# Particle dark matter searches in the anisotropic sky

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INFN Torino

High Energy Messengers 2014 (Kavl, Chicago) – 10.06.2014

Based on:

S. Camera, M. Fornasa, NF, M. Regis
*"A novel approach in the WIMP quest: Cross-Correlation of Gamma-Ray Anisotropies and Cosmic Shear"*
Ap. J. Lett. 771 (2013) L5 (arXiv:1212.5018)

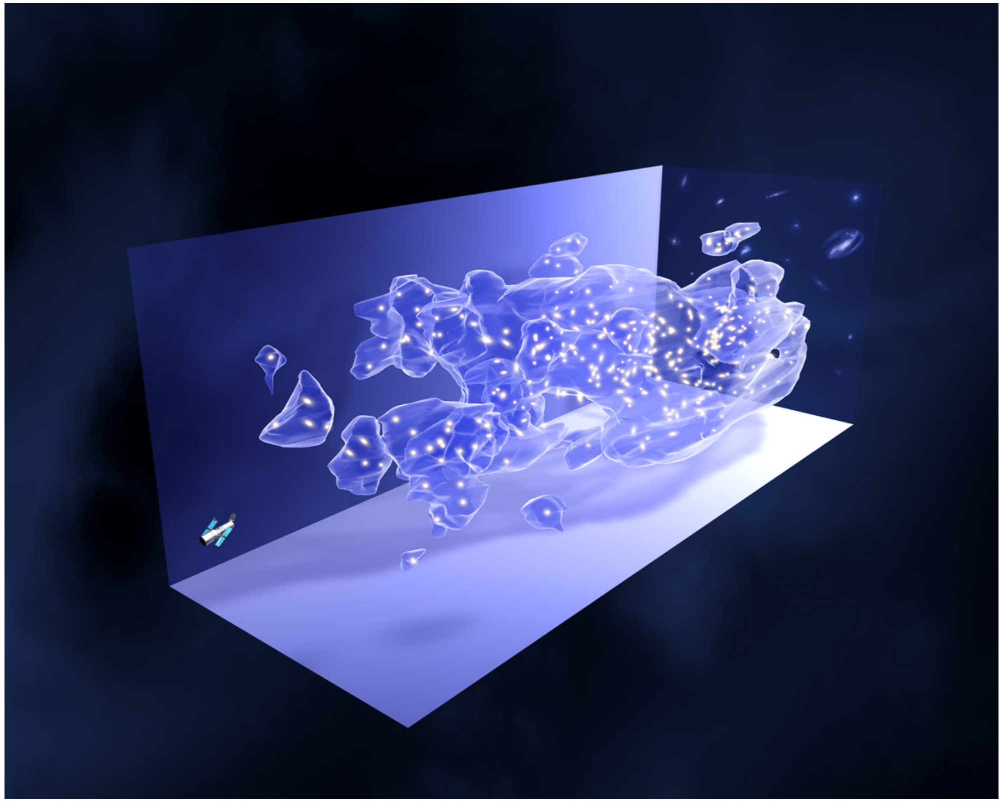
S. Camera, M. Fornasa, NF, M. Regis
*"Detecting Dark Matter Signatures via Cosmic-Shear/Gamma-Rays Tomography"*
to appear

See also:

NF, M. Regis
"Particle dark matter searches in the anistropic sky"
Front. Physics 2 (2014) 6 (arXiv:1312.4835)

# 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

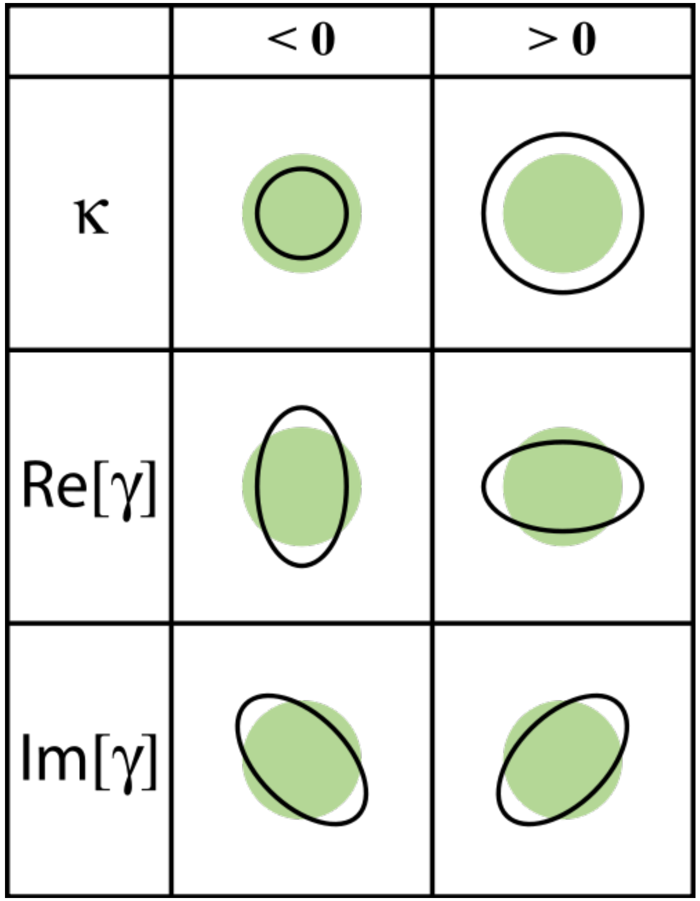


Powerful probe of dark matter distribution in the Universe

# Weak gravitational lensing

Convergence: controls modifications in the size of the image

Shear: accounts for shape distortions




In the flat-sky approximation, they generate identical angular power spectra

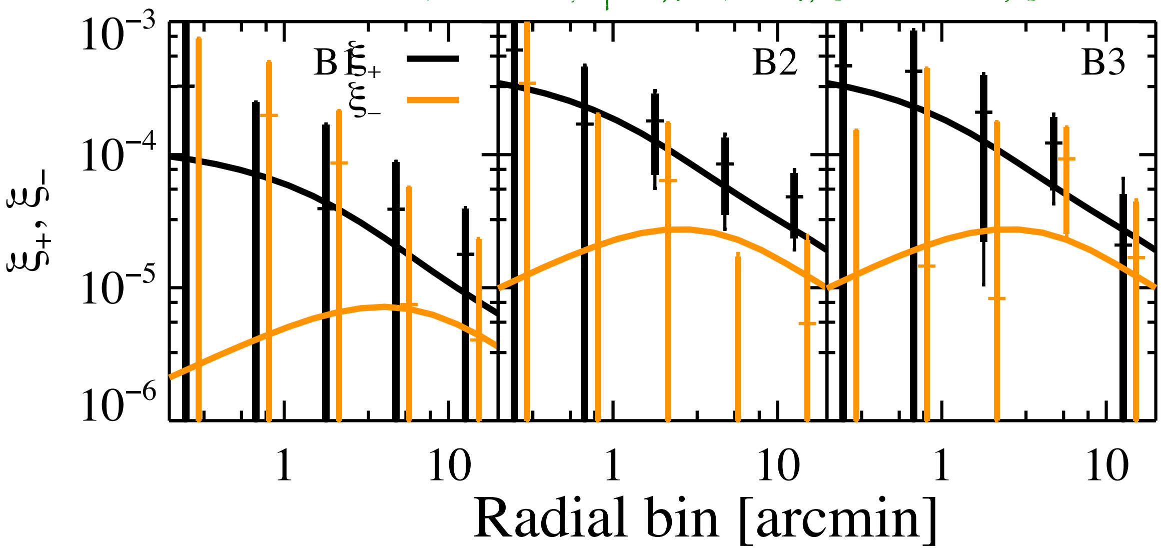
# Cosmic shear auto-correlation

Auto-correlation between gravitational cosmic shear in two different directions can provide information on the clustering of the large scale structures responsible for the lensing effect.

Technique already used with data from COSMOS galaxy survey

Future surveys: Pan-STARRS, Dark Energy Survey, Euclid

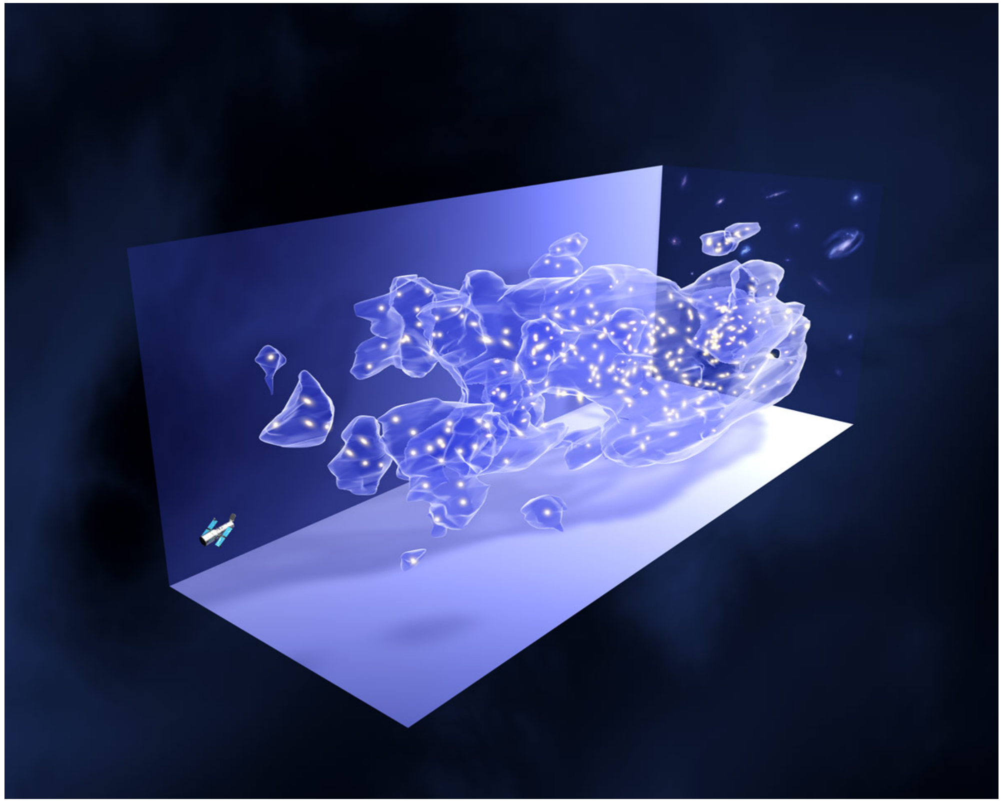
Julio et al. (COSMOS), Ap. J. 750 (2012) 37 [arXiv:1202.6491]



# Cosmic structures and gamma-rays

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

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



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

# Gamma-rays auto-correlation

Ackerman et al. (Fermi), Phys. Rev. 85 (2012) 083007

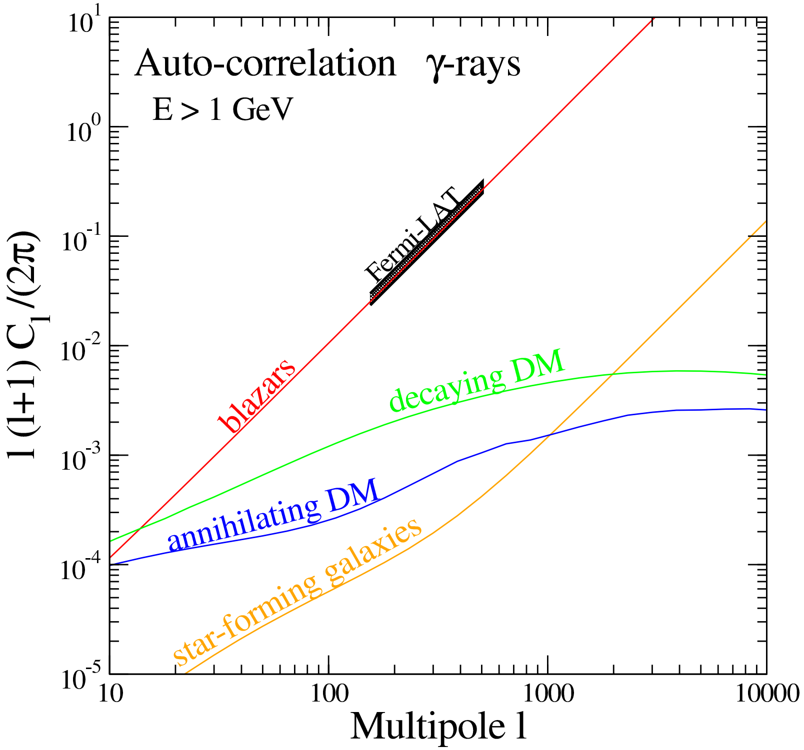
Auto-correlation in the gamma-rays emission has been reported

For l > 100 galactic foreground can be negleted: EGB contribution

Features of the signal (energy and multipole independent) point toward interpretation in therms of blazars

DM likely to play a subdominant role

(as for EGB intensity)



## Signal

Cross-correlation of

gravitational shear with

extragalactic gamma-ray background (the residual radiation contributed by the cumulative emission of *unresolved* gamma-ray sources)

# Correlation functions

## Source Intensity

*Window function*

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

*Density field of the source*

## Cross-correlation angular power spectrum

*3D Power spectrum*

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

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

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

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

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

*Linear matter PS*

*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*

# Window functions

## Lensing

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

*Source redshift distribution*

## Gamma-rays from decaying DM

$$W^{\gamma_d}(E_\gamma, z) = \frac{1}{4\pi} \frac{\Omega_{DM} \rho_c}{m_\chi \tau_d} J_d(E_\gamma, z)$$

*DM photon "emissivity"*

$$J_d = \int_{E_\gamma}^{\infty} dE \frac{dN_d(E(1+z))}{dE} e^{-\tau(E(1+z),z)}$$

## Gamma-rays from annihilating DM

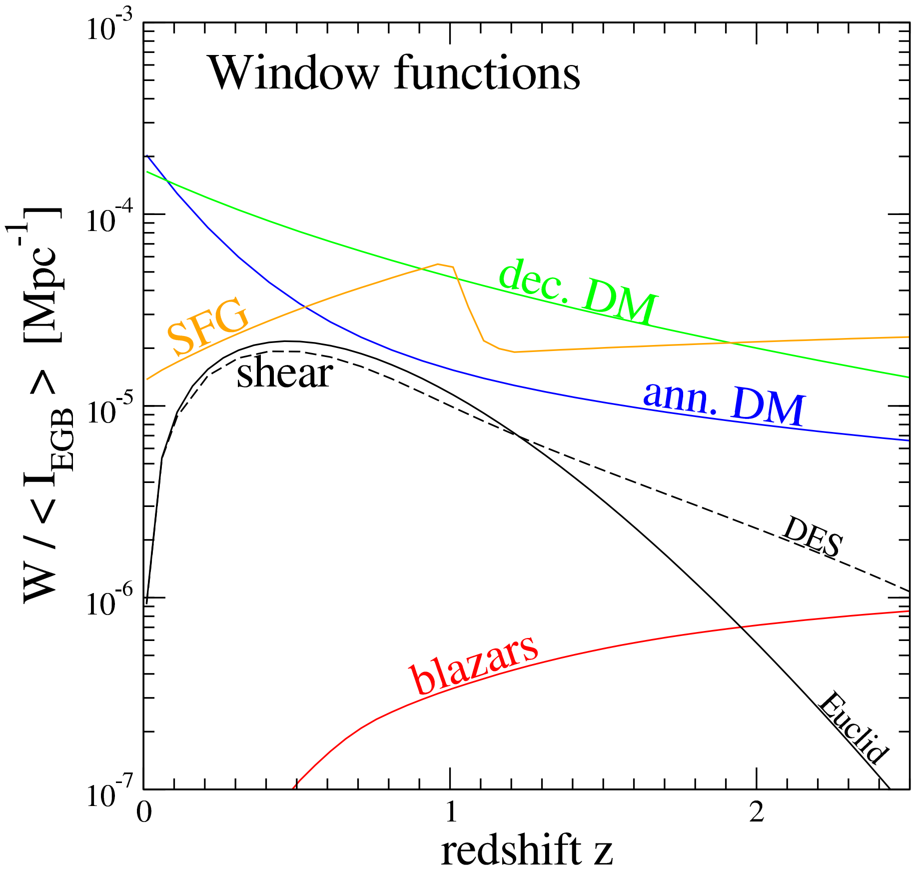
$$W^{\gamma_a}(E_\gamma, z) = \frac{(\Omega_{DM} \rho_c)^2}{4\pi} \frac{(\sigma_a v)}{2 m_\chi^2} (1+z)^3 \, \Delta^2(z) \, J_a(E_\gamma, z)$$

*DM photon "emissivity"*

## Astrophysical sources

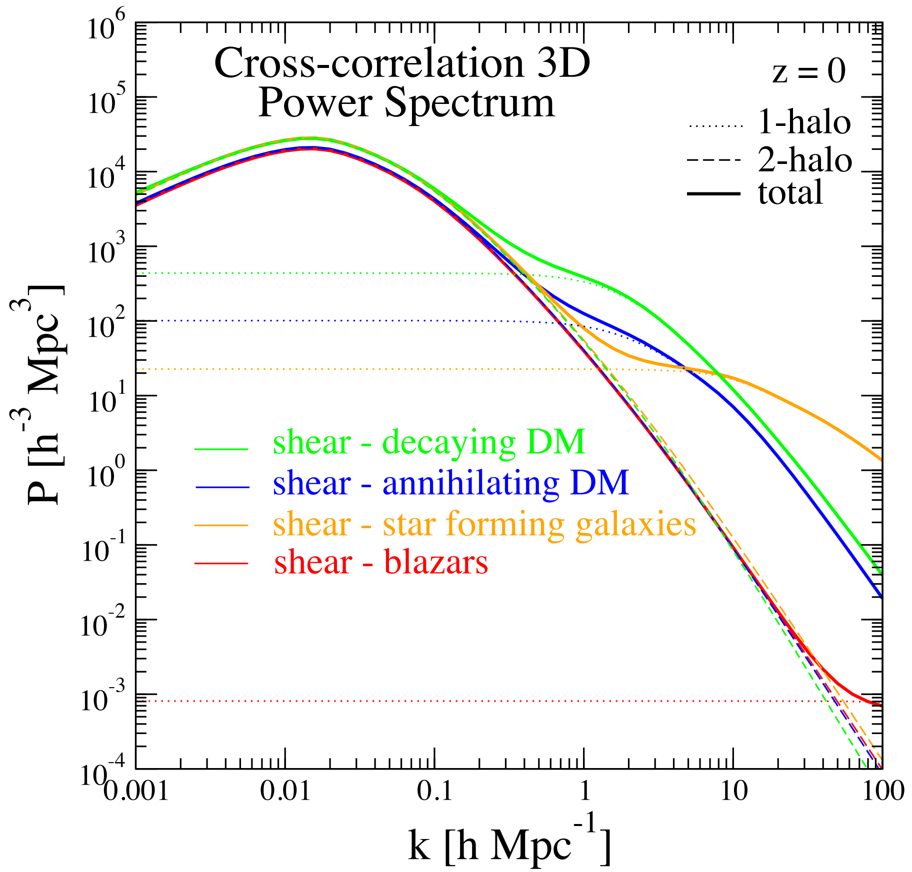
$$W^{\gamma_S}(E_\gamma, z) = \frac{A_S(z) \, \langle g_S(z) \rangle}{4\pi \, E_0^2} \int_{E_\gamma}^{\infty} dE \left( \frac{E}{E_0} \right)^{-\alpha} e^{-\tau(E,z)}$$

# Window functions




DM peaks at lower z

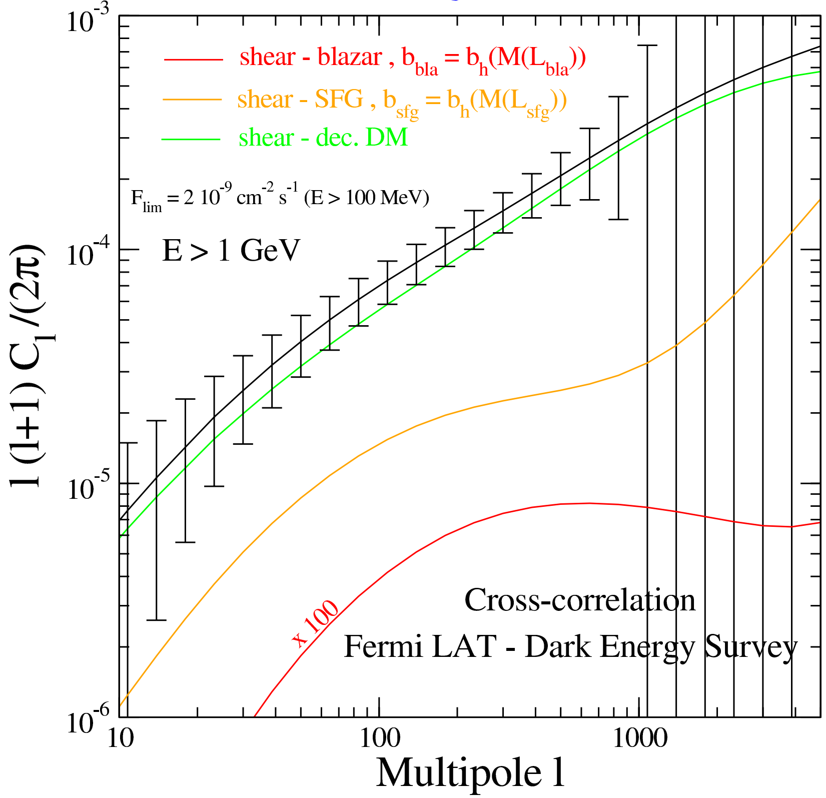
# 3D Power spectrum




DM cross-correlation has more power at intermediate scales

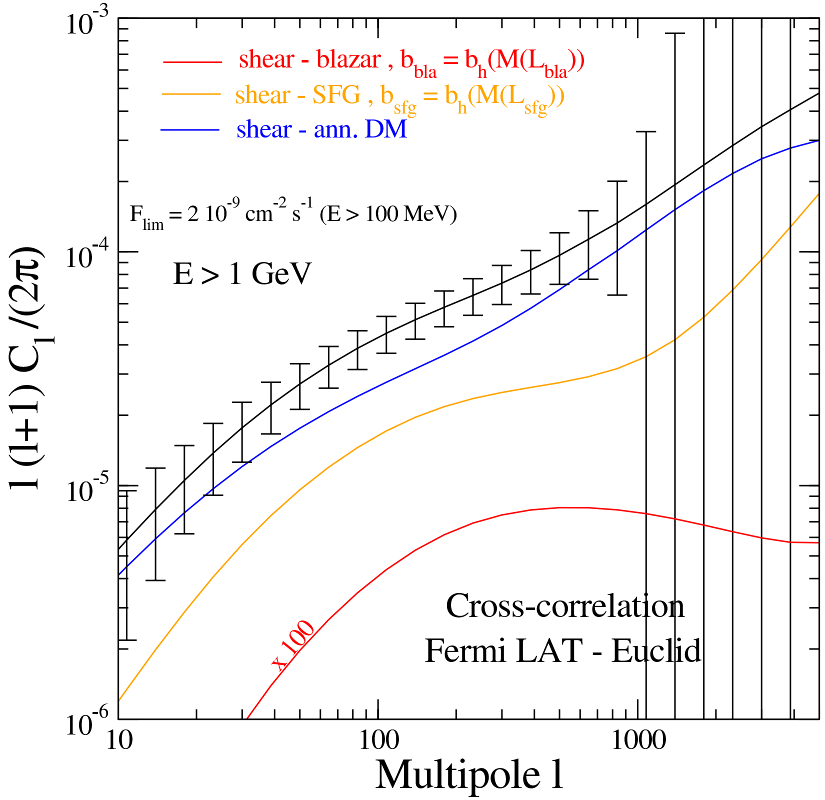
# Cross-correlation predictions

decaying DM




Fermi-LAT/5-yr with DES

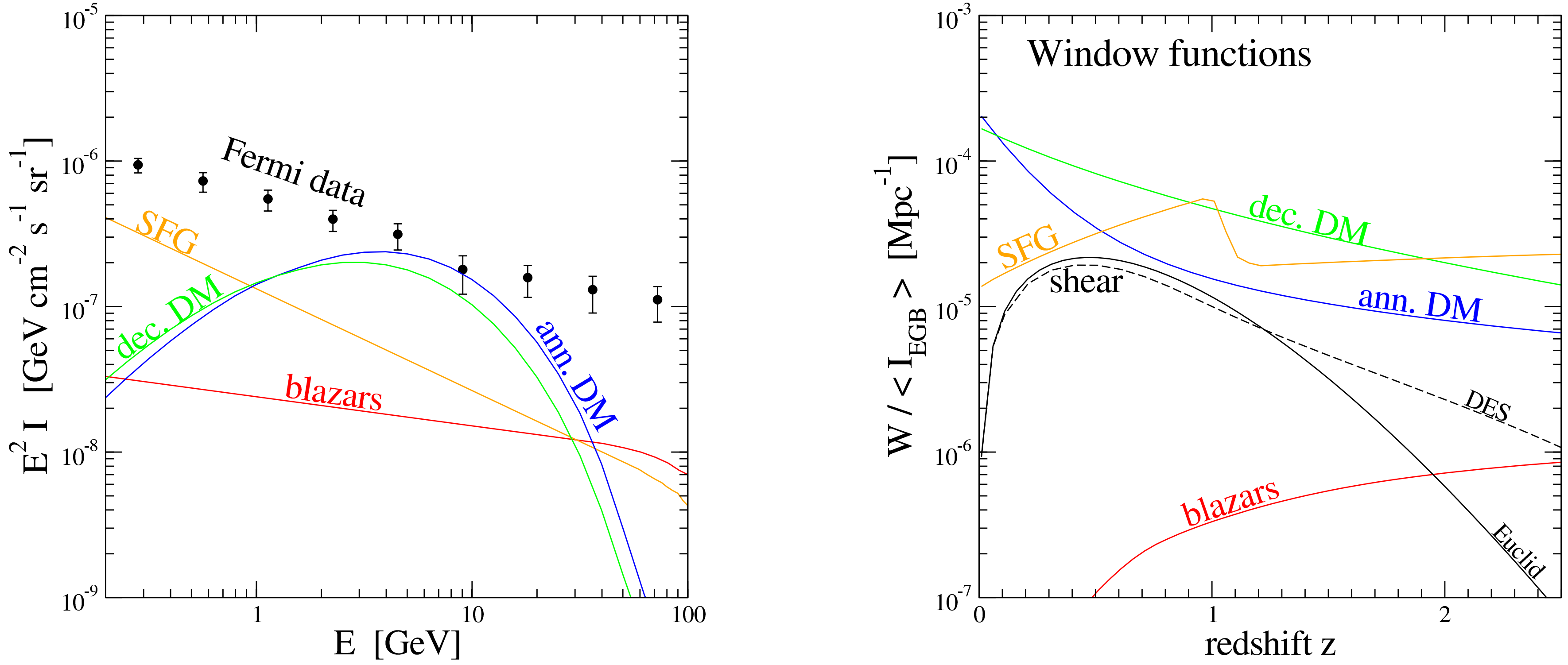
annihilating DM




Fermi-LAT/5-yr with Euclid

Camera, Fornasa, NF, Regis, Ap. J. Lett. 771 (2013) L5 [arXiv:1212.5018]

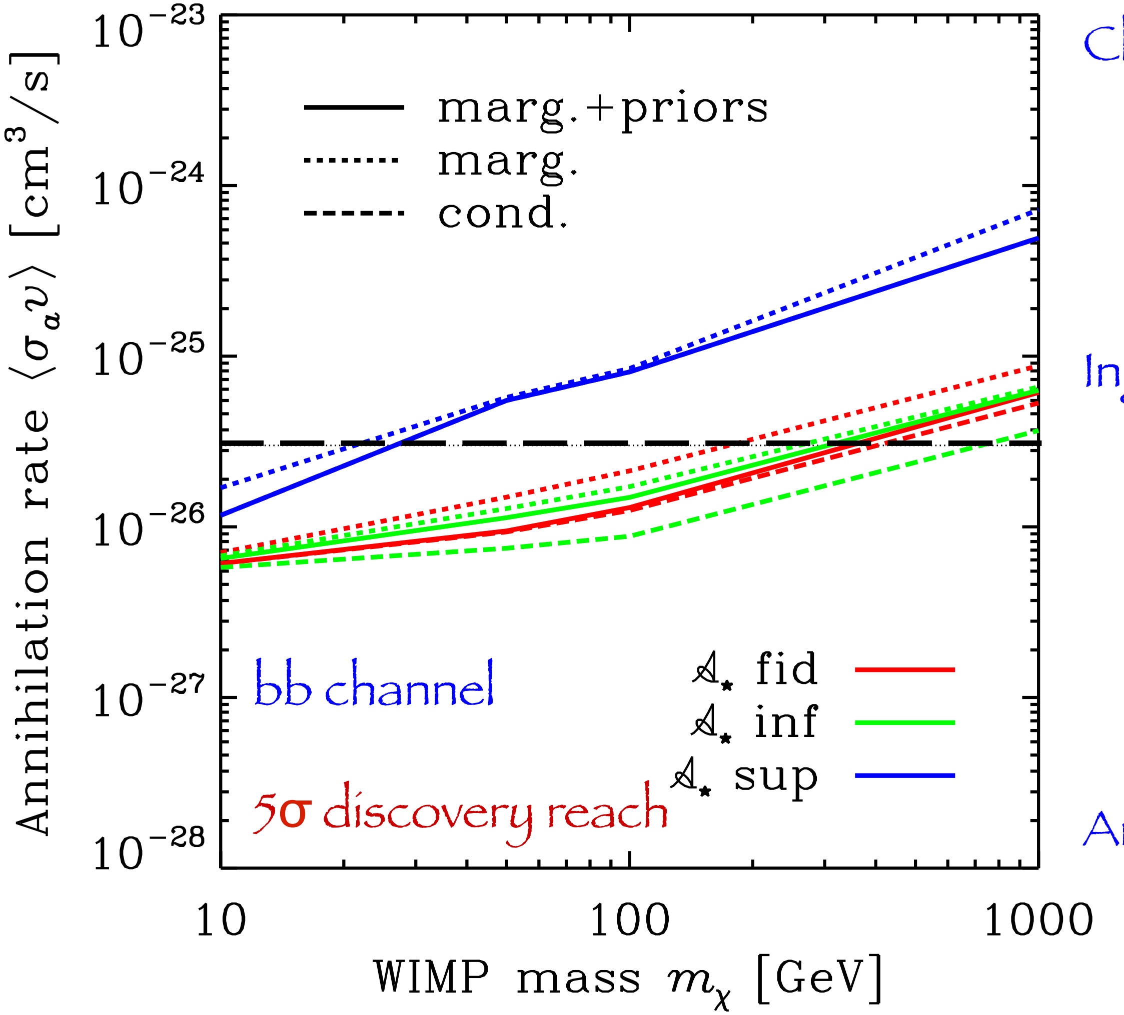
# Energy slicing and redshift tomography




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

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

# Forecasts: discovery potential




Classes of astro sources:
- blazars
- SFR
- mAGN

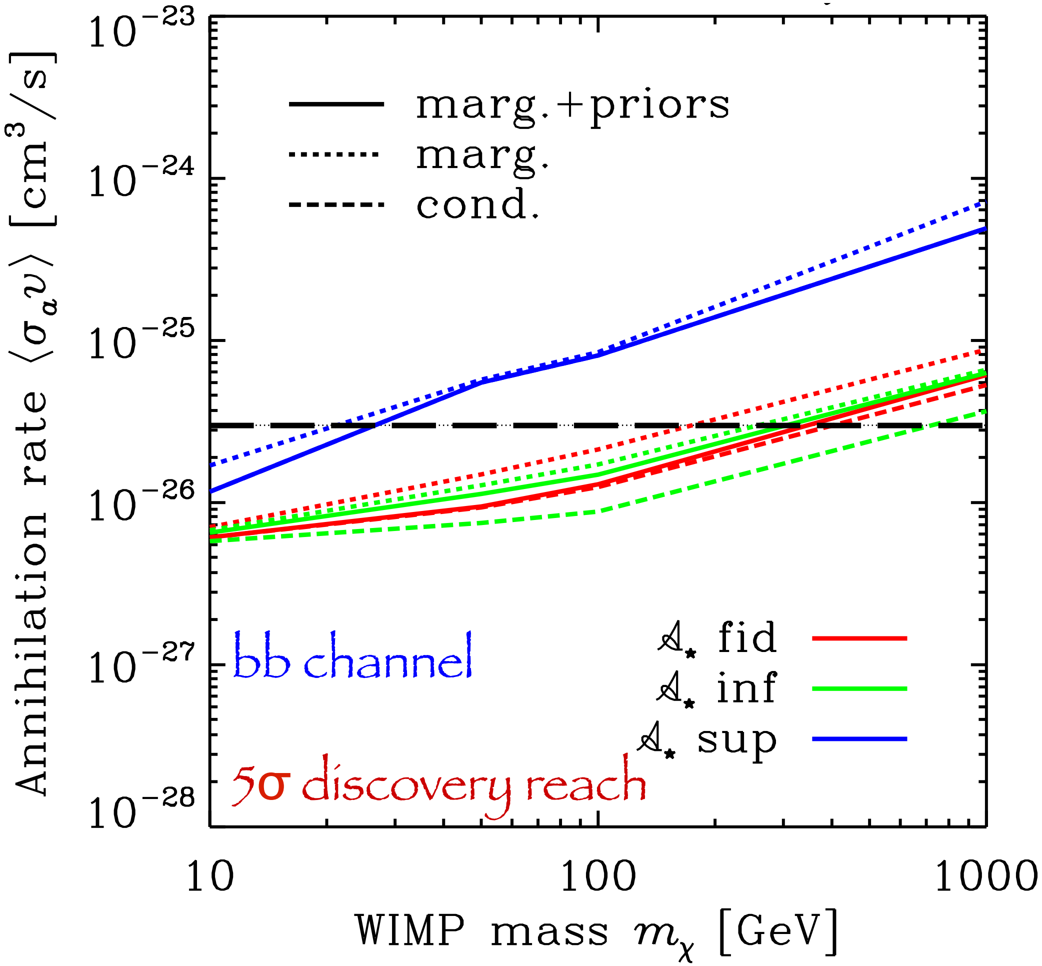
Ingredients:
- gamma-rays luminosity function
- energy spectrum
- relation M(L) between GRL and mass of host halo
- bias

Analysis: marginalized over astro

Fermi-LAT/5-yrs with DES

Camera, Fornasa, NF, Regis, to appear

# Forecasts: discovery potential




Fermi-LAT/5-yrs with DES

Halo mass functions from [a]

Concentration from [b]

Halos profile: NFW

Min halo-mass: $10^{-6}$ $M_{sun}$ (or $10^{7}$ $M_{sun}$)

$c_{vir}$ extrapolation at low M from [c]

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

"Virgo C." substr. : VC1 and VC2 [1+2]

"Via Lactea" substr. : VL [1+3]

"No" substr. and $10^{7}$ $M_{sun}$ : NS

[1] Fornasa et al, MNRAS 429 (2013) 1529
[2] Gao et al, MNRAS 419 (2012) 1721
[3] Kamionkowski et al, PRD 81 (2010) 043532; Sanchez-Conde et al, JCAP 1112 (2011) 011

# Modeling

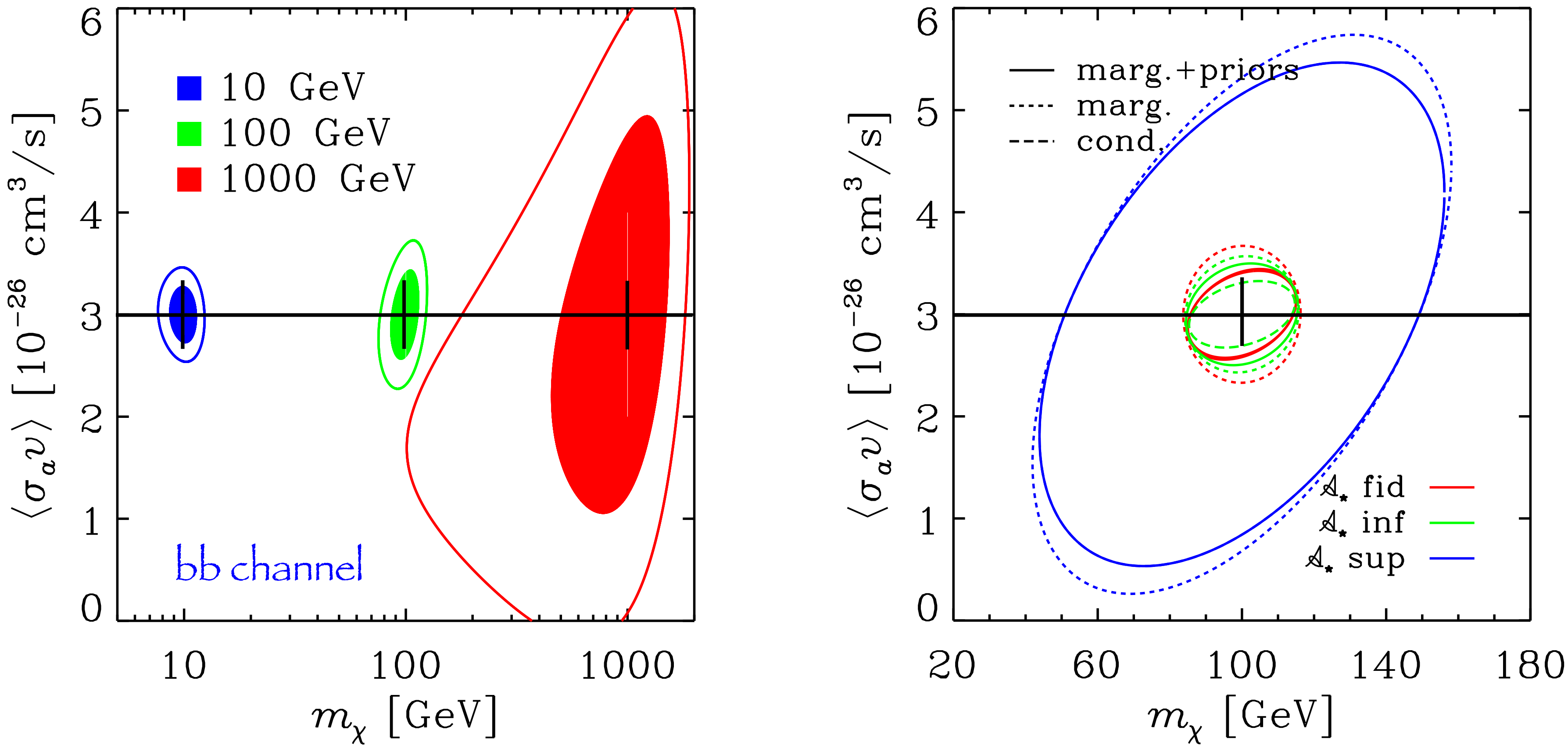
Blazars:
- GLF from [1] with AGN X-ray lumonisity function from [2]
- relation halo-mass/X-ray luminosity from [3]
- second model: gamma-rays luminosity related to smBH-mass, related to halo mass as in [3]

mAGN:
- GLF from [4]
- M(L) from BH-mass relation to radio luminosity [5] (then tranferred to gamma luminosity) and DM-halo mass [3]
- large scatter in M(L), accounted through a free norm in (0.1 - 2.5)

SFG:
- GFL from [6] based on IR luminosity function of [8] and rescaling gamma/IR from [6]
- M(L) from relating gamma-ray luminosity to SFR [9]

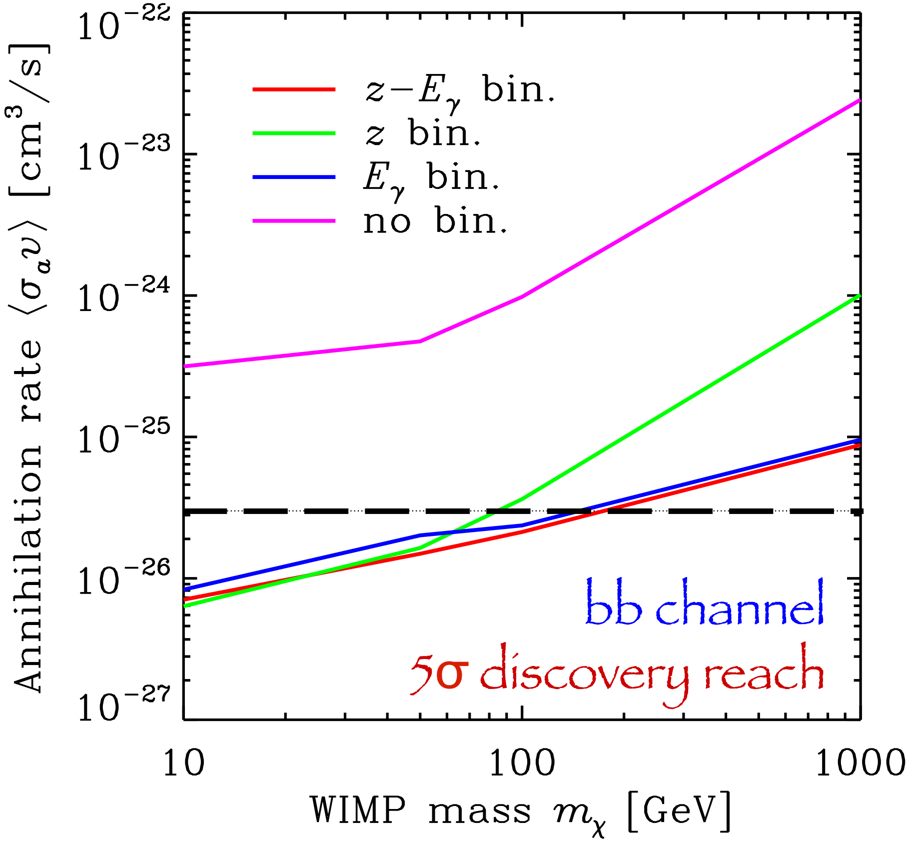

[1] Inoue et al, Ap.J. 702 (2009) 523
[2] Ueda et al, Ap.J. 598 (2003) 886
[3] Hutsi et al, arXiv:1304.3717
[4] Di Mauro et al, Ap.J. 780 (2014) 161
[5] Bettoni et al, AA 399 (2003) 869
[6] Ackermann et al (Fermi C.), Ap.J. 780 (2014) 161
[8] Rodighiero et al, A.A. 515 (2009) 20
[9] Lu et al, arXiv:1306.0650

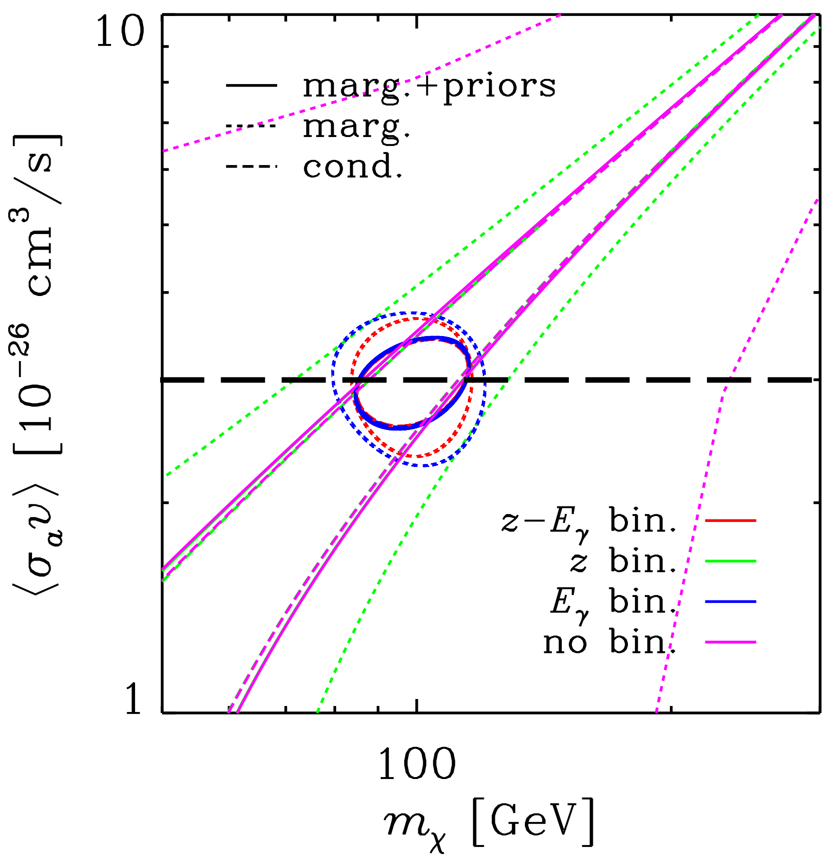
# Forecasts on parameters reconstruction




Fermi-LAT/5-yr with DES

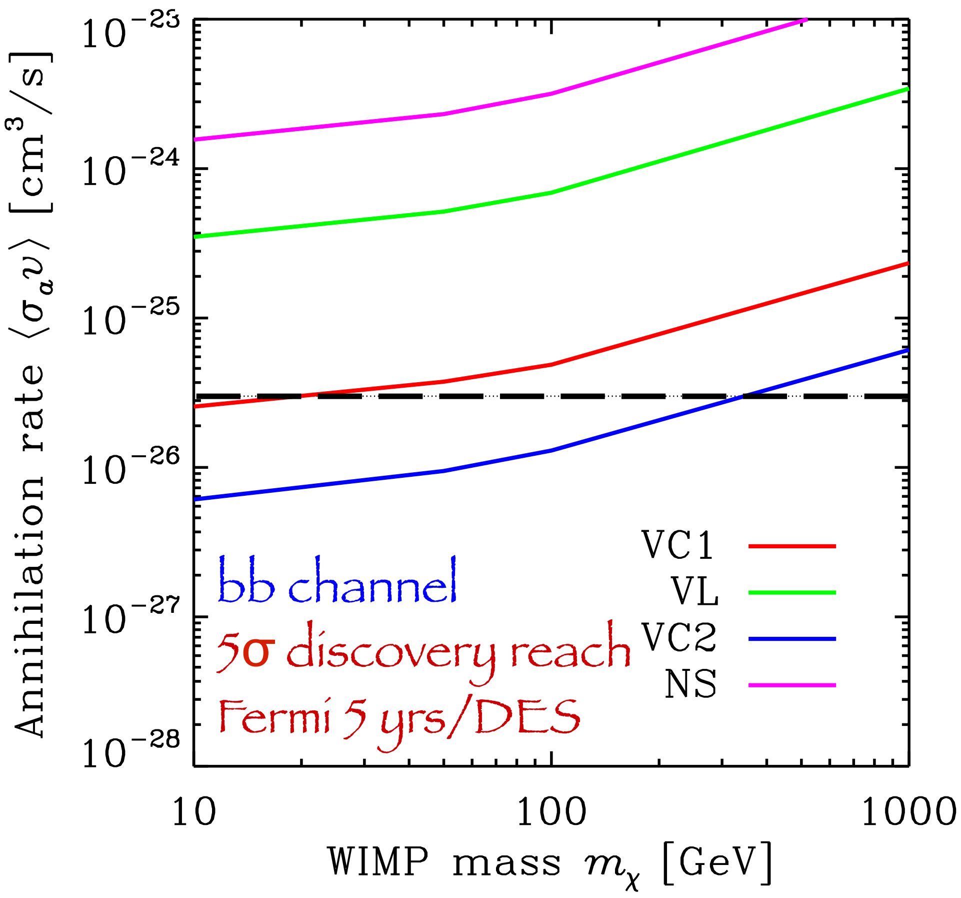
# Effect of energy and redshift infomation




Fermi-LAT/5-yr with DES

# Dependence on clustering model

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For each model, cross-correlations with shear allow better reach than intensity or auto-correlation alone

# Experiments

- Gamma-rays

  Fermi-LAT

  space based
  $0.3 < E < 300$ GeV
  sensitivity: $10^{-9}$ cm-2 $s^{-1}$
  angular resolution: 0.1 deg at high-energy
  sky coverage: 66%
  until 2018

  DAMPE, Gamma400, HERD?

  CTA

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

- Cosmic-shear

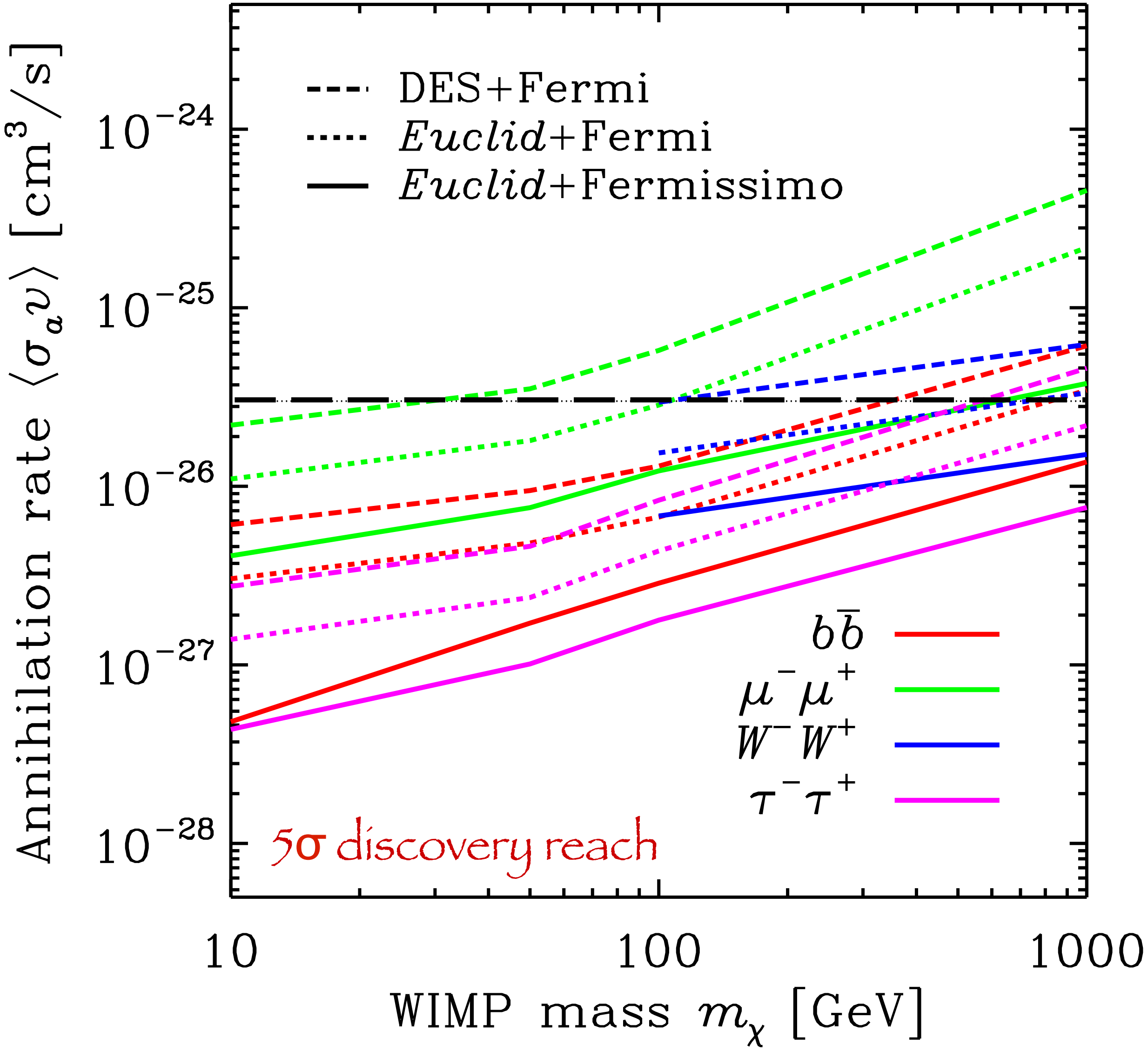
  DES

  $0.3 < z < 1.5$
  13.3 gal / arcmin2
  5000 squared degrees
  2012-2017

  Euclid

  $0 < z < 2.5$
  30 gal / arcmin2
  20000 squared degrees
  2020-2026

# Enhanced experimental sensitivities



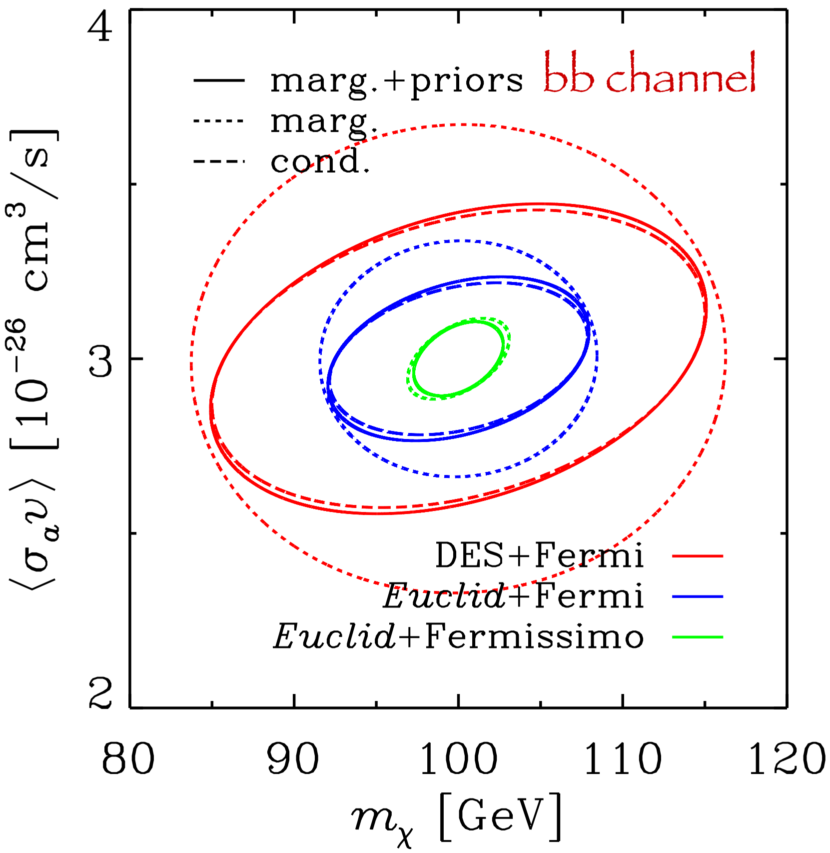

DES: 3 redshift bins

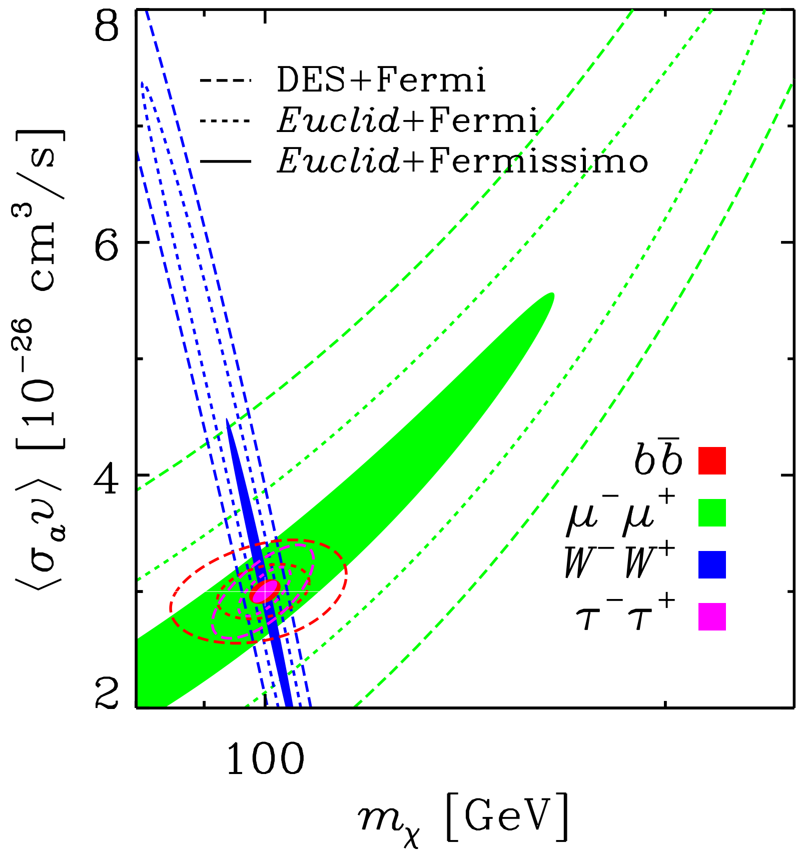
Euclid: 10 redshift bins

Fermi: 5 years

"Fermissimo": gamma rays detector with 2.5x Fermi exposure

# Forecasts on parameters reconstruction




DES: 3 redshift bins
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Fermi: 5 years
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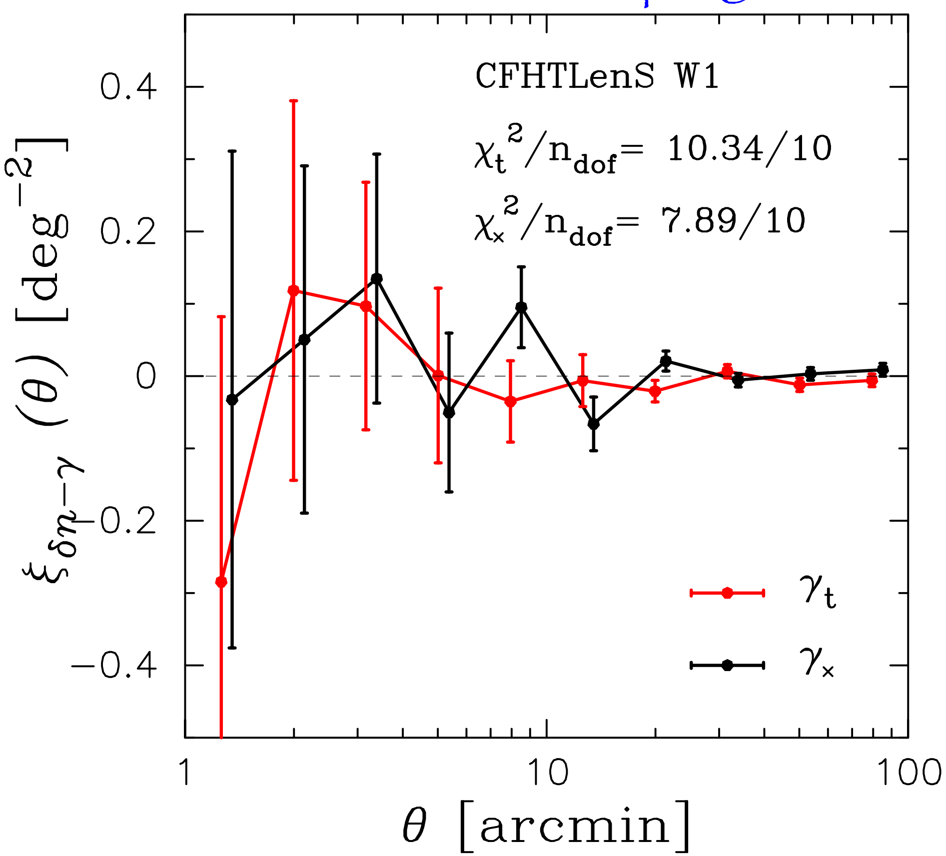
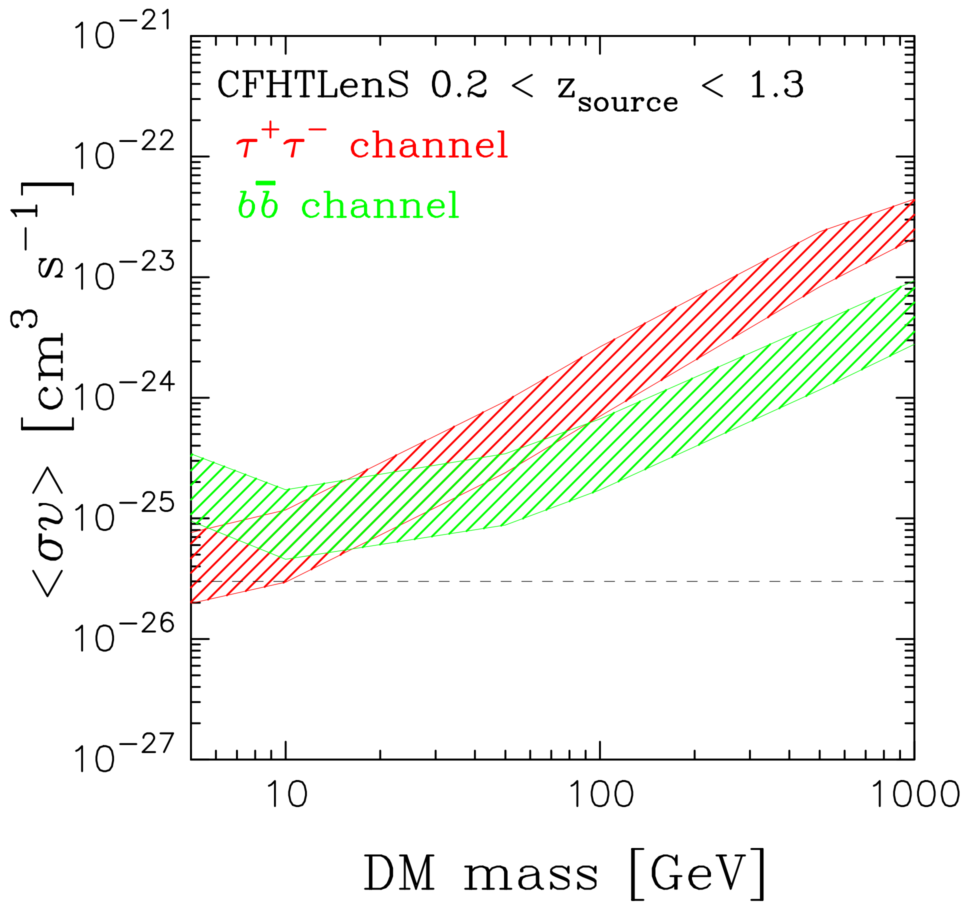
# Attempt on data with a small survey

Patch W1: 72 sq. deg




CFHTLens + Fermi/5yr

Shirasaki, Horiuchi, Yoshida, arXiv:1404.5503

# Conclusions

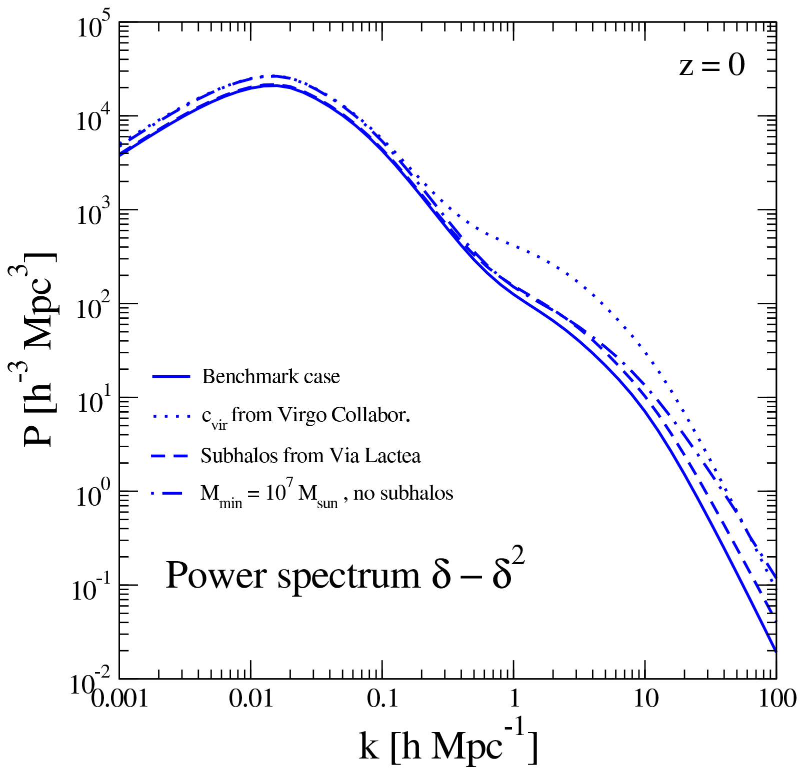
- DM structures in the Universe are the sources of weak lensing observables

- The same structures can themselves emit light at various wavelengths, including the gamma-ray range
  - From astrophysical sources hosted by DM halos
  - From DM itself (annihilation/decay)

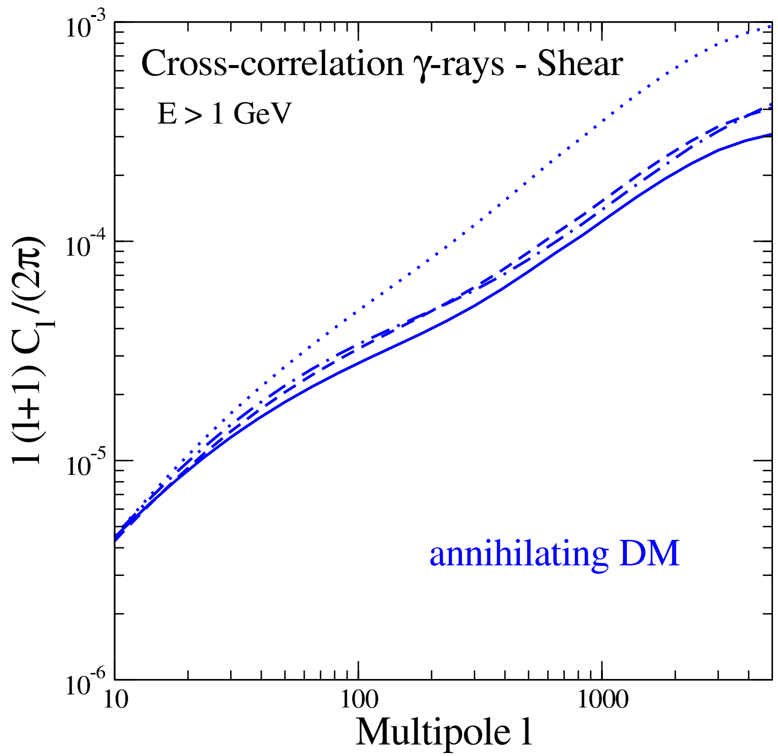
- Cross-correlation of gravitational shear with extragalactic gamma-ray background offers an interesting possibility for signal detection:
  - Reshift information in shear: can help in “filtering” signal sources
  - Energy spectrum of gamma-rays: can help in DM-mass reconstruction

# Backup Slides

# Cross-correlation: shear/DM

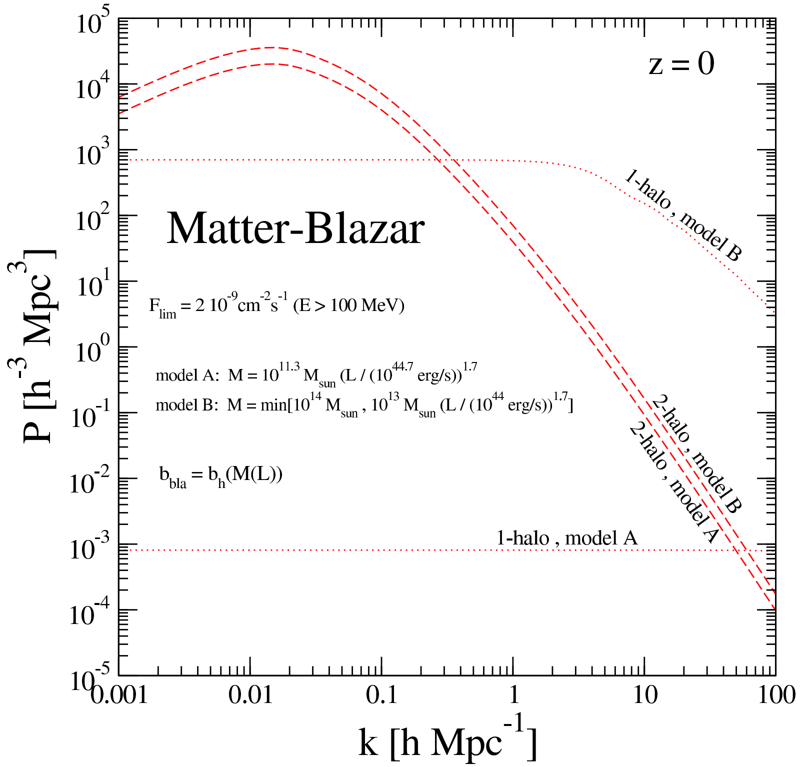



3D power spectrum

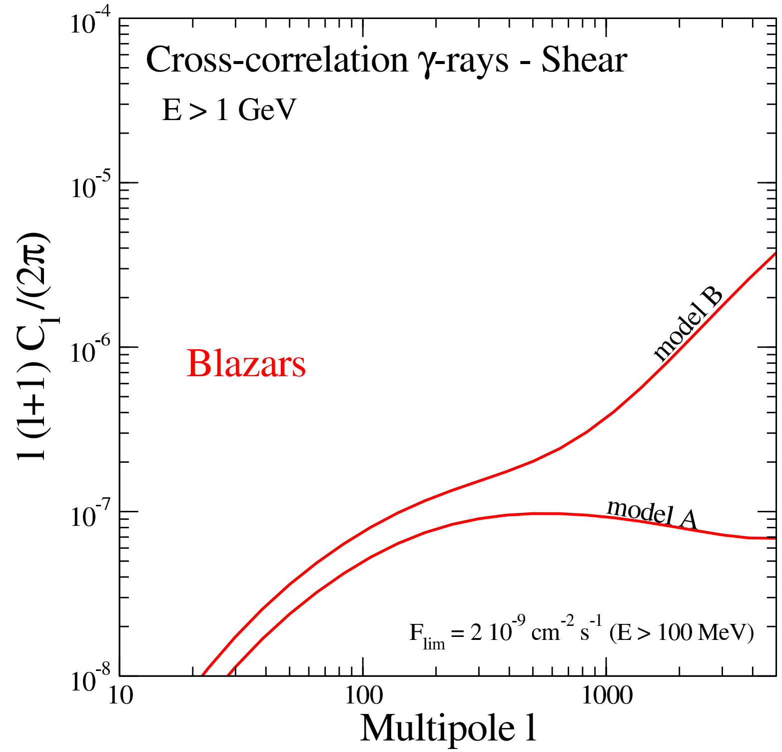



Angular power spectrum

# Cross-correlation: shear/blazars

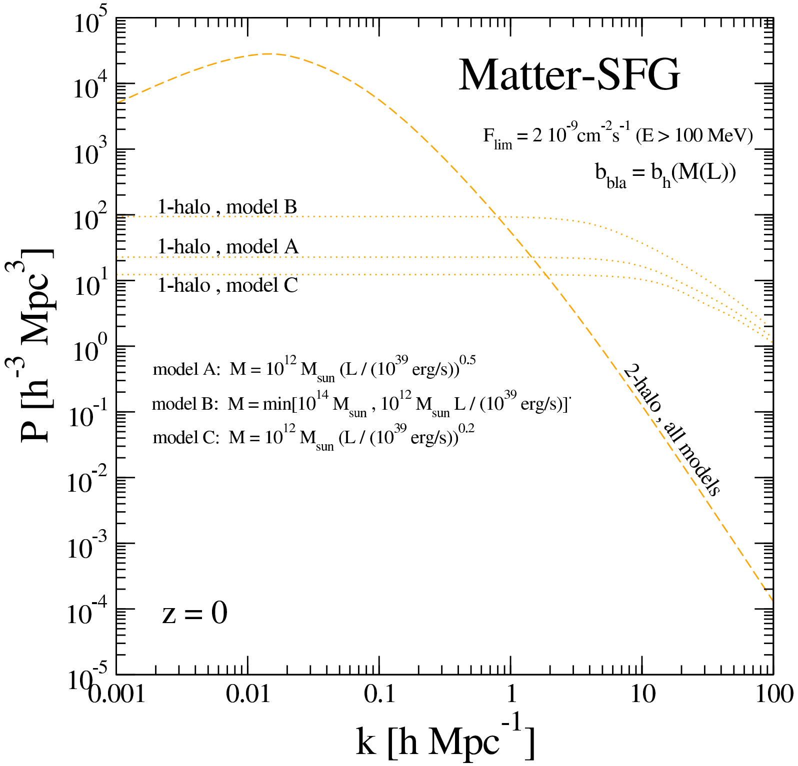



3D power spectrum

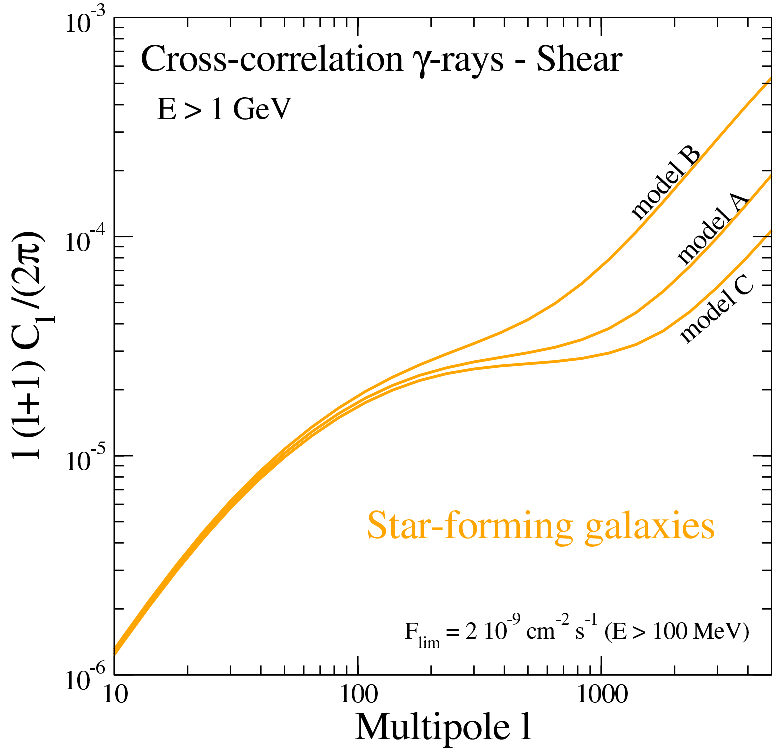



Angular power spectrum

# Cross-correlation: shear/SFG



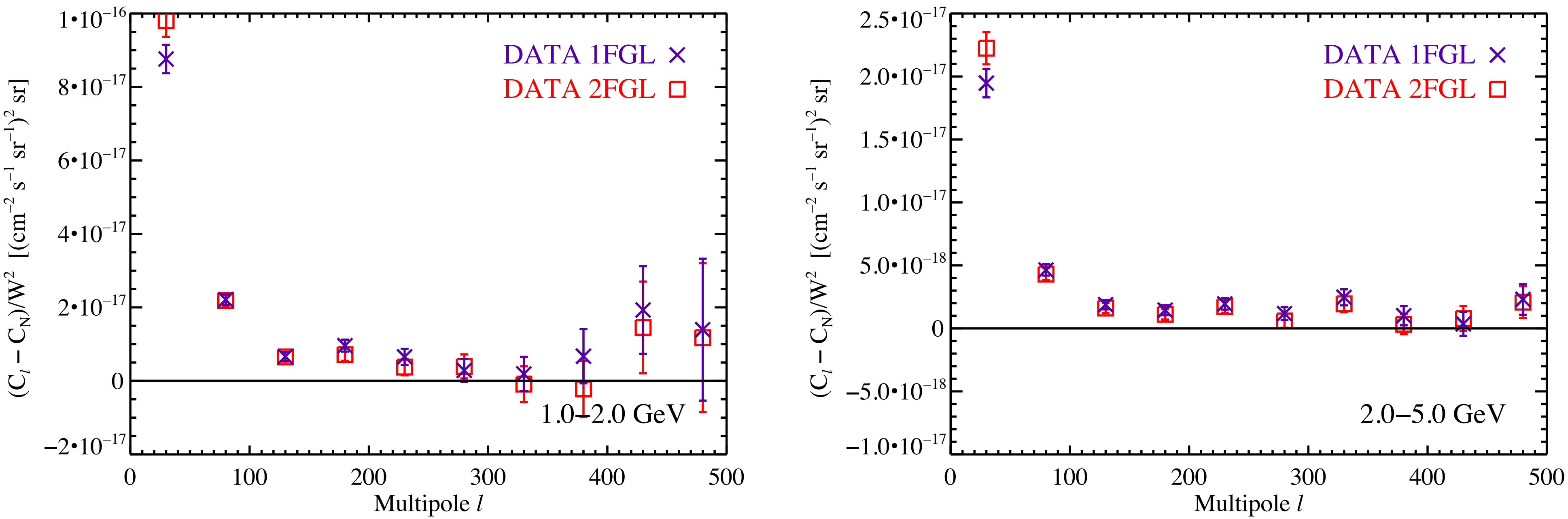

3D power spectrum




Angular power spectrum

# 2-point auto-correlation function

Auto-correlation in the gamma-rays emission has been reported




Ackerman et al. (Fermi), Phys. Rev. 85 (2012) 083007

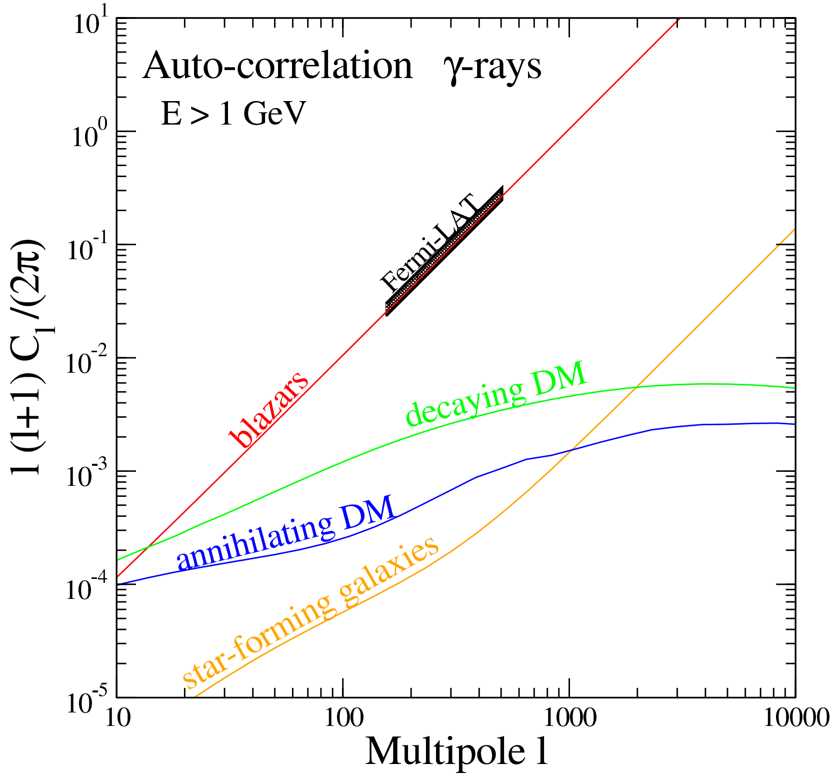
# Gamma-rays auto-correlation

For l > 100 galactic foreground can be negleted: EGB contribution

Features of the signal point toward interpretation in terms of blazars

DM likely plays a subdominant role
(as for total intensity)

Very difficult to extract a clear WIMP signature from the EGB alone





For the gamma autocorrelation signal:

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
Zhang, Sigl, JCAP 0809 (2008) 027 (2008)
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, JConrad, Hannestad, MNRAS 414 (2011) 2040
Cuoco, Komatsu, Siegal-Gaskins, PRD 86 (2012) 063004
Harding, Abazajian, JCAP 11 (2012) 26

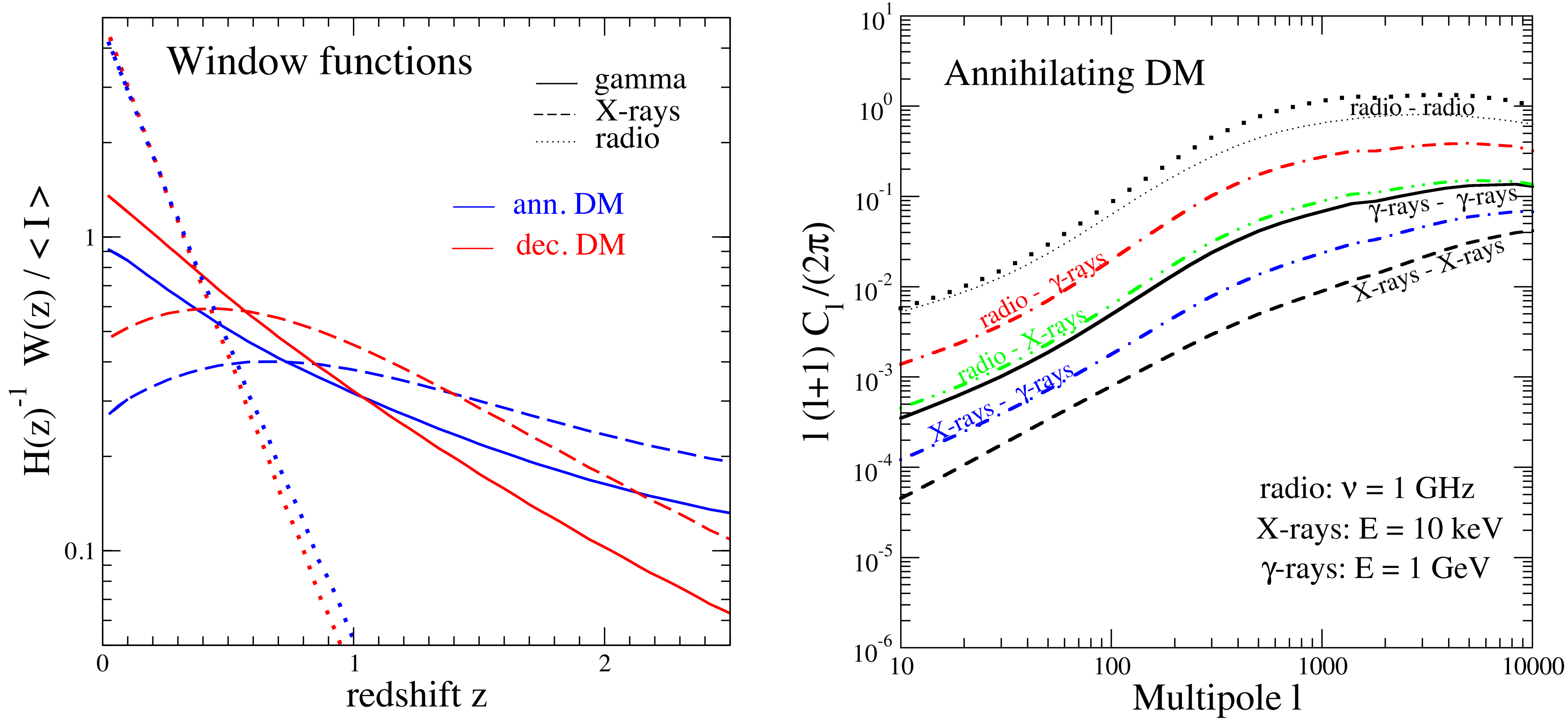
# Extension of the cross-correlation approach

- Cross-correlation of an electromagnetic signal with gravitational probes:
  - LSS surveys
  - Weak lensing surveys (cosmic shear)

- Cross-correlation among signals at different wavelengths

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

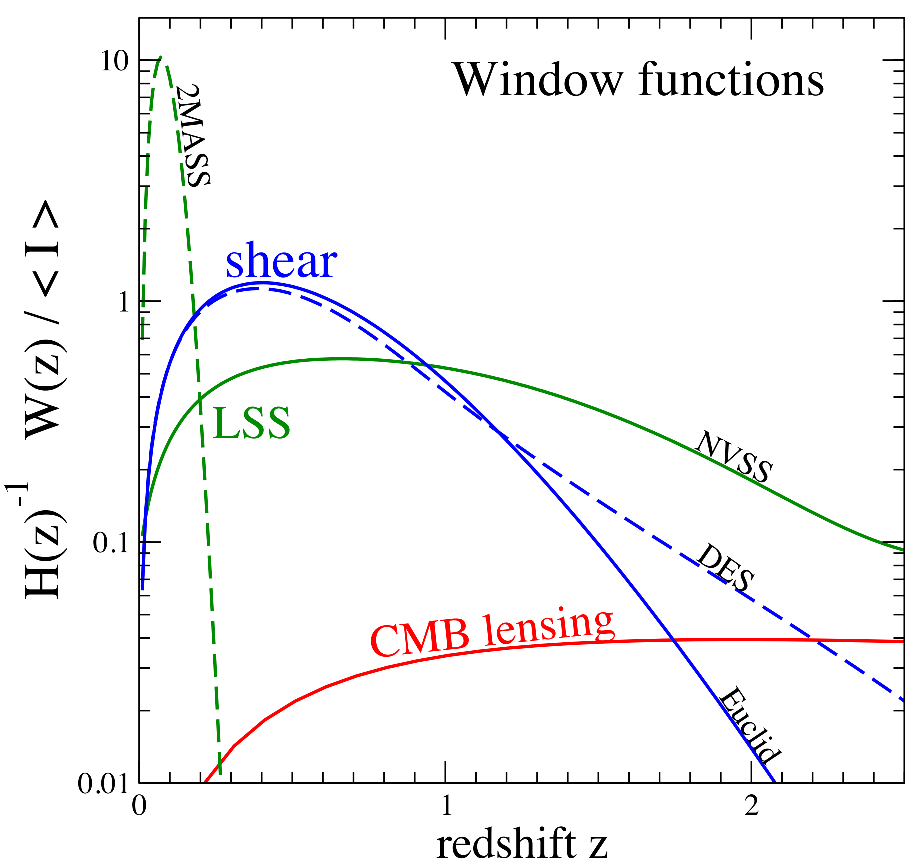
# Auto and Cross Correlations

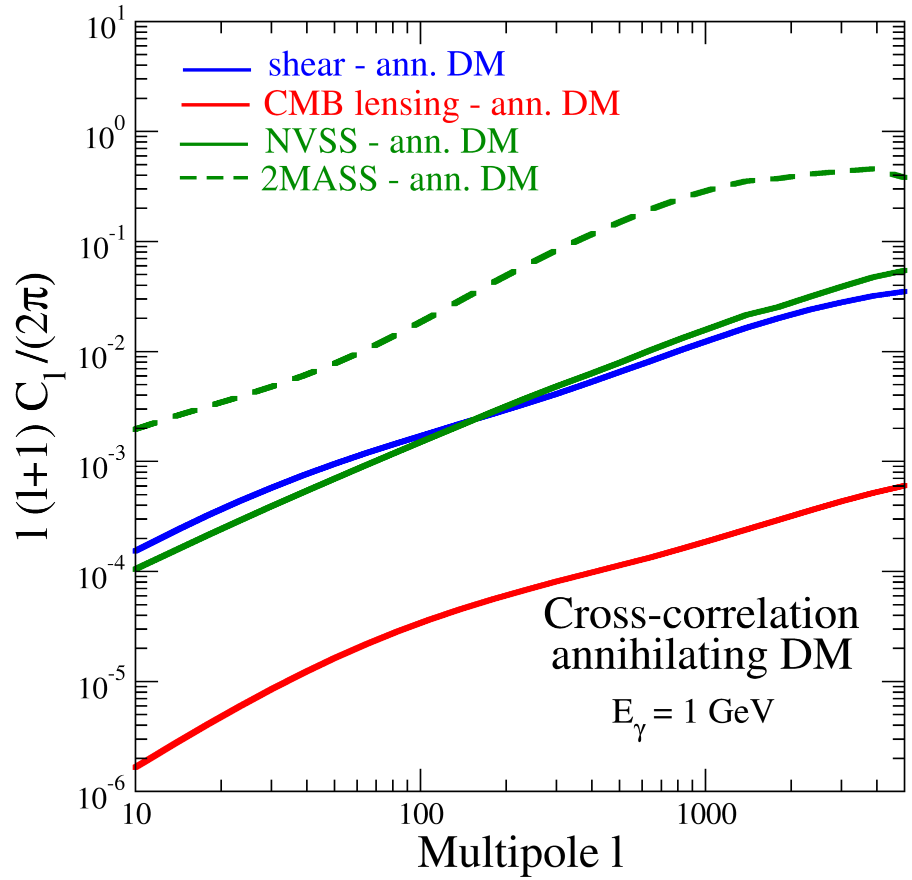



among multiwavelength signals

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

# Auto and Cross Correlations

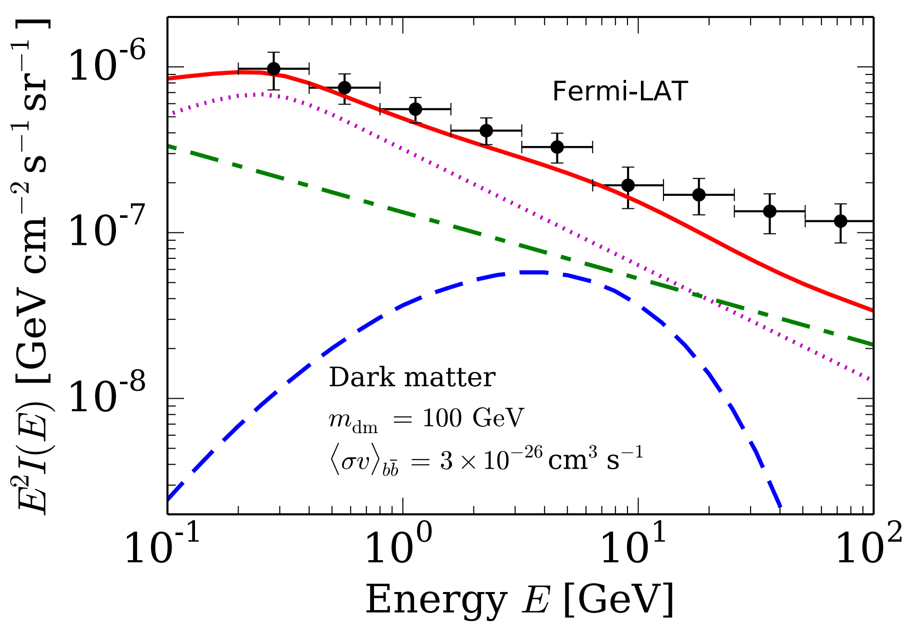


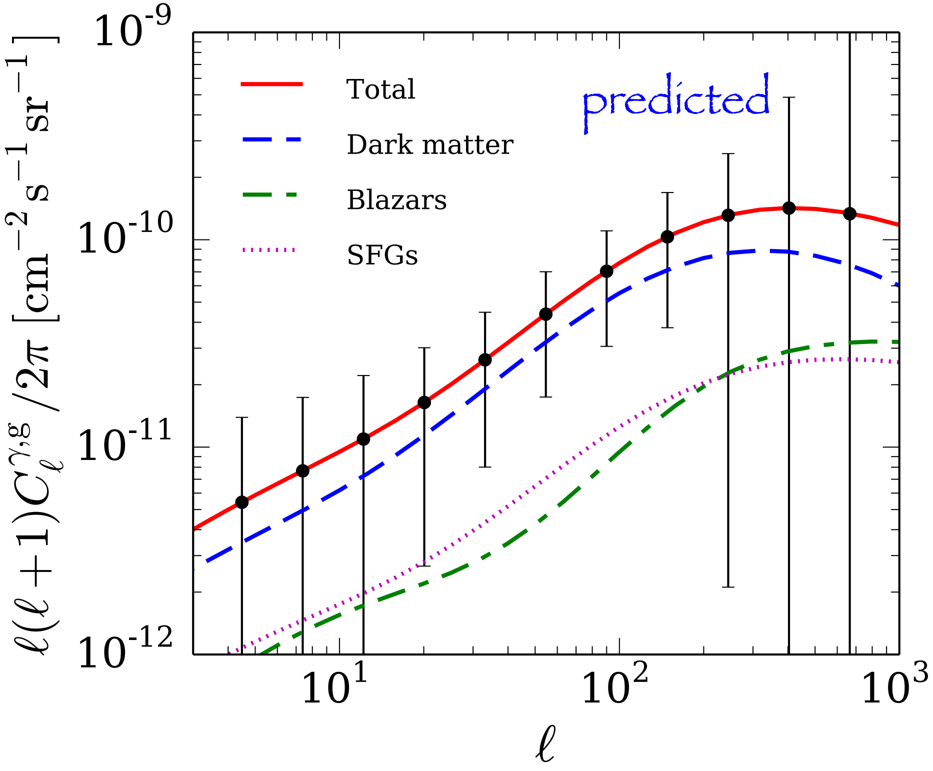



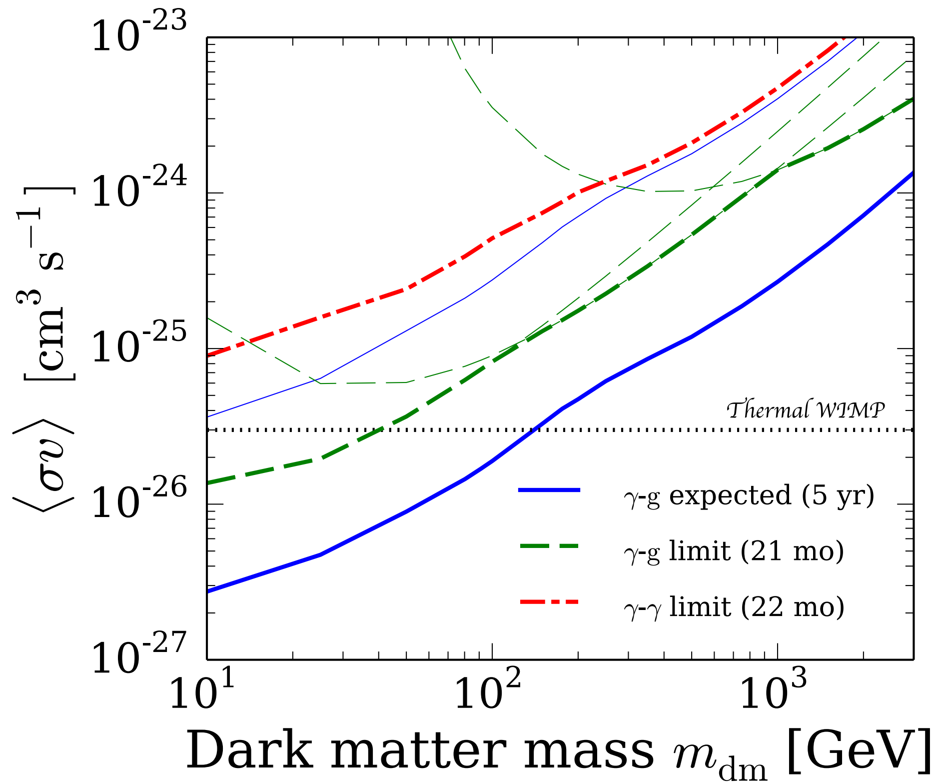

multiwavelength signals with gravitational probes

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

# Fermi + 2MASS




Ando, Benoit-Levy, Komatsu, arXiv:1312.4403