

LOOKING TO DARK MATTER THROUGH GAMMA RAYS ANISOTROPIES

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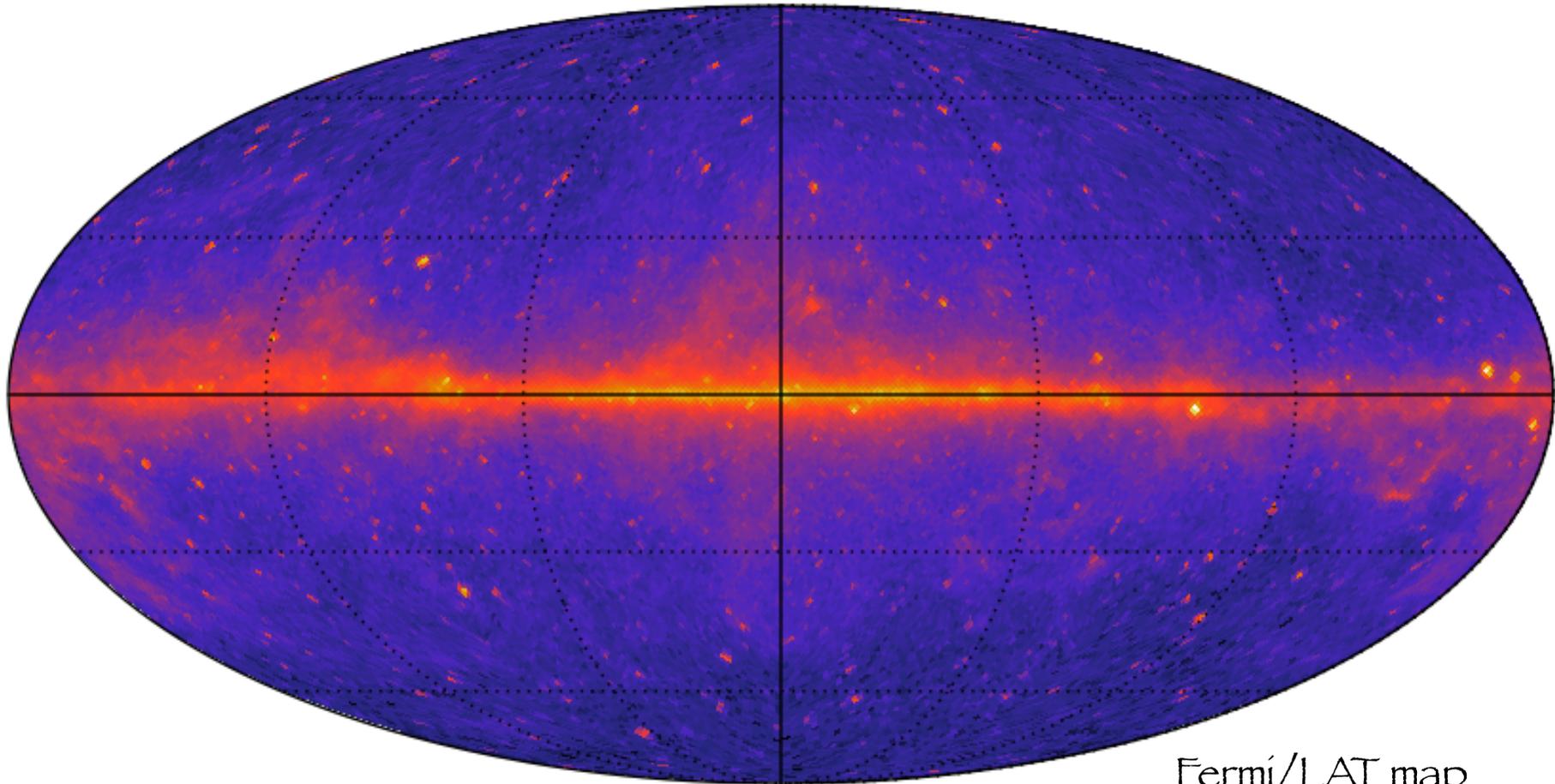


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2nd Anisotropic Universe Workshop: Unveiling the Anisotropic Universe
Amsterdam – 12.04.2016

Gamma ray sky



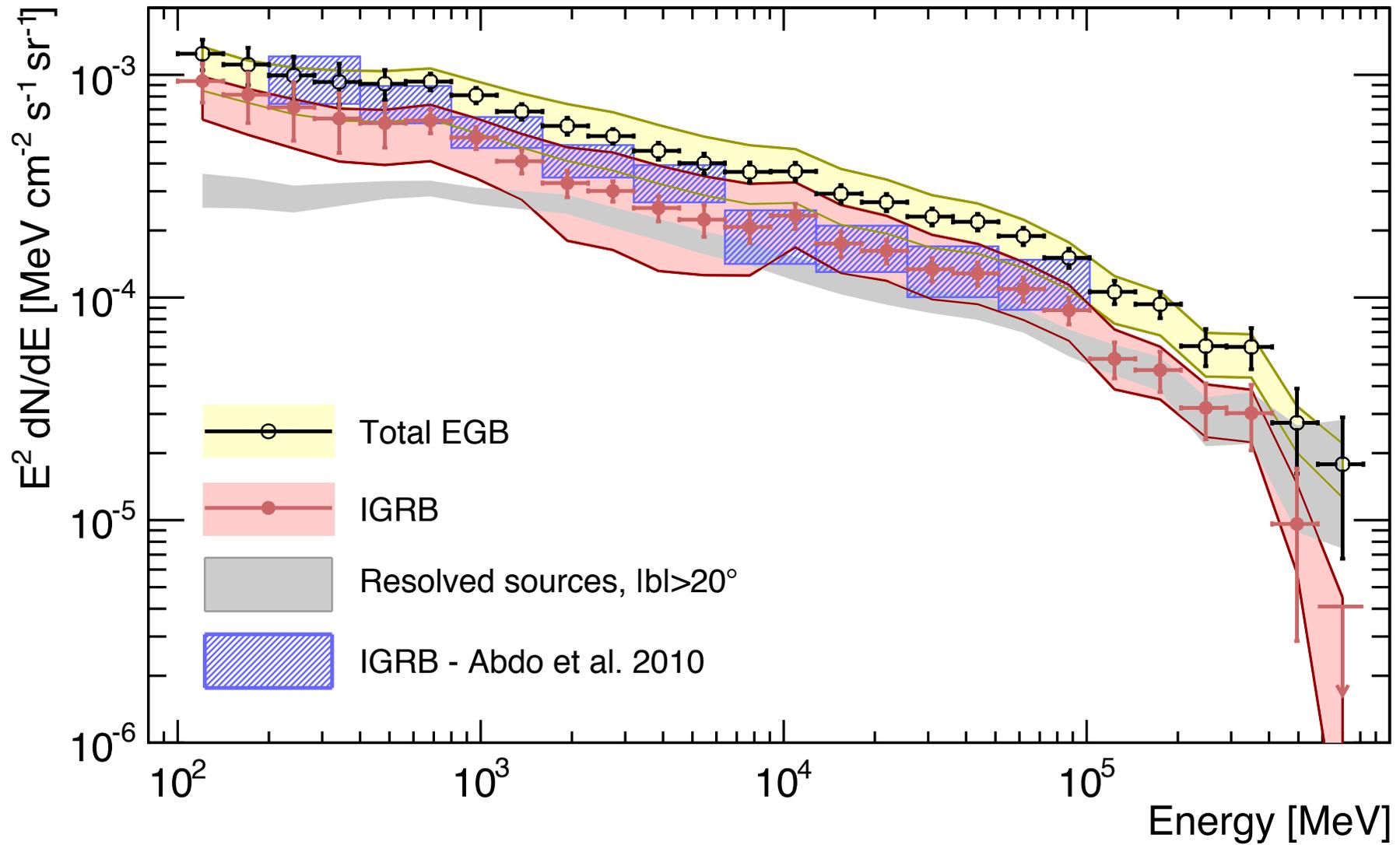
Fermi/LAT map

Galactic foreground emission

Resolved sources

Diffuse Gamma Rays Background (DGRB)

DGRB Intensity



Ackerman et al. (Fermi Collab.) *Ap. J.* 799 (2015) 86

See Zaharijas' talk

DGRB

- Cumulative emission of sources that are not bright enough to be detected individually
- Full composition is under deep scrutiny
- Contributions from:

Blazars

Misaligned AGNs

Star forming galaxies

Millisecond pulsars

Galaxy clusters

UHECR on background radiation

Type Ia supernovae

GRBs

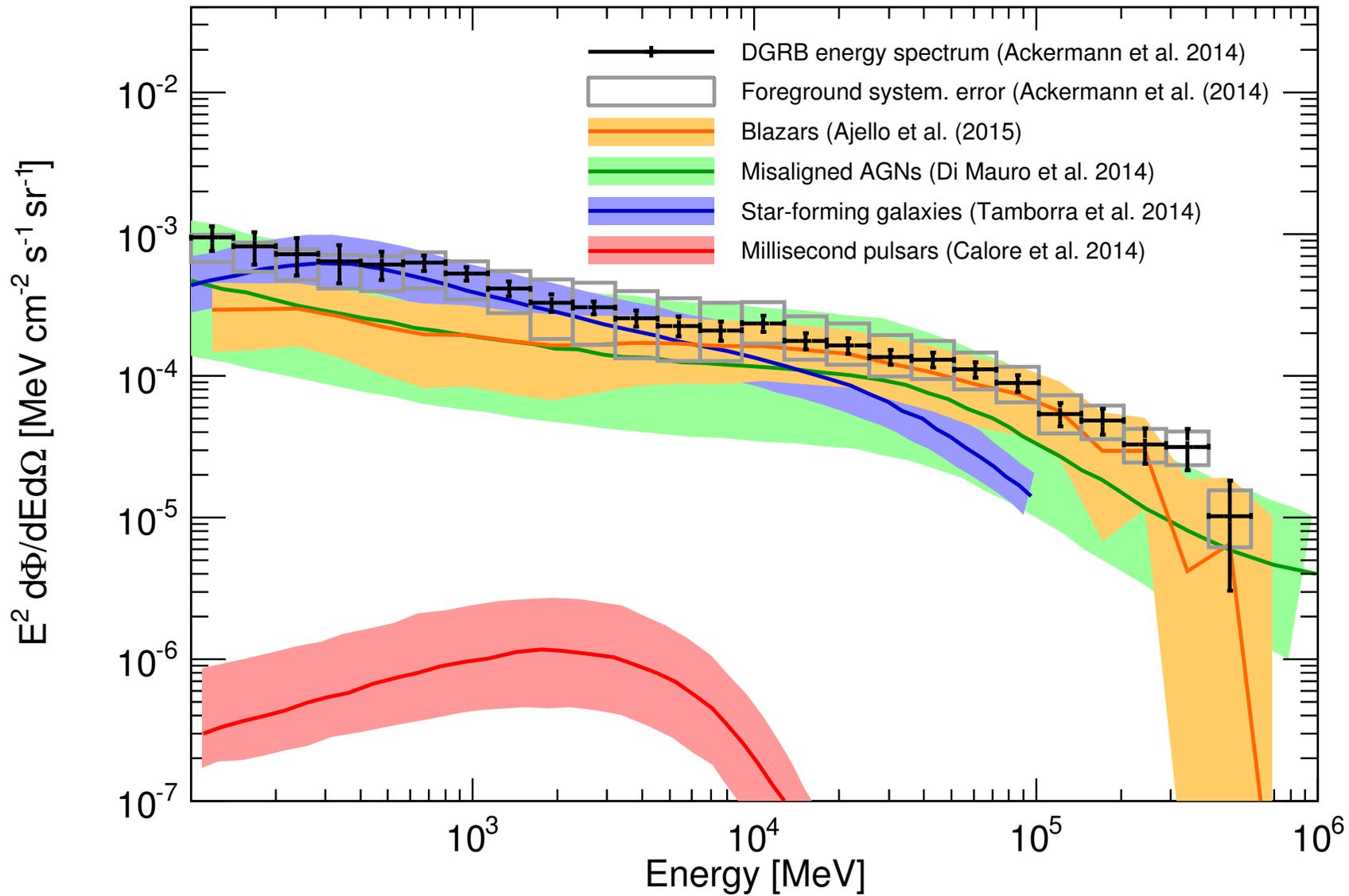
Radio-quiet AGNs

Two recent reviews:

Fornasa, Sanchez-Conde, Phys. Rep. 598 (2015) 1

Gaskins, arXiv:1604.00014

DGRB Intensity



DGRB and Dark Matter

- Contribution from:

Galactic Dark Matter emission

Smooth halo

Substructures

Extragalactic (cosmological) Dark Matter

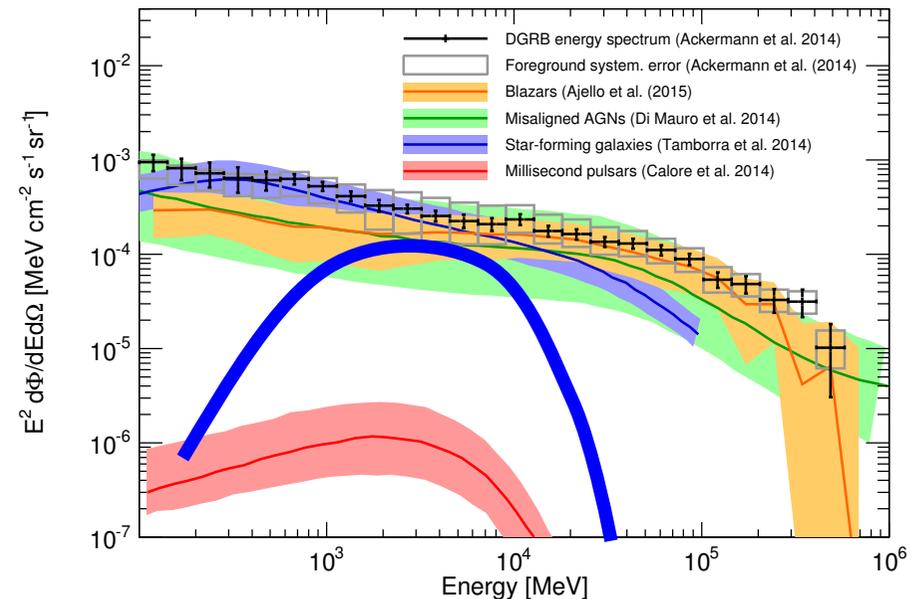
Hierarchical structure: clusters, galaxies, subhalos

- Dark Matter emission:

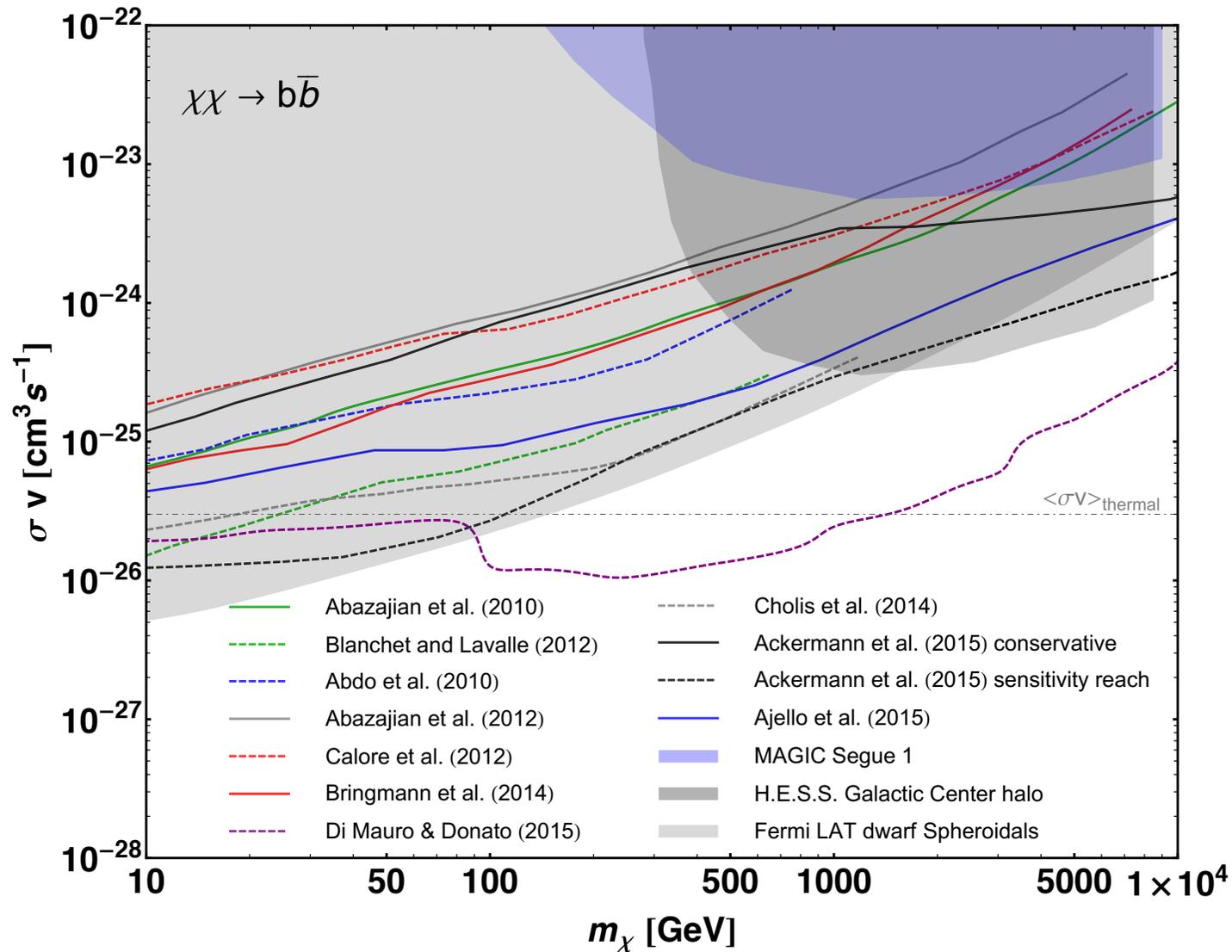
- Has spectral behaviour different from astro sources:

Good, this can be exploited to infer DM particle properties (mass, interactions)

- Can be quite subdominant in intensity: **Bad** ...



DGRB intensity bounds on DM



DGRB: not quite isotropic ...

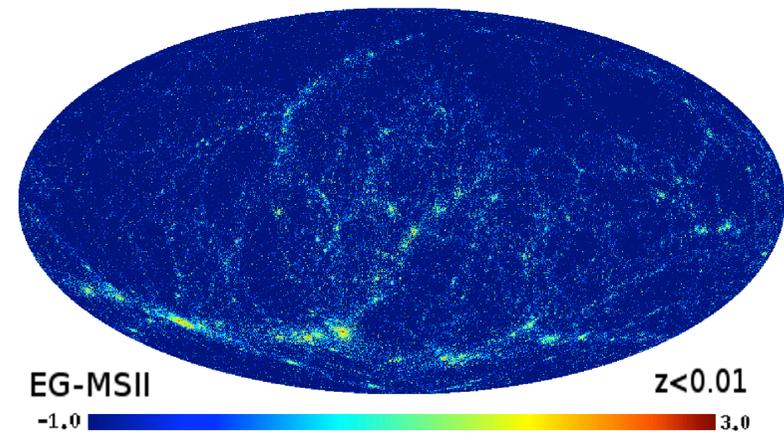
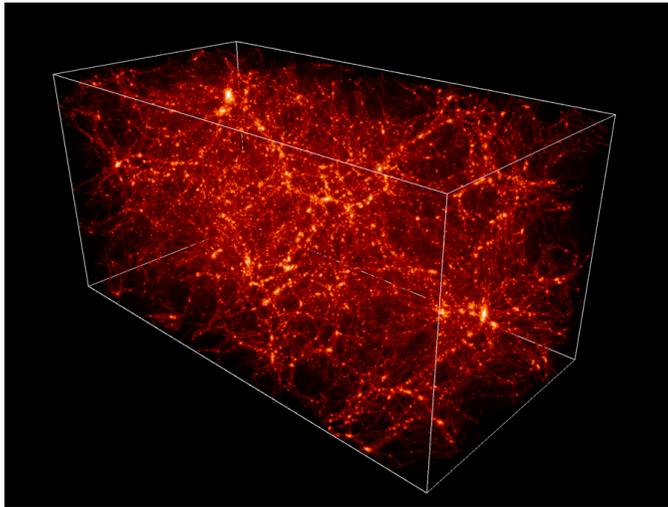
Being the cumulative sum of independent sources (astro/DM)

To first approximation:

isotropic

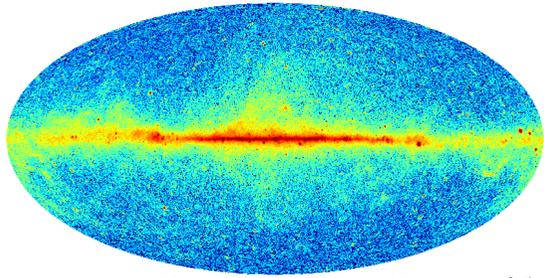
At a deeper level:

anisotropies are present



Even though sources are too dim to be individually resolved, they affect the **statistics of photon** across the sky

Photon statistics



Photon pixel counts (1 point PDF)

Source count number dN/dS below detection threshold

Gamma rays - theory

Lee, Ando, Kamionkowski, JCAP 0907 (2009) 007
Dodelson, Belikov, Hooper, Serpico, PRD 80 (2009) 083504
Baxter, Dodelson, Koushiappas, Strigari, PRD 82 (2010) 123511
Lee, Lisanti, Safdi, JCAP 1505 (2015) 05 056
Feyereisen, Ando, Lee, JCAP 1509 (2015) 027

Gamma rays – high latitudes

Malyshev, Hogg, Astrophys. J. 738 (2011) 181
Zechlin, Cuoco, Donato, NF, Vittino, arXiv:1512.07190
Zechlin, Cuoco, Donato, NF, Regis, to appear

Gamma rays – galactic center

Lee, Lisanti, Safti, Slatyer, Xue, Phys. Rev. Lett. 116 (2016) 5 051103
Linden, Rodd, Safdi, Slatyer, arXiv:1604.01026
Horiuchi, Kaplinghat, Kwa, arXiv:1604.01402

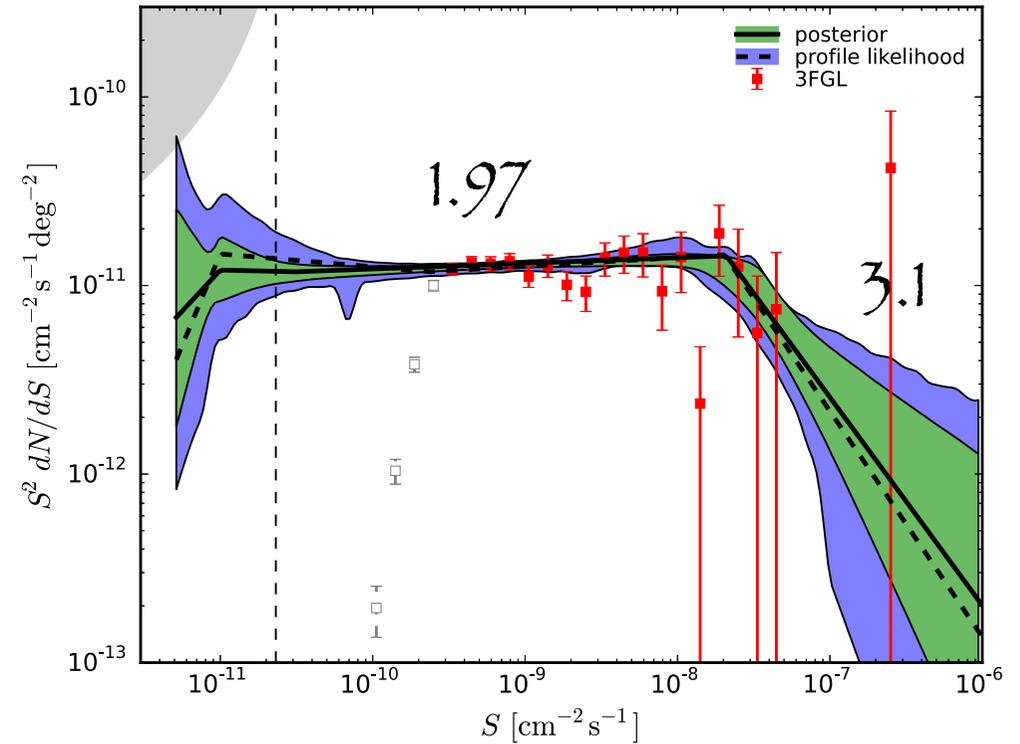
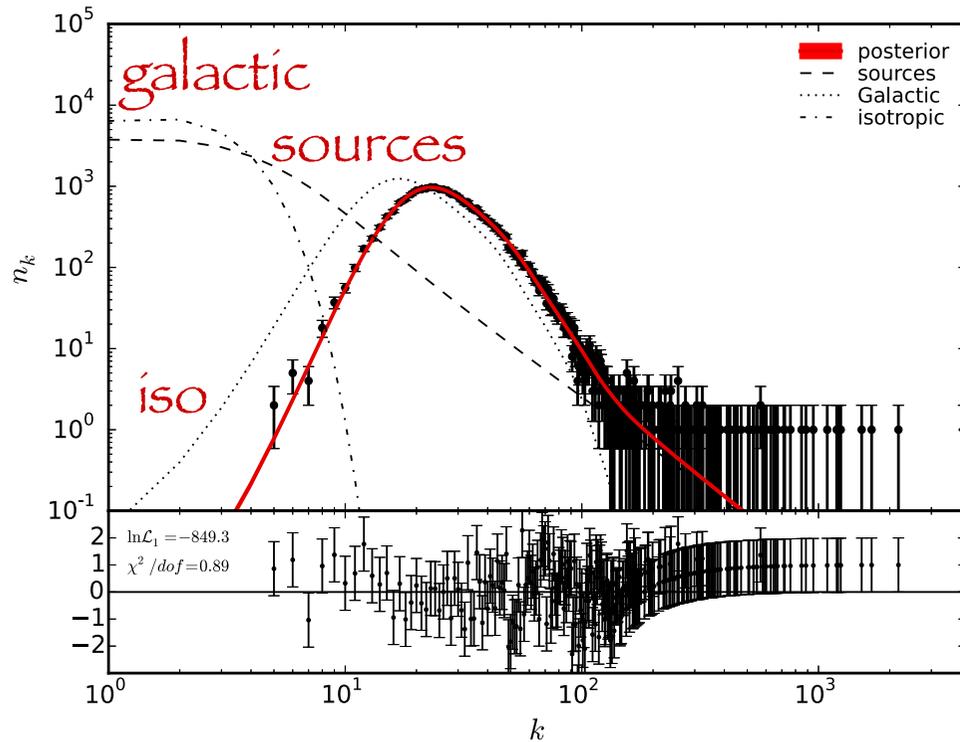
Radio P(D)

Scheuer, PCPS 53 (1957) 764
Condon, ApJ 188 (1974) 279
Venstrom, Scott, Wall, MNRAS 440 (2014) 2781
Vernstrom, Norris, Scott, Wall, MNRAS 447 (2015) 2243

X rays

Hasinger et al. A&A 275 (1993) 1
Soltan, A&A 532 (2011) A19

Photon counts



Point sources

25%

6 years Fermi data

Galactic foreground

69%

$|b| > 30^\circ$

Diffuse isotropic

6%

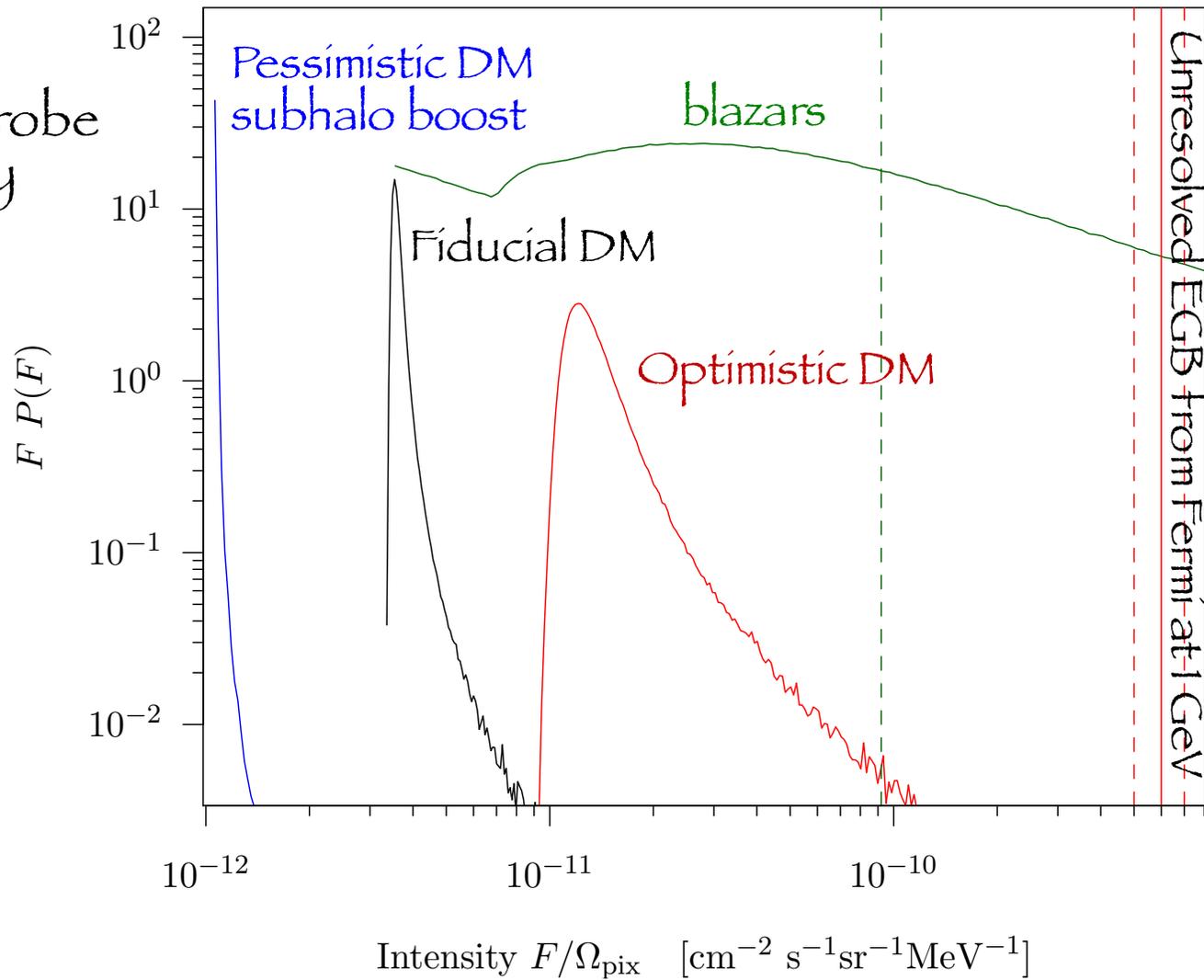
Energy range: (1-10) GeV

Zechlin, Cuoco, Donato, NF, Vittino, arXiv:1512.07190

See Zechlin's talk

Flux PDF

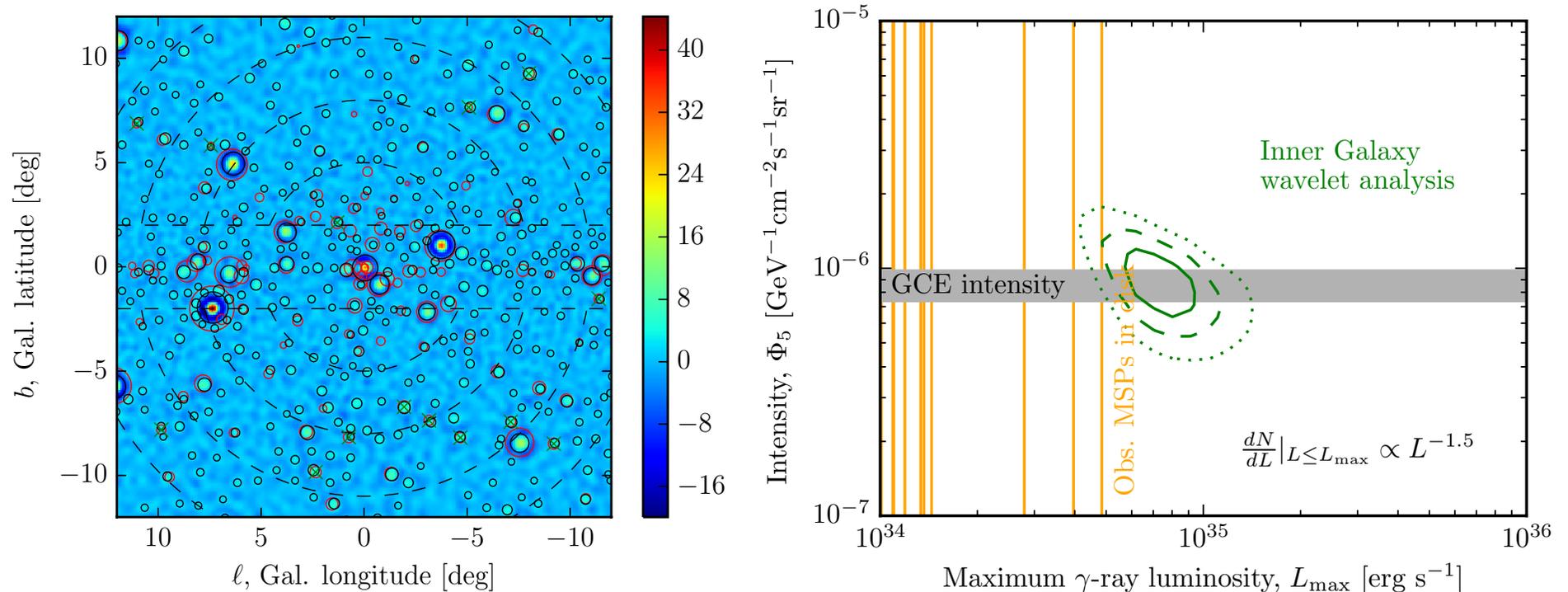
Flux PDF: probe of luminosity function



Feyereisen, Ando, Lee, JCAP 1509 (2015) 027

See Feyereisen's talk

Wavelet analysis



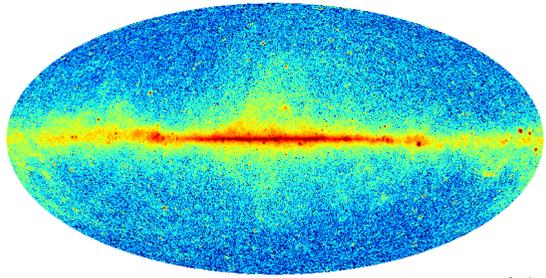
Statistics of maxima in the wavelet-transformed map

Applied to the GC excess: search for a large number of dim MSP-like sources, spatially distributes as the GC excess

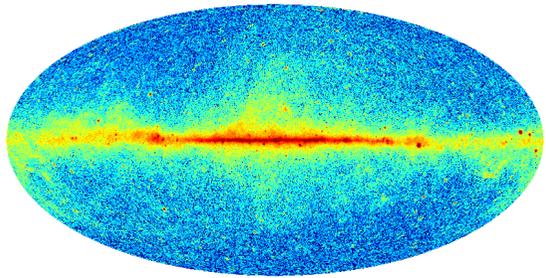
Bartels, Krishnamurthy, Weniger, PRL 116 (2016) 05102

See Bartels's talk

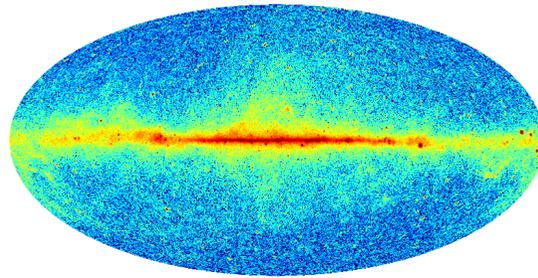
Photon statistics



Photon pixel counts (1 point PDF)



×



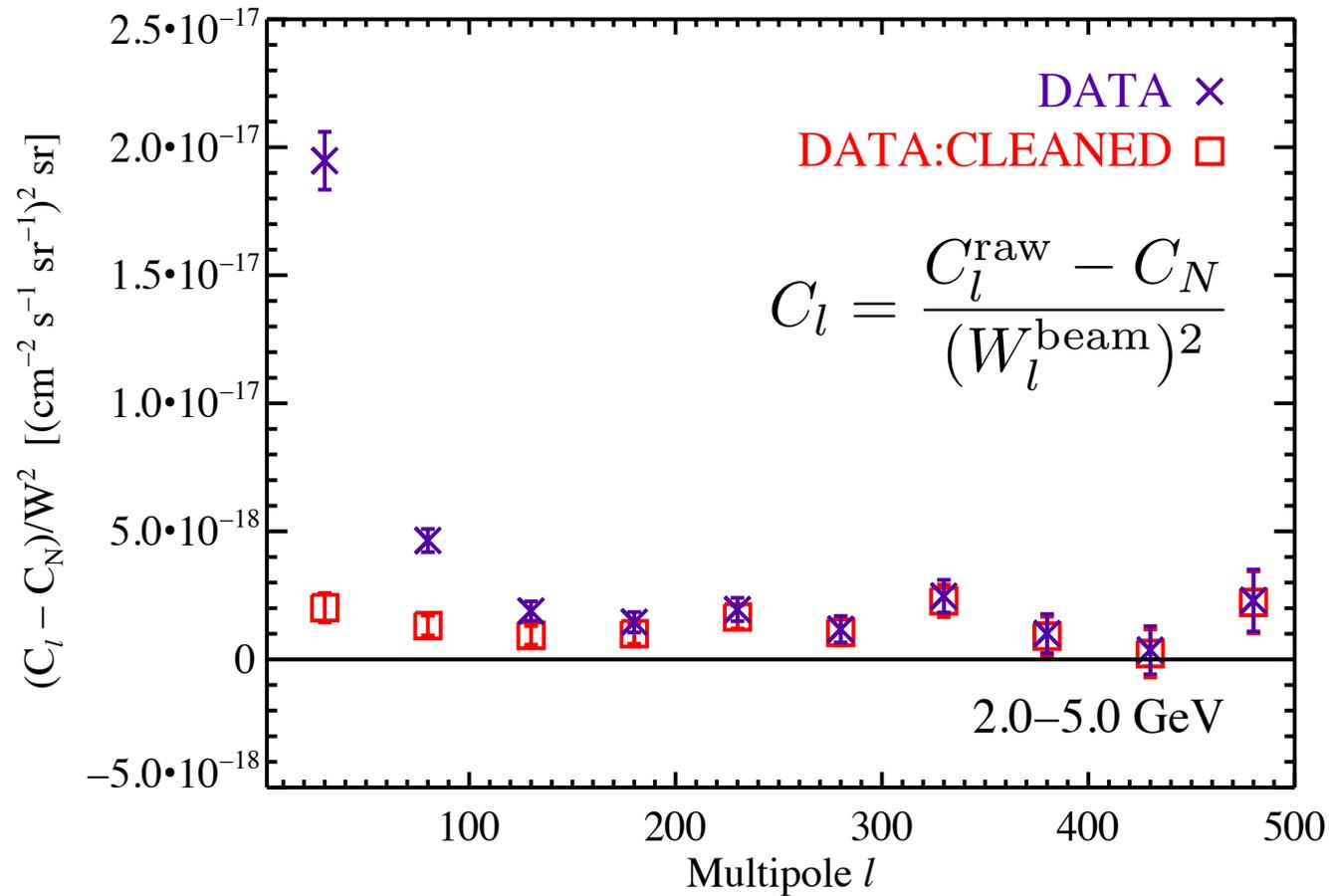
2 point correlator
angular power spectrum

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

Ando, Komatsu, PRD 73 (2006) 023521	DM
Ando, Komatsu, Narumoto, Totani, PRD 75(2007) 063519	DM
Cuoco, Hannestad, Haugbolle, G. Miele, Serpico, Tu, JCAP 0704 (2007) 013	DM
Cuoco, Brandbyge, Hannestad, Haugbolle, Miele, PRD 77 (2008)123518	DM
Siegal-Gaskins, JCAP 0810 (2008) 040	DM
Siegal-Gaskins, Pavlidou, PRL 102 (2009) 241301	DM
Ando, PRD 80 (2009) 023520	DM
Fornasa, Pieri, Bertone, Branchini, PRD D80 (2009) 023518	DM
Taoso, Ando, Bertone, Profumo, PRD 79 (2009) 043521	DM
Ibarra, Tran, Weniger, PRD 81 (2010) 023529	DM
Hensley, Siegal-Gaskins, Pavlidou, ApJ 723 (2010) 277	DM
Zavala, V. Springel, M. Boylan-Kolchin, MNRAS 405 (2010) 593	DM
Cuoco, Sellaerholm, Conrad, Hannestad, MNRAS 414 (3) (2011) 2040	DM
Campbell, Dutta, PRD 84 (2011) 075004	DM
Fornasa, Zavala, Sanchez-Conde, Gaskins, Delahaye, MNRAS 429 (2012) 1526	DM
Ando, Komatsu, PRD 87 (2013) 123539	DM
Campbell, Beacom, arXiv:1312.3945	DM
NF, Regis, Front. Physics 2 (2014) 6	DM
Gomez-Vargas et al, NIM A742(2014) 149	DM

Ando, Komatsu, Narumoto, Totani, MNRAS 376 (2007) 1635	astro
Miniati, Koushiappas, Di Matteo, APJ 667 (2007) L1	astro
Ando, Pavlidou, MNRAS 400 (2009) 2122	SFG
Siegal-Gaskins, Reesman, Pavlidou, Profumo, Walker, MNRAS 415 (2011) 10745	MSP
Cuoco, Komatsu, Siegal-Gaskins, PRD 86 (2012) 063004	astro
Harding, Abazajian, JCAP 1211 (2012) 026	BLA
Di Mauro, Cuoco, Donato, Siegal-Gaskins, JCAP 1411 (2014) 012	AGN
Calore, Di Mauro, Donato, Donato, ApJ 796 (2014) 1	MSP

Gamma rays auto correlation

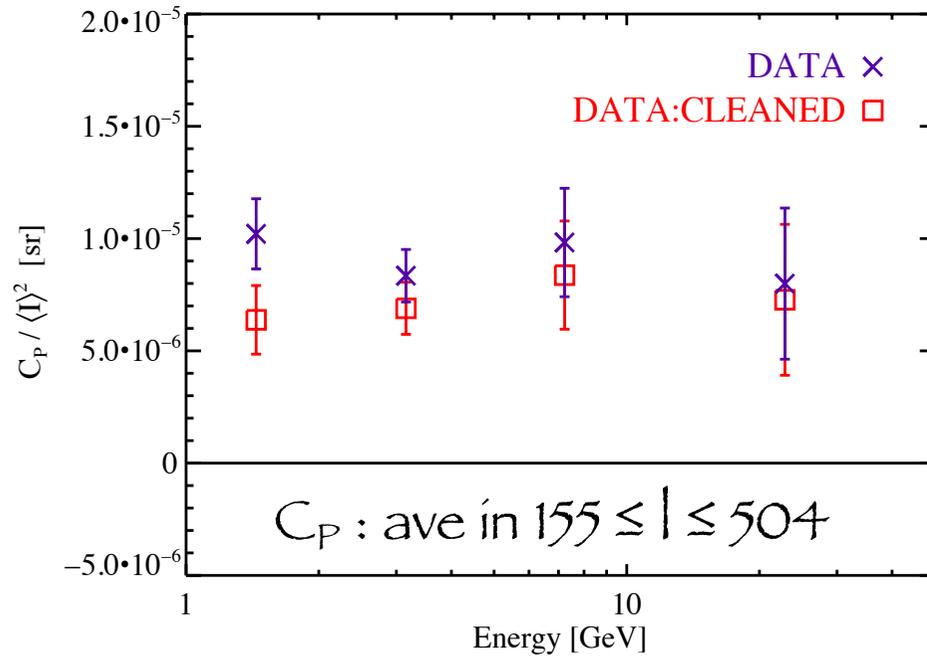


Fermi/LAT (22 months), 4 bins in 1–50 GeV

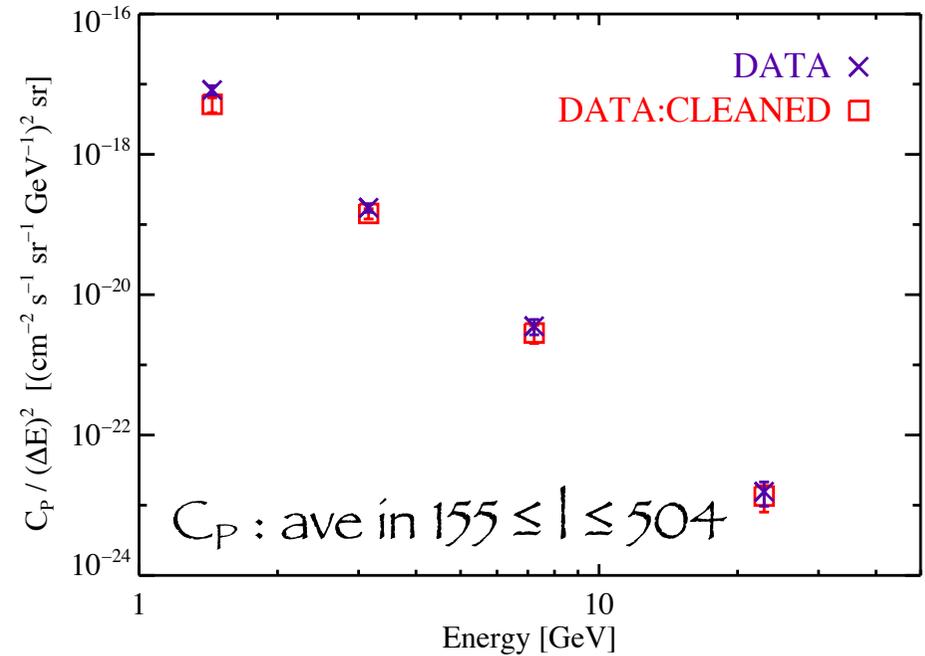
Overall significance: 9σ

See Fornasa's talk

Energy dependence



Fluctuation anisotropy spectrum



Differential anisotropy spectrum

Auto Correlation

$$C_l^{\gamma\gamma} \leftarrow W_\gamma^2(z) P(k, z)$$

window function

An arrow points from the text 'window function' to the $W_\gamma^2(z)$ term in the equation above.

power spectrum

An arrow points from the text 'power spectrum' to the $P(k, z)$ term in the equation above.

Observationally:

Energy dependence is available

Redshift dependence is not available

Correlation functions

Source Intensity

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

Density field of the source *Window function*

$W(z)$: does not depend on direction
depends on redshift
depends on energy

$g(z, n)$: describes how the “field” changes from point to point
contains the dependence on abundance +
distribution of sources

$$I_g(\vec{n}) \longrightarrow a_{lm}^g \longrightarrow C_l^{gg} = \frac{1}{2l+1} \sum_{l=-m}^m |a_{lm}^g|^2$$

Correlation functions

Source Intensity

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

Density field of the source *Window function*

Angular power spectrum

Halo model: see Viola's talk

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

3D Power spectrum (e.g. from the halo model)

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

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

\hat{f}_g : Fourier transform

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

Angular power spectrum

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

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

\hat{f}_g : Fourier transform

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

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

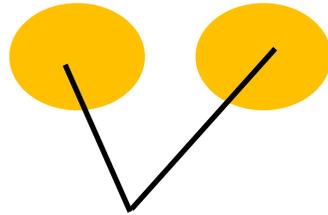
Linear matter PS

Linear bias

1 halo



2 halo



depends on spatial clustering

Astro sources:

typically considered as point-like

1h: poissonian, depends on abundance of sources

2h: traces matter through bias

Dark matter:

extended

Point-like sources:

if rare: 1h flat, large

if abundant: appear as more “isotropic”

1h smaller

2h may emerge and give info on clustering

Extended sources:

1h no longer flat, suppressed at scale $>$ size of sources

Main uncertainties: M_{\min}
subhalo boost

3D Power spectra

Annihilating DM

$$P_{1h}^{\delta^2\delta^2}(k, z) = \int_{M_{\min}}^{M_{\max}} dM \frac{dn}{dM} \left[\frac{\tilde{u}(k|M)}{\Delta^2} \right]^2$$

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

Decaying DM

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

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

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

Window functions

Gamma-rays from annihilating DM

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

Clumping factor : a measure of the clustering
DM photon "emissivity"

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

Subhalo boost

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

Uncertainties coming from:

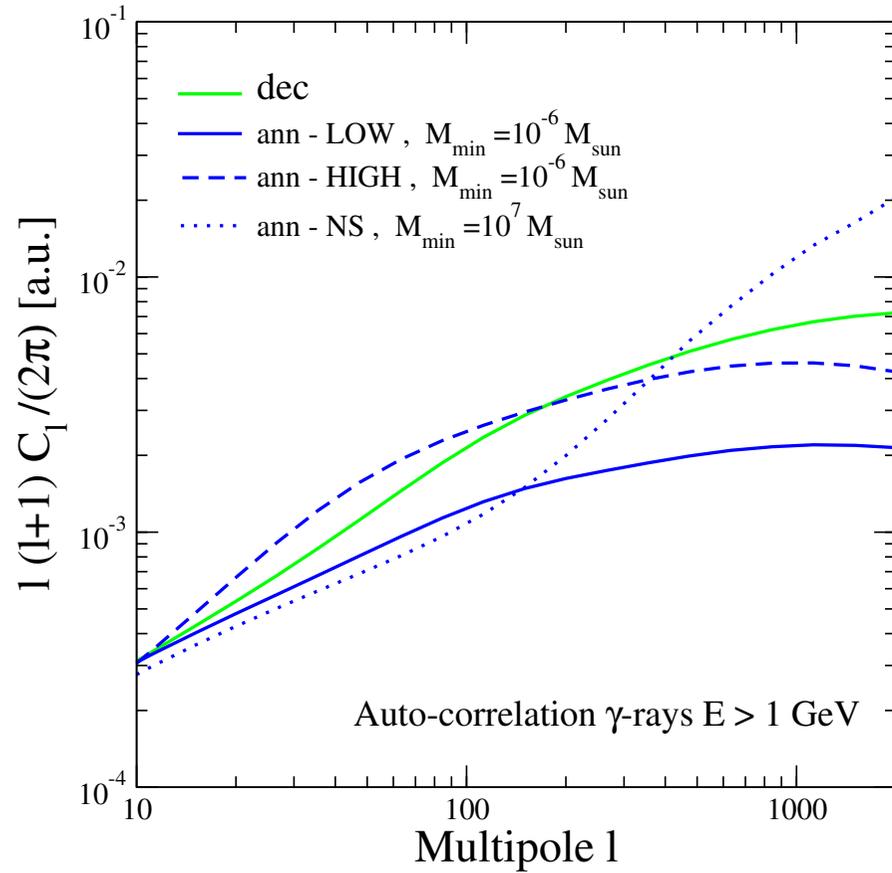
- Minimal halo mass M_{min}
- Halo concentration $c(M)$

Alternative approach to the Halo Model:
Serpico et al. MNRAS 421 (2012) L87
Sefusatti et al. MNRAS 441 (2014) 1861

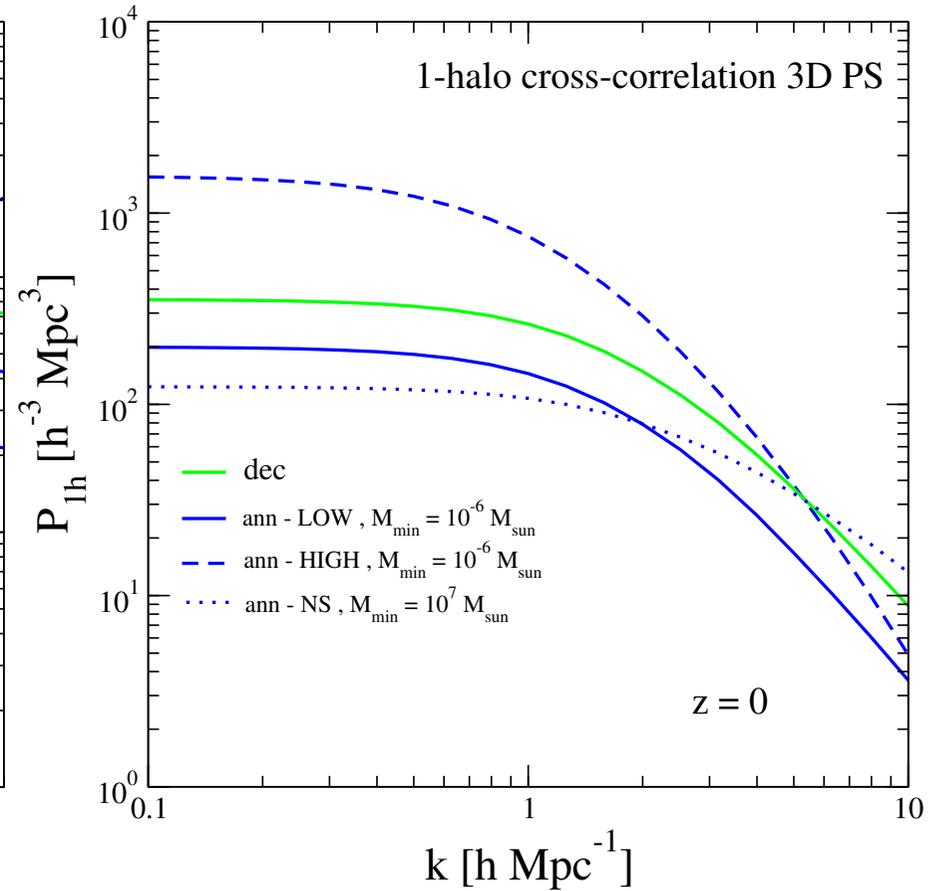
Gamma-rays are also emitted by astrophysical sources, each of which has a specific window function

See Sanchez-Conde + Calore's talk

Auto correlation



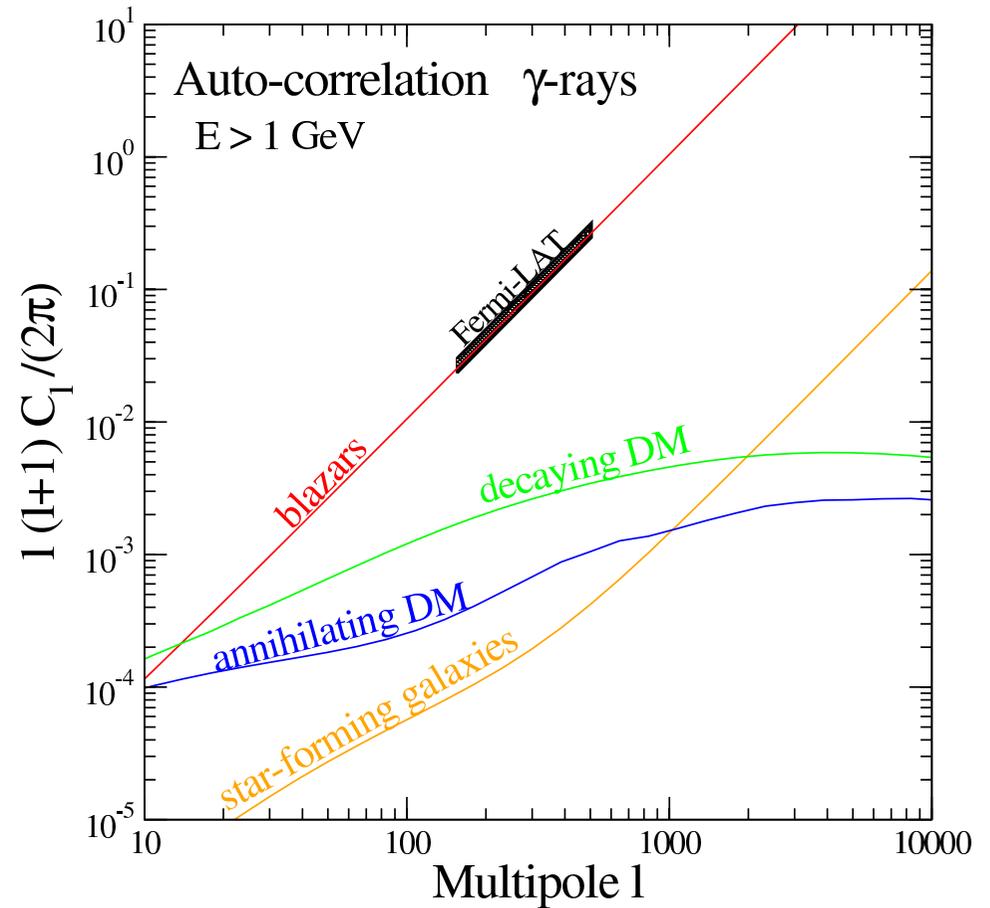
Angular power spectrum



3D power spectrum

Gamma-rays auto-correlation

Features of the signal point toward interpretation in terms of blazars

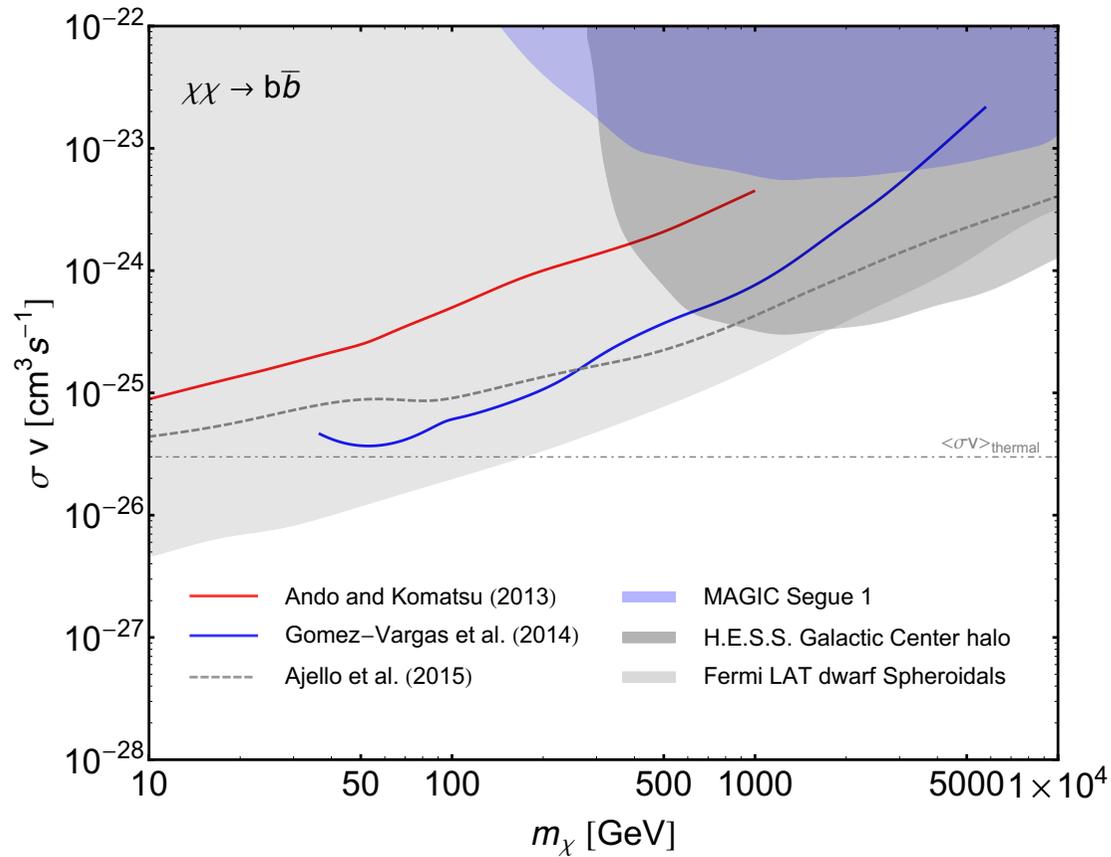


Cuoco, Komatsu, Siegal-Gaskins, PRD 86 (2012) 063004

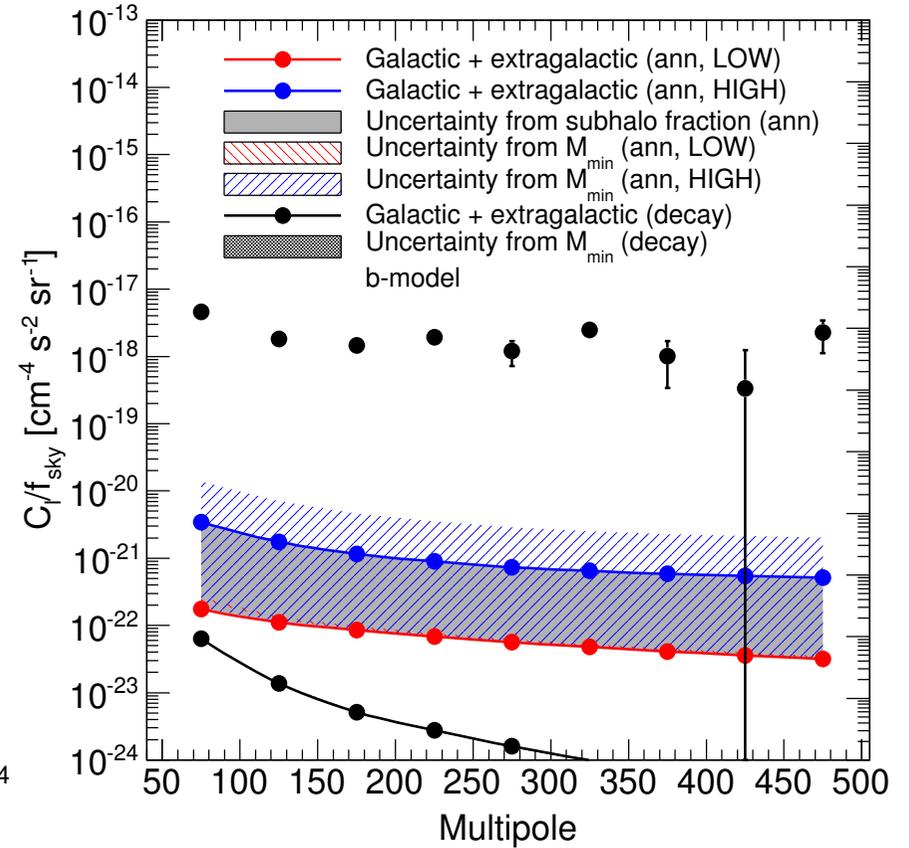
Harding, Abazajian, JCAP 1211 (2012) 026

Di Mauro, Cuoco, Donato, Siegal-Gaskins, JCAP 1411 (2014) 012

DM & Auto Correlation



Bounds



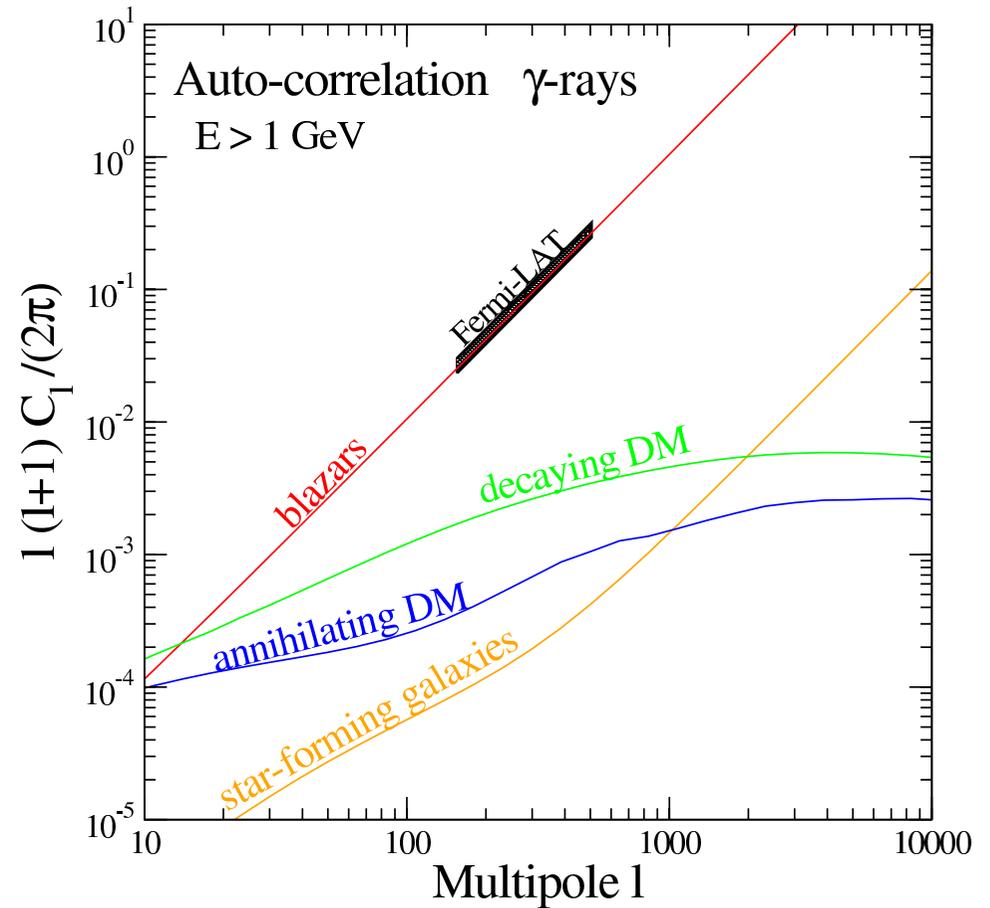
Uncertainties

Gamma-rays auto-correlation

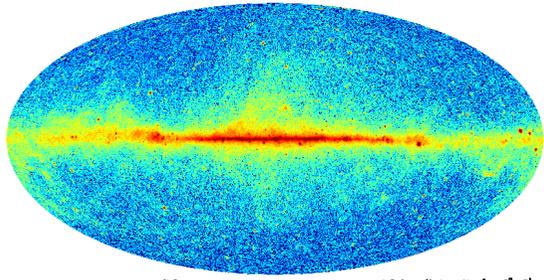
Features of the signal point toward interpretation in terms of blazars

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

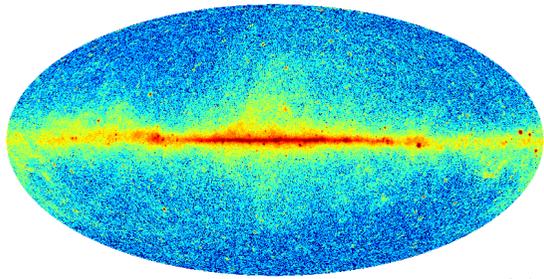
Difficult to extract a clear WIMP signature from the EGB alone



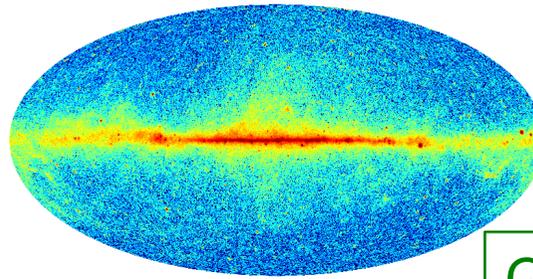
Photon statistics



Photon pixel counts (1 point PDF)

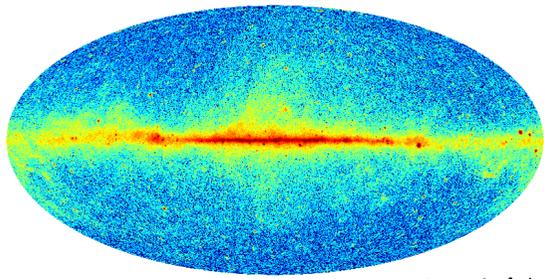


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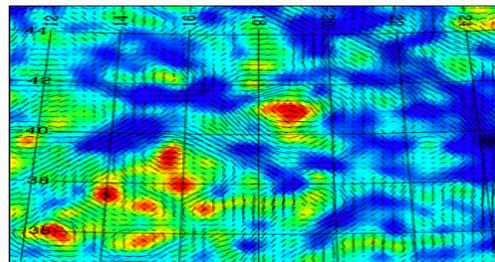


2 point correlator
angular power spectrum

On noise: See Campbell's talk



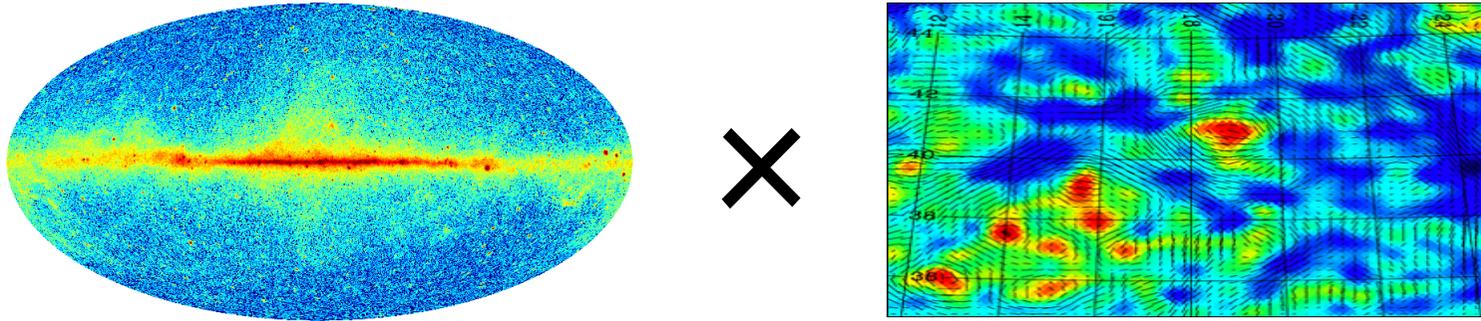
×



2 point correlator
angular power spectrum

$$\langle I_i(\vec{n}_1) I_j(\vec{n}_2) \rangle \longrightarrow C_{ij}(\theta) \longrightarrow C_l^{ij}$$

Cross Correlations



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

Cross Correlations

- Lensing observables

- **Cosmic shear**: directly traces the whole DM distribution

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

Camera, Fornasa, NF, Regis, JCAP 06 (2015) 029

- **CMB lensing**: traces DM imprints on CMB anisotropies

NF, Perotto, Regis, Camera, Ap. J. Lett. 802 (2015) 1 L1

NF, Regis, Frontiers in Physics, 2 (2014) 6

- Large scale structure

- **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

Xia, Cuoco, Branchini, Fornasa, Viel, MNRAS 416 (2011) 2247

Xia, Cuoco, Branchini, Viel, ApJS 217 (2015) 115

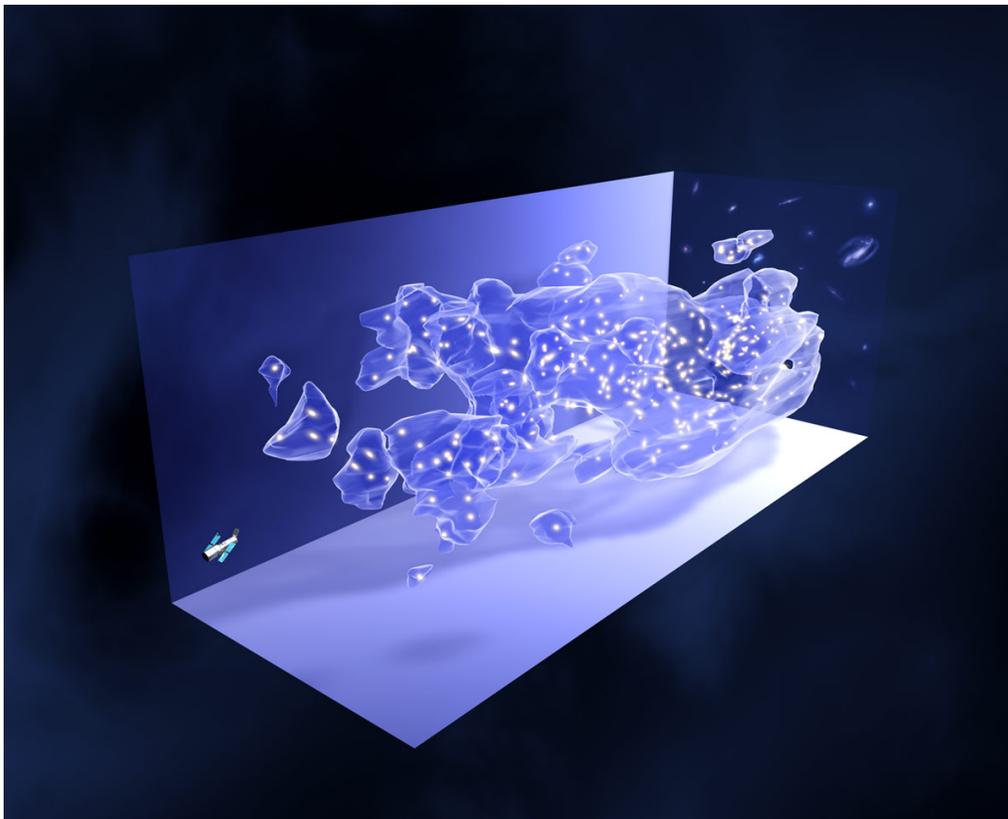
Regis, Xia, Cuoco, Branchini, NF, Viel, PRL 114 (2015) 24 241301

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

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



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 (DM) hidden in a large “noise” (astro)

Furhter advantages

Observationally:

- Auto correlation feels:
 - Detector noise (auto correlates with itself)
 - Galactic foreground (auto correlates with itself: typically GF is subtracted, but residuals may be present)
- Cross correlation “automatically” removes:
 - Detector noises (2 different detectors, noises do not correlate)
 - Galactic foreground (GT signals do not correlate with galactic gamma ray emission)

Life is more complex than that, but these can offer a good help

Cross Correlation

$$C_l^{\gamma\phi} \leftarrow W_\gamma(z)W_\phi(z)P(k, z)$$

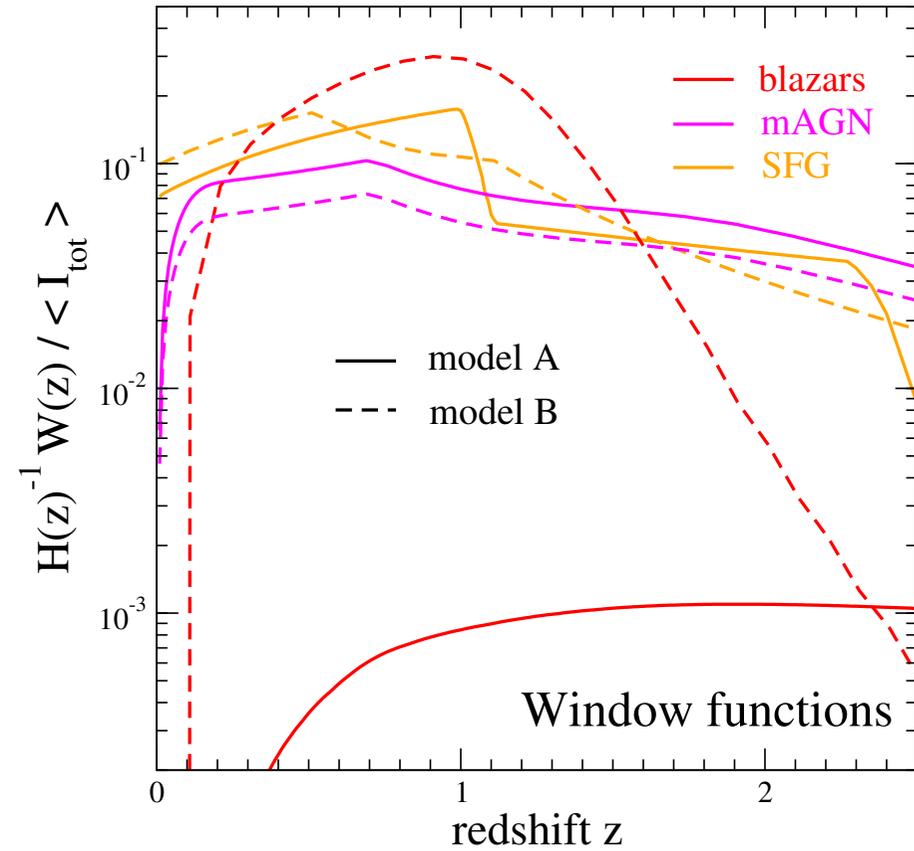
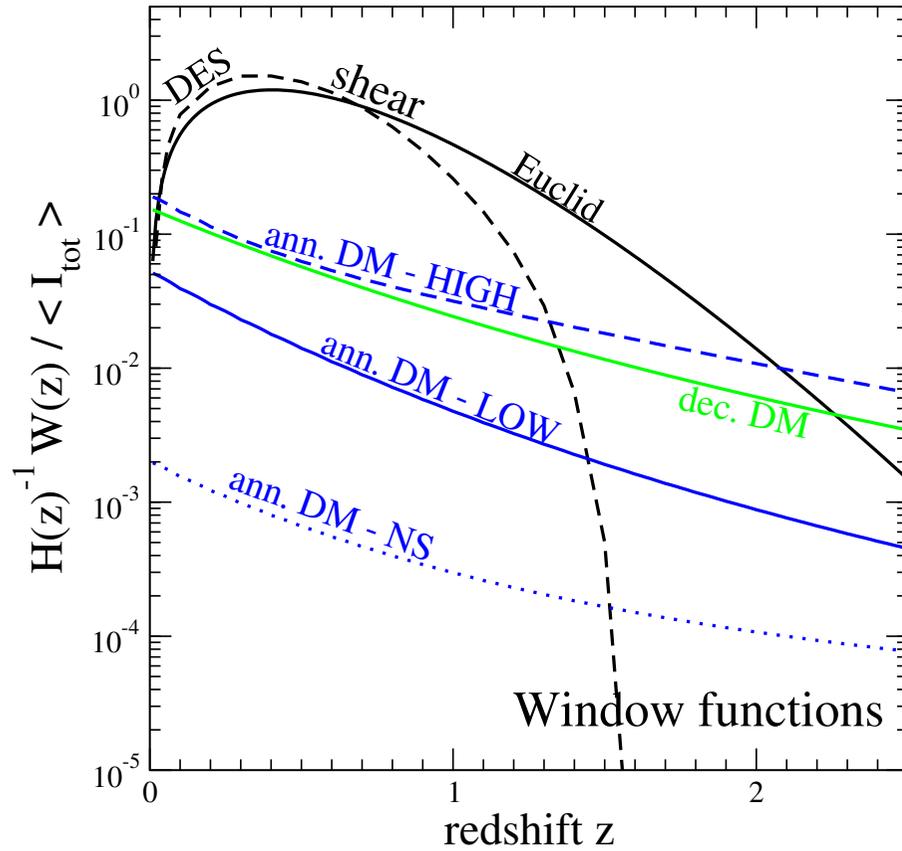
window functions

power spectrum

Observationally:

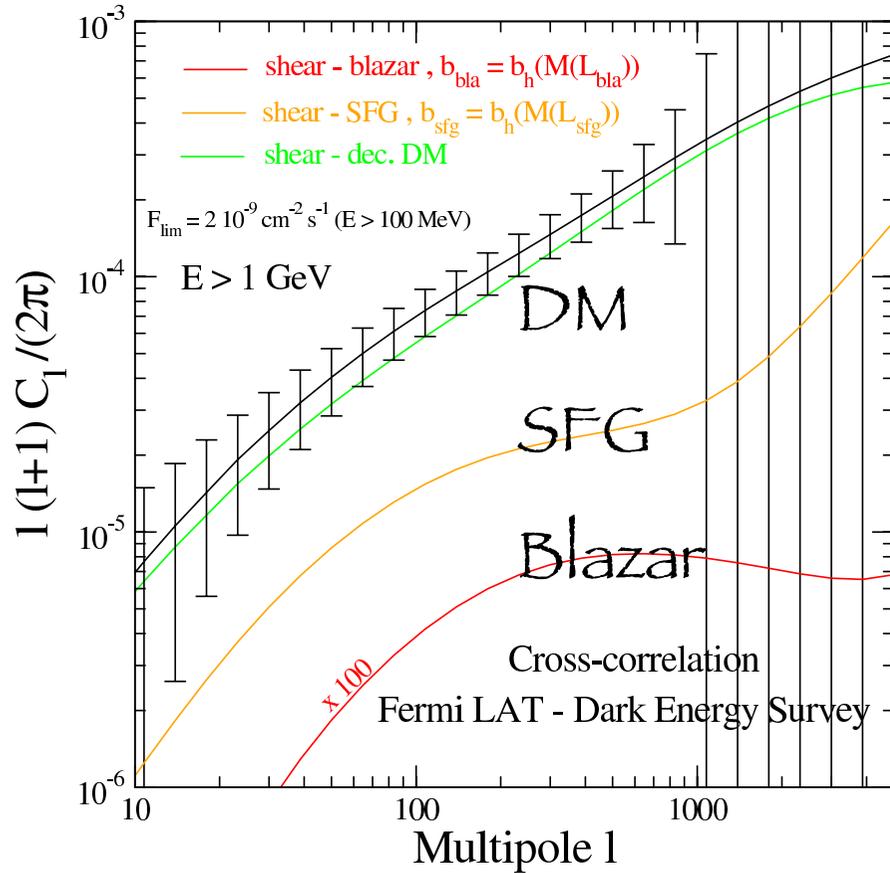
Energy dependence is available for the gamma rays signal
Redshift dependence is available from the GT side

Window functions



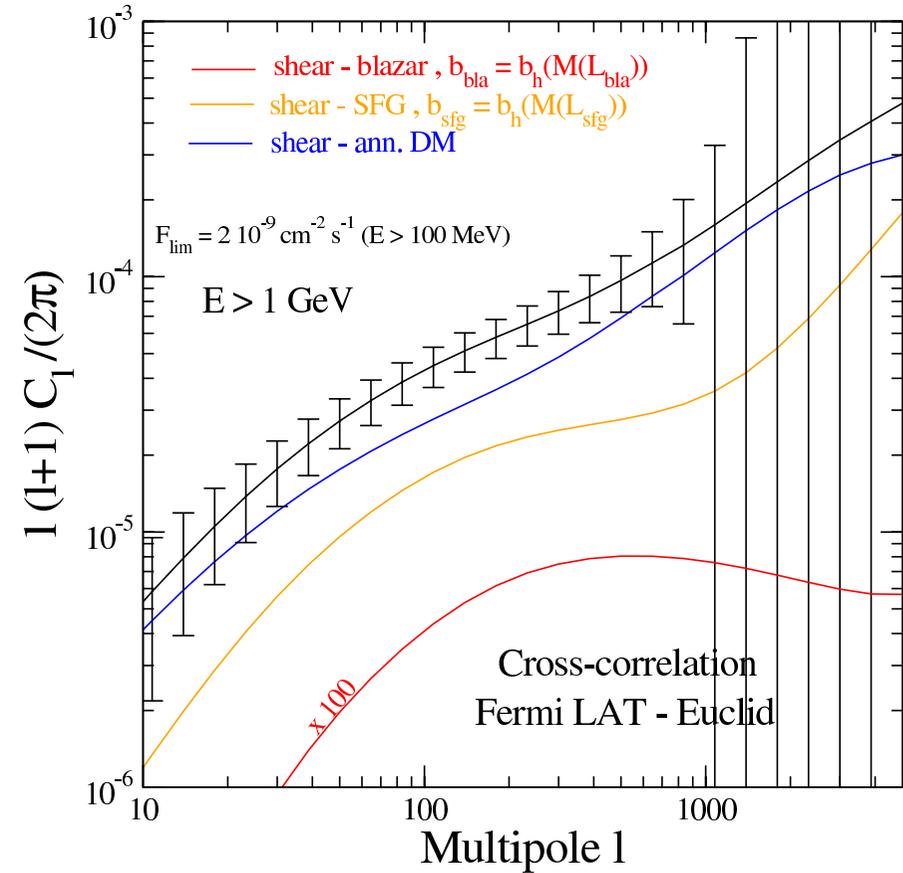
Proof of concept

Decaying DM



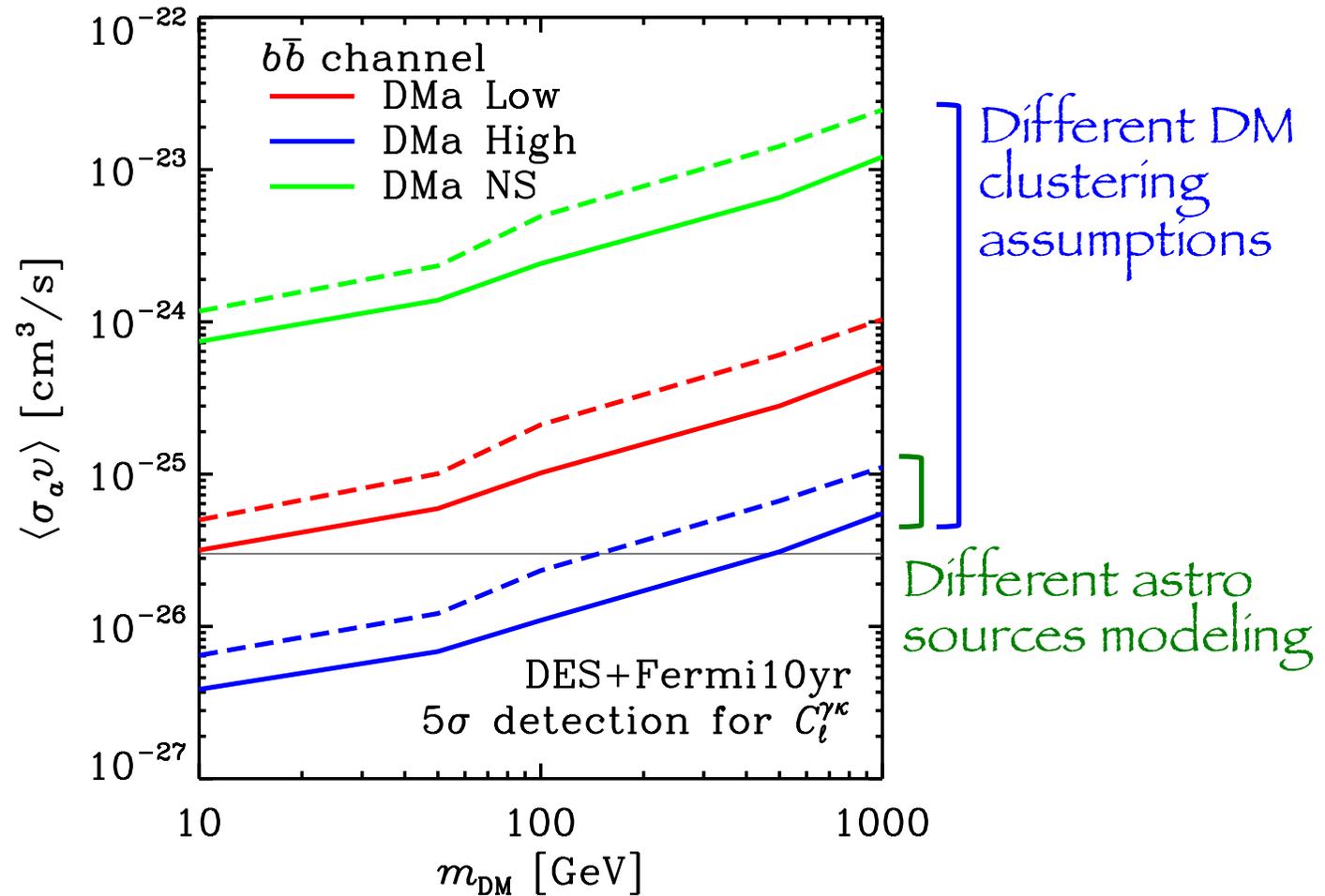
Fermi-LAT/5-yr with DES

Annihilating DM



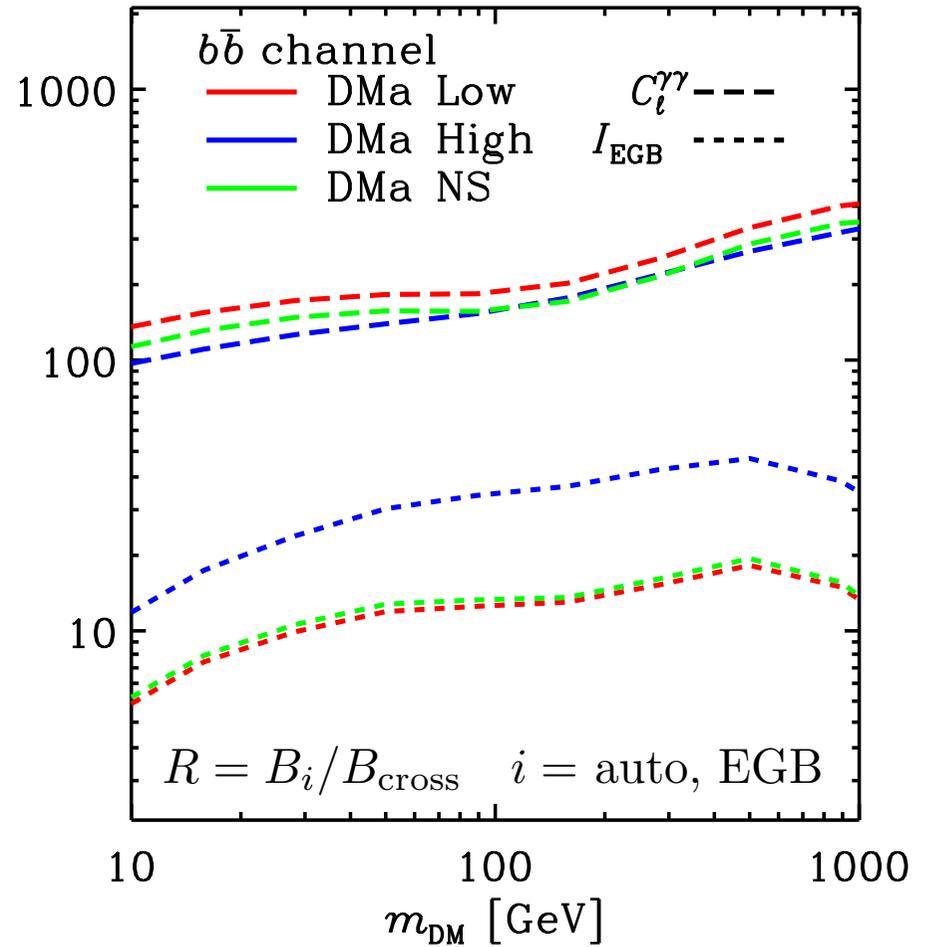
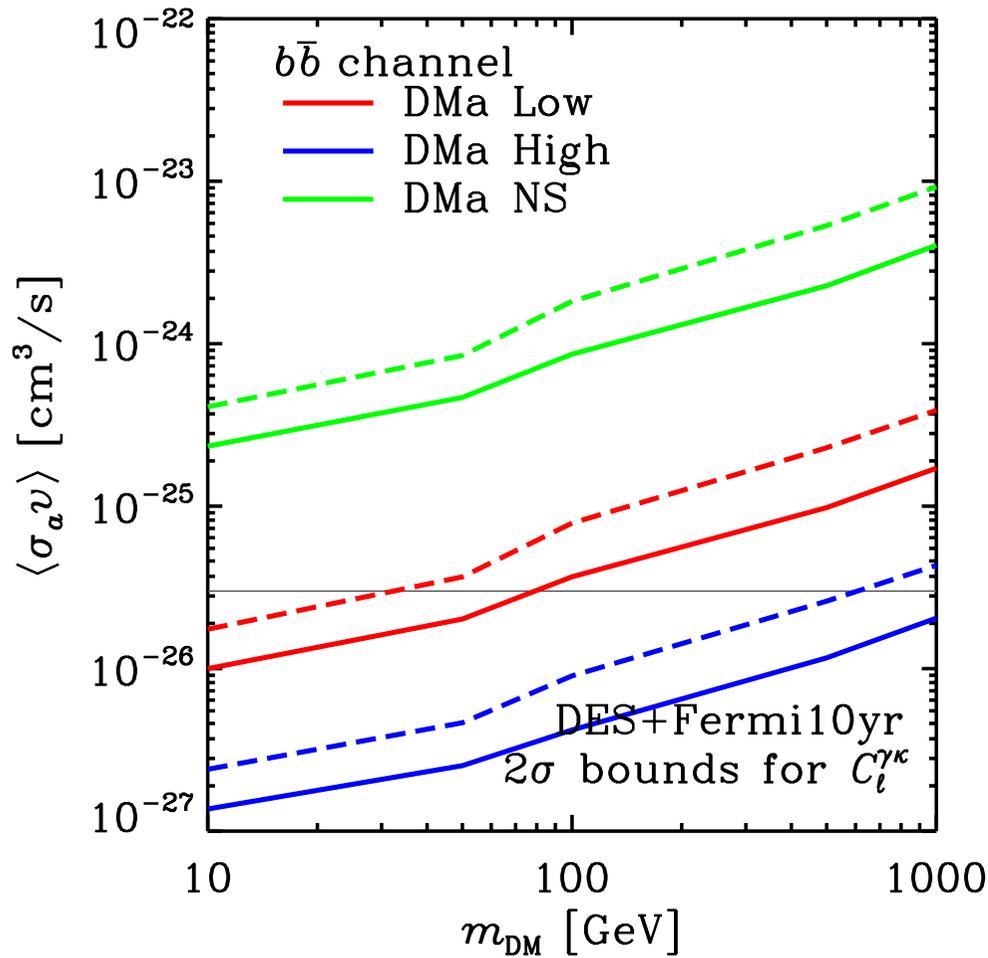
Fermi-LAT/5-yr with Euclid

Detection forecasts



5 σ detection for DES + Fermi 10yr

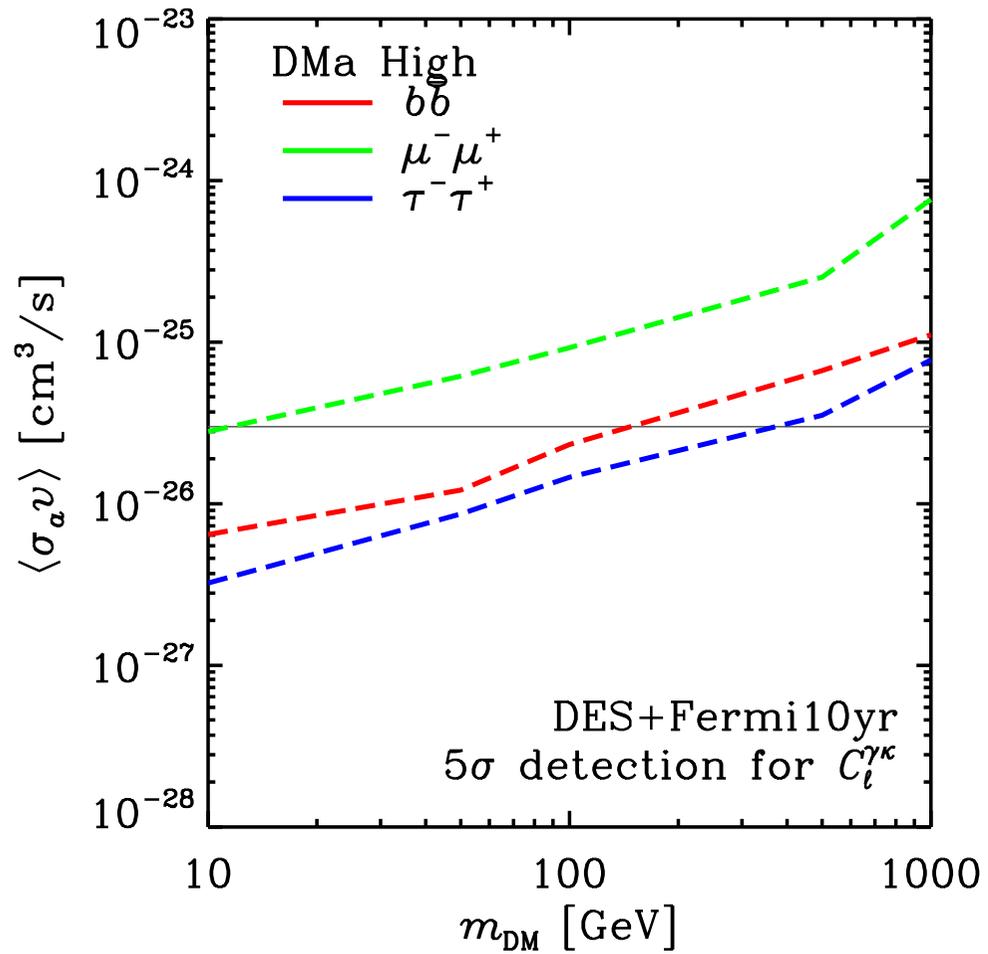
Sensitivity limits



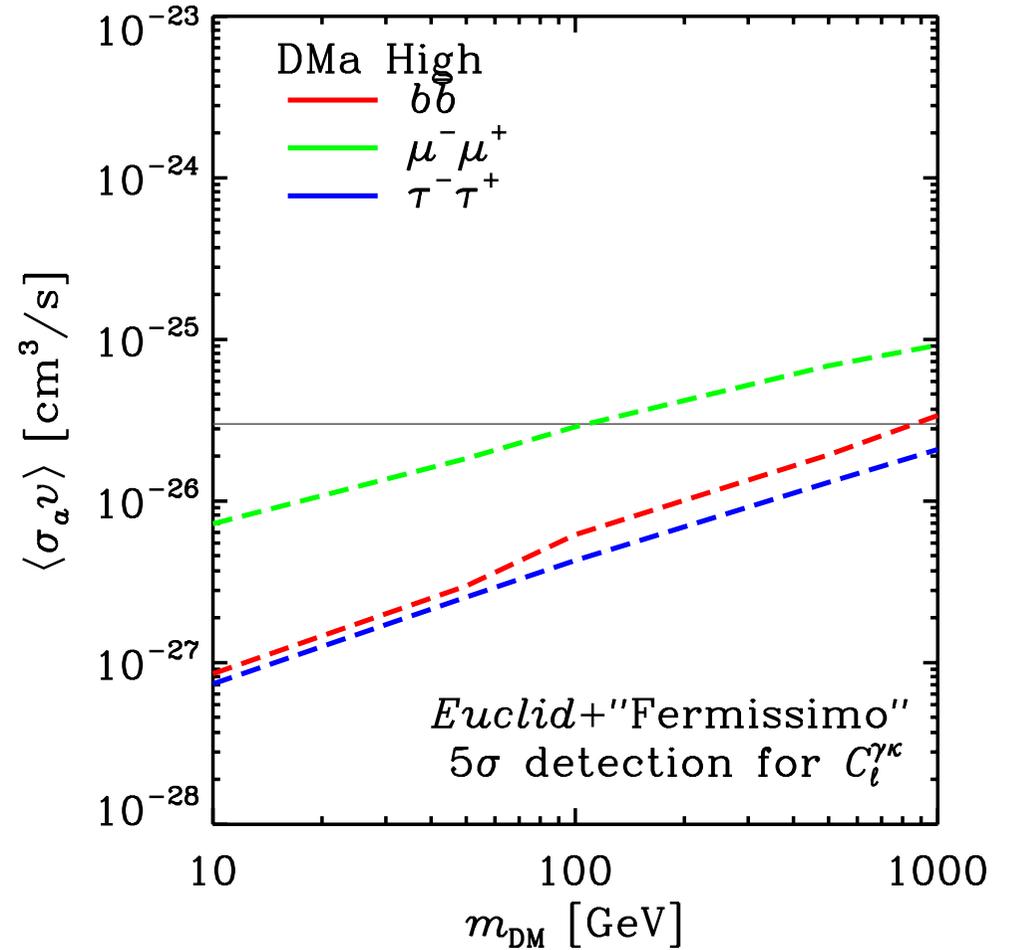
2 σ bounds
 DES + Fermi 10yr

Comparison

Detection forecasts

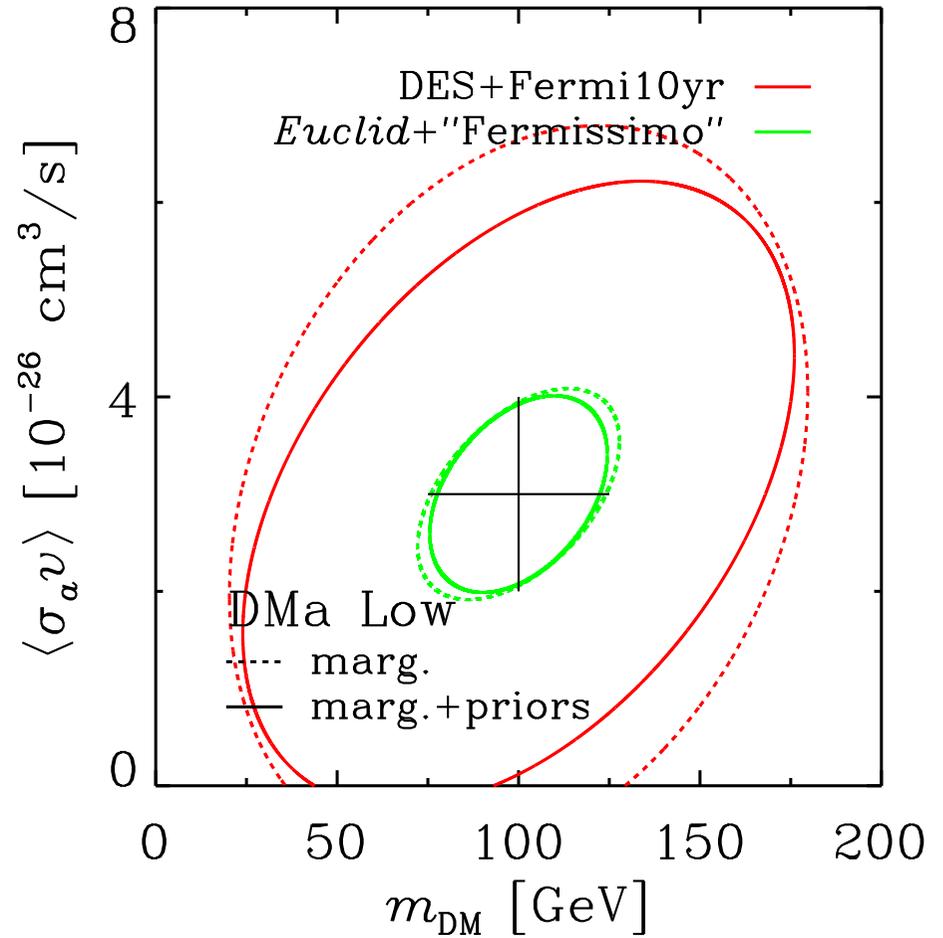
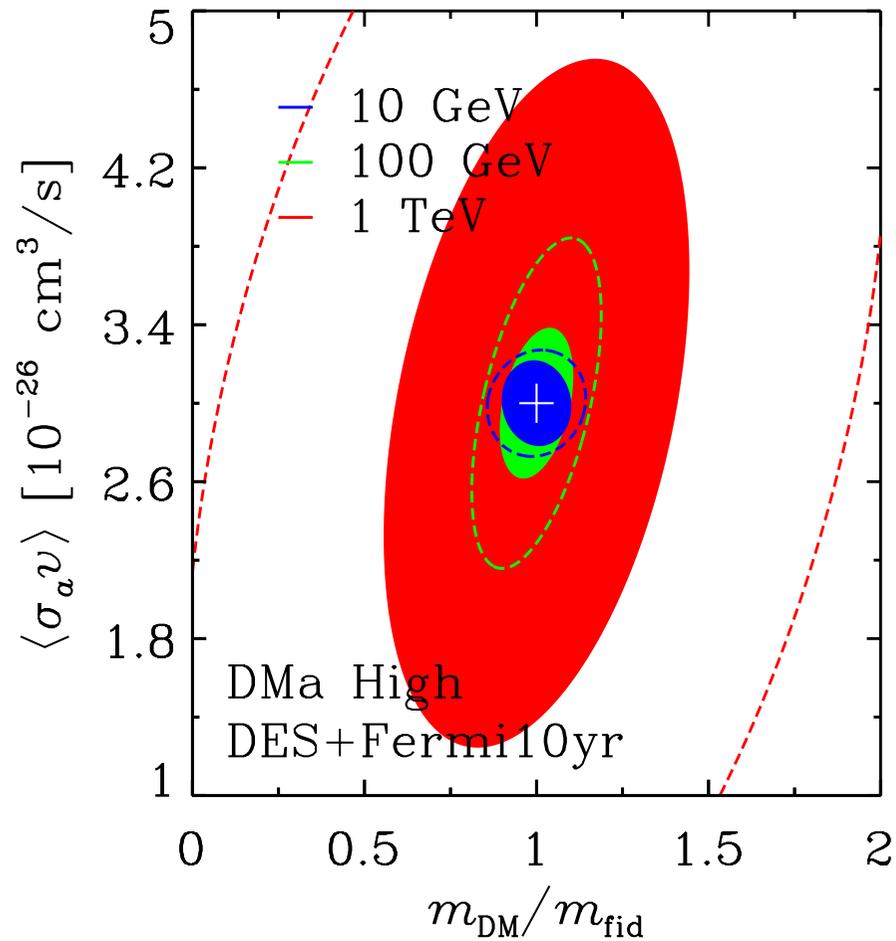


DES + Fermi 10yr



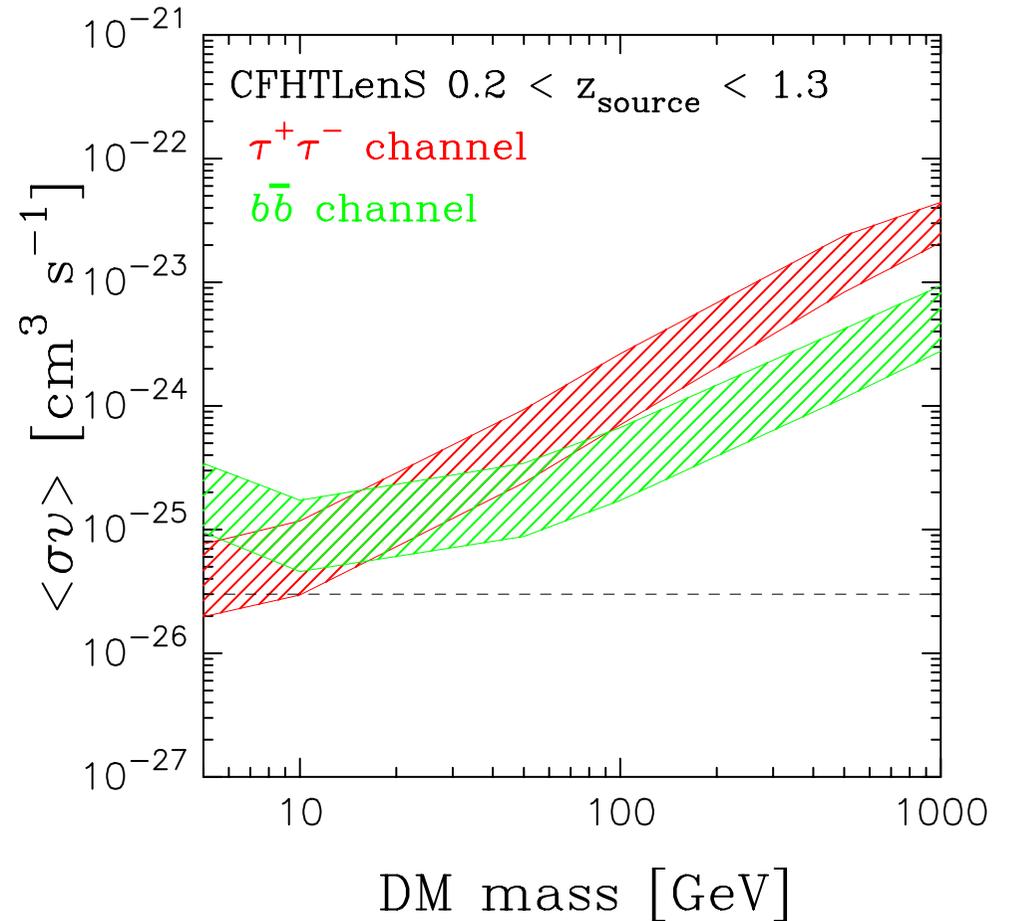
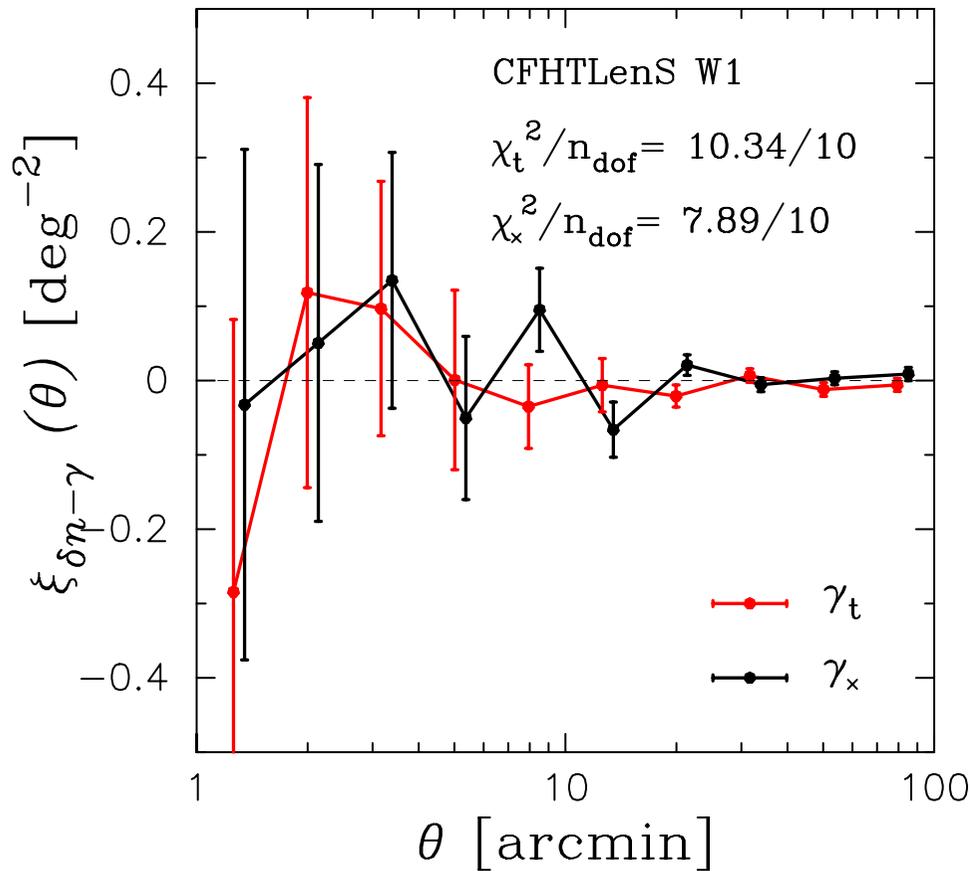
Euclid + “Fermissimo”

Sensitivity on DM parameters



First analysis on data

Patch W1: 72 sq. deg

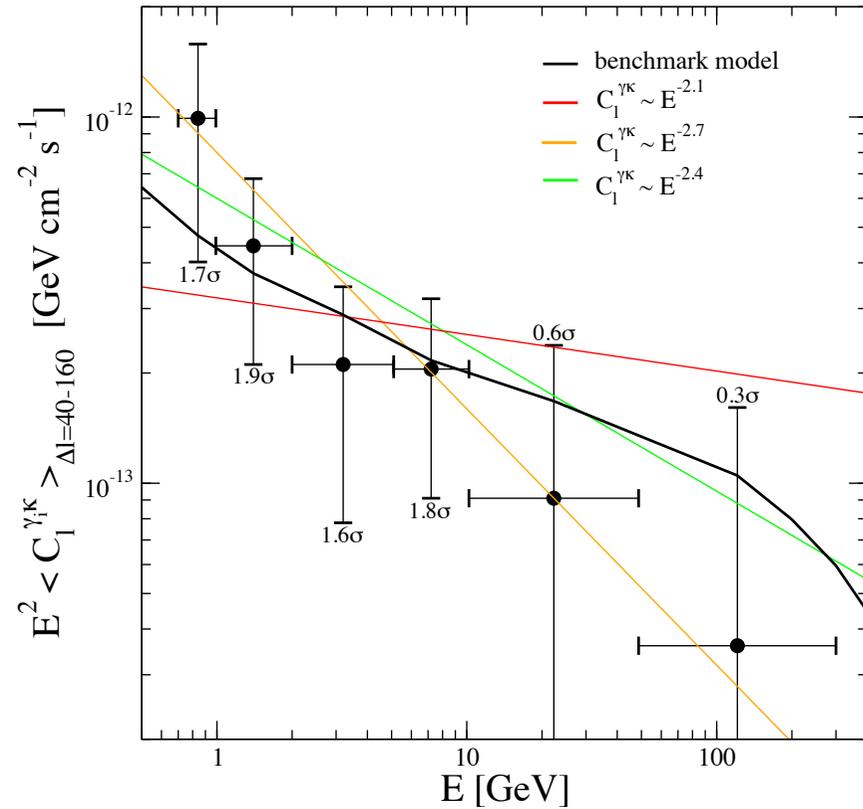
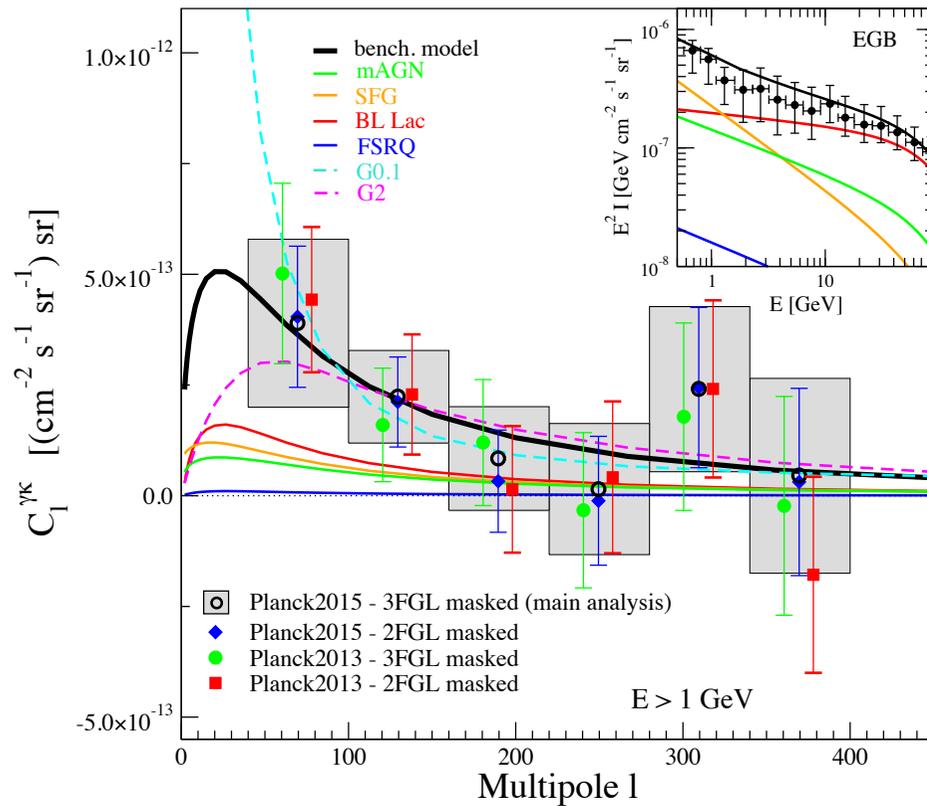


CFHTLenS + Fermi/5yr

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

CFHTLenS, RCSLenS, KiDS: See Troester's talk

Fermi/gamma + Planck/CMB lensing

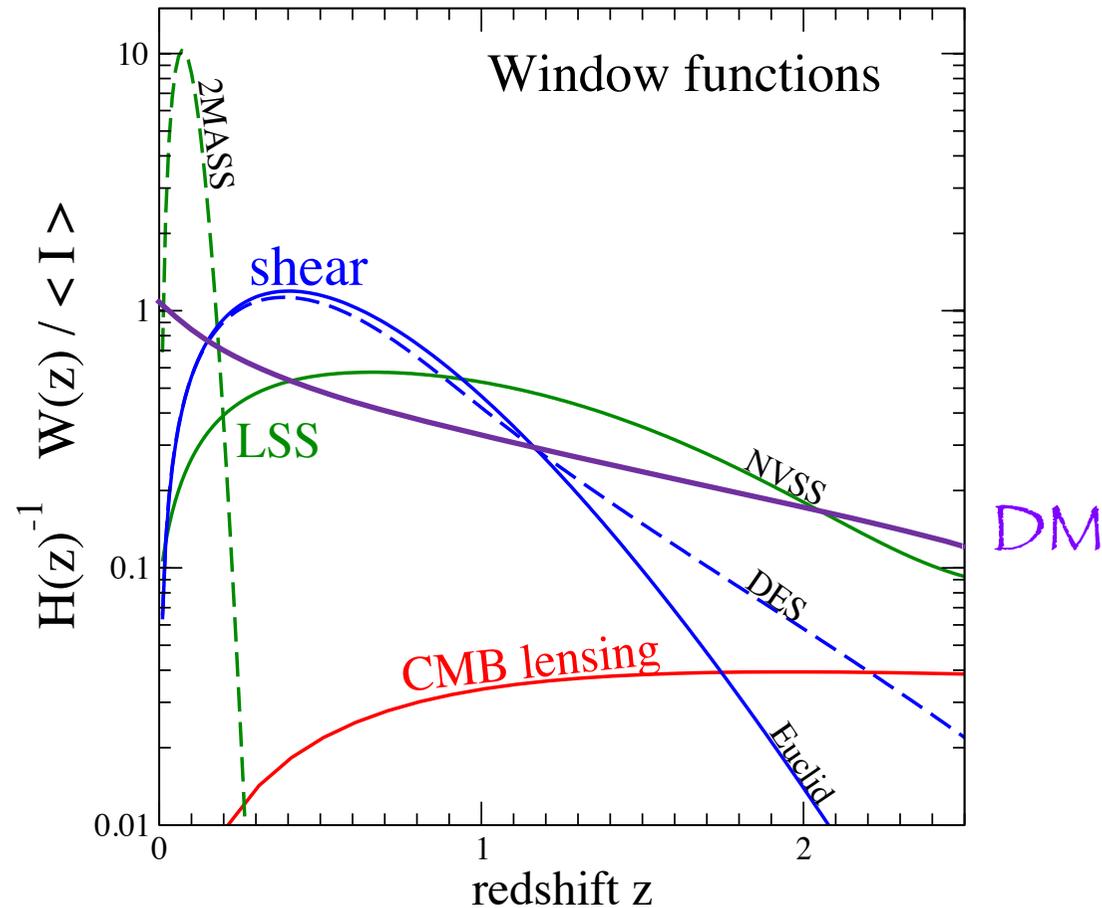


Cross-correlation: 3.0σ evidence

Compatible with AGN + SFG + BLA gamma-rays emission

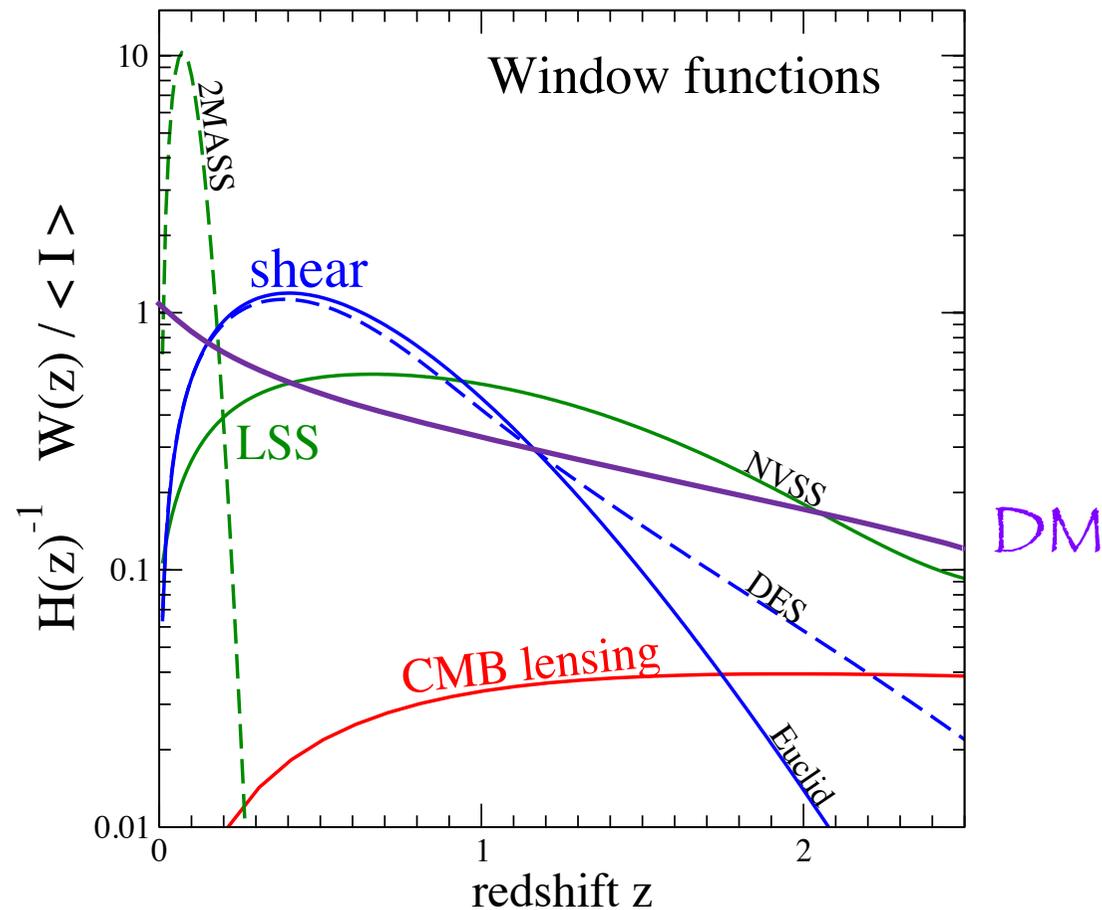
Points toward a direct evidence of extragalactic origin of the IGRB

Window functions: DM x CMB lensing



CMB lensing is likely not the best observable for DM
Instead it can hopefully help in constraining astrophysical sources

Window functions: DM x LSS



Galaxy catalogs (especially low- z ones) can have good overlap with DM
They trace light (while shear directly traces DM), but great potential

Cross correlation with galaxy catalogs

Cuoco, Brandbyge, Hannestad, Haugbolle, Miele, PRD 77 (2008) 123518

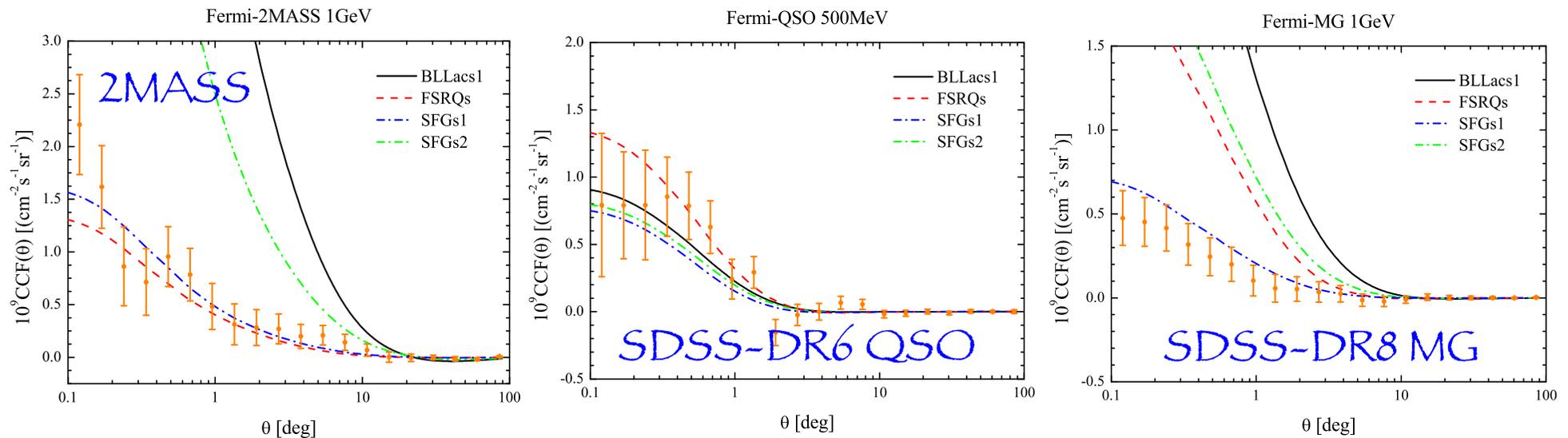
Xia, Cuoco, Branchini, Fornasa, Viel, MNRAS 416 (2011) 2247

SDSS 6, 2MASS, NVSS, SDSS 8 LRG \times Fermi 21 months no signal

Xia, Cuoco, Branchini, Viel, APJS 217 (2015) 15

SDSS 6 QSO, SDSS 8 MGS, SDSS LRG, 2MASS, NVSS
 \times Fermi 60 months

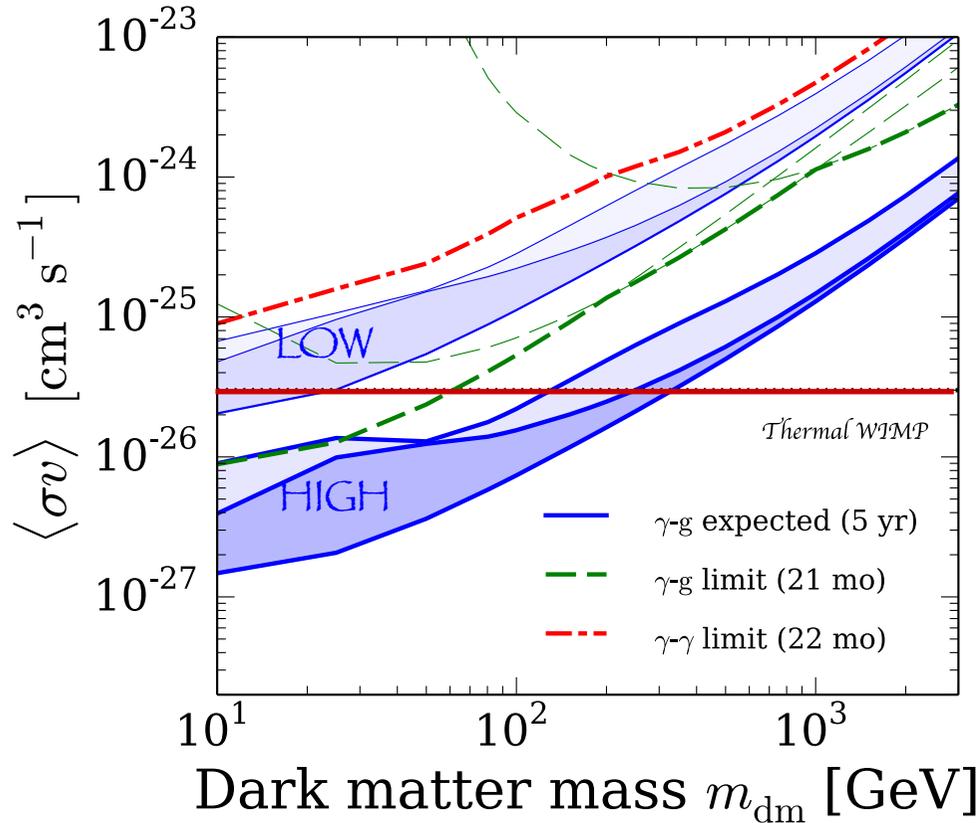
signal



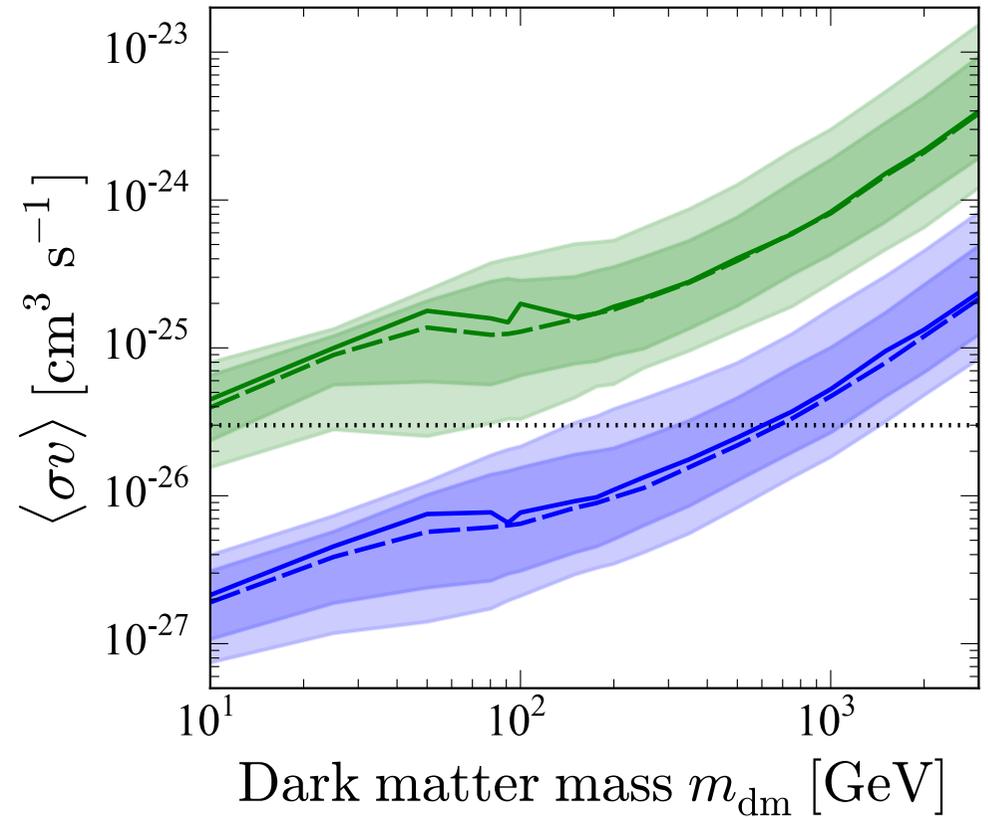
correlation at the degree scale

See Cuoco's talk

Fermi x 2MASS



Bounds based on non-observation
of correlation in (*)

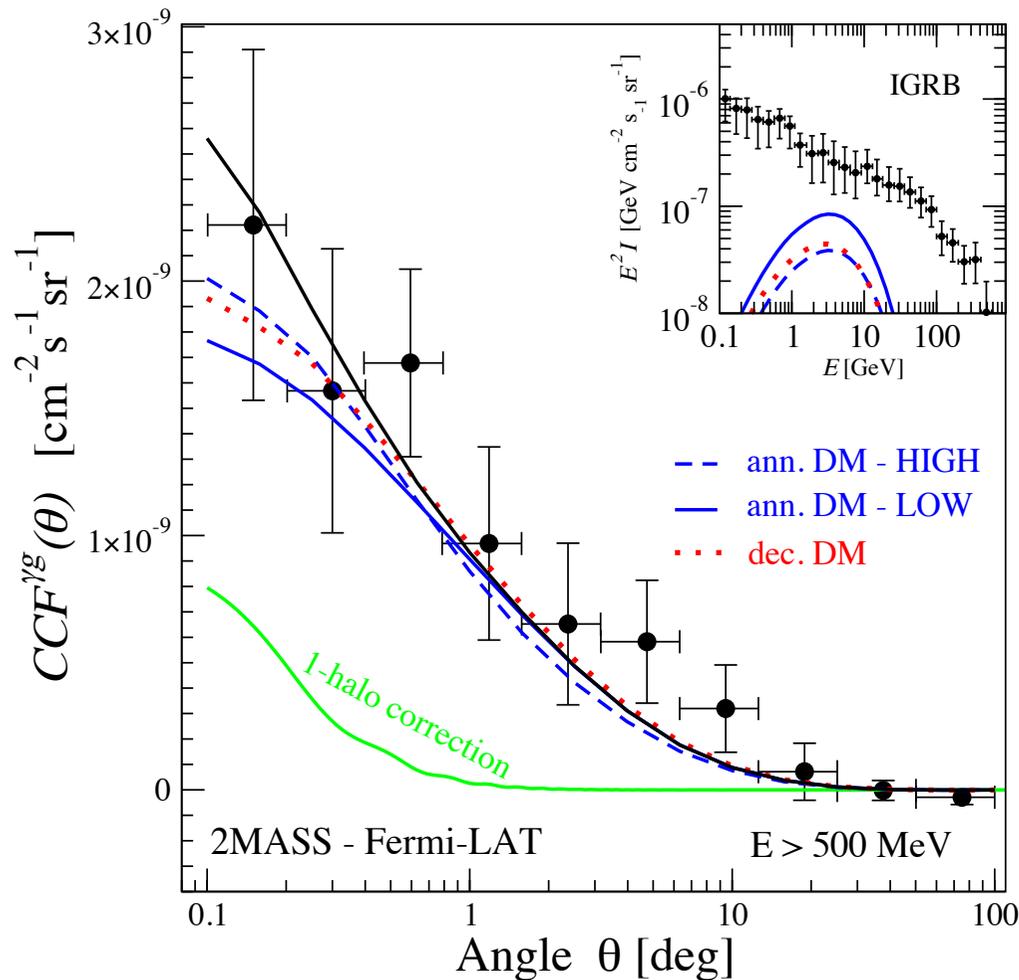


Forecasts
includes tomography

Ando, Benoit-Levy, Komatsu, PRD 90 (2014) 023514
(*) Xia et al. MNRAS 416 (2011) 2247

Ando, JCAP 1410 (2014) 061

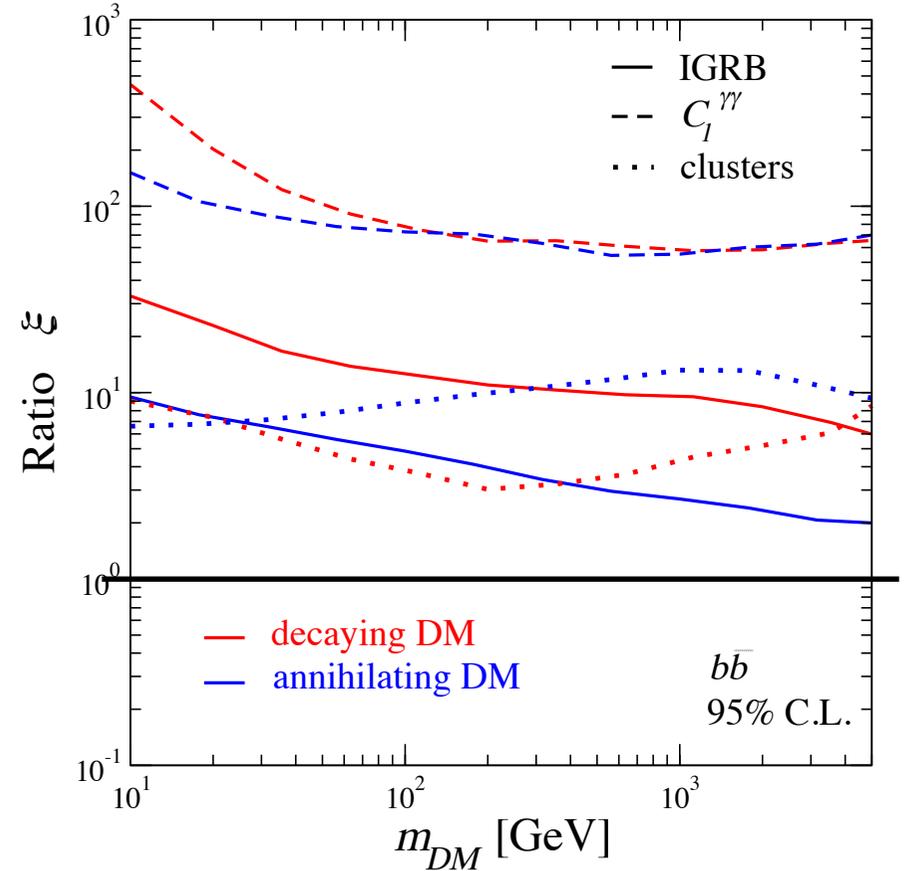
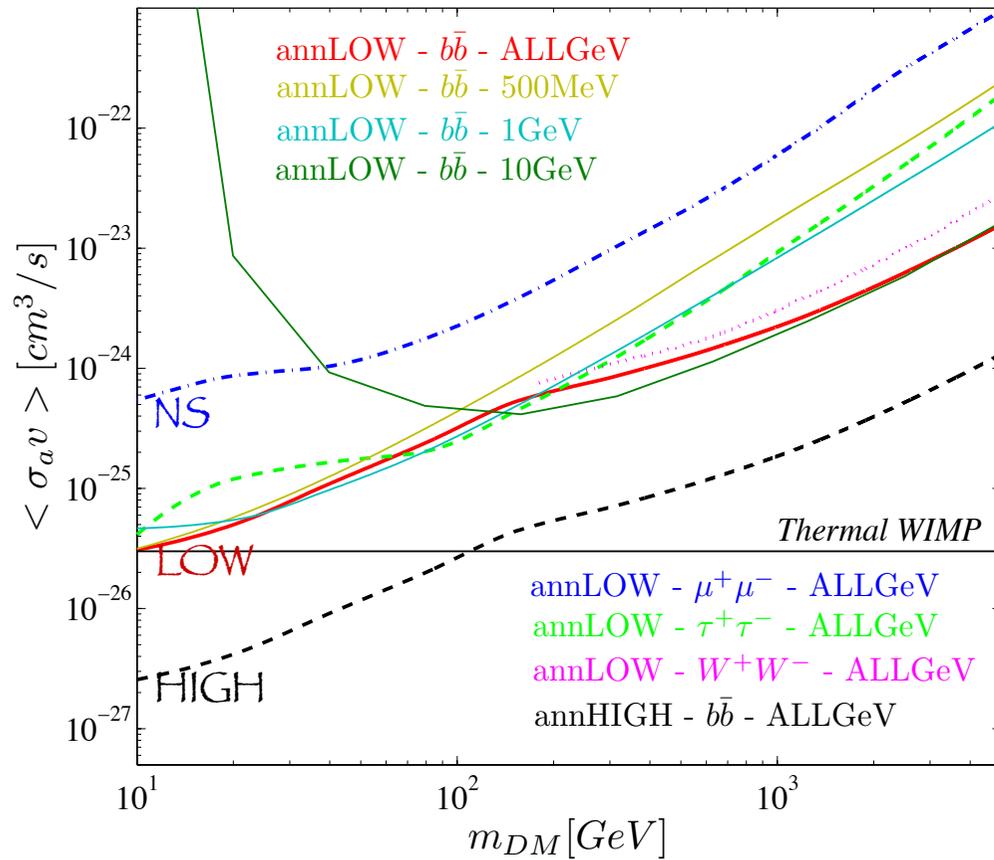
Fermi + 2MASS



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

Regis, Xía, Cuoco, Branchini, NF, Viel, PRL 114 (2015) 241301
(*) Xía, Cuoco, Branchini, Viel, APJS 217 (2015) 15

Fermi + 2MASS



Bound from cross correlation

Bounds ratios
Correlation technique stronger

Regis, Xía, Cuoco, Branchini, NF, Viel, ApJS 221 (2015) 29

For LRG, see also: Shirasaki, Horiuchi, Yoshida, PRD 92 (2015) 123540

Extension of the cross correlation approach

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

- Gravitational tracers:

G_i

- Weak lensing surveys (cosmic shear) traces the whole DM
- CMB lensing
- LSS surveys traces light \rightarrow bias

- Electromagnetic signals:

E_a

- Radio
- X
- Gamma

$$\langle G_i \times E_b \rangle$$

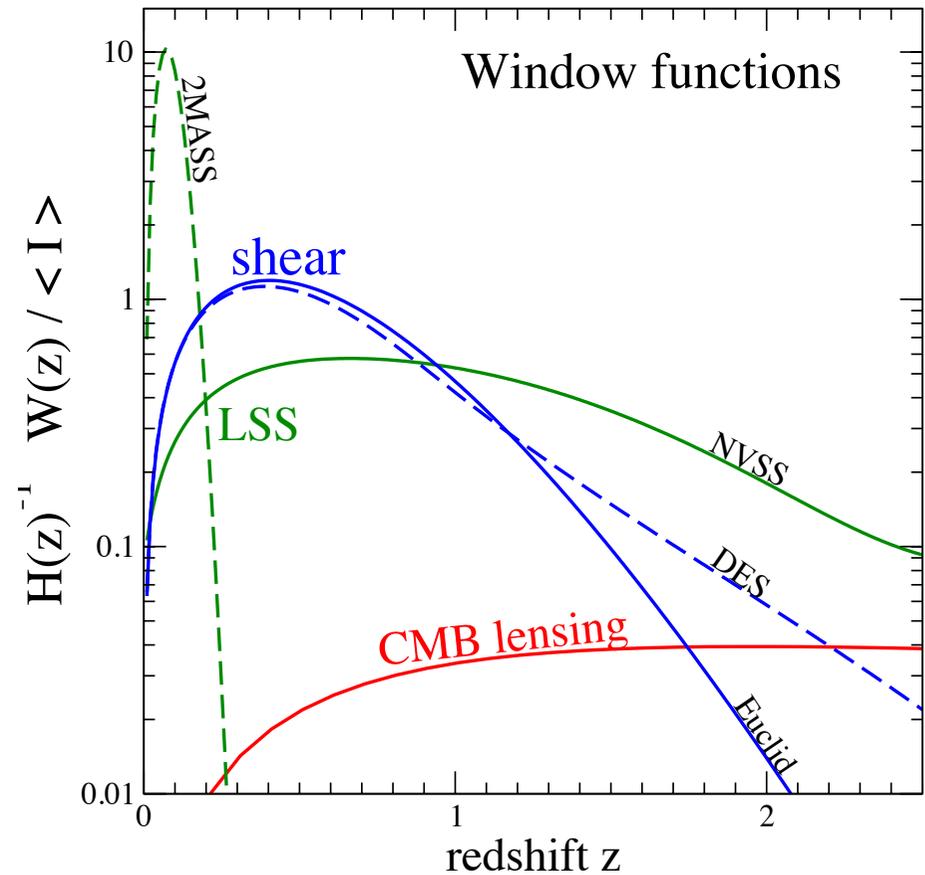
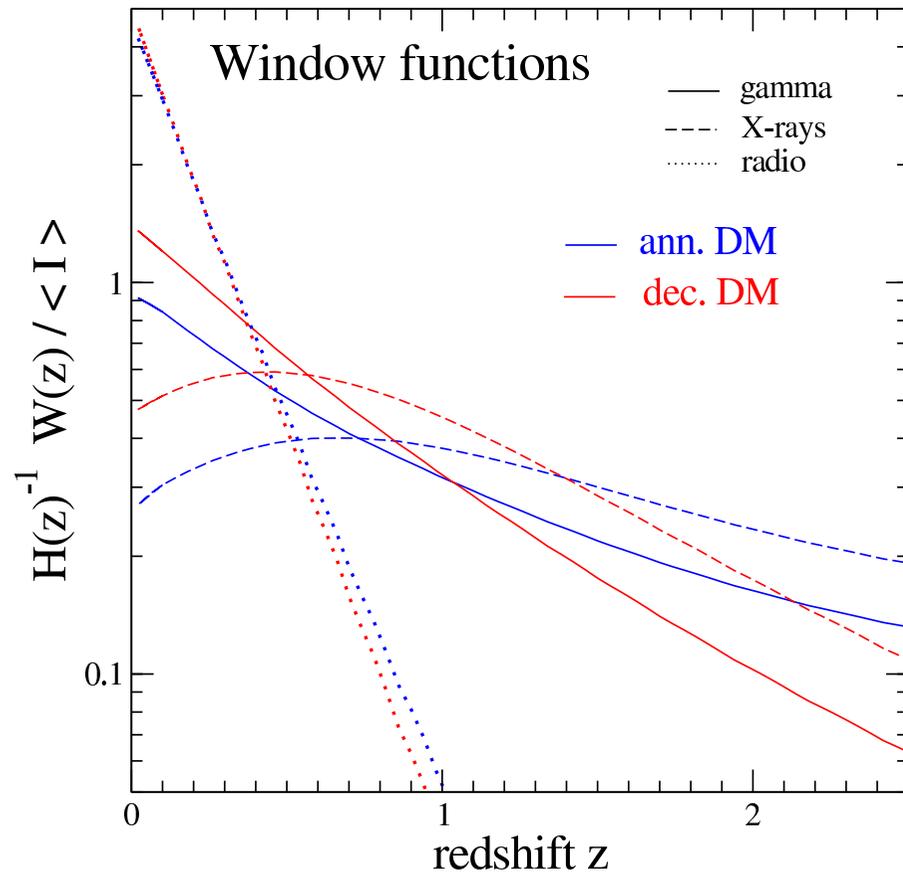
$$\langle E_a \times E_b \rangle$$

Multi frequencies: see Weniger's talk

Radio: see Regis' talk

X rays: Zandanel, Weniger, Ando, JCAP 09 (2015) 060

Additional cross correlations channels



Multiwavelength signals
&

LSS tracers and gravitational probes

Conclusions

- **Anisotropies** and studies of **photon statistics** are an emerging opportunity to study DM (and astrophysical sources) beyond the “tree level” of “isotropic” intensity investigation
- Many opportunities:
 - “One point statistics”: **Pixel counts**
 - “Two point statistics”: **Auto correlation**
 - “Two point statistics”: **Cross correlations**
 - **Wavelet** analyses
- **Autocorrelations have been measured** and, together with **pixel counts**, start (and will even more in the near future) to offer invaluable insights on the DGRB composition

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: **multiwavelength emission** (radio, X, gamma)
 - DM gravitational tracers: **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 soon 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 appear to have been identified:
 - Cross-correlation with galaxy catalogues and LSS objects (3.5σ)
 - Cross-correlation with CMB-lensing (3.0σ)
- Implications for DM might starts to be intriguing
- A lot of fun from here to the Anisotropic Workshop 3!



Backup slides

Auto Correlation

Density field: DM density contrast(²)

δ annihilating DM

δ^2 decaying DM

$$P^{\delta\delta}(k, z)$$

$$P^{\delta^2\delta^2}(k, z)$$

Correlation functions

Source Intensity

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

Density field of the source *Window function*

$W(z)$: does not depend on direction
depends on redshift
depends on energy

$g(z, n)$: describes how the “field” changes from point to point
contains the dependence on abundance of sources
distribution

$$\begin{array}{l} I_g(\vec{n}) \longrightarrow a_{lm}^g \\ I_k(\vec{n}) \longrightarrow a_{lm}^k \end{array} \longrightarrow C_l^{gk} = \frac{1}{2l+1} \sum_{m=-l}^l a_{lm}^{g*} a_{lm}^k$$

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 (e.g. from the halo model)

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

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

\hat{f}_g : Fourier transform

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

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

Linear matter PS

Linear bias

Cross Correlation

Density field: DM density contrast(²)

δ annihilating DM, lensing, LSS

δ^2 decaying DM

$$P^{\delta\delta}(k, z)$$

$$P^{\delta\delta^2}(k, z)$$

3D Power spectra

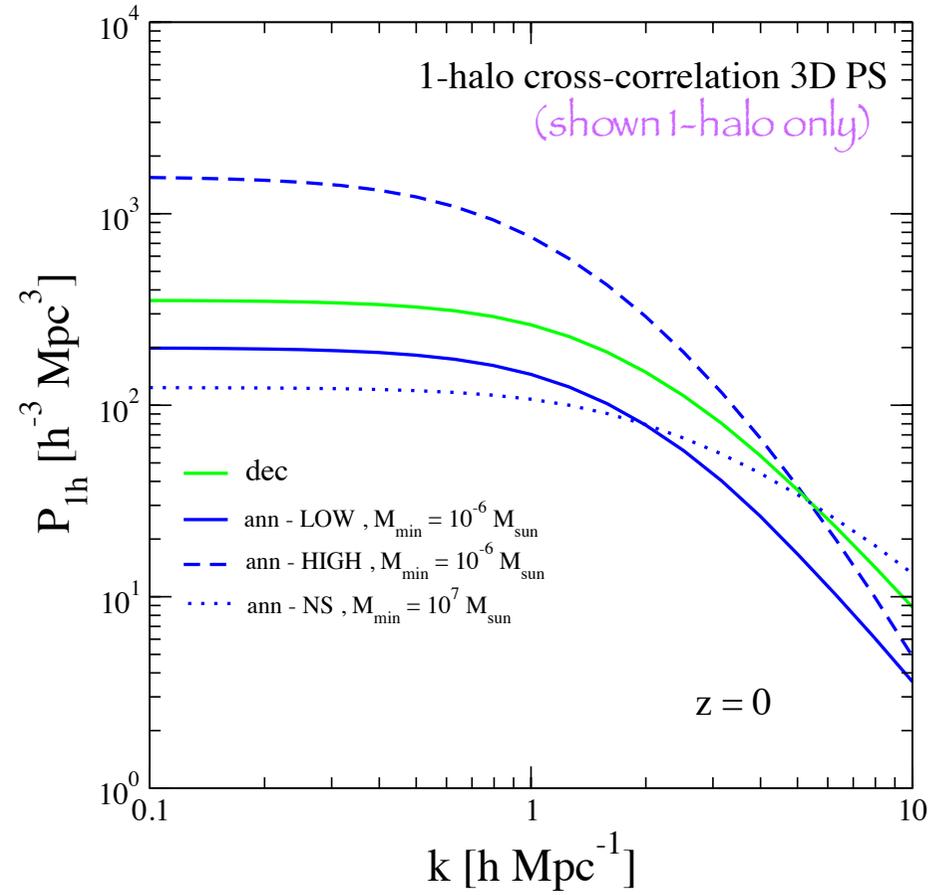
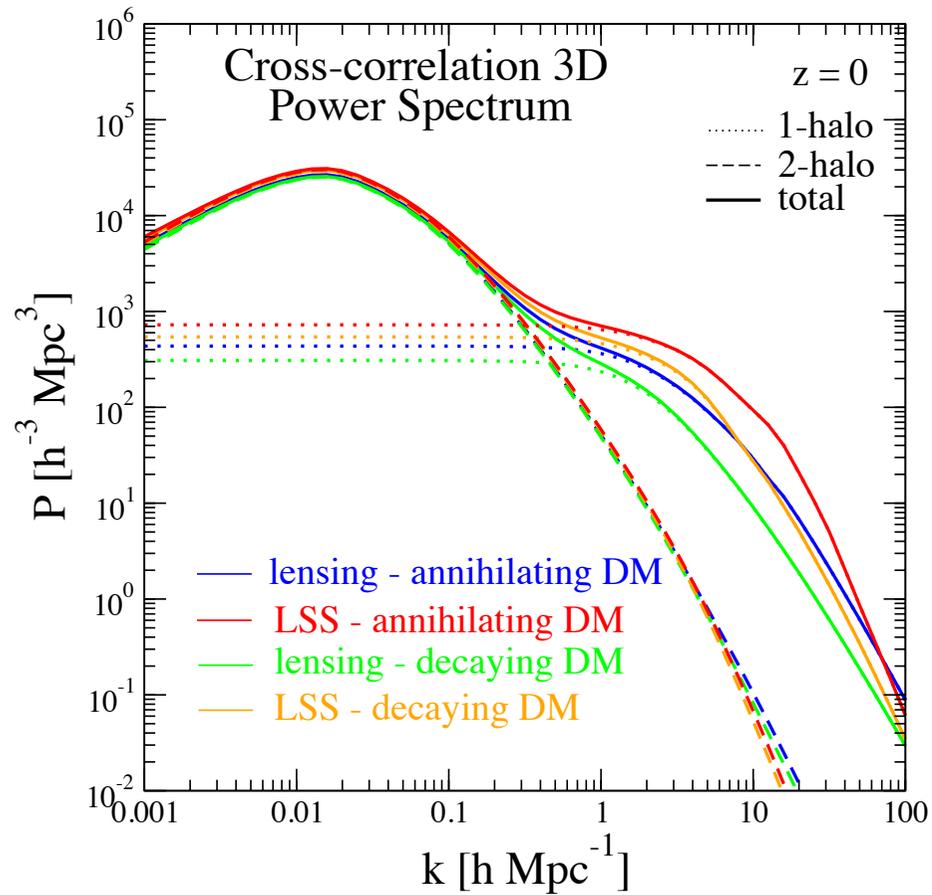
Annihilating DM

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

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

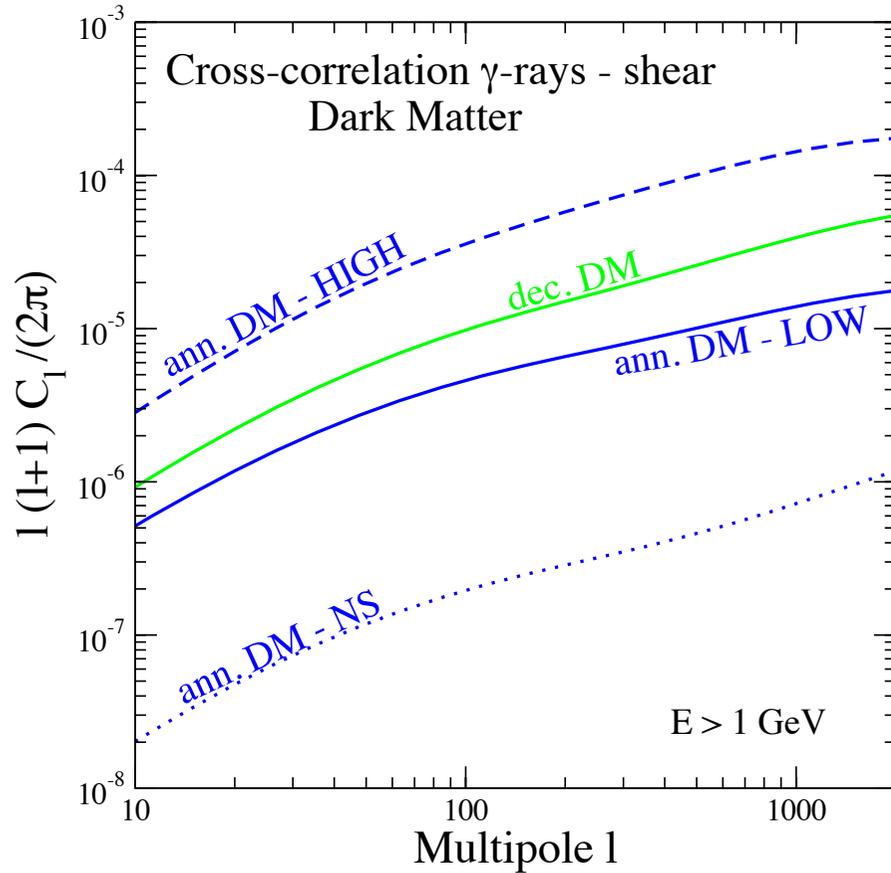
- dn/dM Halo mass function
- $\tilde{v}(k|M)$ Fourier transform of $\rho_{\text{DM}}(\mathbf{x}|M)/\bar{\rho}_{\text{DM}}$
- $\tilde{u}(k|M)$ Fourier transform of $\rho_{\text{DM}}^2(\mathbf{x}|M)[1 + b(M, z)]/\bar{\rho}_{\text{DM}}^2$
- $b_h(M)$ Bias between halo and matter

3D Power spectra

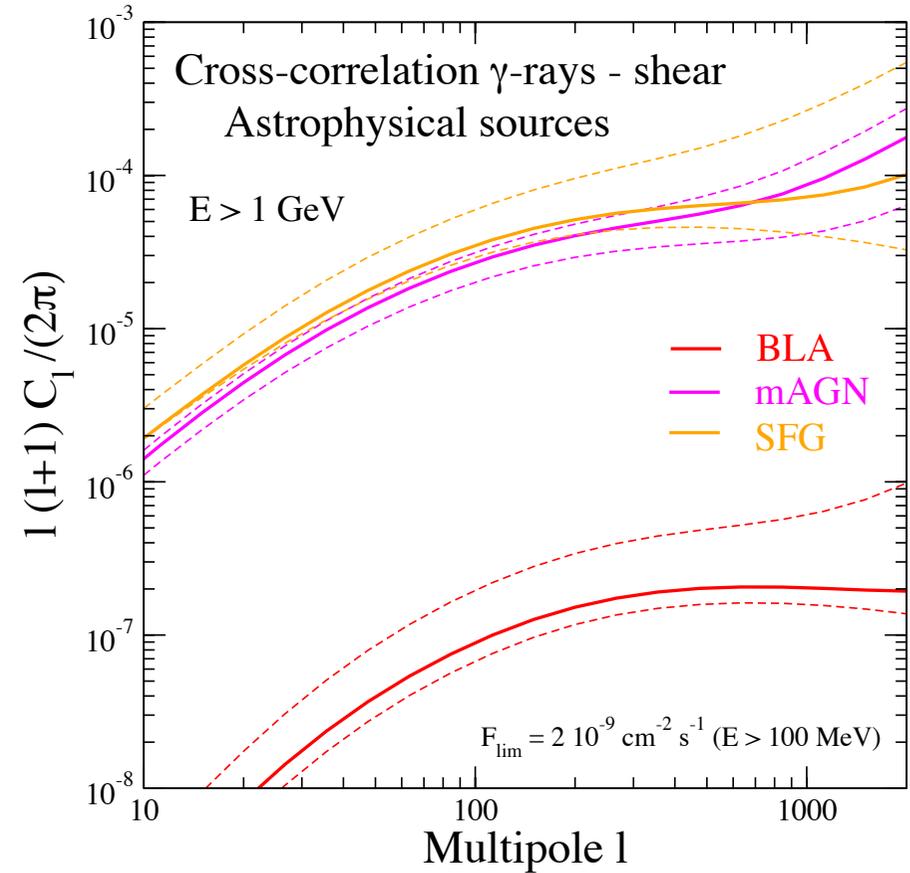


Angular power spectra

Dark Matter APS



Astrophysical sources APS



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

Detectors and configurations

Parameter	Description	DES	Euclid
f_{sky}	Surveyed sky fraction	0.12	0.36
$\bar{N}_g [\text{arcmin}^{-2}]$	Galaxy density	13.3	30
$z_{\text{min}} - z_{\text{max}}$	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

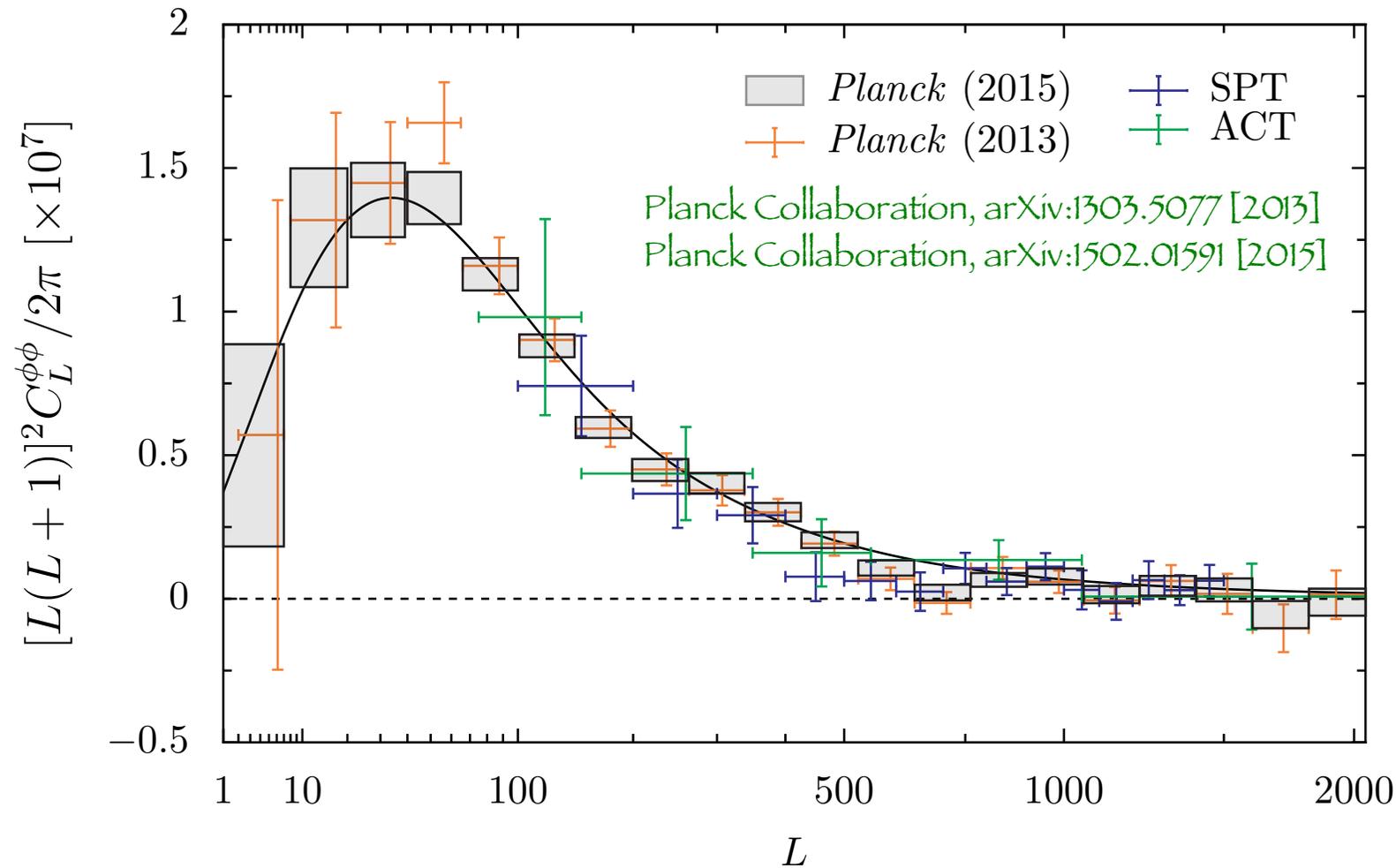
Parameter	Description	Fermi-10yr	Fermissimo
f_{sky}	Surveyed sky fraction	1	1
$E_{\text{min}} - E_{\text{max}} [\text{GeV}]$	Energy range	1 – 300	0.3 – 1000
N_E	Number of bins	6	8
$\epsilon [\text{cm}^2 \text{ s}]$	Exposure	3.2×10^{12}	4.2×10^{12}
$\langle \sigma_b \rangle [\text{deg}]$	Average beam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

Combinations:

DES + Fermi 10 yr

Euclid + “Fermissimo”

Planck CMB lensing



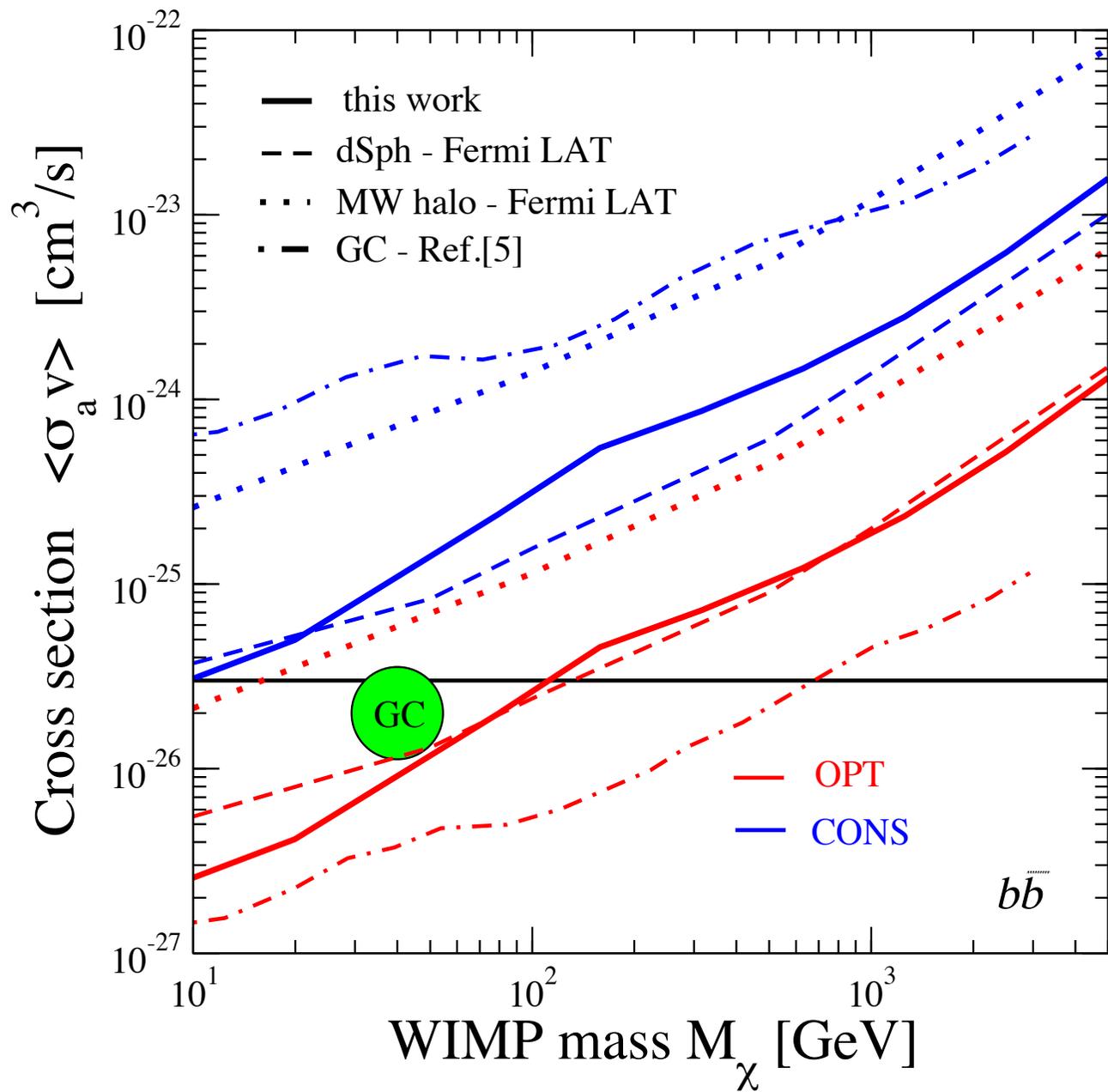
- CMB-lensing autocorrelation is measured: 40σ significance
- CMB-lensing: integrated measure of DM distribution up to last scattering
- It might exhibit correlation with gamma-rays emitted in DM structures

Fermi/gamma + Planck/CMB lensing

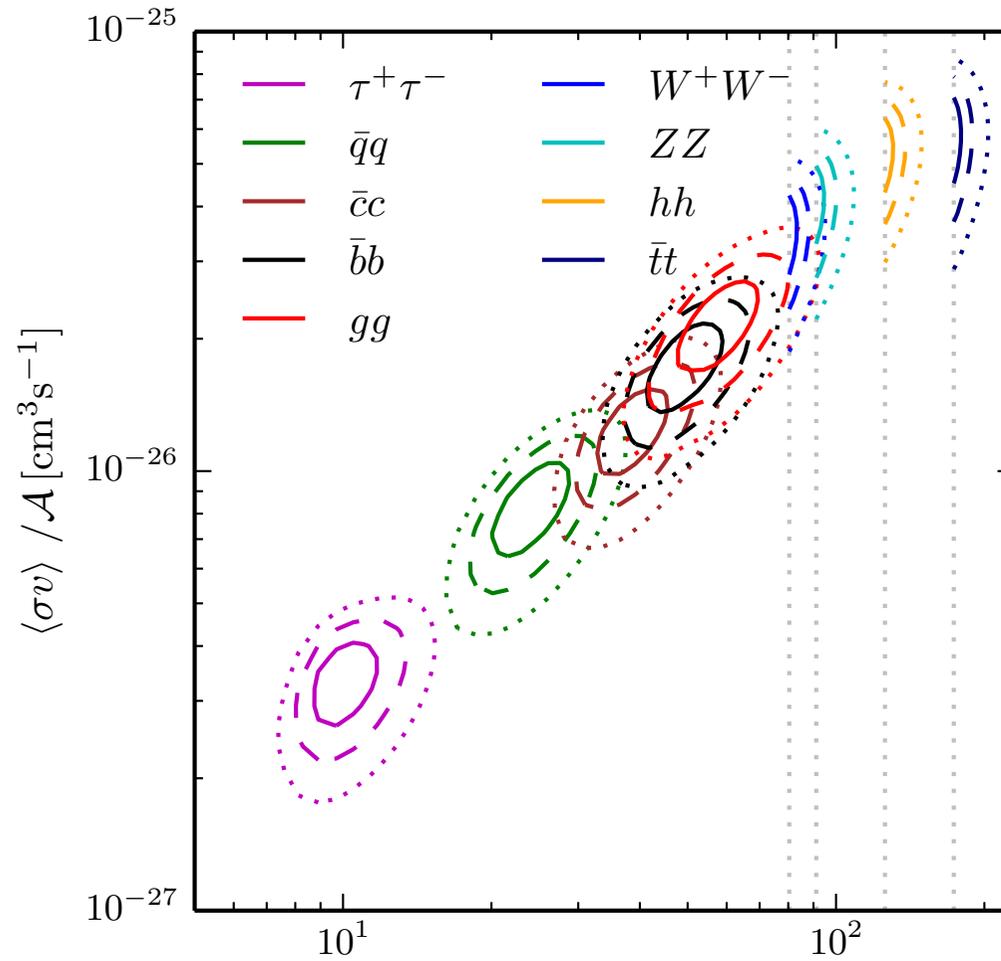
Analysis:

- 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



Galactic center



Dwarf galaxies

