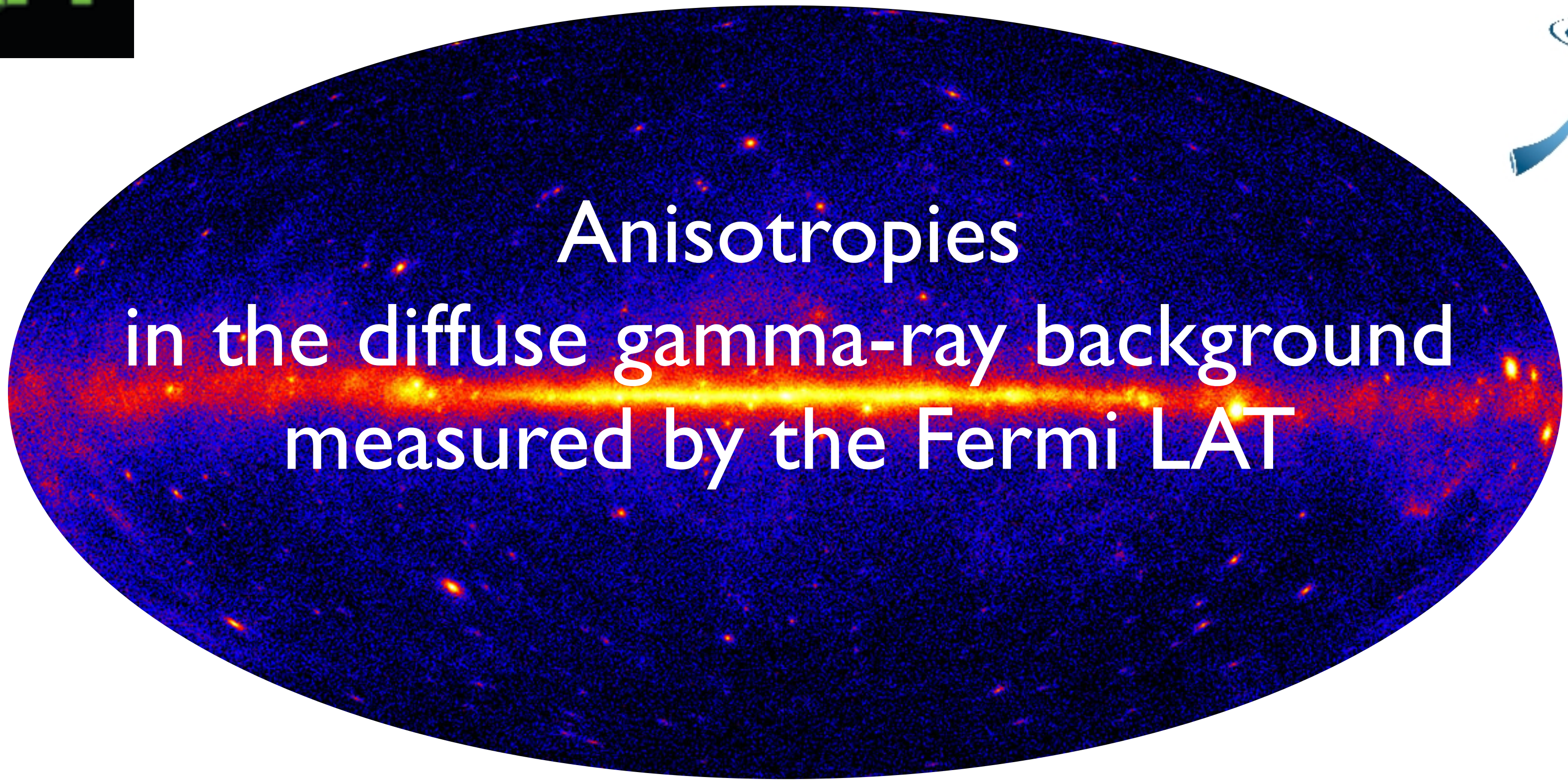
Image Credit: NASA/DOE/International LAT Team



Anisotropies in the diffuse gamma-ray background measured by the Fermi LAT

Jennifer Siegal-Gaskins

CCAPP, Ohio State University (➔ Caltech)

with

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

and

E. Komatsu

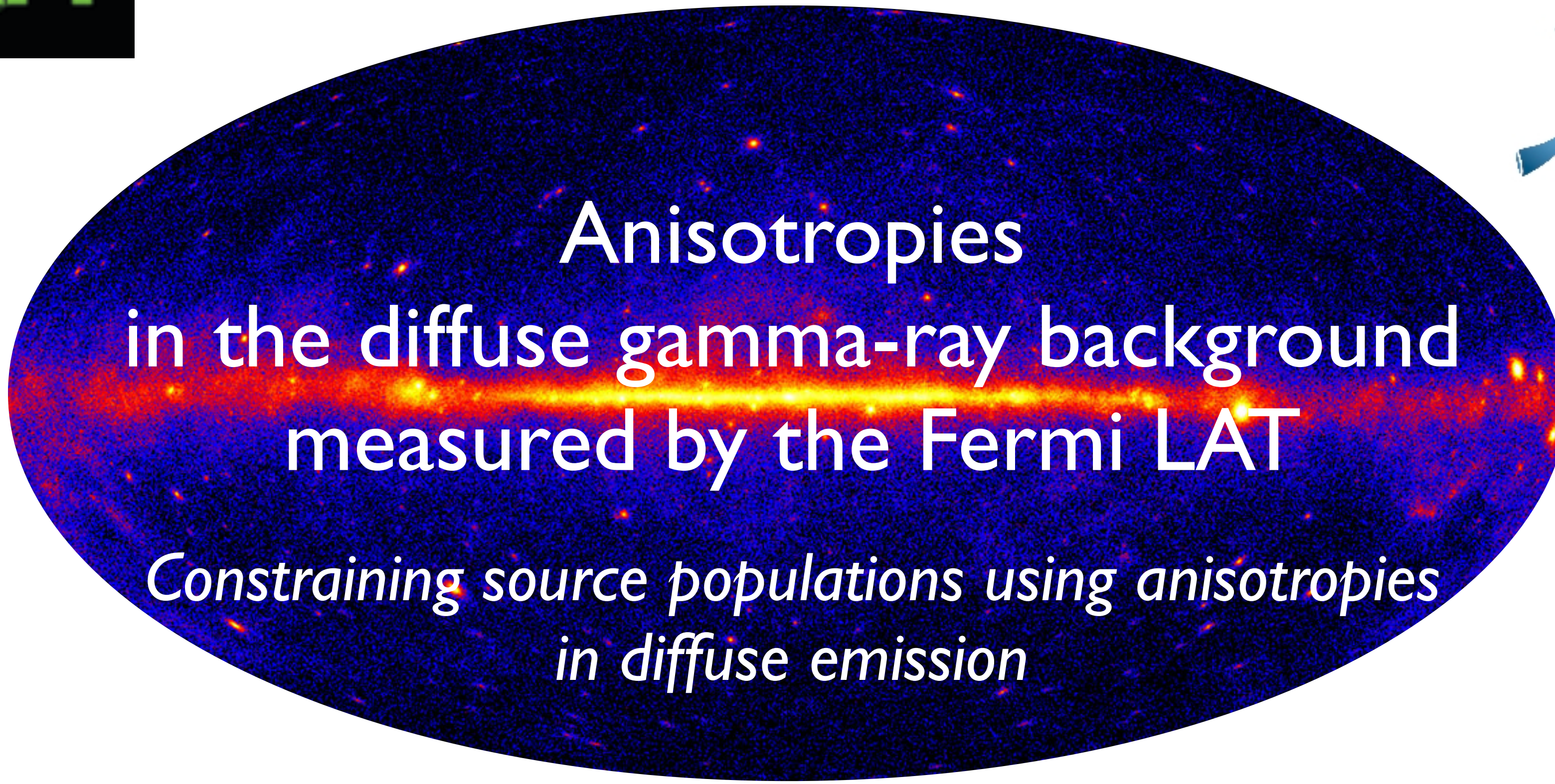
based on

JSG, for the Fermi LAT Collaboration & Komatsu,
arXiv:1012:1206
and talk at the 2011 Fermi Symposium

and

Cuoco, Komatsu, & JSG, *in prep*

Image Credit: NASA/DOE/International LAT Team



Anisotropies in the diffuse gamma-ray background measured by the Fermi LAT

Constraining source populations using anisotropies in diffuse emission

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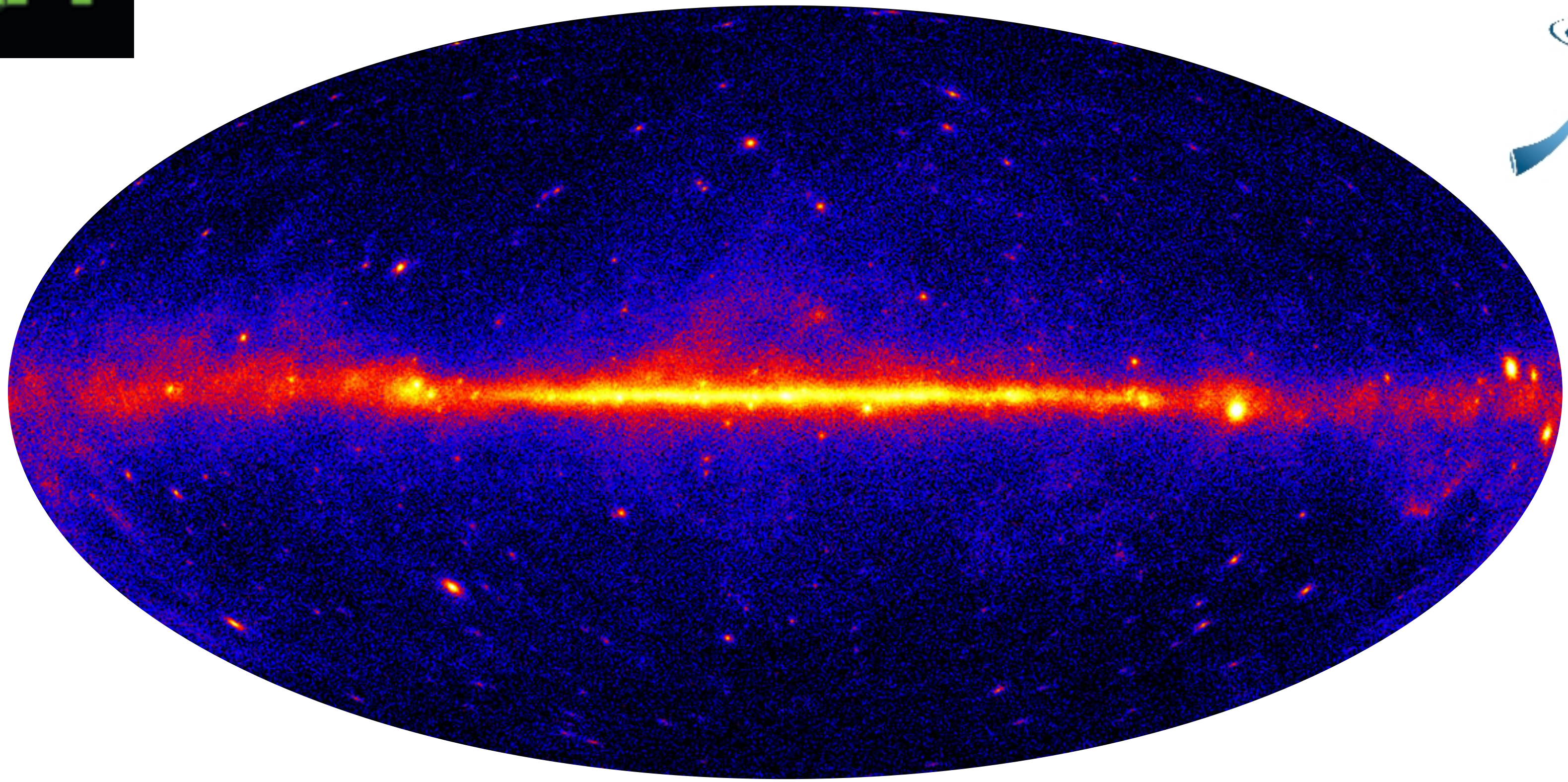

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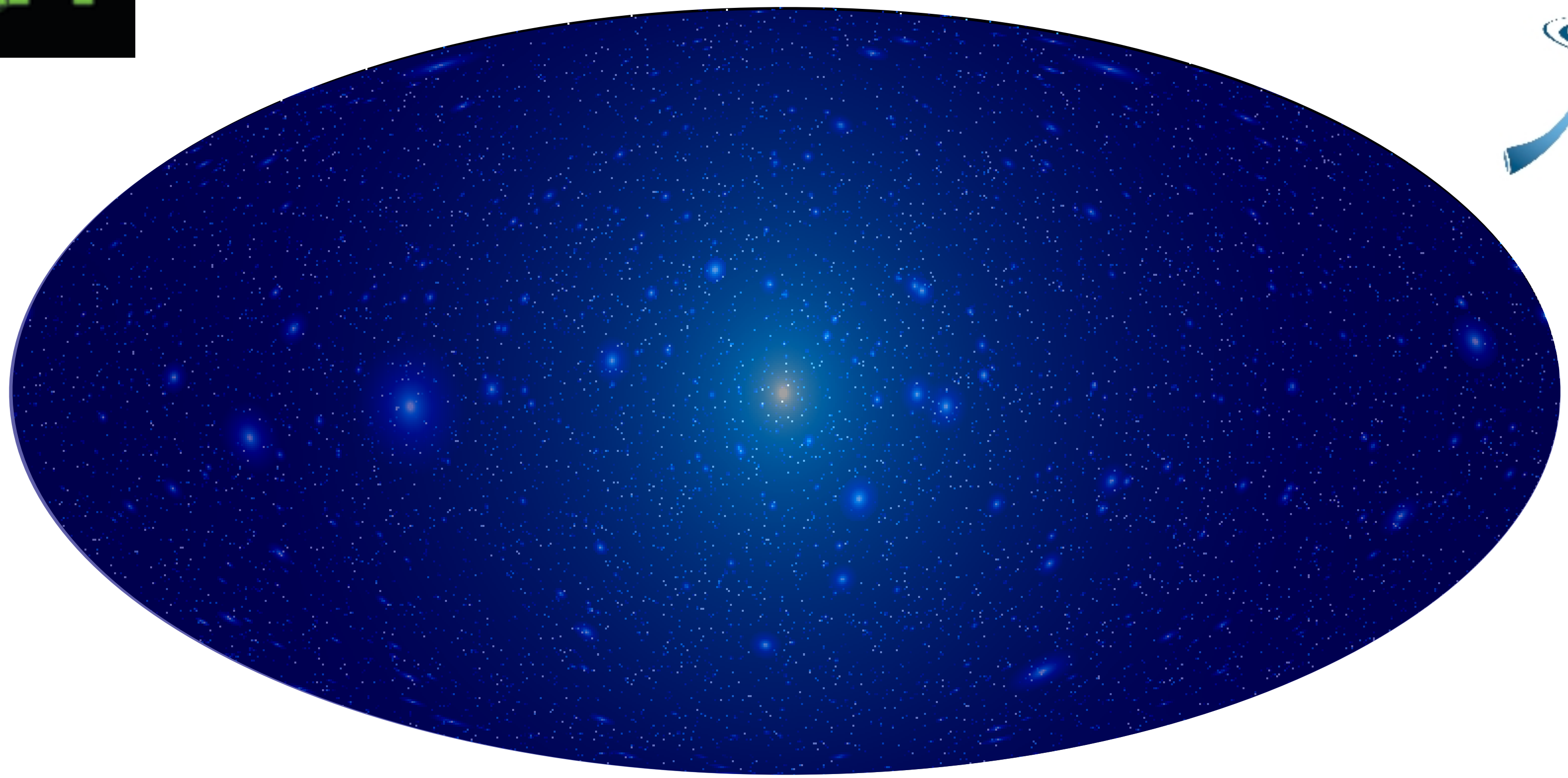

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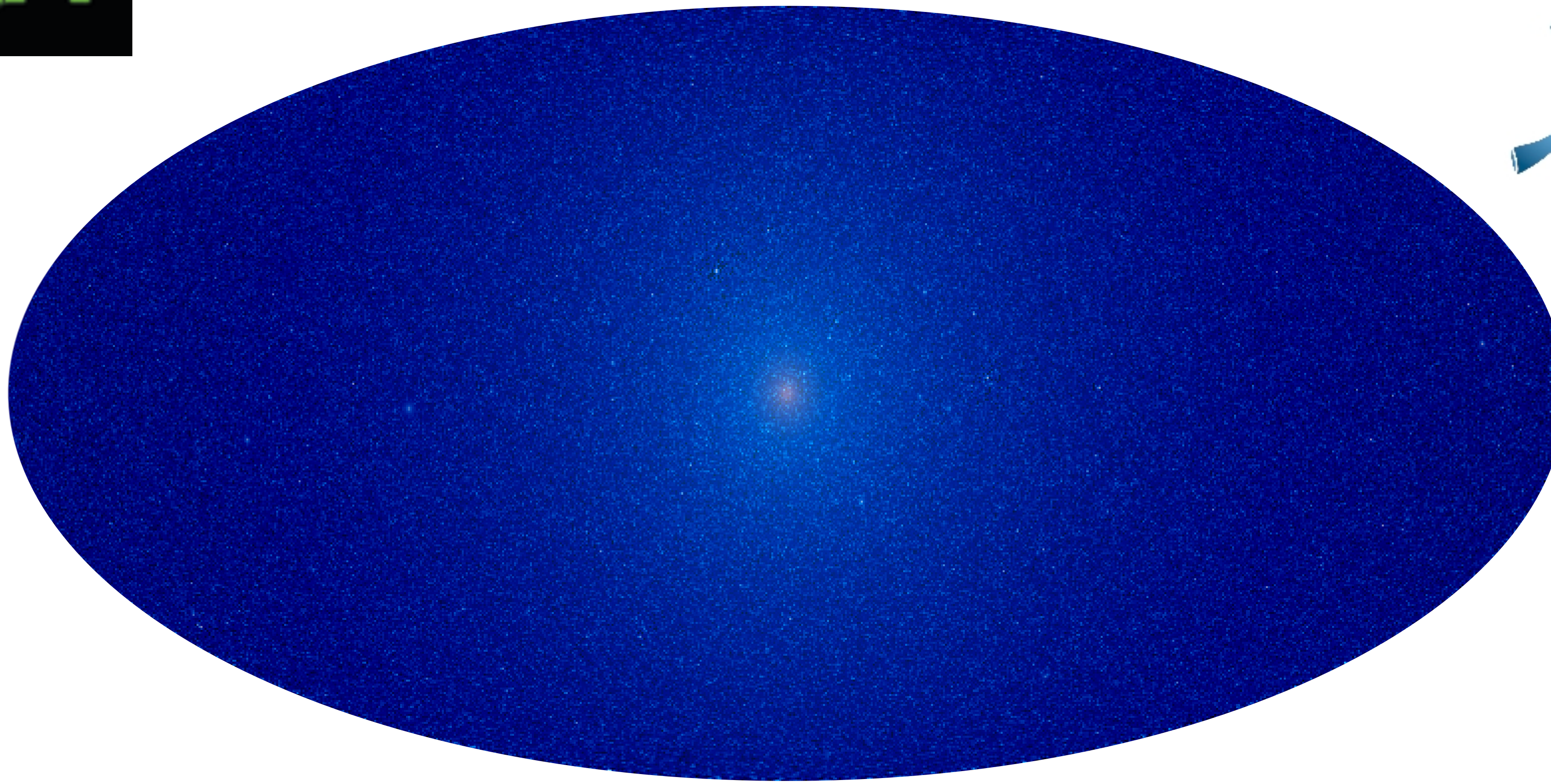

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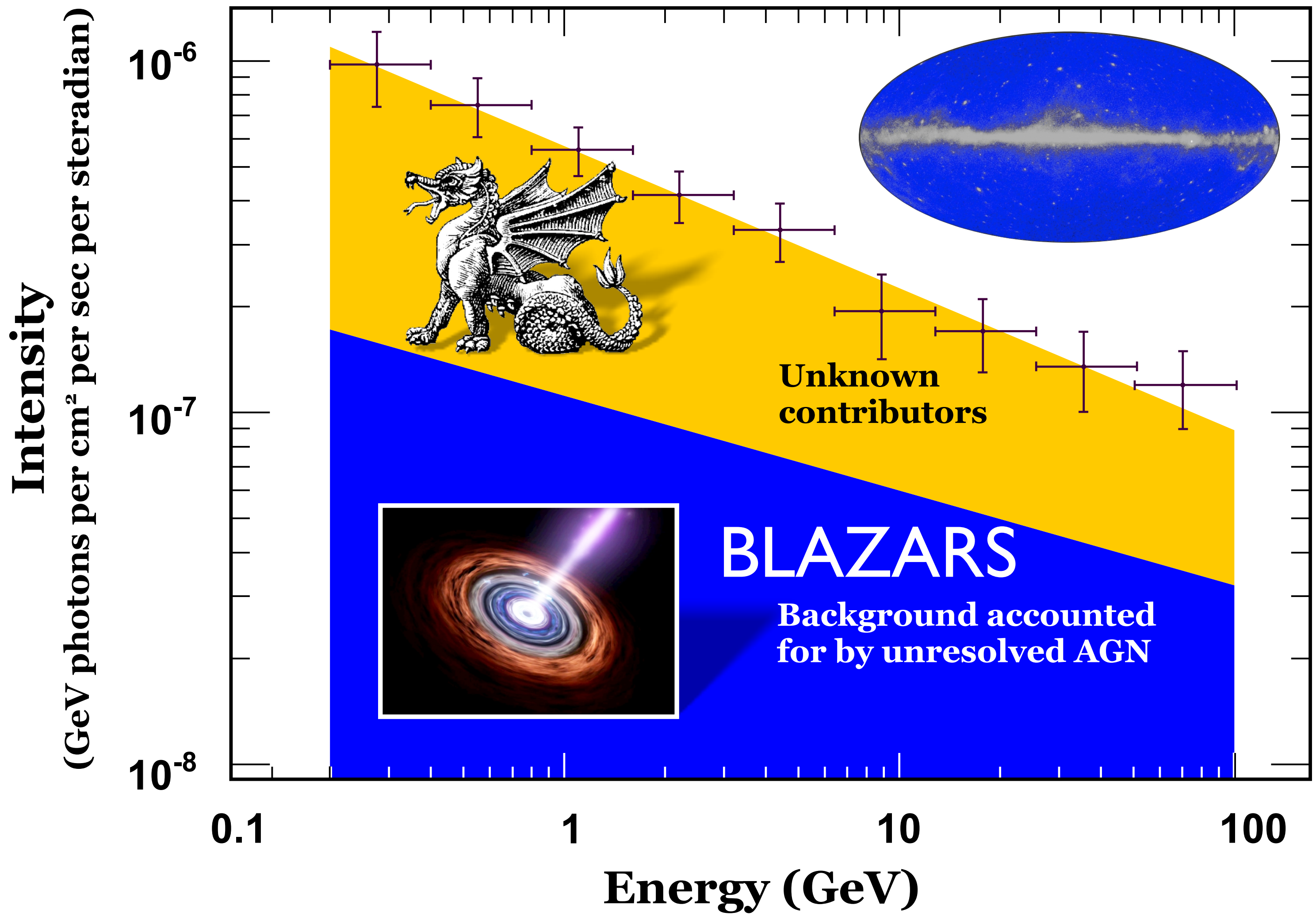
What is making the diffuse gamma-ray background?

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



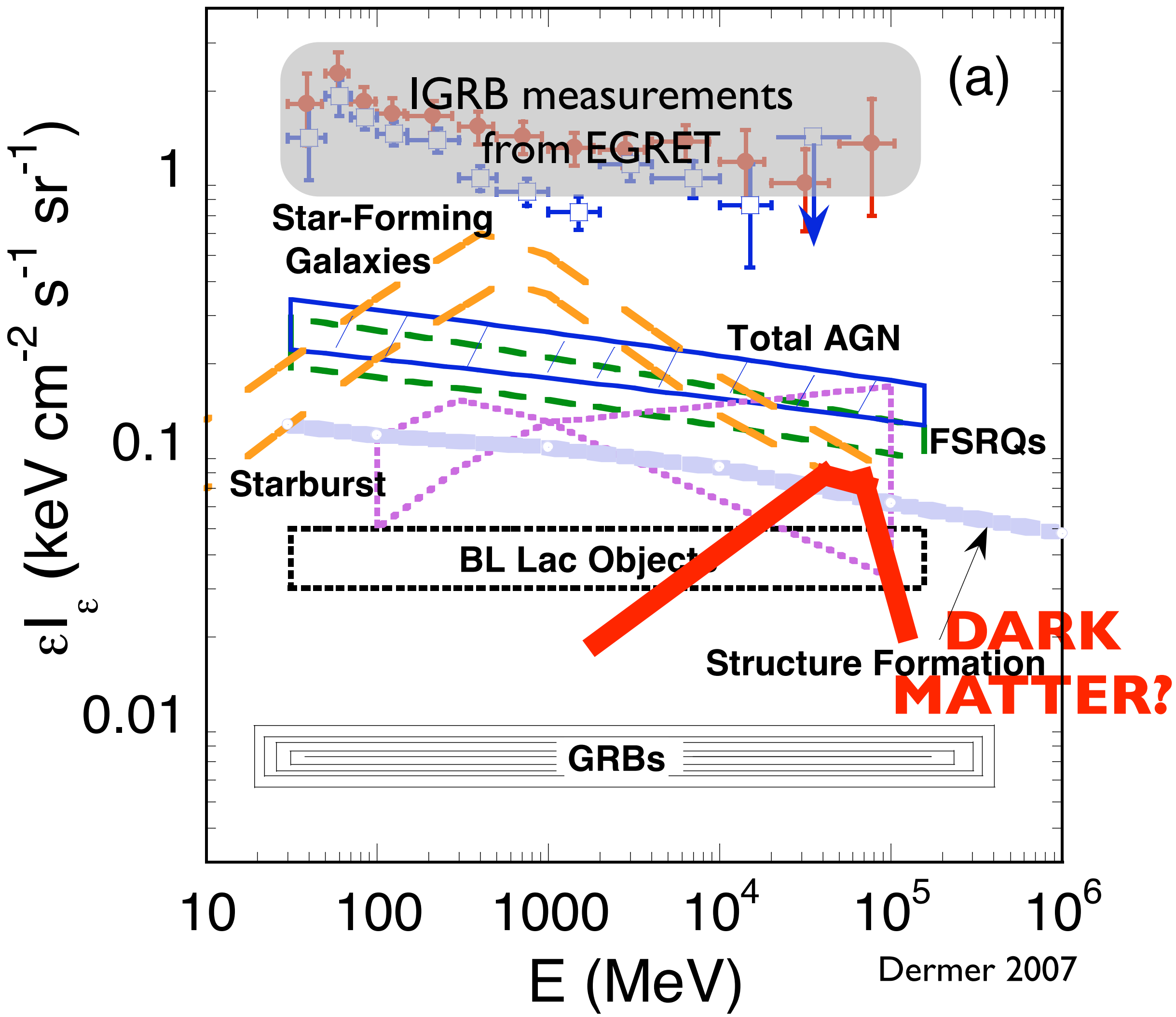
Credit: NASA/DOE/Fermi LAT Collaboration

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



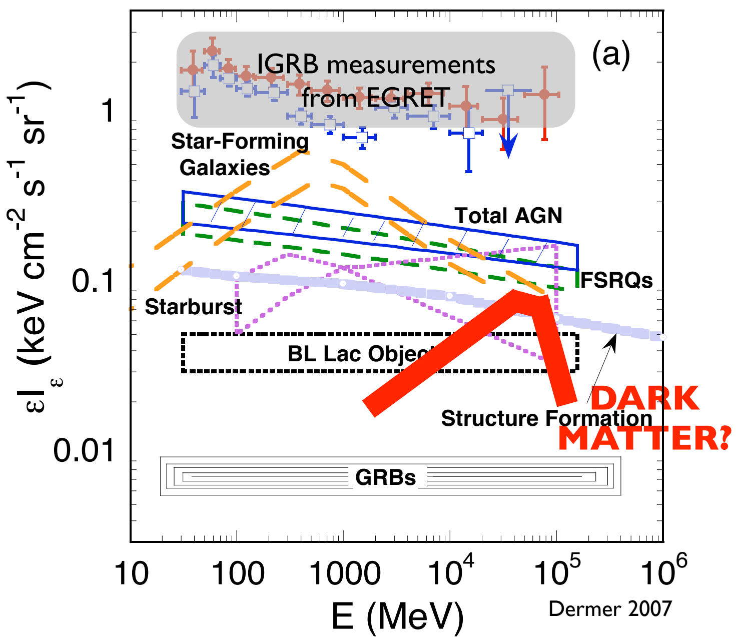
Dermer 2007

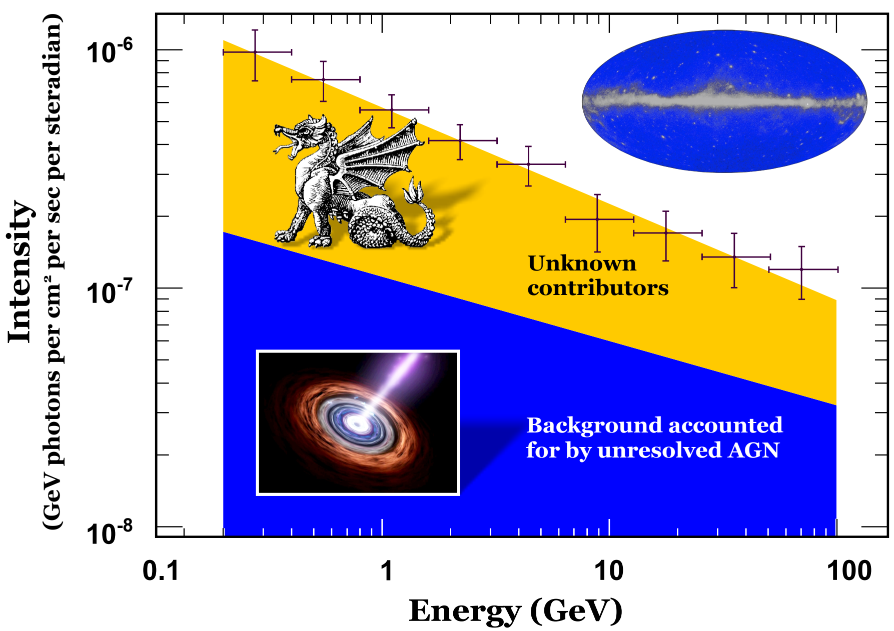
Adding up diffuse GeV emission

- *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
  - ???

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





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

Detecting unresolved sources with anisotropies

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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)

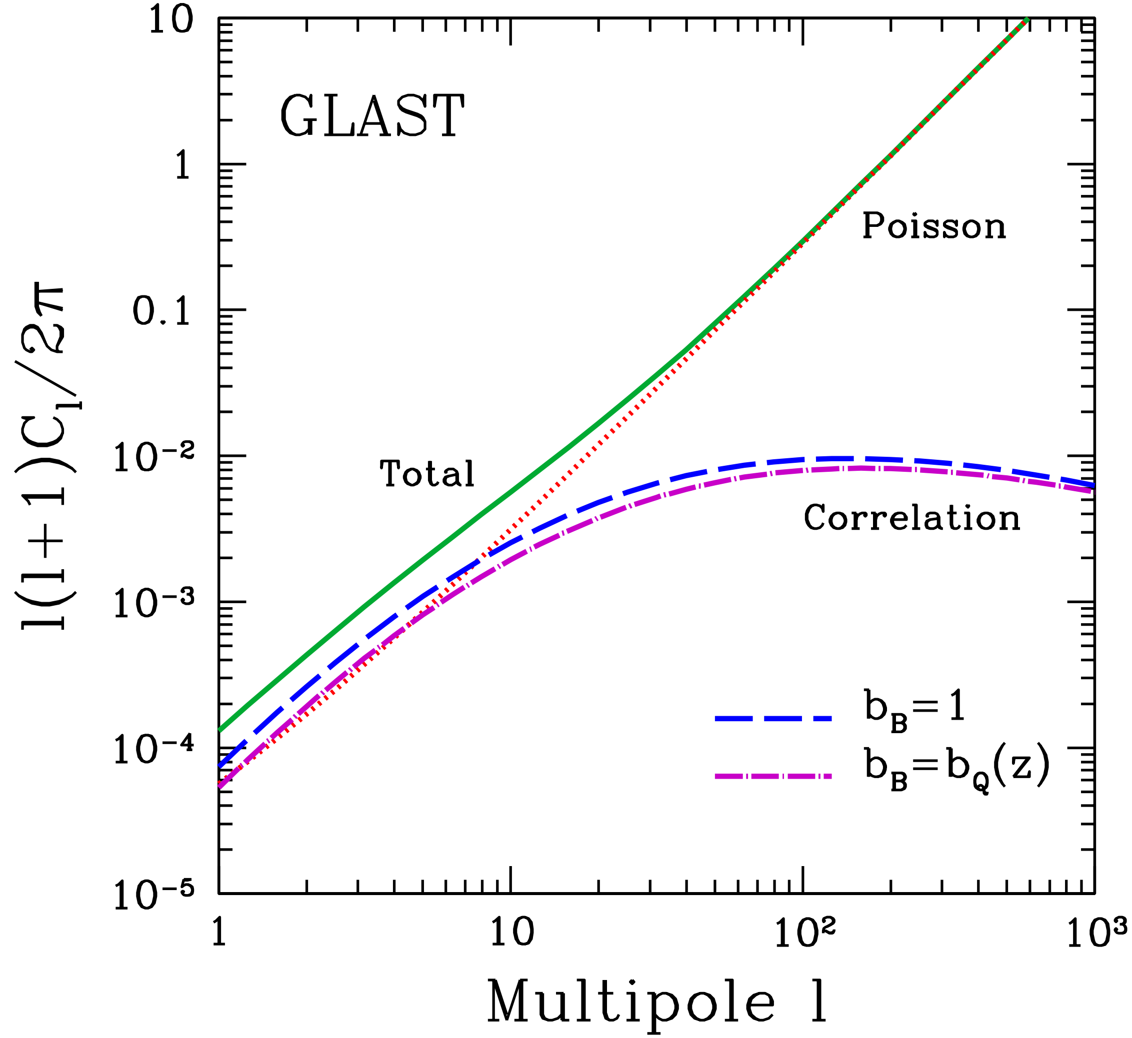
Angular power spectra of unresolved gamma-ray sources

- 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):

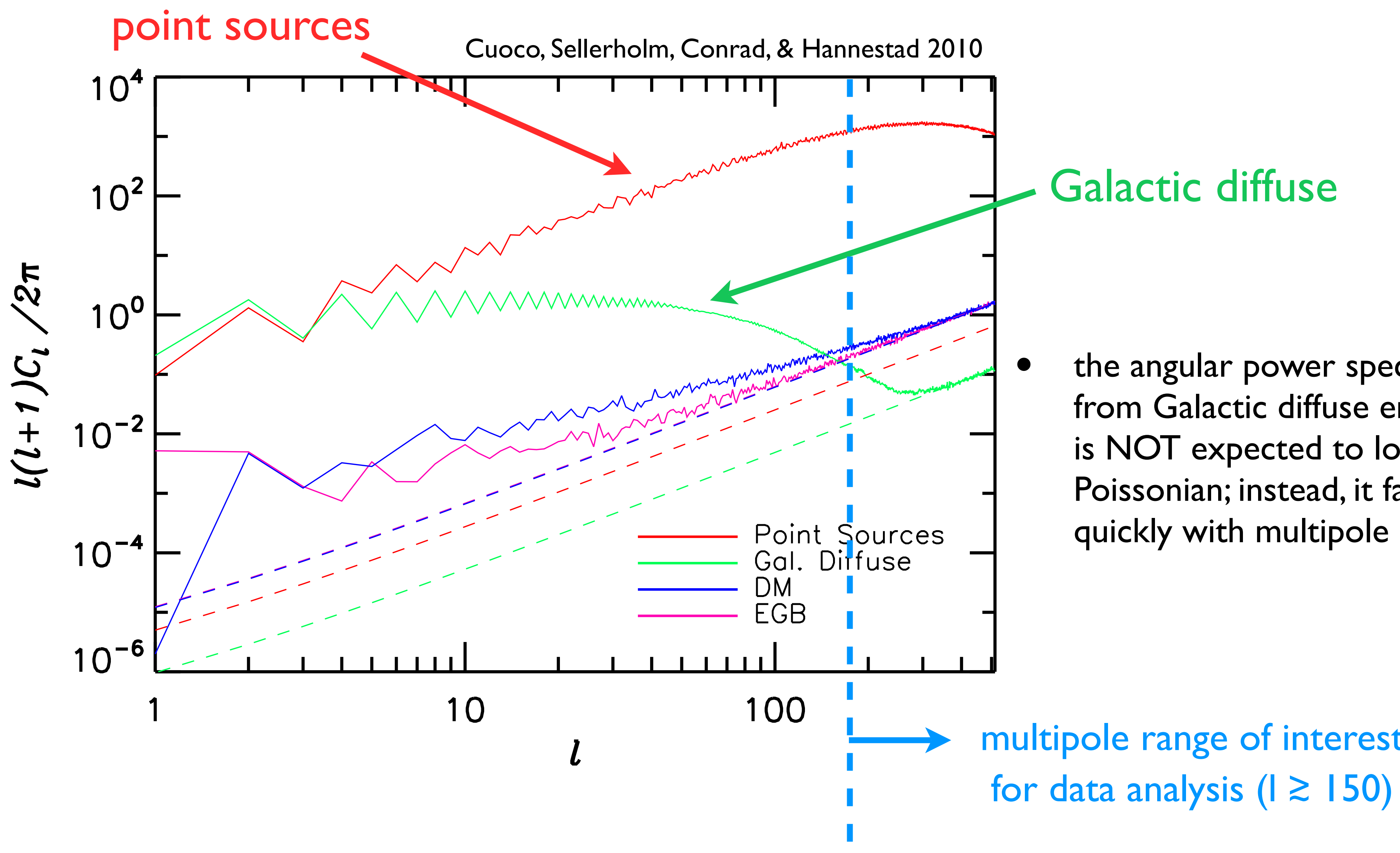
- blazars: ~ 2e-4
- starforming galaxies: ~ 2e-7
- dark matter: ~ 1e-6 to ~ 1e-4
- MSPs: ~ 0.03

Predicted angular power spectrum of unresolved blazars



Ando, Komatsu, Narumoto & Totani 2007

Angular power spectra of foregrounds

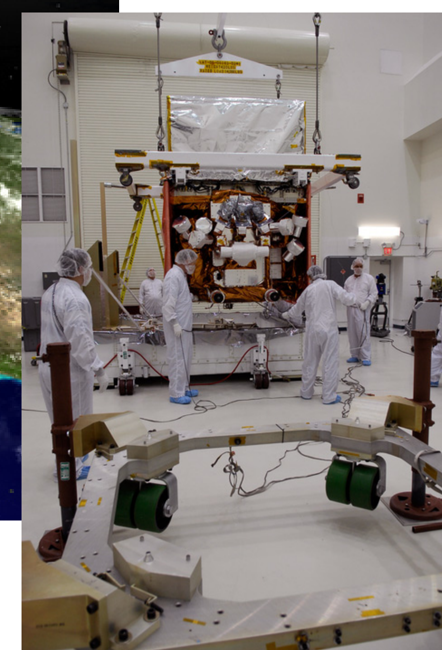


- the angular power spectrum from Galactic diffuse emission is NOT expected to look Poissonian; instead, it falls off quickly with multipole

The Fermi Large Area Telescope (*Fermi* LAT)

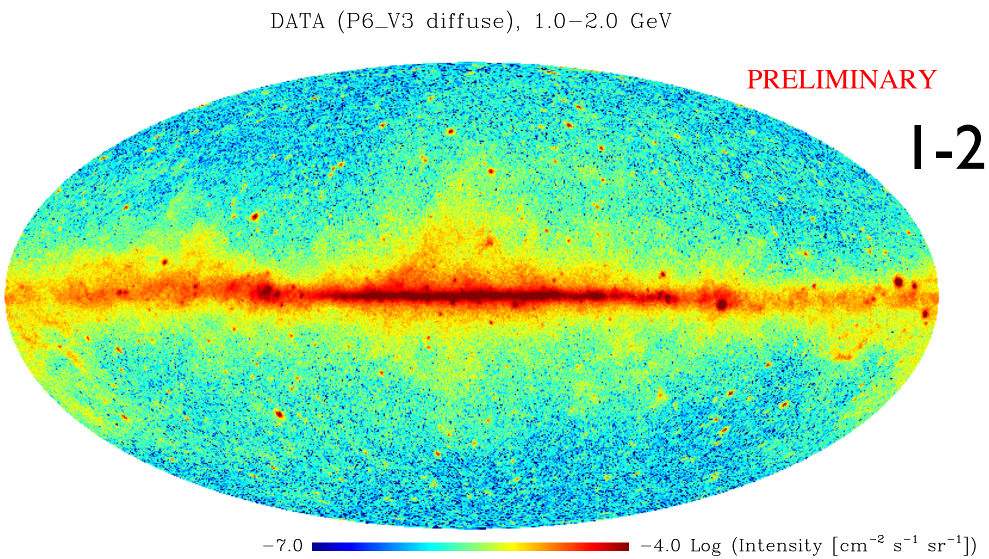
- 20 MeV to > 300 GeV
- Angular resolution ~ 0.1 deg above 10 GeV
- Uniform sky exposure of ~ 30 mins every 3 hrs
- Excellent charged particle background rejection

Credit: NASA/General Dynamics



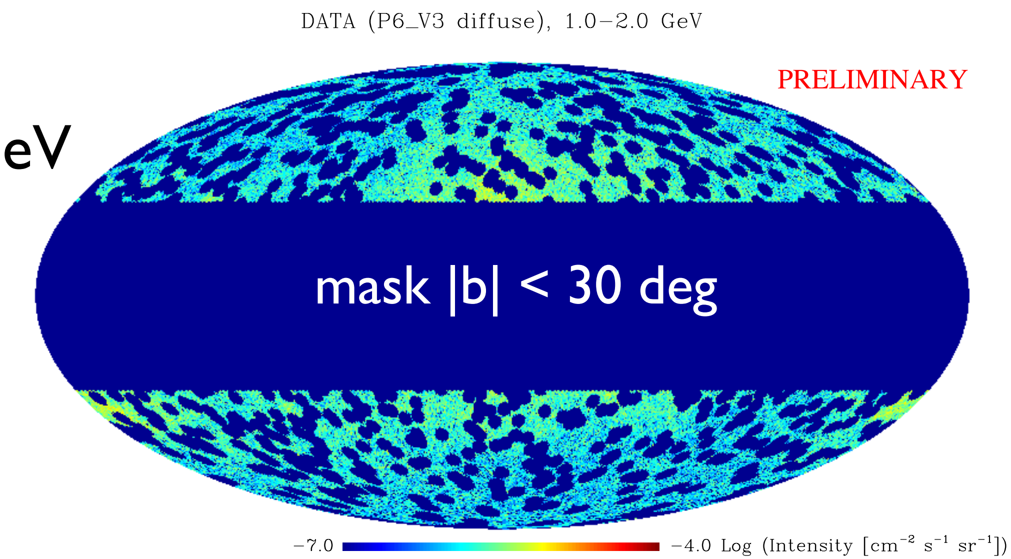
Angular power spectrum analysis of Fermi LAT data

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

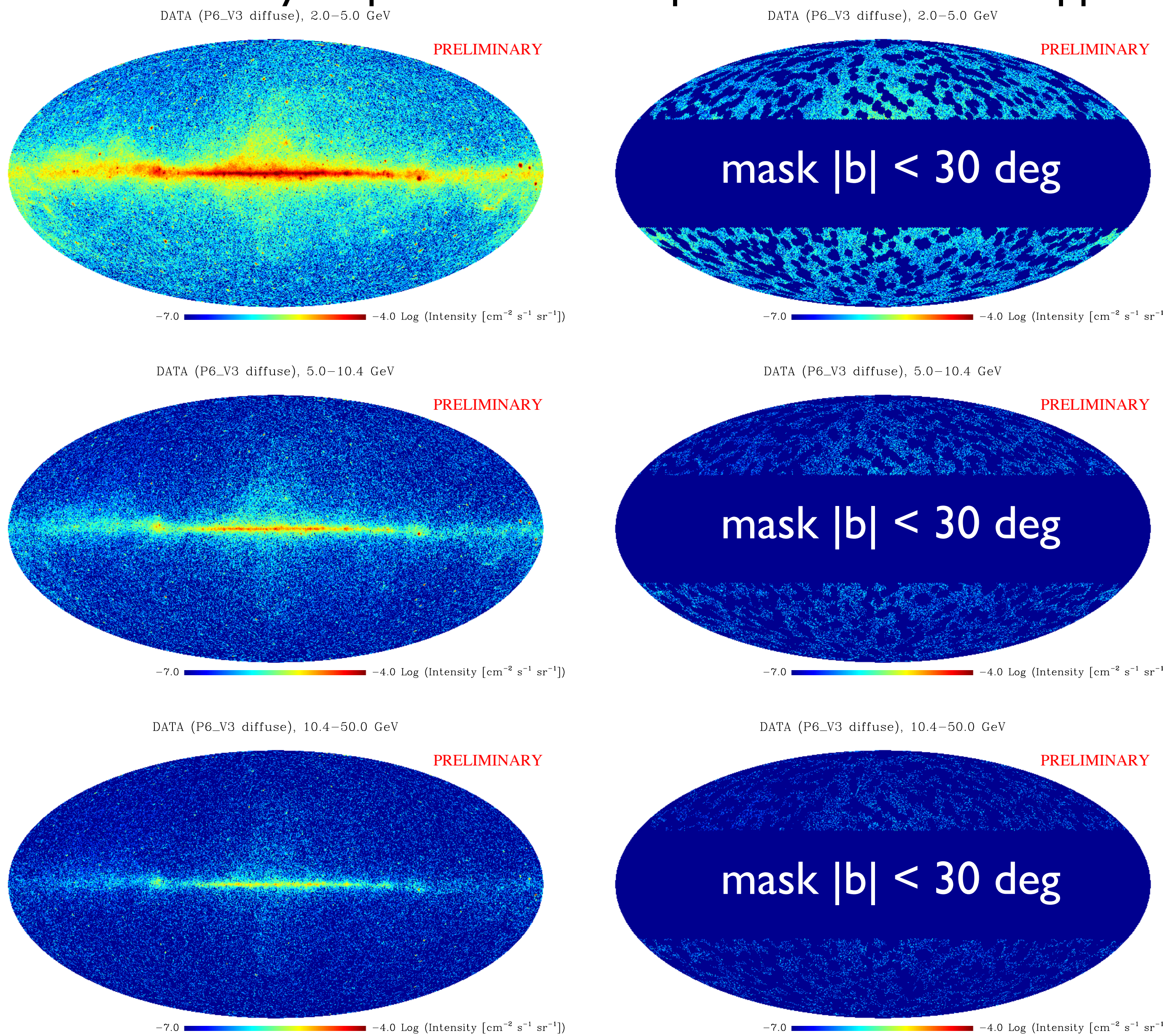
Angular power spectrum analysis of Fermi LAT data

All-sky map | Map with default mask applied

2-5 GeV

5-10 GeV

10-50 GeV



Angular power spectrum analysis of Fermi LAT data

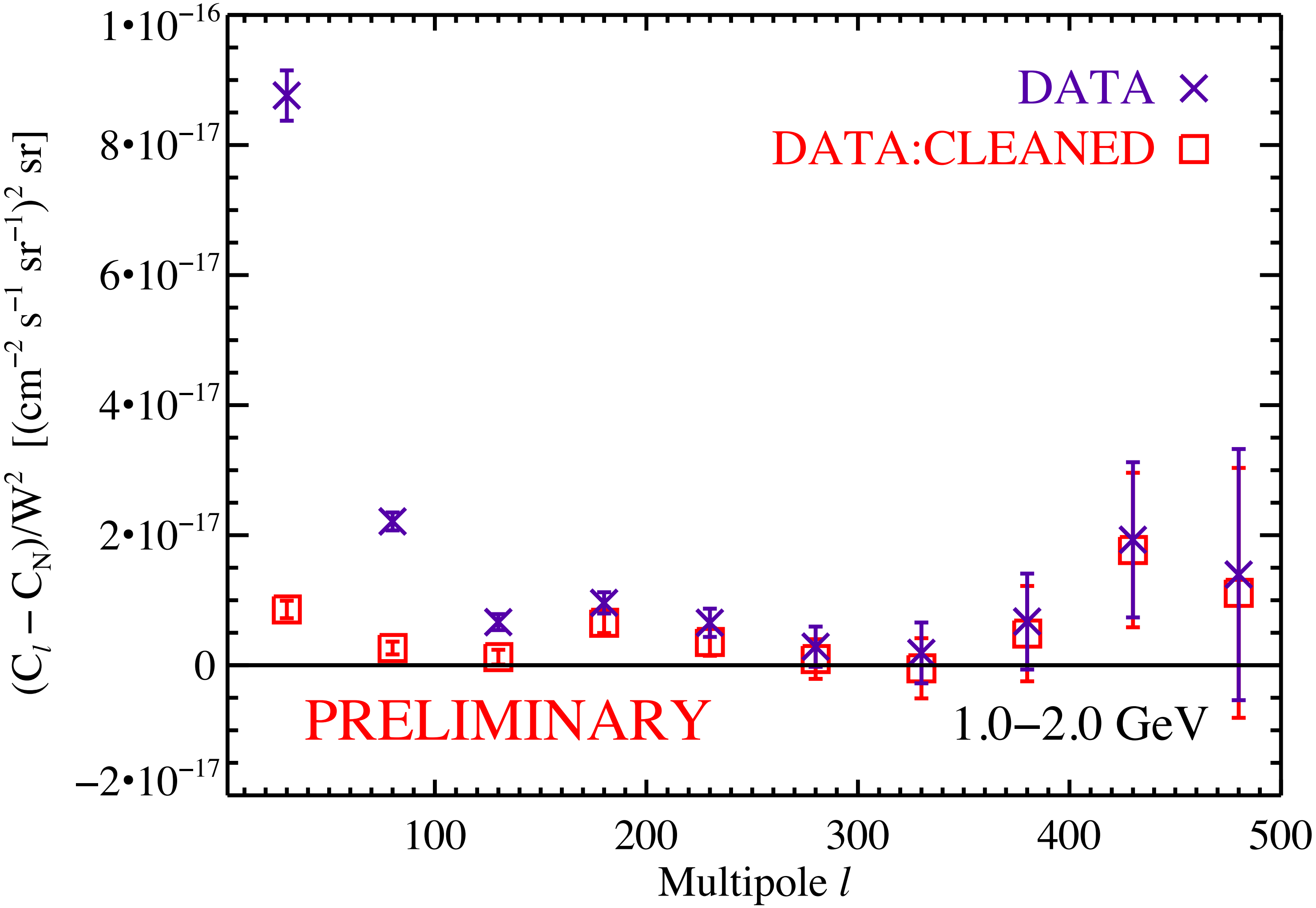
- angular power spectrum calculation: performed using HEALPix (Gorski et al. 2005)
- signal angular power spectrum estimator:

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

  - 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

Angular power spectra of the data

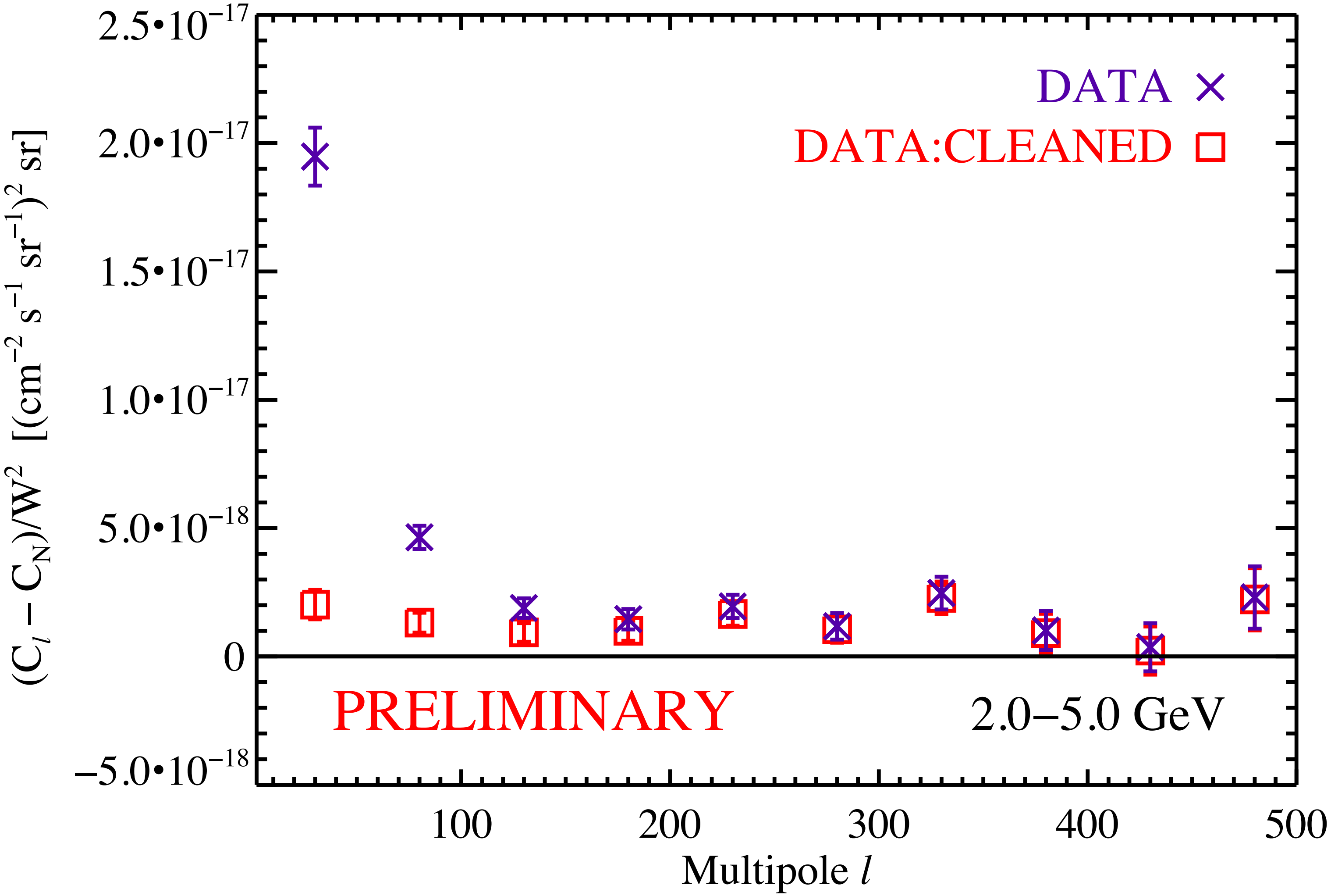
intensity angular power spectra



DATA:CLEANED = DATA - Galactic diffuse model

Angular power spectra of the data

intensity angular power spectra



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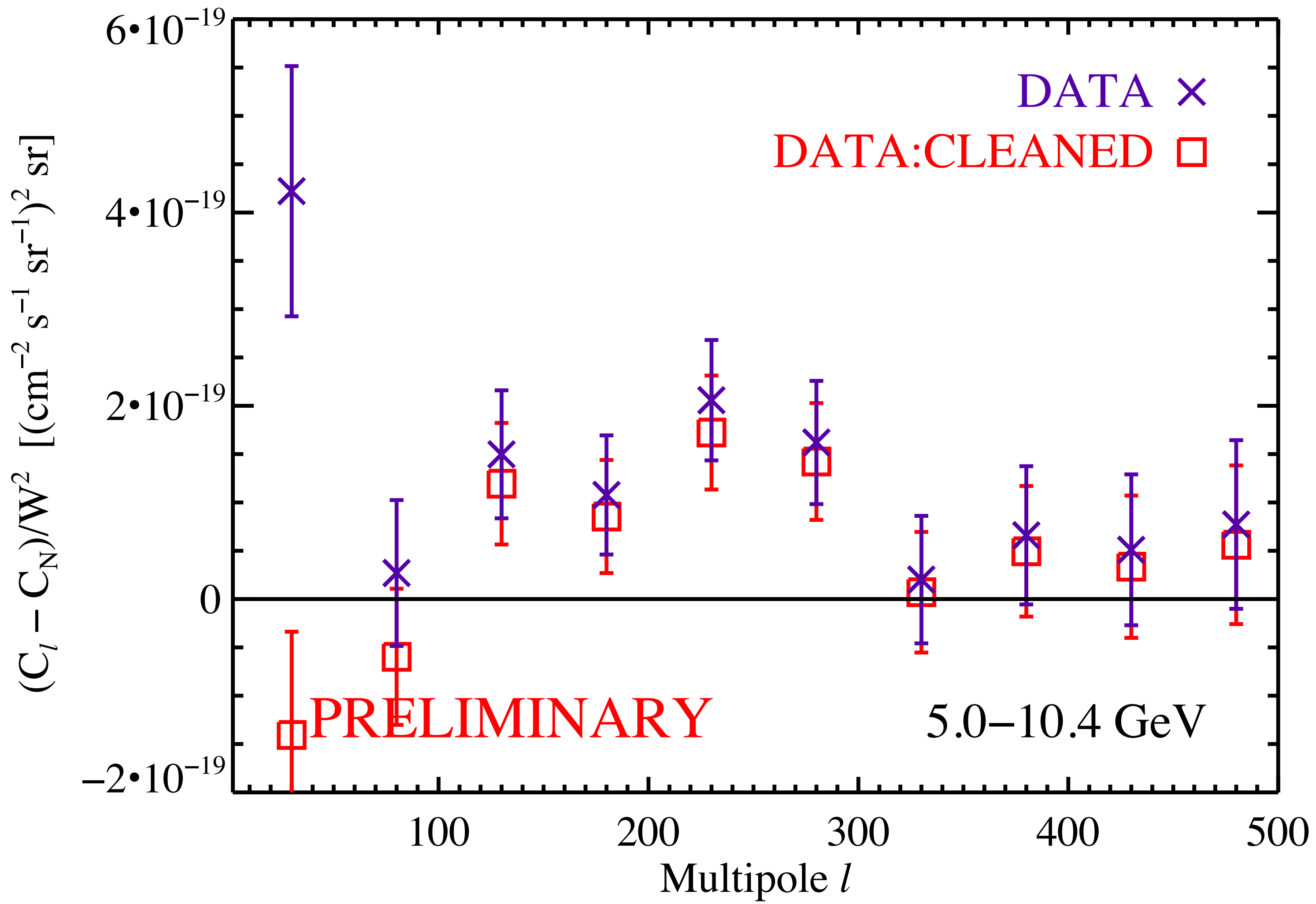
Angular power spectra of the data

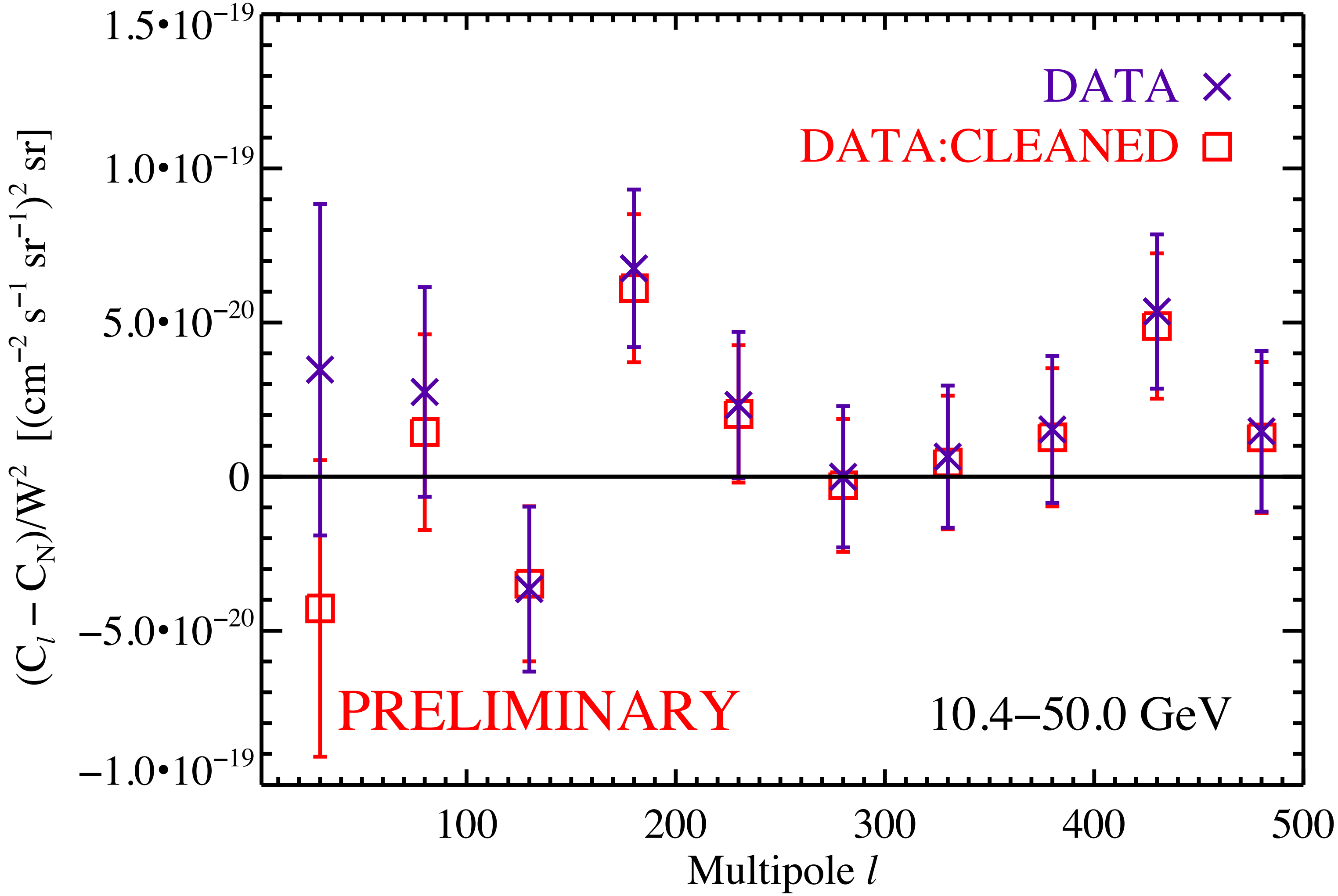
intensity angular power spectra



DATA:CLEANED = DATA - Galactic diffuse model

Angular power spectra of the data

intensity angular power spectra



DATA:CLEANED = DATA - Galactic diffuse model

Angular power spectra of the data

- at l ≳ 150, angular power is roughly constant in multipole; this is Poisson-like, characteristic of unclustered point sources

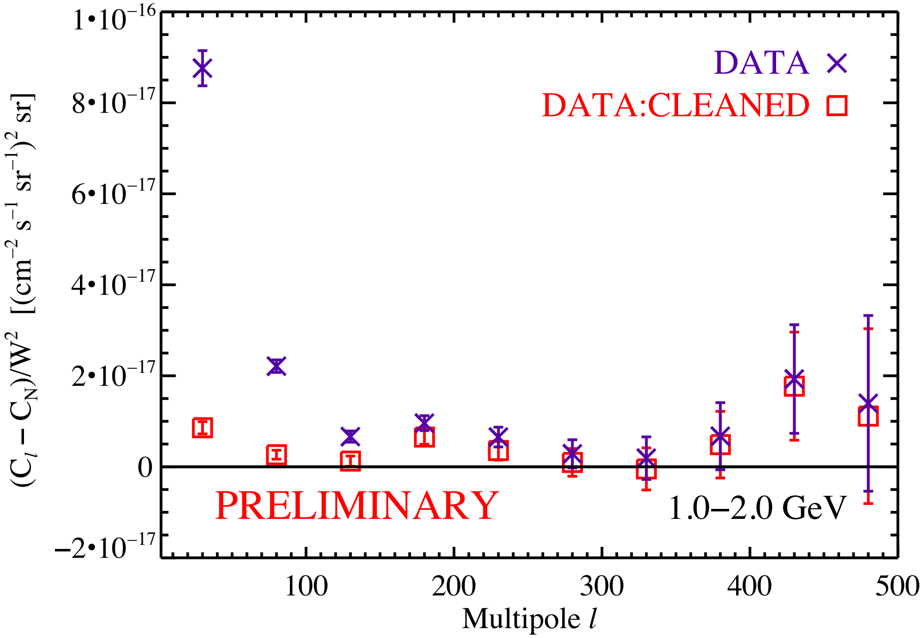
- subtraction of a Galactic diffuse model from the data (foreground cleaning):

  - reduces power at l ≲150 at lower energies

  - indicates low-multipole large angular power likely due in part to contamination by Galactic diffuse emission

  - does not have a substantial impact on the anisotropy above l ~ 150

  - indicates contamination at l ≳ 150 by Galactic diffuse emission is small



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

$E_{\rm min}$ [GeV]	$E_{\rm max}$ [GeV]	$C_{\rm P}$ [(cm^{-2} s^{-1} sr^{-1})^2 sr]	Significance	$C_{\rm P}/\langle I\rangle^2$ [10^{-6} 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

$C_P / \langle I \rangle^2$ $[10^{-6}$ 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 (e.g., MSP constraints in JSG et al, MNRAS 415 (2011) 1074S)

Source population constraints from anisotropy

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

in all energy bins, measured fluctuation angular power (l ≳ 150) is ~ 1 e-5 sr

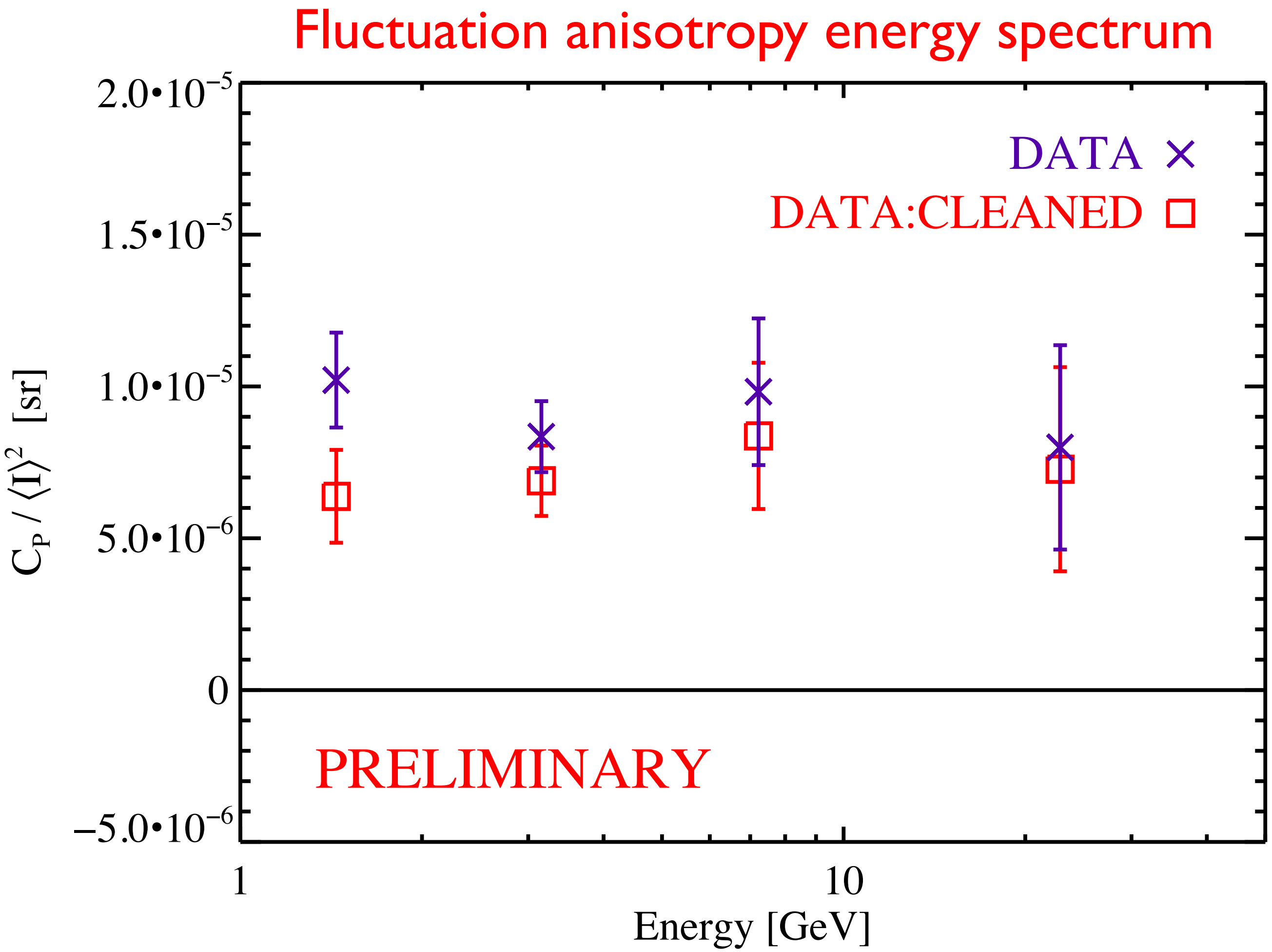
	predicted fluctuation angular power at l = 100 [sr]	max IGRB contribution
blazars	2e-4	22%
starforming galaxies	2e-7	100%
dark matter annihilation/decay	5e-5	45%
MSPs	0.03	2%

NB: these are indicative predicted values 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

These values may not be accurate for your favorite source population model.

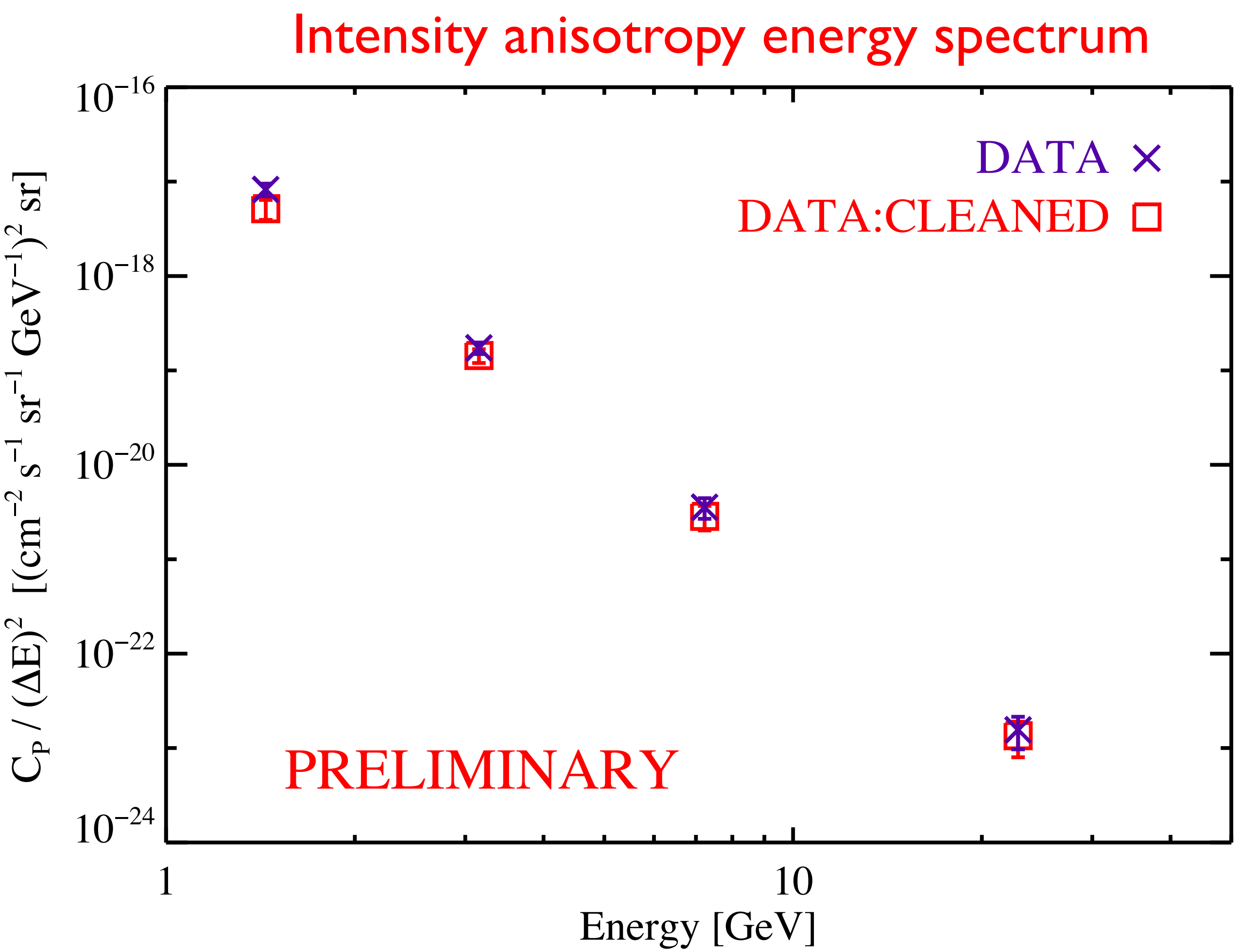
Energy dependence of anisotropy



- 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

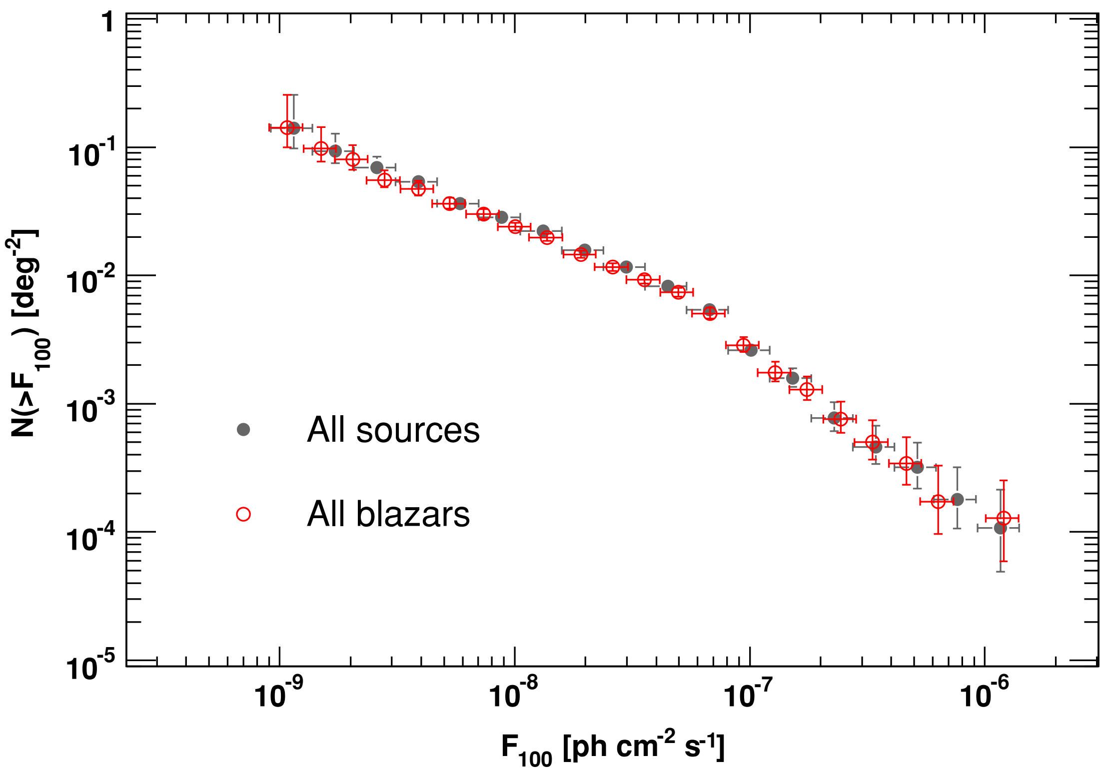


- consistent with that arising from a source class with power-law energy spectrum with $\Gamma = -2.40 \pm 0.07$ (-2.33 ± 0.08 for cleaned data)
- implied source spectral index is good agreement with mean intrinsic spectral index of blazars inferred from detected members

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

$$I = \int_0^{S_t} \frac{dN}{dS} S dS$$

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

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$$I = \int_0^{S_t} \frac{dN}{dS} S dS$$

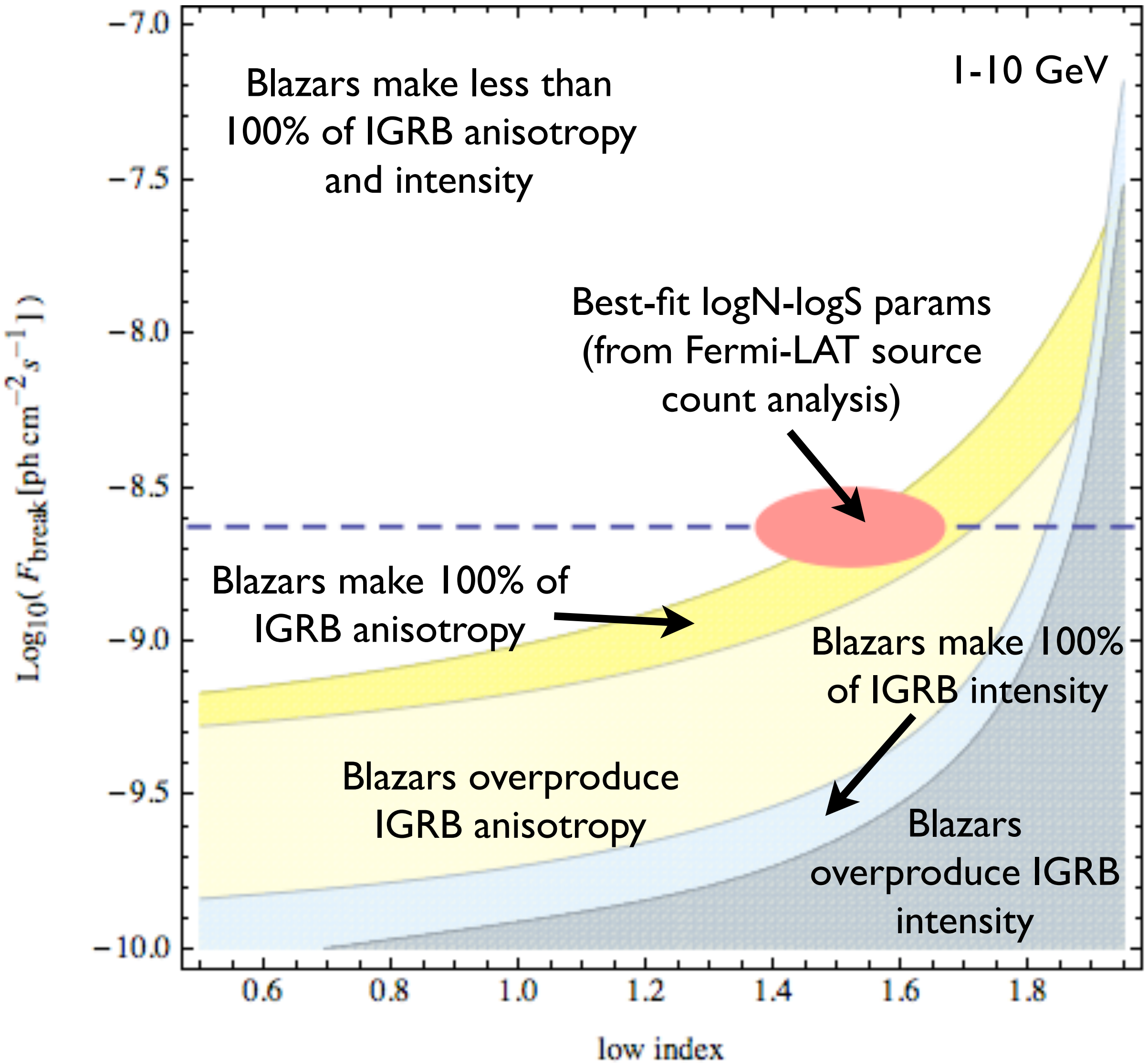
$$C_{\rm P} = \int_0^{S_{\rm t}} \frac{dN}{dS} S^2 dS$$

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

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
- 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

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



Cuoco, Komatsu, & JSG, *in prep*

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

Additional slides

Validation studies

- 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 results of data analyzed with P6_V3 and P6_V8 IRFs

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

- contamination by Galactic diffuse emission: subtraction of a Galactic diffuse model from the data (foreground cleaning) does not have a substantial impact on the anisotropy above $l \sim 100$; indicates contamination in this multipole range by Galactic diffuse is small

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

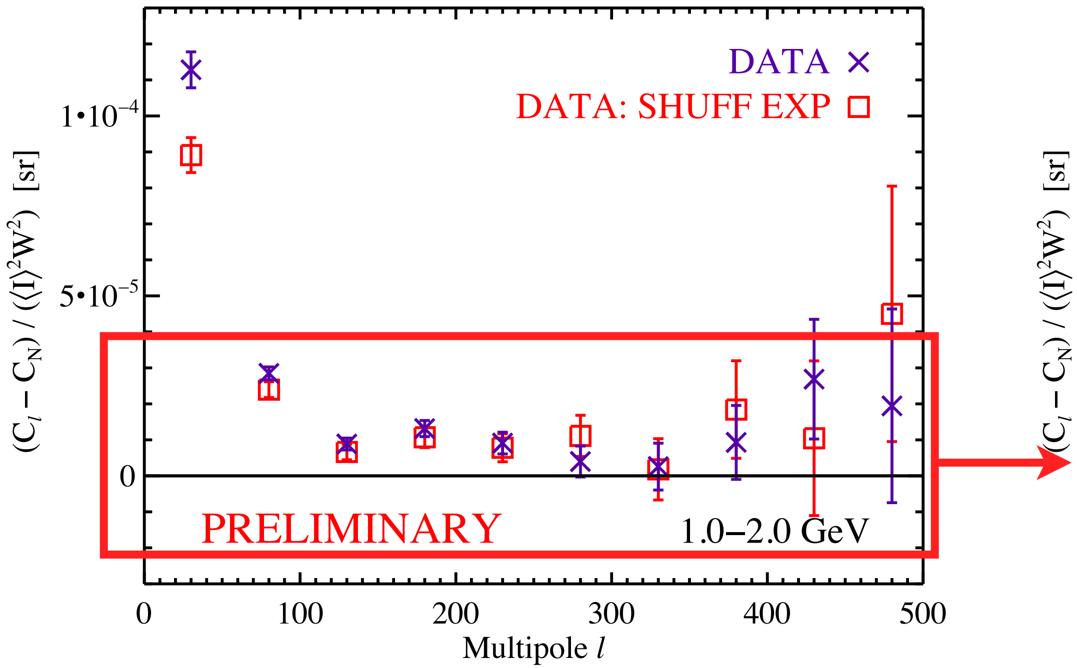
Analysis using an event-shuffling technique

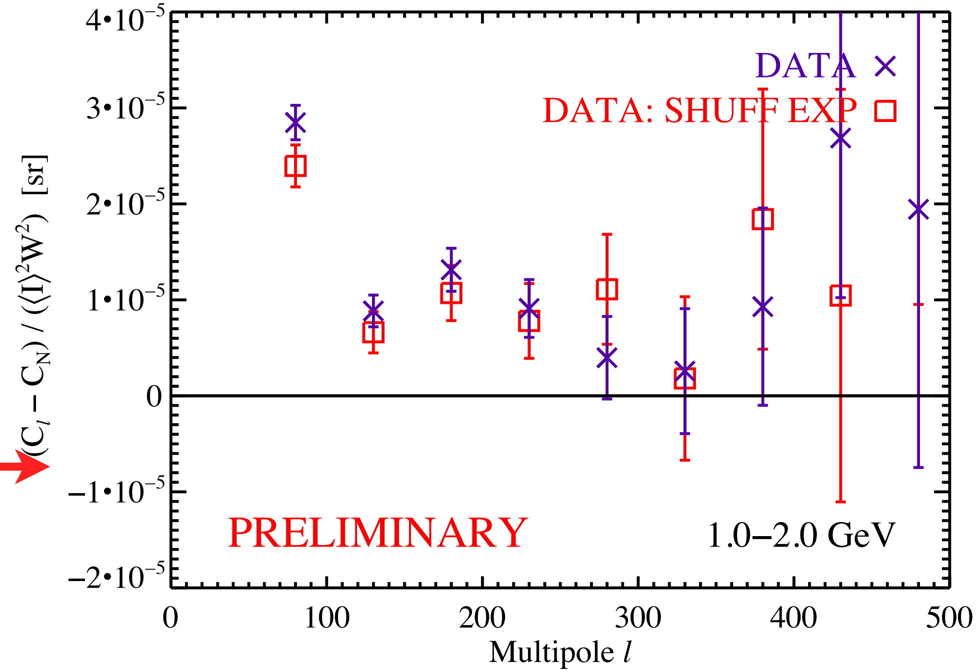
- the exposure map is calculated directly from the data using an event-shuffling technique:
    - shuffling arrival times and arrival directions of real events *in instrument coordinates* generates a map indicating how an isotropic signal would appear in the LAT data
    - shuffled data map is directly 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

Angular power spectra of the data

fluctuation angular power spectra

1 - 2 GeV



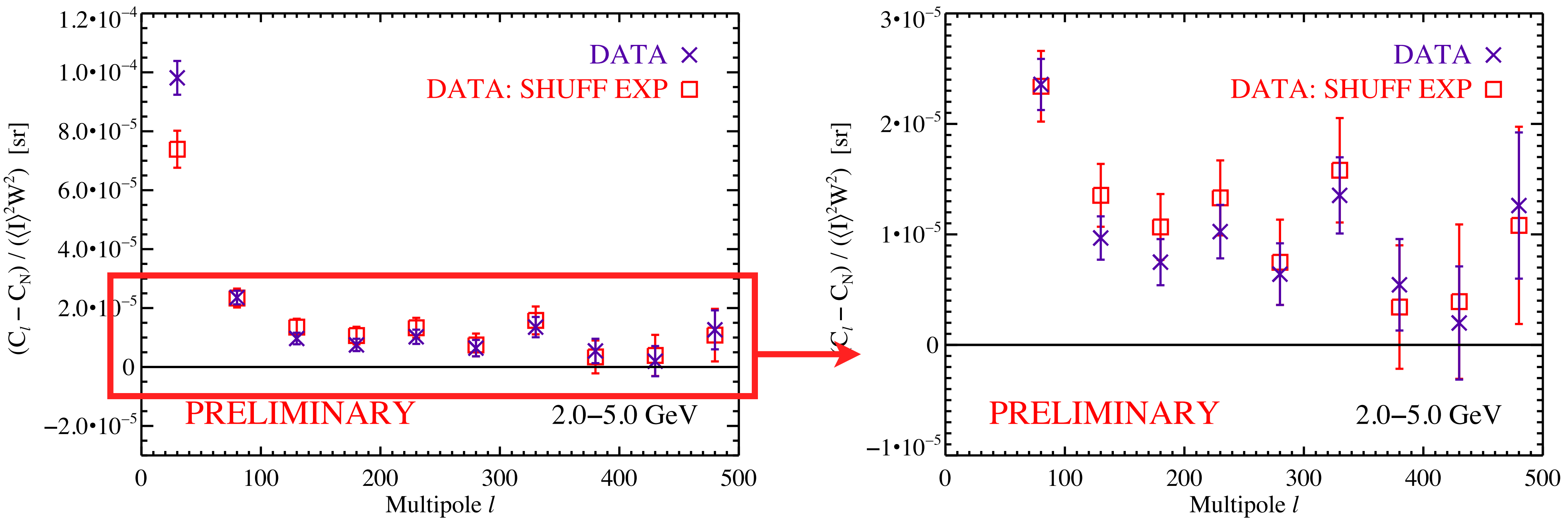


- good agreement between default analysis and analysis with exposure map from shuffling
- at low multipoles excess angular power likely due to contamination by Galactic diffuse emission; angular power is robustly detected at multipoles above l ~ 150
- angular power at high multipoles is also detected in other energy bins

Angular power spectra of the data

fluctuation angular power spectra

2 - 5 GeV



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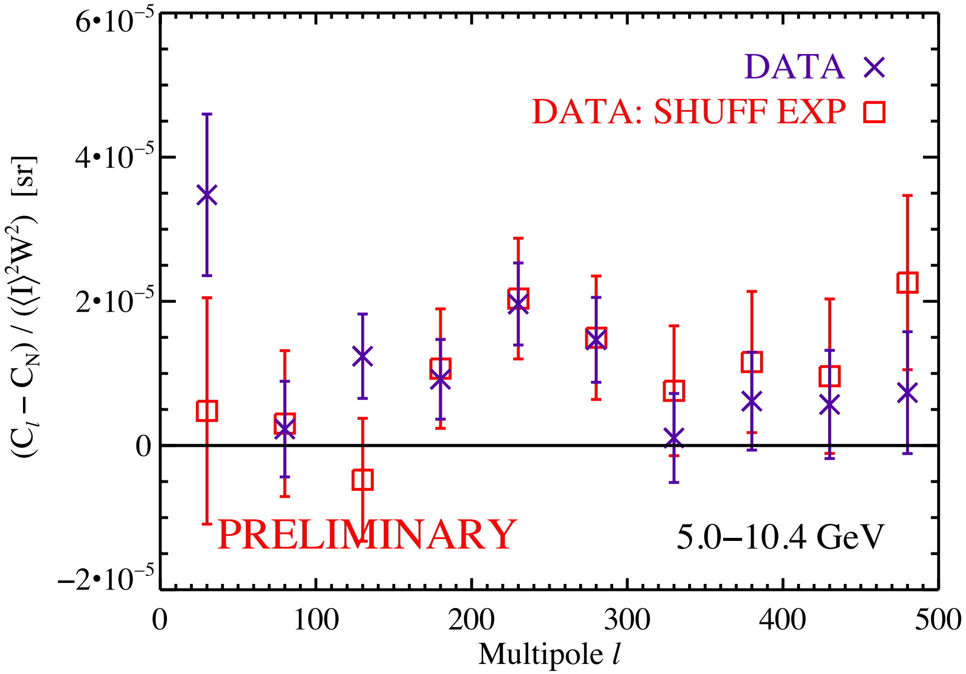
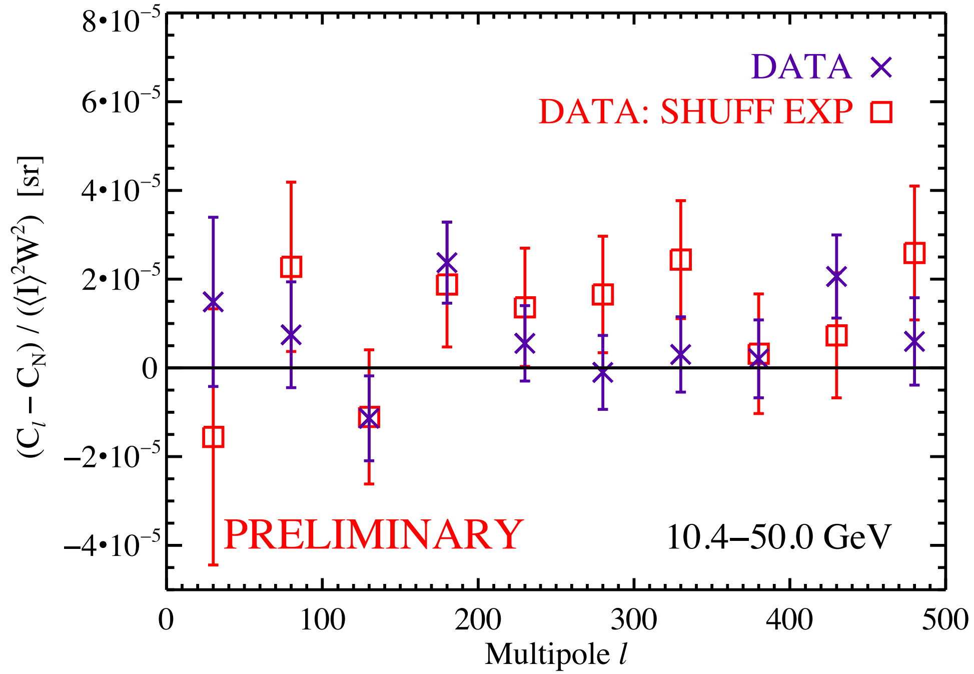
Angular power spectra of the data

fluctuation angular power spectra

5 - 10 GeV



10 - 50 GeV

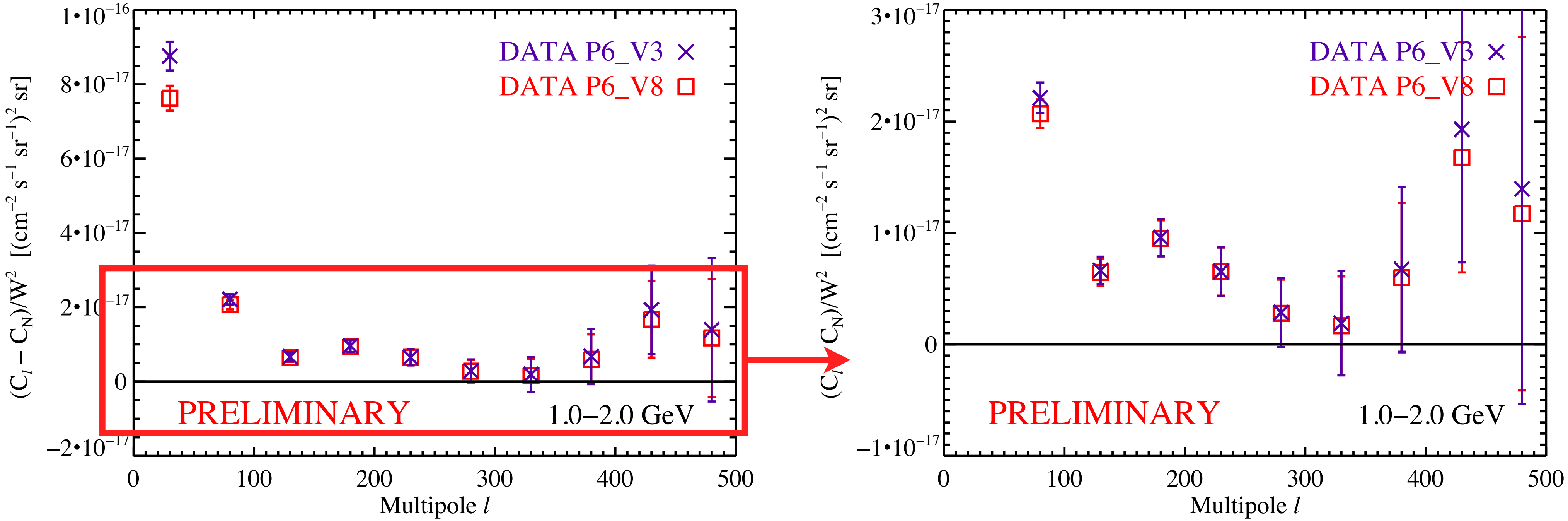


- good agreement between default analysis and analysis with exposure map from shuffling
- at 5-10 GeV angular power is robustly detected at multipoles above l ~ 150
- at 10-50 GeV, angular power is detected at lower significance at multipoles above l ~ 150

Dependence on IRFs

intensity angular power spectra

1 - 2 GeV

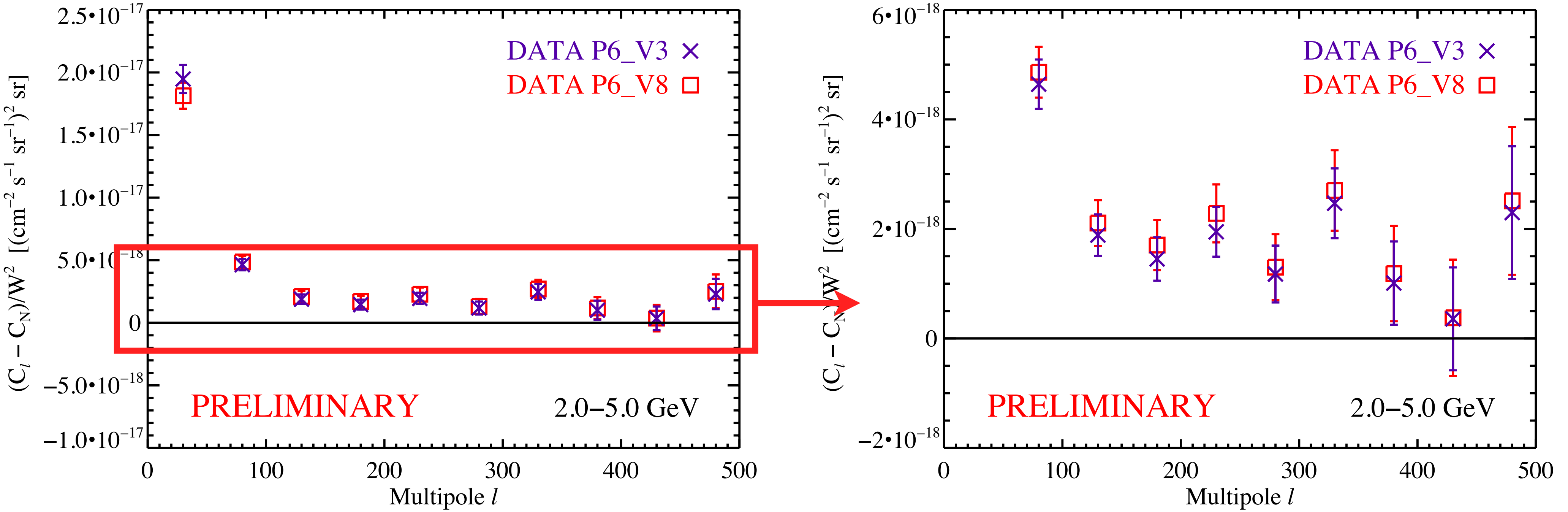


- excellent agreement of angular power spectra of data processed with these two IRFs indicates that the results are not sensitive to the differences in the PSF models implemented in these IRFs

Dependence on IRFs

intensity angular power spectra

2 - 5 GeV



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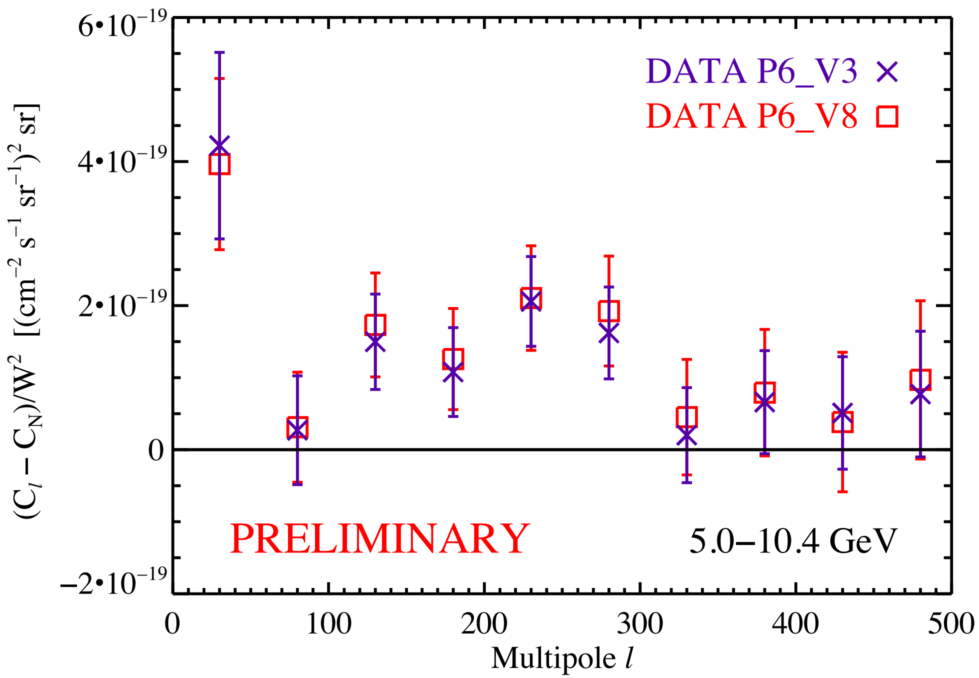
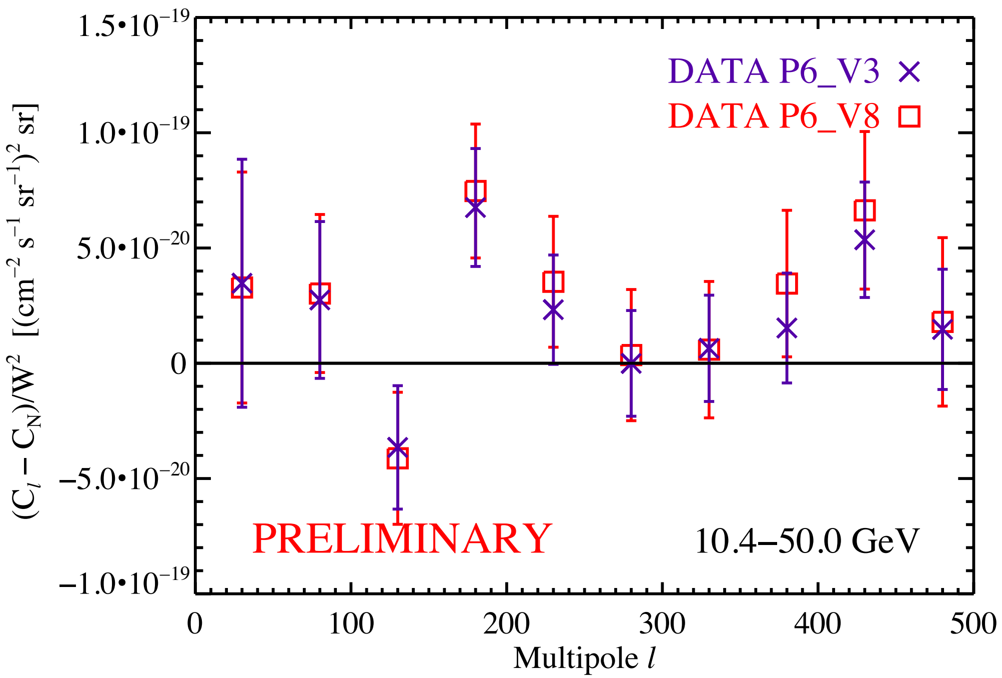
Dependence on IRFs

intensity angular power spectra

5 - 10 GeV



10 - 50 GeV

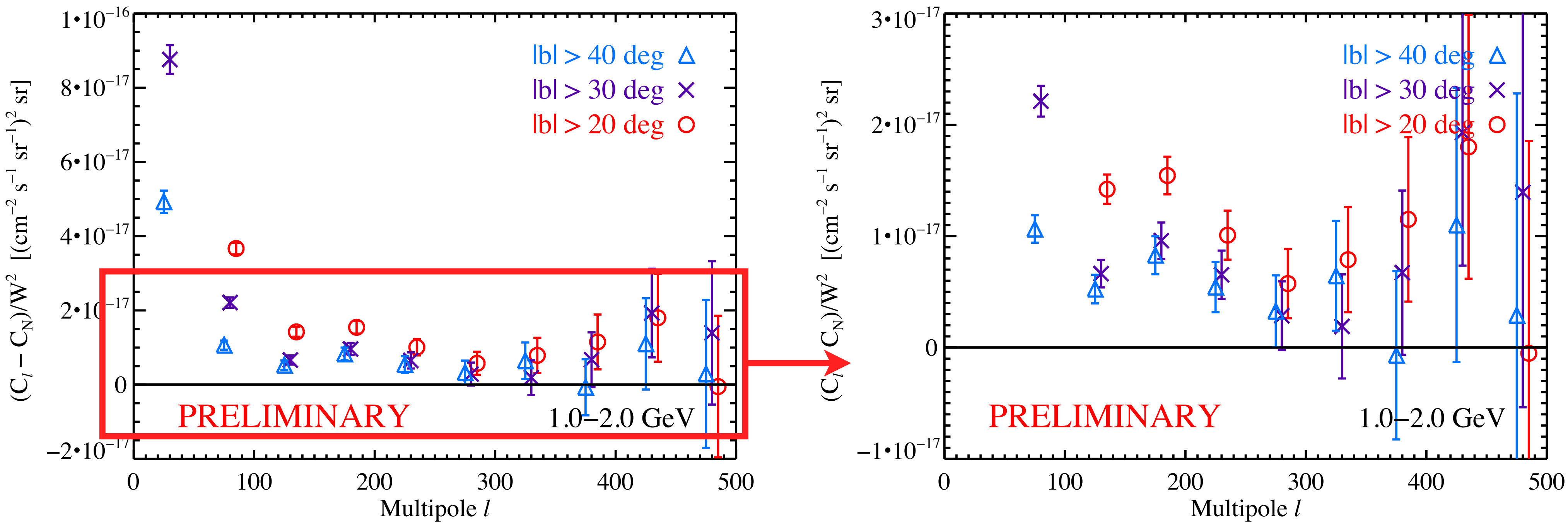


- excellent agreement of angular power spectra of data processed with these two IRFs indicates that the results are not sensitive to the differences in the PSF models implemented in these IRFs

Dependence on latitude mask

intensity angular power spectra

1 - 2 GeV

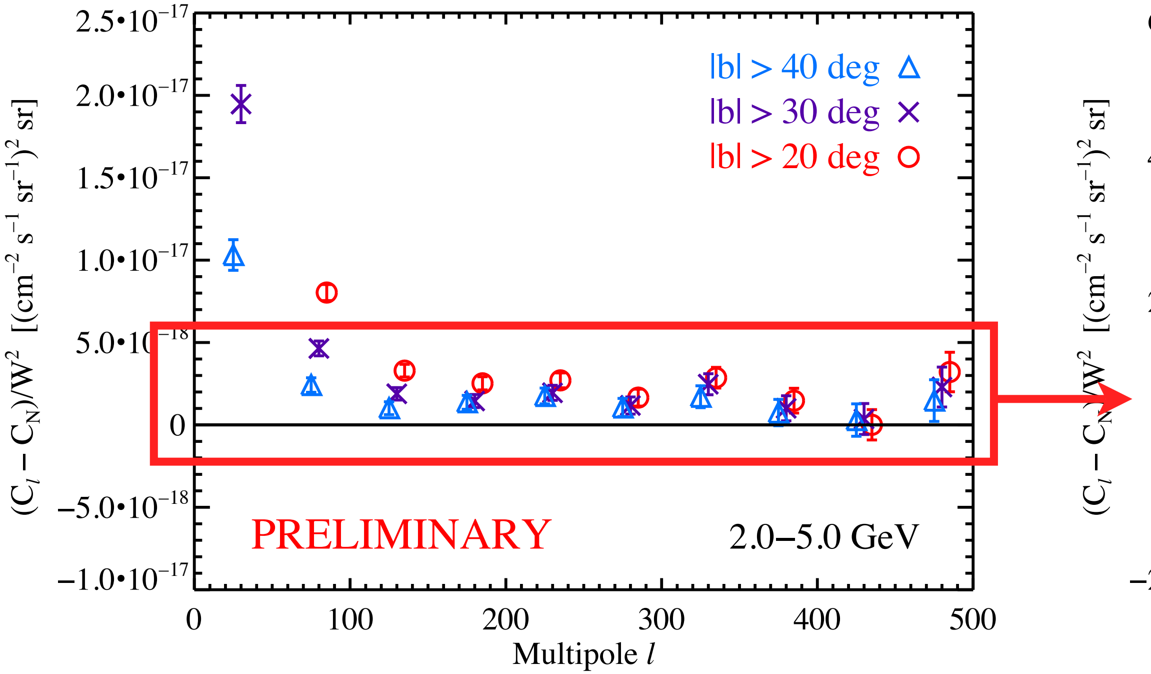


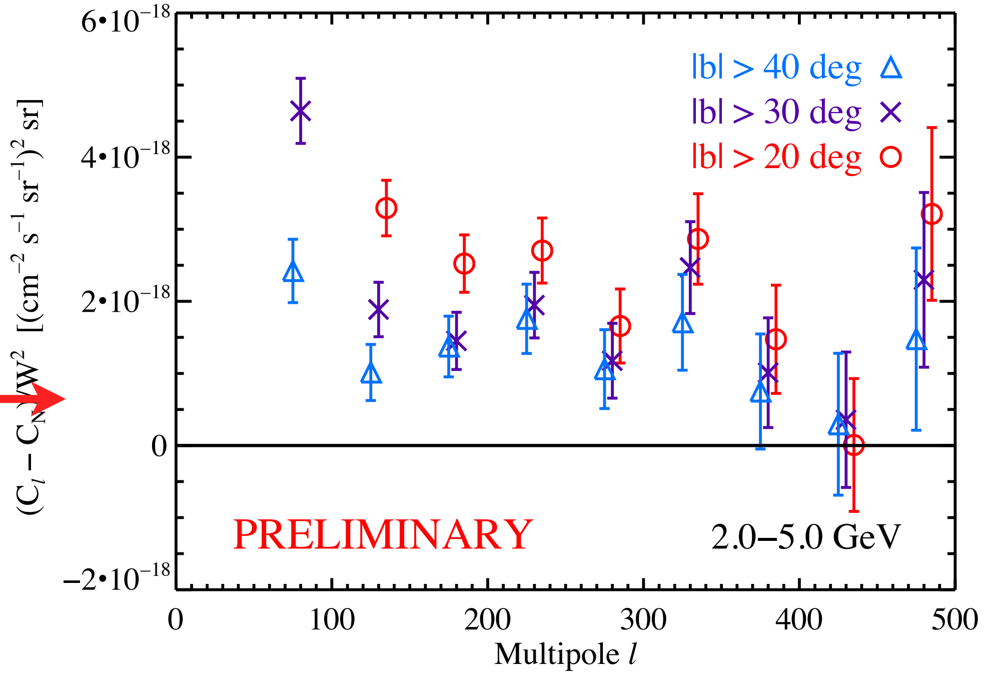
- differences in results masking |b| < 30 deg and |b| < 40 deg are small for multipoles l ≥ 155, demonstrating that detected angular power is not strongly correlated with a component with a significant latitude dependence, such as Galactic diffuse emission

Dependence on latitude mask

intensity angular power spectra

2 - 5 GeV



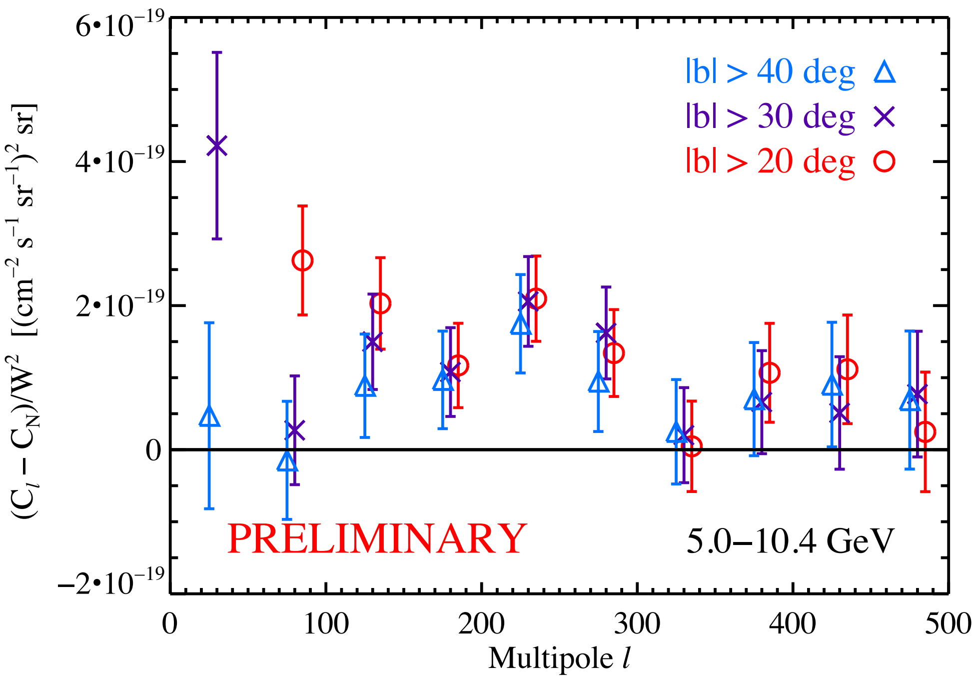


- differences in results masking |b| < 30 deg and |b| < 40 deg are small for multipoles l ≥ 155, demonstrating that detected angular power is not strongly correlated with a component with a significant latitude dependence, such as Galactic diffuse emission

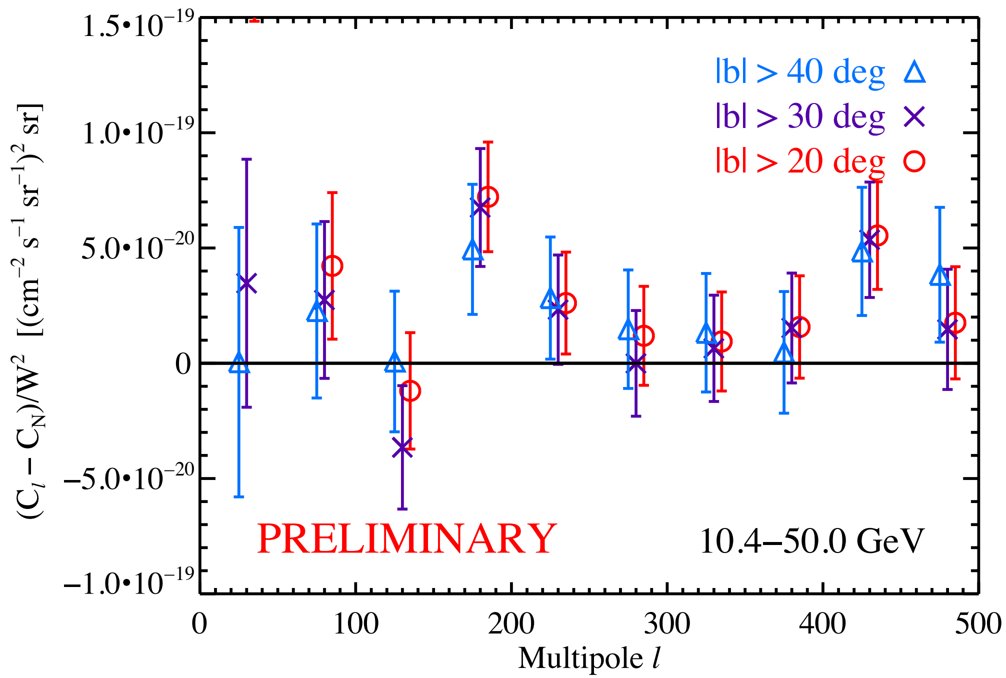
Dependence on latitude mask

intensity angular power spectra

5 - 10 GeV



10 - 50 GeV



- above 10 GeV convergence at multipoles $l \geq 155$ is seen masking only $|b| < 20$ deg

Simulations

two models of the all-sky emission are simulated with gtobssim (Fermi Science Tools) and their angular power spectra are calculated to compare with the data

MODEL = sum of GAL:DEFAULT, CAT, and ISO

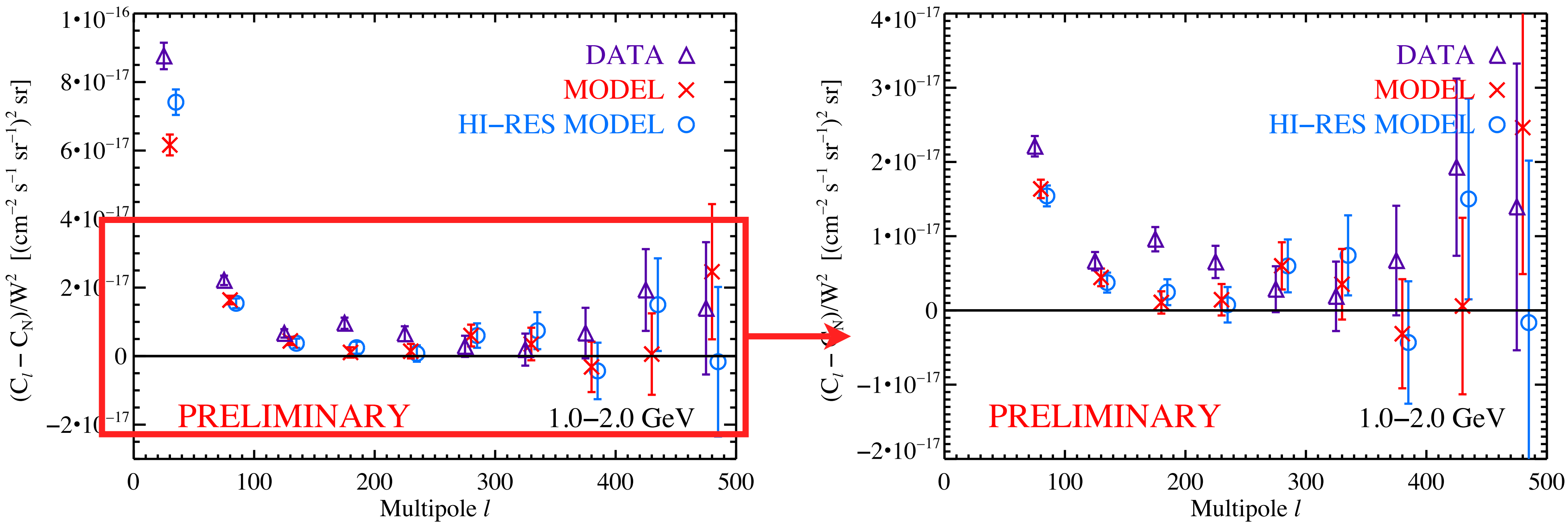
HI-RES MODEL = sum of GAL:HI-RES, CAT, and ISO

- GAL:
  - DEFAULT: standard recommended Galactic diffuse model (gll_iem_v02.fit)
  - HI-RES: updated Galactic diffuse model using higher-resolution CO maps (ring_21month_v1.fit)
- CAT: 11-month source catalog
- ISO: isotropic background = Fermi-measured large-scale isotropic diffuse + unrejected charged particles (isotropic_iem_v02.txt spectrum template)

Comparison with simulated models

intensity angular power spectra

1 - 2 GeV



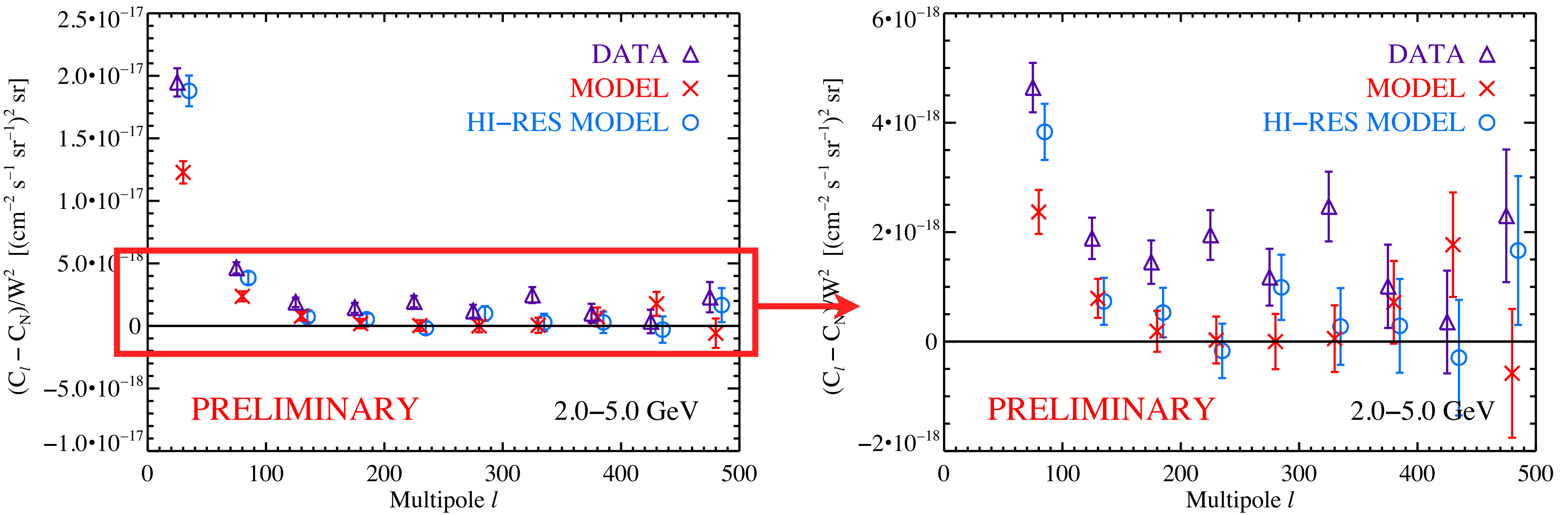
- smaller amplitude angular power detected at low significance in both models at $l \geq 155$ is inconsistent with the excess observed in the data

- angular power spectra of the two models are in good agreement

Comparison with simulated models

intensity angular power spectra

2 - 5 GeV

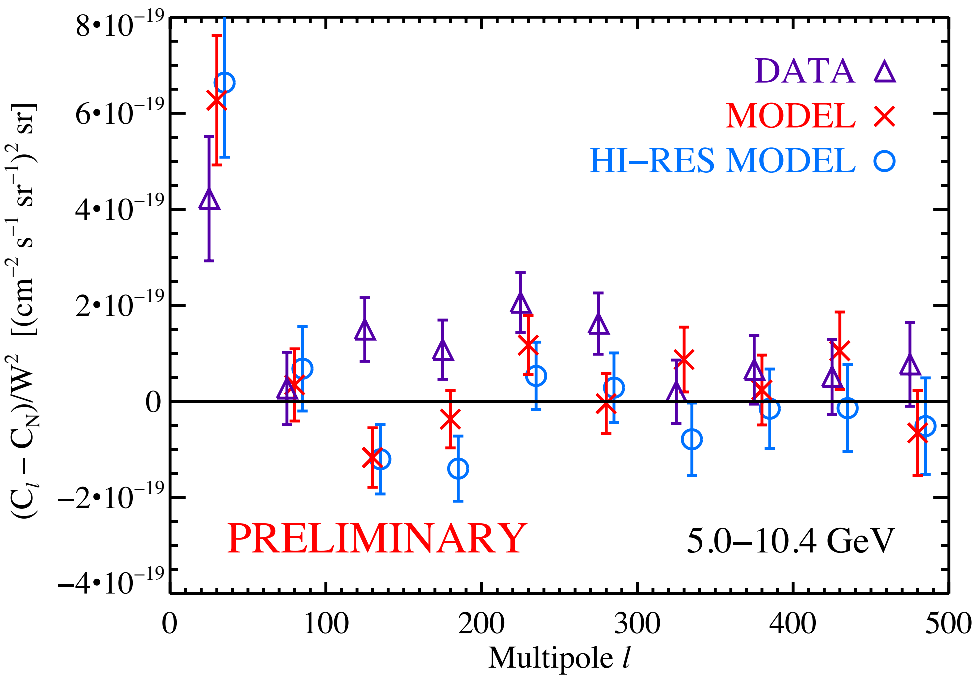


- no significant angular power detected in either model at l ≥ 155
- angular power spectra of the two models are in good agreement

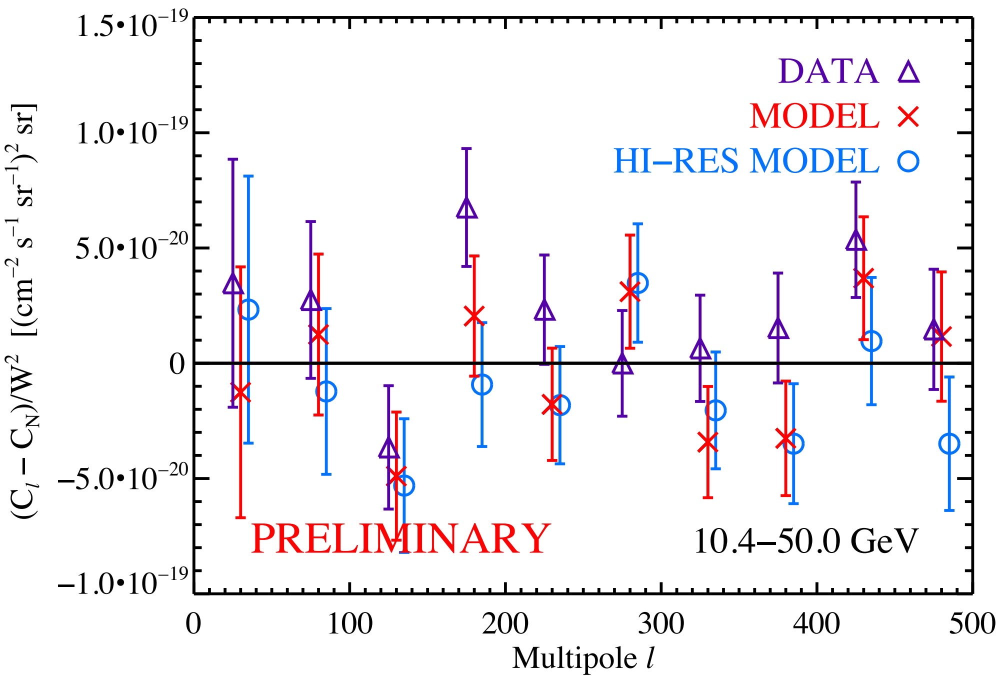
Comparison with simulated models

intensity angular power spectra

5 - 10 GeV



10 - 50 GeV

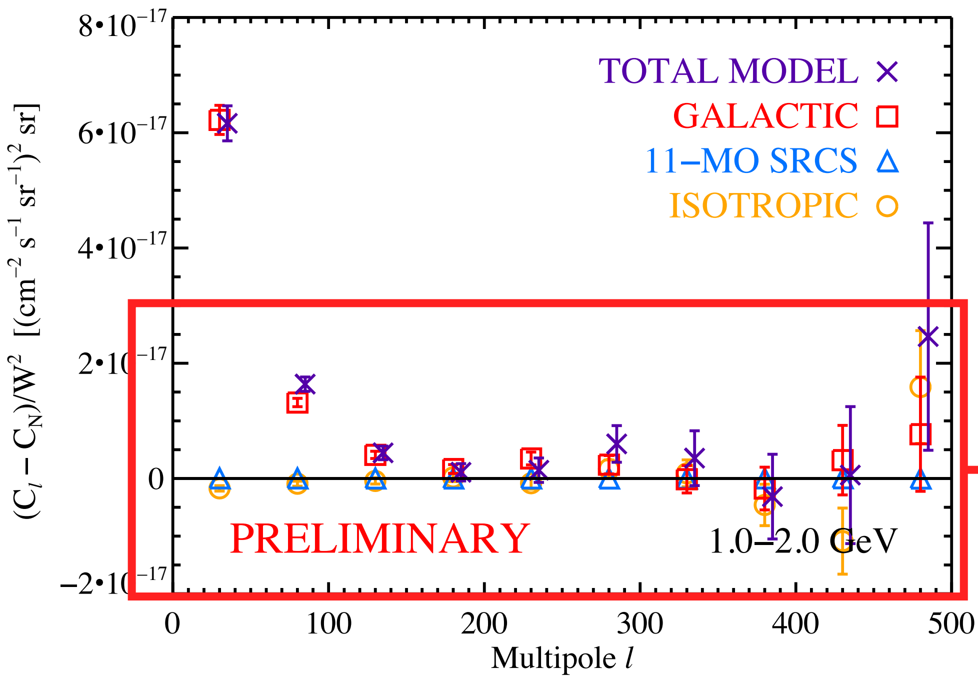


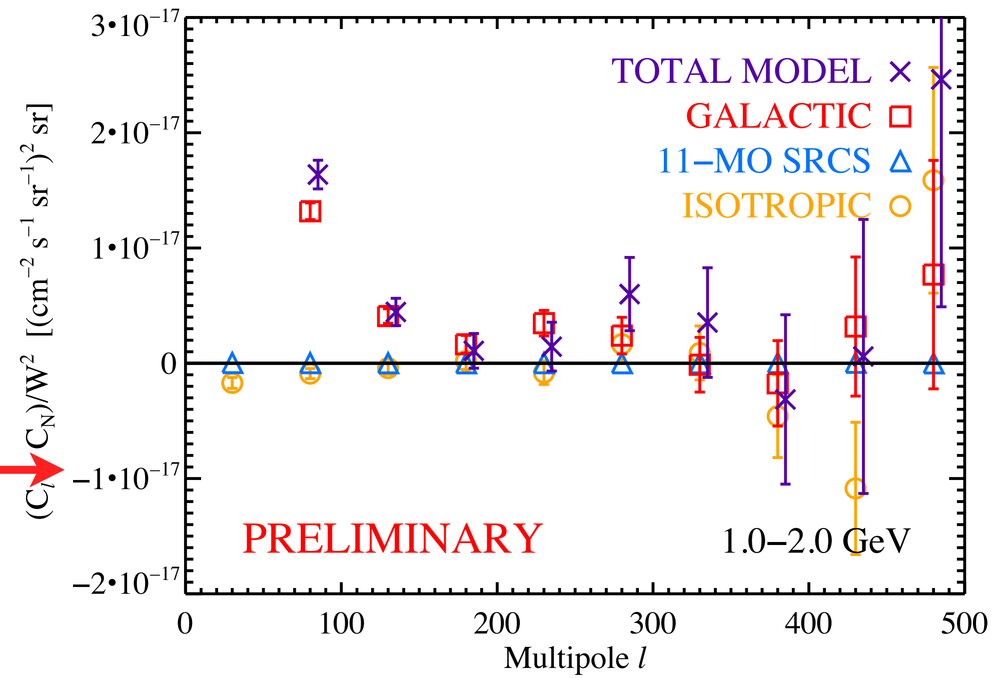
- no significant angular power detected in either model at $l \geq 155$
- angular power spectra of the two models are in good agreement

Simulated model components

intensity angular power spectra

1 - 2 GeV



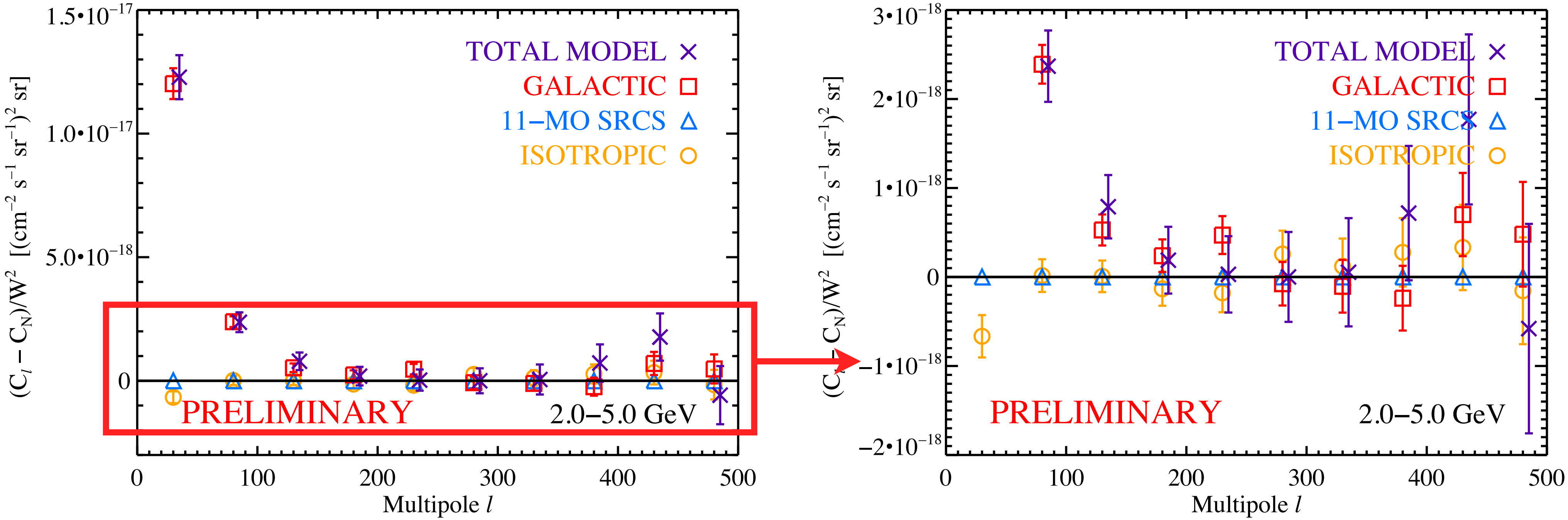


- as expected, most of the total angular power at all multipoles (TOTAL MODEL) is due to the GAL component
- by construction, ISO contributes no significant angular power; CAT provides no contribution because all sources were masked

Simulated model components

intensity angular power spectra

2 - 5 GeV



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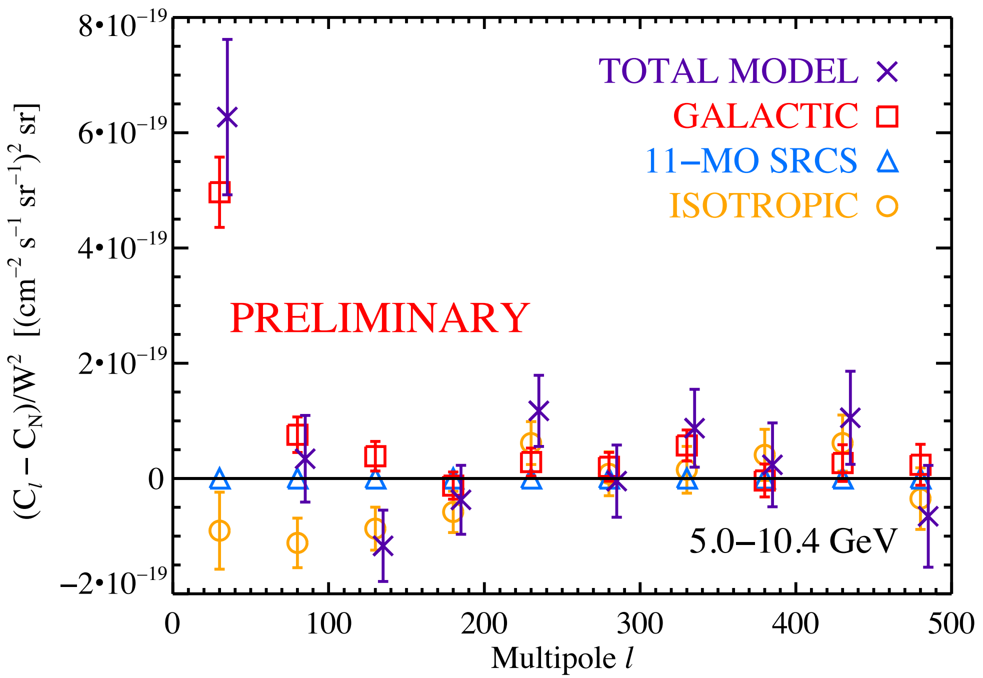
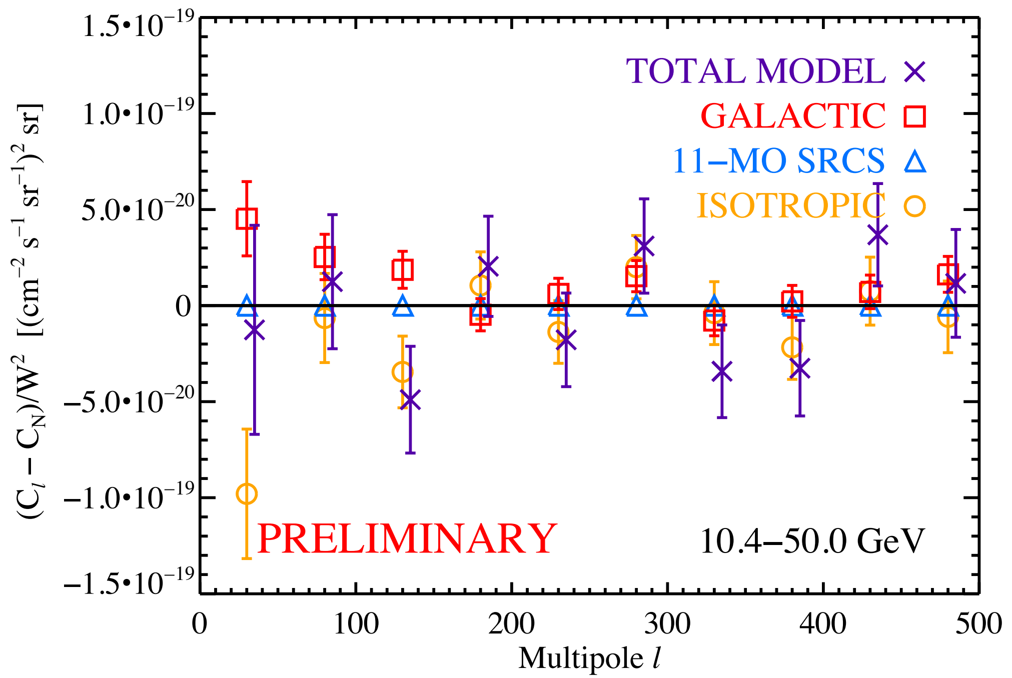
Simulated model components

intensity angular power spectra

5 - 10 GeV



10 - 50 GeV



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