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What can we learn from gamma-ray anisotropies?

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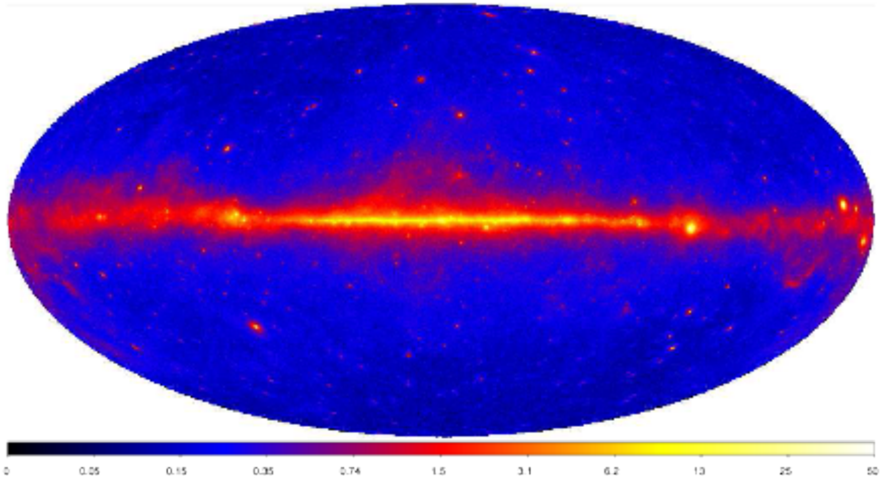
Motivation

Indirect detection of Dark Matter (DM): gamma-rays produced by annihilations or decays of DM particles

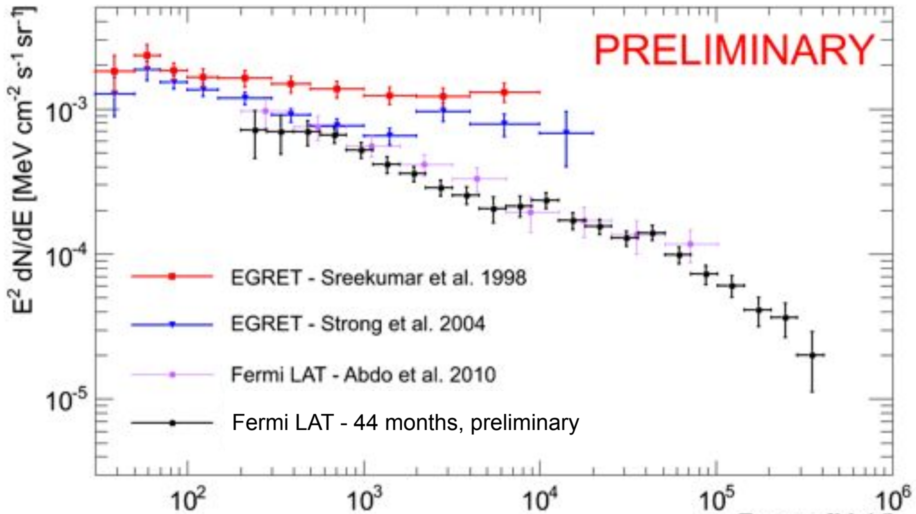
Focus on the Diffuse Gamma-Ray Background (DGRB): looking for the cumulative emission produced by DM annihilations/decays in the all DM halos and subhalos

- unresolved sources (DM is dark!)
- signal depends on the average properties of DM (sub)halos
- tightly connected to astrophysics
- study of anisotropies can be more informative than focusing on intensity and is linked to Large Scale Structure

The Diffuse Gamma-Ray Background (DGRB)



units of 10^{-7} erg $cm^{-2}s^{-1}sr^{-1}$, 24 months, 100 MeV-10 GeV
www-glast.stanford.edu



M.Ackermann's talk at the 4th Fermi Symposium

- **residual** emission after subtraction of Galactic foreground and point-sources

- multicomponent fit to Fermi-LAT data (0.2-820 GeV) in the region $|b|>10$ deg

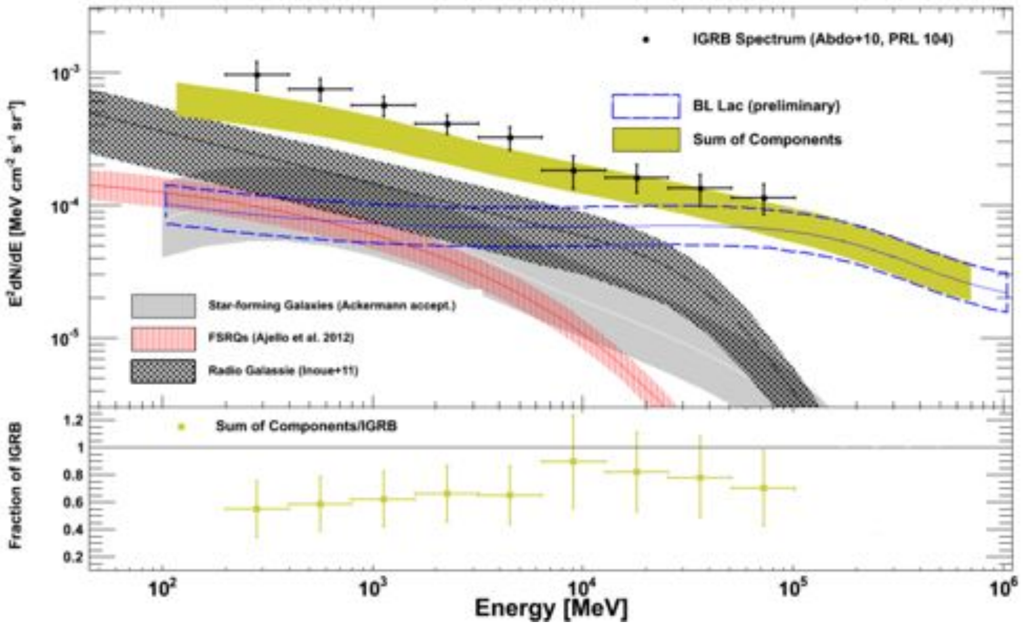
- compatible with **power-law** energy spectrum with a slope of -2.4, possible softening at high energies

The nature of the DGRB

- **unresolved** counterparts of the detected sources (blazars, star-forming galaxies, radio galaxies, ...)

- **population studies** (possibly at higher frequencies) estimate the unresolved component

- room for **additional classes of sources**



M. Ackermann's talk at the 4th Fermi Symposium

DM-induced emission

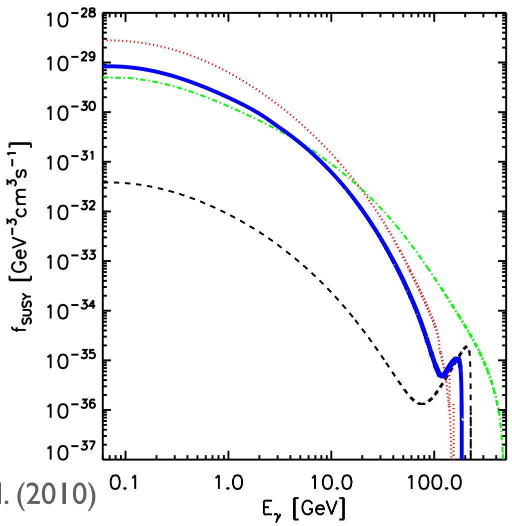
$$\frac{d\Phi}{dE}(E_\gamma, \Psi) = \frac{(\sigma_{ann} v)}{8\pi m_\chi^2} \int_{\mathrm{l.o.s}} d\lambda \sum_i B_i \frac{dN_\gamma^i(E_\gamma(1+z))}{dE} \rho^2(\lambda(z), \Psi) e^{-\tau_{\mathrm{EBL}}(z, E_\gamma)}$$

- photon yield: prompt emission (continuum, lines and spectral features), Inverse Compton and hadronic emission

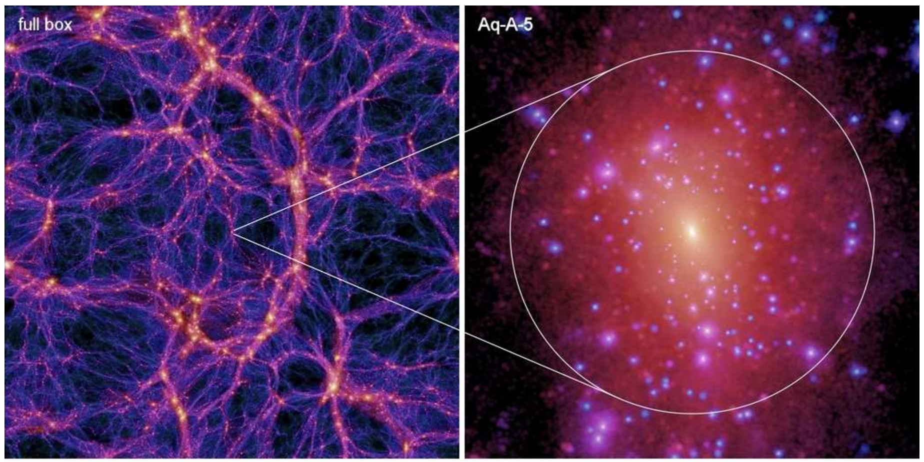
- modelling of DM halos come from *N*-body simulations

- simulations have a mass resolution and (normally) do not include baryonic physics

Springel et al. (2008)



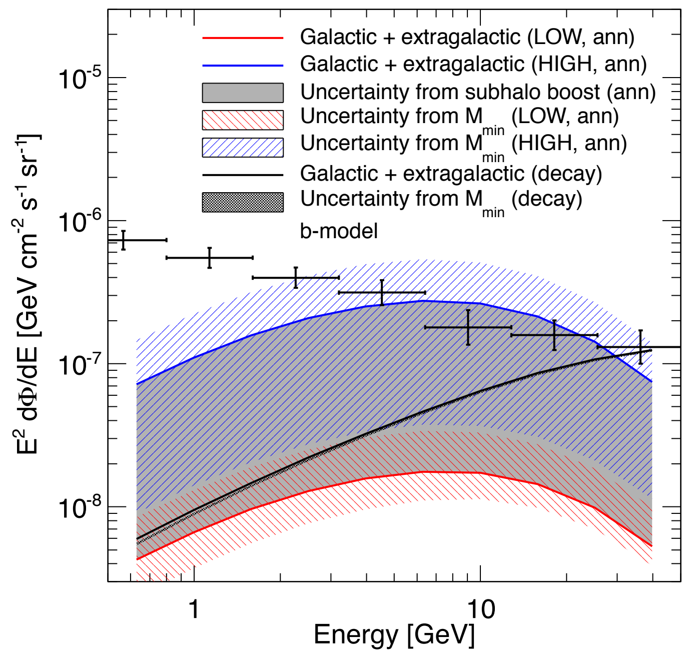
Zavala et al. (2010)



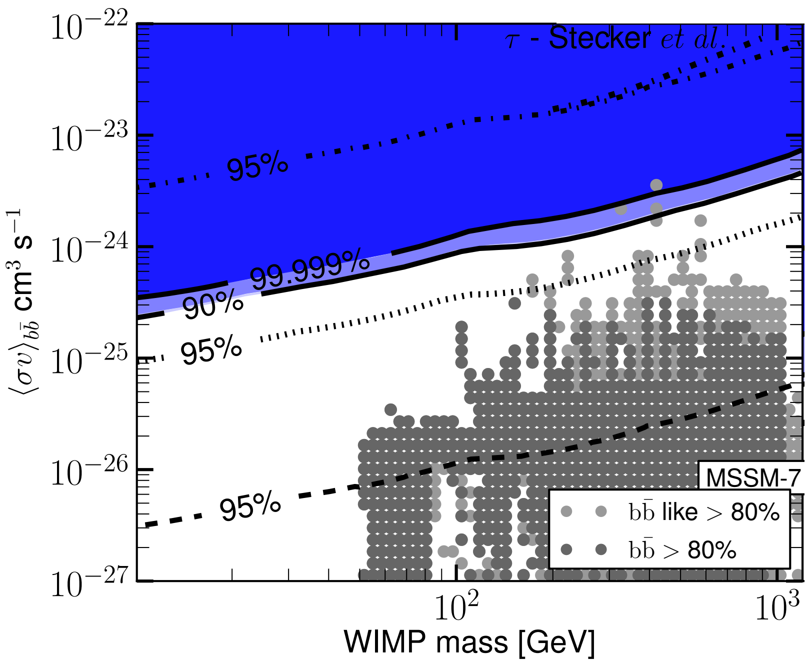
Constraining DM with the DGRB intensity

- estimate DM-induced gamma-ray emission from all halos and subhalos around us

- **main uncertainties** are the value of M_{min} and the amount of subhalos



E=4 GeV, M_{min}=10^{-6}M$_\odot$, m_χ=200 GeV, σv=3x10^{-26}cm^{3}s^{-1} (annihilation), m_χ=2 TeV, τ=2x10^{27}s (decay), *b* quarks
Fornasa et al. (2012)



Abdo et al. (2012)

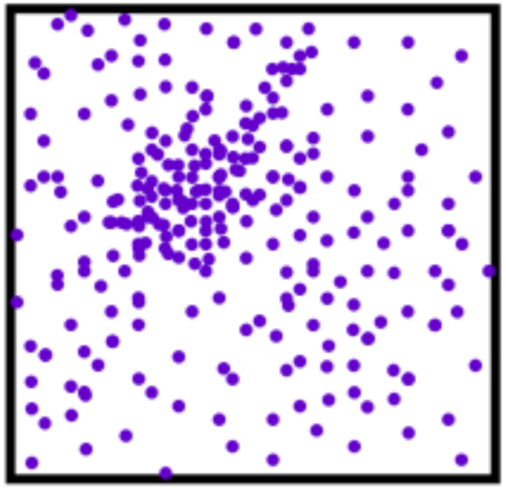
Anisotropies in the DGRB

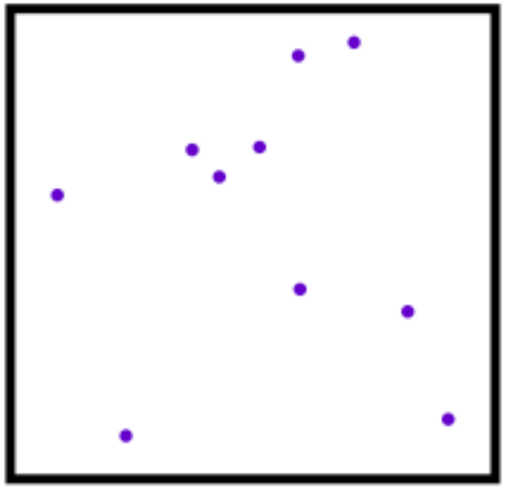
- Angular Power Spectrum (APS) quantifies the fluctuations in a 2D map

$$a_{\ell,m}^{\rm fluct} = \int d\Omega_{\mathbf{n}} \frac{I(\mathbf{n}) - \langle I \rangle}{\langle I \rangle} Y_{\ell,m}^{*}(\mathbf{n}) \qquad C_{\ell}^{\rm fluct} = \sum_{|m|\leq\ell} |a_{\ell,m}^{\rm fluct}|^2$$

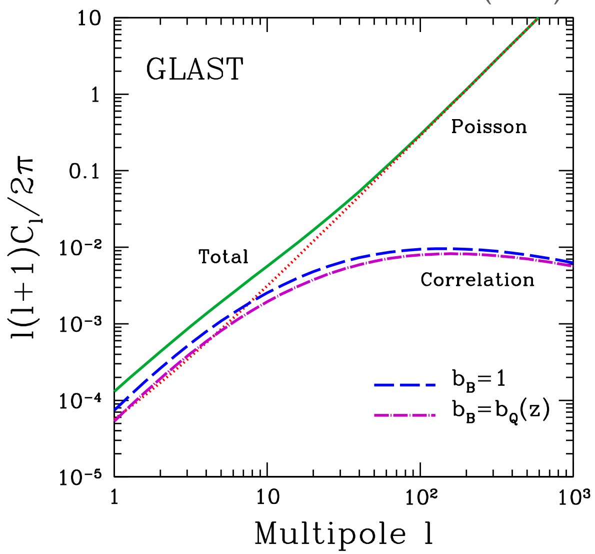
- **Poisson power spectrum** (constant in multipole): depends on the number of sources

- **photon noise** (again Poisson-like)

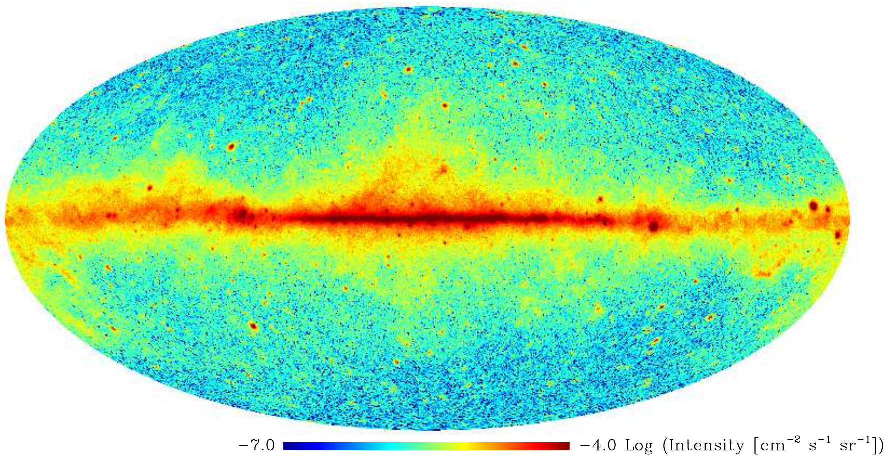


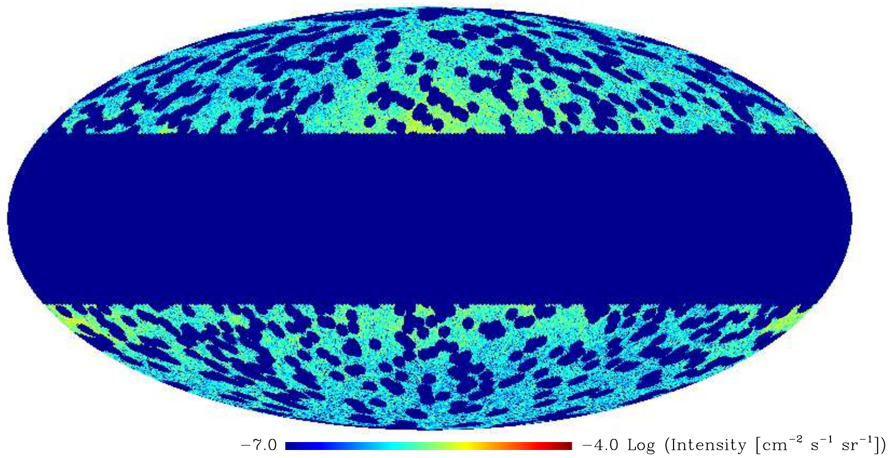


Ando & Komatsu (2006)



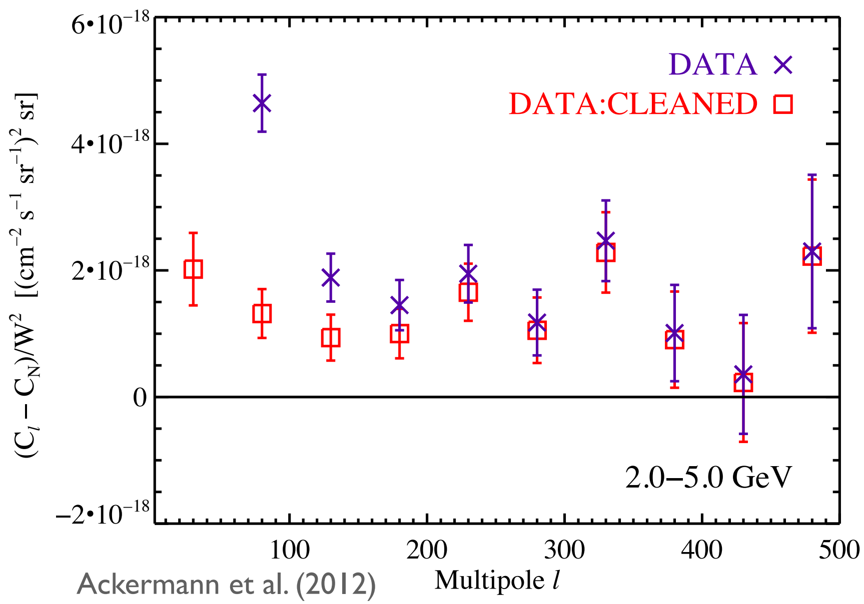
Fermi-LAT measurement of anisotropies





Ackermann et al. (2012)

- Galactic foreground and point sources are masked not subtracted
- 22 months of data
- 4 energy bins between 1 and 50 GeV
- signal region between multipole 155 and 504



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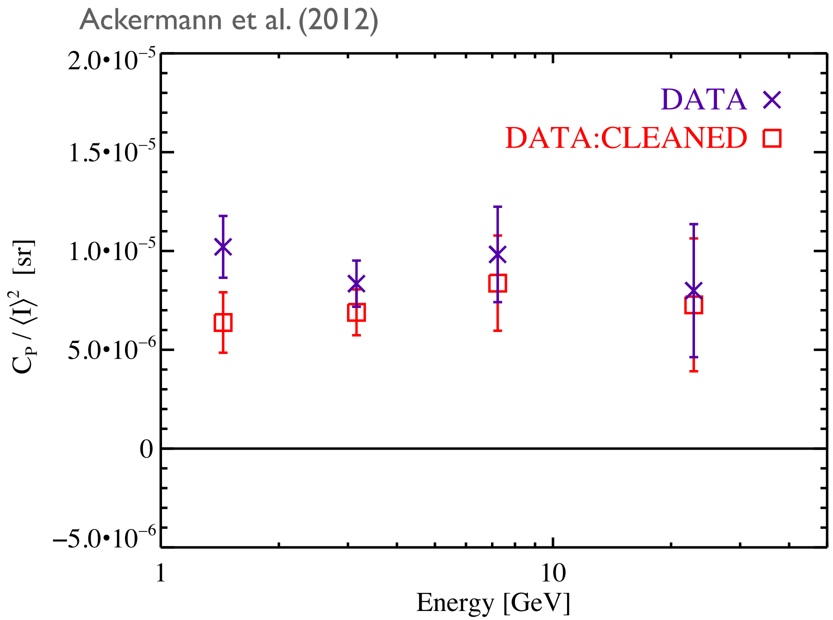
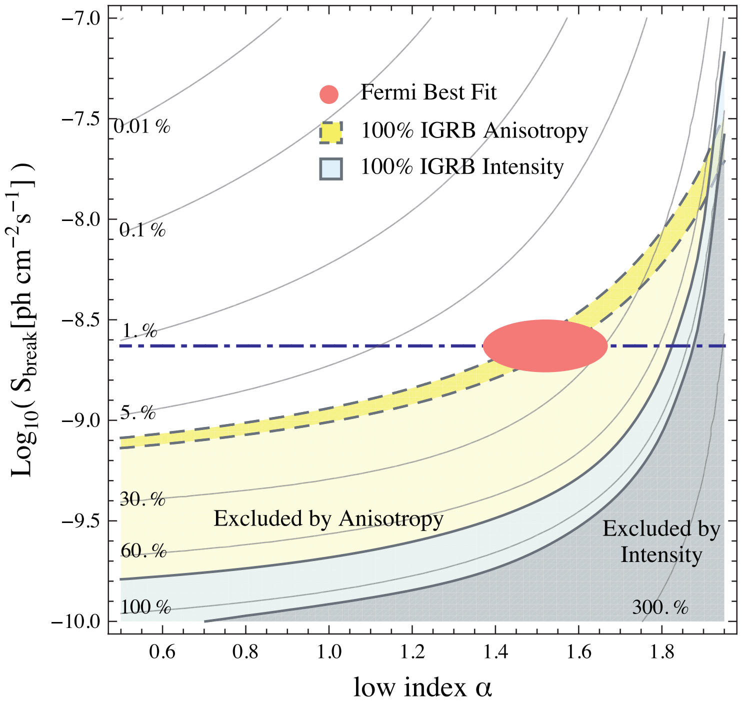
Fermi-LAT measurement of anisotropies



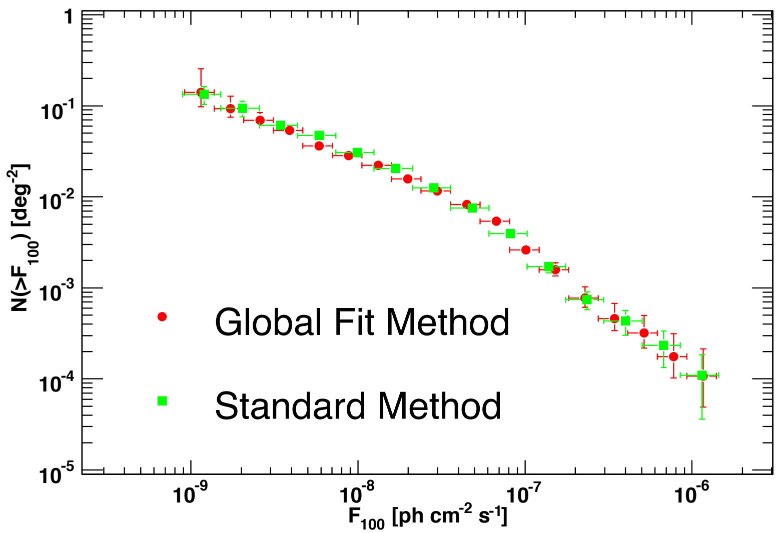
- significance of the detection ranges from **7.1** to 2.4
- **Poisson APS, constant** in energy
- APS dominated by the contribution of **unresolved blazars**

APS constraints on blazars

Cuoco et al. (2012)



Abdo et al. (2010)

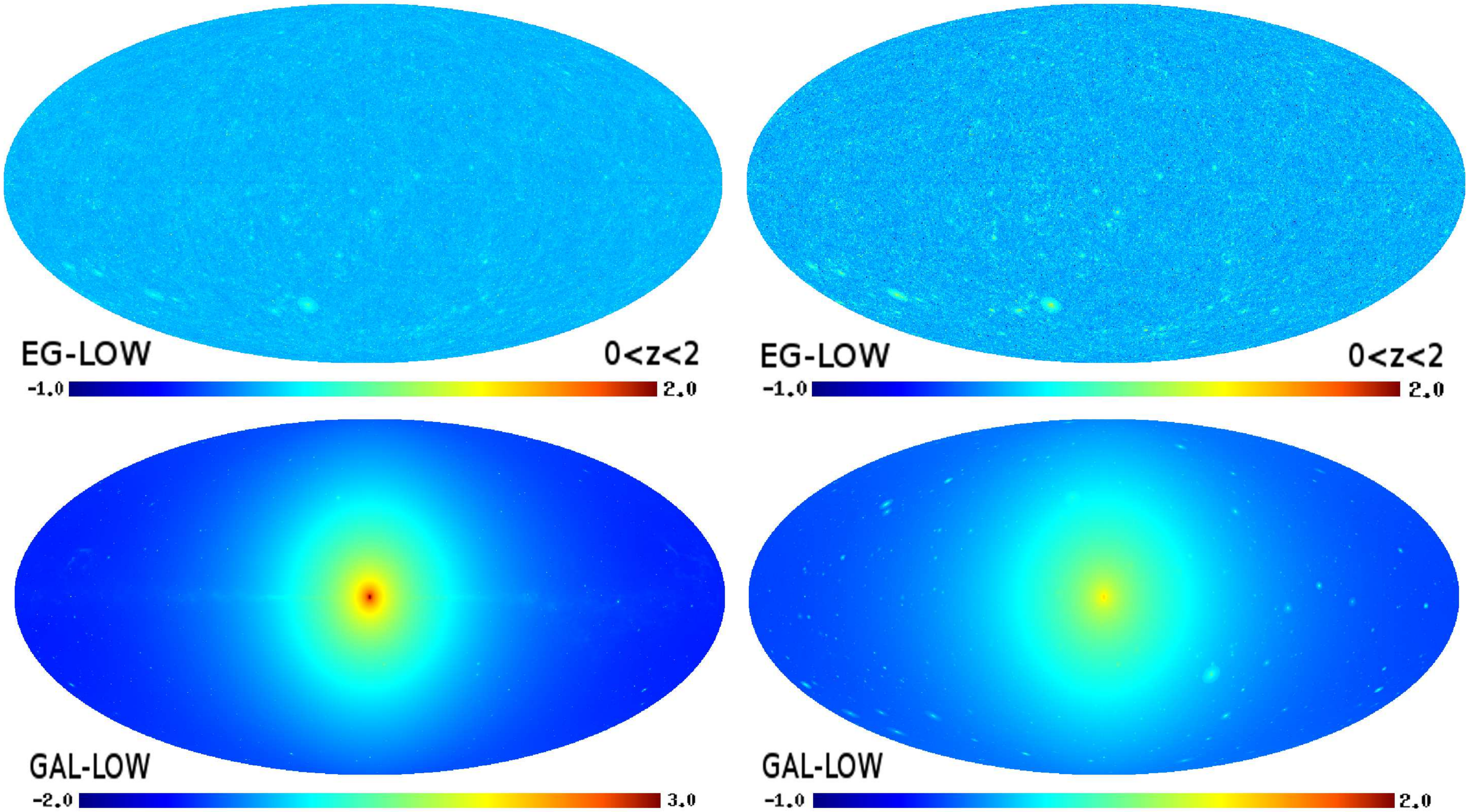


- $S_{\rm break}$ and α: parameters modelling unresolved blazars d*N*/d*S*

- **Poisson** APS constraints are stronger than the one from DGRB intensity

- Fermi-LAT APS measurement **improves our knowledge** of unresolved blazars (<24% of the DGRB intensity)

DM-induced anisotropies



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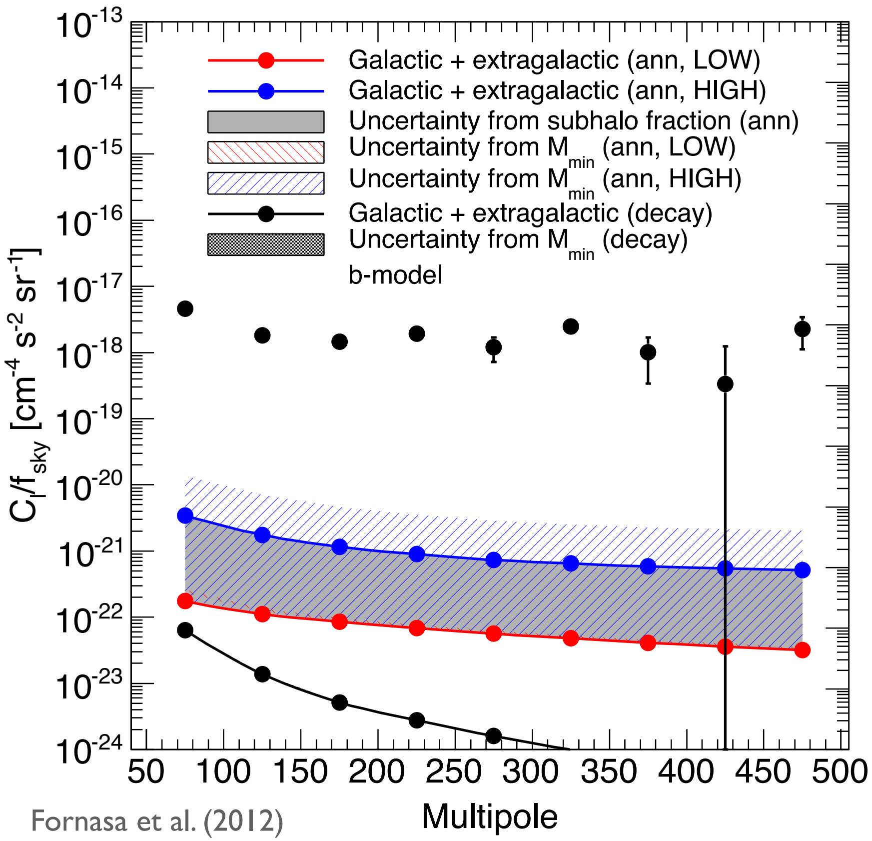
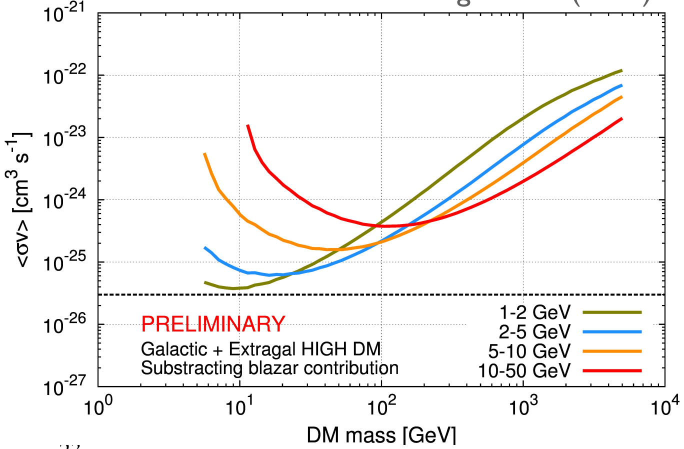
Fornasa et al. (2012)

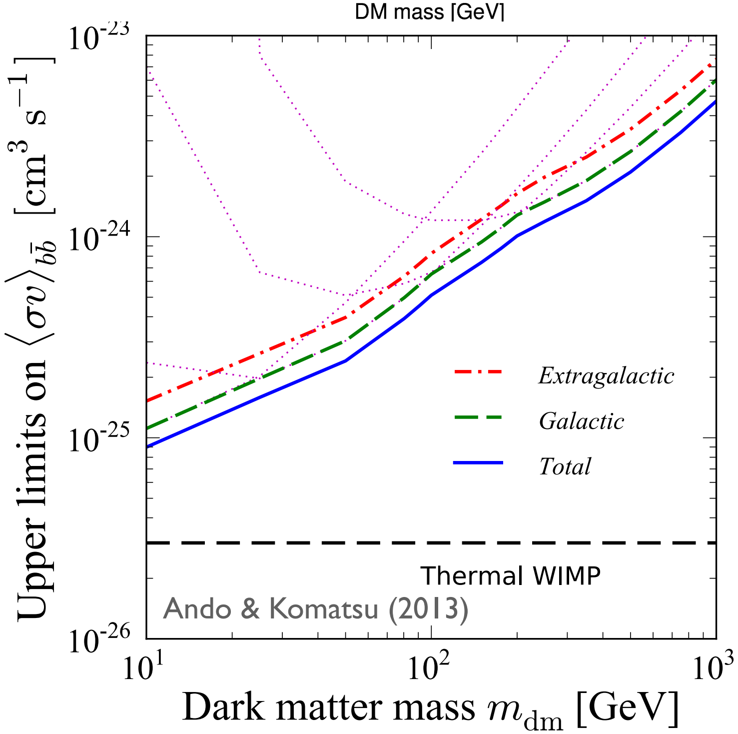
DM-induced angular power spectrum



Fornasa et al. (2012)

Gomez-Vargas et al. (2012)



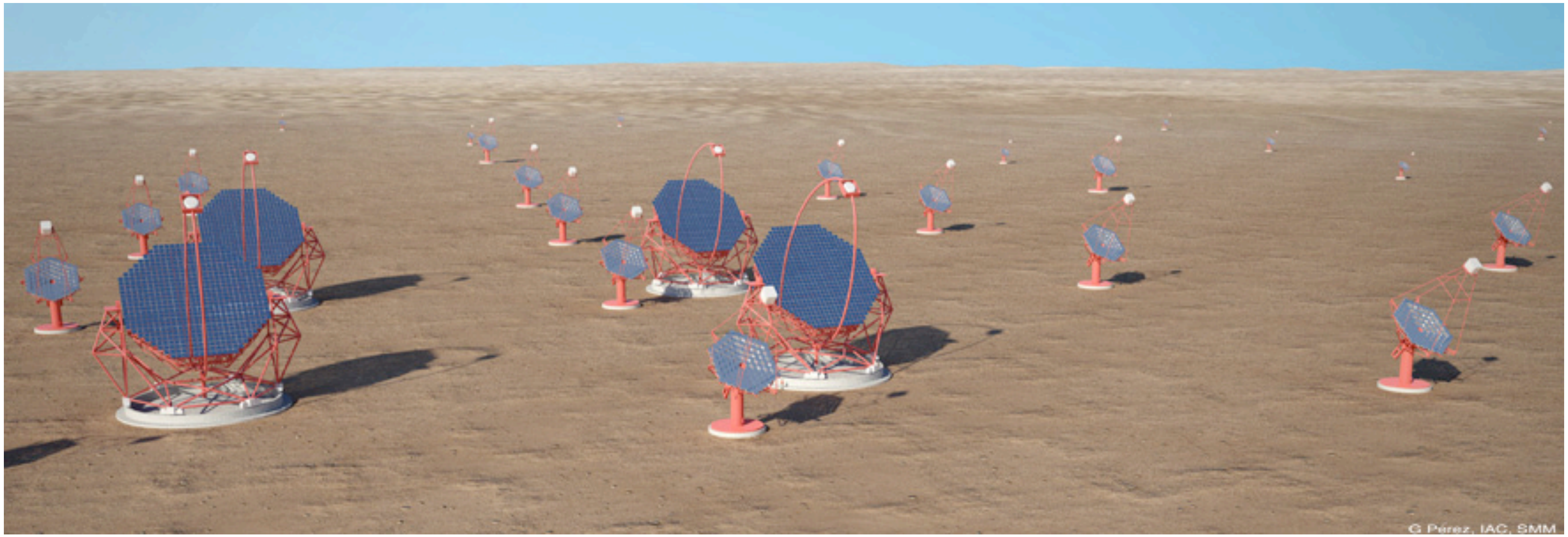


Measuring anisotropies with CTA

- building of CTA (Cherenkov Telescope Array) will start in 2015 and data gathering in 2018-2019

- **improvement in sensitivity** over the whole energy range (few tens of 10 GeV to 100 TeV)

- very large field of view and possibility of surveying the sky



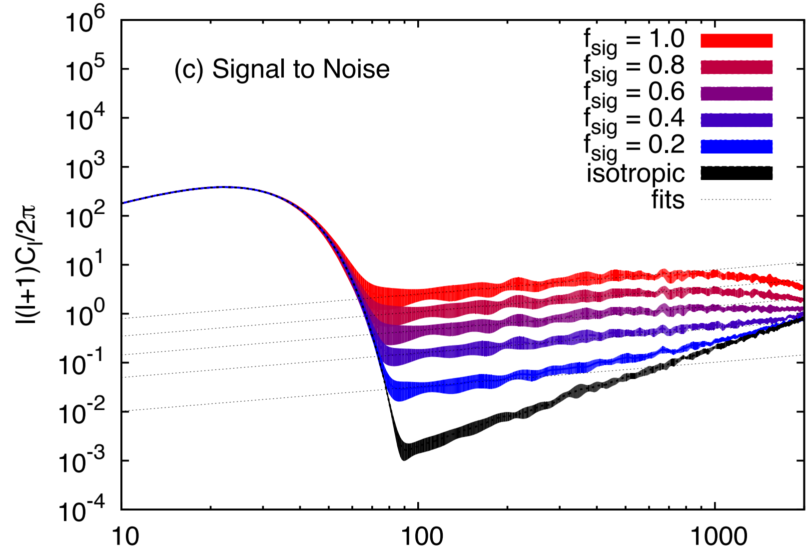
Measuring anisotropies with CTA

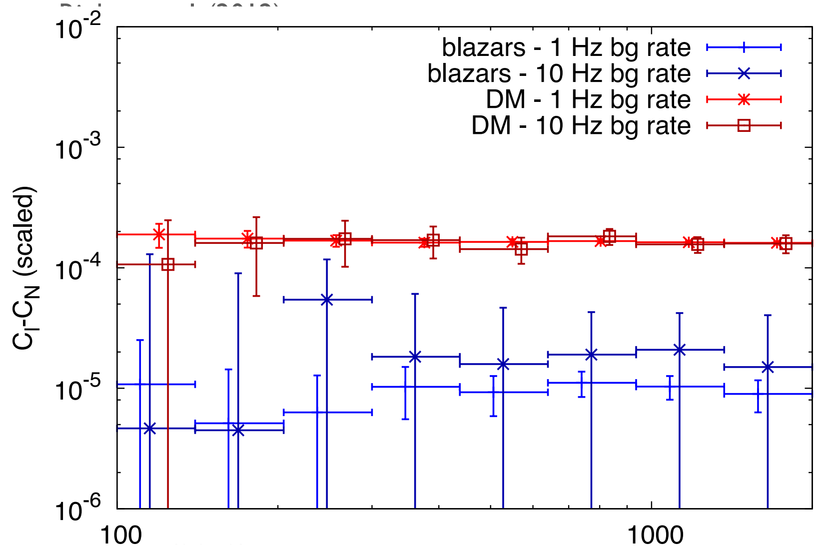
- inside 1 FOV (number of events sets the photon noise)

- fix APS from astrophysical sources (blazars) to $C_P=10^{-5}$ and add a DM component

- what is the contribution of DM to DGRB required to detect a deviation from the expected model APS?

Observation time [h]	Back. rate [Hz]	Sensitivity
100	1 (10)	30% (>46%)
300	1 (10)	15% (>46%)
1000	1 (10)	8% (30%)
10x100	1 (10)	15% (>46%)





Ripken et al. (2012)

Gamma-ray anisotropies and LSS

- gravitational lensing and the distribution of resolved galaxies trace Large Scale Structure (LSS)
- large amount of experimental data expected in the near future
- cross-correlation with the DGRB

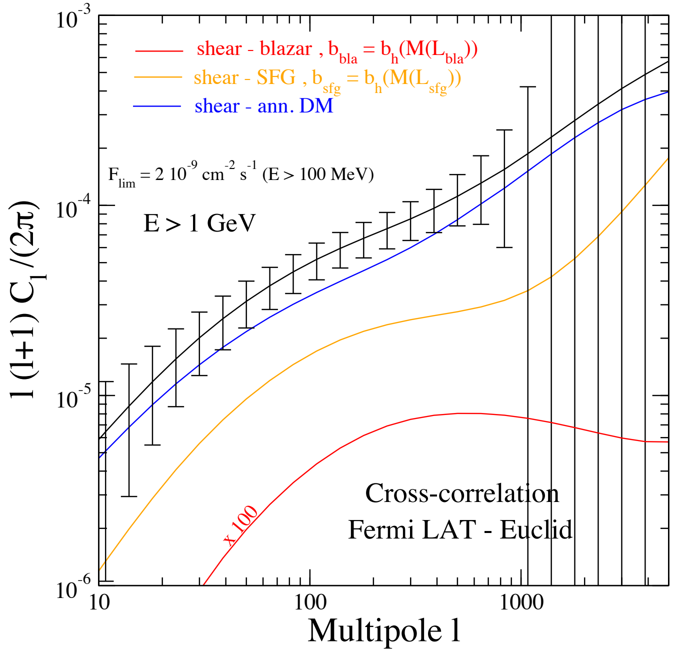
Cross-correlation with cosmic shear

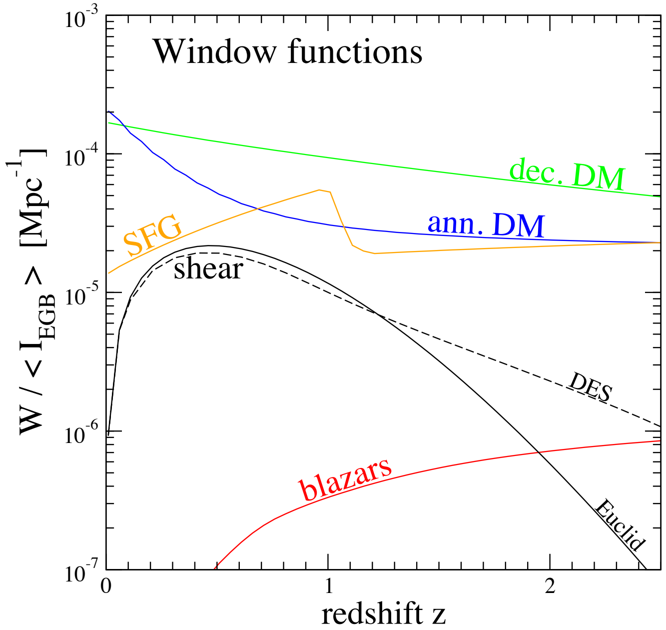
• weak gravitational lensing (**cosmic shear**) is sourced by the same objects that produce gamma-ray emission (DGRB)

• cross-correlation is expected

•cosmic shear is larger for **big objects** (large cross-correlation with DM halos)

Catena et al. (2013)

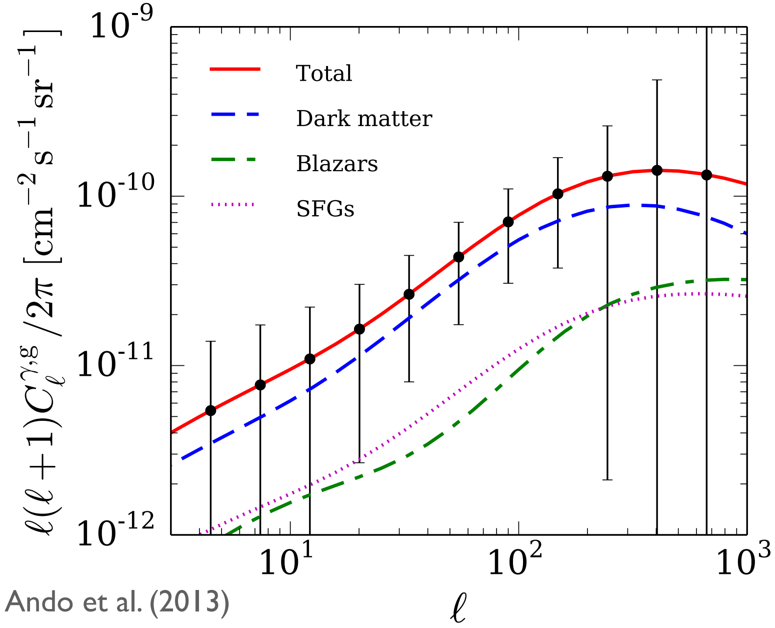




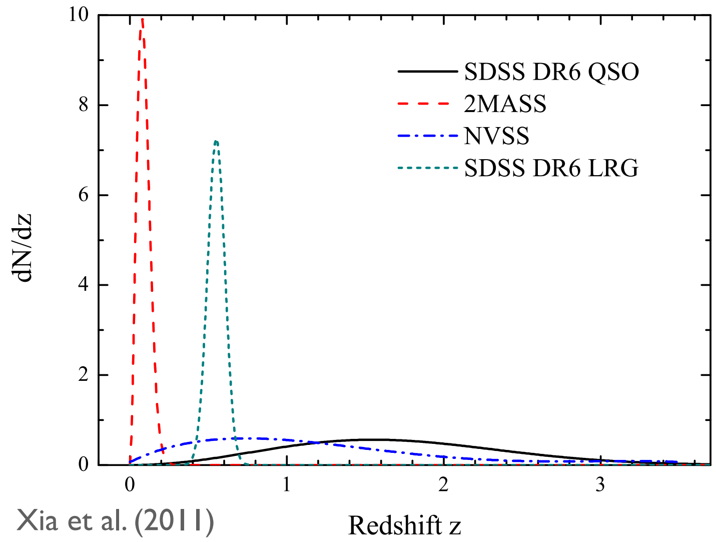
Cross-correlation with galaxy catalogs

- distribution of galaxies traces LSS (again cross correlation is expected)

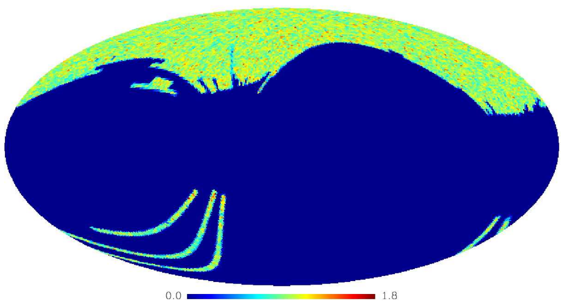
- SDSS Quasi-Stellar Objects
- 2MASS IR-selected galaxies
- NVSS Luminous Radio galaxies
- SDSS Lumionos Red galaxies



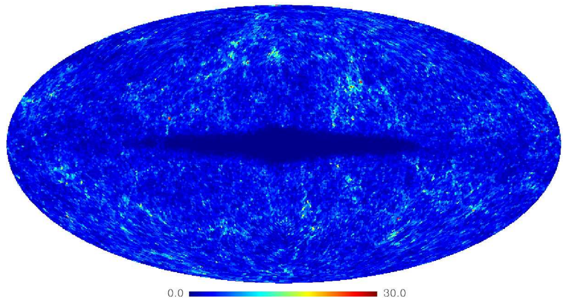
Ando et al. (2013)



Xia et al. (2011)



SDSS Quasi-Stellar objects

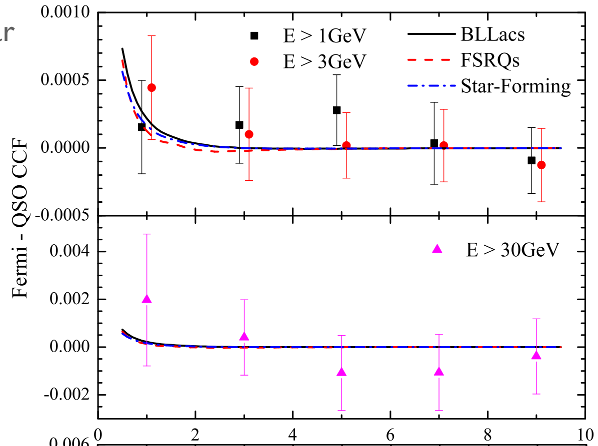


2MASS galaxies

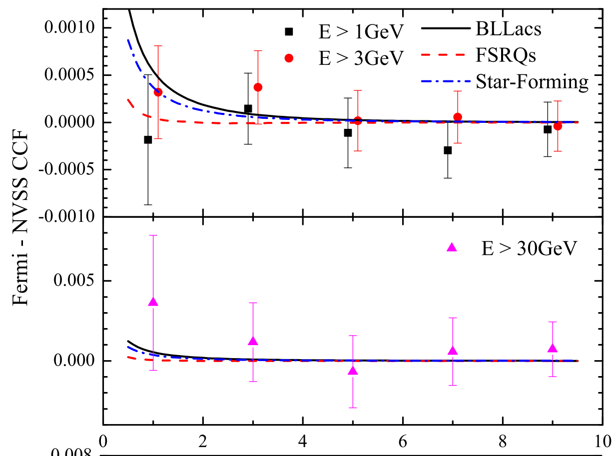
2-point correlation function

$$c(\theta) = \frac{1}{N_\theta} \sum_i \sum_{j \in \mathcal{N}(i,\theta)} \frac{n_i^\gamma - \bar{n}^\gamma}{\bar{n}^\gamma} \frac{n_j^{\rm gal} - \bar{n}^{\rm gal}}{\bar{n}^{\rm gal}}$$

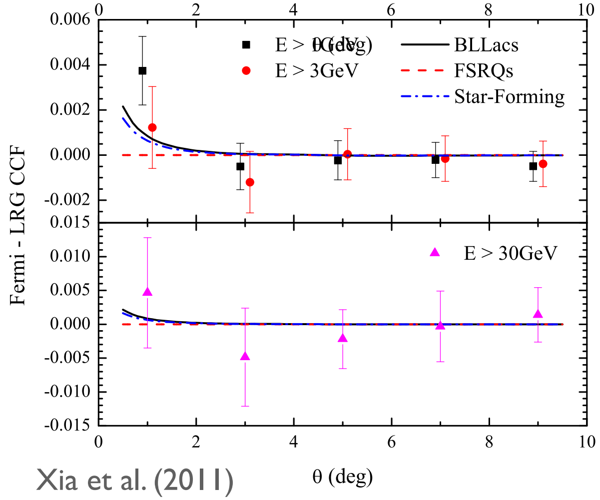
SDSS Quasi-Stellar objects



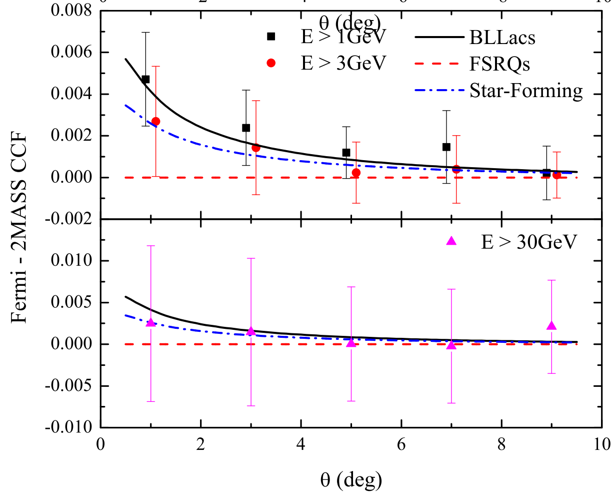
NVSS Luminous Radio galaxies



SDSS Luminous Red galaxies



2MASS galaxies



Xia et al. (2011)

Conclusions

• anisotropies in gamma-ray emission is a very rich and informative observable (both for DM and astrophysics)

• data are available from Fermi-LAT and have been successfully used to extract information on astrophysical sources and to put constraints on DM (compatible with the study of other targets)

• sensitivity of CTA to gamma-ray anisotropies is encouraging

• cross-correlation with cosmic shear and with galaxy catalogs: a way of suppressing astrophysical contribution and being more sensitive to DM

• interesting physics will be delivered by future surveys

Fluctuation vs. intensity APS

- Fluctuation APS is a dimension-less quantity (independent on enegy)

$$a^{\rm fluct}_{\ell,m} = \int d\Omega_{\mathbf{n}} \frac{I(\mathbf{n}) - \langle I \rangle}{\langle I \rangle} Y^*_{\ell,m}(\mathbf{n})$$

$$C^{\rm fluct}_\ell = \sum_{|m|\leq\ell} |a^{\rm fluct}_{\ell,m}|^2$$

- Intenty APS is a dimension-ful quantity (scaling with energy like I^2)

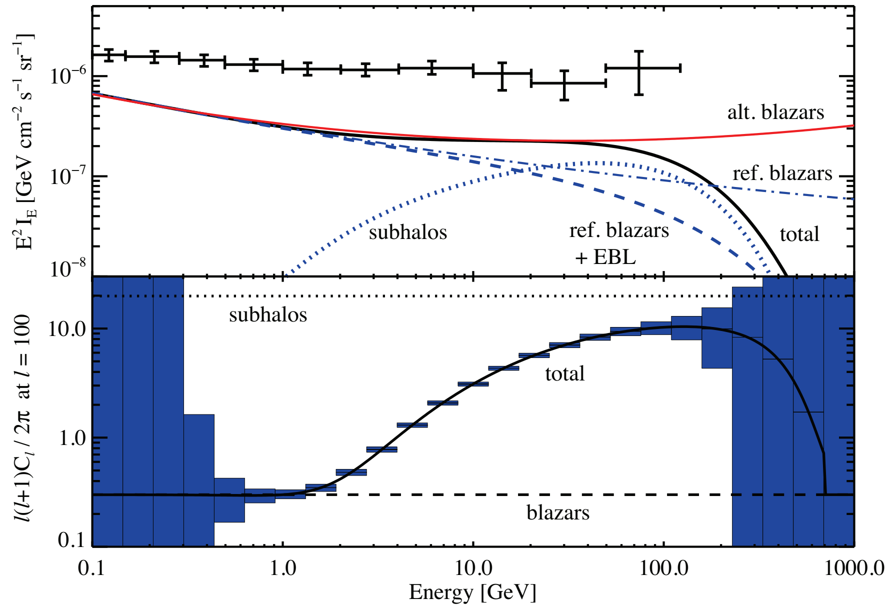
$$C^{\rm int}_\ell = C^{\rm fluct}_\ell \langle I \rangle^2$$

- summation rules

$$C^{\rm int}_\ell = C^{\rm int}_{\ell,1} + C^{\rm int}_{\ell,2}$$

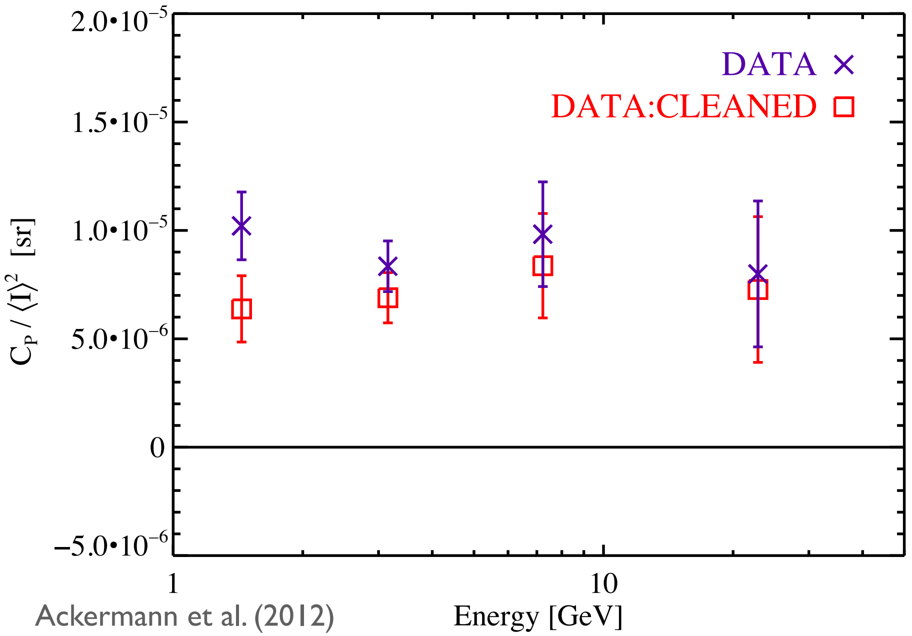
$$C^{\rm fluct}_\ell = \frac{\langle I_1 \rangle^2}{\langle I \rangle^2} C^{\rm fluct}_{\ell,1} + \frac{\langle I_2 \rangle^2}{\langle I \rangle^2} C^{\rm fluct}_{\ell,2}$$

Siegal-Gaskins and Pavlidou (2009)



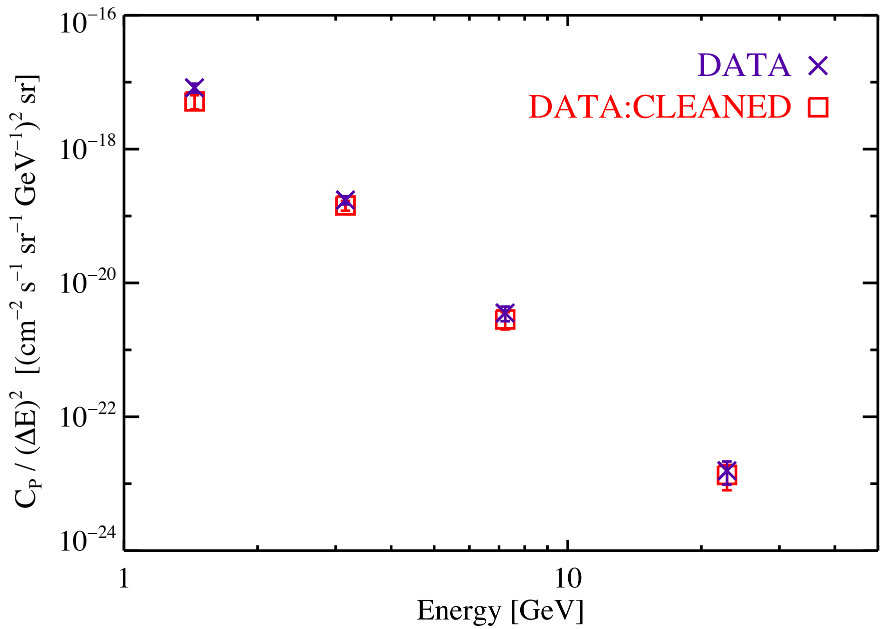
Fluctuation vs. intensity APS

Fluctuation APS



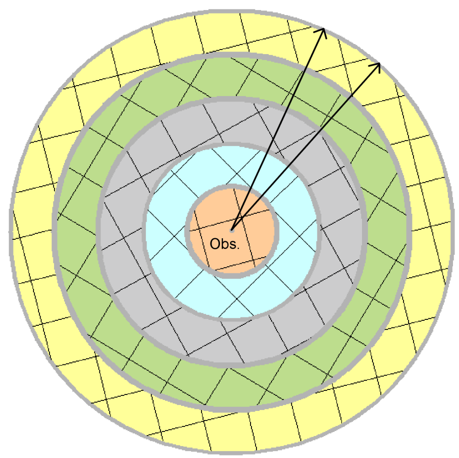
Ackermann et al. (2012)

Intensity APS



DM-induced emission (extragalactic)

Zavala et al. (2010)



- repetition of Millennium-II simulations boxes to cover a large portion of the Universe

- extrapolation below the mass resolution of Millennium-II (assuming low-mass halos trace the smallest halos in Millennium-II)

- unresolved subhalos accounted for analytic through a fit to *P*(ρ,*r*)