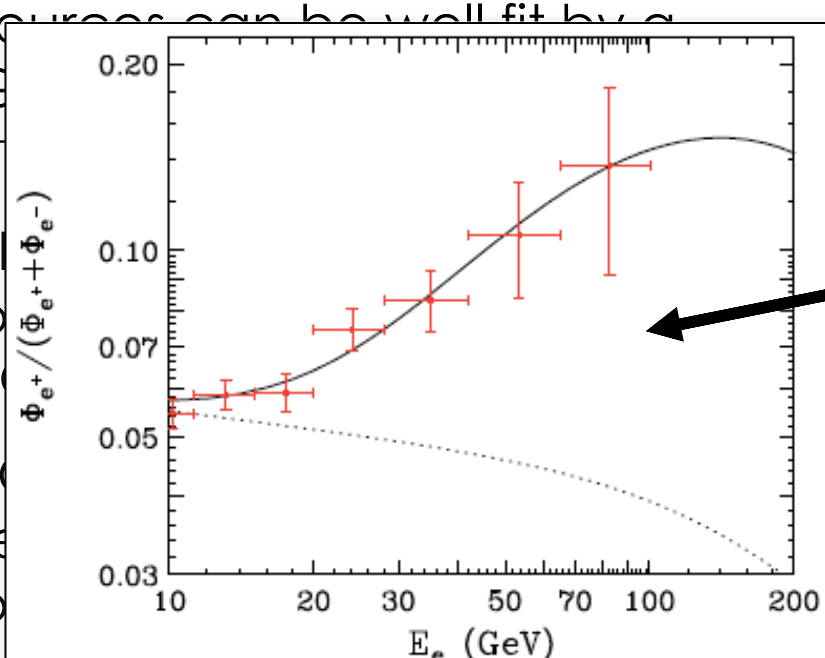


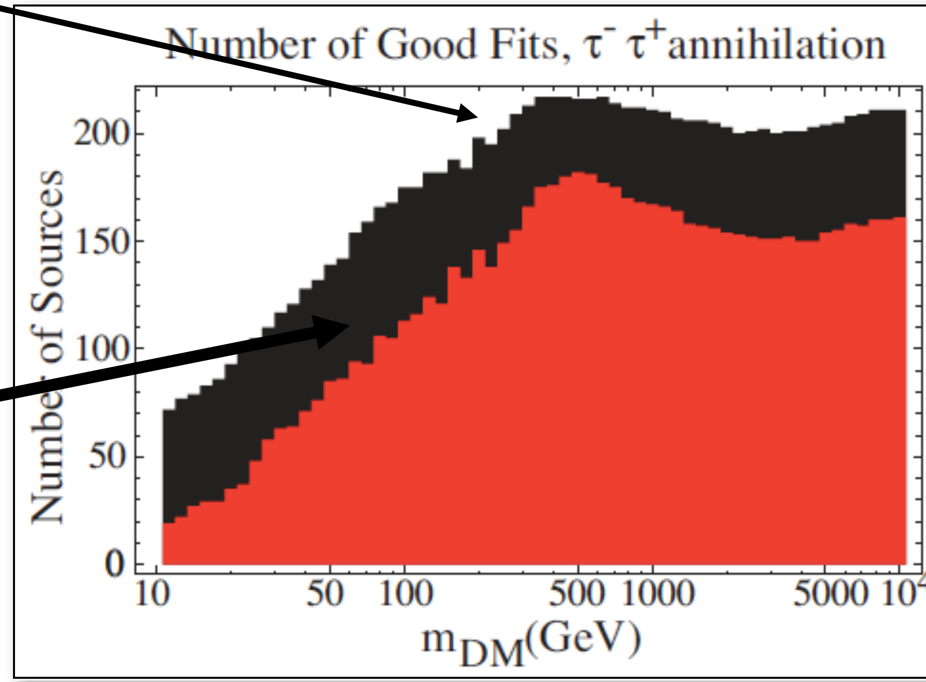


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# Future Subhalo Studies

- For simple low-background searches (dwarf galaxies), sensitivity scales with $(\text{exposure})^{-1}$
- For background limited searches (galactic center), sensitivity improves only slowly with exposure
- Subhalo searches improve with exposure in several ways:

  1) More point sources identified/resolved (detect fainter subhalos)

  2) Spectral measurements of point sources improve (better separation between dark matter subhalos and other sources; 500 GeV $\tau^+\tau^-$ bump will become more narrow and pronounced if actually from dark matter, for example)

  3) Better sensitivity to angular extension

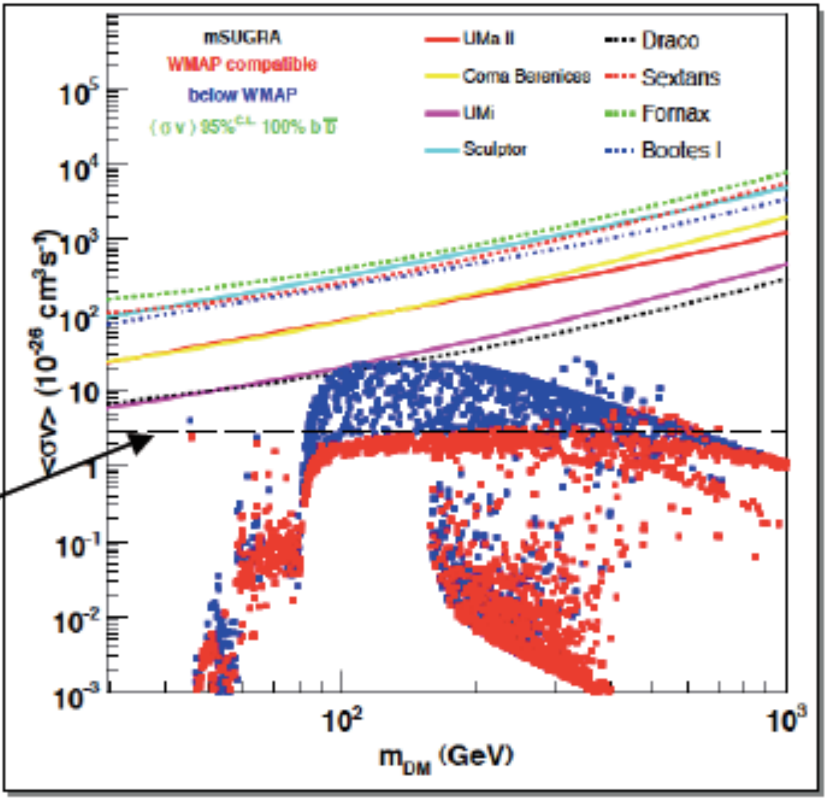
- Net improvement with exposure scales non-linearly, but more rapidly than for other search strategies
- Point source searches will become increasingly competitive as Fermi data continues to accumulate

# Summary

- Standard theory of hierarchical structure formation predicts that a typical weak-scale thermal WIMP should provide roughly ~1-10 dark matter subhalos that are currently observable as point-like sources to FGST
- We have performed a search for subhalos among the sources contained in the Fermi First Source Catalog find that fewer than ~20-60 of the catalog's sources could be dark matter subhalos
- Constraints on annihilation cross section; competitive results from dwarf galaxies, isotropic background
- Intriguing bump-feature corresponding to a 500 GeV WIMP annihilating to $\tau^+\tau^-$ (most likely a characteristic of astrophysical source population, but if distribution narrows with exposure, dark matter case would become more compelling)
- As exposure grows, point source searches will become increasingly competitive with other gamma ray search strategies

# Dwarf Spheroidal Galaxies

- Analysis assumed an NFW profile form, with parameters constrained by stellar velocity measurements
- Ursa Minor and Draco provide the strongest constraints, with several others within a factor of ~3-10
- Constraints for $M_{DM}$~100 GeV or less are within a factor of a few of the value predicted for a simple thermal relic
- Based on only 11 months of data; given the low backgrounds, this curve will come down significantly with exposure

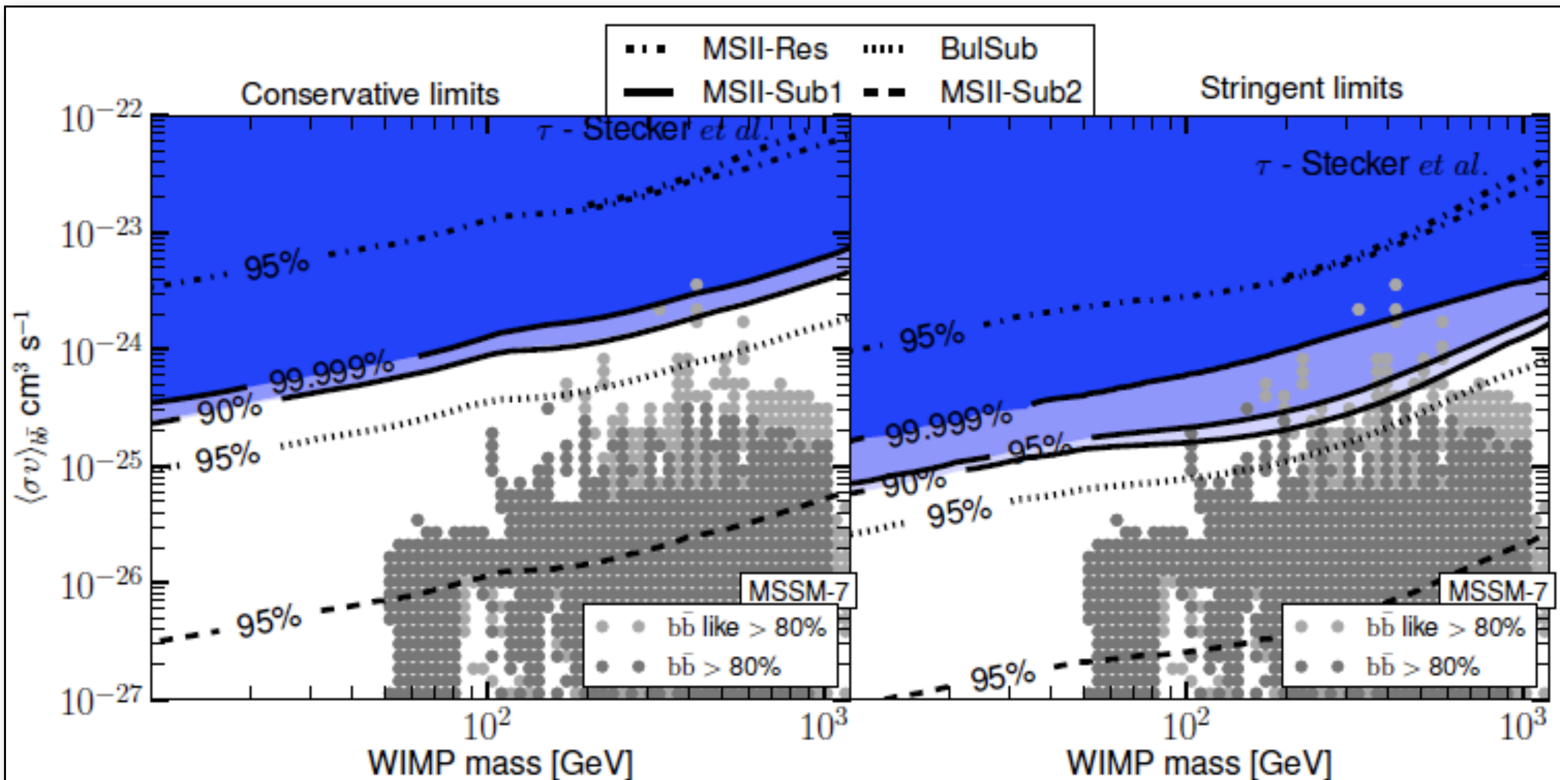



FGST Collaboration, arXiv:1001.4531

See also the analysis of Segue 1 by P. Scott *et al.*, arXiv 0909.3300

# Fermi and the Extragalactic Gamma-Ray Background

- Combining galactic diffuse and isotropic diffuse contributions, limits of ~$10^{-25}$ $cm^3/s$ are found (m~100 GeV), although results depend on substructure assumptions (similar to dwarf limits)




Fermi Collaboration, arXiv:1002.4415