THE CASE FOR A DARK MATTER INTERPRETATION OF THE GALACTIC CENTER EXCESS

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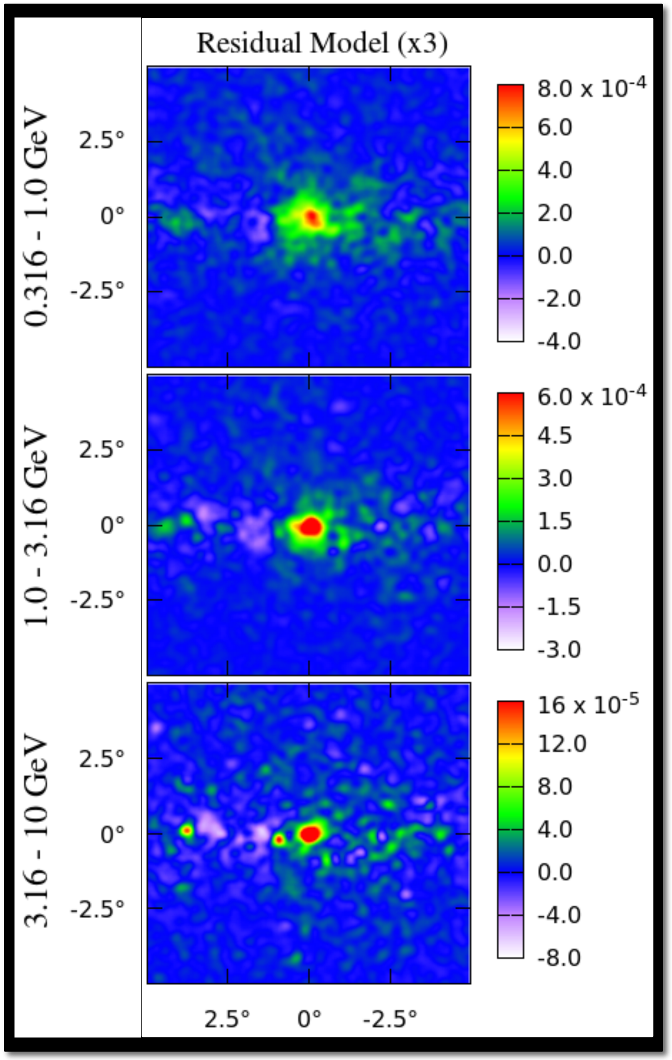
The Galactic Center GeV Excess

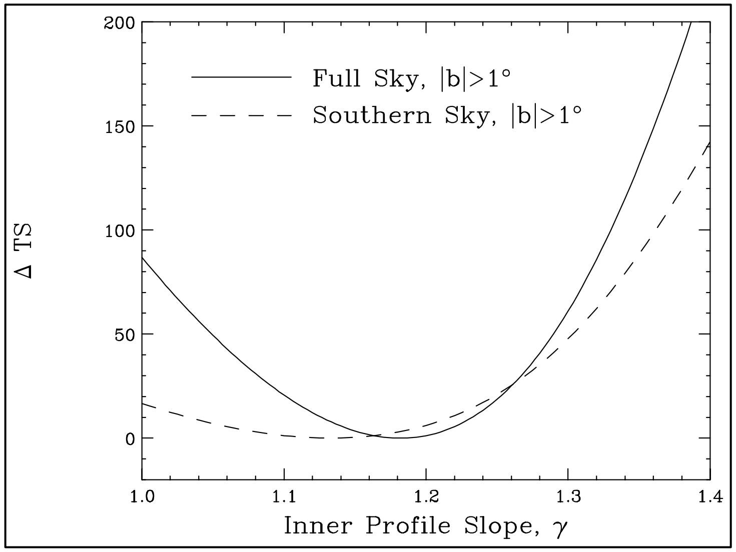
- A bright and highly statistically significant excess of gamma-rays has been observed from the region surrounding the Galactic Center, difficult to explain with astrophysical sources or mechanisms, but very much like the signal predicted from annihilating dark matter

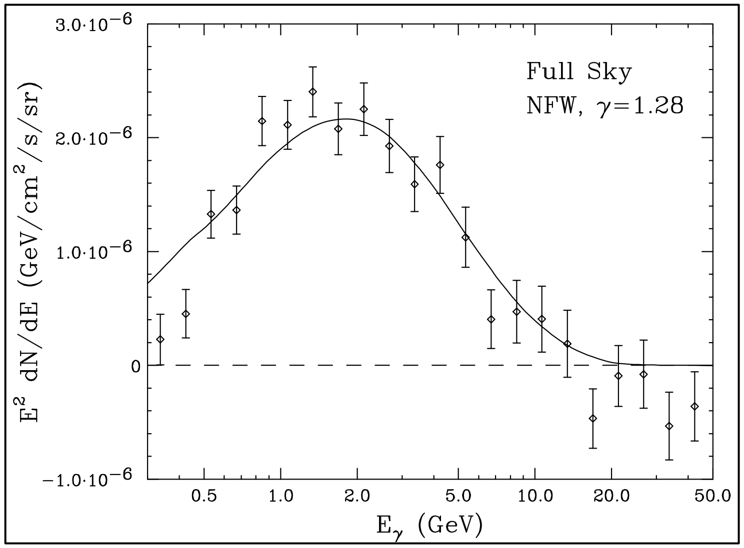


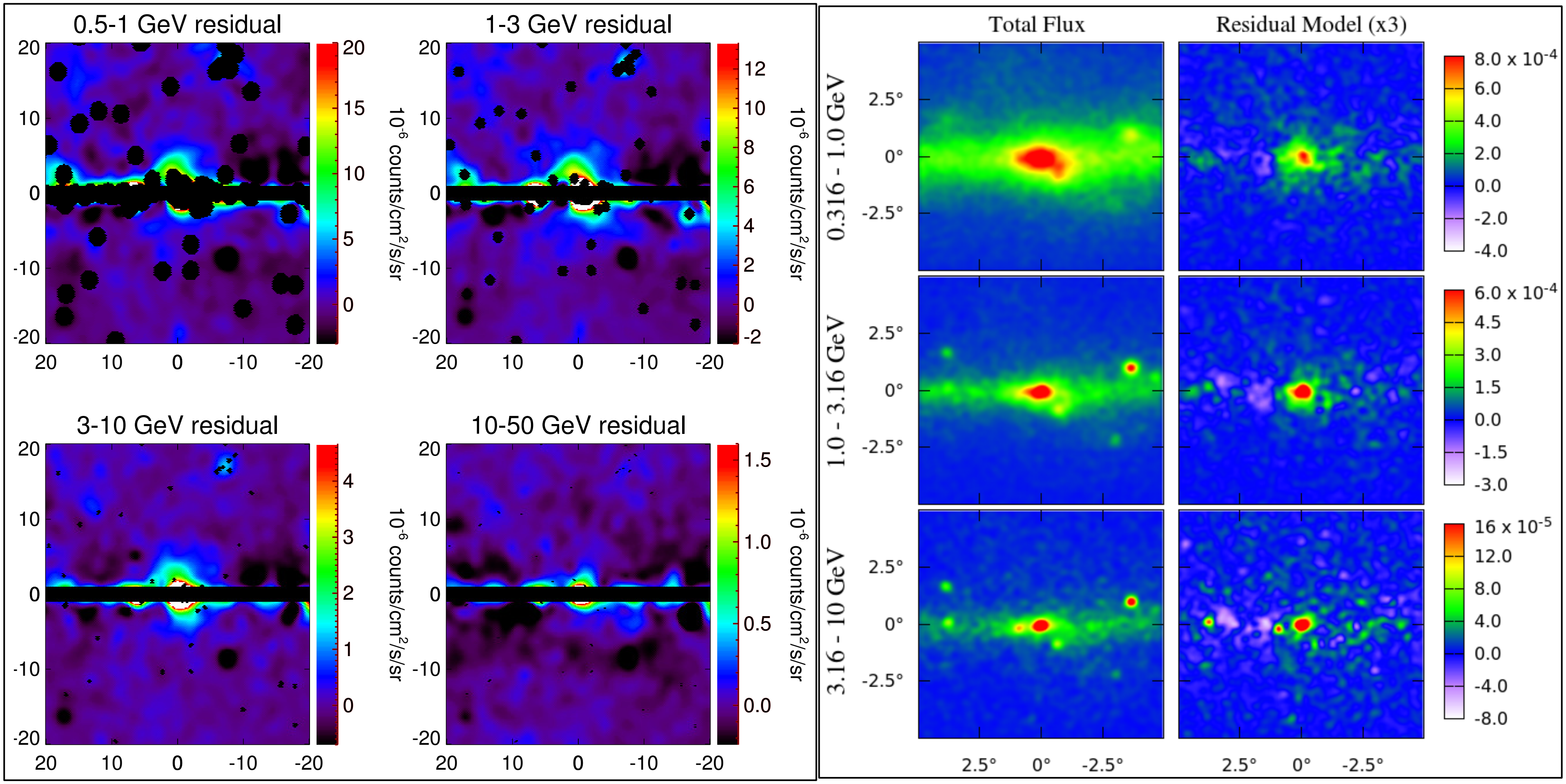
DH, Goodenough (2009, 2010), DH, Linden (2011), Daylan et al (2014), Calore, Cholis, Weniger (2014)

Basic Features of the GeV Excess

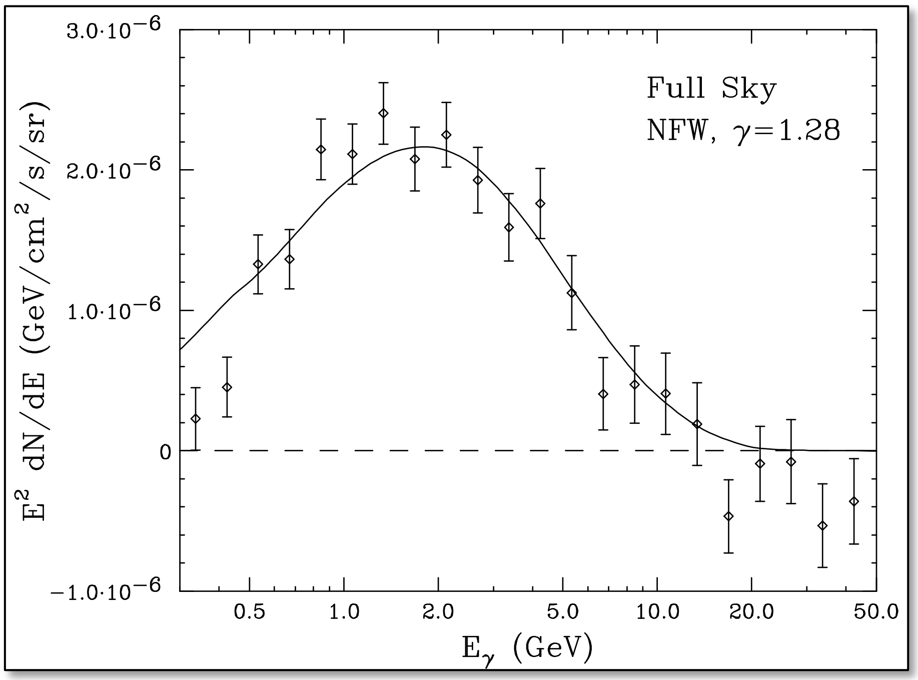
- The excess is distributed spherically around the Galactic Center with a flux that falls as $\sim r^{-2.4}$, between ~0.06° and ~10° (if interpreted as dark matter annihilation products, $\rho_{DM} \sim r^{-1.2}$ between ~10-1500 pc)
- The spectrum of this excess peaks at ~1-3 GeV, and is in good agreement with that predicted from a ~35-50 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

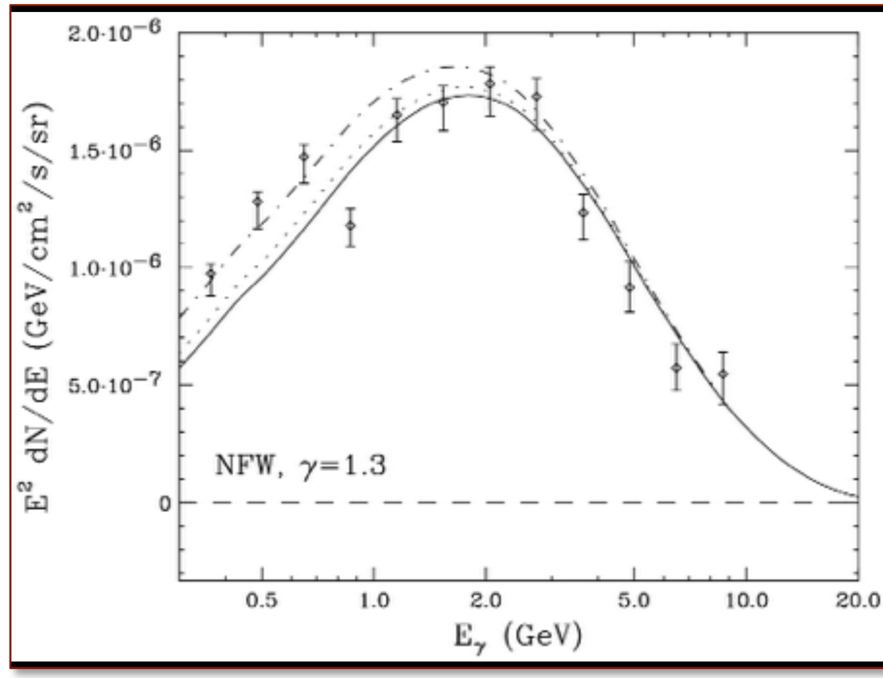






Daylan, Finkbeiner, DH, Linden, Slatyer, Rodd (2014)





Daylan, Finkbeiner, DH, Linden, Slatyer, Rodd (2014)

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?

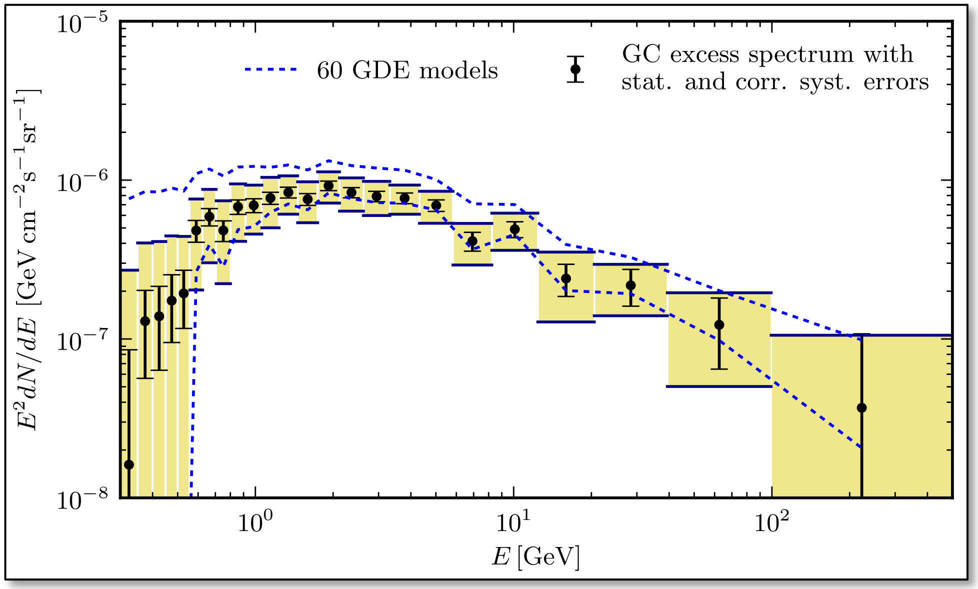
Background model systematics for the Fermi GeV excess

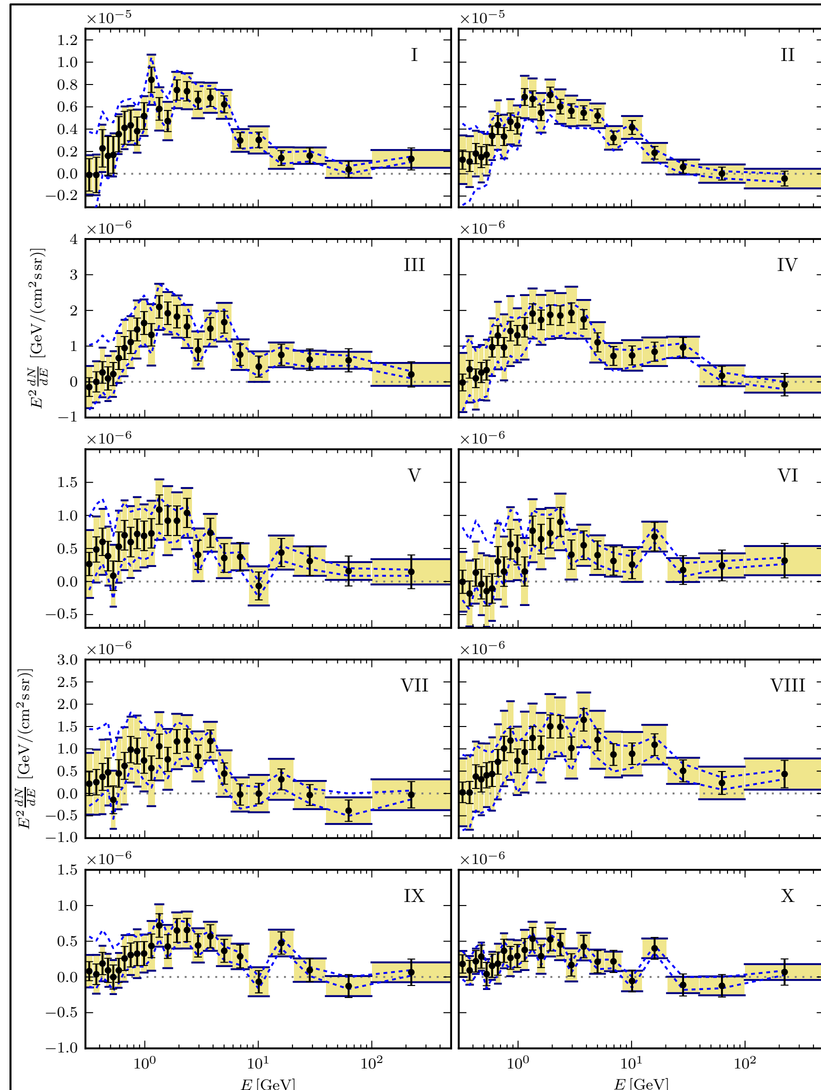
Francesca Calore,[a] Ilias Cholis[b] and Christoph Weniger[a]

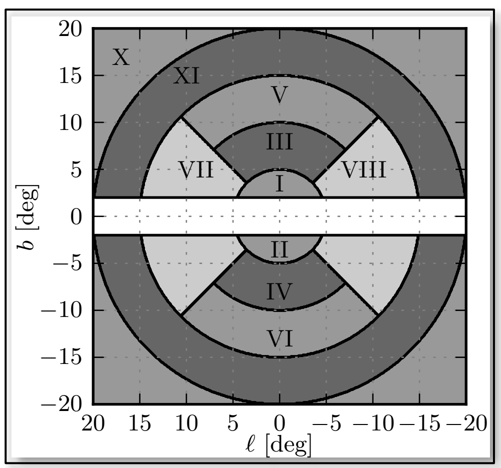
arXiv:1409.0042

Highly Recommended!

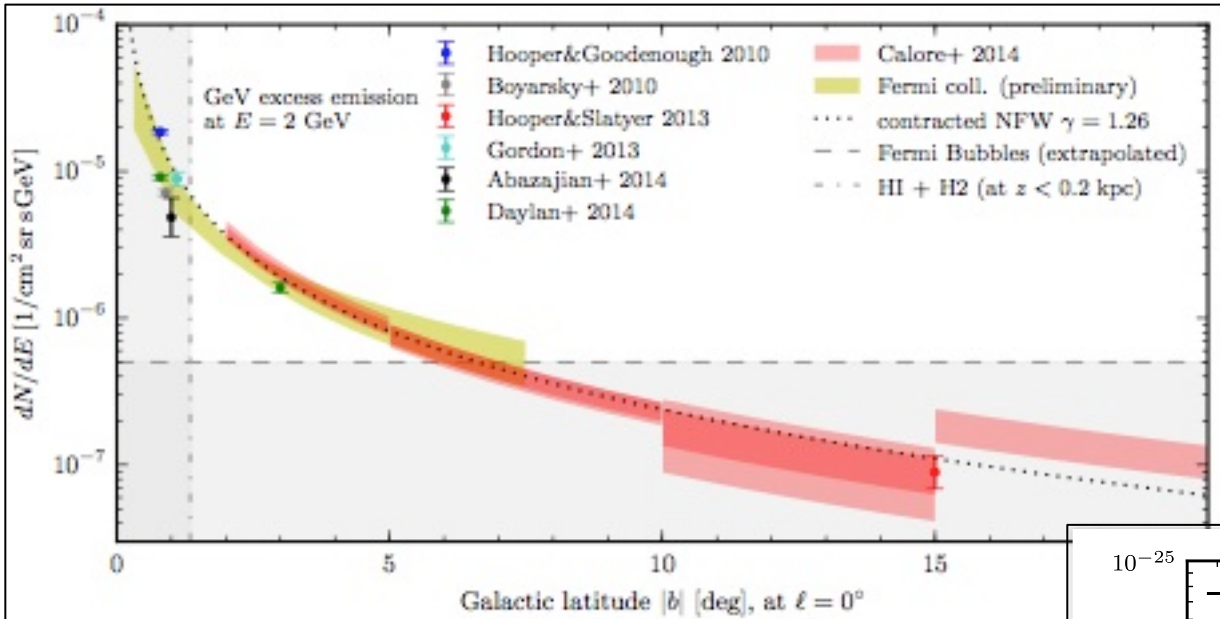
- First comprehensive study of the systematic uncertainties on the relevant astrophysical backgrounds
- Considered a very wide range of models, with extreme variation in cosmic ray source distribution and injection, gas distribution, diffusion, convection, re-acceleration, interstellar radiation and 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

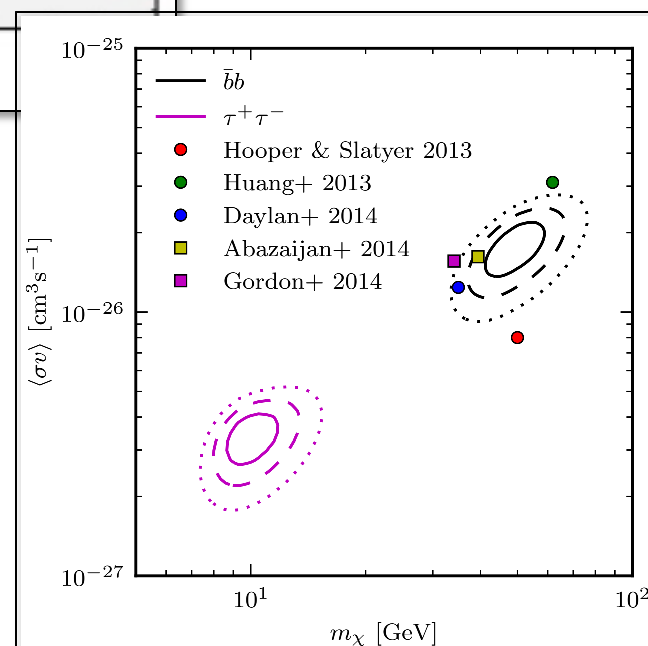






Calore, Cholis, Weniger, arXiv:1409.0042





Calore, Cholis, McCabe, Weniger, 1411.4647;
Calore, Cholis, Weniger, arXiv:1404.0042

The Evolving Nature of the Galactic Center Debate

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Circa 2009-2010

What Galactic Center excess?

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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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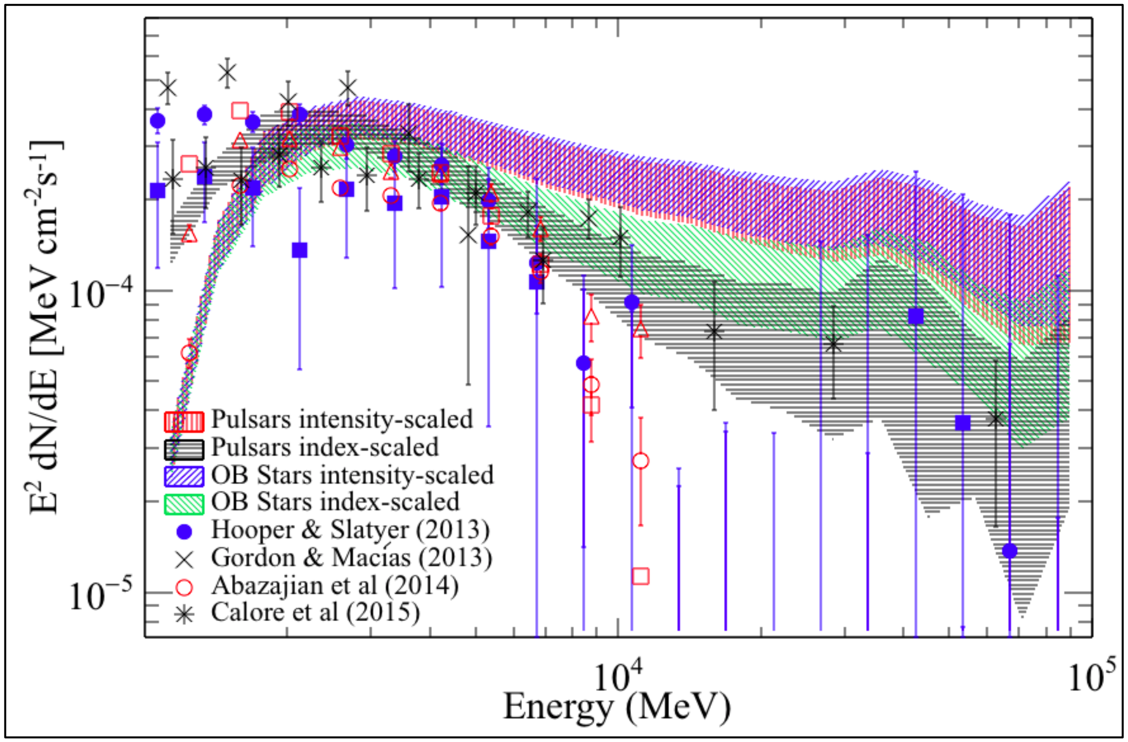
Circa 2014-2015

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?

The Fermi Collaboration has recently presented their first paper on this subject (arXiv:1511.02938), reporting an excess with a similar spectrum and morphology

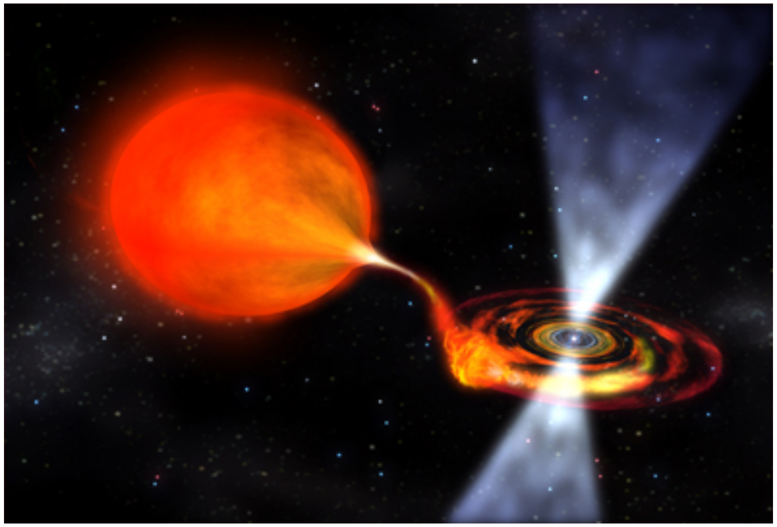


(Improved treatment of point sources, diffuse emission modelling, etc.)

Simona Murgia, et al. (Fermi Collaboration)

What Produces the Excess?

- Non-standard models of cosmic-ray interactions?
- A large population of centrally located millisecond pulsars?
- Annihilating dark matter?



Beyond Standard Diffuse Backgrounds

- Although Calore, Cholis, *et al*. showed that the excess was robust to standard variations in the diffuse background model, one might wonder whether a less standard scenarios might work
- To accommodate the morphology of the observed excess, one needs a very strong and steep concentration of cosmic ray sources and/or gas located symmetrically about the Galactic Center
- Two main difficulties:

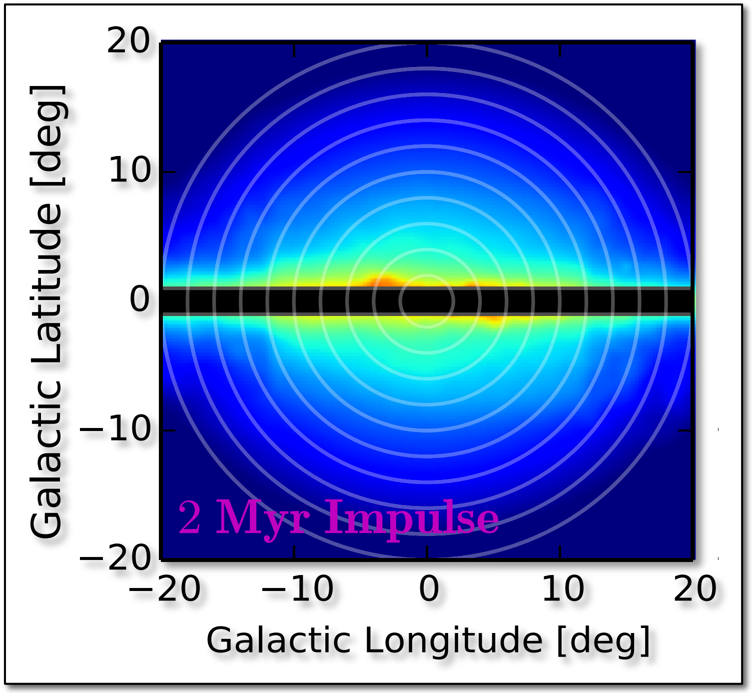
  1) Diffusion broadens the profile of cosmic rays, making it difficult for steady-state models to account for the innermost 1-2° of the excess

  2) The gamma-ray spectrum resulting from cosmic ray processes are less sharply peaked than the observed excess
- Together, these considerations make it very difficult for steady-state cosmic ray scenario to account for the excess (although such models could plausibly alter the inferred characteristics of the excess)

Carlson, et al., arXiv:1510.04698,
Gaggero et al., arXiv:1507.06129

A Series of Cosmic Ray Outbursts?

- To address these challenges, it has been proposed that the recent burst-like injection of cosmic ray protons and/or electrons might be responsible for the excess
- Hadronic scenarios predict a signal that is more disky than spherical; incompatible with the data
- In more generality, the small-scale structure of the excess does *not* correlate with the distribution of gas (Daylan *et al*. 2014), disfavoring a 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?

- Leptonic outburst scenarios (Petrovic *et al.*) are more difficult to rule out
- After exploring a wide range of scenarios, we find that leptonic outburst models face two main challenges:

Cholis, Evoli, Calore, Linden, Weniger, DH, arXiv:1506.05104

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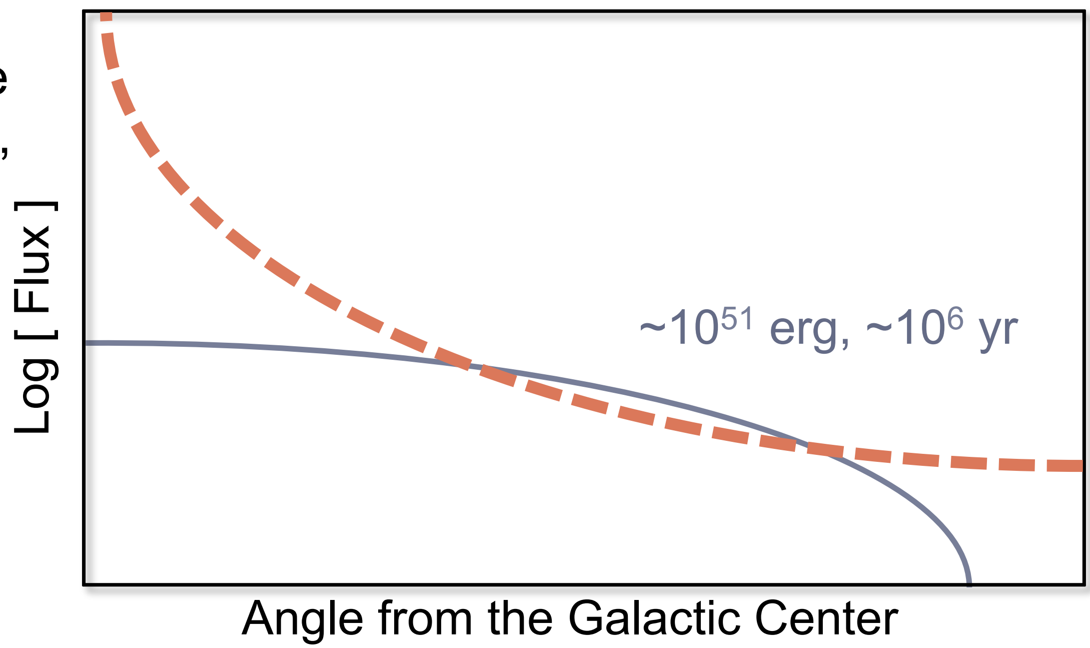
1) The morphology from a given outburst is “convex”, whereas the data is “concave” – to fit the data, we need several outbursts, with highly tuned parameters



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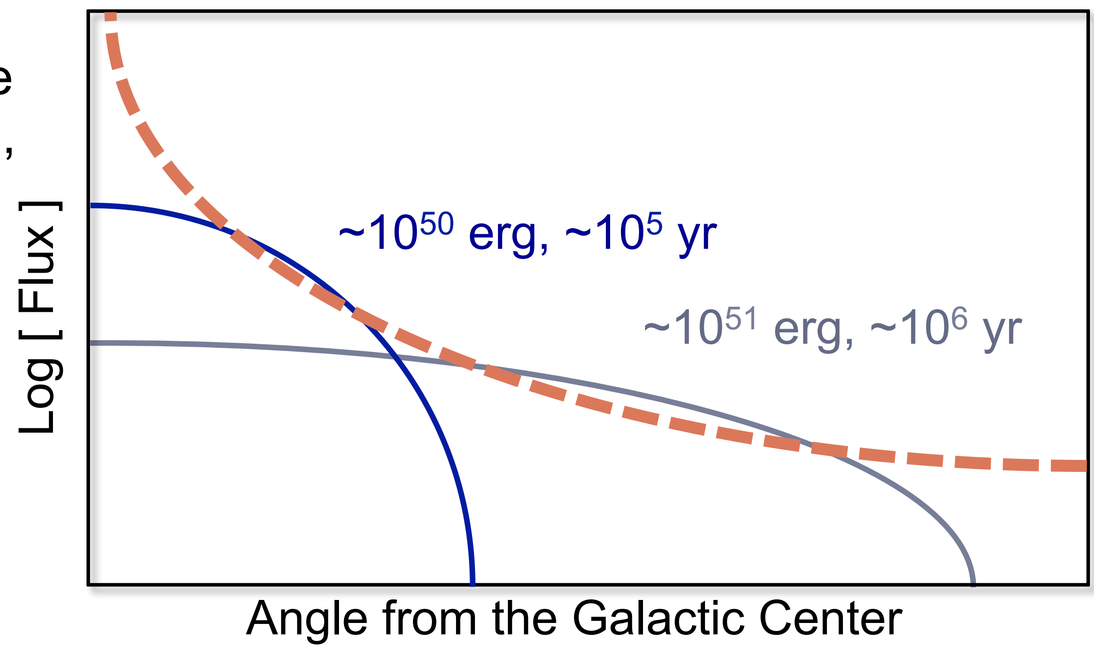

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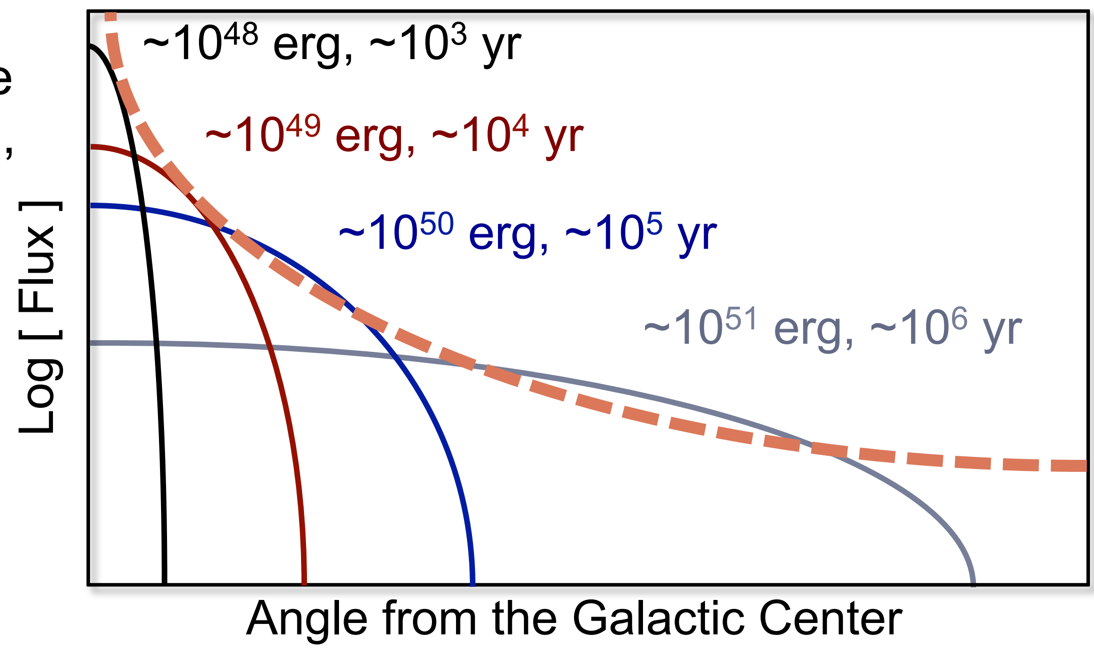

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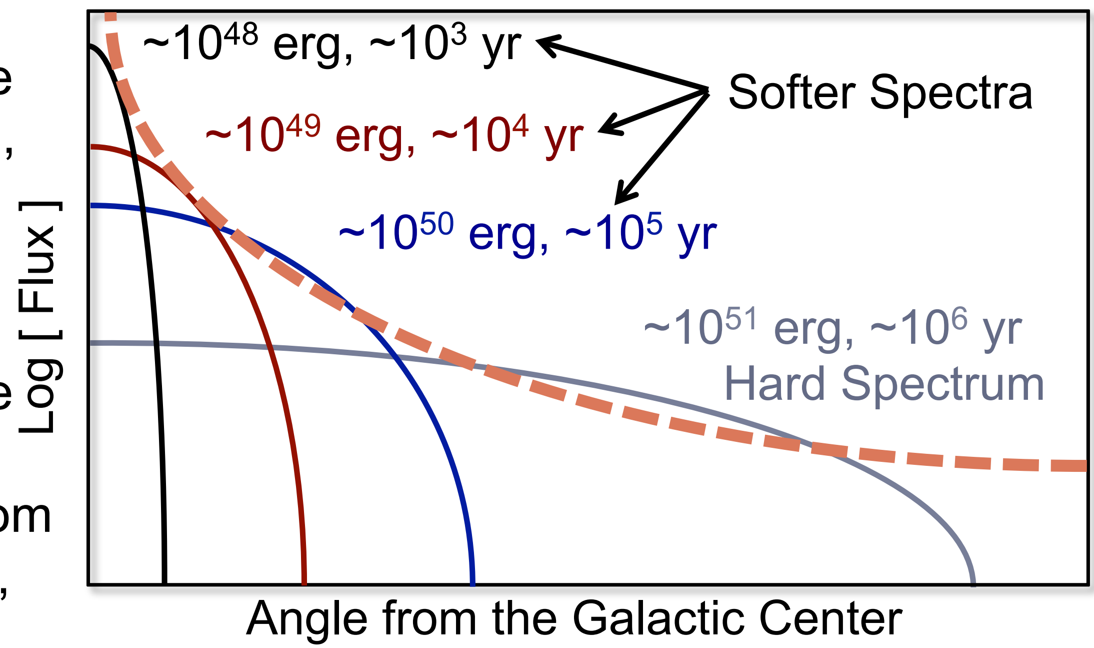
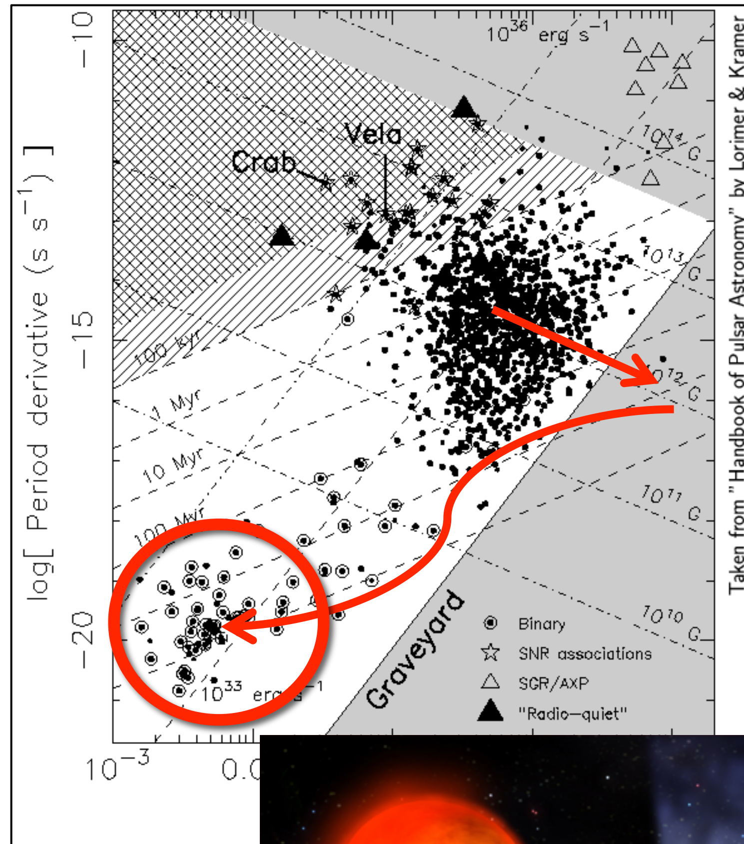
2) The gamma-ray spectrum is approximately uniform across the Inner Galaxy, but energy losses should lead to softer emission from the outer regions – to fit the data, we need the older outbursts to inject electrons with higher energies than more recent outbursts

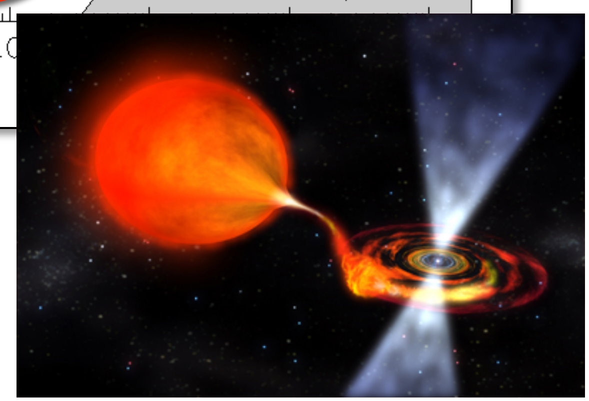


Cholis, Evoli, Calore, Linden, Weniger, DH, arXiv:1506.05104

Millisecond Pulsar Basics

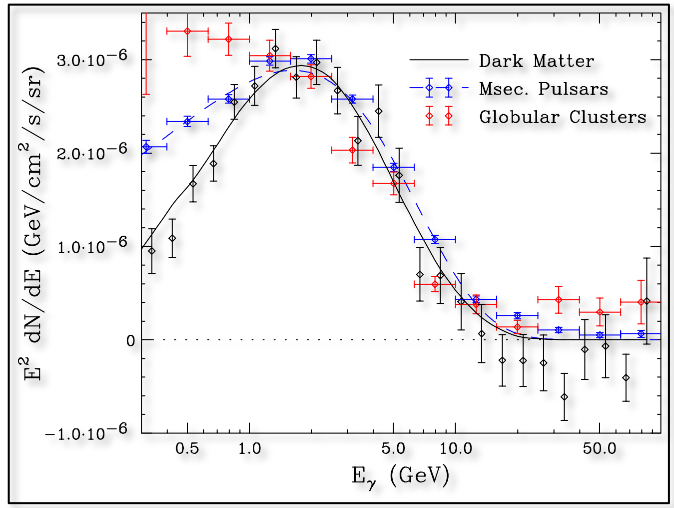
- Pulsars are rapidly spinning neutron stars, which gradually convert their rotational kinetic energy into radio and gamma-ray emission
- Typical pulsars exhibit periods on the order of ~1 second and slow down and become faint over ~10^6 -10^8 years
- Accretion from a companion star can "spin-up" a dead 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 exist in the Galactic Center

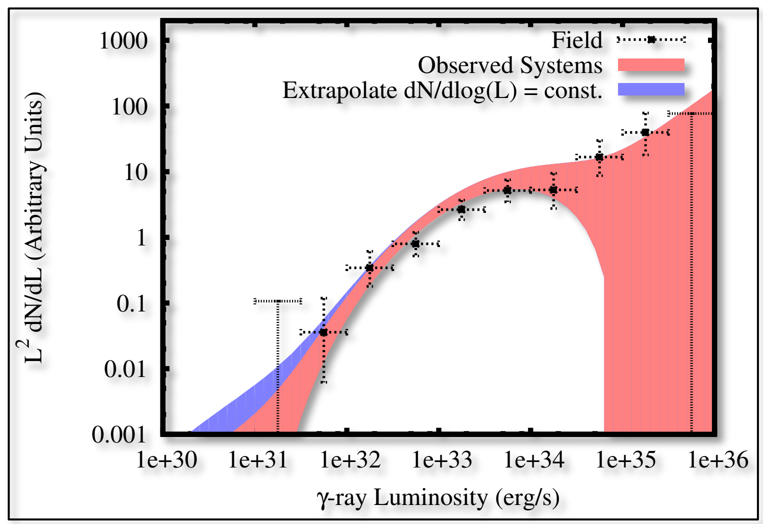




Gamma-Rays From Millisecond Pulsars

- Fermi has observed gamma-ray emission from ~70 MSPs – none of which are located near the Galactic Center
- Their average observed spectra is similar 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)

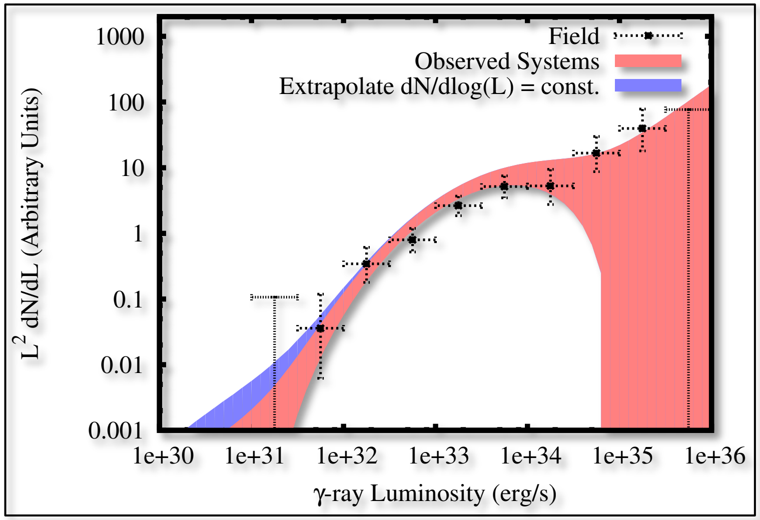




Cholis, DH, Linden, arXiv:1407.5625, 1407.5583

Could Millisecond Pulsars Generate the Galactic Center Excess?

- From the measured luminosity function, we conclude that ~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

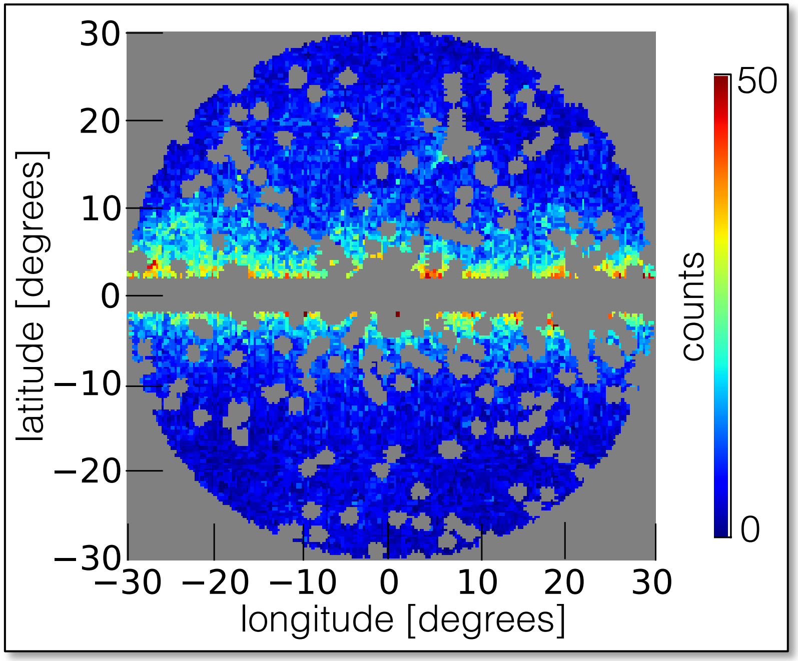
Could We Have the MSP Luminosity Function Really Wrong?

- Distance uncertainties have motivated some to suggest that determinations of the MSP luminosity function are flawed, and that there may be few or no MSPs above Fermi's threshold (for the Inner Galaxy)
- Previous luminosity function determinations using MSPs in the field *and* in globular clusters have largely agreed
- Fermi has detected only one confirmed MSP from the inner 10° around the Galactic Center, J1823-3021A, which is located within the globular cluster NGC 6624 (and thus not part of a NFW^2-like population) – robust distance!
- J1823-3021A demonstrates that bright MSPs ($L_\gamma \sim 7\times10^{34}$ erg/s) exist; if present in the Inner Galaxy, such a source could be resolved by Fermi
- If they were located in the Inner Galaxy, J0218+4232 (3.8×10^{34} erg/s) and J0614-0200 (4.7×10^{34} erg/s) would also likely have been detected by Fermi, perhaps along with J0610-2100, J1747-4036, J1810+1744, J1939+2134, J1959+2048, J2043+1711, and J2215+5135 ($L_\gamma > 10^{34}$ erg/s)

Fermi Collaboration, Second Pulsar Catalog, arXiv:1305.4385

Evidence For Unresolved Point Sources?

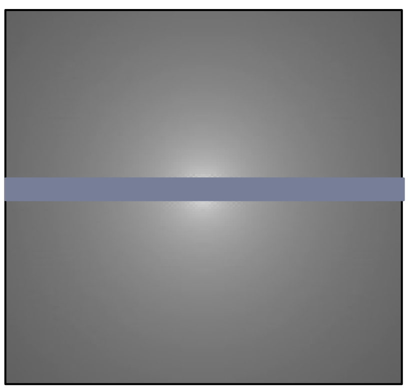
- Two recent studies find that ~1-10 GeV photons from the direction of the Inner Galaxy are more clustered than expected, suggesting that the GeV excess might be generated by a population of unresolved point sources

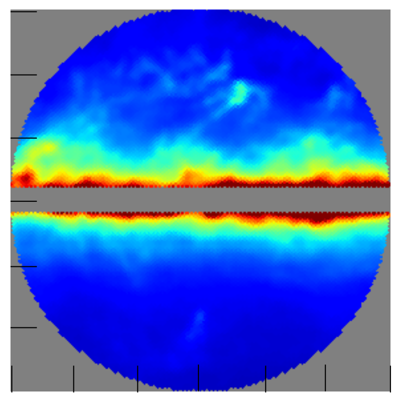


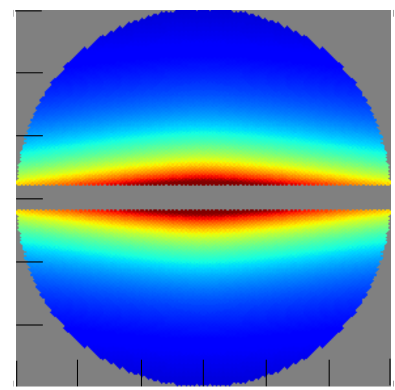
Lee, Lisanti, Safdi, Slatyer, Xue, arXiv:1506.05124
(see also Bartels, Krishnamurthy, Weniger, arXiv:1506.05104)

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 their analysis asks is this: Which of these distributions do any observed gamma-ray clusters most closely trace?

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

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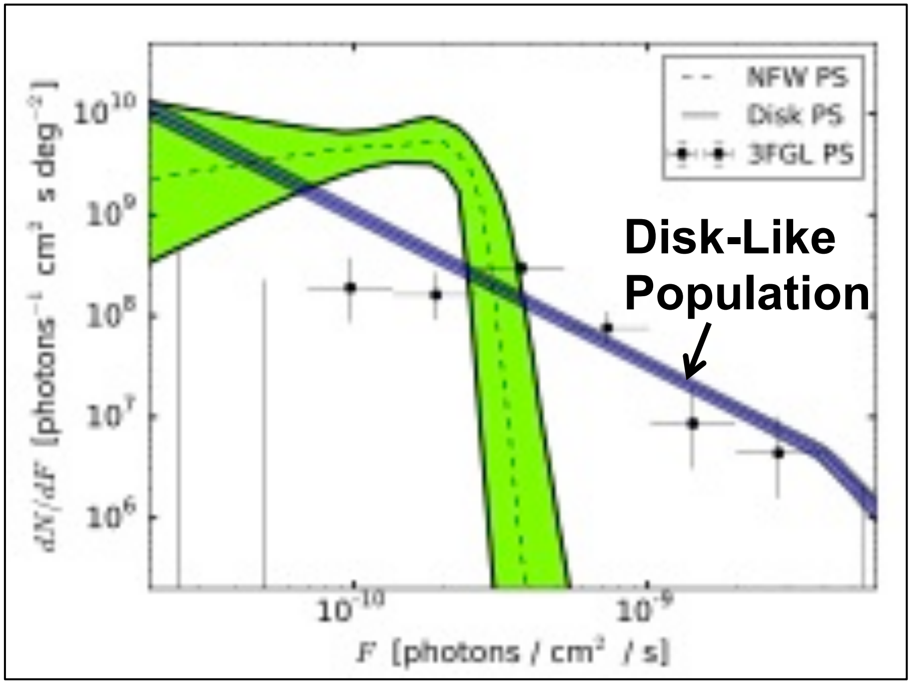
Lee et al.'s Conclusions include the following:

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



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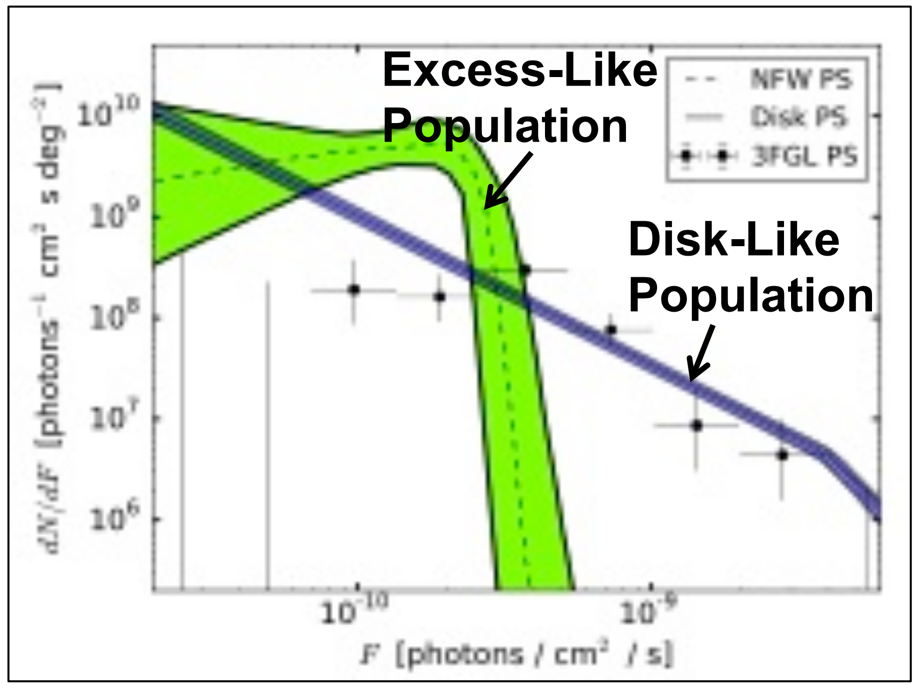

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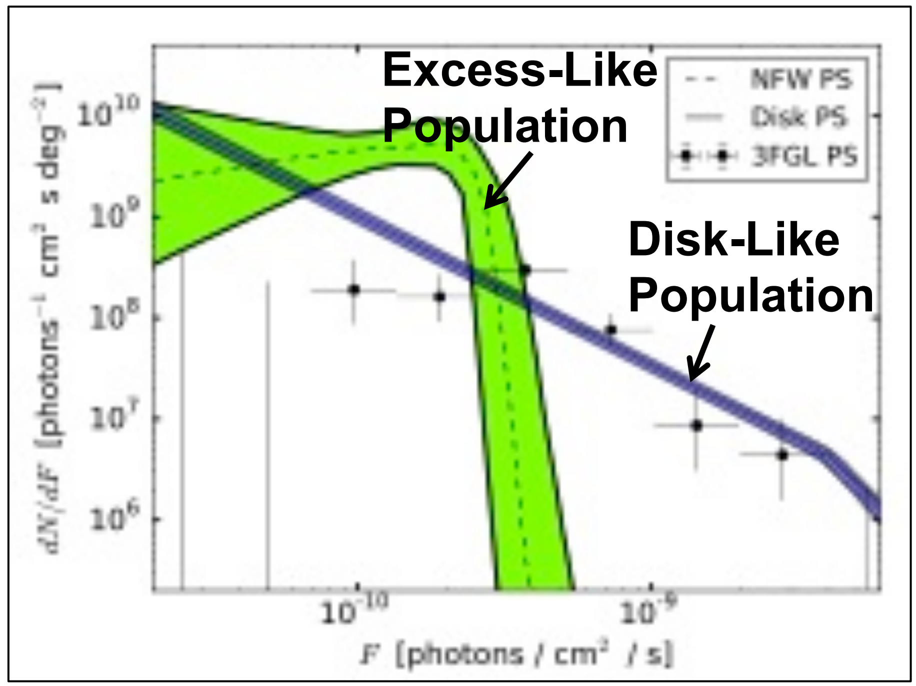
3) The Fermi diffuse model doesn't absorb much of the clustering



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Evidence For Unresolved Point Sources?

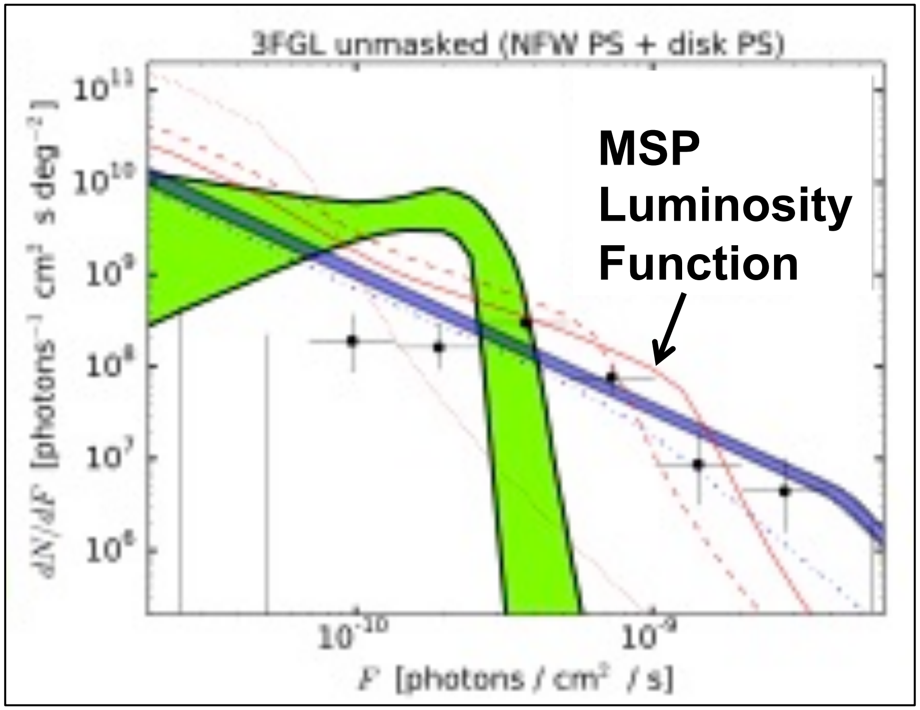
A few comments of my own:

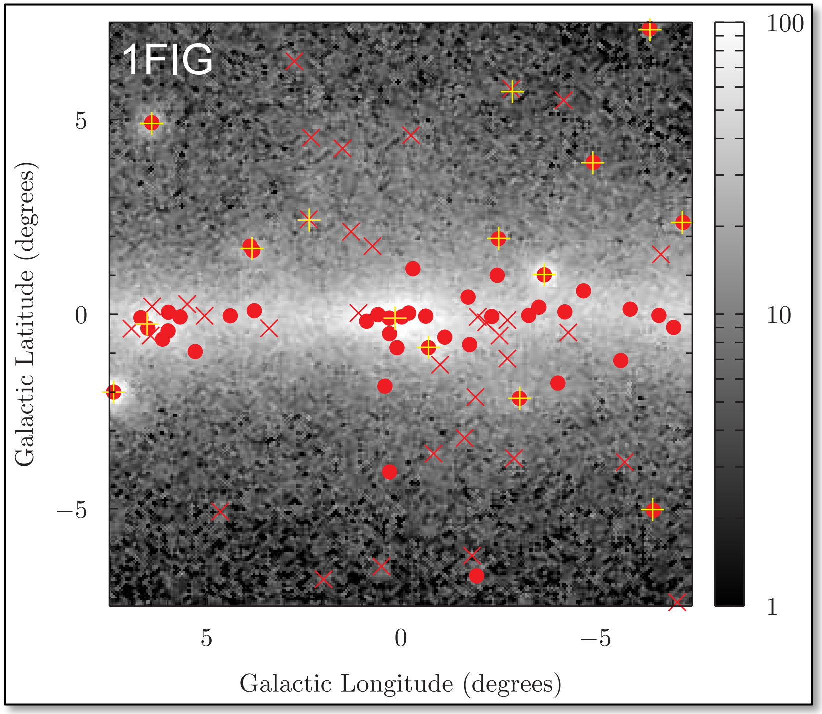
- It is difficult to tell whether these clustered gamma-rays result from unresolved sources, or from backgrounds that are less smooth than are being modeled
- Keep in mind that these clusters consist of only a few photons each, on top of large and imperfectly known backgrounds
- These studies do not 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
(see also Bartels, Krishnamurthy, Weniger, arXiv:1506.05104)

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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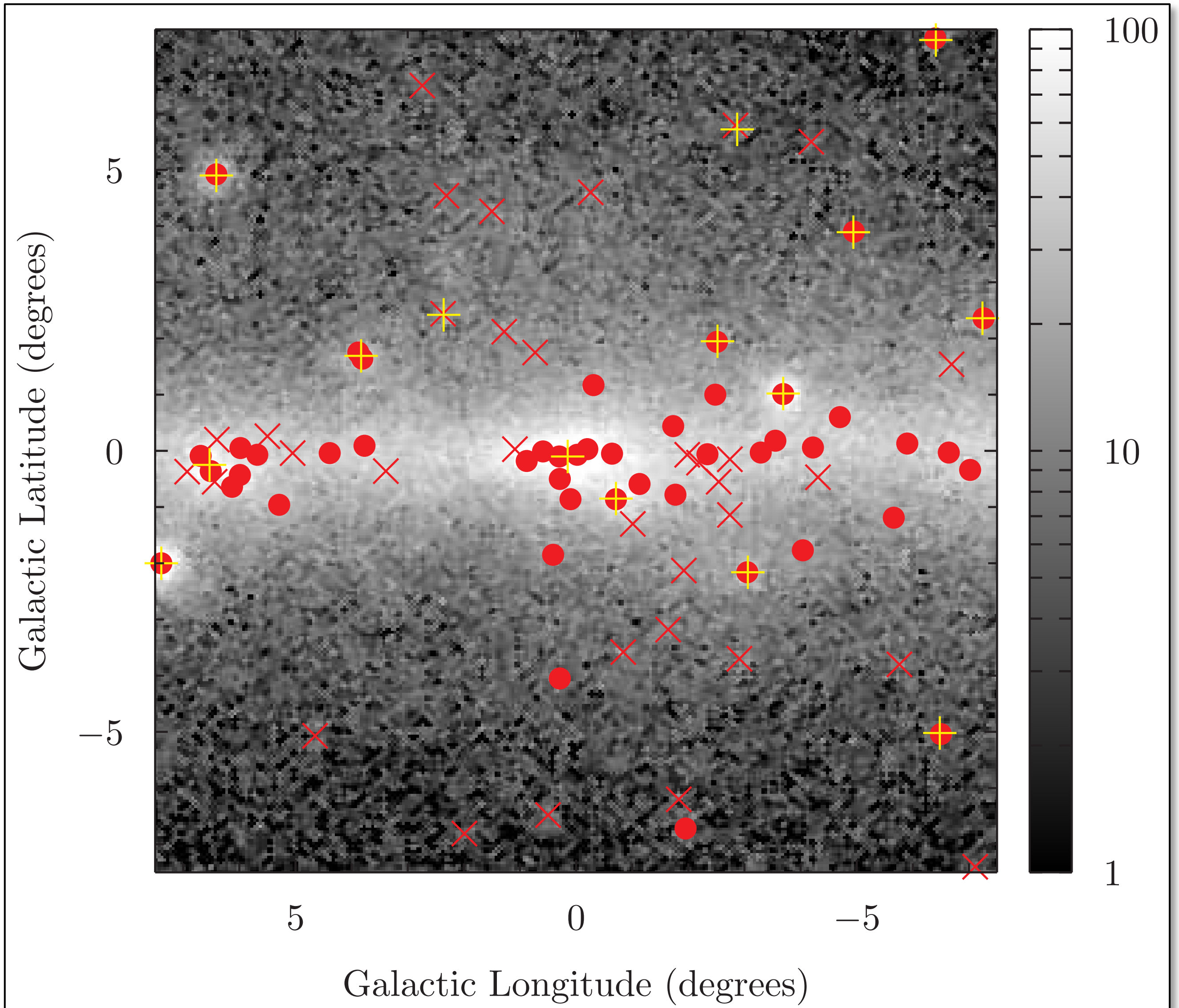
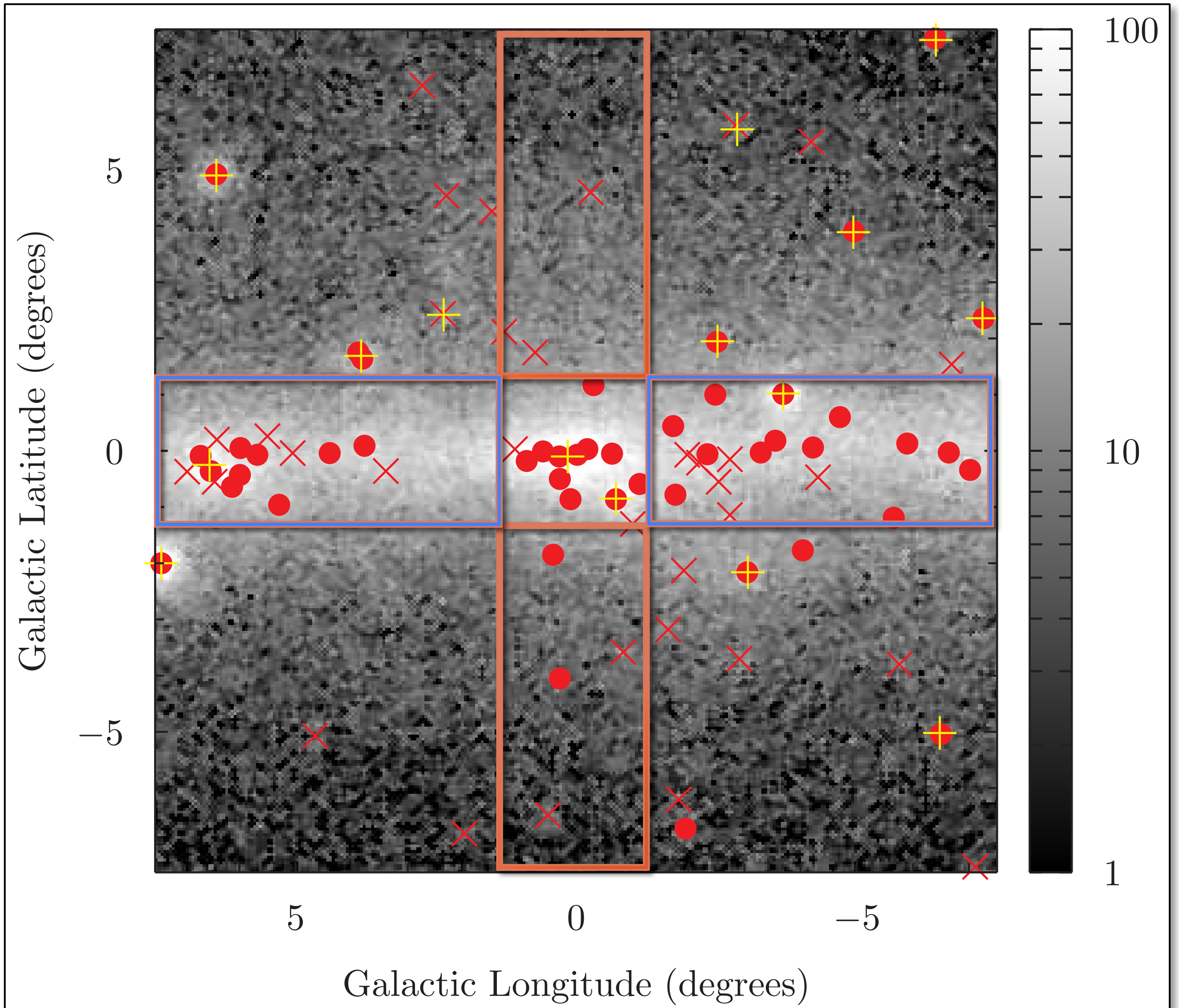


1FIG Catalog, Fermi Collaboration (Murgia, et al.)
arXiv:1511.02938



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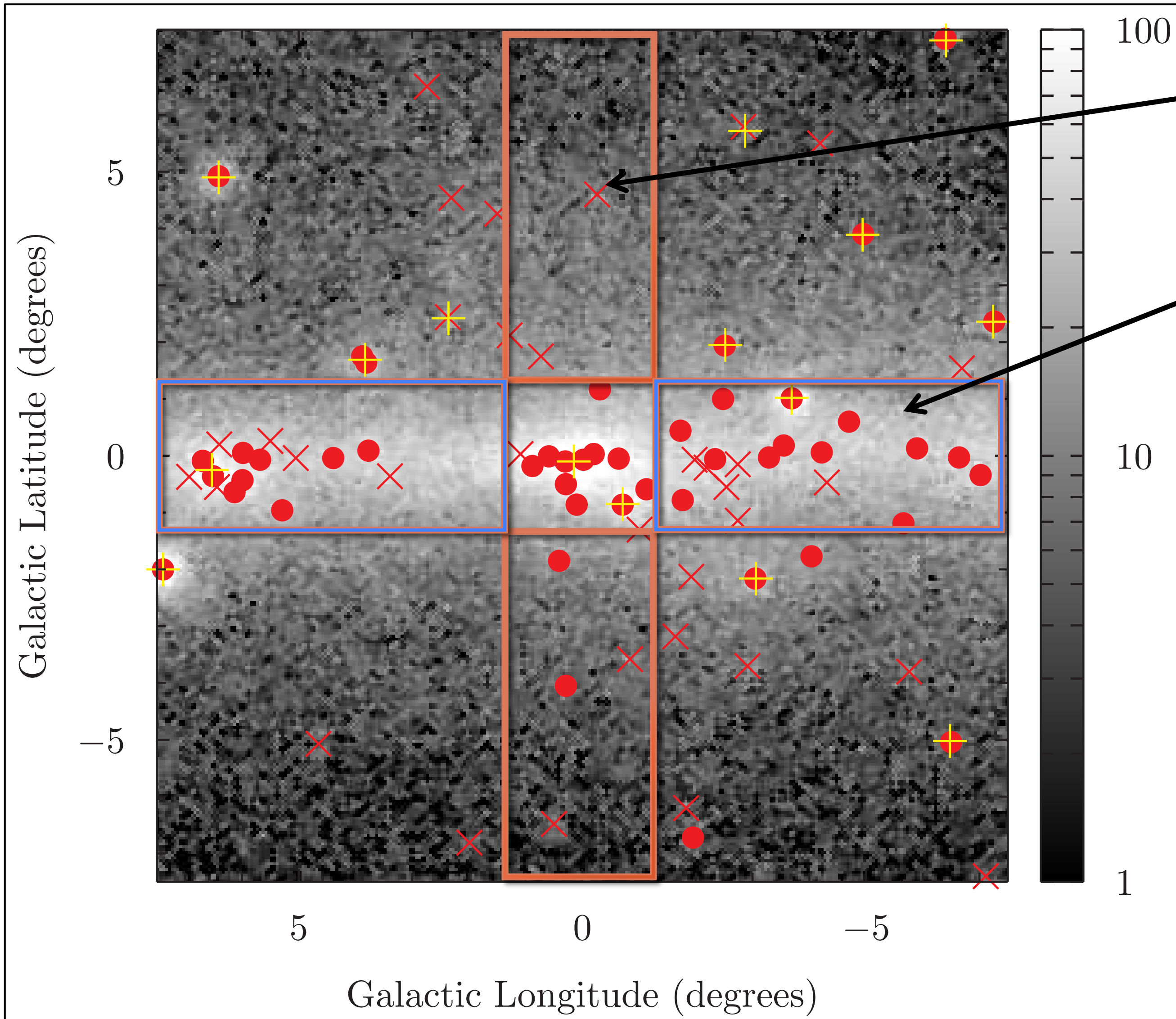


6 N+S Sources
(2 with TS>25,
and 4 with TS<25)

34 W+E Sources
(22 with TS>25,
and 12 with TS<25)

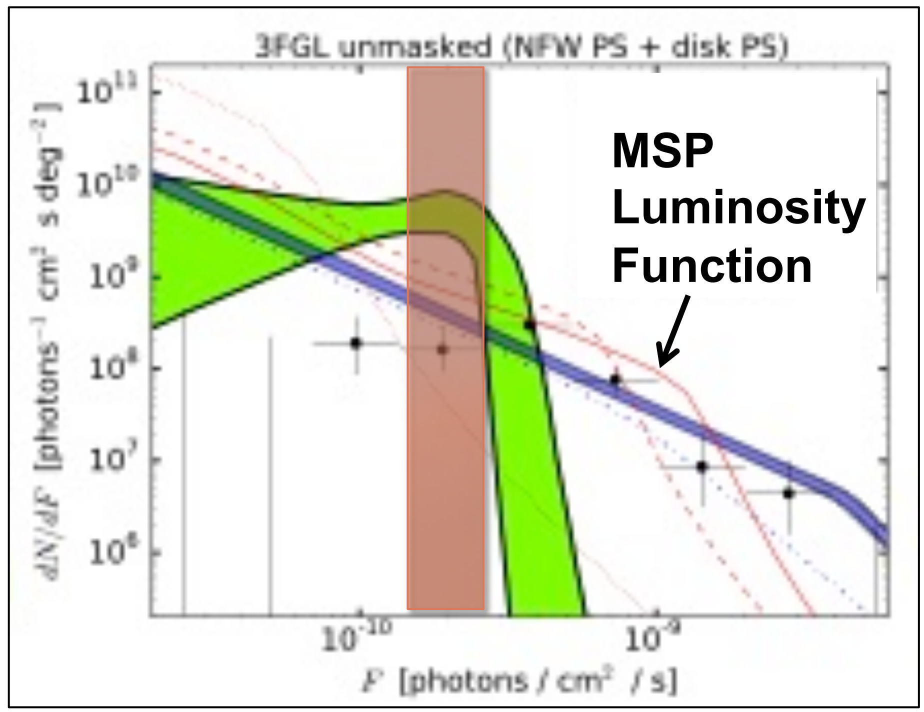
-Fermi's resolved sources are not at all spherical, but are instead concentrated along the disk

-If anything, one expects that sources in the plane would be *more* difficult to detect

1FIG Catalog, Fermi Collaboration (Murgia, et al.)
arXiv:1511.02938

Are These Sources Millisecond Pulsars?

- The measured luminosity function of MSPs extends 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)
- 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 (ΔM ~ 0.4)



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Dark Matter Interpretations

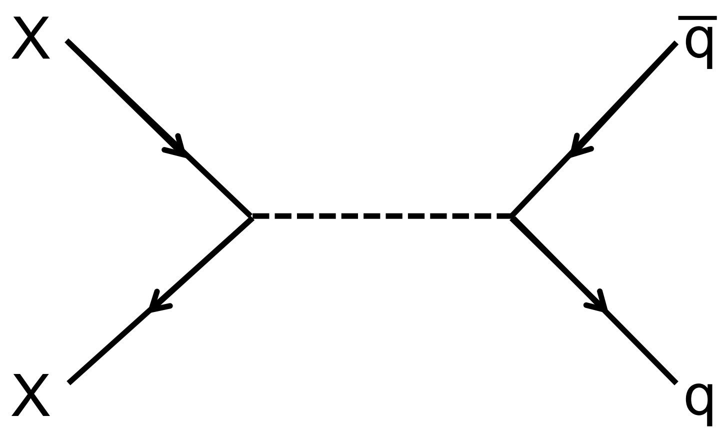
- The best fits to the observed spectrum are for dark matter annihilating to quarks or gluons
- Assuming a generalized NFW profile with a local density of 0.4 GeV/cm^3 and a scale radius of 20 kpc, the required cross section is ~(0.7-2.5)x10^{-26} cm^3/s, in good agreement with the range of values predicted for a naive thermal relic
- Direct detection constraints rule out some models (those with unsuppressed scalar or vector interactions with quarks), but many remain viable
- Somewhat contrary to conventional wisdom, the LHC does not yet exclude many of these models

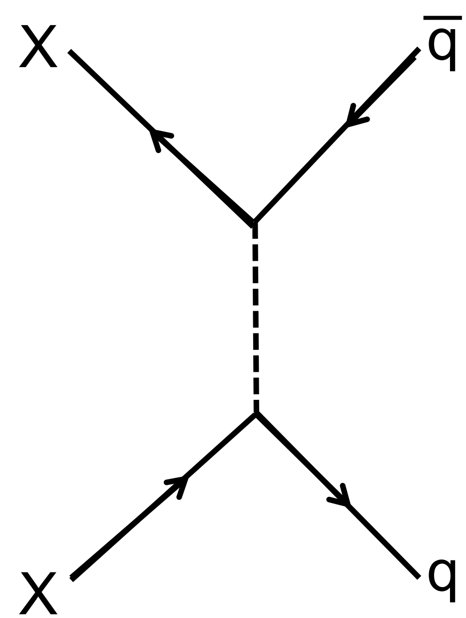
Channel	$\langle\sigma v\rangle$ (10^{-26} cm^3 s^{-1})	m_χ (GeV)	$\chi^2_{\rm min}$	p-value
$\bar{q}q$	$0.83^{+0.15}_{-0.13}$	$23.8^{+3.2}_{-2.6}$	26.7	0.22
$\bar{c}c$	$1.24^{+0.15}_{-0.15}$	$38.2^{+4.7}_{-3.9}$	23.6	0.37
$\bar{b}b$	$1.75^{+0.28}_{-0.26}$	$48.7^{+6.4}_{-5.2}$	23.9	0.35
$\bar{t}t$	$5.8^{+0.8}_{-0.8}$	$173.3^{+2.8}_{-0}$	43.9	0.003
gg	$2.16^{+0.35}_{-0.32}$	$57.5^{+7.5}_{-6.3}$	24.5	0.32
W^+W^-	$3.52^{+0.48}_{-0.48}$	$80.4^{+1.3}_{-0}$	36.7	0.026
ZZ	$4.12^{+0.55}_{-0.55}$	$91.2^{+1.53}_{-0}$	35.3	0.036
hh	$5.33^{+0.68}_{-0.68}$	$125.7^{+3.1}_{-0}$	29.5	0.13
$\tau^+\tau^-$	$0.337^{+0.047}_{-0.048}$	$9.96^{+1.05}_{-0.91}$	33.5	0.055
$[\mu^+\mu^-$	$1.57^{+0.23}_{-0.23}$	$5.23^{+0.22}_{-0.27}$	43.9	$0.0036]_{\rm ICS}$

Calore, Cholis, McCabe, Weinger, arXiv:1411.4647

Simplified Models

Focusing on dark matter models that annihilate directly to the Standard Model, we can identify scenarios that could account for the gamma-ray signal (s-wave annihilation) without conflicting with current direct detection constraints (no unsuppressed vector or scalar scattering with nuclei)





Berlin, DH, McDermott, PRD, 1404.0022

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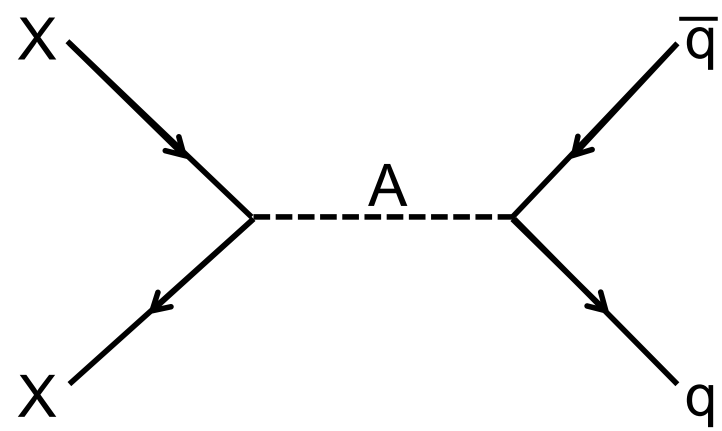
1) Dark matter with a pseudoscalar mediator (Ipek et al., Boehm et al.)

DM	*Mediator*	*Interactions*	Elastic Scattering
Dirac Fermion	Spin-0	$\bar{\chi}\gamma^5\chi,\ \bar{f}f$	$\sigma_{\rm SI} \sim (q/2m_\chi)^2$ (scalar)
Majorana Fermion	Spin-0	$\bar{\chi}\gamma^5\chi,\ \bar{f}f$	$\sigma_{\rm SI} \sim (q/2m_\chi)^2$ (scalar)
Dirac Fermion	Spin-0	$\bar{\chi}\gamma^5\chi,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q^2/4m_n m_\chi)^2$
Majorana Fermion	Spin-0	$\bar{\chi}\gamma^5\chi,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q^2/4m_n m_\chi)^2$
Complex Scalar	Spin-0	$\phi^\dagger\phi,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$
Real Scalar	Spin-0	$\phi^2,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$
Complex Vector	Spin-0	$B^\dagger_\mu B^\mu,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$
Real Vector	Spin-0	$B_\mu B^\mu,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$



Berlin, DH, McDermott, PRD, 1404.0022

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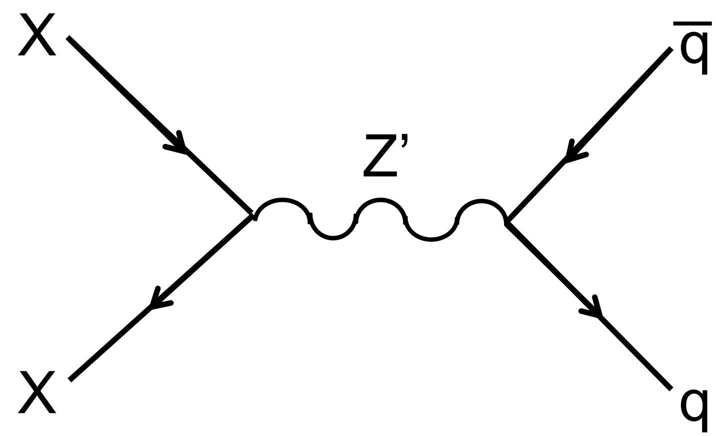
2) Fermionic dark matter with an axial spin-1 mediator (DH, 2014)

DM	*Mediator*	*Interactions*	**Elastic Scattering**
Dirac Fermion	Spin-1	$\bar{\chi}\gamma^{\mu}\chi$, $\bar{b}\gamma_{\mu}b$	$\sigma_{\rm SI} \sim$ loop (vector)
Dirac Fermion	Spin-1	$\bar{\chi}\gamma^{\mu}\chi$, $\bar{f}\gamma_{\mu}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$ or $\sigma_{\rm SD} \sim (q/2m_{\chi})^2$
Dirac Fermion	Spin-1	$\bar{\chi}\gamma^{\mu}\gamma^5\chi$, $\bar{f}\gamma_{\mu}\gamma^5 f$	$\sigma_{\rm SD} \sim 1$
Majorana Fermion	Spin-1	$\bar{\chi}\gamma^{\mu}\gamma^5\chi$, $\bar{f}\gamma_{\mu}\gamma^5 f$	$\sigma_{\rm SD} \sim 1$



Berlin, DH, McDermott, PRD, 1404.0022

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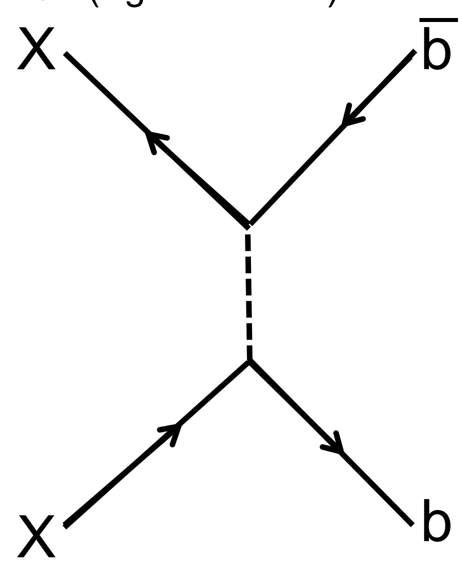
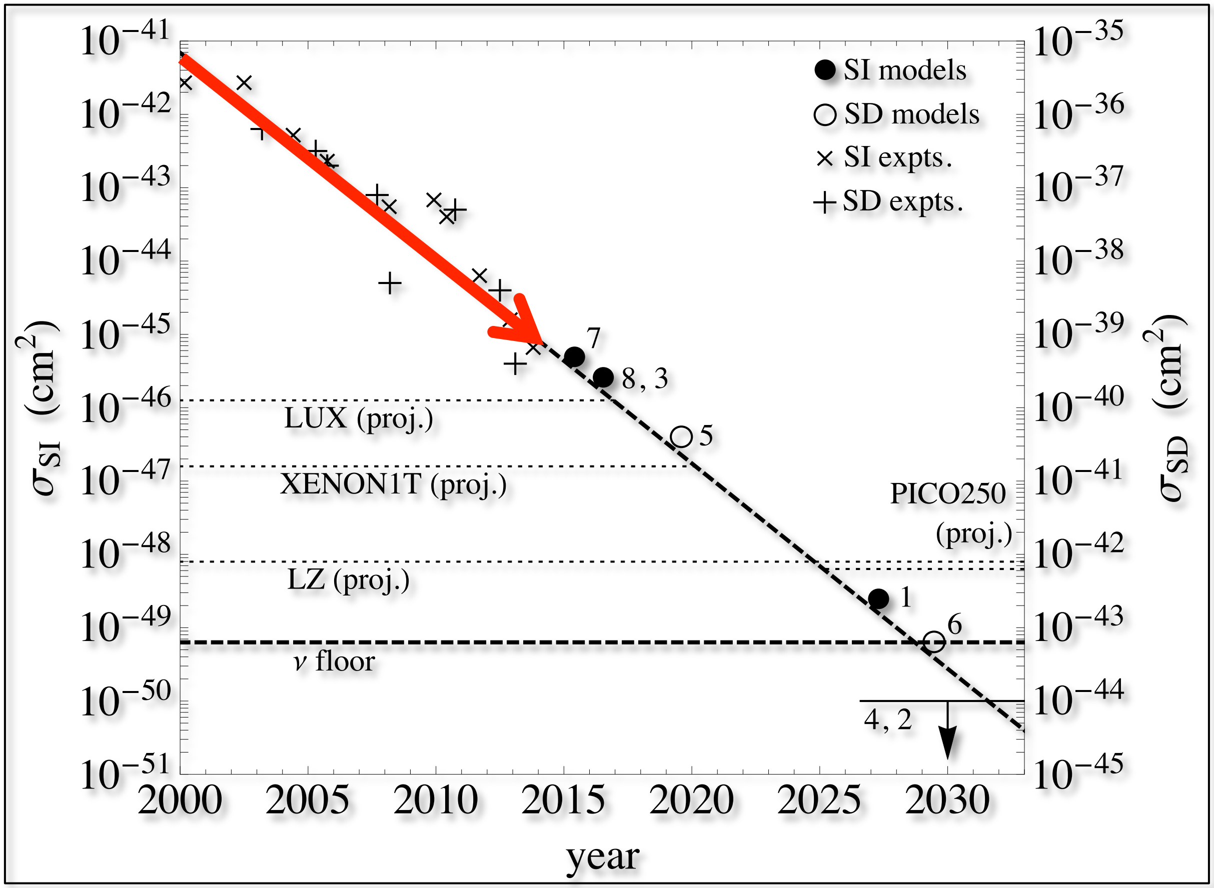
2) Fermionic dark matter with an axial spin-1 mediator (DH, 2014)
3) Models with a colored and charged t-channel mediator (Agrawal et al.)

DM	*Mediator*	*Interactions*	Elastic Scattering
Dirac Fermion	Spin-0 (t-ch.)	$\bar{\chi}(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)
Dirac Fermion	Spin-1 (t-ch.)	$\bar{\chi}\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)
Complex Vector	Spin-1/2 (t-ch.)	$X_\mu^\dagger\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)
Real Vector	Spin-1/2 (t-ch.)	$X_\mu\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)



Berlin, DH, McDermott, PRD, 1404.0022

Prospects for Direct Detection



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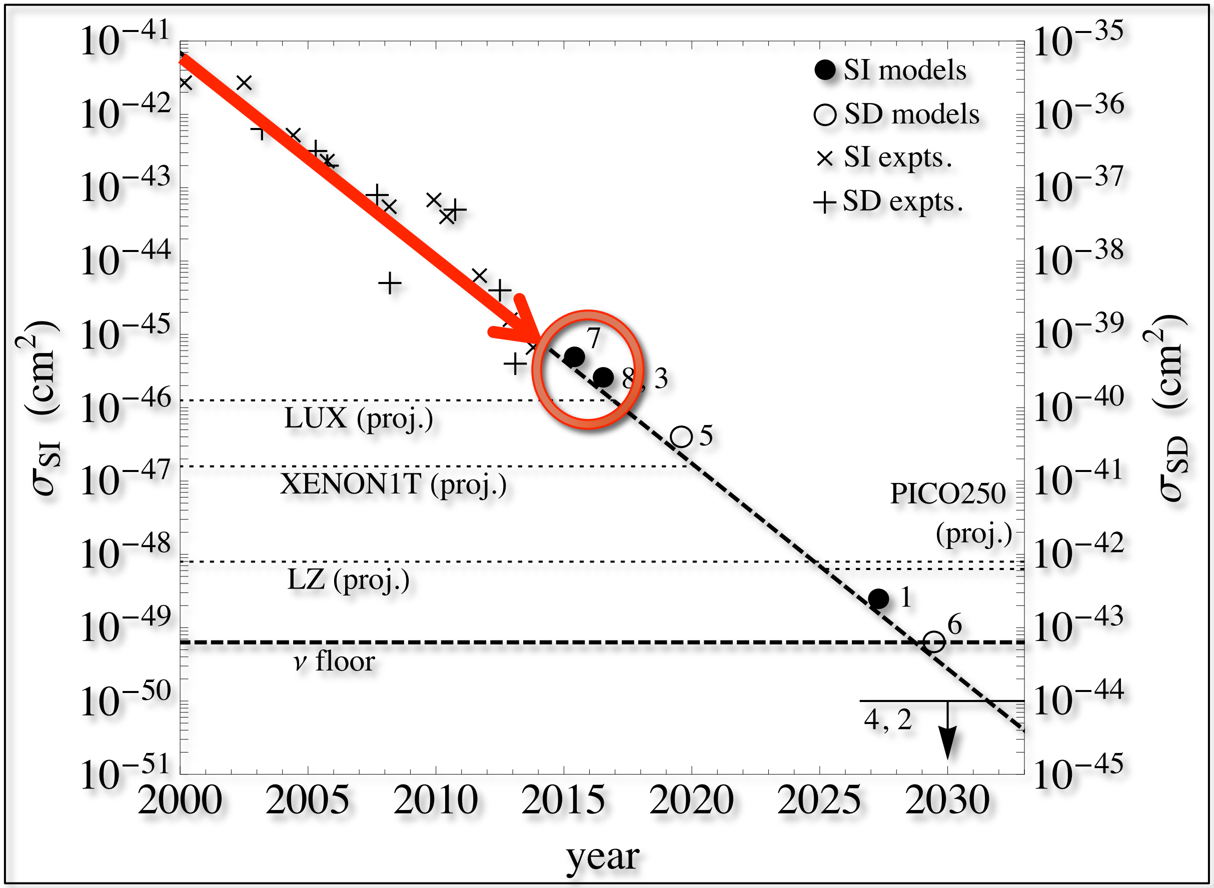

- t-channel models are within the reach of both LUX and LHC14

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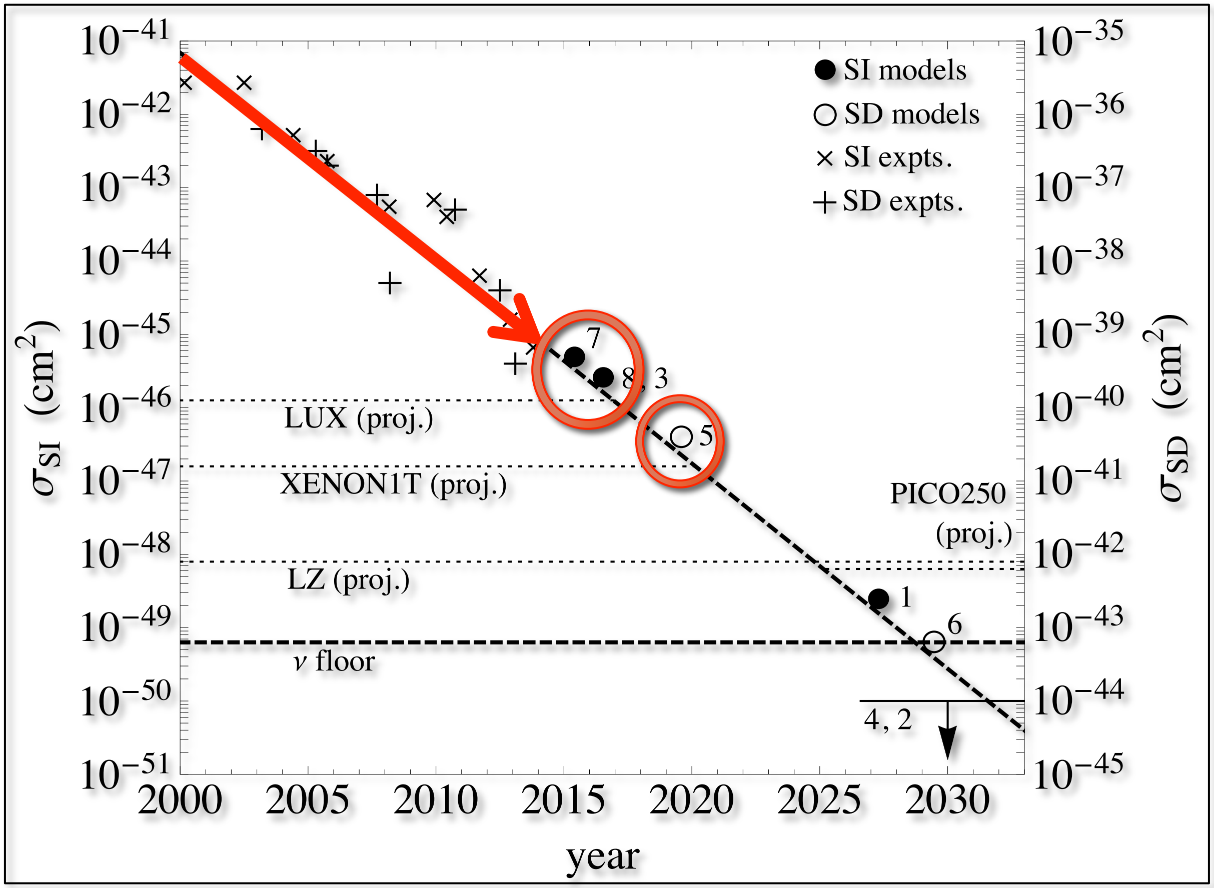

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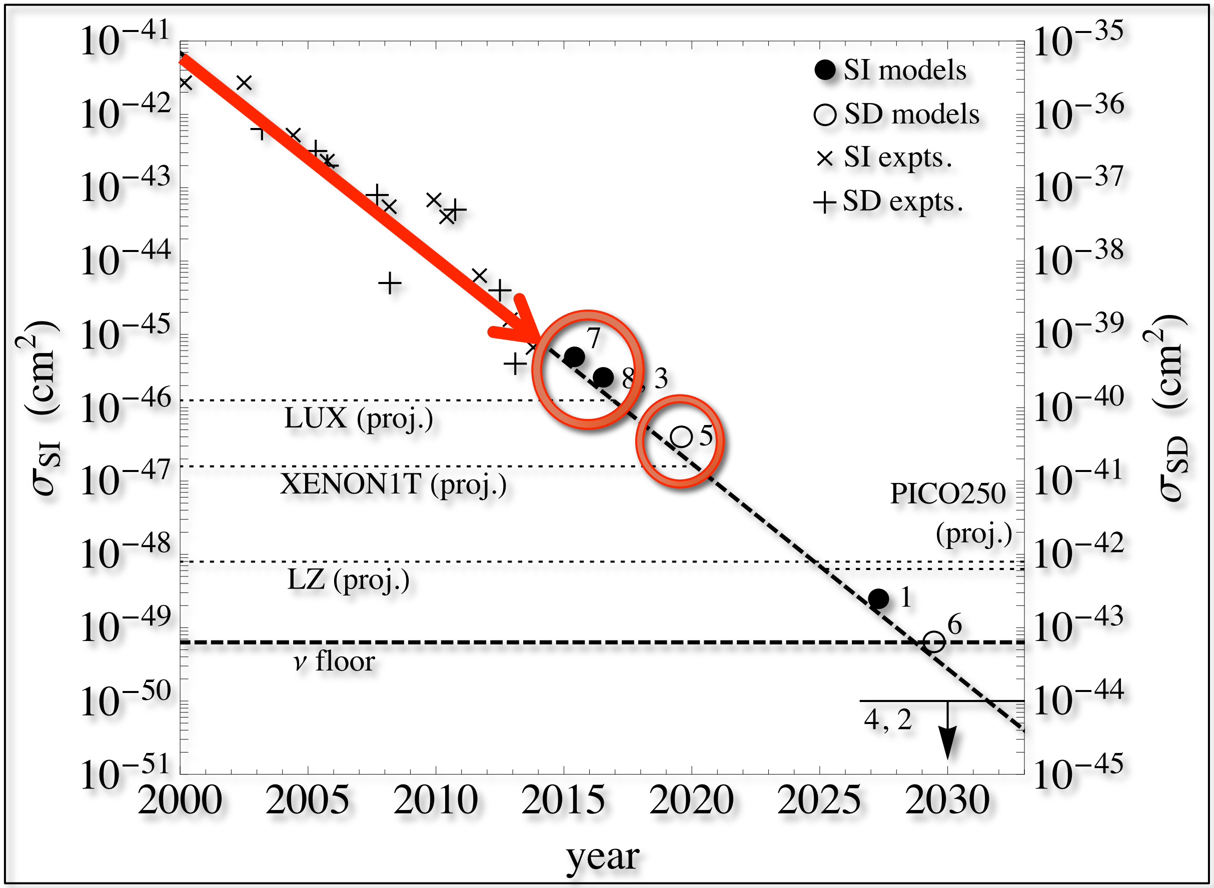
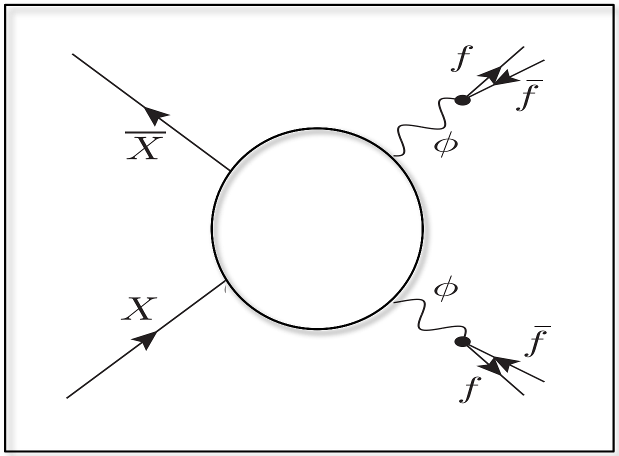


- t-channel models are within the reach of both LUX and LHC14
- Models with purely axial interactions will be tested by XENON1T
- Prospects for pseudoscalar models depend on other particle content

Hidden Sector Models

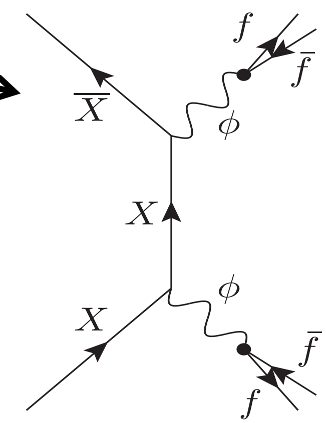
- Although the lack of signals observed in direct detection experiments and at colliders restricts the nature of the dark matter's interactions with the Standard Model, many tree-level annihilation processes continue to be viable
- Alternatively, one could take this as motivation to consider dark matter that does not couple directly to the Standard Model, but instead annihilates into other particles that subsequently decay into Standard Model particles:



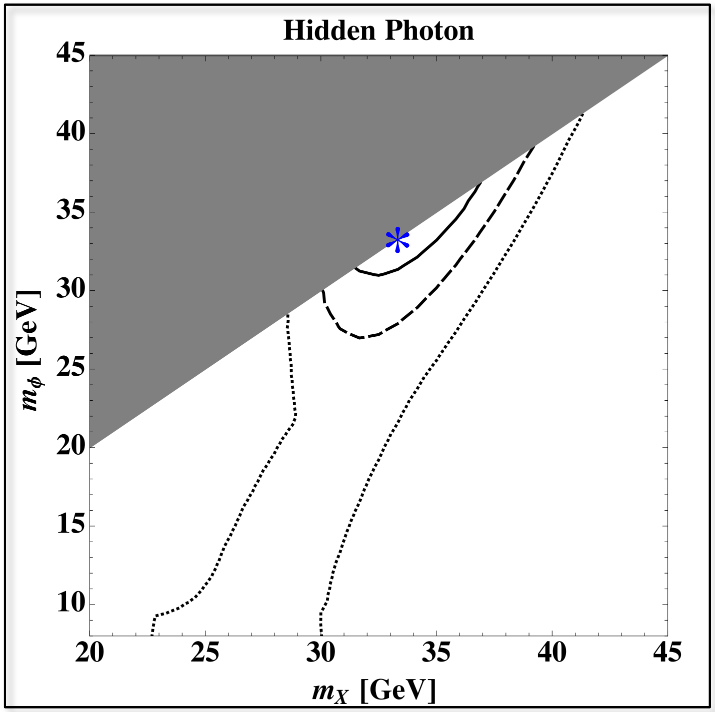
Martin et al. 1405.0272, Abdullah et al. 1404.6528, Boehm et al. 1404.4977

Dark Matter with a Hidden Photon

- Consider dark matter as a Dirac fermion, with no Standard Model gauge charges, but that is charged under a new U(1)
- If the dark matter (X) is more massive than the U(1)'s gauge boson (ϕ), annihilations can proceed through the following:



- Relic abundance and Galactic Center excess require $g_X \sim 0.1$
- The ϕ's decay through a small degree of kinetic mixing with the photon; direct constraints require mixing less than $\varepsilon \sim 10^{-4}$ (near loop-level prediction)



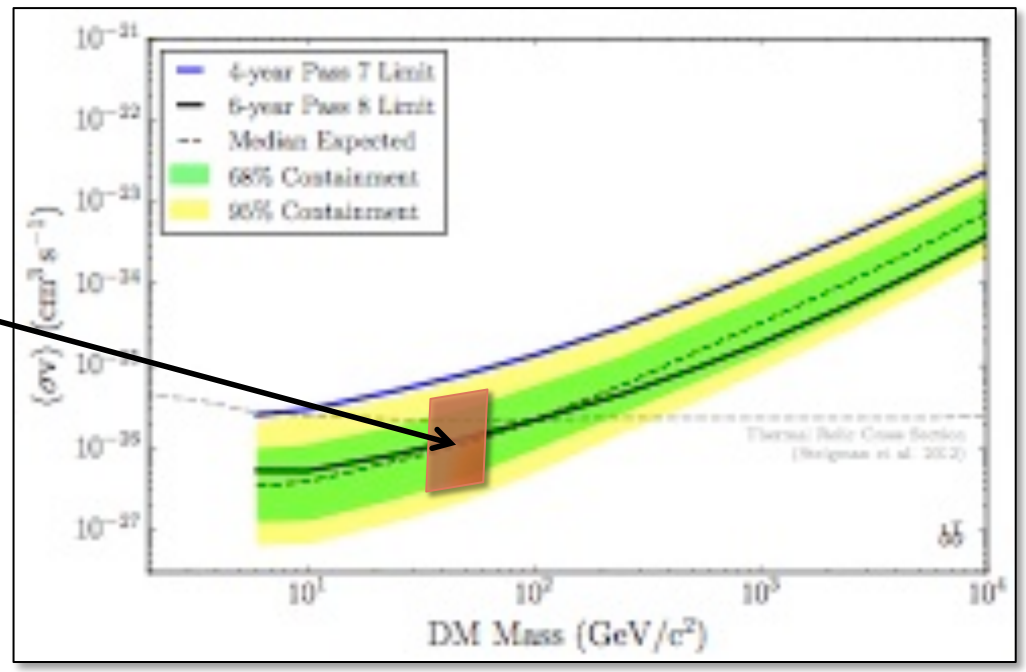
A. Berlin, S. McDermott, DH, PRD, arXiv:1405.5204

What's Next?

- After years of investigation, 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

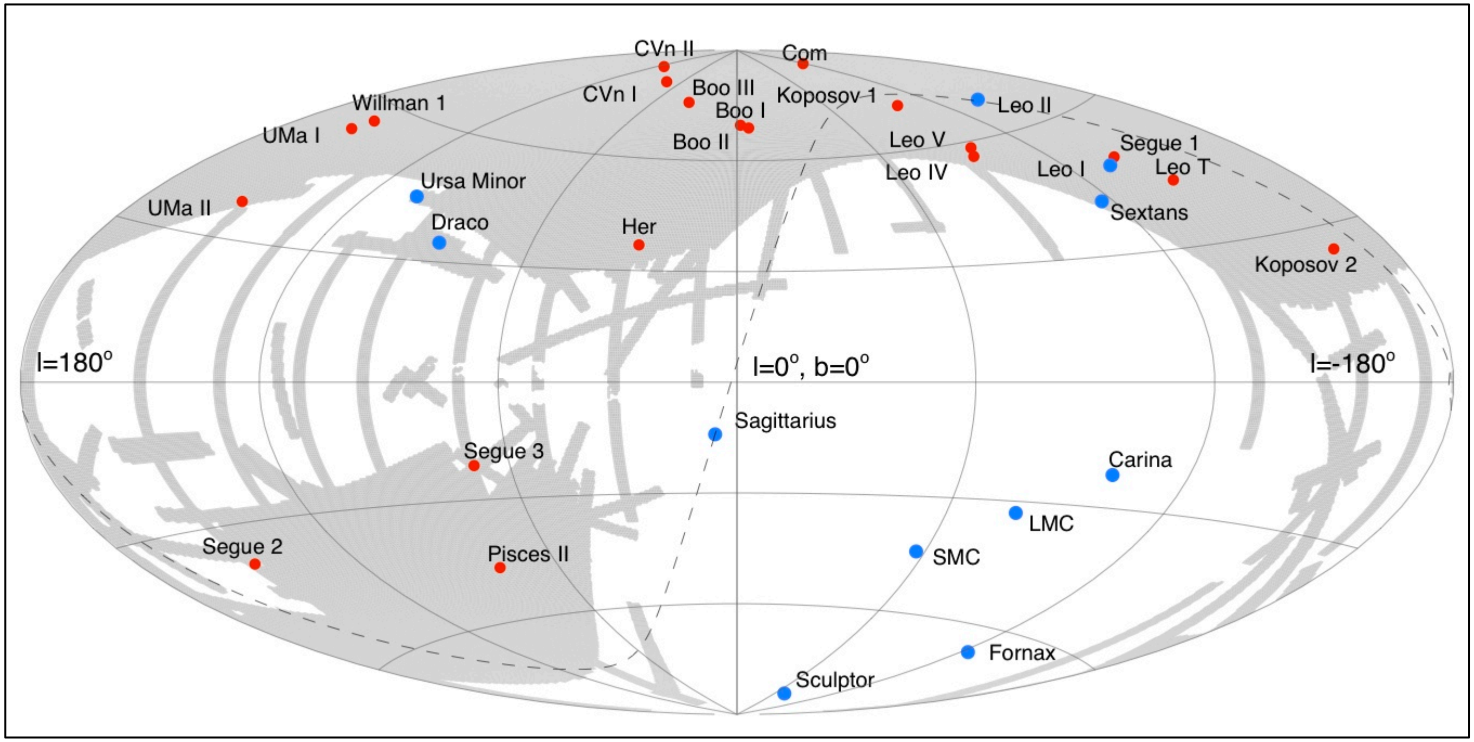
- The most recent analysis by the Fermi Collaboration (making use of 6 years of Pass 8 data) remains compatible with a dark matter interpretation of the Galactic Center excess
- That being said, if the Galactic Center signal is coming from annihilating dark matter, one might expect gamma rays from dwarfs to be detected soon



Fermi Collaboration, 1503.02641

Dwarf Galaxies

- Past searches for gamma rays from dwarf galaxies made use of both "classical" dwarfs (Draco, Sagittarius,...), and "ultra-faint" dwarfs discovered more recently by SDSS (Segue 1, Ursa Major II,...)
- Much of the sky was not explored by SDSS, leaving us with the expectation that many dwarfs remained to be discovered

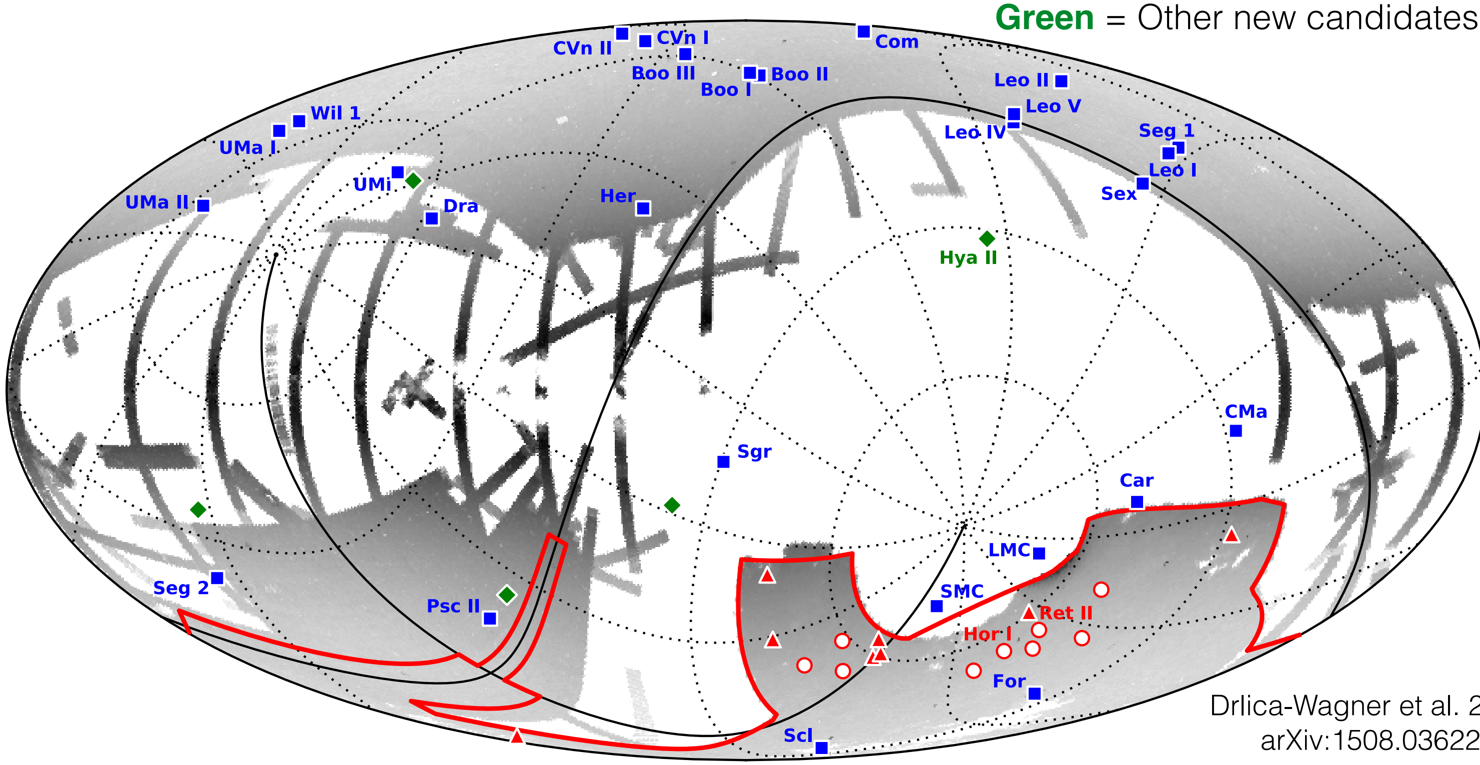


New Dwarf Galaxies!

- In the past year, 22 new dwarf galaxy candidates have been discovered! (most from Dark Energy Survey data, but also SDSS, and Pan-STARRS)
- Particularly exciting are Reticulum II, Tucana III, and Cetus II which are each nearby (~25-30 kpc) and attractive targets for dark matter searches

Stellar density field from SDSS and DES

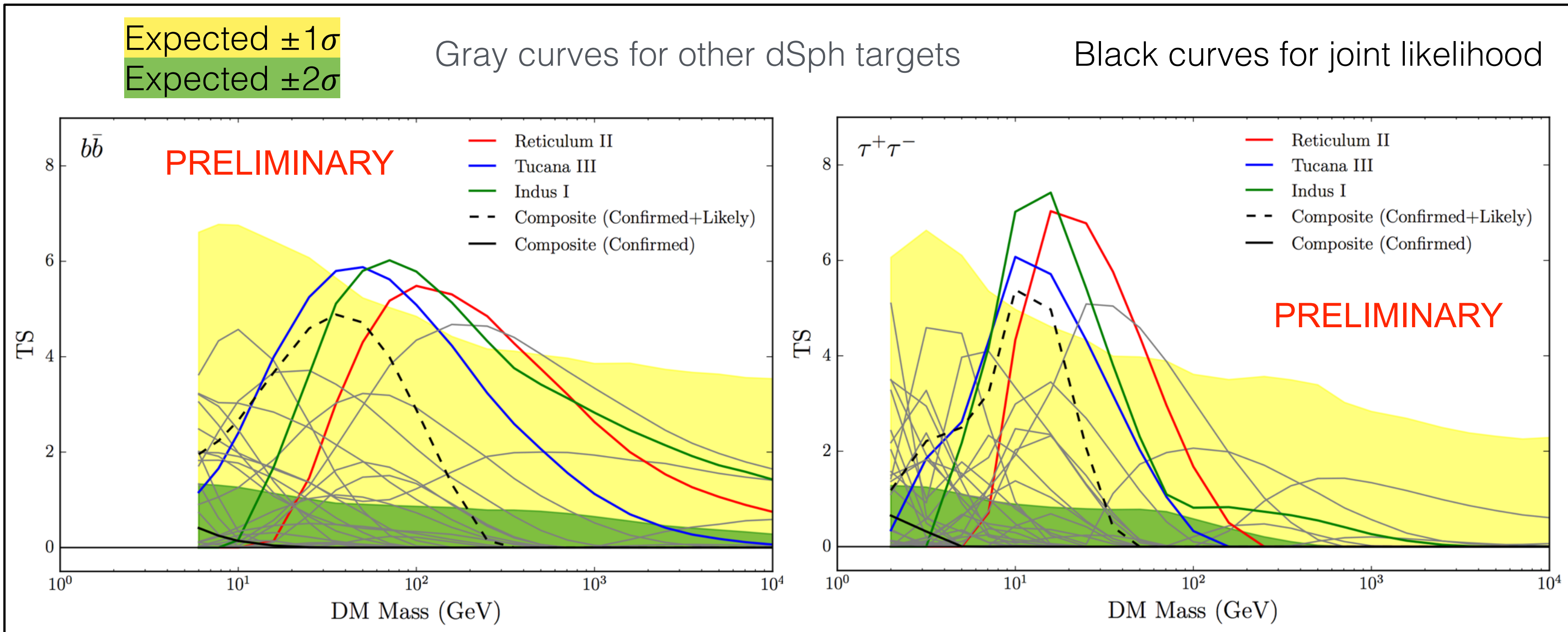
Blue = Known prior to 2015
Red triangles = DES Y2Q1 candidates
Red circles = DES Y1A1 candidates
Green = Other new candidates



Drlica-Wagner et al. 2015
arXiv:1508.03622

Fermi's View of the New Dwarf Galaxies

- This spring, three groups reported an excess from Reticulum II, but with only 2.4-3.2σ significance, (Geringer-Sameth et al. Drlica-Wagner, et al, DH & Linden)
- No papers on Tucana III or the other most recently discovered dwarfs yet, but Fermi's has recent begun presenting preliminary results in talks:



From Keith Bechtol's talk, TAUP 2015 (for the DES and Fermi Collaborations)

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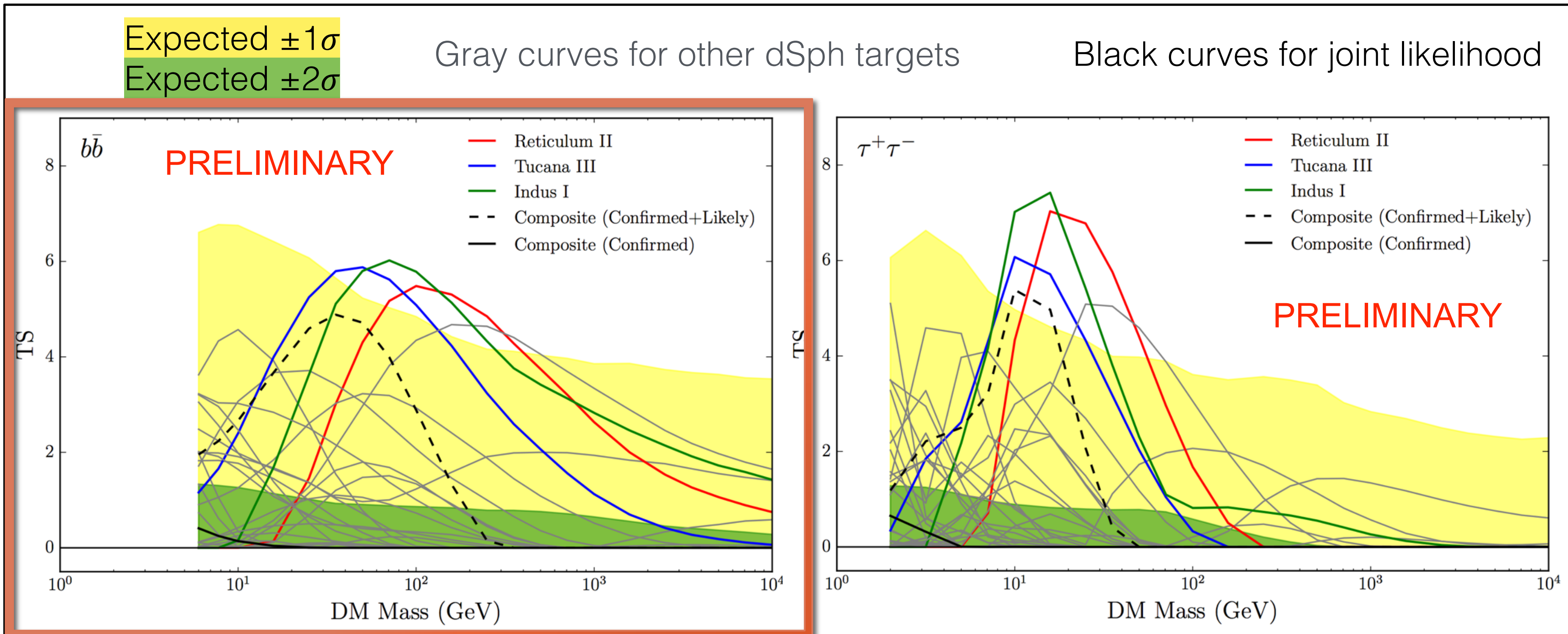

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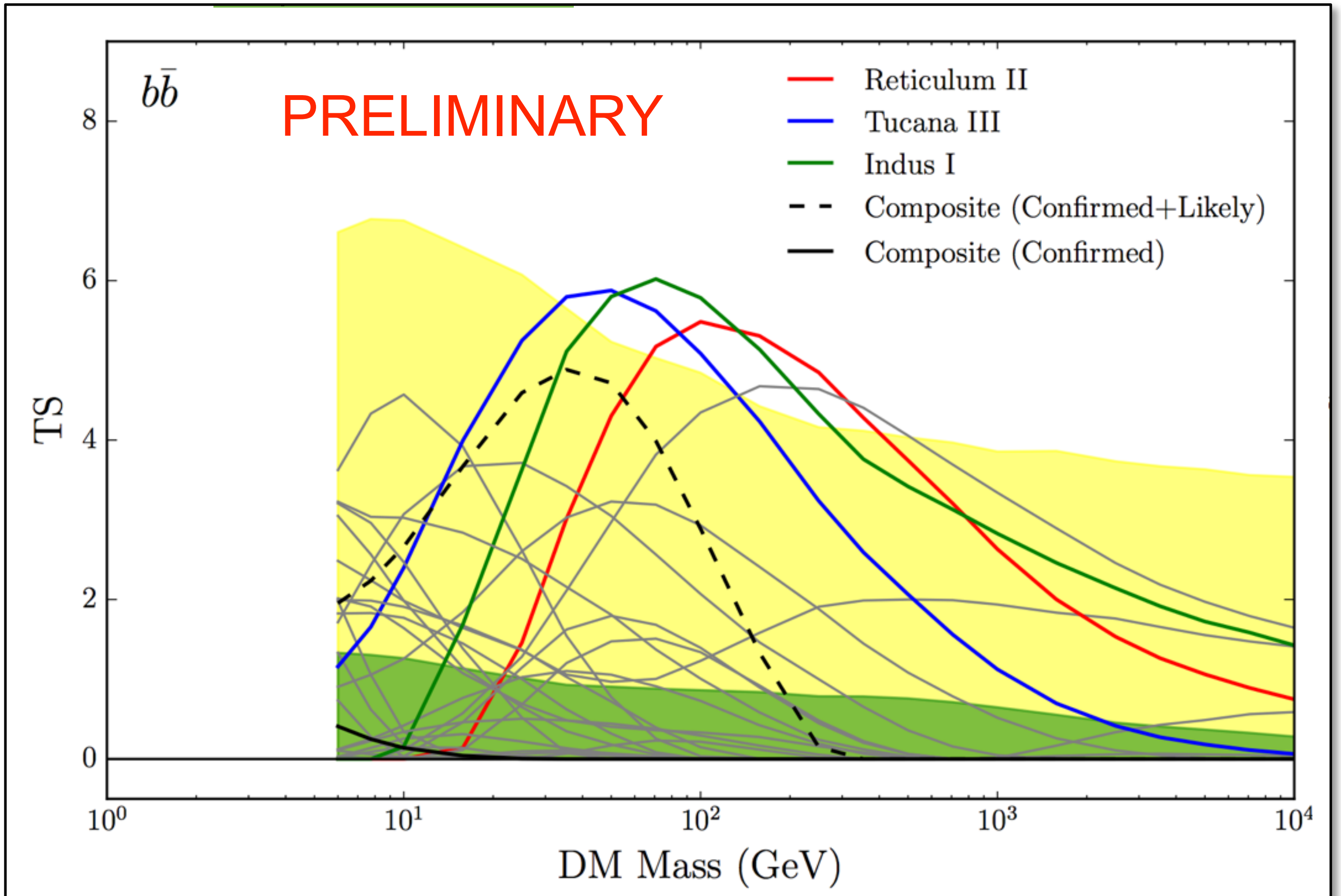

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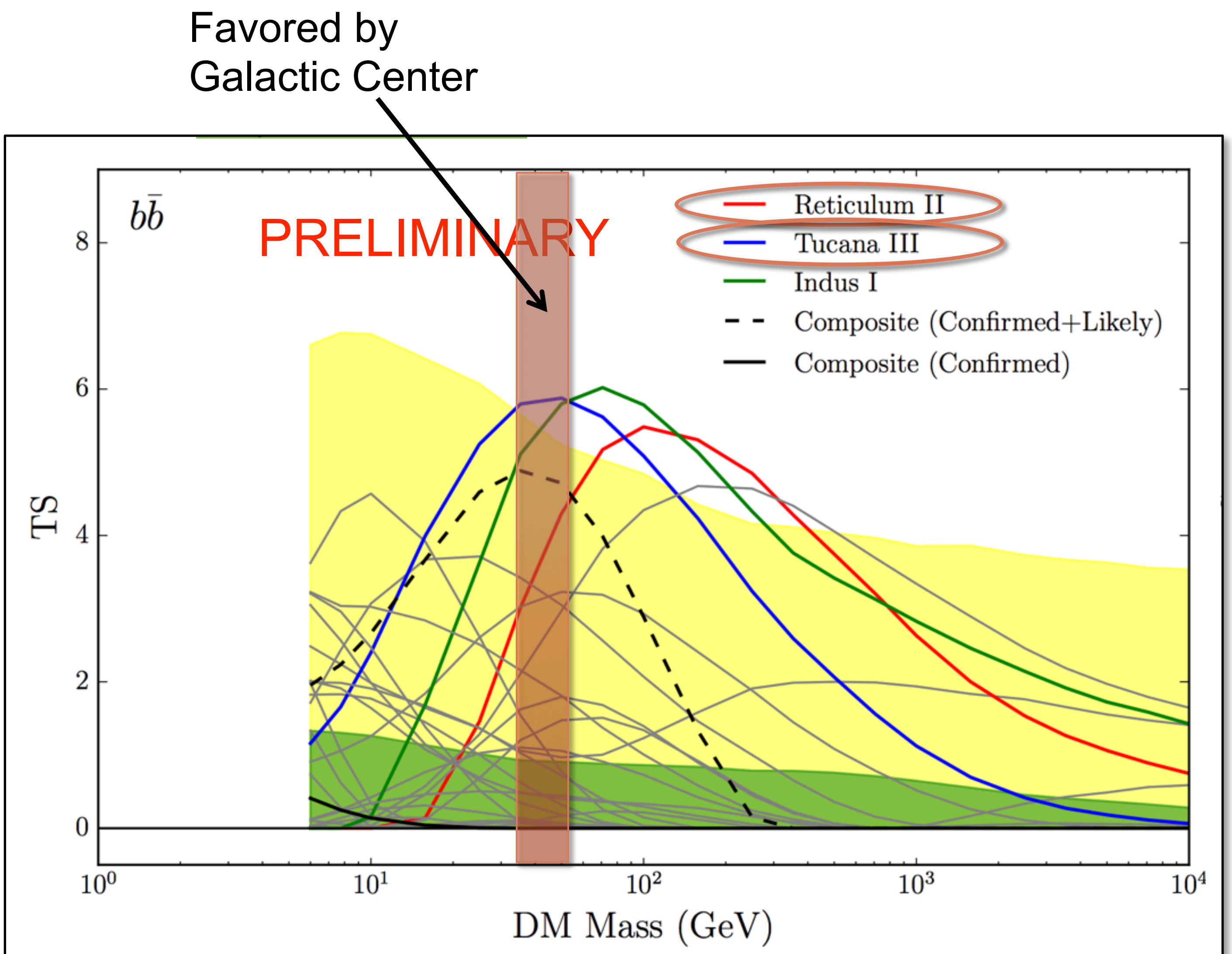

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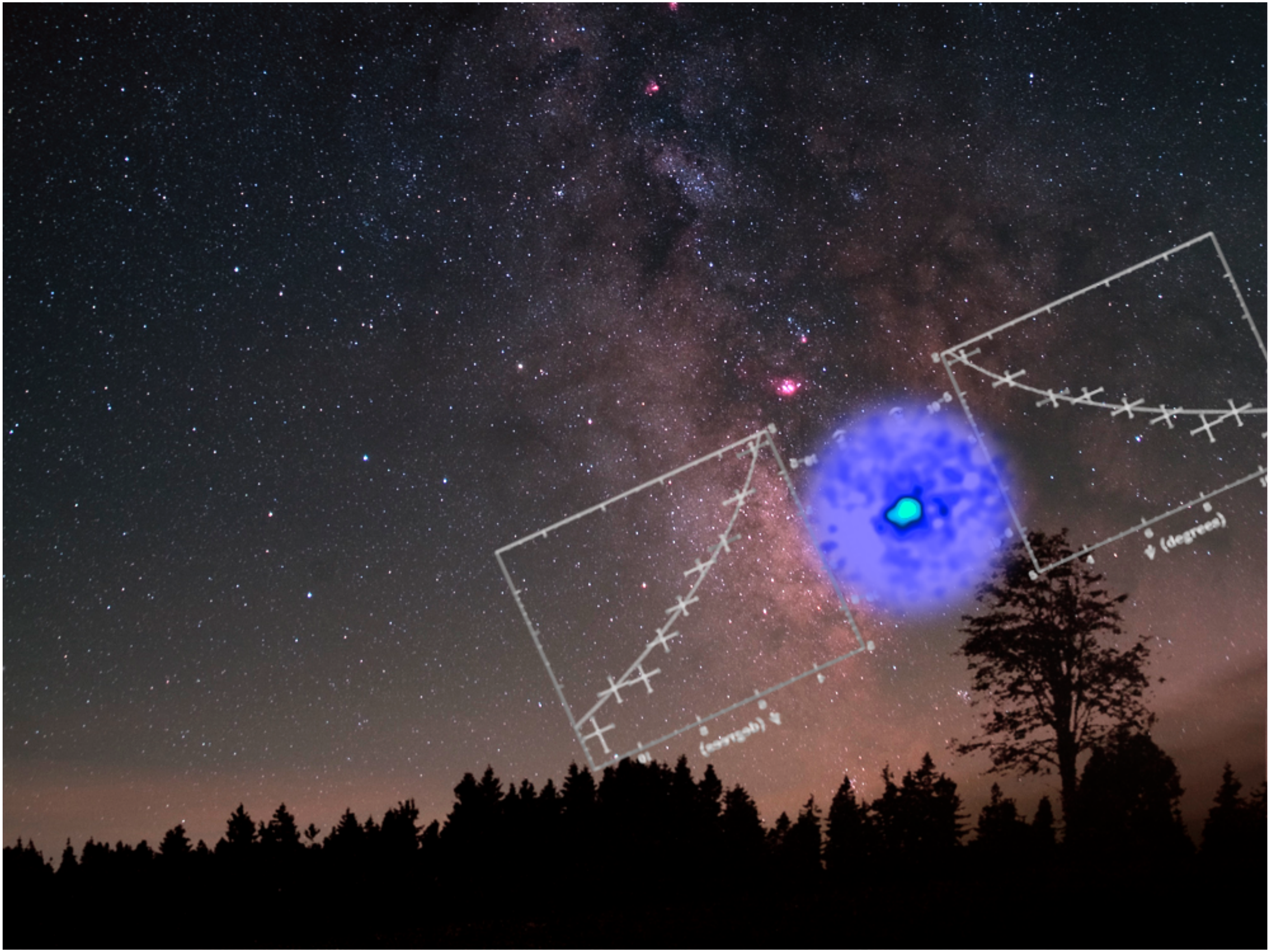
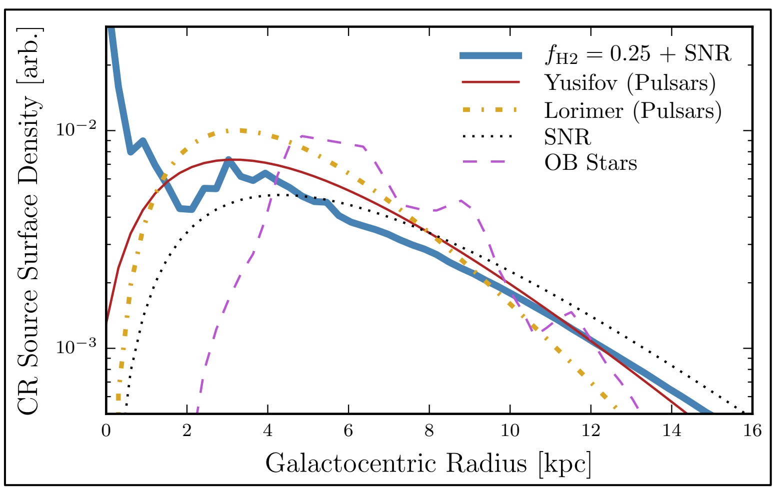
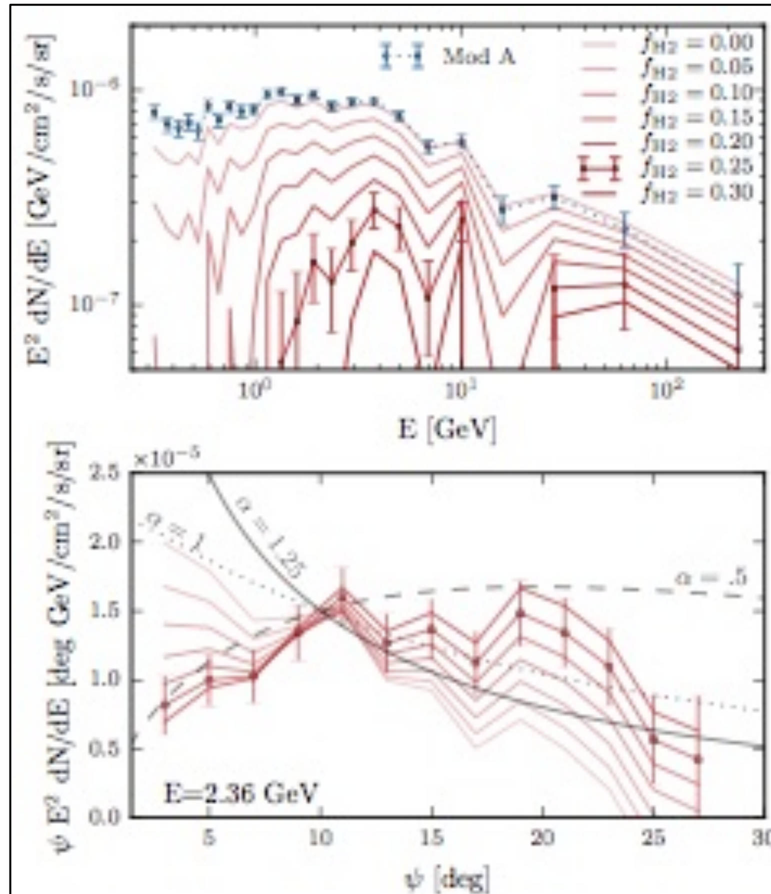

ψ (degrees)

Beyond Standard Diffuse Backgrounds

- Even if it is difficult to account for the entirety of the excess with centrally concentrated cosmic ray models, such models might significantly impact the inferred characteristics of the excess
- Carlson et al.'s H_2-tracing source model, for example, further hardens the spectrum of the excess, and reduces the slope of its angular profile

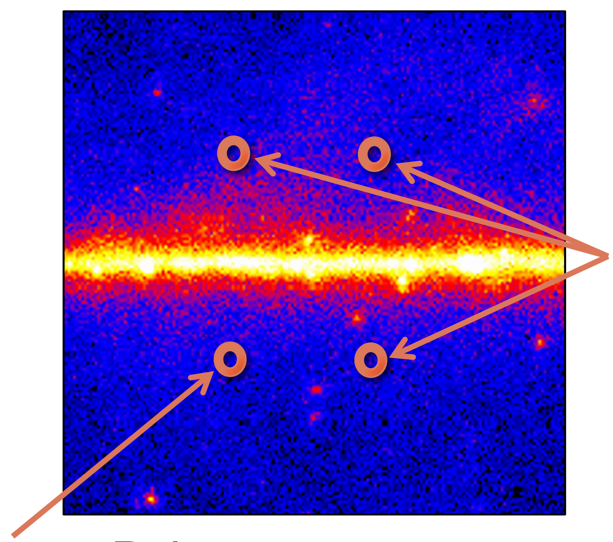




Carlson, et al., arXiv:1510.04698

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, arXiv:1509.02928

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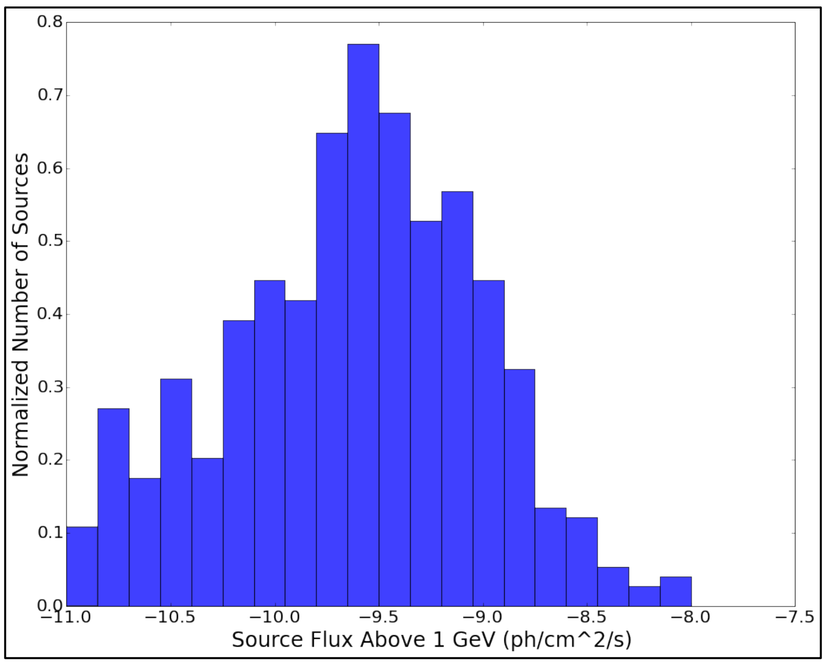
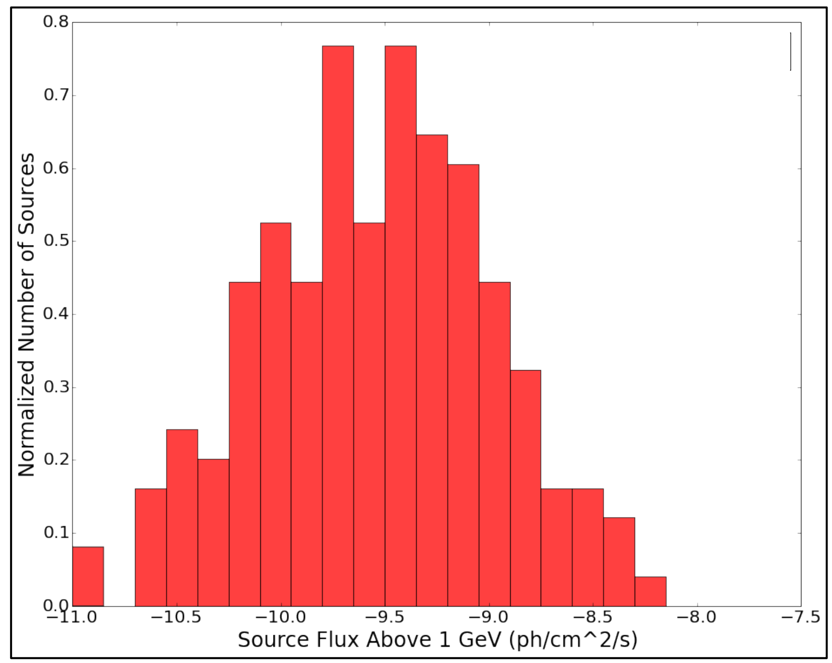
Which plot is the control group?





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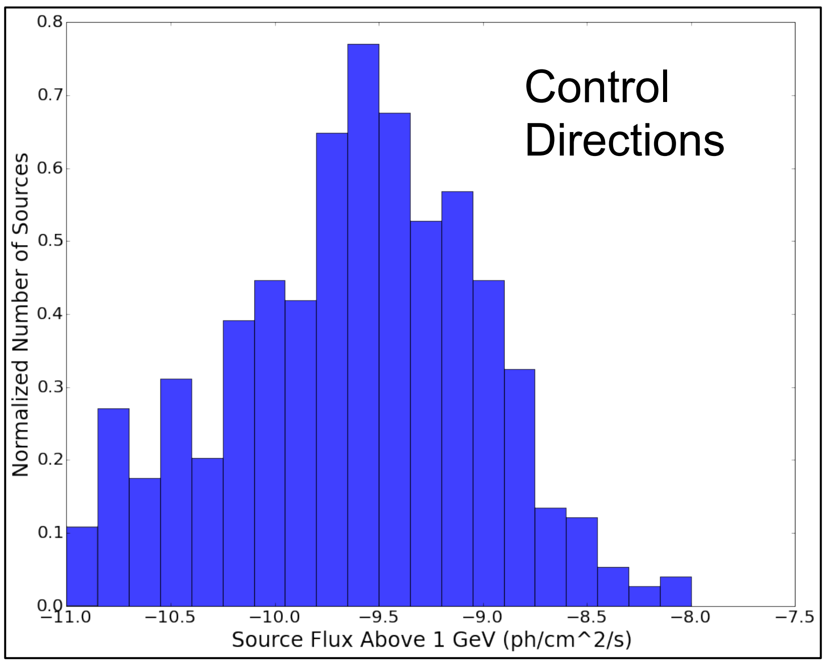

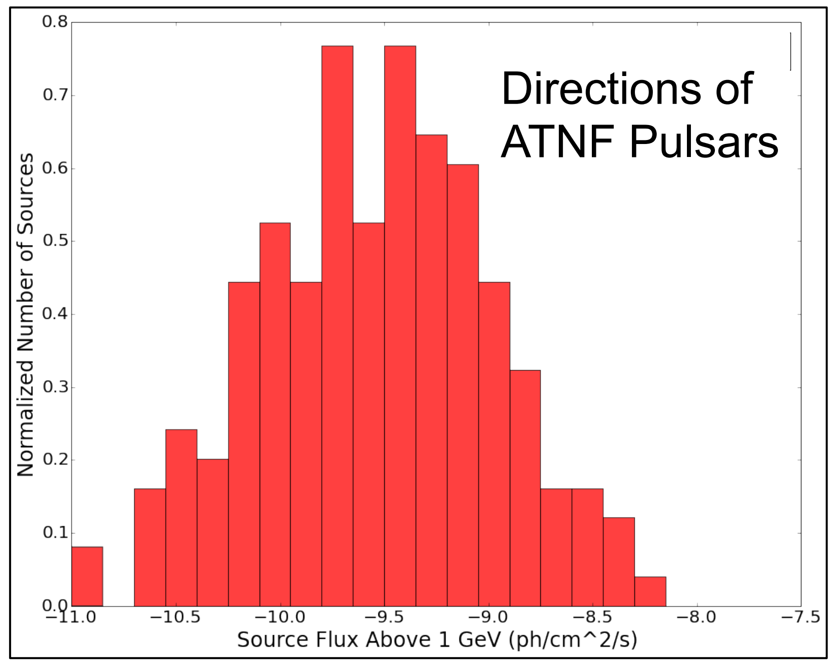

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