DARK MATTER ANNIHILATION IN THE GALACTIC CENTER

Dan Hooper – Fermilab/University of Chicago

Inνisibles15 Workshop

June 25, 2015

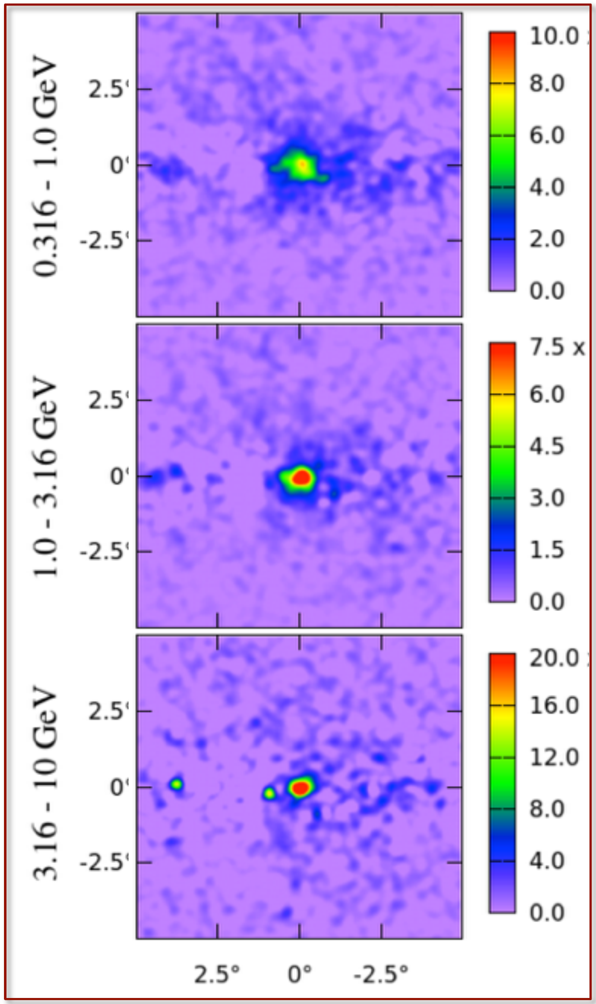
The Galactic Center GeV Excess

Much of this talk is based on:

- T. Daylan, D. Finkbeiner, DH, T. Linden, S. Portillo, N. Rodd, and T. Slatyer, arXiv:1402.6703
- F. Calore, I. Cholis, C. Weniger, arXiv:1409.0042

For earlier work related to this signal and its interpretation, see (among others):

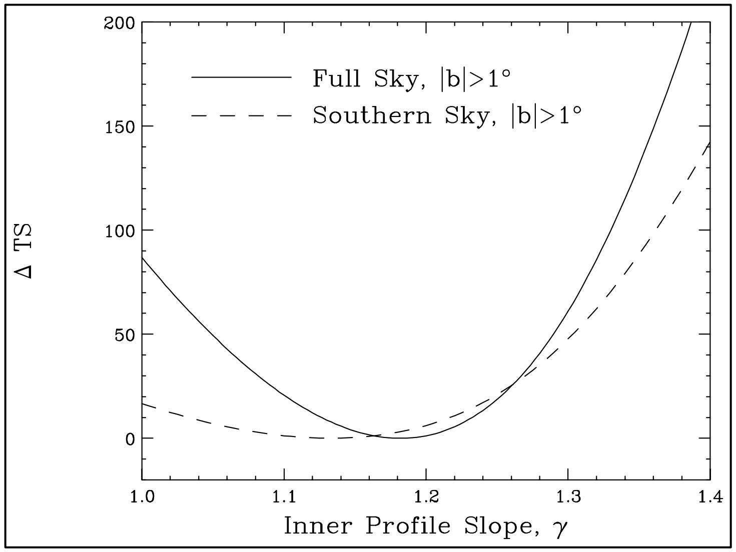
- L. Goodenough, DH, arXiv:0910.2998
- DH, L. Goodenough, PLB, arXiv:1010.2752
- DH, T. Linden, PRD, arXiv:1110.0006
- K. Abazajian, M. Kaplinghat, PRD, arXiv:1207.6047
- DH, T. Slatyer, PDU, arXiv:1302.6589
- C. Gordon, O. Macias, PRD, arXiv:1306.5725
- W. Huang, A. Urbano, W. Xue, arXiv:1307.6862
- K. Abazajian, N. Canac, S.Horiuchi, M. Kaplinghat, arXiv:1402.4090

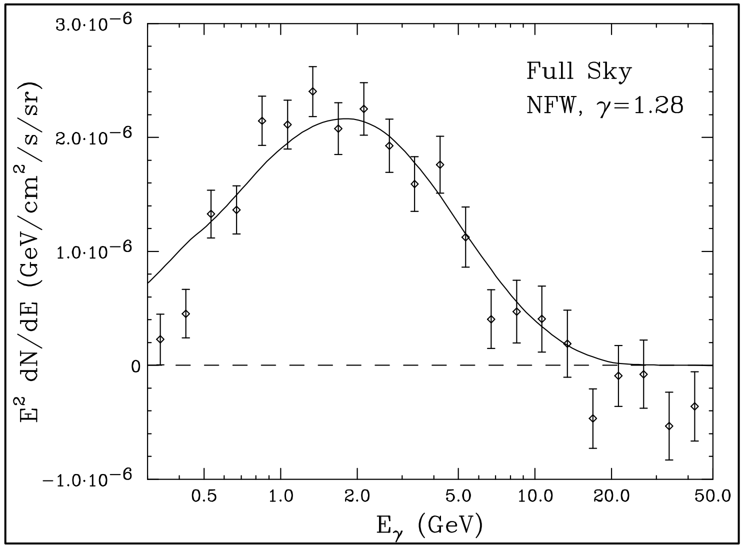


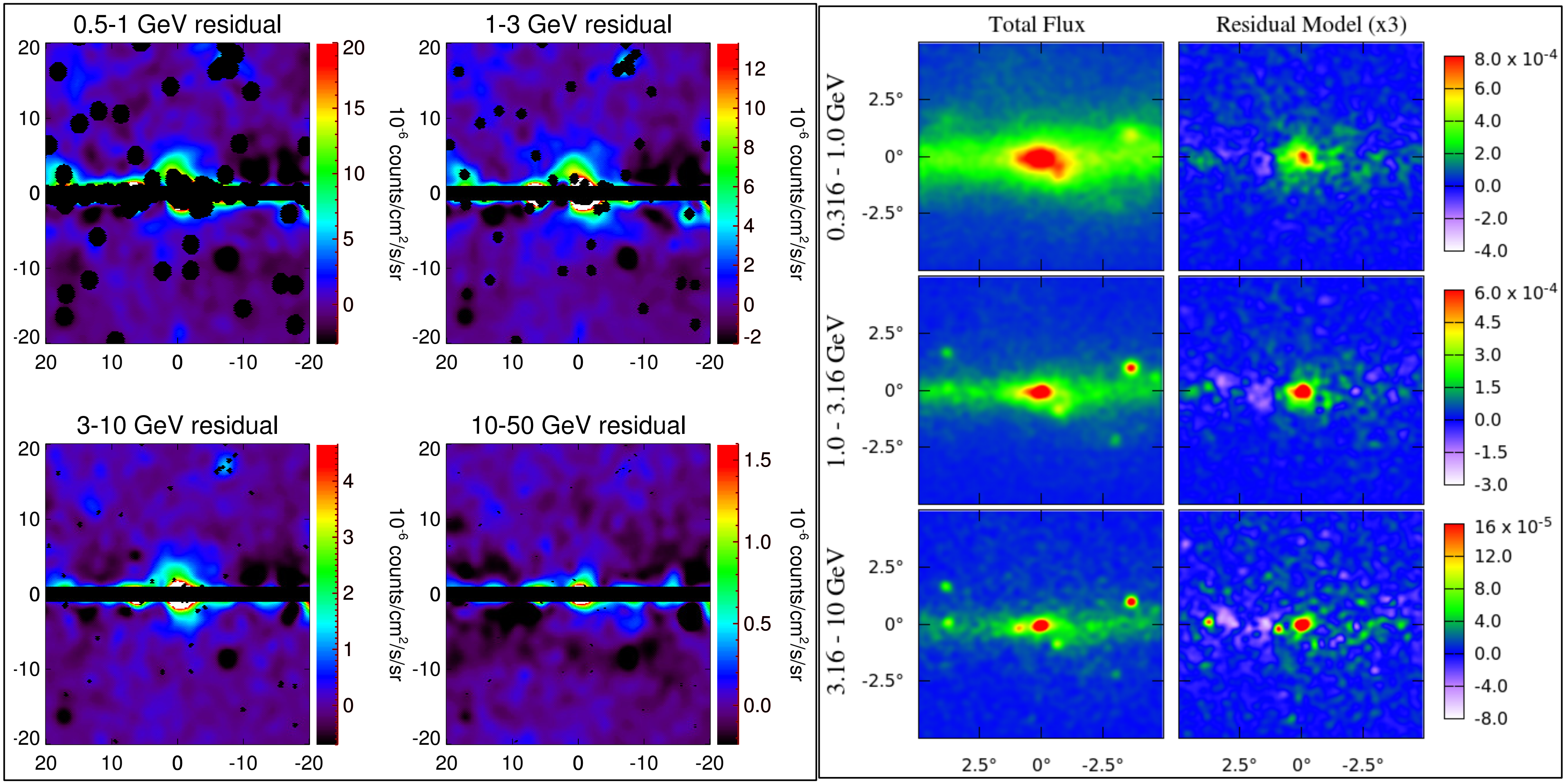
Basic Features of the GeV Excess

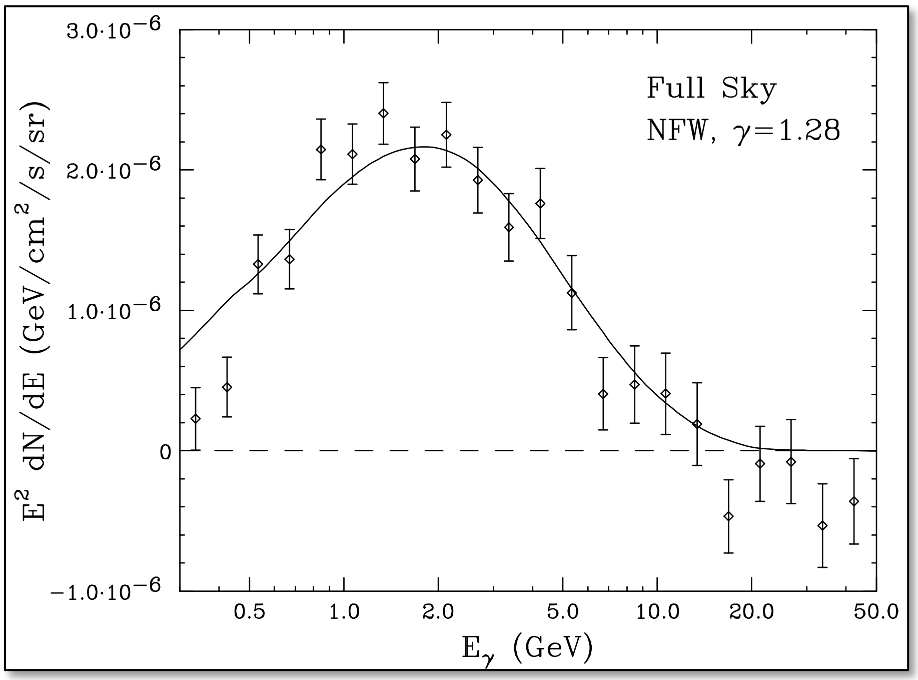
- The excess is distributed around the Galactic Center with a flux that falls off approximately as $r^{-2.4}$ (if interpreted as dark matter annihilation products, $\rho_{DM} \sim r^{-1.2}$)
- The spectrum of this excess peaks at ~1-3 GeV, and is in good agreement with that predicted from a ~45 GeV WIMP annihilating to $b\bar{b}$ (for example)
- To normalize the observed signal with annihilating dark matter, a cross section of $\sigma v \sim 10^{-26}$ cm^3/s is required*

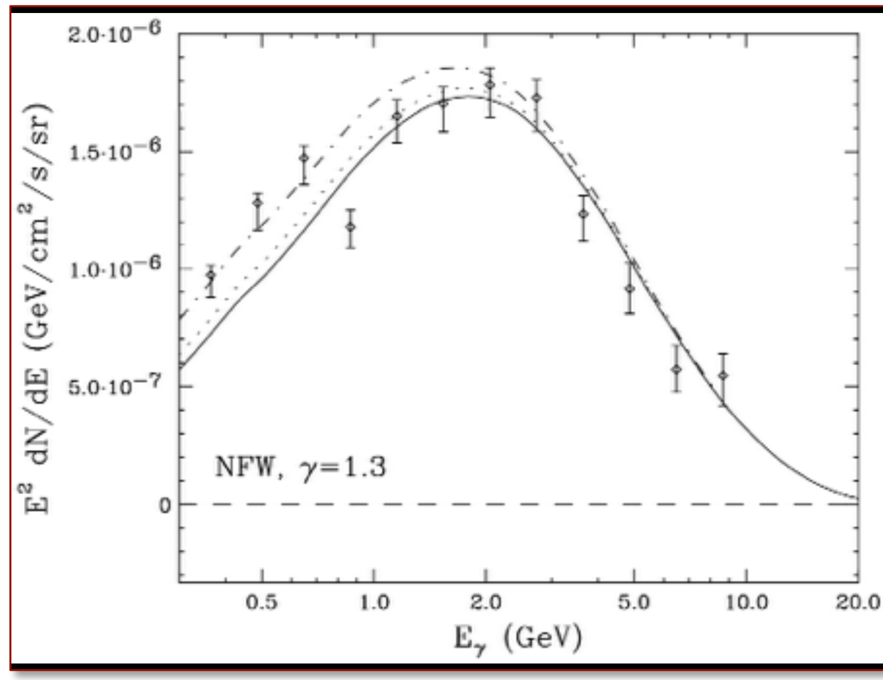
*After marginalizing over halo parameters, we find $\sigma v \approx (0.3\text{-}5) \times 10^{-26}$ cm^3/s



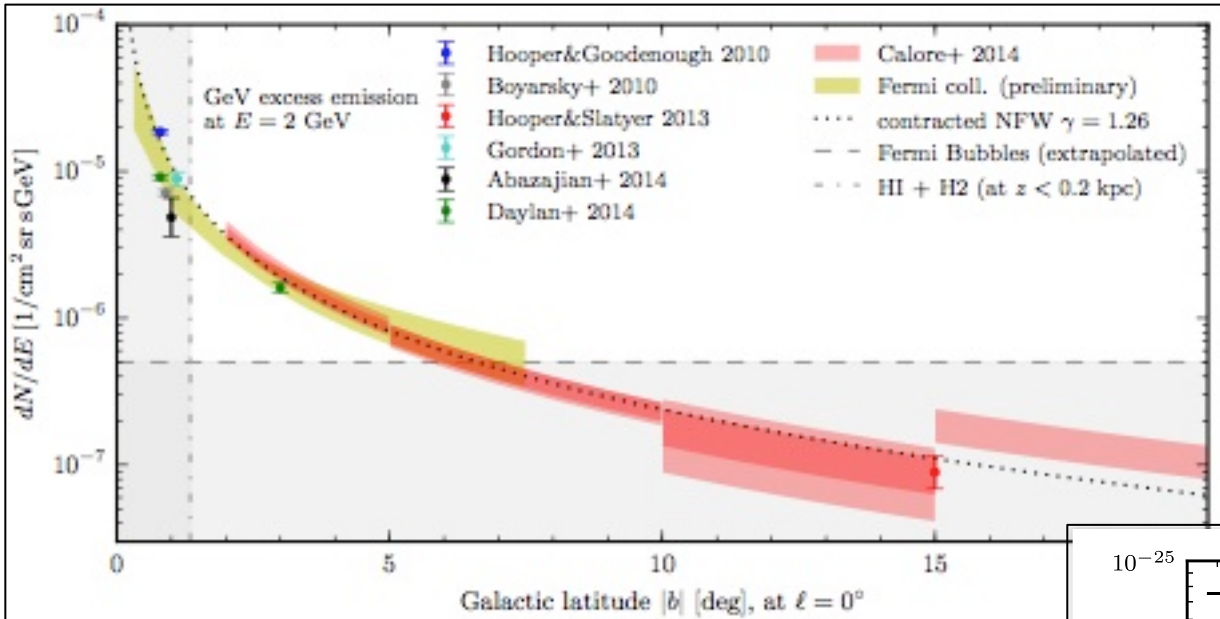


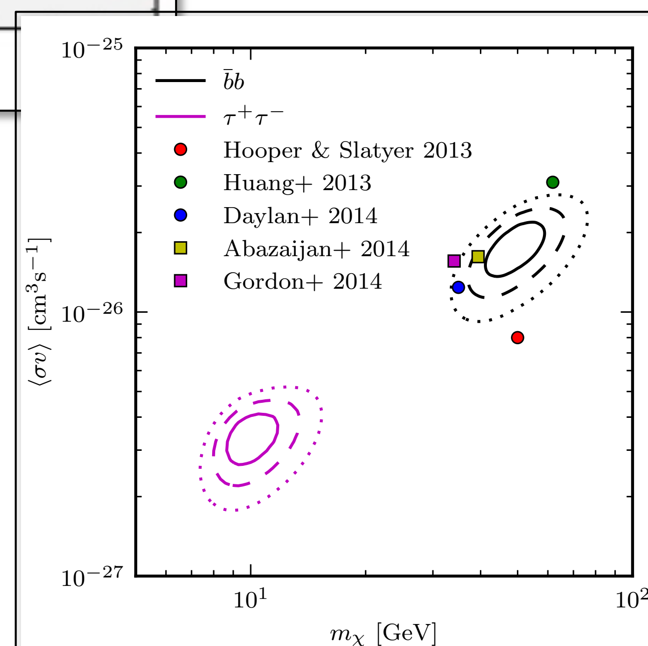

0.5-1 GeV residual
1-3 GeV residual
3-10 GeV residual
10-50 GeV residual
10⁻⁶ counts/cm²/s/sr
Total Flux
Residual Model (x3)
0.316 - 1.0 GeV
1.0 - 3.16 GeV
3.16 - 10 GeV
8.0 x 10⁻⁴
6.0 x 10⁻⁴
16 x 10⁻⁵


Full Sky
NFW, γ=1.28
E² dN/dE (GeV/cm²/s/sr)
Eγ (GeV)
3.0·10⁻⁶
2.0·10⁻⁶
1.0·10⁻⁶
0
−1.0·10⁻⁶
0.5
1.0
2.0
5.0
10.0
20.0
50.0


NFW, γ=1.3
E² dN/dE (GeV/cm²/s/sr)
Eγ (GeV)
2.0·10⁻⁶
1.5·10⁻⁶
1.0·10⁻⁶
5.0·10⁻⁷
0
0.5
1.0
2.0
5.0
10.0
20.0

As far as I am aware, no analysis of this data has disagreed with these conclusions – the signal is there, and it has the basic features described on the previous slides





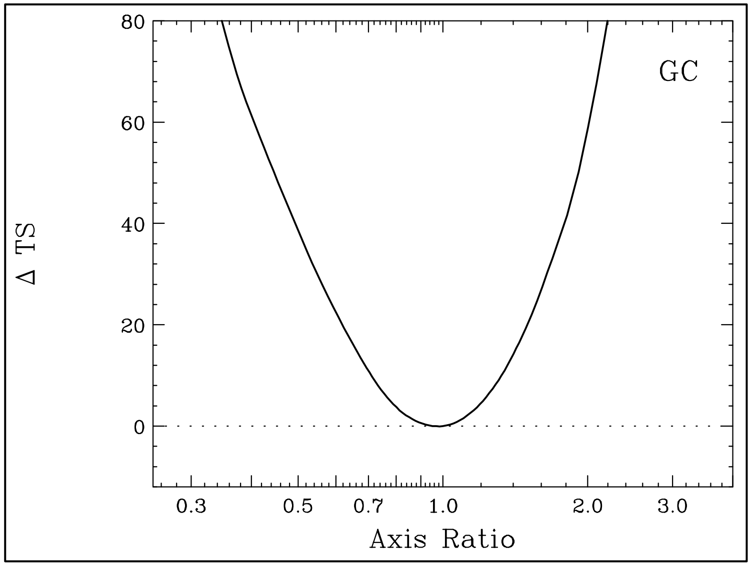
Calore, Cholis, McCabe, Weniger, 1411.4647;
Calore, Cholis, Weniger, arXiv:1409.0042

Overwhelming Statistical Significance

- This excess corresponds to a flux of ~10^4 photons (> 1 GeV) per square meter, per year
- In our Inner Galaxy analysis, the quality of the best-fit found with a dark matter component included improves over the best-fit without a dark matter component by ~30σ
- Signal-to-background is also fairly high (roughly 1-to-2 in the innermost degree)

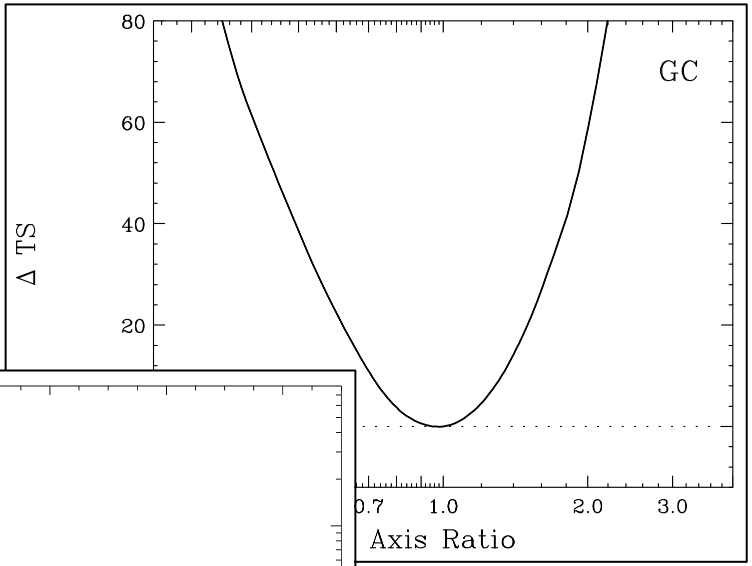
The Morphology of the Excess

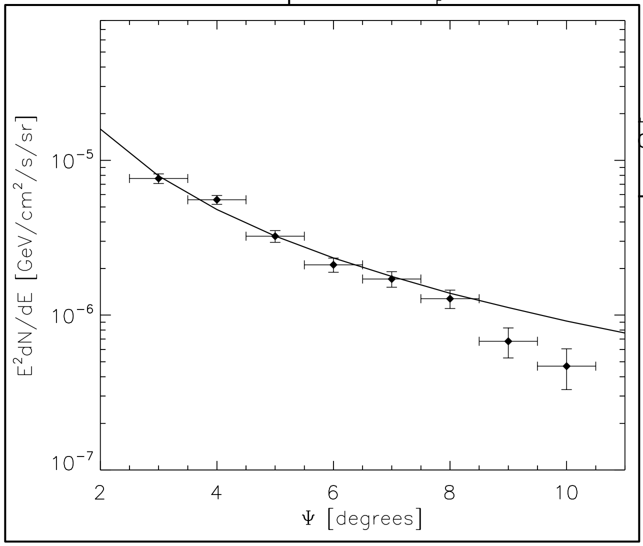
- The excess is spherically symmetric with respect to the Galactic Center, strongly preferring axis-ratios within 20% of unity



The Morphology of the Excess

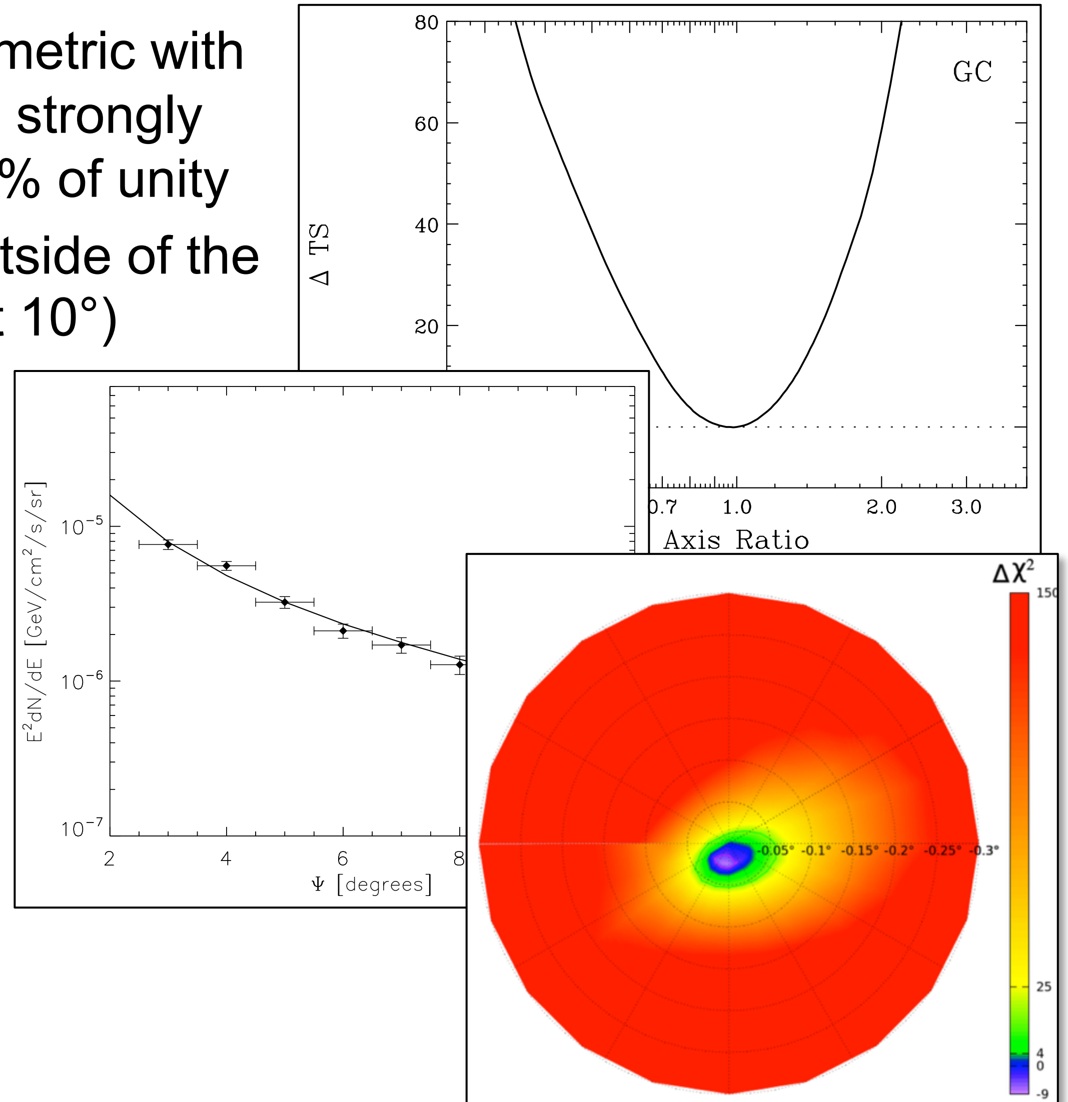
- The excess is spherically symmetric with respect to the Galactic Center, strongly preferring axis-ratios within 20% of unity
- The excess extends to well outside of the Galactic Center (out to at least 10°)





The Morphology of the Excess

- The excess is spherically symmetric with respect to the Galactic Center, strongly preferring axis-ratios within 20% of unity
- The excess extends to well outside of the Galactic Center (out to at least 10°)
- The excess is very precisely centered around Sgr A* (within ~0.03° or ~5 pc)
- The intensity of the excess continues to rise to within ~10 pc of Sgr A* (no flattening or core)



An Excess Relative to What?

Although it is clear at this point that Fermi has observed an excess relative to standard astrophysical background models, it is important and reasonable to be asking to what extent we can trust and rely upon the predictions of such background models

Are there any viable astrophysical models that can explain the excess?

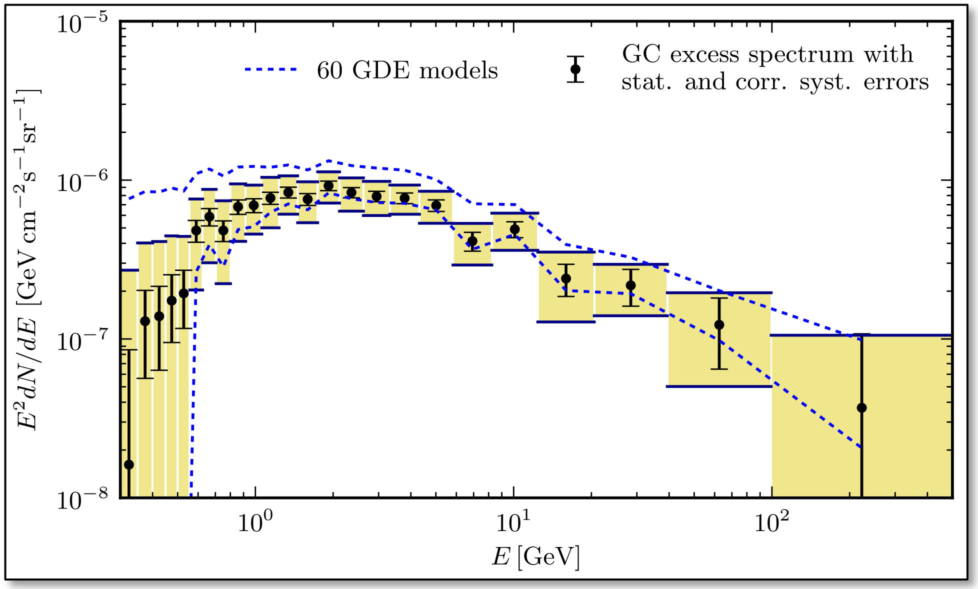
Do variations in the background model significantly impact the characteristics of the residual excess?

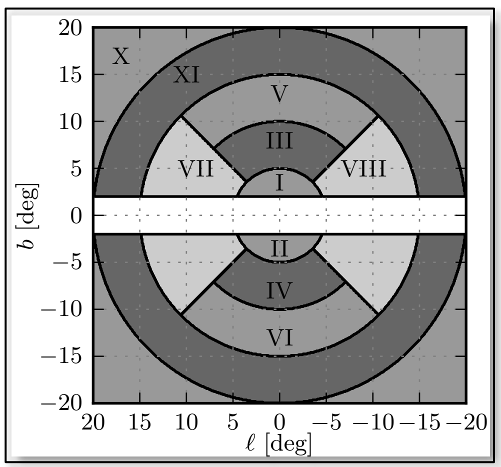
Background model systematics for the Fermi GeV excess

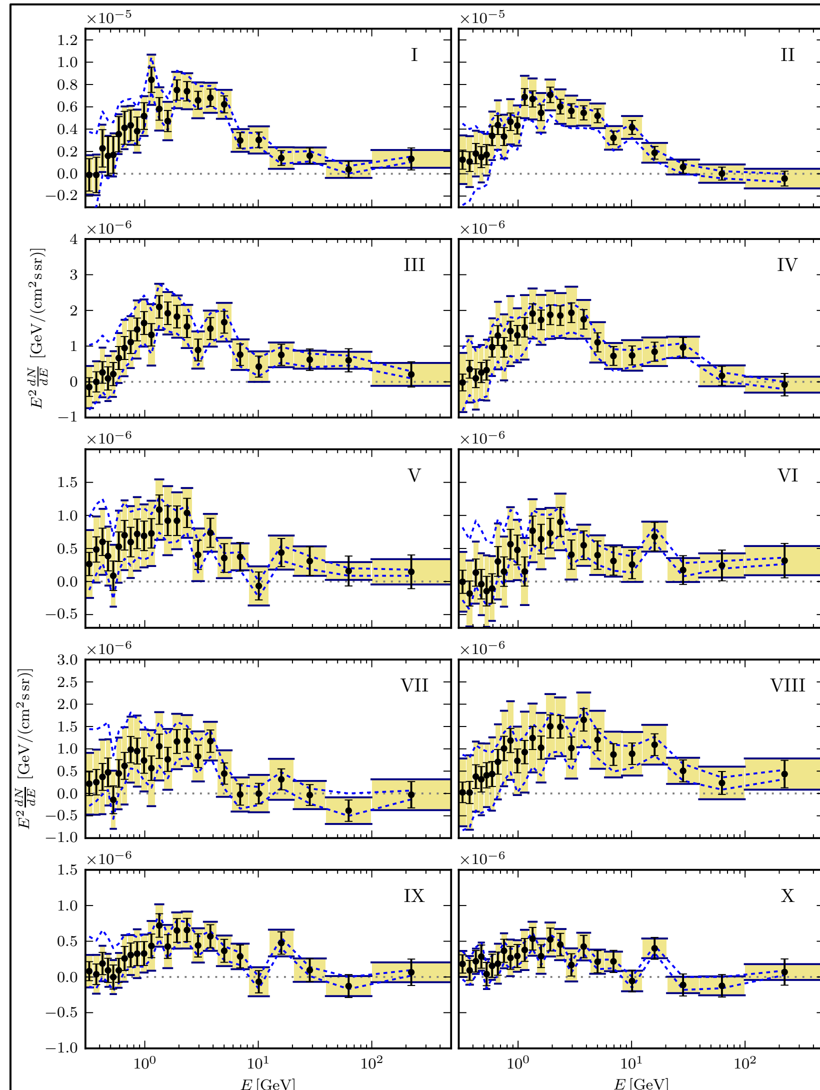
Francesca Calore,[a] Ilias Cholis[b] and Christoph Weniger[a]

arXiv:1409.0042
Highly Recommended!

- First comprehensive study of the systematic uncertainties on the relevant astrophysical backgrounds
- Considered a very wide range of models, with extreme variation in cosmic ray source distribution and injection, gas distribution, diffusion, convection, re-acceleration, interstellar radiation and magnetic fields
- Not only does the excess persist for all such background models, the spectral and morphological properties of the excess are "remarkably stable" to these variations
- The excess does not appear to be the result of the mismodeling of standard astrophysical emission processes







Calore, Cholis, Weniger, arXiv:1409.0042

The Evolving Nature of the Galactic Center Debate

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Circa 2009-2010

What Galactic Center excess?

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What Galactic Center excess?

Circa 2011-2013

Sure there seems to be a Galactic Center excess, but

1) Are we sure that it is spatially extended?
2) Are we mismodeling standard diffuse emission mechanisms?
3) Is there really a Galactic Center excess?

The Evolving Nature of the Galactic Center Debate

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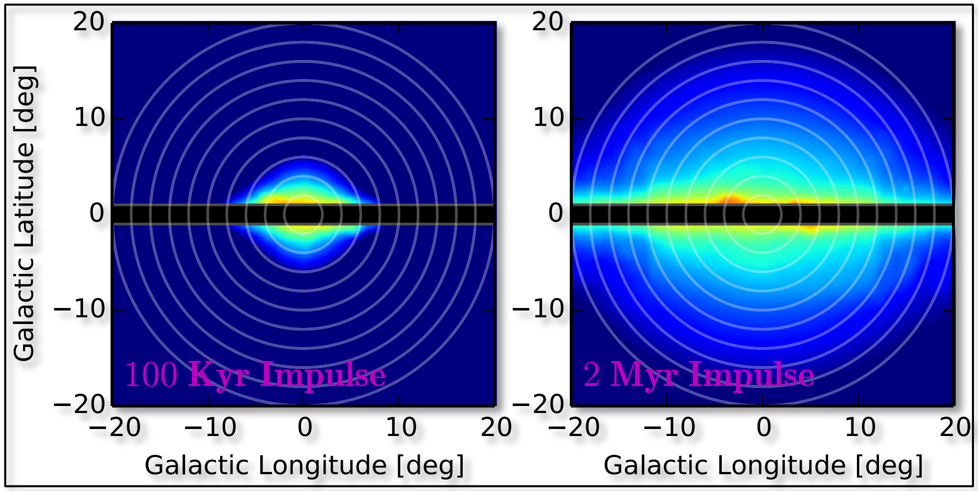
Circa 2014-2015

What is generating this excess?

1) A large population of centrally located millisecond pulsars?
2) A series of recent cosmic ray outbursts?
3) Annihilating dark matter?

A Series of Cosmic Ray Outbursts?

- It has been proposed that the recent (~10^6 yrs) burst-like injection of cosmic rays might be responsible for the excess
- Hadronic scenarios predict a signal that is not at all spherical; highly incompatible with the data
- In more generality, the small-scale structure of excess does *not* correlate with the distribution of gas – this is incompatible with any hadronic cosmic ray origin for the excess



Carlson, Profumo, PRD, arXiv:1405.7685,
Petrovic, Serpico, Zaharijas, arXiv:1405.7928

A Series of Cosmic Ray Outbursts?

- The leptonic scenario proposed by Petrovic *et al*. is more difficult to rule out
- After exploring a wide range of leptonic outburst scenarios, there appear to be two main challenges (among others):

Petrovic, Serpico, Zaharijas, arXiv:1405.7928
Cholis, Evoli, Calore, Linden, Weniger, DH, arXiv:1506.05104

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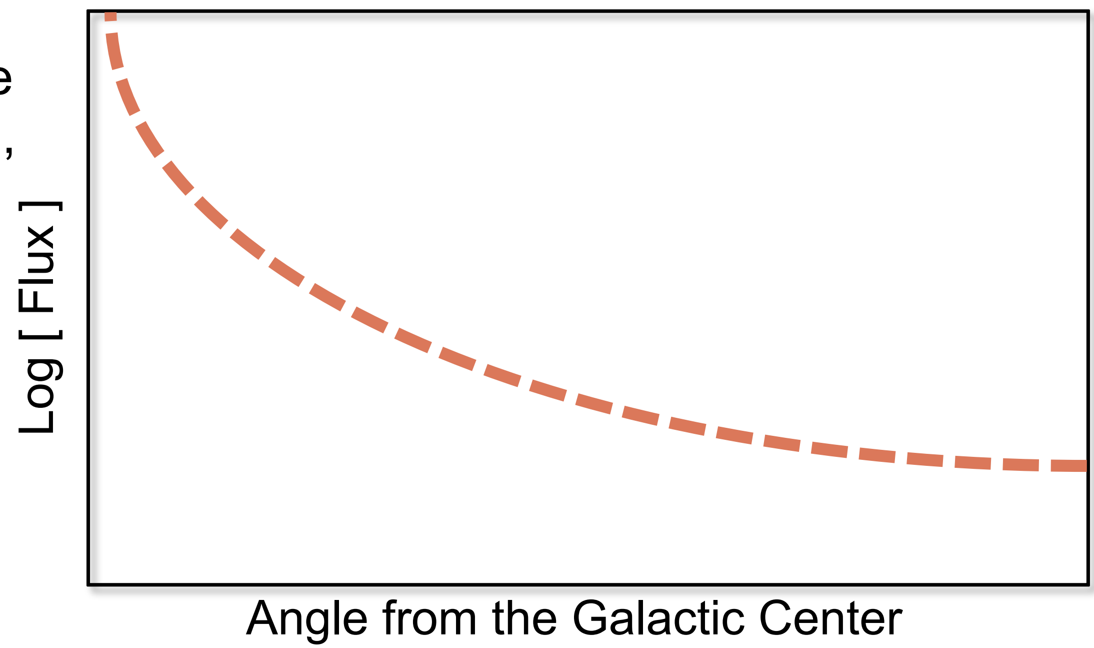

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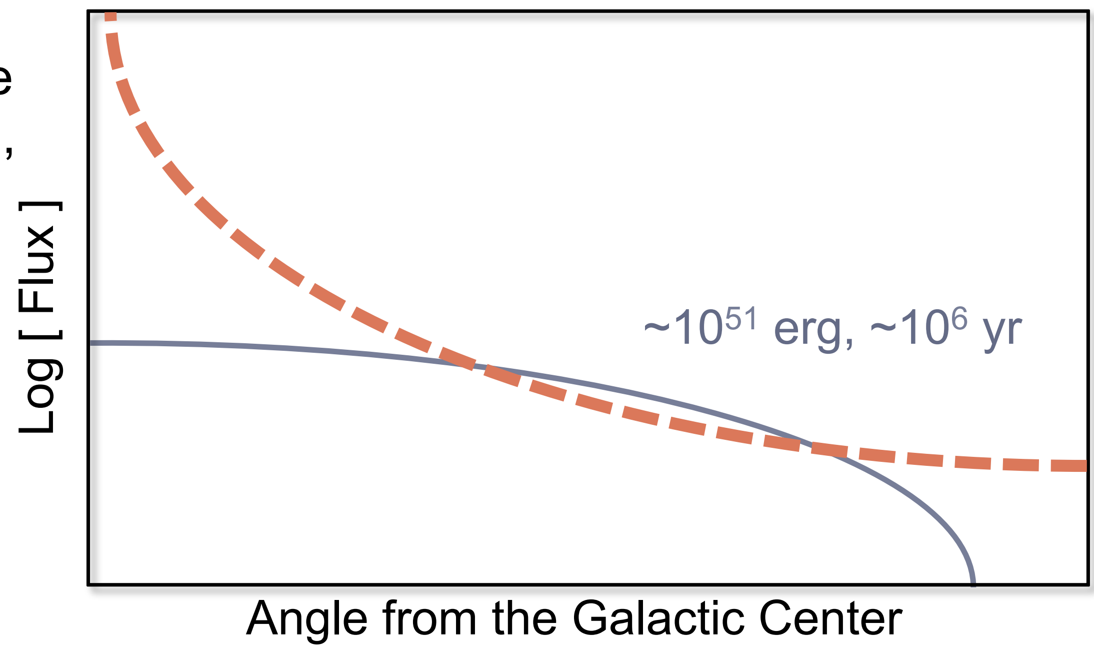

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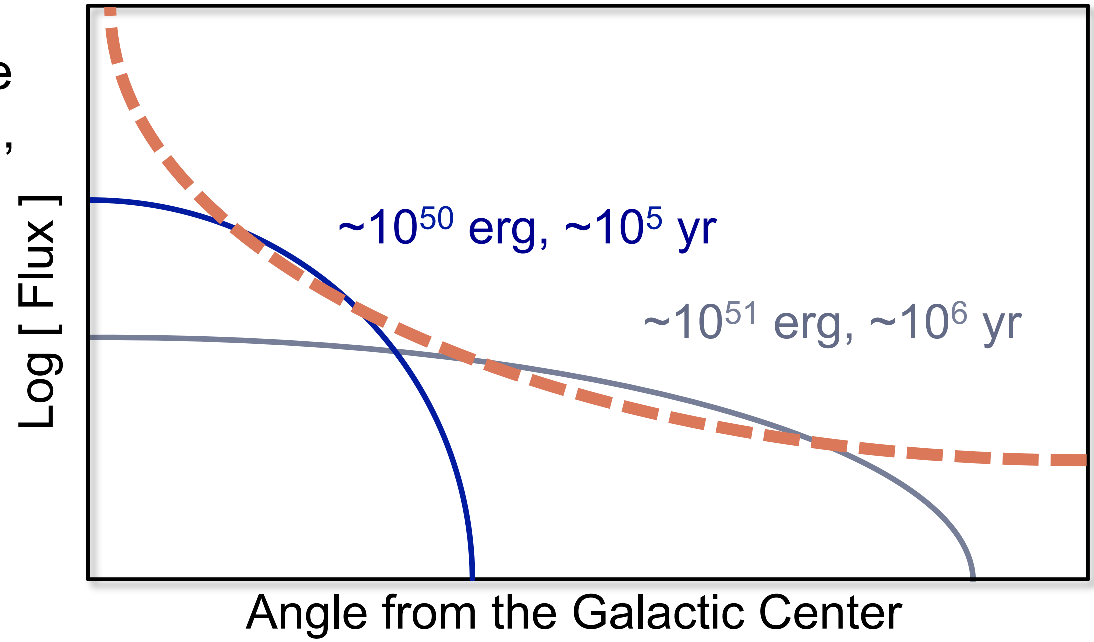

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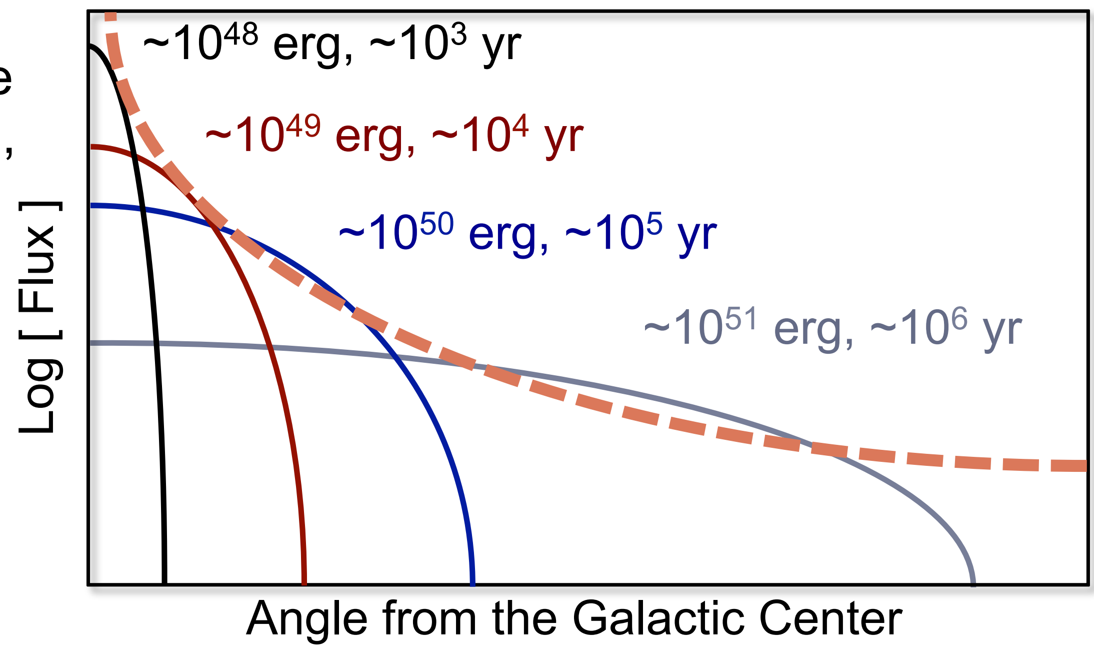

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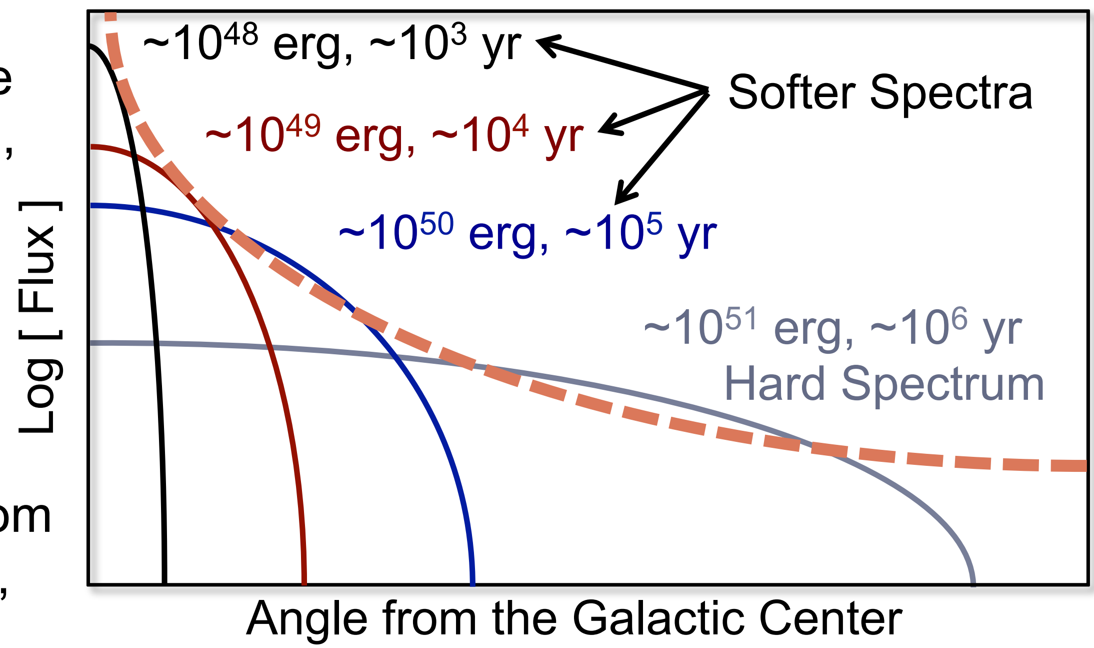
2) The gamma-ray spectrum is approximately uniform over the Inner Galaxy, but energy losses should lead to softer emission from the outer regions – to fit the data, we need the older outbursts to inject electrons with higher energies than more recent outbursts



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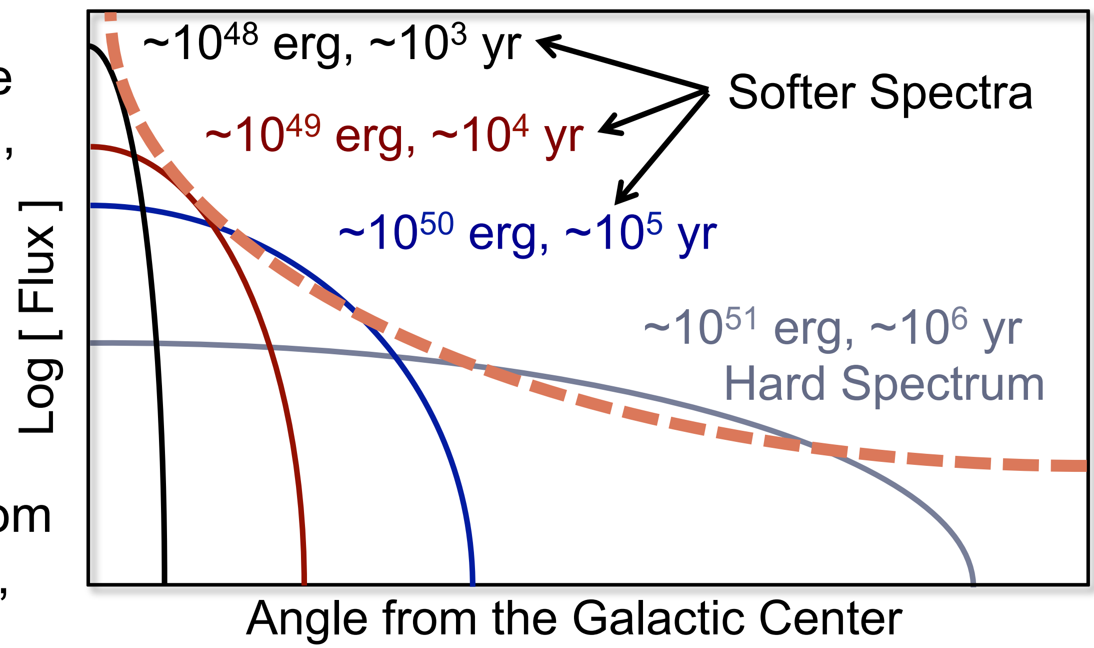
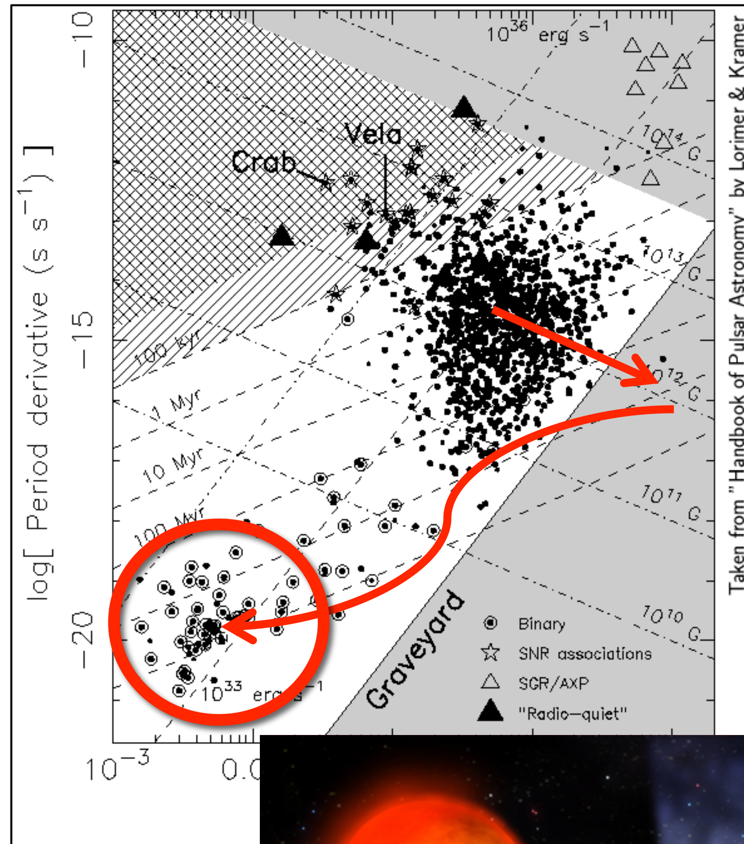


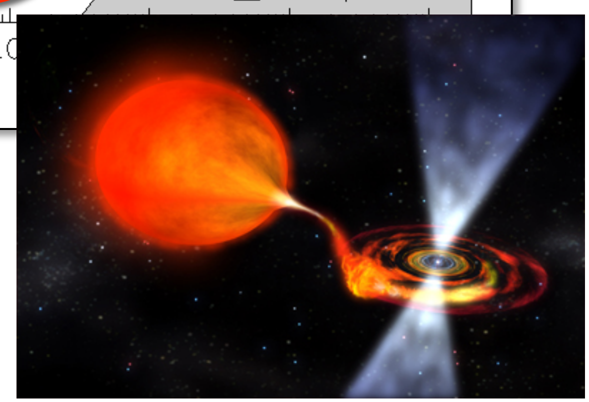
Leptonic outburst models could potentially fit the excess, but they require a number of rather extreme and carefully tuned features

Petrovic, Serpico, Zaharijas, arXiv:1405
Cholis, Evoli, Calore, Linden, Weniger, DH, arXiv:1506.05104

Millisecond Pulsars Basics

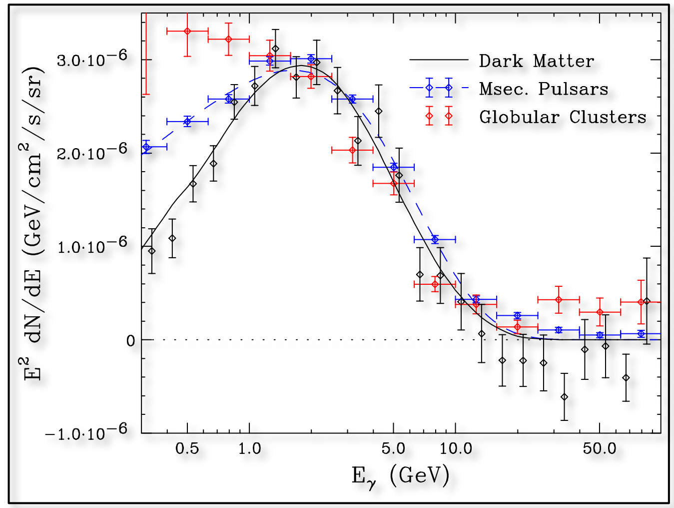
- Pulsars are rapidly spinning neutron stars, which gradually convert their rotational kinetic energy into radio and gamma-ray emission
- Typical pulsars exhibit periods on the order of ~1 second and slow down and become faint over ~10^6 -10^8 years
- Accretion from a companion star can “spin-up” a dead pulsar to periods as fast as ~1.5 msec
- Such millisecond pulsars have low magnetic fields (~10^8-10^9 G) and thus slow down much more gradually, remaining bright for >10^9 years
- It seems plausible that large numbers of MSPs could be in the Galactic Center

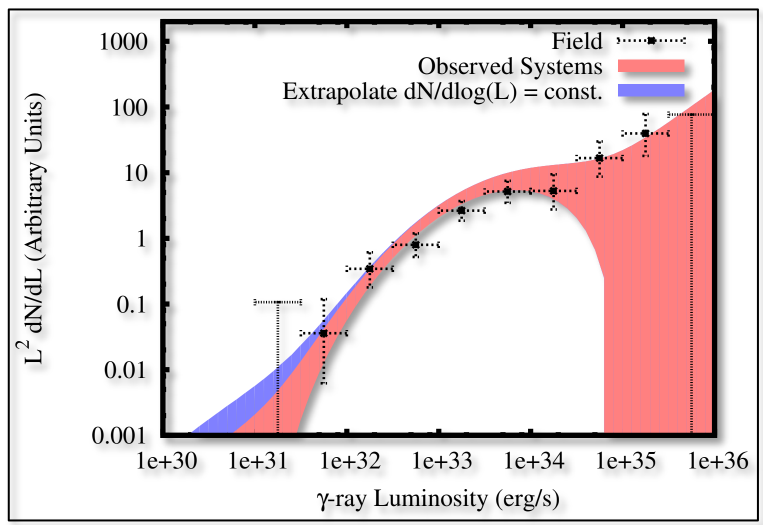




Gamma-Rays From Millisecond Pulsars

- Fermi has observed gamma-ray emission from ~60 MSPs – none of which are located near the Galactic Center
- Their average observed spectra is similar (but not identical) to that of the Galactic Center excess – this is the main reason that MSPs have been considered as a possible explanation for the excess
- The luminosity function of MSPs has been measured from the observed population (both for those MSPs in the field of the Galaxy and within globular clusters)

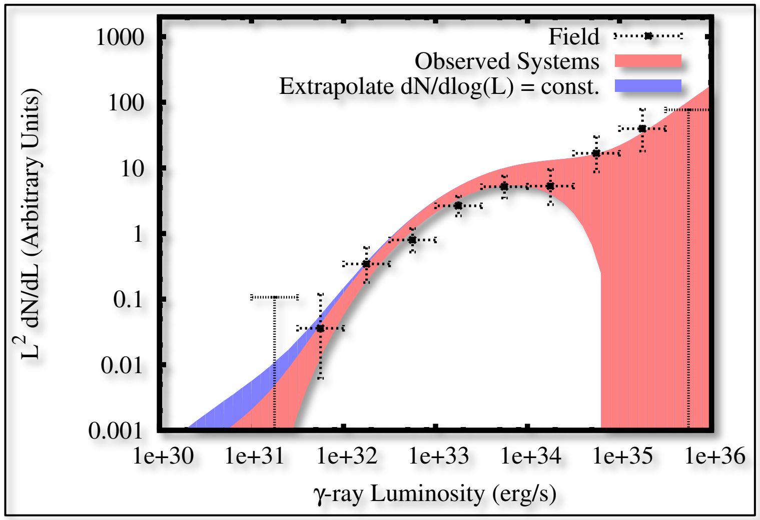




Cholis, DH, Linden, arXiv:1407.5625, 1407.5583

Could Millisecond Pulsars Generate the Galactic Center Excess?

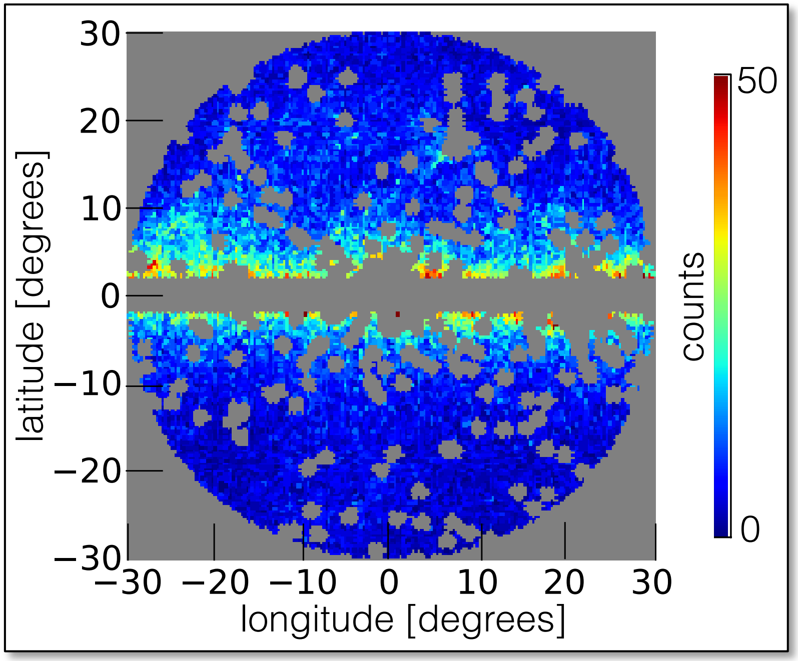
- From the measured luminosity function, we conclude that more than 2000 MSPs within 1.8 kpc of the Galactic Center would be required to account for the excess; this would include ~230 that are quite bright ($L_\gamma > 10^{34}$ erg/s) and ~60 that are very bright ($L_\gamma > 10^{35}$ erg/s)
- Fermi observes only a few MSP candidates from this region, leading us to conclude that less than ~10% of the excess originates from MSPs
- Estimates based on the numbers of bright LMXBs observed in globular clusters and in the Galactic Center lead us to expect that MSPs might account for ~1-5% of the observed excess
- If MSPs account for this signal, the population is very different from that observed elsewhere in the Milky Way, without many bright members



Cholis, DH, Linden, arXiv:1407.5625, 1407.5583

Evidence For Unresolved Point Sources?

- Two recent studies find that ~1-10 GeV photons from the direction of the Inner Galaxy are more clustered than expected, suggesting that the GeV excess might be generated by a population of unresolved point sources



Lee, Lisanti, Safdi, Slatyer, Xue, arXiv:1506.05124
(see also Bartels, Krishnamurthy, Weniger, arXiv:1506.05104)

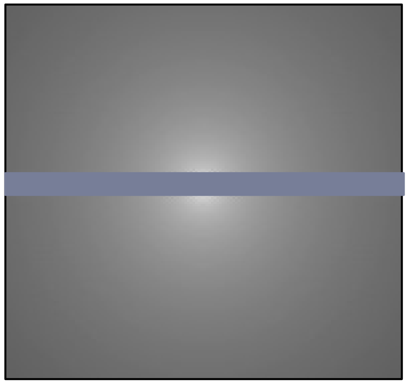
Evidence For Unresolved Point Sources?

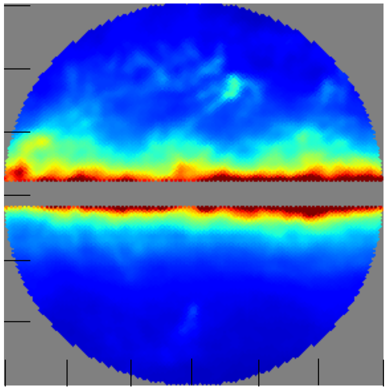
- Lee et al. use smooth and point source population templates that trace the following morphologies:

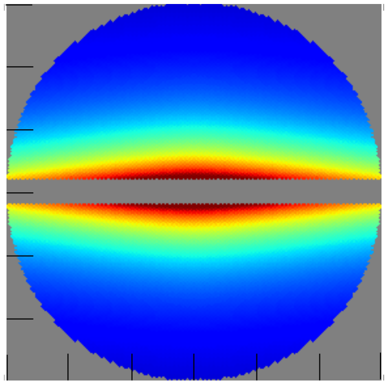
  1) The dark matter density squared (tracing the excess)

  2) The Fermi diffuse model

  3) The Galactic Disk







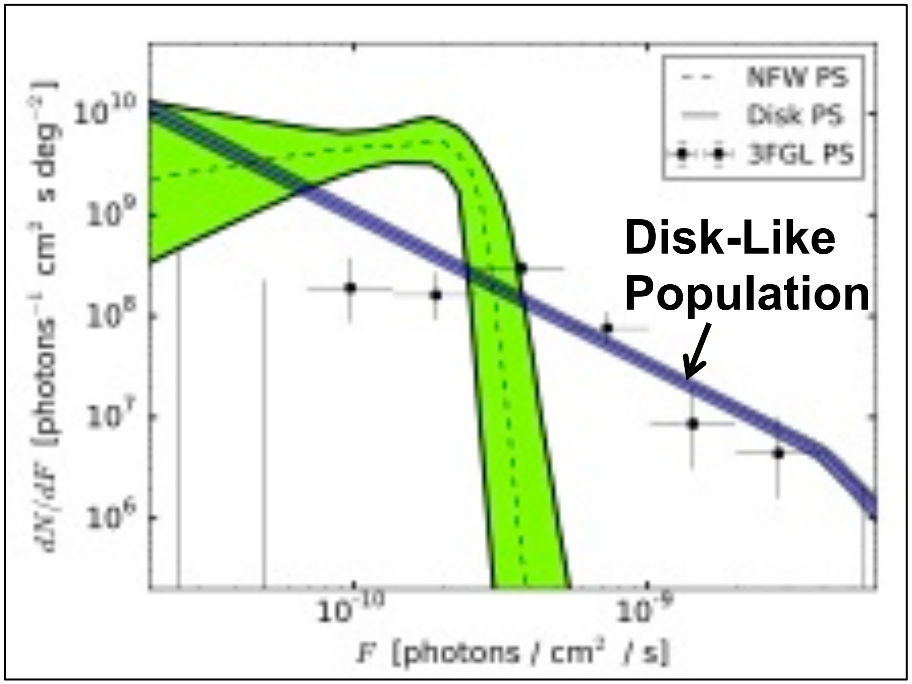
- The question is this: Which of these distributions (if any) do the observed gamma-ray clusters trace?

Lee, Lisanti, Safdi, Slatyer, Xue, arXiv:1506.05124
(see also Bartels, Krishnamurthy, Weniger, arXiv:1506.05104)

Evidence For Unresolved Point Sources?

Lee et al.'s Conclusions include the following:

1) The brightest sources (including those in source catalogs) are distributed along the disk – not tracing the excess



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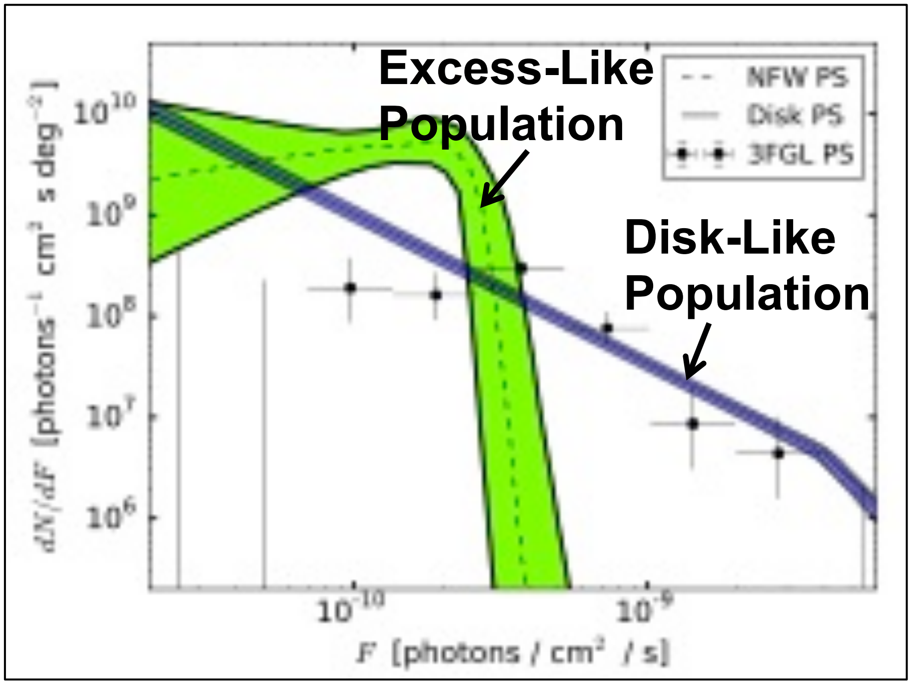

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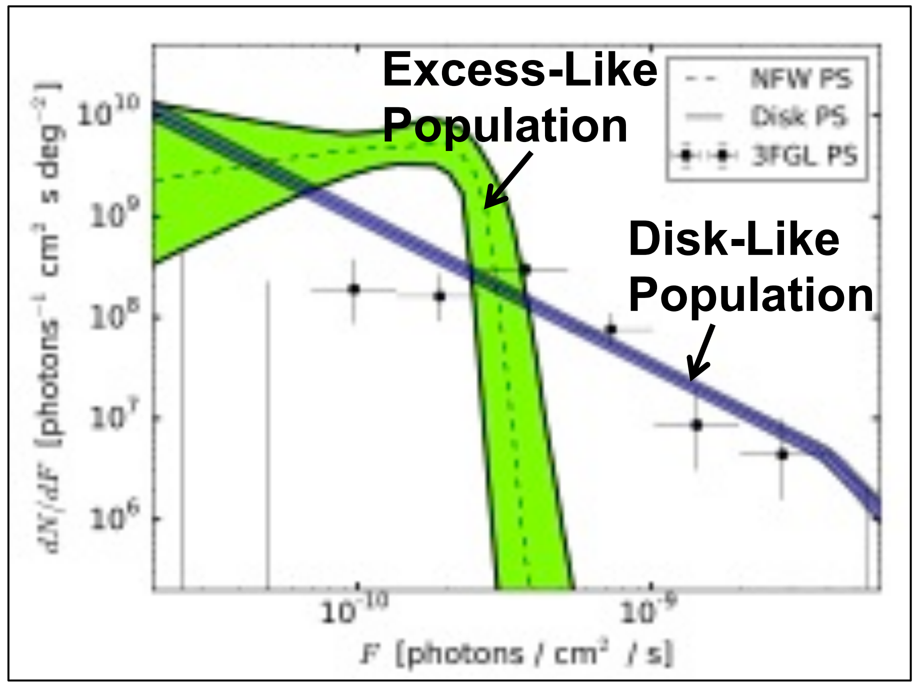
3) The Fermi diffuse model doesn't absorb much of the clustering



Lee, Lisanti, Safdi, Slatyer, Xue, arXiv:1506.05124
(see also Bartels, Krishnamurthy, Weniger, arXiv:1506.05104)

Evidence For Unresolved Point Sources?

A few comments of my own:

- It is difficult to tell whether these clustered gamma-rays result from unresolved sources, or from backgrounds that are less smooth than are being modeled
- Keep in mind that these clusters consist of only a few photons each, on top of large and imperfectly known backgrounds
- These studies do not make use of any spectral information (they use only a single energy bin); whether these putative sources have a spectrum that matches that of the excess will be an important test

Lee, Lisanti, Safdi, Slatyer, Xue, arXiv:1506.05124
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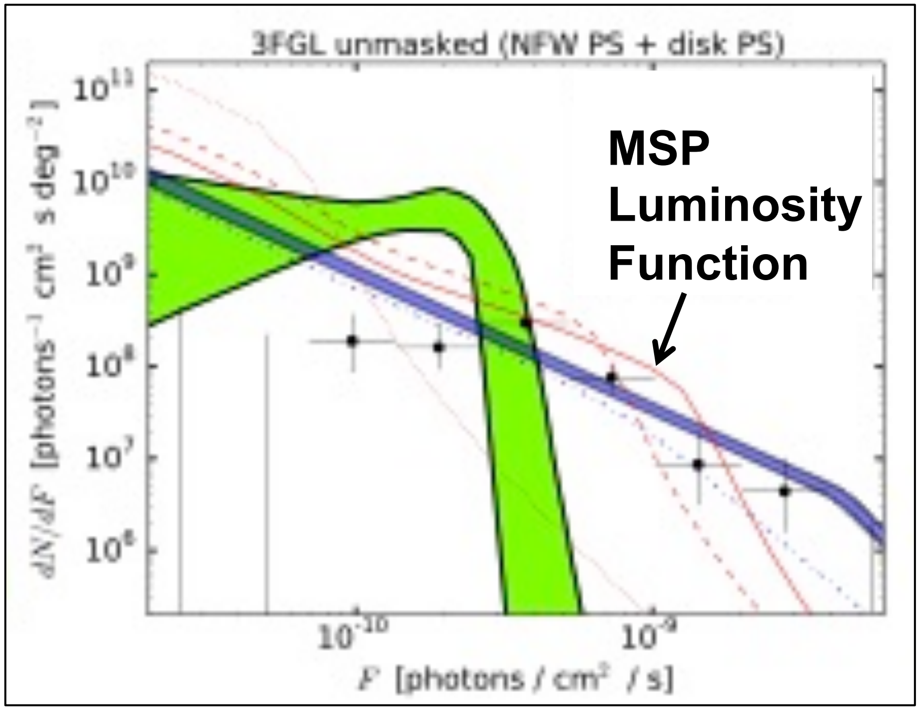
Are These Sources Millisecond Pulsars?

- The measured luminosity function of MSPs extends over several orders of magnitude, and well above the threshold for detection by Fermi; very different than this new putative source population
- Where are all of the bright MSPs? (bright sources are disk-like, not DM-like)



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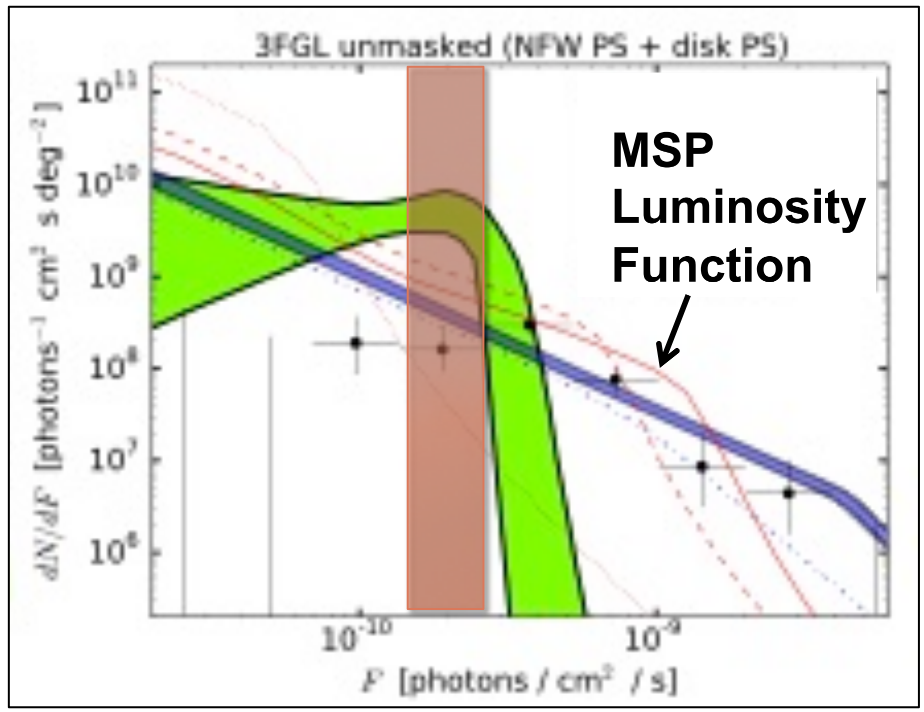
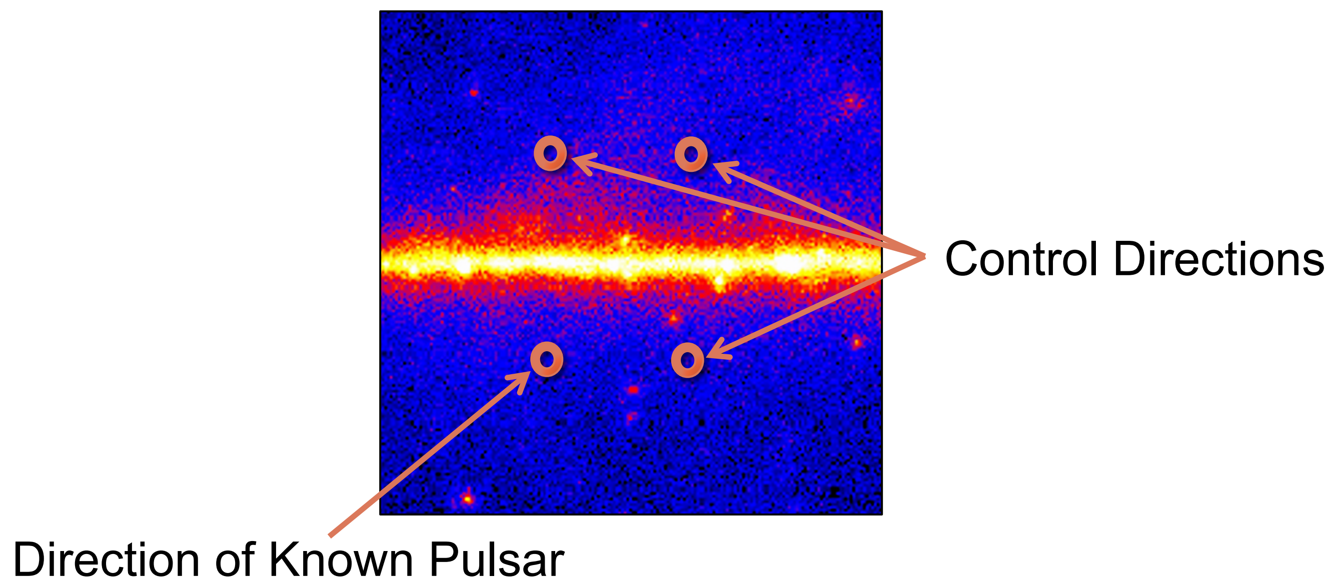
- Where are all of the bright MSPs? (bright sources are disk-like, not DM-like)
- If these are point sources, they are very weird point sources
- A new class of standard candles?! – 68% possess luminosities within a factor of 2 ($\Delta M \sim 0.4$)



Lee, Lisanti, Safdi, Slatyer, Xue, arXiv:1506.05124
(see also Bartels, Krishnamurthy, Weniger, arXiv:1506.05104)

Are These Sources Millisecond Pulsars?

- One interesting test is to see whether the gamma-ray clusters correlate with the locations of known radio pulsars
- Compare the gamma-ray fluxes observed from the directions of ~200 known radio pulsars to those with $(l,b) \rightarrow (-l,b)$, $(l,-b)$, or $(-l,-b)$



Tim Linden (in preparation)

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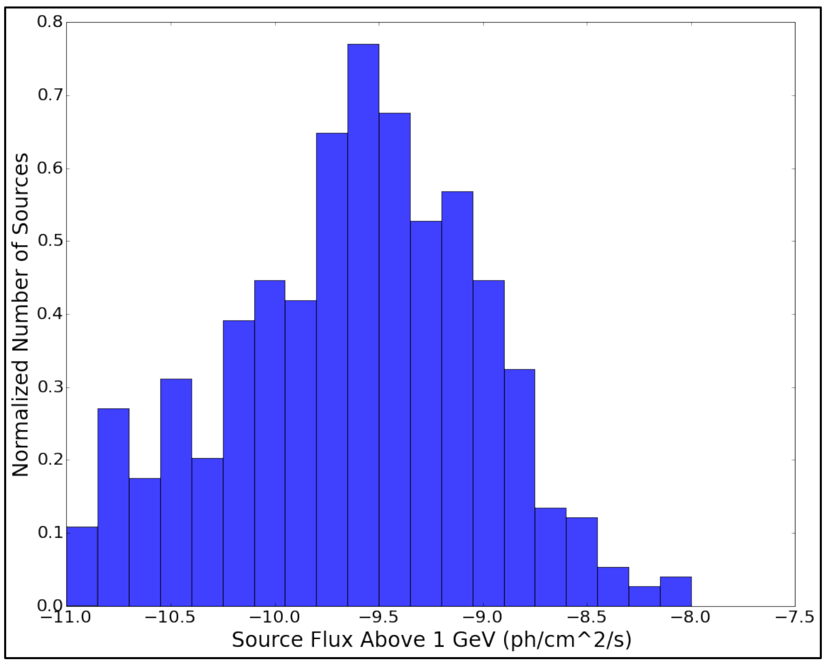

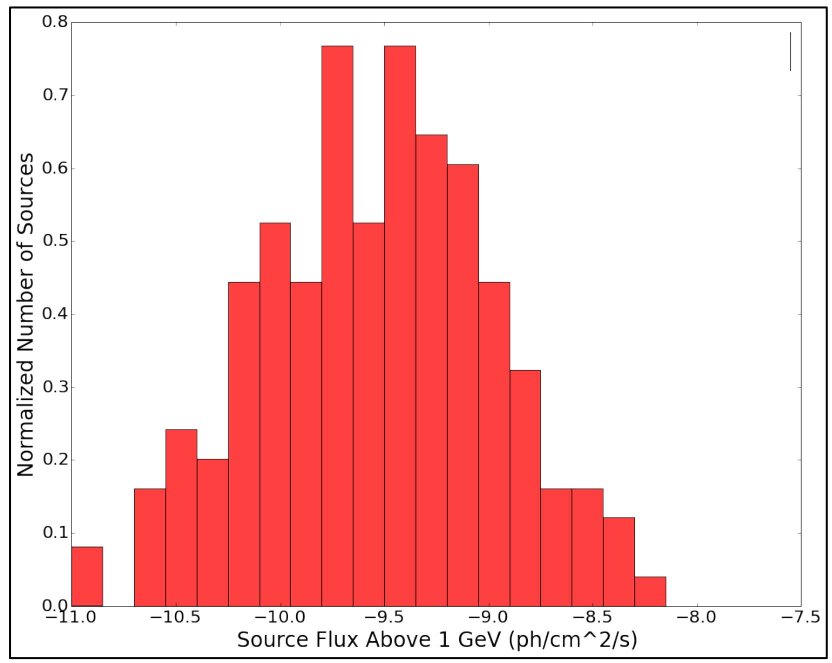

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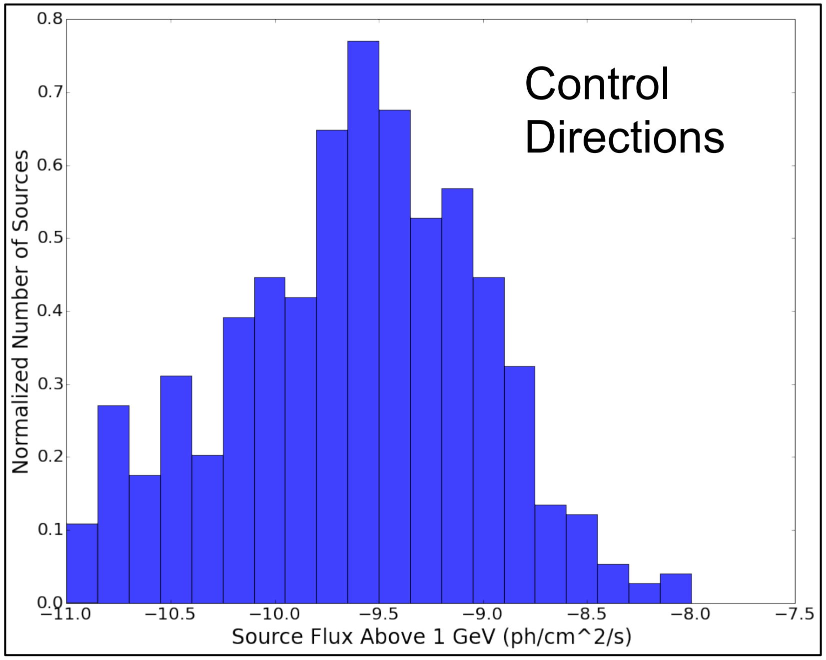
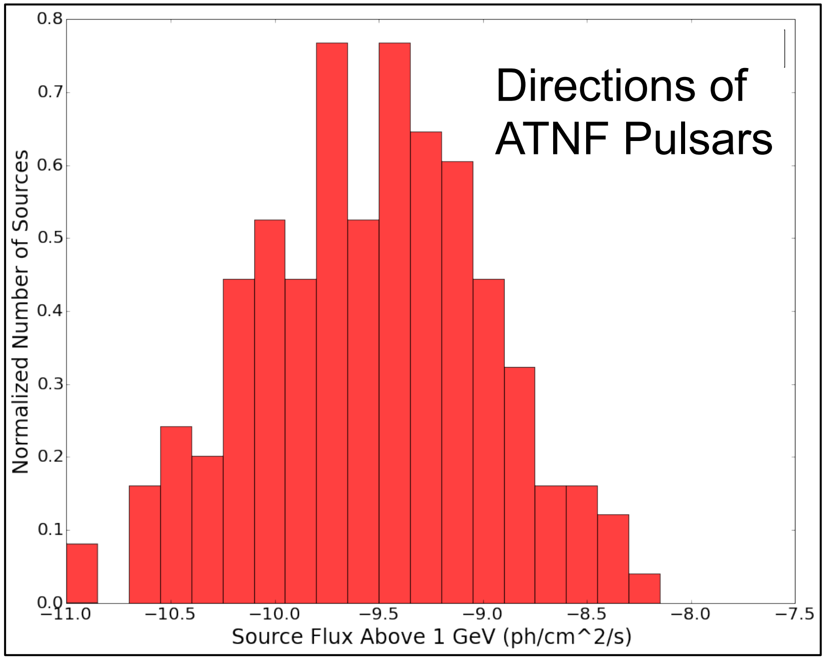




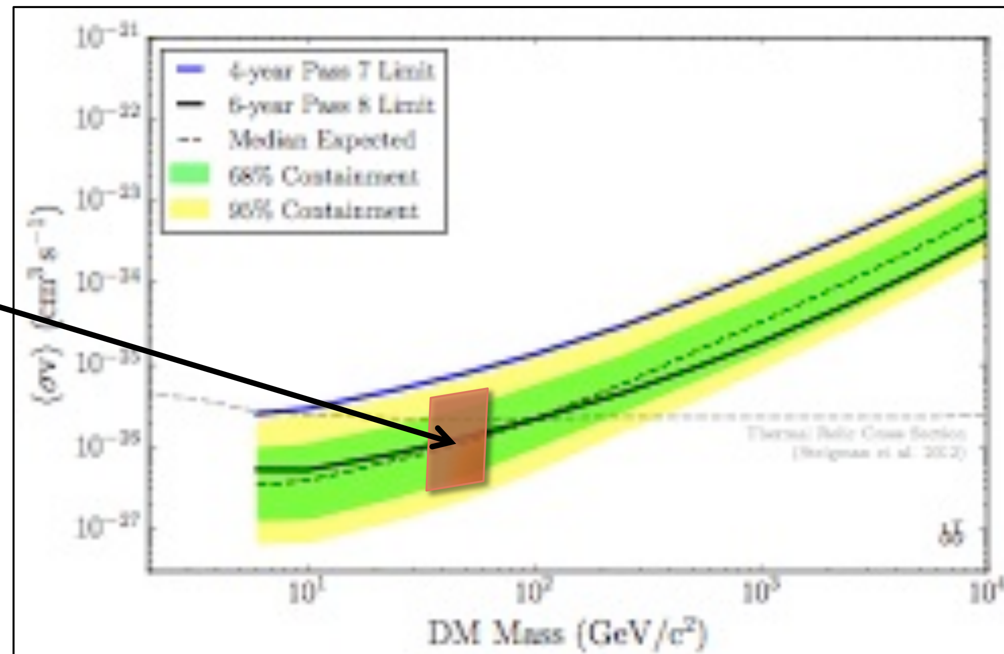
Tim Linden (in preparation)

What's Next?

- After years of effort, the origin of the Galactic Center excess remains unclear – it looks a lot like annihilating dark matter, but we can't rule out other possibilities
- How do we go from establishing a very intriguing signal, to being able to claim discovery?

Dwarf Galaxies

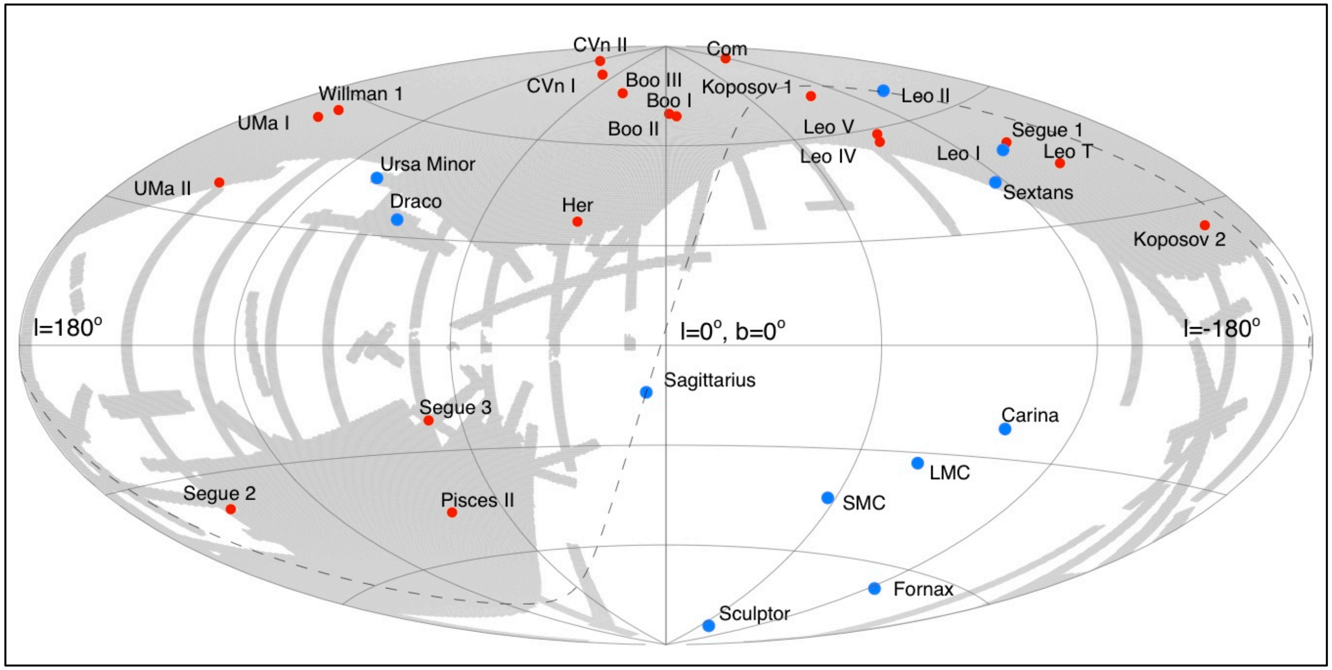
- The Fermi Collaboration recently presented an update of their analysis of dwarf spheroidal galaxies, making use of 5 years of (Pass 8) data
- No significant excess, but constraints remain compatible with a dark matter interpretation of the Galactic Center excess
- That being said, if the Galactic Center signal is coming from annihilating dark matter, one might expect gamma-rays from dwarfs to be detected soon



Fermi Collaboration, 1503.02641
(see also Geringer-Sameth, et al. 2015)

Dwarf Galaxies

- Past gamma-ray searches for dark matter in dwarf galaxies were driven in roughly equal parts by “classical” dwarfs (most importantly, Draco and Sagittarius), and “ultra-faint” dwarfs discovered by SDSS (Segue 1, Ursa Major II, Willman 1, etc.)
- Much of the sky was not explored by SDSS, however, leaving us hopeful that many ultra-faint dwarfs remained to be discovered



New Dwarf Galaxies!

Eight New Milky Way Companions Discovered in First-Year Dark Energy Survey Data

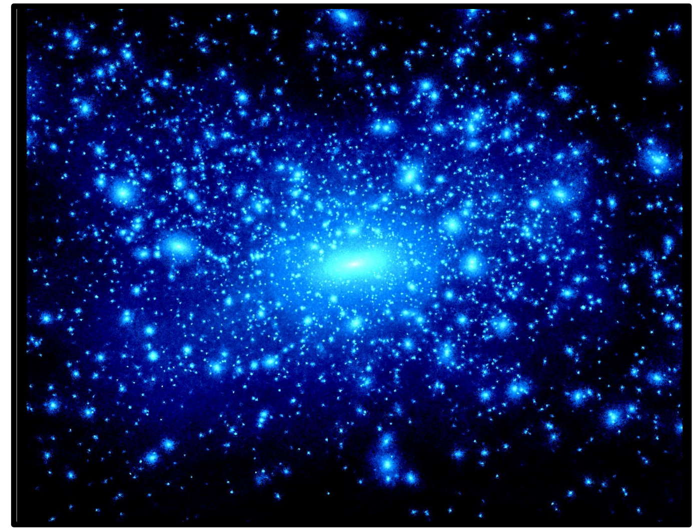
Name	Distance (kpc)	M_* ($10^3 M_\odot$)	M_V (mag)	$r_{1/2}$ (pc)	$\log_{10}(\tau)$ $\log_{10}$(Gyr)	Z
DES J0335.6-5403 (Ret II)	32	$2.6^{+0.2}_{-0.2}$	-3.6 ± 0.1	55^{+5}_{-5}	10.08 ± 0.21	< 0.0003
DES J0344.3-4331 (Eri II)	330	83^{+17}_{-14}	-7.4 ± 0.1	172^{+57}_{-57}	10.10 ± 0.23	< 0.0006
DES J2251.2-5836 (Tuc II)	58	3^{+7}_{-1}	-3.9 ± 0.2	120^{+30}_{-30}	–	–
DES J0255.4-5406 (Hor I)	87	$2.4^{+1.4}_{-0.7}$	-3.5 ± 0.3	60^{+76}_{-30}	9.96 ± 0.21	< 0.0005
DES J2108.8-5109 (Ind I)	69	$0.8^{+0.4}_{-0.4}$	-2.2 ± 0.5	12^{+2}_{-2}	–	–
DES J0443.8-5017 (Pic I)	126	$2.8^{+5.0}_{-1.7}$	-3.7 ± 0.4	43^{+153}_{-21}	10.00 ± 0.16	< 0.0004
DES J2339.9-5424 (Phe II)	95	$2.8^{+1.2}_{-0.7}$	-3.7 ± 0.4	33^{+20}_{-11}	–	–
DES J0222.7-5217 (Eri III)	95	$0.9^{+0.9}_{-0.7}$	-2.4 ± 0.6	11^{+8}_{-5}	–	–

DES Collaboration arXiv:1503.02584; see also 1503.02079

- This spring, discoveries of more than a dozen new dwarf galaxy candidates have been reported, using data from the Dark Energy Survey, SDSS, and Pan-STARRS
- Particularly exciting is Reticulum II, which is nearby (~30 kpc) and has been confirmed with spectroscopy to be an ultra-faint dwarf galaxy
- Three groups have studied the Fermi data from the direction of Reticulum II, each finding a modest (local) excess (2.4-3.2σ)

(Geringer-Sameth et al. Drlica-Wagner, et al, DH & Linden)

Nearby Dark Matter Subhalos



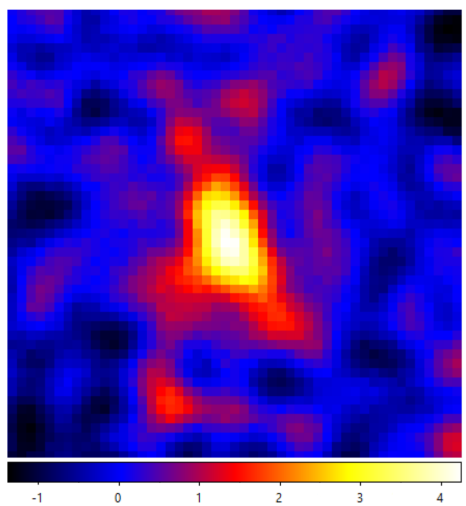
- The Milky Way's dark matter halo is predicted to contain a huge number of smaller subhalos, the vast majority of which are too small to retain gas and form stars, leading to a population of invisible dark matter clumps
- The most massive and nearby of these objects could be detectable as spatially extended gamma-ray sources, without observable emission at other wavelengths
– *a population of such sources would be a smoking gun for dark matter*
- Using the results of the Aquarius simulation, we can estimate the number of bright, |b|>20° subhalos that Fermi should detect:

$$N \sim 4.0 \times \left(\frac{\sigma v}{10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1}}\right)^{1.5} \left(\frac{F_{\rm threshold}}{3\times 10^{-10}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}}\right)$$

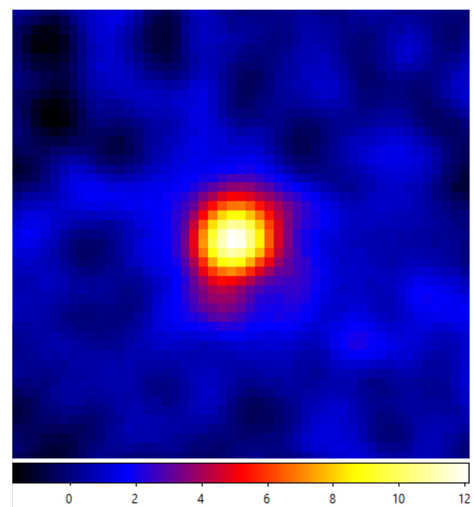
Bertoni, DH, Linden, 1504.02087
Bertoni, DH, Linden, in prep.

The Intriguing Source 3FGL J2212.5+0703

- The Fermi source 3FGL J2212.5+0703 is an exciting subhalo candidate
- This bright, high-latitude source has a ~35 GeV WIMP-like spectrum and is not observed at any other wavelengths
- More telling, this source appears to be spatially extended by ~0.2° (~4σ)
- Although a small fraction of astrophysical gamma-ray sources are extended (PWN, SNRs, molecular clouds, nearby galaxies), these are (and are predicted to be) bright at other wavelengths



J2212.5+0703



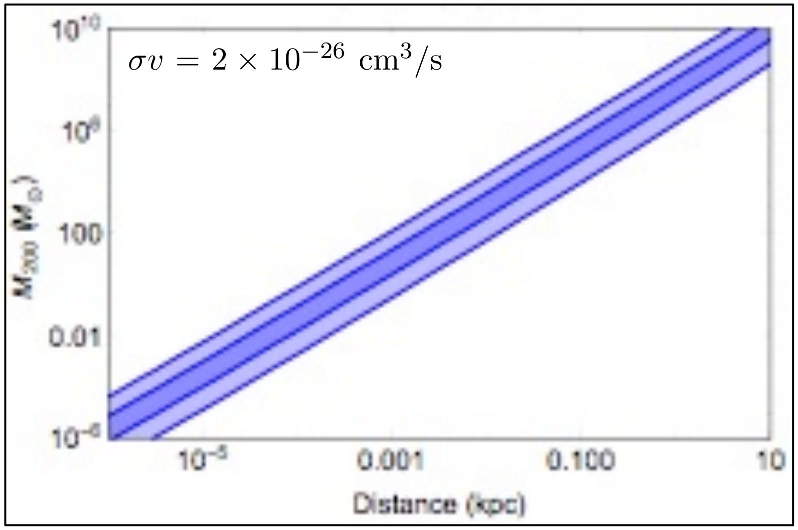
Example Point Source

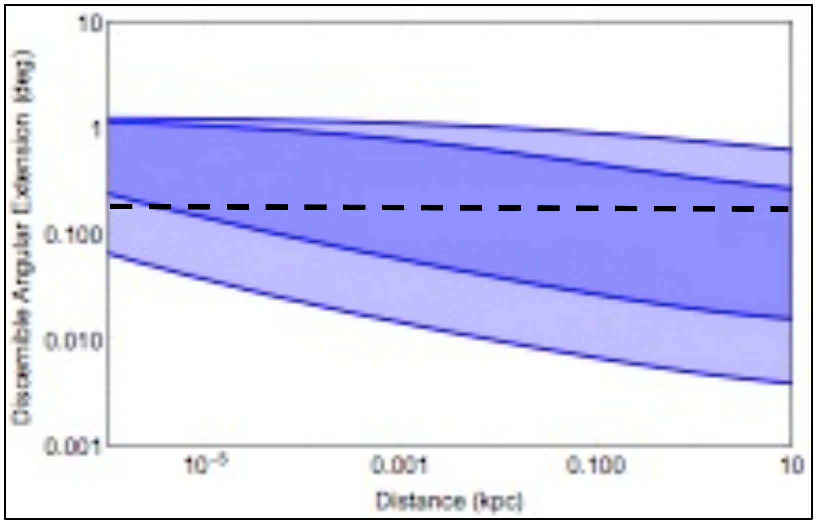
Bertoni, DH, Linden, 1504.02087; and in prep.

The Intriguing Source 3FGL J2212.5+0703

- This source could be a very large subhalo (only slightly less massive than a dwarf galaxy) at a distance of ~10 kpc, or a very small and nearby clump of dark matter, or anything in between
- The observed extension (~0.2°) is consistent for dark matter subhalos over a wide range of masses

This source merits considerably more attention and scrutiny!

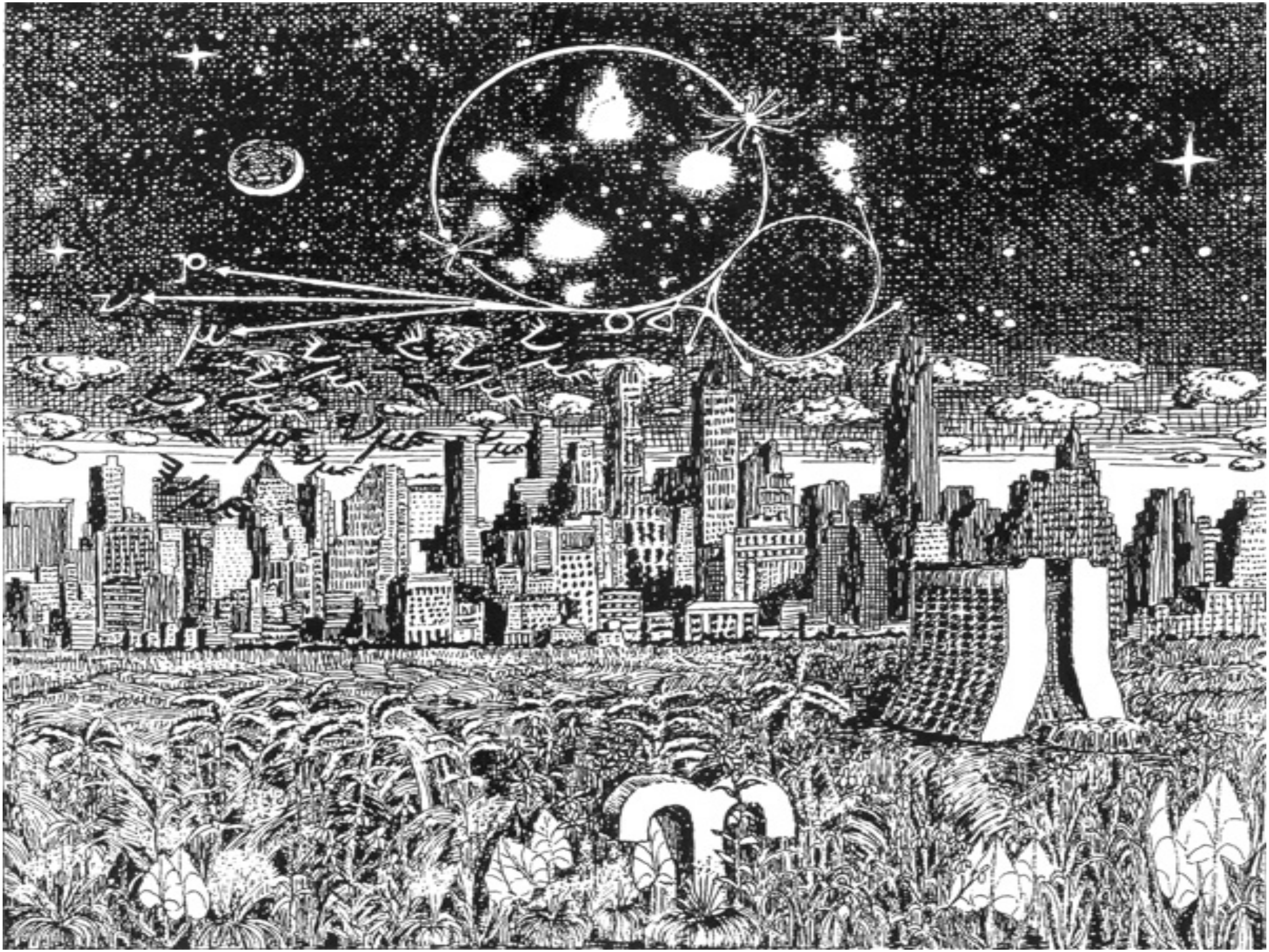




Bertoni, DH, Linden, 1504.02087; and in prep.

Summary

- Indirect searches are currently testing the WIMP paradigm!
- Although many indirect detection anomalies have appeared over the years, the Galactic Center's GeV excess is particularly compelling:
  highly statistically significant, robust, distributed spherically out to at least 10° from the Galactic Center, and very difficult to explain with known/proposed astrophysics
- The spectrum and angular distribution of this signal is very well fit by a ~45 GeV WIMP (annihilating to b quarks), distributed as $\rho \sim r^{-1.2}$
- The normalization of this signal requires a dark matter annihilation cross section of $\sigma v \sim 10^{-26}$ cm^3/s; in good agreement with the range predicted for a simple thermal relic
- Many dark matter models can account for the observed emission without conflicting with constraints from direct detection experiments or colliders – future prospects are encouraging
- Future observations of dwarf galaxies and subhalo candidates will be important to test the origin of this signal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