Hunting for Dark Matter in Anisotropies of Gamma-ray Sky: Predictions and First Observational Results from Fermi-LAT

Eiichiro Komatsu (Texas Cosmology Center, Univ. of Texas at Austin)

Astrophysics Seminar, IAS, April 3, 2012

This work is based on:

- Ando & EK, PRD 73, 023521 (2006)
- Ando, EK, Narumoto & Totani, PRD 75, 063519 (2007)
- Fermi-LAT Collaboration & EK, PRD in press, arXiv: 1202.2856
- Cuoco, EK & Siegal-Gaskins, submitted, arXiv:1202.5309

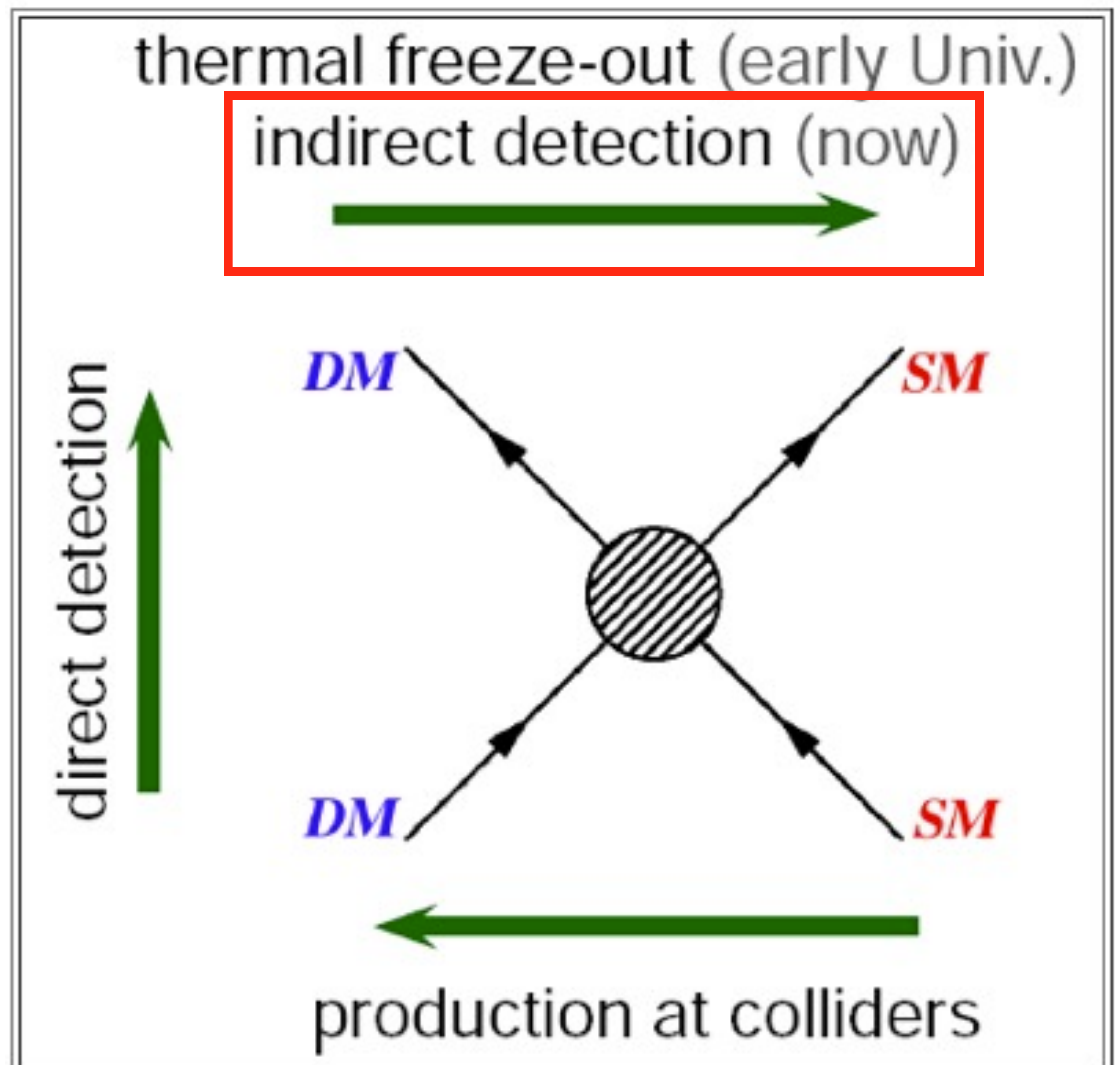
Shin'ichiro Ando

Jenny Siegal-Gaskins

Alex Cuoco

A Simple Motivation

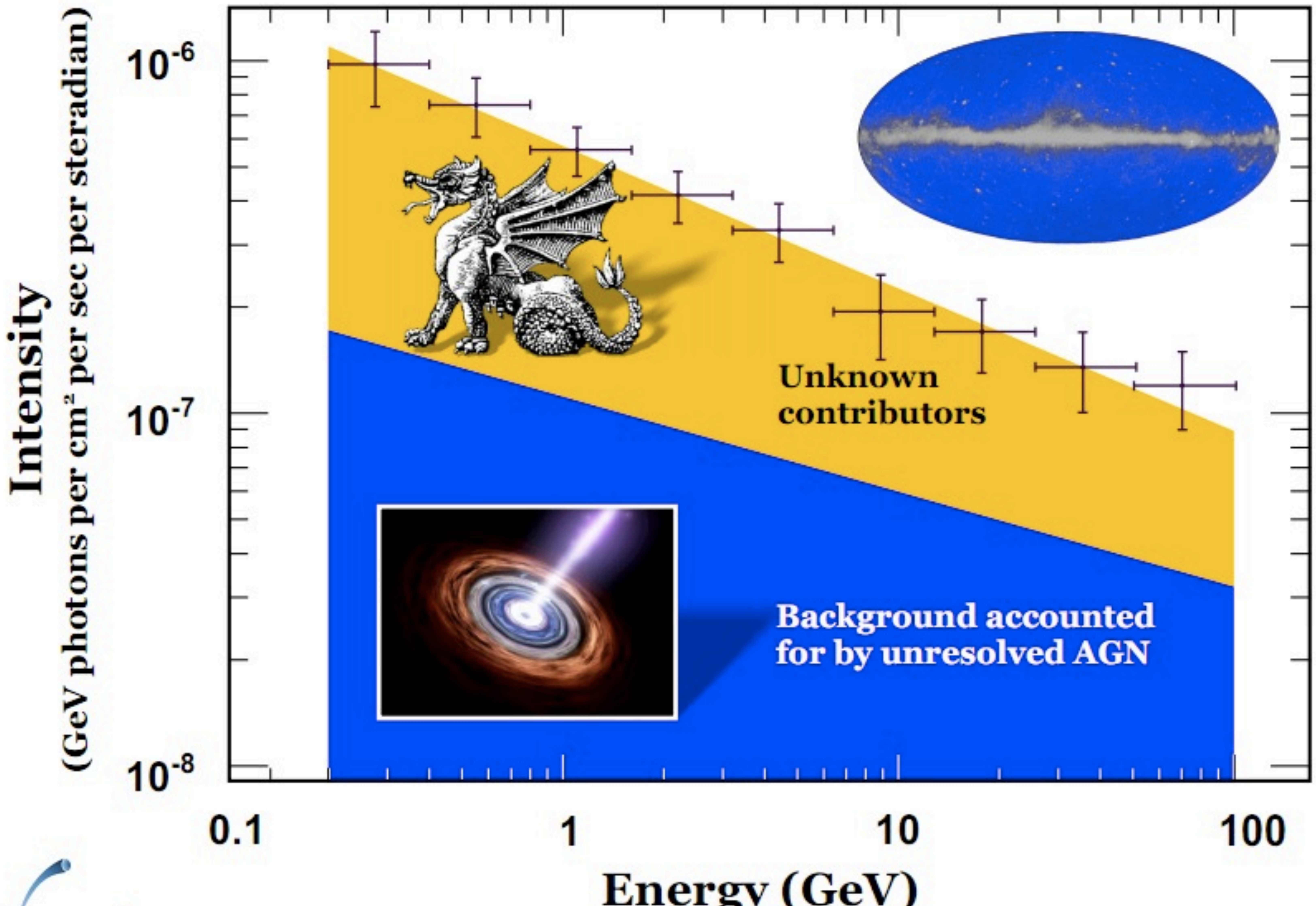
- How can we see photons from annihilation/decay of dark matter particles?



Intriguing Observations

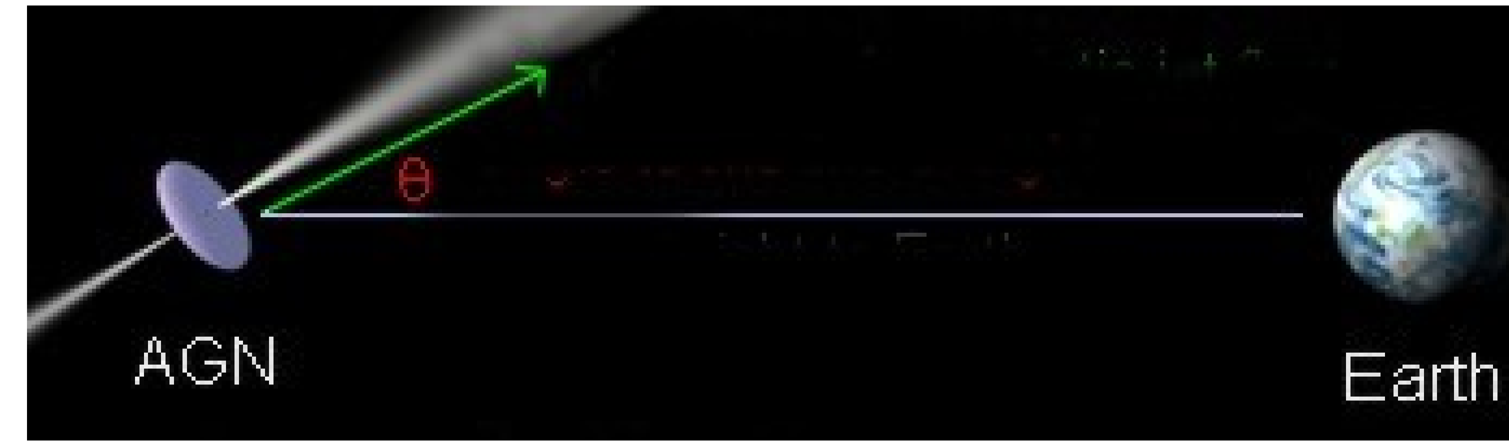
- In gamma-ray energies (E>0.1GeV), the origin of **80%** of the diffuse emission (after removing the known Galactic emission) is unknown!
  - 20% coming from blazars (*Fermi-LAT collaboration*)
- In soft gamma-ray energies (E=1–10MeV), the origin of **>90%** of the diffuse emission is unknown!
  - <10% coming from supernovae (*Ahn, EK and Hoeflich 2005*)

Fermi LAT Extragalactic Gamma-ray Background



Fermi Gamma-ray Space Telescope

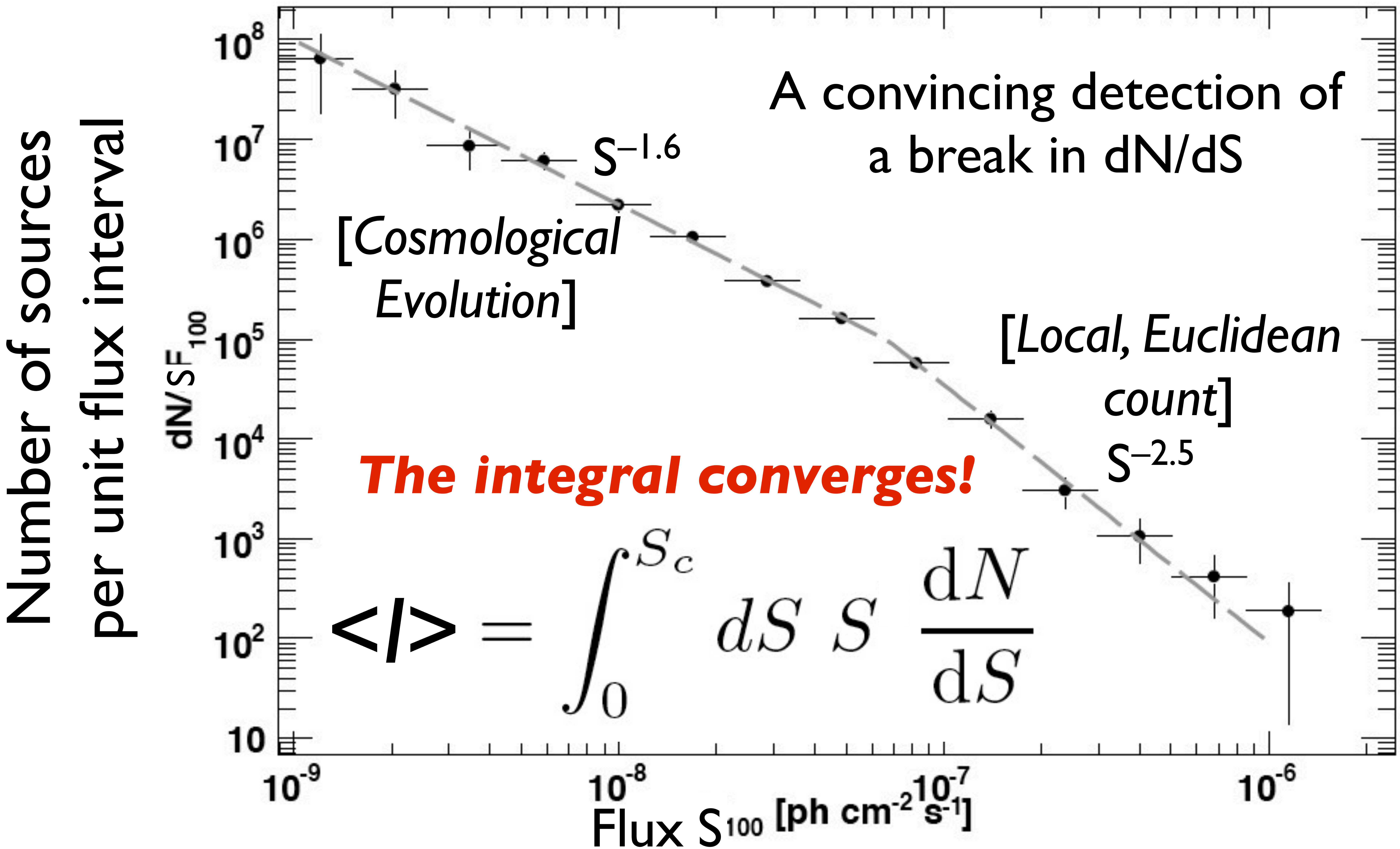
Blazars



- Blazars = A population of AGNs whose relativistic jets are directed towards us.
  - Inverse Compton scattering of relativistic particles in jets off photons -> gamma-rays, detected up to TeV
- How many are there? (They are rare.)
  - EGRET found ~70 blazars (out of ~100 associated sources) over the full sky
  - Fermi-LAT found ~570 blazars (out of ~820 associated sources) over the full sky (LAT 1FGL catalog)

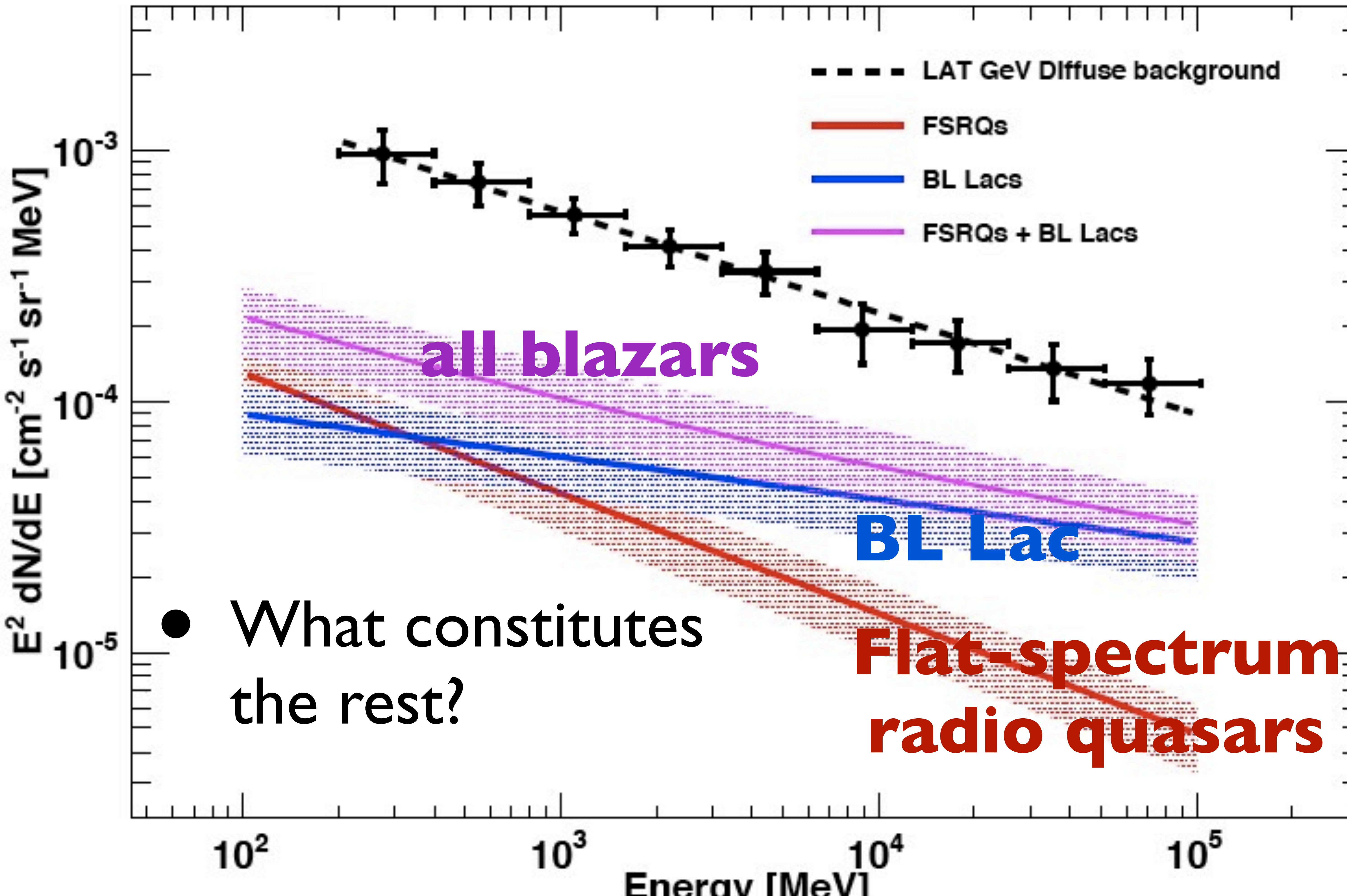
Fermi-LAT Collaboration, ApJ, 720, 435 (2010)

News from Fermi-LAT



Fermi-LAT Collaboration, ApJ, 720, 435 (2010)

Unresolved blazars are not enough to explain the background



- What constitutes the rest?

Origin of Diffuse Gamma-ray Background?

- Where do they come from?
  - Star-forming galaxies?
  - Pulsars?
  - Clusters of galaxies?

Origin of Diffuse Gamma-ray Background?

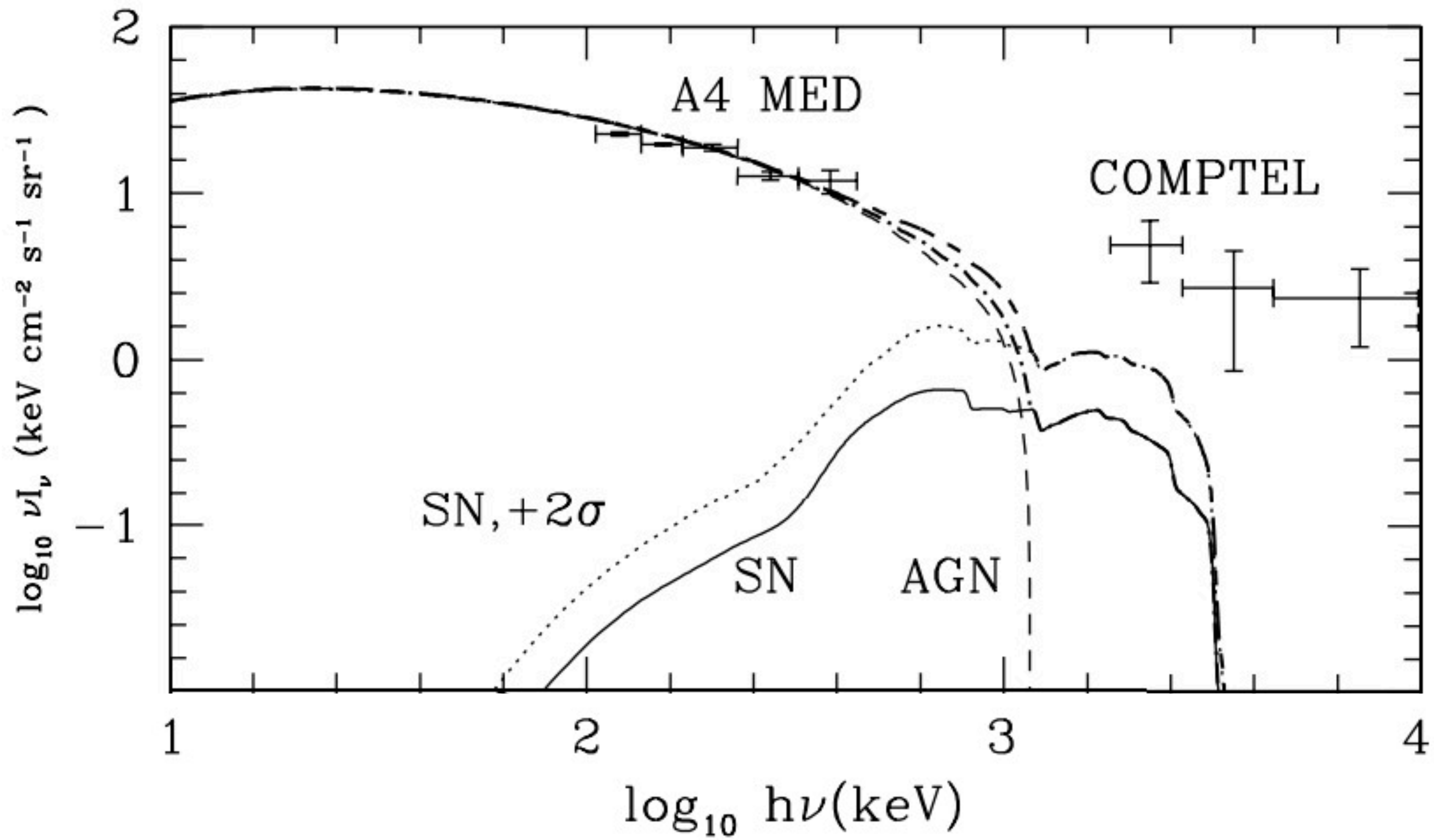
- Where do they come from?
  - Star-forming galaxies?
  - Pulsars?
  - Clusters of galaxies?

or... perhaps... some of them might come from...

- ***Dark matter?***

A Side Note

Ahn, EK & Hoeflich (2005)



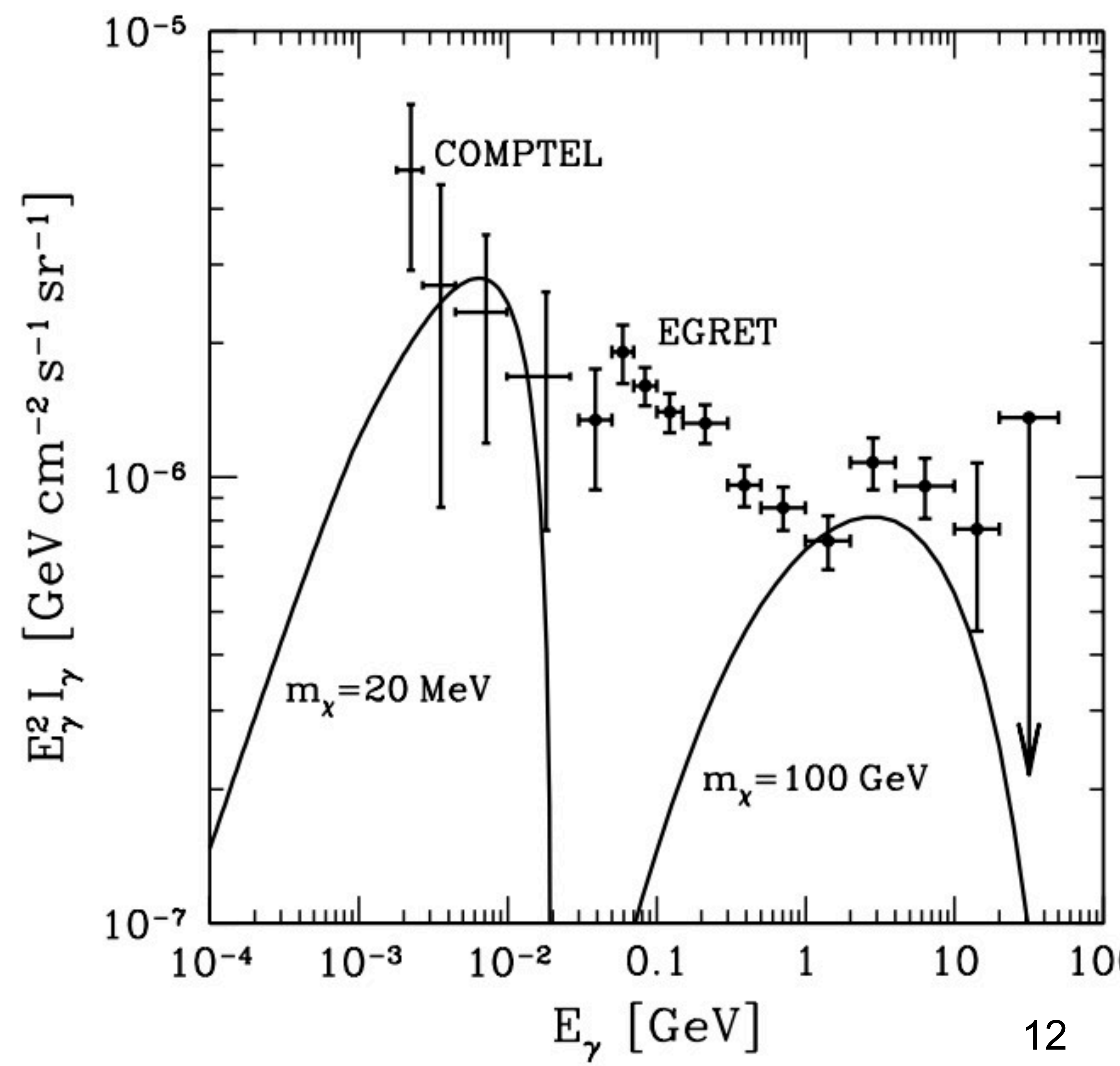
- It was thought that Type Ia supernovae would account for most of the MeV gamma-ray background. It turns out that the measured supernova rate is too small for that! ***The origin of the MeV background is unknown.***

Conventional Method

- Use the energy spectrum of the mean intensity (the number of photons averaged over the sky), and look for spectral features.

However, dark matter is not the only source of gamma-ray photons.

How can we distinguish between dark matter signatures and astrophysical sources?



A General Formula

$$E_\gamma I_\gamma(\hat{\boldsymbol{n}}, E_\gamma) = \frac{c}{4\pi} \int dz \frac{P_\gamma([1+z]E_\gamma, z, \hat{\boldsymbol{n}}\, r)}{H(z)(1+z)^4} e^{-\tau([1+z]E_\gamma, z)}$$

- All we need: P_γ = "volume emissivity" = energy radiated per unit volume, time, and energy.

E.g., for supernovae:

$$P_\nu(\nu, z) = (1+z)^3 \mathrm{SNR}_{\mathrm{Ia}}(z) \bar{E}_\nu$$

A General Formula

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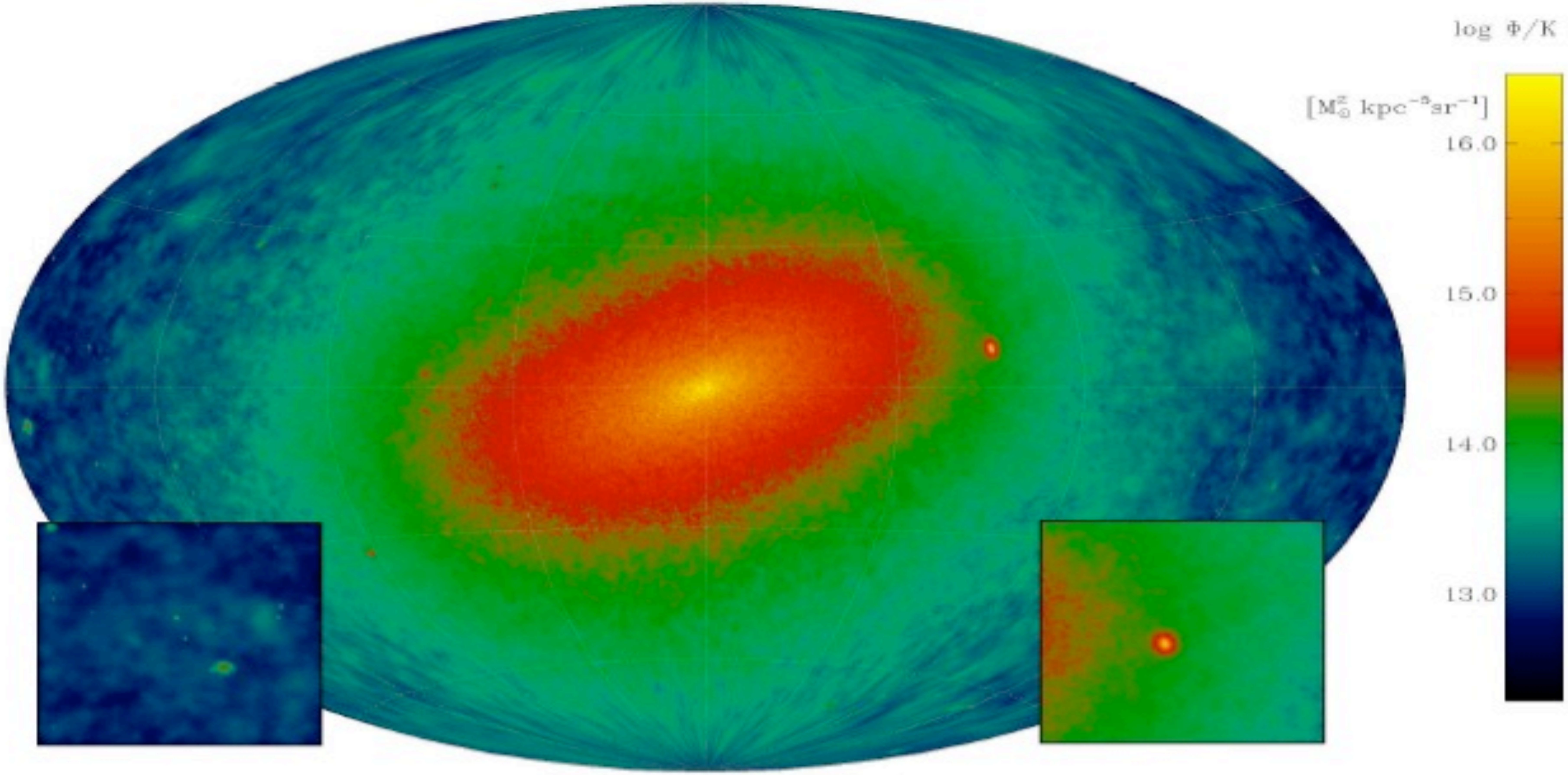
- All we need: P_γ = "volume emissivity" = energy radiated per unit volume, time, and energy.

E.g., for dark matter annihilation:

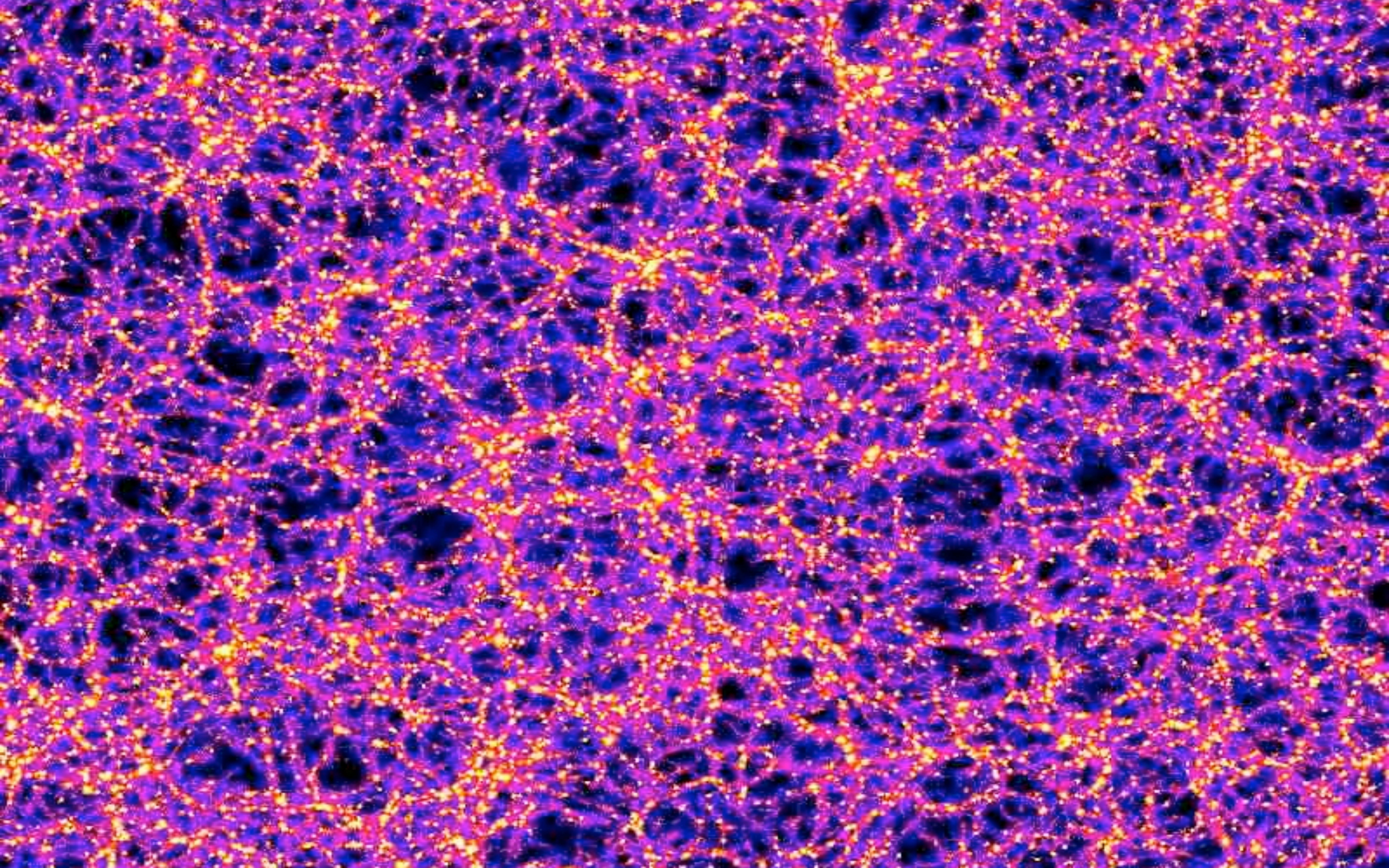
$$P_\gamma(E_\gamma, z, \hat{\boldsymbol{n}}\, r) = E_\gamma \frac{dN_\gamma}{dE_\gamma} \frac{\langle \sigma v \rangle}{2} \left[\frac{\rho_\chi(z, \hat{\boldsymbol{n}}\, r)}{m_\chi} \right]^2$$

Diemand, Khlen & Madau, ApJ, 657, 262 (2007)

Annihilation Signals from Milky Way

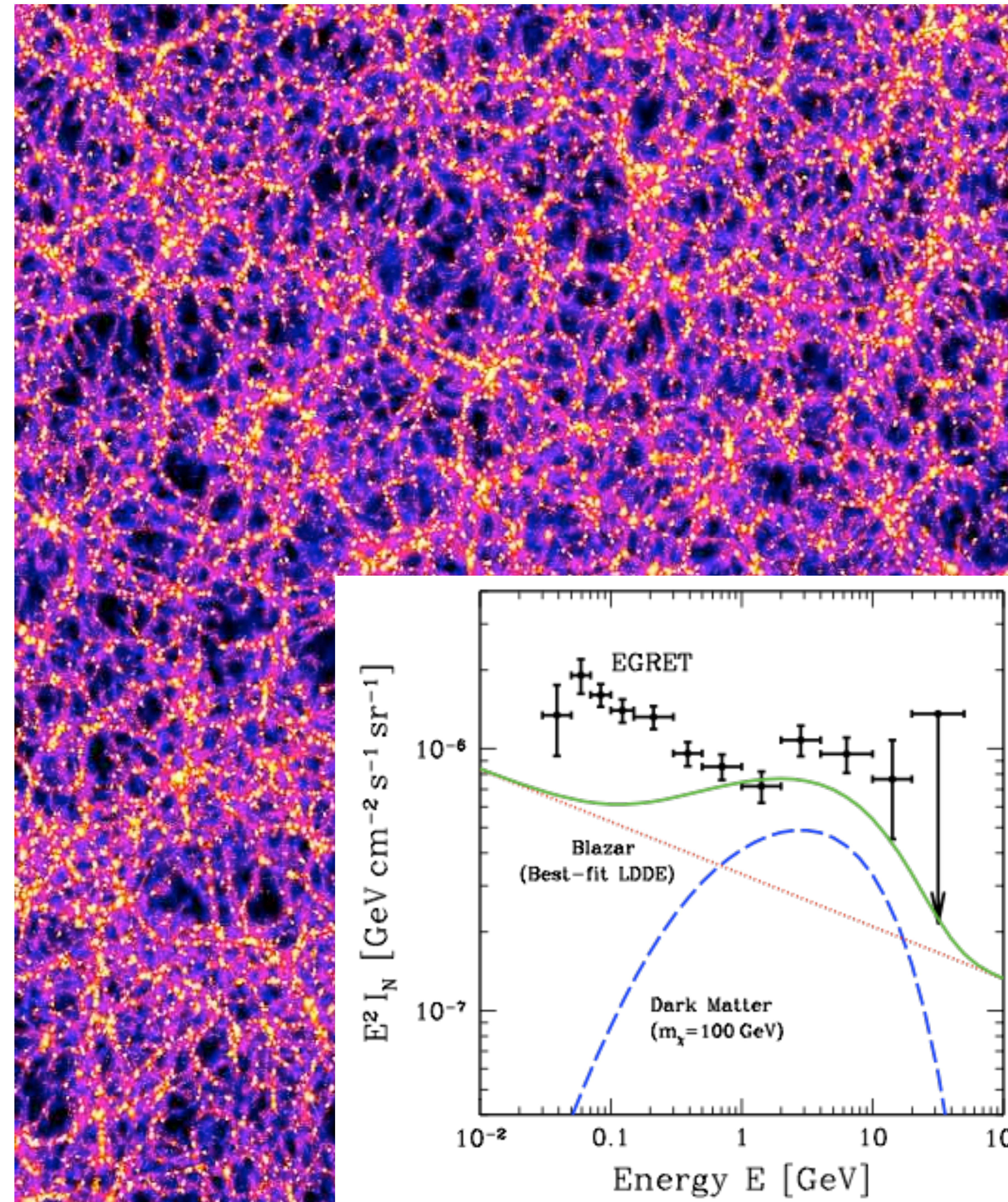


- Why focus only on the energy spectrum?
- Perhaps we can use the spatial distribution.



And, not just Milky Way!

- Dark matter particles are annihilating (or decaying) **everywhere** in the Universe!
  - Why just focus on Milky Way?
- While we cannot resolve individual dark matter halos, the collective signals can be detected in the diffuse gamma-ray background.
  - **How can we detect such signatures unambiguously?**



Ando & EK (2006); Ando, EK, Narumoto & Totani (2007)

Gamma-ray Anisotropy

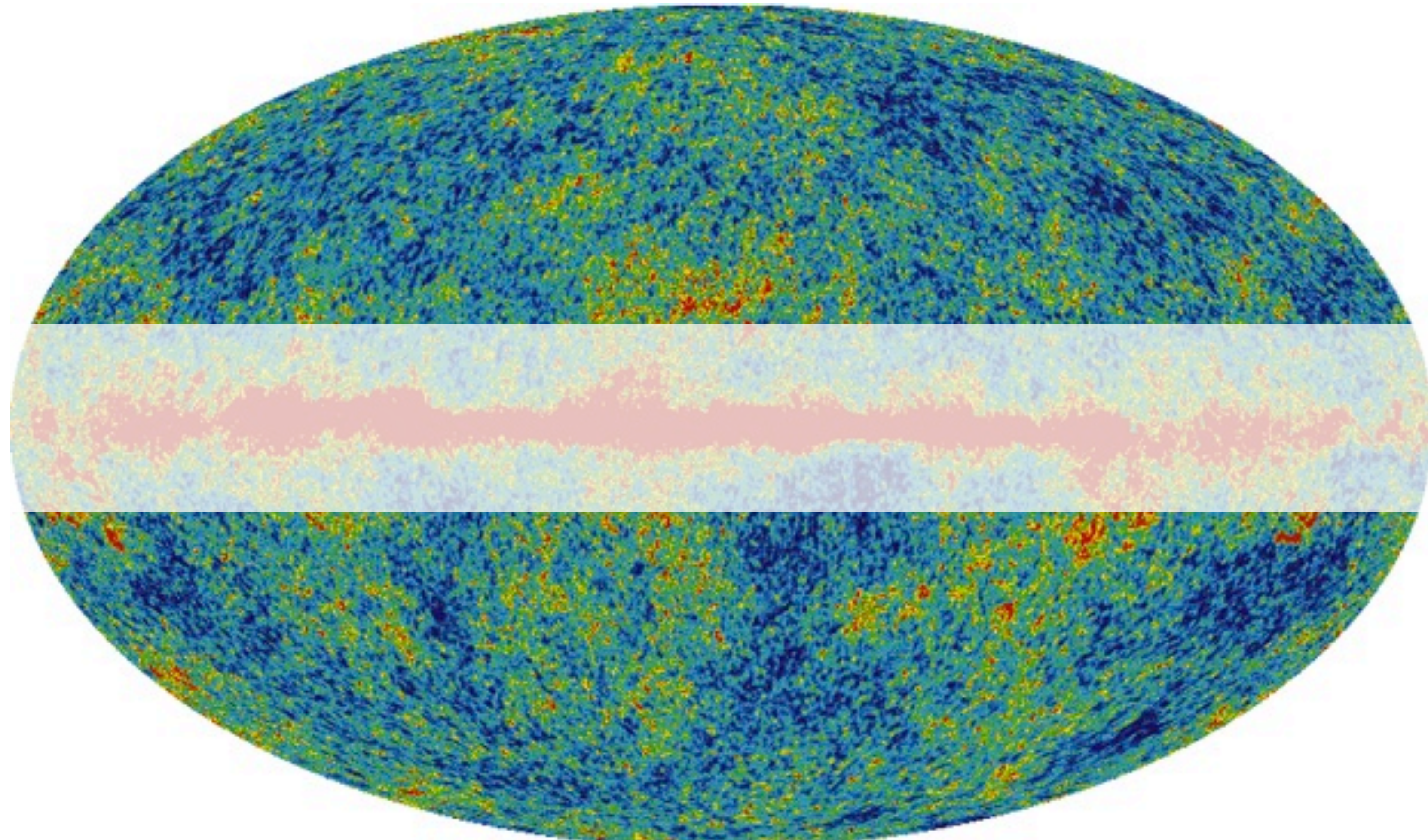
Dark matter halos trace the large-scale structure

- Therefore, the gamma-ray background **must** be anisotropic. If dark matter particles annihilate or decay, anisotropy **must** be there.

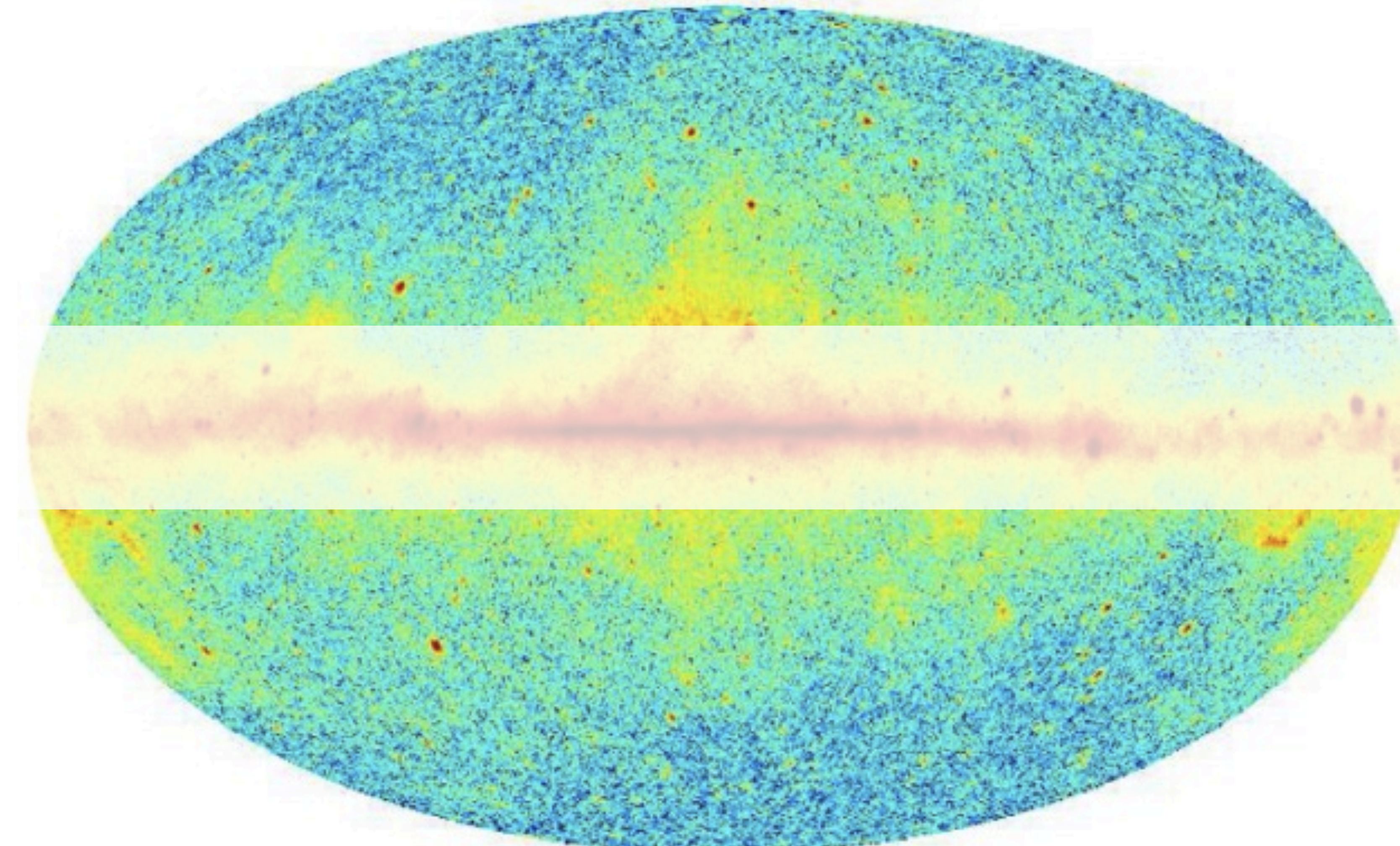
- And, their spatial distribution can be calculated within the framework of Lambda-CDM model (using analytical calculations or numerical simulations)

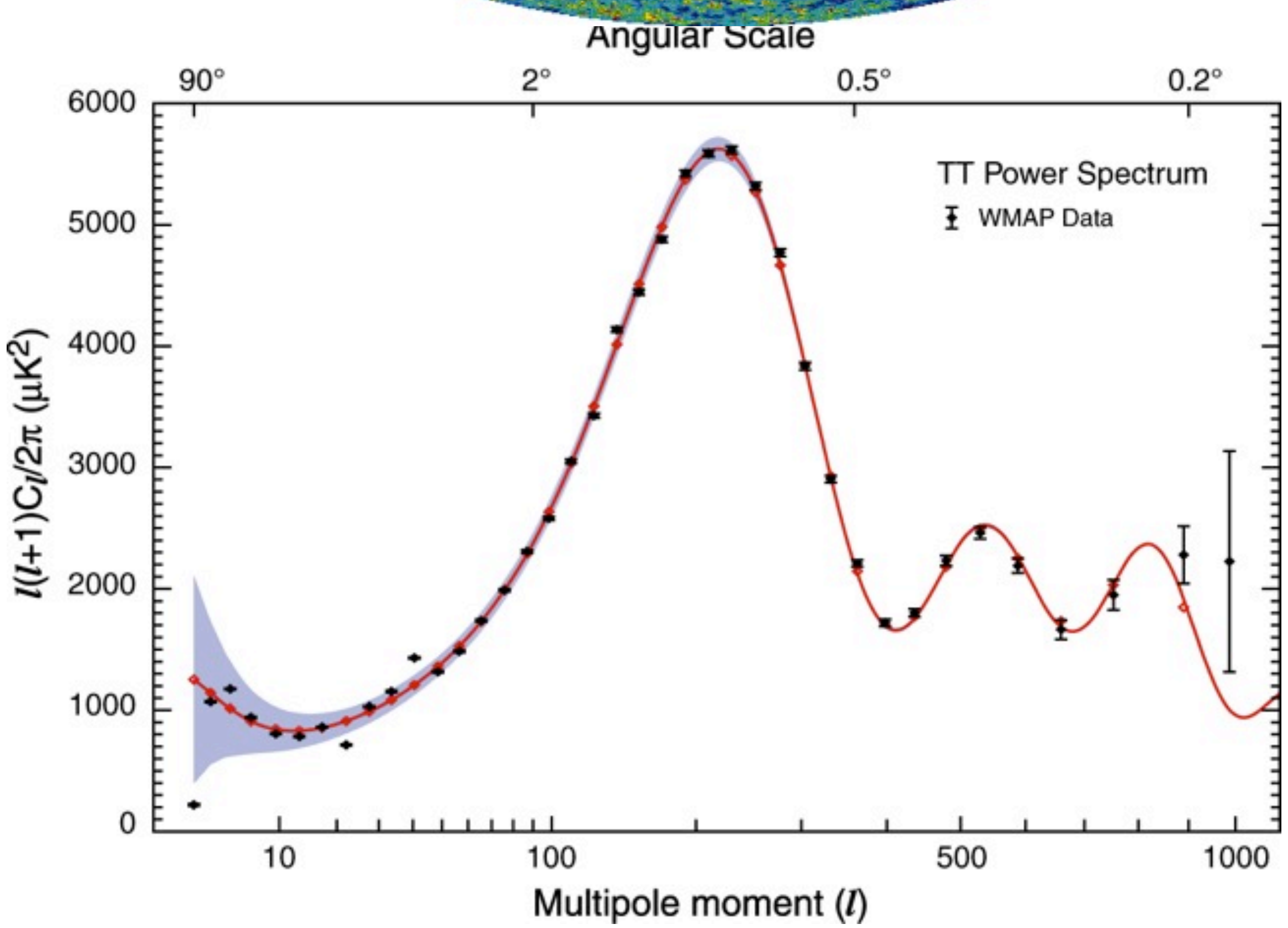
Using Fermi Data, just like WMAP

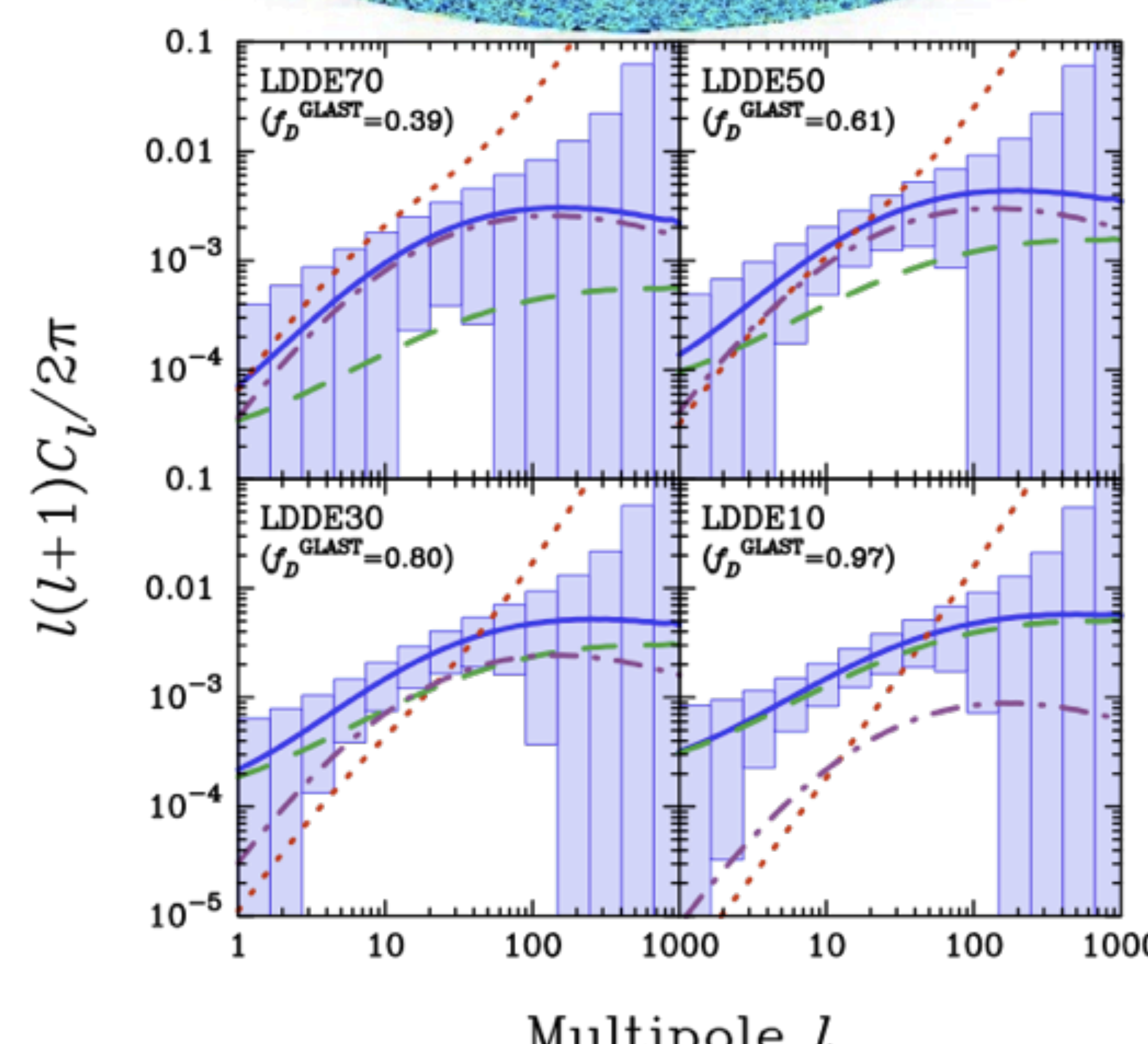
WMAP 94GHz



Fermi-LAT 1–2 GeV







Deciphering Gamma-ray Sky

- ***Astrophysical***:
  - **Galactic origin**
    - Decay of neutral pions produced by cosmic-rays interacting with the interstellar medium
    - pulsars
  - **Extra-galactic origin**
    - AGNs
    - Blazars
    - Gamma-ray bursts
    - Clusters of galaxies

Deciphering Gamma-ray Sky

- ***Exotic***:
  - **Galactic origin**
    - Dark matter annihilation/decay in the Galactic Center
    - Dark matter annihilation/decay in sub-halos within our Galaxy
  - **Extra-galactic origin**
    - Dark matter annihilation/decay in other galaxies

Diffuse Gamma-ray Background

- First, we remove all the resolved (detected) sources from the Fermi-LAT map.
- Then, calculate the mean intensity of the map as a function of energies.
    - The intensity includes contributions from **unresolved sources** (below the detection threshold) and **truly diffuse component** (if any).

Why Anisotropy?

$$P_\gamma(E_\gamma, z, \hat{\boldsymbol{n}} r) = E_\gamma \frac{dN_\gamma}{dE_\gamma} \frac{\langle \sigma v \rangle}{2} \left[\frac{\rho_\chi(z, \hat{\boldsymbol{n}} r)}{m_\chi} \right]^2,$$

- **The shape of the power spectrum is determined by the structure formation, which is well known.**

- Schematically, we have:

(Anisotropy in Gamma-ray Sky)

= (MEAN INTENSITY) x Δ

- The mean intensity depends on particle physics: annihilation cross-section and dark matter mass. The fluctuation power, Δ, depends on structure formation.

A Note on Cross-section

- For this work, we shall assume that the velocity-weighted average annihilation cross section is a constant (i.e., S-wave):
  - $\langle \sigma v \rangle = \boldsymbol{a} + \boldsymbol{b}(v/c)^2$ with $b=0$.
- For $b \neq 0$, one has to incorporate the effect of velocity structures inside a halo - an interesting calculation! See, *Campbell, EK & Dutta (2010)*; *Campbell & Dutta (2011)*
  - The overall effect of $b \neq 0$ is to suppress the signal by $(v/c)^2$.

Power Spectrum

- Spherical harmonics transform of the intensity map:
  - $I(\mathrm{n}) = \sum_{lm} a_{lm}\ Y_{lm}(\mathrm{n})$
- Squaring the coefficients and summing over *m* gives the power spectrum:
  - $C_l = (2l+1)^{-1} \sum_m |a_{lm}|^2$
- Just like we would do for the analysis of the CMB maps measured by WMAP.

Power Spectrum Formula

$$C_l = \int \frac{dr}{r^2} \{W([1+z]E_\gamma, r)\}^2 P_f\left(k = \frac{l}{r}; r\right)$$

$$W(E_\gamma, z) = \frac{\langle \sigma v \rangle}{8\pi} \left(\frac{\Omega_\chi \rho_c}{m_\chi}\right)^2 (1+z)^3 \frac{dN_\gamma}{dE_\gamma} e^{-\tau(E_\gamma, z)}$$

- $P_f(k,z)$ is the power spectrum of "density squared," δ^2

$$\langle \tilde{f}_{\boldsymbol{k}} \tilde{f}_{\boldsymbol{k}'} \rangle = (2\pi)^3 \delta^{(3)}(\boldsymbol{k} + \boldsymbol{k}') P_f(k),$$

where

$$f \equiv \delta^2 - \langle \delta^2 \rangle$$

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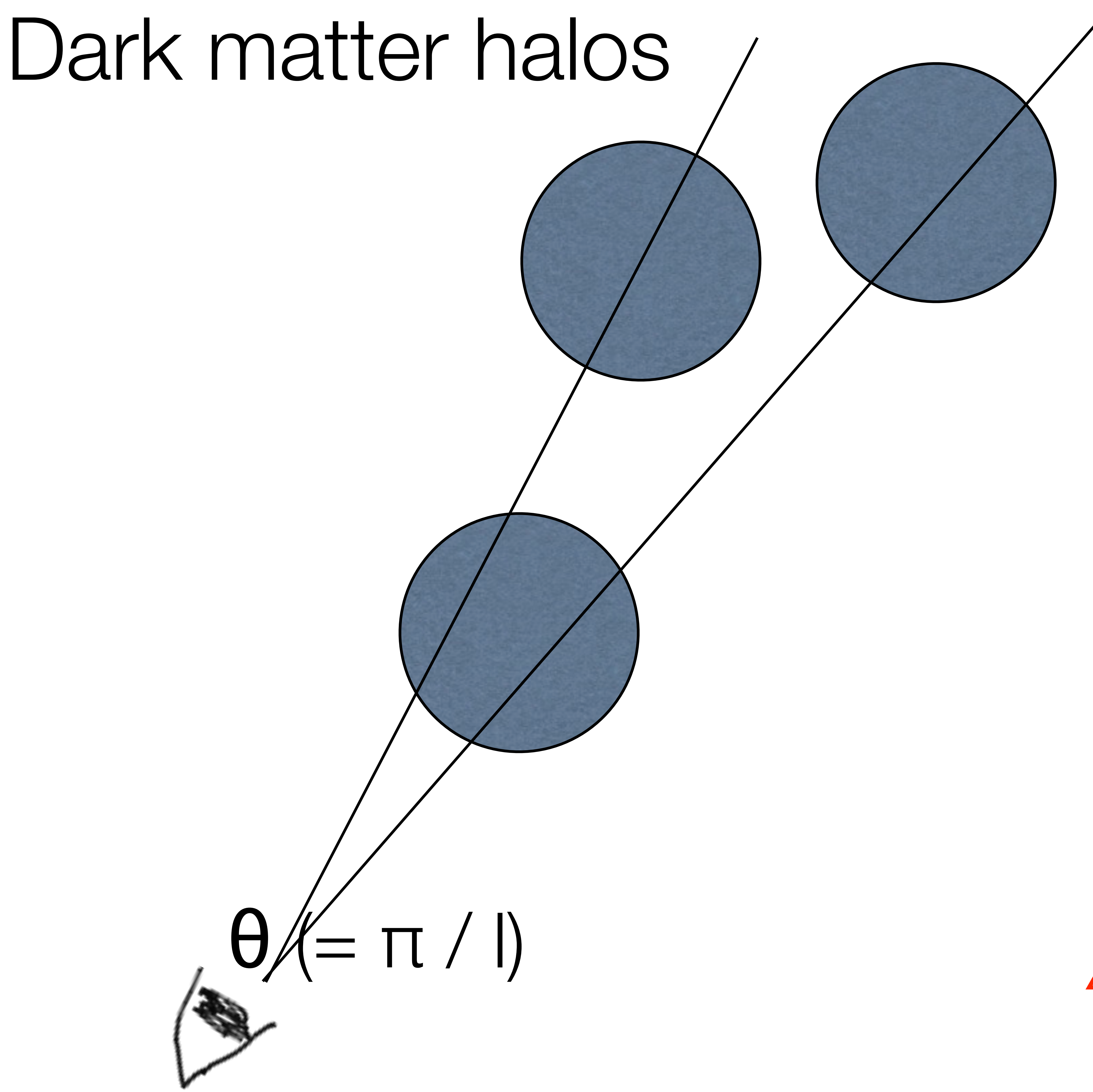
2-point function of δ^2 = 4-point function

A Simple Route to the Power Spectrum



- To compute the power spectrum of anisotropy from dark matter annihilation, we need **three ingredients**:

1. Number of halos as a function of mass,
2. Clustering of dark matter halos, and
3. Dark matter density profile (NFW)
4. Substructure inside of each halo.

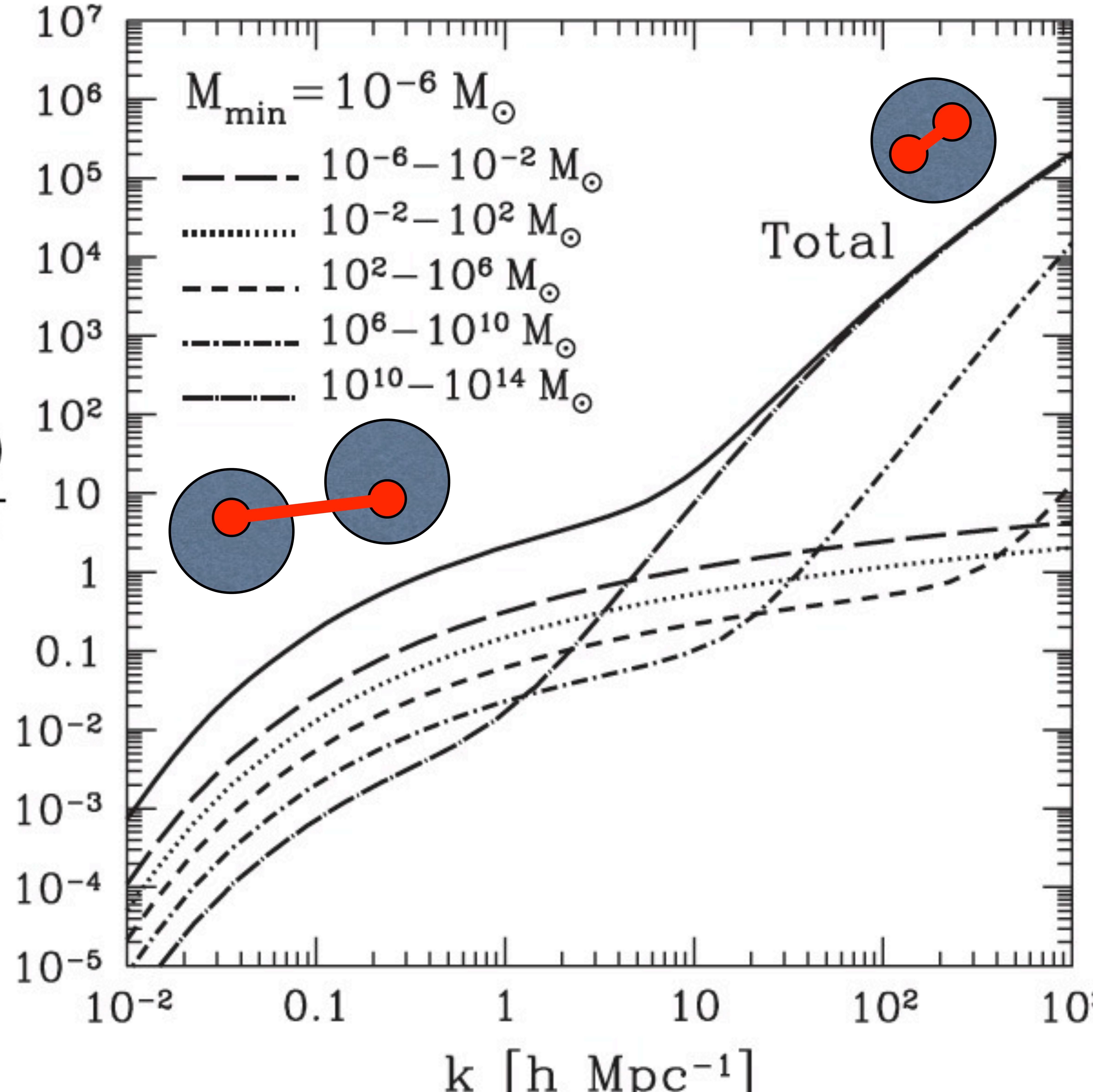
Two Cases

- **Without sub-halos**
  - Halo density distribution is smooth and follows an NFW profile
- **With sub-halos**
  - Halos contain sub-halos whose radial distribution follows an NFW profile
  - This is more realistic, provided that sub-halos survive tidal disruptions

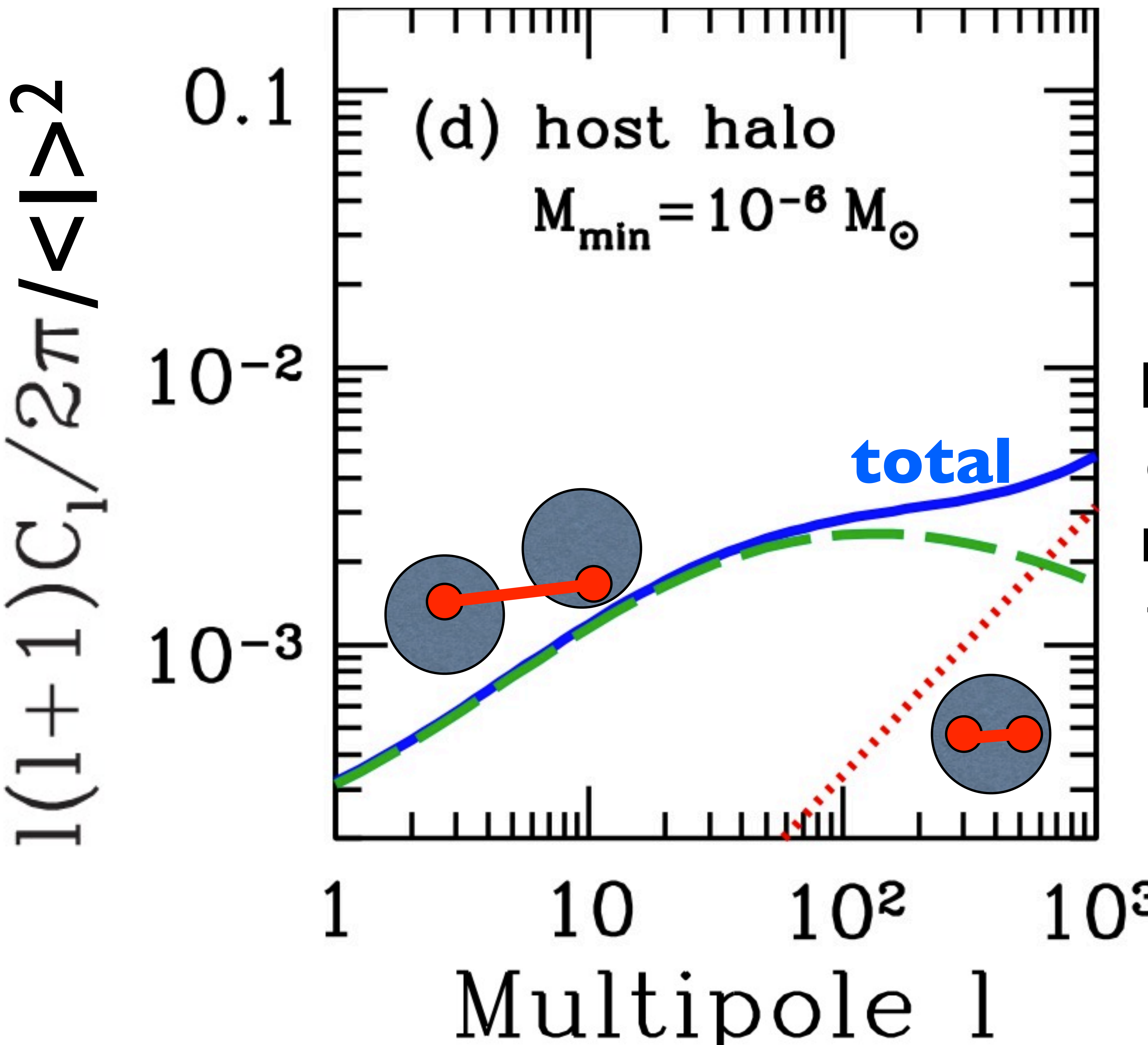
3d Power Spectrum of δ²

Without sub-halos

$$\Delta_f^2(k) \equiv \frac{k^3}{2\pi^2}\frac{P_f(k)}{\langle\delta^2\rangle^2}$$



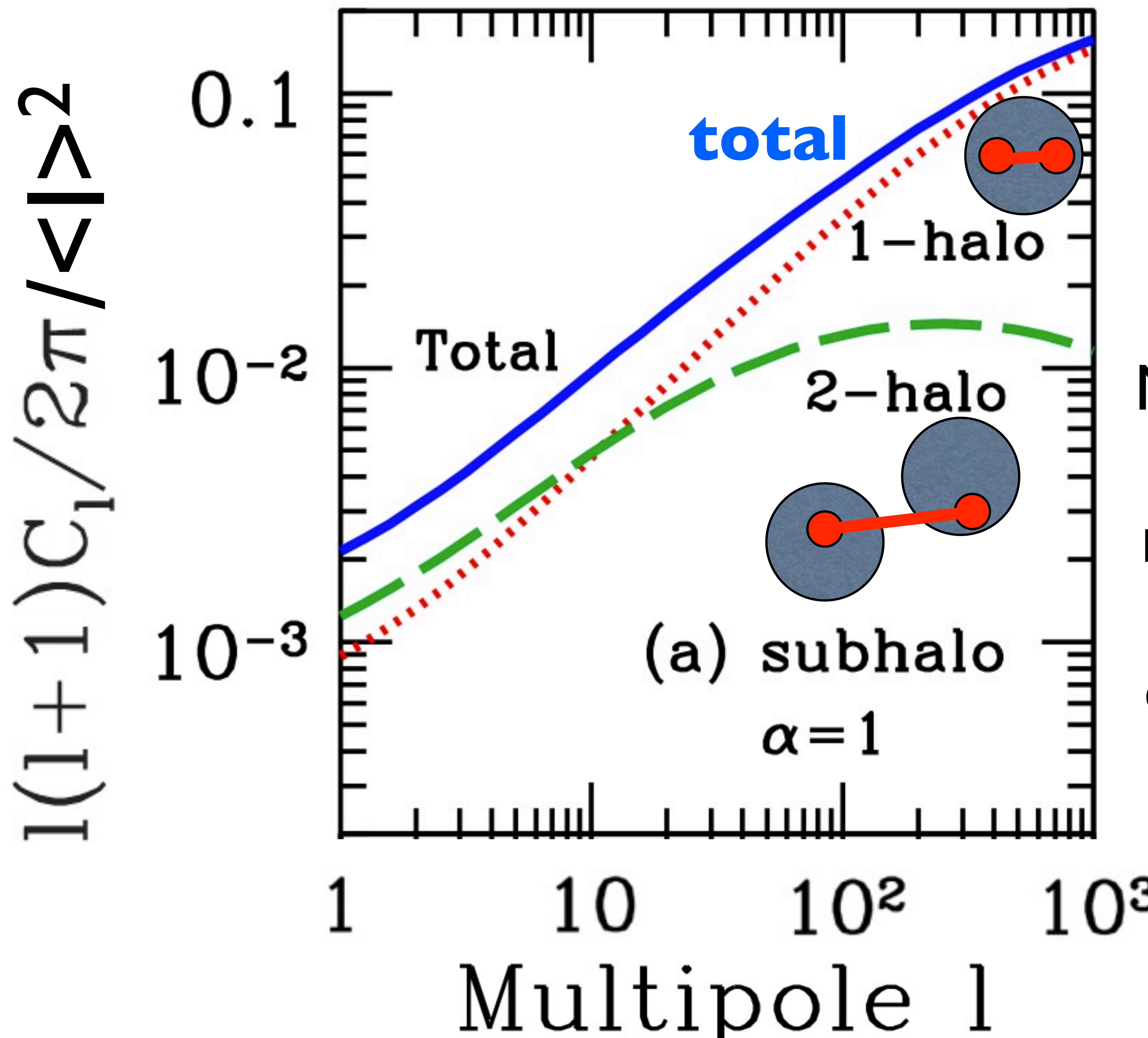
(2d) Angular Power Spectrum



Without sub-halos

Major contributions come from **small-mass halos** in the field (i.e., not inside of large halos)

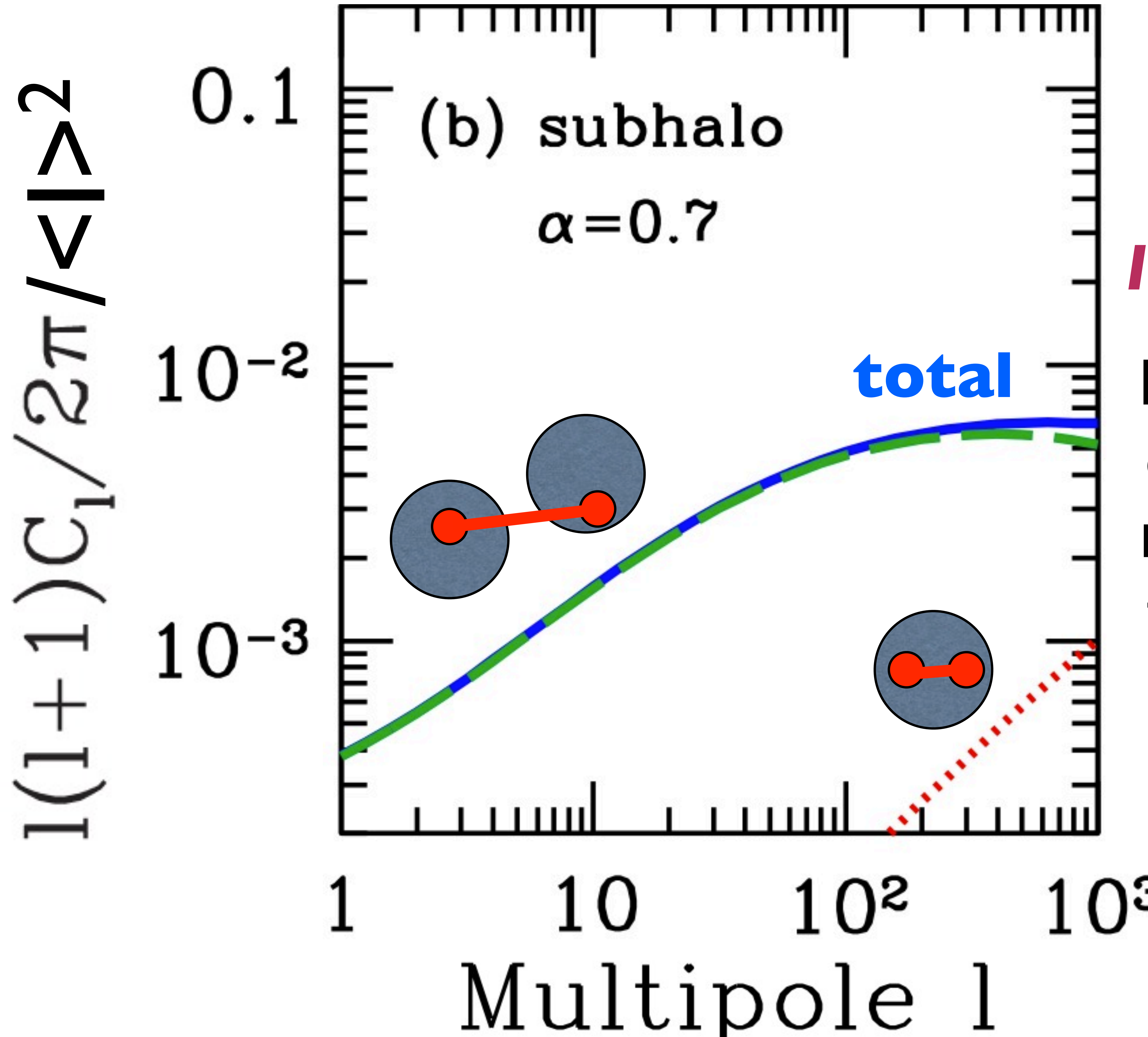
(2d) Angular Power Spectrum



With sub-halos (all surviving)

Major contributions come from **large-mass halos** (such as clusters), which contain lots of sub-halos

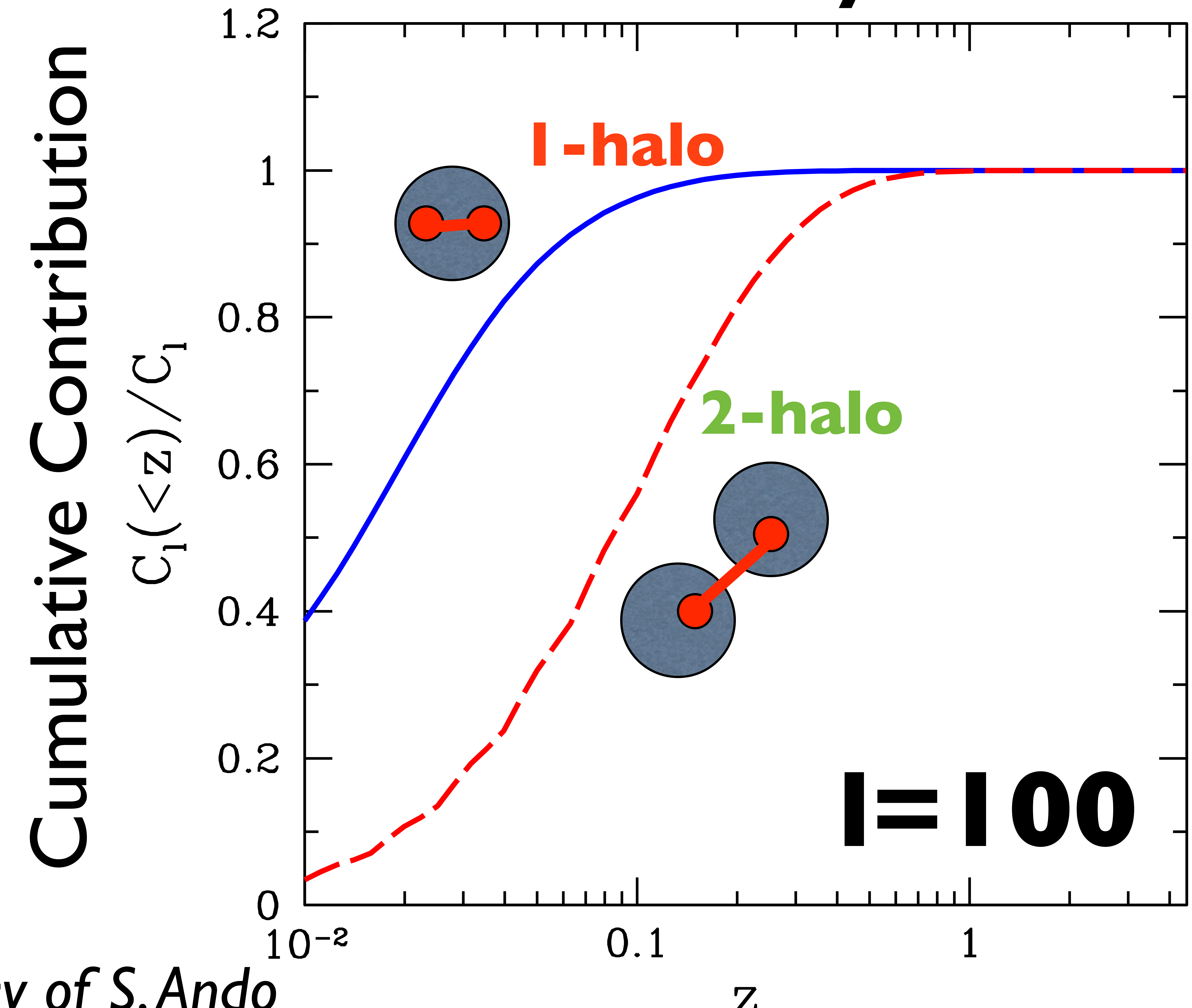
(2d) Angular Power Spectrum



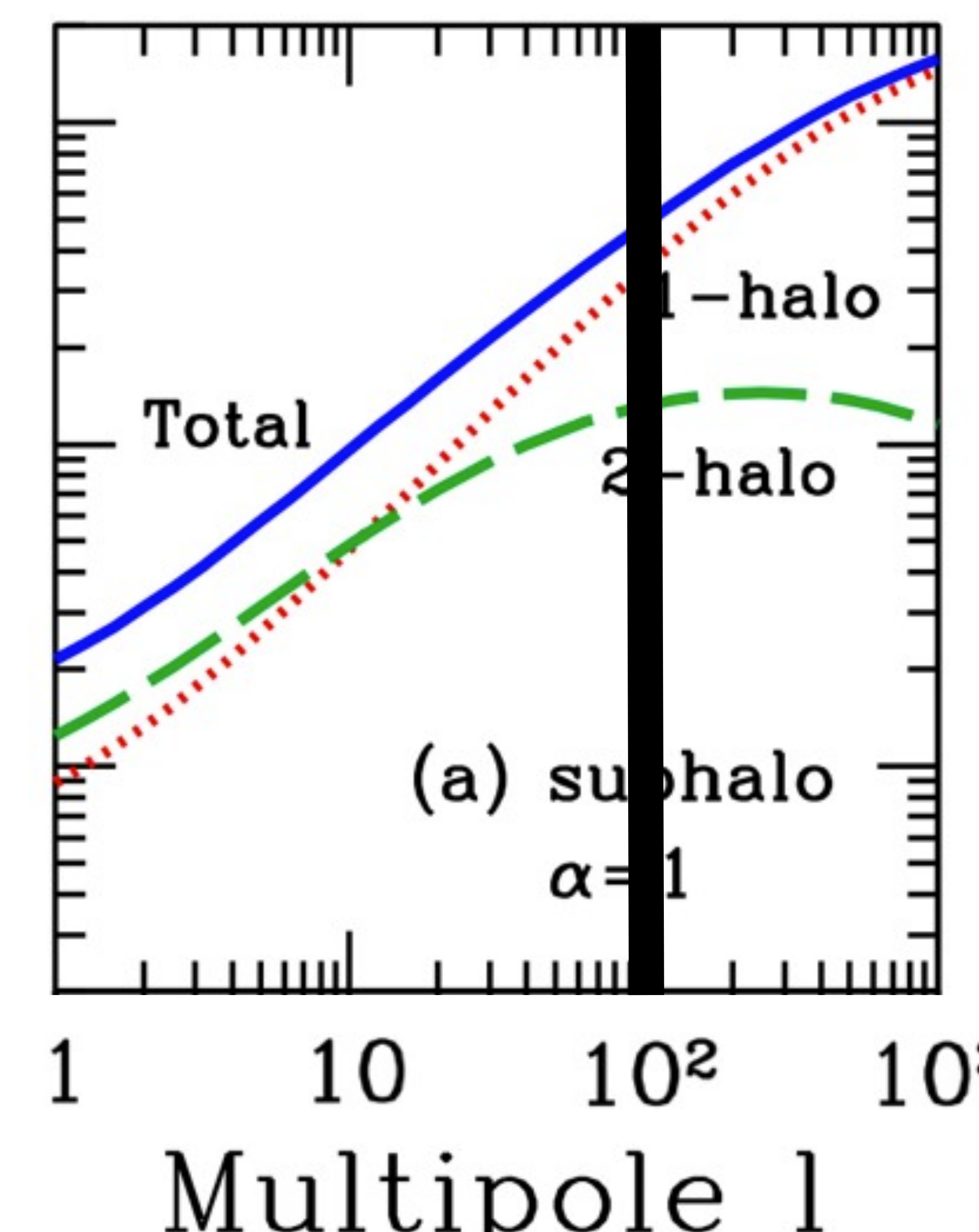
With sub-halos (disrupted in large-mass halos)

Major contributions come from **small-mass halos** in the field (i.e., not inside of large halos)

Which z do they come from?

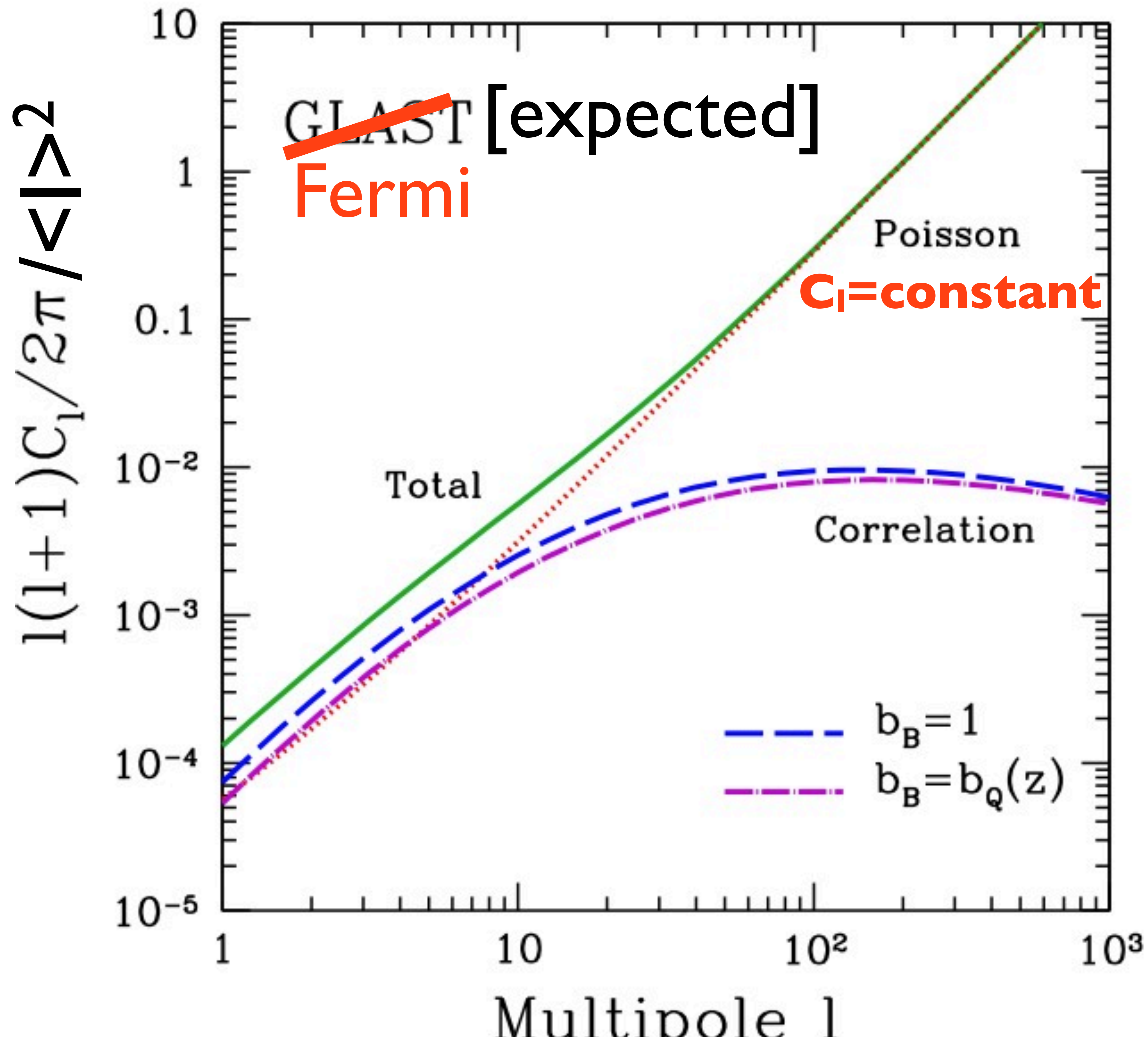


With sub-halos (all surviving)



Courtesy of S.Ando

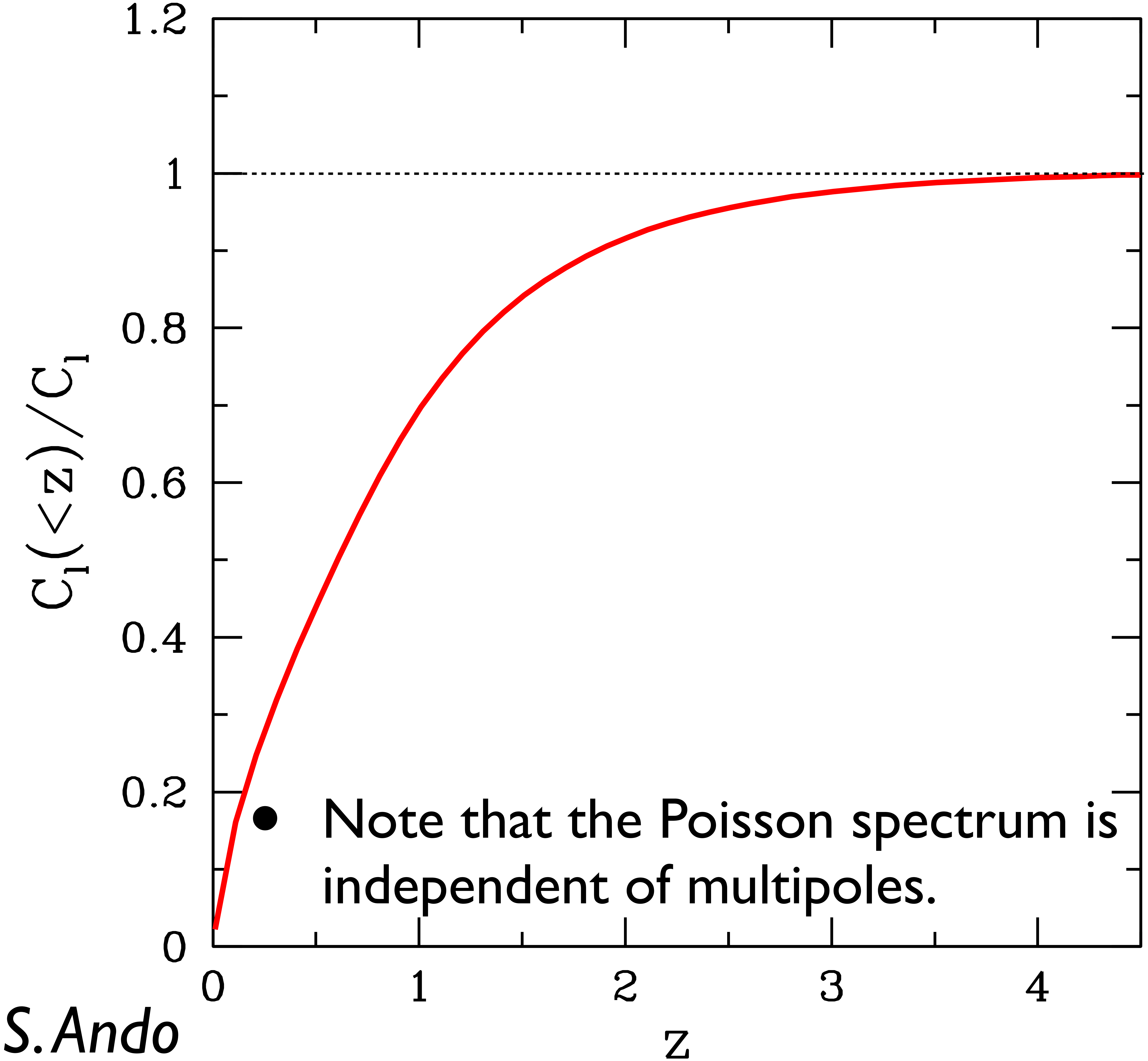
How about blazars?



- Blazars are scarce, so their power spectrum is expected to be completely dominated by the Poisson noise: C_l=constant

Which z do they come from?

Cumulative Contribution



- Note that the Poisson spectrum is independent of multipoles.

Courtesy of S. Ando

OK, those are the predictions.

Ando & EK (2006); Ando, EK, Narumoto & Totani (2007)

- *What do we see in the real data?*

Anisotropies in the Diffuse Gamma-ray Background Measured by the Fermi-LAT

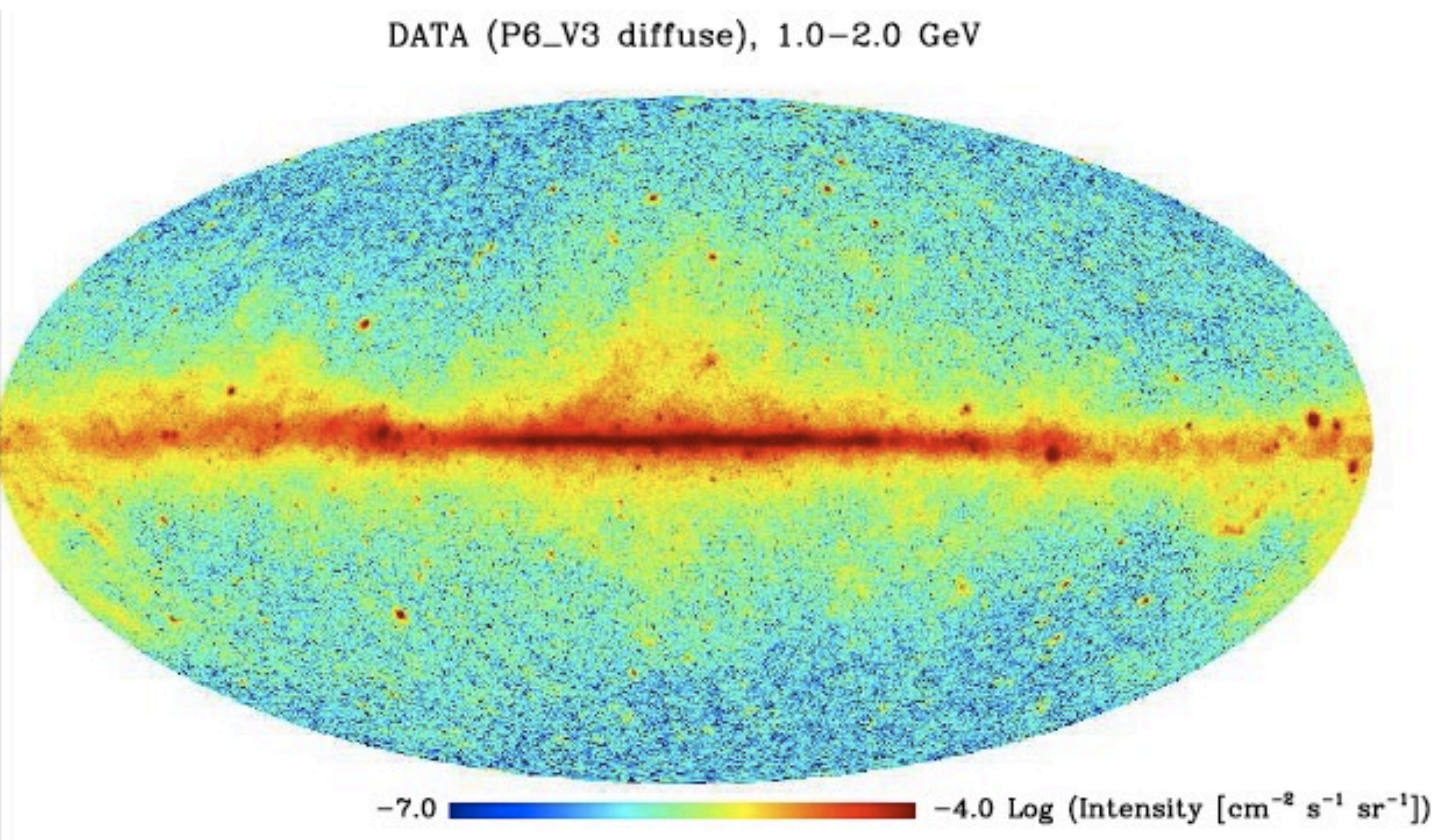
in collaboration with
J. Siegal-Gaskins, A. Cuoco, T. Linden, M.N.Mazziotta, and V.Vitale
(on behalf of Fermi-LAT Team)

PRD, in press (arXiv:1202.2856)

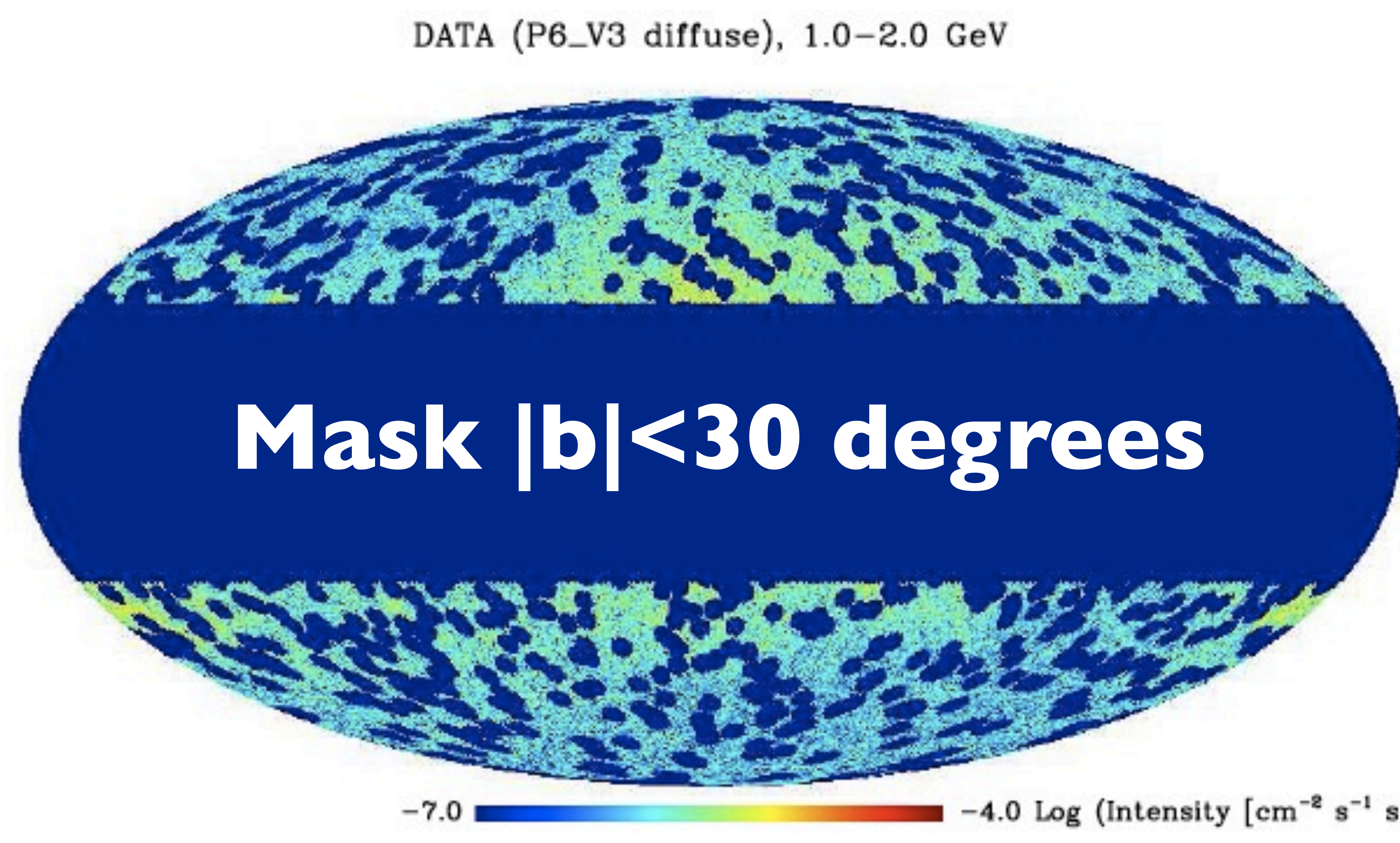
Data Analysis

- Use the same Fermi-LAT map (~22mo, diffuse-class events)
- Apply the usual spherical harmonics transform, and measure the power spectrum!
    - $I(n) = \sum_{lm} a_{lm} Y_{lm}(n)$
    - $C_l = (2l+1)^{-1} \sum_m |a_{lm}|^2$
- Just like we did for the analysis of the CMB maps measured by WMAP.

1.0–2.0 GeV

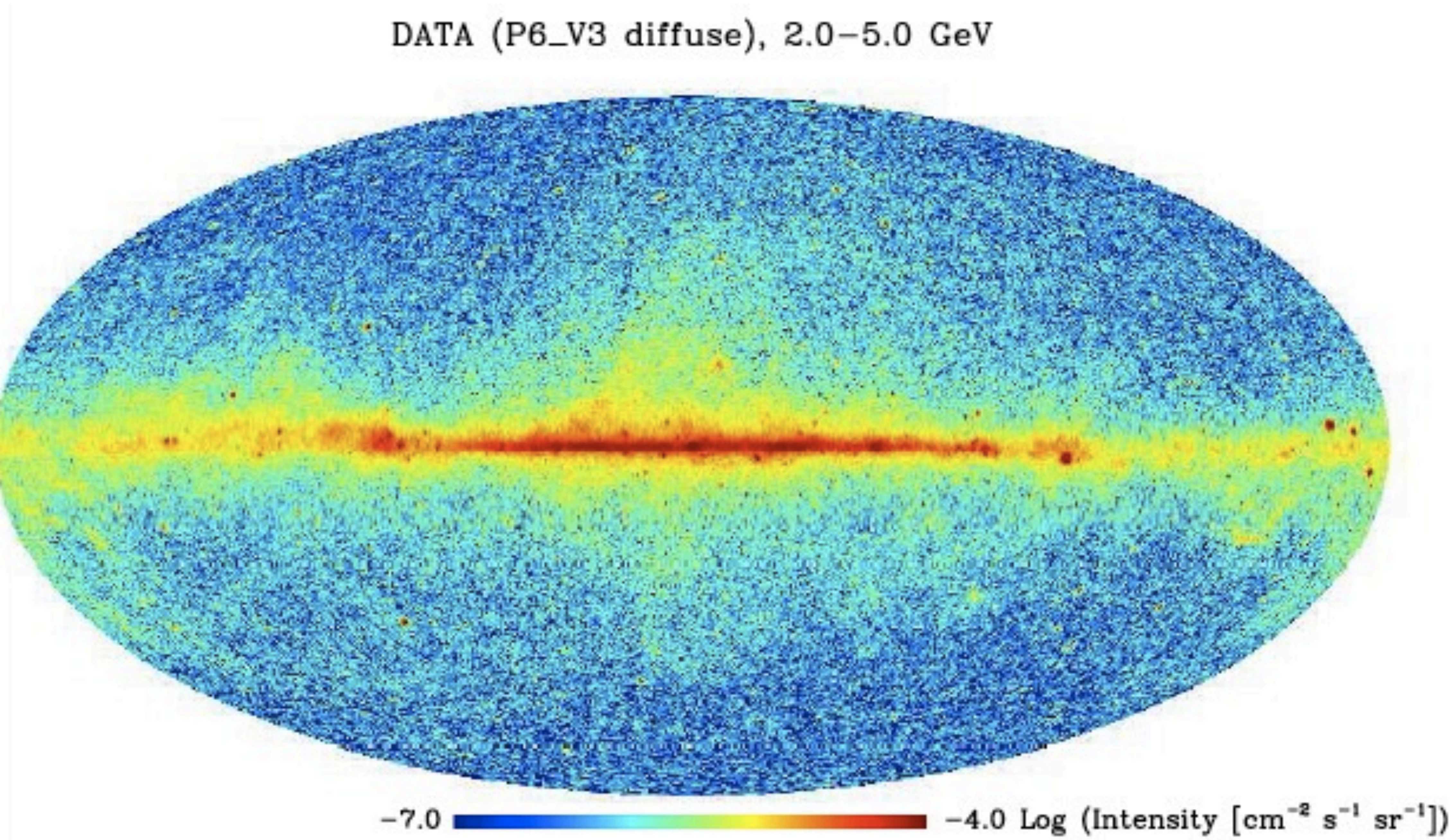


DATA (P6_V3 diffuse), 1.0−2.0 GeV
−7.0
−4.0 Log (Intensity [cm^{-2} s^{-1} sr^{-1}])



DATA (P6_V3 diffuse), 1.0−2.0 GeV
Mask |b|<30 degrees
−7.0
−4.0 Log (Intensity [cm^{-2} s^{-1} s

2.0–5.0 GeV


DATA (P6_V3 diffuse), 2.0−5.0 GeV
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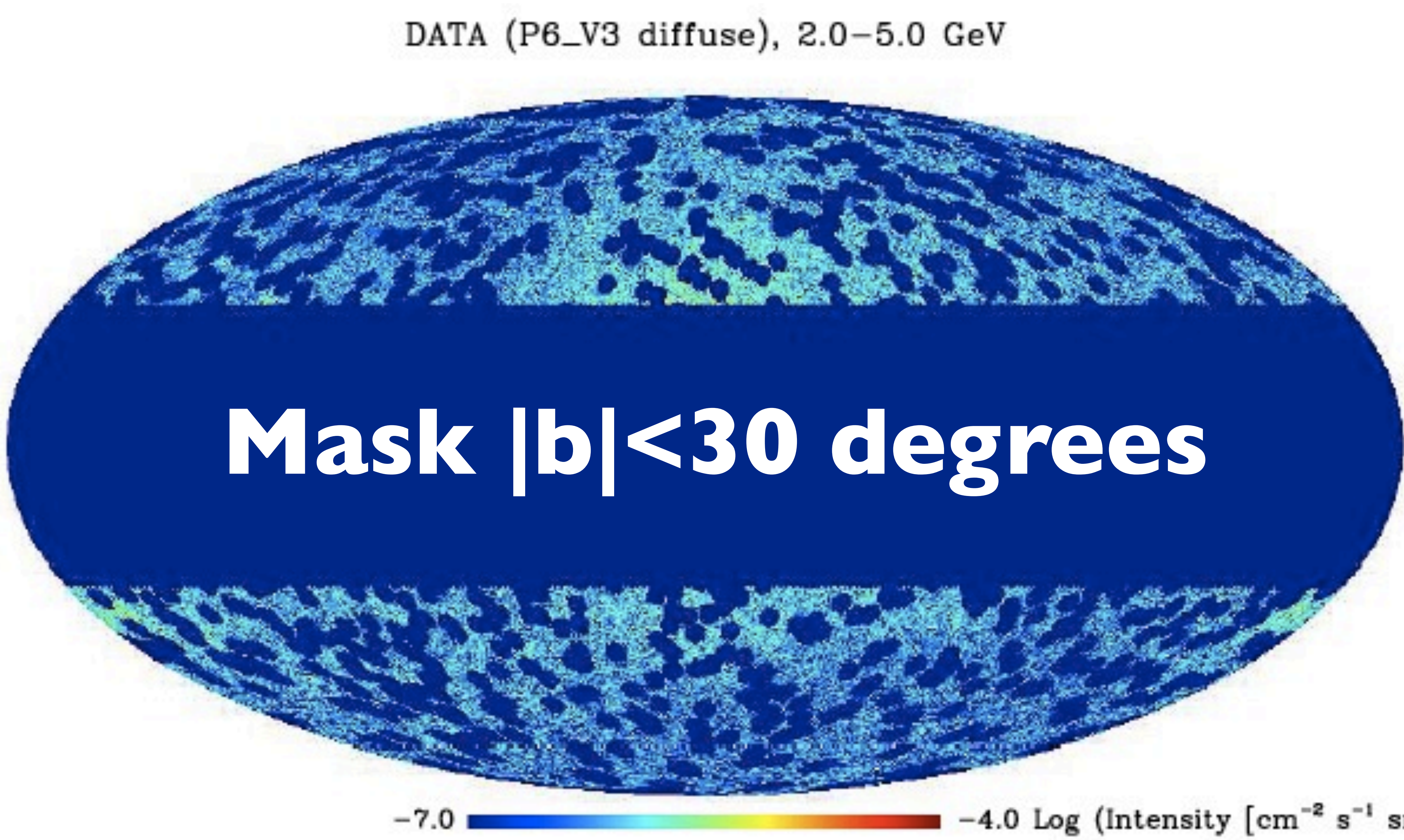
DATA (P6_V3 diffuse), 2.0−5.0 GeV
Mask |b|<30 degrees
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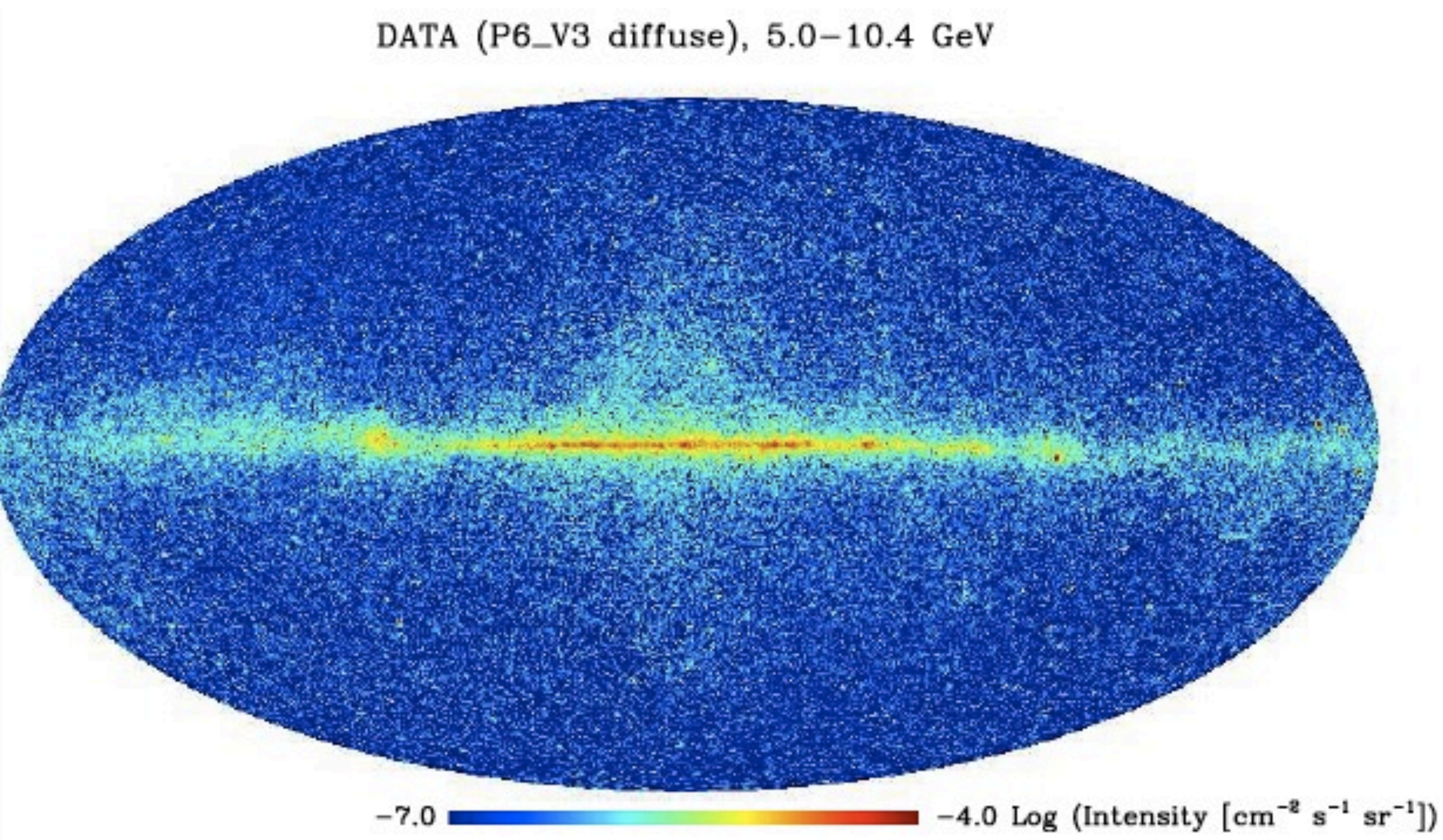
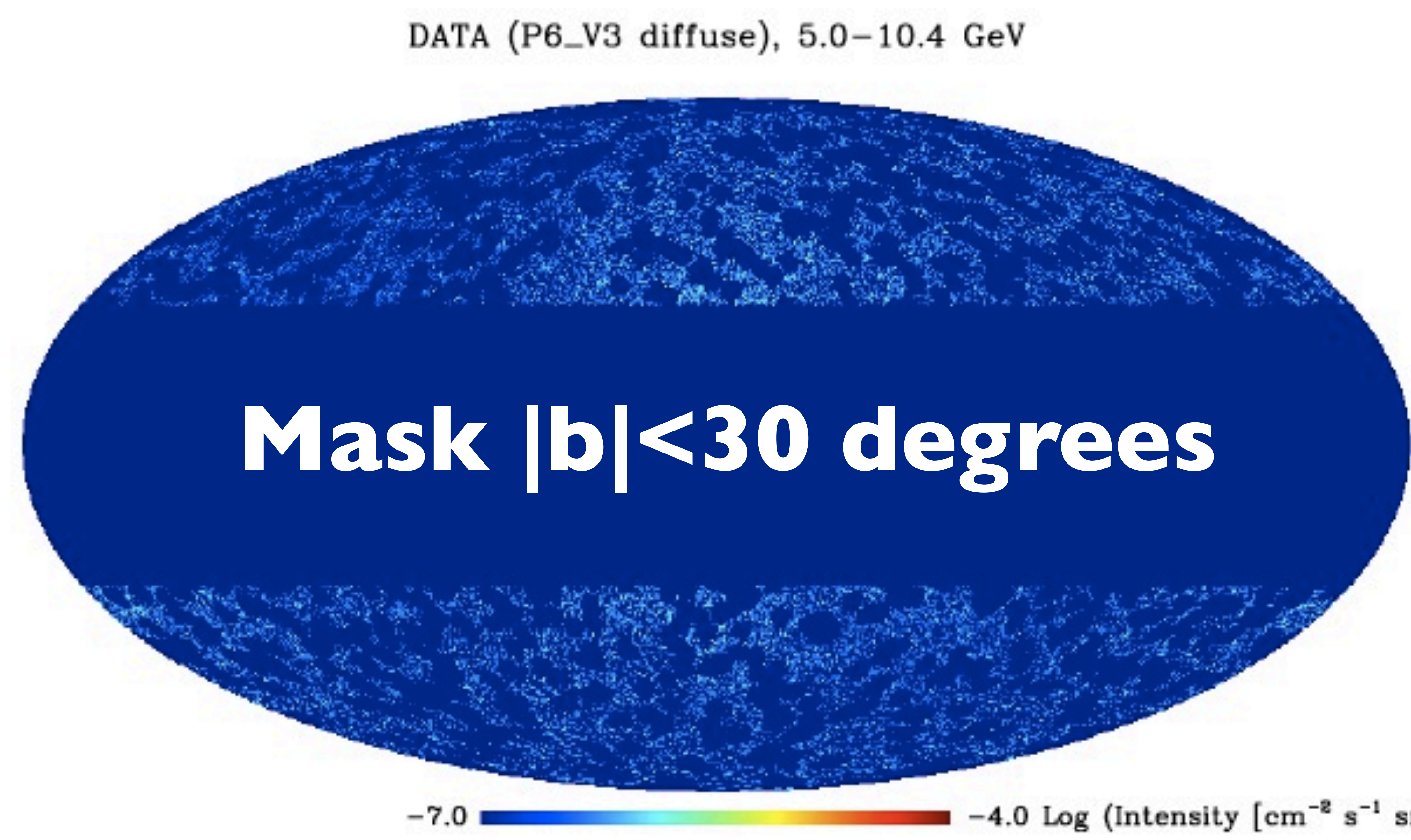
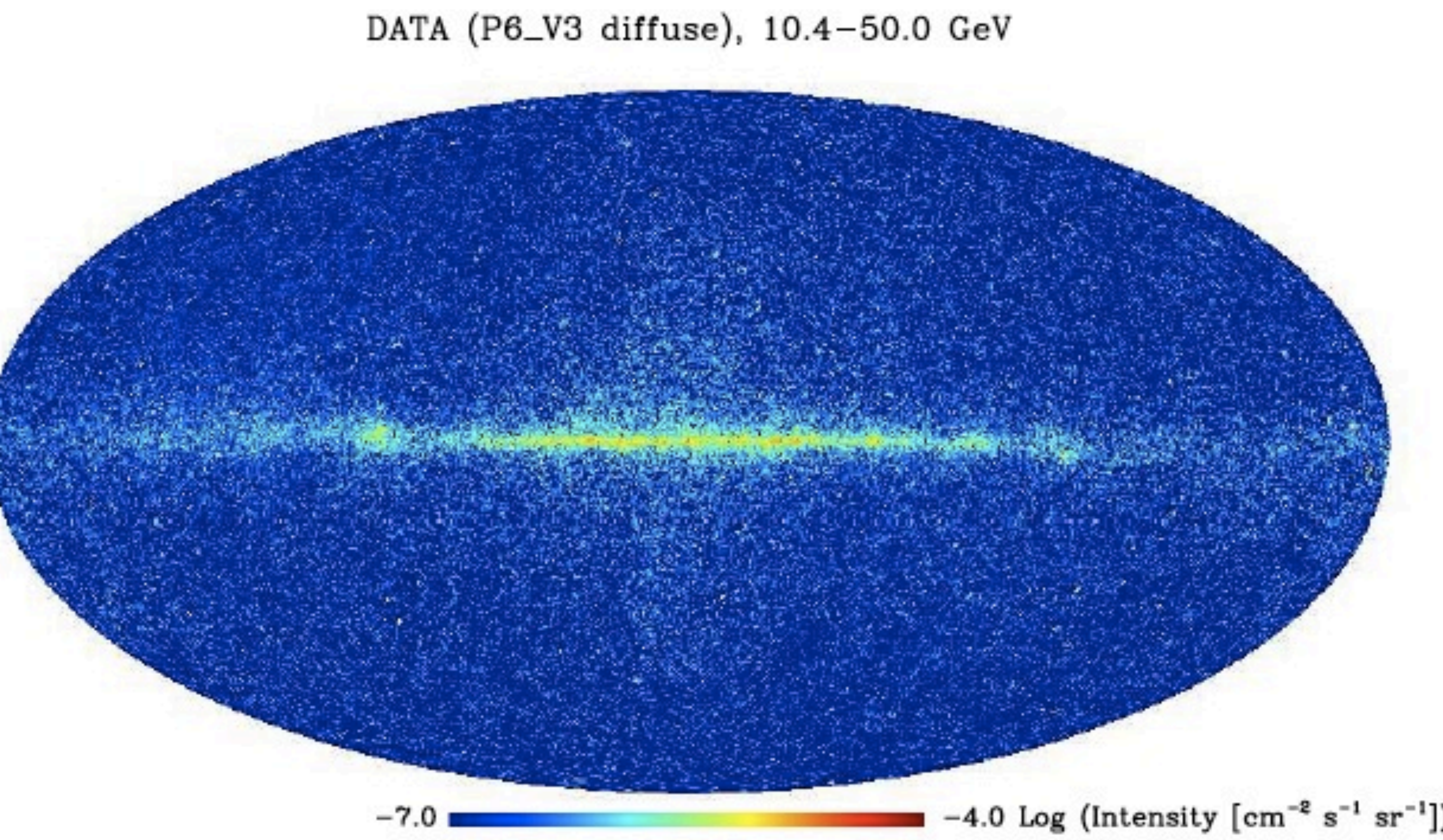
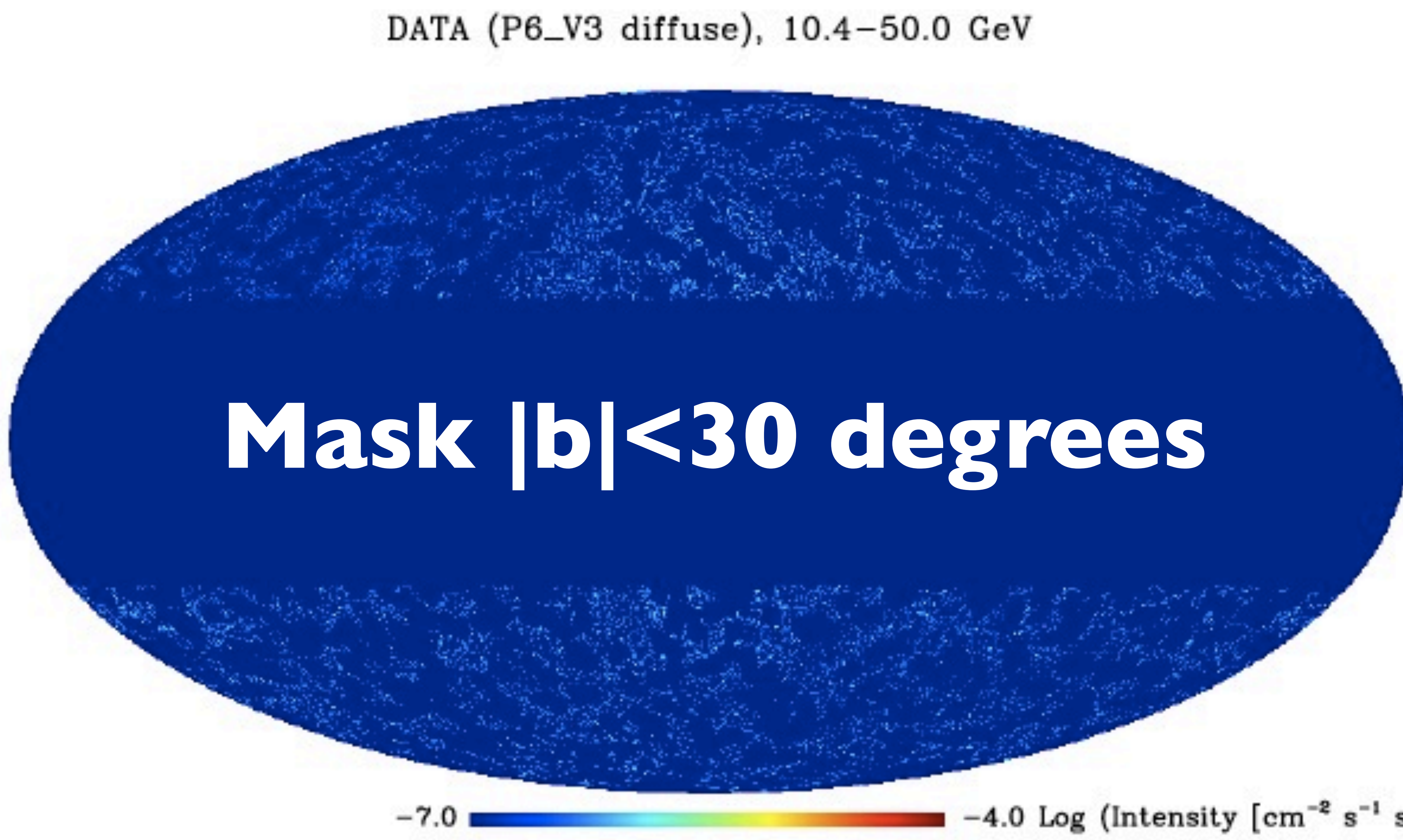
5.0–10.4 GeV


DATA (P6_V3 diffuse), 5.0−10.4 GeV
−7.0
−4.0 Log (Intensity [cm^{-2} s^{-1} sr^{-1}])


DATA (P6_V3 diffuse), 5.0−10.4 GeV
Mask |b|<30 degrees
−7.0
−4.0 Log (Intensity [cm^{-2} s^{-1} s

10.4–50.0 GeV


DATA (P6_V3 diffuse), 10.4−50.0 GeV
−7.0
−4.0 Log (Intensity [cm^{-2} s^{-1} sr^{-1}])


DATA (P6_V3 diffuse), 10.4−50.0 GeV
Mask |b|<30 degrees
−7.0
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Fermi vs WMAP

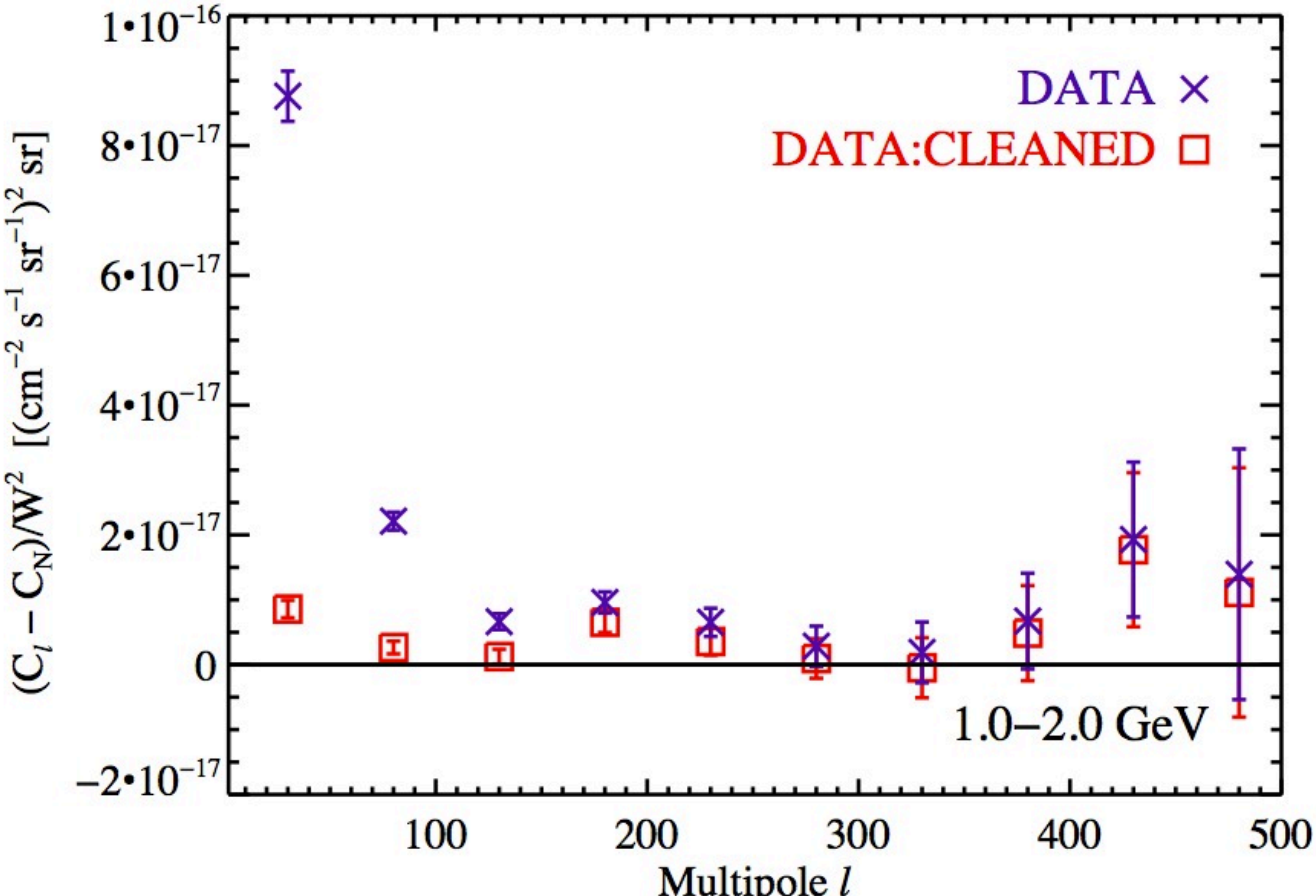
- There is an important difference between Fermi and WMAP maps
  - We count photons to produce Fermi maps; thus, there is the "photon noise" (Poisson statistics) in the power spectrum, which we must subtract.
  - Photon noise, C_N, is independent of multipoles, and is given by the mean number density of photons over the sky (which is precisely calculable).

Point Spread Function

- The measured power spectrum is the true power spectrum multiplied by the harmonic transform of the "point spread function" (PSF). (It is called the "beam transfer function" in the WMAP analysis.)
- PSF is by no means a Gaussian - we use two different versions of Fermi-LAT instrument response functions and compute PSF.
- We then compute $W_\ell^{\rm beam}(E) = 2\pi \int_{-1}^{1} d\cos\theta P_\ell(\cos(\theta)){\rm PSF}(\theta;{\rm E})$
- The attenuation by PSF is corrected as **$(C_l - C_N)/W_l^2$**.
  - Two versions of PSF gave consistent answers.

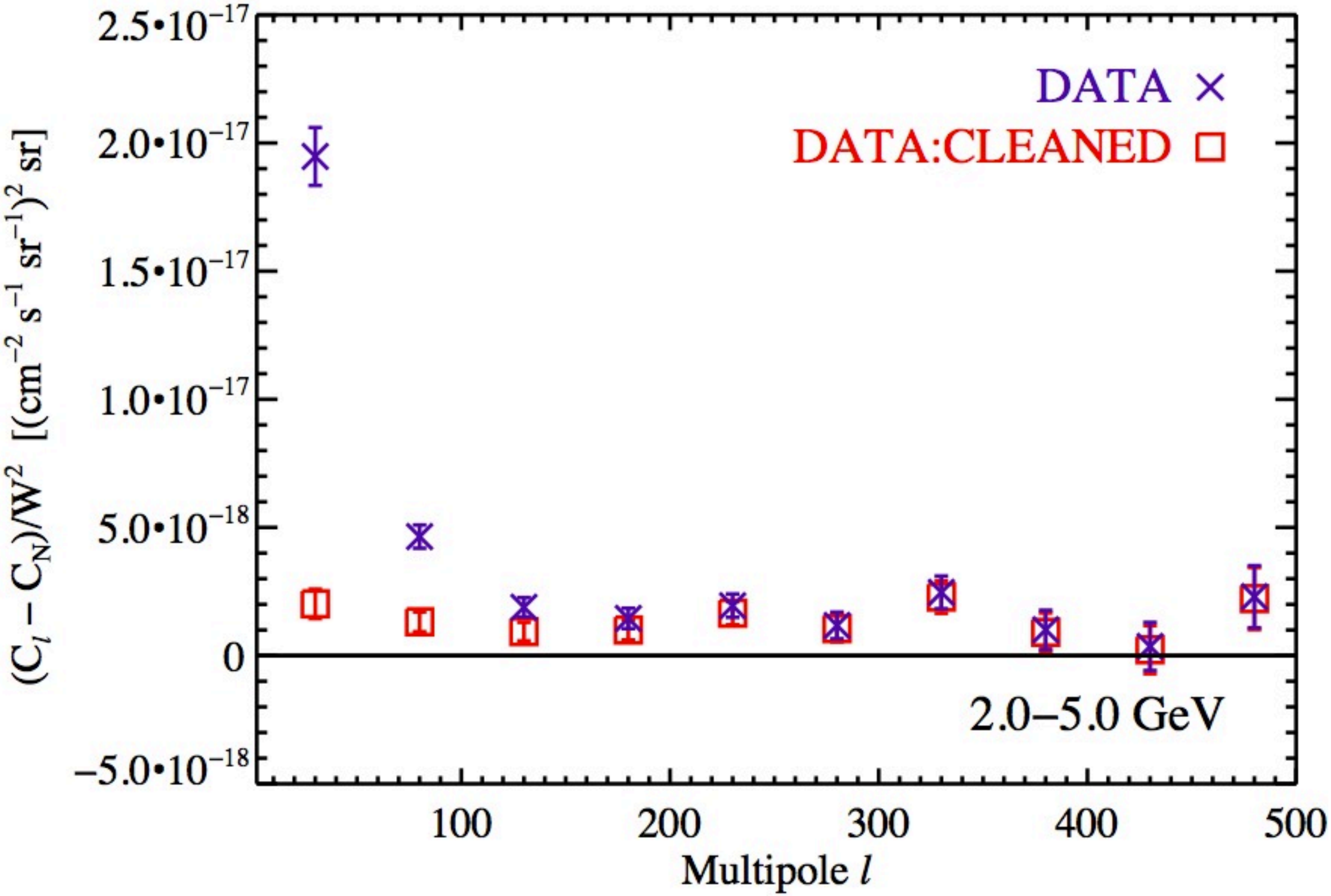
DATA: CLEANED = Galactic Model Map Subtracted

1.0–2.0 GeV



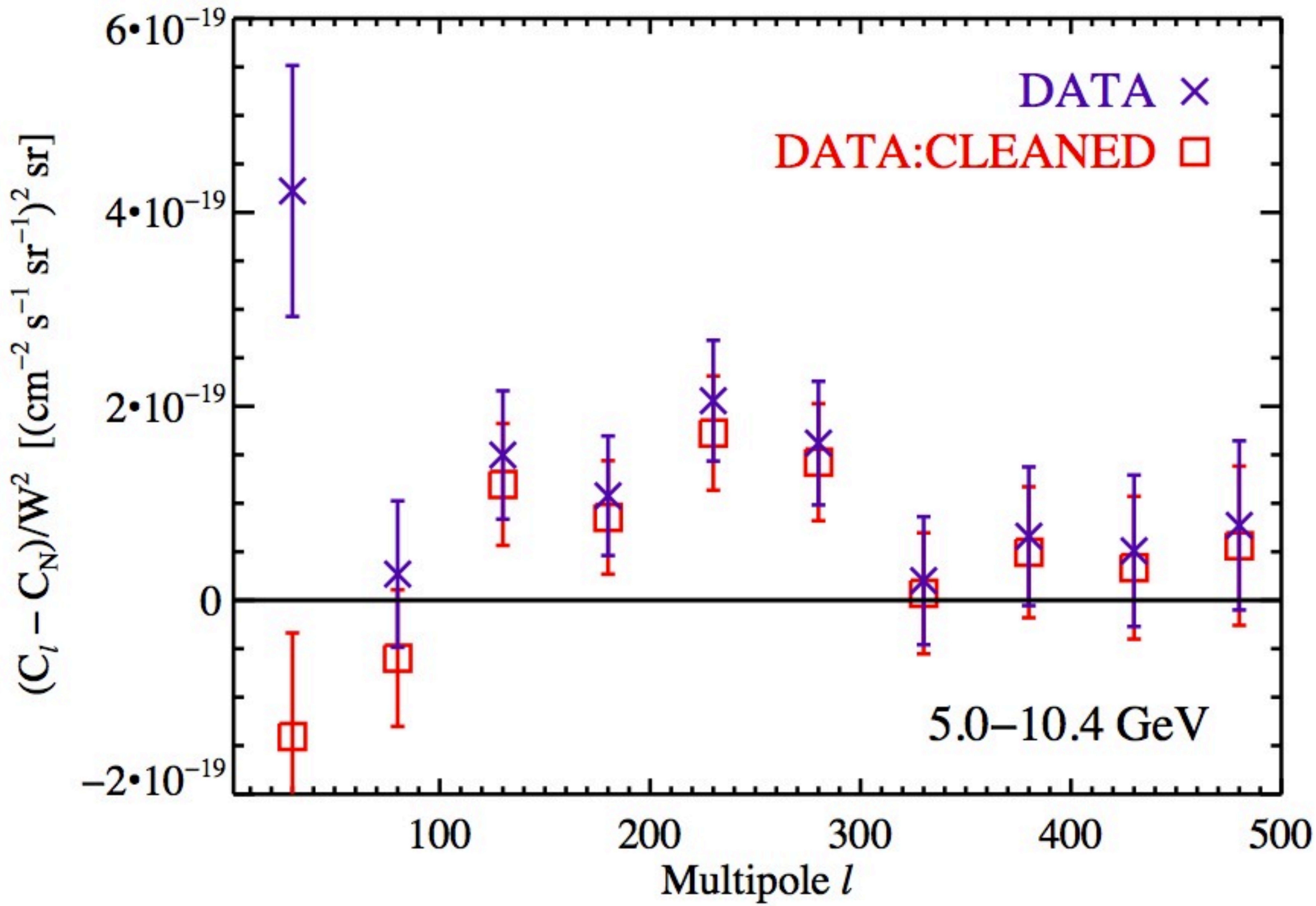
DATA: CLEANED = Galactic Model Map Subtracted

2.0–5.0 GeV



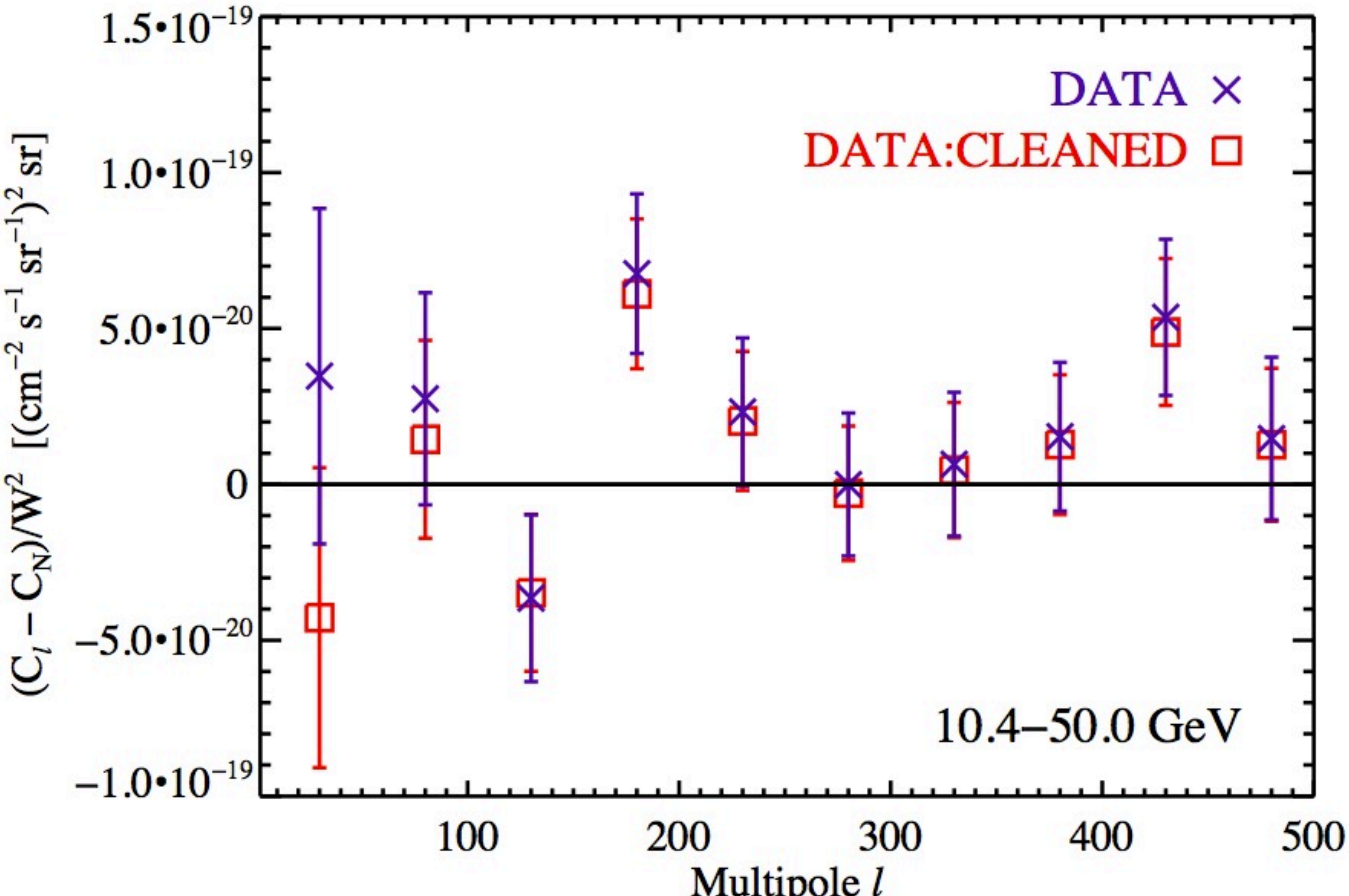
DATA: CLEANED = Galactic Model Map Subtracted

5.0–10.4 GeV



DATA: CLEANED = Galactic Model Map Subtracted

10.4–50.0 GeV



Observations

- At l<150, the power spectrum rises towards lower multipoles (larger angular scales).
  - The Galactic foreground contribution
- At l>150, we detect the excess power over the photon noise.
  - The excess power appears to be constant over multipoles, indicating the contribution from unclustered point sources (more later)

Focus on l>150

- The Galactic model maps indicate that the power we see at l<150 is largely coming from the Galactic foreground.
- The small-scale power at l>150 is not very much affected by the foreground, and thus is usable for investigating the **extra-galactic gamma-ray background**.

Advantage of C_l

- When working with the mean intensity spectrum, one always has to worry about:
  - Diffuse Galactic emission
  - Background due to unrejected charged particles
- However, in C_l, these components appear only at low multipoles, cleanly separating, spatially, the extra-galactic signals and the contamination. **This is a big advantage!**

No Scale Dependence

- Fitting the measured power spectrum at l>150 to a single power-law: $C_l \sim l^n$

$E_{\rm min}$	$E_{\rm max}$	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

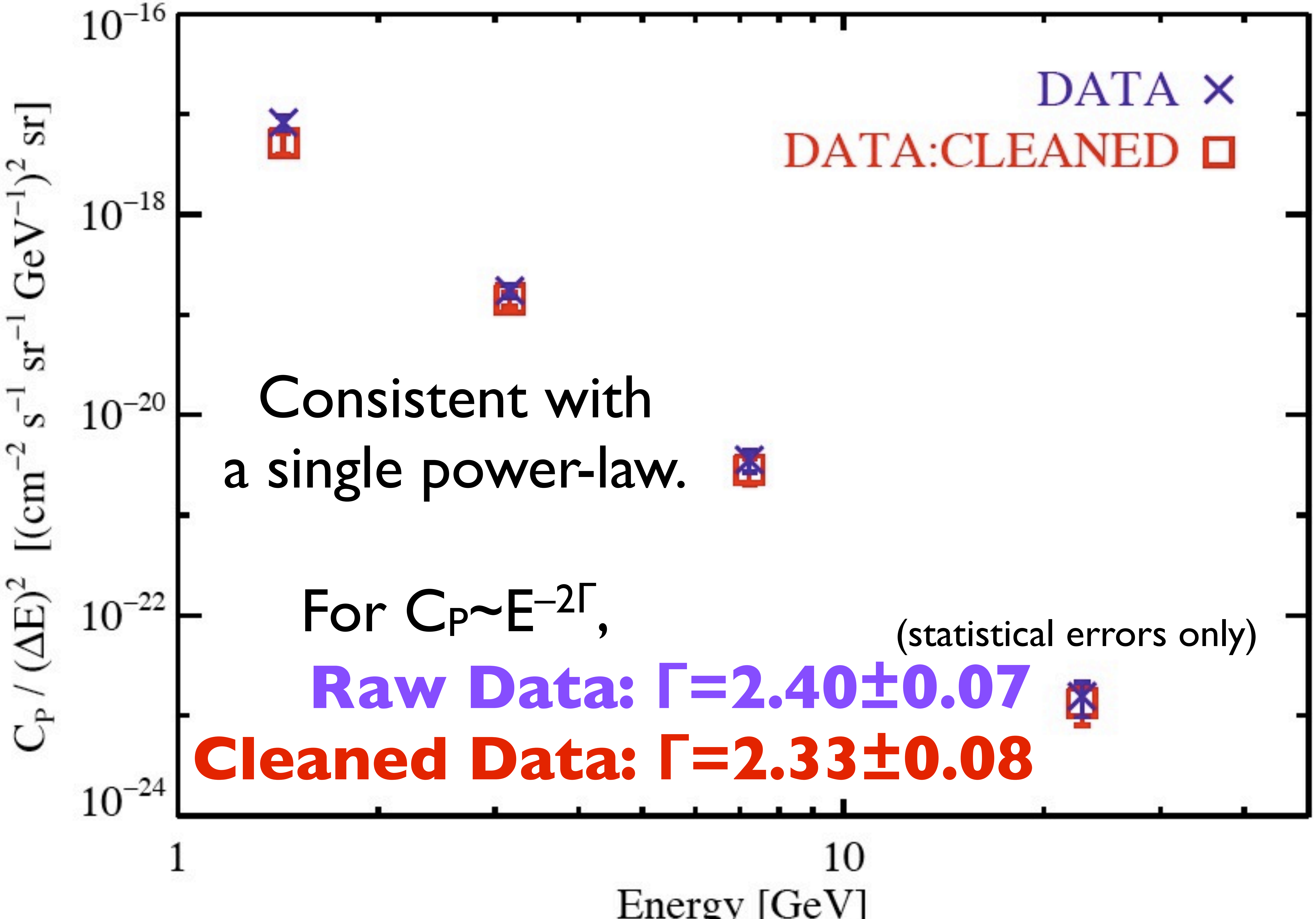
Therefore, we will find the best-fitting constant power, C_P.
("P" stands for "Poisson contribution")

First detection of the extra-galactic γ-ray anisotropy

	$E_{\rm min}$ [GeV]	$E_{\rm max}$ [GeV]	$C_{\rm P}$ $[({\rm cm}^{-2}\ {\rm s}^{-1}\ {\rm sr}^{-1})^2\ {\rm sr}]$	Significance
DATA	1.04	1.99	$7.39 \pm 1.14 \times 10^{-18}$	6.5σ
	1.99	5.00	$1.57 \pm 0.22 \times 10^{-18}$	7.2σ
	5.00	10.4	$1.06 \pm 0.26 \times 10^{-19}$	4.1σ
	10.4	50.0	$2.44 \pm 0.92 \times 10^{-20}$	2.7σ
DATA:CLEANED	1.04	1.99	$4.62 \pm 1.11 \times 10^{-18}$	4.2σ
	1.99	5.00	$1.30 \pm 0.22 \times 10^{-18}$	6.0σ
	5.00	10.4	$0.845 \pm 0.246 \times 10^{-19}$	3.4σ
	10.4	50.0	$2.11 \pm 0.86 \times 10^{-20}$	2.4σ

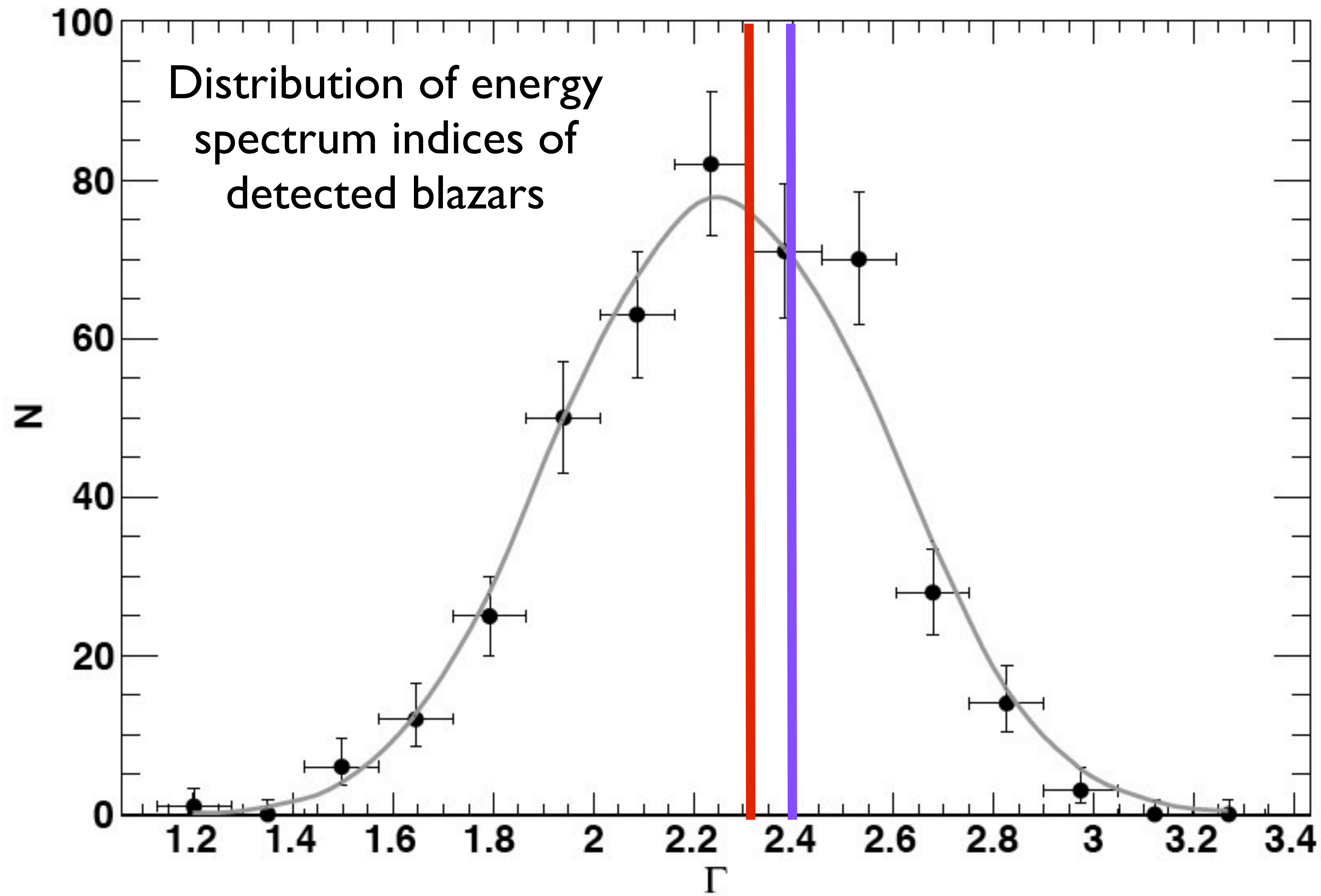
- Many-sigma detections up to 10 GeV!

Energy Spectrum



Fermi-LAT Collaboration, ApJ, 720, 435 (2010)

Are we seeing blazars?

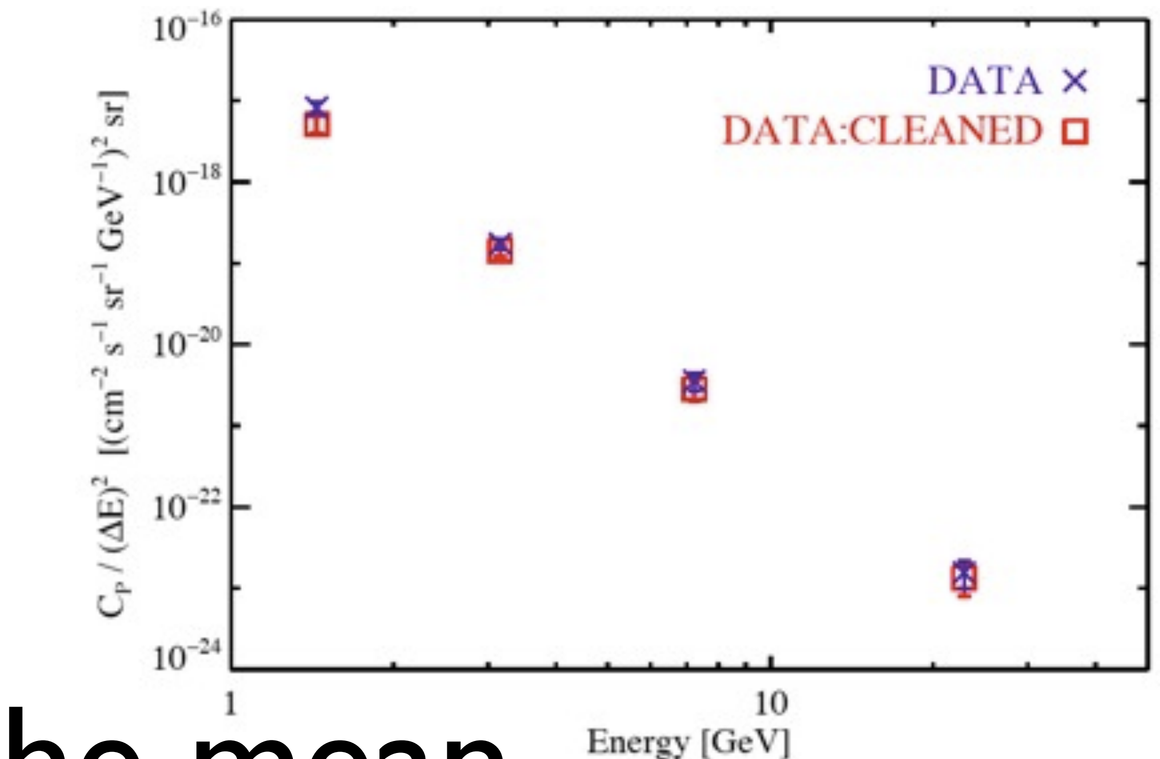


- The energy spectrum of anisotropy (from unresolved sources) agrees with that of **detected** blazars.

Interpreting the Results

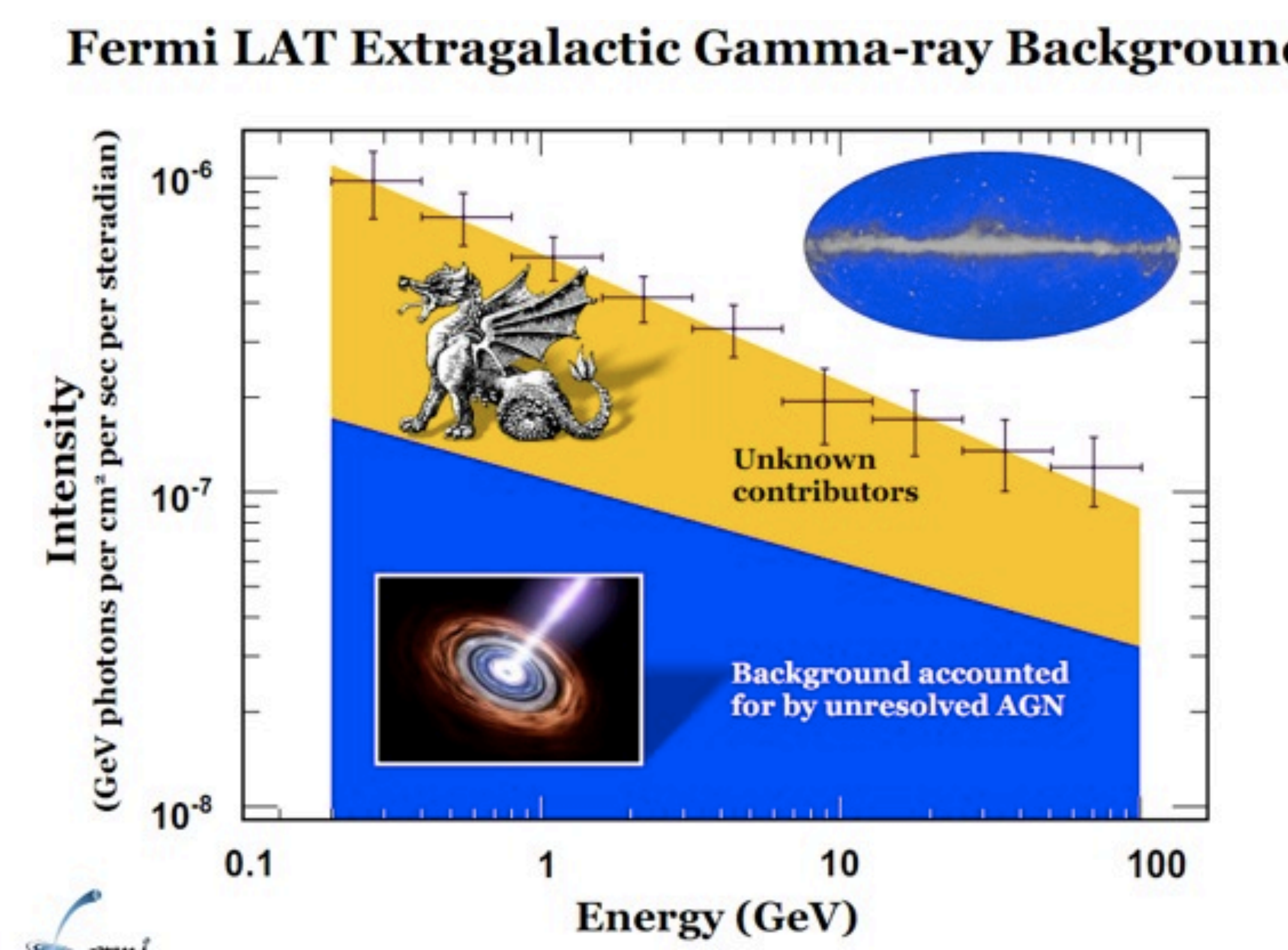
- Unresolved, unclustered point sources contribute to C_P as

$$C_{\rm P} = \int_0^{S_c} dS \; S^2 \frac{{\rm d}N}{{\rm d}S}$$



- Unresolved, point sources contribute to the mean intensity as

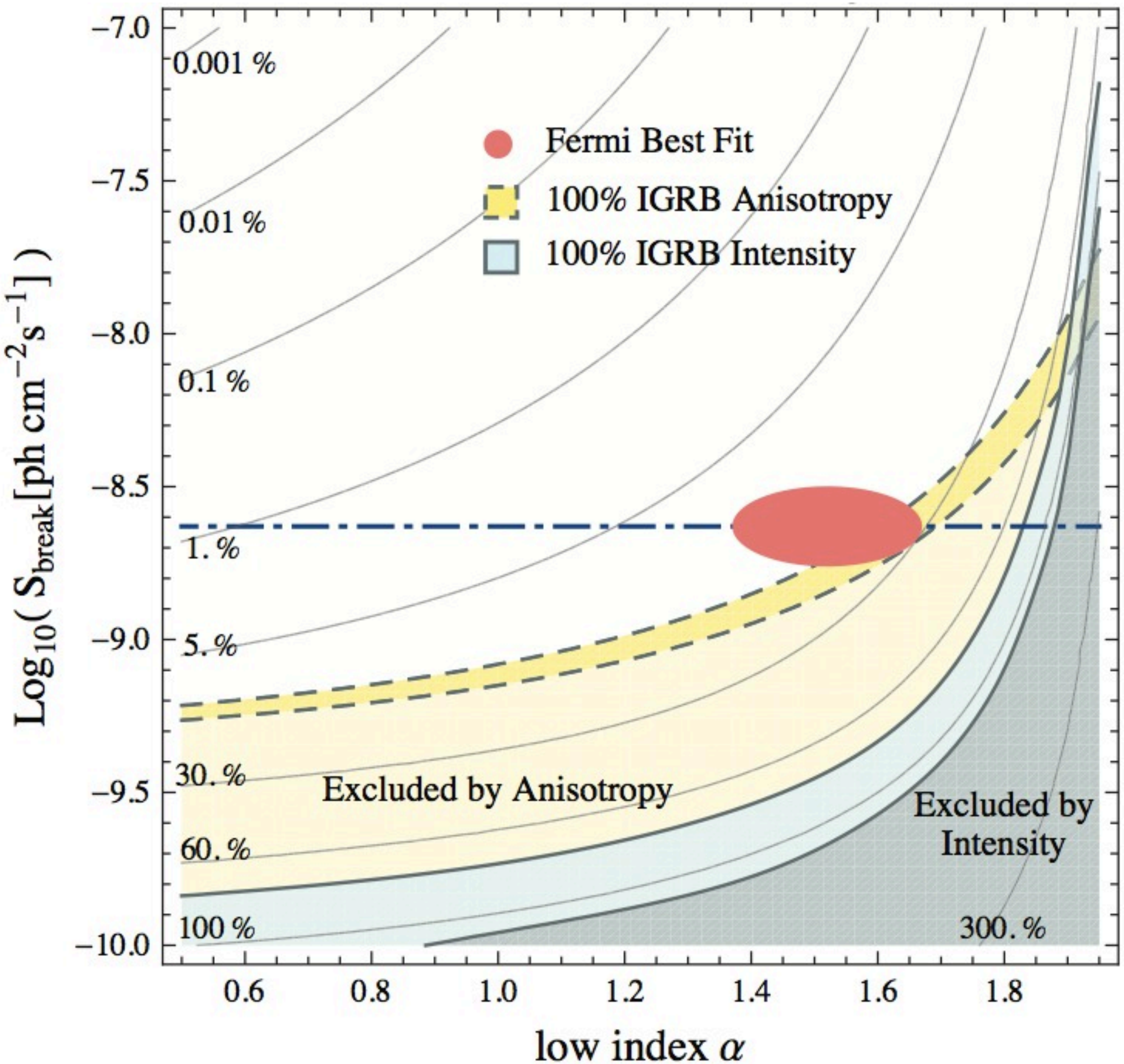
$$</> = \int_0^{S_c} dS \; S \; \frac{{\rm d}N}{{\rm d}S}$$



- ***Are they consistent with the data?***

Cuoco, EK & Siegal-Gaskins, arXiv:1202.5309

The answer seems YES



$$C_{\mathrm{P}} = \int_0^{S_c} dS\ S^2 \frac{\mathrm{d}N}{\mathrm{d}S}$$

$$\langle I \rangle = \int_0^{S_c} dS\ S\ \frac{\mathrm{d}N}{\mathrm{d}S}$$

$$\frac{dN}{dS} = \begin{cases} A\ S^{-\beta} & S \geq S_{\mathrm{b}} \\ A\ S_{\mathrm{b}}{}^{-\beta+\alpha} S^{-\alpha} & S < S_{\mathrm{b}} \end{cases}$$

Vary S_b and α

(Fix a bright-end slope, β, to the measured value, β=2.38)

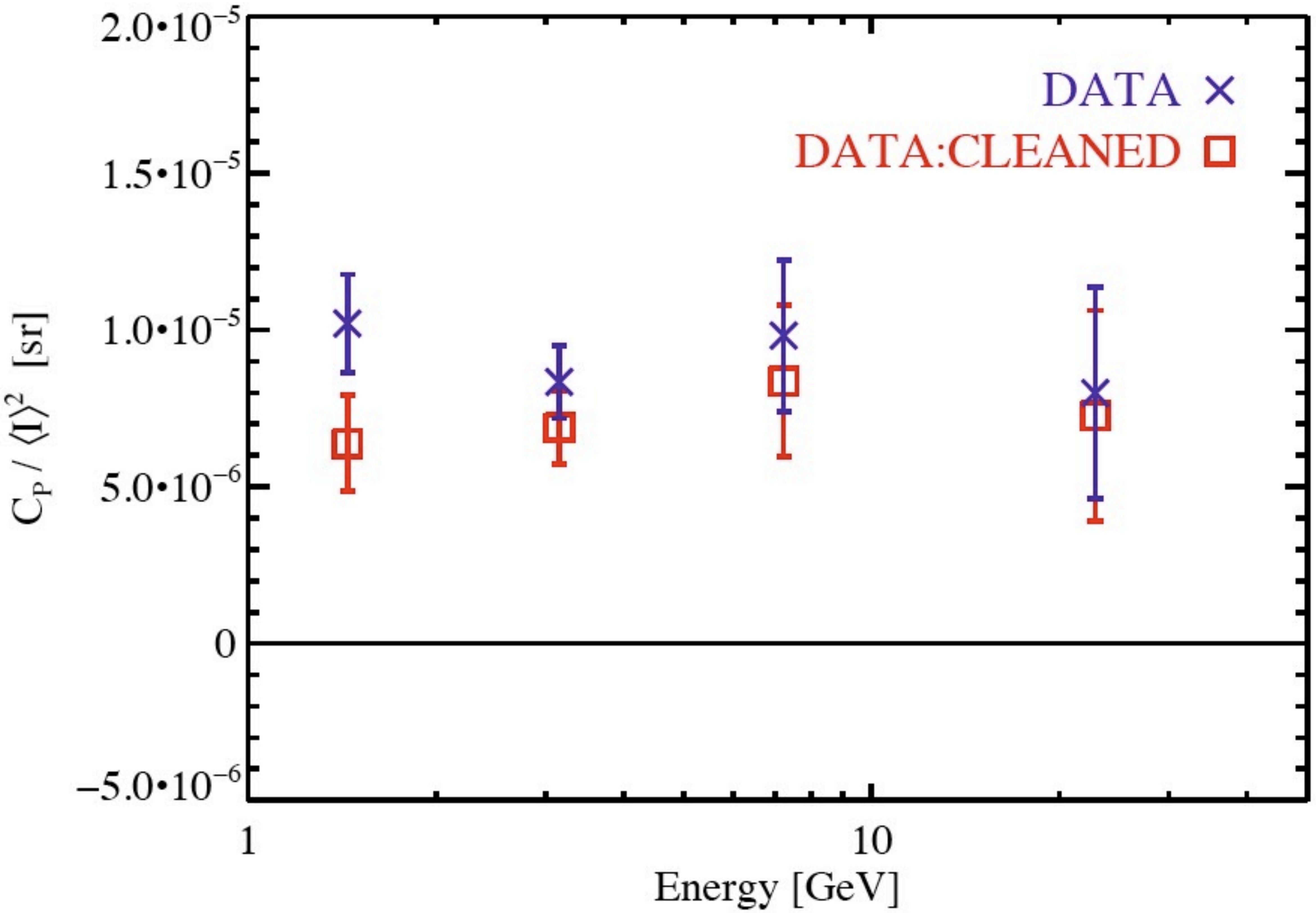
Cuoco, EK & Siegal-Gaskins, arXiv:1202.5309

The answer seems YES

- Our results are consistent with the following interpretation:
  - The detected anisotropy is largely due to unresolved blazars.
  - The amplitude of anisotropy is consistent with the fact that the same unresolved blazars contribute only to a fraction (~30%) of the mean gamma-ray background.
- These two, independent measurements give us a consistent picture of the gamma-ray sky.

Another Look

- Define the "dimensionless fluctuation power" by dividing C_P by the measured mean intensity squared:
  - $C_P \to C_P/\langle I\rangle^2 \sim$ **0.91** (**0.69**) $\pm$ 0.08 $\times 10^{-5}$ sr
(statistical errors only)



$E_{\rm min}$ [GeV]	$E_{\rm max}$ [GeV]	$C_{\rm P}/\langle I\rangle^2$ [10^{-6} sr]	Significance
1.04	1.99	10.2 ± 1.6	6.5σ
1.99	5.00	8.35 ± 1.17	7.1σ
5.00	10.4	9.83 ± 2.42	4.1σ
10.4	50.0	8.00 ± 3.37	2.4σ
1.04	1.99	6.38 ± 1.53	4.2σ
1.99	5.00	6.90 ± 1.16	5.9σ
5.00	10.4	8.37 ± 2.41	3.5σ
10.4	50.0	7.27 ± 3.36	2.2σ

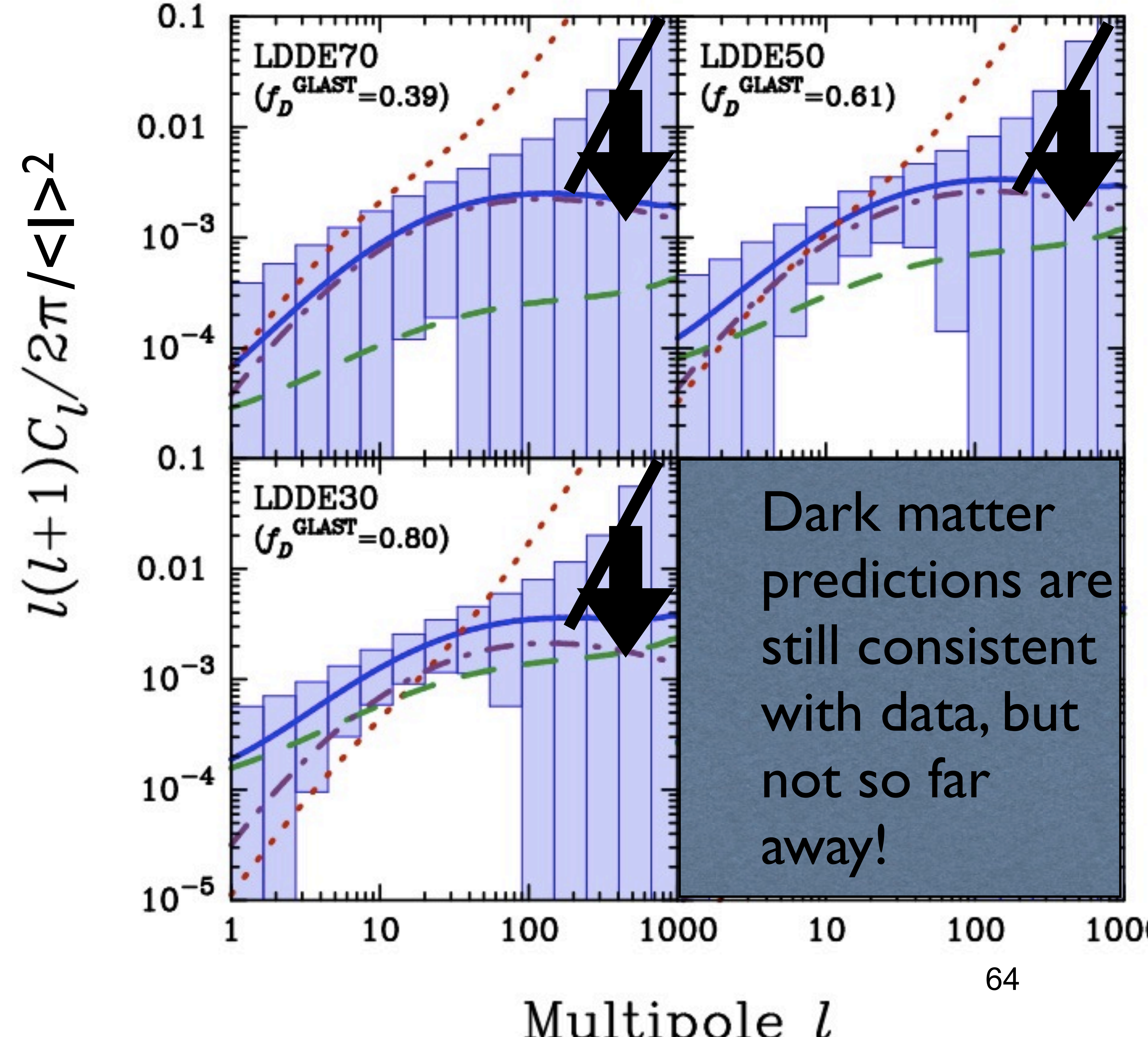
What about Dark Matter?

- Our results can be used to place limits on the dark matter properties.
- Subtracting the blazar contribution, the upper limit on the constant power at l>150 is
    - **$C_P/\langle I\rangle^2 < 10^{-6}$ sr**
- What would this mean?

2006/2007 Predictions

DM ann.
Blazars

- Watch out for the factor of l(l+1).
  - Poisson spectrum gives ~l^2
- We constrain C_l only at l>150

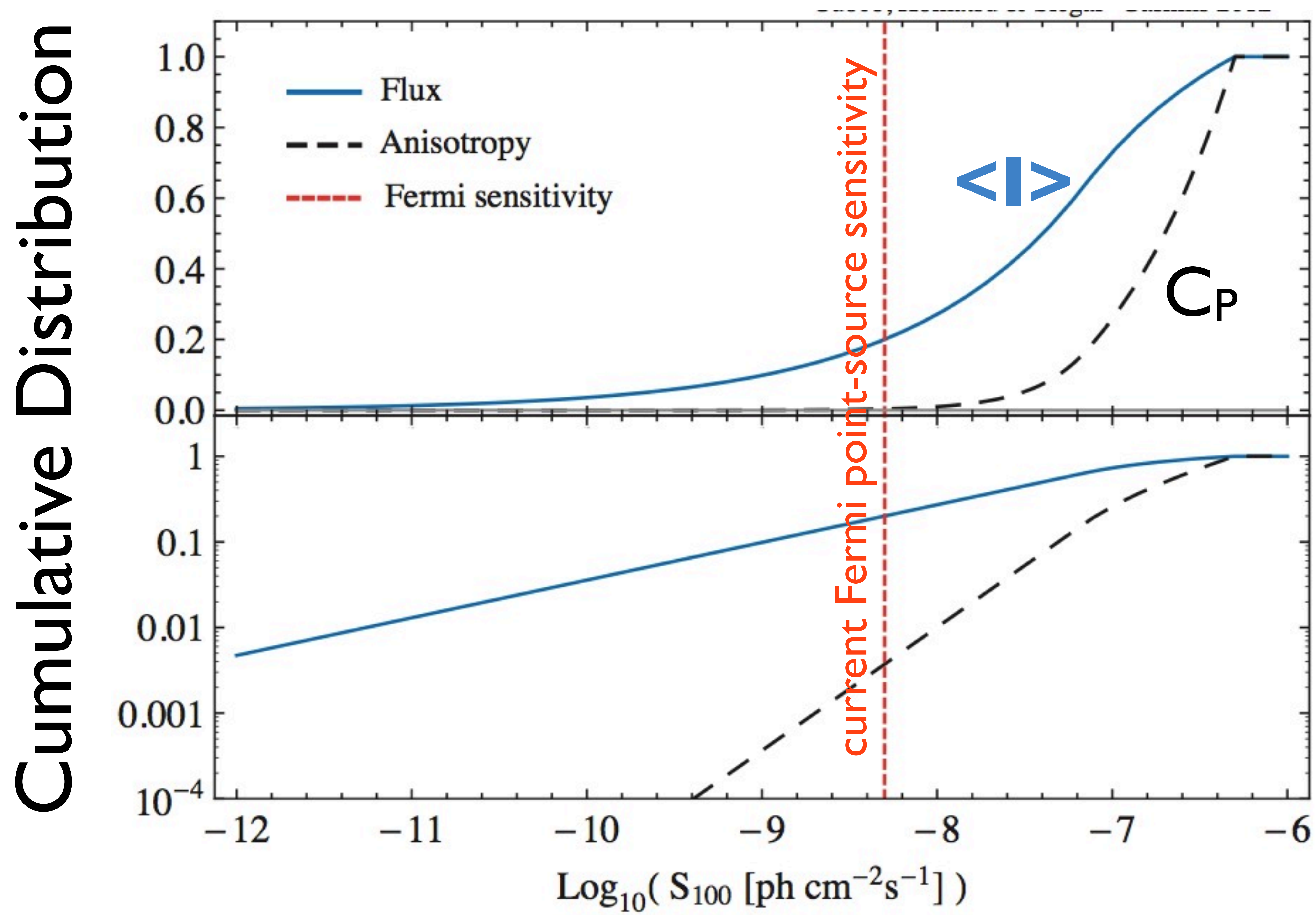


Bottom-line Message

- We have the new observable: **power spectrum of the gamma-ray background**.
- And, it has been detected from the data.

Cuoco, EK & Siegal-Gaskins, arXiv:1202.5309

How far can we push?



- For blazars, 80% of the mean intensity and 99% of anisotropy have been resolved. We will soon resolve out C_P from blazars!

Conclusions

- We have detected anisotropy in the extra-galactic diffuse gamma-ray background from Fermi-LAT 22mo maps.
- The detected anisotropy is consistent with the contribution from unresolved blazars
  - Also consistent with the mean intensity data
  - The origin of the bulk of diffuse background remains a mystery
- Dark matter annihilation contributions may not be so far away from the current limit. Wait for results from the future Fermi analysis (3 to 7 more years to go!)