Novel techniques for decomposing diffuse backgrounds

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based on
Hensley, Pavlidou, and JSG, arXiv:1210.7239
What is making the diffuse gamma-ray background?

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

Intensity
(GeV photons per cm² per sec per steradian)

10⁻⁸
10⁻⁷
10⁻⁶

Energy (GeV)

0.1
1
10
100

DARK MATTER???
Unknown contributors

BLAZARS
Background accounted for by unresolved AGN

Credit: NASA/DOE/Fermi LAT Collaboration

J. Siegal-Gaskins
What is making the diffuse gamma-ray background?

Expected contribution of source populations to the IGRB

Sum is ~ 60-100% of IGRB intensity (energy-dependent)
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!
The angular power spectrum

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

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

- fluctuation angular power spectrum: \( \frac{C_\ell}{\langle I \rangle^2} \)
  - *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 $\ell = 100$ 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: $\sim 0.03$

Ando, Komatsu, Narumoto & Totani 2007
Fermi LAT anisotropy measurement

Map with default mask applied

- identifying the signal at $155 \leq l \leq 504$ as Poisson angular power $C_P$, best-fit value of $C_P$ is determined

- significant ($>3\sigma$) detection of angular power up to 10 GeV, lower significance power measured at 10-50 GeV

Ackermann et al. [Fermi LAT Collaboration], PRD 85, 083007 (2012)
Energy dependence of anisotropy

Fluctuation anisotropy energy spectrum

- consistent with no energy dependence, but mild or localized energy dependence not excluded
- consistent with all anisotropy contributed by one or more source classes contributing same fractional intensity at all energies considered

Acknowledgments

Ackermann et al. [Fermi LAT Collaboration], PRD 85, 083007 (2012)
Decomposing diffuse emission with anisotropy

assumptions:

• two-component scenario
• uncorrelated components
• each component defined by a single energy spectrum
• one component dominates the intensity at some energy

under these assumptions,

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!

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

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

\[
\hat{C}_{\ell,\text{tot}}(E) = \left( \frac{I_1(E)}{I_{\text{tot}}(E)} \right)^2 \hat{C}_{\ell,1} + \left( \frac{I_2(E)}{I_{\text{tot}}(E)} \right)^2 \hat{C}_{\ell,2}
\]
We also define the fluctuation angular power spectrum determined. We discuss the conditions under which such power spectra of the individual components can also be recovered; in some cases the absolute nor-
ground are both measured with su-
and highlight multiwavelength applications in a population change with energy (e.g., harder sources gular power which is energy dependent because the rel-
di
do variations between the source spectra of individual
| section 110
| page 110

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

\[ I_1 = I_{\text{tot}} \left( \frac{\hat{C}_{\ell,2} \pm \sqrt{\hat{C}_{\ell,1} \hat{C}_{\ell,\text{tot}} + \hat{C}_{\ell,2} \hat{C}_{\ell,\text{tot}} - \hat{C}_{\ell,1} \hat{C}_{\ell,2}}}{\hat{C}_{\ell,1} + \hat{C}_{\ell,2}} \right) \]

\[ I_2 = I_{\text{tot}} \left( \frac{\hat{C}_{\ell,1} \mp \sqrt{\hat{C}_{\ell,1} \hat{C}_{\ell,\text{tot}} + \hat{C}_{\ell,2} \hat{C}_{\ell,\text{tot}} - \hat{C}_{\ell,1} \hat{C}_{\ell,2}}}{\hat{C}_{\ell,1} + \hat{C}_{\ell,2}} \right) \]
Example IGRB decomposition

Example observed intensity spectrum and anisotropy energy spectrum

Hensley, Pavlidou & JSG (in prep)

- infer that one component dominates the intensity at the low plateau and one at the high plateau
- this yields the fluctuation anisotropy of each component; the intensity spectrum of each component can now be solved for

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

Example observed intensity spectrum and anisotropy energy spectrum

Hensley, Pavlidou & JSG (in prep)

Decomposed energy spectra

Double Plateau

$t_{\text{obs}} = 10 \text{ yrs}$

$E^2 I_E [\text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}]$

$C_{175} [\text{sr}]$

$C_{200} [(\text{cm}^2 \text{s}^{-1} \text{sr}^{-1})^2 \text{sr}]$

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

Double Plateau

Broken Power Law

Dark Matter
Example IGRB decomposition

- infer that one component dominates the intensity at the plateau
- at higher energies, the anisotropy falls, indicating that a more isotropic source is making an increasing fractional contribution

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

$$\hat{C}_{\ell,\text{tot}} \approx \left( \frac{I_1}{I_{\text{tot}}} \right)^2 \hat{C}_{\ell,1}.$$
Example IGRB decomposition

Example observed intensity spectrum and anisotropy energy spectrum

Hensley, Pavlidou & JSG (in prep)

Decomposed energy spectra

Hensley, Pavlidou & JSG (in prep)

\[ E^2 I_E \] [GeV cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\)]

\[ C_{175} \] [sr]

\[ C_p \] [cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\)]

Energy [GeV]

\( t_{obs} = 10 \) yrs

\[ \text{red} = \text{published LAT measurements} \]

\[ \text{black} = \text{example scenario for 10 yrs LAT observations} \]
Separating signals with energy-dependent anisotropy

TABLE I: Summary of two-component decomposition techniques.

<table>
<thead>
<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>
</tr>
</thead>
<tbody>
<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>
</tr>
<tr>
<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>
<td>No</td>
</tr>
<tr>
<td>High-Anisotropy Plateau</td>
<td>Anisotropy energy spectrum falls from (rises to) a high-anisotropy plateau at low (high) energy</td>
<td>Source that is subdominant in intensity is much less anisotropic than the dominant source</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<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>
<td>No</td>
<td>No</td>
</tr>
<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>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<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>
</tr>
</tbody>
</table>
Summary

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

• combining the intensity energy spectrum and the anisotropy energy spectrum of diffuse emission can enable individual component spectra to be decomposed without *a priori* assumptions about the component spectral shapes or their anisotropy

• model-independent collective spectra of source populations can reveal important information about the properties of the source class

• a model-independent measurement of the dark matter annihilation or decay spectrum can yield information about the dark matter mass, dominant annihilation or decay modes, and annihilation or decay rate
Additional slides
Angular power spectra of dark matter signals

**Predicted angular power spectrum of DM annihilation**

- The angular power spectrum of dark matter annihilation and decay falls off faster than Poisson at multipoles above \( \sim 100 \)

- 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**

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J. Siegal-Gaskins

4th Fermi Symposium, October 31, 2012
Energy-dependent anisotropy

example patches of sky showing intensity fluctuations in units of the mean intensity

blazars

blazars + dark matter

dark matter

JSG & Pavlidou 2009