The DM-induced multiwavelength background

Cosmological emission

Given by adding up the contributions from all the DM structures in the Universe at all redshits: nearly isotropic (FLRW universe) but the study of small angular fluctuations can be important.

Clustering at different scales obviously plays a crucial role.

Many different possible astrophysical contributions.

Galactic DM substructures might also appear as an nearly isotropic component.

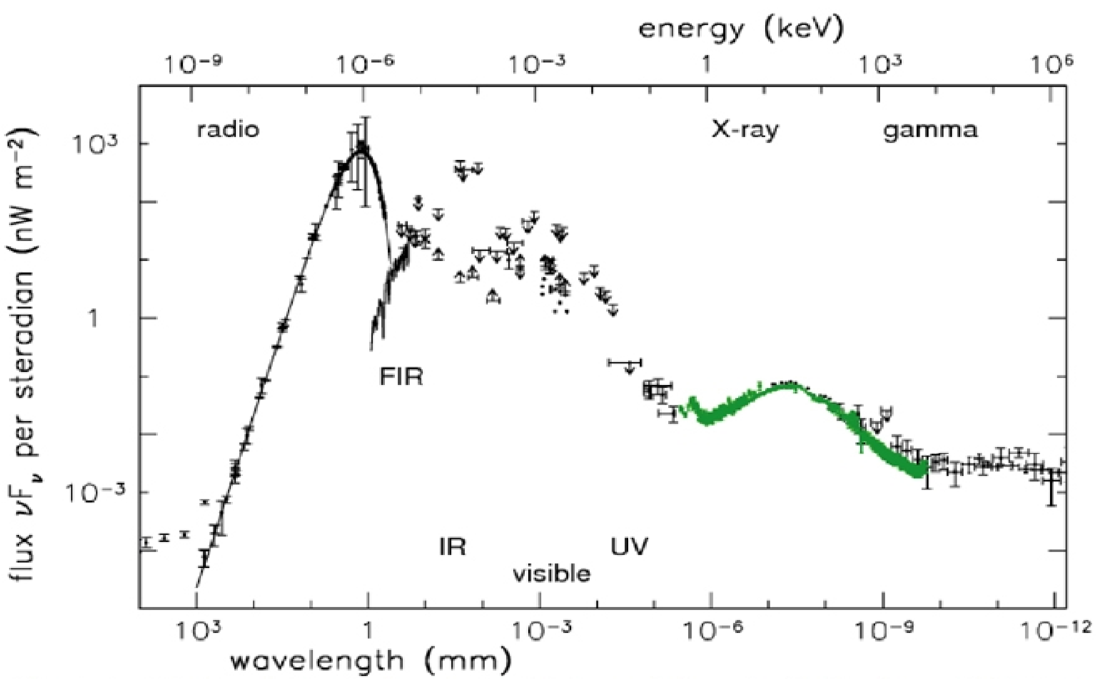
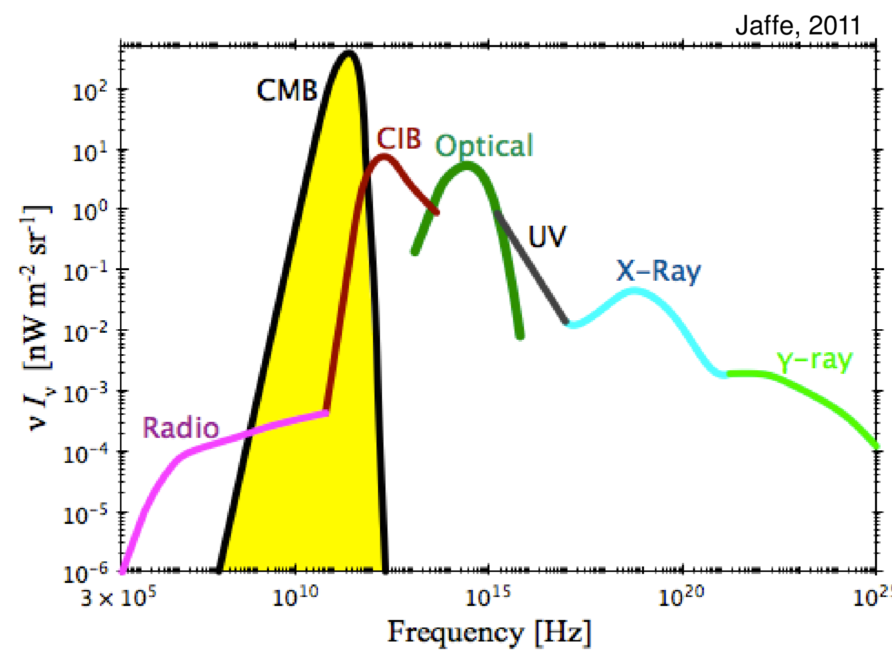
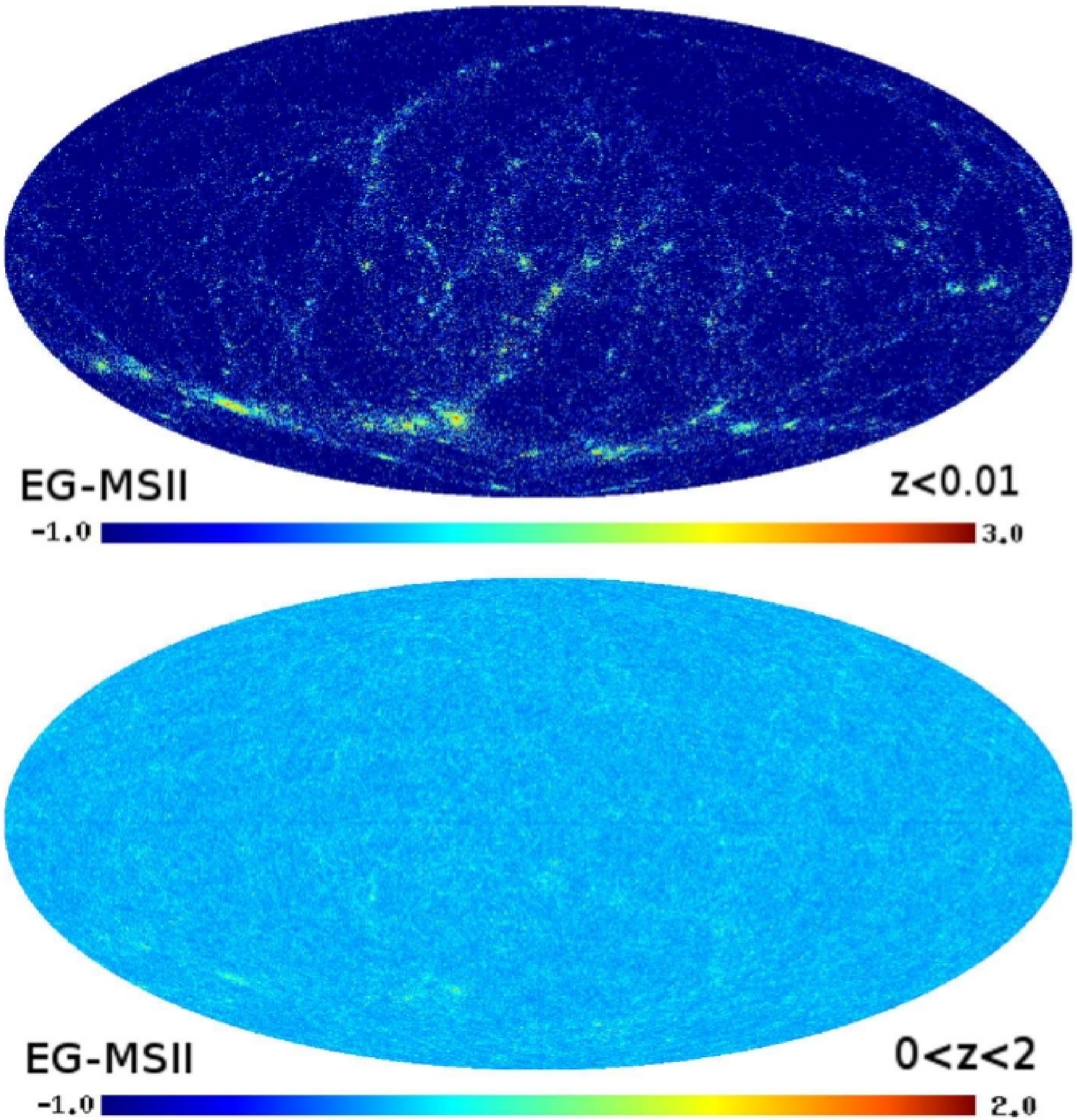


Fig 1.19 (D. Scott) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007



Extragalactic DM background



γ-ray background
from annihilating DM

Fornasa et al., 2013

DM-induced "isotropic" background

See, Fornengo et al., JCAP 2012
Fornengo&Regis, 2013

density field of the source

Intensity: $I_g(\vec{n}) = \int d\chi \, g(\chi, \vec{n}) \, \tilde{W}(\chi)$

Window function

Normalized window function $W(\chi) = \langle g \rangle \, \tilde{W}(\chi)$

$$\bar{g}(z) = \langle g(z, \vec{n}) \rangle = \int dm \, \frac{dn}{dm} \int d^3\boldsymbol{x} \; g(\boldsymbol{x}|m, z)$$

Average intensity: $\langle I_g \rangle = \int d\chi \, W(\chi)$

$$\frac{dz}{d\chi} = \frac{H(z)}{c}$$

Annihilating DM

$$W(E, z) = \frac{(\Omega_{DM}\rho_c)^2}{4\pi} \frac{\langle \sigma_a v \rangle}{2m_\chi^2} (1+z)^3 \, \Delta^2(z) \, \frac{dN_a[E(1+z)]}{dE} \, e^{-\tau[E(1+z),z]}$$

Clumping factor

$$\Delta^2(z) = \frac{\langle \rho^2 \rangle}{\bar{\rho}^2} = \int_{m_{\min}}^{m_{\max}} dm \, \frac{dn}{dm} \int d^3\boldsymbol{x} \, \frac{\rho^2(\boldsymbol{x}|m)}{\bar{\rho}^2}$$

Decaying DM

$$W(E, z) = \frac{1}{4\pi} \frac{\Omega_{\rm DM}\rho_c}{m_\chi \tau_d} \frac{dN_d[E(1+z)]}{dE} e^{-\tau[E(1+z),z]}$$

DM-induced "isotropic" background

$$I_\nu = \frac{c}{4\pi}\int dz \frac{e^{-\tau(z)}}{(1+z)\,H(z)}\int dM\,\frac{dn}{dM}(M,z)\,\mathcal{L}(E=E_\nu(1+z),z,M)$$

$$\mathcal{L}_a^{hh}(E,z,M) = E\,\frac{(\sigma_a v)}{2\,M_\chi^2}\int_0^{R_v} d^3r\,\frac{d\tilde{N}_i}{dE}\,[(1-f)\,\rho(M,r,z)]^2 \qquad \text{for the host halo}$$

$$\mathcal{L}_a^{sh}(E,z,M) = E\,\frac{(\sigma_a v)}{2\,M_\chi^2}\int_{M_{cut}^s}^{M} dM_s\,\frac{dn_s}{dM_s}(M_s,f,M)\int_0^{R_v} d^3r_s\,\frac{d\tilde{N}_i}{dE}\,\rho_s^2(M_s,r_s,z) \qquad \text{for subhalos}$$

$$\frac{d\tilde{N}_\gamma}{dE} = \frac{dN_\gamma}{dE}, \qquad \text{for prompt emission}$$

$$\frac{d\tilde{N}_{\rm syn,IC}}{dE} = 2\int_{m_e}^{M_\chi} dE'\,\frac{P_{\rm syn,IC}}{E}\cdot\tilde{n}_e, \qquad \text{for radiative emission .}$$

where $\tilde{n}_e(r,E) = n_e/A$, with $A_a = (\sigma v)/2\cdot(\rho/M_\chi)^2$

For prompt emission (or if you can neglect other spatial dependencies in the radiative emissivity) use previous page.

A simpler effective way to introduce substructures: $\rho^2(\boldsymbol{x},m,z) \longrightarrow B(\boldsymbol{x},m,z)\rho^2(\boldsymbol{x},m,z)$

For the expression of B, see (Kamionkowski, Koushiappas and Kuhlen, 2010)

DM-induced "isotropic" background

In this halo model approach, we need:

Halo mass function $\frac{dn}{dm}$ (e.g., Sheth and Tormen, 1999)

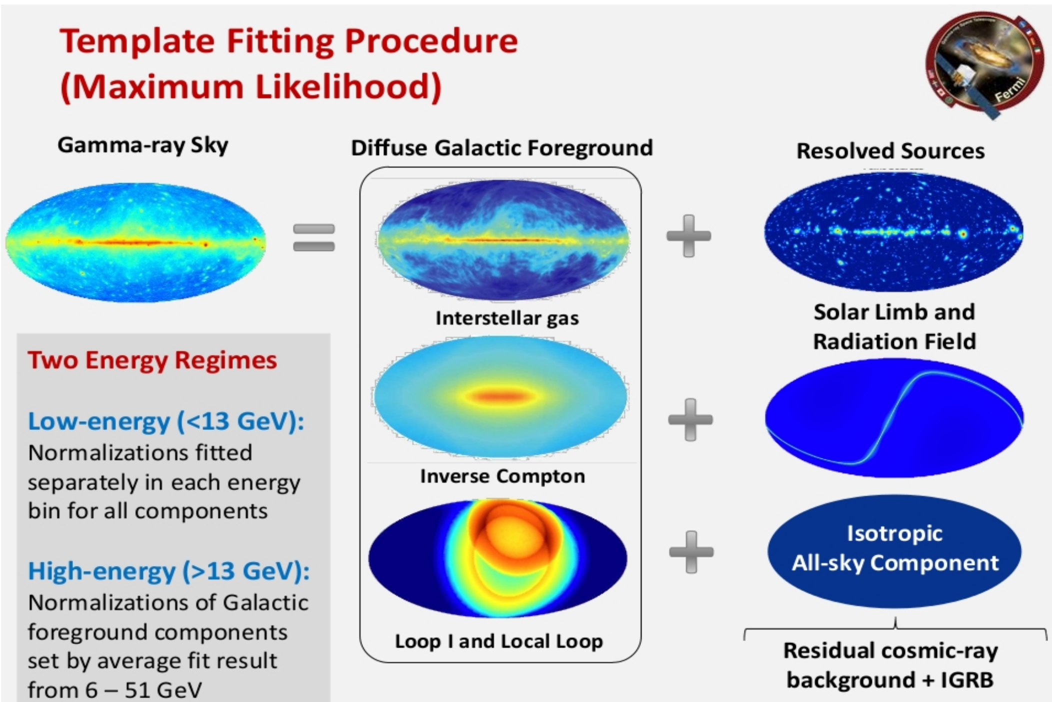
Concentration of halos c(m) (e.g., Bullock et al., 1999)

DM distribution in halos (NFW, Einasto, Burkert, ...)

and the same for subhalos, or $B(\boldsymbol{x}, m, z)$

Critical points: choice of the **minimum halo mass m_{min} and extrapolation** from the resolution of numerical simulations down to m_{min}

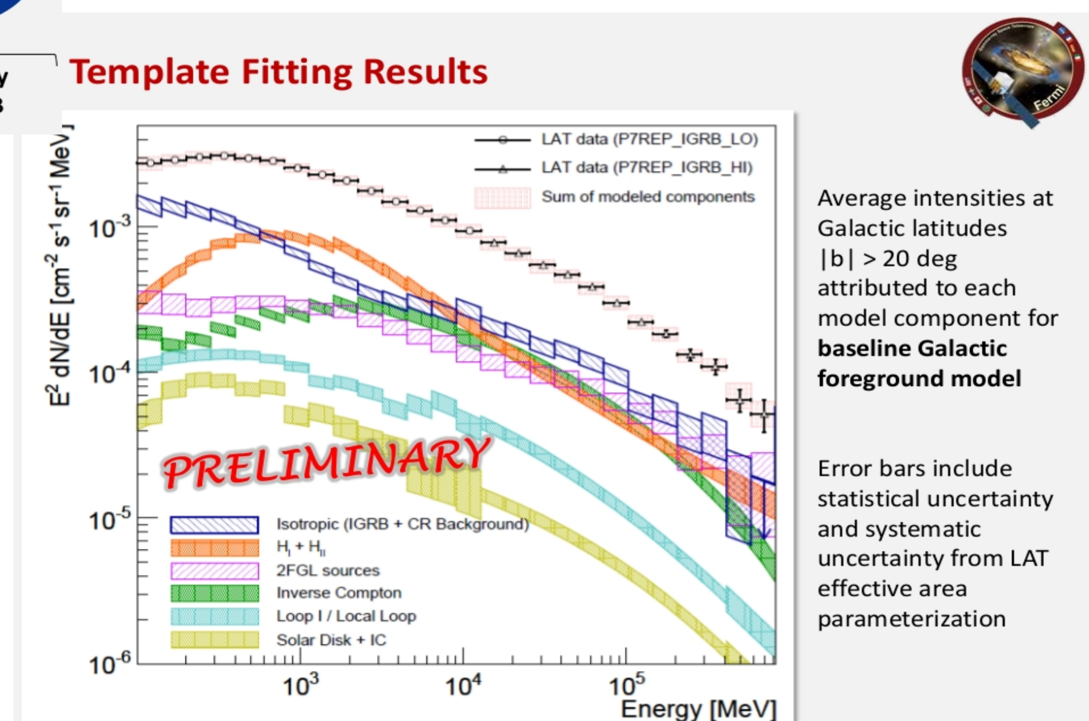
Extragalactic gamma-ray background



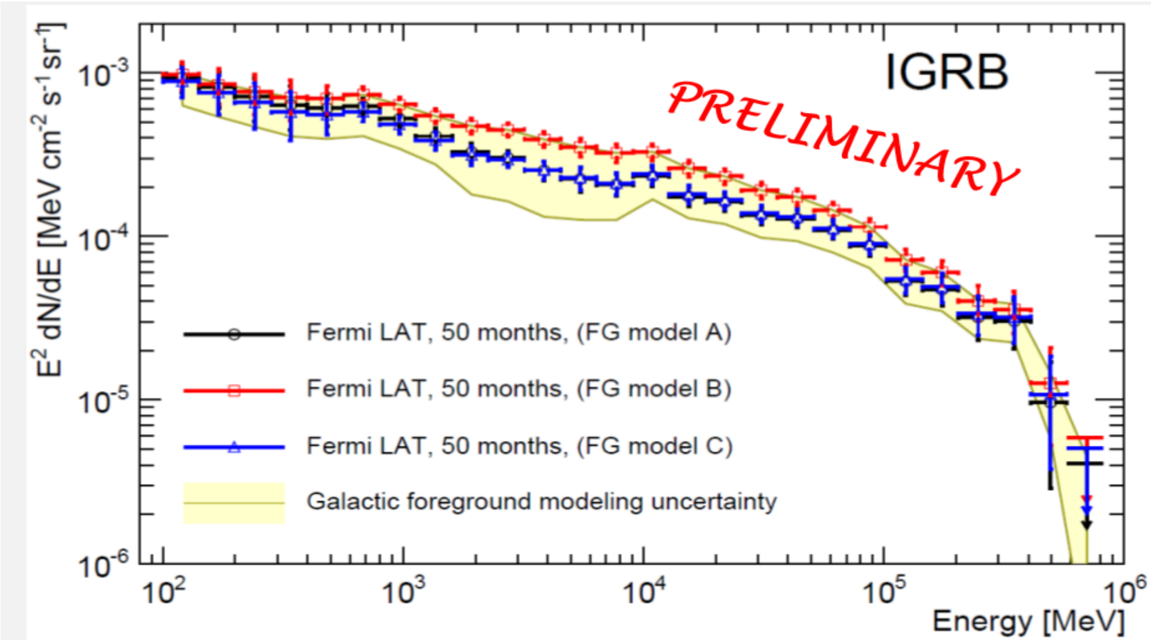
Fermi-LAT method

and measurement

(from Bechtol's talk at KICP)

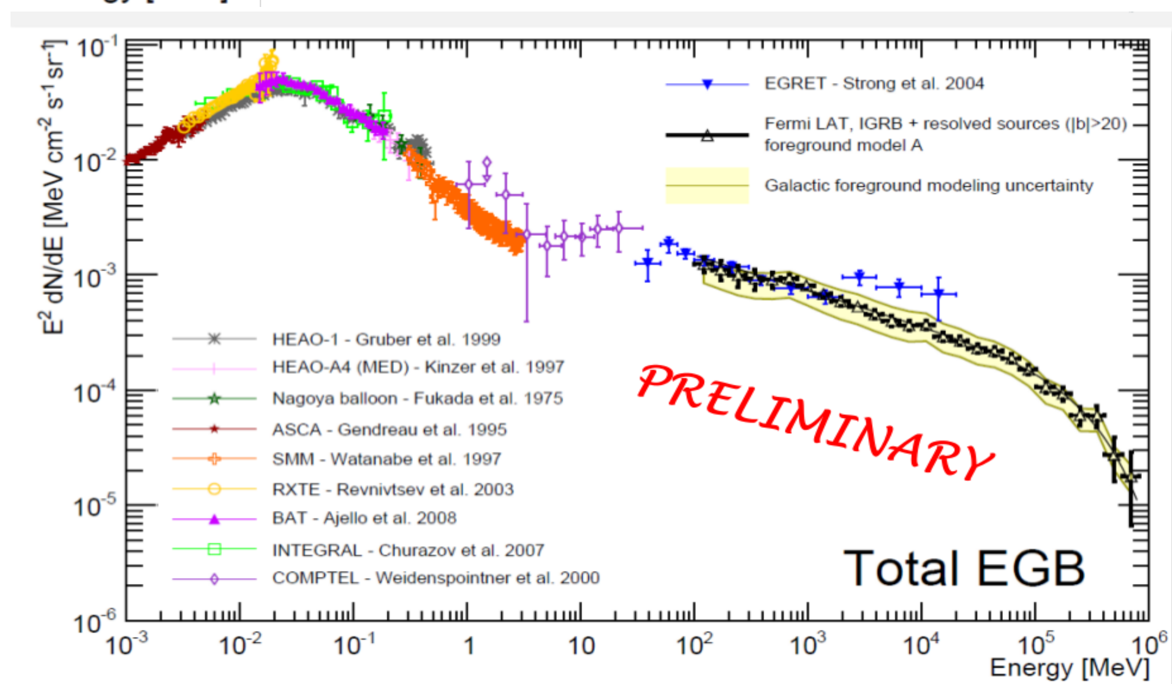


Extragalactic gamma-ray background

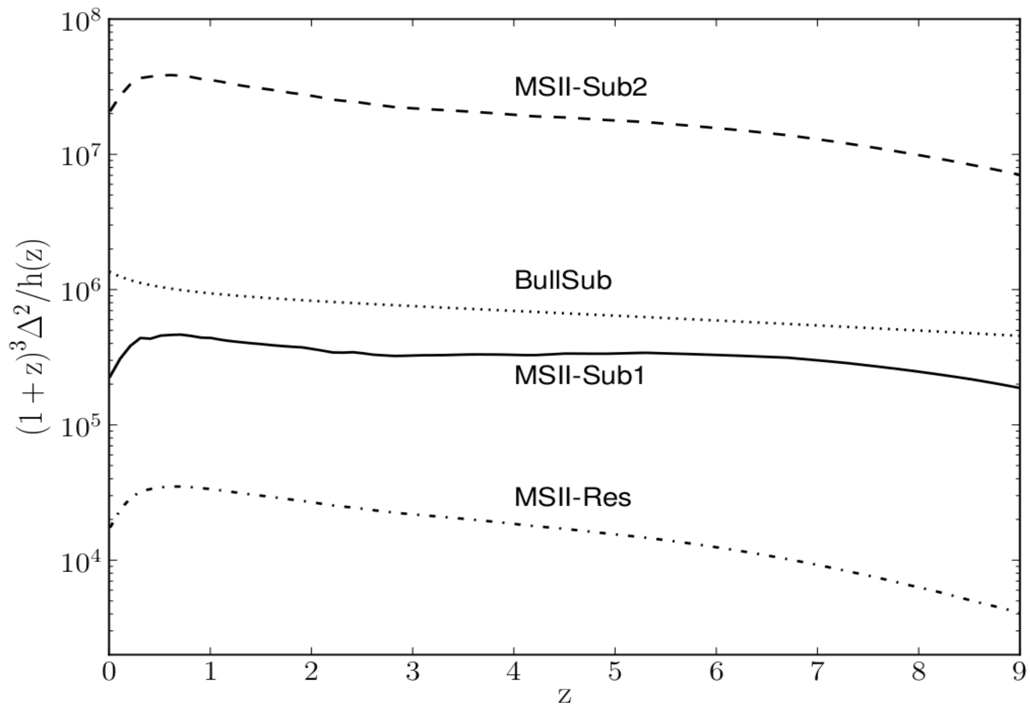


Systematic uncertainty from Galactic foreground is important

high-energy extragalactic background light – 2014

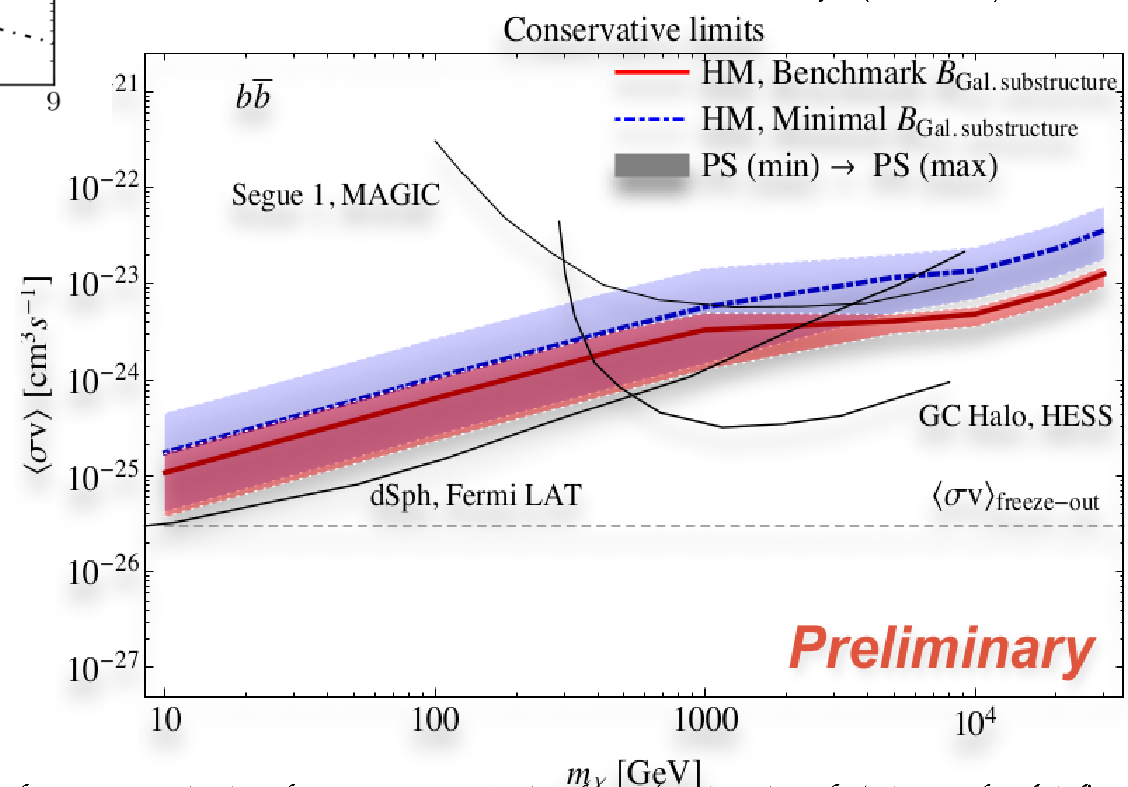


Extragalactic gamma-ray background



Clumping factor

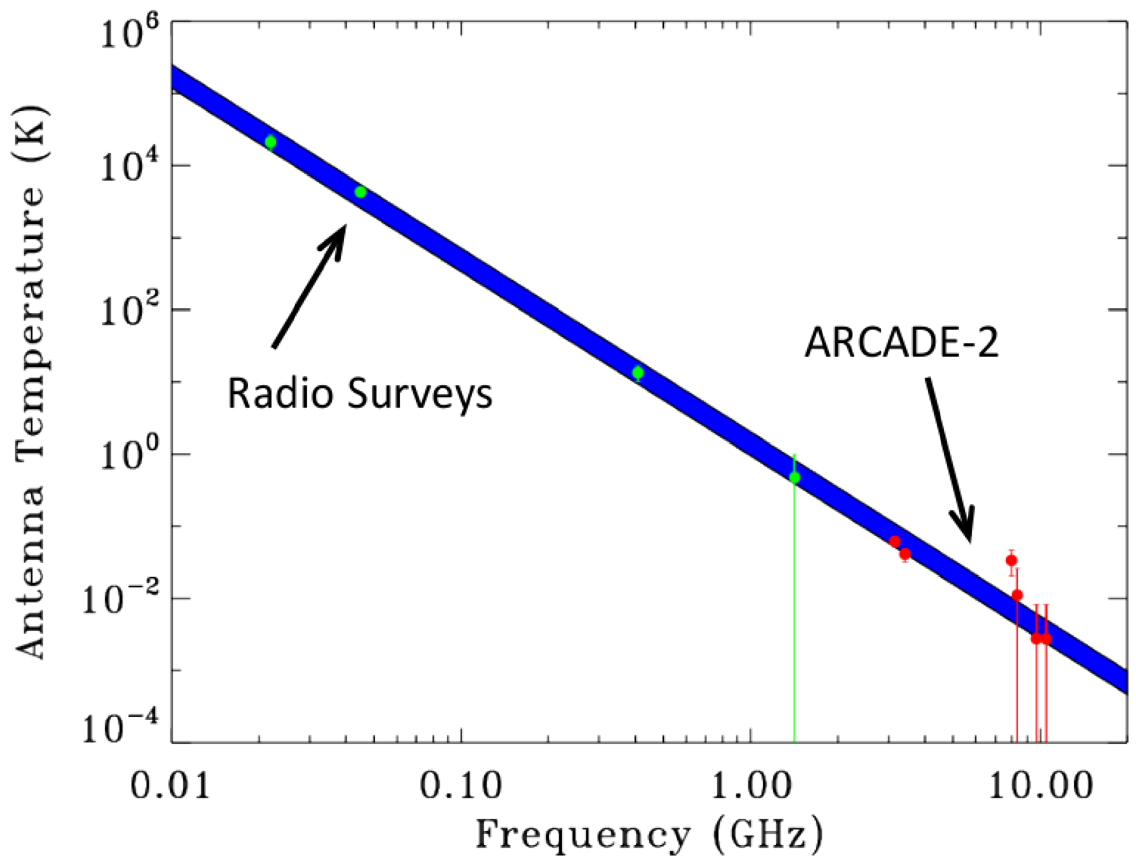
Zaharijas (Fermi-LAT) talk, 2014



Upper bounds on WIMP annihilation rate

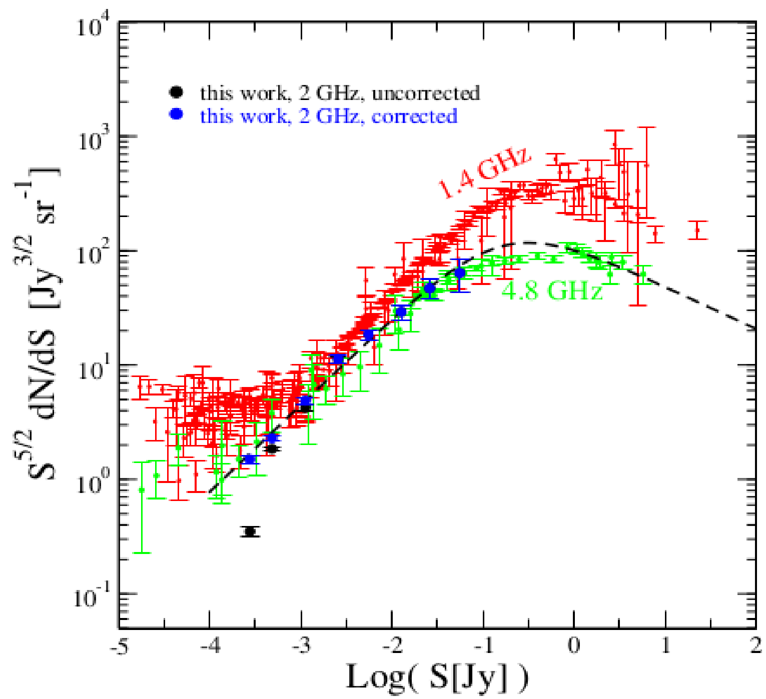
Extragalactic radio background

Recent measurements by the ARCADE collaboration (Fixsen at al.. 2009)



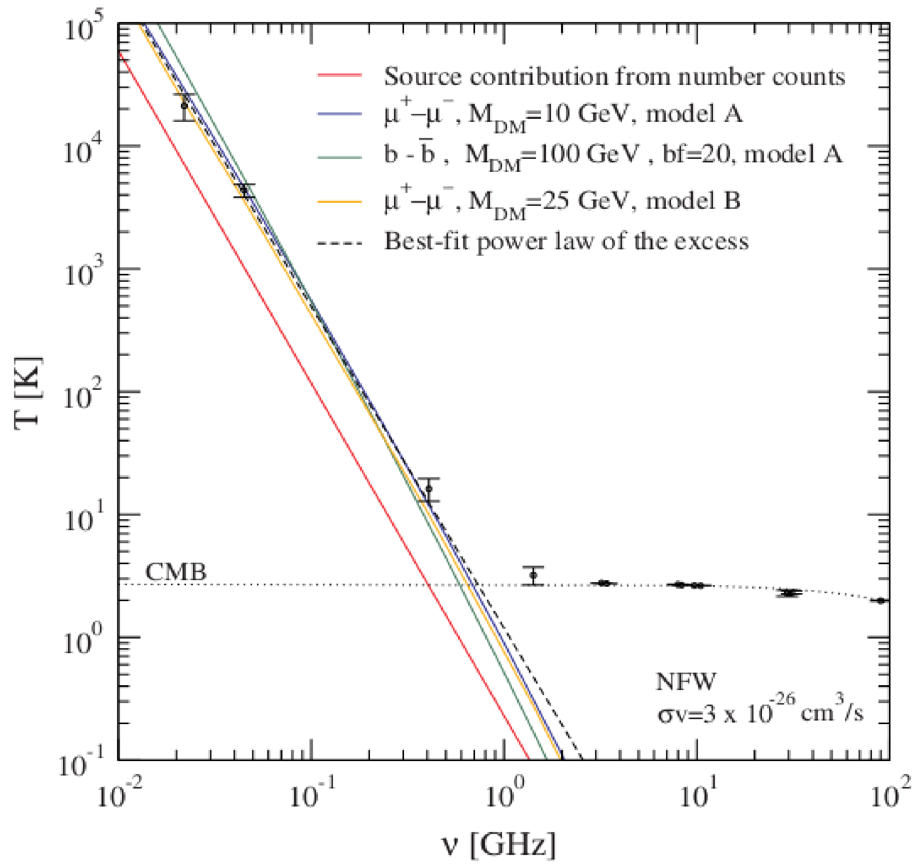
Total intensity can be estimated through differential number counts:

$$I_\nu = \int_0^{S_0} dS \frac{dN}{dS_\nu} S$$



Extragalactic radio background

The extragalactic radio background appears to be significantly brighter than extrapolation from number counts of AGN and SFG (**ARCADE-2** Collaboration, 2009)



The excess can be explained in terms of synchrotron emission induced by WIMP annihilations

(Fornengo, Lineros, MR, Taoso, 2011)

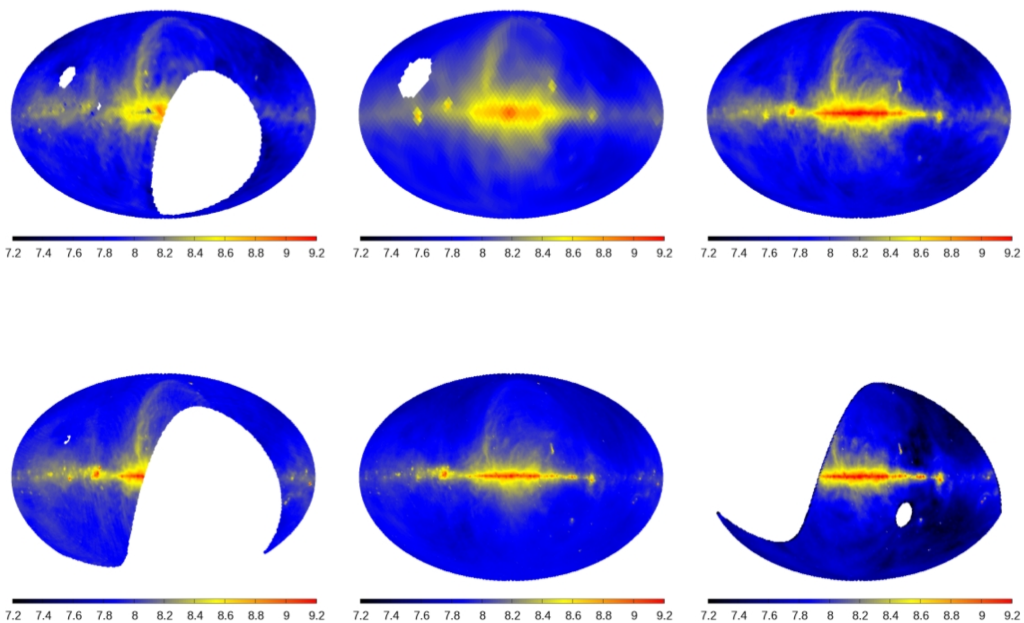
Simplest solution for ARCADE excess:

Radio background is produced by radio sources taking over at sub-mJy (Singal et al, 2010)

PROBLEM for "normal" astrophysical sources because they would violated FIR-radio relation.

Extragalactic radio background

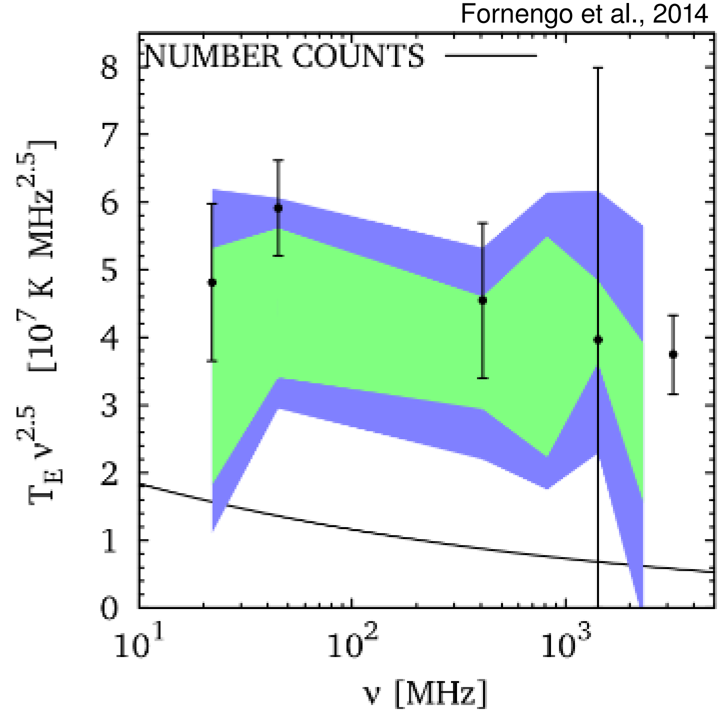
Is it a residual Galactic contribution?



Template fitting of 6 radio maps with:

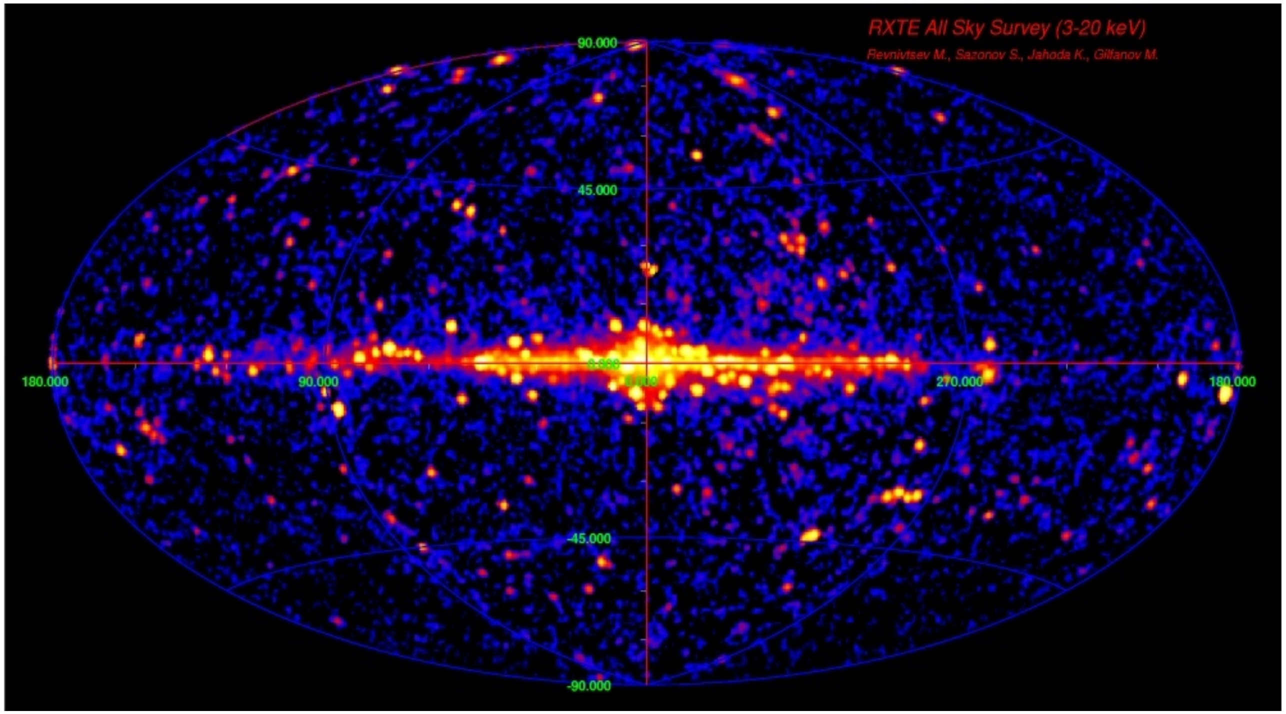
- extragalactic component
- free-free (Hα map)
- synchrotron from CRs (GALPROP)
- sources

Fornengo et al., 2014



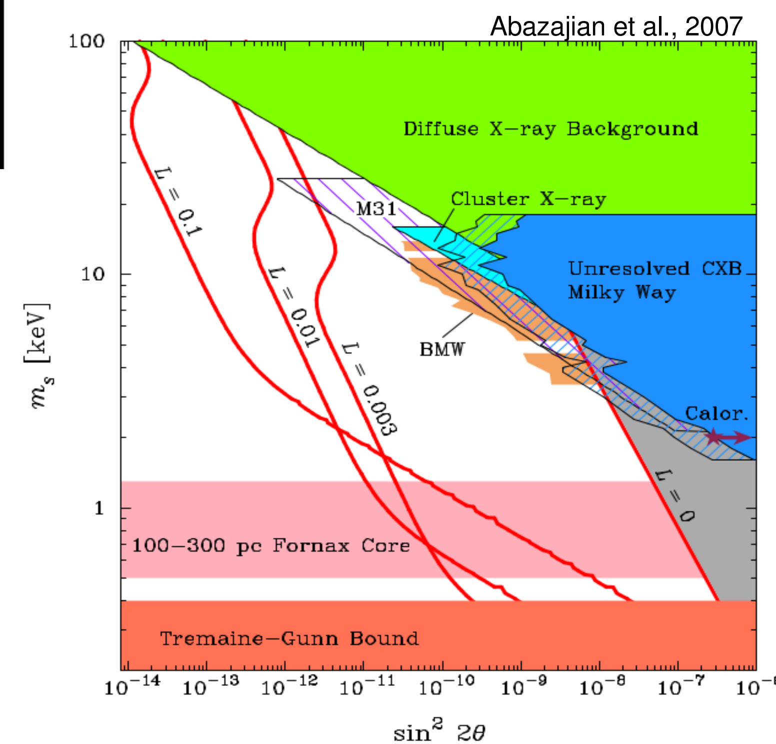
Unless peculiar underhanded Galactic aspects, extragalactic sources below the current observational threshold seem to account for the majority of the brightness of the extragalactic radio sky

Extragalactic X-ray background



Vast majority of EXB associated to sources

Not very constraining for WIMP DM
but interesting probe for keV decaying DM



Statistical correlations in the anisotropic DM sky

Extragalactic DM background

We look for a non-gravitational signal of Dark Matter.

The source we want to discover is:

- faint

Promising strategy:
Go for deep observations of single objects
(this is what we discussed so far)

Extragalactic DM background

We look for a non-gravitational signal of Dark Matter.

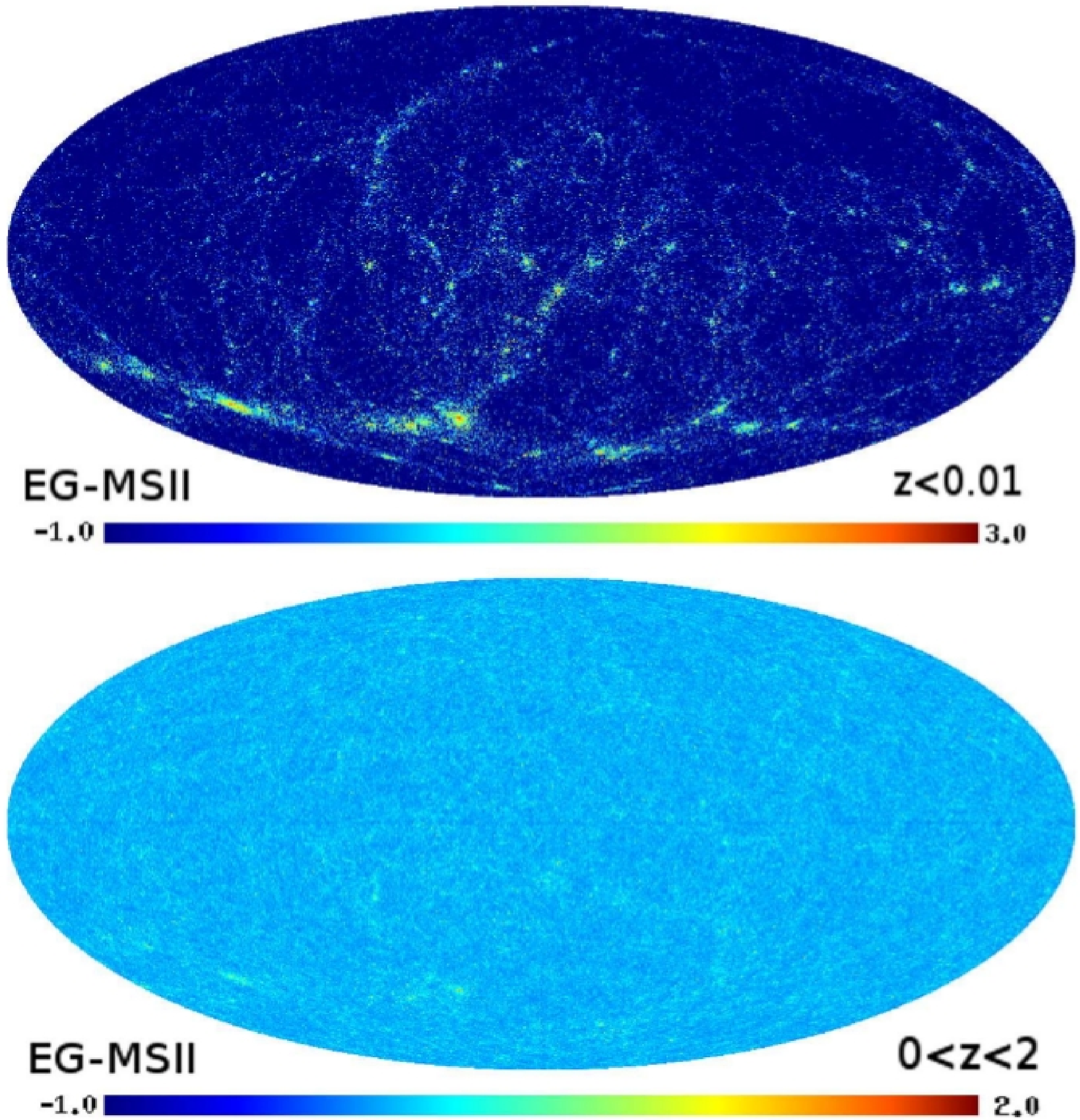
The source we want to discover is:

- faint
- very numerous
  (any luminous source is embedded in a DM halo)

DM sources can affect the statistics of photons across the sky
(even in the case they are too dim to be individually detected)

→ Statistical correlations

Extragalactic DM background



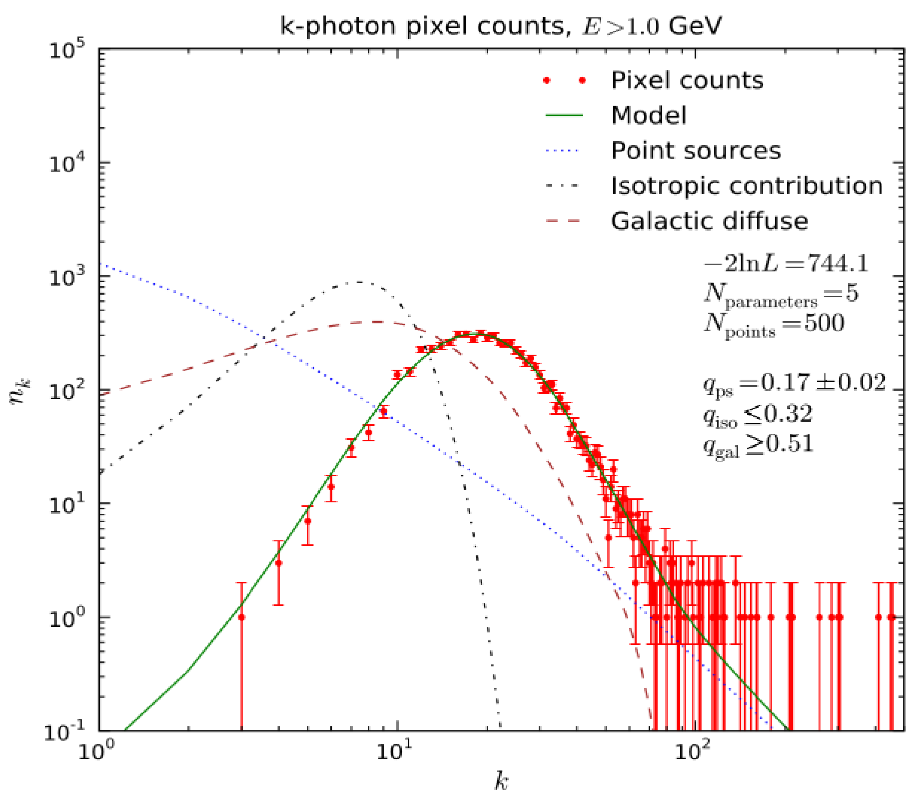
Fornasa et al., 2013

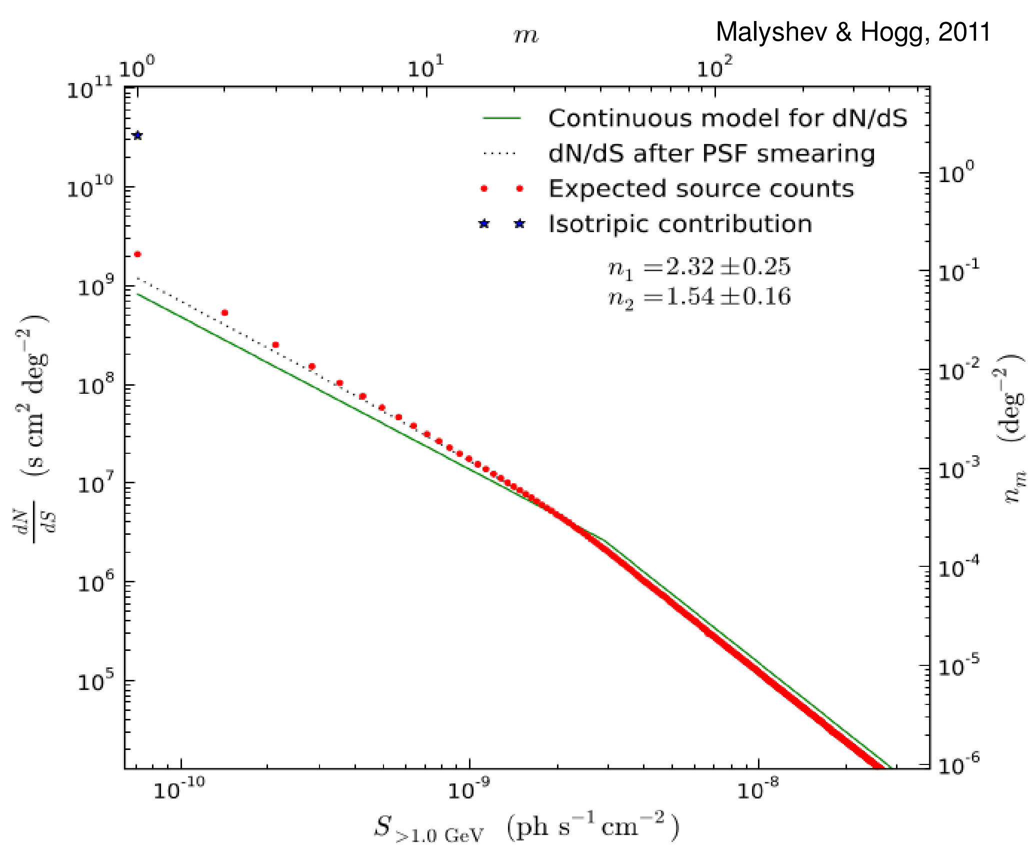
γ-ray background from annihilating DM

1-point correlation

(also called P(D) distribution or photon/pixel counts)

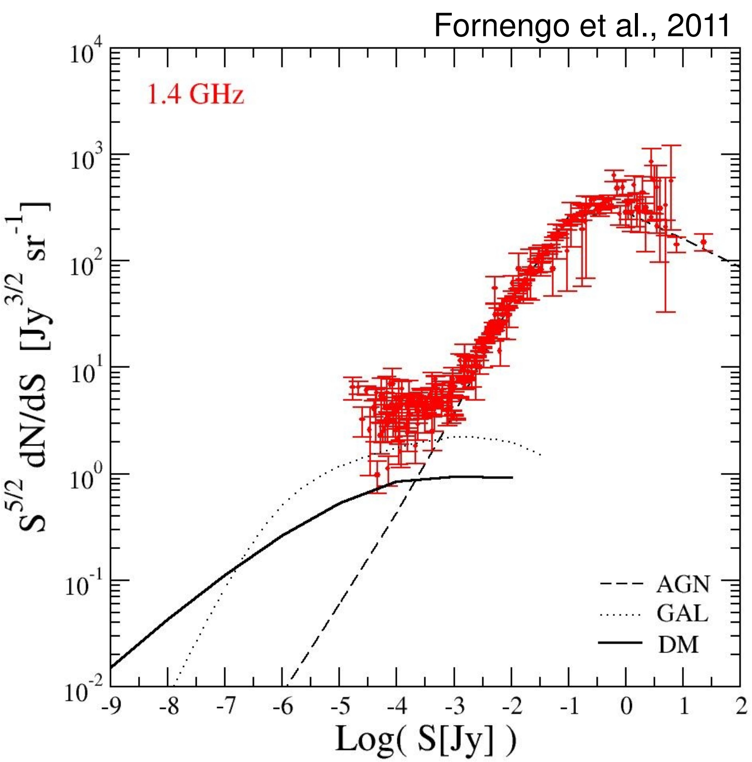
It is useful to constrain the **source number counts dN/dS** below the detection threshold.

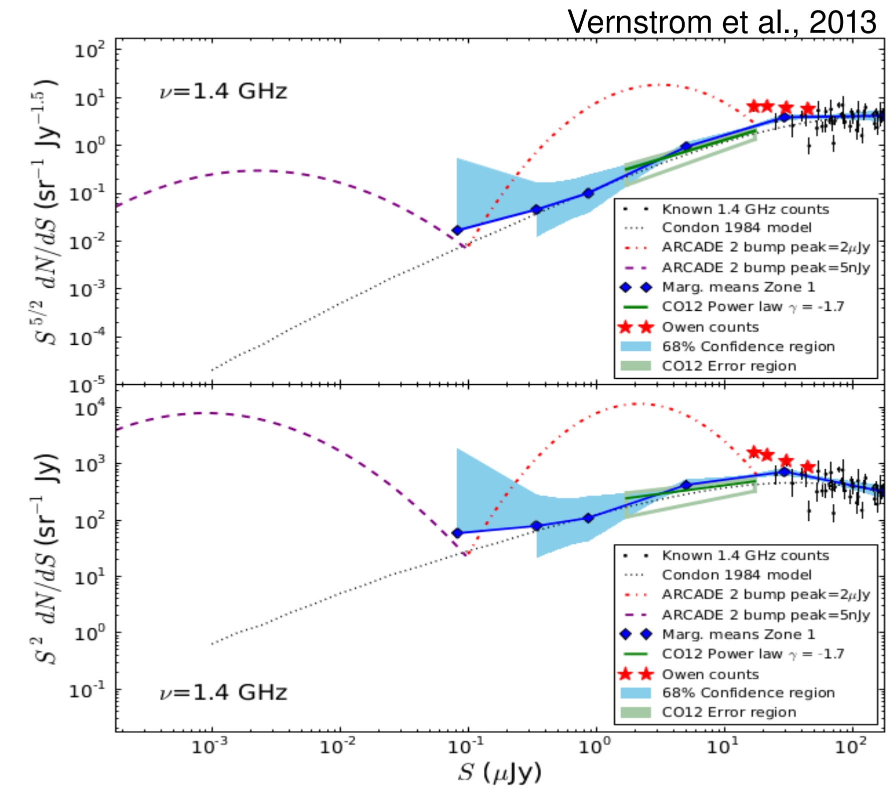




1-point correlation

Test for ARCADE-excess explanations





2-point correlation

We will focus on the 2-point angular power spectrum (APS) of intensity fluctuations C_ℓ

Analogous to the CMB studies, but now exploring the non-thermal extragalactic sky (radio, X-ray and g-ray frequencies).

Linked to the 2-point angular correlation function (ACF) by means of a Legendre transformation:

$$\omega(\theta) = \frac{1}{4\pi} \sum_{\ell=1}^{\infty} (2\,\ell + 1)\, C_\ell\, P_\ell(\cos\theta)$$

Won't discuss higher-order statistics.

2-point APS / derivation

See Fornengo&Regis, 2013

$$I_g(\vec{n}) = \int d\chi\, g(\chi, \vec{n})\, \tilde{W}(\chi) \qquad W(\chi) = \langle g \rangle\, \tilde{W}(\chi) \qquad \langle I_g \rangle = \int d\chi\ W(\chi).$$

Intensity fluctuations: $\delta I_g(\vec{n}) \equiv I_g(\vec{n}) - \langle I_g \rangle$

Expansion in spherical harmonics: $\delta I_g(\vec{n}) = \langle I_g \rangle \sum_{\ell m} a_{\ell m} Y_{\ell m}(\vec{n})$

$$a_{\ell m} = \frac{1}{\langle I_g \rangle} \int d\vec{n}\, \delta I_g(\vec{n})\, Y^*_{\ell m}(\vec{n}) = \frac{1}{\langle I_g \rangle} \int d\vec{n}\, d\chi\ f_g(\chi, \boldsymbol{r}) W(\chi)\, Y^*_{\ell m}(\vec{n})$$

fluctuation density field $f_g \equiv g/\langle g \rangle - 1$

2-point APS / derivation

$$\vec{r} = \chi\,\vec{n}$$

$$\begin{aligned} a_{\ell m} &= \frac{1}{\langle I_g \rangle} \int d\vec{n}\, d\chi\, \frac{d\boldsymbol{k}}{(2\pi)^3} \hat{f}_g(\chi, \boldsymbol{k}) e^{i\boldsymbol{k}\cdot\boldsymbol{r}} W(\chi) Y^*_{\ell m}(\vec{n}) \\ &= \frac{1}{\langle I_g \rangle} \int d\vec{n}\, d\chi\, \frac{d\boldsymbol{k}}{2\pi^2} \hat{f}_g(\chi, \boldsymbol{k}) \left[\sum_{\ell' m'} i^{\ell'} j_{\ell'}(k\chi) Y^*_{\ell' m'}(\hat{\boldsymbol{k}}) Y_{\ell' m'}(\vec{n}) \right] W(\chi) Y^*_{\ell m}(\vec{n}) \\ &= \frac{i^{\ell}}{\langle I_g \rangle} \int d\chi\, W(\chi) \int \frac{d\boldsymbol{k}}{2\pi^2}\, \hat{f}_g(\chi, \boldsymbol{k}) j_\ell(k\chi) Y^*_{\ell m}(\hat{\boldsymbol{k}}) \end{aligned}$$

Let's consider two different emissions i and j
(e.g., radio and gamma-rays from annihilating DM)

Definition of APS: $$C_\ell^{(ij)} = \frac{1}{2\ell+1} \langle \sum_{m=-\ell}^{\ell} a^{(i)}_{\ell m} a^{(j)*}_{\ell m} \rangle$$

We'll keep notation valid for both auto-correlation (i=j) and cross-correlation (i≠j)

2-point APS / derivation

$$
\begin{aligned}
C_\ell^{(ij)} &= \frac{1}{\langle I_i\rangle\langle I_j\rangle}\int d\chi\, W_i(\chi)\int d\chi'\, W_j(\chi')\int\frac{d\boldsymbol{k}}{2\pi^2}\int\frac{d\boldsymbol{k}'}{2\pi^2}\,\langle\hat f_{g_i}(\chi,\boldsymbol{k})\hat f^*_{g_j}(\chi',\boldsymbol{k}')\rangle j_\ell(kr)j_\ell(k'r')\sum_{m=-\ell}^{\ell}\frac{1}{2\ell+1}Y_{\ell m}(\hat{\boldsymbol{k}})Y^*_{\ell m}(\hat{\boldsymbol{k}}')\\
&= \frac{2}{\pi\langle I_i\rangle\langle I_j\rangle}\int d\chi\, W_i(\chi)\int d\chi'\, W_j(\chi')\int d\boldsymbol{k}\; P_{ij}(k,\chi,\chi')j_\ell(kr)j_{\ell'}(kr')\sum_{m=-\ell}^{\ell}\frac{1}{2\ell+1}Y_{\ell m}(\hat{\boldsymbol{k}})Y^*_{\ell m}(\hat{\boldsymbol{k}})\\
&= \frac{2}{\pi\langle I_i\rangle\langle I_j\rangle}\int d\chi\, W_i(\chi)\int d\chi'\; dk\, k^2\; W_j(\chi')P_{ij}(k,\chi,\chi')j_\ell(kr)j_\ell(kr')\\
&= \frac{1}{\langle I_i\rangle\langle I_j\rangle}\int\frac{d\chi}{\chi^2}W_i(\chi)\,W_j(\chi)P_{ij}(k=\ell/\chi,\chi)
\end{aligned}
$$

We used:

Definition of

3D power spectrum: $\langle\hat f_{g_i}(\chi,\boldsymbol{k})\hat f^*_{g_j}(\chi',\boldsymbol{k}')\rangle = (2\pi)^3\delta^3(\boldsymbol{k}-\boldsymbol{k}')P_{ij}(k,\chi,\chi')$

Limber approximation:

$$\frac{2}{\pi}\int k^2dk\; P_f(k;r,r')j_l(kr)j_l(kr') \simeq \frac{1}{r^2}P_f\left(k=\frac{l}{r};r\right)\delta^{(1)}(r-r')$$

2-point APS / derivation

$$P_{ij}(k) = P_{ij}^{1h}(k) + P_{ij}^{2h}(k)$$

For the 3D PS derivation see:
Scherrer and Bertschinger, 1991
Cooray and Sheth, 2002
and Ravi's lectures!

$$P_{ij}^{1h}(k) = \int dm \, \frac{dn}{dm} \hat{f}_i^*(k|m) \, \hat{f}_j(k|m)$$

$$P_{ij}^{2h}(k) = \left[\int dm_1 \, \frac{dn}{dm_1} b_i(m_1) \hat{f}_i^*(k|m_1)\right] \left[\int dm_2 \, \frac{dn}{dm_2} b_j(m_2) \hat{f}_j(k|m_2)\right] P^{\rm lin}(k)$$

$$C_\ell^{(ij)} = \frac{1}{\langle I_i \rangle \langle I_j \rangle} \int \frac{d\chi}{\chi^2} W_i(\chi) \, W_j(\chi) P_{ij}(k = \ell/\chi, \chi)$$

Two key ingredients:

Window functions and 3D power spectrum

Auto-correlation angular power spectrum

3D power spectrum

Decaying DM

$$P^{1h}_{\delta\delta}(k) = \int_{m_{\min}}^{m_{\max}} dm \, \frac{dn}{dm} \tilde{v}(k|m)^2$$

$$P^{2h}_{\delta\delta}(k) = \left[\int_{m_{\min}}^{m_{\max}} dm \, \frac{dn}{dm} b_h(m) \tilde{v}(k|m) \right]^2 P^{\rm lin}(k)$$

where $\tilde{v}(k|m)$ is the Fourier transform of $\rho(\boldsymbol{x}|m)/\bar{\rho}$

Annihilating DM

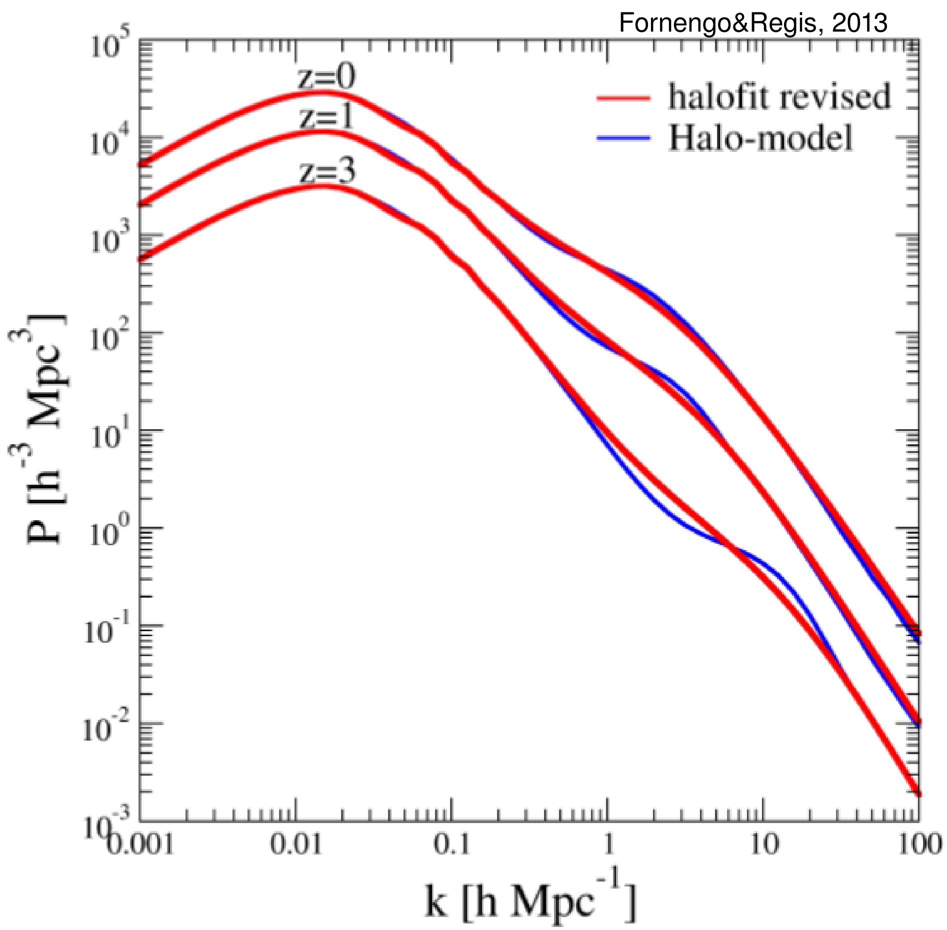
$$P^{1h}_{\delta^2\delta^2}(k) = \int_{m_{\min}}^{m_{\max}} dm \, \frac{dn}{dm} \left(\frac{\tilde{u}(k|m)}{\Delta^2} \right)^2$$

$$P^{2h}_{\delta^2\delta^2}(k) = \left[\int_{m_{\min}}^{m_{\max}} dm \, \frac{dn}{dm} b_h(m) \frac{\tilde{u}(k|m)}{\Delta^2} \right]^2 P^{\rm lin}(k)$$

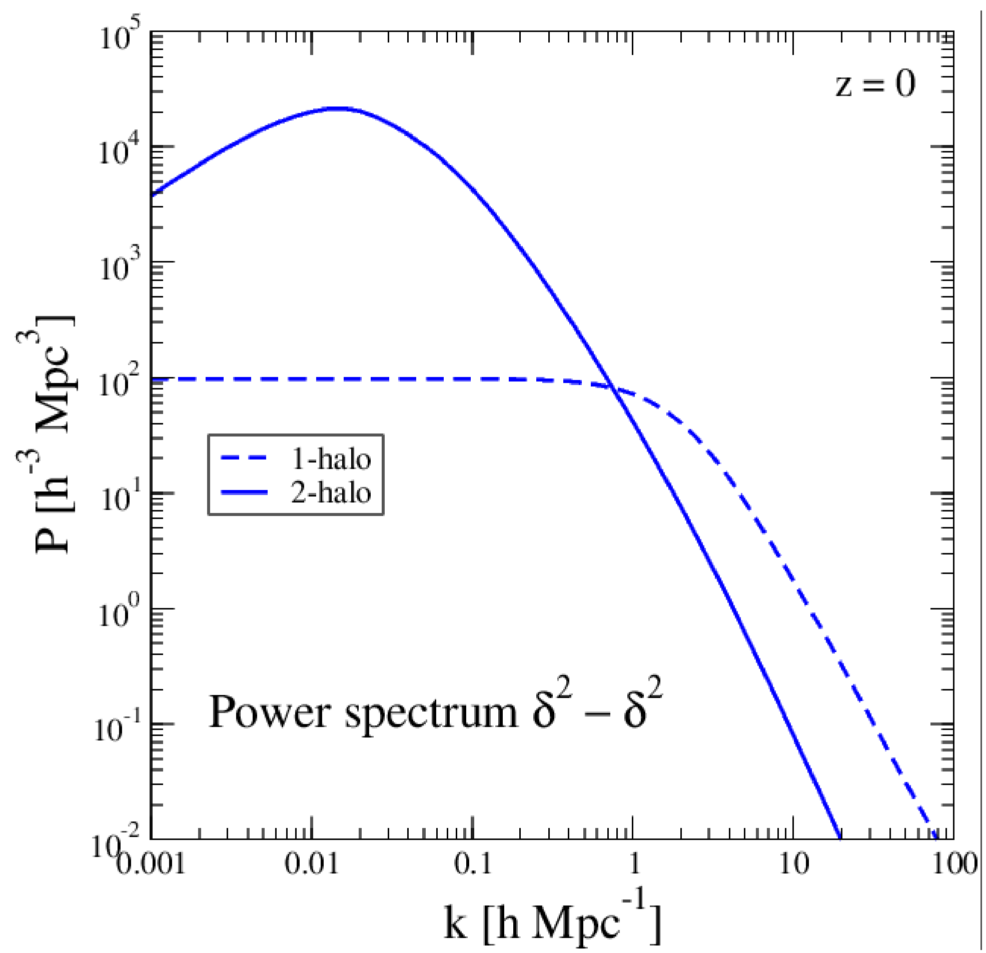
where $\tilde{u}(k|m)$ is the Fourier transform of $\rho^2(\boldsymbol{x}|m)/\bar{\rho}^2$

3D power spectrum

Power spectrum δ–δ

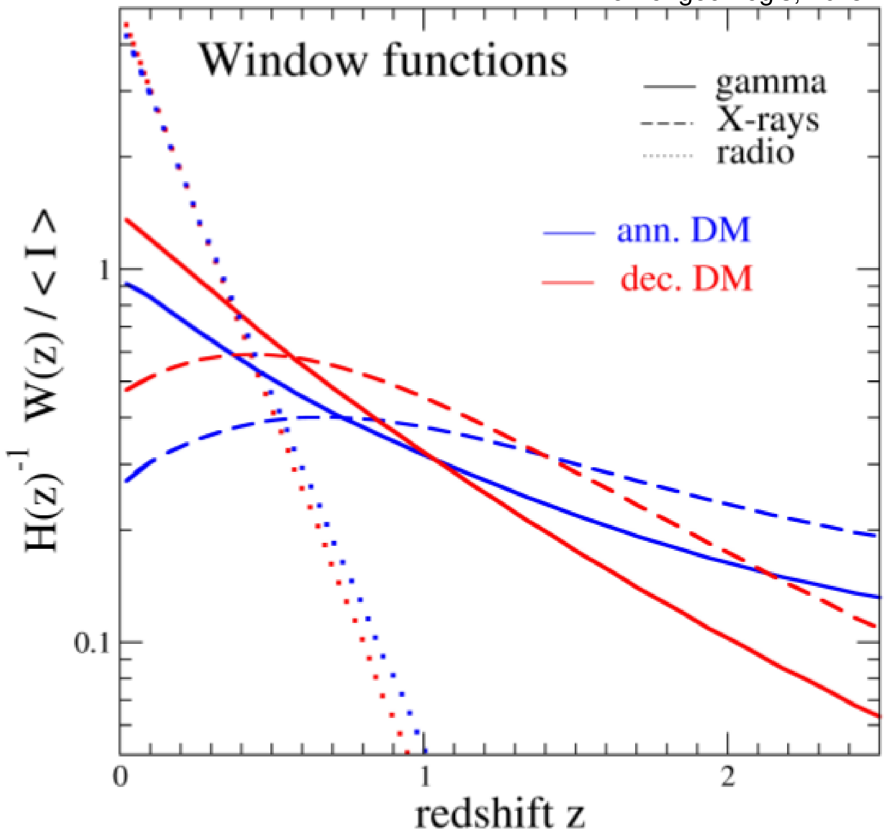


Power spectrum δ^2–δ^2

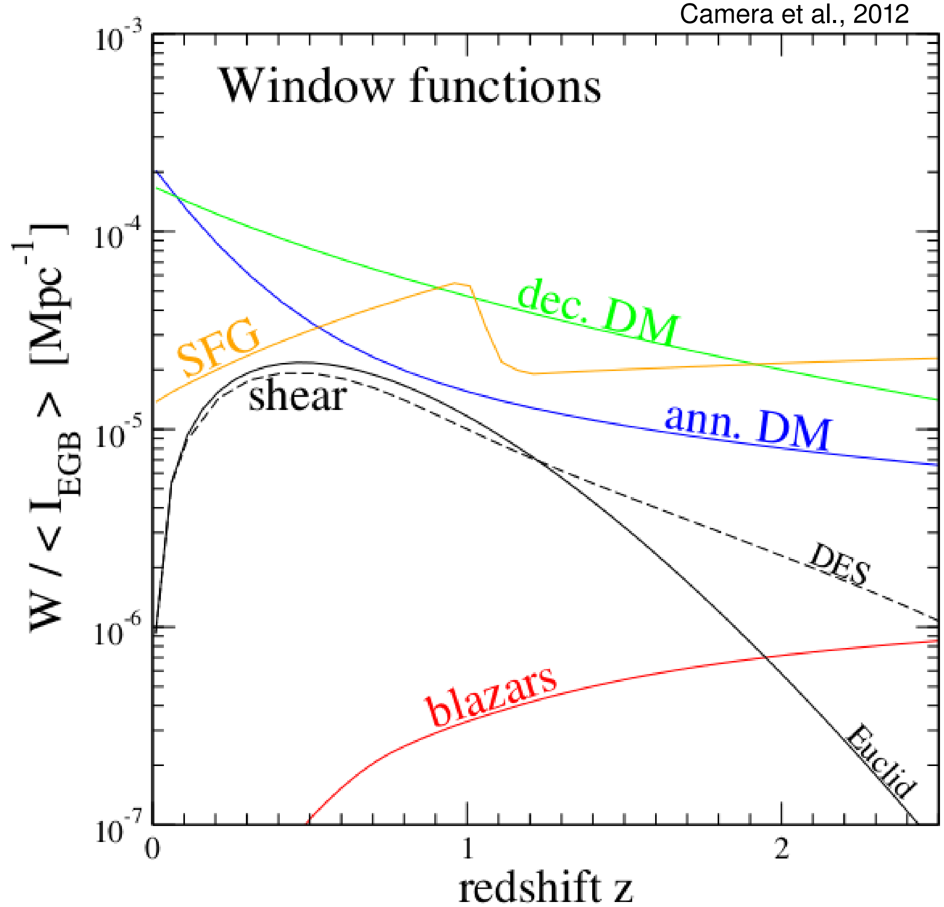


Window function

Fornengo&Regis, 2013



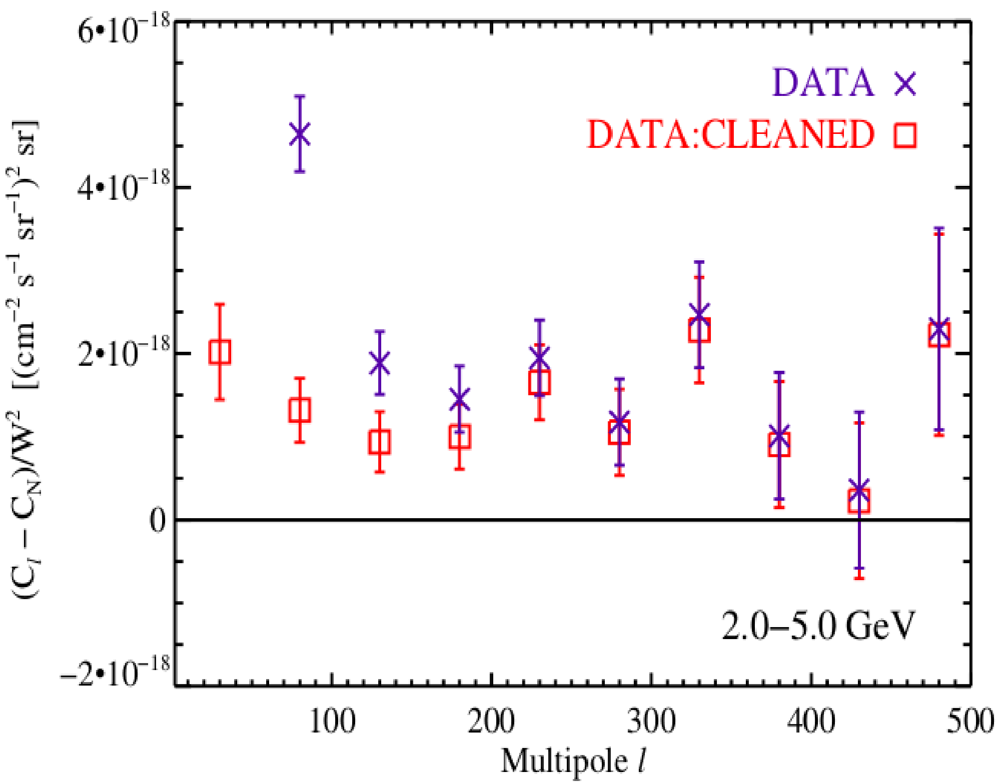
Camera et al., 2012

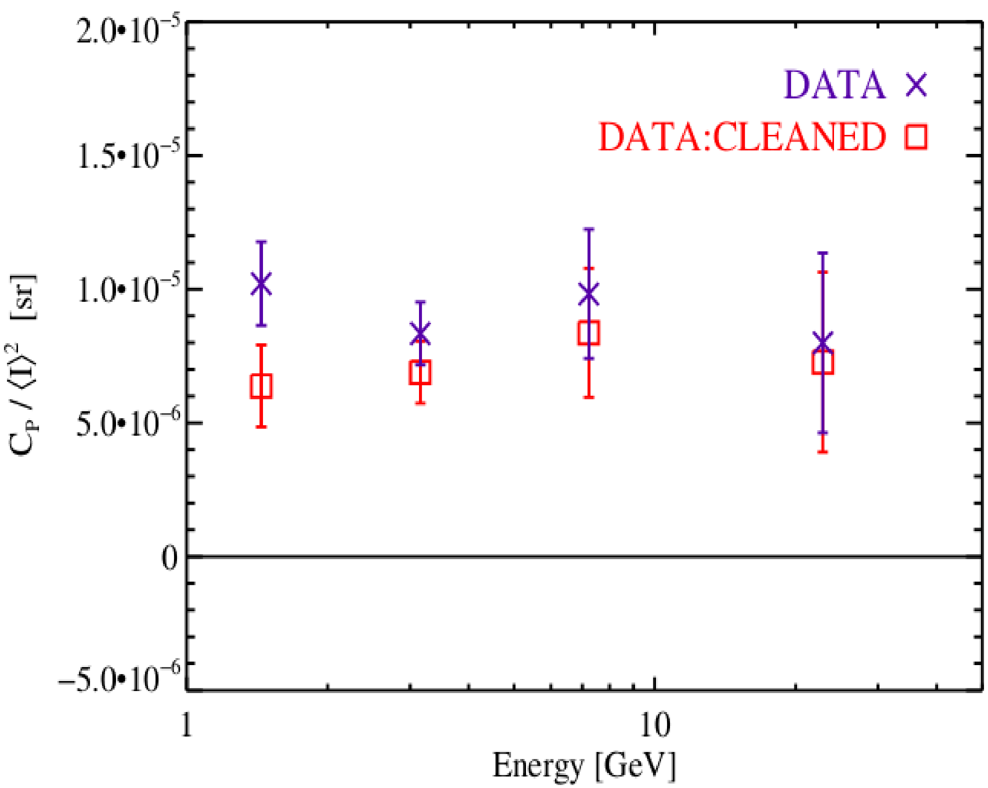


The peak of the WIMP **window function** is at lower z than for astrophysical sources.

Auto-correlation gamma APS

Fermi-LAT measurement of APS of unresolved sources (2012)





Consistent with a flat (“Poisson-noise”) APS with an energy spectrum following a power law as for the EGB (Γ~-2.4)

Auto-correlation "astro" APS

$$dn/dm \longrightarrow dn/d\mathcal{L} \equiv \Phi(\mathcal{L}, z)$$

Point-source approximation: $g_S(\mathcal{L}, \boldsymbol{x} - \boldsymbol{x}') = \mathcal{L}\,\delta^3(\boldsymbol{x} - \boldsymbol{x}')$

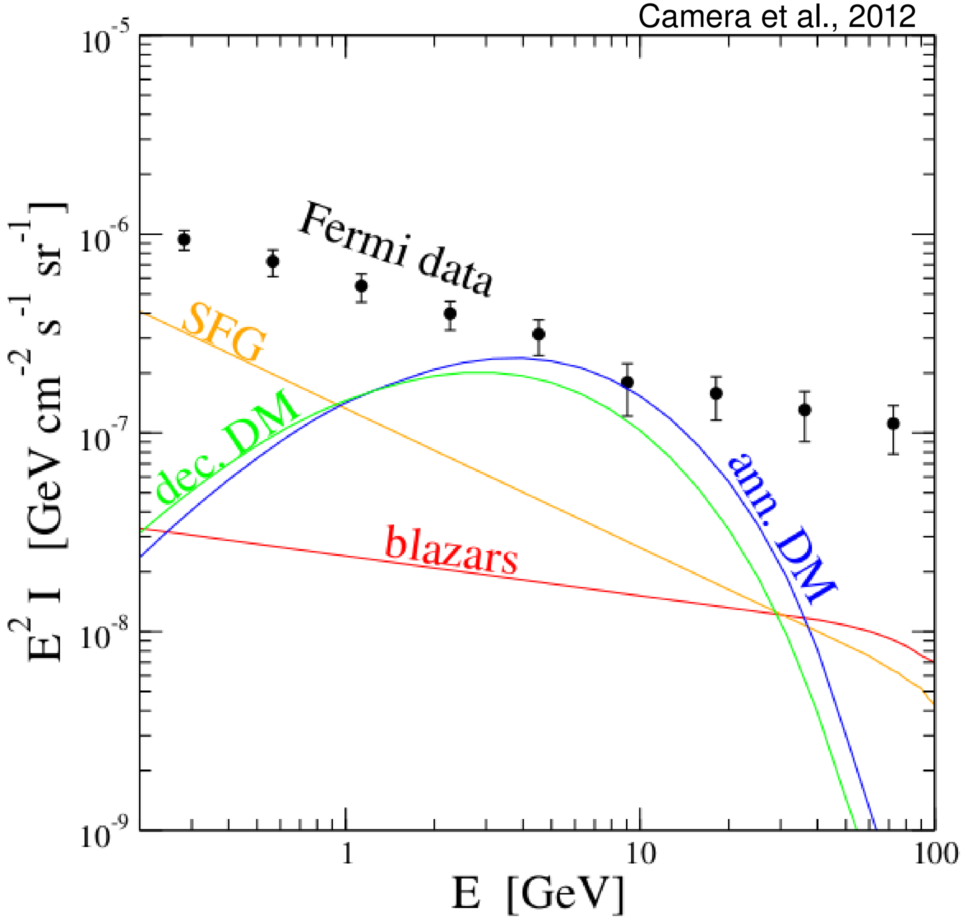
$$P_{SS}^{1h}(k,z) = \int_{\mathcal{L}_{\min}(z)}^{\mathcal{L}_{\max}(z)} d\mathcal{L}\;\Phi(\mathcal{L},z)\left(\frac{\mathcal{L}}{\langle g_S\rangle}\right)^2$$

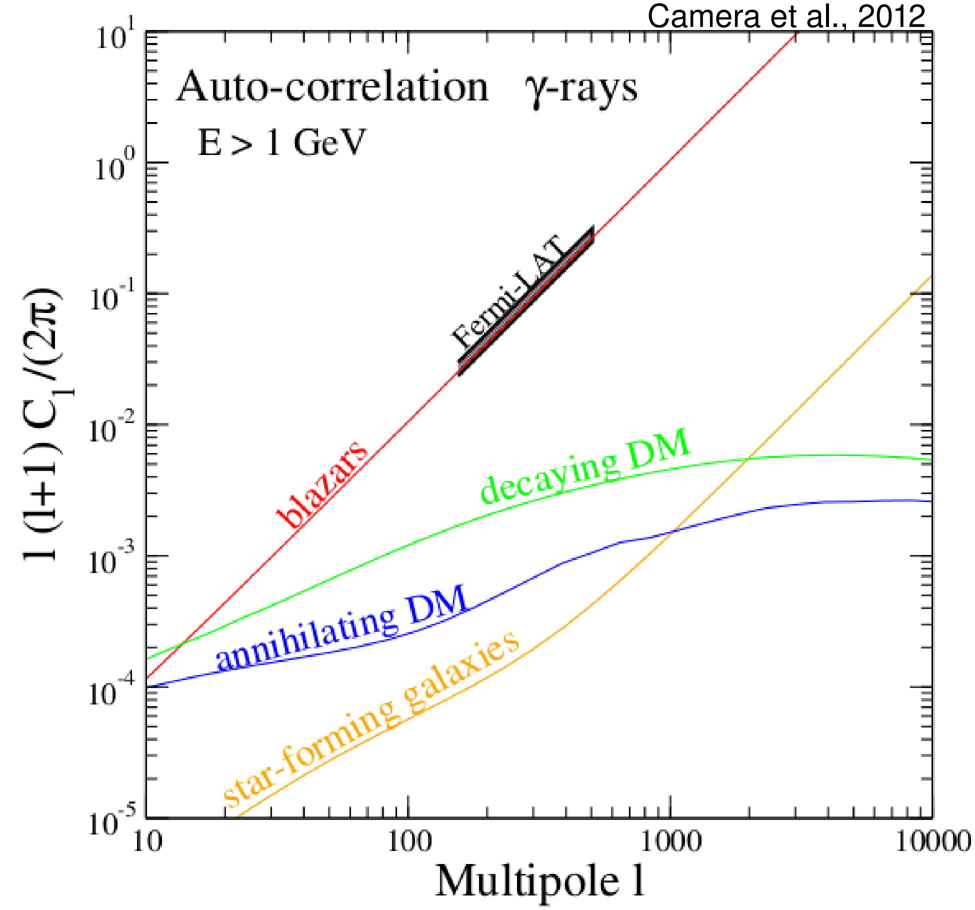
$$P_{SS}^{2h}(k,z) = \left[\int_{\mathcal{L}_{\min}(z)}^{\mathcal{L}_{\max}(z)} d\mathcal{L}\;\Phi(\mathcal{L},z)\,b_S(\mathcal{L},z)\,\frac{\mathcal{L}}{\langle g_S\rangle}\right]^2 P^{\rm lin}(k,z)$$

$$\langle g_S\rangle = \int_{\mathcal{L}_{\min}(z)}^{\mathcal{L}_{\max}(z)} d\mathcal{L}\,\Phi\,\mathcal{L}$$

Since the **Fermi-LAT detection threshold is relatively high**, the unresolved population is dominated by "bright" objects (blazars) for which the power spectrum is almost entirely given by the 1-halo term

Auto-correlation gamma APS

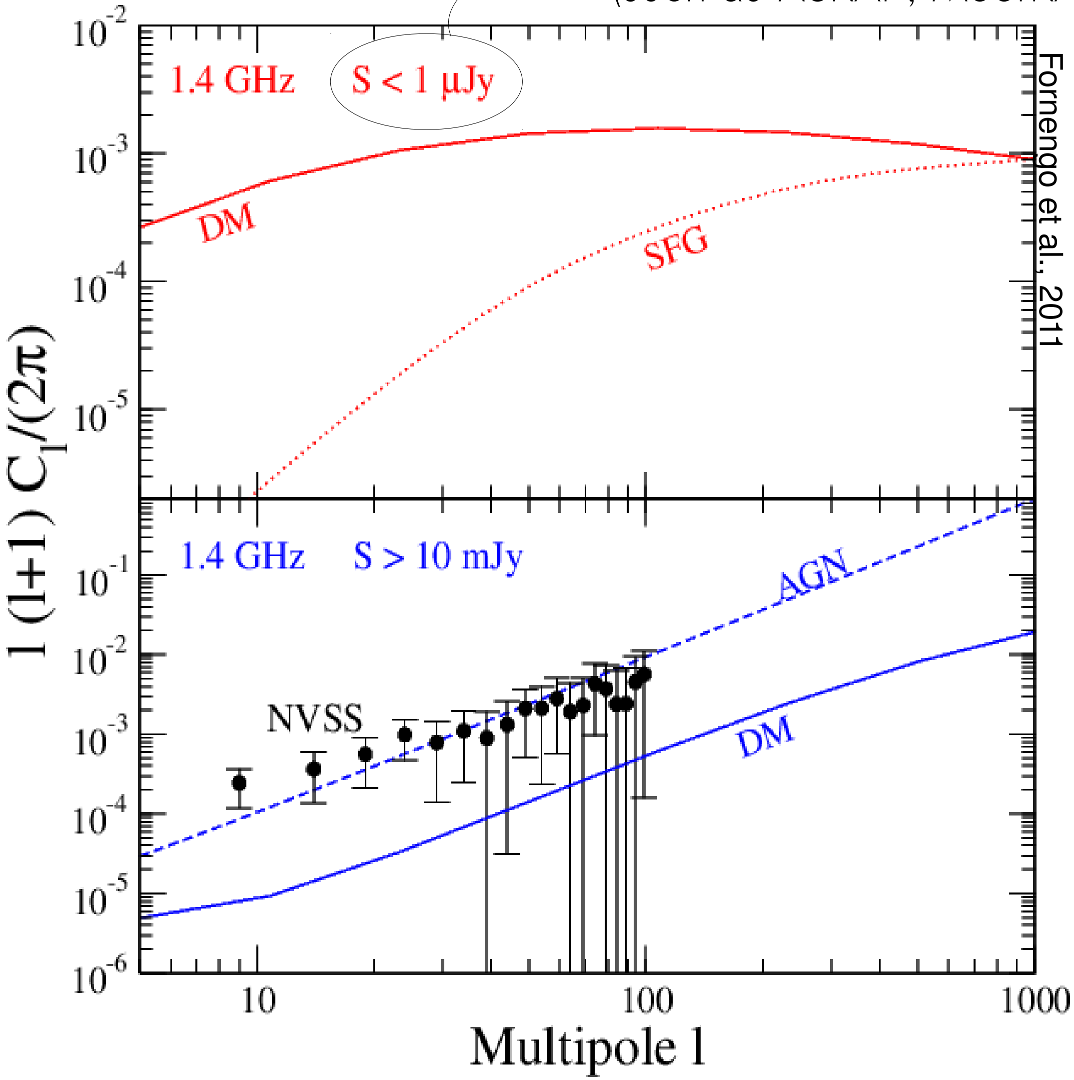




Gamma-ray anisotropies seem to be dominated by blazars with **little room** for DM.

Auto-correlation radio APS

Achievable by SKA and its "precursors" (such as ASKAP, MeerKAT, JVLA)



With low-enough detection-threshold, the anisotropies of the **unresolved extragalactic background** is dominated by **"faint" (but numerous)** populations

Cross-correlation angular power spectrum

Cross-correlation APS

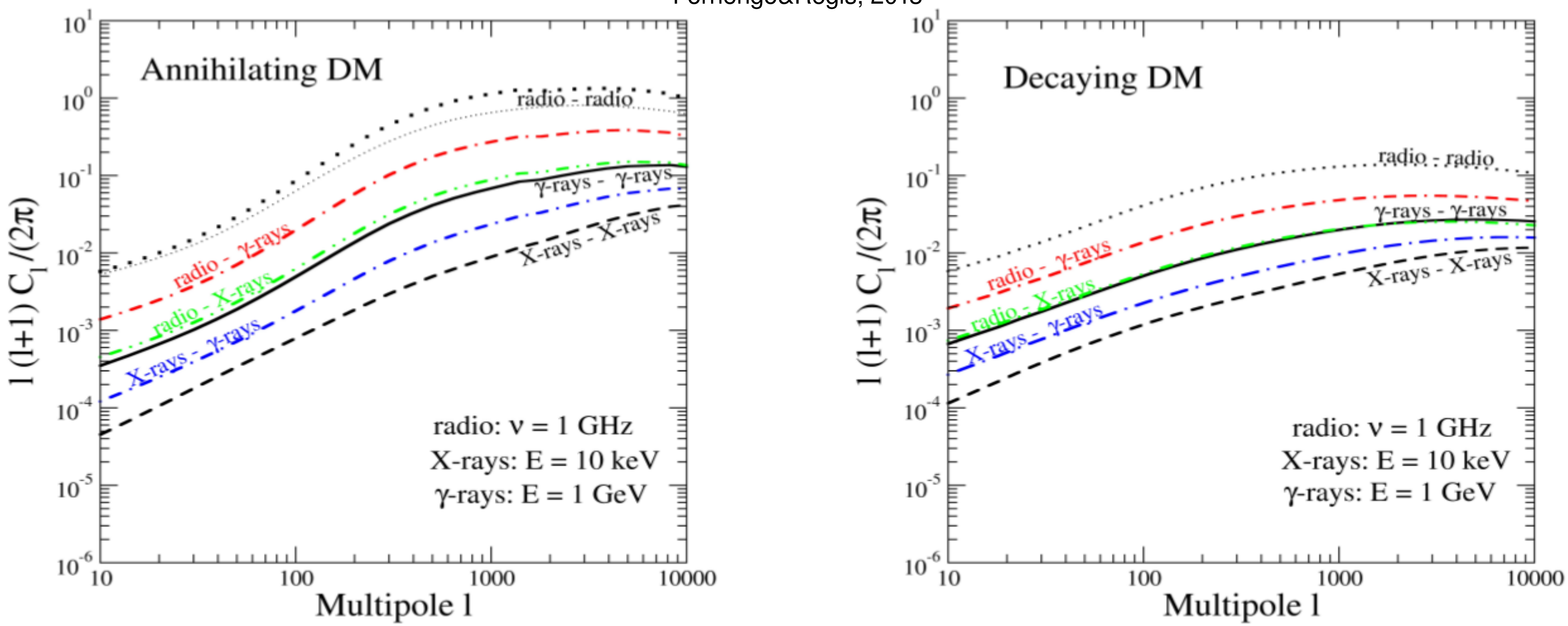
Let's start with the simplest case:

Cross-correlation between different electromagnetic signals induced by the same type of DM (and neglecting spatial dependencies in terms other than ρ in the emissivity of radiative signals)

$$C_\ell^{(ij)} = \frac{1}{\langle I_i \rangle \langle I_j \rangle} \int \frac{d\chi}{\chi^2} W_i(\chi)\, W_j(\chi) P_{ij}(k = \ell/\chi, \chi)$$

Same as for auto-correlation PS

Fornengo&Regis, 2013



Cross-correlation APS

Annihilating-decaying or annihilating-gravitational tracers

$$P^{1h}_{\delta\delta^2}(k) = \int_{m_{\min}}^{m_{\max}} dm\, \frac{dn}{dm}\tilde{v}(k|m)\, \frac{\tilde{u}(k|m)}{\Delta^2}$$

$$P^{2h}_{\delta\delta^2}(k) = \left[\int_{m_{\min}}^{m_{\max}} dm\, \frac{dn}{dm} b_h(m)\tilde{v}(k|m)\right] \left[\int_{m_{\min}}^{m_{\max}} dm\, \frac{dn}{dm} b_h(m)\frac{\tilde{u}(k|m)}{\Delta^2}\right] P^{\rm lin}(k)$$

Annihilating-astrophysical EM sources

$$P^{1h}_{S\delta^2}(k,z) = \int_{\mathcal{L}_{\min}(z)}^{\mathcal{L}_{\max}(z)} d\mathcal{L}\, \Phi(\mathcal{L},z)\, \frac{\mathcal{L}}{\langle g_S\rangle}\, \frac{\tilde{u}(k|m(\mathcal{L}))}{\Delta^2}$$

$$P^{2h}_{S\delta^2}(k,z) = \left[\int_{\mathcal{L}_{\min}(z)}^{\mathcal{L}_{\max}(z)} d\mathcal{L}\, \Phi(\mathcal{L},z)\, b_S(\mathcal{L},z)\, \frac{\mathcal{L}}{\langle g_S\rangle}\right] \left[\int_{m_{\min}}^{m_{\max}} dm\, \frac{dn}{dm} b_h(m)\frac{\tilde{u}(k|m)}{\Delta^2}\right] P^{\rm lin}(k,z)$$

Annihilating-LSS tracers

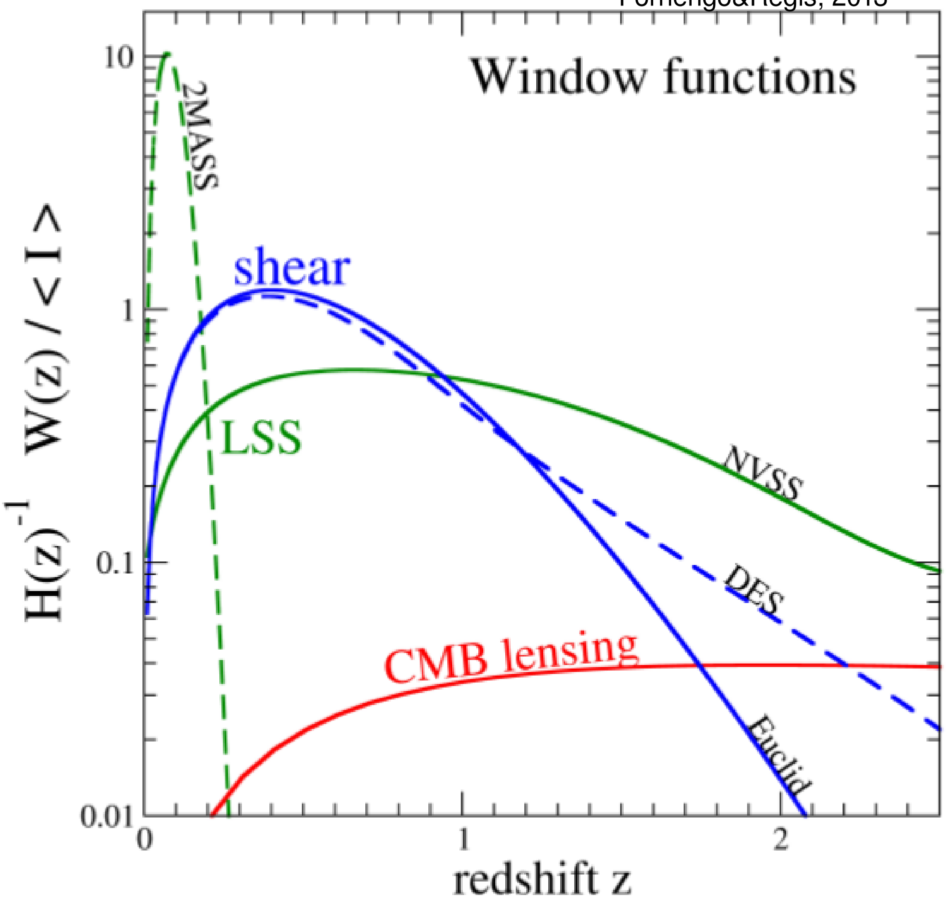
$$P^{1h}_{{\rm gal},\delta^2}(k) = \int_{m_{\min}}^{m_{\max}} dm\, \frac{dn}{dm}\frac{\langle N_{gal}\rangle}{\bar{n}_{gal}}\tilde{v}(k|m)\, \frac{\tilde{u}(k|m)}{\Delta^2}$$

$$P^{2h}_{{\rm gal},\delta^2}(k) = \left[\int_{m_{\min}}^{m_{\max}} dm\, \frac{dn}{dm} b_h(m)\frac{\langle N_{gal}\rangle}{\bar{n}_{gal}}\tilde{v}(k|m)\right] \left[\int_{m_{\min}}^{m_{\max}} dm\, \frac{dn}{dm} b_h(m)\frac{\tilde{u}(k|m)}{\Delta^2}\right] P^{\rm lin}(k)$$

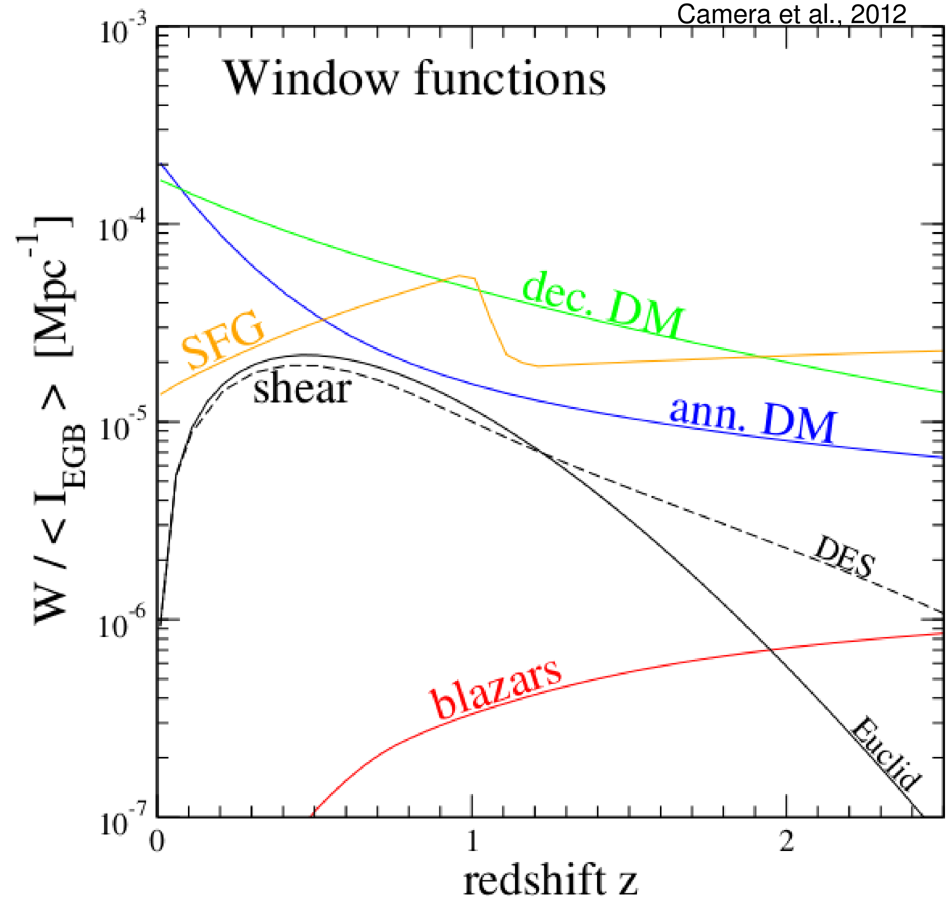
for LSS tracers: $g(\boldsymbol{x}, M, z) = \rho(\boldsymbol{x}, M, z)\langle N_{\rm gal}(M,z)\rangle/\bar{n}_{\rm gal}(z)$, where $\bar{n}_{\rm gal} = \int dM\, dn/dM\, \langle N_{\rm gal}\rangle$

Cross-correlation with gravitational tracers

Fornengo&Regis, 2013



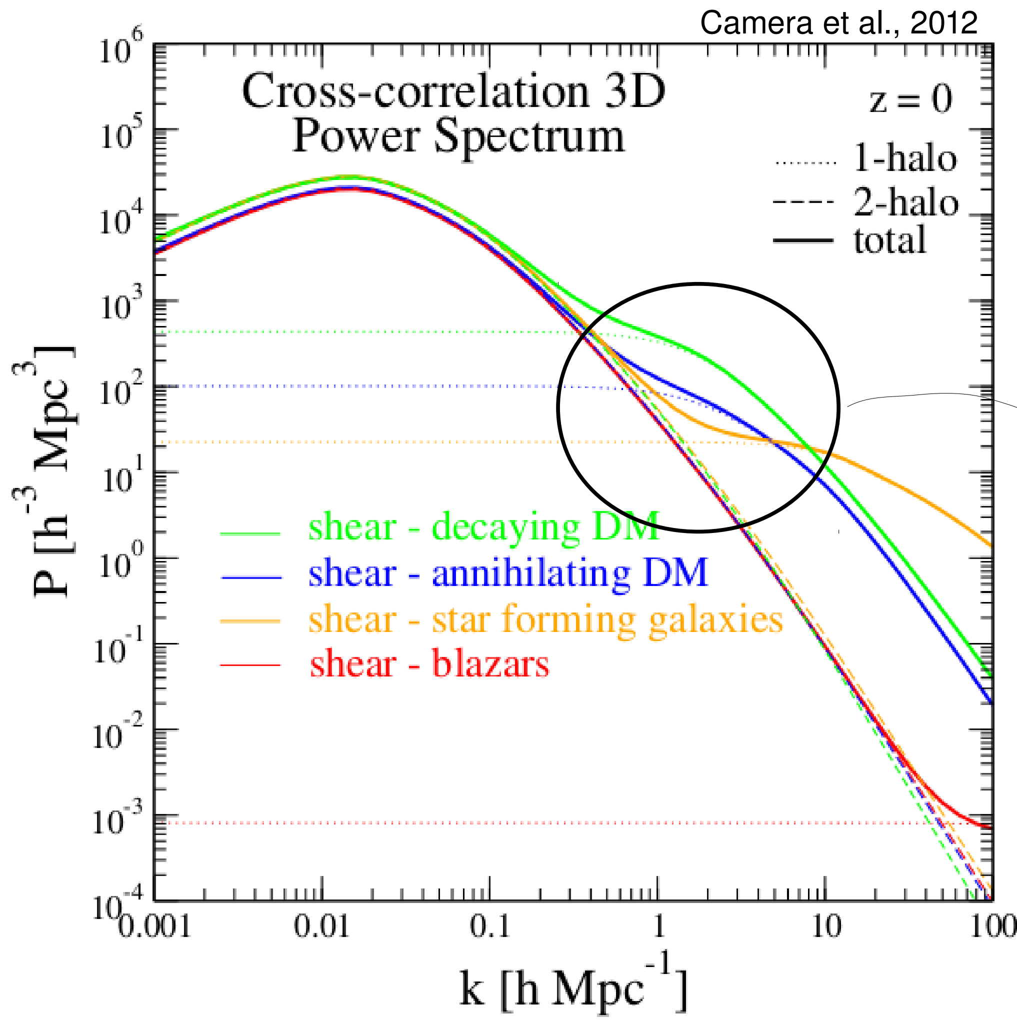
Camera et al., 2012

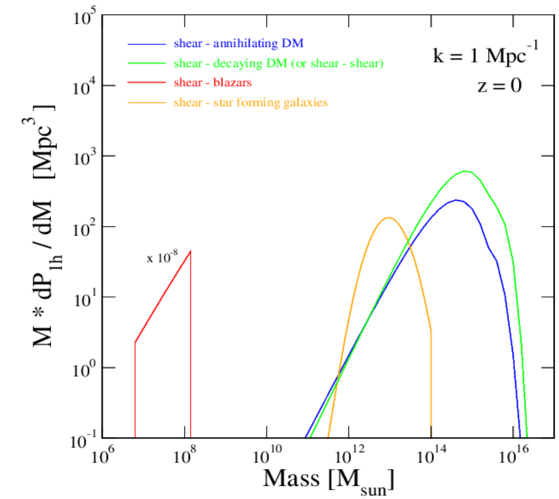


Tomographic approach with the z-bins of weak lensing survey

“Effective” tomographic approach using different galaxy catalogs.

Cross-correlation with gravitational tracers



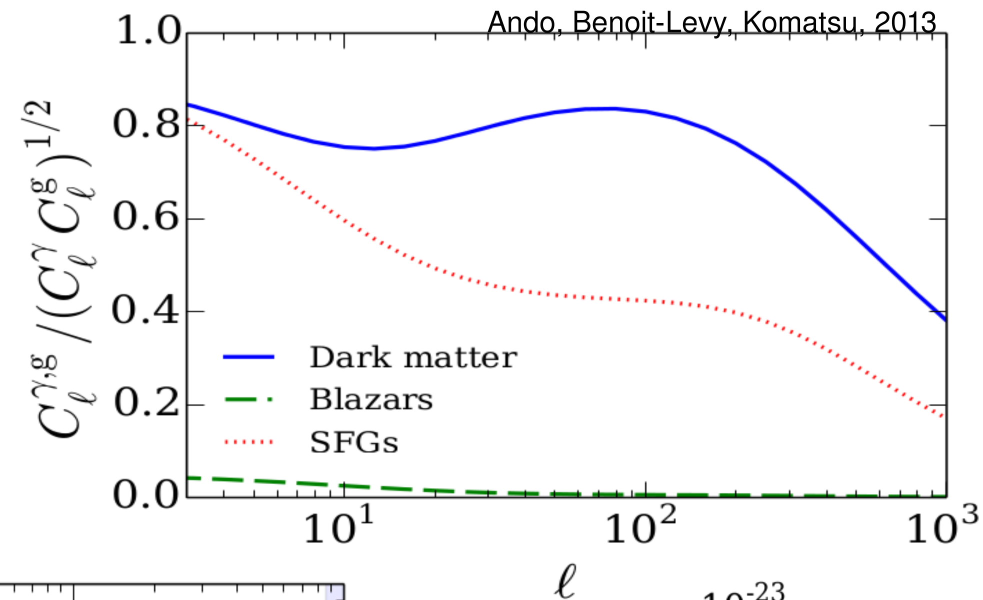


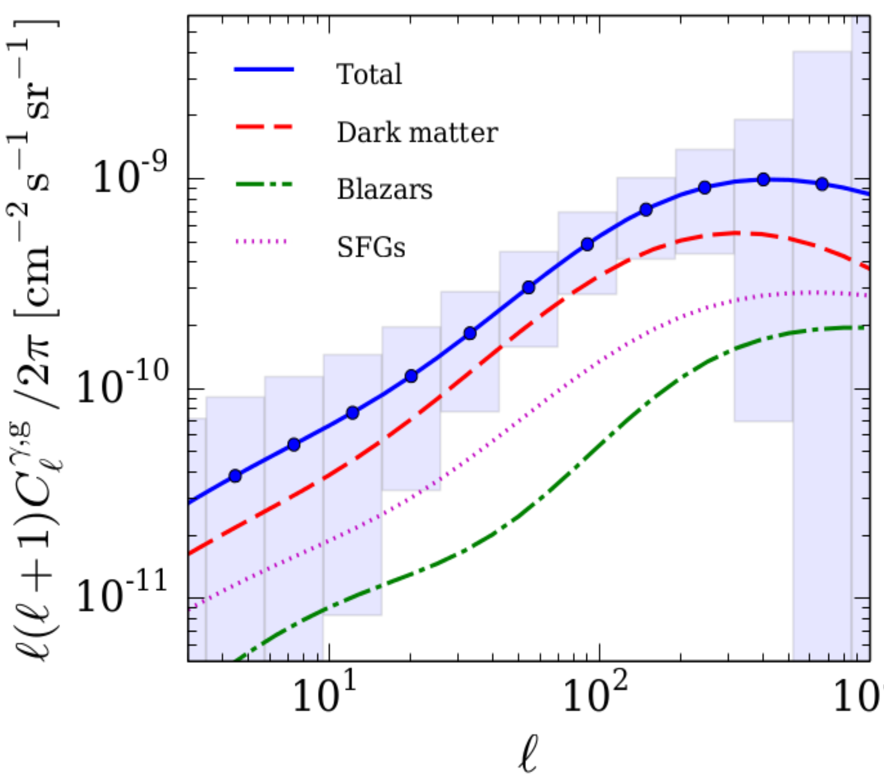
It is (roughly speaking) mapped in the multipole range $100 < l < 1000$

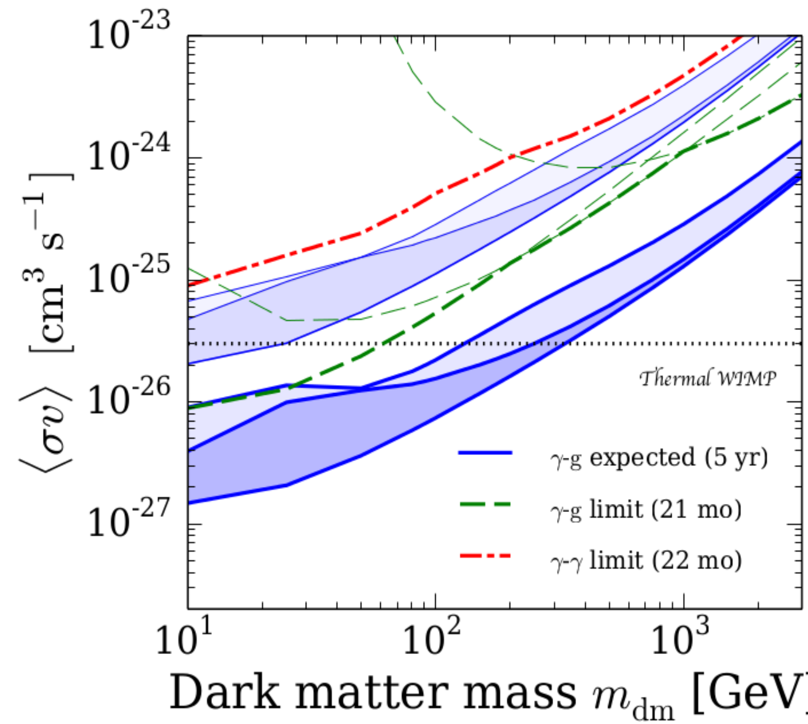
The WIMP **power spectrum** has more power at intermediate scales ($k \sim 1-10$ h Mpc^{-1}).

Cross-correlation with LSS tracers

Cross-correlations of gamma-rays from DM with 2MASS galaxies

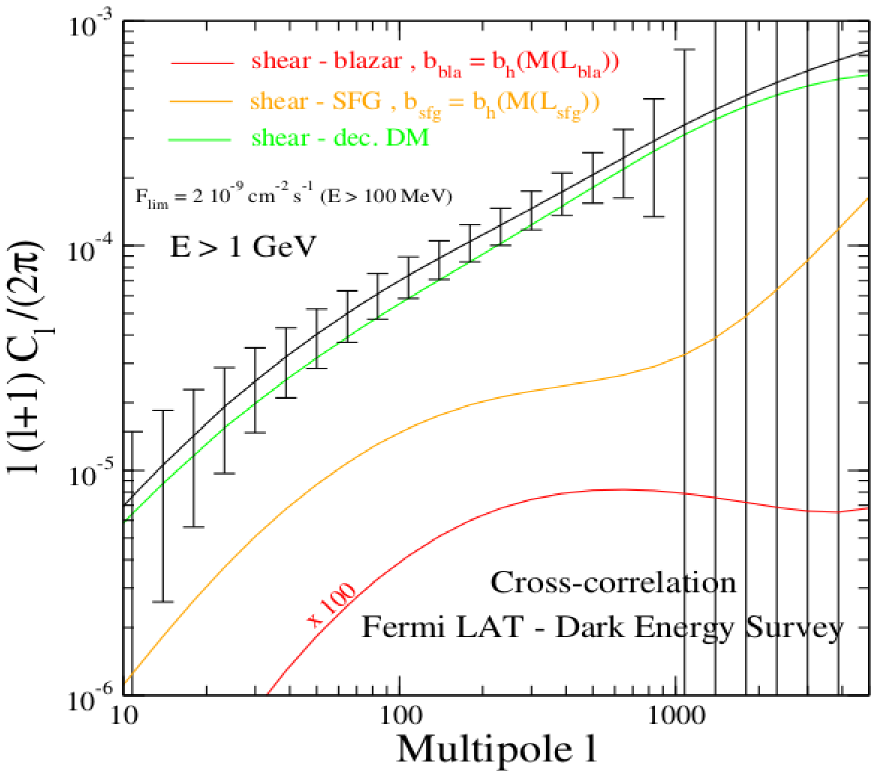


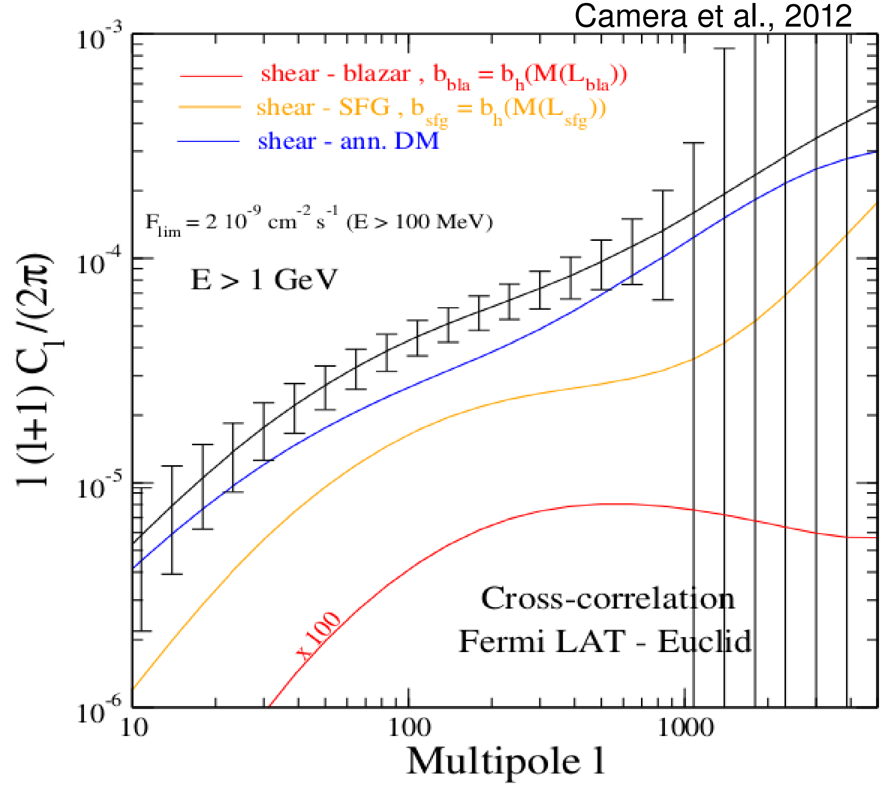




Cross-correlation with gravitational tracers

Camera et al., 2012





WIMP models, which are undetectable

if looking at extragalactic gamma-rays alone,

could be accessible through the correlation with gravitational tracers.

This test can be performed in the forthcoming future (DES + Fermi LAT).

Conclusions

If you want to have fun with **indirect searches of particle DM**, we saw there is **a variety of signals/targets**!

A **multi-messenger/multi-wavelength approach** is mandatory.

However, I would predominantly untertake it in the optimistic sense (**looking for converging hints**) rather than in the pessimistic sense (**looking for the killer bound**).