THE SEARCH FOR DARK MATTER'S PARTICLE IDENTITY (CIRCA 2015)

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DESY Theory Workshop

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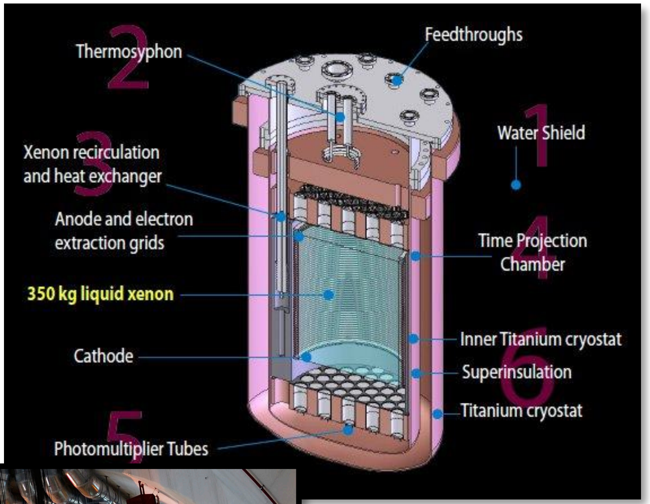
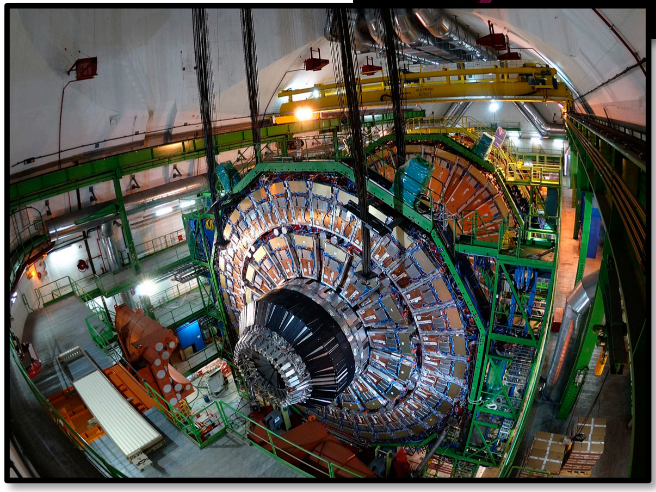
A Changing Dark Matter Landscape

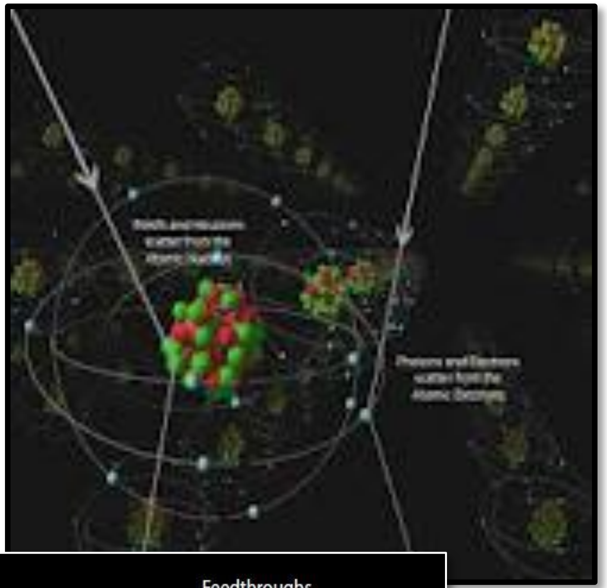
- Over the past few years, the attitudes of many within the dark matter community have noticeably shifted; driven in large part by the fact that dark matter particles have not yet been observed in underground detectors, or at the LHC
- My personal view is that this is response is somewhat premature; I continue to find WIMPs very compelling
- That being said, if a discovery does not occur within the next decade or so, it will force us to revisit our ideas about what the dark matter is likely to be made up of

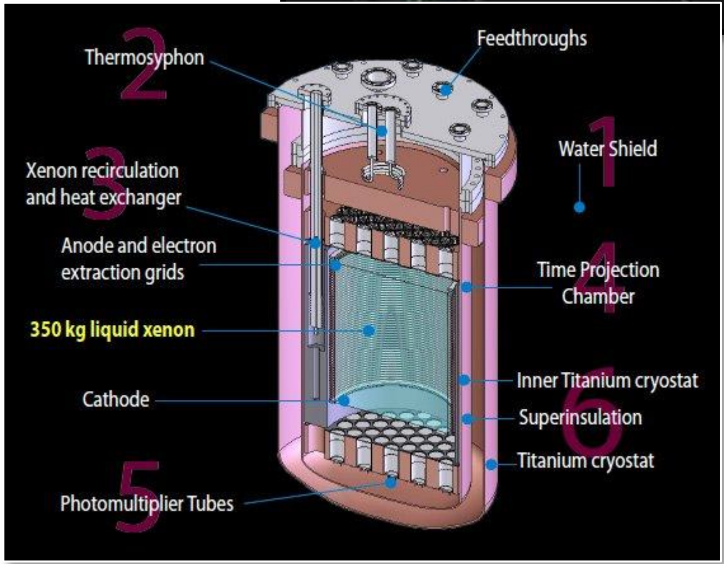




Direct Detection (scattering with nuclei)

- A GeV-TeV particle moving a typical halo velocities (~300 km/s) striking a nucleus imparts a recoil of ~1-100 keV; potentially observable combinations of scintillation, ionization and phonons
- Current state-of-the-art experiments make use of ton-scale targets of heavy nuclei, instrumented and located deep underground to minimize backgrounds

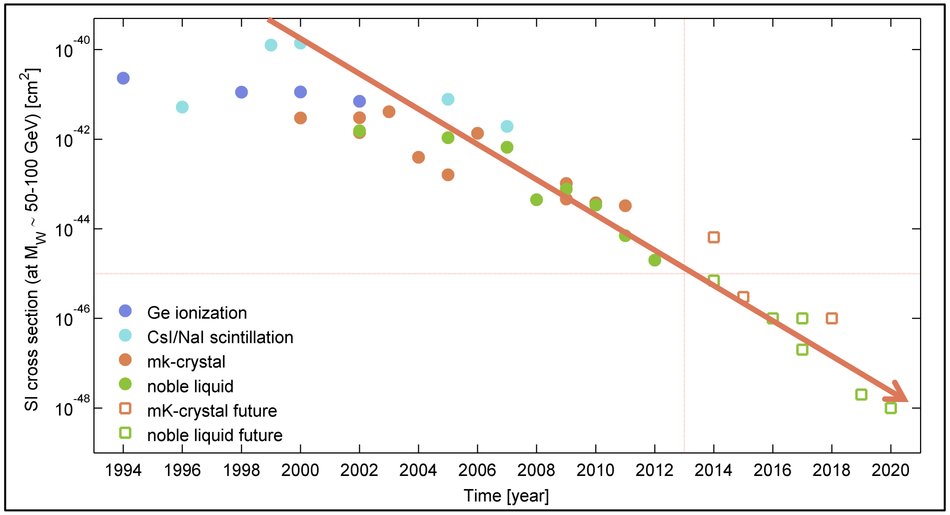




The LUX Experiment

Direct Detection

- Over the past 15 years, constraints from direct detection experiments have improved with a Moore's-law like behavior (a factor of 2 every 15 months)



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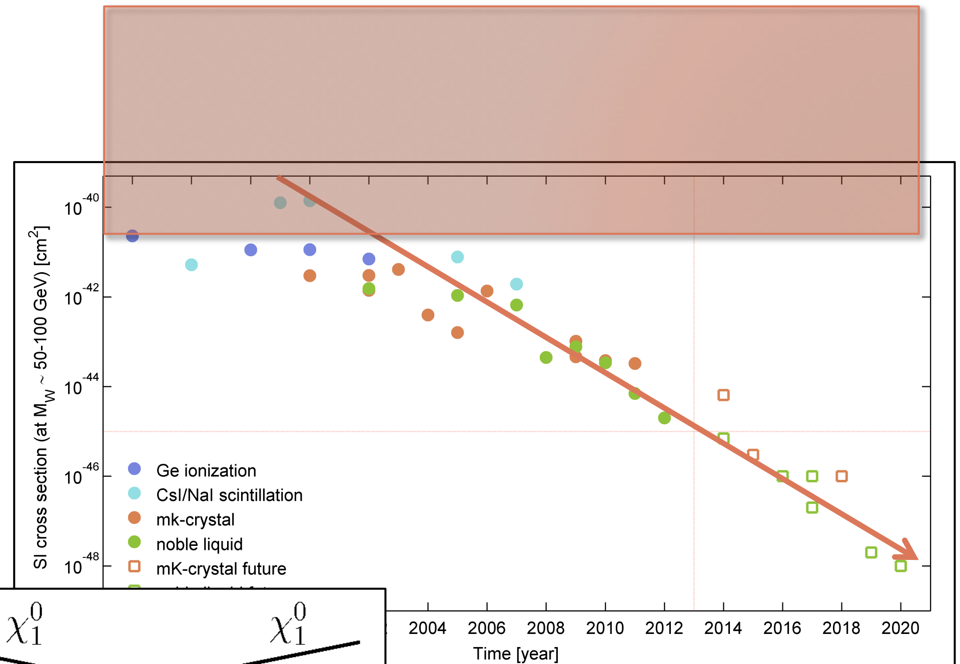
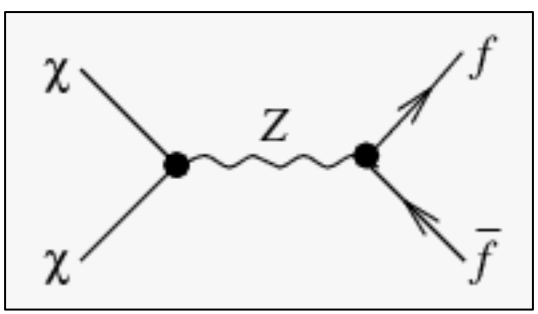
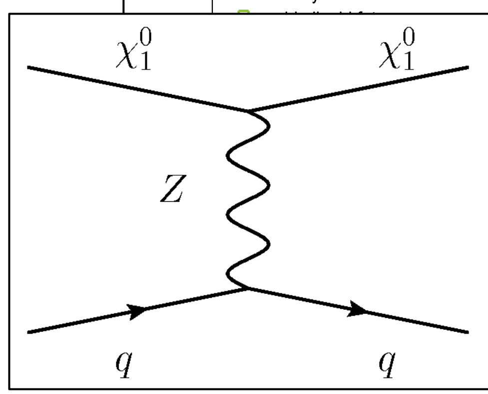
  -1990s: Experiments excluded the cross sections predicted for a WIMP that scatters and annihilates through Z-exchange







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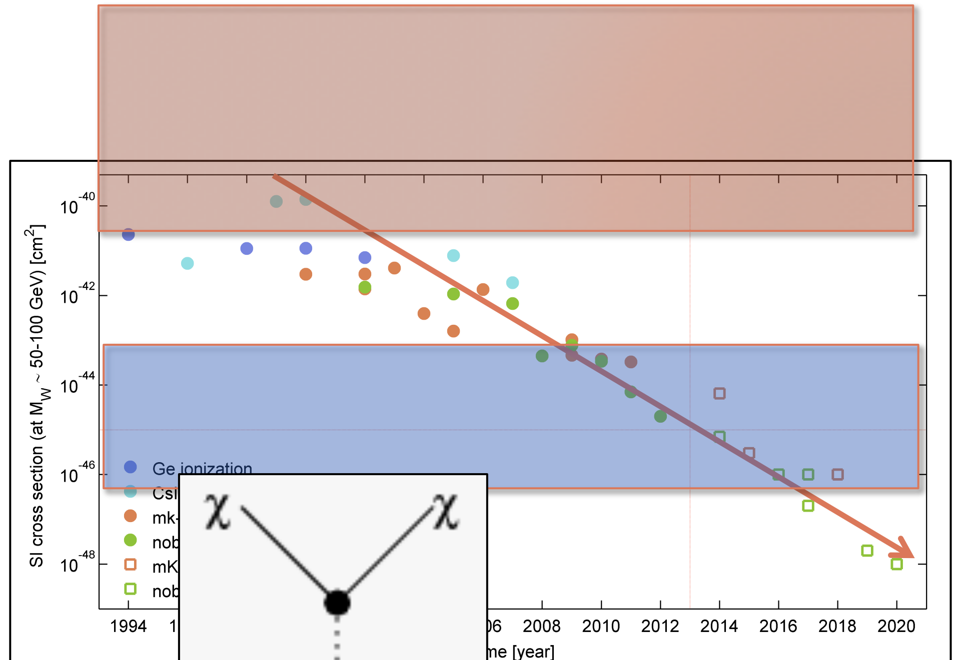
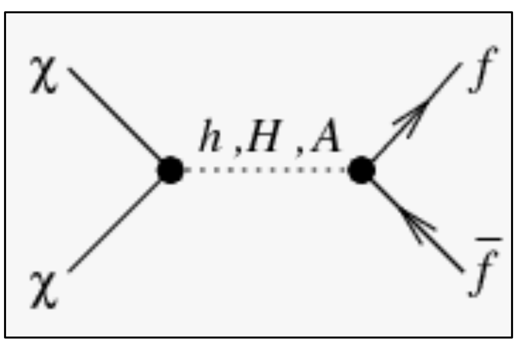
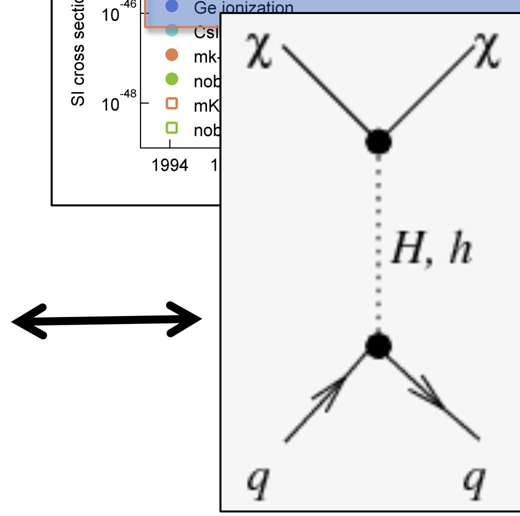
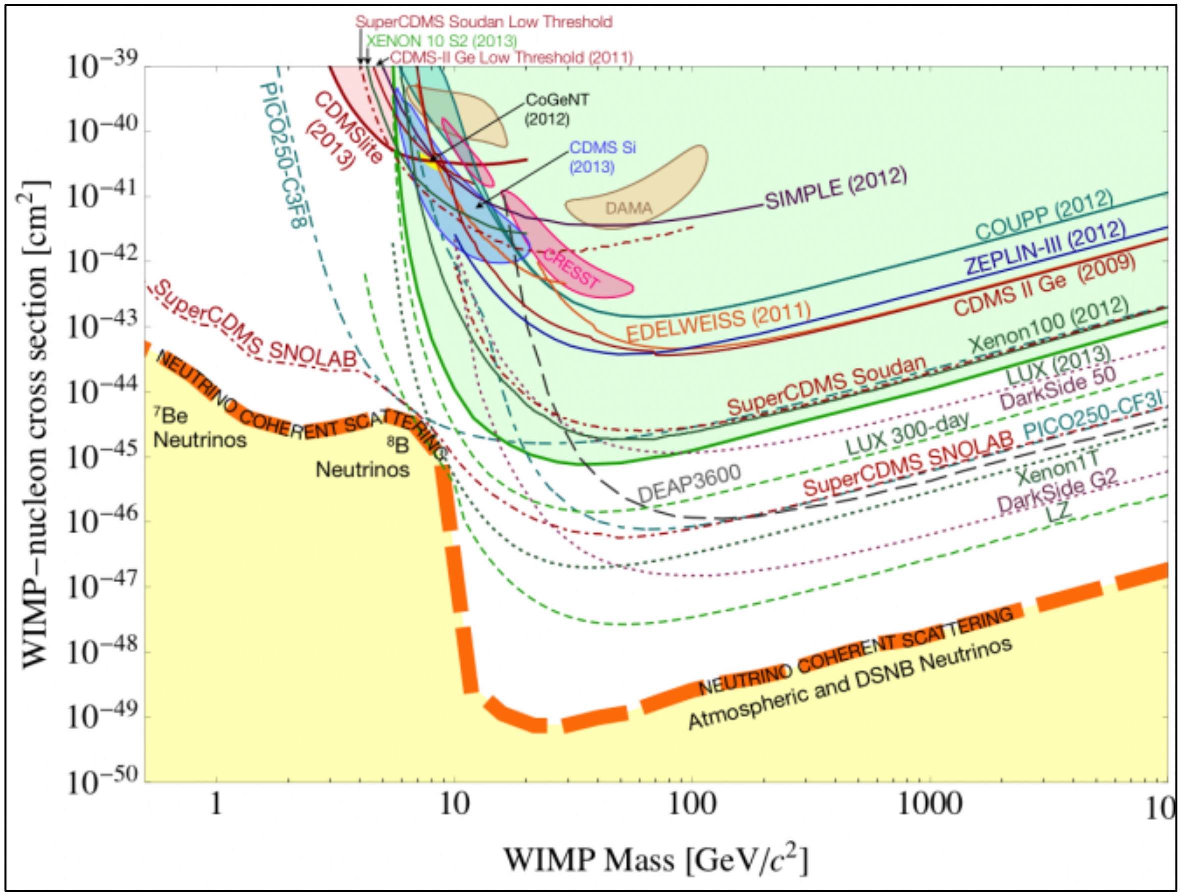
  -Current and recent experiments are testing WIMPs that interact through Higgs exchange (including many SUSY models)







The Future of Direct Detection



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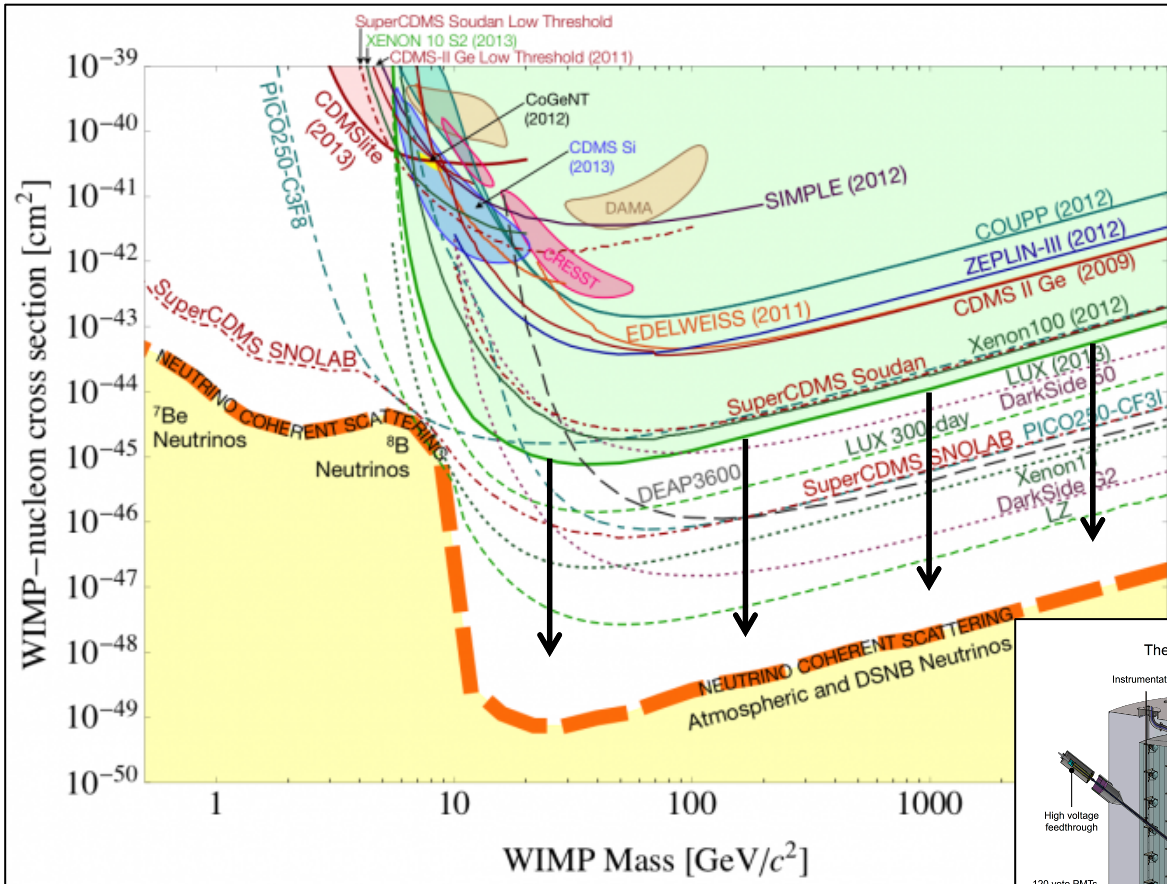

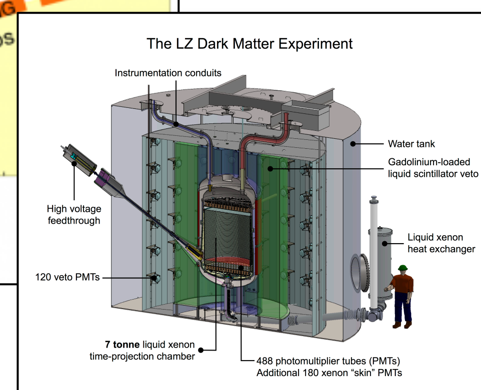

- Further extending the reach of LUX are planned large volume liquid xenon experiments, XENON1T and LZ

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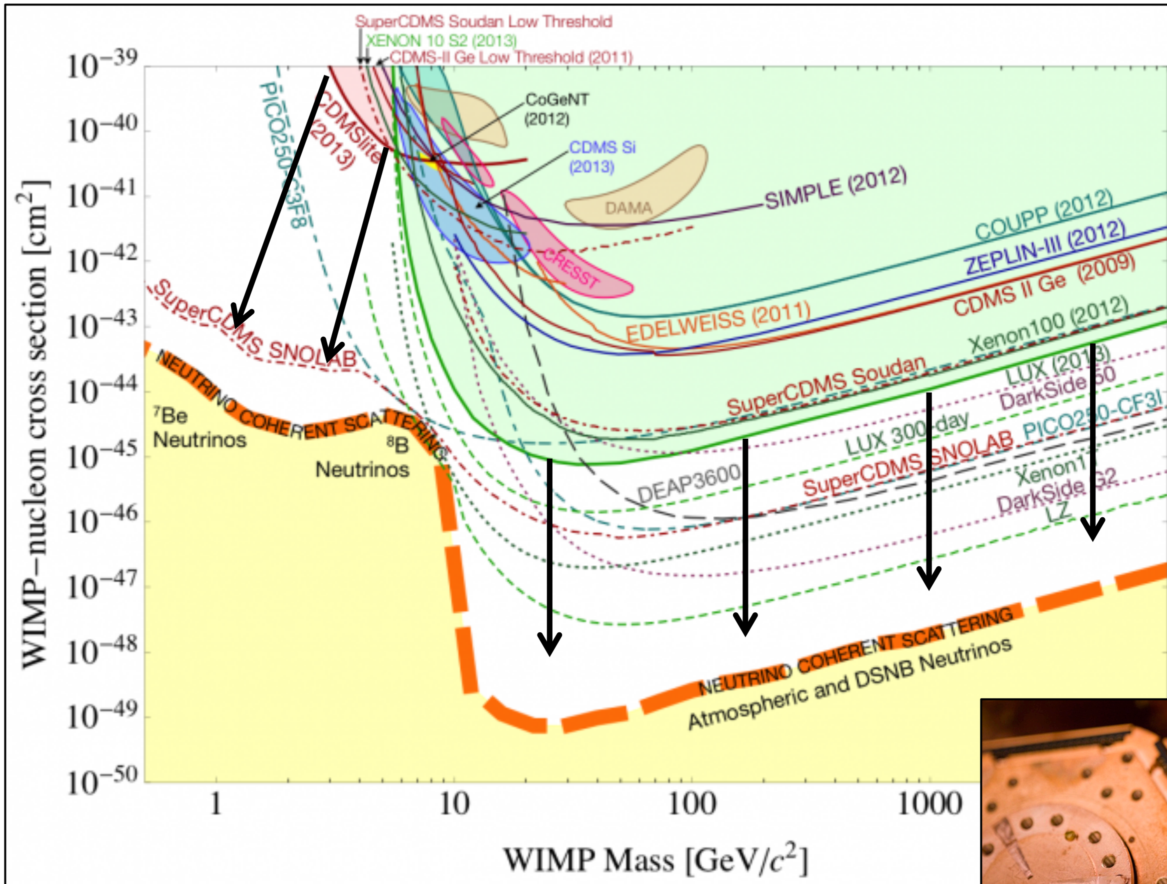
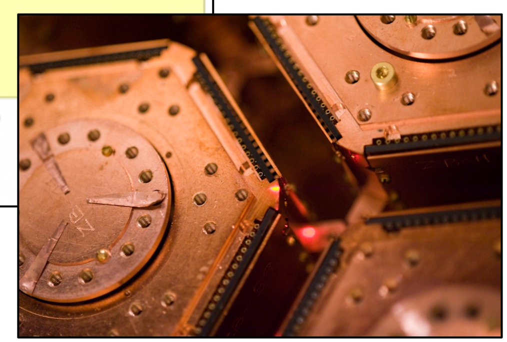




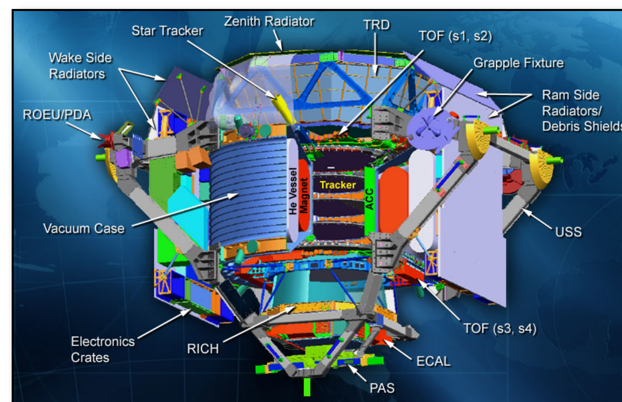
- Further extending the reach of LUX are planned large volume liquid xenon experiments, XENON1T and LZ
- In parallel, SuperCDMS, DAMIC, CRESST and other experiments will advance our sensitivity to low-mass WIMPs

The Motivation for Indirect Searches

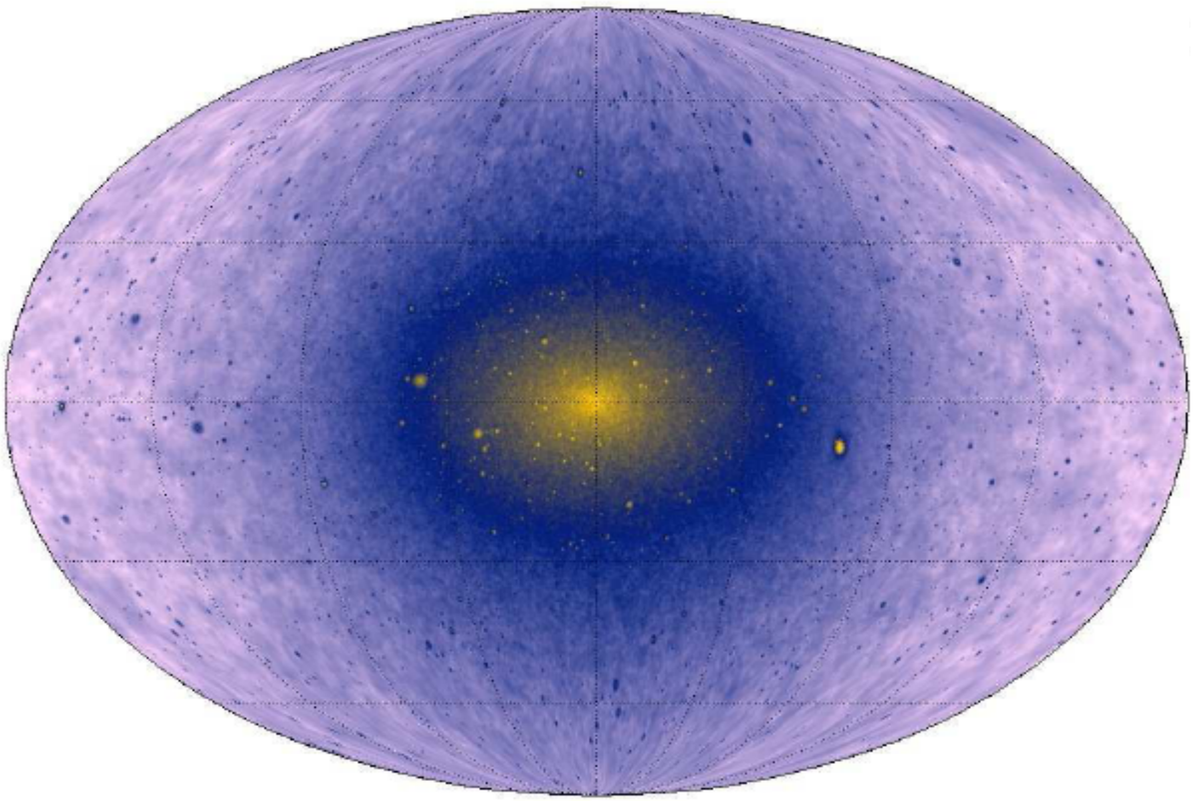
- To account for the observed dark matter abundance, a thermal relic must have an annihilation cross section (at freeze-out) of $\sigma v \sim 2\times10^{-26}$ cm^3/s
- Although many model-dependent factors can cause the dark matter to possess a somewhat lower annihilation cross section today, most models predict current annihilation rates that are within an order of magnitude or so of this estimate
- Indirect detection experiments that are sensitive to dark matter annihilating at approximately this rate will be able to test a large fraction of WIMP models

Fermi

AMS-02



Where To Look With Fermi?



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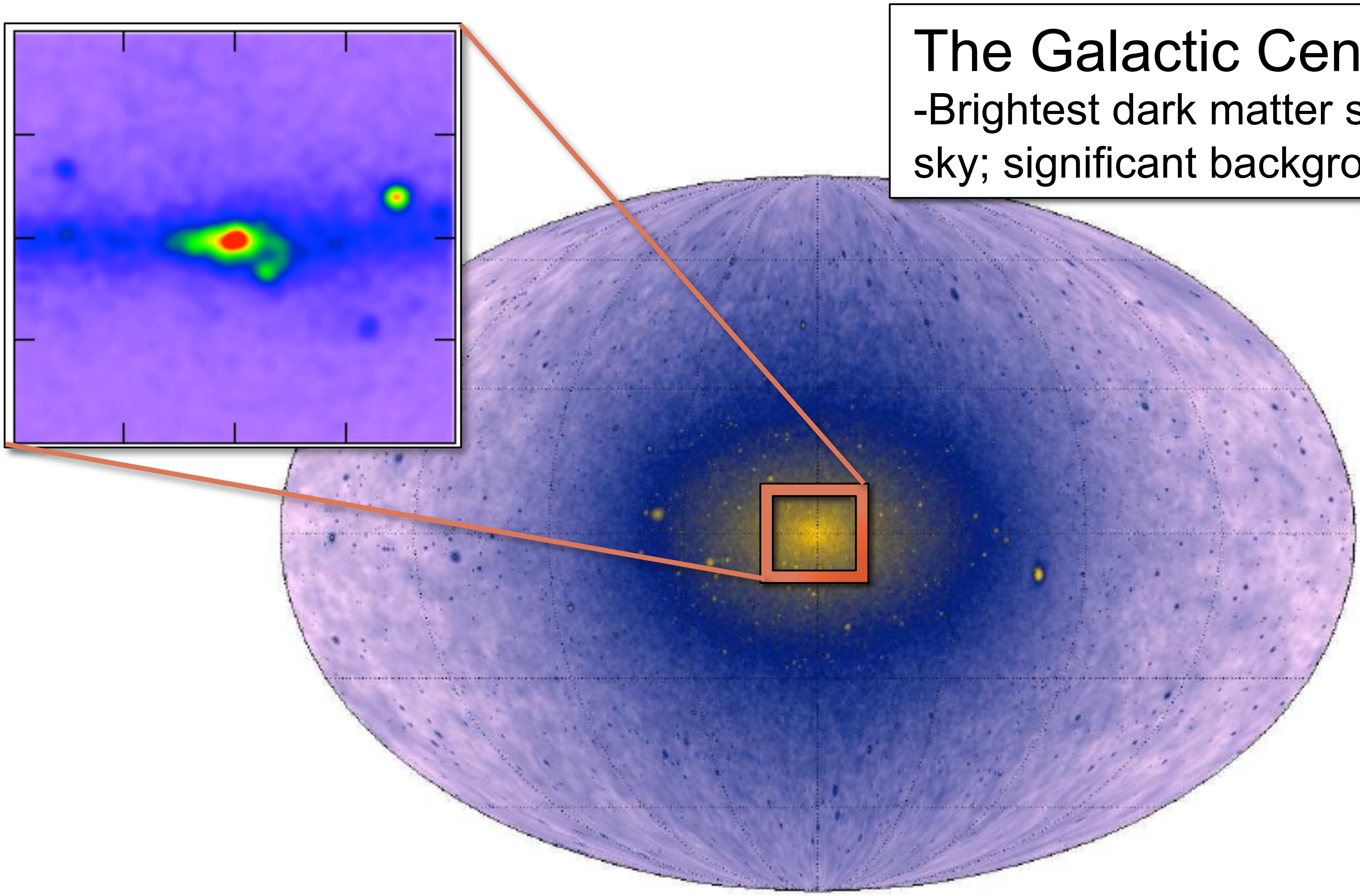

The Galactic Center

-Brightest dark matter signal on the sky; significant backgrounds

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Dwarf Spheroidal Galaxies
-Faint, but low background
-Direct measurements of dark matter profiles

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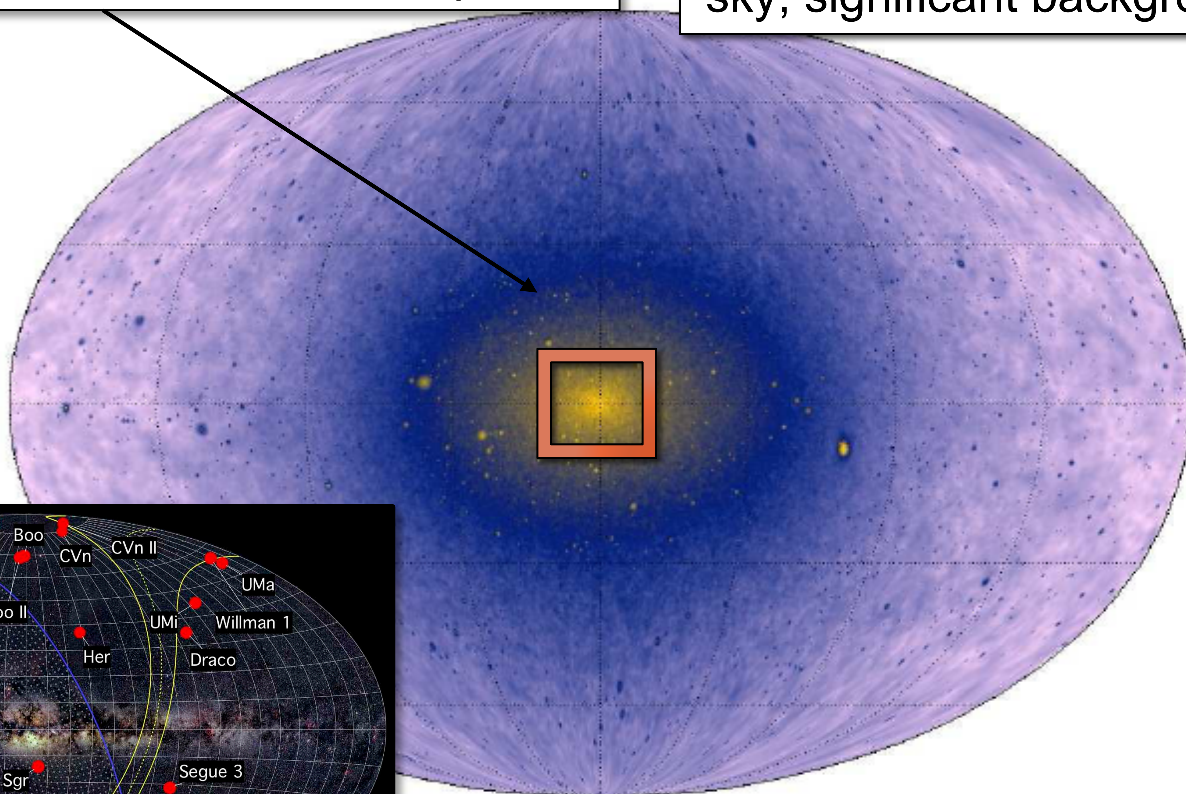

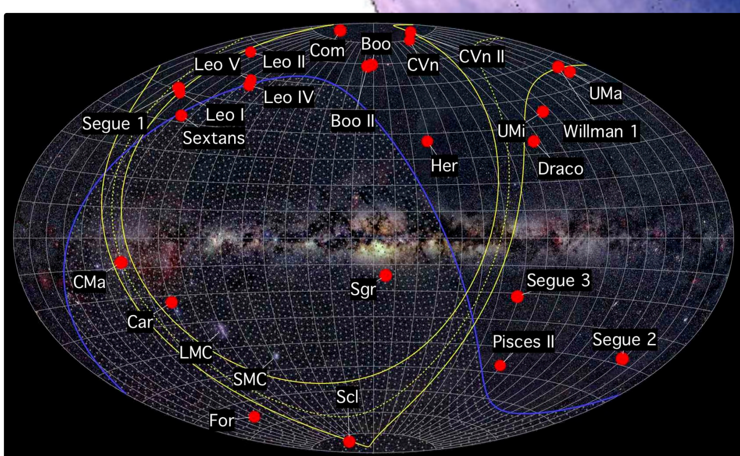

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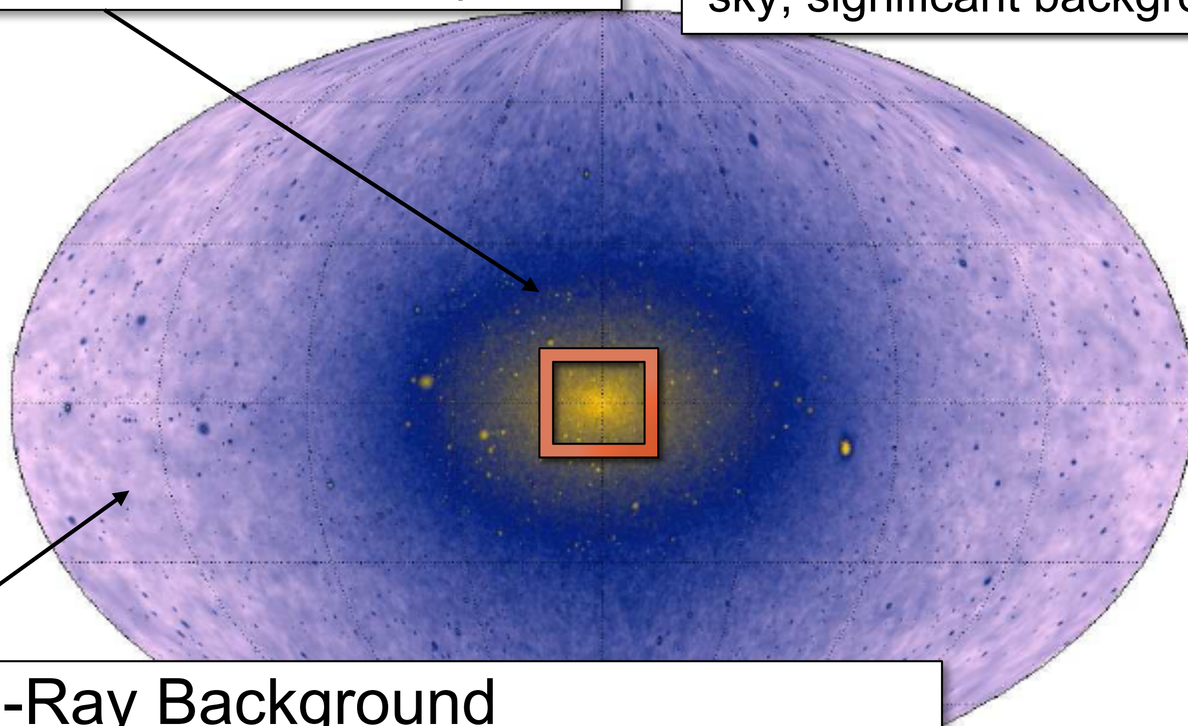

The Gamma-Ray Background

-Largely from blazars, radio galaxies, starforming galaxies; but still room for dark matter

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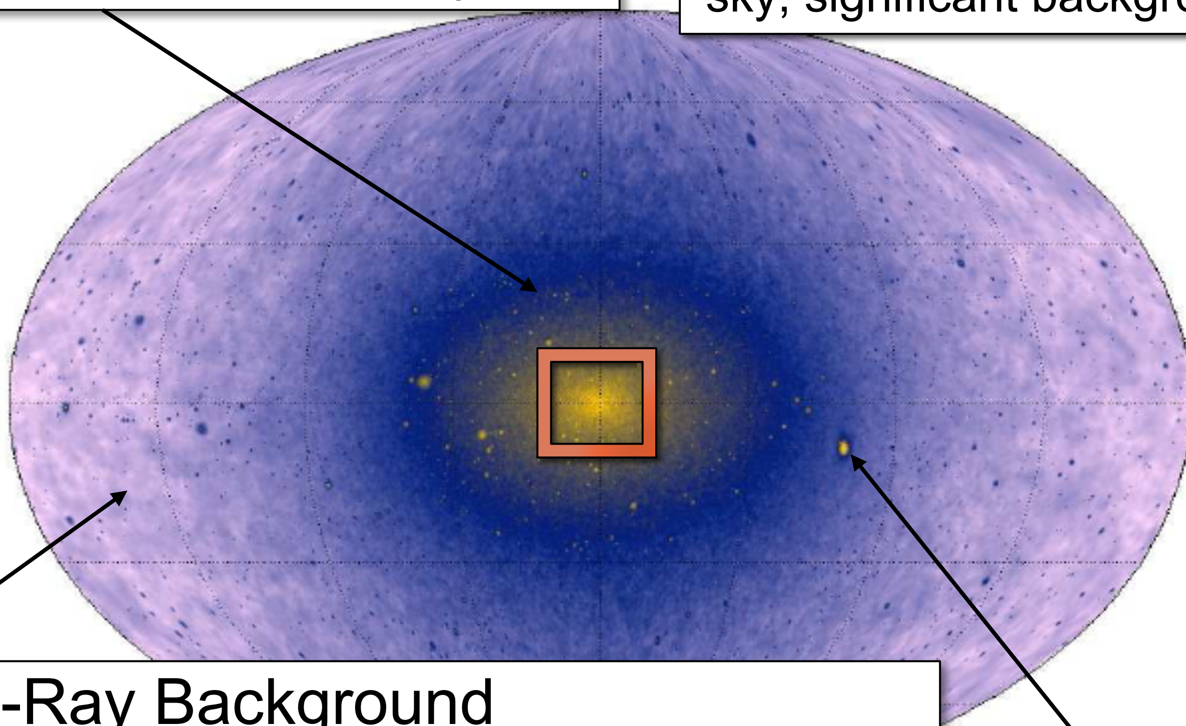

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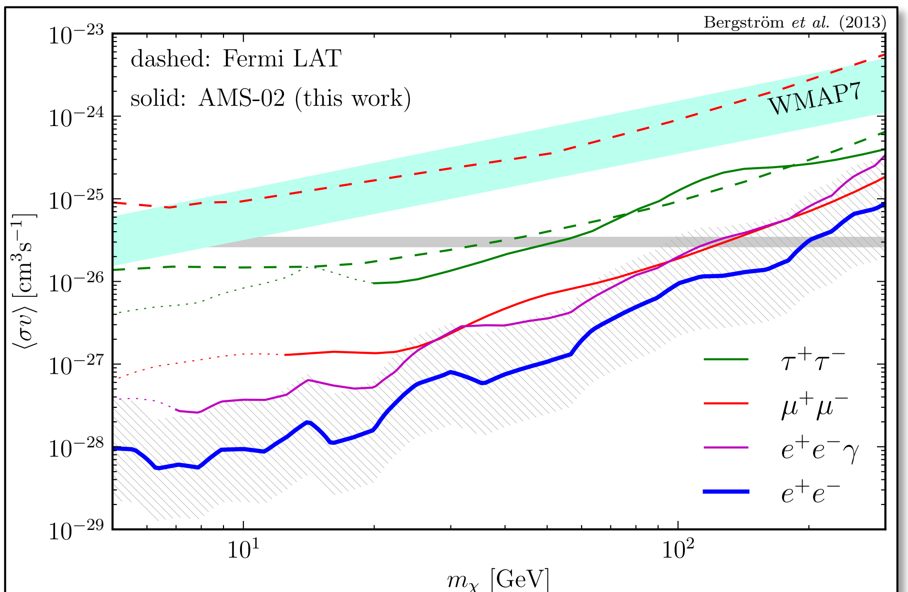
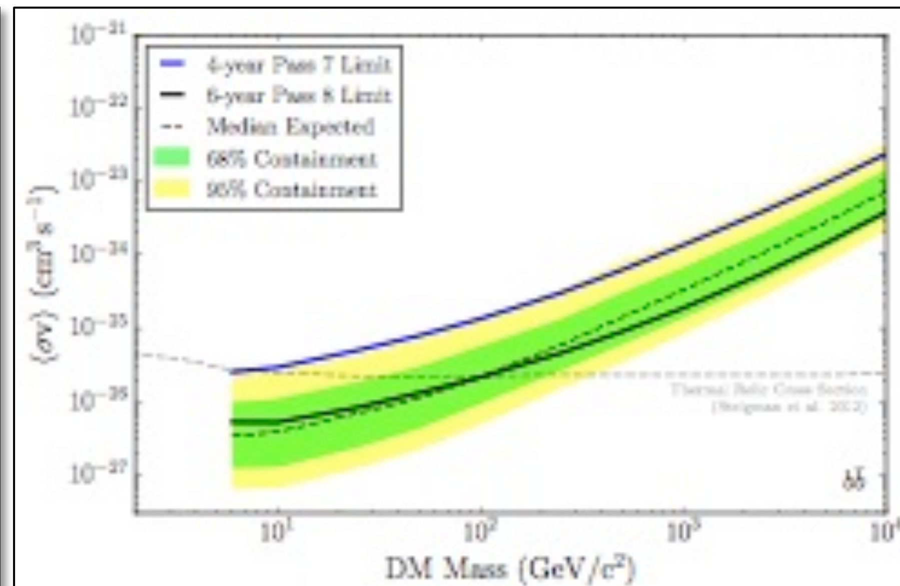
Searches for Nearby Subhalos
-Population studies of unidentified Fermi sources

We Are Testing the Thermal Relic Paradigm!

- Each of these gamma-ray strategies (GC, dwarfs, subhalos, EGRB) as well as cosmic-ray antiproton and positron measurements from AMS, are sensitive to dark matter with the annihilation cross section predicted for a simple thermal relic, for masses up to ~100 GeV
- This program is not a fishing expedition, but is testing a wide range of well-motivated dark matter models



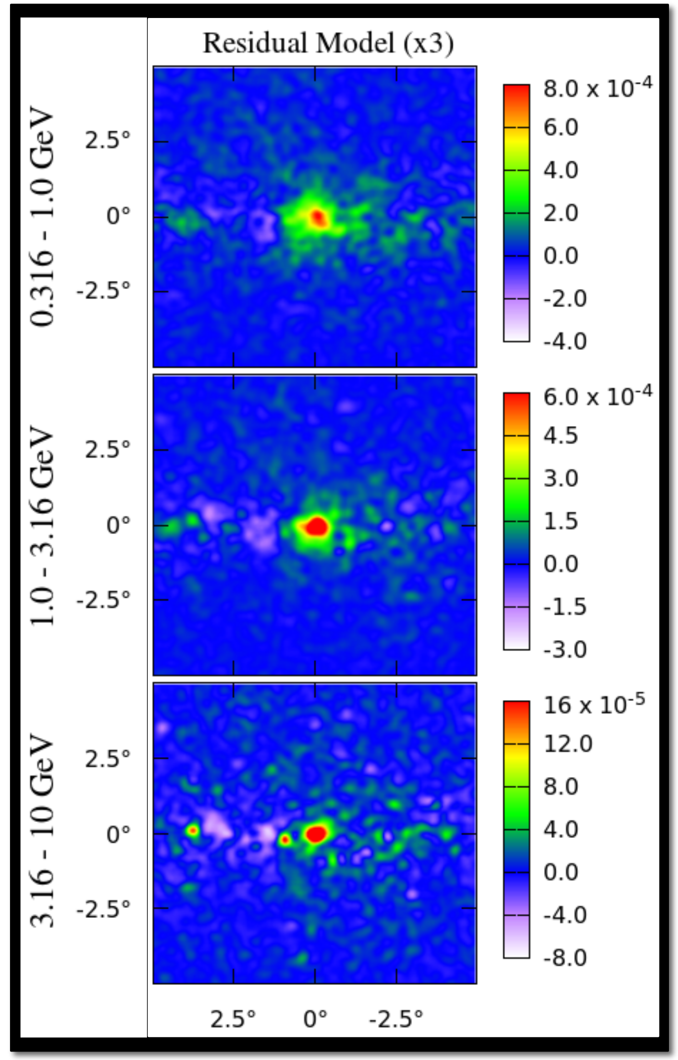
Bergstrom, Bringmann, Cholis, DH, Weniger, arXiv:1306.3983



Fermi Collaboration, Dwarf Galaxies arXiv:1503.02641

The Galactic Center GeV Excess

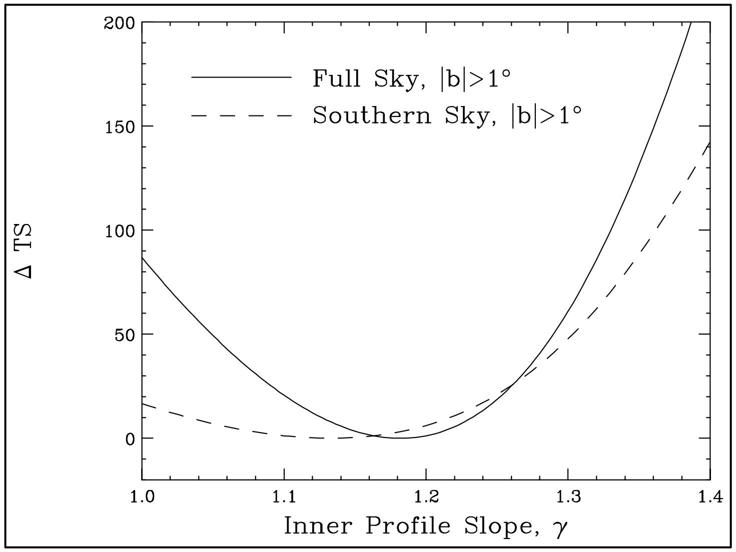
- A bright and highly statistically significant excess of gamma-rays has been observed from the region surrounding the Galactic Center, difficult to explain with astrophysical sources or mechanisms, but very much like the signal predicted from annihilating dark matter

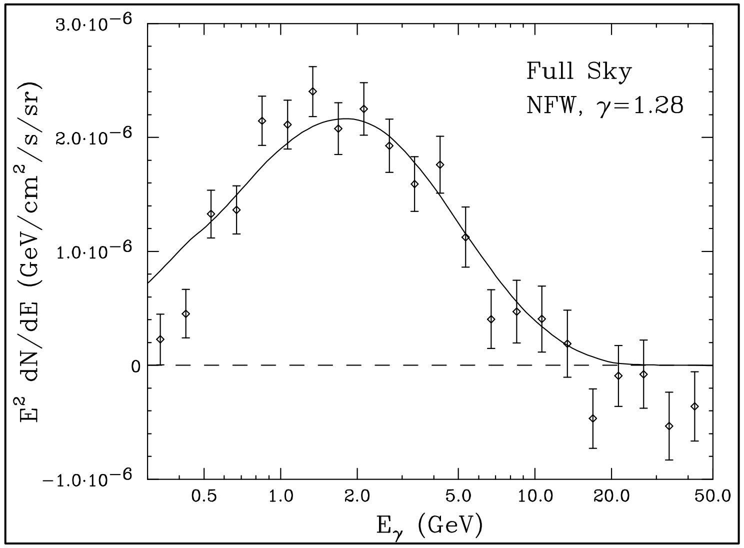


DH, Goodenough (2009, 2010), DH, Linden (2011), Daylan et al (2014) Calore, Cholis, Weniger (2014)

Basic Features of the GeV Excess

- The excess is distributed with spherical symmetry 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, this implies $\rho_{DM} \sim r^{-1.2}$ 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





The Evolving Nature of the Galactic Center Debate

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Circa 2009-2010

What Galactic Center excess?

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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?

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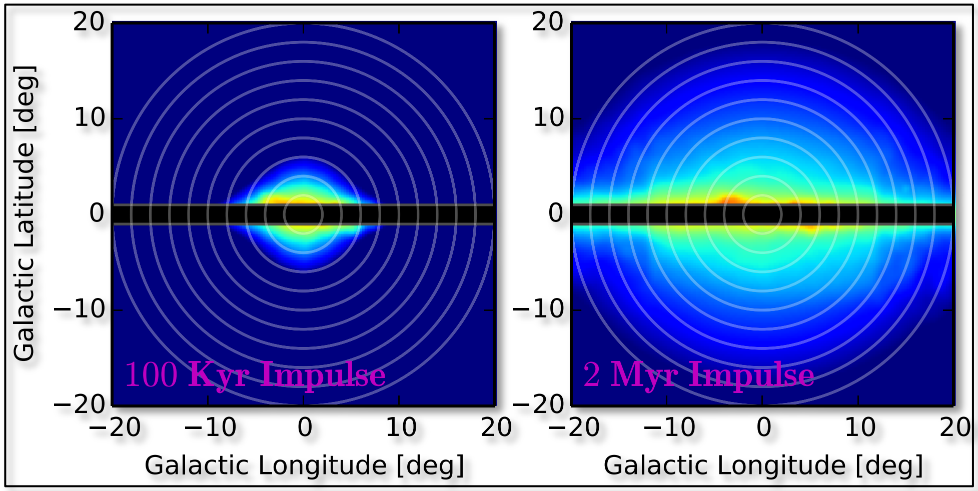
Circa 2014-2015

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 of 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):

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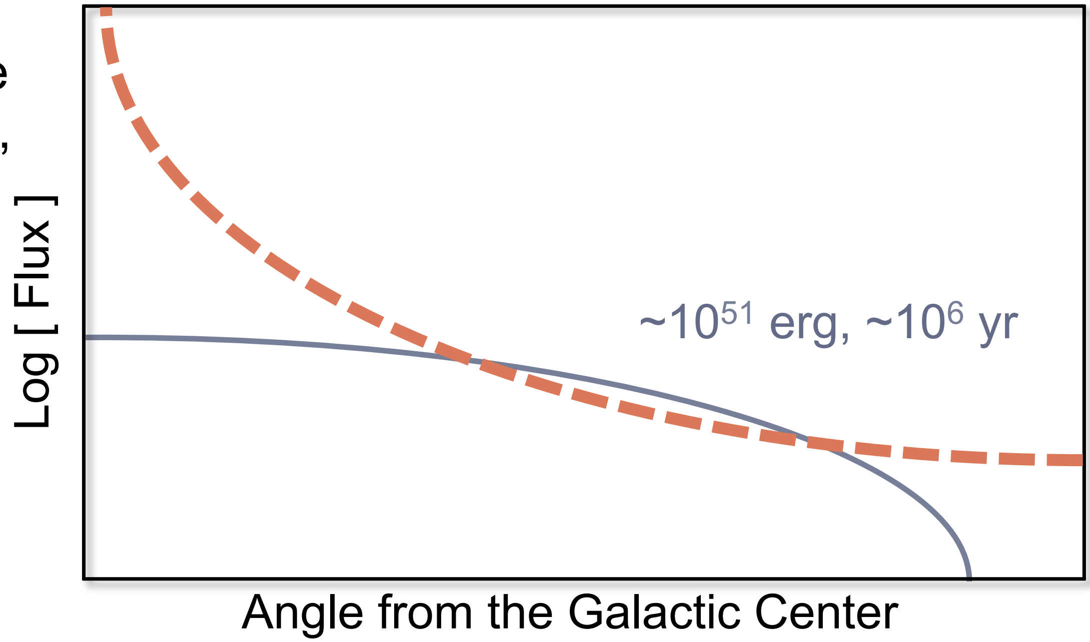

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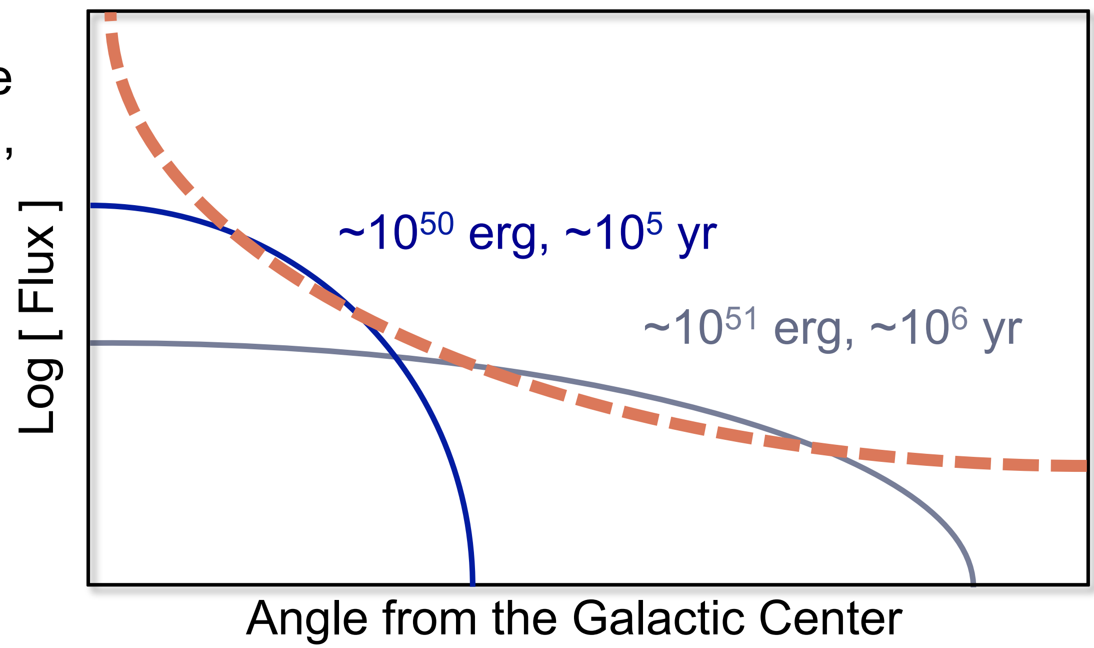

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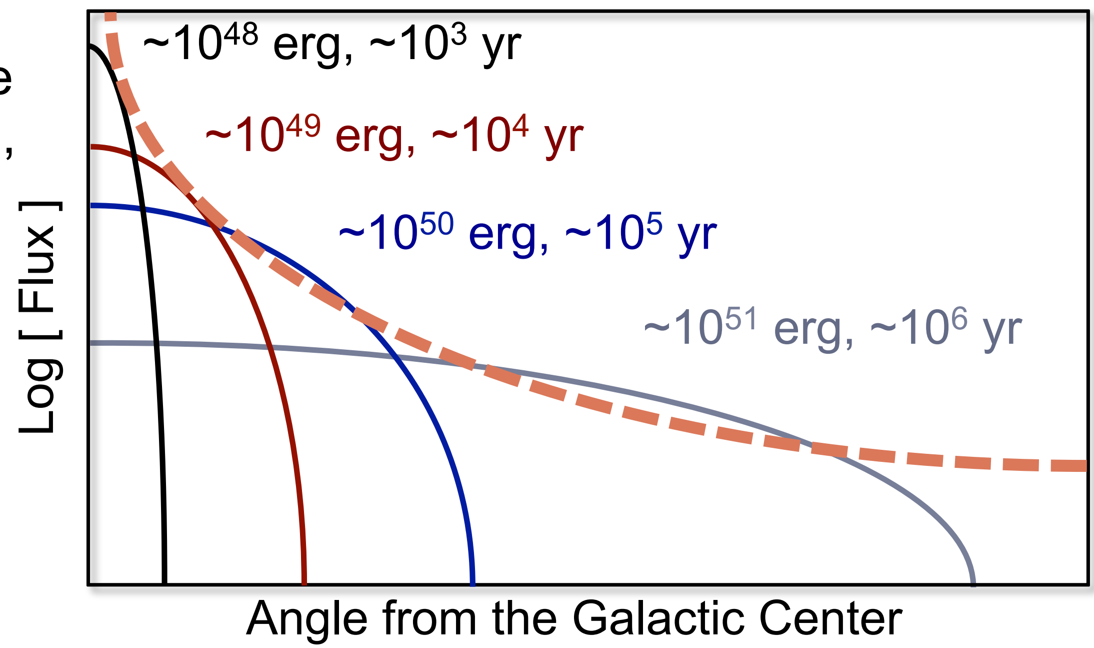

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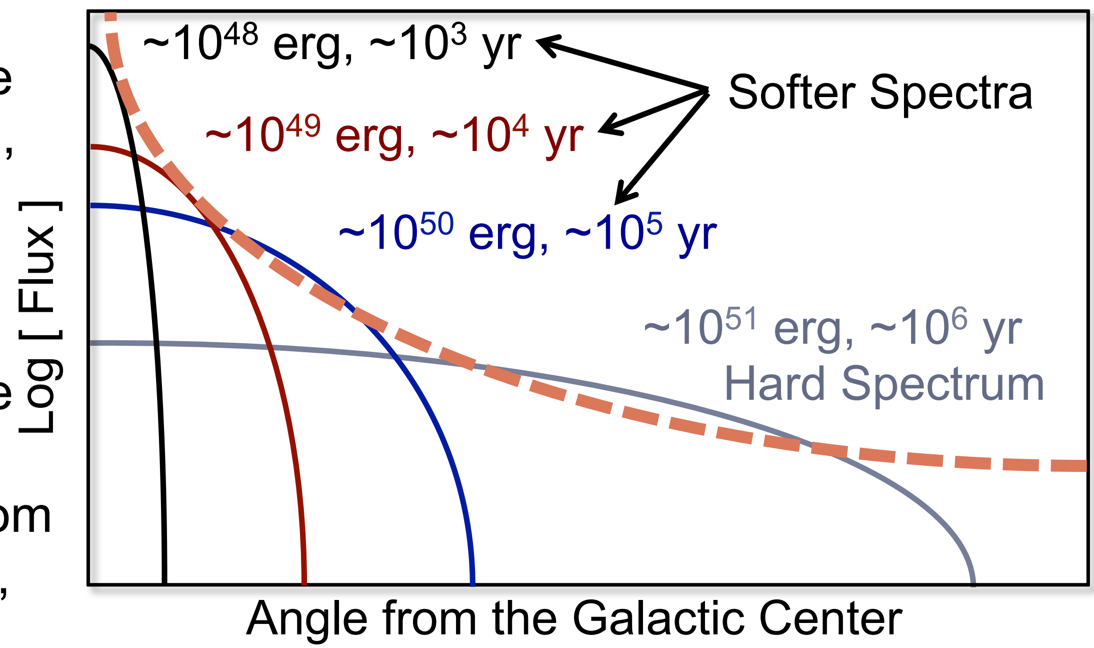
2) The gamma-ray spectrum is approximately uniform across the Inner Galaxy, but energy losses should lead to softer emission from the outer regions – to fit the data, we need the older outbursts to inject electrons with higher energies than more recent outbursts



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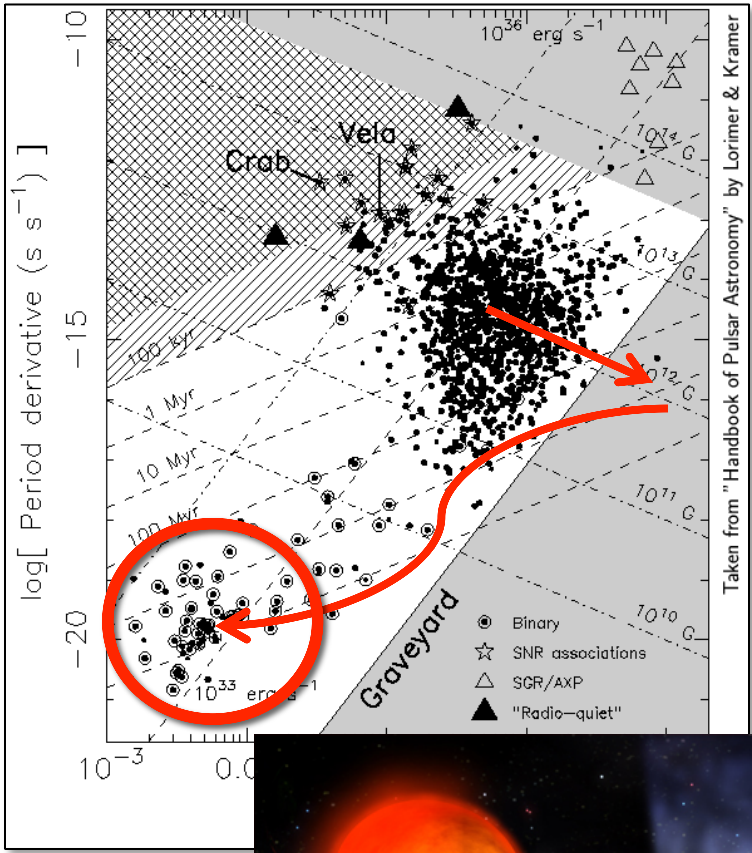
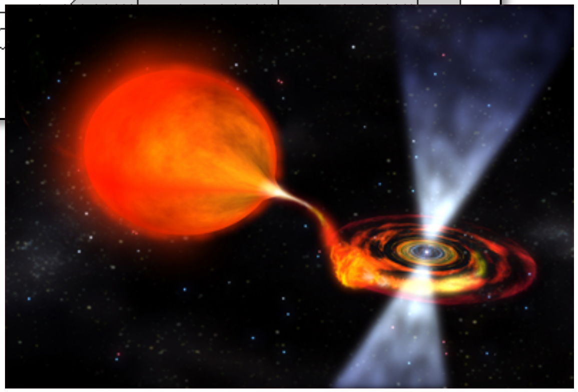
Millisecond Pulsar Basics

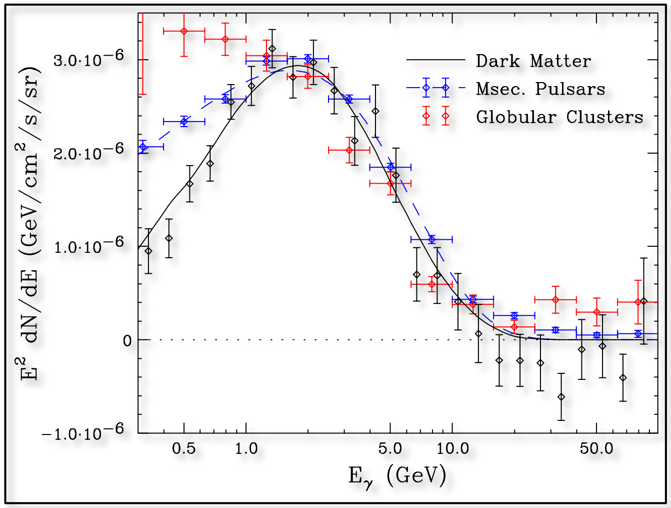
- Pulsars are rapidly spinning neutron stars which gradually convert their rotational kinetic energy into radio and gamma-ray emission
- Typical pulsars exhibit periods on the order of ~1 second and slow down and become faint over ~10^6 -10^8 years
- Accretion from a companion star can "spin-up" a dead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

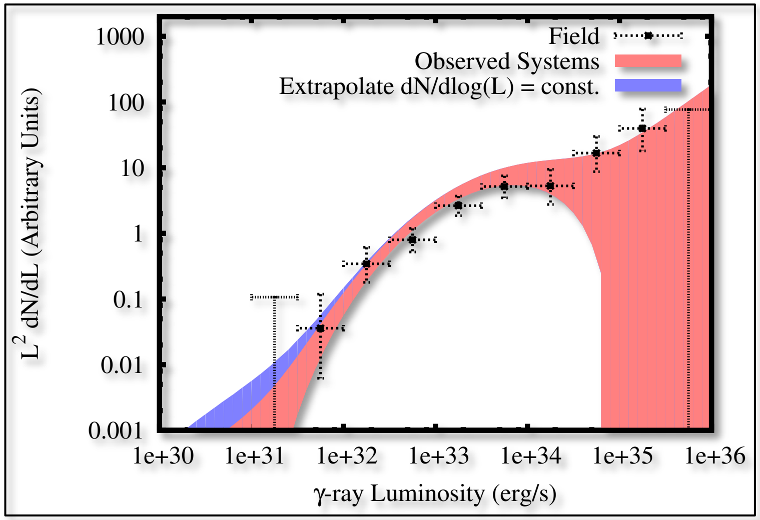




Gamma-Rays From Millisecond Pulsars

- 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)

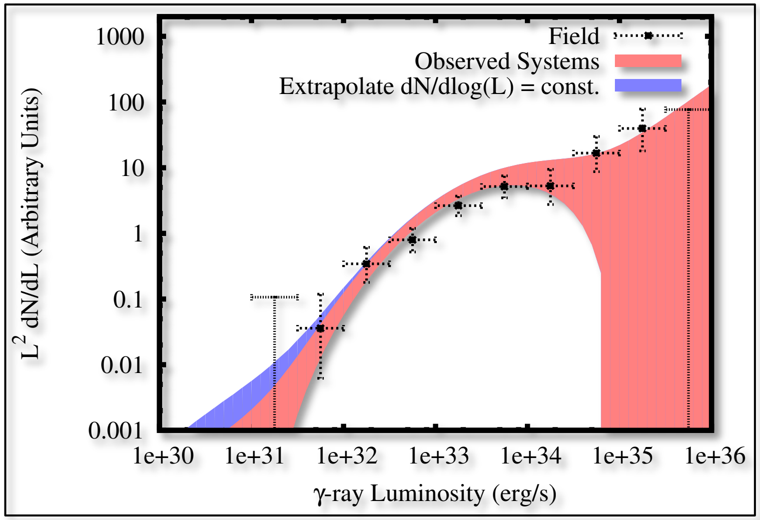




Cholis, DH, Linden, arXiv:1407.5625, 1407.5583

Could Millisecond Pulsars Generate the Galactic Center Excess?

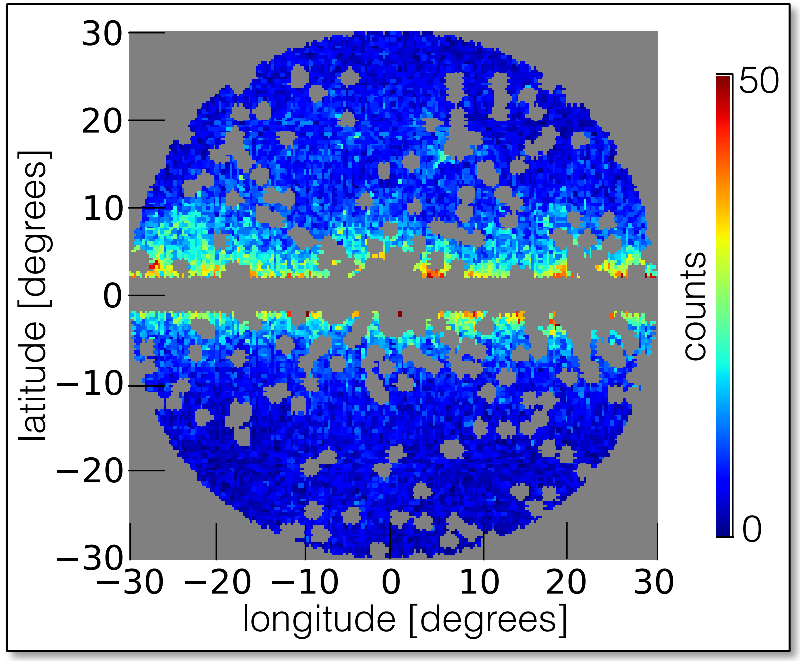
- From the measured luminosity function, we conclude that more than 2000 MSPs within 1.8 kpc of the Galactic Center would be required to account for the excess; this would include ~230 that are quite bright ($L_\gamma > 10^{34}$ erg/s) and ~60 that are very bright ($L_\gamma > 10^{35}$ erg/s)
- Fermi observes very 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



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



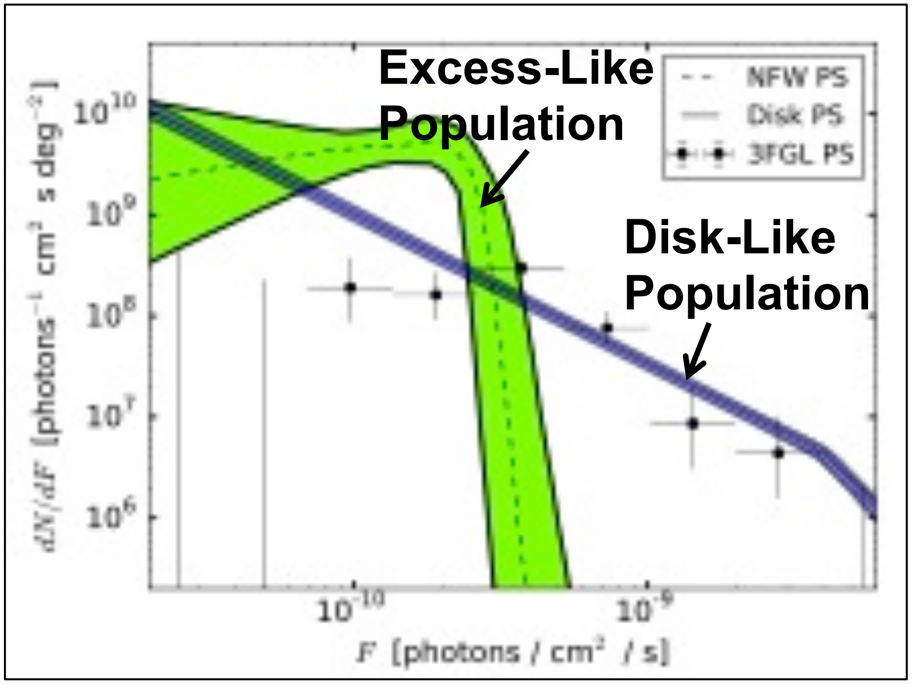
Lee, Lisanti, Safdi, Slatyer, Xue, arXiv:1506.05124
(see also Bartels, Krishnamurthy, Weniger, arXiv:1506.05104)

Evidence For Unresolved Point Sources?

Lee et al.'s Conclusions include the following:

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

2) The fit suggests that the GeV excess could be generated by $\sim 10^3$ unresolved sources, most with a flux that is just slightly below Fermi's threshold for point source detection



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Evidence For Unresolved Point Sources?

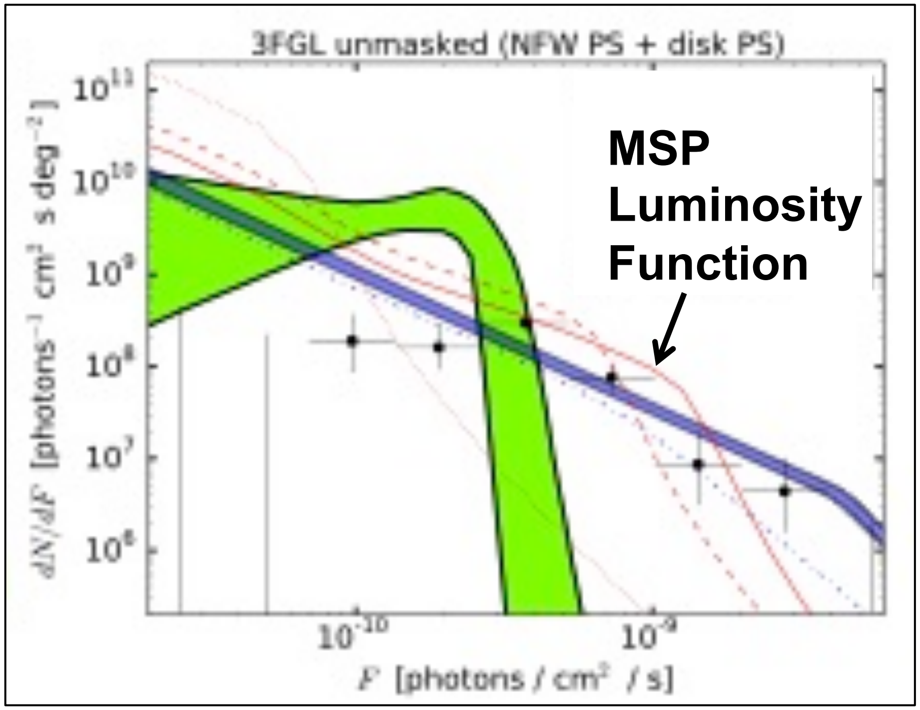
A few comments of my own:

- It is difficult to tell whether these clustered gamma-rays result from unresolved sources, or from backgrounds that are less smooth than the models
- 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 is very different from that of this new putative source population
- Where are all of the bright MSPs? (bright sources are disk-like, not DM-like)



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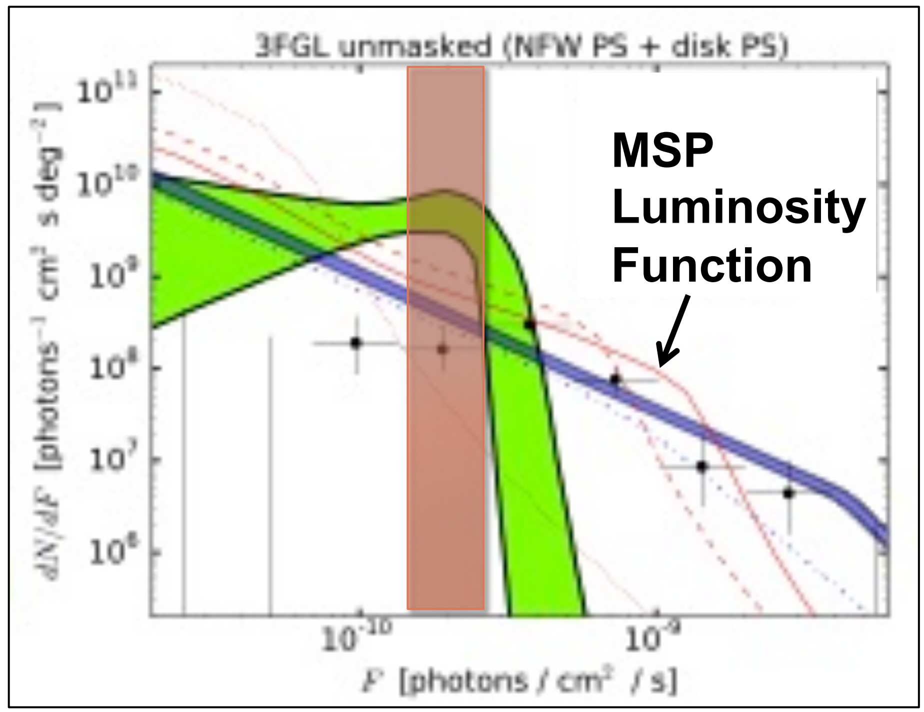
- A new class of standard candles?! – 68% possess luminosities within a factor of 2 ($\Delta M \sim 0.4$)



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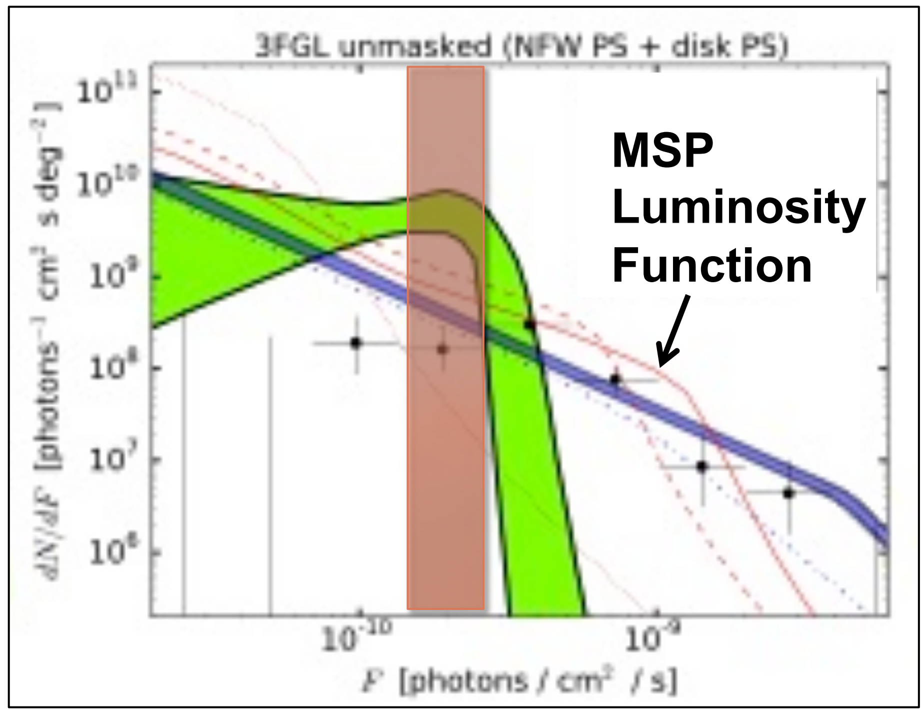
- Furthermore, these gamma-ray clusters show no correlation with the locations of known radio pulsars (T. Linden, arXiv:1509.02928)



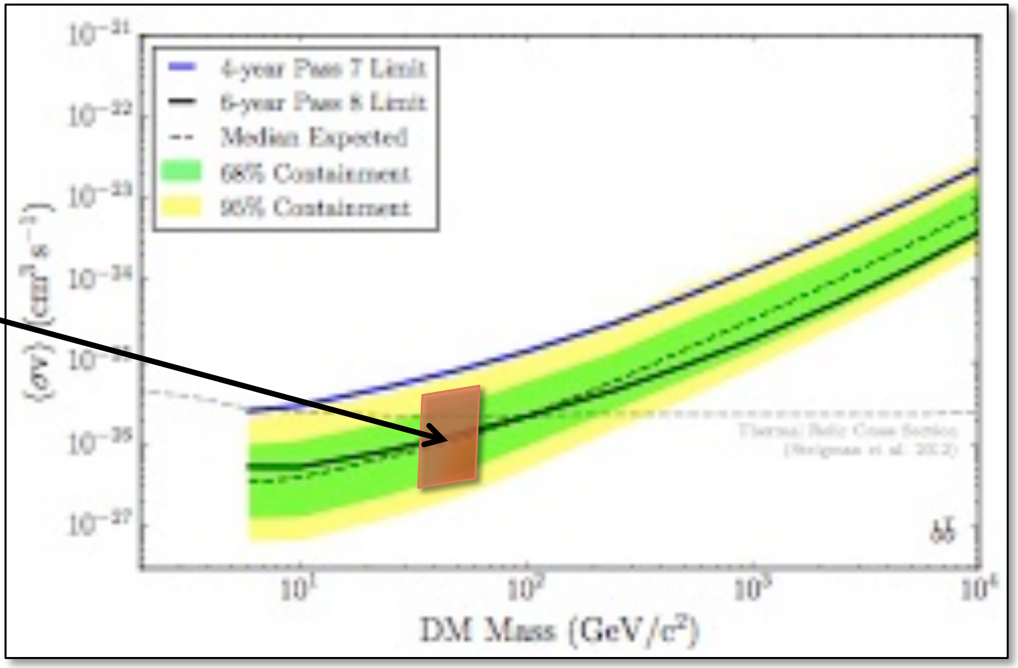
Lee, Lisanti, Safdi, Slatyer, Xue, arXiv:1506.05124
(see also Bartels, Krishnamurthy, Weniger, arXiv:1506.05104)

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 entirely rule out other possibilities
- How do we go from establishing a very intriguing signal, to being able to claim discovery?

Dwarf Galaxies

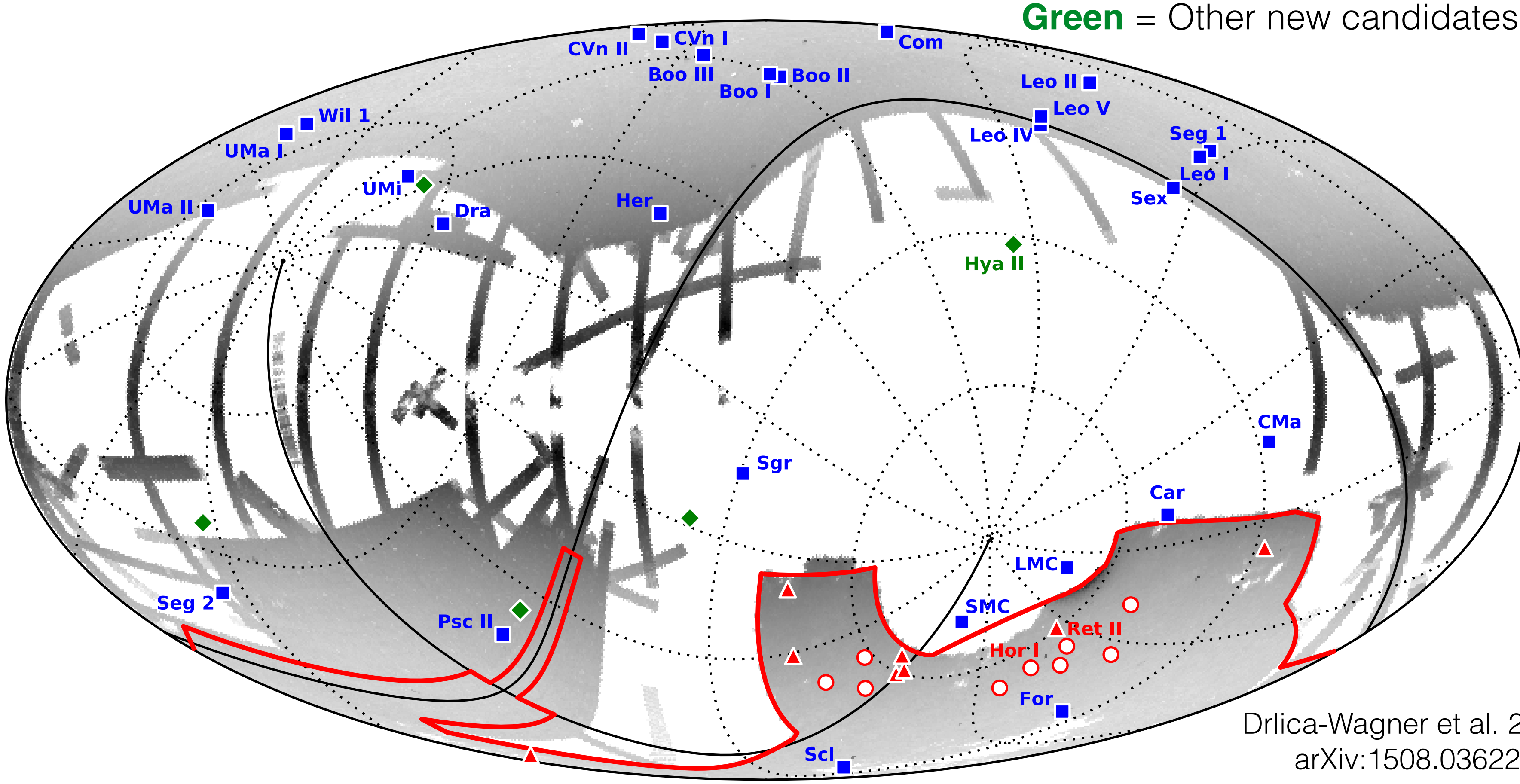
- The most recent analysis by the Fermi Collaboration (making use of 6 years data) remains compatible with a dark matter interpretation of the Galactic Center excess
- That being said, if the Galactic Center signal is coming from annihilating dark matter, one might expect gamma rays from dwarfs to be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



Fermi Collaboration, 1503.02641

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

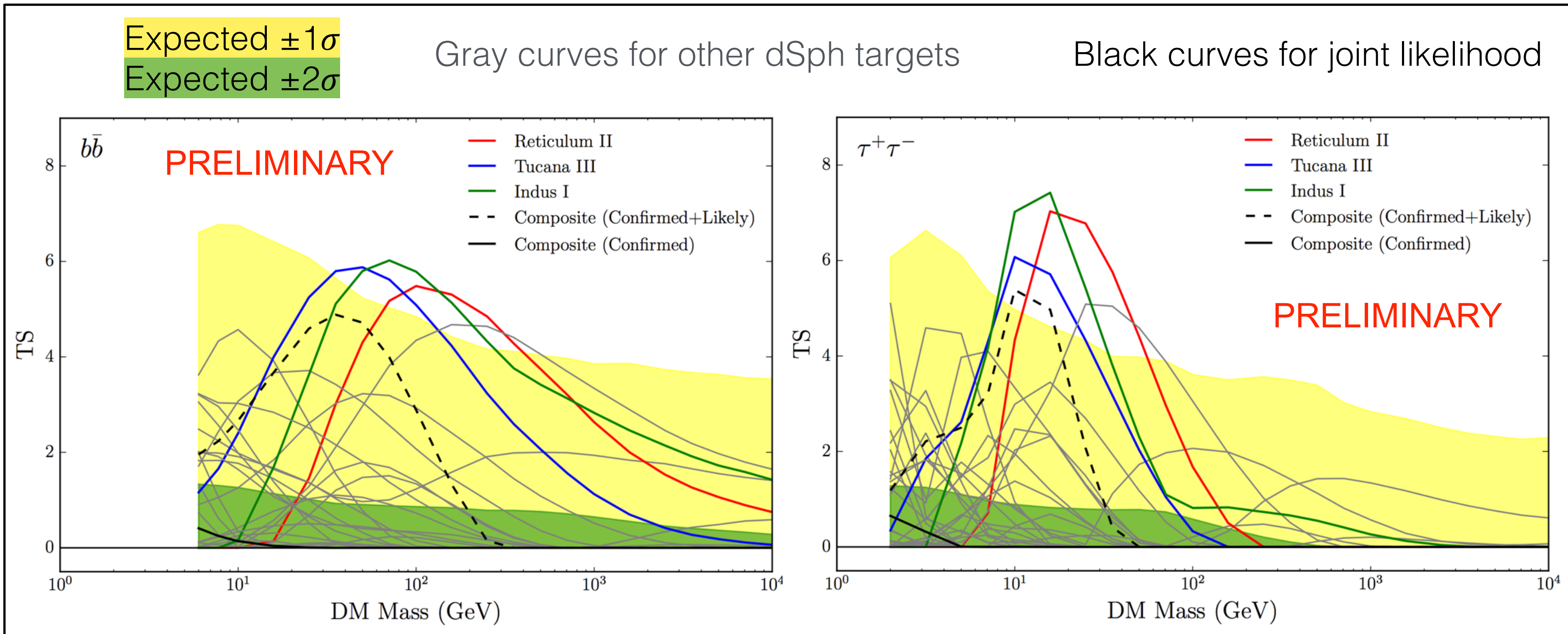


Drlica-Wagner et al. 2015
arXiv:1508.03622

Reticulum II, Tucana III, and Cetus II are each nearby (~25-30 kpc)

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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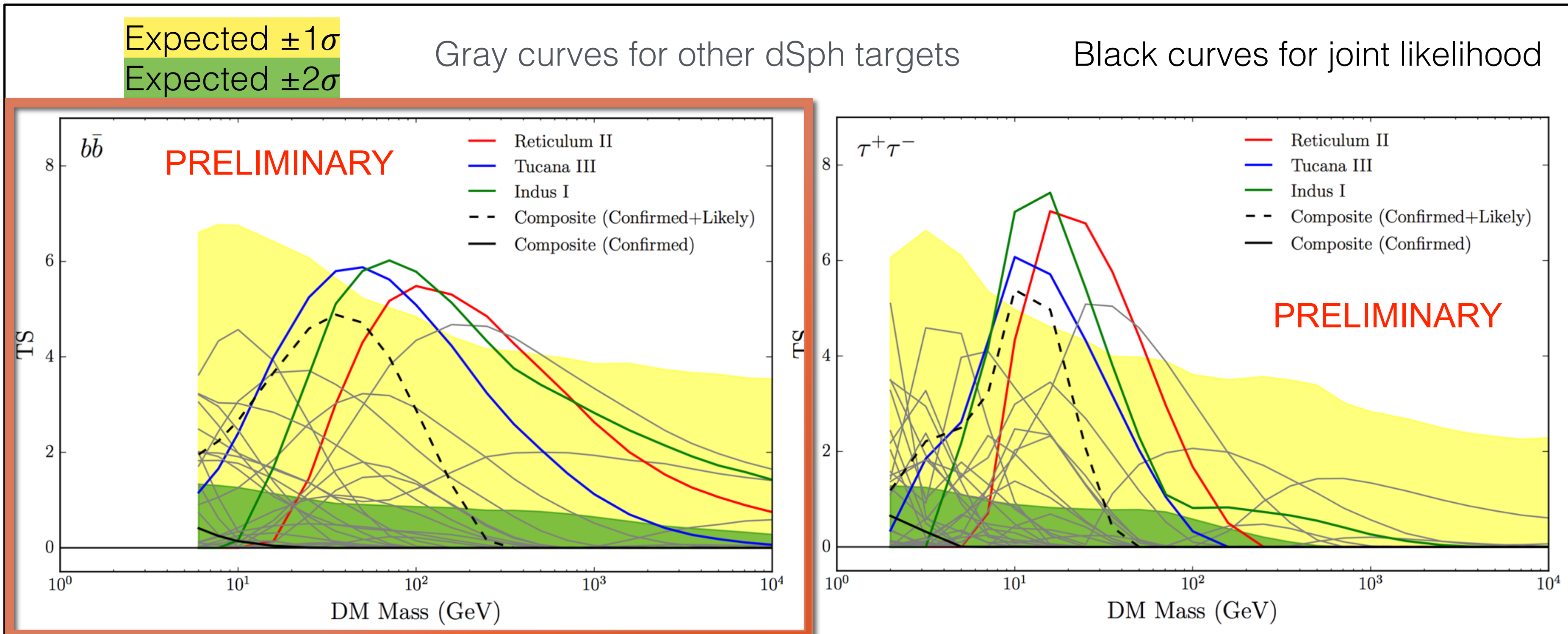

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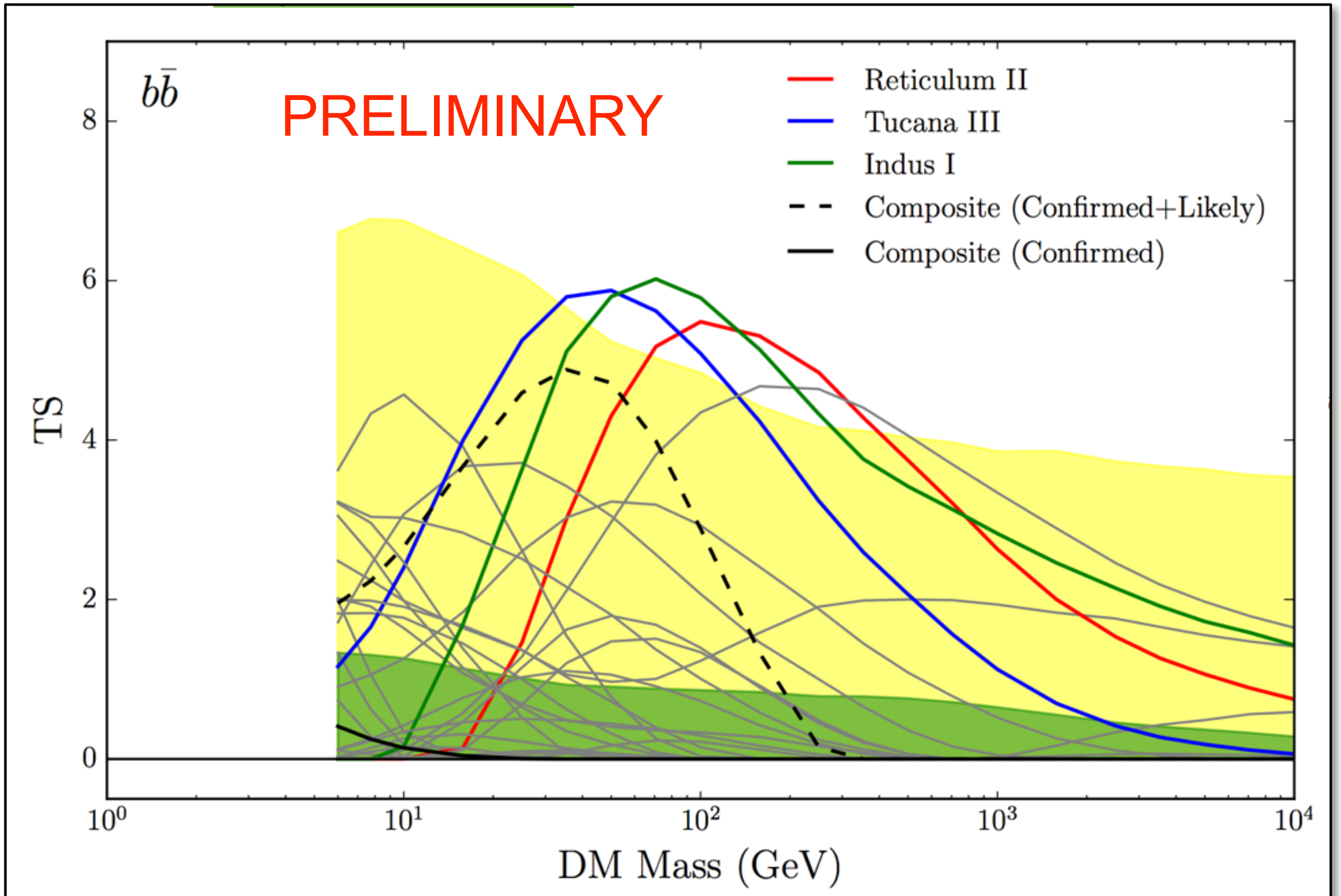
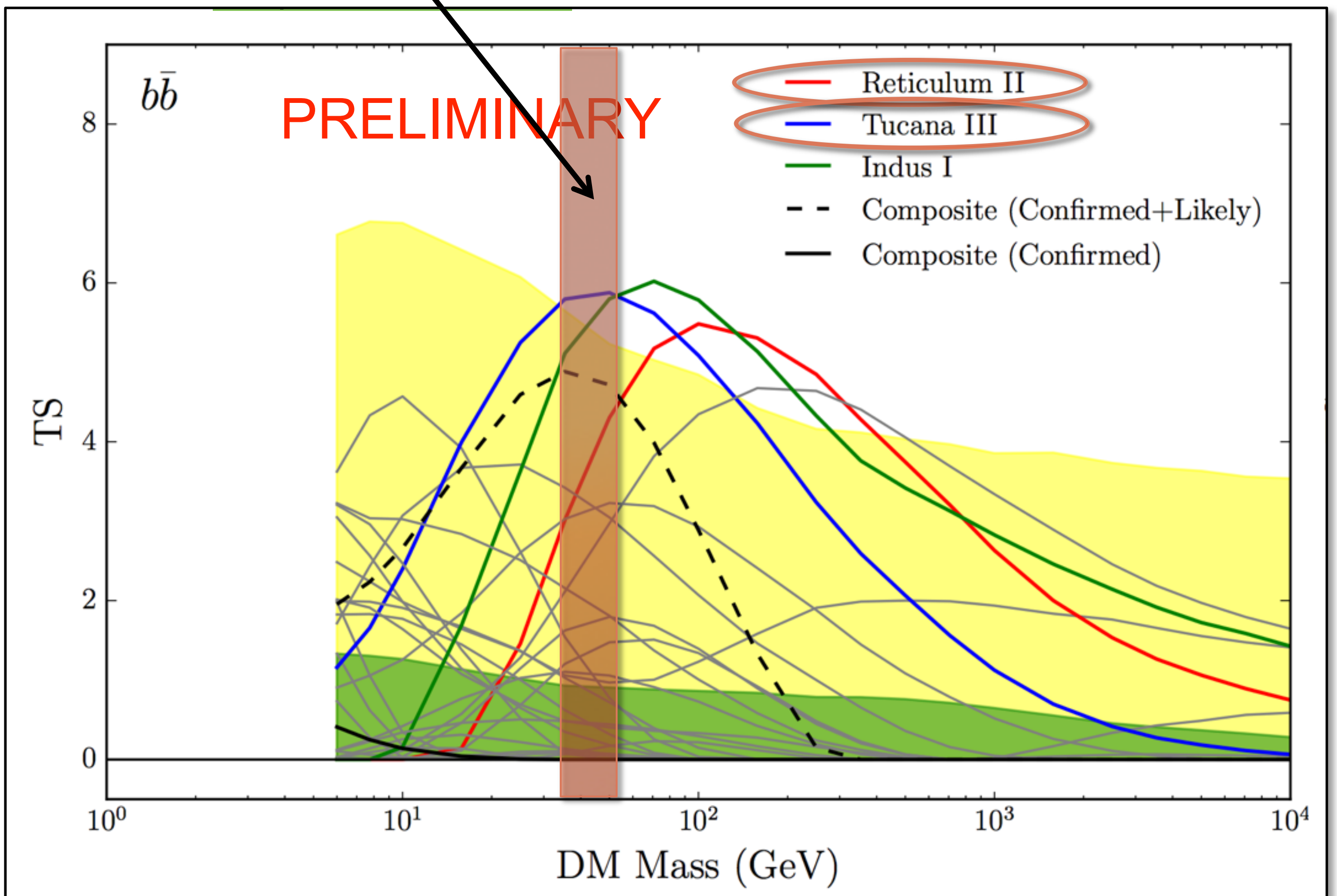


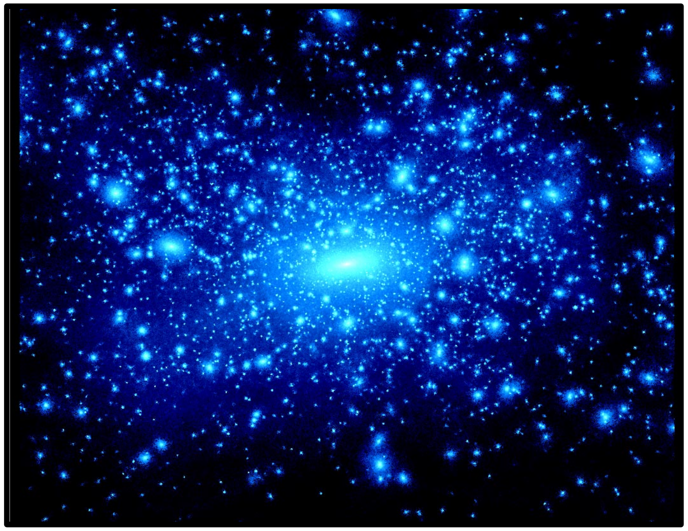
From Keith Bechtol's talk, TAUP 2015 (for the DES and Fermi Collaborations)

Galactic Center Favored



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

Nearby Dark Matter Subhalos



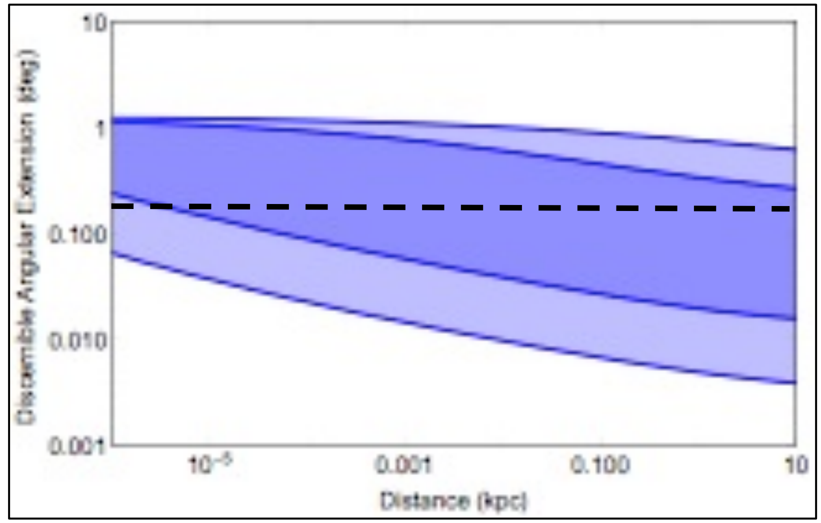
- The Milky Way's dark matter halo is predicted to contain a huge number of smaller subhalos, the vast majority of which are too small to retain gas and form stars, leading to a population of invisible dark matter clumps
- The most massive and nearby of these objects could be detectable as spatially 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:

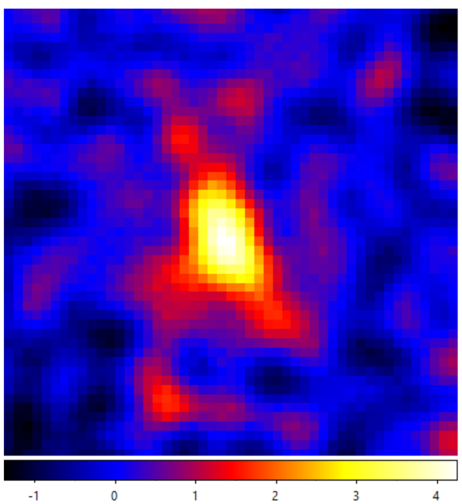
$$N \sim 4.0 \times \left(\frac{\sigma v}{10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1}} \right)^{1.5} \left(\frac{F_{\mathrm{threshold}}}{3 \times 10^{-10}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}} \right)$$

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

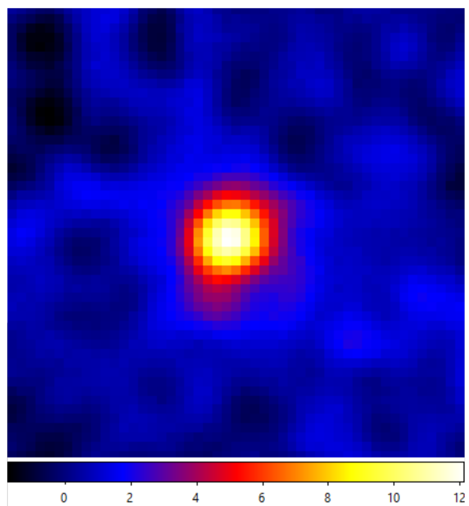
The Intriguing Source 3FGL J2212.5+0703

- The Fermi source 3FGL J2212.5+0703 is a very promising subhalo candidate
- This bright, high-latitude source has a Galactic Center-like spectrum and is not observed at any other wavelengths
- More important, this source appears to be spatially extended by ~0.2° (~4σ)





J2212.5+0703



Example Point Source

This source merits greater attention and scrutiny!

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

Summary

- Direct detection experiments have improved in sensitivity at an exponential rate over the past 15 years, and have ruled out many well-motivated models; many others will be explored over the next decade
- Indirect searches using gamma rays and cosmic rays are currently testing the range of annihilation cross sections predicted for a thermal relic, for masses up to ~100 GeV
- ***Direct, LHC, indirect searches are collectively testing the WIMP paradigm!***

Summary

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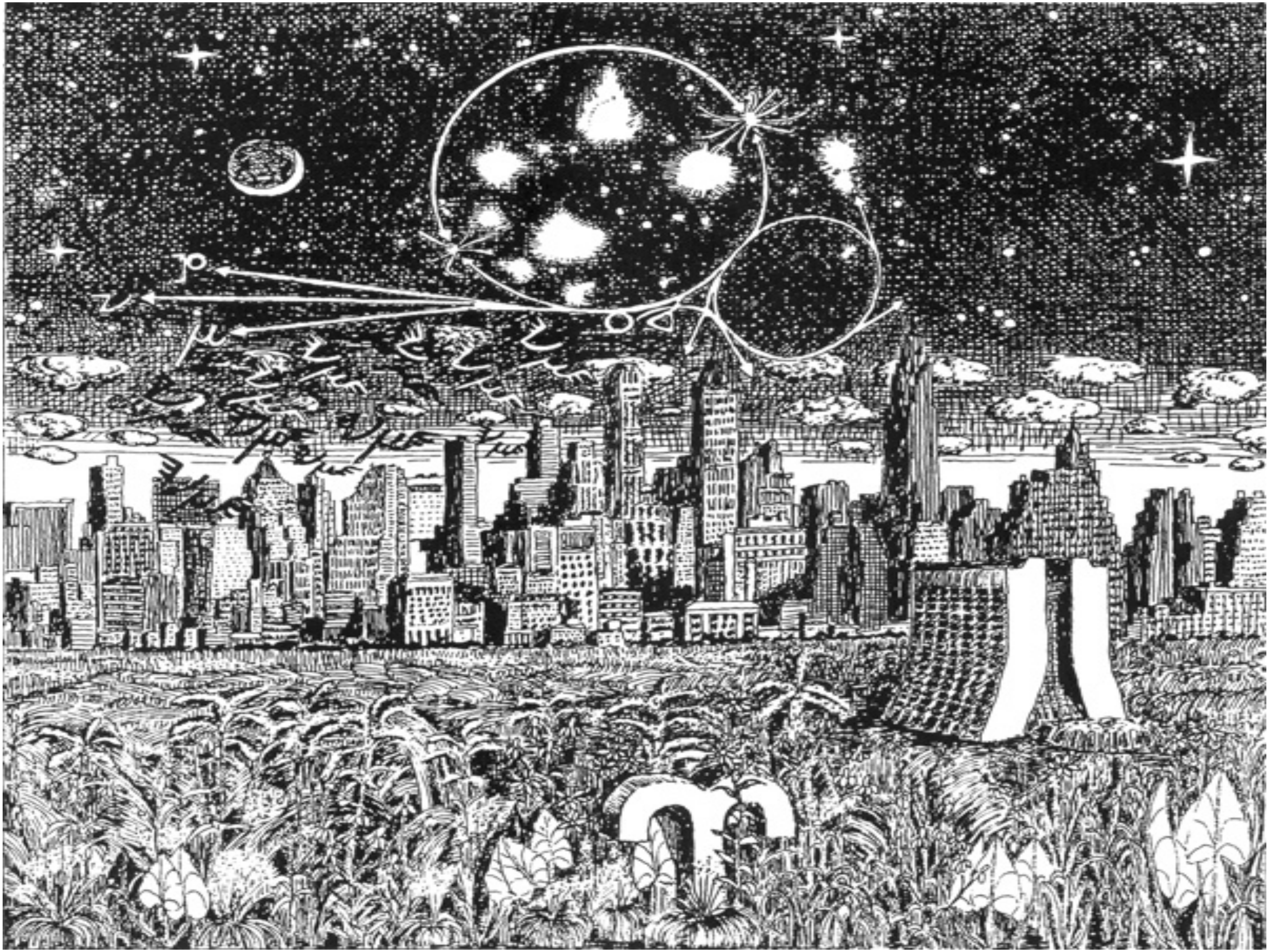
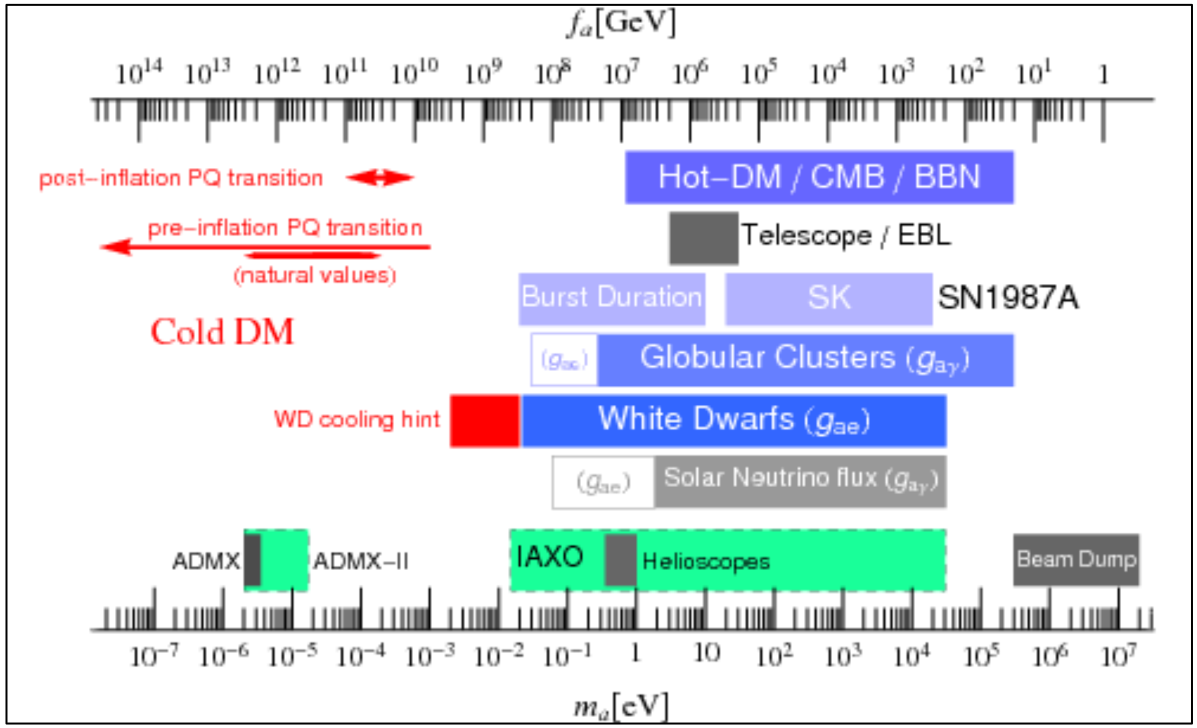
- Indirect searches using gamma rays and cosmic rays are currently testing the range of annihilation cross sections predicted for a thermal relic, for masses up to ~100 GeV
- ***Direct, LHC, indirect searches are collectively testing the WIMP paradigm!***

- 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 difficult to explain with known or proposed astrophysics
- The spectrum and angular distribution of this signal is very well fit by a ~45 GeV WIMP; observations of dwarf galaxies and searches for subhalos will be important to confirm a dark matter origin of this signal



Axions

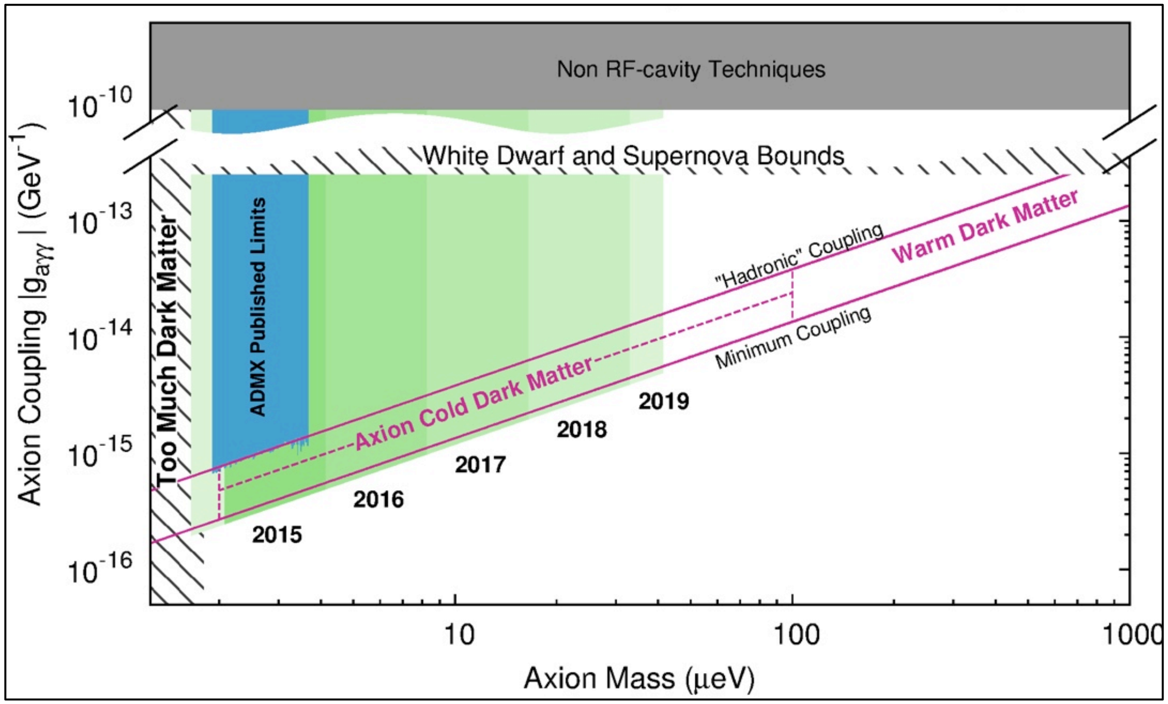
- Proposed in 1977 as part of an effort to solve the Standard Model's Strong CP problem, axions are among the best motivated candidates for dark matter
- The first axion models were quickly ruled out; presently viable models include axions with masses below ~10^{-3} eV and with extremely feeble couplings



Essig et al., New Light Weakly Coupled Particles Working Group, arXiv:1311.0029

Axions as Dark Matter

- It is difficult to reliably calculate the abundance of axions produced in the Big Bang – depends on the temperature of post-inflation reheating, and on how many axions were produced in the decays of topological strings and domain walls
- That being said, under reasonable assumptions, one finds that ~10^{-5} eV axions could make up all of the dark matter
- The microwave cavity experiment ADMX is working to obtain sensitivity to this mass range
- Fermilab is playing a leading role in the development of ADMX's high frequency cavities, enabling them to push toward higher masses



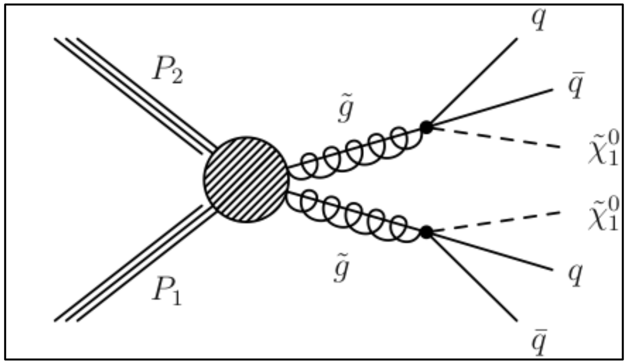
Dark Matter at the LHC

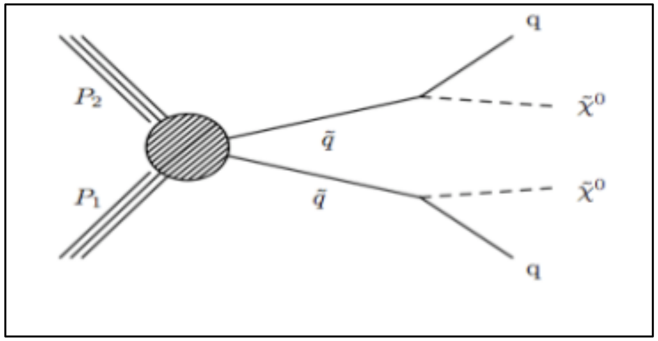
- The LHC provides us with our most comprehensive view of the TeV scale, possibly including the physics of dark matter
- Very different search strategies could be optimal, depending on the nature of dark matter

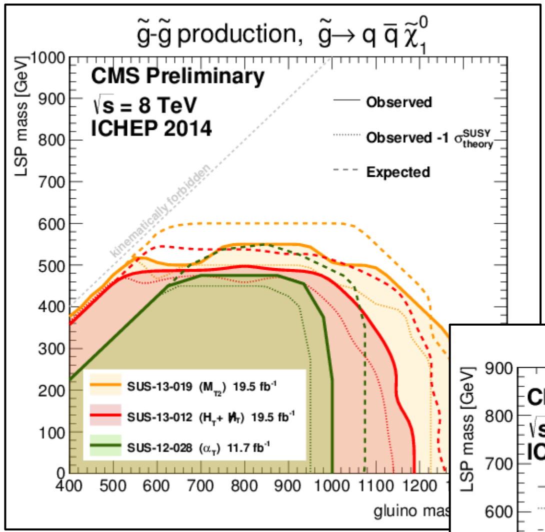
Dark Matter at the LHC

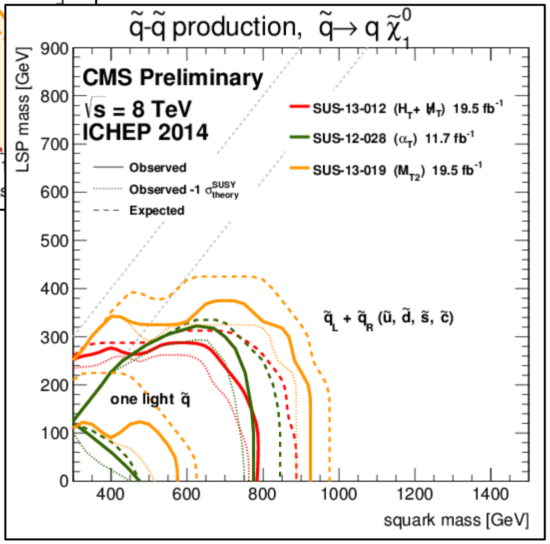
Case 1: Models with strongly interacting particles (typical SUSY-like)

- Produce colored superparticles (squarks, gluinos), and detect missing energy in their decays
- Very powerful and broad coverage… if such strongly interacting states exist below a few TeV





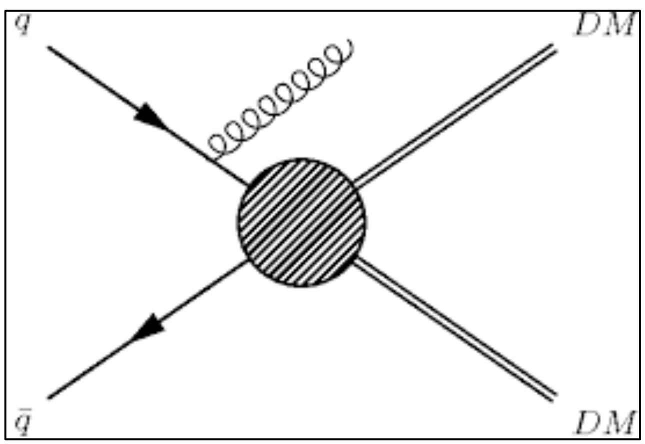




Dark Matter at the LHC

Case 2: Models without strongly interacting partners

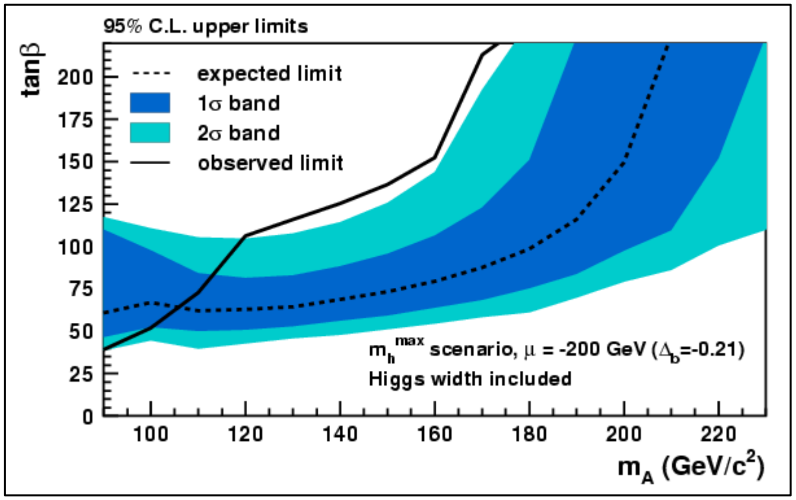
- Processes that allow dark matter particles to annihilate into Standard Model particles in the early universe can be reversed in colliders
- Dark matter production leads to events with one or more jets and missing energy (among many other possible signals)

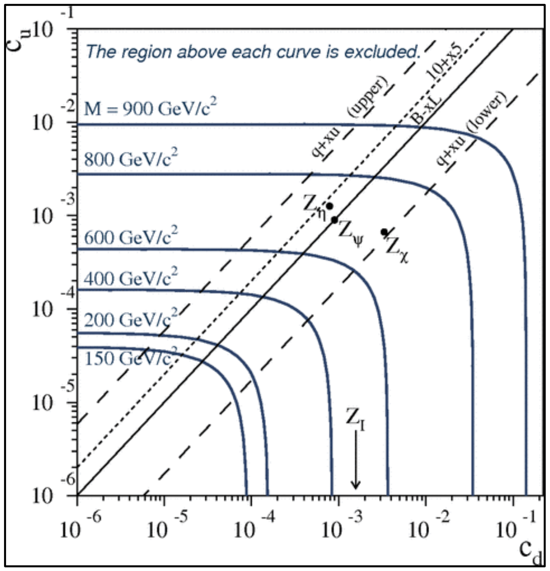


Dark Matter at the LHC

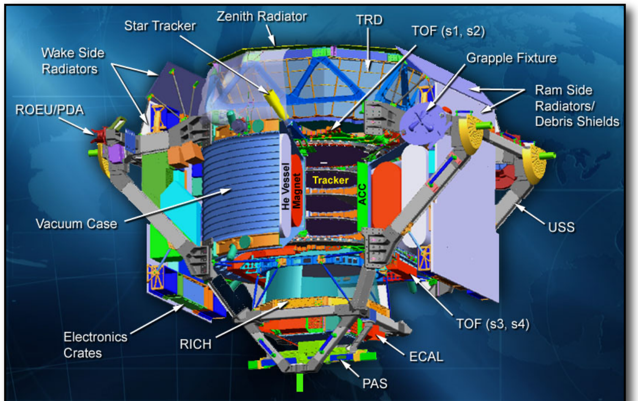
Case 2: Models without strongly interacting partners

- Processes that allow dark matter particles to annihilate into Standard Model particles in the early universe can be reversed in colliders
- Dark matter production leads to events with one or more jets and missing energy (among many other possible signals)
- In many models, dark matter interacts with the Standard Model through new mediators, with masses near the electroweak-scale
- Searches for Z's, additional Higgs bosons, sleptons, etc. have direct consequences for dark matter



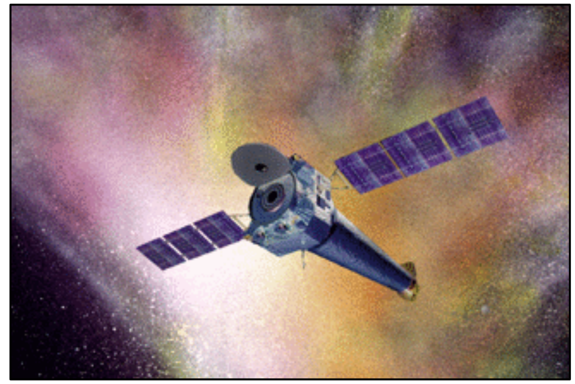


Indirect Detection (annihilation/decay products)

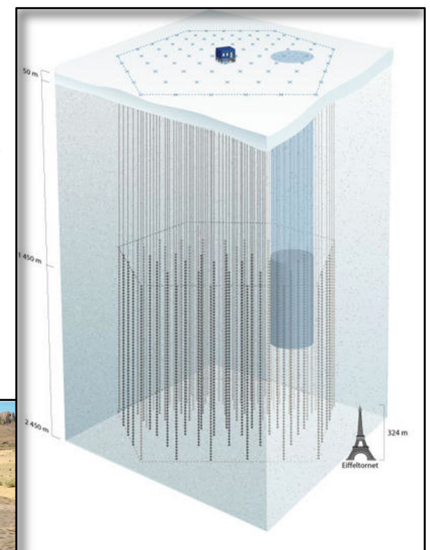


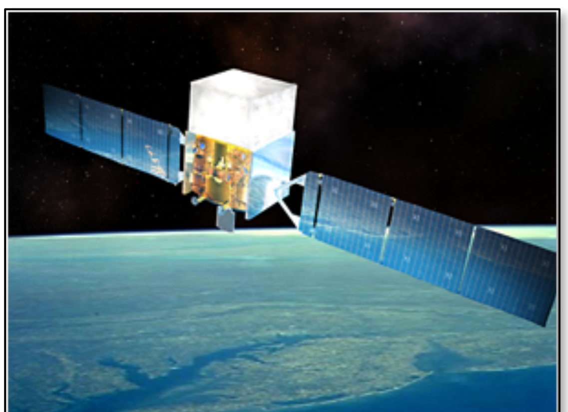
Cosmic Rays

X-Rays/Multi-Wavelength

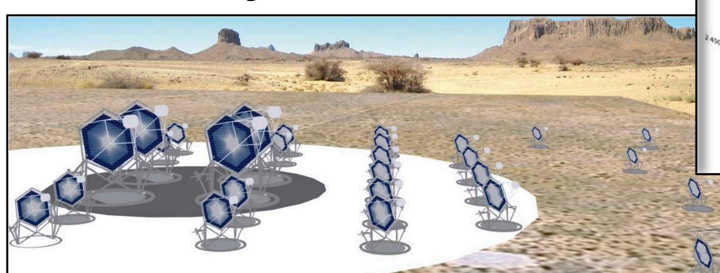


Neutrinos



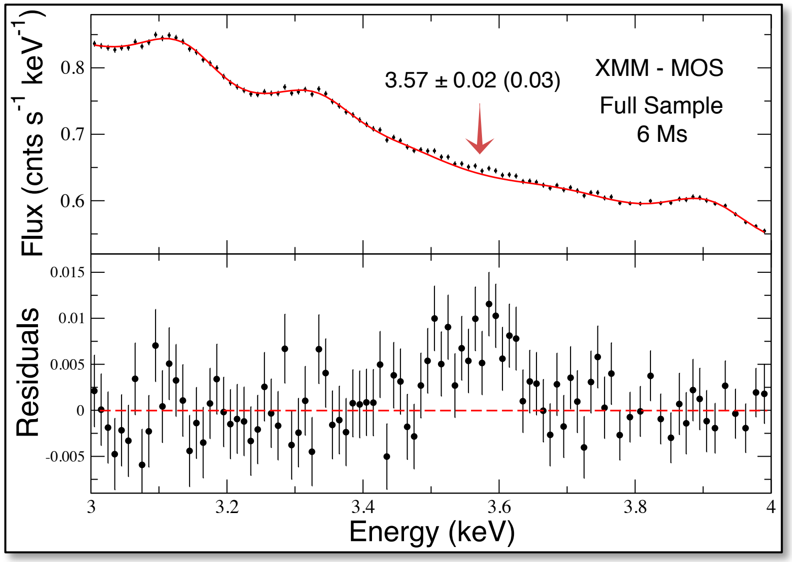


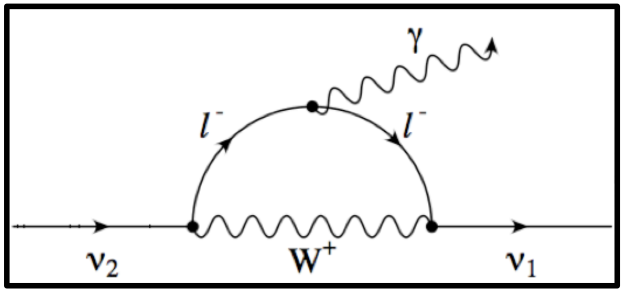
Gamma Rays



A 3.57 keV Line?

- In early 2014, two groups reported the observation of an unexpected X-ray line from a collection of galaxy clusters
- A signal of decaying dark matter? Perhaps sterile neutrinos?





Bulbul *et al.* (1402.2301), Boyarsky *et al.* (1402.4119)

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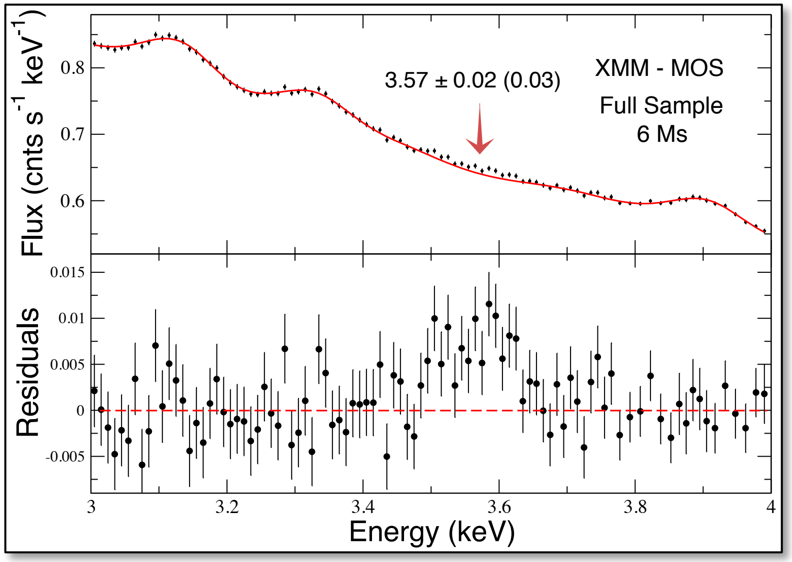
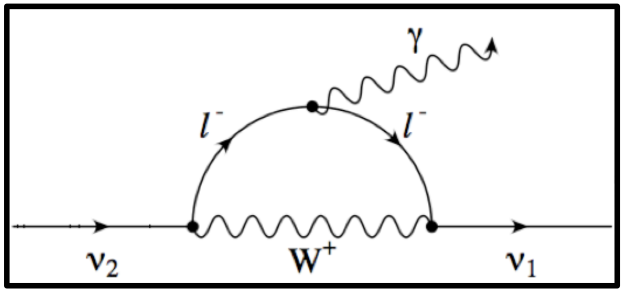


- Searches for such a line from dwarf galaxies (Malyshev *et al.*) and galaxies (Anderson *et al.*, Riemer-Sorensen) appear to be in tension with a decaying dark matter interpretation
- Future observations by high-resolution X-ray telescopes (ASTRO-H) should be able to clarify this situation



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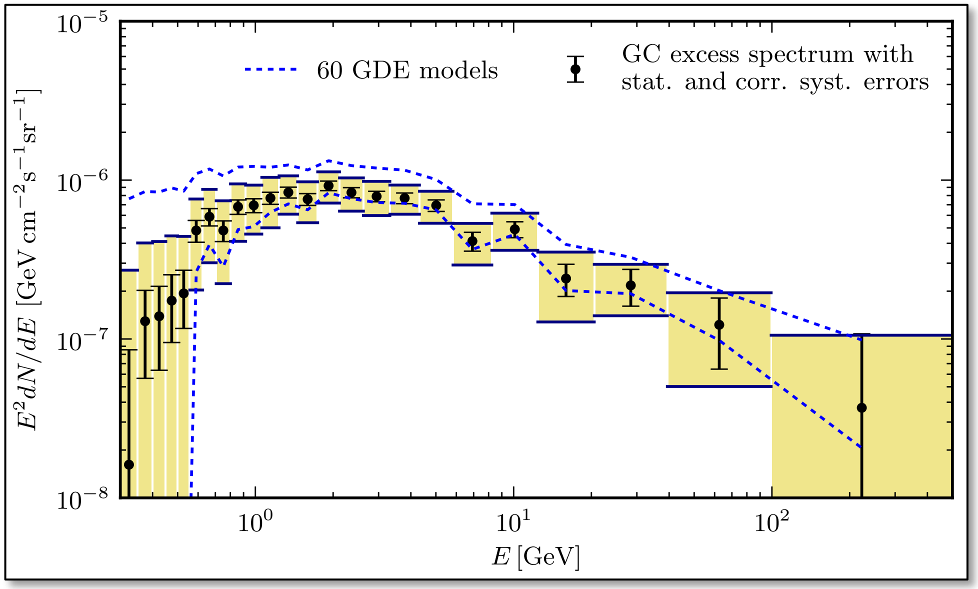
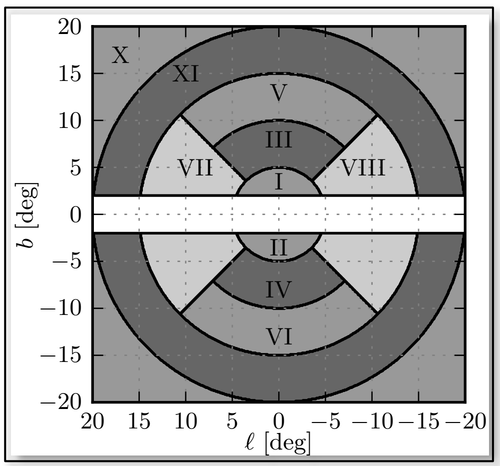
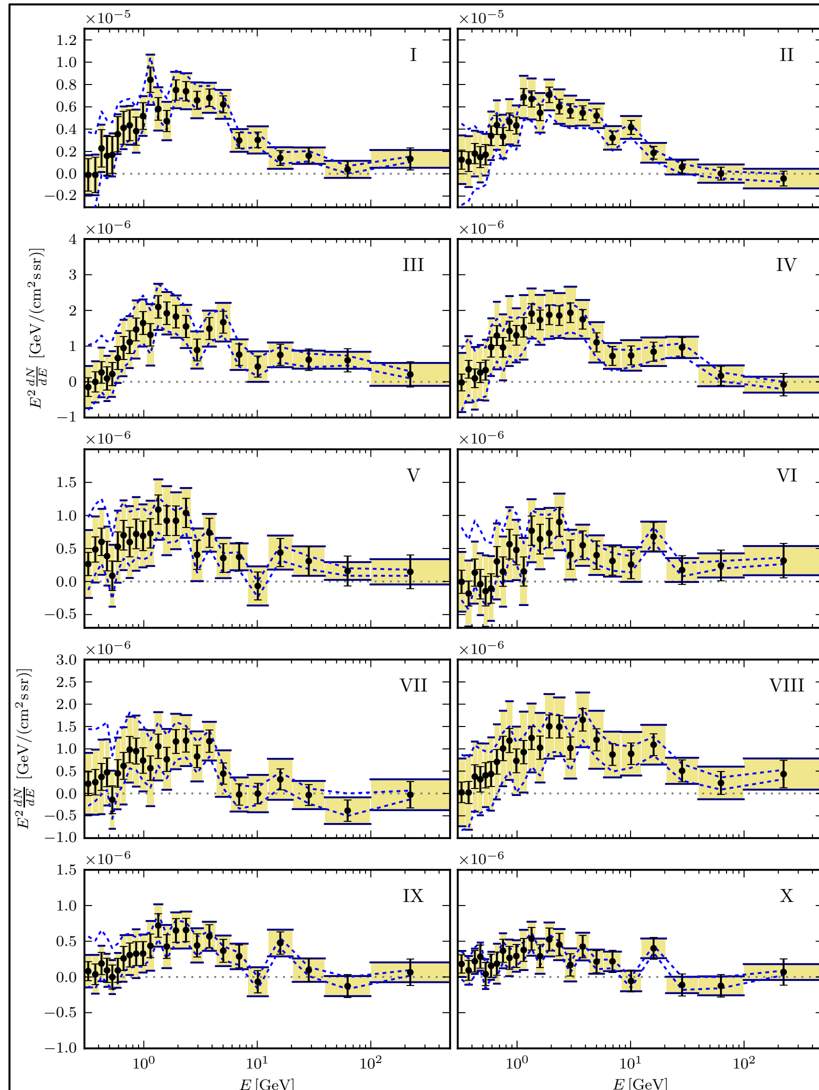
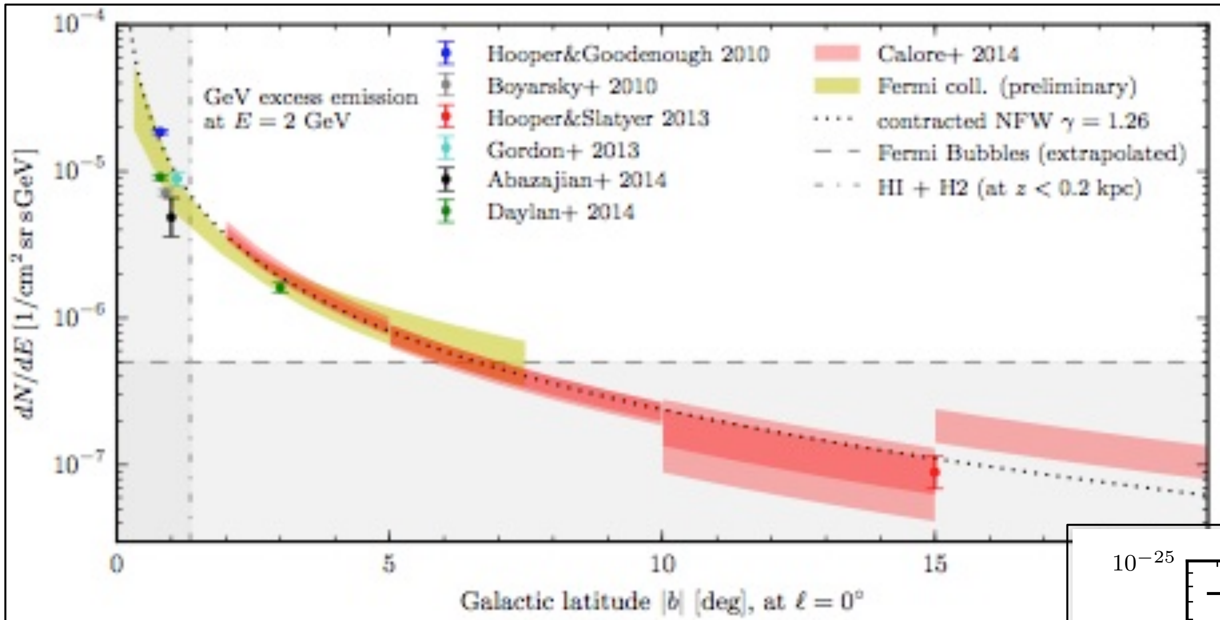
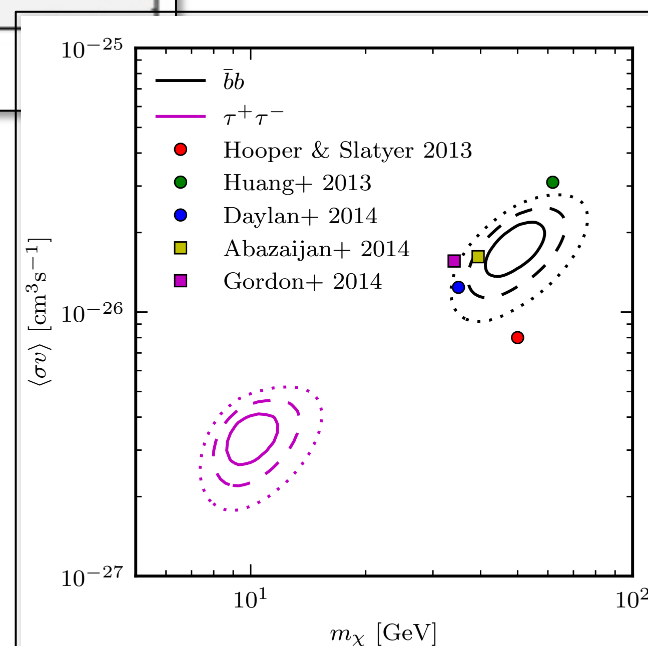






Calore, Cholis, Weniger, arXiv:1409.0042

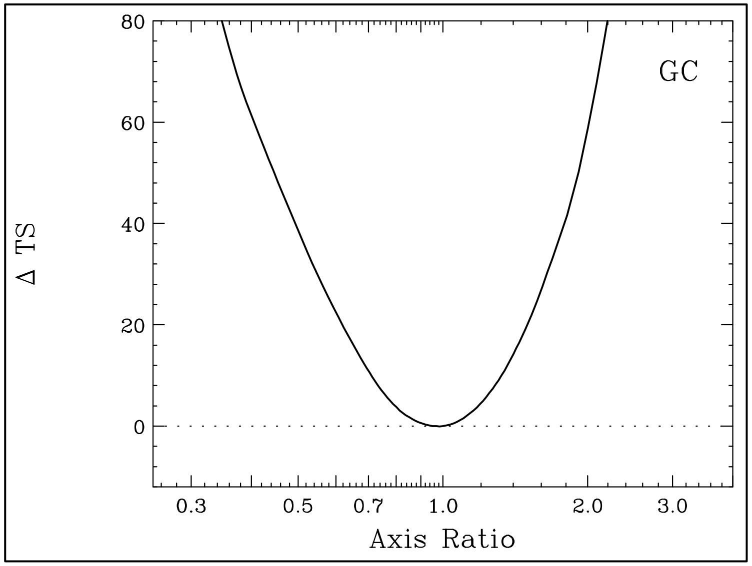




Calore, Cholis, McCabe, Weniger, 1411.4647;
Calore, Cholis, Weniger, arXiv:1409.0042

The Morphology of the Excess

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



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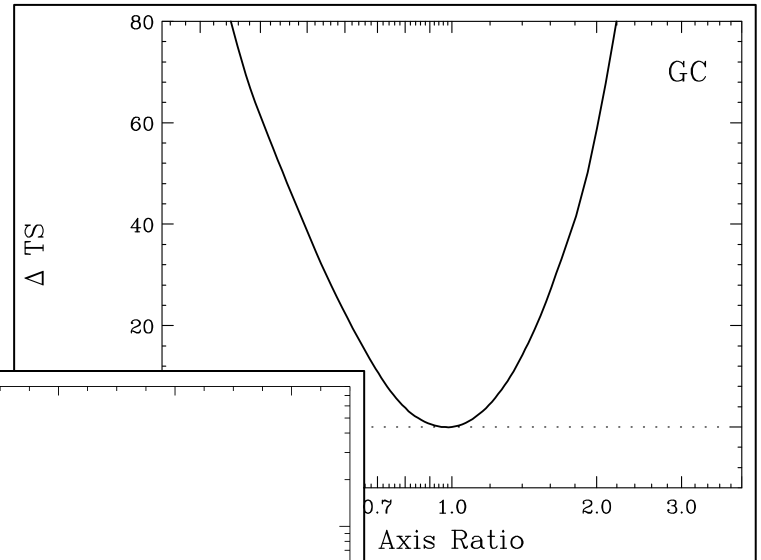

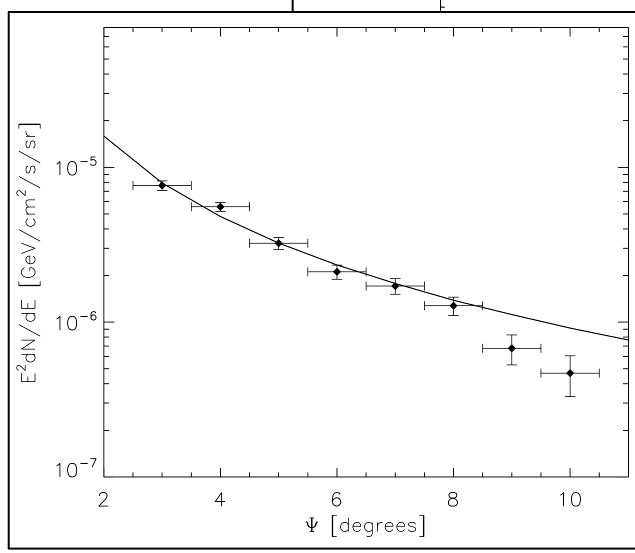

The Morphology of the Excess

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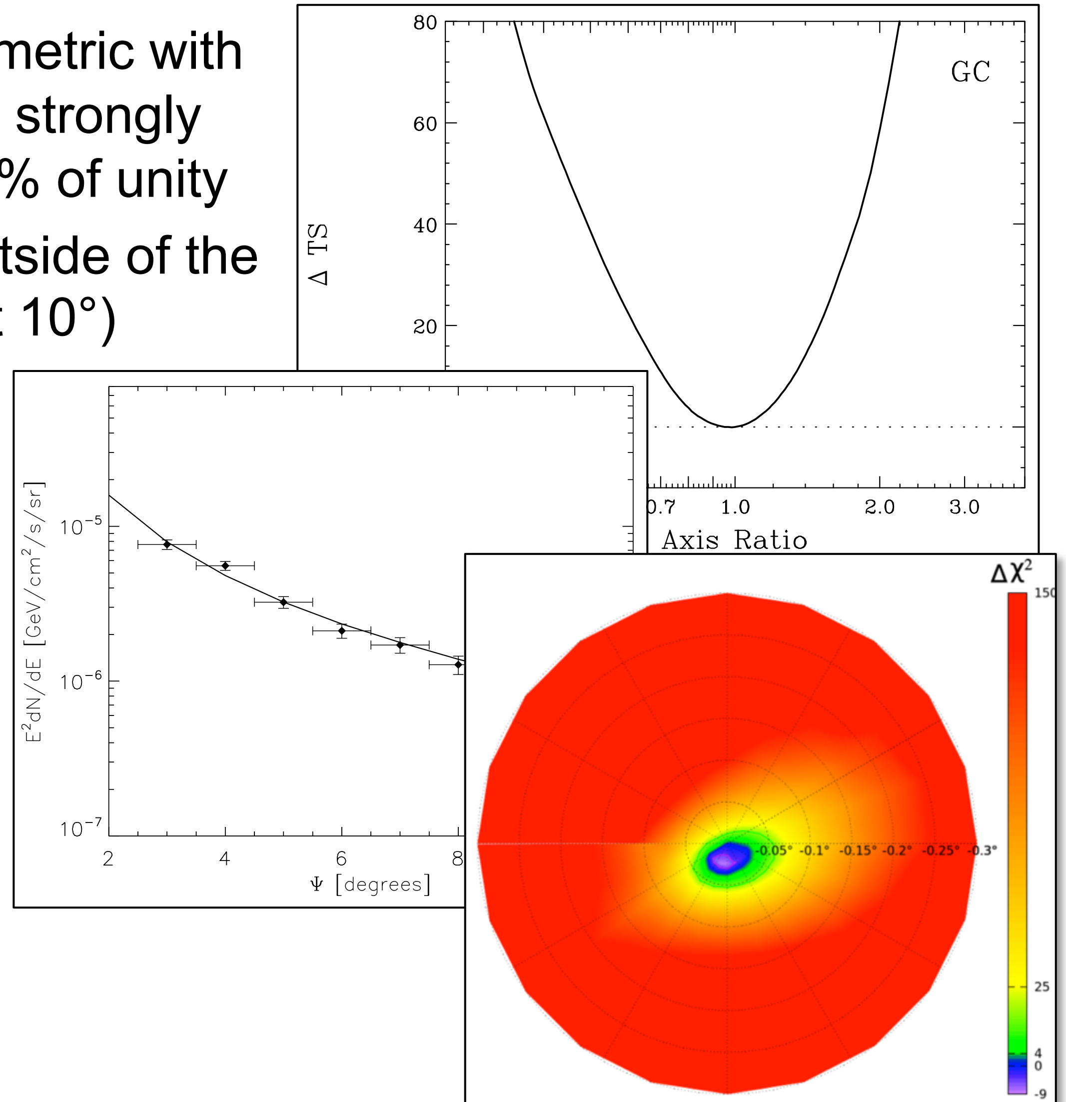
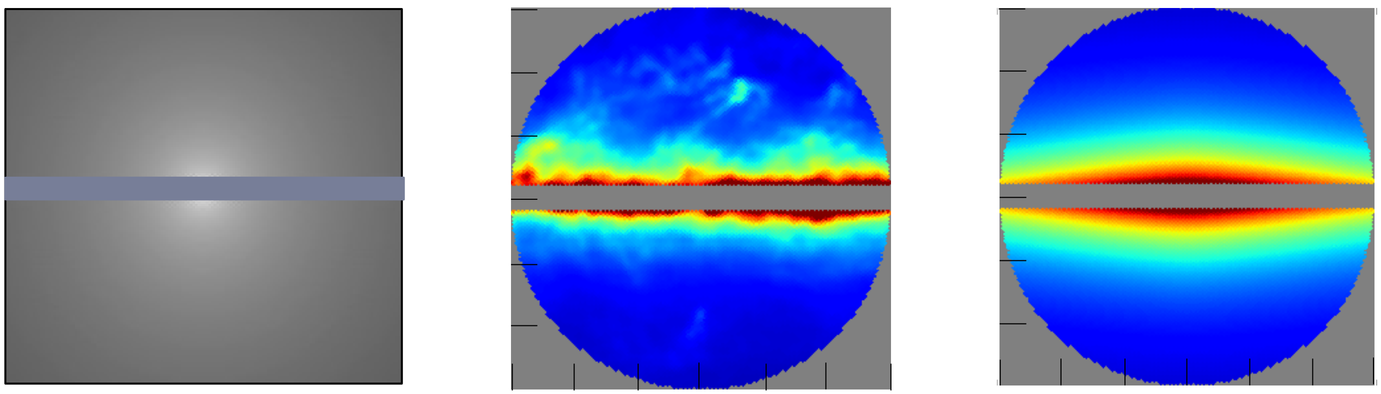
- The excess extends to well outside of the Galactic Center (out to at least 10°)
- The excess is very precisely centered around Sgr A* (within ~0.03° or ~5 pc)
- The intensity of the excess continues to rise to within ~10 pc of Sgr A* (no flattening or core)



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

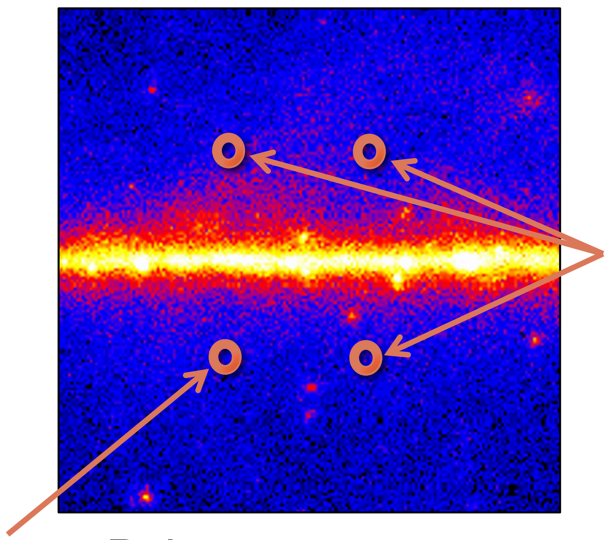


- The question their analysis asks is this: Which of these distributions do the observed gamma-ray clusters most trace?

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 $(\ell,b) \rightarrow (-\ell,b)$, $(\ell,-b)$, or $(-\ell,-b)$



Tim Linden, arXiv:1509.02928

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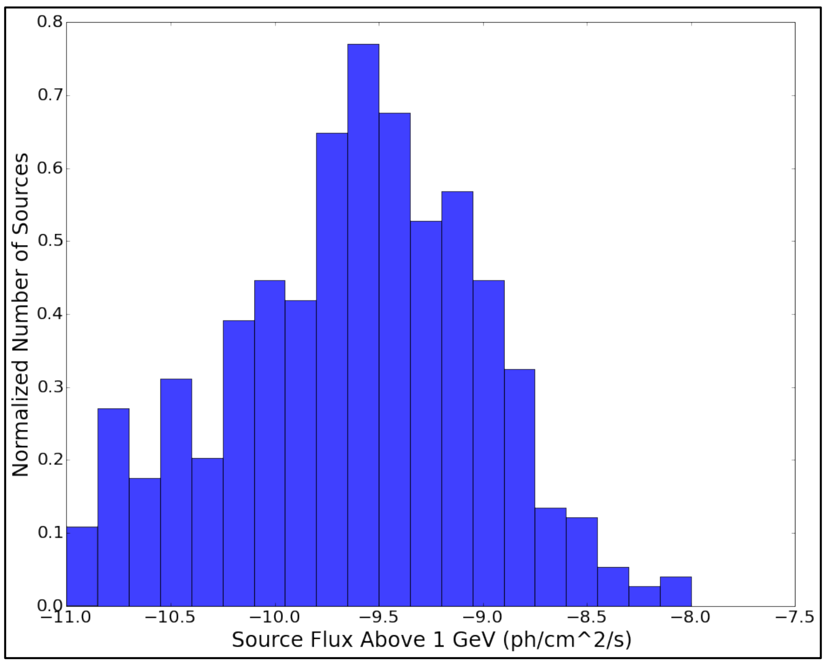
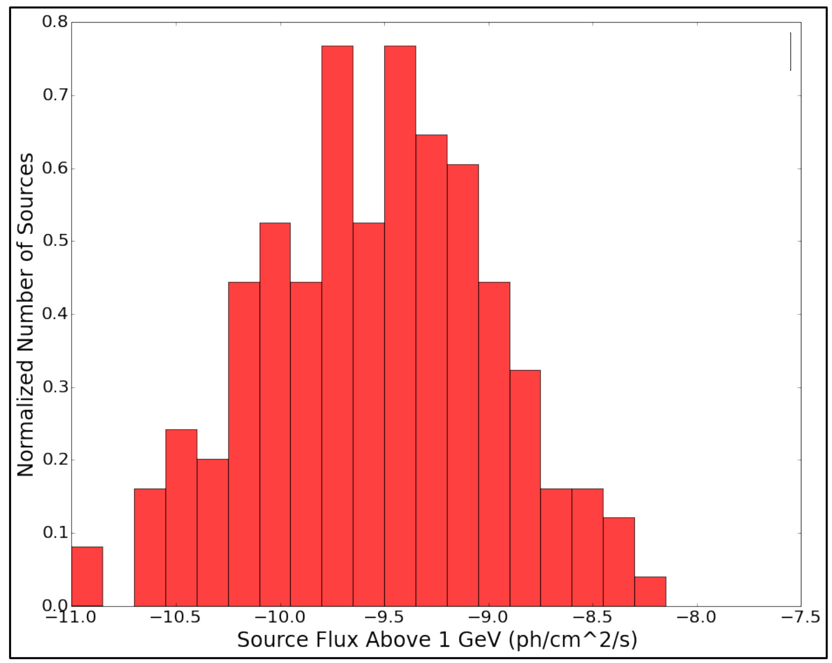
Which plot is the control group?





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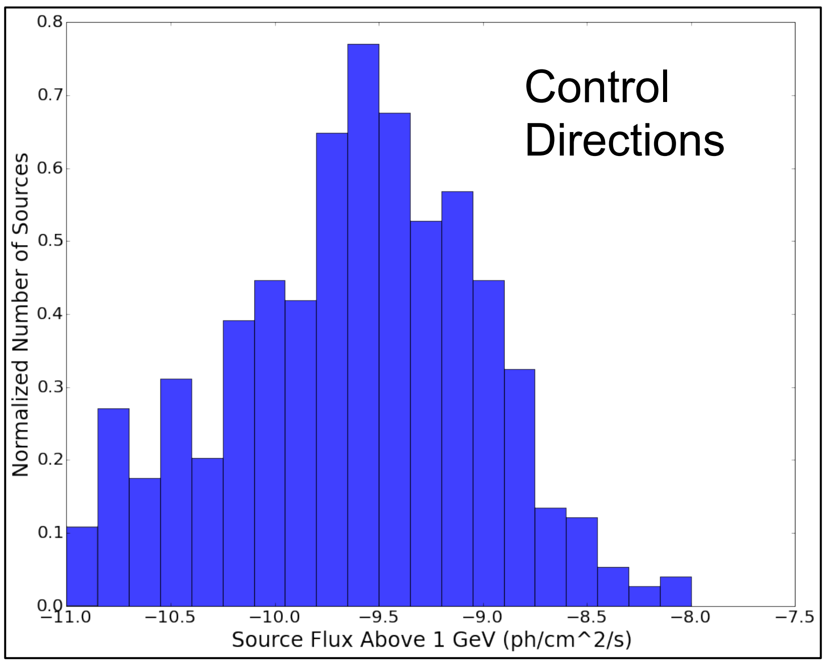

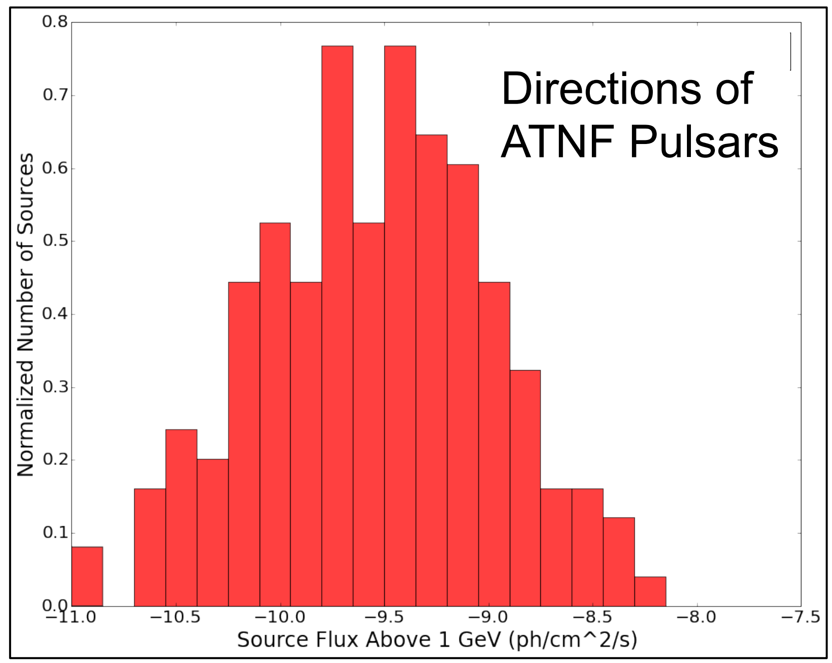

Tim Linden, arXiv:1509.02928