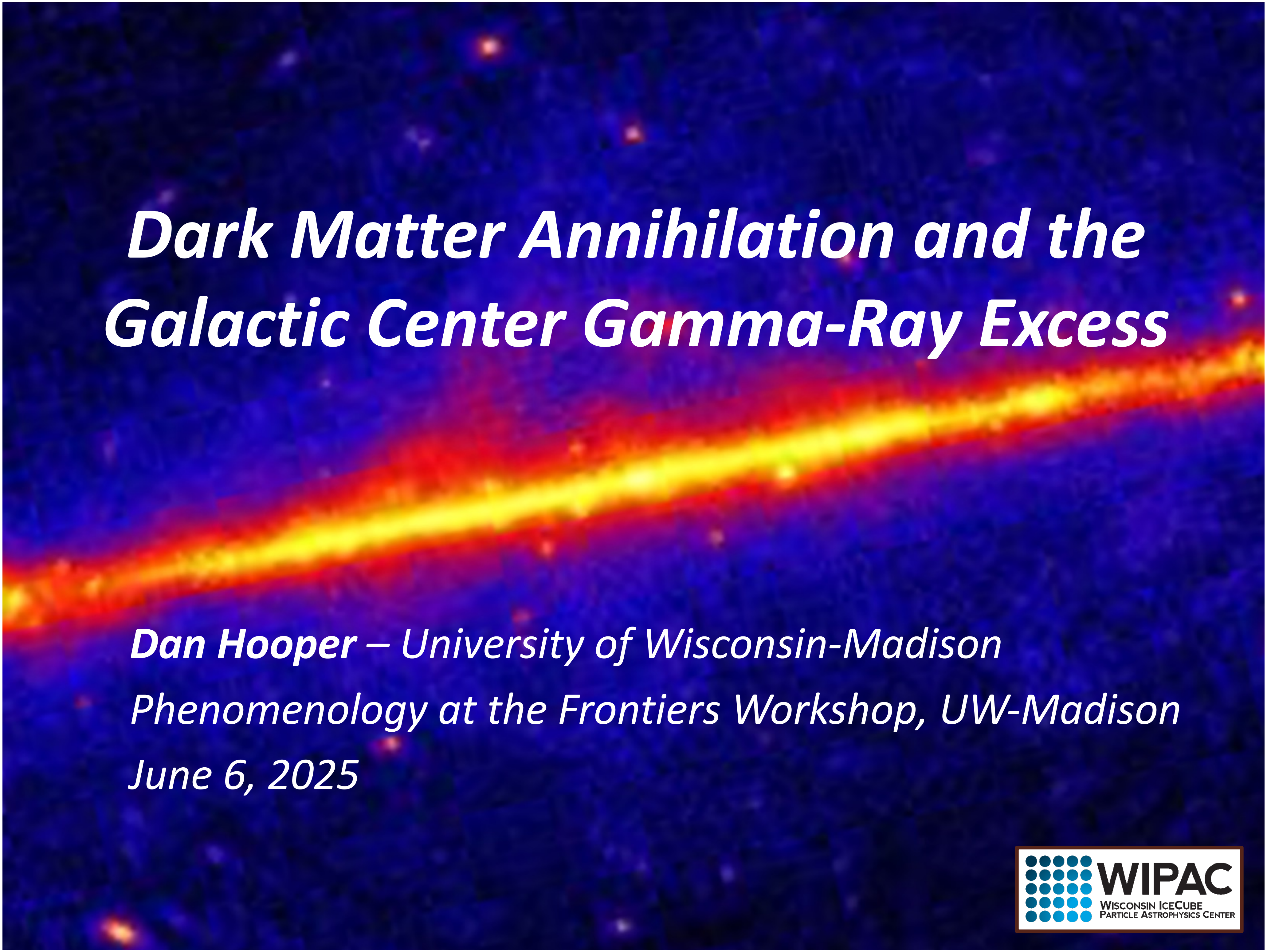


Dark Matter Annihilation and the Galactic Center Gamma-Ray Excess

Dan Hooper *– University of Wisconsin-Madison*

Phenomenology at the Frontiers Workshop, UW-Madison

June 6, 2025

WIPAC
Wisconsin IceCube Particle Astrophysics Center

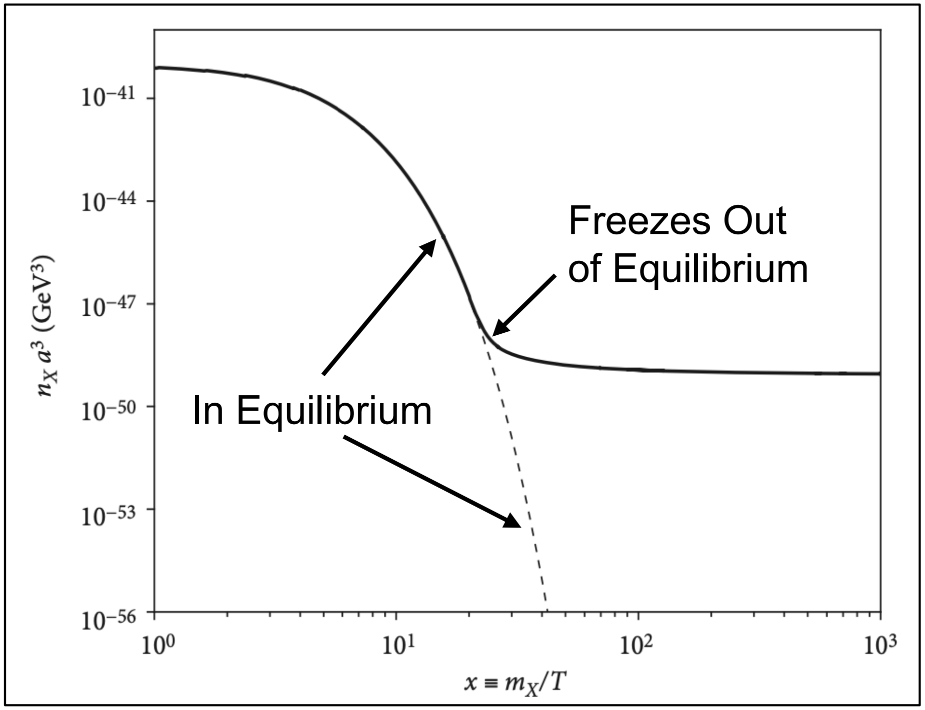
The Abundance of a Thermal Relic

- Consider a stable particle species that was in equilibrium with the thermal bath in the early universe; the abundance of these particles will evolve according to the following Boltzmann equation:

$$\frac{dn_X}{dt} = -3Hn_X - \langle \sigma v \rangle \left[n_X^2 - (n_X^{\rm Eq})^2 \right]$$

- The number density of these particles will be held near their equilibrium value until their production/annihilation rate falls below the rate of Hubble expansion – *thermal freeze out*
- After a particle species has frozen-out, it is no longer created or destroyed in significant numbers
- The resulting abundance of such a relic is set by the temperature at which it froze out of equilibrium, which is directly related to its annihilation cross section:

$$\Omega_X \sim 0.27 \times \left(\frac{2.2 \times 10^{-26}\,{\rm cm}^3/{\rm s}}{\langle \sigma v \rangle} \right)$$

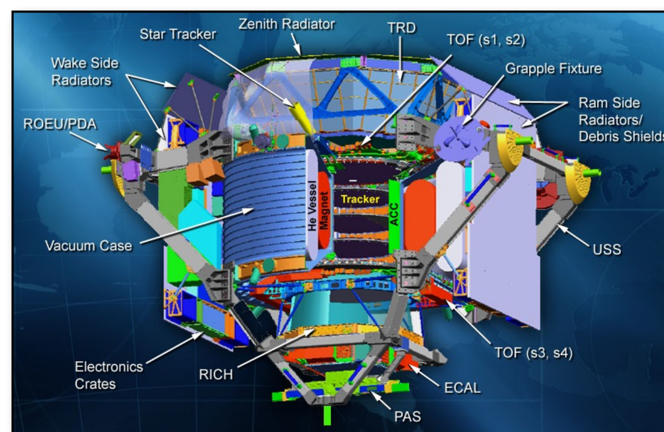


The Motivation for Indirect Searches

- This cross section of $\sigma v \sim 2 \times 10^{-26}$ cm^3/s represents a key benchmark for indirect dark matter searches and it provides much of the motivation for what I am going to be talking about today
- Although many model-dependent factors can cause the dark matter to possess a somewhat lower or higher annihilation cross section today, most models predict current annihilation rates that are within an order of magnitude or so of this estimate
- Indirect searches that are sensitive to dark matter annihilating at approximately this rate will be able to test a significant fraction of WIMP models

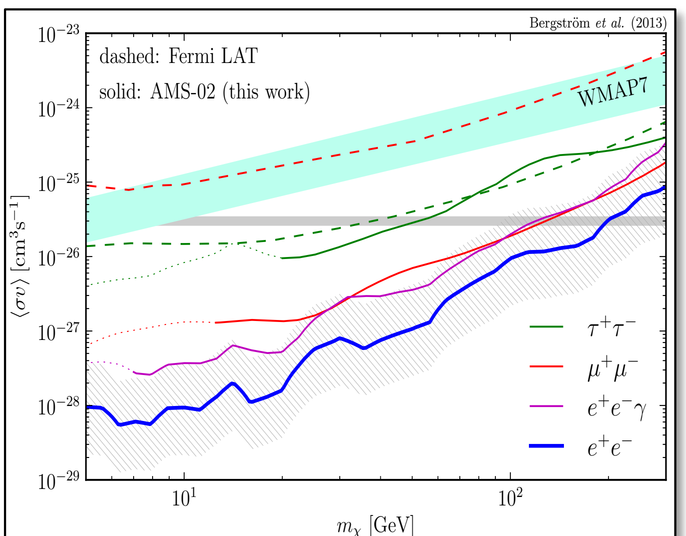
Fermi

AMS-02

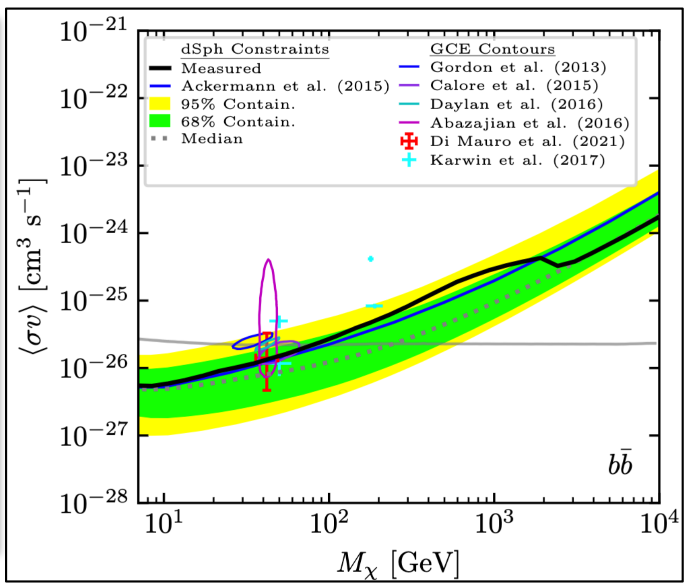


Constraints from Indirect Detection

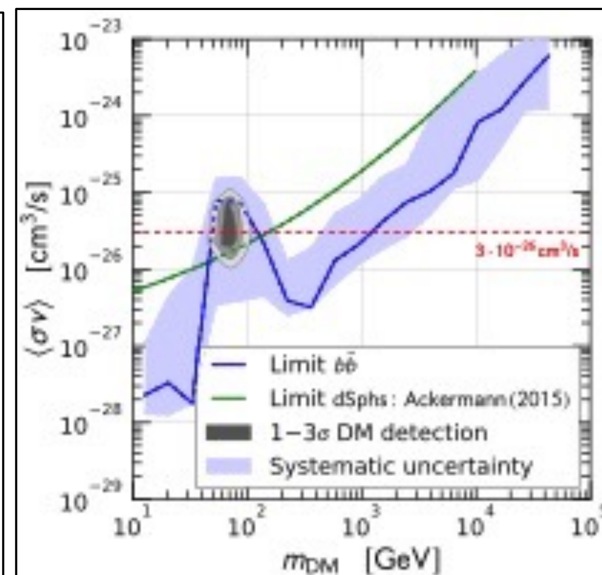
- A variety of gamma-ray searches (GC, dwarfs, IGRB, etc.) as well as cosmic-ray antiproton and positron measurements are currently sensitive to dark matter with annihilation cross sections in the range predicted for a simple thermal relic, for masses up to $\mathcal{O}(100)$ GeV
- This program is not a fishing expedition, but is testing a wide range of our most well-motivated dark matter models



Bergstrom, *et al.*, arXiv:1306.3983



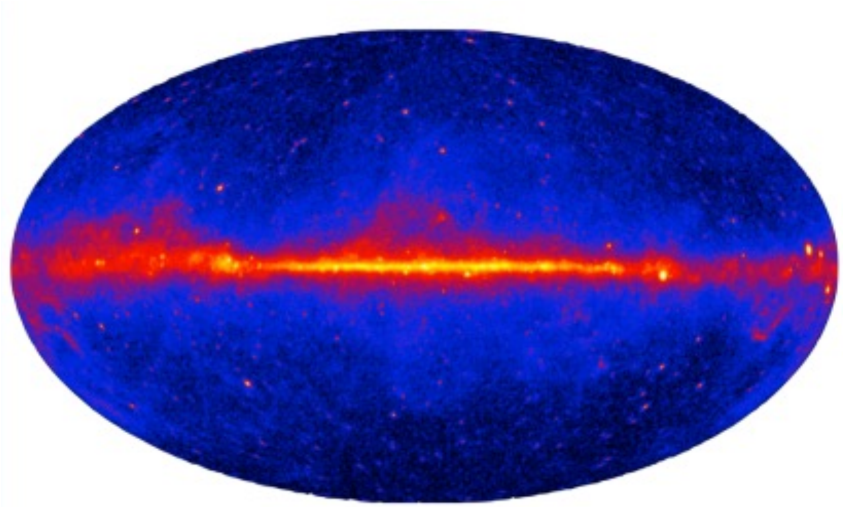
Fermi Collaboration, arXiv: 2311.04982



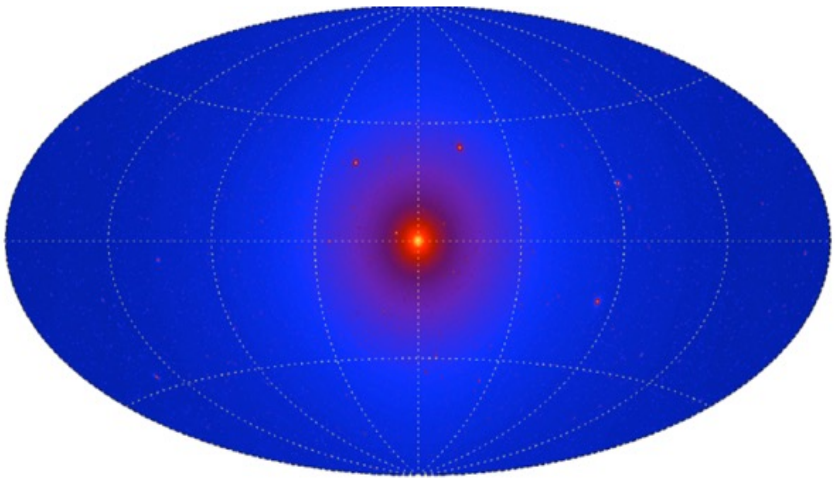
Cuoco, *et al.*, arXiv:1610.03071
Cui, *et al.*, arXiv:1610.03840

Gamma Ray Searches for Dark Matter

- The brightest gamma-ray signal from annihilating dark matter (by far) is predicted to come from the direction of the Galactic Center
- The astrophysical backgrounds are also bright in this region of this sky, and can be difficult to model
- Despite these backgrounds, the signal that would be expected from a ~1-200 GeV thermal relic was widely expected to be within reach of the Fermi telescope



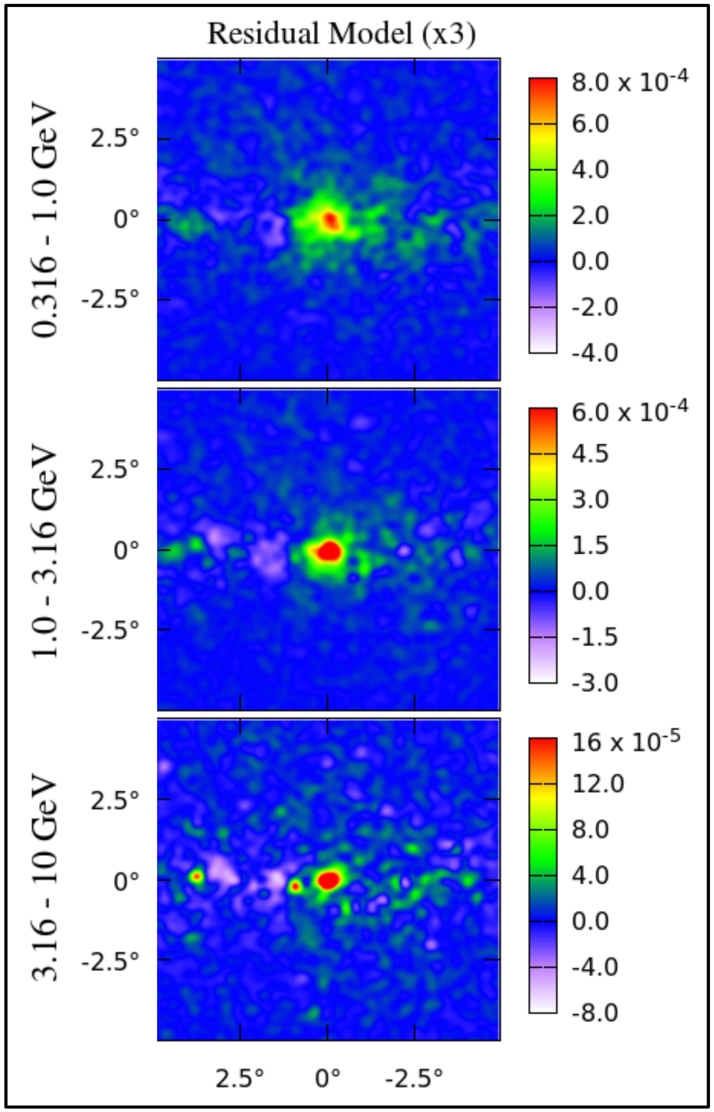
Gamma-Rays Measured by Fermi



Signal Predicted From Dark Matter

The Galactic Center Gamma-Ray Excess

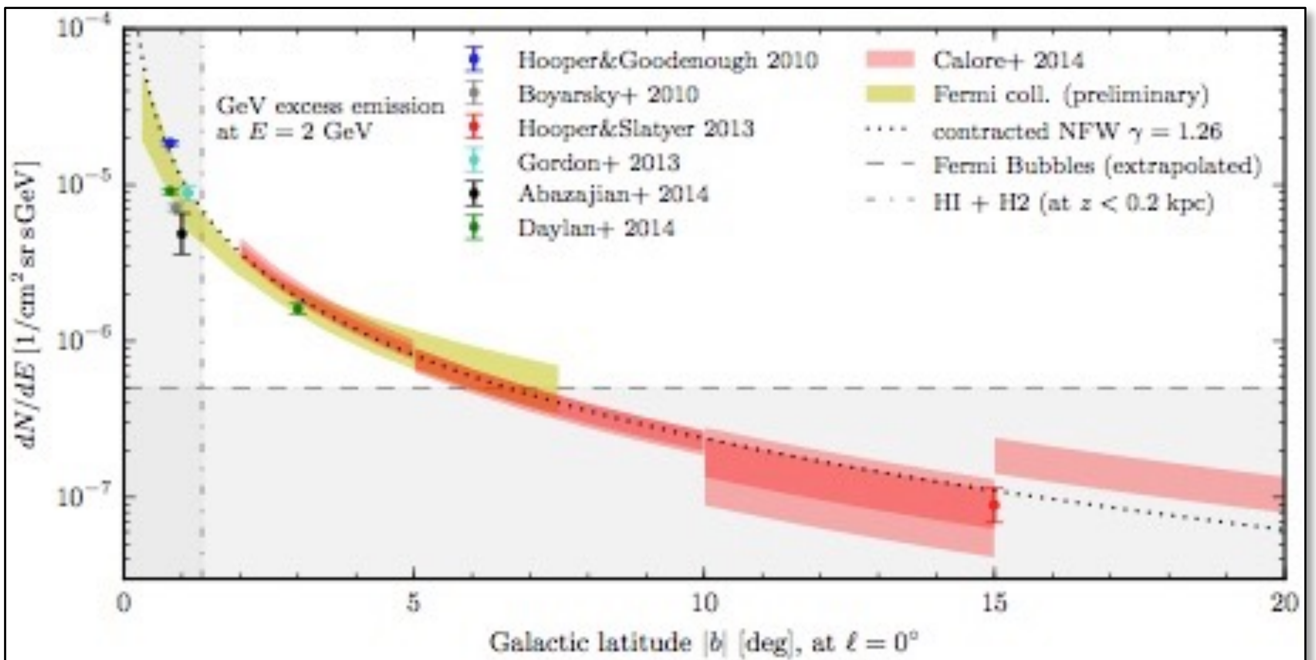
- There is an excess of GeV-scale emission from the direction of the Inner Galaxy in the Fermi data, relative to *all models* of known astrophysical backgrounds
- This signal is bright and highly statistically significant – its existence is not in dispute
- It is very difficult to explain this signal with known astrophysical sources or mechanisms
- The observed characteristics of this signal are consistent with those expected from annihilating dark matter



Among other references, see:
DH, Goodenough (2009, 2010)
DH, Linden (2011)
Abazajian, Kaplinghat (2012)
Gordon, Macias (2013)
Daylan, DH, et al. (2014)
Calore, Cholis, Weniger (2014)
Murgia, et al. (2015)
Ackermann et al. (2017)

Morphology

- The gamma-ray excess exhibits approximate spherical symmetry about the Galactic Center (axis ratios within ~20% of unity), with a flux per volume that falls as $\propto r^{-2.4}$ out to at least ~20°
- If interpreted as annihilating dark matter, this implies $\rho_{\rm DM} \propto r^{-1.2}$ out to at least ~3 kpc, only slightly steeper than the canonical NFW profile

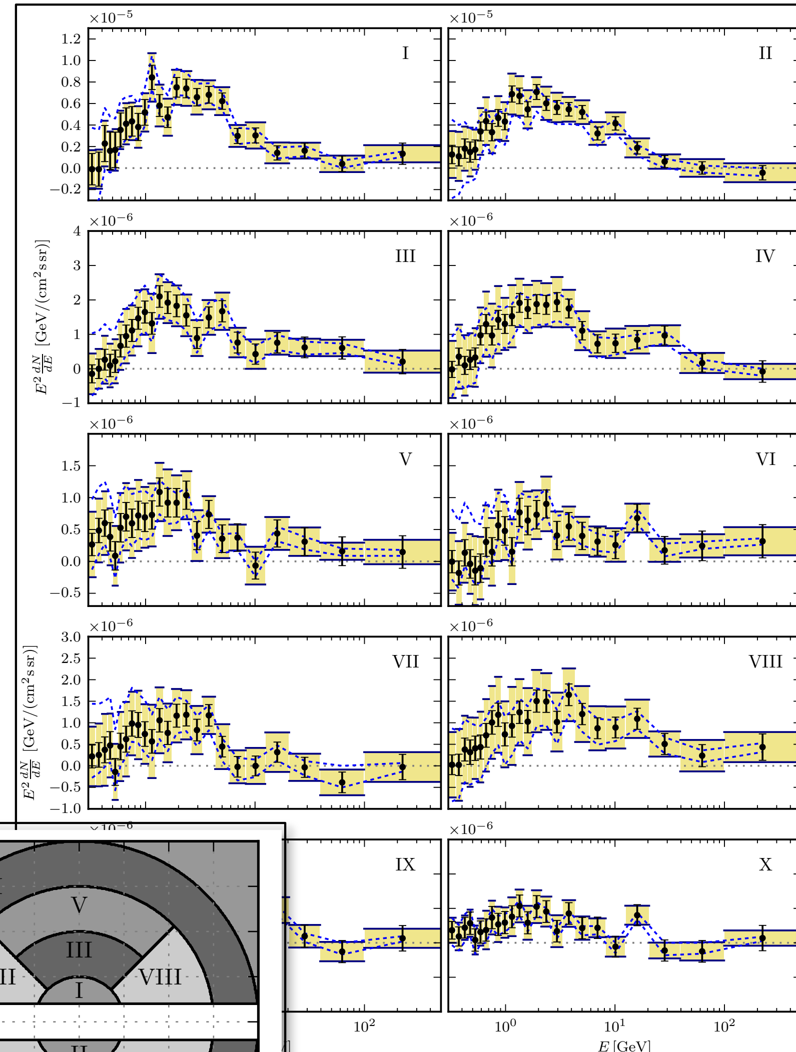


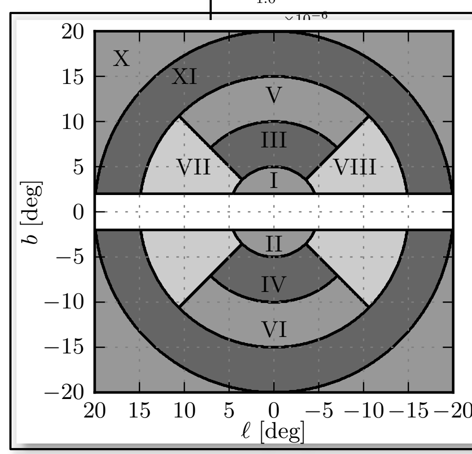
Calore, Cholis, Weniger (2014)

Spectrum

- The spectrum of the excess is well fit by a ~20-65 GeV particle annihilating to quarks or gluons
- The shape of the spectrum is uniform across the Inner Galaxy

Channel	$\langle\sigma v\rangle$ (10^{-26} cm^3 s^{-1})	m_χ (GeV)	$\chi^2_{\rm min}$	p-value
$\bar{q}q$	$0.83^{+0.15}_{-0.13}$	$23.8^{+3.2}_{-2.6}$	26.7	0.22
$\bar{c}c$	$1.24^{+0.15}_{-0.15}$	$38.2^{+4.7}_{-3.9}$	23.6	0.37
$\bar{b}b$	$1.75^{+0.28}_{-0.26}$	$48.7^{+6.4}_{-5.2}$	23.9	0.35
gg	$2.16^{+0.35}_{-0.32}$	$57.5^{+7.5}_{-6.3}$	24.5	0.32



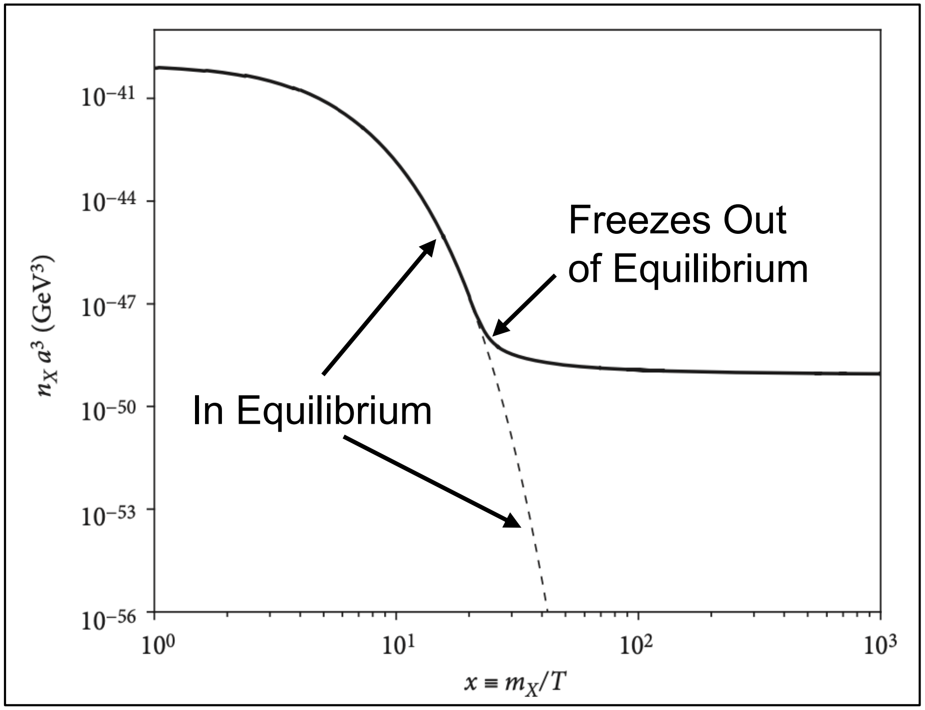


Calore, Cholis, Weniger; Calore, Cholis, McCabe, Weinger (2014)

Intensity

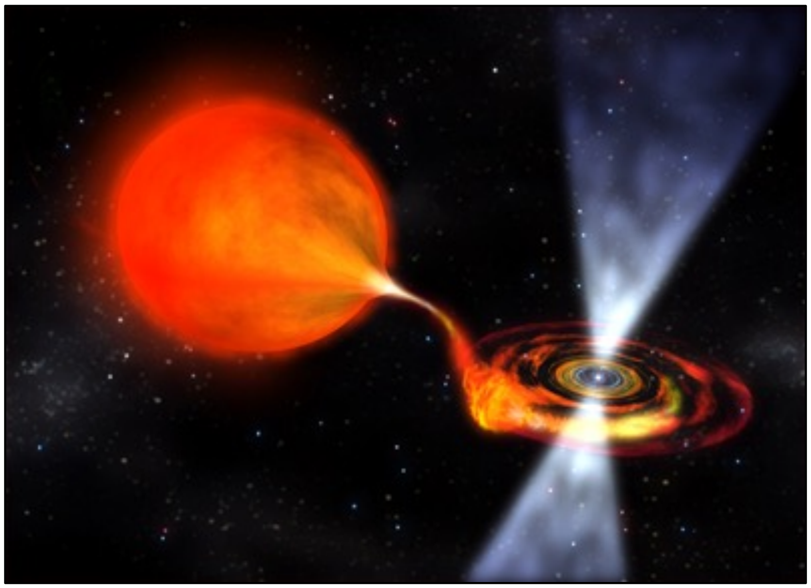
- To produce the observed intensity of the excess, the dark matter particles must annihilate with a cross section of $\sigma v \sim (1-2)\times 10^{-26}$ cm^3/s
- This is in remarkably good agreement with the value of the annihilation cross section that is required to generate the measured dark matter abundance through thermal freeze-out in the early universe:

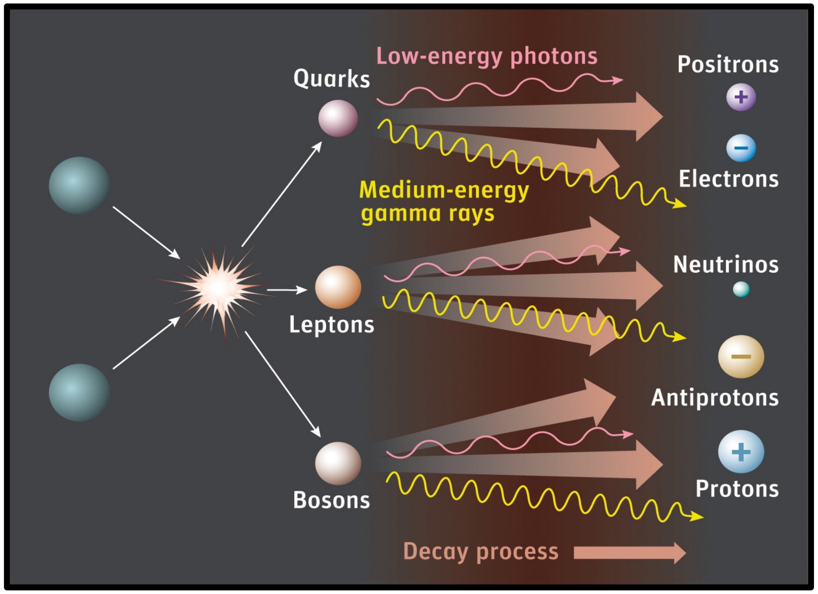
$$\Omega_X \sim 0.27 \times \left(\frac{2.2 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{s}}{\langle \sigma v \rangle}\right)$$



What Produces the Galactic Center Excess?

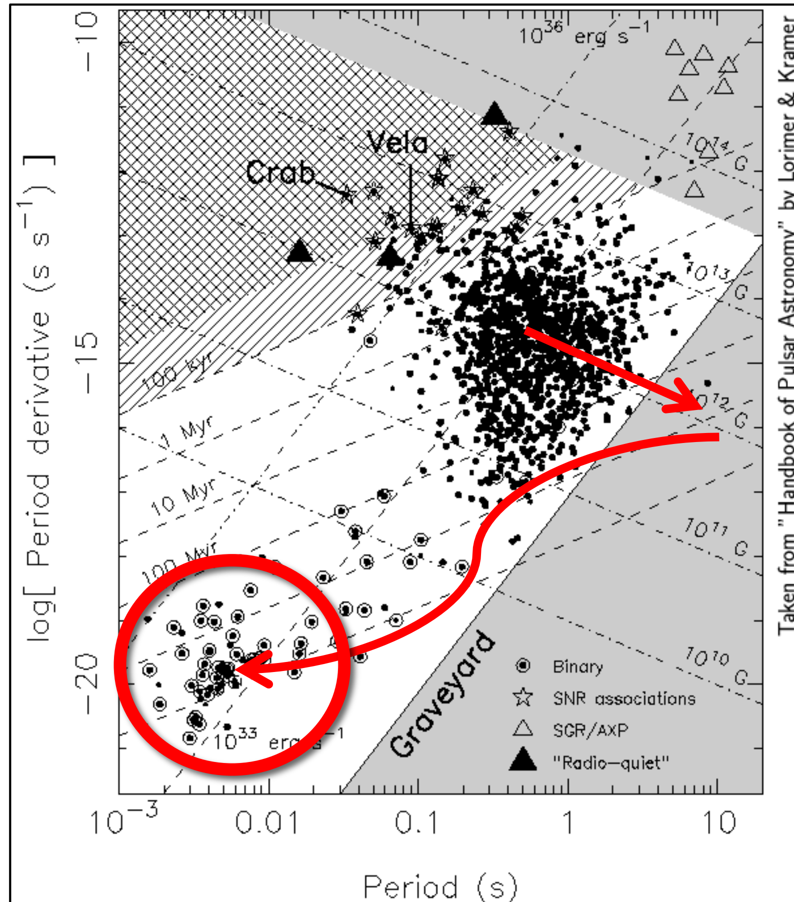
- A large population of centrally located millisecond pulsars?
- Annihilating dark matter?

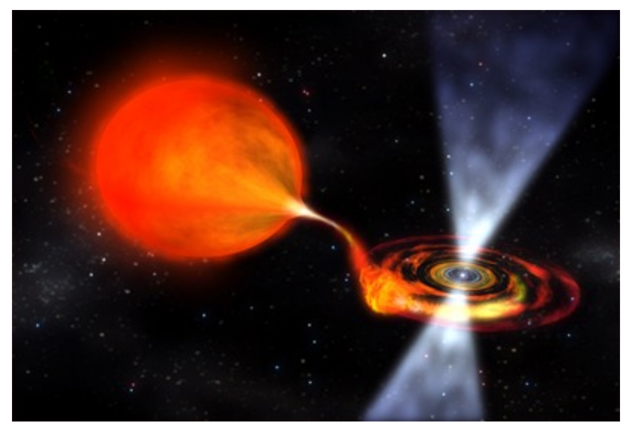




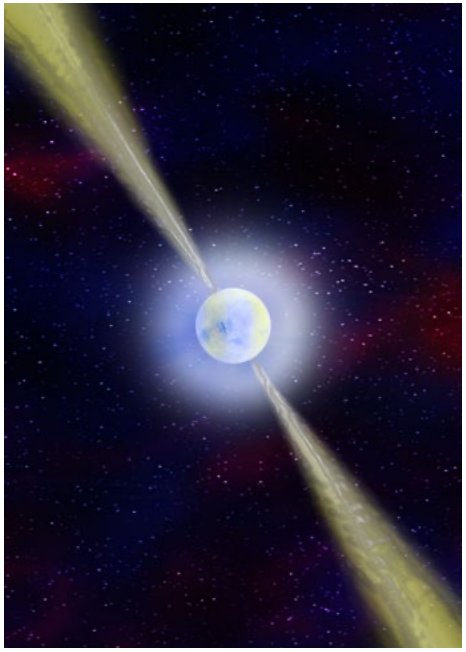
Millisecond Pulsars

- Pulsars are rapidly spinning neutron stars, which gradually convert their rotational kinetic energy into radio and gamma-ray emission
- When new pulsars are formed, they typically exhibit periods on the order of ~1 second and slow down and become faint over ~10^6 -10^8 years
- Later, accretion from a companion star can “spin-up” a dormant neutron star to periods as short as ~1.5 msec
- Such millisecond pulsars have low magnetic fields (~10^8-10^9 G) and thus spin down much more slowly than young pulsars, remaining bright for >10^9 years
- It seems plausible that large numbers of MSPs could exist near the Galactic Center





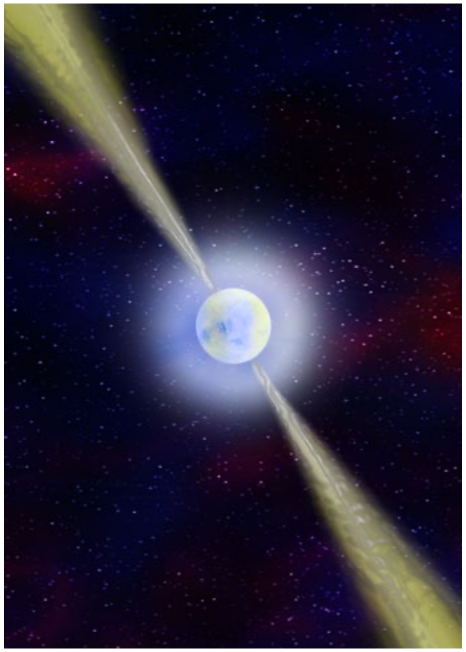
Millisecond Pulsars and The Galactic Center Gamma-Ray Excess



Arguments in Favor of Pulsars:

- The gamma-ray spectrum of observed pulsars
- Claims of small-scale power in the gamma-ray emission from the Inner Galaxy
- Claims that the excess traces the Galactic Bulge/Bar

Millisecond Pulsars and The Galactic Center Gamma-Ray Excess



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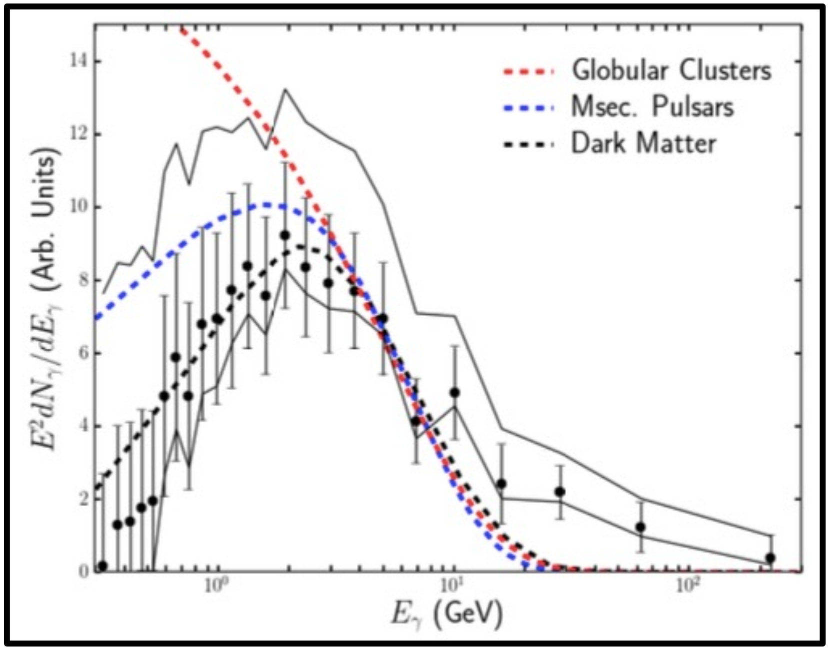
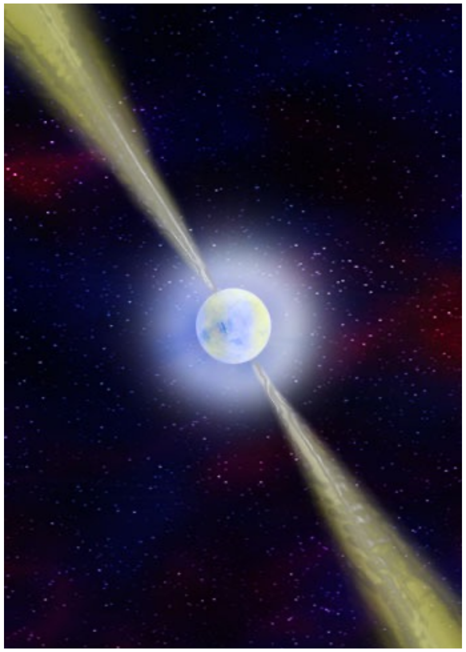


Cholis, DH, Linden (2014)
Cholis, Zhong, McDermott, Surdutovich (2021)

Millisecond Pulsars and The Galactic Center Gamma-Ray Excess



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Evidence of Unresolved Gamma-Ray Sources?

- In 2015, two groups (Lee, *et al*., 1506.05124, Bartels *et al*., 1506.05104) found that the gamma rays from the Inner Galaxy are more clustered than expected from smooth backgrounds, suggesting that the excess might be generated by a population of unresolved gamma-ray point sources

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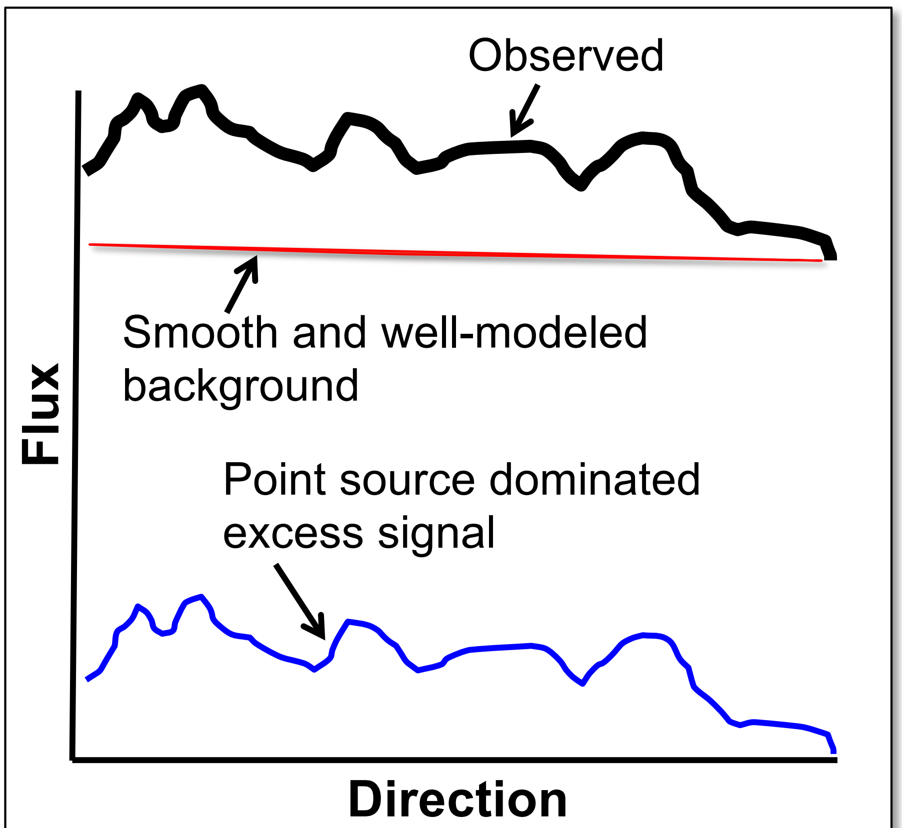

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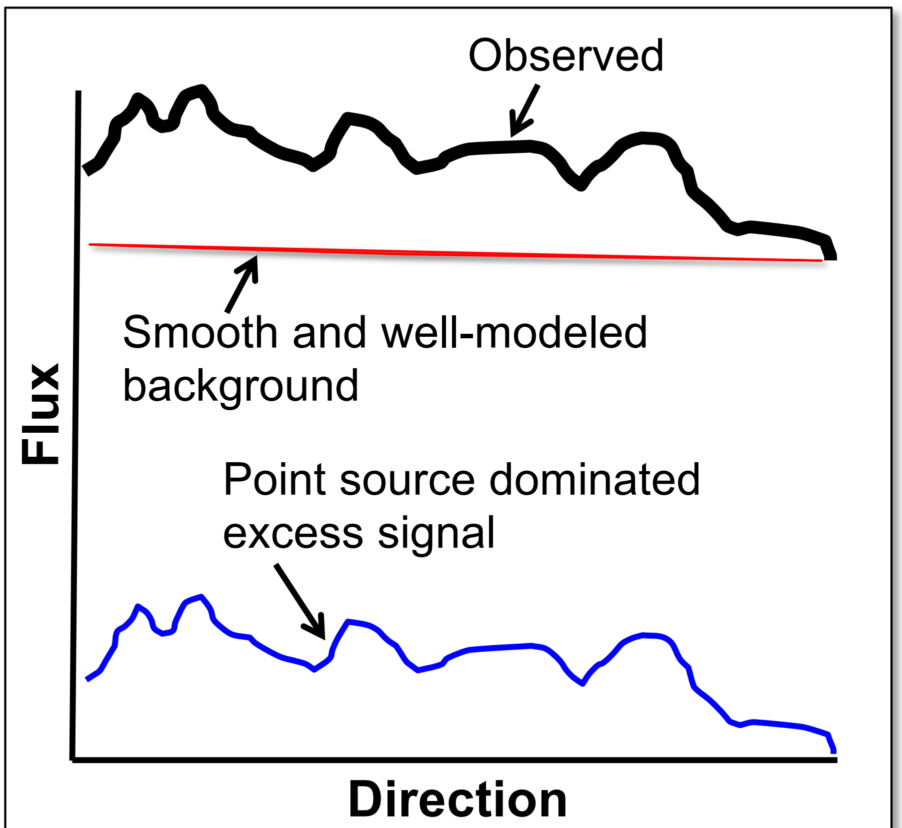

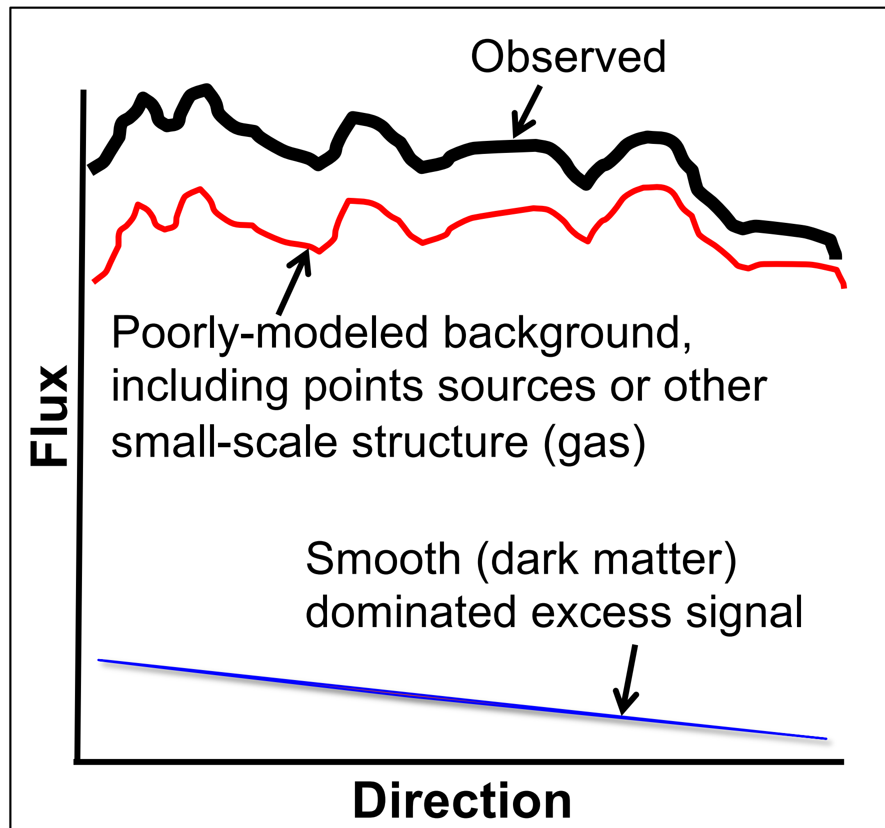

DARK MATTER STRIKES BACK AT THE GALACTIC CENTER

See Leane and Slatyer, arXiv:1904.08430

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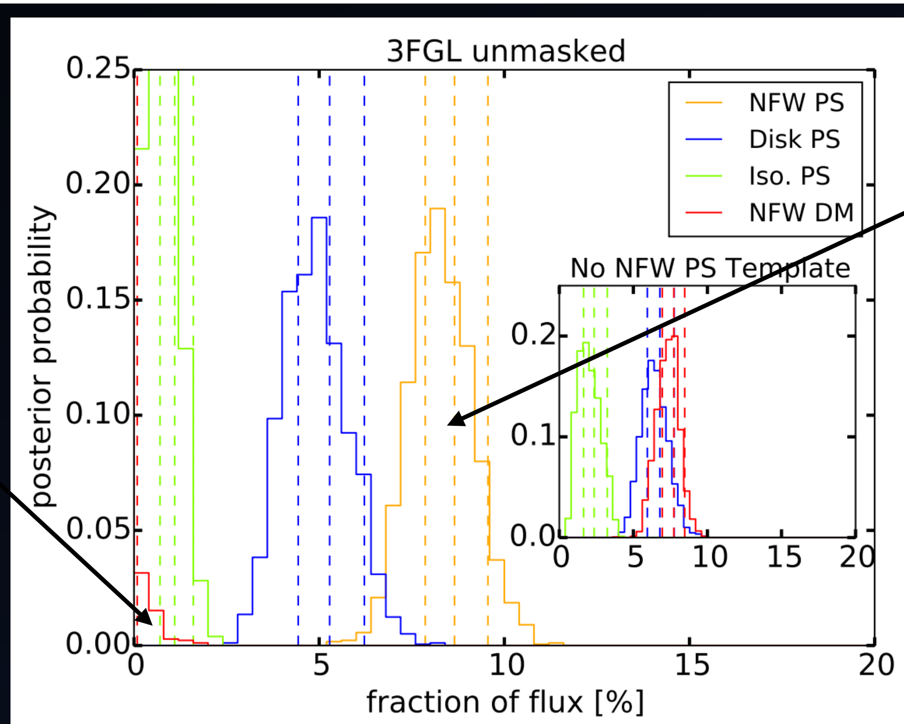
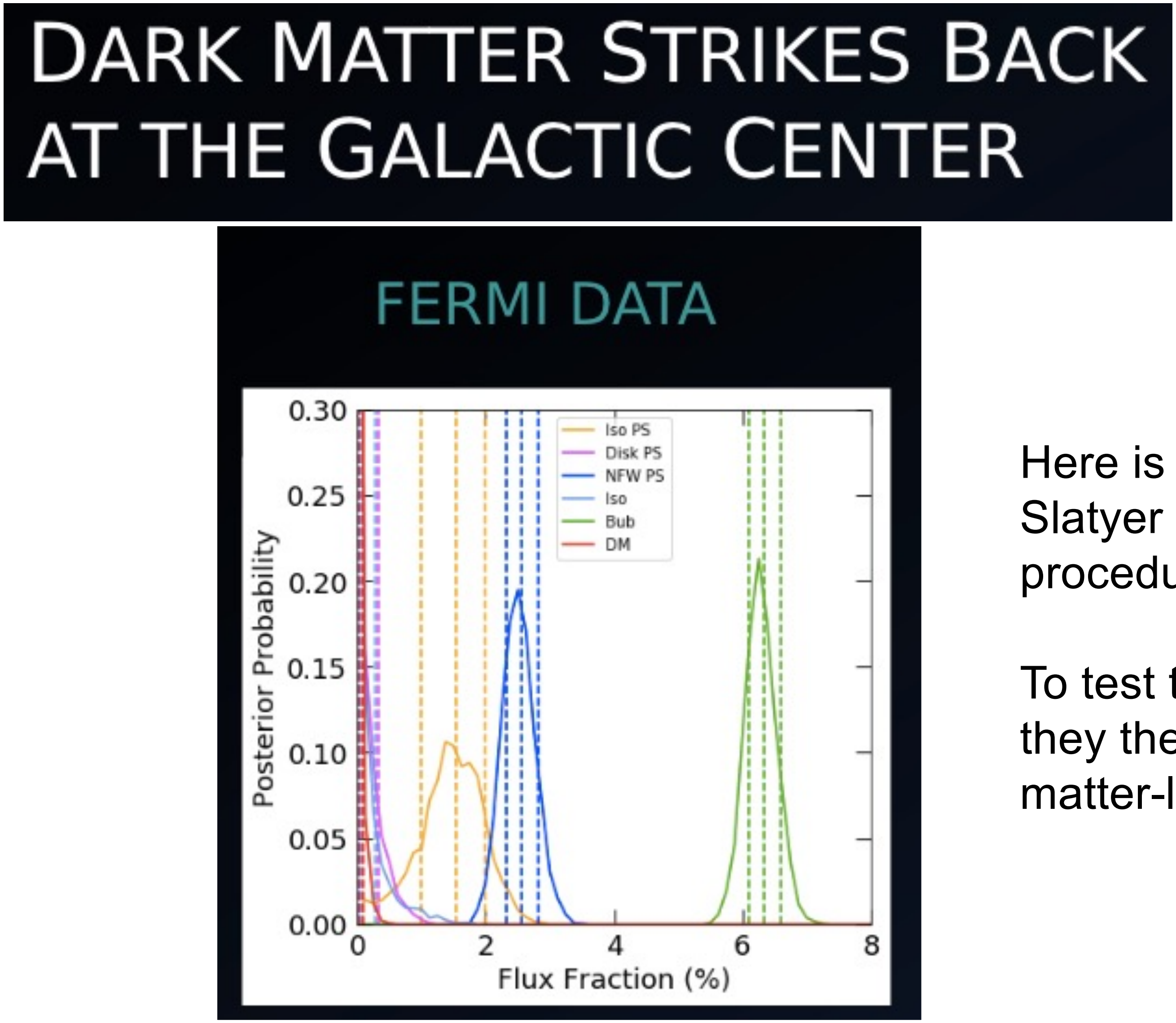
Flux attributed to dark matter annihilation (smooth)



Lee, Lisanti, Safdi, Slatyer, Xue (PRL ‘15)

Flux attributed to NFW^2 Distributed Point Sources (clumpy)

To what extent could inadequate background templates be biasing these results?



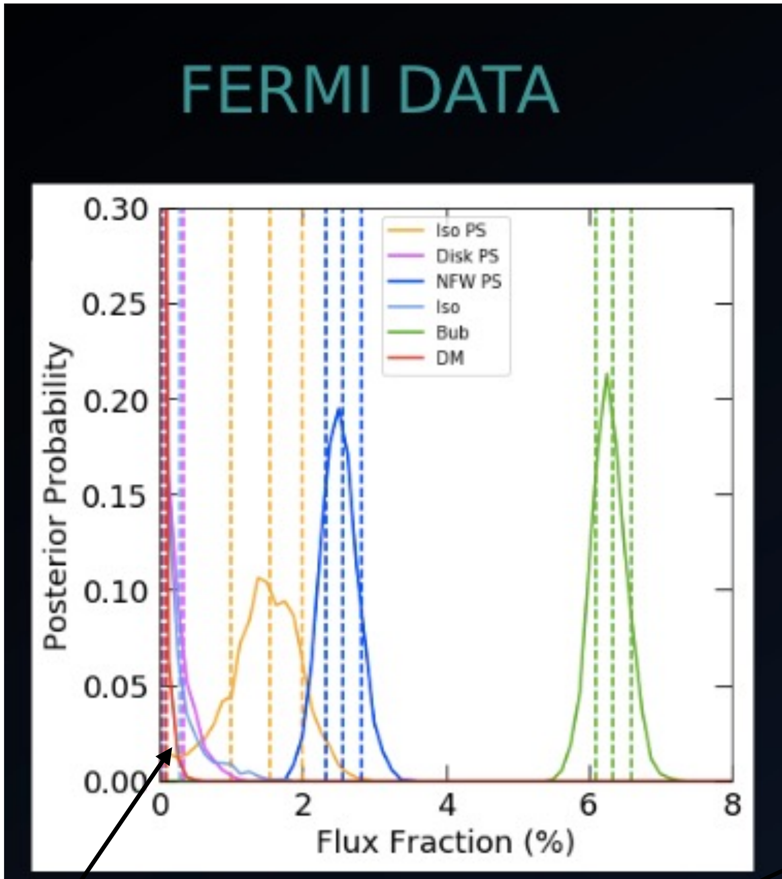
See Leane and Slatyer, arXiv:1904.08430

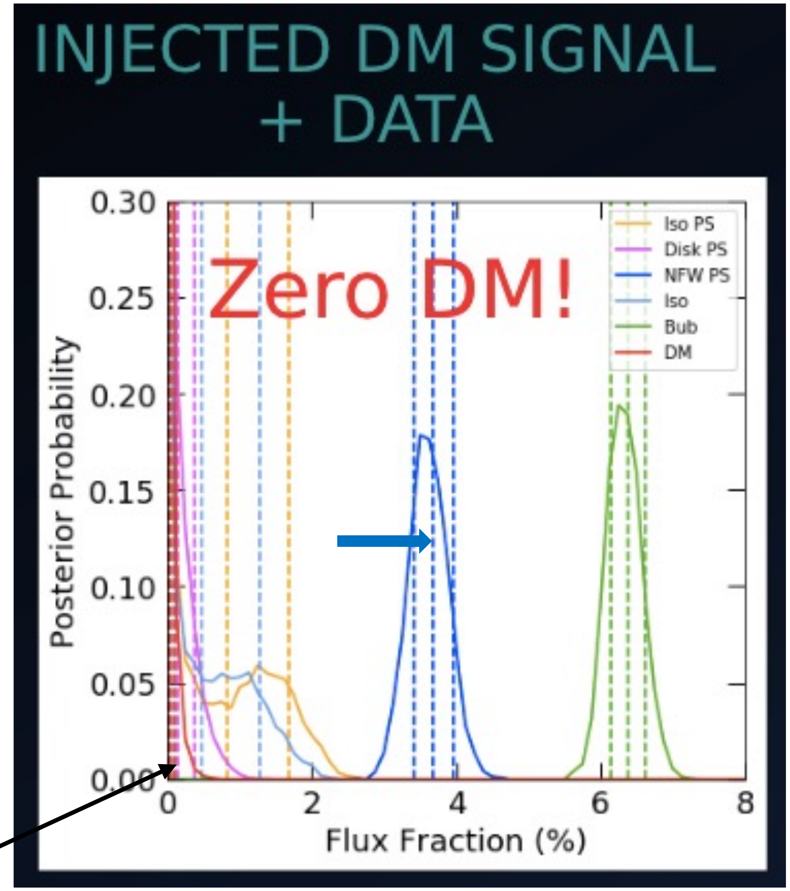
Here is the result that Leane and Slatyer obtain using the same procedure as Lee *et al.*

To test the reliability of this result, they then *added* a (smooth) dark matter-like signal to the Fermi data

Dark Matter Strikes Back at the Galactic Center

See Leane and Slatyer, arXiv:1904.08430





Despite having just added a dark matter-like signal to the data, the fit *does not* ascribe any of it to the dark matter template

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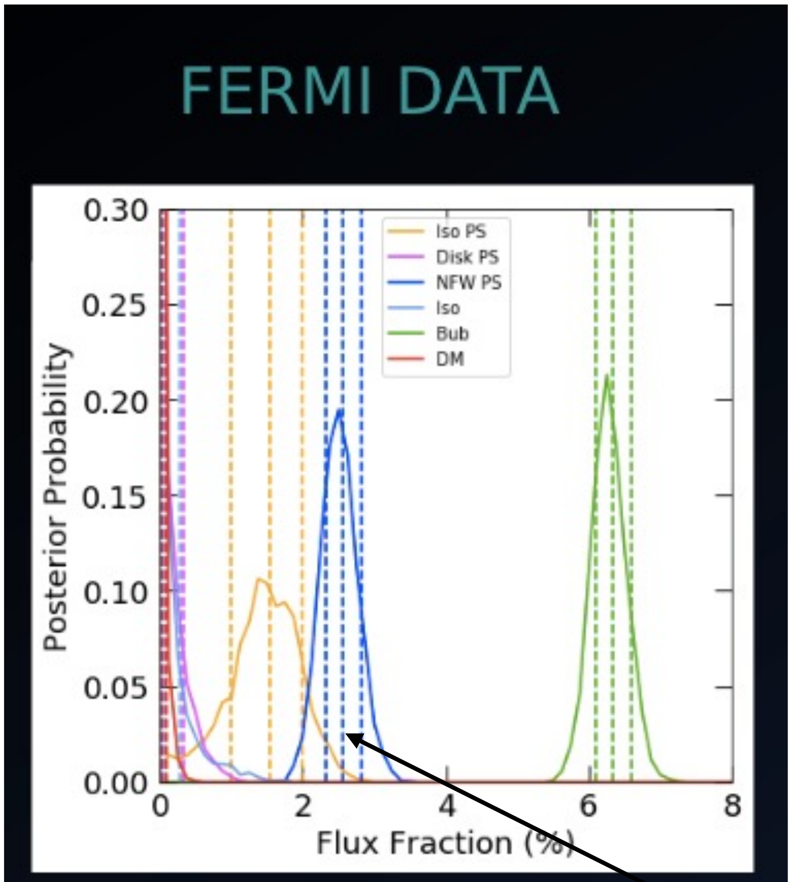
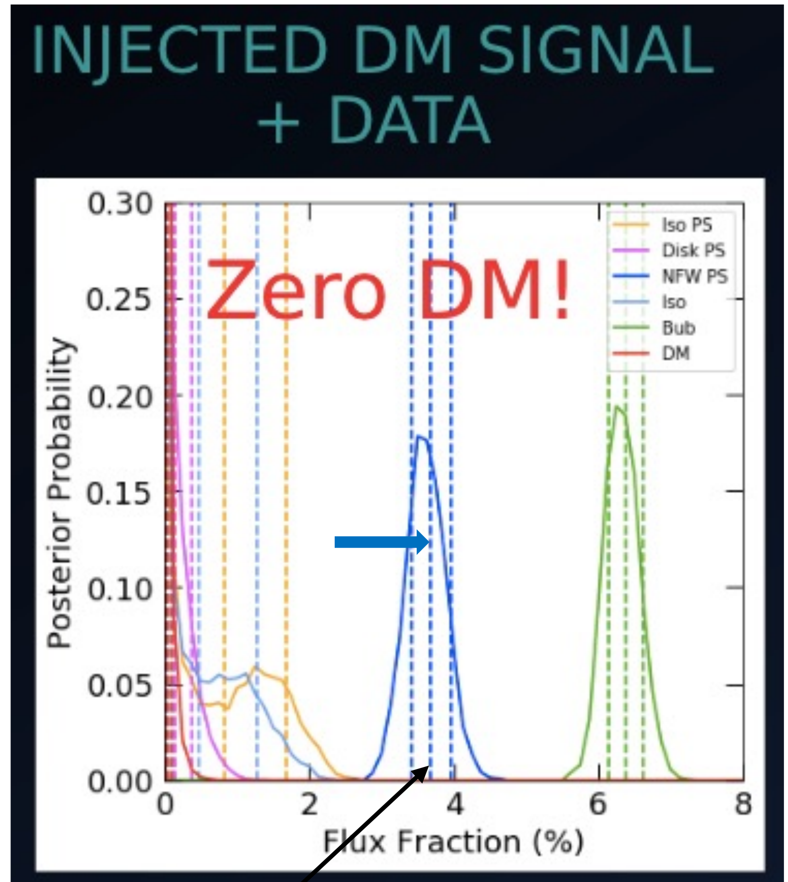
See Leane and Slatyer, arXiv:1904.08430





Despite having just added a dark matter-like signal to the data, the fit *does not* ascribe any of it to the dark matter template

Instead, the fit identifies the injected dark matter-like signal as coming from point sources

DARK MATTER STRIKES BACK AT THE GALACTIC CENTER

See Leane and Slatyer, arXiv:1904.08430

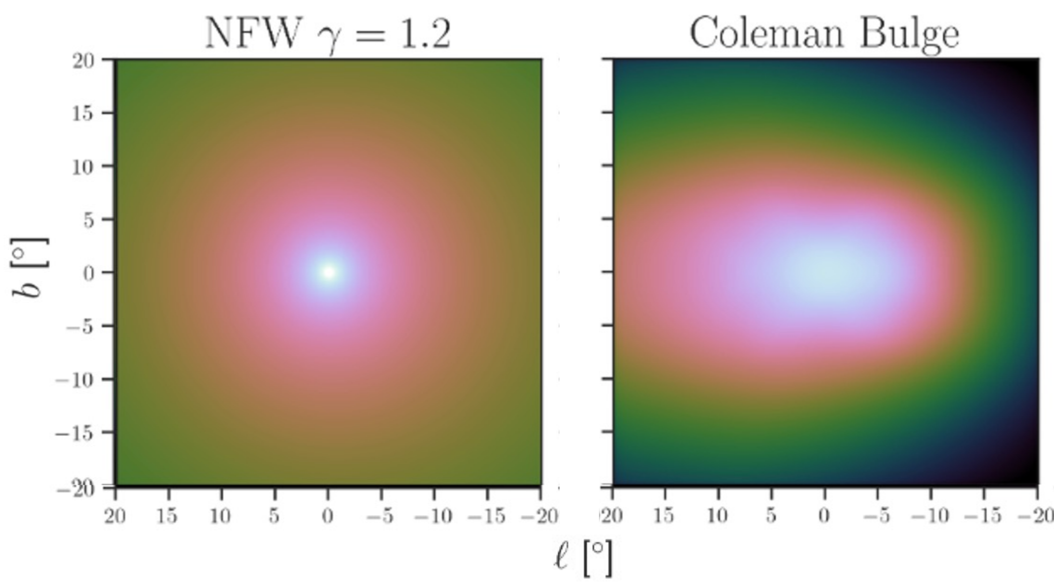
Bottom Line:

The non-Poissonian template fit is clearly **misattributing** the dark matter-like signal to point sources, demonstrating that the background models being used here are **not adequate to describe the data**, strongly biasing the results of the fit

The gamma-ray excess could still be generated by a very large number of very faint point sources, but there is **no evidence of this**

Bulge/Bar-Like vs DM-Like Morphology

- Another important test of the Galactic Center excess is to establish whether this signal is spherical and dark matter-like or instead traces some combination of known stellar populations (*ie*., the Galactic Bulge and Bar)



- In papers by Macias *et al.* (arXiv:1611.06644, 1901.03822) and Bartels *et al.* (1711.04778), it was argued that the excess is better fit by models which trace the stellar distribution than by dark matter-like models
- If confirmed, this would favor astrophysical interpretations of the gamma-ray excess

Bulge/Bar-Like vs DM-Like Morphology

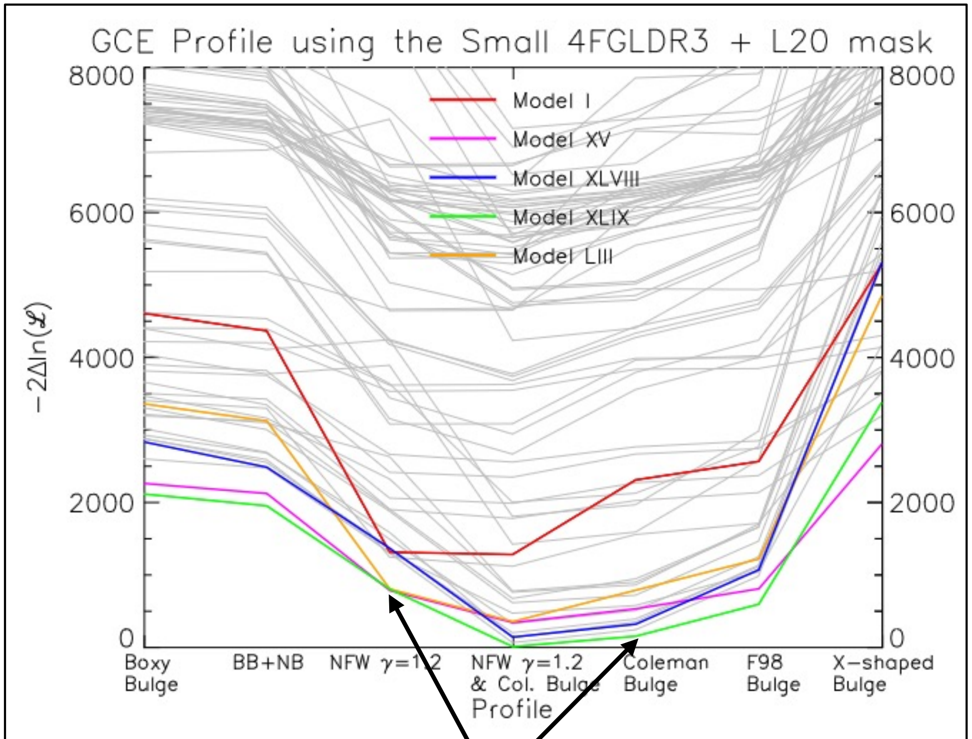
- Much of the recent work on this question, however, has not confirmed this preference for bulge-like morphology
- Instead, it is now clear that the answer you get to this question depends strongly on the choices and assumptions that you make in your analysis, including:
    1) The model that is used for the Galactic diffuse emission
    2) The regions of the sky that are included in the fit (*ie*., the mask)
- For these reasons, different groups, making different (but seemingly reasonable) analysis choices, have reached different conclusions regarding the detailed morphology of the GCE

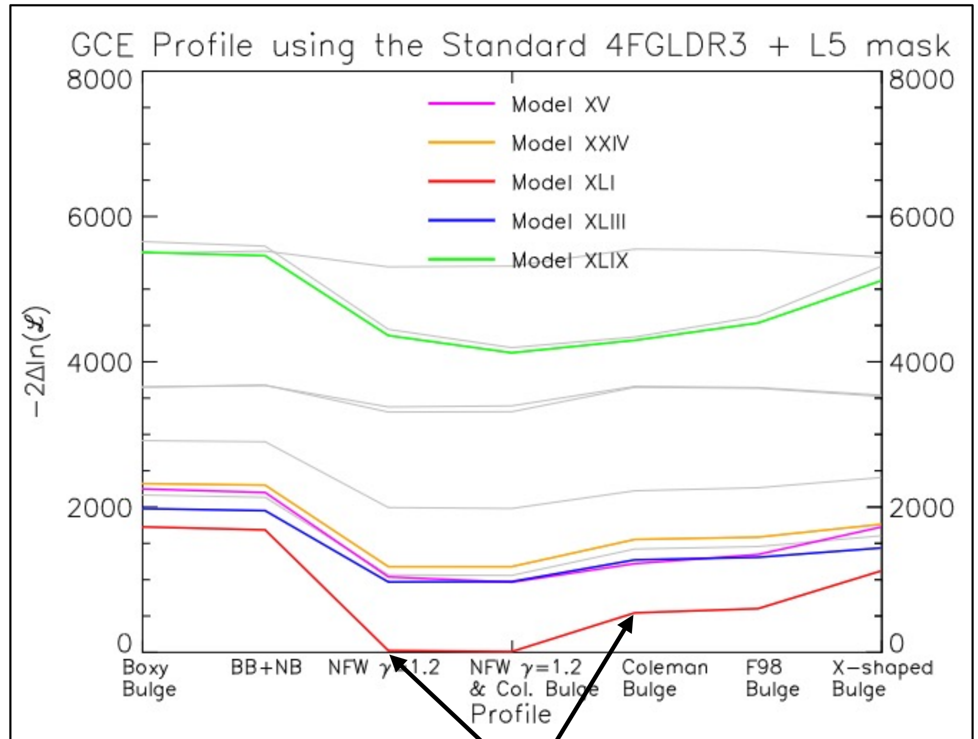
Zhong, Cholis, 2401.02481
McDermott *et al*., 2209.00006; 2112.09706
Di Mauro, 2101.04694

Bulge/Bar-Like vs DM-Like Morphology

Zhong, Cholis, arXiv:2401.02481

Better Fit





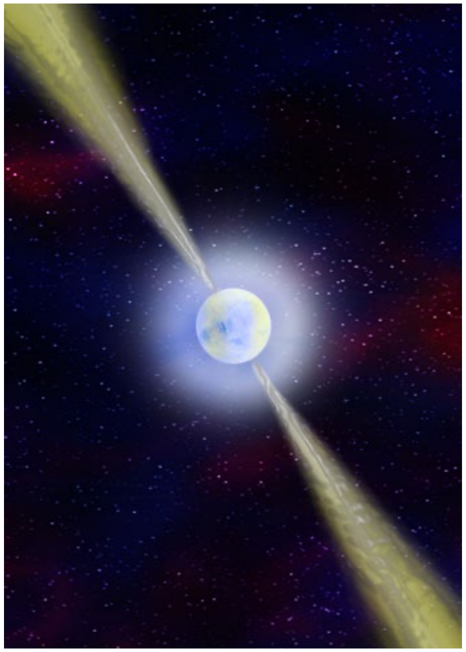
For this choice of mask, the fits prefers the Coleman bulge model over a dark matter model for the GCE

For other choices, the fit prefers dark matter models over bulge models

Bottom Line: The detailed morphology of the GCE is systematics-limited; we can't currently differentiate between dark matter and bulge-like models

(see also McDermott *et al*., 2209.00006; 2112.09706; Di Mauro, 2101.04694)

Millisecond Pulsars and The Galactic Center Gamma-Ray Excess



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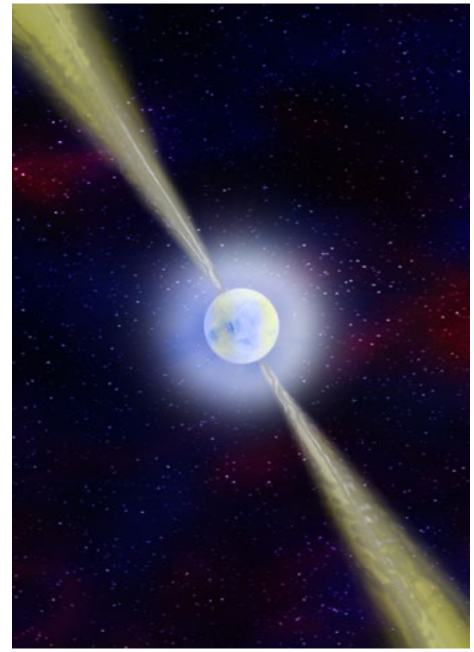

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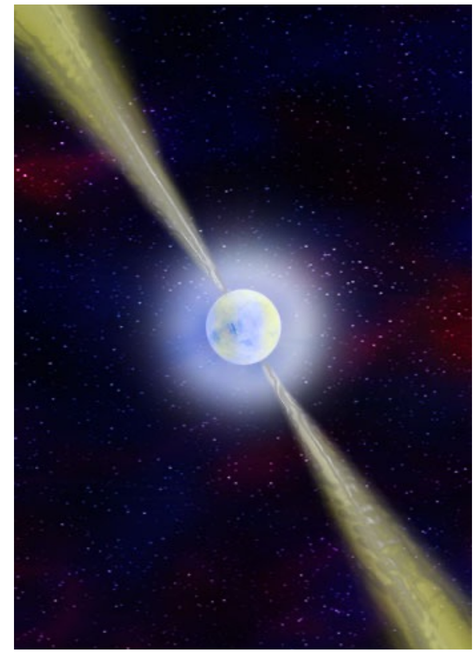

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Arguments Against Pulsars:

- The lack of pulsars detected in the Inner Galaxy
- The lack of low-mass X-ray binaries in the Inner Galaxy

Why Don't We See More Pulsars in the Inner Galaxy?

- To date, Fermi has detected only three gamma-ray pulsars that could potentially be located within a few kpc of the Galactic Center (PSR J1747-4036, PSR J1649-3012, and PSR J1833-3840)
- These three gamma-ray sources could be the first detected members of an Inner Galaxy pulsar population, but they could also easily be part of the Galactic Disk's pulsar population

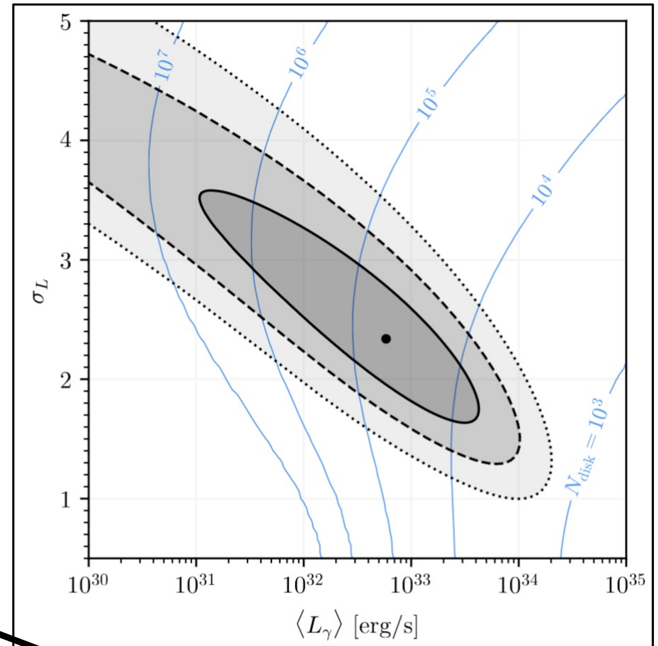
Why Don't We See More Pulsars in the Inner Galaxy?

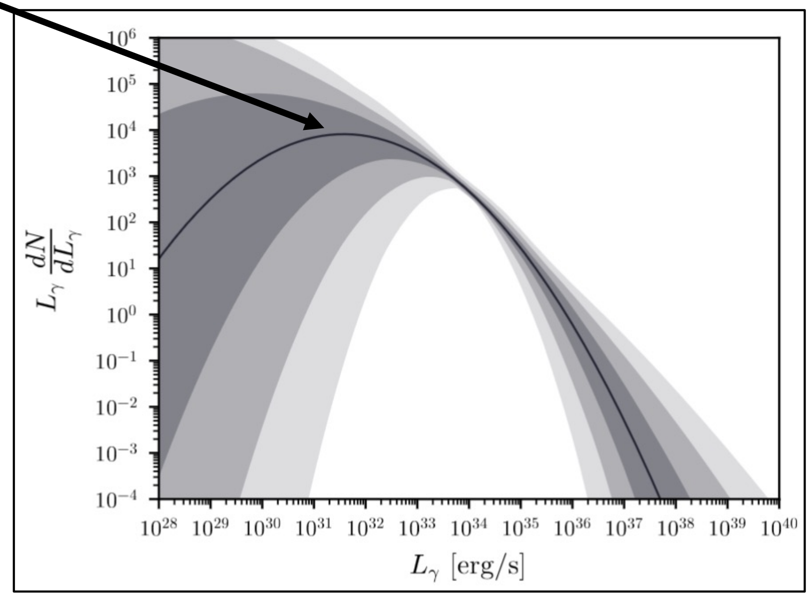
- From the contents of gamma-ray pulsar catalogs, we can measure the spatial distribution and luminosity function of known MSP populations

- These analyses find that the MSP gamma-ray luminosity peaks at around $L_\gamma \sim 10^{31} - 10^{32}$ erg/s

- For this luminosity function, we conclude that Fermi should be able to detect a non-negligible fraction of any individual MSPs that might be located in the Inner Galaxy

$$\frac{dN}{dL_\gamma} \propto \frac{1}{L_\gamma} \exp\left(-\frac{(\ln L_\gamma - \ln L_0)^2}{2\sigma_L^2}\right)$$



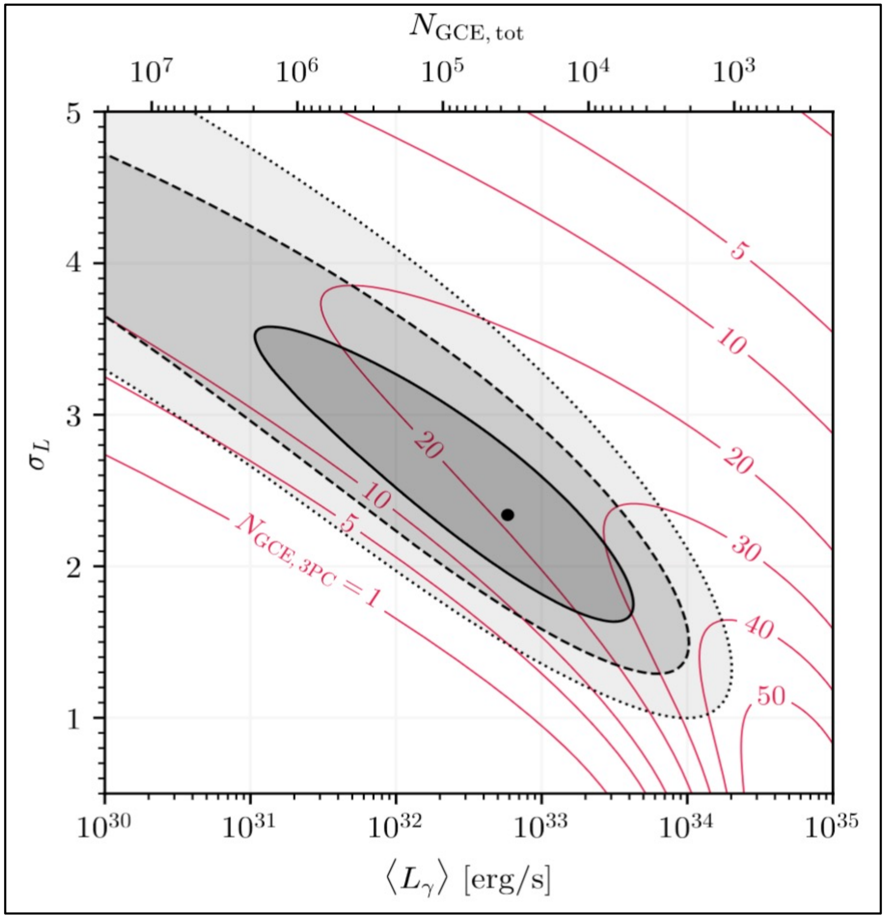


Holst, DH, arXiv:2403.00978

Why Don't We See More Pulsars in the Inner Galaxy?

Bottom Line:

- If the Galactic Center Excess is produced by pulsars with the same characteristics as those observed elsewhere, Fermi should have already detected ~20 of these pulsars in the Inner Galaxy
- To produce the Galactic Center Excess with pulsars would require at least ~200,000 of these sources which, on average, are at least ~5 times less luminous than those pulsars we observe elsewhere



Holst, DH, arXiv:2403.00978

(See also Dinsmore & Slatyer, 2112.09699; List, et al., 2107.09070; Mishra-Sharma & Cranmer, 2110.06931; Zhong, et al., 1911.12369)

Why Don't We See More Low-Mass X-Ray Binaries?

- Millisecond pulsars are formed when they are spun up by a binary companion; these precursors to MSPs are low-mass X-ray binaries (LMXBs)
- By measuring the ratio of the gamma-ray emission (from MSPs) to the number of bright LMXBs in globular clusters, and comparing this to the number of bright LMXBs in the Inner Galaxy, we can estimate the number of MSPs in the Inner Galaxy:

Infer

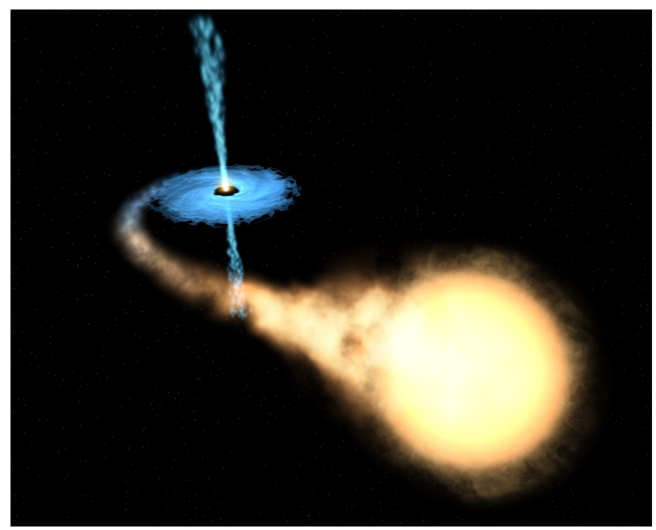
Measure

$$\frac{F_\gamma}{N_{\mathrm{LMXB}}}\bigg|_{\text{Globular Clusters}} = \frac{F_\gamma}{N_{\mathrm{LMXB}}}\bigg|_{\text{Inner Galaxy}}$$

Measure

Measure

- This procedure finds that only 5-10% of the gamma-ray excess is attributable to MSPs
- If the entire gamma-ray excess was from MSPs, INTEGRAL should have detected ~10^3 LMXBs in the Inner Galaxy; but they actually detected 42



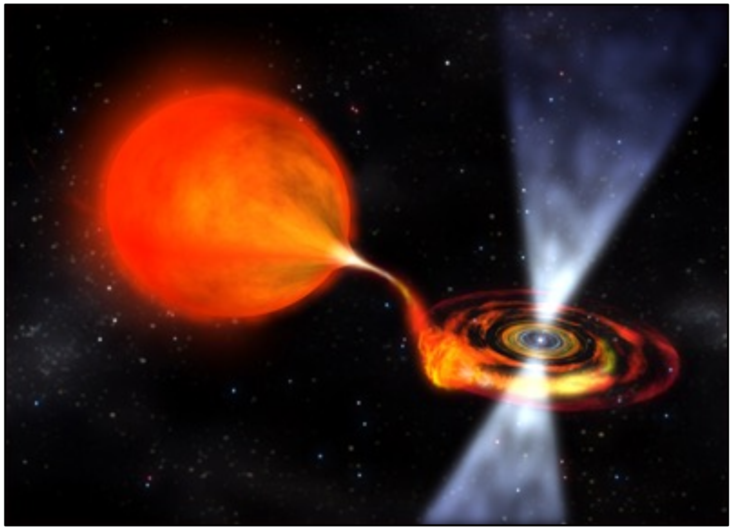
Haggard, Heinke, DH, Linden, arXiv:1701.02726
(see also Cholis, DH, Linden, arXiv:1407.5625)

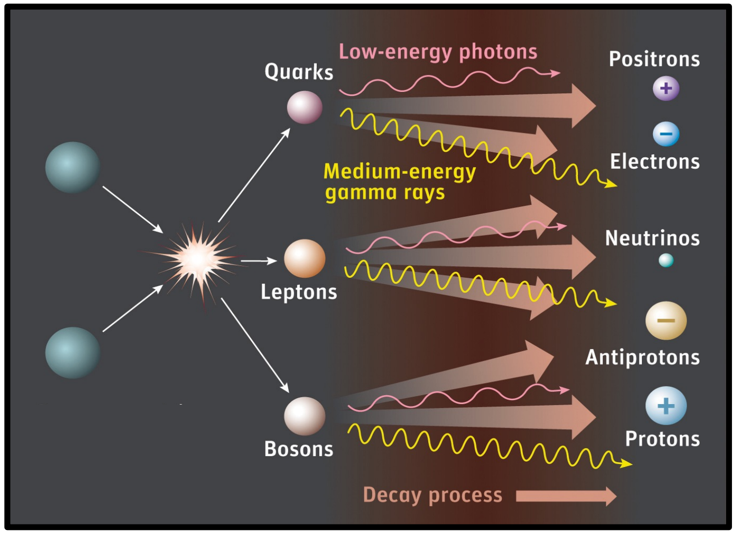
What Produces the Galactic Center Excess?

Bottom Line:

The measured spectrum, morphology, and intensity of the Galactic Center Gamma-Ray Excess each agree well with the predictions of annihilating dark matter in the form of a ~50 GeV thermal relic

The excess could be generated by pulsars, but this would require a very large and exotic population of low-luminosity millisecond pulsars, with few accompanying low-mass X-ray binaries



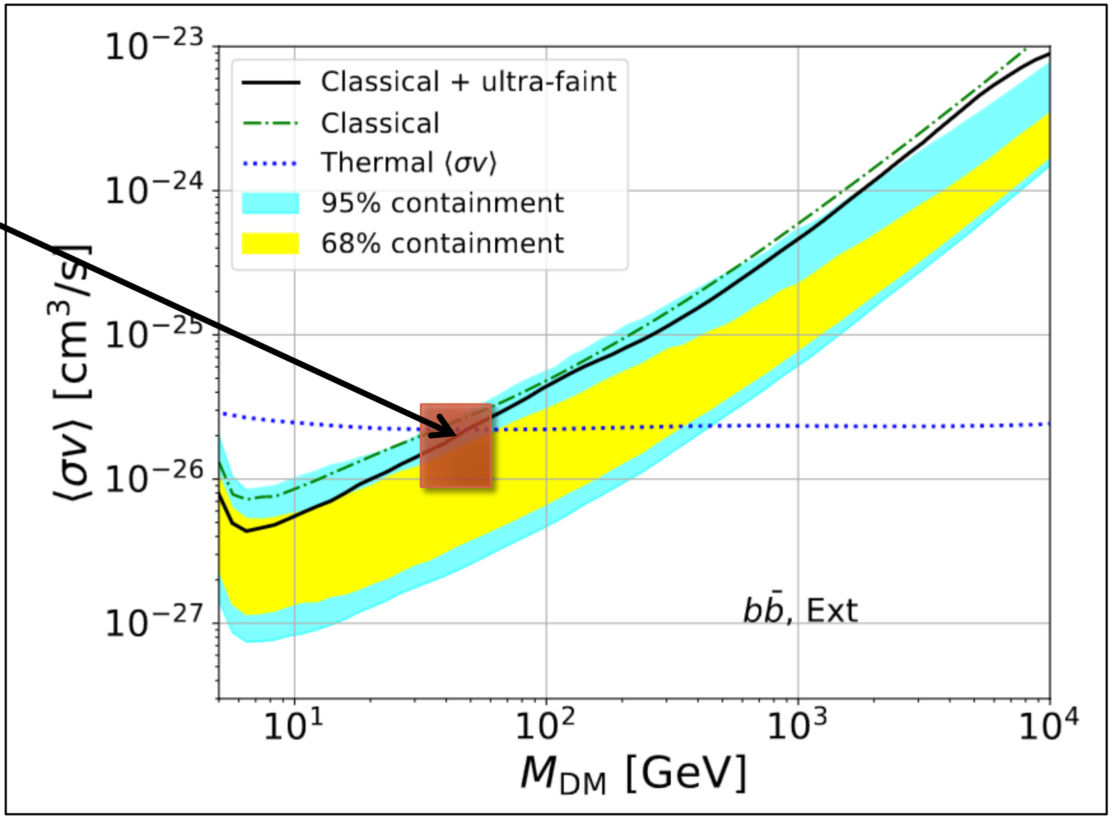


If the Galactic Center Excess is the result of annihilating dark matter, where else would we expect to see evidence of this process?

Fermi Observations of Dwarf Galaxies

- Current Fermi dwarf constraints are based on observations of several dozen dwarf galaxies, including many that were discovered by DES and other recent surveys
- Although these constraints are currently compatible with dark matter interpretations of the Galactic Center excess, even modest improvements in sensitivity would shed significant light on this interpretation

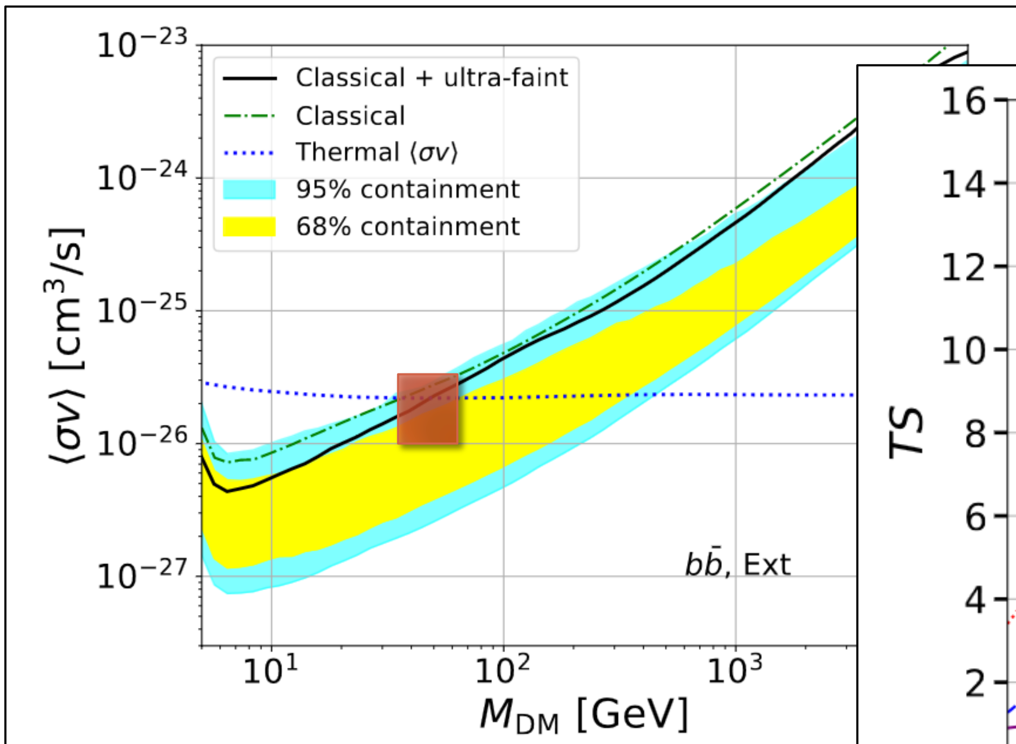
Region favored by the GCE



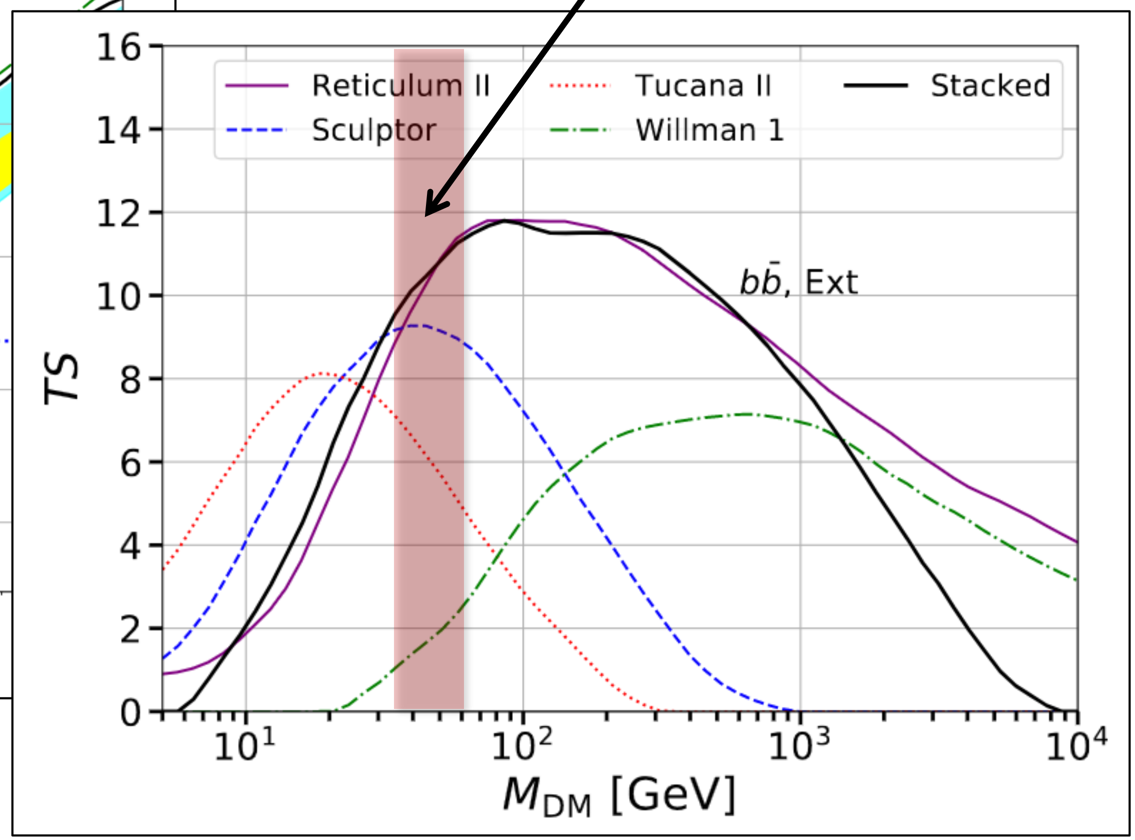
Di Mauro, Stref, Calore, arXiv:2212.06850
(see also, Fermi Collaboration, arXiv:2311.04982)

Fermi Observations of Dwarf Galaxies

- Small excesses have been observed from a handful of dwarf galaxies (Reticulum II, Tucana II, Sculptor, and Willman 1)
- The combination of this data favors the presence of a GCE-like WIMP at a level of TS~10-12 (corresponding to a local significance of ~3σ)



GCE-Favored Region



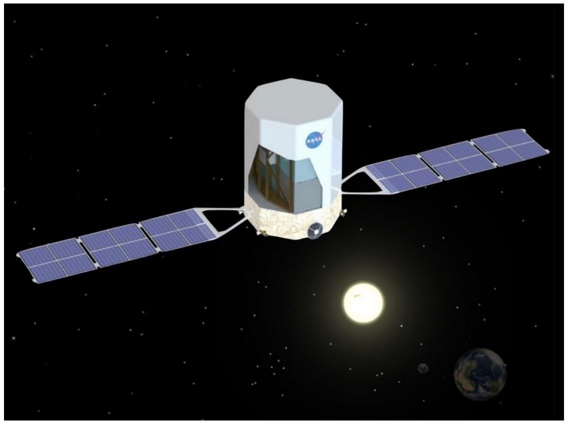
Di Mauro, Stref, Calore, arXiv:2212.06850

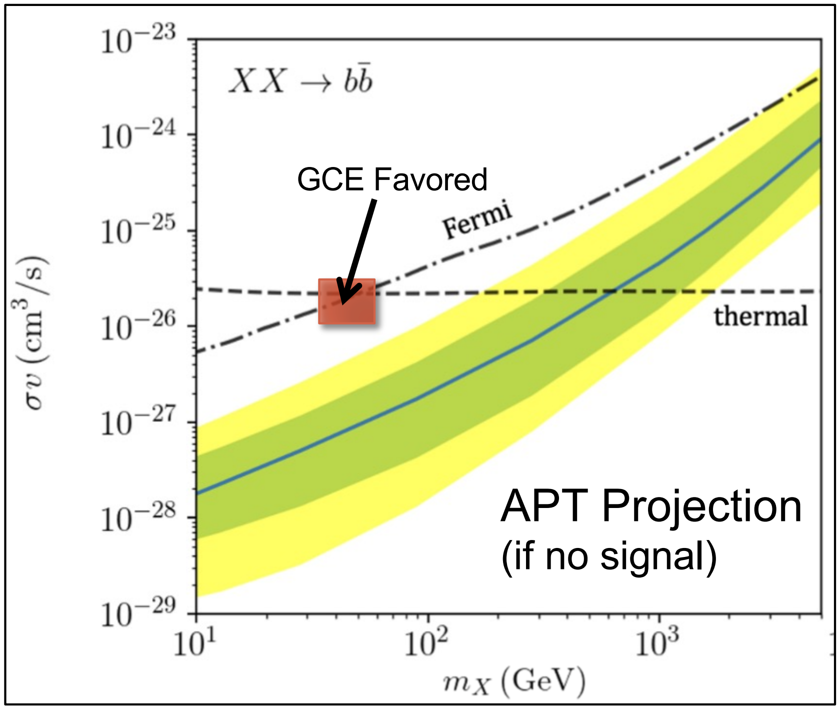
Dwarf Galaxies in the Rubin Era

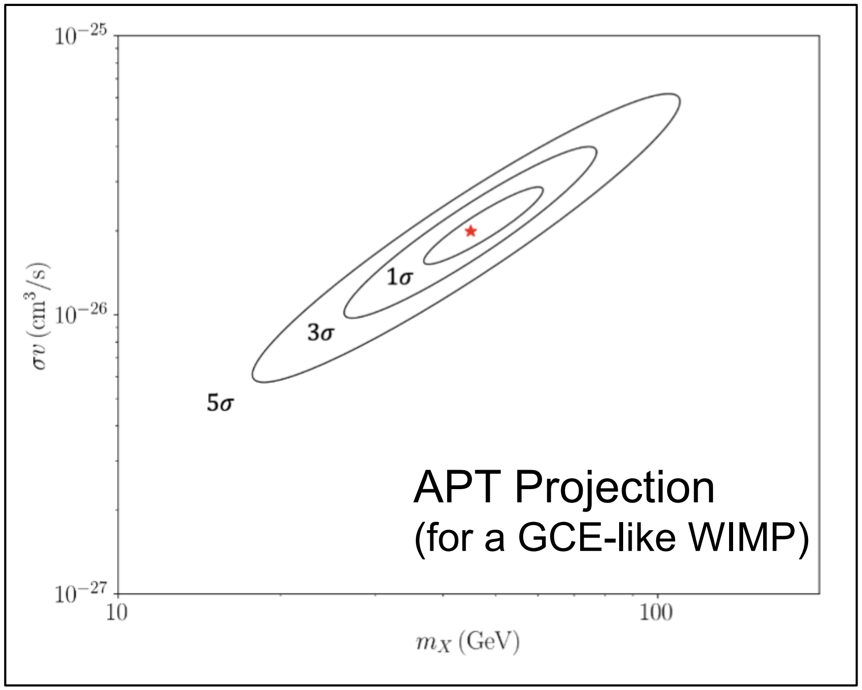
- The Rubin Observatory (first light in 2025!) is expected to discover ~150-250 new Milky Way dwarf galaxies (compared to ~50 at present)
- Once these new dwarfs are discovered, we can use already existing Fermi data to look for gamma-ray signals from annihilating dark matter
- With Rubin, Fermi's sensitivity to dark matter annihilation in dwarf galaxies could plausibly increase by a factor of ~2-3, finally enabling us to test much (perhaps all?) of parameter space favored by the Galactic Center excess

Telescopes Beyond Fermi

- Dark matter searches using gamma rays from dwarf galaxies are limited by statistics; their sensitivity could be dramatically improved by larger telescopes
- As an example, consider the projected sensitivity of the proposed *Advanced Particle-astrophysics Telescope* (APT):







F. Xu and DH, arXiv:2308.15538

Summary

- WIMPs remain an extremely well-motivated class of dark matter candidates
- Indirect searches using gamma rays and cosmic rays are currently testing the range of annihilation cross sections that are predicted for a thermal relic for masses up to $\sim\mathcal{O}(100)$ GeV; this program is testing the WIMP paradigm!
- The Galactic Center's GeV excess remains compelling: highly statistically significant, robust, extended, spherical, and not easily explained with known or proposed astrophysics
- Earlier arguments claiming that this excess is generated by unresolved point sources have not held up to scrutiny; recent studies have found that the morphology of this signal is consistent with expectations from dark matter
- Arguments based on the number of gamma-ray bright MSPs and bright LMXBs each disfavor pulsars as the source of this emission
- Gamma-ray observations of dwarf galaxies in the Rubin-era, and with future gamma-ray telescopes could provide a critical test of this signal's origin

Indirect Search for Neutralino Dark Matter with High Energy Neutrinos

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Abstract

We investigate the prospects of indirect searches for supersymmetric neutralino dark matter. Relic neutralinos gravitationally accumulate in the Sun and their annihilations produce high energy neutrinos. Muon neutrinos of this origin can be seen in large detectors like AMANDA, IceCube and ANTARES. We evaluate the relic density and the detection rate in several models — the minimal supersymmetric model, minimal supergravity, and supergravity with non-universal Higgs boson masses at the grand unification scale. We make realistic estimates for the indirect detection rates including effects of the muon detection threshold, quark hadronization, and solar absorption. We find good prospects for detection of neutralinos with mass above 200 GeV.

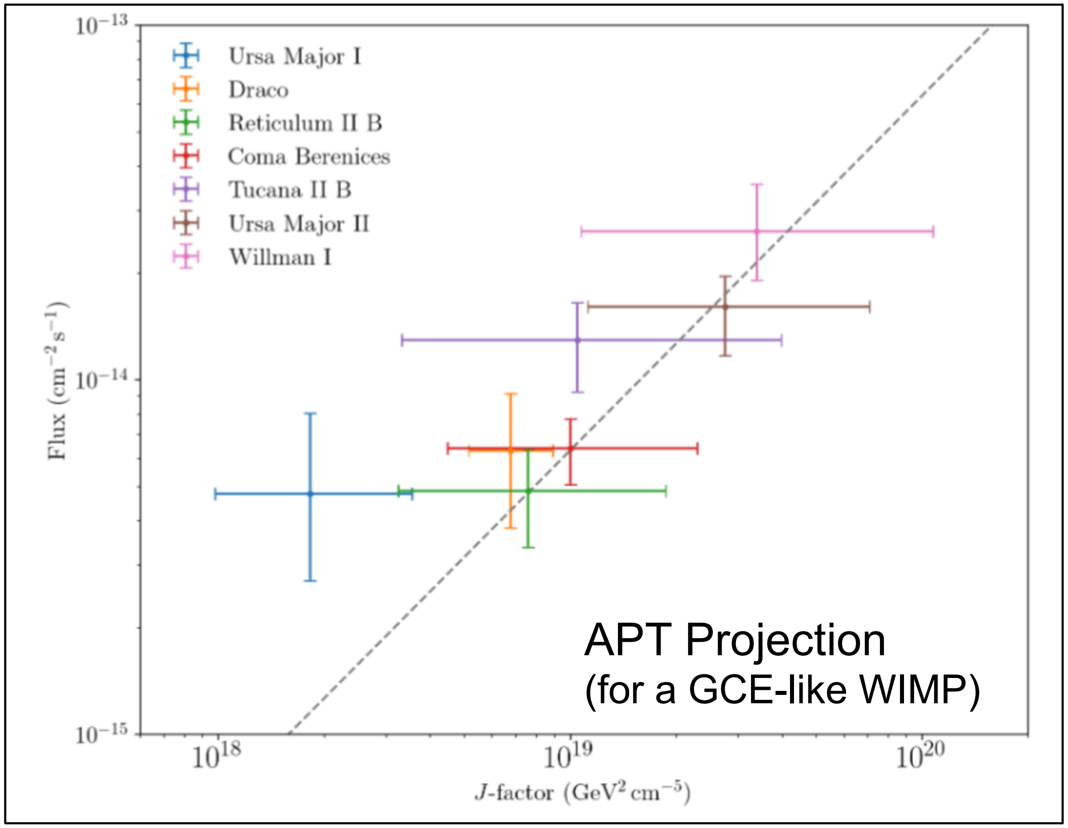
Telescopes Beyond Fermi

- Dark matter annihilation signals from dwarf galaxies are proportional to their independently measured *J*-factors:

$$J(\Delta\Omega) = \int_{\Delta\Omega} \int_{\rm los} \rho_X^2 \, dl \, d\Omega$$

- No astrophysical backgrounds are expected to have this scaling

- For dark matter candidates that could produce the Galactic Center Excess, APT would detect gamma rays from several dwarfs, allowing it to clearly establish whether this proportionality holds
- If this scaling is observed, it would be an unambiguous signature of annihilating dark matter – a smoking gun



F. Xu and DH, arXiv:2308.15538