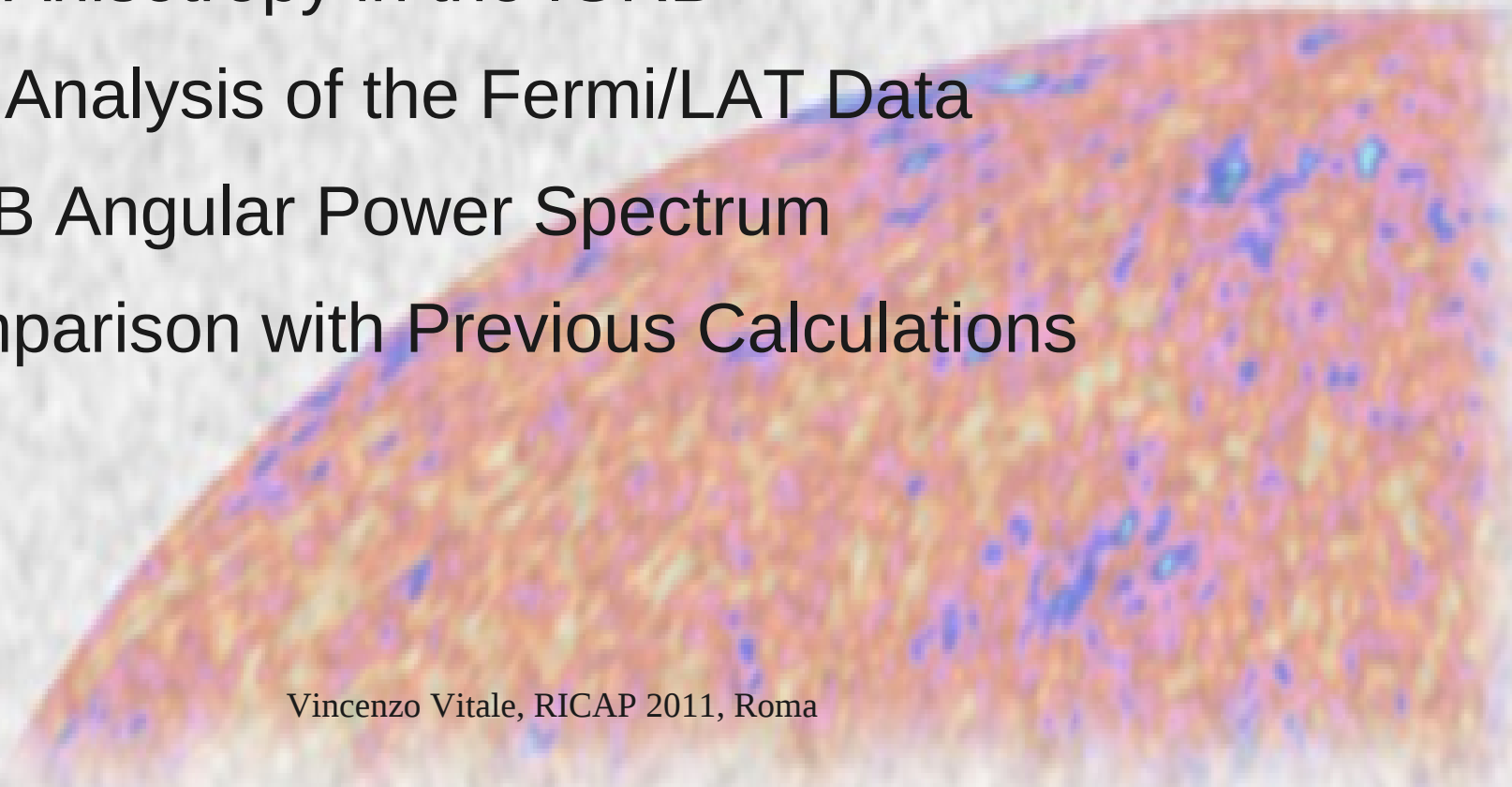
Anisotropies in the Diffuse Gamma-Ray Background measured by Fermi-LAT

V.Vitale

A. Cuoco, T. Linden, M.N. Mazziotta, J. Siegal-Gaskins* on behalf of the Fermi LAT Collaboration
and
E. Komatsu

Outline

- Detection of un-resolved sources populations
- Measurement of the large scale Isotropic Gamma-Ray Background (IGRB)
- The Anisotropy in the IGRB
- The Analysis of the Fermi/LAT Data
- IGRB Angular Power Spectrum
- Comparison with Previous Calculations



Sources Populations and Anisotropies

- A diffuse background can be built by the sum of a large number of un-resolved faint sources
- Fluctuations on small angular scales are different for un-resolved source populations and a truly isotropic emission

Angular Power Spectrum (APS)

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

L.Knox
1995PhRvD..52.4307K

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

$$\delta C_\ell^{\rm s} = \sqrt{\frac{2}{(2\ell+1)\,\Delta\ell\, f_{\rm sky}}} \left(C_\ell^{\rm s} + \frac{C_{\rm N}}{W_\ell^2} \right)$$

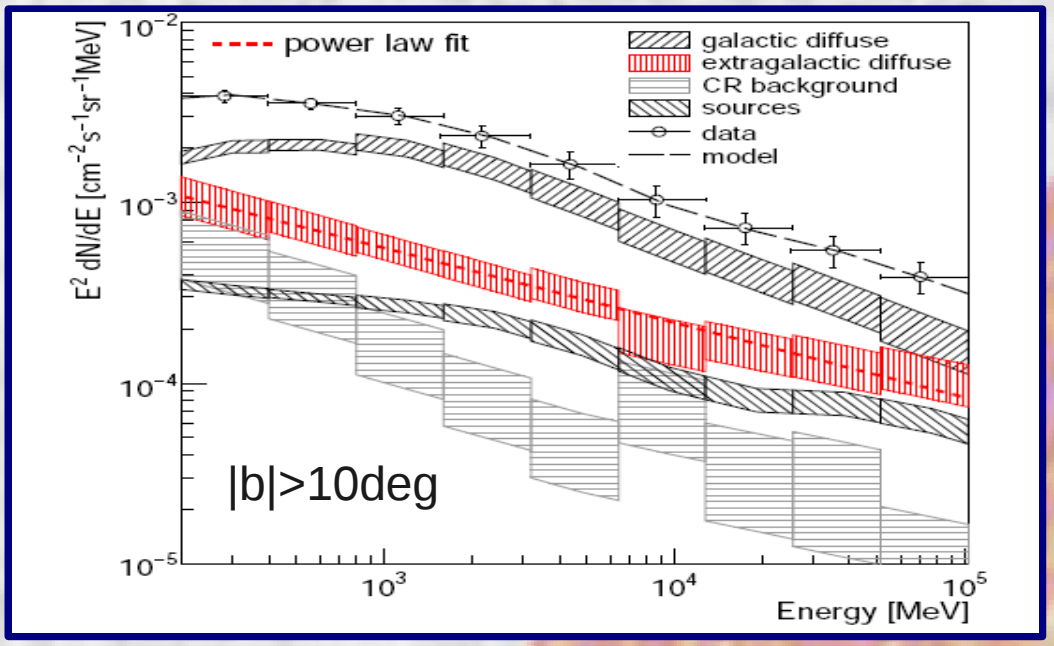
- Diffuse emission fluctuations are studied with spher. harmonics expansions
- **C_l = intensity APS** : indicates dimensionful amplitude of anisotropy
- **C_l / < I >^{2} = fluctuation APS**: dimensionless, independent of intensity

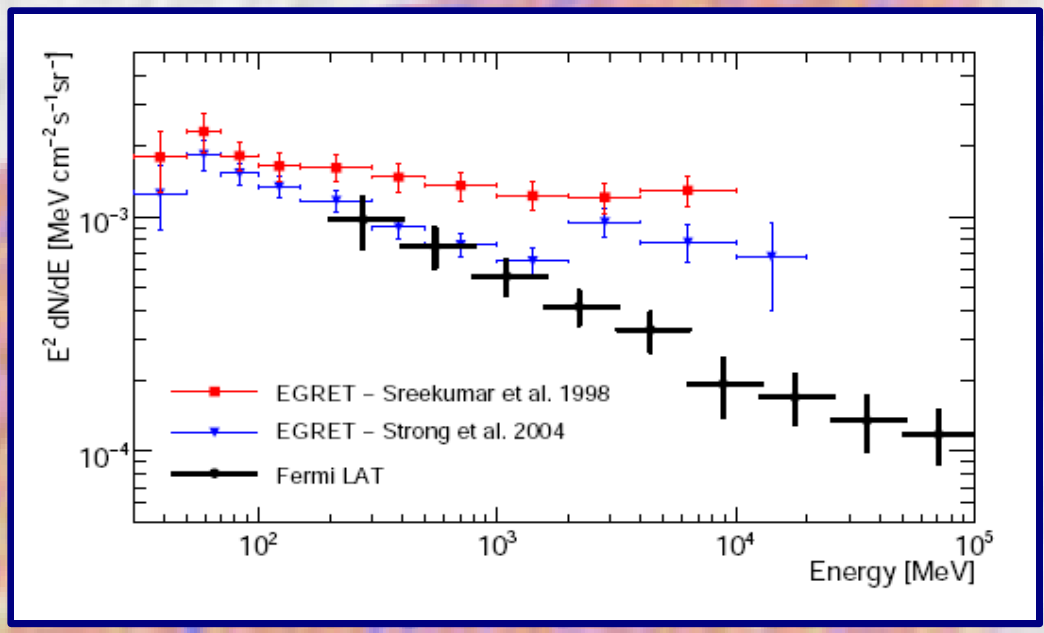
normalization, with **f_{sky}** = un-masked fraction of the sky, **W_l**=window function; **Δl** =multipole bin, **C_n**= noise angular power;

- Fluctuations from source populations can be identified, if different from the Poisson noise ones;
- the energy-dependence of the anisotropy can reveal/constrain multiple populations

Measurement of the IGRB

- Galactic Diffuse Emission component
- Extra-Galactic Diffuse Emission component, with photon index -2.40+-0.05 and I(E>0.1GeV) = (1.03+-0.17)X 10^{-5} cm^{-2} s^{-1} sr^{-1}
- Residual Charged Cosmic Rays component
- Guaranteed contributions to IGRB: blazars, star forming galaxies, milli-second pulsars
- Possible contributions: Dark matter structures, etc



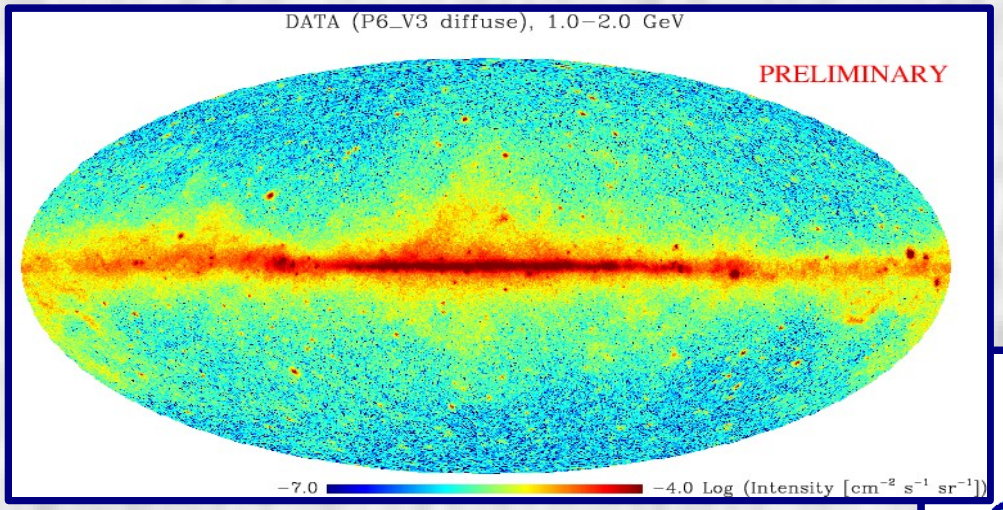


2010PhRvL.104j1101A

Studying Anisotropy in the IRGB

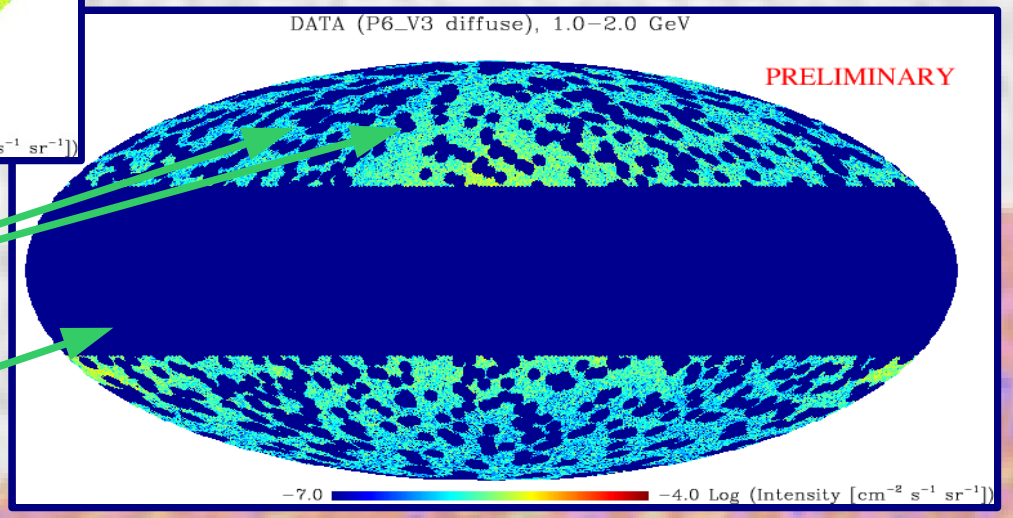
- **Fermi/LAT** all-sky observations from the first 22 months of operation
- The APS of the data are obtained from binned **Intensity maps**;
- **HEALPix** (Gorski et al 2005) used;
- Known sources and Galactic diff. em. minimized with **masking**;
- In the main analysis branch gtools were used for the exposure maps calc.
- An independent method (**Shuffling**) used to cross-check the exposure calculation effects;
- APS of real data and detailed **all-sky simulations** have been obtained and compared;
- A **Foreground Cleaning** has been used to estimate the possible effects of residual Galactic diffuse emission

Data Intensity Maps



Counts Map (1-2GeV)

Masked Counts Map



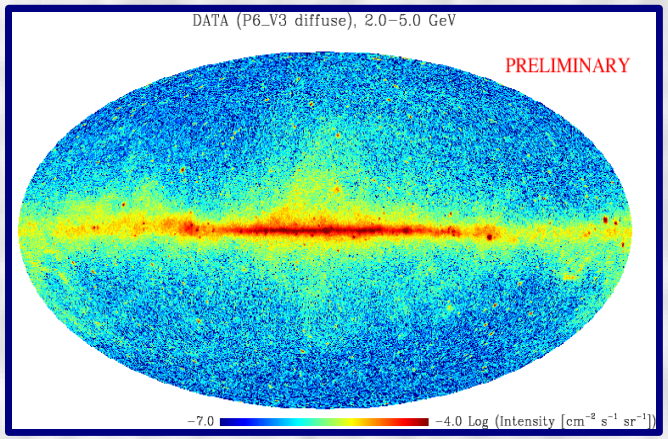
Sources Masking

Galactic Plane Masking

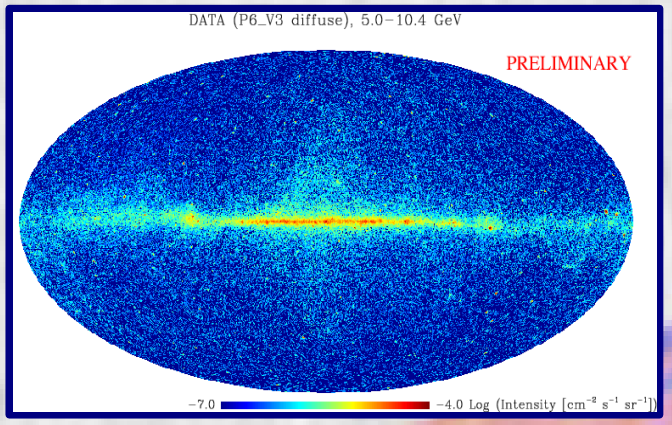
- **22 months** of data, diffuse class events
- energy from **1 to 50 GeV, 4 energy bins** for APS calculation
- **Masking** of 11-month catalog sources (2deg radius) and |b| < 30 deg diffuse emission
- front- and back-converting events: processed separately through angular power spectrum calculation, then results are combined by weighted average

Data Intensity Maps

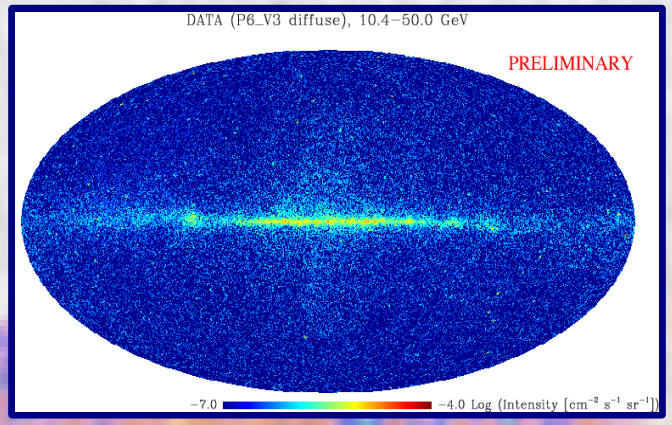
2-5 GeV

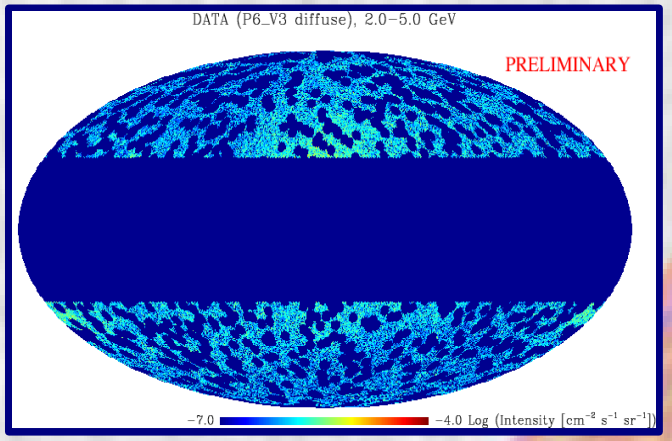


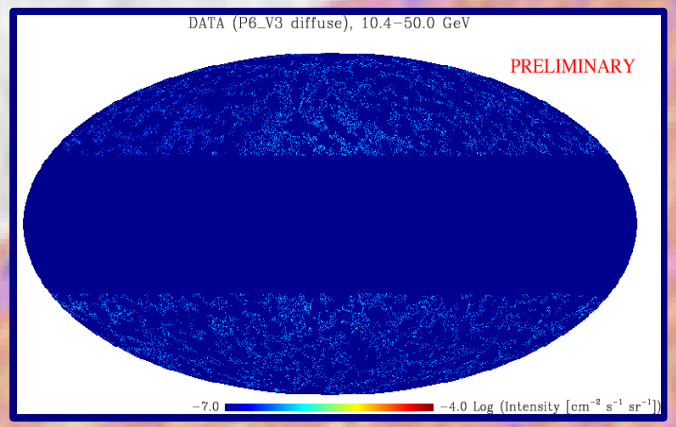
5-10.4 GeV

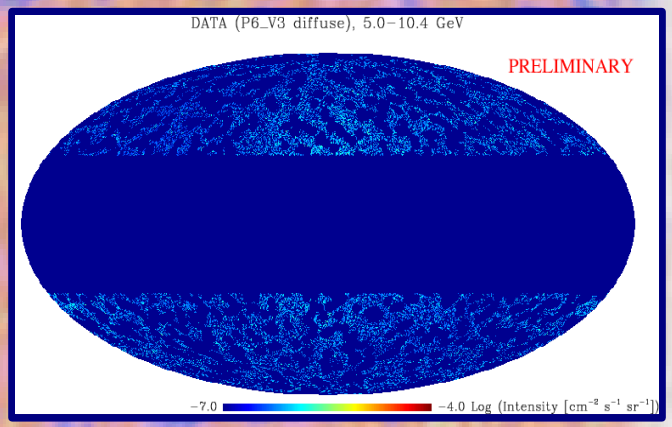


10.-50GeV







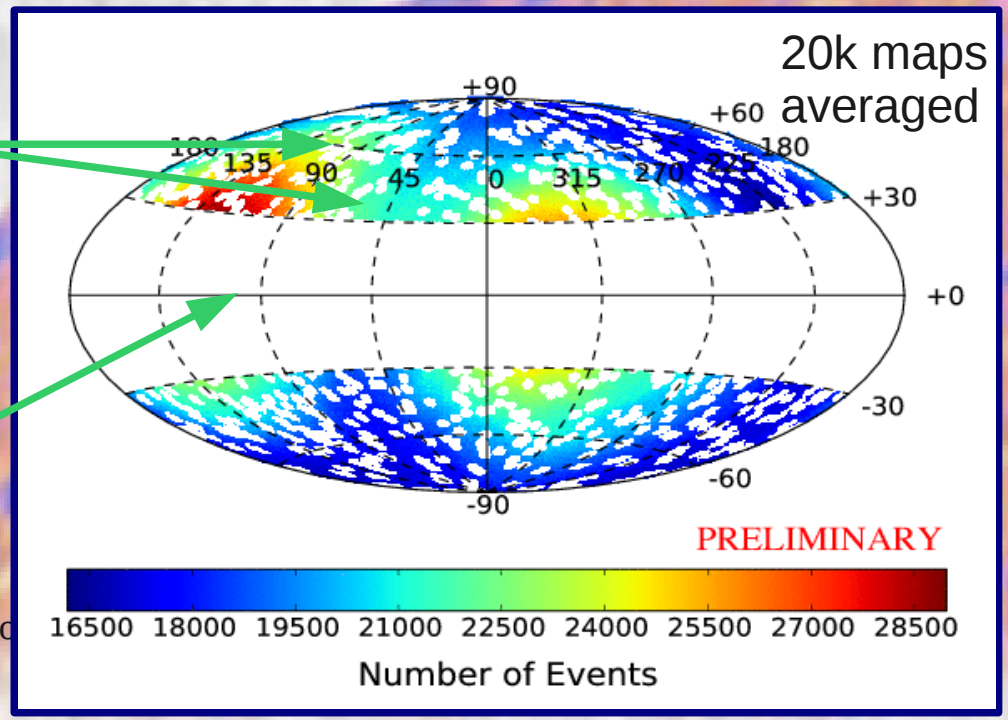


LAT Data Analysis (ii)

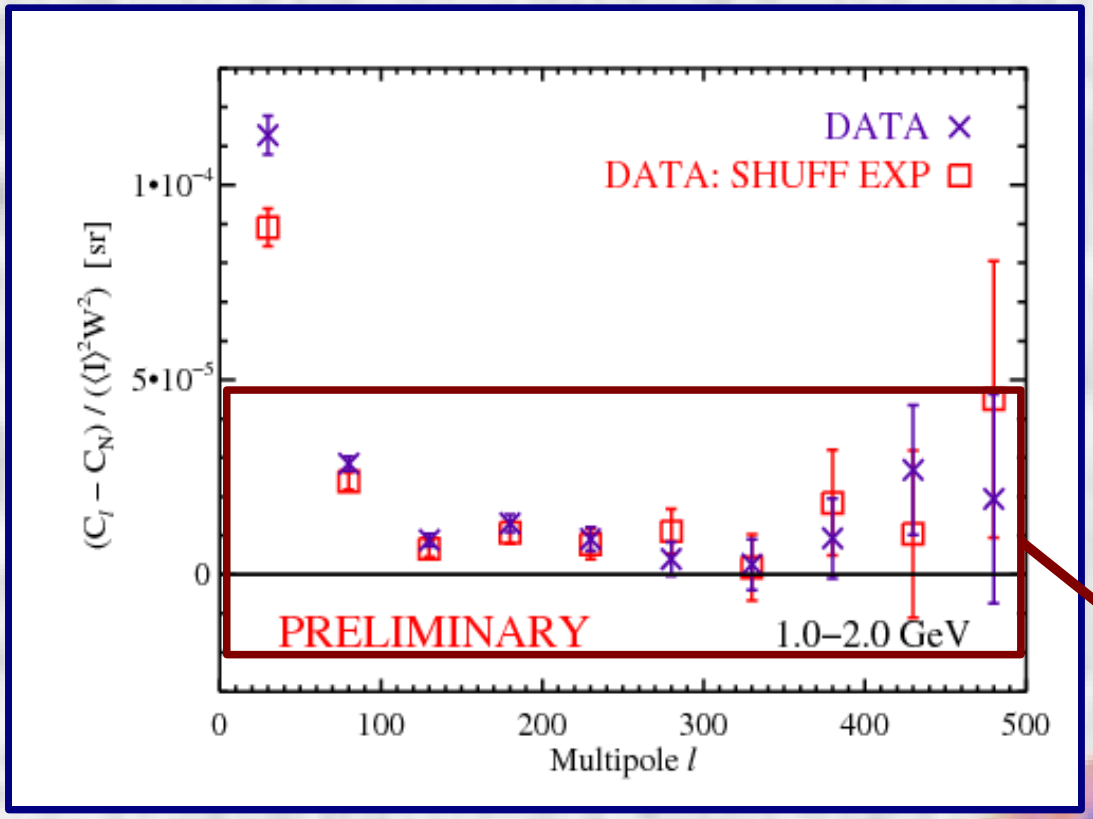
- the exposure map is calculated directly from the data using an **event-shuffling** technique:
- arrival times and directions of real events in instrument coordinates are randomly coupled
- shuffling in this way generates a map representing the null hypothesis of how an **isotropic signal** would appear in the LAT data
- shuffled data map is directly proportional to the exposure map, with arbitrary normalization
- data 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
- **only fluctuation APS** can be analyzed due to the arbitrary normalization of the exposure

Sources Masking

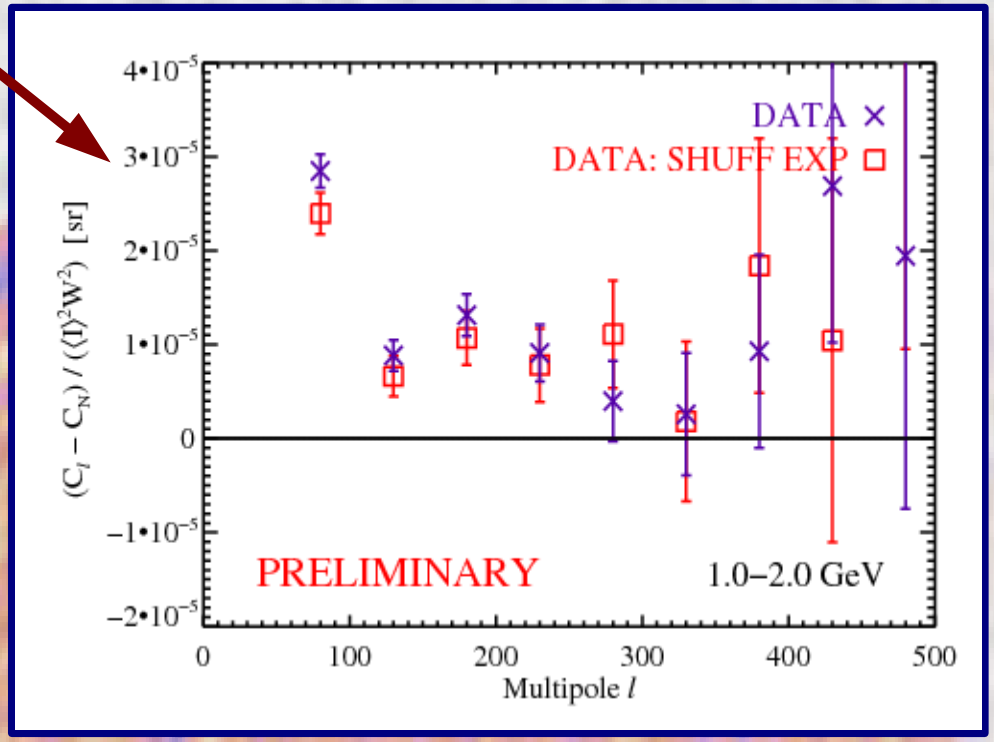
Galactic Plane Masking



APS of the Data

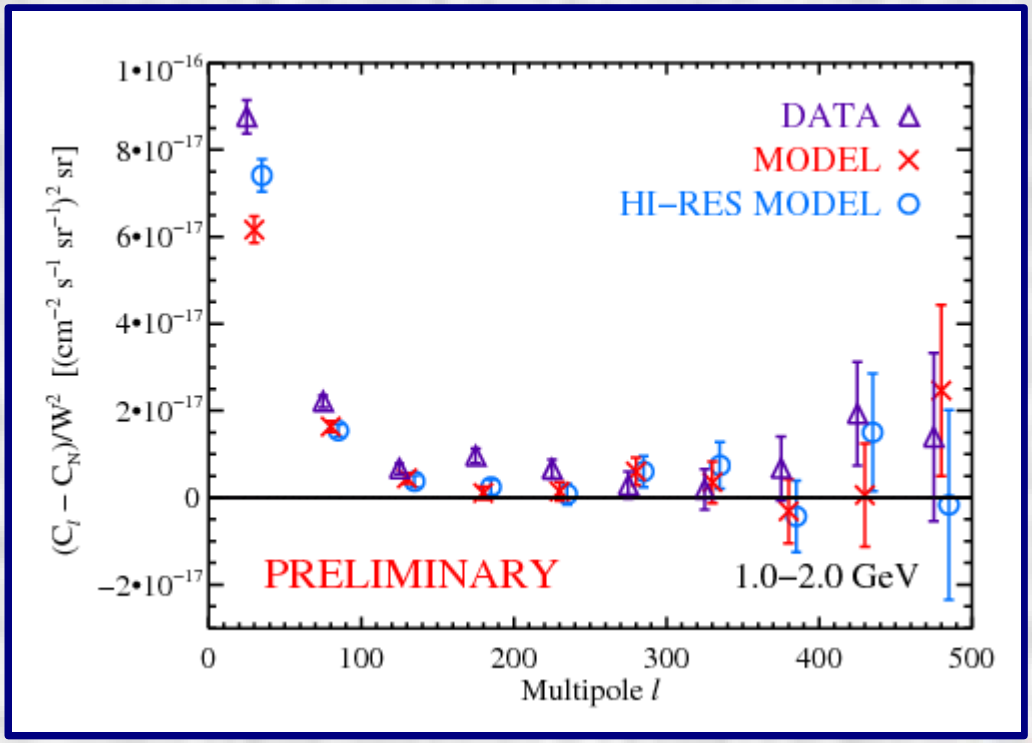


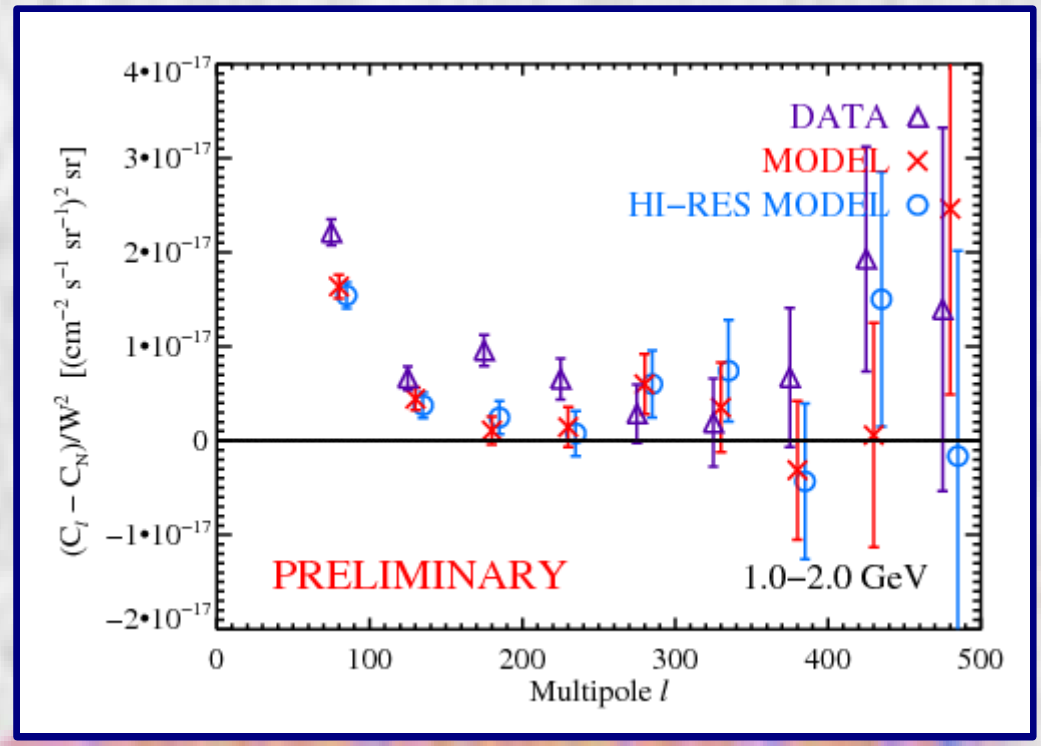
- For multipoles < 100 excess of angular power likely coming from the Galactic diffuse background
- For multipoles > 150 an excess of angular power is detected



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

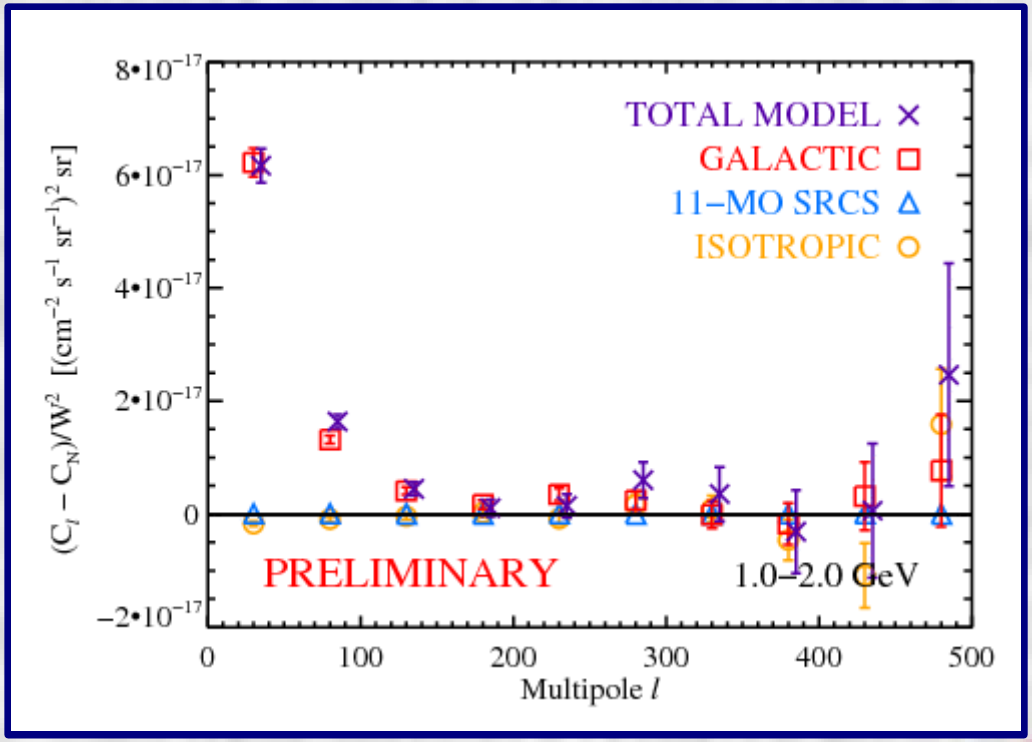
Simulated Sky Comparison (i)

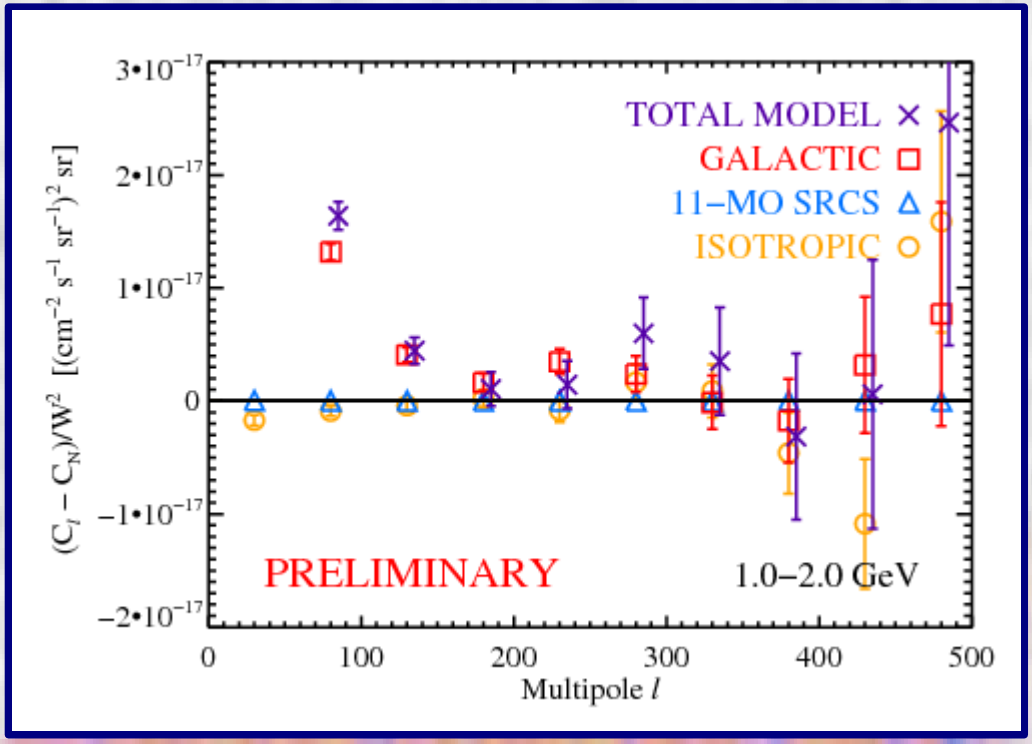




- All-sky simulations APS compared to real data ones
- Simulated: 1FGL sources (1451), Galactic diffuse emission (the standard gll_iem_v02.fit at 0.5deg resolution and a version at 0.125deg resolution), Isotropic diffuse emission;
- Other energy bins in backup slides

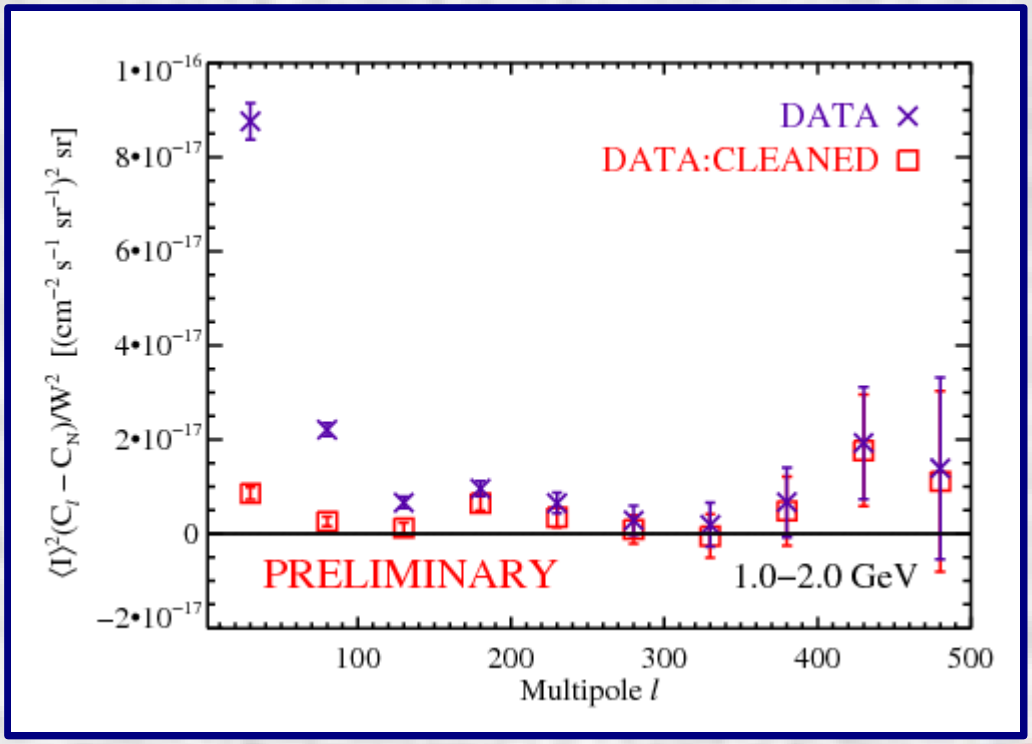
Simulated Sky Comparison(ii)

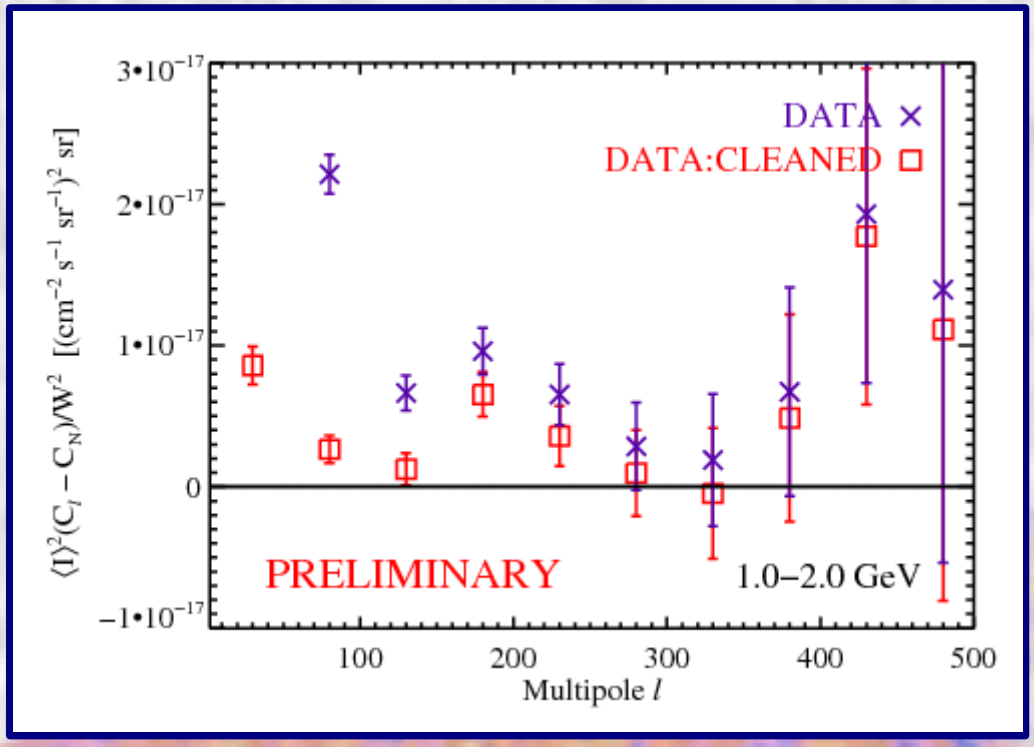




- Galactic diff. Model shows low multipole (l<100) excess
- Isotropic diffuse and sources follow expected behaviour
- Other energy bins in backup slides

Foreground Cleaning





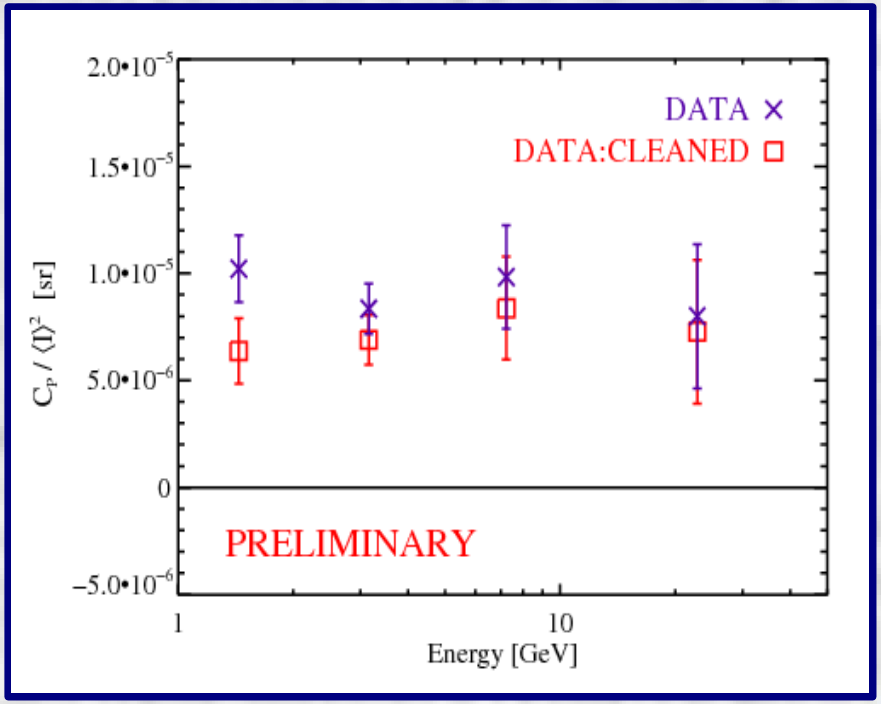
- Foreground cleaning primarily reduces angular power at l < 155, with the most significant reductions at l < 105
- Indicates that contamination of detected angular power at high multipoles by Galactic foregrounds is small
- Other energy bins in backup slides

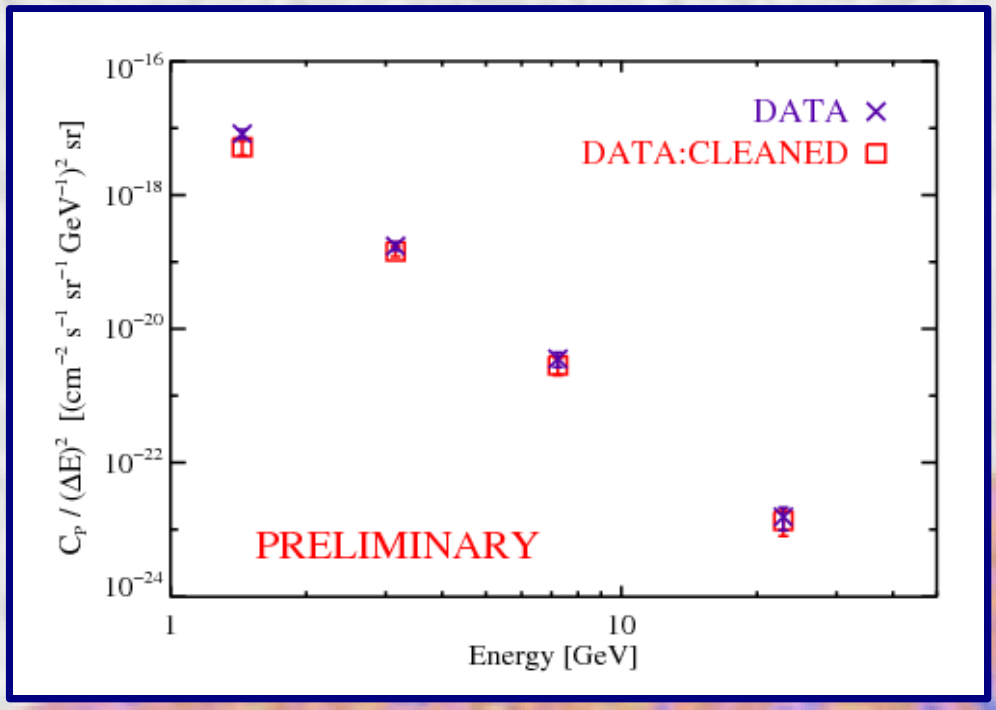
Angular Power in the Data

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

- Angular power detect with high significance up to 10GeV, and with a lower one at larger energies;
- Fluctuation angular power of 10^{-5} sr in the range predicted for astrophysical source classes and some DM scenarios

Energy Dependence of APS

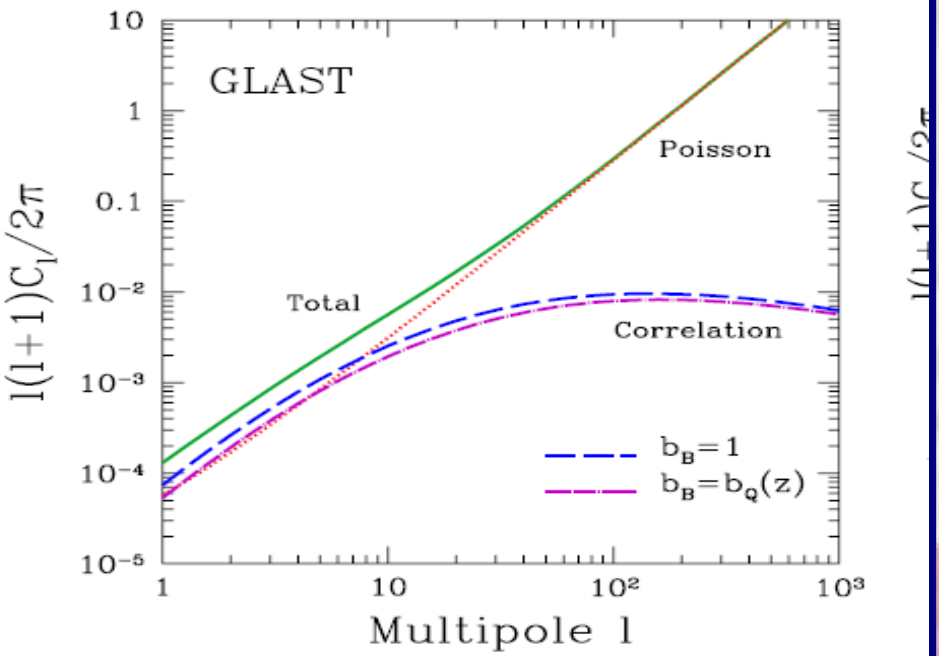




- Fluctuation anisotropy energy spectrum consistent with no energy dependence and contributed by one or more source classes providing same fractional intensity contribution at all energies
- Intensity anisotropy energy spectrum consistent with one or more source classes with photon index -2.40+-0.07 (such as FSRQs and BL Lacs)

APS from Sources

- The Poisson angular power arises from un-clustered point sources and takes the same value at all multipoles
- The APS of many gamma-ray source pop. are dominated by the Poisson components for multipoles l>10
- The measured one is ~ 1e-5 sr, then within the range predicted for some astrophysical source classes and some dark matter scenarios
- Other source popolations APS in the backup



Blazars (Ando, Komatsu, Narumoto & Totani 2007)

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

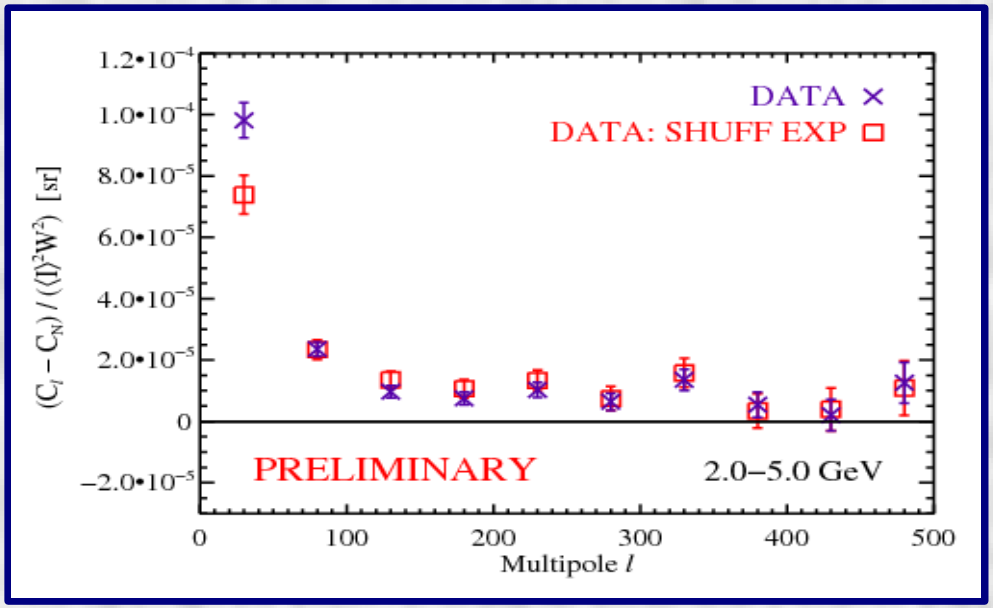
Summary (i)

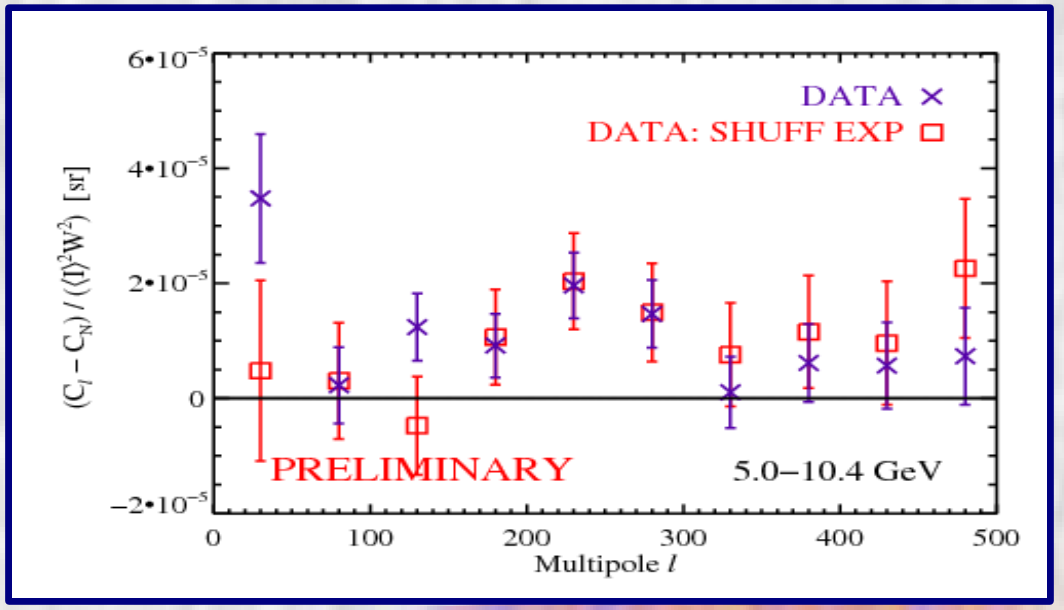
- Angular power is detected in the data at multipoles between 155 and 504, at energies from 1 to 10 GeV
- lower significance angular power is detected in the 10-50 GeV range
- Scale-independence of the power at these multipoles suggests a contribution to the IGRB from one or more unclustered point source populations
- The fluctuation angular power measured in all energy bins is consistent with a constant value ~ 1e-5 sr
- This value is in the range of predicted angular power for some astrophysical source populations and dark matter scenarios
- It can be used to constrain the IGRB contribution from these sources

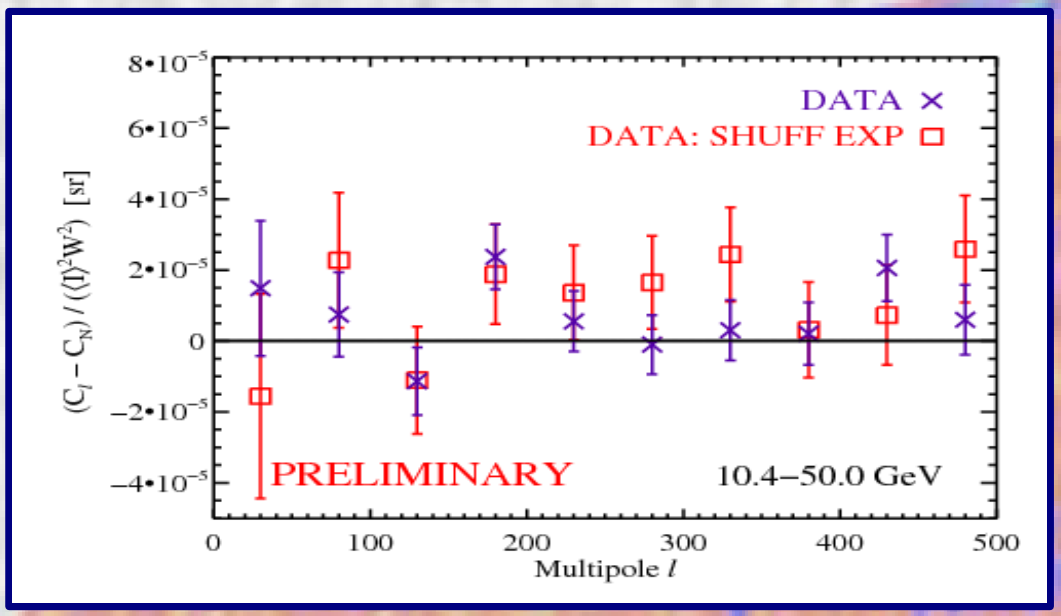
Summary (ii)

- Energy dependence in the fluctuation angular power is not evident
- This suggests that the anisotropy is contributed by one or more source populations with a constant fractional contribution 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 single 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

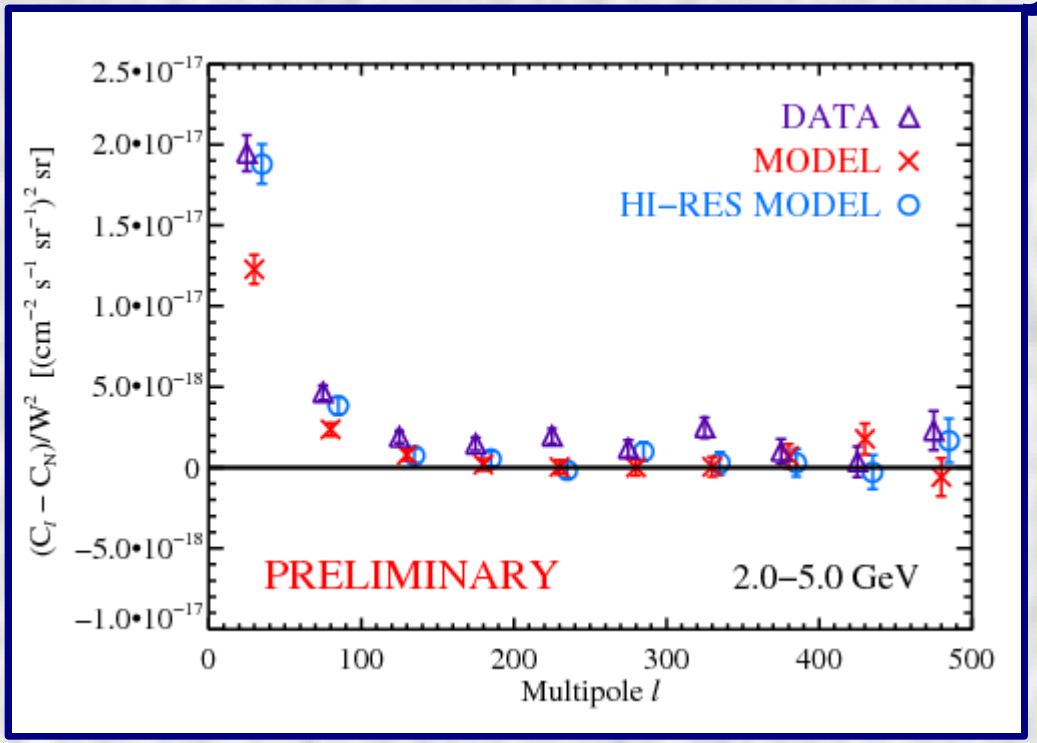
APS of the Data

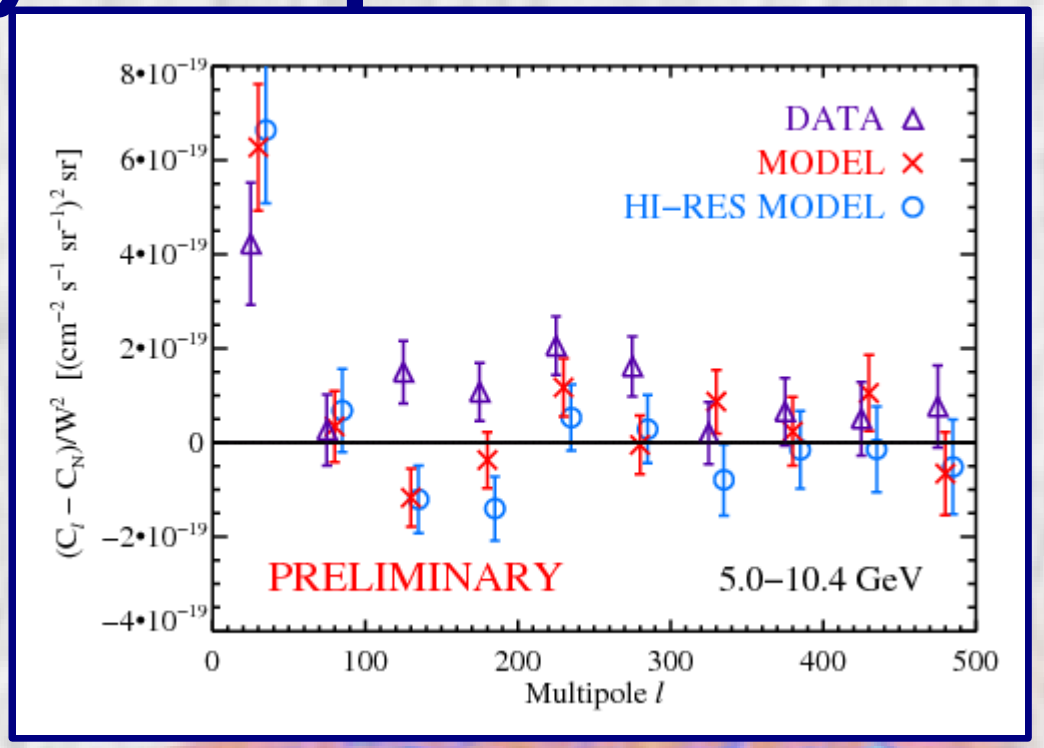


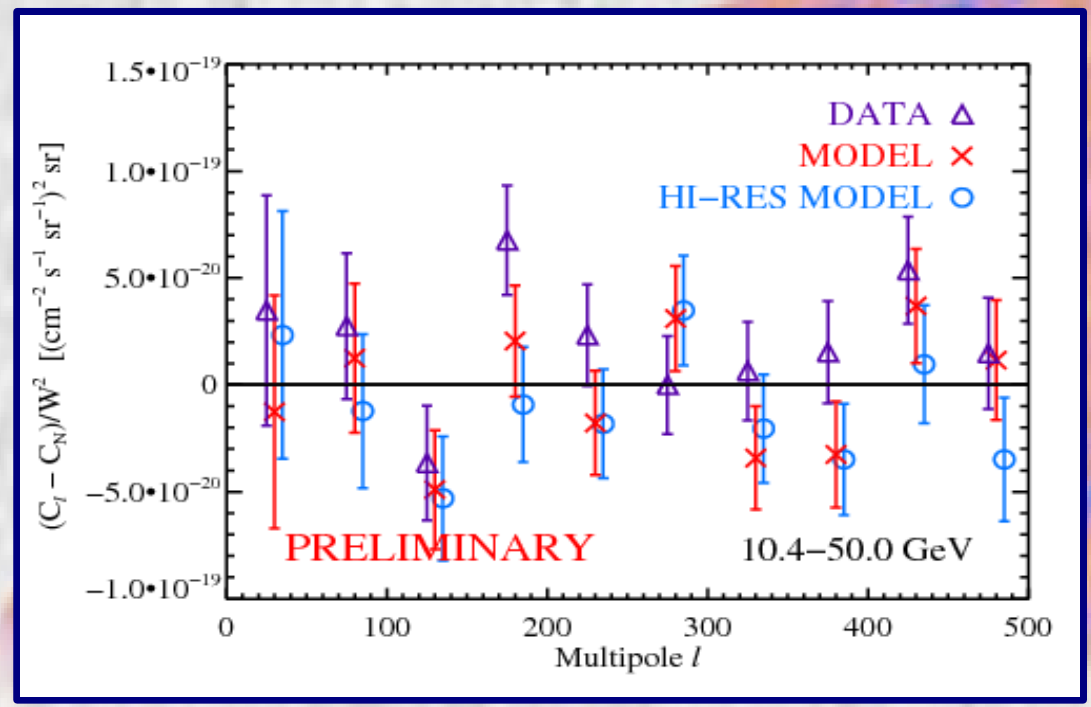




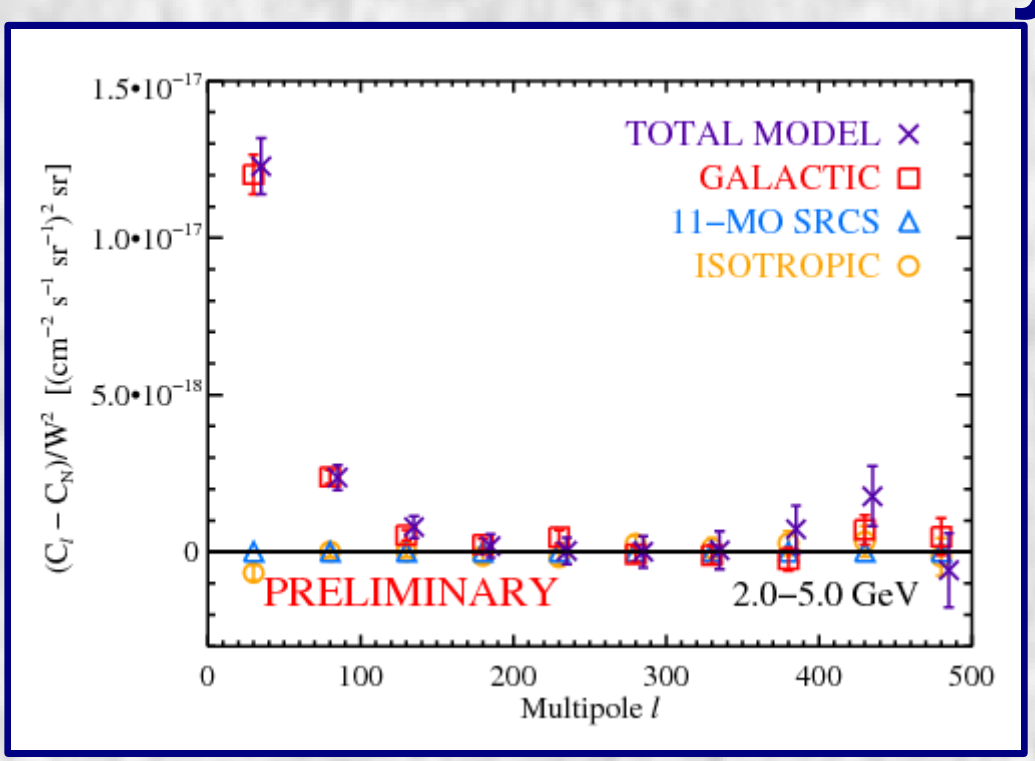
Simulated Sky Comparison

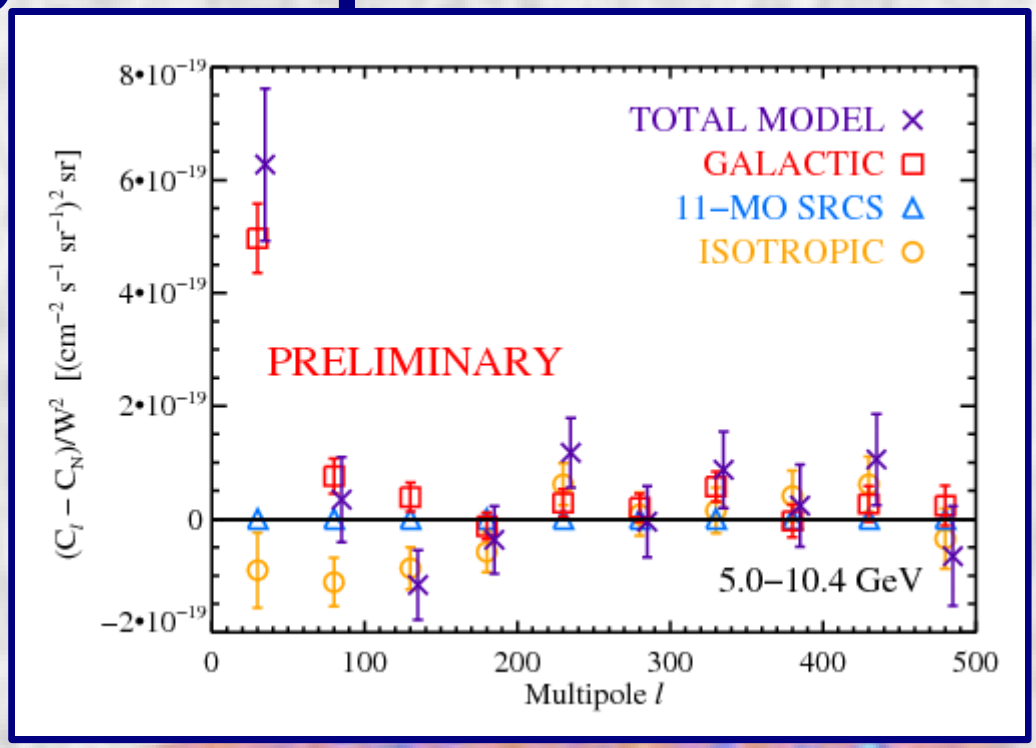


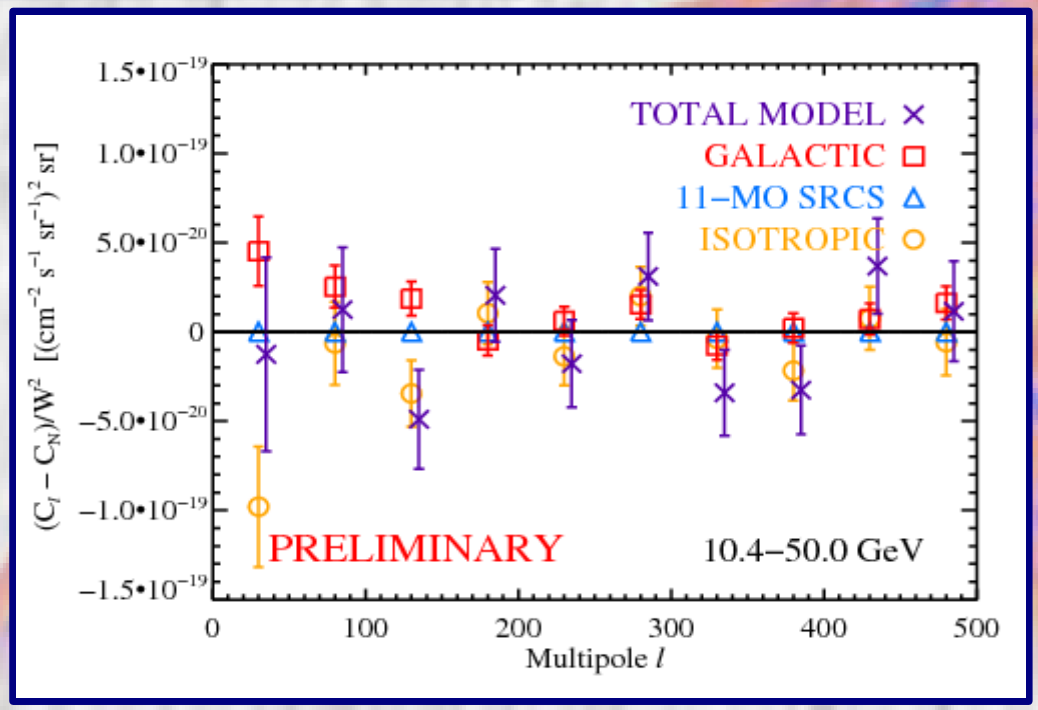




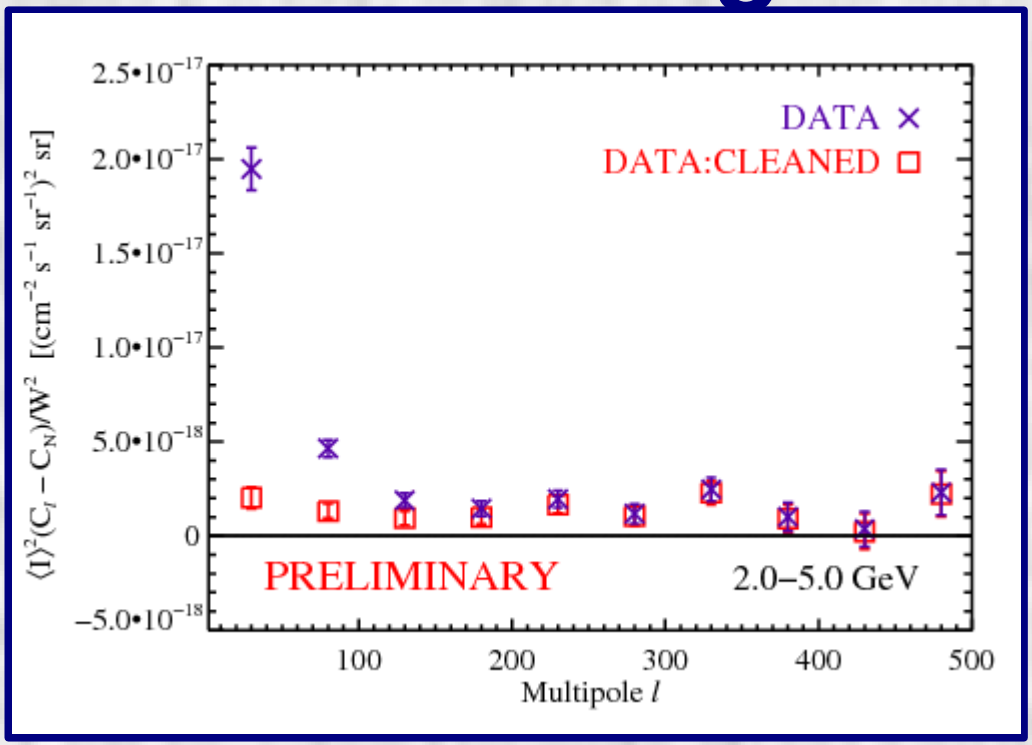
Simulated Sky Comparison

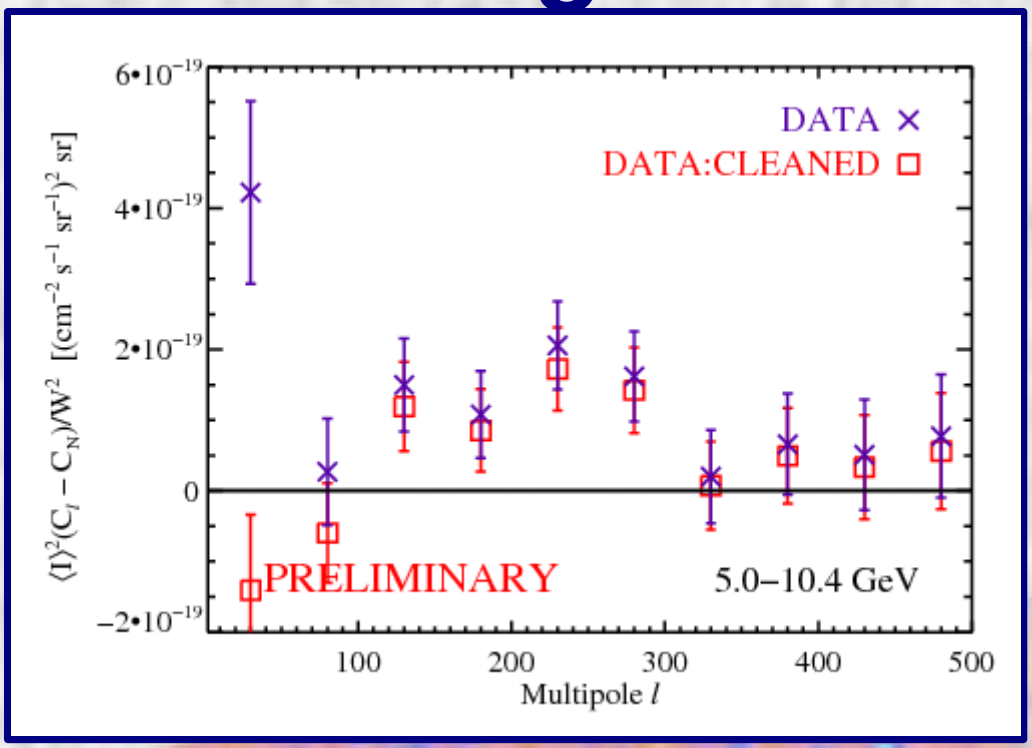


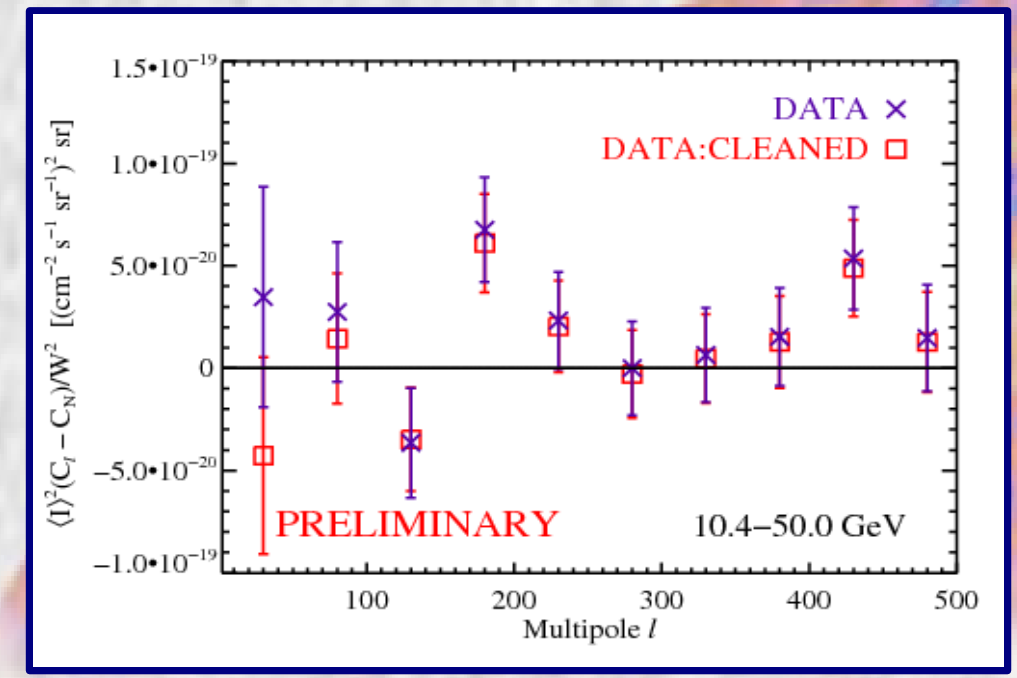




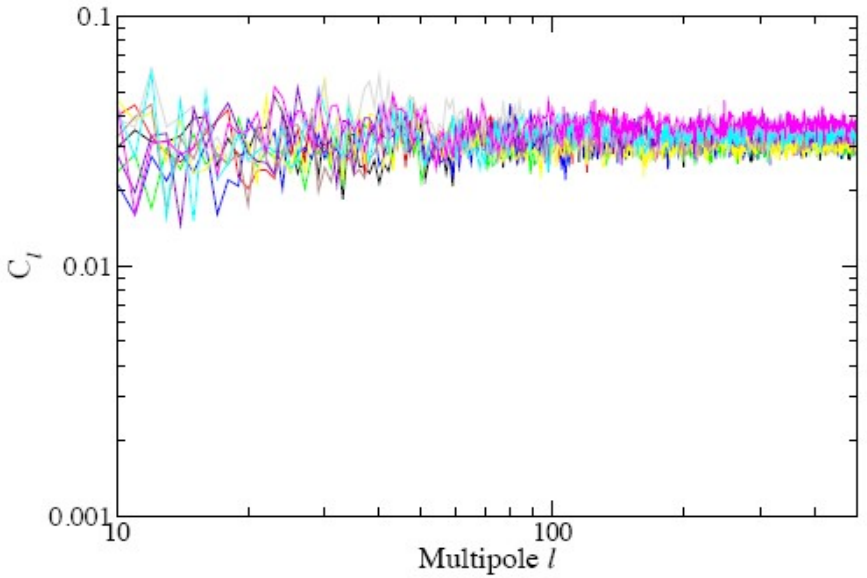
Foreground Cleaning



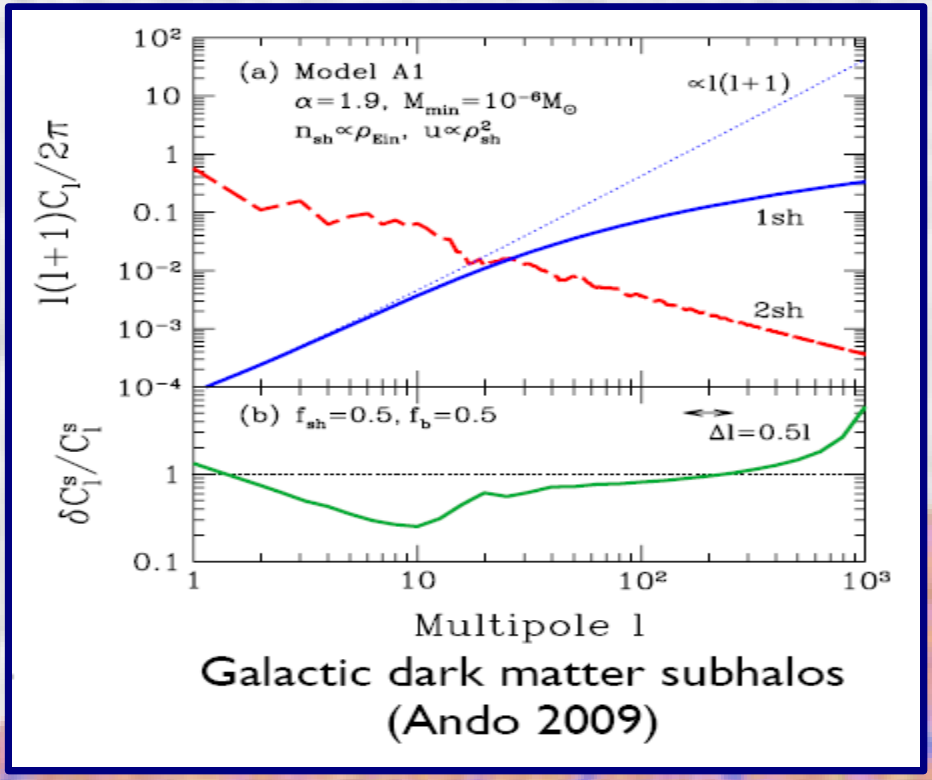




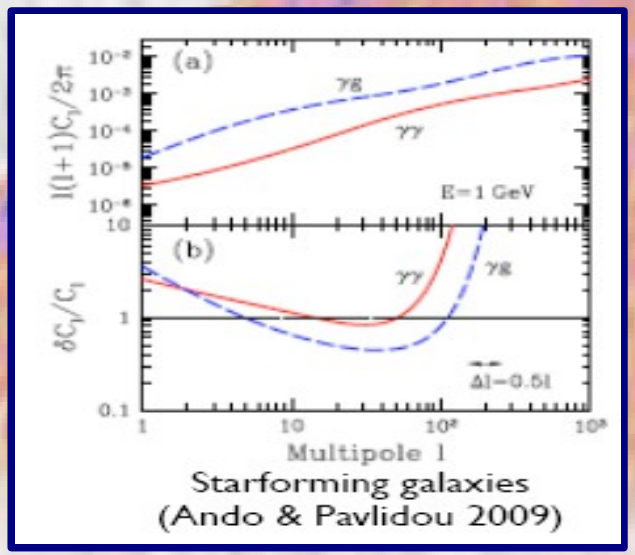
APS from Sources



Galactic millisecond pulsars (JSG et al 2010)



Galactic dark matter subhalos (Ando 2009)



Starforming galaxies (Ando & Pavlidou 2009)