

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

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OKC Colloquium, Osker Klein Centre, February 14, 2017

This work is based on:

*Original Idea
& Predictions*

- Ando & EK, PRD 73, 023521 (2006)
- Ando, EK, Narumoto & Totani, PRD 75, 063519 (2007)

*First
Measurement*

- Fermi-LAT Collaboration & EK, PRD 85, 083007 (2012)

Interpretation

- Cuoco, EK & Siegal-Gaskins, PRD 86, 063004 (2012)

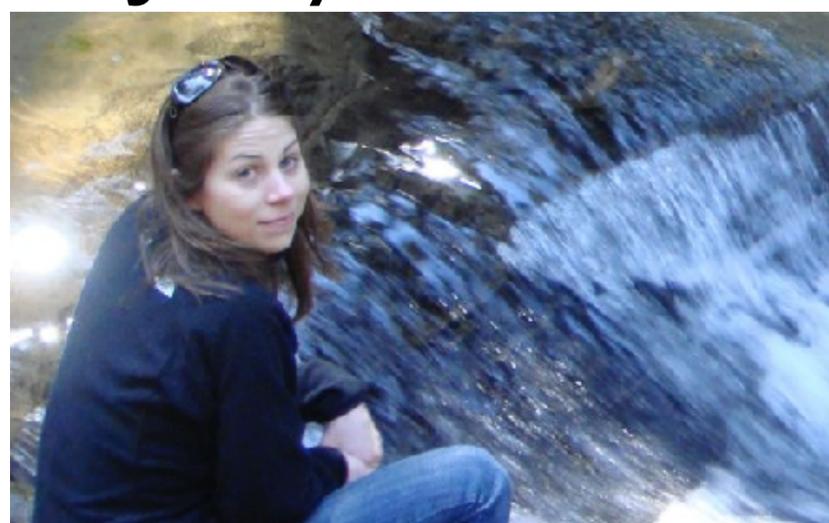
*New
Measurement*

- Fornasa et al., PRD, 94, 123005 (2016)

Shin'ichiro Ando



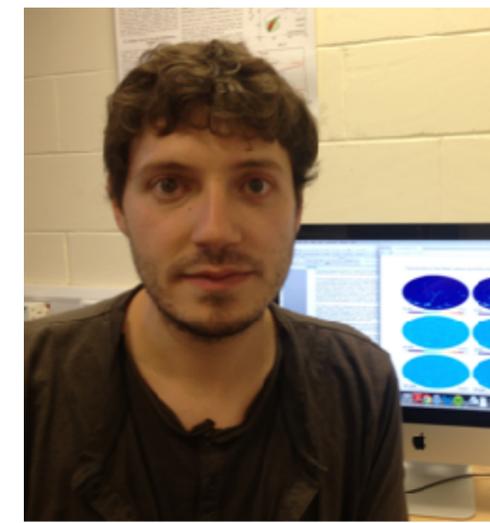
Jenny Gaskins



Alex Cuoco

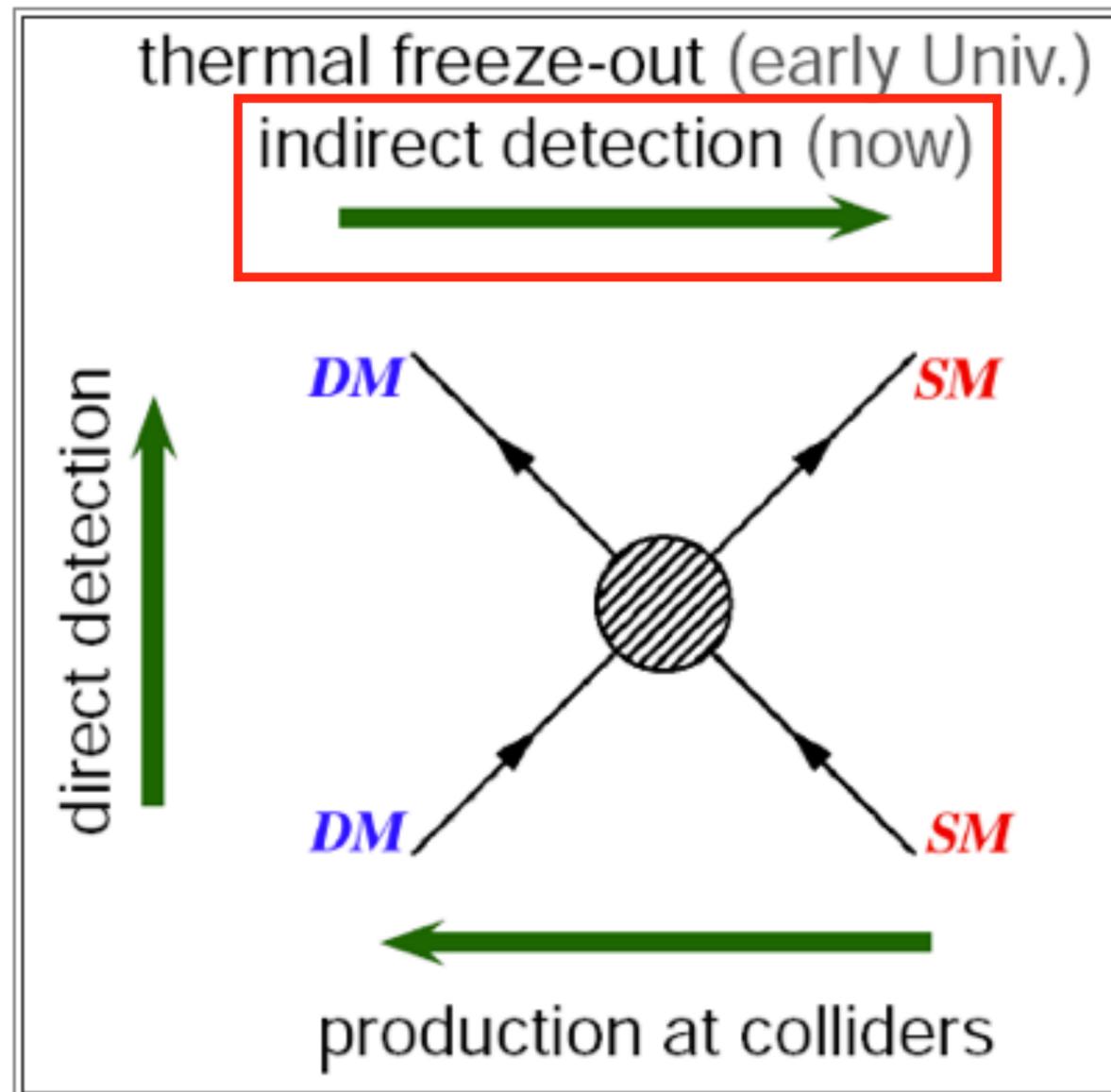


Mattia Fornasa



A Simple Motivation

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



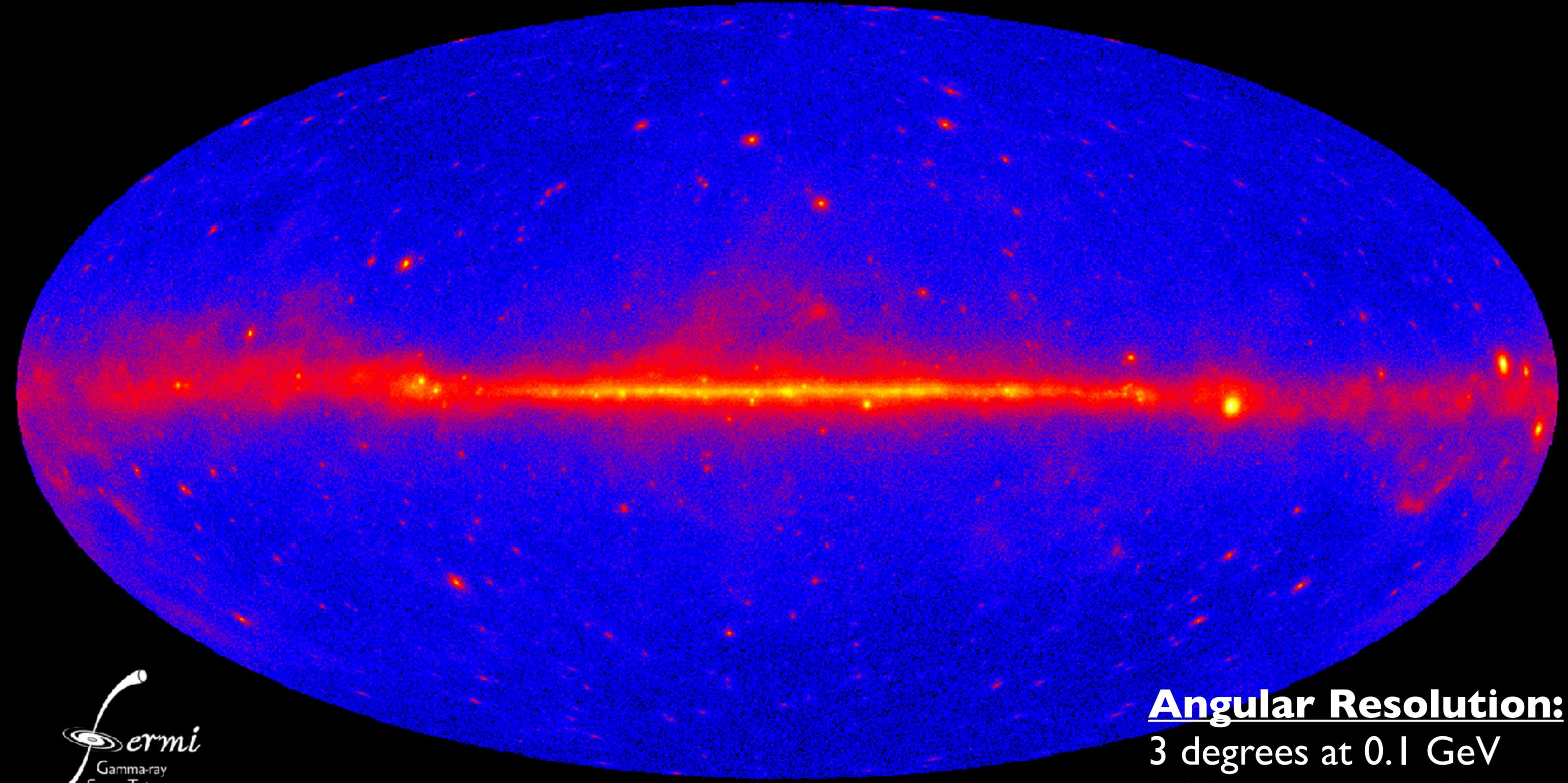
DM: Dark Matter

SM: Standard Model Particles

Big Assumptions:

- Dark Matter consists of particles
- These particles annihilate to produce Standard Model particles

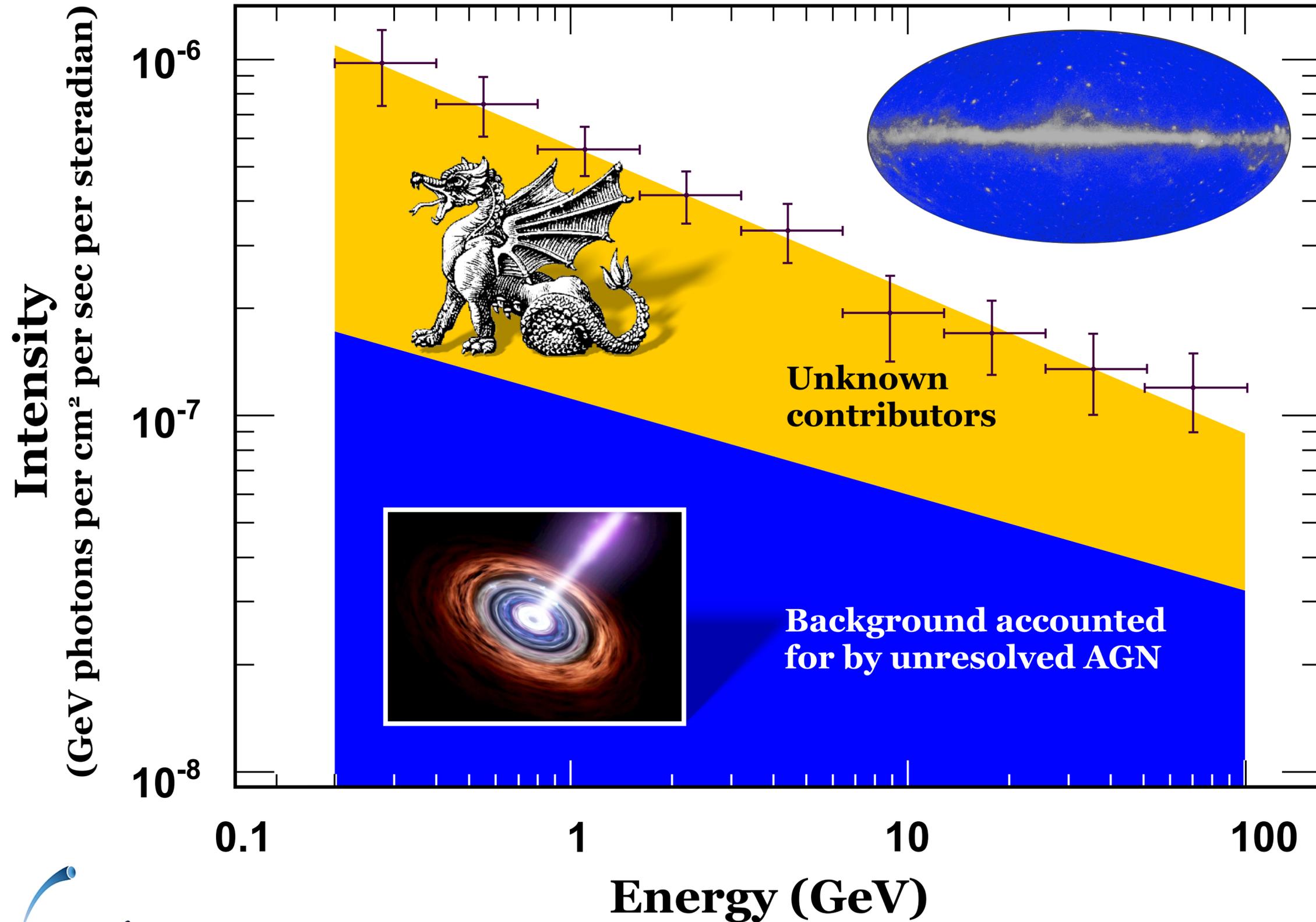
Gamma-ray Sky, integrated from 0.3 GeV



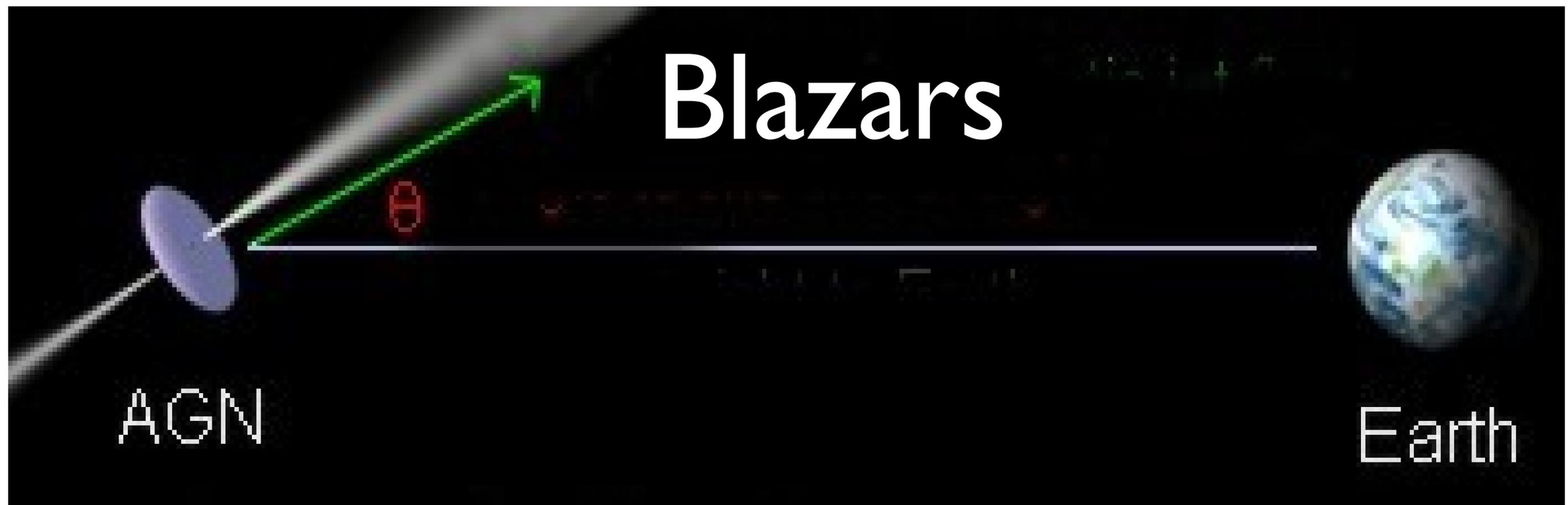
Intriguing Observations

- In gamma-ray energies ($E=0.1-100$ GeV), the origin of **80%** of the **unresolved** diffuse emission (after removing the known, detected sources) is not completely understood!
 - Only ~20% coming from blazars (*Fermi-LAT collaboration*)
- In soft gamma-ray energies ($E=1-10$ MeV), the origin of **>90%** of the diffuse emission is unknown!
 - Only <10% coming from supernovae (*Ahn, EK and Höflich 2005*)

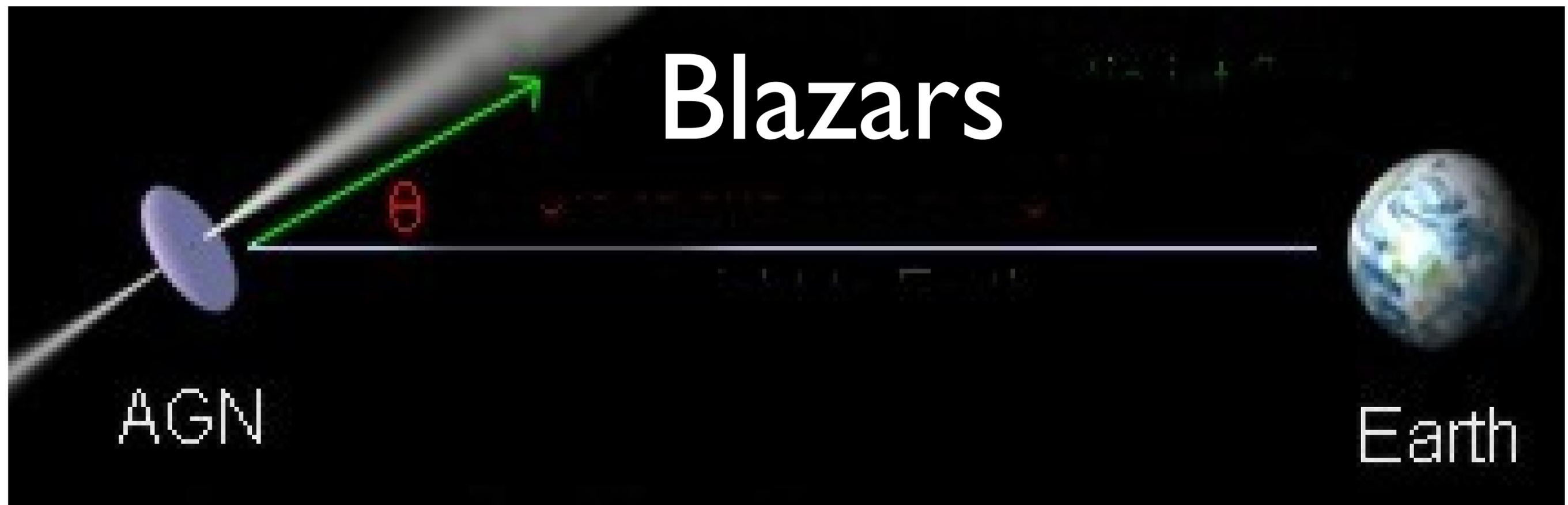
Fermi LAT Extragalactic Gamma-ray Background



Blazars



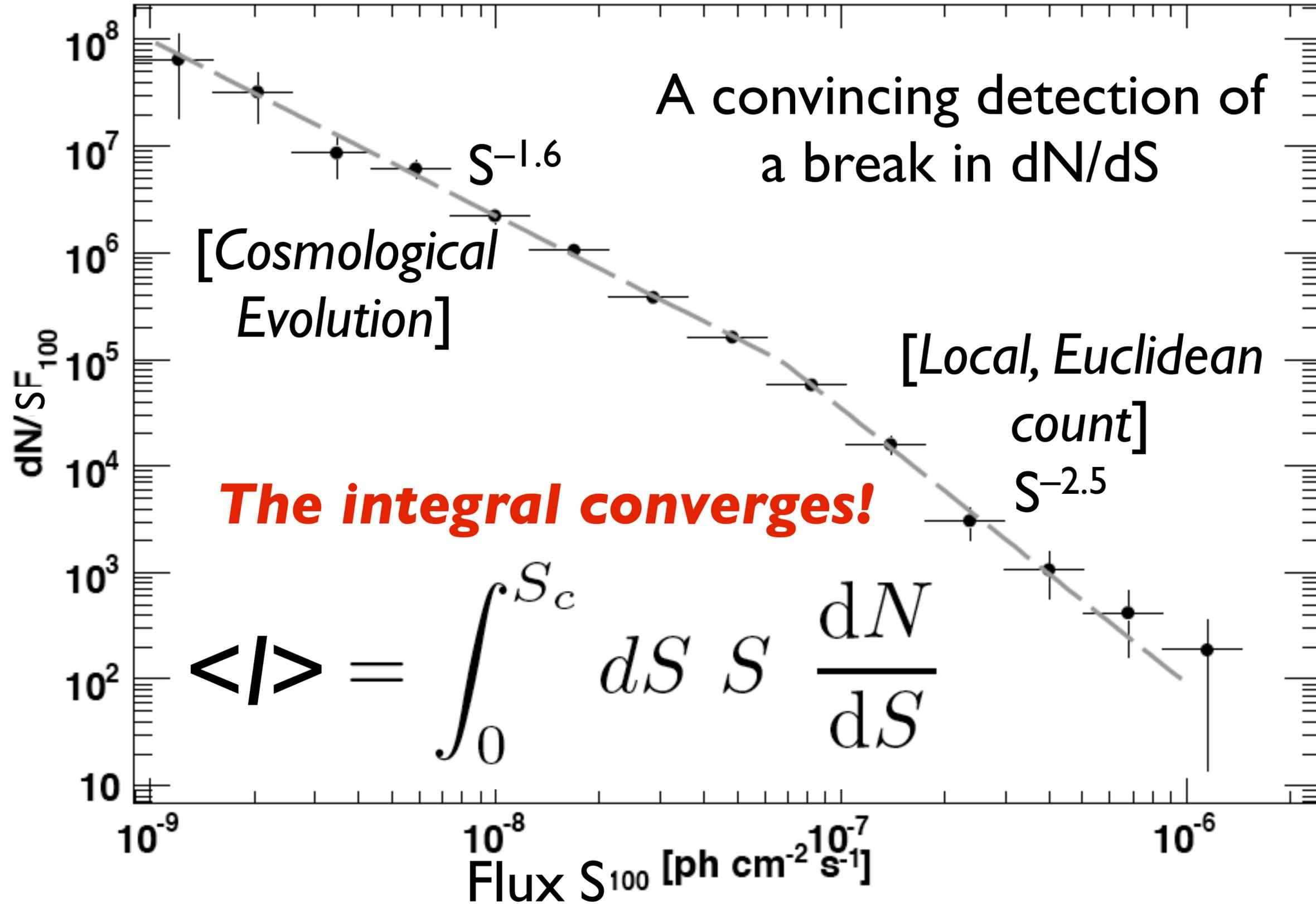
- Blazars = A population of active galactic nuclei (AGNs) whose relativistic jets are directed towards us.
- Inverse Compton scattering of relativistic particles in jets off photons \rightarrow gamma-rays, detected up to TeV



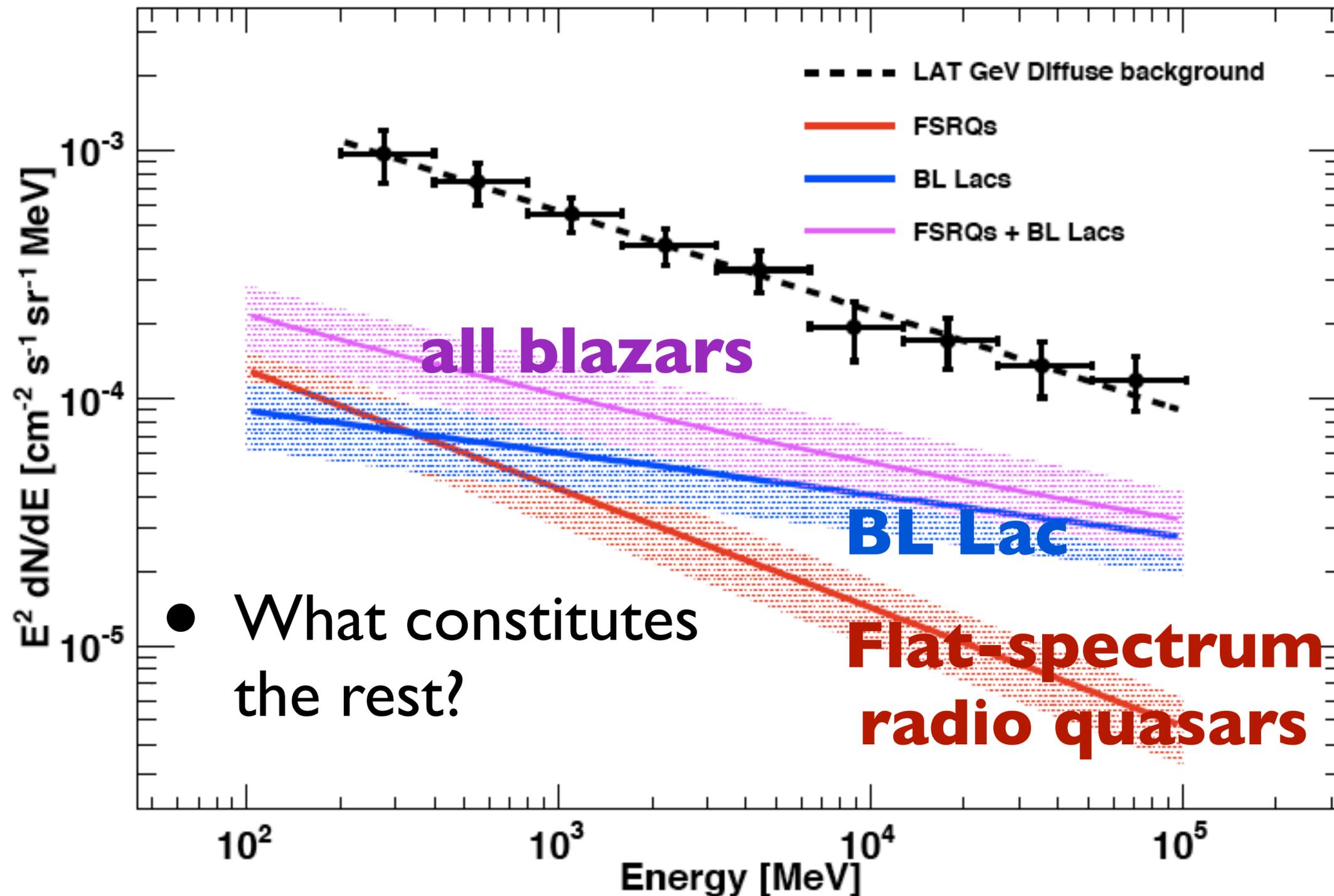
- How many are there? (They are rare.)
- Fermi-LAT found 1145 blazars and 573 blazar candidates (out of 2023 associated sources) over the full sky (LAT 3FGL catalog)

News from Fermi-LAT

Number of sources
per unit flux interval



Unresolved blazars are not enough to explain the unresolved background



Origin of Diffuse Gamma-ray Background?

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

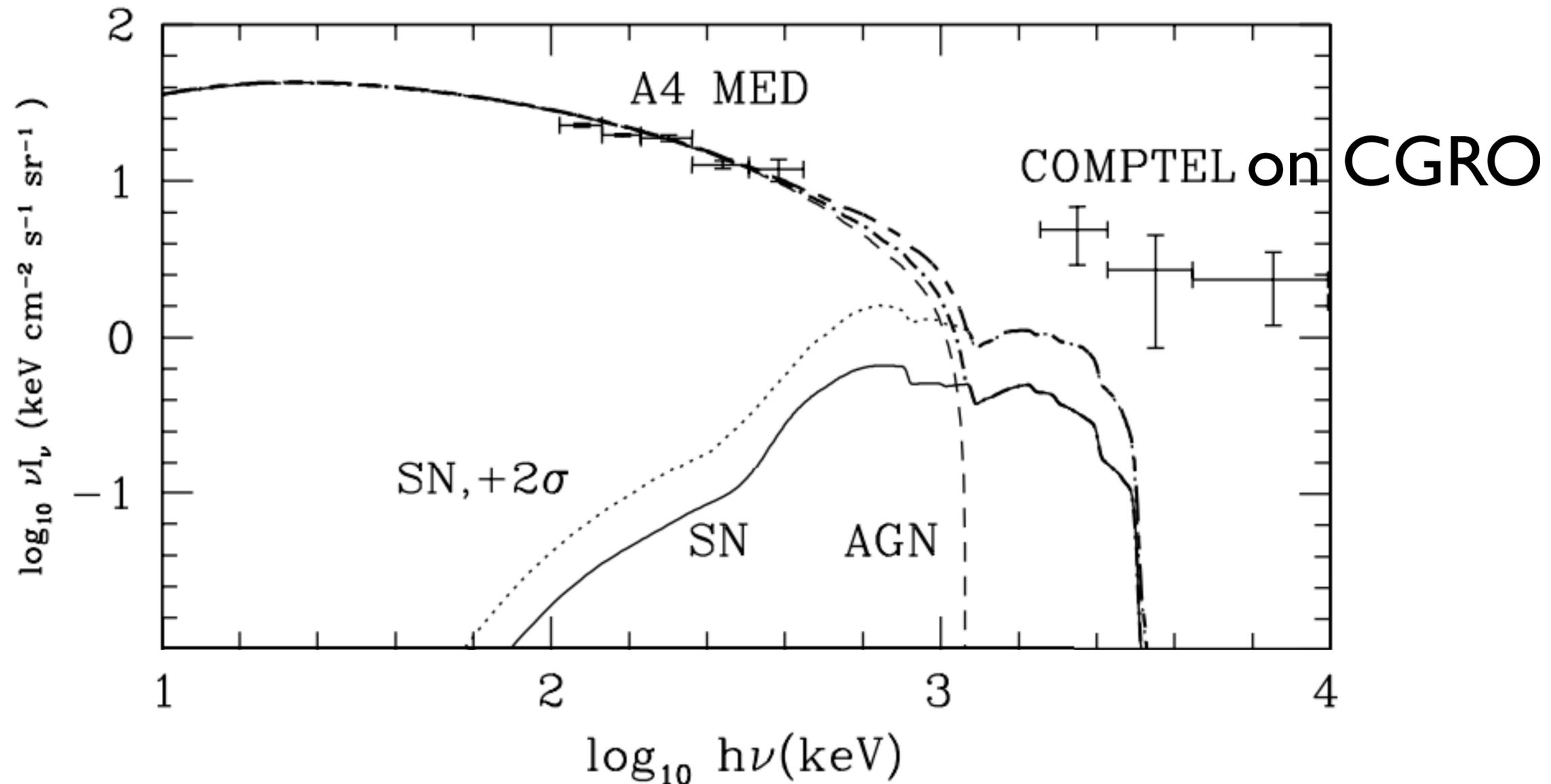
Origin of Diffuse Gamma-ray Background?

- 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



- 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!

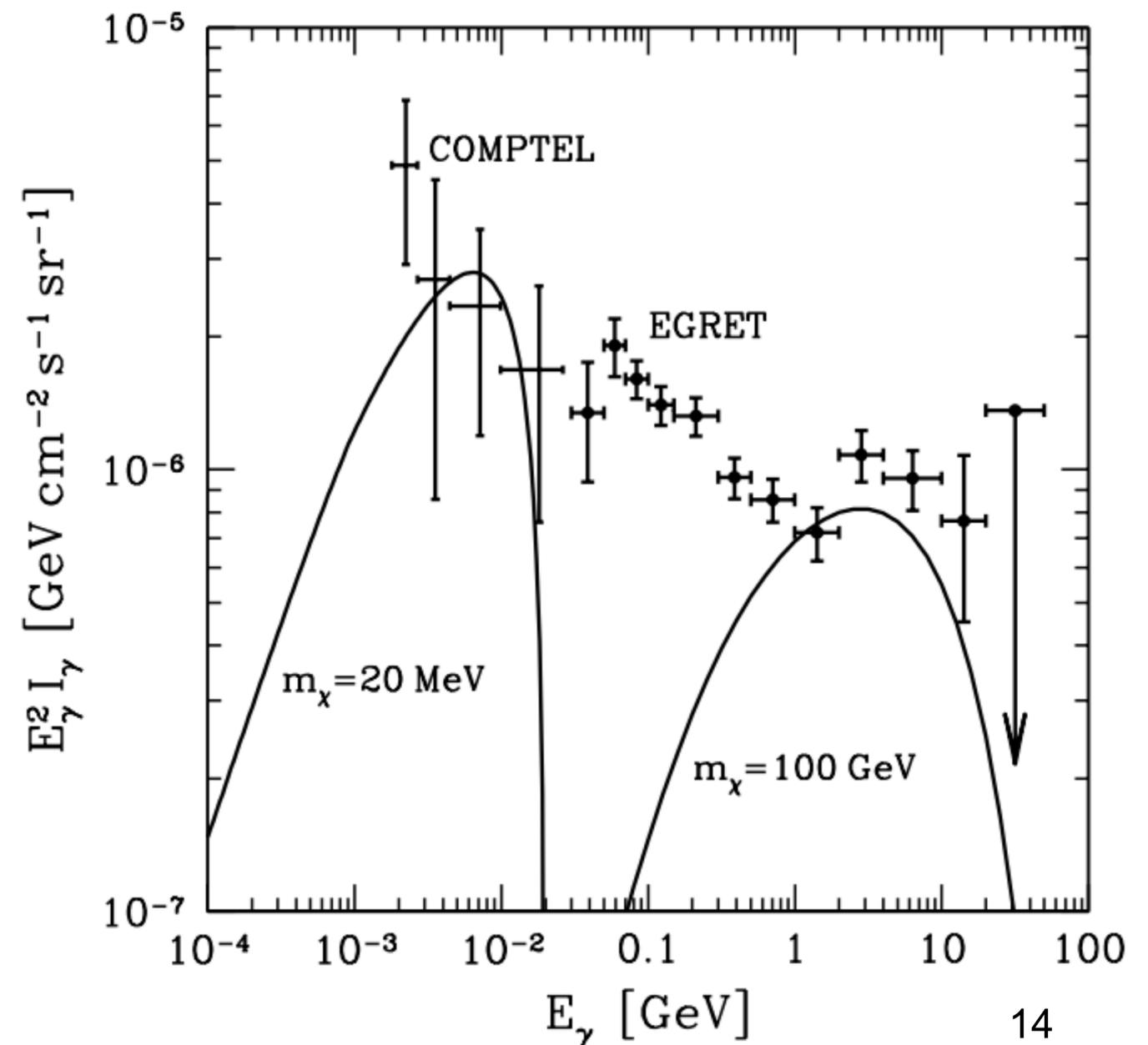
The origin of the MeV background is unknown.

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

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

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

E.g., for supernovae:

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

A General Formula

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

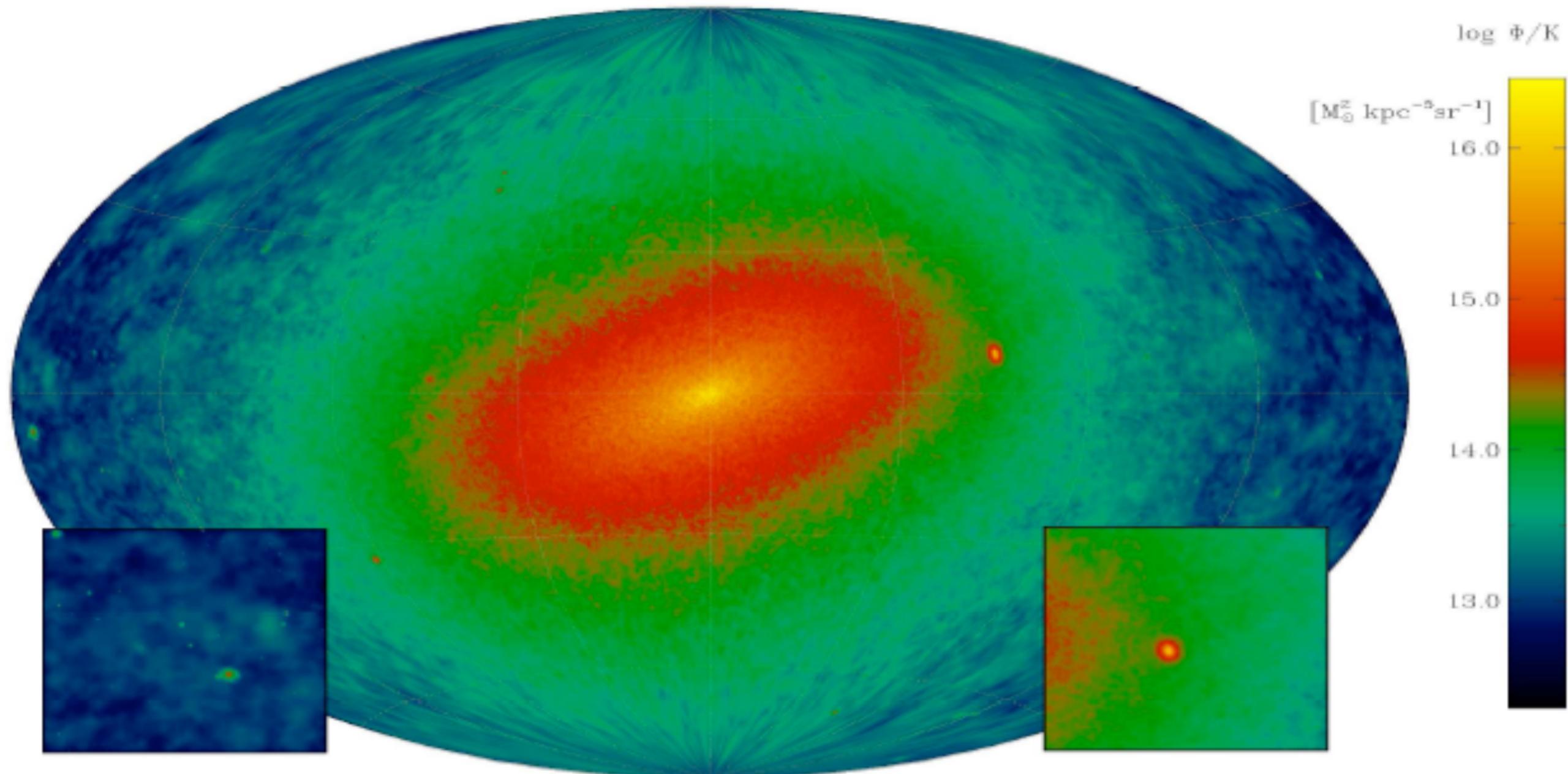
- All we need: P_γ = “volume emissivity” = energy radiated per unit volume, time, and energy.

E.g., for dark matter annihilation:

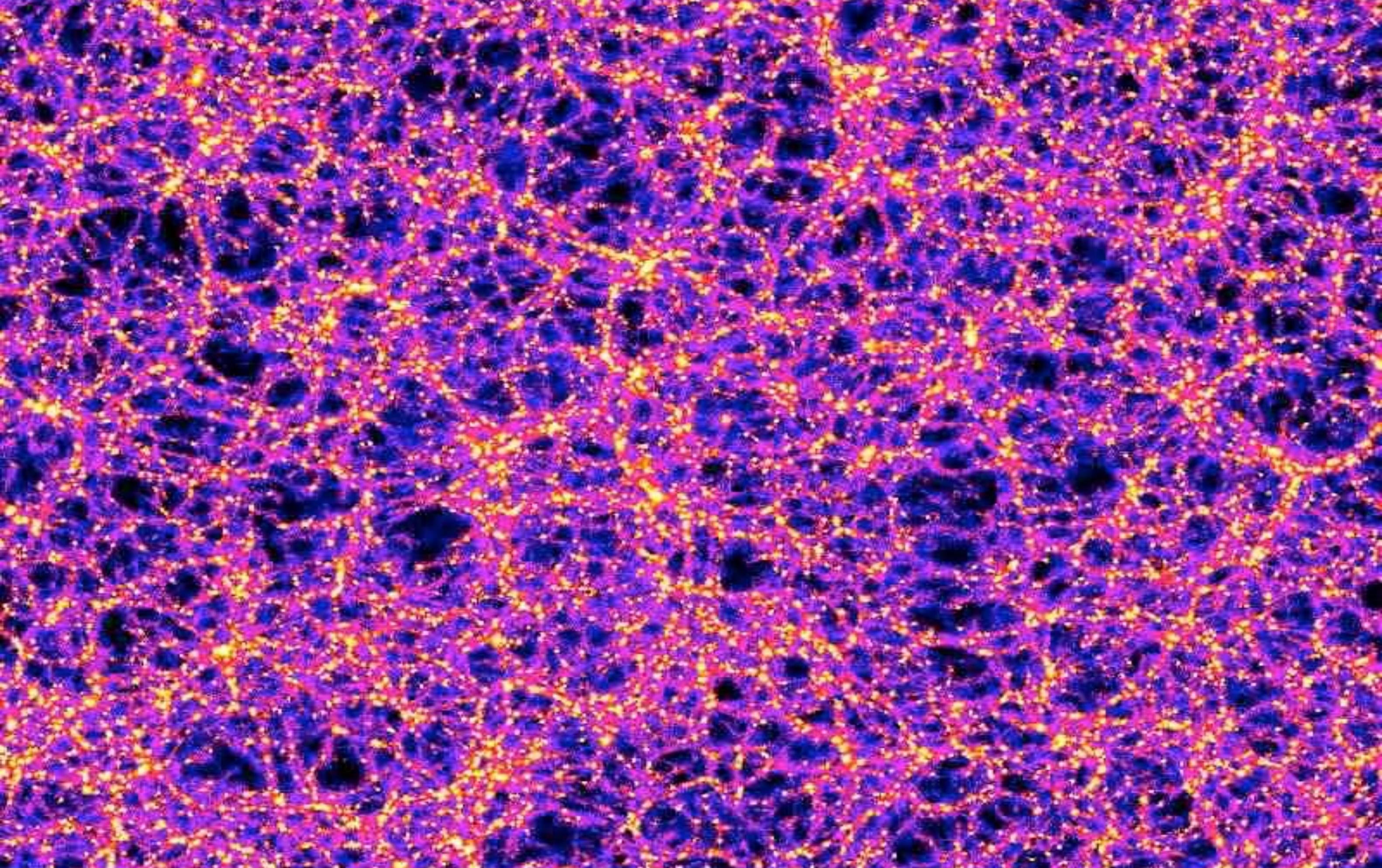
$$P_\gamma(E_\gamma, z, \hat{\mathbf{n}}r) = E_\gamma \frac{dN_\gamma}{dE_\gamma} \frac{\langle \sigma v \rangle}{2} \left[\frac{\rho_\chi(z, \hat{\mathbf{n}}r)}{m_\chi} \right]^2$$



Annihilation Signals from Milky Way

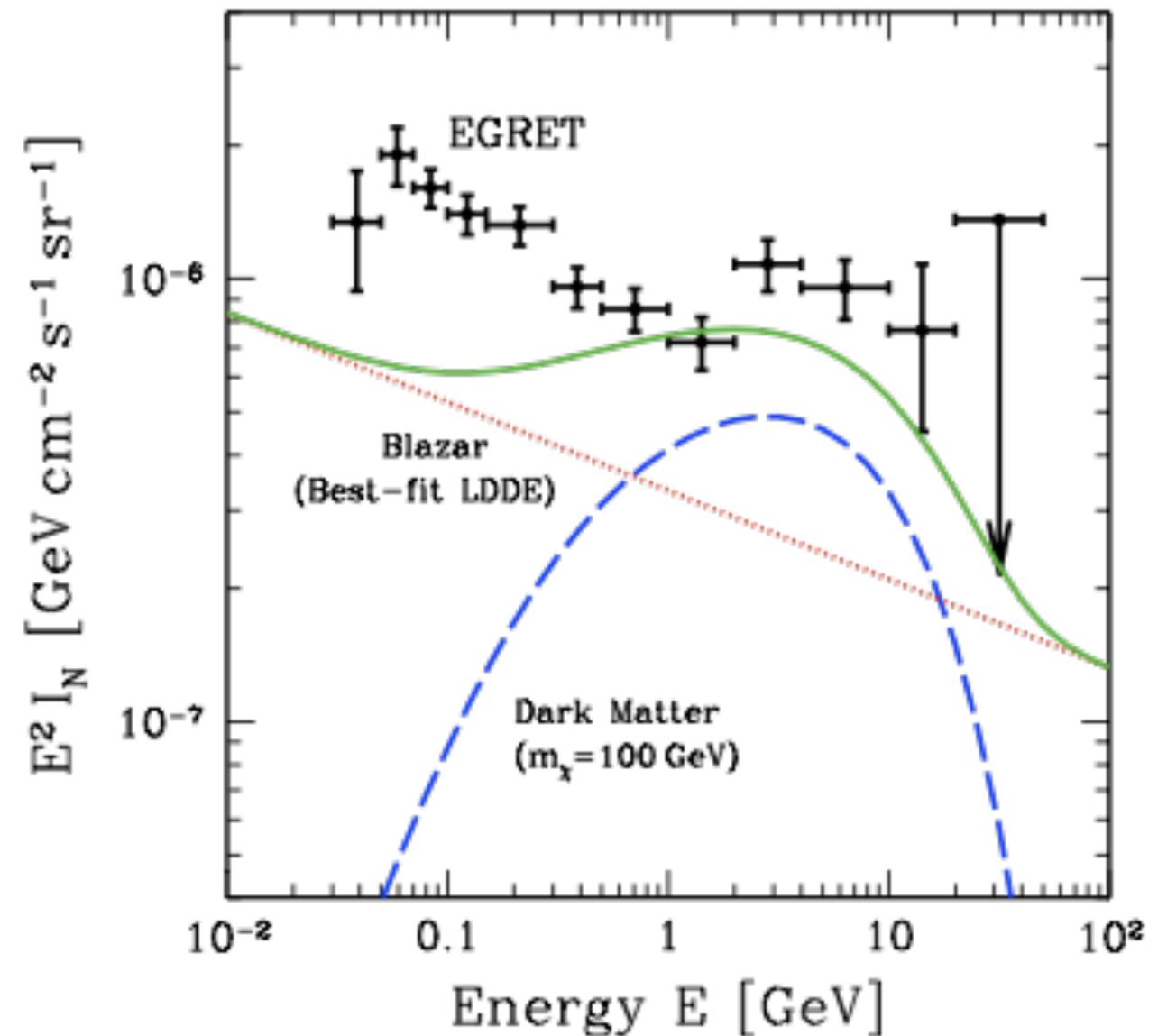
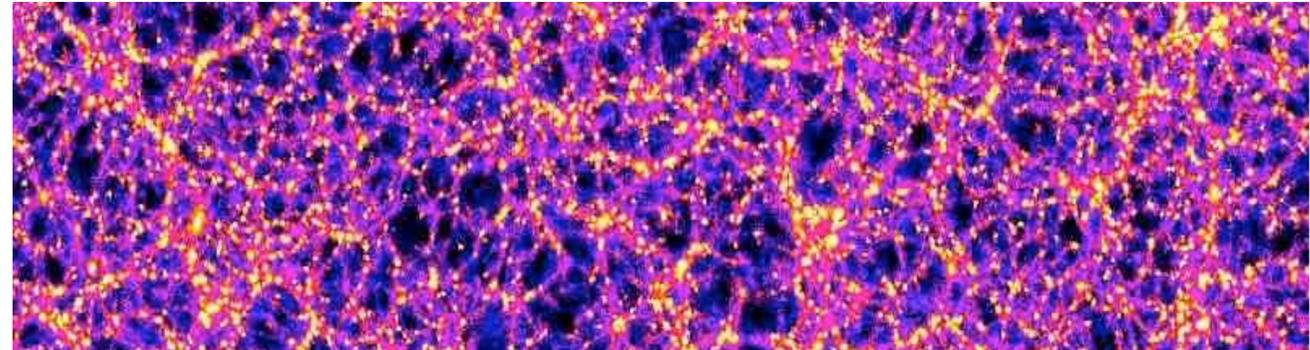


- Why focus only on the energy spectrum?
- Perhaps we can use the spatial distribution.



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*?



Gamma-ray Anisotropy

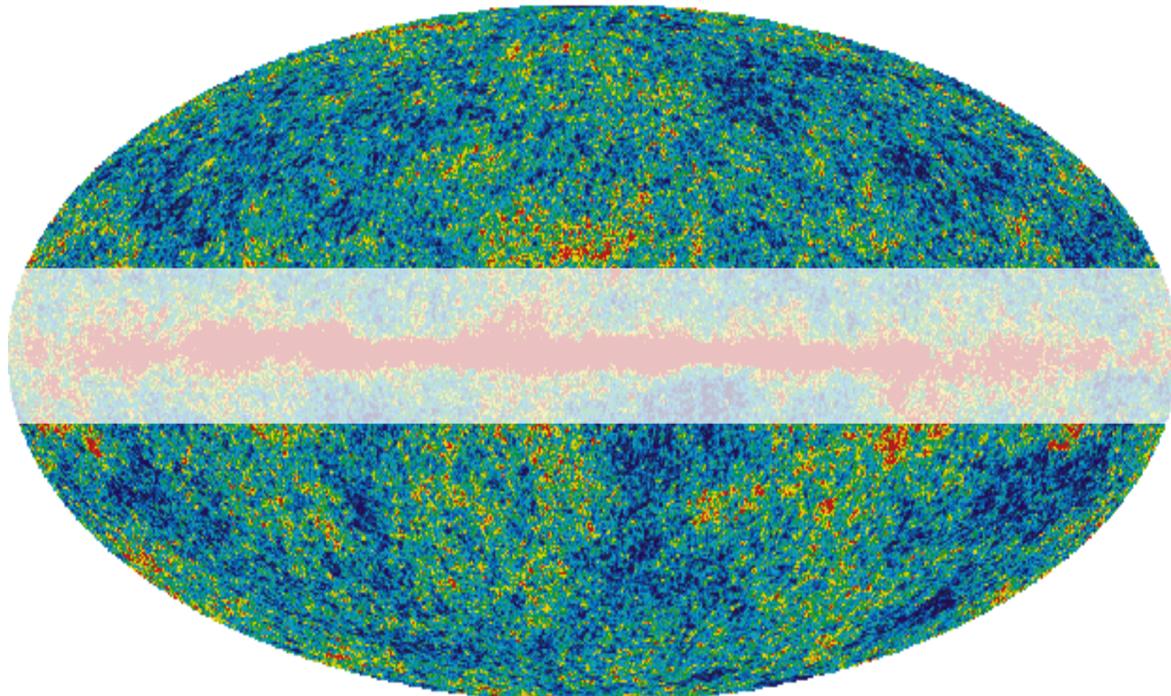
Dark matter halos* trace the large-scale structure

(*) “halos” = gravitationally bound objects

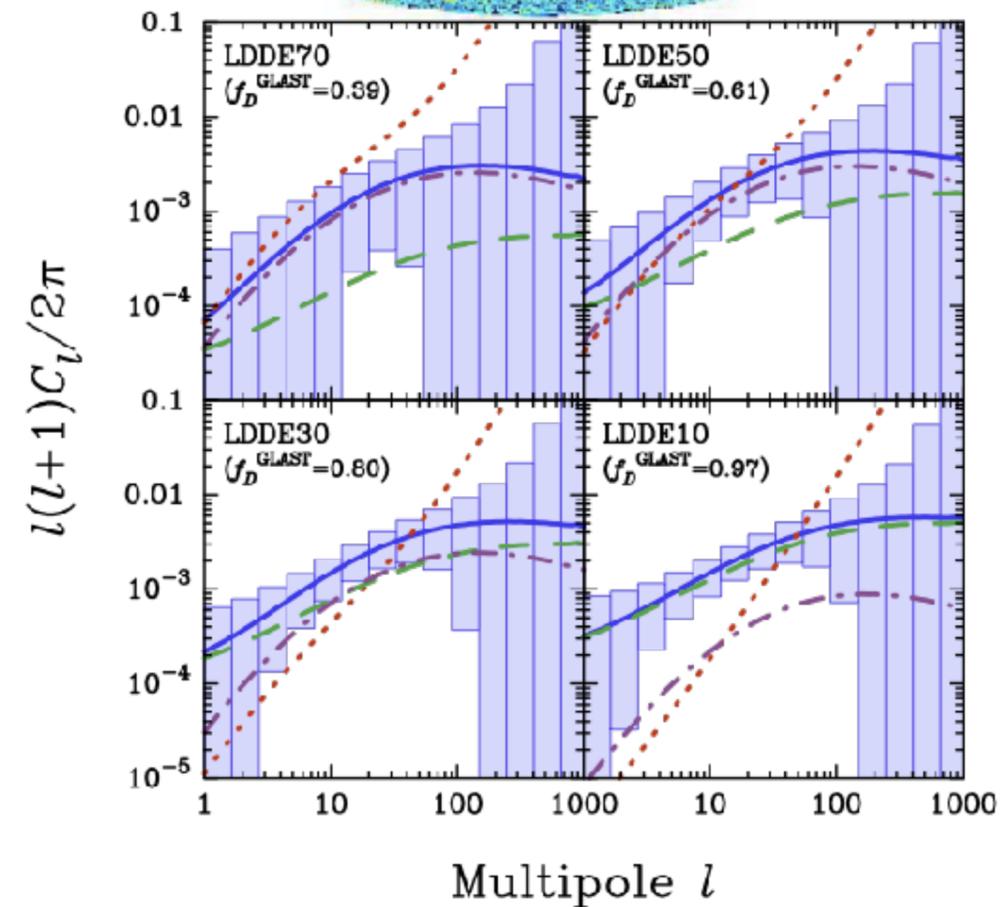
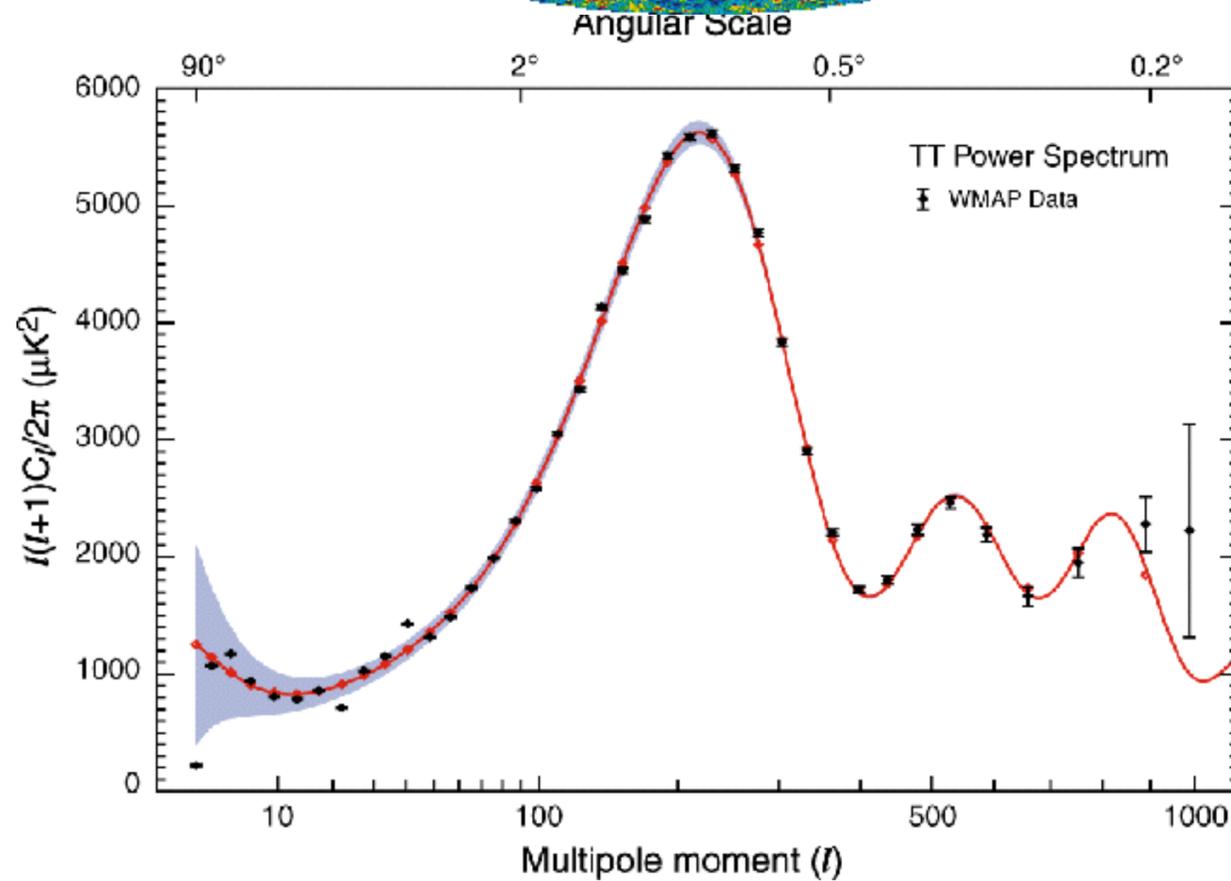
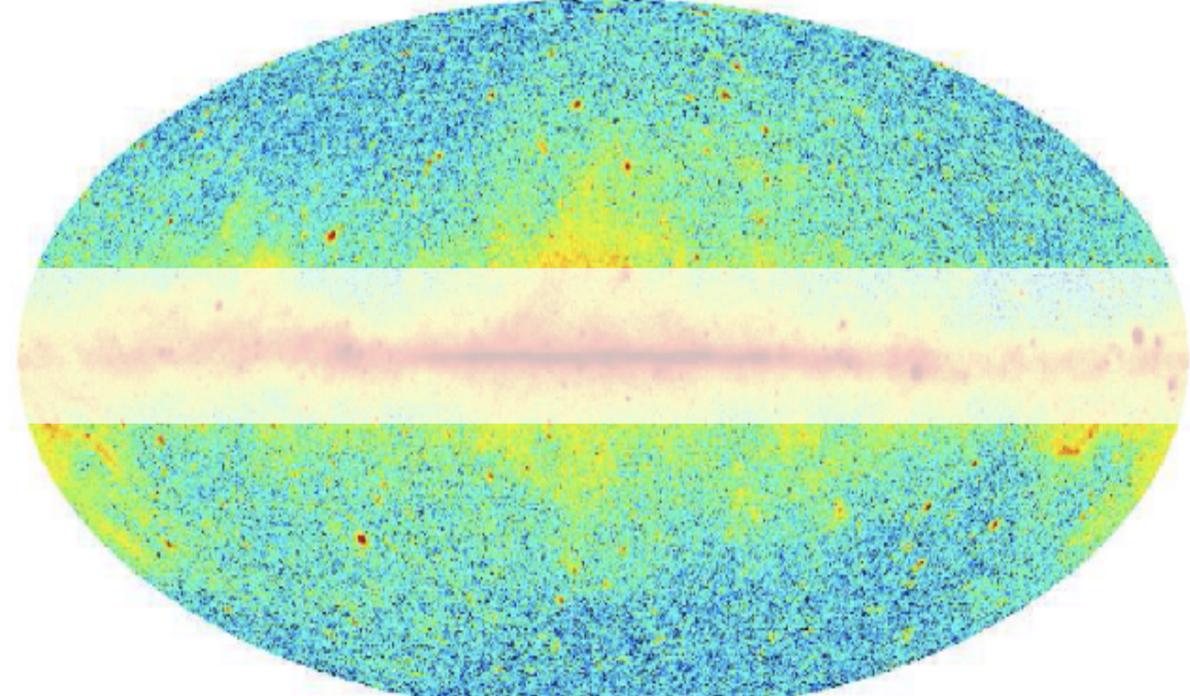
- Therefore, the gamma-ray background **must** be anisotropic. If dark matter particles annihilate or decay, anisotropy **must** be there.
- And, their spatial distribution can be calculated within the framework of the standard cosmological model (Λ CDM model) using analytical calculations or numerical N-body 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**

- Active Galactic Nuclei (AGNs)
- Blazars
- Star-forming galaxies
- 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, *Unresolved* Gamma-ray Background

- First, we remove/mask 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?

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

- **The statistics of the matter distribution is determined by the structure formation, which can be calculated from (almost) first principles**
- Schematically, we have:

$$\text{(Anisotropy in Gamma-ray Sky)} = \text{(MEAN INTENSITY)} \times \Delta$$

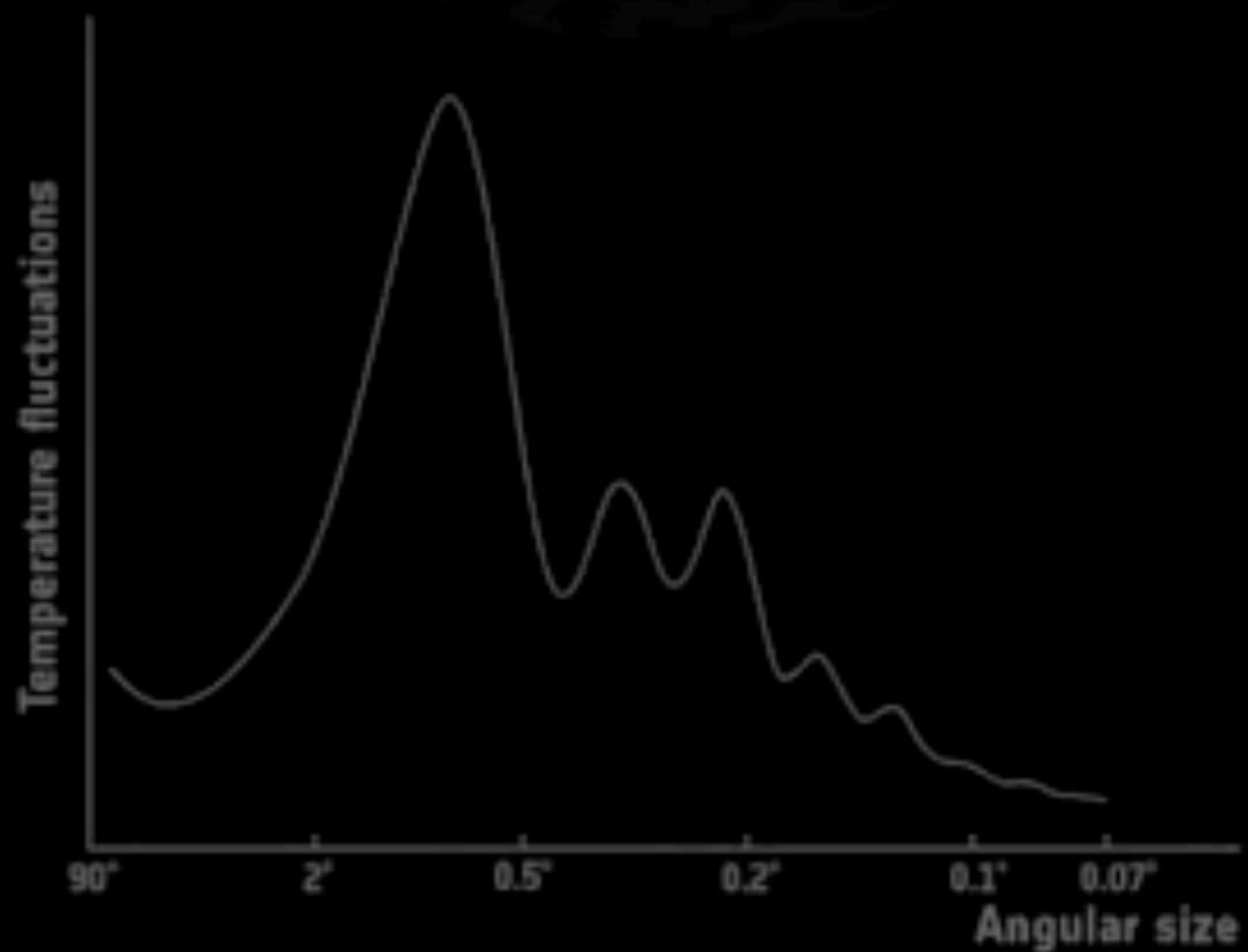
- The mean intensity depends on particle physics: annihilation cross-section and dark matter mass. The fluctuation power, Δ , depends on structure formation.

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):
 - $\langle\sigma v\rangle = a + b(v/c)^2$ 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:
 - $I(n) = \sum_{lm} a_{lm} Y_{lm}(n) \quad [m=-l, -l+1, \dots, l-1, l]$
- 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 Cosmic Microwave Background 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

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

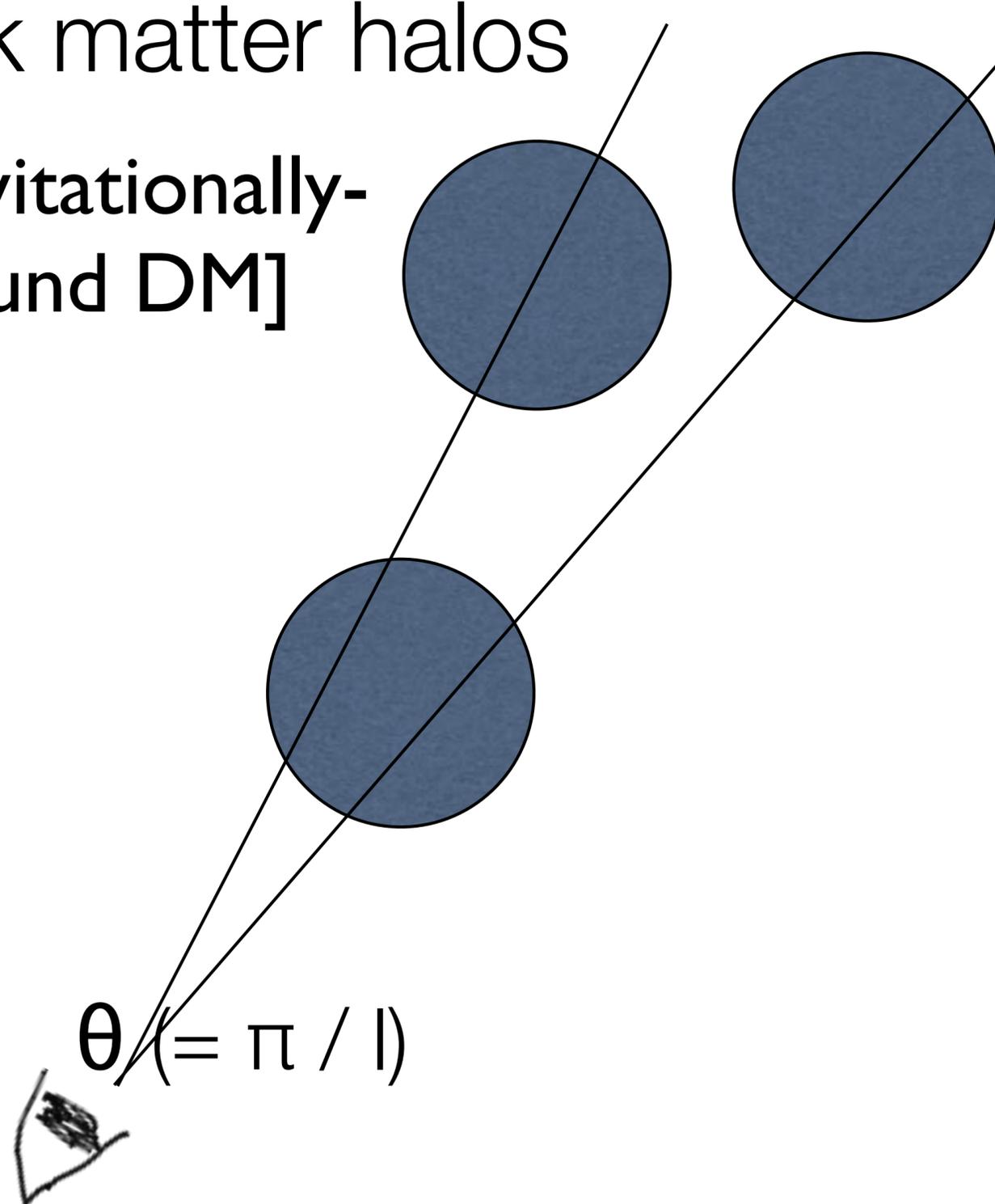
where

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

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

A Simple Route to the Power Spectrum

Dark matter halos
[Gravitationally-
bound DM]

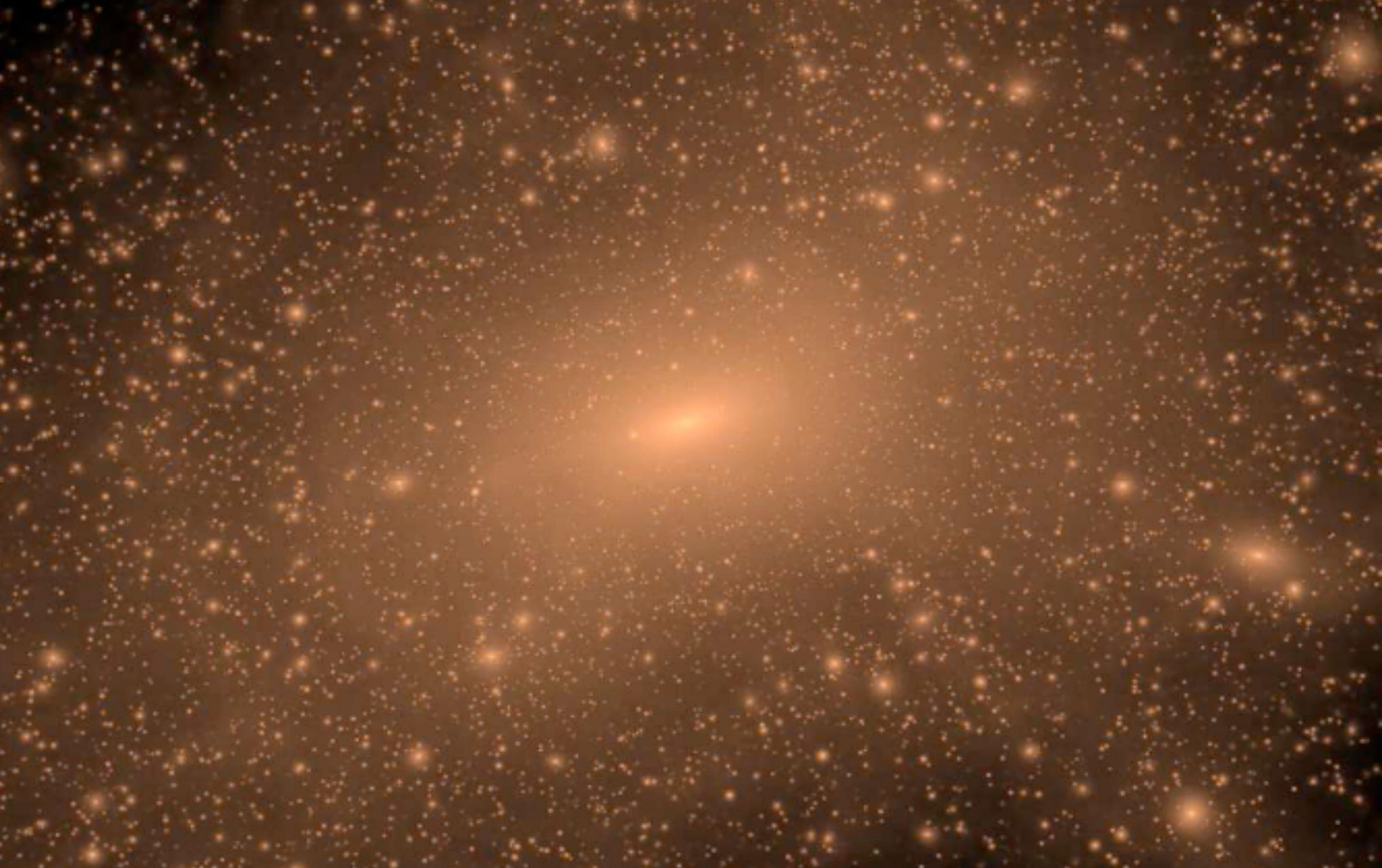


■ To compute the power spectrum of anisotropy from dark matter annihilation, we need **three ingredients**:

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

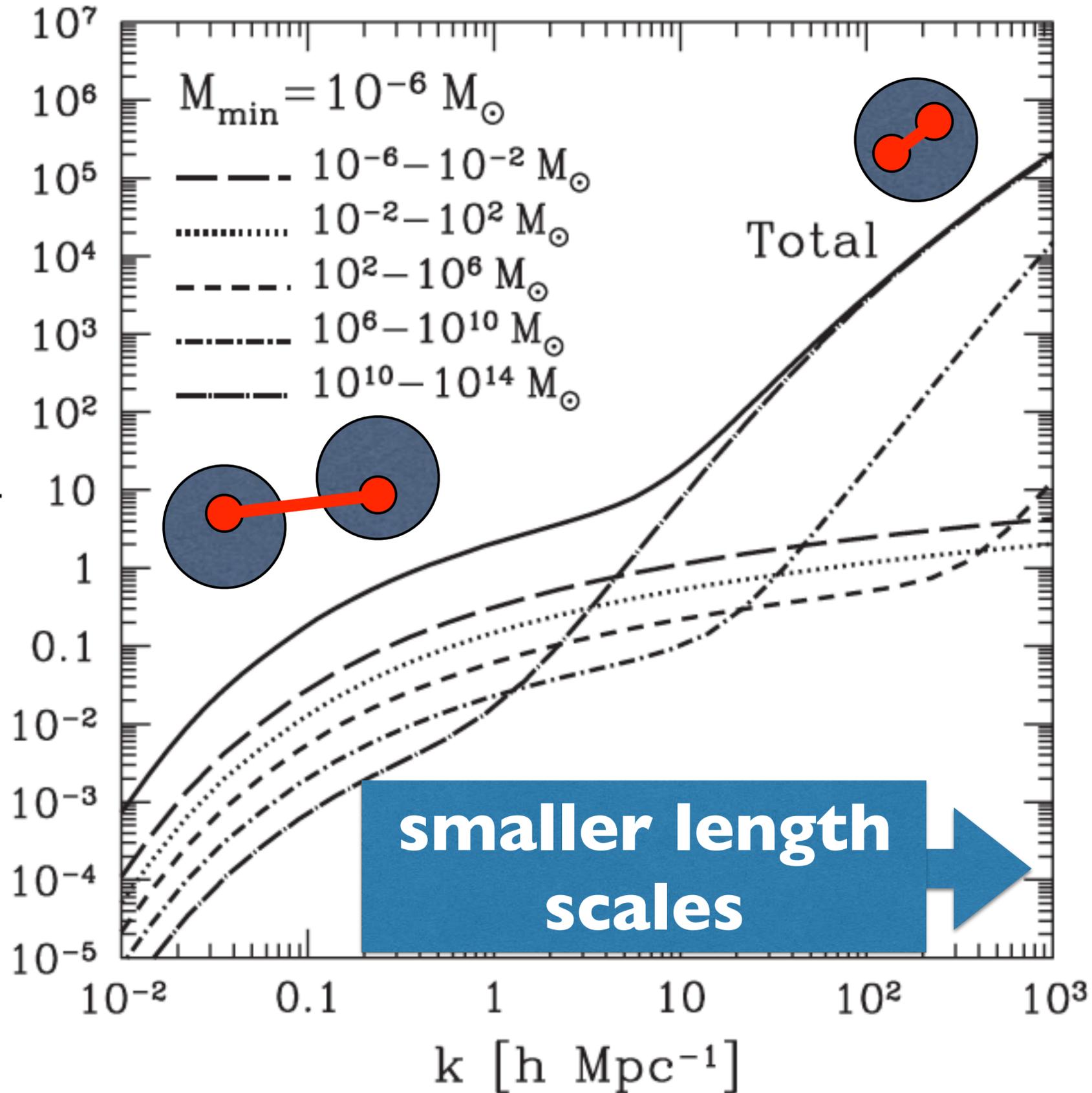
- **Without sub-halos**
 - Halo density distribution is smooth and follows a profile measured from N-body simulations (NFW)
- **With sub-halos**
 - Halos contain sub-halos whose radial distribution follows an NFW profile
 - This is more realistic, provided that sub-halos survive tidal disruptions



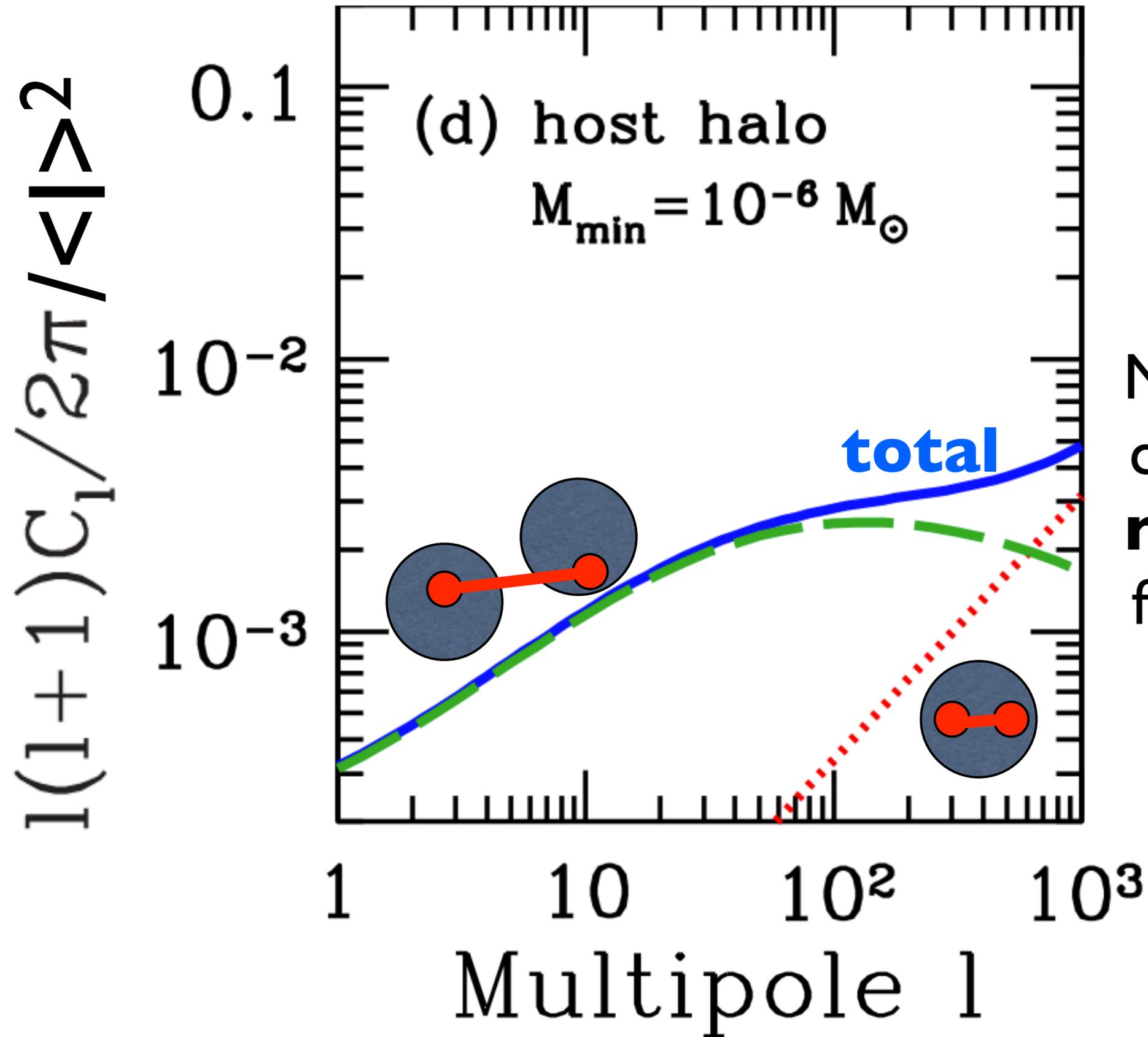
3d Power Spectrum of δ^2

**Without
sub-halos**

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



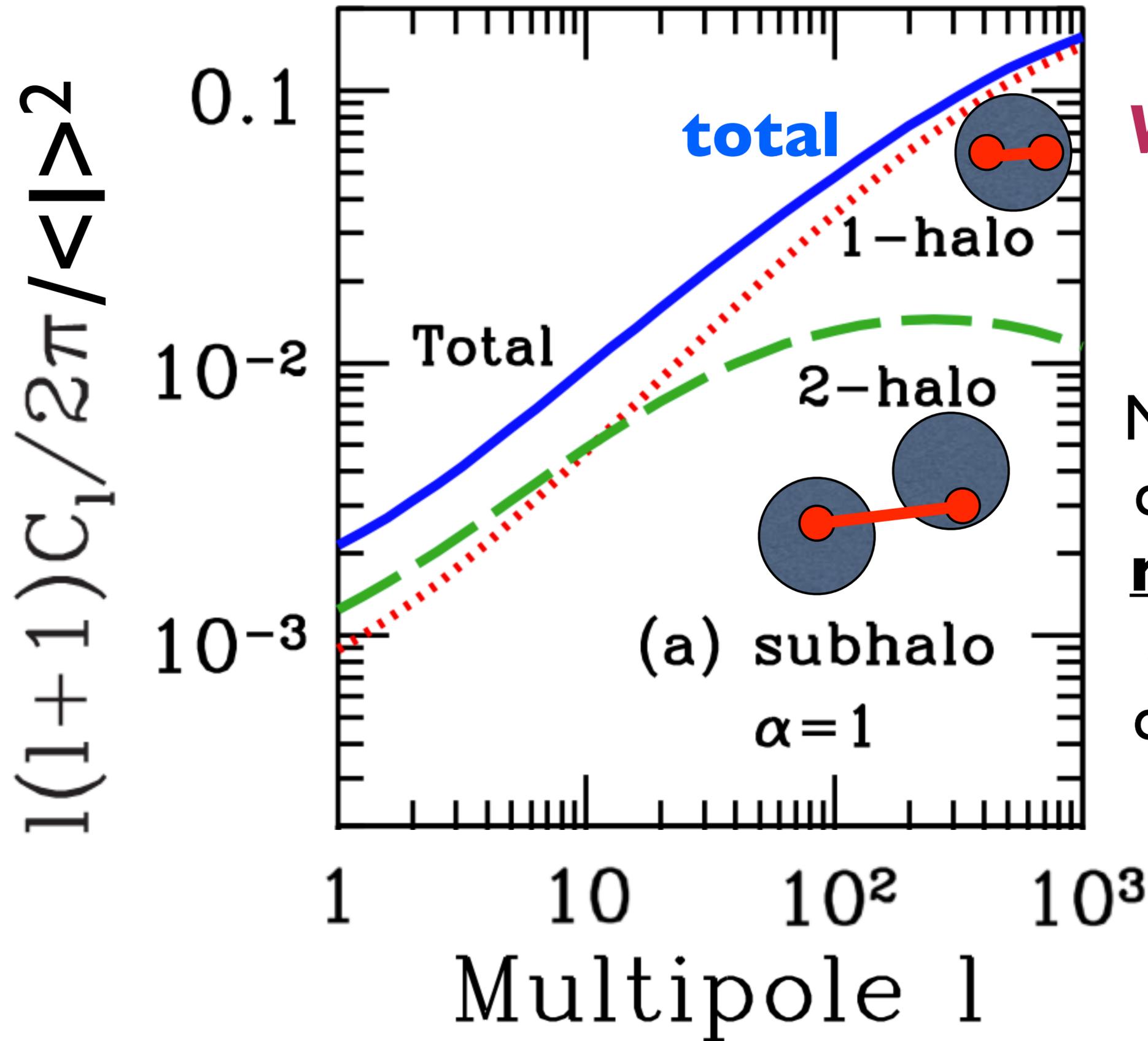
(2d) Angular Power Spectrum



***Without
sub-halos***

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

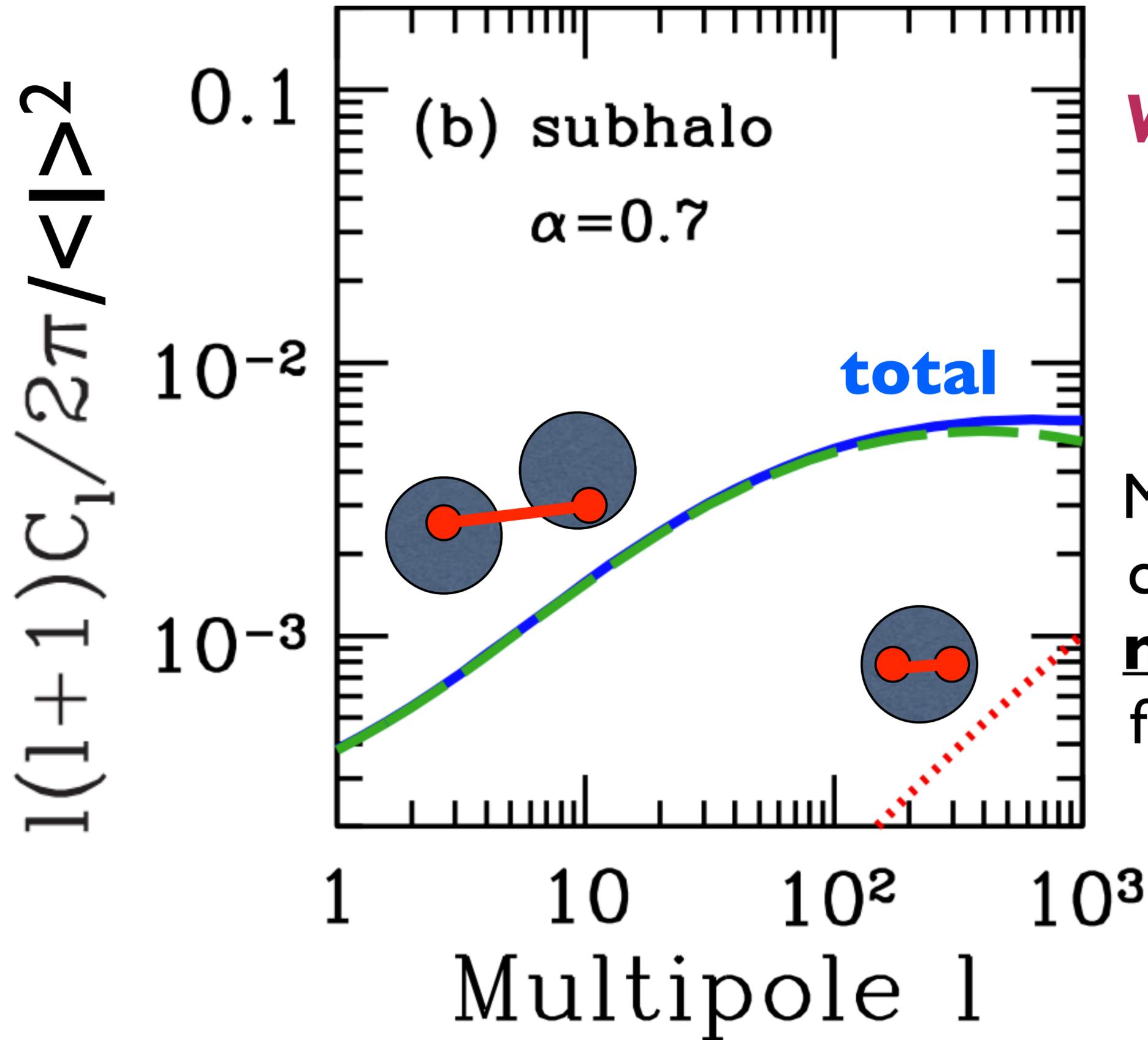
(2d) Angular Power Spectrum



*With sub-halos
(all surviving)*

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

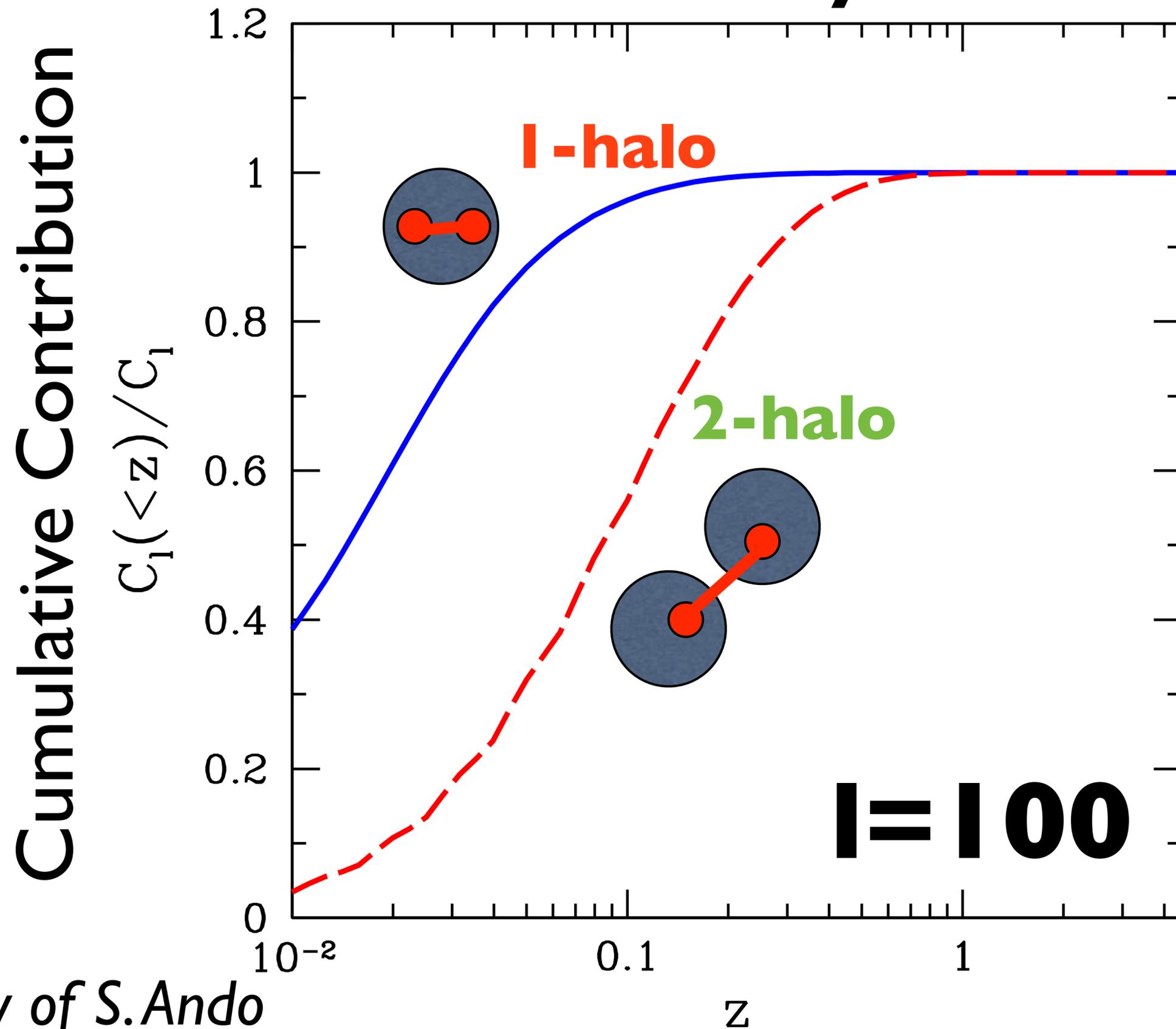
(2d) Angular Power Spectrum



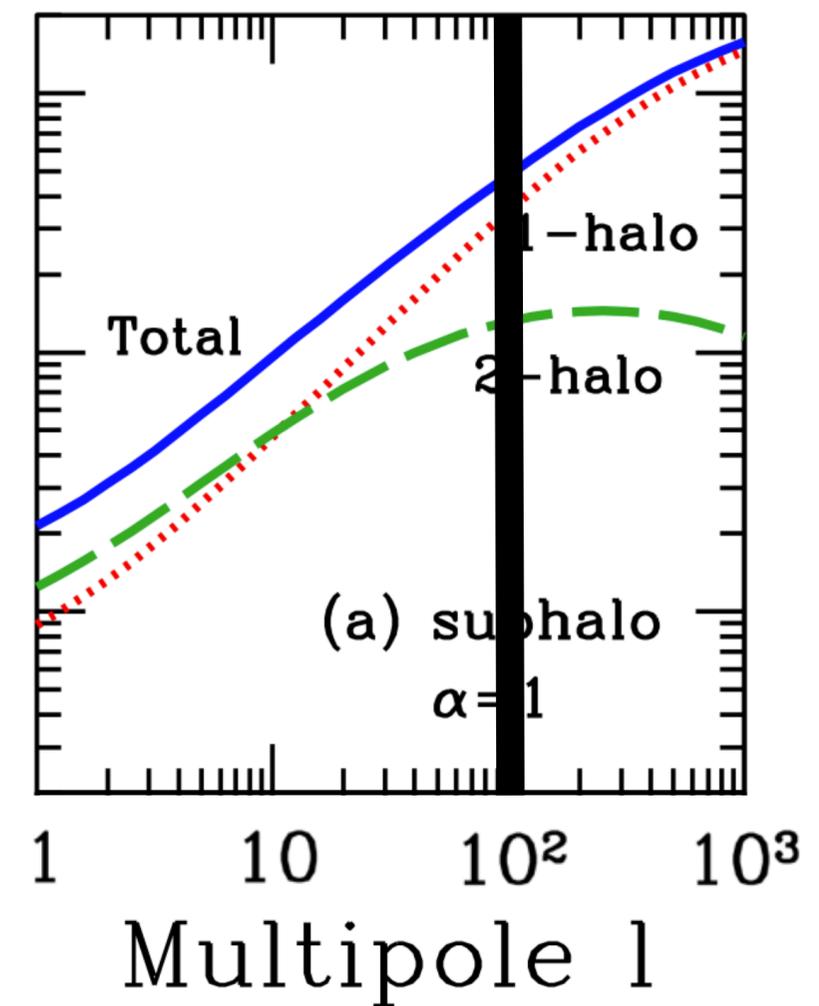
*With sub-halos
(disrupted in
large halos)*

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

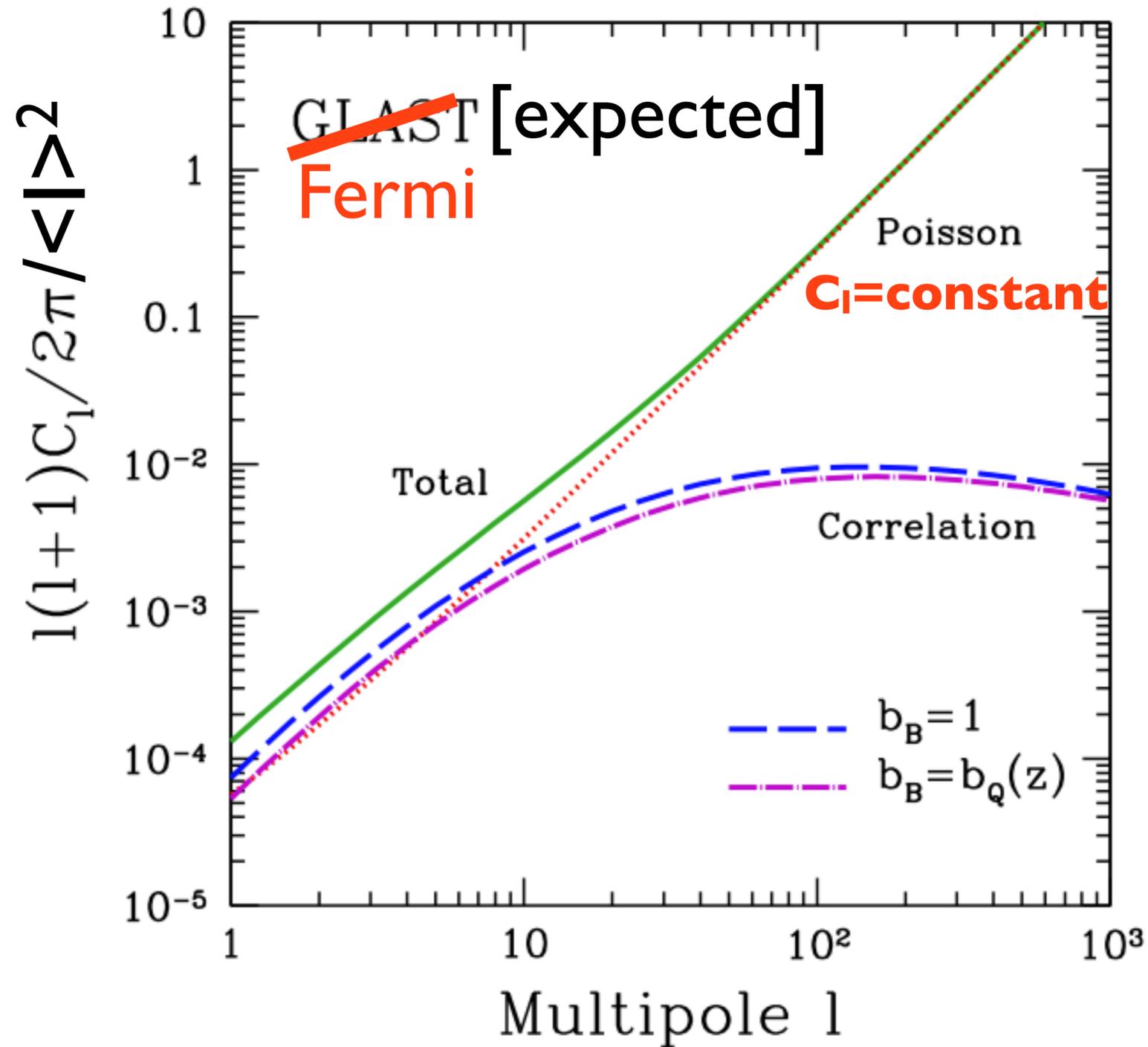
Which z do they come from?



**With
sub-halos
(all surviving)**

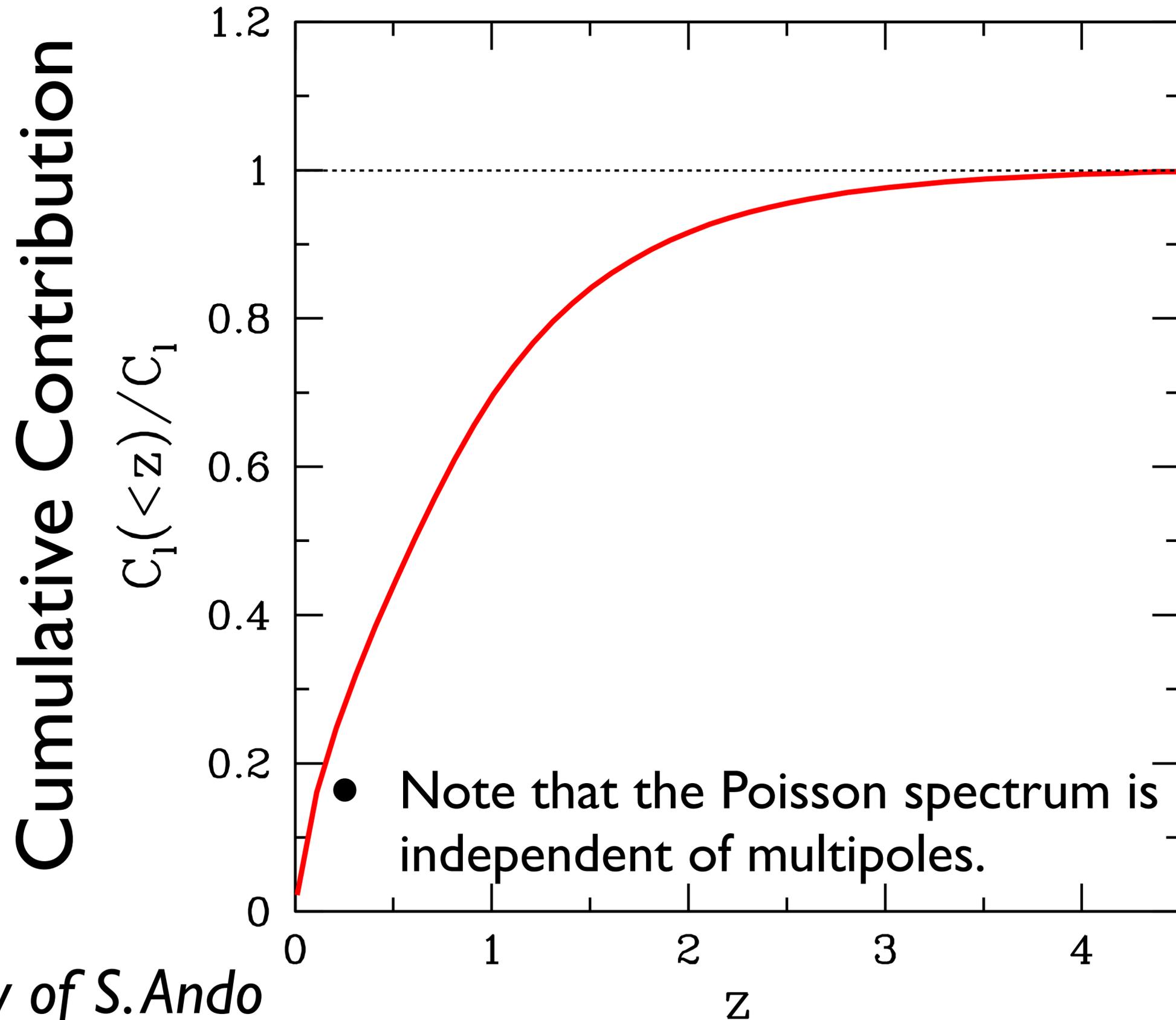


How about blazars?



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

Which z do blazars contribute?



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

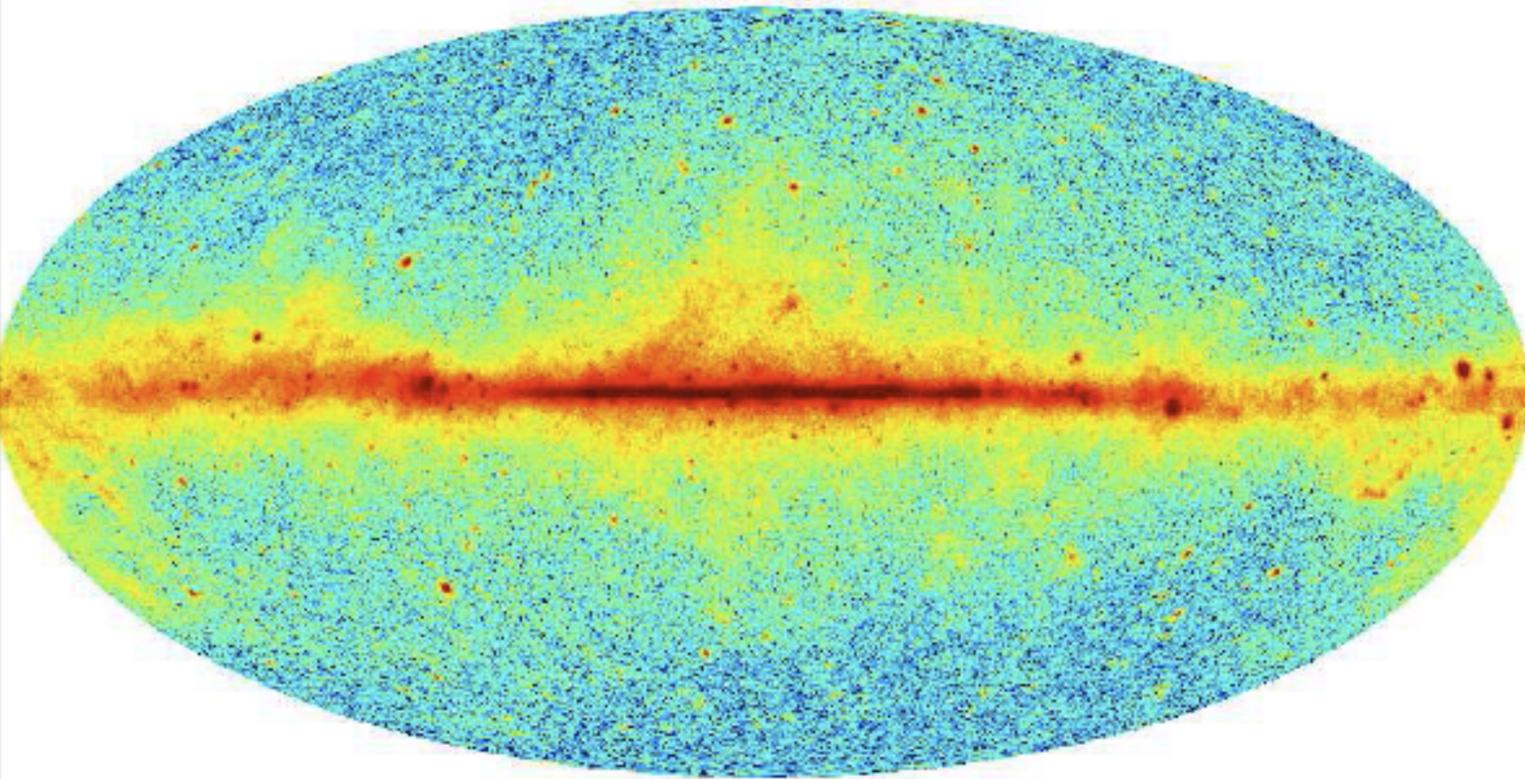
Phys. Rev. D 85, 083007 (2012)

Data Analysis

- Use ~20-month of the Fermi-LAT map (diffuse-class events). *8 1-month results will be presented at the end of this talk!*
- 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

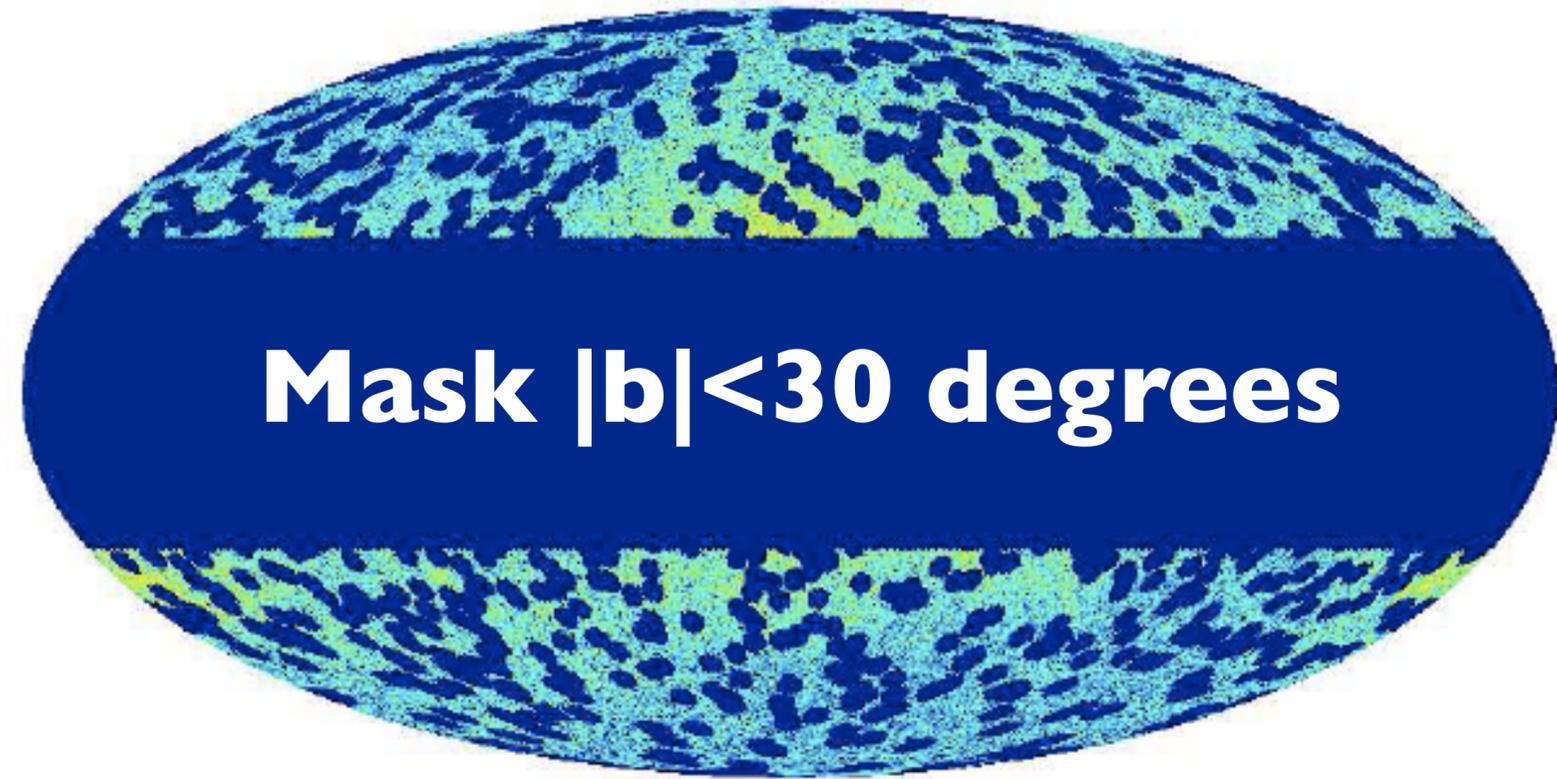
1.0–2.0 GeV

DATA (P6_V3 diffuse), 1.0–2.0 GeV



-7.0  -4.0 Log (Intensity [$\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$])

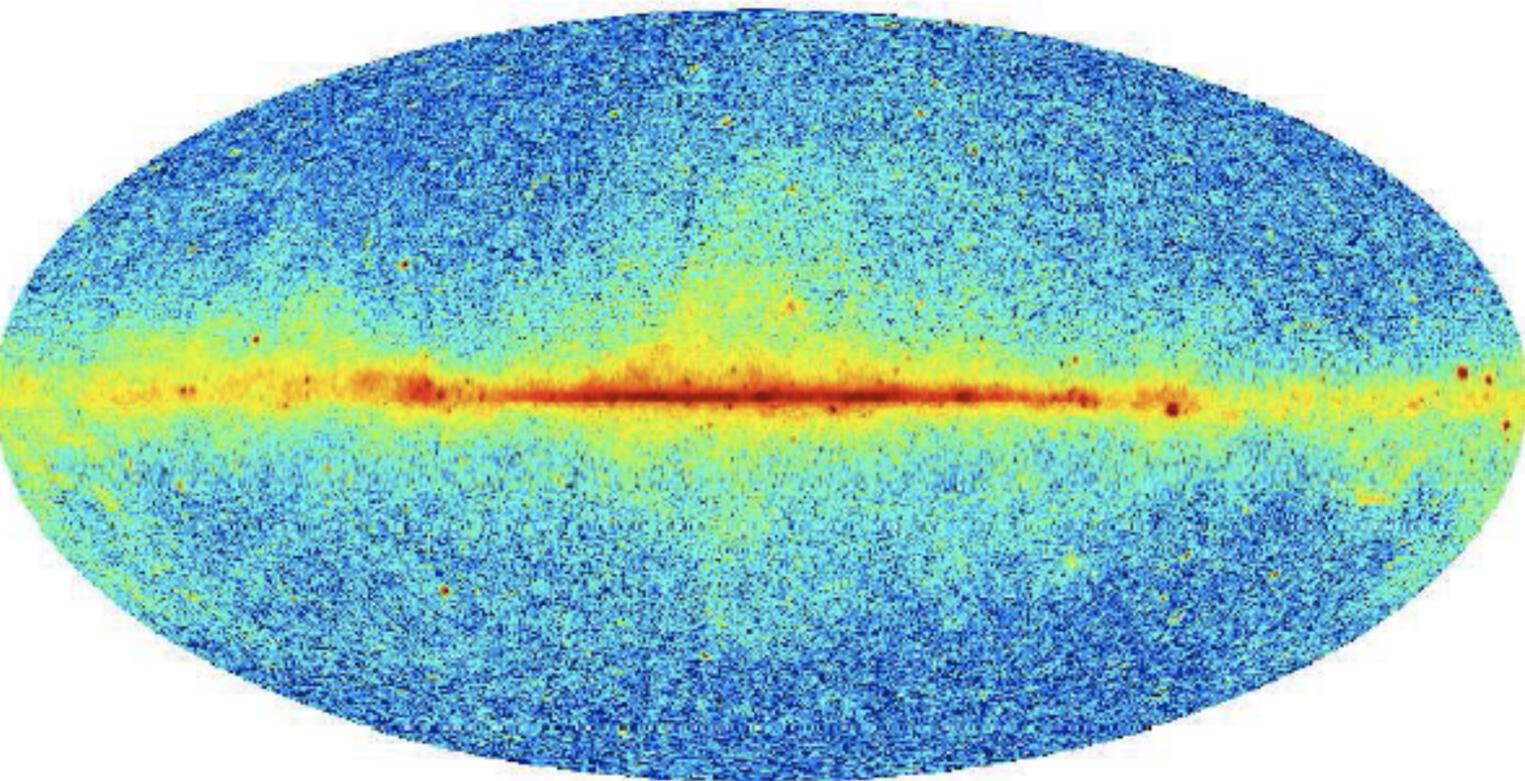
DATA (P6_V3 diffuse), 1.0–2.0 GeV



-7.0  -4.0 Log (Intensity [$\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$])

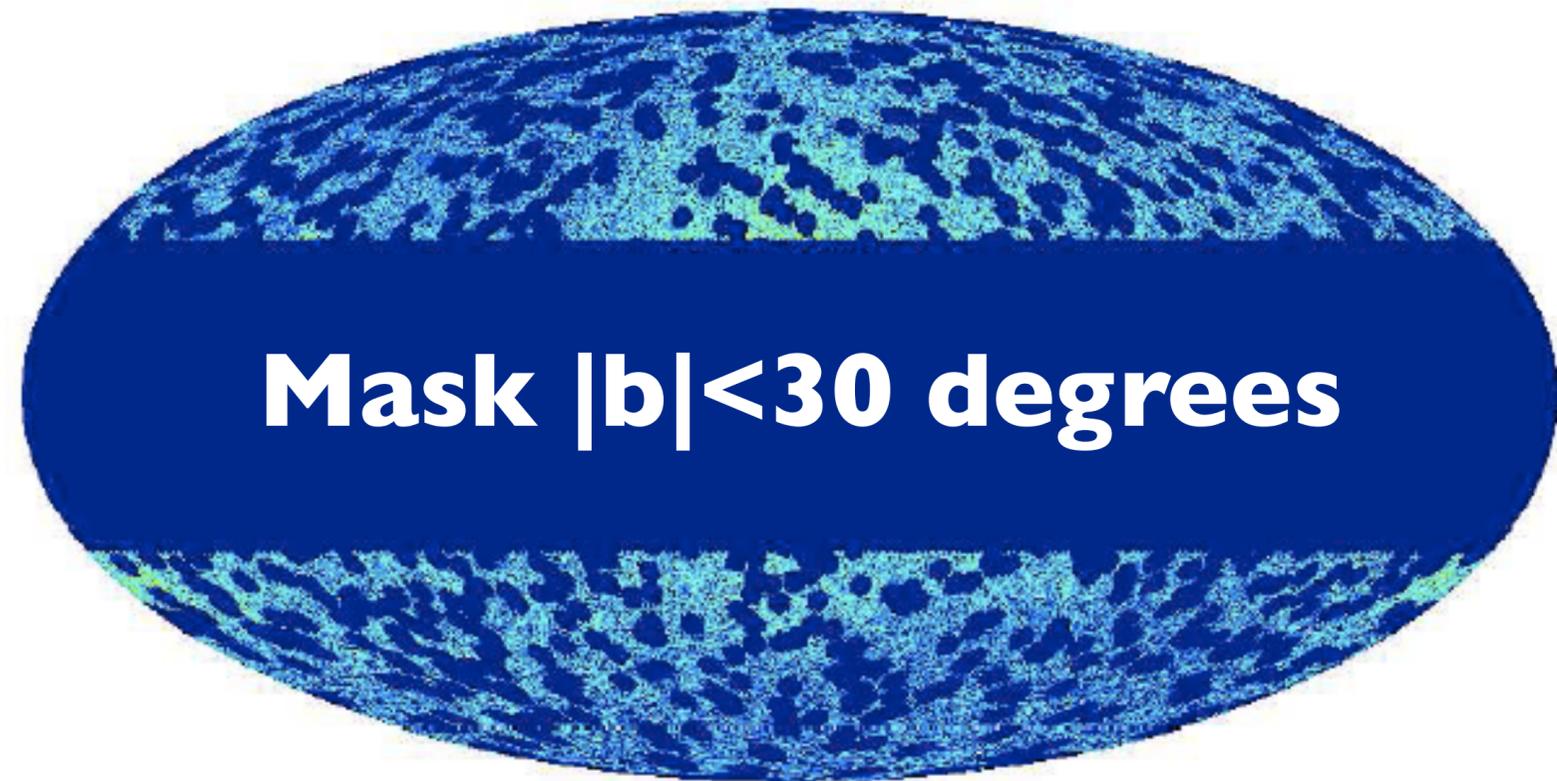
2.0–5.0 GeV

DATA (P6_V3 diffuse), 2.0–5.0 GeV



-7.0  -4.0 Log (Intensity [$\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$])

DATA (P6_V3 diffuse), 2.0–5.0 GeV

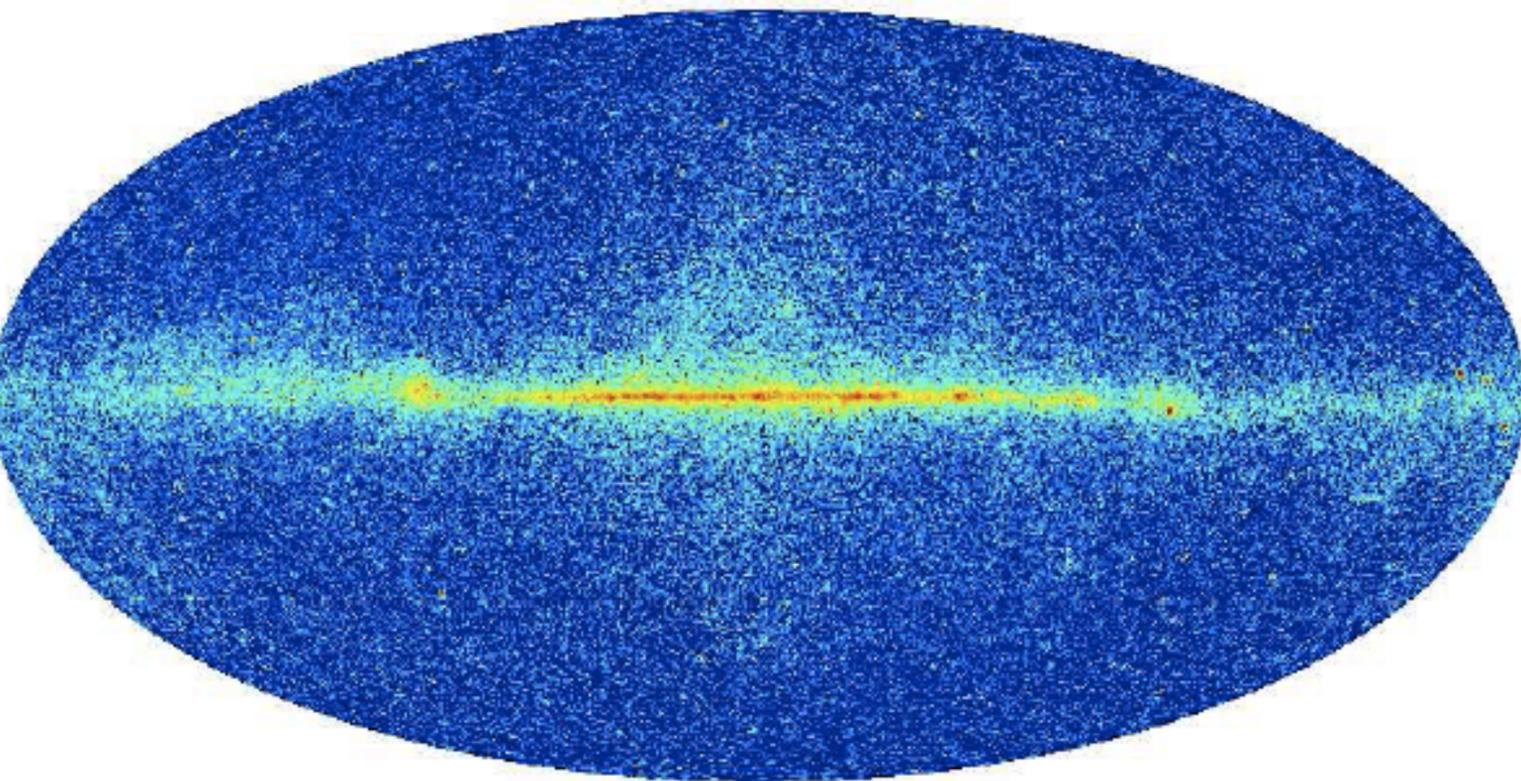


Mask $|b| < 30$ degrees

-7.0  -4.0 Log (Intensity [$\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$])

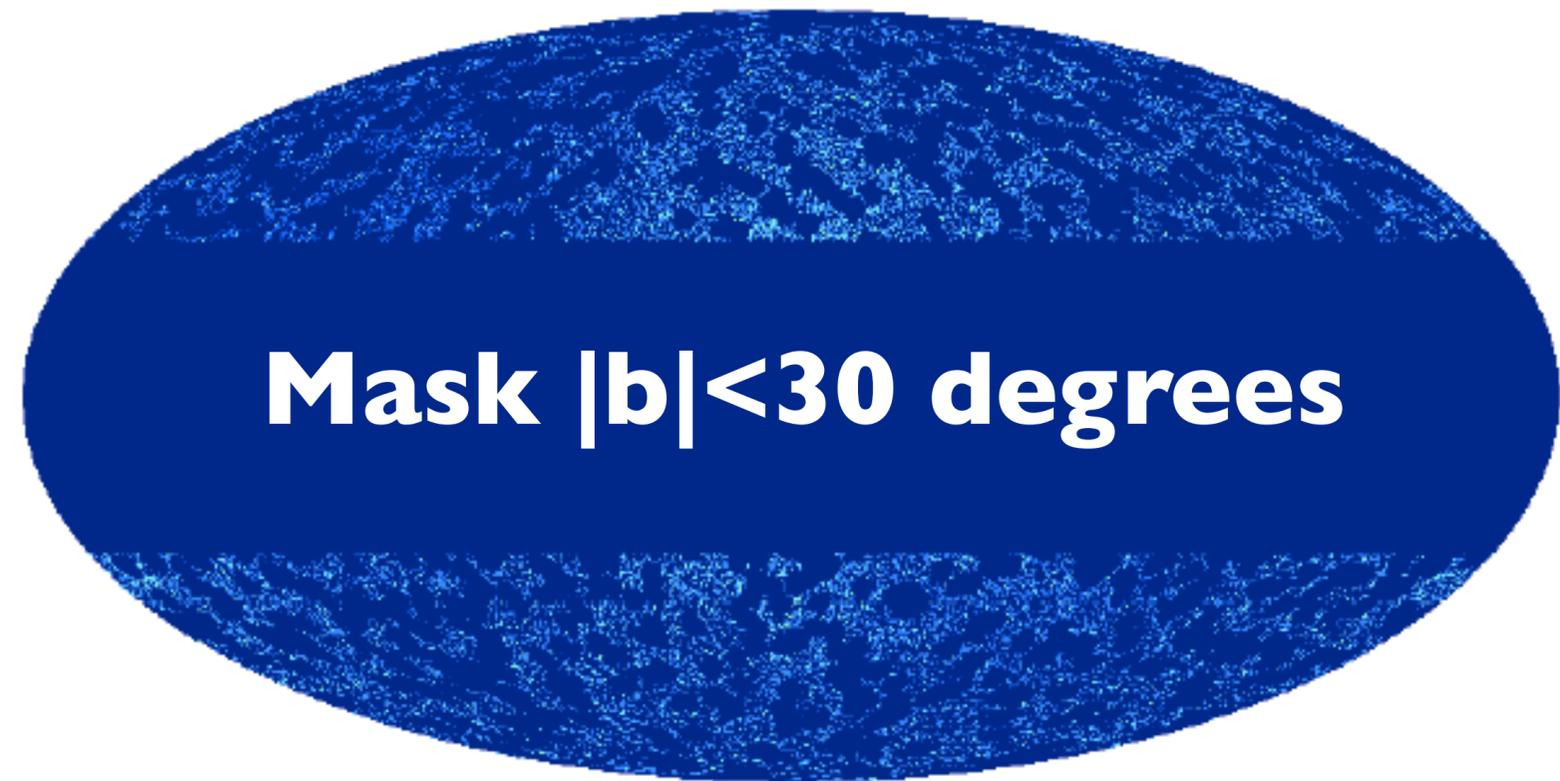
5.0–10.4 GeV

DATA (P6_V3 diffuse), 5.0–10.4 GeV



-7.0  -4.0 Log (Intensity [$\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$])

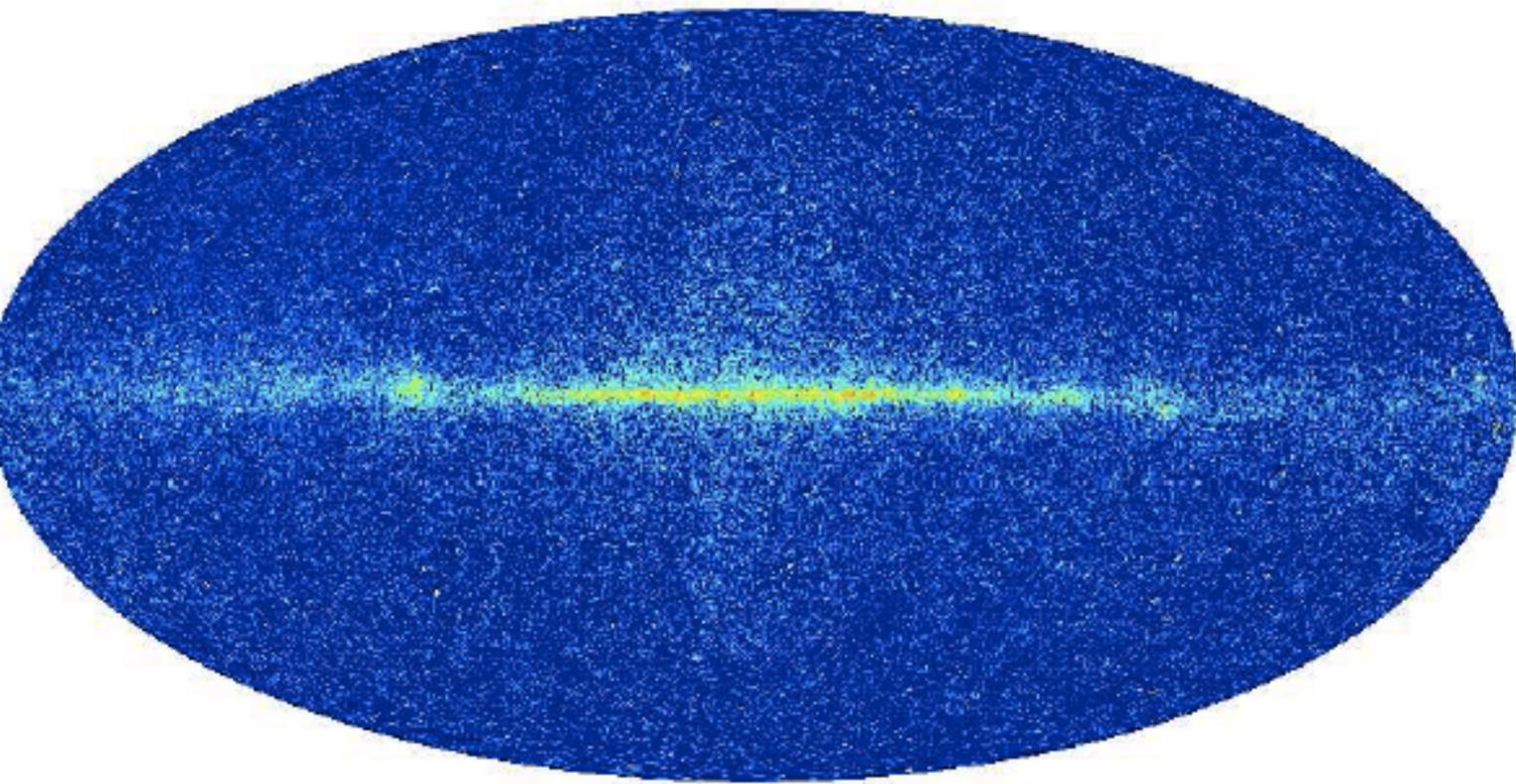
DATA (P6_V3 diffuse), 5.0–10.4 GeV



-7.0  -4.0 Log (Intensity [$\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$])

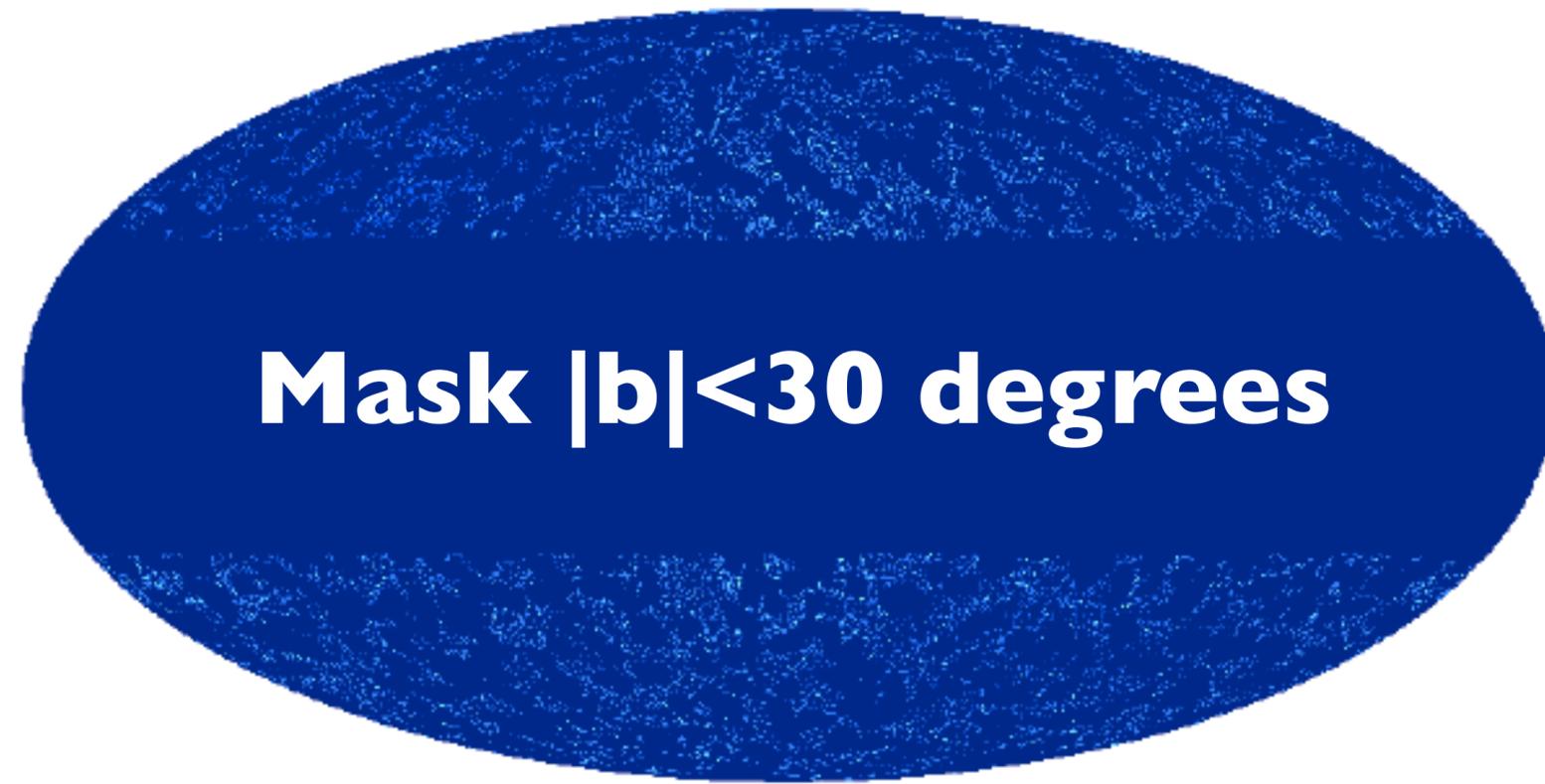
10.4–50.0 GeV

DATA (P6_V3 diffuse), 10.4–50.0 GeV



-7.0  -4.0 Log (Intensity [$\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$])

DATA (P6_V3 diffuse), 10.4–50.0 GeV



Mask $|b| < 30$ degrees

-7.0  -4.0 Log (Intensity [$\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$])

Fermi vs WMAP

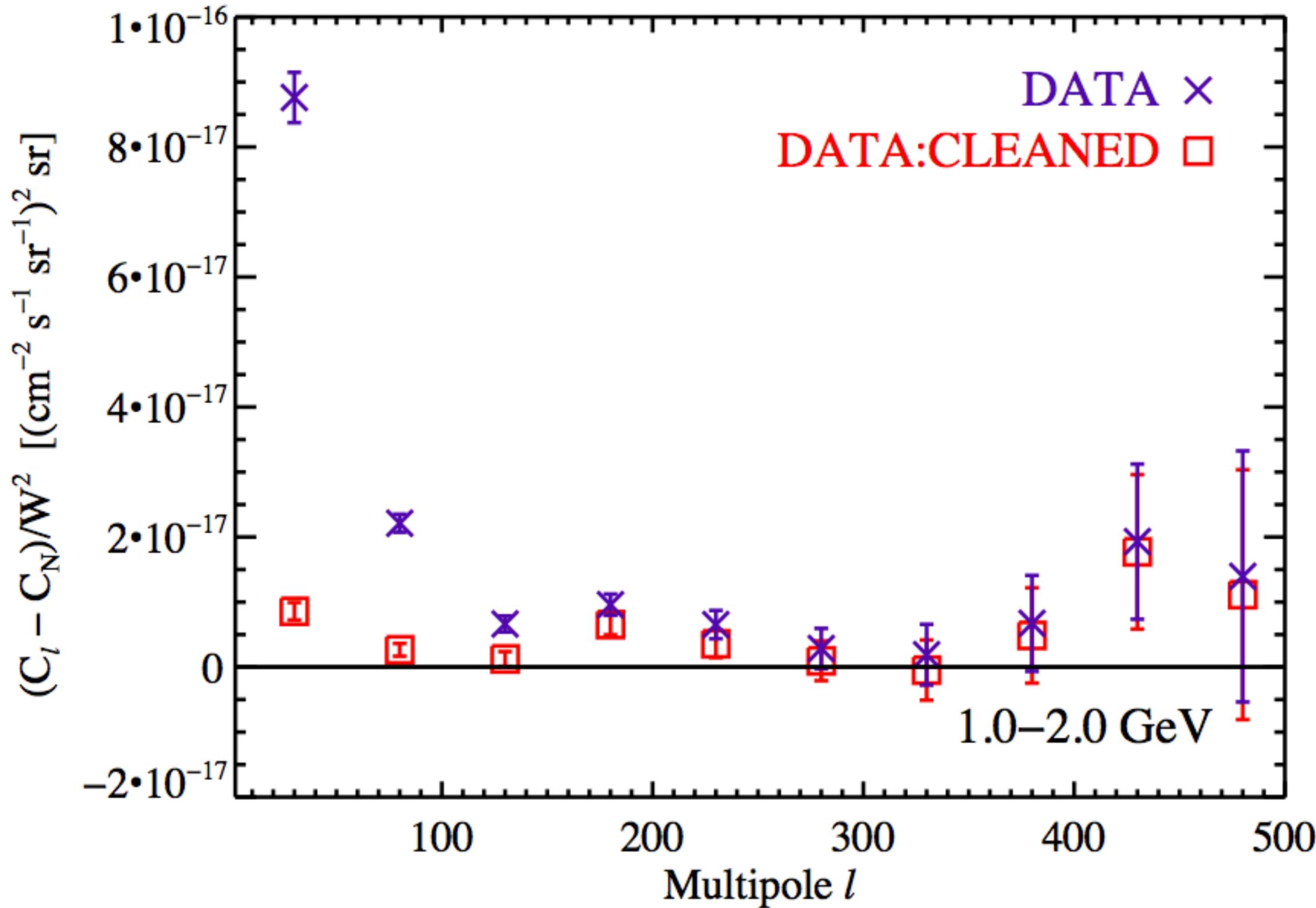
- There is an important difference between Fermi and WMAP maps
- We count photons to produce Fermi maps; thus, there is the “photon noise” (Poisson statistics) in the power spectrum, which we must subtract.
- Photon noise, C_N , is independent of multipoles, and is given by the mean number density of 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)
- PSF is by no means a Gaussian - we use the Fermi-LAT instrument response function and compute PSF
- We then compute $W_\ell^{\text{beam}}(E) = 2\pi \int_{-1}^1 d \cos \theta P_\ell(\cos(\theta)) \text{PSF}(\theta; E)$
- The attenuation by PSF is corrected as **$(C_I - C_N) / W_I^2$**

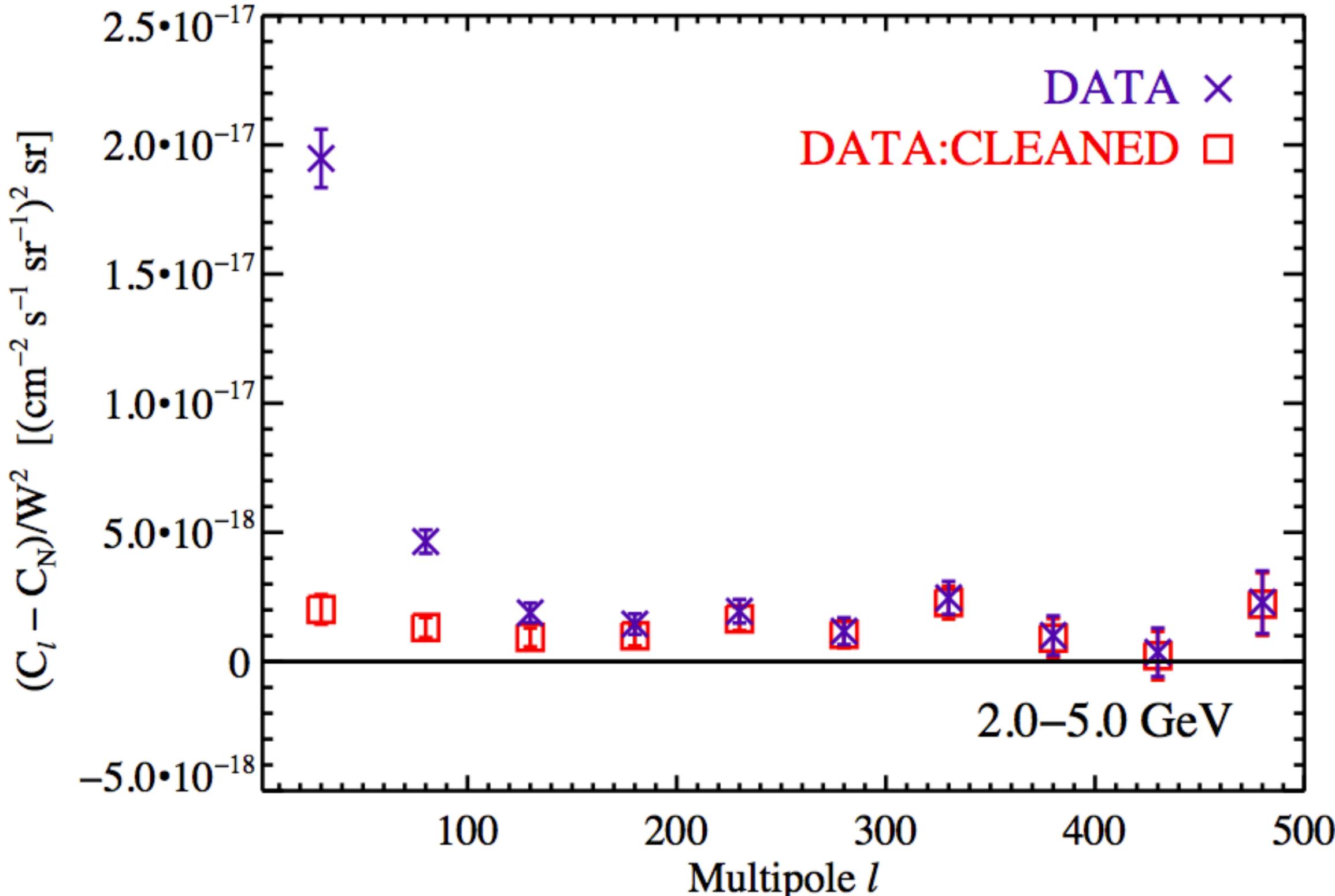
DATA: CLEANED = Galactic Model Map Subtracted

1.0–2.0 GeV



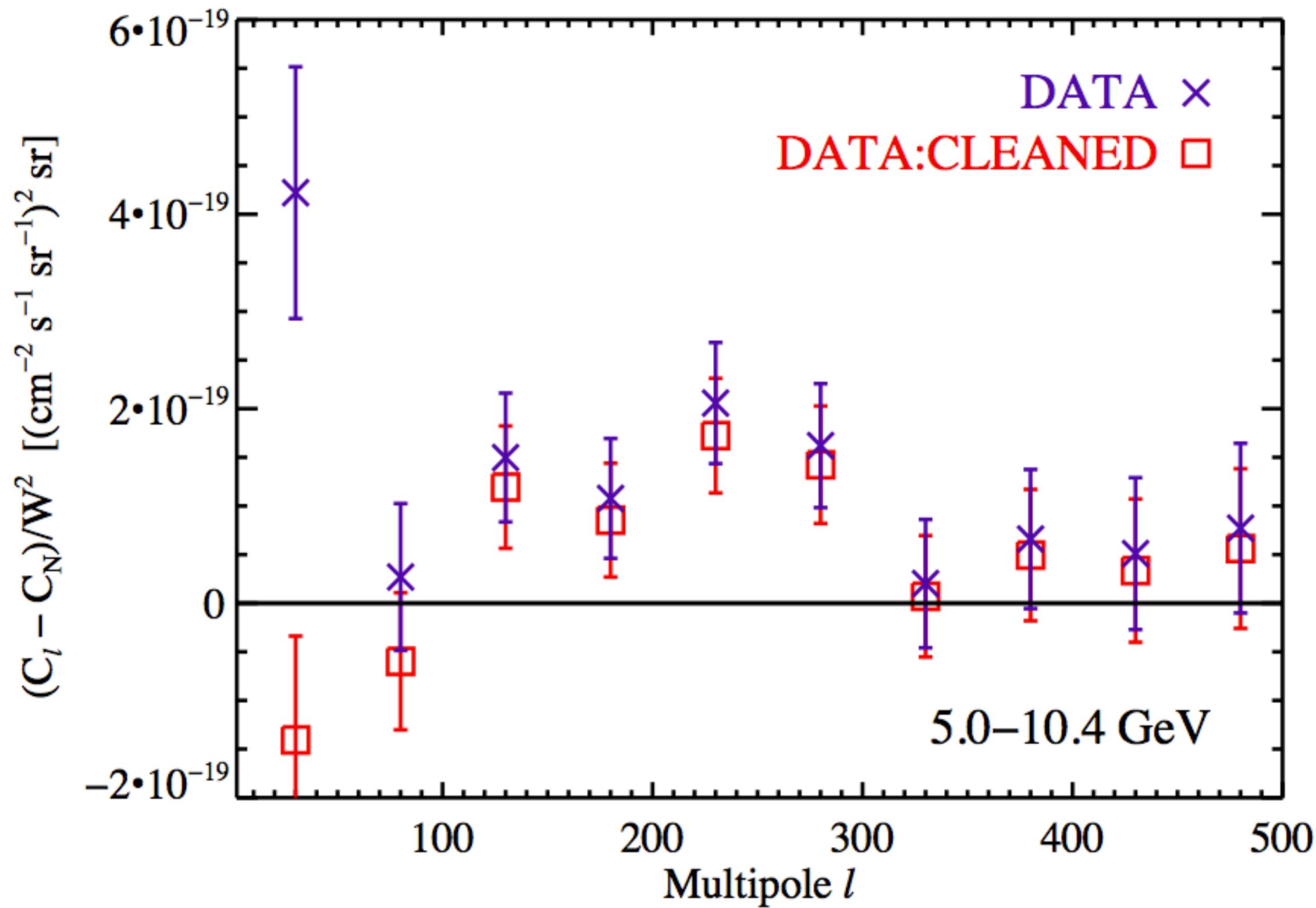
DATA: CLEANED = Galactic Model Map Subtracted

2.0–5.0 GeV



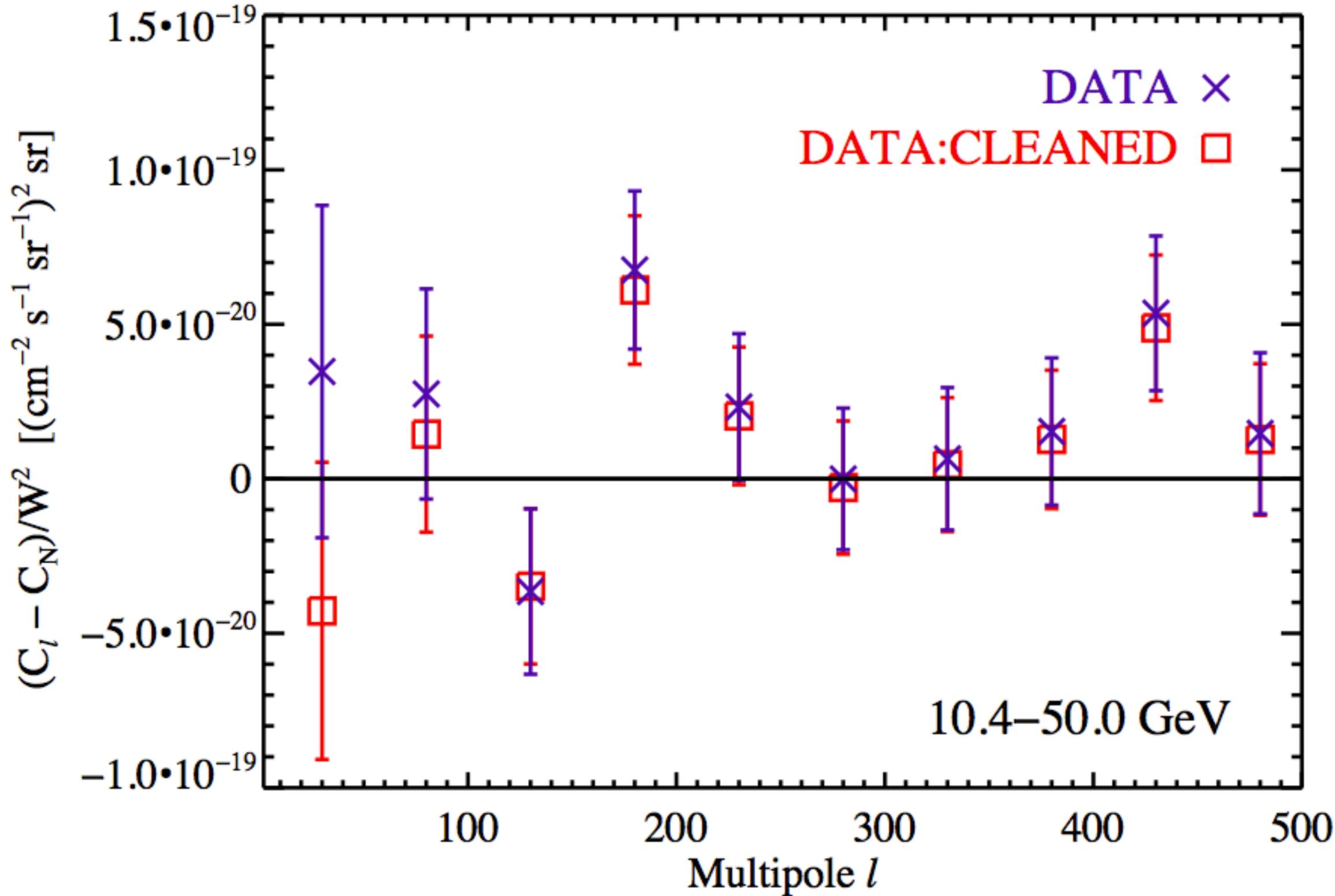
DATA: CLEANED = Galactic Model Map Subtracted

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

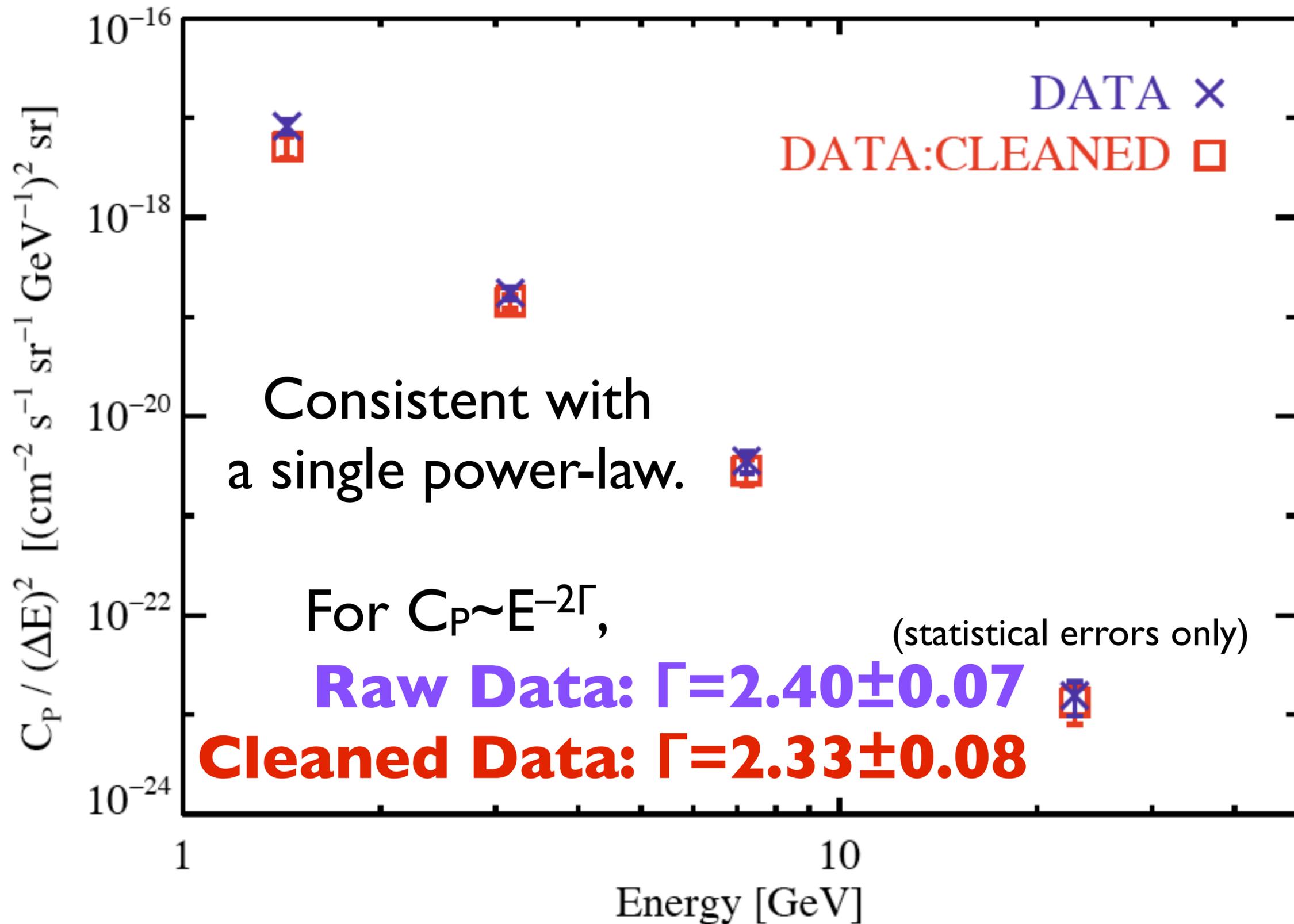
- When working with the mean intensity spectrum, one always has to worry about:
 - Diffuse Galactic emission
 - Background due to unrejected charged particles
- However, in C_l , these components appear only at low multipoles, cleanly separating, spatially, the extra-galactic signals and the contamination.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

First detection of the extra-galactic γ -ray anisotropy

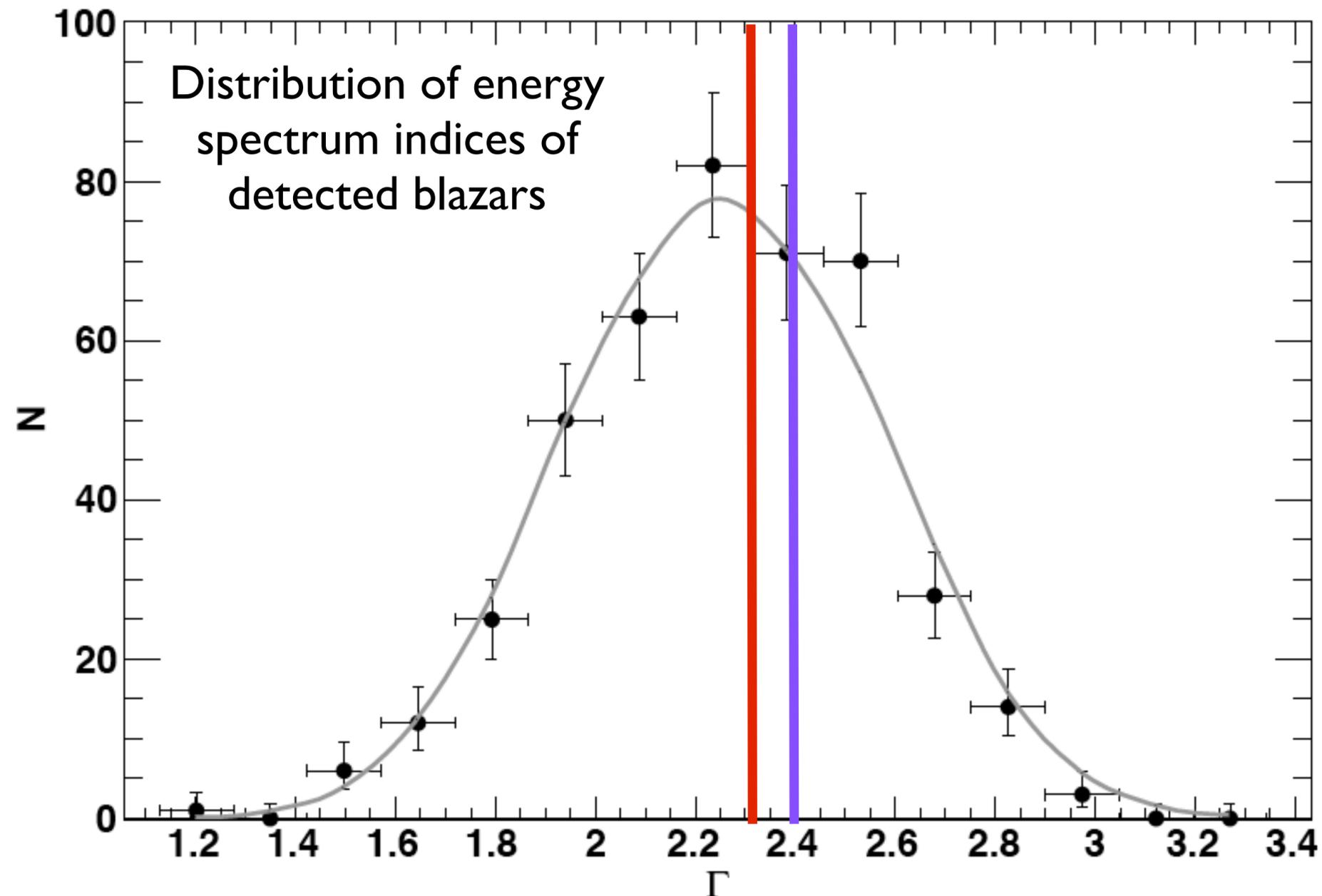
	E_{\min} [GeV]	E_{\max} [GeV]	C_P [[cm ⁻² s ⁻¹ sr ⁻¹) ² sr]	Significance
DATA	1.04	1.99	$7.39 \pm 1.14 \times 10^{-18}$	6.5σ
	1.99	5.00	$1.57 \pm 0.22 \times 10^{-18}$	7.2σ
	5.00	10.4	$1.06 \pm 0.26 \times 10^{-19}$	4.1σ
	10.4	50.0	$2.44 \pm 0.92 \times 10^{-20}$	2.7σ
DATA:CLEANED	1.04	1.99	$4.62 \pm 1.11 \times 10^{-18}$	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



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

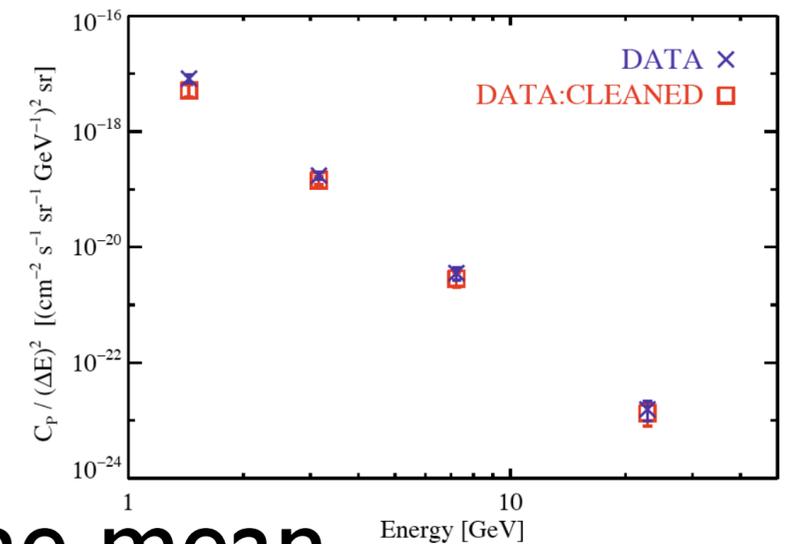
as

$$C_P = \int_0^{S_c} dS S^2 \frac{dN}{dS}$$

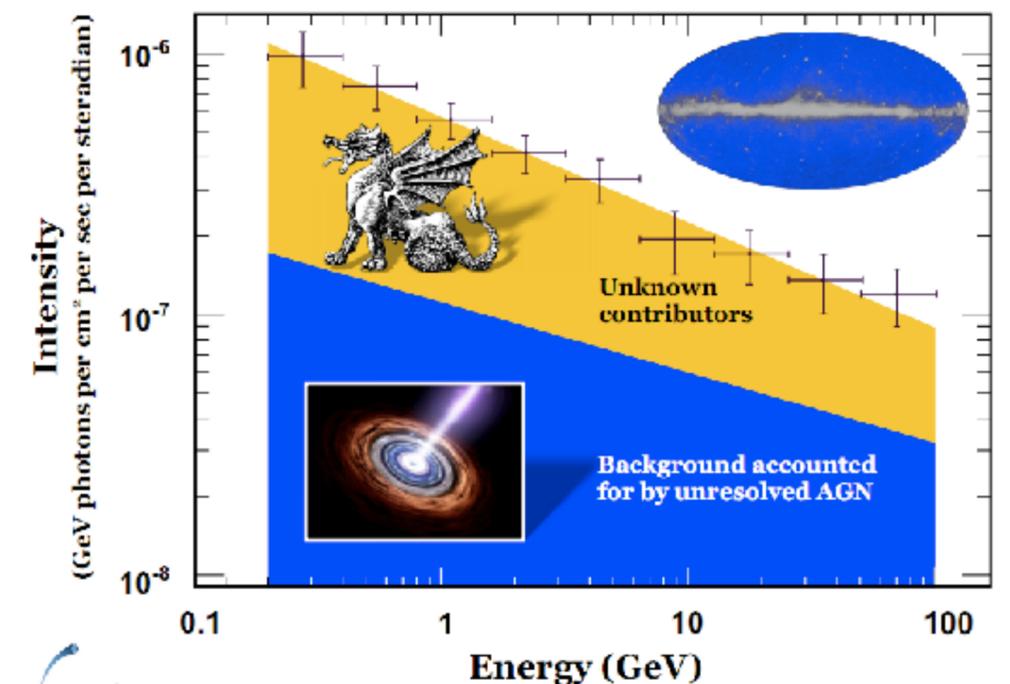
- Unresolved, point sources contribute to the mean intensity as

$$\langle I \rangle = \int_0^{S_c} dS S \frac{dN}{dS}$$

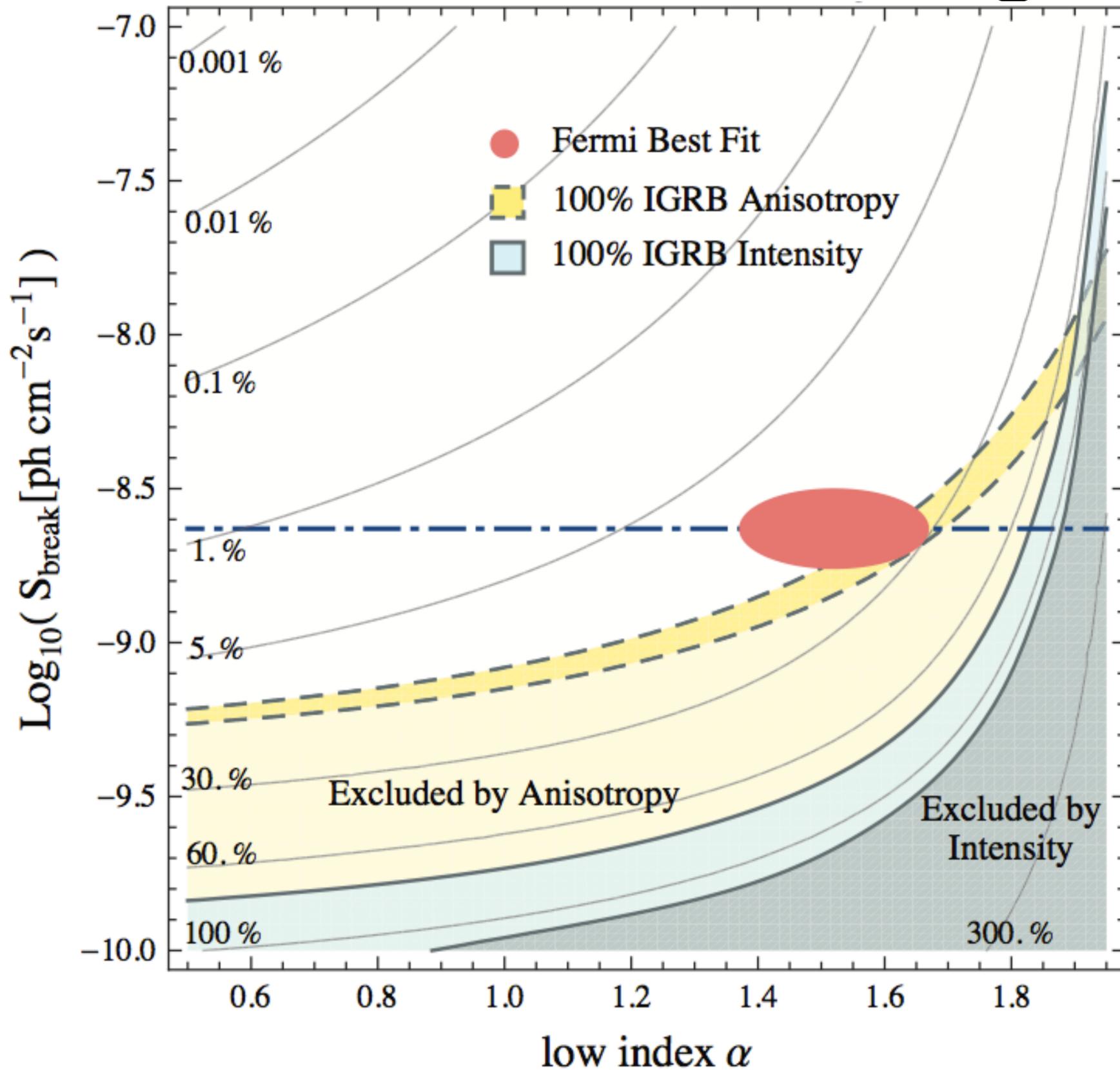
- Are they consistent with the data?**



Fermi LAT Extragalactic Gamma-ray Background



Are we seeing blazars? YES



$$C_P = \int_0^{S_c} dS S^2 \frac{dN}{dS}$$

$$\langle I \rangle = \int_0^{S_c} dS S \frac{dN}{dS}$$

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

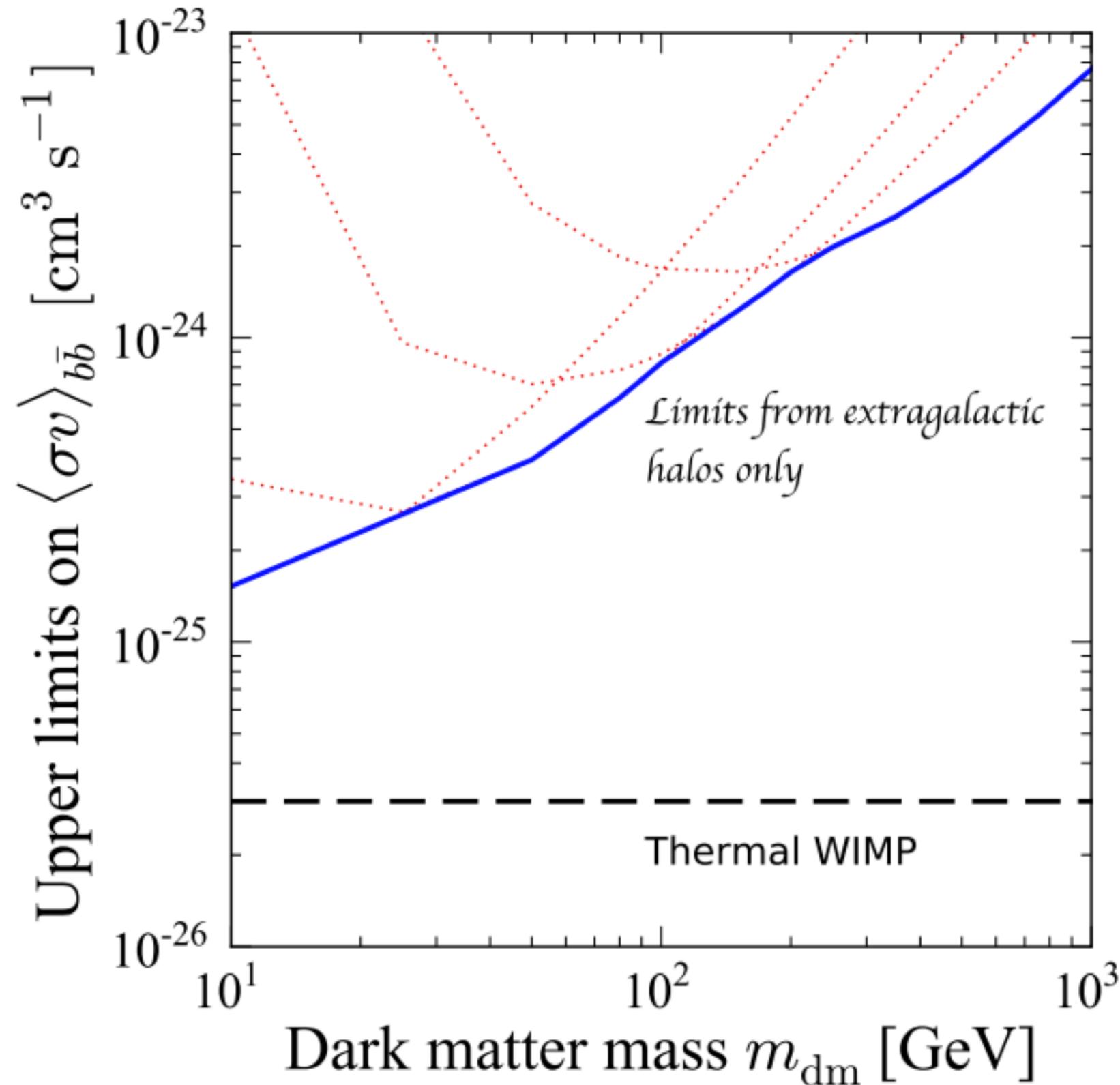
Vary S_b and α

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

Are we seeing blazars? 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 ($\sim 30\%$) of the mean gamma-ray background.
- These two, independent measurements give us a consistent picture of the gamma-ray sky.

What about Dark Matter?



New Measurement using 81-month data!

in collaboration with

M. Fornasa, A. Cuoco, J. Zavala, J. Gaskins, M.A. Sanchez-Conde, G.
Gomez-Vargas, T. Linden, F. Prada, F. Zandanel, A. Morselli

Phys. Rev. D 94, 123005 (2016)

All the power spectrum data
are publicly available at:

https://www-glast.stanford.edu/pub_data/552/



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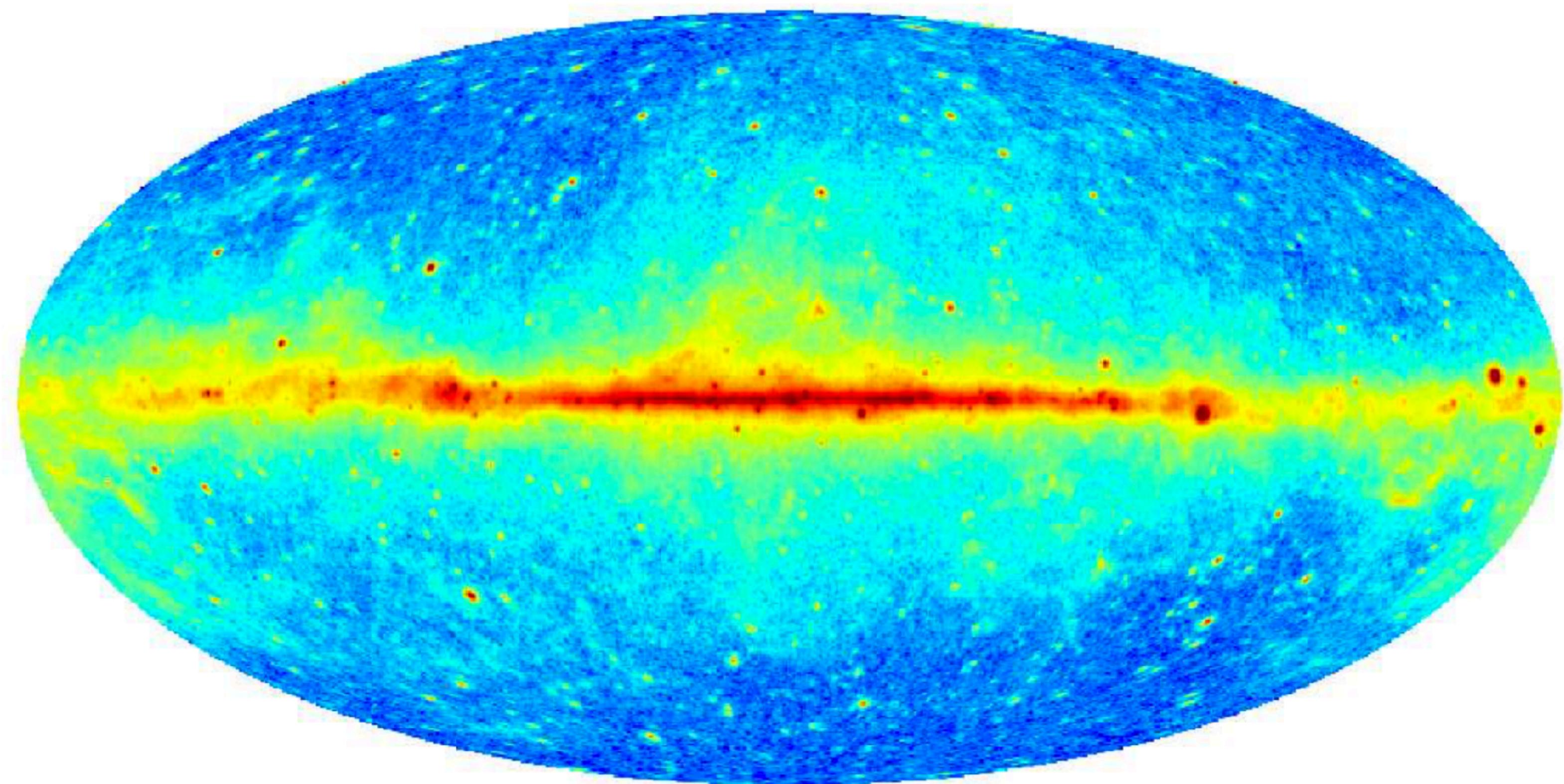
Fluctuations in extragalactic gamma rays reveal two source classes but no dark matter

December 19, 2016

Researchers from the Max Planck Institute for Astrophysics and the University of Amsterdam GRAPPA Center of Excellence just published the most precise analysis so far of the fluctuations in the gamma-ray background. They used more than six years of data gathered by the Fermi Large Area Telescope and found two different source classes contributing to the gamma-ray background. No traces of a contribution of dark matter particles were found in the analysis. The study was performed with an international collaboration of researchers and is published in the journal *Physical Review D*.

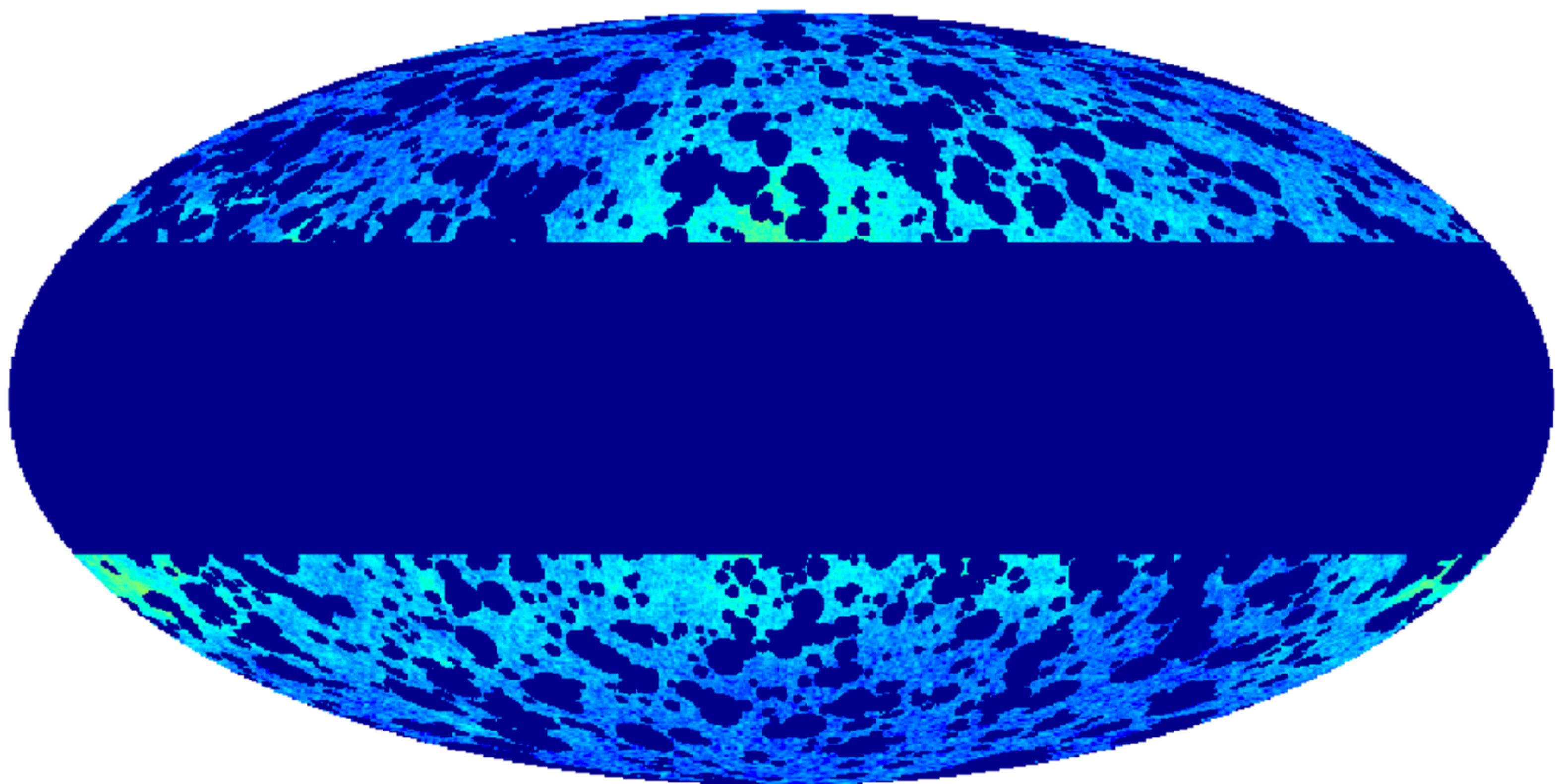
Gamma rays are particles of light, or photons, with the highest energy in the universe, invisible to the human eye. The most common emitters of gamma rays are blazars: supermassive black holes at the centres of galaxies. In smaller numbers, gamma rays are also produced by a certain kind of stars called pulsars and in huge stellar explosions such as supernovae.

DATA P7REP_ULTRACLEAN_V15, 1-2 GeV



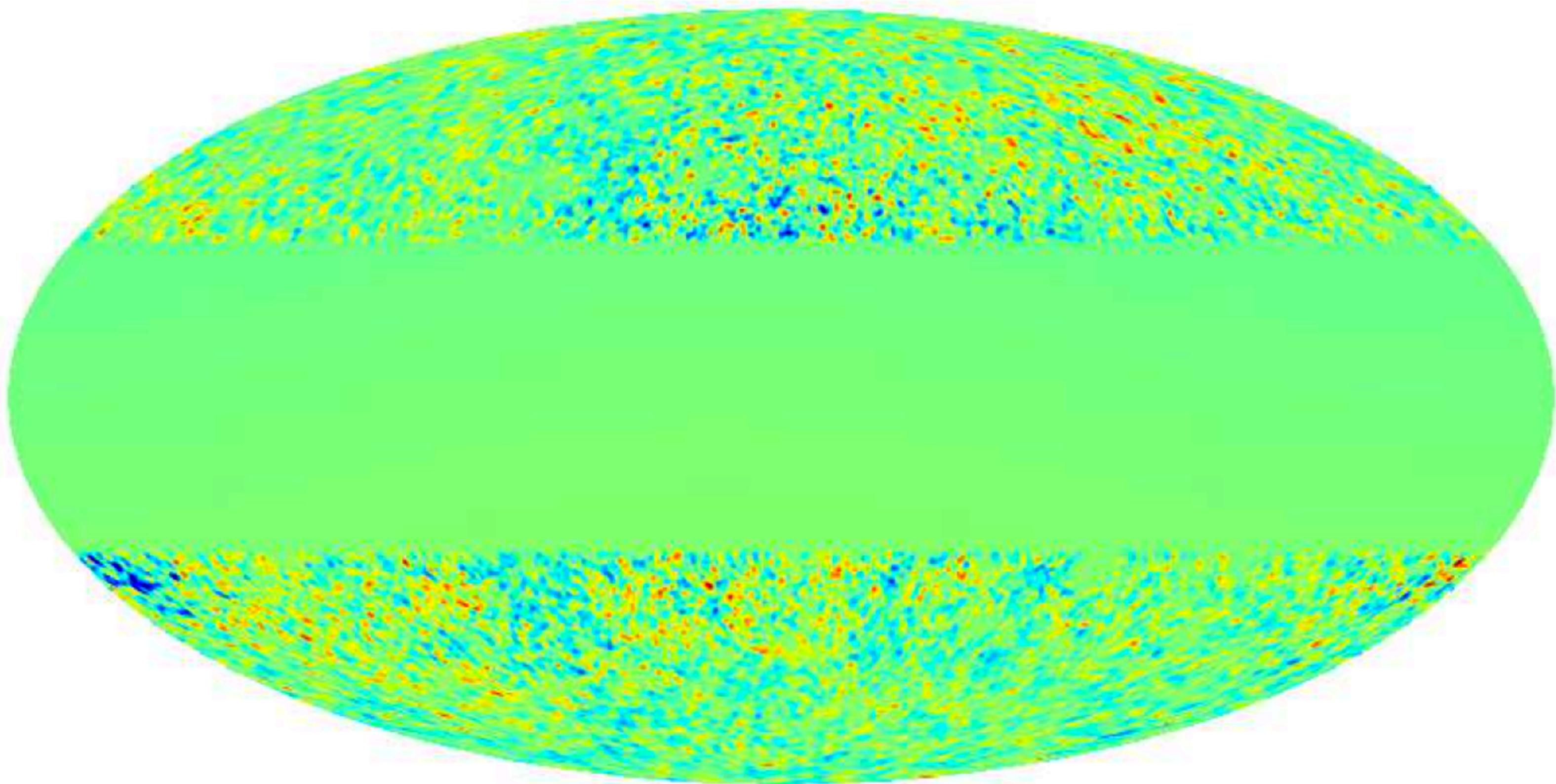
-7.0  -4.0 Log (Intensity [$\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$])

DATA P7REP_ULTRACLEAN_V15, 1-2 GeV

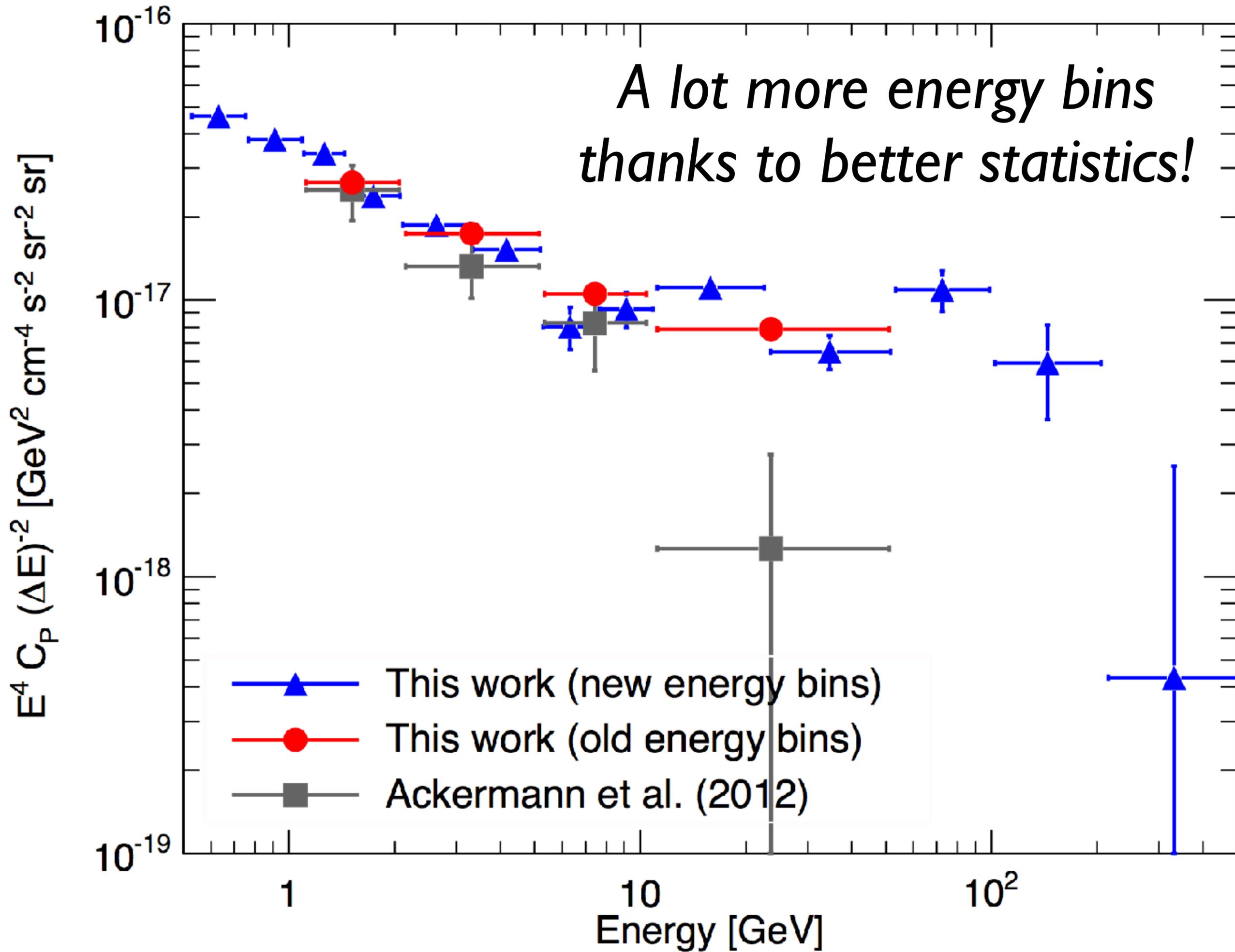


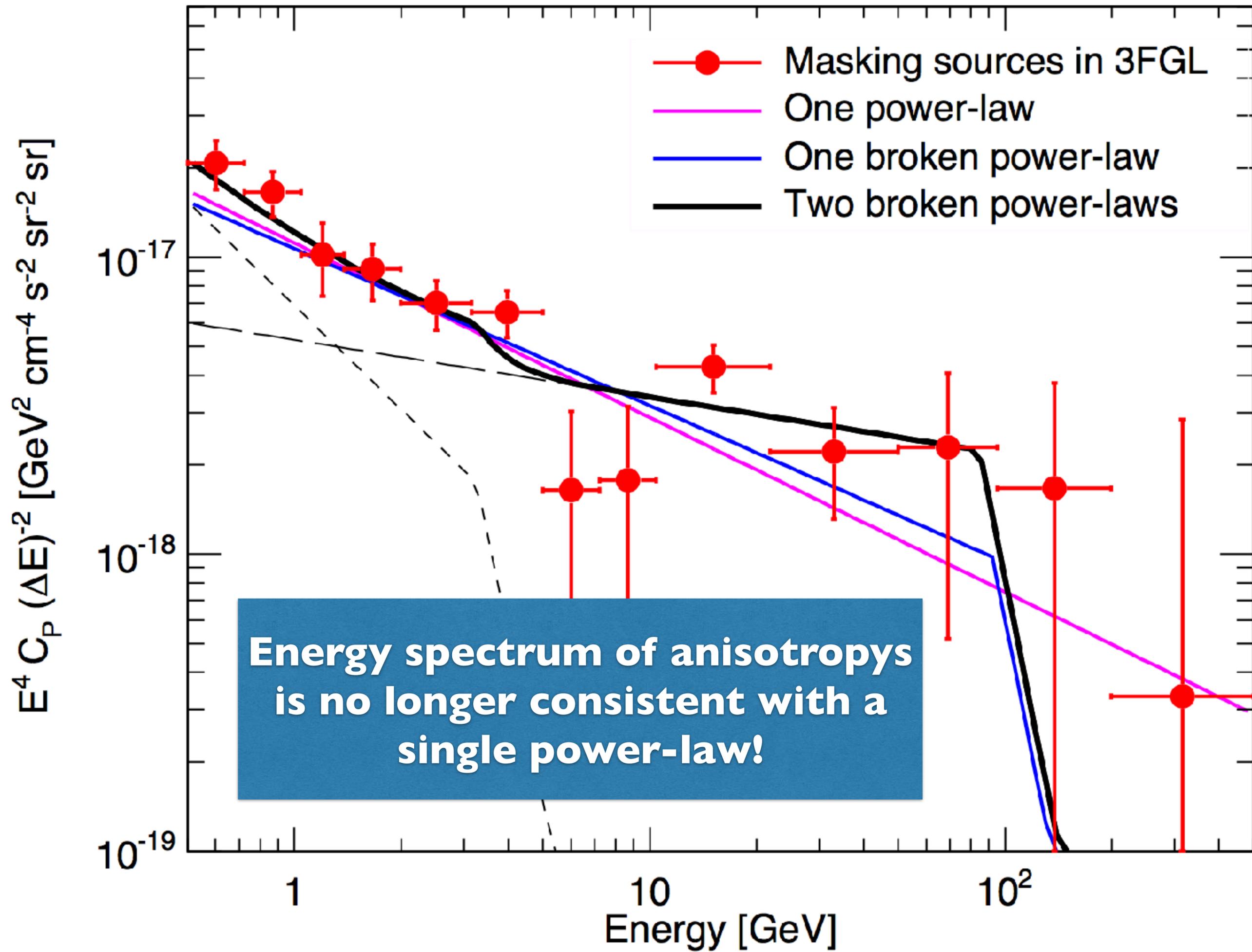
-7.0  -4.0 Log (Intensity [$\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$])

RESIDUALS P7REP_ULTRACLEAN_V15, 1-2 GeV



$-5.0e-07$  $5.0e-07$ Intensity [$\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$]

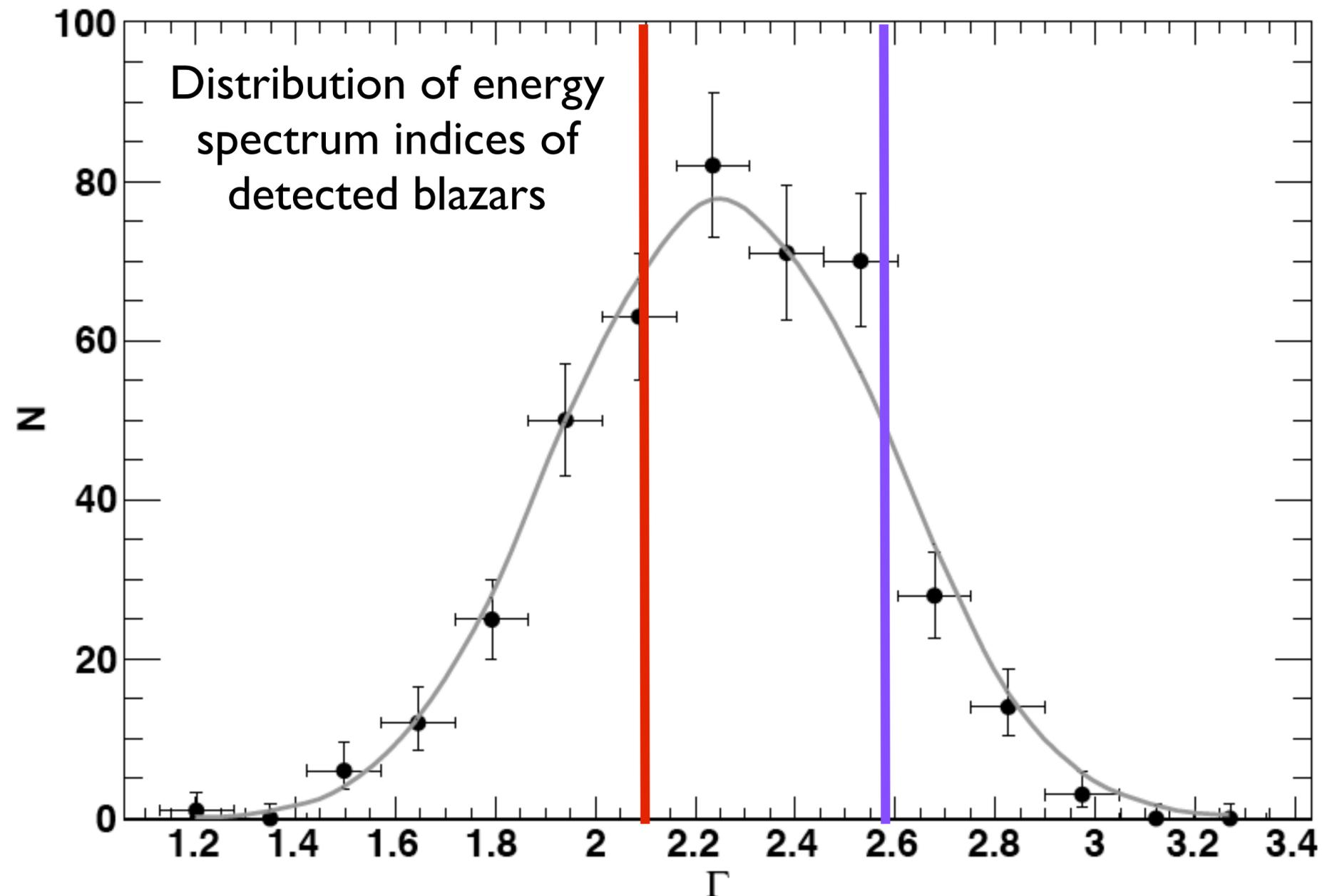




Energy Spectrum

- Energy spectrum $\sim E^{-\Gamma}$
- High-energy component: $\Gamma = 2.10 \pm 0.05$
- Low-energy component: $\Gamma = 2.58^{+0.18}_{-0.12}$

Are we seeing blazars?



- The energy spectra of two components are within the distribution of detected blazars

Two Scenarios

1. We are seeing the same sources at all energies

- Sources have complex spectra, given by two broken power-laws

2. We are NOT seeing the same sources at all energies

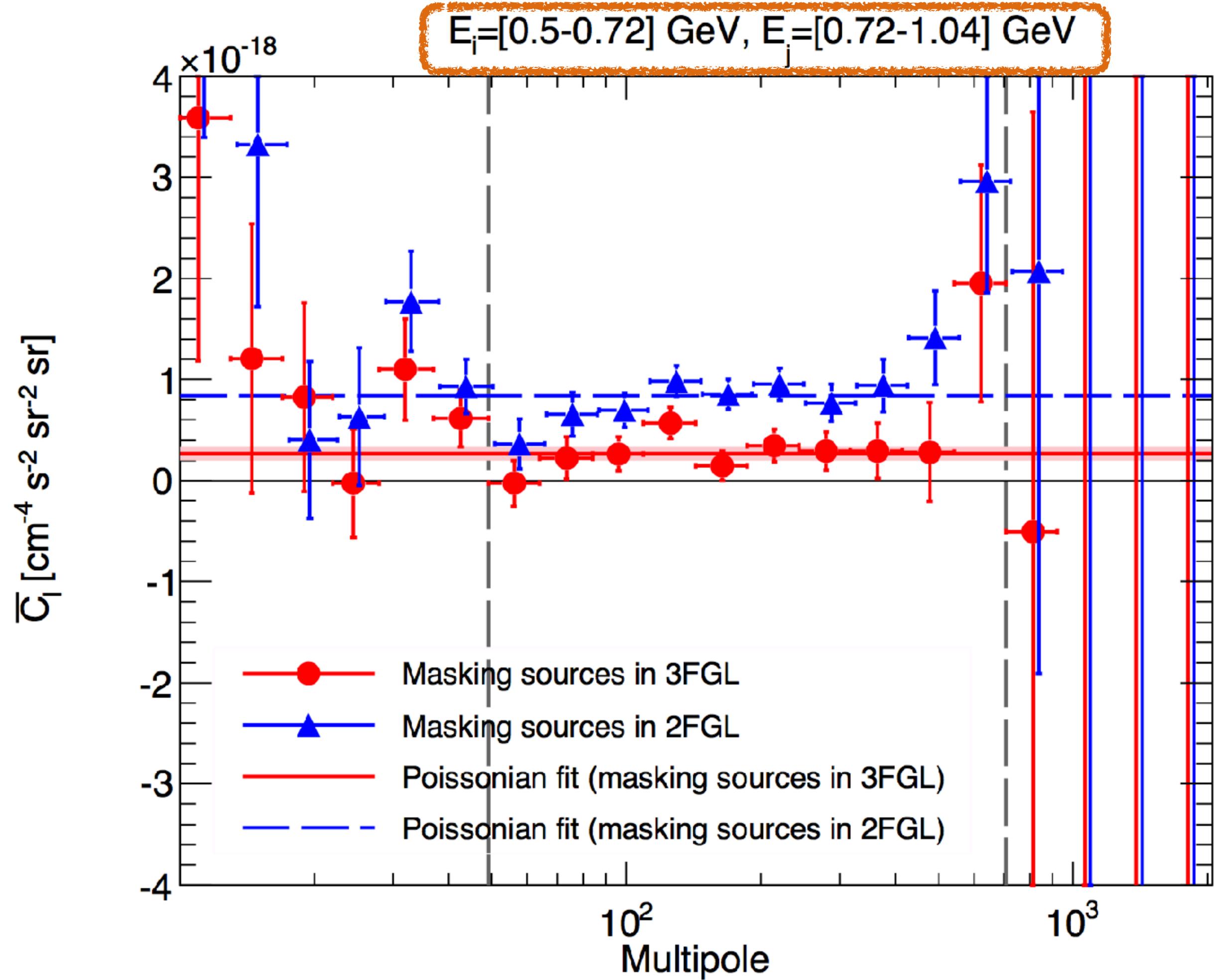
- There are two [or more] source classes contributing to low and high energies with different spectra

How can we distinguish between two scenarios? Cross-energy power spectrum!!

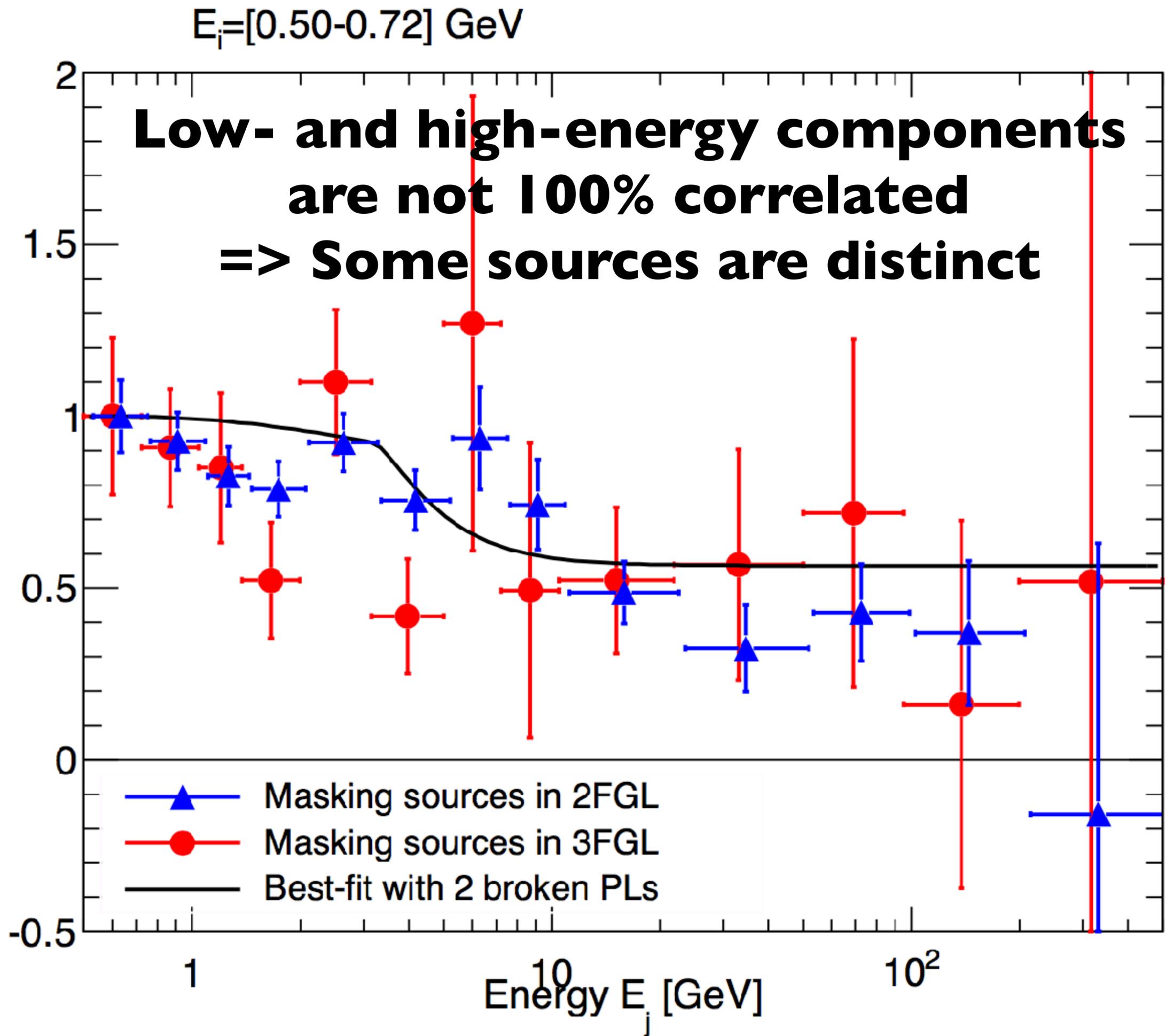
New: Cross-energy power spectrum

$$C_l^{ij} = \frac{1}{2l+1} \sum_{m=-l}^l a_{l,m}^i a_{l,m}^{j*}$$

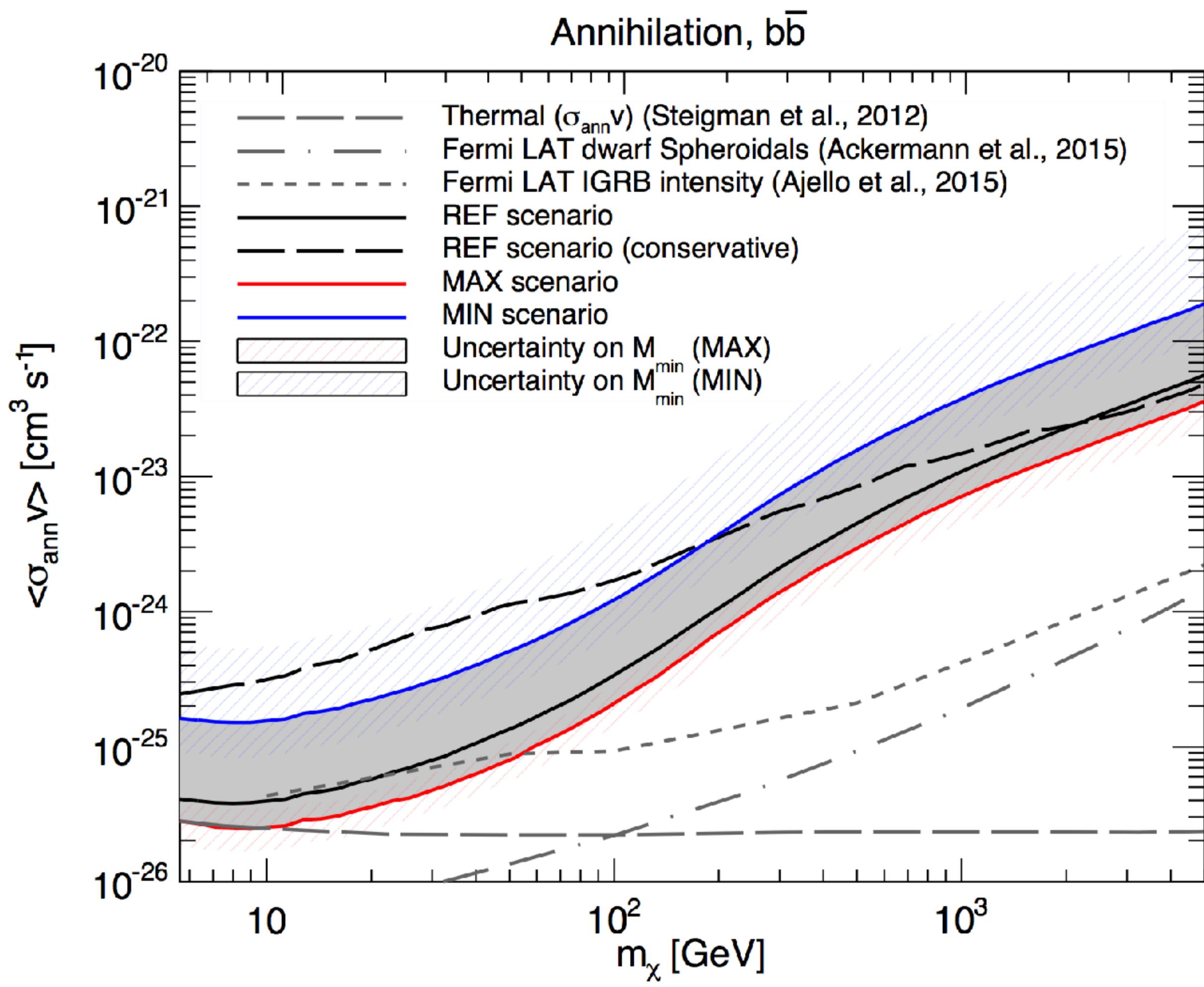
***Are we seeing the same sources
at all energies?***



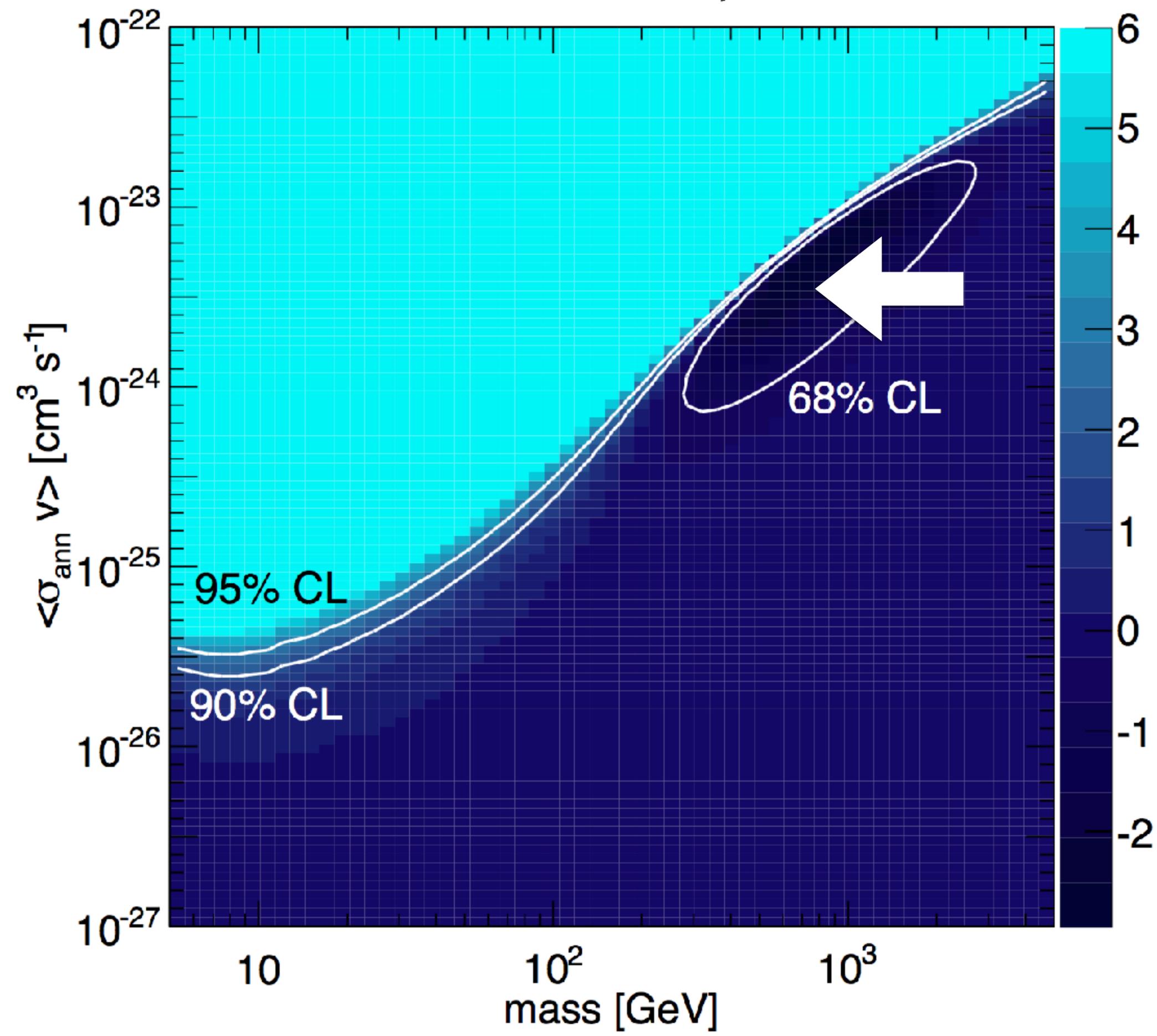
Cross-correlation coefficient



Constraint on the annihilation cross section



Annihilation, $b\bar{b}$



Conclusions

- We have detected anisotropy in the extra-galactic diffuse gamma-ray background from Fermi-LAT 22mo maps. **This is the first detection!**
- The new data, especially cross-energy spectra, reveal **two source classes**. High energy component can be explained by the contribution from unresolved blazars.
- Nature of the low-energy component is unclear (Ando et al., arXiv:1701.06988)
- **New limits** on the DM annihilation and decay rates from anisotropies

