Separating astrophysical sources from indirect dark matter signals

Jennifer Siegal-Gaskins
Caltech
The nature of dark matter

Observational evidence indicates:
- non-baryonic
- neutral
- virtually collisionless

Additional assumptions for this talk:
- dark matter is a weakly-interacting massive particle (WIMP)
- GeV - TeV mass scale
- can pair annihilate or decay to produce standard model particles
- accounts for the measured dark matter density
The challenge

Image Credit: NASA/DOE/International LAT Team
The challenge

\[ \log_{10} \left( \frac{\text{Intensity}}{K \ [10^{-30} \ \text{cm}^{-2} \ \text{s}^{-1} \ \text{sr}^{-1}]} \right) \]
The challenge

\[ \log_{10} \left( \frac{\text{Intensity}}{K \times 10^{30}} \right) \] cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\)
The challenge
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The challenge

To detect an uncertain (and likely subdominant) signal in the presence of uncertain backgrounds
The challenge
The challenge

[Image of a haystack with a needle in it]
Strategy

- The "best" approach depends on both the expected dark matter signal and the target source or emission.

- Complementarity is key for making the most of the data: info from other dark matter searches (indirect and otherwise) and from studies of astrophysical sources is essential.

  - Multiwavelength (and multimessenger) studies can leverage searches beyond a single experiment and help alleviate issues with systematics.

  - Making full use of complementary results will help to efficiently direct future efforts.
Tools

1. spectral information

2. spatial information

3. know your backgrounds and impostor signals better
Energy spectra

- dark matter gives bumps, lines, cut-offs
- many astrophysical sources make power laws and may have exponential cut-offs
- some astrophysical sources (e.g., pulsars) also give bumps

Spectra calculated with PPPC 4 DM ID [Cirelli et al. 2010]
• dark matter gives bumps, lines, cut-offs
• many astrophysical sources make power laws and may have exponential cut-offs
• some astrophysical sources (e.g., pulsars) also give bumps

J. Siegal-Gaskins

JSG et al. MNRAS 415, 1074–1082 (2011)
The Fermi Large Area Telescope (LAT)

Credit: NASA/General Dynamics
The Cherenkov Telescope Array (CTA)
Current and future capabilities

The sensitivity of gamma-ray detectors is determined by three basic characteristics: the effective collection area, residual background rate, and angular resolution, all of which are typically a strong function of gamma-ray energy.

- **Angular Resolution (68% Containment) (deg)**
  - Fermi-LAT
  - HAWC
  - H.E.S.S.
  - CTA
  - Limit (Hofmann, 2006)
  - (limit for IACTs)

- **Energy Resolution (68% Containment)**
  - Fermi-LAT
  - CTA

Funk et al. 2012
GAMMA-400

launch scheduled for 2018
Fermi LAT and GAMMA-400 capabilities

but, GAMMA-400 has a smaller effective area

Galper et al. 2012
Comparison of gamma-ray experiments

<table>
<thead>
<tr>
<th></th>
<th>Space-based experiments</th>
<th>Ground-based experiments</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Fermi</td>
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<td>Energy range, GeV</td>
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<td>Effective area, m²</td>
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<td>Angular resolution (E_γ &gt; 100 GeV)</td>
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Galper et al. 2012
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Galper et al. 2012
Selected gamma-ray dark matter search targets

The inner galaxy

The isotropic gamma-ray background
The inner galaxy
The high-energy inner galaxy

Fermi LAT \( \sim 1 \) GeV
0.69 – 0.95 GeV

HESS > 380 GeV

spatially extended emission
consistent with point source

Abazajian & Kaplinghat 2012
Aharonian et al. 2006

see also: Hooper & Goodenough (2011); Abazajian (2011)
Fermi + HESS GC energy spectrum

Cases G.1 and G.2 (data set A)

\[ E^2 \frac{dN_\gamma}{dE} \text{ (GeV/cm}^2\text{/s)} \]

- **Top, left panel**: single power law, case G.1 (dashed, blue curve) and a power law combined with a heavy dark matter annihilation spectrum, case G.2 (solid, black curve).
- **Top, right panel**: log-parabola spectrum, modeling an average pulsar, and a heavy dark matter annihilation spectrum, case G.3 (solid curve).
- **Bottom, left panel**: a power law and two dark annihilation spectra, case G.5 (solid, black curve) and a power law with an exponential cut-off, modeling the pulsar contribution, case G.4 (dashed, blue curve).
- **Bottom, right panel**: same as bottom left panel but for data set C, cases G.7 (dashed, blue curve) and G.8 (solid, black curve).

In all panels, the dark matter annihilation spectra, the power laws and the exponential cut-off function are plotted separately as dotted lines. See Table I for details.
The multiwavelength inner galaxy

VLA @ 330 MHz

HESS > 380 GeV

Aharonian et al. 2006
Dark matter in the inner galaxy

\[ \rho r \text{ in pc GeV/cm}^3 \]

- Moore
- NFW
- Einasto, \( \alpha = 0.17 \)
- ISO
- IR-GC
- radio-GC
- Galactic Center
- Galactic Ridge
- Earth

GAMMA-400 @ 100 GeV
CTA / FERMI LAT @ 100 GeV
GAMMA-400 / FERMI LAT @ 1 GeV

"circumnuclear ring"

\[ r \text{ in pc} \]

Bertone et al. 2009
Point source or extended emission?  
Testing this hypothesis with CTA

Cumulative counts

Azimuthal counts distribution

χ^2 /d.o.f. = 106
CTA 500h
- Point Source
- Hadronic

Linden & Profumo 2012
Dark matter in the inner galaxy

- likely the brightest dark matter source in the gamma-ray sky, but...
- embedded in large and complicated backgrounds:
  - resolved sources
  - unresolved sources
  - diffuse emission
The inner galaxy

1. **spectrally**: DM signal may be subdominant, making a spectral signature difficult to identify

2. **spatially**: strong spatial signatures may be present (source of uncertainty), but not accessible with current data

3. **know your backgrounds and impostor signals better**: pulsars and other astrophysical sources, hadronic emission...
The inner galaxy

1. **spectrally:** DM signal may be subdominant, making a spectral signature difficult to identify

2. **spatially:** strong spatial signatures may be present (source of uncertainty), but not accessible with current data

3. **know your backgrounds and impostor signals better:** pulsars and other astrophysical sources, hadronic emission...

\[1+2 = \text{improved angular resolution could help to determine morphology of emission and address differences between GeV and TeV results}\]

\[2+3 = \text{multiwavelength studies can access smaller angular scales and could pin down origin and spatial distribution of some components}\]
The isotropic gamma-ray background
What is making the diffuse gamma-ray background?

Energy spectrum of the Fermi-LAT isotropic gamma-ray background (IGRB)

Credit: NASA/DOE/Fermi LAT Collaboration
What is making the diffuse gamma-ray background? 

Expected contribution of source populations to the IGRB

Sum is \(~60\text{-}100\%\) of IGRB intensity (energy-dependent)

- **Contributions**
  - Star-forming galaxies
  - BL Lacs (radio galaxies)
  - FSRQs

**Preliminary**

\[\text{Courtesy of M. Ajello}\]
Dark matter signals in the IGRB

Figure 3. The vertically hatched band illustrates the span in the expected isotropic extragalactic (EG) gamma-ray signal, defined by being the region enclosed by our MSII-Sub1 and MSII-Sub2 cases. The horizontally hatched band is the flux that can be expected from Galactic substructure. The filled grey band is the signal range that could be expected from the main DM Galactic halo, at a latitude of $10^\circ$, which would by itself produce an anisotropic signal. The data points show the measurement of the IGRB by the Fermi-LAT [Abdo et al., JCAP 04 014 (2010)] (horizontal bars are the energy bin range, and vertical bars are our later used $1\sigma$ errors). The gamma-ray spectra are from DM particles with mass of $400$ GeV, a total annihilation cross section $\langle \sigma v \rangle = 3 \times 10^{-26} \text{ cm}^{-3} \text{s}^{-1}$ into $b \bar{b}$ quarks, and a minimal subhalo mass cut-off at $10^6 M_\odot$. See the text for more details.
Constraints from the IGRB

Figure 5. Cross section limits on dark matter annihilation into $b\bar{b}$ final states. The blue regions mark the (90, 95, 99.999)% exclusion regions in the MSII-Sub1 ($z$) DM structure scenario (and for the other structure scenarios only 95% upper limit lines). The absorption model in Gilmore et al. [68] is used, and the relative effect if instead using the Stecker et al. [69] model is illustrated by the upper branching of the dash-dotted line in the MSII-Res case. Our conservative limits are shown on the left and the stringent limits on the right panel. The grey regions show a portion of the MSSM7 parameter space where the annihilation branching ratio into final states of $b\bar{b}$ (or $b\bar{b}$ like states) is $>80\%$. See main text for more details.

Figure 6 shows the exclusion region for the leptonic DM model, together with the 2 best fit region for this model to the PAMELA and Fermi-LAT positron and electron data. The sharp upper endings of the gray best fit regions come from the constrain to not overshoot HESS data [104]. Both the best fit regions and the exclusion regions for all our discussed DM scenarios are calculated in a self-consistent way, modulo minor corrections. Below a DM mass of about 500 GeV, the limits on these models are determined by the FSR signal at the high-energy end of the DM spectra, see figure 4, and therefore depend more substantially on the choice of the absorption model. We note here that this conclusion holds even if one considers the constraints that the low energy COMPTEL [105] and EGRET [25, 26] data would pose on the first (IC) peak in the spectra. The difference between the Stecker et al. [69] and the Gilmore et al. [68] absorption model results in a difference in the FSR signal calculated in the two cases by a factor 2, and a effect our limits correspondingly.

Constraints from the IGRB

Abdo et al., JCAP 04 014 (2010)
Getting rid of the IGRB

- the IGRB is time-dependent: will get smaller as more sources are resolved
- future IGRB measurements will lead to improved DM sensitivity

These are consistent with previous work \cite{8}, though more constrained because we are also fitting the source-count distribution function \( dN/dF \). The model reproduces the DGRB and blazar \( dN/dF \), with a reduced \( \chi^2/\text{DOF} = 0.63 \). The value of \( q \) indicates that the bolometric luminosity of a blazar jet is roughly 15 thousand times more luminous than the x ray from the accretion disk. Here, \( \chi^2/\text{DOF} > 1 \) so low-luminosity blazars have significant contributions to the total blazar flux. Therefore, a ten or more order-of-magnitude lower value of \( L/\text{min} \) would modify the calculation considerably, though no blazars have been detected below our \( L/\text{min} \) threshold, and therefore it seems unlikely that there is a large population of very-low-luminosity blazars. The fraction \( \chi^2/\text{DOF} \leq 2.4 \) implies that there is roughly one blazar for every 420 thousand nonblazar AGN. Our fit to the DGRB spectrum is shown in Fig. 3 and the fit to \( dN/dF \) is in Fig. 4.

Our value for the AGN XLF and blazar GLF ratio \( \chi^2/\text{DOF} \), is similar to and slightly larger than the central value derived by Inoue & Totani \cite{8}, 1.7/10/6 (at 95% CL), This implies that only a small fraction of x-ray loud AGN is visible as gamma-ray blazars. The intrinsic jet opening angle of a blazar has been found to be \( \chi^2/\text{DOF} = 1 \text{ deg} (\text{subtending an area of} \chi^2/\text{DOF} = 2 \text{ steradian}) \). Following from this is that only \( \chi^2/\text{DOF} \) of the AGN jets are potentially visible as blazars. Our model then requires that only &20% of AGN jets are gamma-ray blazars. This is not inconsistent with jet models \cite{51}, though if this fraction drops considerably (i.e., \( \chi^2/\text{DOF} \) is required to be much smaller), then it would call into question the blazar model analyzed here.

Note that using the \( dN/dF \) estimated from a power-law blazar spectrum model is not perfect, due to the fact that the detection efficiency estimate depends on the spectral model \cite{4}. However, Ref. \cite{4} tested the \( dN/dF \) dependence on the sensitivity estimate with a non-power-law fit to the blazar spectra and found it did not significantly change the measurement of \( dN/dF \). We also verified this.

FIG. 3 (color online). Shown are the best-fit model for the current DGRB spectrum (solid black line) and our upper/lower 95% CL forecast for the Fermi-LAT 5-year sensitivity (magenta star/green circle points). The low-energy dominating red line is the AGN flux from Ref. \cite{10}. The high-energy dominating blue lines are the blazar contribution to the DGRB for the current (solid), and predictions for the most-optimistic (dashed) and least-optimistic (dotted) 95% CL 5-year Fermi-LAT resolved fractions. The grey lines are the combined 95% CL AGN plus blazar predicted flux for the corresponding blazar contribution. The DGRB data (triangles) are from FS10 and the COMPTEL data (diamonds) are from Ref. \cite{60}.

FIG. 2. Shown are contours with 68% and 95% confidence level (CL) regions for the parameters of the luminosity scale \( q \) and GLF faint-end index \( \chi^2/\text{DOF} \), \( q \) vs \( \chi^2/\text{DOF} \), and \( \chi^2/\text{DOF} \) vs \( \chi^2/\text{DOF} \). The best-fit value is labeled by the cross.
but... we can do better than just detecting more of the unresolved sources:

we can model them or use other techniques and observables to identify their contribution to the IGRB
Detecting unresolved sources with anisotropies

• diffuse emission that originates from one or more unresolved source populations will contain fluctuations on small angular scales due to variations in the number density of sources in different sky directions

• the amplitude and energy dependence of the anisotropy can reveal the presence of multiple source populations and constrain their properties
Detecting unresolved sources with anisotropies

- diffuse emission that originates from one or more unresolved source populations will contain fluctuations on small angular scales due to variations in the number density of sources in different sky directions

- the amplitude and energy dependence of the anisotropy can reveal the presence of multiple source populations and constrain their properties

Anisotropy is another IGRB observable!!!
Gamma-ray anisotropies from dark matter

gamma rays from DM annihilation and decay in Galactic and extragalactic dark matter structures could imprint small angular scale fluctuations in the diffuse gamma-ray background.

Gamma rays from Galactic DM

before accounting for instrument PSF

after convolving with 0.1° beam

JSG, JCAP 10(2008)040
The angular power spectrum

\[
I(\psi) = \sum_{\ell, m} a_{\ell m} Y_{\ell m}(\psi) \quad C_\ell = \langle |a_{\ell m}|^2 \rangle
\]

- intensity angular power spectrum: \( C_\ell \)
  - indicates \textit{dimensionful} amplitude of anisotropy

- fluctuation angular power spectrum: \( \frac{C_\ell}{\langle I \rangle^2} \)
  - \textit{dimensionless}, independent of intensity normalization
  - amplitude for a single source class is the same in all energy bins (if all members have same energy spectrum)
Angular power spectra of unresolved gamma-ray sources

- The angular power spectrum of many gamma-ray source classes (except dark matter) is dominated by the Poisson (shot noise) component for multipoles greater than ~ 10

- Poisson angular power arises from unclustered point sources and takes the same value at all multipoles

Predicted fluctuation angular power $C_\ell/\langle I \rangle^2$ [sr] at $l = 100$ for a single source class (LARGE UNCERTAINTIES):

- Blazars: $\sim 2\times10^{-4}$
- Starforming galaxies: $\sim 2\times10^{-7}$
- Dark matter: $\sim 1\times10^{-6}$ to $\sim 1\times10^{-4}$
- MSPs: $\sim 0.03$
Angular power spectra of dark matter signals

**Predicted angular power spectrum of DM annihilation**

![Graph showing angular power spectra of DM annihilation](image)

*Fornasa, Zavala, Sanchez-Conde et al. 2012*

- the angular power spectrum of dark matter annihilation and decay falls off faster than Poisson at multipoles above ~ 100

- current measurement uncertainties are too large to identify a dark matter component via scale dependence; may be possible with future measurements

**Predicted angular power spectrum of DM decay**

![Graph showing angular power spectra of DM decay](image)
Anisotropy constraints on dark matter

- small angular scale IGRB anisotropy measured for the first time with the Fermi LAT
- angular power measurement constrains contribution of individual source classes, including DM, to the IGRB intensity

Fluctuation anisotropy energy spectrum

Constraints from best-fit constant fluctuation angular power \((\ell \approx 150)\) measured in the data and foreground-cleaned data

<table>
<thead>
<tr>
<th>Source class</th>
<th>Predicted (C_{100}/\langle I \rangle^2) [sr]</th>
<th>Maximum fraction of IGRB intensity</th>
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<tbody>
<tr>
<td>Blazars</td>
<td>(2 \times 10^{-4})</td>
<td>21%</td>
</tr>
<tr>
<td>Star-forming galaxies</td>
<td>(2 \times 10^{-7})</td>
<td>100%</td>
</tr>
<tr>
<td>Extragalactic dark matter annihilation</td>
<td>(1 \times 10^{-5})</td>
<td>95%</td>
</tr>
<tr>
<td>Galactic dark matter annihilation</td>
<td>(5 \times 10^{-5})</td>
<td>43%</td>
</tr>
<tr>
<td>Millisecond pulsars</td>
<td>(3 \times 10^{-2})</td>
<td>1.7%</td>
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Identifying IGRB contributions

\[
I_{\text{tot}}(E) = I_1(E) + I_2(E)
\]

\[
C_{\ell,\text{tot}}(E) = C_{\ell,1}(E) + C_{\ell,2}(E)
\]

\[
\hat{C}_{\ell,\text{tot}}(E) = \left( \frac{I_1(E)}{I_{\text{tot}}(E)} \right)^2 \hat{C}_{\ell,1} + \left( \frac{I_2(E)}{I_{\text{tot}}(E)} \right)^2 \hat{C}_{\ell,2}
\]

in a two-component IGRB scenario, where the components are uncorrelated, and one component dominates the anisotropy at low energies, features observed in the anisotropy energy spectrum can be used to extract each component's intensity spectrum without a priori assumptions about the shape of the intensity spectra or anisotropy properties!
Separating signals with energy-dependent anisotropy

Table I: Summary of two-component decomposition techniques.

<table>
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<tr>
<th>Method</th>
<th>Observational Signature</th>
<th>Inferred Properties of Components</th>
<th>Intensity Normalization Recovered?</th>
<th>Fluctuation Angular Power Recovered?</th>
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<tr>
<td>Double plateau</td>
<td>Plateaus at both high and low energies observed in anisotropy energy spectrum</td>
<td>One source dominant in anisotropy at low energies, other source dominant at high energies</td>
<td>Yes</td>
<td>Yes</td>
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<td>Low-Anisotropy Plateau</td>
<td>Anisotropy energy spectrum rises from (falls to) a low-anisotropy plateau at low (high) energy</td>
<td>Source that is subdominant in intensity is much more anisotropic than the dominant source</td>
<td>No</td>
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<td>High-Anisotropy Plateau</td>
<td>Anisotropy energy spectrum falls from (rises to) a high-anisotropy plateau at low (high) energy</td>
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<td>Known Zero-Anisotropy Component</td>
<td>None; requires a priori knowledge that one of the two components is isotropic</td>
<td>One source is completely isotropic</td>
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<td>No</td>
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<tr>
<td>Minimum</td>
<td>Minimum observed in the anisotropy energy spectrum</td>
<td>Both source components have comparable intensity and anisotropy such that Eq. 20 is satisfied at some energy</td>
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<td>Yes</td>
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<td>Multiple-ℓ Measurements</td>
<td>Two distinct anisotropy energy spectra can be obtained at two different ℓ</td>
<td>(\hat{C}_\ell) is a function of ℓ for at least one source such that two distinct anisotropy energy spectra can be obtained at different ℓ</td>
<td>Yes</td>
<td>Yes</td>
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Example IGRB decomposition

Example observed intensity spectrum and anisotropy energy spectrum

red = published LAT measurements
black = example scenario for 10 yrs LAT observations

PRELIMINARY
Example IGRB decomposition

Example observed intensity spectrum and anisotropy energy spectrum

Decomposed energy spectra

\[ t_{\text{obs}} = 10 \text{ yrs} \]

red = published LAT measurements
black = example scenario for 10 yrs LAT observations

Hensley, Pavlidou & JSG (in prep)
The IGRB

1. **spectrally**: DM signal must be subdominant since a spectral signature is not obvious in the IGRB energy spectrum

2. **spatially**: signal and backgrounds are mostly isotropic but with potentially different small-scale features

3. **know your backgrounds and impostor signals better**: pinning down contribution from astrophysical sources a major challenge but could significantly improve dark matter sensitivity
The IGRB

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\[1 + 2 = \text{combining spectral and spatial information could allow contributions from multiple components to be disentangled}\]
Summary

• this is an exciting time! searches already reaching interesting regions of parameter space and some targets show hints of a detection!

• search strategies need to be optimized for different dark matter models, targets, and instruments

• complementarity should be an important factor in designing searches and should be taken advantage of wherever possible

• improved angular resolution of future gamma-ray instruments may be key to disentangling a dark matter signal by separating emission regions, associating astrophysical sources, and mapping spatial signatures of a dark matter signal

• combining spectral and spatial features can improve sensitivity to subdominant signals