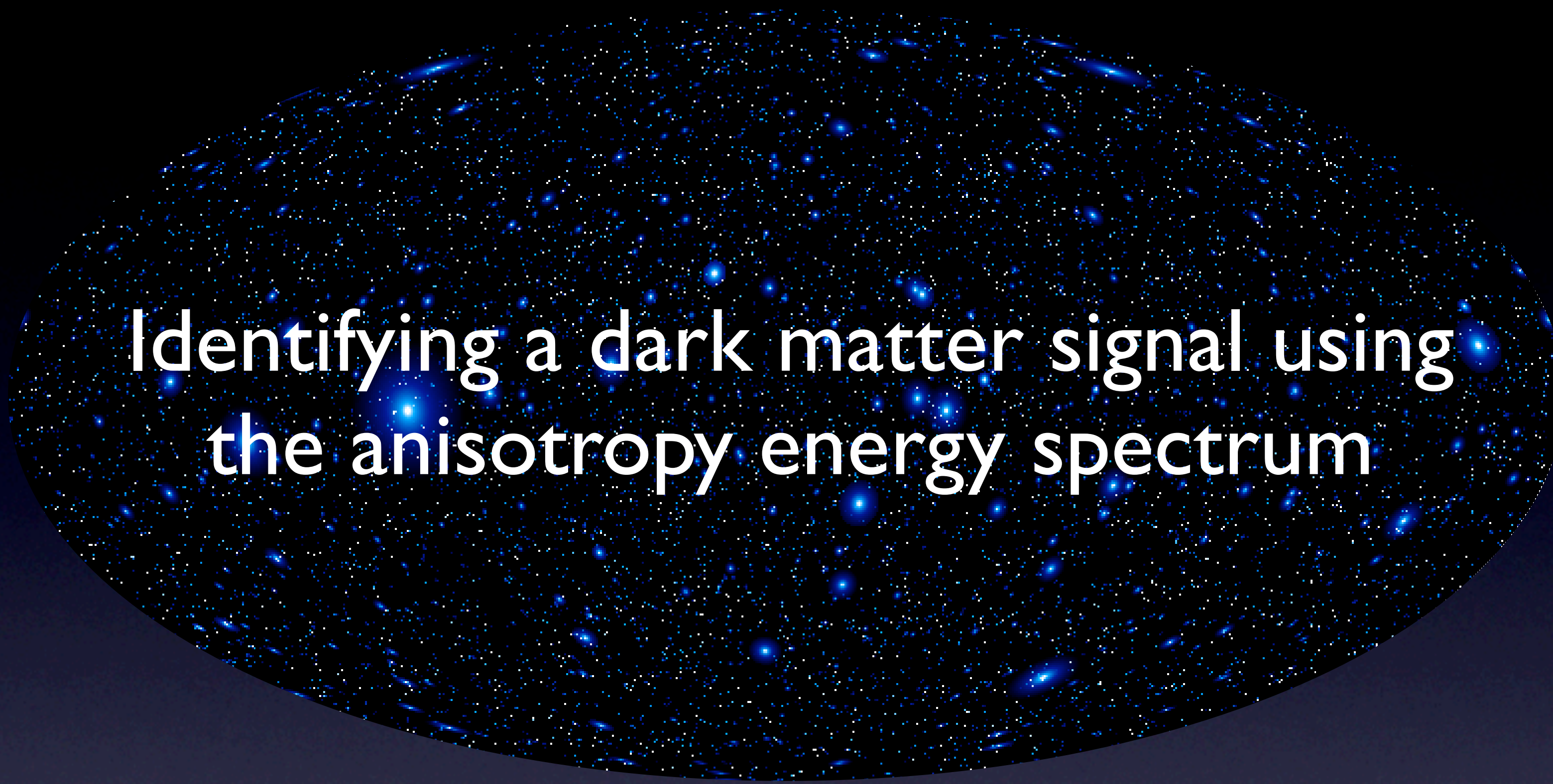
Identifying a dark matter signal using the anisotropy energy spectrum



Jennifer Siegal-Gaskins

CCAPP, Ohio State University

based on
JSG & Pavlidou, PRL, 102, 241301 (2009); arXiv:0901.3776

Identifying a dark matter signal using the anisotropy energy spectrum

Jennifer Siegal-Gaskins

CCAPP, Ohio State University

based on
JSG & Pavlidou, PRL, 102, 241301 (2009); arXiv:0901.3776

Diffuse gamma-rays from Galactic dark matter

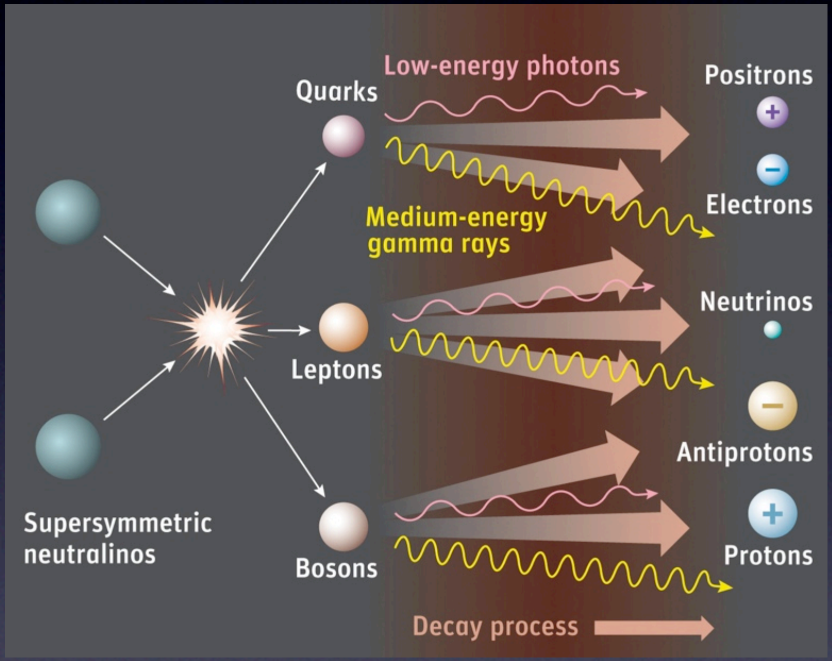
Diffuse gamma-rays from Galactic dark matter

- cold dark matter models predict an abundance of substructure in the halo of the Galaxy

Springel et al. (Virgo Consortium)

Diffuse gamma-rays from Galactic dark matter

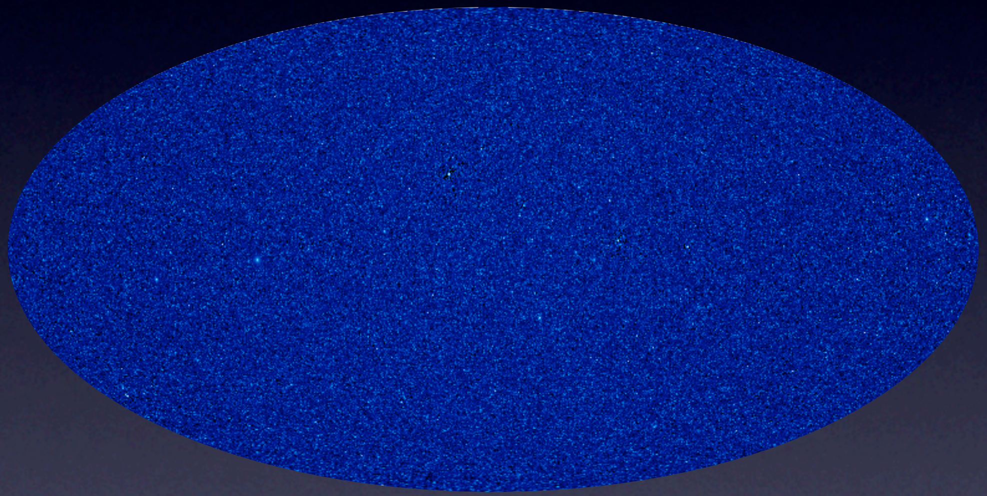
- cold dark matter models predict an abundance of substructure in the halo of the Galaxy
- annihilation of dark matter particles produces gamma-rays which could be detected by Fermi (formerly GLAST)



Credit: Sky & Telescope / Gregg Dinderman

Diffuse gamma-rays from Galactic dark matter

- cold dark matter models predict an abundance of substructure in the halo of the Galaxy
- annihilation of dark matter particles produces gamma-rays which could be detected by Fermi (formerly GLAST)
- few if any subhalos will be detectable individually, but collectively Galactic substructure will produce a significant flux of diffuse gamma-rays

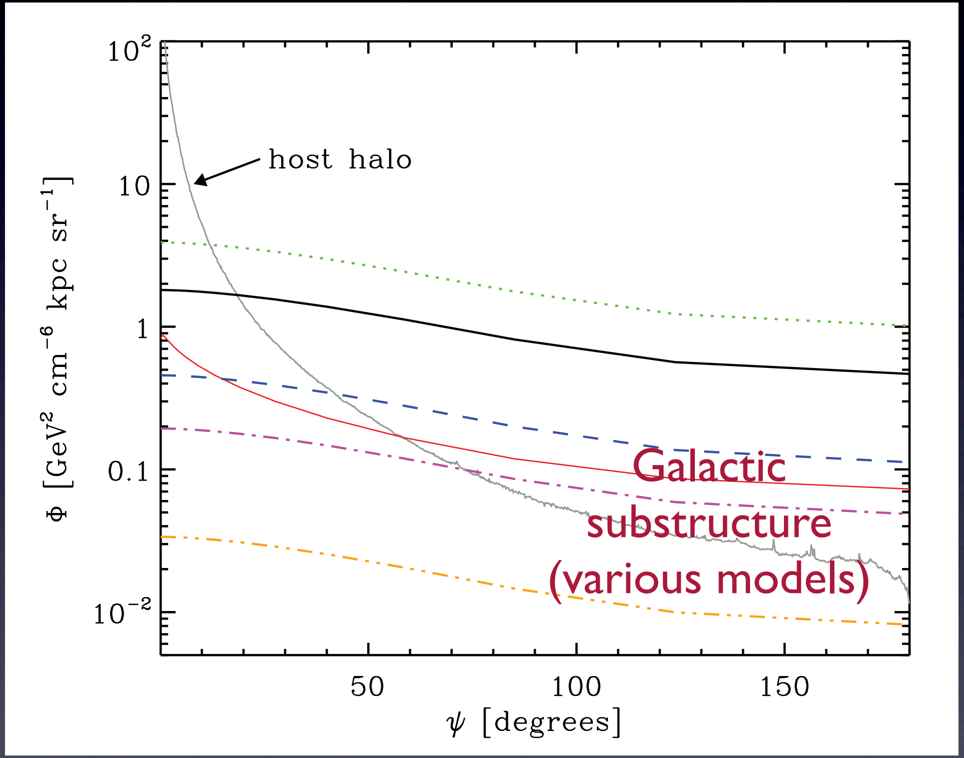


JSG 2008

Diffuse gamma-rays from Galactic dark matter

- cold dark matter models predict an abundance of substructure in the halo of the Galaxy
- annihilation of dark matter particles produces gamma-rays which could be detected by Fermi (formerly GLAST)
- few if any subhalos will be detectable individually, but collectively Galactic substructure will produce a significant flux of diffuse gamma-rays
- diffuse 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

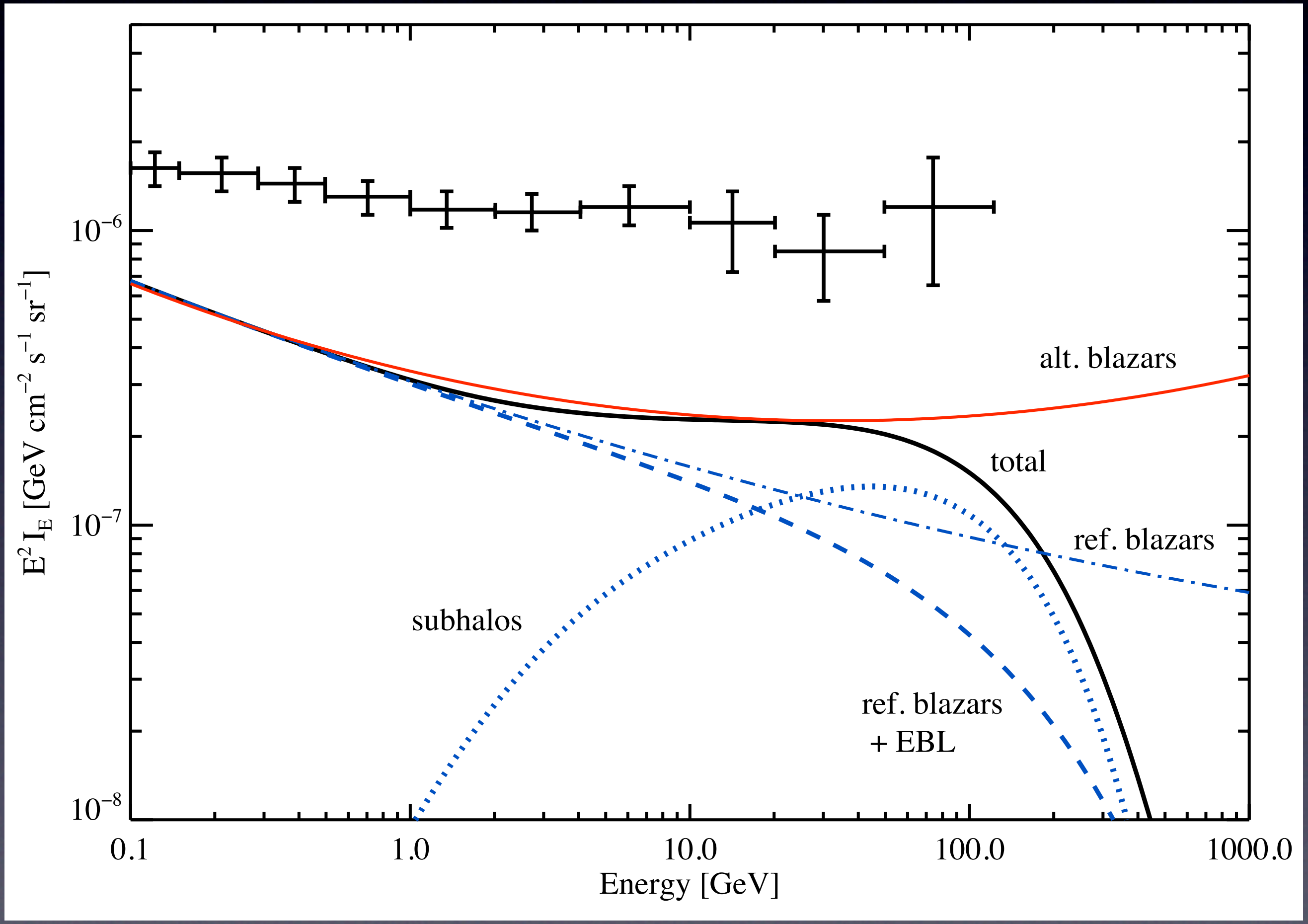
The intensity energy spectrum
(or why we need anisotropy too)

what contributes to the "total" measured emission?

interactions with the extragalactic background light (EBL) may substantially attenuate extragalactic gamma-rays above ~ 10 GeV, producing an exponential cutoff in the observed spectrum

#1: ref. blazar model w/ DM
#2: alt. blazar model w/o DM
intensity spectra are degenerate!

example isotropic diffuse intensity spectrum



JSG & Pavlidou 2009

Using anisotropy to find the dark matter signal

- the angular power spectrum: characterizes intensity fluctuations as a function of angular scale

$$C_\ell \text{ vs. } \ell$$

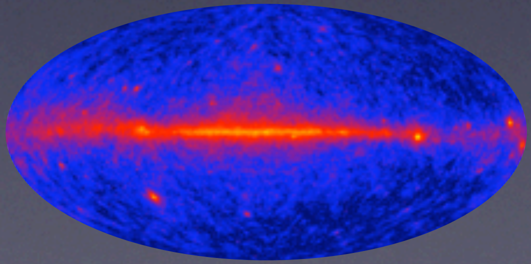
- the intensity energy spectrum: intensity as a function of energy

$$I \text{ vs. } E$$

- the anisotropy energy spectrum: characterizes intensity fluctuations at a *fixed* angular scale as a function of energy

$$C_\ell \text{ vs. } E$$
$$(\text{at a fixed } \ell)$$

- large-scale angular distribution: tests whether emission is correlated with Galactic structures



Credit: NASA/DOE/International LAT Team

The total angular power spectrum

- the total measured 'isotropic' diffuse emission has contributions from multiple source classes

- 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

$$C_\ell^{\mathrm{tot}} = f_{\mathrm{EG}}^2 C_\ell^{\mathrm{EG}} + f_{\mathrm{DM}}^2 C_\ell^{\mathrm{DM}} + 2 f_{\mathrm{EG}} f_{\mathrm{DM}} C_\ell^{\mathrm{EG}\times\mathrm{DM}}$$

$$\delta I(\psi) \equiv \frac{I(\psi) - \langle I \rangle}{\langle I \rangle} \Rightarrow \delta I(\psi) = \sum_{\ell,m} a_{\ell m} Y_{\ell m}(\psi) \Rightarrow C_\ell = \langle\, |a_{\ell m}|^2 \rangle$$

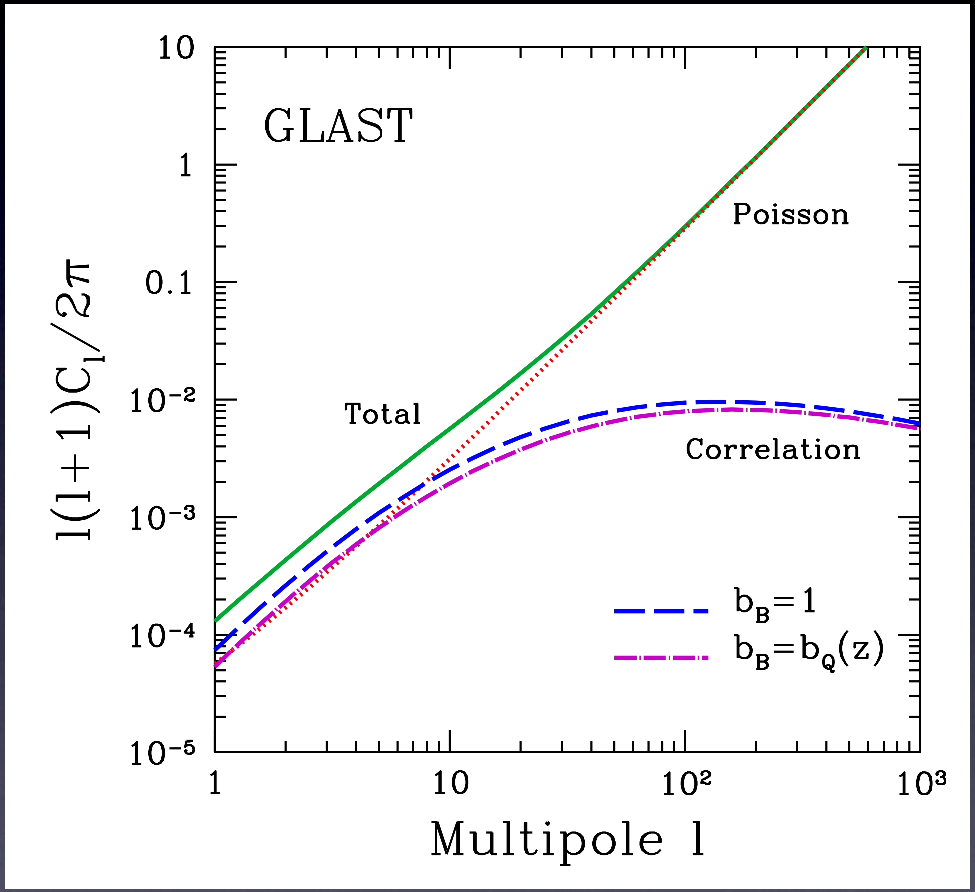
- predictions exist for the angular power spectrum of
  - extragalactic source classes, including unresolved blazars and extragalactic dark matter (e.g., Ando & Komatsu 2006, Ando et al. 2007 x 2, Miniati et al. 2007, Cuoco et al. 2008, Taoso et al. 2008, Fornasa et al. 2009)
  - Galactic dark matter (JSG 2008, Fornasa et al. 2009, Ando 2009)

The angular power spectrum of diffuse gamma-ray emission

The angular power spectrum of diffuse gamma-ray emission

- unresolved blazars are typically the dominant contributor to the angular power spectrum over other extragalactic source classes for $\ell \gtrsim 100$

angular power spectrum from unresolved blazars



Ando et al. 2007

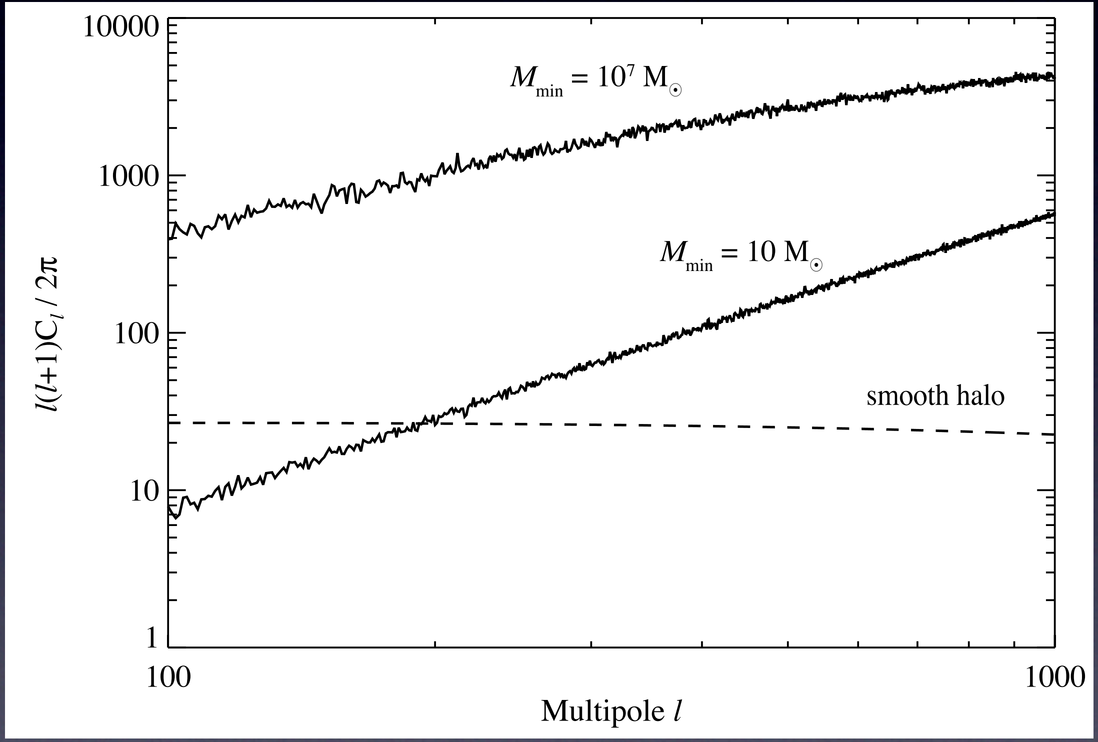
NB: normalization is for each individual source class, relative contribution to total power spectrum depends on relative intensities!

The angular power spectrum of diffuse gamma-ray emission

- unresolved blazars are typically the dominant contributor to the angular power spectrum over other extragalactic source classes for $\ell \gtrsim 100$

- Galactic dark matter substructure generally produces a much higher amplitude angular power spectrum than extragalactic source classes

angular power spectrum from Galactic substructure



JSG 2008

NB: normalization is for each individual source class, relative contribution to total power spectrum depends on relative intensities!

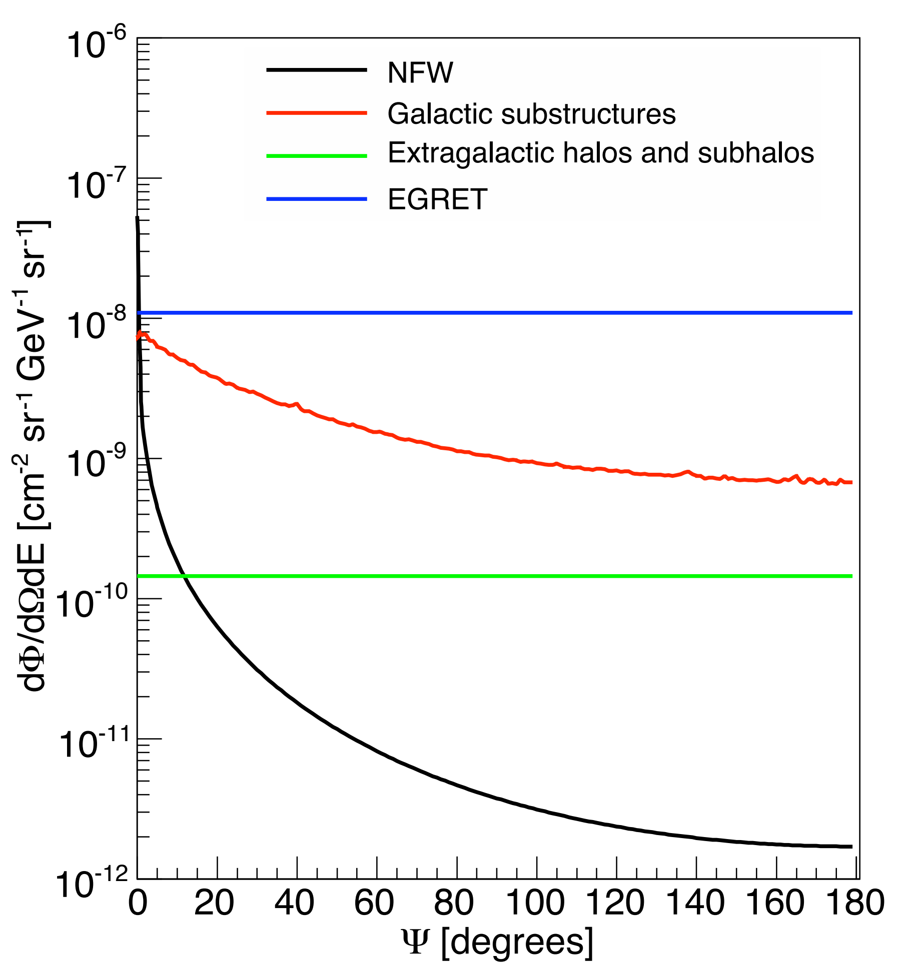
The angular power spectrum of diffuse gamma-ray emission

- unresolved blazars are typically the dominant contributor to the angular power spectrum over other extragalactic source classes for $\ell \gtrsim 100$

- Galactic dark matter substructure generally produces a much higher amplitude angular power spectrum than extragalactic source classes

- Galactic dark matter always dominates over extragalactic dark matter in the intensity energy spectrum and angular power spectrum

G and EG relative contributions



Fornasa et al. 2009

The angular power spectrum of diffuse gamma-ray emission

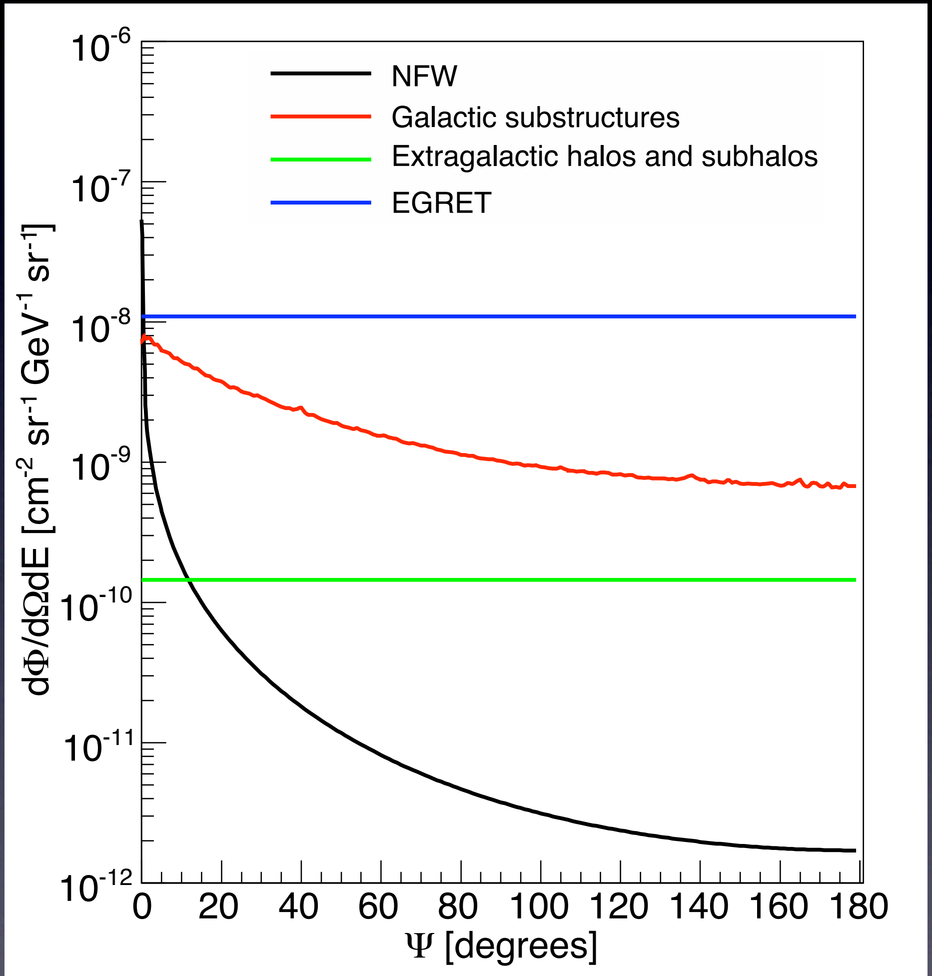
- unresolved blazars are typically the dominant contributor to the angular power spectrum over other extragalactic source classes for $\ell \gtrsim 100$

- Galactic dark matter substructure generally produces a much higher amplitude angular power spectrum than extragalactic source classes

- Galactic dark matter always dominates over extragalactic dark matter in the intensity energy spectrum and angular power spectrum

- NB: relative amplitudes of the *intensity* of different source classes are uncertain, leading to variations in predicted shape and amplitude of the total angular power spectrum

G and EG relative contributions



Fornasa et al. 2009

The anisotropy energy spectrum

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:

$$C_\ell^{\rm tot}(E) = f_{\rm EG}^2(E) C_\ell^{\rm EG} + f_{\rm DM}^2(E) C_\ell^{\rm DM} + 2 f_{\rm EG}(E) f_{\rm DM}(E) C_\ell^{\rm EG \times DM}$$

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:

$$C_\ell^{\rm tot}(E) = f_{\rm EG}^2(E)C_\ell^{\rm EG} + f_{\rm DM}^2(E)C_\ell^{\rm DM} + 2f_{\rm EG}(E)f_{\rm DM}(E)\cancel{C_\ell^{\rm EG\times DM}}$$

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:

$$C_\ell^{\rm tot}(E) = f_{\rm EG}^2(E) C_\ell^{\rm EG} + f_{\rm DM}^2(E) C_\ell^{\rm DM} + \cancel{2 f_{\rm EG}(E) f_{\rm DM}(E) C_\ell^{\rm EG \times DM}}$$

- 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

*EBL attenuation, redshifting of features in the source spectrum, source evolution with redshift, and variation between individual source spectra within a source class can in principle produce an energy dependence

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:

$$C_\ell^{\rm tot}(E) = f_{\rm EG}^2(E)C_\ell^{\rm EG} + f_{\rm DM}^2(E)C_\ell^{\rm DM} + 2f_{\rm EG}(E)f_{\rm DM}(E)\cancel{C_\ell^{\rm EG\times DM}}$$

- 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 Galactic dark matter and extragalactic source classes to the total measured emission
  - a transition in energy from an angular power spectrum dominated by the EGRB and one dominated by Galactic dark matter will show up as a modulation in the anisotropy energy spectrum

*EBL attenuation, redshifting of features in the source spectrum, source evolution with redshift, and variation between individual source spectra within a source class can in principle produce an energy dependence

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:

$$C_\ell^{\rm tot}(E) = f_{\rm EG}^2(E) C_\ell^{\rm EG} + f_{\rm DM}^2(E) C_\ell^{\rm DM} + \cancel{2 f_{\rm EG}(E) f_{\rm DM}(E) C_\ell^{\rm EG \times DM}}$$

- 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

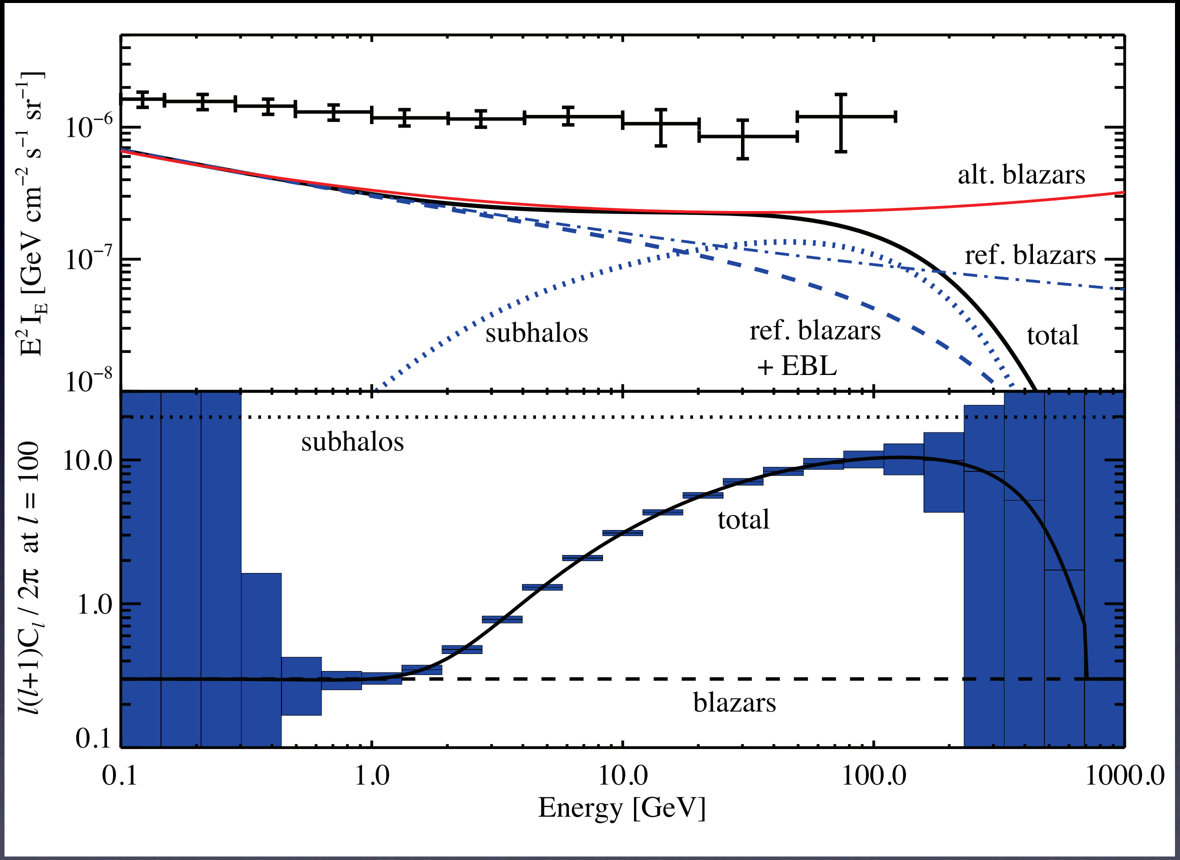
- how does the anisotropy energy spectrum help?
  - exploits the different energy dependences of the contributions of Galactic dark matter and extragalactic source classes to the total measured emission
  - a transition in energy from an angular power spectrum dominated by the EGRB and one dominated by Galactic dark matter will show up as a modulation in the anisotropy energy spectrum

- this is a generally applicable method for identifying and understanding the properties of contributing source populations (NOT just for dark matter!)

*EBL attenuation, redshifting of features in the source spectrum, source evolution with redshift, and variation between individual source spectra within a source class can in principle produce an energy dependence

The anisotropy energy spectrum at work

neutralino mass = 700 GeV



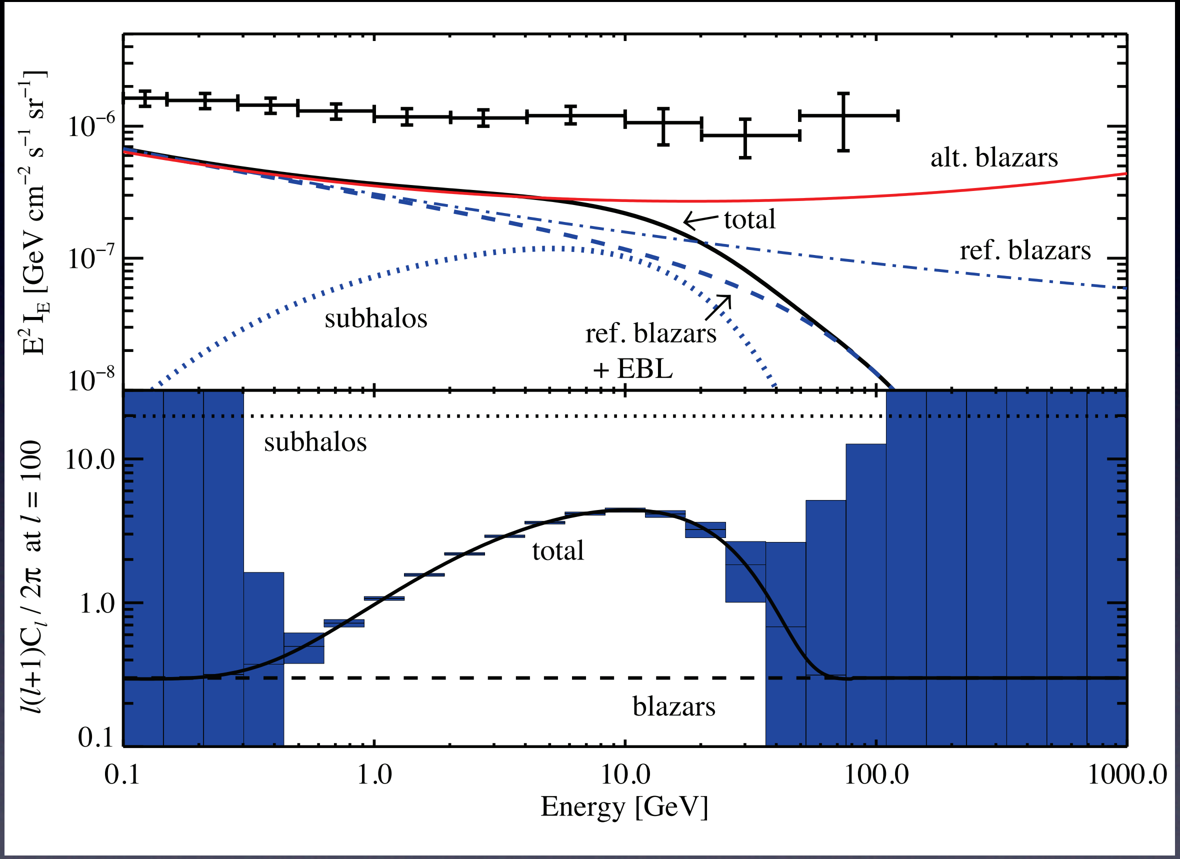
JSG & Pavlidou 2009

- 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 ~20 GeV, but spectral cut-off is consistent with EBL attenuation of blazars
- modulation of anisotropy energy spectrum is easily detected!

The anisotropy energy spectrum at work

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

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

Summary

Summary

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

Summary

- a modulation in the anisotropy energy spectrum robustly indicates a transition in energy in the spatial distribution of contributing source population(s)
- confident identification of a specific source population requires joint examination of several diagnostics:
    1. anisotropy energy spectrum
    2. intensity energy spectrum
    3. total angular power spectrum
    4. large-scale angular distribution of the emission
    - Galactic dark matter has a unique anisotropy signature: the combined properties of (1)-(4) for Galactic dark matter *are not reproduced by any known source class*!
    - spurious detections can usually be rejected with multiple diagnostics: e.g., modulation due to EBL attenuation is accompanied by suppression in intensity at same energies

Summary

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

- confident identification of a specific source population requires joint examination of several diagnostics:

  1. anisotropy energy spectrum
  2. intensity energy spectrum
  3. total angular power spectrum
  4. large-scale angular distribution of the emission

  - Galactic dark matter has a unique anisotropy signature: the combined properties of (1)-(4) for Galactic dark matter *are not reproduced by any known source class*!

  - spurious detections can usually be rejected with multiple diagnostics: e.g., modulation due to EBL attenuation is accompanied by suppression in intensity at same energies

- 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 the intensity spectrum alone (analysis by Brandon Hensley in prep)

$$C_\ell^{\rm tot}(E) = f_{\rm EG}^2(E)\, C_\ell^{\rm EG} + f_{\rm DM}^2(E)\, C_\ell^{\rm DM}$$

Detectability of the angular power spectrum

noise power spectrum
(Poisson noise of signal
and background, independent of ℓ)

sample variance

$$\delta C_\ell^{\mathrm{s}} = \sqrt{\frac{2}{(2\ell+1)\,\Delta\ell\, f_{\mathrm{sky}}}}\left(C_\ell^{\mathrm{s}} + \frac{C_{\mathrm{N}}}{W_\ell^2}\right)$$

window function of the experiment

$$W_\ell = e^{-\ell^2 \sigma_{\mathrm{b}}^2/2}$$