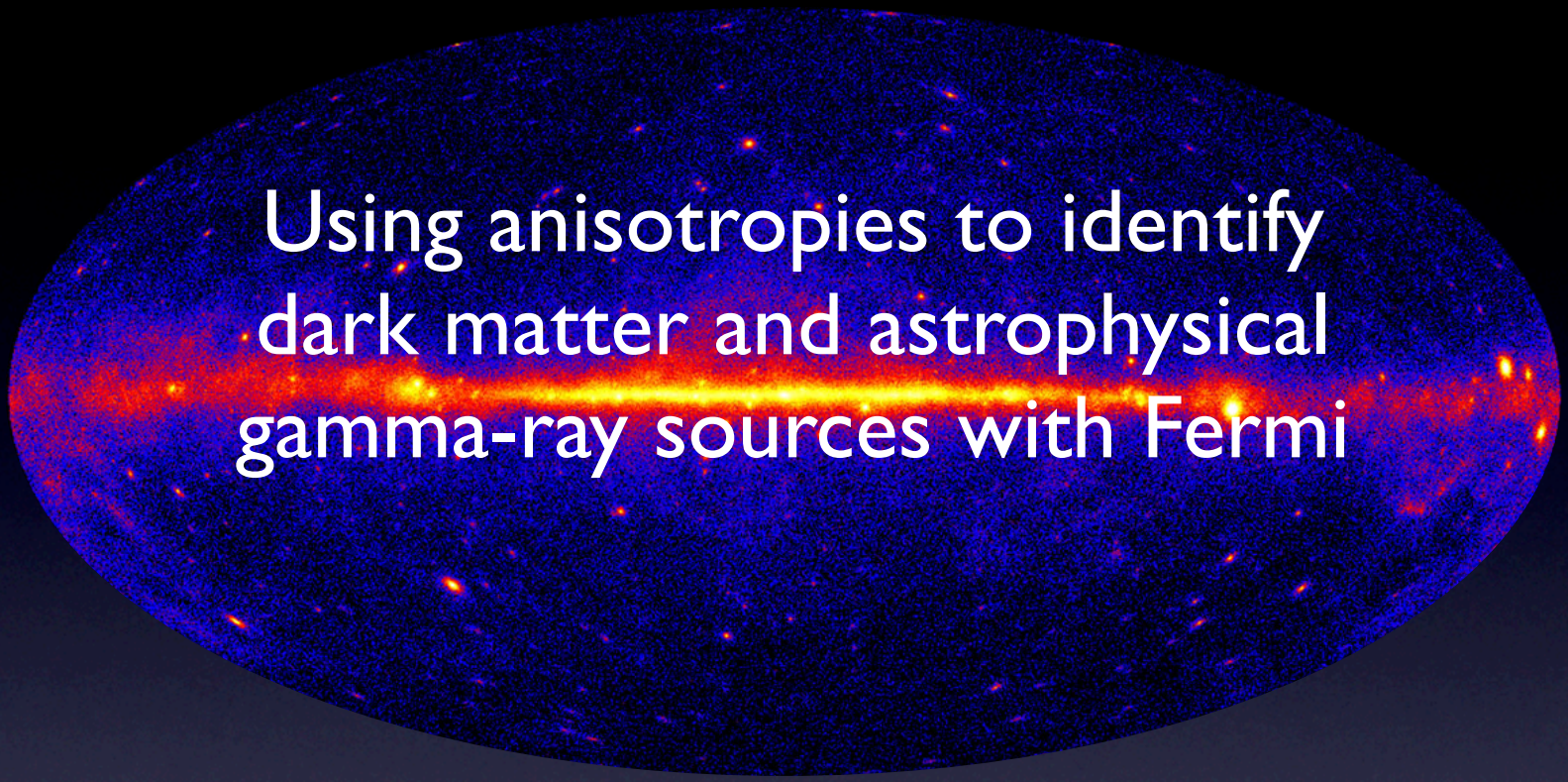
Image Credit: NASA/DOE/International LAT Team



Using anisotropies to identify dark matter and astrophysical gamma-ray sources with Fermi

Jennifer Siegal-Gaskins

CCAPP, Ohio State University

with
Brandon Hensley (Caltech)
Vasiliki Pavlidou (Caltech)

based on
JSG, JCAP, 10, 040 (2008)
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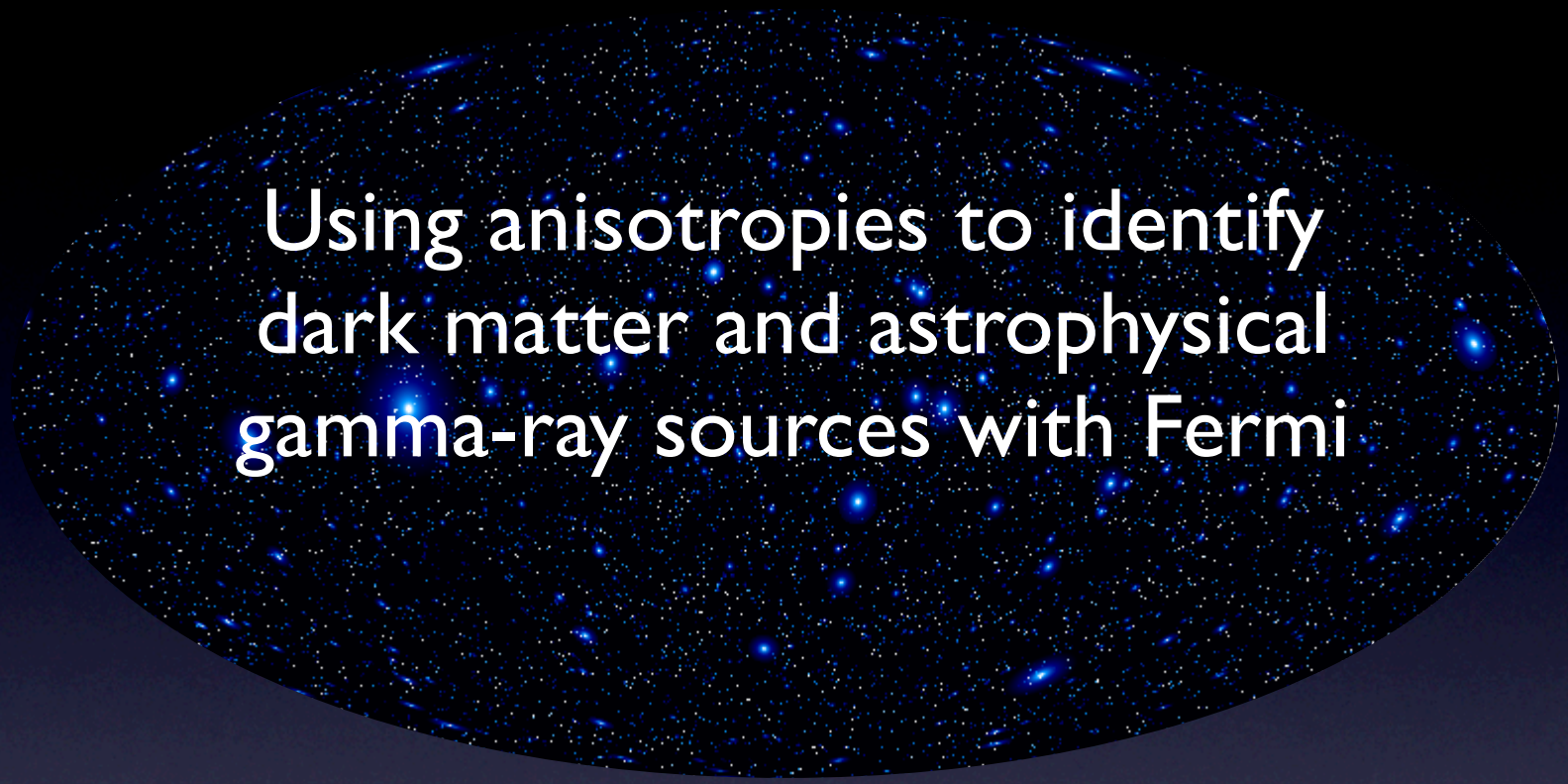
Hensley, Pavlidou, & JSG, in prep



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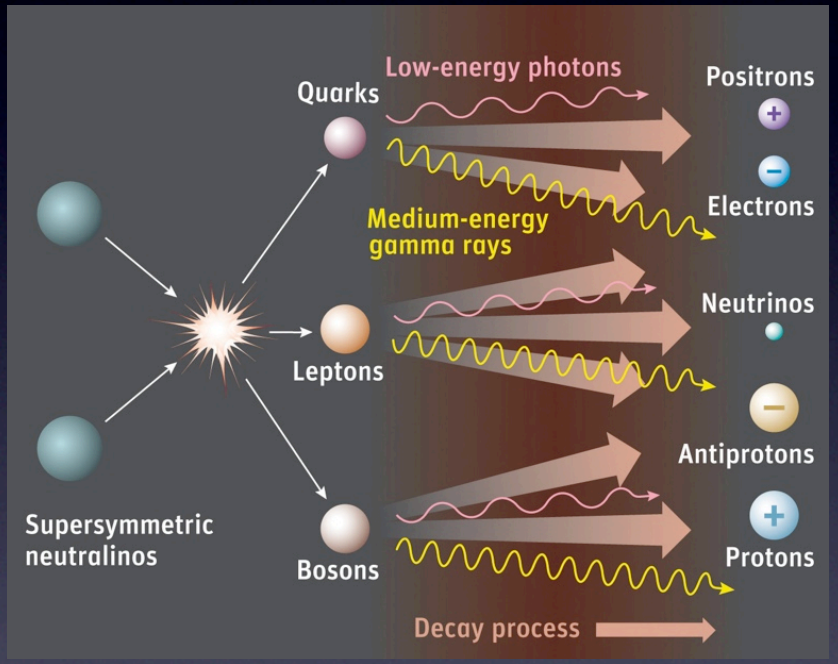
A potential dark matter signal in diffuse gamma-ray emission

- annihilation of dark matter particles produces gamma-rays which could be detected by Fermi



Credit: Sky & Telescope / Gregg Dinderman

A potential dark matter signal in diffuse gamma-ray emission

- annihilation of dark matter particles produces gamma-rays which could be detected by Fermi
- 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 dark matter signal in diffuse gamma-ray emission

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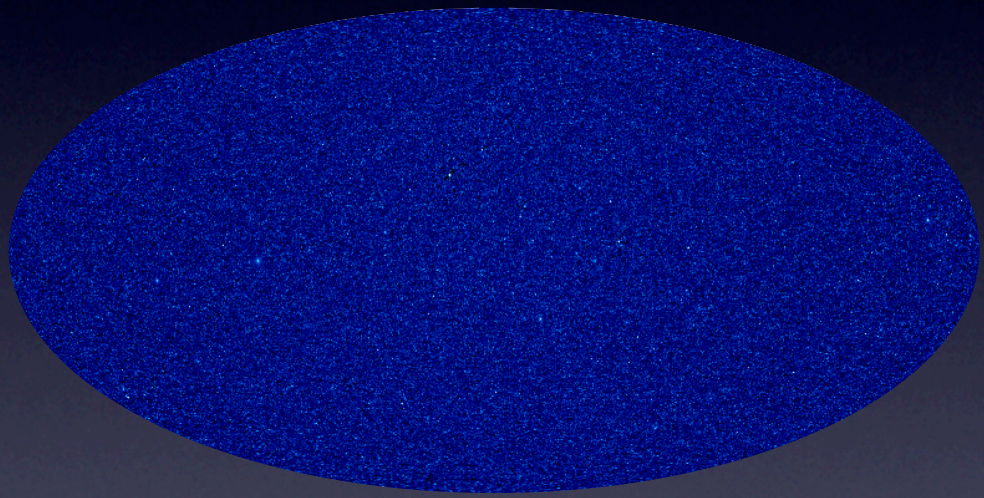
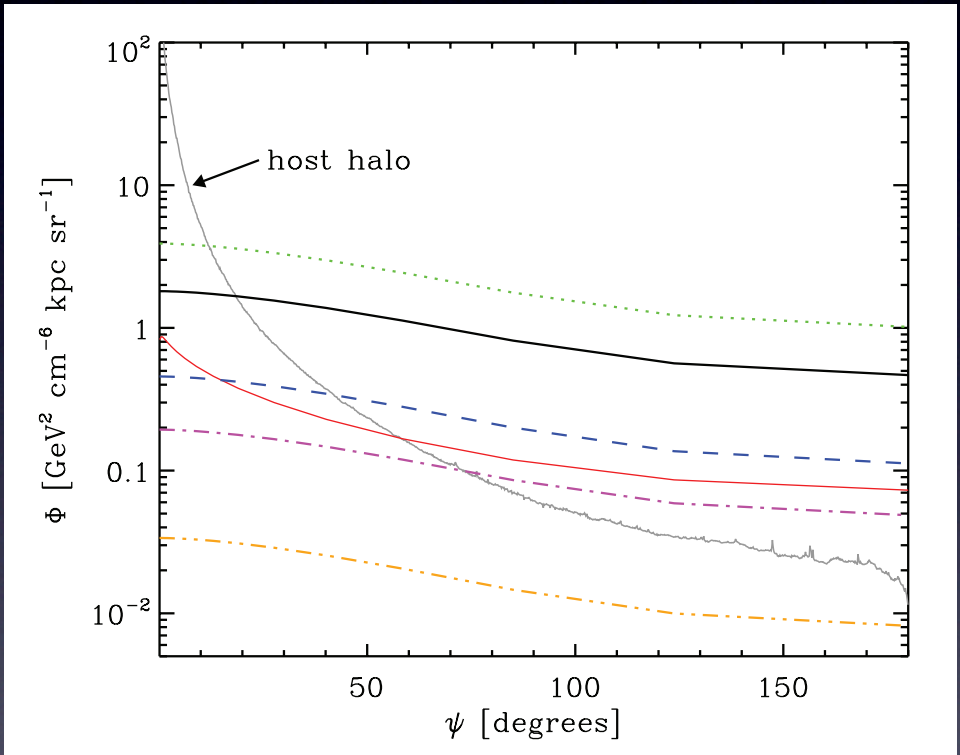


JSG 2008

A potential dark matter signal in diffuse gamma-ray emission

- annihilation of dark matter particles produces gamma-rays which could be detected by Fermi
- 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
- 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

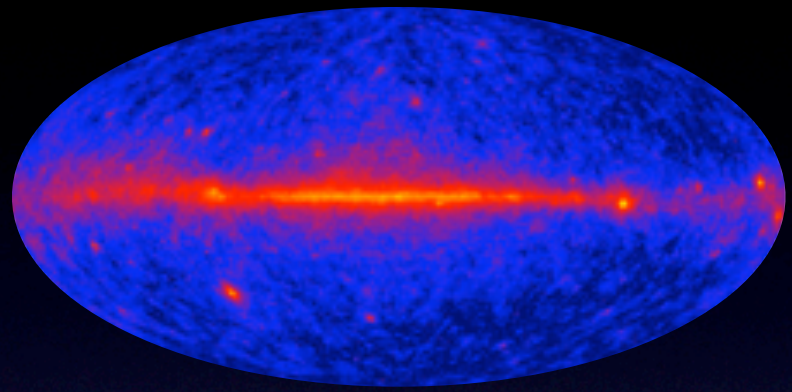


Kuhlen, Diemand, & Madau 2008

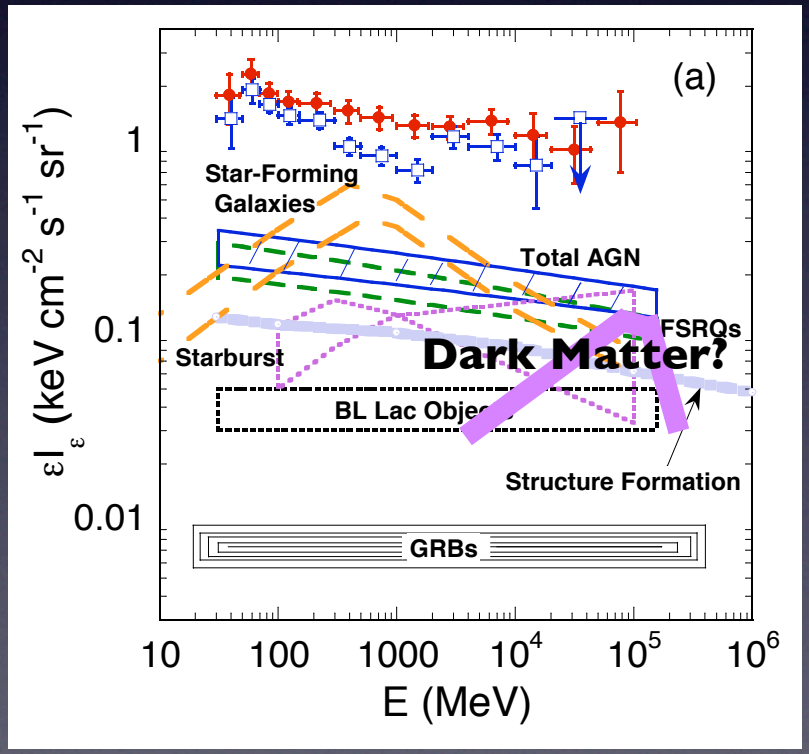
What is making the large-scale isotropic diffuse emission?

- 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!



Credit: NASA/DOE/International LAT Team



Dermer 2007

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

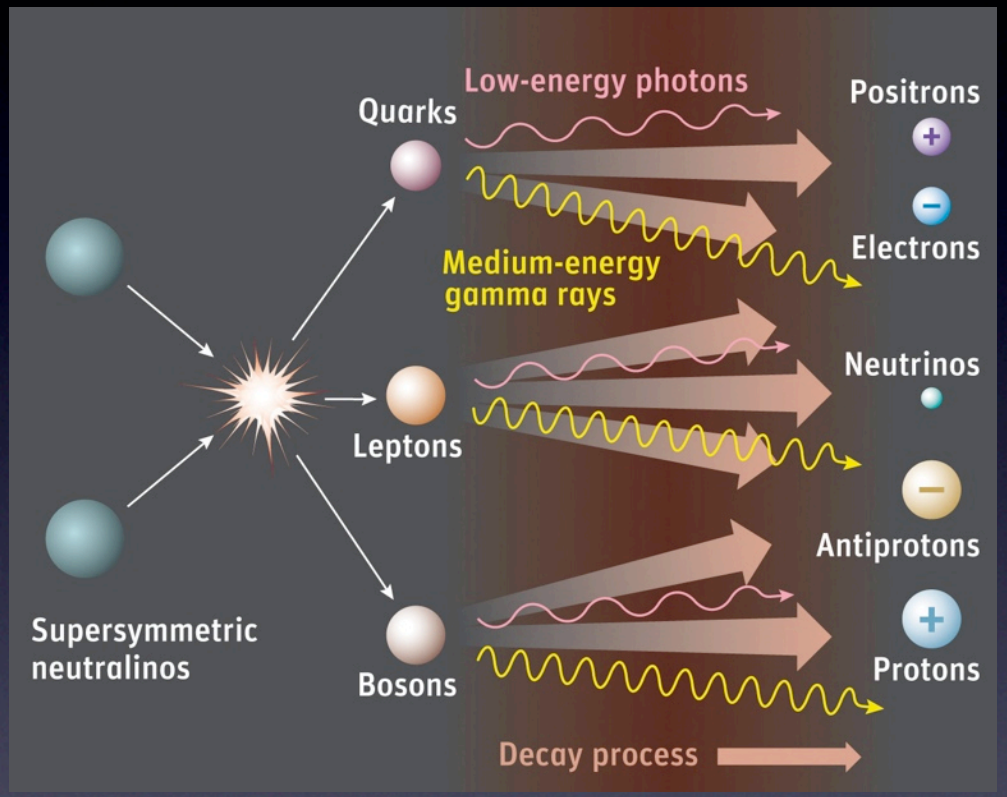
The Fermi Gamma-ray Space Telescope

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

Credit: NASA/General Dynamics

The dark matter annihilation signal

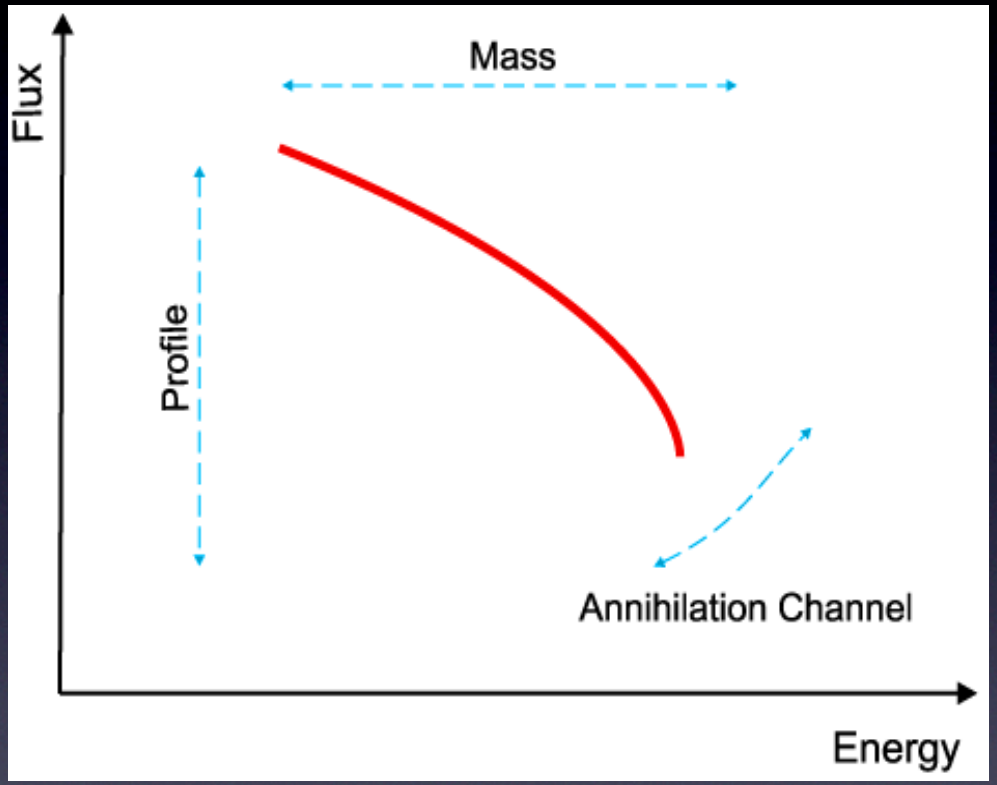
- annihilation of dark matter can produce a variety of potentially detectable particles
- gamma-rays and neutrinos point back to source, can map dark matter distribution



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



Bertone 2007

$$I(\psi) = \frac{K}{4\pi} \int_{los} \mathrm{d}s \; \rho^2(s,\psi) \qquad K = \frac{N_\gamma \langle \sigma v \rangle}{2 m_\chi^2}$$

Using anisotropy to find unresolved source populations

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

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

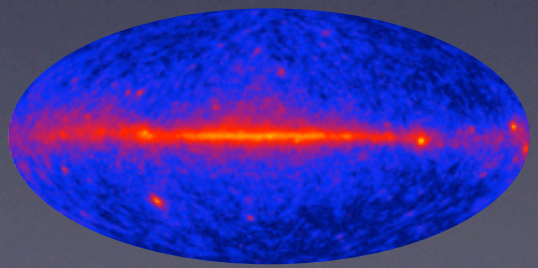
- the intensity energy spectrum: intensity as a function of energy

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

- 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

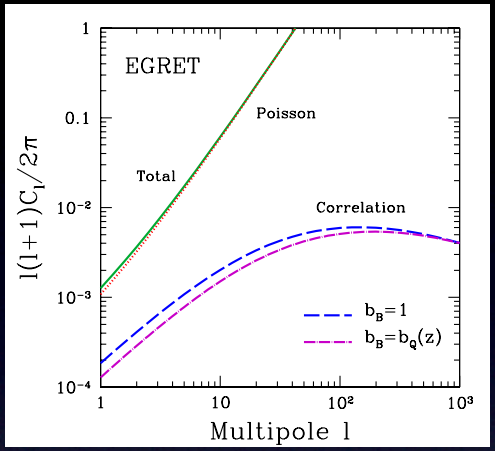
Characterizing the anisotropy

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

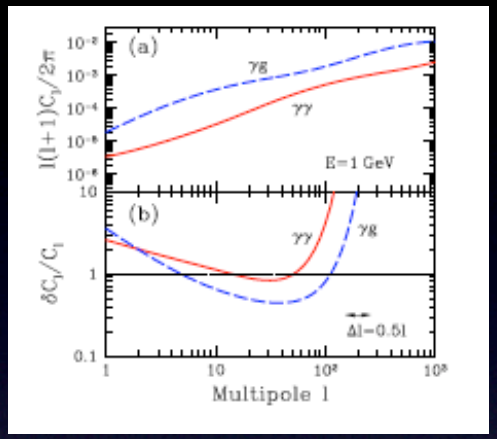
$$\delta I(\psi) \equiv \frac{I(\psi) - \langle I \rangle}{\langle I \rangle} \rightarrow \delta I(\psi) = \sum_{\ell,m} a_{\ell m} Y_{\ell m}(\psi) \rightarrow C_\ell = \langle |a_{\ell m}|^2 \rangle$$

- fluctuation power spectra are *independent of intensity normalization*
  - shape of the angular power spectrum is determined *exclusively* by the source distribution ↔ 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)

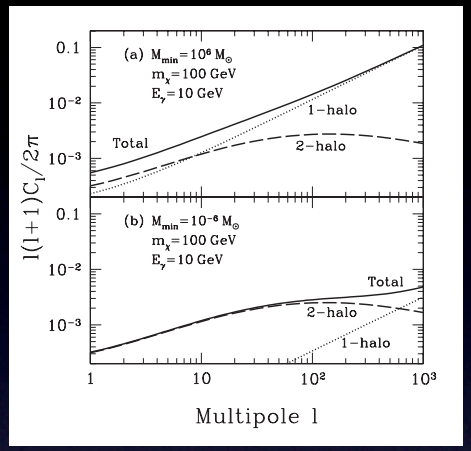
Angular power spectra of unresolved gamma-ray populations



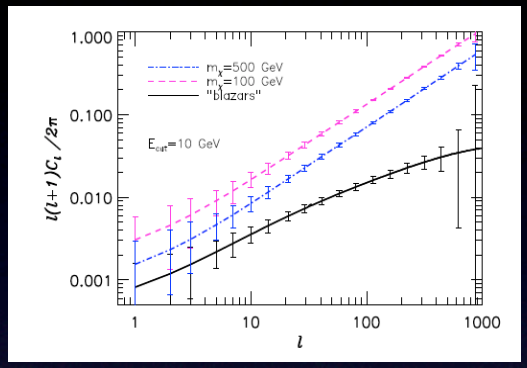
Blazars
Ando, Komatsu, Narumoto & Totani 2007



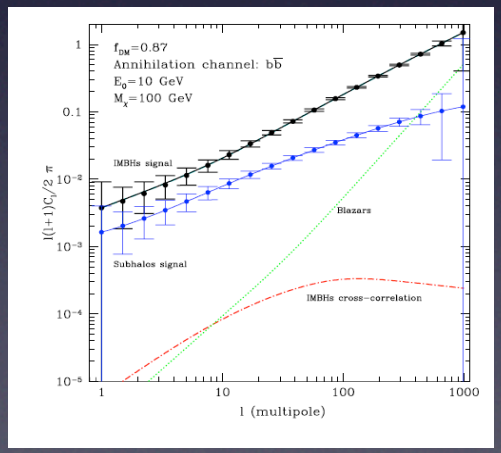
Starforming Galaxies
Ando & Pavlidou 2009



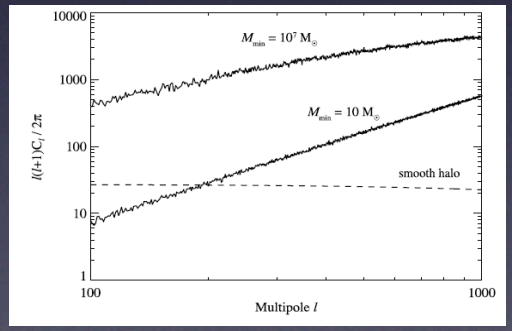
Extragalactic DM
Ando & Komatsu 2006



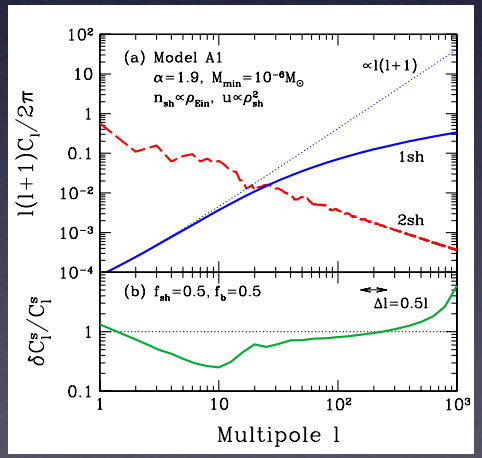
Extragalactic DM
Cuoco et al 2008



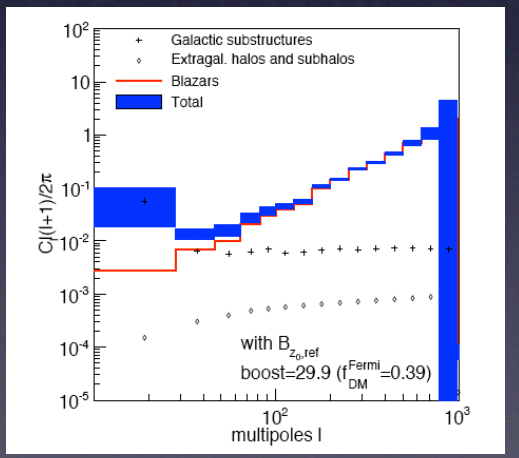
DM around EG IMBHs
Taoso, Ando, Bertone & Profumo 2008



Galactic subhalos
JSG 2008



Galactic subhalos
Ando 2009



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

How to identify source populations with anisotropy?

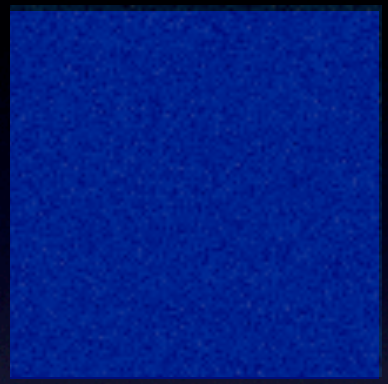
- the angular power spectrum of the total emission is determined by
  1. the fractional contributions of each source class to the intensity
  2. the amplitude of their individual angular power spectra

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

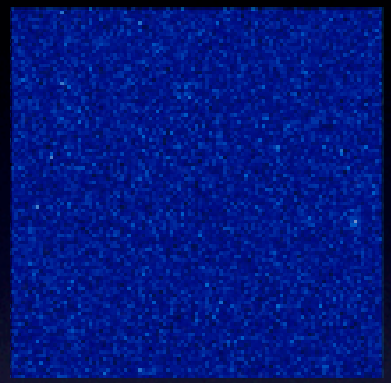
- most gamma-ray source classes are effectively uncorrelated (i.e., cross-correlation term is negligible)
- most gamma-ray source populations produce similarly-shaped, relatively featureless angular power spectra (shot-noise--like), the total angular power spectrum is likely to look shot-noise--like
- 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!

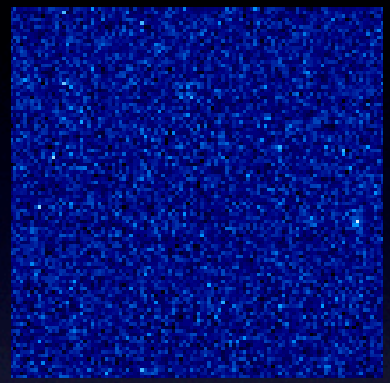
Energy-dependent anisotropy



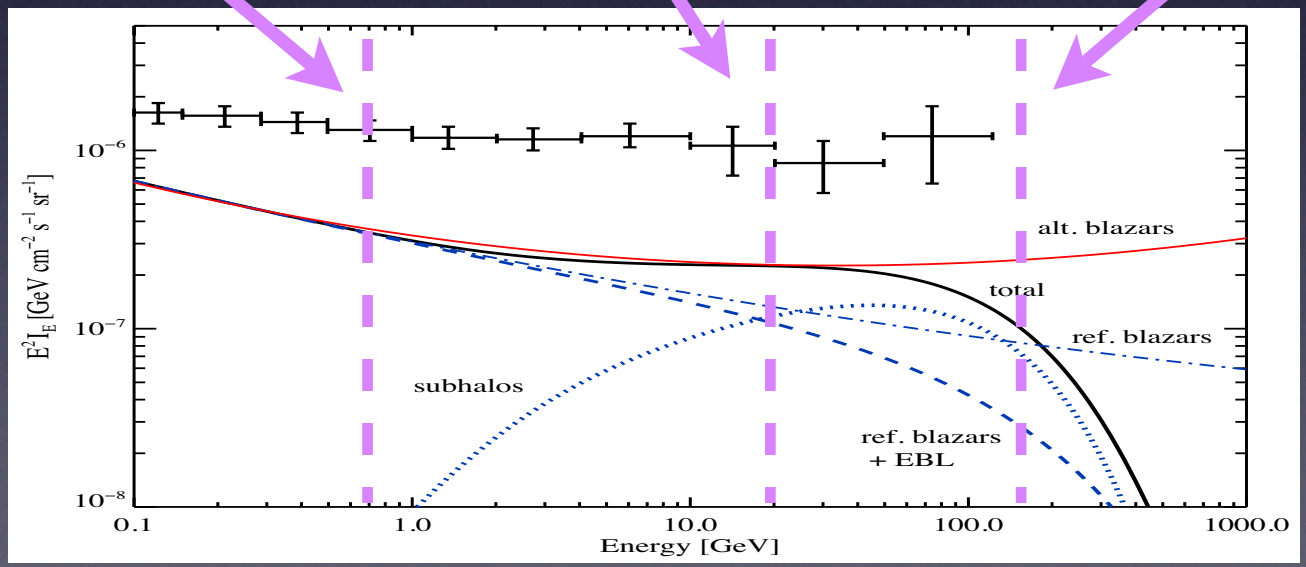
blazars



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:

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

- 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

- 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

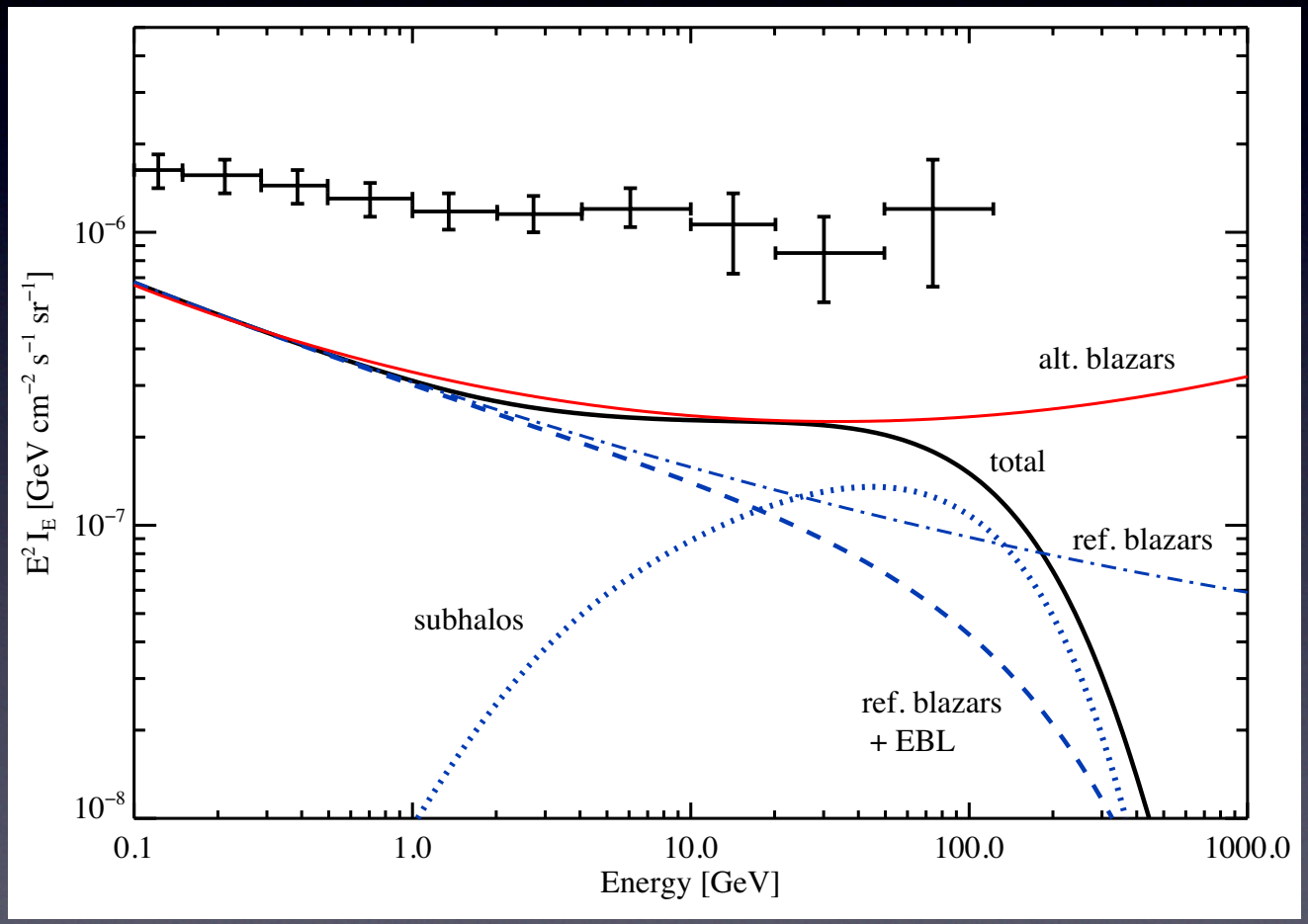
A dark matter feature in the intensity energy spectrum?
(or why we need anisotropy too)

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!

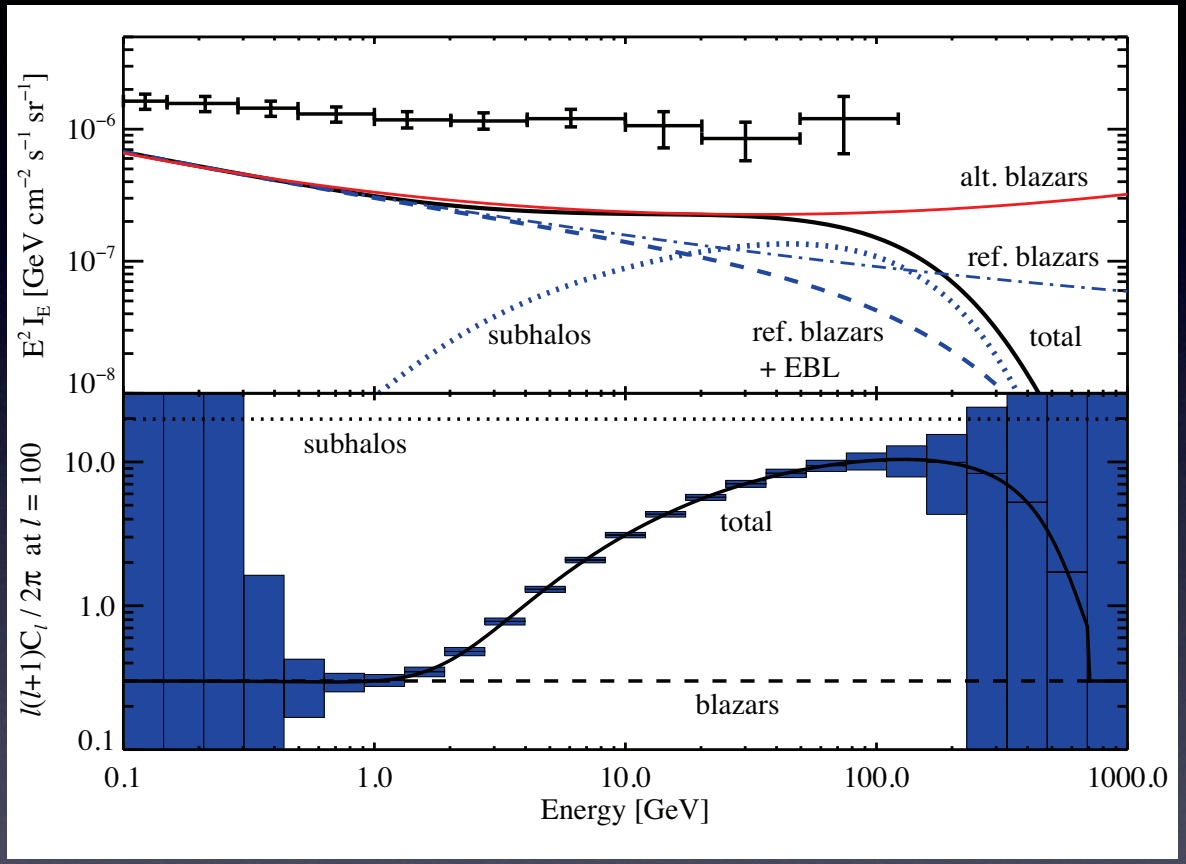
example isotropic diffuse intensity spectrum



JSG & Pavlidou 2009

The anisotropy energy spectrum at work

neutralino mass = 700 GeV



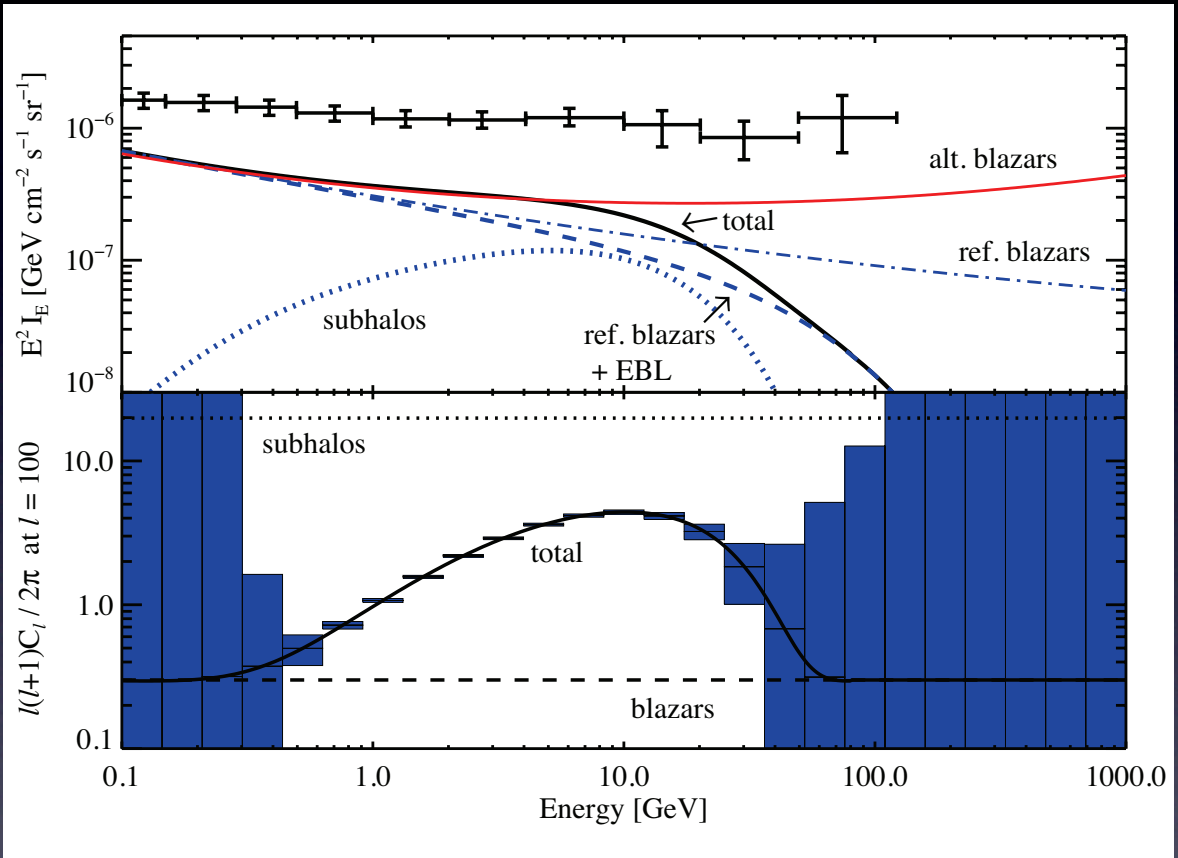
JSG & Pavlidou 2009

- 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



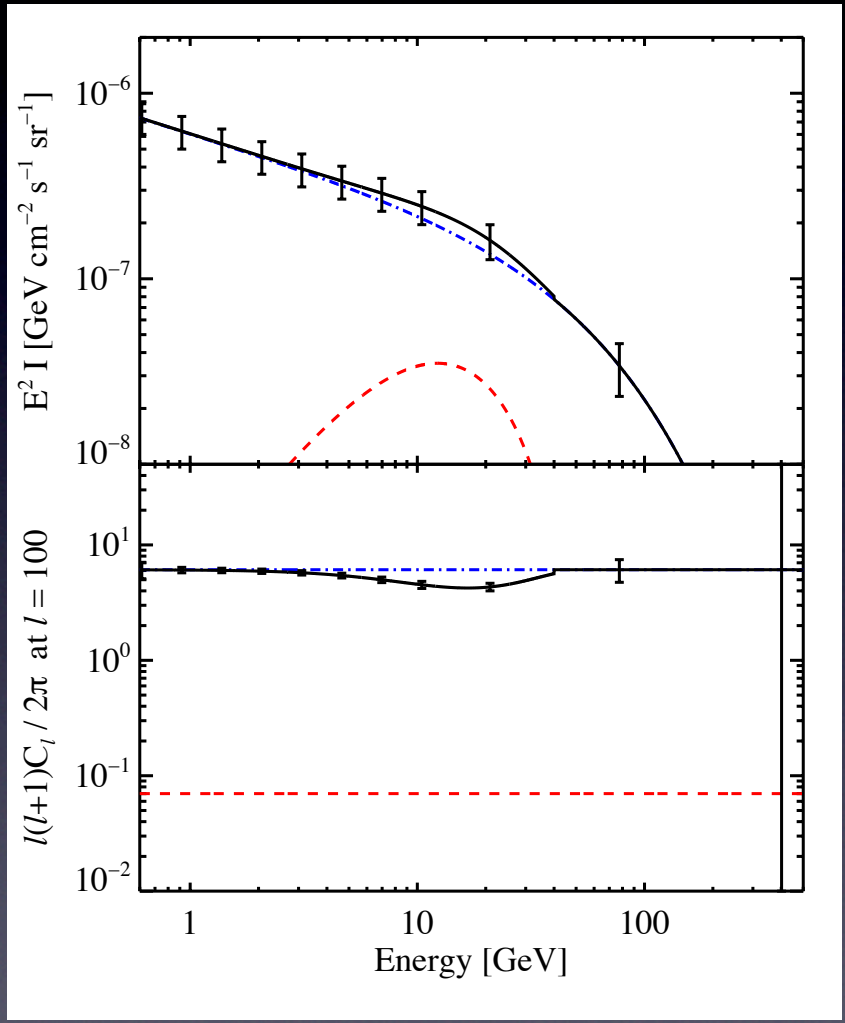
- 1-sigma errors
  - 5 years of Fermi all-sky observation
  - 75% of the sky usable
  - $N_b/N_s = 10$!!!!
- error bars blow up at low energies due to angular resolution, at high energies due to lack of photons

- 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

- 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:

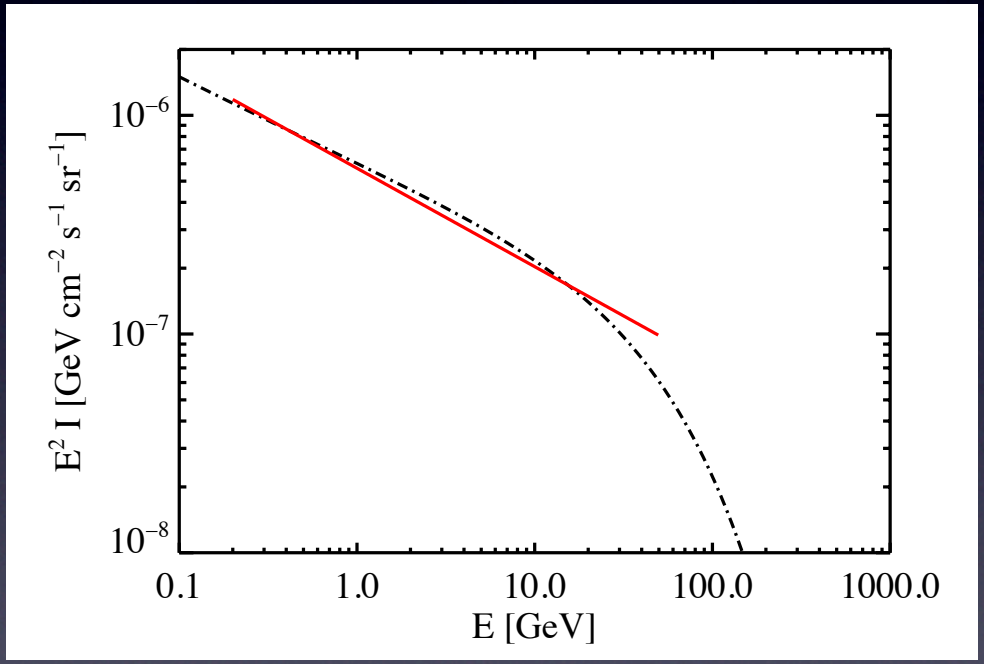
  is the anisotropy energy spectrum at E ≥ 0.5 GeV consistent with a constant value, equal to the weighted average of all energy bins?
- dark matter model is considered detectable if this hypothesis is rejected by a χ^2 test at the 95% CL level
- NB: this test is not optimized to find specific dark matter models; tailored likelihood analysis could significantly improve sensitivity!



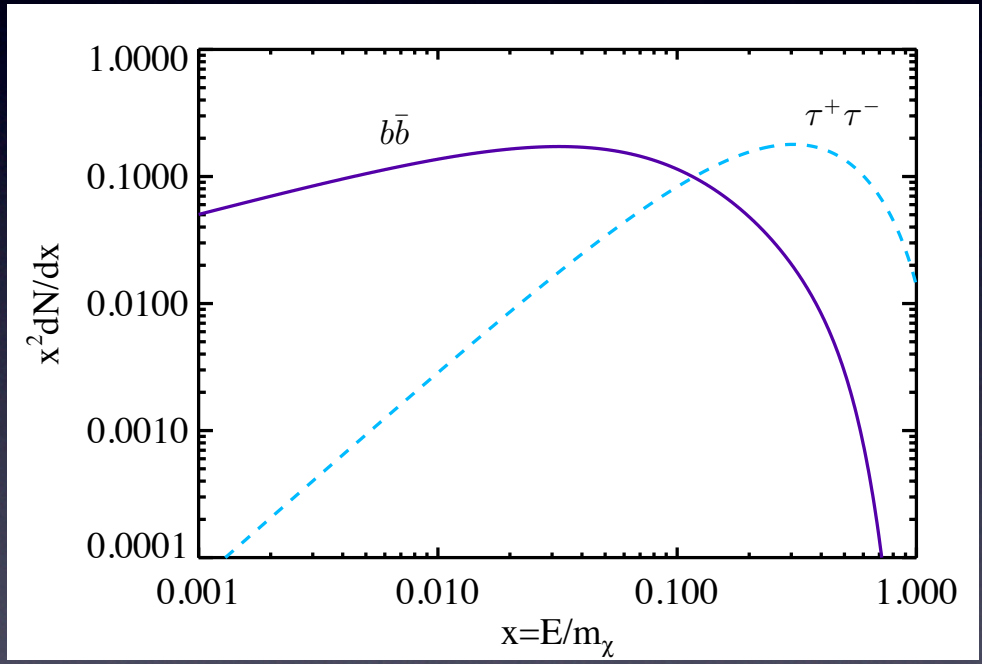
Hensley, JSG, & Pavlidou (2009)

Blazar and dark matter intensity spectra

reference blazar intensity spectrum

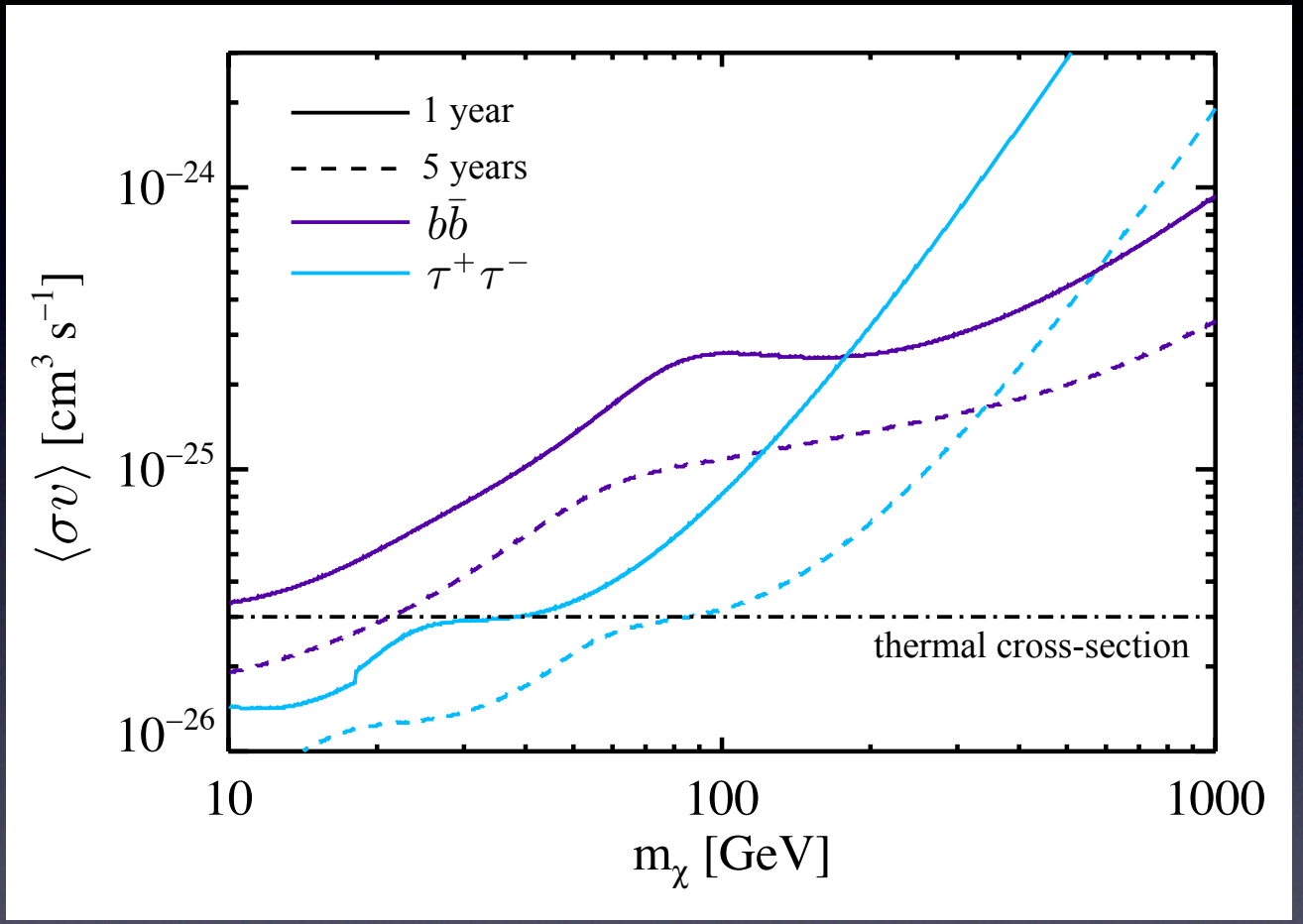


dark matter annihilation spectra



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!



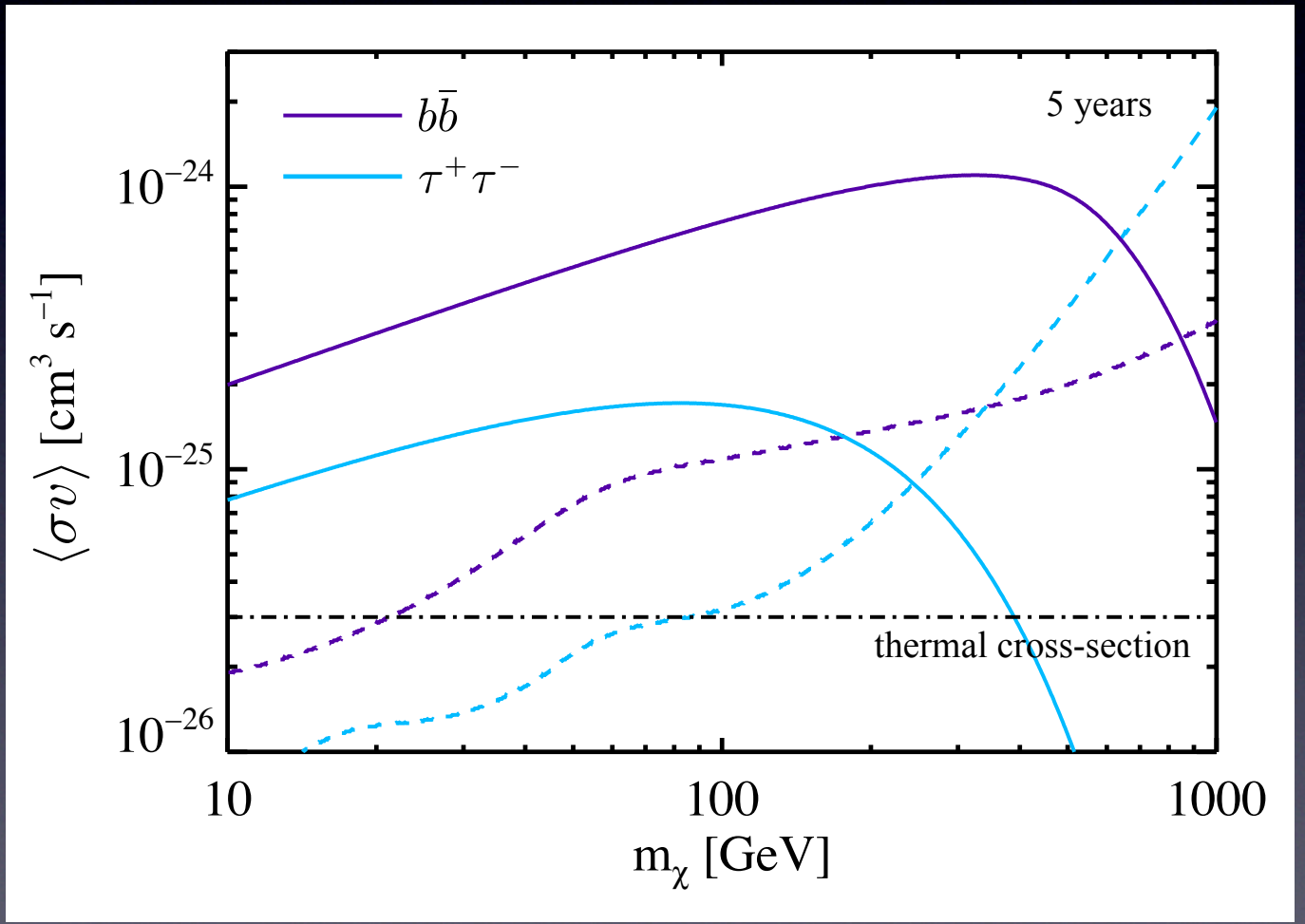
Hensley, JSG, & Pavlidou (2009)

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

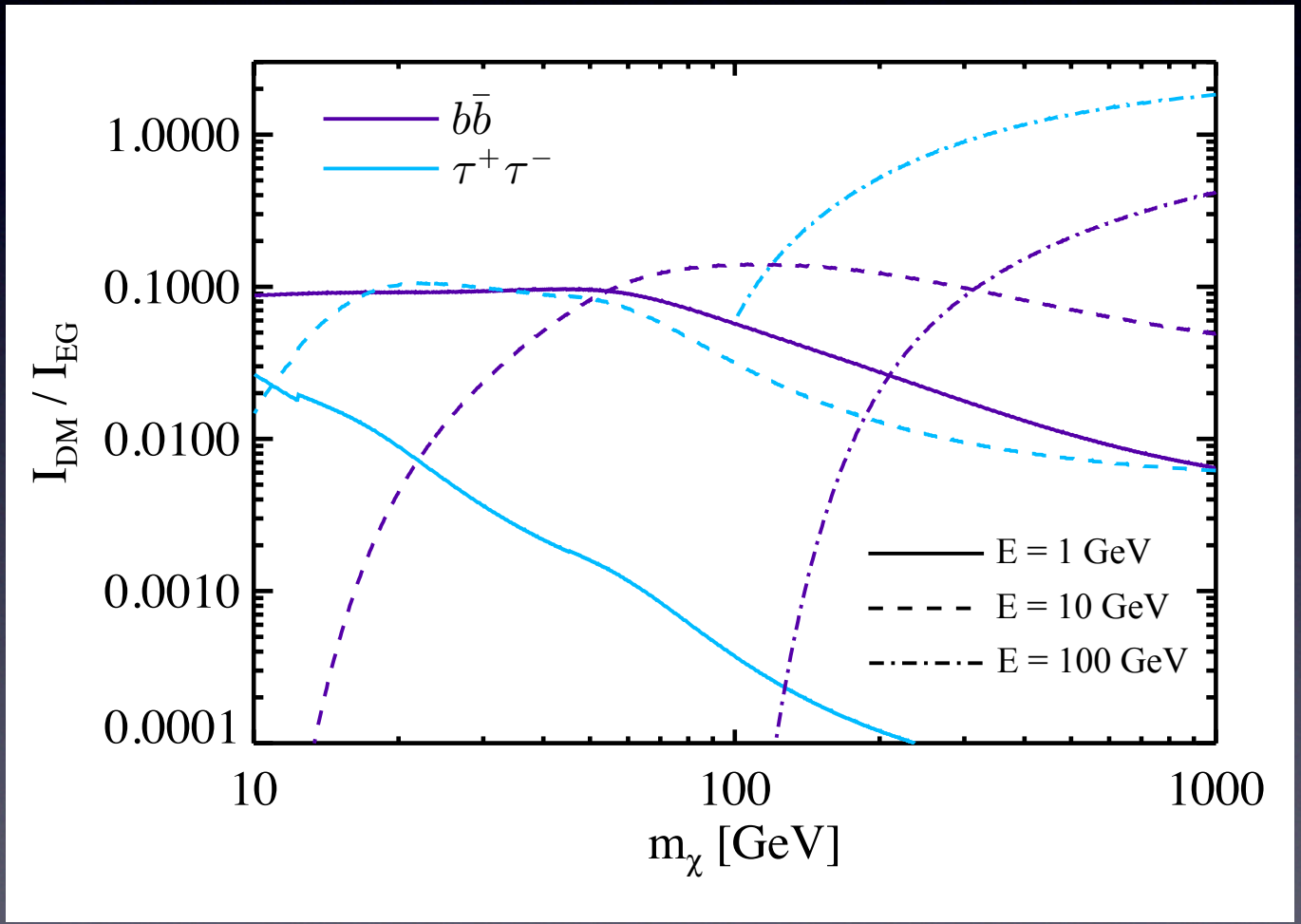


Hensley, JSG, & Pavlidou (2009)

Relative intensity of the required DM signal

ratio of dark matter to blazar intensity for 3 reference energies as a function of DM mass for detectable models corresponding to 5-yr sensitivity curves

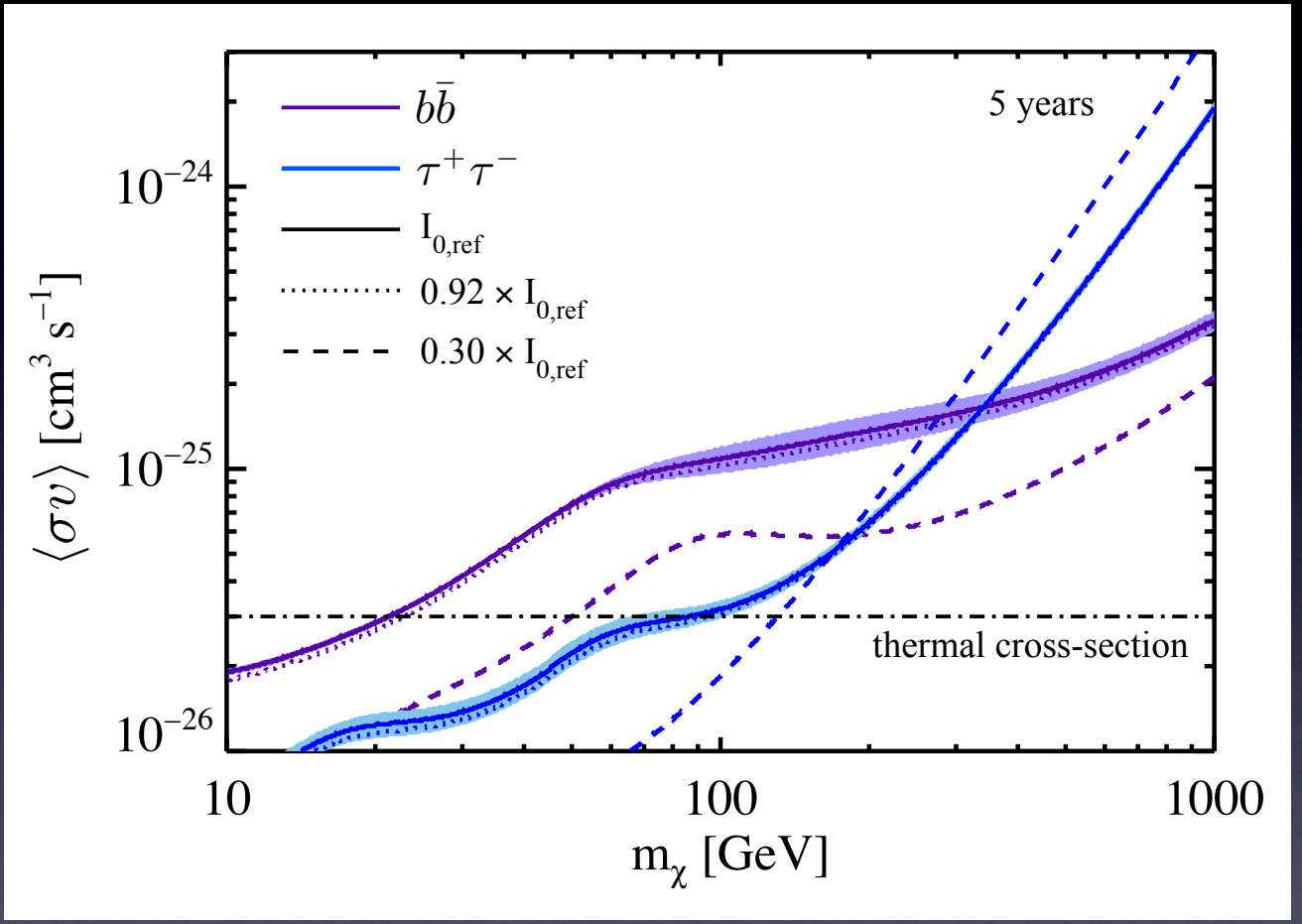
test is sensitive to models with DM intensity ~10% or less of blazar intensity at 1 and 10 GeV



Hensley, JSG, & Pavlidou (2009)

Dependence on blazar model parameters

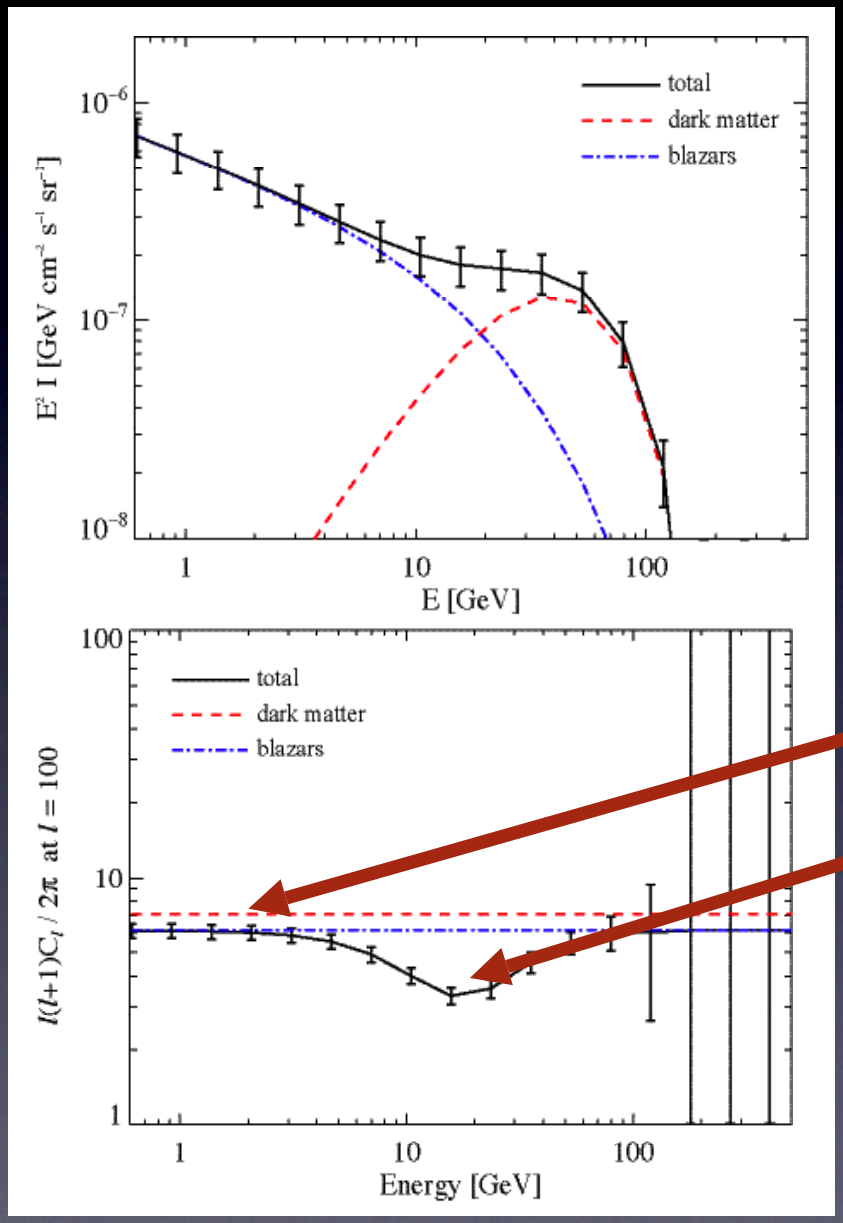
- shaded bands represent uncertainty from varying blazar spectral params within 1-sigma of their max likelihood values
- uncertainty in blazar spectrum impacts test sensitivity negligibly
- reducing blazar normalization increases DM detectability (but two-component scenario less plausible for small blazar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



Hensley, JSG, & Pavlidou (2009)

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

Separating the intensity spectra of 2 components



Hensley, Pavlidou & JSG (in prep)

in a two-component scenario with one component dominating the anisotropy at low energies,

when a dip or plateau in the anisotropy energy spectrum is observed,

each component's intensity spectrum can be extracted *without* a priori *assumptions about the shape of the intensity spectra or anisotropy properties!*

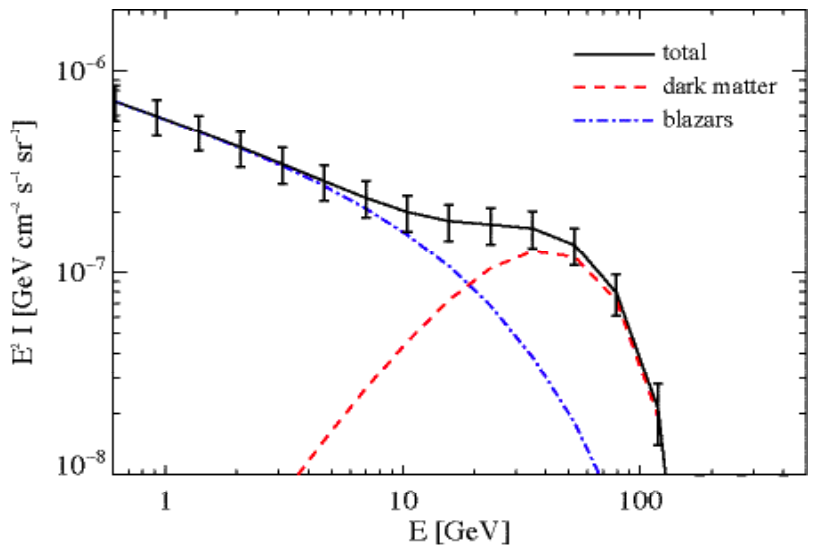
$$C_\ell^{\rm tot} = f_{\rm EG}^2 C_\ell^{\rm EG} + f_{\rm DM}^2 C_\ell^{\rm DM}$$

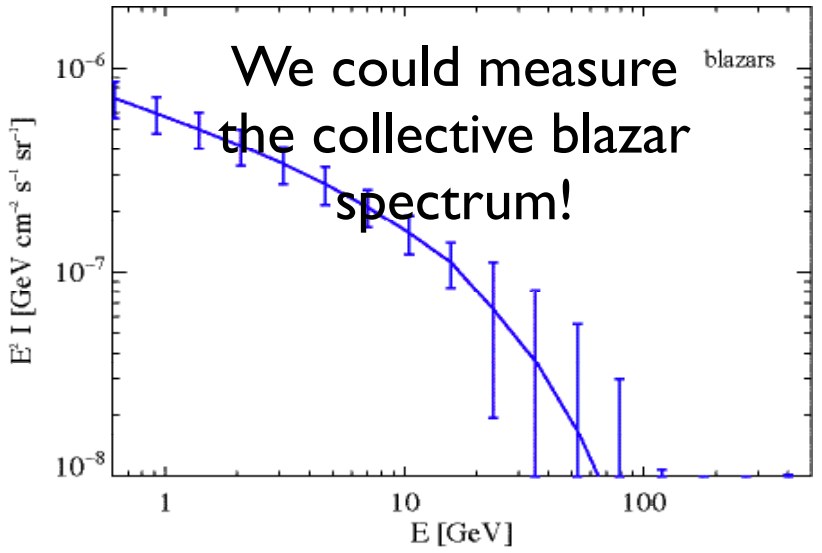
$$f_{EG} + f_{DM} = 1$$

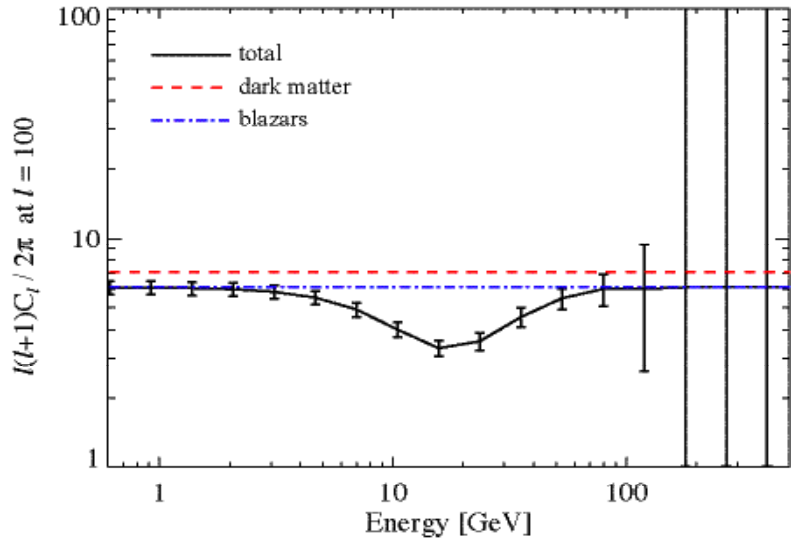
At minimum:

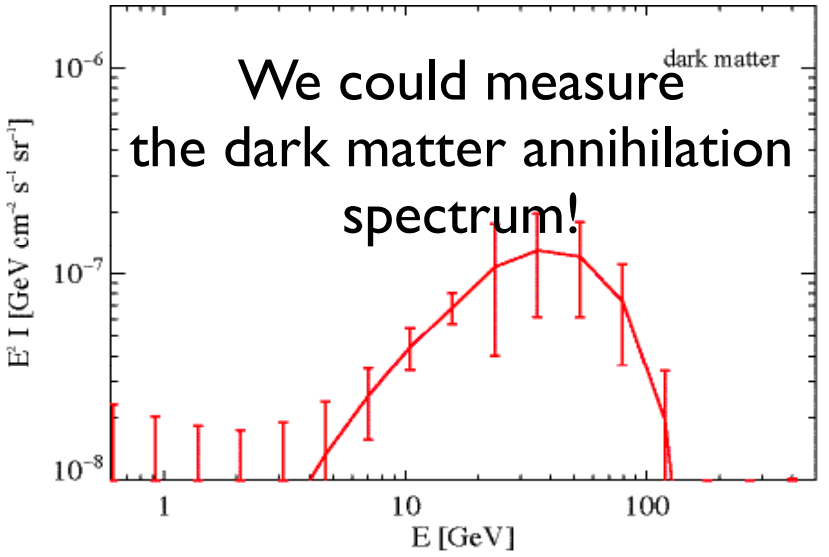
$$C_\ell^{\rm DM} = \frac{C_\ell^{\rm EG} C_\ell^{\rm tot}}{C_\ell^{\rm EG} - C_\ell^{\rm tot}}$$

Source spectra deconvolved!









Hensley, Pavlidou & JSG (in prep)

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
- 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
- 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!