Uncovering dark matter (and other unresolved source populations) with anisotropies

Jennifer Siegal-Gaskins
CCAPP, Ohio State University

based on
JSG, JCAP, 10, 040 (2008)
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with
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A potential indirect dark matter signal in diffuse emission

- Annihilation of dark matter particles produces gamma-rays, neutrinos, and other standard model particles.
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- Cold dark matter models predict structure down to very small scales, including an abundance of substructure in the halo of the Galaxy.

Springel et al. (Virgo Consortium)
A potential indirect dark matter signal in diffuse emission

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- Cold dark matter models predict structure down to very small scales, including an abundance of substructure in the halo of the Galaxy.
- Few if any subhalos or extragalactic structures will be detectable individually, but collectively could produce a significant flux of diffuse gamma-rays or neutrinos.

JSG 2008
A potential indirect dark matter signal in diffuse emission

- Annihilation of dark matter particles produces gamma-rays, neutrinos, and other standard model particles
- Cold dark matter models predict structure down to very small scales, including an abundance of substructure in the halo of the Galaxy
- Few if any subhalos or extragalactic structures will be detectable individually, but collectively could produce a significant flux of diffuse gamma-rays or neutrinos
- Diffuse gamma-ray emission from unresolved Galactic substructure will be virtually isotropic (on large angular scales), thus in Fermi data will appear as a contribution to the extragalactic gamma-ray background (EGRB)

Galactic DM annihilation flux

Kuhlen, Diemand, & Madau 2008
What is making the large-scale isotropic diffuse emission?

- many astrophysical sources are 
  **guaranteed** to contribute to the diffuse emission, e.g.:
  - blazars
  - star-forming galaxies
  - millisecond pulsars
  - unknown/unconfirmed source classes could also contribute:
    - dark matter
    - ???

the diffuse emission contains a great deal of information about the contributors!
Overview

Using the angular information in the diffuse gamma-ray background to identify dark matter and other source classes

- in addition to the energy spectrum and average intensity, the diffuse background contains angular information
- if the diffuse emission originates from an unresolved source population, rather than from a truly isotropic, smooth source distribution, the diffuse emission will contain fluctuations on small angular scales
- if these fluctuations are different from the fluctuations expected from the Poisson noise due to finite event statistics, we could use these fluctuations to identify the presence of unresolved source populations, such as dark matter
- combining anisotropies with energy information could enable a robust detection of specific source classes, and could extend the sensitivity of current gamma-ray experiments to dark matter signals
The Fermi Gamma-ray Space Telescope

- satellite
- energy range: 100 MeV to a few hundred GeV
- effective area $\sim 10^4 \text{ cm}^2$ (size-limited detector!)
- angular resolution $\sim 0.1 \text{ deg}$ above 10 GeV
- FOV $\sim 2.4 \text{ sr}$
- primarily observes in sky-scanning mode; $\sim 24 \text{ hr per day livetime}$
- excellent charged particle background rejection

Credit: NASA/General Dynamics
The dark matter annihilation signal

- Annihilation of dark matter can produce a variety of potentially detectable particles.
- Gamma-rays and neutrinos point back to source, can map dark matter distribution.

Credit: Sky & Telescope / Gregg Dinderman
The dark matter annihilation signal

- Annihilation of dark matter can produce a variety of potentially detectable particles.
- Gamma-rays and neutrinos point back to source, can map dark matter distribution.
- Spectrum of annihilation products encodes info about intrinsic particle properties.
- Variation in the intensity of the signal along different lines of sight is determined exclusively by the distribution of dark matter.

\[ I(\psi) = \frac{K}{4\pi} \int_{los} ds \, \rho^2(s, \psi) \]

\[ K = \frac{N_\gamma \langle \sigma v \rangle}{2m_\chi^2} \]
Characterizing the anisotropy

- we use the angular power spectrum of intensity fluctuations in units of mean intensity (dimensionless)

\[ \delta I(\psi) = \frac{I(\psi) - \langle I \rangle}{\langle I \rangle} \]

\[ \delta I(\psi) = \sum_{\ell,m} a_{\ell m} Y_{\ell m}(\psi) \]

\[ C_{\ell} = \langle |a_{\ell m}|^2 \rangle \]

- fluctuation power spectra are independent of intensity normalization
- shape of the angular power spectrum is determined exclusively by the source distribution \( \leftrightarrow \) independent of uncertainties in the intensity or energy spectrum of the signal (e.g., unknown properties of the dark matter particle)
- avoids common difficulty of extracting a signal of uncertain amplitude and spectrum from uncertain foregrounds
- avoids different amplitude angular power spectra in different energy bins
- related anisotropy probe: 1-pt flux PDF could be used to test for dark matter signal (Lee et al. 2009, Dodelson et al. 2009, Baxter et al. 2010)
Angular power spectra of unresolved gamma-ray populations

Blazars
Ando, Komatsu, Narumoto & Totani 2007

Starforming Galaxies
Ando & Pavlidou 2009

Extragalactic DM
Ando & Komatsu 2006

Extragalactic DM
Cuoco et al 2008

DM around EG IMBHs
Taoso, Ando, Bertone & Profumo 2008

Galactic subhalos
JSG 2008

Galactic subhalos
Ando 2009

Galactic and EG subhalos
Fornasa, Pieri, Bertone & Branchini 2009

adapted from slide by V. Pavlidou
How to identify source populations with anisotropy?

- The angular power spectrum of the total emission is determined by

1. the fractional contributions of each source class to the intensity
2. the amplitude of their individual angular power spectra

\[ C_{\ell}^{\text{tot}} = f_{\text{EG}}^2 C_{\ell}^{\text{EG}} + f_{\text{DM}}^2 C_{\ell}^{\text{DM}} + 2 f_{\text{EG}} f_{\text{DM}} C_{\ell}^{\text{EG} \times \text{DM}} \]

- Most gamma-ray source classes are effectively uncorrelated (i.e., cross-correlation term is negligible)

- Most gamma-ray source populations produce similarly-shaped, relatively featureless angular power spectra (shot-noise-like), the total angular power spectrum is likely to look shot-noise-like

- Intensity and angular power spectrum (especially amplitude) of each individual source class is uncertain (and may not be independent!)

- How can we break the degeneracy to know which sources are making the total measured anisotropy?

examine the energy dependence!
Energy-dependent anisotropy

blazars

blazars + dark matter

dark matter

JSG & Pavlidou 2009
The anisotropy energy spectrum

- ‘the anisotropy energy spectrum’ = the angular power spectrum of the total measured emission at a fixed angular scale (multipole) as a function of energy:

\[ C_{\ell}^{\text{tot}}(E) = f_A^2(E)C_{\ell}^A + f_B^2(E)C_{\ell}^B + 2f_A(E)f_B(E)C_{\ell}^{A \times B} \]

- the anisotropy energy spectrum of a SINGLE source population is flat in energy as long as the angular distribution (and hence angular power spectrum) of the emission from a single source population is independent of energy.

- how does the anisotropy energy spectrum help?
  - exploits the different energy dependences of the contributions of different source classes to the total measured emission
  - a transition in energy from an angular power spectrum dominated by one source class to one dominated by another will show up as a modulation in the anisotropy energy spectrum
A dark matter feature in the intensity energy spectrum? (or why we need anisotropy too)

what makes up the “total” measured emission?

#1: ref. blazar model w/ DM
#2: alt. blazar model w/o DM

Intensity spectra are degenerate!

- interactions with the extragalactic background light (EBL) may attenuate extragalactic gamma-rays above ~ 10 GeV
- EBL attenuation produces an exponential cutoff in the observed spectrum
- observed blazar spectrum could hide a DM feature!

example isotropic diffuse intensity spectrum

JSG & Pavlidou 2009
The anisotropy energy spectrum at work

neutralino mass = 700 GeV

- 1-sigma errors
- 5 years of Fermi all-sky observation
- 75% of the sky usable
- $N_b/N_s = 10$ !!!!
- error bars blow up at low energies due to angular resolution, at high energies due to lack of photons

Galactic dark matter dominates the intensity above $\sim 20$ GeV, but spectral cut-off is consistent with EBL attenuation of blazars

modulation of anisotropy energy spectrum is easily detected!
Galactic dark matter never dominates the intensity and spectral cut-off is consistent with EBL attenuation of blazars.

- modulations of anisotropy energy spectrum are still strong!

neutralino mass = 80 GeV

- 1-sigma errors
- 5 years of Fermi all-sky observation
- 75% of the sky usable
- $N_b/N_s = 10$ !!!!
- error bars blow up at low energies due to angular resolution, at high energies due to lack of photons
we assume the large-scale isotropic diffuse (IGRB) is composed primarily of emission from blazars and dark matter

we fix the anisotropy properties of both populations, fix the blazar emission to a reference model, and vary the dark matter model parameters (mass, cross-section, annihilation channel)

we define a simple, ‘model-independent’ test criterion:

is the anisotropy energy spectrum at $E \geq 0.5$ GeV consistent with a constant value, equal to the weighted average of all energy bins?

dark matter model is considered detectable if this hypothesis is rejected by a $\chi^2$ test at the 95% CL level

NB: this test is not optimized to find specific dark matter models; tailored likelihood analysis could significantly improve sensitivity!

Hensley, JSG, & Pavlidou (2009)
Blazar and dark matter intensity spectra

reference blazar intensity spectrum

dark matter annihilation spectra
Sensitivity of the anisotropy energy spectrum

- DM produces a detectable feature in the anisotropy energy spectrum for a substantial region of parameter space in this scenario
- technique could probe cross-sections below thermal; extends the reach of current indirect searches
- NB: this test is highly sensitive to choice of test parameters (multipole, energy binning) and assumed dark matter and blazar angular power spectra amplitudes!

Hensley, JSG, & Pavlidou (2009)

dark matter models above the curves are detectable by this test!
Comparison of DM and blazar intensities

annihilation cross-section below which dark matter is subdominant in intensity at all $E > 0.5$ GeV (SOLID); 5-yr sensitivity curves (DASHED)

dark matter intensity is subdominant relative to blazar intensity for a large region of detectable dark matter parameter space

Hensley, JSG, & Pavlidou (2009)
Dependence on blazar model parameters

- shaded bands represent uncertainty from varying blazar spectral params within 1-sigma of their max likelihood values
- uncertainty in blazar spectrum impacts test sensitivity negligibly
- reducing blazar normalization increases DM detectability (but two-component scenario less plausible for small blazar normalizations)

Hensley, JSG, & Pavlidou (2009)

dark matter models above the curves are detectable by this test!
Summary

- A modulation in the anisotropy energy spectrum robustly indicates a transition in energy in the spatial distribution of contributing source population(s).

- Combining anisotropy and energy information can enable the detection of unresolved source populations that are subdominant in the intensity, such as dark matter, without requiring a firm prediction for the expected signal.

- The anisotropy energy spectrum is sensitive to a large parameter space of dark matter models, and could extend the reach of current indirect dark matter searches in gamma-rays.

- The anisotropy energy spectrum could in principle be used to extract the shape of the dark matter intensity spectrum even if the dark matter contribution cannot be disentangled from the intensity spectrum alone.

- Component separation with anisotropies could provide a model-independent way to extract the collective blazar energy spectrum.

- These techniques are generally applicable for unresolved source populations!