Particle dark matter signals in the anisotropic sky: A cross correlation approach

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Neutrino and Dark Matter in Nuclear Physics (NDM 2015)
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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) L 1*	gamma + CMB lensing
Regis, Xia, Cuoco, NF, Branchini, Viel, *arXiv:1503.05922*	gamma + LSS
Cuoco, Xia, Regis, NF, Branchini, Viel, *to appear*	gamma + LSS

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

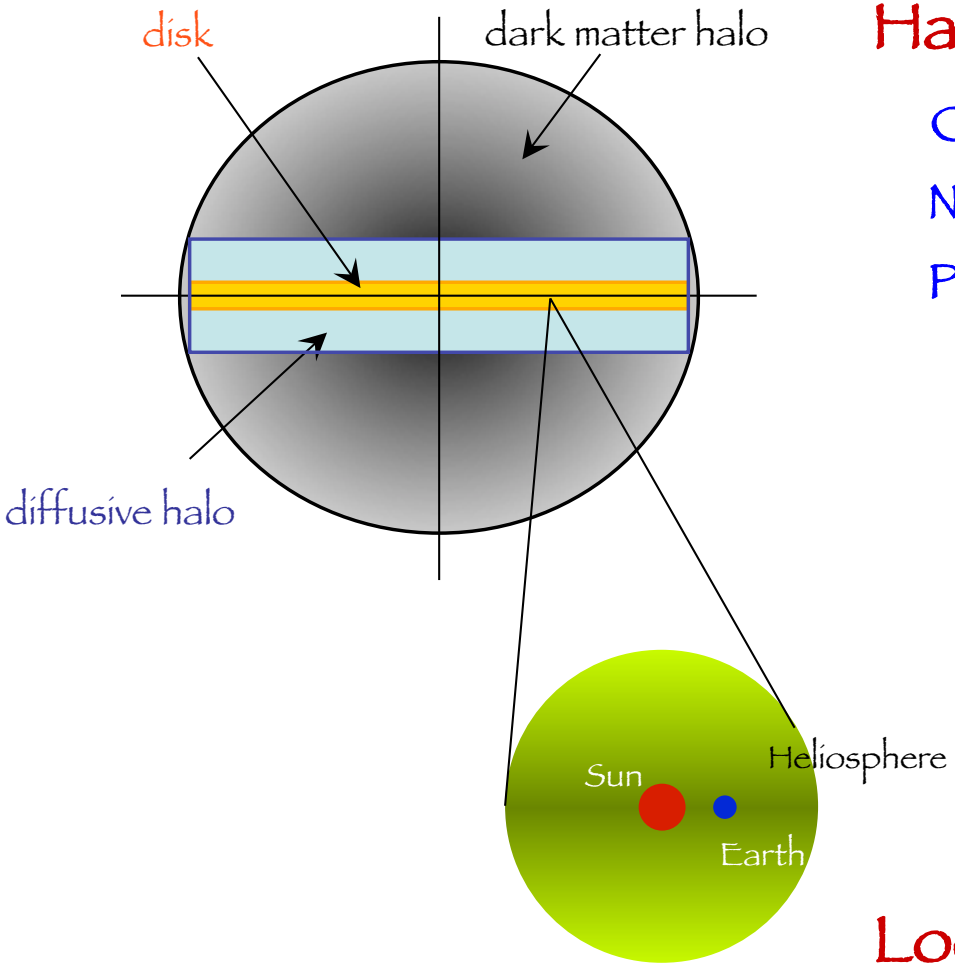
- This evidence can be ascribed either to:
  - Modification of the theory of Gravity
  - DM = elementary particle, relic from the early Universe
    - No viable candidate in the SM: New Physics BSM
    - However, if DM is a new particle, a non-gravitational signal (due to it's particle physics nature)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

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



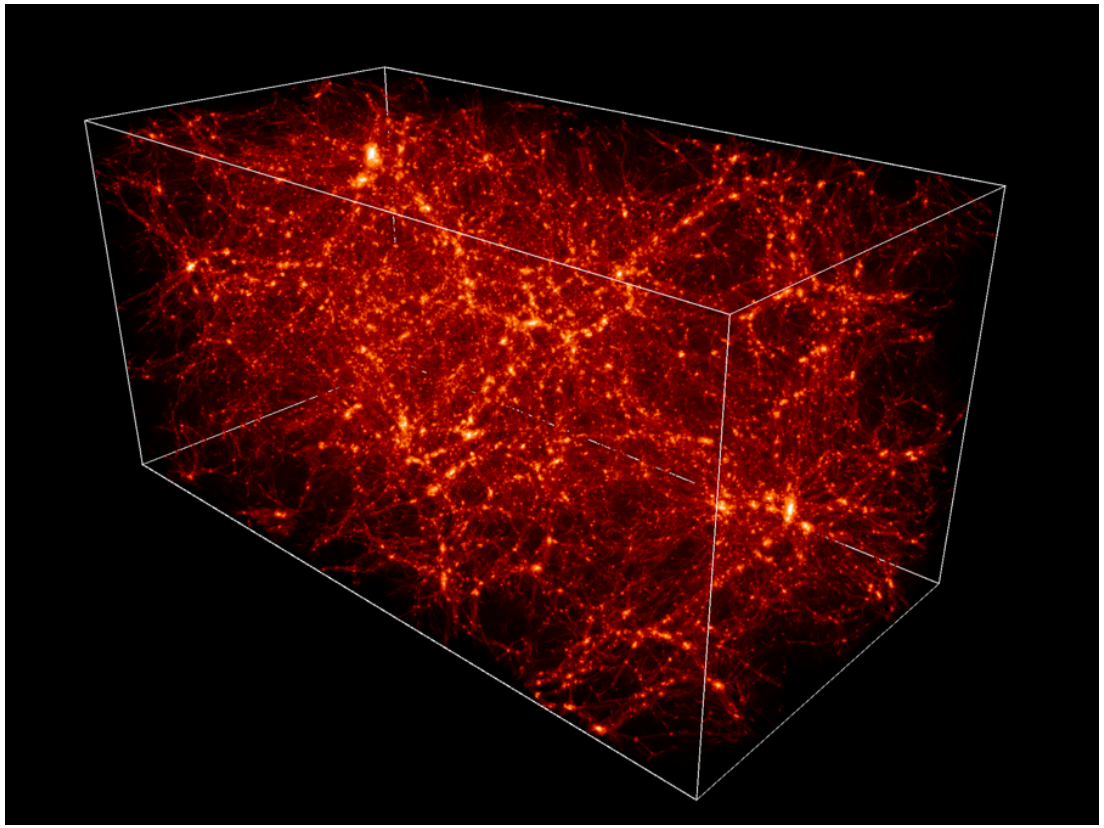
Halo signals

- 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

Extragalactic/Cosmological signals



Photons: gamma, X, radio

Neutrinos

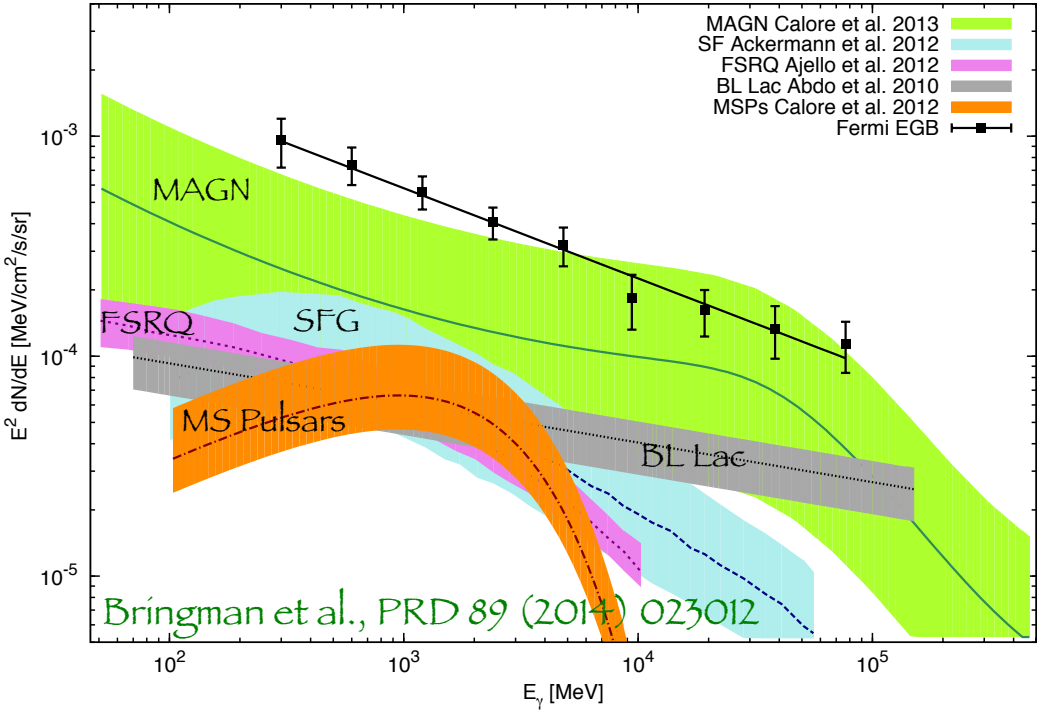
Impact on CMB:

SZ effect in clusters

Back to recombination

Features of the Extra Galactic DM signal

- Sources of DM signals are:
  - Faint
  - Very numerous
- The DM emission is very likely subdominant in the "IGRB"

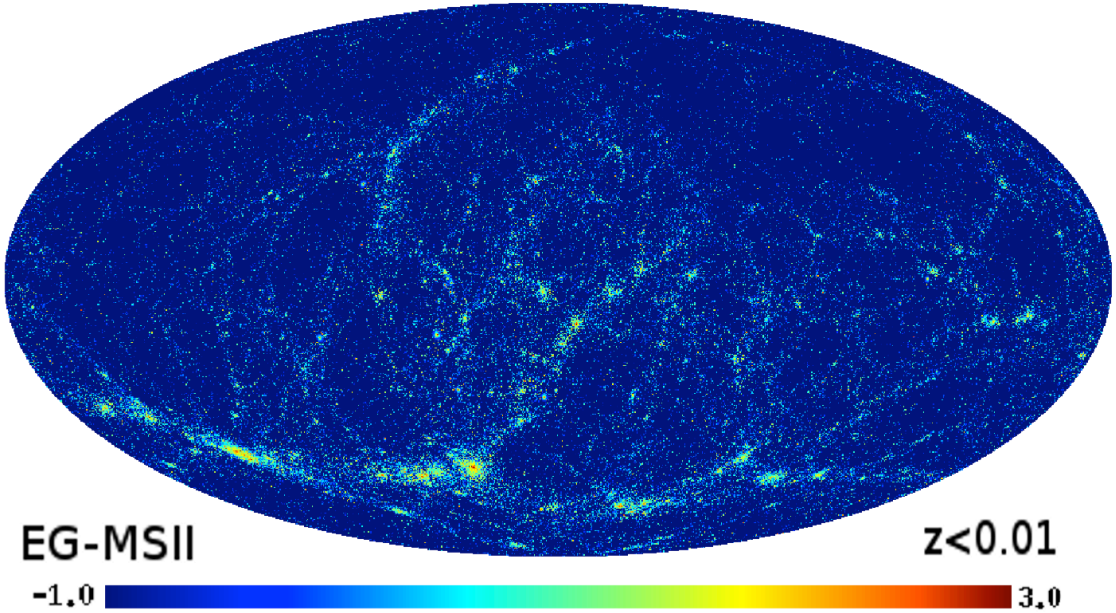


Features of the Extra Galactic DM signal

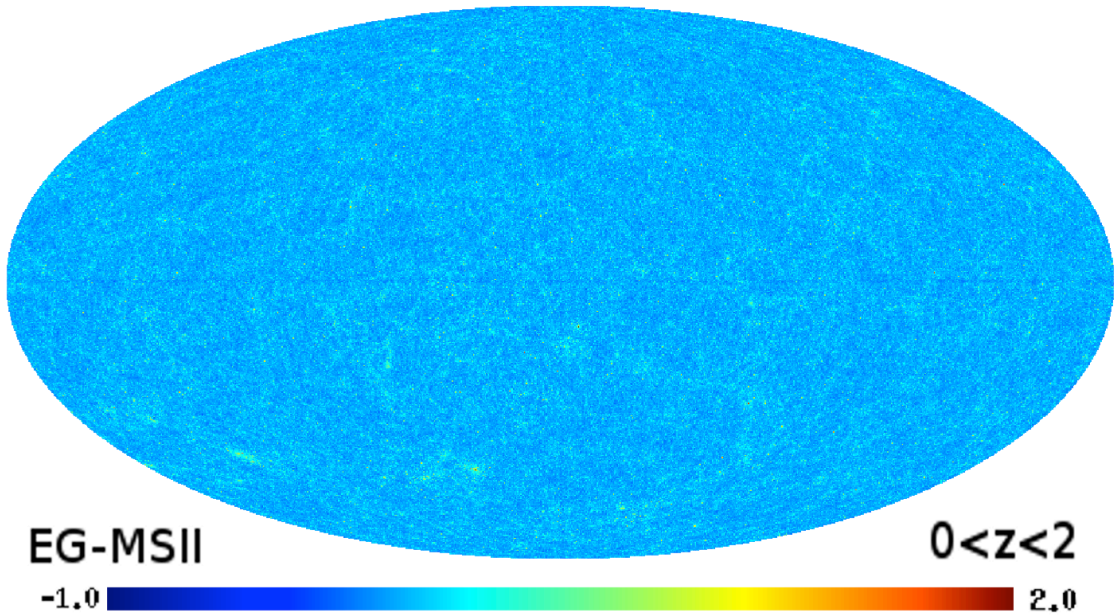
- Sources of DM signals are:
  - Faint
  - Very numerous
- The cumulative emission from these *unresolved* sources produces a nearly "isotropic" component, but …
- DM sources can affect the statistics of photons across the sky, even though they are too dim to be individually detected

Statistical Correlations

Simulation of extraGalactic γ ray emission



Intensity at 4 GeV
m_{DM} = 200 GeV
$\langle\sigma v\rangle$ thermal
bb channel

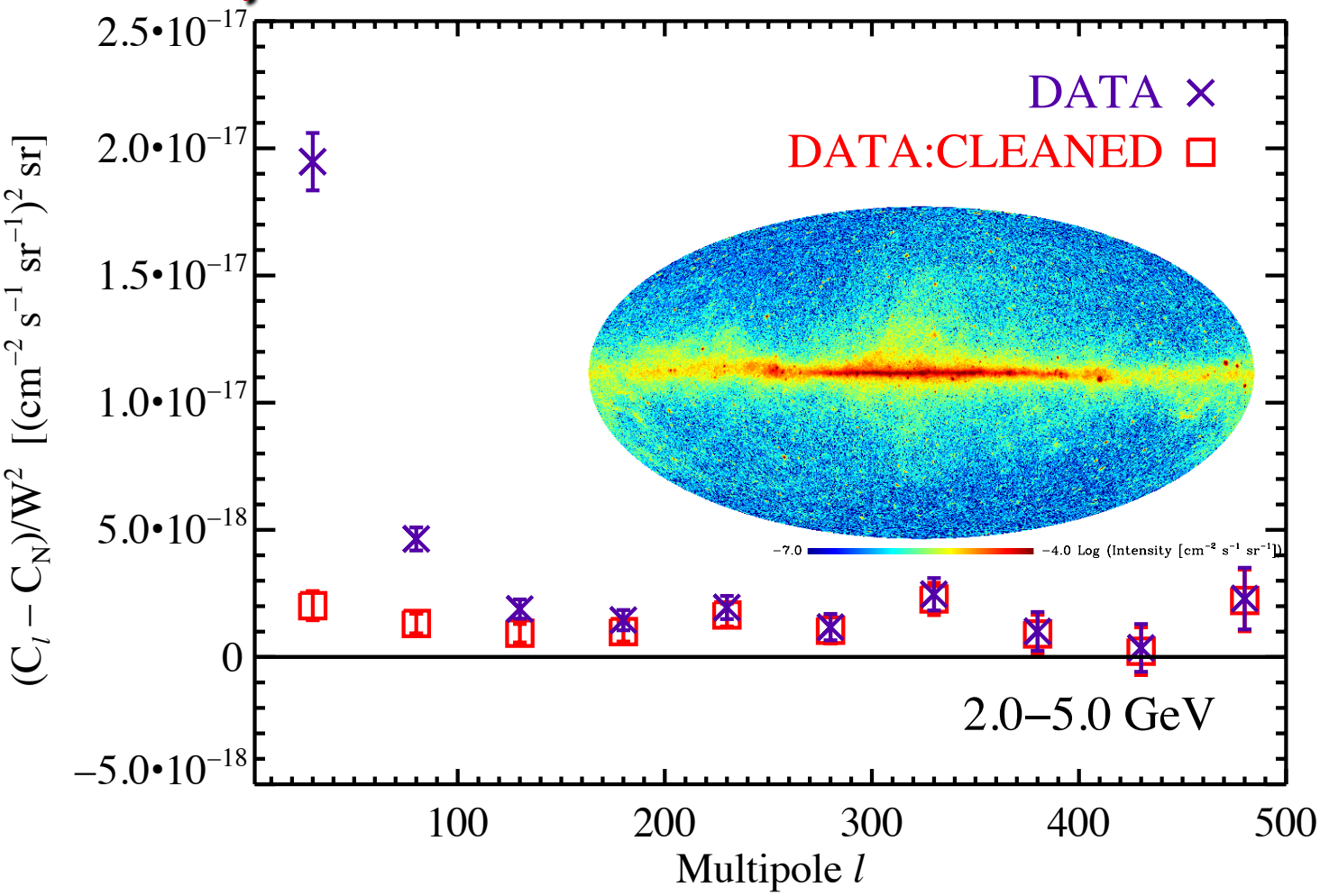


Fornasa et al., MNRAS 329 (2013) 1529

Statistical correlators

- 1-point correlator: pixel count
  - Useful to constrain the source number count dN/dS below detection threshold
- 2-point correlator: angular power spectrum
  - Auto-correlation

2-point auto-correlation function



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

Overall significance: 9σ

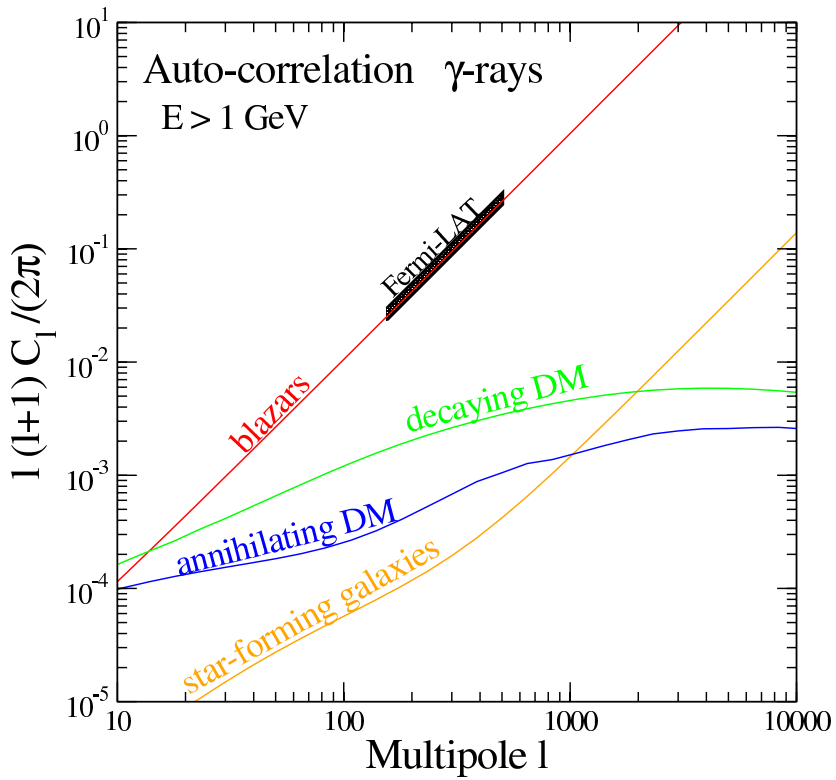
Ackerman et al. (Fermi) PRD 85 (2012) 083007

Gamma-rays auto-correlation

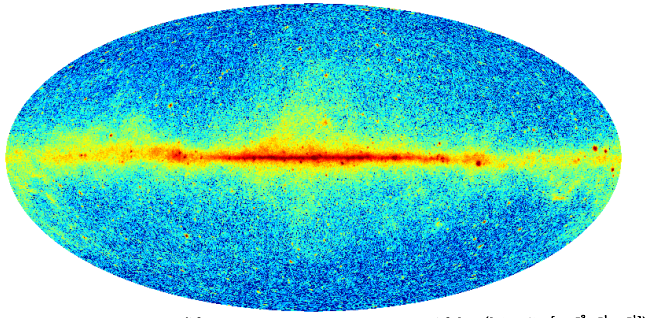
Features of the signal point toward interpretation in terms of blazars

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

Difficult to extract a clear WIMP signature from the EGB alone



Can we do more ?



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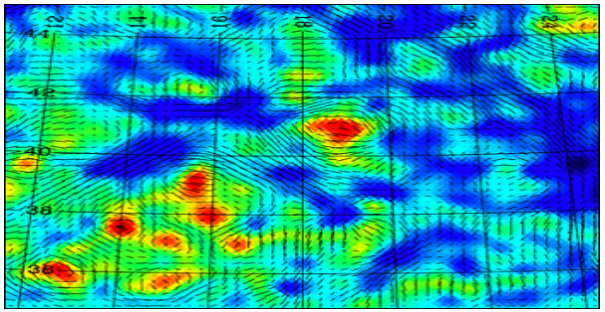


Cross-correlation of EM signal with gravitational tracer of DM

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

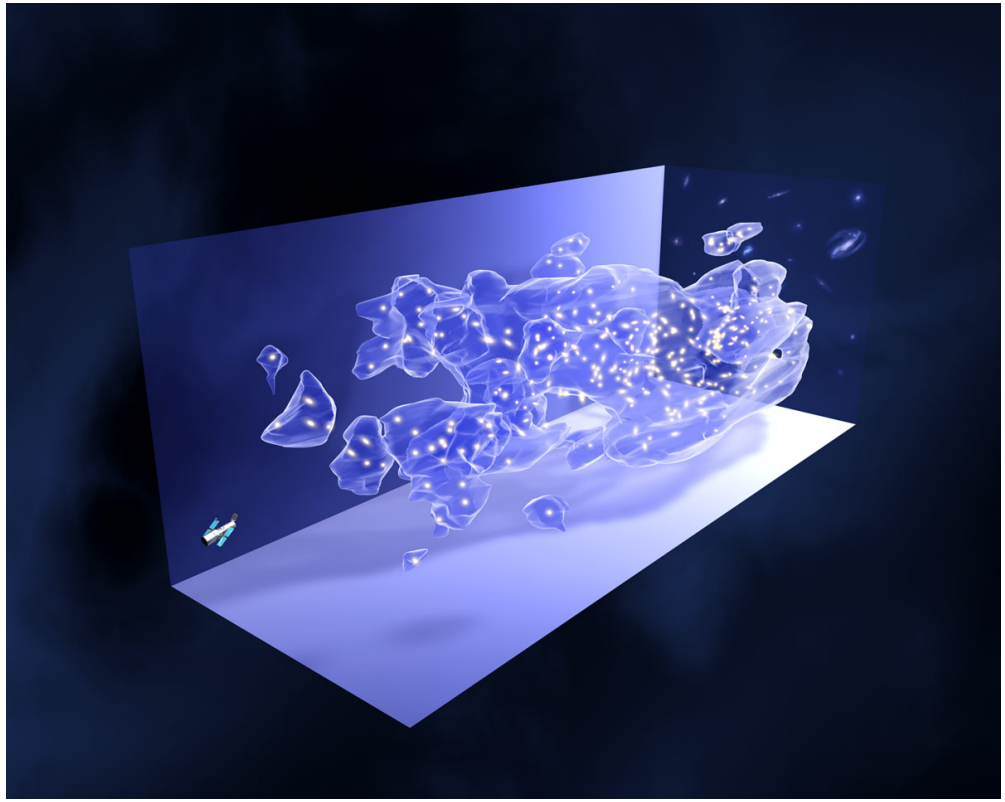
It can offer a direct evidence that what is measured by means of gravity is indeed due to DM in terms of an elementary particle

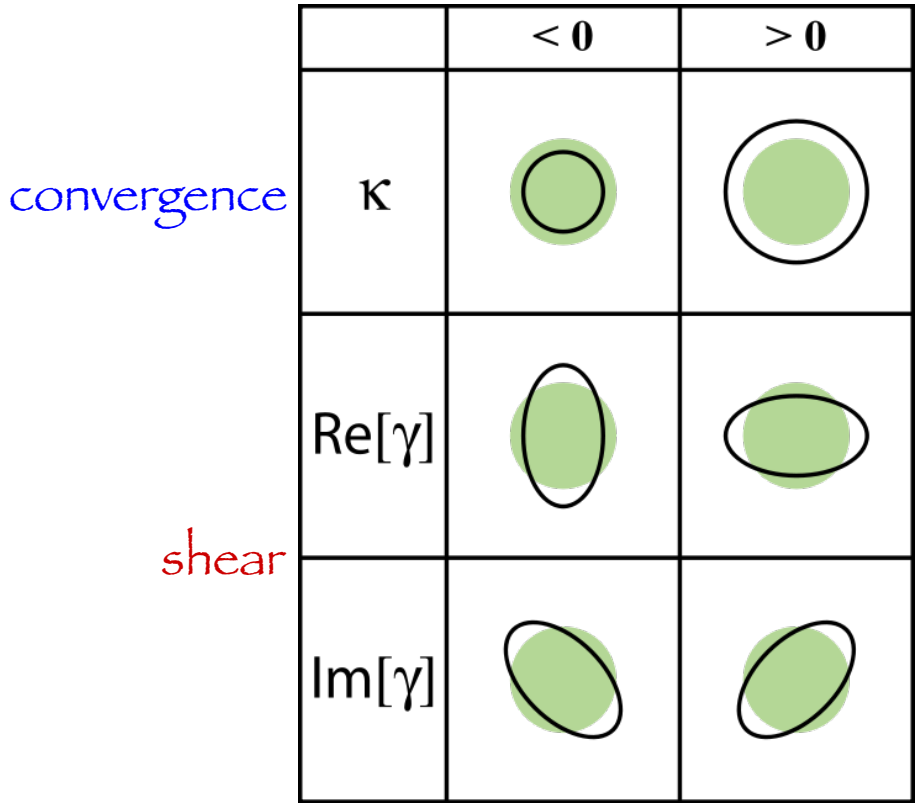
Camera, Fornasa, NF, Regis, Ap. J. 771 (2013) L5

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

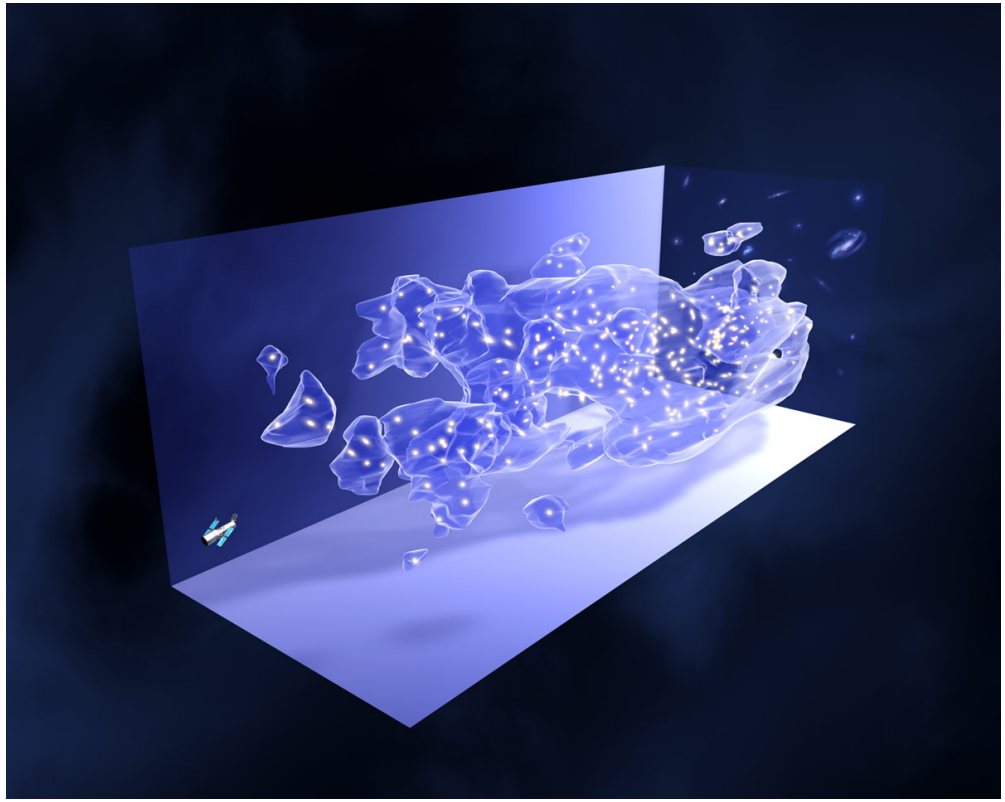




Cosmic structures and gamma-rays

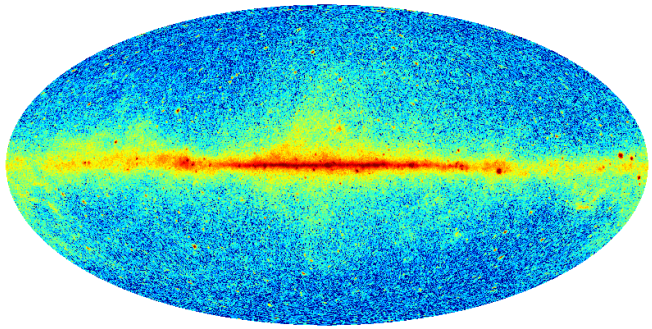
The same Dark Matter structures that act as lenses can themselves emit light at various wavelengths, including the gamma-rays range

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

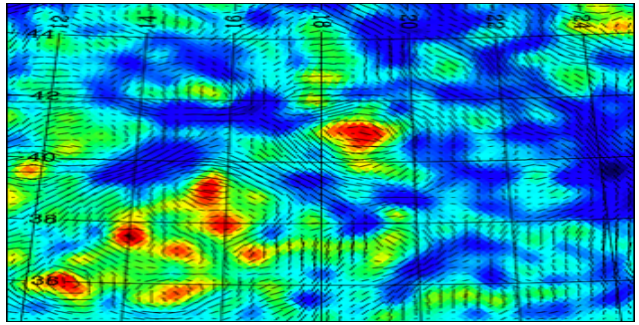


Gamma-rays emitted by DM may exhibit strong correlation with lensing signal

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

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

Camera, Fornasa, NF, Regis, Ap. J. Lett. 771 (2013) L5
Camera, Fornasa, NF, Regis, arXiv:1411.4651, to appear in JCAP
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

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

Gamma-rays from annihilating DM

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

Clumping factor

DM photon "emissivity"

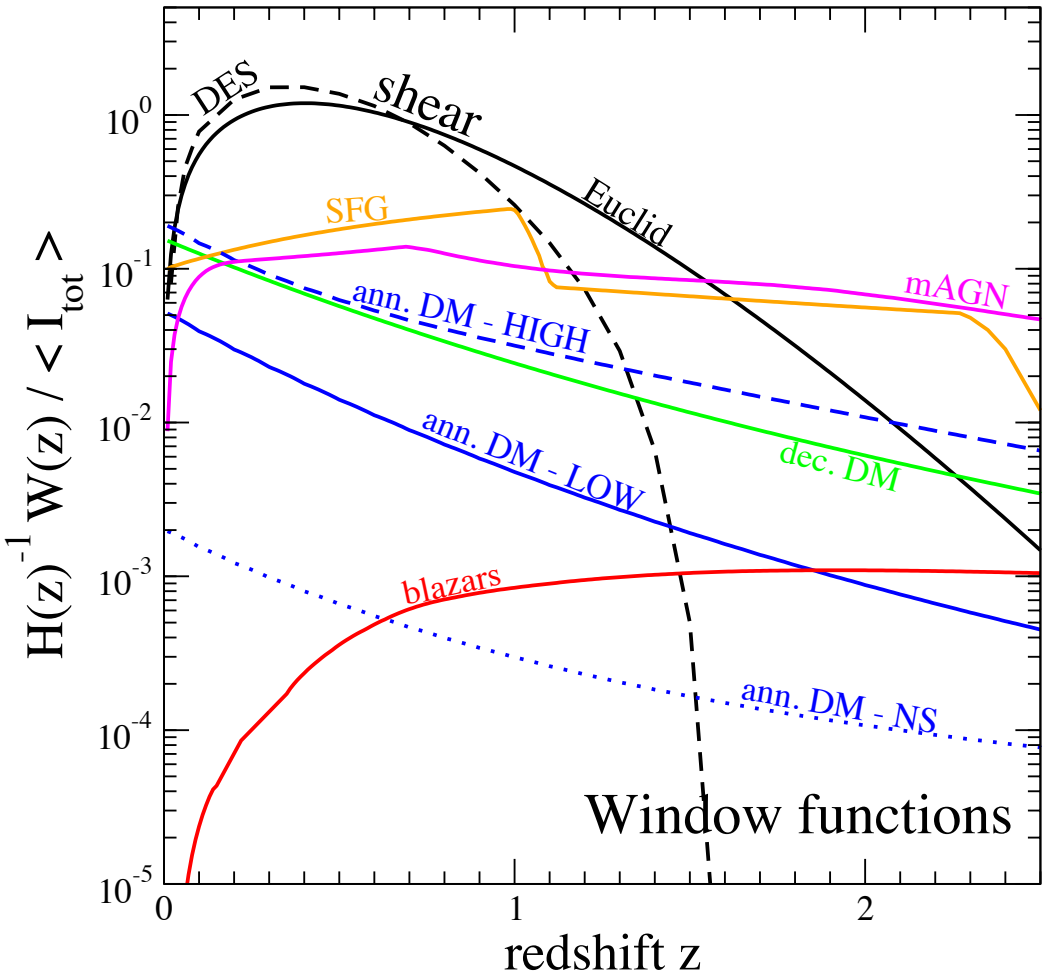
$$\Delta^2(\chi) \equiv \frac{\langle\rho^2_{\mathrm{DM}}\rangle}{\bar{\rho}^2_{\mathrm{DM}}} = \int_{M_{\mathrm{min}}}^{M_{\mathrm{max}}} \mathrm{d}M\,\frac{\mathrm{d}n}{\mathrm{d}M}\int \mathrm{d}^3\mathbf{x}\,\frac{\rho_h^2(\mathbf{x}|M,\chi)}{\bar{\rho}^2_{\mathrm{DM}}}[1+B(M,\chi)]$$

Subhalo boost

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

Gamma-rays are also emitted by astrophysical sources, each of which has a specific window function

Window functions



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, to appear in JCAP

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

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

Linear matter PS

Linear bias

3D Power spectra

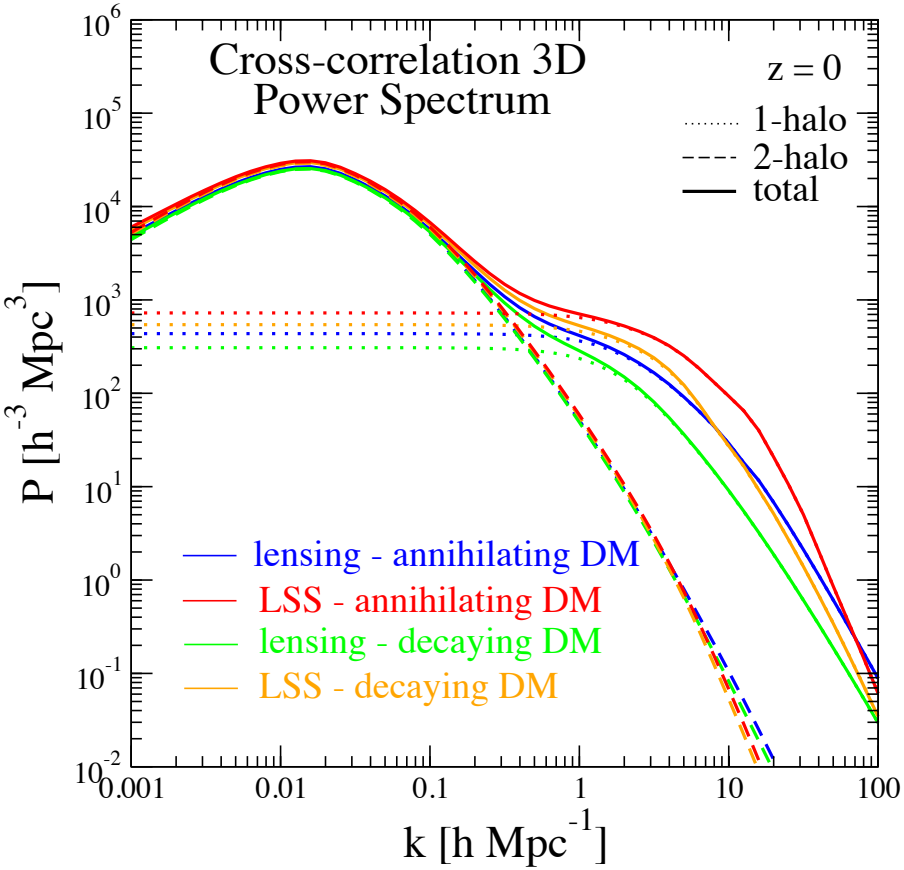
Annihilating DM

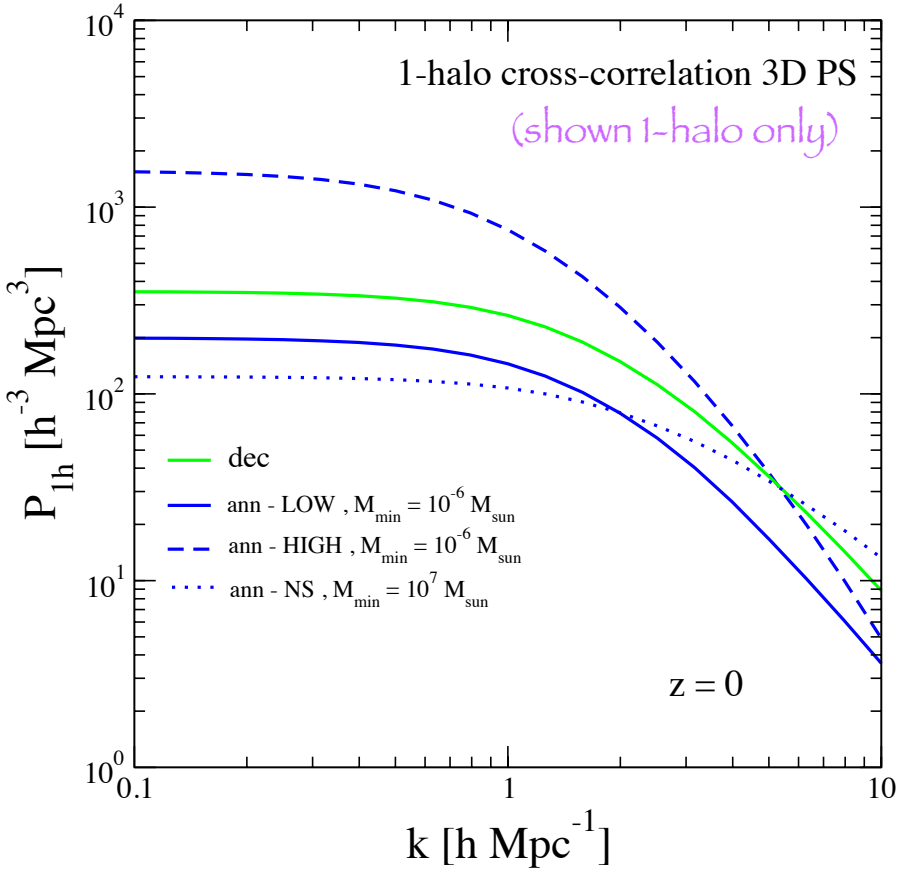
$$P_{1h}^{\delta\delta^2}(k,z) = \int_{M_{\rm min}}^{M_{\rm max}} {\rm d}M \, \boxed{\frac{{\rm d}n}{{\rm d}M}} \boxed{\tilde{v}(k|M)} \frac{\boxed{\tilde{u}(k|M)}}{\Delta^2}$$

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

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

3D Power spectra: dark matter

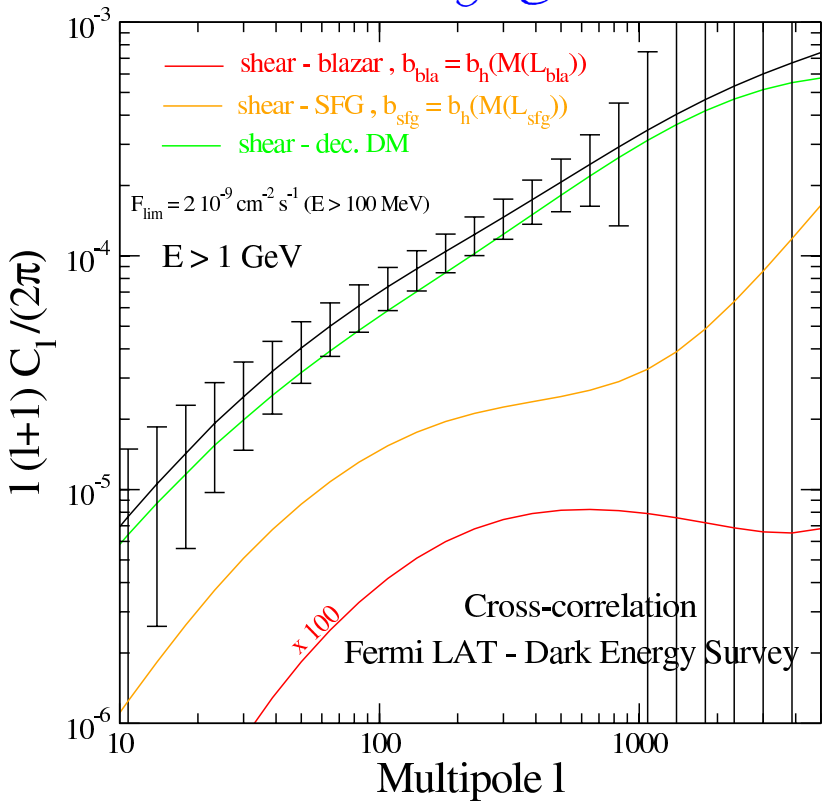




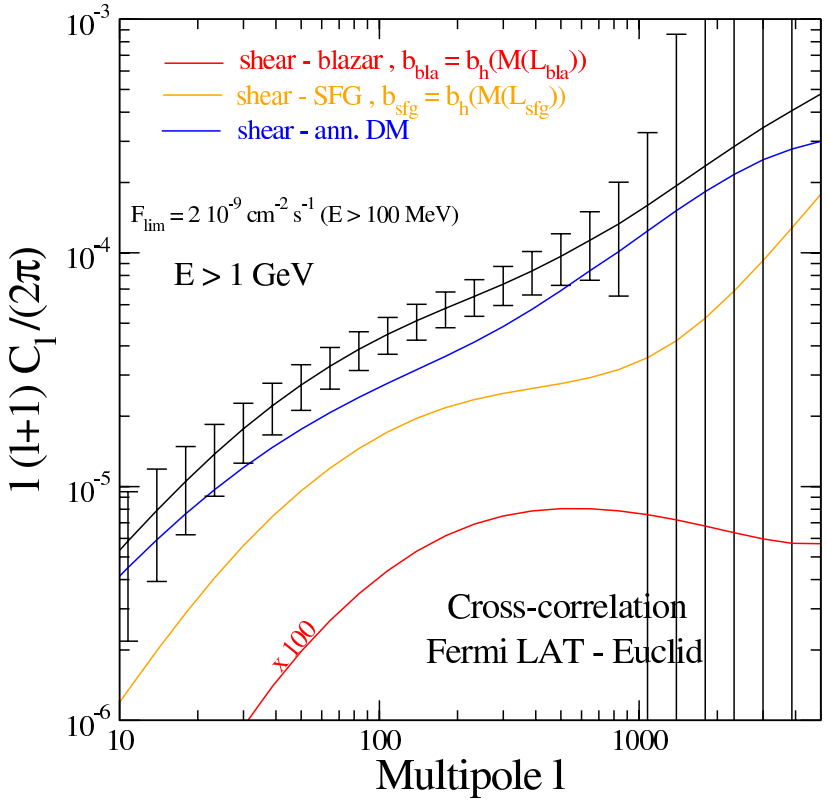
NF, Regis, Front. Physics 2 (2014) 6

Cross-correlation predictions

Decaying DM



Annihilating DM



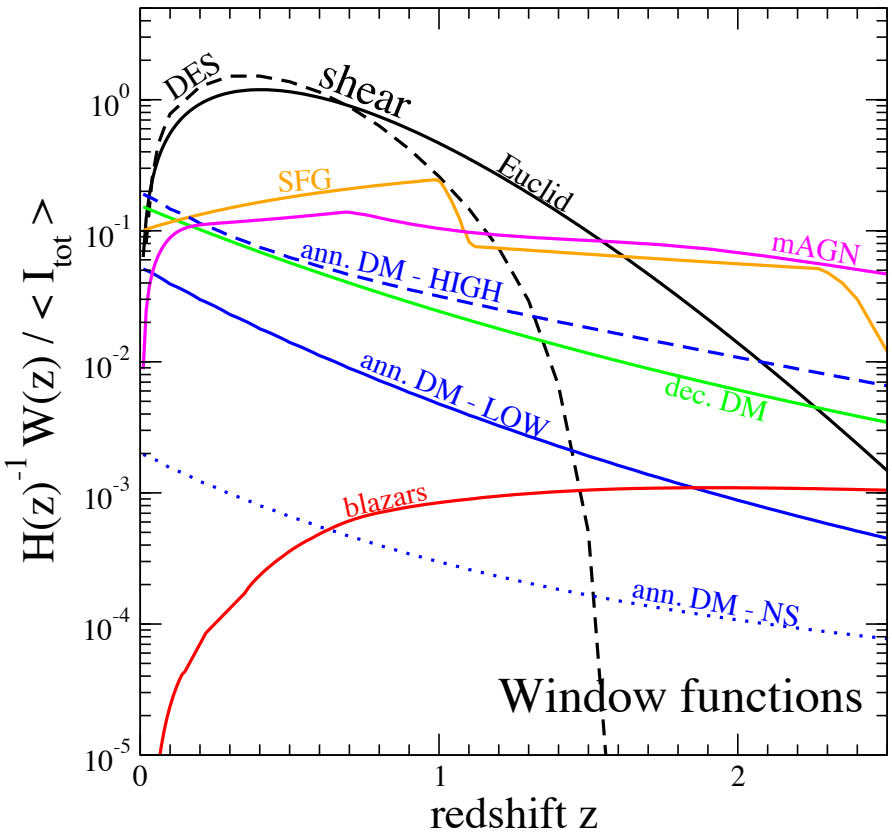
Fermi-LAT/5-yr with DES

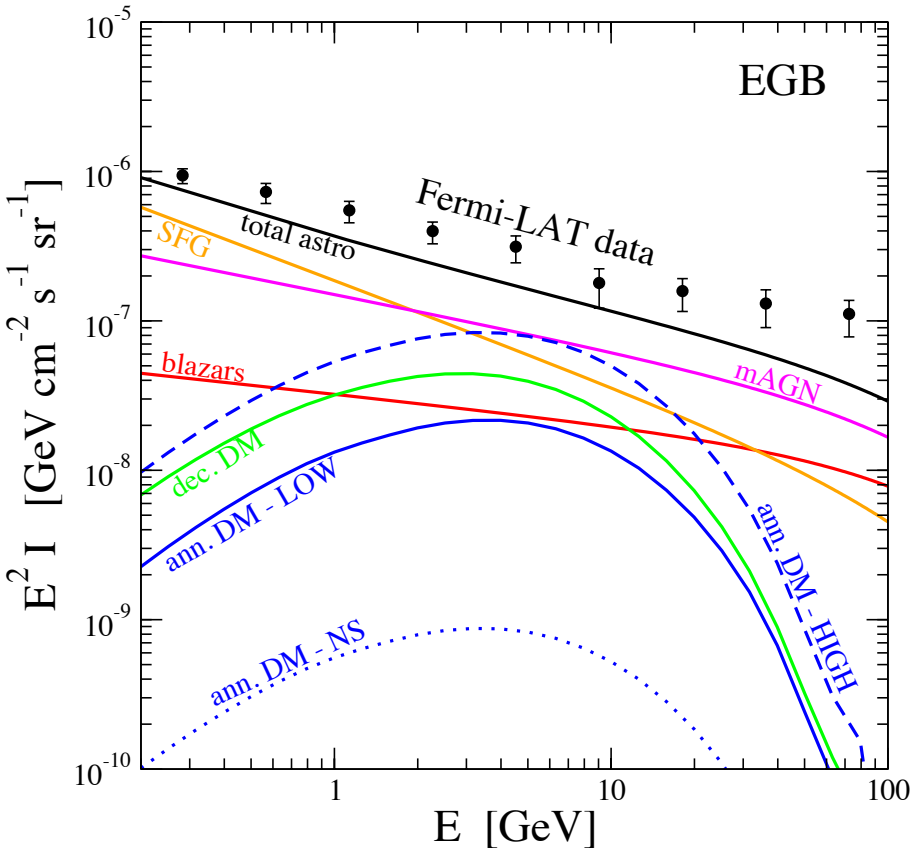
Fermi-LAT/5-yr with Euclid

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

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, to appear in JCAP

Bayesian Forecasts

- Discovery potential (5σ) in the (m_{DM}, $\langle\sigma v\rangle$) plane

- Bounds in the (m_{DM}, $\langle\sigma v\rangle$) plane in case the DM contribution is strongly suppressed

- 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

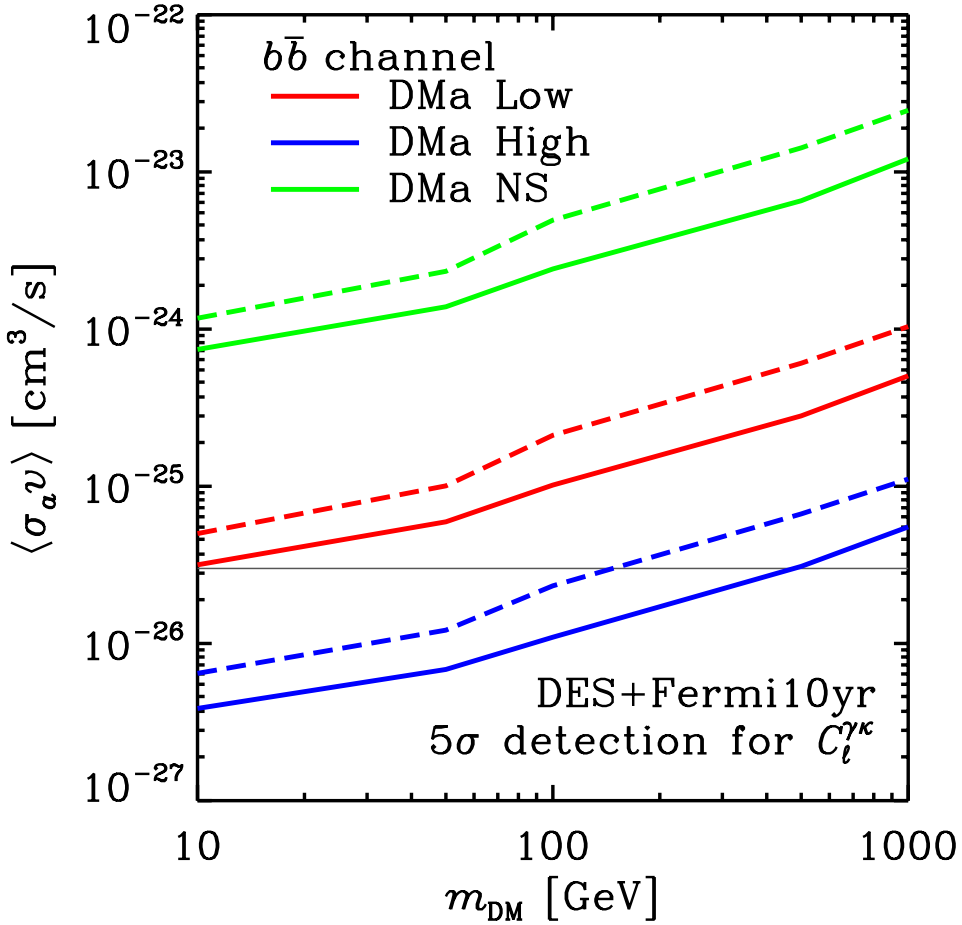
Parameter	Description	Fermi-10yr	Fermissimo
$f_{\rm sky}$	Surveyed sky fraction	1	1
$E_{\rm min} - E_{\rm max}$ [GeV]	Energy range	$1 - 300$	$0.3 - 1000$
N_E	Number of bins	6	8
ε [cm^2 s]	Exposure	3.2×10^{12}	4.2×10^{12}
$\langle \sigma_b \rangle$ [deg]	Average beam size	0.18	0.027

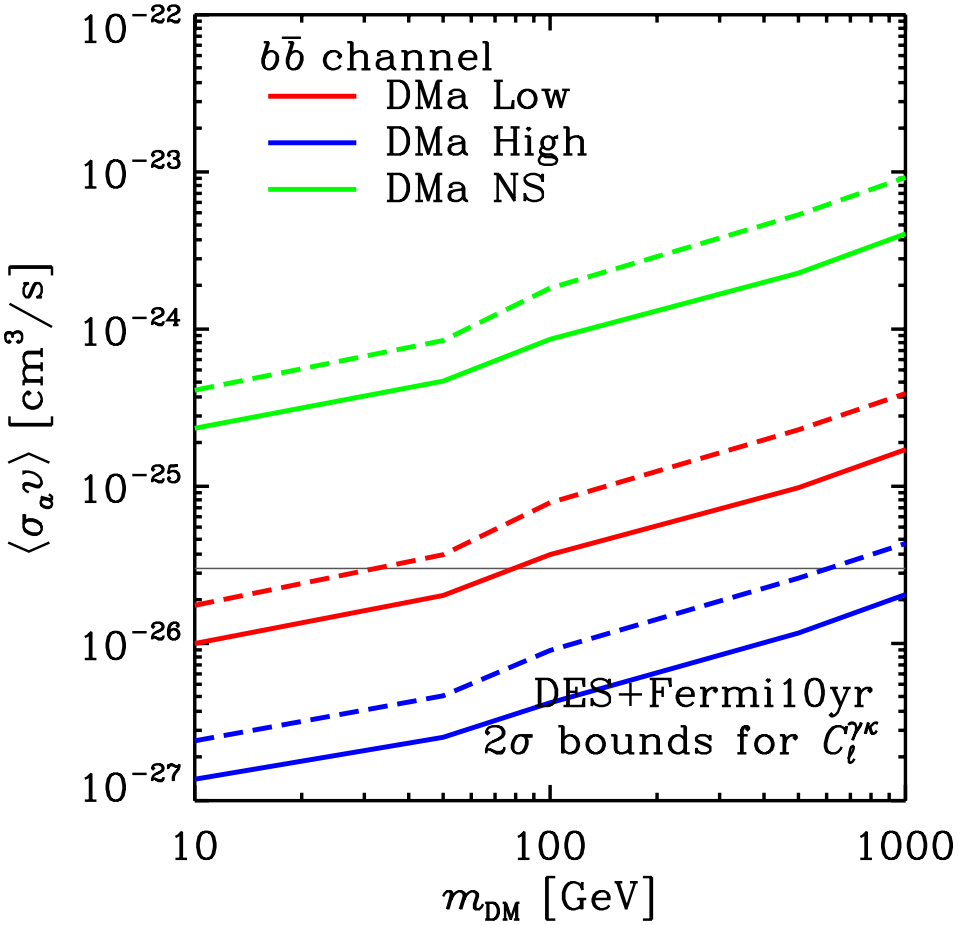
Combinations:

DES + Fermi 10 yr

Euclid + "Fermissimo"

Forecasts



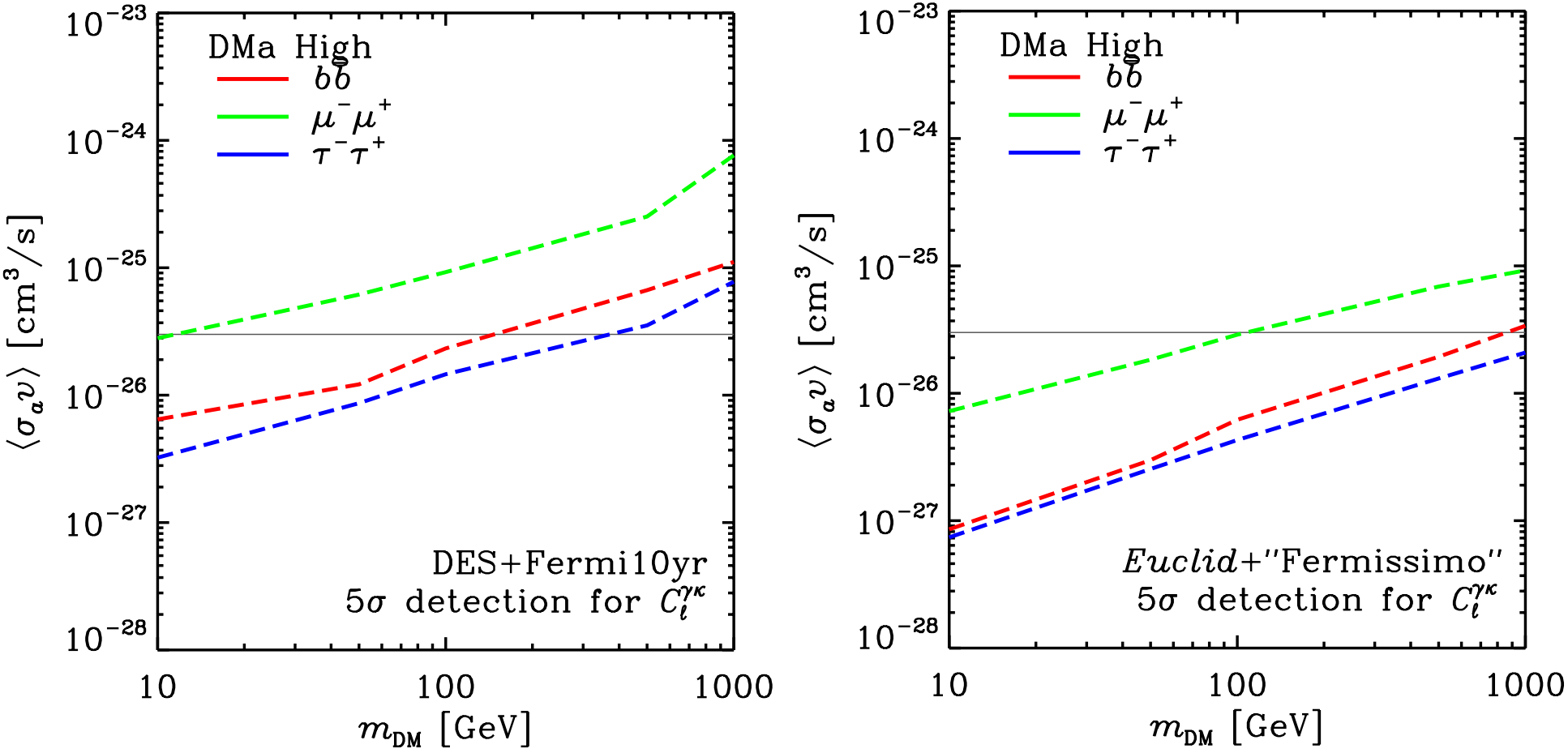


5σ detection

sensitivity limit

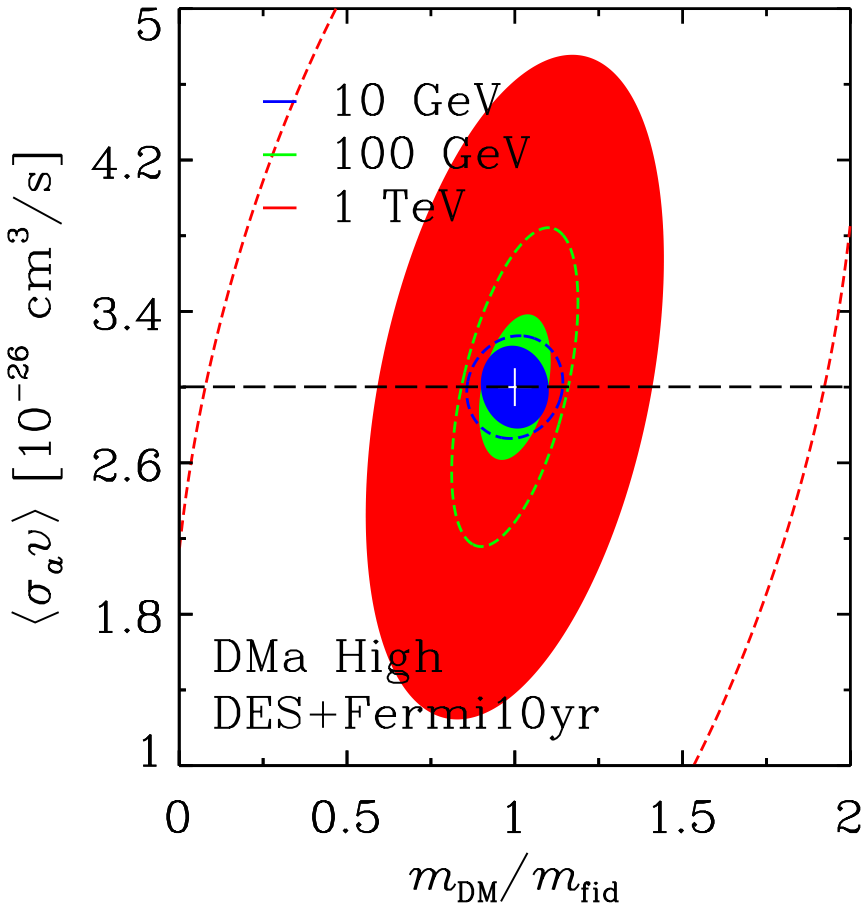
Camera, Fornasa, NF, Regis, arXiv:1411.4651, to appear in JCAP

Forecasts: detection reach



Camera, Fornasa, NF, Regis, arXiv:1411.4651, to appear in JCAP

Forecasts: reconstruction capabilities



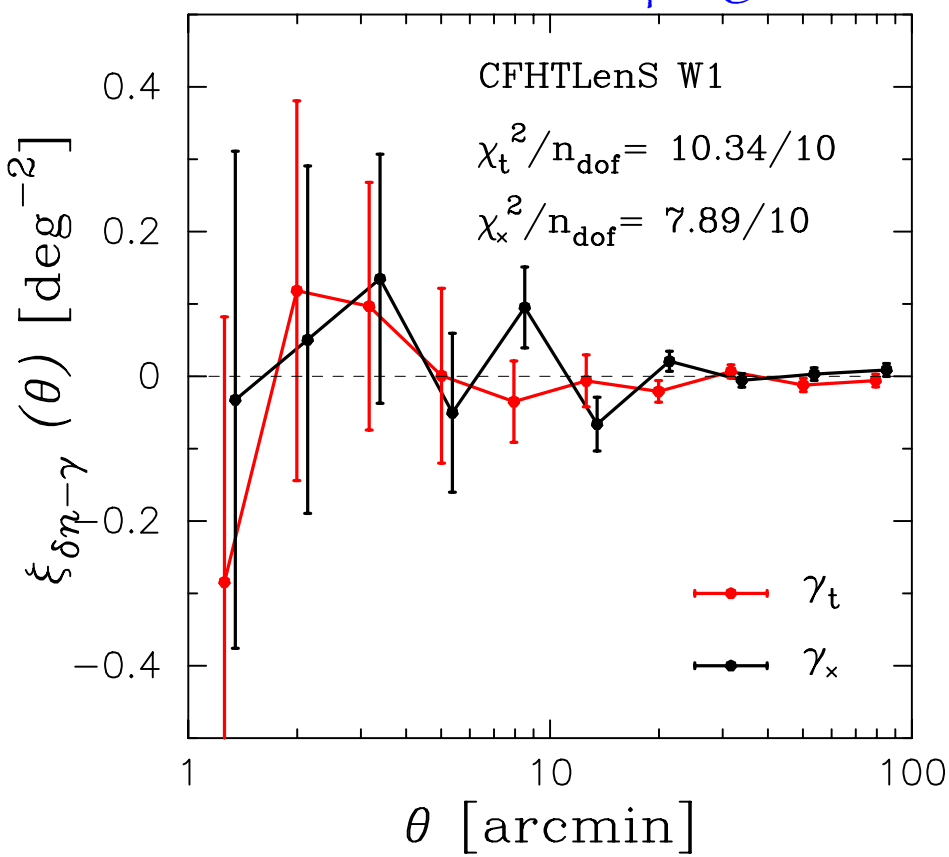
Camera, Fornasa, NF, Regis, arXiv:1411.4651, to appear in JCAP

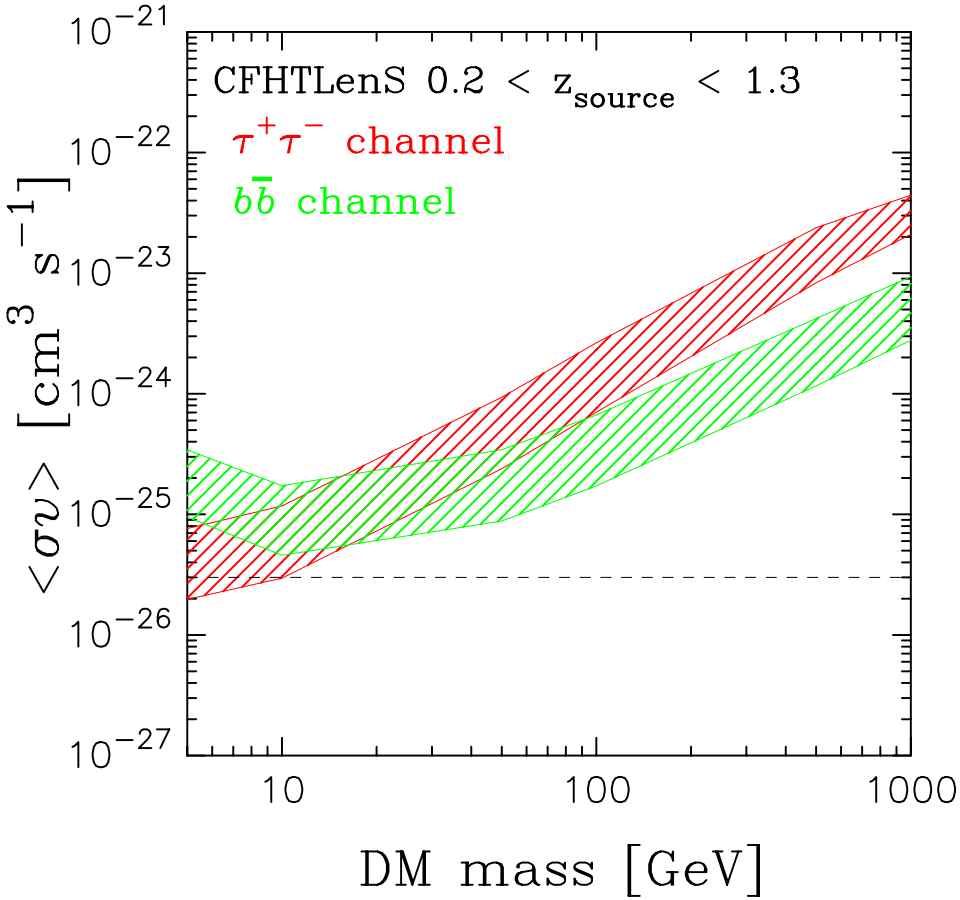
Comments

- 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 in a few years
- For the future:
  - Fermi will likely 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

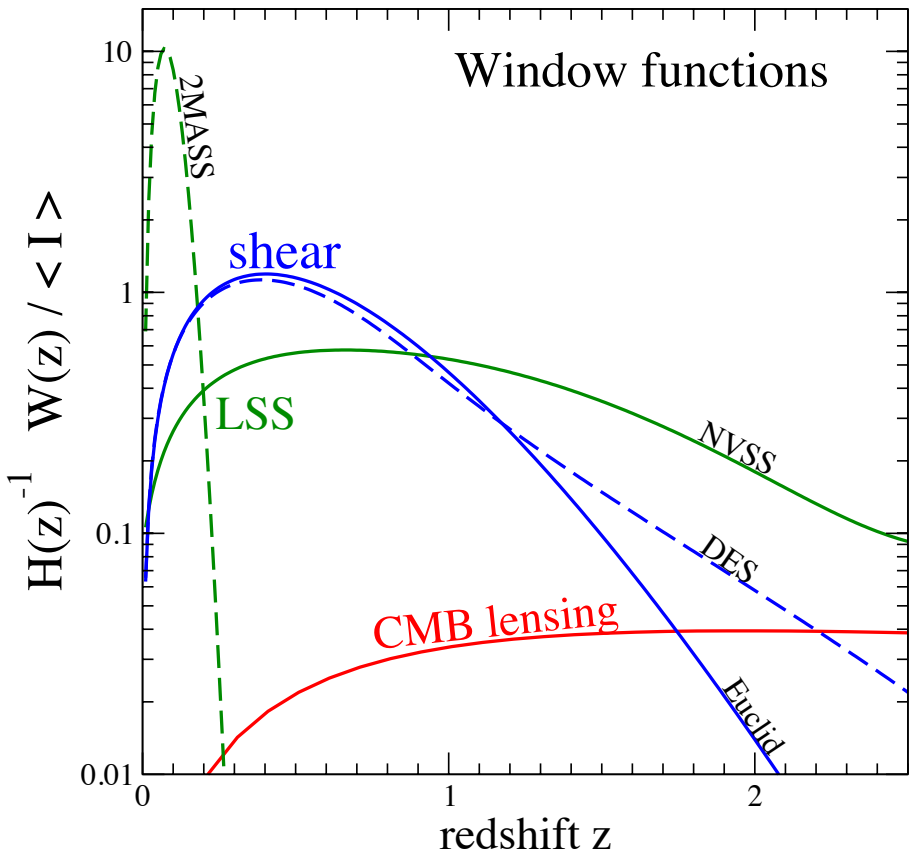
- Gravitational tracers: G_i
  - Weak lensing surveys (cosmic shear) traces the whole DM
  - CMB lensing
  - LSS surveys traces light -> bias

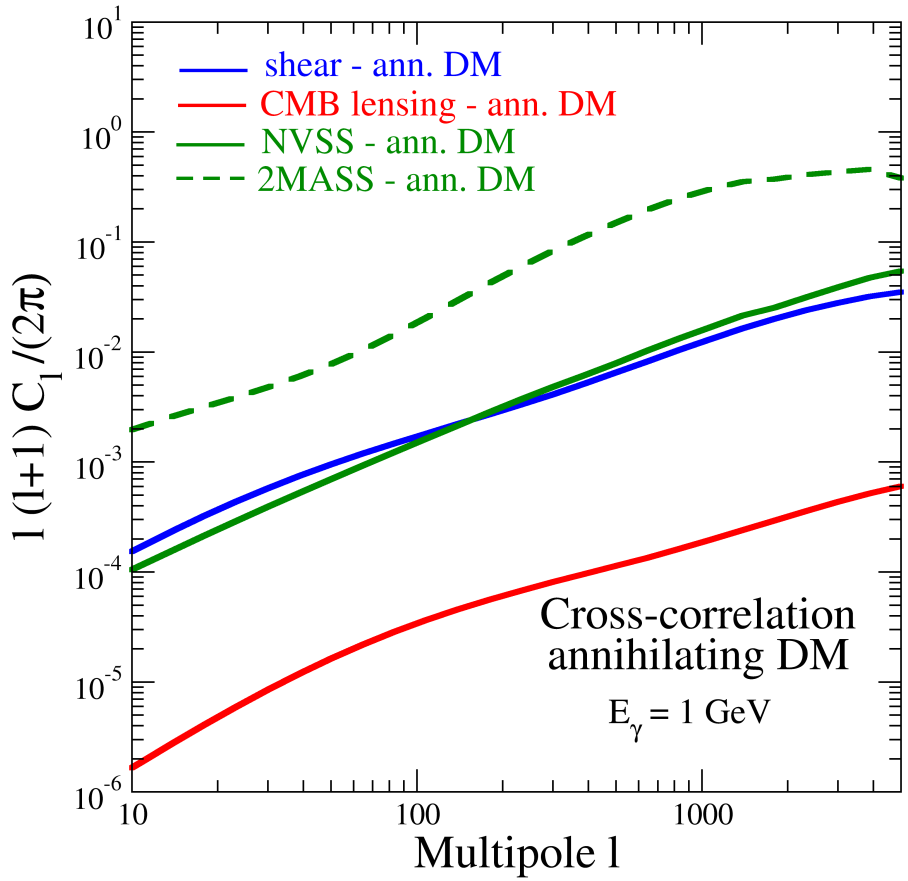
- Electromagnetic signals: E_a
  - Radio
  - X
  - Gamma

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

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

Additional cross correlations channels

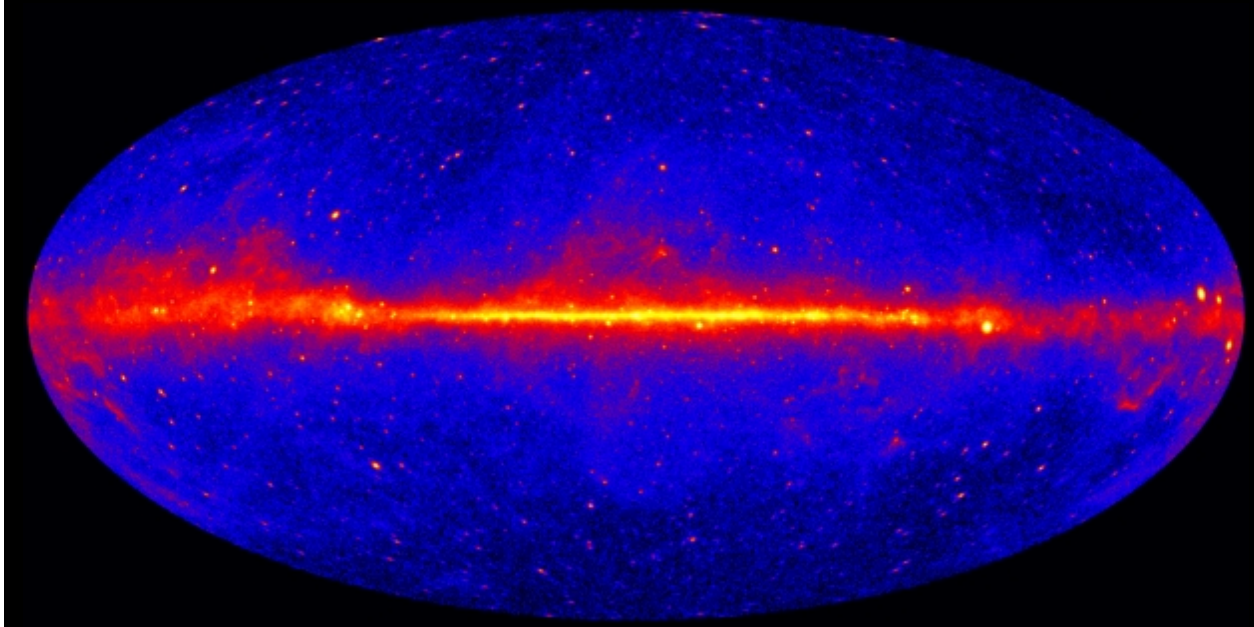


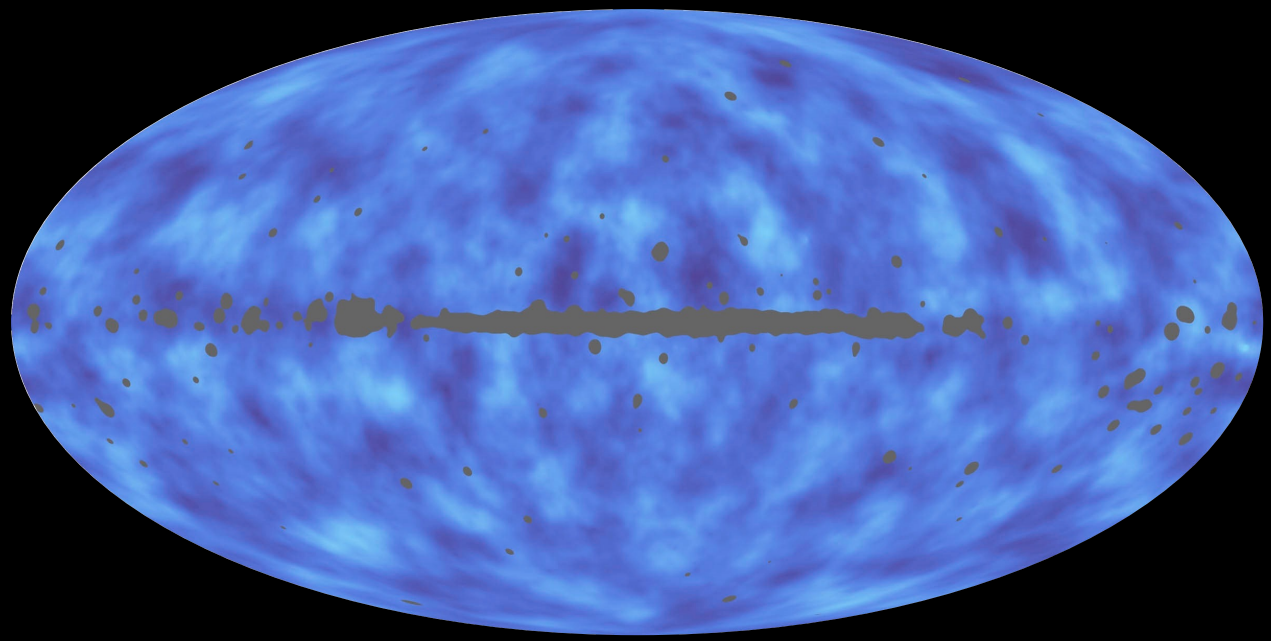


Multiwavelength signals with
LSS tracers and gravitational probes

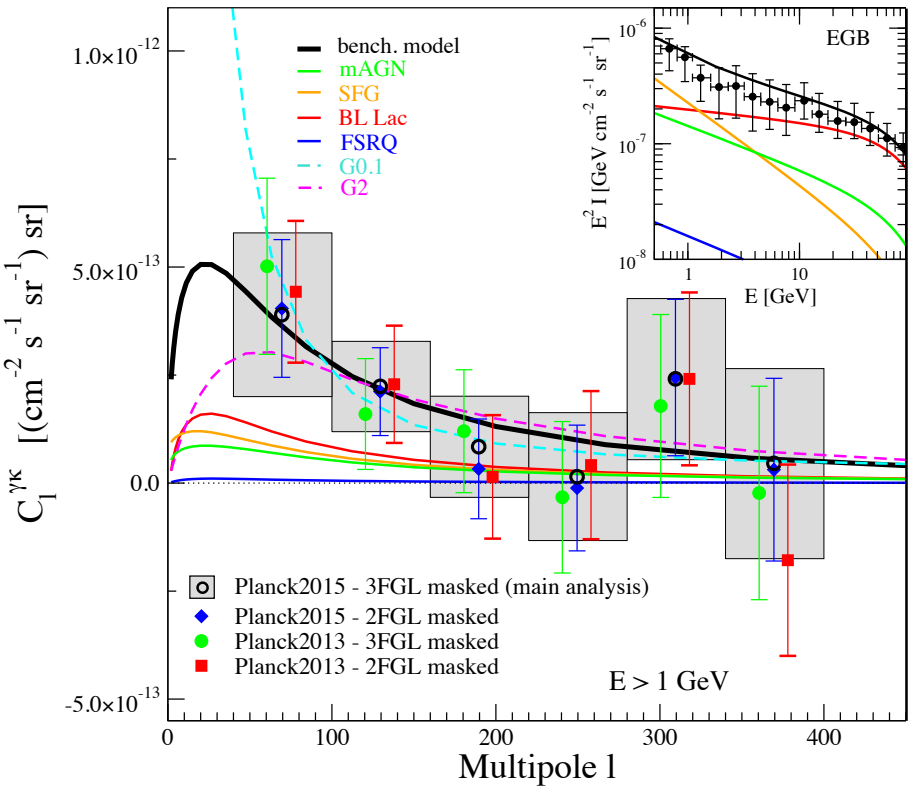
NF, Regis, Front. Physics 2 (2014) 6

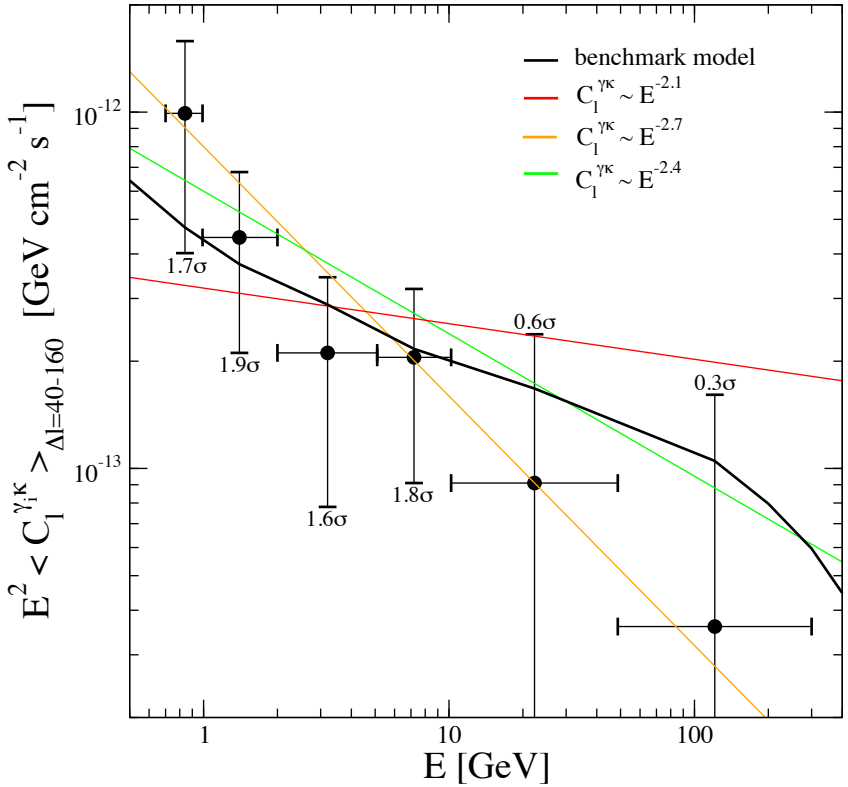
Fermi/gamma + Planck/CMB lensing





Fermi/gamma + Planck/CMB lensing





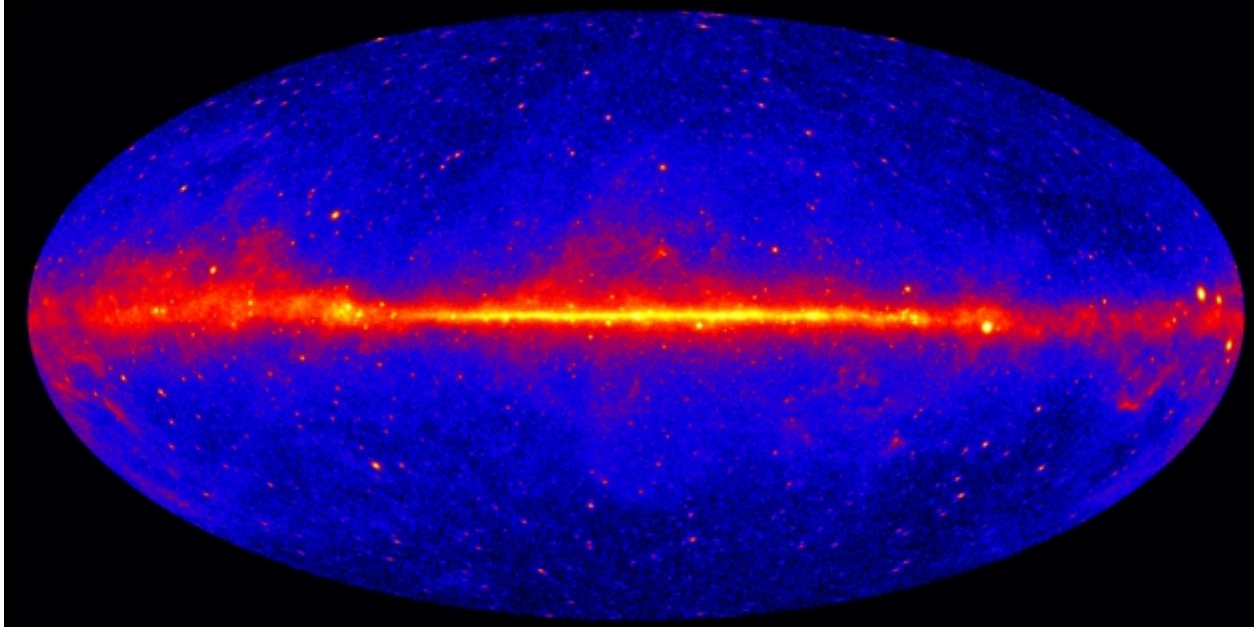
Cross-correlation: 3.0σ evidence

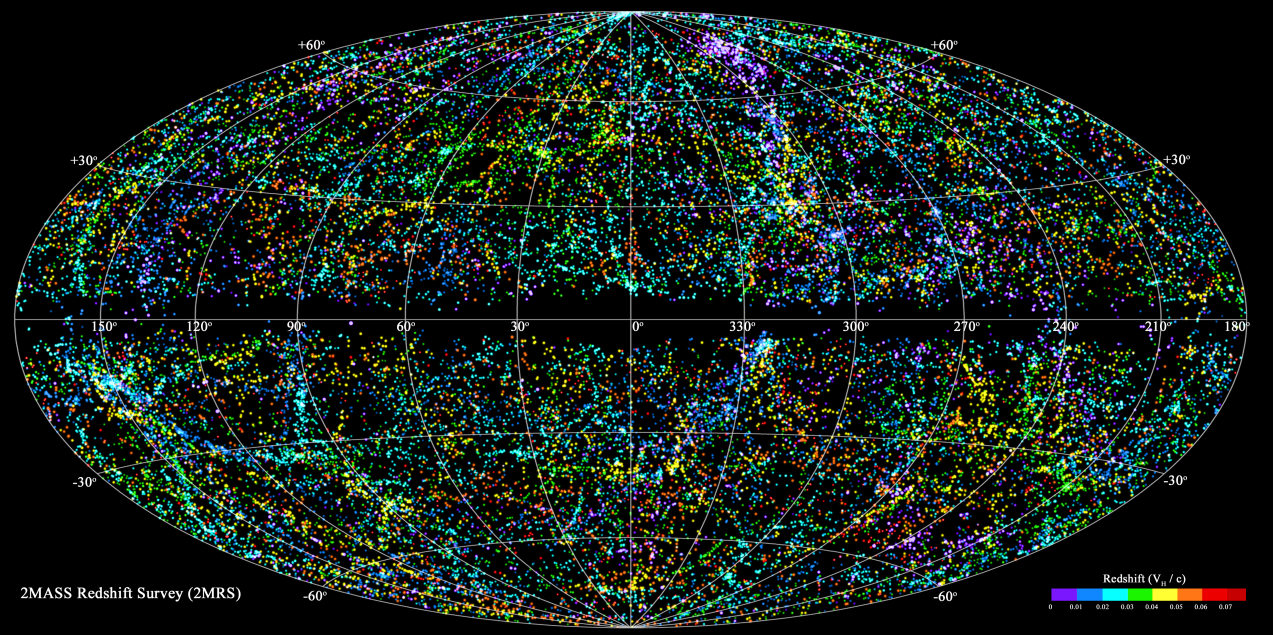
Compatible with AGN + SFG + BLA gamma-rays emission

Points toward a direct evidence of extragalactic origin of the IGRB

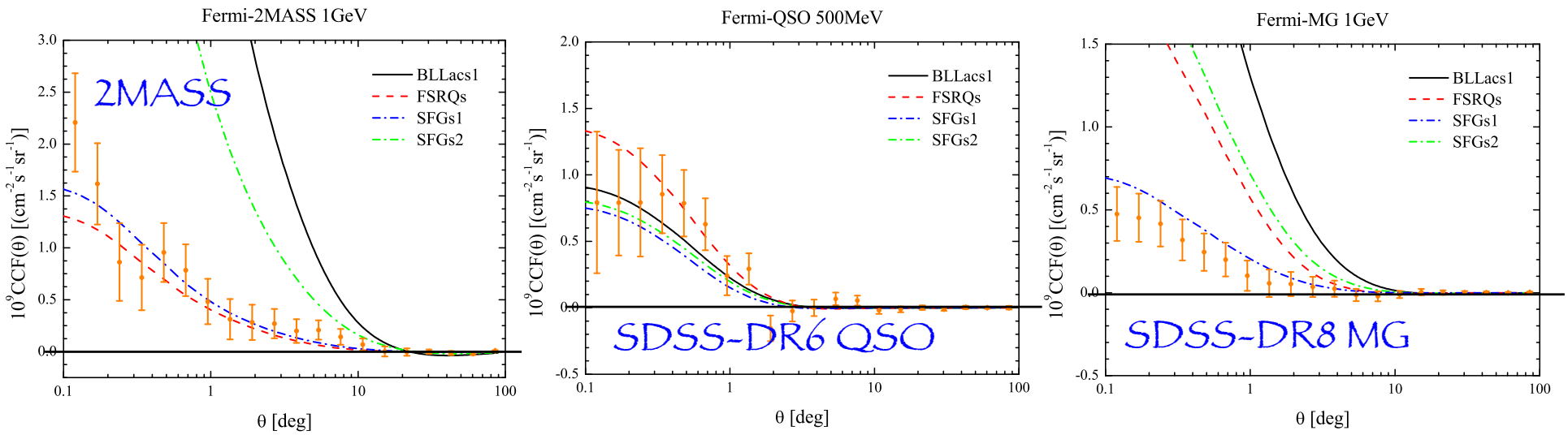
NF, Perotto, Regis, Camera, ApJ 802 (2015) L1

Fermi/gamma + Galaxy catalogs





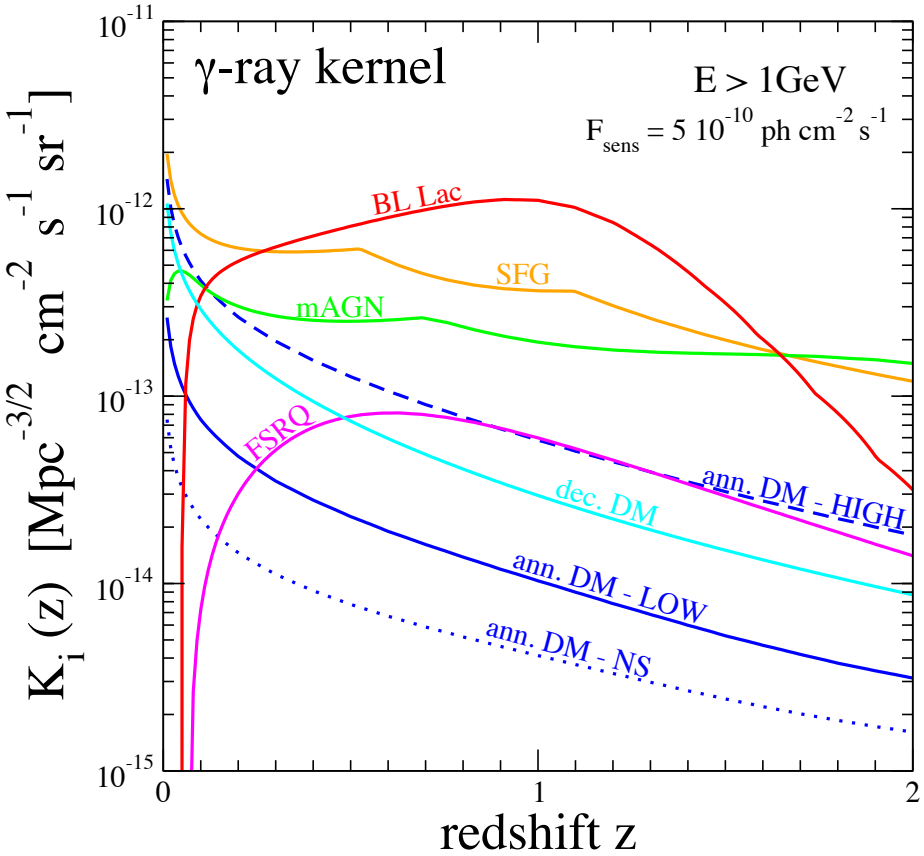
Fermi/gamma + LSS: correlation observed

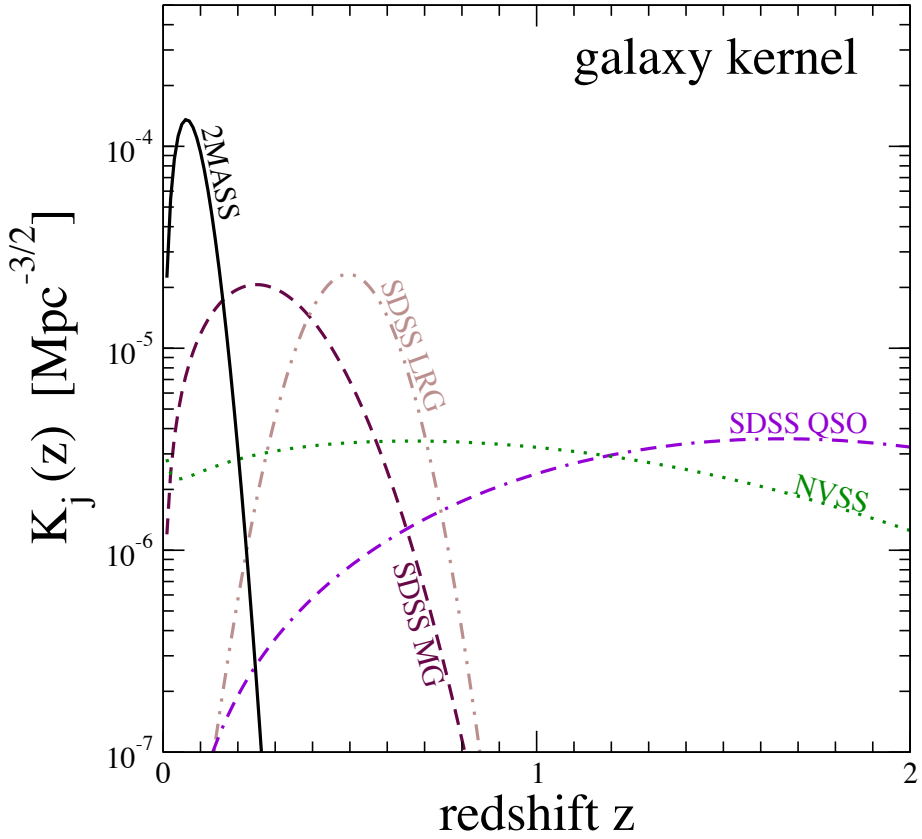


- 2MASS, SDSS-QSO and NVSS: >3.5 σ
- SDSS galaxies: 3.0 σ
- Signal is stronger in two energy bands: E > 0.5 GeV and E > 1 GeV
- Also seen at E > 10 GeV
- Results robust against the choice of statistical estimator, estimate of errors, map cleaning procedure and instrumental effects

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

Fermi + 2MASS: DM interpretation





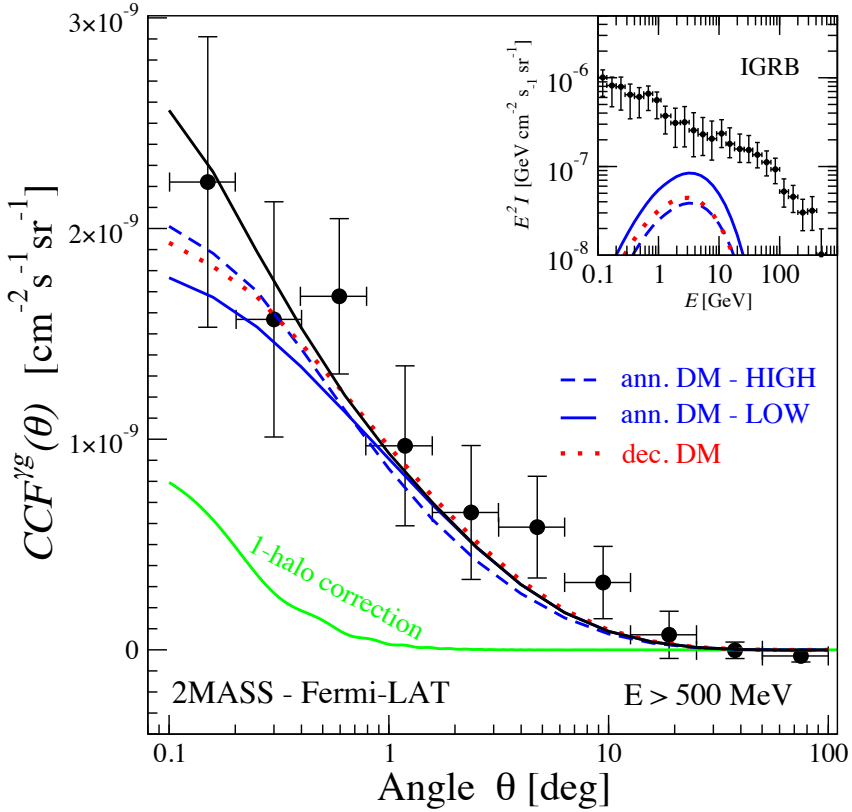
The DM kernel peaks at low redshift, as well as the 2MASS one

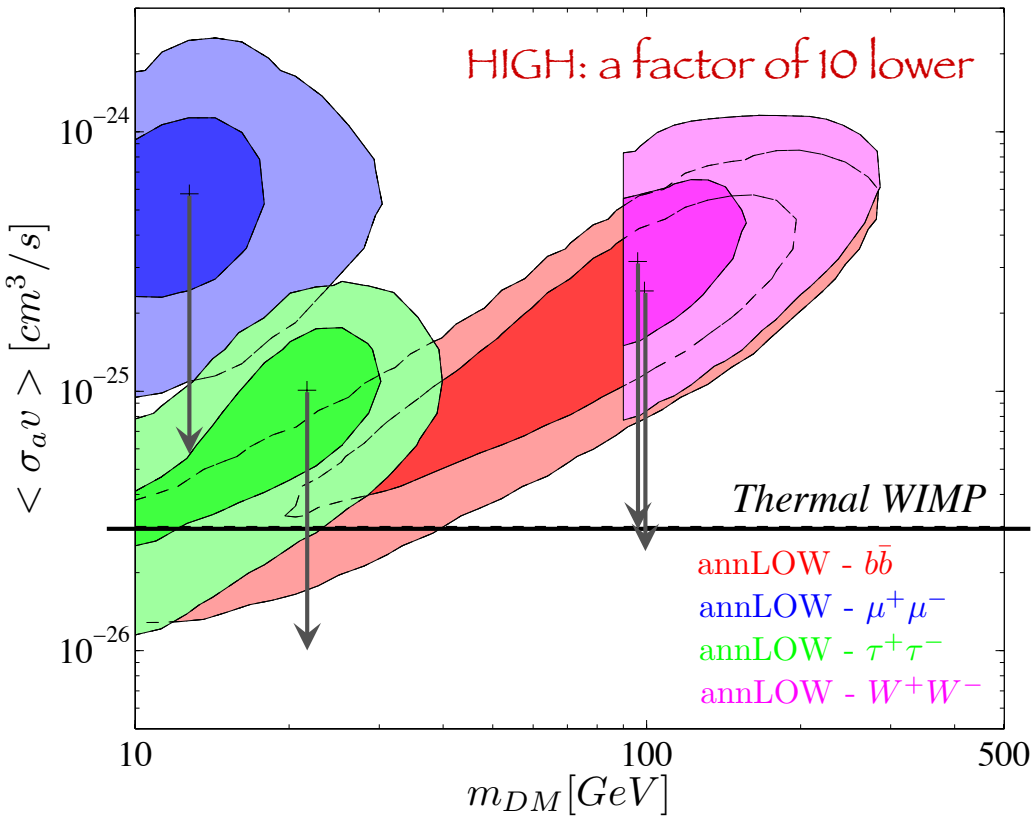
Best option for DM studies: cross-correlate with 2MASS

The different behaviour of kernels can help to discriminate the sources

Regis, Xia, Cuoco, Branchini, NF, Viel, arXiv:1503.05922, to appear in PRL

Fermi + 2MASS: DM analysis





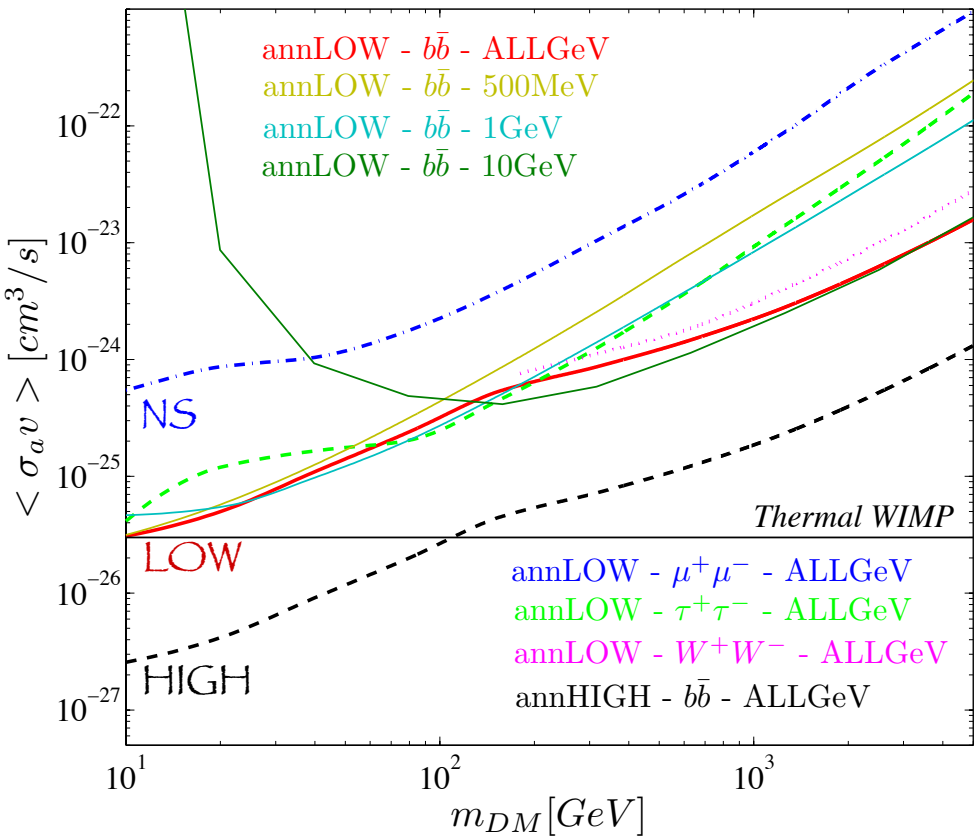
The observed cross-correlation is perfectly reproduced (both in shape and size) by a DM contribution

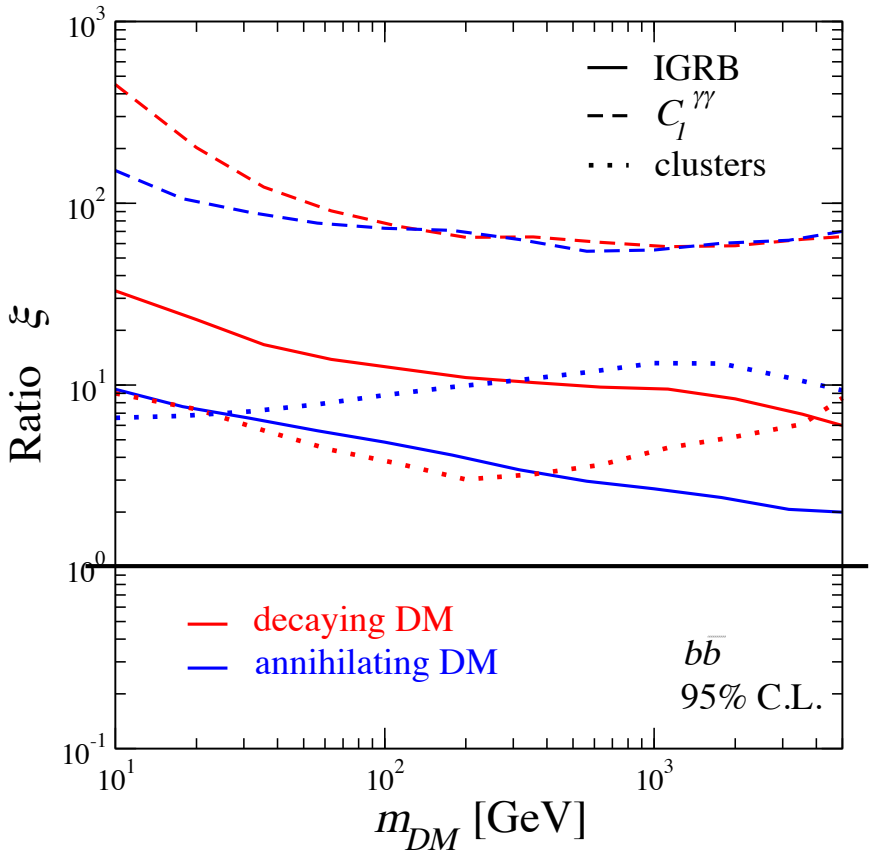
While the DM emission is largely subdominant in the total intensity

Analysis includes spectral information (3 energy bins)

Regis, Xia, Cuoco, Branchini, NF, Viel, arXiv:1503.05922, to appear in PRL

Fermi + 2MASS: DM analysis



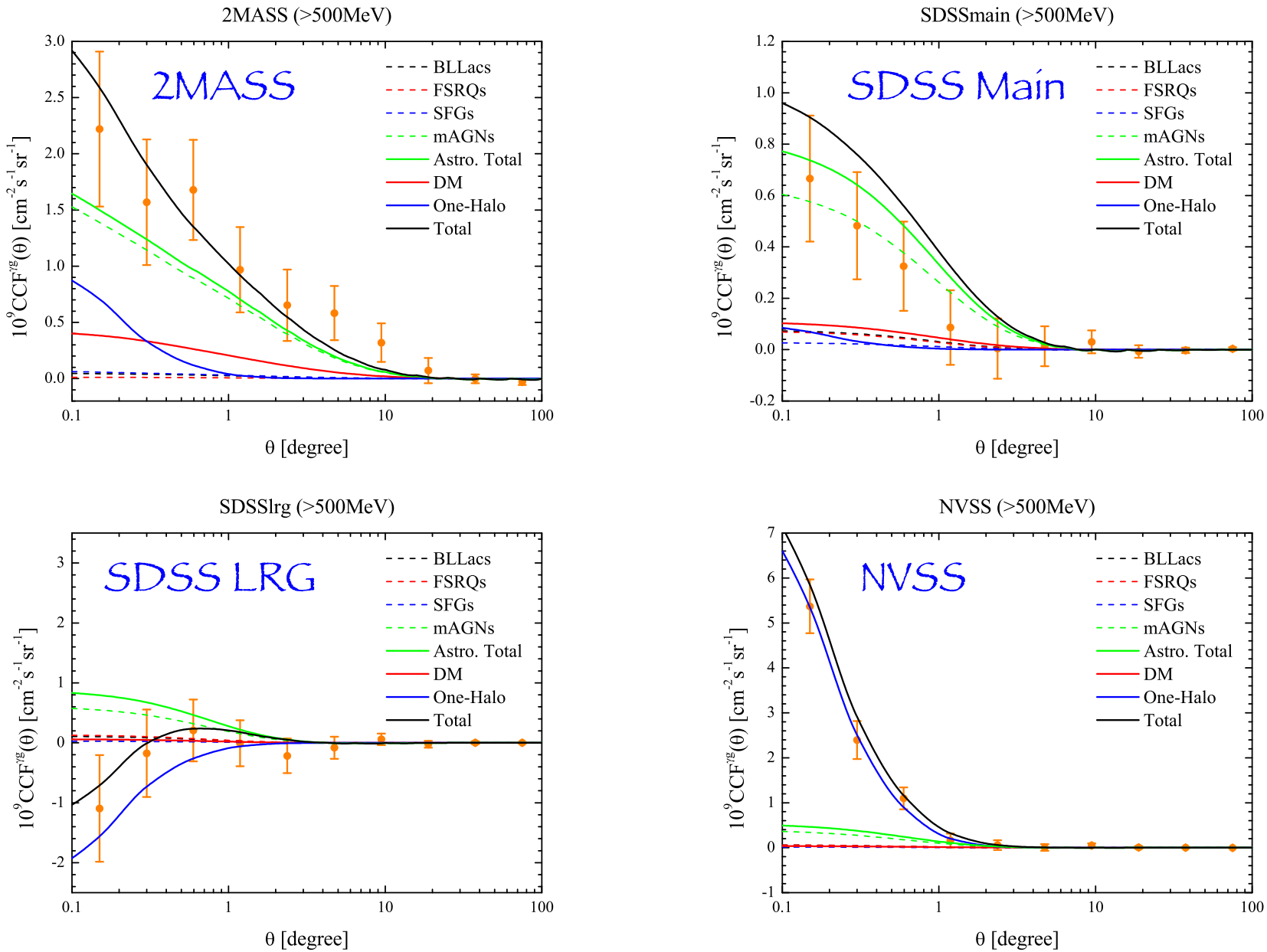


Bound from cross correlation

Bounds ratios
Correlation technique stronger

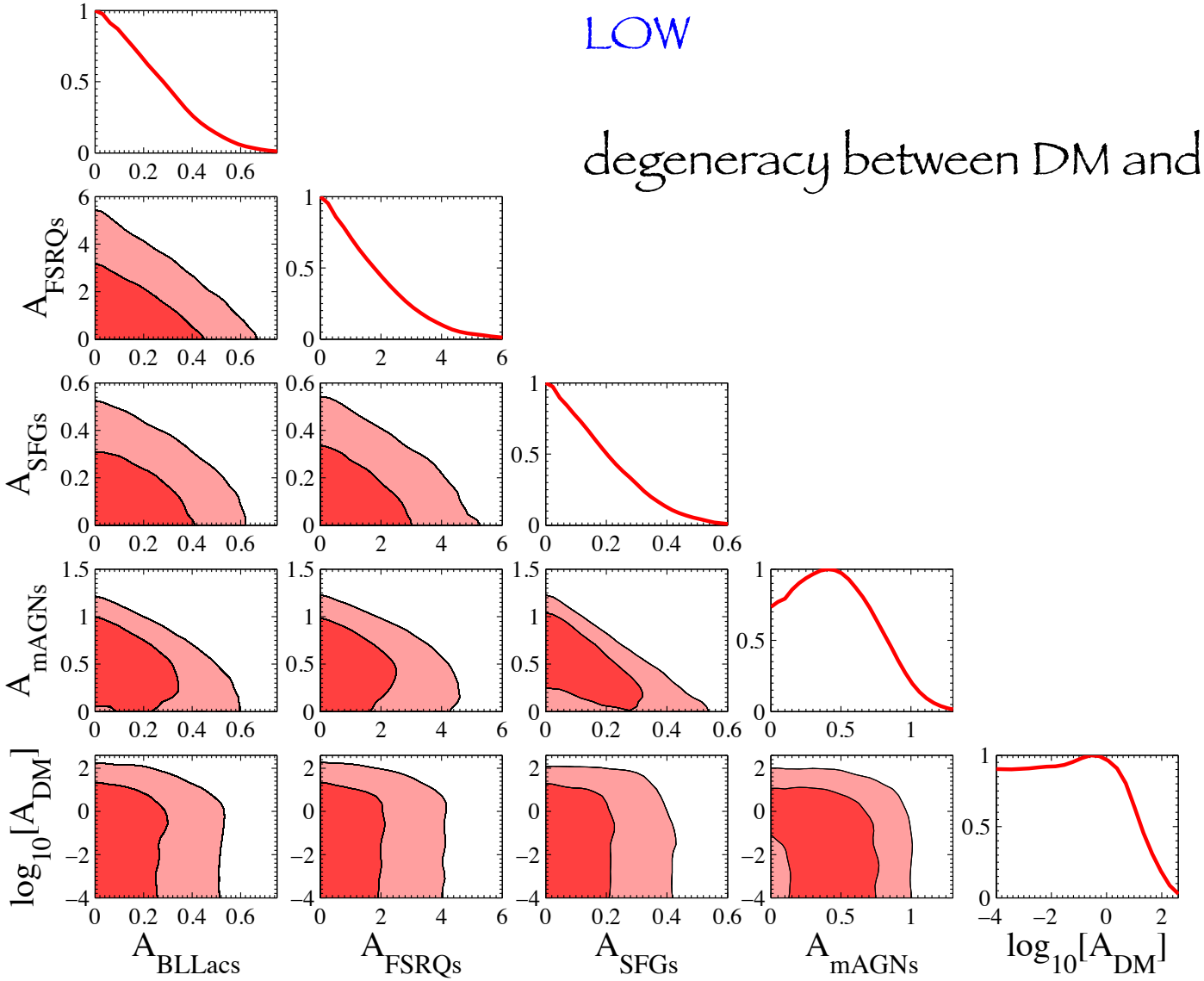
Regis, Xia, Cuoco, Branchini, NF, Viel, arXiv:1503.05922, to appear in PRL

Fermi + all LSS catalogs: DM + astro sources



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

Fermi + LSS catalogs: DM + astro sources

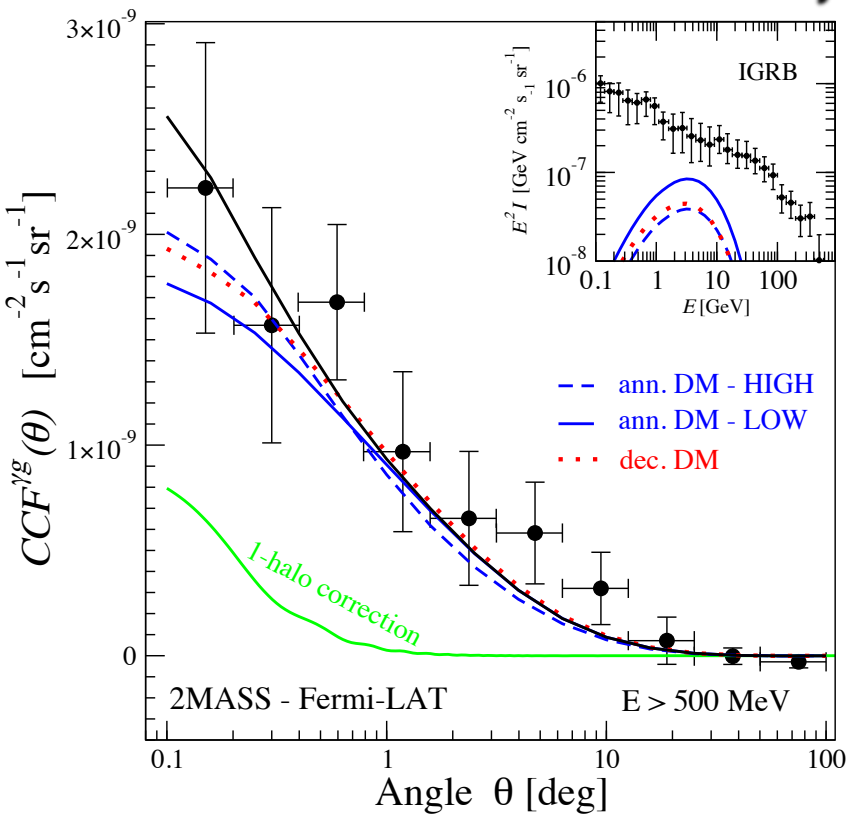


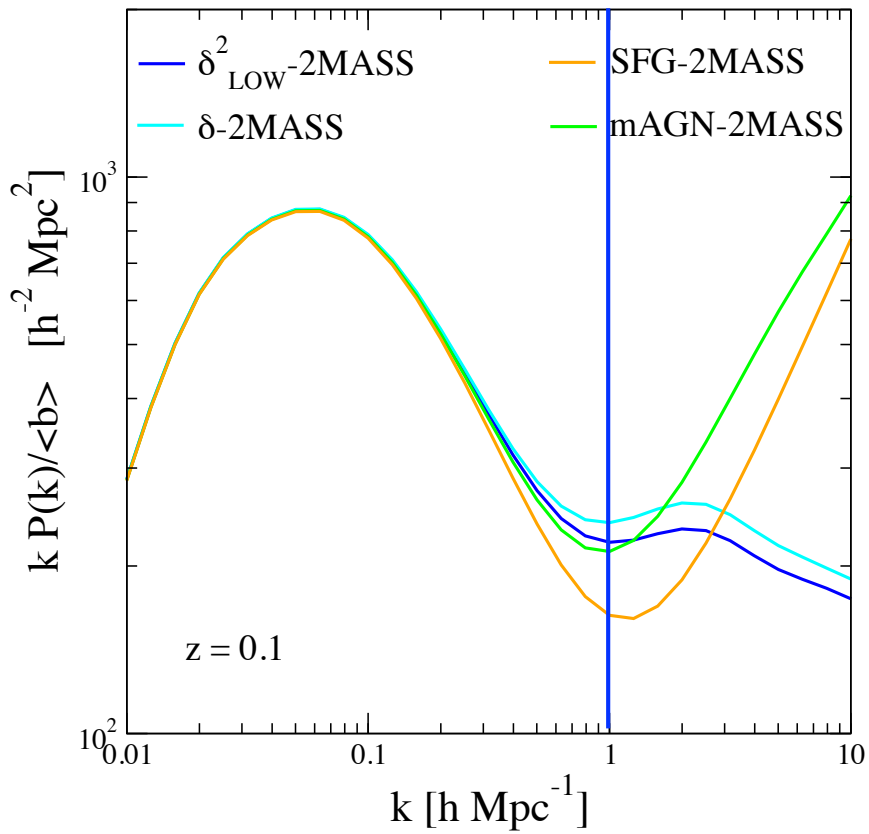
Cuoco, Xia, Regis, Branchini, NF, Viel, to appear

- DM signal:
  - peaks at low redshift
  - mostly contributed by massive halos

- To mimic this, an astrophysical source must be hosted in large halos at low z:
  - mAGN likely hosted in large halos
  - SFG typically populate galaxy-size halos

Measured power and scales





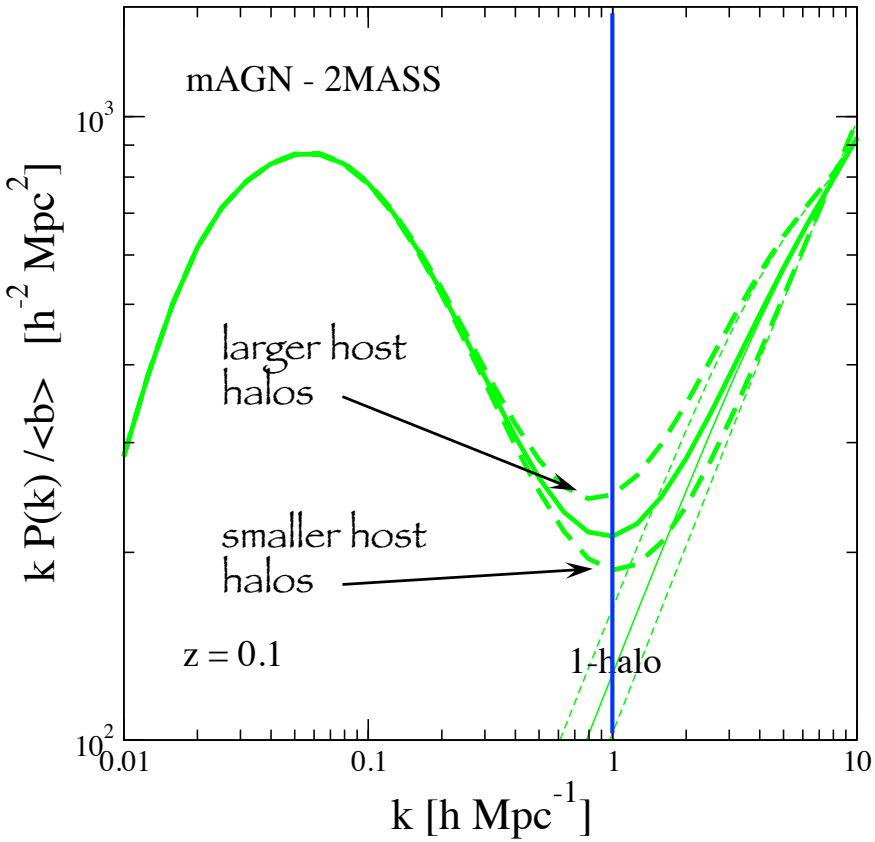
Data show power at the sub-degree scale

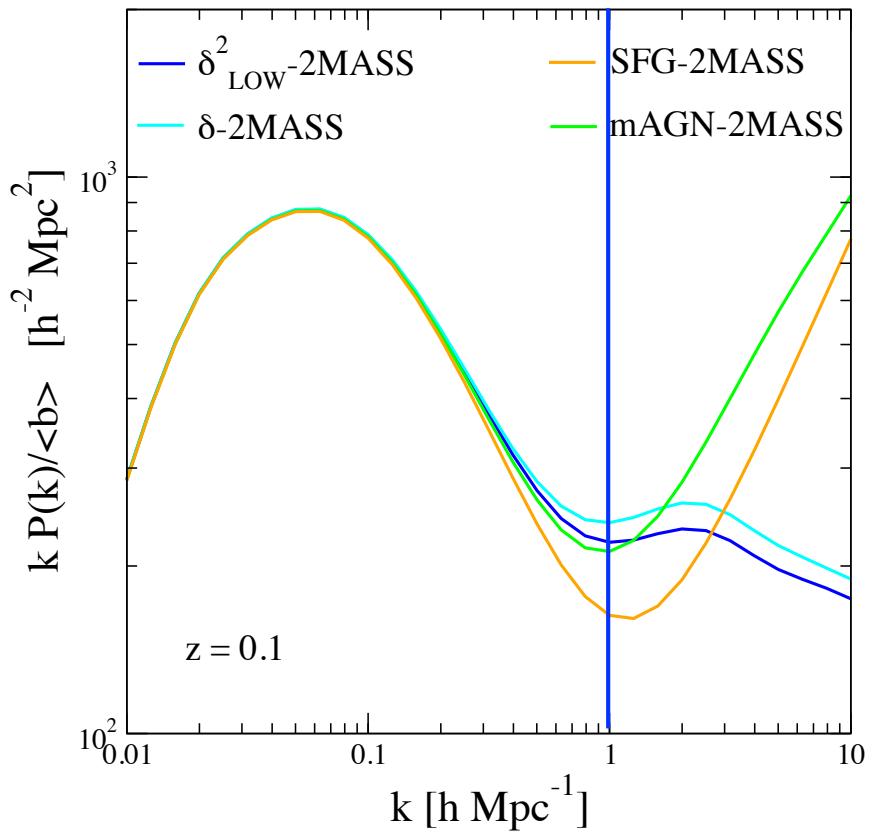
At the 2MASS redshift, sub-deg corresponds to Mpc scales, which are more compatible with DM or mAGN, rahter than SFG

Clear separation requires improved γ rays angular resolution

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

Model uncertainty for mAGN

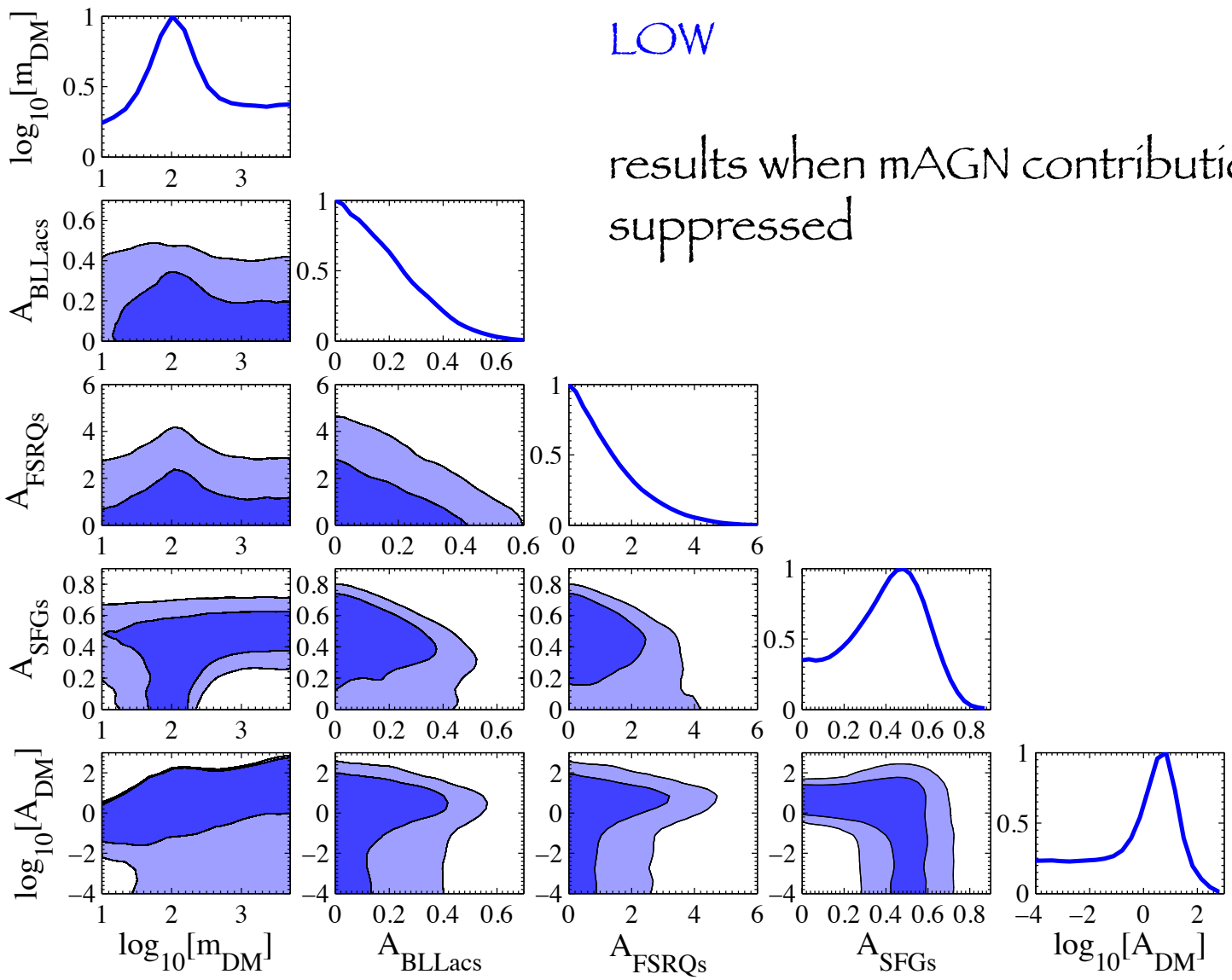




Model uncertainty on mAGN is large (only few detected in γ rays so far)

Key quantity: γ-rays -luminosity vs host-halo-mass relation

Fermi + LSS catalogs: DM + astro sources

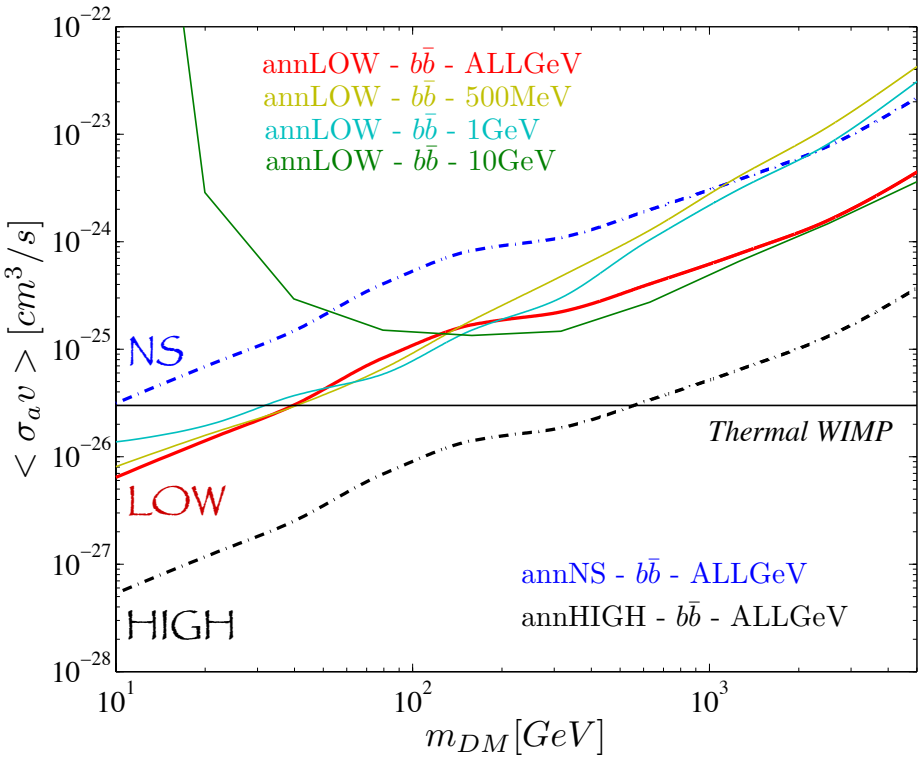


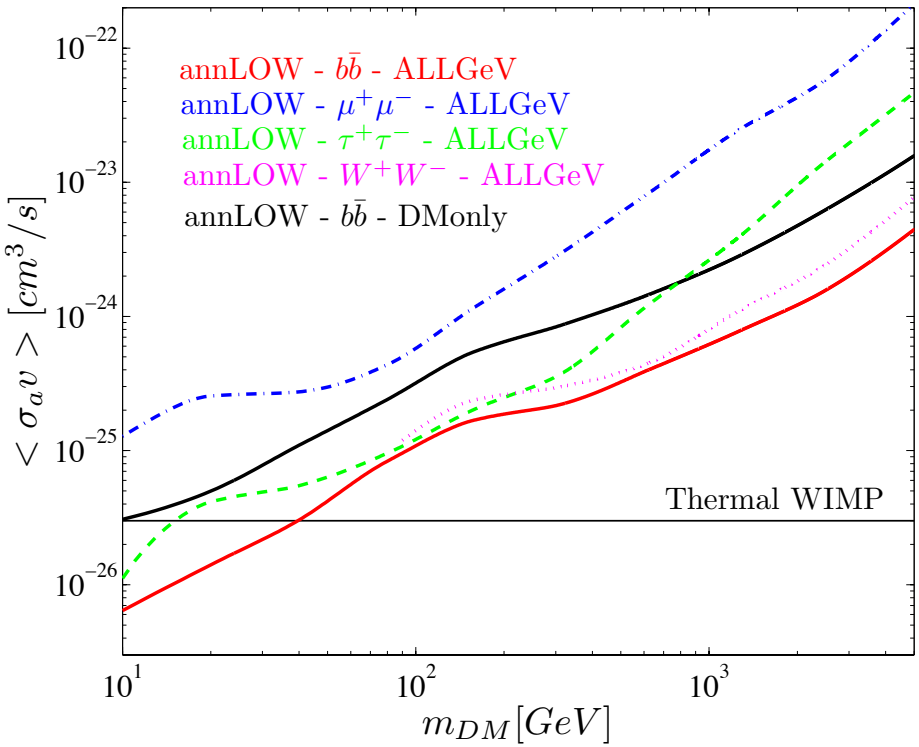
LOW

results when mAGN contribution is suppressed

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

Fermi + all LSS catalogs: DM bounds





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

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 in a few years with DES

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

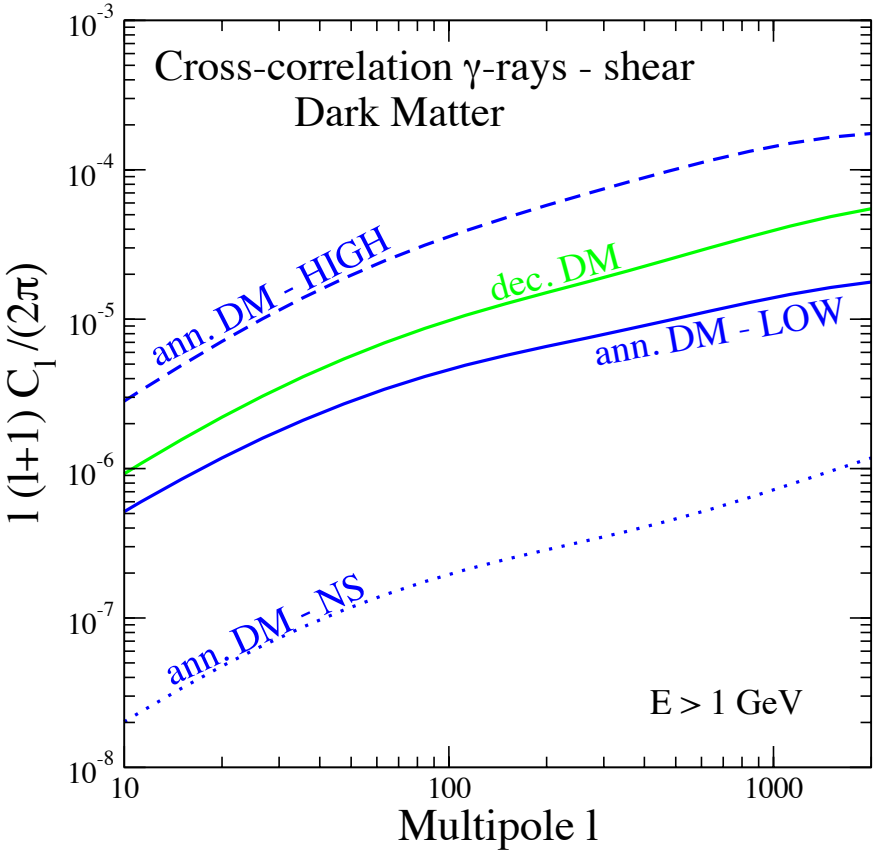
Conclusions

- 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 starts 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

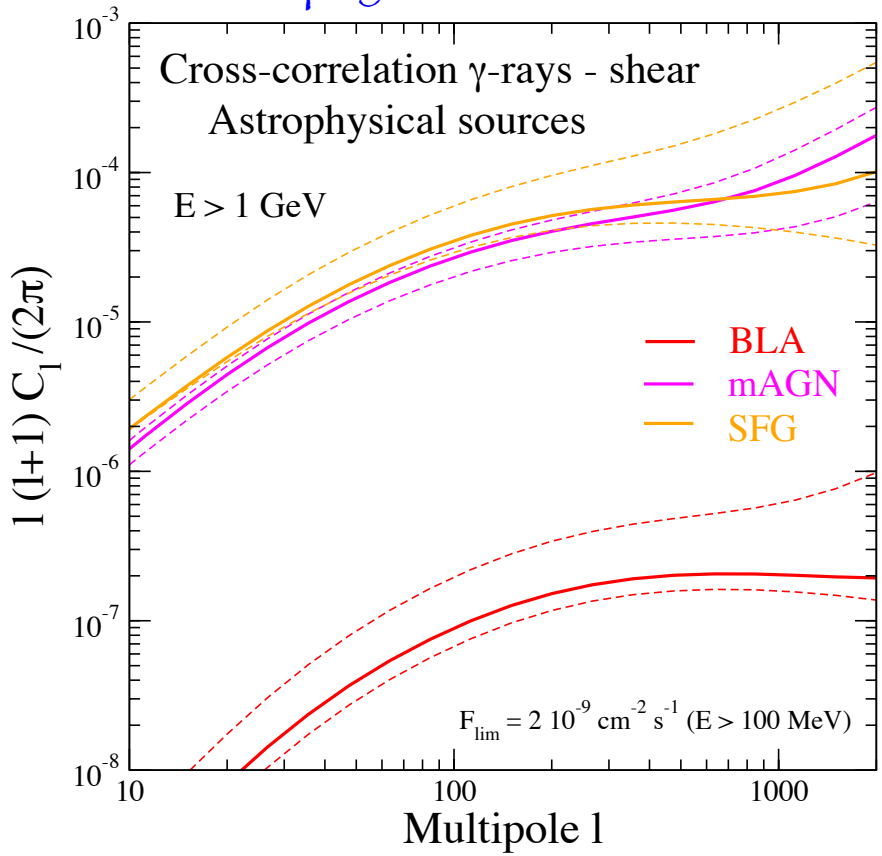
Backup slides

Angular power spectra

Dark Matter APS



Astrophysical sources APS



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

Camera, Fornasa, NF, Regis, arXiv:1411.4651, to appear in JCAP

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

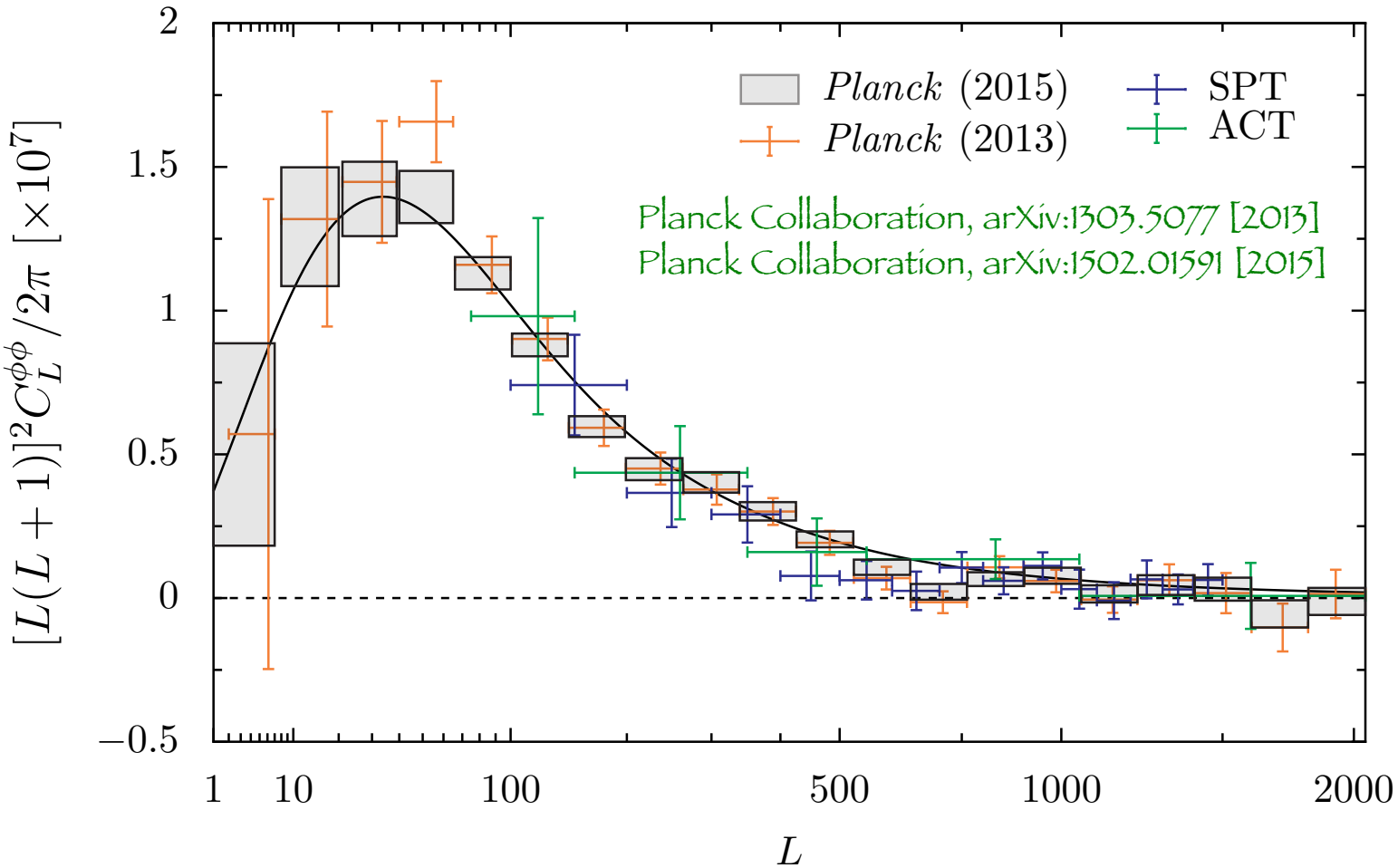
Parameter	Description	Fermi-5yr	Fermi-10yr	"Fermissimo"
$f_{\rm sky}$	Surveyed sky fraction	1	1	1
$E_{\rm min} - E_{\rm max}$ [GeV]	Energy range	$1 - 300$	$1 - 300$	$0.3 - 1000$
N_E	Number of bins	6	6	8
ε [cm^2 s]	Exposure	1.6×10^{12}	3.2×10^{12}	4.2×10^{12}
$\langle \sigma_b \rangle$ [deg]	Average beam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

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

Euclid + Fermi 10 yr

Euclid + "Fermissimo"

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

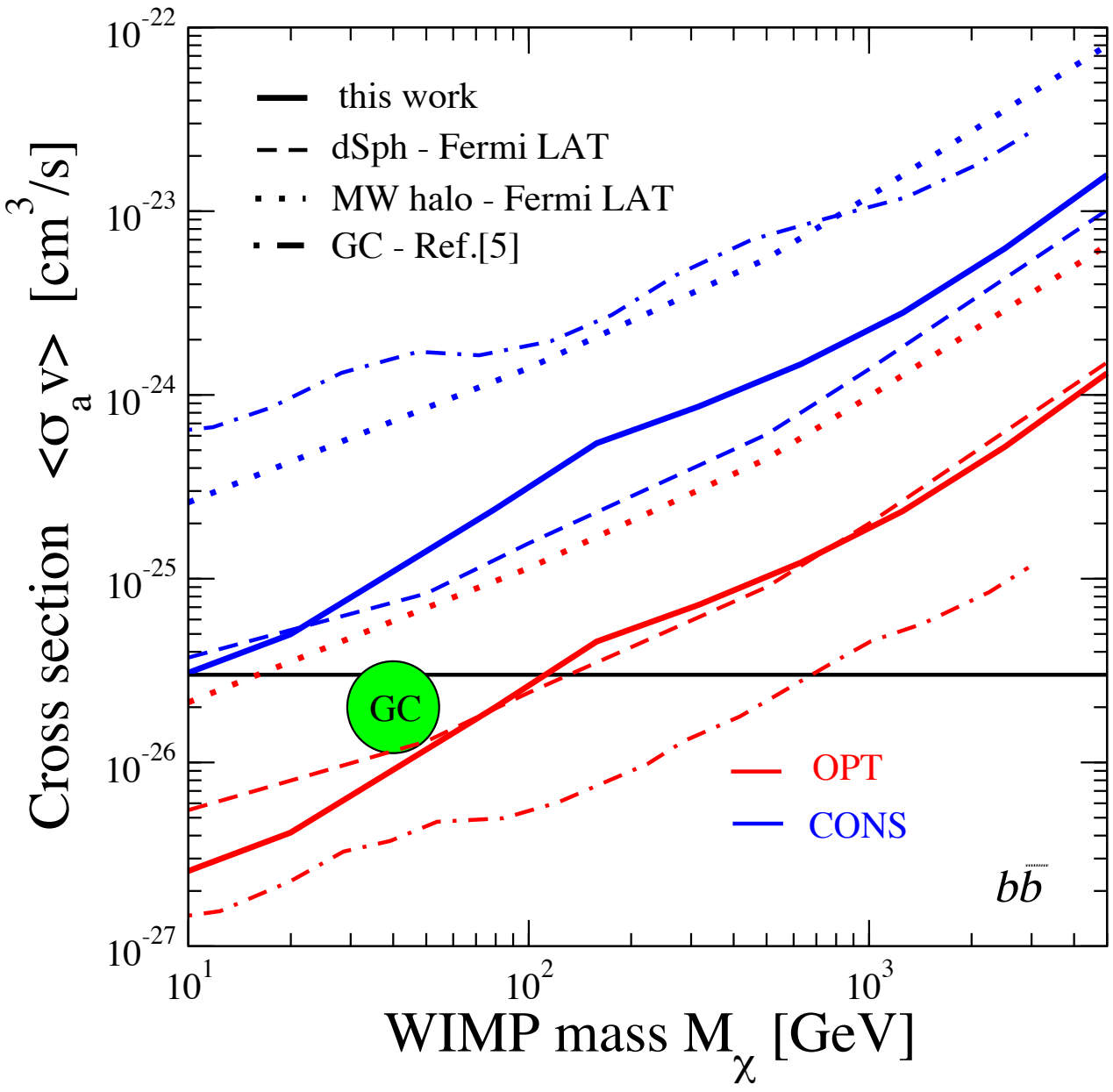
Analysis:

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

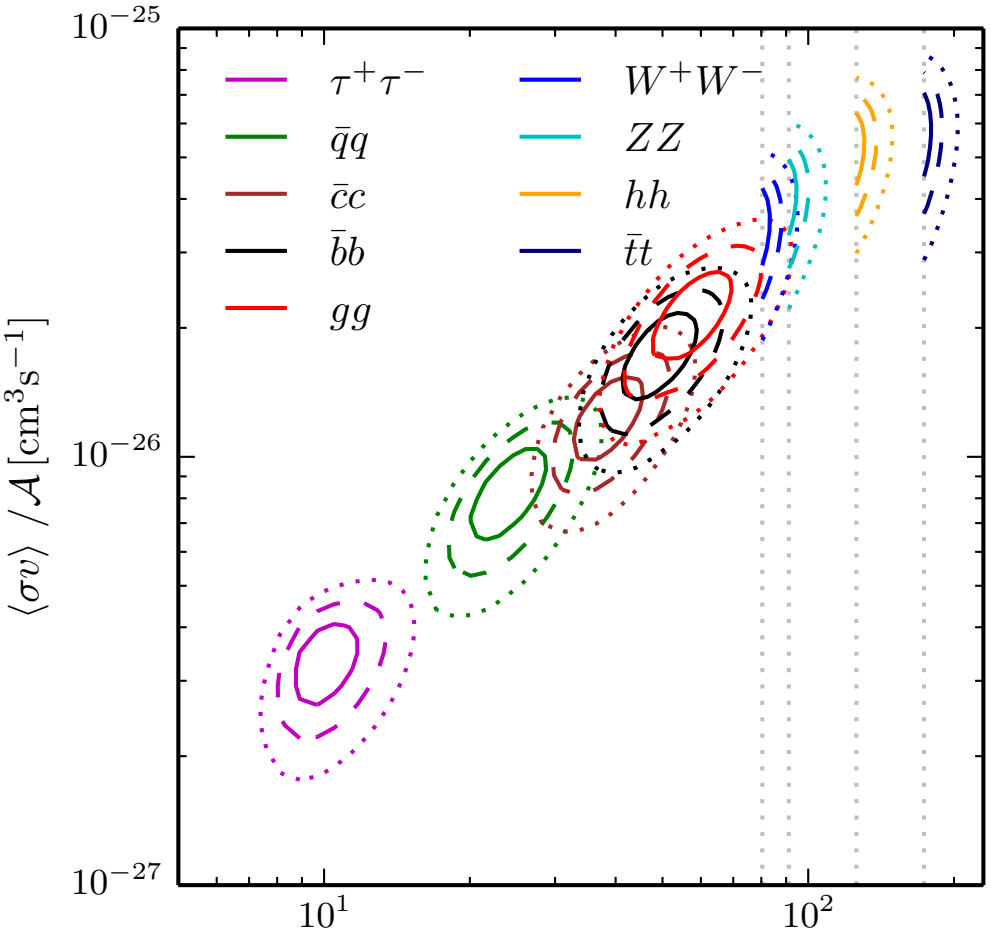
- Galactic emission subtracted
- Masks for CMB lensing:
  - Planck official masks (available sky fraction 70%)
  - 5 deg apodized
- Masks for gamma rays:
  - Planck masks + |b| < 25 deg cut
  - 1 deg cut around 2FGL (3FGL) Fermi source catalogs apodized 3 deg/2 deg
    sky fraction 24% (23%)

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

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

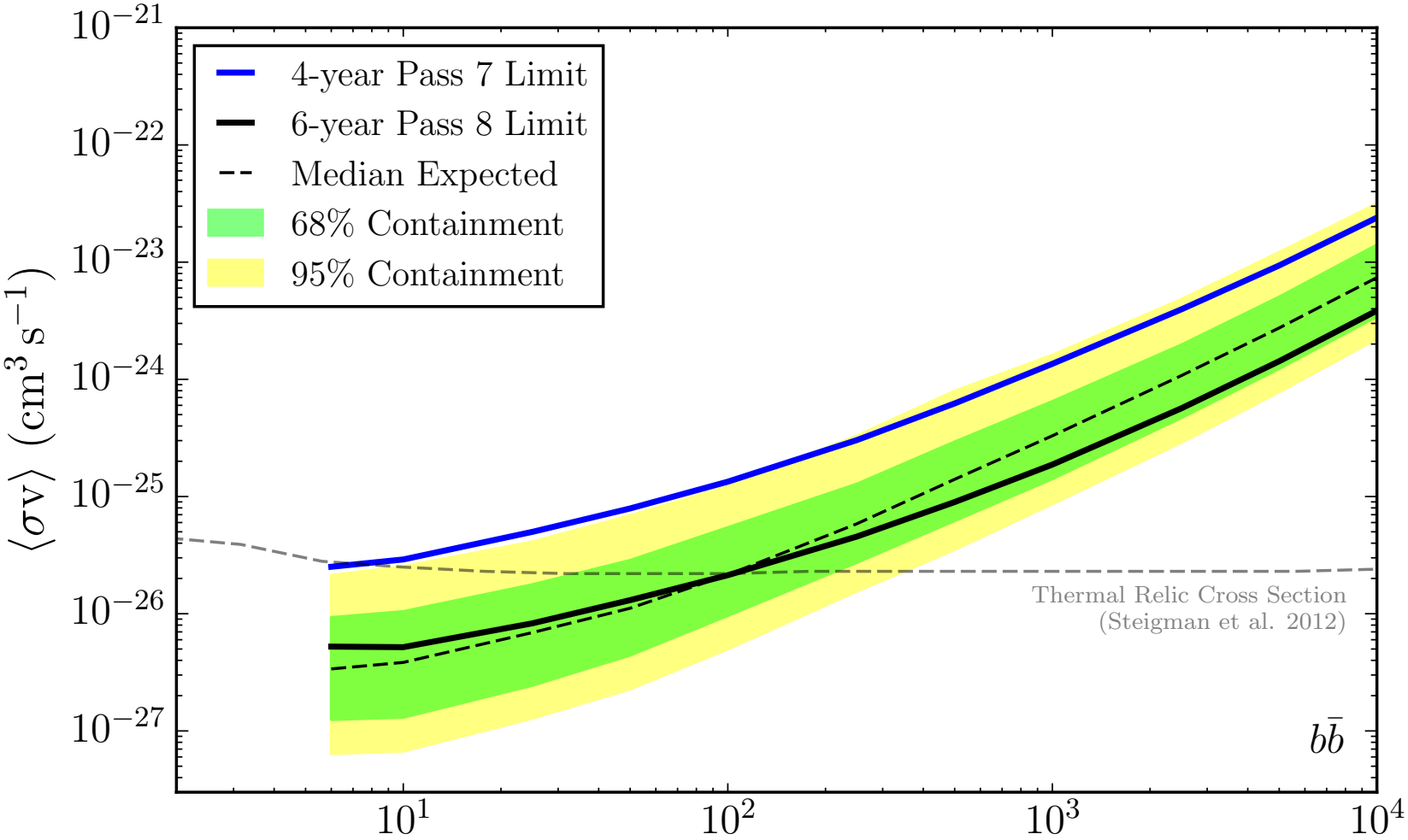

this work
dSph - Fermi LAT
MW halo - Fermi LAT
GC - Ref.[5]
GC
OPT
CONS
$b\bar{b}$
Cross section $<\sigma_a v>$ [cm^3/s]
WIMP mass M_χ [GeV]
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^1
10^2
10^3

Galactic center



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

Dwarf galaxies



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