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

Eiichiro Komatsu (Max-Planck-Institut für Astrophysik)
Physics Colloquium, Columbia University, February 9, 2015

This work is based on:

Idea & Predictions

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

Measurement

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

Interpretations

- Cuoco, EK & Siegal-Gaskins, PRD 86, 063004 (2012)
- Ando & EK, PRD 87, 123539 (2013)

New Idea

- Ando, Benoit-Lévy & EK, PRD 90, 023514 (2014)

Shin'ichiro Ando

Jenny Siegal-Gaskins

Alex Cuoco

Aurélien Benoit-Lévy

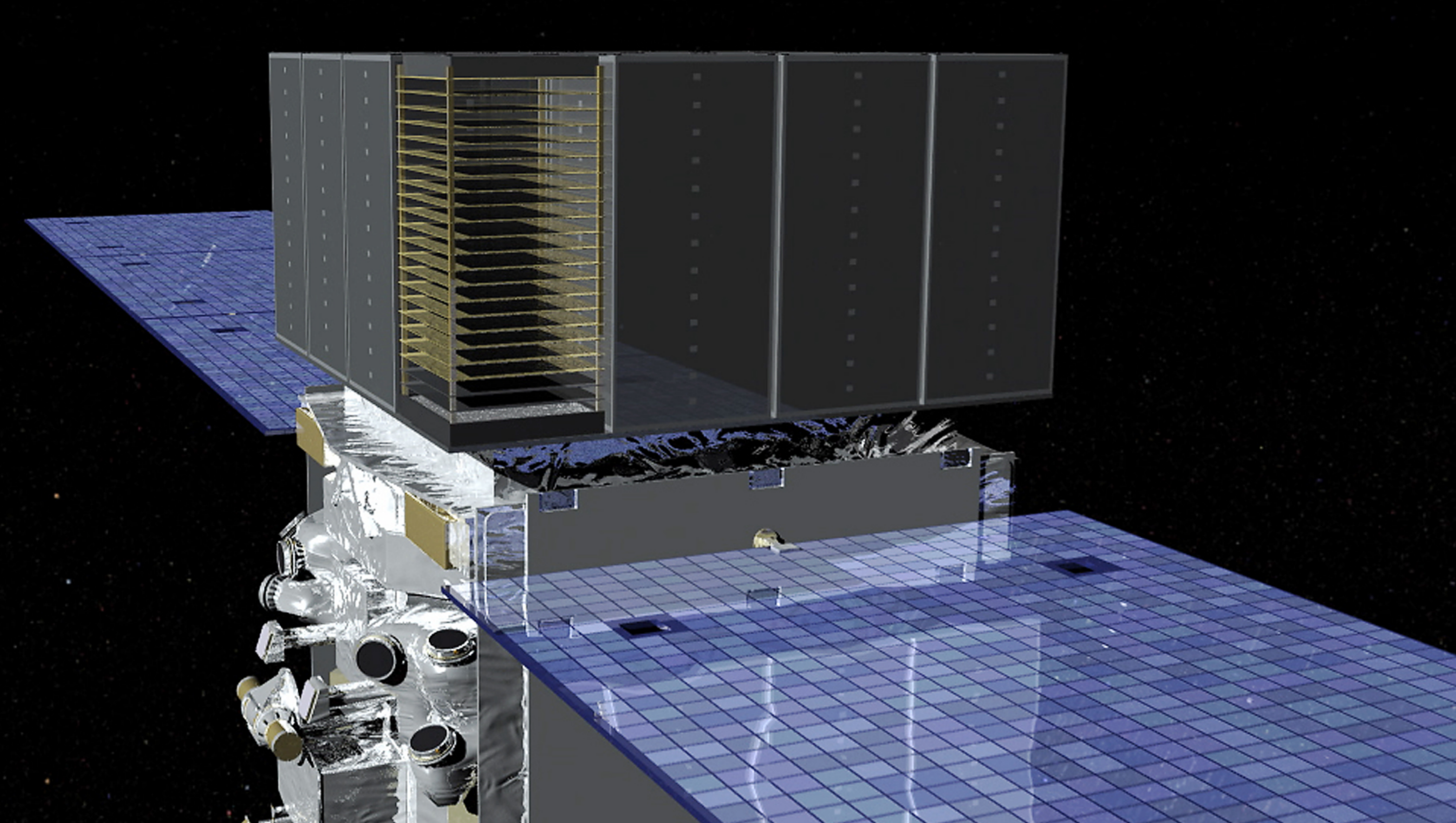
Fermi Gamma-ray Satellite

<u>Fermi Gamma-ray Satellite</u>

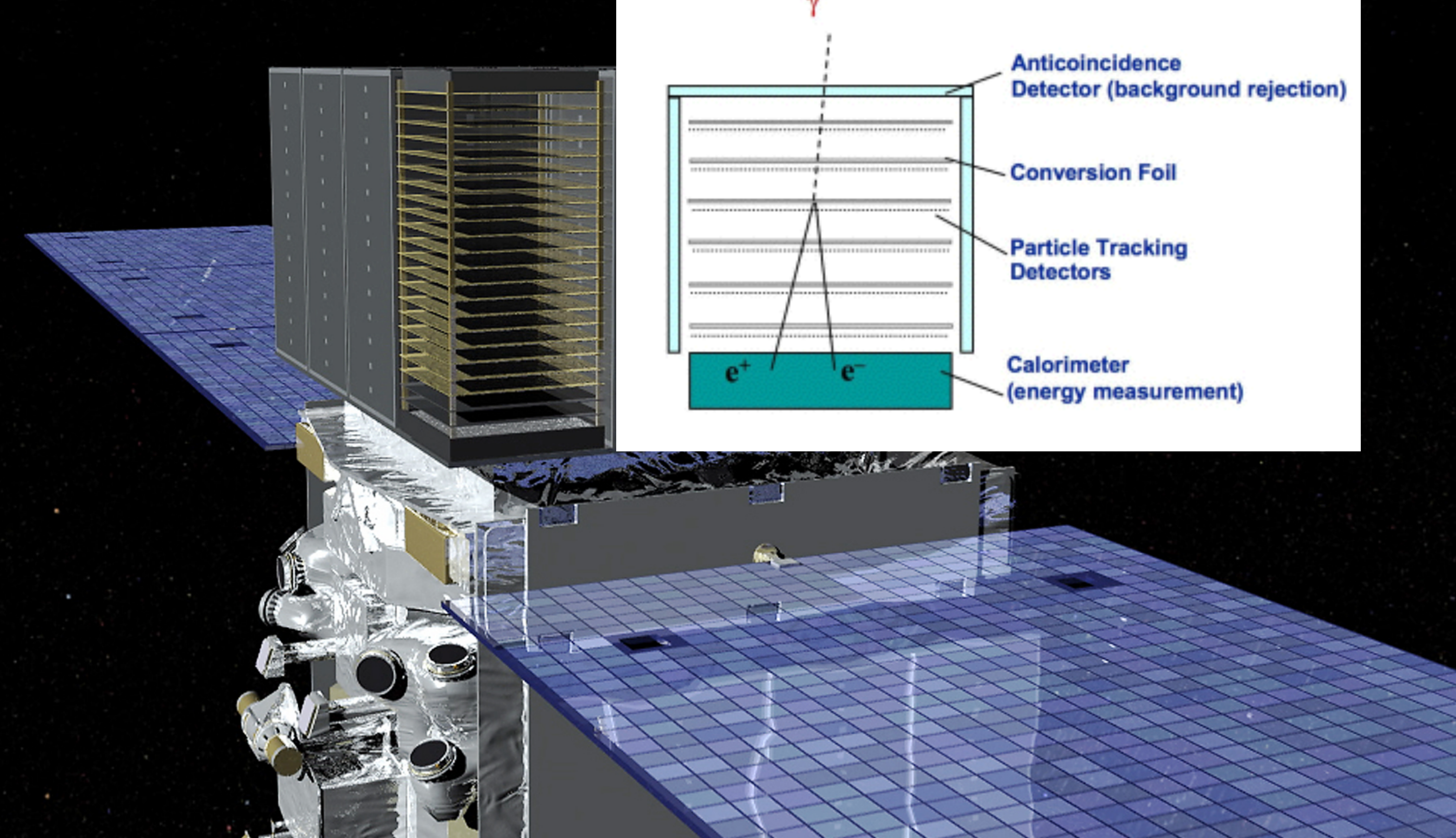
In this talk, I will focus on the results from the Fermi Large Area Telescope (LAT) instrument.

Energy Range in This Talk: 1 to 50 GeV

Fermi Gamma-ray Satellite



Fermi Gamma-ray Satellite

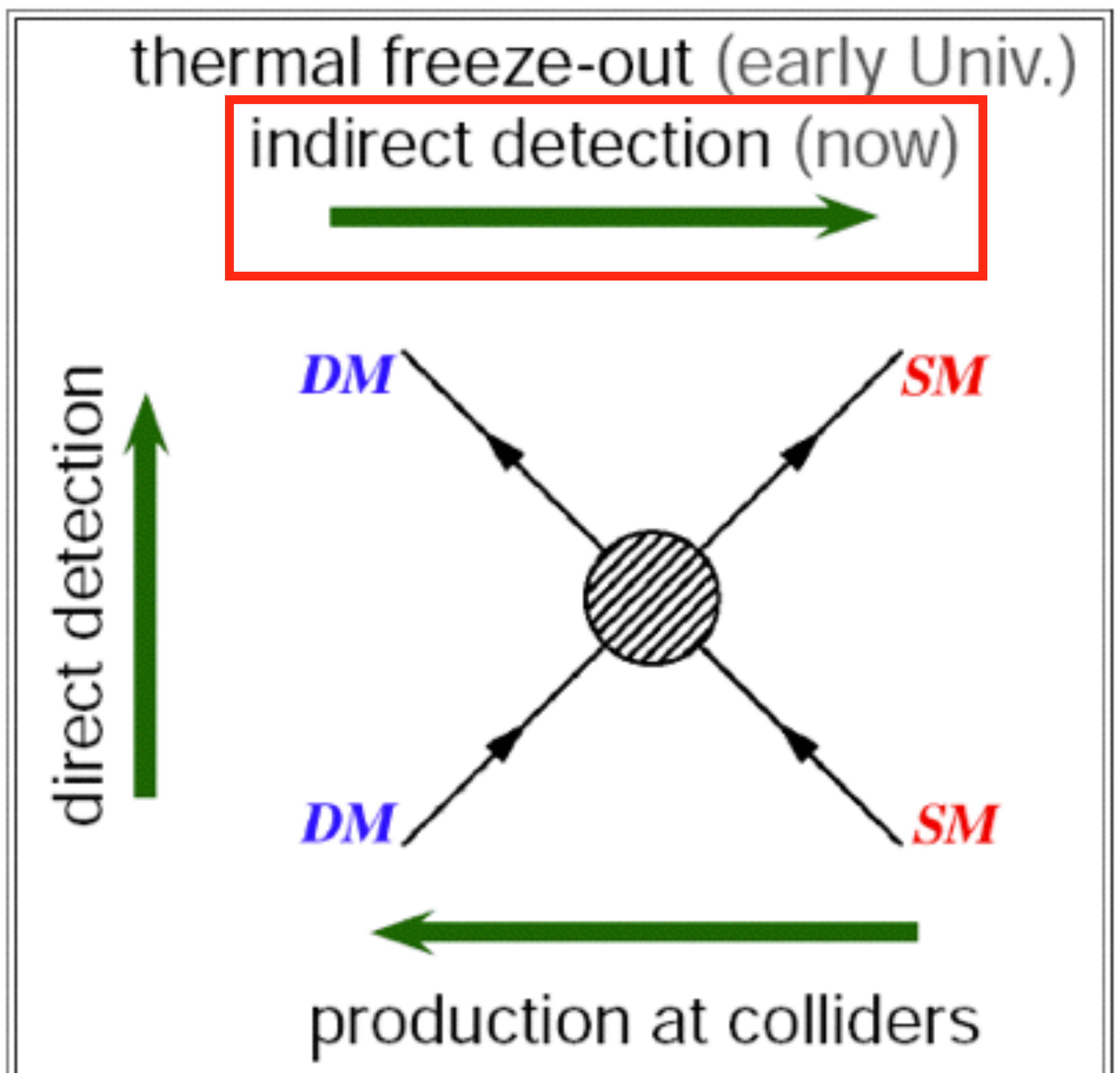


Fermi Gamma-ray Satellite

Disclaimer: I am **not** a part of the Fermi collaboration,
but am an external collaborator for the "Anisotropy Working Group"

A Simple Motivation

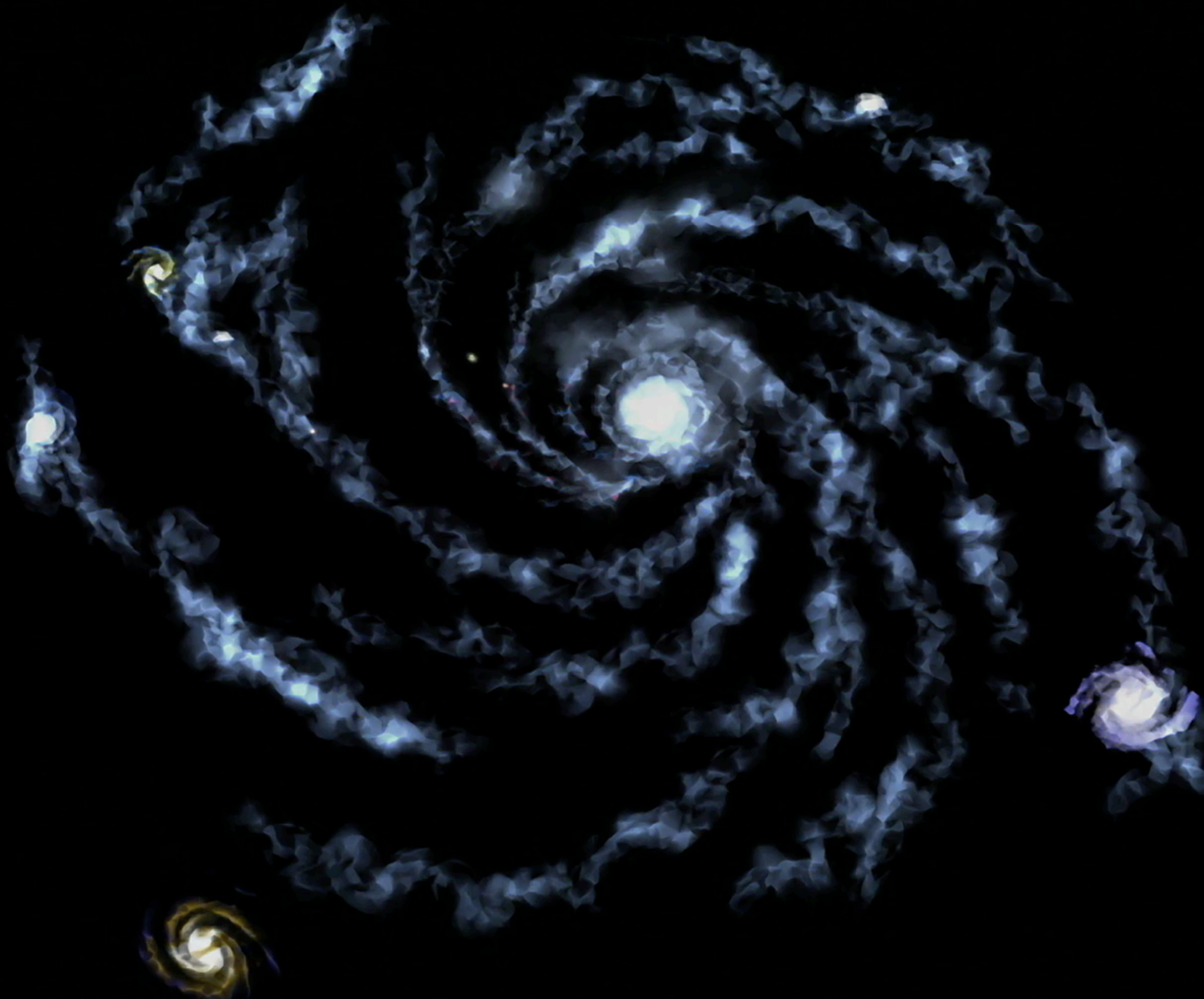
- How can we see photons from annihilation/decay of dark matter particles?



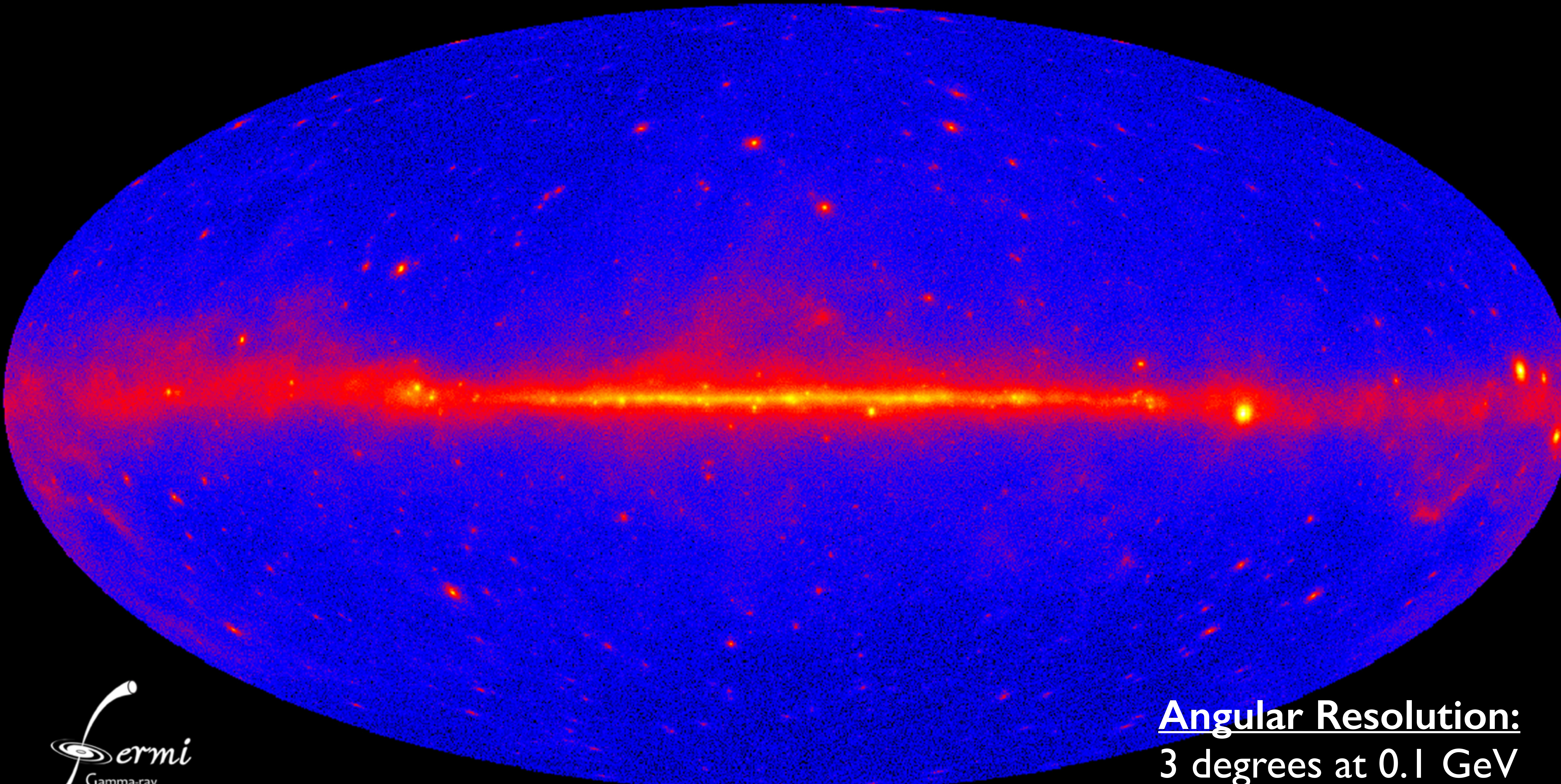
DM: Dark Matter
SM: Standard Model Particles

Big Assumptions:

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



Gamma-ray Sky, integrated from 0.3 GeV



Fermi Gamma-ray Space Telescope

Angular Resolution:

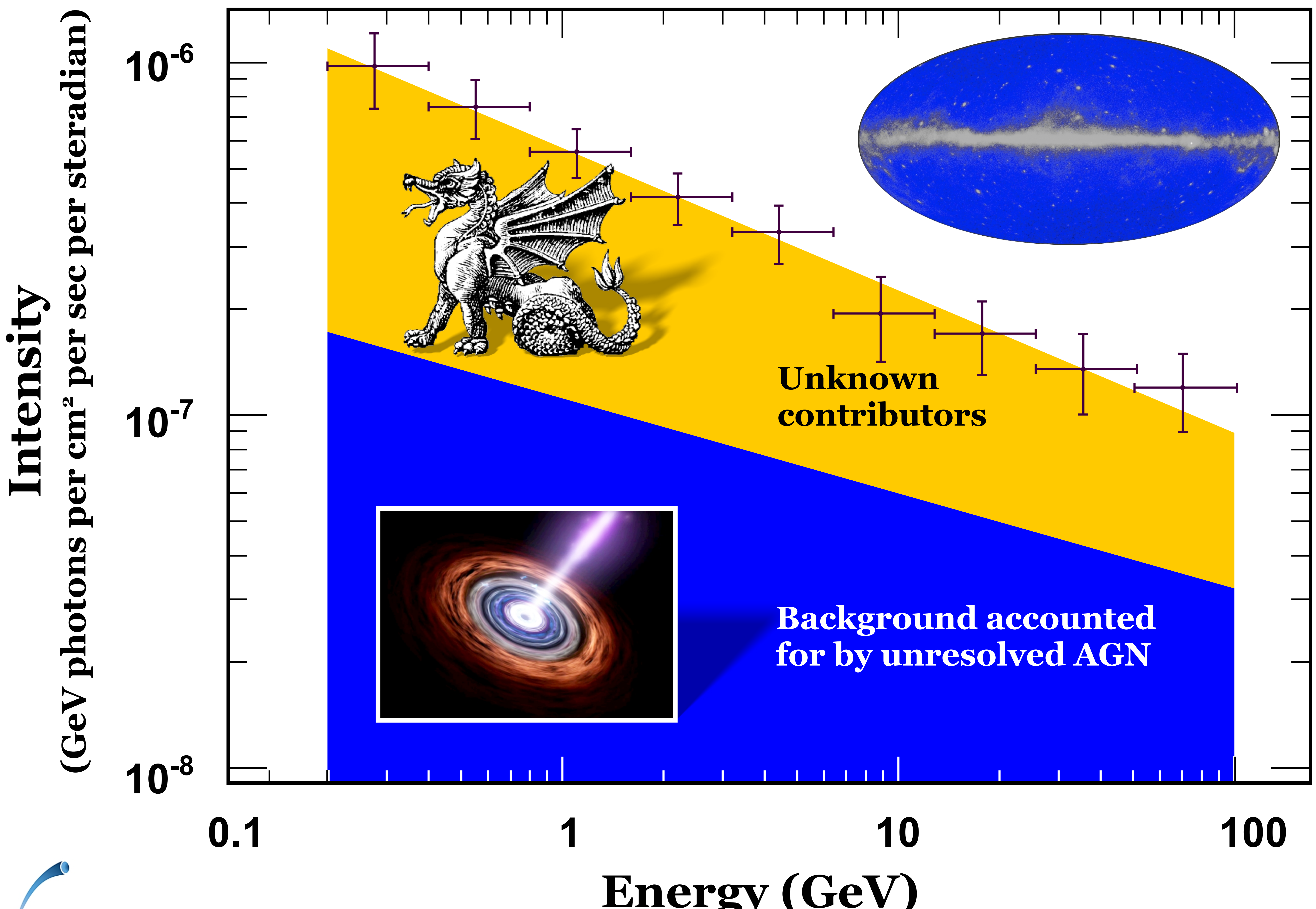
3 degrees at 0.1 GeV

0.04 degrees at 100 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 unknown!
  - Only ~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!
  - Only <10% coming from supernovae (*Ahn, EK and Höflich 2005*)

Fermi LAT Extragalactic Gamma-ray Background



Fermi Gamma-ray Space Telescope

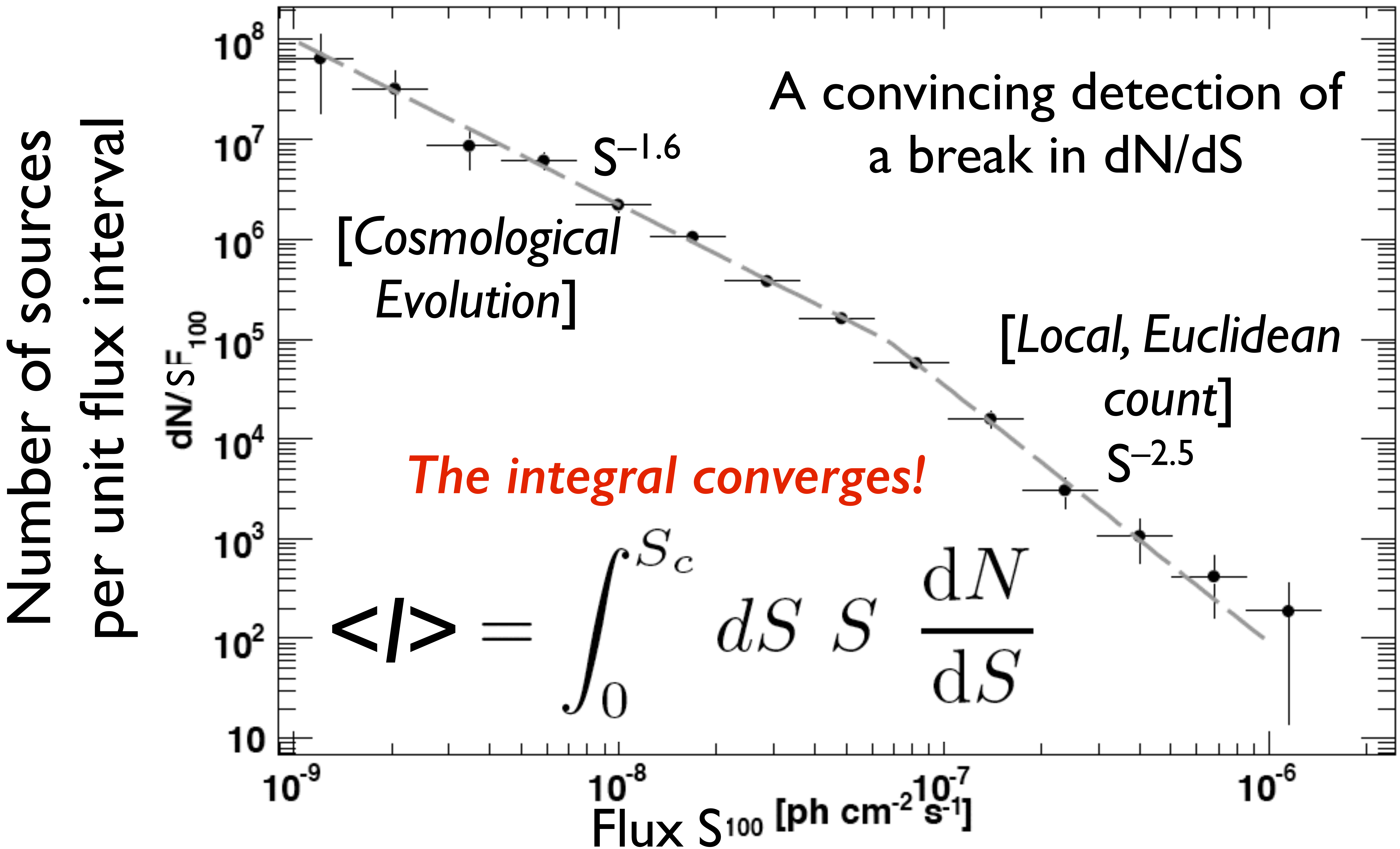
- Blazars = A population of active galactic nuclei (AGNs) whose relativistic jets are directed towards us.

  - Inverse Compton scattering of relativistic particles in jets off photons -> gamma-rays, detected up to TeV

- How many are there? (They are rare.)
  - The predecessor of Fermi, Compton Gamma-ray Observatory (CGRO) found ~70 blazars (out of ~100 associated sources) over the full sky
  - Fermi-LAT found 806 blazars (out of 1298 associated sources) over the full sky (LAT 2FGL catalog)

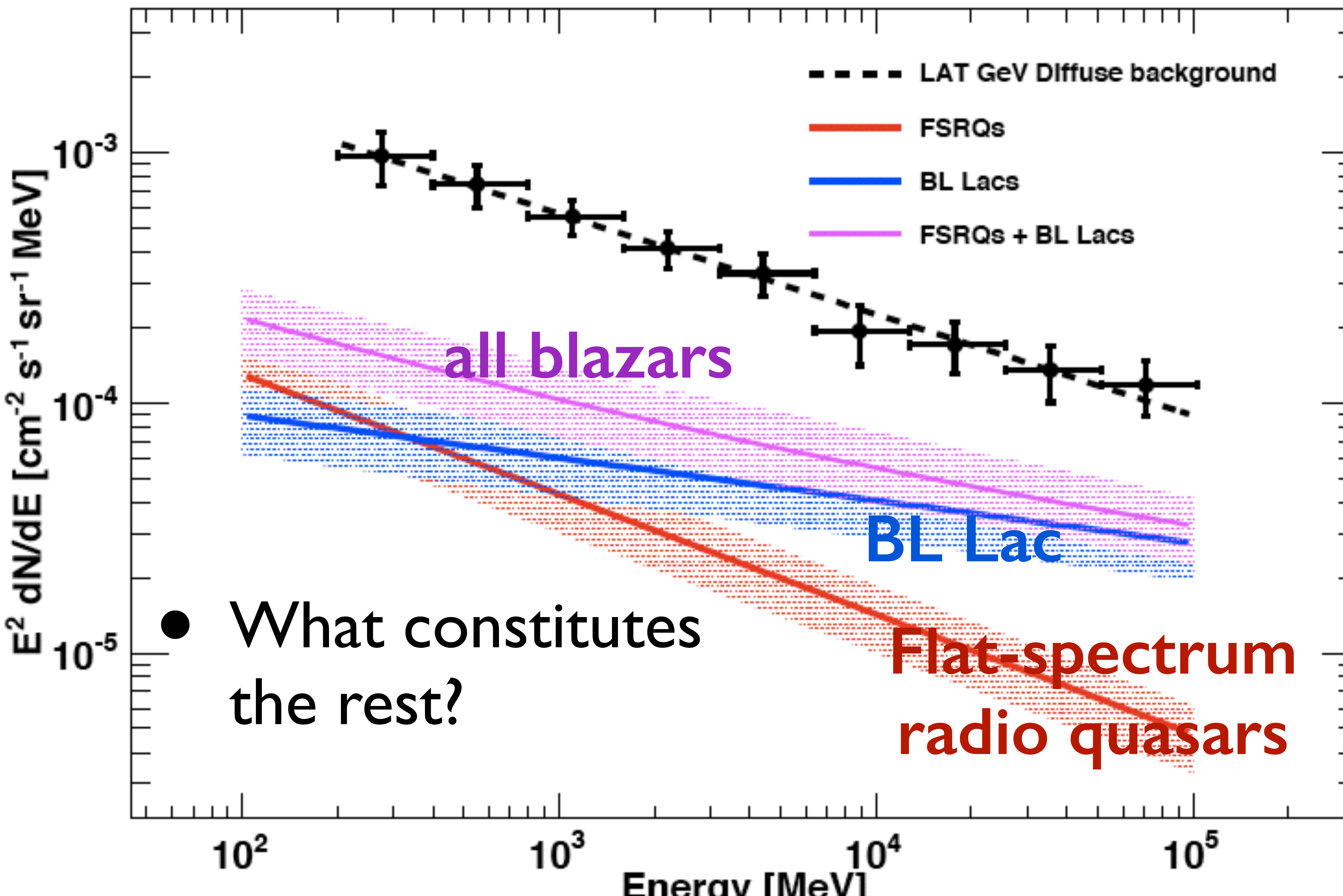
Fermi-LAT Collaboration, ApJ, 720, 435 (2010)

News from Fermi-LAT



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

Unresolved blazars are not enough to explain the unresolved 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?

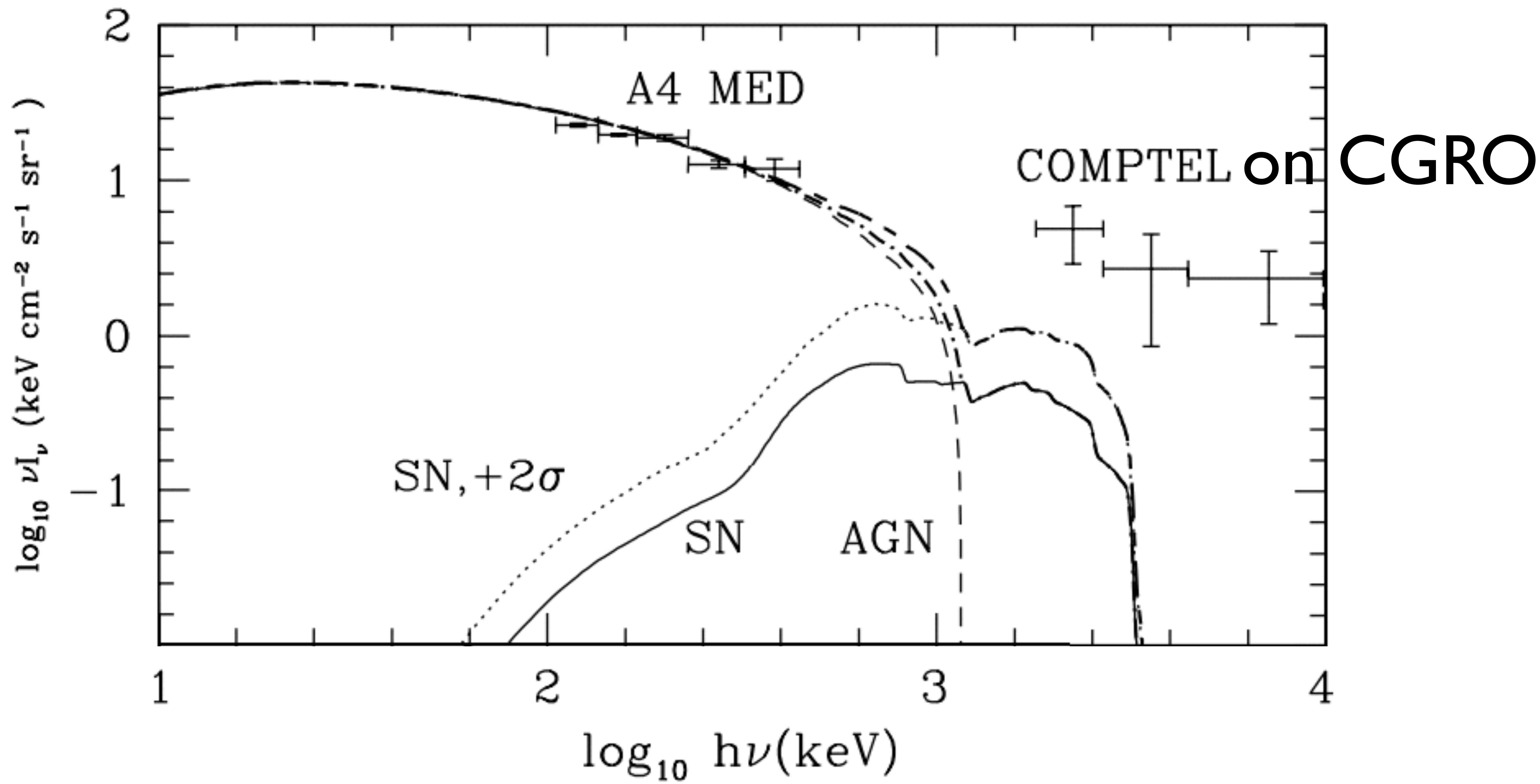
- Where do they come from?
  - Star-forming galaxies?
  - Pulsars?
  - Clusters of galaxies?

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

- *Dark matter?*

A Side Note

Ahn, EK & Höflich (2005)



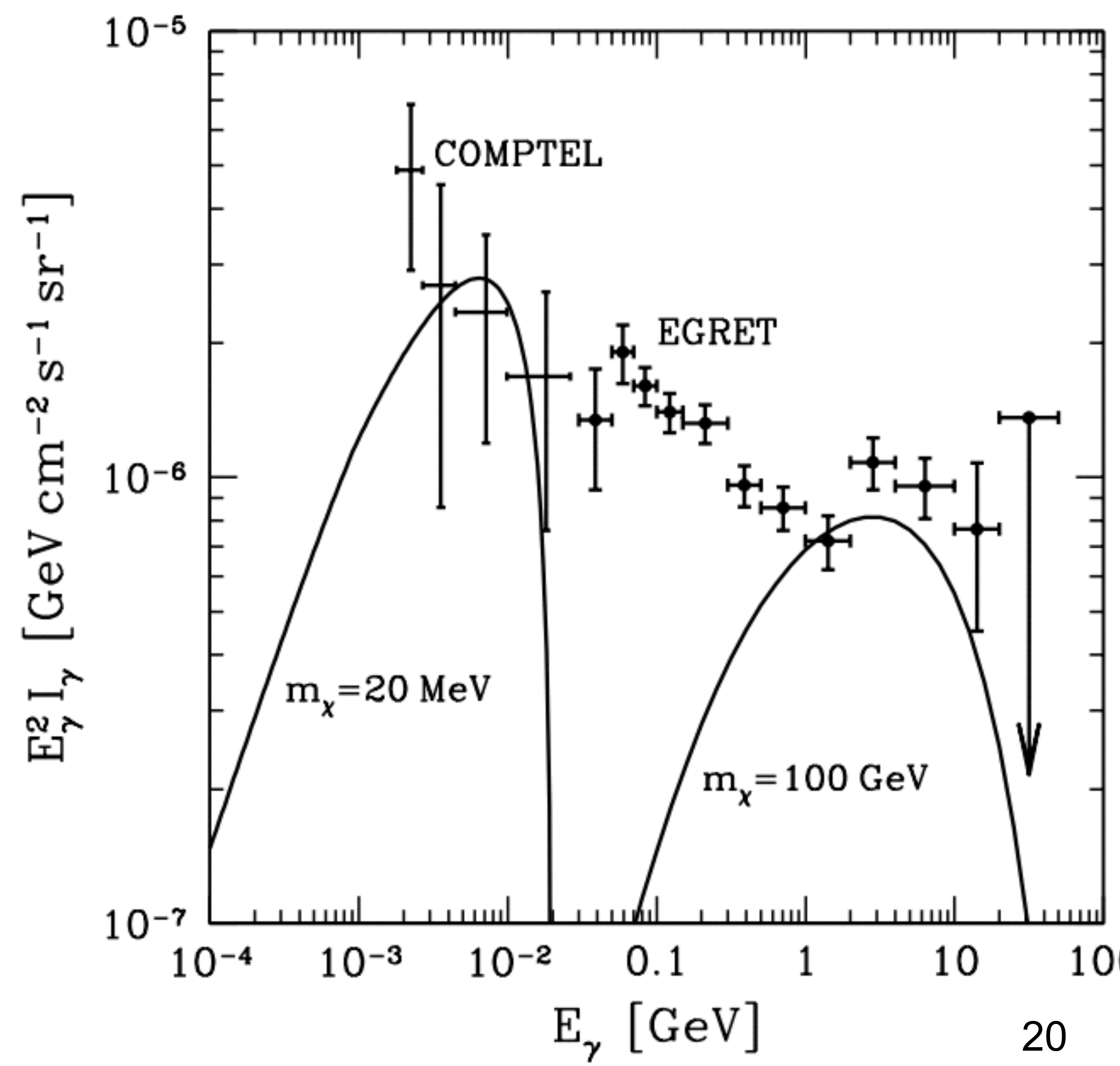
- It was thought that Type Ia supernovae would account for most of the MeV gamma-ray background. It turns out that the measured supernova rate is too small for that! *The origin of the MeV background is unknown.*

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:

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

[it's easy!] *Students: you can start computing this today!*

A General Formula

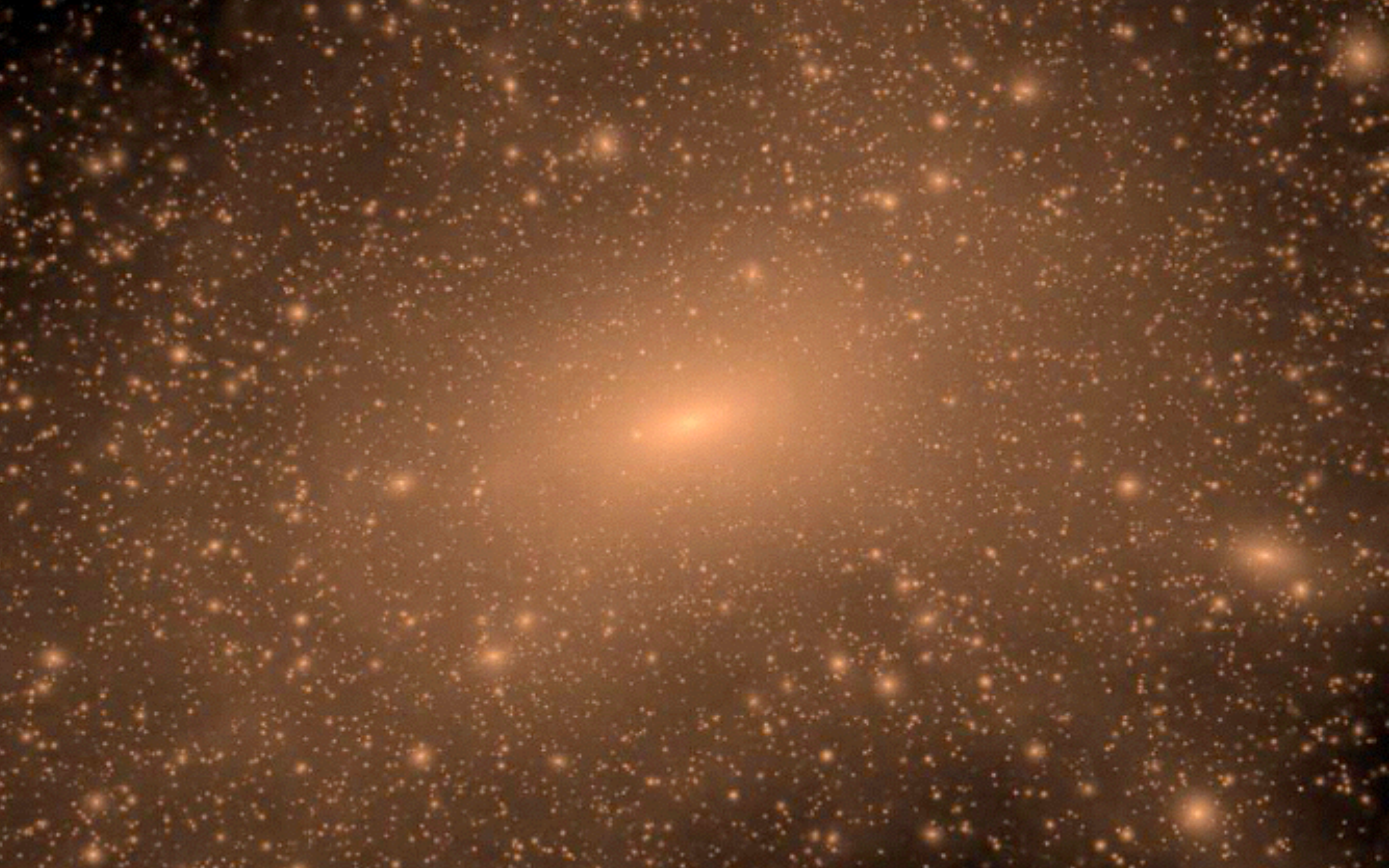
$$E_\gamma I_\gamma(\hat{\boldsymbol{n}}, E_\gamma) = \frac{c}{4\pi} \int dz \frac{P_\gamma([1+z]E_\gamma, z, \hat{\boldsymbol{n}}\, r)}{H(z)(1+z)^4} e^{-\tau([1+z]E_\gamma, z)}$$

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

E.g., for dark matter annihilation:

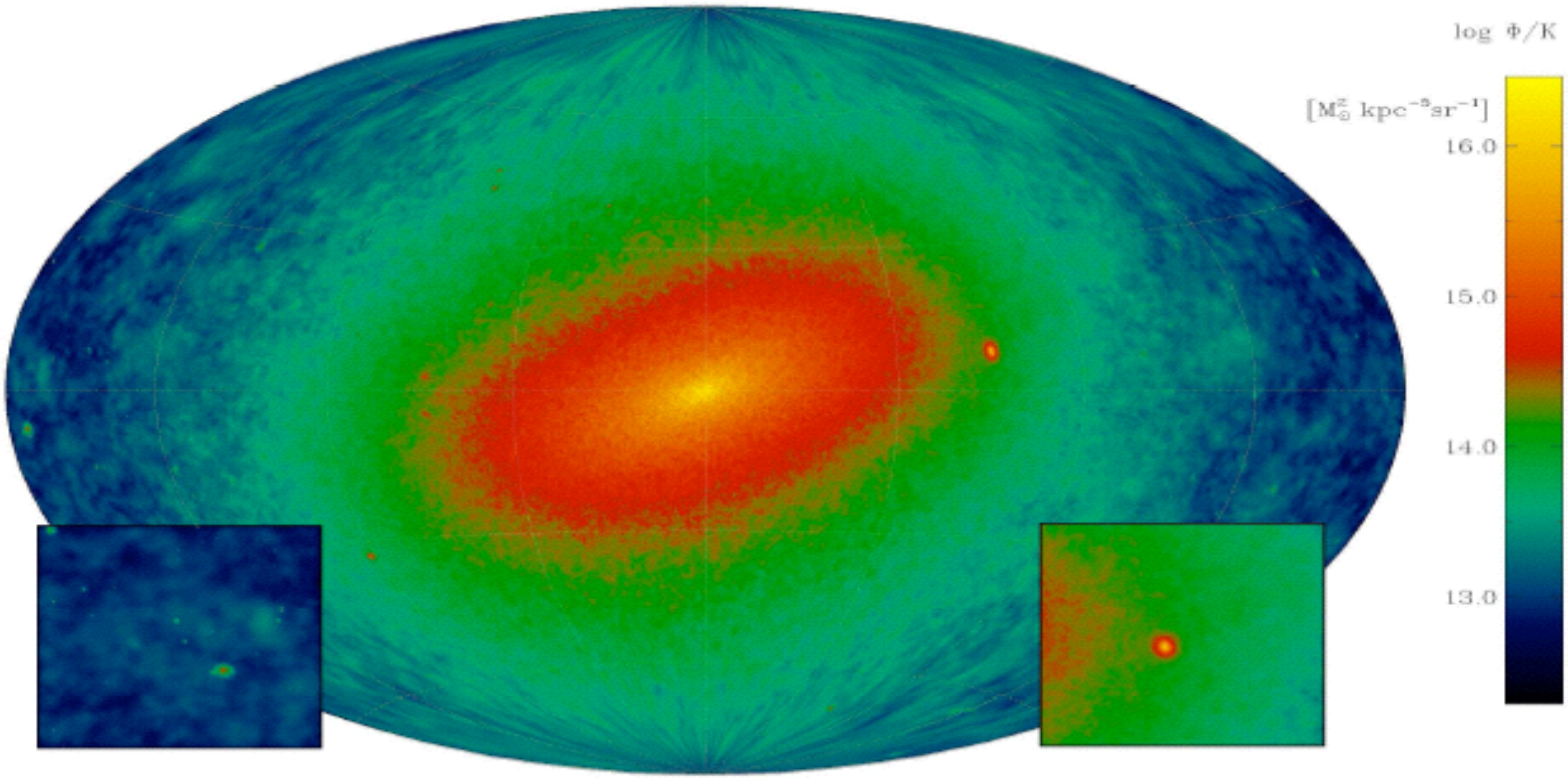
$$P_\gamma(E_\gamma, z, \hat{\boldsymbol{n}}\, r) = E_\gamma \frac{dN_\gamma}{dE_\gamma} \frac{\langle \sigma v \rangle}{2} \left[\frac{\rho_\chi(z, \hat{\boldsymbol{n}}\, r)}{m_\chi} \right]^2$$

[it's easy!] *Students: you can start computing this today!*

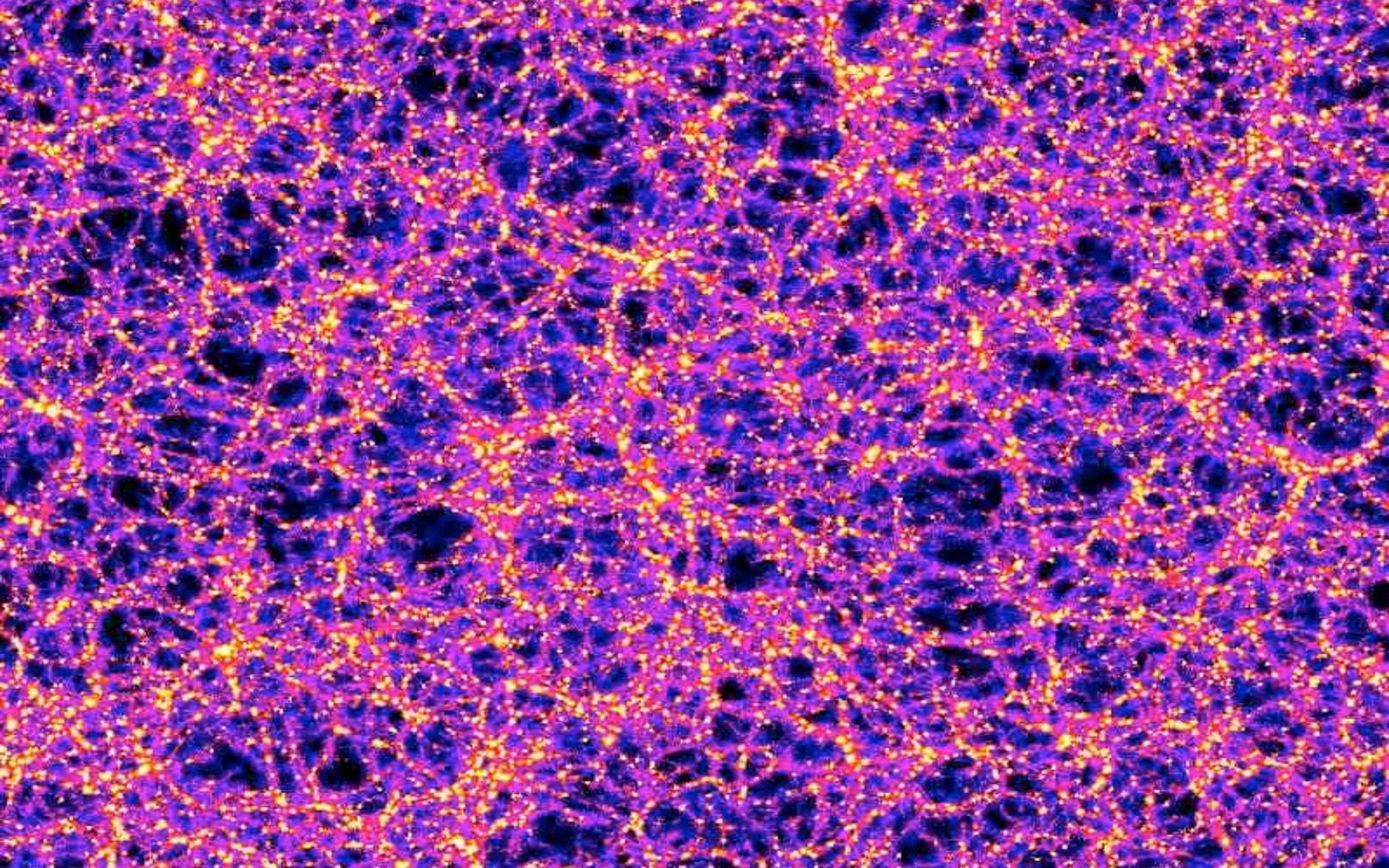


Diemand, Khlen & Madau, ApJ, 657, 262 (2007)

Annihilation Signals from Milky Way



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



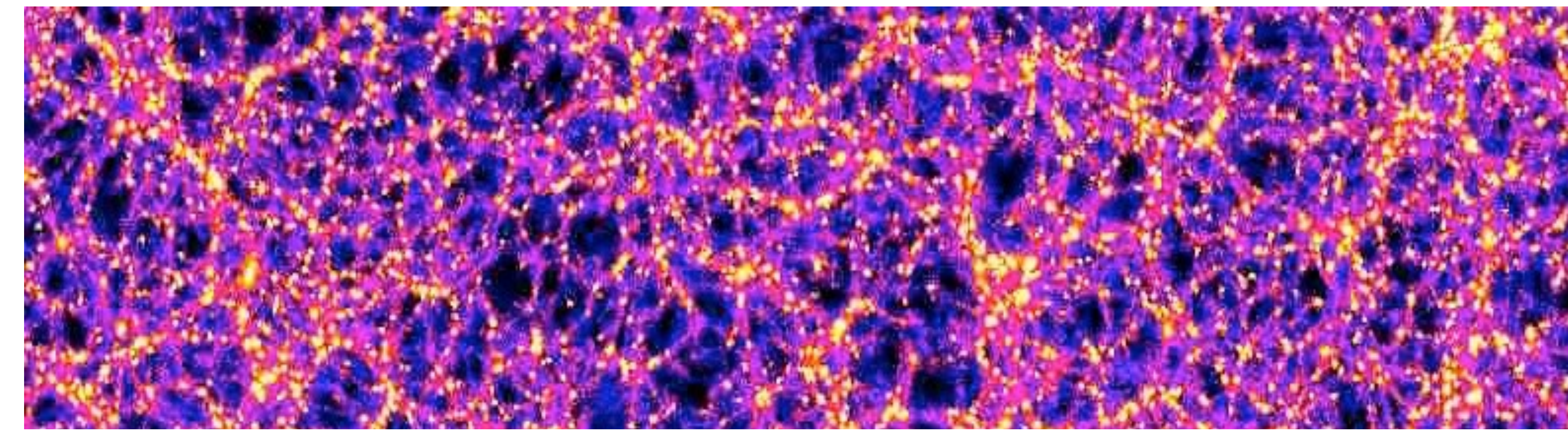
And, not just Milky Way!

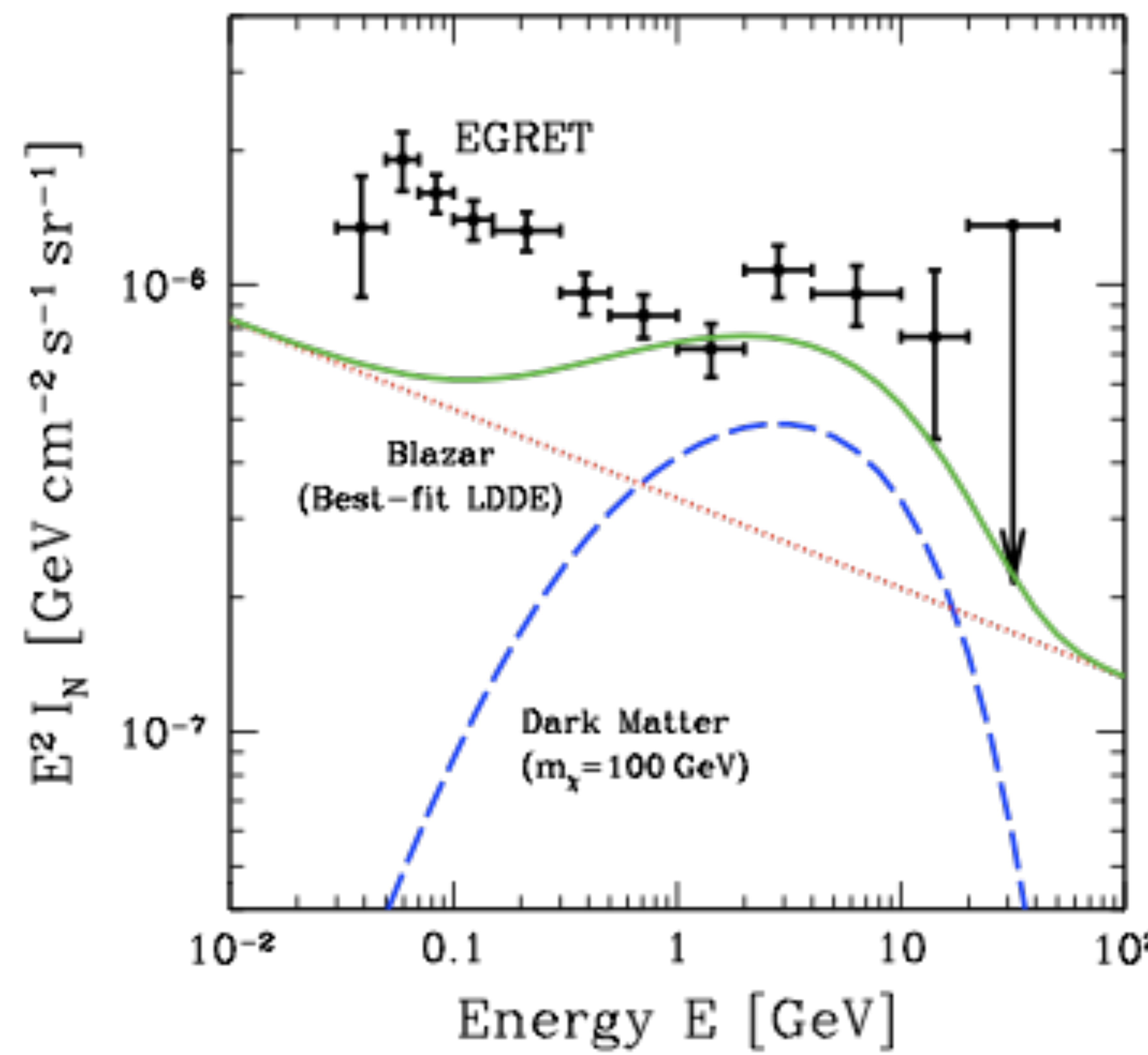
- Dark matter particles are annihilating (or decaying) **everywhere** in the Universe!

  - 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

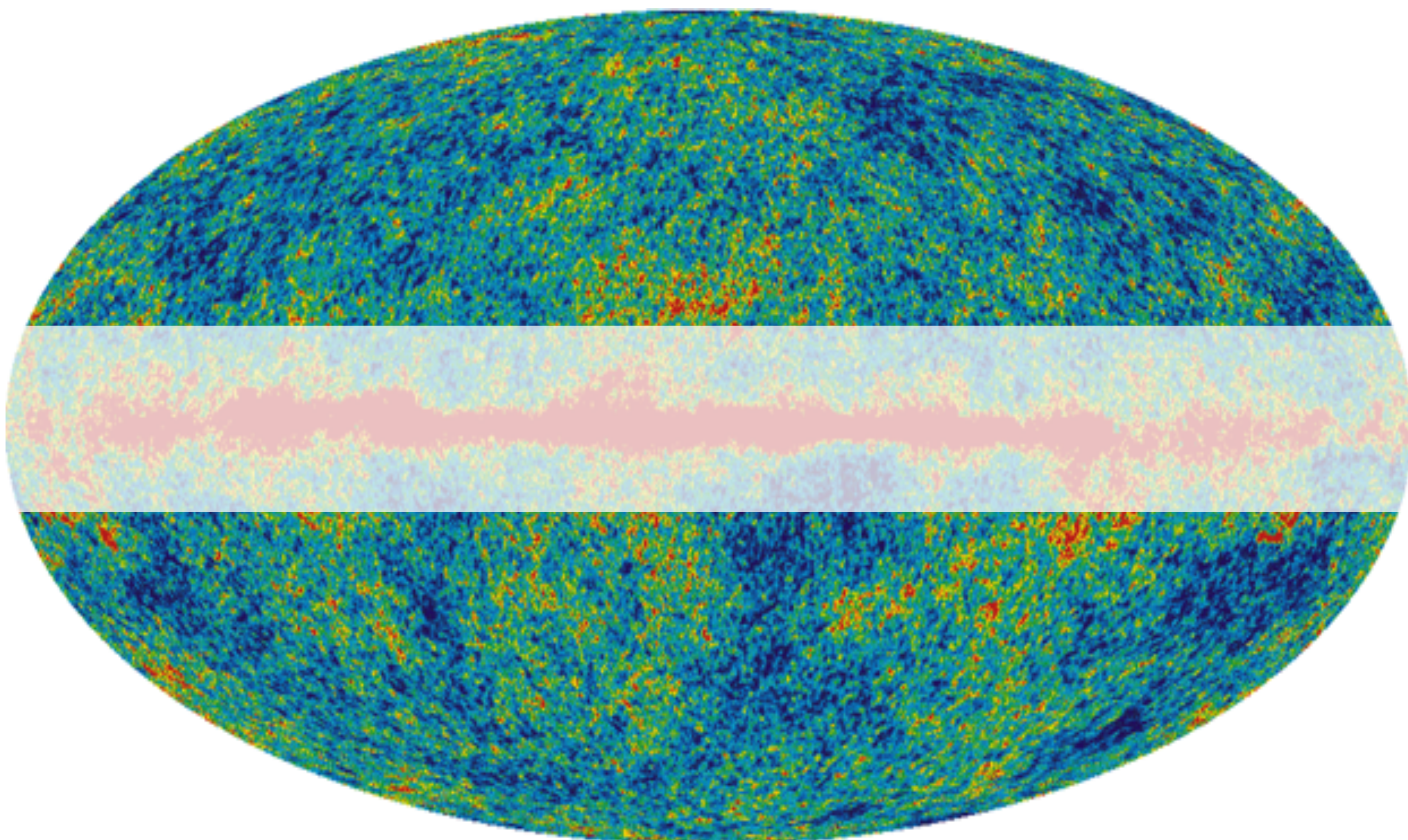
(*) "halos" = gravitationally bound objects

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

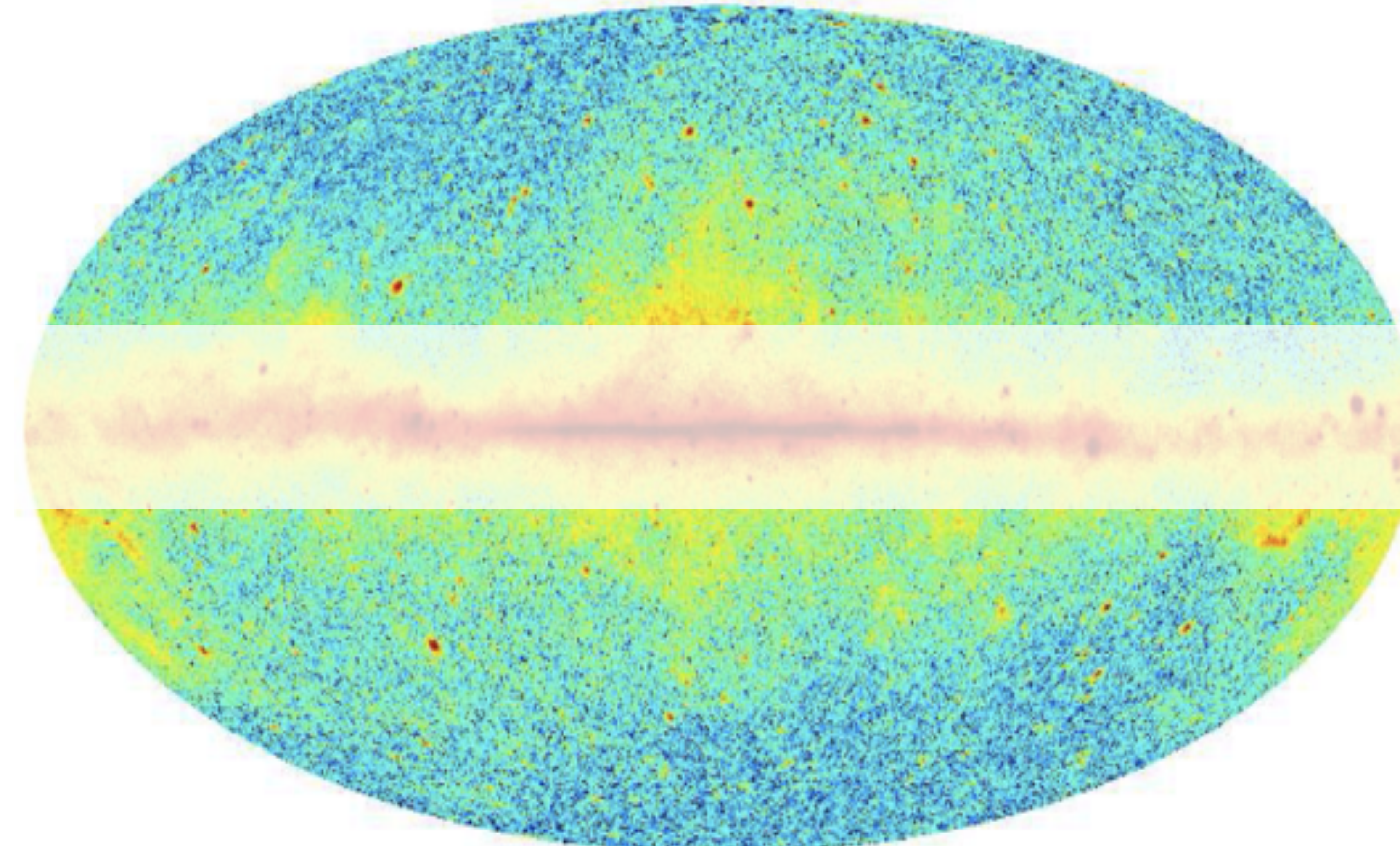
- And, their spatial distribution can be calculated within the framework of the standard cosmological model (ΛCDM model) using analytical calculations or numerical N-body simulations.

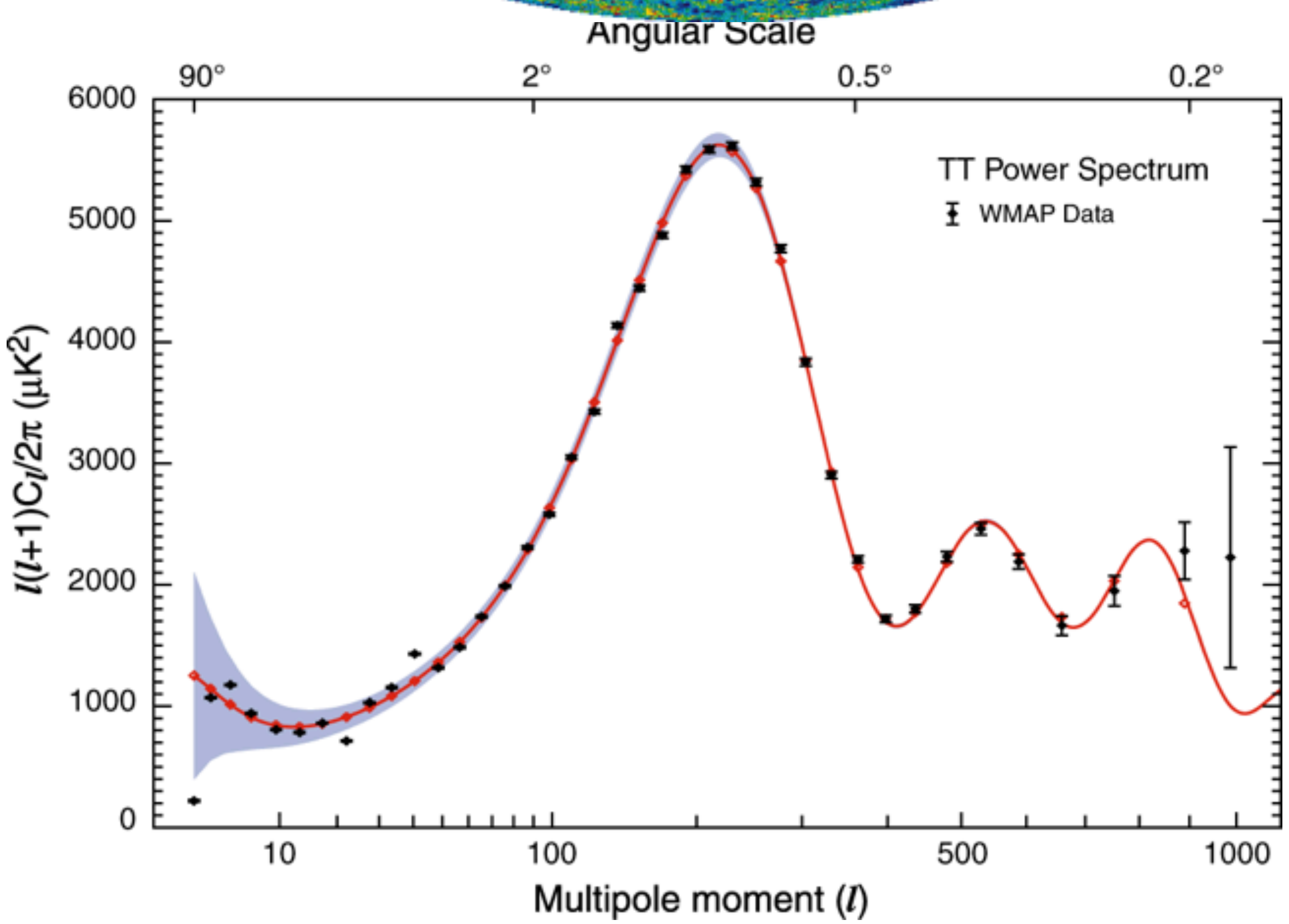
Using Fermi Data, just like WMAP

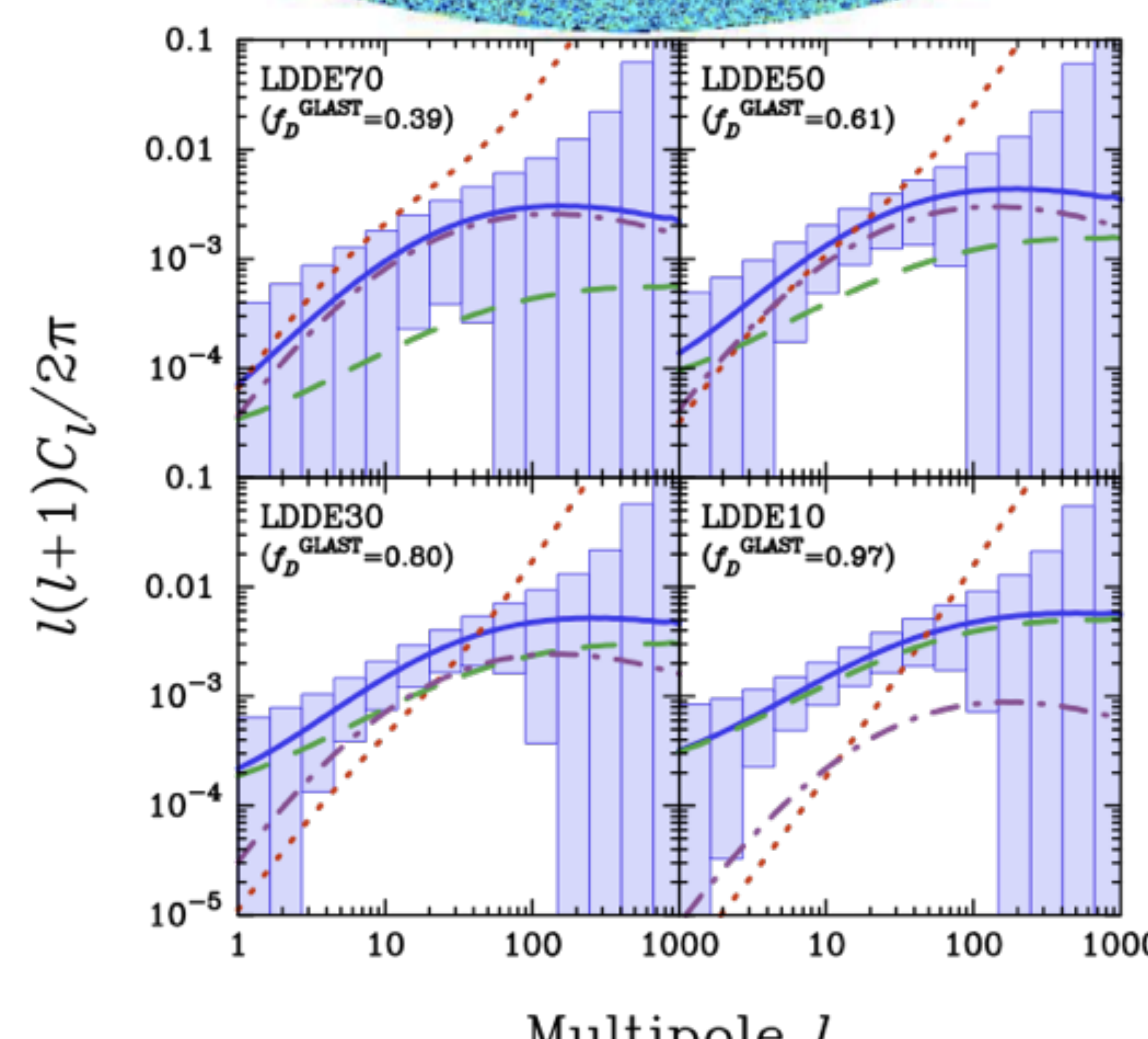
WMAP 94GHz



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?

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

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

- Schematically, we have:

(Anisotropy in Gamma-ray Sky) = (MEAN INTENSITY) x Δ

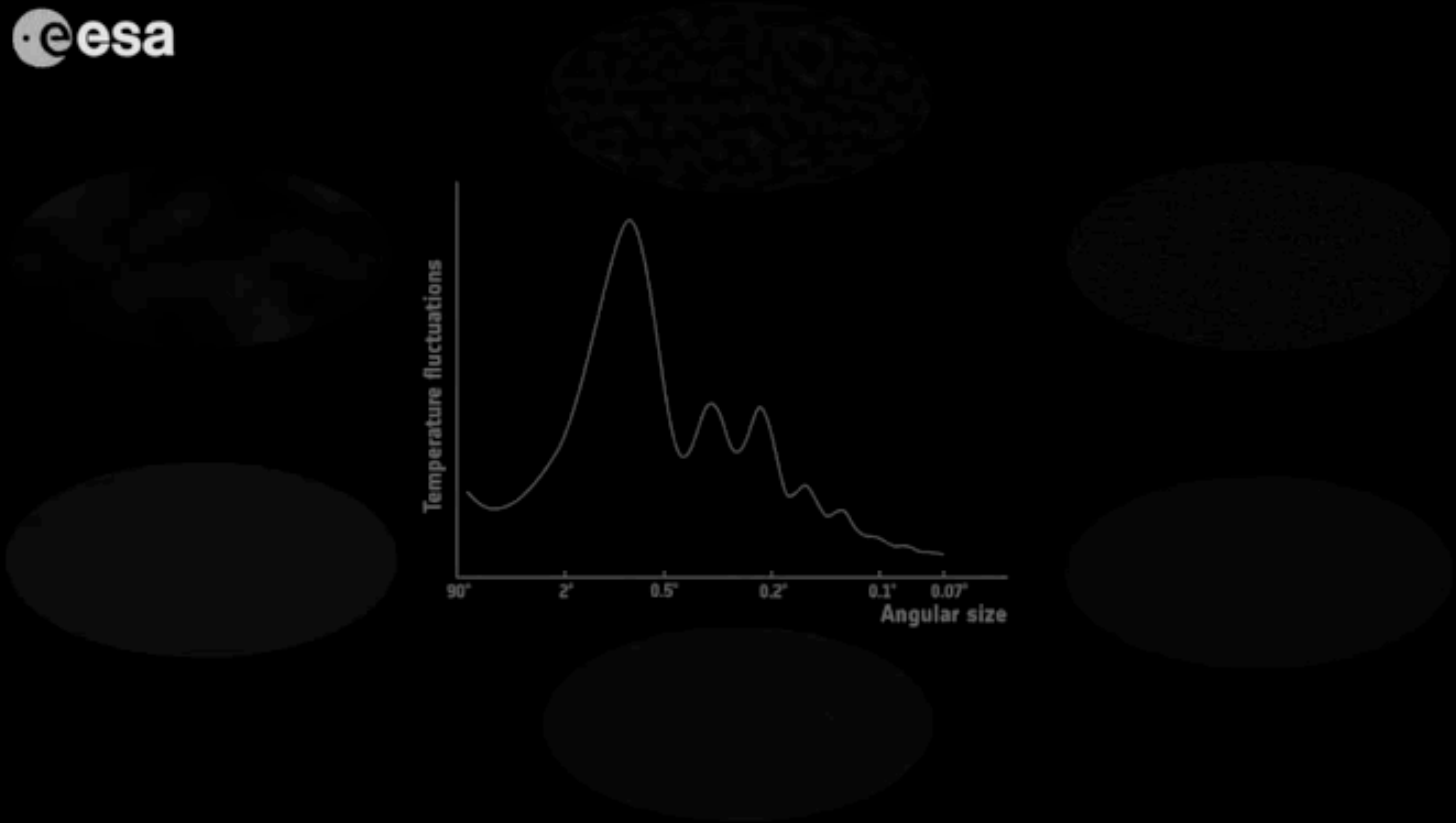
- The mean intensity depends on particle physics: annihilation cross-section and dark matter mass. The fluctuation power, Δ, depends on structure formation.

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):
  - $\langle \sigma v \rangle = a + b(v/c)^2$ with $b=0$.
- For b≠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≠0 is to suppress the signal by $(v/c)^2$.

Power Spectrum

- Spherical harmonics transform of the intensity map:
  - $I(\mathrm{n}) = \sum_{\mathrm{lm}} a_{\mathrm{lm}}\, Y_{\mathrm{lm}}(\mathrm{n})$ [m=–l,–l+1,…,l–1,l]
- Squaring the coefficients and summing over *m* gives the power spectrum:
  - $C_\mathrm{l} = (2\mathrm{l}+1)^{-1} \sum_\mathrm{m} |a_{\mathrm{lm}}|^2$
- Just like we would do for the analysis of the Cosmic Microwave Background maps measured by WMAP



Temperature fluctuations
90°
2°
0.5°
0.2°
0.1°
0.07°
Angular size

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

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

where

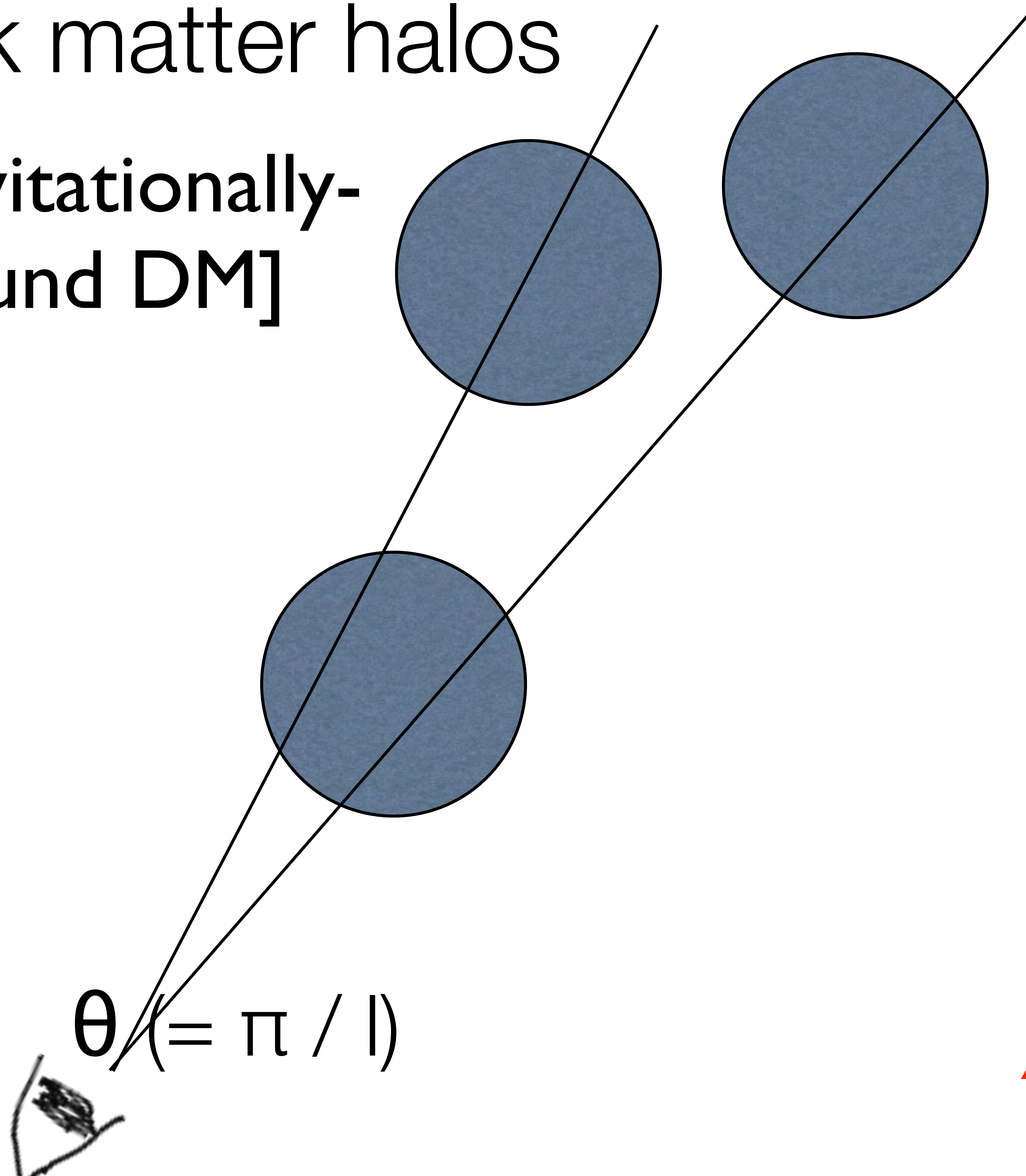
$$f \equiv \delta^2 - \langle \delta^2 \rangle$$

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

A Simple Route to the Power Spectrum

Dark matter halos

[Gravitationally-bound DM]

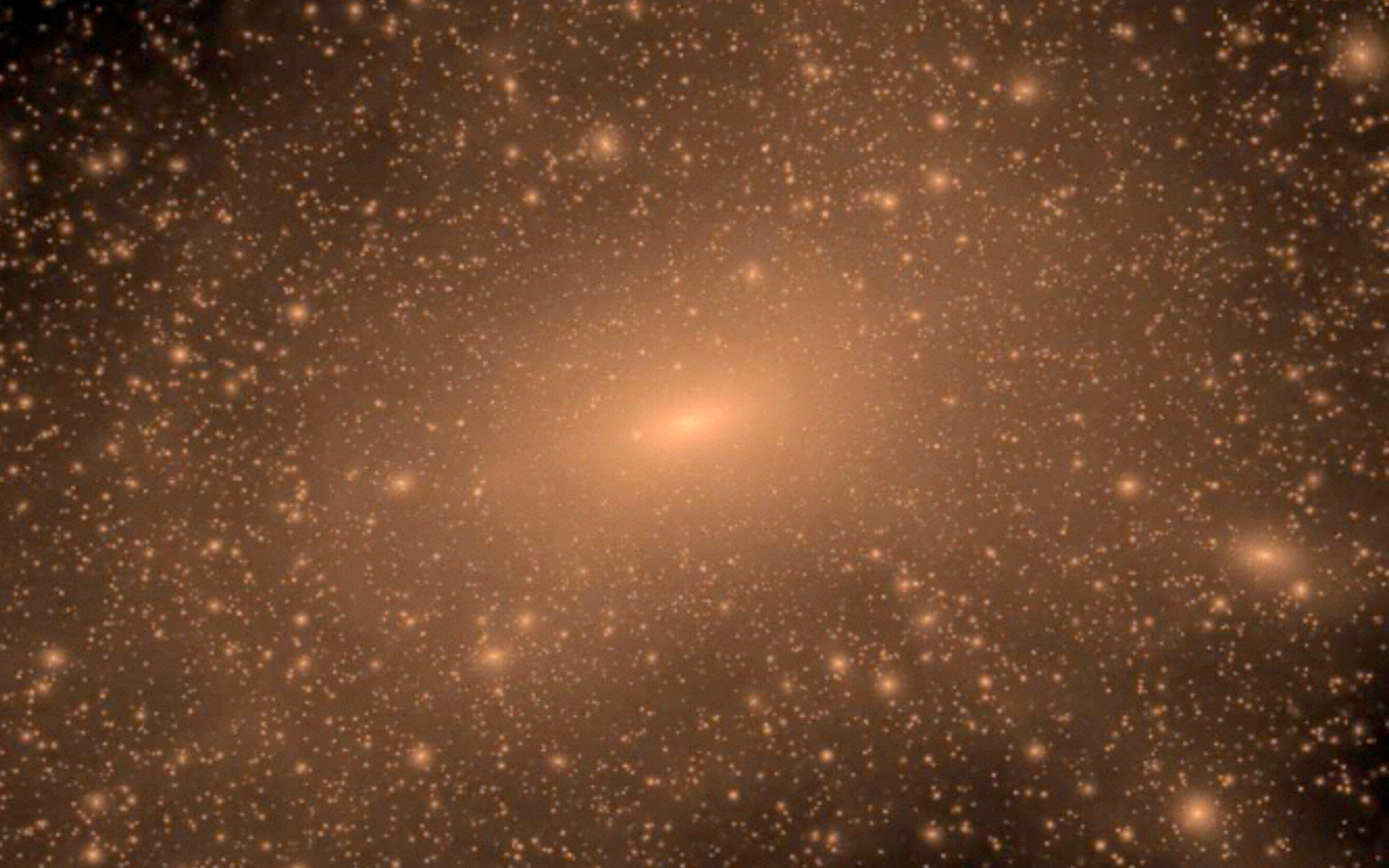


- To compute the power spectrum of anisotropy from dark matter annihilation, we need **three ingredients**:

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

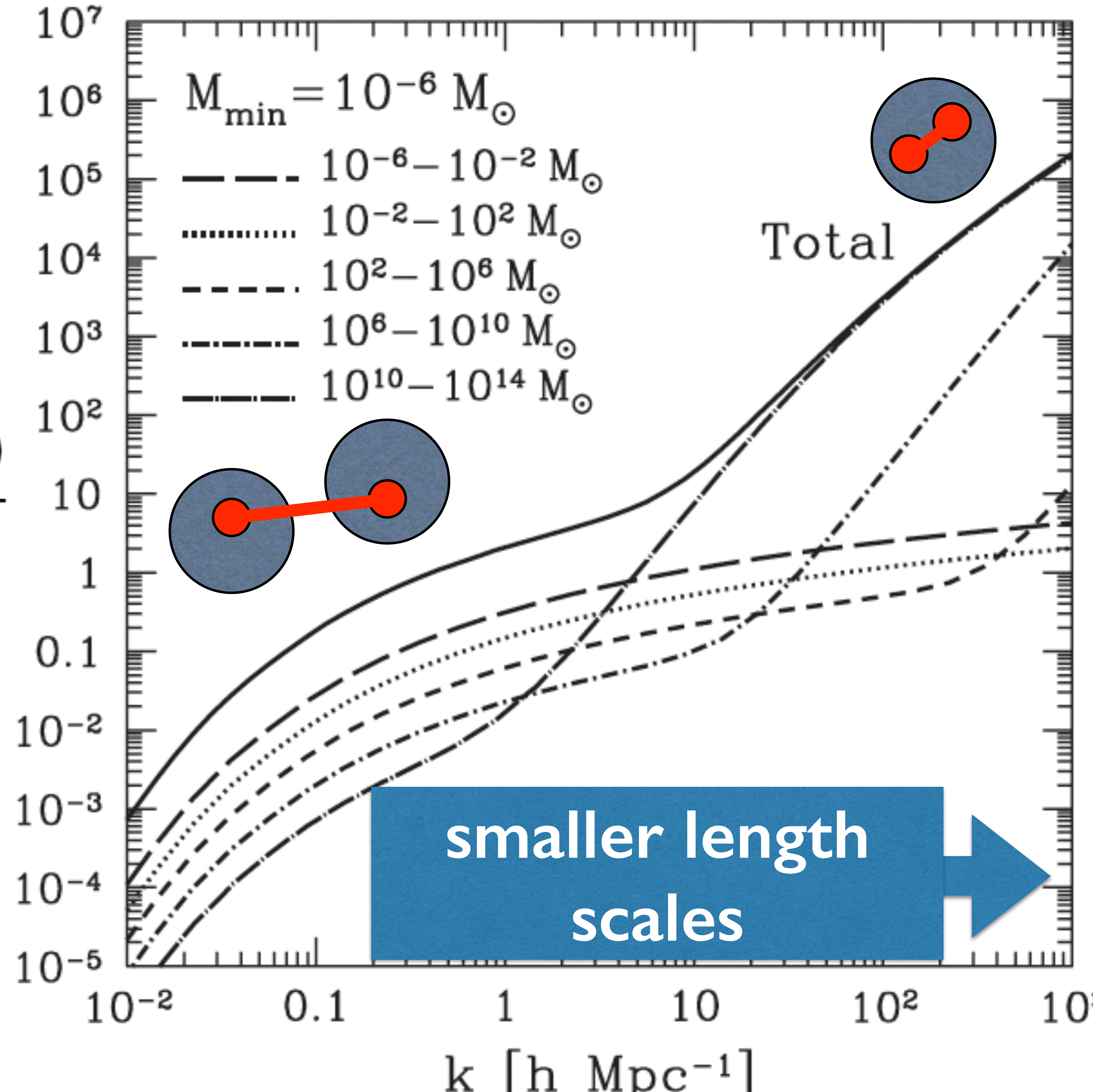
- **Without sub-halos**
  - Halo density distribution is smooth and follows a profile measured from N-body simulations (NFW)
- **With sub-halos**
  - Halos contain sub-halos whose radial distribution follows an NFW profile
  - This is more realistic, provided that sub-halos survive tidal disruptions



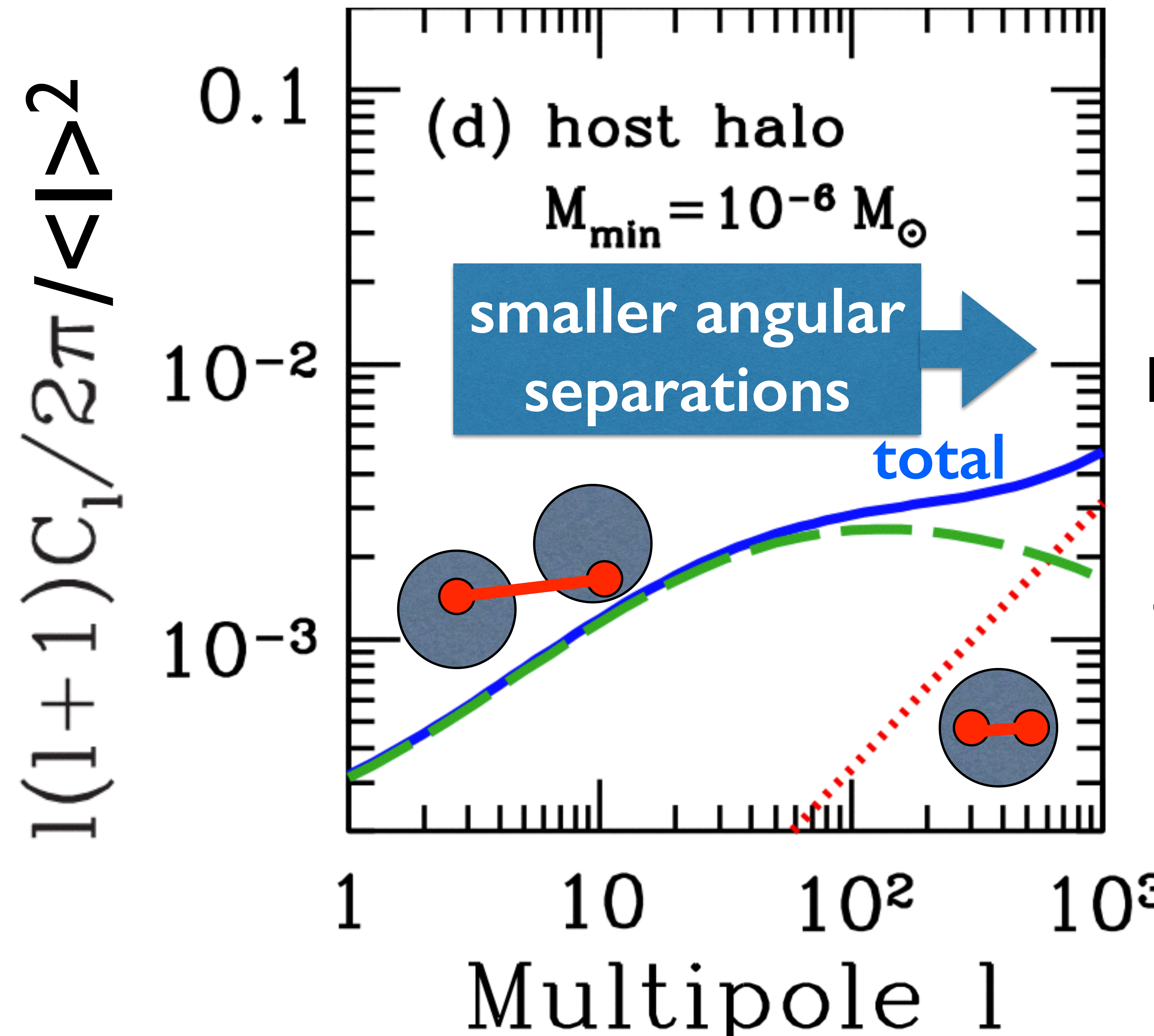
3d Power Spectrum of δ²

Without sub-halos

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



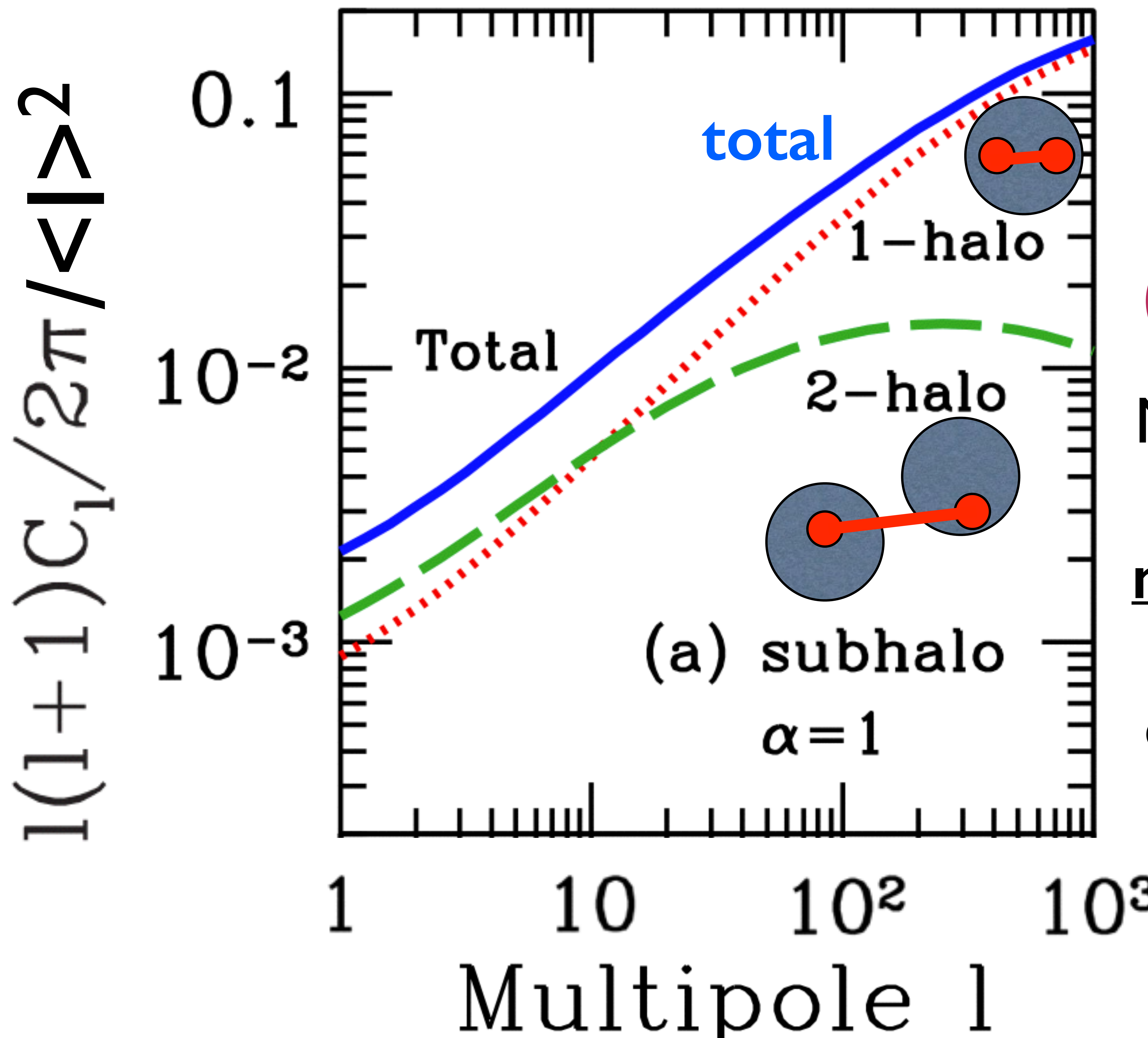
(2d) Angular Power Spectrum



Without sub-halos

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

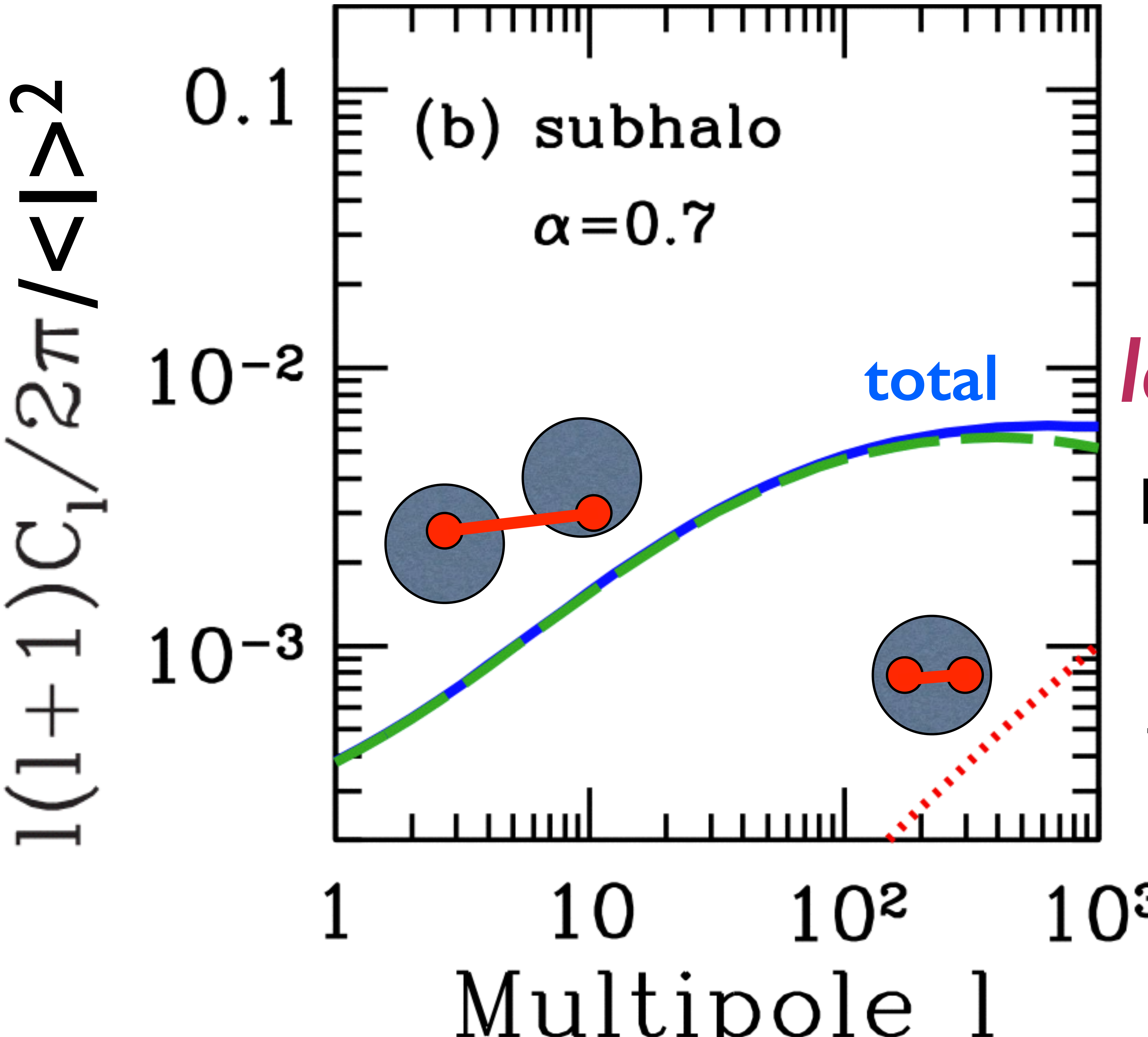
(2d) Angular Power Spectrum



With sub-halos (all surviving)

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

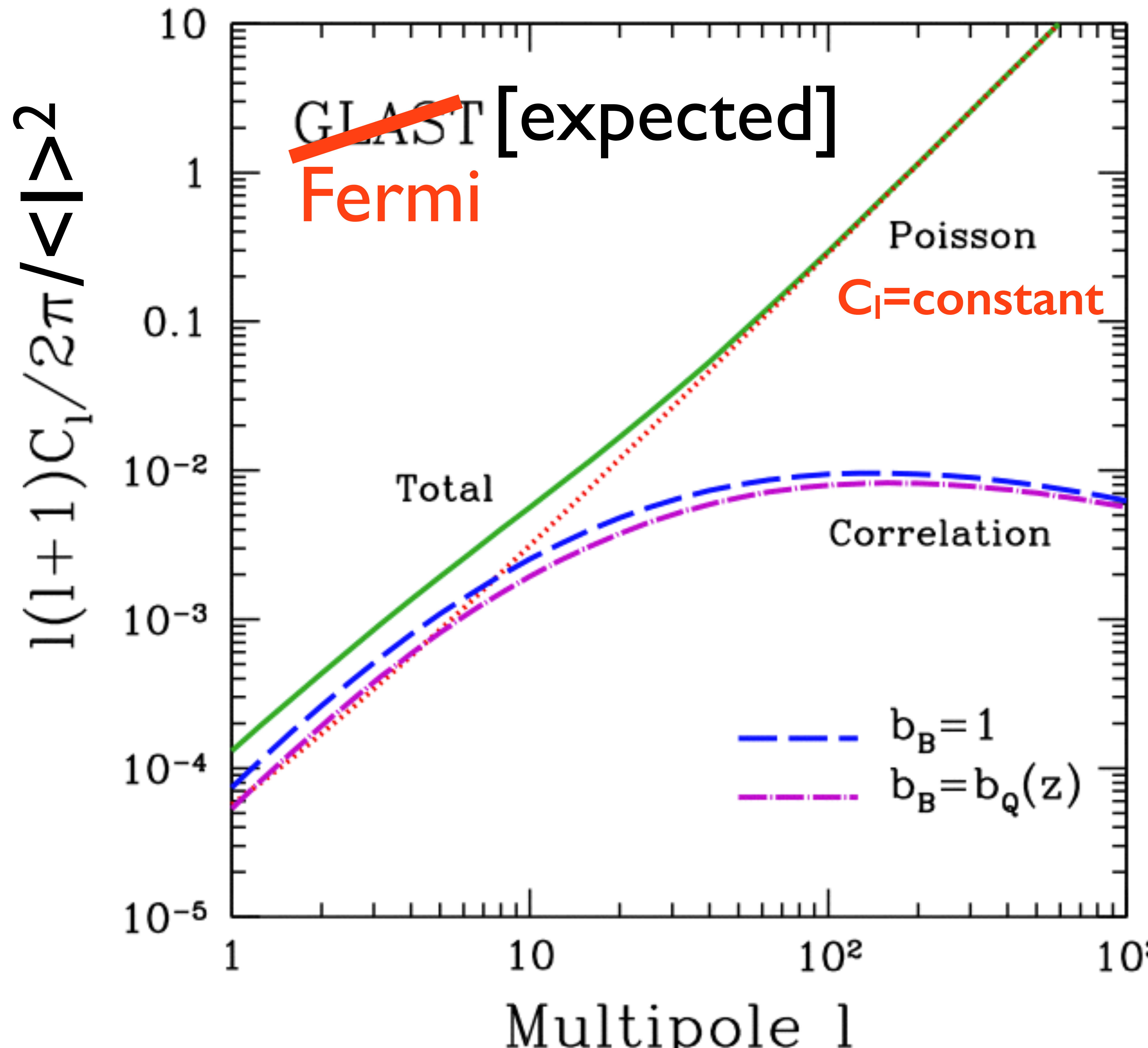
(2d) Angular Power Spectrum



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

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

How about blazars?



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

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

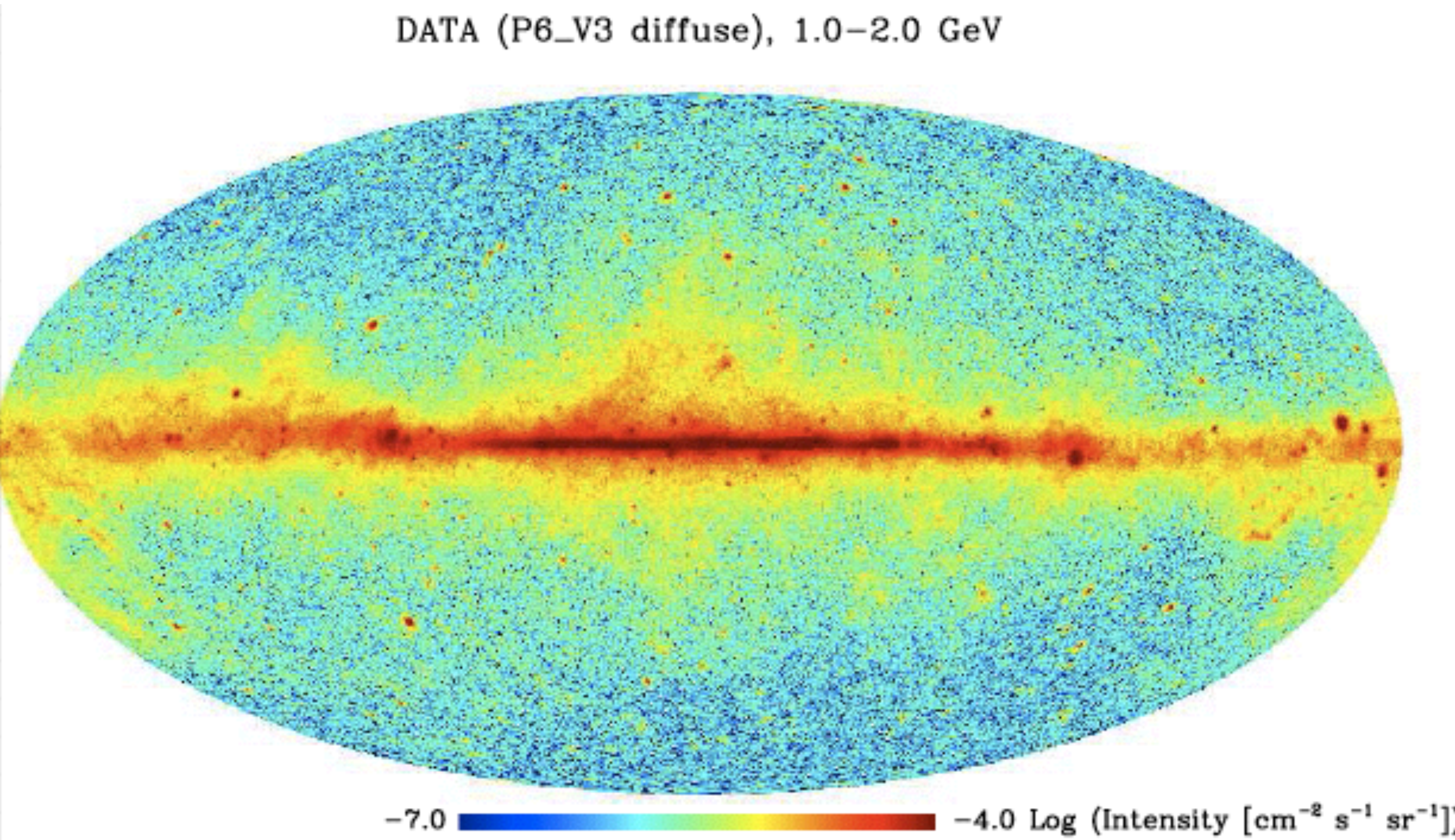
in collaboration with
J. Siegal-Gaskins, A. Cuoco, T. Linden, M.N.Mazziotta, and V.Vitale
(on behalf of Fermi-LAT Team)

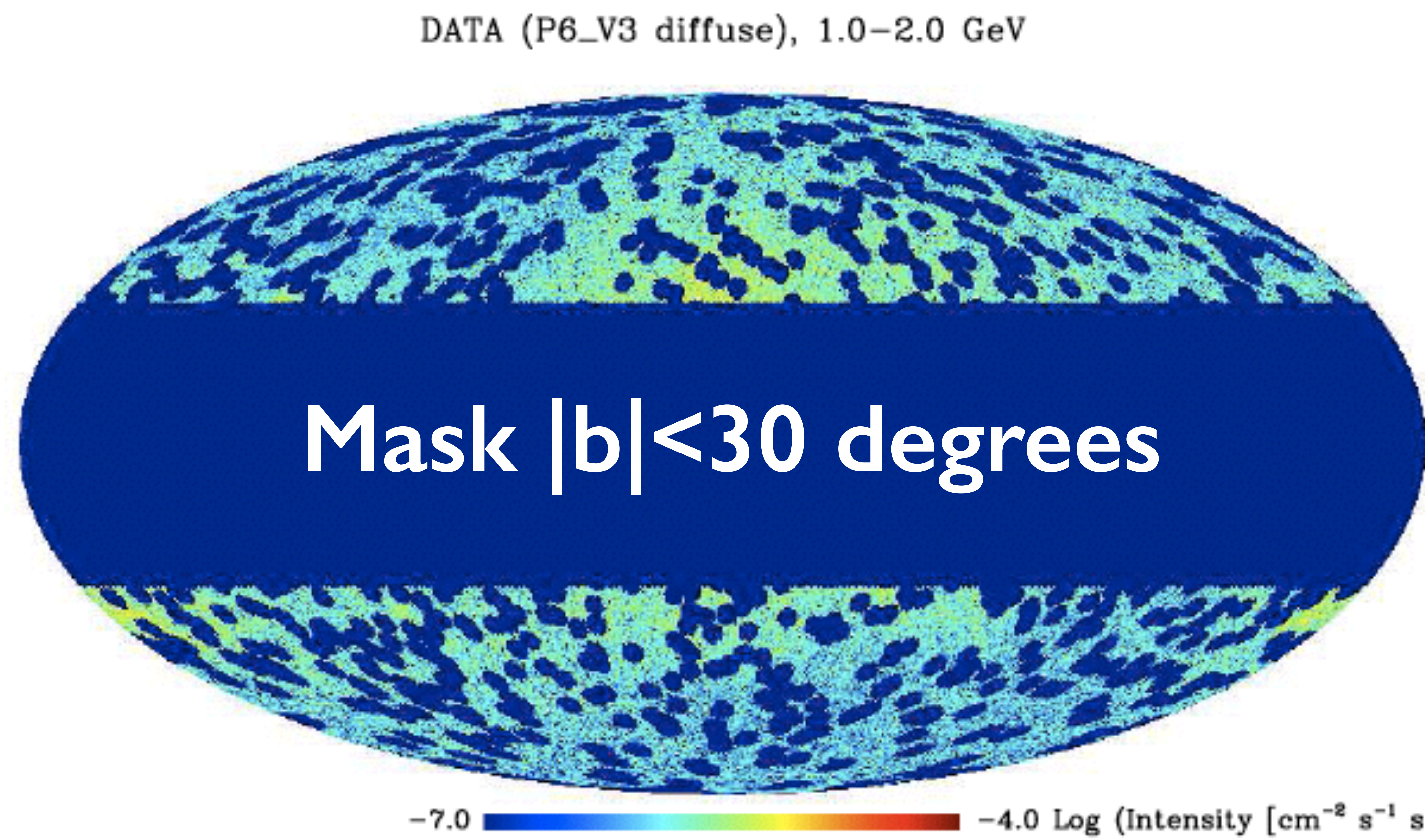
Phys. Rev. D 85, 083007 (2012)

Data Analysis

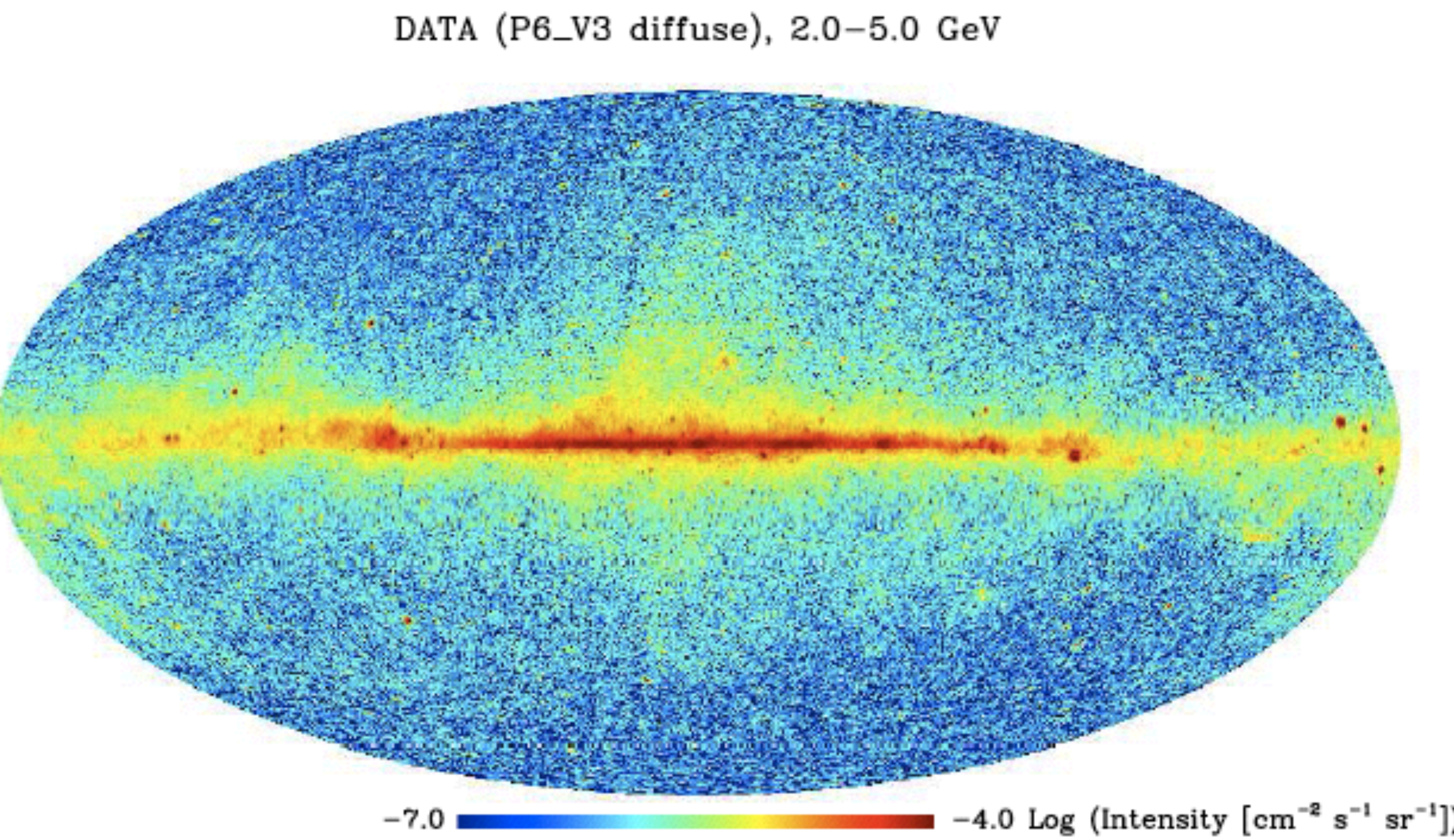
- Use the same Fermi-LAT map (~22mo, diffuse-class events)
- Apply the usual spherical harmonics transform, and measure the power spectrum!
  - $I(n) = \sum_{lm} a_{lm} Y_{lm}(n)$
  - $C_l = (2l+1)^{-1} \sum_m |a_{lm}|^2$
- Just like we did for the analysis of the CMB maps measured by WMAP

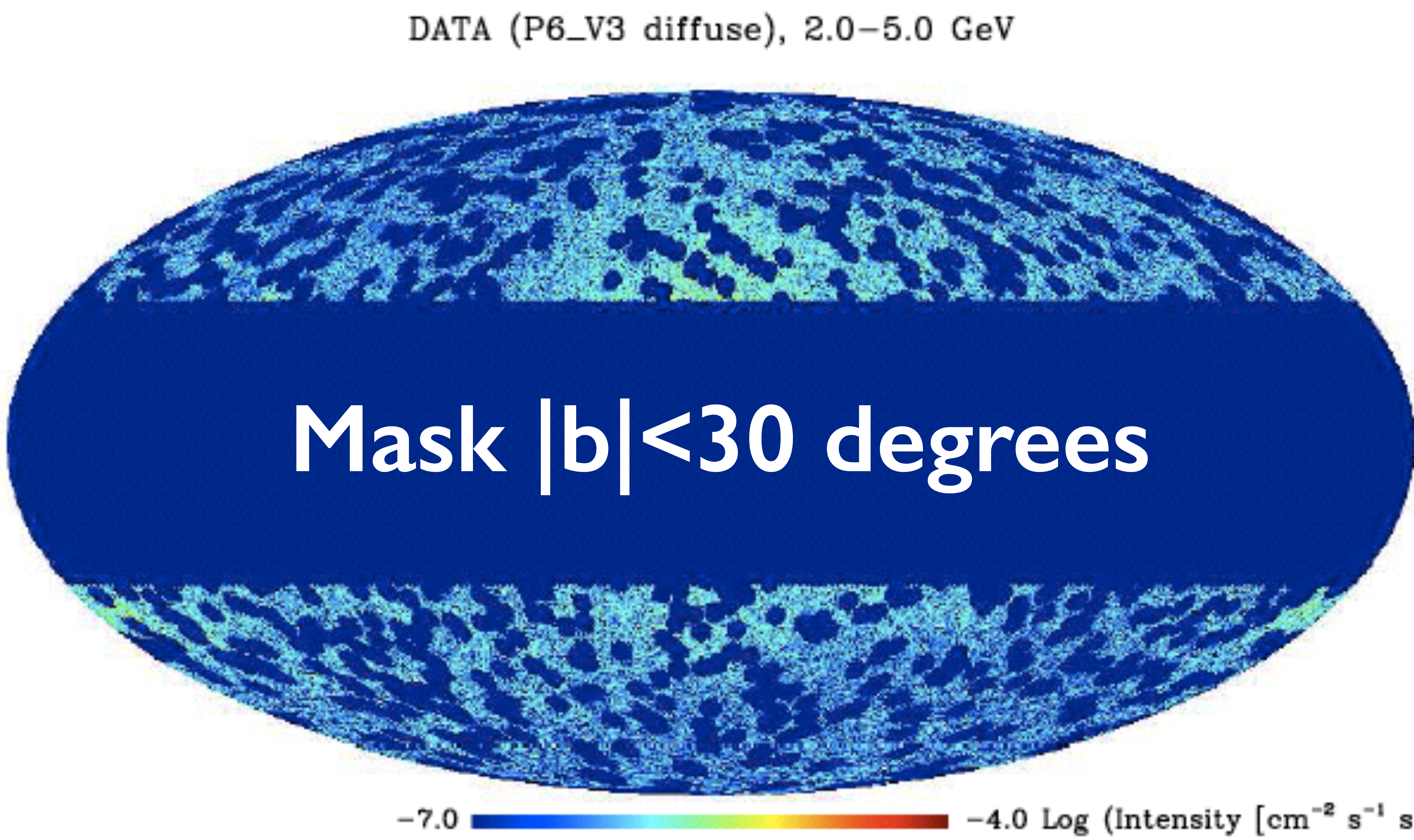
1.0–2.0 GeV


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

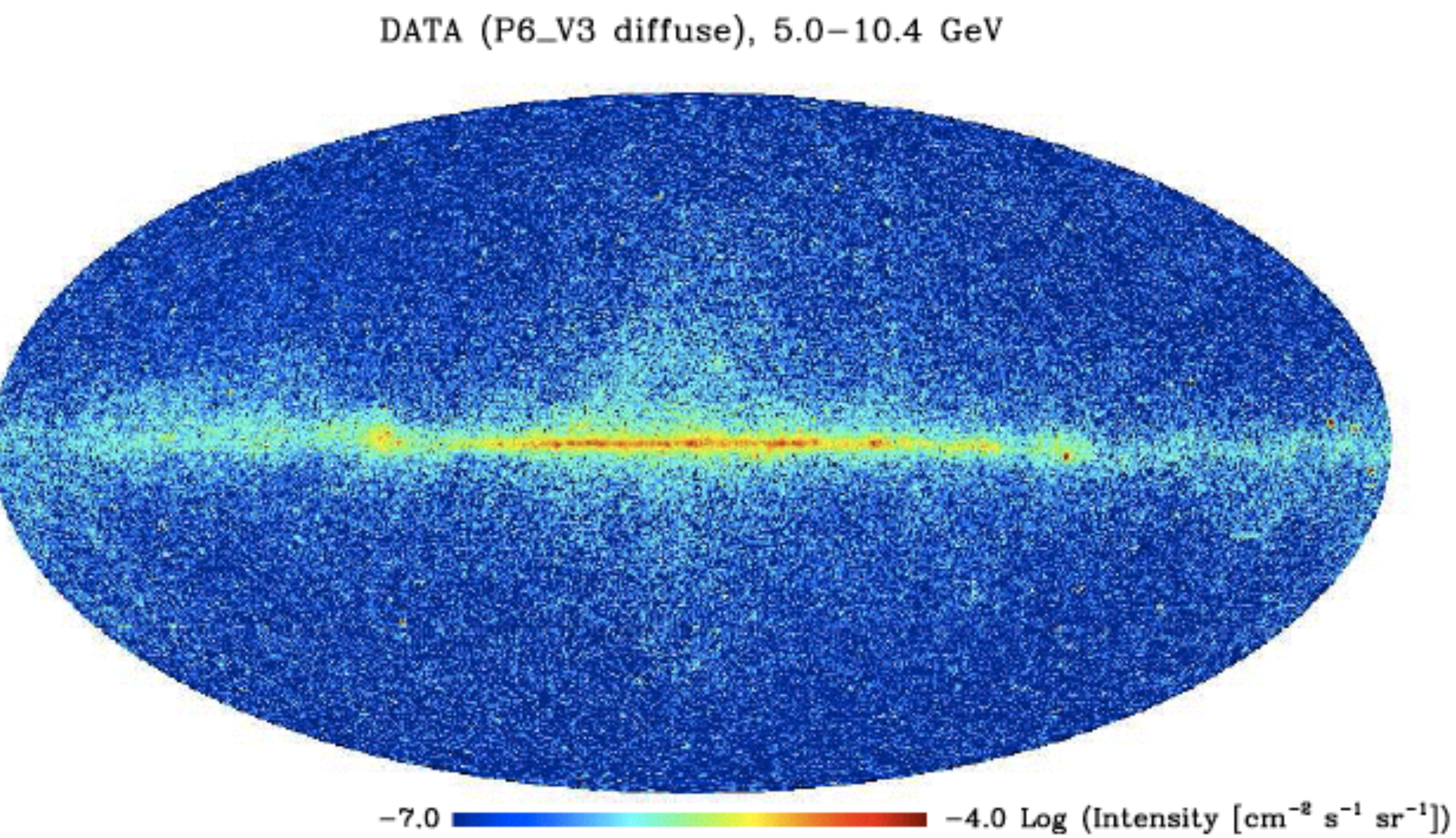

DATA (P6_V3 diffuse), 1.0–2.0 GeV
Mask |b|<30 degrees
−7.0
−4.0 Log (Intensity [cm^{-2} s^{-1} s

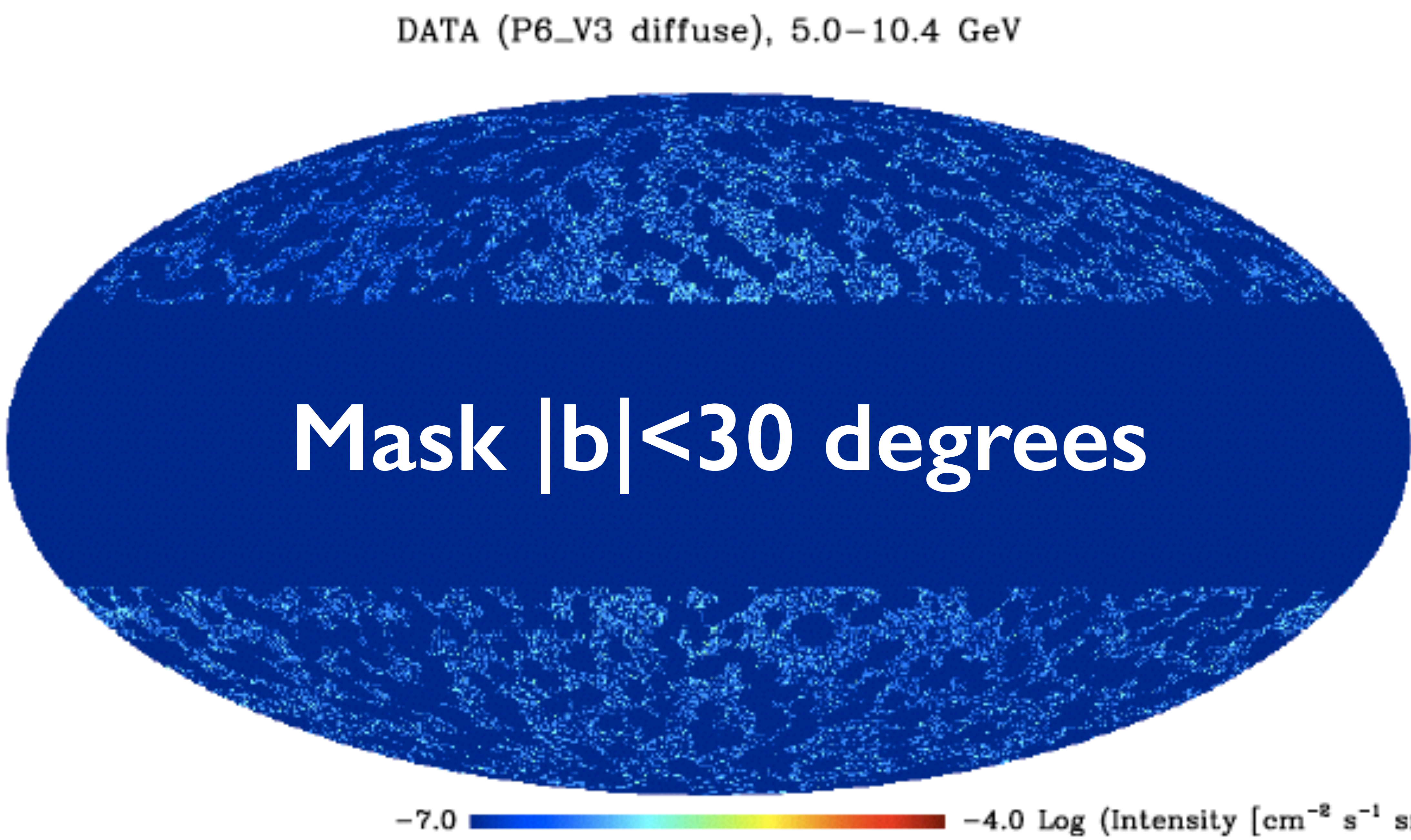
2.0–5.0 GeV


DATA (P6_V3 diffuse), 2.0−5.0 GeV
−7.0
−4.0 Log (Intensity [cm^{-2} s^{-1} sr^{-1}])

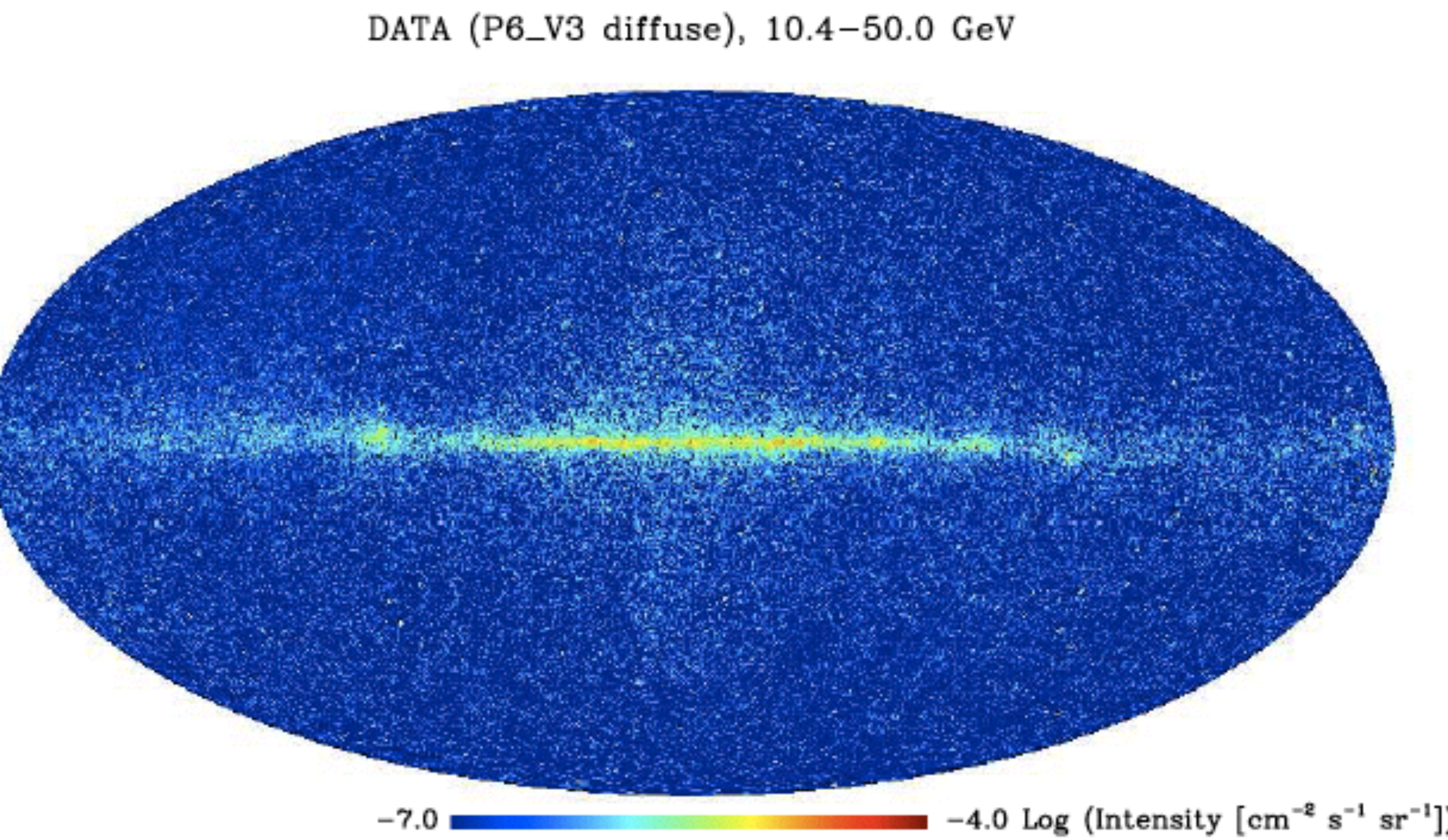

DATA (P6_V3 diffuse), 2.0−5.0 GeV
Mask |b|<30 degrees
−7.0
−4.0 Log (Intensity [cm^{-2} s^{-1} s

5.0–10.4 GeV

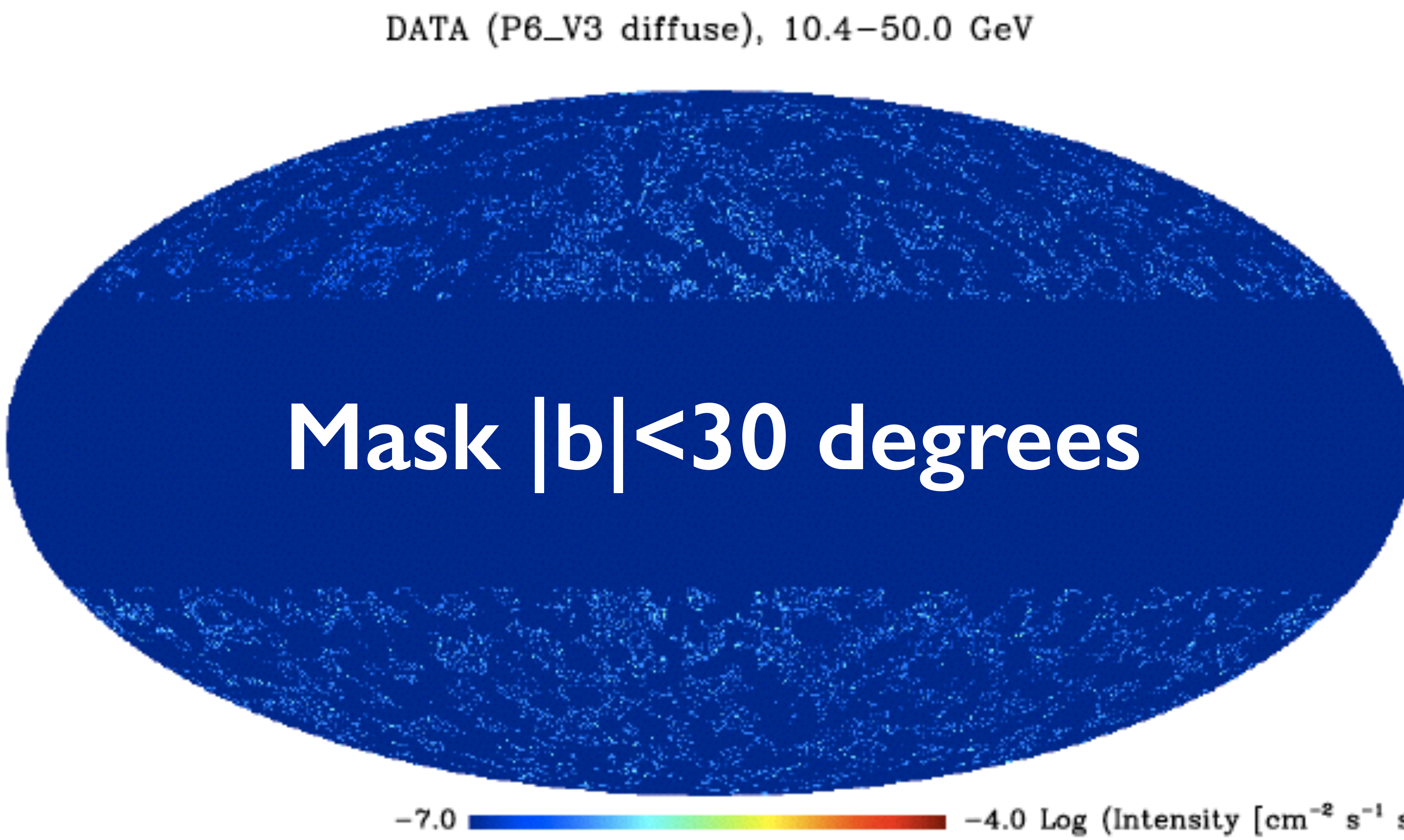

DATA (P6_V3 diffuse), 5.0−10.4 GeV
−7.0
−4.0 Log (Intensity [cm^{-2} s^{-1} sr^{-1}])


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

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
−4.0 Log (Intensity [cm^-2 s^-1

Fermi vs WMAP

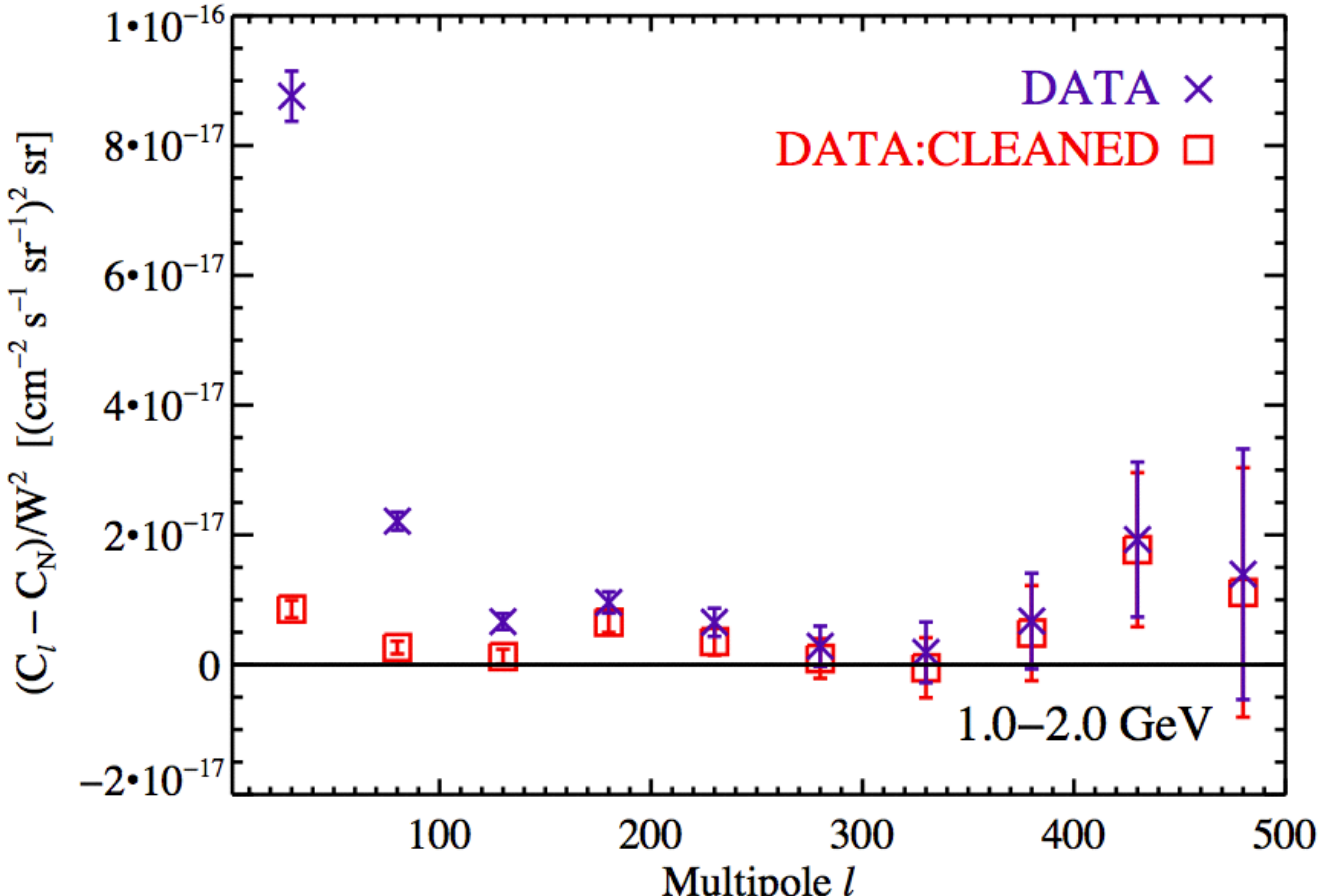
- There is an important difference between Fermi and WMAP maps
  - We count photons to produce Fermi maps; thus, there is the "photon noise" (Poisson statistics) in the power spectrum, which we must subtract.
  - Photon noise, C_N, is independent of multipoles, and is given by the mean number density 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 $W_\ell^{\rm beam}(E) = 2\pi \int_{-1}^{1} d\cos\theta P_\ell(\cos(\theta)) {\rm PSF}(\theta; {\rm E})$
- The attenuation by PSF is corrected as **$(C_l - C_N)/W_l^2$**

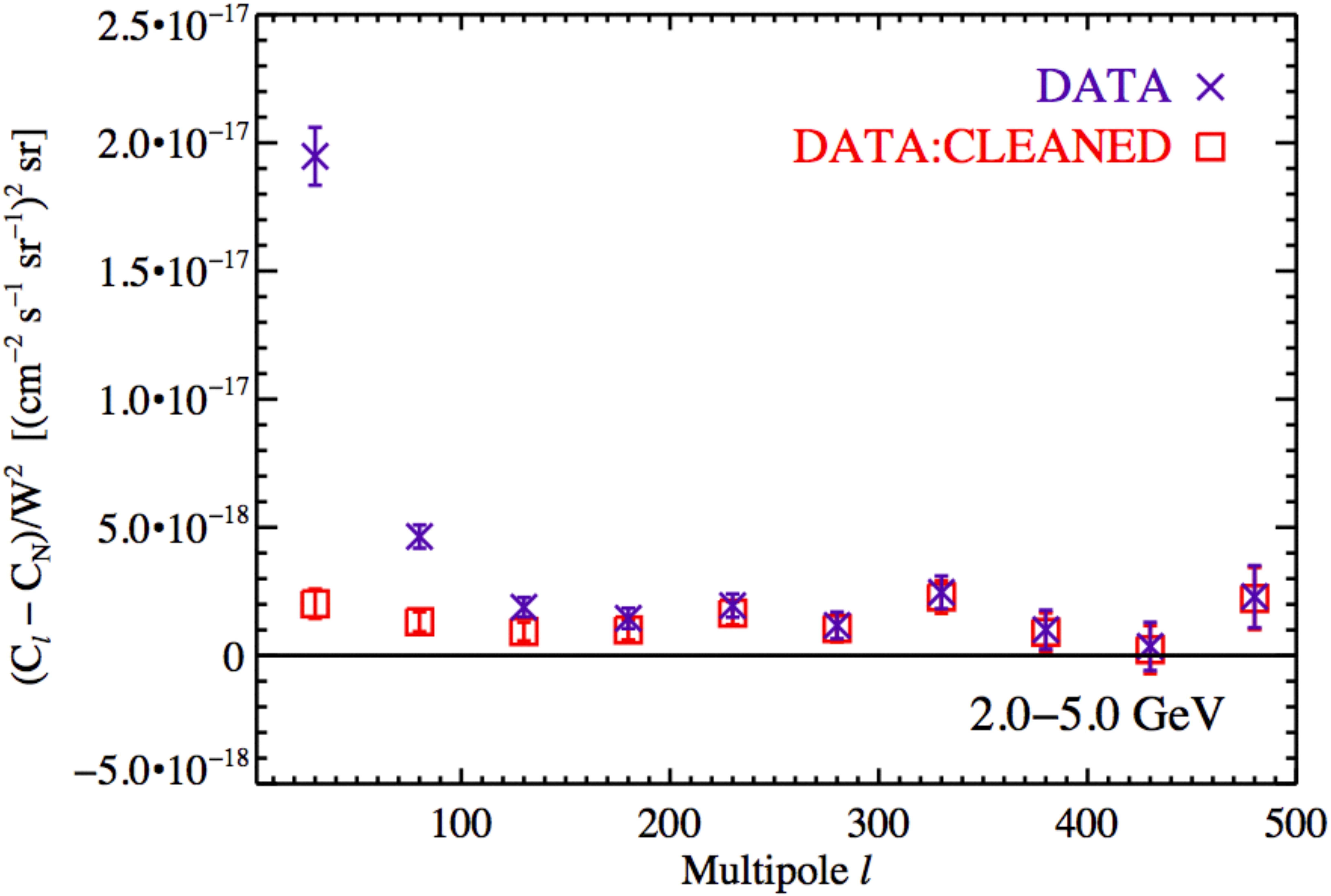
DATA: CLEANED = Galactic Model Map Subtracted

1.0–2.0 GeV



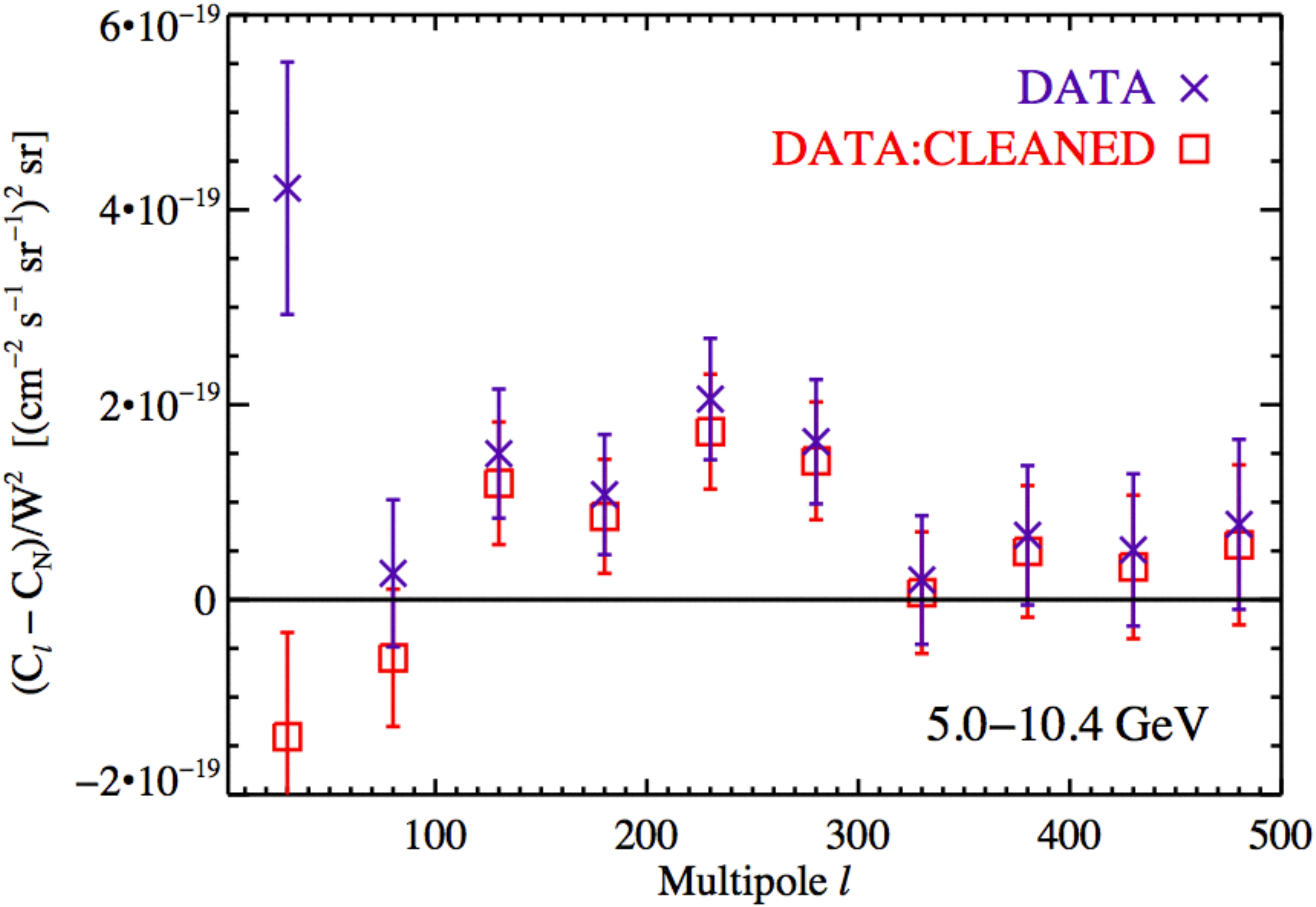
DATA: CLEANED = Galactic Model Map Subtracted

2.0–5.0 GeV



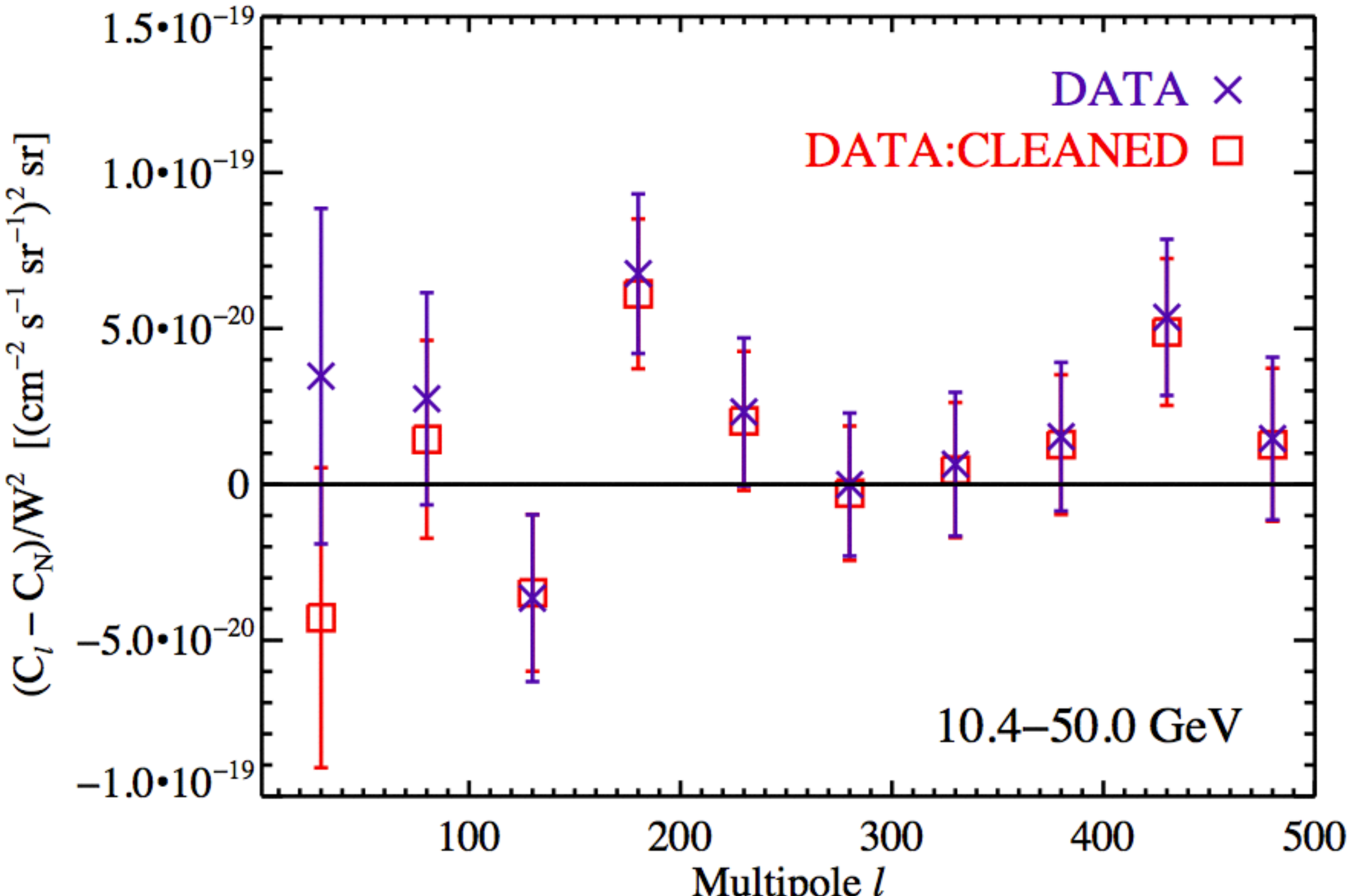
DATA: CLEANED = Galactic Model Map Subtracted

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

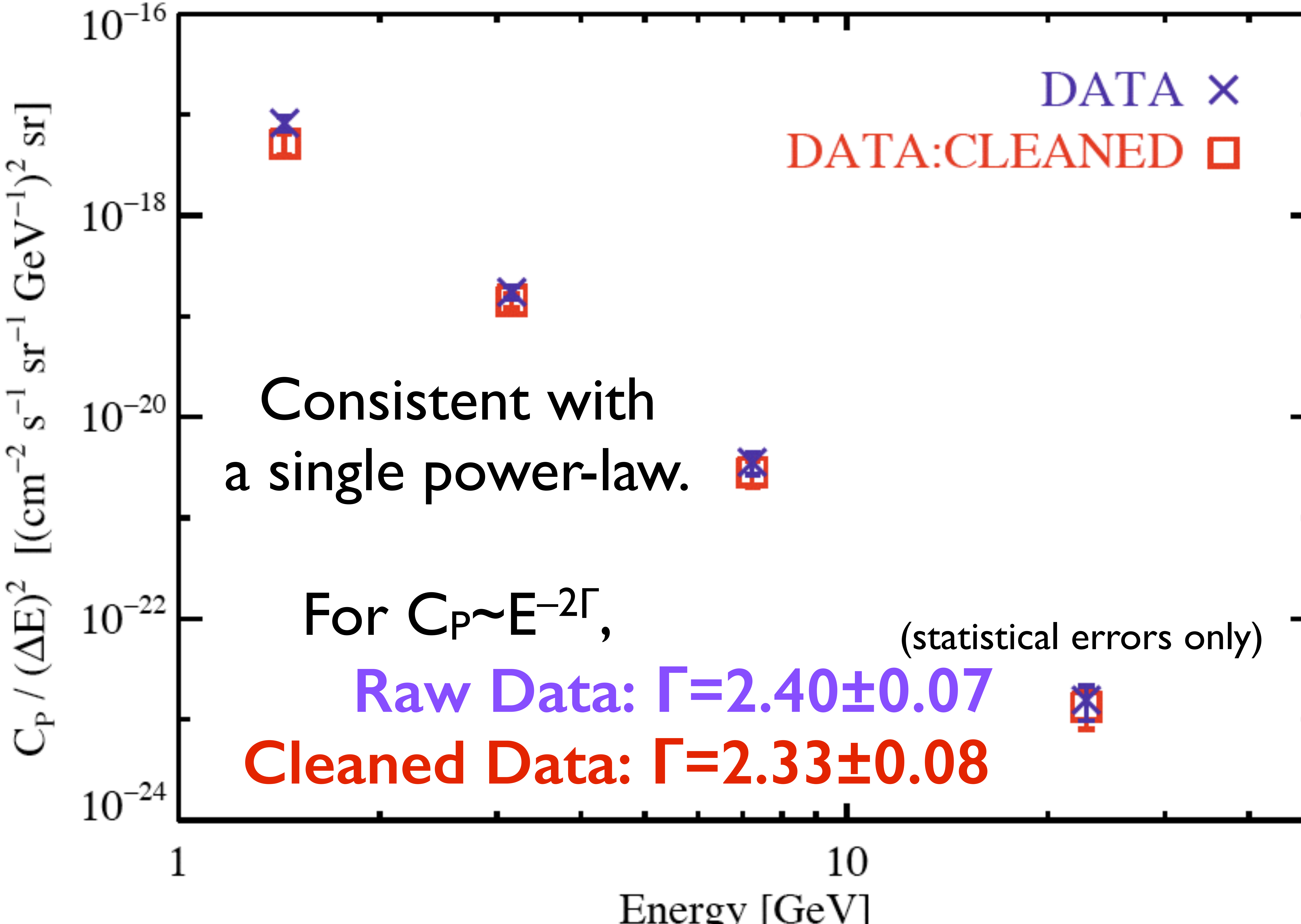
Therefore, we will find the best-fitting constant power, C_P.
("P" stands for "Poisson contribution")

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



Consistent with a single power-law.

For $C_P \sim E^{-2\Gamma}$,

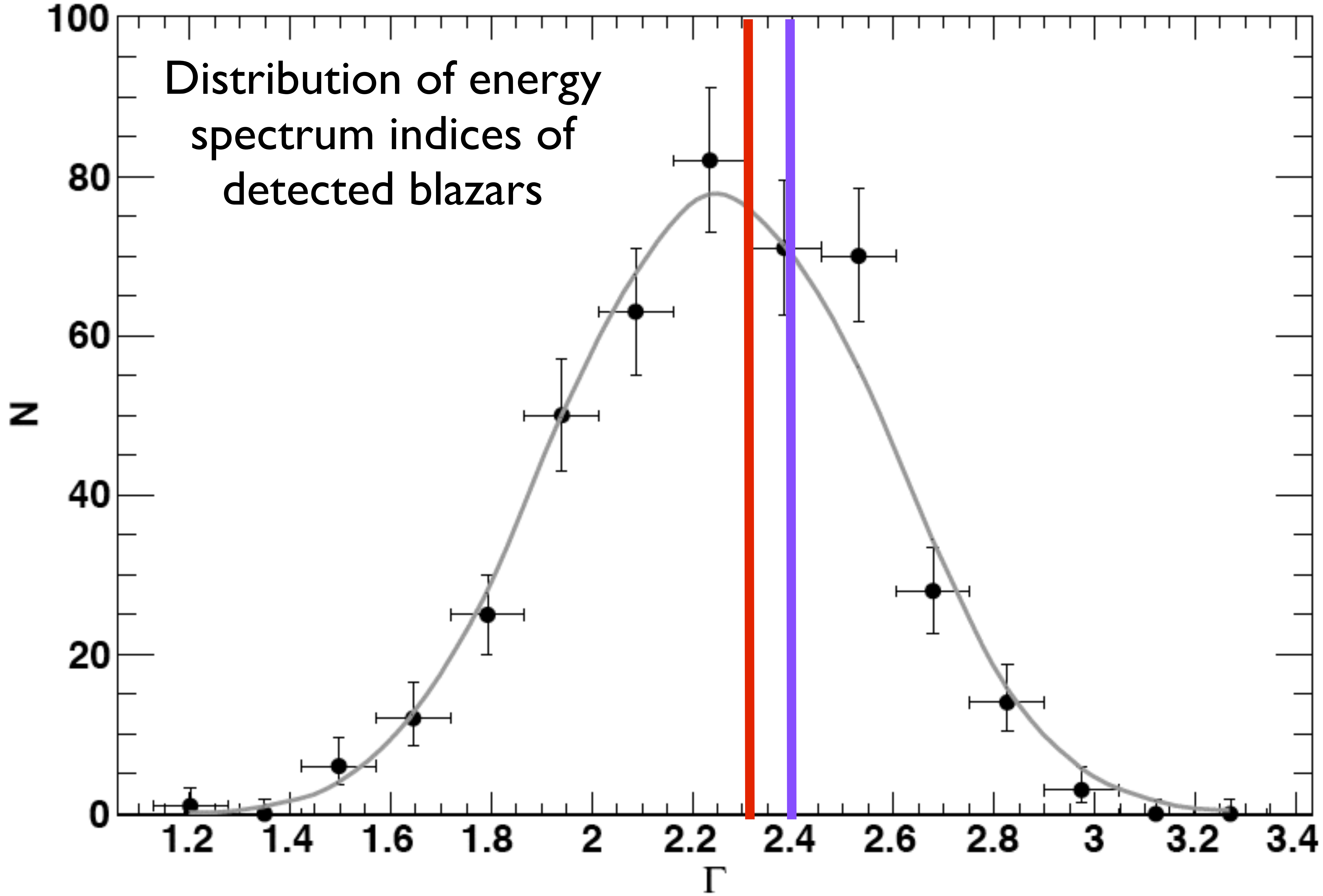
(statistical errors only)

Raw Data: Γ=2.40±0.07

Cleaned Data: Γ=2.33±0.08

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

Are we seeing blazars?

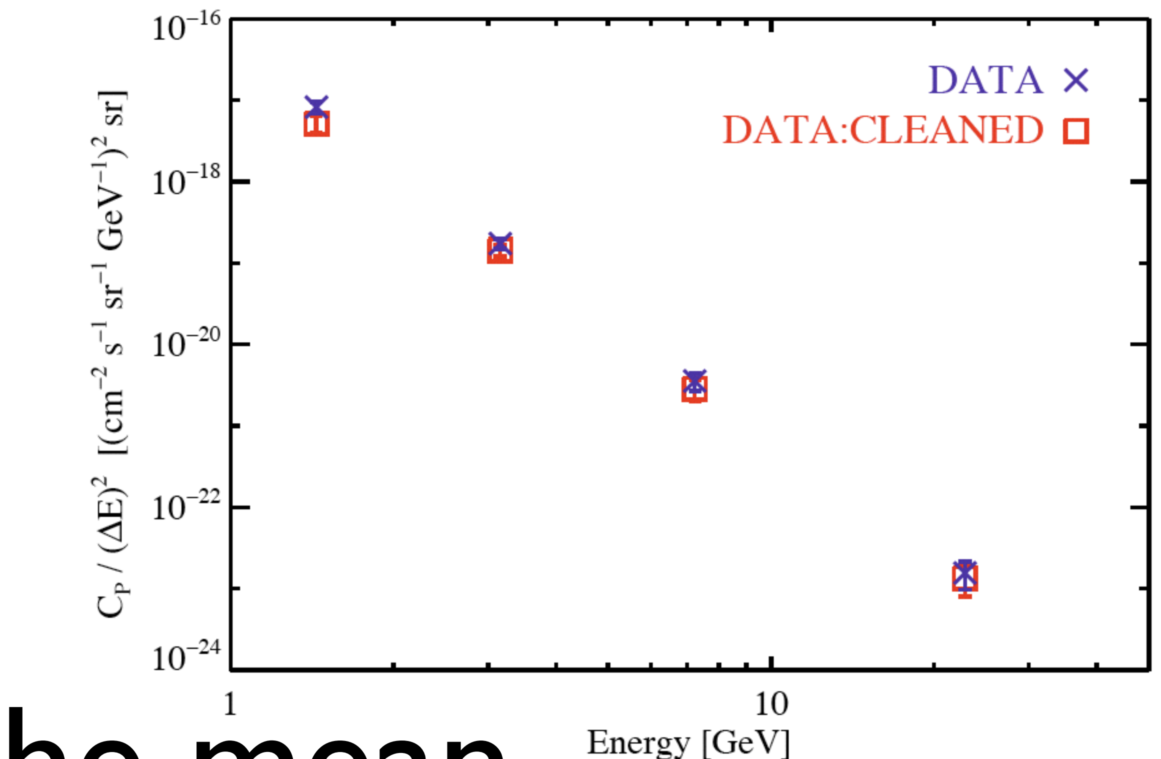


- The energy spectrum of anisotropy (from unresolved sources) agrees with that of **detected** blazars.

Interpreting the Results

- Unresolved, unclustered point sources contribute to C_P as

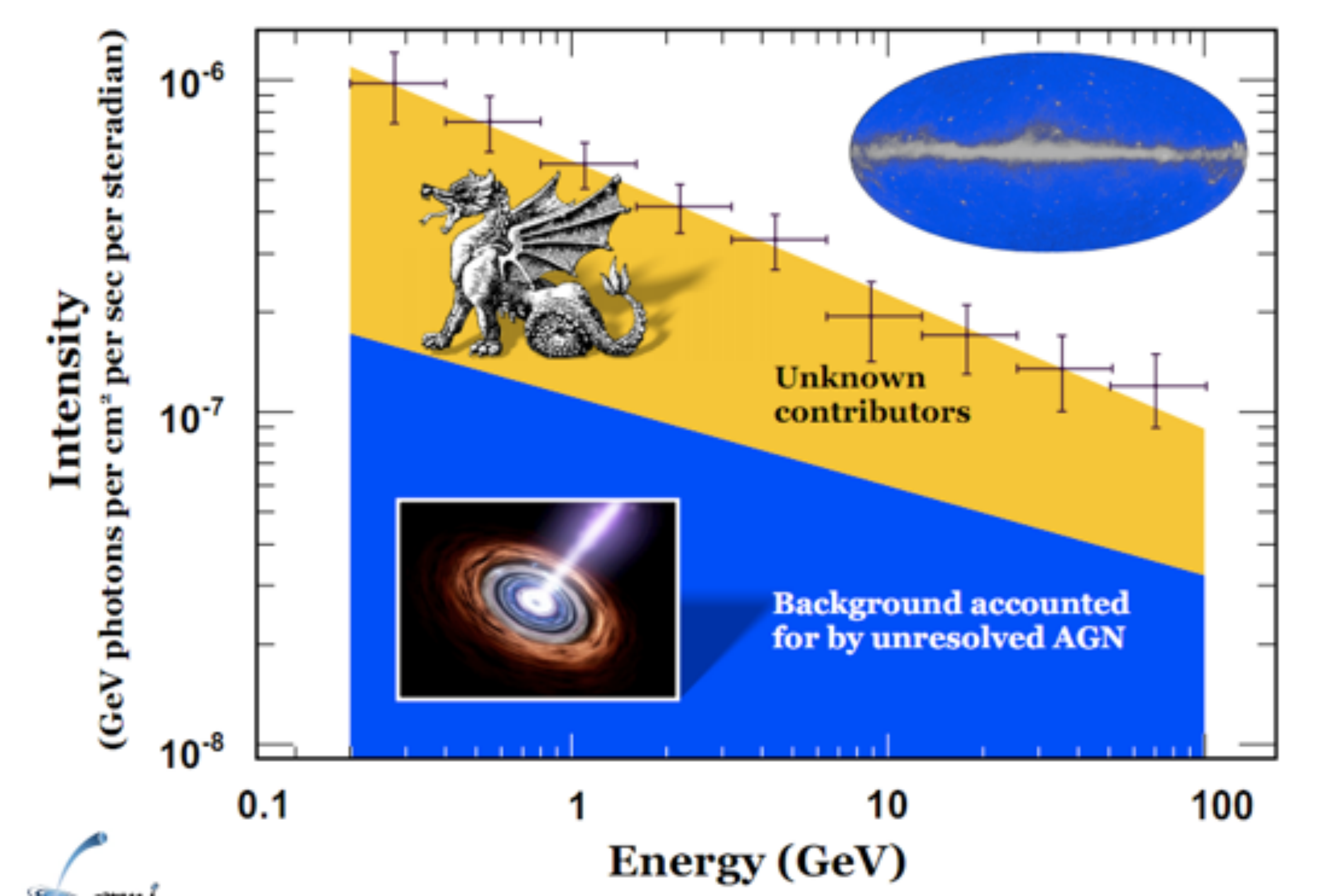
$$C_{\rm P} = \int_0^{S_c} dS\ S^2 \frac{{\rm d}N}{{\rm d}S}$$



- Unresolved, point sources contribute to the mean intensity as

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

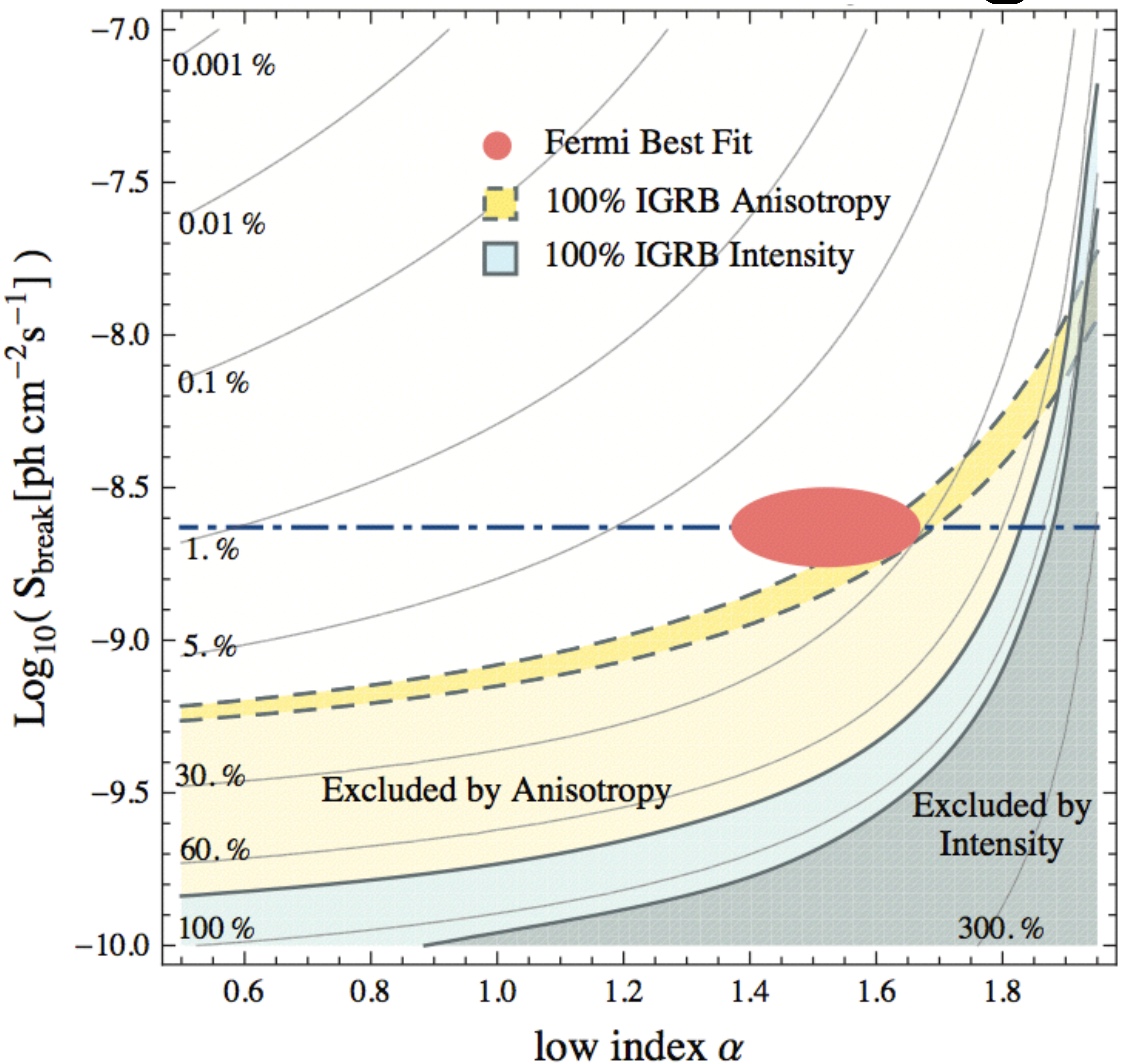
Fermi LAT Extragalactic Gamma-ray Background



- *Are they consistent with the data?*

Cuoco, EK & Siegal-Gaskins (2013)

Are we seeing blazars? YES



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

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

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

$\boxed{\text{Vary } S_b \text{ and } \alpha}$

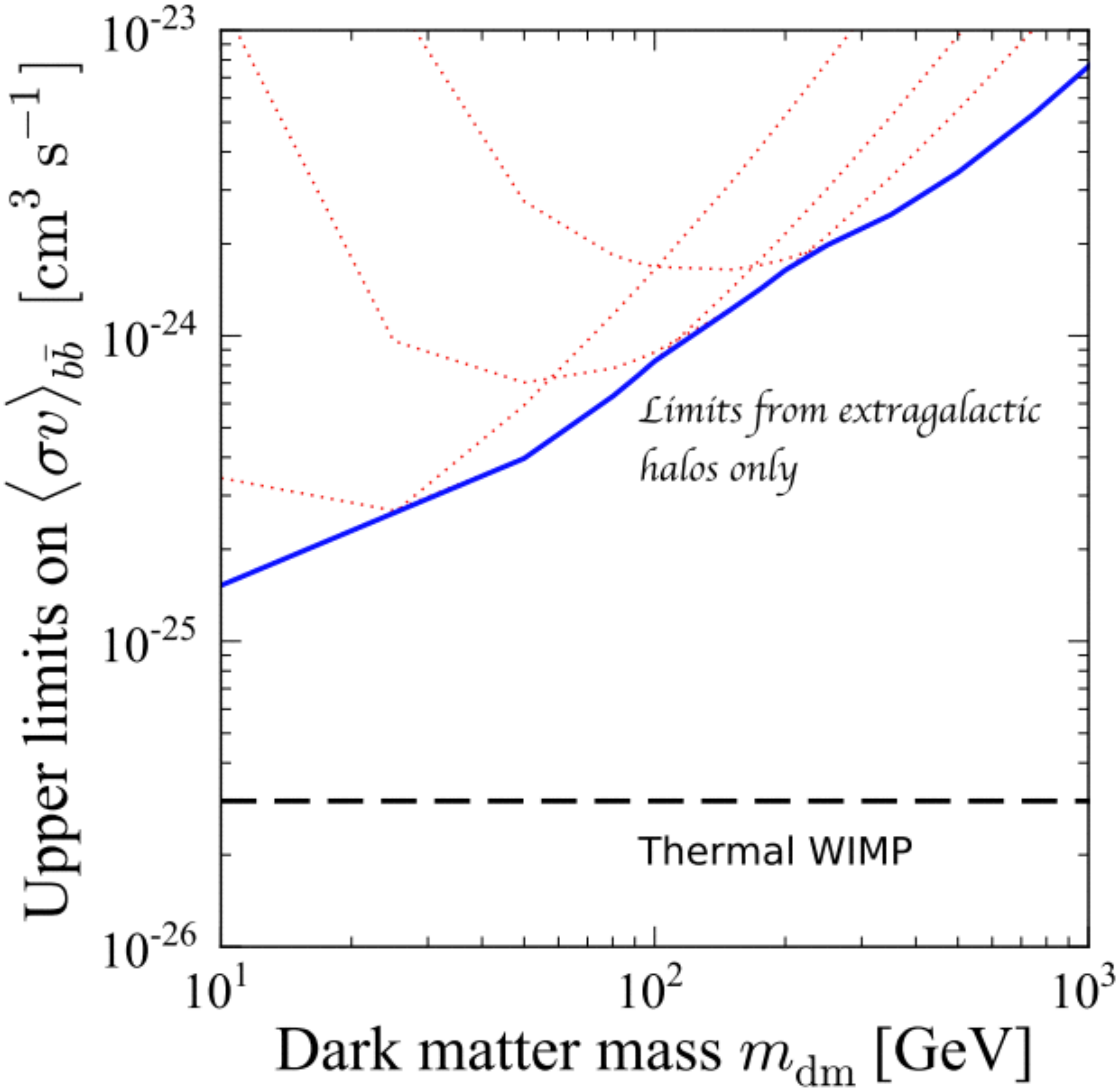
(Fix a bright-end slope, β,
to the measured value, β=2.38)

Cuoco, EK & Siegal-Gaskins (2013)

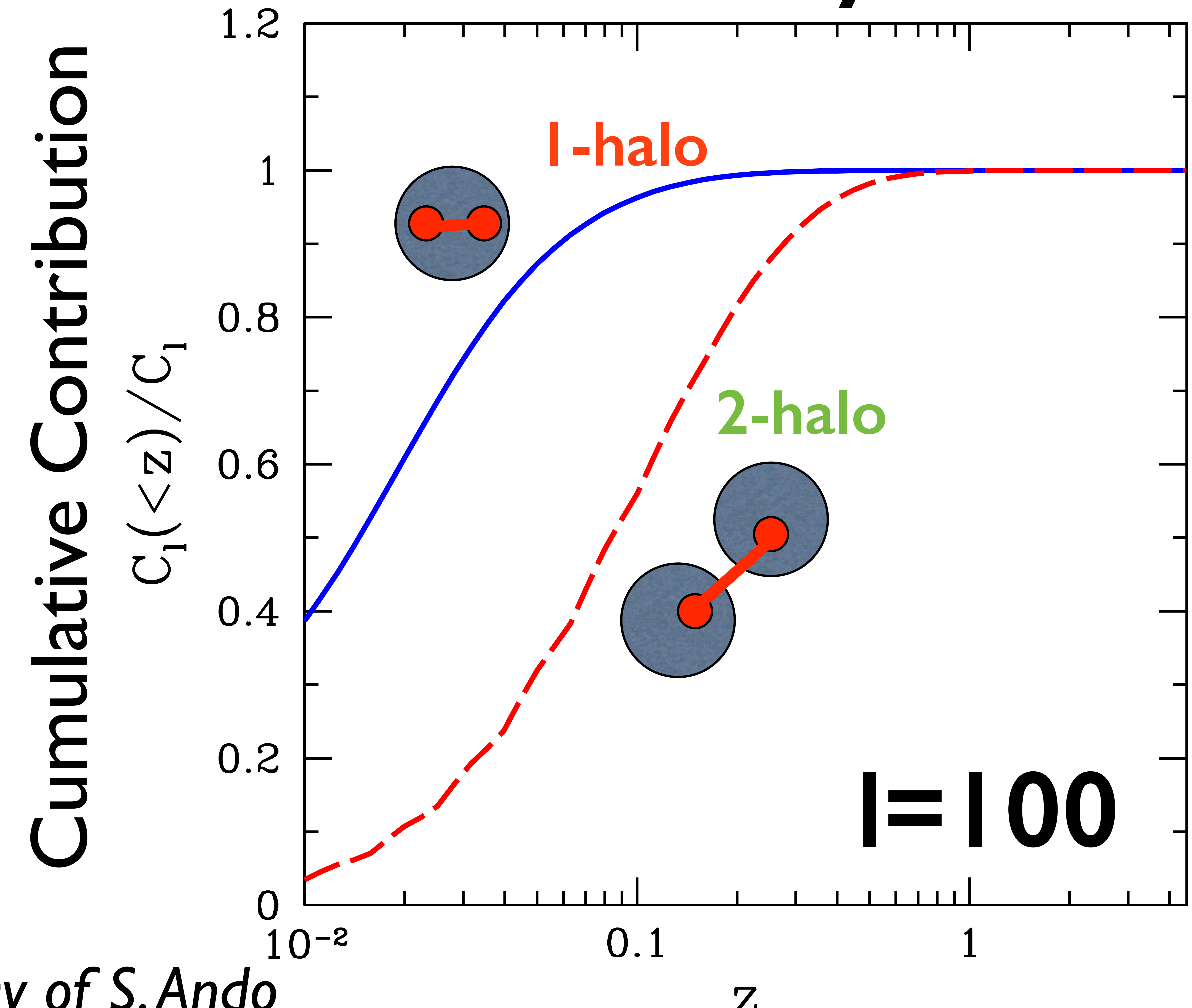
Are we seeing blazars? YES

- 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 (~30%) of the mean gamma-ray background.
- These two, independent measurements give us a consistent picture of the gamma-ray sky.

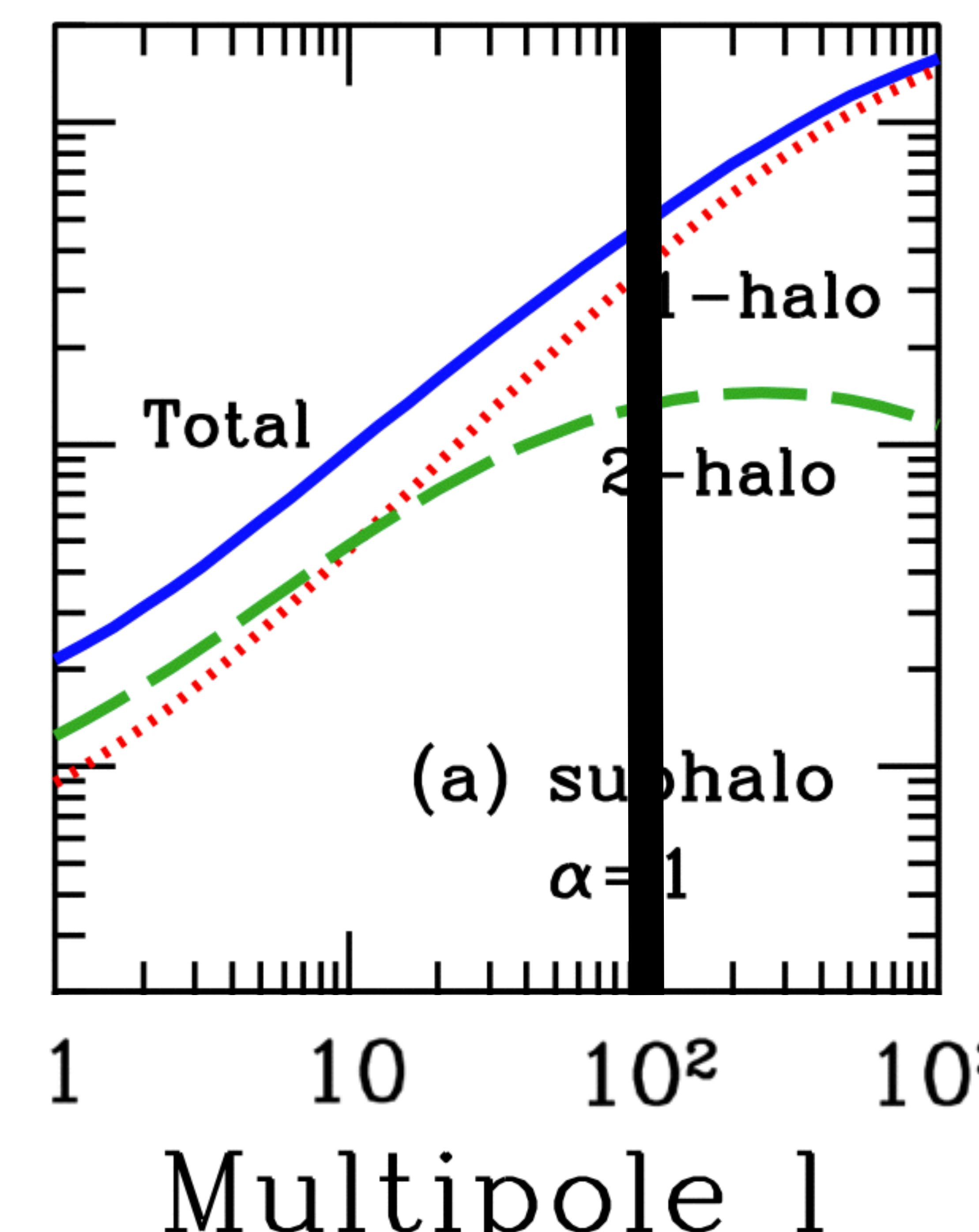
What about Dark Matter?



Which z do they come from?

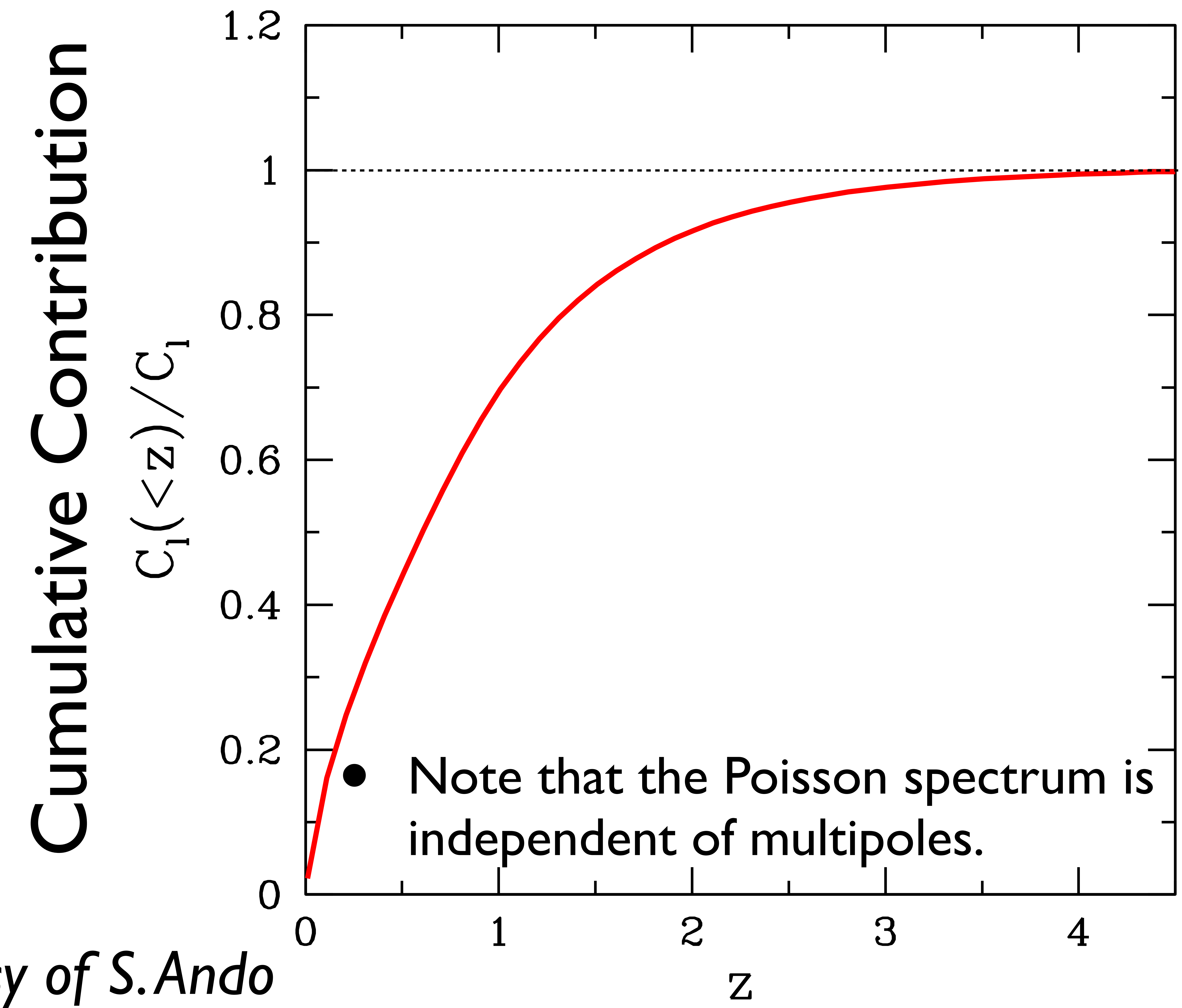


With sub-halos (all surviving)



Courtesy of S. Ando

Which z do blazars contribute?



- Note that the Poisson spectrum is independent of multipoles.

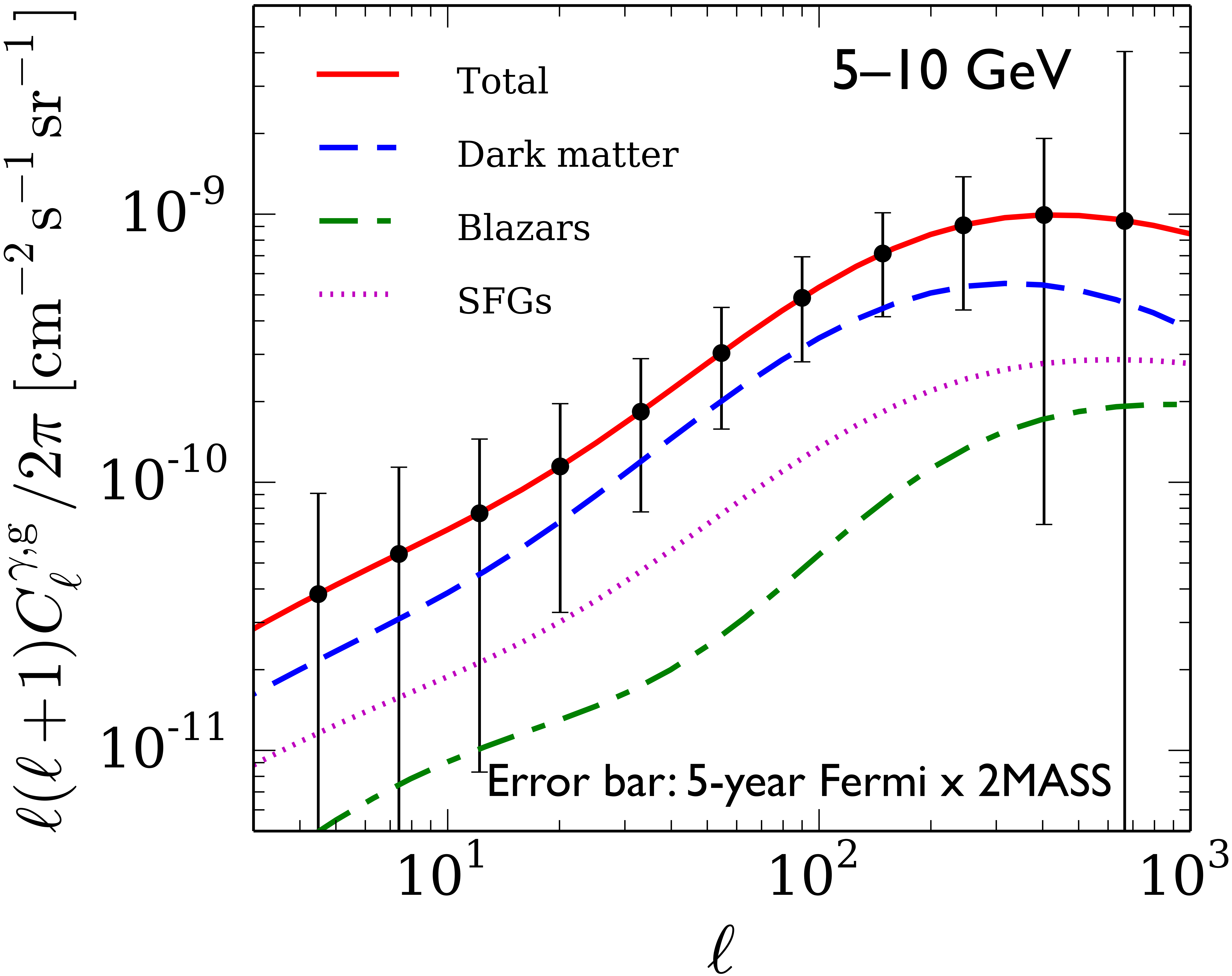
Courtesy of S. Ando

New Idea

- If we have a tracer of the large-scale structure in a low redshift universe ($z<0.1$), we can effectively extract the dark matter contribution by cross-correlating the low-redshift tracer with the gamma-ray data

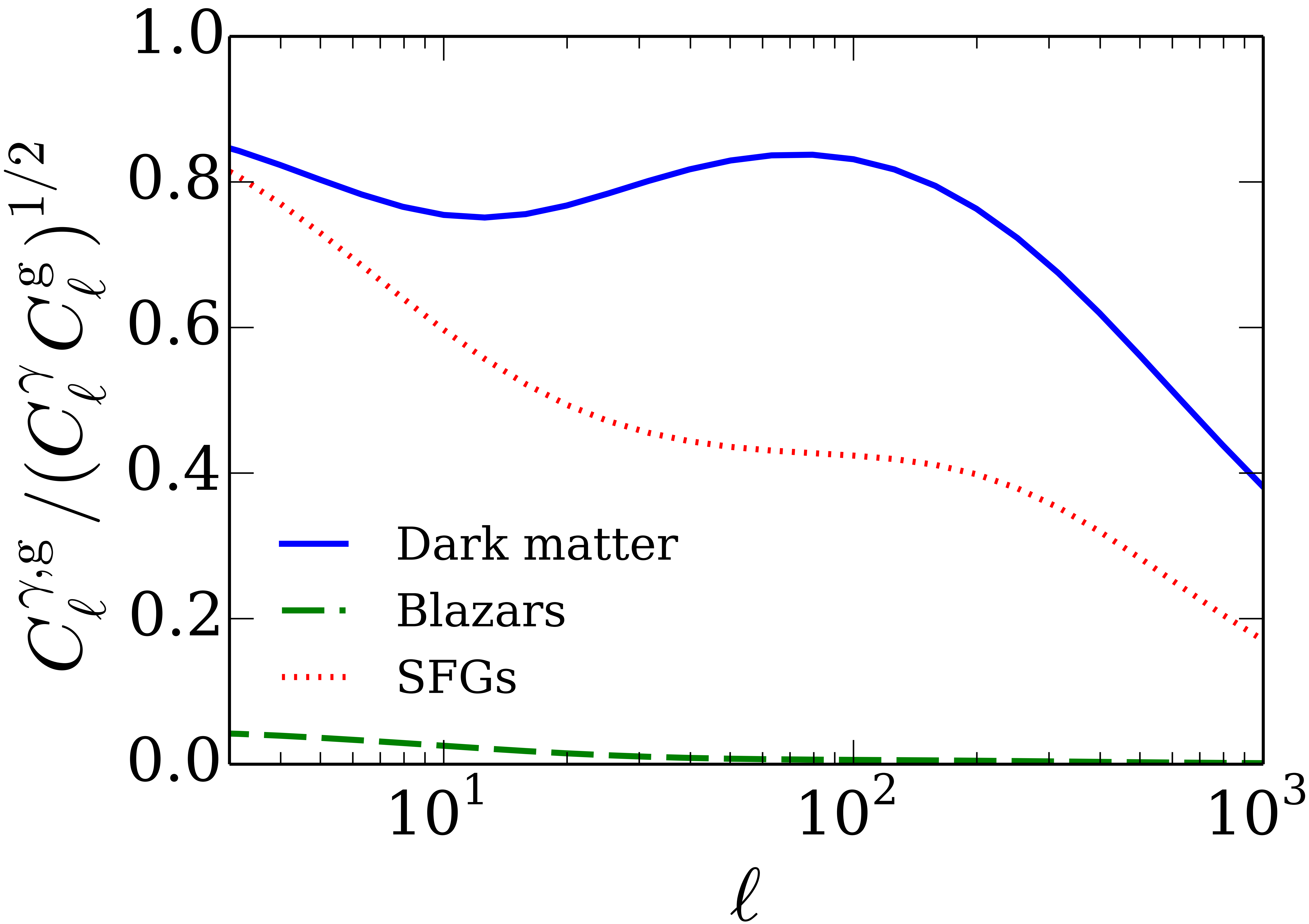
- Such a tracer already exists! Two-micron All Sky Survey (2MASS)

Ando, Benoit-Lévy & EK (2014)

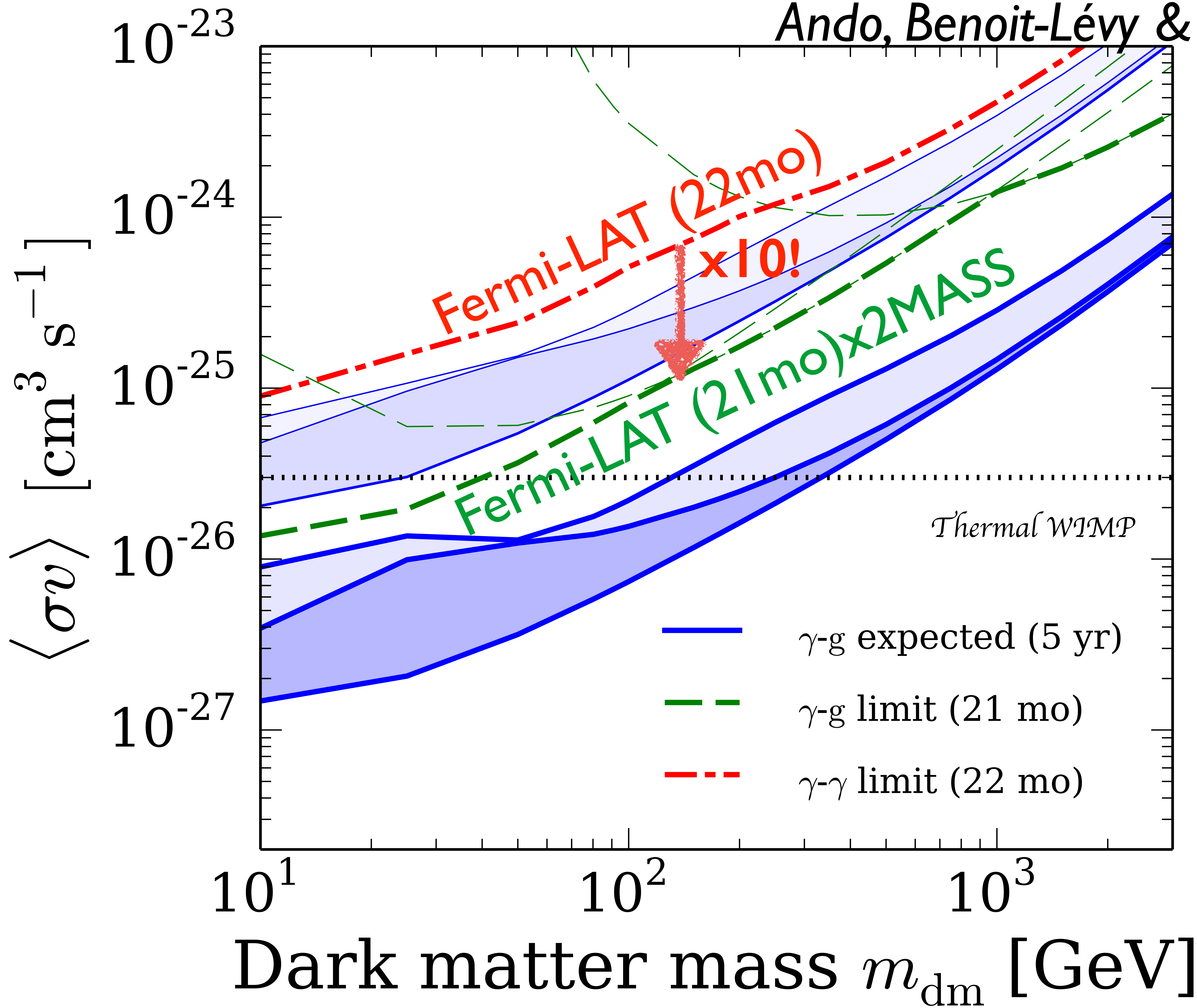


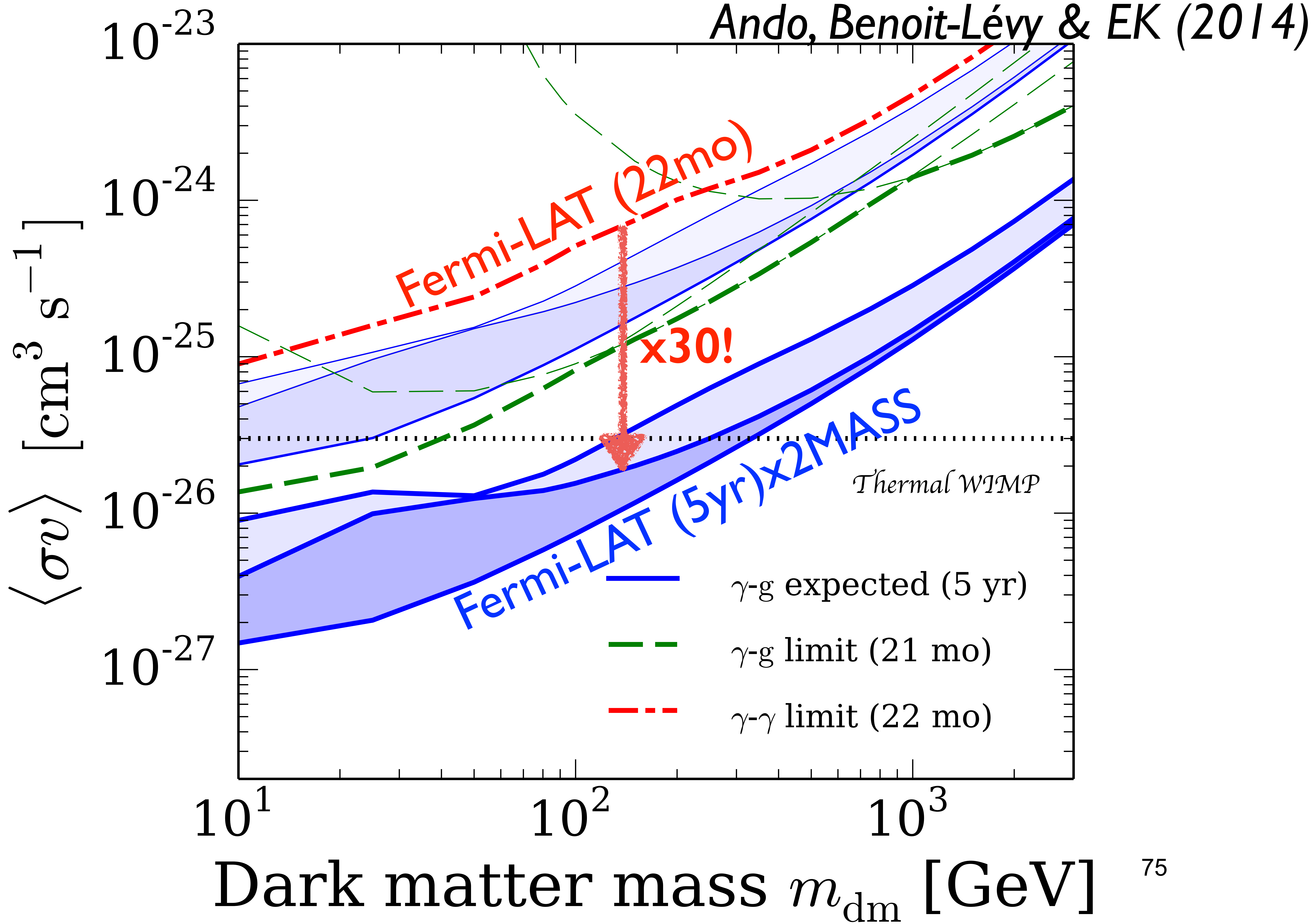
Ando, Benoit-Lévy & EK (2014)

Blazars are effectively eliminated by the cross-correlation; however, star-forming galaxies still show a moderate correlation

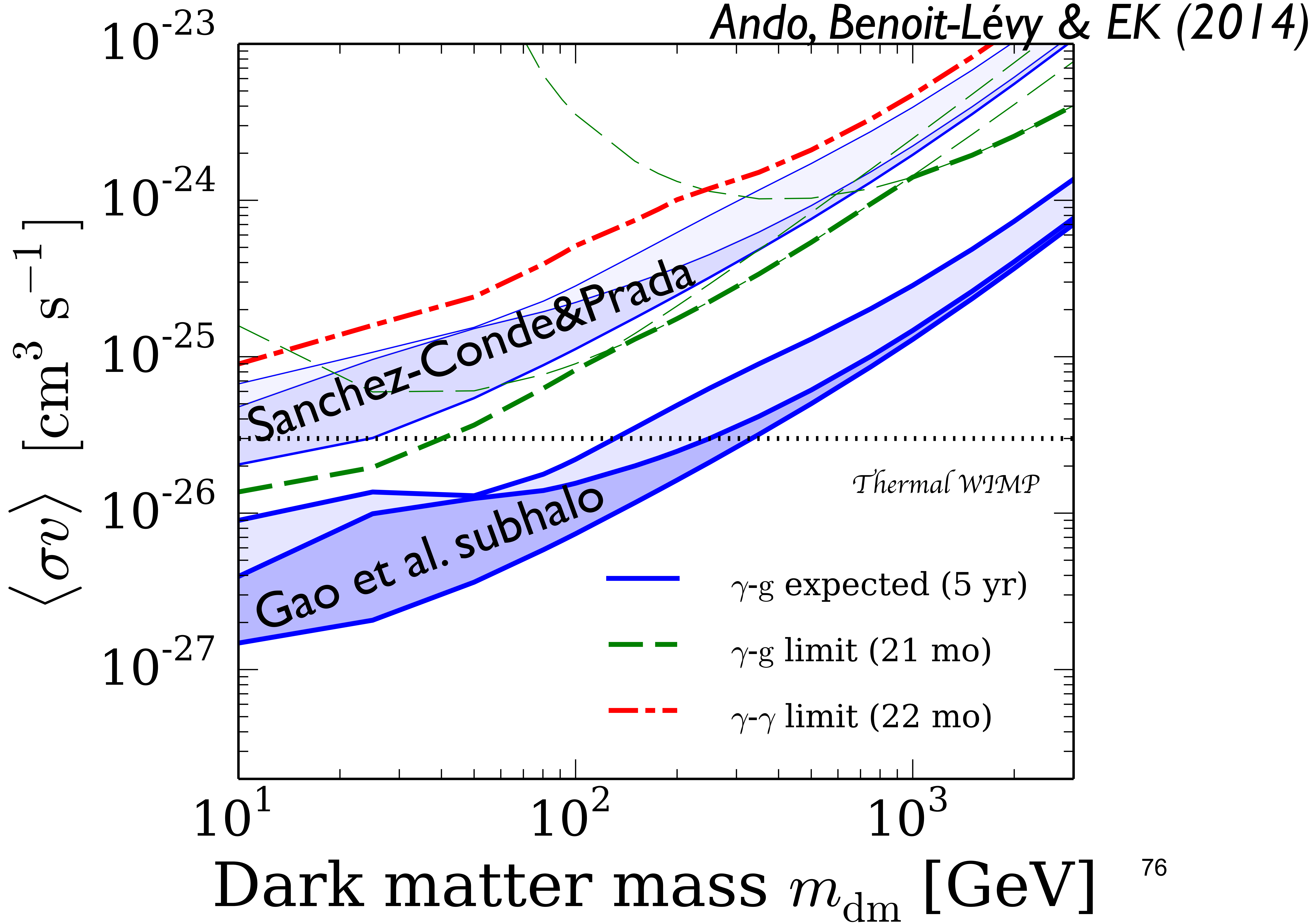


Ando, Benoit-Lévy & EK (2014)





Ando, Benoit-Lévy & EK (2014)
Fermi-LAT (22mo)
x30!
Fermi-LAT (5yr)x2MASS
Thermal WIMP
γ-g expected (5 yr)
γ-g limit (21 mo)
γ-γ limit (22 mo)
$\langle \sigma v \rangle$ [cm^3 s^{-1}]
Dark matter mass $m_{\rm dm}$ [GeV]
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^1
10^2
10^3



Ando, Benoit-Lévy & EK (2014)
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
$\langle \sigma v \rangle$ [cm^3 s^{-1}]
Sanchez-Conde&Prada
Gao et al. subhalo
Thermal WIMP
γ-g expected (5 yr)
γ-g limit (21 mo)
γ-γ limit (22 mo)
10^1
10^2
10^3
Dark matter mass $m_{\rm dm}$ [GeV]

Conclusions

- We have detected anisotropy in the extra-galactic diffuse gamma-ray background from Fermi-LAT 22mo maps. **This is the first detection!**
- The detected anisotropy is consistent with the contribution from unresolved blazars. **The method seems to work!**
    - Also consistent with the mean intensity data
    - The origin of the bulk of diffuse background remains a mystery
- Cross-correlation is a promising way to go forward