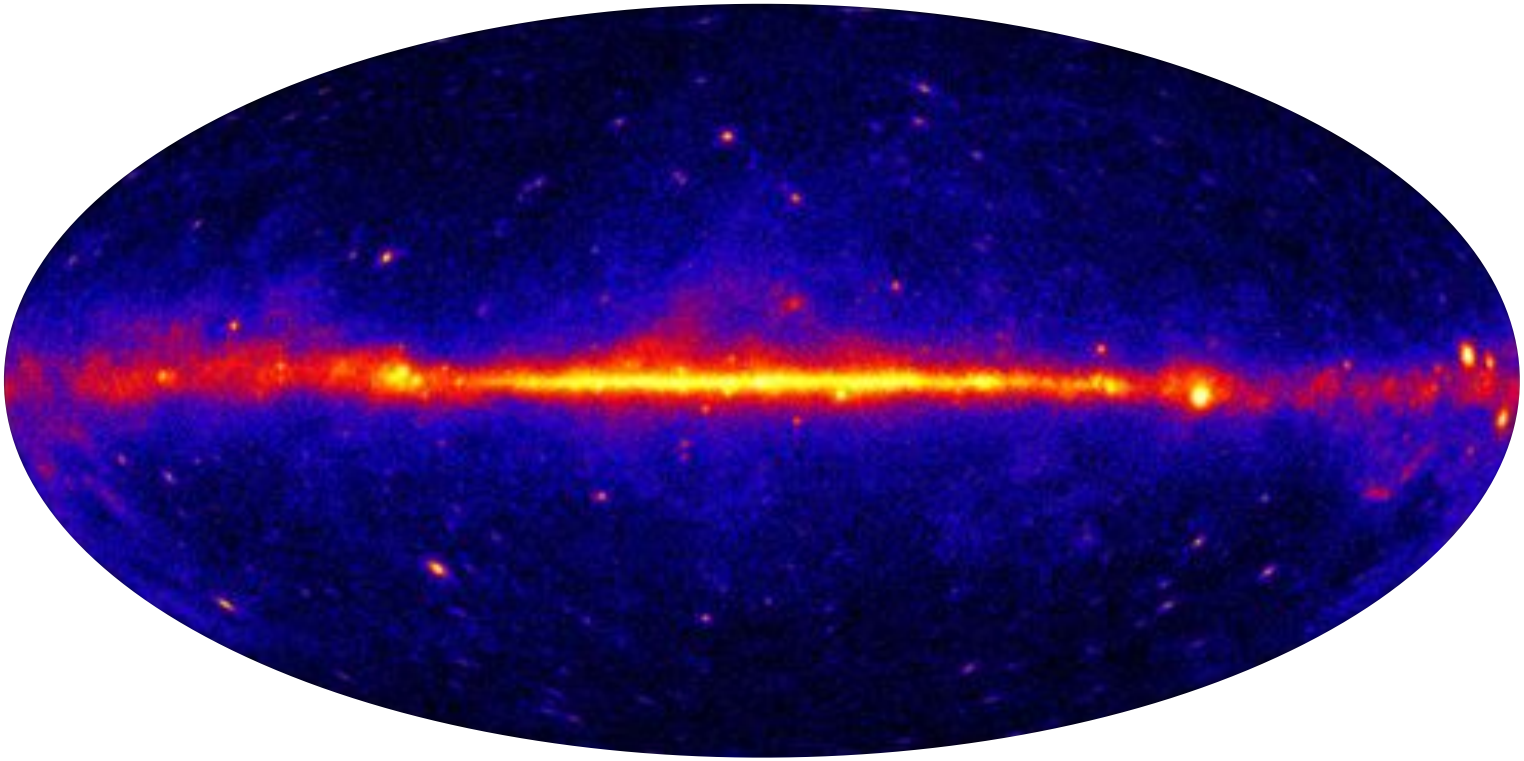
Novel techniques for decomposing diffuse backgrounds



Jennifer Siegal-Gaskins

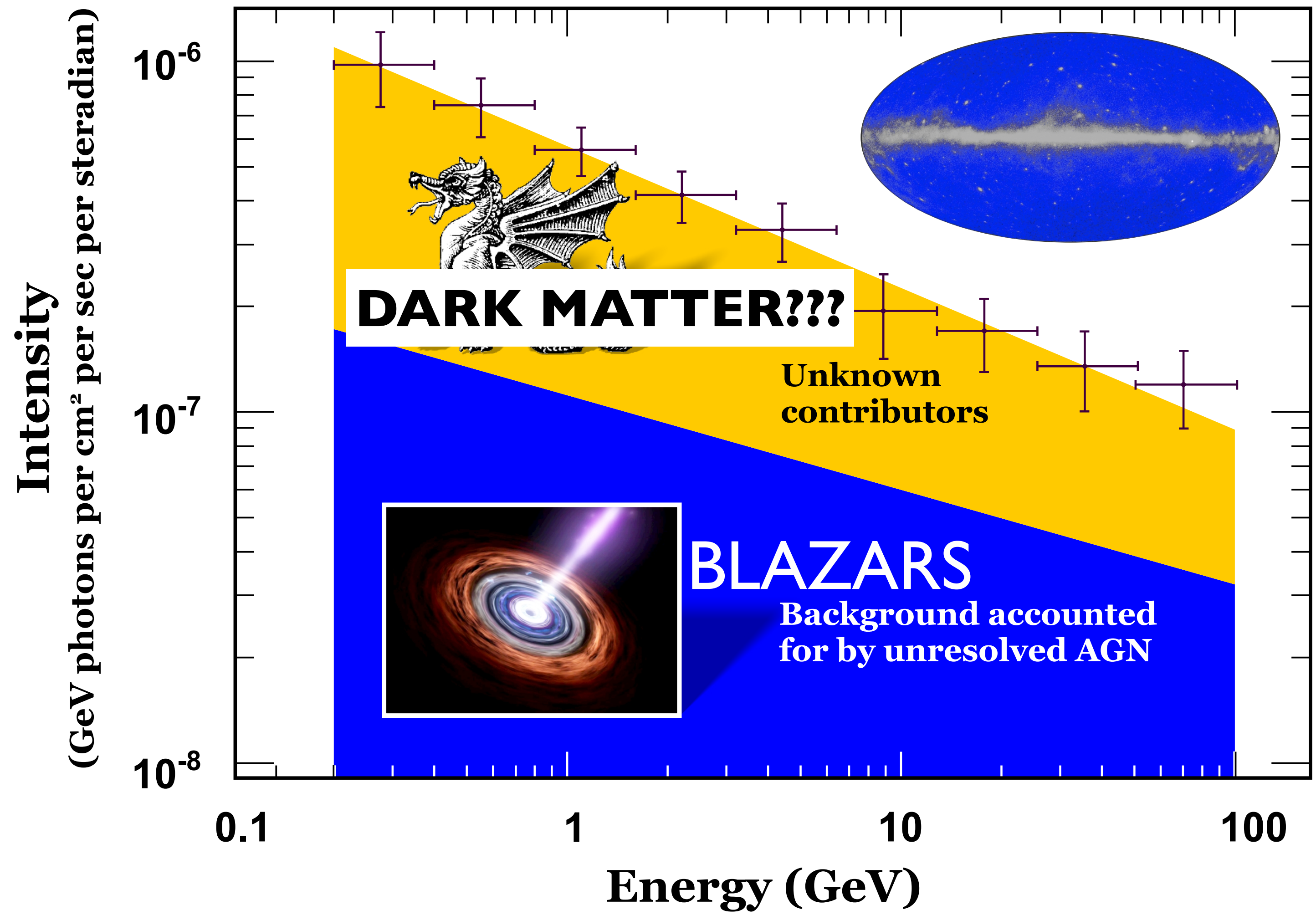
Caltech

based on

Hensley, Pavlidou, and JSG, arXiv:1210.7239

What is making the diffuse gamma-ray background?

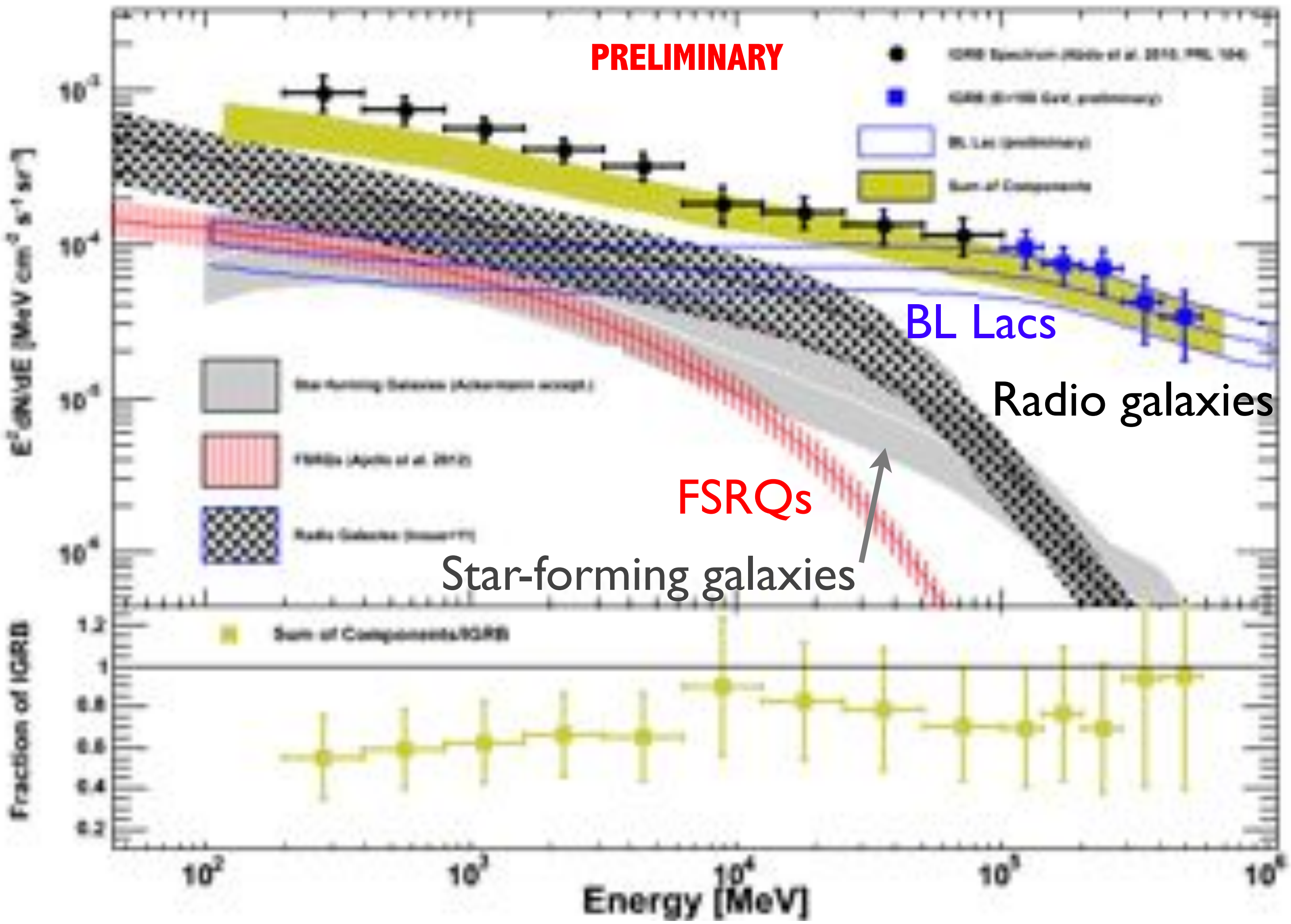
Energy spectrum of the Fermi-LAT
isotropic gamma-ray background (IGRB)



Credit: NASA/DOE/Fermi LAT Collaboration

What is making the diffuse gamma-ray background?

Expected contribution of source populations to the IGRB



Sum is ~ 60-100% 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

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

- intensity angular power spectrum: C_ℓ
  - indicates *dimensionful* amplitude of anisotropy
- fluctuation angular power spectrum: $\dfrac{C_\ell}{\langle I \rangle^2}$
  - *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)

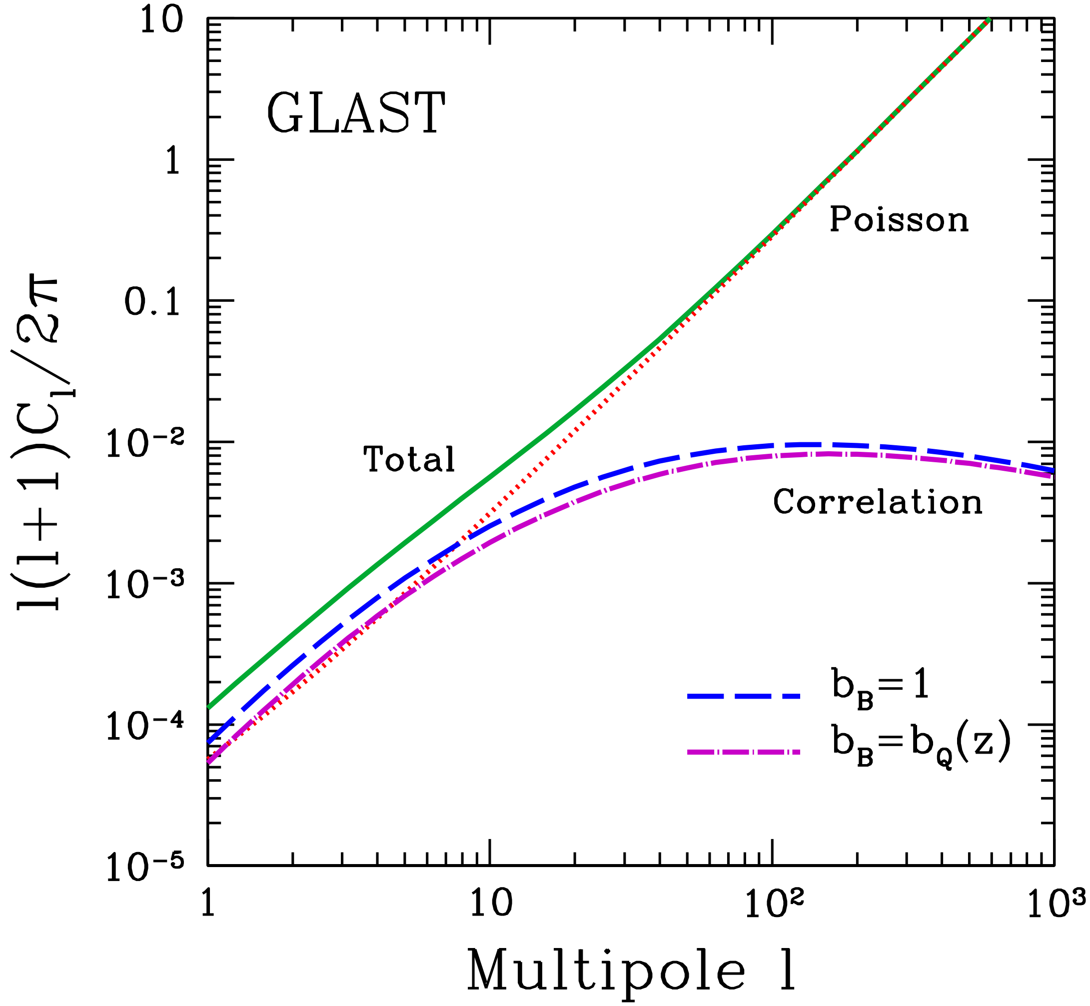
Angular power spectra of unresolved gamma-ray sources

- 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 <u>takes the same value at all multipoles</u>

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

- blazars: ~ 2e-4
- starforming galaxies: ~ 2e-7
- dark matter: ~ 1e-6 to ~ 1e-4
- MSPs: ~ 0.03

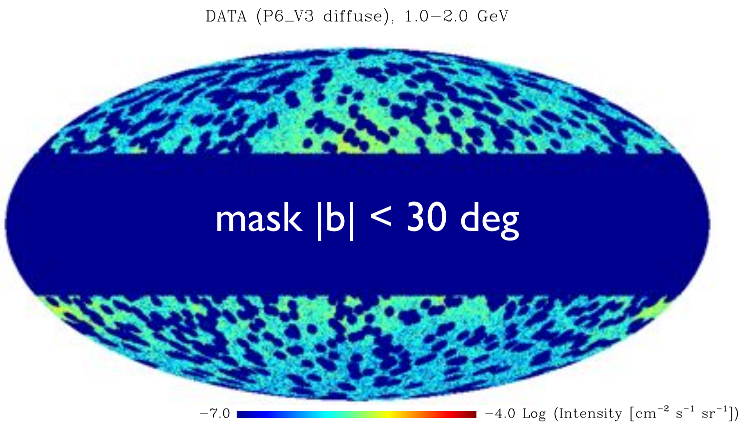
Predicted angular power spectrum of unresolved blazars



Ando, Komatsu, Narumoto & Totani 2007

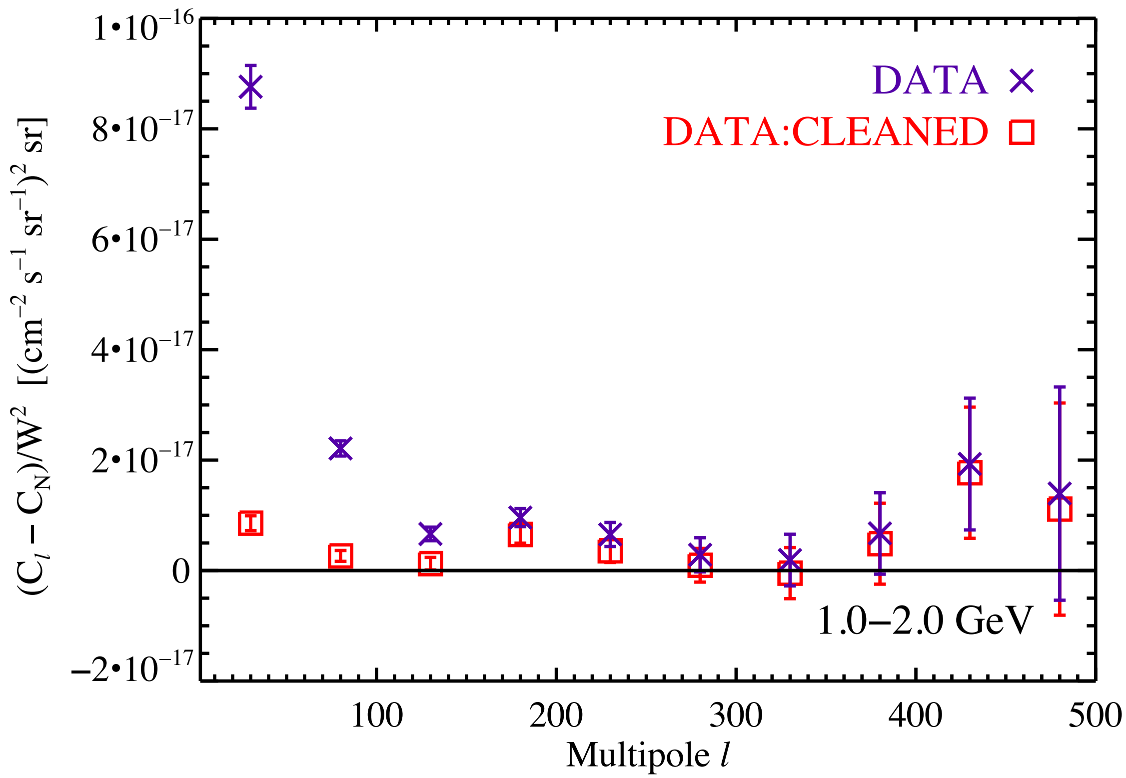
Fermi LAT anisotropy measurement

Map with default mask applied



intensity angular power spectrum

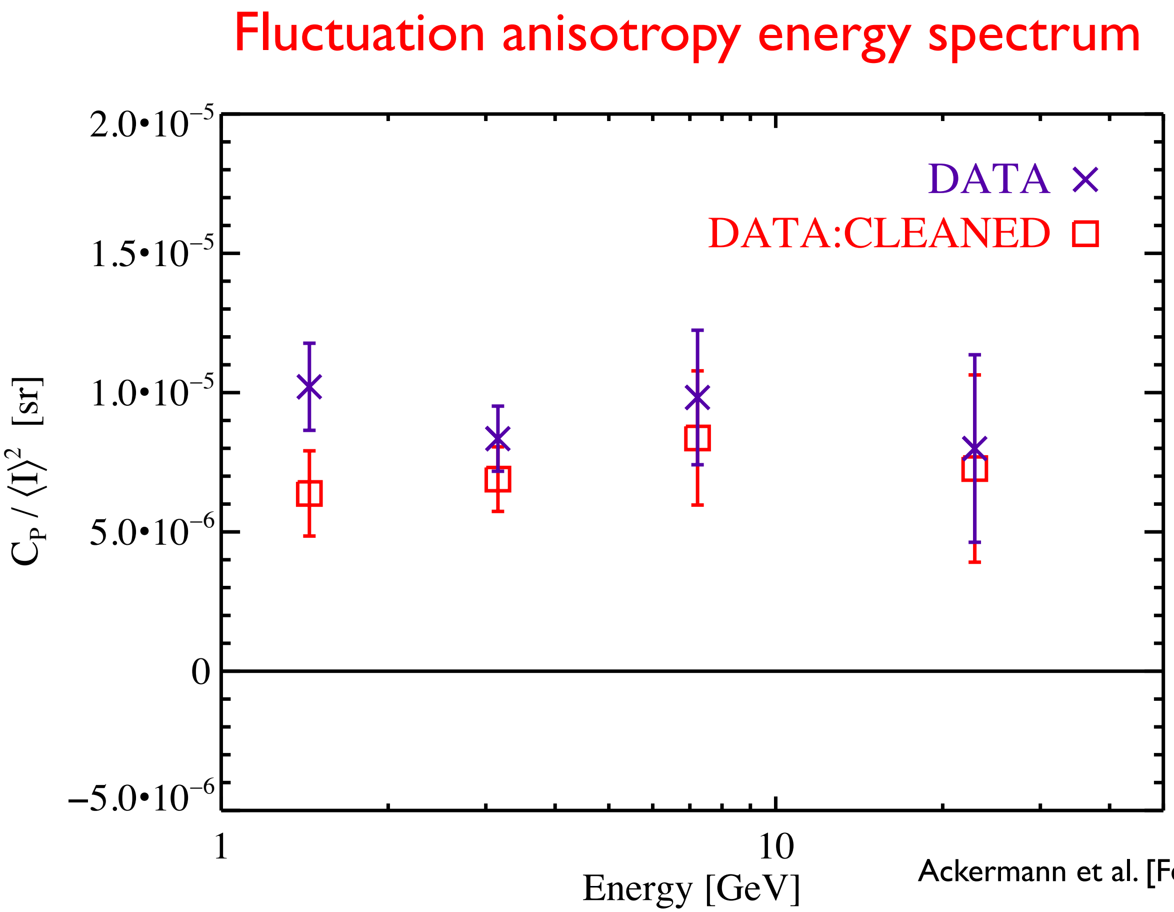
DATA:CLEANED = DATA - Galactic diffuse model



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

- identifying the signal at $155 \leq l \leq 504$ as Poisson angular power C_P, best-fit value of C_P is determined
- significant (>3σ) detection of angular power up to 10 GeV, lower significance power measured at 10-50 GeV

Energy dependence of anisotropy



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

- 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

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

observables

model parameters

$$I_{\rm tot}(E) = I_1(E) + I_2(E)$$

$$C_{\ell,{\rm tot}}(E) = C_{\ell,1}(E) + C_{\ell,2}(E)$$

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

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!*

The magic of algebra!

$$I_{\mathrm{tot}}(E) = I_1(E) + I_2(E)$$

+

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

$$\downarrow$$

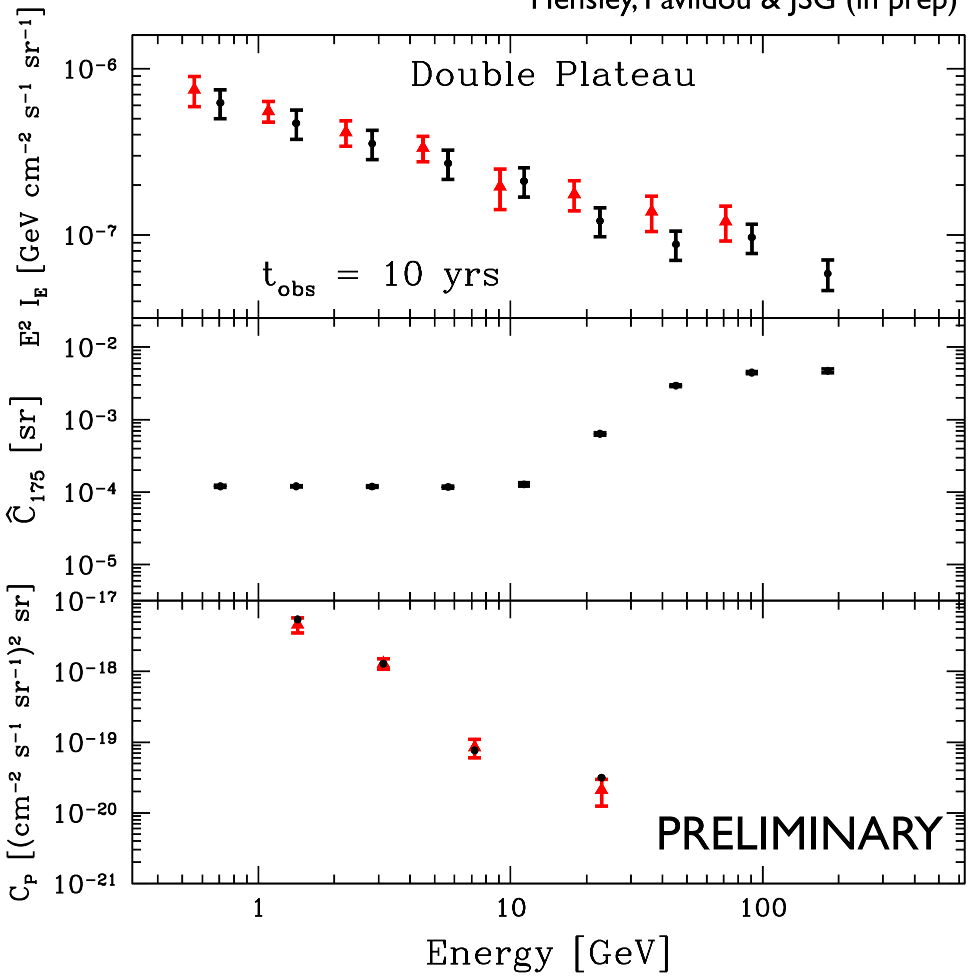
$$I_1 = I_{\mathrm{tot}} \left(\frac{\hat{C}_{\ell,2} \pm \sqrt{\hat{C}_{\ell,1}\hat{C}_{\ell,\mathrm{tot}} + \hat{C}_{\ell,2}\hat{C}_{\ell,\mathrm{tot}} - \hat{C}_{\ell,1}\hat{C}_{\ell,2}}}{\hat{C}_{\ell,1} + \hat{C}_{\ell,2}}\right)$$

$$I_2 = I_{\mathrm{tot}} \left(\frac{\hat{C}_{\ell,1} \mp \sqrt{\hat{C}_{\ell,1}\hat{C}_{\ell,\mathrm{tot}} + \hat{C}_{\ell,2}\hat{C}_{\ell,\mathrm{tot}} - \hat{C}_{\ell,1}\hat{C}_{\ell,2}}}{\hat{C}_{\ell,1} + \hat{C}_{\ell,2}}\right)$$

Example IGRB decomposition

Example observed intensity spectrum and anisotropy energy spectrum

Hensley, Pavlidou & JSG (in prep)



red = published LAT measurements

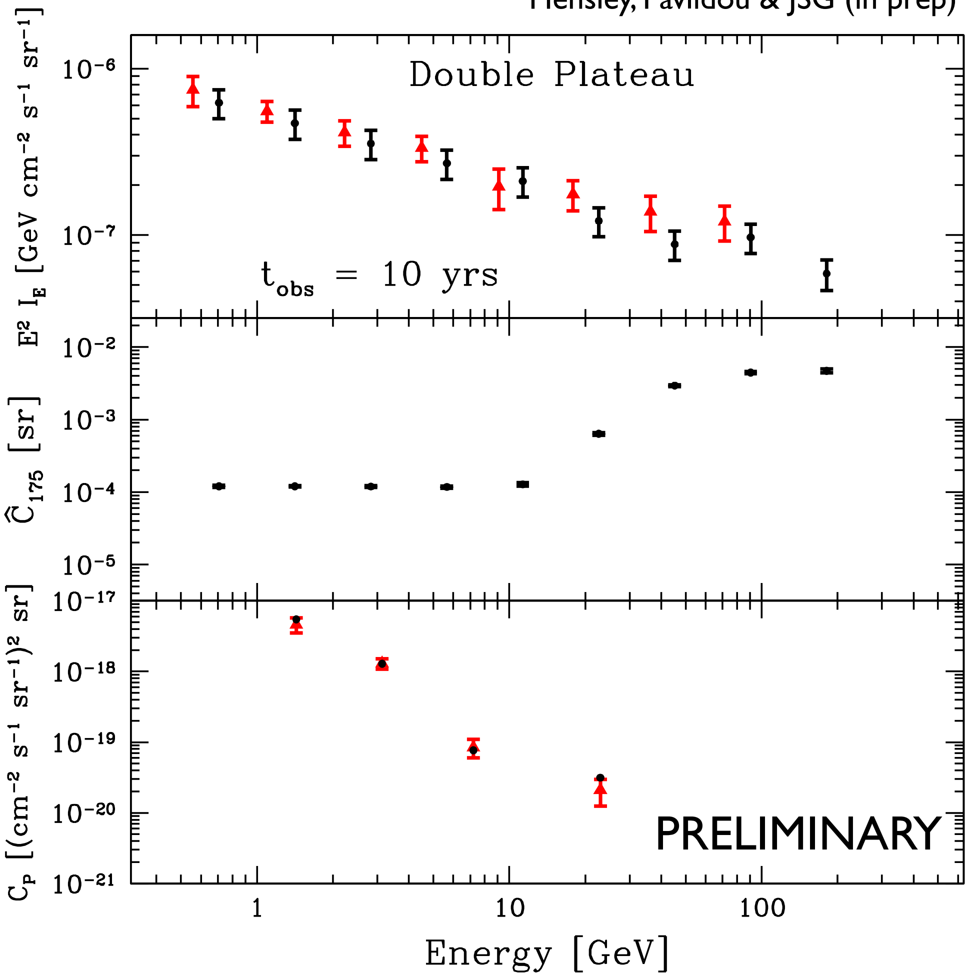
black = example scenario for 10 yrs LAT observations

- 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

Example IGRB decomposition

Example observed intensity spectrum and anisotropy energy spectrum

Hensley, Pavlidou & JSG (in prep)



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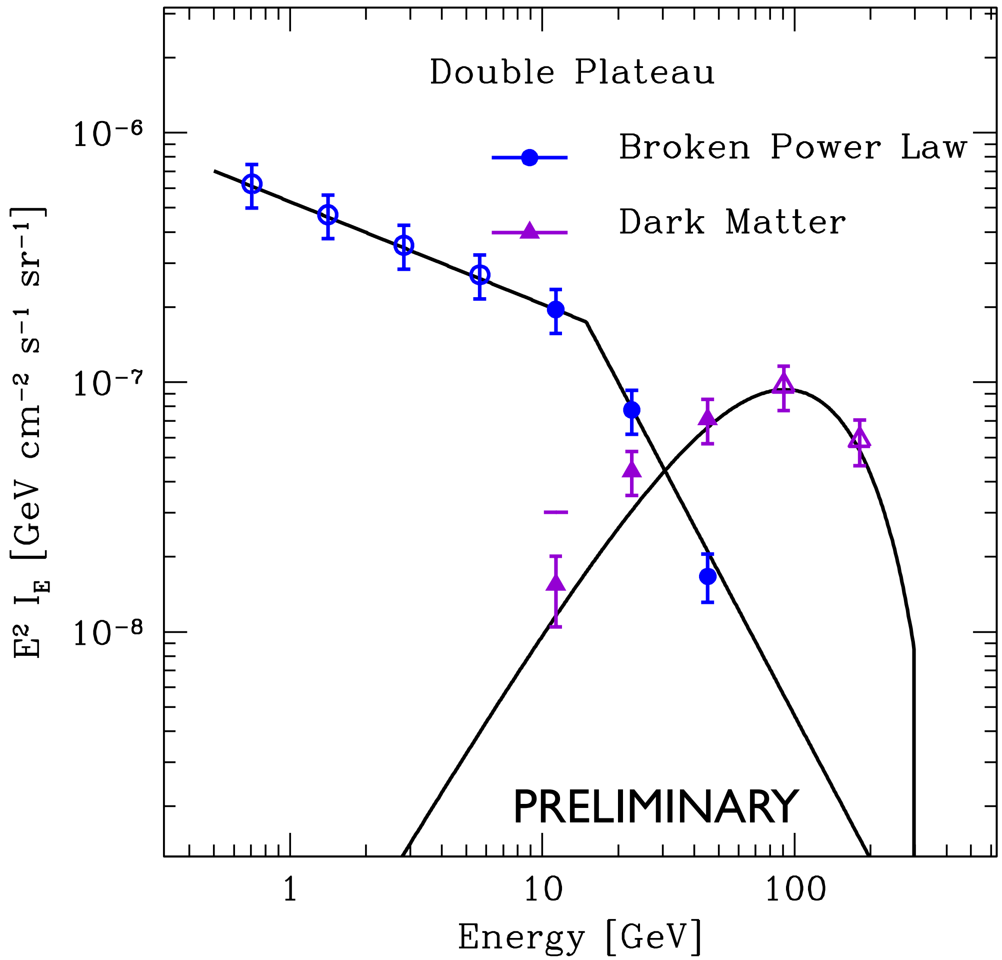
Decomposed energy spectra



Example IGRB decomposition

Example observed intensity spectrum and anisotropy energy spectrum

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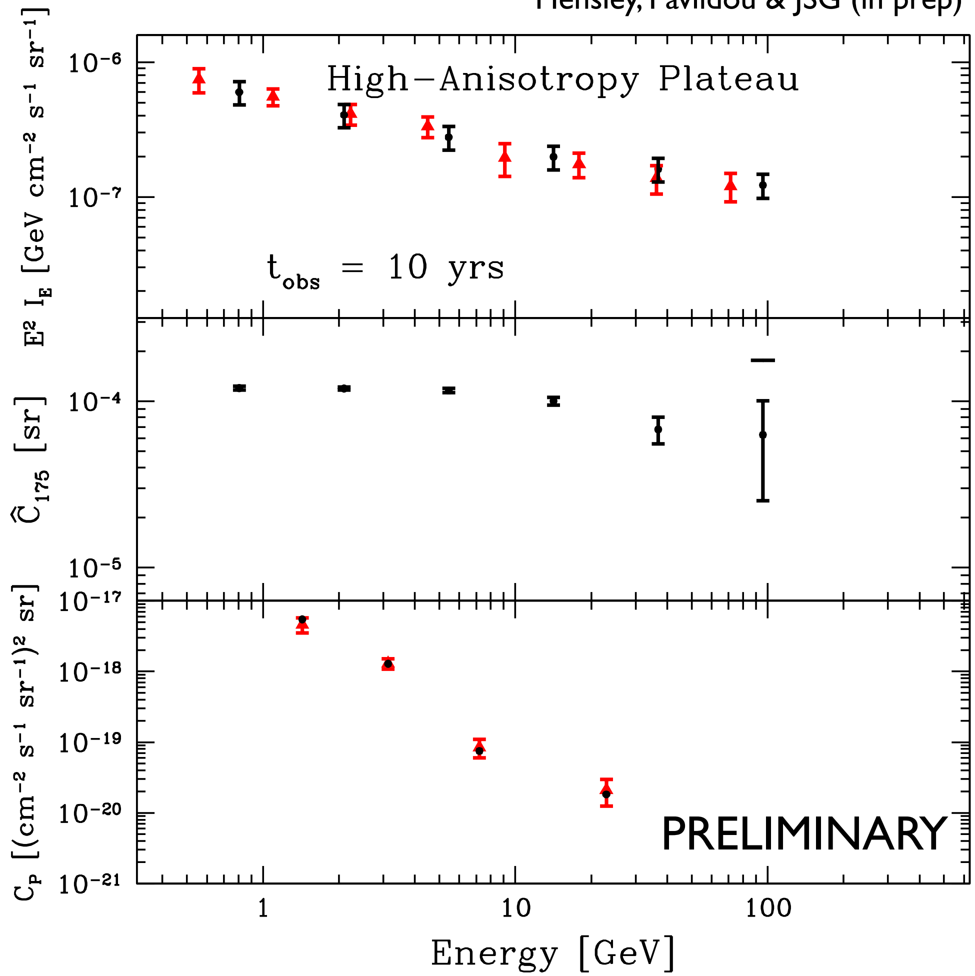


red = published LAT measurements

black = example scenario for 10 yrs LAT observations

- 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

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

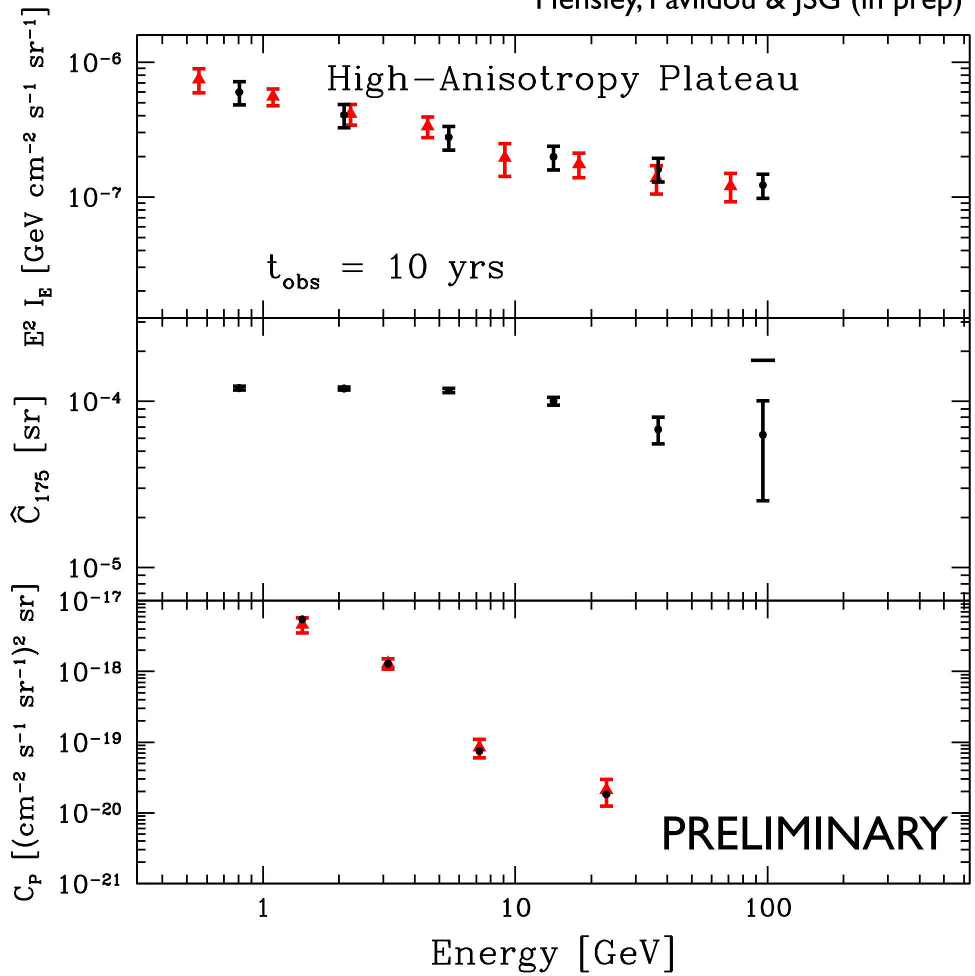
$$\hat{C}_{\ell,\mathrm{tot}} \approx \left(\frac{I_1}{I_{\mathrm{tot}}}\right)^2 \hat{C}_{\ell,1}$$

$$I_1 \approx I_{\mathrm{tot}}\sqrt{\frac{\hat{C}_{\ell,\mathrm{tot}}}{\hat{C}_{\ell,1}}} \qquad I_2 \approx I_{\mathrm{tot}}\left(1 - \sqrt{\frac{\hat{C}_{\ell,\mathrm{tot}}}{\hat{C}_{\ell,1}}}\right)$$

Example IGRB decomposition

Example observed intensity spectrum and anisotropy energy spectrum

Hensley, Pavlidou & JSG (in prep)



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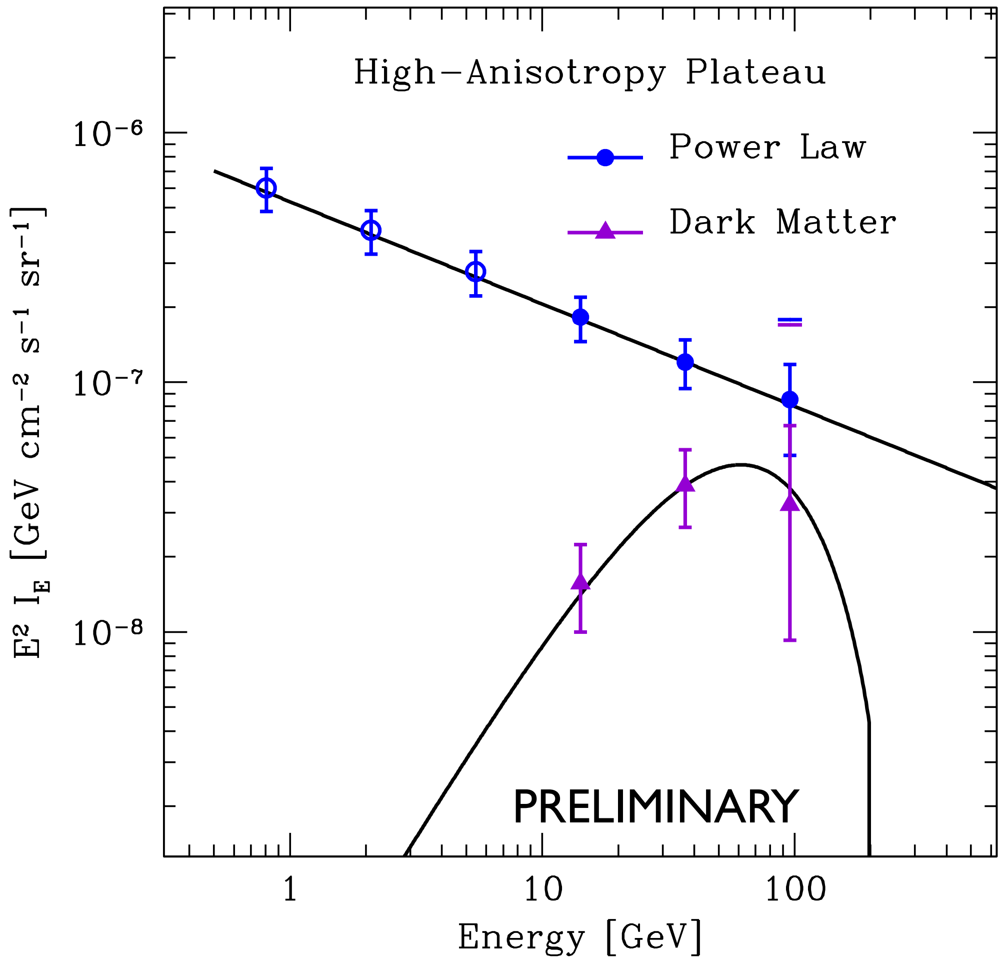
Decomposed energy spectra



Separating signals with energy-dependent anisotropy

TABLE I: Summary of two-component decomposition techniques.

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

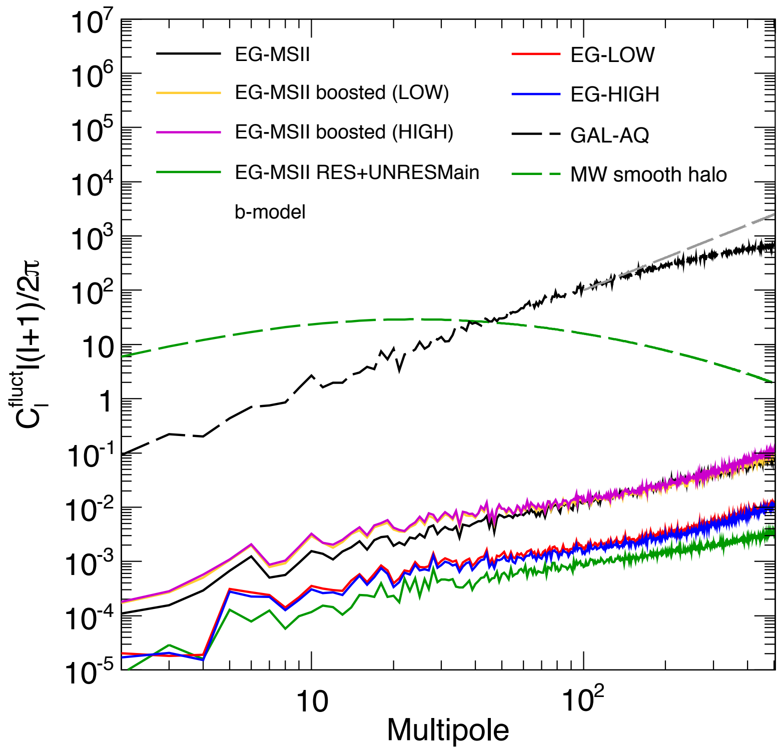
Summary

- 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

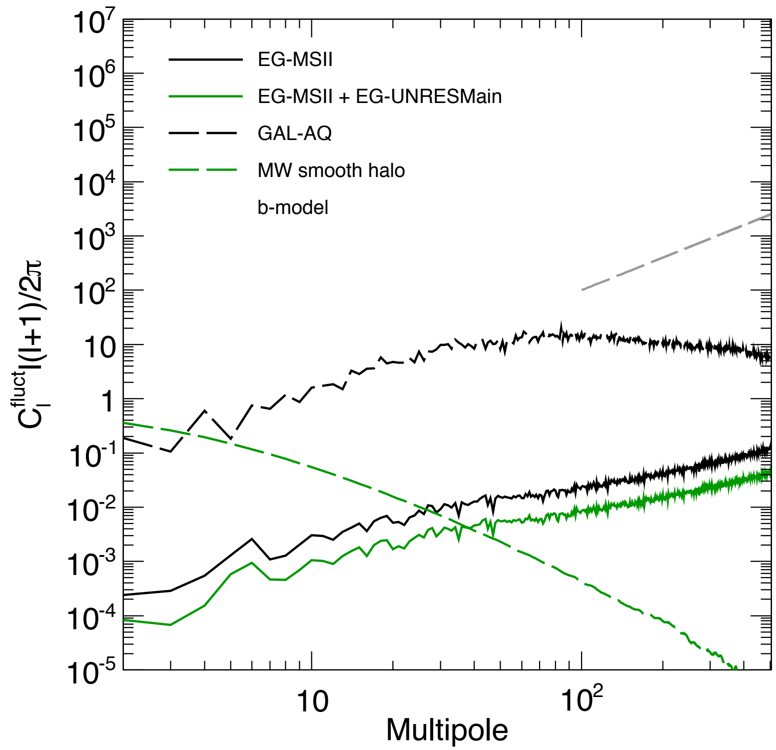
Additional slides

Angular power spectra of dark matter signals

Predicted angular power spectrum of DM annihilation



Predicted angular power spectrum of DM decay

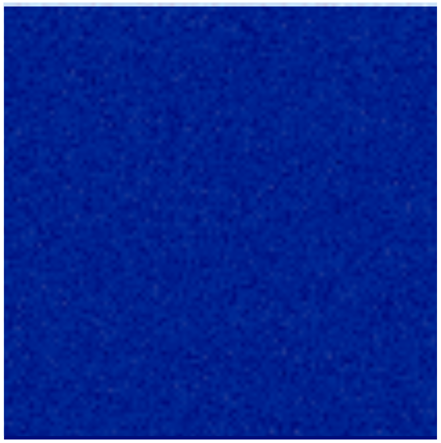


Fornasa, Zavala, Sanchez-Conde et al. 2012

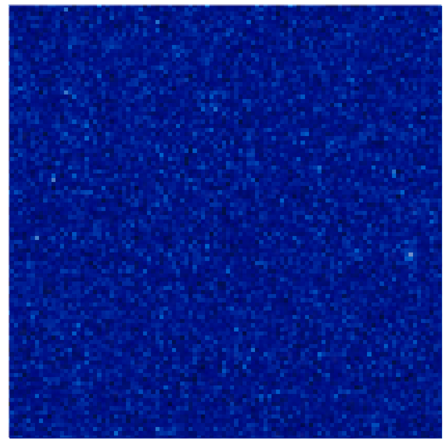
- the angular power spectrum of dark matter annihilation and decay falls off faster than Poisson at multipoles above ~ 100
- current measurement uncertainties are too large to identify a dark matter component via scale dependence; may be possible with future measurements

Energy-dependent anisotropy

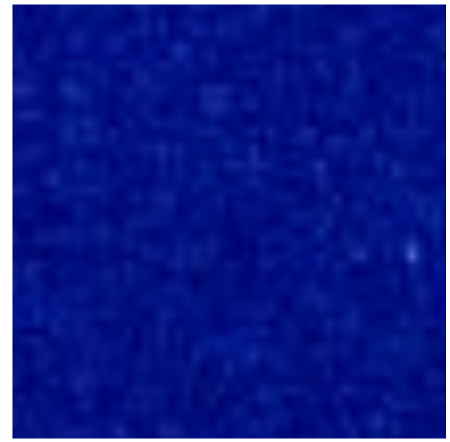
example patches of sky showing intensity fluctuations in units of the mean intensity



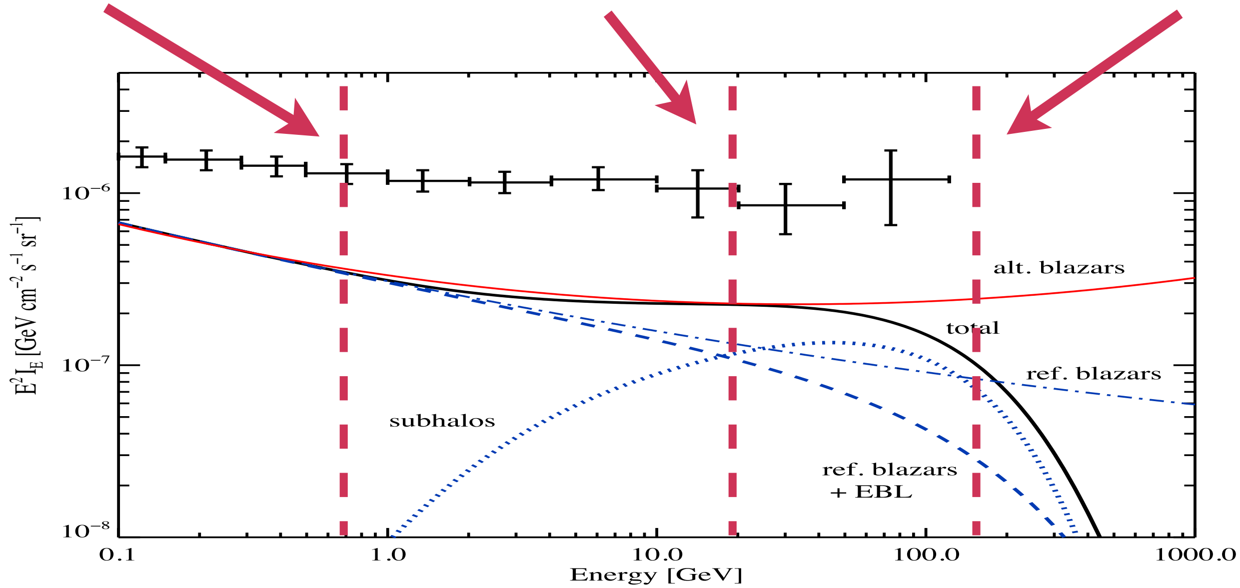
blazars



blazars + dark matter



dark matter



JSG & Pavlidou 2009