DARK MATTER ANNIHILATING IN THE GALACTIC CENTER

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The Abundance of WIMPs (for non-particle physicists)

- WIMPs are the most studied and (perhaps) the best motivated class of dark matter candidates
- The abundance of such particles in the universe today is determined by when they undergo thermal freeze-out

Before Freeze-Out: WIMPs are in equilibrium with the bath of radiation; the annihilation rate equals the production rate	→	***After Freeze-Out:*** WIMPs have essentially stopped annihilating; their abundance is sufficiently low that most WIMPs survive until the present era

- The time/temperature at which freeze-out occurs is determined by the WIMP-WIMP annihilation cross section (large σv postpones freeze-out)
- In order for WIMPs to account for the observed dark matter abundance, they must have an annihilation cross section (at the temperature of freeze-out) of $\sigma v \sim 2\times10^{-26}\ \mathrm{cm}^3/\mathrm{s}$

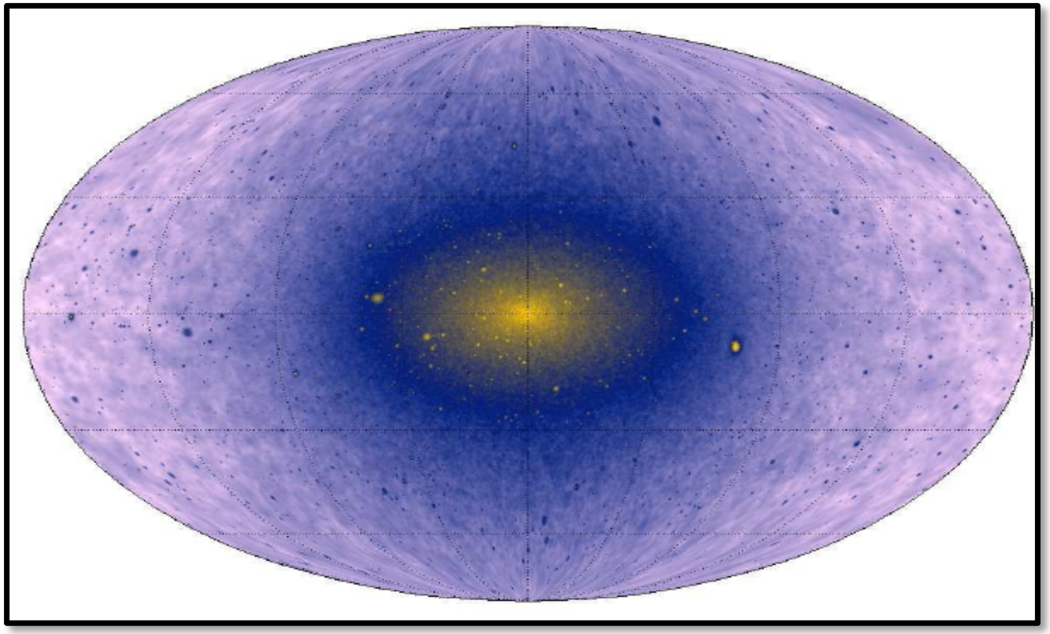
The Goal and Motivation of Indirect Searches

- Although many factors can lead the dark matter to annihilate with a somewhat different cross section today (strong velocity dependence, co-annihilations, resonances), most models predict low-velocity annihilation cross sections that are within an order of magnitude or so of this estimate (roughly $\sigma v \sim 10^{-27}$ cm^3/s to 3×10^{-26} cm^3/s)
- Indirect detection experiments that are sensitive to dark matter annihilating at approximately this rate will be able to test the majority of WIMP models
- Fermi's searches for dark matter in dwarfs, subhalos, the IGRB, and the Galactic Center are each sensitive to the gamma-ray flux predicted for approximately this range of cross sections (for masses up to ~100 GeV)

Fermi dark matter searches are not a fishing expedition; Fermi is testing the WIMP paradigm!

Why the Galactic Center?

- The brightest dark matter annihilation signal on the sky
- Any dark matter signal from dwarf galaxies (or elsewhere on the sky) would almost certainly have been seen first from the Galactic Center



M. Kuhlen *et al.*

The Predicted Signal

The gamma-ray signal from annihilating dark matter 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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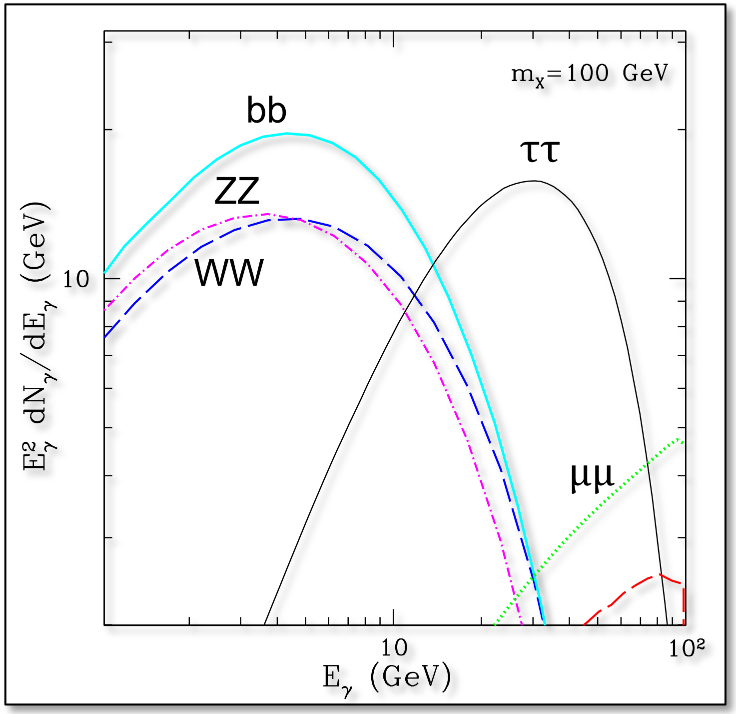
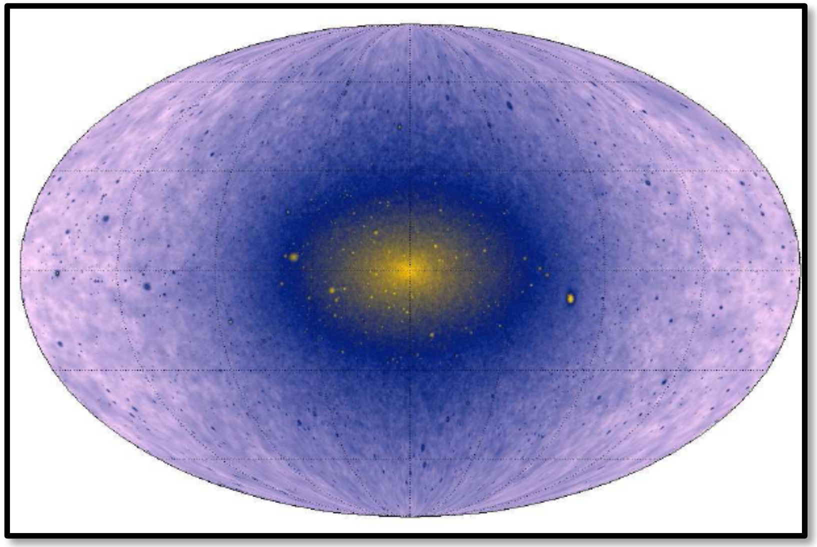
1) Distinctive "bump-like" spectrum

2) Normalization of the signal is largely set by the annihilation cross section

(Recall benchmark of $\sigma v \sim 10^{-26}$ cm^3/s)

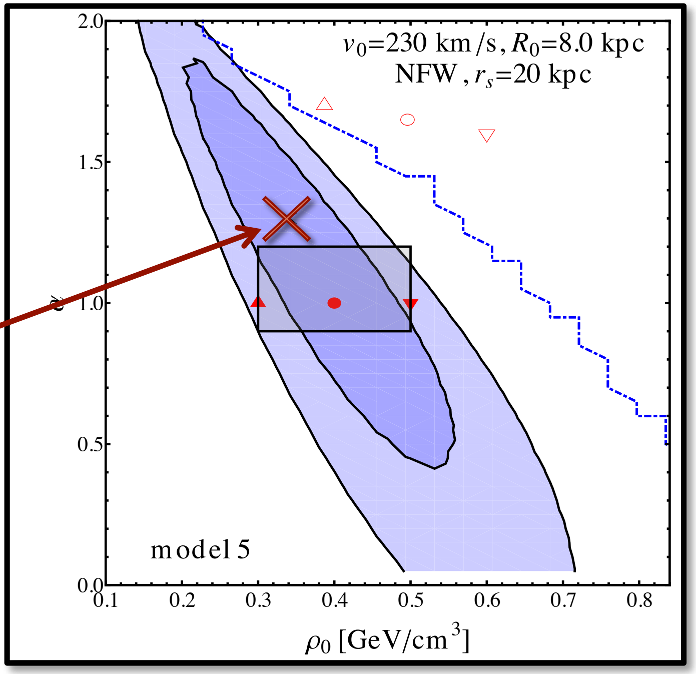
3) Signal highly concentrated around the Galactic Center (but not point-like); precise morphology is determined by dark matter distribution





The Milky Way's Dark Matter Distribution

- Dark matter only simulations (Via Lactea, Aquarius, etc.) predict halos with inner profiles of $\rho \propto r^{-\gamma}$ where γ~1.0-1.2
- Existing microlensing and dynamical data are not capable of determining the inner slope, although γ~1.3 currently provides the best fit



Iocco, Pato, Bertone, Jetzer, JCAP, arXiv:1107.5810

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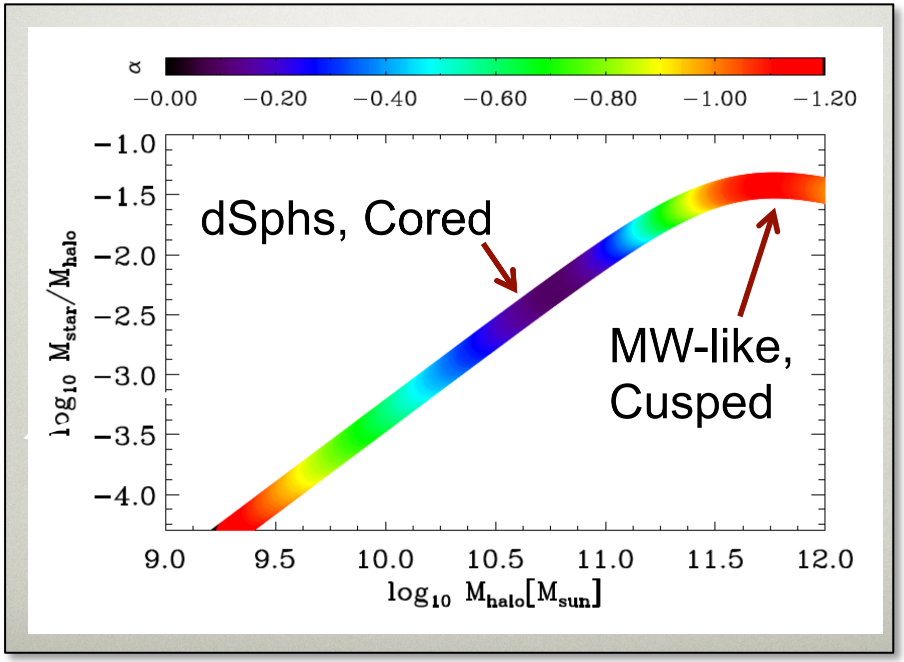
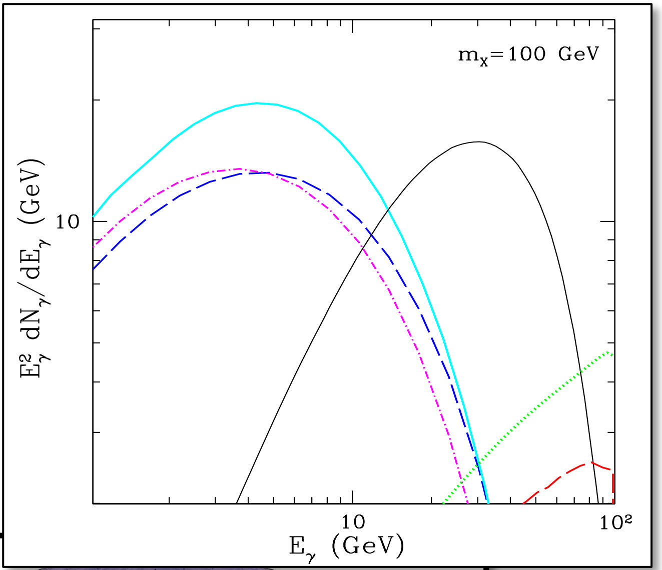
- Existing microlensing and dynamical data are not capable of determining the inner slope, although γ~1.3 currently provides the best fit
- The inner volume (~10 kpc) of the Milky Way is dominated by baryons, not dark matter – significant departures from results of dark matter-only simulations may be expected
- Recent hydrodynamical simulations show that Milky Way-like systems are expected to retain their cusps, and may even be contracted, γ~1.0-1.3 (although some dwarfs may be cored)

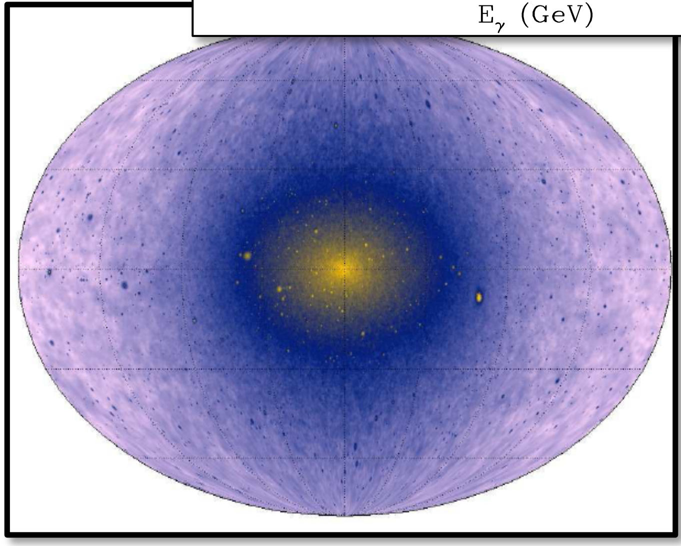


Di Cintio et al., arXiv:1404.5959

Summary: The Signal Predicted From WIMPs

1. A peaked gamma-ray spectrum
2. An angular distribution that is spherically symmetric around the Galactic center, falling as $\sim r^{-2}$ to $r^{-2.6}$
3. An overall flux that corresponds to an annihilation cross section on the order of $\sigma v \sim 10^{-26}$ cm^3/s

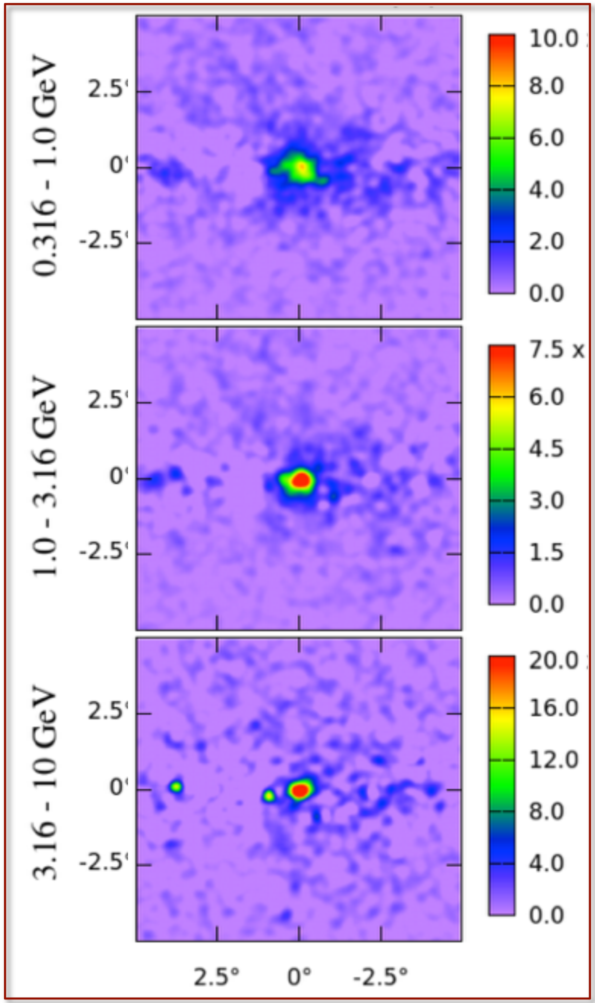




The Galactic Center GeV Excess

This remainder of this talk is largely based on:

- T. Daylan, D. Finkbeiner, DH, T. Linden, S. Portillo, N. Rodd, and T. Slatyer, arXiv:1402.6703



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

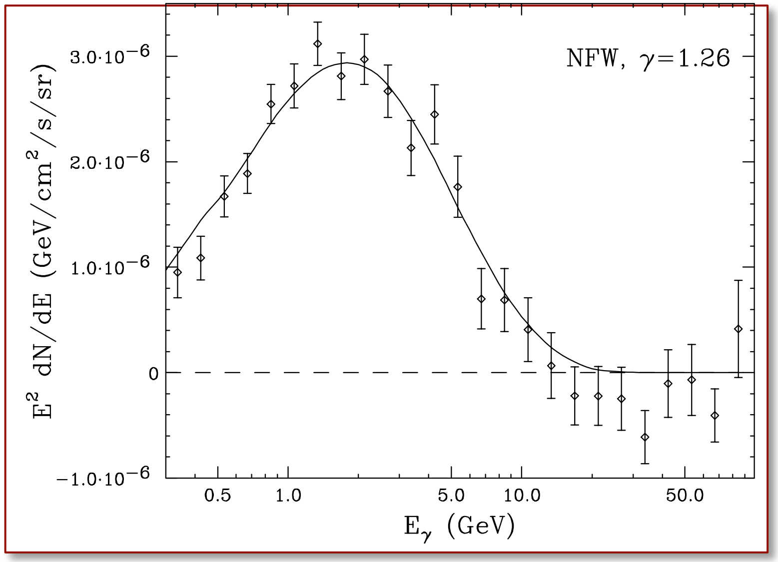
- L. Goodenough, DH, arXiv:0910.2998
- DH, L. Goodenough, PLB, arXiv:1010.2752
- DH, T. Linden, PRD, arXiv:1110.0006
- K. Abazajian, M. Kaplinghat, PRD, arXiv:1207.6047
- DH, T. Slatyer, PDU, arXiv:1302.6589
- C. Gordon, O. Macias, PRD, arXiv:1306.5725
- W. Huang, A. Urbano, W. Xue, arXiv:1307.6862
-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

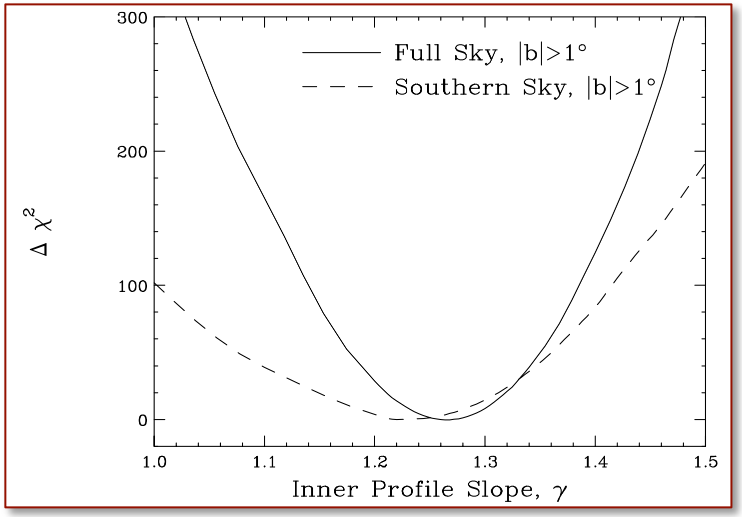
(see also talks by Tim Linden, Francesa Calore, Christoph Weniger, Gabrijela Zaharjias, Stephen Portillo, Simona Murgia, Anna Kwa)

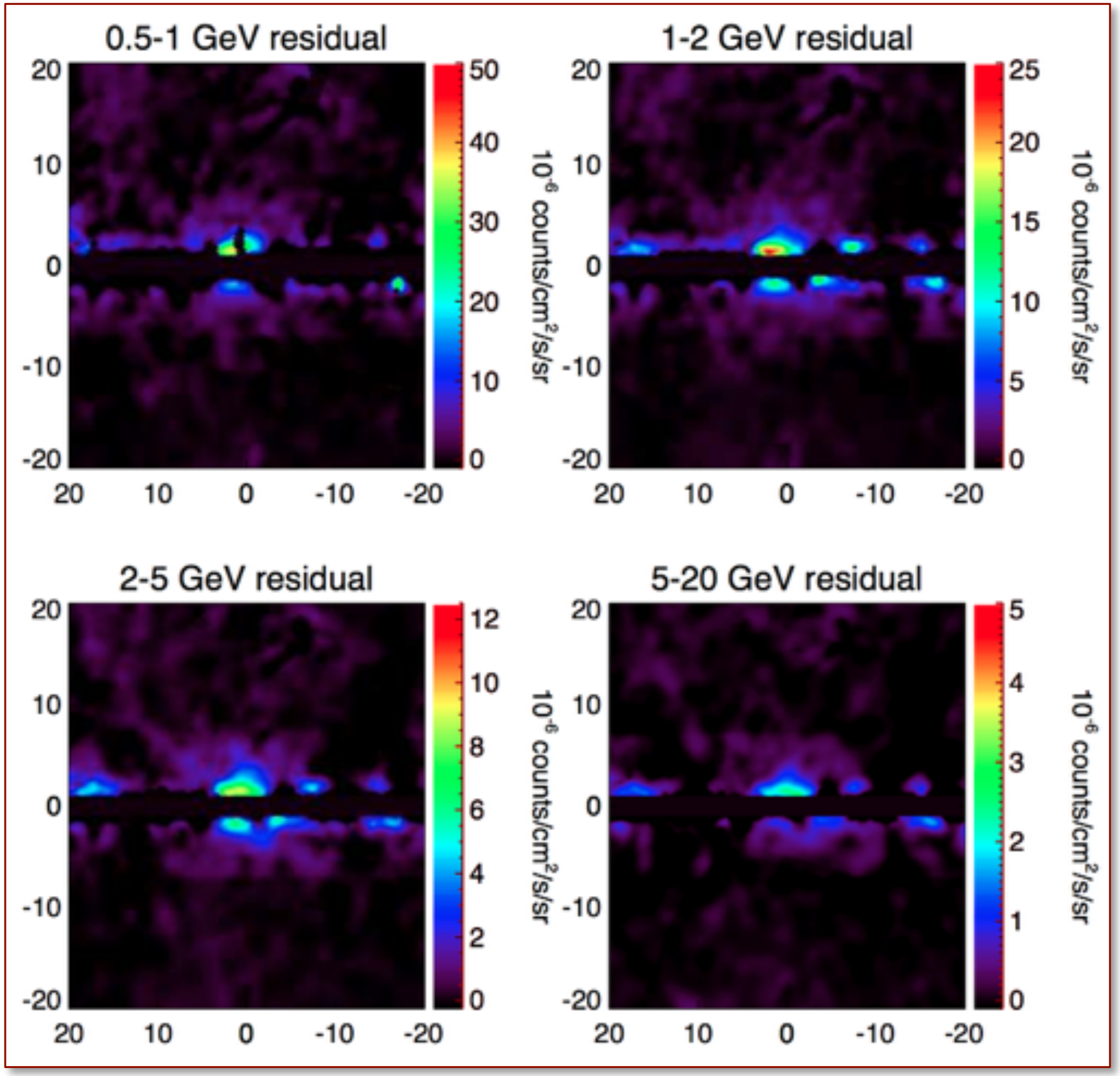
Basic Features of the GeV Excess

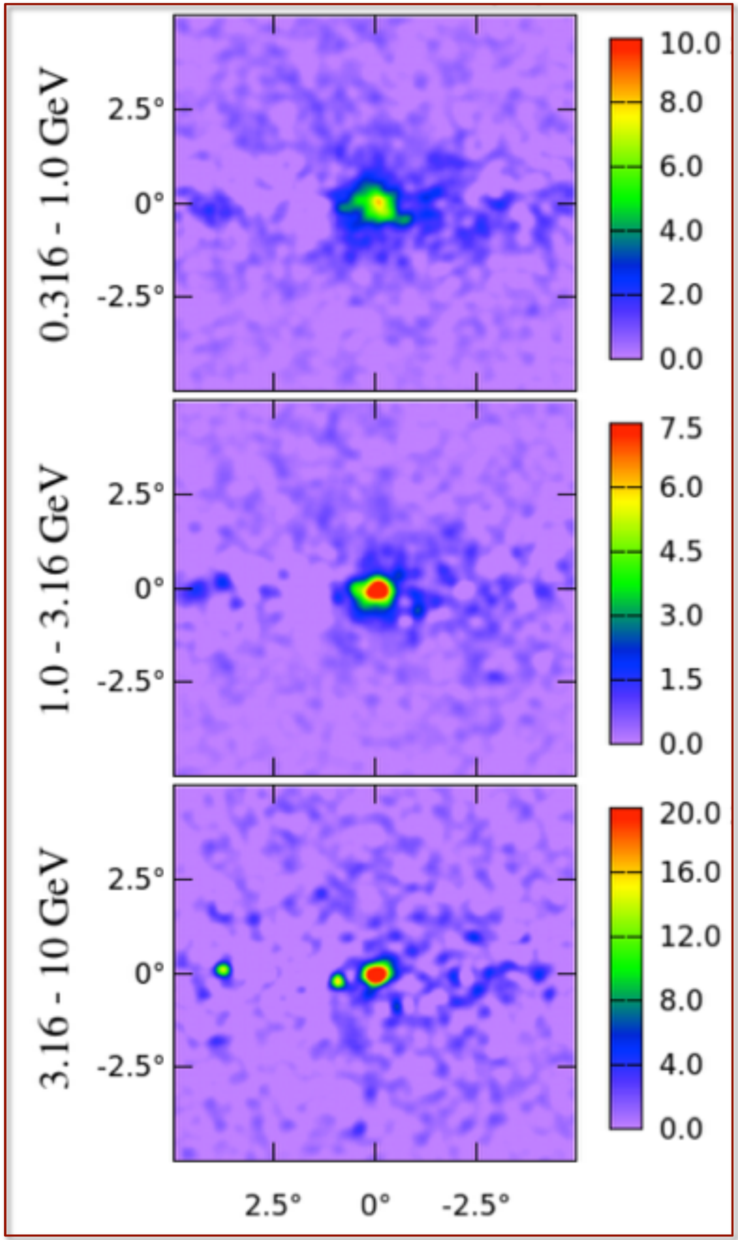
- The spectrum of the excess peaks at ~1-3 GeV, in good agreement with that predicted from ~40 GeV WIMPs annihilating to quarks
- The excess is distributed symmetrically around the Galactic Center, with a flux that falls off approximately as $r^{-2.5}$ (if interpreted as dark matter annihilation products,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

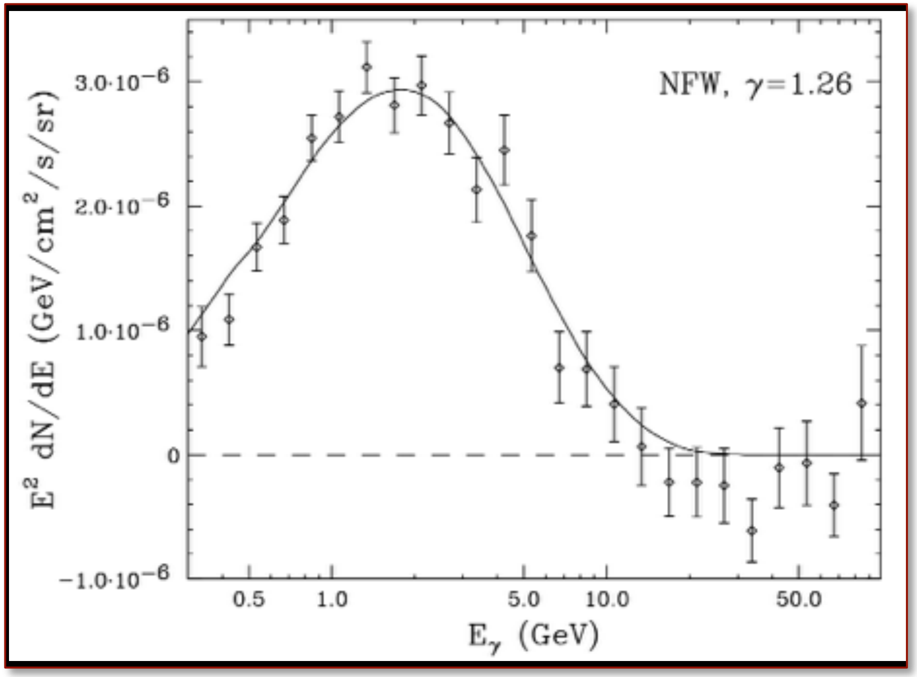
(note the similarity to the predictions listed two slides ago)

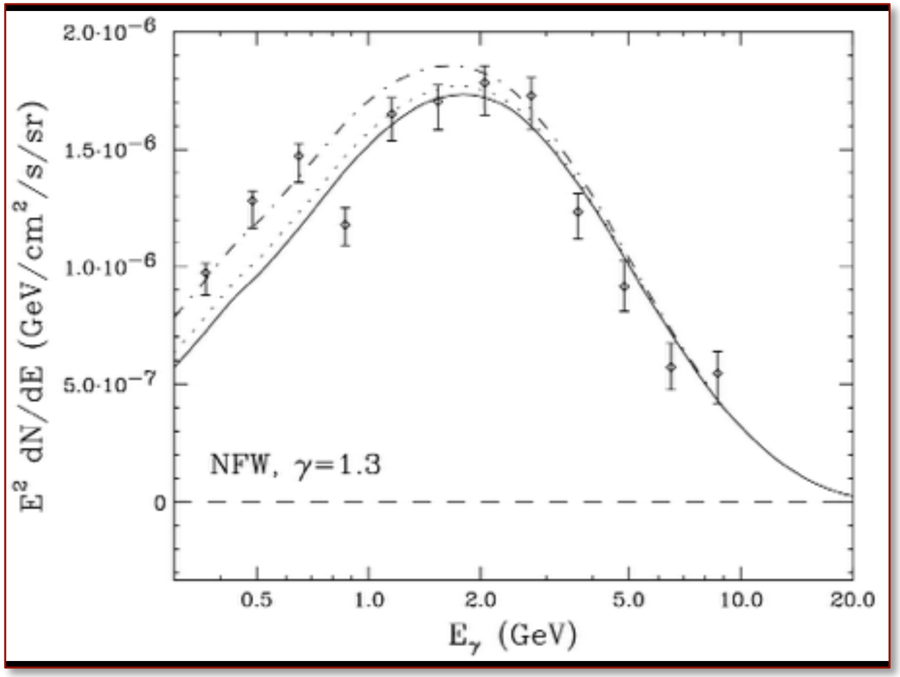





0.5-1 GeV residual
1-2 GeV residual
2-5 GeV residual
5-20 GeV residual
10^{-6} counts/cm^2/s/sr


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)
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
E_γ (GeV)


NFW, γ=1.3
E² dN/dE (GeV/cm²/s/sr)
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
E_γ (GeV)

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

An Excess Relative to What?

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

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

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

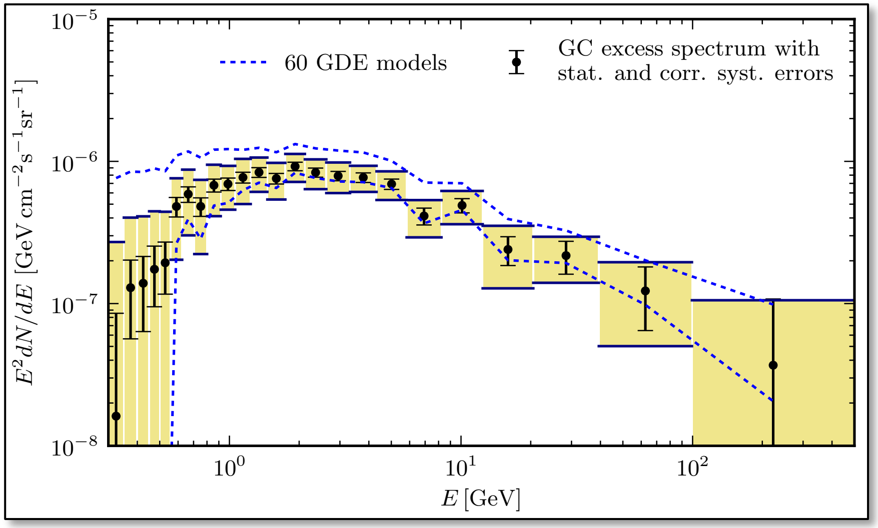
Background model systematics for the Fermi GeV excess

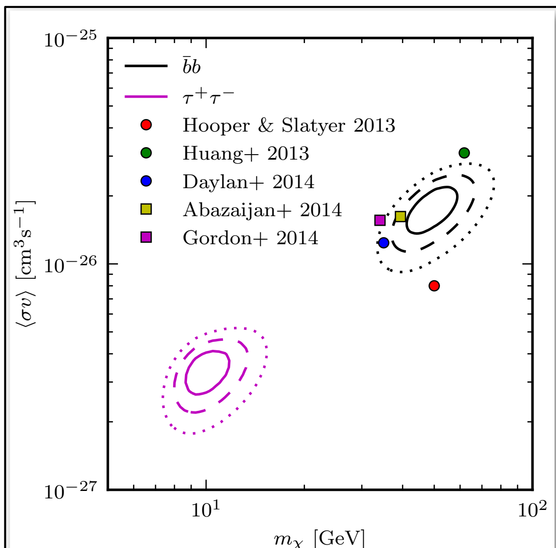
Francesca Calore,[a] Ilias Cholis[b] and Christoph Weniger[a]

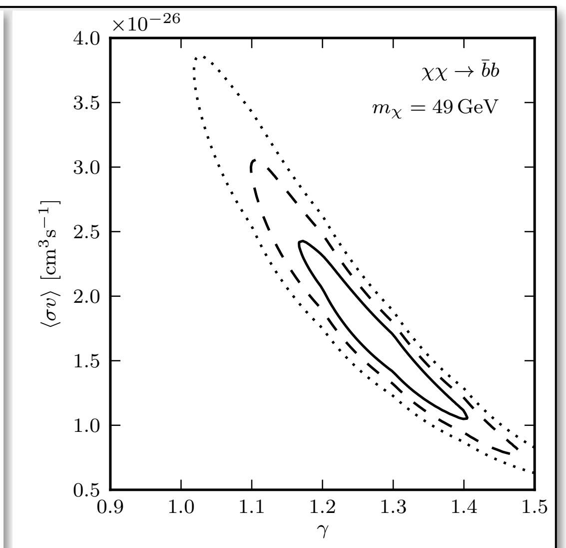
arXiv:1404.0042
Highly Recommended!

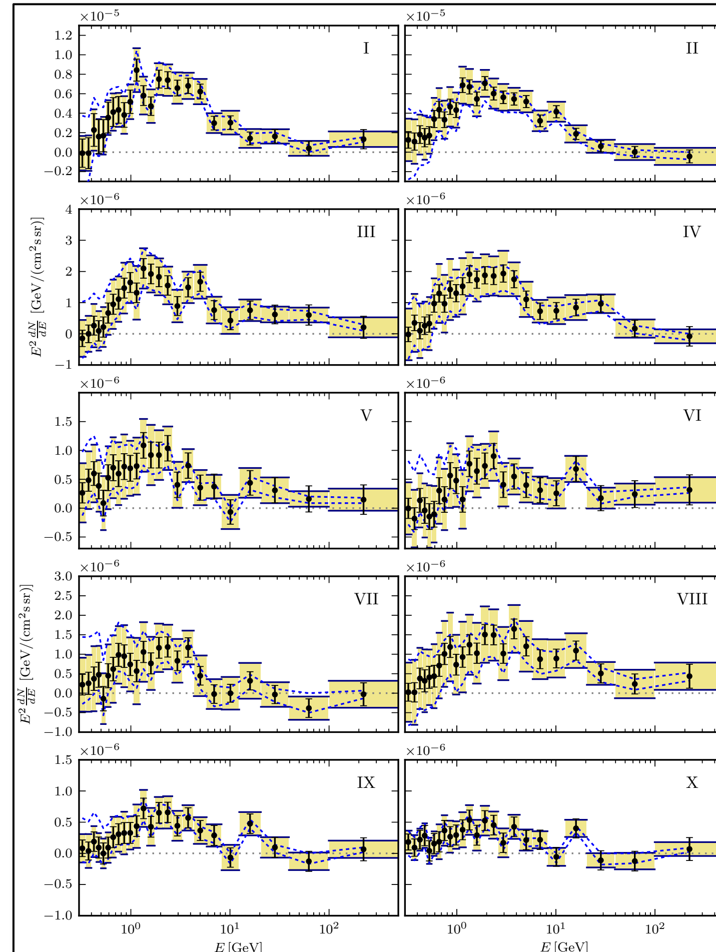
- First comprehensive study of the systematic uncertainties on the relevant astrophysical backgrounds
- Considered a very wide range of models, with extreme variation in cosmic ray source distribution and injection, gas distribution, diffusion, convection, re-acceleration, interstellar radiation and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

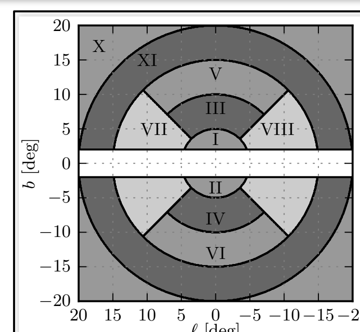
(See talks by Francesca Calore, Christoph Weniger)











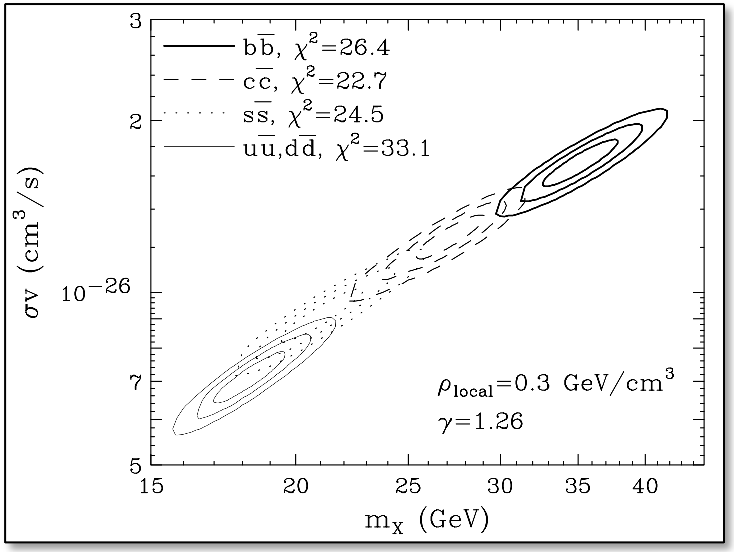
Calore, Cholis, Weniger, arXiv:1404.0042

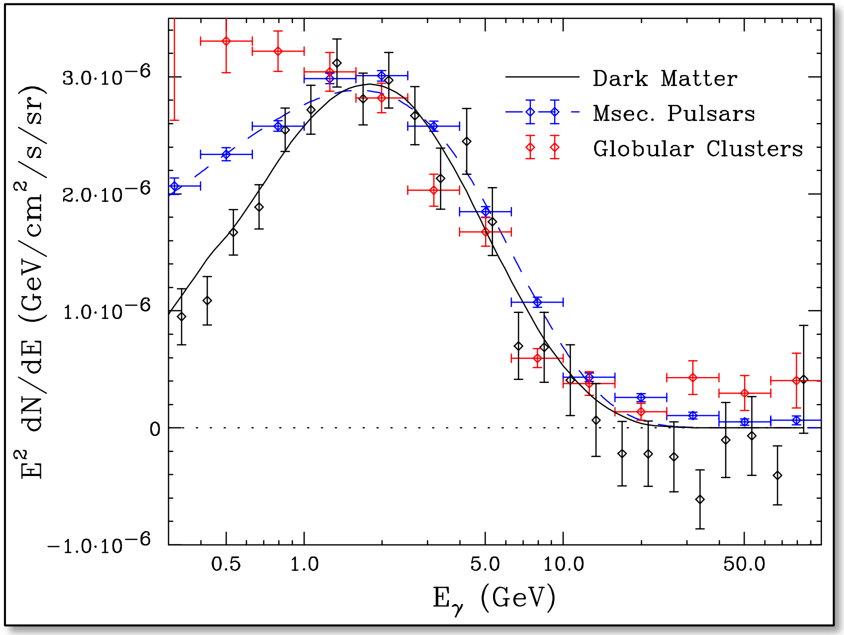
What Produces the Excess?

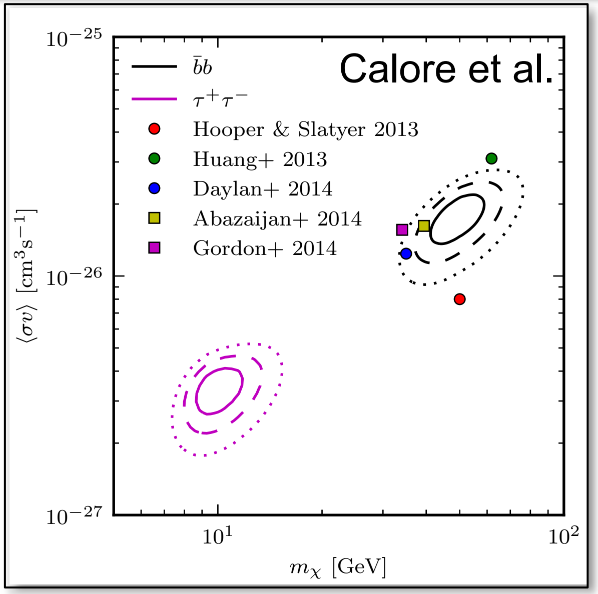
- A large population of centrally located millisecond pulsars
- A recent outburst of cosmic rays
- Annihilating dark matter

The Spectrum of the Excess

- The spectrum of the excess peaks at ~1-3 GeV, and well fit by annihilating dark matter
- Also similar to that observed from millisecond pulsars
- All groups are in agreement

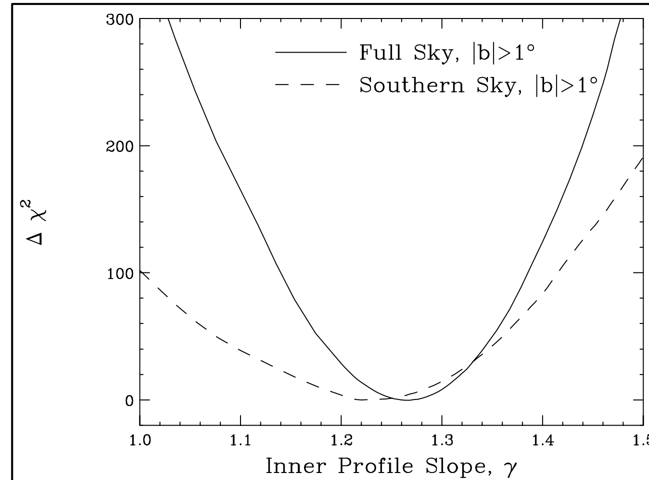


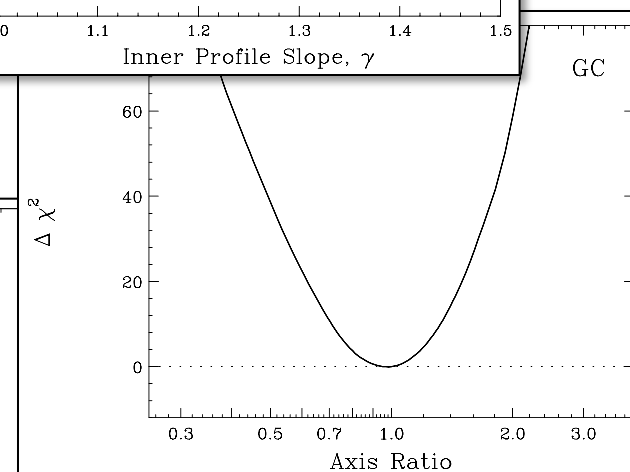


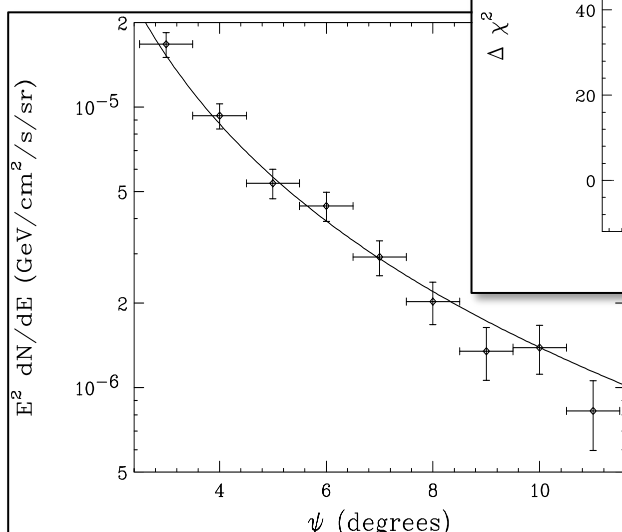


The Morphology of the Excess

- The excess is very concentrated, fitting a source distribution that falls off as $\sim r^{-2.5}$ (if interpreted as dark matter, $\rho_{DM} \sim r^{-1.25}$)
- The excess is spherically symmetric with respect to the Galactic Center, strongly preferring axis-ratios within 20% of unity
- The excess extends to well outside of the Galactic Center (out to at least 10°)
- The excess is very precisely centered around Sgr A* (within ~0.03° or ~5 pc)
- The intensity of the excess continues to rise to within ~10 pc of Sgr A* (no flattening or core)



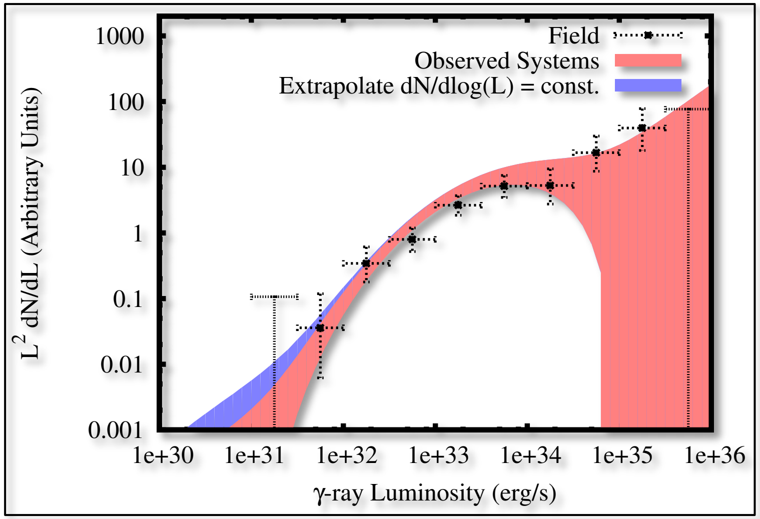


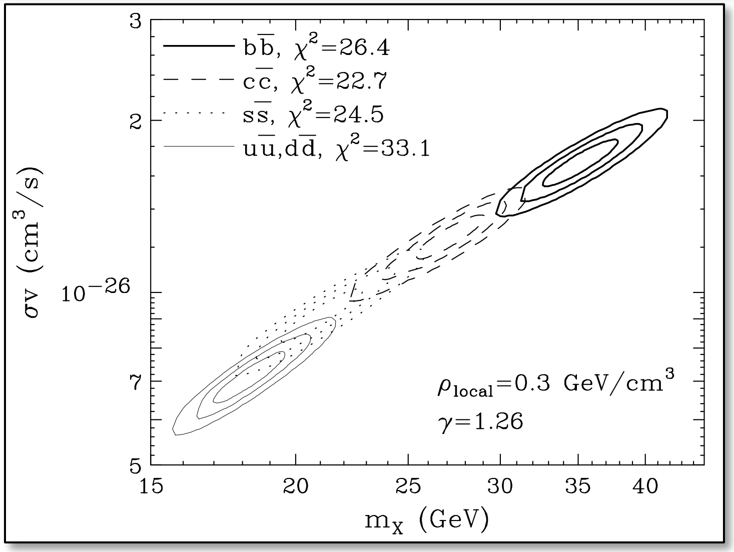


The Normalization of the Excess

- The excess is very bright; within the innermost square degree, it constitutes ~30% of the total flux at 1-3 GeV
- Using a luminosity function derived from Fermi's observations of field MSPs (and of globular clusters), we find that >2000 of such sources would be required to generate the excess (~60 of which with $L_\gamma > 10^{35}$ erg/s)
- To normalize the observed signal with annihilating dark matter, a cross section of $\sigma v \sim 10^{-26}$ cm^3/s is required
- This value could shift upward or downward by a factor of ~5-10 for reasonable variations of the Milky Way's halo profile

Cholis, et al., arXiv:1407.5625, 1407.5583





Scenario	Spectrum	Morphology	Overall Flux
Millisecond Pulsars			
Cosmic Ray Outburst(s)			
Annihilating Dark Matter			

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Millisecond Pulsars	✔	>10° extension is highly unexpected	✗ (lack of bright/ detectable sources)
Cosmic Ray Outburst(s)			
Annihilating Dark Matter			

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Cosmic Ray Outburst(s)	Difficult	✗ (signal is spherical and not correlated with gas)	✔
Annihilating Dark Matter			

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Annihilating Dark Matter	✔	✔	✔

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Annihilating Dark Matter	✔	✔	✔

- Of the ideas proposed so far, dark matter annihilation seems to be the only viable explanation for this signal
- Proofs by lack of imagination are not particularly compelling, however
- New ideas and greater scrutiny are needed (a new class of faint point sources, restricted to the bulge? A hybrid pulsar/outburst scenario?)

Implications for Particle Physics

If the excess is in fact generated by annihilating dark matter, we can narrow down the a classes of particle physics models that could be responsible:

1) Dark matter that annihilates through the exchange of a new pseudoscalar (two higgs doublet models, etc.)

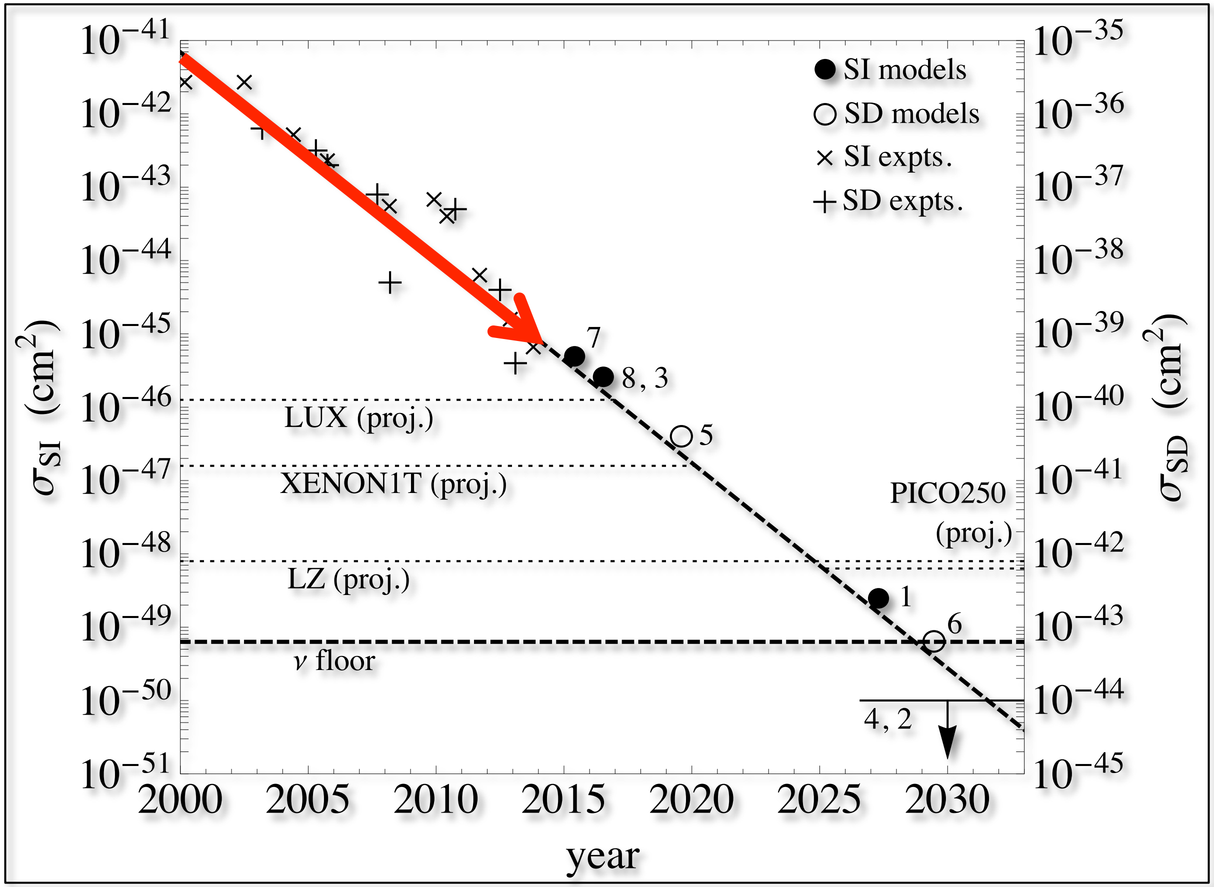
2) Dark matter that annihilates through the exchange of a new gauge boson (a Z')

3) Dark matter that annihilates through the (t-channel) exchange of a new colored state (similar to a bottom squark)

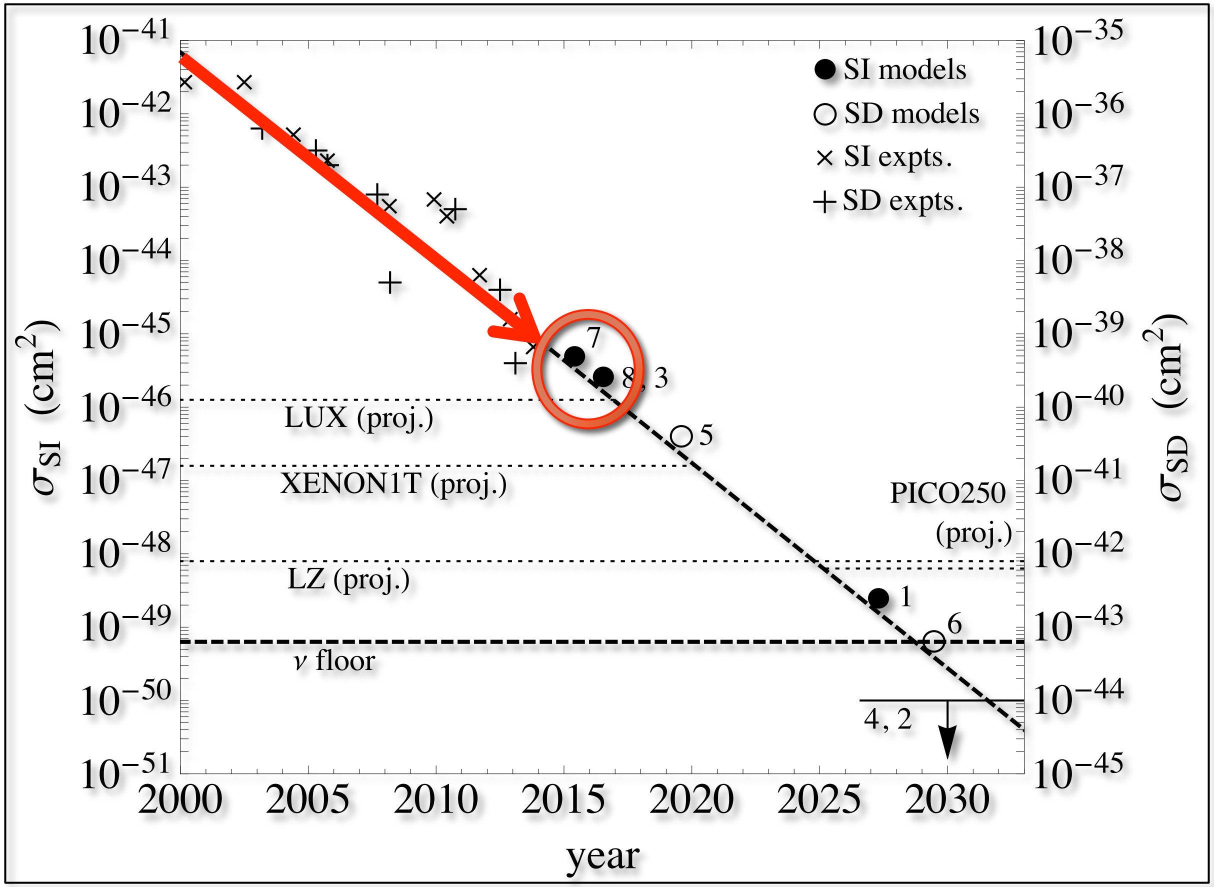
4) Dark matter that annihilates into other weakly interacting particles, which then decay into standard model particles (*ie*. hidden sector models)

- Each of these four scenarios can generate the observed characteristics of the GeV excess, while evading all existing collider and direct detection constraints
- Prospects for discovery by direct detection experiments and at the 13-14 LHC are very encouraging

Prospects for Direct Detection

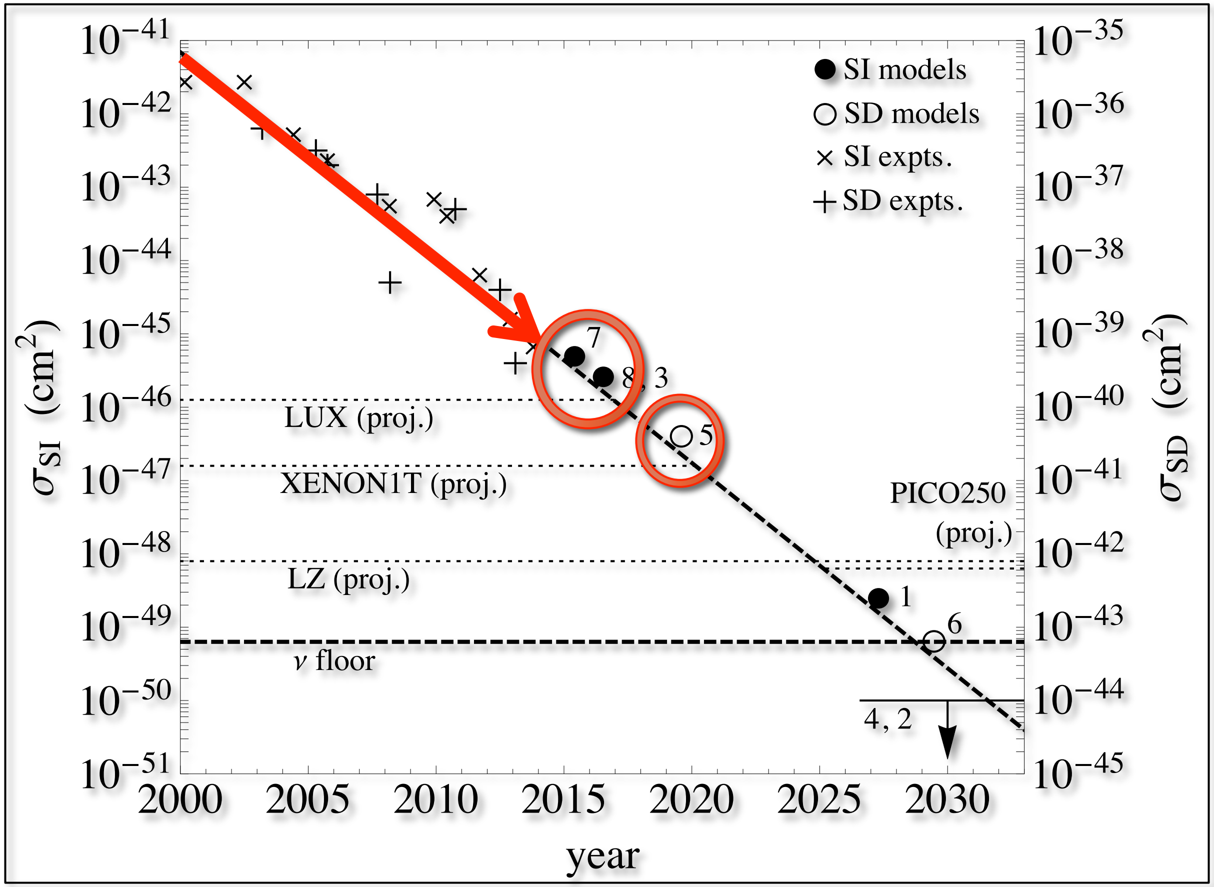


Prospects for Direct Detection



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

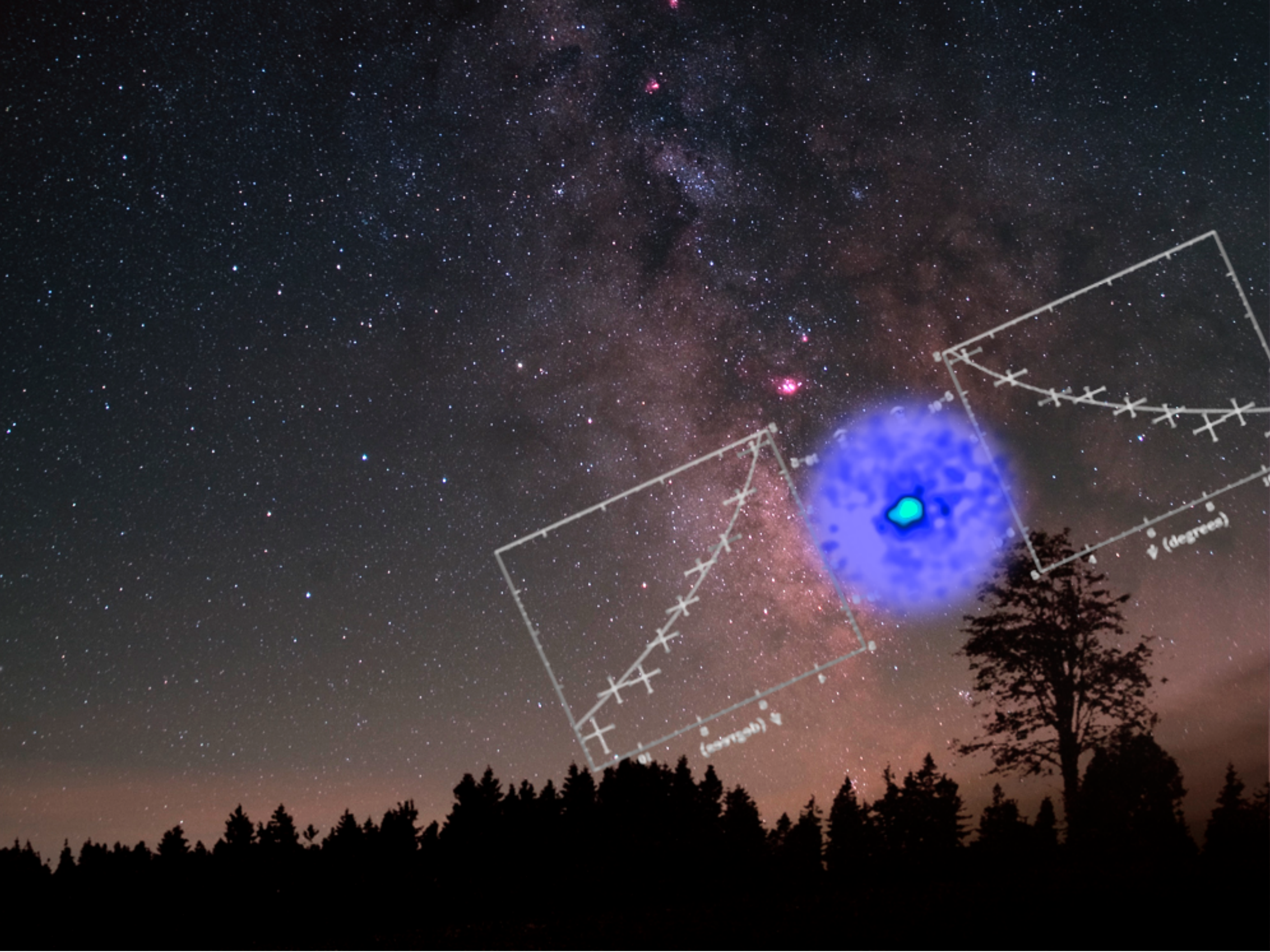
Prospects for Direct Detection



- t-channel models are within the reach of both LUX and LHC14
- Most models with a Z' will be tested by LUX and XENON1T

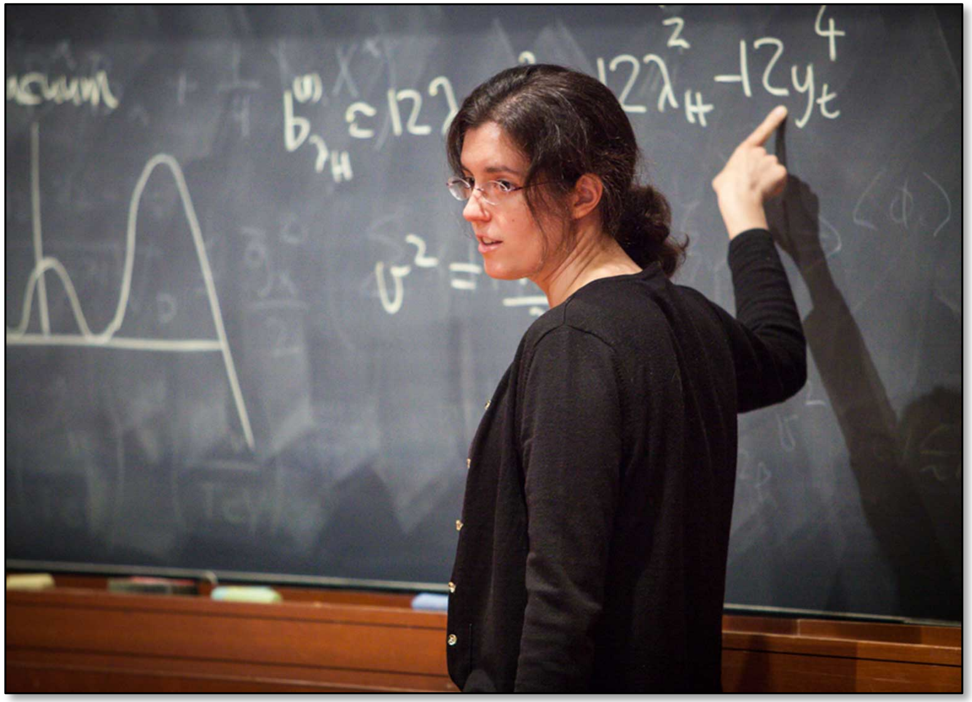
Summary

- Although many indirect detection anomalies have appeared over the years, the Galactic Center's GeV excess is particularly compelling: highly statistically significant, robust to background variations, distributed spherically out to at least 10° from the Galactic Center – very difficult to explain with known/proposed astrophysics
- The spectrum and angular distribution of this signal is very well fit by a ~30-40 GeV WIMP, distributed as $\rho \sim r^{-1.25}$
- The normalization of this signal requires a dark matter annihilation cross section of $\sigma v \sim 10^{-26}$ cm^3/s, in remarkable agreement with the prediction for a thermal relic
- Many dark matter models can account for the observed emission without conflicting with constraints from direct detection experiments or colliders – future prospects are encouraging


ψ (degrees)

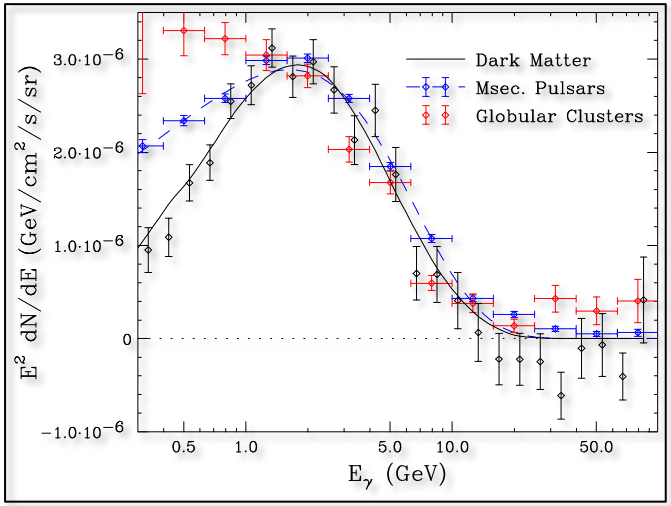
Acknowledgement

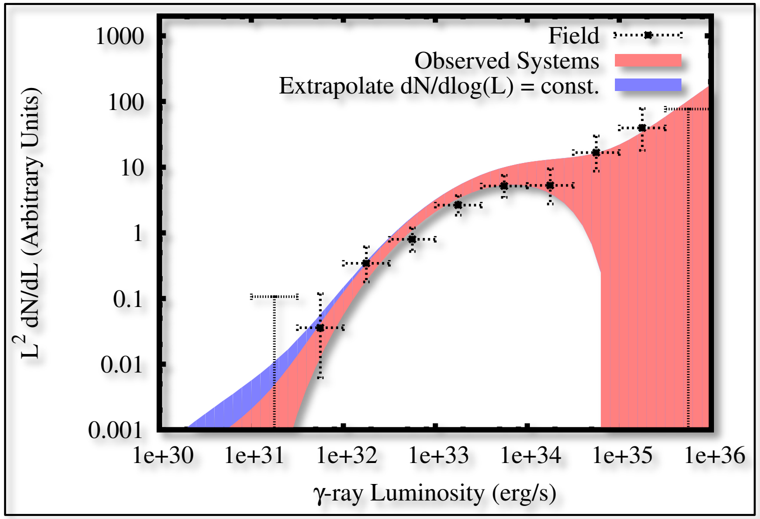
- In 2007, Kathryn Zurek and I made a bet regarding whether dark matter would be definitely discovered by 2012 (I bet that it would be)
- In 2012, the situation was not clear – we agreed to wait and see whether direct detection anomalies persisted to determine the winner (in 2012, the gamma-ray excess 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…)



Gamma-Rays From Millisecond Pulsars

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

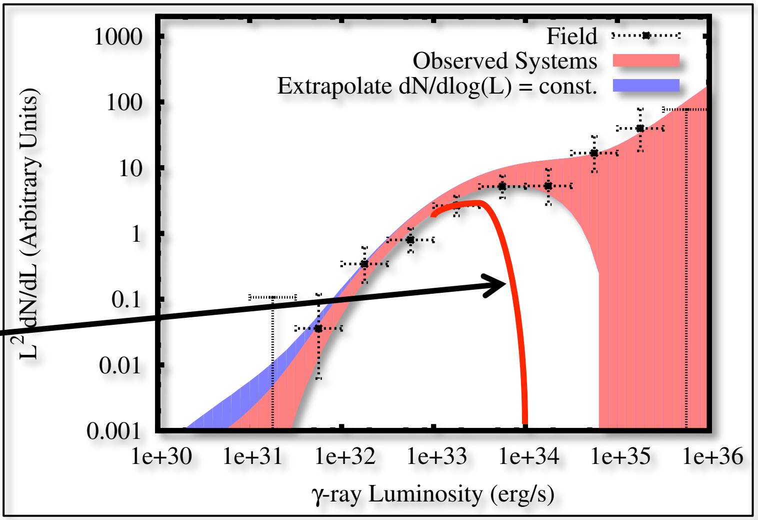




Cholis, DH, Linden, arXiv:1407.5625, 1407.5583

Could Millisecond Pulsars Generate the Galactic Center Excess?

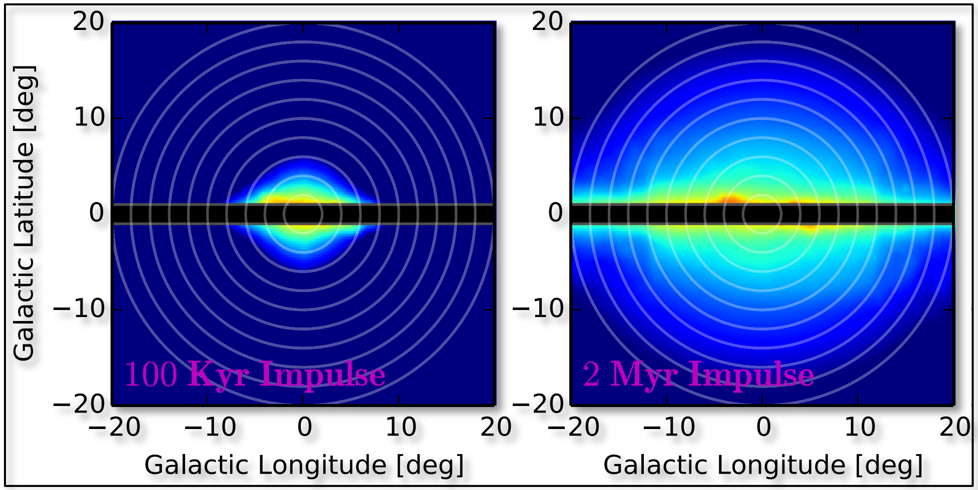
- From the measured luminosity function, we conclude that more than 2000 MSPs within 1.8 kpc of the Galactic Center would be required to account for the excess; this would include ~227 that are quite bright ($L_\gamma > 10^{34}$ erg/s) and ~61 that are very bright ($L_\gamma > 10^{35}$ erg/s)
- The fact that Fermi observes no such sources from this region forces 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, requiring ~14,000 such sources without any bright ($L_\gamma < 10^{34}$ erg/s) members



Cholis, DH, Linden, arXiv:1407.5625, 1407.5583

A Cosmic Ray Outburst?

- Recently, two studies have proposed that a recent (~10^6 yrs) burst-like injection of cosmic rays might be responsible for the excess
- Carlson and Profumo's hadronic scenario, however, predicts a signal that (among other very significant problems) is not at all spherical, and that is simply incompatible with the data

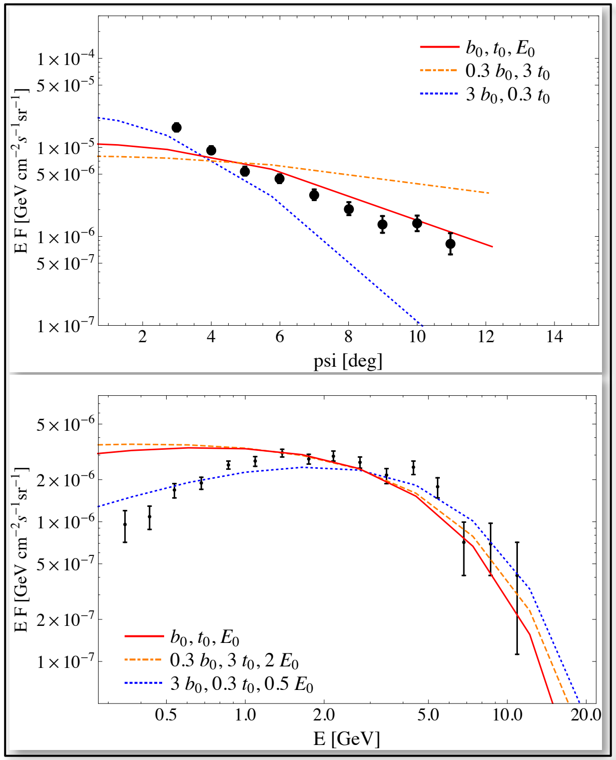


- In more generality, we have also shown (see Appendix D4 of arXiv:1402.6703) that the fine structure of the excess' morphology does *not* correlate with the distribution of gas – this is incompatible with any hadronic cosmic ray origin for the excess

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

A Cosmic Ray Outburst?

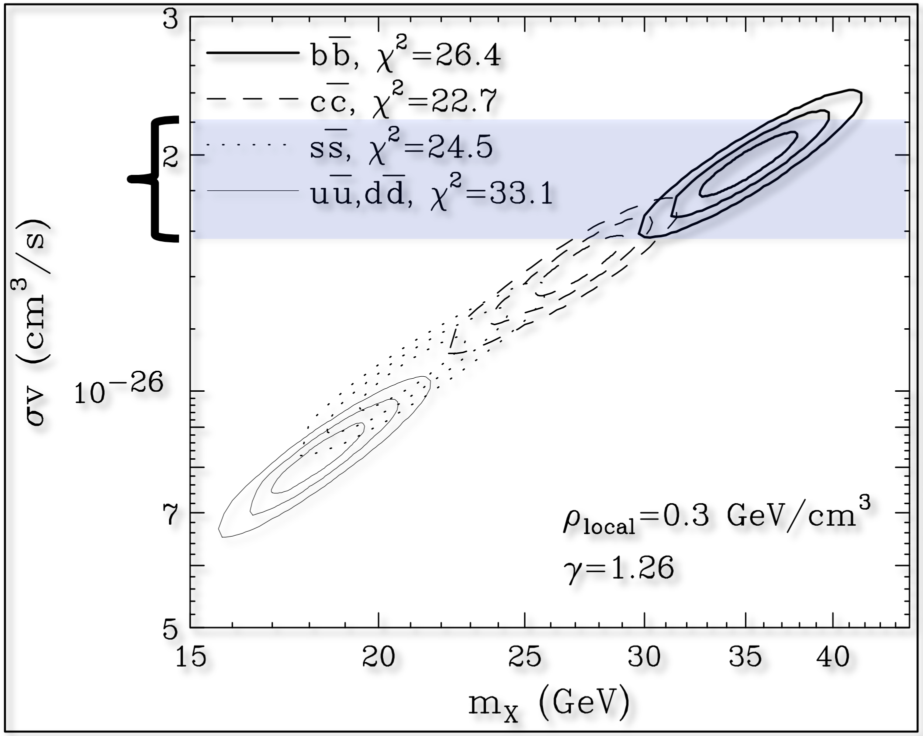
- Petrovic *et al.*'s Inverse Compton scenario is more difficult to evaluate
- Although the models considered by Petrovic *et al.* are not capable of simultaneously explaining the spectrum *and* morphology of the excess, one could imagine a more complex scenario that might approximately match the observed signal
- More generally speaking, however, the ISRF is *not* spherically symmetric, and the corresponding inverse Compton signal will be approximately spherically symmetric only if the cosmic ray electron distribution is carefully tuned
- Furthermore, as the intensity of the excess is observed to rise to within ~10 pc of the Galactic Center, the origin of such an outburst would have to be the SMBH (not supernovae) – no stellar population is so concentrated



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

Dark Matter Interpretations

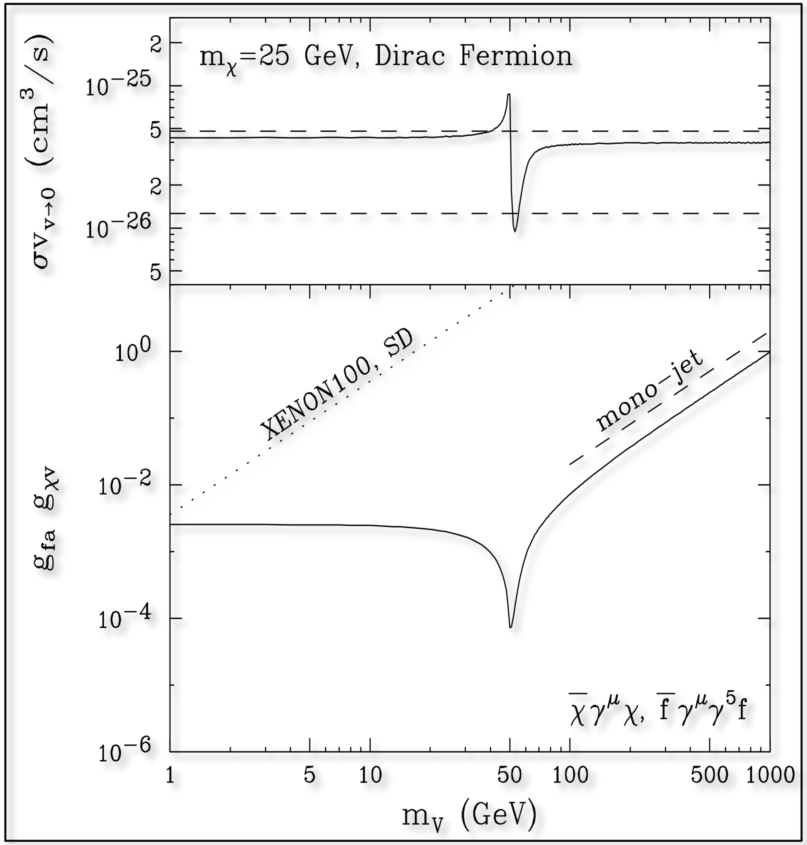
- The cross section required to normalize the observed excess is remarkably well-matched to the range of values predicted for a simple thermal relic (without strong p-wave suppression, coannihilations, resonances, sommerfeld enhancements, etc.)
- Direct detection constraints rule out some models (those with unsuppressed scalar or vector interactions with quarks), but many remain viable
- Somewhat contrary to conventional wisdom, the LHC does not yet exclude many of these models



LHC Constraints 1: Monojets

- Constraints from mono-jet searches at the LHC constrain the coefficients of effective operators, roughly corresponding to $(g_f\, g_X)^{1/2}/M_{med}$ (assuming $M_{med} >> E_{CM}$)
- In general, LHC mono-jet constraints are within a factor of a few of that required to test dark matter typical models capable of accounting for the Galactic Center gamma-ray excess, so long as the mass of the mediator is heavier than a few GeV (where EFT breaks down)

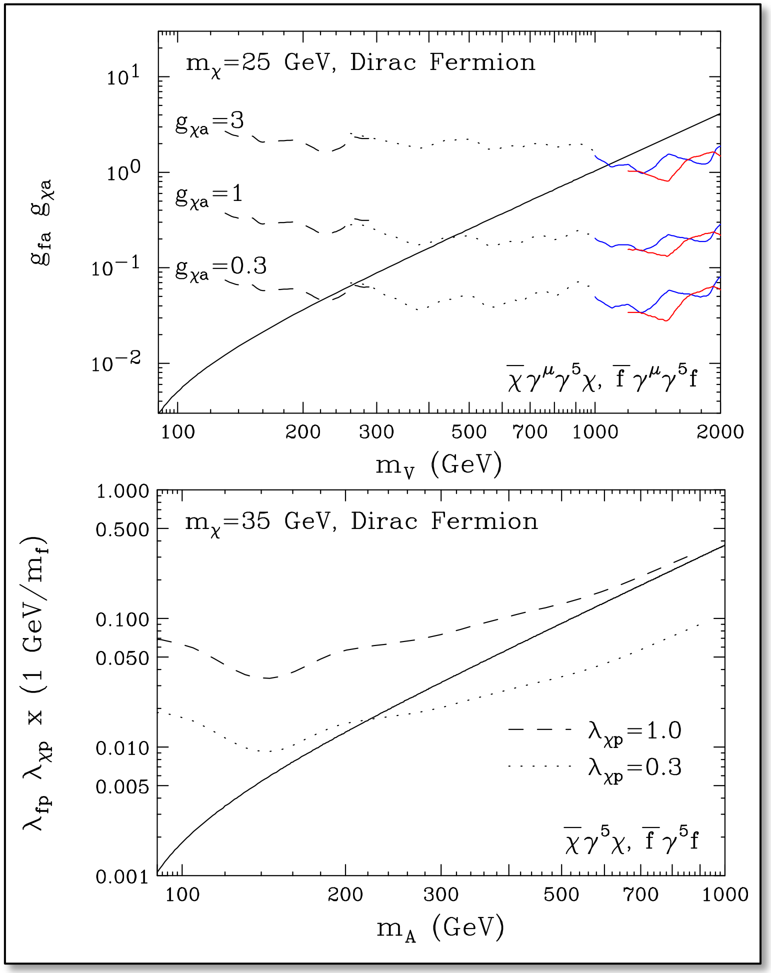
-Although not yet constraining, data at 13-14 TeV should be able to test many of these models!



A. Berlin, S. McDermott, DH, 1404.0022

LHC Constraints 2: Mediators

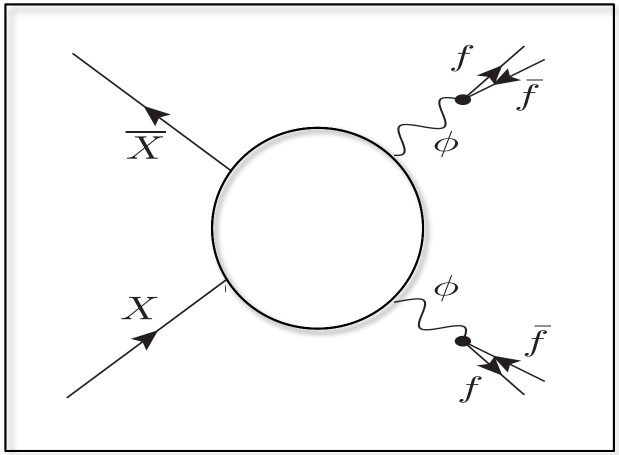
- The LHC (and other colliders) can also place direct constraints on the production of particles that might mediate the dark matter's interactions
- 1) Spin-1 mediators with the required couplings are all but ruled out by Z' searches if their mass is greater than ~1 TeV (lighter and less coupled mediators are viable)
- 2) Constraints on MSSM-like Higgs Bosons can be applied to other spin-0 mediators, ruling out a range of masses and couplings
- 3) Searches for sbottom pair production rule out t-channel mediators lighter than ~600 GeV



A. Berlin, S. McDermott, DH, PRD, 1404.0022

Hidden Sector Models

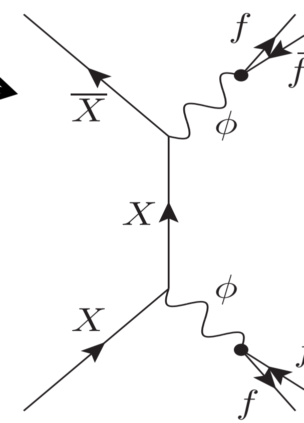
- Although the lack of signals observed in direct detection experiments and at colliders restricts the nature of the dark matter's interactions with the Standard Model, many tree-level annihilation processes continue to be viable
- Alternatively, one could take this as motivation to consider dark matter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



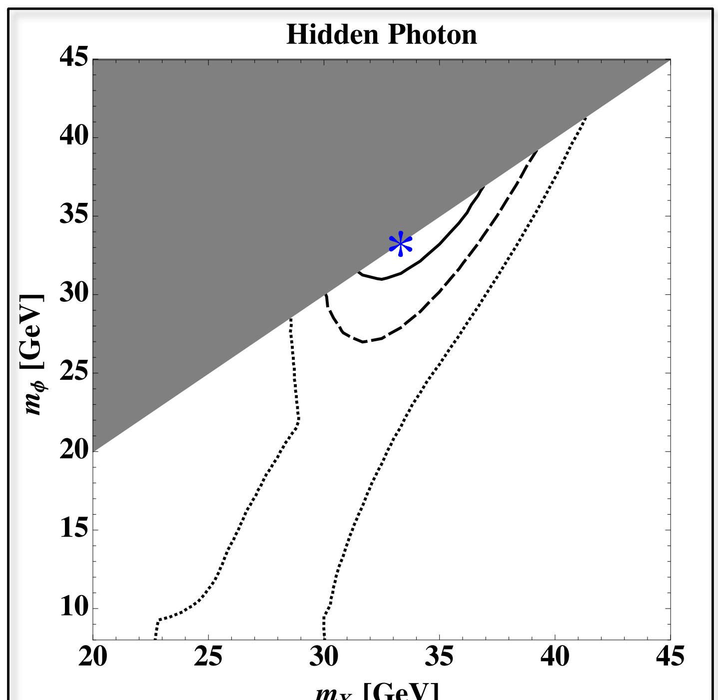
Martin et al. 1405.0272,
Abdullah et al. 1404.6528,
Boehm et al. 1404.4977

Dark Matter with a Hidden Photon

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



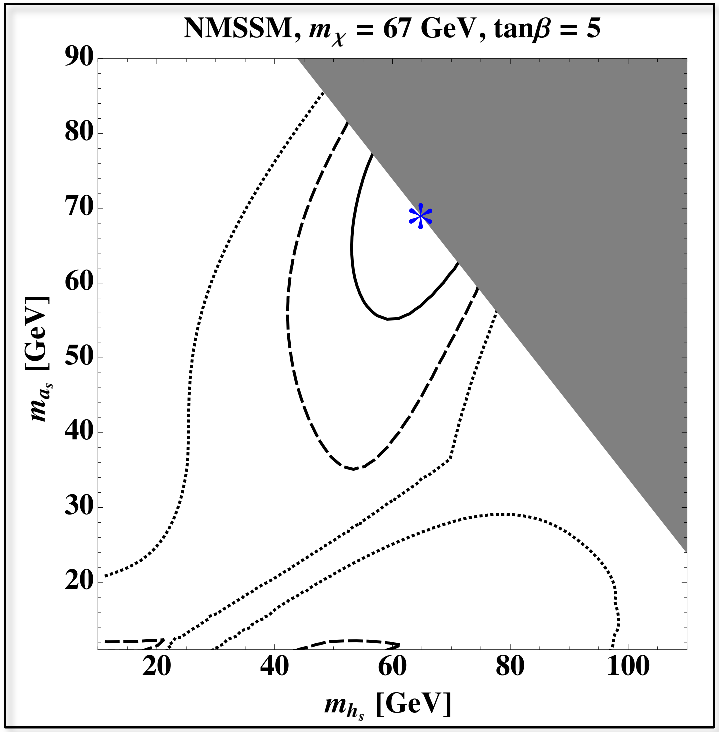
- Relic abundance and Galactic Center excess require $g_X \sim 0.1$
- The ϕ's decay through a small degree of kinetic mixing with the photon; direct constraints require mixing less than $\varepsilon \sim 10^{-4}$ (near loop-level prediction)

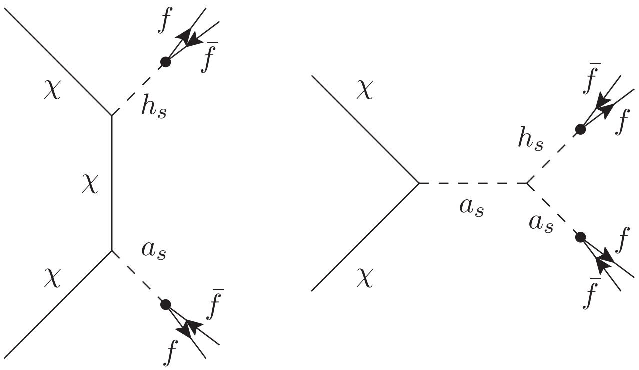


A. Berlin, S. McDermott, DH, PRD, arXiv:1405.5204

A Supersymmetric Model with a Hidden Sector

- 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 excess 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, PRD, arXiv:1405.5204

Focusing on dark matter models that annihilate directly to the standard model, we have 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, PRD, 1404.0022

These scenarios roughly fall into three categories:

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

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

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These scenarios roughly fall into three categories:

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

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	$B^\dagger_\mu B^\mu,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	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, PRD, 1404.0022

These scenarios roughly fall into three categories:

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

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

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

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

Berlin, DH, McDermott, PRD, 1404.0022