# Anomalous Gamma-Ray Emission from the Inner Galaxy

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partly based on arXiv:1402.6703 [astro-ph.HE]
with
Douglas P. Finkbeiner (Harvard), Dan Hooper (UChicago), Tim Linden (UChicago), Stephen K. N. Portillo (Harvard), Nicholas L. Rodd (MIT) and Tracy R. Slatyer (MIT)

Fermi Summer School 2014

May 31, 2014

# Overview

# Historical Background


L. Goodenough, D. Hooper, 0910.2998 (2009)
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**Possible Evidence For Dark Matter Annihilation In The Inner Milky Way From The Fermi Gamma Ray Space Telescope**

Lisa Goodenough[1] and Dan Hooper[2,3]

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We study the gamma rays observed by the Fermi Gamma Ray Space Telescope from the direction of the Galactic Center and find that their angular distribution and energy spectrum are well described by a dark matter annihilation scenario. In particular, we find a good fit to the data for dark matter particles with a 25-30 GeV mass, an annihilation cross section of $\sim 9 \times 10^{-26}$ cm$^3$/s, and that are distributed with a cusped halo profile, $\rho(r) \propto r^{-1.1}$, within the inner kiloparsec of the Galaxy. We cannot, however, exclude the possibility that these photons originate from an astrophysical source or sources with a similar morphology and spectral shape to those predicted in an annihilating dark matter scenario.

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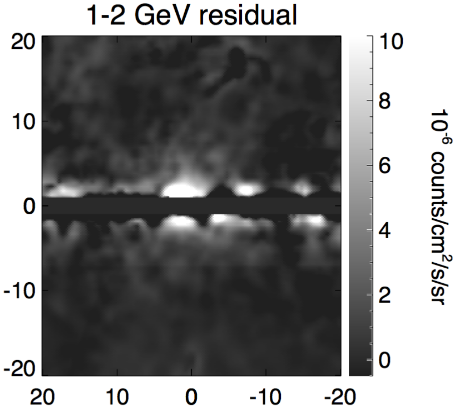
**Pulsars Cannot Account for the Inner Galaxy's GeV Excess**

Dan Hooper[1,2], Ilias Cholis[1], Tim Linden[3], Jennifer Siegal-Gaskins[4], and Tracy Slatyer[5]

# Introduction to the Gamma-Ray Excess

Analysis of Fermi-LAT data reveals a gamma-ray excess in the inner galaxy featuring:

- approximate rotational symmetry around the dynamical center of the Milky Way



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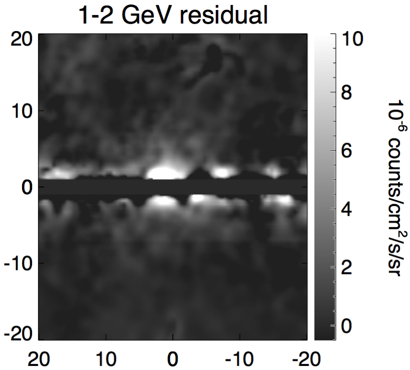


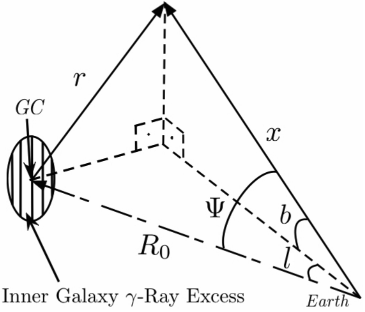

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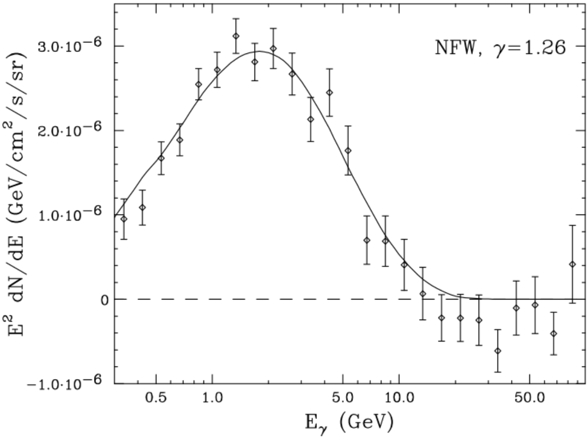
- a bump-like spectrum that peaks at 1-3 GeV



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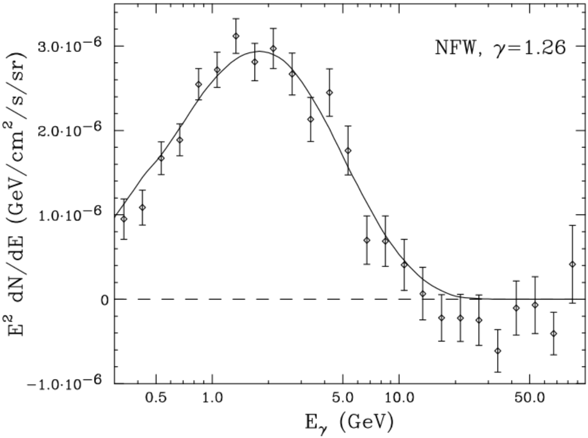

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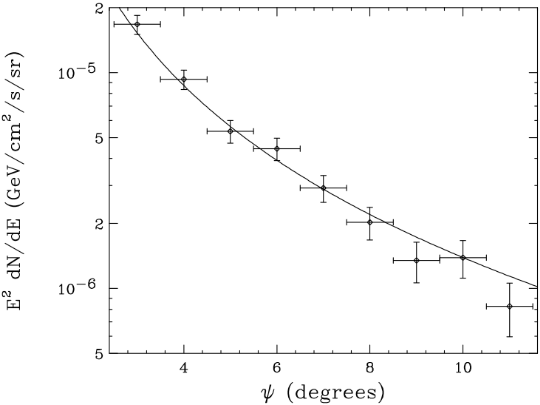

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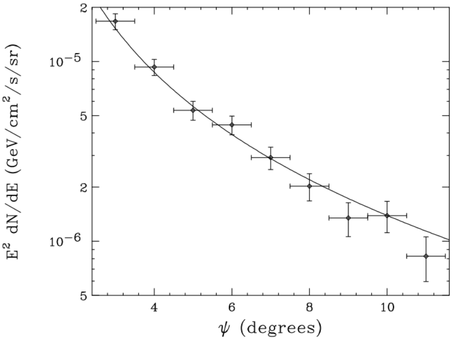
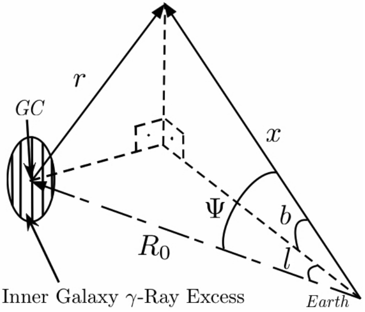


# Components of the Diffuse Gamma-Ray Sky

## Pion decay

$\mathrm{p\ (CR) + p(gas) \rightarrow p + p + \pi^0}$
$\pi^0 \rightarrow \gamma\gamma$

## Electron Braking Radiation (aka Bremsstrahlung)

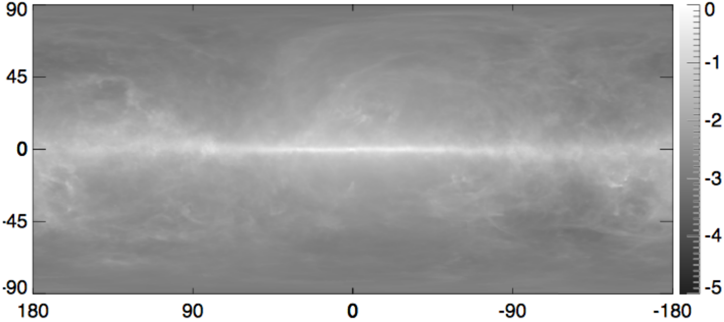
$e^-\ \mathrm{(hot)} \xrightarrow{gas} e^-\ \mathrm{(cold)} + \gamma$

## Inverse Compton Scattering on CMB, Optical or UV

$e^-\ \mathrm{(hot)} + \gamma \rightarrow e^-\ \mathrm{(cold)} + \gamma$

# Fermi Diffuse Model

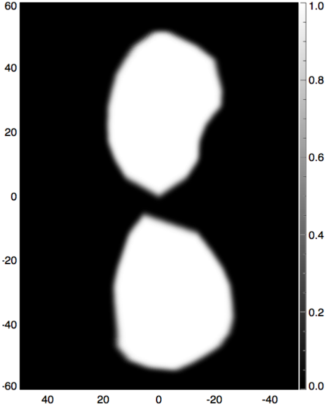
The Fermi Diffuse Emission Model, produced by the Fermi Collaboration, can be used as a template for emission correlated with the three components.



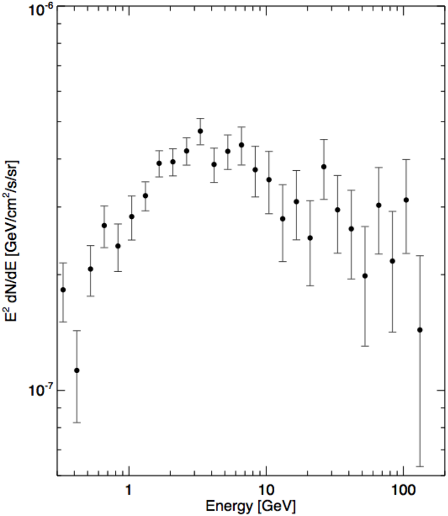
# Fermi Bubbles

Fermi Bubbles are two large regions of hard gamma radiation 50° above and below and symmetric with respect to the galactic center[Su, Slatyer, Finkbeiner, 2010]. Their main features are:

- approximately constant surface brightness and spectrum over the whole emission region
- a hard spectrum, dN/dE $\sim E^{-2}$ between $\sim$ 1 GeV and $\sim$ 100 GeV



# The Spectrum of the Fermi Bubbles



# Suppressing the tails of the PSF

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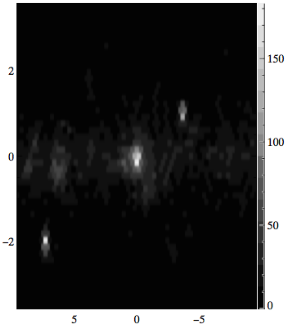
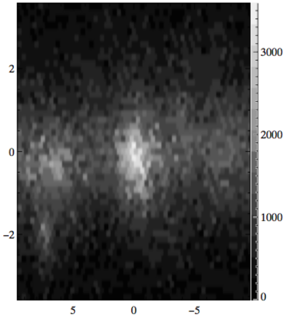



3.0 GeV




0.3 GeV

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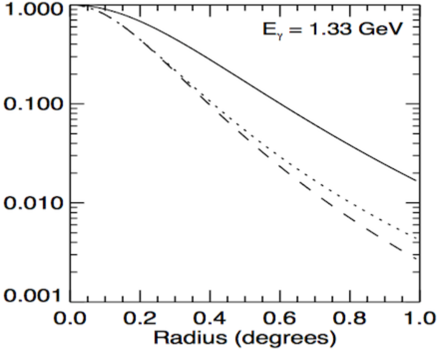

# Likelihood Analysis

- Using the publicly available Fermi Science Tools, sky maps of photon fluxes are produced for each logarithmic energy bin from 0.3 GeV up to 300 GeV.
- The data and templates are smoothed to a common resolution of 2 degrees.
- Using exposure maps and the effective area of the telescope count maps are produced.
- Point sources are handled either by
  1. not fitting over pixels near the known point sources taking into account the PSF (Point Spread Function) at each energy.
  2. adding a fixed-spectrum template
- The galactic plane is masked.

# Likelihood Analysis

The number of photon counts in a pixel has the Poisson distribution. Given k data counts in a data cube the likelihood of having $\mu$ model counts is:

$$\mathcal{L}(\mu; k) = \frac{\mu^k}{k!} e^{-\mu} \tag{1}$$

But there are N such independent data cubes.

$$\mathcal{L}(\vec{\mu}; \vec{k}) = \prod_i \frac{\mu_i^{k_i}}{k_i!} e^{-\mu_i} \tag{2}$$

$$\ln \mathcal{L}(\vec{\mu}; \vec{k}) = \sum_i k_i \ln \mu_i - \mu_i - \ln k_i! \tag{3}$$

$$\chi^2 = -2\Delta \ln \mathcal{L} \tag{4}$$

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- The data is fitted by a linear combination of templates, i.e., FDM, Fermi bubbles at each energy by maximizing the Poisson likelihood.

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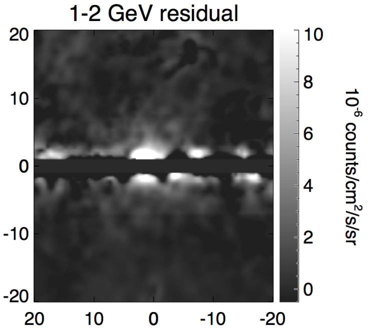
- This is what we get:

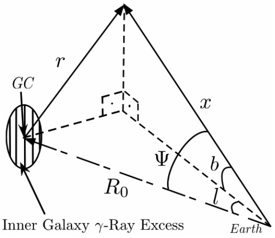


# NFW Profile

The prompt photon spectrum from 2 body DM annihilation is:

$$\frac{d\phi}{dE}(\vec{r}, E) = \frac{1}{2}\frac{\langle \sigma v \rangle}{4\pi m_\chi^2}\frac{dN_\gamma}{dE}\rho^2(r) \quad (5)$$

$$\frac{d\phi}{dE}(b, l, E) = \frac{1}{2}\frac{\langle \sigma v \rangle}{4\pi m_\chi^2}\frac{dN_\gamma}{dE}\underbrace{\int_{los}\rho^2(r)dx}_{J(b,l)} \quad (6)$$



# NFW Profile

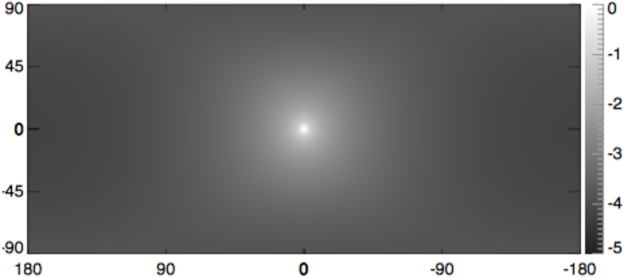
NFW (Navarro Frenk White) profile is an approximation for the equilibrium configuration of collisionless DM in N-body simulations.

$$\rho(r) = \frac{\rho_0}{(r/r_s)(1 + r/r_s)^2} \tag{7}$$

The cuspiness can be tuned using a generalized profile with the inner slope parameter, $\gamma$.

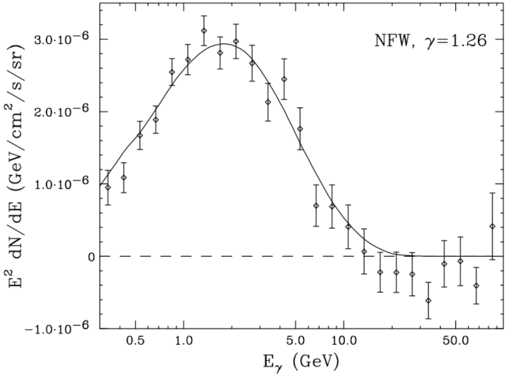
$$\rho(r) = \frac{\rho_0}{(r/r_s)^\gamma(1 + r/r_s)^{3-\gamma}} \tag{8}$$

# NFW Profile



# In short

Adding the NFW template reduces $\chi^2$ by more than 100 depending on the background modeling.



# Further Tests

- The sphericity of the excess is tested by elongating the NFW template.
- In a variant of the template fit, the spectrum of the excess is fixed and its morphology is allowed to float in the form of concentric rings.
- In a different variant of the analysis the region of interest is restricted to the Galactic center only.

# Interpretations of the Excess

There are three views on the origin of the anomaly:

- Millisecond Pulsar explanation
- Dark Matter Annihilation explanation
- GC-agnostic stance

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DM hunters compensate by:

$$P(\text{DM Exists}) \sim 1$$

Therefore we need to make sure we exhaust the available evidence space.

# Pulsars

- Pulsars are highly magnetized (B $\sim 10^{11} - 10^{13}$ G) rapidly rotating neutron stars.
- Because their magnetic axes are not necessarily aligned with their rotation axes they produced electromagnetic radiation.
- Due to the intense curvature radiation their rotational energies are quickly depleted and they stop radiating in $\sim 100$ Myrs. Hence they cannot produce an extended signal out to $\sim 10^\circ$ from the GC.
- They also have large kick velocities $\sim 400$ km/s, therefore cannot have a dense distribution like $\sim r^{-2.4}$ around the GC.

# Millisecond Pulsar Explanation

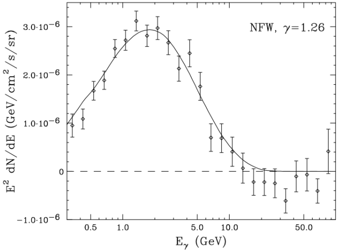
- But if the pulsar has a companion, then it can be spun up by accretion and radiate at long time scales.
- It also gains lower kick velocities compared to ordinary pulsars.
- Therefore an unresolved population of $\sim$ a few thousand MSPs have been proposed as a source of the excess.

# Millisecond Pulsar Explanation

[Hooper et al., 2013] provides two arguments against the pulsar interpretation:

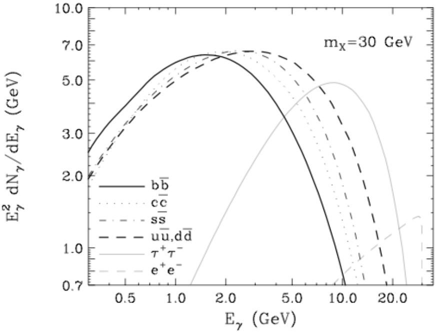
- Only $\sim$ 10% of the amplitude of the signal can be explained by extrapolating the resolved number of MSPs by Fermi.
- The pulsar spectrum is too soft in the sub-GeV energies.

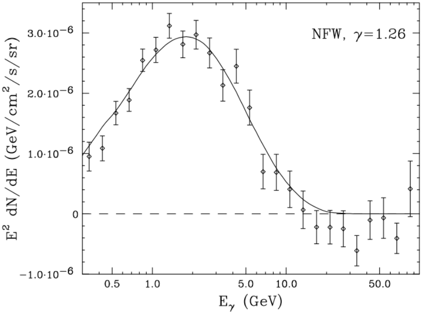
$$E^2 \frac{dN}{dE} \sim E^{0.52} exp\left(-\frac{E}{3.3\text{GeV}}\right) \tag{9}$$



# DM Annihilation Explanation

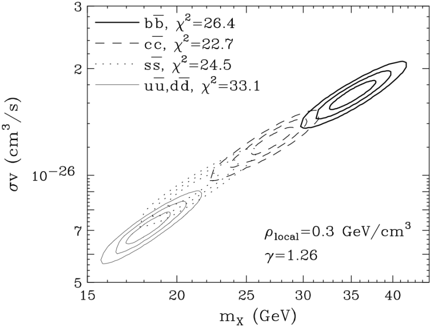
$$\frac{d\phi}{dE}(b,l,E) = \frac{1}{2}\frac{\langle \sigma v \rangle}{4\pi m_\chi^2}\frac{dN_\gamma}{dE} J(b,l) \tag{10}$$



# DM Annihilation Explanation

The best fit is a 31-40 GeV WIMP annihilating to $b\bar{b}$ with an annihilation cross section of $\sigma v = (1.7 \pm 0.3) \times 10^{-26}$ cm$^3$/s assuming a local DM density of $(0.3 \pm 0.1)$ GeV/cm$^3$.



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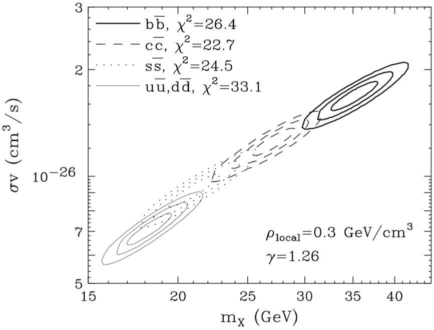


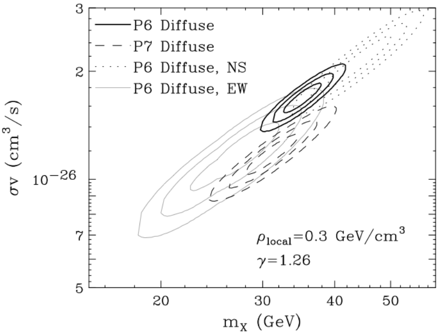

# Outlook

- Assuming $\sigma v = (1.7 \pm 0.3) \times 10^{-26}$ cm$^3$/s, the signal from dwarf galaxies is below current detection limits, but could be accessible with 5-10 more years of Fermi-LAT data.
- Bremsstrahlung becomes important close to the galactic plane. The secondary radiation from Bremsstrahlung softens the prompt emission spectrum.
- Annihilation processes to multiple pairs of states give larger phase space to the prompt photon spectrum.

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