Fermi Gamma-ray Space Telescope

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

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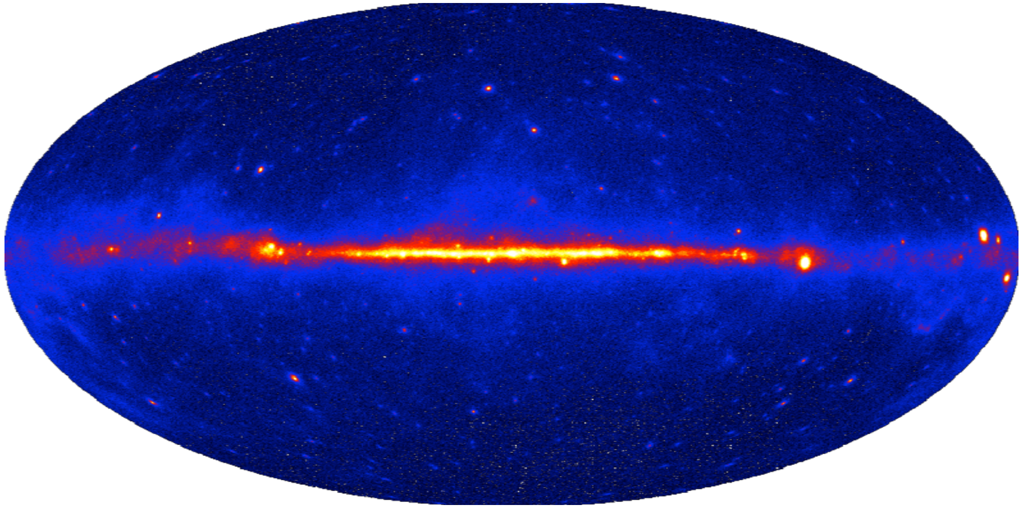
Sources of Anisotropies in the Gamma-ray Sky

Fermi Gamma-Sky 30 MeV-300 GeV



- Besides the Galactic Component the Gamma-ray sky contains a large-scale isotropic gamma-ray background (IGRB) which can have small scale fluctuations.
- Poisson noise from unresolved point sources, for example, is the main sources of such fluctuations on small angular scales
- The correlations term of unresolved point sources is instead typically subdominant.
- Dark Matter, on Galactic or Extra-Galactic scale can be another source of anisotropy.
- the amplitude and energy dependence of the anisotropy can reveal the presence of multiple contributions and constrain their properties

The origin of the IGRB

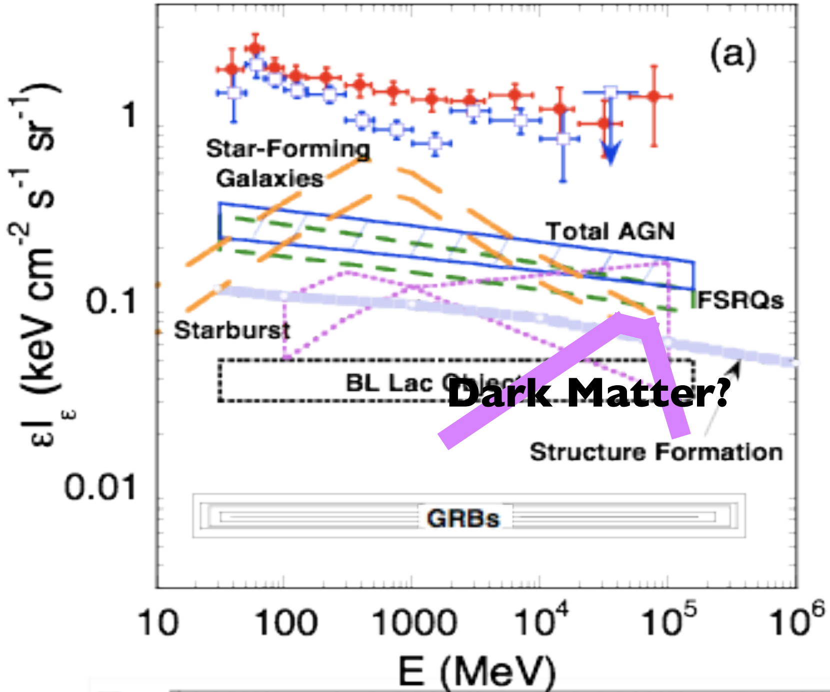
- many astrophysical sources are *guaranteed* to contribute, e.g.:
- blazars
- star-forming galaxies
- millisecond pulsars
- AGNs
- clusters of Galaxies
- clusters Shocks
- cascades from UHECRs

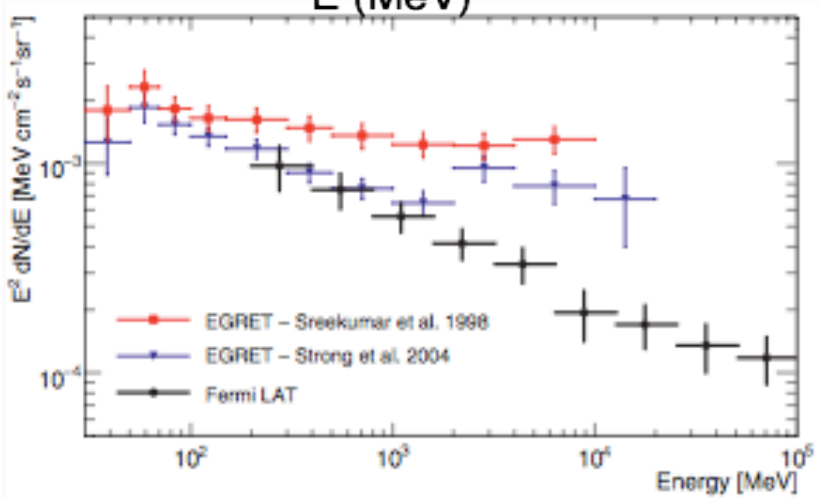
and…

- Dark matter(?)

- relatively featureless total IGRB intensity spectrum → lack of spectral handles to ID individual components
- the amplitude and energy dependence of the anisotropy is a complementary tool to disentangle different contributions

Dermer 2007





Abdo et al., PRL 104 (2010) 101101

The angular power spectrum

$$I(\psi) = \sum_{\ell,m} a_{\ell m} Y_{\ell m}(\psi)$$

$$C_\ell = \langle |a_{\ell m}|^2 \rangle$$

- Spherical Harmonic transform of the intensity map
- Intensity angular power spectrum: Ensemble average of the armonic coefficients; indicates *dimensionful* amplitude of anisotropy

$$\frac{C_\ell}{\langle I \rangle^2}$$

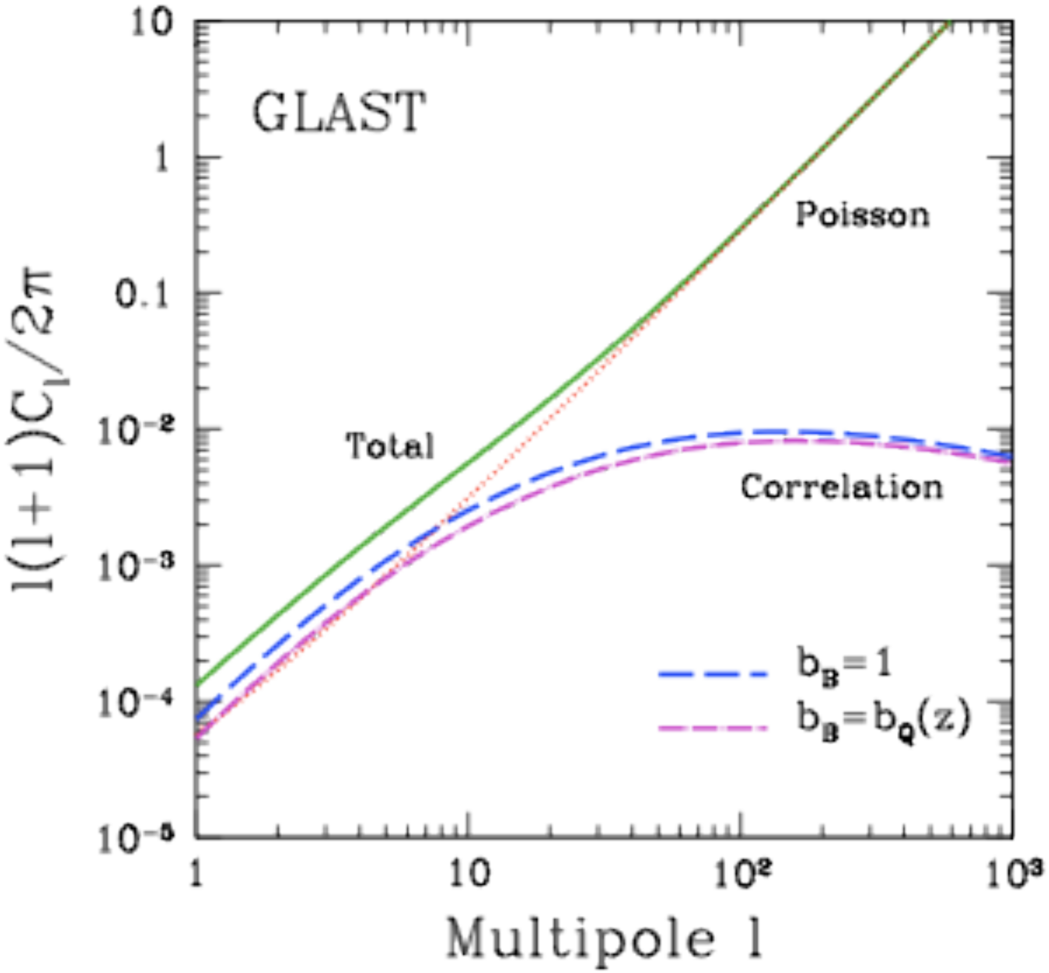
- Also widely used is the fluctuation angular power spectrum:
  - *dimensionless*, independent of intensity normalization
  - amplitude for a single source class is the same in all energy bins (if source distribution is independent of energy)

Angular power spectra of unresolved gamma-ray sources

- the angular power spectrum of many gamma-ray source classes 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

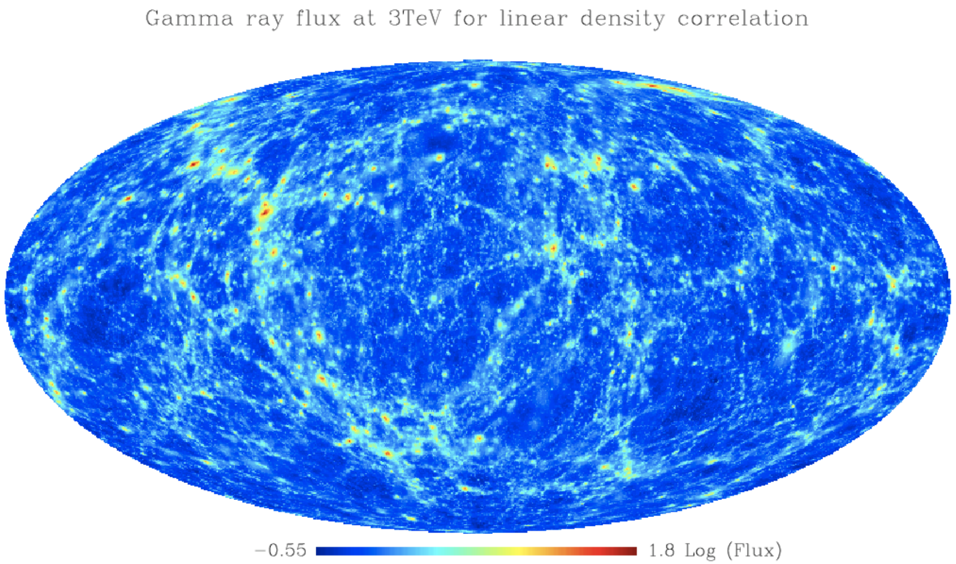
predicted fluctuation angular power $C_\ell / \langle I \rangle^2$ [sr] at l = 100 for a single source class (LARGE UNCERTAINTIES):

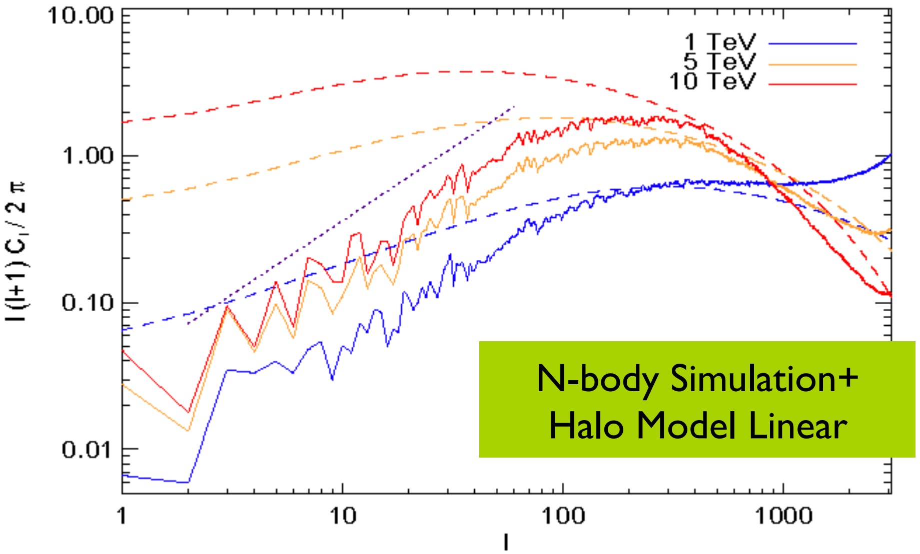
- blazars: ~ 1e-4
- starforming galaxies: ~ 1e-7
- dark matter: ~ 1e-4 to ~ 0.1
- MSPs: ~ 1e-2

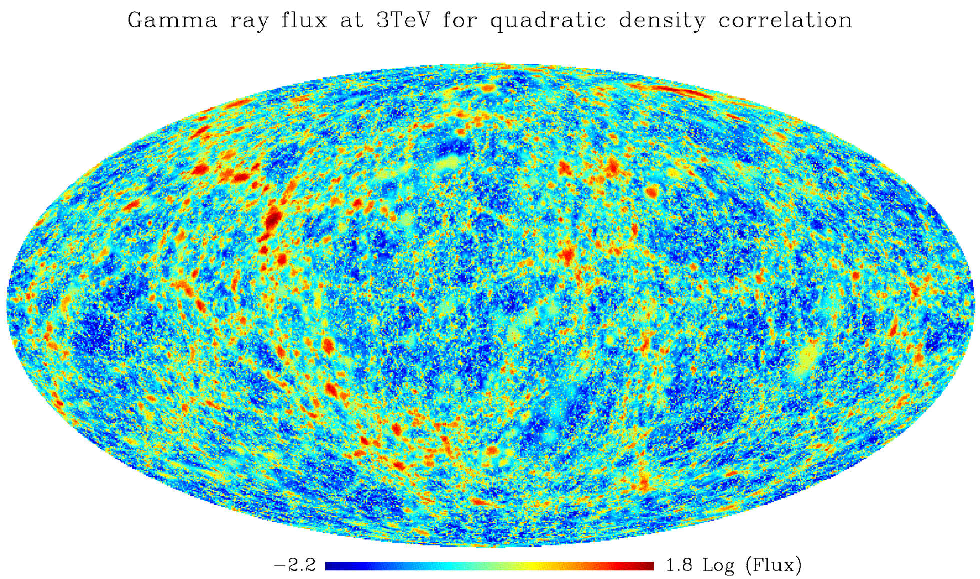


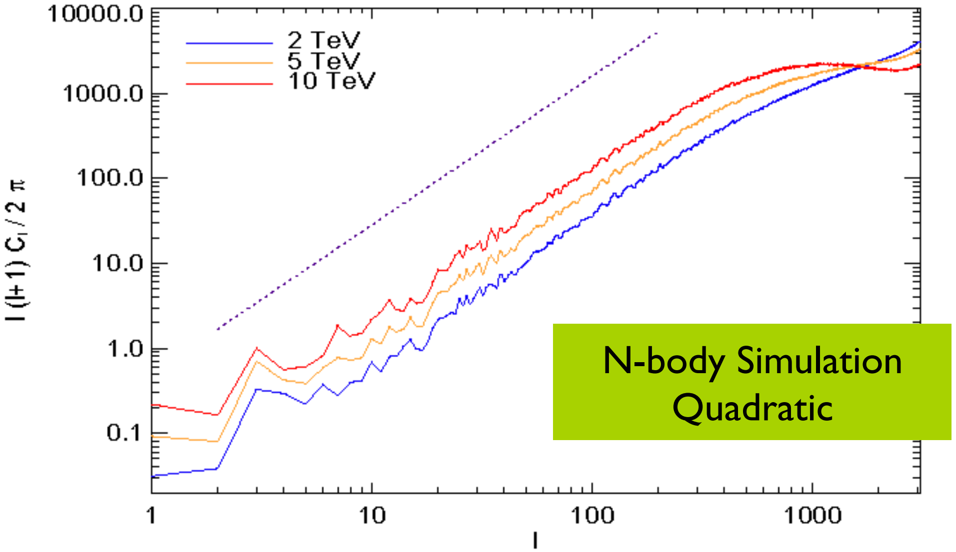
Blazars (Ando, Komatsu, Narumoto & Totani 2007)

The IGRB angular power spectrum from N-body Simulations of Large Scale Structures (LSSs)





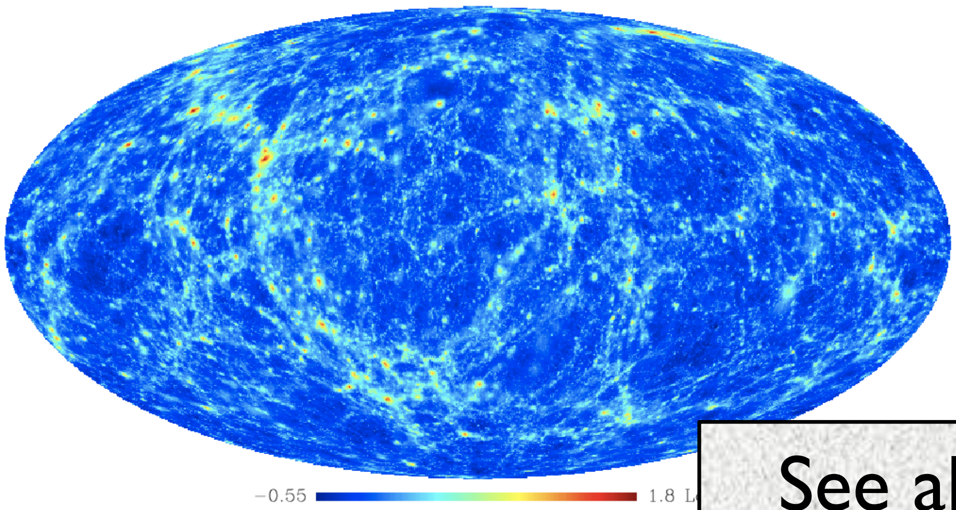


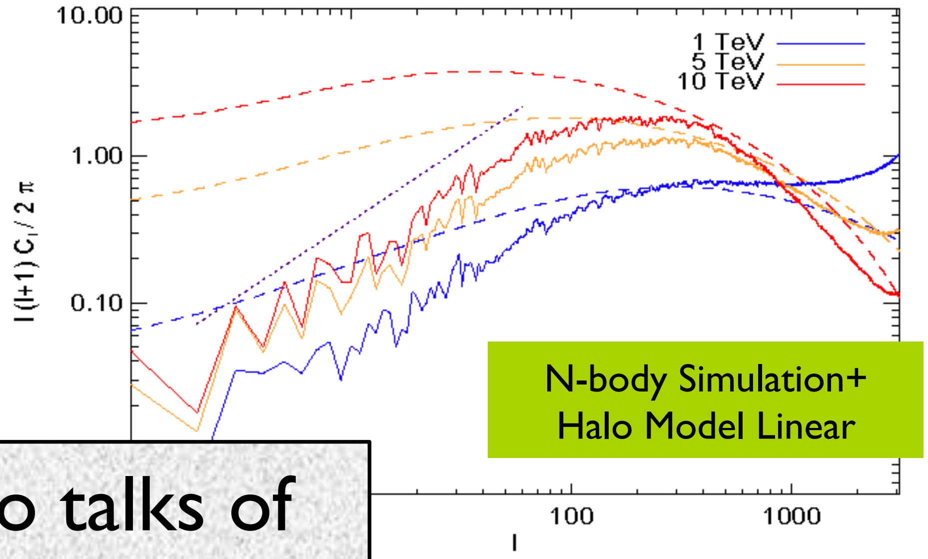


A.Cuoco, S.Hannestad, T.Haugbolle, G.Miele, P.D.Serpico, JCAP 0704:013,2007

The IGRB angular power spectrum from N-body Simulations of Large Scale Structures (LSSs)

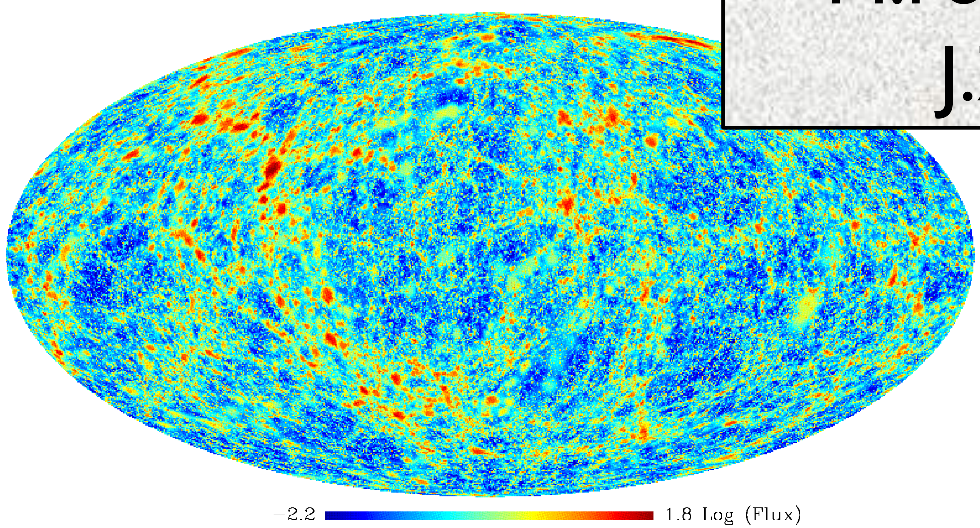
Gamma ray flux at 3TeV for linear density correlation

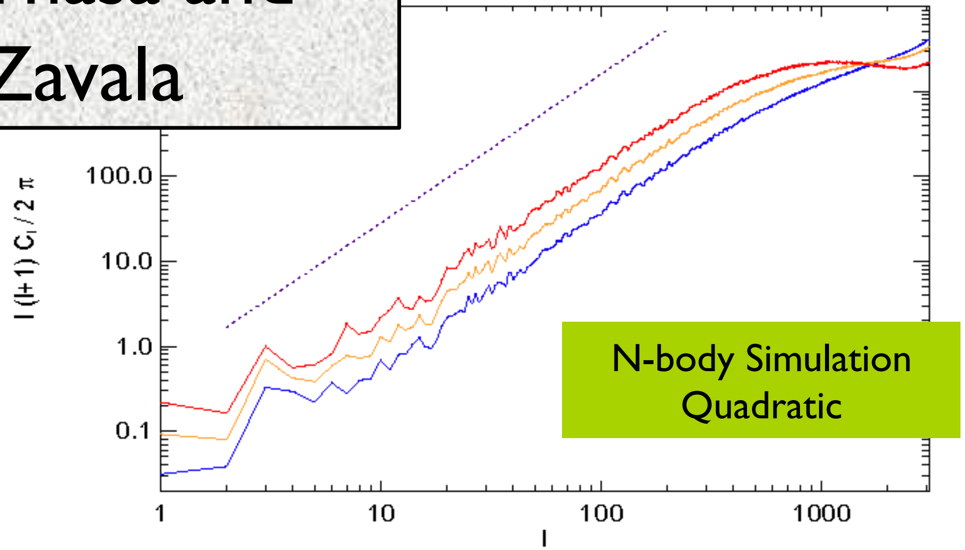




See also talks of M.Fornasa and J.Zavala

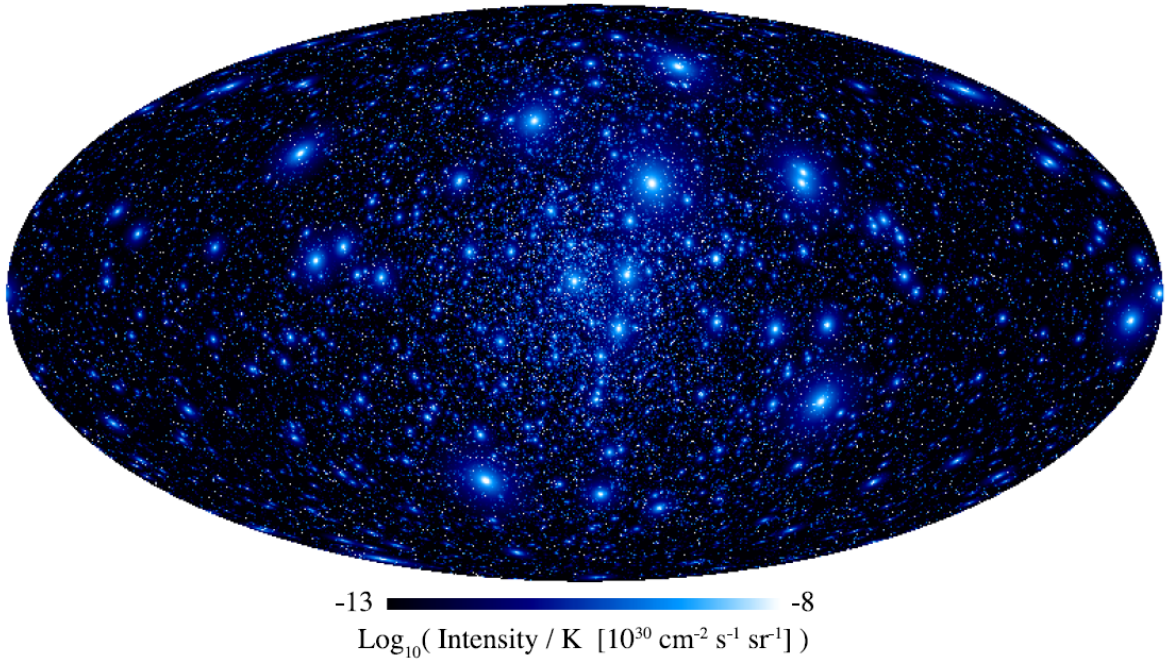
Gamma ray flux at 3TeV for quadratic density





A.Cuoco, S.Hannestad, T.Haugbolle, G.Miele, P.D.Serpico, JCAP 0704:013,2007

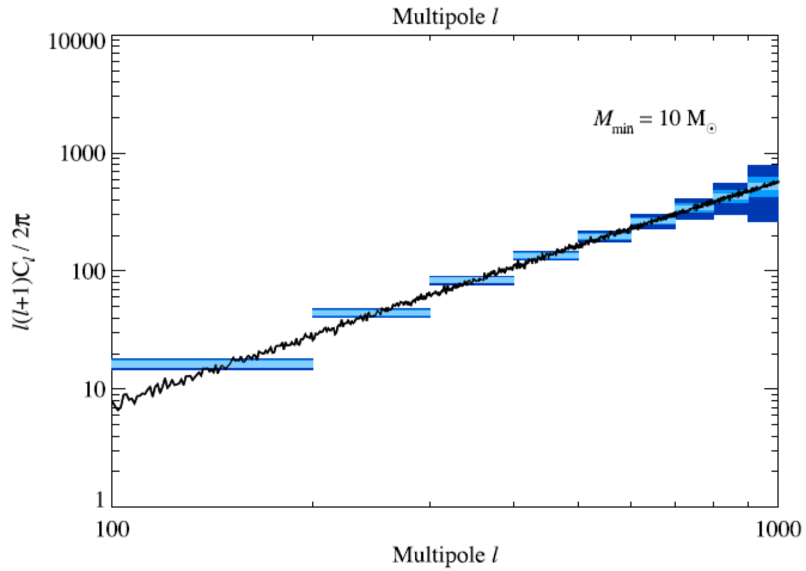
Anisotropies: The Galactic Case

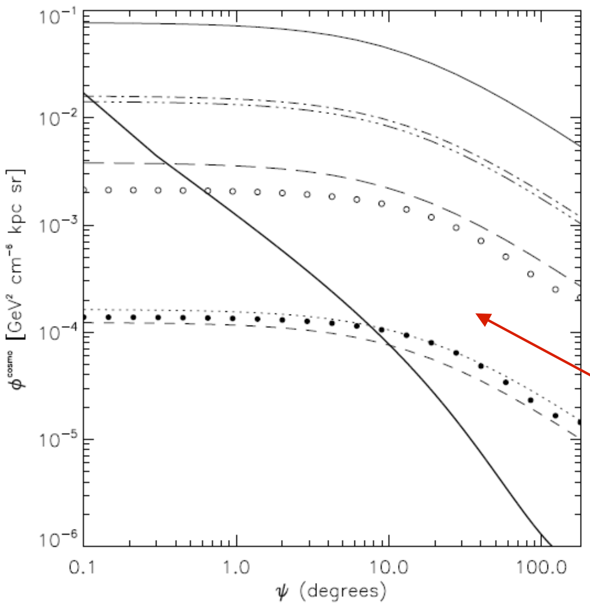


J. Siegal-Gaskins, JCAP 0810:040,2008.

M.Fornasa, L.Pieri, G.Bertone, E.Branchini, Phys.Rev.D80:023518,2009.

L.Pieri, G.Bertone, E.Branchini, Mon.Not.Roy.Astron.Soc.384:1627,2008.





But… huge uncertainties in the normalization of the signal: sub-halo concentration? Minimum sub-halo mass?

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 with three complementary techniques

- Standard analysis: the intensity maps are calculated with exposure derived from the Fermi tools

- Event-shuffling analysis: the exposure map is calculated directly from the data. Provides a cross-check to ensure that the result is not biased by inaccuracies in the exposure calculation which could introduce spurious anisotropy signals:

  - 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

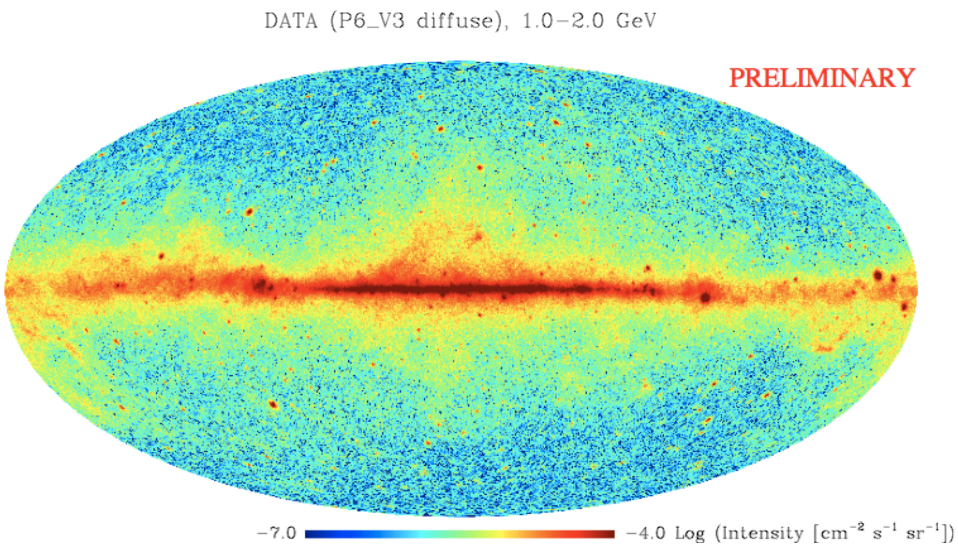
  - shuffled data map is directly proportional to the exposure map, with arbitrary normalization (hence only fluctuation angular power spectra can be calculated)

- Foreground cleaning analysis: a model of the galactic foregrounds is subtracted from the intensity maps before calculating the APS. Provides a cross-check to estimate the residual level of foreground contamination in the APS.

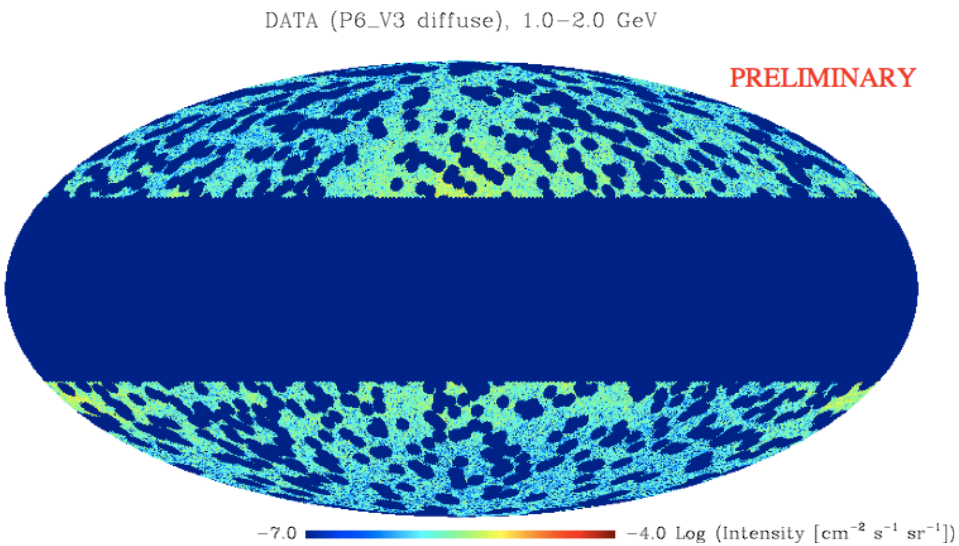
Intensity maps of the data

1-2 GeV

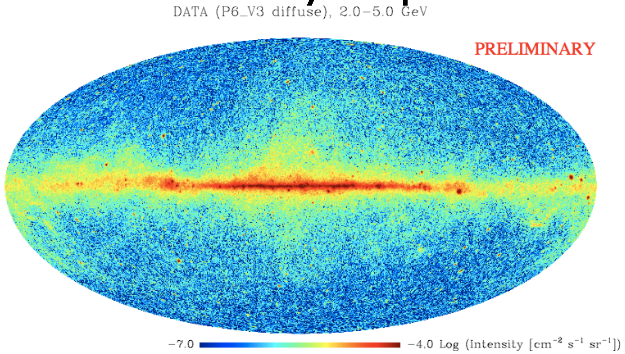
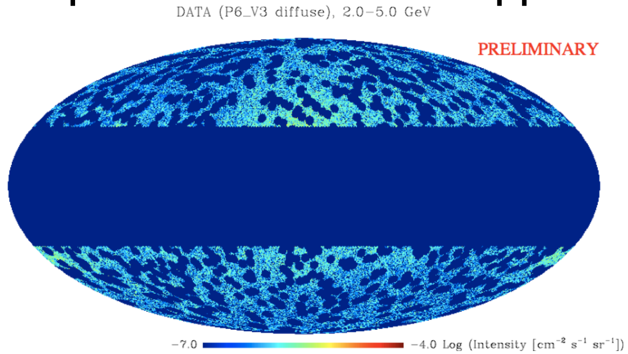
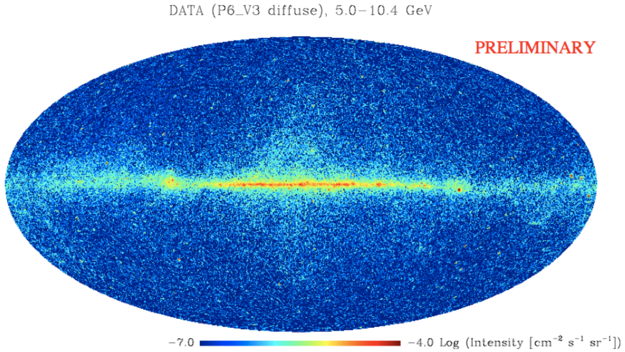
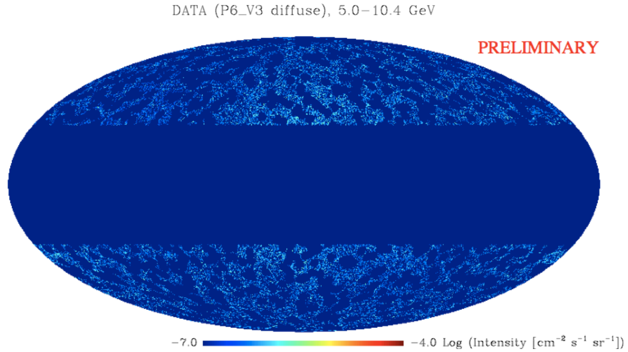
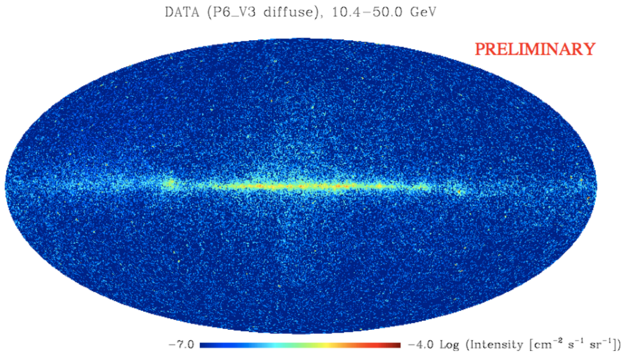
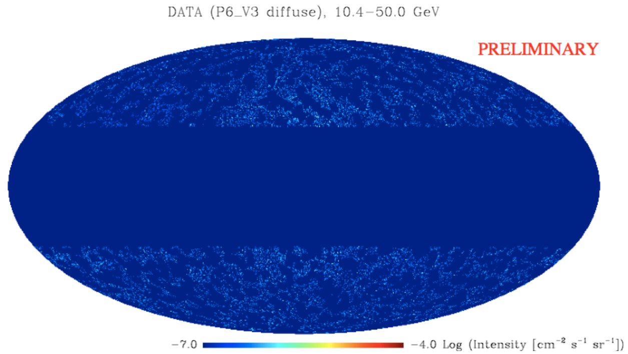
All-sky map



Map with default mask applied



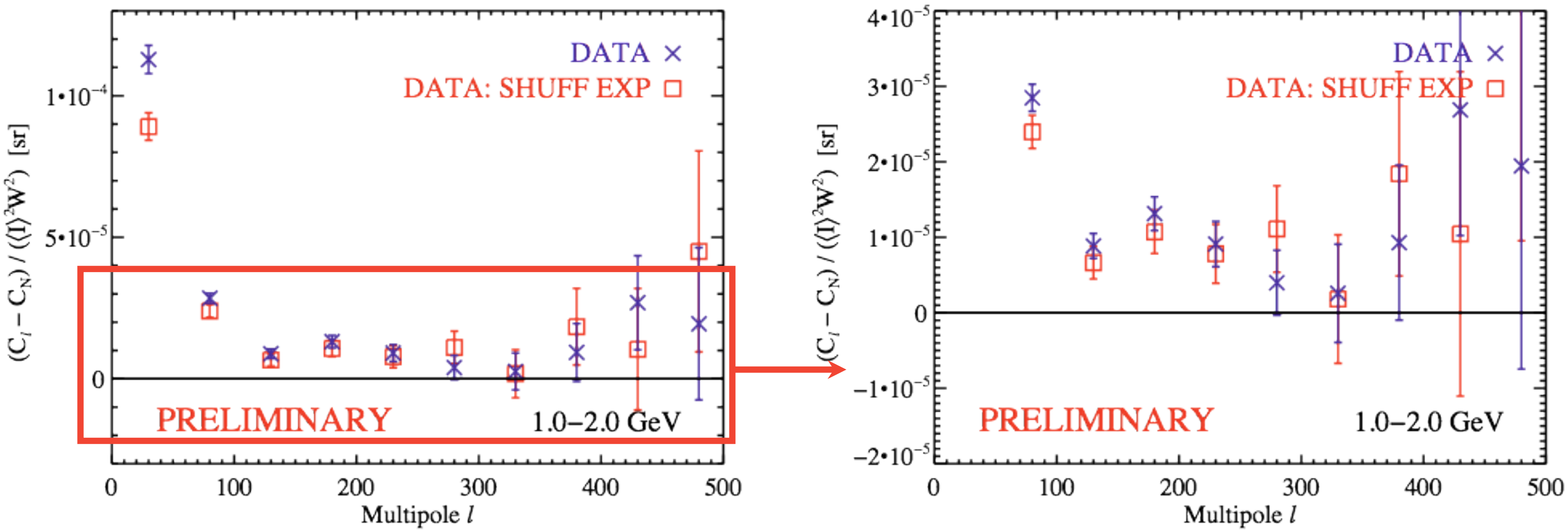
Intensity maps of the data

	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

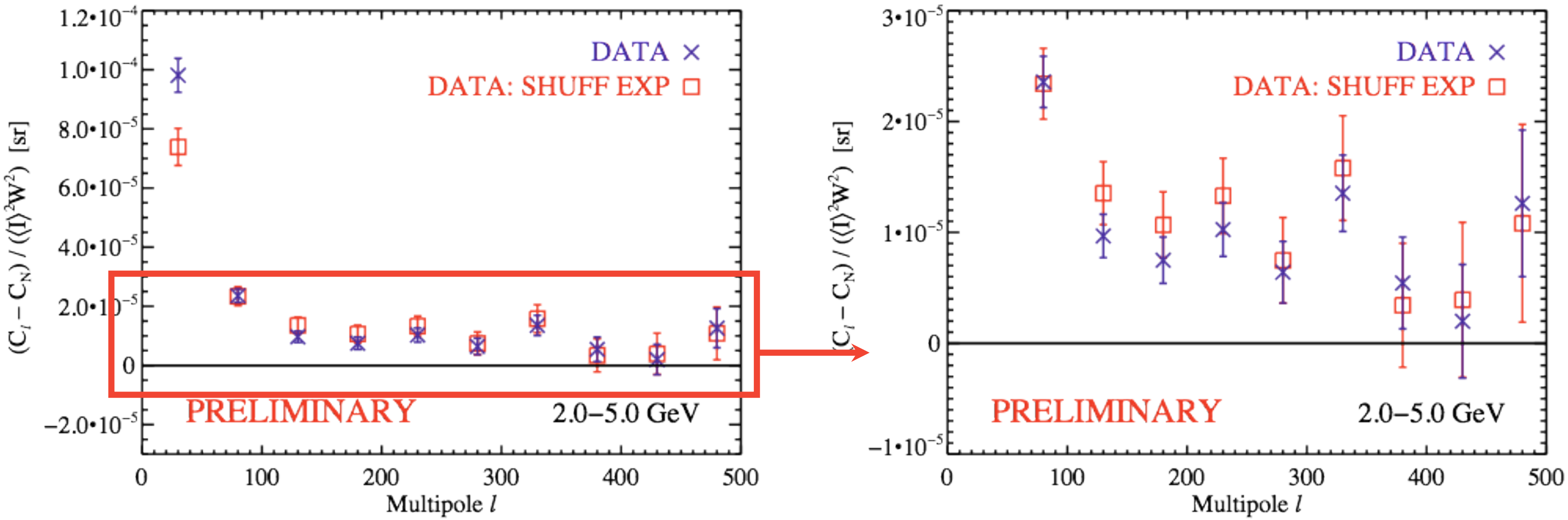


- good agreement between default analysis and analysis with exposure map from shuffling
- at low multipoles excess angular power likely due to contamination by Galactic diffuse emission; angular power is robustly detected at multipoles above l ~ 150

Angular power spectra of the data

fluctuation angular power spectra

2 - 5 GeV



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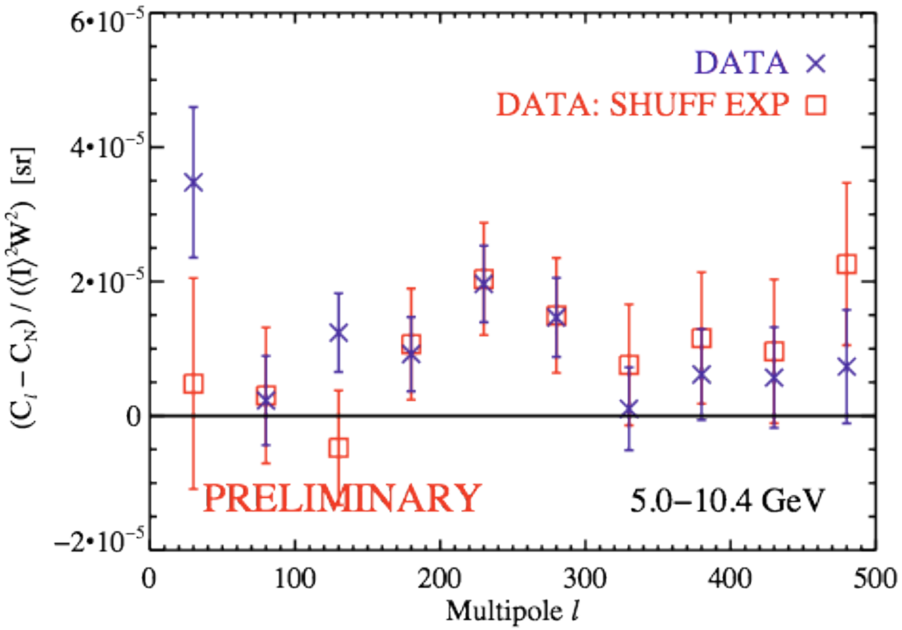
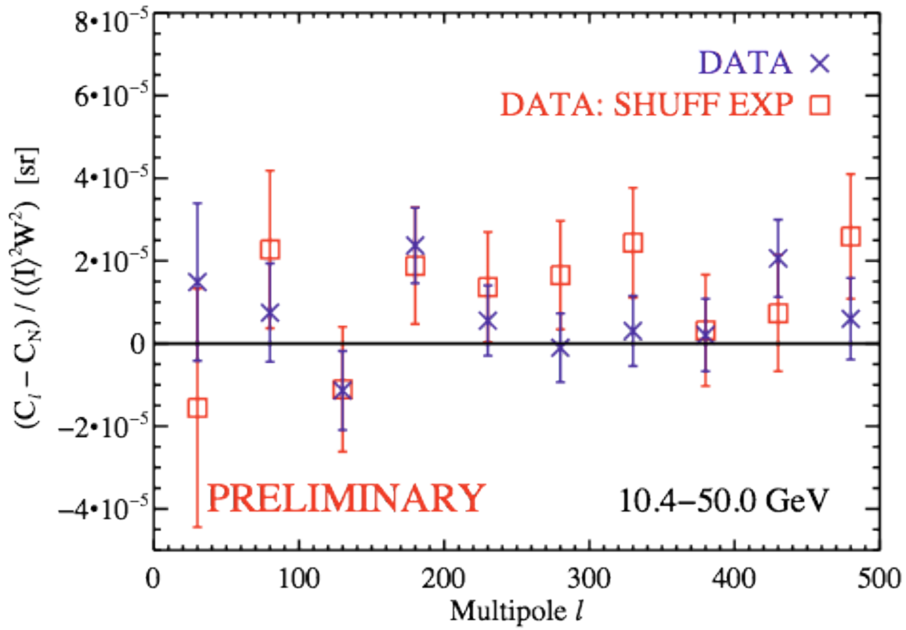
Angular power spectra of the data

fluctuation angular power spectra

5 - 10 GeV



10 - 50 GeV

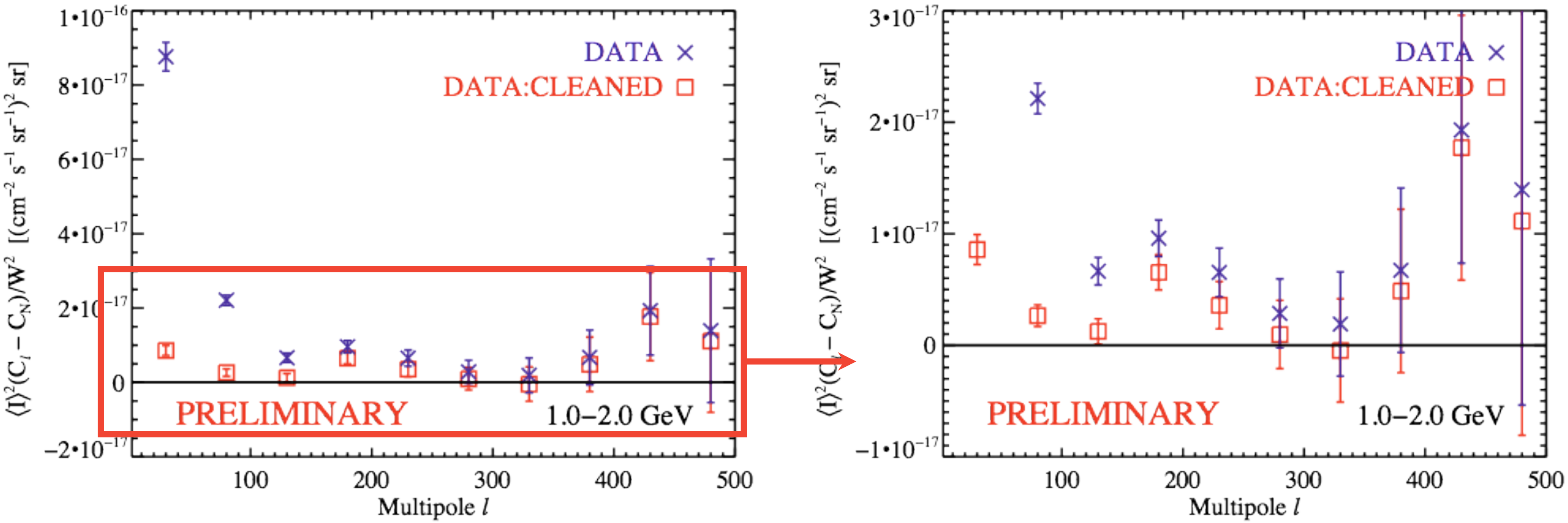


- good agreement between default analysis and analysis with exposure map from shuffling
- at 5-10 GeV angular power is robustly detected at multipoles above l ~ 150
- at 10-50 GeV, angular power is detected at lower significance at multipoles above l ~ 150

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	χ^2/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

$C_{\rm P}/\langle I\rangle^2$ $[10^{-6}$ 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):

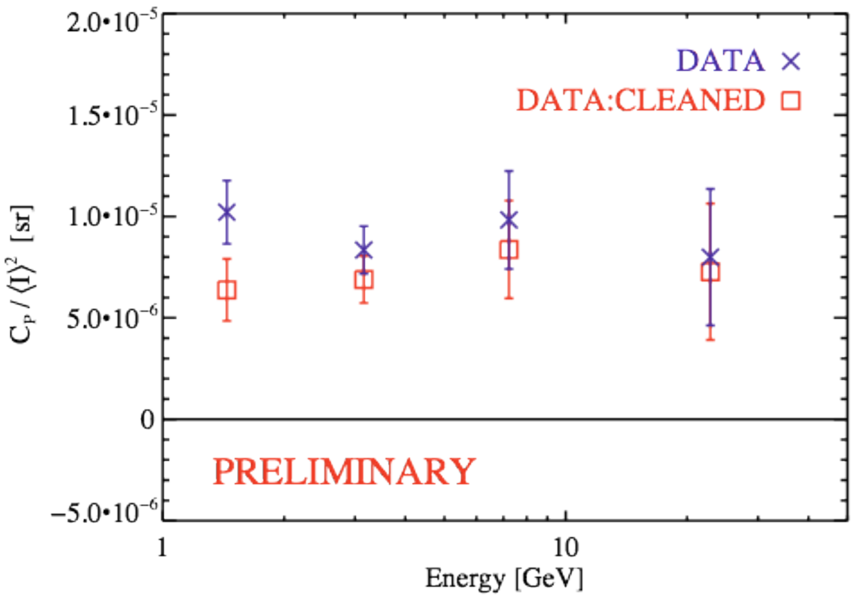
- blazars: ~ 1e-4
- starforming galaxies: ~ 1e-7
- dark matter: ~ 1e-4 to ~ 0.1
- MSPs: ~ 1e-2

- 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

Energy dependence of anisotropy

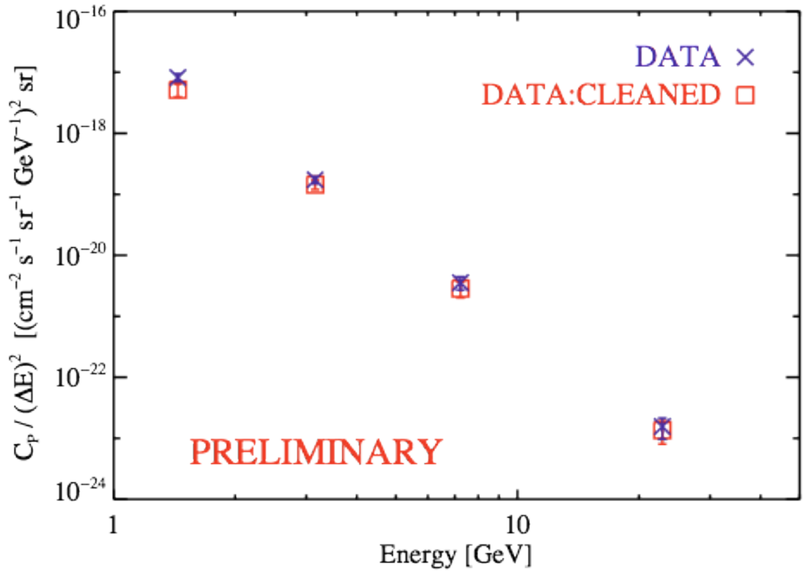
Fluctuation anisotropy energy spectrum

- 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



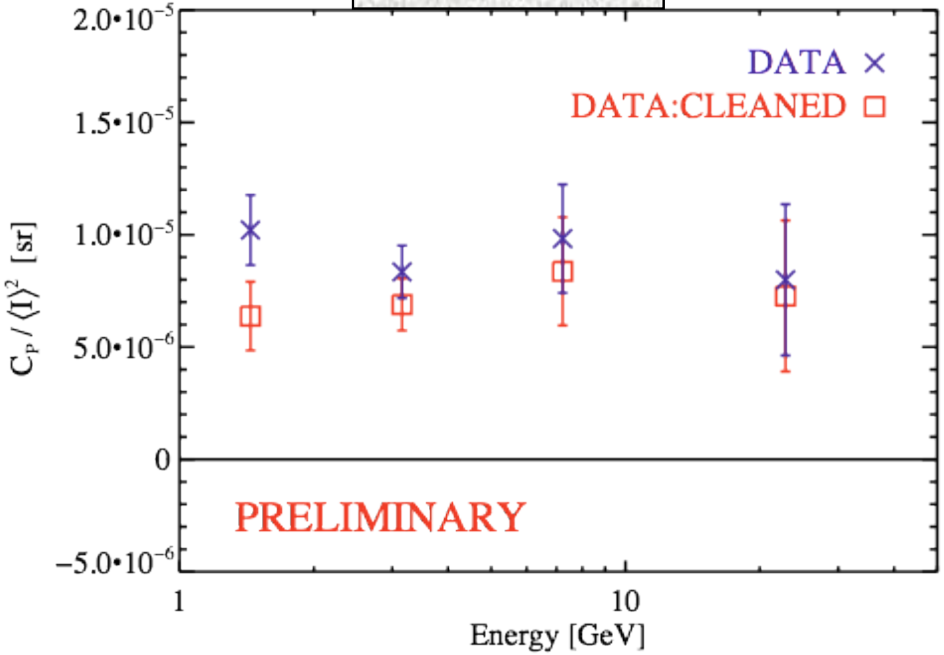
Intensity anisotropy energy spectrum

- 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

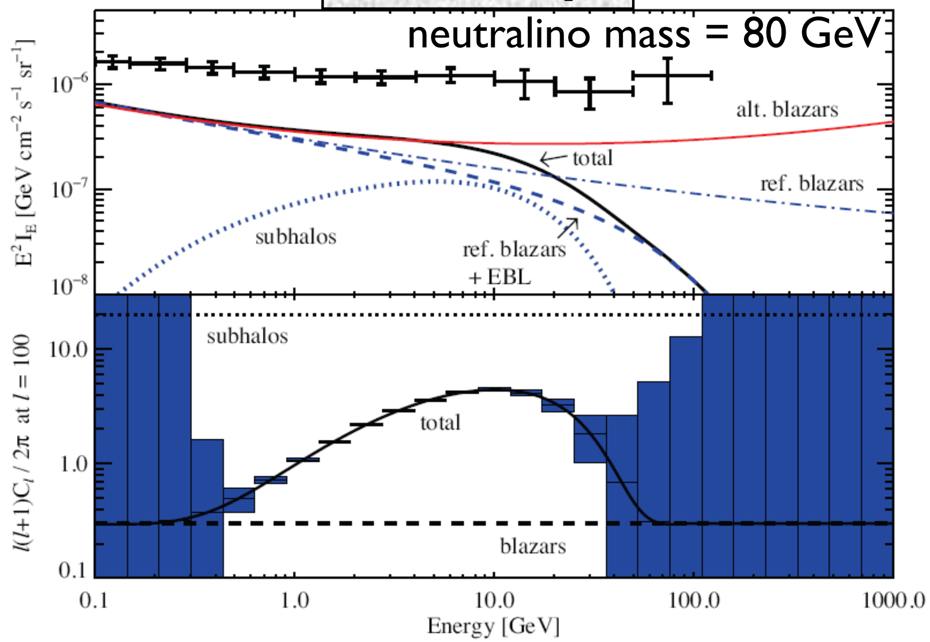


Data vs Theory

Data



Theory



J. Siegal-Gaskins, V. Pavlidou, Phys.Rev.Lett. 102:241301,2009.

- No bump yet in the data…
- More statistics is needed to improve on the error bars and to increase the number of bins in energy. This will be provided by Fermi in the next few years.

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

Summary

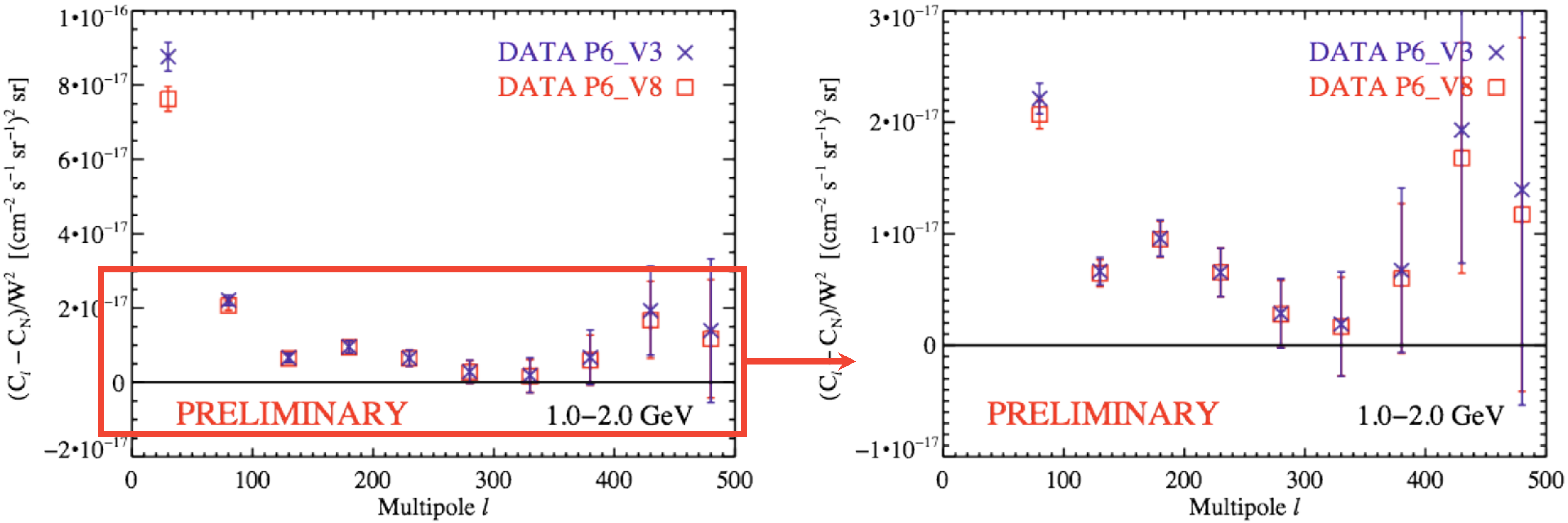
- at multipoles $155 \leq l \leq 504$, angular power is robustly measured in the data at energies from 1 to 10 GeV; lower significance angular power is detected in the 10-50 GeV energy bin
  - scale independence of the power at these multipoles suggests a contribution to the IGRB from one or more unclustered 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

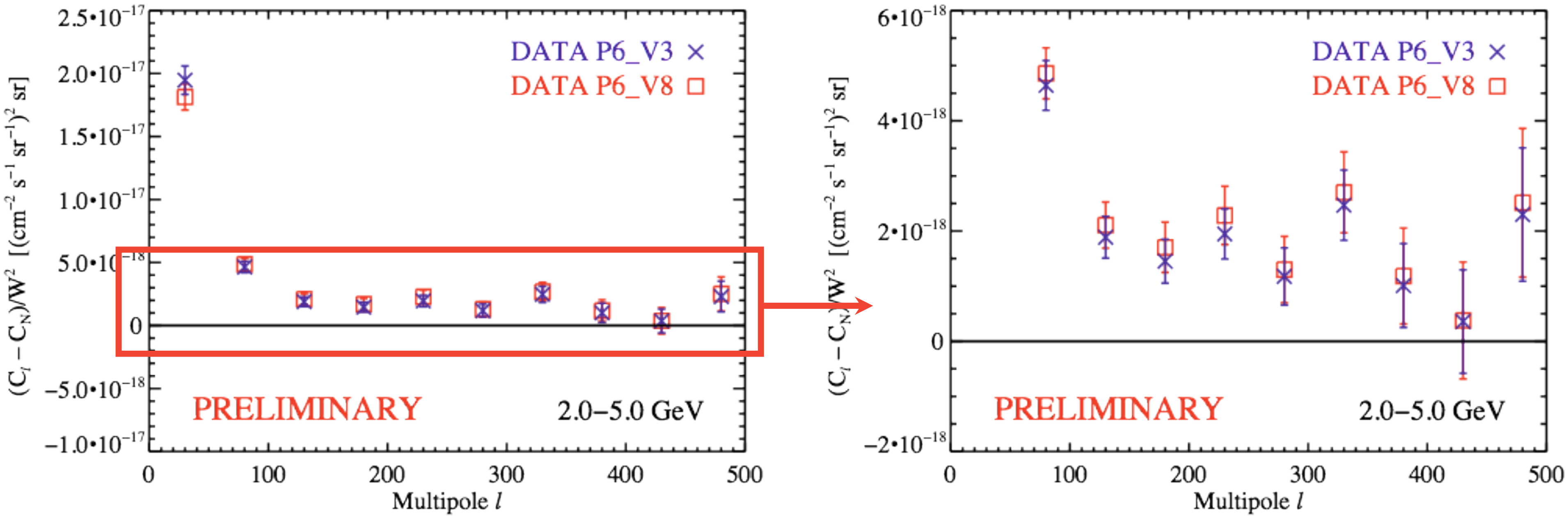


- excellent agreement of angular power spectra of data processed with these two IRFs indicates that the results are not sensitive to the differences in the PSF models implemented in these IRFs

Dependence on IRFs

intensity angular power spectra

2 - 5 GeV



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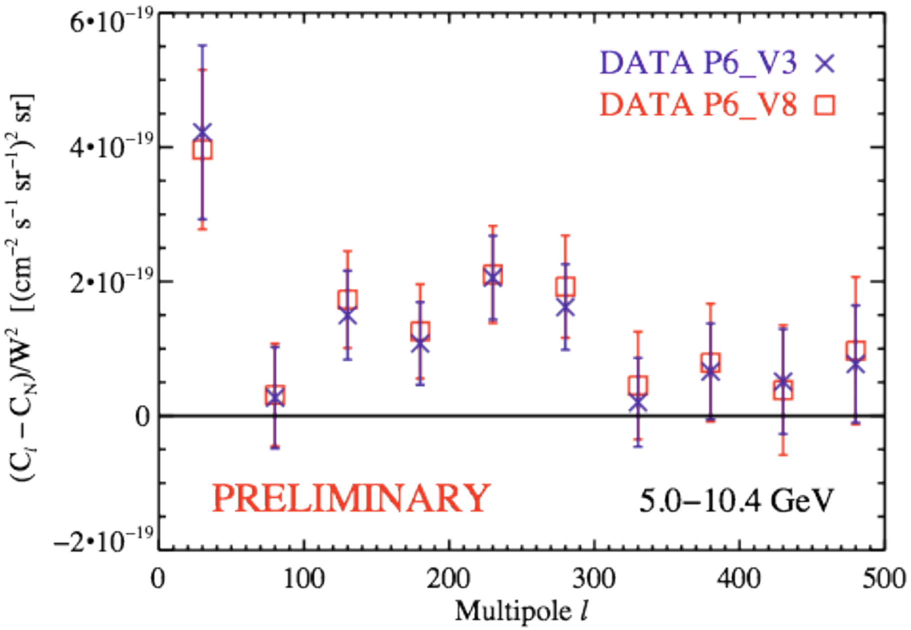
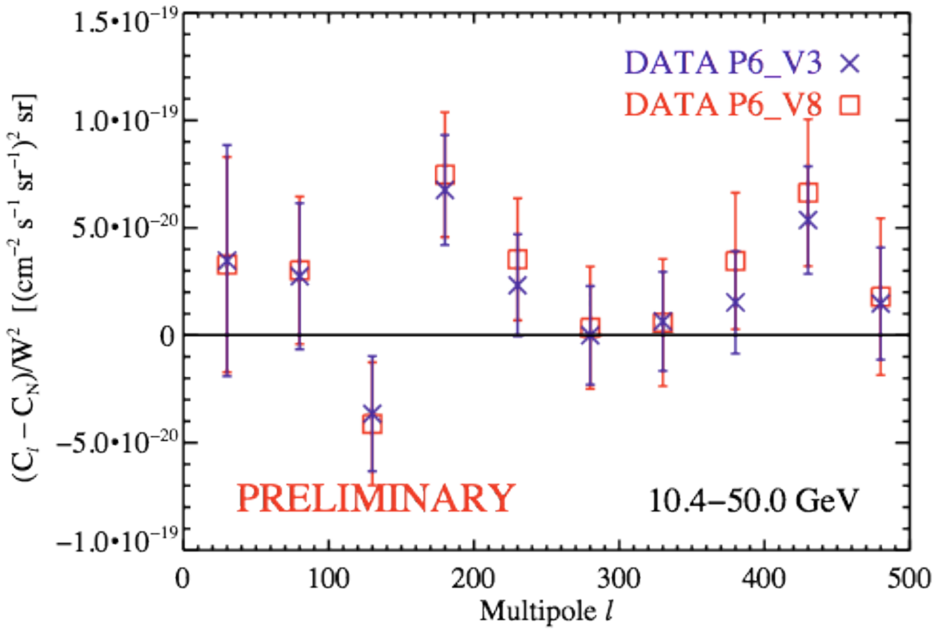
Dependence on IRFs

intensity angular power spectra

5 - 10 GeV



10 - 50 GeV

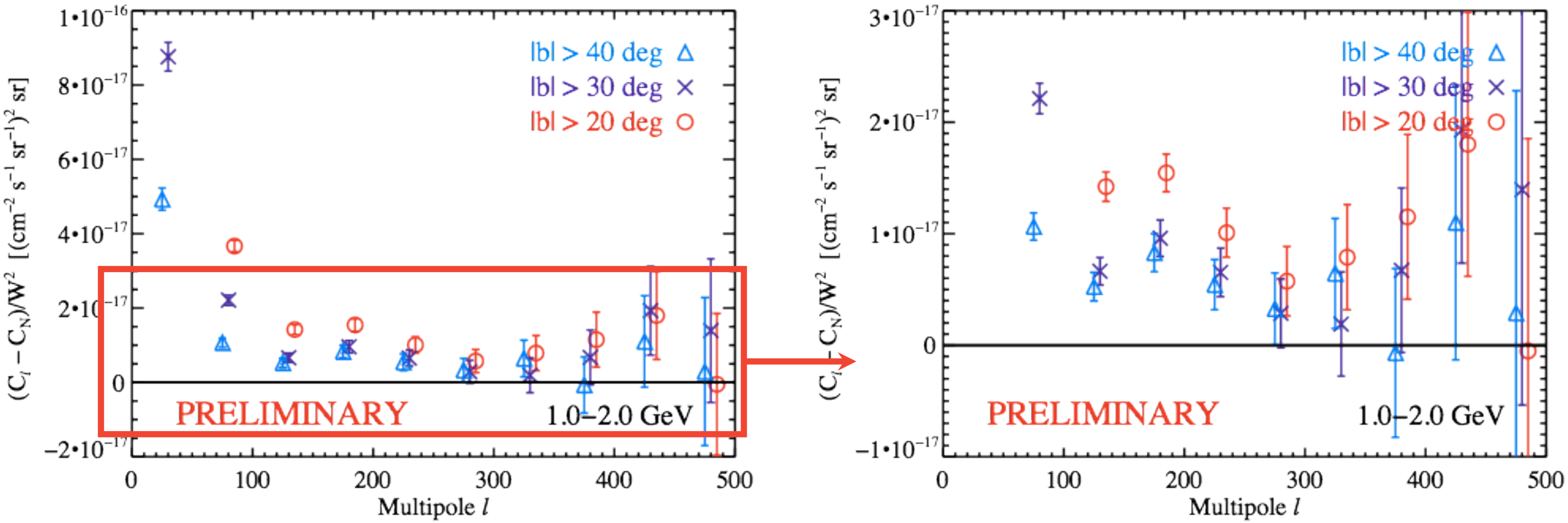


- excellent agreement of angular power spectra of data processed with these two IRFs indicates that the results are not sensitive to the differences in the PSF models implemented in these IRFs

Dependence on latitude mask

intensity angular power spectra

1 - 2 GeV

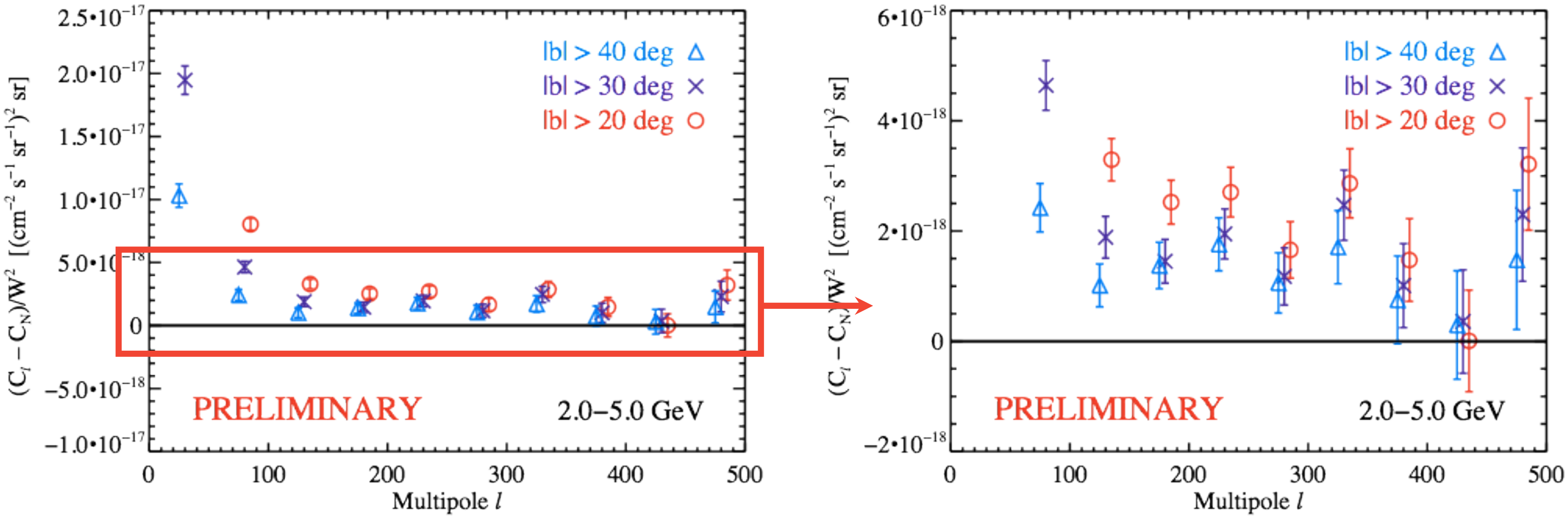


- differences in results masking |b| < 30 deg and |b| < 40 deg are small for multipoles l ≥ 155, demonstrating that detected angular power is not strongly correlated with a component with a significant latitude dependence, such as Galactic diffuse emission

Dependence on latitude mask

intensity angular power spectra

2 - 5 GeV



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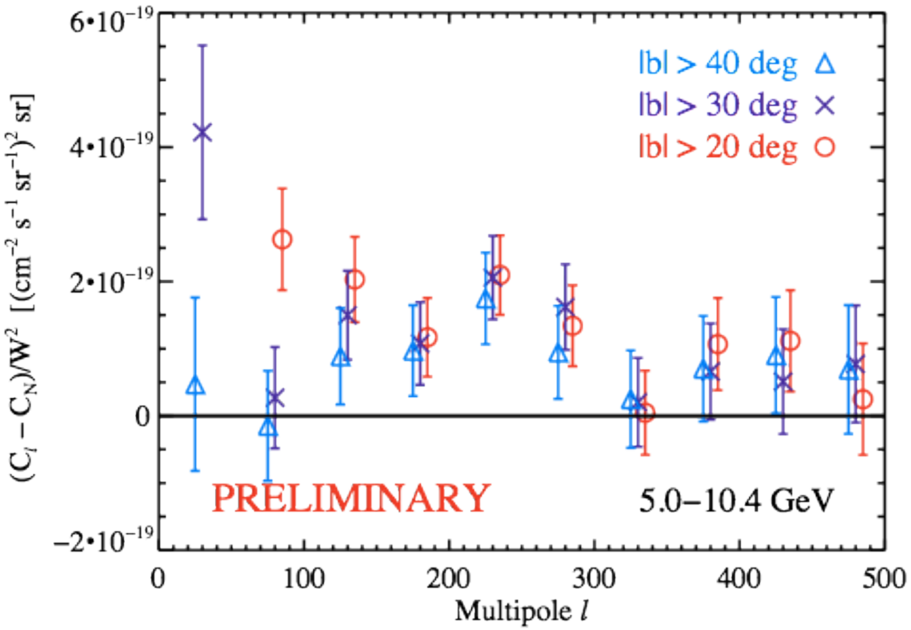
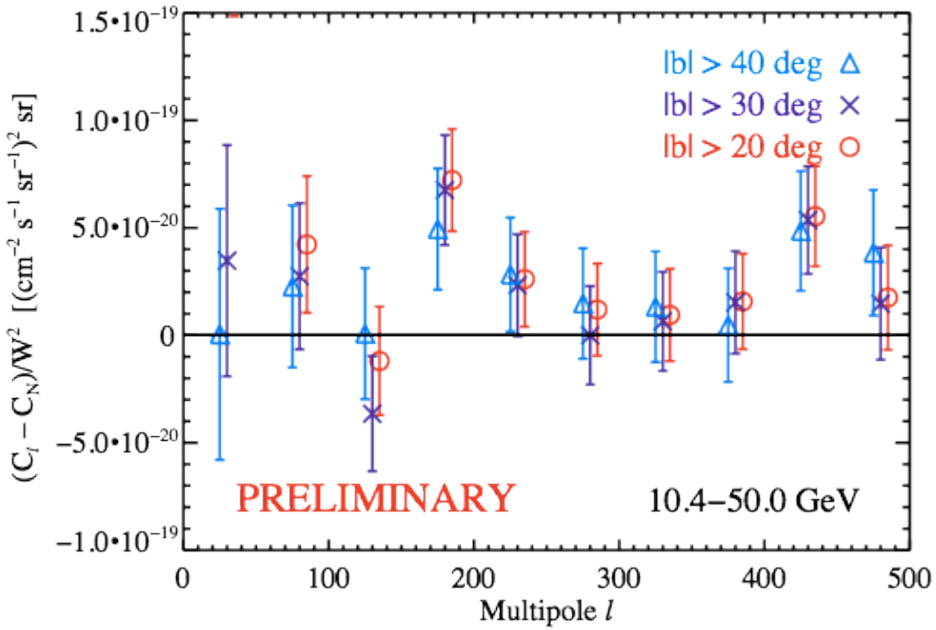
Dependence on latitude mask

intensity angular power spectra

5 - 10 GeV



10 - 50 GeV

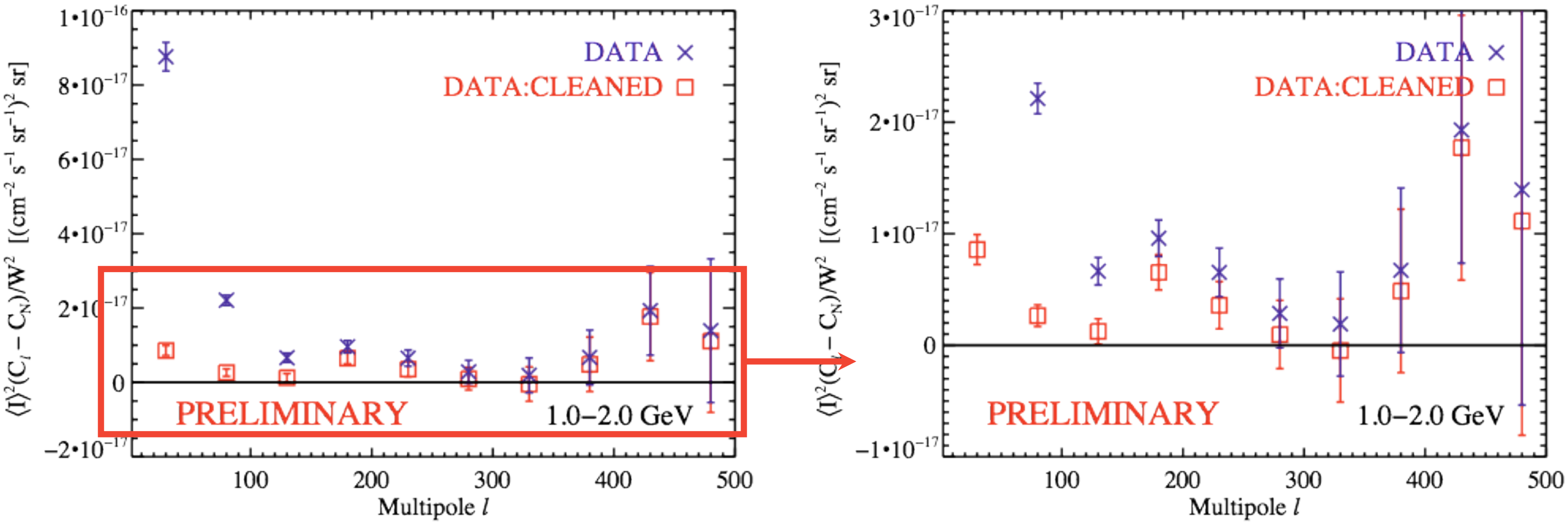


- above 10 GeV convergence at multipoles $l \geq 155$ is seen masking only $|b| < 20$ deg

Foreground cleaning

intensity angular power spectra

1 - 2 GeV

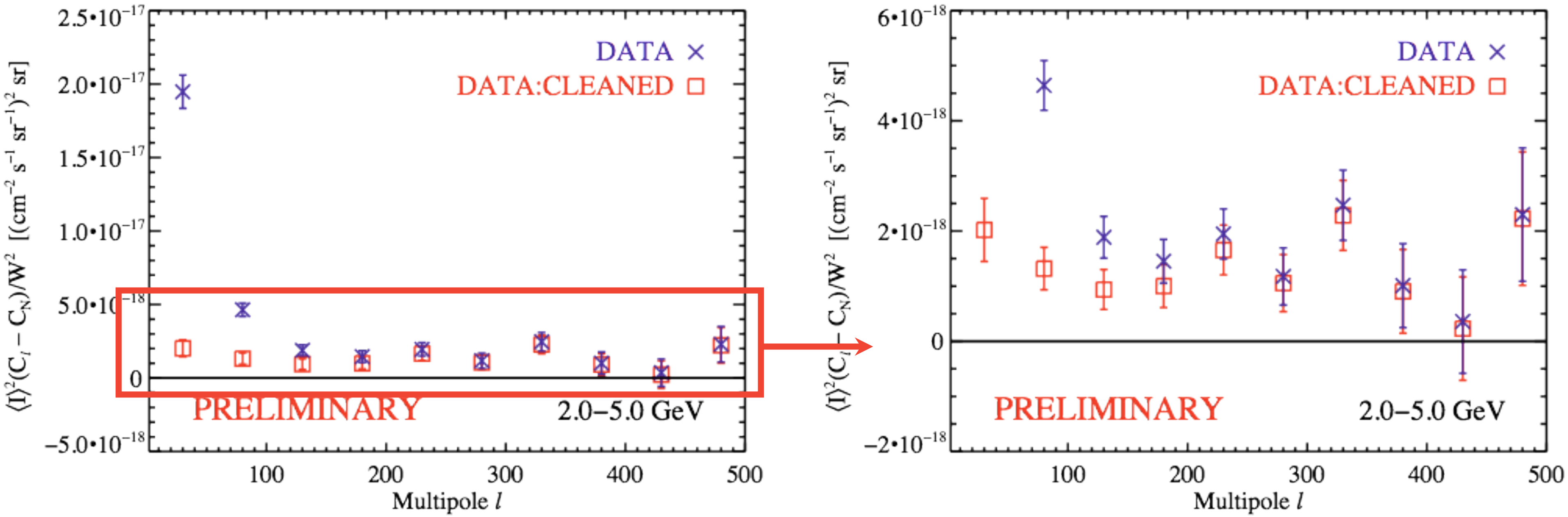


- foreground cleaning primarily reduces angular power at l < 155, with the most significant reductions at l < 105
- indicates that contamination of detected angular power at high multipoles by Galactic foregrounds is small

Foreground cleaning

intensity angular power spectra

2 - 5 GeV



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Foreground cleaning

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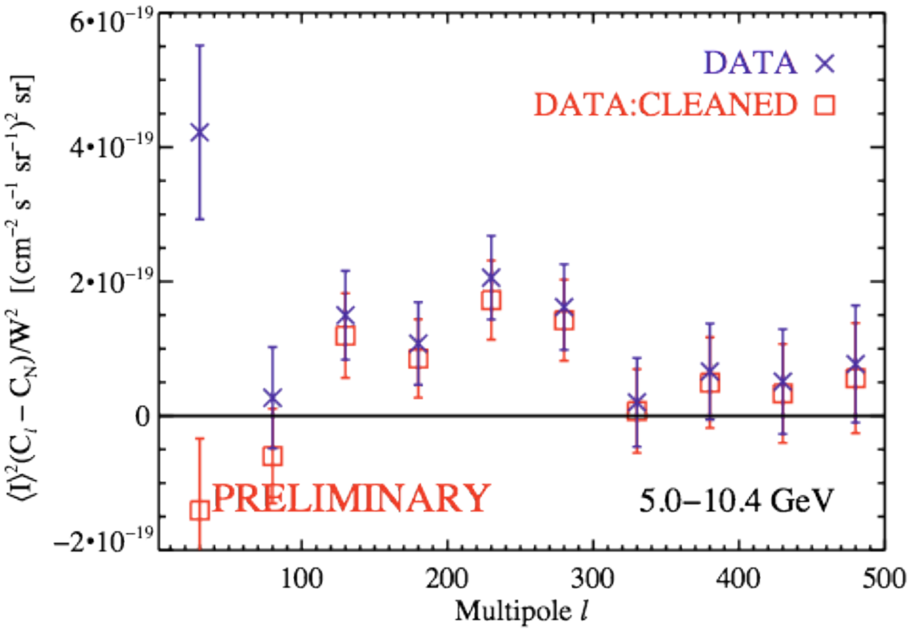
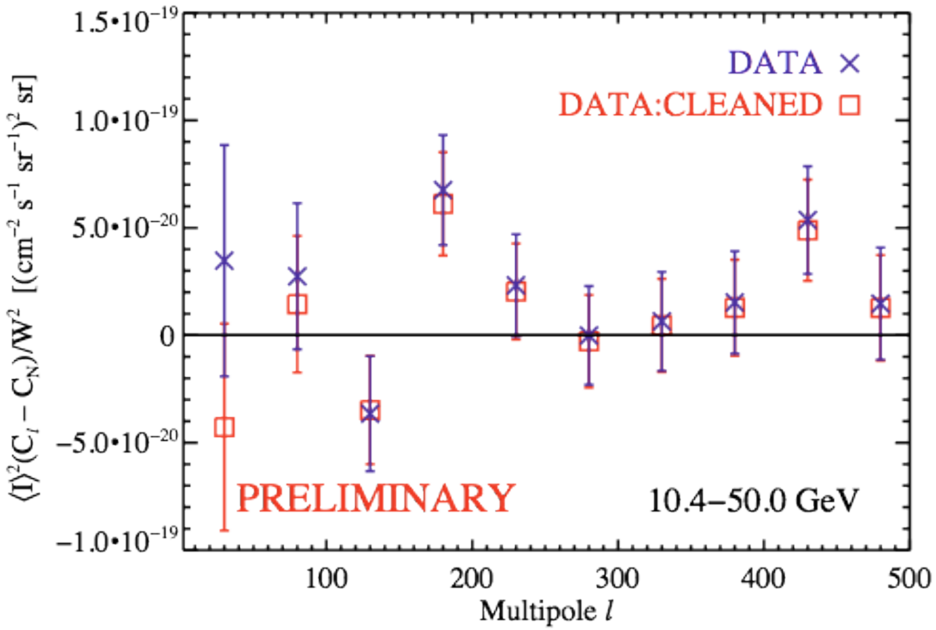


10 - 50 GeV



- the effect of foreground cleaning is small for $l \geq 55$
- 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

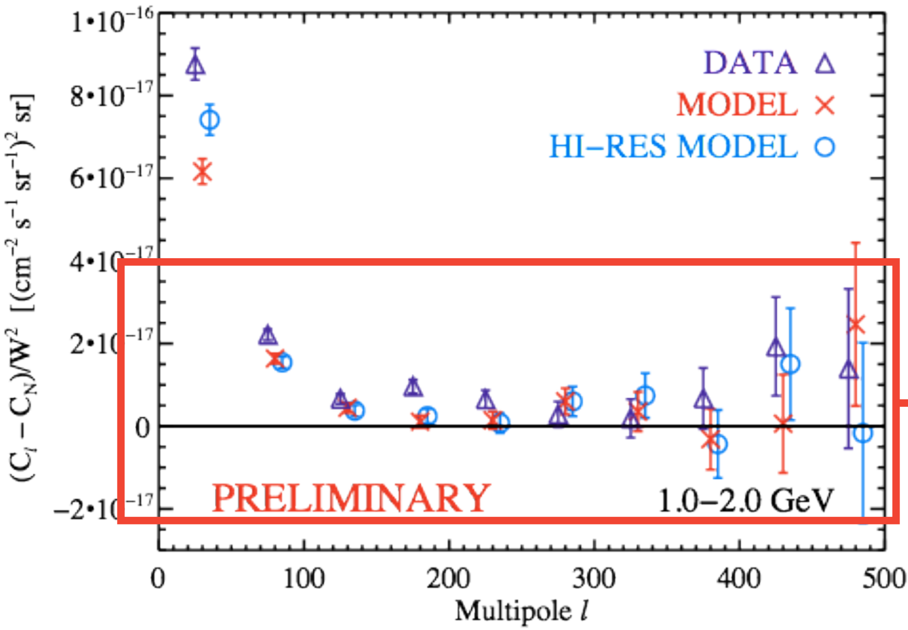
HI-RES MODEL = sum of GAL:HI-RES, CAT, and ISO

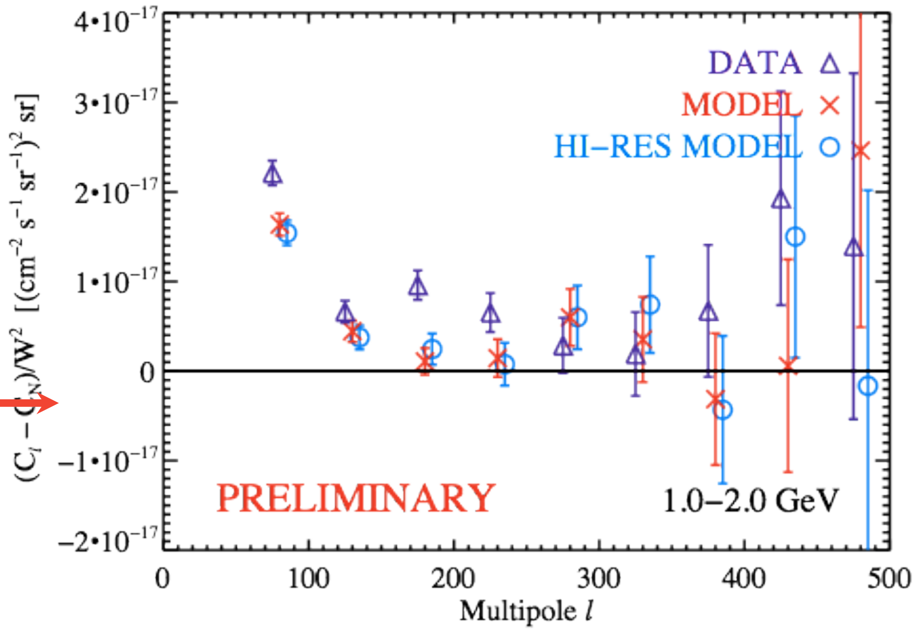
- GAL:
  - DEFAULT: standard recommended Galactic diffuse model (gll_iem_v02.fit)
  - HI-RES: updated Galactic diffuse model using higher-resolution CO maps (ring_21month_v1.fit)
- CAT: 11-month source catalog
- ISO: isotropic background = Fermi-measured large-scale isotropic diffuse + unrejected charged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

Comparison with simulated models

intensity angular power spectra

1 - 2 GeV



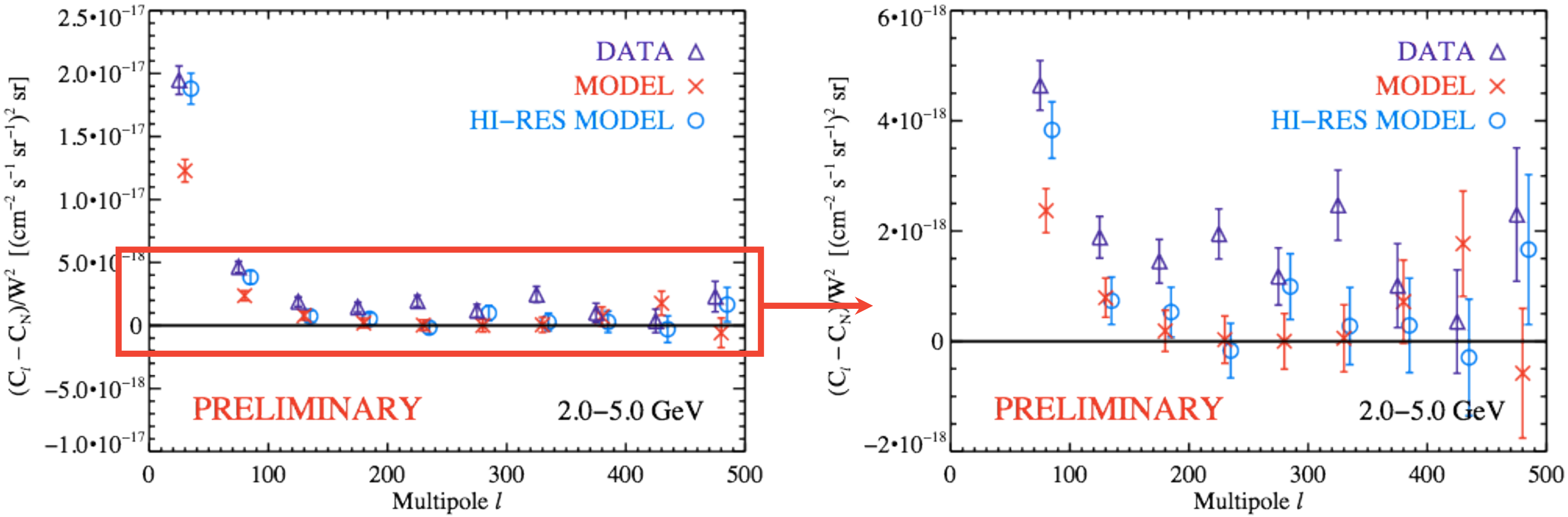


- smaller amplitude angular power detected at low significance in both models at $l \geq 155$ is inconsistent with the excess observed in the data
- angular power spectra of the two models are in good agreement

Comparison with simulated models

intensity angular power spectra

2 - 5 GeV

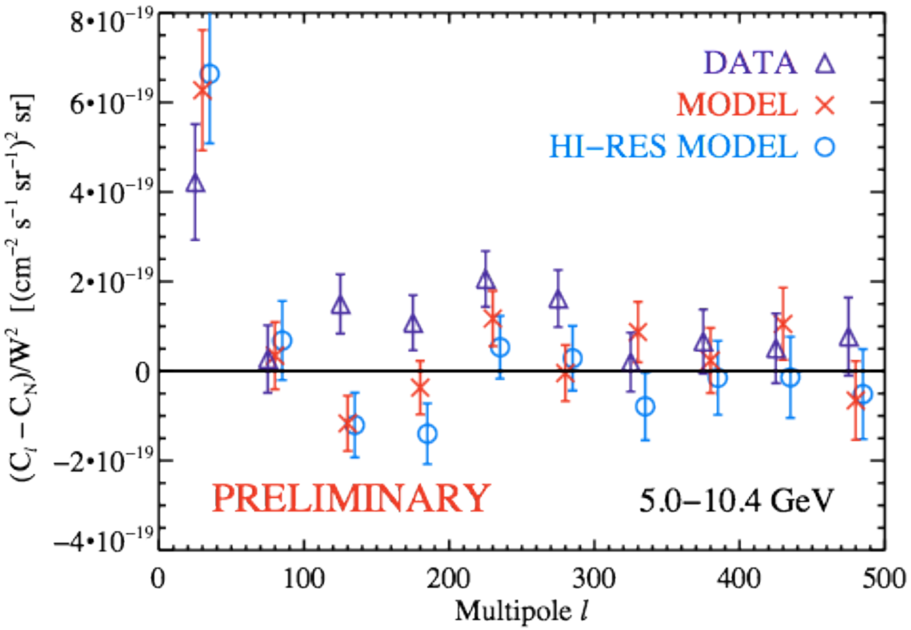


- no significant angular power detected in either model at $l \geq 155$
- angular power spectra of the two models are in good agreement

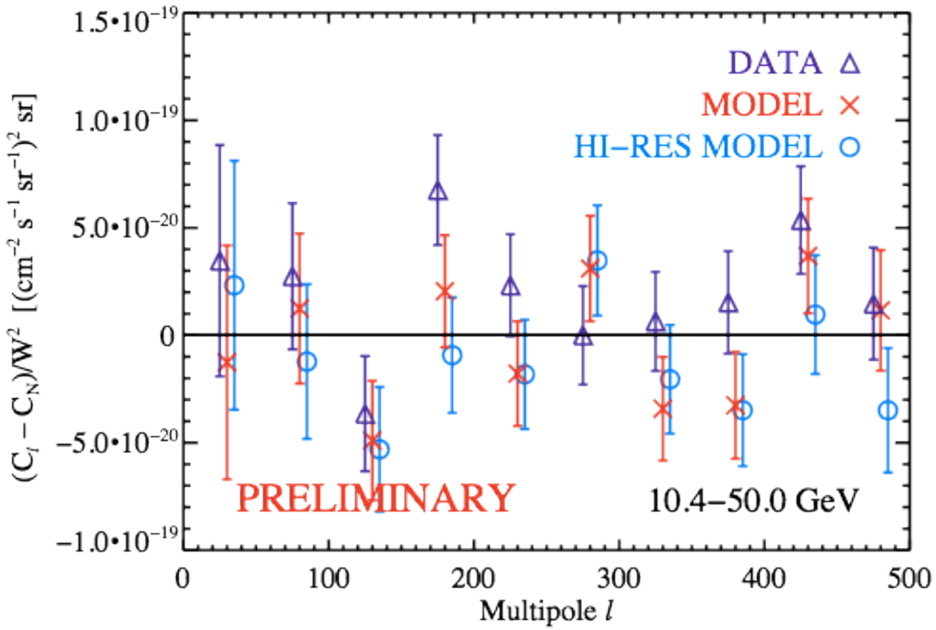
Comparison with simulated models

intensity angular power spectra

5 - 10 GeV



10 - 50 GeV

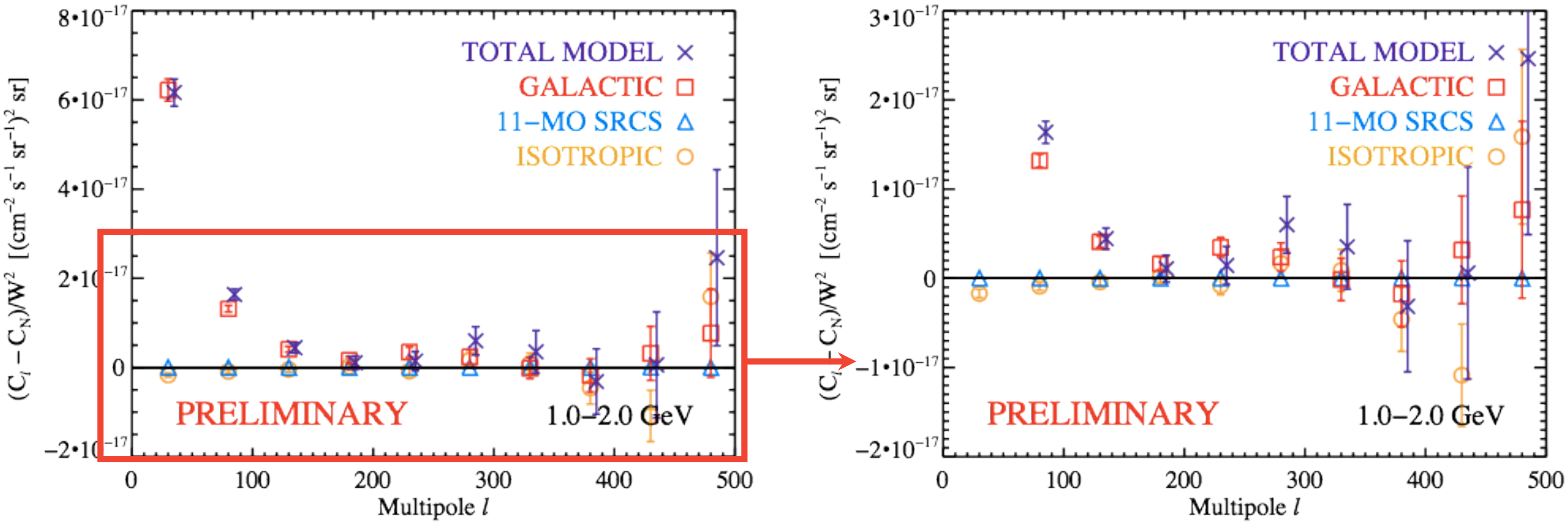


- no significant angular power detected in either model at $l \geq 155$
- angular power spectra of the two models are in good agreement

Simulated model components

intensity angular power spectra

1 - 2 GeV



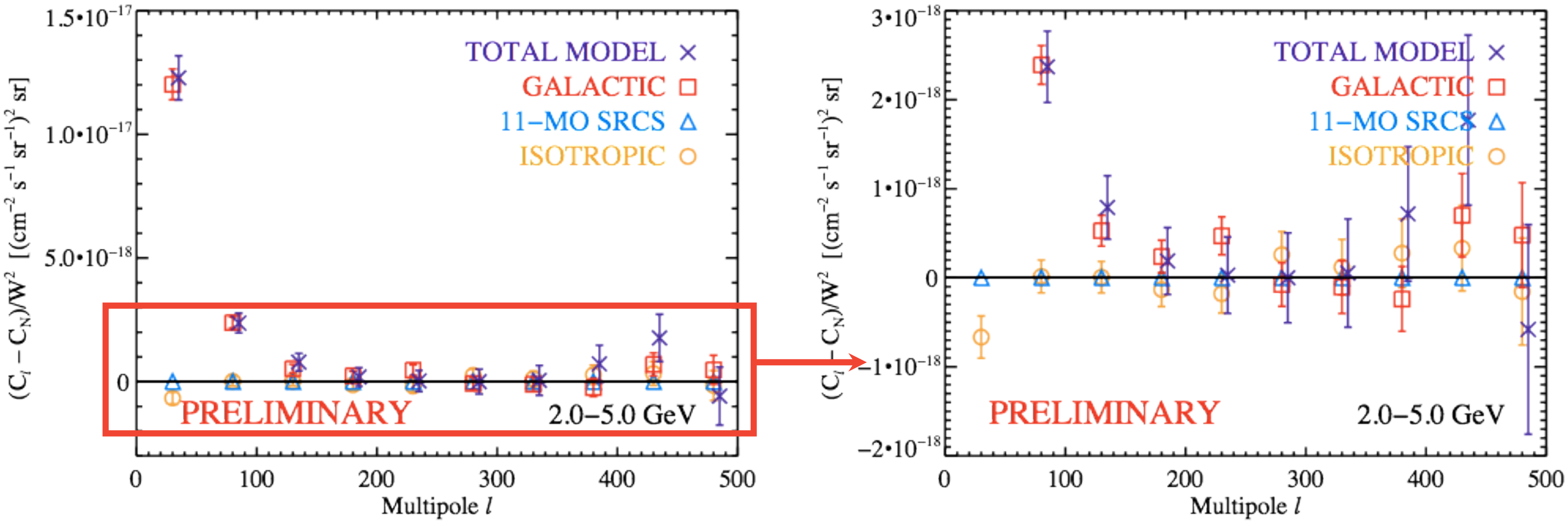
- as expected, most of the total angular power at all multipoles (TOTAL MODEL) is due to the GAL component

- 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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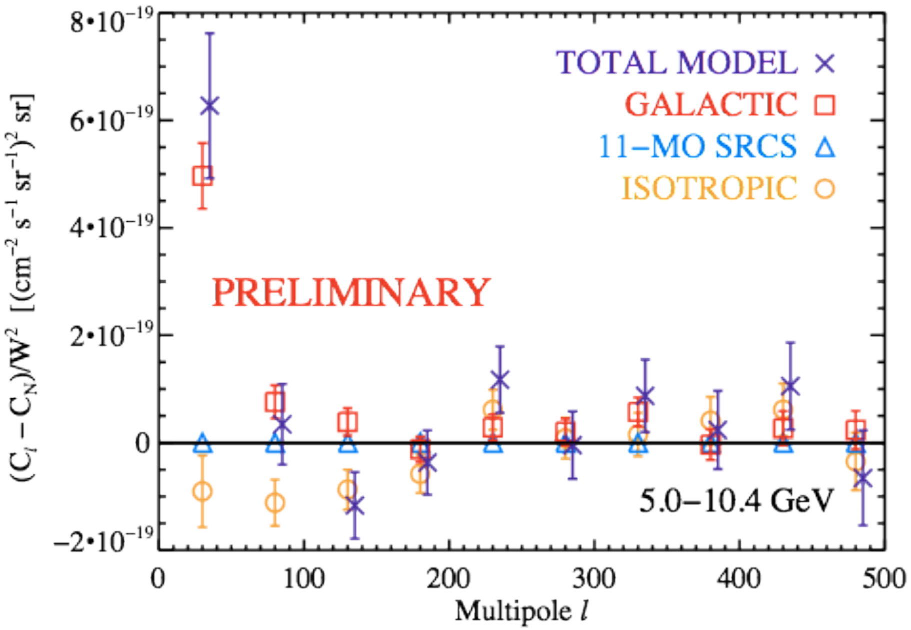
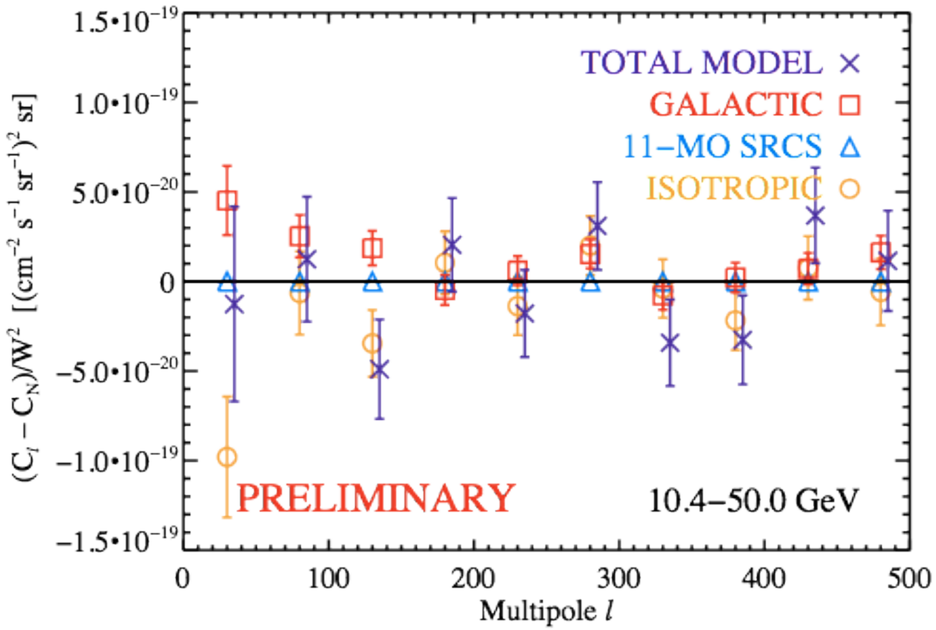
Simulated model components

intensity angular power spectra

5 - 10 GeV



10 - 50 GeV



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- by construction, ISO contributes no significant angular power; CAT provides no contribution because all sources were masked