Particle dark matter searches through anisotropies and cross correlations

Nicolao Fornengo

Department of Physics (Theory Division) – University of Torino
and Istituto Nazionale di Fisica Nucleare (INFN) – Torino
Italy

UNIVERSITA' DEGLI STUDI DI TORINO
ALMA UNIVERSITAS TAURINENSIS

fornengo@to.infn.it
nicolao.fornengo@unito.it

www.to.infn.it/~fornengo
www.astroparticle.to.infn.it

Torino
INFN

University of Warsaw

27.04.2015

Based on:

Camera, Fornasa, NF, Regis, *Ap. J. 771 (2013) L5*	gamma + cosmic shear
Camera, Fornasa, NF, Regis, *arXiv:1411.4651*	gamma + cosmic shear
NF, Regis, *Front. Physics 2 (2014) 6*	general theory
NF, Regis, Perotto, Camera, *Ap.J. 802 (2015) L1*	gamma + CMB lensing
Regis, Xia, Cuoco, NF, Branchini, Viel, *arXiv:1503.05922*	gamma + LSS
Cuoco, Xia, Regis, NF, Branchini, Viel, *to appear*	gamma + LSS
Zechlin et al., *to appear*	gamma 1PDF

Dark Matter

- The presence of DM is supported by copious and consistent astrophysical and cosmological probes
  - Horizon-scale: average DM density about 6 times baryon density
  - Smaller scales: DM distribution is quite anisotropic and hierarchical

    clusters – galaxies – subhalos

- Observations are consistent with a theoretical understanding of cosmic structure formation through gravitational instability, based on the LCDM model

  Although:
  - Some problem on very small scales
  - Role of baryons in galaxy formation just started to be investigated

Dark Matter

- DM evidence purely gravitational
  - Galaxy clusters dynamics
  - Rotational curves of spiral galaxies
  - Gravitational lensing
  - Hydrodynamical equilibrium of hot gas in galaxy clusters
  - Energy budget of the Universe
  - The same theory of structure formation

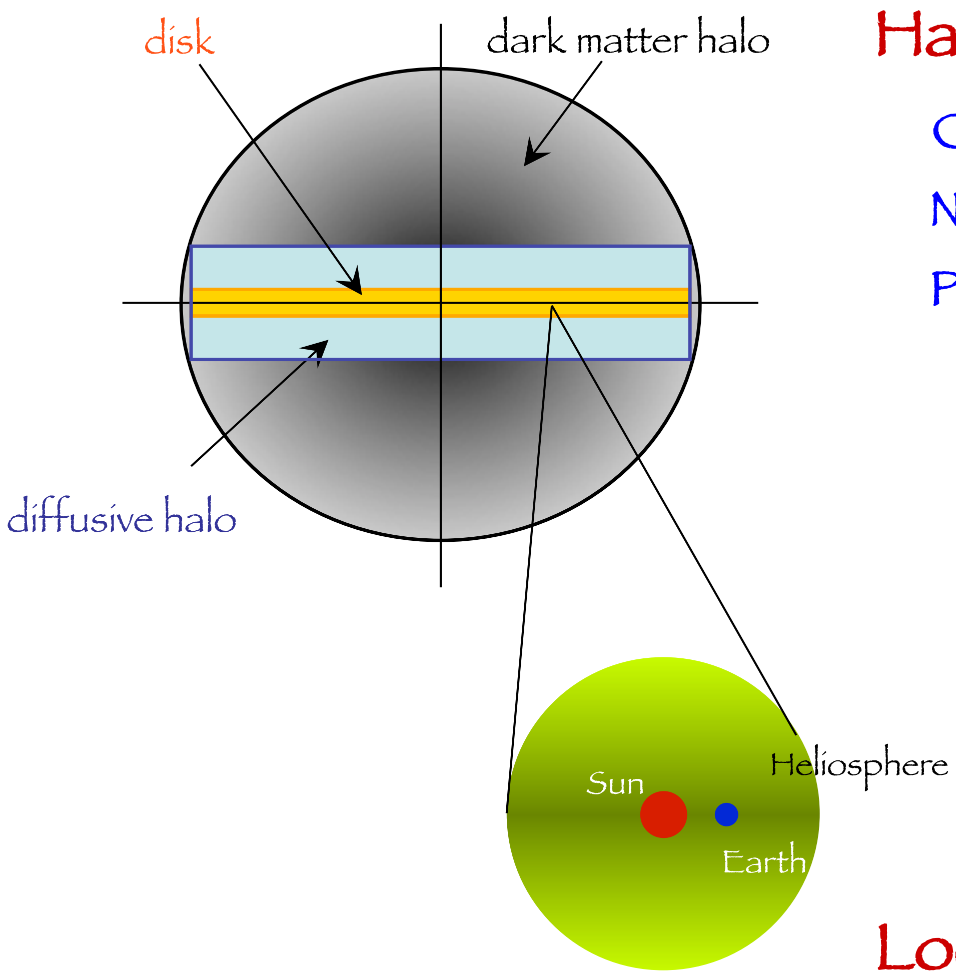
- This evidence can be ascribed either to:
  i. Modification of the theory of Gravity
  ii. DM = elementary particle, relic from the early Universe
     - No viable candidate in the SM: New Physics BSM
     - However, to demonstrate that DM is a new particle, a non-gravitational signal (due to it's particle physics nature) is needed

Where to search for a signal

We can try to exploit every structure where DM is known to be present:

- Our Galaxy
  - Smooth component
  - Subhalos
- Satellite galaxies (dwarfs)
- Galaxy clusters
  - Smooth component
  - Individual galaxies
  - Galaxies subhalos
- "Cosmic web"

Galactic dark matter signals



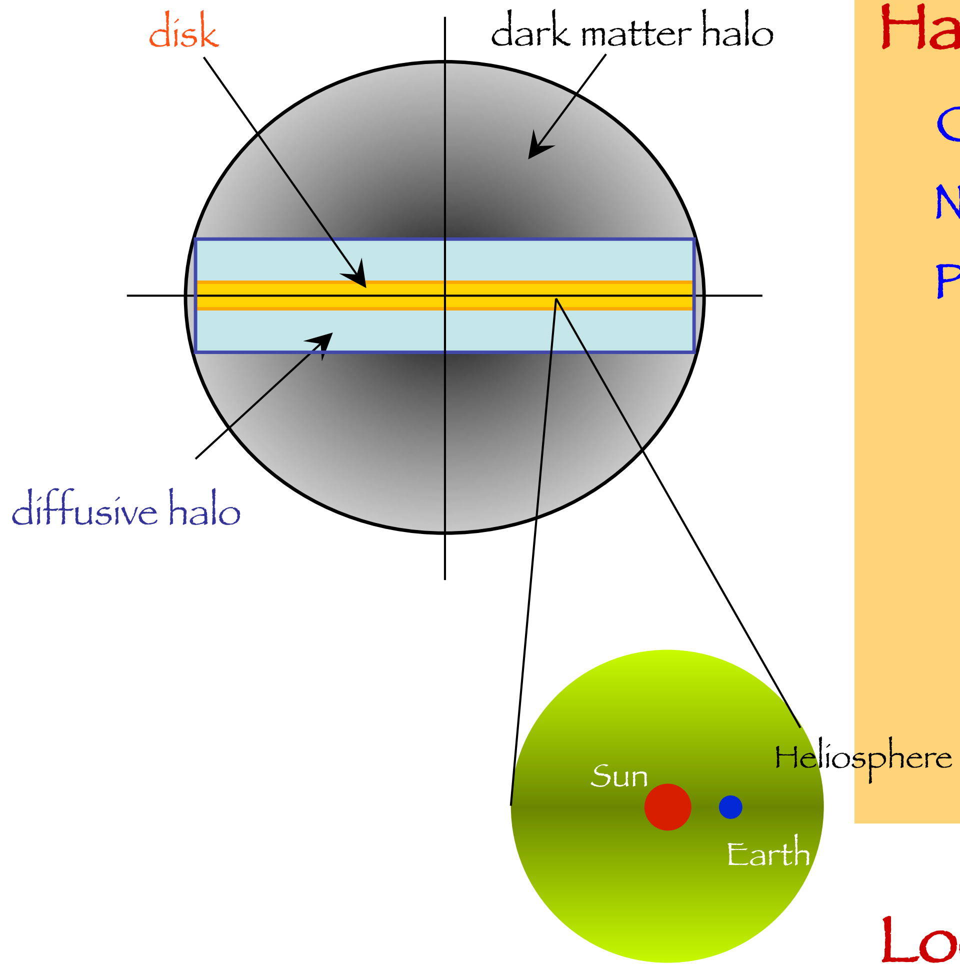
Halo signals

- Charged CR ($e^{\pm}$, antip, antiD)
- Neutrinos
- Photons
  - Gamma-rays
    - Prompt production
    - IC from $e^{\pm}$ on ISRF and CMB
  - X-rays
    - IC from $e^{\pm}$ on ISRF and CMB
  - Radio
    - Synchro from $e^{\pm}$ on mag. field

Local signals

- Direct detection
- Neutrinos from Earth and Sun

Galactic dark matter signals



Halo signals

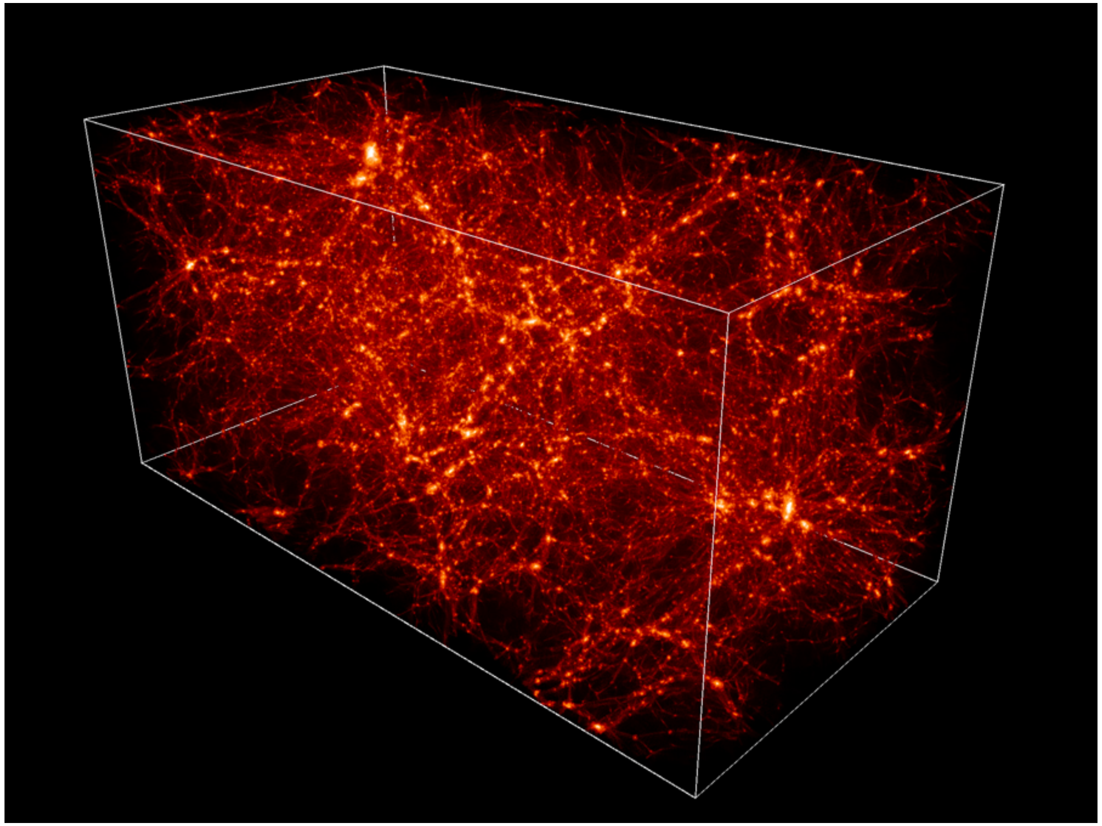
- Charged CR ($e^{\pm}$, antip, antiD)
- Neutrinos
- Photons
  - Gamma-rays
    - Prompt production
    - IC from $e^{\pm}$ on ISRF and CMB
  - X-rays
    - IC from $e^{\pm}$ on ISRF and CMB
  - Radio
    - Synchro from $e^{\pm}$ on mag. field

Local signals

- Direct detection
- Neutrinos from Earth and Sun

$$\chi\chi \longrightarrow (...) \longrightarrow \gamma\,,\,\nu\,,\,e^{\pm}\,,\,\bar{p}\,,\,\bar{D}$$

Extragalactic/Cosmological signals



Photons: gamma, X, radio

Neutrinos

Impact on CMB:

SZ effect in clusters

Back to recombination

Dark Matter signals

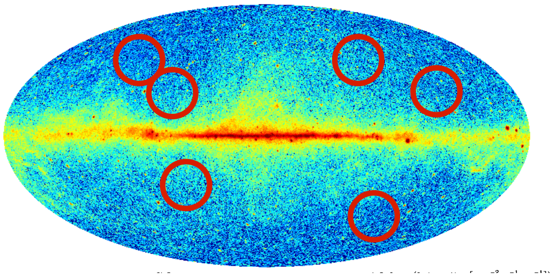
- Indirect detection signals are intrinsically anisotropic
  (being produced by DM structures, present at any scale)

- EM signals (and neutrinos) more directly trace the underlying DM distribution: they need to exhibit some level of anisotropy

  - Bright DM objects: would appear as *resolved* sources
    - e.g: gamma or radio halo around clusters, dwarf galaxies or even subhalos

  - Faint DM objects: would be *unresolved* (i.e. below detector sensitivity)
    - Diffuse flux: at first level isotropic
      at a deeper level anisotropic

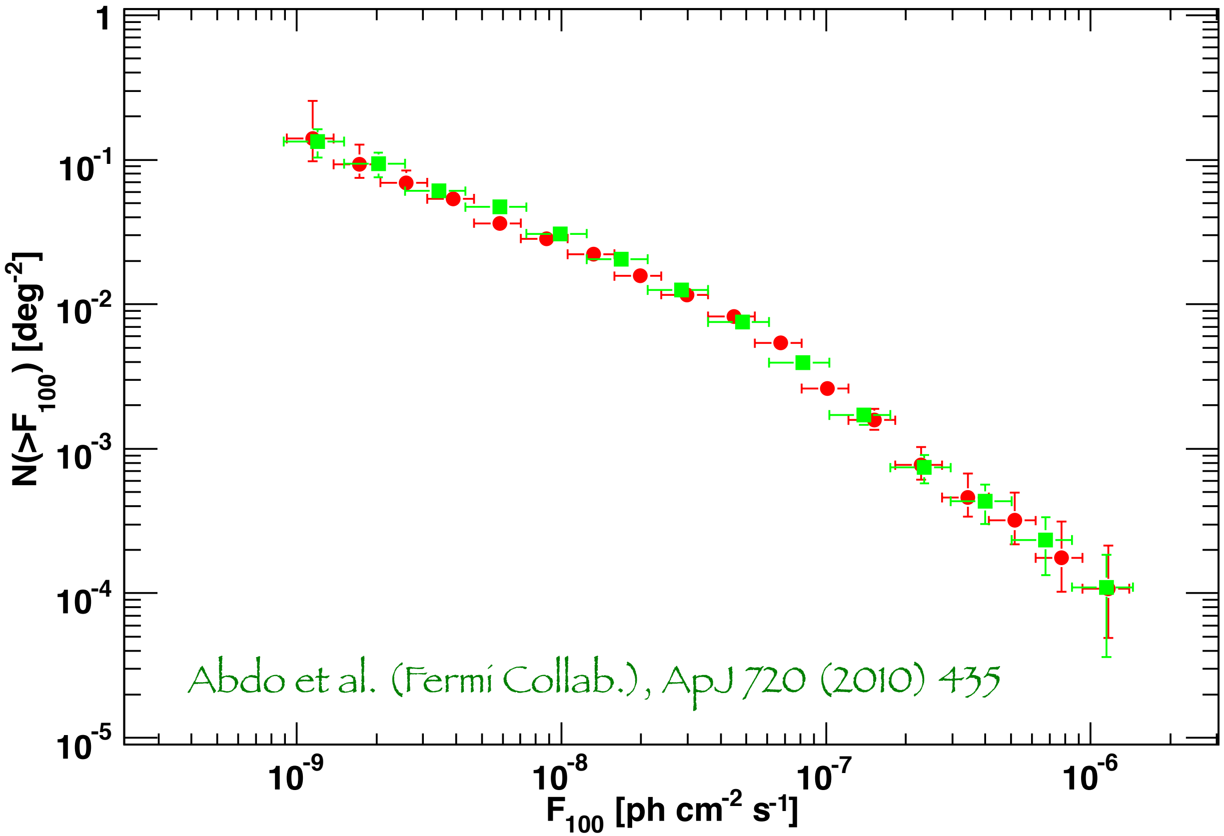
- Even though DM objects are unresolved, the effect of anisotropies can affect the statistics of photons

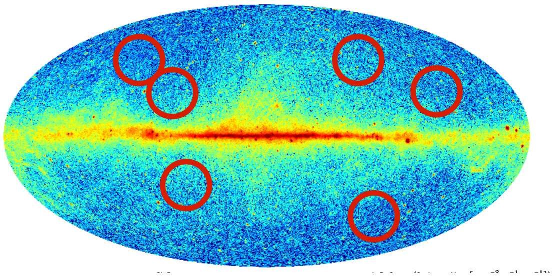


Resolved sources

Source number count dN/dS

Source spectral features

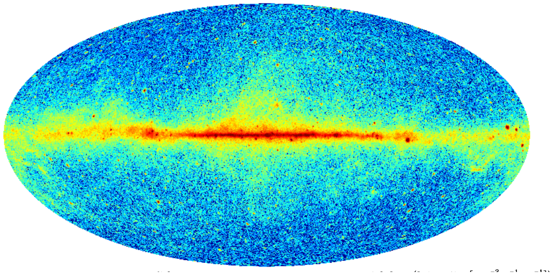




Resolved sources

Source number count dN/dS

Source spectral features



Galactic emission — modeled and subtracted

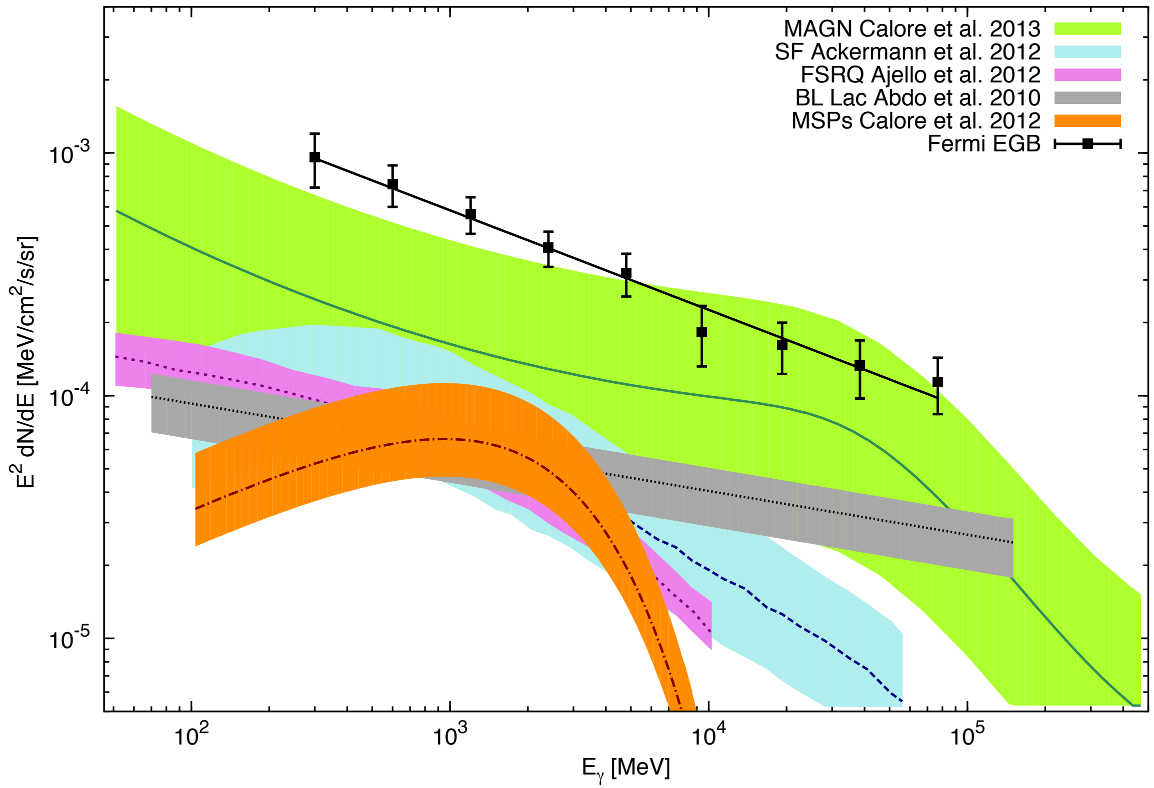
“Isotropic” emission — cumulative from unresolved srcs

Total intensity I(E)

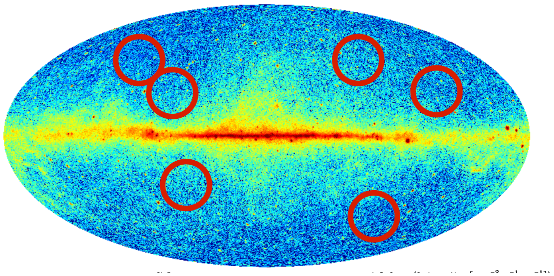
To a closer look, this residual emission is not truly isotropic

Galactic center issue

A galactic plane cut is typically adopted



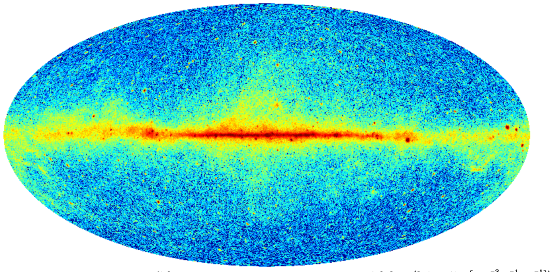
Bringman et al., PRD 89 (2014) 023012



Resolved sources

Source number count dN/dS

Source spectral features

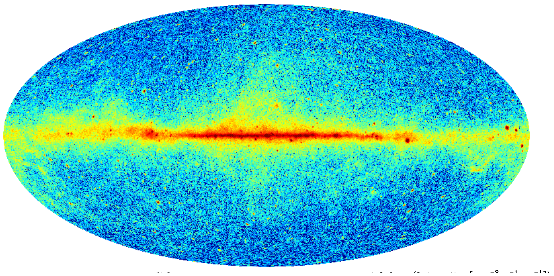


Galactic emission modeled and subtracted

"Isotropic" emission cumulative from unresolved srcs

Total intensity I(E)

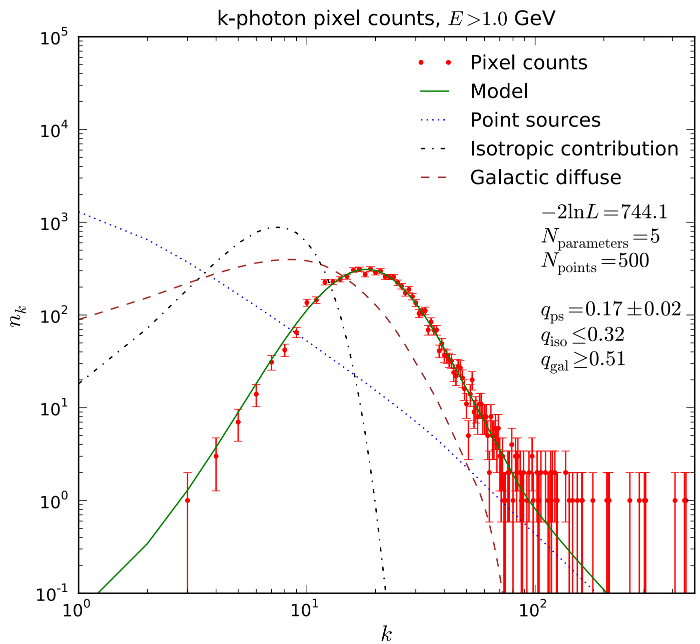
Photon Statistics



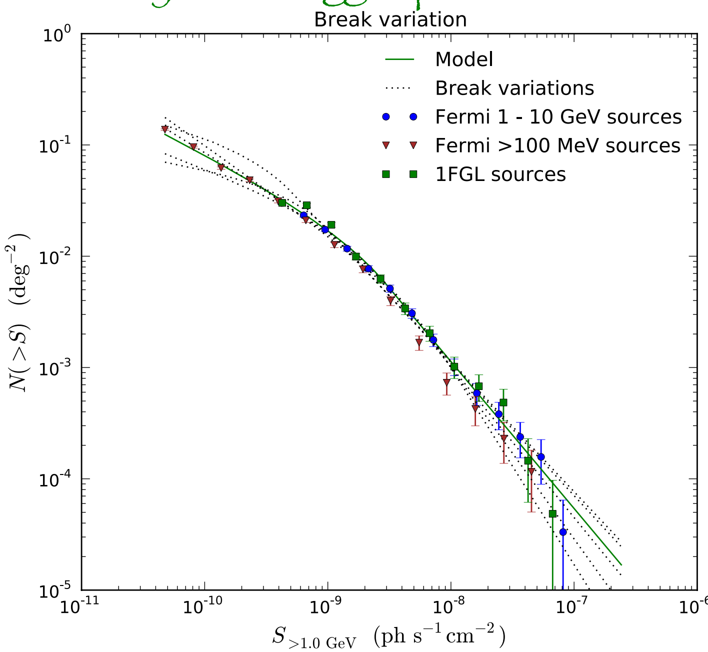
Photon pixel counts

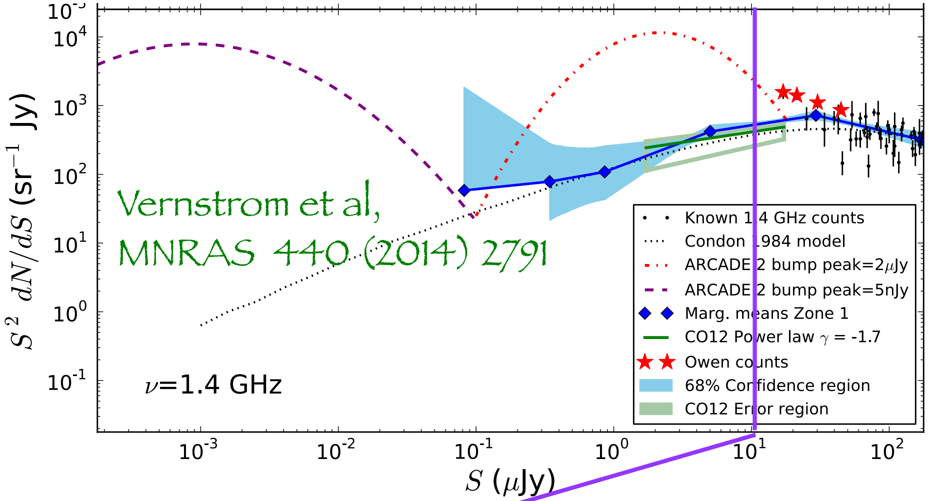
Source count number dN/dS below detection threshold

Pixel counts ("1 PDF")

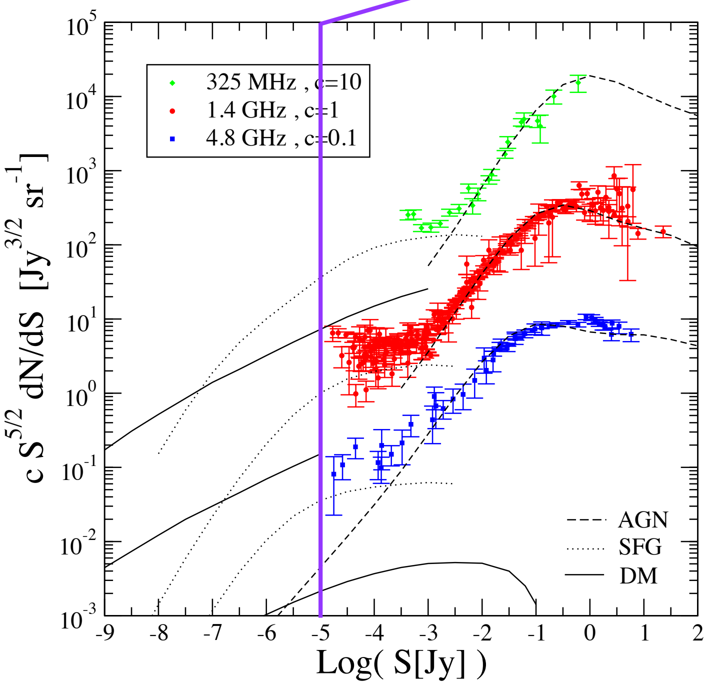


Malyshev, Hogg, ApJ 738 (2011) 181





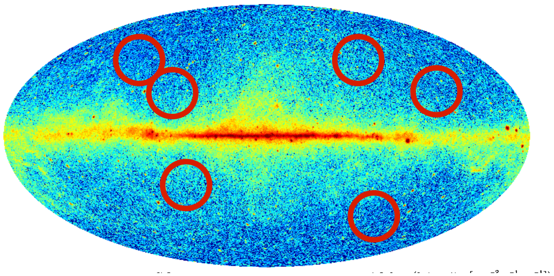
Vernstrom et al, MNRAS 440 (2014) 2791



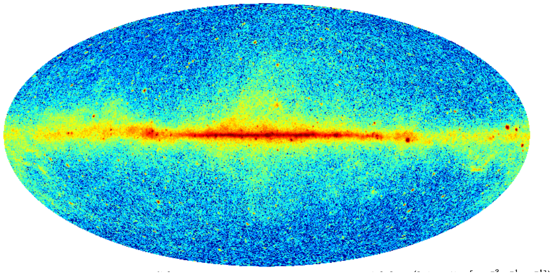
NF, Lineros, Regis, Taoso, PRL 107 (2011) 2727

Gamma rays

Radio

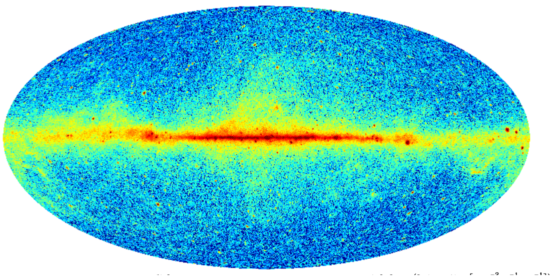


Resolved sources
Source number count dN/dS
Source spectral features

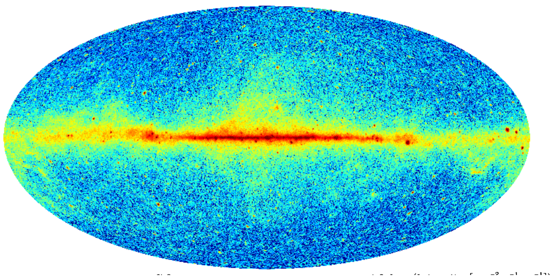


Galactic emission — modeled and subtracted
"Isotropic" emission — cumulative from unresolved srcs
Total intensity I(E)

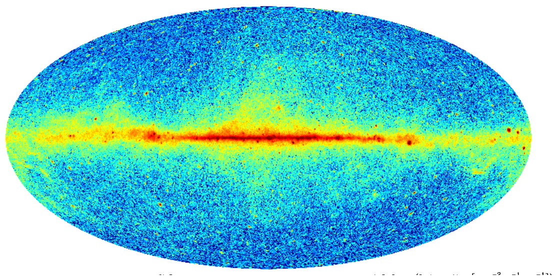
Photon Statistics



Photon pixel counts
Source count number dN/dS below detection threshold



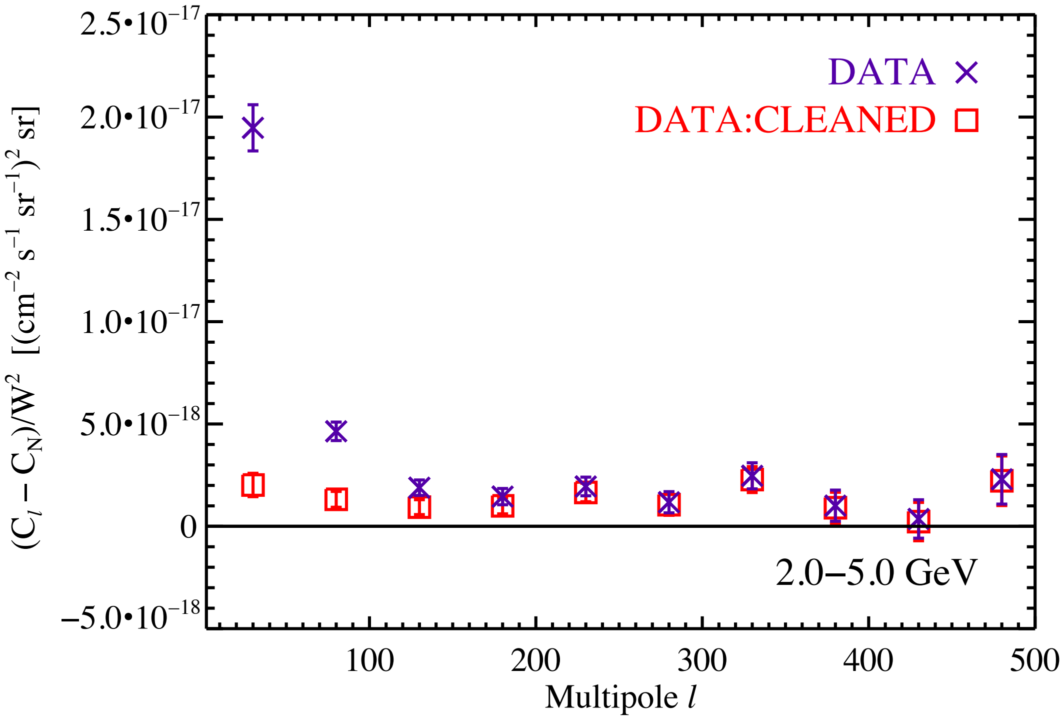
×

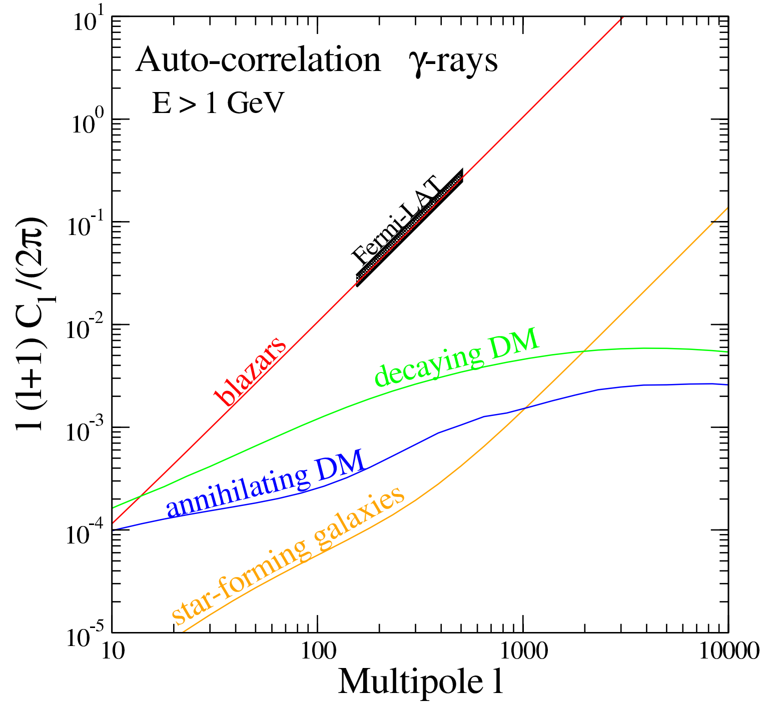


2 point correlator
angular power spectrum

$$\langle\, I(\vec{n}_1) I(\vec{n}_2)\,\rangle \;\longrightarrow\; C(\theta) \;\longrightarrow\; C_l$$

Gamma rays auto-correlation





APS of the gamma-rays auto-correlation observed by Fermi/LAT

Overall significance: 9σ

Ackerman et al. (Fermi) PRD 85 (2012) 083007

Auto-correlation of EM signals

- Gamma-rays

  Ando, Komatsu, PRD 73 (2006) 023521
  Ando, Komatsu, Narumoto, Totani, PRD D75 (2007) 063519
  Miniati, Koushiappas, Di Matteo, ApJ 667 (2007) L1
  Siegal-Gaskins, JCAP 0810 (2008) 040
  Cuoco, Brandbyge, Hannestad, Haugboelle, Miele, PRD 77 (2008) 123518
  Fornasa, Pieri, Bertone, Branchini, PRD 80 (2009) 023518
  Taoso, Ando, Bertone, Profumo, PRD 79 (2009) 043521
  Ibarra, Tran, Weniger, PRD 81 (2010) 023529
  Cuoco, Sellerholm, Conrad, Hannestad, MNRAS 414 (2011) 2040
  Cuoco, Komatsu, Siegal-Gaskins, PRD 86 (2012) 063004
  Harding, Abazajian, JCAP 11 (2012) 26
  Fornasa, Zavala, Sanchez-Conde, Siegal-Gaskins, Delahaye, Prada, MNRAS 1529 (2013) 429
  Hensley, Pavlidou, Siegal-Gaskins, MNRAS 591 (2013) 433
  Ando, Komatsu, PRD 87 (2013) 87
  Calore, Di Mauro, Donato, Maccio', Maccione, MNRAS 442 (2014) 1151
  Ripken, Cuoco, Zechlin, Conrad, Horns, JCAP 01 (2014) 049

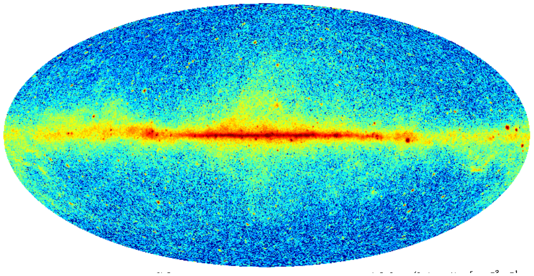
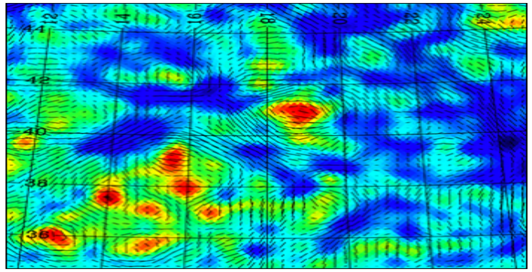
- Radio

  Zhang, Sigl, JCAP 0809 (2008) 027 (2008)
  Blake, Ferreira, Borrill, MNRAS 351 (2004) 923
  NF, Lineros, Regis, Taoso, JCAP 1203 (2012) 033

- X rays

  Inoue, Murase, Madejski, Uchiyama, Ap. J. 776 (2013) 776

Can we do more ?

 × 

Cross-correlation of EM signal with gravitational tracer of DM

It exploits two distinctive features of particle DM:

- An electromagnetic signal, manifestation of the particle nature of DM
- A gravitational probe of the existence of DM

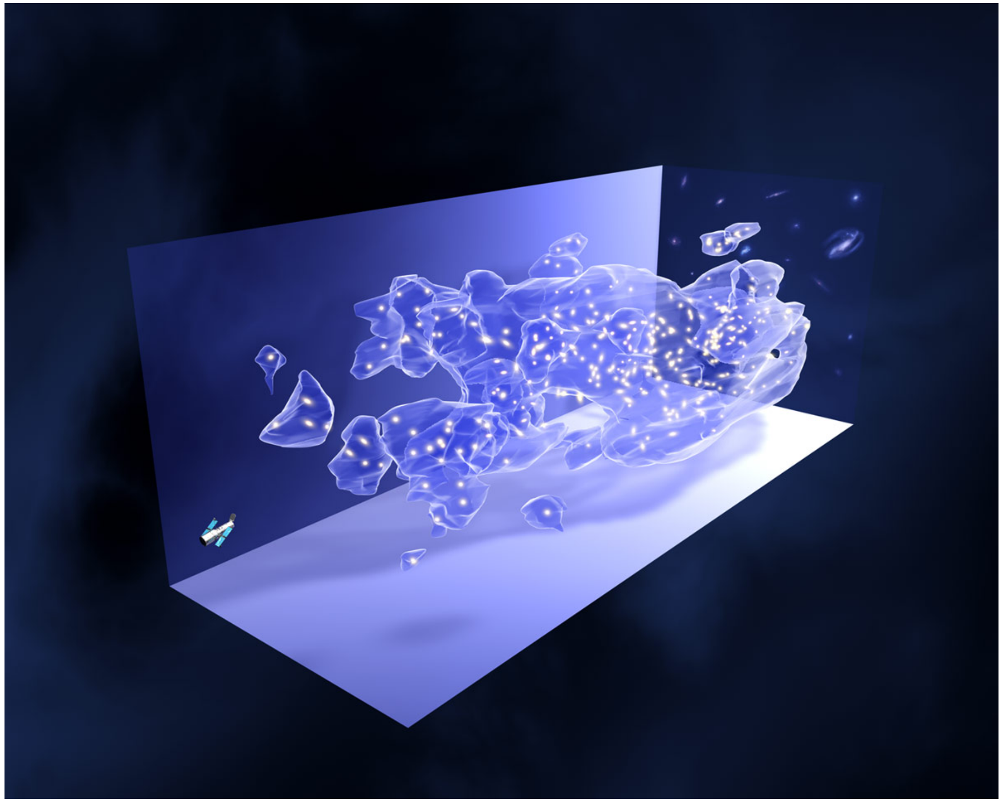
It can offer a direct evidence that what is measured by means of gravity is indeed due to DM in terms of an elementary particle

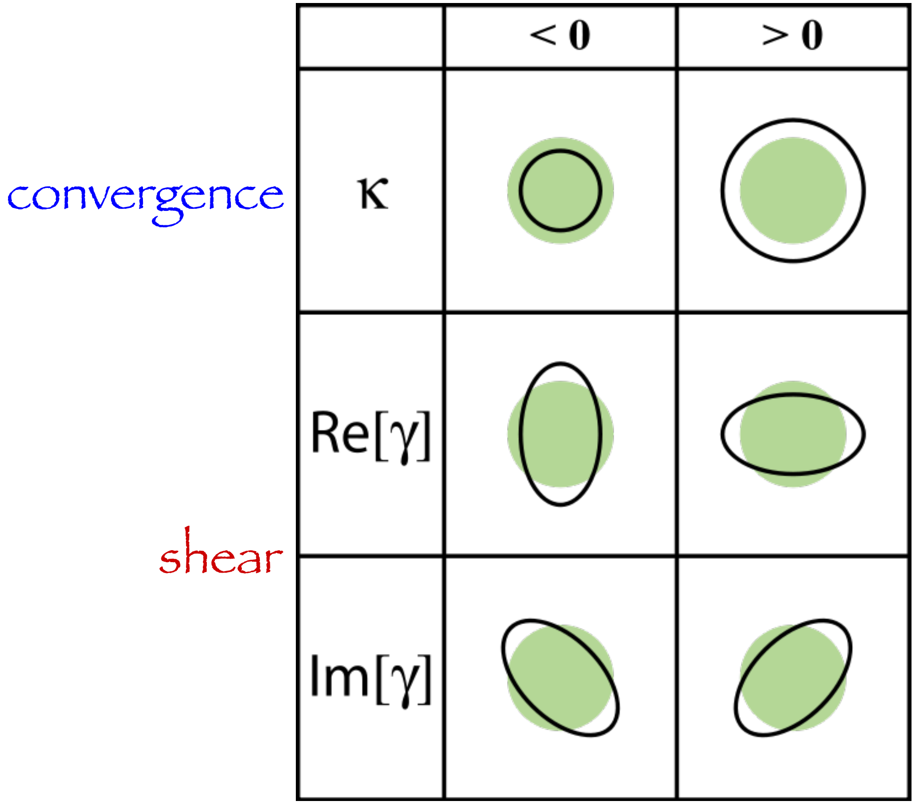
S. Camera, M. Fornasa, NF, M. Regis, Ap. J. 771 (2013) L5

GAMMA RAYS/COSMIC SHEAR CROSS CORRELATIONS

Weak gravitational lensing

- Weak lensing: small distortions of images of distant galaxies, produced by the distribution of matter located between background galaxies and the observer
- Powerful probe of dark matter distribution in the Universe

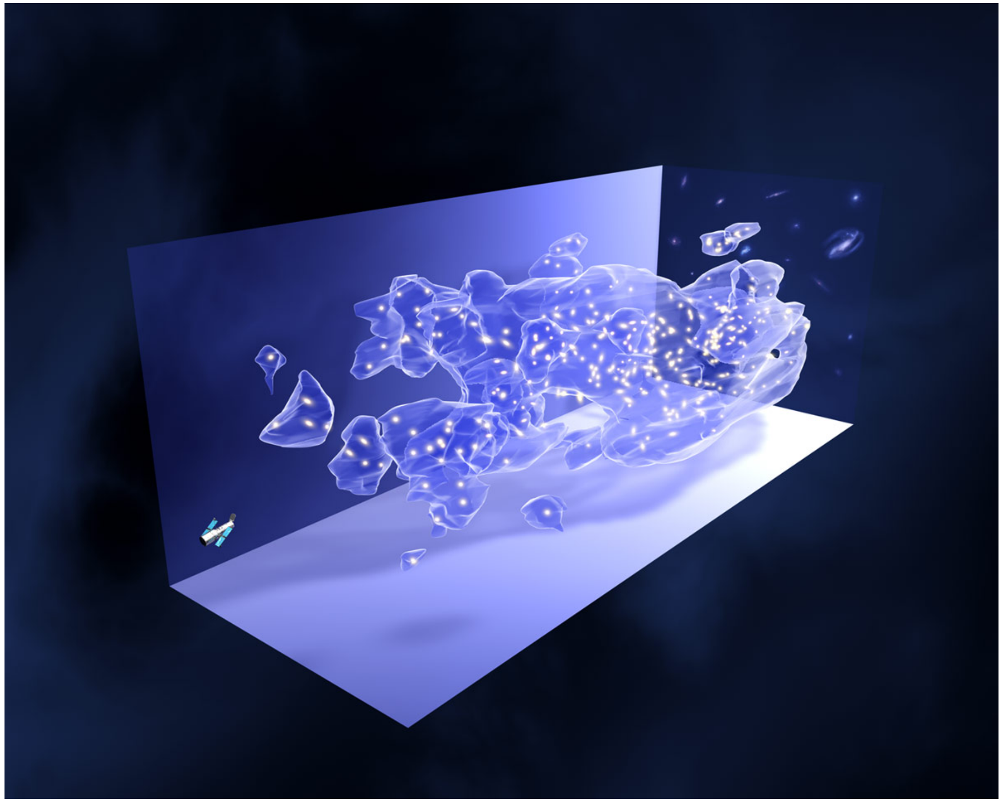




Cosmic structures and gamma-rays

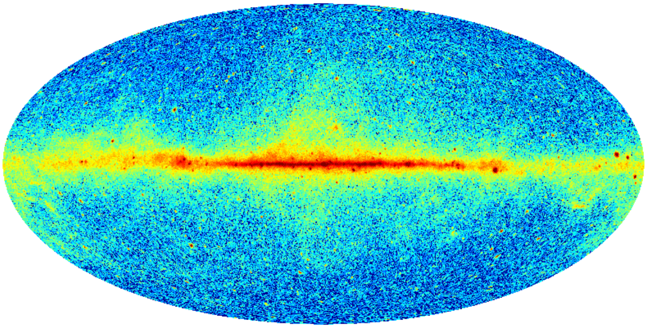
The same Dark Matter structures that act as lenses can themselves emit light at various wavelengths, including the gamma-rays range

- From astrophysical sources hosted by DM halos (AGN, SFG, ...)
- From DM itself (annihilation/decay)

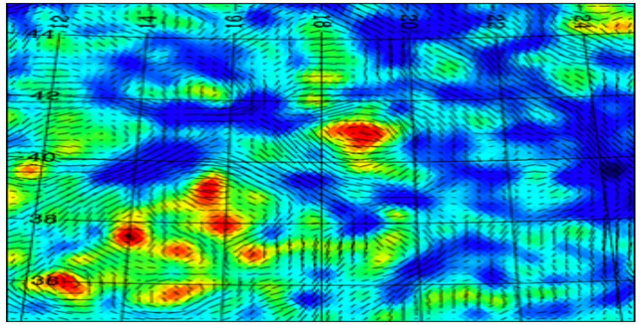


Gamma-rays emitted by DM may exhibit strong correlation with lensing signal

The lensing map can act as the filter needed to isolate the signal hidden in a large "noise"



The signal



Cross-correlation of:

- Gravitational shear with
- Extragalactic gamma-ray background (the residual radiation contributed by the cumulative emission of *unresolved* gamma-ray sources)

Looked through the statistical correlations encoded in its
cross angular power spectrum

$$C_l^{\gamma\phi}$$

S. Camera, M. Fornasa, NF, M. Regis, Ap. J. Lett. 771 (2013) L5
S. Camera, M. Fornasa, NF, M. Regis, arXiv:1411.4651
NF, Regis, Front. Physics 2 (2014) 6

Correlation functions

Source Intensity

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

Window function

Density field of the source

Cross-correlation angular power spectrum

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

3D Power spectrum (we use the halo model)

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

$$f_g \equiv [g(\boldsymbol{x}|m, z)/\bar{g}(z) - 1]$$

$\hat{f}_g$: *Fourier tranform*

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

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

Linear bias

Linear matter PS

Window functions

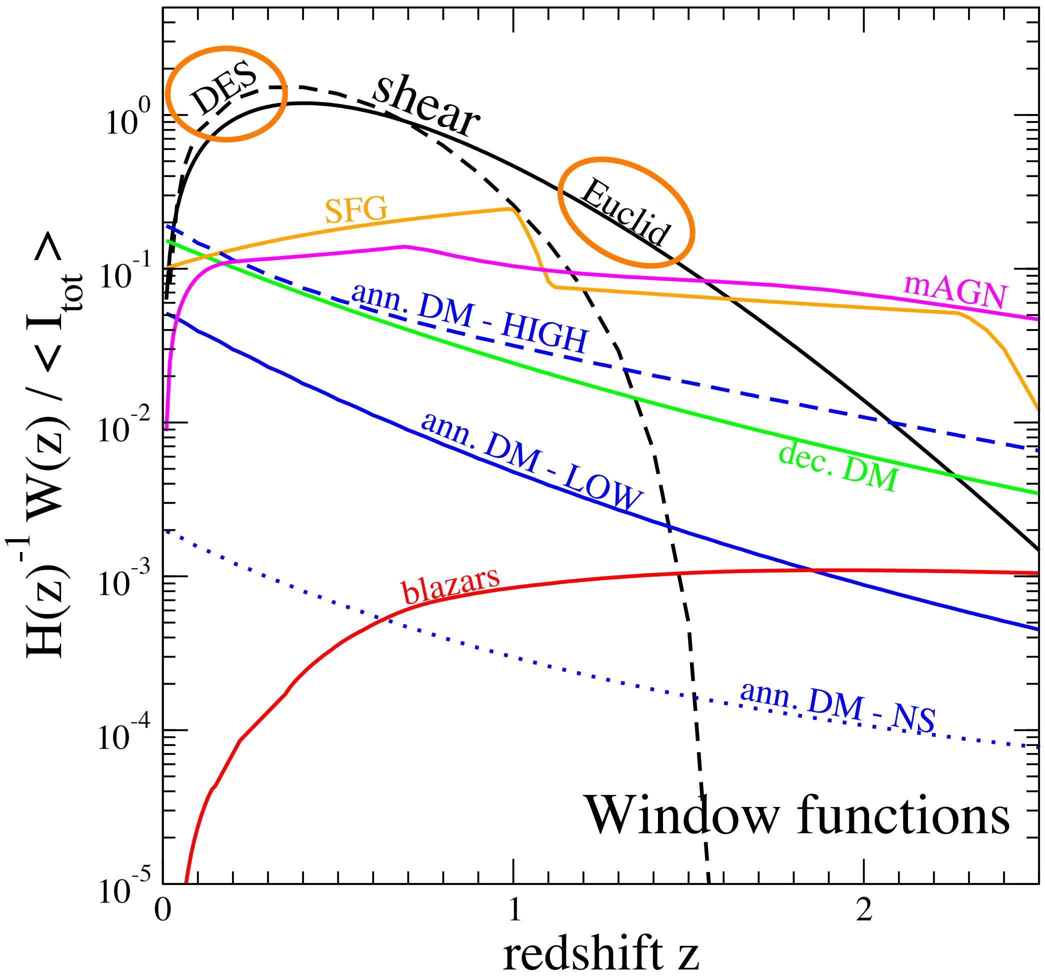
Lensing

$$W^{\kappa}(\chi) = \frac{3}{2} {H_0}^2 \Omega_m \left[1 + z(\chi)\right] \chi \int_{\chi}^{\infty} \mathrm{d}\chi' \, \frac{\chi' - \chi}{\chi'} \frac{\mathrm{d}N_g}{\mathrm{d}\chi'}(\chi')$$

Redshift distribution of background galaxies

Window functions

Shear



Camera, Fornasa, NF, Regis, arXiv:1411.4651

Window functions

Gamma-rays from annihilating DM

Clumping factor

$$W^{\gamma_a \mathrm{DM}}(\chi) = \frac{(\Omega_{\mathrm{DM}}\rho_c)^2}{4\pi} \frac{\langle \sigma_a v \rangle}{2{m_{\mathrm{DM}}}^2} \left[1 + z(\chi)\right]^3 \Delta^2(\chi) J_a(E,\chi)$$

DM photon "emissivity"

$$\Delta^2(\chi) \equiv \frac{\langle \rho_{\mathrm{DM}}^2 \rangle}{\bar{\rho}_{\mathrm{DM}}^2} = \int_{M_{\min}}^{M_{\max}} \mathrm{d}M \frac{\mathrm{d}n}{\mathrm{d}M} \int \mathrm{d}^3\mathbf{x} \frac{\rho_h^2(\mathbf{x}|M,\chi)}{\bar{\rho}_{\mathrm{DM}}^2} [1 + B(M,\chi)]$$

Subhalo boost

Gamma-rays from decaying DM

$$W^{\gamma_d \mathrm{DM}}(\chi) = \frac{\Omega_{\mathrm{DM}}\rho_c}{4\pi} \frac{\Gamma_{\mathrm{d}}}{m_{\mathrm{DM}}} J_d(E,\chi)$$

DM photon "emissivity"

$$J_{a/d}(E,\chi) = \int_{\Delta E_\gamma} \mathrm{d}E_\gamma \frac{\mathrm{d}N_{a/d}}{\mathrm{d}E_\gamma} \left[E_\gamma(\chi)\right] e^{-\tau[\chi, E_\gamma(\chi)]}$$

DM modeling

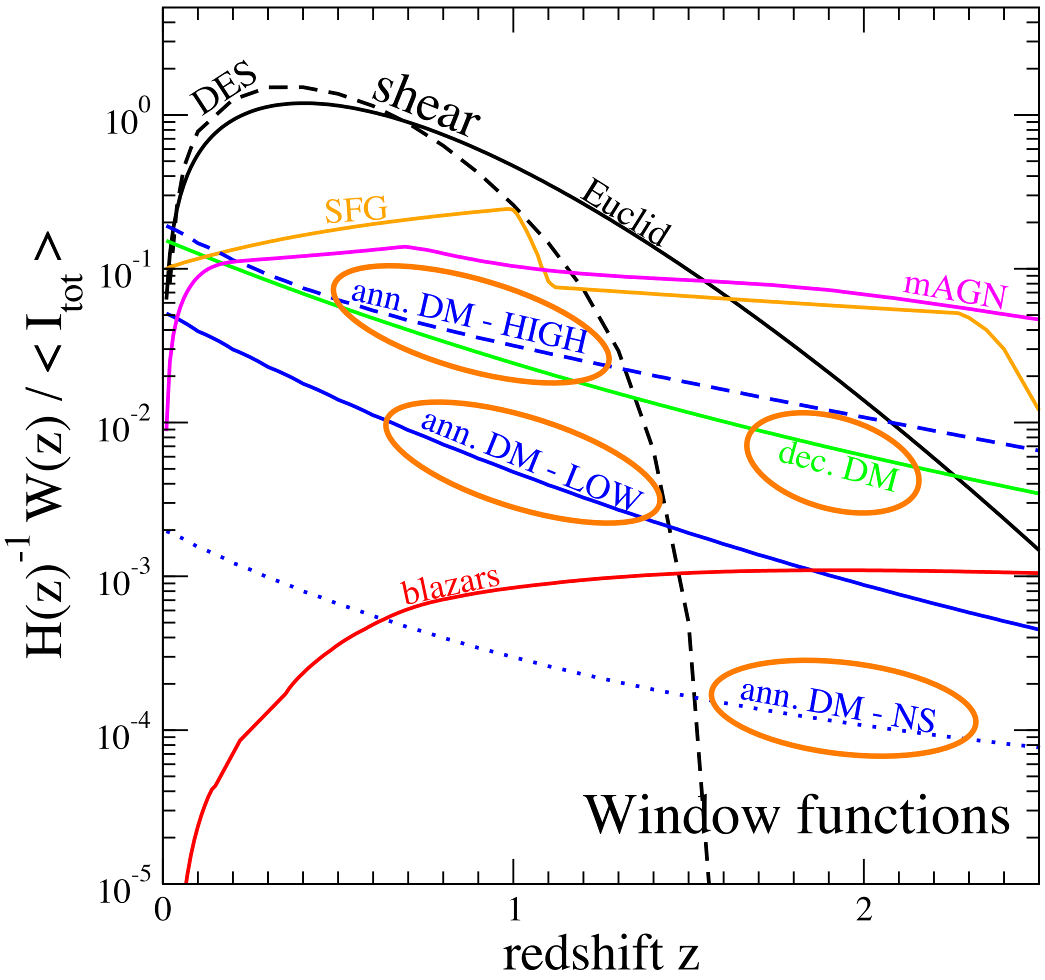
Halo mass functions	[a]
Halos profile: NFW	
Min halo-mass: $10^{-6}\ M_{sun}$	
Concentration c(M)	[b]
c(M) extrapolation at low M	[c+b]
Amount of subhalos:	
LOW	[1 + 2]
HIGH	[3 + 4]
NS (no sub-halo)	

[a] Sheth, Tormen, MNRAS 308 (1999) 119
[b] Munoz-Cuartas et al, MNRAS 411 (2011) 584
[c] Bullock et al, MNRAS 321 (2001) 559

[1] Kamionkowski et al, PRD 81 (2010) 043532
[2] Sanchez-Conde et al, JCAP 1112 (2011) 011
[3] Gao et al, MNRAS 419 (2012) 1721
[4] Ando, Komatsu, PRD87 (2013) 123539

Window functions

DM



Annihilating DM

$m_{\rm DM} = 100$ GeV

$\langle \sigma_a v \rangle = 3 \times 10^{-26}$ cm^3 s^{-1}

Decaying DM

$m_{\rm DM} = 200$ GeV

$\Gamma_d = 0.33 \times 10^{-27}$ s^{-1}

Camera, Fornasa, NF, Regis, arXiv:1411.4651

Window functions

Astrophysical sources

Mean luminosity by unresolved class of objects

$$W^{\gamma_i}(\chi) = \frac{A_i(\chi)\langle g_{\gamma_i}(\chi)\rangle}{4\pi E_0^2} \int_{\Delta E_\gamma} \mathrm{d}E_\gamma \left(\frac{E_\gamma}{E_0}\right)^{-\alpha_i} e^{-\tau[\chi, E_\gamma(\chi)]}$$

$i =$ blazars, mAGN, SFG

Maximal luminosty resolved with a sensitivity F_{sens}

$$\langle g_{\gamma_i}(\chi)\rangle = \int_{\mathcal{L}_{\min}}^{\mathcal{L}_{\max}(F_{\rm sens}, z)} \mathrm{d}\mathcal{L}\,\mathcal{L}\,\rho_{\gamma_i}(\mathcal{L}, z)$$

Gamma rays luminosity function

Astrophysical modeling

Blazars

- $\alpha_{BLA} \approx 2.2$
- GRLF from [1]
- M(L) determined from [2]

mAGN

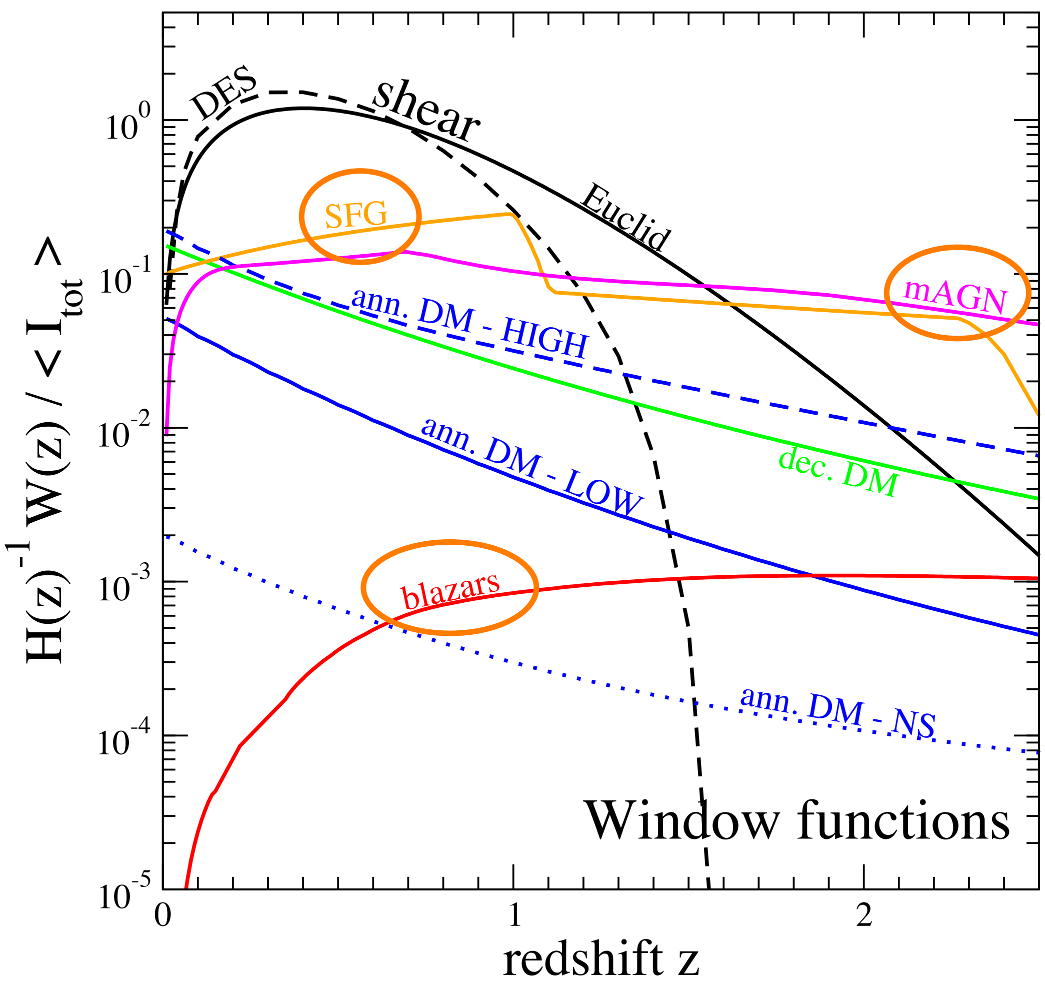
- $\alpha_{mAGN} \approx 2.37$
- GRLF from [3]
- M(L) from BH-mass relation to radio luminosity [4] transferred to gamma luminosity [2,3]

SFG

- $\alpha_{mAGN} \approx 2.7$
- GRFL from [5] based on IR luminosity function of [6]
- M(L) from relating gamma-ray luminosity to SFR [7]

[1] Harding et al. JCAP 1211 (2012) 026
[2] Hutsi et al, arXiv:1304.3717
[3] Di Mauro et al, Ap.J. 780 (2014) 161
[4] Franceschini et al., astro-ph/9801129
[5] Ackermann et al (Fermi C.), Ap.J. 780 (2014) 161
[6] Rodighiero et al, A.A. 515 (2009) 20
[7] Lu et al, arXiv:1306.0650

Window functions



Annihilating DM

$m_{\rm DM} = 100$ GeV

$\langle \sigma_a v \rangle = 3 \times 10^{-26}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$

Decaying DM

$m_{\rm DM} = 200$ GeV

$\Gamma_d = 0.33 \times 10^{-27}\ \mathrm{s}^{-1}$

Camera, Fornasa, NF, Regis, arXiv:1411.4651

Correlation functions

Source Intensity

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

Window function

Density field of the source

Cross-correlation angular power spectrum

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

3D Power spectrum (we use the halo model)

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

$$f_g \equiv [g(\boldsymbol{x}|m, z)/\bar{g}(z) - 1]$$

$\hat{f}_g$: *Fourier tranform*

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

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

Linear bias

Linear matter PS

3D Power spectrum

DM gravitational tracer:	δ	feels the density
Decaying-DM signal:	δ	feels the density
Annihilating-DM signal:	δ^2	feels the density squared
Astrophysical sources:	S	$g_S(\mathcal{L}, \mathbf{x} - \mathbf{x}') = \mathcal{L}\ \delta^3(\mathbf{x} - \mathbf{x}')$

Cross correlations power spectrum:

Decaying DM + Gravitational tracer	$P^{\delta\delta}$
Annihilating DM + Gravitational tracer	$P^{\delta\delta^2}$
Astrophysical sources + Gravitational tracer	$P^{S\delta}$

3D Power spectra

Decaying DM

$$P_{1h}^{\delta\delta}(k,z) = \int_{M_{\min}}^{M_{\max}} dM \, \frac{\mathrm{d}n}{\mathrm{d}M} \tilde{v}^2(k|M)$$

$$P_{2h}^{\delta\delta}(k,z) = \left[\int_{M_{\min}}^{M_{\max}} dM \, \frac{\mathrm{d}n}{\mathrm{d}M} b_h(M) \tilde{v}(k|M)\right]^2 P_{\mathrm{lin}}(k,z)$$

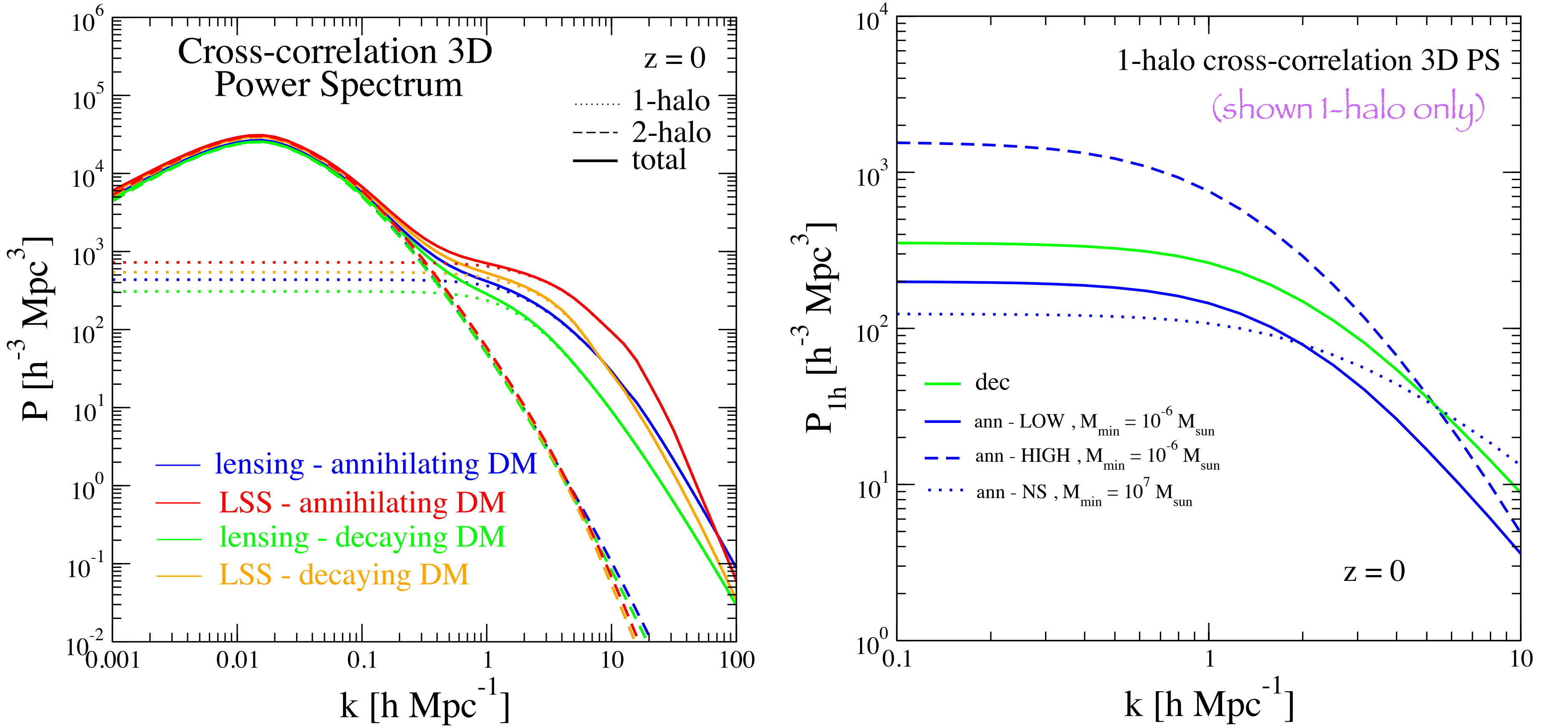
Annihilating DM

$$P_{1h}^{\delta\delta^2}(k,z) = \int_{M_{\min}}^{M_{\max}} \mathrm{d}M \, \frac{\mathrm{d}n}{\mathrm{d}M} \tilde{v}(k|M) \frac{\tilde{u}(k|M)}{\Delta^2}$$

$$P_{2h}^{\delta\delta^2}(k,z) = \left[\int_{M_{\min}}^{M_{\max}} \mathrm{d}M \, \frac{\mathrm{d}n}{\mathrm{d}M} b_h(M) \tilde{v}(k|M)\right] \left[\int_{M_{\min}}^{M_{\max}} \mathrm{d}M \, \frac{\mathrm{d}n}{\mathrm{d}M} b_h(M) \frac{\tilde{u}(k|M)}{\Delta^2}\right] P_{\mathrm{lin}}(k,z)$$

dn/dM	Halo mass function	
$\tilde{v}(k\|M)$	Fourier transform of	$\rho_{\mathrm{DM}}(\mathbf{x}\|M)/\bar{\rho}_{\mathrm{DM}}$
$\tilde{u}(k\|M)$	Fourier transform of	$\rho_{\mathrm{DM}}^2(\mathbf{x}\|M)[1+b(M,z)]/\bar{\rho}_{\mathrm{DM}}^2$
$b_h(M)$	Bias between halo and matter	

3D Power spectra: dark matter



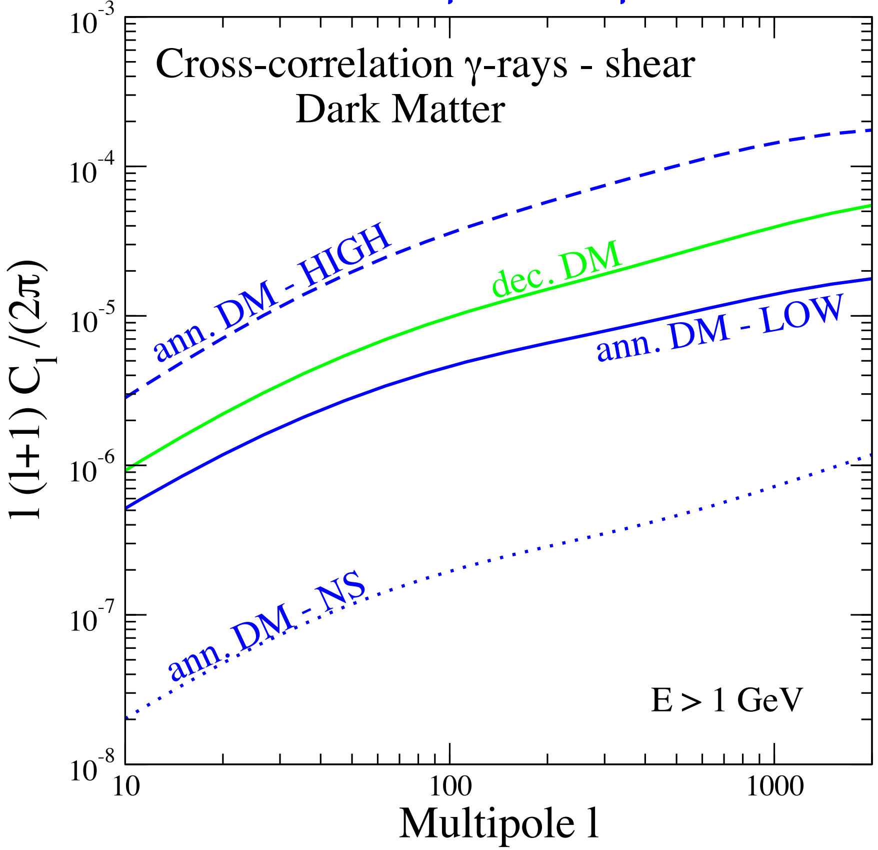
NF, Regis, Front. Physics 2 (2014) 6

Angular power spectrum

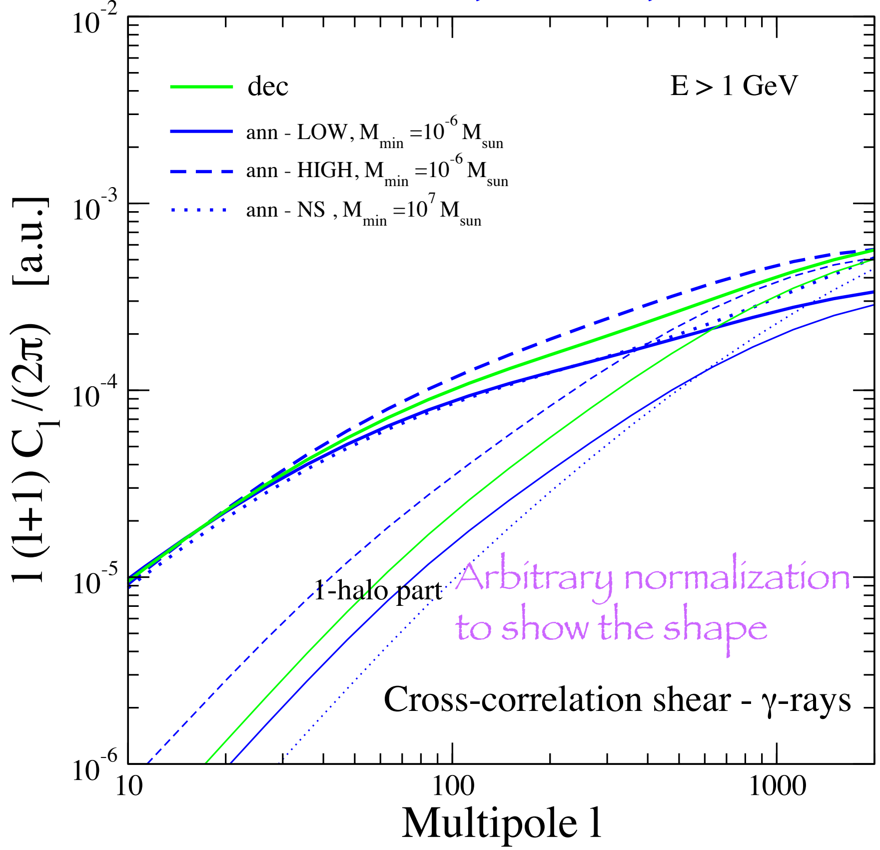
$$C_\ell^{(ij)} = \frac{1}{\langle I_i \rangle \langle I_j \rangle} \int \frac{d\chi}{\chi^2} W_i(\chi)\, W_j(\chi) P_{ij}(k = \ell/\chi, \chi)$$

Angular power spectra

DM angular power spectrum



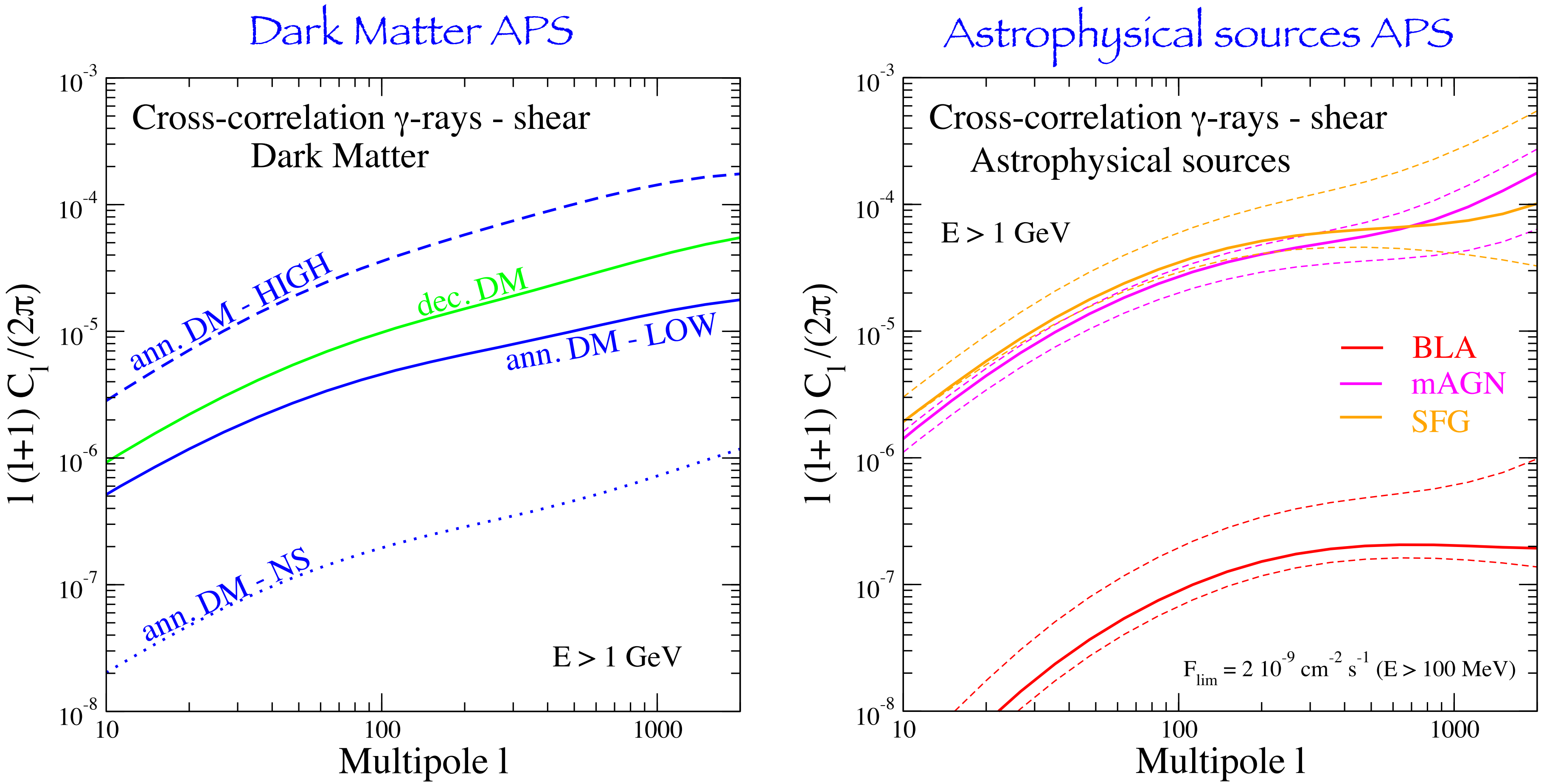
DM Angular power spectrum



$$C_l^{(i,j)} \longleftarrow W_i(\chi)\, W_j(z)\, P_{ij}(k = l/\chi, \chi)$$

Camera, Fornasa, NF, Regis, arXiv:1411.4651

Angular power spectra



Camera, Fornasa, NF, Regis, arXiv:1411.4651

Detectors

- Gamma-rays

  Fermi-LAT — DAMPE, Gamma400, HERD

  space based
  $0.3 < E < 300$ GeV
  sensitivity: 10^{-9} cm^{-2} s^{-1}
  angular resolution: 0.1 deg at high-energy
  full sky survey
  until at least 2018

  CTA

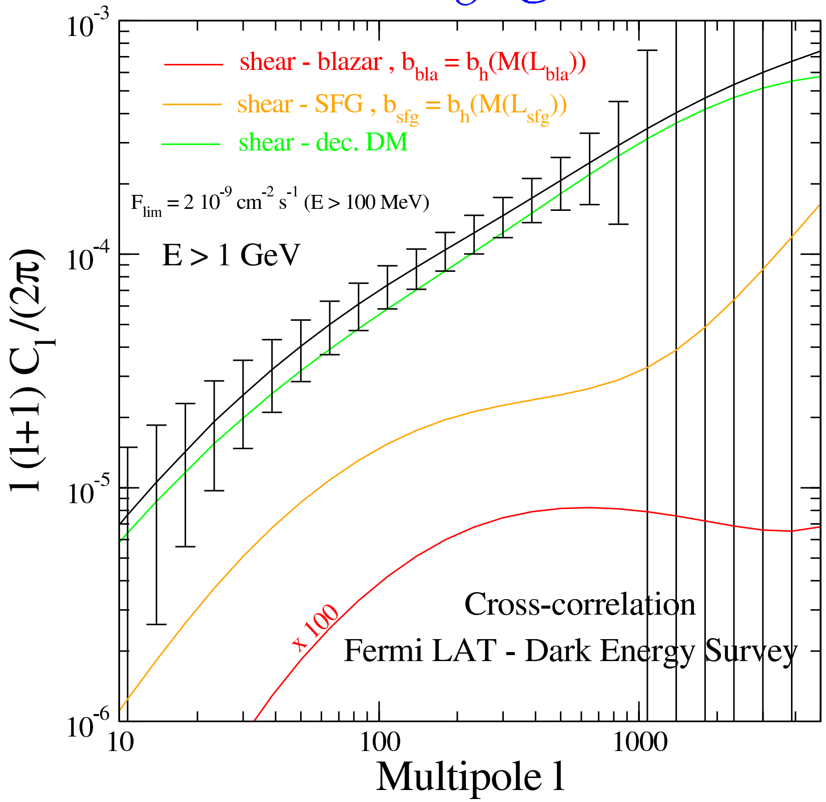
  ground based
  "10 GeV" < E < "10 TeV"
  few square degrees, but allows to explore higher multipoles

- Cosmic-shear

DES	Euclid
$0.3 < z < 1.5$	$0 < z < 2.5$
13.3 gal / arcmin^2	30 gal / arcmin^2
5000 squared degrees	20000 squared degrees
3 redshift bins	10 redshift bins
2012-2017	2020-2026

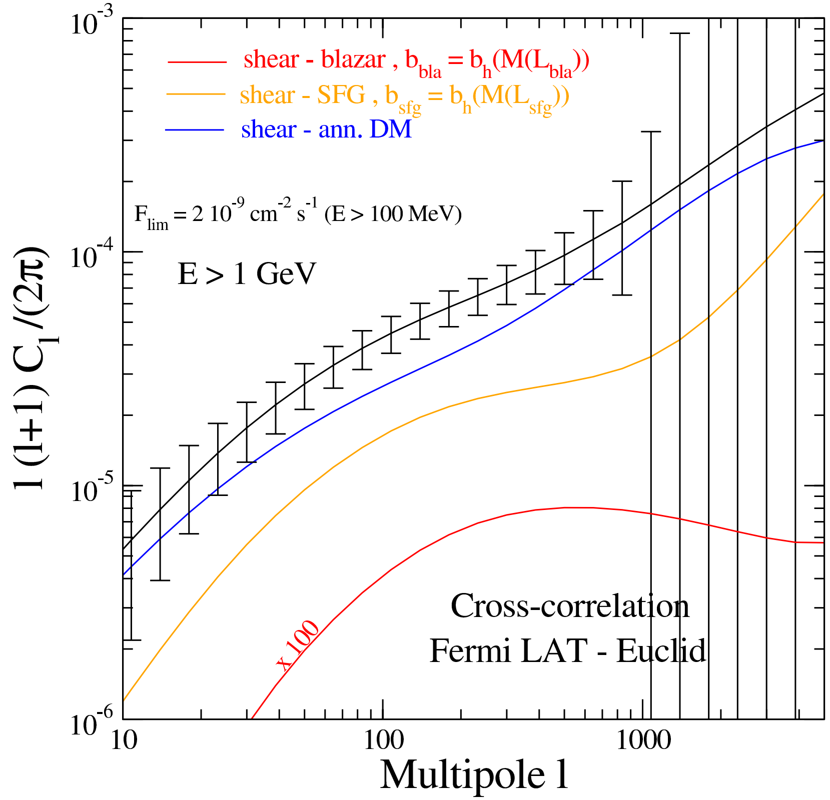
Cross-correlation predictions

Decaying DM



Fermi-LAT/5-yr with DES

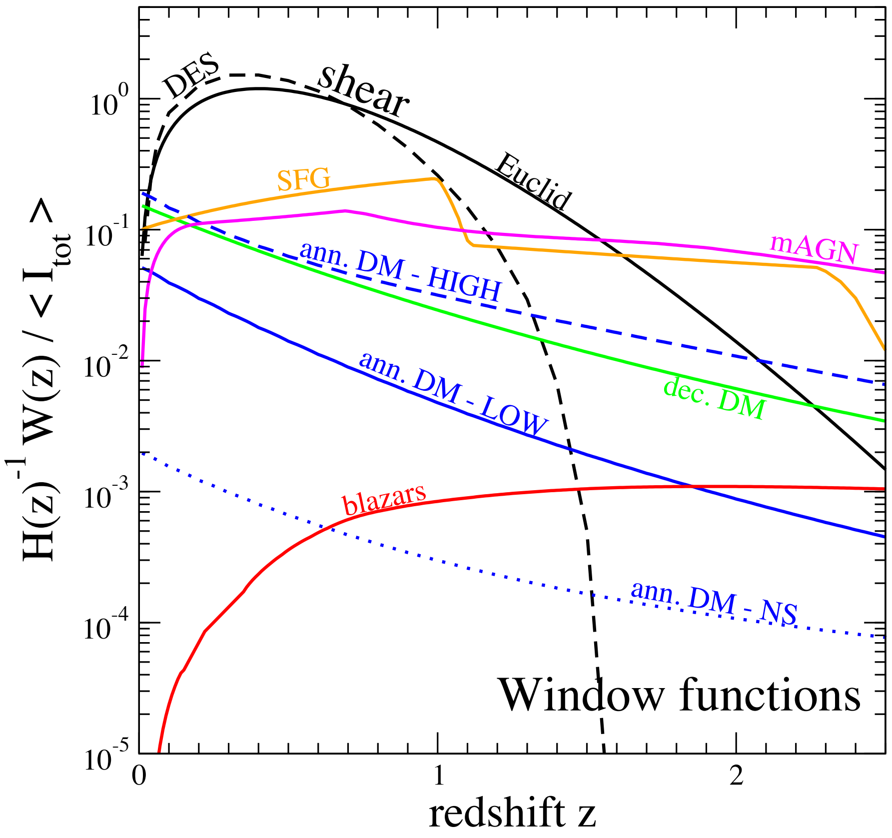
Annihilating DM

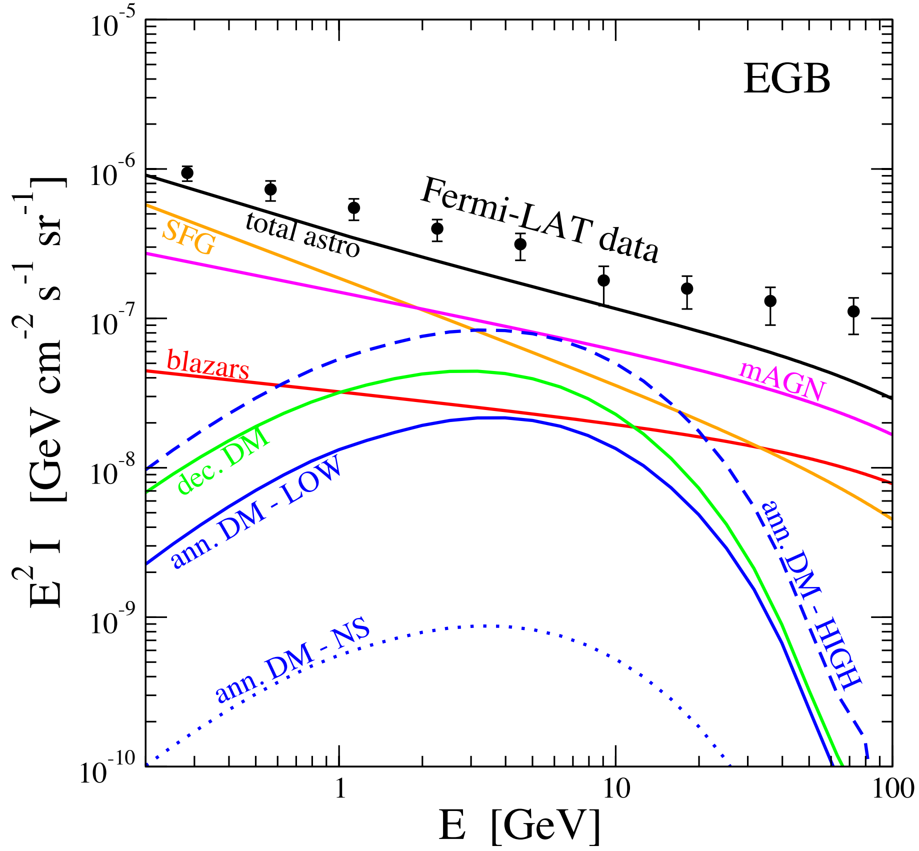


Fermi-LAT/5-yr with Euclid

Camera, Fornasa, NF, Regis, Ap. J. Lett. 771 (2013) L5

Tomographic-Spectral approach





Reshift information in shear: can help in "filtering" signal sources

Energy spectrum of gamma-rays: can help in DM-mass reconstruction

Camera, Fornasa, NF, Regis, arXiv:1411.4651

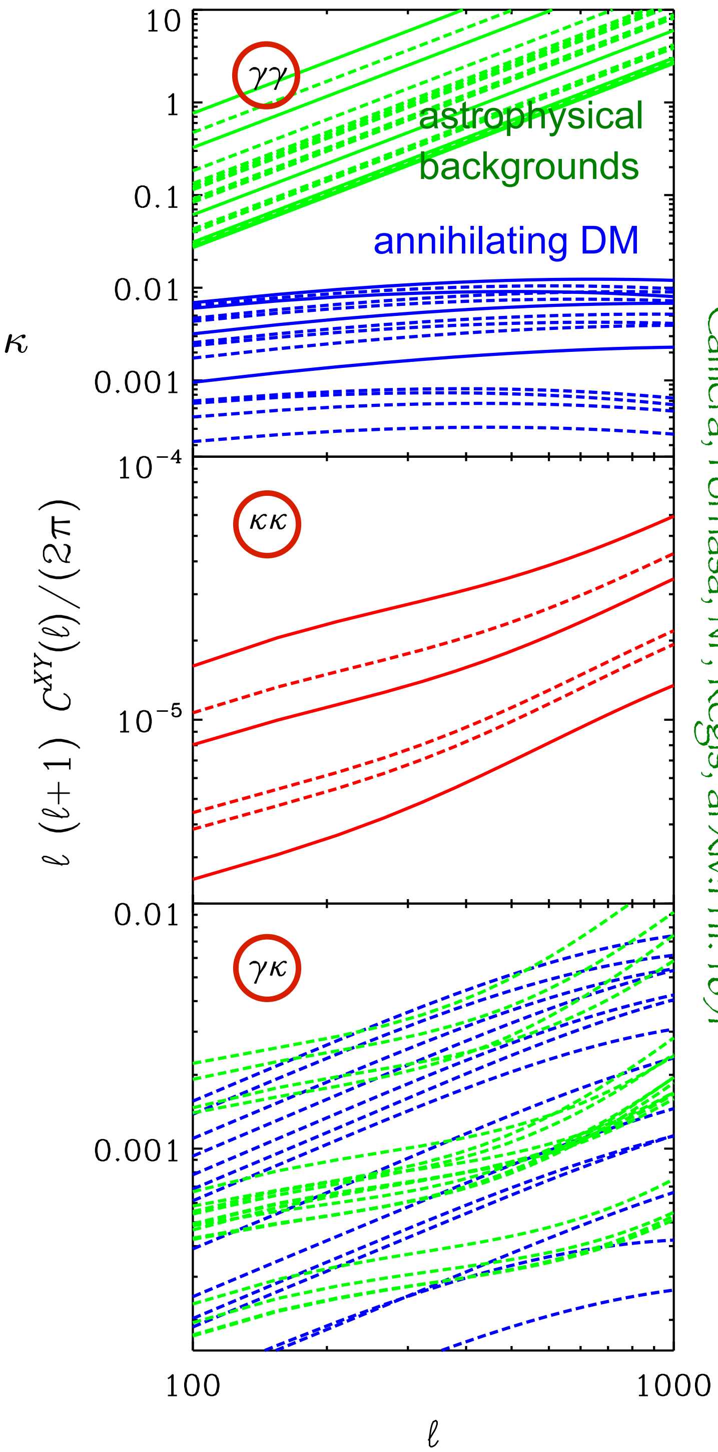
Cross-correlation matrix

$$C_\ell^{\gamma\kappa} = C_\ell^{\gamma\mathrm{DM}\,\kappa} + C_\ell^{\gamma\mathrm{BLA}\,\kappa} + C_\ell^{\gamma\mathrm{mAGN}\,\kappa} + C_\ell^{\gamma\mathrm{SFG}\,\kappa}$$

$$\mathbf{C}_\ell^{\gamma\kappa} = \begin{pmatrix} C_\ell^{\gamma_1\kappa_1} & \cdots & C_\ell^{\gamma_1\kappa_{N_z}} \\ \vdots & \ddots & \vdots \\ C_\ell^{\gamma_{N_E}\kappa_1} & \cdots & C_\ell^{\gamma_{N_E}\kappa_{N_z}} \end{pmatrix}$$

energy bin

redshift bin



Camera, Fornasa, NF, Regis, arXiv:1411.4651

Bayesian forecasts

Likelihood function $L(\boldsymbol{\vartheta})$

Parameters $\vartheta = \{m_{\rm DM},\, \langle\sigma_a v\rangle,\, \mathcal{A}_{\rm BLA},\, \mathcal{A}_{\rm SFG},\, \mathcal{A}_{\rm mAGN}\}$

Covariance matrix
$$[\Gamma^{\gamma\kappa}_{\ell\ell'}]^{ai,bj} = \frac{\widehat{C}^{\gamma_a\kappa_j}_\ell \widehat{C}^{\gamma_b\kappa_i}_\ell + \widehat{C}^{\gamma_a\gamma_b}_\ell \widehat{C}^{\kappa_i\kappa_j}_\ell}{(2\ell+1)\Delta\ell f_{\rm sky}}\delta_K^{\ell\ell'}$$

Observables
$$\widehat{\mathbf{C}}^{XY}_\ell = \mathbf{C}^{XY}_\ell + \boldsymbol{\mathcal{N}}^{XY}_\ell$$

Signal Noise

$$\mathcal{N}^{\gamma_a\gamma_b}_\ell = \delta_K^{ab}\frac{4\pi f_{\rm sky}}{\bar{N}_{\gamma_a}}\mathcal{W}_\ell^{-2}$$

$$\mathcal{N}^{\kappa_i\kappa_j}_\ell = \delta_K^{ij}\frac{\sigma_\epsilon^2}{\bar{N}_{g_i}}$$

$$\mathcal{N}^{\gamma\kappa}_\ell = 0$$

Fisher matrix
$$\mathbf{F}_{\alpha\beta} = \sum_{\ell,\ell'=\ell_{\rm min}}^{\ell_{\rm max}} \frac{\partial \mathbf{C}^{\gamma\kappa}_\ell}{\partial\vartheta_\alpha}[\boldsymbol{\Gamma}^{\gamma\kappa}_{\ell\ell'}]^{-1}\frac{\partial \mathbf{C}^{\gamma\kappa}_{\ell'}}{\partial\vartheta_\beta}$$

1-sigma marginal error
$$\sigma(\vartheta_\alpha) = \sqrt{(\mathbf{F}^{-1})_{\alpha\alpha}}$$

Bayesian Forecasts

- Bounds in the (m_{DM}, <σv>) plane in case the DM contribution is strongly suppressed

- Discovery potential (5σ) in the (m_{DM}, <σv>) plane

- Strength in parameter reconstruction (on specific benchmark models)

- In all cases, the astrophysical components in the gamma emission (AGN, Blazars, SFG) are allowed to vary and are marginalized over

$\mathcal{A}_{\rm AGN} : (0.2 - 2)$ $\mathcal{A}_{\rm SFG} : (0.1 - 10)$ $\mathcal{A}_{\rm BLA} : (0.05 - 50)$

Detectors and configurations

Parameter	Description	DES	Euclid
$f_{\rm sky}$	Surveyed sky fraction	0.12	0.36
$\bar{N}_g$ [arcmin^{-2}]	Galaxy density	13.3	30
$z_{\rm min} - z_{\rm max}$	Redshift range	0.3 – 1.5	0 – 2.5
N_z	Number of bins	3	10
Δ_z	Bin width	0.4	0.25
$\sigma_z/(1+z)$	Redshift uncertainty	–	0.03
σ_ϵ	Intrinsic ellipticity	0.3	0.3

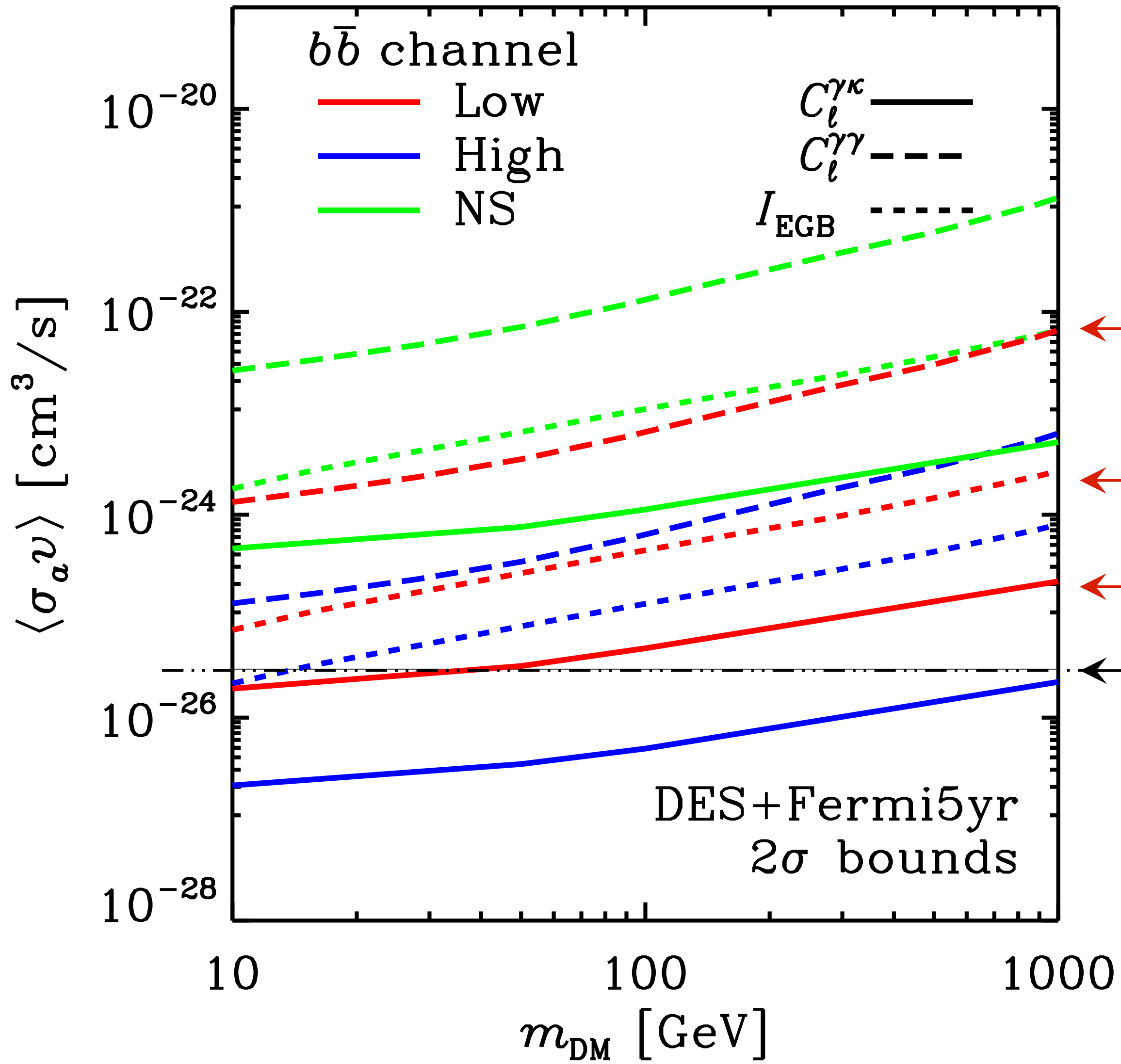
Parameter	Description	Fermi-5yr	Fermi-10yr	"Fermissimo"
$f_{\rm sky}$	Surveyed sky fraction	1	1	1
$E_{\rm min} - E_{\rm max}$ [GeV]	Energy range	1 – 300	1 – 300	0.3 – 1000
N_E	Number of bins	6	6	8
ε [cm^2 s]	Exposure	1.6×10^{12}	3.2×10^{12}	4.2×10^{12}
$\langle \sigma_b \rangle$ [deg]	Average beam size	0.18	0.18	0.027

DES + Fermi 5 yr (expected to be available this year)

Euclid + Fermi 10 yr

Euclid + "Fermissimo"

Forecasts: 2σ bounds



Correlation technique stronger among methods to probe extragalactic DM

γγ auto correlation

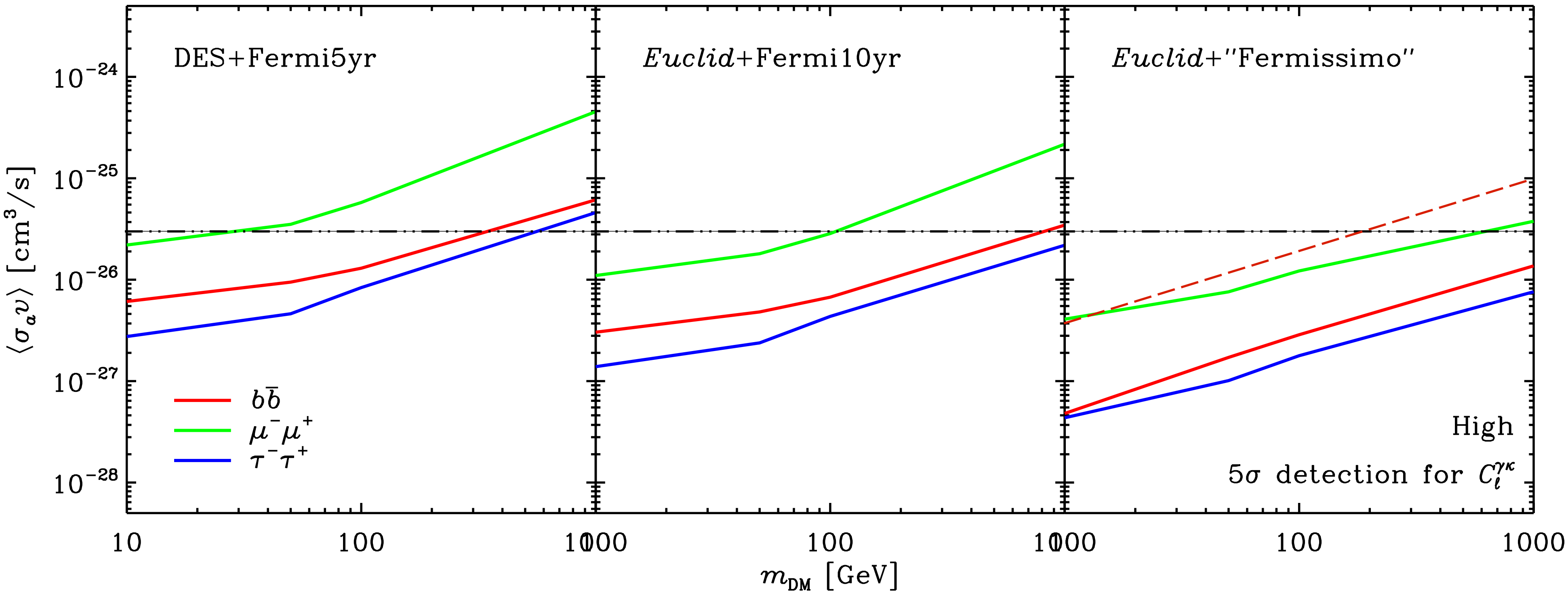
EGB Intensity

γκ cross correlation

Thermal <σv>

Camera, Fornasa, NF, Regis, arXiv:1411.4651

Forecasts: 5σ discovery potential

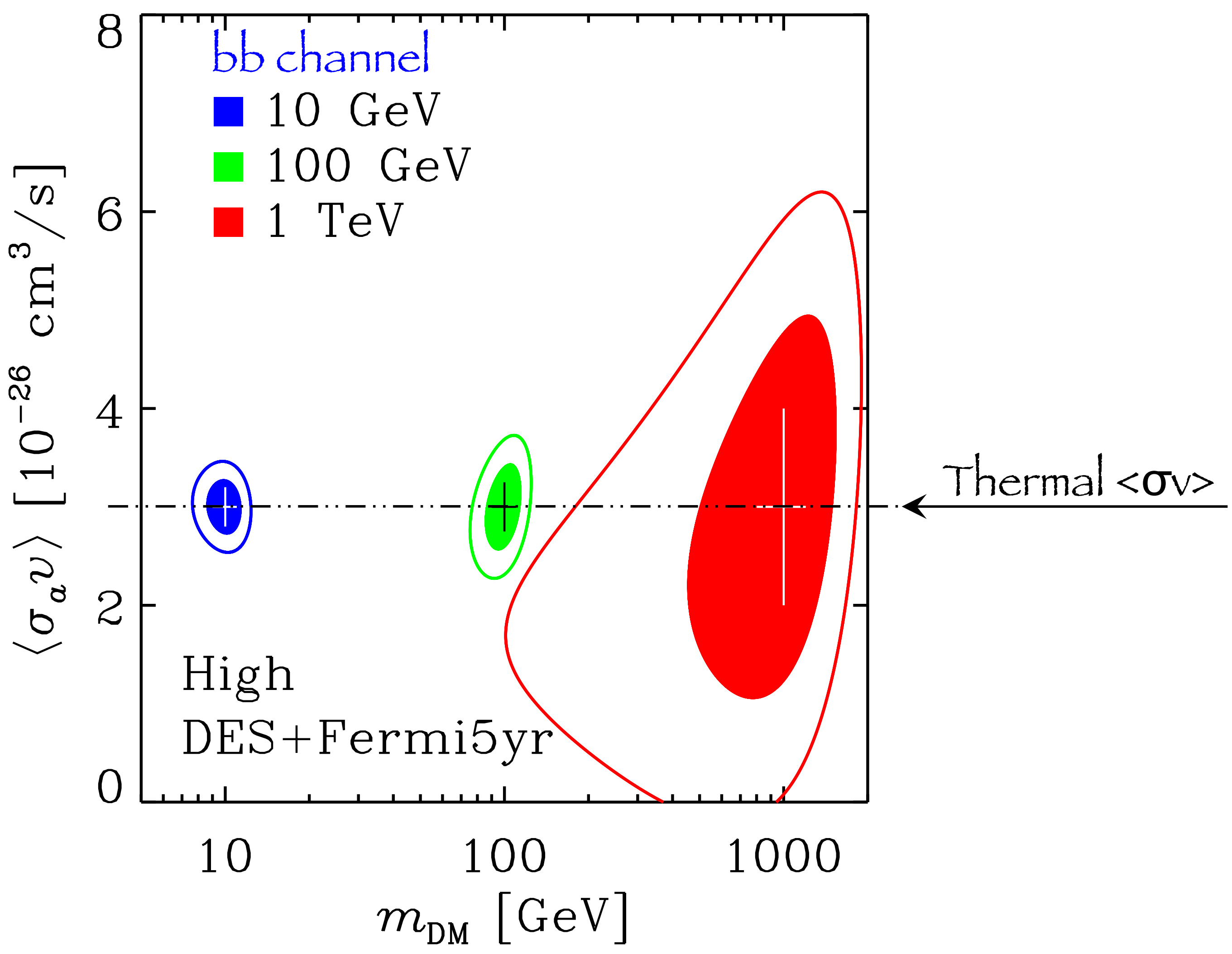


LOW clustering model: one order of magnitude less

Contributions from astrophysical components (AGN, Blazars, SFG) are modeled and marginalized over

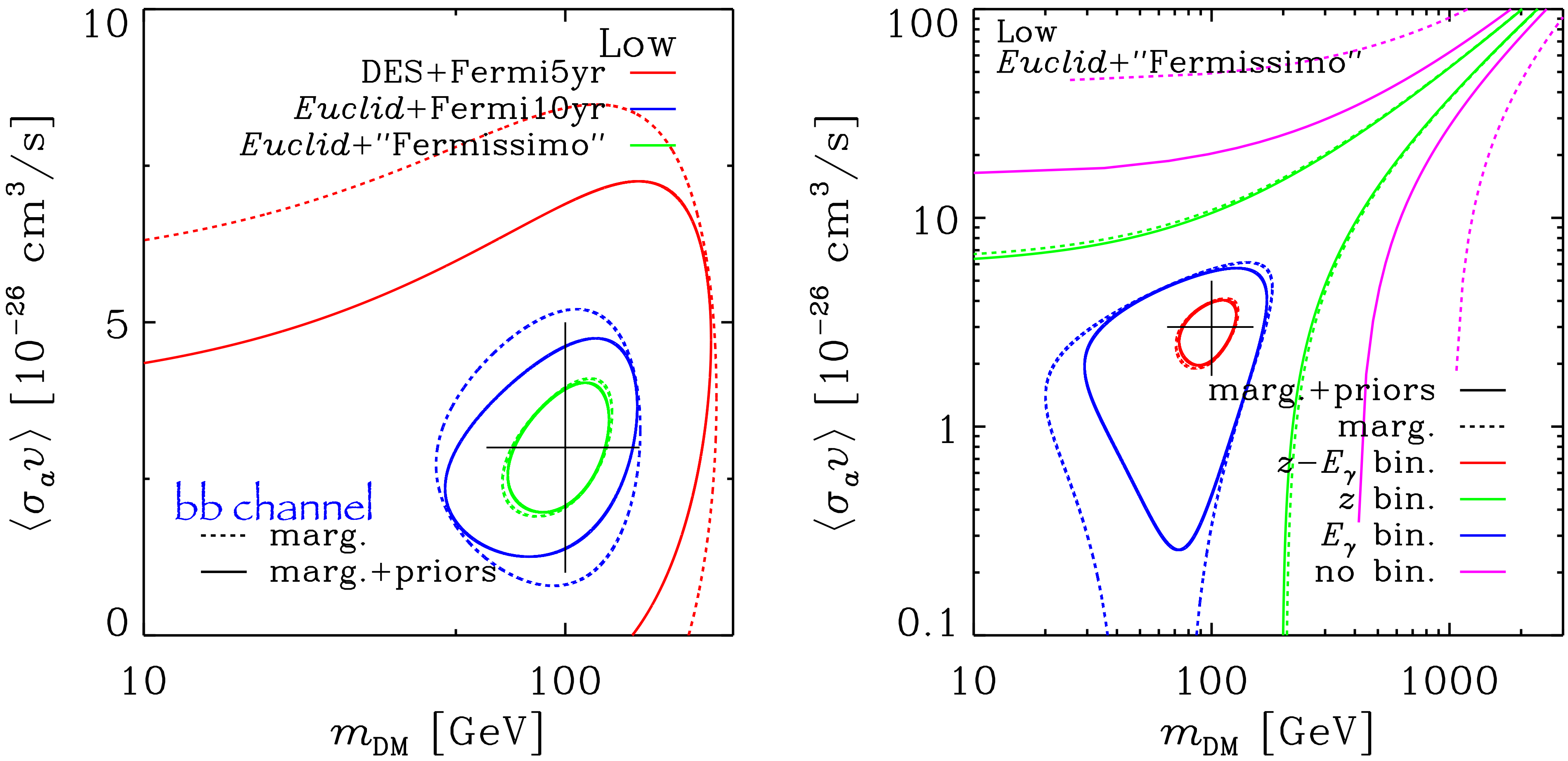
Camera, Fornasa, NF, Regis, arXiv:1411.4651

Forecasts on parameter reconstruction



Camera, Fornasa, NF, Regis, arXiv:1411.4651

Forecasts on parameters reconstruction



$m_{\rm DM}$ [GeV]	$\langle\sigma_a v\rangle$ [10^{-26} cm^{3}s^{-1}]	$m_{\rm DM}$ [GeV]	Γ_d [10^{-27} s^{-1}]
10 ± 0.53	3 ± 0.20	20 ± 4.9	0.33 ± 0.062
100 ± 18	3 ± 0.68	200 ± 19	0.33 ± 0.039
1000 ± 951	3 ± 3.7	2000 ± 119	0.33 ± 0.020

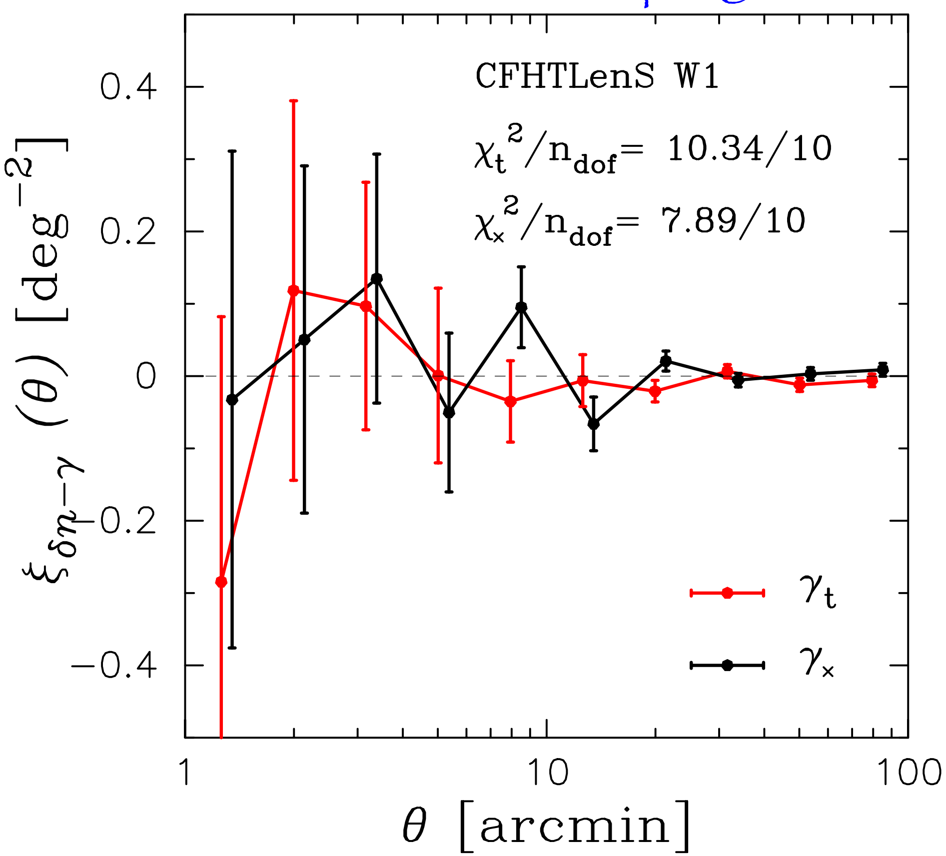
Camera, Fornasa, NF, Regis, arXiv:1411.4651

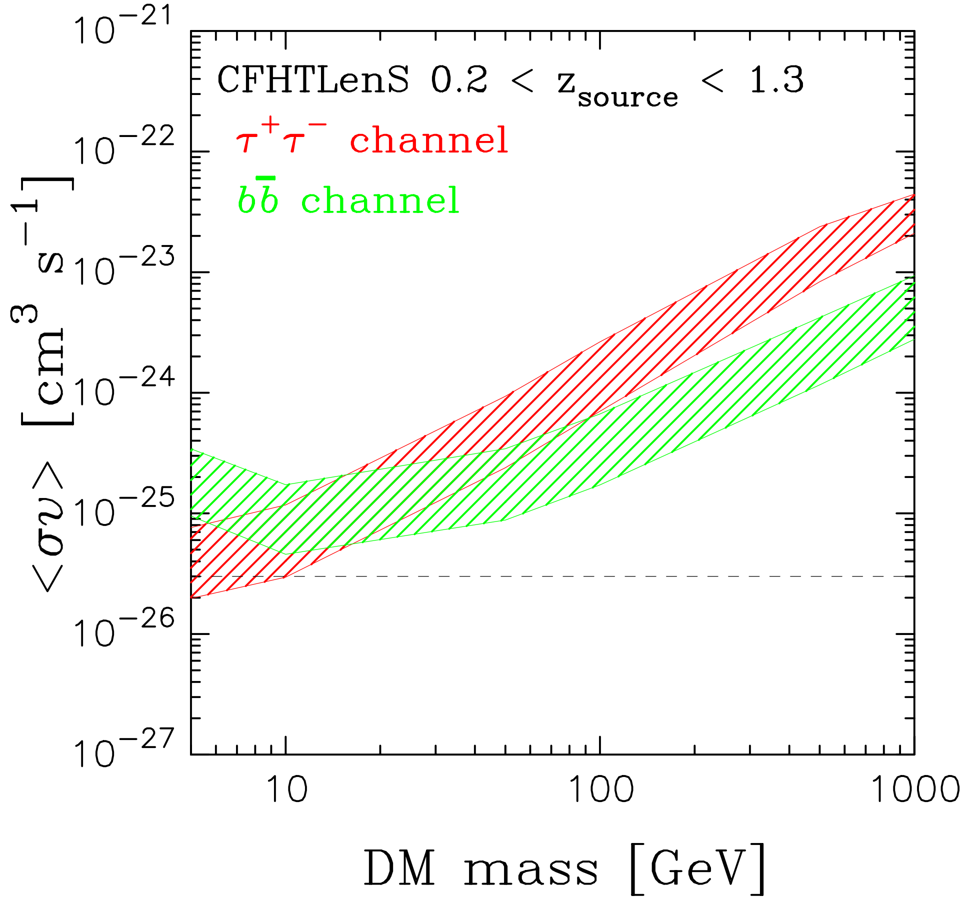
Comments

- The cross-correlation between gamma-rays + cosmic-shear looks promising
- Fermi has alreasy accumulated 6+ yr of data
- DES will likely release its first data this or next year
- For the future:
  - Fermi will double its statistics
  - Successors of Fermi are under discussion/preparation
  - Euclid will largely improve over DES

Attempt on data with a small survey

Patch W1: 72 sq. deg





CFHTLens + Fermi/5yr

Shirasaki, Horiuchi, Yoshida, PRD 90 (2014) 063502

CROSS CORRELATIONS
EXTENSION OF THE APPROACH

Extension of the cross-correlation approach

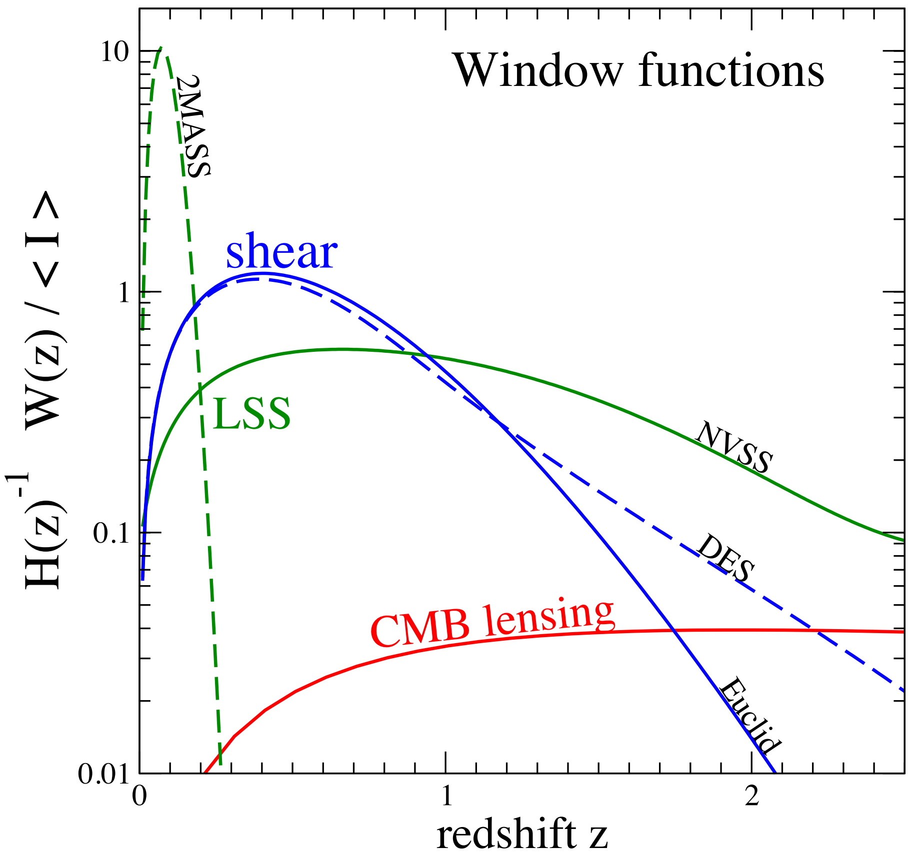
- Gravitational tracers: G_i
  - Weak lensing surveys (cosmic shear) traces the whole DM
  - CMB lensing
  - LSS surveys traces light -> bias

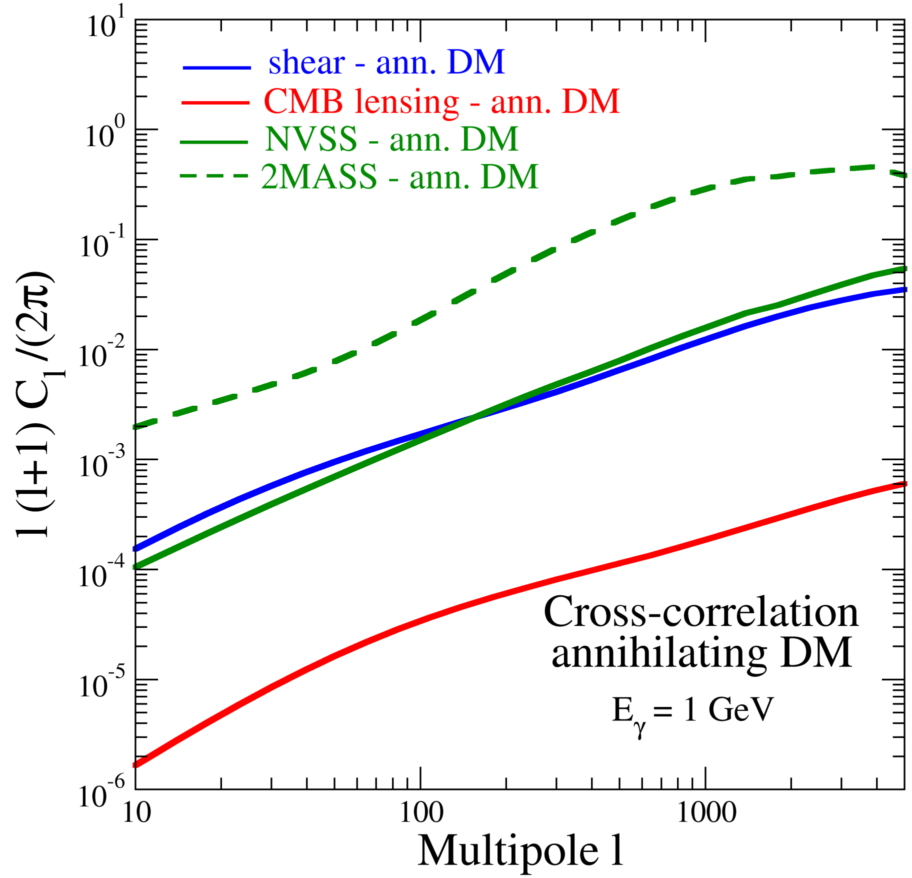
- Electromagnetic signals: E_a
  - Radio
  - X
  - Gamma

$$\langle G_i \times E_b \rangle \qquad \langle E_a \times E_b \rangle$$

NF, Regis, Front. Physics 2 (2014) 6

Additional cross correlations channels

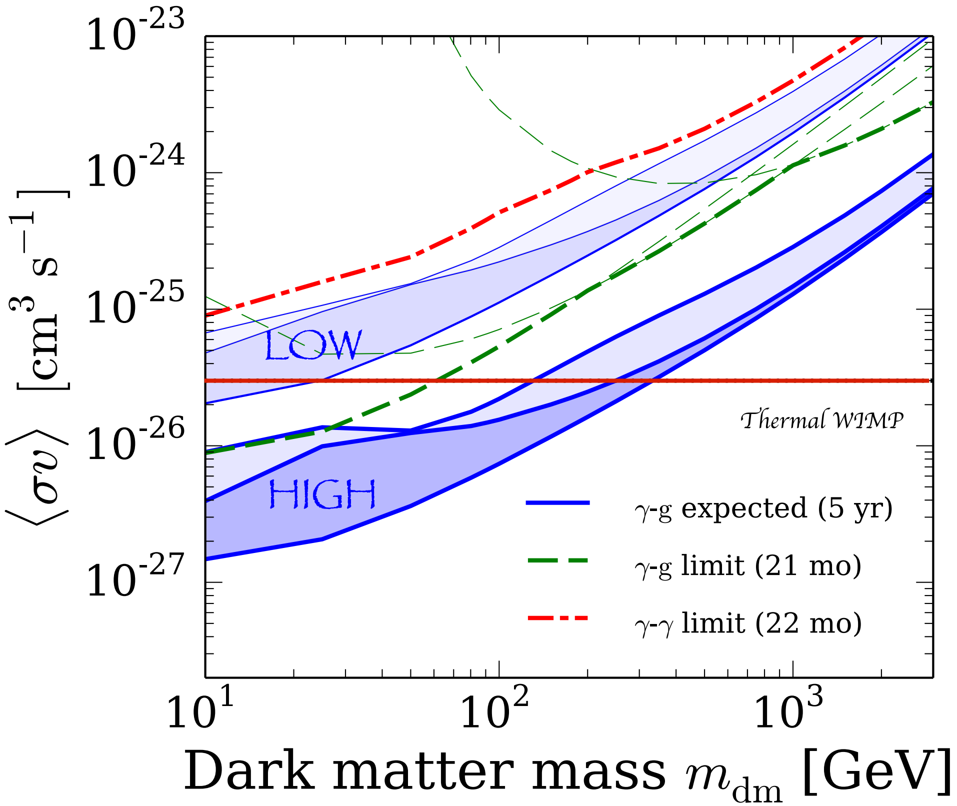




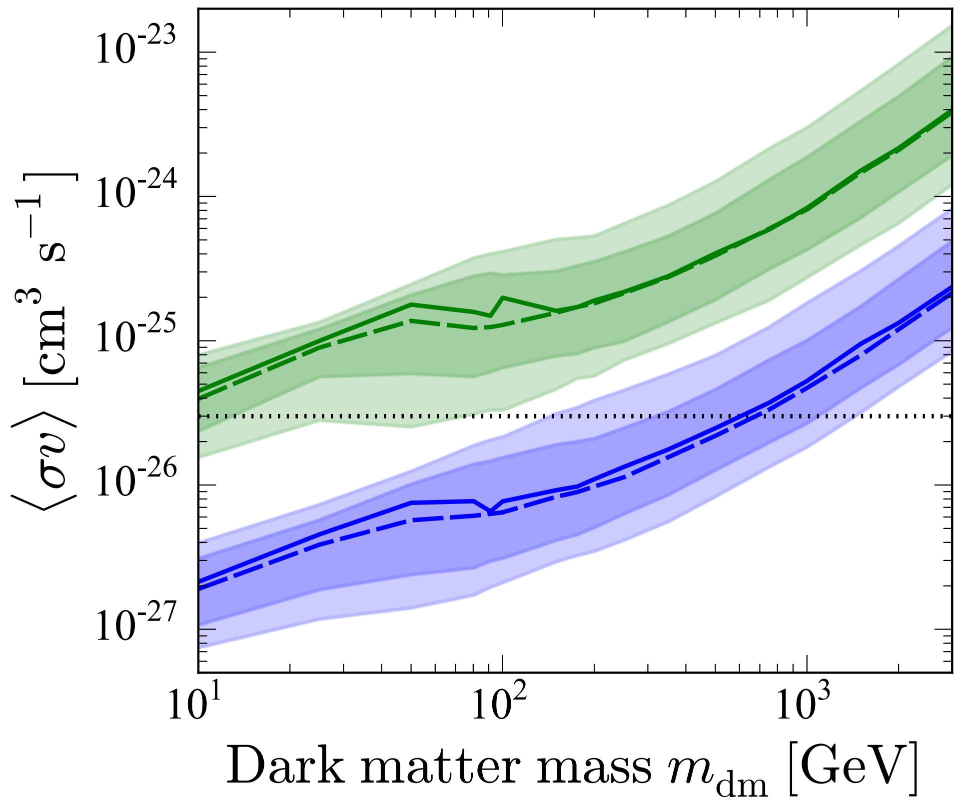
Multiwavelength signals with
LSS tracers and gravitational probes

NF, Regis, Front. Physics 2 (2014) 6

Fermi + 2MASS



Bounds based on non-observation of correlation in [*]

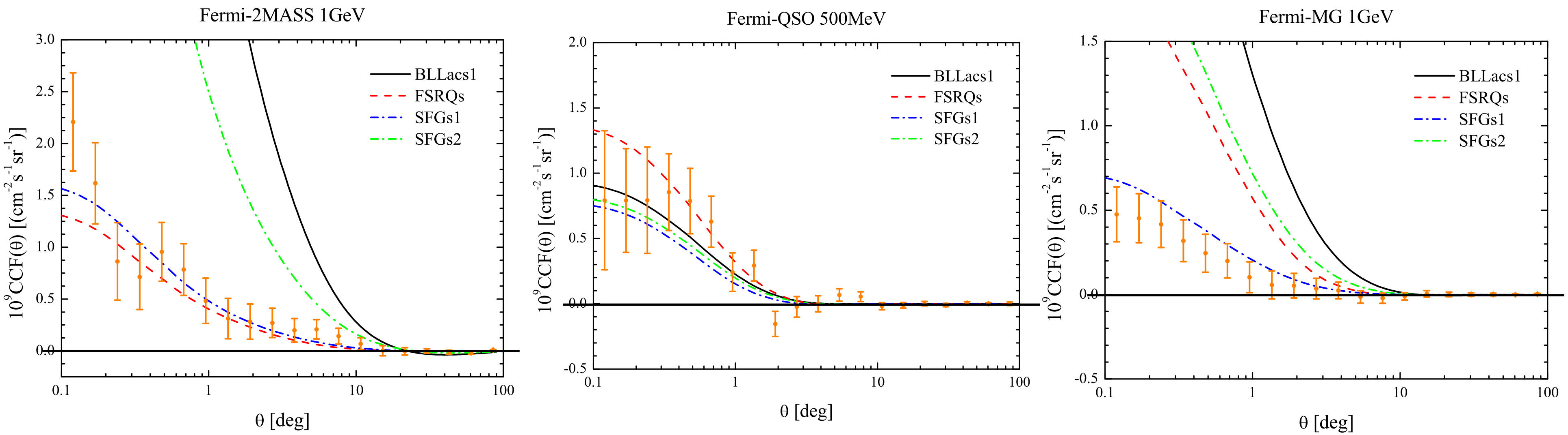


Forecasts
includes tomography

Ando, Benoit-Levy, Komatsu, PRD 90 (2014) 023514
[*] Xia, Cuoco, Branchini, Fornasa, Viel, MNRAS 416 (2011) 2247

Ando, JCAP 1410 (2014) 061

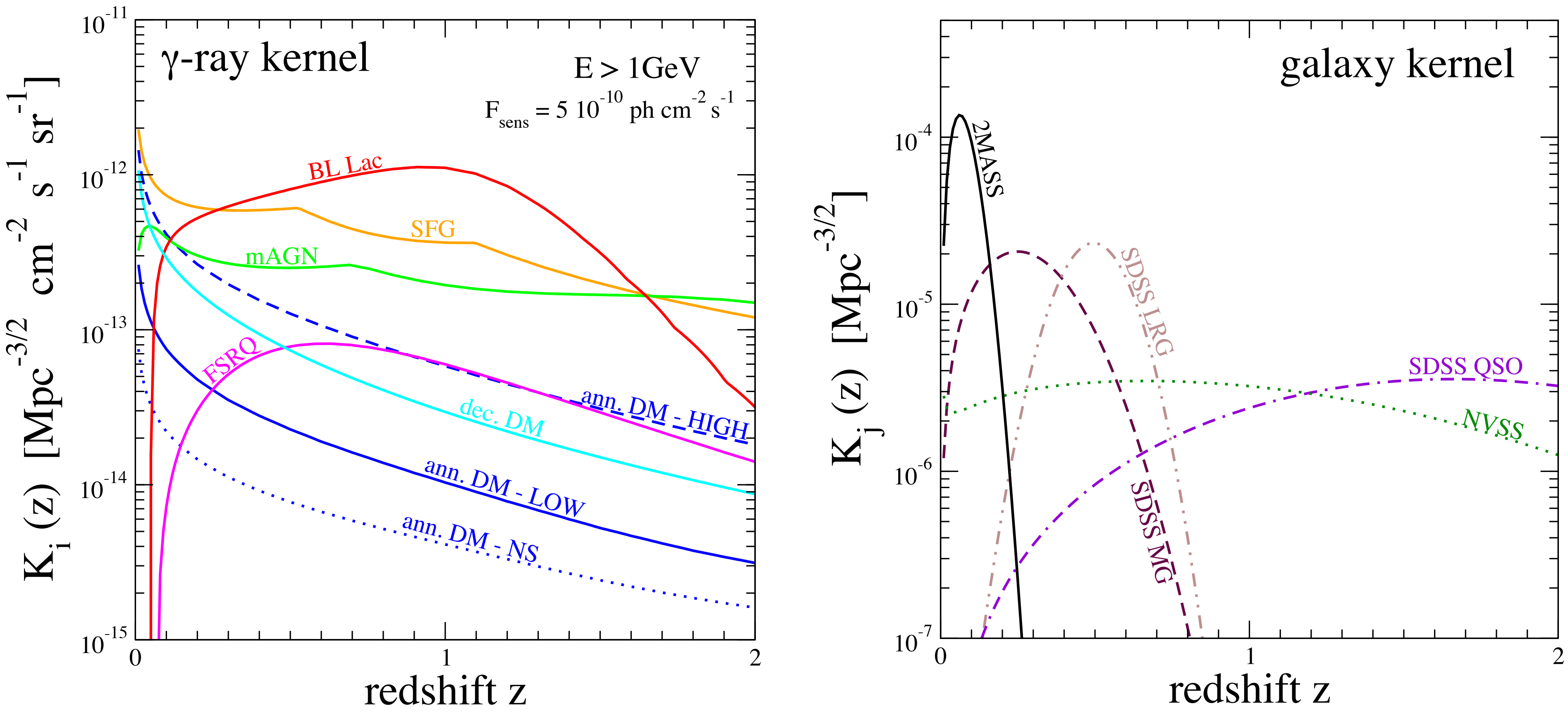
Fermi/gamma + LSS: correlation now observed



- 2MASS, QSO and NVSS: >3.5 σ
- SDSS galaxies: 3.0 σ
- Signal is stronger in two energy bands: E > 0.5 GeV and E > 1 GeV
- Also seen at E > 10 GeV
- Results robust against the choice of statistical estimator, estimate of errors, map cleaning procedure and instrumental effects

Xia, Cuoco, Branchini, Viel, ApJS 217 (2015) 1

Fermi + 2MASS: DM interpretation

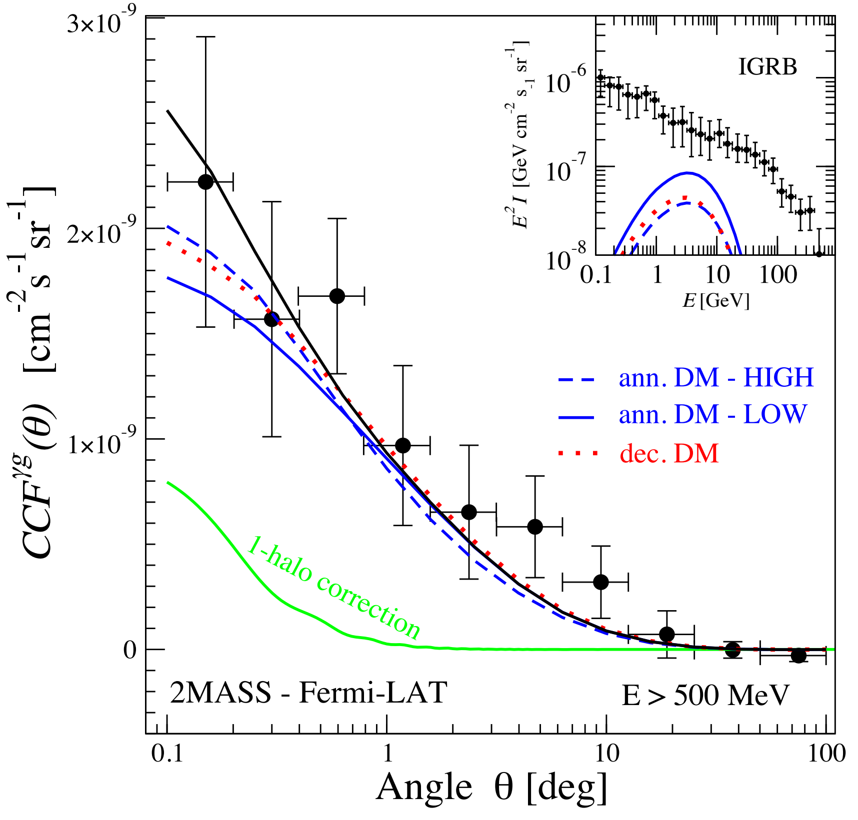


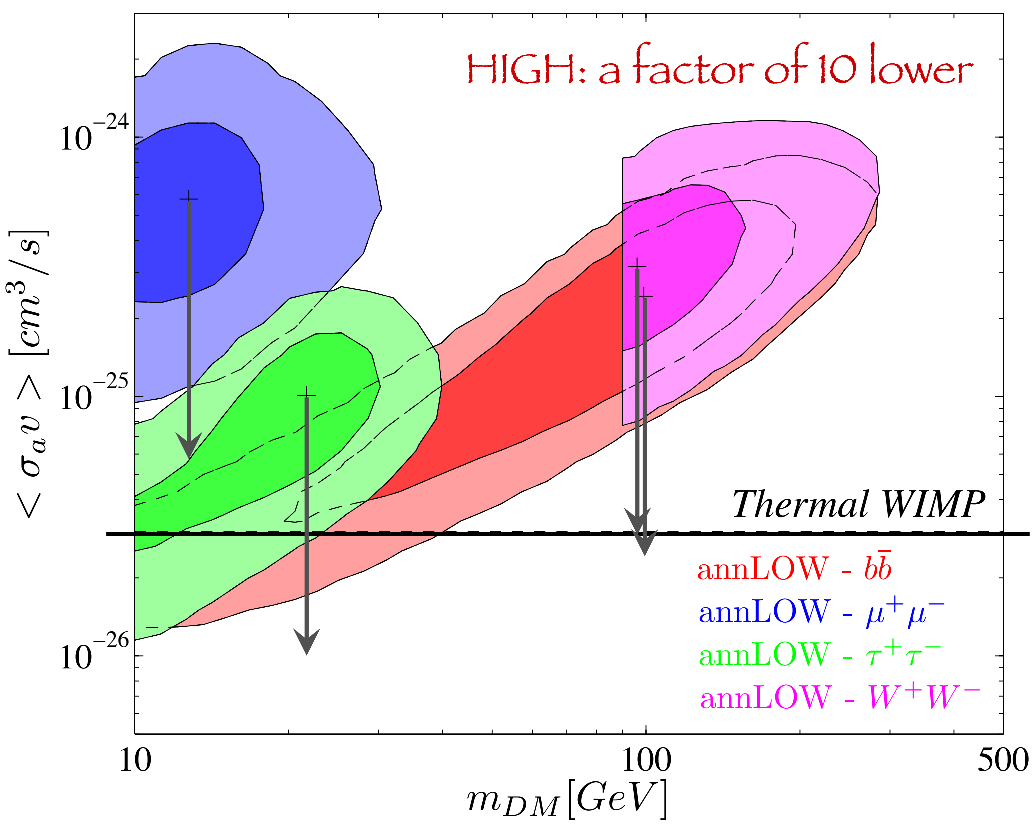
The DM kernel peaks at low redshift, as well as the 2MASS one

Best option for DM studies: cross-correlate with 2MASS

Regis, Xia, Cuoco, Branchini, NF, Viel, arXiv:1503.05922

Fermi + 2MASS: DM analysis





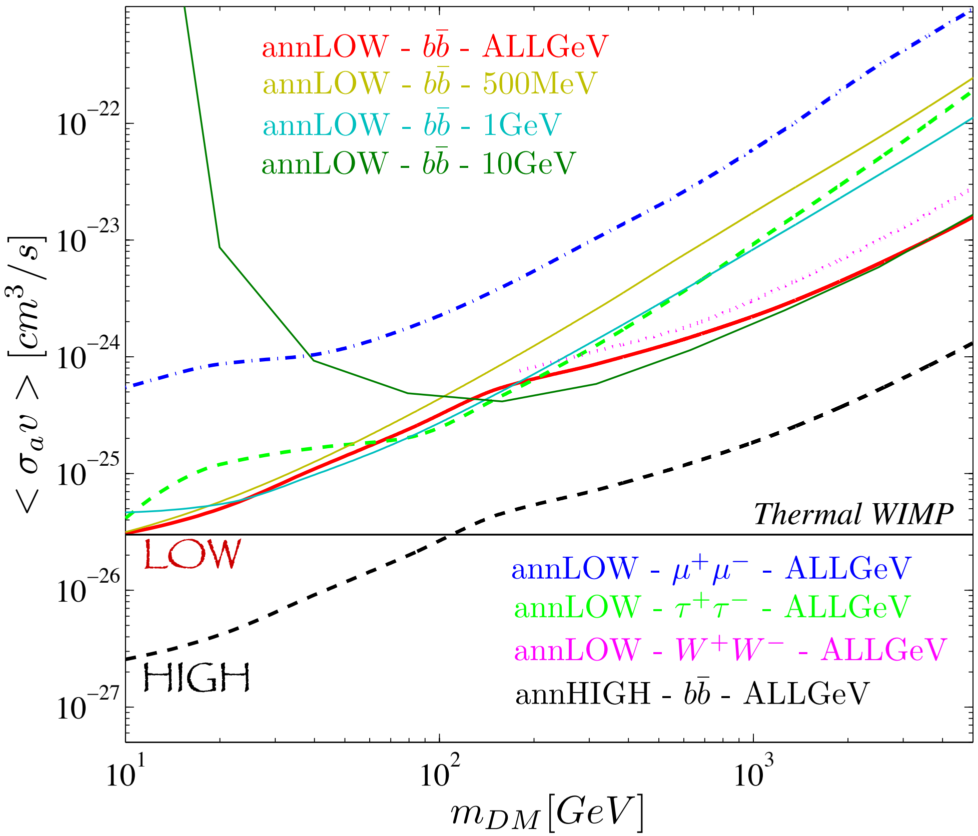
The observed cross-correlation is perfectly reproduced (both in shape and size) by a DM contribution

While the DM emission is largely subdominant in the total intensity

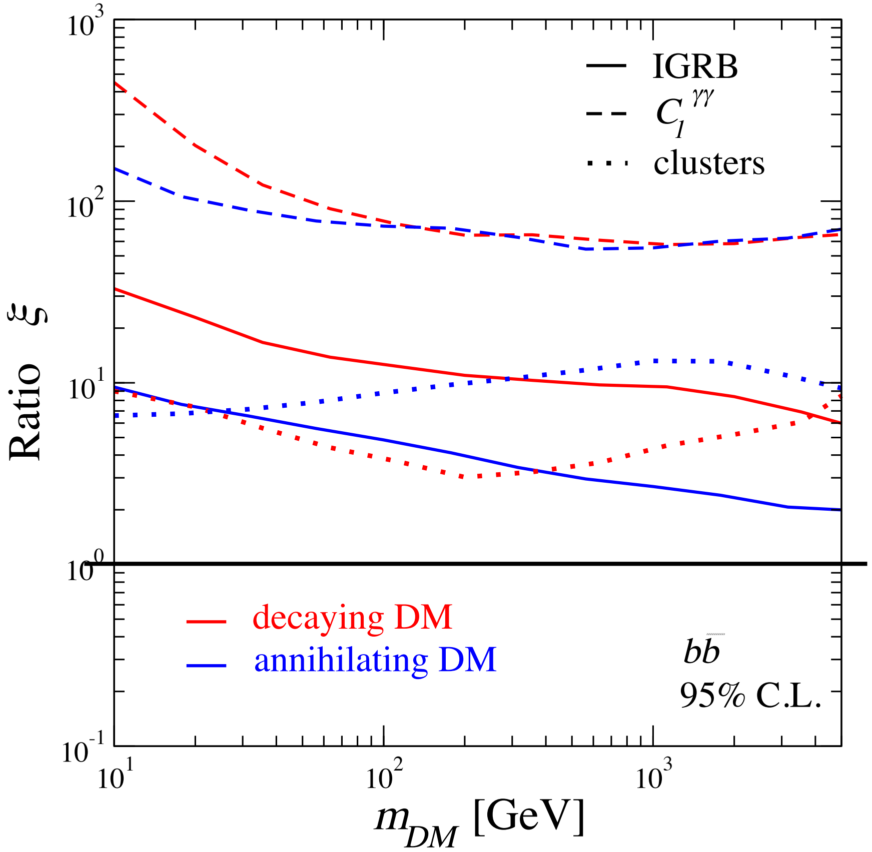
Analysis includes spectral information (3 energy bins)

Regis, Xia, Cuoco, Branchini, NF, Viel, arXiv:1503.05922

Fermi + 2MASS: DM analysis



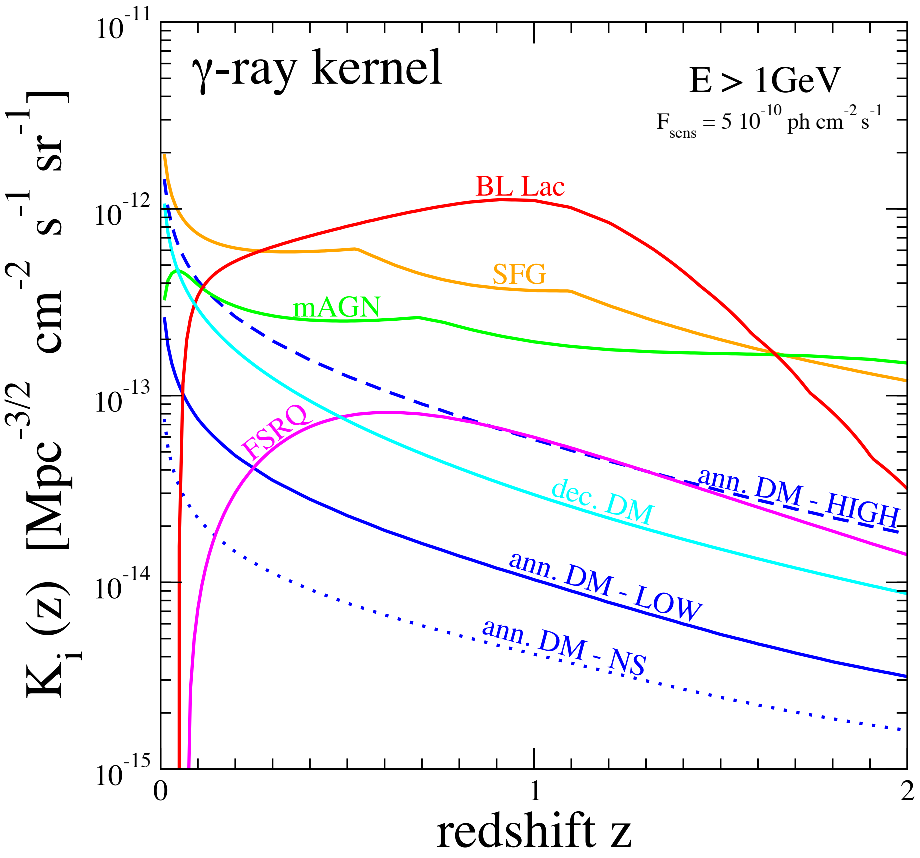
Bound from cross correlation

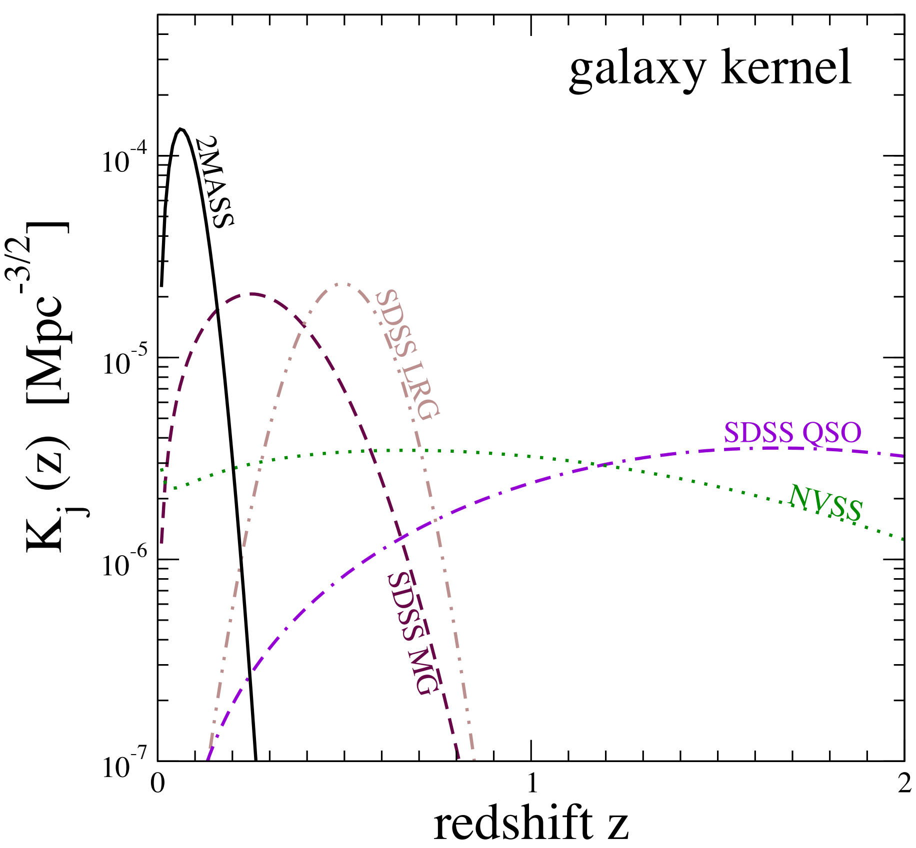


Bounds ratios
Correlation technique stronger

Regis, Xia, Cuoco, Branchini, NF, Viel, arXiv:1503.05922

Fermi + all LSS catalogs: DM + astro sources

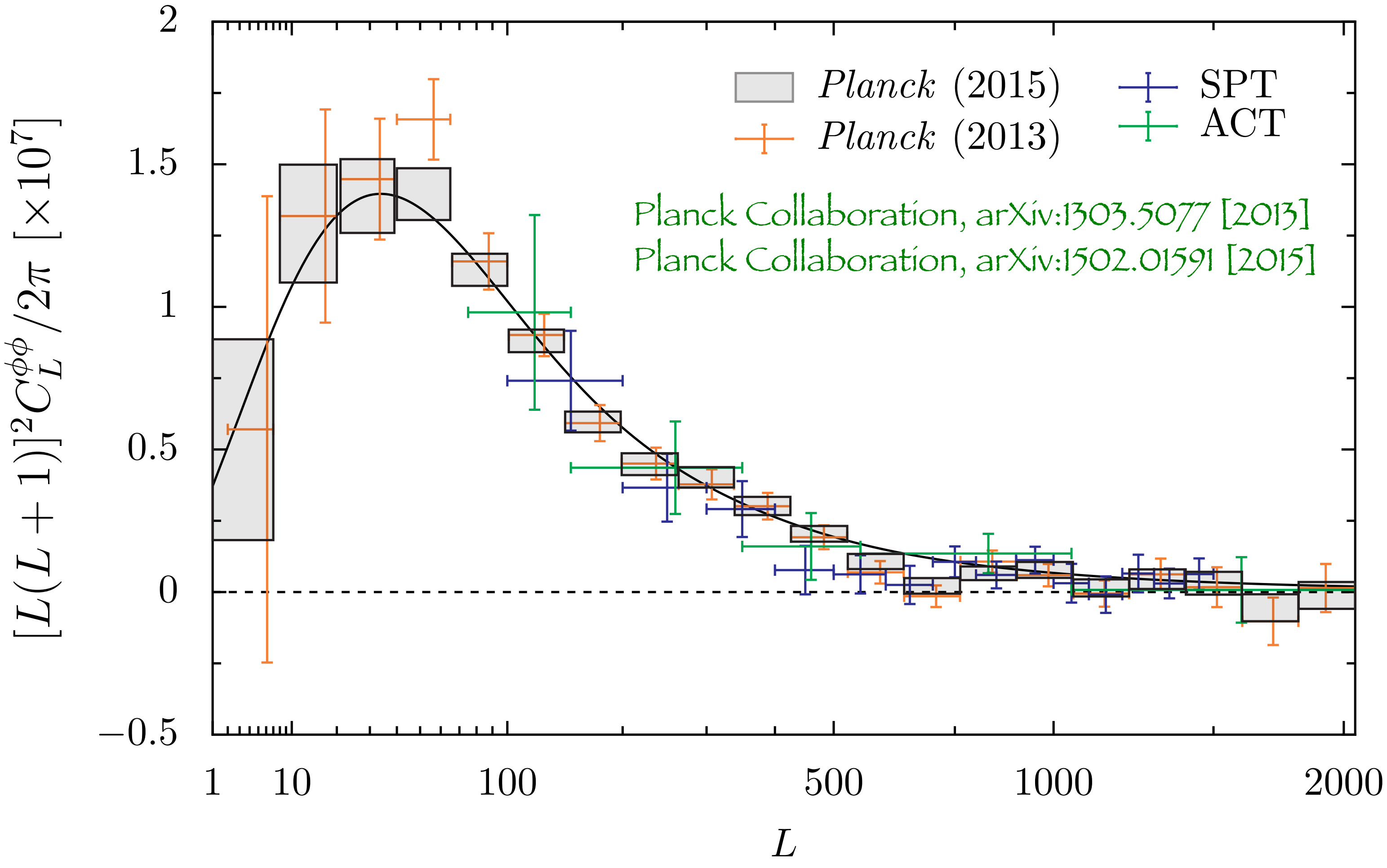




The different behaviour of kernels can help to discriminate the sources
(Analysis is under way)

Cuoco, Xia, Regis, Branchini, NF, Viel, to appear

Planck CMB lensing



- CMB-lensing autocorrelation is measured: 40σ significance
- CMB-lensing: integrated measure of DM distribution up to last scattering
- It might exhibit correlation with gamma-rays emitted in DM structures

Fermi/gamma + Planck/CMB lensing

Analysis:

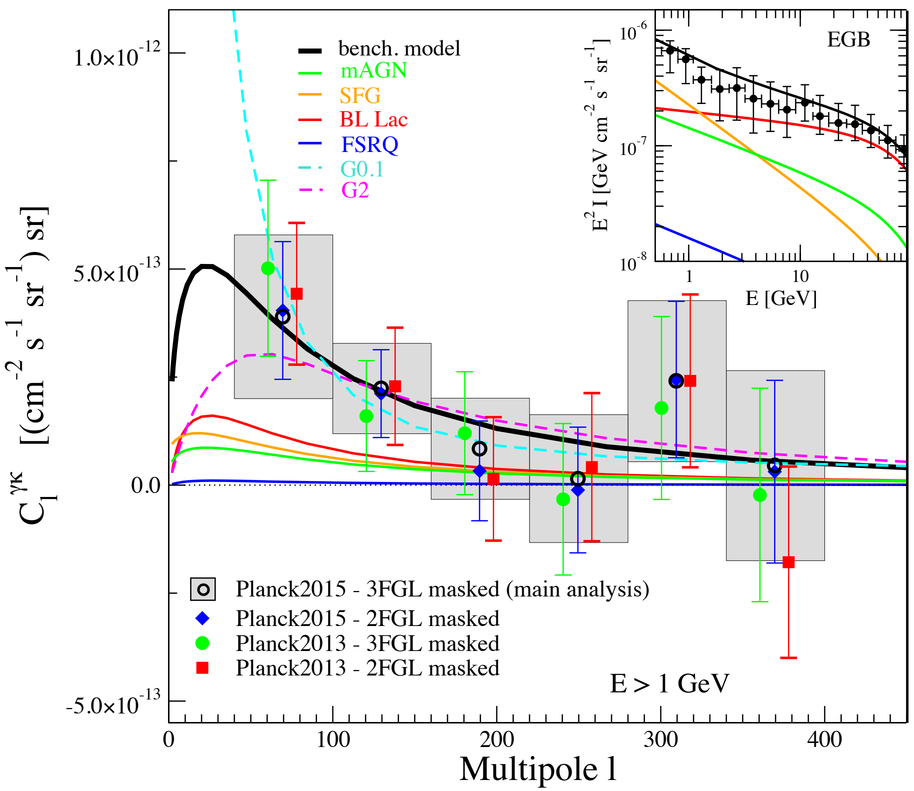
- Fermi-LAT 68 months
- Planck 2013 and 2015 lensing releases

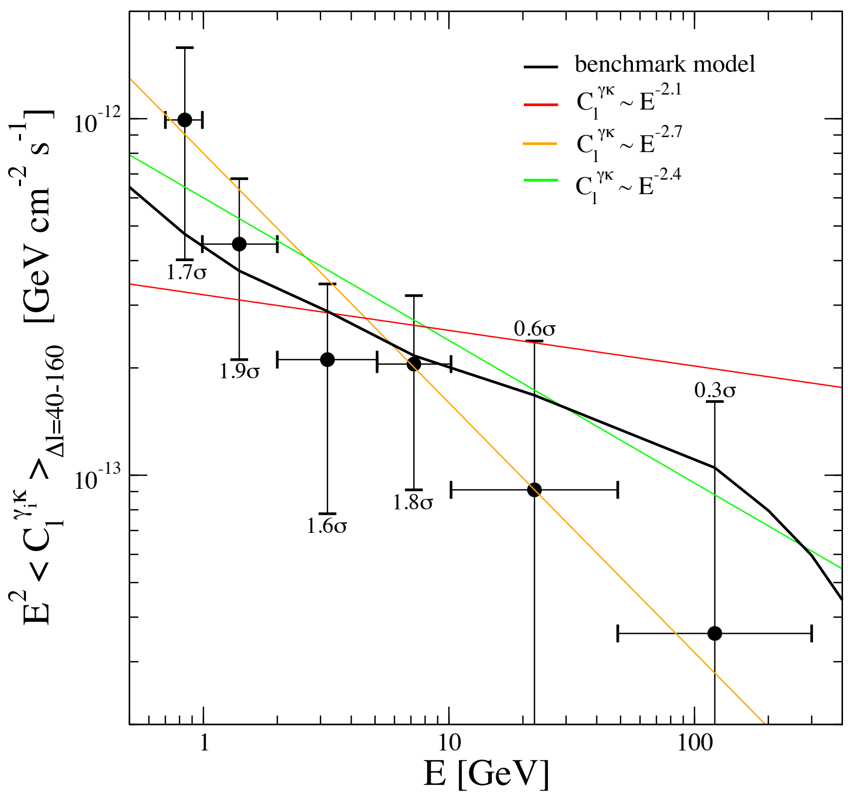
- Galactic emission subtracted
- Masks for CMB lensing:
  - Planck official masks (available sky fraction 70%)
  - 5 deg apodized
- Masks for gamma rays:
  - Planck masks + |b| < 25 deg cut
  - 1 deg cut around 2FGL (3FGL) Fermi source catalogs apodized 3 deg/2 deg sky fraction 24% (23%)

Results stable for different sets of apodization and galactic masks, including Fermi bubble mask

NF, Perotto, Regis, Camera, ApJ 802 (2015) L1

Fermi/gamma + Planck/CMB lensing

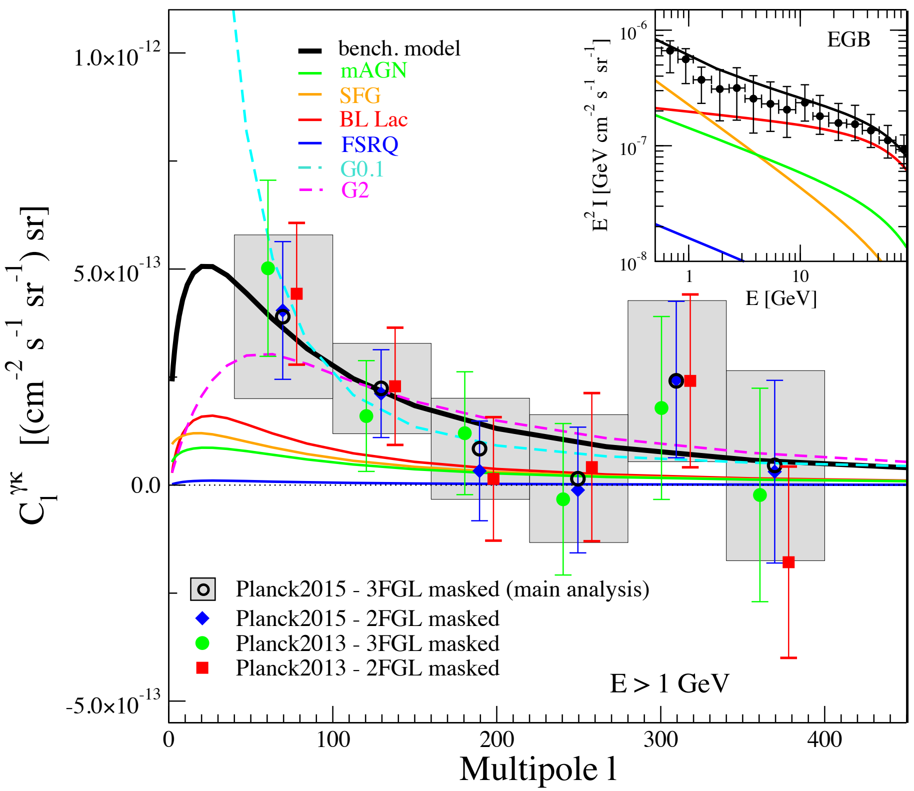


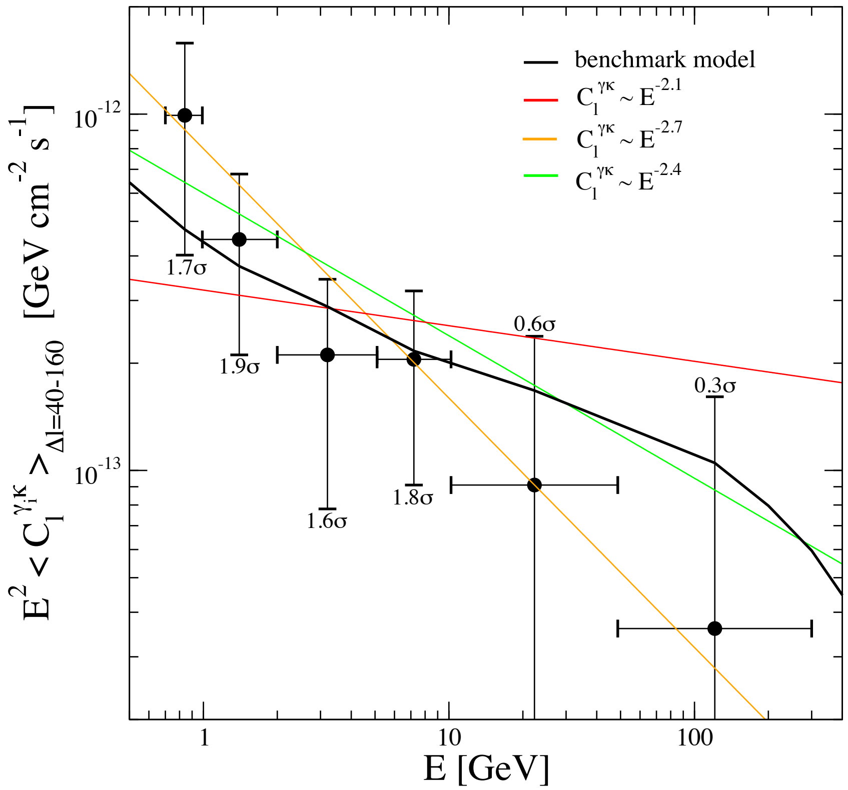


Energy		Multipole		Statistical test	Significance			
					P15-3FGL	P15-2FGL	P13-3FGL	P13-2FGL
Single E-bin	$[1, 300]$ GeV	Single ℓ-bin	$40 \leq \ell < 160$	$\langle \ell C_\ell^{\gamma\kappa} \rangle / \delta \langle \ell C_\ell^{\gamma\kappa} \rangle$	1.7σ	1.8σ	1.5σ	2.1σ
6 E-bins	$[0.7, 300]$ GeV	Single ℓ-bin	$40 \leq \ell < 160$	$\langle \ell C_\ell^{\gamma\kappa} \rangle / \delta \langle \ell C_\ell^{\gamma\kappa} \rangle$	3.0σ	3.3σ	2.8σ	3.2σ
6 E-bins	$[0.7, 300]$ GeV	6 ℓ-bins, $\Delta\ell = 60$	$40 \leq \ell < 400$	Model fitting	3.0σ	3.2σ	2.7σ	3.0σ

NF, Perotto, Regis, Camera, ApJ 802 (2015) L1

Fermi/gamma + Planck/CMB lensing





Cross-correlation: 3.0σ evidence

Compatible with AGN + SFG + BLA gamma-rays emission

Points toward a direct evidence of extragalactic origin of the IGRB

NF, Perotto, Regis, Camera, ApJ 802 (2015) L1

Conclusions

- In order to separate a DM non-gravitational signal from other astrophysical emissions, a filter based on the DM properties (i.e. the associated gravitational potential) appears to be very promising

- Cross-correlations offer an emerging opportunity:
  - DM particle signal: multiwavelenght emission (radio, X, gamma)
  - DM gravitational signal: cosmic-shear, LSS surveys, CMB lensing

- Gamma rays + cosmic shear is the cleanest possibility and it appears to be quite powerful

- First relevant observational opportunity hopefully this year with DES

- High-sensitivity will require Euclid (or LSST), together with the total accumulated Fermi statistics (plus possible novel gamma-ray detectors)

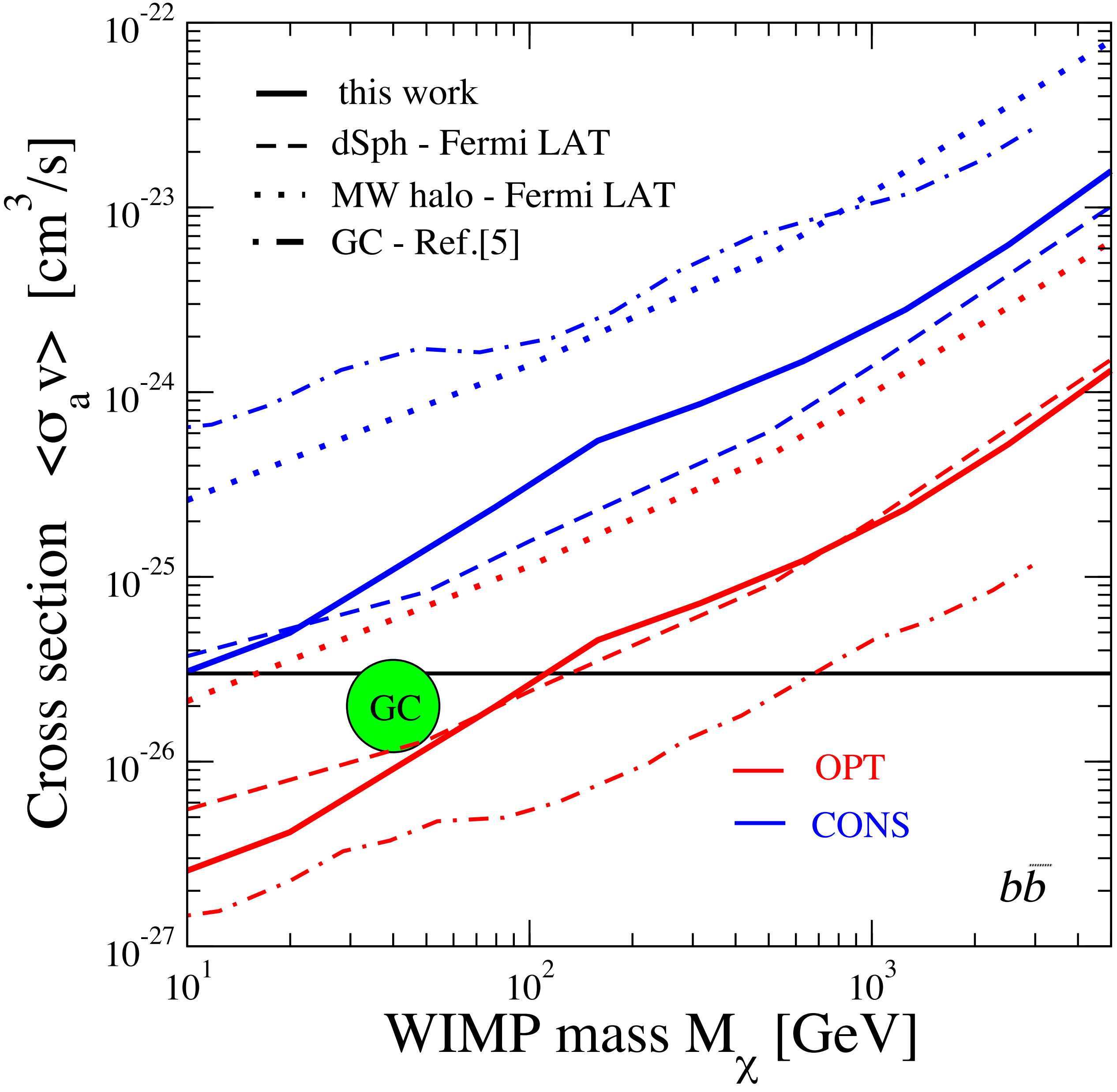
Conclusions

- In the meanwhile, two gamma-rays/gravity-tracers correlations have been measured:
  - Cross-correlation with galaxy catalogues and LSS objects (3.5 σ)
  - Cross-correlation with CMB-lensing (3.0 σ)

- Implications for DM start to be intriguing

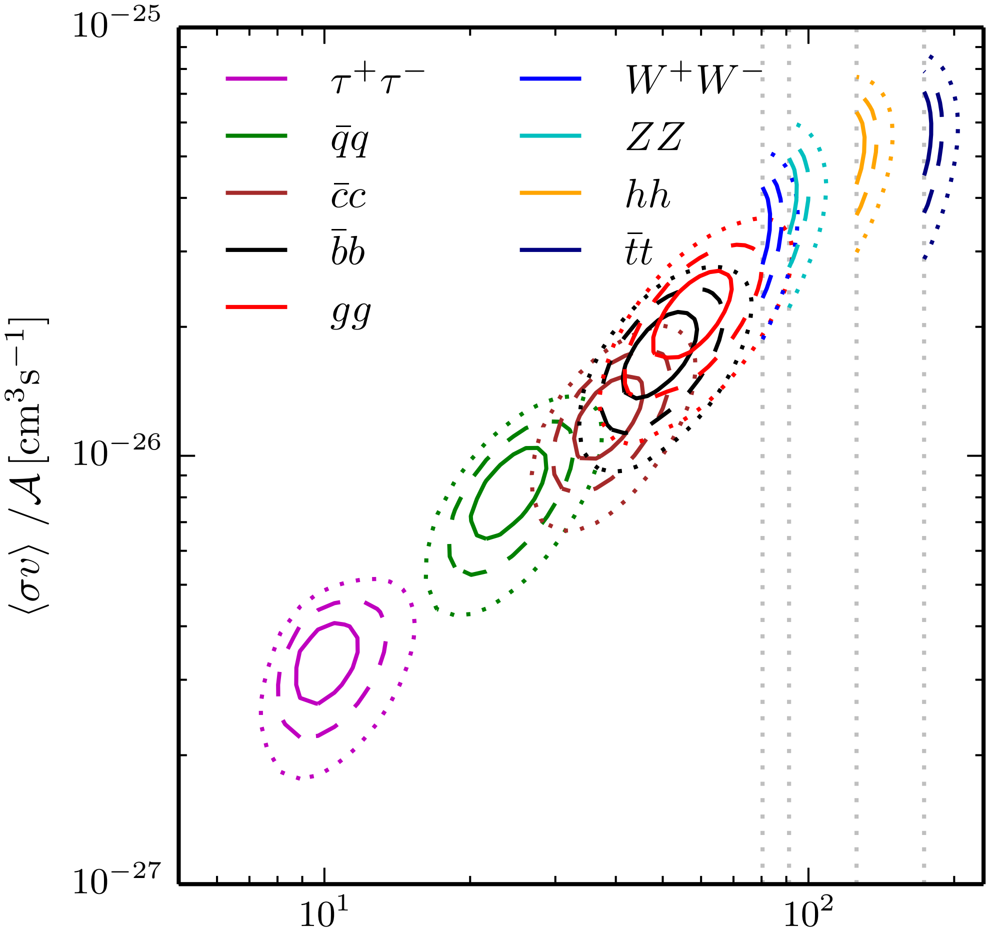
- Cross-correlations represent the strongest technique to investigate DM and its clustering properties outside the local neighbourhood, setting a critical bridge between the CMB and the local enviromnent (galactic center, dwarf galaxies) scales

Backup slides



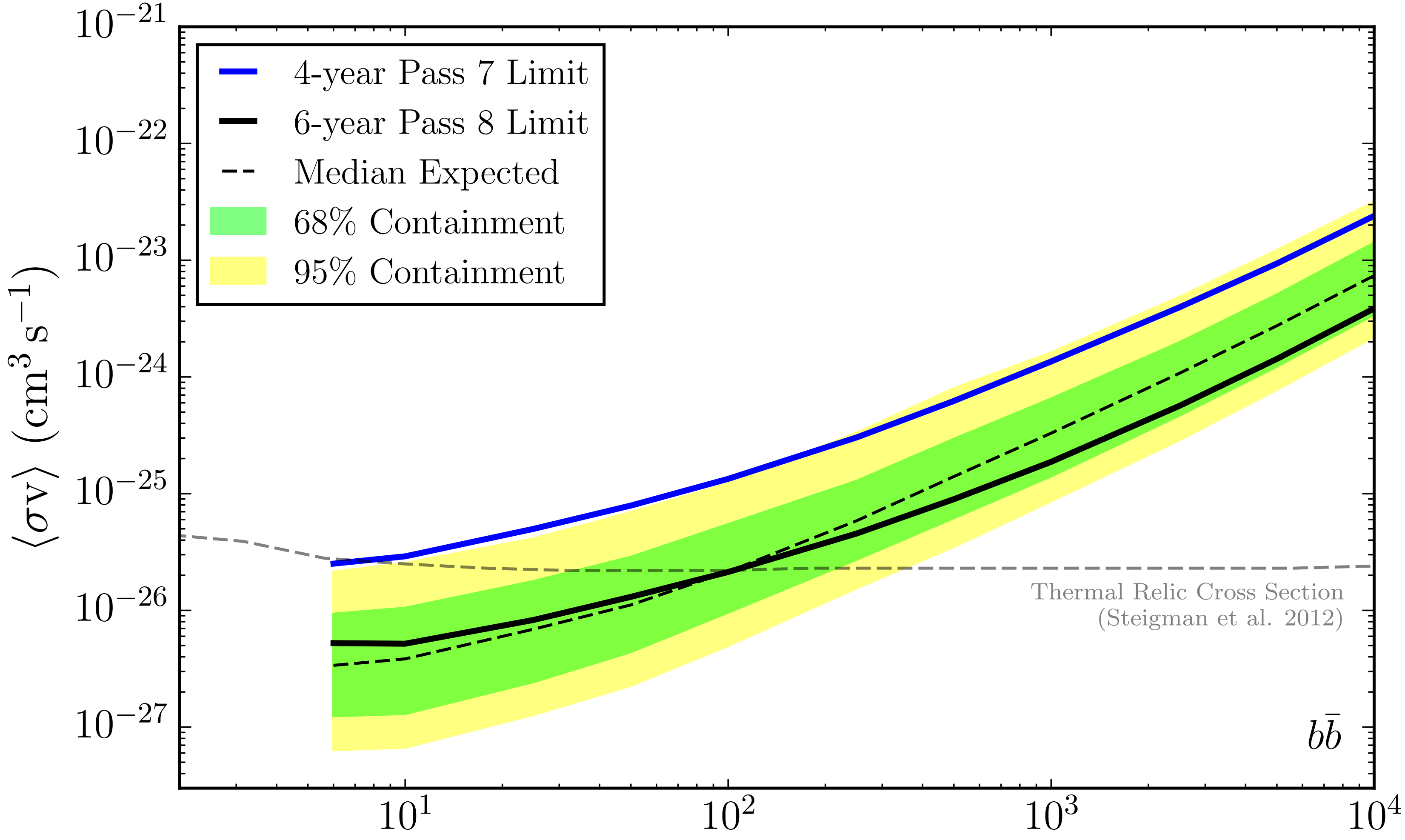
this work
dSph - Fermi LAT
MW halo - Fermi LAT
GC - Ref.[5]
GC
OPT
CONS
bb̄
Cross section <σ_a v> [cm^3/s]
WIMP mass M_χ [GeV]
10^-22
10^-23
10^-24
10^-25
10^-26
10^-27
10^1
10^2
10^3

Galactic center



Calore, Cholis, McCabe, Weniger, PRD 91 (2015) 063003

Dwarf galaxies



Ackermann et al. (Fermi Collab.), arXiv:1503.02641