理論懇シンポジウム

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Anisotropy in the gamma-ray sky and prospects for GLAST

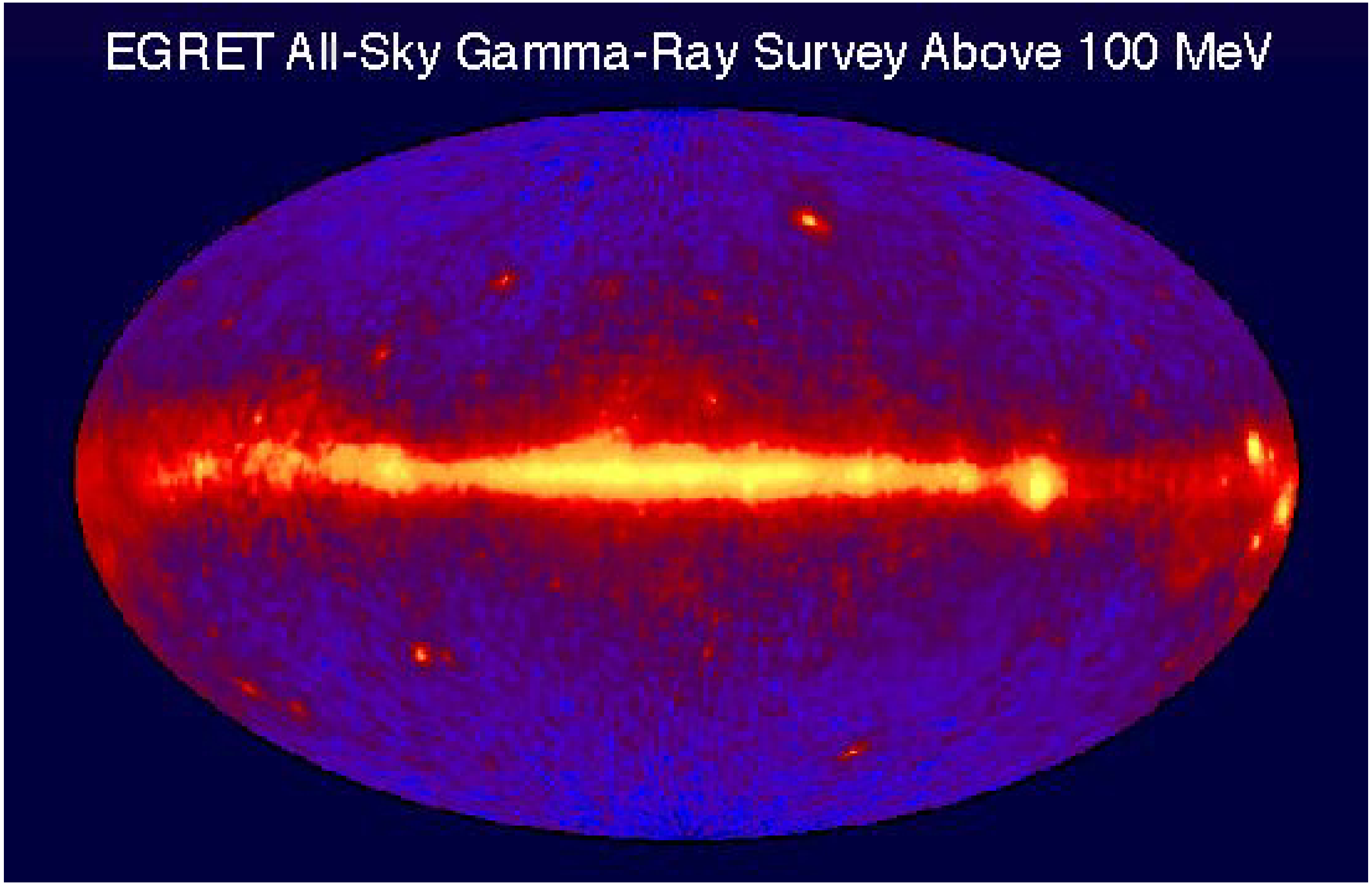
Shin'ichiro Ando

Theoretical Astrophysics, California Institute of Technology

In collaboration with

E. Komatsu (Texas), T. Narumoto, T. Totani (Kyoto)

1. Introduction:
Unresolved mystery in the high-energy sky



1. Introduction:
Unresolved mystery in the high-energy sky

- What are blazars?
  - ~60 were detected with EGRET
  - What are the emission mechanisms?
  - Are they beamed AGNs?—Is AGN unification picture really right?
- What is the origin of cosmic gamma-ray background?
  - EGRET discovered isotropic gamma-ray background in GeV region
  - Can unresolved astrophysical sources explain all the flux?
  - Do we have chance to see signature of dark matter annihilation?

GLAST: Gamma Ray Large Area Space Telescope

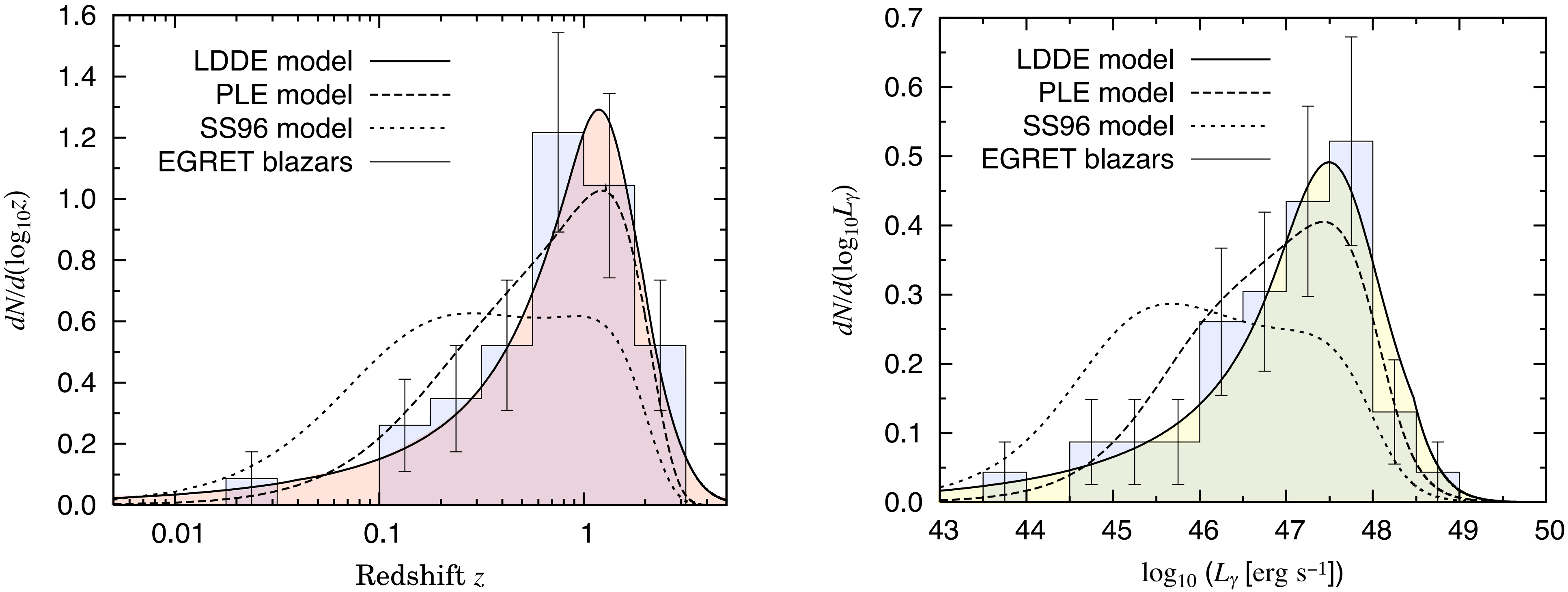
- GLAST is equipped with a large volume gamma-ray detector (LAT)
  - Sensitivity covers 30 MeV–300 GeV
  - Very large field of view (2.4 sr), enabling all sky survey
  - Point source flux sensitivity: 2×10^{-9} cm^{-2} s^{-1}, 50 times better than EGRET
  - Better map of (1) point sources and (2) diffuse radiation

2. Point source anisotropy: blazars for GLAST

Ando, Komatsu, Narumoto, & Totani,
MNRAS in press; astro-ph/0610155

Blazar luminosity function: How many at GLAST?

Narumoto & Totani 2006



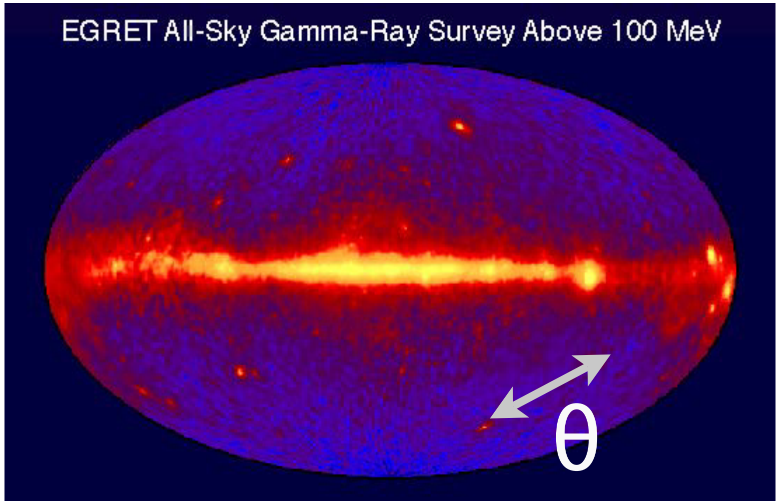
- Luminosity-dependent density evolution (LDDE) model motivated by X-ray AGN observation fits the data very well
- The best fit model predicts ~3,000 blazars from all sky

Is blazar clustering detectable with GLAST?

- Blazars should cluster spatially tracing the dark matter distribution
- Given the large number statistics (~3,000), can the spatial clustering be detectable with GLAST?
- We can compare data immediately with prediction of angular power spectrum
  - One can directly get blazar bias
  - This provides an independent test of AGN unification picture
- This is a very straightforward and important thing to do; nevertheless has not been done by anybody

Formulation: Angular power spectrum

- Everything is in textbook by Peebles (1980)



Angular correlation function:

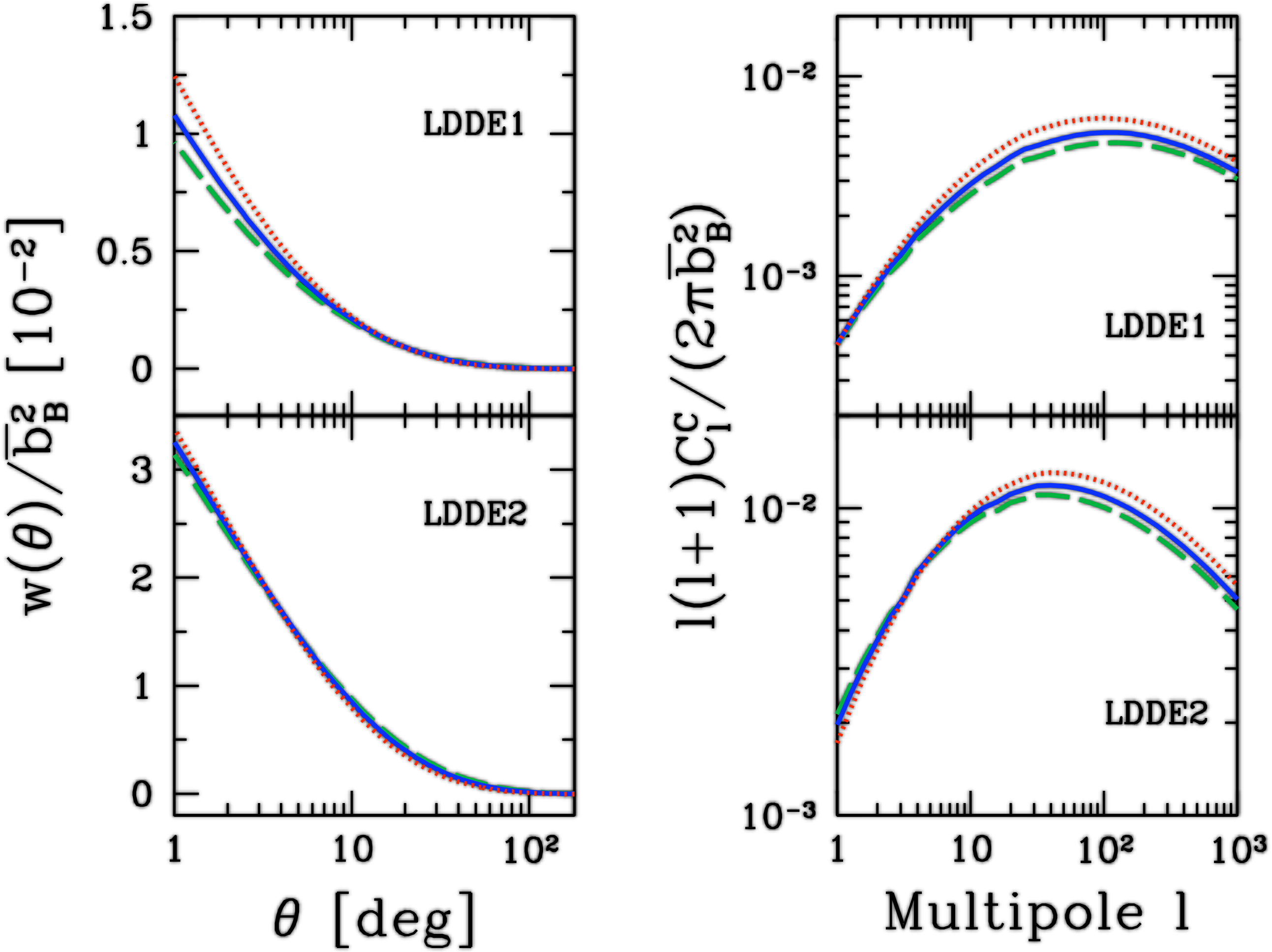
Blazar bias

$$\mathcal{N}^2 w(\theta) = \int_0^{z_{\rm max}} dz \frac{d^2V}{dz d\Omega} \chi(z)^2 \phi(z)^2 \overline{b}_B(z)^2 \times \int_{-\infty}^{\infty} du\, \xi_{\rm lin}\left(\sqrt{u^2 + \chi(z)^2\theta^2}, z\right)$$

Angular power spectrum:

$$C_l = C_l^P + C_l^C$$
$$C_l^P = \mathcal{N}^{-1}$$
$$C_l^C = 2\pi \int_{-1}^{1} d\cos\theta\; P_l(\cos\theta) w(\theta)$$

Results:
(i) Angular correlation and power spectrum



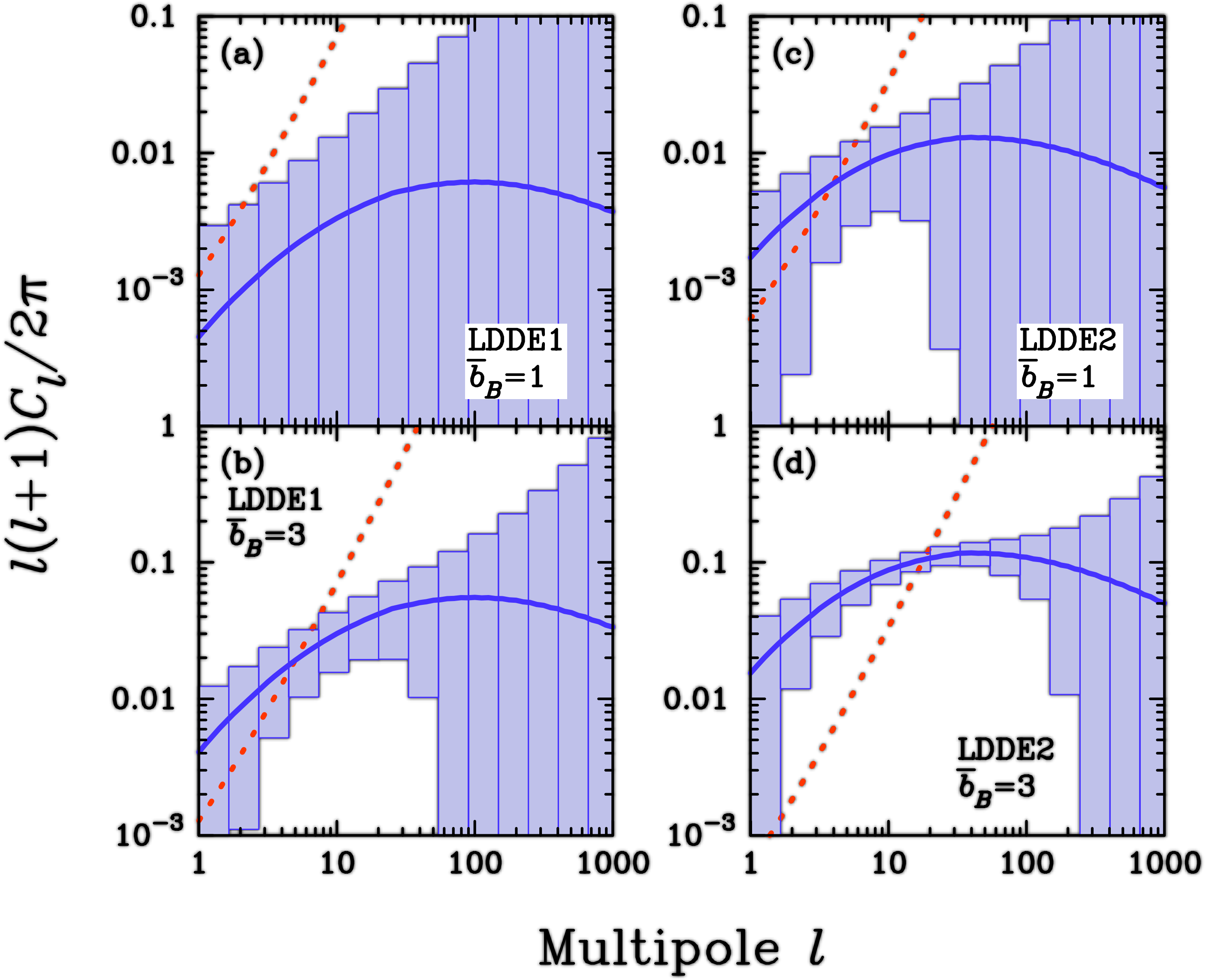
LDDE1	Best fit model
LDDE2	Explains 100% of gamma-ray background

Point source flux limit:
2, 3, 4 × 10^{-9} cm^{-2} s^{-1}

Ando et al., astro-ph/0610155

(ii) Errors of angular power spectrum

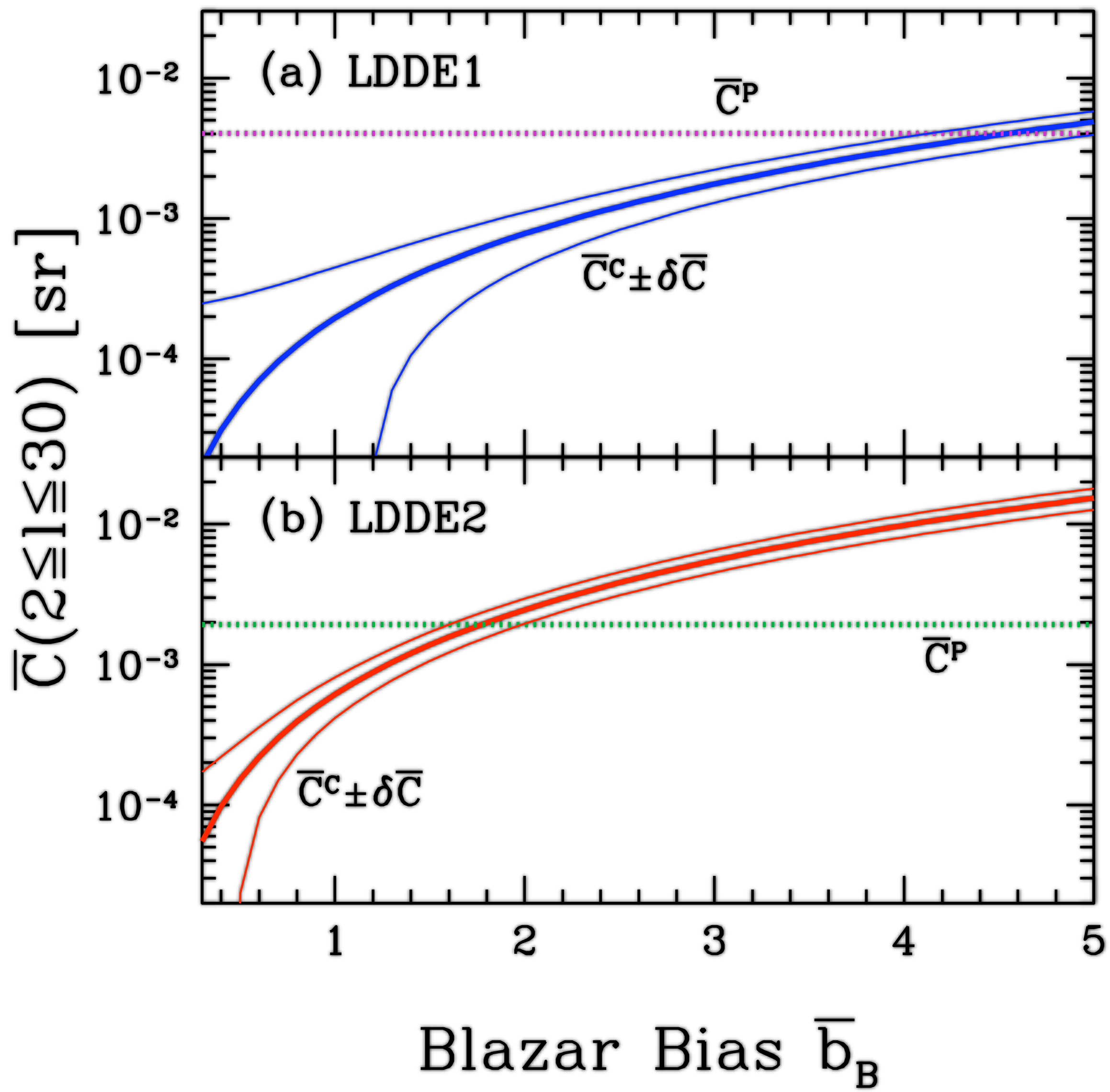
Ando et al., astro-ph/0610155



$$(\delta C_l)^2 = \frac{2C_l^2}{(2l+1)\Delta l f_{\rm sky}}$$

- We can detect blazar correlation at large angular scale
- This directly tells us blazar bias

(iii) Dependence on blazar bias and other observations



- Average over large scale: $2 \leq l \leq 30$
- Correlation is detectable for $b_B > 1.2$ (LDDE1), and $b_B > 0.5$ (LDDE2)
- Optical quasar gives: $b_Q \sim 0.8$ at relevant redshift range
- X-ray AGNs seem more strongly clustered with $b \sim 3$–4

Ando et al., astro-ph/0610155

Discussion:
Example strategy for GLAST point source survey

1. **Source detection**
2. **Removing galaxy clusters**

   Catalog may contain galaxy clusters. These can be removed by using the FIRST radio survey

3. **Updating blazar luminosity function**

   According to the source number, we may update the luminosity function

4. **Analysis of angular power spectrum**

   We can constrain the blazar bias, even before follow-up observations

5. **Completion of follow-ups: beginning of precision study**

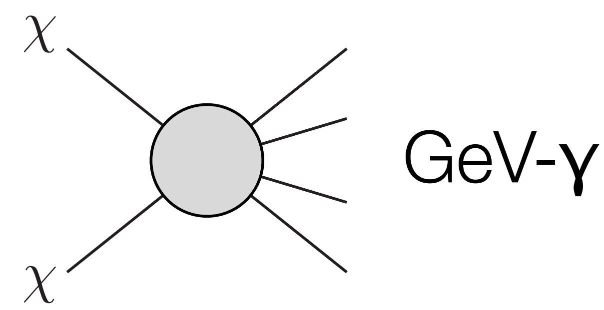
   Analysis with more precise luminosity function. One may also use 3D power spectrum

3. Anisotropy of cosmic gamma-ray background (CGB) and dark matter annihilation

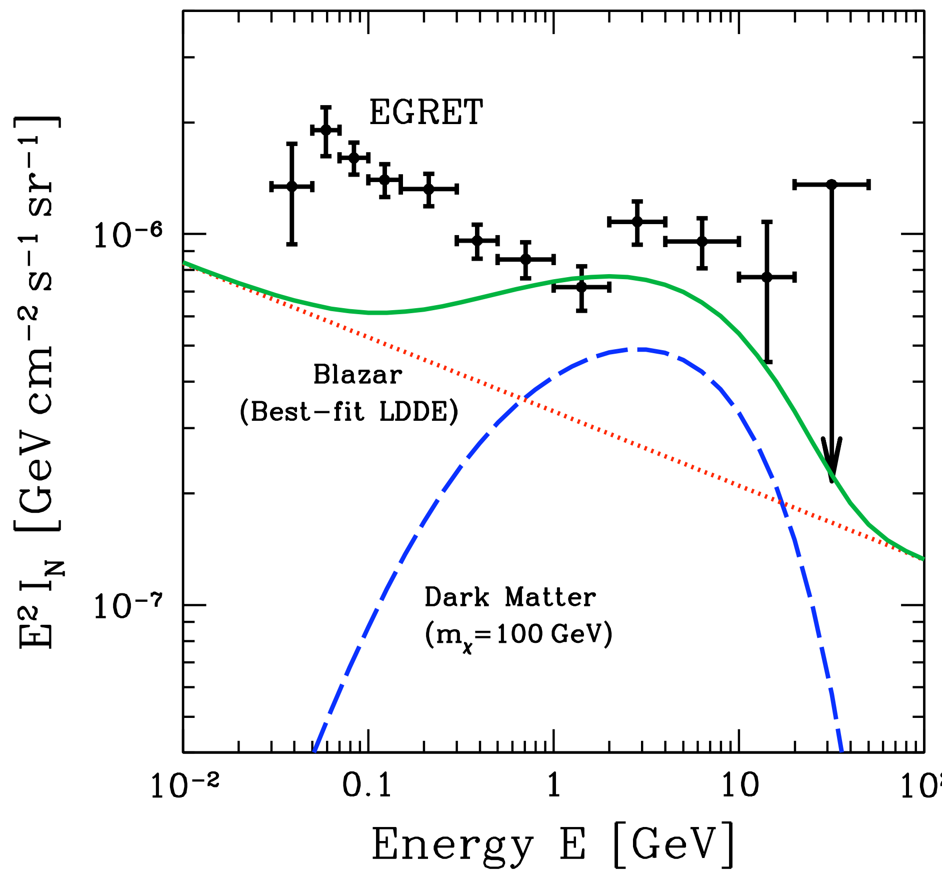
Ando & Komatsu, Phys. Rev. D **73**, 023521 (2006)
Ando, Komatsu, Narumoto, & Totani, astro-ph/0612467

Dark matter (WIMP) annihilation

- If dark matter is WIMP, it may annihilates into visible photons



- WIMP mass is likely around GeV–TeV, so GLAST might have good chance to detect the signature

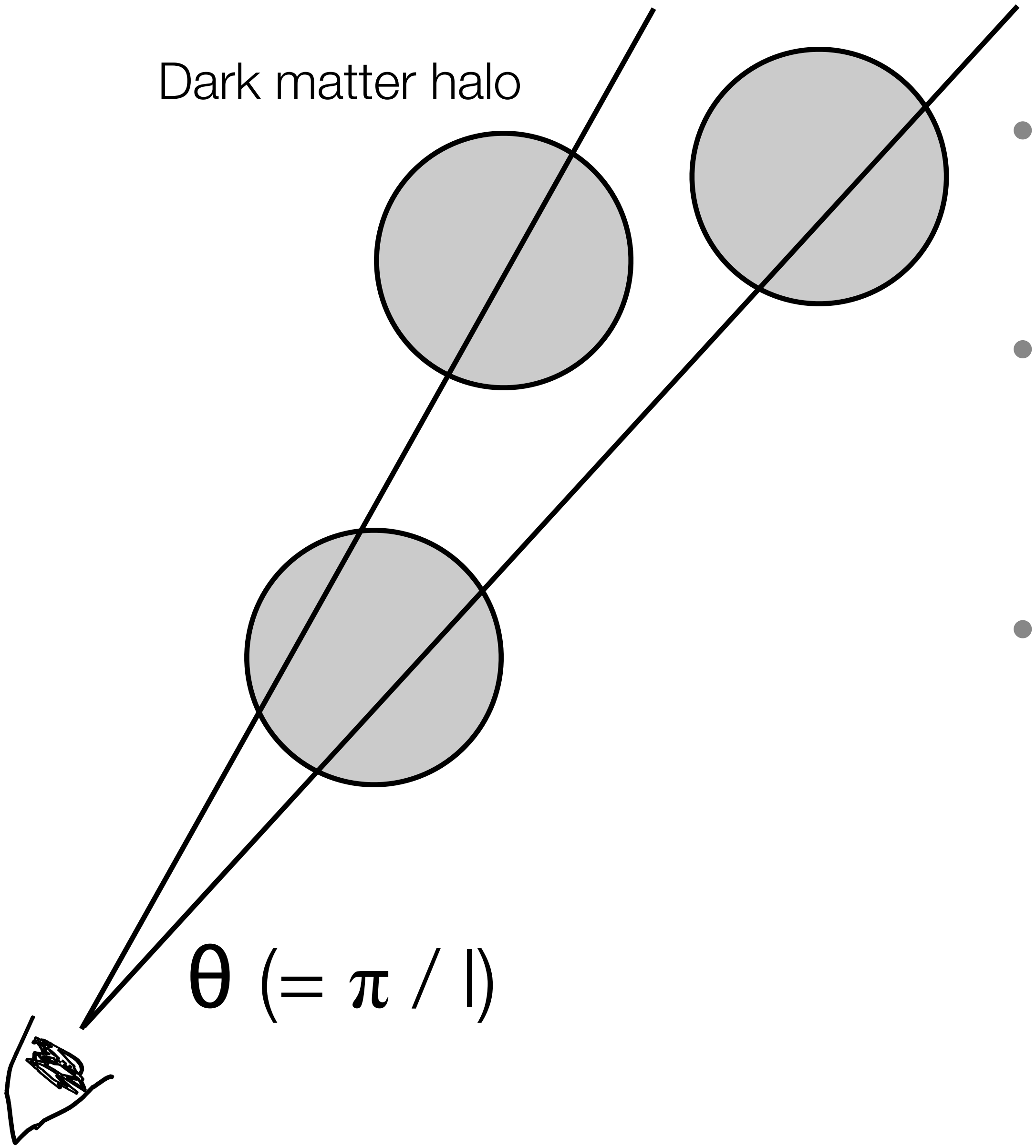


- WIMP annihilation in cosmological dark halos may thus contribute significantly to the CGB flux

CGB anisotropy from dark matter annihilation

- Astrophysical sources like blazars and clusters of galaxies cannot fully explain the observed CGB
  - but only 25–50% using the latest blazar luminosity function (Narumoto & Totani 2006)
- If dark matter annihilation contributes significantly, it might be observed through anisotropy signature of the CGB
  - Potentially a smoking gun of dark matter annihilation
  - Energy spectrum might not be sufficient for such a strong claim

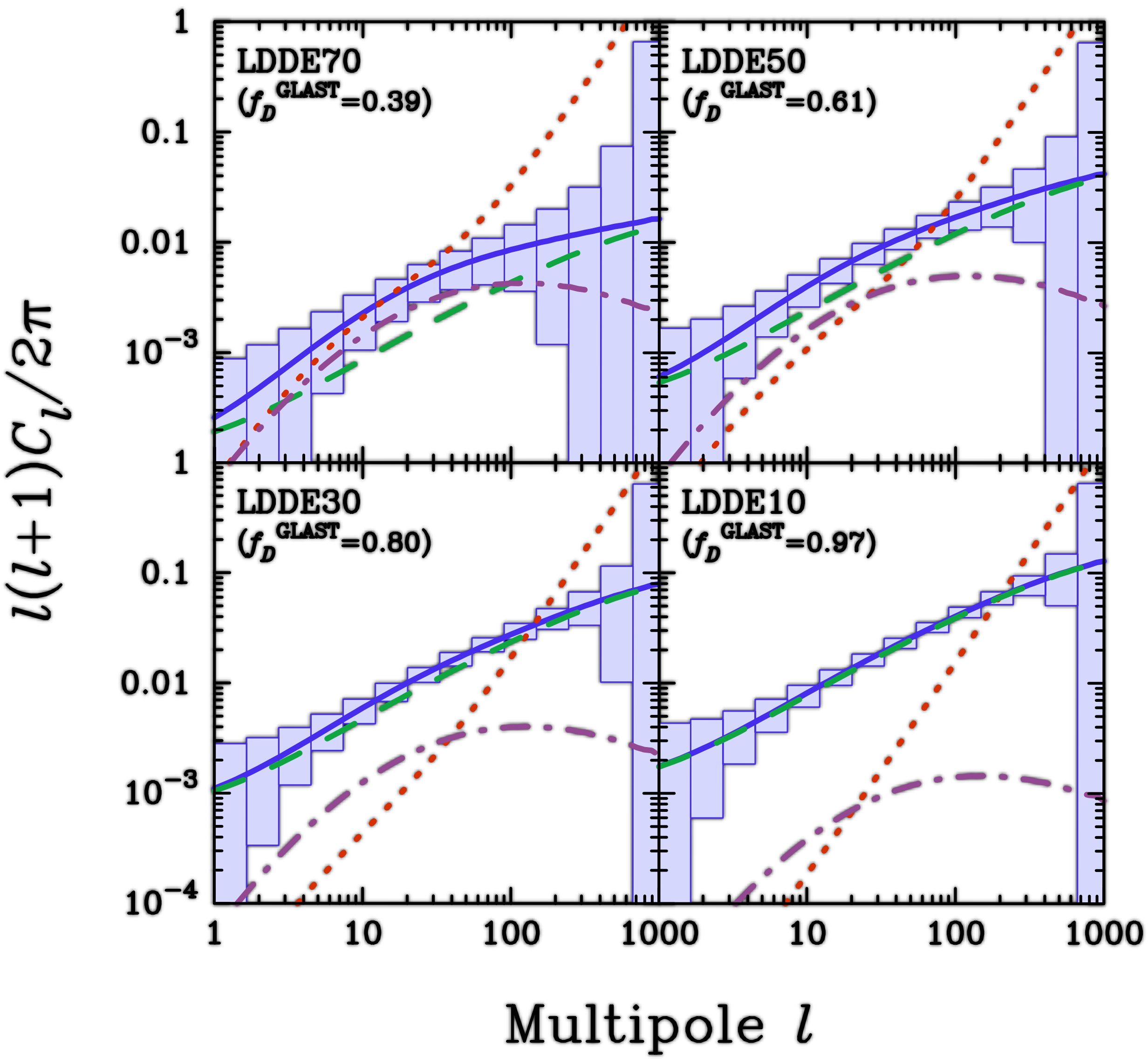
Angular power spectrum



- Projected along the line of sight is the CGB intensity
- Angular power spectrum, C_l, is related to the spatial power spectrum via Limber's equation
- 3D correlation can be modeled, using
  - halo mass function, and
  - density profile in each halo

Result: angular power spectrum

Ando et al., astro-ph/0612467



- At 10 GeV for 2-year observation
- If dark matter annihilation contributes > 30% of the CGB, GLAST should be able to detect anisotropy
- Detector background is negligible
- Galactic emission (foreground) is small at 10 GeV

4. Conclusions I:
Point source anisotropy

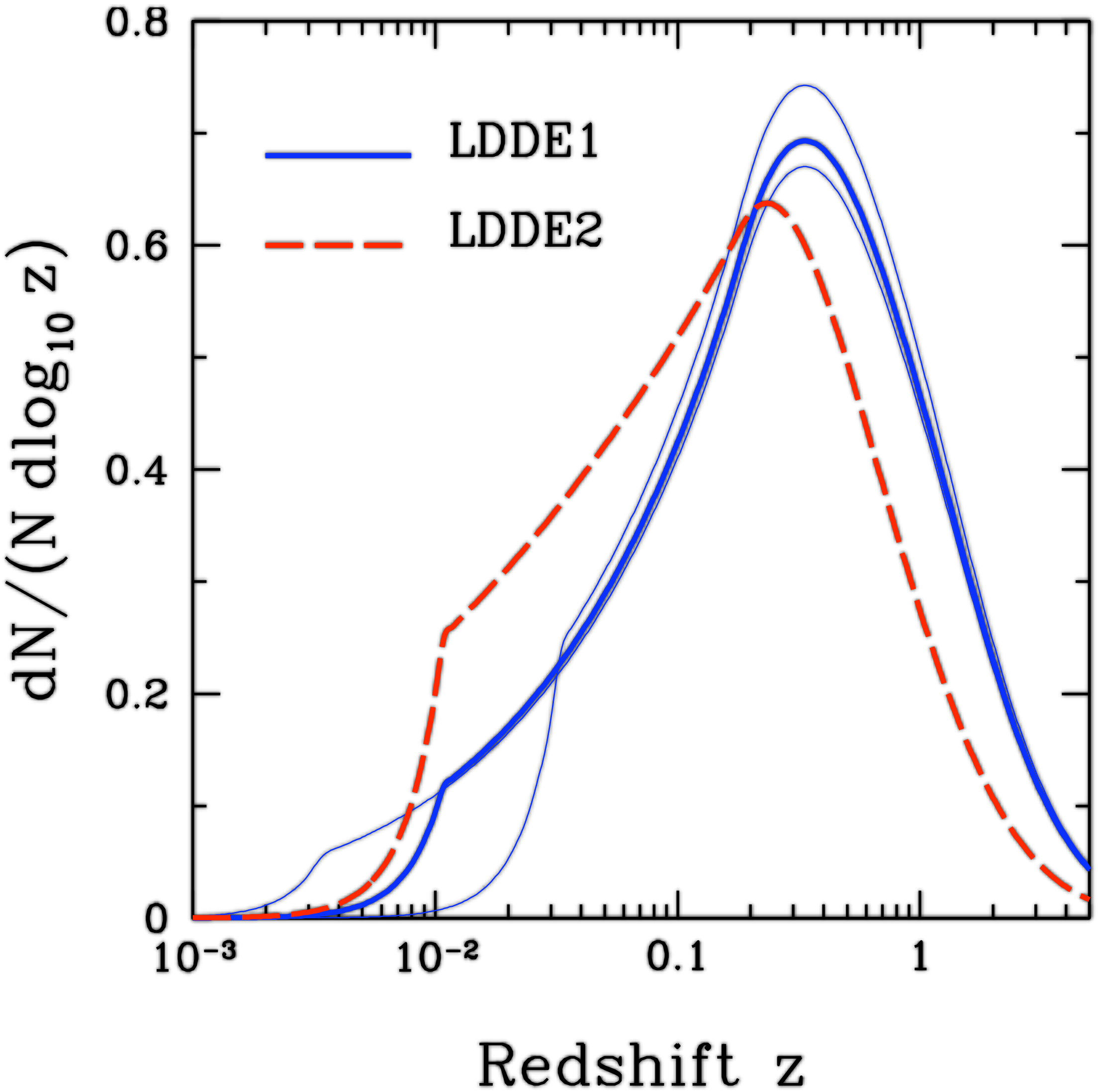
- Blazars are the most promising source for GLAST: 1,000–10,000 are expected from all-sky survey
- We calculated angular power spectrum of these blazars and showed that
  - it would be detectable at large angular scales, dominated by low-redshift (faint blazars);
  - spatial clustering would be measurable *if* blazar bias were larger than 1.2 (0.5) for the best-fit (optimistic) luminosity function
- This would be a first direct measurement of blazar bias, and could provide further test of AGN unification picture

4. Conclusions II:
Anisotropy of background radiation

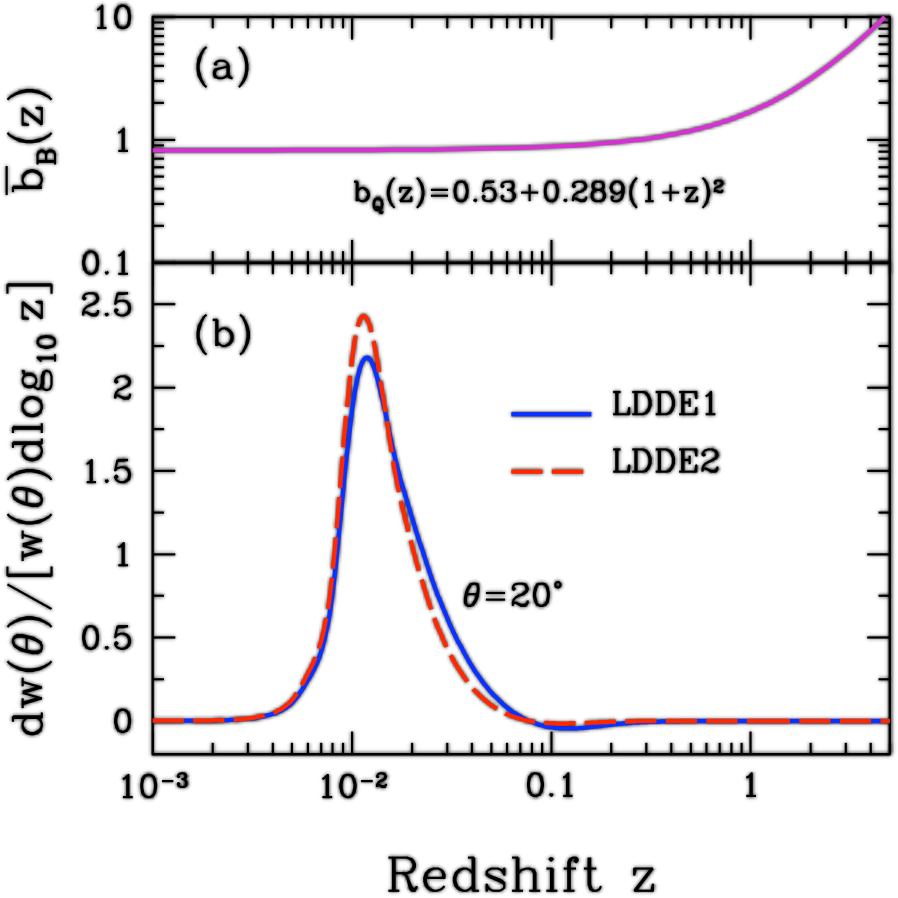
- The CGB anisotropy would be a key to revealing the origin of CGB, and potentially be a smoking gun of annihilating dark matter
- The resulting angular spectrum would be very different from the case of other sources
- We developed a new formalism for that calculation
- We showed that if the annihilating dark matter is a main CGB constituent, GLAST can detect anisotropy in a few years
- This is also true even with the existence of other sources like blazars, if the current dark matter contribution exceeds 30% at 10 GeV

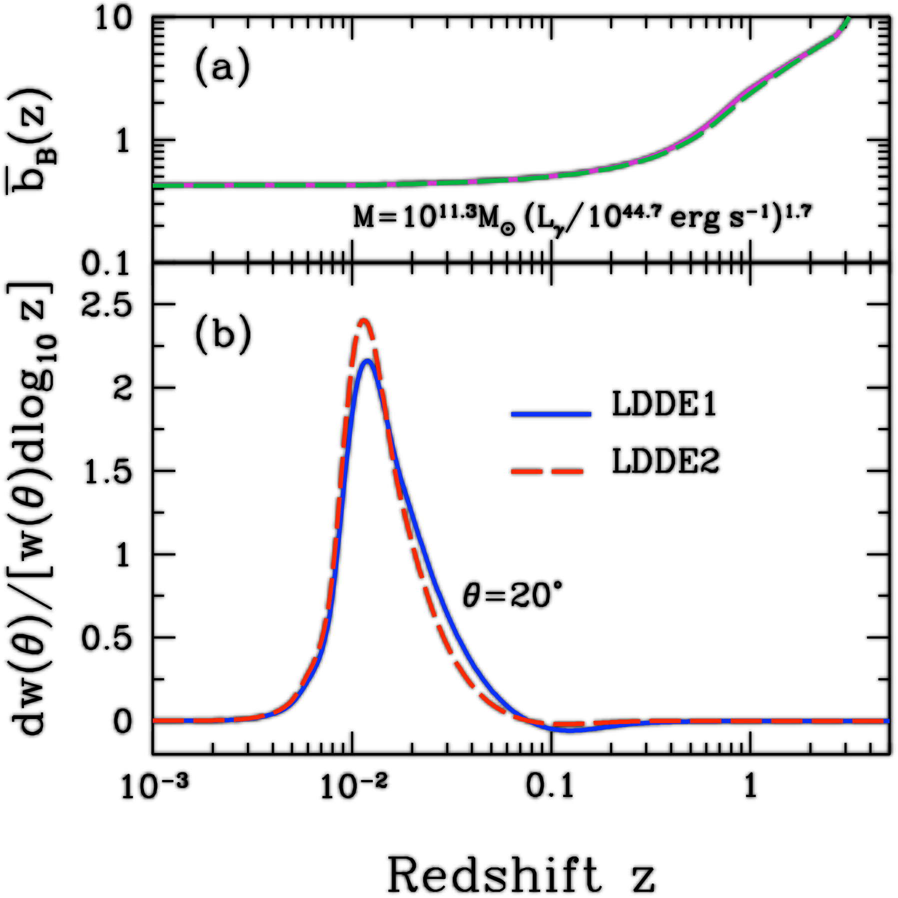
Appendix: Supplementary materials

Redshift distribution of blazars

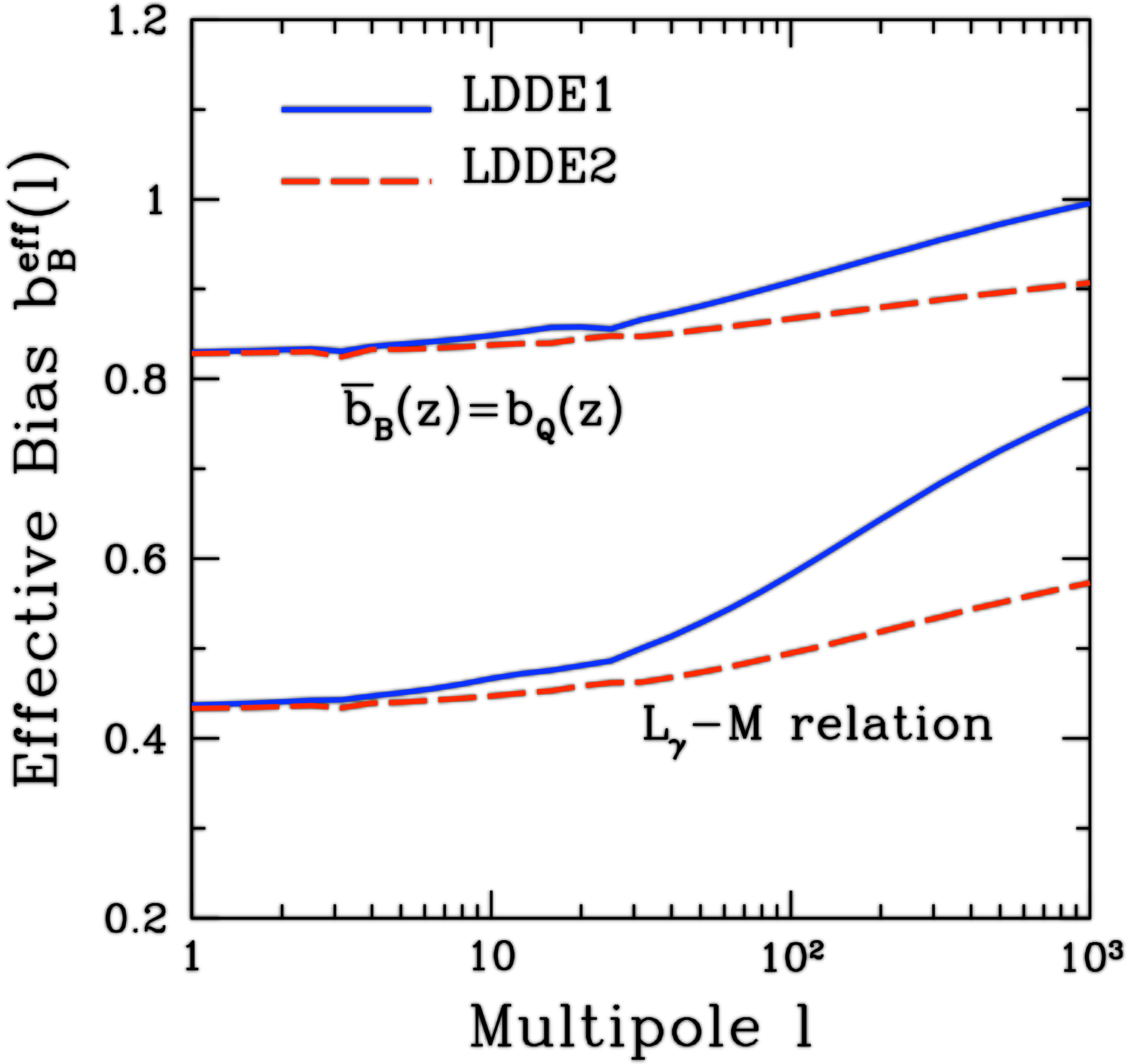


Bias modeling

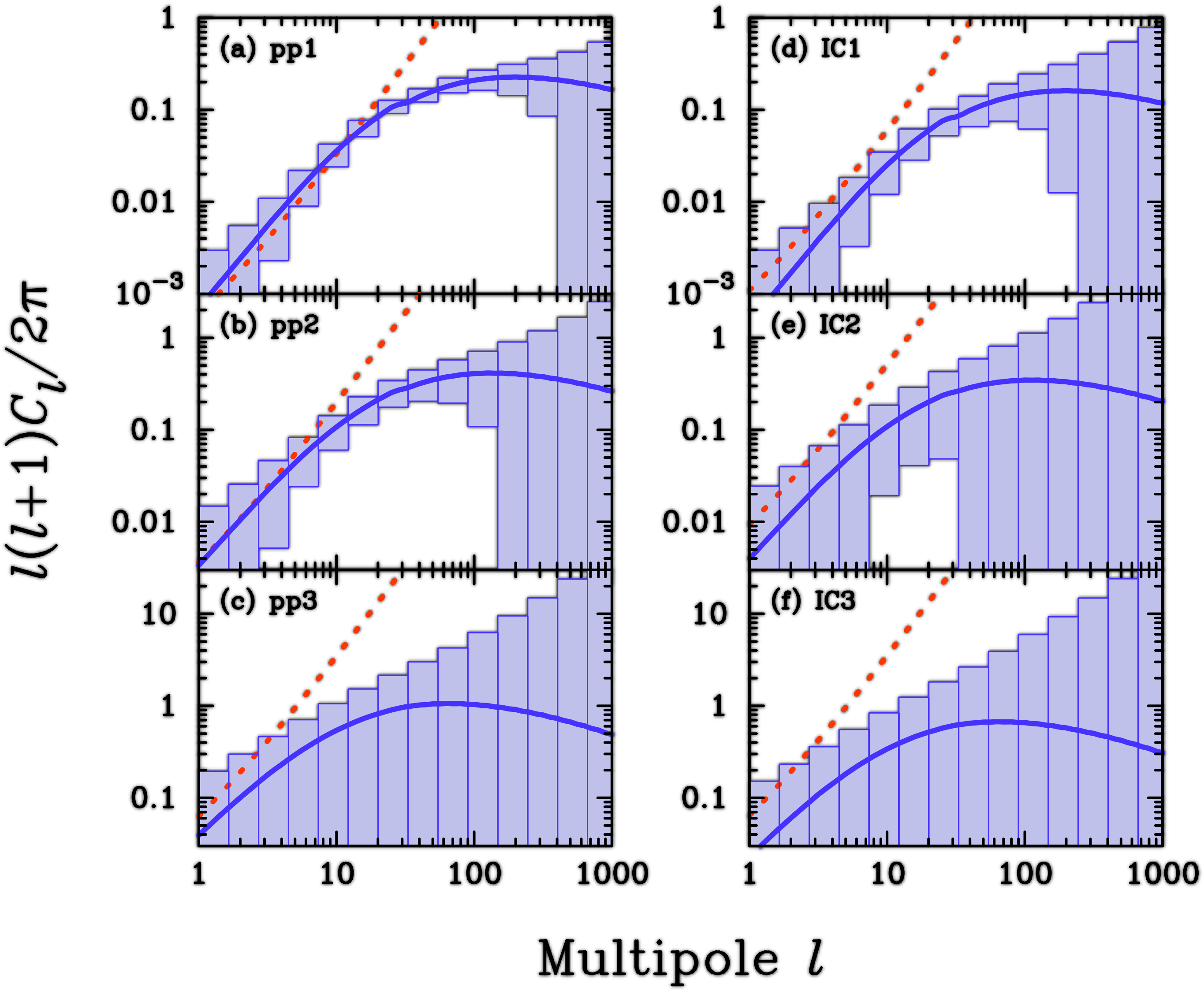




Effective bias

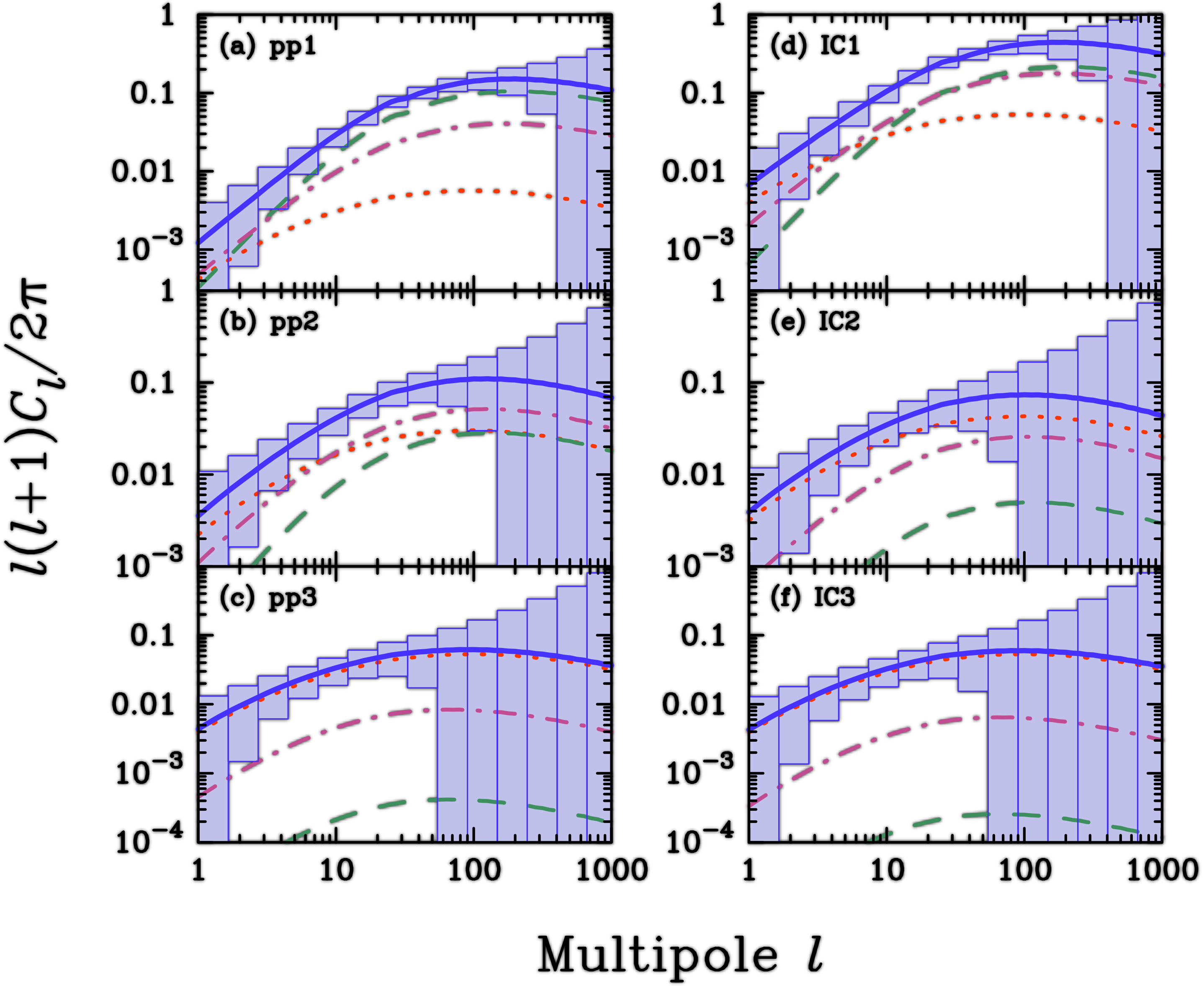


Clusters of galaxies



Model	$\alpha_{p,e}$	$\epsilon_{p,e}$	N	$\mathcal{N}$ (sr^{-1})
$pp1$	2.2	0.5	6600	530
$pp2$	2.2	0.1	1100	88
$pp3$	2.2	0.01	63	5.0
IC1	2	0.05	3700	290
IC2	2	0.01	430	34
IC3	2.2	0.01	62	4.9

Mixed case of blazars and galaxy clusters



A few equations..., if you want

Gamma-ray intensity:

$$I_\gamma(\hat{\boldsymbol{n}}, E_\gamma) = \int dr\ \delta^2(r, \hat{\boldsymbol{n}}r) W([1+z]E_\gamma, r)$$

Spherical harmonic expansion:

$$\frac{\delta I_\gamma(\hat{\boldsymbol{n}})}{\langle I_\gamma \rangle} = \sum_{lm} a_{lm} Y_{lm}(\hat{\boldsymbol{n}}) \qquad C_l = \langle |a_{lm}|^2 \rangle$$

Limber's equation:

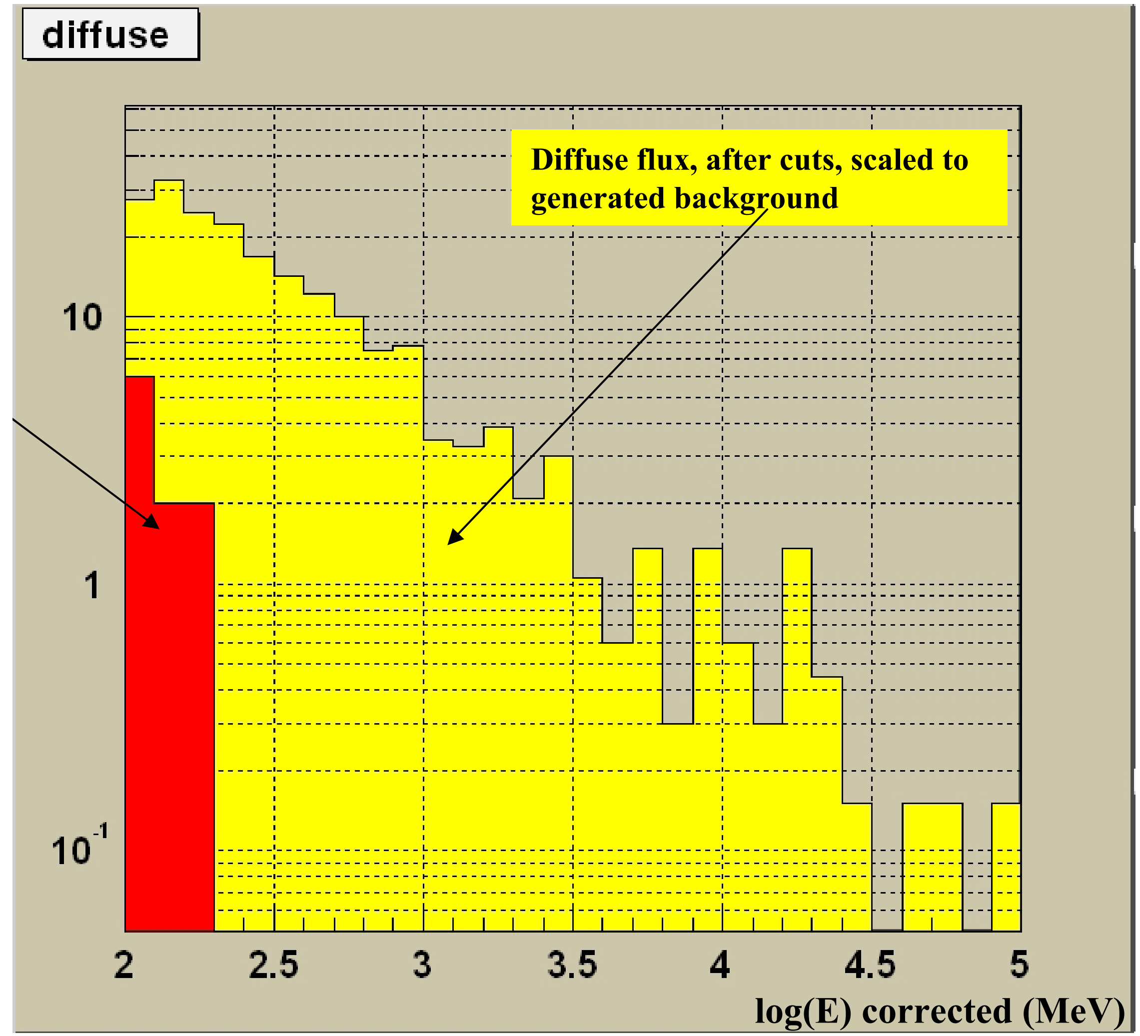
$$\langle I_\gamma \rangle^2 C_l = \int \frac{dr}{r^2}\ \{W([1+z]E_\gamma, r)\}^2 P_f\left(k = \frac{l}{r}; r\right)$$

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

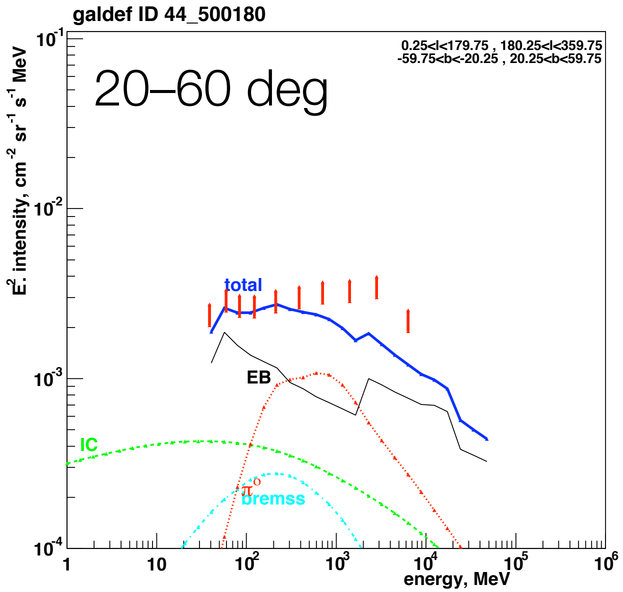
What are backgrounds?

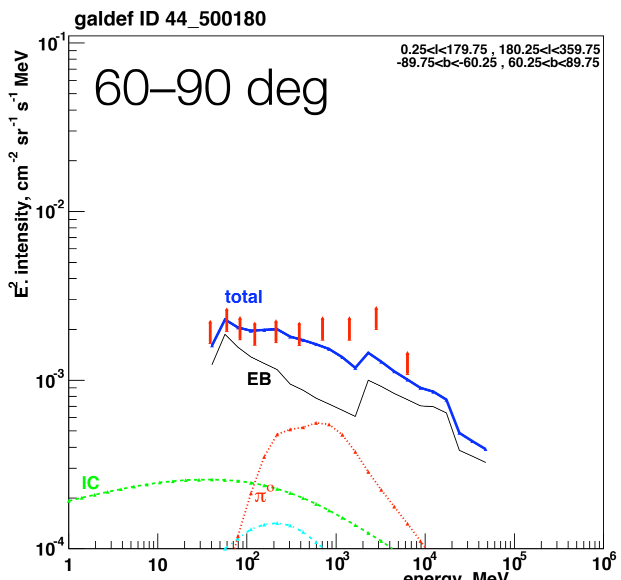
- Detector background
    - Negligible, being 5% of the CGB above 100 MeV (even smaller at 10 GeV)

From http://www-glast.stanford.edu/



What are backgrounds?

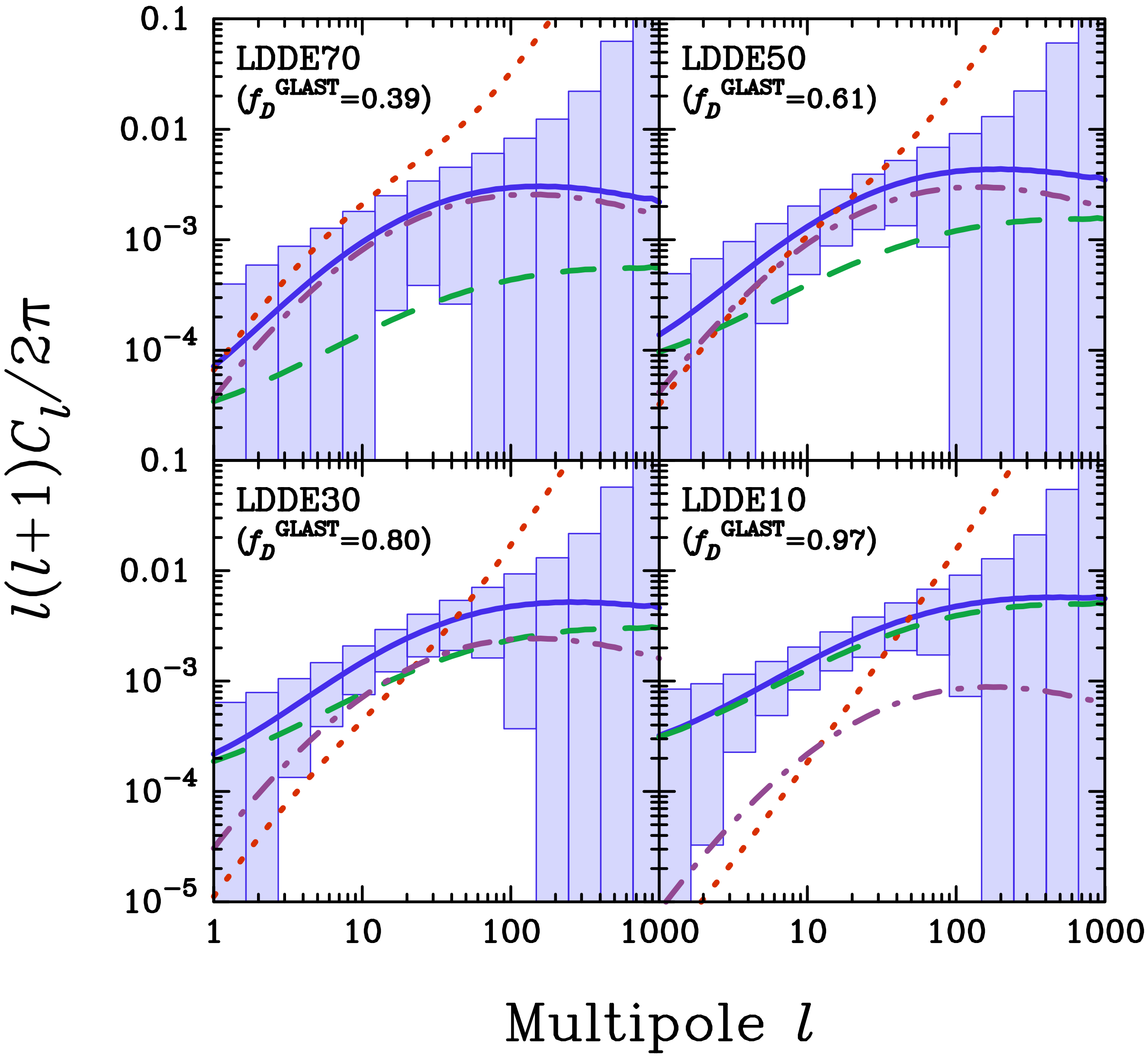




Strong et al. 2004

- Galactic cosmic rays — a foreground
- It strongly depends on the galactic latitude
- The flux is about one order of magnitude smaller than CGB for |b| > 20 deg, safely negligible

Substructure with disruption



Host-halo dominated case