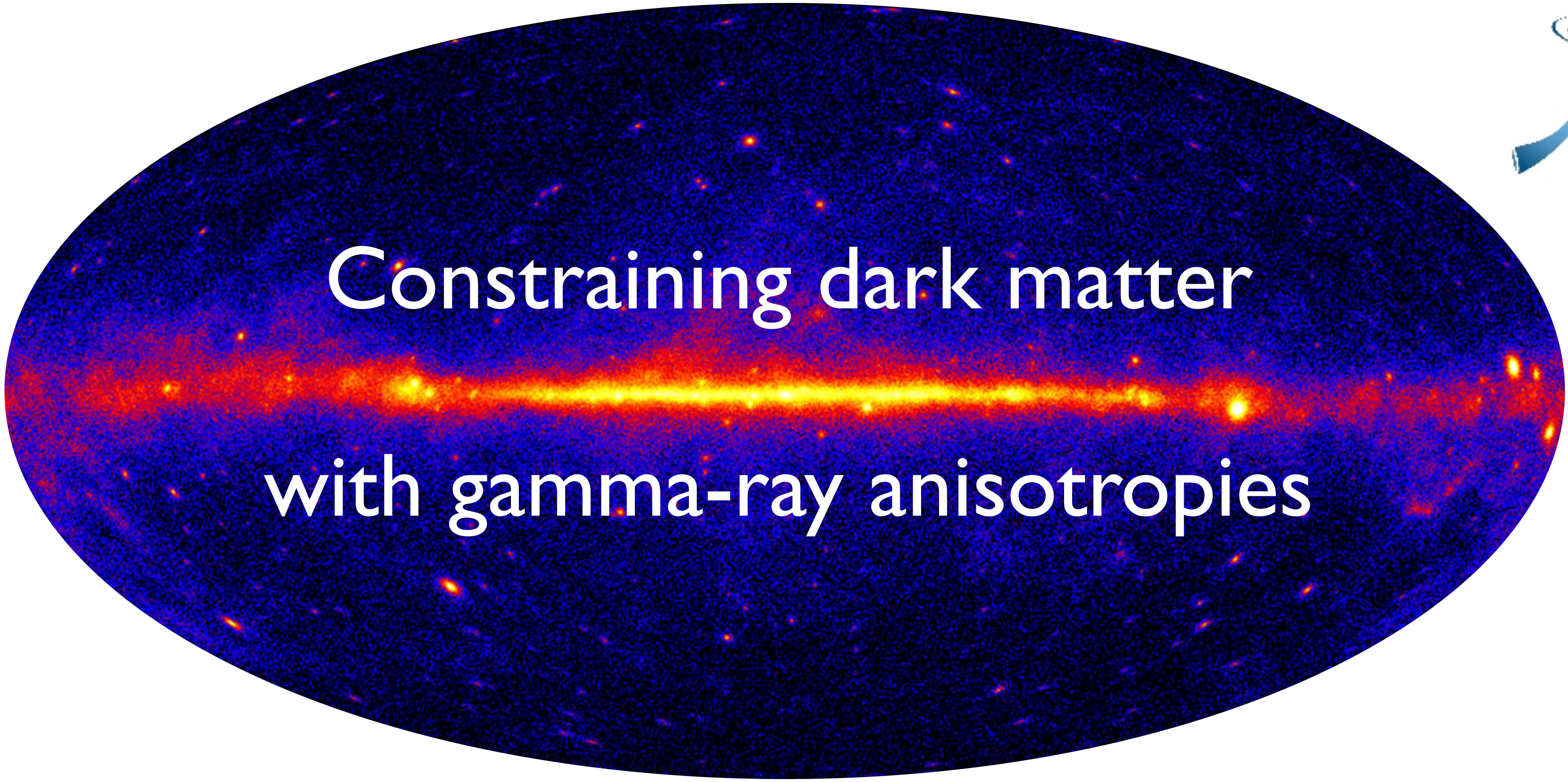
Image Credit: NASA/DOE/International LAT Team



Constraining dark matter with gamma-ray anisotropies

Jennifer Siegal-Gaskins

Caltech

with

A. Cuoco, T. Linden, M.N. Mazziotta, and V.Vitale
on behalf of
the Fermi LAT Collaboration
and
E. Komatsu

based on

The Fermi LAT Collaboration & Komatsu,
arXiv:1202.2856; Phys. Rev. D 85, 083007 (2012)

Cuoco, Komatsu, and JSG, arXiv:1202.5309

JSG, 2012, *in prep*

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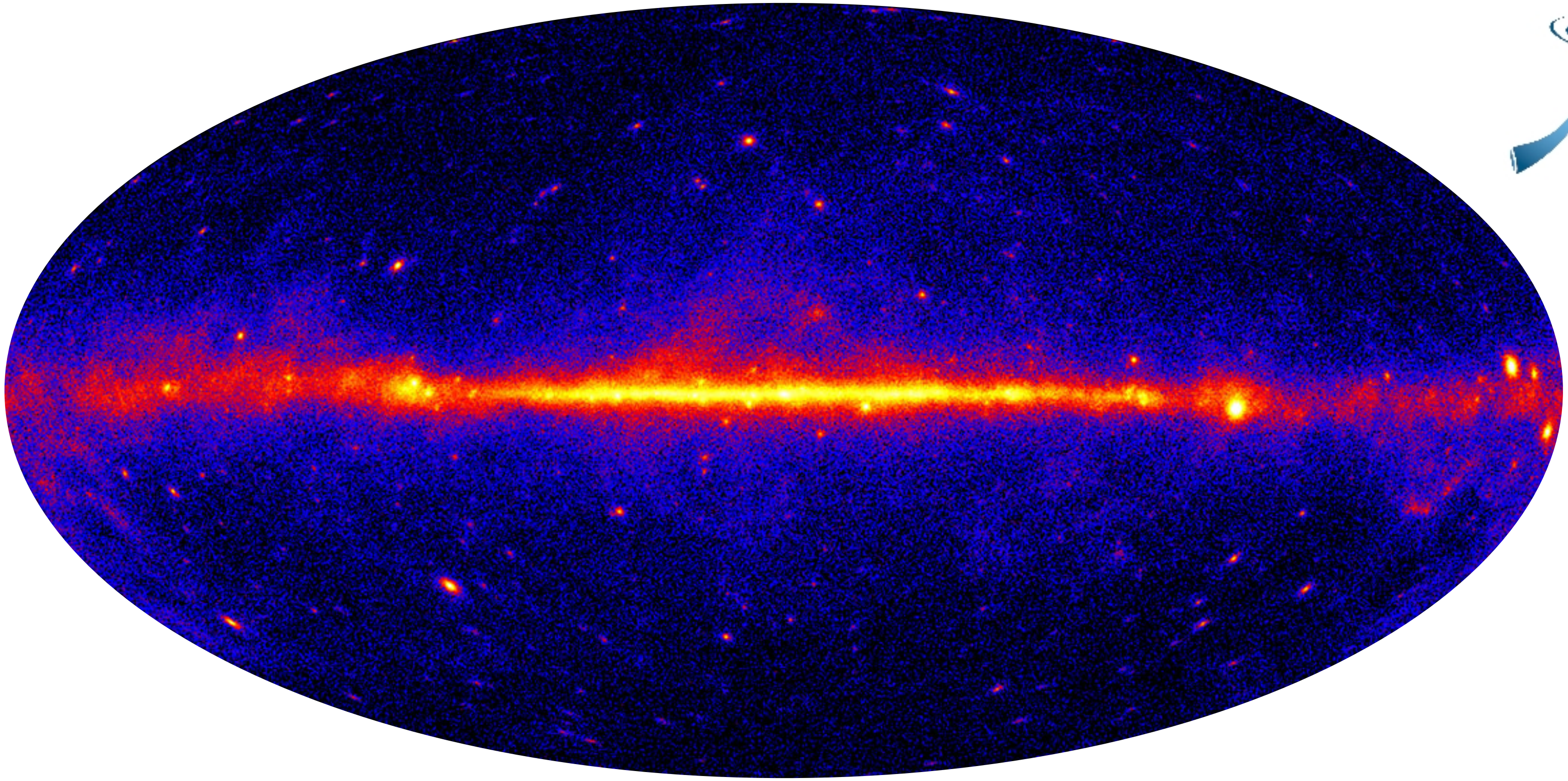

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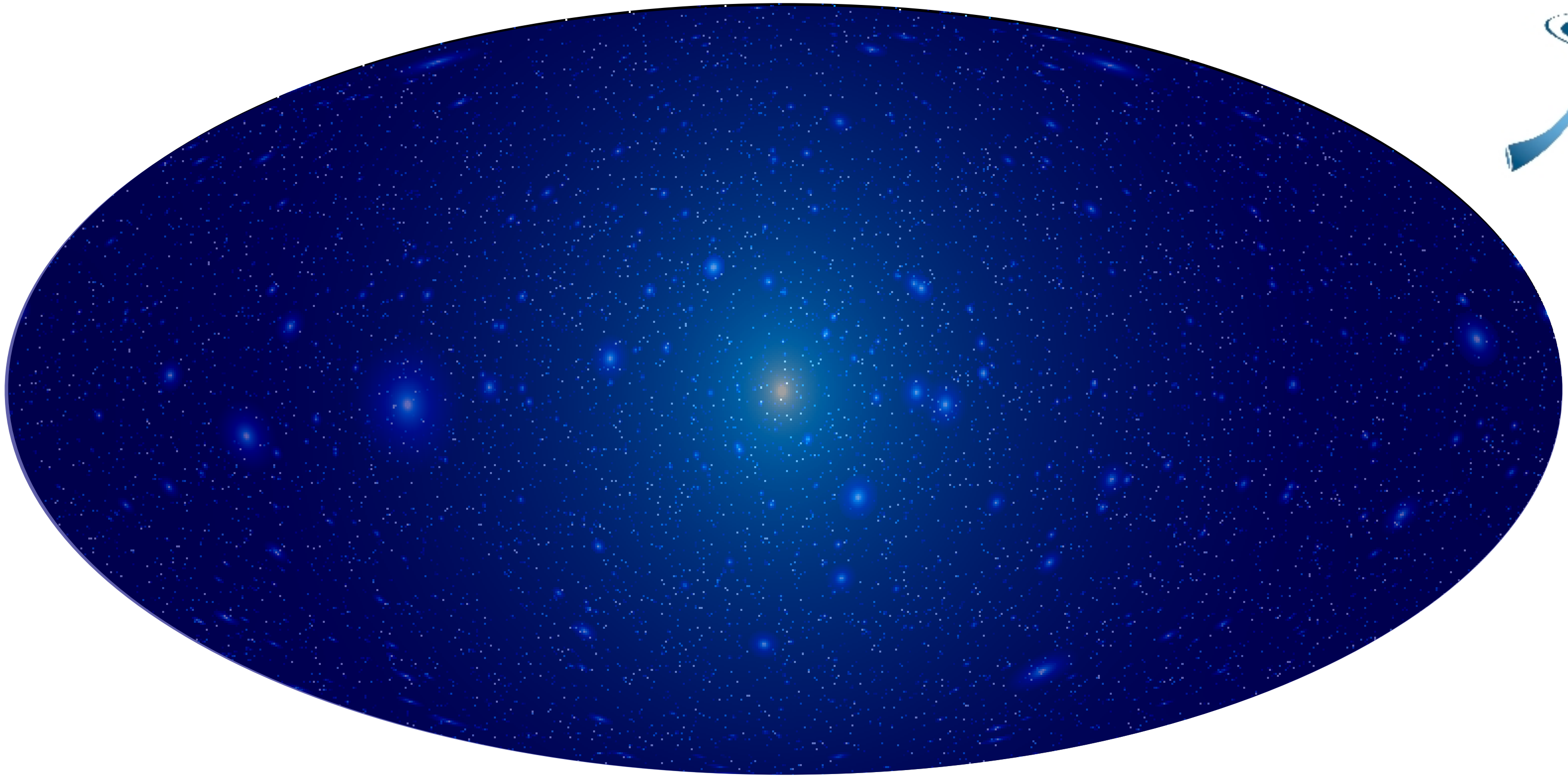

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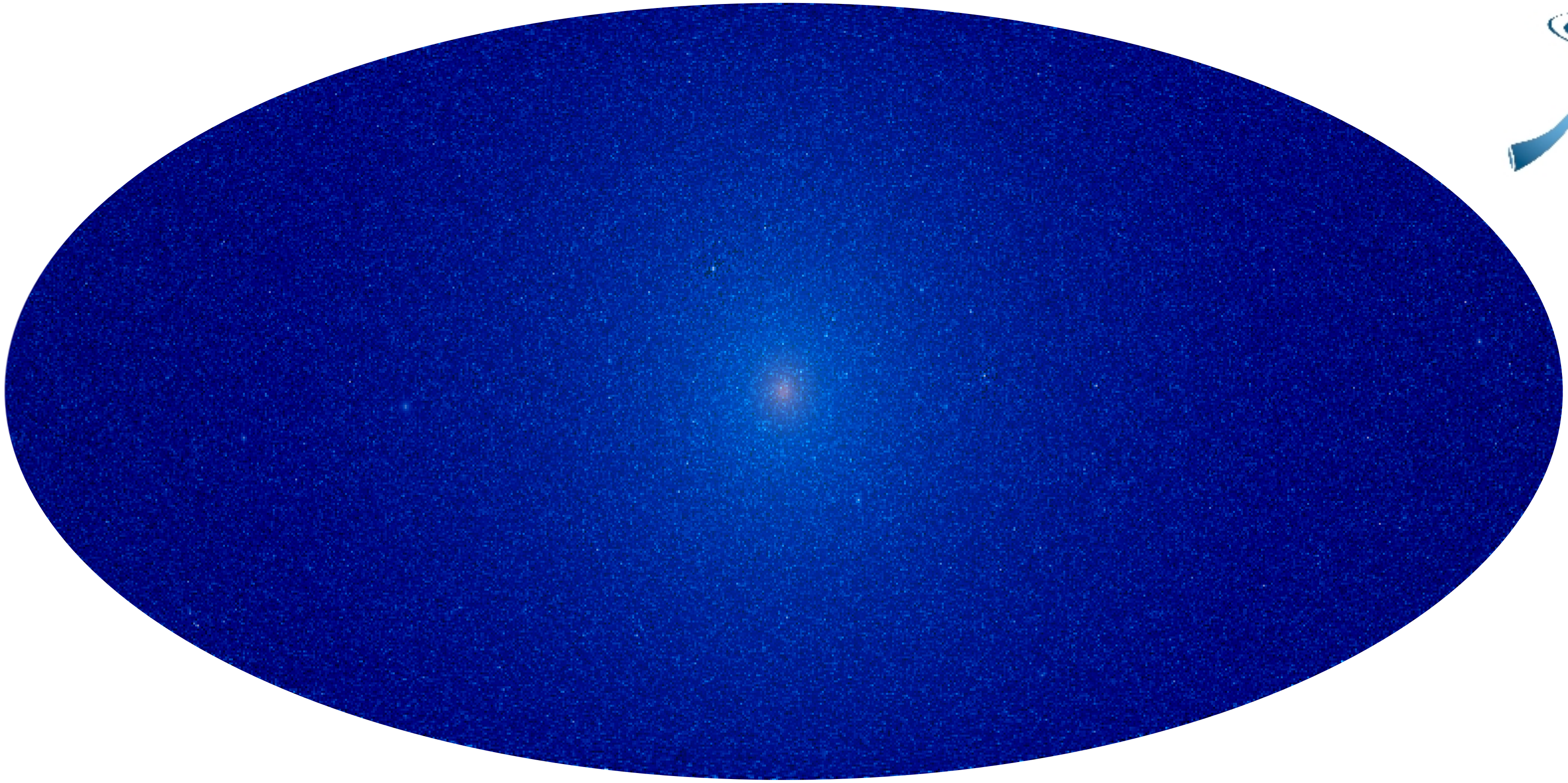

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Outline

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- Anisotropies in the gamma-ray sky: motivation and measurement

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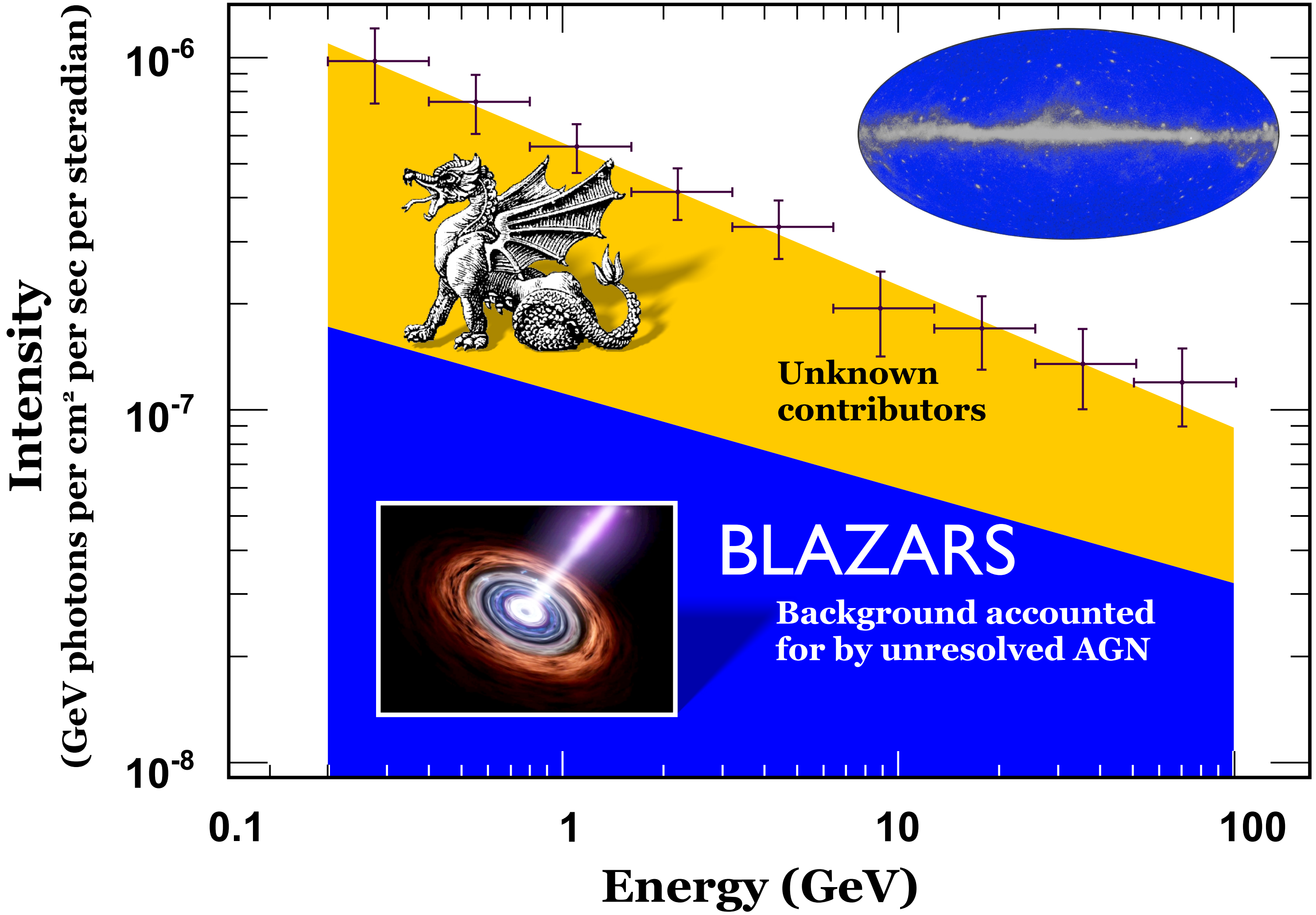
- Something provocative

Outline

- Anisotropies in the gamma-ray sky: motivation and measurement
- Something provocative
- Something really new

What is making the diffuse gamma-ray background?

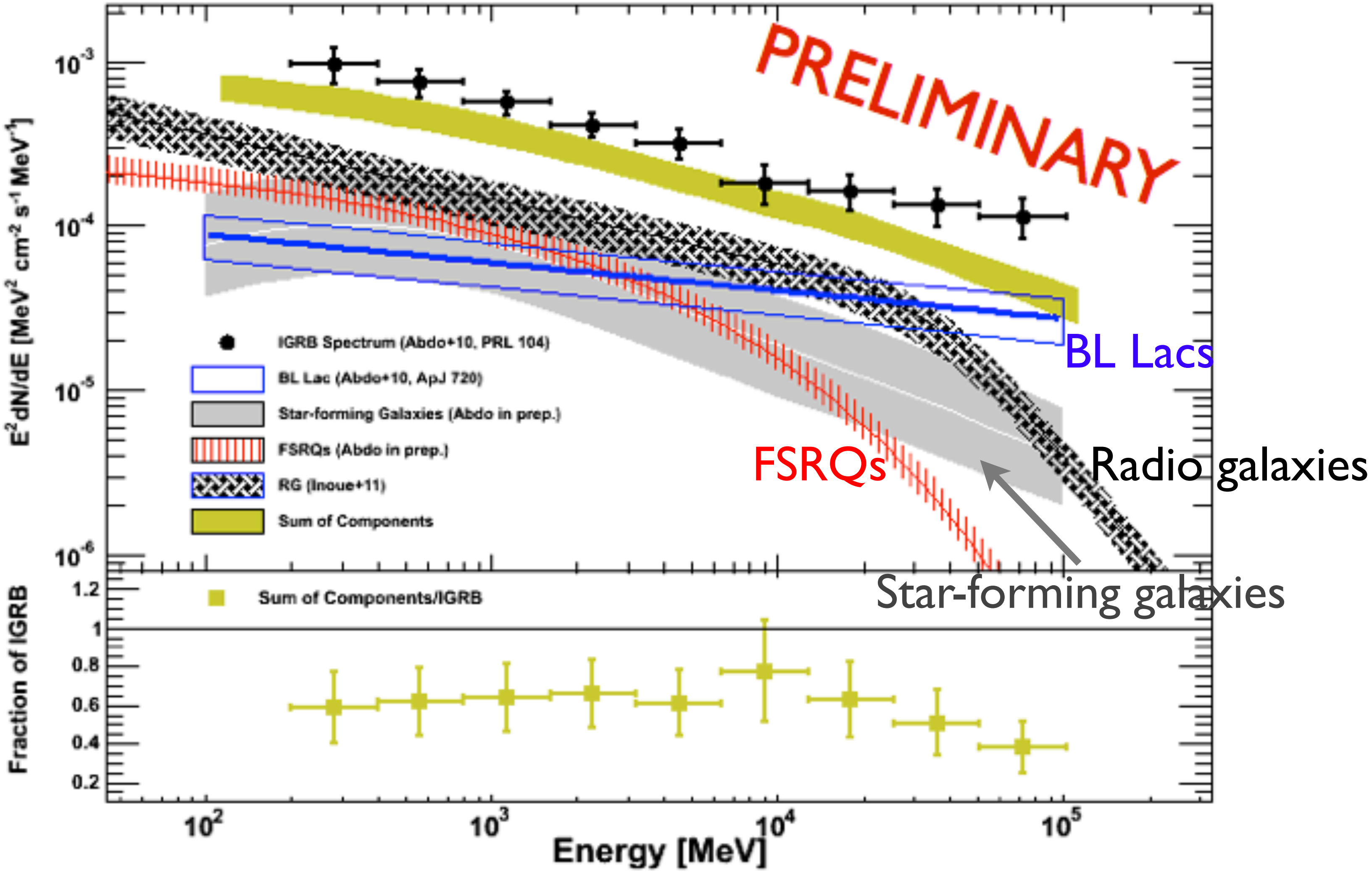
Energy spectrum of the Fermi-LAT
isotropic gamma-ray background (IGRB)



Credit: NASA/DOE/Fermi LAT Collaboration

What is making the diffuse gamma-ray background?

Expected contribution of source populations to the IGRB

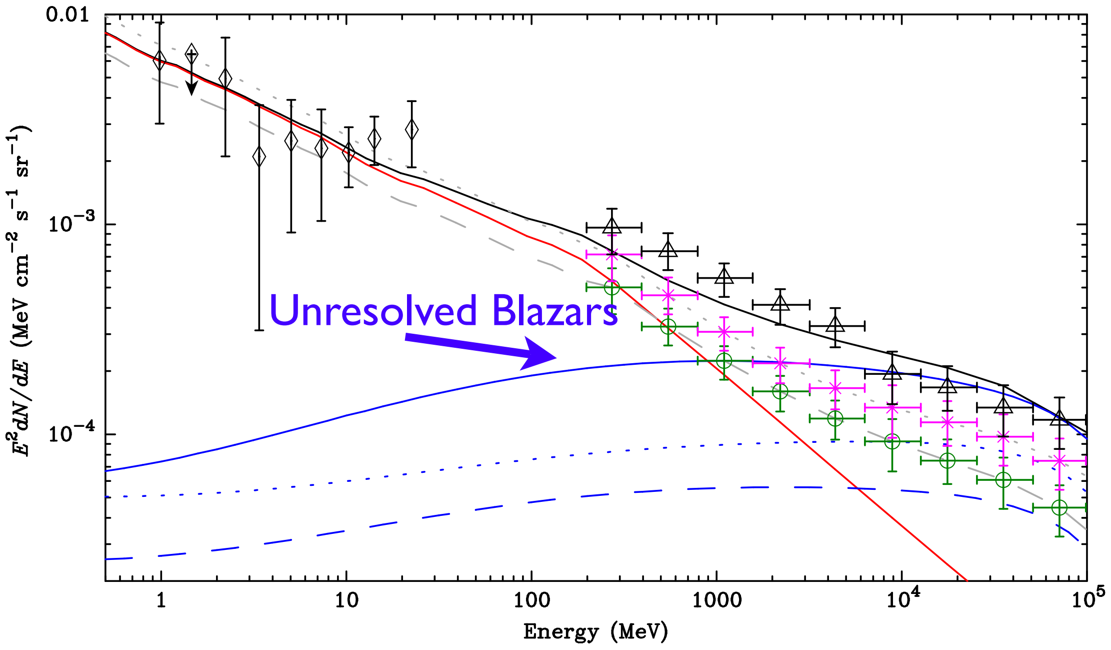


Fermi-LAT Collaboration (preliminary)

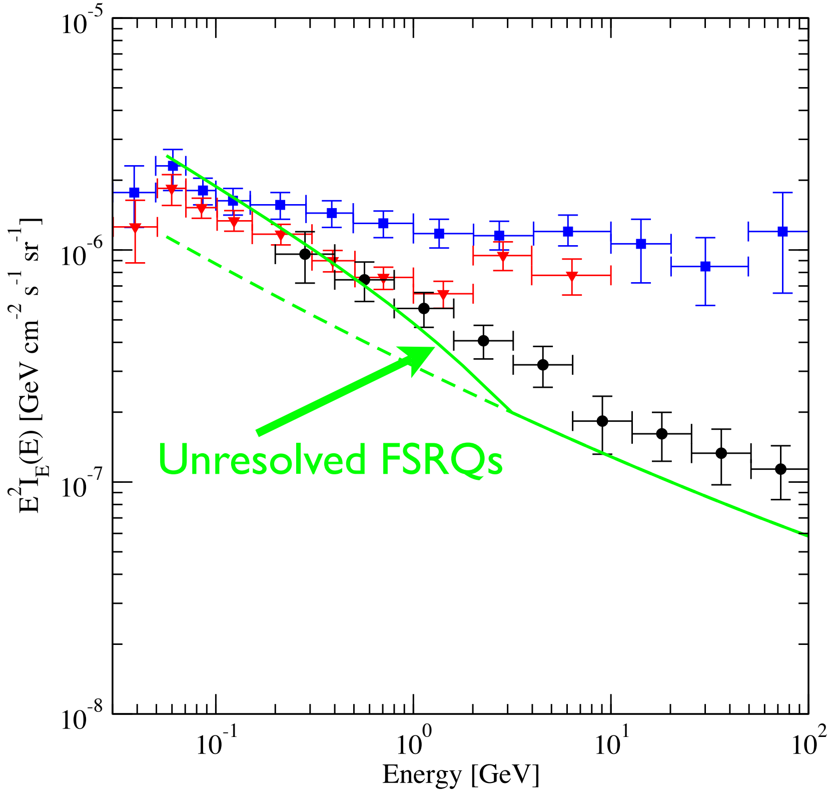
Sum is ~ 40-70% of IGRB intensity (energy-dependent)

What is making the diffuse gamma-ray background?

Other predictions for the blazar contribution to the IGRB



Abazajian et al 2011



Stecker & Venters 2011

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

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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: $\frac{C_\ell}{\langle I \rangle^2}$
  - *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)

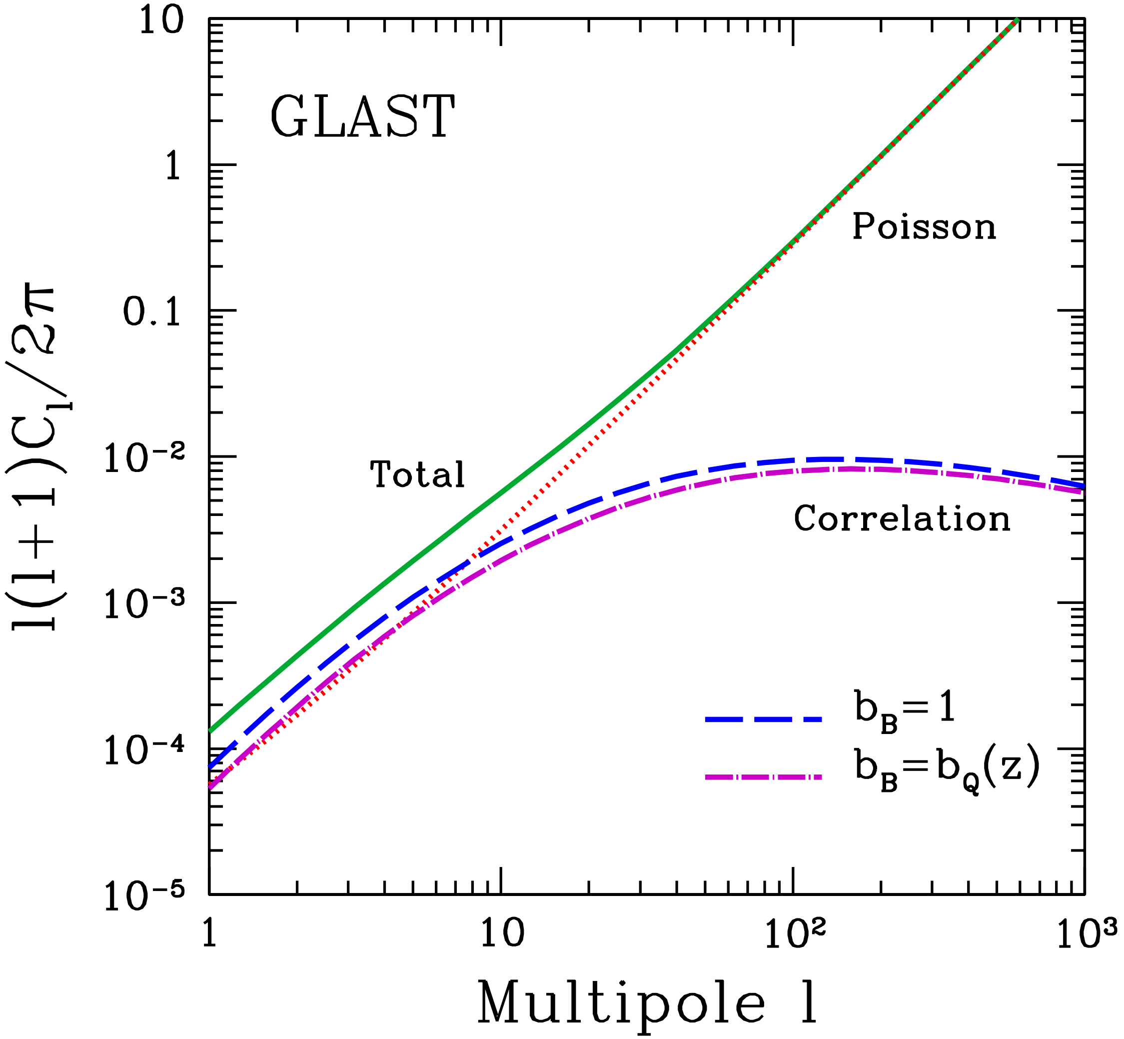
Angular power spectra of unresolved gamma-ray sources

- 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 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

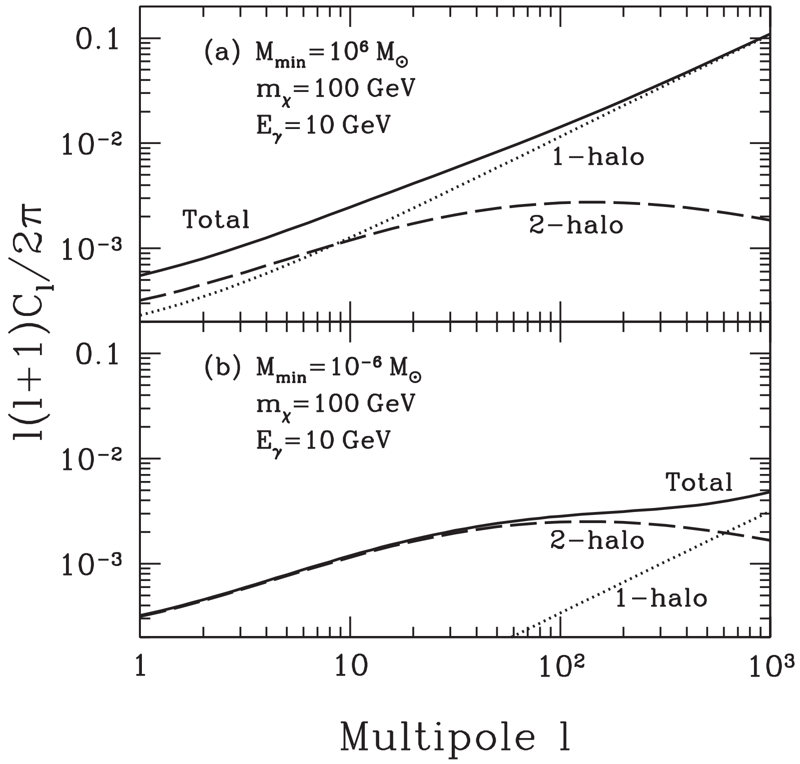


Ando, Komatsu, Narumoto & Totani 2007

Gamma-ray anisotropies from dark matter

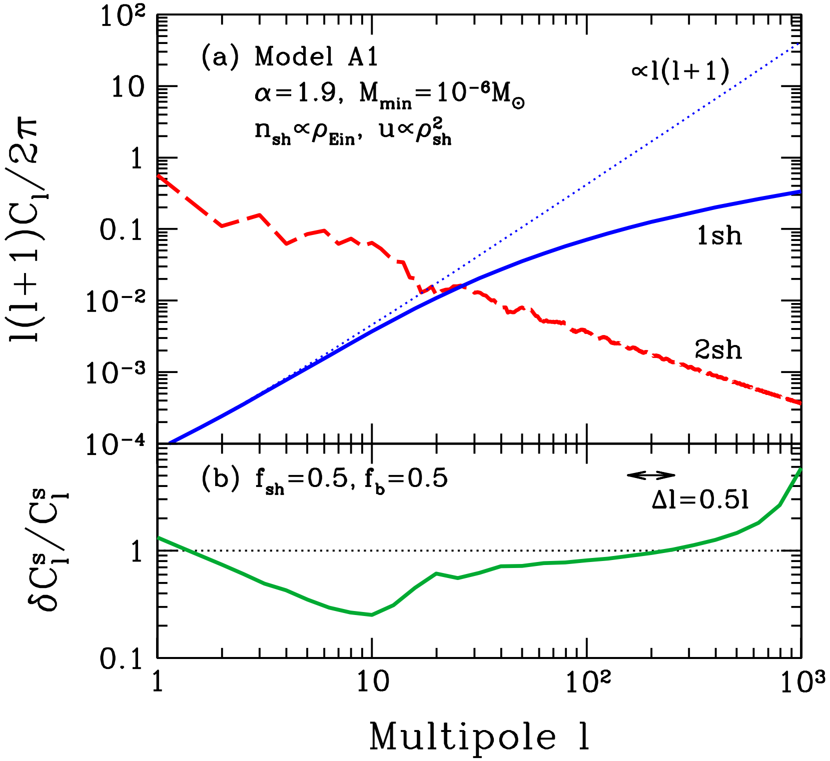
gamma rays from DM annihilation (and decay) in Galactic and extragalactic dark matter structures could imprint small angular scale fluctuations in the diffuse gamma-ray background

Anisotropy from extragalactic DM



Ando & Komatsu 2006

Anisotropy from Galactic DM

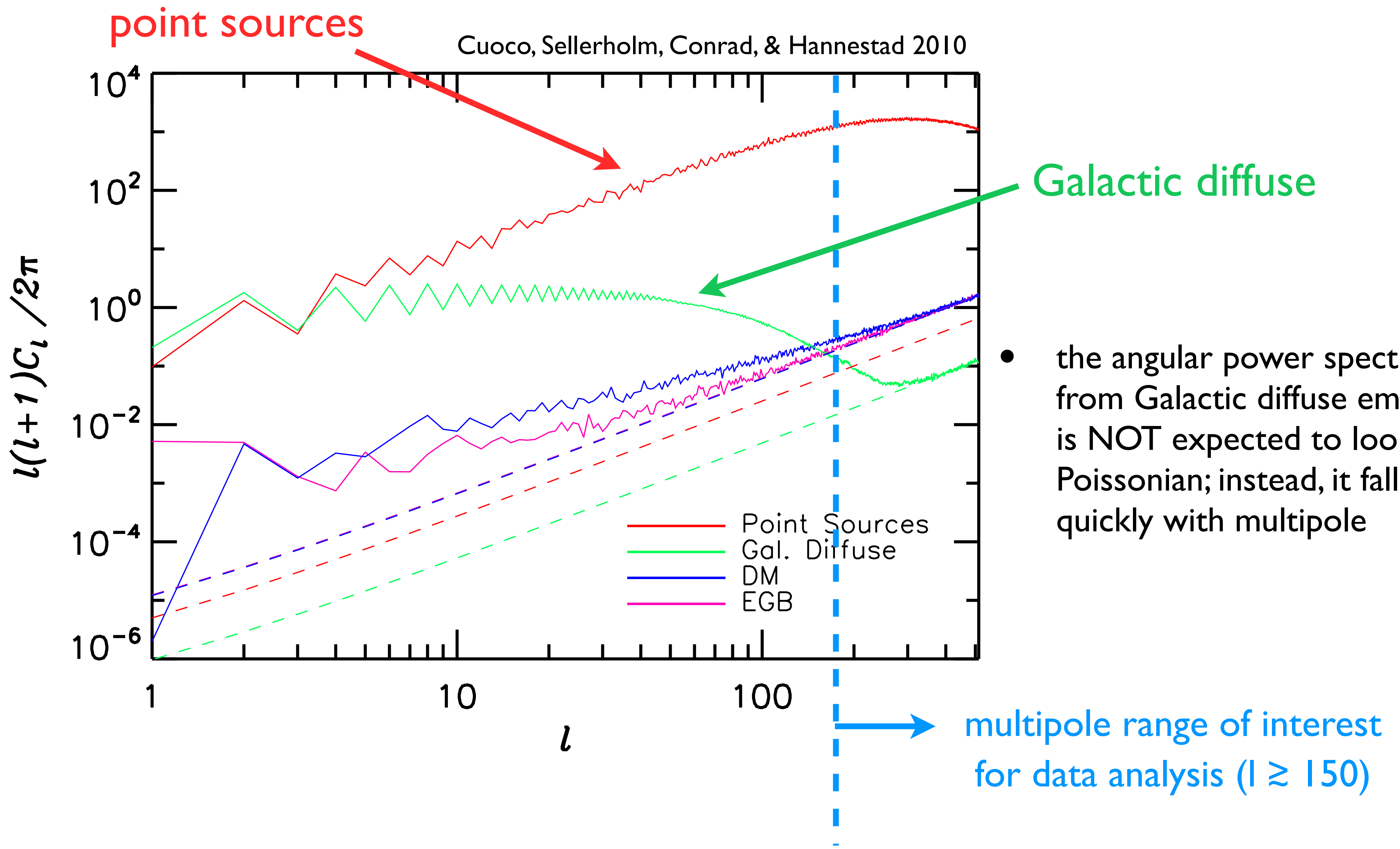


Ando 2009

see also: Ando et al 2007, Miniati et al 2007, JSG 2008, Cuoco et al 2008, Fornasa et al 2009, Zavala et al 2010, Cuoco et al 2011, Campbell & Dutta 2011

and Jesus' talk!

Angular power spectra of foregrounds



multipole range of interest for data analysis (l ≳ 150)

- the angular power spectrum from Galactic diffuse emission is NOT expected to look Poissonian; instead, it falls off quickly with multipole

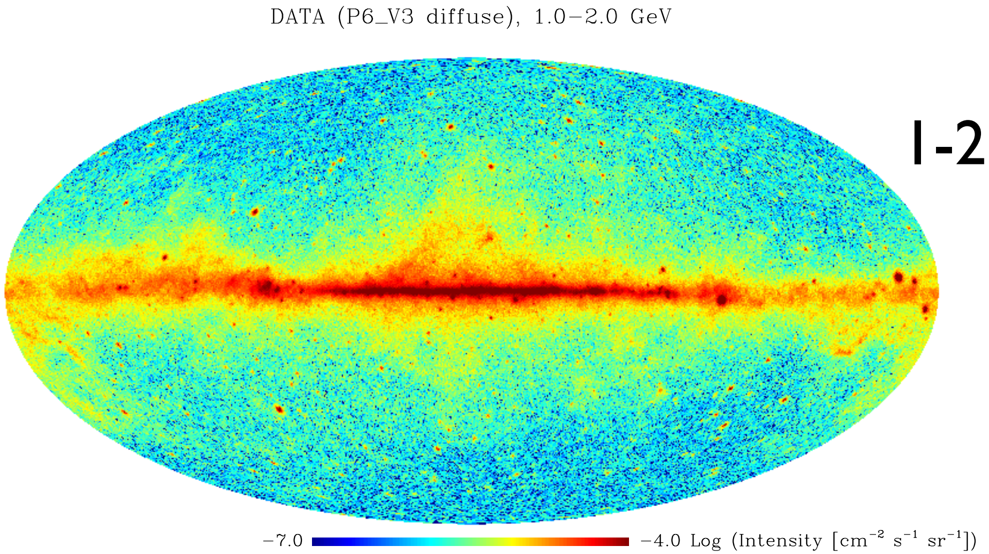
The Fermi Large Area Telescope (*Fermi* LAT)

- 20 MeV to > 300 GeV
- Angular resolution ~ 0.1 deg above 10 GeV
- Uniform sky exposure of ~ 30 mins every 3 hrs
- Excellent charged particle background rejection

Credit: NASA/General Dynamics

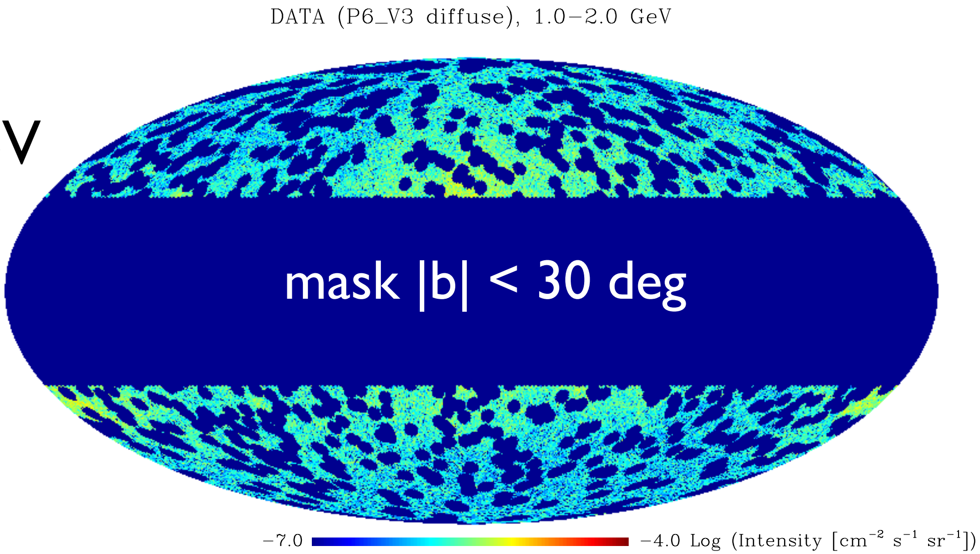
Angular power spectrum analysis of Fermi LAT data

All-sky map



1-2 GeV

Map with default mask applied



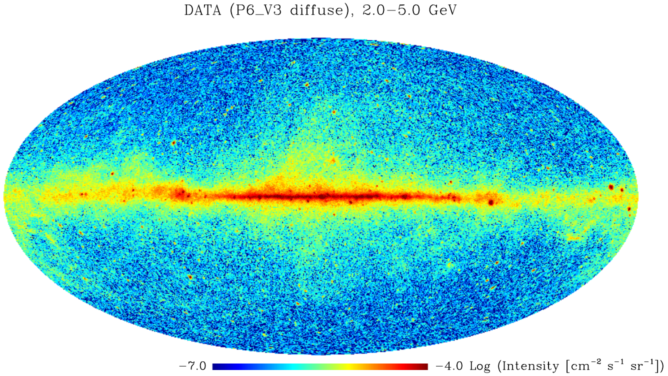
- data selection: ~ 22 months of data, diffuse class events
- energy range: 1 GeV - 50 GeV, divided into 4 energy bins for angular power spectrum analysis
- masking: 11-month catalog sources are masked within a 2 deg angular radius, and |b| < 30 deg masked to reduce contamination by Galactic diffuse emission

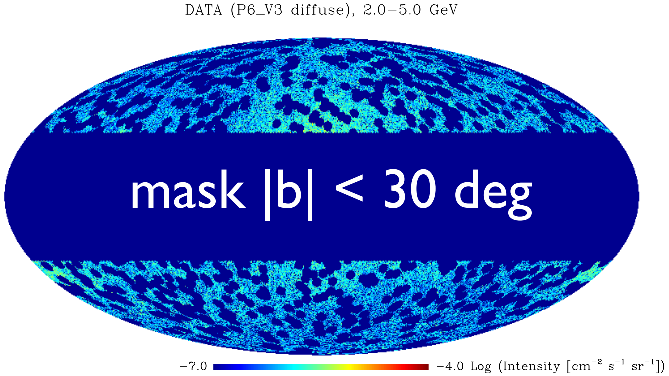
Angular power spectrum analysis of Fermi LAT data

All-sky map

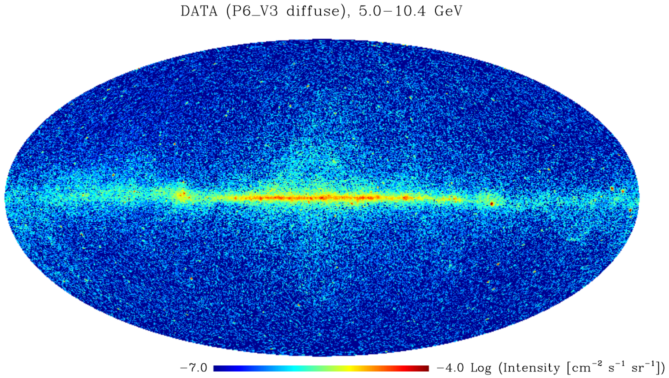
Map with default mask applied

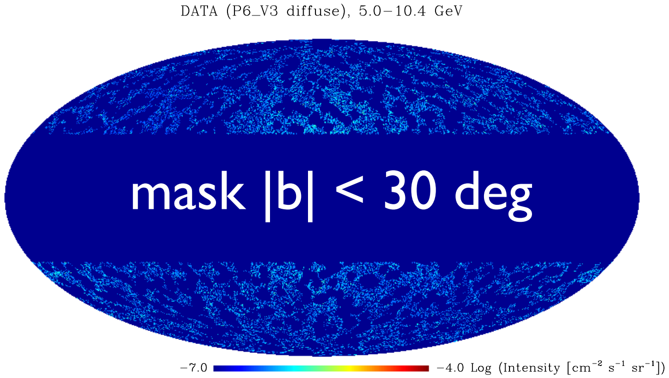
2-5 GeV



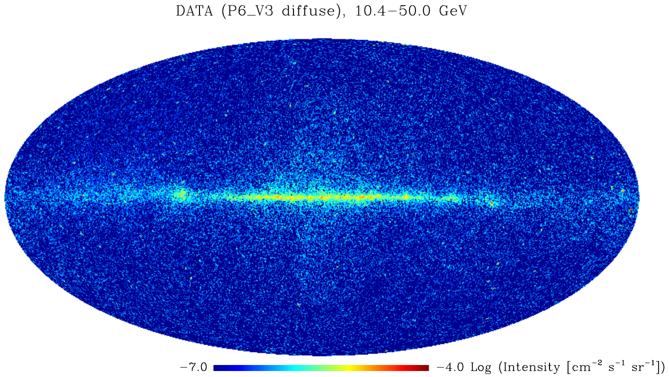


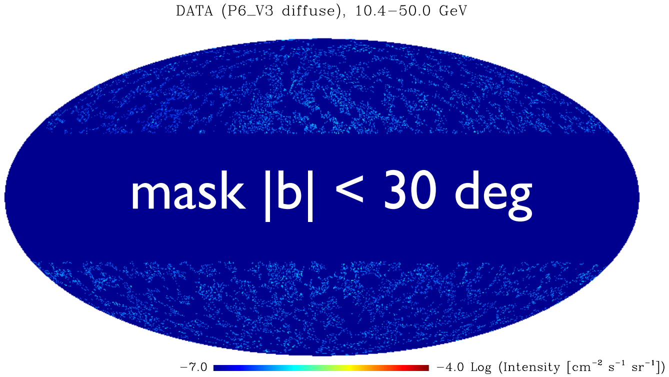
5-10 GeV





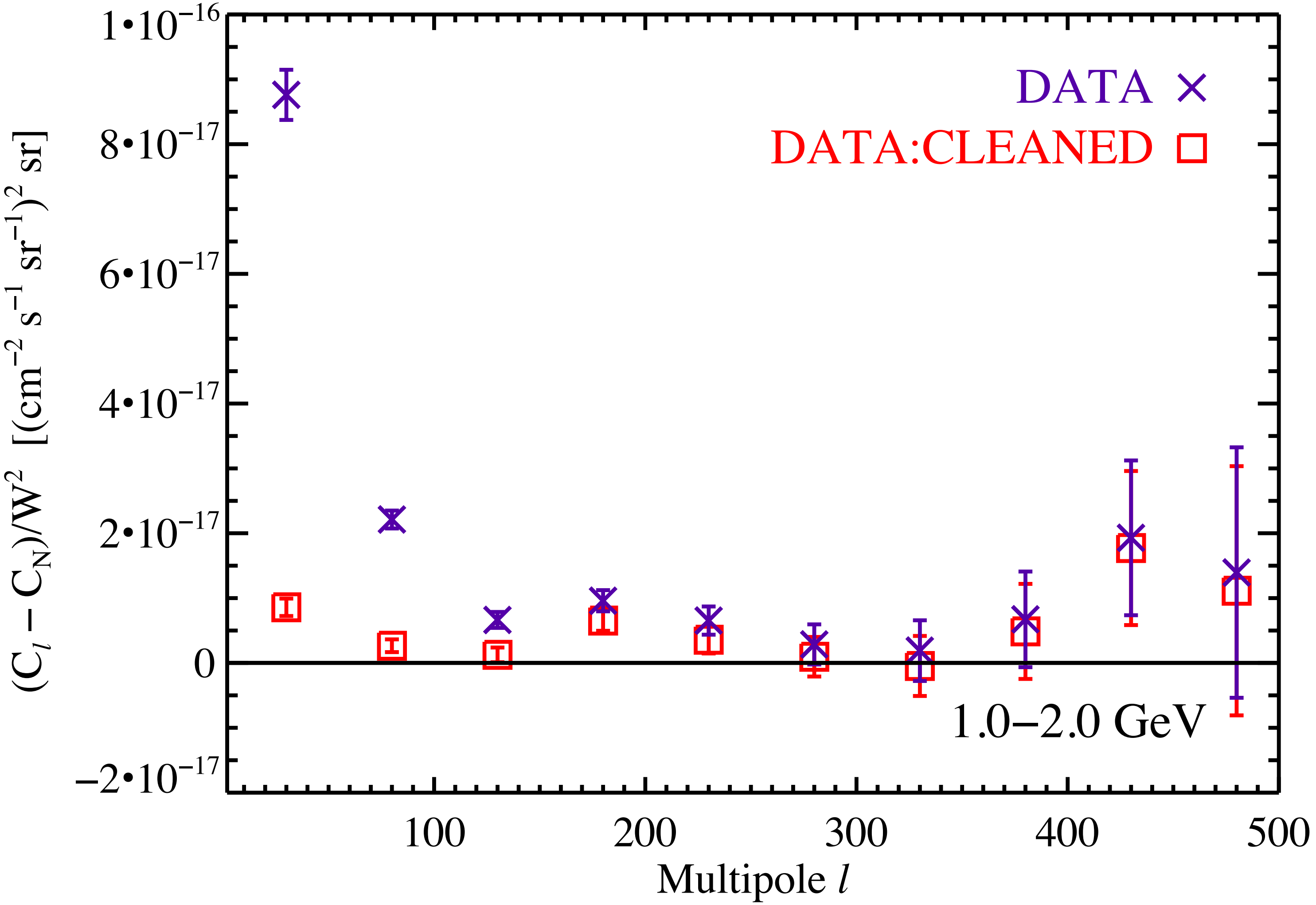
10-50 GeV





Angular power spectra of the data

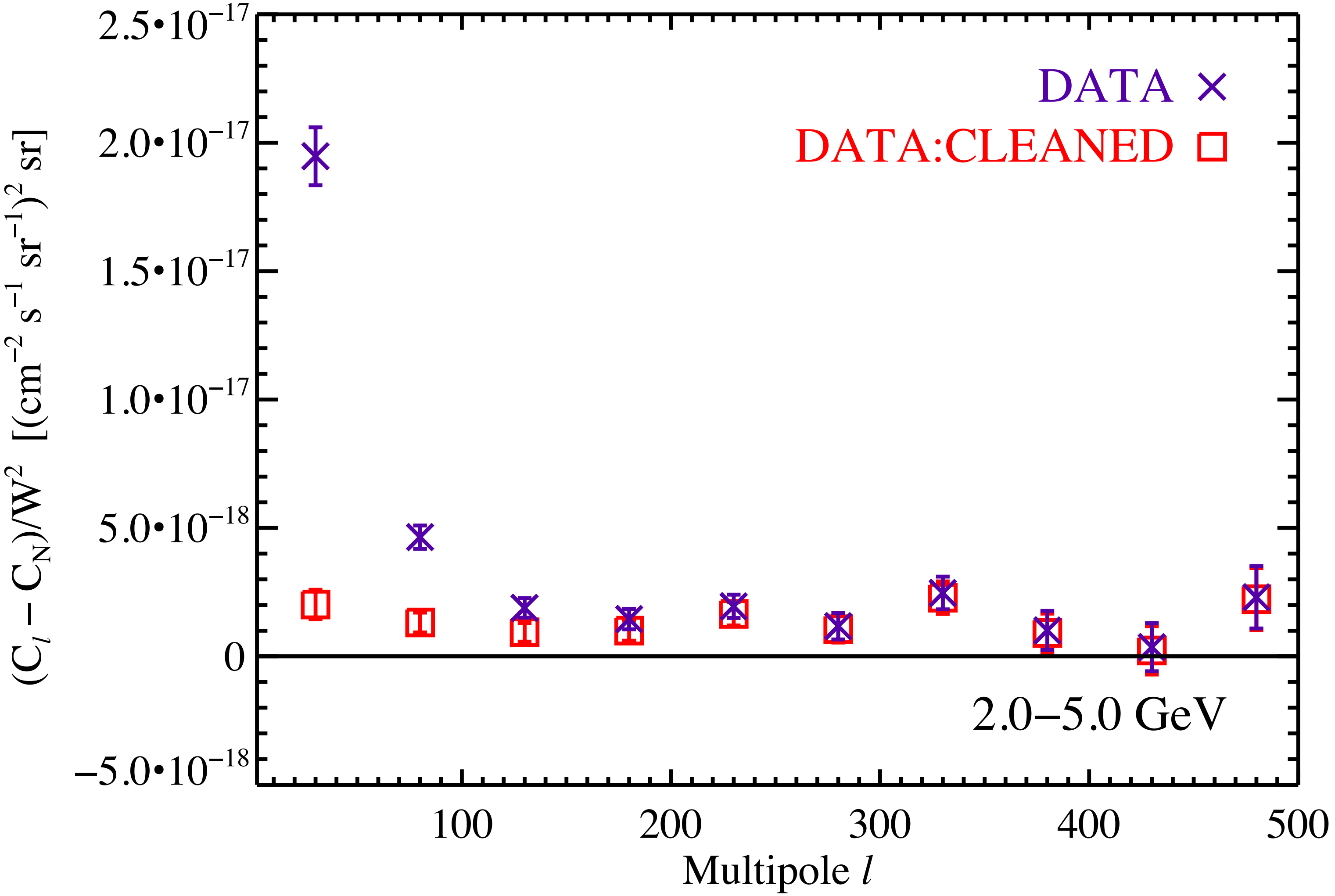
intensity angular power spectra



DATA:CLEANED = DATA - Galactic diffuse model

Angular power spectra of the data

intensity angular power spectra



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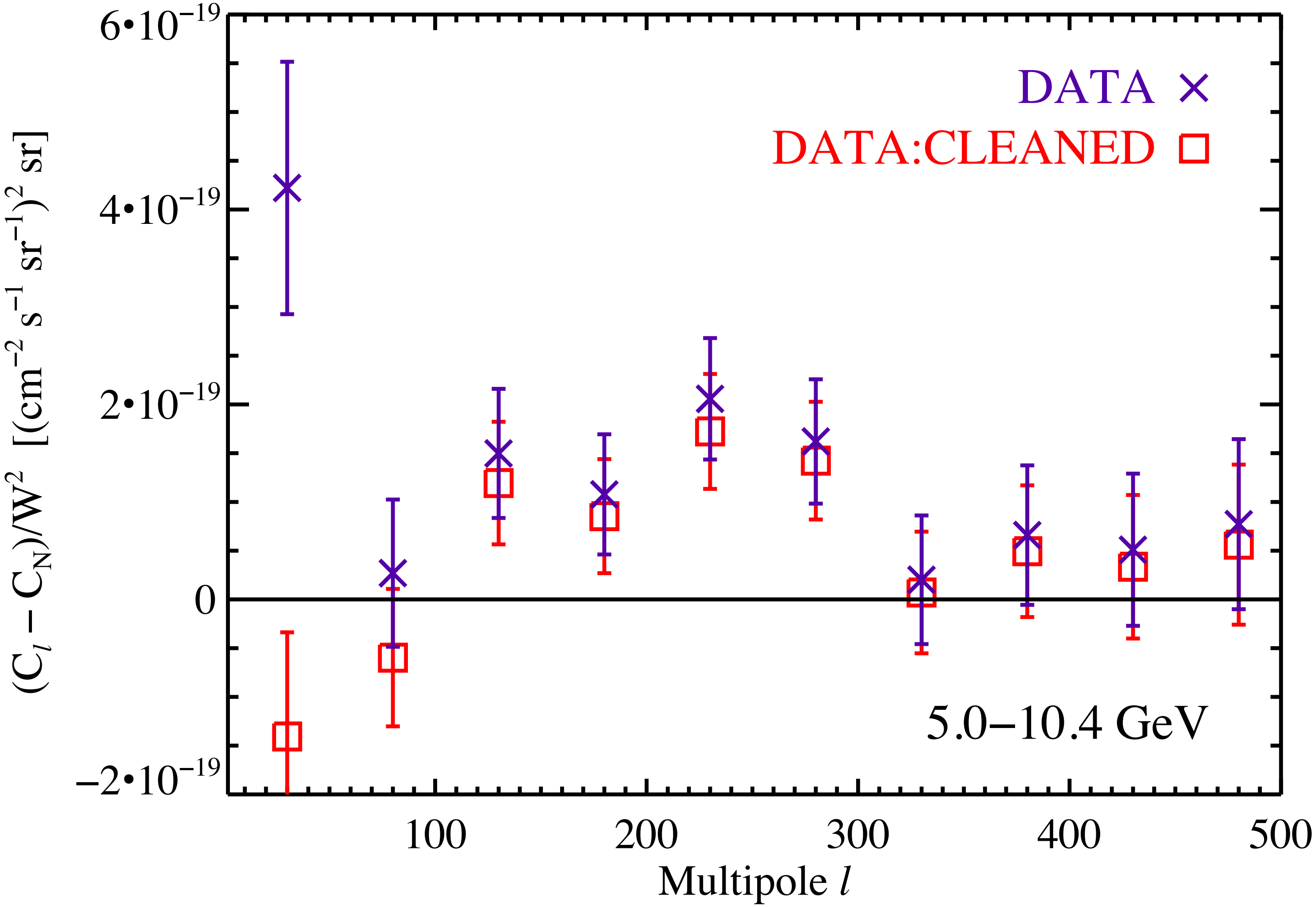

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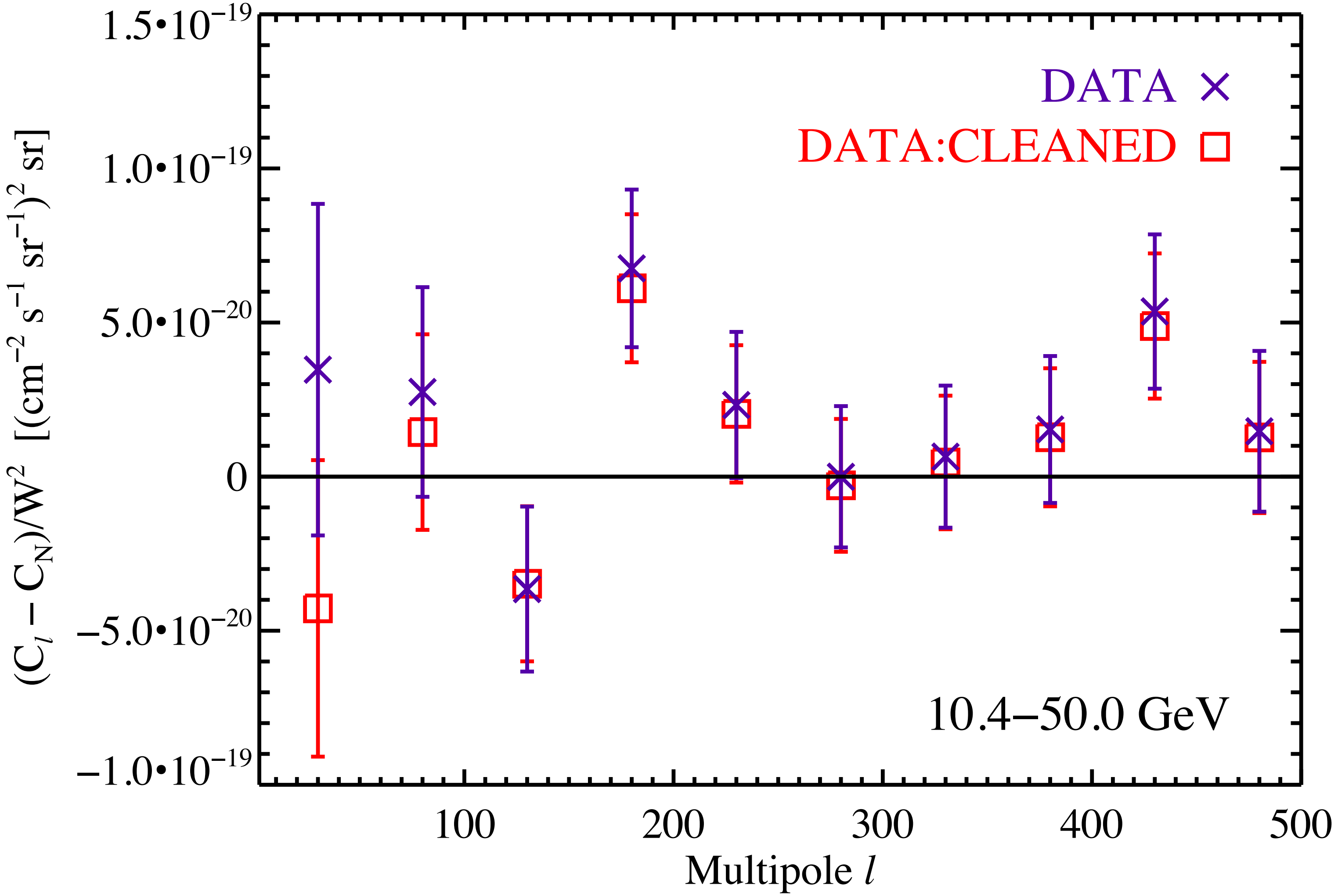


DATA:CLEANED = DATA - Galactic diffuse model

Angular power in the data

- identifying the signal at 155 ≤ l ≤ 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

E_{min} [GeV]	E_{max} [GeV]	C_{P} $[(\mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1})^2\ \mathrm{sr}]$	Significance	$C_{\mathrm{P}}/\langle I \rangle^2$ $[10^{-6}\ \mathrm{sr}]$
1.04	1.99	$7.39 \pm 1.14 \times 10^{-18}$	6.5σ	10.2 ± 1.6
1.99	5.00	$1.57 \pm 0.22 \times 10^{-18}$	7.2σ	8.35 ± 1.17
5.00	10.4	$1.06 \pm 0.26 \times 10^{-19}$	4.1σ	9.83 ± 2.42
10.4	50.0	$2.44 \pm 0.92 \times 10^{-20}$	2.7σ	8.00 ± 3.37

Comparison with predicted angular power

Fluctuation angular power in data

$C_\mathrm{P}/\langle I\rangle^2$ $[10^{-6}\ \mathrm{sr}]$
10.2 ± 1.6
8.35 ± 1.17
9.83 ± 2.42
8.00 ± 3.37

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

- fluctuation angular power of ~ 1e-5 sr falls in the range predicted for some astrophysical source classes and some dark matter scenarios
- can be used to constrain the IGRB contribution from these populations

Source population constraints from anisotropy

- intensity angular power can constrain the absolute IGRB contribution from a single population

$$C_{\mathrm{P},i} \leq C_{\mathrm{P,tot}}$$

- fluctuation angular power can constrain the fractional IGRB contribution from a single population

$$f_i^2 \leq \frac{C_{\mathrm{P,tot}}/\langle I_{\mathrm{tot}}\rangle^2}{C_{\mathrm{P},i}/\langle I_i\rangle^2}$$

Constraints from the fluctuation angular power

Constraints from best-fit constant fluctuation angular power (l ≳ 150)
measured in the data and foreground-cleaned data

Source class	Predicted $C_{100}/\langle I\rangle^2$ [sr]	Maximum fraction of IGRB intensity DATA	DATA:CLEANED
Blazars	2×10^{-4}	21%	19%
Star-forming galaxies	2×10^{-7}	100%	100%
Extragalactic dark matter annihilation	1×10^{-5}	95%	83%
Galactic dark matter annihilation	5×10^{-5}	43%	37%
Millisecond pulsars	3×10^{-2}	1.7%	1.5%

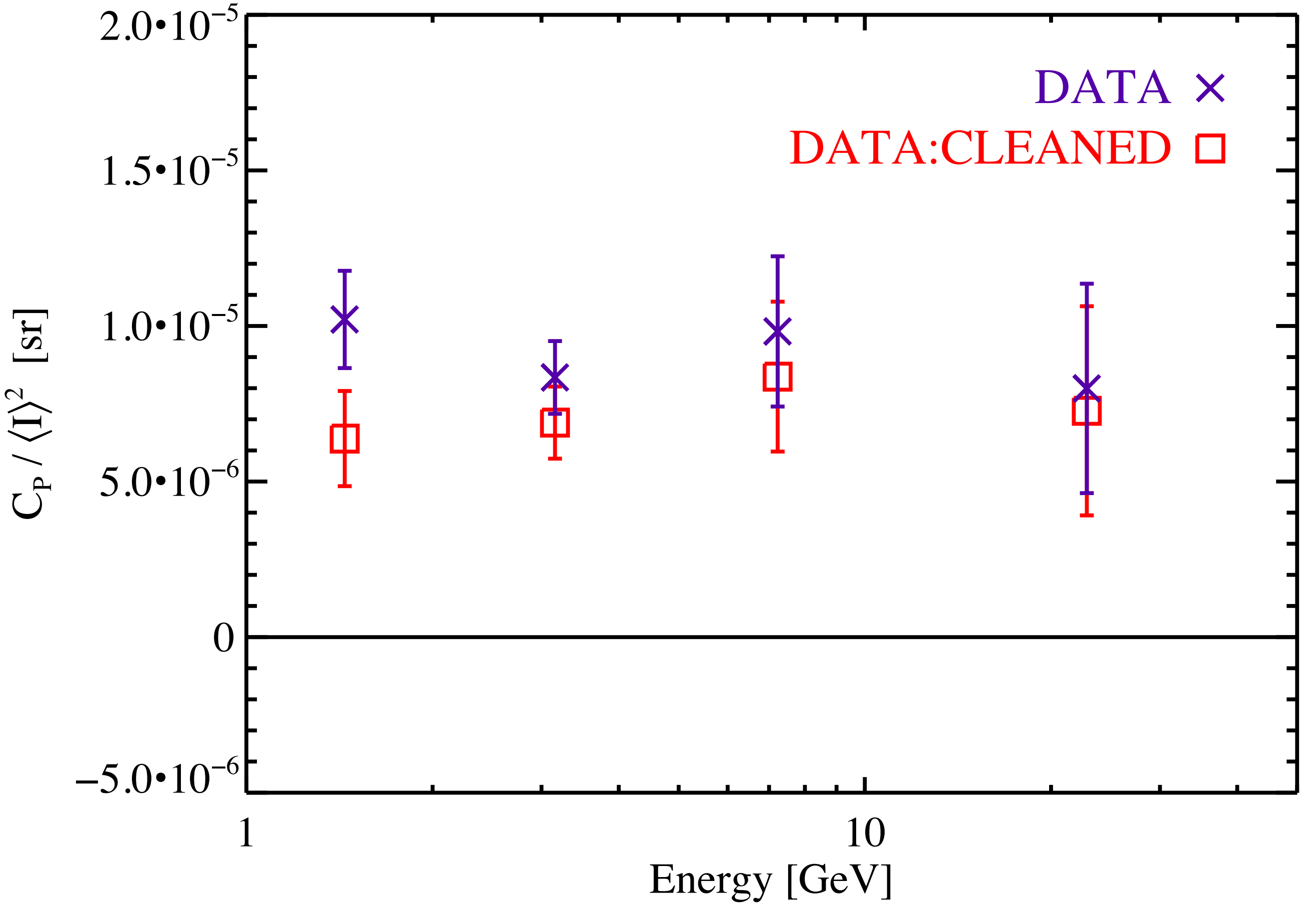
NB: these are <u>indicative predicted values</u> for source populations, taken from the literature.

- dependent on source model (large variations possible, especially for dark matter scenarios)
- dependent on source detection threshold
- for cosmological populations, dependent on EBL assumptions

<u>These values may not be accurate for your favorite source population model.</u>

Energy dependence of anisotropy

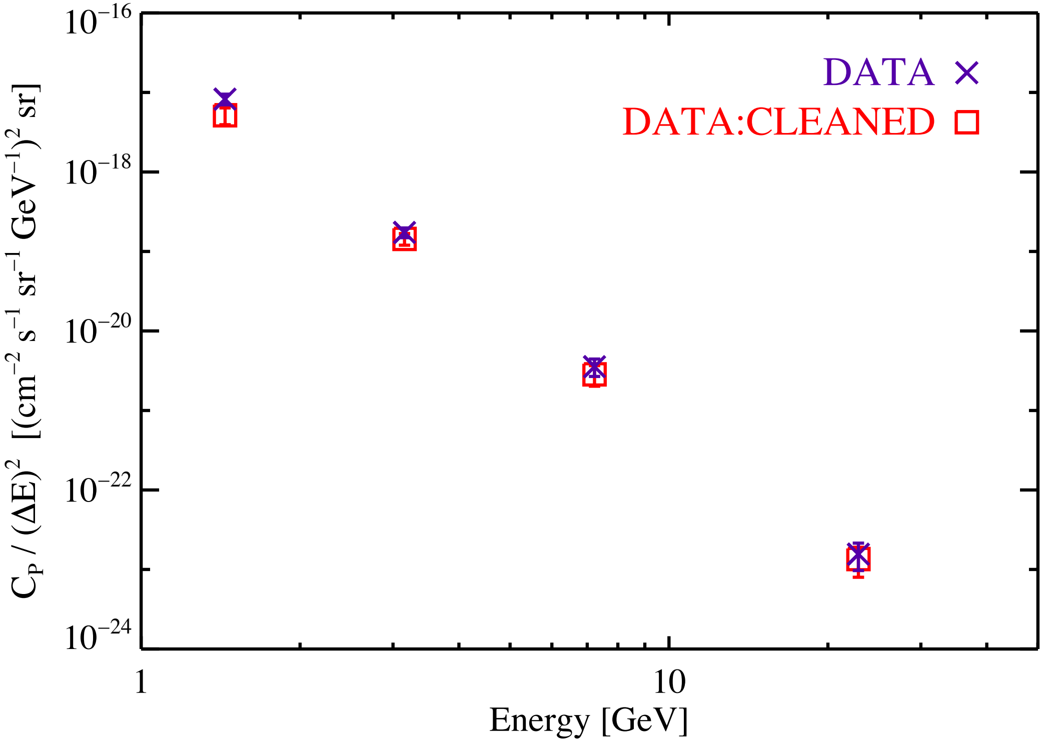
Fluctuation anisotropy energy spectrum



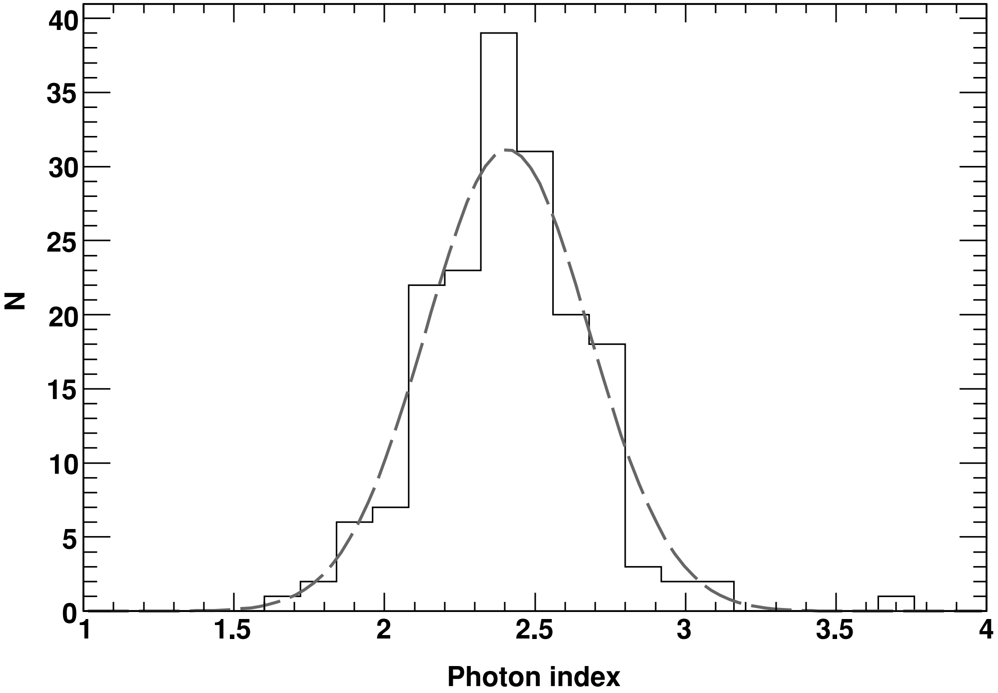
- consistent with no energy dependence, but mild or localized energy dependence not excluded
- consistent with all anisotropy contributed by one or more source classes contributing same fractional intensity at all energies considered

Energy dependence of anisotropy

Intensity anisotropy energy spectrum



Spectral indices of Fermi-LAT sources



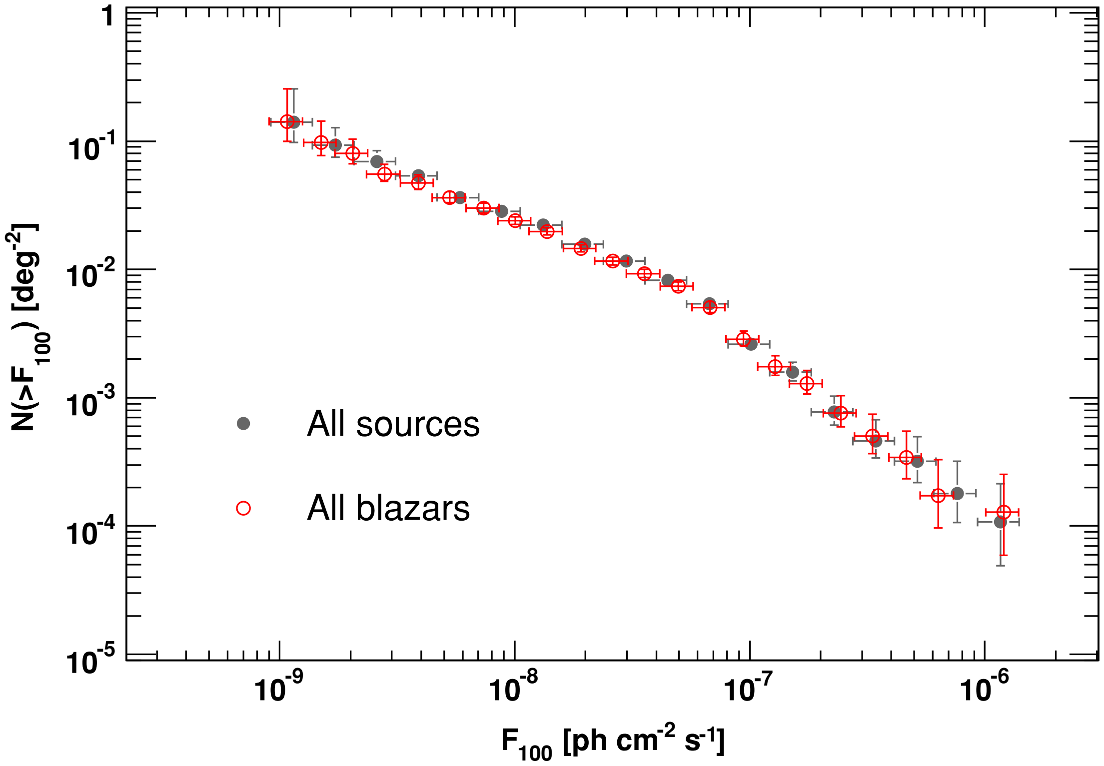
Abdo et al. (Fermi LAT Collaboration), ApJ 720, 435 (2010)

- consistent with that arising from a source class with power-law energy spectrum with Γ = -2.40 ± 0.07 (-2.33 ± 0.08 for cleaned data)
- implied source spectral index is good agreement with mean intrinsic spectral index of blazars inferred from detected members

The source count distribution

the source count distribution ("LogN-LogS") of Fermi-LAT–detected sources is consistent with a broken power law

LogN-LogS of Fermi LAT sources



Abdo et al. (Fermi LAT Collaboration), ApJ 720, 435 (2010)

high (bright-end) spectral index

break flux

$$\frac{dN}{dS} = \begin{cases} A\ S^{-\beta} & S \geq S_b \\ A\ S_b{}^{-\beta+\alpha} S^{-\alpha} & S < S_b \end{cases}$$

low (faint-end) spectral index

Anisotropy and source counts

the total intensity and Poisson angular power (C_P) from *unresolved* sources can be predicted from the source count distribution

$$I = \int_0^{S_t} \frac{dN}{dS} S dS \qquad C_{\rm P} = \int_0^{S_{\rm t}} \frac{dN}{dS} S^2 dS$$

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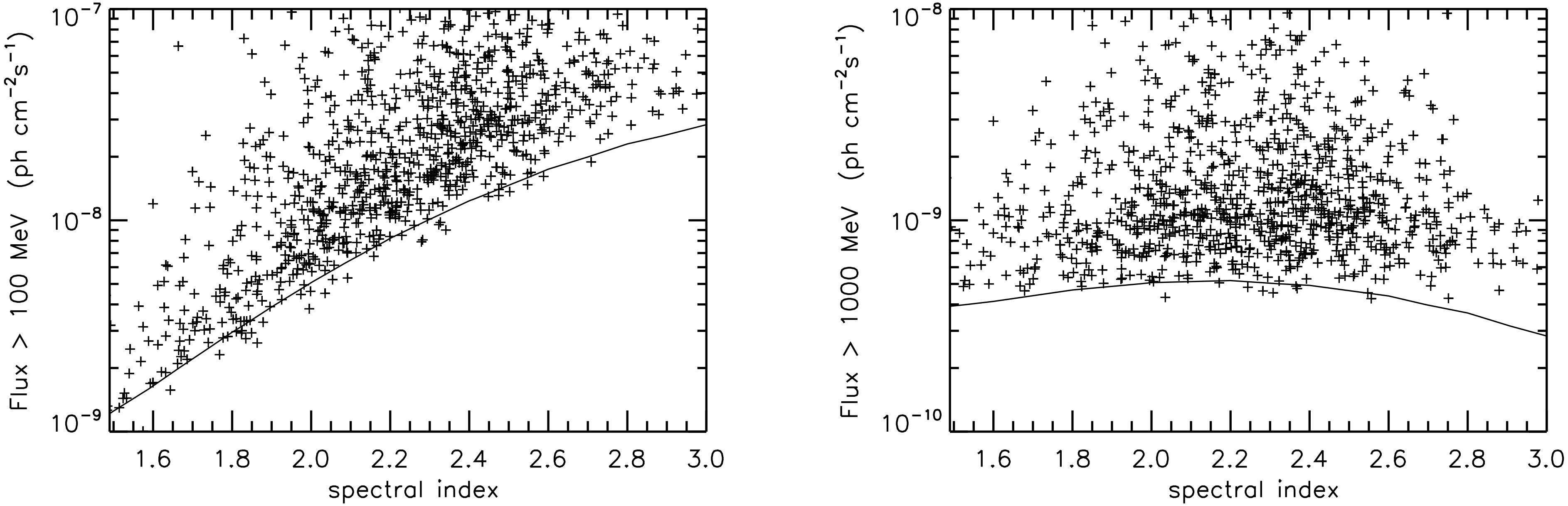
$$C_{\rm P} = \int_0^{S_{\rm t}} \frac{dN}{dS} S^2 dS$$

How do the predicted intensity and angular power from unresolved blazars compare to the measured values?

Aside: threshold fluxes and spectral index bias

In general, the source detection threshold can depend
on the spectral index of the source (*spectral index bias*)



Source flux vs spectral index (E > 100 MeV)

Source flux vs spectral index (E > 1 GeV)

(points are 1FGL sources, lines are derived threshold flux as a function of spectral index)

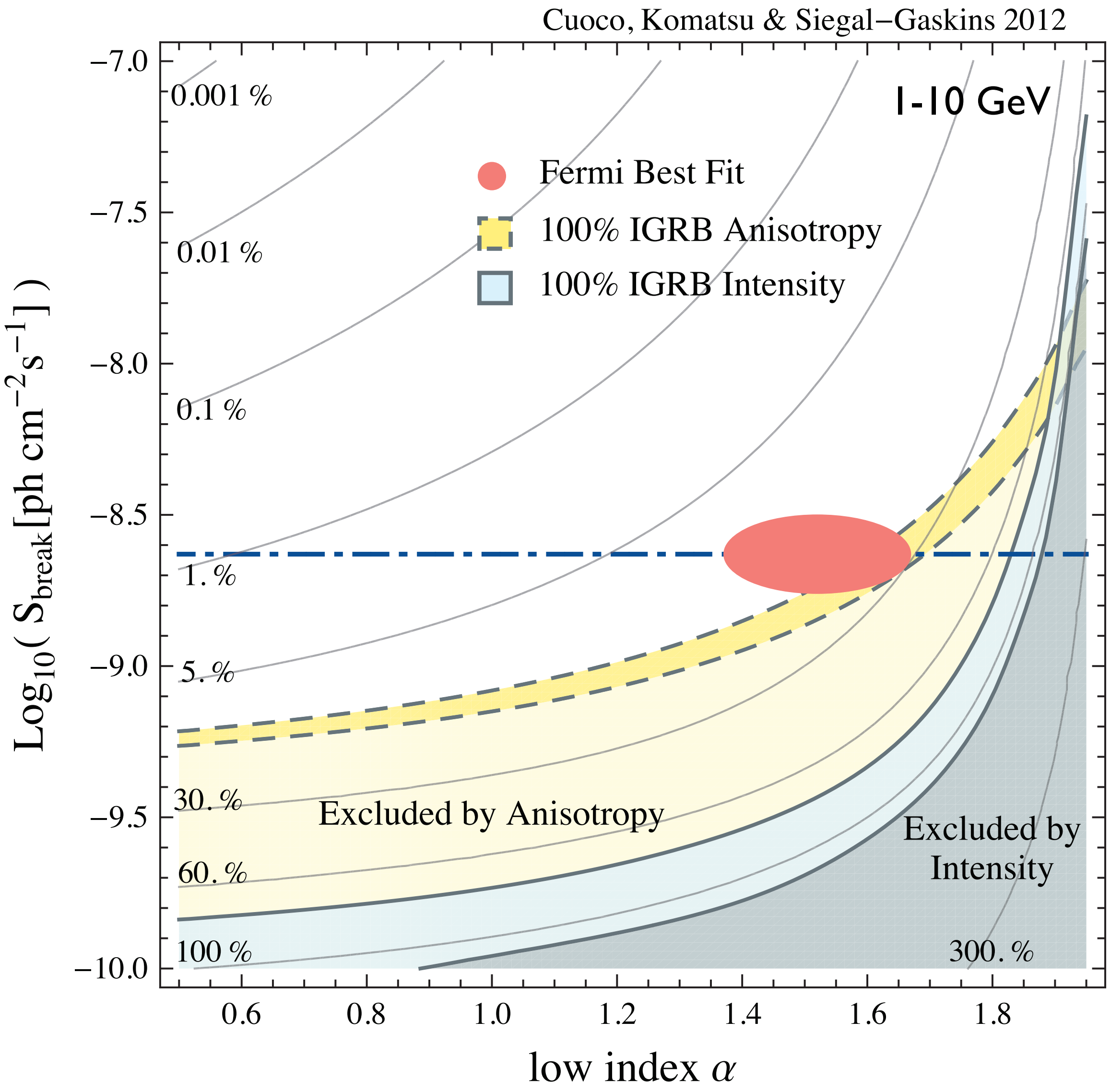
Spectral index bias is strong for fluxes > 100 MeV,
but small for fluxes > 1 GeV (1-10 GeV is used in this study)

Constraints on unresolved gamma-ray sources

- we fix the high index and normalization of the source count distribution to the measured best-fit values

- we vary the low index and break flux, and calculate the intensity and anisotropy produced by the unresolved sources in the 1-10 GeV band

Constraints on source count distribution (logN-logS) parameter space



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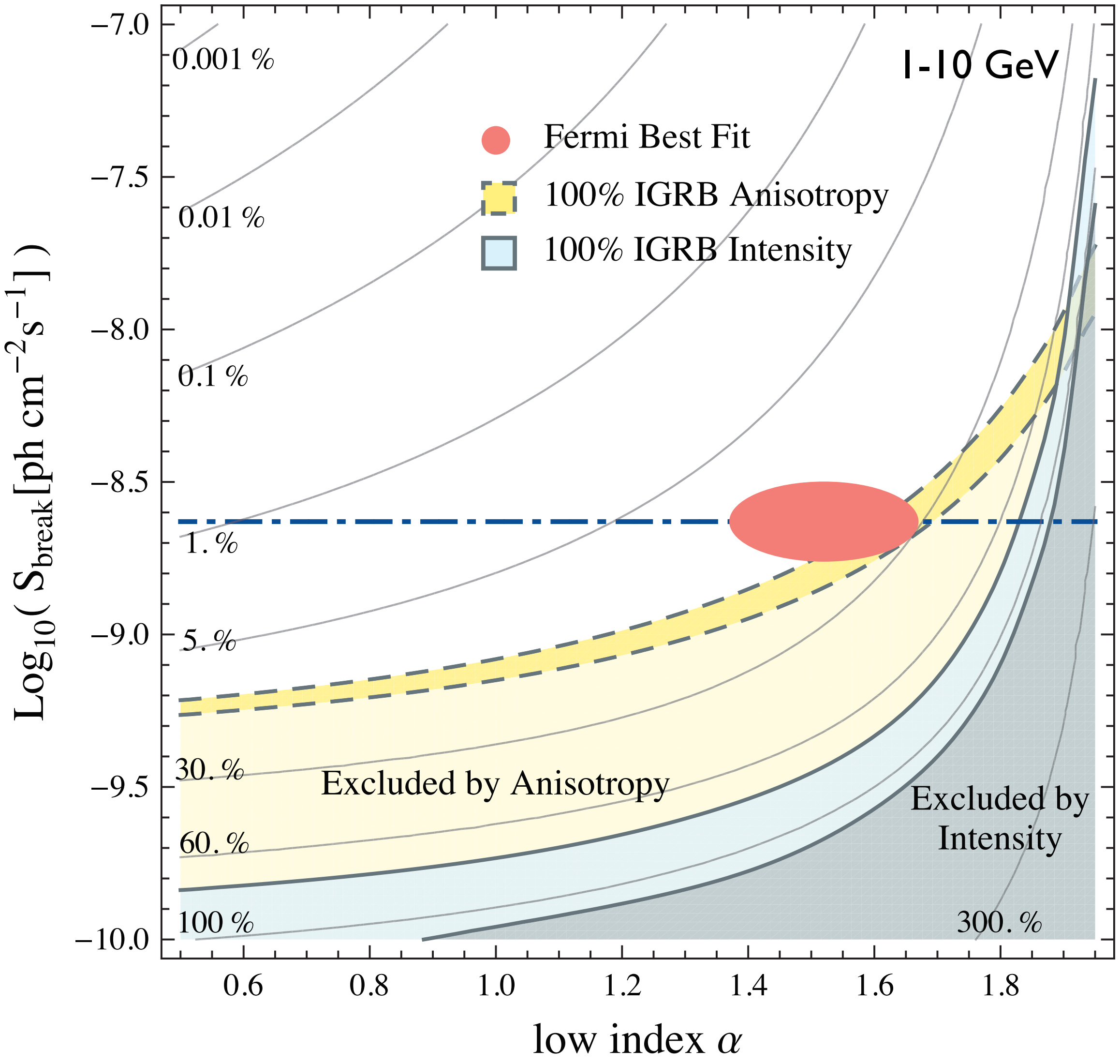
Constraints on source count distribution (logN-logS) parameter space

Cuoco, Komatsu & Siegal−Gaskins 2012



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- this result implies that component(s) making ~70% of IGRB intensity have very low level of anisotropy

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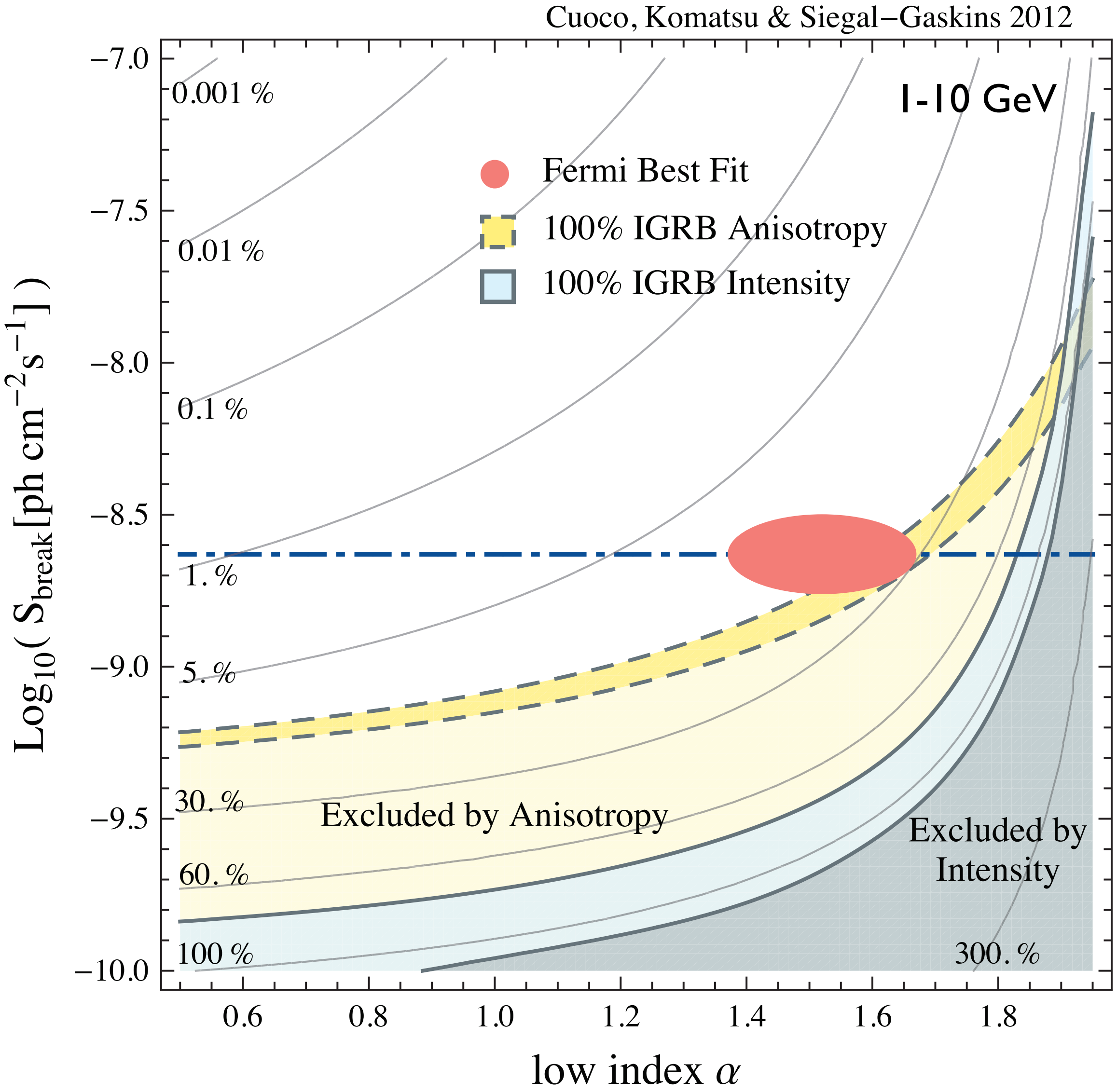

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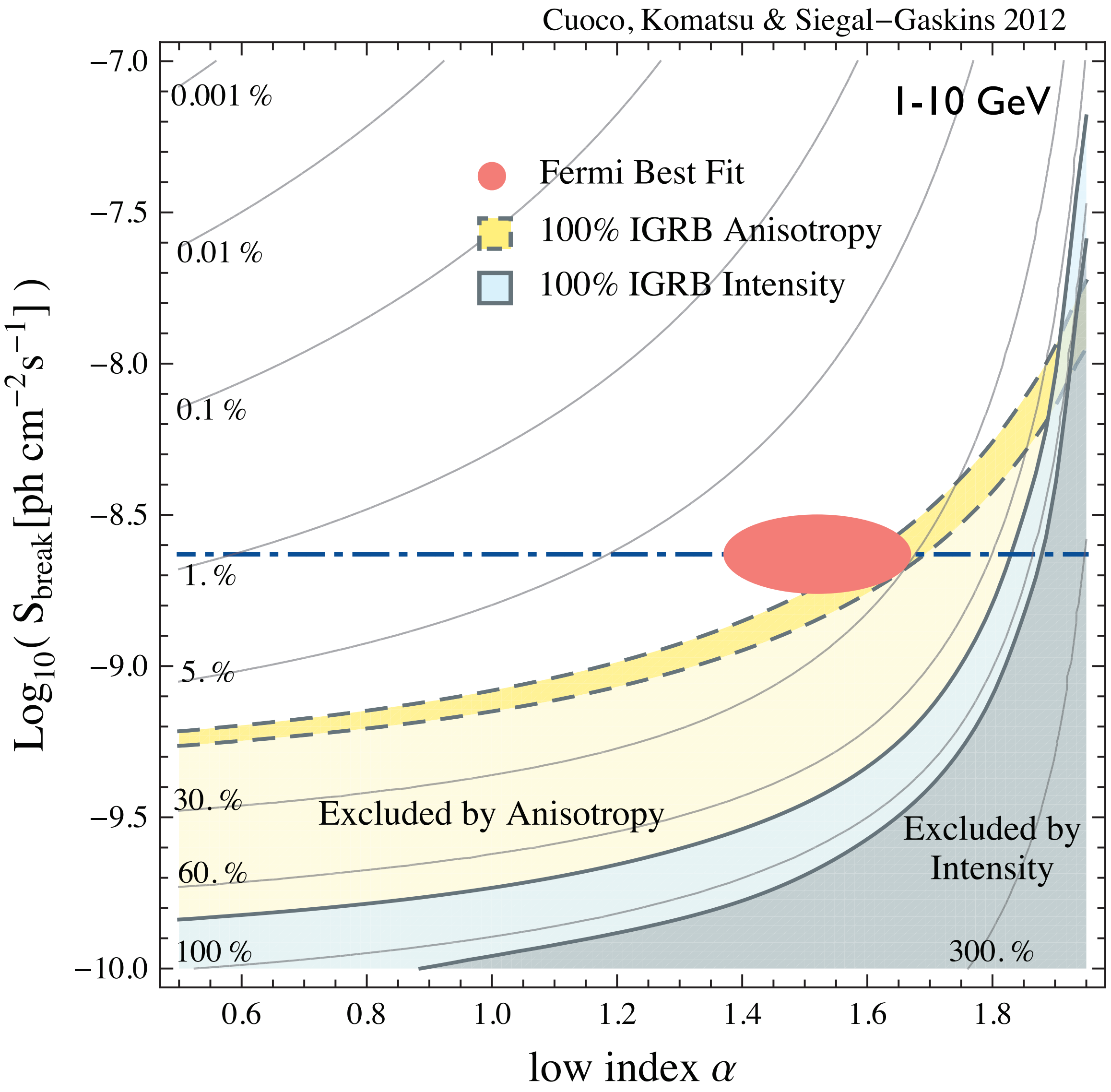
- anisotropy and source count analysis point to blazars contributing ~30% of IGRB intensity and ~100% of IGRB anisotropy
- this result implies that component(s) making ~70% of IGRB intensity have very low level of anisotropy
- anisotropy is a powerful constraint: measured angular power excludes Stecker & Venters 2011 model

Constraints on source count distribution (logN-logS) parameter space



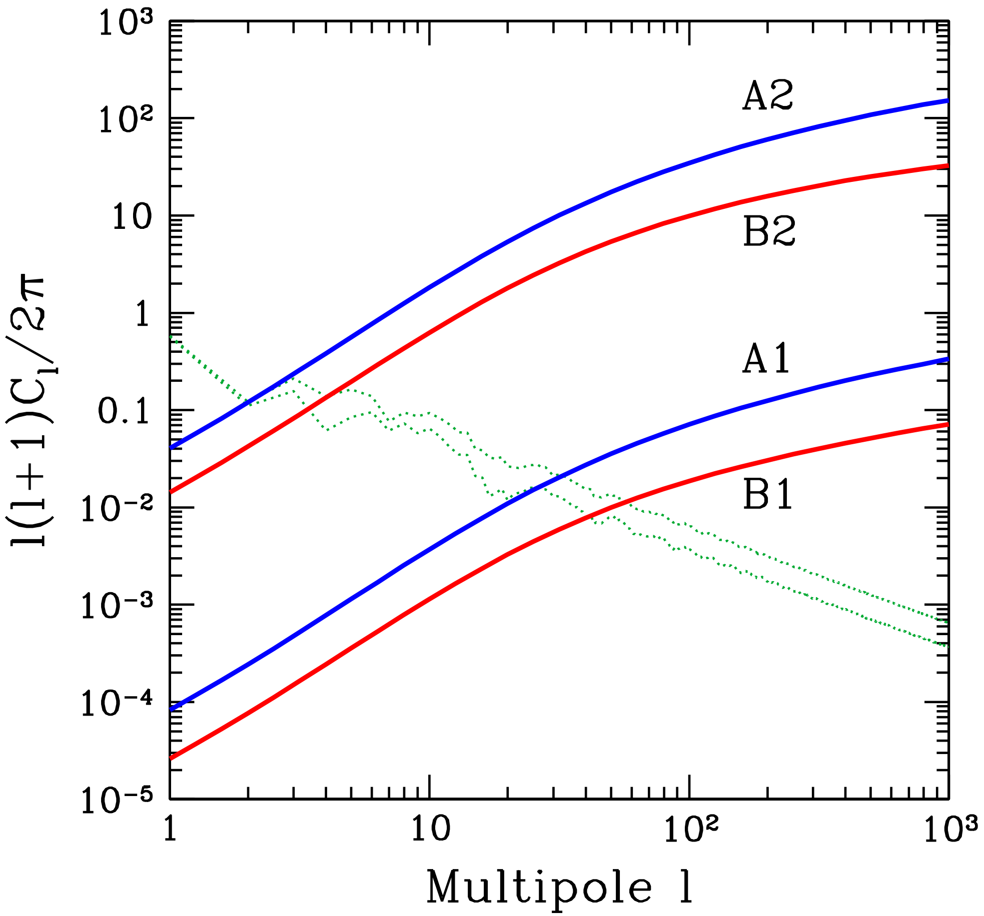
Anisotropy constraints on dark matter

- using formalism in Ando 2009, the angular power from Galactic dark matter annihilation can be calculated for a variety of dark matter models

- using Model B1 as a reference, I derive constraints requiring that the predicted (intensity) angular power from DM does not exceed the measured value + 2 sigma (using foreground-cleaned results for angular power)

- Model B1:
    - M_{min} = 1e-6 M☉
    - f_{sub} = 0.2
    - mass function slope = 1.9
    - unbiased radial subhalo distribution (NFW)
    - sub-subhalo "boost" = 2

Fluctuation anisotropy from Galactic DM

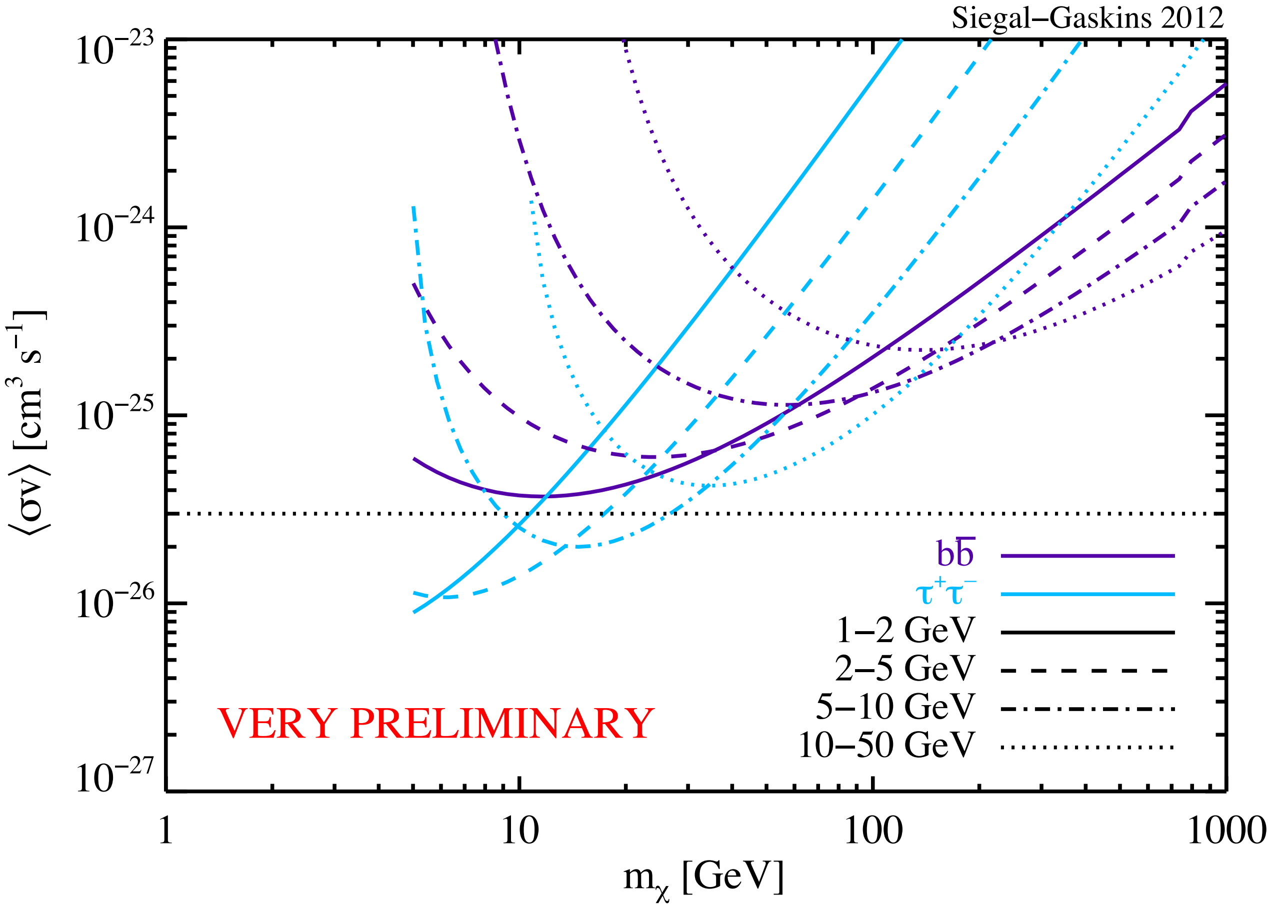


Ando 2009

Preliminary dark matter constraints

- match Fermi anisotropy analysis: mask |b| < 30 deg, and average angular power over multipoles 155-504
- luminosity $\propto$ mass$^{0.77}$
- benchmark annihilation channels: b-bbar and tau+tau-
- preliminary constraints strongest at low masses for tau channel but competitive at high masses for b-bbar channel
- suggests that both lower and higher energy anisotropy measurements could be very sensitive probes of dark matter models

Constraints on dark matter from the Fermi anisotropy measurement

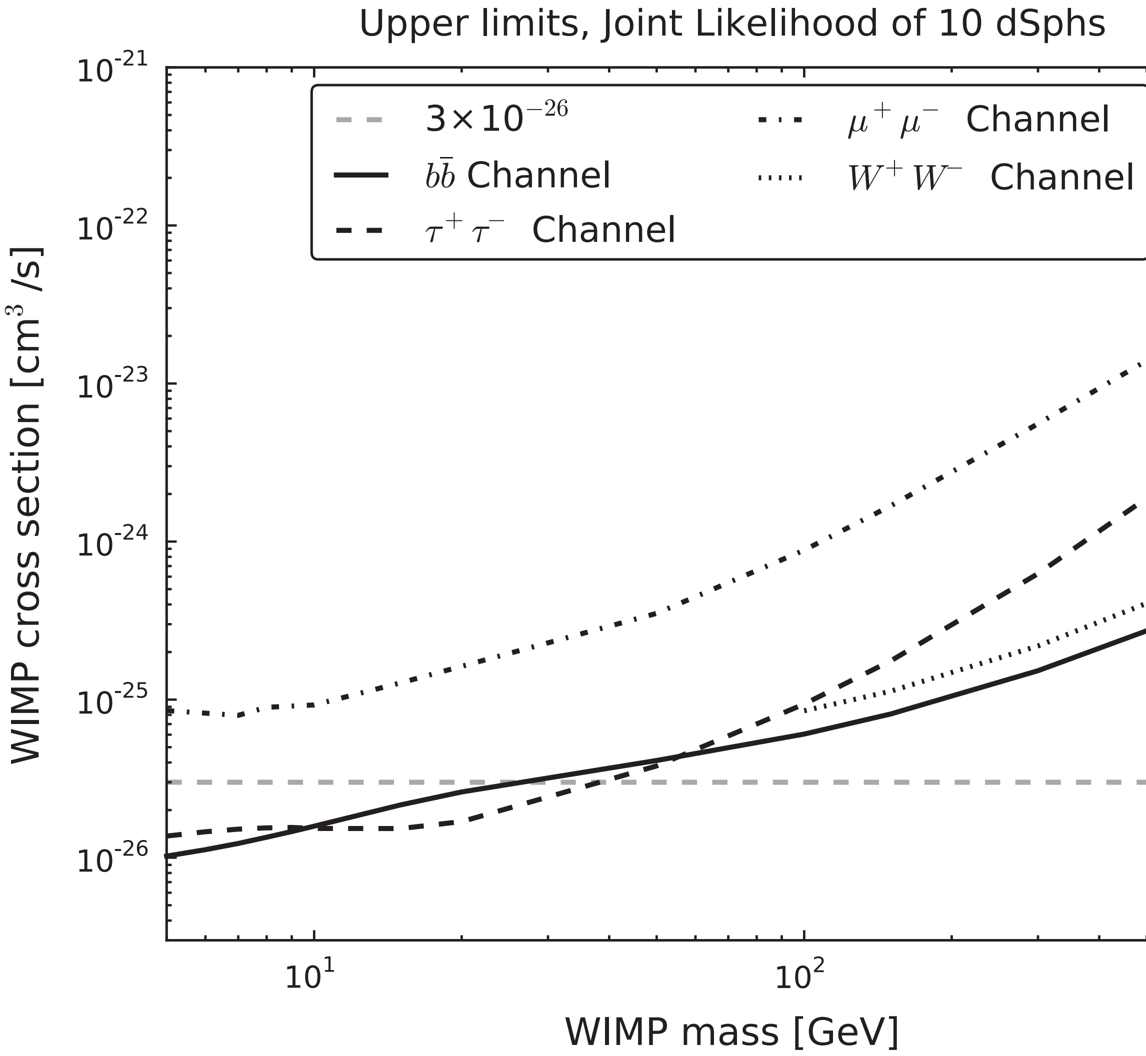


Summary

- IGRB small-scale anisotropy has been detected for the first time!
- scale independence of high-multipole angular power suggests contribution from one or more unclustered point source populations
- measured angular power can be used to constrain the IGRB contribution from specific source classes
- lack of energy dependence of the fluctuation angular power suggests that the anisotropy is contributed primarily by one or more source populations with constant fractional contributions to the IGRB intensity over 1-50 GeV
- energy dependence of the intensity angular power is consistent with the anisotropy originating from a source population with a power-law energy spectrum with $\Gamma = -2.40 \pm 0.07$; this spectral index closely matches the inferred mean intrinsic spectral index of blazars
- source count analysis and anisotropy measurements point to blazars contributing ~100% of the anisotropy but only ~30% of the intensity of the IGRB; angular power available to other IGRB contributors, including dark matter, is constrained
- preliminary results indicate anisotropy constraints on Galactic dark matter annihilation are competitive

Additional slides

Constraints from combined dwarf analysis



Ackermann et al [Fermi LAT Collaboration] 2011

Angular power spectrum analysis of Fermi LAT data

- angular power spectrum calculation: performed using HEALPix (Gorski et al. 2005)
- signal angular power spectrum estimator:

$$C_\ell^{\rm signal} = \frac{C_\ell^{\rm raw}/f_{\rm sky} - C_N}{(W_\ell^{\rm beam})^2}$$

  - corrected for effects of masking (valid above l ~ 10)
  - photon noise is subtracted
  - corrected for effects of the PSF ("beam window function")
- measurement uncertainties: indicate 1-sigma statistical uncertainty, systematic uncertainty not included

Analysis pipeline validation

- validation with a simulated source model: a source model with known anisotropy properties is simulated and analyzed using the same analysis pipeline as the data; the theoretically-predicted angular power spectrum is recovered

- dependence on the PSF model: no significant differences found between beam window functions for P6_V3 and P6_V11 IRFs

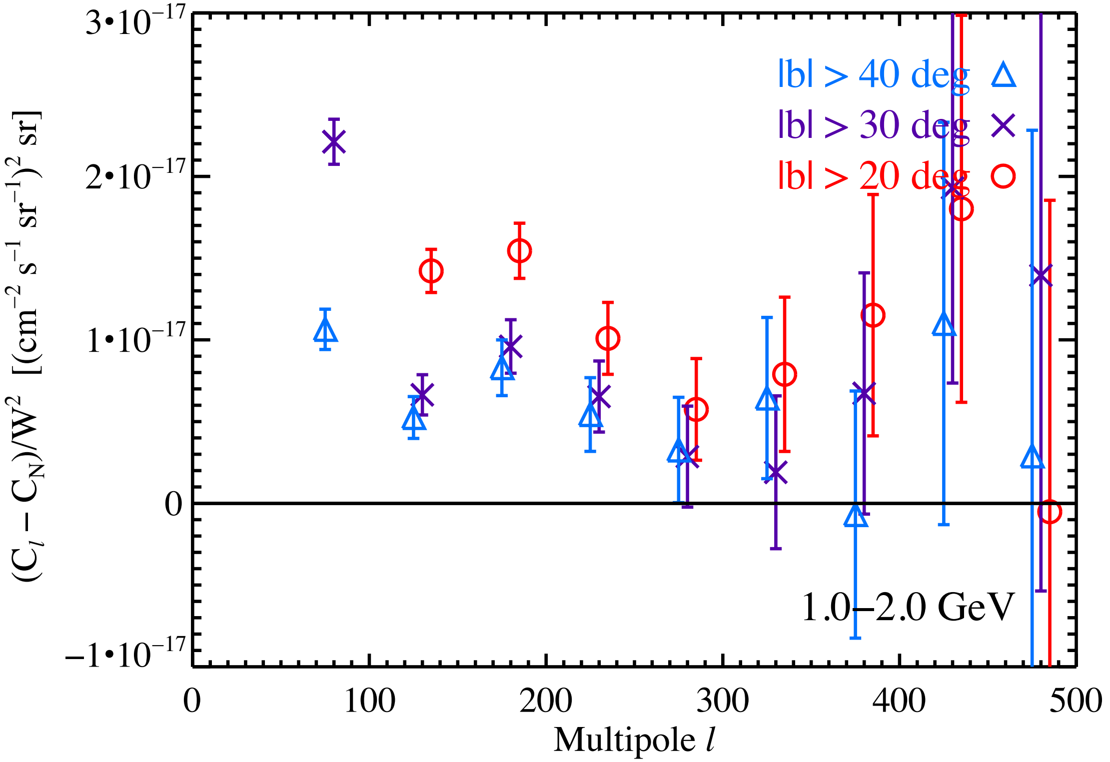
- test for anisotropies induced by inaccuracies in the exposure map: an alternate exposure map is calculated directly from the data using an event-shuffling technique; angular power spectra are consistent with those using the exposure map from the Fermi Science Tools

Robustness to variations in masking

- dependence on the latitude mask: masking |b| < 30 deg is found to be sufficient to exclude significant contamination of the anisotropy above l ~ 100 by a component with a strong latitude dependence (e.g., Galactic diffuse emission)

- dependence on the source mask radius: no significant differences seen in multipole range of interest when mask angular radius is reduced from 2 deg to 1deg

Dependence on latitude mask



Comparison with simulated models

- comparison with simulated all-sky models: two simulated models of the gamma-ray sky are analyzed; little or no angular power above l ~ 100 is found, in contrast to the results from the data

	$E_{\rm min}$ [GeV]	$E_{\rm max}$ [GeV]	$C_{\rm P}$ $[({\rm cm}^{-2}\ {\rm s}^{-1}\ {\rm sr}^{-1})^2\ {\rm sr}]$	Significance	$C_{\rm P}/\langle I \rangle^2$ $[10^{-6}\ {\rm sr}]$
MODEL	1.04	1.99	$1.89 \pm 1.08 \times 10^{-18}$	1.7σ	2.53 ± 1.47
	1.99	5.00	$1.92 \pm 2.10 \times 10^{-19}$	0.9σ	0.99 ± 1.12
	5.00	10.4	$3.41 \pm 2.60 \times 10^{-20}$	1.3σ	3.04 ± 2.34
	10.4	50.0	$0.62 \pm 9.63 \times 10^{-21}$	0.1σ	0.24 ± 3.02

Significance of difference in angular power between data and model

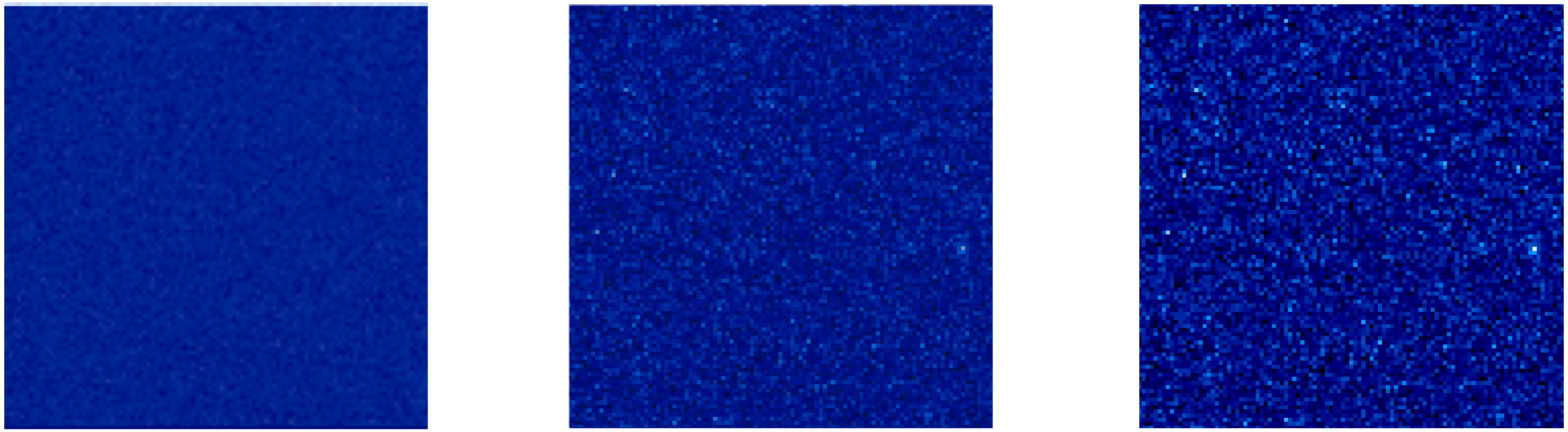
$E_{\rm min}$	$E_{\rm max}$	Significance of $\Delta C_{\rm P}$
1.04	1.99	3.5σ
1.99	5.00	4.5σ
5.00	10.4	2.0σ
10.4	50.0	1.7σ

Exposure maps from an event-shuffling technique

- the exposure map is calculated directly from the data using an event-shuffling technique:
  - shuffling arrival times and arrival directions of real events *in instrument coordinates* generates a map indicating how an isotropic signal would appear in the LAT data
  - shuffled data map is directly proportional to the exposure map, with arbitrary normalization (hence only fluctuation angular power spectra can be calculated)
- data is analyzed as in default analysis, except shuffled map is used for the exposure
- provides a cross-check to ensure that the result is not biased by inaccuracies in the exposure calculation which could introduce spurious anisotropy signals

Energy-dependent anisotropy

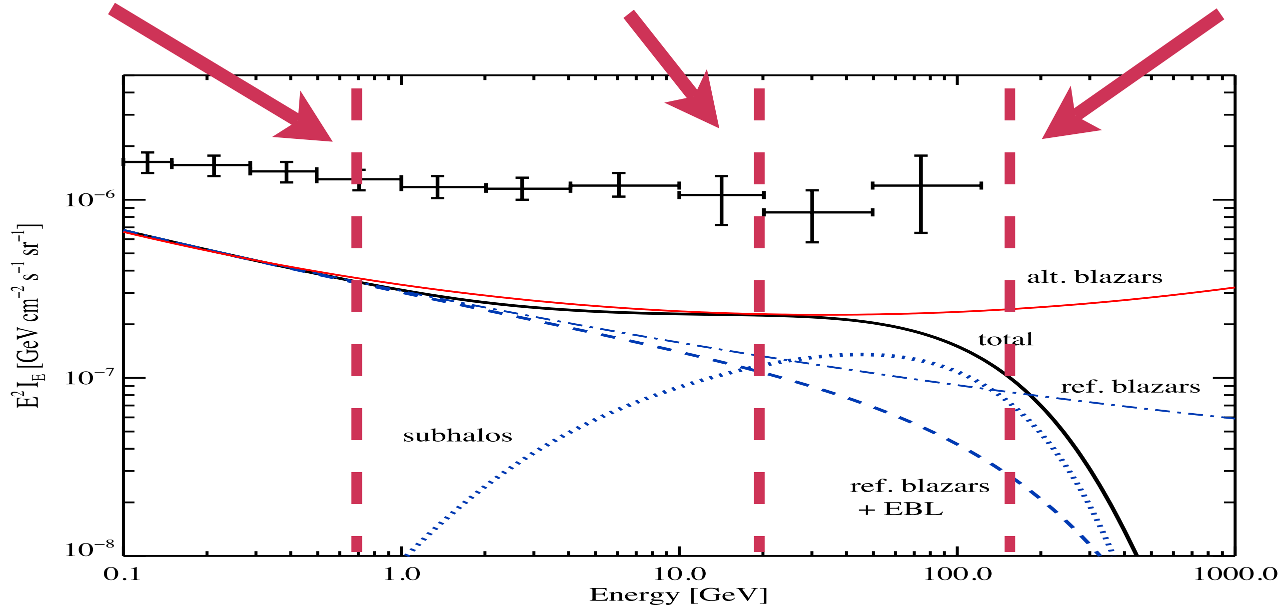
example patches of sky showing intensity fluctuations in units of the mean intensity



blazars

blazars + dark matter

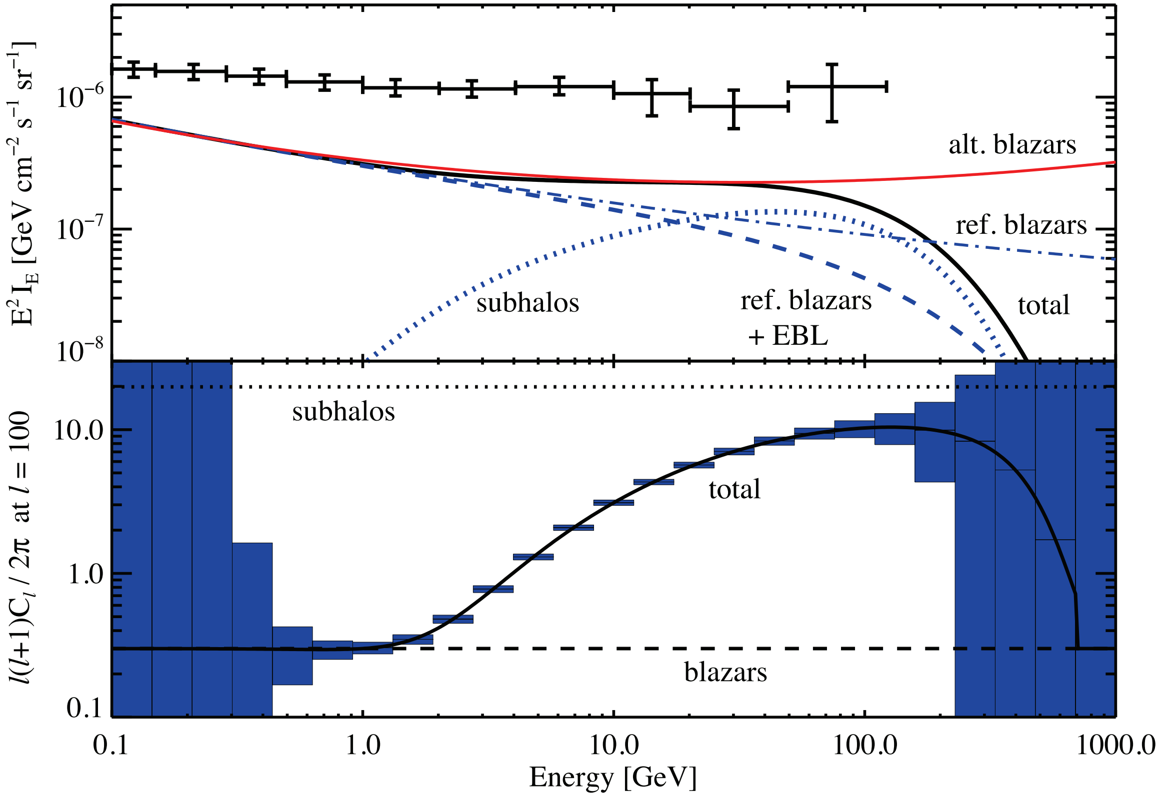
dark matter



JSG & Pavlidou 2009

The anisotropy energy spectrum at work

neutralino mass = 700 GeV



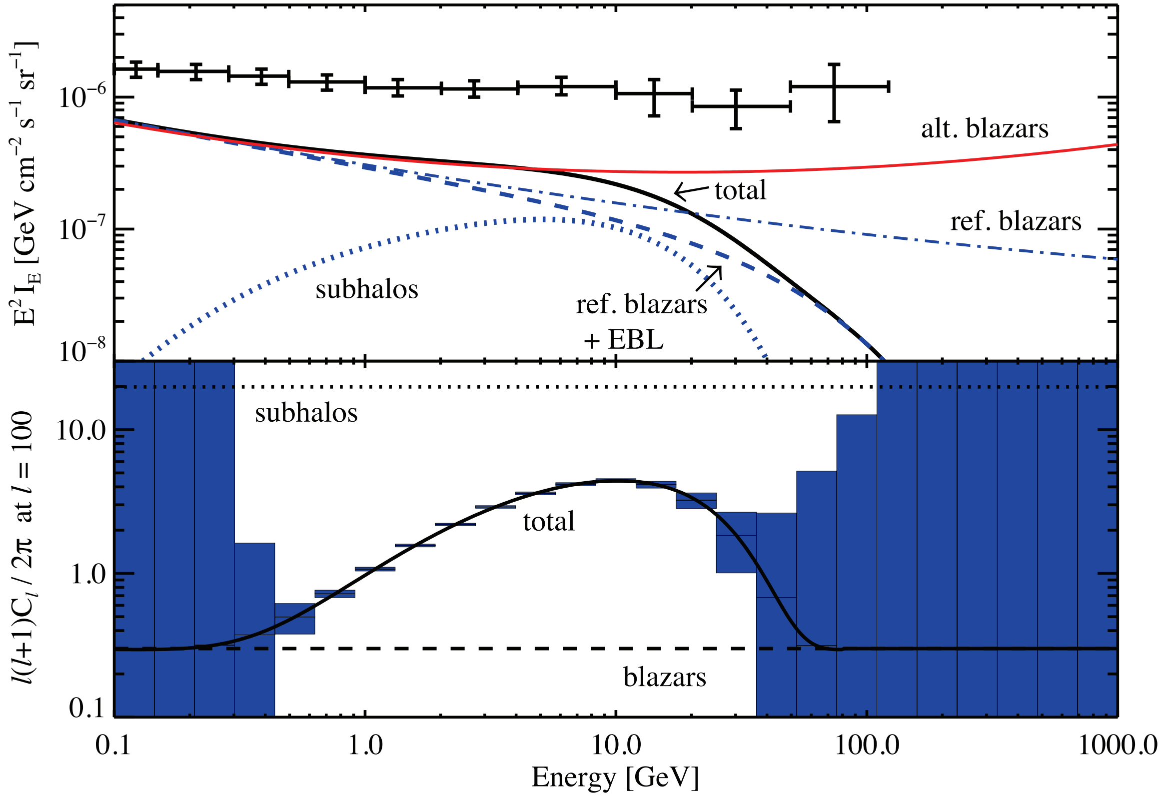
JSG & Pavlidou 2009

- 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)

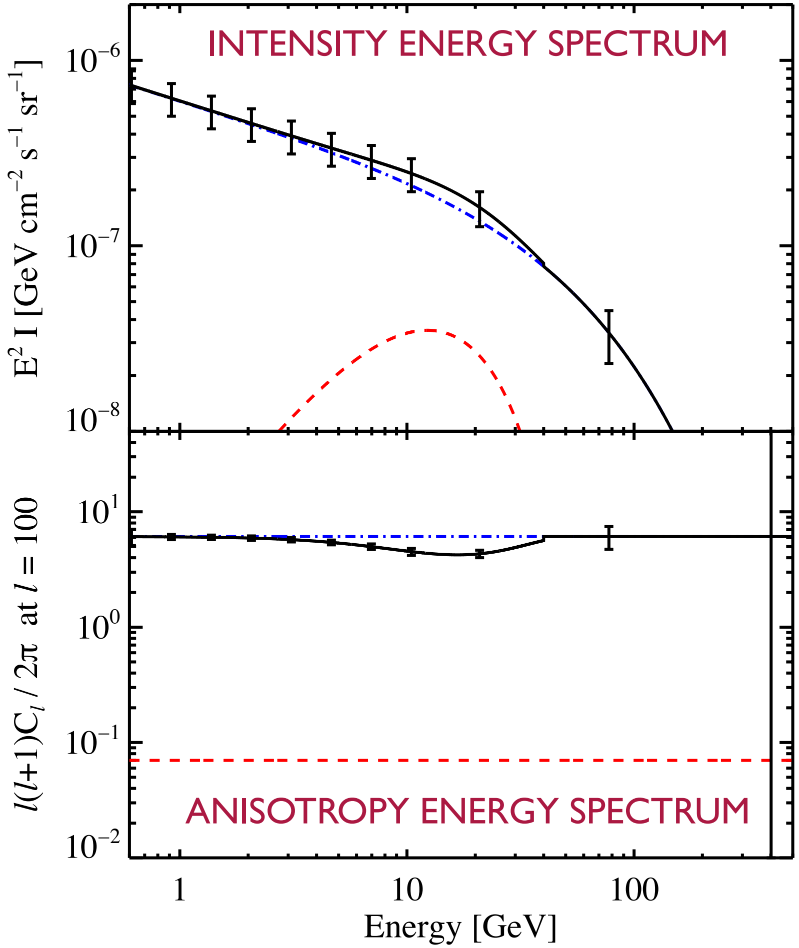
- define a simple, 'model-independent' test criterion:

  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

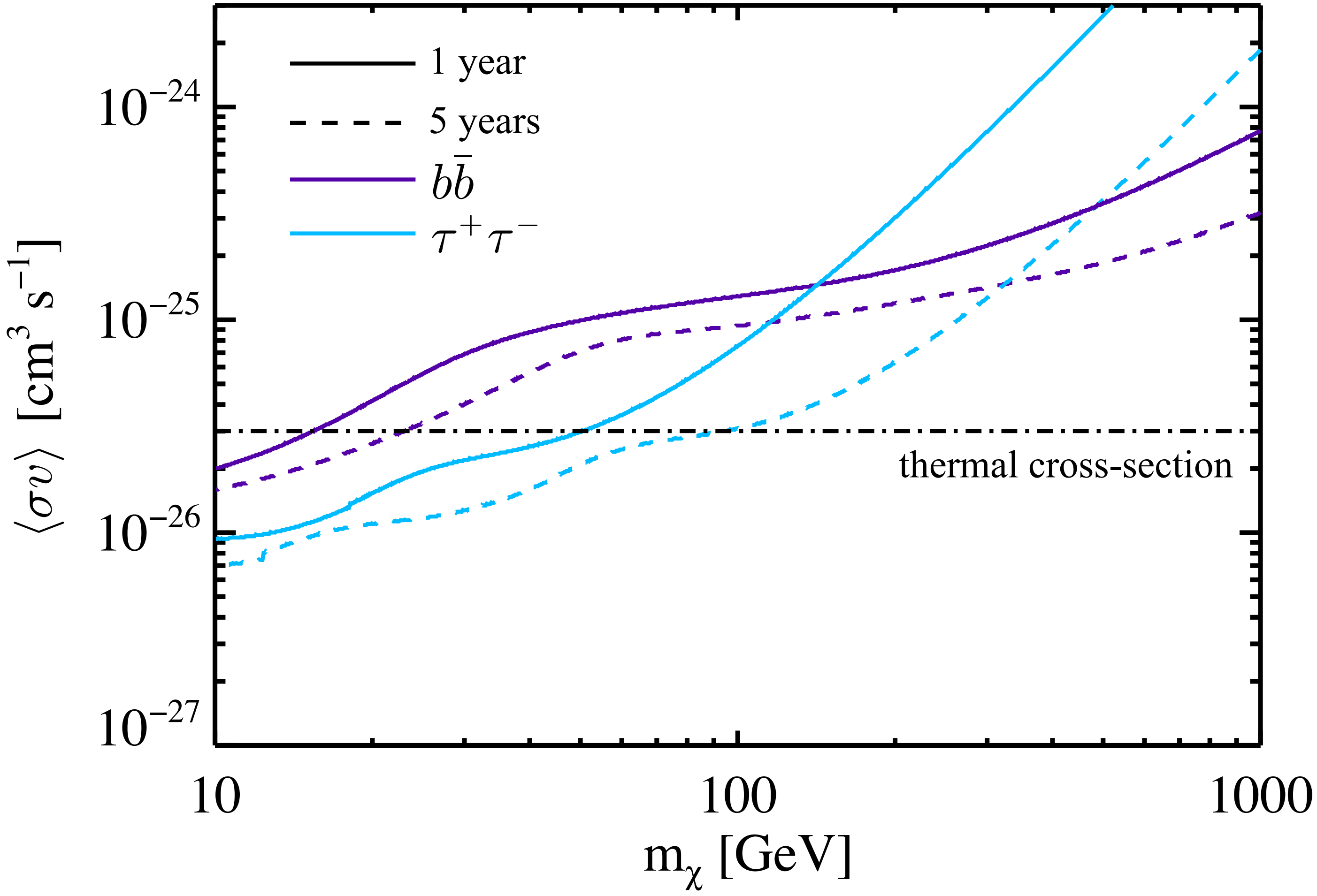


Hensley, JSG, & Pavlidou 2010

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



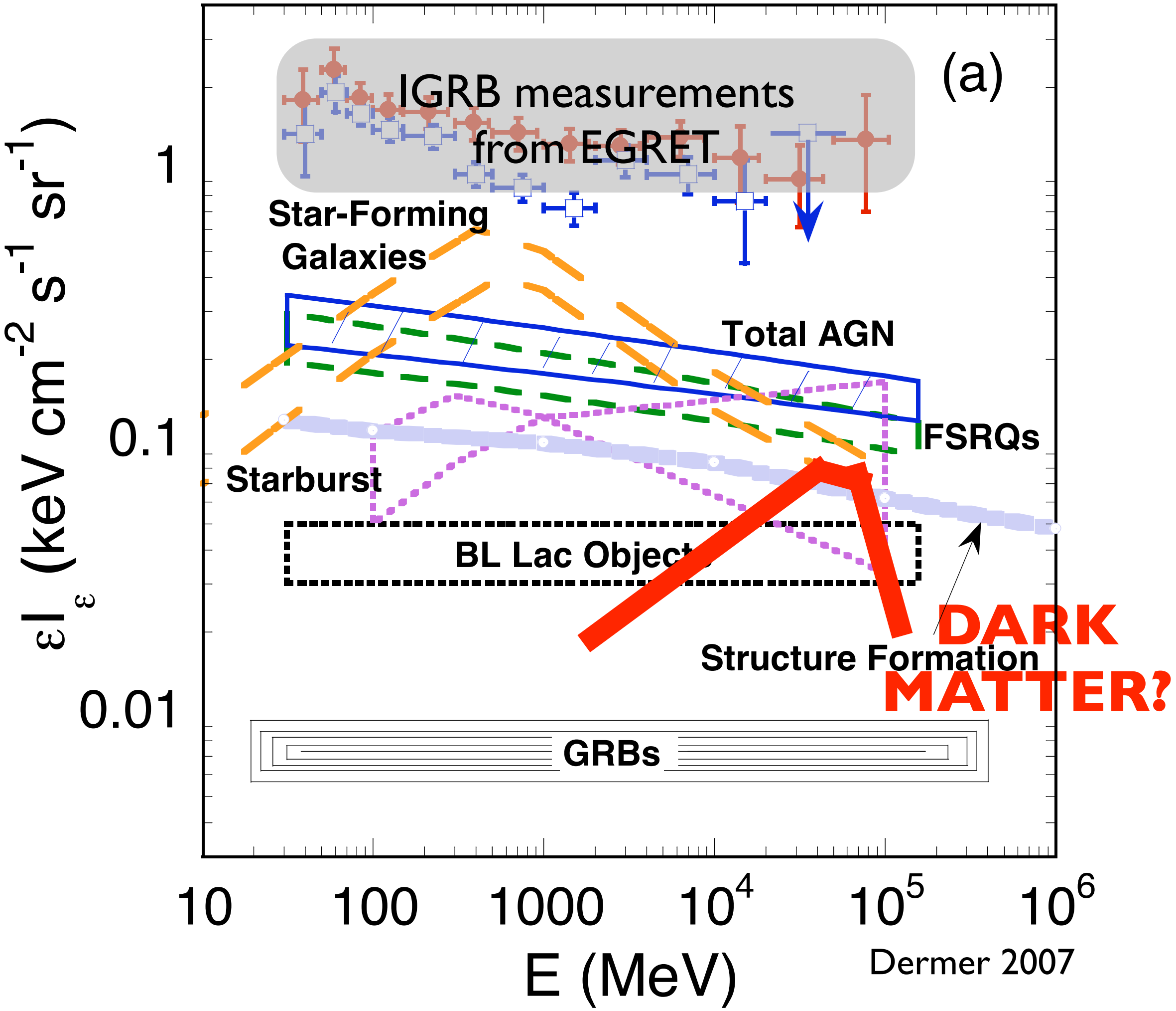
Hensley, JSG, & Pavlidou 2010

Adding up diffuse GeV emission

- *guaranteed* contributors include:
  - blazars (but no consensus on size of contribution!)
  - star-forming galaxies
  - millisecond pulsars

- *possible* contributions from unknown/unconfirmed source classes:
  - dark matter
  - ???

Energy spectra of possible contributors to the IGRB

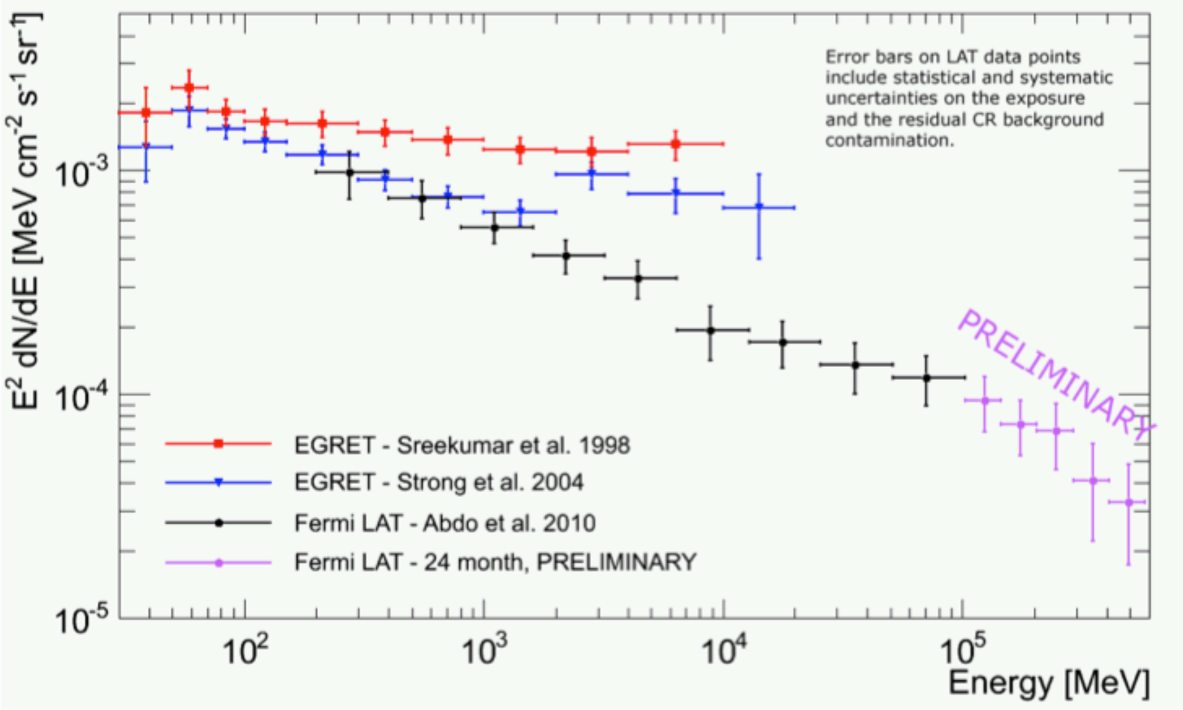


Dermer 2007

Relatively featureless total IGRB intensity spectrum ➔ lack of spectral handles to ID individual components!

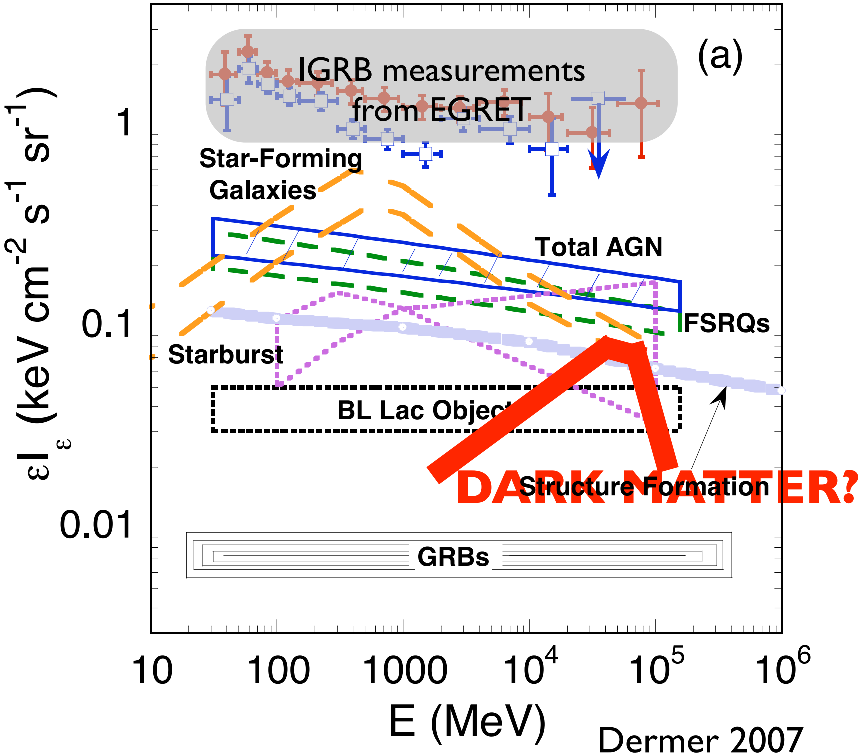
Adding up diffuse GeV emission

Energy spectrum of the Fermi-LAT IGRB



Fermi-LAT Collaboration (preliminary)

Energy spectra of possible contributors to the IGRB



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