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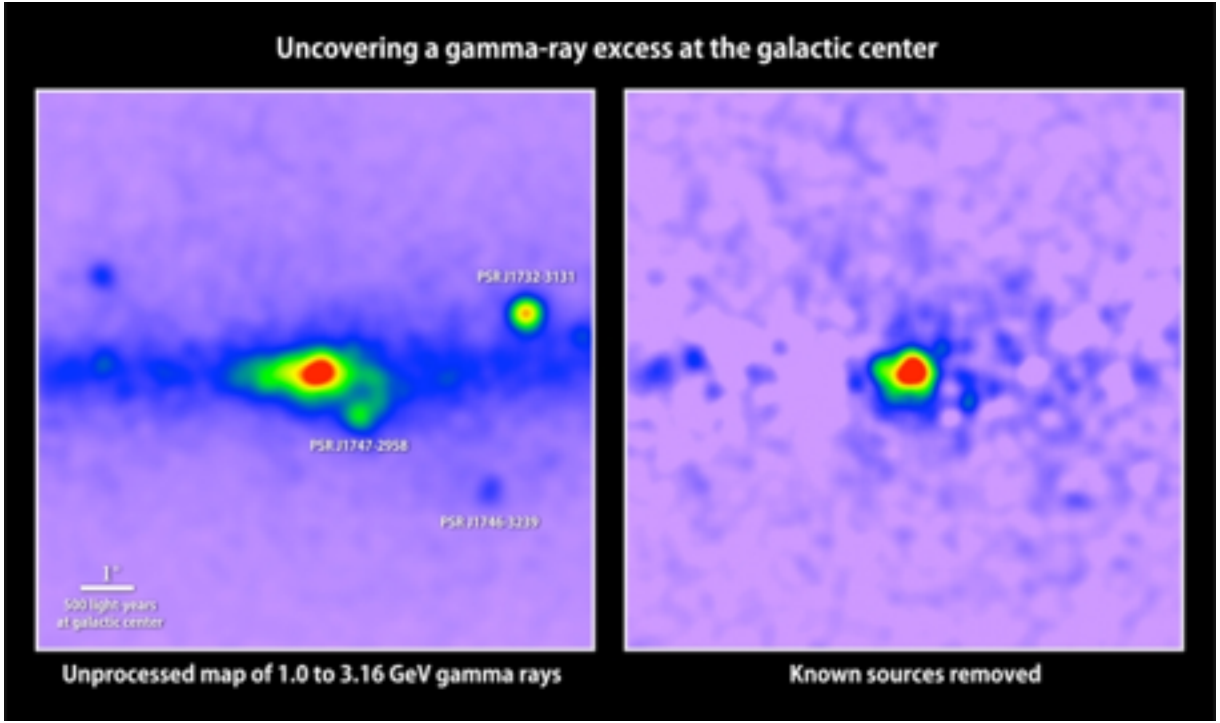
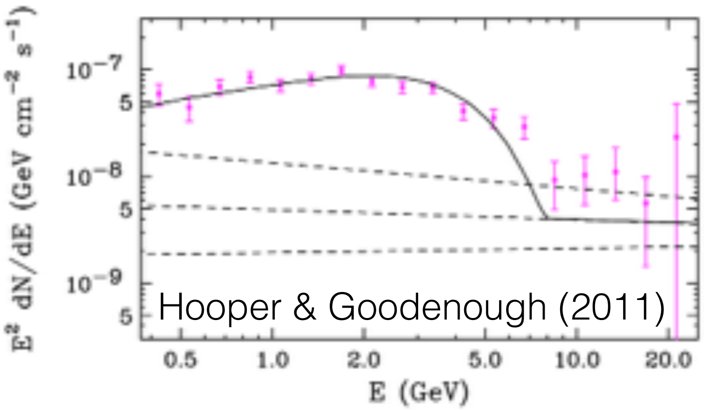
The Characterization of the Gamma-Ray Signal from the Central Milky Way: A Compelling Case for Annihilating Dark Matter

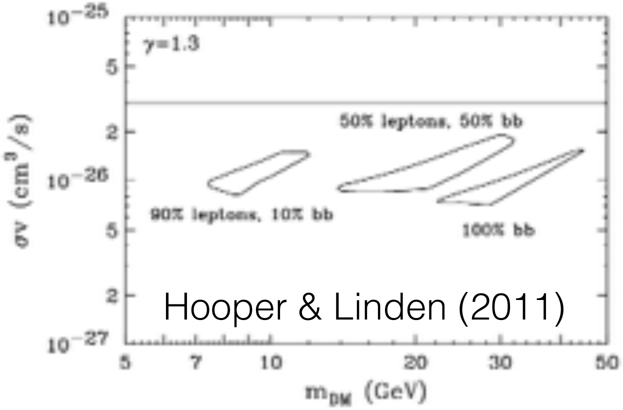
Tim Linden

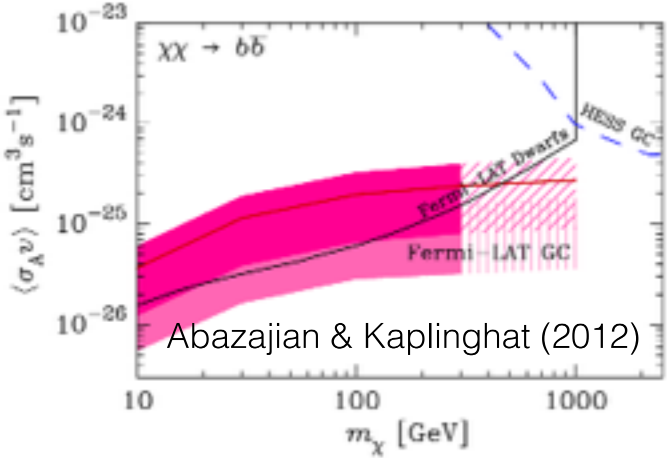


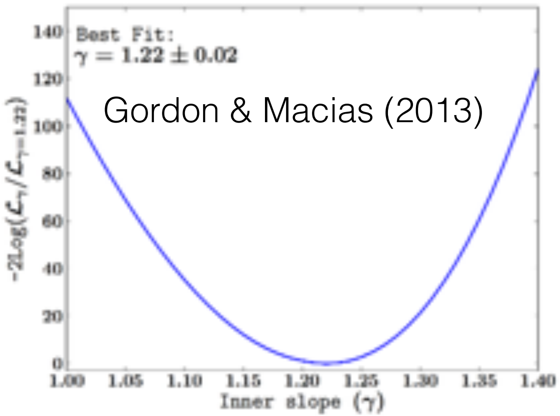
with:
Tansu Daylan, Doug Finkbeiner, Dan Hooper, Stephen Portillo, Nick Rodd, Tracy Slatyer

Early Observations of An Anomalous Signal at the Galactic Center



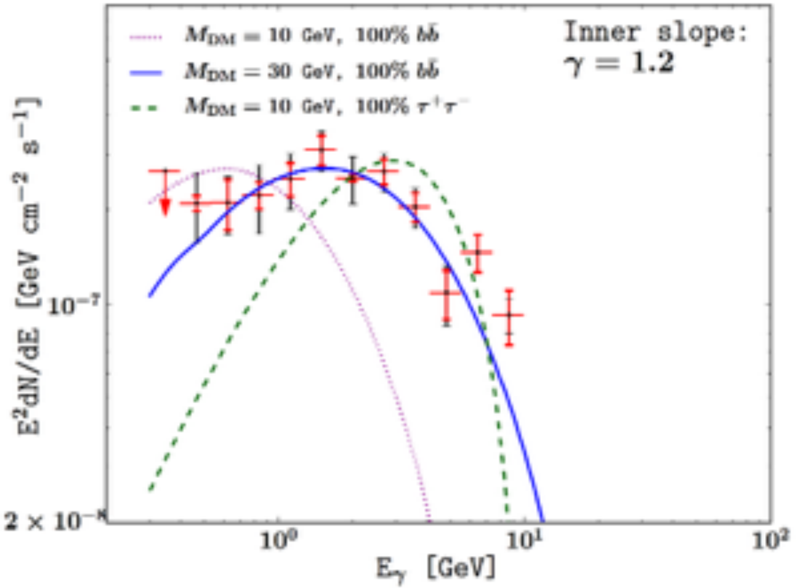






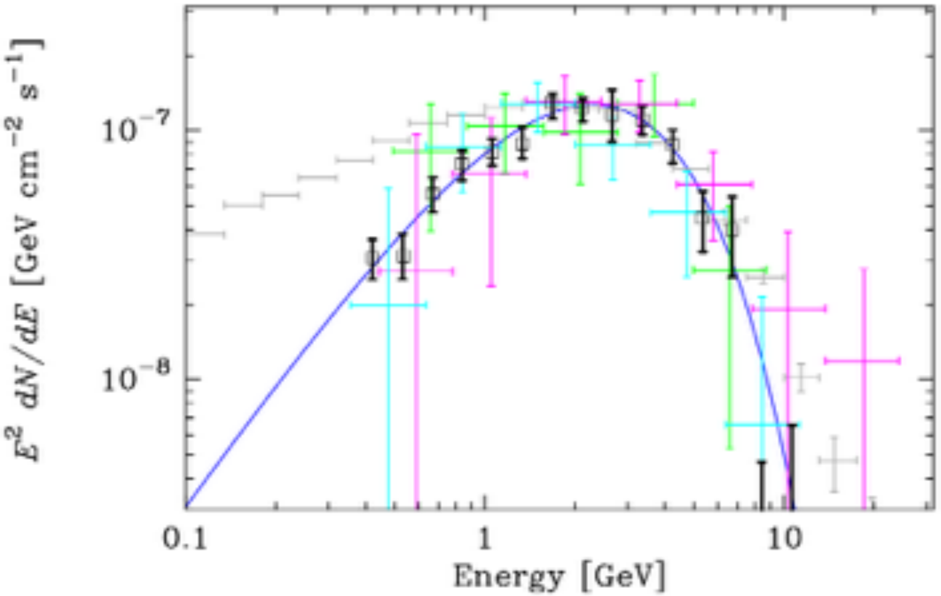
Two Interpretations of the Previous Data

Dark Matter



Gordon & Macias (2013)

Millisecond Pulsars



Abazajian (2011)

Spatial Extension of the Galactic Center Signal

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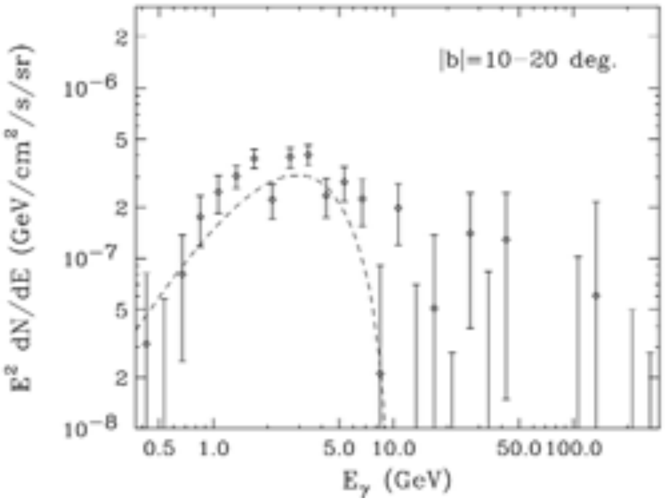
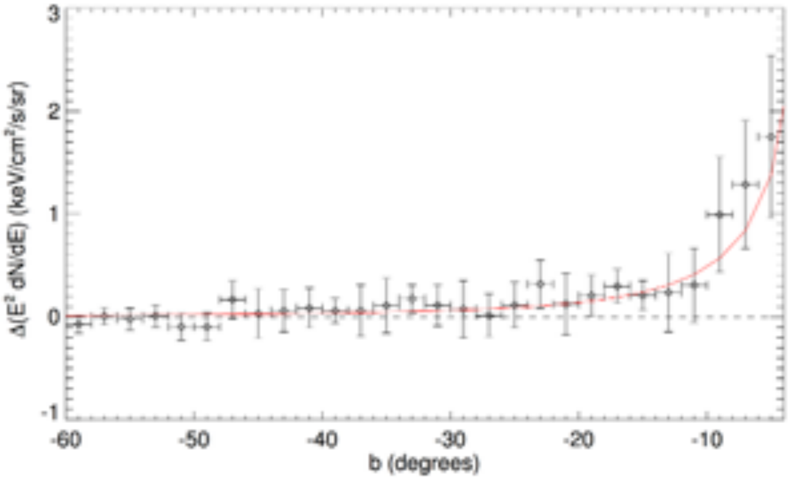
Work by Hooper & Slatyer found evidence of the same spectral feature out to a distance of at least 10^{o} from the galactic center





This disfavors the pulsar interpretation of the data. A large population of MSPs 10^{o} from the galactic center should be observable by the Fermi-LAT

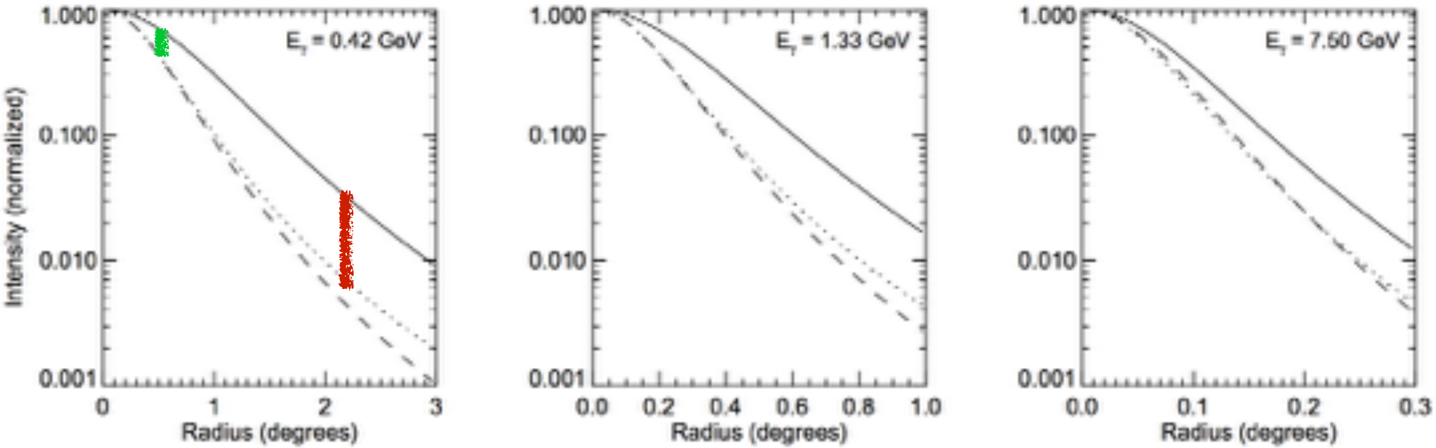
Three objectives of the Current Analysis

- Produce a significantly enhanced version of the Fermi-LAT dataset, using only photons with the best directional reconstruction

- Test the compatibility of the excess in the Galactic Center and Inner Galaxy

- Produce Multiple tests of the dark matter interpretation of the data - concentrating on tests which can differentiate a dark matter or pulsar signal

CTBCORE Quality Cuts



1.) Each photon observed by Fermi has a different uncertainty in its directional reconstruction

2.) The most recent Fermi analysis includes a parameter, CTBCORE, which indicates how well each photons direction was measured

3.) We select only the 50% best reconstructed photons for our analysis. This not only greatly improves the PSF, but also cuts down on the non-Gaussian tails of the PSF.

Two Parallel Analyses

The CTBCORE Cuts are applied to two different selections of the Fermi-LAT data:

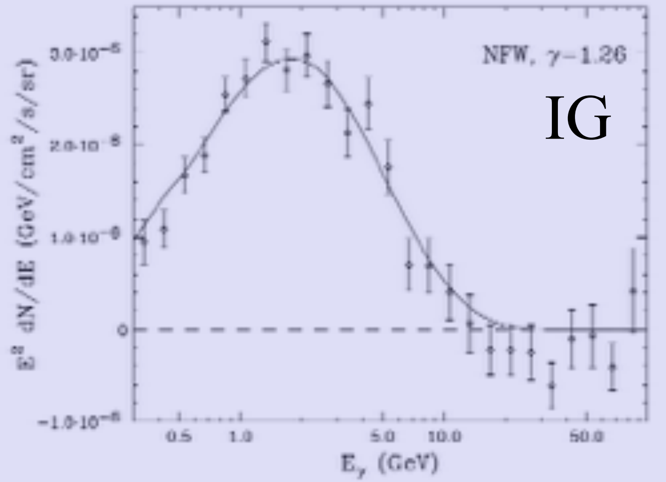
1.) Inner Galaxy Region ($|b| > 1^o$)

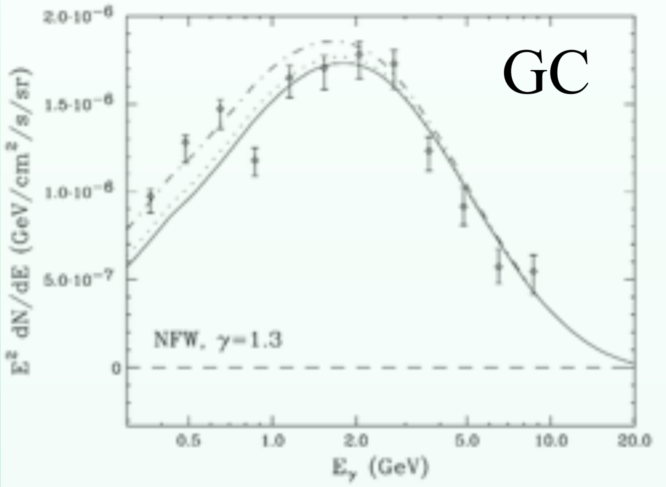
- Mask bright point sources at 2^o
- Let the normalization of the diffuse, isotropic, Fermi bubble, and dark matter templates to vary independently in each energy bin

2.) Galactic Center Region ($|b| < 5^o$, $|l| < 5^o$)

- Allow the normalization of point sources, as well as the spectrum of bright point sources, to vary
- Fit each component to a spectral model and calculate the LG(likelihood) of the best fits with and without a dark matter component

Spectrum of the Residuals

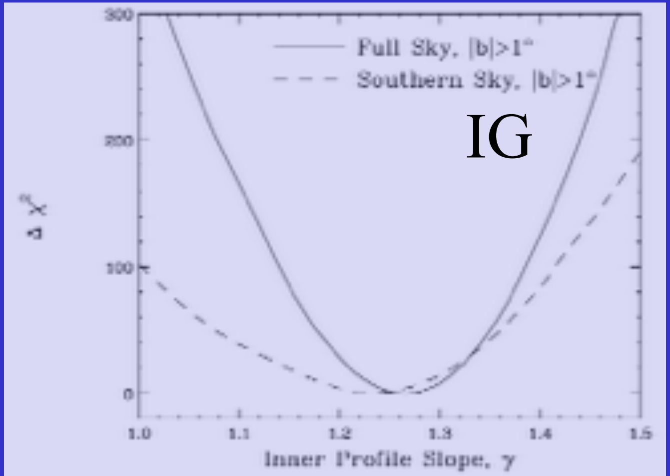


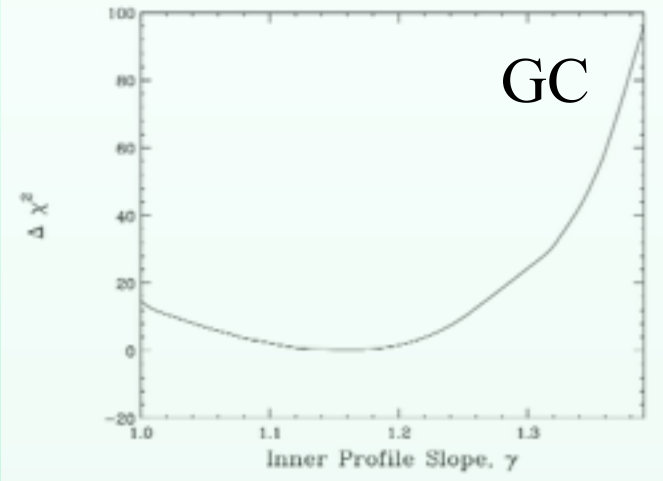


Inner Galaxy - The normalization of the dark matter template is allowed to float independently in every energy bin, and naturally picks up the following shape.

Galactic Center - Different initial seeds are used for the dark matter spectrum. The resulting dark matter spectrum is fed back into the fitting algorithm, which converges iteratively. We find the final spectrum to be independent of the initial seed.

Morphology of the Residuals

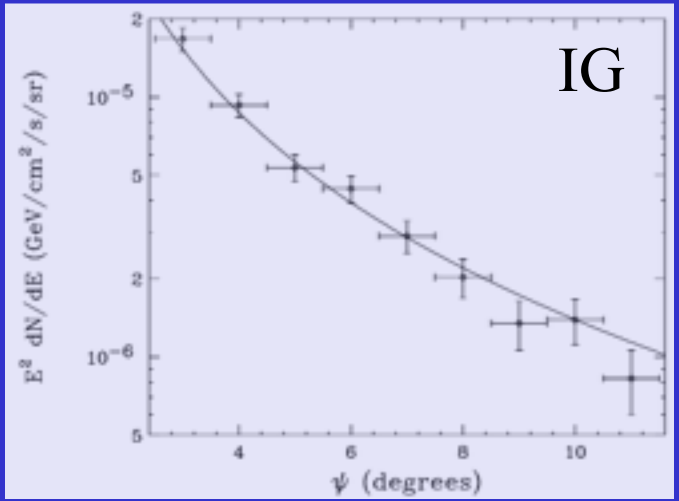




Inner Galaxy - The best fit is given by a generalized NFW profile with an inner power law slope of 1.26. The morphology of the southern sky is consistent with the morphology of the full sky.

Galactic Center - The best fit is given by a generalized NFW profile with an inner power-law slope of 1.17.

Morphology of the Residuals



Inner Galaxy - In this analysis, we can change which parameters float. Instead of forcing the morphology to fit an NFW profile and letting the spectrum vary in each energy bin, we can force the spectrum to fit our dark matter model and let the normalization float in each radial bin. We find the excess to be statistically significant out to 12° from the Galactic Center.

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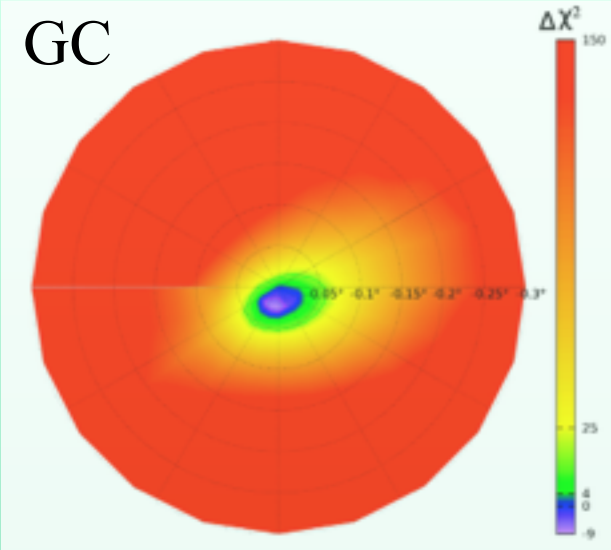
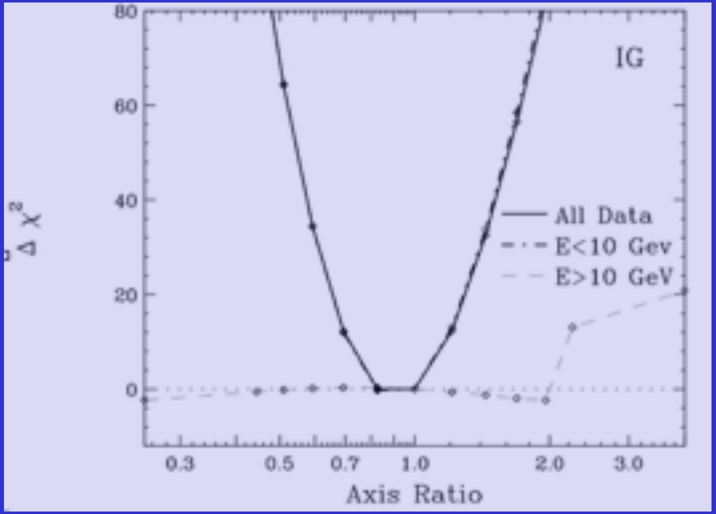
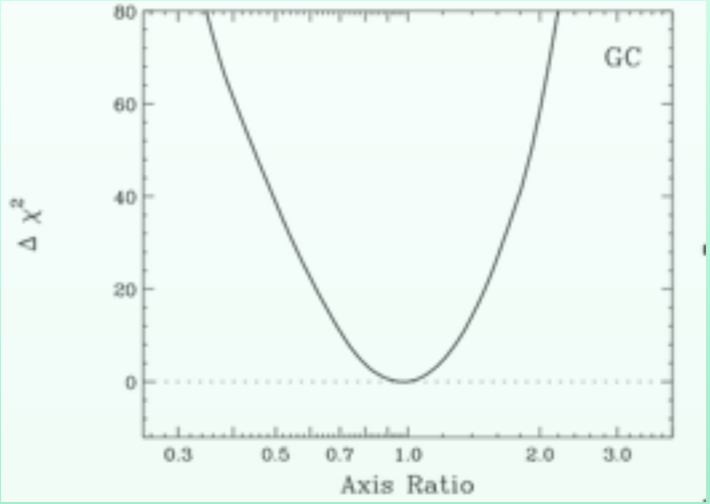
Morphology of the Residuals



Galactic Center - We can also test whether the excess is spatially centered on the true position of the galactic center, as is predicted in most dark matter models. We find the data prefer a NFW profile that is centered on the position of Sgr A* to within 0.05°.

Morphology of the Residuals





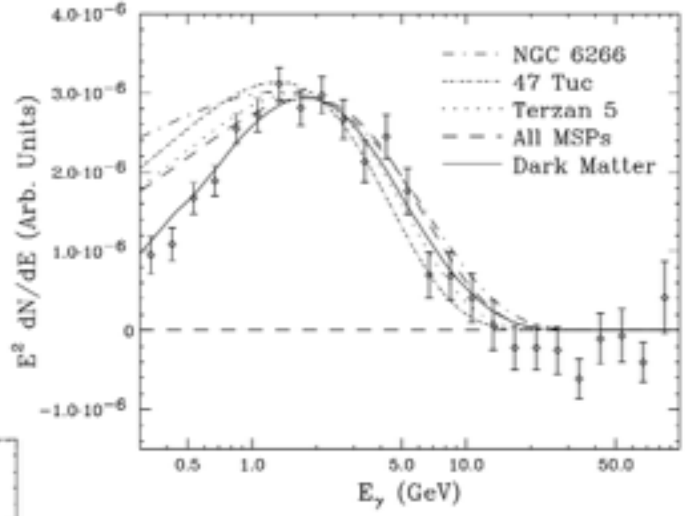
We can ask if the data prefer the gamma-ray residual to be spherically symmetric

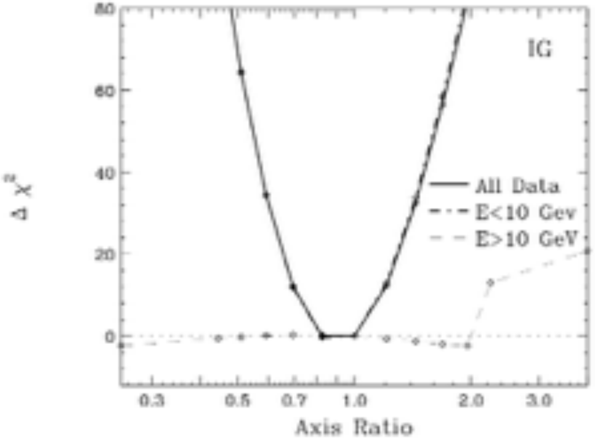
For both the Inner Galaxy and the Galactic Center, axis ratios (along or perpendicular to the galactic plane) of greater than 20% are disfavored by the data

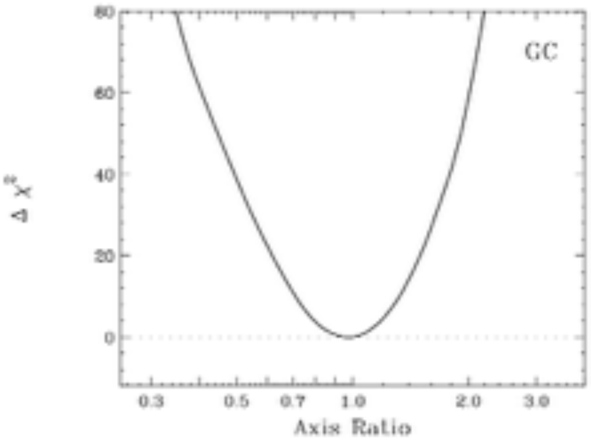
Interpretations of the Excess

1.) The spectrum of the gamma-ray excess does not look like the average spectrum of observed milli-second pulsars

2.) The spherical symmetry of the excess is hard to reconcile with the predicted morphology of milli-second pulsars

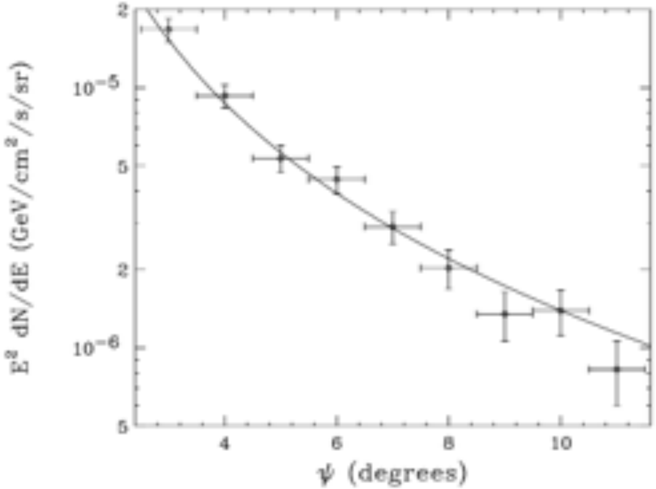


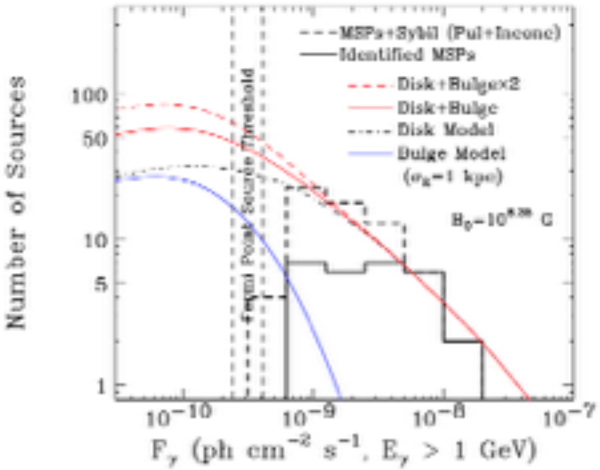


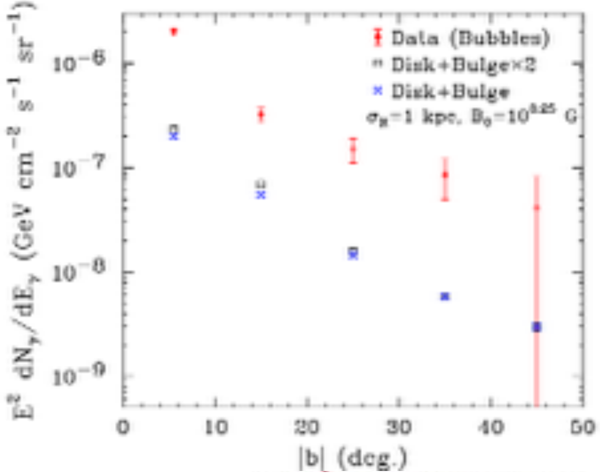


Interpretations of the Excess

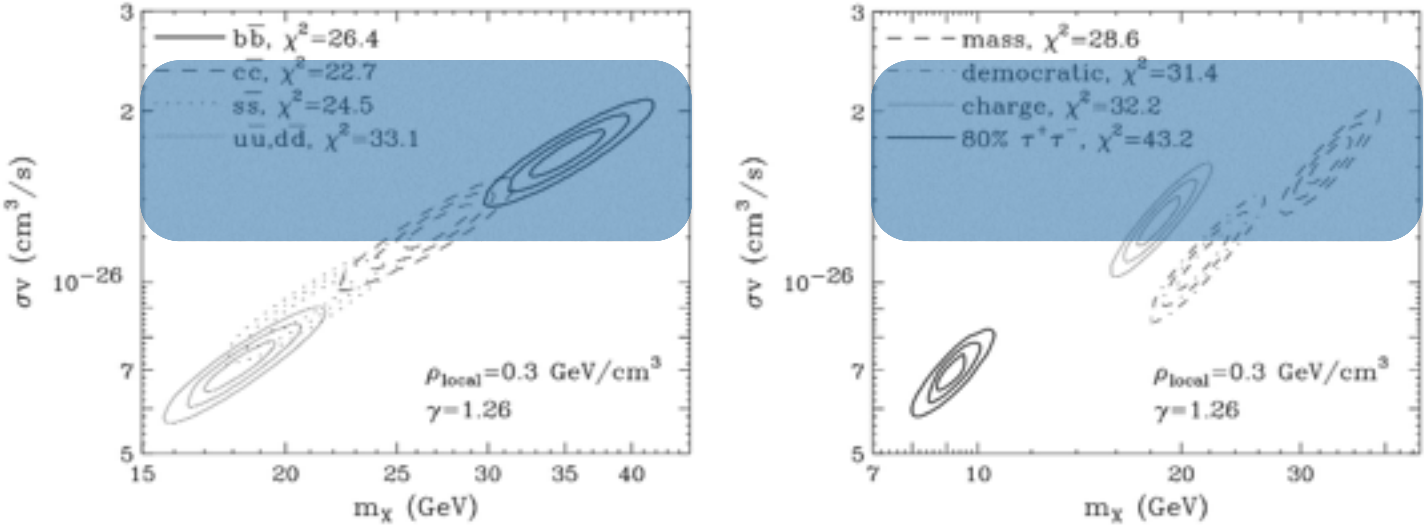
The extension of the source out to 12° from the galactic center makes it difficult to reproduce the intensity of the excess with milli-second pulsars, without producing a large population of systems we would have already observed







Dark Matter Interpretations of the Excess



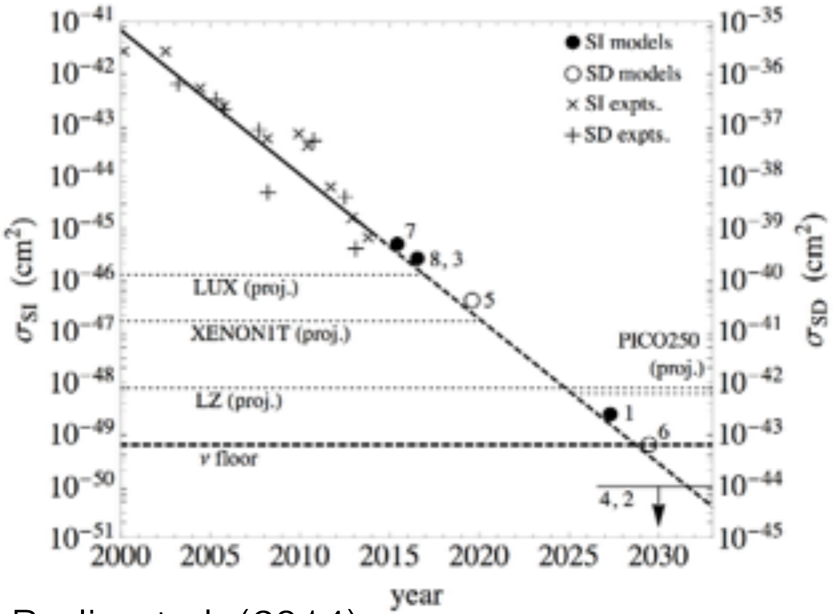
The gamma-ray signal is very well fit by simple, theoretically-motivated, dark matter models:

We vary only:

1.) The dark matter mass and annihilation final state
2.) The dark matter profile slope
3.) The dark matter annihilation cross-section

Dark Matter Interpretations of the Excess

Approximately half of the dark matter models which explain the gamma-ray excess are currently compatible with constraints from direct detection and collider searches.



Berlin et al. (2014)

$\langle S\rangle_{DM}$	Type	Interaction	Elastic Scattering	Kinematic Suppression
1/2	Dirac	$\bar\chi\gamma^5\chi\bar q q$	SI (scalar)	$(q/2m_\chi)^2$
1/2	Majorana	$\bar\chi\gamma^5\chi\bar q q$	SI (scalar)	$(q/2m_\chi)^2$
1/2	Dirac	$\bar\chi\gamma^5\chi\bar q\gamma^5 q$	SD	$(q^2/4m_n m_\chi)^2$
1/2	Majorana	$\bar\chi\gamma^5\chi\bar q\gamma^5 q$	SD	$(q^2/4m_n m_\chi)^2$
1/2	Dirac	$\bar\chi\gamma^\mu\chi\bar q\gamma_\mu q$	SI (vector)	1
1/2	Dirac	$\bar\chi\gamma^\mu\chi\bar q\gamma_\mu\gamma^5 q$	SD	$(q/2m_n)^2$ or $(q/2m_\chi)^2$
1/2	Dirac	$\bar\chi\gamma^\mu\gamma^5\chi\bar q\gamma_\mu\gamma^5 q$	SD	1
1/2	Majorana	$\bar\chi\gamma^\mu\gamma^5\chi\bar q\gamma_\mu\gamma^5 q$	SD	1
0	Complex	$\phi^\dagger\phi\bar q q$	SI (scalar)	1
0	Real	$\phi^2\bar q q$	SI (scalar)	1
0	Complex	$\phi^\dagger\phi\bar q\gamma^5 q$	SD (scalar)	$(q/2m_n)^2$
0	Real	$\phi^2\bar q\gamma^5 q$	SD (scalar)	$(q/2m_n)^2$
1	Complex	$B^\dagger_\mu B^\mu\bar q q$	SI (scalar)	1
1	Real	$B_\mu B^\mu\bar q q$	SI (scalar)	1
1	Complex	$B^\dagger_\mu B^\mu\bar q\gamma^5 q$	SD	$(q/2m_n)^2$
1	Real	$B_\mu B^\mu\bar q\gamma^5 q$	SD	$(q/2m_n)^2$

Dark Matter Interpretations of the Excess

This is in marked contrast to all previous excesses which have claimed to be due to a dark matter signal:

1.) PAMELA/AMS - Need leptophilic dark matter, with a significant Sommerfeld enhancement to the cross-section (100 - 1000x thermal). Need a cored dark matter profile to avoid Fermi-LAT constraints

2.) DAMA/LIBRA - Require a finely tuned inelastic dark matter interaction with nearly degenerate dark matter states in order to avoid constraints from other direct detection experiments

3.) 130 GeV Line - Need to significantly enhance (x100) the loop-level annihilation to **$\gamma\ \gamma$** compared to tree-level processes

The Current State of the Excess

1.) The excess is hugely statistically robust (40σ for the Inner Galaxy, 17σ for the Galactic Center). This gives us ~30,000 photons in the gamma-ray excess from which we can extract the spectral and morphological properties of the signal

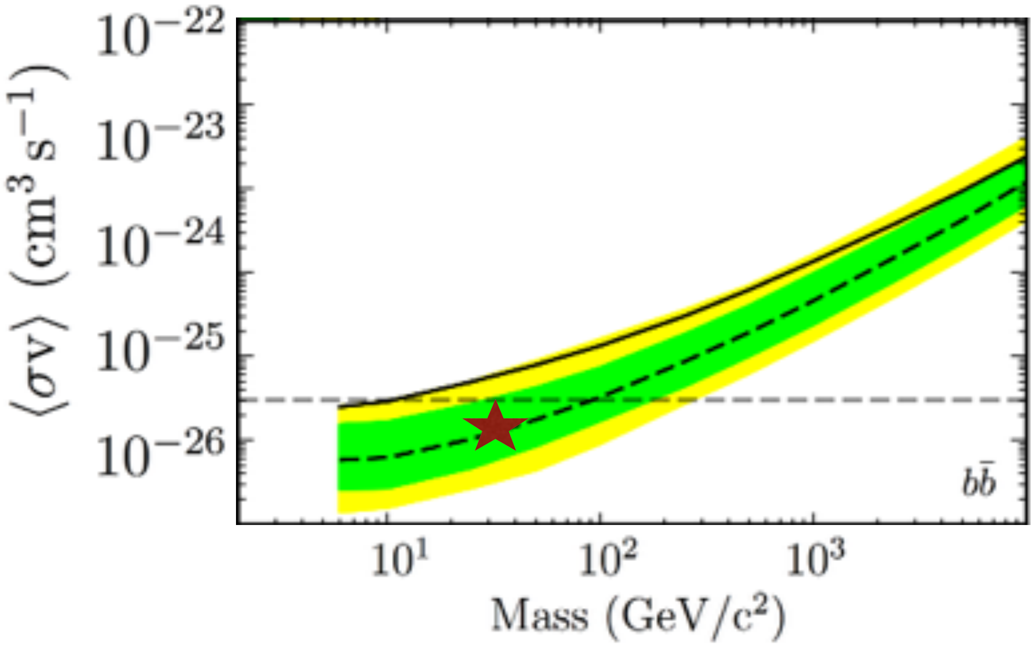
2.) The excess is extraordinarily well fit by simple, well-motivated dark matter models

3.) There is no other reasonable astrophysical explanation for the spectrum and morphology of the excess

Future Tests of the Excess

Dwarf galaxies are another natural target for dark matter indirect detection.

Interestingly, the Fermi-LAT finds an excess with a local significance of 2.7σ at the mass most favored by our galactic center models.



The Fermi-LAT Collaboration (2013)

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Is This How the Story Should Unfold?

$$\Phi_\gamma \propto J = \frac{1}{\Delta\Omega}\int d\Omega \int_{l.o.s} \rho^2 dl(\phi)$$

Name	GLON (deg)	GLAT (deg)	Distance (kpc)	$\overline{\log_{10}(J^{NFW})}^{a}$ ($\log_{10}[\mathrm{GeV^2\,cm^{-5}\,sr}]$)
Bootes I	358.1	69.6	66	18.8 ± 0.22
Bootes II	353.7	68.9	42	–
Bootes III	35.4	75.4	47	–
Canes Venatici I	74.3	79.8	218	17.7 ± 0.26
Canes Venatici II	113.6	82.7	160	17.9 ± 0.25
Canis Major	240.0	-8.0	7	–
Carina	260.1	-22.2	105	18.1 ± 0.23
Coma Berenices	241.9	83.6	44	19.0 ± 0.25
Draco	86.4	34.7	76	18.8 ± 0.16
Fornax	237.1	-65.7	147	18.2 ± 0.21
Hercules	28.7	36.9	132	18.1 ± 0.25
Leo I	226.0	49.1	254	17.7 ± 0.18
Leo II	220.2	67.2	233	17.6 ± 0.18
Leo IV	265.4	56.5	154	17.9 ± 0.28
Leo V	261.9	58.5	178	–
Pisces II	79.2	-47.1	182	–
Sagittarius	5.6	-14.2	26	–
Sculptor	287.5	-83.2	86	18.6 ± 0.18
Segue 1	220.5	50.4	23	19.5 ± 0.29
Segue 2	149.4	-38.1	35	–
Sextans	243.5	42.3	86	18.4 ± 0.27
Ursa Major I	159.4	54.4	97	18.3 ± 0.24
Ursa Major II	152.5	37.4	32	19.3 ± 0.28
Ursa Minor	105.0	44.8	76	18.8 ± 0.19
Willman 1	158.6	56.8	38	19.1 ± 0.31

The Fermi-LAT Collaboration (2013)

The J-Factor of the Galactic center is:

$\log_{10}(J) = 21.02$

for a region within 100 pc of the Galactic center and an NFW profile

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Thank You!