An anisotropy analysis of the diffuse gamma-ray background measured by the Fermi LAT

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on behalf of
the Fermi LAT Collaboration

and

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Detecting unresolved sources with anisotropies

- in addition to the energy spectrum and average intensity, the large-scale isotropic gamma-ray background (IGRB) contains angular information

- 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

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: $\dfrac{C_\ell}{\langle I \rangle^2}$

  - *dimensionless*, independent of intensity normalization

  - amplitude for a single source class is the same in all energy bins (if source distribution is independent of energy)

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: ~ 1e-4

- starforming galaxies: ~ 1e-7

- dark matter: ~ 1e-4 to ~ 0.1

- MSPs: ~ 1e-2

GLAST

Poisson

Total

Correlation

$b_B = 1$

$b_B = b_Q(z)$

$l(l+1)C_l/2\pi$

Multipole l
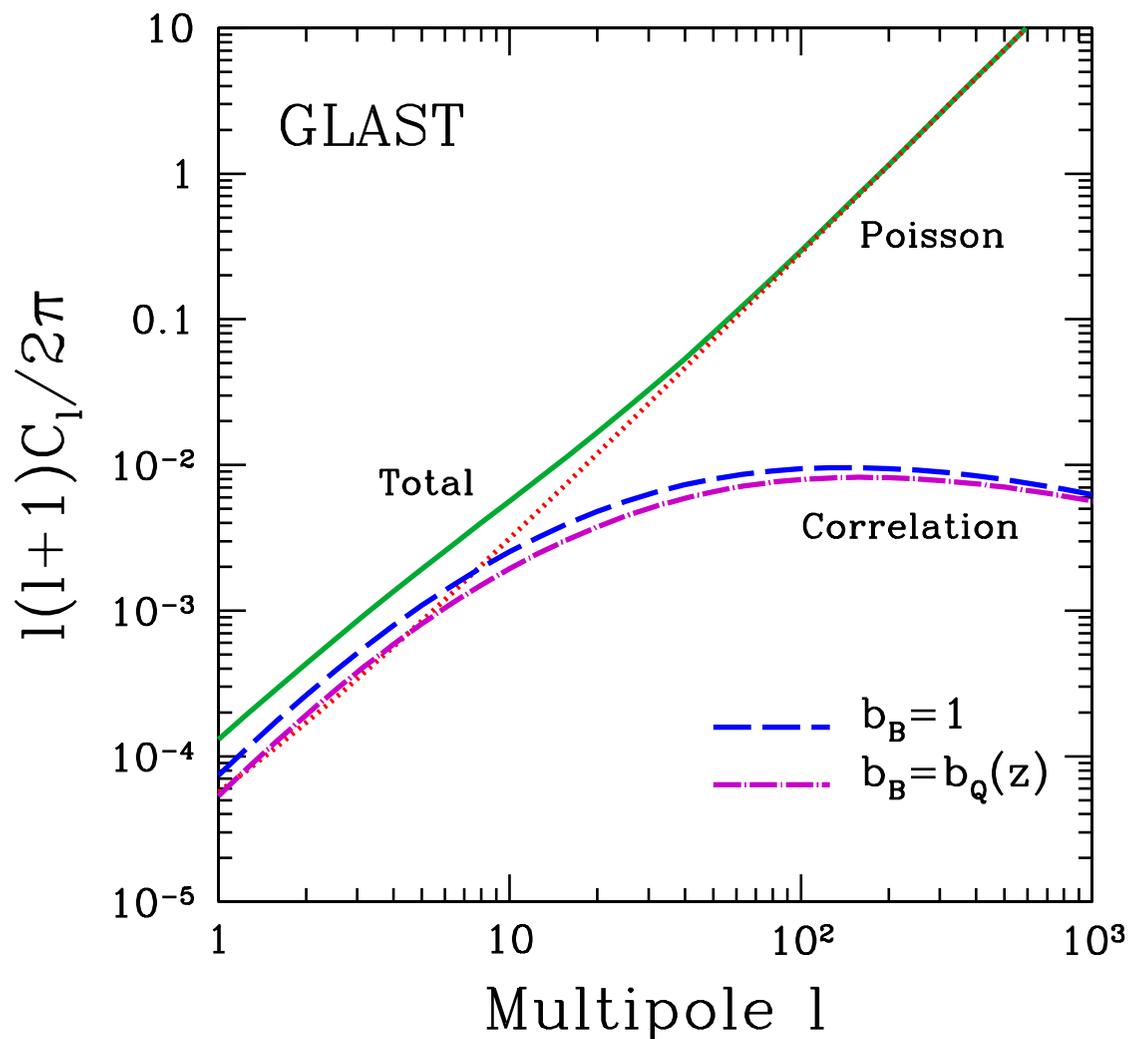
Blazars (Ando, Komatsu, Narumoto & Totani 2007)

Angular power spectrum analysis of *Fermi* data

- **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

- **data processing:** Fermi Science Tools used to handle instrument response and exposure calculation

- **masking:** sources in the 11-month catalog are masked within a 2 deg angular radius, and regions heavily contaminated by Galactic diffuse are masked by excluding |b| < 30 deg

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

- **front- and back-converting events:** processed separately through angular power spectrum calculation, then results are combined by weighted average

- **measurement uncertainties:** indicate 1-sigma statistical uncertainty, systematic uncertainty not included

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

Intensity maps of the data

1-2 GeV

All-sky map

DATA (P6_V3 diffuse), 1.0−2.0 GeV
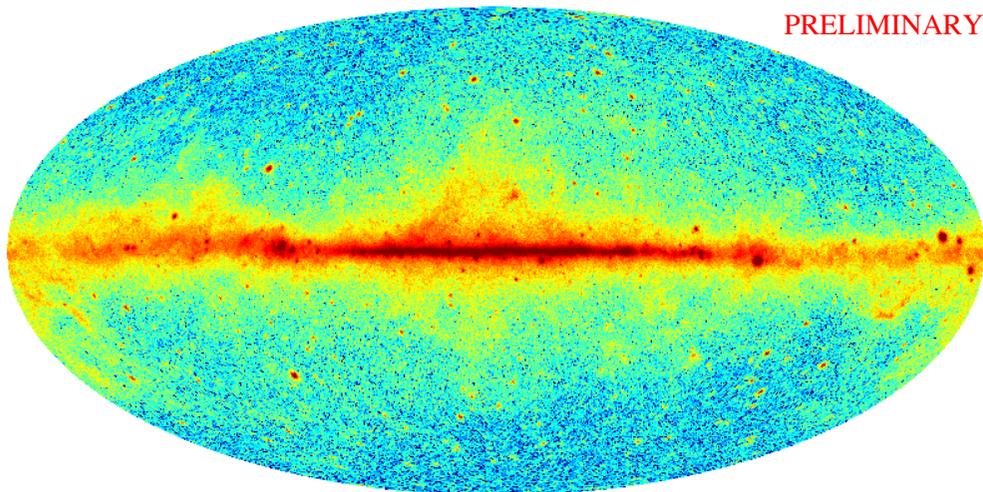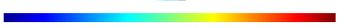
PRELIMINARY

−7.0 ▬ −4.0 Log (Intensity [cm⁻² s⁻¹ sr⁻¹])

Map with default mask applied

DATA (P6_V3 diffuse), 1.0−2.0 GeV
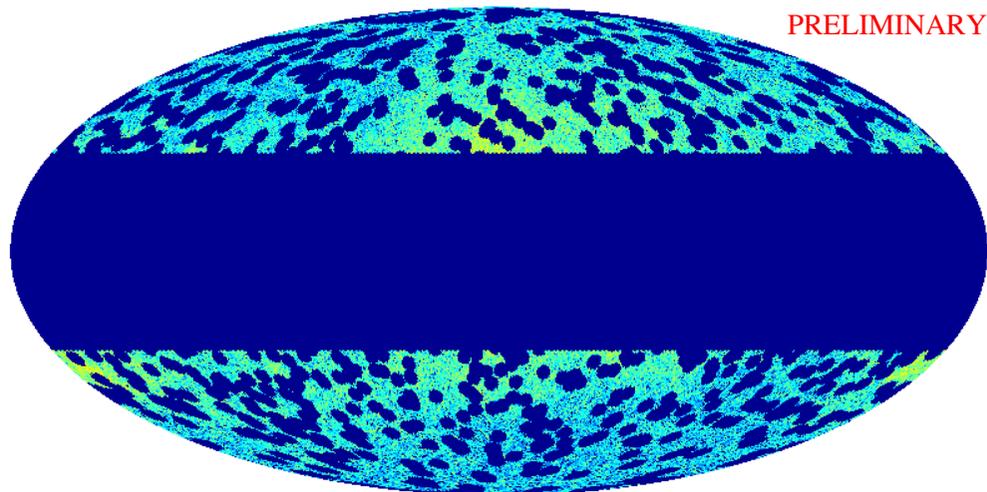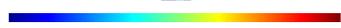
PRELIMINARY

−7.0 ▬ −4.0 Log (Intensity [cm⁻² s⁻¹ sr⁻¹])

Intensity maps of the data

All-sky map

Map with default mask applied

2-5 GeV

5-10 GeV
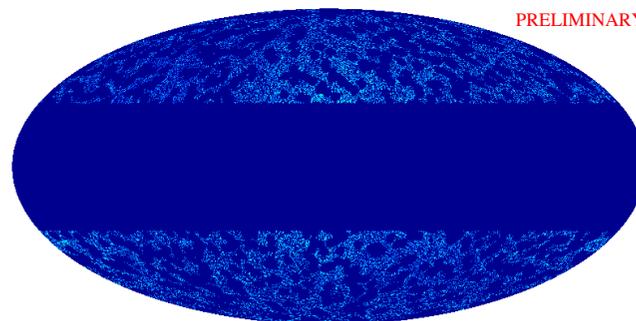
10-50 GeV
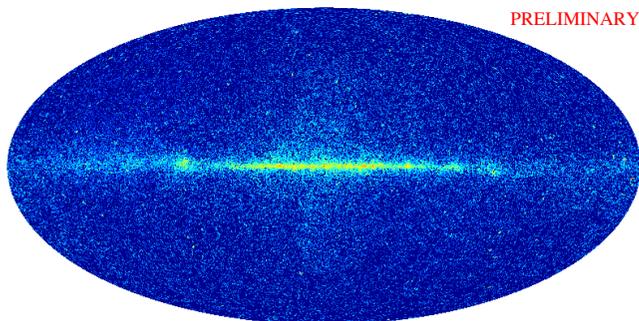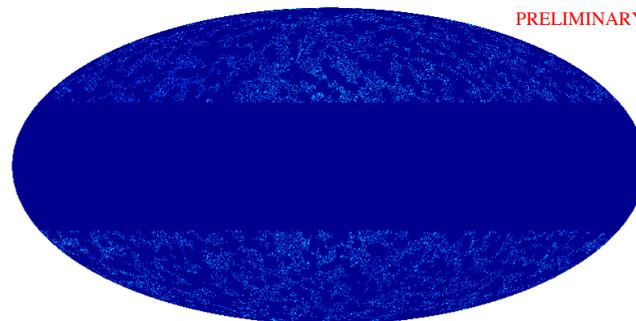
Angular power spectra of the data

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

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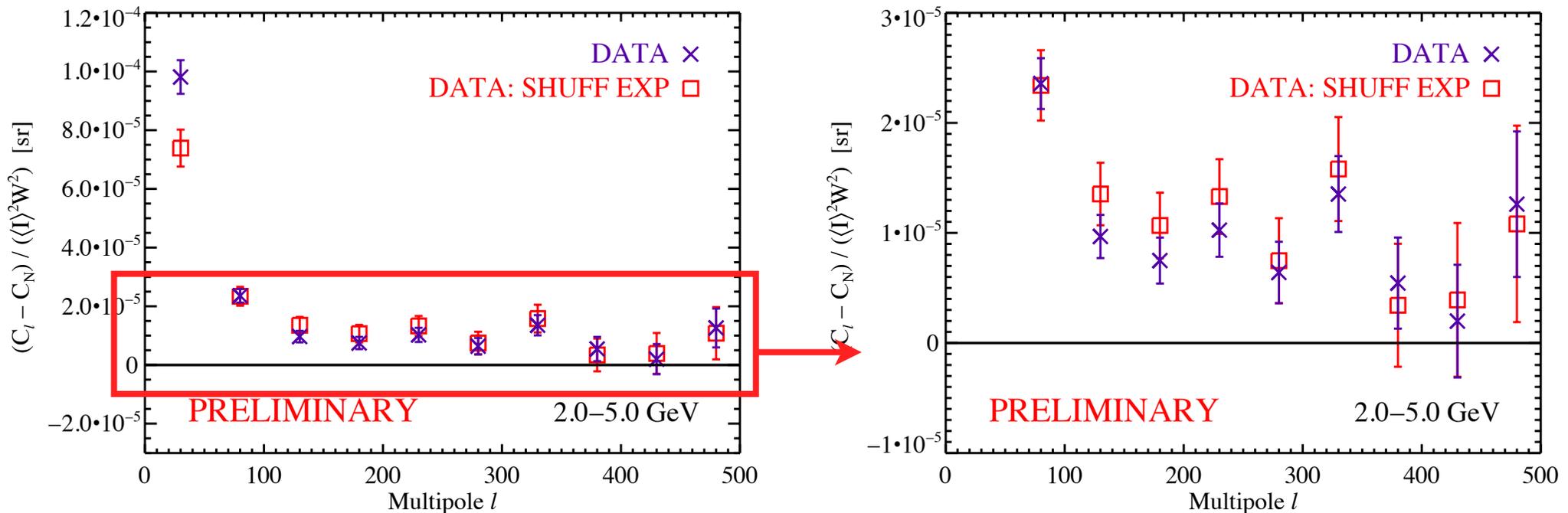
fluctuation angular power spectra
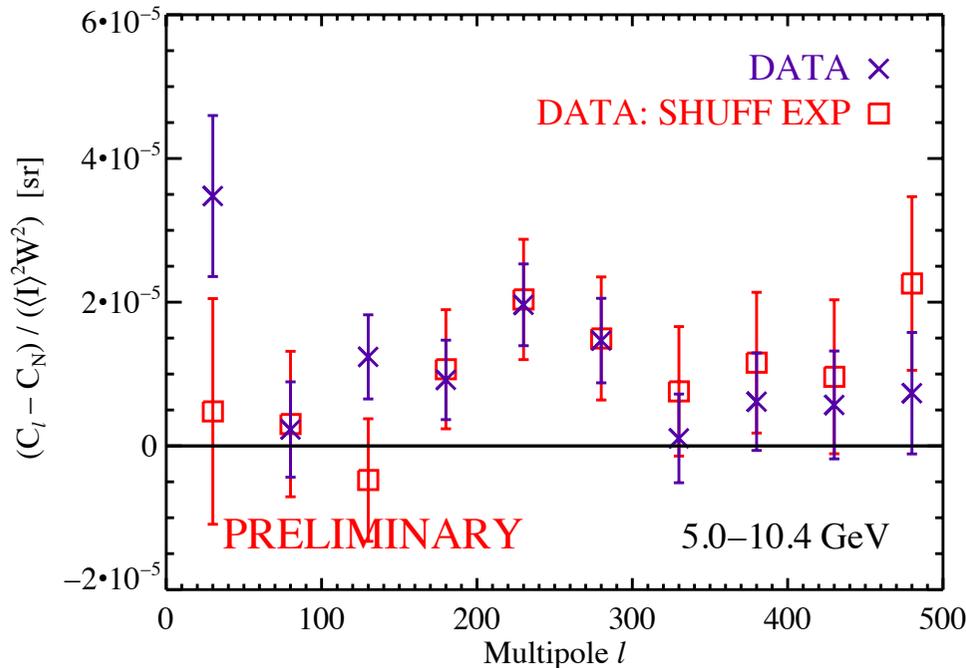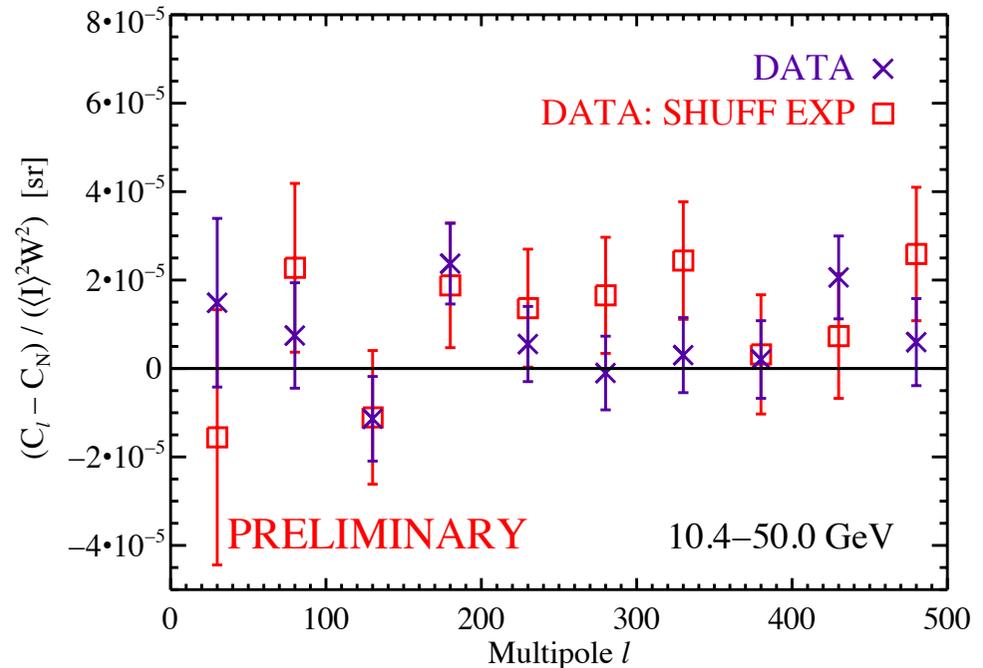
5 - 10 GeV

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

Foreground cleaning

intensity angular power spectra

1 - 2 GeV
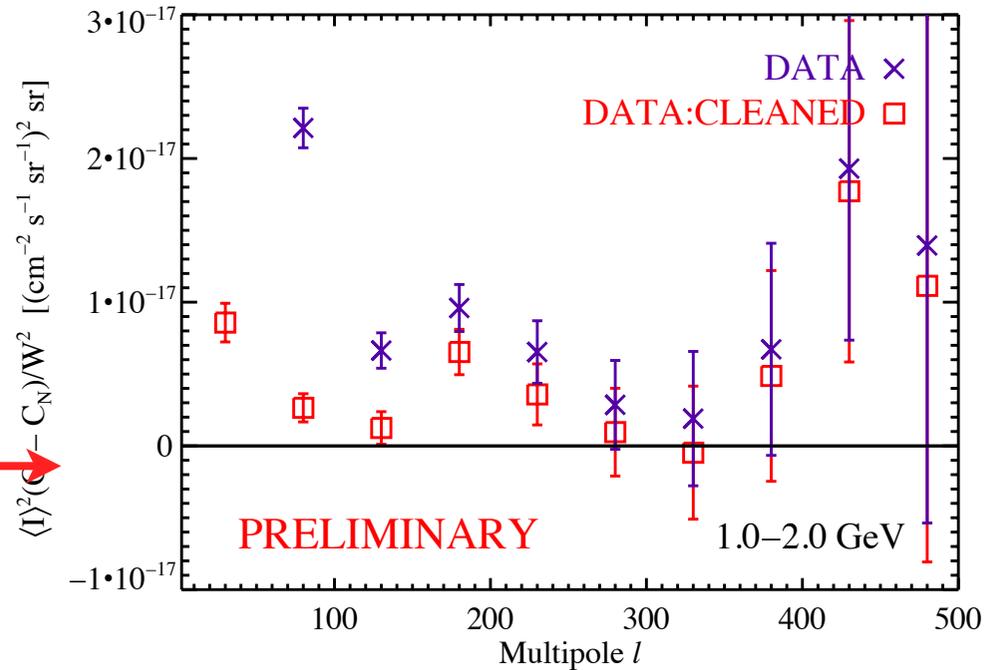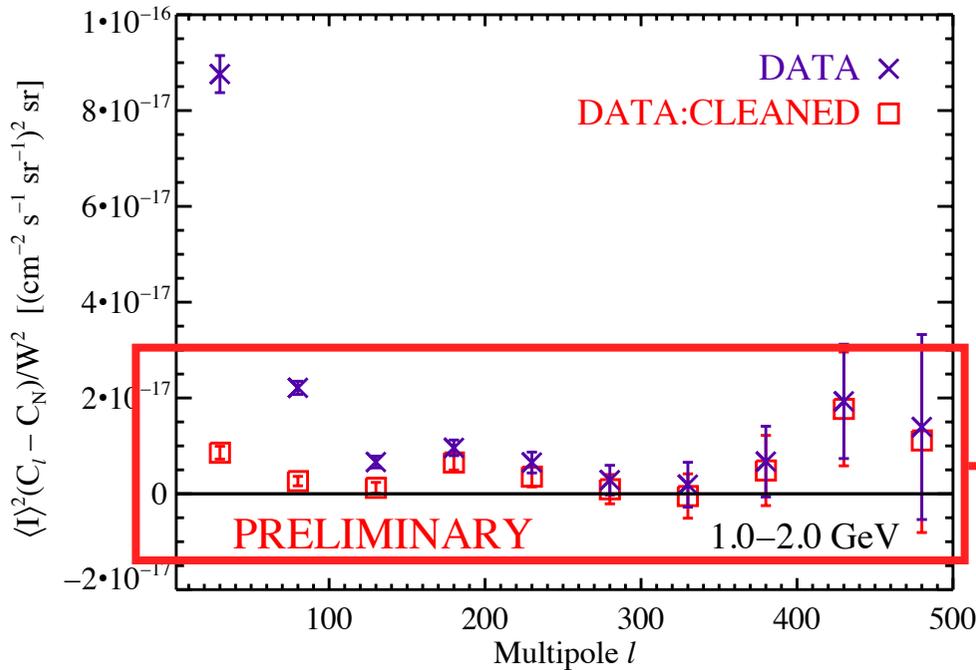
- subtraction of a Galactic diffuse model from the data (foreground cleaning) does not have a substantial impact on the anisotropy above l ~ 150

- indicates contamination in this multipole range by the Galactic diffuse is small

- yields similar results at high energies

Angular power in the data

$$C_\ell^{\text{signal}} \propto (\ell/\ell_0)^n$$

- in each energy bin, for 155 ≤ l ≤ 504, angular power consistent with constant value (but large uncertainties, some scale dependence not excluded)

$E_{\min}$	$E_{\max}$	n	$\chi^2/\text{d.o.f.}$
1.04	1.99	-1.33 ± 0.78	0.38
1.99	5.00	-0.07 ± 0.45	0.43
5.00	10.4	-0.79 ± 0.76	0.37
10.4	50.0	-1.54 ± 1.15	0.39

- identifying the signal at 155 ≤ l ≤ 504 as Poisson angular power, best-fit value of angular power is determined

- angular power detected at high significance up to 10 GeV, and at lower significance at 10-50 GeV

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

$C_{\mathrm{P}}/\langle I \rangle^2$ $[10^{-6}$ 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: ~ 1e-4
- starforming galaxies: ~ 1e-7
- dark matter: ~ 1e-4 to ~ 0.1
- MSPs: ~ 1e-2

- 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

(see poster by M. Fornasa)

Energy dependence of anisotropy

Fluctuation anisotropy energy spectrum

- consistent with no energy dependence, although 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
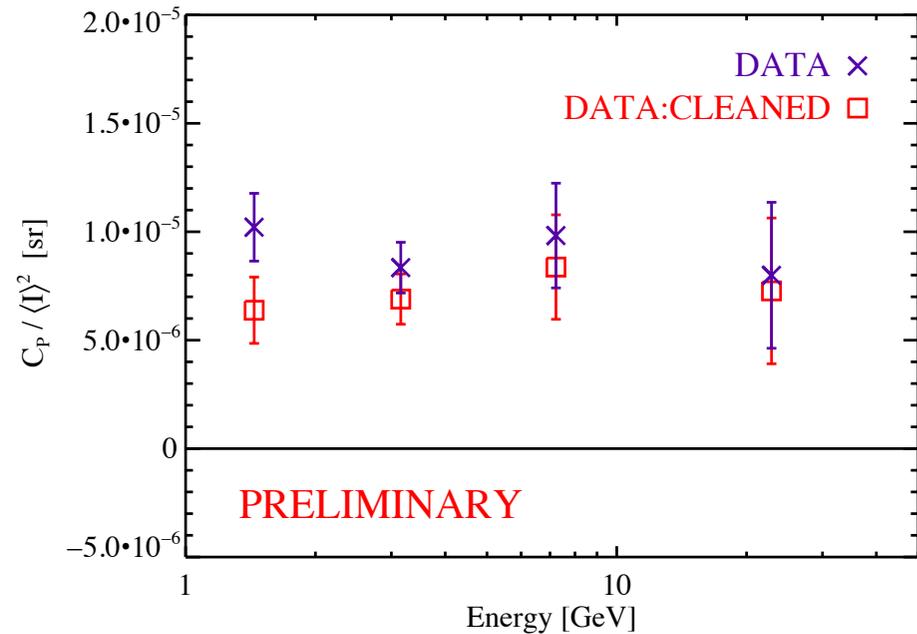
Intensity anisotropy energy spectrum

- consistent with that arising from a source class with power-law energy spectrum with $\Gamma = -2.40 \pm 0.07$

- implied source spectral index is good agreement with mean intrinsic spectral index of blazars inferred from detected members
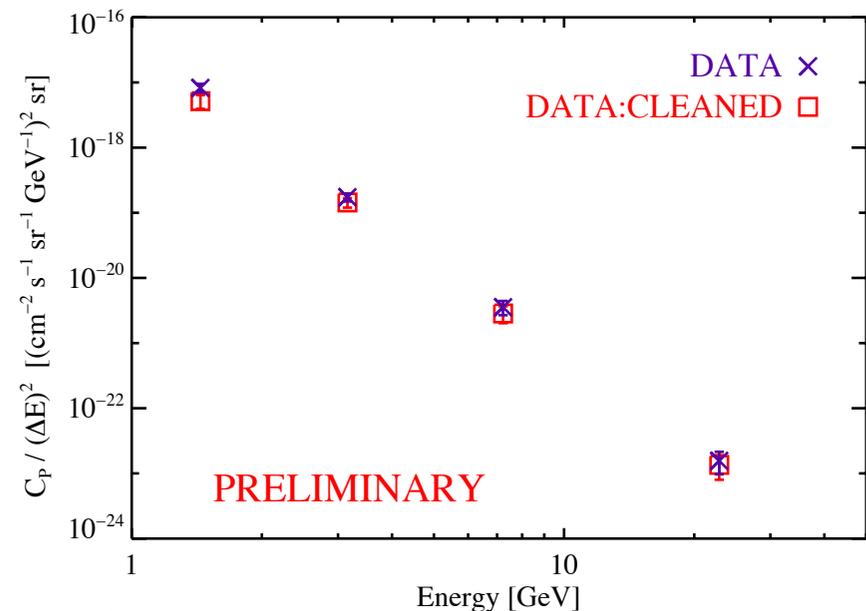
Summary

- at multipoles $155 \le l \le 504$, angular power is robustly measured in the data at energies from 1 to 10 GeV; lower significance angular power is detected in the 10-50 GeV energy bin

  - scale independence of the power at these multipoles suggests a contribution to the IGRB from one or more unclustered point source populations

- the fluctuation angular power measured in all energy bins is consistent with a constant value ~ 1e-5 sr

  - falls in the range of predicted angular power for some astrophysical source populations and dark matter scenarios

  - can be used to constrain the IGRB contribution from these sources

- energy dependence in the fluctuation angular power is not evident

  - suggests that the anisotropy is contributed primarily by one or more source populations with constant fractional contributions to the IGRB intensity over this energy range

- the measured energy dependence of the intensity angular power is consistent with the IGRB 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

Additional slides

Dependence on IRFs
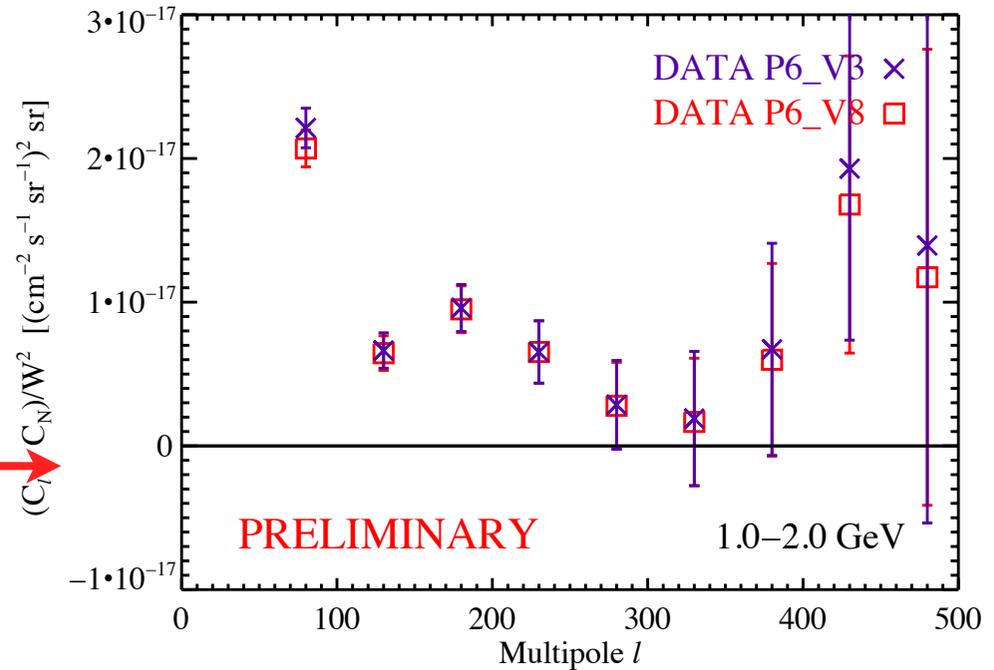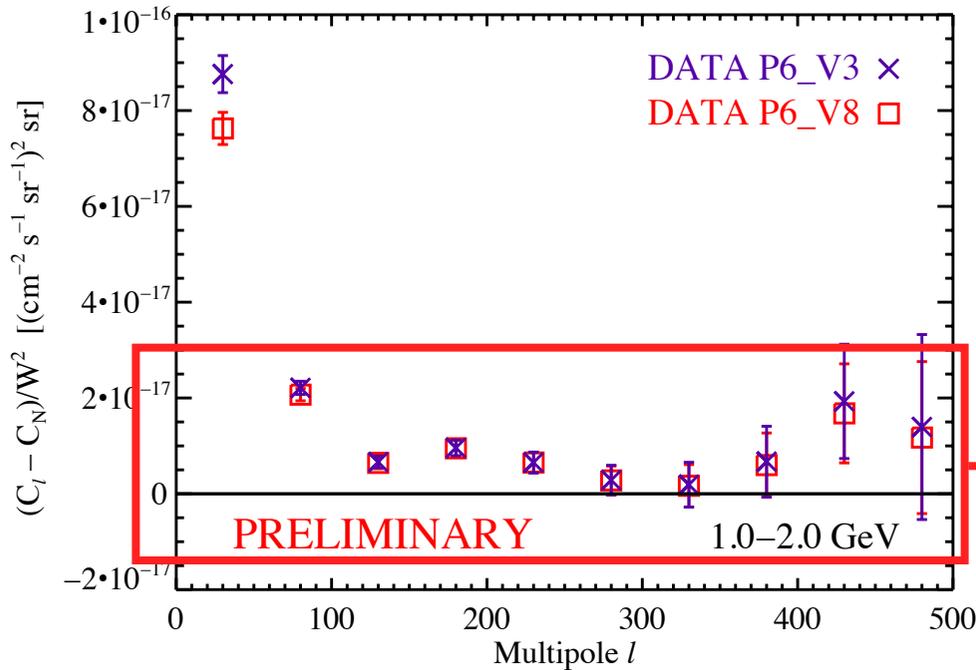
intensity angular power spectra

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
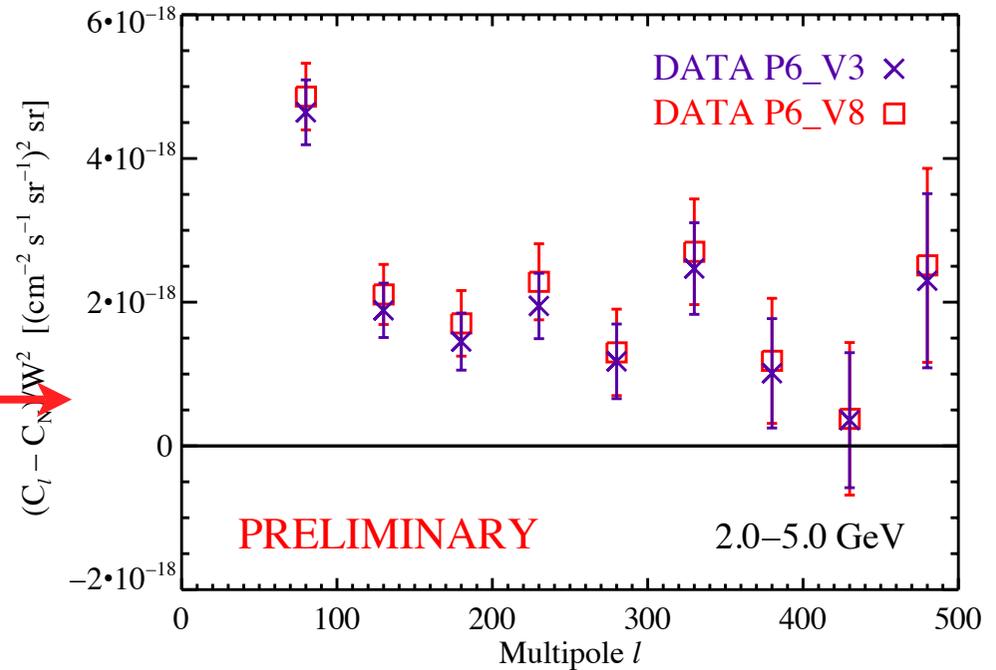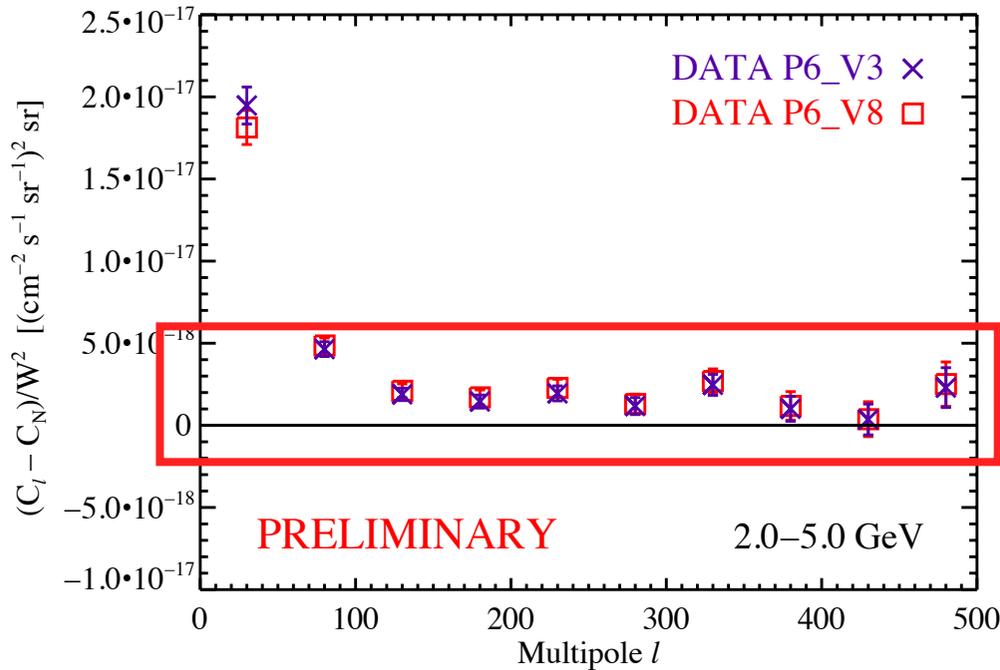
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Dependence on IRFs

intensity angular power spectra

5 - 10 GeV
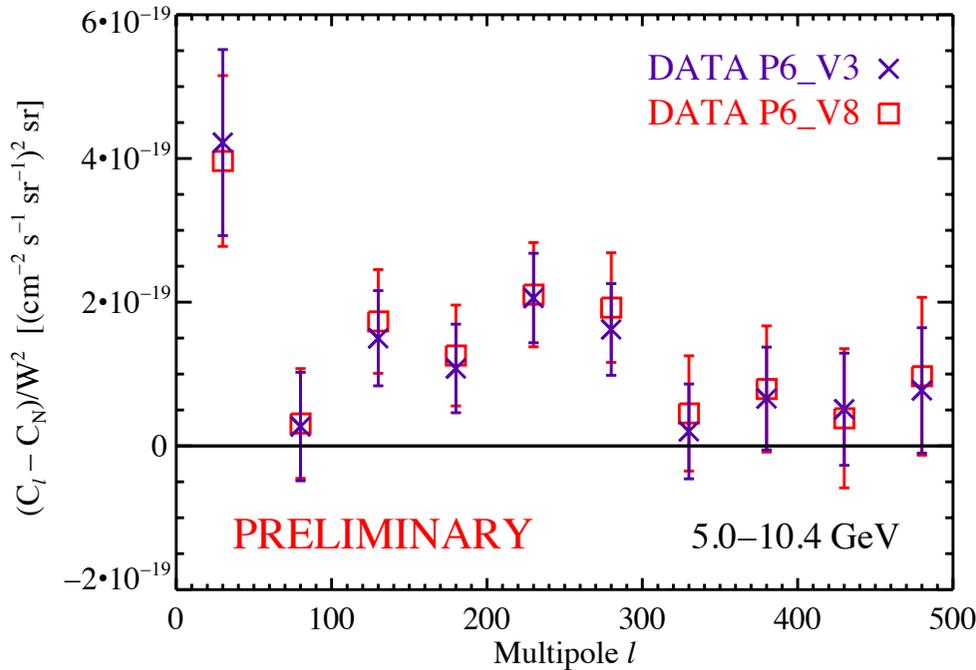
10 - 50 GeV
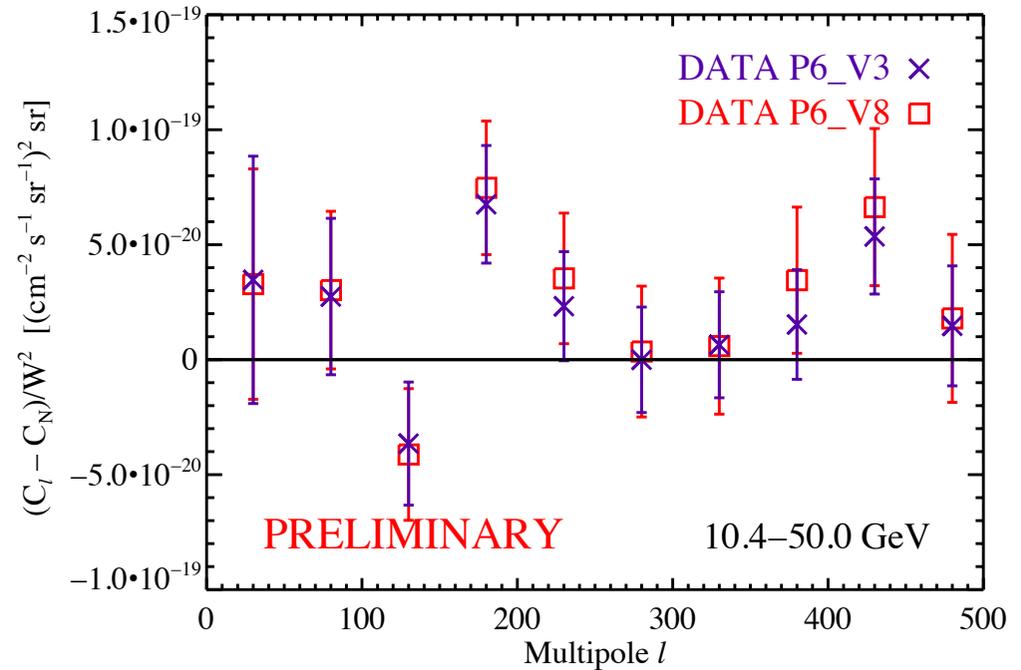
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Dependence on latitude mask
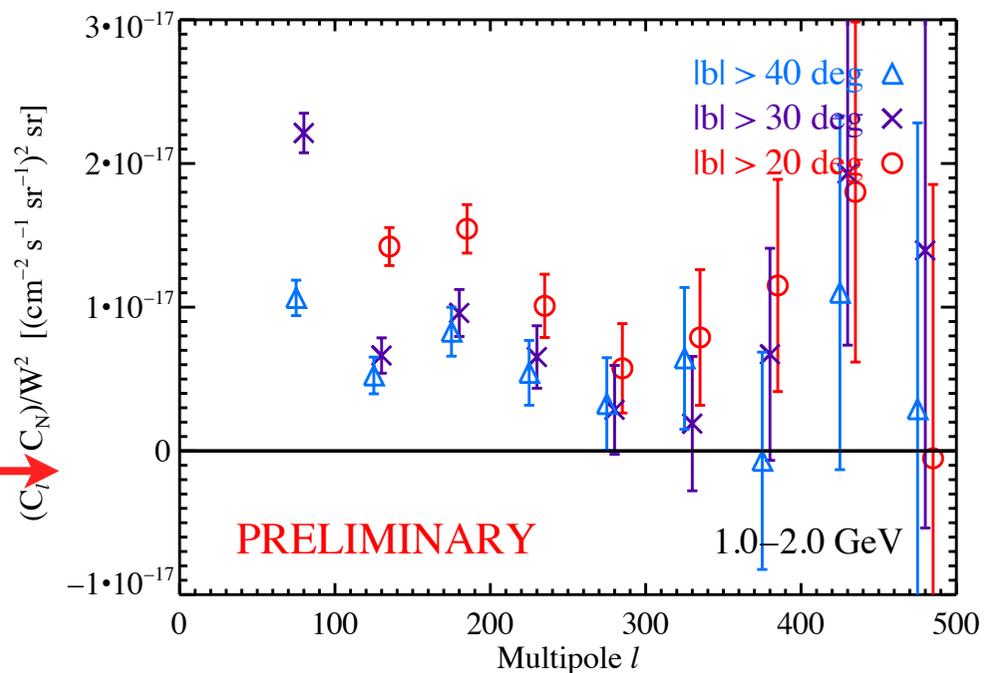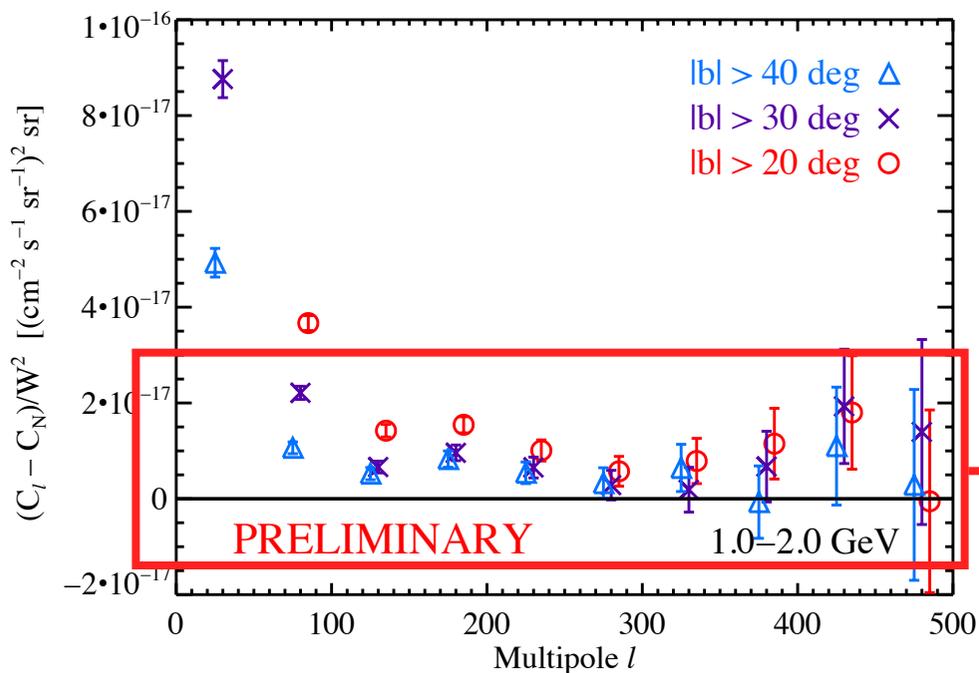
intensity angular power spectra

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
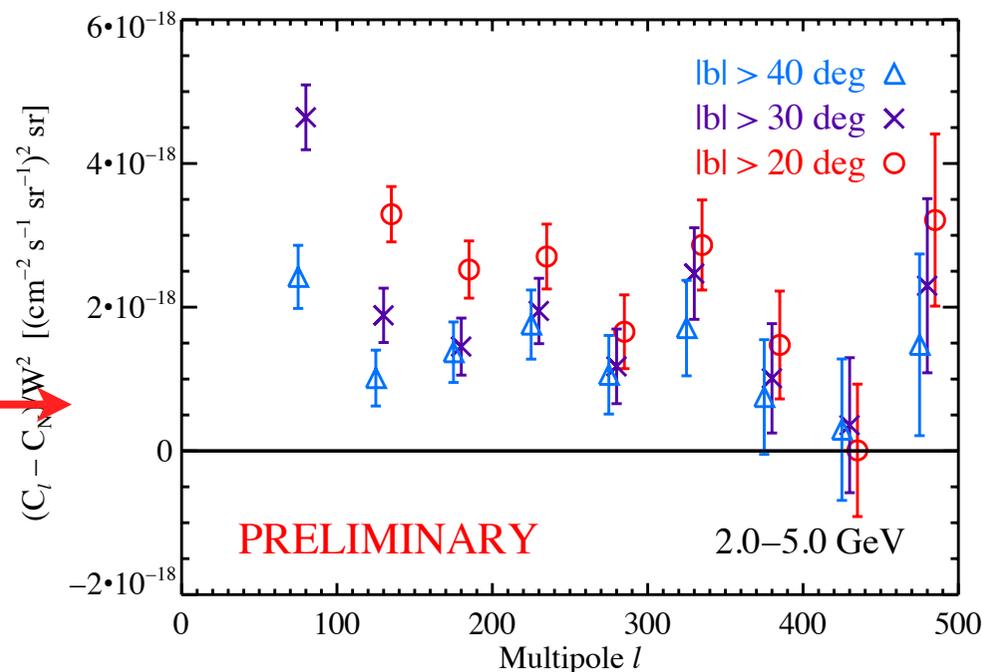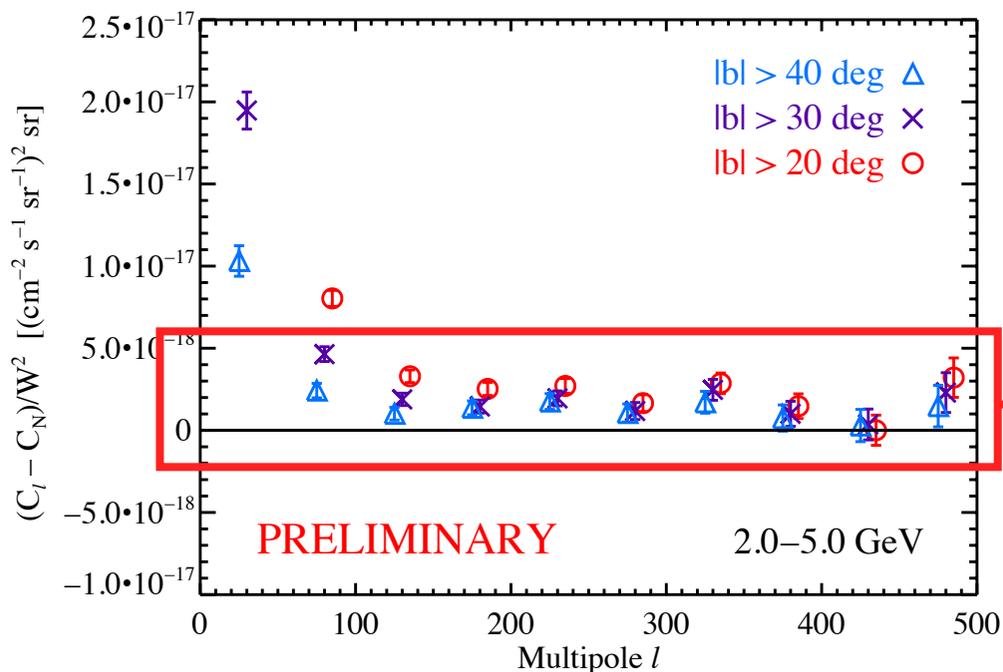
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Dependence on latitude mask

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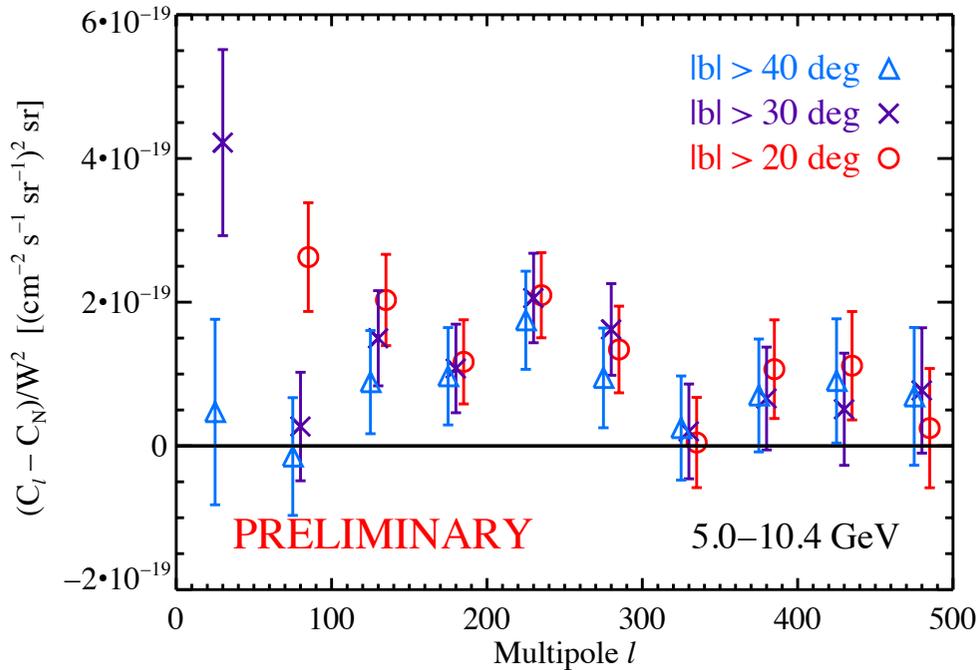
5 - 10 GeV

10 - 50 GeV
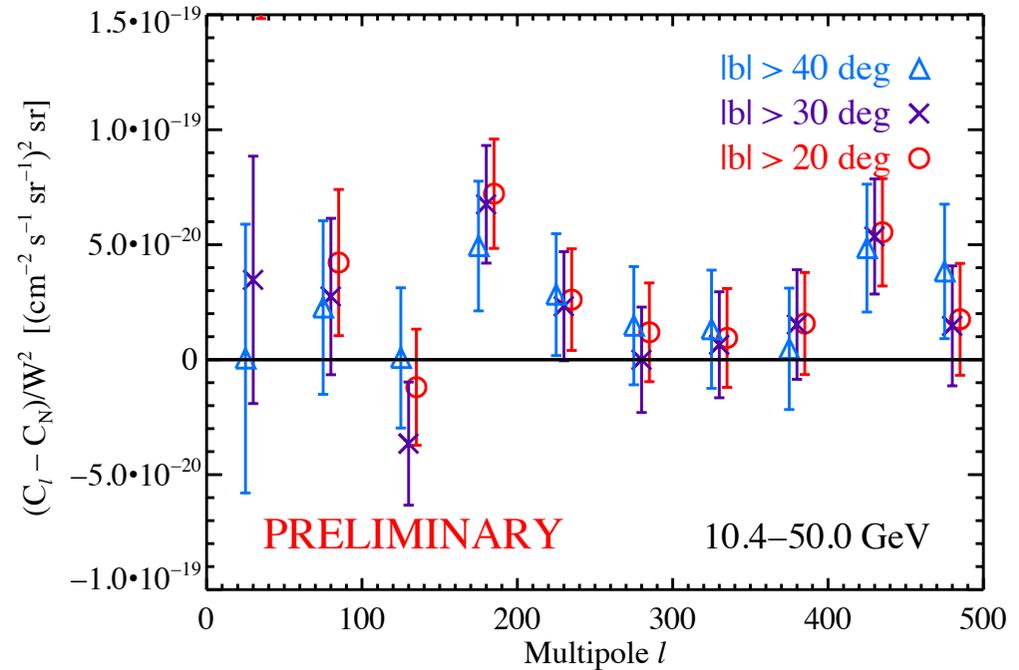
- above 10 GeV convergence at multipoles l ≥ 155 is seen masking only |b| < 20 deg

Foreground cleaning
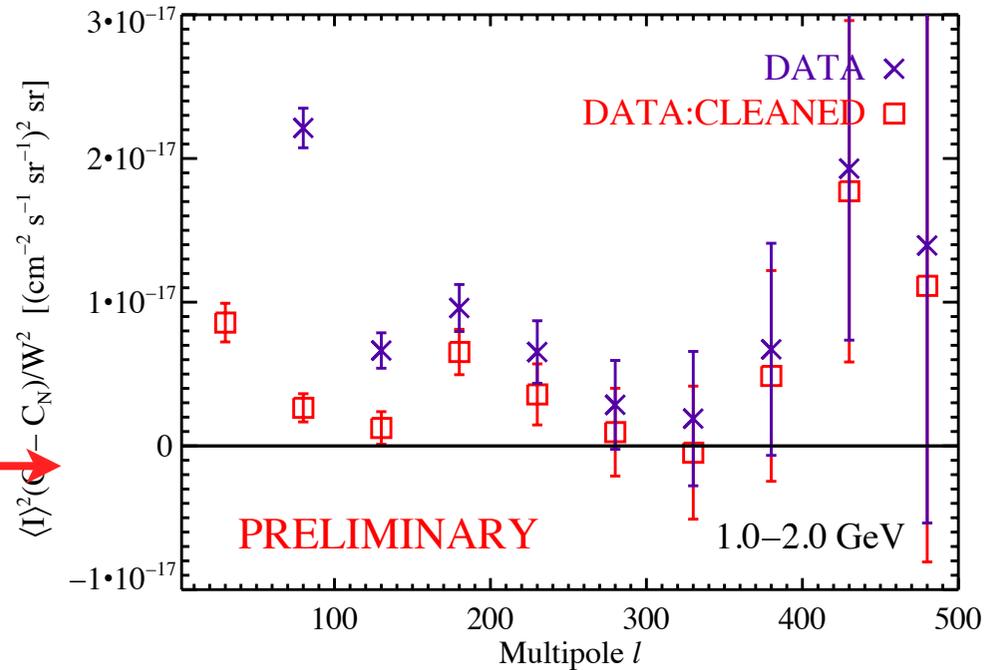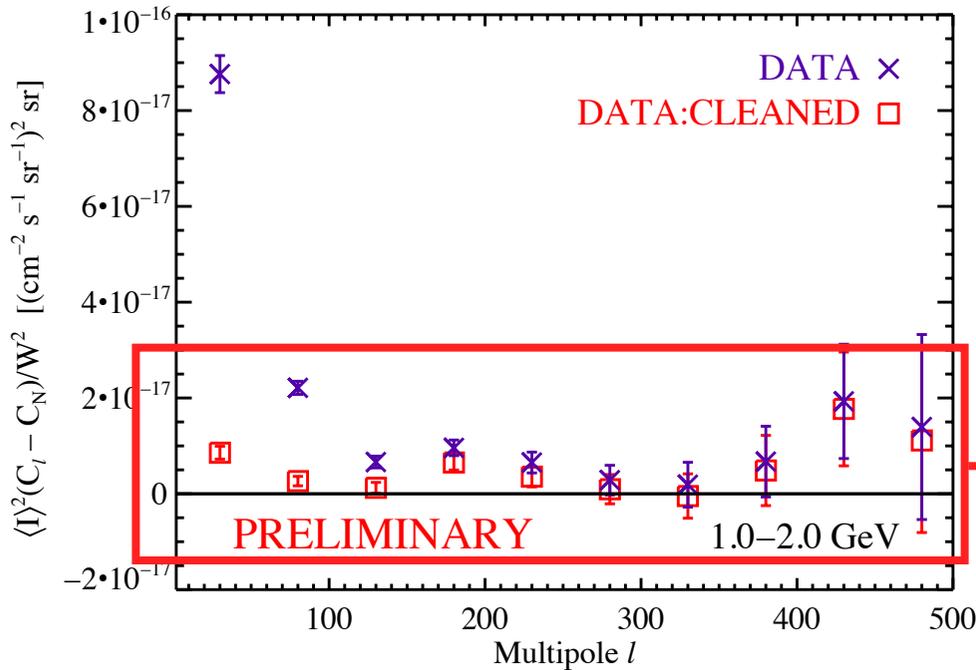
intensity angular power spectra

1 - 2 GeV

- foreground cleaning primarily reduces angular power at l < 155, with the most significant reductions at l < 105

- indicates that contamination of detected angular power at high multipoles by Galactic foregrounds is small

Foreground cleaning

intensity angular power spectra

2 - 5 GeV
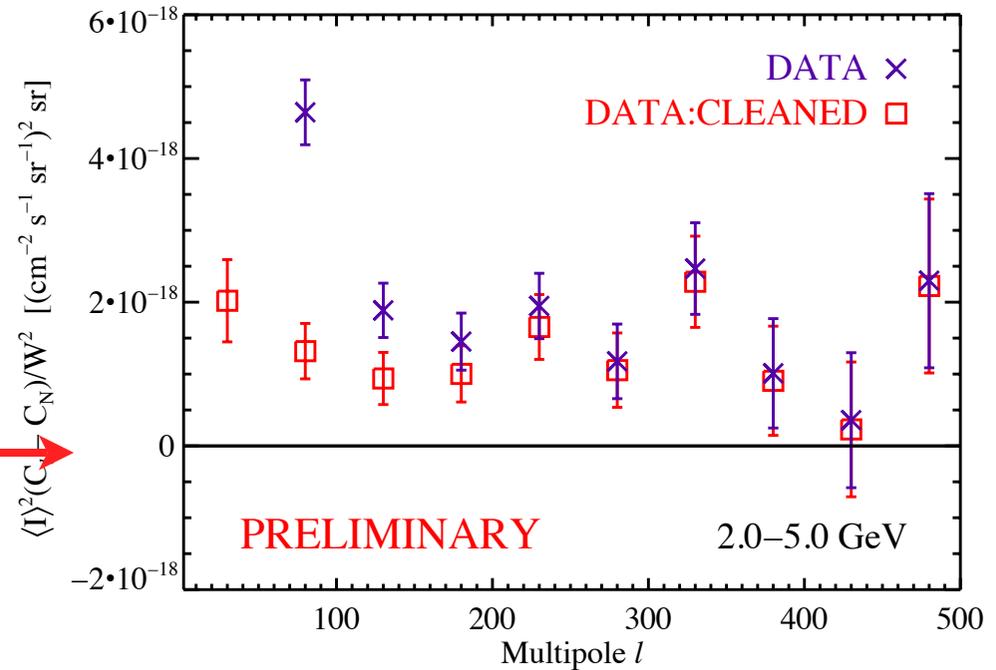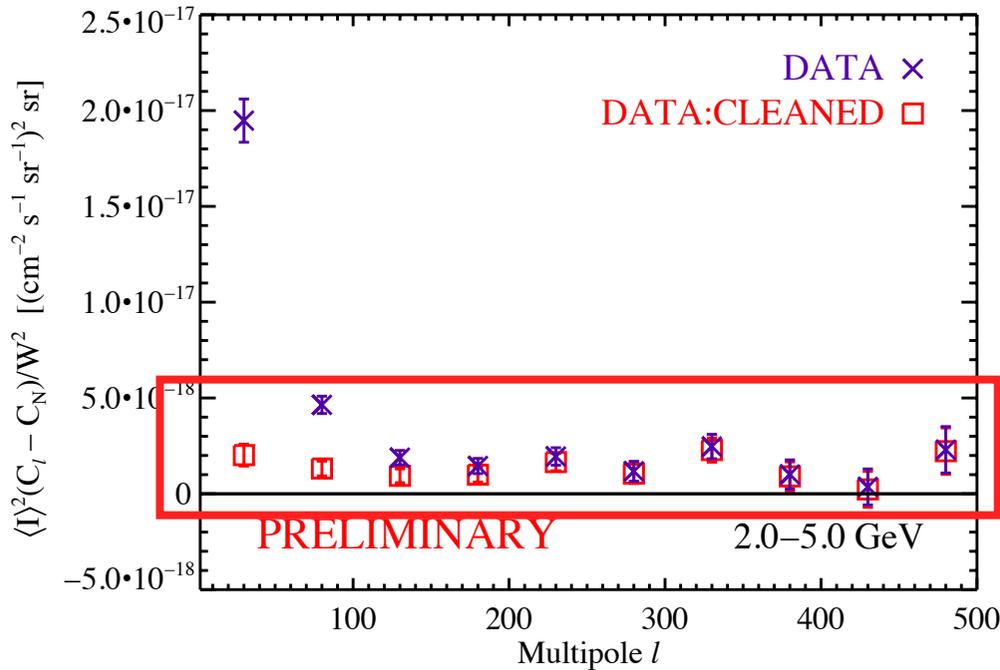
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Foreground cleaning

intensity angular power spectra

5 - 10 GeV
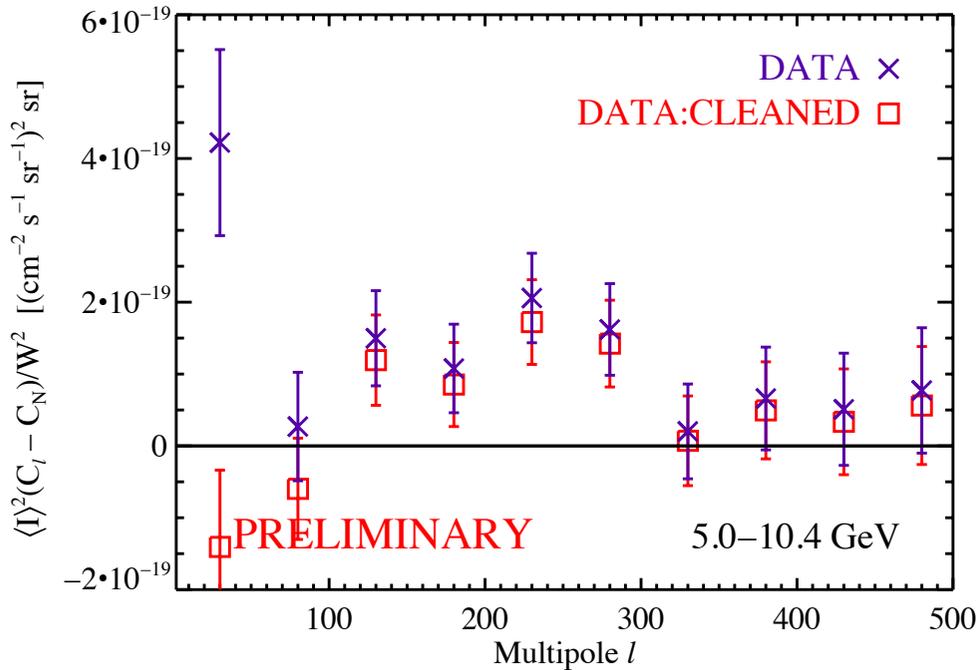
10 - 50 GeV
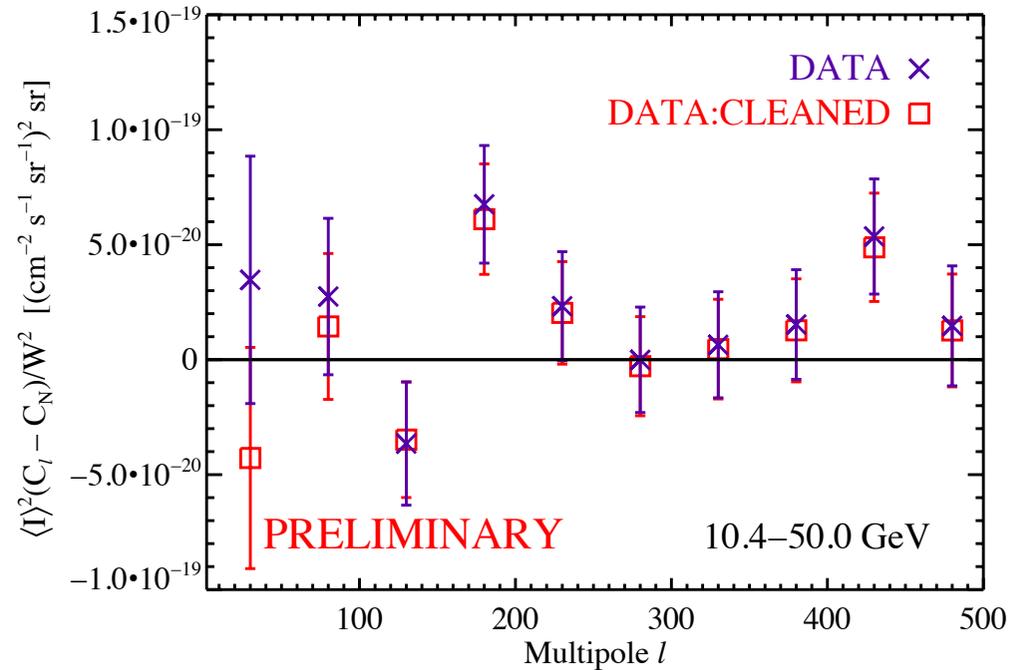
- the effect of foreground cleaning is small for l ≥ 55

- indicates that contamination of detected angular power at high multipoles by Galactic foregrounds is small

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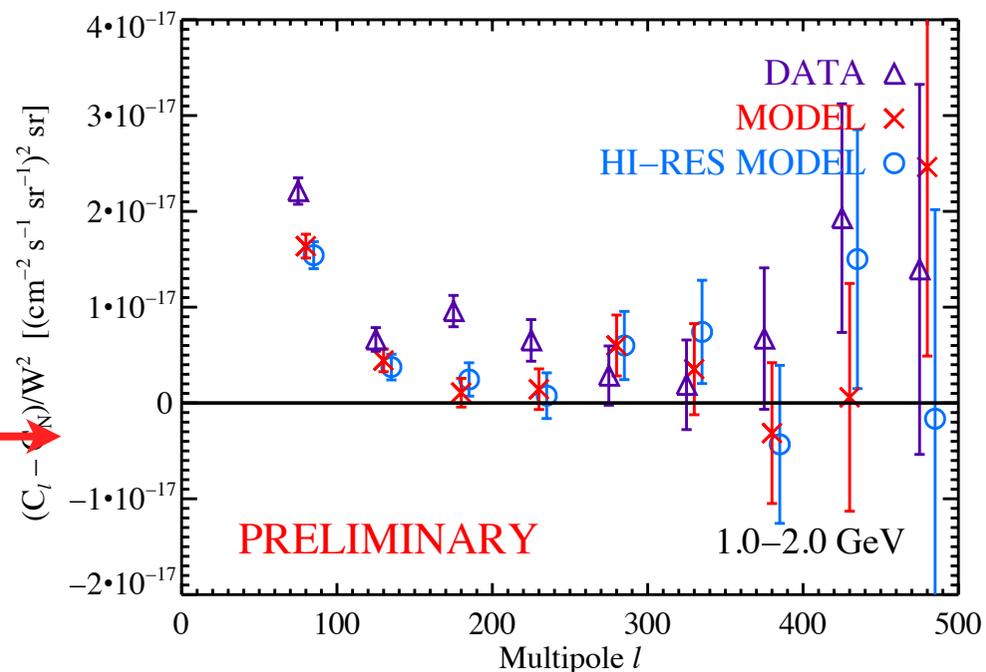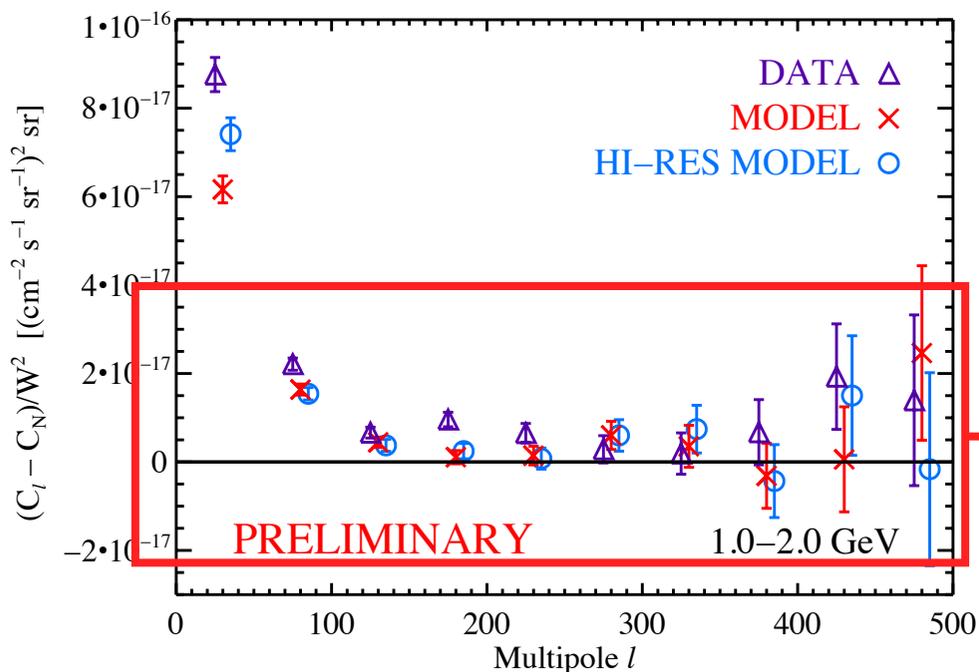
- smaller amplitude angular power detected at low significance in both models at $l \geq 155$ is inconsistent with the excess observed in the data

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

Comparison with simulated models

intensity angular power spectra

2 - 5 GeV
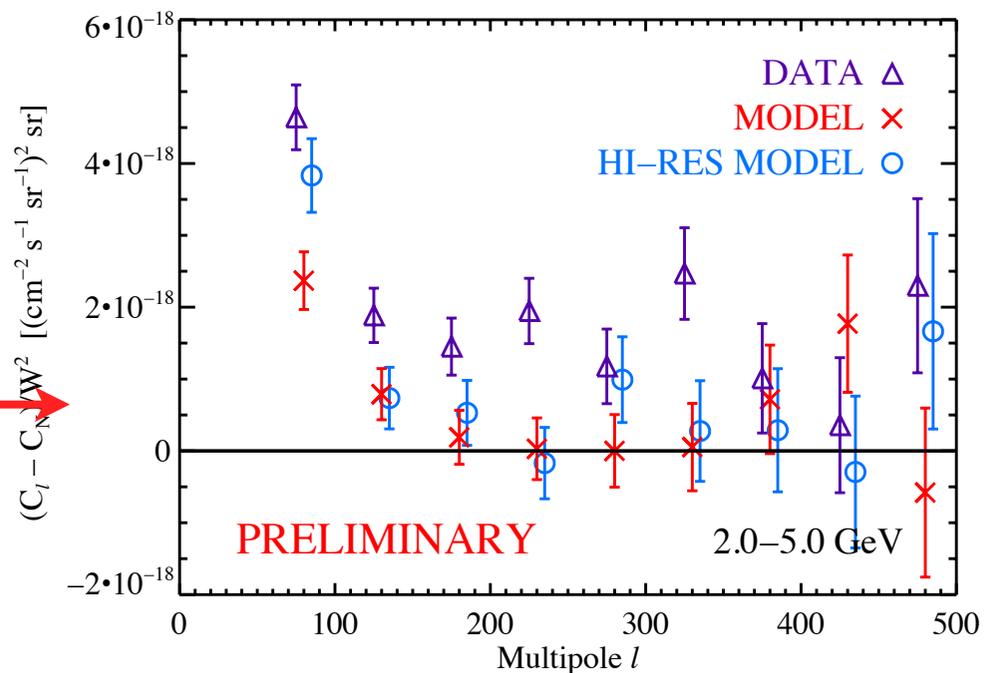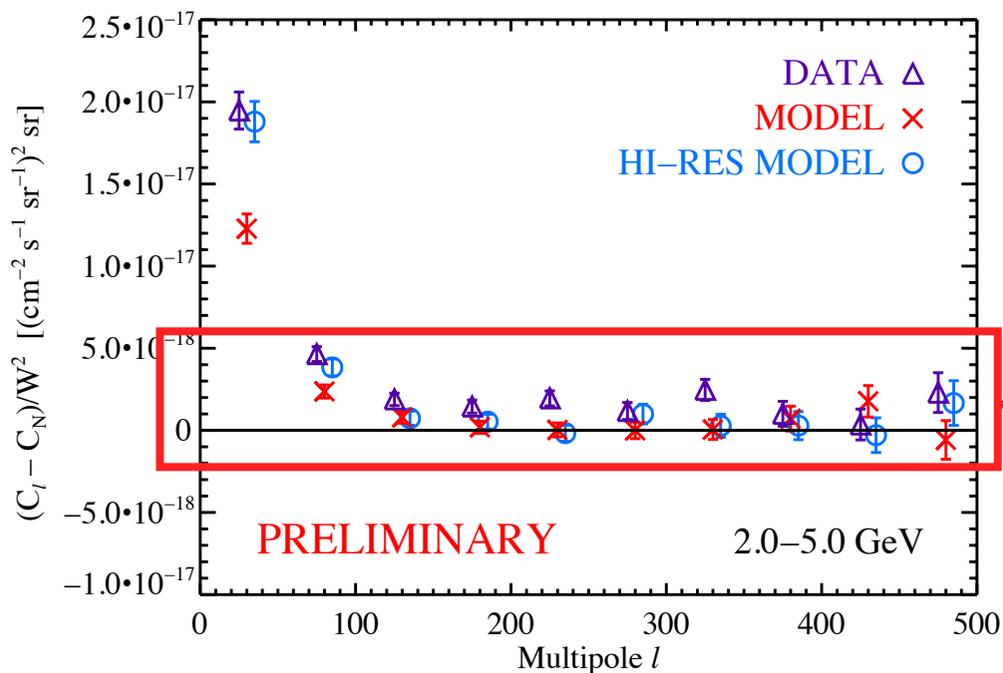
- no significant angular power detected in either model at l ≥ 155

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Comparison with simulated models

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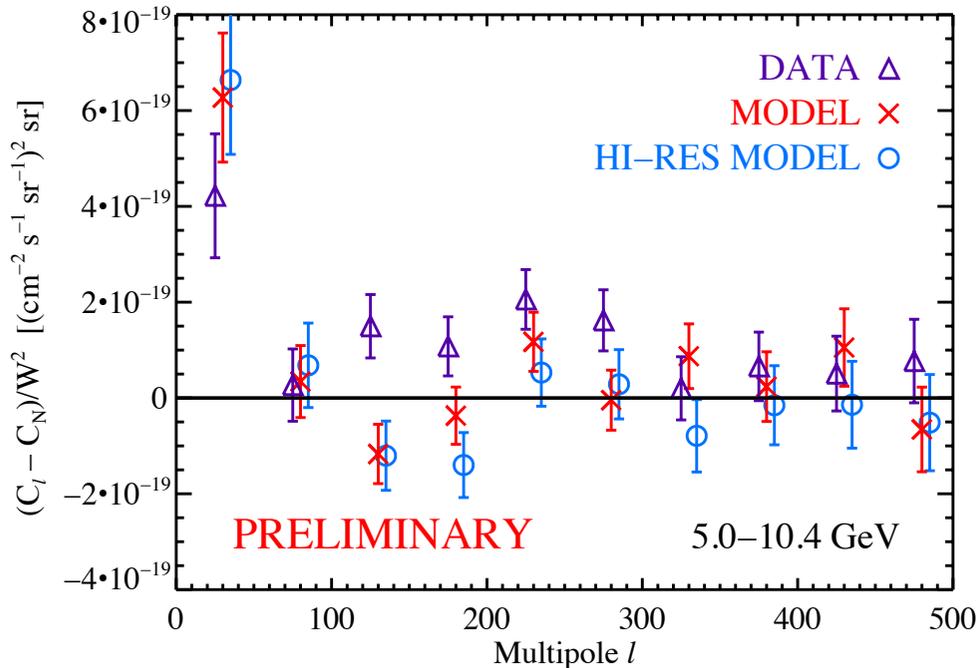
5 - 10 GeV   ## 10 - 50 GeV
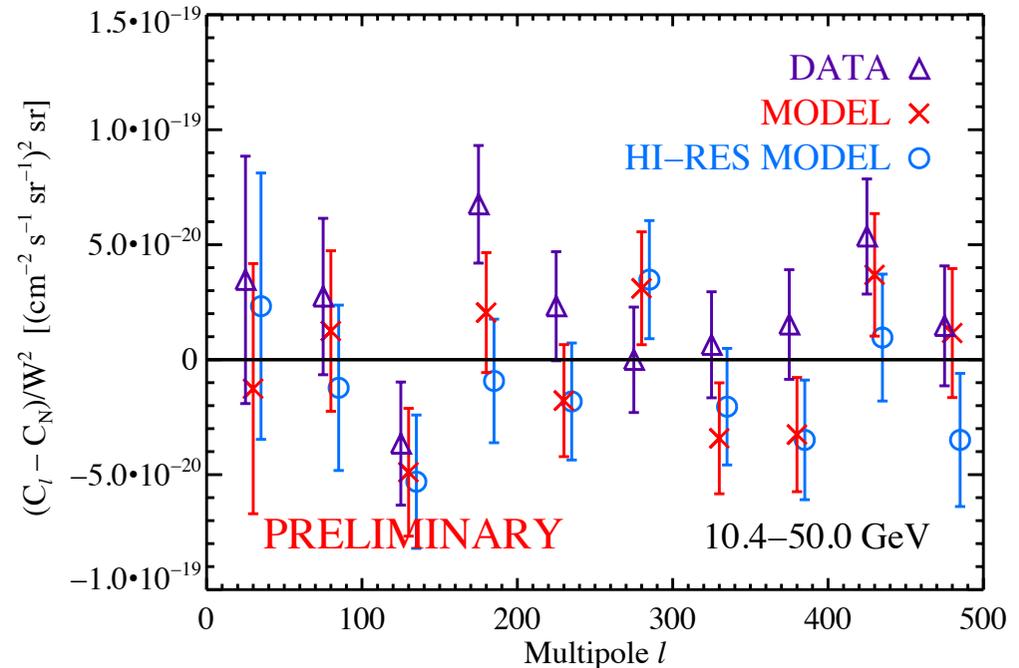
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Simulated model components
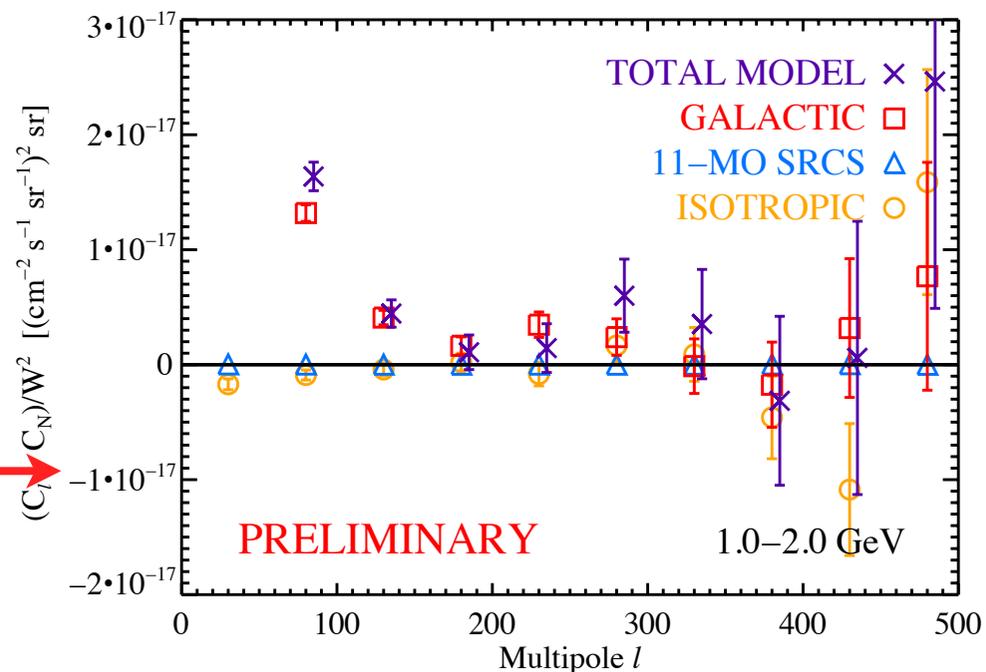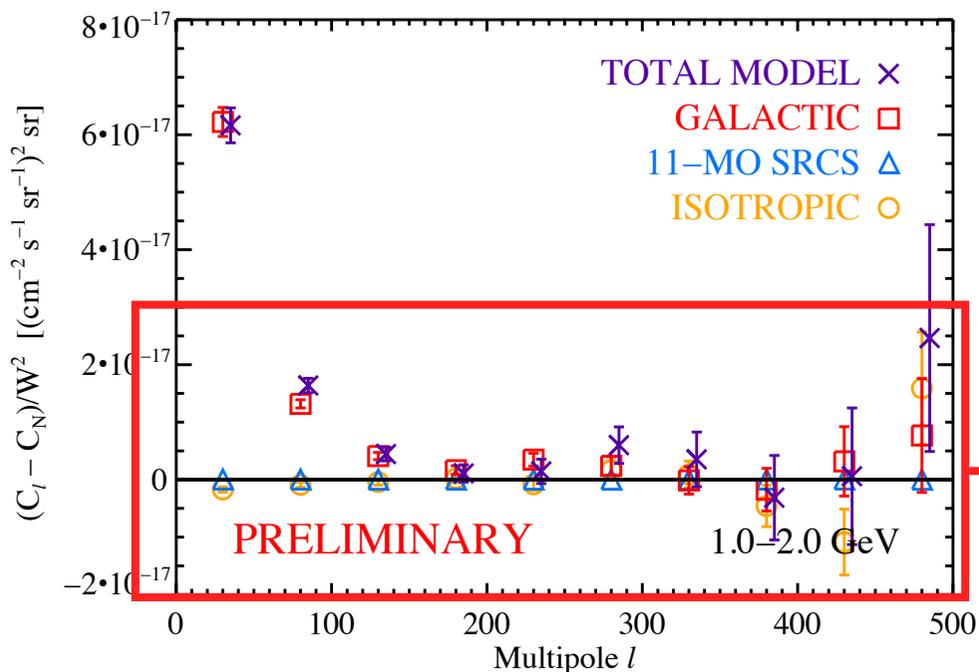
intensity angular power spectra

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
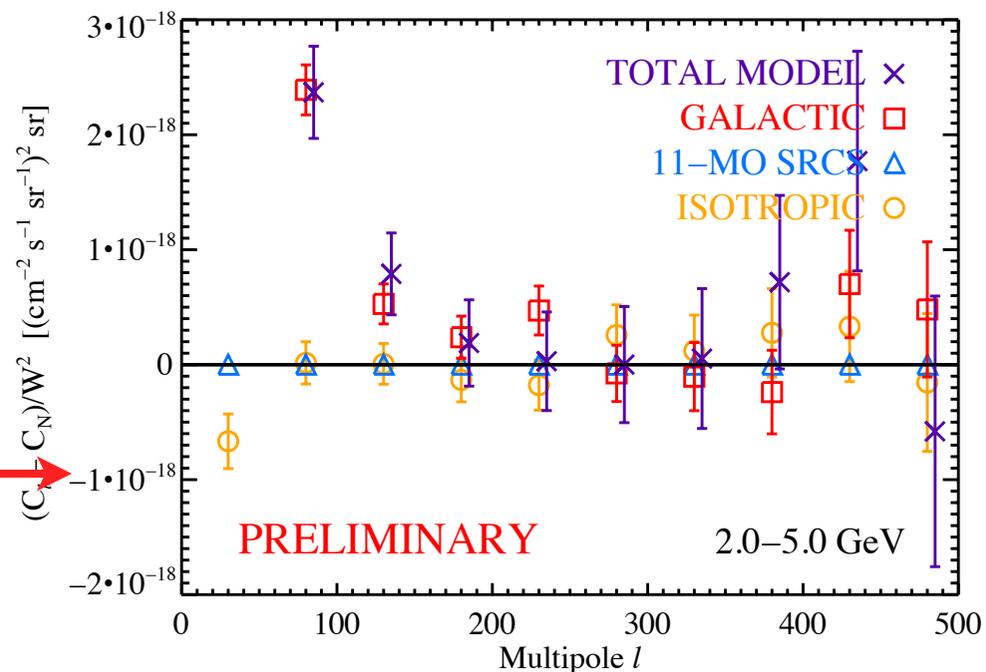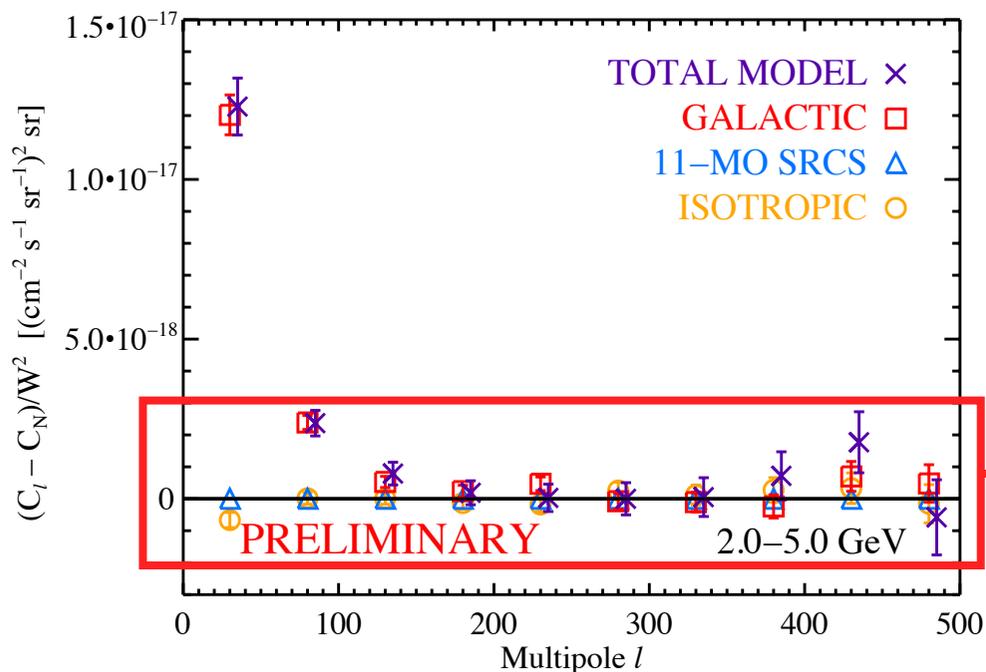
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