GLAST science for lunch@SLAC
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Anisotropy in the GeV gamma-ray sky

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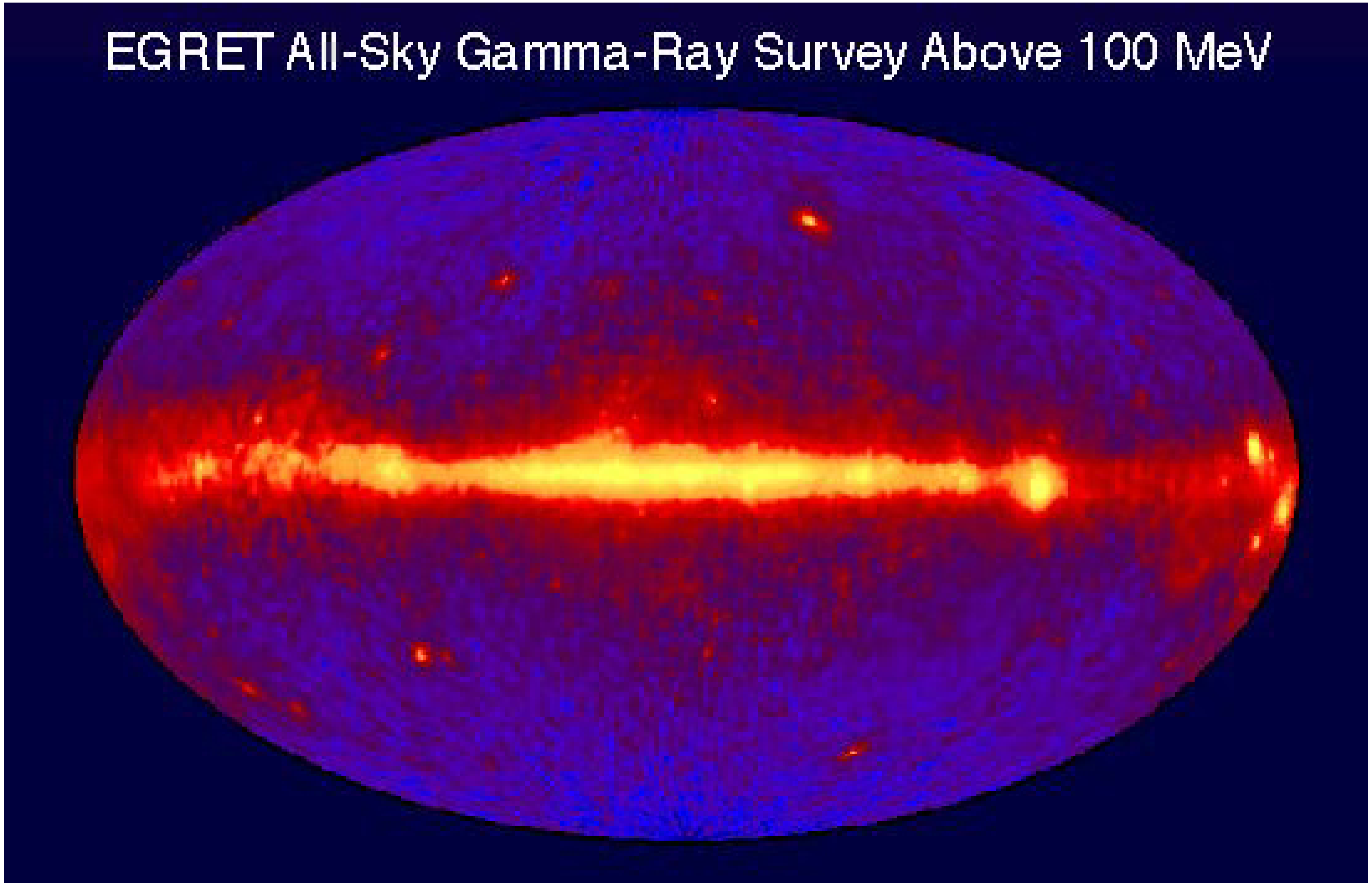
1. Introduction



Unresolved mystery in the high-energy sky among many

- What are blazars?
  - ~60 were detected with EGRET
  - What are the emission mechanisms?
  - Are they beamed AGNs?—Is AGN unification picture really right?
- What are unidentified EGRET sources?
- 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

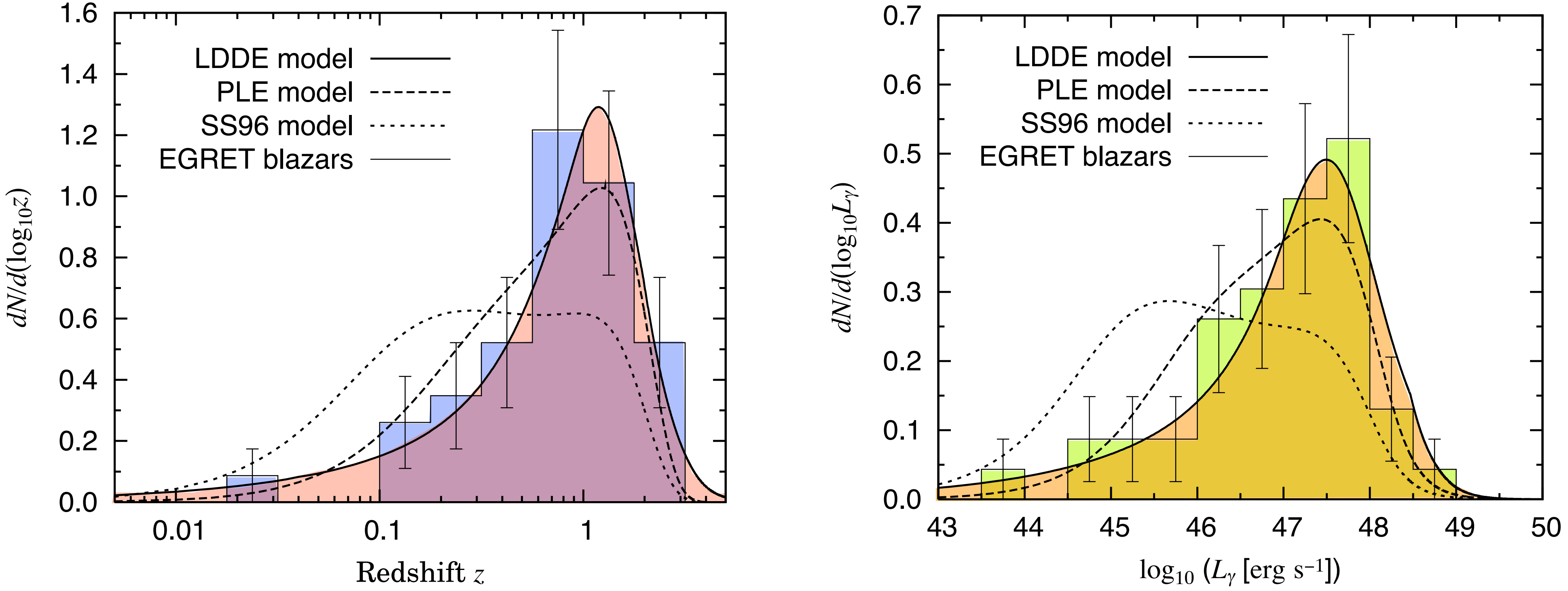
- GLAST is equipped with a large volume gamma-ray detector (LAT)
  - Sensitivity covers 30 MeV–300 GeV
  - Very large field of view (2.4 sr), enabling all sky survey
  - Point source flux sensitivity: 2×10^{-9} cm^{-2} s^{-1}, 50 times better than EGRET
  - Better map of (1) point sources and (2) diffuse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

2. Point source anisotropy: blazars and clusters of galaxies

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 (Ueda et al. 2003; Hasinger et al. 2005) fits the data very well
- Pure-luminosity evolution (PLE; Stecker & Salamon 1996; Chiang & Mukherjee 1998) model still gives a reasonable fit
- The best fit model predicts ~3,000 blazars from all sky

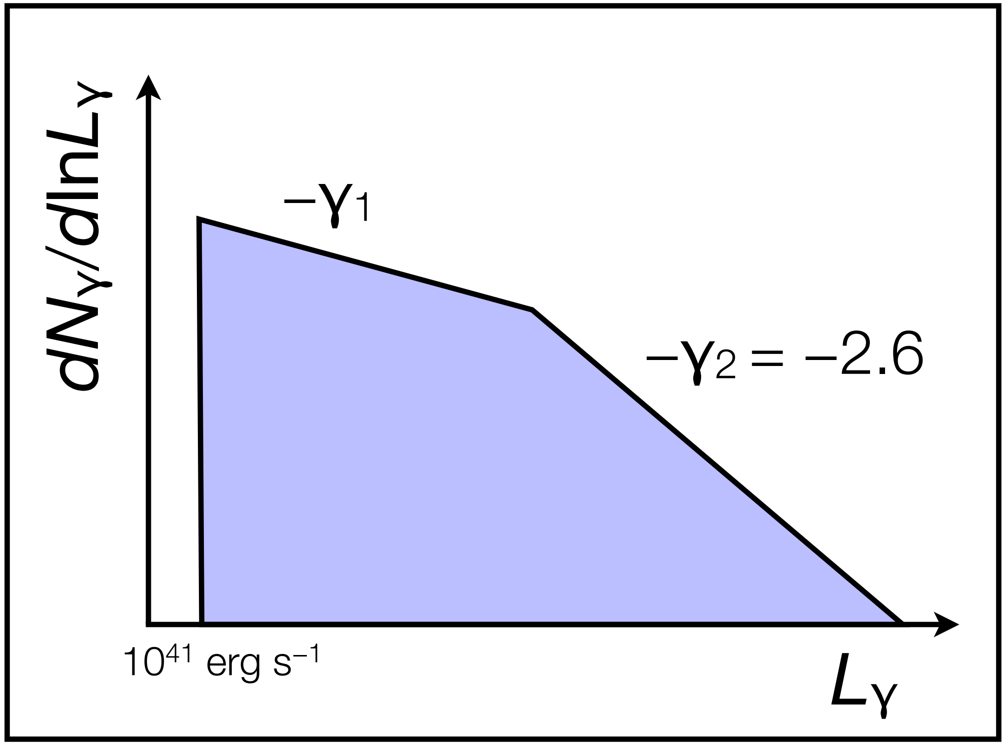
LDDE models used in the calculation

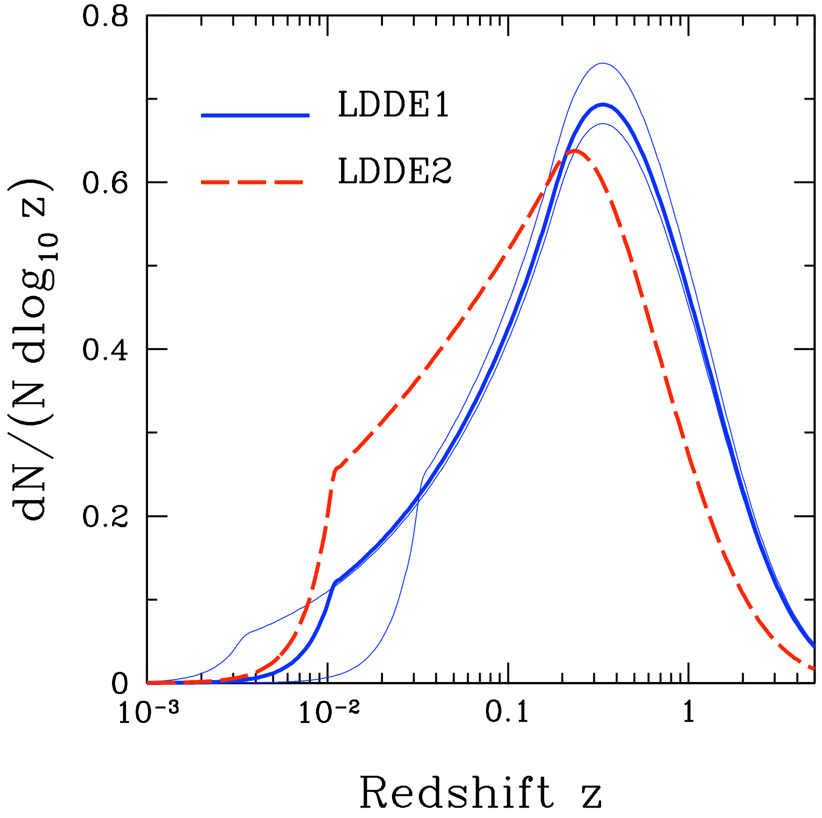
Model	(q, γ_1)	κ	N	$\mathcal{N}$ (sr^{-1})
LDDE1[a]	(3.80, 1.19)	5.11×10^{-6}	3100	250
LDDE2[b]	(3.80, 1.31)	3.90×10^{-6}	6500	520

[a] Best-fitting model of the EGRET blazar distribution.

[b] A model explaining 100 per cent of the EGRB intensity.

$$\boxed{\begin{aligned} L_\gamma &= 10^q L_X \\ \rho_\gamma(L_\gamma, z) &= \kappa \frac{L_X}{L_\gamma} \rho_X(L_X, z) \end{aligned}}$$



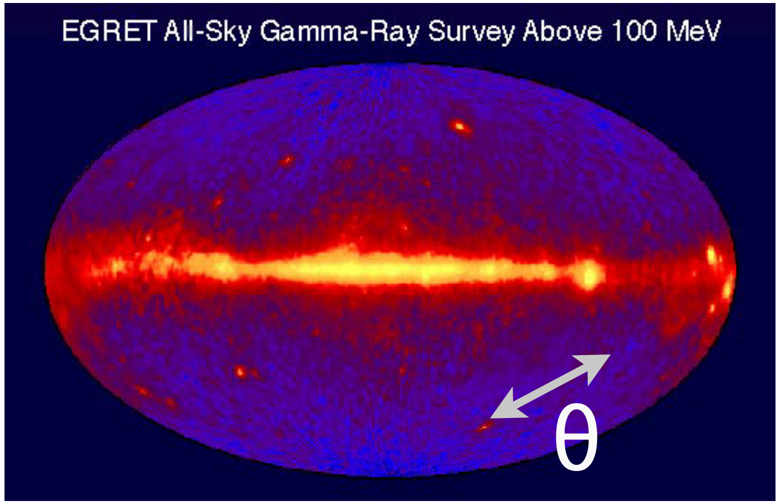


Is blazar clustering detectable with GLAST?

- 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 immediately get the idea about the source idensitiy
  - One can directly get blazar bias, providing independent test of AGN unification picture as well as AGN formation
- 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

$$\mathcal{N}^2 w(\theta) = \int_0^{z_{\rm max}} \mathrm{d}z\, \frac{\mathrm{d}^2 V}{\mathrm{d}z\, \mathrm{d}\Omega} \chi(z)^2 \phi(z)^2 \overline{b}_{\rm B}(z)^2$$

$$\times \int_{-\infty}^{\infty} \mathrm{d}u\, \xi_{\rm lin}\left(\sqrt{u^2 + \chi(z)^2\theta^2}, z\right)$$

$$\phi(z) \equiv \int_{L_\gamma(F_{\gamma,{\rm lim}}, z)}^{\infty} \mathrm{d}L_\gamma\ \rho_\gamma(L_\gamma, z)$$

3D linear matter correlation function

Angular power spectrum:

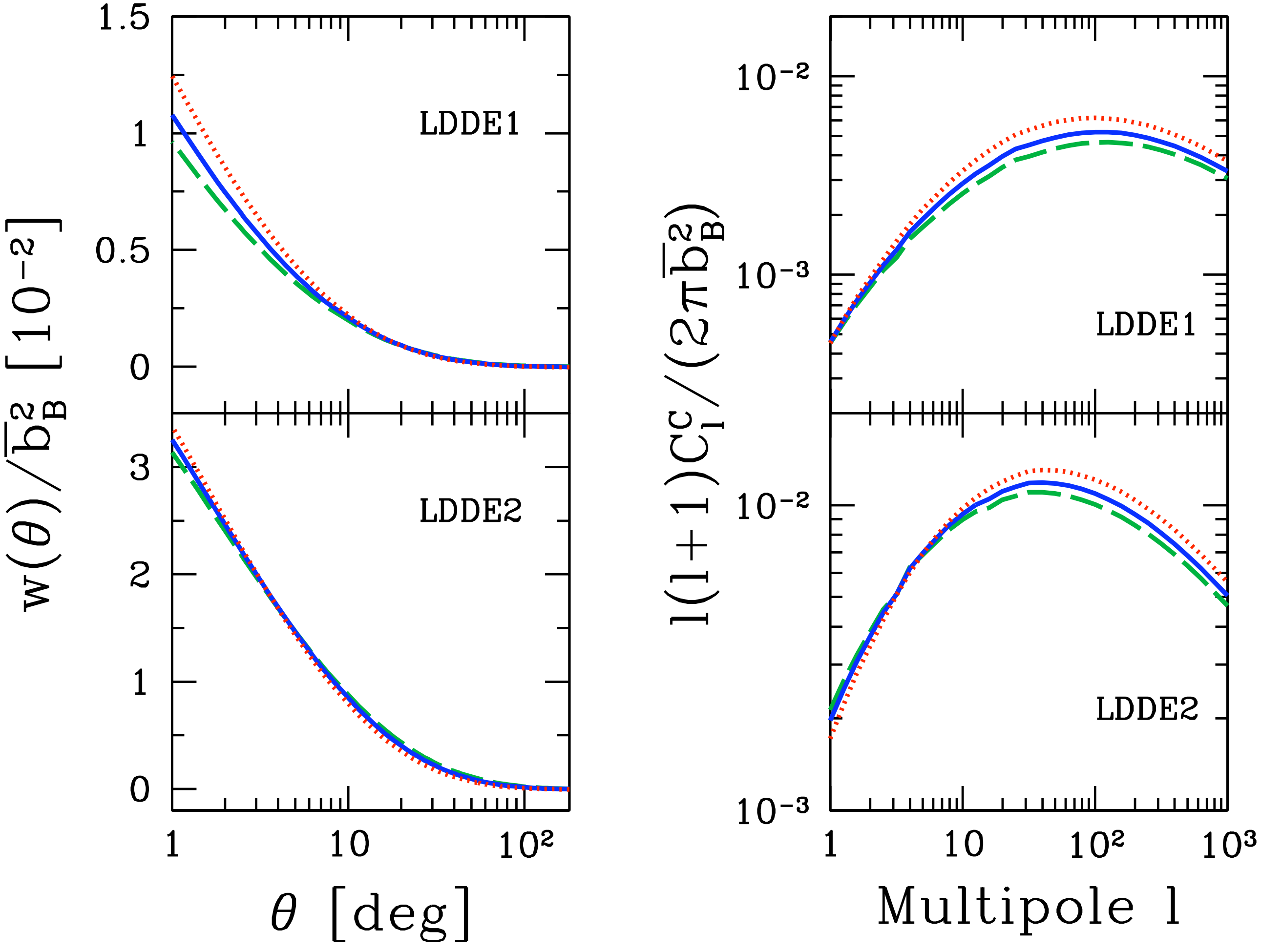
$$C_l = C_l^P + C_l^C$$

$$C_l^P = \mathcal{N}^{-1}$$

$$C_l^C = 2\pi \int_{-1}^{1} \mathrm{d}\cos\theta\ P_l(\cos\theta) w(\theta)$$

Results:

(i) Angular correlation and power spectrum



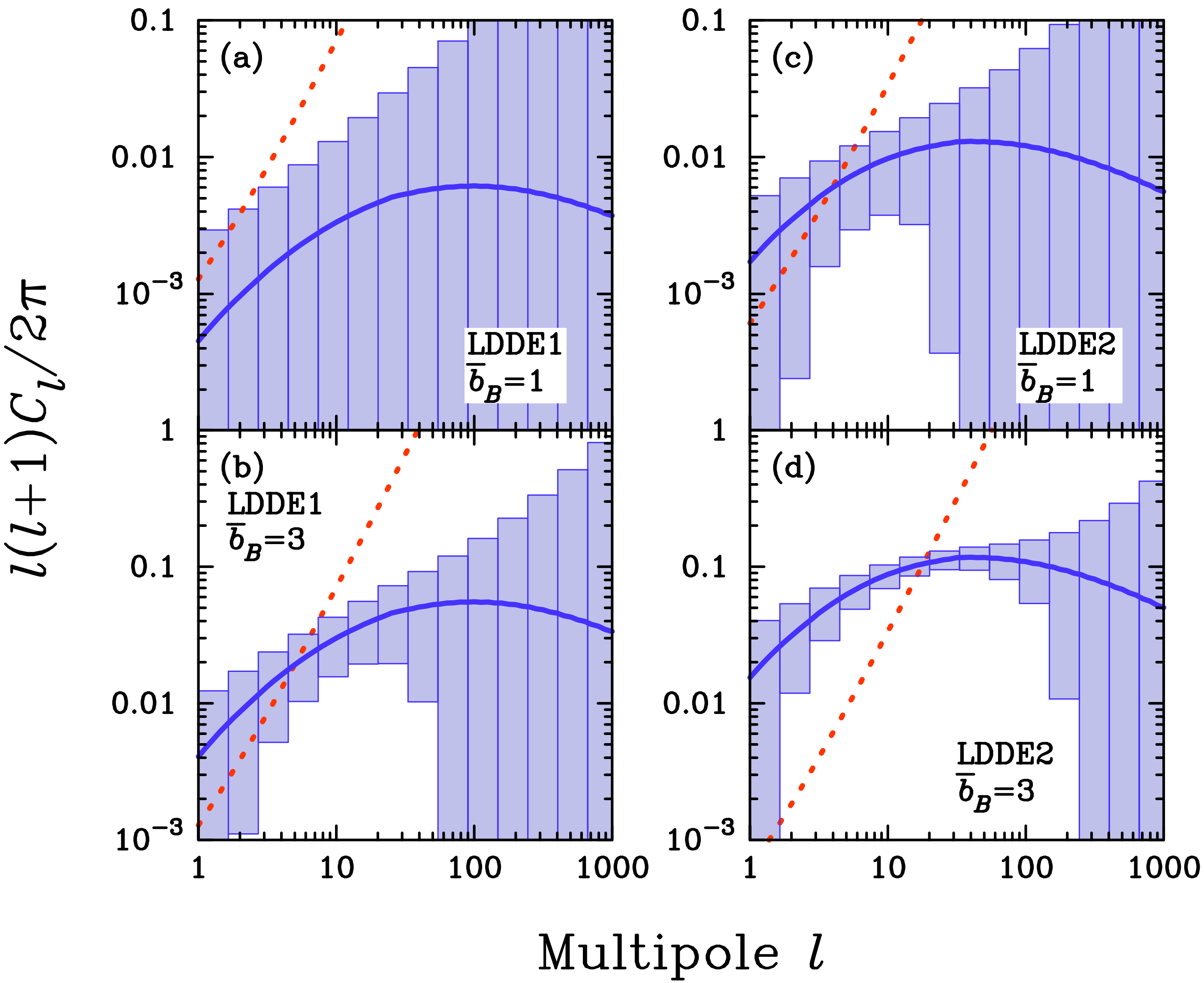
LDDE1	Best fit model
LDDE2	Explains 100% of gamma-ray background

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

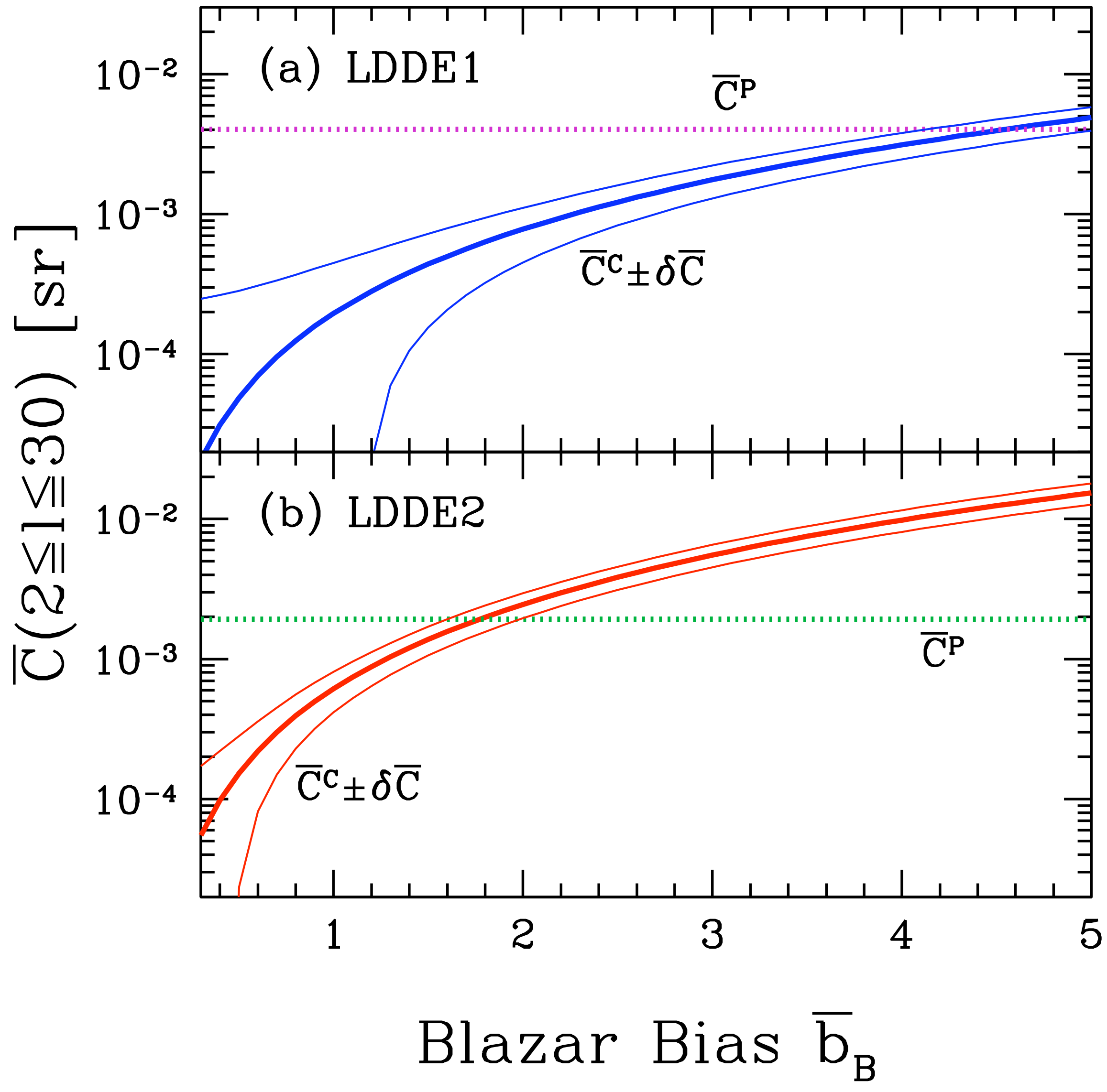
Ando et al., astro-ph/0610155



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

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

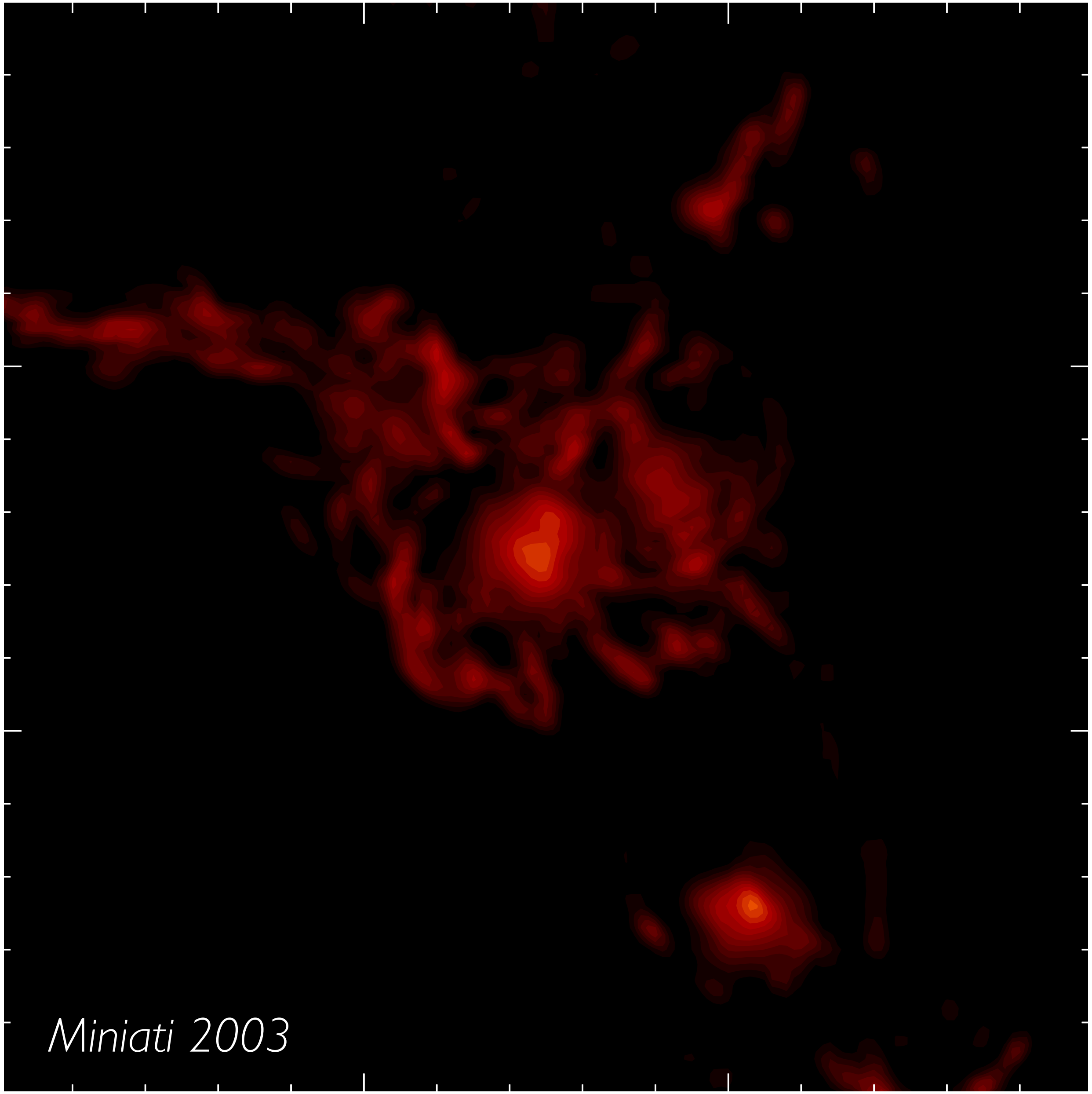
(iii) Dependence on blazar bias and other observations



Ando et al., astro-ph/0610155

- Average over large scale: $2 \leq l \leq 30$
- Correlation is detectable for $b_B > 1.2$ (LDDE1), and $b_B > 0.5$ (LDDE2)
- For the PLE model, the required is $b_B > 3$
- Optical quasar gives: $b_Q \sim 0.8$ at relevant redshift range (Croom et al. 2005; Myers et al. 2006)
- X-ray AGNs seem more strongly clustered with $b \sim 3$–4 (Yang et al. 2003; Basilakos et al. 2005; Gandhi et al. 2006)

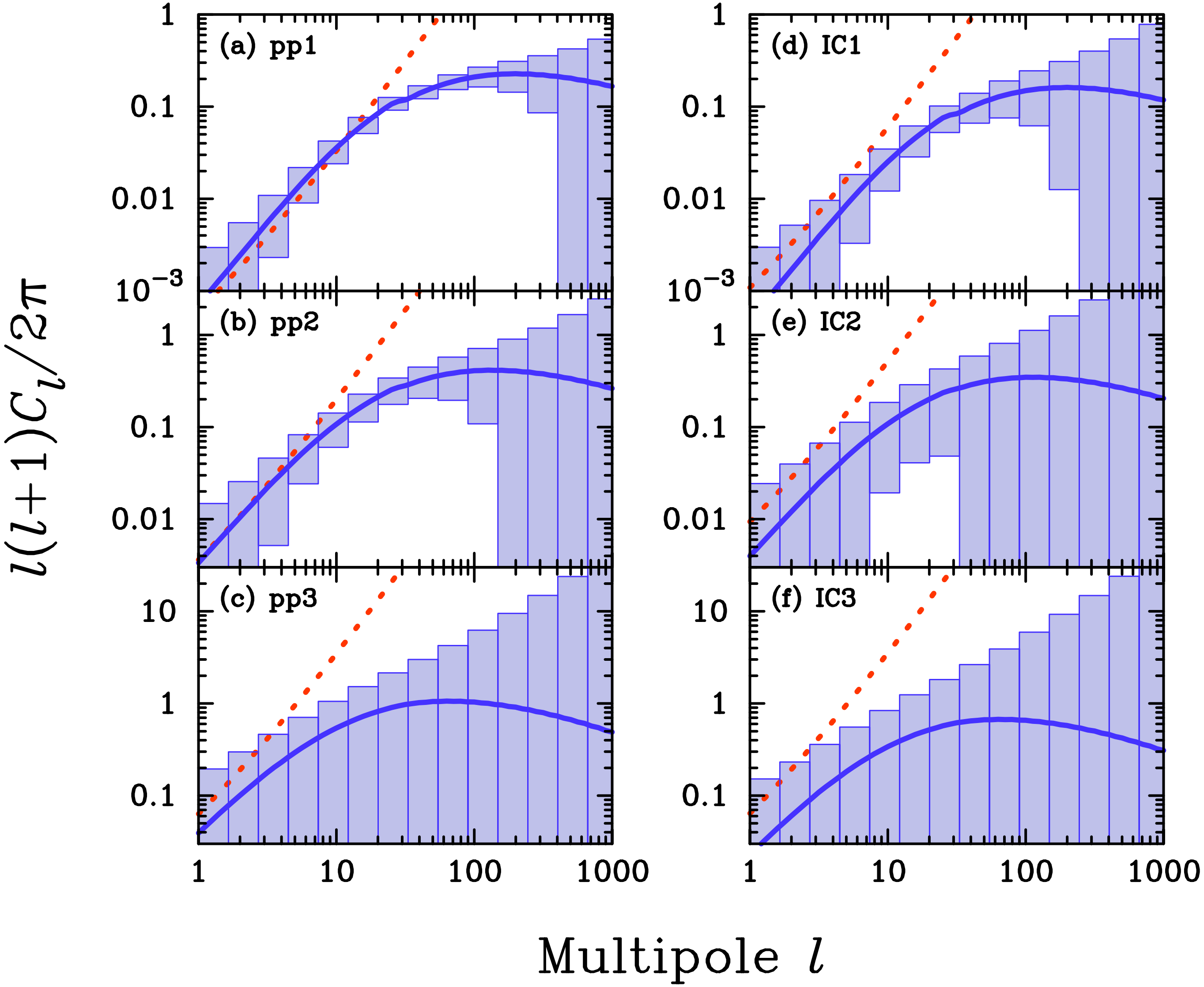
(iv) Clusters of galaxies



Miniati 2003

(iv) Clusters of galaxies

Ando et al., astro-ph/0610155



Model	$\alpha_{p,e}$	$\epsilon_{p,e}$	N	$\mathcal{N}$ (sr^{-1})
*pp*1	2.2	0.5	6600	530
*pp*2	2.2	0.1	1100	88
*pp*3	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

- Proton-proton collision (pp) model

  Berezinsky et al. 1997;
  Colafrancesco & Blasi 1998

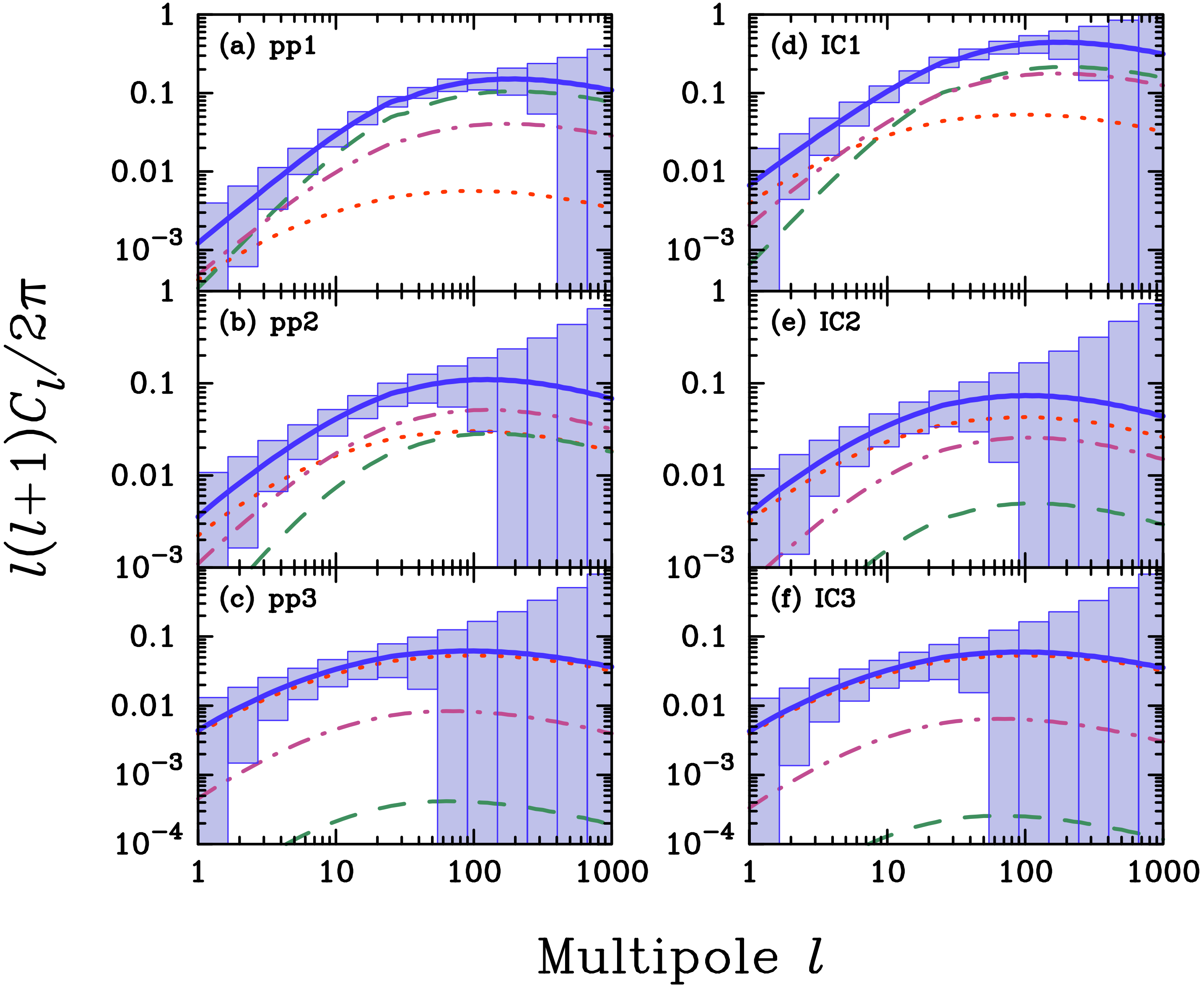
- Inverse-Compton (IC) model

  Loeb & Waxman 2000; Totani & Kitayama 2000; Keshet et al. 2003; Miniati 2003

Discussion:

How to discriminate blazars and galaxy clusters (1)

Ando et al., astro-ph/0610155



- LDDE1 and $b_B = 3$ blazar model
- The shape of angular power spectrum is different for blazars and galaxy clusters
- This is potentially a useful tool to distinguish the source population

How to discriminate blazars and galaxy clusters (2)

- Radio survey such as FIRST (Faint Images of the Radio Sky at Twenty Centimeters) is useful for source discrimination
  - Designed to produce the radio equivalent of the Palomar Observatory Sky Survey over 10,000 square degrees of the North and South Galactic Caps. Using the NRAO Very Large Array (VLA) and an automated mapping pipeline, we produce images with 1.8" pixels, a typical rms of 0.15 mJy, and a resolution of 5". At the 1 mJy source detection threshold, there are ~90 sources per square degree, ~35% of which have resolved structure on scales from 2-30" (from *http://sundog.stsci.edu/*)
- Blazars are also bright in radio unlike galaxy clusters
  - Using the known correlation between gamma-ray and radio luminosities, the radio flux corresponding to the GLAST sensitivity is 10 mJy, an order of magnitude brighter than the FIRST limiting flux

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

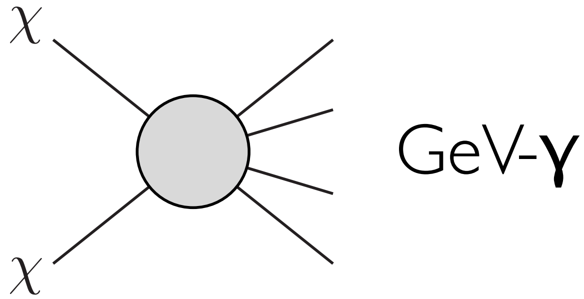
3. Anisotropy of cosmic gamma-ray background (CGB) and dark matter annihilation

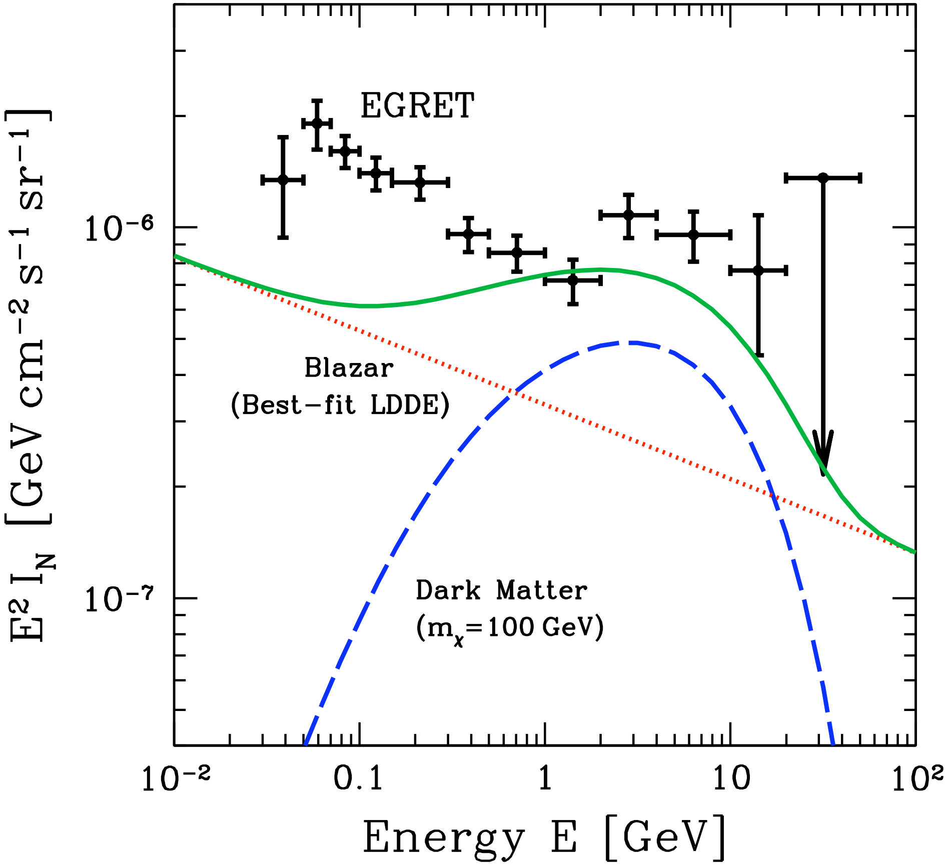
Ando & Komatsu, Phys. Rev. D **73**, *023521 (2006)*
Ando, Komatsu, Narumoto & Totani, Phys. Rev. D **75**, *063519 (2007)*

Dark matter (WIMP) annihilation

- If dark matter is WIMP, it may annihilate 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

Bergstrom et al. 1998; Ullio et al. 2002; Taylor & Silk 2003; Elsaesser & Mannheim 2005; Ando 2005





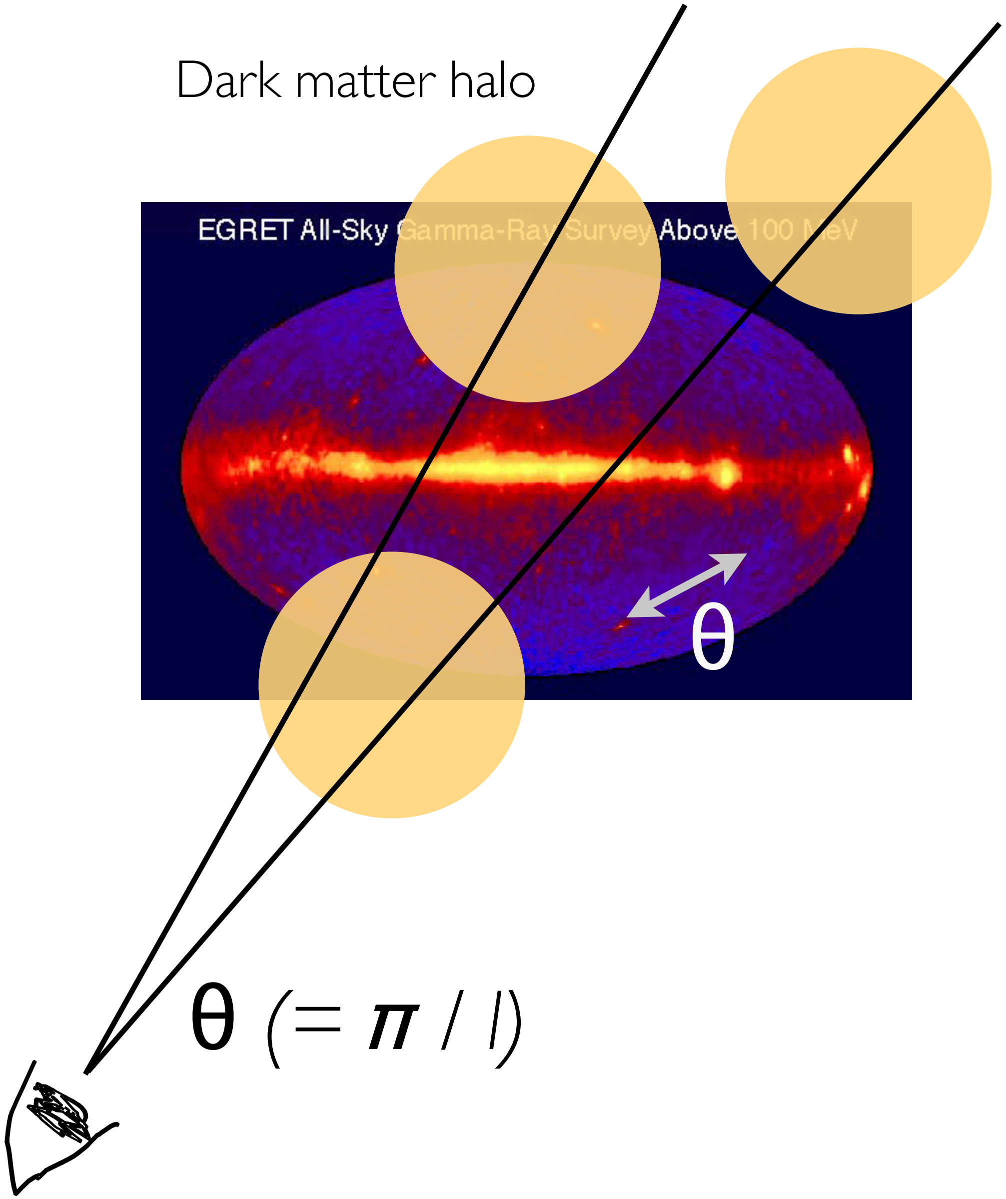
CGB anisotropy from dark matter annihilation

- 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
    - Powerful tool in addition to energy spectrum for Galactic sources (Baltz, Taylor & Wai, astro-ph/0610731)

Procedure of this study (*Ando et al. 2007; PRD* ***75****, 063519*)

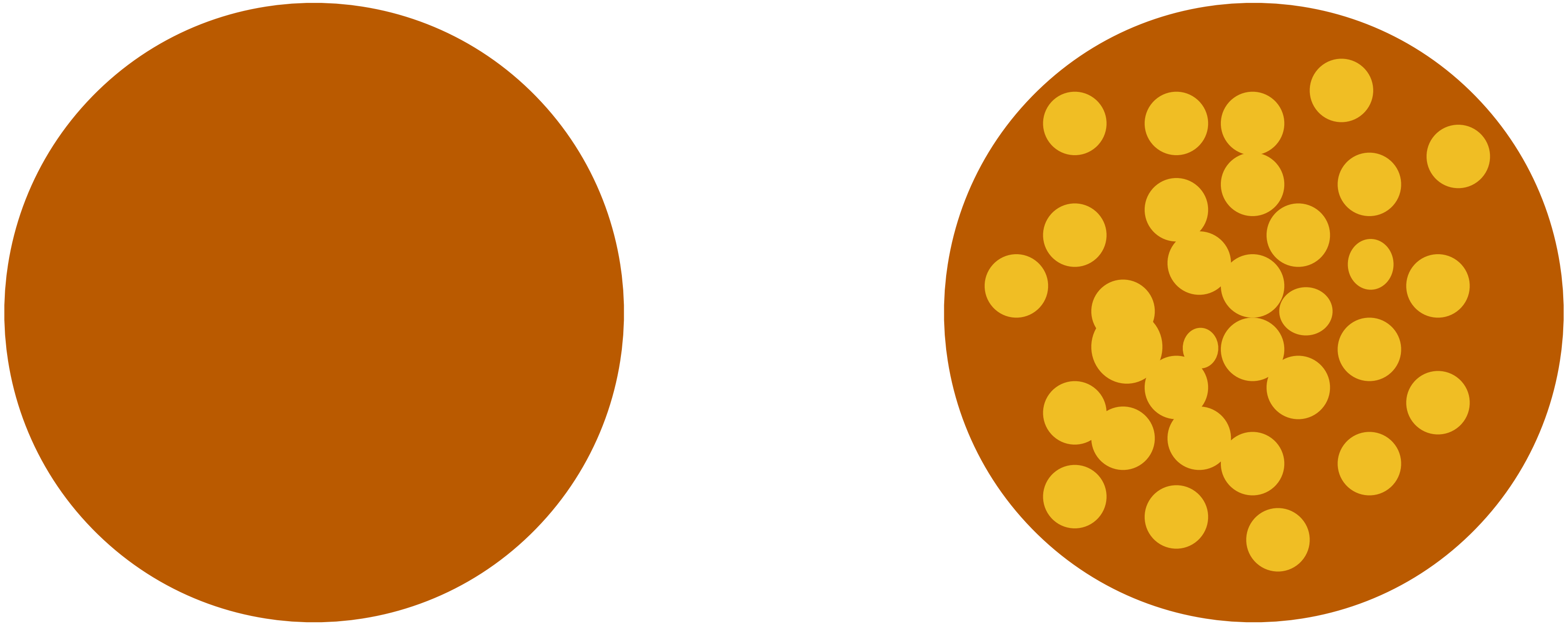
- We consider two origins as the CGB components:
    - Blazars (astrophysical point sources) and dark matter annihilation
- Evaluate angular power spectrum for each component
- Treat dark matter as a *signal* and blazars as *background*
    - As we should know blazar clustering relatively well from the point source analysis
- We argue under which condition, GLAST can detect dark matter component from the CGB angular power spectrum

Angular power spectrum of annihilation gamma rays



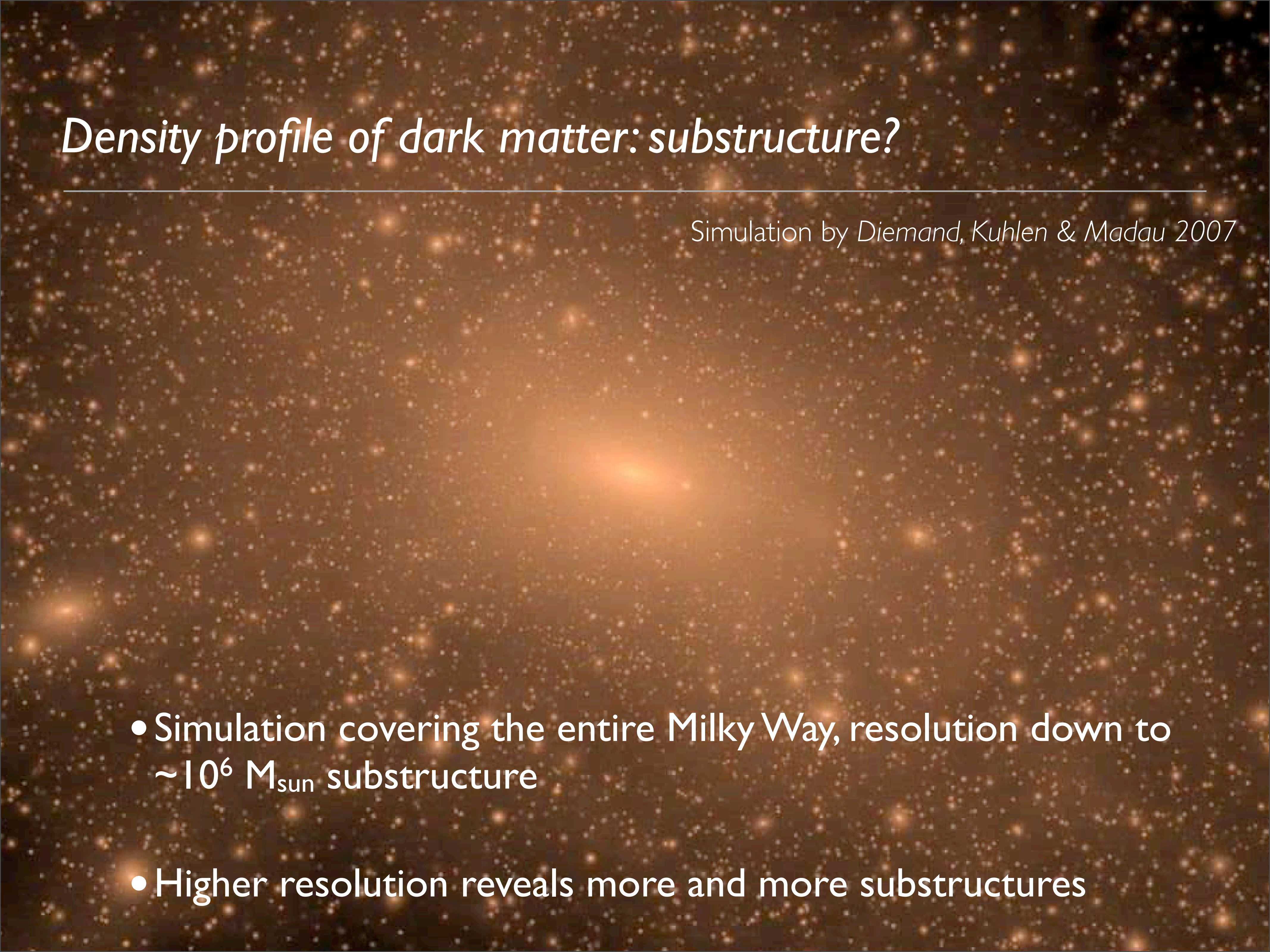
- Projected along the line of sight is the CGB intensity
- Angular power spectrum, C_l, is related to the spatial power spectrum via Limber's equation
- 3D correlation can be modeled, using
  - linear matter correlation function
  - halo mass function, and
  - density profile in each halo

Density profile of dark matter: substructure?



- Case 1: A smooth density profile like Navarro, Frenk & White (1996; NFW)
    - Gamma luminosity $\propto \rho^2$
- Case 2: Density profile dominated by substructures
    - Gamma luminosity $\propto \rho$

Density profile of dark matter: substructure?



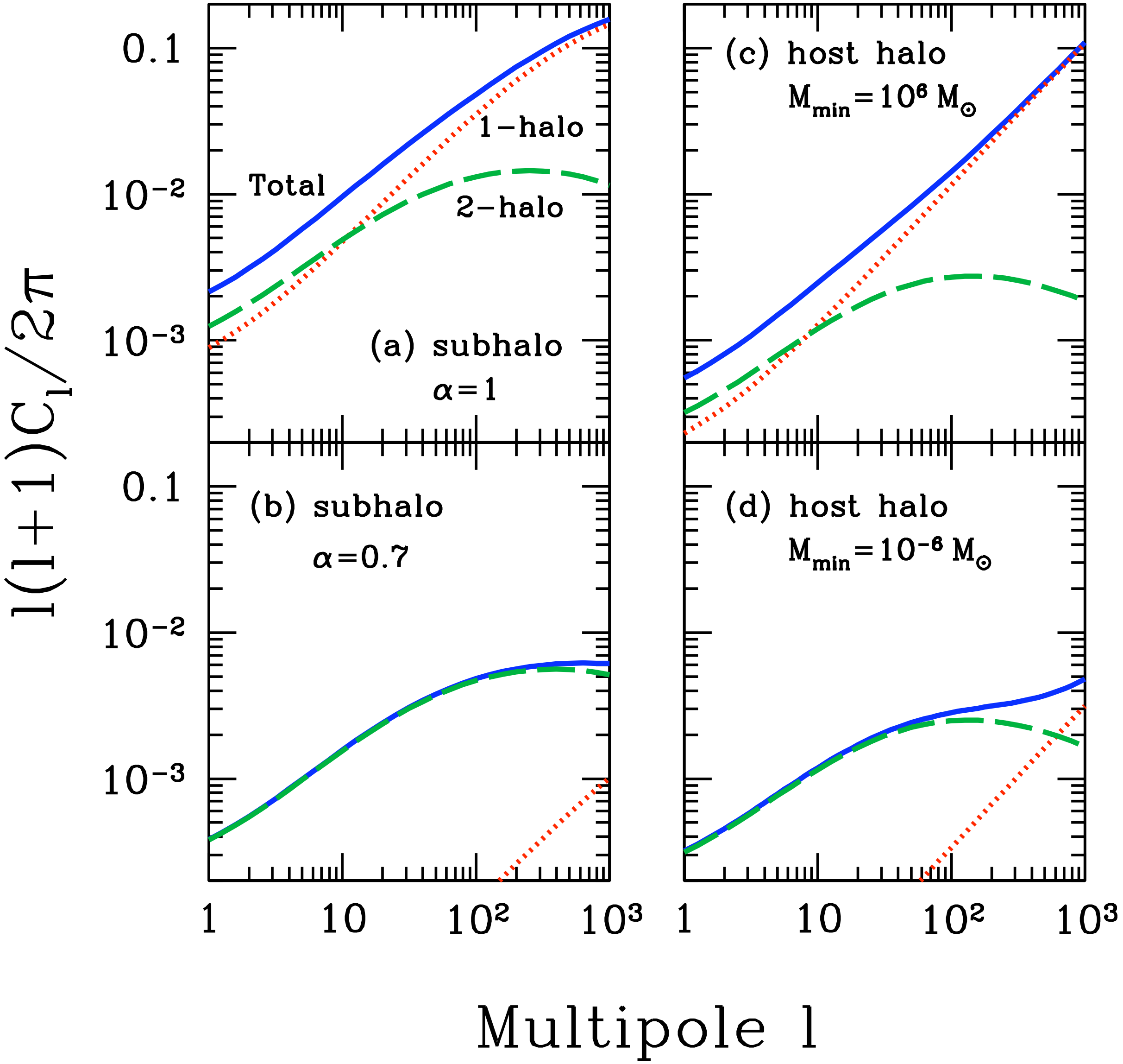
Simulation by *Diemand, Kuhlen & Madau 2007*

- Simulation covering the entire Milky Way, resolution down to $\sim 10^6\ M_{sun}$ substructure
- Higher resolution reveals more and more substructures

Results:

Angular power spectrum from dark matter annihilation

*Ando et al., PRD **75**, 063519 (2007)*



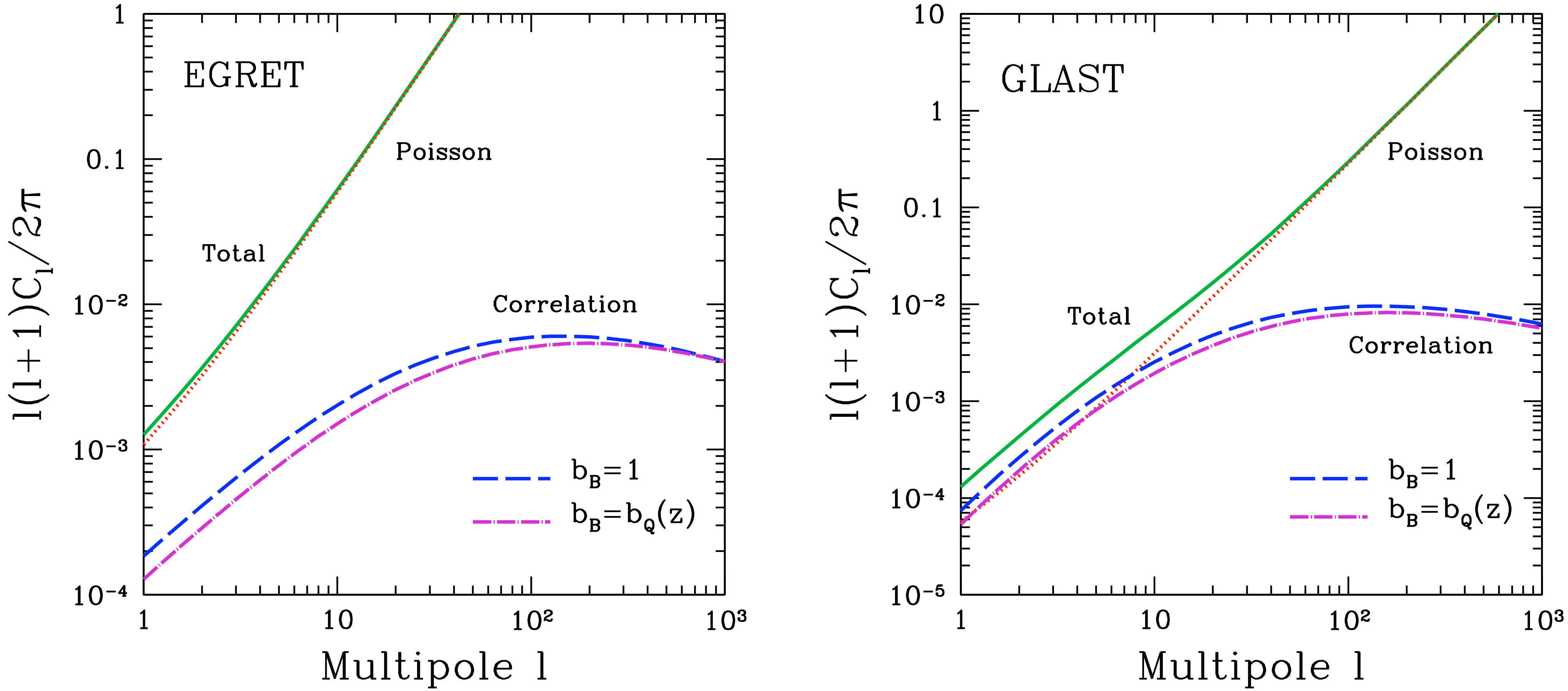
- Dark matter mass 100 GeV, gamma-ray energy 10 GeV
- Subhalo-dominated case
  - Number of subhalos in a parent halo *M*

$$\langle N|M\rangle = \left(\frac{M}{M_0}\right)^{\alpha}$$

- Host-halo-dominated case
  - Minimum halo mass as a free parameter
- 1(2)-halo term: correlation between two points in one identical (two distinct) halo(s)

Angular power spectrum from blazars

*Ando et al., PRD **75**, 063519 (2007)*



- Independent of gamma-ray energy
- Blazar contributions are treated as background, calibrated at lower energies (e.g., 100 MeV)

Discussion:

Detectability and backgrounds

- Error of the signal can be given by

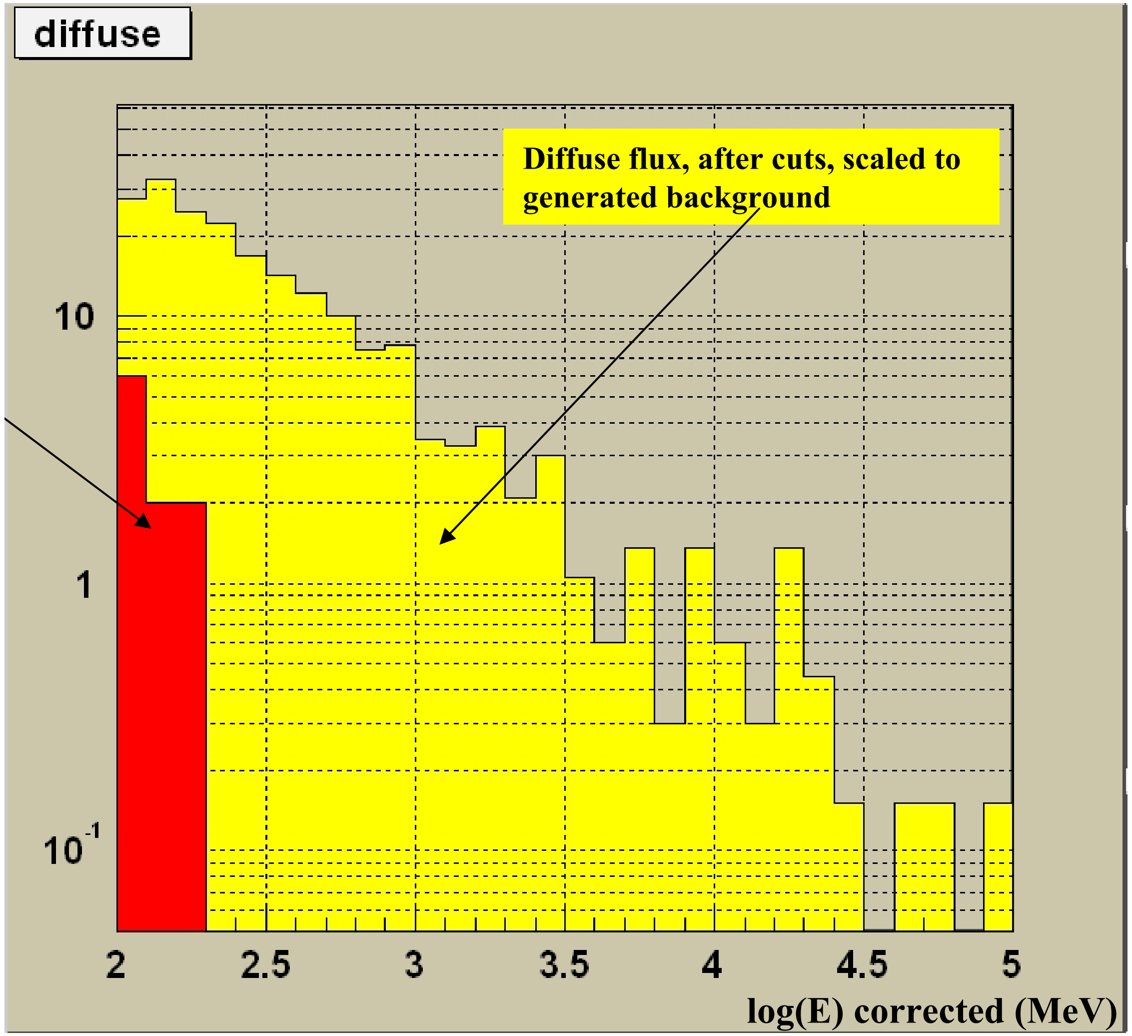
$$\delta C_l^s = \sqrt{\frac{2}{(2l+1)\Delta l f_{\rm sky}}}\left(\underset{\text{signal}}{C_l^s} + \overset{\text{background}}{C_l^b} + \frac{\overset{\text{photo-count noise}}{C_N}}{\underset{\text{window function}}{W_l^2}}\right)$$

- Detector noise and Galactic emission (foreground)???

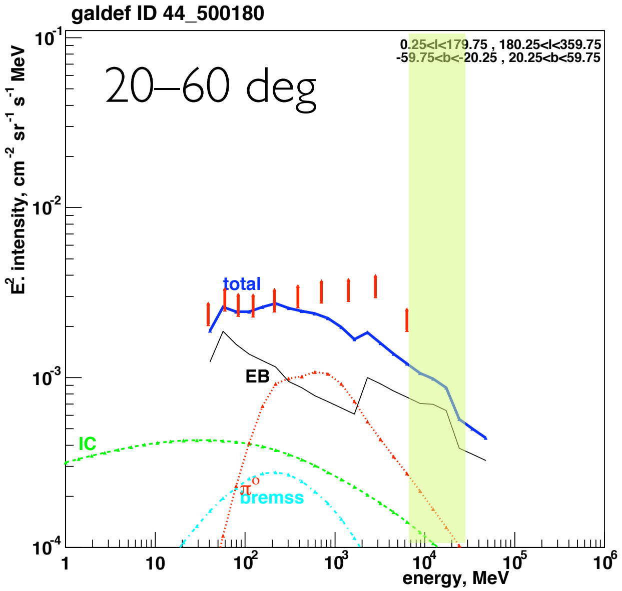
Detector backgrounds

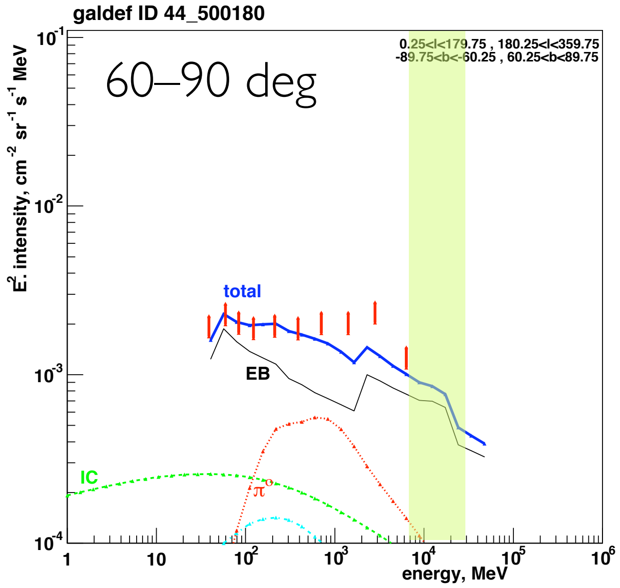
- Detector background
  - Negligible, being 5% of the CGB above 100 MeV (even smaller at 10 GeV)

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



Galactic foregrounds





- Galactic cosmic rays — 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

Strong, Moskalenko & Reimer et al. 2004

Discussion:
Detectability and backgrounds

- Error of the signal can be given by

$$\delta C_l^s = \sqrt{\frac{2}{(2l+1)\Delta l f_{\rm sky}}}\left(\underset{\text{signal}}{C_l^s} + \overset{\text{background}}{C_l^b} + \frac{\overset{\text{photo-count noise}}{C_N}}{\underset{\text{window function}}{W_l^2}}\right)$$

- Detector noise and Galactic emission (foreground)???—can be negligible

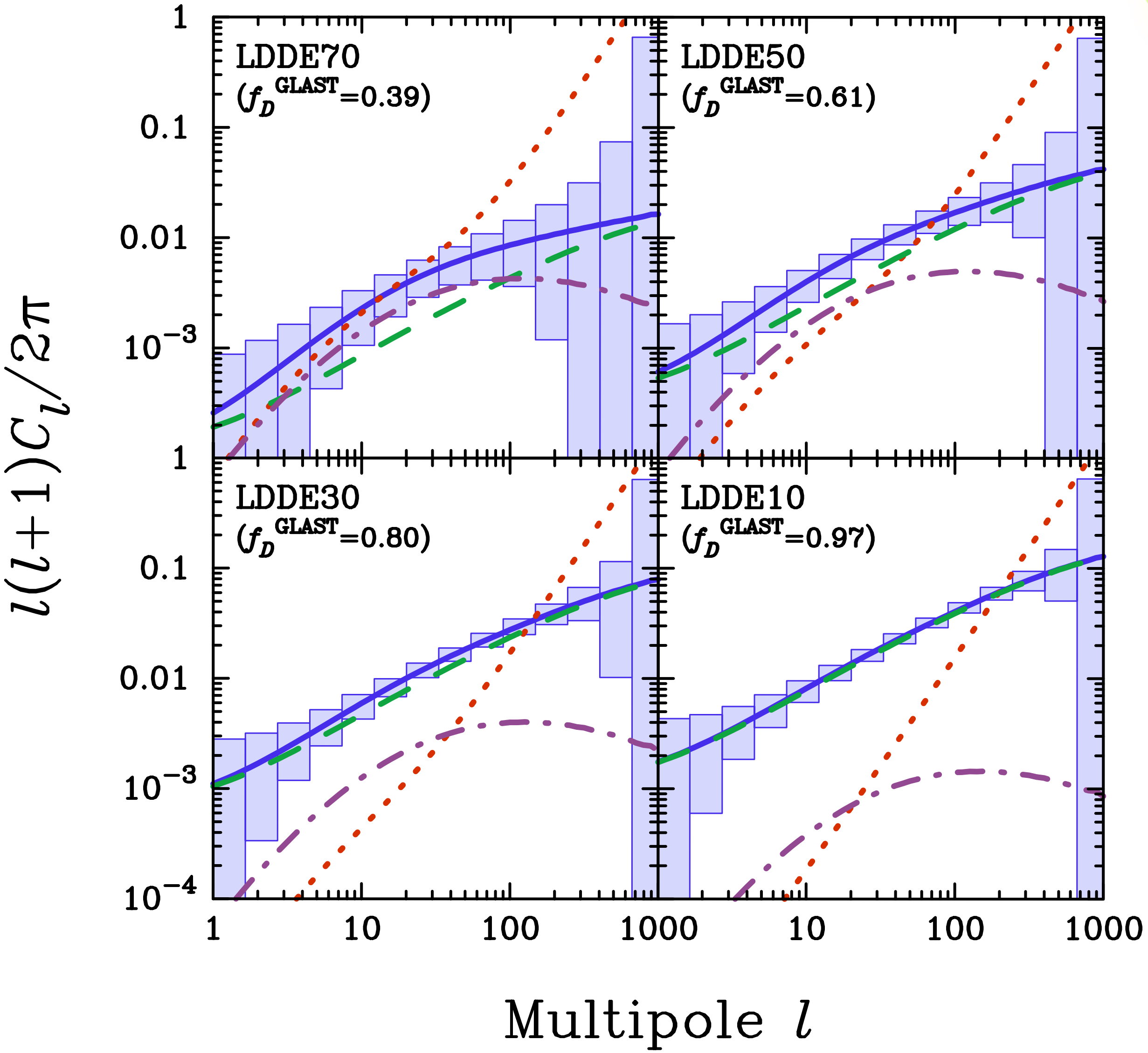
$$\begin{aligned} C_N &= \Omega_{\rm sky} N_{\rm total}/N_{\rm CGB}^2 \simeq \Omega_{\rm sky}/N_{\rm CGB} \\ &= 8\times 10^{-5}(E/10\ {\rm GeV})\ {\rm sr} \\ N_{\rm CGB} &\simeq E I_{\rm CGB} A_{\rm eff} T \Omega_{\rm fov} \\ &= 10^5 (E/10\ {\rm GeV})^{-1} \end{aligned}$$

$$W_l = \exp(-l^2\sigma_b^2/2)$$

$A_{\rm eff}$	10^4 cm^2
$\Omega_{\rm fov}$	2.4 sr
$\Omega_{\rm sky}$	8.3 sr
T	2 yr
σ_b	0.115°

Detectability of angular power spectrum

*Ando et al., PRD **75**, 063519 (2007)*



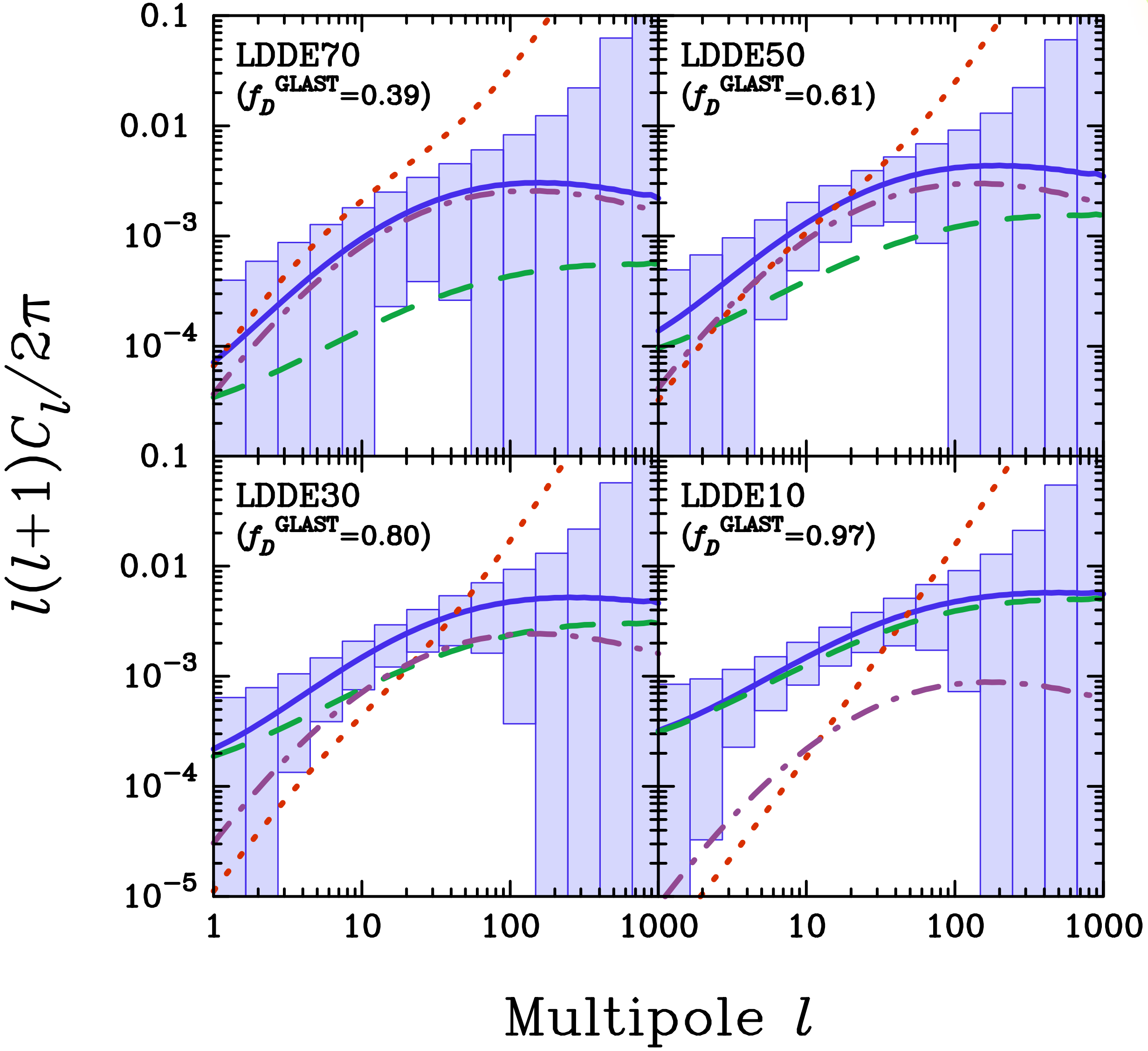
Subhalo-dominated + α=1

Dark matter signal
Dark matter correlation
Blazar background
Dark matter-blazar cross corretation

- At 10 GeV for 2-year observation
- 1-halo term dominated
- Dark matter signal would be detected very well in any case investigated

Detectability of angular power spectrum

*Ando et al., PRD **75**, 063519 (2007)*



Subhalo-dominated + α=0.7

Dark matter signal

Dark matter correlation

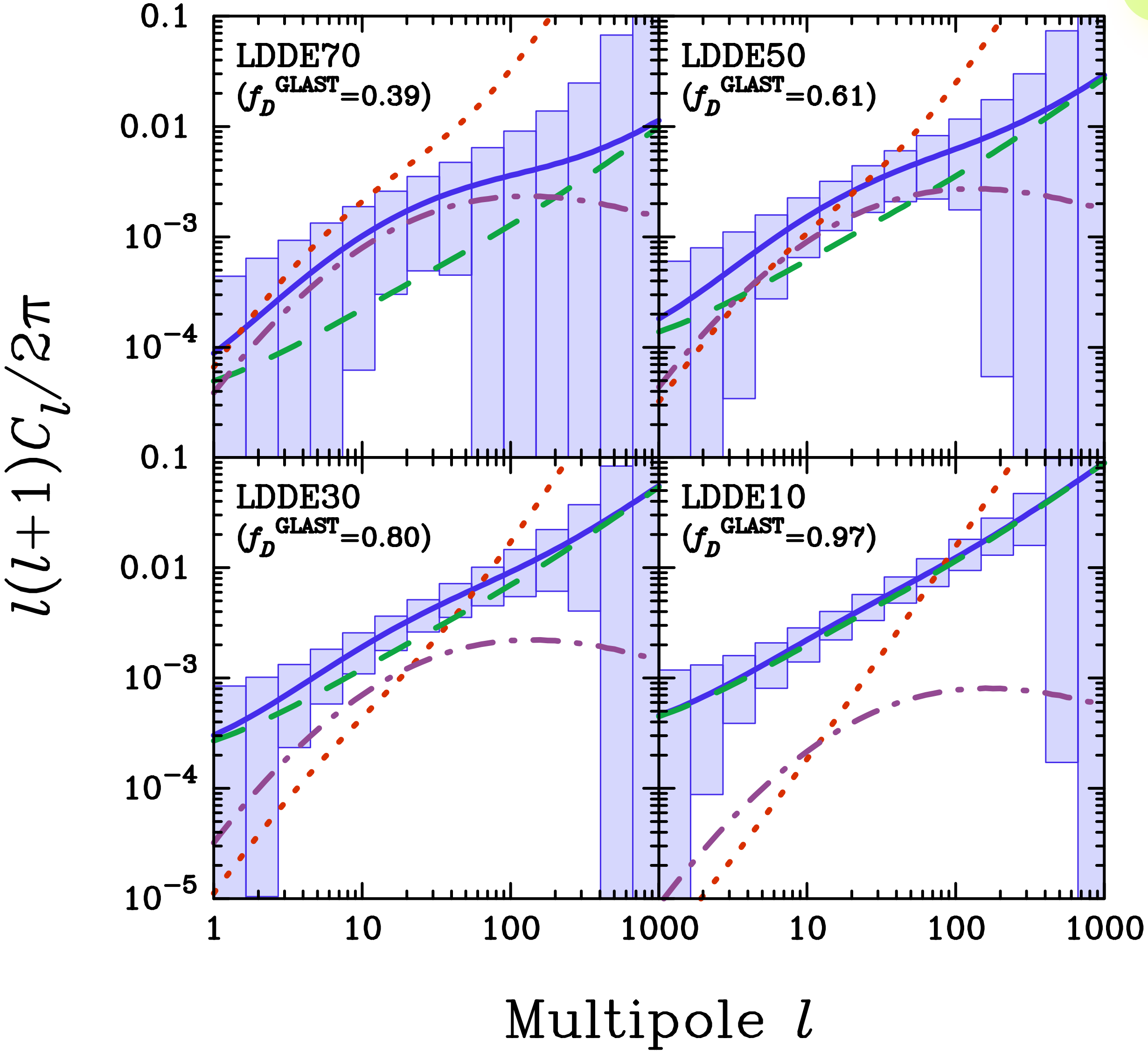
Blazar background

Dark matter-blazar cross corretation

- At 10 GeV for 2-year observation
- 2-halo term dominated
- Still detectable if contribution exceeds 30%

Detectability of angular power spectrum

*Ando et al., PRD **75**, 063519 (2007)*



Host-halo-dominated + $M_{min}=10^6\ M_{sun}$

Dark matter signal

Dark matter correlation

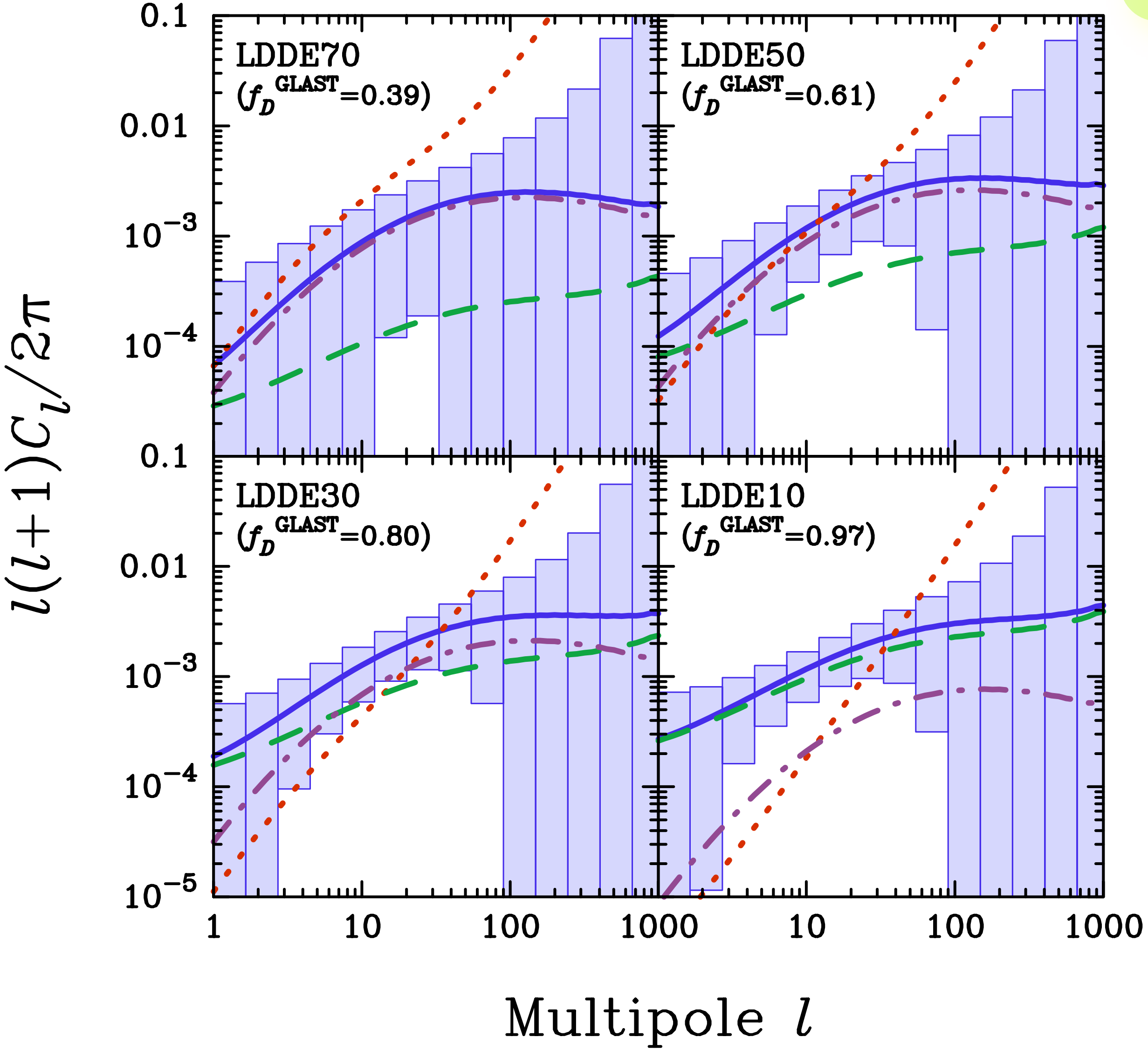
Blazar background

Dark matter-blazar cross corretation

- At 10 GeV for 2-year observation
- 1-halo term dominated
- Again detectable if contribution exceeds 30%

Detectability of angular power spectrum

*Ando et al., PRD **75**, 063519 (2007)*



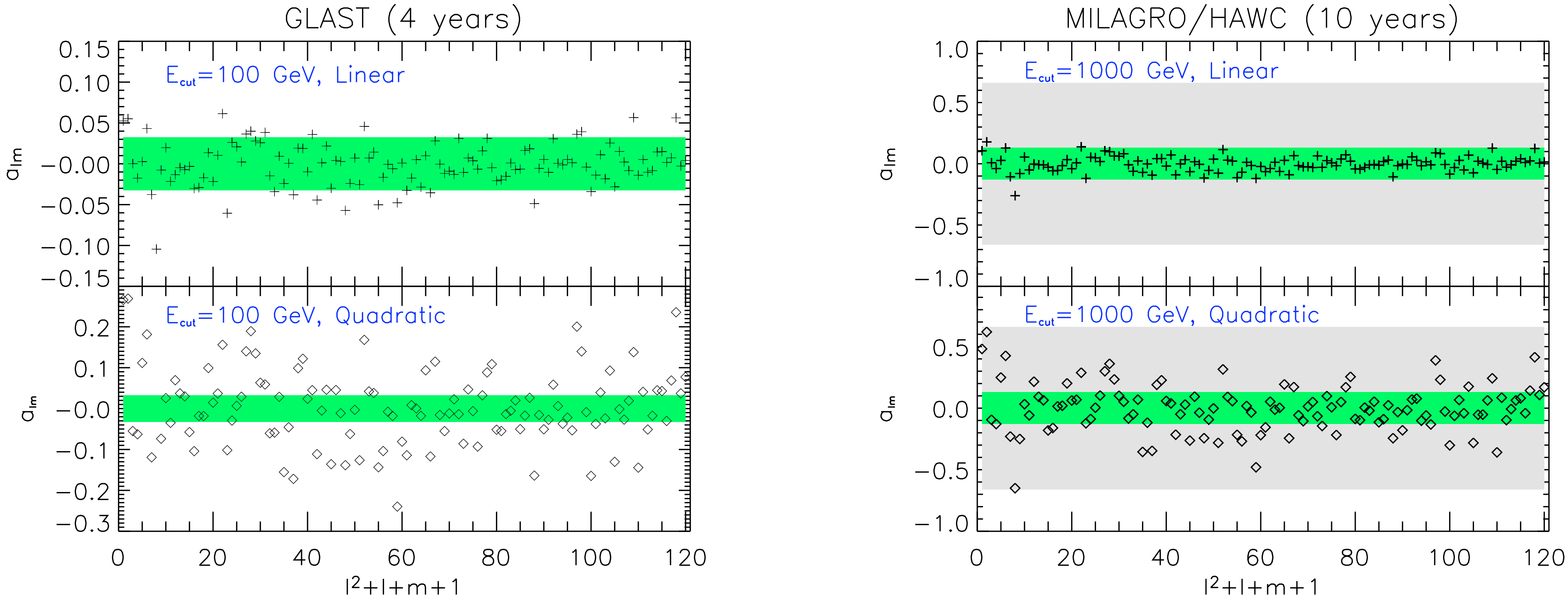
Host-halo-dominated + $M_{min}=10^{-6}\,M_{sun}$

Dark matter signal
Dark matter correlation
Blazar background
Dark matter-blazar cross corretation

- At 10 GeV for 2-year observation
- 2-halo term dominated
- Again detectable if contribution exceeds 30%

Other related studies

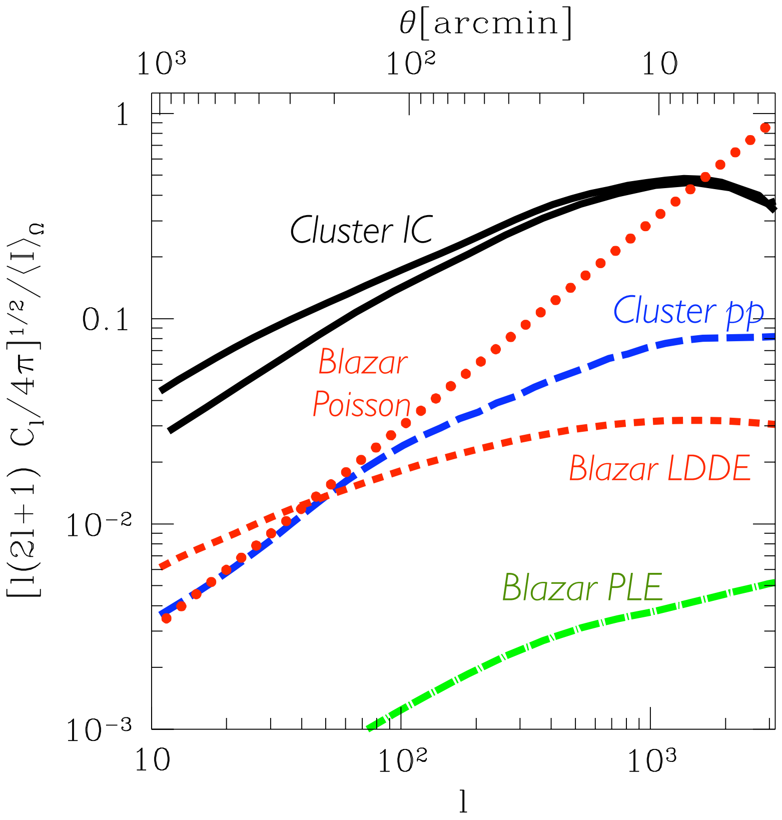
Cuoco et al., astro-ph/0612559



- At higher energies E > 100 GeV, where gamma absorption is important
- The signature of large-scale structure should be seen at large angular scales

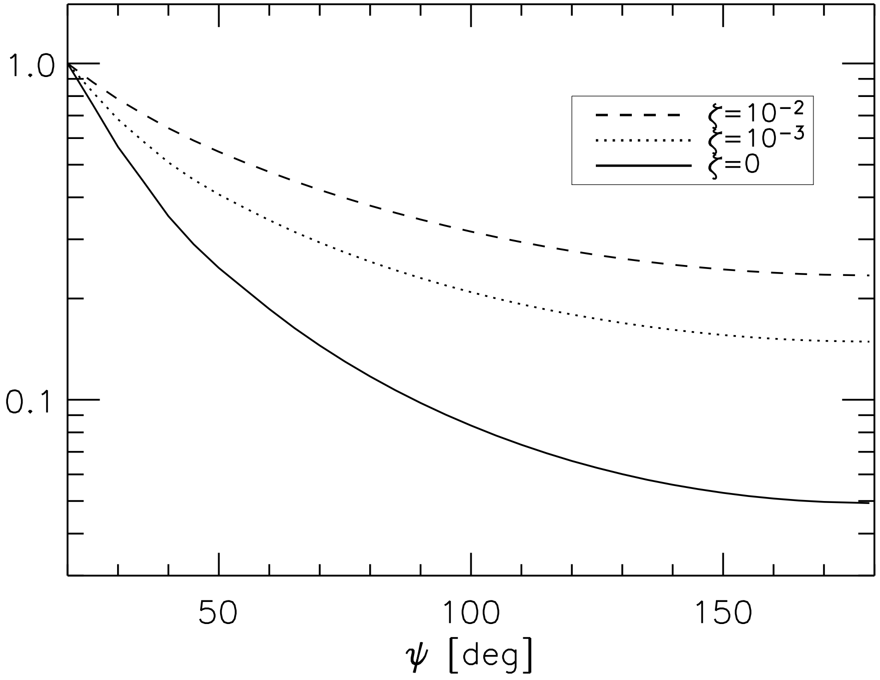
Other related studies

Miniati et al., astro-ph/0702083



- The effect of large-scale structure shocks in galaxy clusters

Hooper & Serpico, astro-ph/0702328



- Effect of Galactic emission from dark matter annihilation

4. Conclusions

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

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