



Anisotropies in the diffuse gamma-ray background

measured by the Fermi-LAT

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#### Overview

Using the angular information in the diffuse gamma-ray background to identify dark matter and other source classes

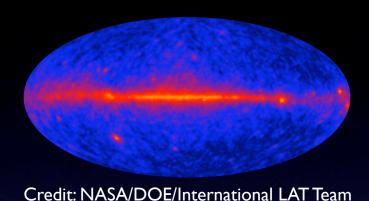
- in addition to the energy spectrum and average intensity, the diffuse background contains angular information
- if the diffuse emission originates from an unresolved source population, rather than from a truly isotropic, smooth source distribution, the diffuse emission will contain fluctuations on 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

## The Fermi Gamma-ray Space Telescope

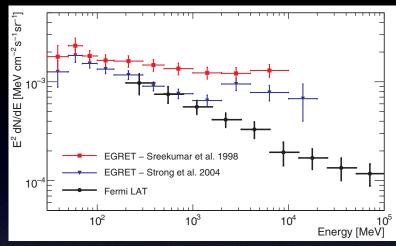
- + 20 MeV to > 300 GeV
- angular resolution ~ 0.1 deg above 10 GeV
- + FOV ~ 2.4 sr
- uniform sky exposure of ~30 mins every 3 hrs
- excellent charged particle background rejection



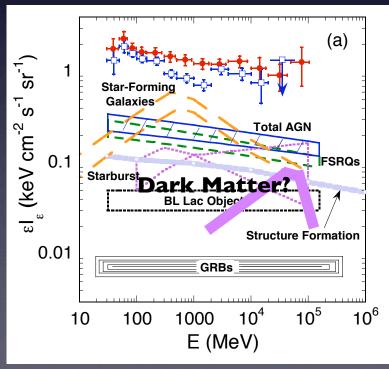
## What is making the large-scale isotropic diffuse emission?



- + 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
  - + 777
- relatively featureless total intensity spectrum
   lack of spectral handles to ID individual
   components



Abdo et al., PRL 104 (2010) 101101



the angular power spectrum of fluctuations characterizes fluctuations in units of mean intensity (dimensionless) and is independent of the intensity normalization

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

- enables comparison of angular distribution of two components which may have different intensities
- angular power spectrum normalization for a single source class is the same in all energy bins (if source distribution is independent of energy)
- + DOES NOT indicate the relative contribution of a component to the anisotropy of the total emission (the contributions of components ARE NOT linearly additive)

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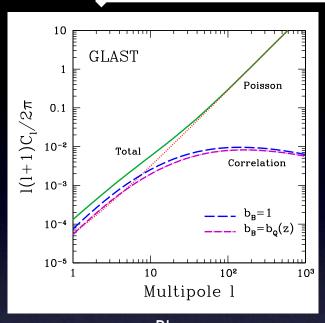
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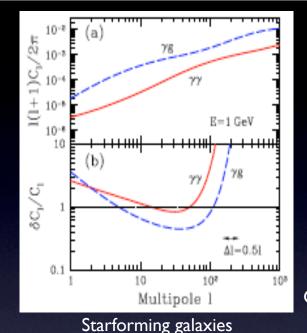
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- intensity and fluctuation angular power spectra are related by

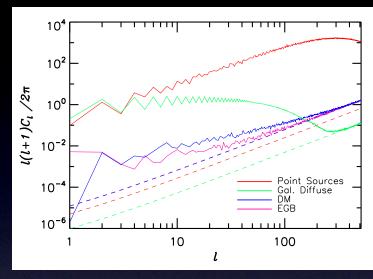
$$C_\ell^{
m intens} = \langle I \rangle^2 C_\ell^{
m fluct}$$

+  $\langle I \rangle$  is the mean intensity in the sky region used for the analysis

#### Angular power spectra of unresolved gamma-ray populations







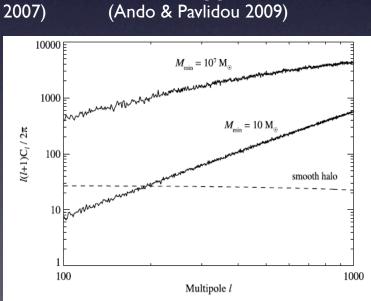
Galactic diffuse, EG, point sources, DM; arbitrary norm. (Cuoco, Sellerholm, Conrad, & Hannestad 2010)

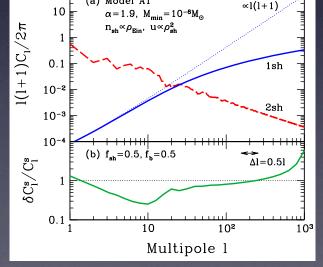
Blazars (Ando, Komatsu, Narumoto & Totani 2007)

fluctuation angular power spectra

predictions for  $C_{\ell}$  at I = 100 for a single source class (LARGE UNCERTAINTIES):

- + blazars: ~ le-4
- starforming galaxies: ~ Ie-7
- dark matter: ~ le-4 to ~ 0.1





tic subhalos (JSG 2008) Galactic subhalos (Ando 2009)

- select regions of the sky which are relatively "clean"
  - \* mask sources in the 11-month catalog within a 2 deg angular radius
  - \* mask regions of the sky heavily contaminated by Galactic diffuse emission by excluding |b| < 30 deg

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- calculate angular power spectrum of the data in several energy bins
  - using several energy bins increases sensitivity to source populations which contribute significantly to the anisotropy in a limited energy range
  - energy-dependence may aid in interpretation of measurement in terms of a detection of or constraints on specific source populations (Hensley, JSG, & Pavlidou 2009, Cuoco et al. 2010)
  - PSF and event statistics depend strongly on energy:
    - low-energy bins have better statistics, poorer PSF; high-energy bins have poorer statistics, better PSF

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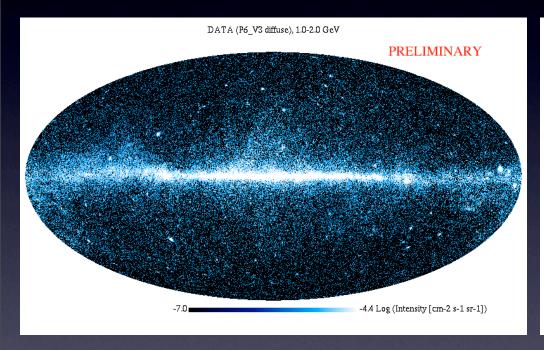
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- compare results from data and simulated model (Galactic diffuse + 11-mo
   sources + isotropic) to identify significant differences in anisotropy properties

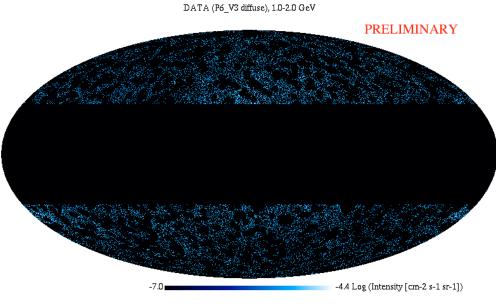
### Data selections and processing

- ~ 22 months of data
- diffuse class events
- energy range: I GeV 50 GeV, divided into 5 energy bins for angular power spectrum analysis
- data and simulations processed using the Fermi Science Tools with P6\_V3 IRFs to handle instrument response and exposure calculation
- + binned into order 9 HEALPix maps, corresponding to pixels of  $\sim 0.1$  deg/side
  - the suppression of angular power due to pixelation of the map (pixel window function)
    is subdominant compared to the suppression of angular power due to the PSF (beam
    window function) at order 9 map resolution
- front- and back-converting events processed separately through angular power spectrum calculation, then results are combined by weighted average
  - PSF is much poorer for back-converting events than front-converting events
  - processing front/back separately results in a more accurate estimation of measurement uncertainties which depend strongly on PSF

- 2 GeV

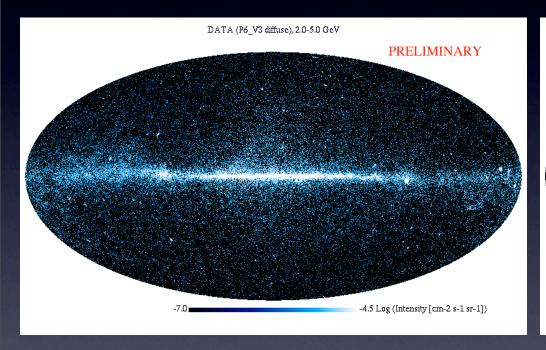
All-sky map

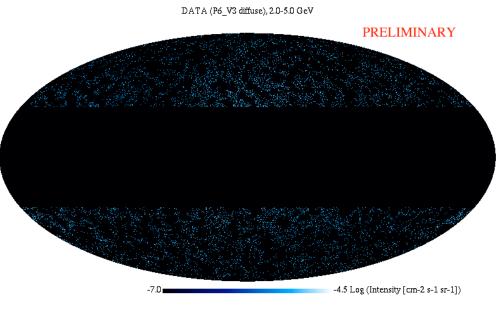




2 - 5 GeV

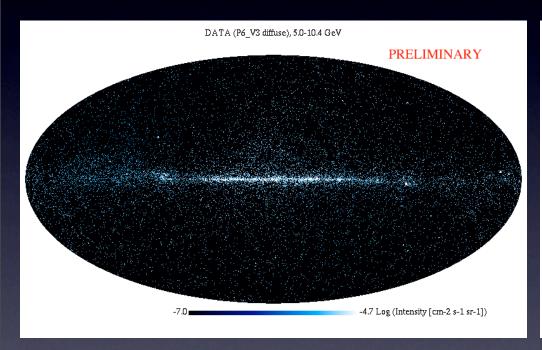
All-sky map

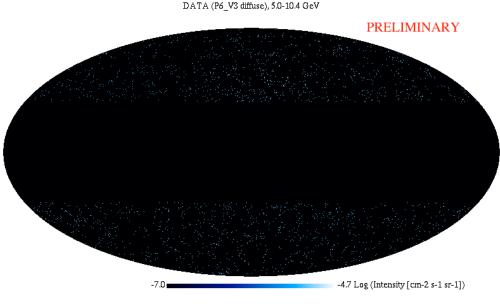




5 - 10 GeV

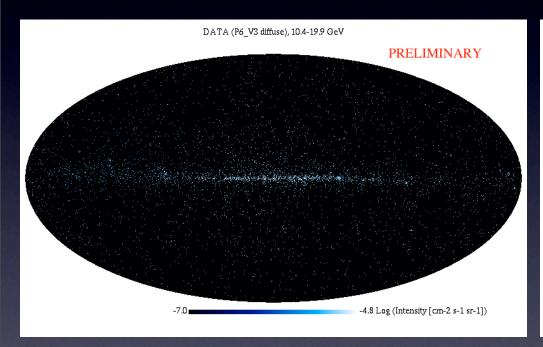
All-sky map

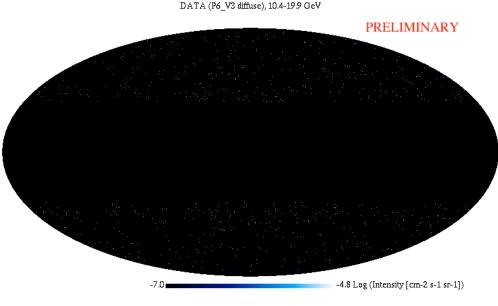




10 - 20 GeV

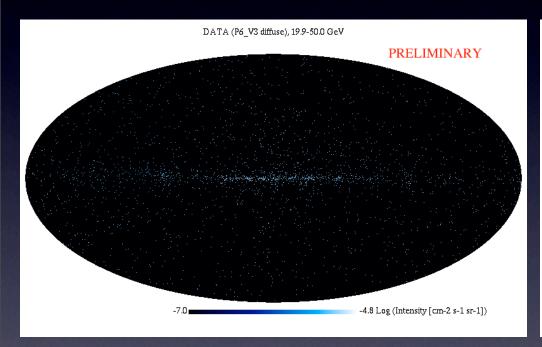
All-sky map

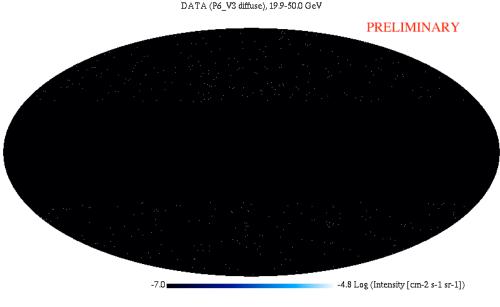




20 - 50 GeV

All-sky map





#### Simulations

a model of the all-sky emission is simulated with gtobssim (Fermi Science Tools) and its angular power spectrum is calculated to compare with the data

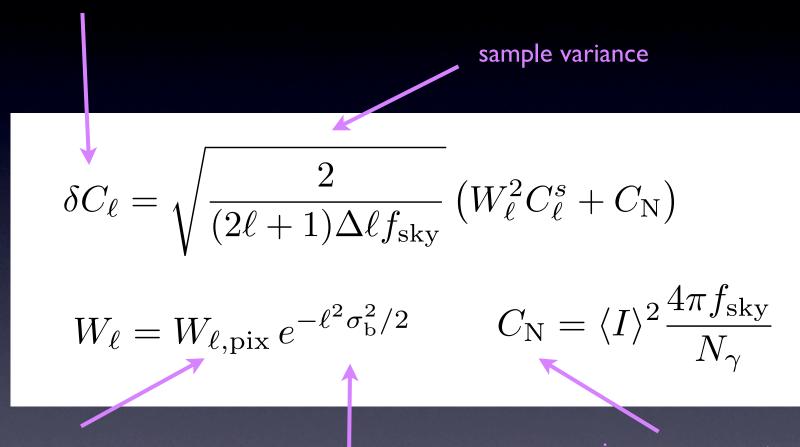
- GAL: Galactic diffuse model (gll\_iem\_v02.fit)
- CAT: I I-month source catalog
- ISO: isotropic background = Fermi-measured large-scale isotropic diffuse + unrejected charged particles (isotropic\_iem\_v02.txt spectrum template)
- MODEL = sum of GAL, CAT, and ISO

## Angular power spectrum calculation

- angular power spectra are calculated using the HEALPix package (Gorski et al. 2005)
- approximate correction for the power suppression from masking is applied, valid at multipoles greater than ~ 100
- correction is applied for power suppression due to beam and pixel window functions
- error bars on points indicate I-sigma statistical uncertainty in the measurement; systematic uncertainties are NOT included
  - uncertainties in the determination of the PSF can affect the calculation of the measurement uncertainties and the correction for the beam window function
- angular power spectra are shown with photon noise level subtracted, so a measurement above 0 indicates the presence of angular power above the noise level

#### Measurement uncertainties

I-sigma statistical uncertainty on the measurement



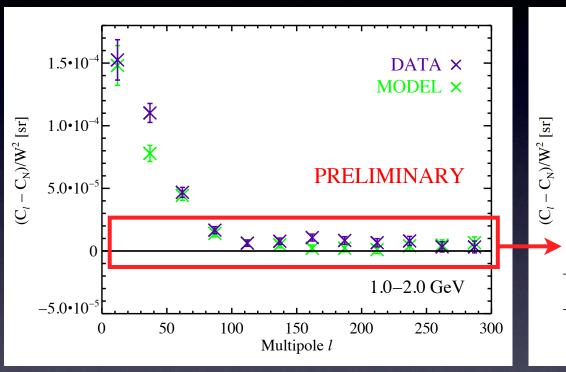
pixel window function of the map

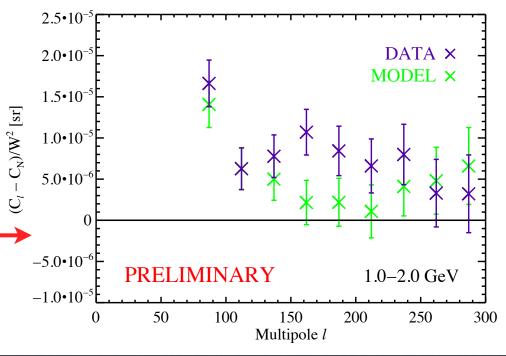
beam window function of the experiment

noise power spectrum (Poisson noise from finite event statistics, independent of  $\ell$ )

fluctuation angular power spectra

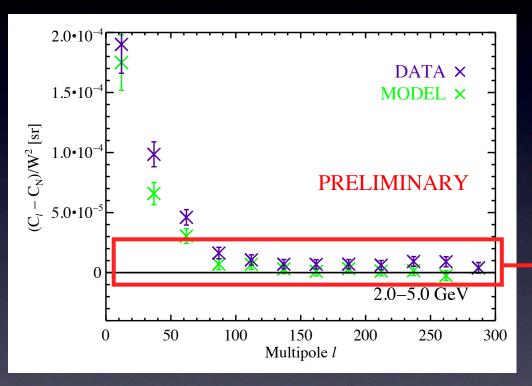
1 - 2 GeV

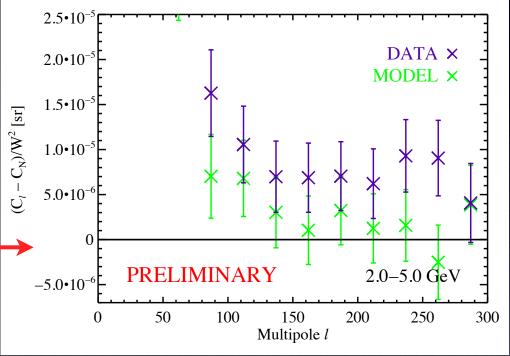




fluctuation angular power spectra

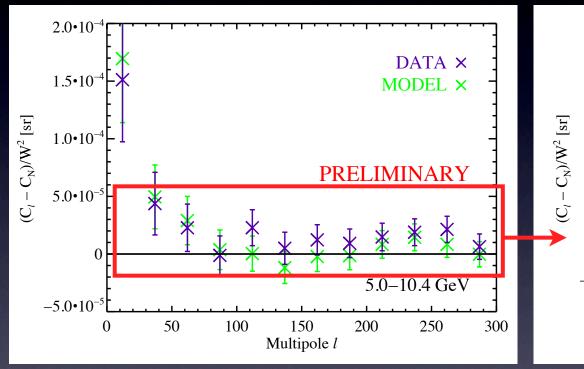
2 - 5 GeV

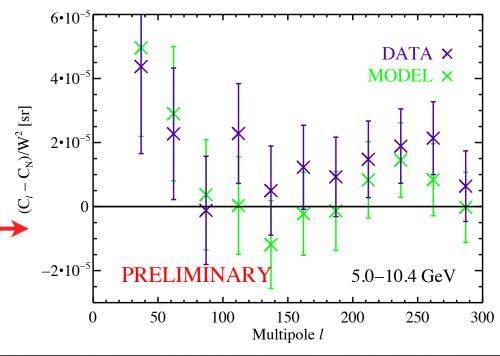




fluctuation angular power spectra

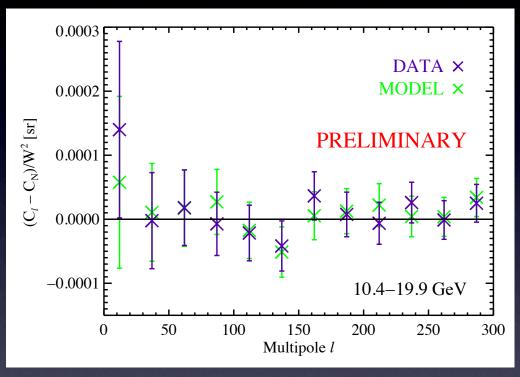
5 - 10 GeV



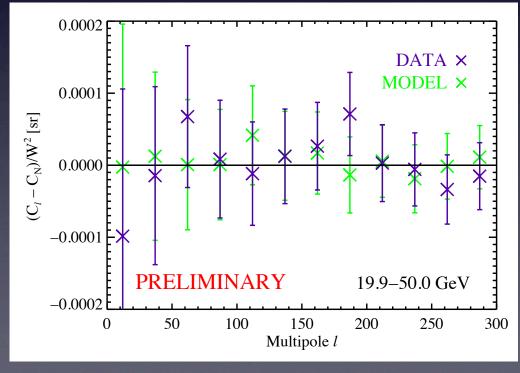


fluctuation angular power spectra

#### 10 - 20 GeV



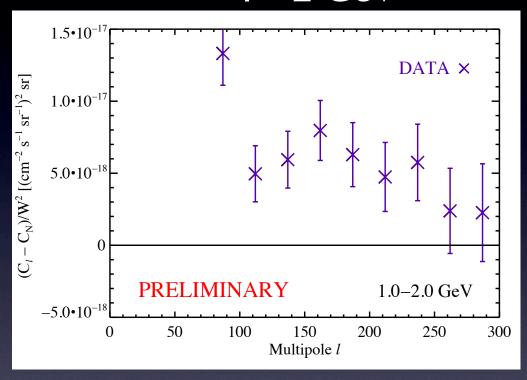
#### 20 - 50 GeV



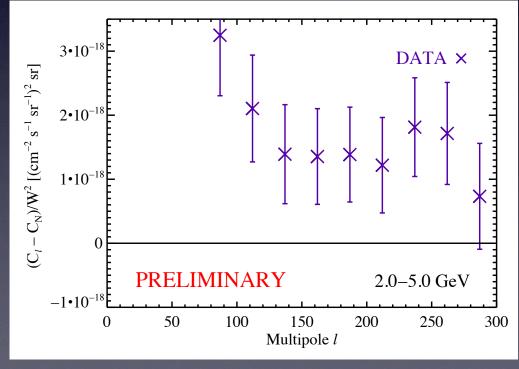
#### Data

intensity angular power spectra

#### 1 - 2 GeV



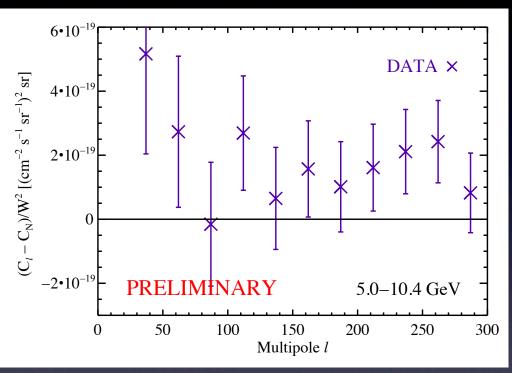
#### 2 - 5 GeV



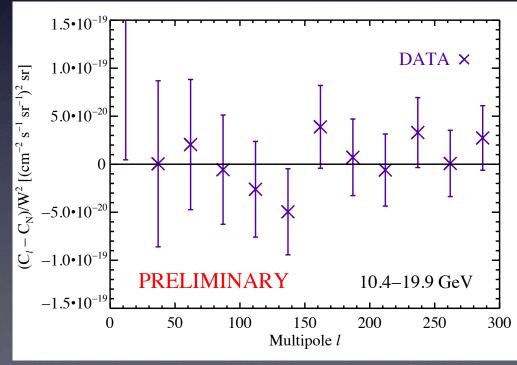
#### Data

intensity angular power spectra

#### 5 - 10 GeV



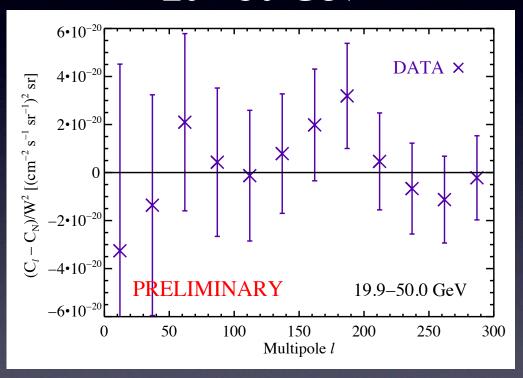
#### 10 - 20 GeV



#### Data

intensity angular power spectra

#### 20 - 50 GeV



## Comparison with (rough) predictions

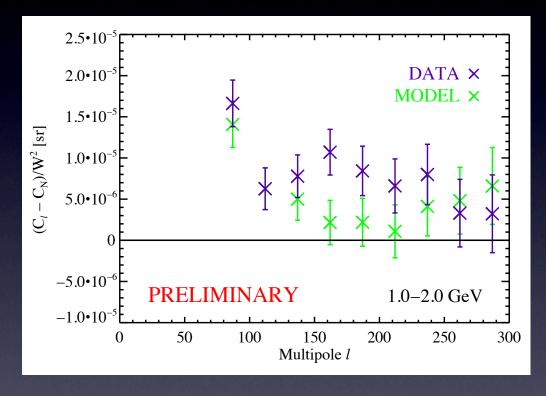
fluctuation angular power spectra

I - 2 GeV

fluctuation angular power spectra

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- + dark matter: ~ le-4 to ~ 0.1



measured fluctuation  $C_\ell$  of ~ 1e-5 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



- at multipoles greater than ~ 100
  - angular power above the photon noise level is measured in the data at energies from 1 to 5 GeV; excess power is found at lower significance up to energies of 10 GeV
  - no significant angular power is seen in the model
  - the excess power in the data at these multipoles suggests a contribution from a point source population not present in the model

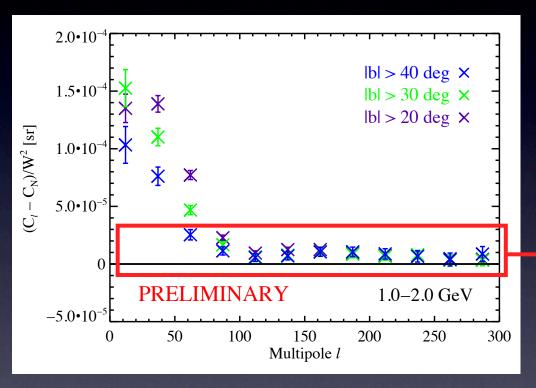
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- at multipoles less than ~ 100
  - \* angular power above the noise is seen in the data and model, and is likely due to contamination from the Galactic diffuse

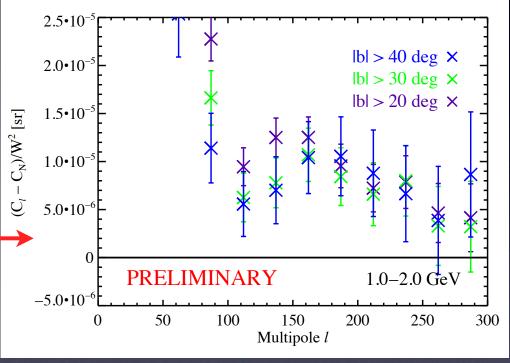
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- \* NB: due to decreasing photon statistics, the amplitude of anisotropies detectable by this analysis decreases with increasing energy, hence the measurements at higher energies currently do not exclude the presence of anisotropies at those energies at the level detected at 1 10 GeV

fluctuation angular power spectra

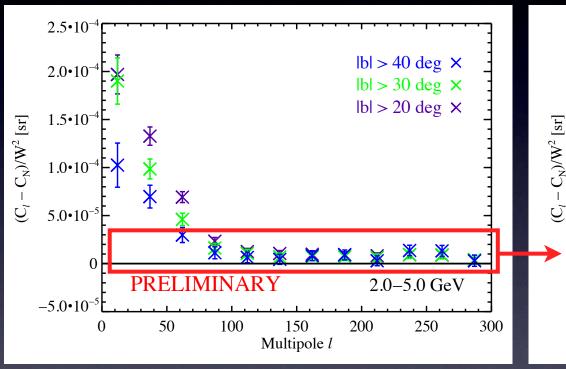
1 - 2 GeV

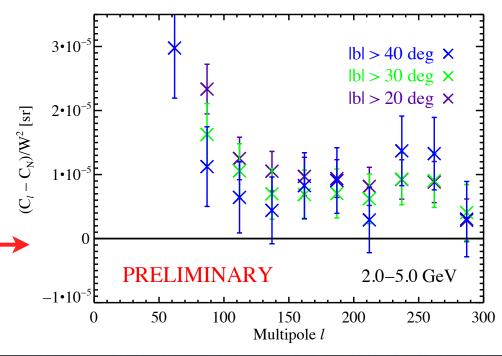




fluctuation angular power spectra

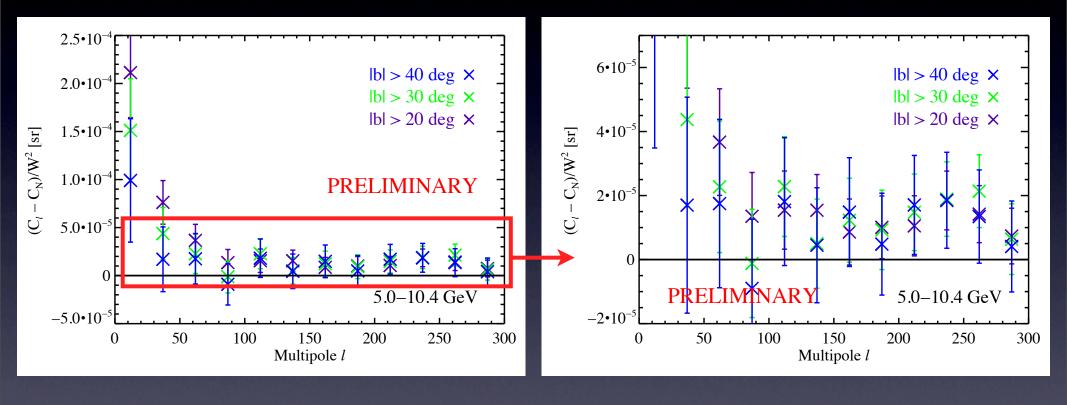
2 - 5 GeV





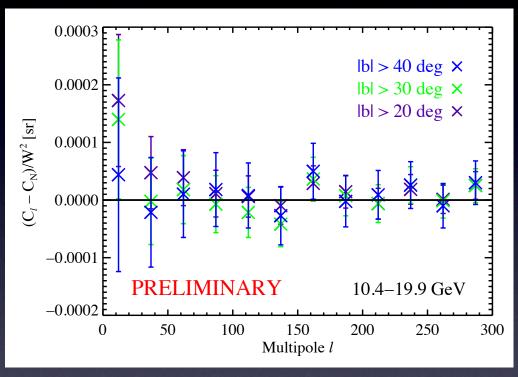
fluctuation angular power spectra

5 - 10 GeV



fluctuation angular power spectra

#### 10 - 20 GeV



#### 20 - 50 GeV

