Image Credit: NASA/DOE/International LAT Team

Searching for dark matter and astrophysical sources with gamma-ray anisotropies

Jennifer Siegal-Gaskins

CCAPP, Ohio State University

with

Brandon Hensley (Caltech→Princeton)
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The Fermi-LAT Collaboration

based on

JSG & Pavlidou, PRL, 102, 241301 (2009)
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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, it will contain fluctuations on small angular scales due to the variation in the number density of sources in each sky direction
- if these fluctuations are different from those expected from Poisson noise due to finite event statistics, we could use these fluctuations to identify the presence of unresolved source populations, such as dark matter
- the energy-dependence of the anisotropy can reveal/constrain the presence of multiple source populations and help identify specific populations

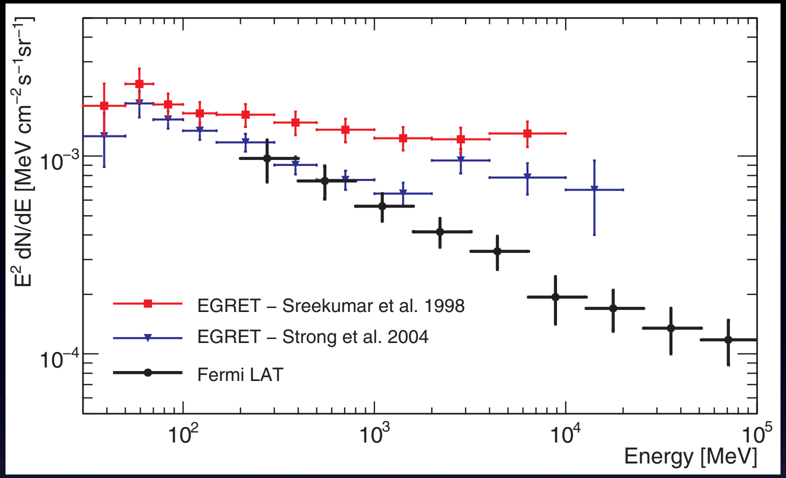
The Fermi Gamma-ray Space Telescope

- 20 MeV to > 300 GeV
- angular resolution ~ 0.1 deg above 10 GeV
- FOV ~ 2.4 sr
- uniform sky exposure of ~ 30 mins every 3 hrs
- excellent charged particle background rejection

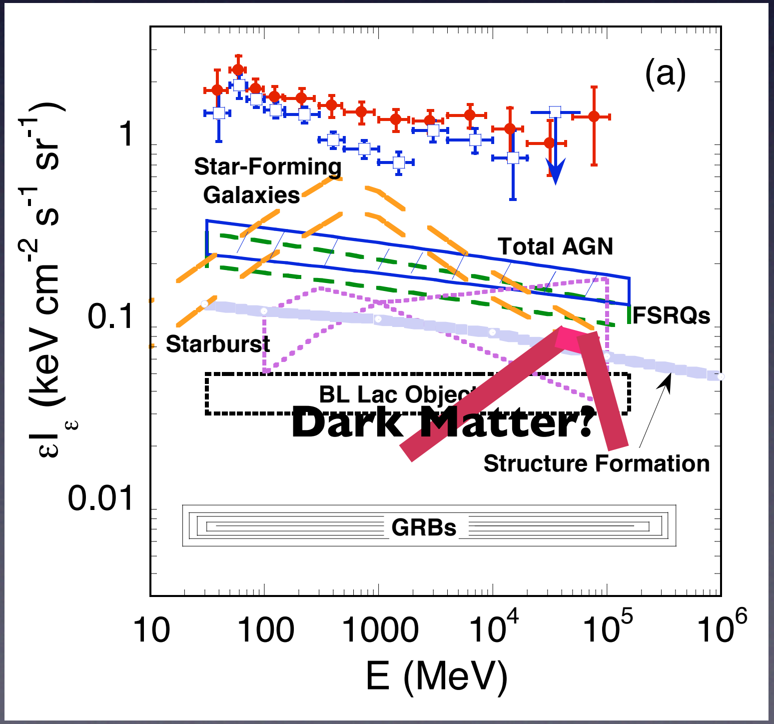
Credit: NASA/General Dynamics

What is making the large-scale isotropic diffuse background (IGRB)?

- many astrophysical sources are *guaranteed* to contribute to the diffuse emission, e.g.:
  - blazars (but maybe only ~15-25%!)
  - star-forming galaxies
  - millisecond pulsars
- unknown/unconfirmed source classes could also contribute:
  - dark matter
  - ???
- relatively featureless total intensity spectrum = lack of spectral handles to ID individual components



Abdo et al., PRL 104 (2010) 101101



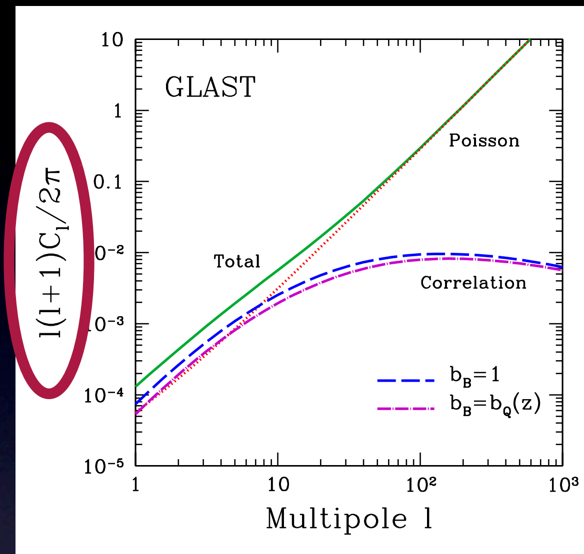
Dermer 2007

The angular power spectrum

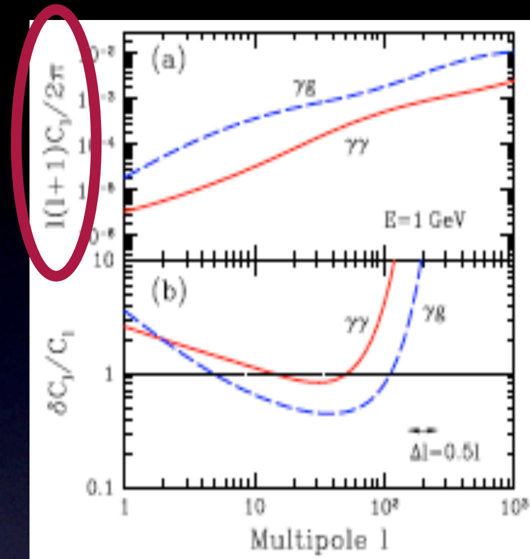
$$\delta I(\psi) \equiv \frac{I(\psi) - \langle I \rangle}{\langle I \rangle} \Rightarrow \delta I(\psi) = \sum_{\ell,m} a_{\ell m} Y_{\ell m}(\psi) \Rightarrow C_\ell = \langle\, |a_{\ell m}|^2 \rangle$$

- the angular power spectrum (C_ℓ vs. ℓ) characterizes intensity fluctuations as a function of angular scale (multipole)
- here we use the angular power spectrum of intensity fluctuations in units of mean intensity (dimensionless)
  - independent of intensity normalization, avoids uncertainty in intensity of signal
  - avoids different amplitude angular power spectra in different energy bins for the same source distribution

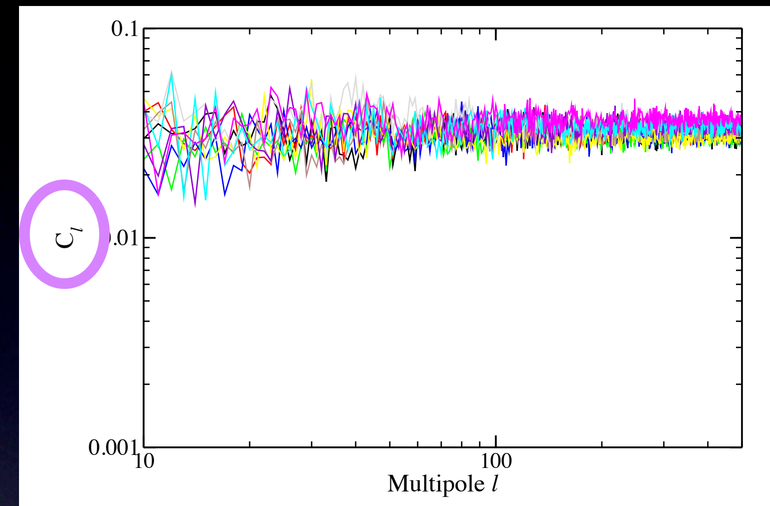
Angular power spectra of unresolved gamma-ray populations



Blazars
(Ando, Komatsu, Narumoto & Totani 2007)



Starforming galaxies
(Ando & Pavlidou 2009)

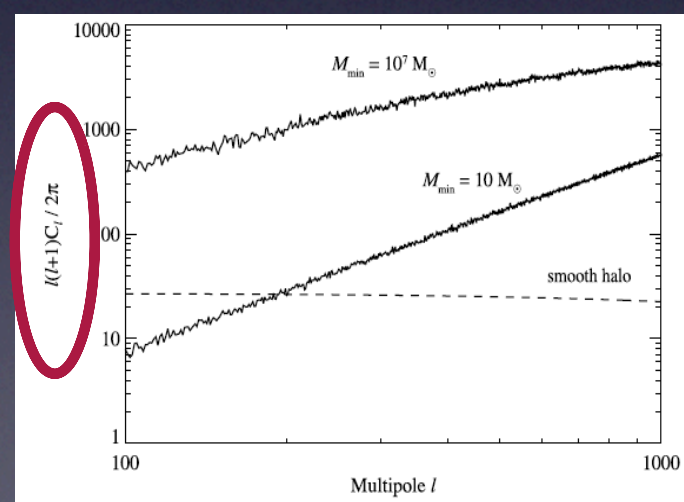


Millisecond pulsars (JSG et al 2010)

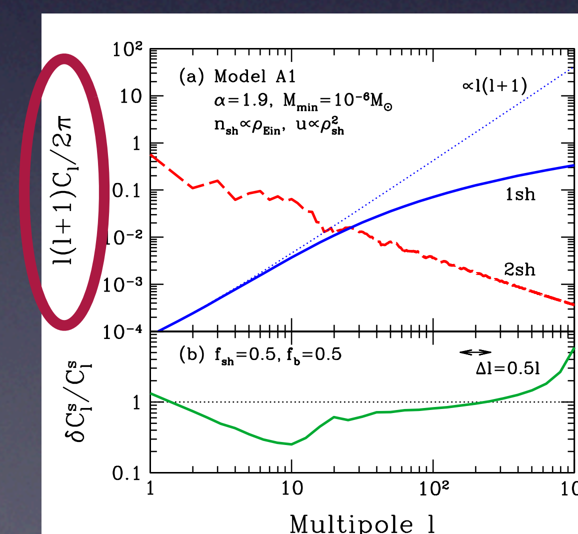
fluctuation angular power spectra

predictions for C_ℓ [sr] at l = 100 for a single source class (LARGE UNCERTAINTIES):

- blazars: ~ 1e-4
- starforming galaxies: ~ 1e-7
- dark matter: ~ 1e-4 to ~ 0.1
- MSPs: ~ 1e-2



Galactic subhalos (JSG 2008)

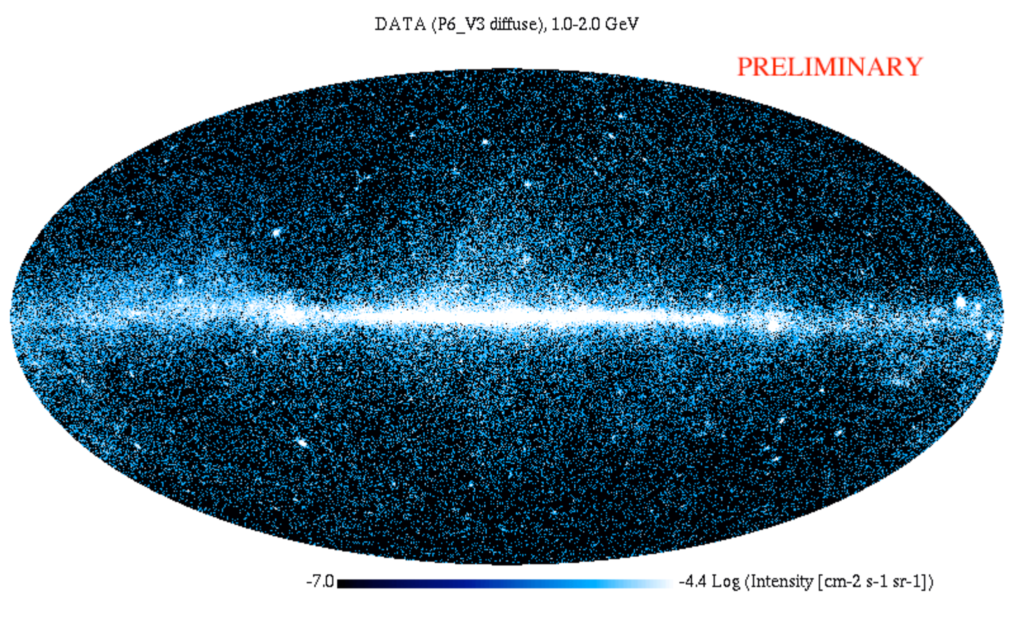


Galactic subhalos (Ando 2009)

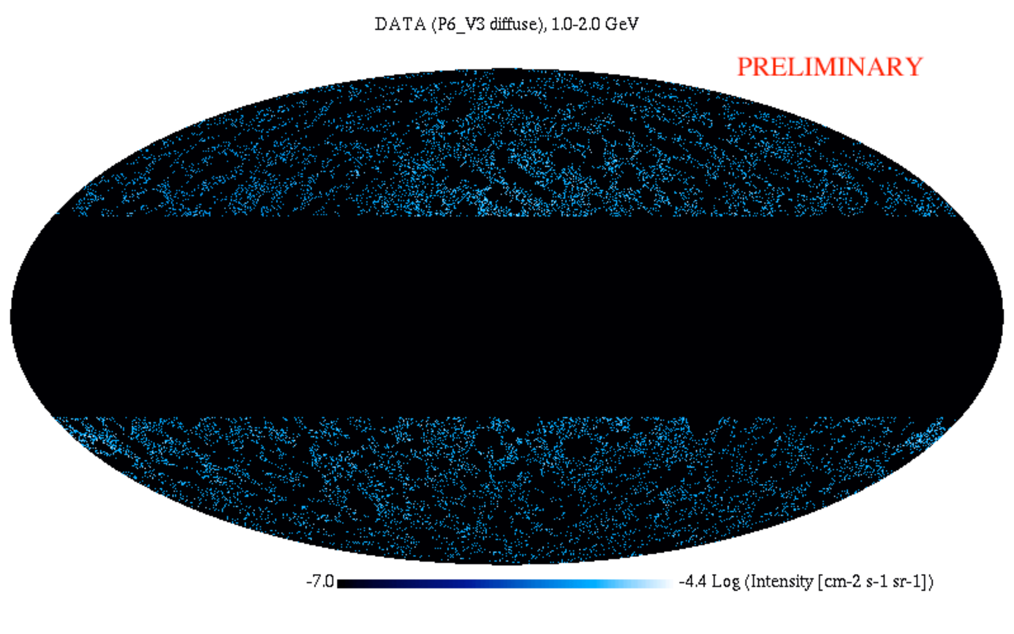
Fermi anisotropy analysis

1 - 2 GeV

All-sky map



Masked-sky map used in the analysis

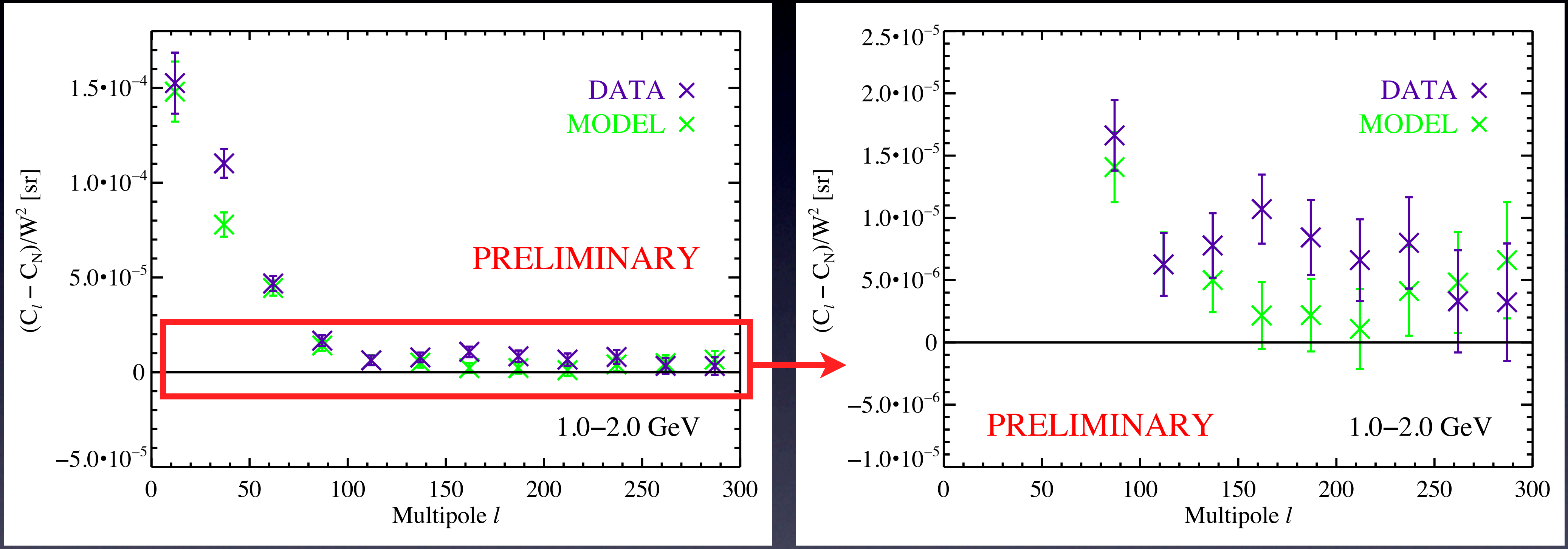


JSG for the Fermi-LAT Collaboration and Komatsu 2010

Data and Model comparison

fluctuation angular power spectra

1 - 2 GeV



JSG for the Fermi-LAT Collaboration and Komatsu 2010

- angular power detected in the data for multipoles greater than ~ 100, not detected in the model
- excess power approximately constant in multipole → characteristic of unclustered point sources
- anisotropies are also detected at lower significance up to E ~ 10 GeV
- NB: the sensitivity of the analysis decreases with increasing energy due to decreasing photon statistics

Comparison with (rough) predictions

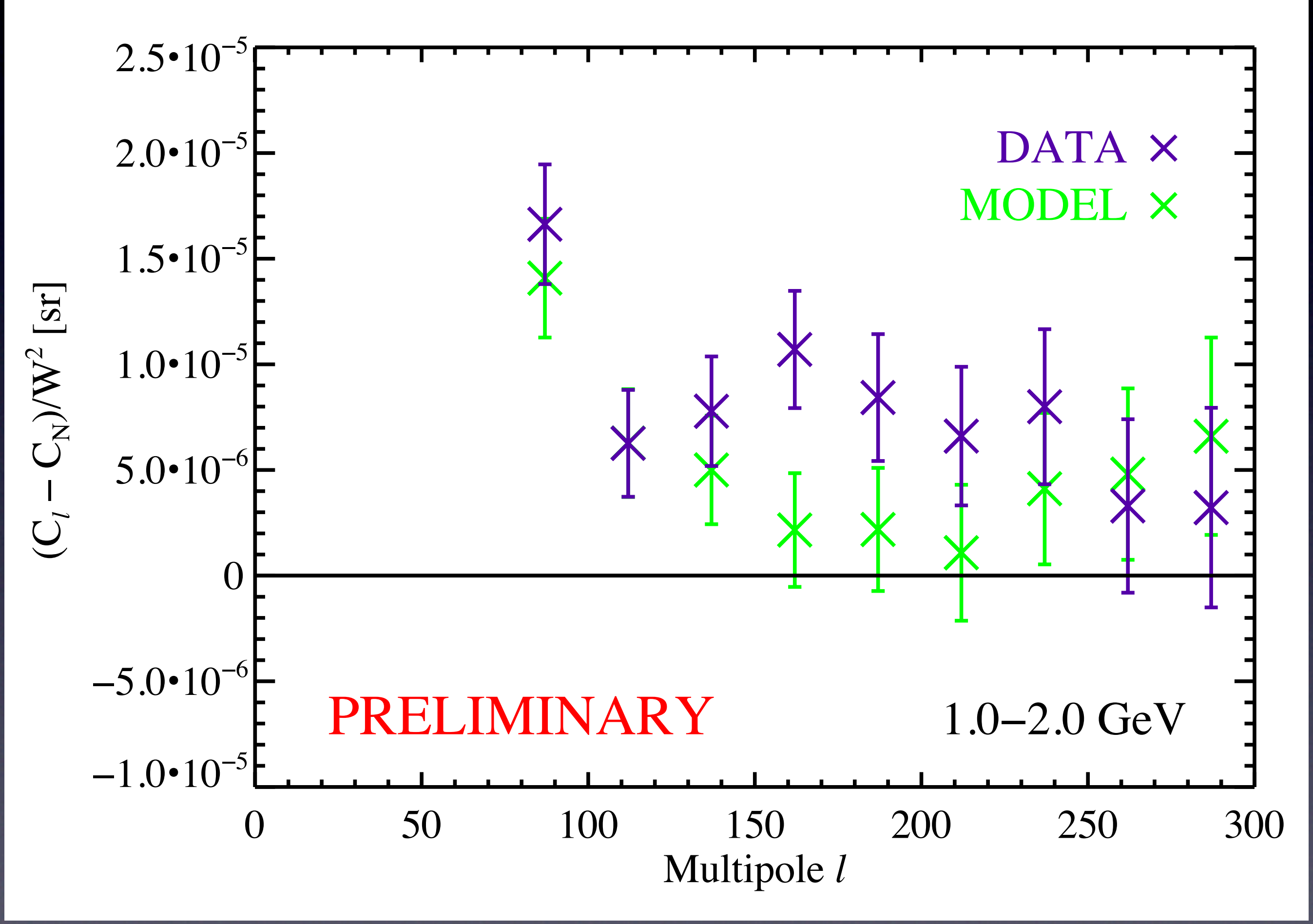
fluctuation angular power spectra

predictions for C_ℓ [sr] at l = 100 for a single source class (LARGE UNCERTAINTIES):

- blazars: ~ 1e-4
- starforming galaxies: ~ 1e-7
- dark matter: ~ 1e-4 to ~ 0.1
- MSPs: ~ 1e-2

measured fluctuation C_ℓ of ~ 1e-5 sr at multipoles above ~ 100 at low energies falls generally in the range predicted for some astrophysical source classes and some dark matter scenarios for emission from a single source class

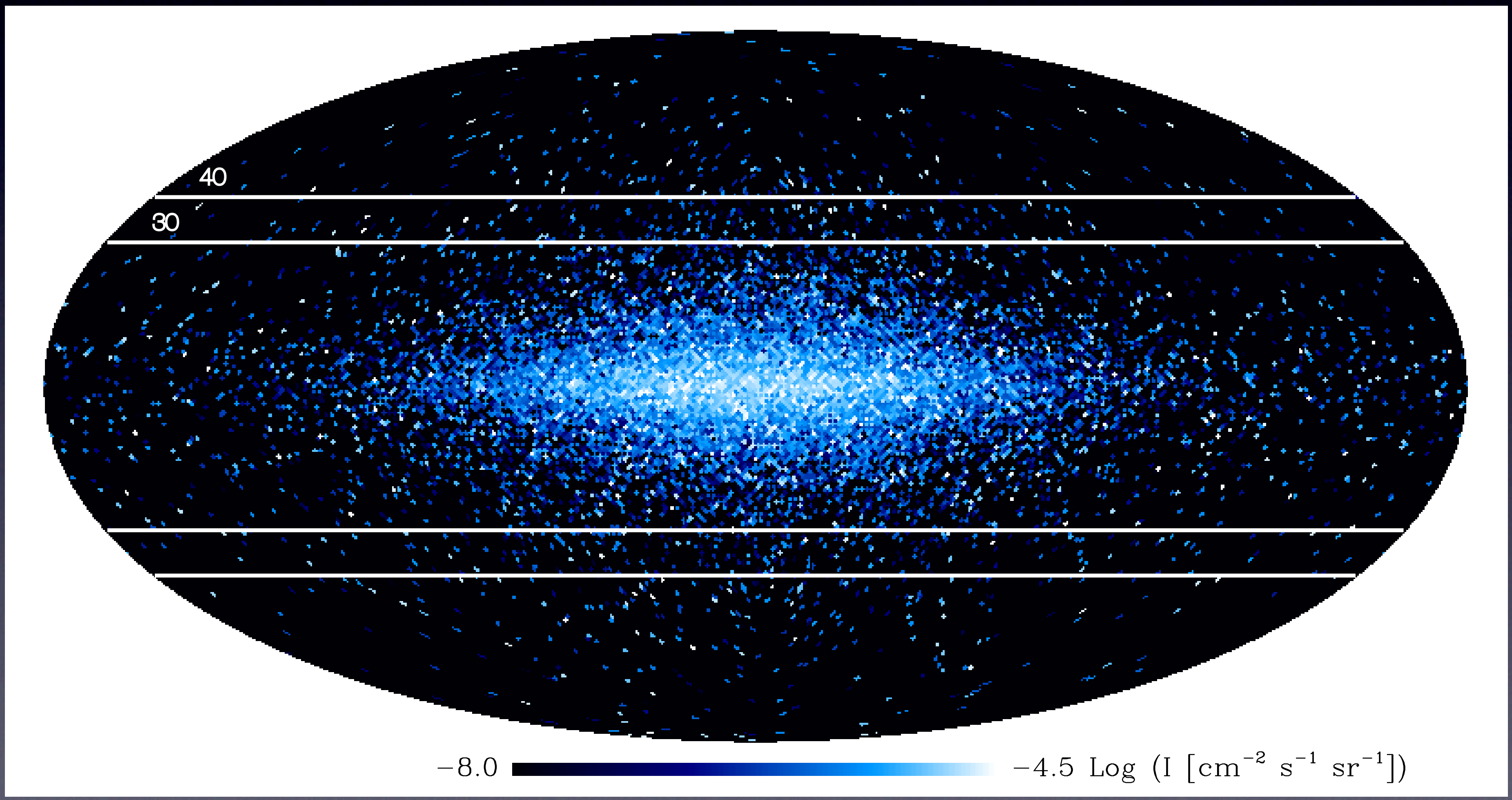
fluctuation angular power spectra



JSG for the Fermi-LAT Collaboration and Komatsu 2010

IGRB anisotropies from millisecond pulsars

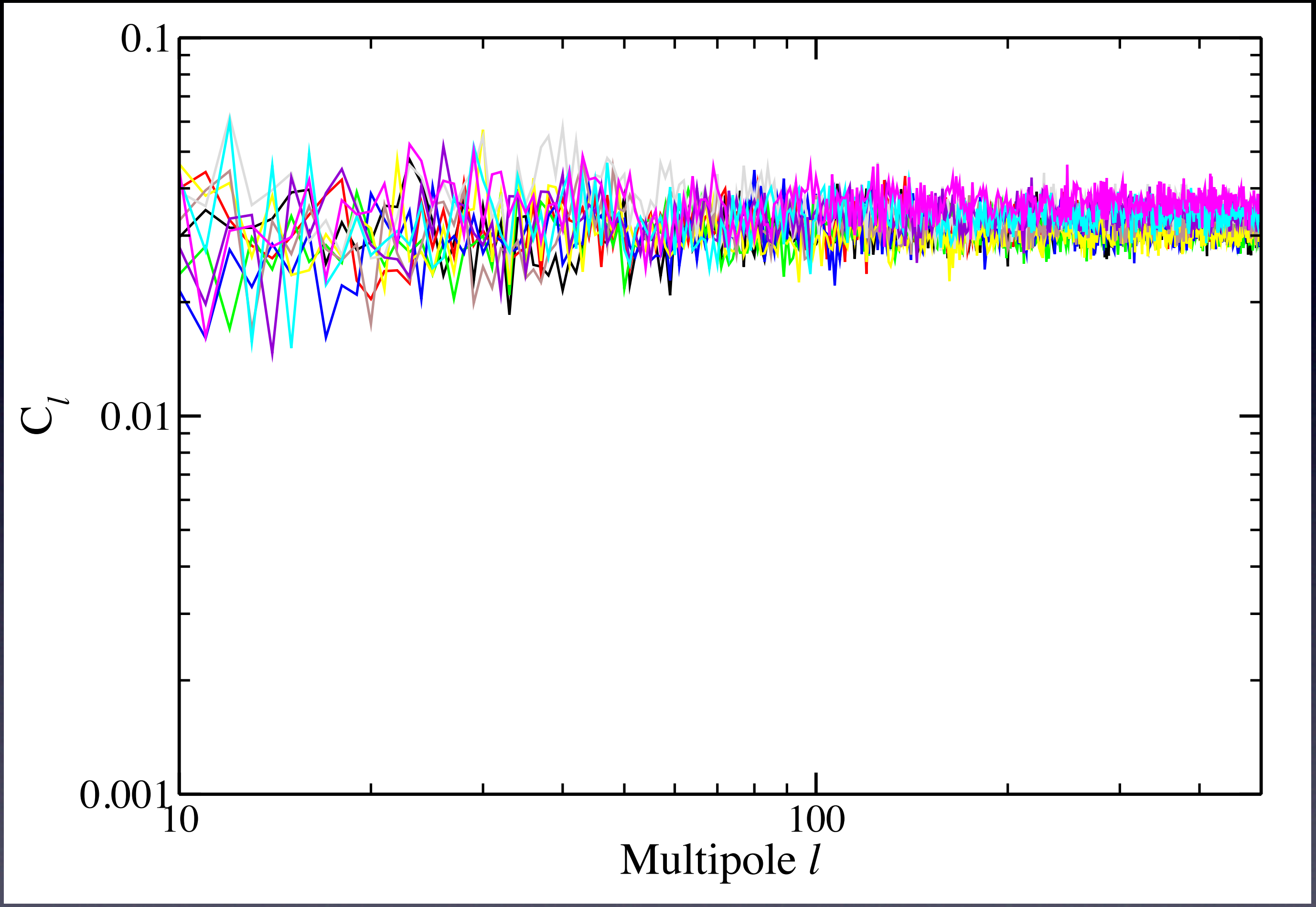
unresolved MSPs could contribute significantly to the high-latitude gamma-ray emission (e.g., Faucher-Giguere & Loeb 2009)



JSG, Reesman, Pavlidou, Profumo, & Walker 2010

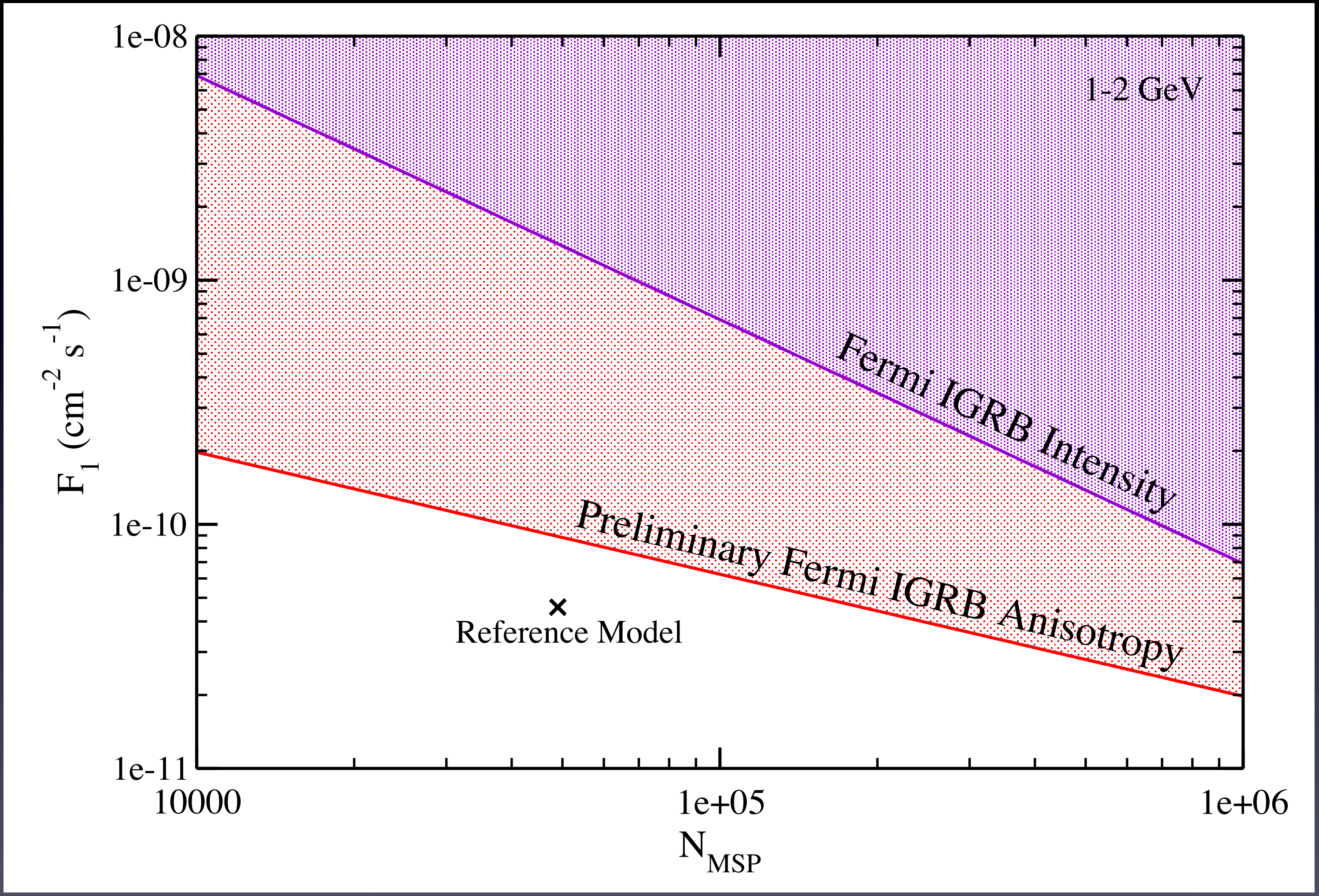
Angular power spectrum of MSPs

- remarkably constant in multipole → looks like emission from an unclustered source population ("Poisson-noise--like")
- large amplitude anisotropy → their diffuse contribution may be detectable/ constrainable from Fermi data



JSG, Reesman, Pavlidou, Profumo, & Walker 2010

Constraints on the MSP population



JSG, Reesman, Pavlidou, Profumo, & Walker 2010

- MSP models in shaded regions exceed measured IGRB intensity/anisotropy + 2-sigma
- anisotropy constraints ~ 1 order of magnitude stronger than intensity constraints

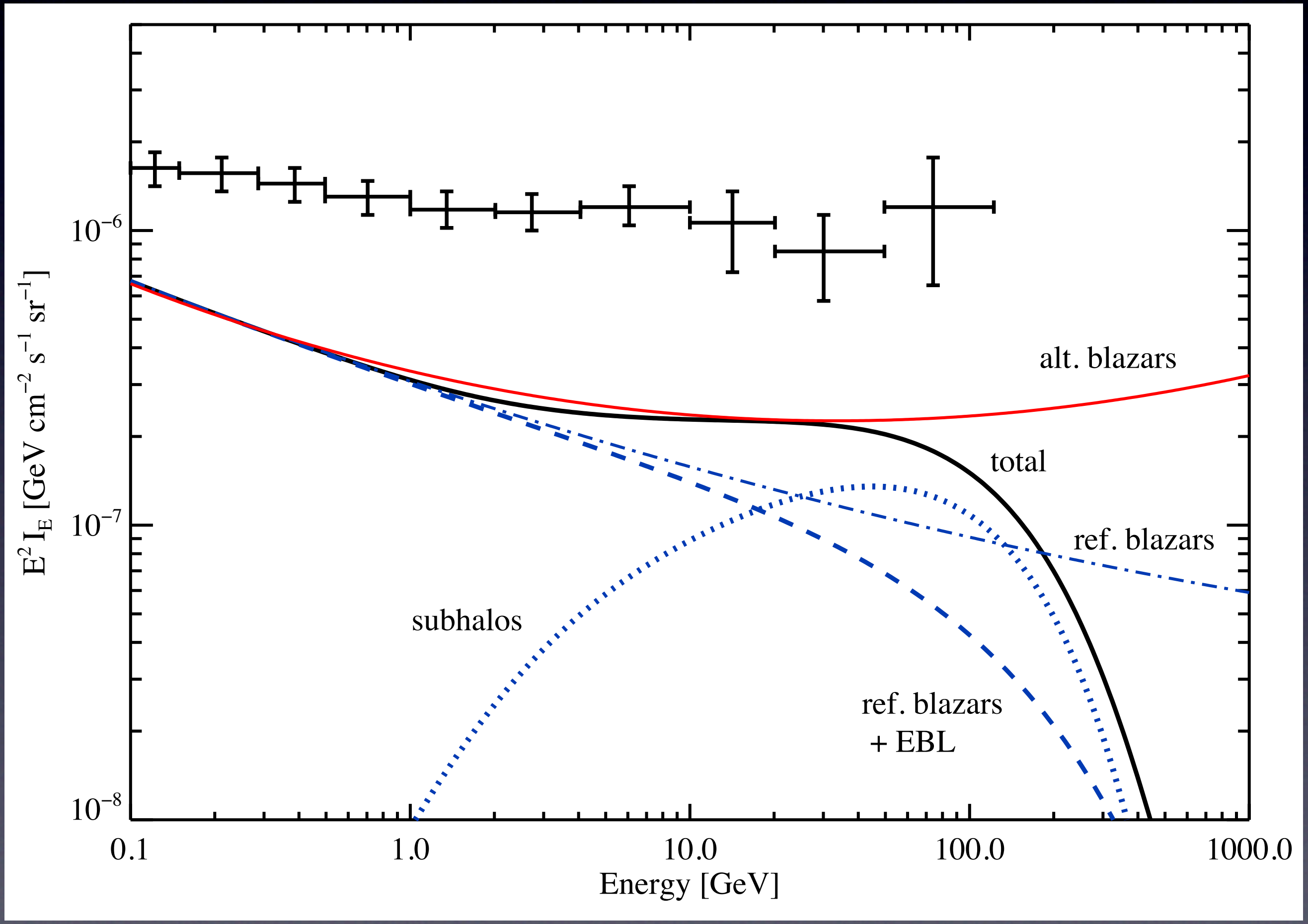
The intensity energy spectrum
(or why we need anisotropy too)

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!

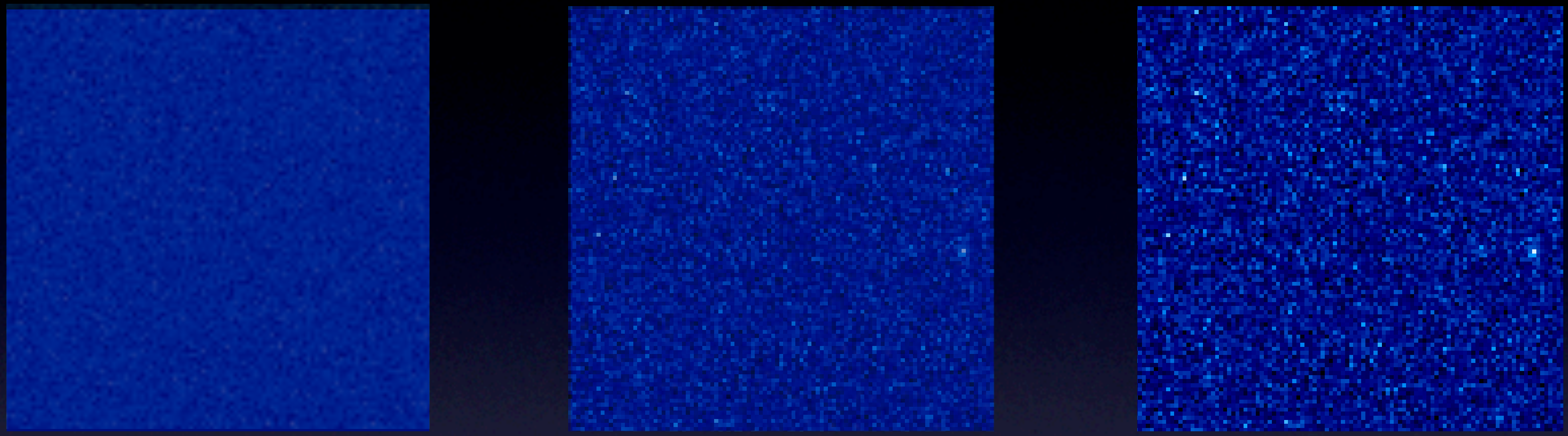
example isotropic diffuse intensity spectrum



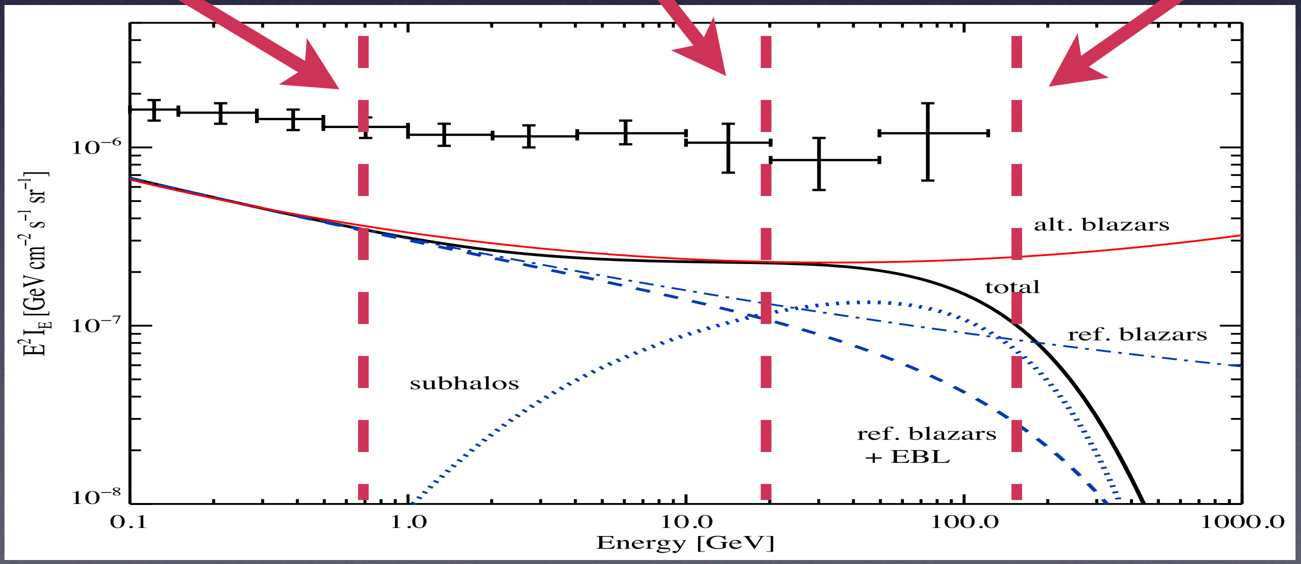
JSG & Pavlidou 2009

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

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:

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

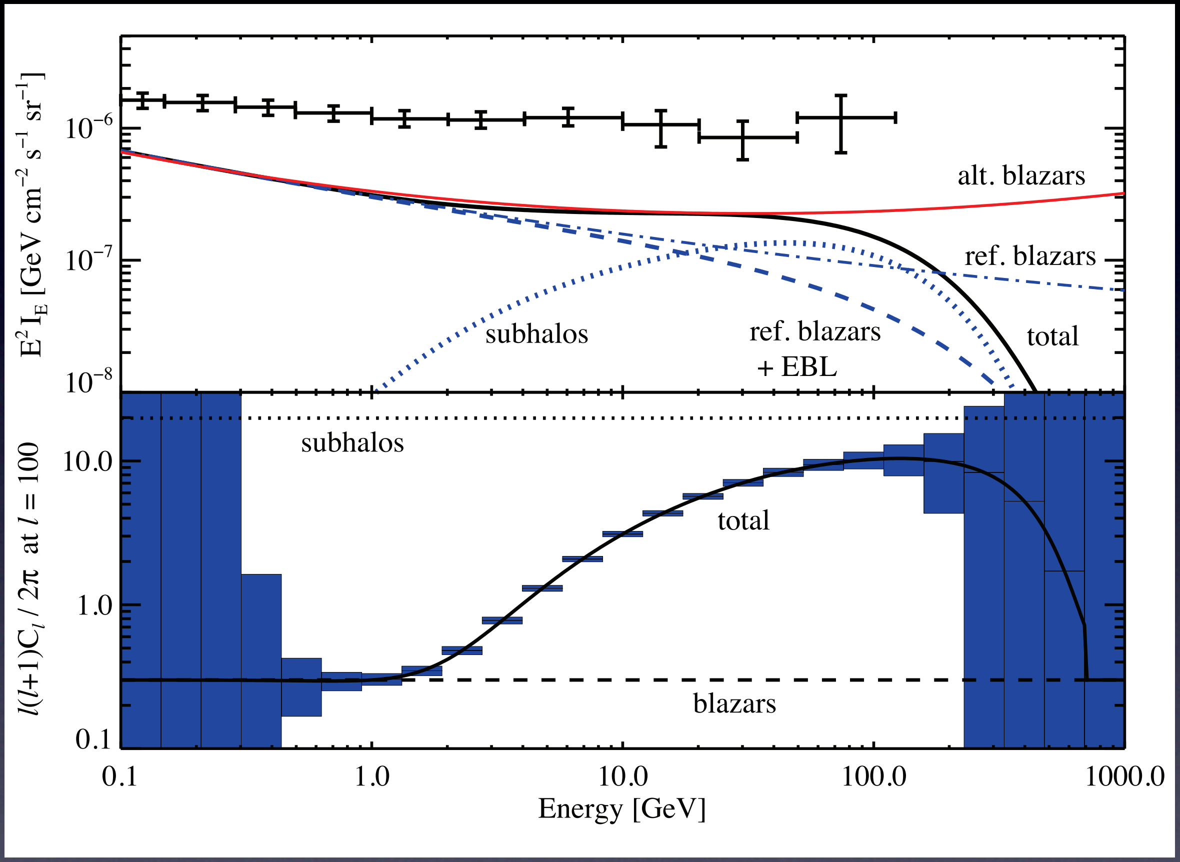
- the anisotropy energy spectrum of a SINGLE source population is flat in energy as long as the angular distribution (and hence angular power spectrum) of the emission from a single source population is independent of energy

- a transition in energy from an angular power spectrum dominated by one source class to one dominated by a different source class 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!)

The anisotropy energy spectrum at work

neutralino mass = 700 GeV



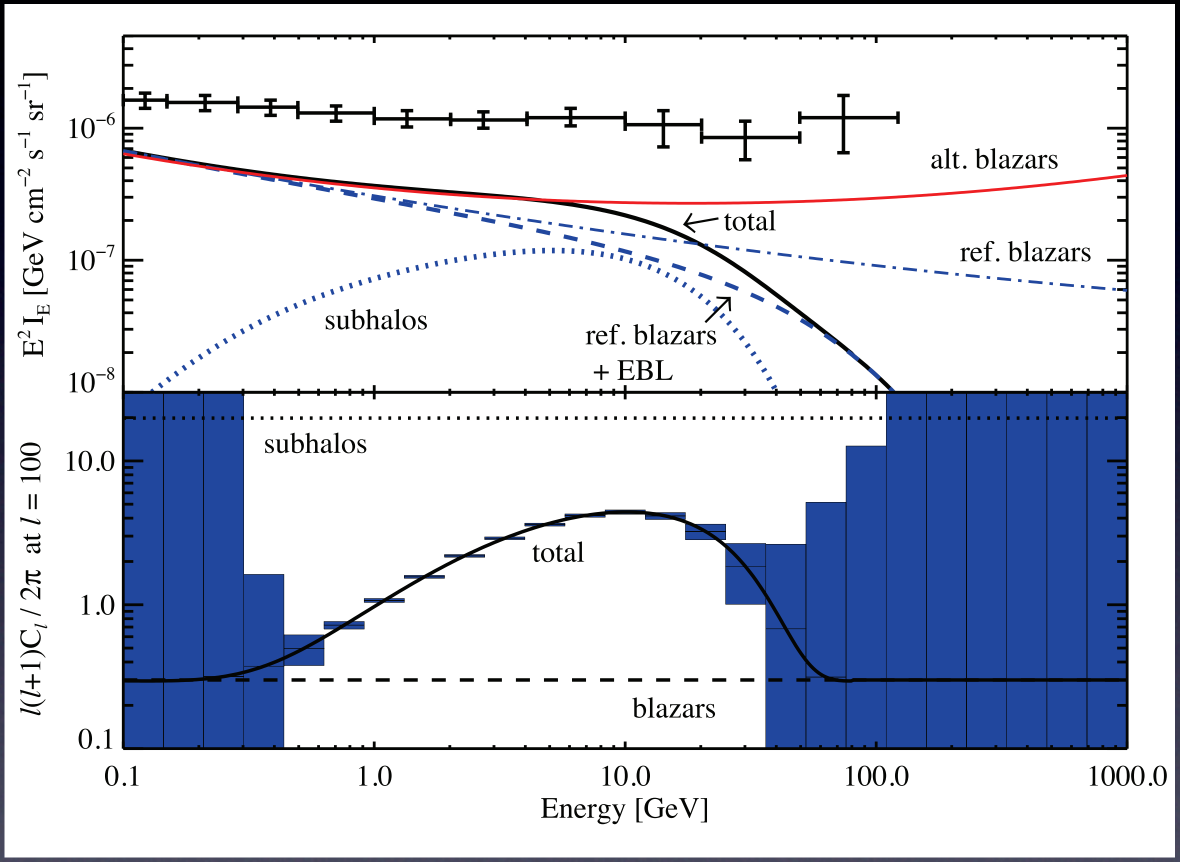
JSG & Pavlidou 2009

- 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!

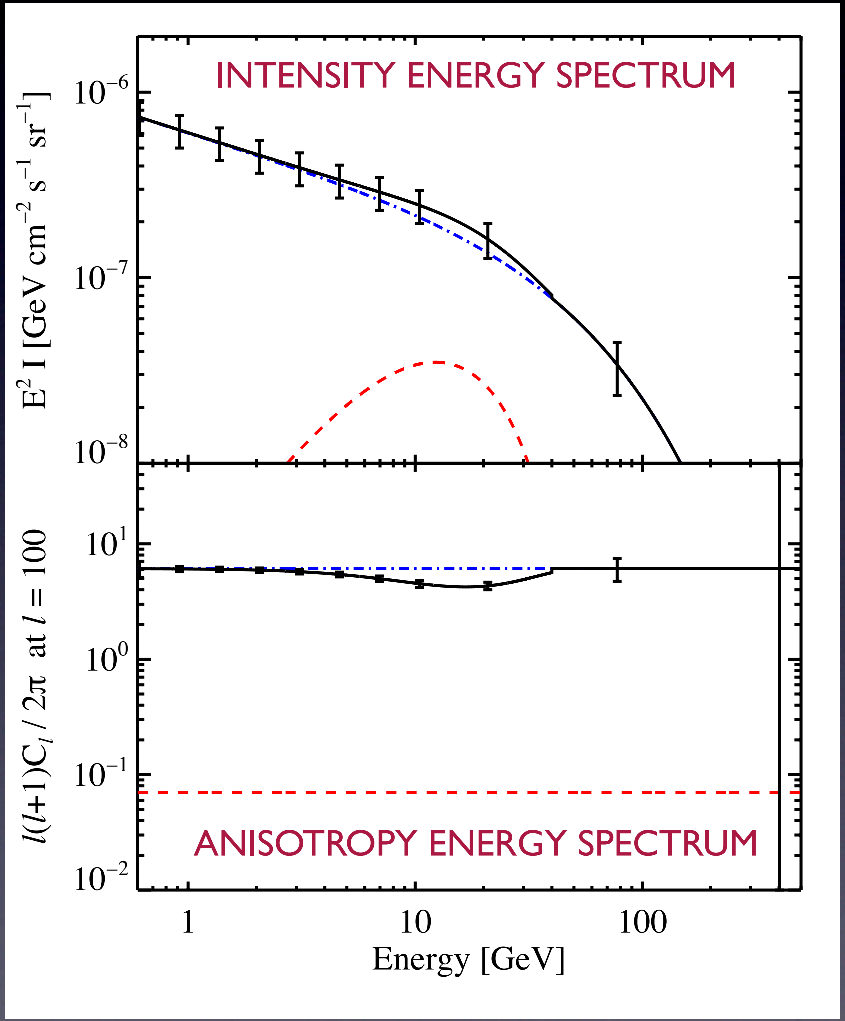
A simple test to find multiple populations

- assume the large-scale isotropic diffuse (IGRB) is composed primarily of emission from blazars and dark matter
- 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)
- define a simple, 'model-independent' test criterion:

  is the anisotropy energy spectrum at E ≥ 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 χ^2 test at 95% CL
- NB: this test is not optimized to find specific dark matter models; tailored likelihood analysis could significantly improve sensitivity!

example measurement with 5 years of Fermi data

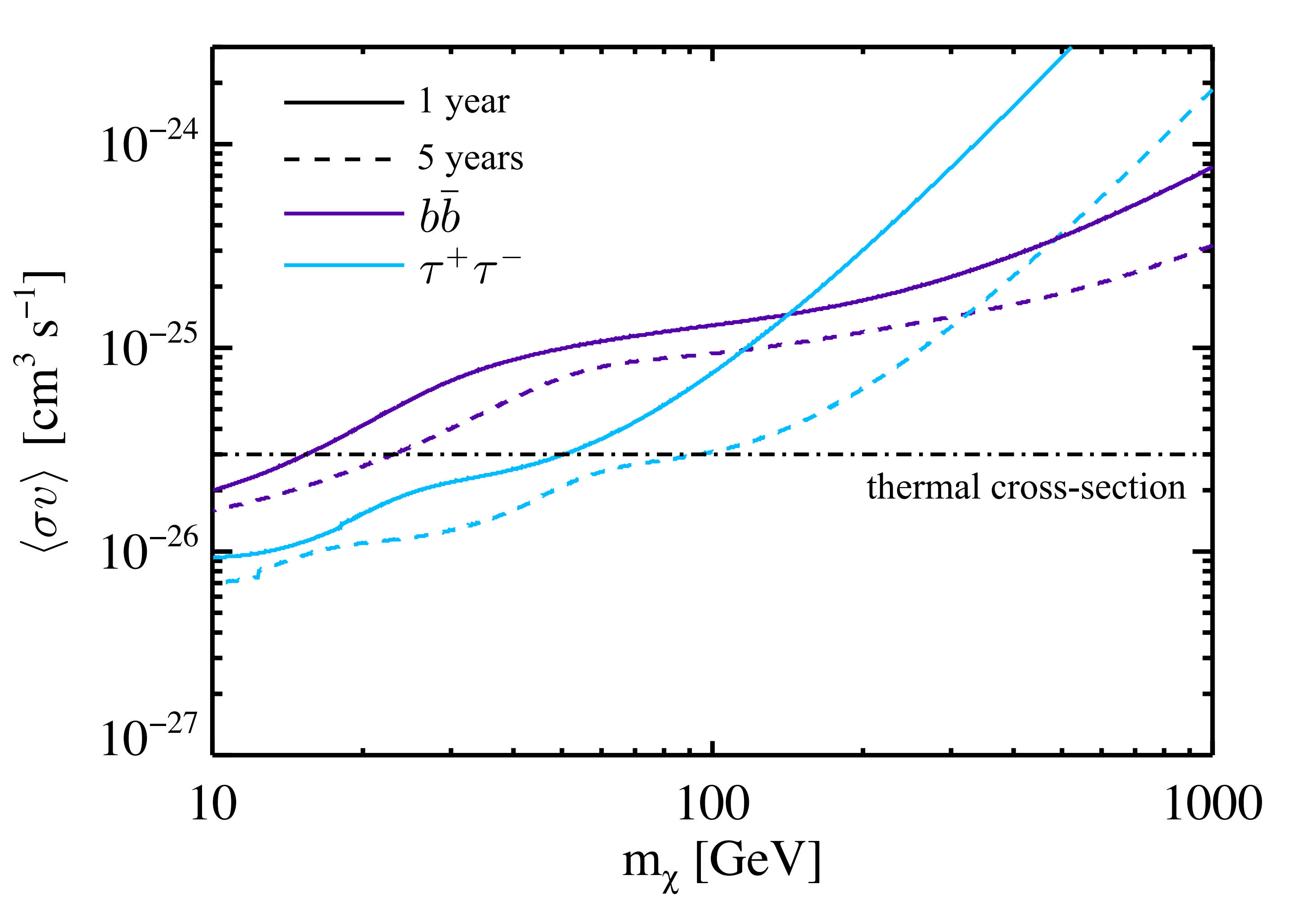


Hensley, JSG, & Pavlidou 2010

Sensitivity of the anisotropy energy spectrum

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

- 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 close to thermal; extends the reach of current indirect searches



Hensley, JSG, & Pavlidou 2010

Summary

- using anisotropy 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
- there is a preliminary Fermi detection of anisotropies in the IGRB at energies of a few GeV consistent with a signal from an unclustered point source population
- the preliminary Fermi anisotropy measurement can be used to constrain gamma-ray source populations, such as millisecond pulsars
- combining anisotropy and energy information can improve sensitivity to specific populations and help identify contributors
- the anisotropy energy spectrum of the IGRB is sensitive to a large parameter space of dark matter models, and could extend the reach of current indirect dark matter searches