Particle dark matter searches through cross-correlations

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From the Planck to the Electroweak scale (Planck 2025)

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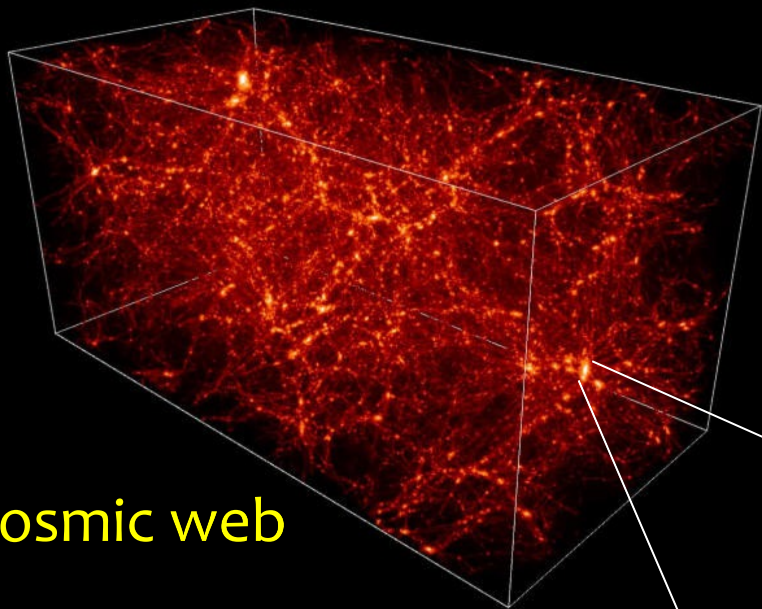
Dark Matter as a particle

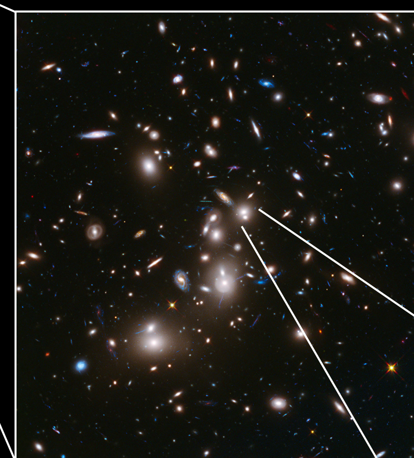
DM evidence purely gravitational

If DM is a new particle, a non-gravitational signal (emission of some kind of radiation) is expected

We can exploit every structure where DM is present as a target, including the total average emission in the Universe (diffuse background)

Unfortunately, DM signals are faint and astrophysical backgrounds dominant





Specific targets

- Galactic center
- Dwarf galaxies
- Individual galaxy clusters
- (Galactic subhalos)

Diffuse

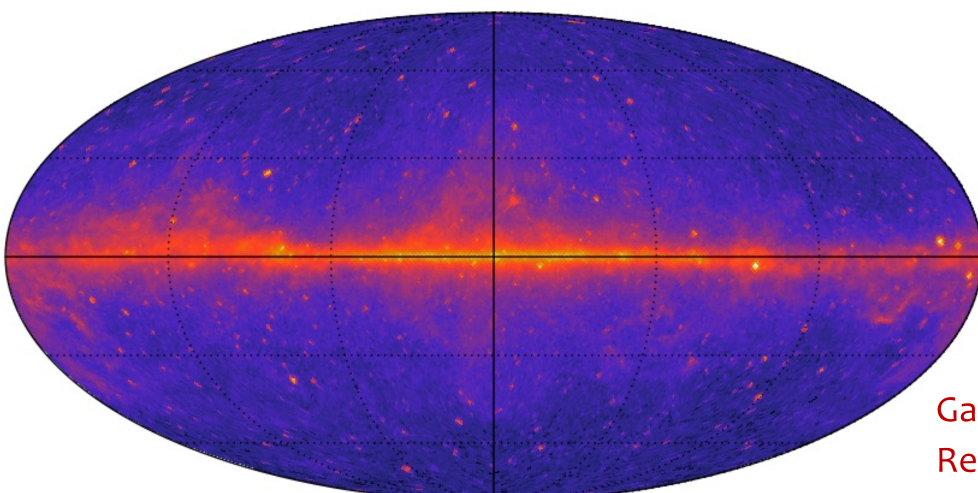
- Galactic halo emission
- Extragalactic emission (“isotropic”)

Can we exploit more information?

- Indirect detection signals are intrinsically anisotropic

  (being produced by DM structures, present at any scale)

- Even though sources are too dim to be individually resolved, they can affect the statistics of photons across the sky, due to fluctuations in the emission field



Fermi/LAT map

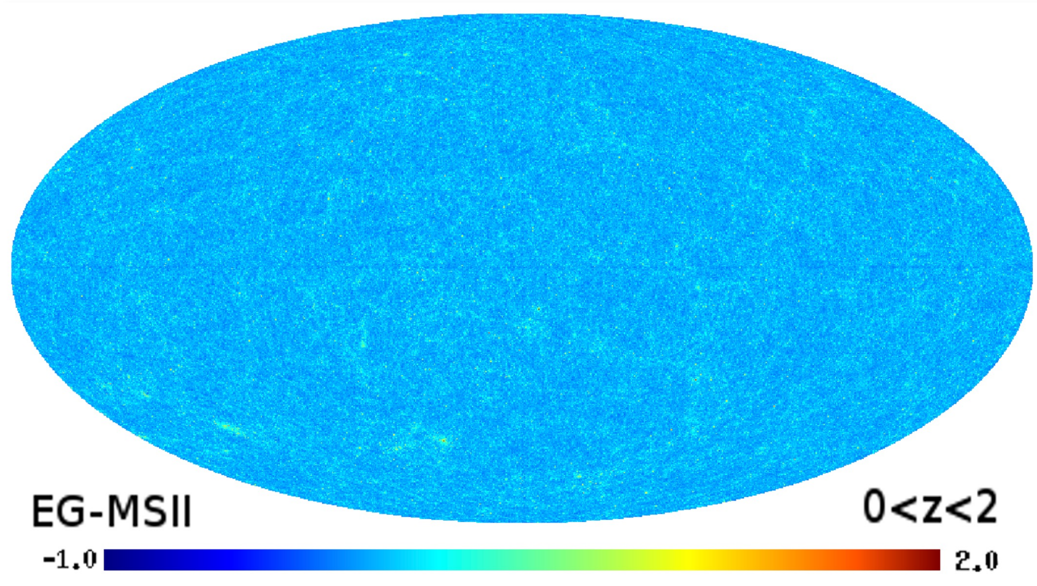
Galactic foreground emission

Resolved sources

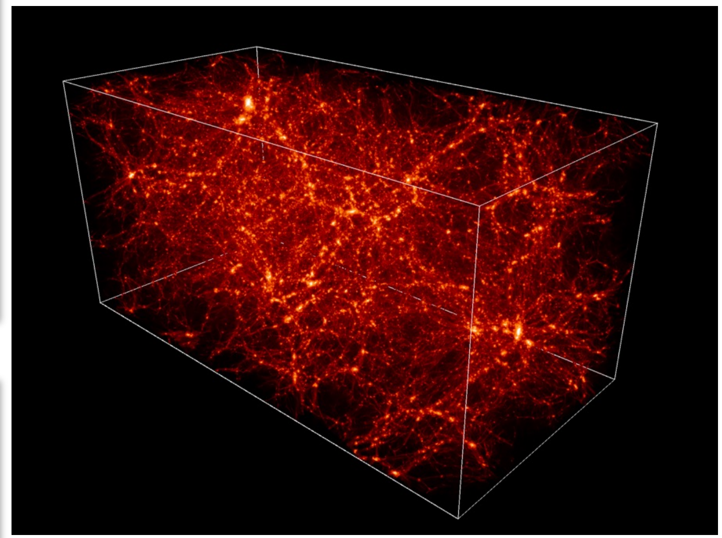
Diffuse Unresolved Gamma-Ray Backgound (∂UGRB)

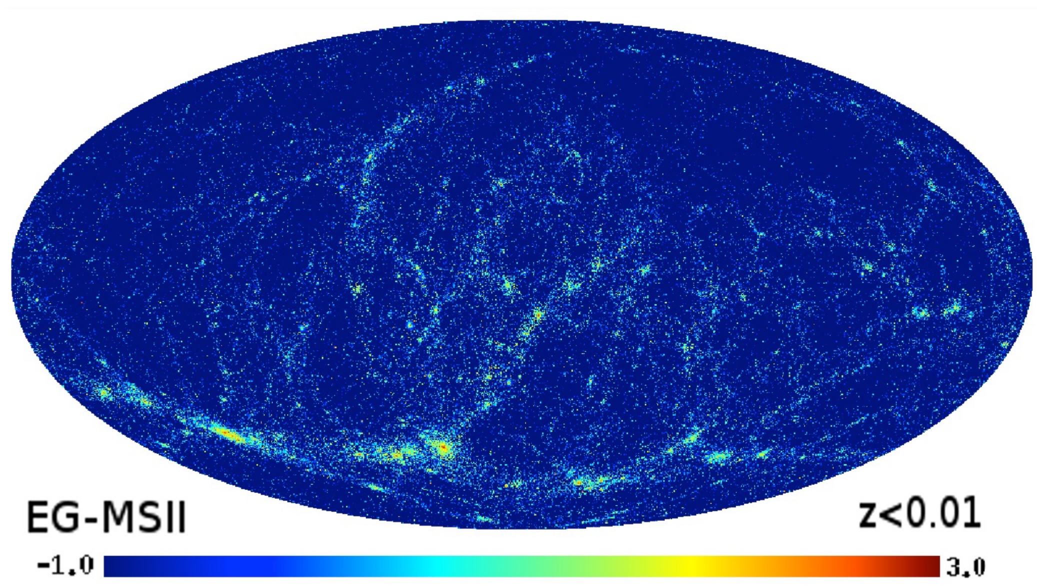
Anisotropic DM gamma-ray emission

(simulated maps)



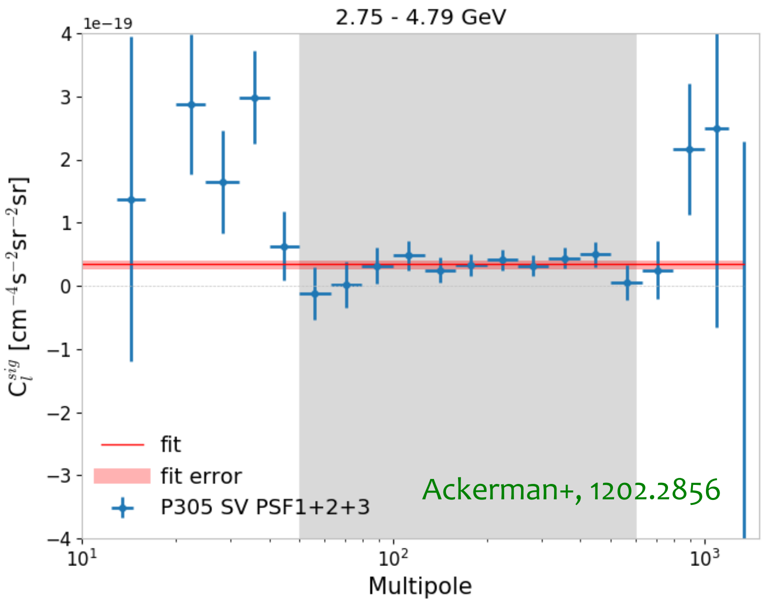
Extra galactic emission
Higher redshift

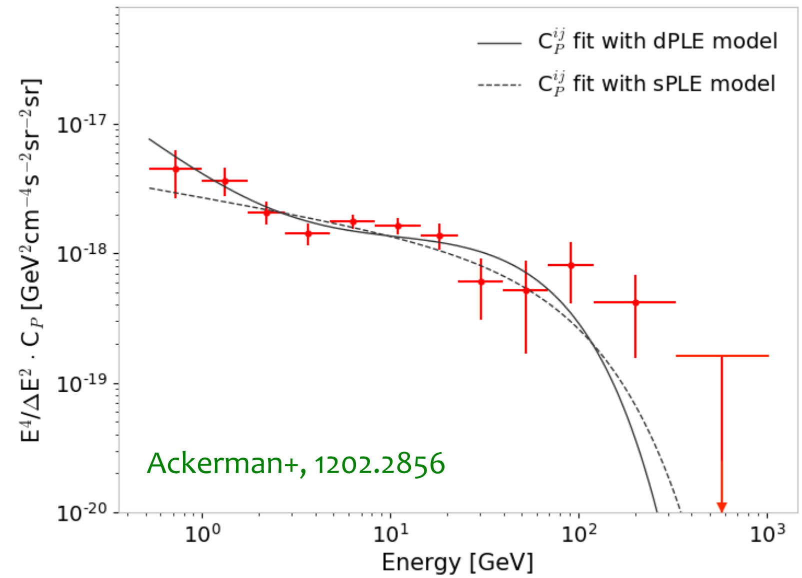




Extra galactic emission
Lower redshift

Observed spectrum of fluctuations



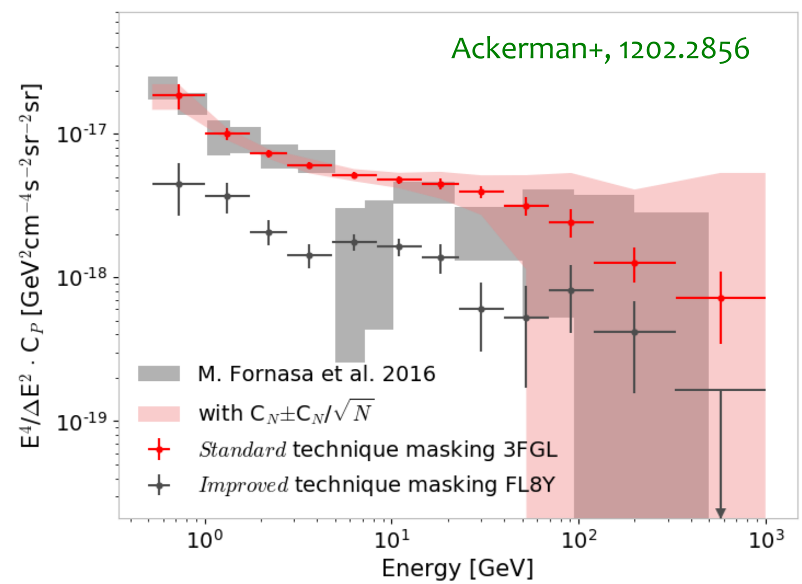


Fermi-LAT data

8 years, Pass8, P8R3 SOURCEVETO V2, PSF1+2+3

FL8Y Catalog

Compatible with astrophysical ‘point’ sources

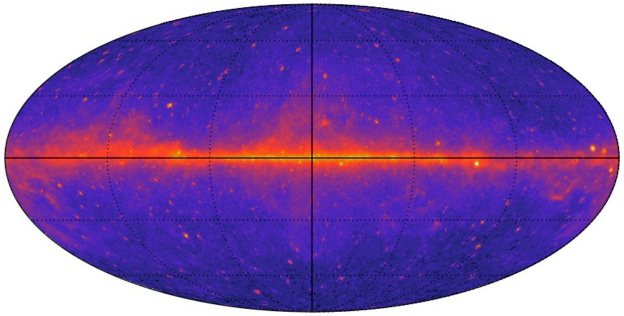


Ackerman+, 1202.2856

Fornasa+, 1608.07289

Ackerman+, 1812.02079

Cross Correlations



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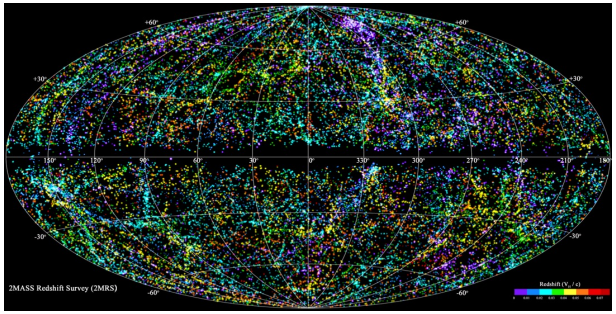


The fluctuations in the gamma-ray field need to be statistically correlated to the DM distribution in the universe (i.e. the DM fluctuations on top of a smooth Universe)

This cross-correlation is a statistical observable (it allows to infer global information, not identify individual sources) and exploits in a unified way 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 allows to 'add' distance (redshift) information to a probe (like gamma-rays) that does not have it

Correlation function

Density field of the source

$$I_i(\vec{n}) = \int \mathrm{d}\chi \, g_i(\chi, \vec{n}) \, \tilde{W}(\chi)$$

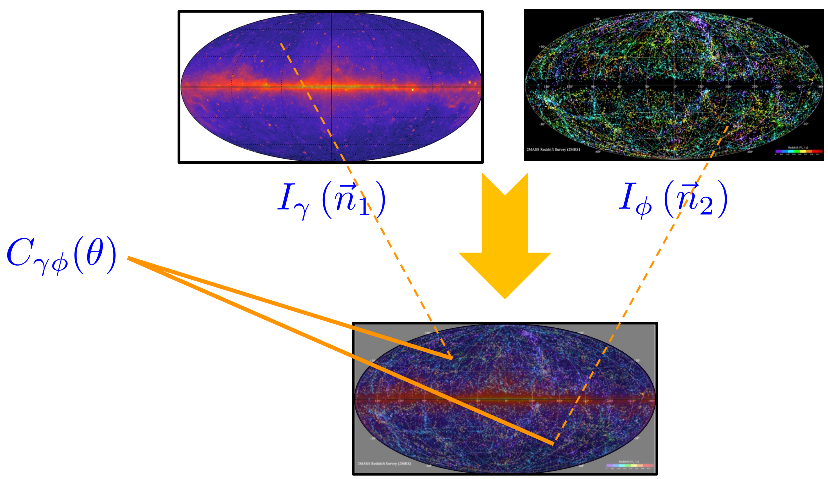
Window function

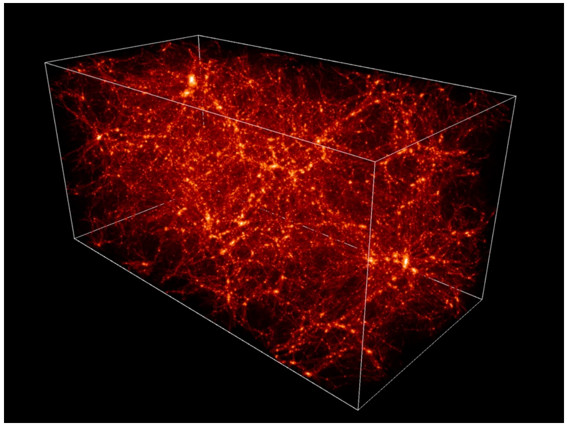
i = galaxies, shear
j = gamma-rays from DM decay or annihilation

Angular power spectrum

$$\langle I_i(\vec{n}_1) I_j(\vec{n}_2) \rangle \longrightarrow C_{ij}(\theta_{12}) \longrightarrow C_\ell^{ij} = \int \frac{\mathrm{d}\chi}{\chi^2} W_i(\chi) W_j(\chi) P_{ij}\left(k = \frac{\ell}{\chi}, \chi\right)$$

Power spectrum of the fluctuations





Power spectra

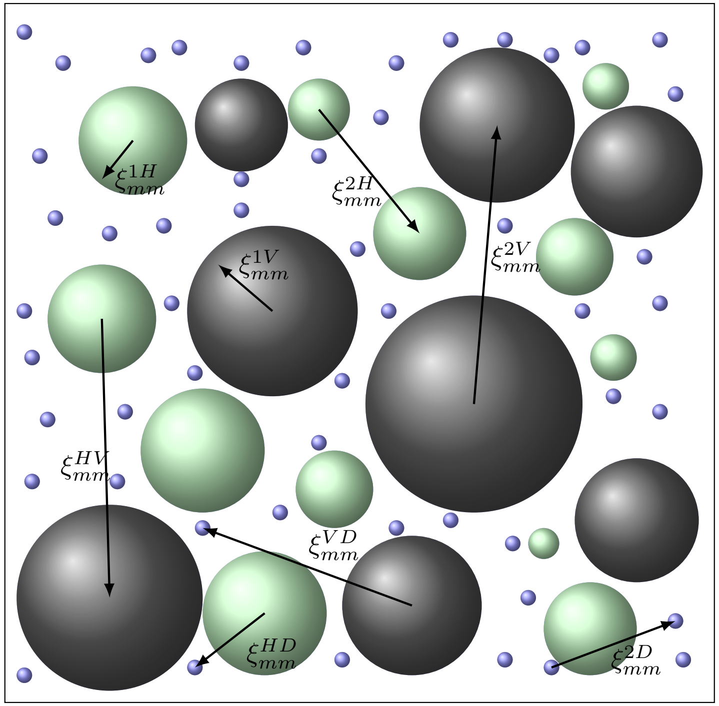
$$\rho(\mathbf{x}) = \sum_i^{\text{halos}} \rho_h\left(\mathbf{x} - \mathbf{x}_i \mid M_i\right)$$

$$\xi(\mathbf{r}) = \frac{1}{\bar{\rho}_m^2}\langle\rho(\mathbf{x})\rho(\mathbf{x}+\mathbf{r})\rangle - 1$$

Fourier Transform

1halo 2halo

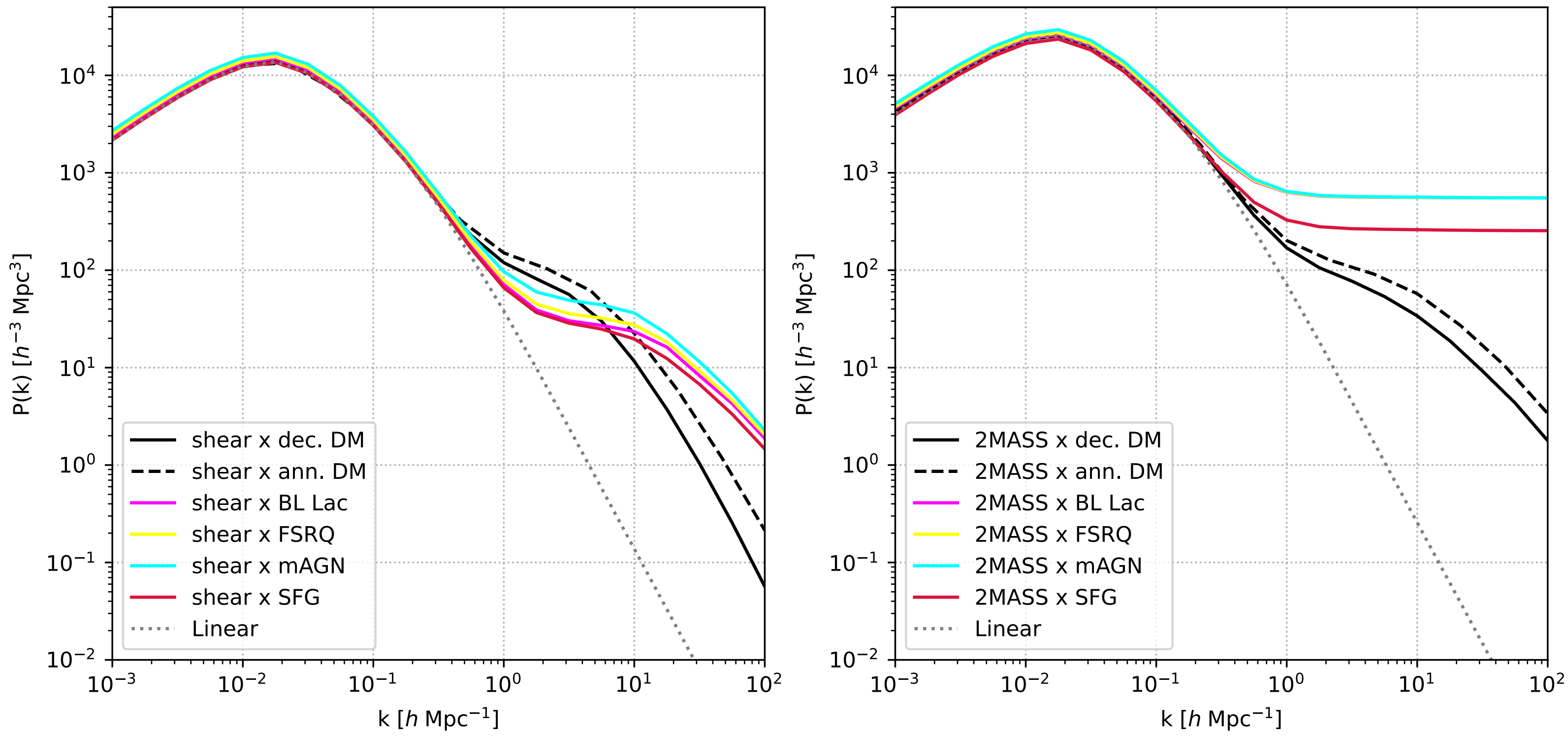
$$P(k) = P^{1H}(k) + P^{2H}(k)$$



$$P_{ij}^{1H}(k) = \int \mathrm{d}M \frac{\mathrm{d}n_h}{\mathrm{d}M} f_i^{h*}(k \mid M) f_j^h(k \mid M)$$

$$P_{ij}^{2H}(k) = \int \mathrm{d}M_1 \frac{\mathrm{d}n_h}{\mathrm{d}M_1} f_i^{h*}\left(k \mid M_1\right) b_h\left(M_1\right) \int \mathrm{d}M_2 \frac{\mathrm{d}n_h}{\mathrm{d}M_2} f_j^h\left(k \mid M_2\right) b_h\left(M_2\right) P^L(k)$$

Power spectra



Arcari, NF, Pinetti, JCAP 11 (2022) 011

Window Functions

Decaying DM

$$W_d(E,z) = \frac{1}{4\pi}\frac{\Omega_{\rm DM}\rho_c}{m_{\rm DM}\tau_d}\frac{{\rm d}N_d}{{\rm d}E}[E(1+z)]{\rm e}^{-\tau[E(1+z),z]}$$

Annihilating DM

$$W_a^x(E,z) = \frac{(\Omega_{\rm DM}\rho_c)^2}{4\pi}\frac{\langle\sigma_a v\rangle}{2m_{\rm DM}^2}\left(1+z^3\right)\Delta_x^2(z)\frac{{\rm d}N_a}{{\rm d}E}[E(1+z)]{\rm e}^{-\tau[E(1+z),z]}$$

Astrophysical sources

$$W_s^x(E,z) = \left(\frac{d_L(z)}{1+z}\right)^2\int_{L_{\rm min}}^{L_{\rm max}(z)}{\rm d}L\,\frac{{\rm d}F}{{\rm d}E}(E,L,z)\phi_x(L,z)$$

Lensing

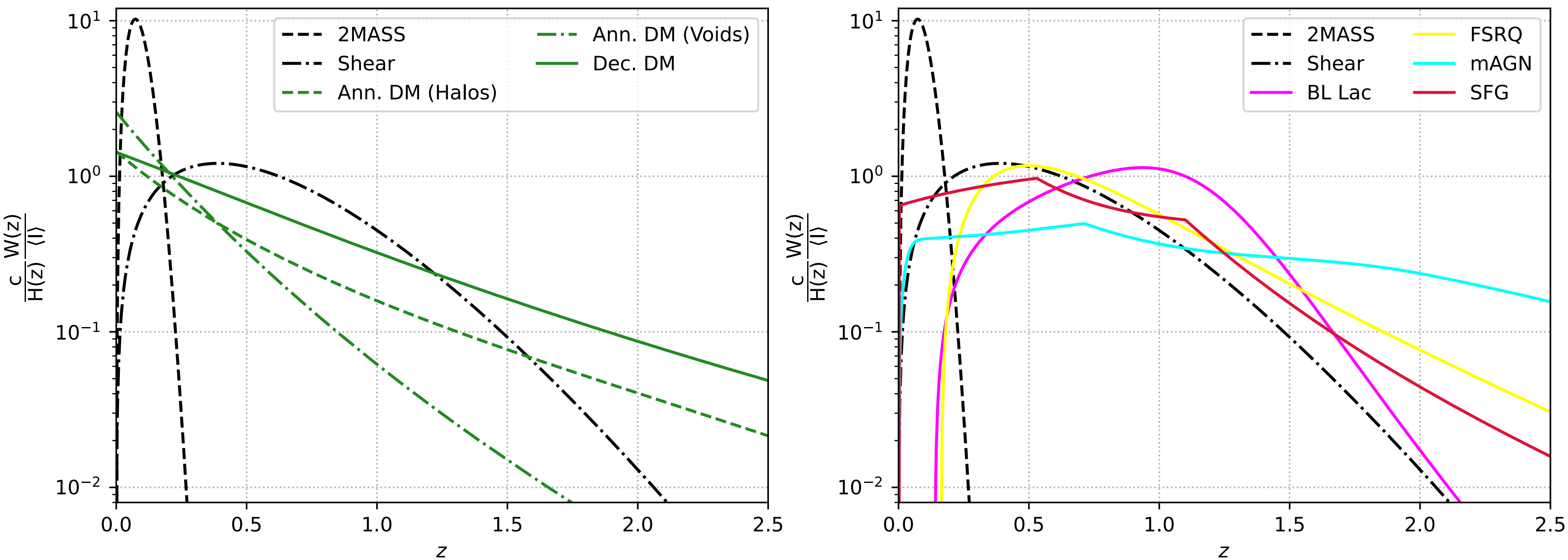
$$W_l(\chi) = \frac{3}{2}\frac{H_0^2}{c^2}\Omega_m(1+z)\chi\int_\chi^\infty {\rm d}\chi'\,\frac{\chi'-\chi}{\chi'}\frac{{\rm d}N}{{\rm d}\chi'}(\chi')$$

Galaxies

$$W_g(\chi) = \frac{{\rm d}N_g}{{\rm d}z}\frac{{\rm d}z}{{\rm d}\chi} = \frac{{\rm d}N_g}{{\rm d}z}\frac{H(z)}{c}$$

Window functions

(for E_γ = 5 GeV)



Arcari, NF, Pinetti, JCAP 11 (2022) 011

$$C_\ell^{ij} = \int \frac{\mathrm{d}\chi}{\chi^2} W_i(\chi) W_j(\chi) P_{ij}\left(k = \frac{\ell}{\chi}, \chi\right)$$

Cross-Correlations w/ Gamma Rays

Lensing observables

- Cosmic shear: directly traces the whole DM distribution

  Camera, Fornasa, NF, Regis, ApJLett 771 (2013) L5
  Camera, Fornasa, NF, Regis, JCAP 06 (2015) 029

- CMB lensing: traces DM imprints on CMB anisotropies

  NF, Regis, Frontiers in Physics, 2 (2014) 6
  NF, Perotto, Regis, Camera, Ap. J. Lett. 802 (2015) 1 L1

Large scale structure observables:

- Galaxy catalogs: trace DM by tracing light

  Cuoco, Brandbyge, Hannestad, Haugbolle, Miele, PRD 77 (2008) 123518
  Ando, Benoit-Levy, Komatsu, PRD 90 (2014) 023514
  NF, Regis, Front. Physics 2 (2014) 6
  Ando, JCAP 1410 (2014) 061

- Cluster catalogs

  Branchini, Camera, Cuoco, NF, Regis, Viel, Xia, ApJS 228 (2017) 1

- Neutral hydrogen (through HI intensity mapping)

  Pinetti, Camera, NF, Regis, JCAP 07 (2020) 044

- Cosmic voids

  Arcari, NF, Pinetti, JCAP 11 (2022) 011

Measured cros-correlation signals

- w/ galaxy catalogs (3.5 σ (*) /8σ (^))

(*) Cuoco+, ApJS 221 (2015) 29
(*) Regis+, Phys. Rev. Lett. 114, 241301 (2015)
Shirasaki+, Phys. Rev. D 92, 123540 (2015)
Cuoco+, ApJS 232, 1 (2017)
Ammazzalorso+, Phys. Rev. D 98, 103007 (2018)
(^) Paopiamsap+, Phys. Rev. D 109 (2024) 10, 103517

- w/ CMB-lensing (3.0 σ (*))

(*) Fornengo+, Ap. J. Lett. 802 (2015) 1 L1

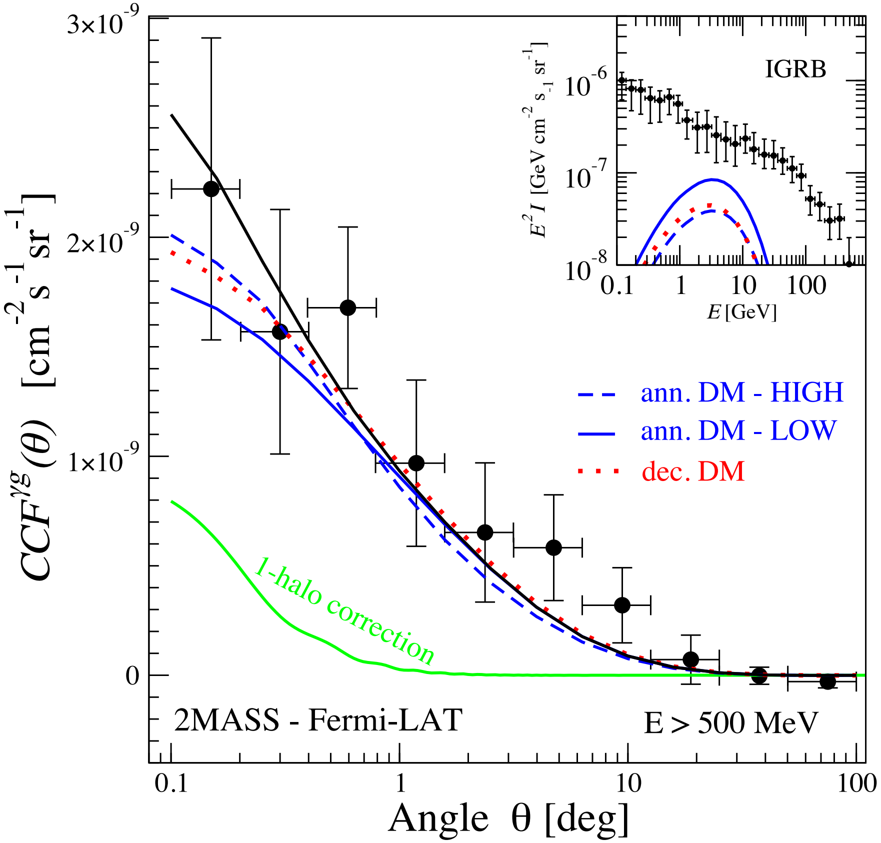
- w/ cluster catalogs (4.7 σ (*))

(*) Branchini+, ApJS 228 (2017) 1
Hashimoto, MNRAS 484, 5256 (2019)
Colavincenzo+, MNRAS 491, 3225 (2020)

- w/ cosmic shear (5.3 σ (*)/SNR 8.9(^))

Shirasaki+, Phys. Rev. D 90, 063502 (2014)
Shirasaki+, Phys. Rev. D 94, 063522 (2016)
Troster, MNRAS 467, 2706 (2017)
Shirasaki+, Phys. Rev. D 97, 123015 (2018)
(*) Ammazzalorso+, PRL 124 (2020) 101102
(^) Takhore+, 2501.10506

Galaxies: Fermi x 2MASS

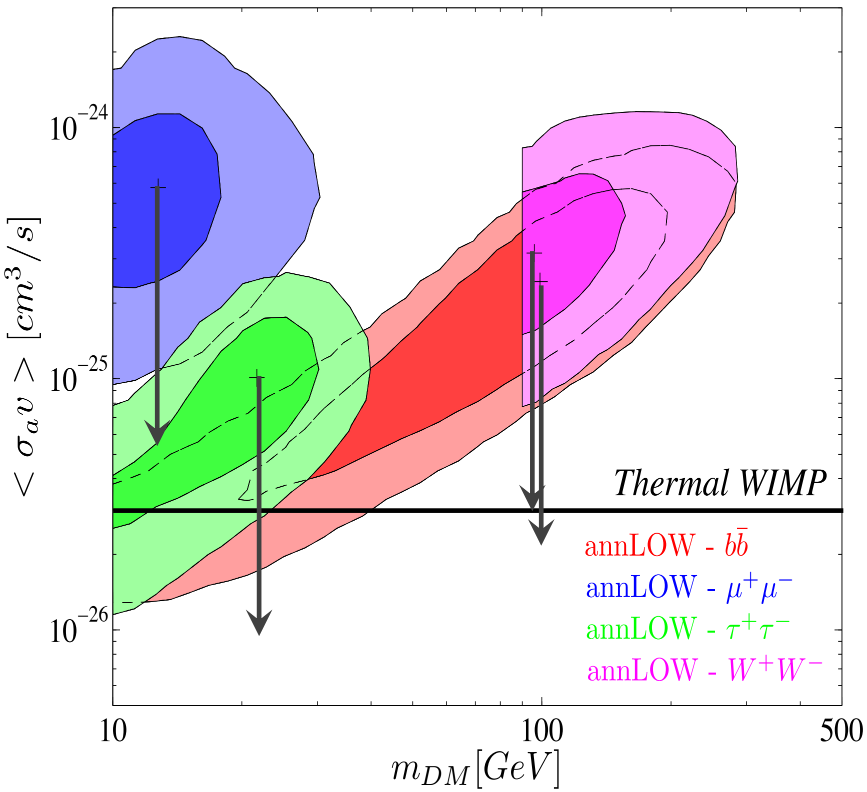


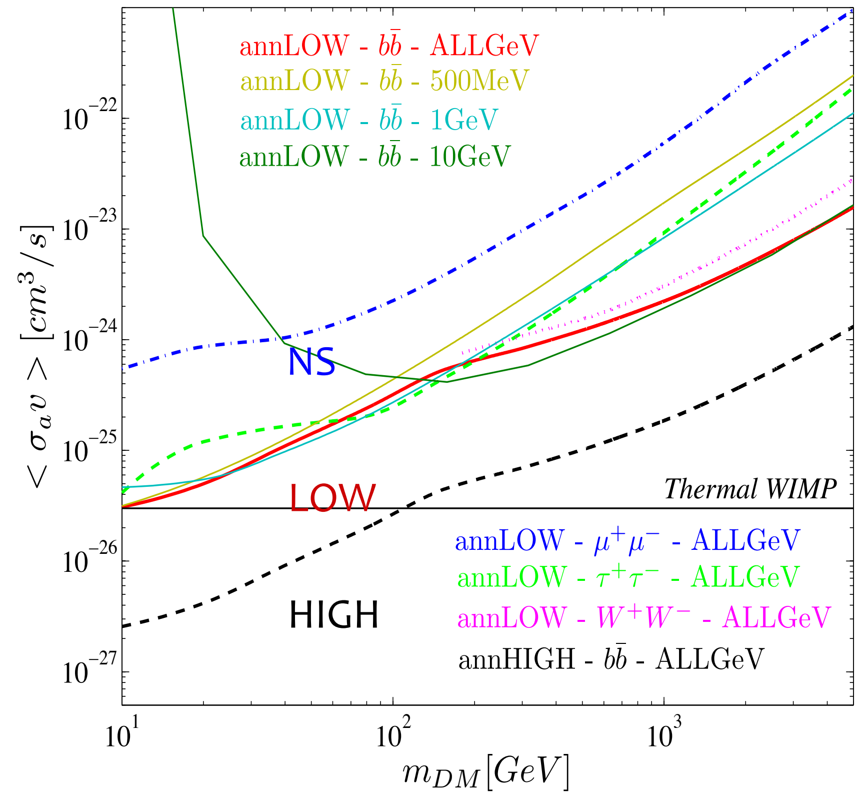
Correlation hint (3.5σ) at the degree scale

The observed cross-correlation can be reproduced (both in shape and size) by a DM contribution that is largely subdominant in the total intensity

Cuoco, Xia, Regis, NF, Branchini, Viel, ApJS 221 (2015) 29
Regis, Xia, Cuoco, Branchini, NF, Viel, PRL 114 (2015) 241301

Fermi x 2MASS

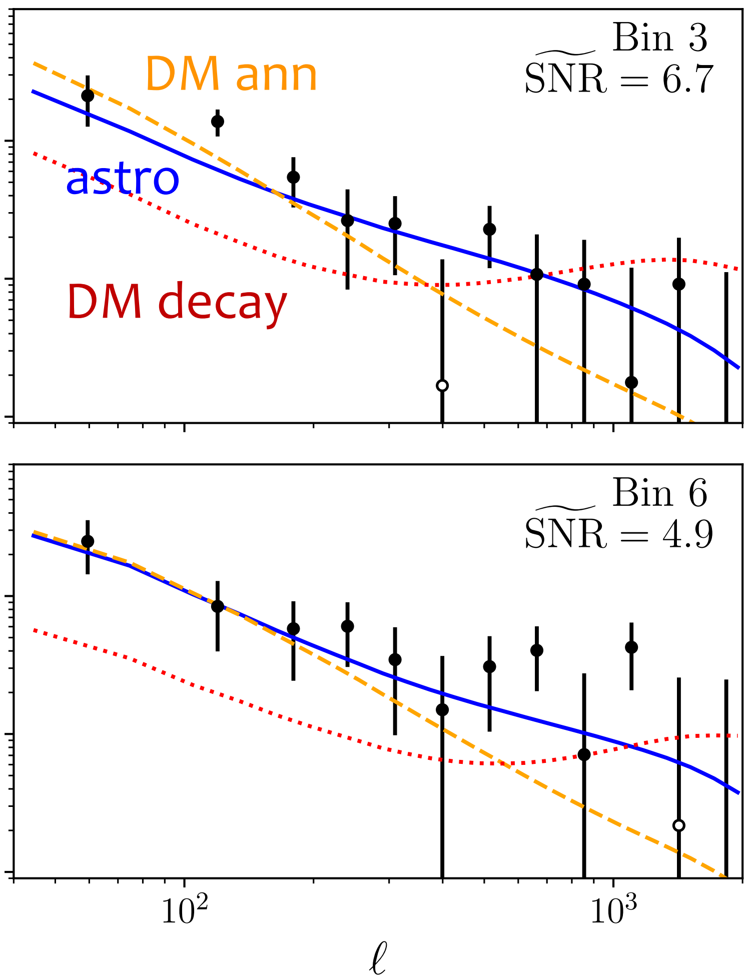


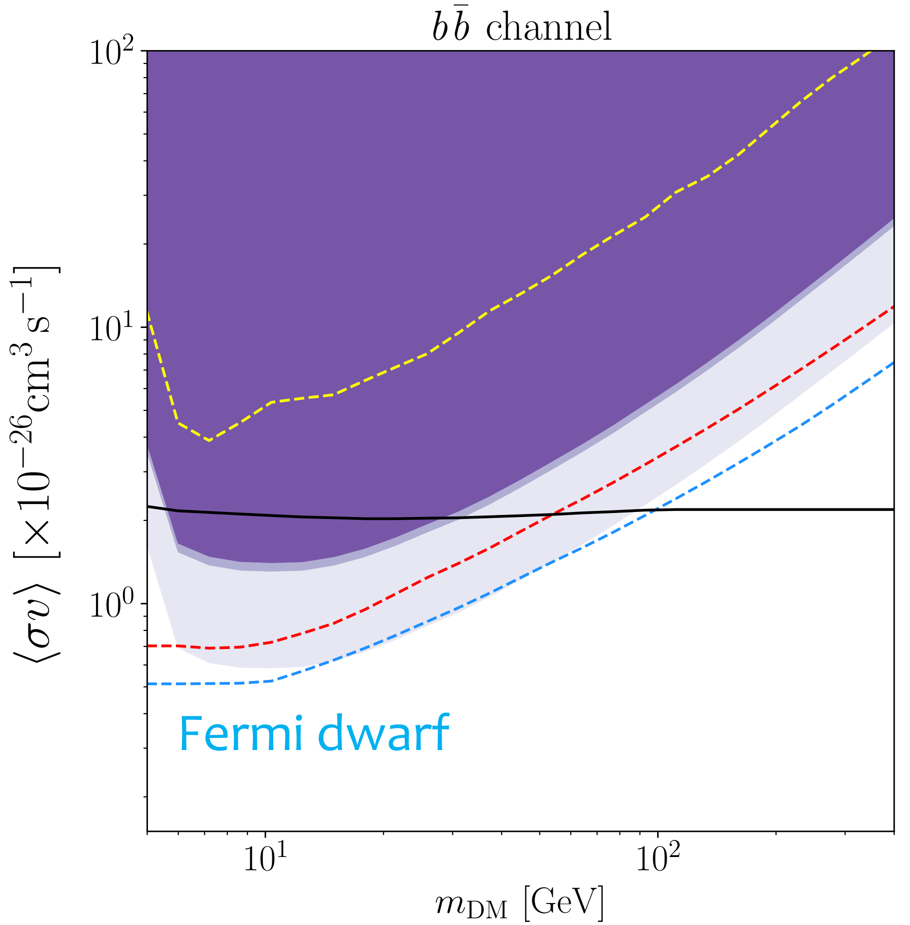


Regis, Xia, Cuoco, Branchini, NF, Viel, PRL 114 (2015) 241301
See also: Shirasaki, Horiuchi, Yoshida, PRD 90 (2014) 063502
Shirasaki, Horiuchi , Yoshida, PRD 92 (2015) 123540

Galaxies: Fermi x (2MASS + WISE)

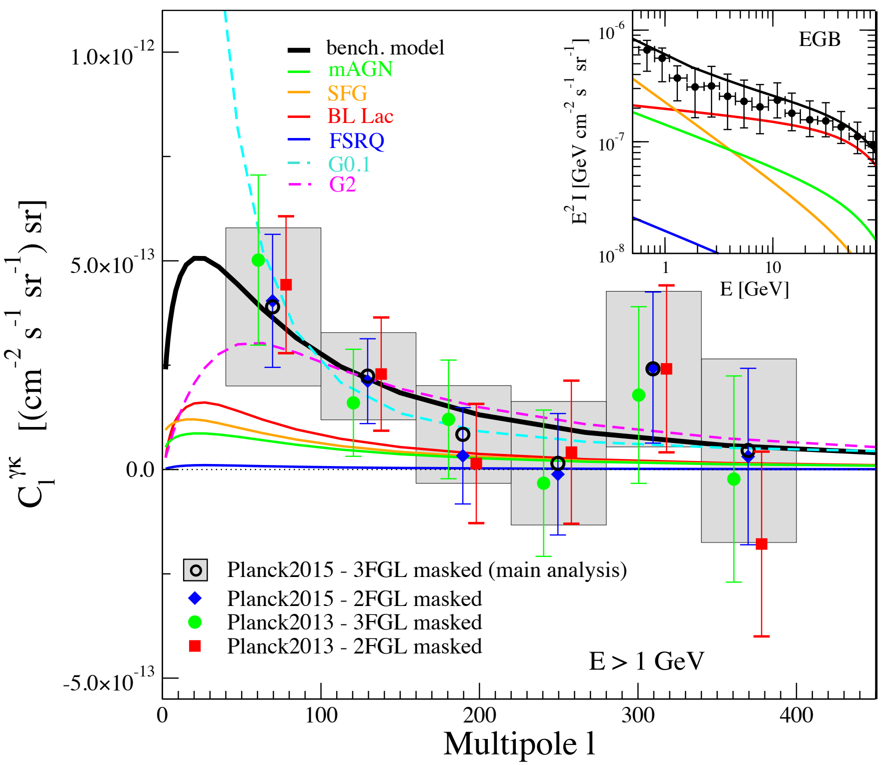
Signal at 8σ

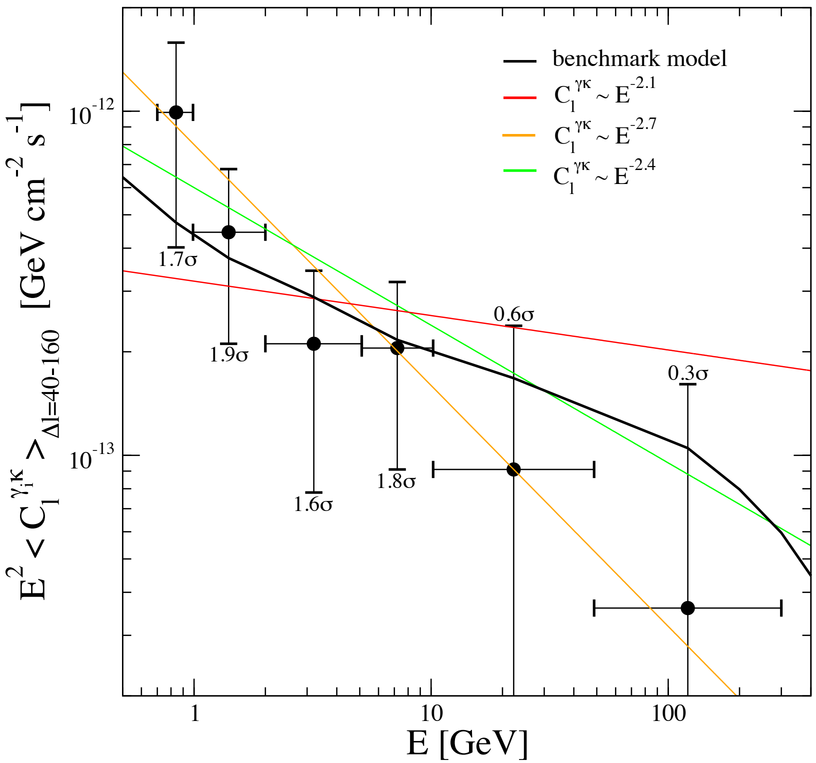




Paopiamsap +, Phys.Rev.D 109 (2024) 10, 103517

CMB lensing: Fermi x Planck





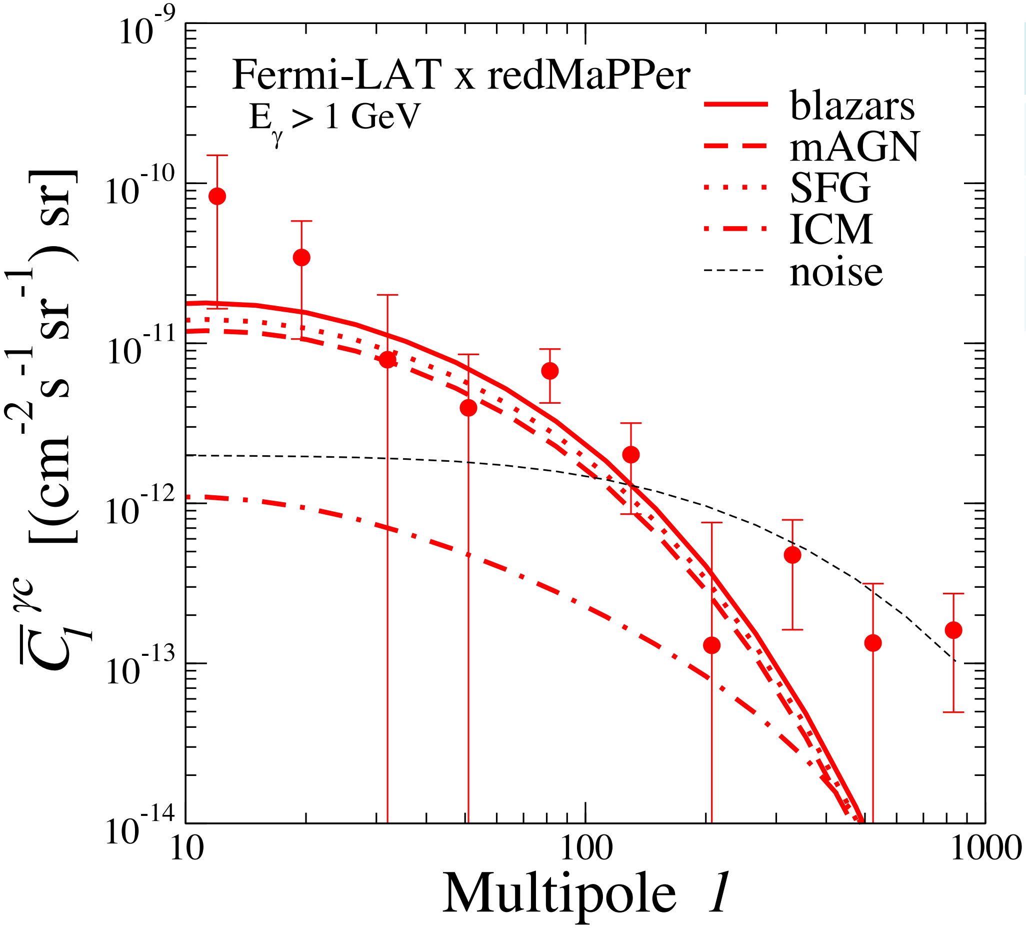
Cross-correlation: 3.0σ evidence

Compatible with AGN + SFG + BLA gamma-rays emission

Points toward a direct evidence of extragalactic origin of the UGRB

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

Galaxy Clusters



Branchini, Camera, Cuoco, NF, Regis, Viel, Xia, ApJS 228 (2017) 8

	1 halo	2 halo
redMaPPer	4.7 σ	2.1 σ
WHL12	3.9 σ	2.6 σ
Planck SZ	2.3 σ	1.8 σ

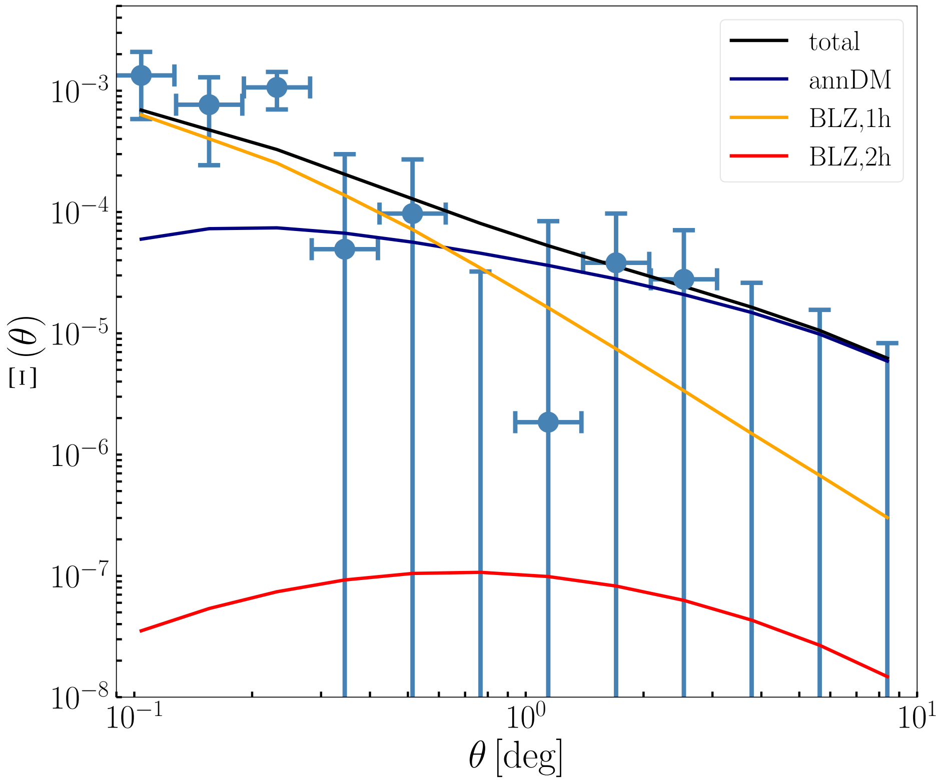
Correlation observed out to 1 deg, i.e. beyond the Fermi PSF (4.7σ)

This corresponds to a linear scale of 10 Mpc: a fraction of the correlation signal seems to be not physically associated to the clusters

Signal produced by AGNs or SFGs residing in the larger scale structures that surround the high density peaks where clusters reside (or by DM itself)

Tangential shear: Fermi x DES (2010)

Ammazzalorso, Gruen, Regis, Camera, Ando, NF et al,
PRL 124 (2020) 101102



DES 1 year (1786 deg^2)

Fermi 9 years

Evidence of a signal at 5.3σ

- The signal is mostly localized at small angular scales and high gamma-ray energies, with a hint of correlation at extended separation
- Blazar emission is likely the origin of the small-scale effect
- Statistics is still not enough to allow interpretation of the large-scale component and to determine impact on DM parameters

Tangential shear: Fermi x DES (2024)

Thakore, Negro, Regis, Camera, Gruen, NF +, 2501.10506

DES
- 3 years (4946 deg^2)
- GOLD catalog for galaxy selection
- METACALIBRATION shear catalog
- 4 redshift bins in (0,2)

Bin	No. of objects	$n_{\rm eff}$ (gal/arcmin^2)	σ_e	$z_{\rm mean}$
Full	100 204 026	5.590	0.268	0.633
1	24 940 465	1.476	0.243	0.336
2	25 280 405	1.479	0.262	0.521
3	24 891 859	1.484	0.259	0.742
4	25 091 297	1.461	0.301	0.964

Fermi
- 12 years
- Pass8 – R3
- SOURCEVETO v2 event class
- PSF 1 + 2 +3
- 9 energy bins in (631 MeV, 1 TeV)
- Mask: point sources in 4FGL-DR2 + $|b_{lat}| < 30^o$

	Bin number								
	1	2	3	4	5	6	7	8	9
$E_{\rm min}$ [GeV]	0.631	1.202	2.290	4.786	9.120	17.38	36.31	69.18	131.8
$E_{\rm max}$ [GeV]	1.202	2.290	4.786	9.120	17.38	36.31	69.18	131.8	1000.0
$\theta_{\rm cont}$ 68% [deg]	0.50	0.58	0.36	0.22	0.15	0.12	0.11	0.10	0.10
Photon counts	351380	780646	551996	221181	81514	34374	10690	3352	1422

2-Point Correlation Estimator

Tangential ellipticity of source galaxy i
in redshift bin r
relative to pixel j

Photon intensity flux
in energy bin a
and pixel j

$$\Xi^{ar}(\theta) = \Xi^{\text{signal}}_{\Delta\theta_h,\Delta E_a,\Delta z_r} - \Xi^{\text{random}}_{\Delta\theta_h,\Delta E_a,\Delta z_r} = \frac{\sum_{i,j} e^r_{ij,\text{t}} I^a_j}{R\sum_{i,j} I^a_j} - \frac{\sum_{i,j} e^r_{ij,\text{t}} I^a_{j,\text{random}}}{R\sum_{i,j} I^a_{j,\text{random}}}$$

Angular bin

Energy bin a

Redshift bin r

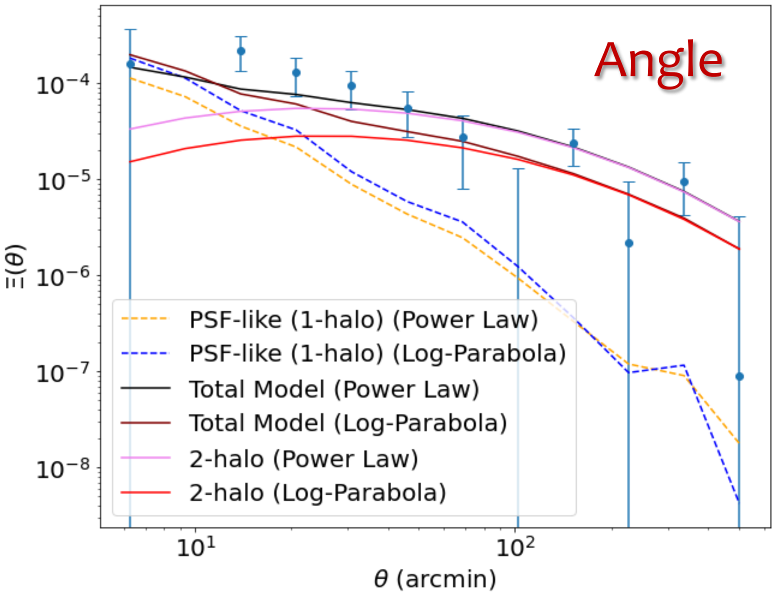
Sum over umasked pixels and DES sources

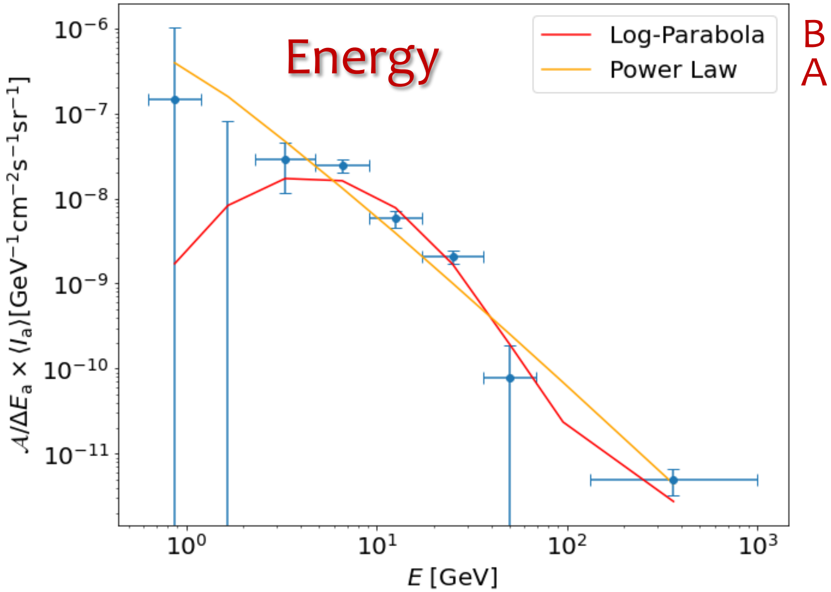
Analysis performed in:

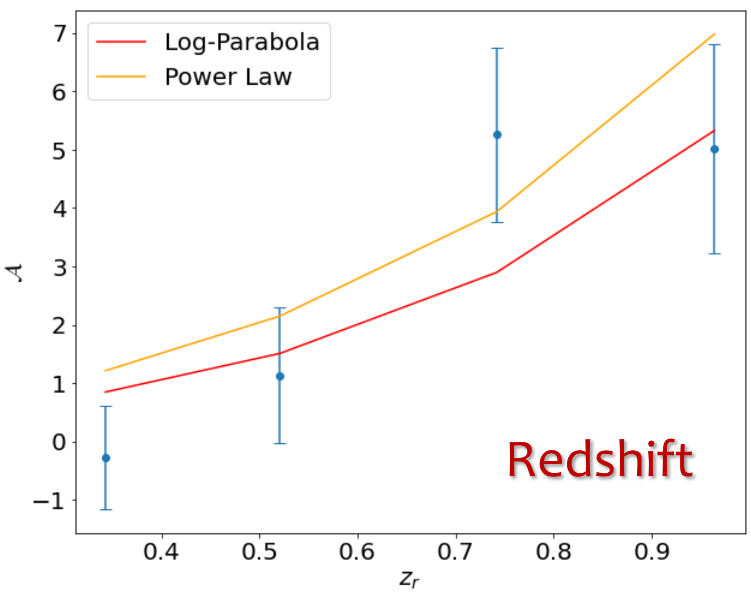
- 12 log-spaced angular bins in (5, 600) arcmin
- 9 photon energy bins
- 4 redshift bins

Random term, subtracted from the signal to reduce additive shear systematic effects, random very-large-scale structures or chance shear alignments relative to the mask (lowers the variance)

Tangential shear: Fermi x DES (2024)





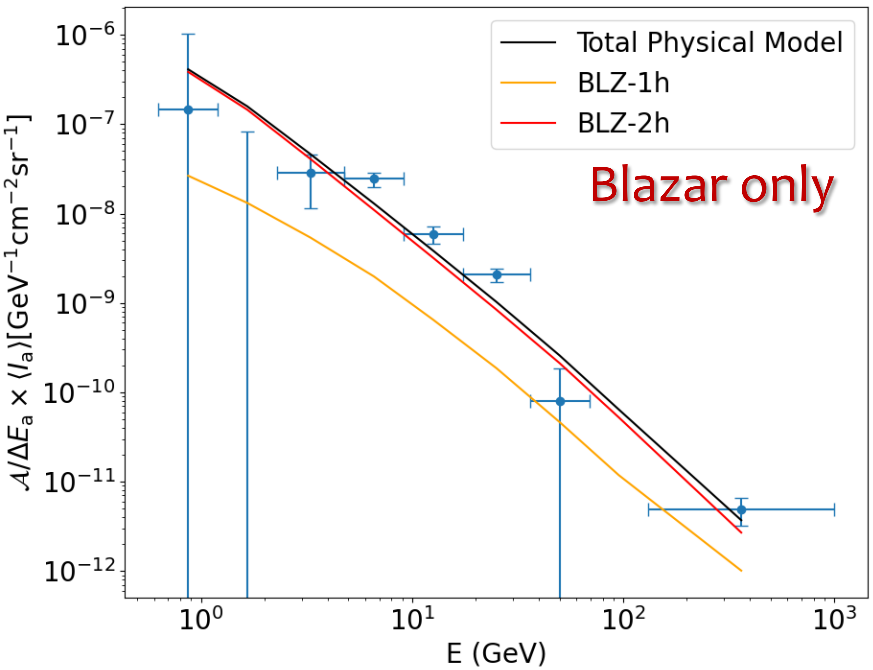


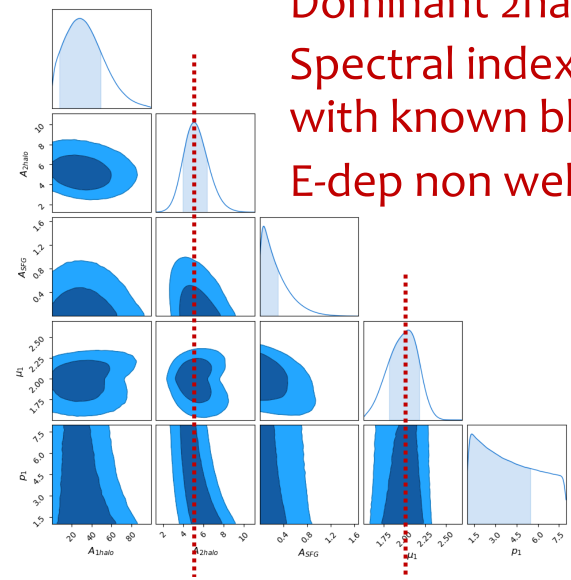
	Data set							
	Full	Low-z	High-z	Low-E	High-E	Small-θ	Large-θ	
$\Delta\chi^2_{\rm lp}$	78.92	3.40	75.28	23.29	55.36	5.82	73.73	B
$\mathrm{SNR_{lp}}$	8.88	2.45	8.70	4.89	7.49	2.42	8.58	
$\Delta\chi^2_{\rm pl}$	51.43	0.84	53.66	15.77	38.72	8.72	47.32	A
$\mathrm{SNR_{pl}}$	7.17	1.66	7.34	4.03	6.24	2.96	6.88	

Evidence for a signal at SNR 8.9 / 7.2

Comments

- Clear evidence for the presence of a cross-correlation signal
- The signal is mostly concentrated at:
  - High energies
  - Large angular scales
  - High redshift
- Higher significance from higher redshift bins is somewhat expected because those bins have a higher lensing signal by integrating over longer distances
- The evidence for correlation at large angles suggests that the measurement is not dominated by few very massive and very bright objects, but rather it comes from a clustered population of extragalactic sources
- The evidence at large energies points towards an interpretation in terms of the presence of sources with hard energy spectrum (low-energies have low significance, due to the degradation of the Fermi energy resolution below 1 GeV)
- The hard spectrum suggests a possible preference for blazars, rather than star-forming galaxies or misaligned AGNs, although its curvature might be indicative of more than one component

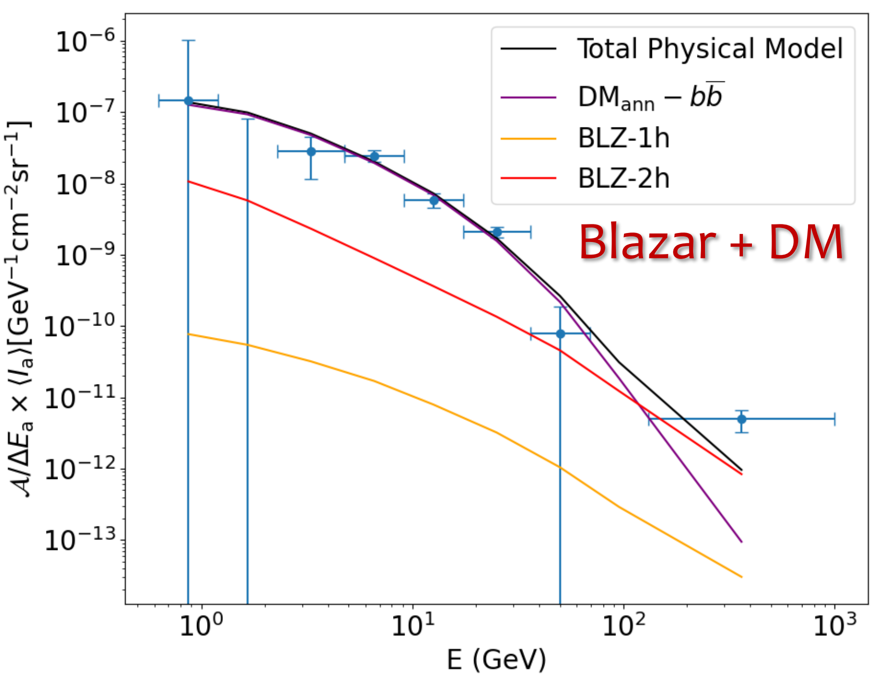


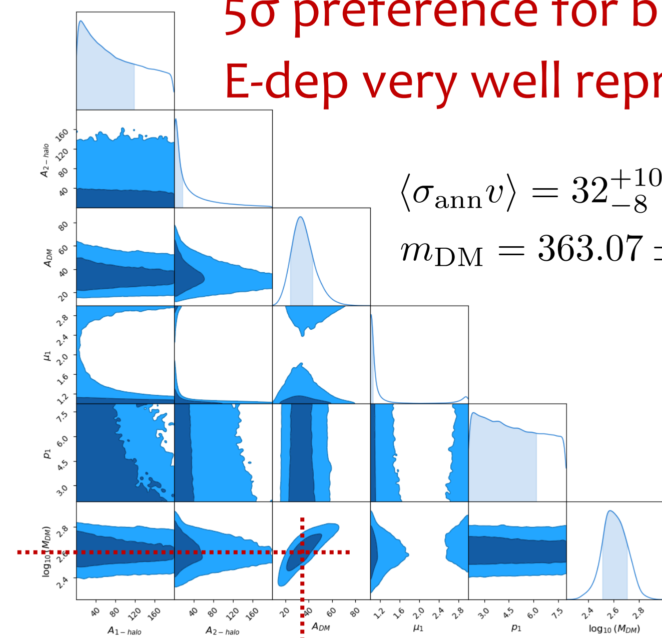


Dominant 2halo component

Spectral index consistent with known blazar

E-dep non well reproduced





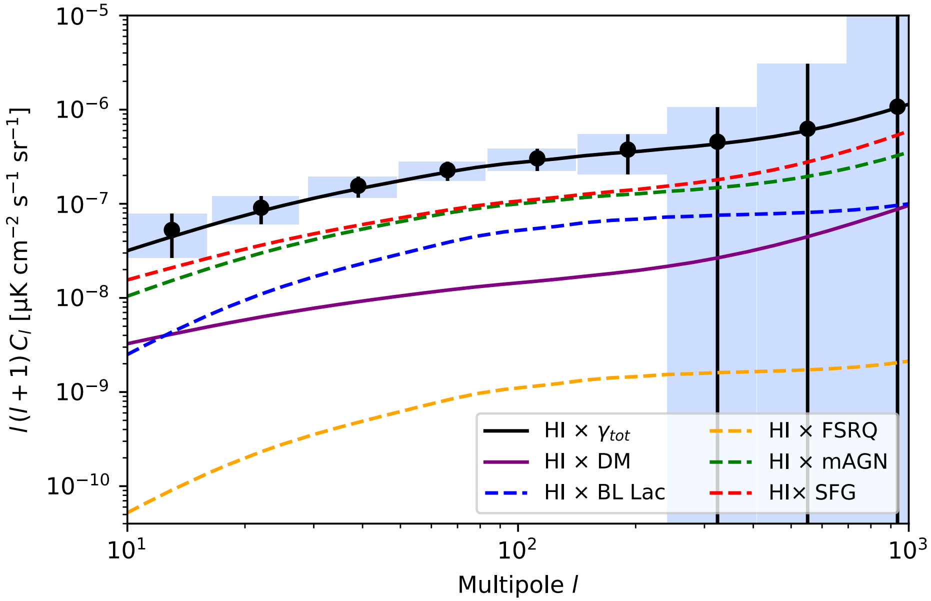
5σ preference for blazar + DM

E-dep very well reproduced

$$\langle \sigma_{\mathrm{ann}} v \rangle = 32^{+10}_{-8} \langle \sigma_{\mathrm{ann}} v \rangle_{\mathrm{th}}$$

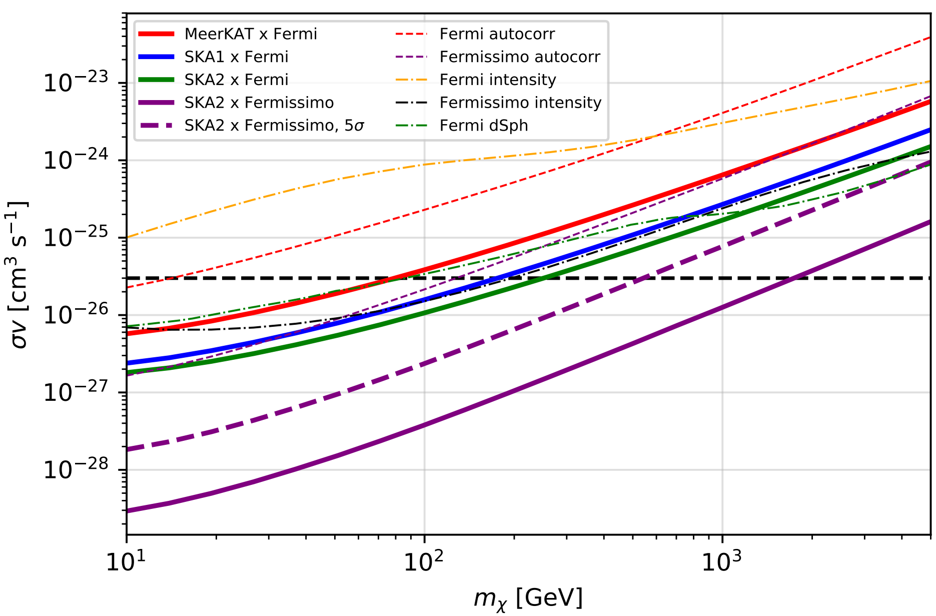
$$m_{\mathrm{DM}} = 363.07 \pm {}^{138.10}_{39.48} \text{ GeV}$$

HI intensity mapping (forecast)



		Single-dish	Dish+Interferometer
MeerKAT	L-band	3.6	3.6
	UHF-band	3.7	3.7
SKA-1	Band 1	4.5	4.6
	Band 2	5.7	5.7
SKA-2	Band 1	7.1	8.2
	Band 2	6.7	7.0

SNR



Pinetti, Camera, NF, Regis, JCAP 07 (2020) 044

Over vs under densities

Cross-correlations have been considered as originated by the DM overdensities (halos)

However, the anisotropic mass distribution in the Universe is much more complex, exhibiting:

halos — dominate by mass

filaments and sheets

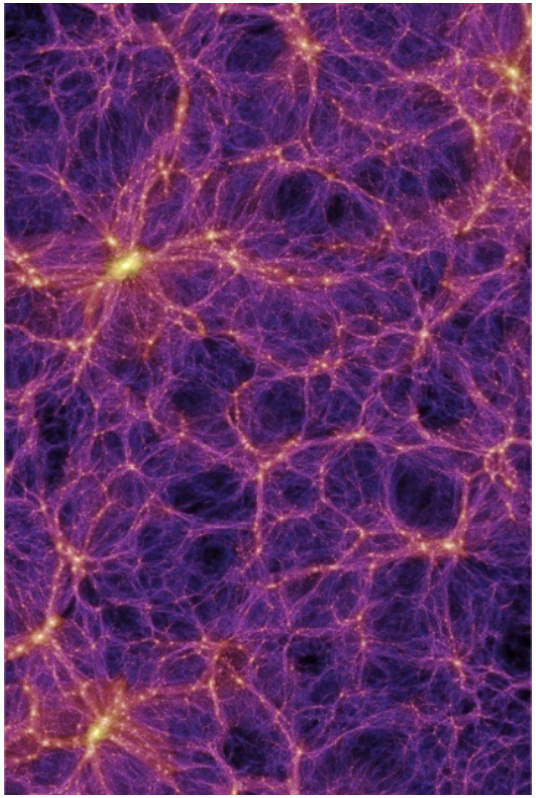
voids — dominate by volume

↓

Underdense regions

Probe galaxy evolutions, structure formation, cosmological evolution, including DE

Voids catalogs start to be built



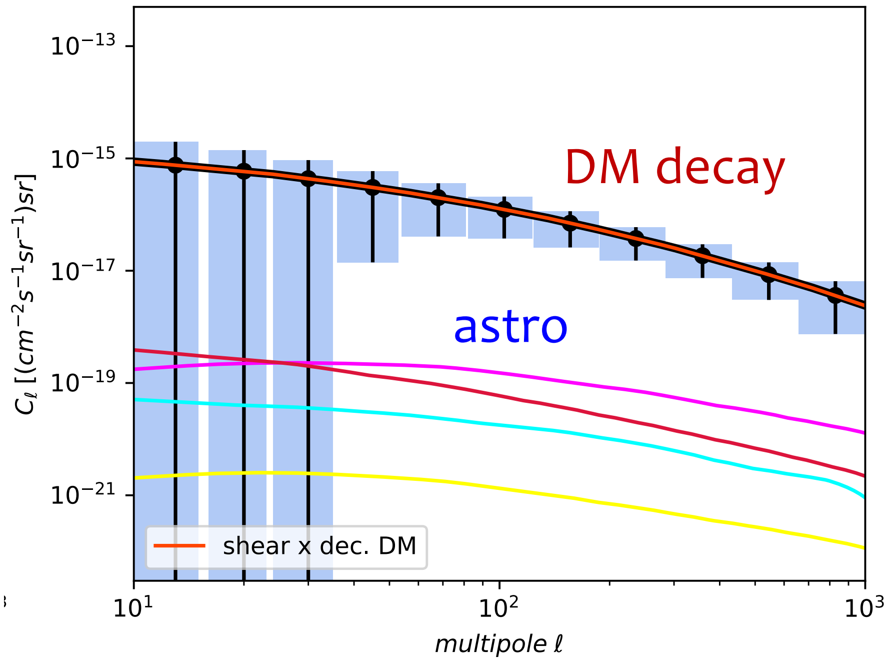
Cosmic voids

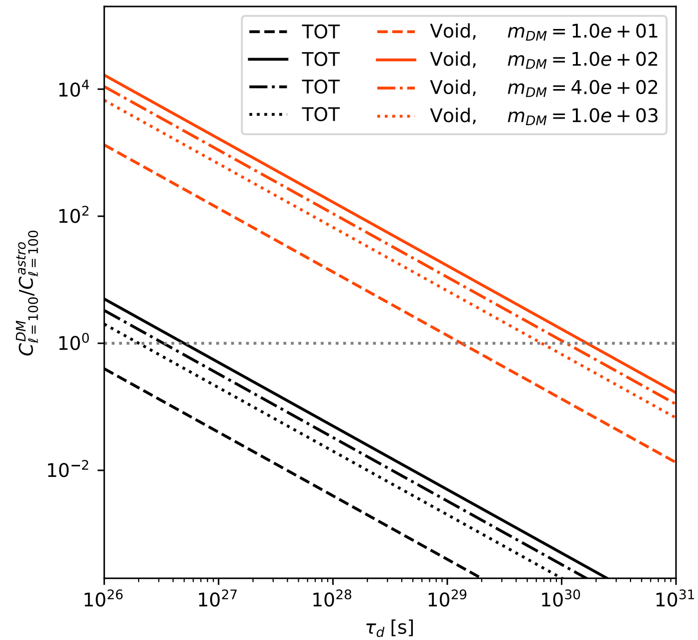
With void identification becoming available, what would be the relevance of using the under-density information for cross-correlations?

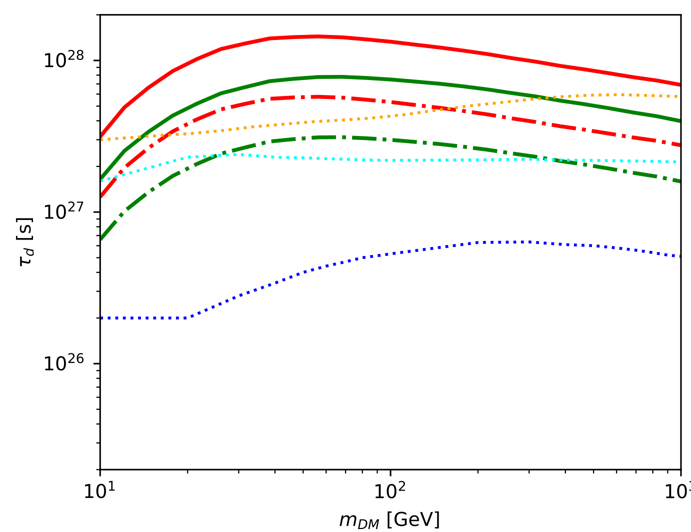
DM emission is suppressed, but emission from astrophysical sources is expected to be suppressed, too

Physical sizes of voids (10-100 Mpc) largely exceed those of halos (clusters: few Mpc), thus probing physical scales differently

Cosmic voids (forecast)







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Conclusions

- DM indirect signals are faint and affected by masking astrophysical backgrounds
- Using correlated information between DM distribution with fluctuations of the cosmic radiation fields could help in setting apart a pure DM signal from astrophysical emissions (spatial fluctuations for astrophysical sources and DM emission have different features)
- The cross correlation technique has been proposed and adopted by looking at DM halos (overdensities) and proposed for voids
- Clear evidence (at the level of about 8σ) has emerged for the presence of a cross-correlation signal between the cosmological gamma-ray background radiation and:
  - Cosmic shear, for angular scales up to a few hundreds of arcmins and for gamma-ray energies in (few GeV, 1 TeV)
  - Galaxy distribution, on similar angular scales and for the same photon energy range
- Astrophysical sources are likely the origin of the signal on small scales, while the larger scale effect (which might be due to dark matter) is still under study