Dan Hooper (Fermilab/University of Chicago)
Dark Interactions Workshop, Brookhaven National Lab
June 12, 2014

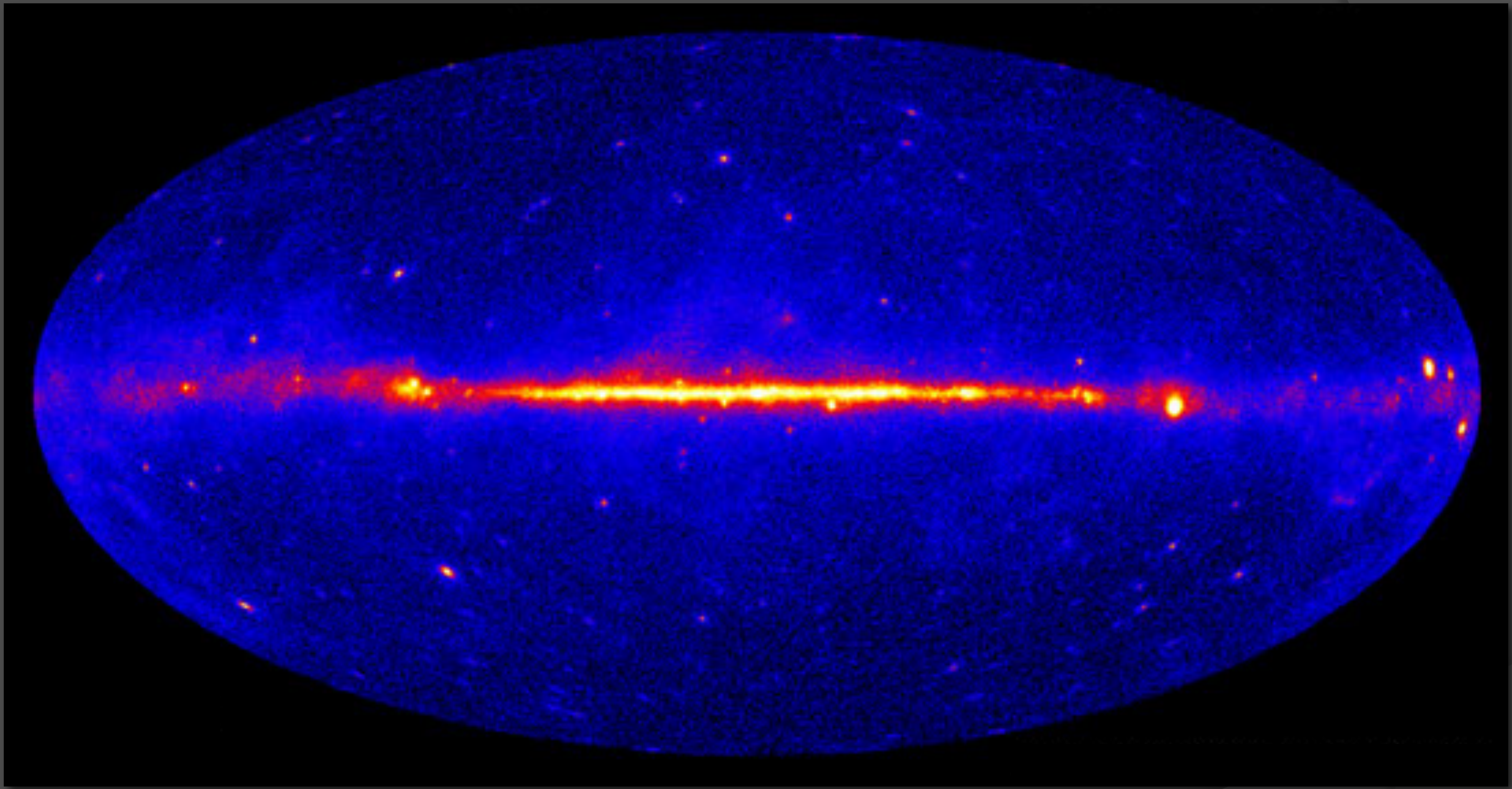
Dark Matter Annihilations in the Galactic Center

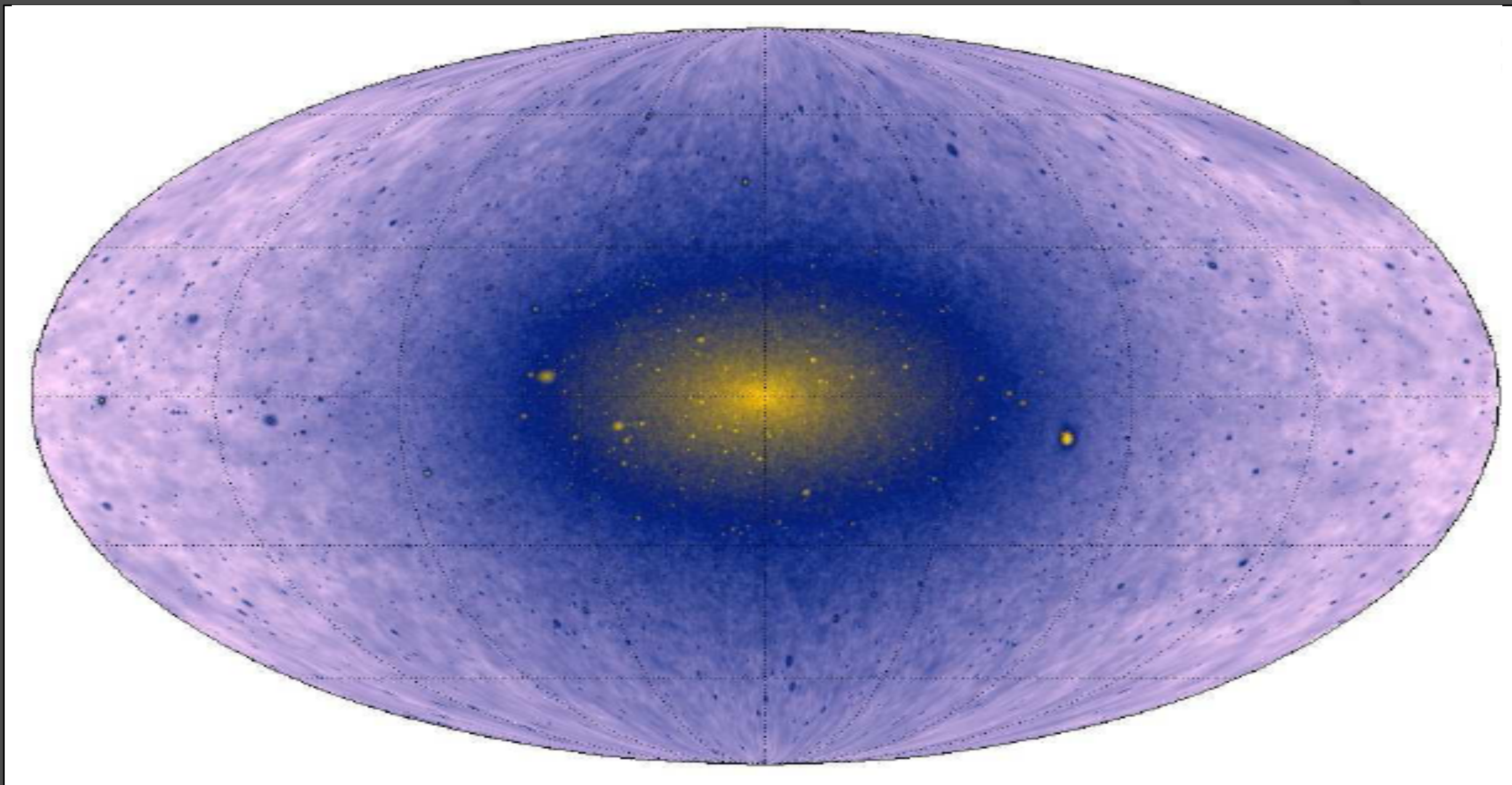
This talk is based on:

T. Daylan, D. Finkbeiner, DH, T. Linden, S. Portillo, N. Rodd, and T. Slatyer, arXiv:1402.6703 (submitted to PRD)

For other work related to this signal and its interpretation, see:

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





The Signal:
Gamma Rays from Dark Matter Annihilations

The gamma-ray signal from dark matter annihilations is described by:

$$\Phi_\gamma(E_\gamma, \psi) = \frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma} \frac{\langle \sigma v \rangle}{8\pi m_X^2} \int_{\mathrm{los}} \rho^2(r) \mathrm{d}l$$

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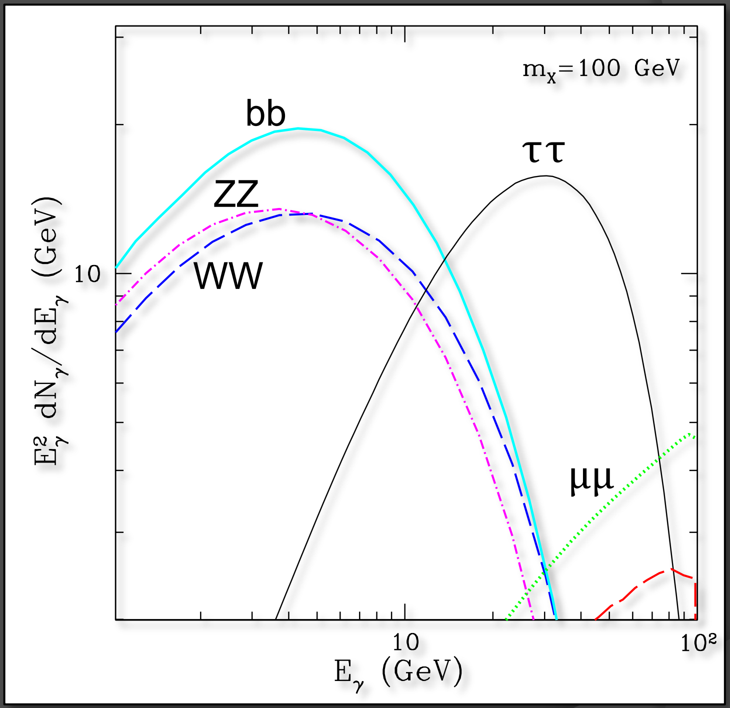
1) Distinctive "bump-like" spectrum



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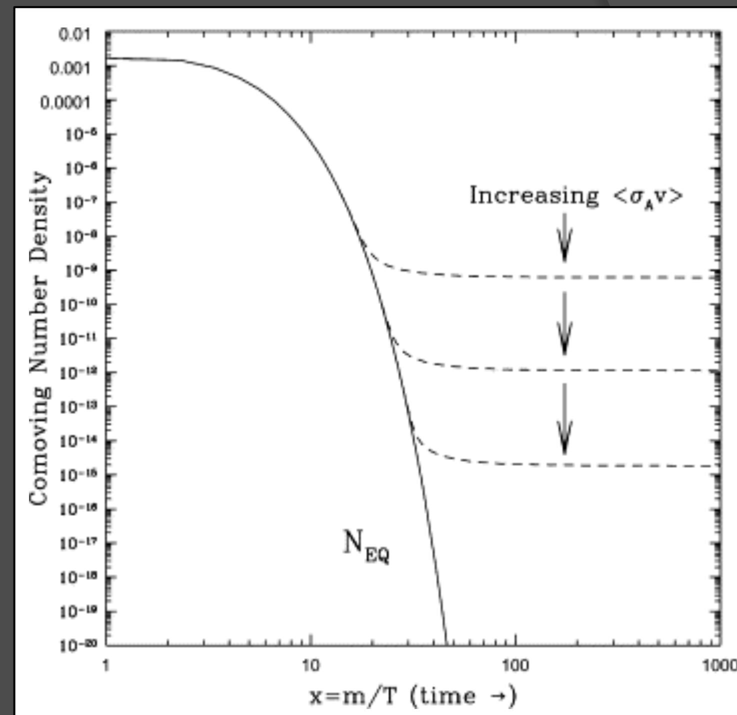

1) Distinctive “bump-like” spectrum

2) Normalization of the signal is set by the dark matter’s mass and annihilation cross section (in the low-velocity limit)

-To be produced with the observed dark matter abundance, a GeV-TeV thermal relic must annihilate at a rate equivalent to $\sigma v \sim 2\times10^{-26}$ cm^3/s (at freeze-out)

-Although many model-dependent factors can lead to a somewhat different annihilation cross section today (velocity dependence, co-annihilations, resonances), most models predict current annihilation rates that are not far from $\sim10^{-26}$ cm^3/s

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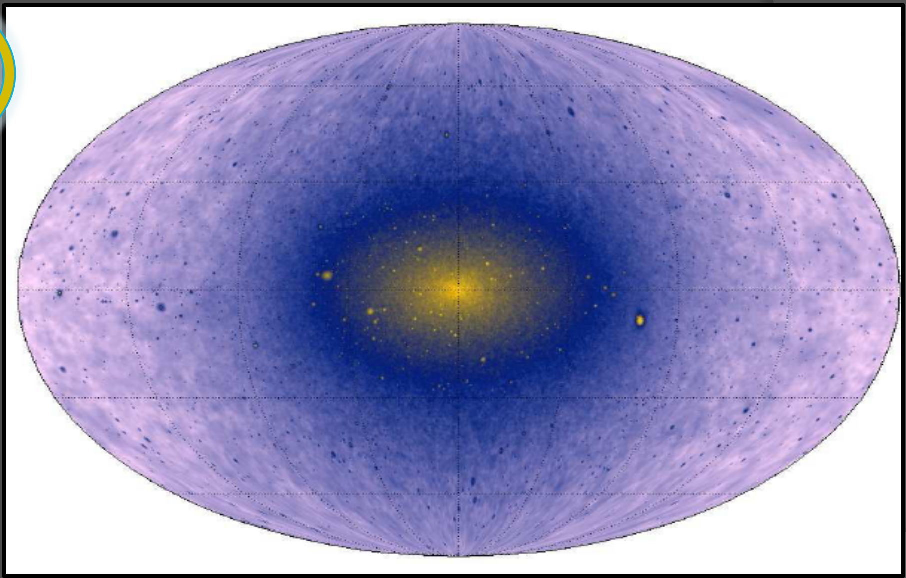
1) Distinctive "bump-like" spectrum

2) Normalization of the signal is set by the dark matter's mass and annihilation cross section (in the low-velocity limit)

3) Signal concentrated around the Galactic Center (but not point-like) with approximate spherical symmetry; precise morphology determined by the dark matter distribution



M. Kuhlen *et al*.

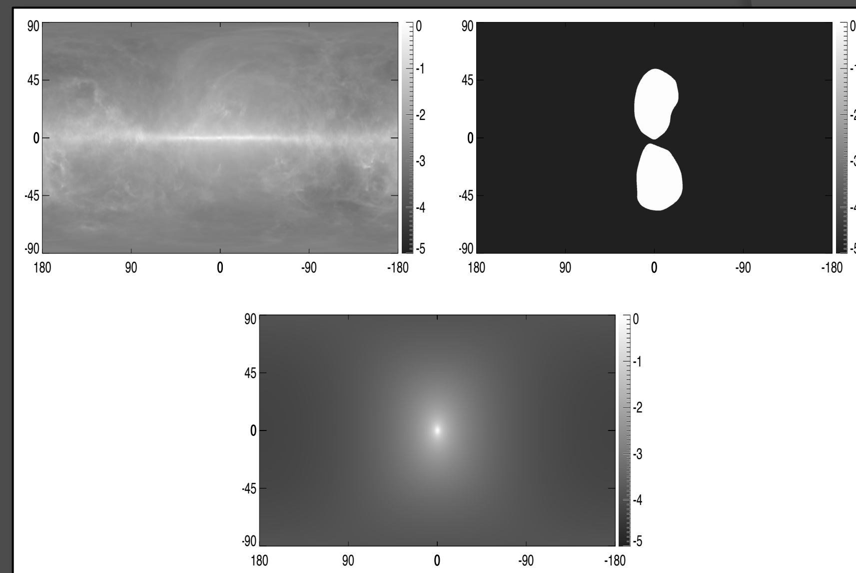
Basic Analysis Approach

1) Inner Galaxy Analysis:

Sum spatial templates (diffuse+bubbles+isotropic+dark matter), and constrain the intensity of each component independently in each energy bin across the entire sky (except within 1° of the plane or within 2° of bright sources)

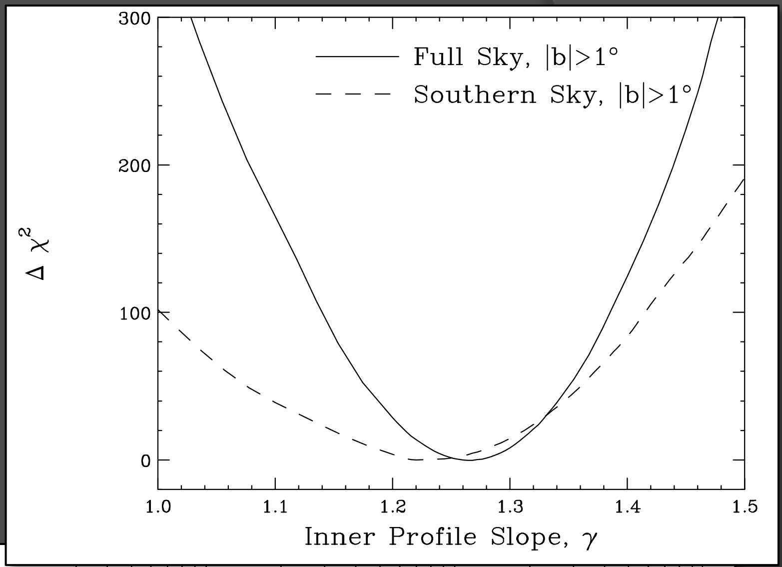
2) Galactic Center Analysis:

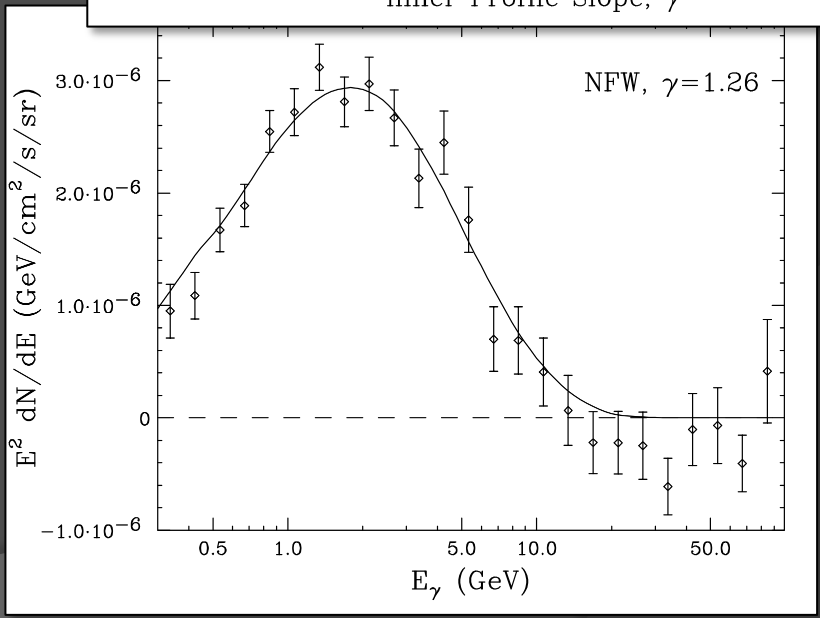
In the inner 10°x10° box around the GC, fit the data to the sum of the diffuse model, all known point sources, 20 cm template, isotropic template, and dark matter

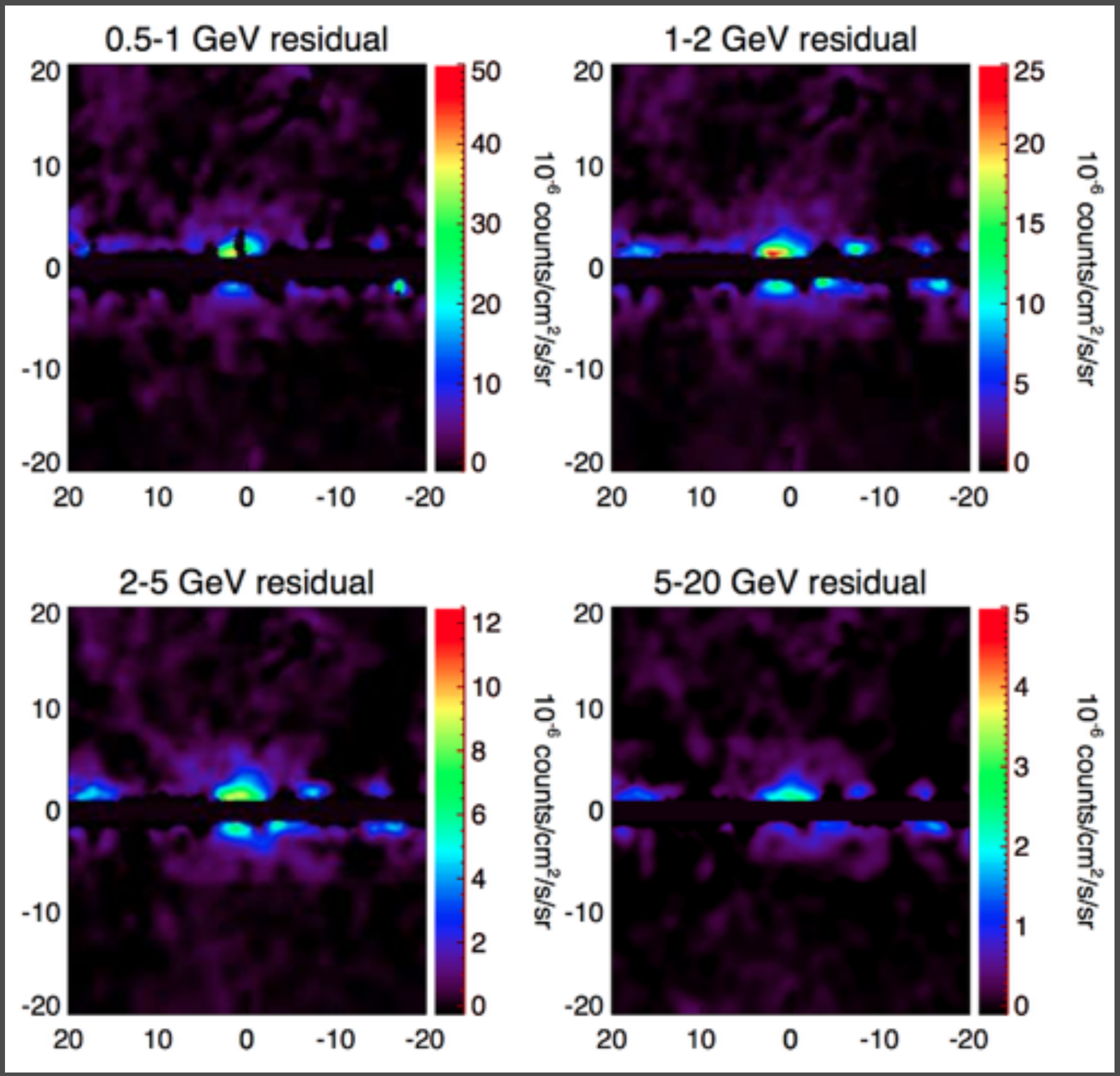


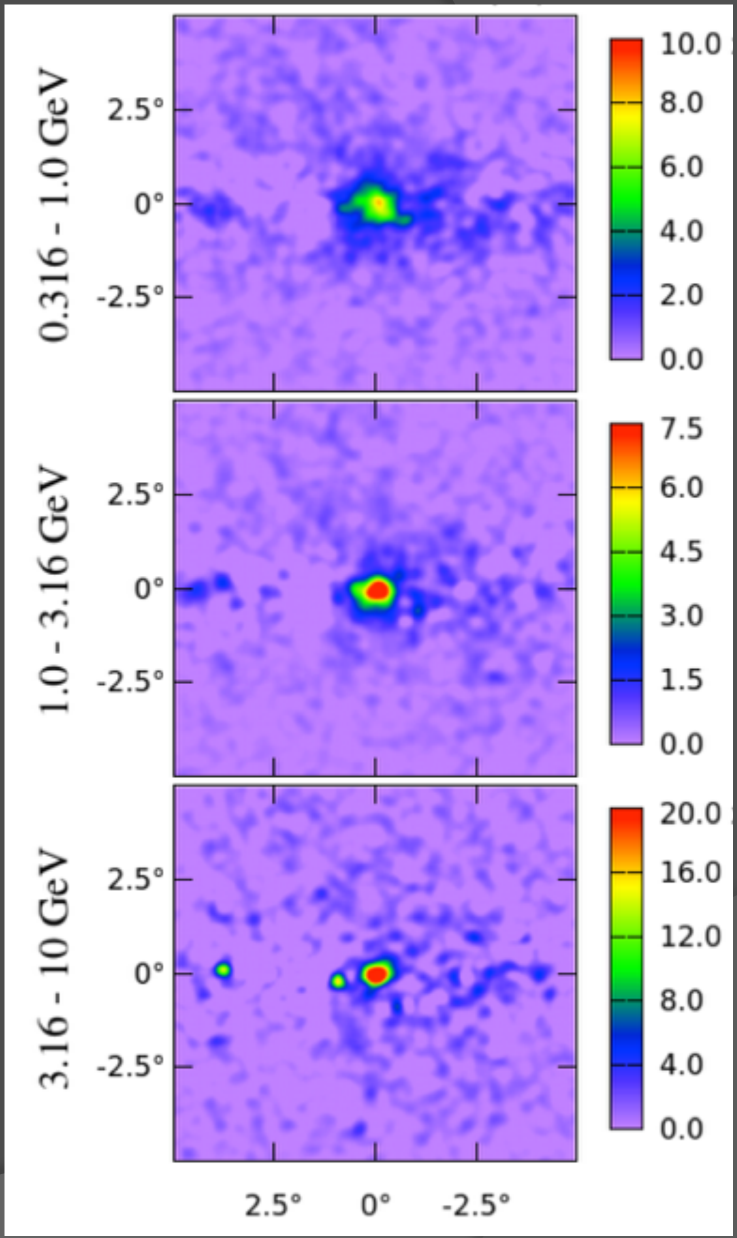
Basic Features of the GeV Excess

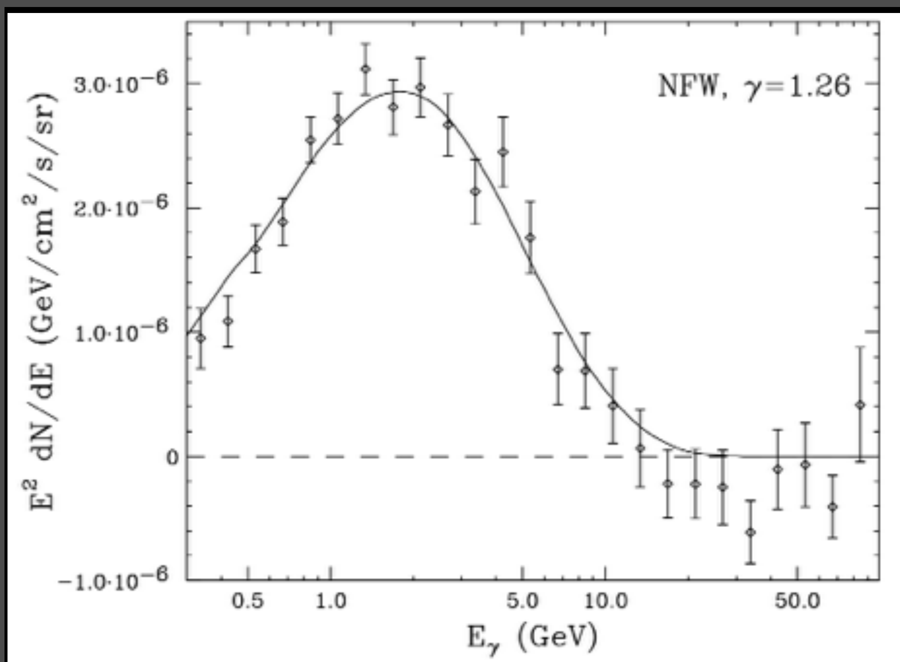
- The excess is distributed around the Galactic Center with a flux that falls off approximately as $r^{-2.5}$ (if interpreted as dark matter annihilation products, this implies $\rho_{DM} \sim r^{-1.25}$)
- The spectrum of this excess peaks at ~1-3 GeV, and is in very good agreement with that predicted from a 30-40 GeV WIMP (annihilating to b quarks)
- To normalize the observed signal with annihilating dark matter, a cross section of $\sigma v \sim 2 \times 10^{-26}$ cm^3/s is required (for $\rho_{local} = 0.3$ GeV/cm^3)

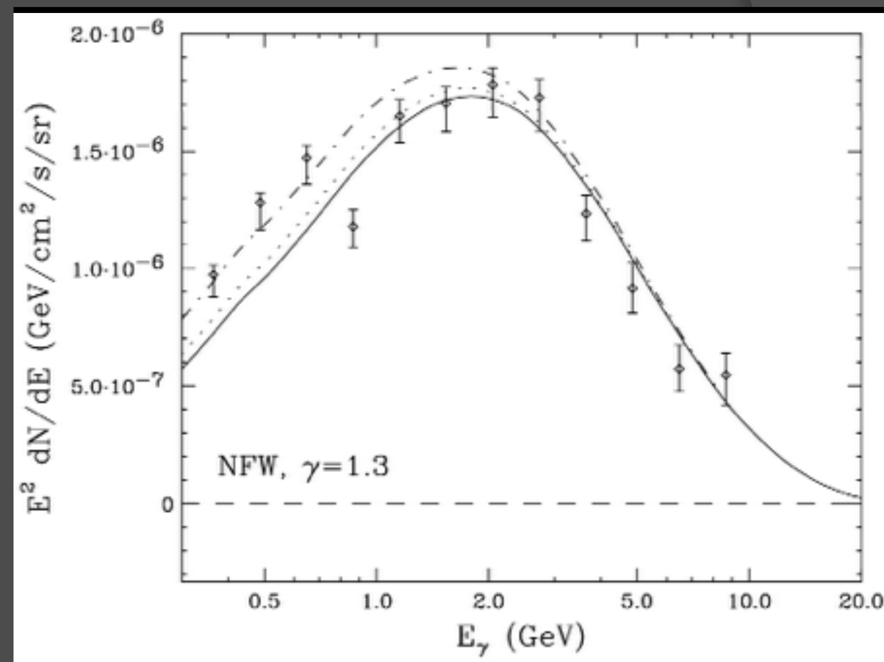





0.5-1 GeV residual
1-2 GeV residual
2-5 GeV residual
5-20 GeV residual
10^-6 counts/cm^2/s/sr
20
10
0
-10
-20


0.316 - 1.0 GeV
1.0 - 3.16 GeV
3.16 - 10 GeV
2.5°
0°
-2.5°


NFW, γ=1.26
E² dN/dE (GeV/cm²/s/sr)
E_γ (GeV)
3.0·10⁻⁶
2.0·10⁻⁶
1.0·10⁻⁶
0
−1.0·10⁻⁶
0.5
1.0
5.0
10.0
50.0


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

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

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In our most recent paper, we set out to address questions such as:

- Are the more detailed characteristics of this signal consistent with the predictions for annihilating dark matter?

- Could this signal arise from plausible astrophysical sources or mechanisms? Diffuse emission processes? Unresolved pulsars?

- Are the characteristics of this signal robust to the details of the analysis procedure? How confident are we that we have correctly characterized the properties of this excess?

In my opinion, this gamma-ray excess is – by a significant margin – the most compelling evidence for particle dark matter interactions reported to date

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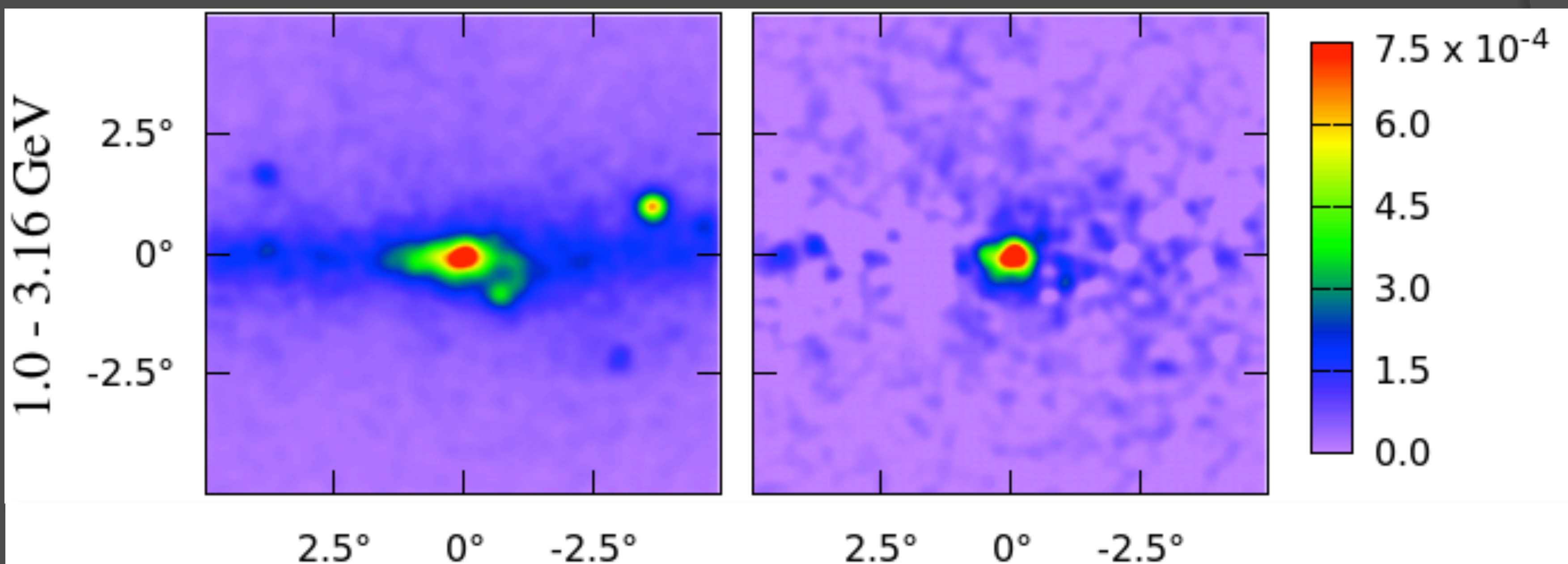
What makes this so different from prospective signals observed by *INTEGRAL, PAMELA, ATIC, WMAP, DAMA/LIBRA, CoGeNT, CDMS, CRESST*, *Fermi*'s 130 GeV line, etc?

Reason 1: Overwhelming Statistical Significance and Detailed Information

- This excess consists of ~10^4 photons per square meter, per year (>1 GeV, within 10° of the Galactic Center)

Raw Map | Residual Map (x3)

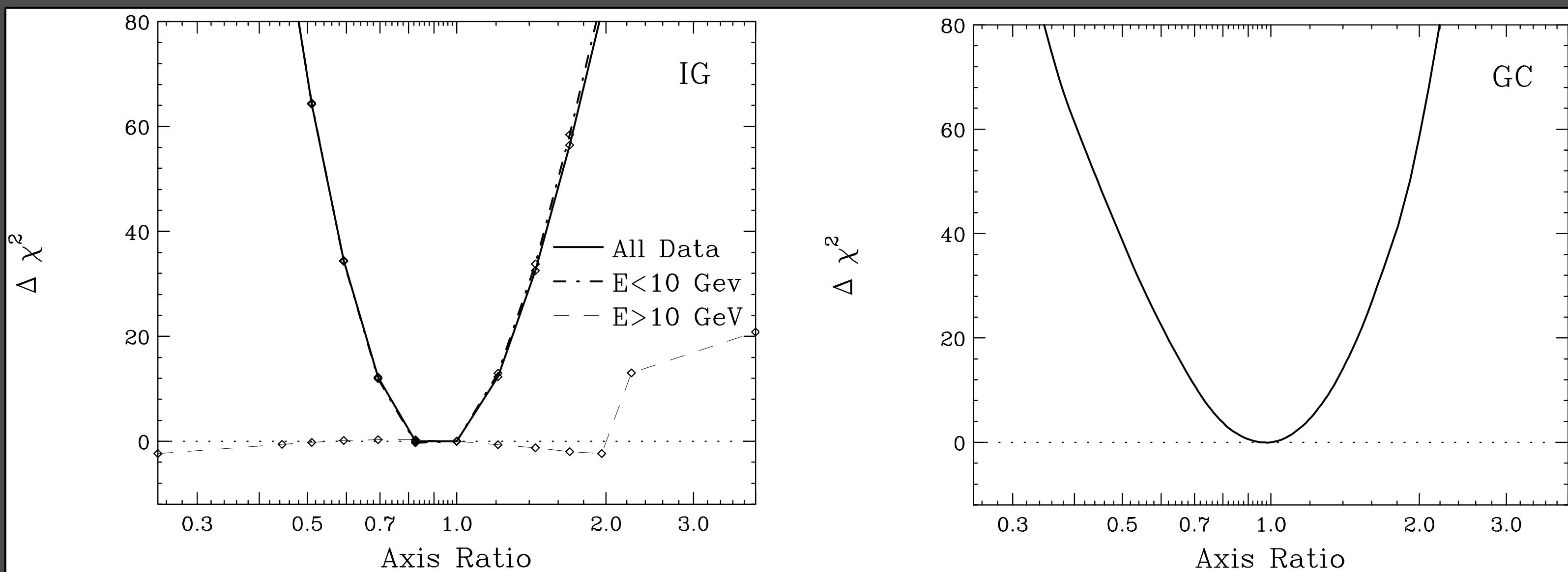


Reason 1: Overwhelming Statistical Significance and Detailed Information

- This excess consists of ~10^4 photons per square meter, per year (>1 GeV, within 10° of the Galactic Center)
- In our Inner Galaxy analysis, the quality of the best-fit found with a dark matter component improves over the best-fit without a dark matter component by over 40 σ (the Galactic Center analysis "only" prefers a dark matter component at the level of 17 σ)
- This huge data set allows us to really scrutinize the signal, extracting its characteristics in some detail
- For example, we can ask (and address) questions such as "is the excess really spherically symmetric, or might it be elongated along the Galactic Plane?" (as we might expect for many hypothetical backgrounds)

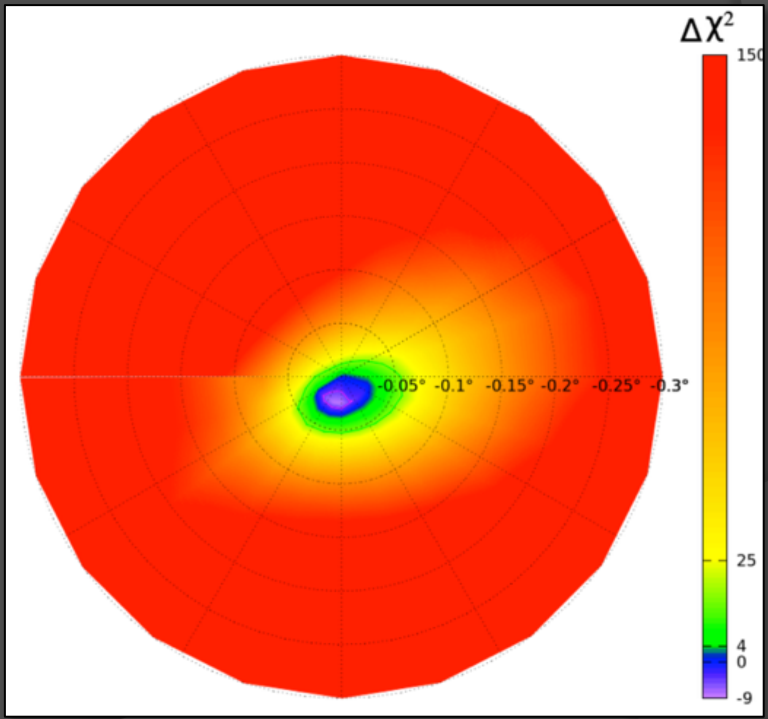
The Detailed Morphology of the Excess

- When we replace the spherically symmetric template (motivated by dark matter) with an elongated template, the fit uniformly worsens
- The axis-ratio of the excess is strongly preferred to be within ~20% of unity



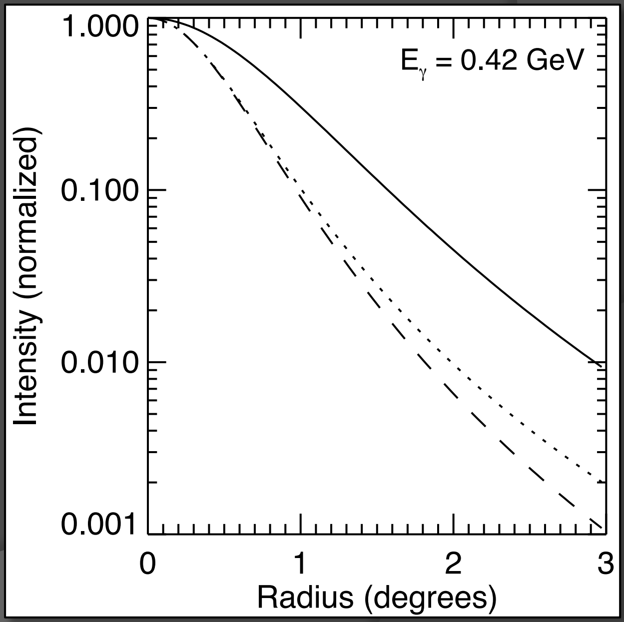
The Detailed Morphology of the Excess

- When we replace the spherically symmetric template (motivated by dark matter) with an elongated template, the fit uniformly worsens
- The axis-ratio of the excess is strongly preferred to be within ~20% of unity
- The excess is also very precisely centered around the dynamical center of the Milky Way, within ~0.03° (~5 pc) of Sgr A*



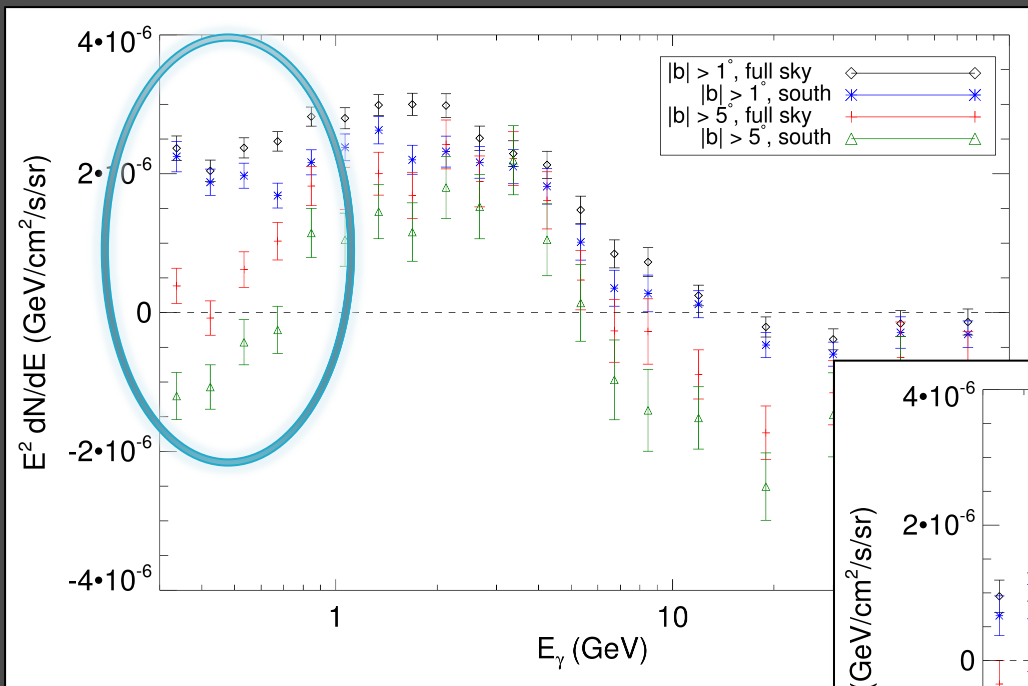
A Robust Determination of the Signal's Spectrum

- In past studies of this signal (including my own), it was difficult to control systematic uncertainties at low energies (<1 GeV), where Fermi's point spread function (PSF) is large, allowing astrophysical backgrounds from the Galactic Plane and bright point sources to bleed into other regions of interest
- We largely avoid this problem in our analysis by cutting on the parameter CTBCORE, which strongly suppresses the PSF tails

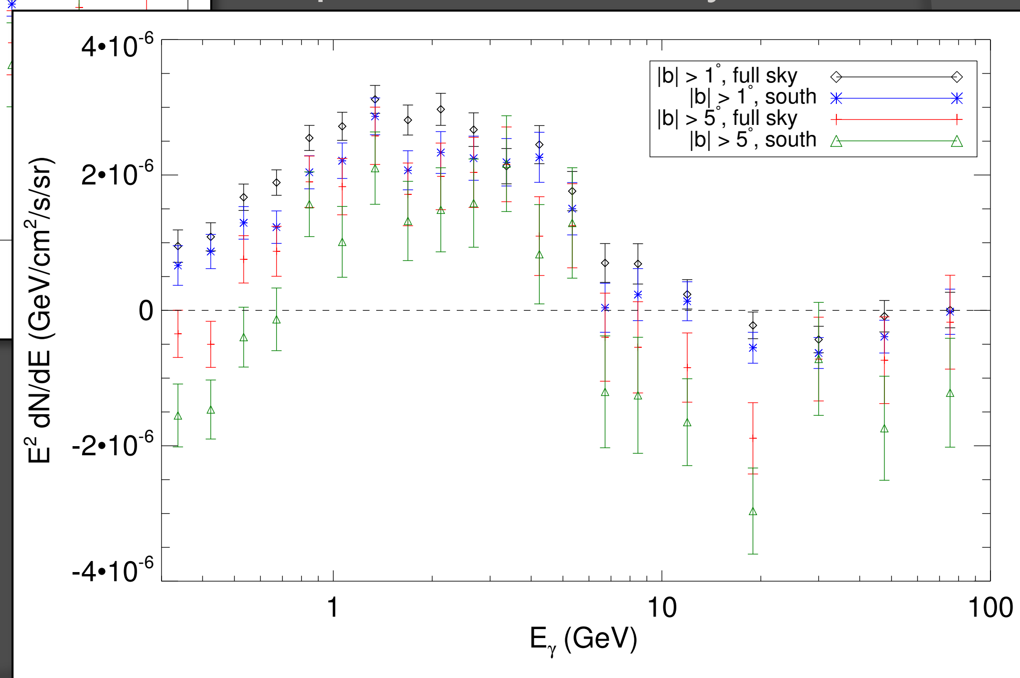


The Utility of Cutting by CTBCORE

Without additional CTBCORE Cuts



Top 50% of Events by CTBCORE



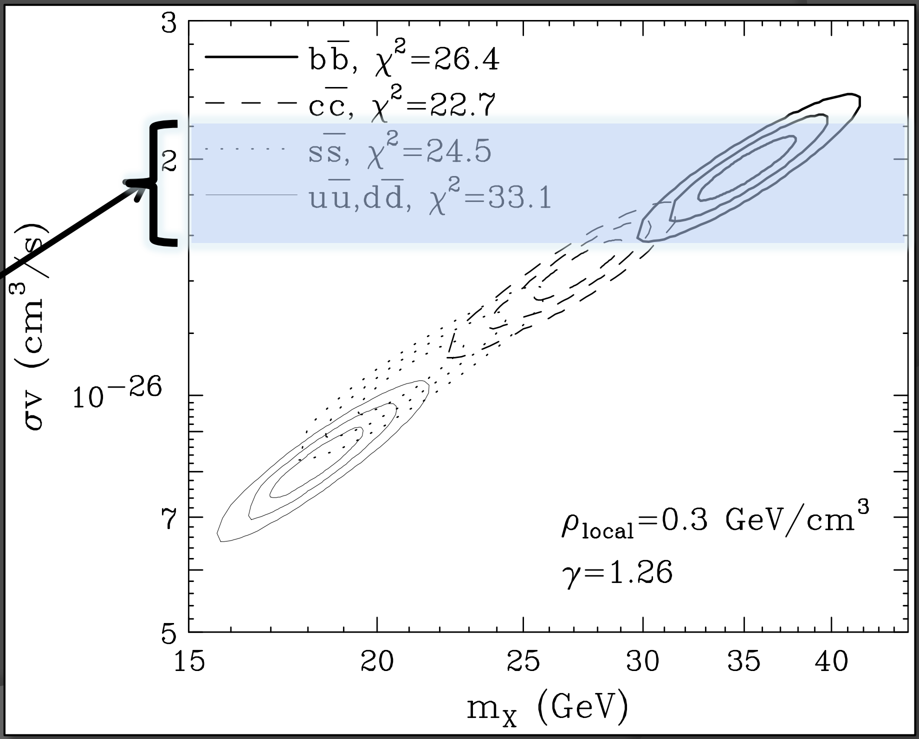
Reason 2: The Signal is Well-Fit by Simple, Predictive Dark Matter Models

The gamma-ray excess can be easily fit by very simple and predictive dark matter models.

We tune only 1) the halo profile's slope, 2) the dark matter's mass, and 3) the dark matter's annihilation cross section and final state

No other astrophysical or model parameters are required (gamma rays are simple)

Also, the required cross section is remarkably well-matched to the value predicted for a simple (s-wave dominated) thermal relic



Reason 3: The Lack of a Plausible Alternative Interpretation

This signal does not correlate with the distribution of gas, dust, magnetic fields, cosmic rays, star formation, or radiation

(It does, however, trace quite well the square of the dark matter density, for a profile slightly steeper than NFW)

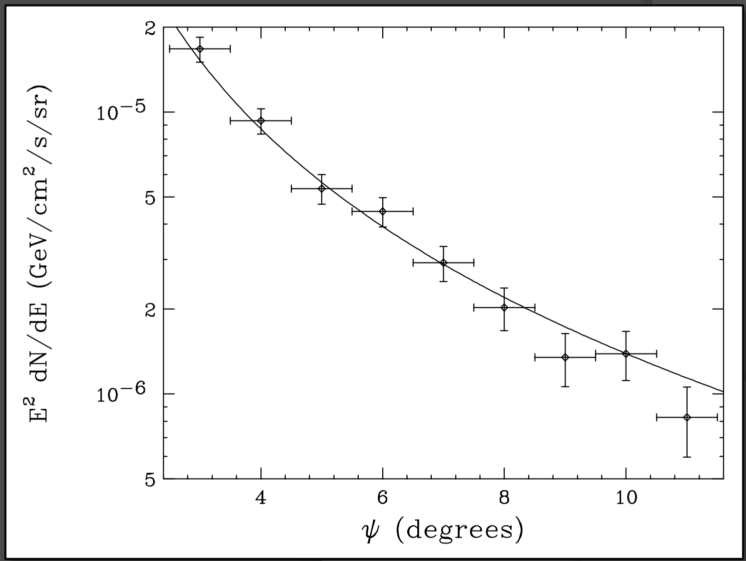
No known diffuse emission mechanisms can account for this excess

Reason 3: The Lack of a Plausible Alternative Interpretation

The most often discussed astrophysical interpretation for this signal is a population of several thousand millisecond pulsars (MSPs) associated with the Milky Way's central stellar cluster – such a population could plausibly account for much of the excess observed within the innermost ~1-2° of the Galaxy

But we observe this excess to extend out to at least ~10° from the Galactic Center

If MSPs were distributed in a way that could account for this extended excess, Fermi should have resolved many more as individual point sources than they did



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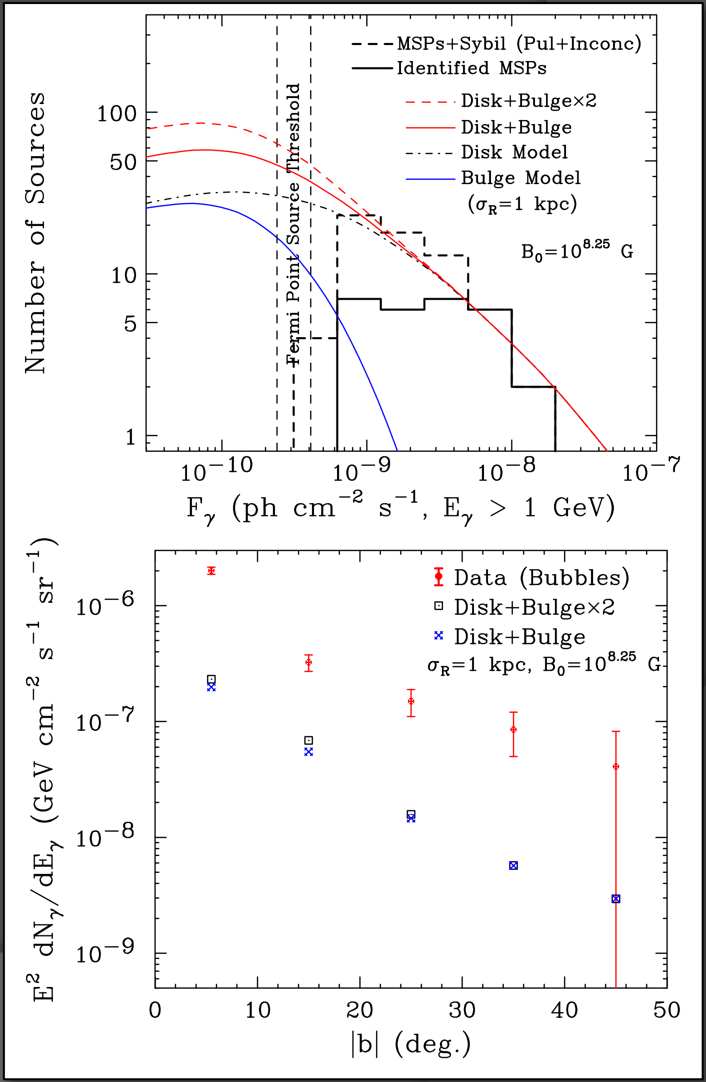
We find that no more than ~5-10% of the excess beyond ~ 5° can come from MSPs (Hooper, Cholis, Linden, Siegal-Gaskins, Slatyer, PRD, arXiv:1305.0830)



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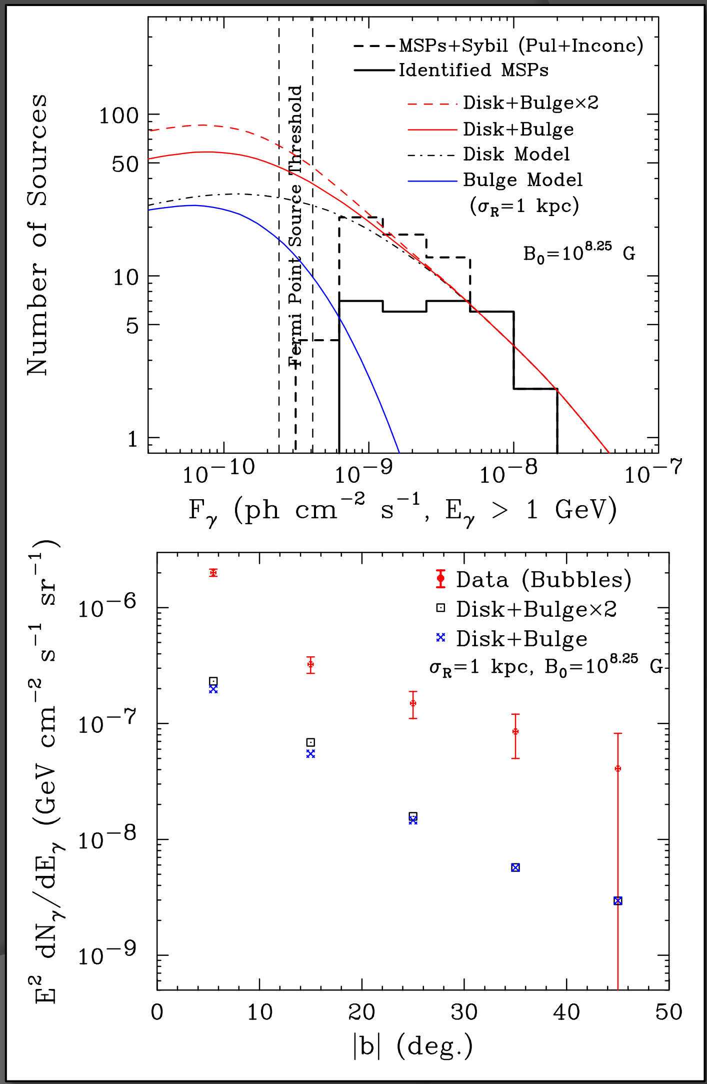
To evade this conclusion:

1) The luminosity function of bulge MSPs would have to be very different from the luminosity function of observed MSPs, consistently less bright than ~10^{37} GeV/s

and

2) The distribution of MSPs in the Inner Galaxy would have to be much more extended than dynamical models predict



What kind of WIMP could produce this signal?

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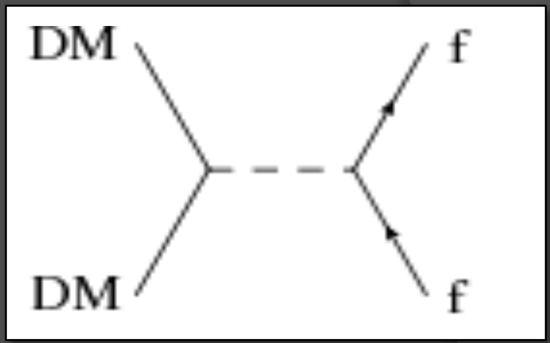
A simple approach:

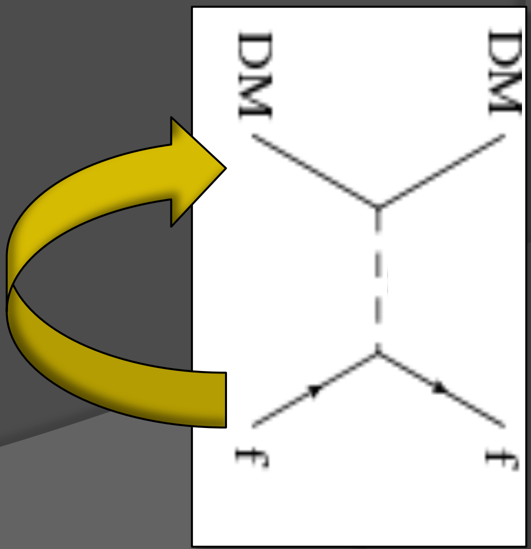
For each tree-level process for dark matter annihilation (specifying the spins and interactions), and fixing the couplings to obtain the desired relic abundance, we ask:

1) Can we get a gamma-ray signal that is compatible the observed excess?

2) Is the related diagram compatible with direct detection constraints?

3) Is the model compatible with constraints from colliders (including the LHC)?



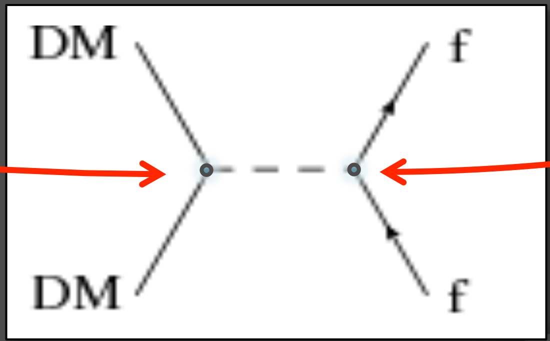


Berlin, DH, McDermott,1404.0022
(see also Alves et al. 1403.5027; Izaguirre et al. 1404.2018)

What kind of WIMP could produce this signal?

For example, consider fermionic (Majorana or Dirac) dark matter, annihilating through the exchange of a spin-0 or spin-1 mediator:

DM bilinear	***SM fermion bilinear***			
	$\bar{f}f$	$\bar{f}\gamma^5 f$	$\bar{f}\gamma^\mu f$	$\bar{f}\gamma^\mu\gamma^5 f$
$\bar{\chi}\chi$	$\sigma v \sim v^2,\ \sigma_{\rm SI} \sim 1$	$\sigma v \sim v^2,\ \sigma_{\rm SD} \sim q^2$	–	–
$\bar{\chi}\gamma^5\chi$	$\boldsymbol{\sigma v \sim 1,\ \sigma_{\rm SI} \sim q^2}$	$\boldsymbol{\sigma v \sim 1,\ \sigma_{\rm SD} \sim q^4}$	–	–
$\bar{\chi}\gamma^\mu\chi$ (Dirac only)	–	–	$\sigma v \sim 1,\ \sigma_{\rm SI} \sim 1$	$\boldsymbol{\sigma v \sim 1,\ \sigma_{\rm SD} \sim v_\perp^2}$
$\bar{\chi}\gamma^\mu\gamma^5\chi$	–	–	$\sigma v \sim v^2,\ \sigma_{\rm SI} \sim v_\perp^2$	$\boldsymbol{\sigma v \sim 1,\ \sigma_{\rm SD} \sim 1}$



Berlin, DH, McDermott,1404.0022

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$\bar{\chi}\gamma^5\chi$	$\boldsymbol{\sigma v \sim 1,\ \sigma_{\rm SI} \sim q^2}$	$\boldsymbol{\sigma v \sim 1,\ \sigma_{\rm SD} \sim q^4}$	–	–
$\bar{\chi}\gamma^\mu\chi$ (Dirac only)	–	–	$\sigma v \sim 1,\ \sigma_{\rm SI} \sim 1$	$\boldsymbol{\sigma v \sim 1,\ \sigma_{\rm SD} \sim v_\perp^2}$
$\bar{\chi}\gamma^\mu\gamma^5\chi$	–	–	~~$\sigma v \sim v^2,\ \sigma_{\rm SI} \sim v_\perp^2$~~	$\boldsymbol{\sigma v \sim 1,\ \sigma_{\rm SD} \sim 1}$

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Berlin, DH, McDermott,1404.0022

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$\bar{\chi}\gamma^\mu\gamma^5\chi$	–	–	~~$\sigma v \sim v^2,\ \sigma_{\rm SI} \sim v_\perp^2$~~	$\boldsymbol{\sigma v \sim 1,\ \sigma_{\rm SD} \sim 1}$

-Models with velocity suppressed annihilation cross sections cannot account for the gamma-ray excess

-Models with unsuppressed vector or scalar interactions with nuclei are ruled out by direct detection constraints

Berlin, DH, McDermott,1404.0022

What kind of WIMP could produce this signal?

In general, we find:

It is not difficult to write down dark matter models with a ~30 GeV thermal relic that can produce the gamma-ray signal in question (satisfied for a wide range of models with s-wave interactions)

Direct detection constraints rule out models with unsuppressed scalar or vector interactions with quarks

Somewhat contrary to conventional wisdom, the LHC does not yet exclude many of these models (although the 14 TeV reach is expected to be much more expansive)

What kind of WIMP could produce this signal?

All together, we identified 16 scenarios that could account for the gamma-ray signal without conflicting with current constraints:

DM	*Mediator*	*Interactions*	Elastic Scattering	Near Future Reach? Direct	LHC
Dirac Fermion	Spin-0	$\bar{\chi}\gamma^5\chi,\ \bar{f}f$	$\sigma_{\rm SI} \sim (q/2m_\chi)^2$ (scalar)	No	Maybe
Majorana Fermion	Spin-0	$\bar{\chi}\gamma^5\chi,\ \bar{f}f$	$\sigma_{\rm SI} \sim (q/2m_\chi)^2$ (scalar)	No	Maybe
Dirac Fermion	Spin-0	$\bar{\chi}\gamma^5\chi,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q^2/4m_n m_\chi)^2$	Never	Maybe
Majorana Fermion	Spin-0	$\bar{\chi}\gamma^5\chi,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q^2/4m_n m_\chi)^2$	Never	Maybe
Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\chi,\ \bar{b}\gamma_\mu b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Maybe
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 $\sigma_{\rm SD} \sim (q/2m_\chi)^2$	Never	Maybe
Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\gamma^5\chi,\ \bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD} \sim 1$	Yes	Maybe
Majorana Fermion	Spin-1	$\bar{\chi}\gamma^\mu\gamma^5\chi,\ \bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD} \sim 1$	Yes	Maybe
Complex Scalar	Spin-0	$\phi^\dagger\phi,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
Real Scalar	Spin-0	$\phi^2,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
Complex Vector	Spin-0	$B^\dagger_\mu B^\mu,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
Real Vector	Spin-0	$B_\mu B^\mu,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
Dirac Fermion	Spin-0 (t-ch.)	$\bar{\chi}(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
Dirac Fermion	Spin-1 (t-ch.)	$\bar{\chi}\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
Complex Vector	Spin-1/2 (t-ch.)	$X^\dagger_\mu\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
Real Vector	Spin-1/2 (t-ch.)	$X_\mu\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes

Berlin, DH, McDermott,1404.0022

These scenarios roughly fall into three categories:

DM	*Mediator*	*Interactions*	**Elastic Scattering**	**Near Future Reach?**	
				Direct	**LHC**
Dirac Fermion	Spin-0	$\bar{\chi}\gamma^5\chi,\ \bar{f}f$	$\sigma_{\rm SI} \sim (q/2m_\chi)^2$ (scalar)	No	Maybe
Majorana Fermion	Spin-0	$\bar{\chi}\gamma^5\chi,\ \bar{f}f$	$\sigma_{\rm SI} \sim (q/2m_\chi)^2$ (scalar)	No	Maybe
Dirac Fermion	Spin-0	$\bar{\chi}\gamma^5\chi,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q^2/4m_n m_\chi)^2$	Never	Maybe
Majorana Fermion	Spin-0	$\bar{\chi}\gamma^5\chi,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q^2/4m_n m_\chi)^2$	Never	Maybe
Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\chi,\ \bar{b}\gamma_\mu b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Maybe
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 $\sigma_{\rm SD} \sim (q/2m_\chi)^2$	Never	Maybe
Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\gamma^5\chi,\ \bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD} \sim 1$	Yes	Maybe
Majorana Fermion	Spin-1	$\bar{\chi}\gamma^\mu\gamma^5\chi,\ \bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD} \sim 1$	Yes	Maybe
Complex Scalar	Spin-0	$\phi^\dagger\phi,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
Real Scalar	Spin-0	$\phi^2,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
Complex Vector	Spin-0	$B^\dagger_\mu B^\mu,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
Real Vector	Spin-0	$B_\mu B^\mu,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
Dirac Fermion	Spin-0 (t-ch.)	$\bar{\chi}(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
Dirac Fermion	Spin-1 (t-ch.)	$\bar{\chi}\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
Complex Vector	Spin-1/2 (t-ch.)	$X^\dagger_\mu\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
Real Vector	Spin-1/2 (t-ch.)	$X_\mu\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes

Berlin, DH, McDermott,1404.0022

These scenarios roughly fall into three categories:

1) Models with pseudoscalar interactions (see also Boehm et al. 1401.6458, Ipek et al. 1404.3716)

DM	*Mediator*	*Interactions*	Elastic Scattering	Near Future Reach? Direct	LHC
Dirac Fermion	Spin-0	$\bar{\chi}\gamma^5\chi$, $\bar{f}f$	$\sigma_{\rm SI} \sim (q/2m_\chi)^2$ (scalar)	No	Maybe
Majorana Fermion	Spin-0	$\bar{\chi}\gamma^5\chi$, $\bar{f}f$	$\sigma_{\rm SI} \sim (q/2m_\chi)^2$ (scalar)	No	Maybe
Dirac Fermion	Spin-0	$\bar{\chi}\gamma^5\chi$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q^2/4m_n m_\chi)^2$	Never	Maybe
Majorana Fermion	Spin-0	$\bar{\chi}\gamma^5\chi$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q^2/4m_n m_\chi)^2$	Never	Maybe
Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\chi$, $\bar{b}\gamma_\mu b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Maybe
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 $\sigma_{\rm SD} \sim (q/2m_\chi)^2$	Never	Maybe
Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\gamma^5\chi$, $\bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD} \sim 1$	Yes	Maybe
Majorana Fermion	Spin-1	$\bar{\chi}\gamma^\mu\gamma^5\chi$, $\bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD} \sim 1$	Yes	Maybe
Complex Scalar	Spin-0	$\phi^\dagger\phi$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
Real Scalar	Spin-0	ϕ^2, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
Complex Vector	Spin-0	$B^\dagger_\mu B^\mu$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
Real Vector	Spin-0	$B_\mu B^\mu$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
Dirac Fermion	Spin-0 (t-ch.)	$\bar{\chi}(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
Dirac Fermion	Spin-1 (t-ch.)	$\bar{\chi}\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
Complex Vector	Spin-1/2 (t-ch.)	$X^\dagger_\mu\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
Real Vector	Spin-1/2 (t-ch.)	$X_\mu\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes

Berlin, DH, McDermott, 1404.0022

These scenarios roughly fall into three categories:

1) Models with pseudoscalar interactions

2) Models with axial interactions (or vector interactions with 3rd generation)

DM	*Mediator*	*Interactions*	Elastic Scattering	Near Future Reach? Direct	LHC
Dirac Fermion	Spin-0	$\bar{\chi}\gamma^5\chi,\ \bar{f}f$	$\sigma_{\rm SI} \sim (q/2m_\chi)^2$ (scalar)	No	Maybe
Majorana Fermion	Spin-0	$\bar{\chi}\gamma^5\chi,\ \bar{f}f$	$\sigma_{\rm SI} \sim (q/2m_\chi)^2$ (scalar)	No	Maybe
Dirac Fermion	Spin-0	$\bar{\chi}\gamma^5\chi,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q^2/4m_n m_\chi)^2$	Never	Maybe
Majorana Fermion	Spin-0	$\bar{\chi}\gamma^5\chi,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q^2/4m_n m_\chi)^2$	Never	Maybe
Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\chi,\ \bar{b}\gamma_\mu b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Maybe
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 $\sigma_{\rm SD} \sim (q/2m_\chi)^2$	Never	Maybe
Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\gamma^5\chi,\ \bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD} \sim 1$	Yes	Maybe
Majorana Fermion	Spin-1	$\bar{\chi}\gamma^\mu\gamma^5\chi,\ \bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD} \sim 1$	Yes	Maybe
Complex Scalar	Spin-0	$\phi^\dagger\phi,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
Real Scalar	Spin-0	$\phi^2,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
Complex Vector	Spin-0	$B_\mu^\dagger B^\mu,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
Real Vector	Spin-0	$B_\mu B^\mu,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
Dirac Fermion	Spin-0 (t-ch.)	$\bar{\chi}(1\pm\gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
Dirac Fermion	Spin-1 (t-ch.)	$\bar{\chi}\gamma^\mu(1\pm\gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
Complex Vector	Spin-1/2 (t-ch.)	$X_\mu^\dagger\gamma^\mu(1\pm\gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
Real Vector	Spin-1/2 (t-ch.)	$X_\mu\gamma^\mu(1\pm\gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes

Berlin, DH, McDermott,1404.0022

These scenarios roughly fall into three categories:

1) Models with pseudoscalar interactions

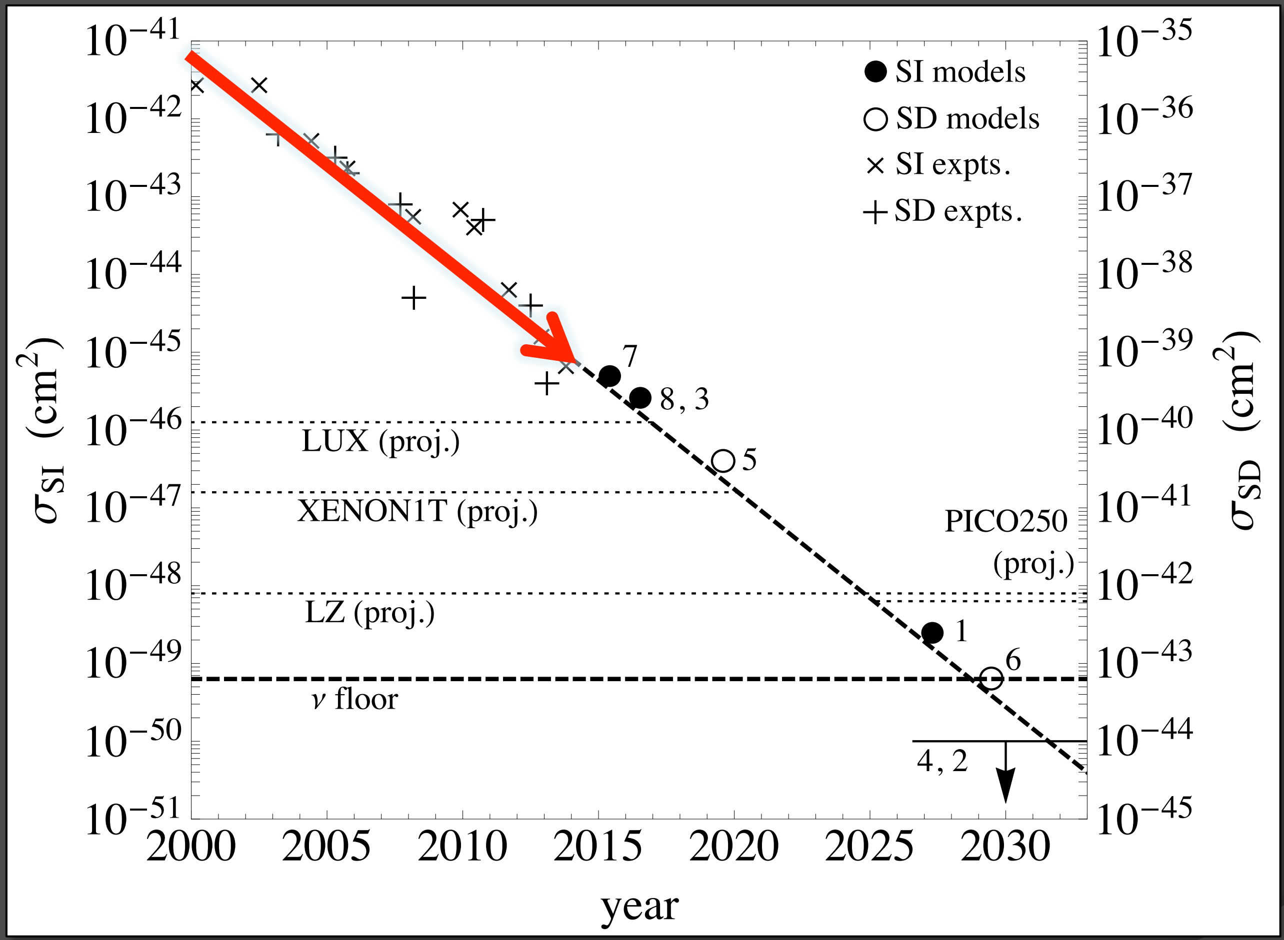
2) Models with axial interactions (or vector interactions with 3rd generation)

3) Models with a colored and charged t-channel mediator (see Agrawal et al. 1404.1373)

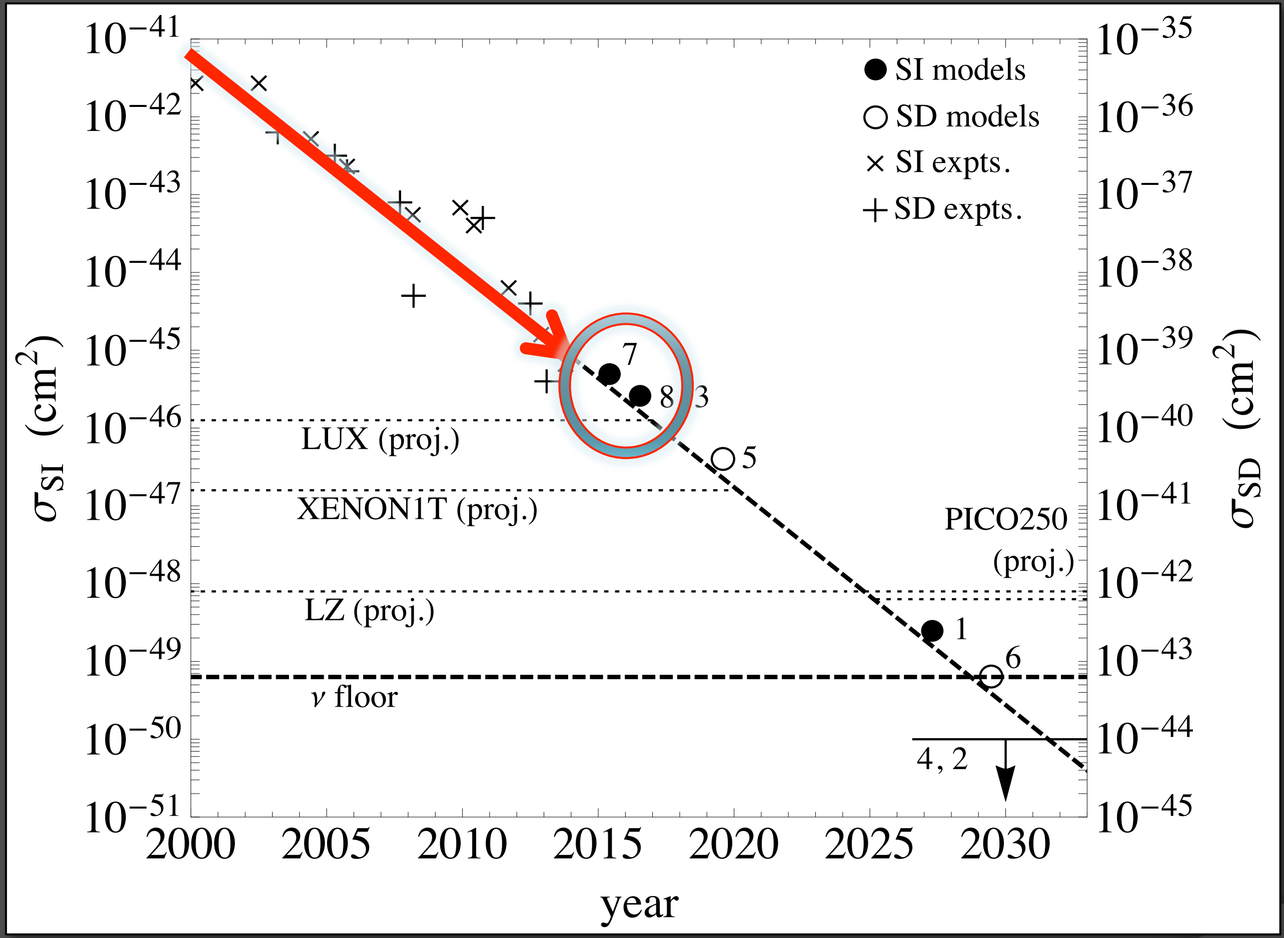
DM	*Mediator*	*Interactions*	Elastic Scattering	Near Future Reach?	
				Direct	LHC
Dirac Fermion	Spin-0	$\bar{\chi}\gamma^5\chi,\ \bar{f}f$	$\sigma_{\rm SI} \sim (q/2m_\chi)^2$ (scalar)	No	Maybe
Majorana Fermion	Spin-0	$\bar{\chi}\gamma^5\chi,\ \bar{f}f$	$\sigma_{\rm SI} \sim (q/2m_\chi)^2$ (scalar)	No	Maybe
Dirac Fermion	Spin-0	$\bar{\chi}\gamma^5\chi,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q^2/4m_n m_\chi)^2$	Never	Maybe
Majorana Fermion	Spin-0	$\bar{\chi}\gamma^5\chi,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q^2/4m_n m_\chi)^2$	Never	Maybe
Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\chi,\ \bar{b}\gamma_\mu b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Maybe
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 $\sigma_{\rm SD} \sim (q/2m_\chi)^2$	Never	Maybe
Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\gamma^5\chi,\ \bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD} \sim 1$	Yes	Maybe
Majorana Fermion	Spin-1	$\bar{\chi}\gamma^\mu\gamma^5\chi,\ \bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD} \sim 1$	Yes	Maybe
Complex Scalar	Spin-0	$\phi^\dagger\phi,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
Real Scalar	Spin-0	$\phi^2,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
Complex Vector	Spin-0	$B^\dagger_\mu B^\mu,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
Real Vector	Spin-0	$B_\mu B^\mu,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
Dirac Fermion	Spin-0 (t-ch.)	$\bar{\chi}(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
Dirac Fermion	Spin-1 (t-ch.)	$\bar{\chi}\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
Complex Vector	Spin-1/2 (t-ch.)	$X^\dagger_\mu\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
Real Vector	Spin-1/2 (t-ch.)	$X_\mu\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes

Berlin, DH, McDermott,1404.0022

Prospects for Direct Detection

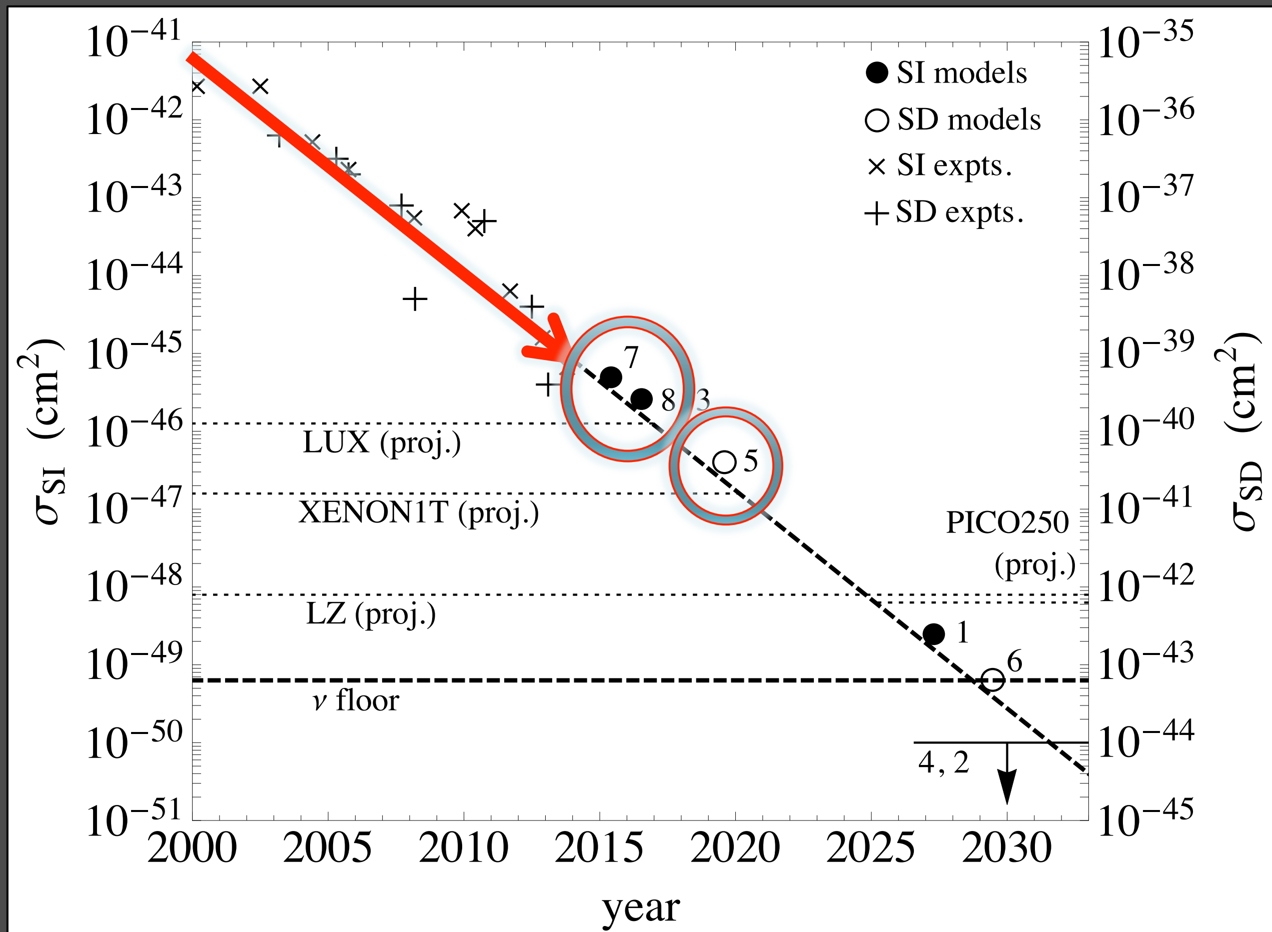


Prospects for Direct Detection



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

Prospects for Direct Detection

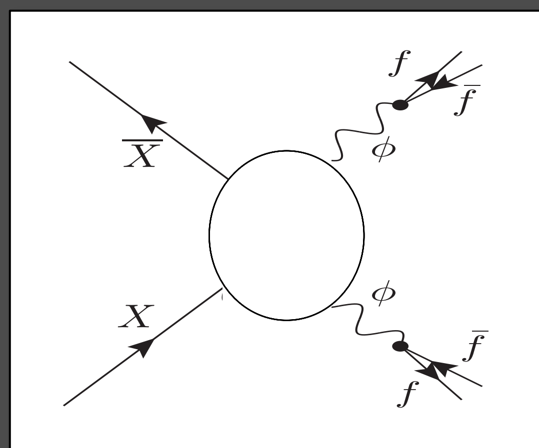


t-channel models are within the reach of both LUX and LHC14

Models with purely axial interactions will be tested by XENON1T

Hidden Sector Models

Alternatively (to tree-level annihilation models), one could consider dark matter that does not couple directly to the Standard Model, but instead annihilates into other particles that subsequently decay into Standard Model fermions:

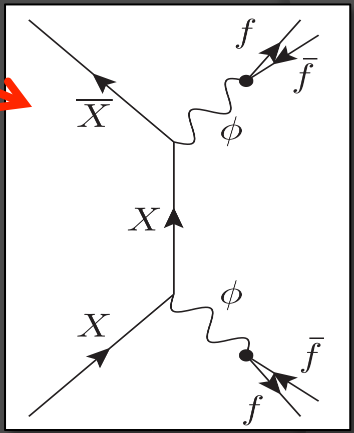


Martin et al. 1405.0272,
Abdullah et al. 1404.6528,
Boehm et al. 1404.4977
A. Berlin, S. McDermott,
DH, 1405.5204

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:



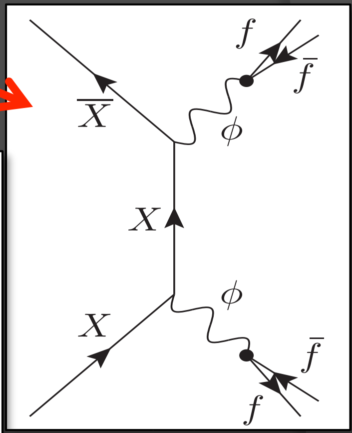
Relic abundance and Galactic Center annihilation rate require $g_X \sim 0.1$

Berlin, DH, McDermott,1405.5404

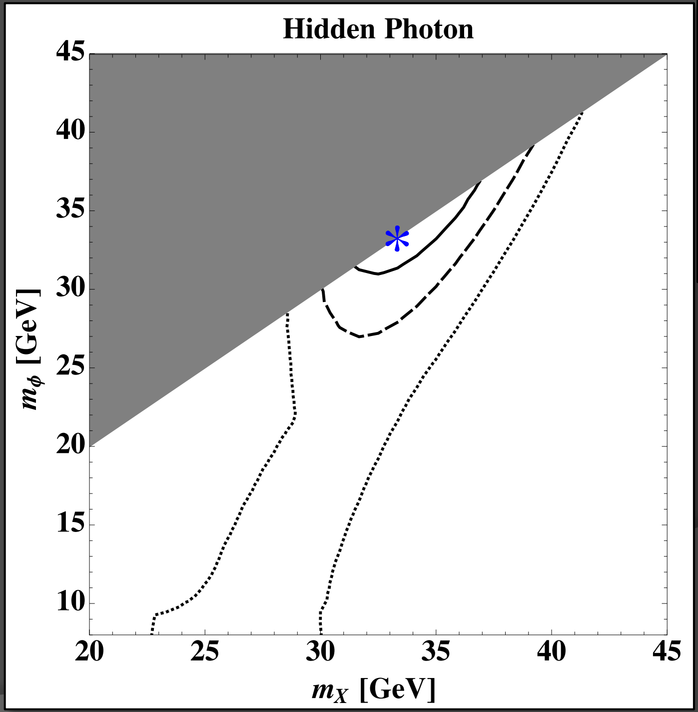
Dark Matter with a Hidden Photon

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 annihilation rate require $g_X \sim 0.1$



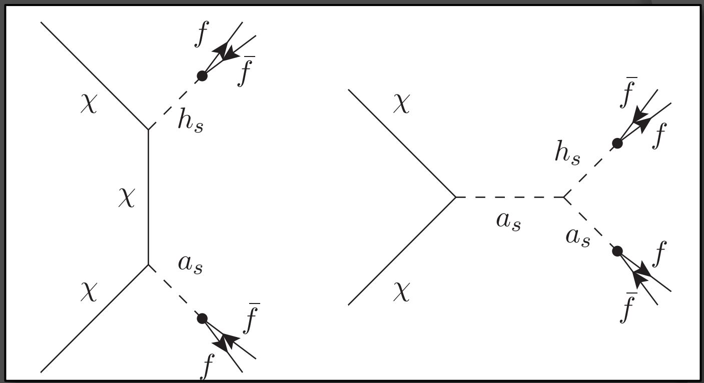
The ϕ's decay through a small degree of kinetic mixing with the photon; direct constraints require mixing less than $\varepsilon \sim 10^{-4}$ (near loop-level prediction)

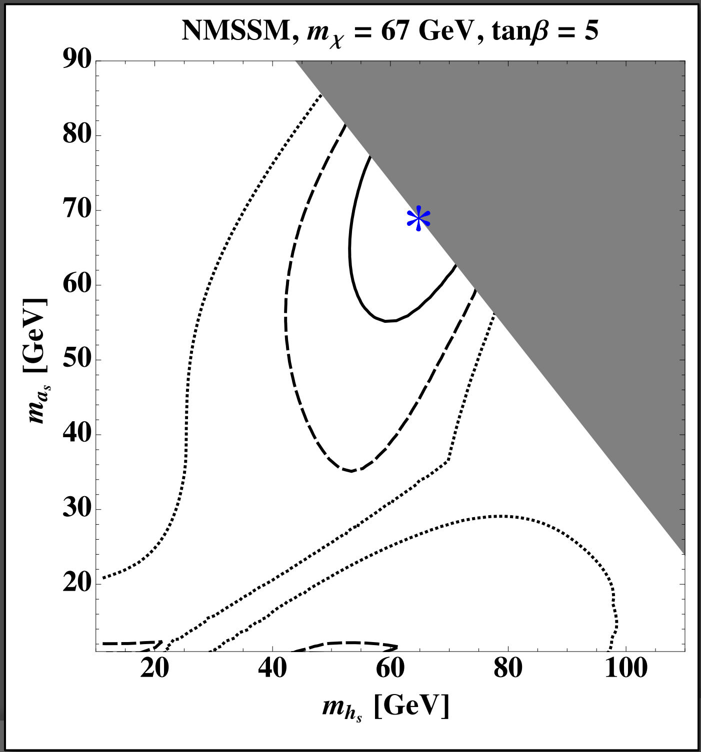
Berlin, DH, McDermott,1405.5404

A Supersymmetric Model

Within the context of the generalized NMSSM, the singlino and the complex higgs singlet can be effectively sequestered from the MSSM, allowing for phenomenology similar to in the hidden photon case

Relic abundance and Galactic Center annihilation rate require κ ~ 0.1





The h_s, a_s decay through mass mixing with the MSSM h, A

Direct direct constraints require λ ~ 10^{-3} or less

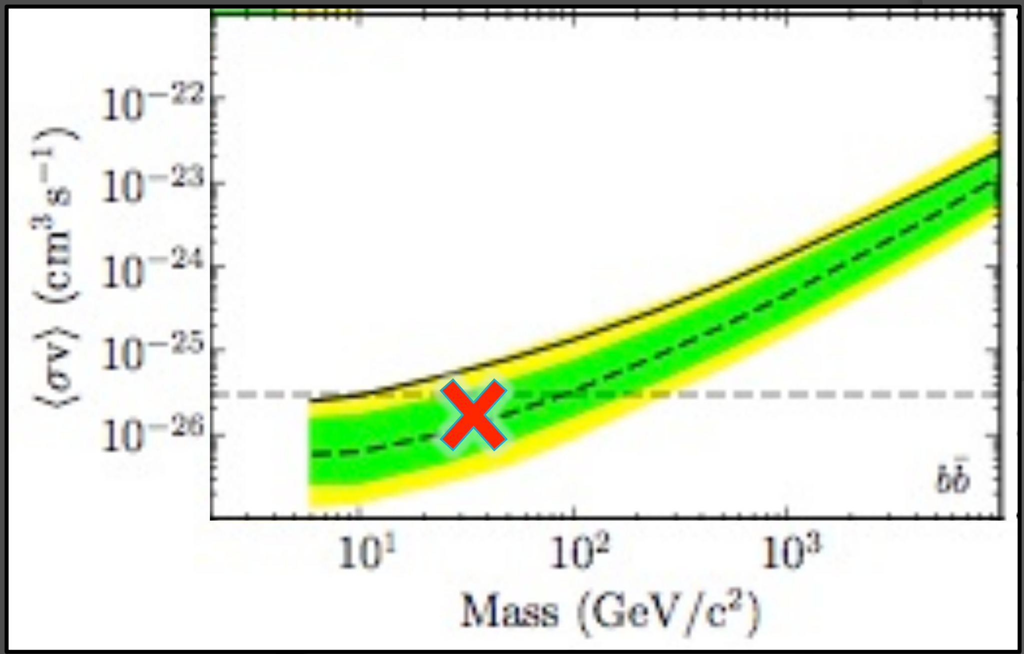
A. Berlin, S. McDermott, DH, 1405.5204

What Next?

Although the Galactic Center is almost certainly the brightest source of dark matter annihilation products in the sky, a dark matter candidate able to generate the observed excess would also be expected to be potentially observable in other Fermi analyses as well (although probably marginally)

Dwarf Spheroidal Galaxies

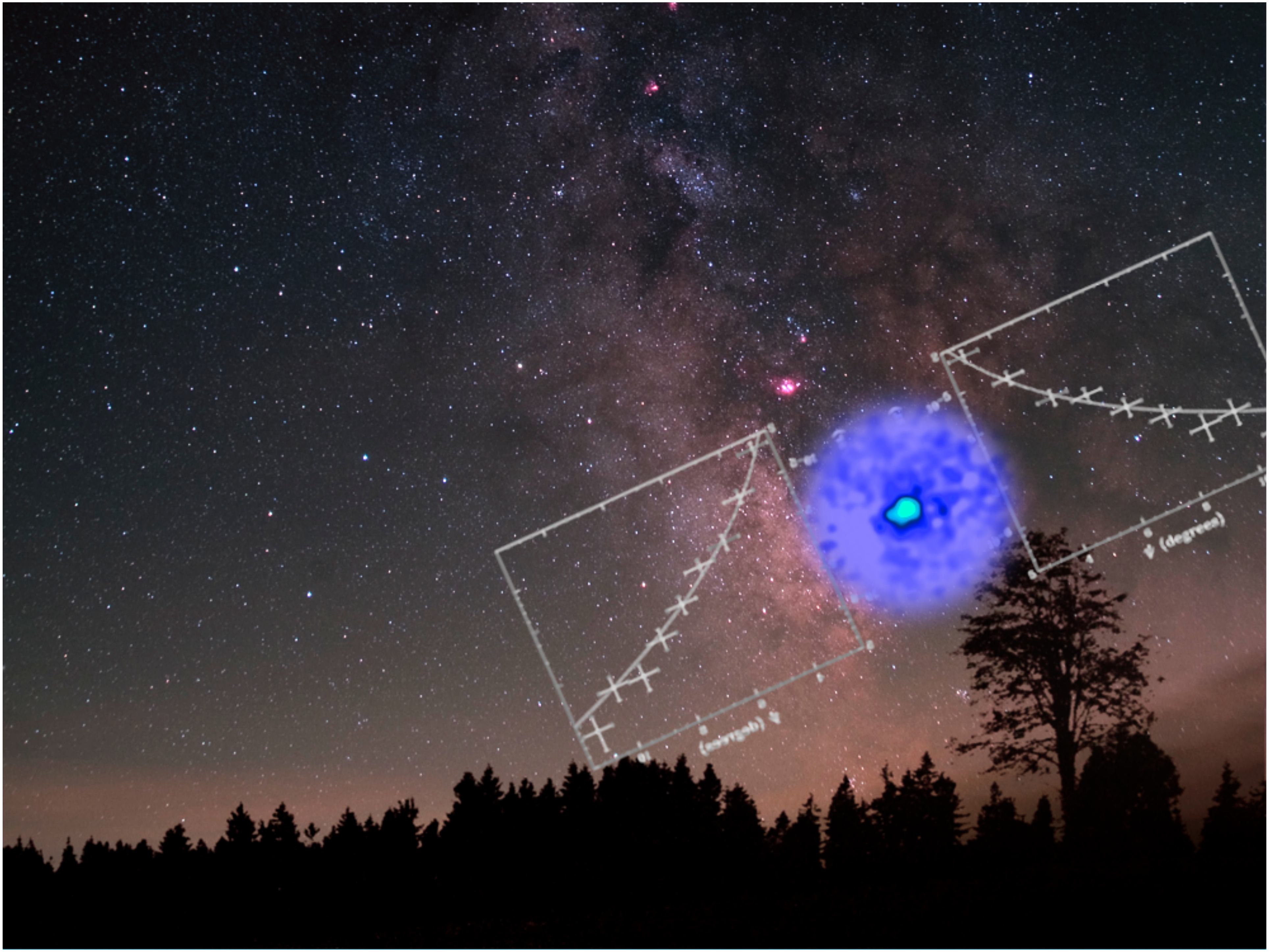
- The Fermi Collaboration has recently presented their analysis of 25 dwarf spheroidal galaxies, making use of 4 years of data
- They find a modest excess, ~2-3σ (local)
- If interpreted as a signal of dark matter, this would imply a mass and cross section that is very similar to that required to account for the Galactic Center and Inner Galaxy excess
- With more data from Fermi, this hint could potentially become statistically significant
- For 10 years of data, we very naively estimate: $(2\text{-}3)\,\sigma \times (10/4)^{1/2} \rightarrow (3.2\text{-}4.7)\,\sigma$ (not including transition to pass 8)



Fermi Collaboration, arXiv:1310.0828

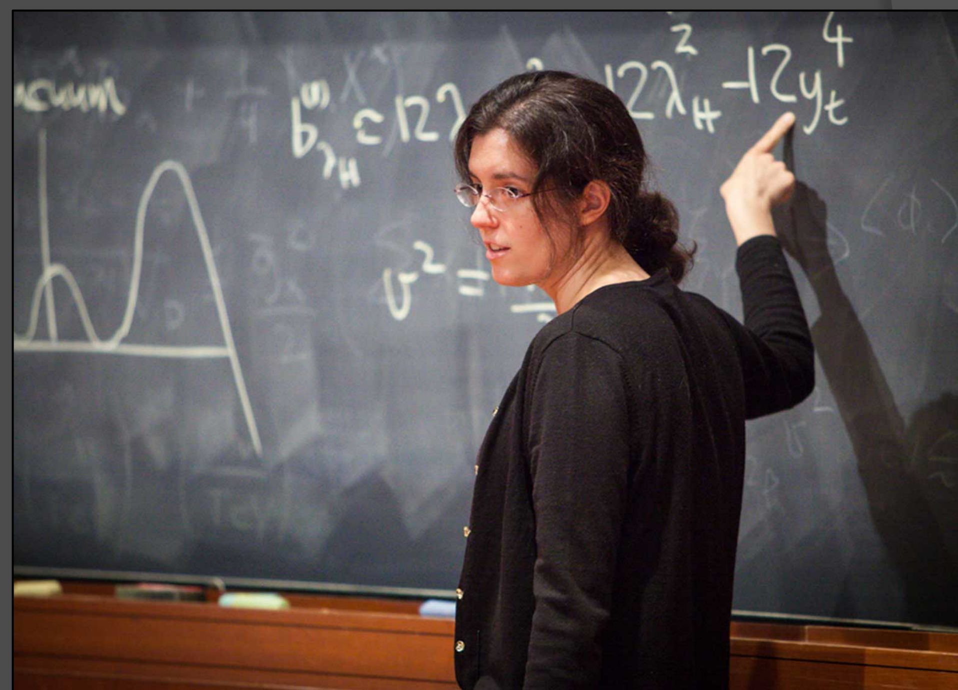
Summary

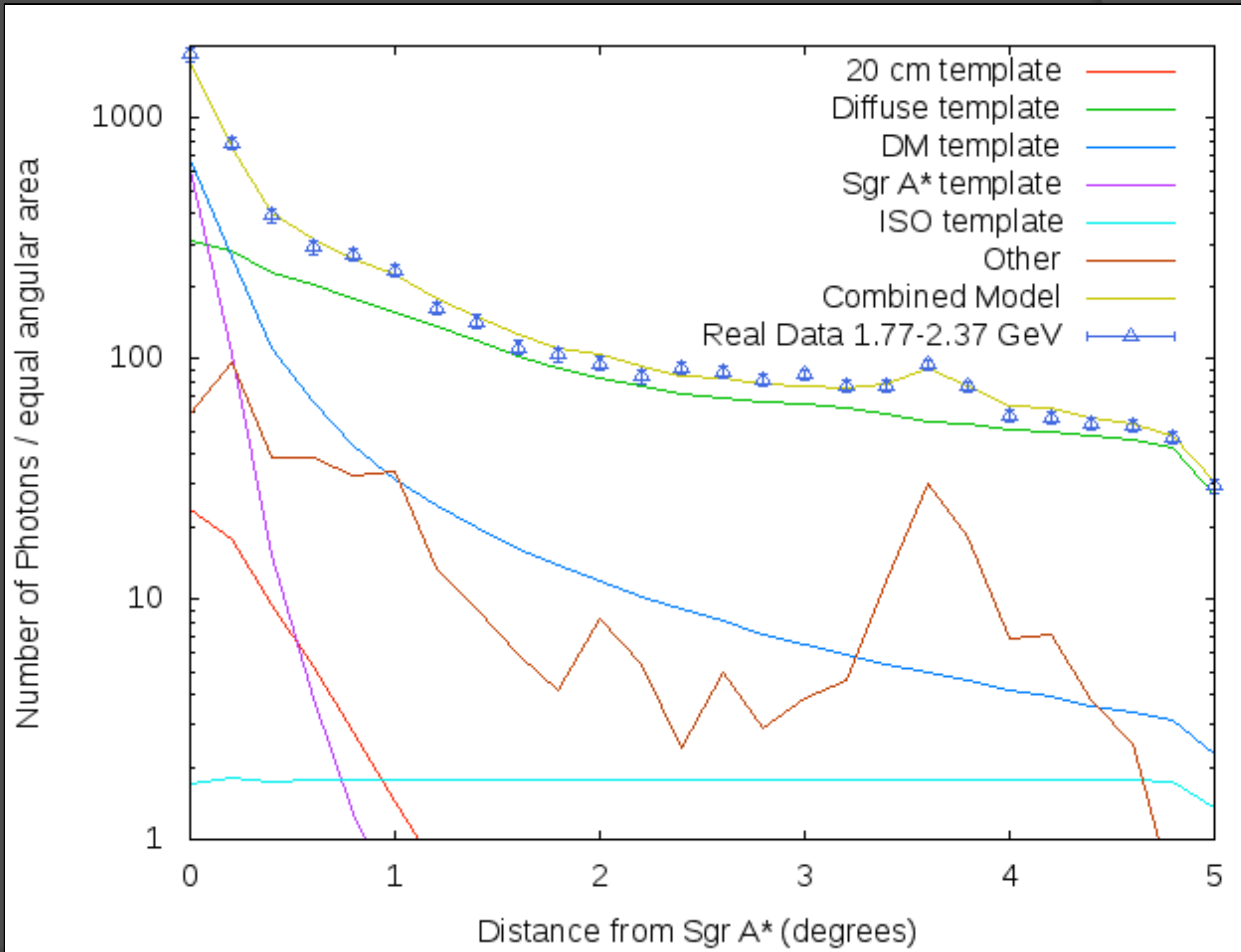
- In revisiting and scrutinizing the gamma-ray emission from the Central Milky Way, we confirm a highly statistically significant and robust excess
- The spectrum and angular distribution of this signal is very well fit by a 31-40 GeV WIMP (annihilating to b quarks), distributed as $\rho \sim r^{-1.25}$
- The normalization of this signal requires a dark matter annihilation cross section of $\sigma v \sim (1.7\text{-}2.3) \times 10^{-26}$ cm^3/s (for ρ_{local} = 0.3 GeV/cm^3); in remarkable agreement with the value predicted for a simple thermal relic
- The excess is distributed with approximate spherical symmetry and extends out to at least 10° from the Galactic Center
- Many simple dark matter models can account for the observed emission without conflicting with constraints from direct detection experiments or colliders – future prospects are encouraging
- Future observations (dwarfs, clusters, cosmic-ray antiprotons, etc.) will be important to confirm a dark matter origin of this signal


ψ (degrees)

Acknowledgement

- In 2007, Kathryn Zurek and I made a bet regarding whether dark matter would be definitely discovered by 2012 (I bet that it would be)
- In 2012, the situation was not clear – we agreed to wait and see whether direct detection anomalies persisted to determine the winner (in 2012, the gamma-ray excess was not yet as clear as it is today)
- In light of the null results from SuperCDMS and LUX, I recently conceded our bet
- In the language of the original bet, the loser agreed to acknowledge their loss in every talk they give for an entire year (and thus this slide…)

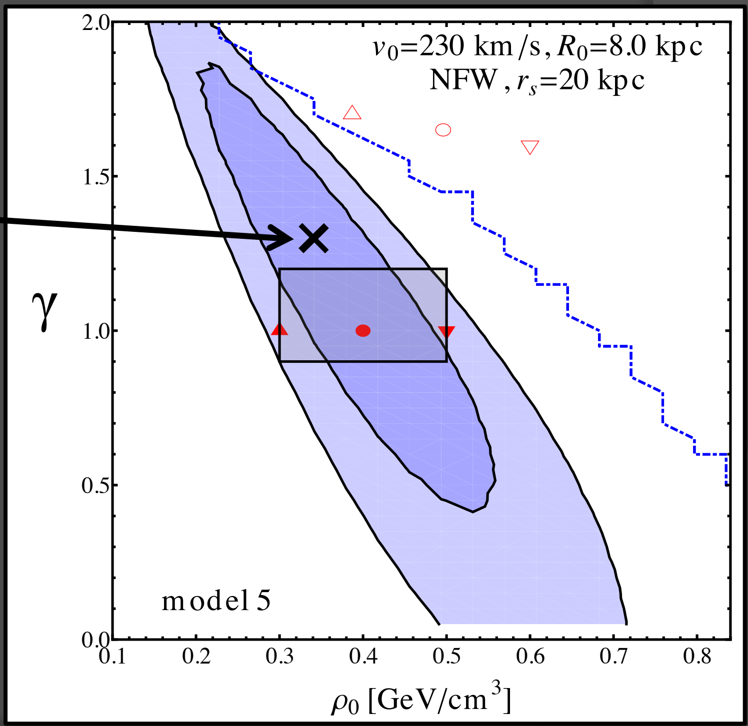




20 cm template
Diffuse template
DM template
Sgr A* template
ISO template
Other
Combined Model
Real Data 1.77-2.37 GeV
Number of Photons / equal angular area
1000
100
10
1
0
1
2
3
4
5
Distance from Sgr A* (degrees)

The Distribution of Dark Matter in the Inner Milky Way

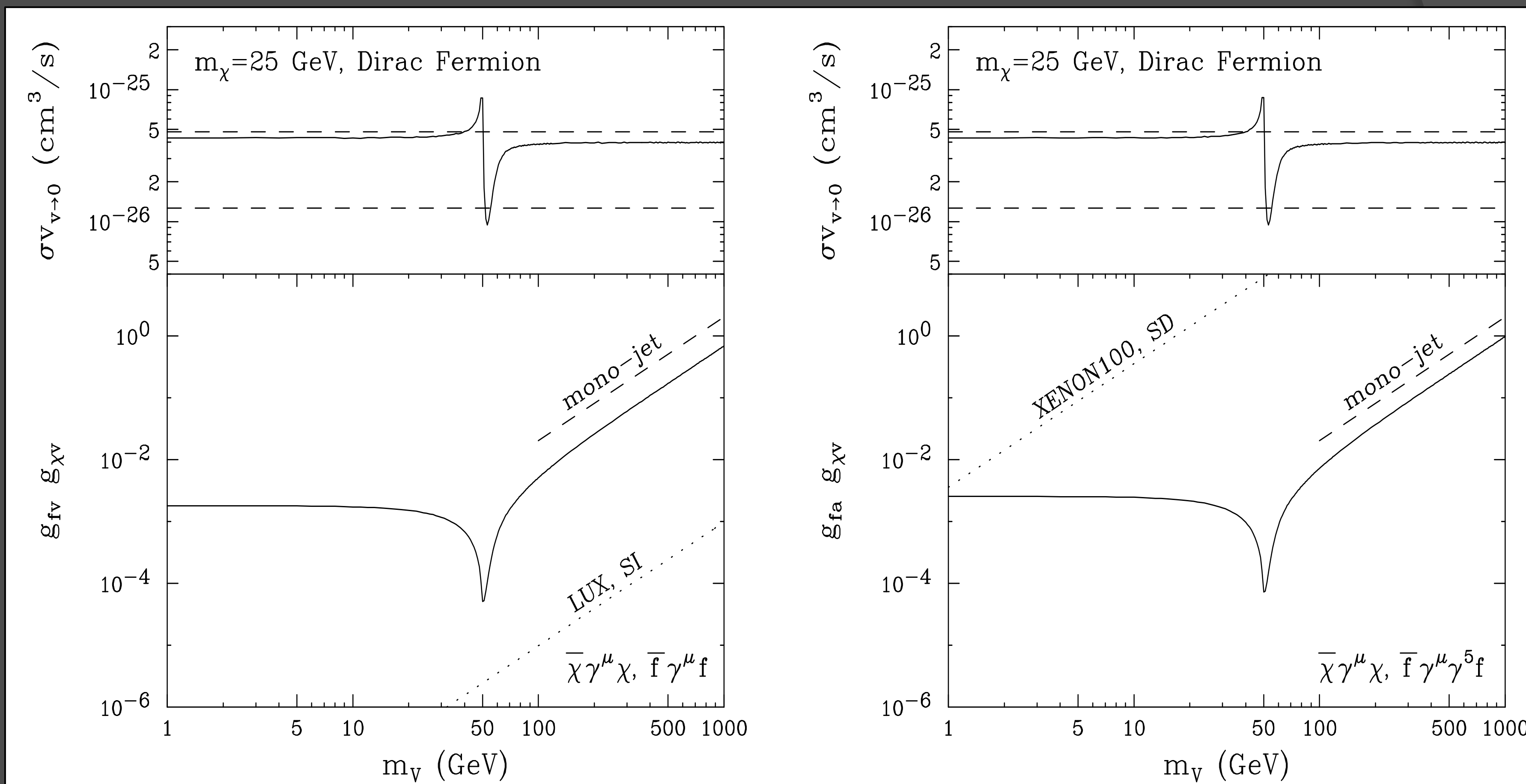
- Dark matter only simulations (Via Lactea, Aquarius, etc.) produce halos that possess inner profiles of $\rho \propto r^{-\gamma}$ where $\gamma \sim 1.0$ to 1.2
- The inner volume (~10 kpc) of the Milky Way is dominated by baryons, not dark matter – significant departures from the results of dark matter-only simulations may be expected
- Existing microlensing and dynamical data are not capable of determining the inner slope, although $\gamma \sim 1.3$ provides the best fit
- Although hydrodynamical simulations have begun to converge in favor of a moderate degree of contraction in Milky Way-like halos (favoring $\gamma \sim 1.2$-1.5), other groups find that cusps may be flattened if baryonic feedback processes are very efficient ($\gamma < 1$)
- We keep an open mind and adopt a generalized profile with an inner slope, γ



Iocco, et al., arXiv:1107.5810; Gnedin, et al., arXiv:1108.5736

What kind of WIMP could produce this signal?

Shown another way (for a couple of examples):



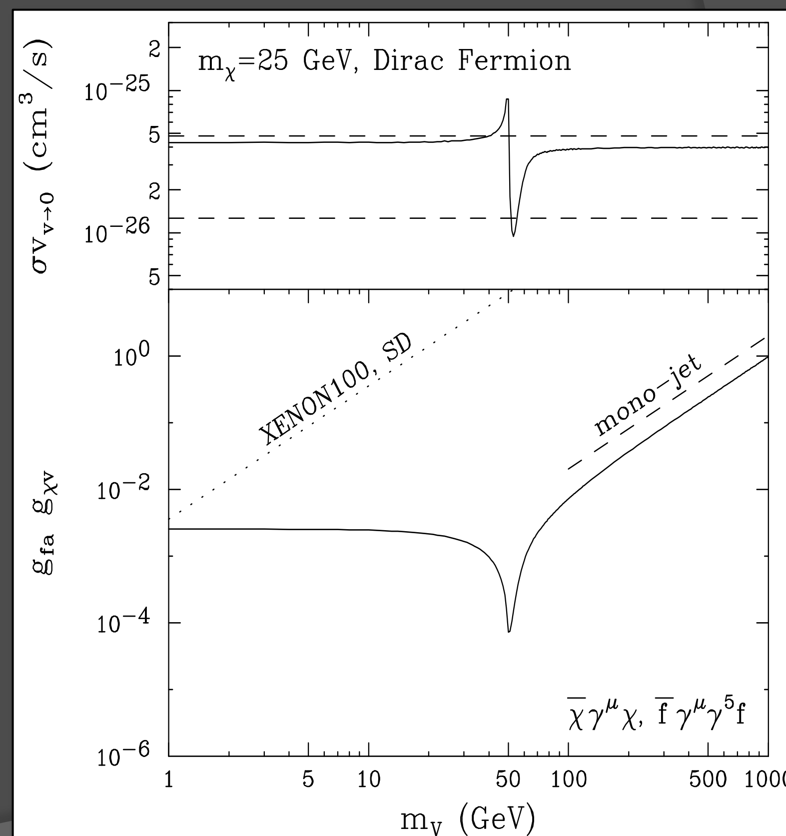
Berlin, DH, McDermott,1404.0022

Constraints from Mono-X

We considered constraints (and projected constraints) from mono-jet, mono-b, and mono-W/Z searches

-Such searches constrain the coefficients of effective operators, roughly corresponding to $(g_f\, g_X)^{1/2}/M_{med}$

-Reality, however, is only imperfectly described by effective operators



A. Berlin, S. McDermott, DH, 1404.0022

Sidebar: The Validity of Effective Field Theory

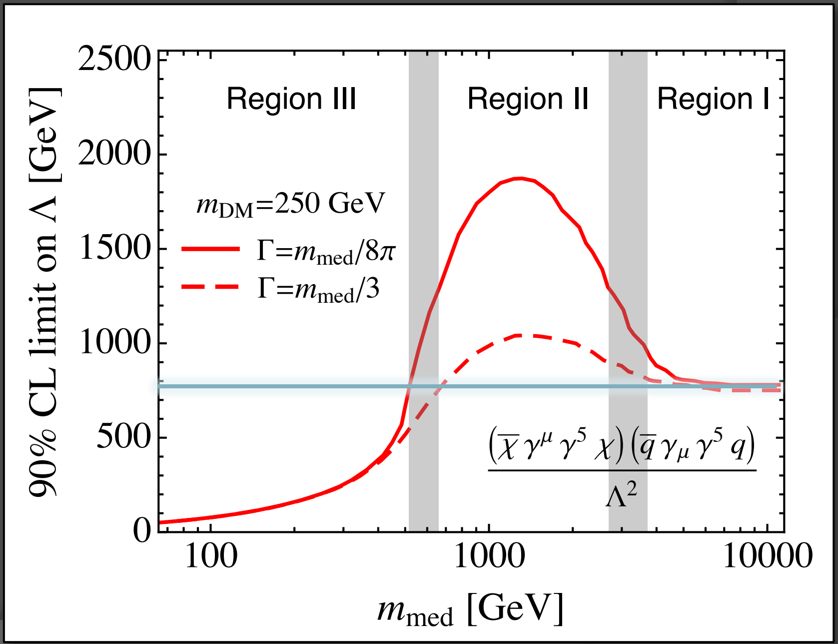
When one derives a constraint on the coefficient of an effective operator, they are implicitly assuming that all of the particles being exchanged are much heavier than the center-of-mass energy of the interaction

This assumption can either overestimate or underestimate the actual constraint on the mediator mass and couplings:

$M_{med} >> E_{CM}$, the correct limit is obtained

$M_{med} \sim E_{CM}$, the limit is *underestimated*

$M_{med} << E_{CM}$, the limit is *overestimated*

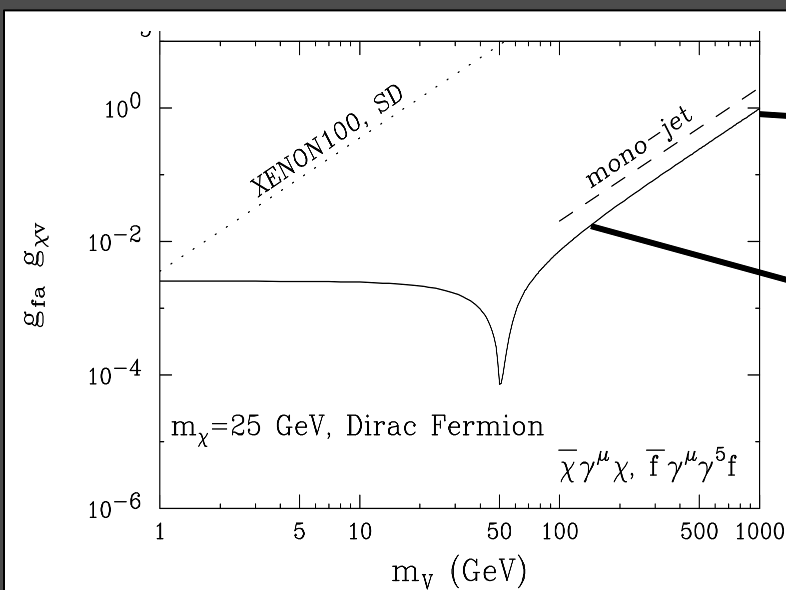


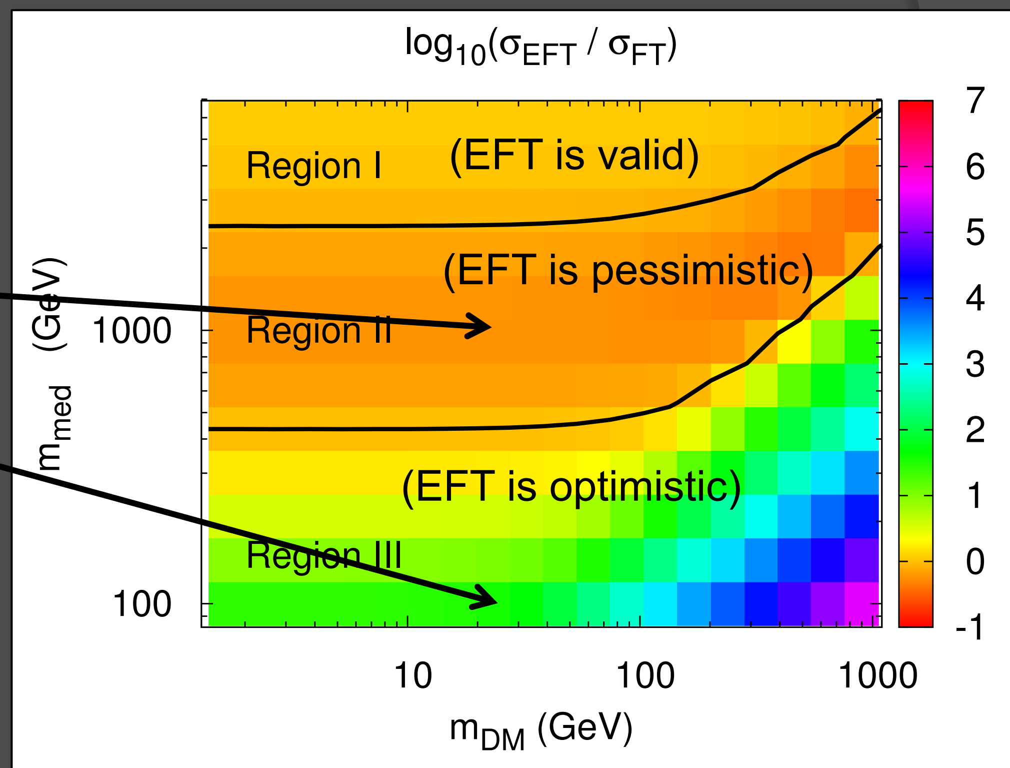
Buckmueller, Dolan, McCabe, 1308.6799
(highly recommended reading!)

Sidebar: The Validity of Effective Field Theory

For LHC 8 TeV, typical dark matter models do not lie in the "Region I" where EFT is valid

This provides strong motivation to move beyond EFT and toward simplified models





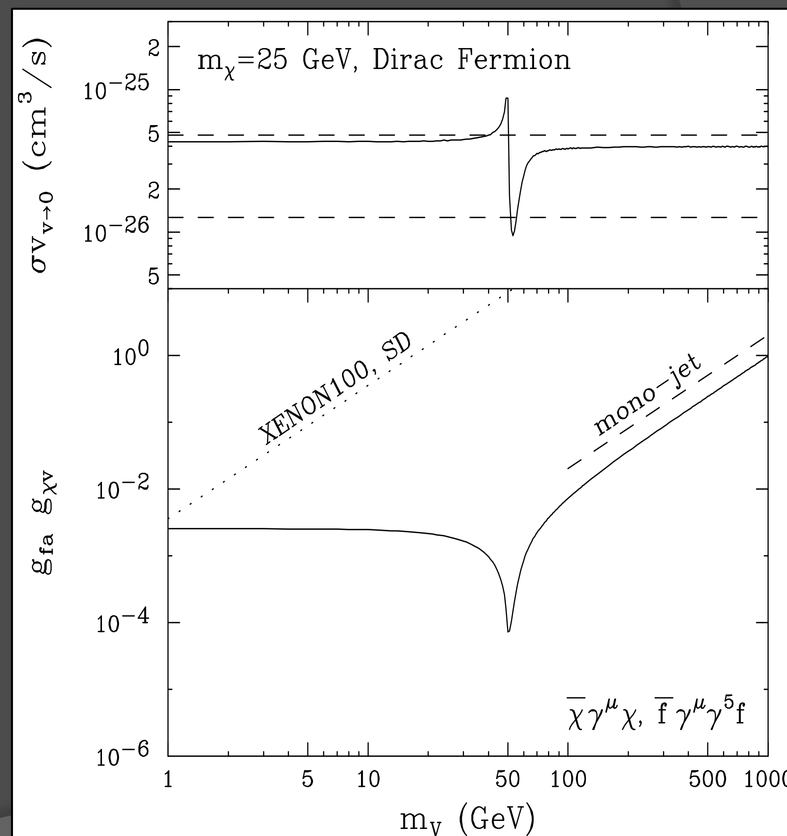
Buckmueller, Dolan, McCabe, 1308.6799 (highly recommended reading!)

Constraints from Mono-X

In general, we found that the current ATLAS mono-jet constraint is within a factor of a few of that required to test dark matter models for the Galactic Center gamma-ray excess, so long as:

1) The mediating particles couple to light quarks (if couple only to heavy quarks, mono-b constraints are more important)
Data at 13-14 TeV should be able to reach this target!

2) The mass of the mediator is not less than a few hundred GeV
(where EFT breaks down)
A simplified model analysis would help to clarify this considerably!



A. Berlin, S. McDermott, DH, 1404.0022

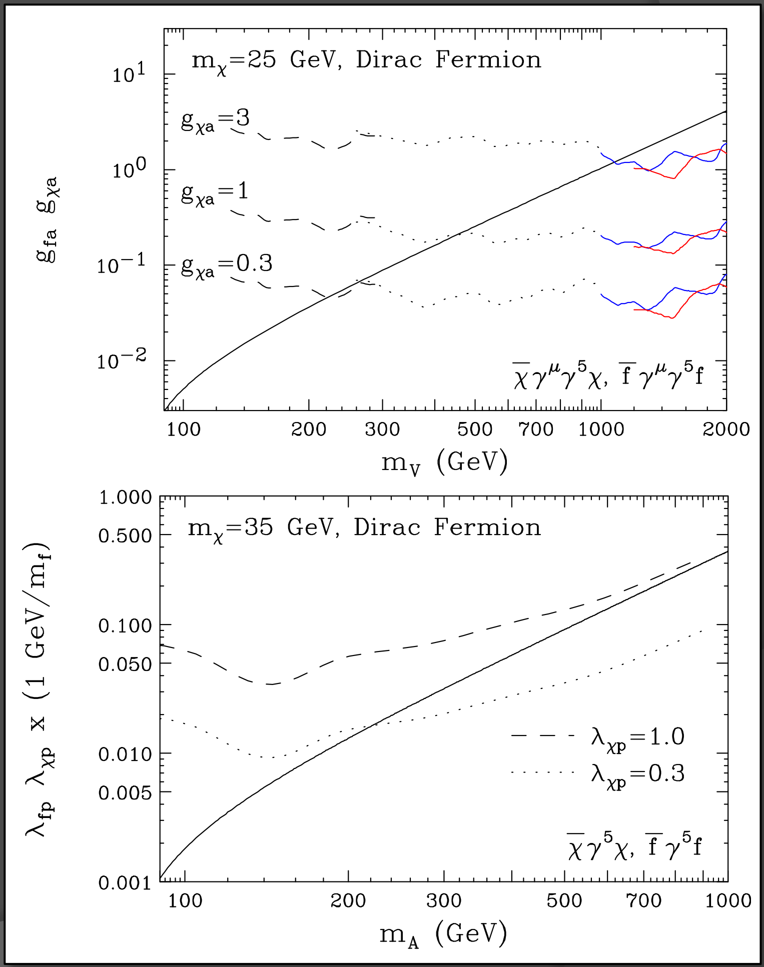
Mediator Constraints

The LHC (and other colliders) can also place direct constraints on the production of particles that might mediate the dark matter's interactions

1) Spin-1 mediators with the required couplings are all but ruled out by Z' searches if their mass is greater than ~1 TeV (lighter and less coupled mediators are more easily hidden)

2) Constraints on MSSM-like Higgs Bosons can be applied to other spin-0 mediators, ruling out some ranges of couplings

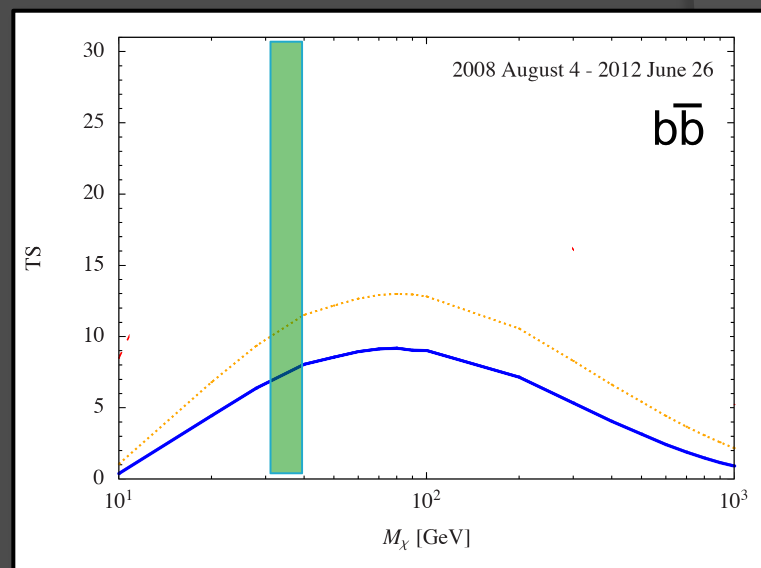
3) Searches for sbottom pair production rule out t-channel mediators lighter than ~600 GeV



A. Berlin, S. McDermott, DH, 1404.0022

Galaxy Clusters

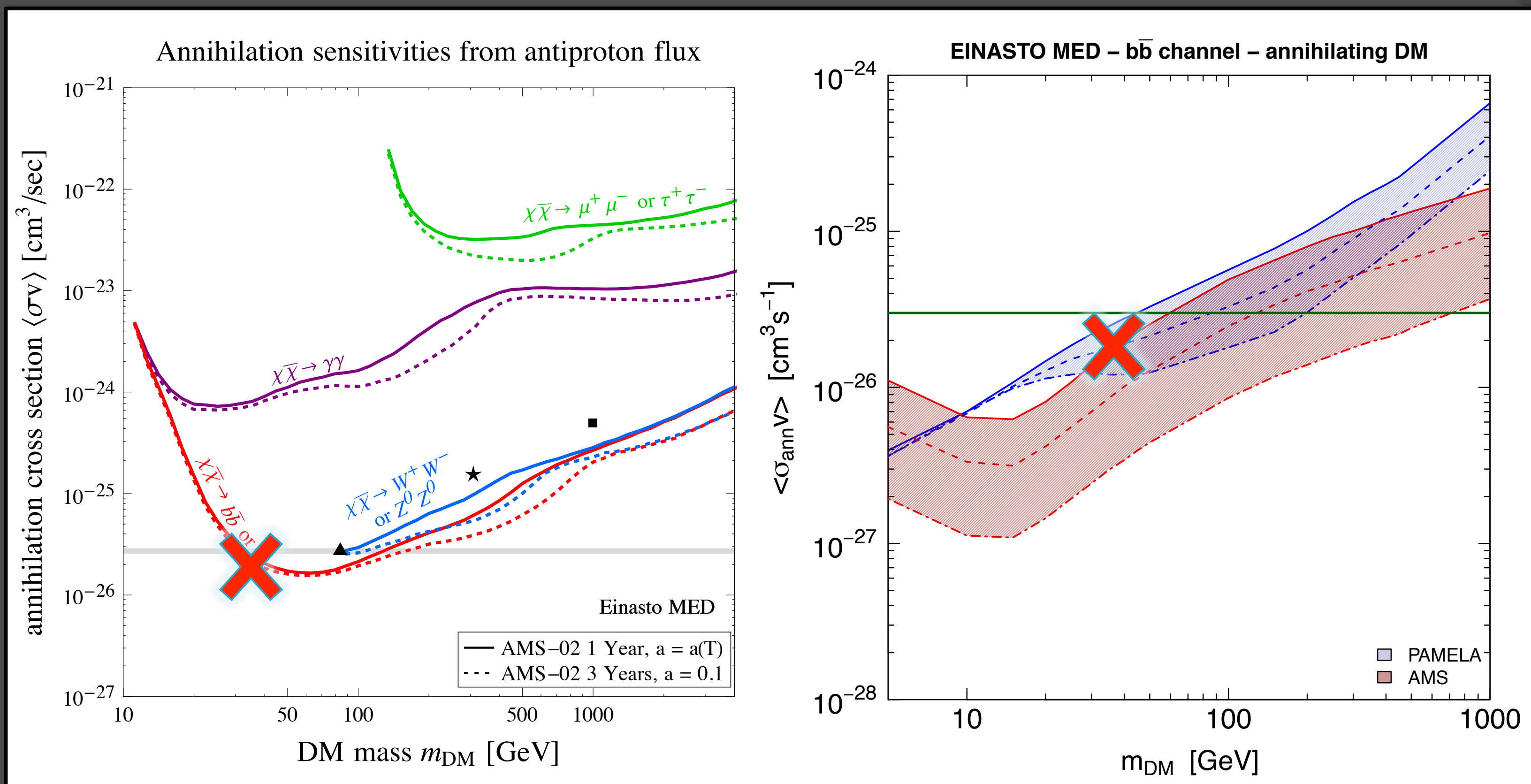
- Galaxy clusters are also promising targets for indirect dark matter searches, competitive with dwarfs galaxies
- Two groups have reported a gamma-ray excess from the Virgo cluster, at the level of ~2-3σ
- The results of these analyses depend critically on the treatment of point sources and diffuse cosmic ray induced emission, making it difficult to know how seriously one should take this result
- If the excess from Virgo arises from dark matter annihilation, it also suggests a similar mass and cross section that that implied by the Galactic Center excess (up to uncertainties in the boost factor)
- Again, more data should help to clarify



Han, et al., arXiv:1207.6749; Macias-Ramirez, Gordon, Brown and Adams, arXiv:1207.6257

Cosmic Ray Antiprotons

- Although PAMELA wasn't sensitive to the dark model models in question, AMS might be (depending on the details of diffusion and other astrophysical assumptions)



Cirelli, Giesen, 1301.7079

Fornengo et al.1312.3579
(see also Kong and Park, 1404.3741)