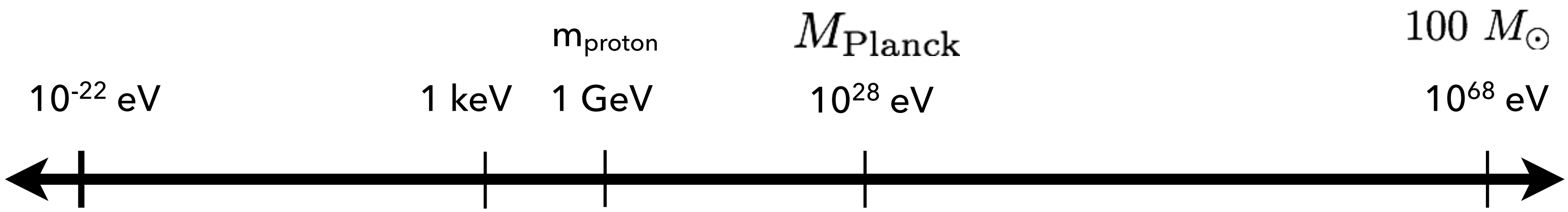
THE WIMP IS DEAD!
LONG LIVE THE WIMP!

Dan Hooper – Fermilab and the University of Chicago

Lake Louise Winter Institute

February 19, 2018

The Dark Matter Landscape



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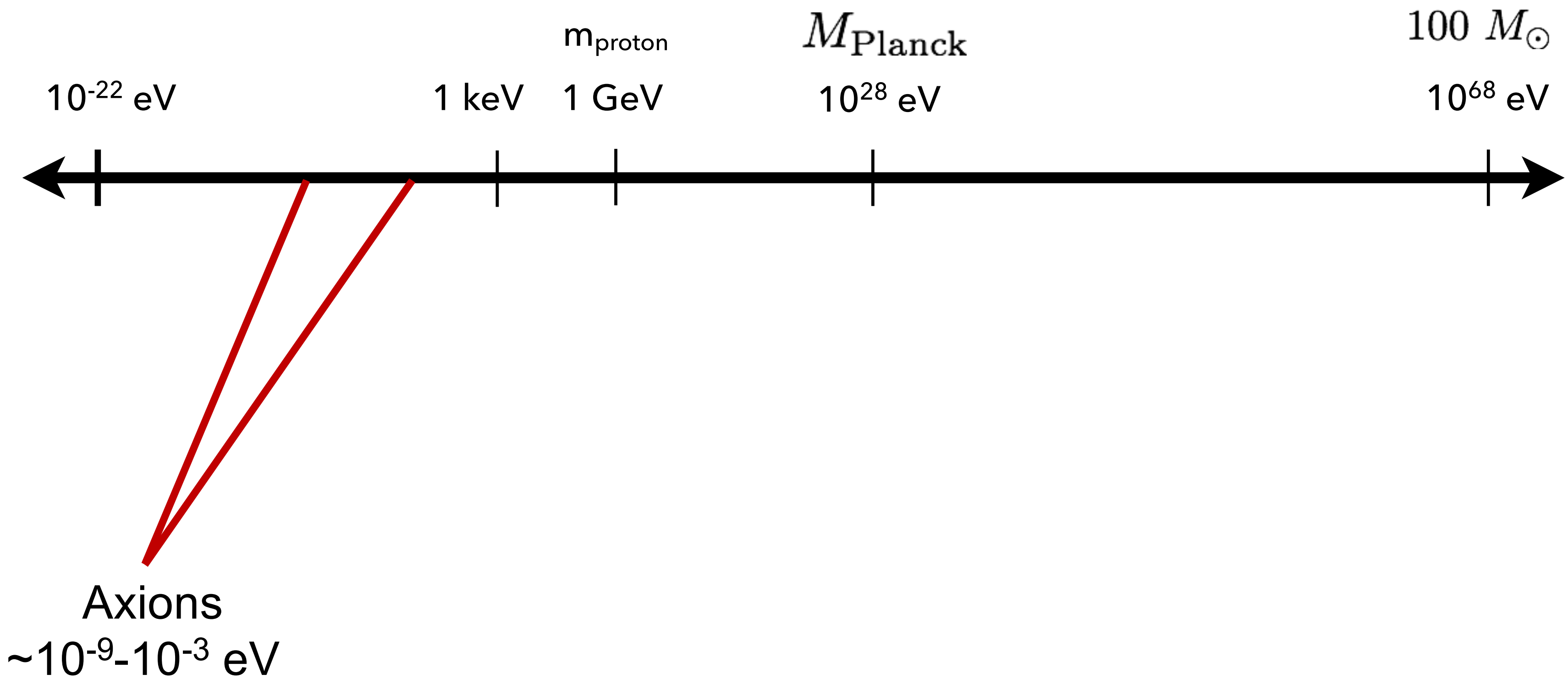

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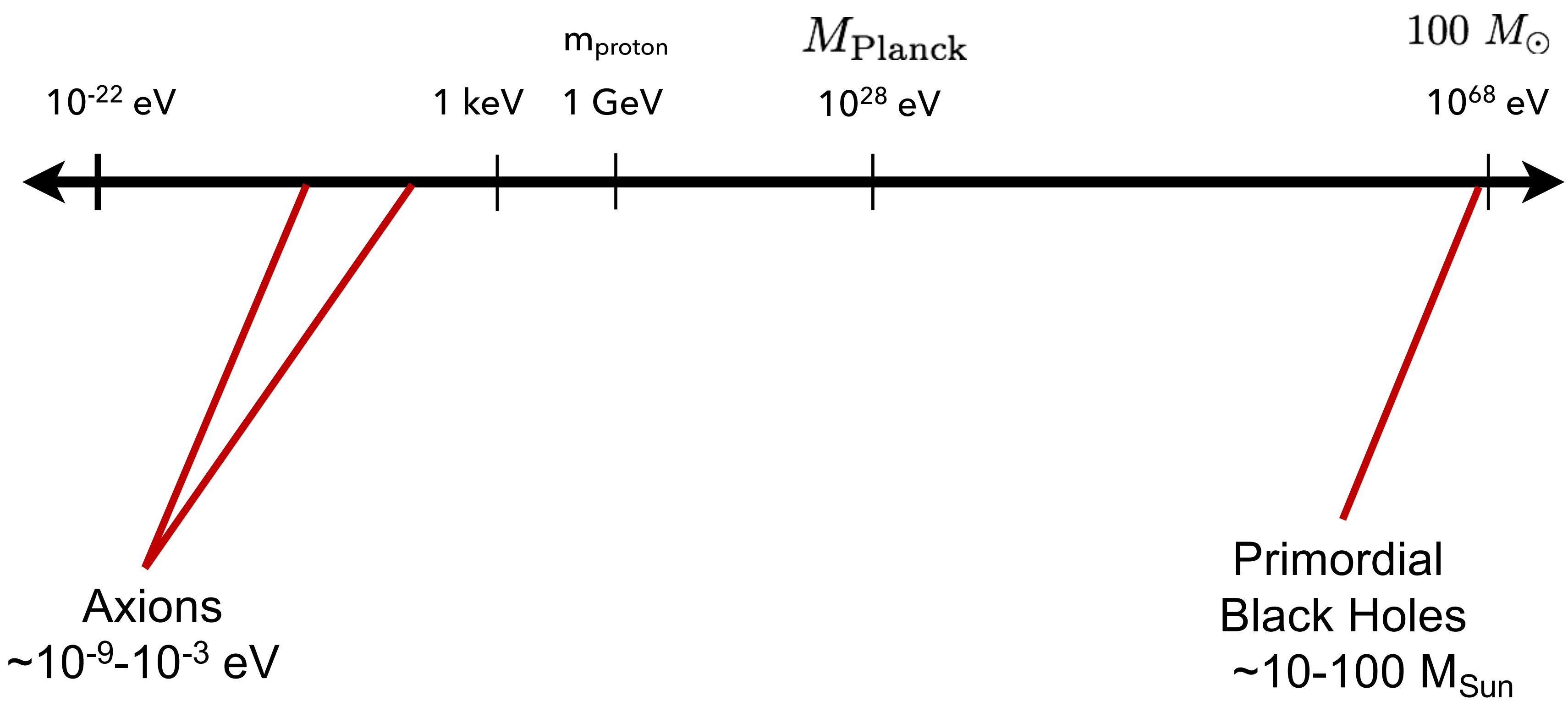

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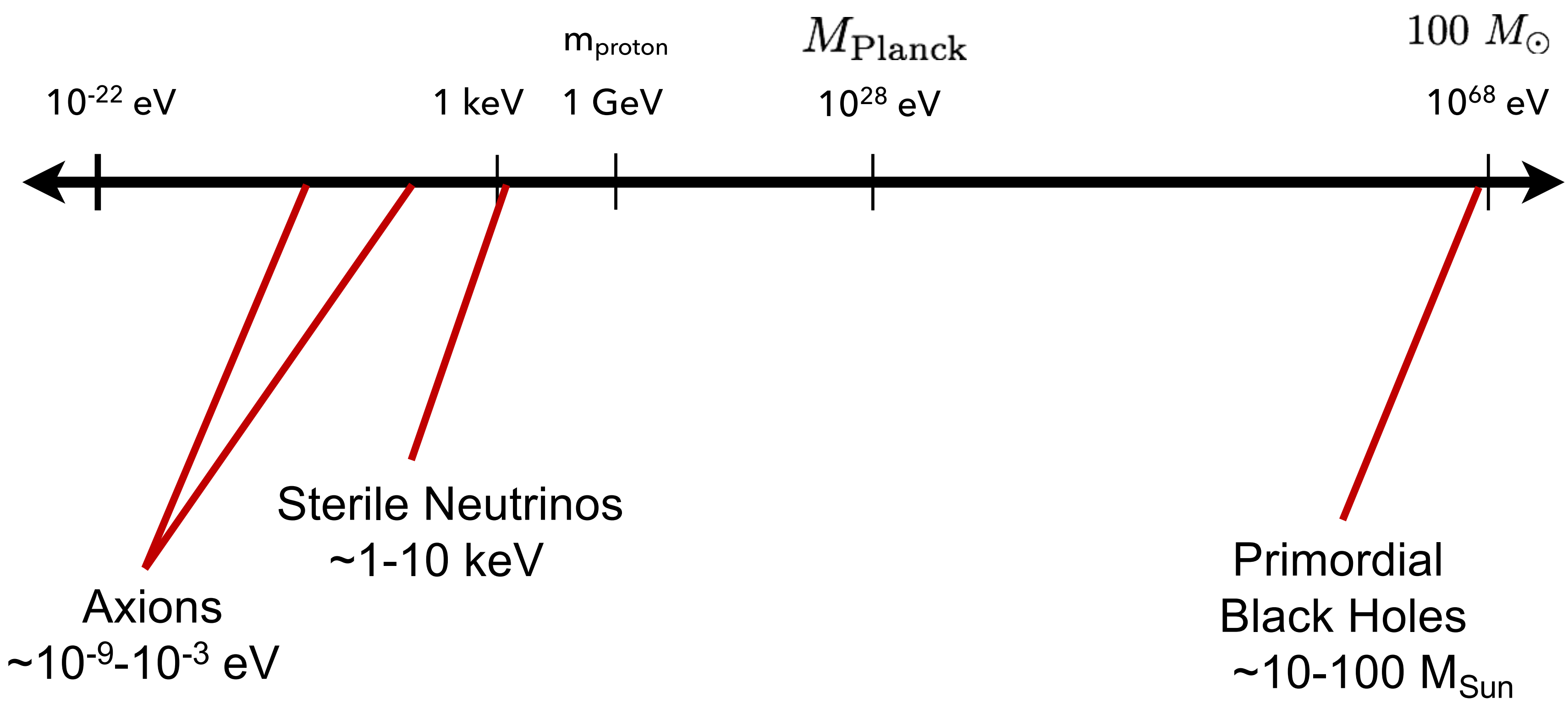

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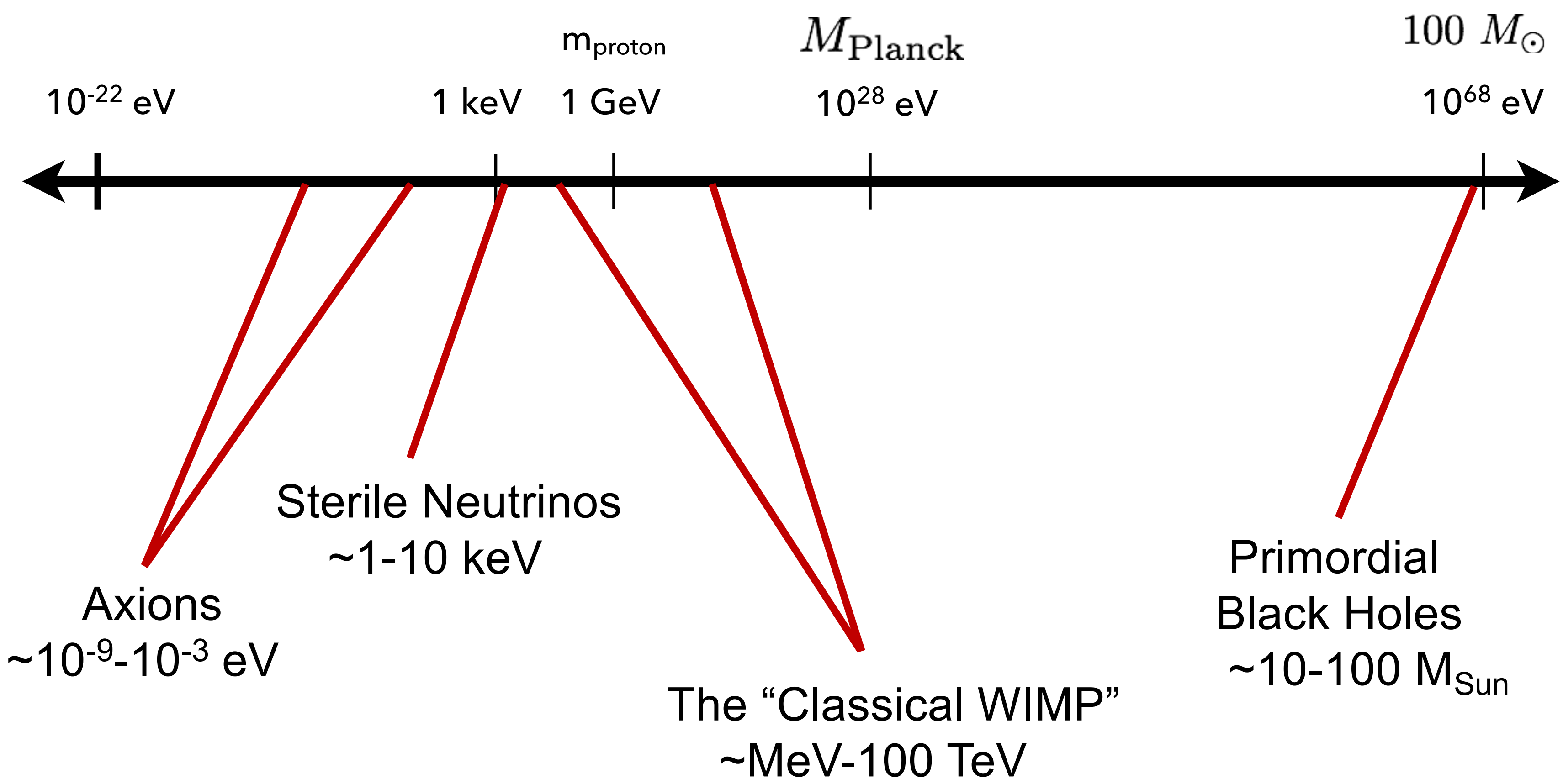


The Classical WIMP

- Historically, a huge fraction of the papers on particle dark matter have focused on WIMPs – they have dominated the dark matter landscape
- This started with massive Standard Model neutrinos (Gershtein and Zeldovich 1966; Cowsik and McClelland 1972; Szalay and Marx 1976; P. Hut 1977; Lee and Weinberg 1977; Sato and Kobayashi 1977; Dicus, Kolb and Teplitz 1977), but expanded to include other candidates, including supersymmetric particles (P. Hut 1977; Pagels and Primack 1982; Weinberg and Goldberg 1983; Ellis, Hagelin, Nanopoulos, Olive and Srednicki 1983)
- By the late 1980s, it was widely appreciated that these specific candidates were but a few examples of a broader class of "WIMPs"

(Coined by Mike Turner and Gary Steigman in 1984, but has since evolved in meaning)

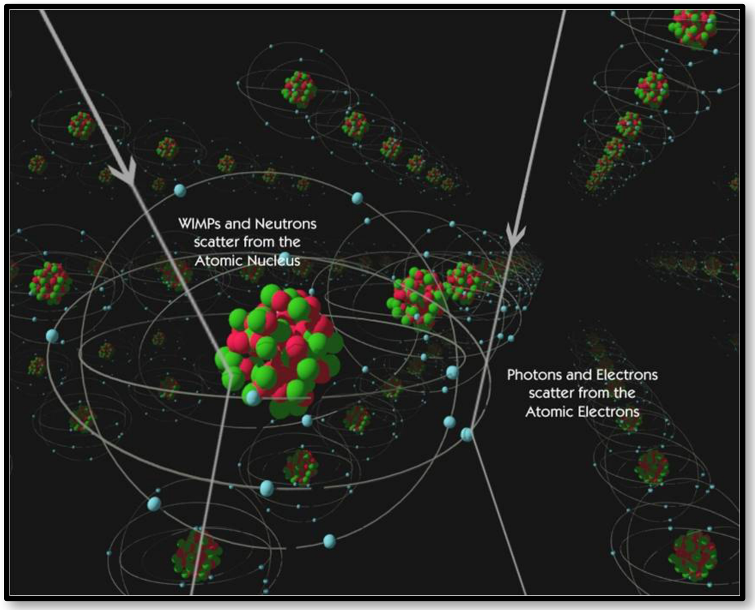
For a history of dark matter, see Bertone and Hooper, arXiv:1605.04909

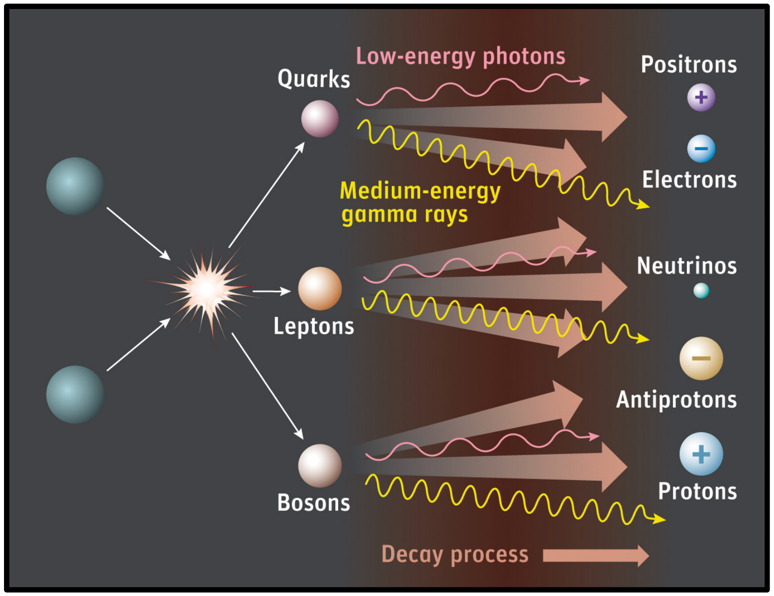
The Case for the Classical WIMP

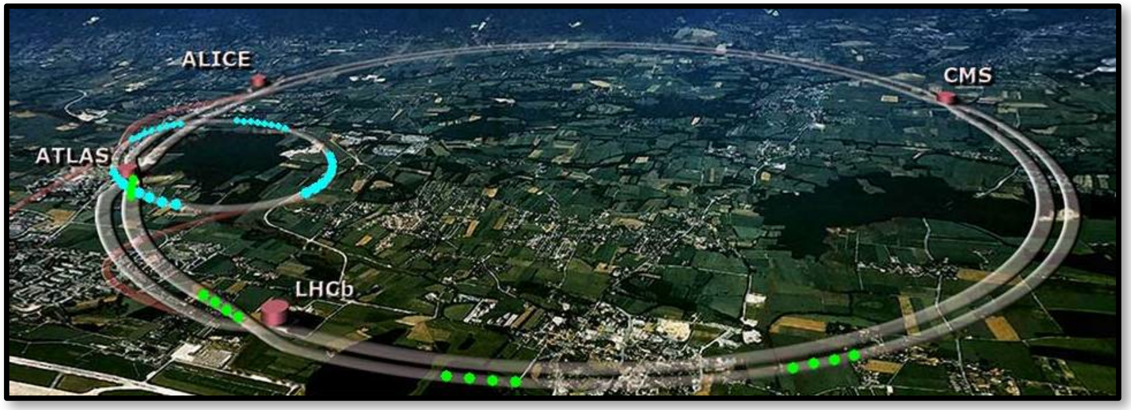
- To simplify the discussion, lets make two well-motivated assumptions:
  1) Standard expansion history in the early universe (radiation dominated)
  2) The dark matter was in thermal equilibrium (at some point in time)

- The abundance of dark matter that emerges from the Big Bang depends on the dark matter's mass and couplings
- A thermal relic with very small couplings will exceed the measured dark matter density, while one with very large couplings will constitute only a small fraction of the dark matter – to accommodate the measured abundance, something comparable to the weak force is required
- Under these well-motivated assumptions, viable dark matter candidates must fall within a mass range of ~1 MeV to ~100 TeV
- From this perspective, dark matter candidates with weak-scale masses and interactions – "WIMPs" – are particularly well motivated
- This argument has also played a significant role in guiding our experimental program

Putting the WIMP Paradigm to the Test

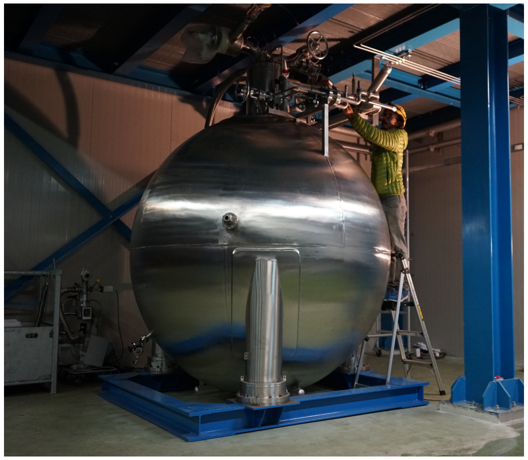


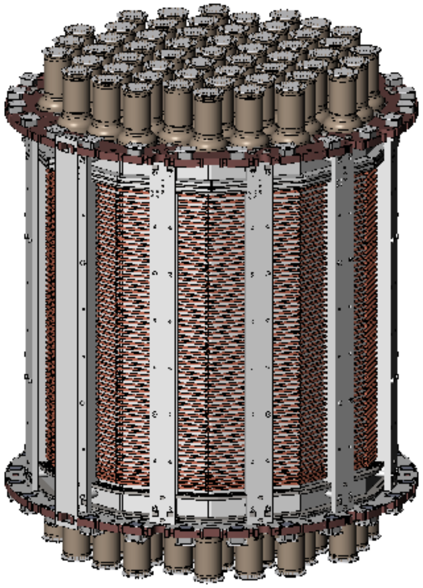


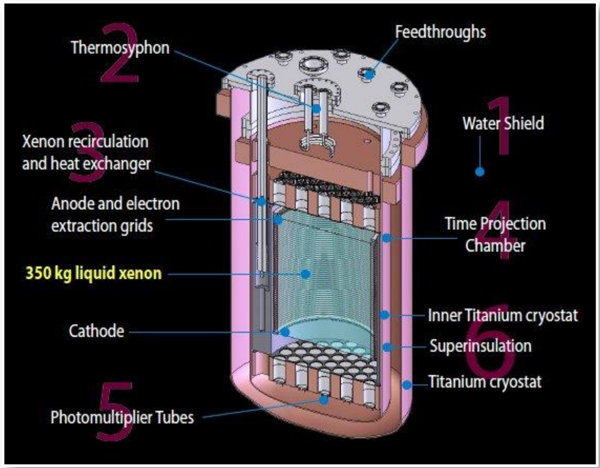


Direct Detection (scattering with nuclei)

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







XENON1T, LUX, PandaX-II

Direct Detection

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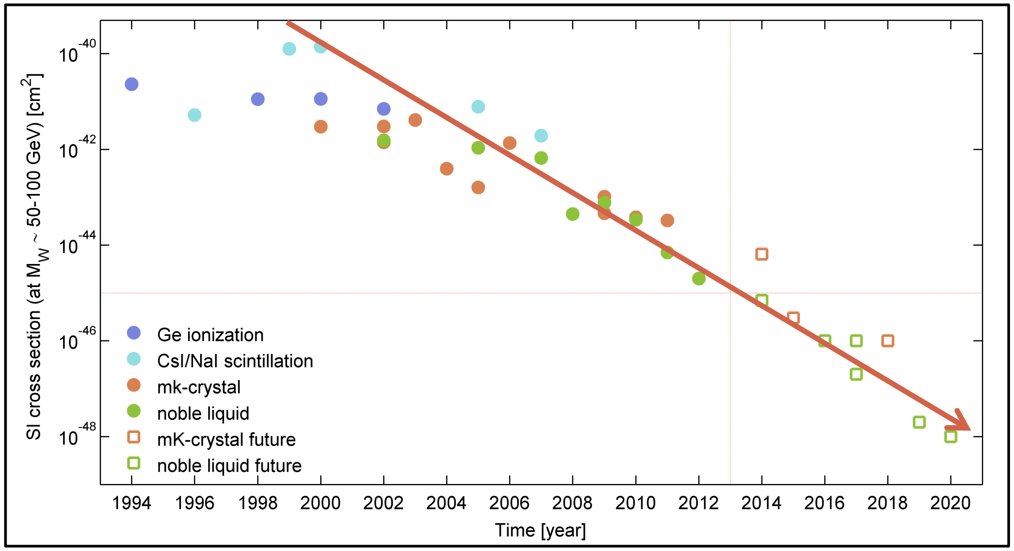

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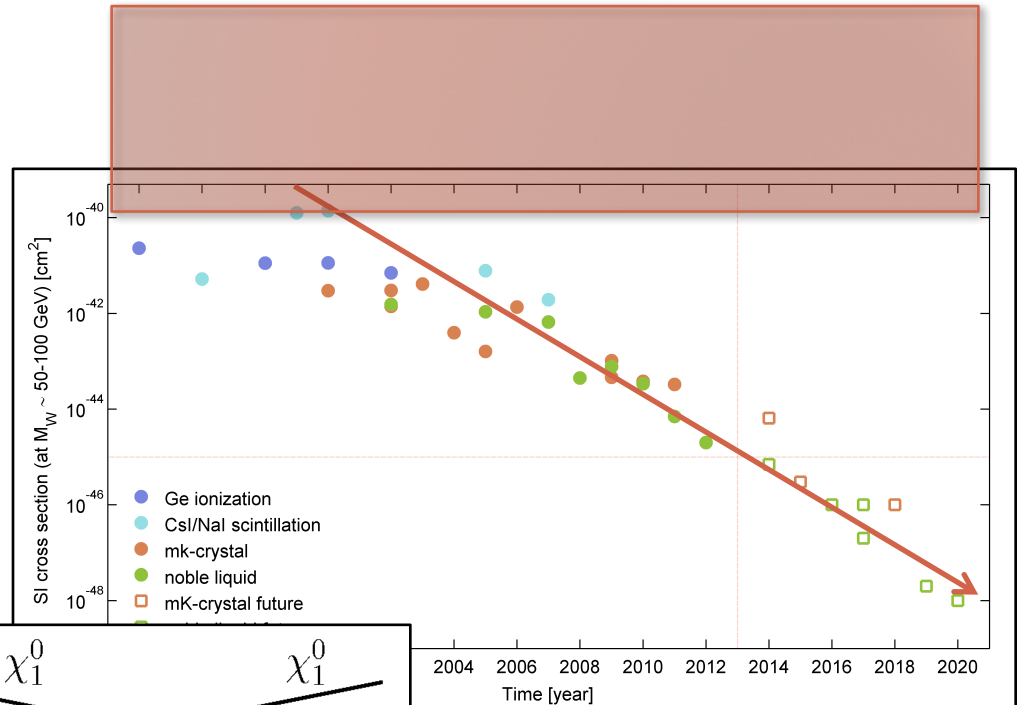

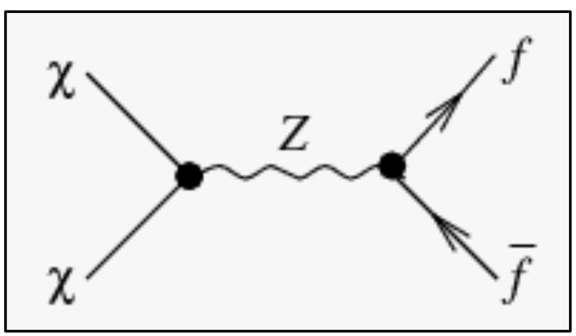

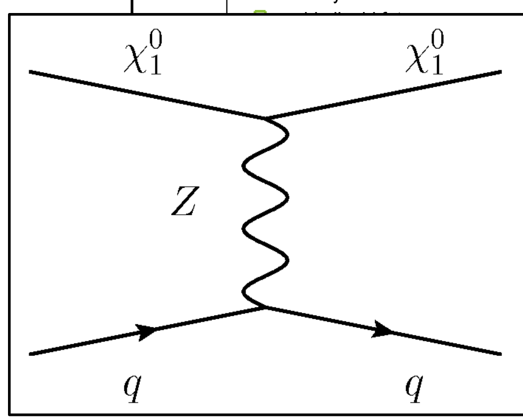

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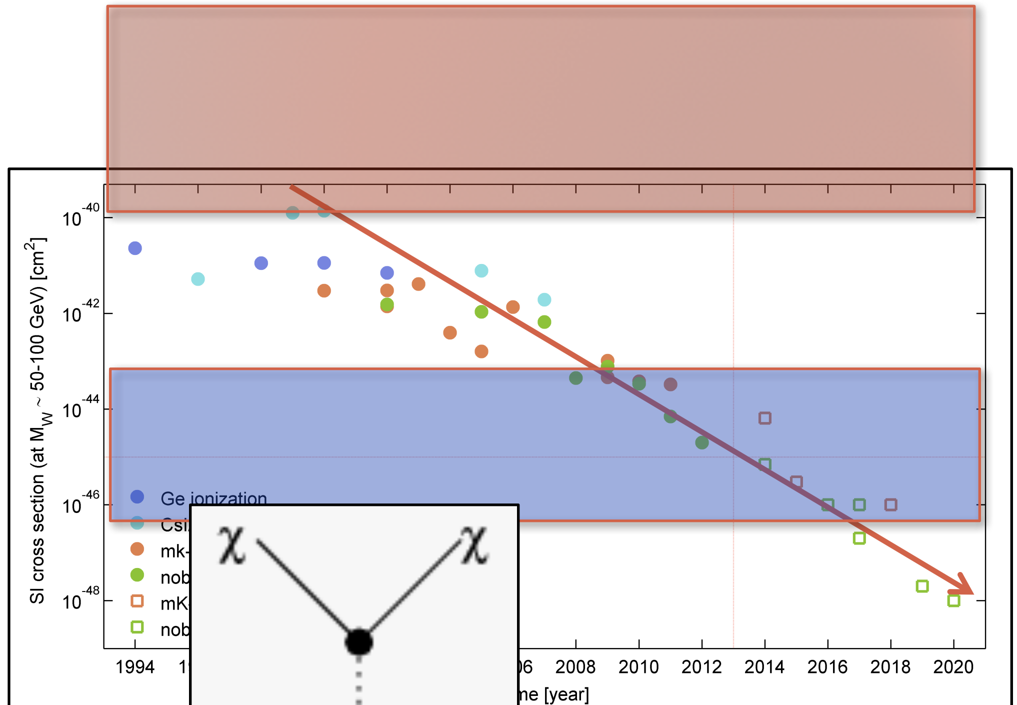
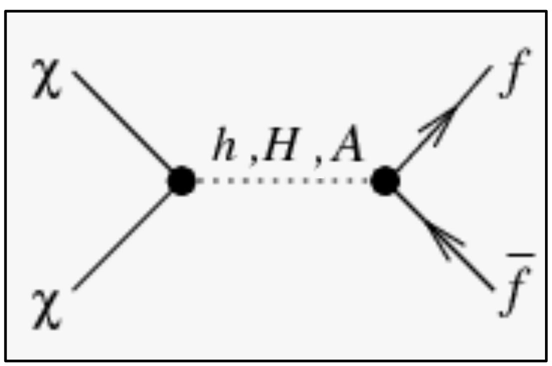
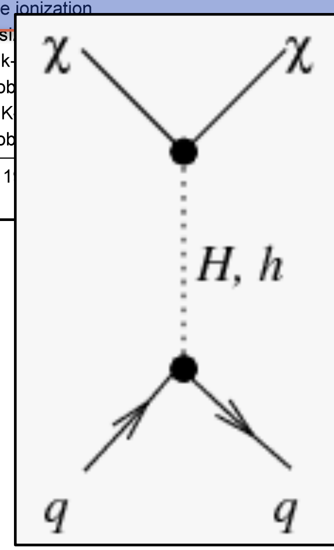
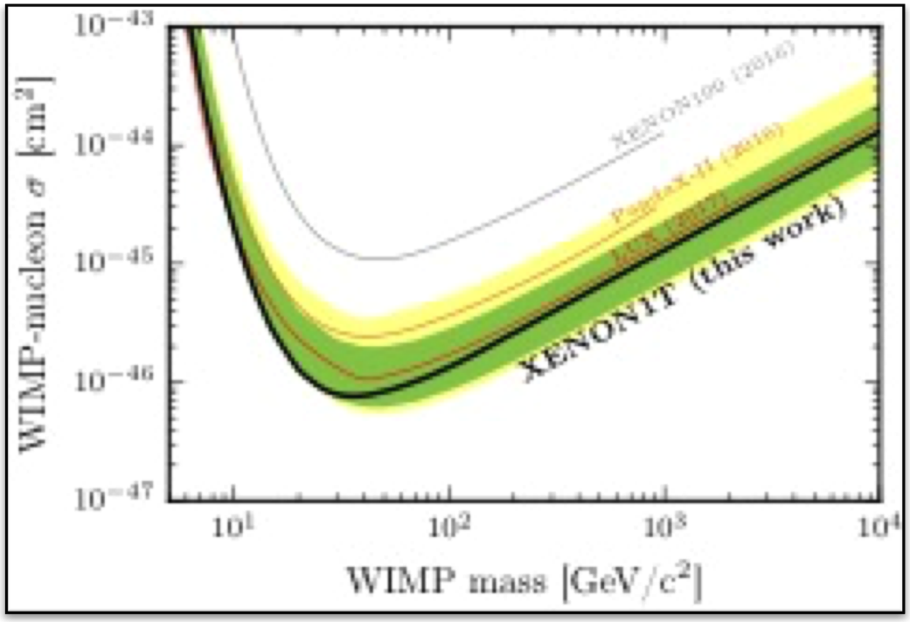
  -Now!: Experiments are currently testing WIMPs that interact through Higgs exchange (including many SUSY models)

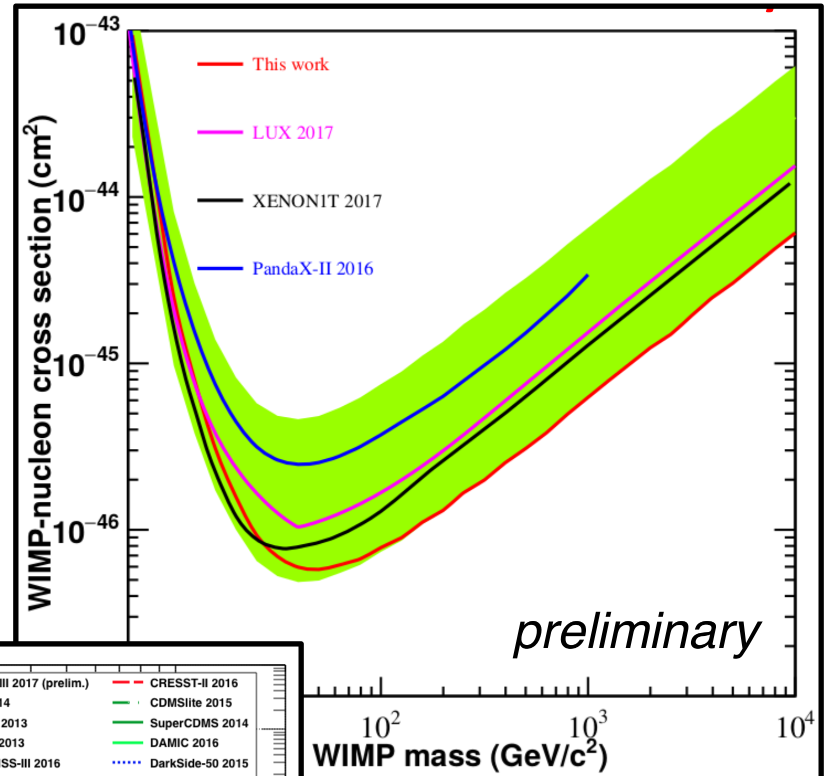


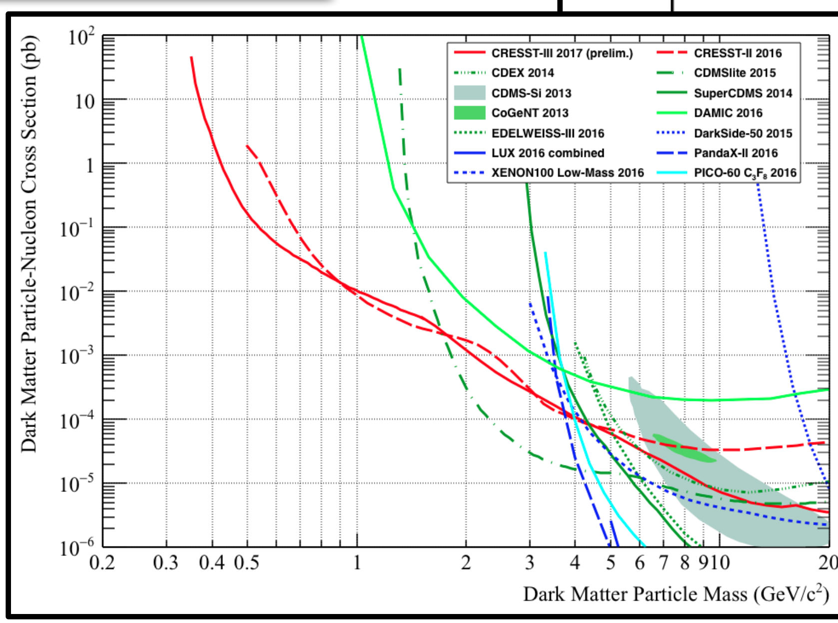




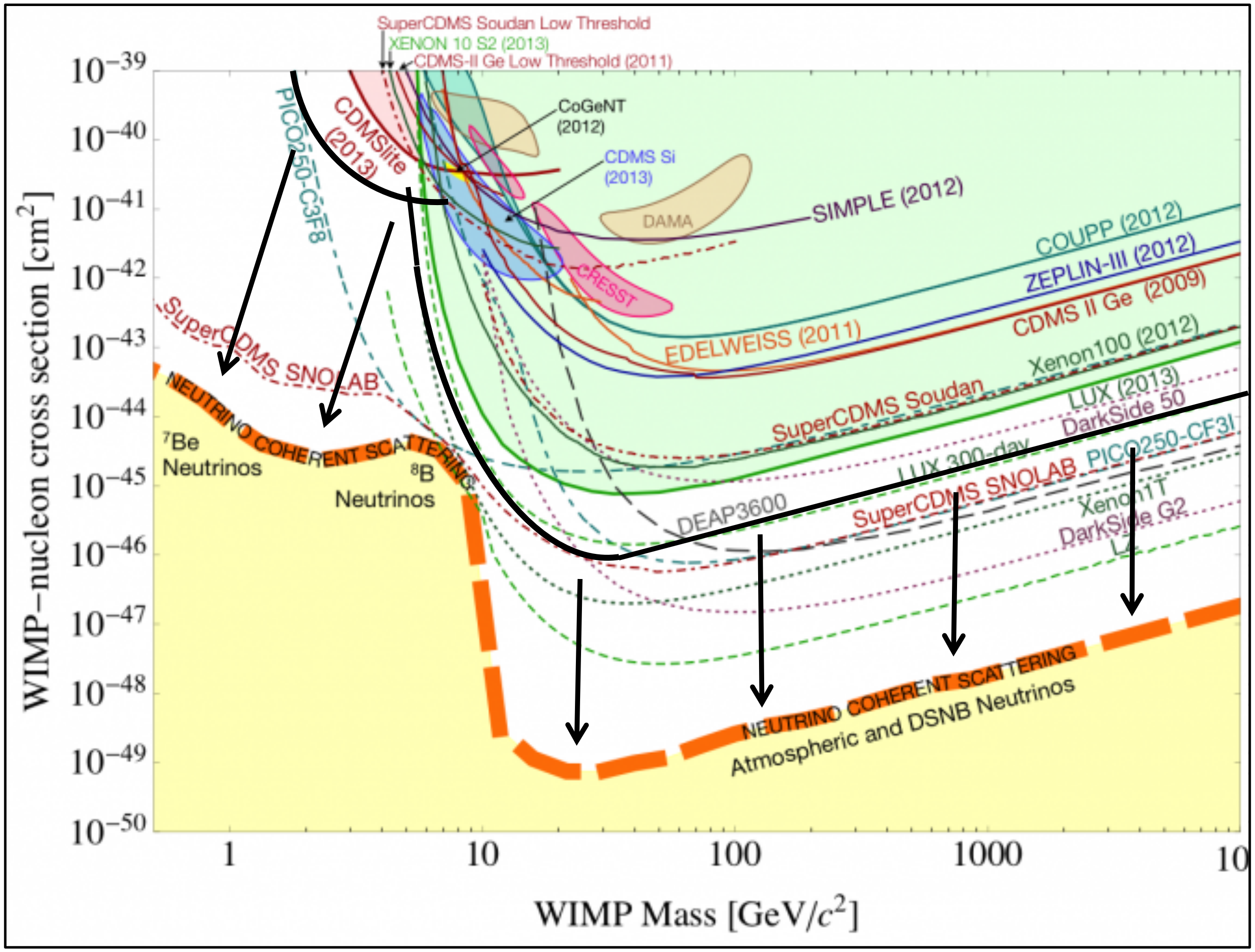
Recent Results From XENON1T, PandaX-II, CRESST-III





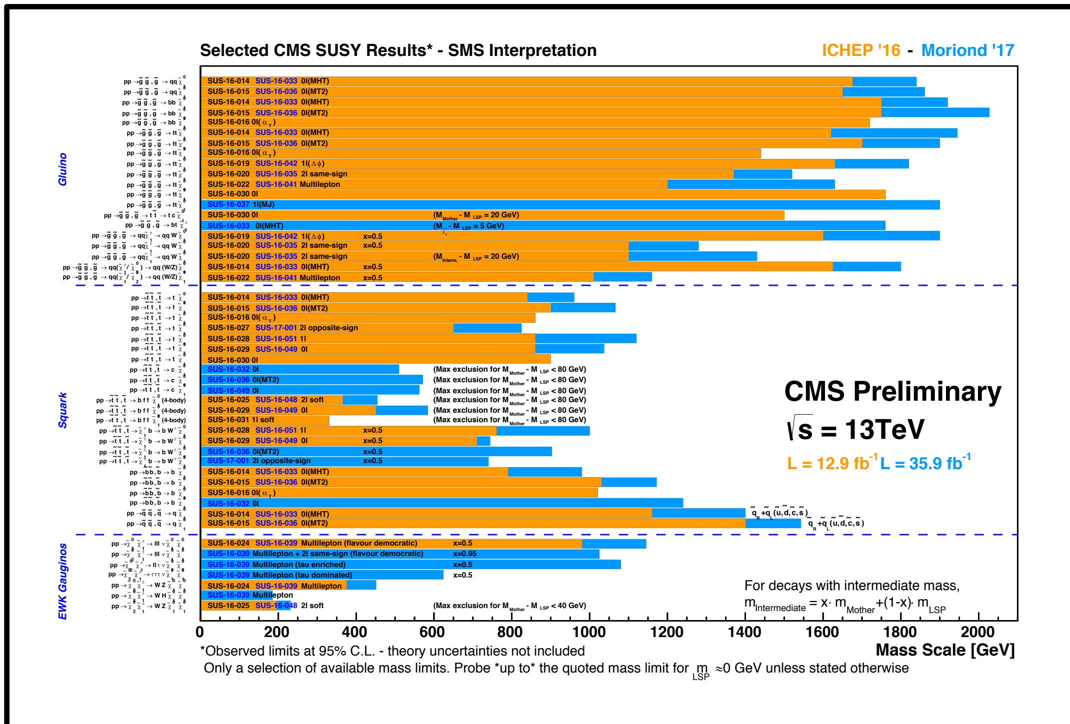


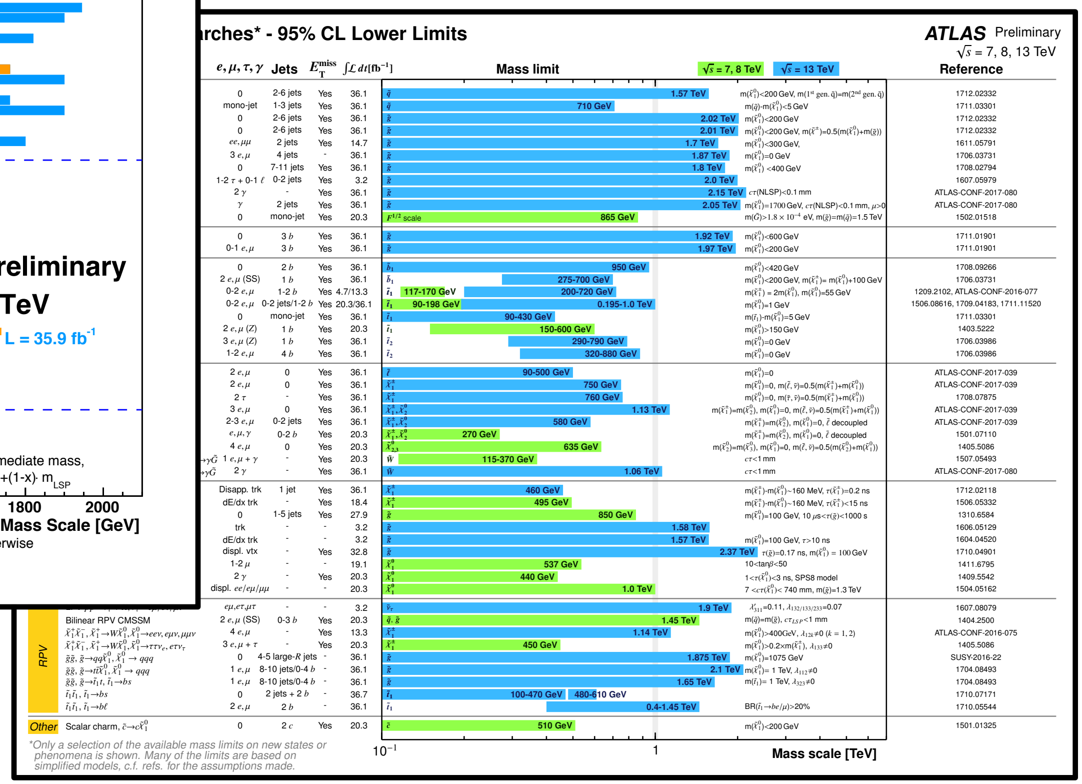
The Future of Direct Detection



Dark Matter at the LHC

- With the exception the Higgs Boson, no evidence of new physics has appeared at the Large Hadron Collider
- For the first time, much of the electroweak scale has now been explored; although there still exists room for SUSY (or your favorite EW scale theory)



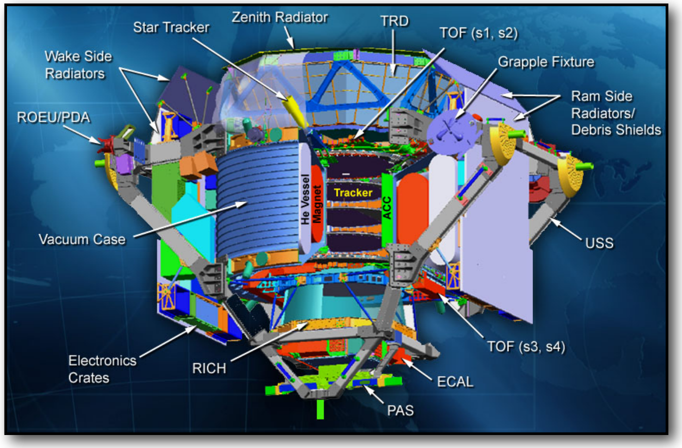


The Motivation for Indirect Searches

- To account for the observed dark matter abundance, a thermal relic must have an annihilation cross section (at freeze-out) of $\sigma v \sim 2 \times 10^{-26}$ cm^3/s
- Although many model-dependent factors can cause the dark matter to possess a somewhat lower or higher annihilation cross section today, most models predict current annihilation rates that are within an order of magnitude or so of this estimate
- Indirect detection experiments that are sensitive to dark matter annihilating at approximately this rate will be able to test a significant fraction of WIMP models

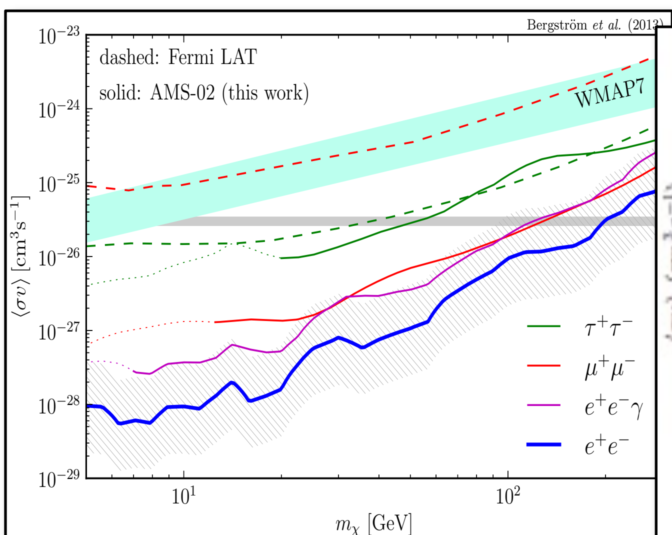
Fermi

AMS-02

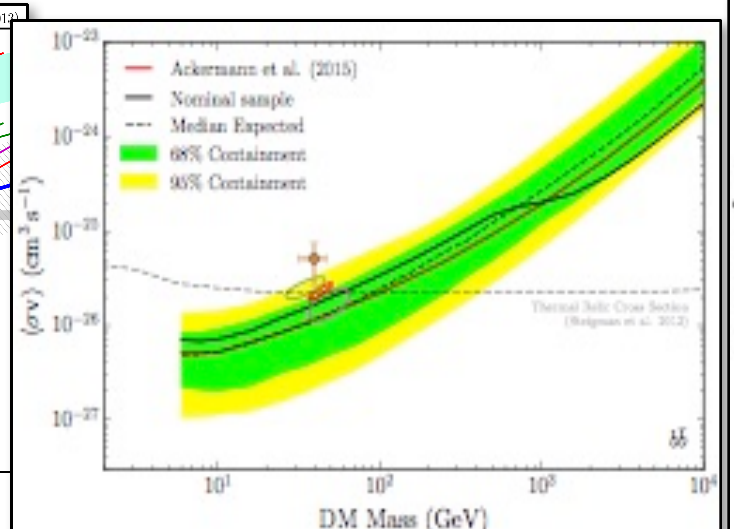


Recent Constraints from Indirect Detection

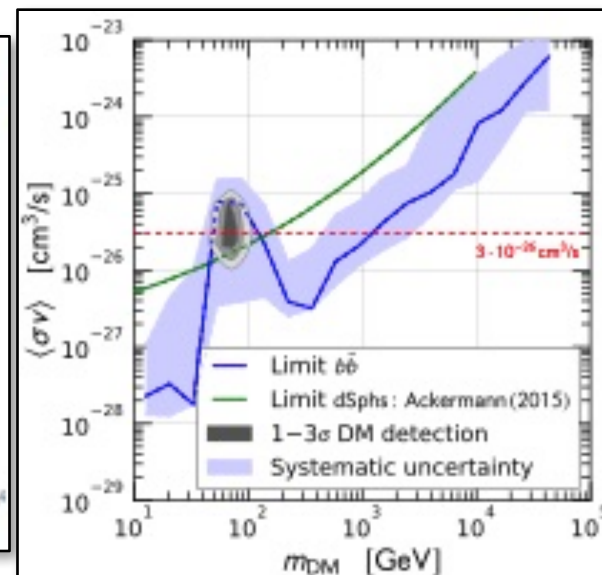
- A variety of gamma-ray strategies (GC, dwarfs, IGRB, etc.) as well as cosmic-ray antiproton and positron measurements from AMS, are sensitive to dark matter with the annihilation cross section predicted for a simple thermal relic, for masses up to ~100 GeV
- This program is not a fishing expedition, but is testing a wide range of well-motivated dark matter models – *we are testing the WIMP paradigm!*



Bergstrom, et al, arXiv:1306.3983



Fermi Collaboration, arXiv:1611.03184



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

Severely Constraining the WIMP Paradigm

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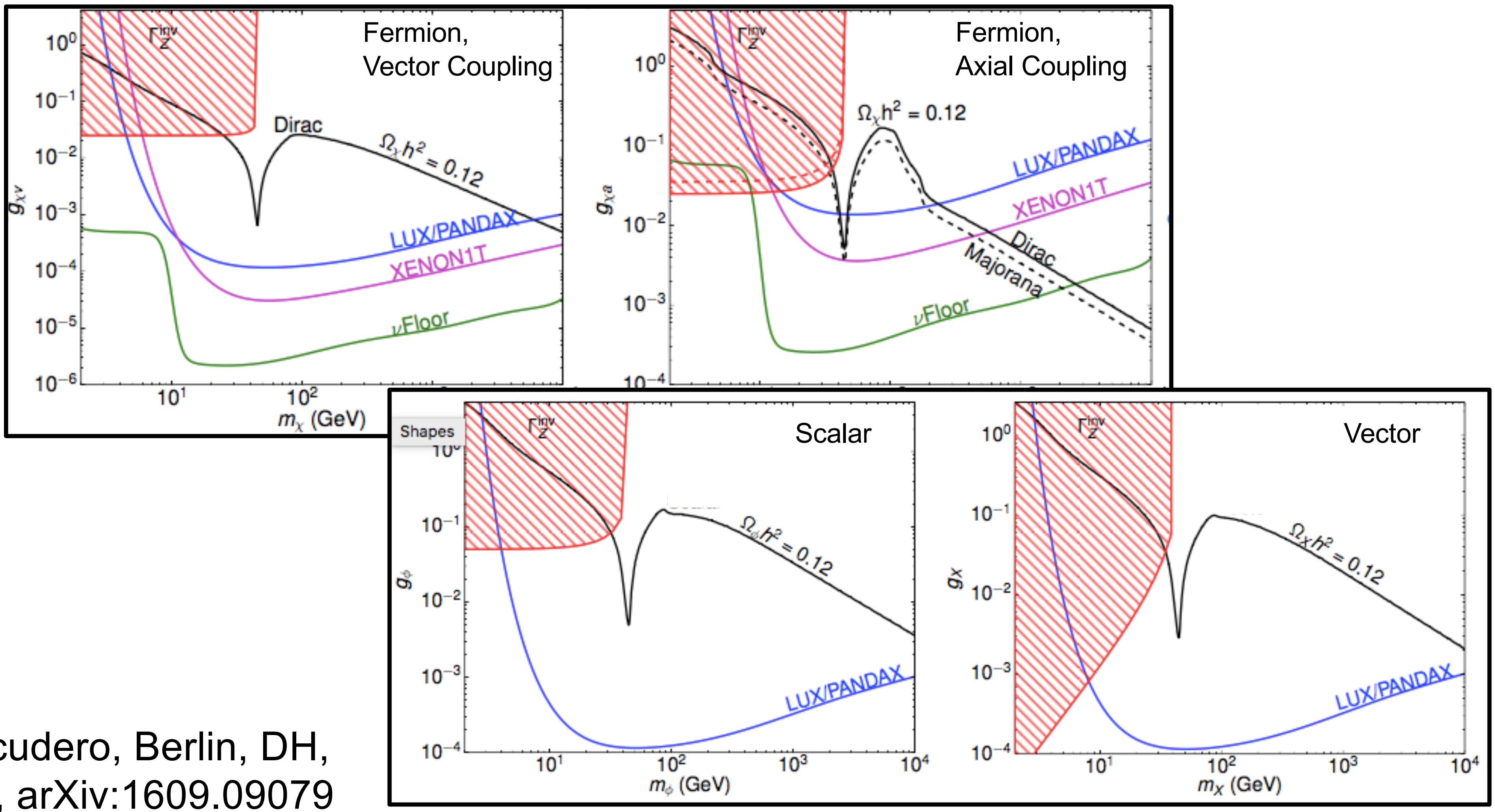

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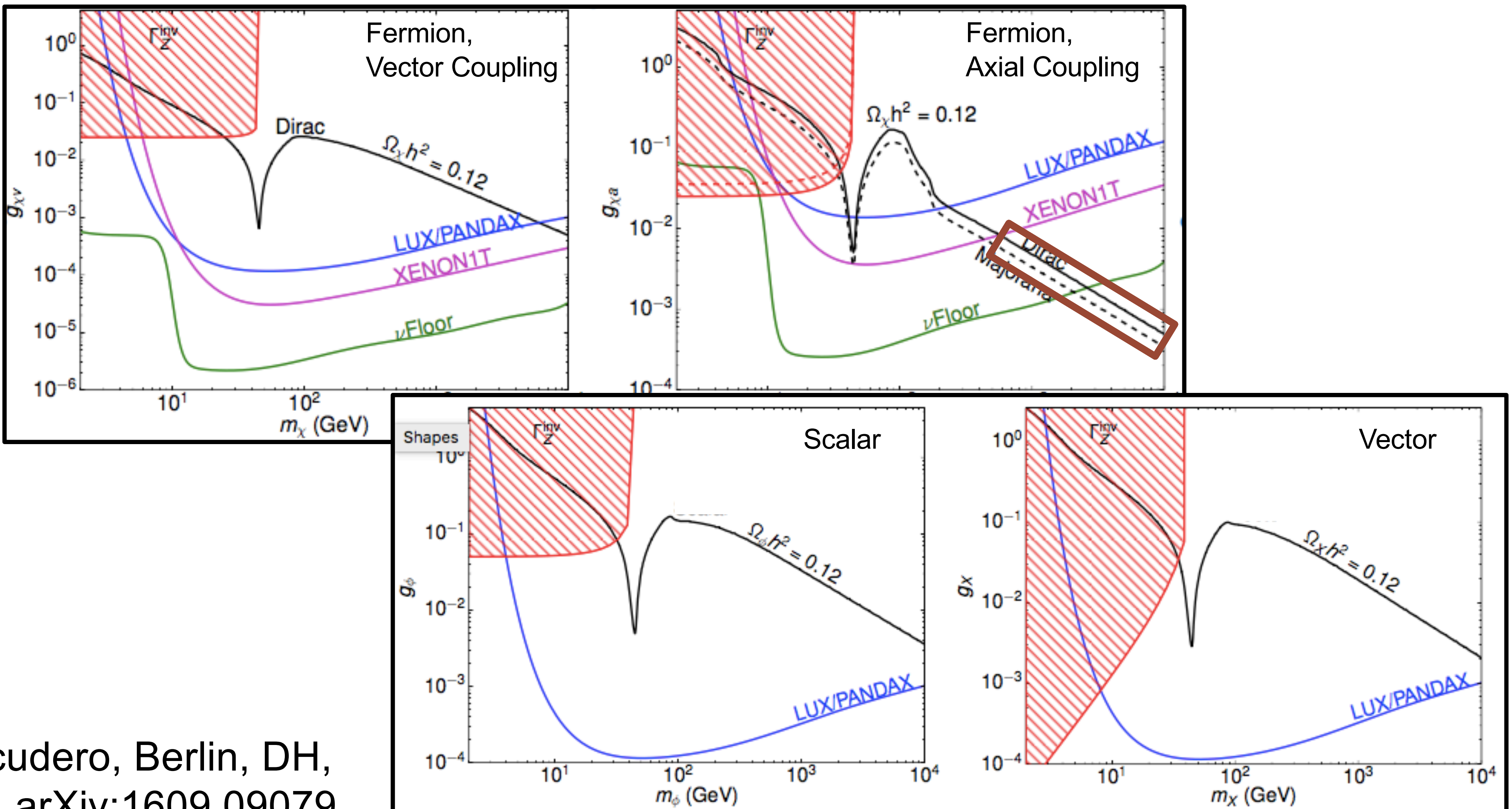

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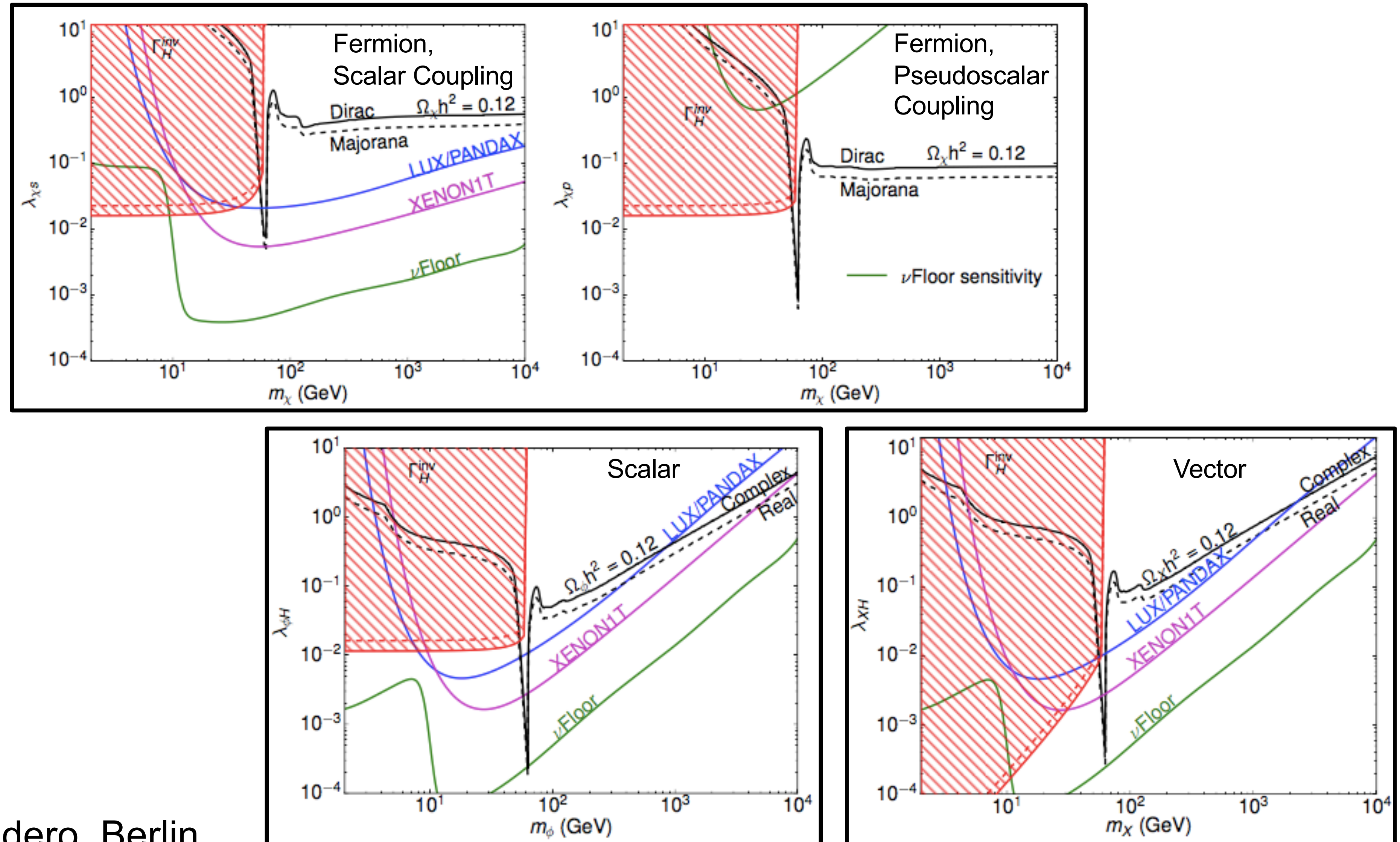
- We reach similar conclusions for Higgs mediated dark matter models:



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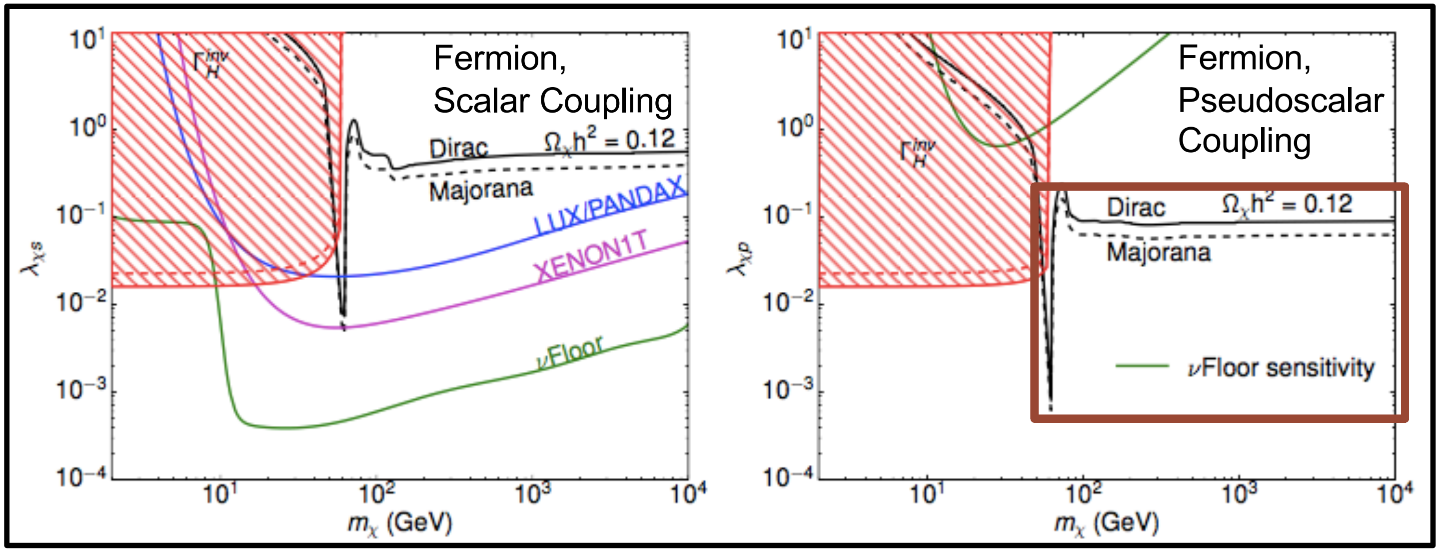

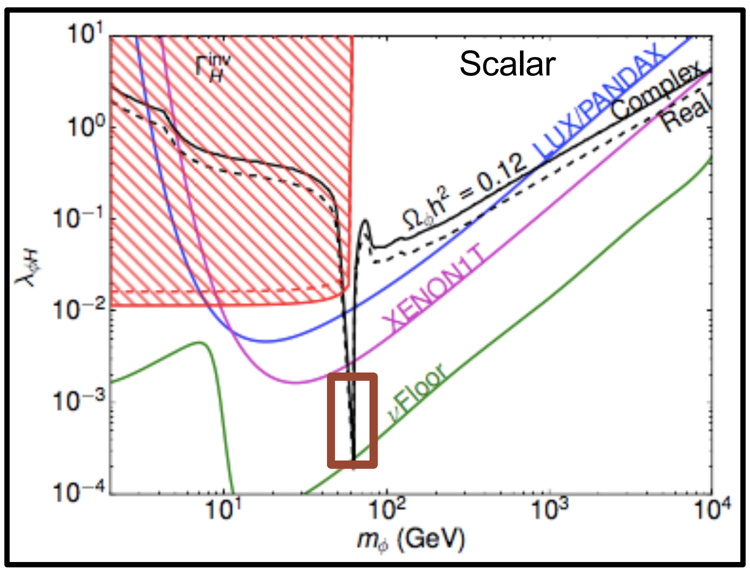

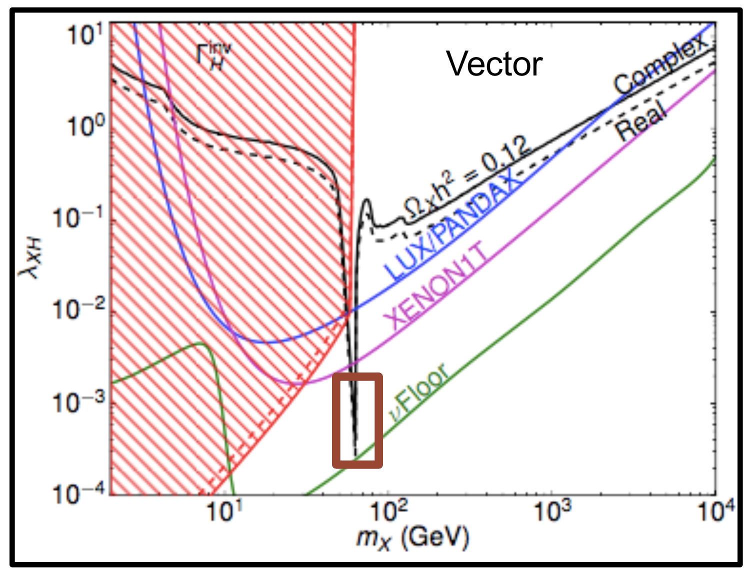

Escudero, Berlin,
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So, is the WIMP Paradigm Dead?

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No.

Despite these very stringent constraints, there remain many viable options for WIMP model building

An (Incomplete) List of Ways to Reconcile WIMP Dark Matter With All Current Constraints:

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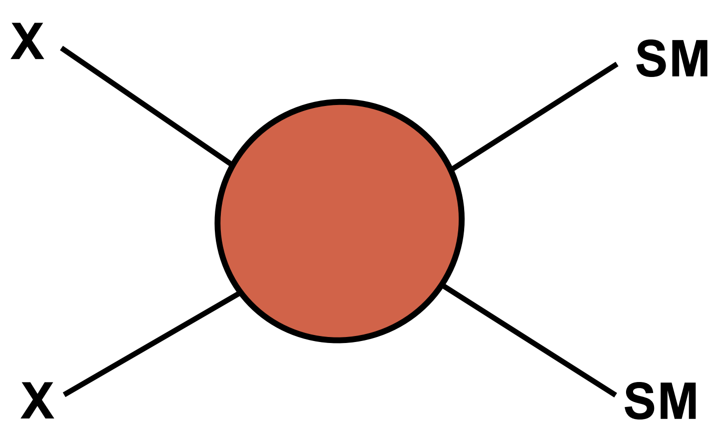
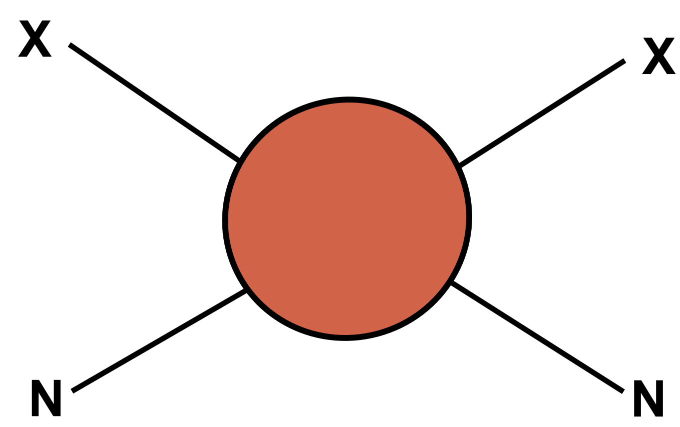
Common Theme: Mechanisms that deplete the dark matter abundance in the early universe without leading to large elastic scattering rates with nuclei or large annihilation rates in the universe today

Unsuppressed



Suppressed



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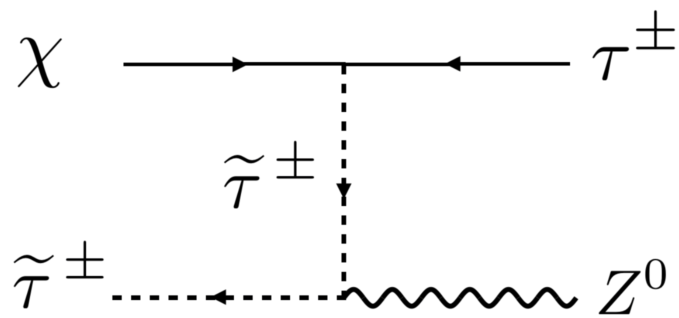

Griest, Seckel (1991)

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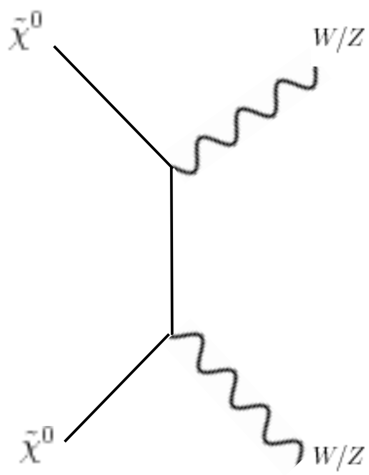

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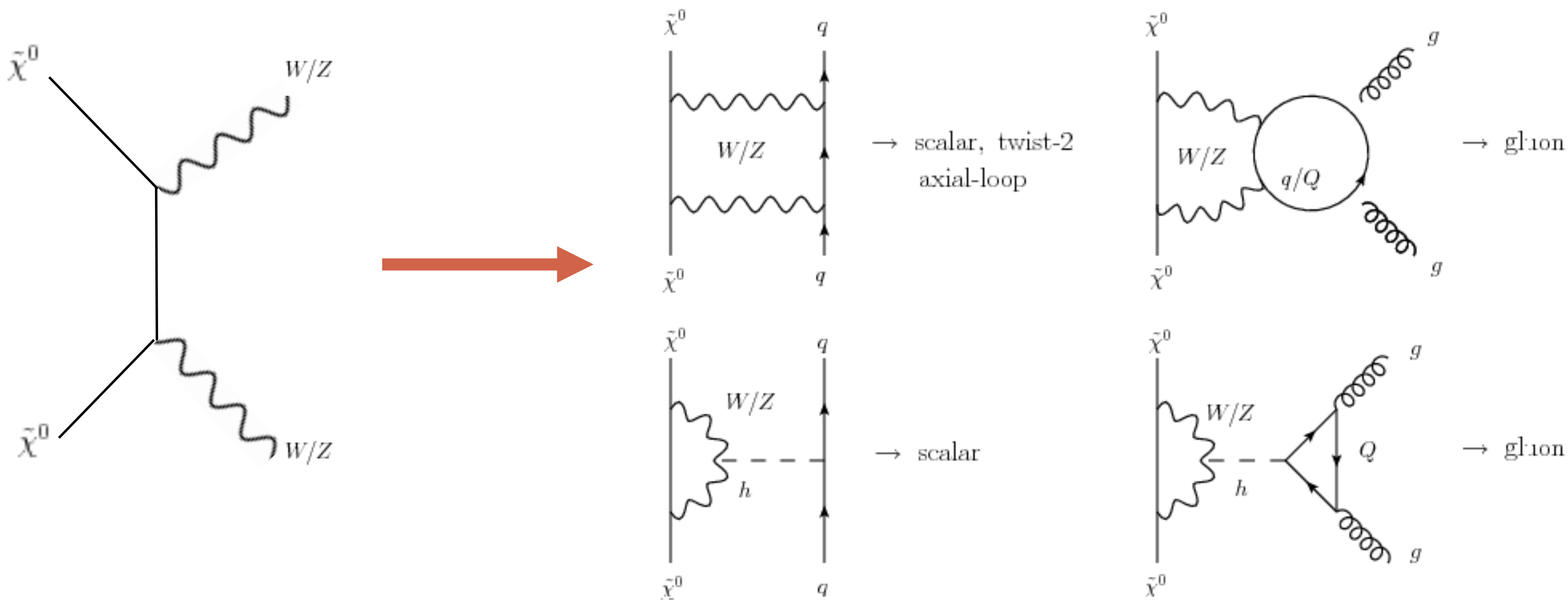

Hisano, et al., arXiv:1007.2601, 1104.0228, 1504.00915;
Hill, Solon, arXiv:1309.4092, 1409.8290;
Berlin, DH, McDermott, arXiv:1508.05390

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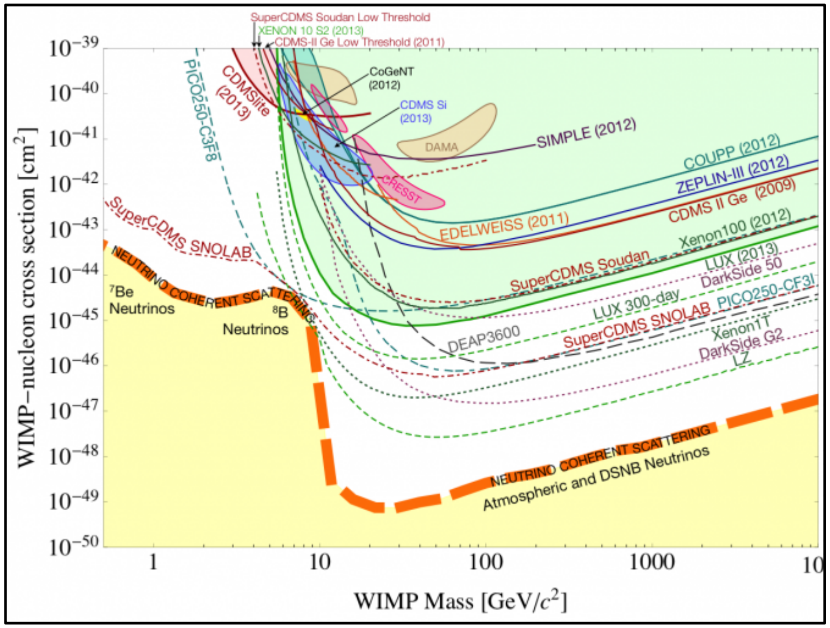
4) Dark matter that is lighter than a few GeV (evading direct constraints)



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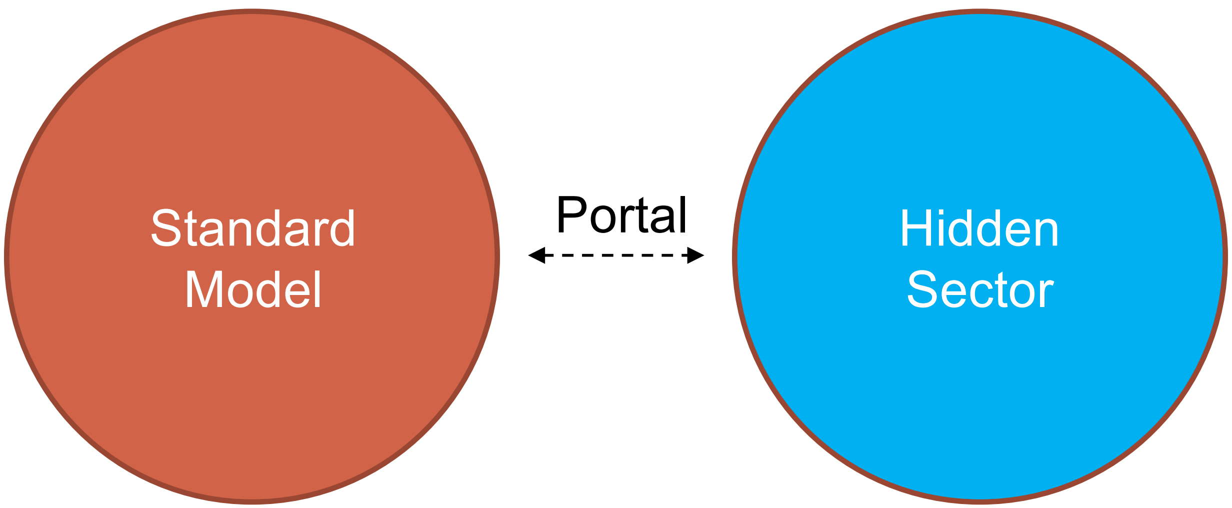
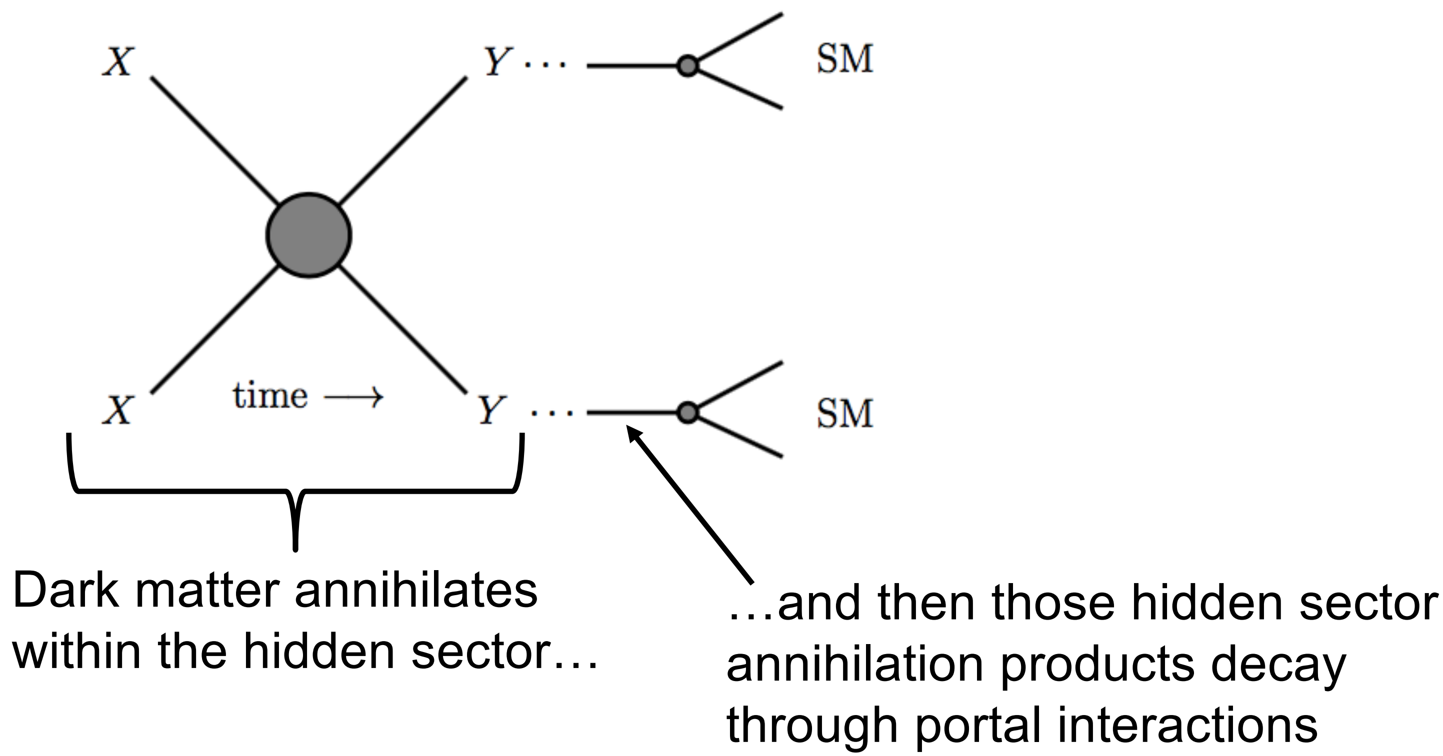
Dark Matter Within a Hidden Sector

- Lets hypothesize that the dark matter is one of several particle species within a hidden sector, which is entirely uncharged under the Standard Model
- Even without any direct couplings between these two sectors, small “portal” interactions could very plausibly have kept them in kinetic equilibrium with each other in the early universe



Dark Matter Within a Hidden Sector

- The dark matter, *X*, freezes-out of thermal equilibrium entirely within its own hidden sector (annihilating to produce lighter particles within the hidden sector, *Y*)
- These lighter hidden sector particles then decay through portal interactions into Standard Model particles



Dark Matter Within a Hidden Sector

Hidden sector dark matter models offer a number of very attractive features:

1) Elastic scattering with nuclei is highly suppressed

2) Production at colliders is highly suppressed

3) Relic abundance is easily accommodated; similar to ordinary WIMPs

4) Simple model building possibilities, including the three renormalizable "portal" interactions: the vector portal, Higgs portal, and lepton portal

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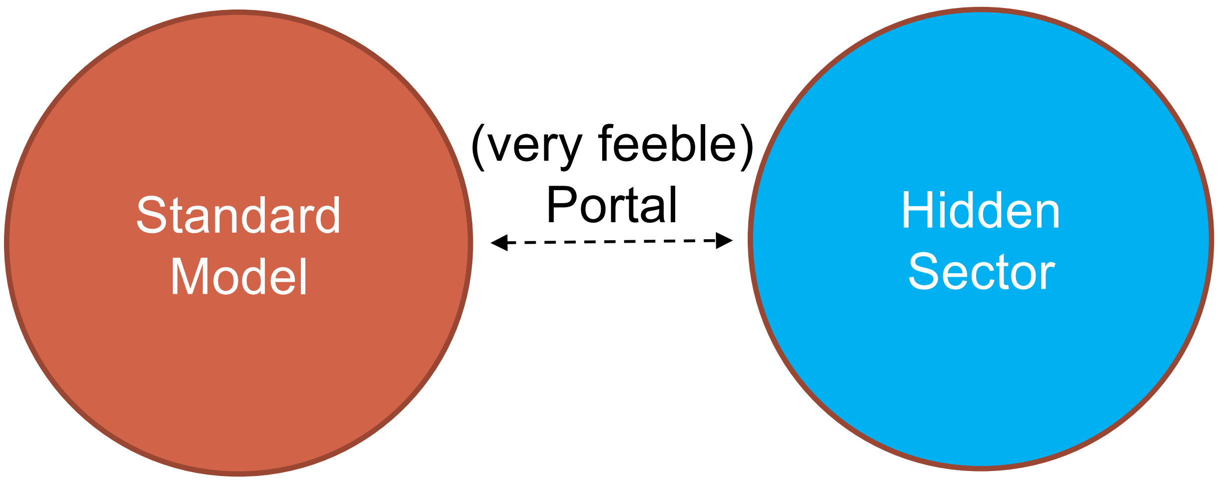
For example, consider the vector portal scenario, which is described by the following Lagrangian:

$$\mathcal{L} \supset -\frac{\epsilon}{2} B^{\mu\nu} Z'_{\mu\nu} + i g_{Z'} \, Z'_{\mu}(\phi^* \partial_\mu \phi - \phi \partial_\mu \phi^*) + g^2_{Z'} \, Z'^{\mu} Z'_{\mu} \, |\phi|^2$$

- This includes a new vector gauge boson, *Z'*, which undergoes kinetic mixing with the Standard Model photon and/or *Z*
- This portal interaction allows the *Z'* to decay into the Standard Model, but leads to negligible direct detection and collider constraints (for small ϵ)

A Well-Motivated Variant of Hidden Sector Dark Matter

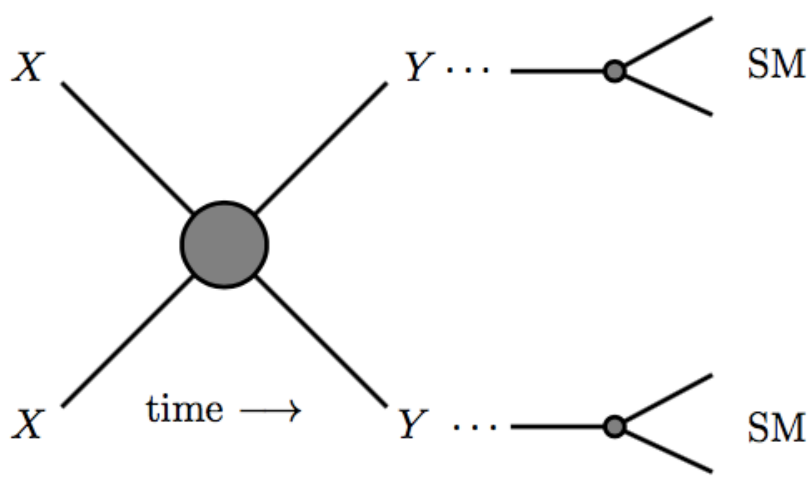
- In most discussions of hidden sector dark matter scenarios, the portal interactions are assumed to be strong enough for kinetic equilibrium to be reached between the two sectors; this need not be the case
- Lets hypothesize that the dark matter resides within a heavy (> TeV) hidden sector, which is not only uncharged under the Standard Model, but is **highly decoupled** from the Standard Model bath
- Both the Standard Model sector and the hidden sector are populated during reheating (after inflation); we treat the ratio of their initial temperatures as a free parameter and an initial condition



Berlin, DH, Krnjaic, arXiv:1609.02555, 1602.08490

A Well-Motivated Variant of Hidden Sector Dark Matter

- As the universe expands, the temperatures of the two sectors remain independent of each other, and evolve according to entropy conservation
- The dark matter freezes-out of thermal equilibrium entirely within its own hidden sector, annihilating to produce lighter particles within the hidden sector, which become non-relativistic and evolve to increasingly dominate the energy density of the early universe
- When this hidden sector state ultimately decays, it can reheat the universe, diluting the abundances of any relics, including dark matter



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Dark Matter Within a Heavy Decoupled Hidden Sector

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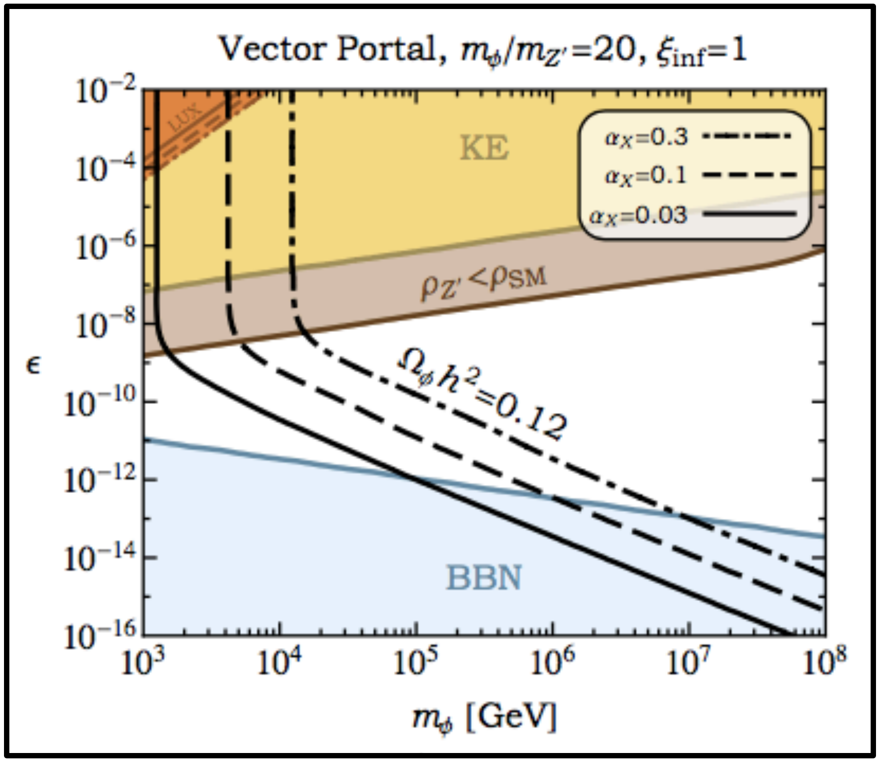

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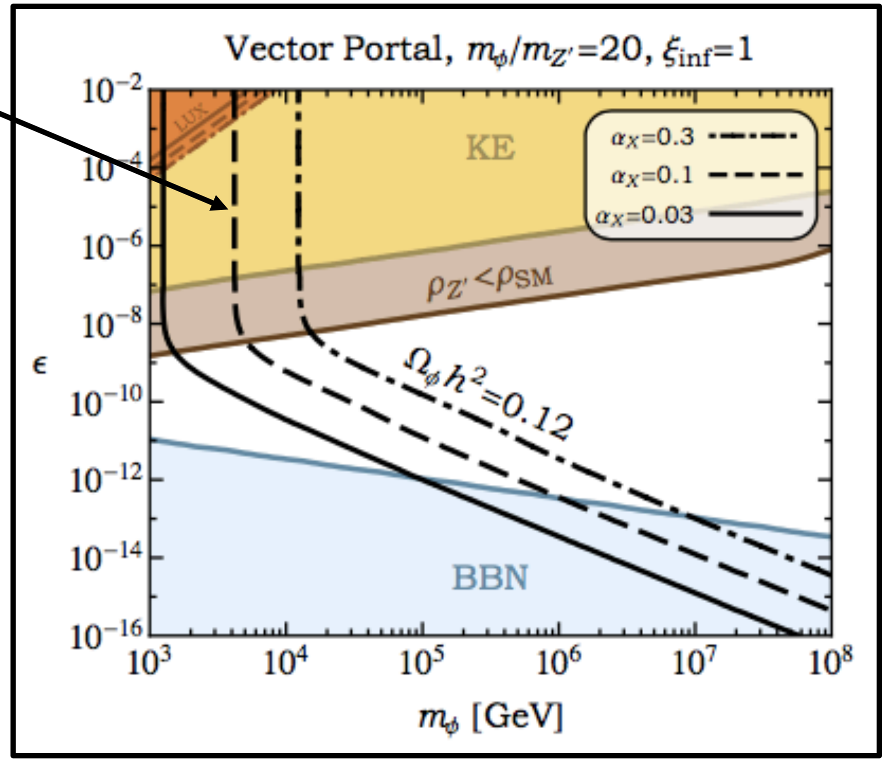
- For a sizeable portal interaction strength (ϵ ~10^{-7} or higher), kinetic equilibrium between the sectors is reached, and the early universe undergoes a standard thermal history

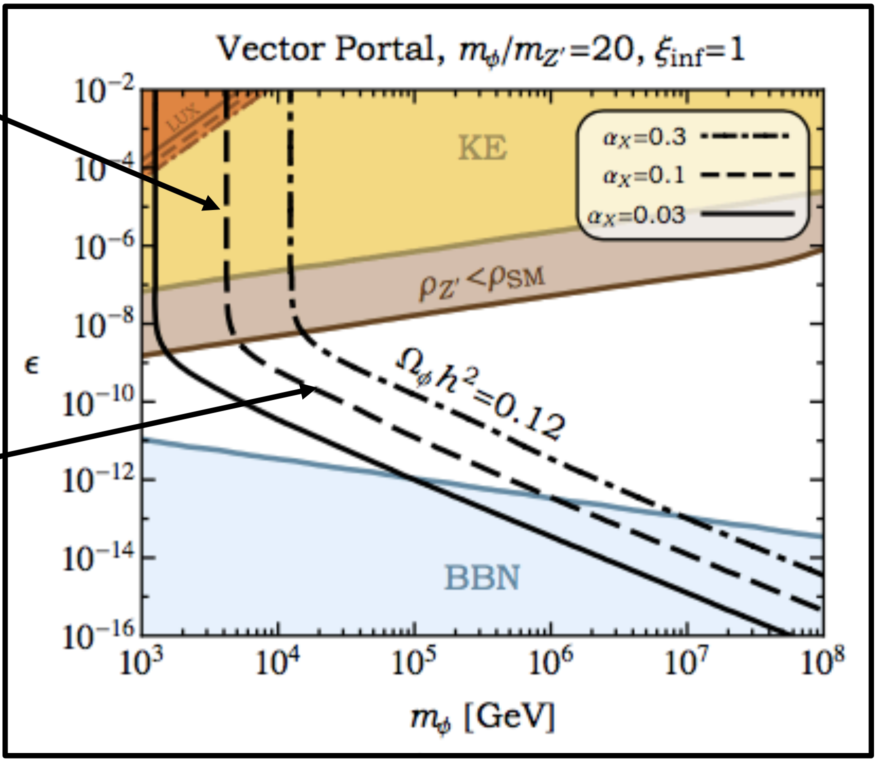


Berlin, DH, Krnjaic, arXiv:1609.02555, 1602.08490

Dark Matter Within a Heavy Decoupled Hidden Sector

Here's an example of a vector portal dark matter scenario:

- For a sizeable portal interaction strength (ϵ ~10^{-7} or higher), kinetic equilibrium between the sectors is reached, and the early universe undergoes a standard thermal history
- For very weak portal interactions, however, there is an early matter-dominated era, followed by late-time reheating
- This dilution can easily facilitate an acceptable dark matter abundance for masses as high as ~10-100 PeV; well outside of the range of a classical WIMP



Berlin, DH, Krnjaic, arXiv:1609.02555, 1602.08490

Prospects Moving Forward?

I've just listed many ways in which the dark matter's detection prospects can be almost arbitrarily suppressed

Does this mean that efforts to detect dark matter particles could be doomed from the start?

An (Incomplete) List of Ways to Reconcile WIMP Dark Matter With All Current Constraints:

1) Co-annihilations between the dark matter and another state

2) Annihilations to W, Z and/or Higgs bosons; scattering with nuclei only through highly suppressed loop diagrams

3) Interaction which suppress elastic scattering with nuclei by powers of velocity or momentum

4) Dark matter that is lighter than a few GeV (evading direct constraints)

5) Departures from radiation domination in the early universe (early matter domination; late-time reheating, etc.) which result in the depletion of the dark matter's relic abundance

6) The dark matter annihilates to unstable non-Standard Model states (*ie*. hidden sector models)

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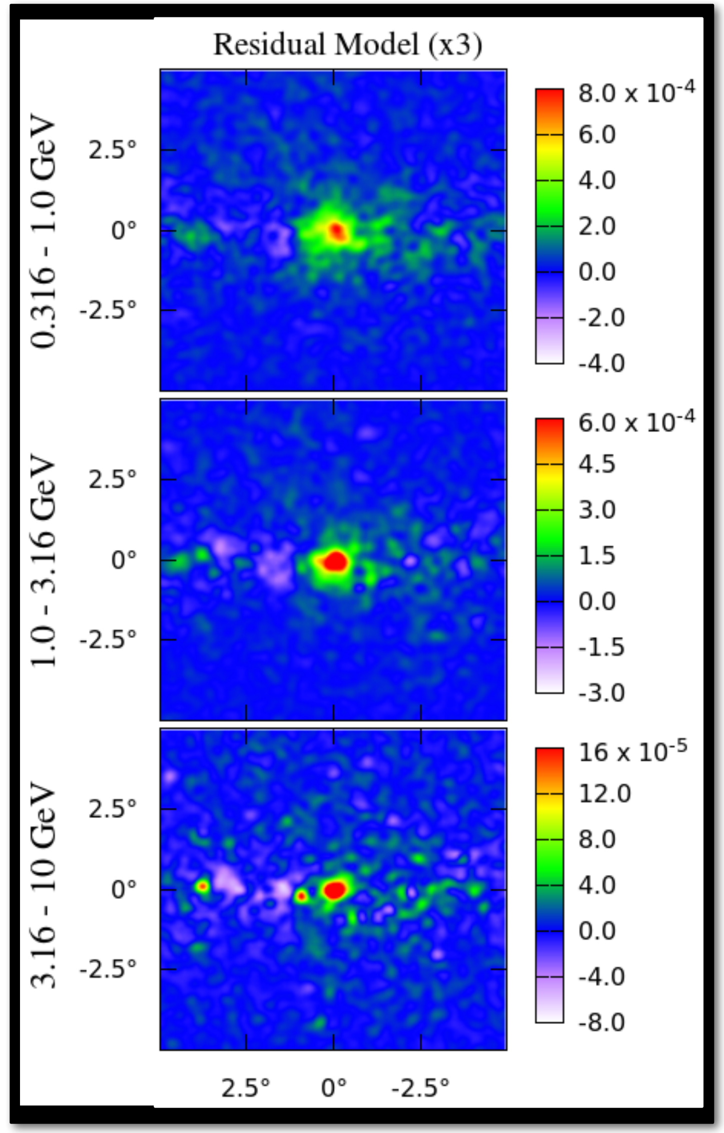
Although potentially invisible to both underground detectors and colliders, many of these scenarios are testable with indirect searches

In this sense, the lack of such signals has strengthened the motivation for gamma ray, cosmic ray and neutrino searches for dark matter

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
- This signal is difficult to explain with astrophysical sources or mechanisms, but is very much like the signal predicted from annihilating dark matter

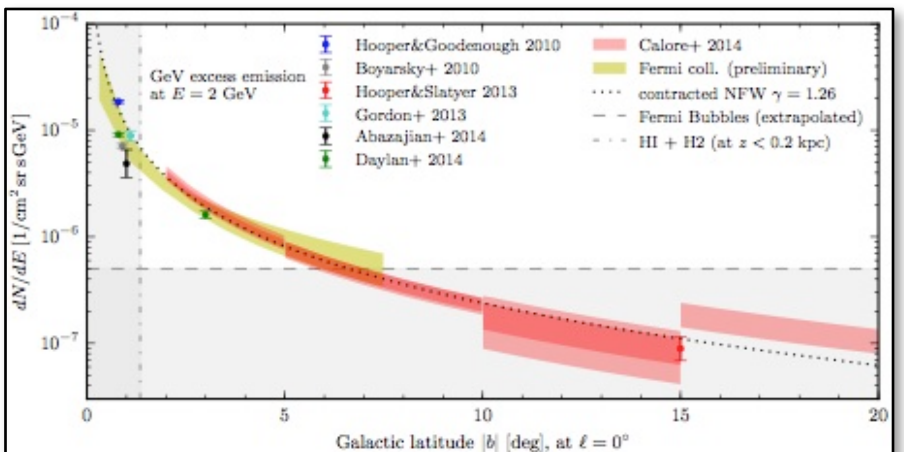


Among other references, see:

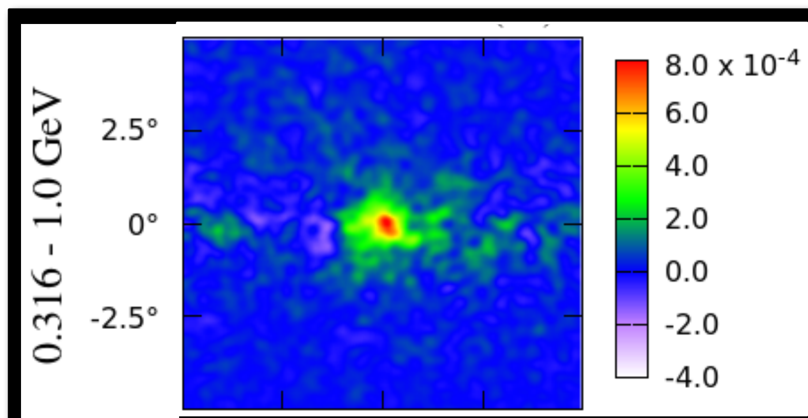
DH, Goodenough (2009, 2010)
DH, Linden (2011)
Abazajian, Kaplinghat (2012)
Gordon, Macias (2013)
Daylan, et al, (2014)
Calore, Cholis, Weniger (2014)

Morphology

- The GeV excess exhibits approximate spherical symmetry about the Galactic Center (axis ratios within ~20% of unity), with a flux that falls as $\sim r^{-2.4}$ between ~0.06° and ~10°
- If interpreted as annihilating dark matter, this implies $\rho_{DM} \sim r^{-1.2}$ between ~10 pc and ~1.5 kpc, only slightly steeper than the canonical NFW profile
- Unlike stellar populations, we expect dark matter annihilation products to exhibit approximate spherical symmetry (see, for example, Bernal, Necib and Slatyer, arXiv:1606.00433)



Calore, Cholis, Weniger (2014)

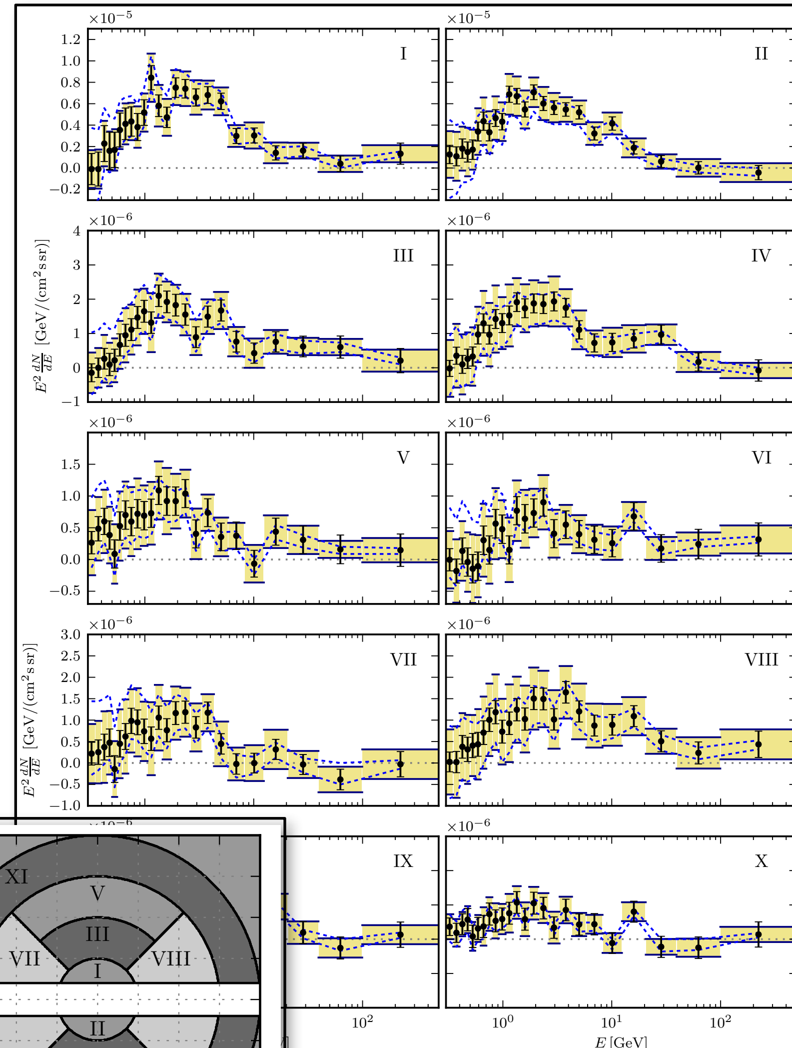


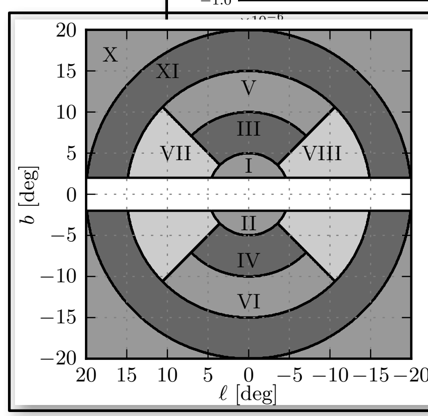
Daylan, et al. (2014)

Spectrum

- The spectrum of the excess is well fit by a ~20-65 GeV particle annihilating to quarks or gluons (and also by a wide range of hidden sector dark matter models)
- The shape of the spectrum appears to be uniform across the Inner Galaxy

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

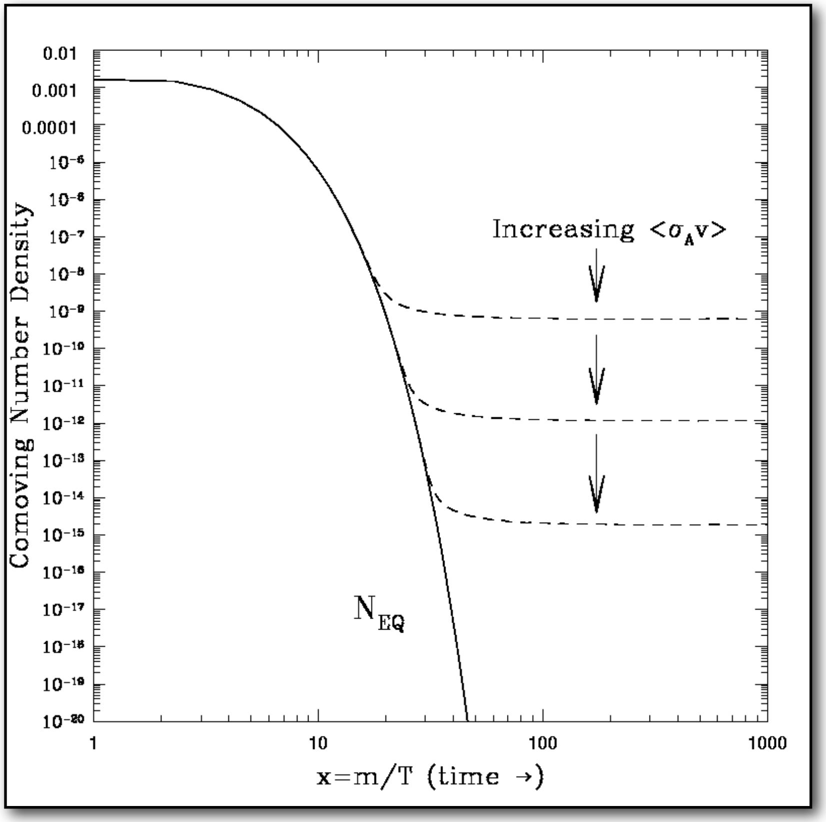




Calore, Cholis, Weniger; Calore, Cholis, McCabe, Weinger (2014); Escudero, Witte, DH, arXiv:1709.07002

Intensity

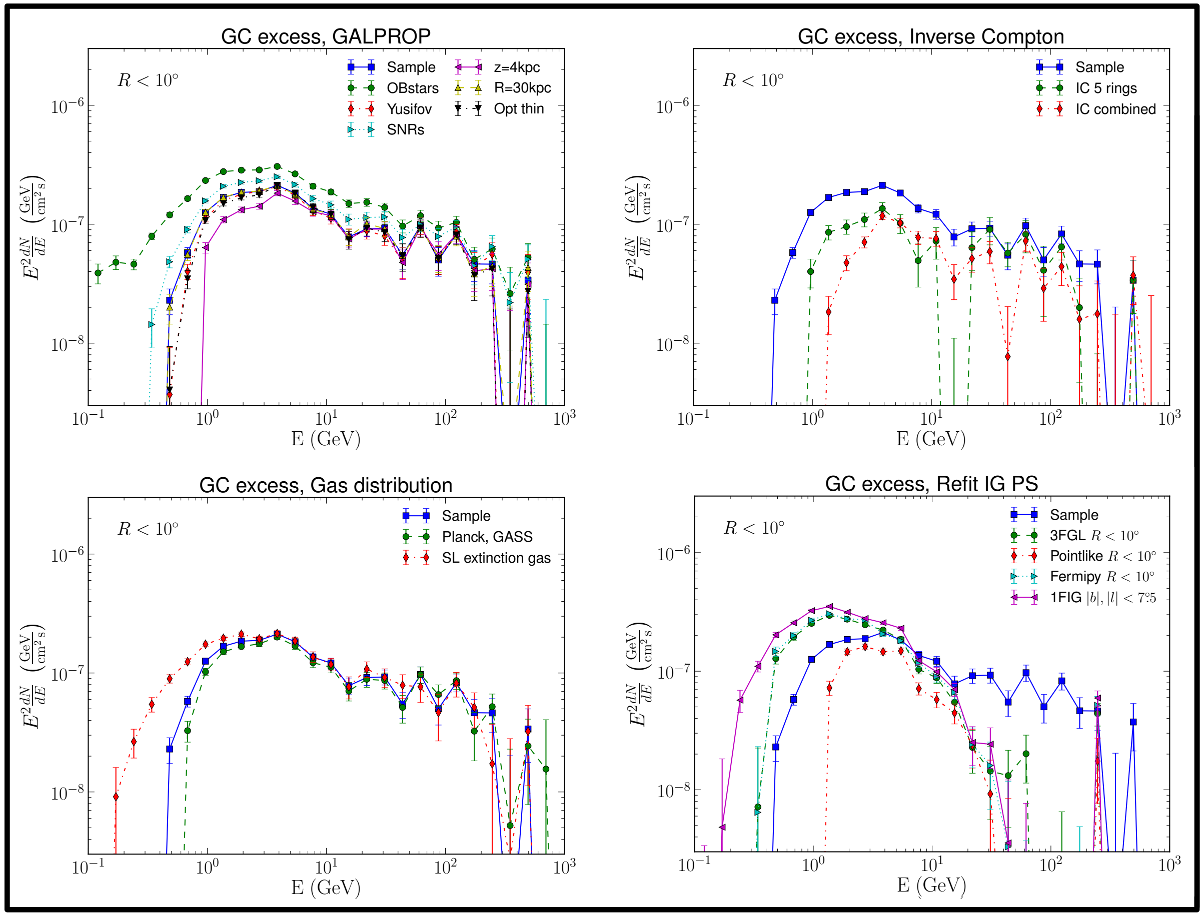
- To normalize the observed excess, the dark matter particles must annihilate with a cross section of $\sigma v \sim 10^{-26}$ cm^3/s
- This is approximately equal to the value of the cross section that is required to generate the measured dark matter abundance through thermal freeze-out in the early universe



From The Fermi Collaboration

The Fermi Collaboration has presented two papers on this subject, each reporting an excess with a similar spectrum and morphology

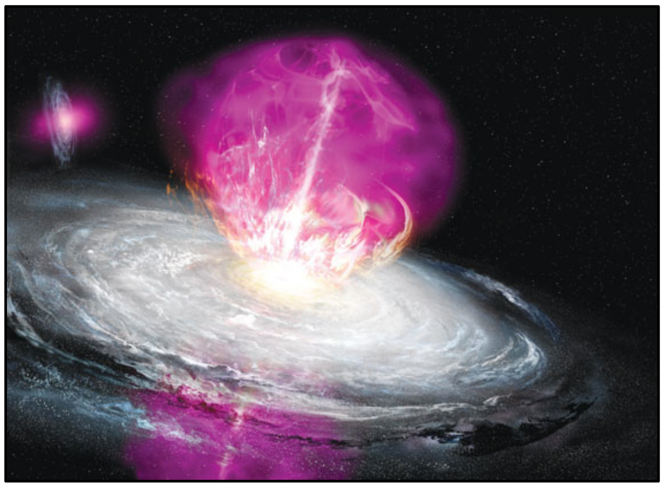
The Bottom Line:
The excess persists across the entire range of models considered, although the modeling of point sources and the Fermi Bubbles can non-negligibly impact the spectral shape of the excess

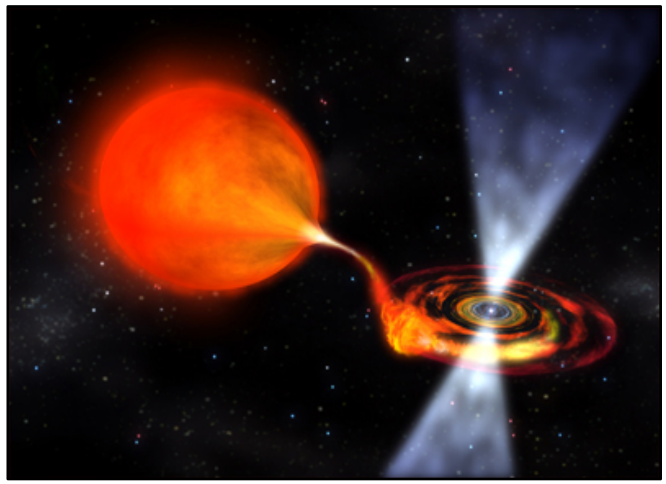


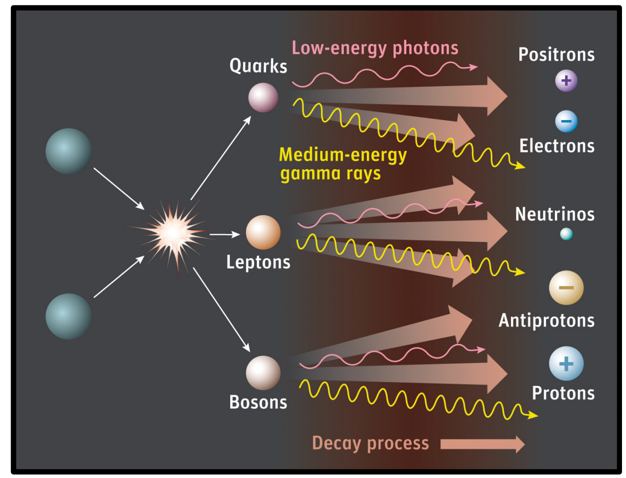
Murgia, et al. arXiv:1511.02938;
Ackermann et al. arXiv:1704.03910

What Produces the Excess?

- A recent outburst of cosmic rays?
- A large population of centrally located millisecond pulsars?
- Annihilating dark matter?

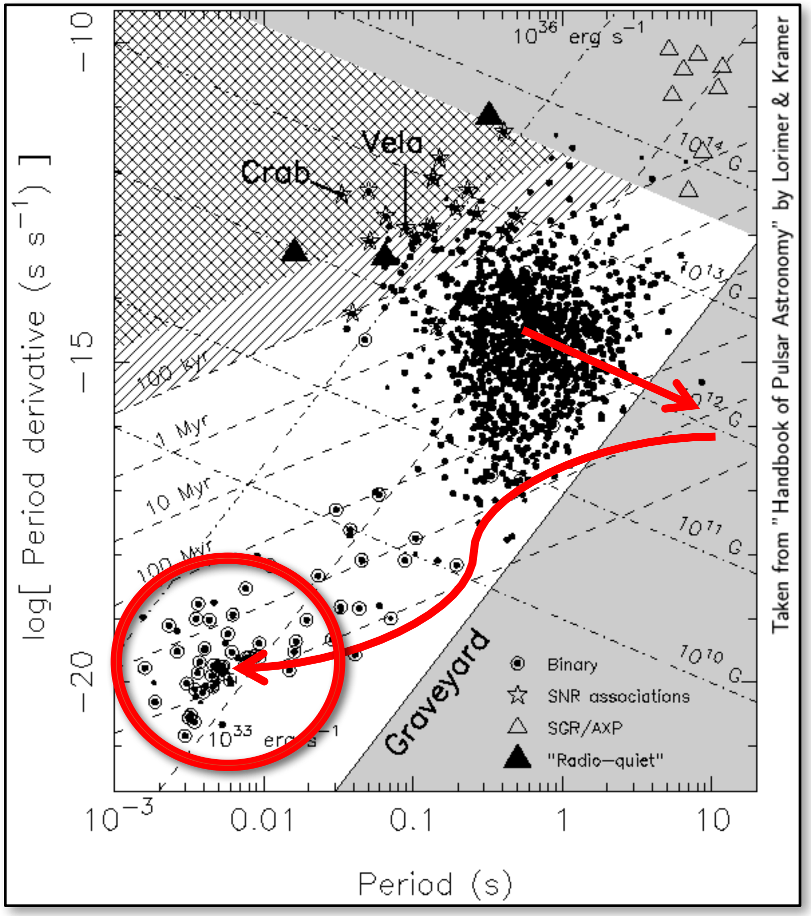


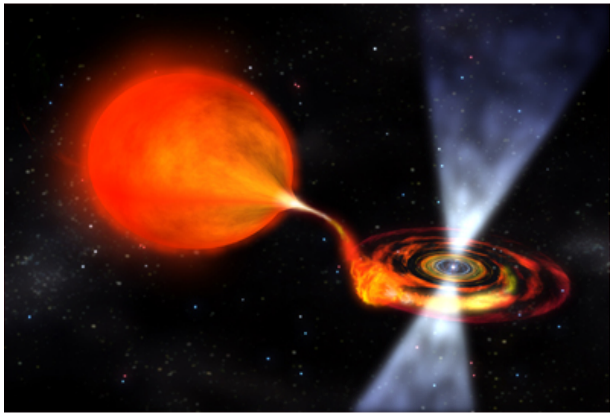




Millisecond Pulsars

- Pulsars are rapidly spinning neutron stars, which gradually convert their rotational kinetic energy into radio and gamma-ray emission
- 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 ms
- Such millisecond pulsars have low magnetic fields (~10^8-10^9 G) and thus spin down much more gradually, remaining bright for >10^9 years
- It seems plausible that large numbers of MSPs could exist near the Galactic Center





Dark Matter vs. Pulsars

In Favor of Pulsars:

In Favor of Annihilating Dark Matter:

Dark Matter vs. Pulsars

In Favor of Pulsars:

- The gamma-ray spectrum of observed pulsars

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- The morphology, intensity and spectrum of the excess

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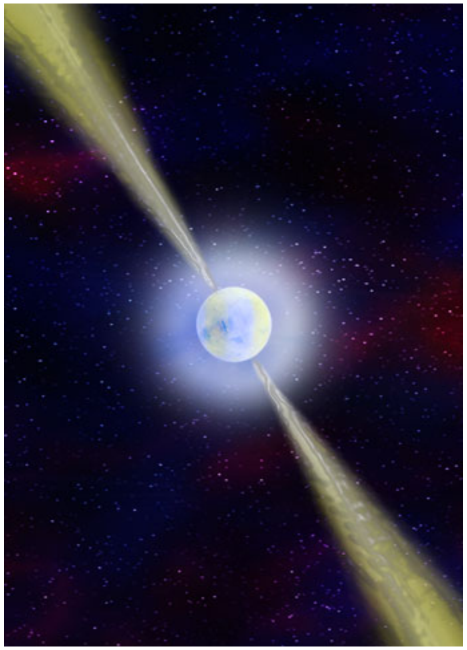

In Favor of Pulsars:

- The gamma-ray spectrum of observed pulsars
- Pulsars are actually known to exist

In Favor of Annihilating Dark Matter:

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Dark Matter vs. Pulsars

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- The morphology, intensity and spectrum of the excess
- The lack of bright gamma-ray pulsars in the Inner Galaxy
- The lack of low-mass X-ray binaries in the Inner Galaxy

(arXiv:1407.5625, 1407.5583, 1512.04966, 1606.09250)
(arXiv:1701.04406)

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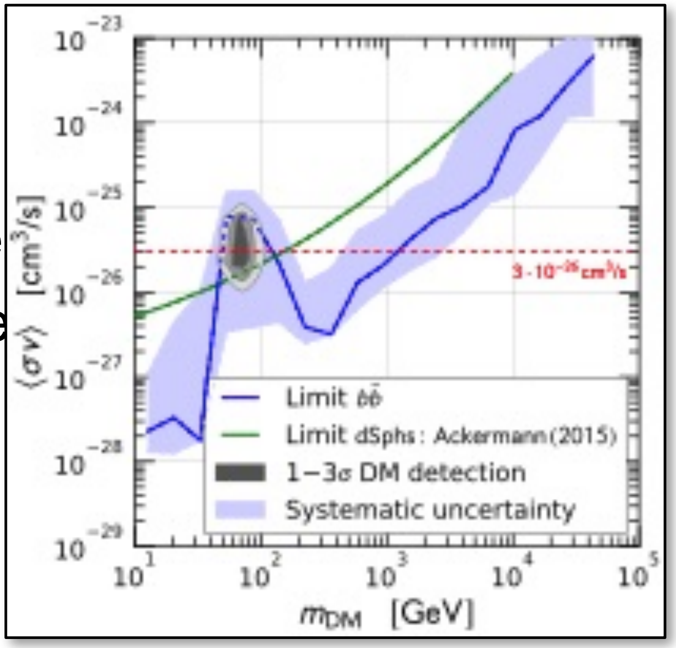


Cuoco, Kramer, Korsmeier, arXiv:1610.03071
Cui, Yuan, Tsai, Fan, arXiv:1610.03840

Dark Matter vs. Pulsars

In Favor of Pulsars:

- The gamma-ray spectrum of observed pulsars
- Pulsars are actually known to exist
- Small-scale power in the gamma-ray emission from the Inner Galaxy

In Favor of Annihilating Dark Matter:

- The morphology, intensity and spectrum of the excess
- The lack of bright gamma-ray pulsars in the Inner Galaxy
- The lack of low-mass X-ray binaries in the Inner Galaxy
- An excess of cosmic-ray antiprotons?

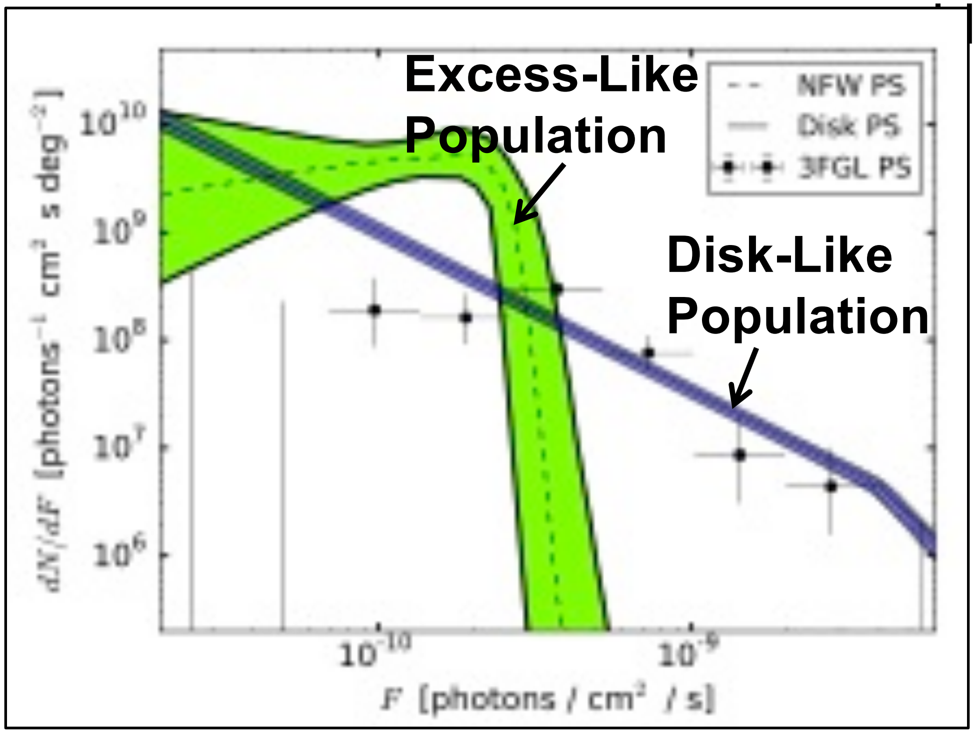
Evidence For Unresolved Point Sources?

Two groups have found 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

Their conclusions include the following:

1) The brightest sources are distributed along the disk

2) The fit suggests that the GeV excess may be generated by ~10^3 unresolved sources, most with a flux near Fermi's detection threshold



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

Evidence For Unresolved Point Sources?

- 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

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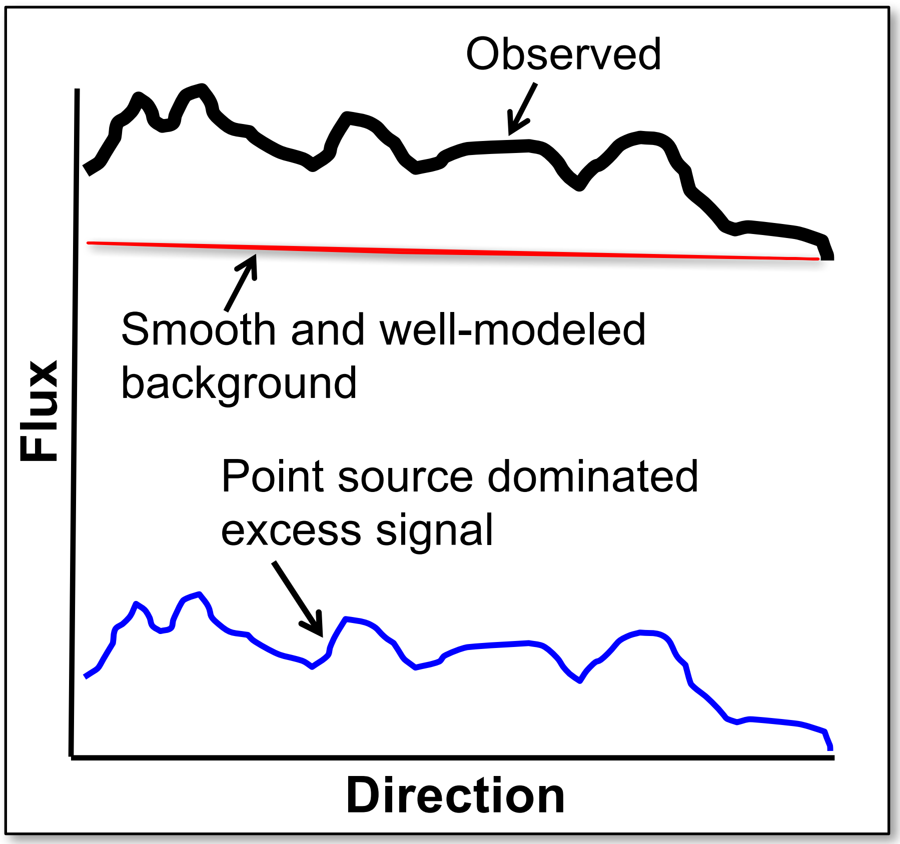

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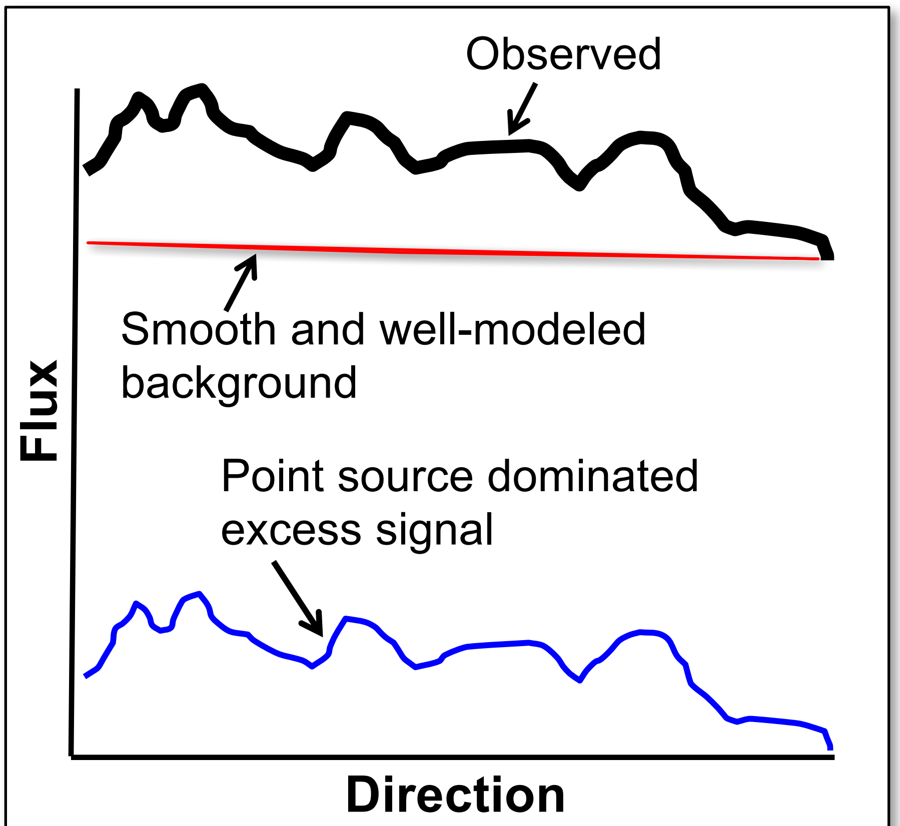

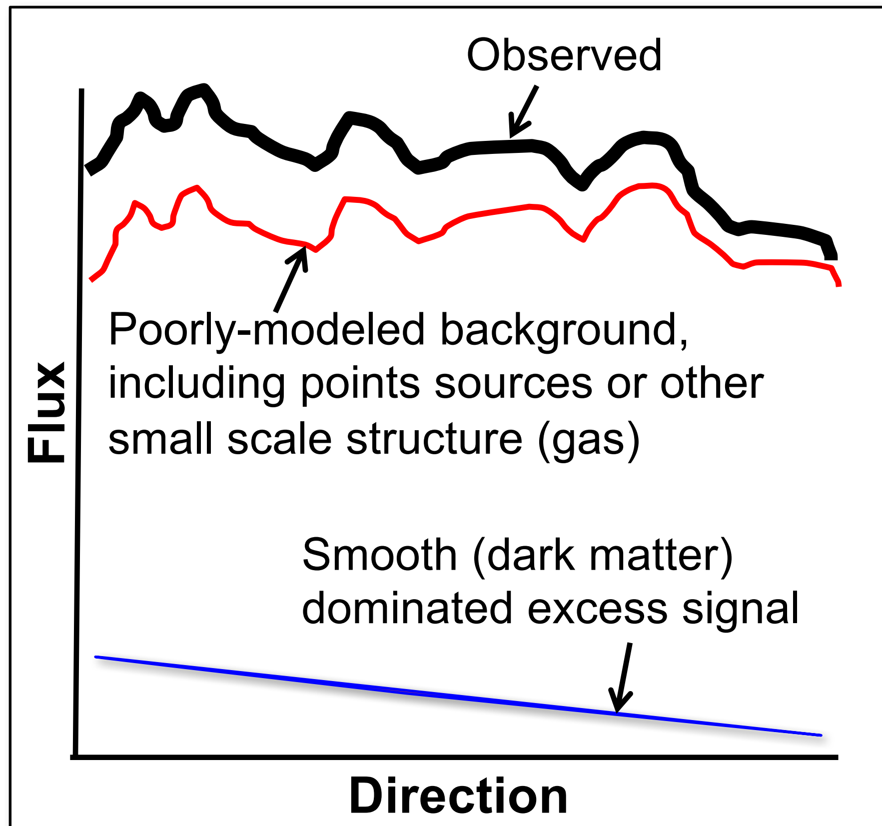

Evidence For Unresolved Point Sources?

- 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

Lee, Lisanti, Safdi, Slatyer, Xue, arXiv:1506.05124
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Evidence For Unresolved Point Sources?

- 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
- Gamma-ray point source identification is difficult in the Galactic Center region – even for bright sources – and the contents of source catalogs depend strongly on how one treats diffuse backgrounds (compare, for example, Fermi's Third Source Catalog to Fermi's First or Second Inner Galaxy Source Catalogs)

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

Evidence of a Central Pulsar Population?

- In May, the Fermi Collaboration posted a paper which purported to present strong evidence (~7$\boldsymbol{\sigma}$) for a large centrally located pulsar population
- Taken at face value, this result would seem to resolve the question at hand, favoring pulsars over a dark matter interpretation of the GeV excess

CHARACTERIZING THE POPULATION OF PULSARS IN THE GALACTIC BULGE WITH THE *FERMI* LARGE AREA TELESCOPE.

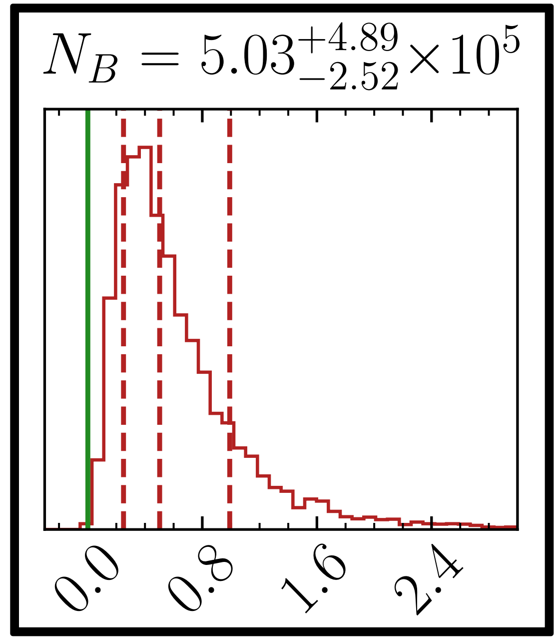
ABSTRACT

An excess of γ-ray emission from the Galactic Center (GC) region with respect to predictions based on a variety of interstellar emission models and γ-ray source catalogs has been found by many groups using data from the *Fermi* Large Area Telescope (LAT). Several interpretations of this excess have been invoked. In this paper we test the interpretation that the excess is caused by an unresolved population of γ-ray pulsars located in the Galactic bulge. We use cataloged LAT sources to derive criteria that efficiently select pulsars with very small contamination from blazars. We search for point sources in the inner $40^\circ \times 40^\circ$ region of the Galaxy, derive a list of approximately 400 sources, and apply pulsar selection criteria to extract pulsar candidates among our source list. We also derive the efficiency of these selection criteria for γ-ray pulsars as a function of source energy flux and location. We demonstrate that given the observed spatial and flux distribution of pulsar candidates, a model that includes a population with about 2.7 γ-ray pulsars in the Galactic disk (in our $40^\circ \times 40^\circ$ analysis region) for each pulsar in the Galactic bulge is preferred at the level of 7 standard deviations with respect to a disk-only model. The properties of these disk and bulge pulsar populations are consistent with the population of known γ-ray pulsars as well as with the spatial profile and energy spectrum of the GC excess. Finally, we show that the dark matter interpretation of the GC excess is strongly disfavored since a distribution of dark matter is not able to mimic the observed properties of the population of sources detected in our analysis.

Fermi Collaboration, arXiv:1705.00009

Evidence of a Central Pulsar Population?

- In examining this paper, my collaborators and I found that we were unable to reproduce these results; our fit favored only a ~2**σ** preference for a central source component
- As a result of the ensuing discussions with the Fermi Collaboration, an error was identified in their code, and a replacement (v2) of their paper was posted in conjunction with our paper



Bartels, DH, Linden, Mishra-Sharma, Rodd, Safdi, Slatyer, arXiv:1710.10266

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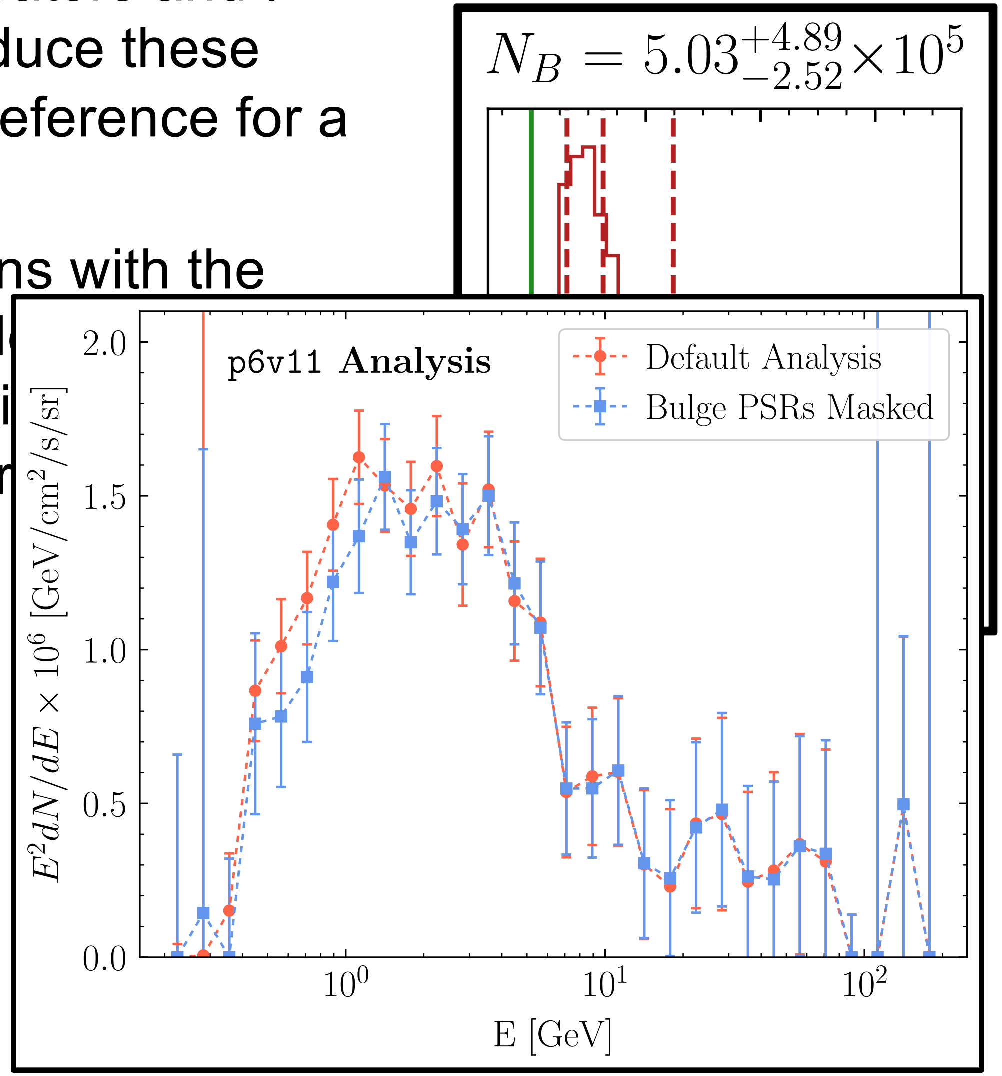
- In our paper, we also note that masking the pulsar candidate sources listed in the new Fermi catalog does *not* impact the characteristics of the excess; a negligible fraction of the excess emission originates from these sources



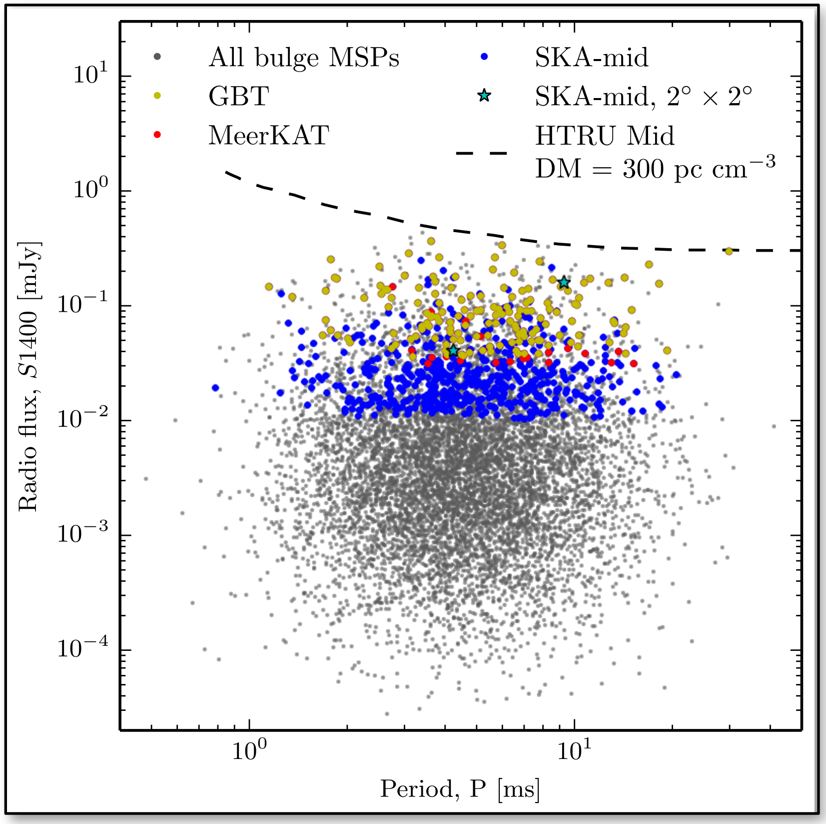
Bartels, DH, Linden, Mishra-Sharma, Rodd, Safdi, Slatyer, arXiv:1710.10266

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? (or rule out a dark matter interpretation)

Millisecond Pulsars and Next Generation Radio Telescopes

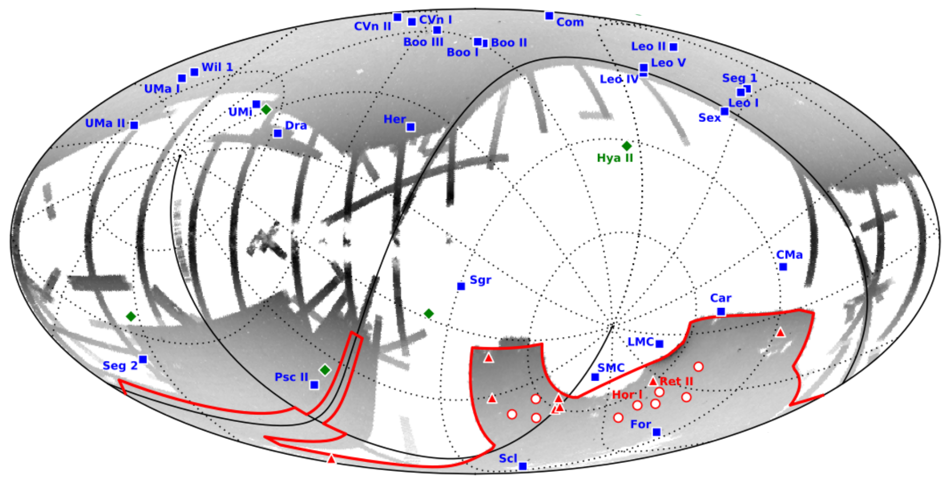
- Although no radio MSPs have been detected in the Inner Galaxy (in mild tension with pulsar interpretations of the gamma-ray excess), upcoming large-area surveys (utilizing MeerKAT, and later SKA) are expected to detect ***dozens*** to ***hundreds*** of MSPs if they are, in fact, responsible for the excess
- This seems like a reasonably clear and straightforward path to test the hypothesis that MSPs are responsible for the gamma-ray excess

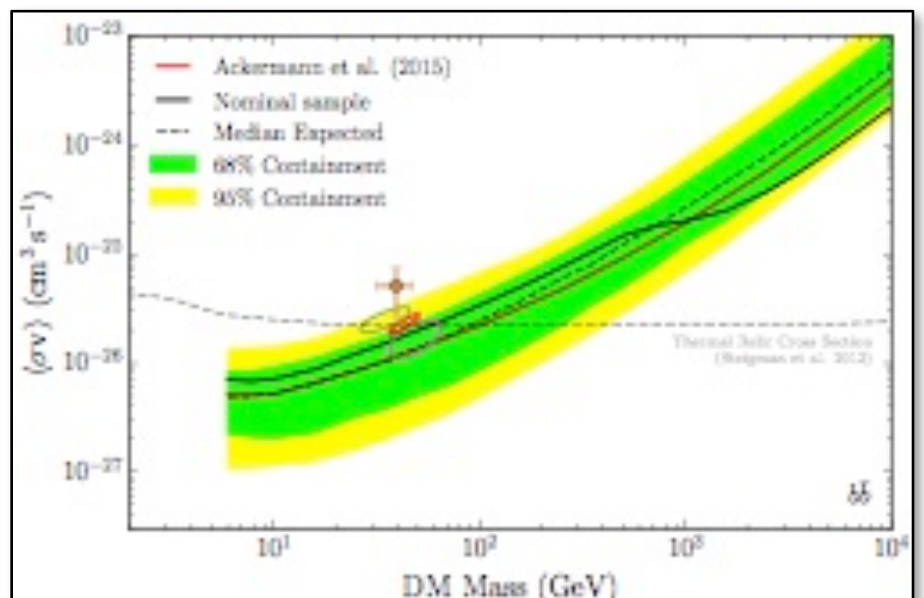


Calore, et al. arXiv:1512.06825

Fermi Observations of Dwarf Galaxies

- Fermi searches for dark matter in dwarf galaxies make use of both “classical” dwarfs and more recently discovered “ultra-faint” dwarfs
- In the last few years, ~25 new dwarf galaxy candidates have been discovered (most in Dark Energy Survey data, but also with SDSS, Pan-STARRS, Subaru)
- Particularly exciting are Reticulum II, Tucana III and Cetus II which are each nearby (~25-30 kpc) and represent attractive targets for dark matter searches
- The current sensitivity of these searches is near the thermal relic benchmark cross section for dark matter as heavy as ~100 GeV

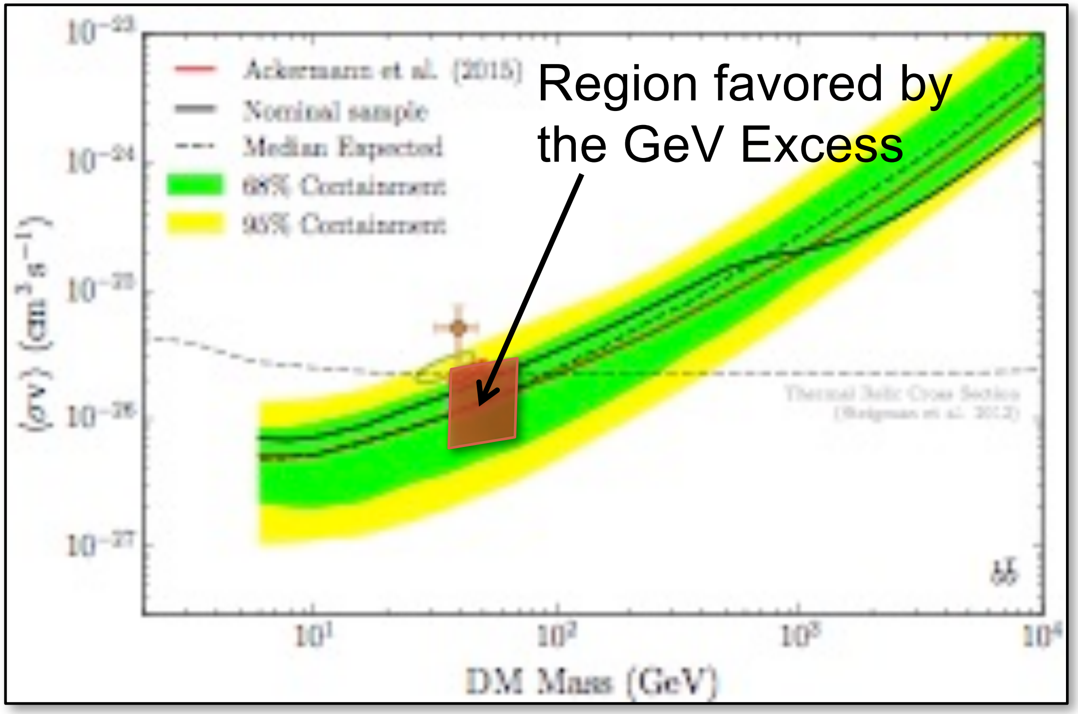




DES Collaboration, arXiv:1508.03622
Fermi Collaboration, arXiv:1611.03184

Testing The GC Excess With Dwarf Galaxies

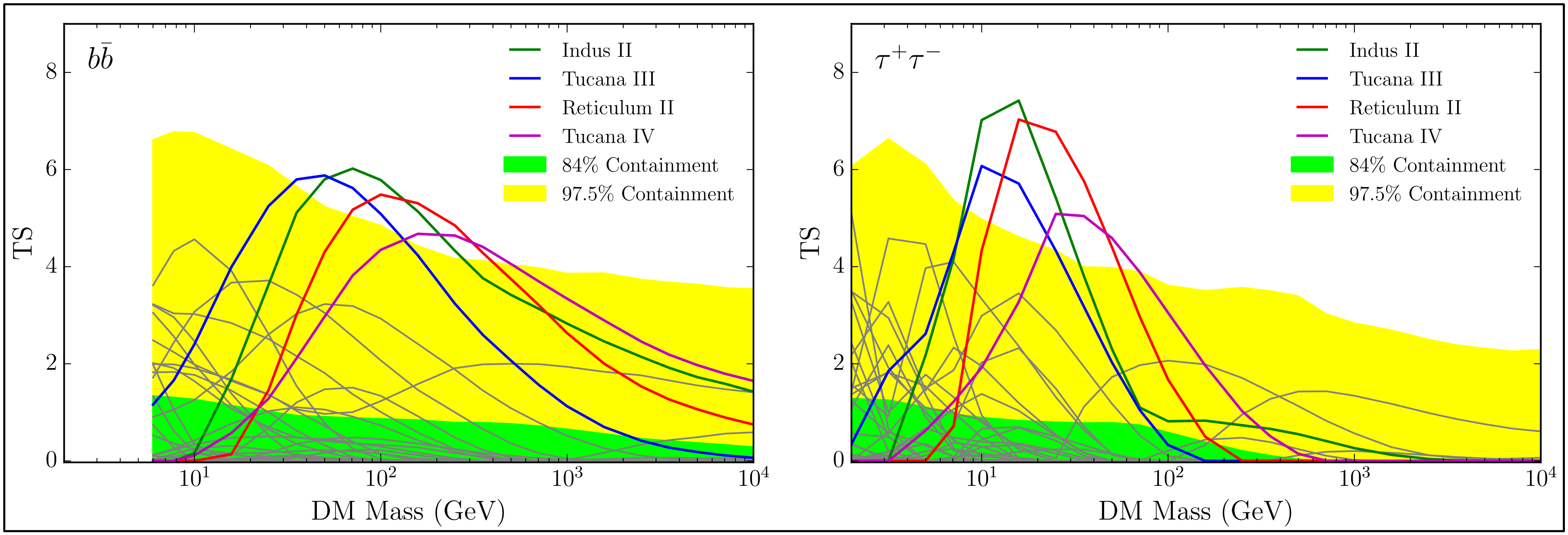
- Current Fermi dwarf constraints are compatible with dark matter interpretations of the Galactic Center excess (when appropriate uncertainties are taken into account)
- That being said, if the Galactic Center signal is coming from annihilating dark matter, one should expect gamma rays to be detected from dwarfs soon
- Dwarfs may be the final arbiter of the Galactic Center debate



Fermi Collaboration, arXiv:1611.03184 (see also 1503.02641)

Fermi's View of the New Dwarf Galaxies

- In 2015, three groups reported an excess from the newly discovered Reticulum II, with a significance of 2.4-3.2σ (Geringer-Sameth et al. Drlica-Wagner, et al, DH & Linden)
- More recently, Fermi has presented an updated analysis of 48 dwarf galaxy candidates, including several newly discovered dwarfs:



Fermi Collaboration, 1611.03184

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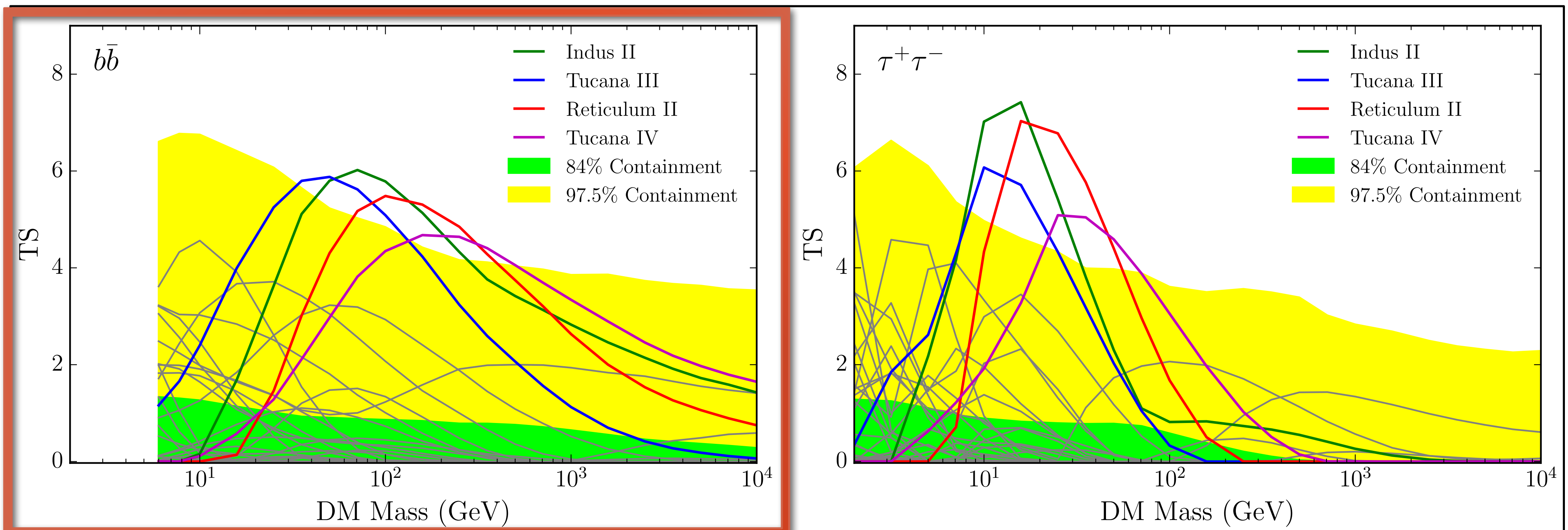

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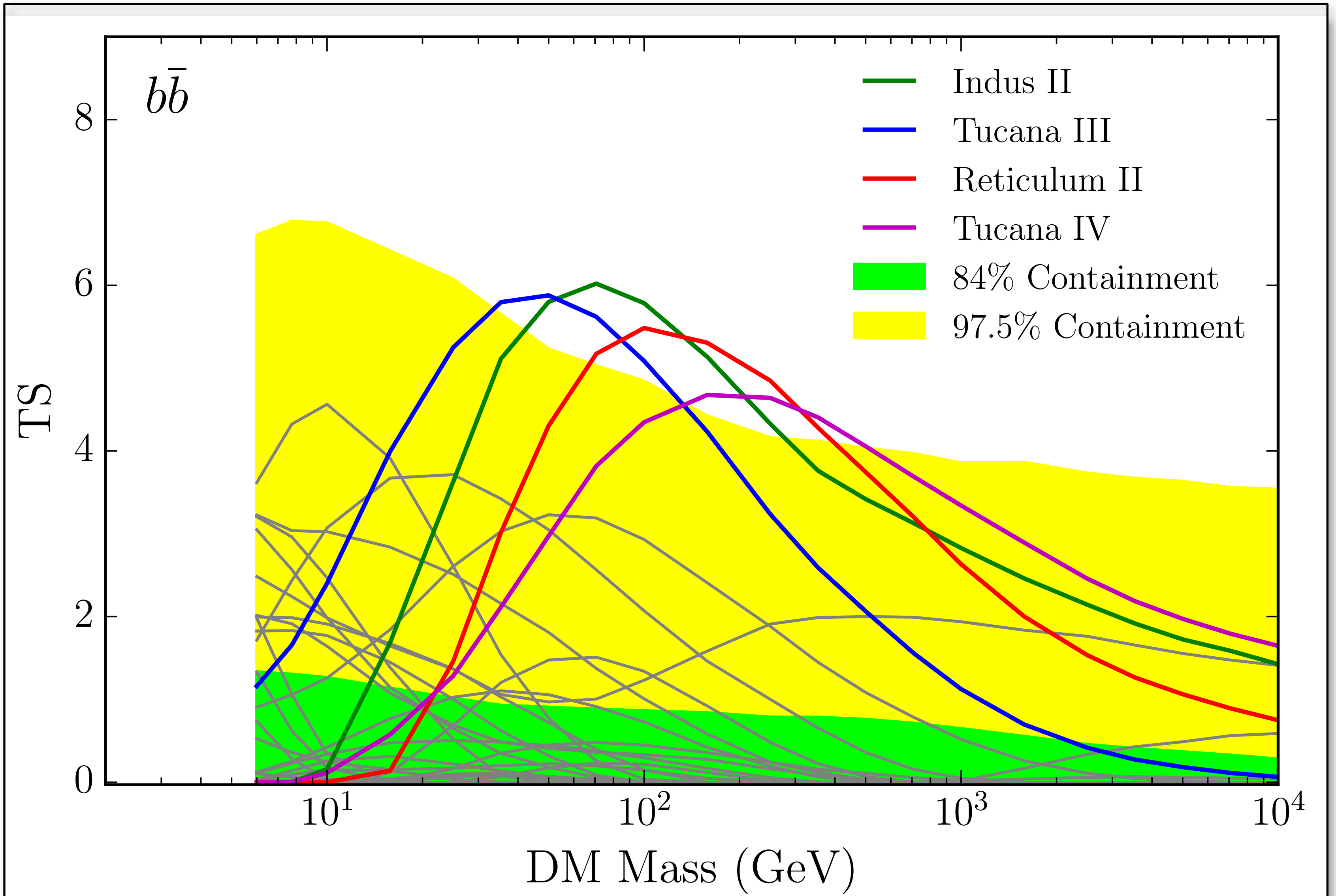
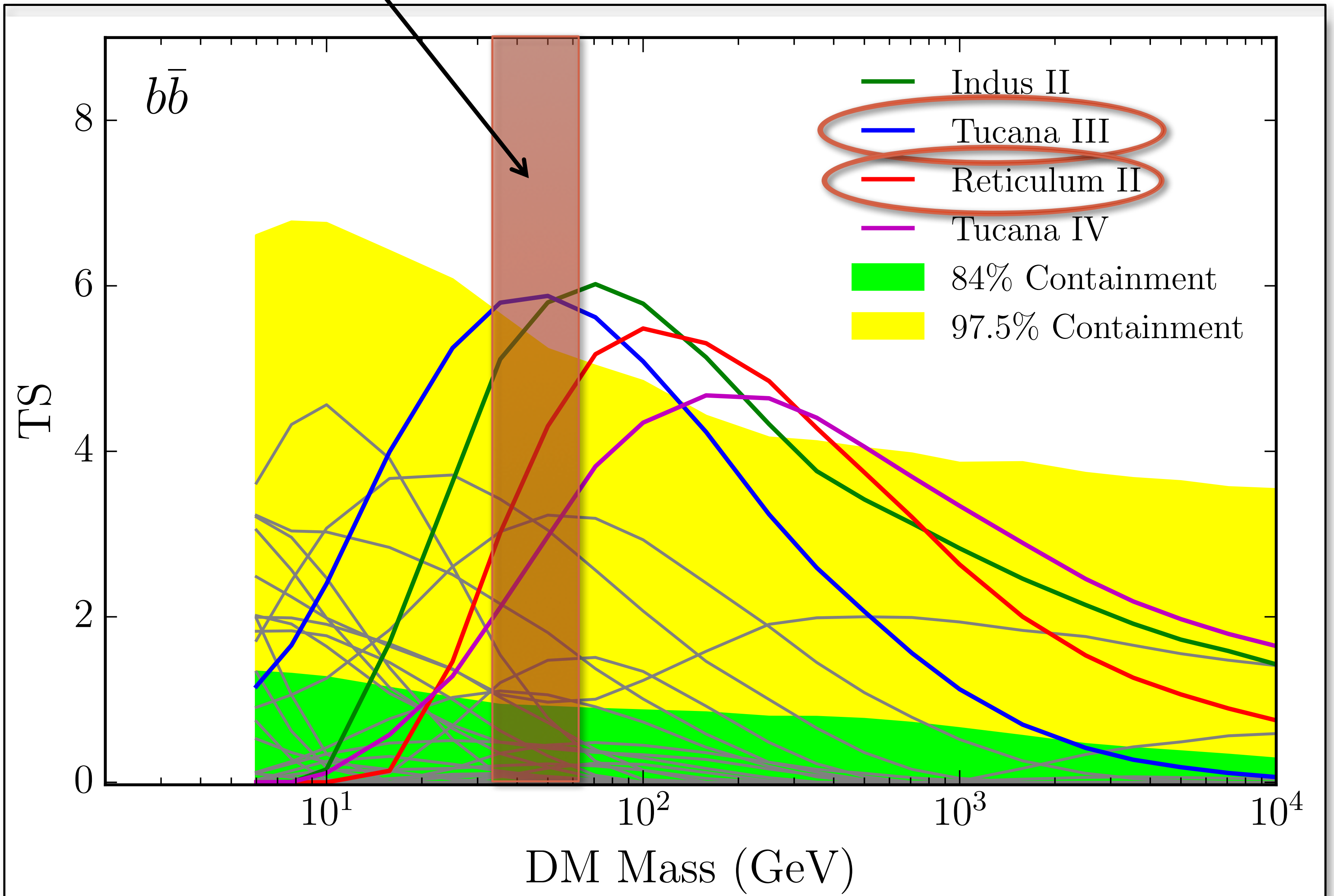


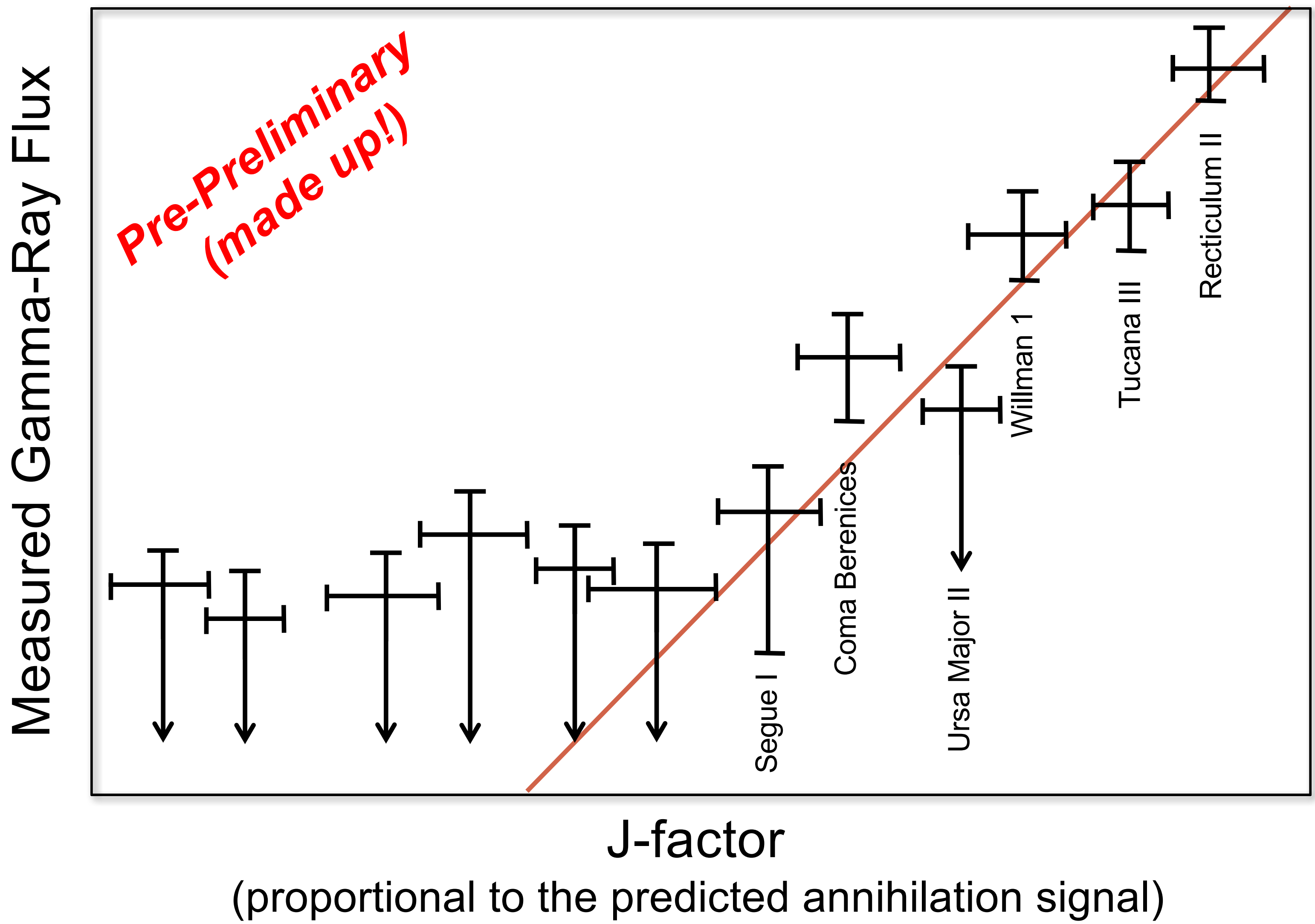
Fermi Collaboration, 1611.03184

Range Favored by
Galactic Center



Fermi Collaboration, 1611.03184

The plot I see in my dreams…



Reasons to be Optimistic About Dwarfs

There are several factors that will make searches for dark matter annihilation in dwarf galaxies more powerful in the coming years:

- More Fermi data (and data from next generation space-based experiments; AMIGO, e-ASTROGAM)
- Many more (~100-200) dwarf discoveries – from DES and especially from LSST
- Multi-wavelength information has thus far been neglected in these studies; a gamma-ray excess from the direction of a dwarf without bright radio or IR sources nearby is more likely to be an authentic signal of dark matter, and less likely to be emission from an unresolved blazar or radio galaxy (Carlson, DH, Linden, arXiv:1409.1572)

Summary

- Direct detection experiments have improved in sensitivity at an exponential rate over the past 15 years, and have ruled out many well-motivated dark matter models; many others will be explored over the next decade
- The LHC is our most comprehensive tool to explore the TeV-scale; many different analyses and search strategies are of relevance to dark matter
- Indirect searches using gamma rays and cosmic rays are currently testing the range of annihilation cross sections that are predicted for a thermal relic, for masses up to ~100 GeV
- These experiments are collectively testing the WIMP paradigm

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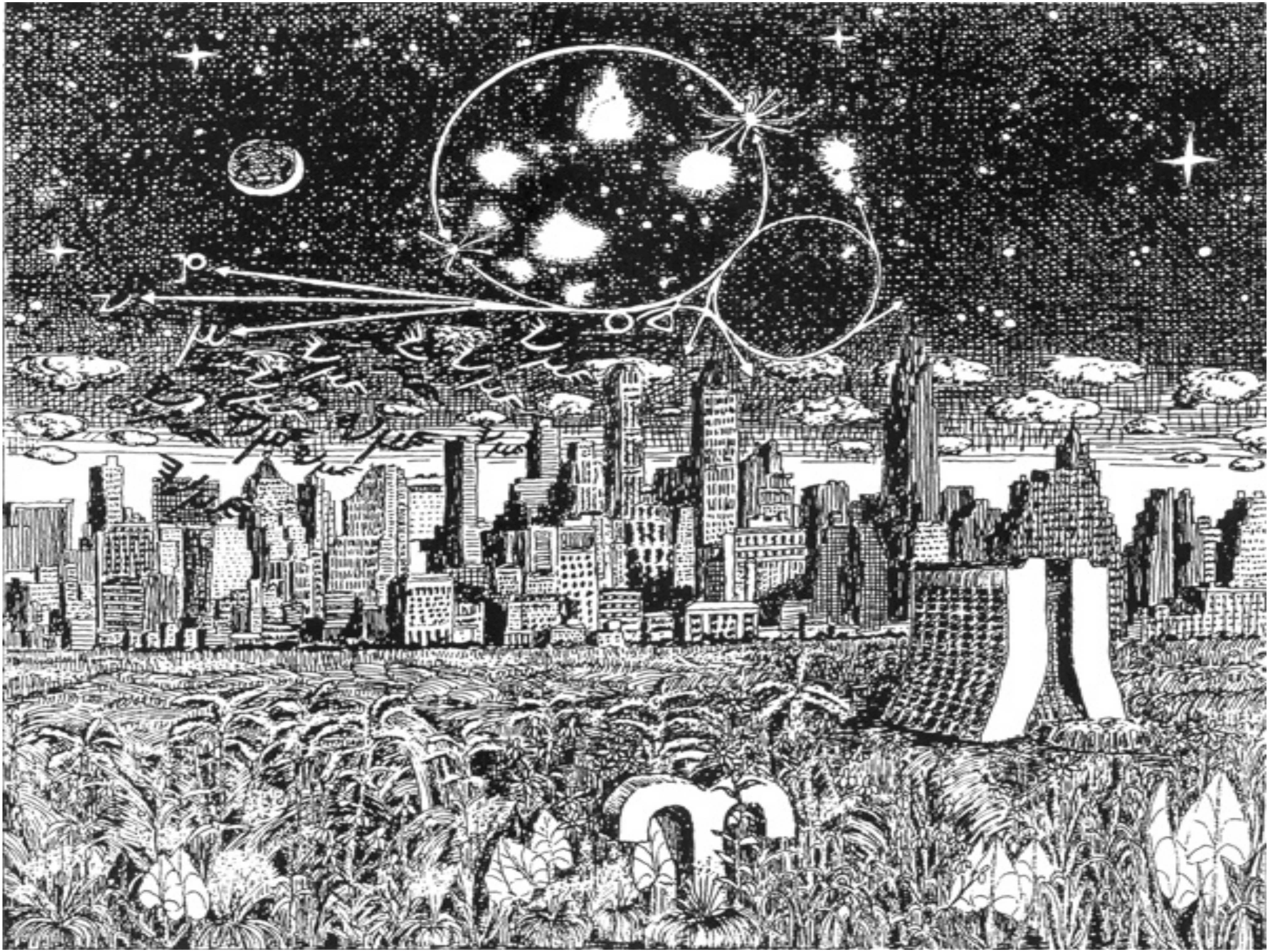
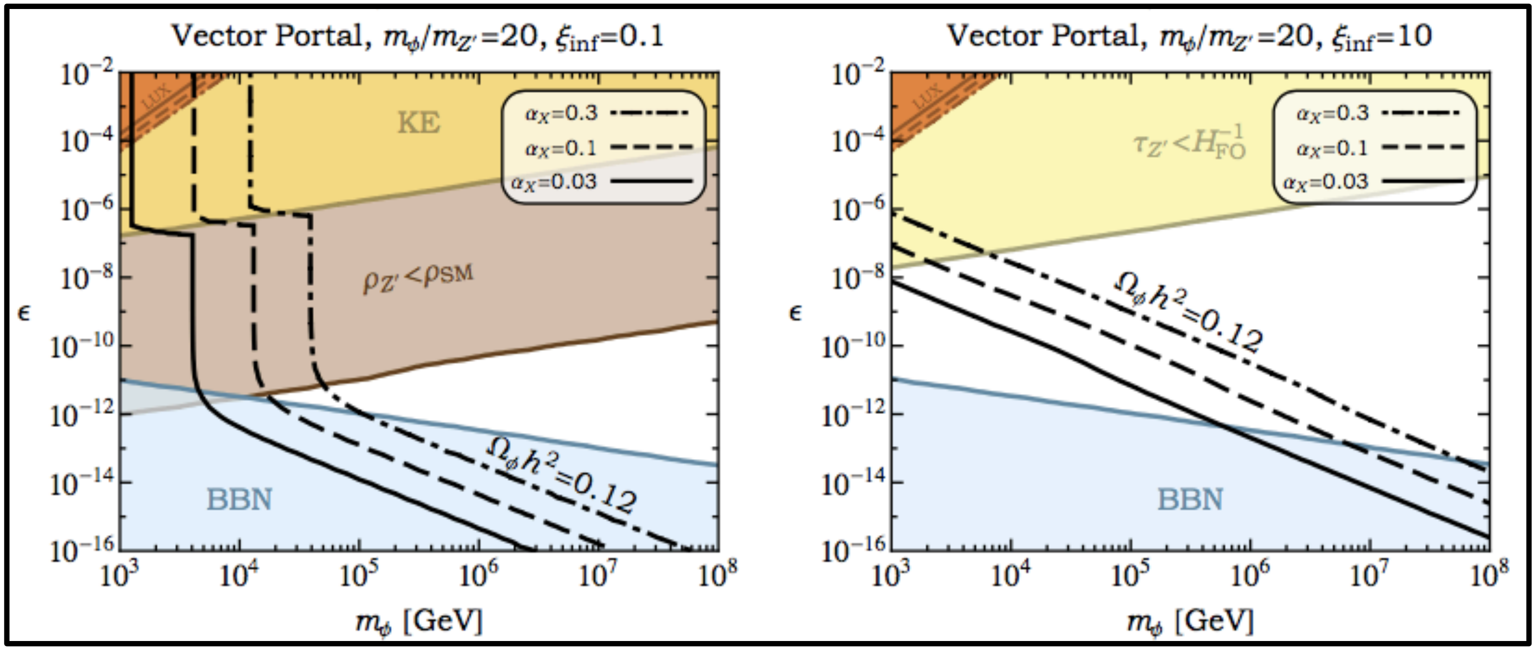
- Indirect searches using gamma rays and cosmic rays are currently testing the range of annihilation cross sections that are predicted for a thermal relic, for masses up to ~100 GeV
- These experiments are collectively testing the WIMP paradigm
- Although the WIMP is far from dead, the lack of a clear discovery has redirected the field and has lead to an explosion in beyond-WIMP model building
- The Galactic Center's GeV excess remains compelling: highly statistically significant, robust, extended, spherical, and difficult to explain with known or proposed astrophysics; future gamma-ray observations of dwarf galaxies and radio searches for millisecond pulsars will provide critical tests to establish the origin of this signal



Dark Matter Within a Heavy Decoupled Hidden Sector

- The history of the early universe in these scenarios depends on the ratio of the initial temperatures of the hidden and visible sectors



- For T_{hidden}<<T_{SM}, no early matter-dominated era, no late-time reheating
- For T_{hidden}>>T_{SM}, the Standard Model bath almost entirely originates from the decay of the hidden sector