Dark Matter Theory

and

(Indirect) Searches

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Strongest evidence for dark matter comes from its gravitational interactions with visible matter.

Particle physics properties (e.g., mass, couplings) remain an open question.

We can make educated guesses for the dark matter mass based on its interactions in the early Universe.
Thermal Dark Matter

Dark matter is in equilibrium in the early Universe

As temperature cools, eventually

$$n_\chi \langle \sigma_A v \rangle \sim H$$

Dark matter stops annihilating and falls out of equilibrium

Relic abundance for dark matter is thus established
Thermal Dark Matter

Weakly interacting particle with mass $\sim 10^{2-3}$ GeV gives density observed today

$$\Omega_\chi h^2 \approx \frac{3 \times 10^{-27} \text{ cm}^3 / \text{s}}{\langle \sigma_A v \rangle}$$

$$\approx 0.1 \cdot \left( \frac{0.01}{\alpha} \right)^2 \left( \frac{m_\chi}{100 \text{ GeV}} \right)^2$$

Planck + WMAP:
$$\Omega_\chi h^2 = 0.1199 \pm 0.0027$$
The WIMP paradigm has been the primary guide for the current dark matter experimental program.

However, one does not have to do much to open up the parameter space for thermal dark matter:

e.g., If the dark matter annihilates to a new, slightly heavier state

\[ \chi \chi \rightarrow \phi \phi \]

then, the correct relic density can be obtained down to keV masses.

Griest and Seckel (1991); D’Agnolo and Ruderman [1505.07107]
WIMPs Today

Dark matter self-annihilations are rare today, but do occur.

Increase chances of observing these rare events by looking in densest dark-matter regions of the sky.

Searching for high-energy gamma rays from dark matter annihilation is the most direct way to probe the thermal hypothesis.
The *Fermi* LAT is one of the best probes of high-energy gamma rays from dark matter annihilation

Launched June 11, 2008

Sensitive to energies from 20 MeV to > 300 GeV

Scans over the whole sky every three hours
Indirect Detection

**Monochromatic Photons**

Direct annihilation to photons, a line in photon energy spectrum

**Continuum Photons**

Annihilation to SM final states that shower into photons

[Diagrams showing annihilation processes and photon energy spectra]
Photon Flux

The intensity profile for dark matter annihilation is given by

\[ \Phi(E, \psi) = \frac{\sigma_A \nu}{8\pi m^2_\chi} \frac{dN_\gamma}{dE} \int d\ell \rho [r(\ell, \psi)]^2 \]

- \( \sigma_A \nu \) is the annihilation cross section.
- \( \frac{dN_\gamma}{dE} \) is the photon energy spectrum.
- \( \rho \) is the dark matter density.
- \( r(\ell, \psi) \) is the distance from the annihilation site to the observer.
- GC is the Galactic Center.
Astrophysical uncertainties are absorbed by the “J-factor”

\[ J \propto \int d\ell \rho[r(\ell, \psi)]^2 \]

Generalized NFW Profile

\[ \rho(r) \propto \frac{(r/r_s)^{-\gamma}}{(1 + r/r_s)^{3-\gamma}} \]

Most dense regions at the centers of dark-matter halos
Dwarf Galaxies

These faint galaxies are dark-matter dominated and thus excellent targets for annihilation searches.
Excess in Reticulum?

Analysis of *Fermi* data yields no significant excesses in most candidates, though Reticulum still debated.
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Analysis of *Fermi* data yields no significant excesses in most candidates, though Reticulum still debated
Dwarf Galaxies

Six years of data from *Fermi* LAT used to search for gamma-ray emission from 15 dwarf spheroidal satellite galaxies

Constraints fall below the thermal relic cross section for dark matter masses less than \(~100\) GeV (bb annihilation channel)
Isotropic Background

Unresolved gamma-ray emission at high-latitudes can arise from dark matter annihilation in:

Extragalactic Halos  The Milky Way

Zavala, Springel, Boylan-Kolchin [0908.2428]

http://www.ucolick.org/~diemand/vl/
Fermi sensitivities in figure very large for such gamma rays. WIMP signals are heavily suppressed at the highest energies as the optical depth is DM particle masses above up to and imaging air Cherenkov telescopes [Way substructure signal strength is taken to its lowest value as calculated in ref. of section REF’ shows the theoretical uncertainty in the extragalactic signal as given by the PS approach see section µ procedure. From top to bottom and left to right, the limits are for the $\sigma v$ channels. The channels were also derived, and can be found in Appendix into limits on dark-matter annihilation Isotropic Background 100 TeV [161

It is interesting to compare the conservative limits of figure 10 channels. The channels were also derived, and can be found in Appendix into limits on dark-matter annihilation

isotropic background can be converted into limits on dark-matter annihilation

\textit{Fermi} measurement of isotropic background can be converted into limits on dark-matter annihilation

$\langle \sigma v \rangle$ [cm$^3$ s$^{-1}$]

$m_\chi$ [GeV]

$\langle \sigma v \rangle$$_{\text{freeze-out}}$

Segue 1, MAGIC

GC Halo, HESS

Stacked dSph, LAT

$\bar{b}_b$
Galactic Center
GeV Photon Excess

Observed at the Galactic Center and Inner Galaxy (≤ 10°)

Constitutes ~10% total flux

High statistical significance

Goodenough and Hooper [0910.2998]
Hooper and Goodenough [1010.2752]
Boyarsky, Malyshev, Ruchayskiy [1012.5839]
Hooper and Linden [1110.0006]
Abazajian and Kaplinghat [1207.6047]
Gordon and Macias [1306.5725]
Abazajian et al. [1402.4090]
Daylan et al. [1402.6703]
Calore, Cholis, and Weniger [1409.0042]
Fermi Collaboration [1511.02938]
The Signal

Approximately spherically symmetric, centered on Sgr A*

Flux falls off radially as $\sim r^{-(2.2-2.6)}$

Extends up to 10° off the plane

![Graph showing the energy spectrum](image-url)
Best-Fit Dark Matter

Figure 18. Left panel: Constraints on the $h v_i$-vs-$m_X$ plane for three different DM annihilation channels, from a fit to the spectrum shown in figure 14 (cf. table 4). Colored points (squares) refer to best-fit values from previous Inner Galaxy (Galactic center) analyses (see discussion in section 6.2).

Right panel: Constraints on the $h v_i$-vs-$m_X$ plane, based on the fits with the ten GCE segments.

Figure 19. Constraints on the $h v_i$-vs-$m_X$ plane at 95% CL, individually for the GCE template segments shown in figure 15, for the channel $\chi \chi \rightarrow \bar{b}b$. The cross indicates the best-fit value from a fit to all regions simultaneously ($m_X = 46.6$ GeV, $h v_i' = 1.60 \times 10^{-26}$ cm$^3$s$^{-1}$). Note that we assume a NFW profile with an inner slope of $\gamma = 1.28$. The individual $p$-values are shown in the figure legend; the combined $p$-value is 0.11.

mass fixed at 49 GeV. This plot is based on the fluxes from the segmented GCE template, see figure 16. As expected, the cross-section is strongly correlated with the profile slope. We

Calore, Cholis, & Weniger [1409.0042]
Diffuse Background

High-energy $\gamma$-rays produced from cosmic rays propagating in the Galaxy

Depends on location of cosmic-ray sources and on the gas distribution

Modeling of diffuse emission in the Inner Galaxy is uncertain; local measurements do not set very tight constraints in this region
Diffuse Background

Evidence for excess emission may be robust even under uncertainties in diffuse emission models

\[ E^2 \frac{dN}{dE} \text{ [GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}] \]

- 60 GDE models
- GC excess spectrum with stat. and corr. syst. errors

Table 3

<table>
<thead>
<tr>
<th>ROI</th>
<th>Definition</th>
<th>( \text{ROI} ) [sr]</th>
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<tbody>
<tr>
<td>I, II</td>
<td>( p_2 + b_2 &lt; 5 ), ( \pm</td>
<td>b</td>
</tr>
<tr>
<td>III, IV</td>
<td>( &lt; p_2 + b_2 &lt; 10 ), ( \pm</td>
<td>b</td>
</tr>
<tr>
<td>V, VI</td>
<td>( &lt; p_2 + b_2 &lt; 15 ), ( \pm</td>
<td>b</td>
</tr>
<tr>
<td>VII, VIII</td>
<td>( &lt; p_2 + b_2 &lt; 15 ), ( \pm</td>
<td>b</td>
</tr>
<tr>
<td>IX</td>
<td>( &lt; p_2 + b_2 &lt; 20 ), ( \pm</td>
<td>b</td>
</tr>
<tr>
<td>X</td>
<td>( &lt; p_2 + b_2 &lt; 1 ), ( \pm</td>
<td>b</td>
</tr>
</tbody>
</table>

To facilitate the study of morphological properties of the excess, we furthermore allow additional latitudinal variations in the ICS components of the individual GDE models. We split our ICS component into nine ICS segments, corresponding to 9 latitude strips with boundaries at \( |b| = 2, 2.6, 3.3, 4.3, 5.6, 7.2, 9.3, 12.0, 15.5 \). We then allow the normalization of the ICS strips to vary independently, though we keep the normalization...
Astrophysical Sources

Unresolved young and millisecond pulsars may account for gamma-ray excess

![Young Pulsars](image1)

![Millisecond Pulsars](image2)

Hooper et al. [1305.0830]; Cholis, Hooper, Linden [1407.5583, 1407.5625]; Brandt and Kocsis [1507.0561]; O'Leary et al. [1601.05797]
Dark matter *versus* Astrophysical Sources

Can we improve discrimination power?
Photon Counts

Malyshev and Hogg [1104.0010]
Lee, ML, Safdi [1412.6099]
Photon Counts

Malyshev and Hogg [1104.0010]
Lee, ML, Safdi [1412.6099]
Inner Galaxy Analysis

Lee, ML, Safdi, Slatyer, Xue [1506.05124]

Extended Pass 7 Reprocessed *Fermi* data (8/4/08-12/5/13)

HEALPix pixelization with *nside* = 128
Inner Galaxy Analysis

Photon count statistics can distinguish point sources from dark matter.

Excess flux in the Inner Galaxy can be entirely explained by a population of unresolved point sources.

Lee, ML, Safdi, Slatyer, Xue [1506.05124]
Bartels, Krishnamurthy, Weniger [1506.05104]
What are these point sources?

Our analysis is model-independent in that any sub-pixel structure is identified as a point source.

So, what exactly is the nature of this point-source population?

Localized structure in the diffuse background?

Population of pulsars?

Dark matter substructure?
Presence of all-sky, diffuse gamma-ray emission has been known for decades, but its origin remains an open question.

Potential wealth of information can be extracted from isotropic background if components are resolved.
High-Latitude Analysis

ML, S. Mishra Sharma, L. Necib, B. Safdi [to appear]

Use photon statistics to characterize the population of unresolved point sources at high latitudes and understand implications for dark matter

Recent High-Latitude Studies: Zechlin et al. [1512.07190], Ackermann et al. [1508.04449]
Wide program of indirect searches currently looking for signals of dark matter annihilation

The biggest challenge is distinguishing a potential signal from the astrophysical backgrounds

Photon statistics has proved useful in the Inner Galaxy, where evidence suggests the presence of an unresolved point source population, disfavoring the dark matter interpretation

The wealth of gamma-ray data presently available is strong motivation to continue developing novel analysis methods that increase potential for dark matter discovery