Particle Dark Matter
A Multimessenger Endeavour

Nicolao Fornengo

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

UNIVERSITA' DEGLI STUDI DI TORINO
ALMA UNIVERSITAS TAURINENSIS

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

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

Torino INFN

Dipartimento di Fisica, Universita' di Genova

18.05.2016

Dark Matter

The presence of DM is supported by copious and consistent astrophysical and cosmological probes

- Large scales: Average DM density about 6 times baryon density
- Smaller scales: DM distribution is quite anisotropic and hierarchical clusters – galaxies – subhalos

Observations are compatible 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

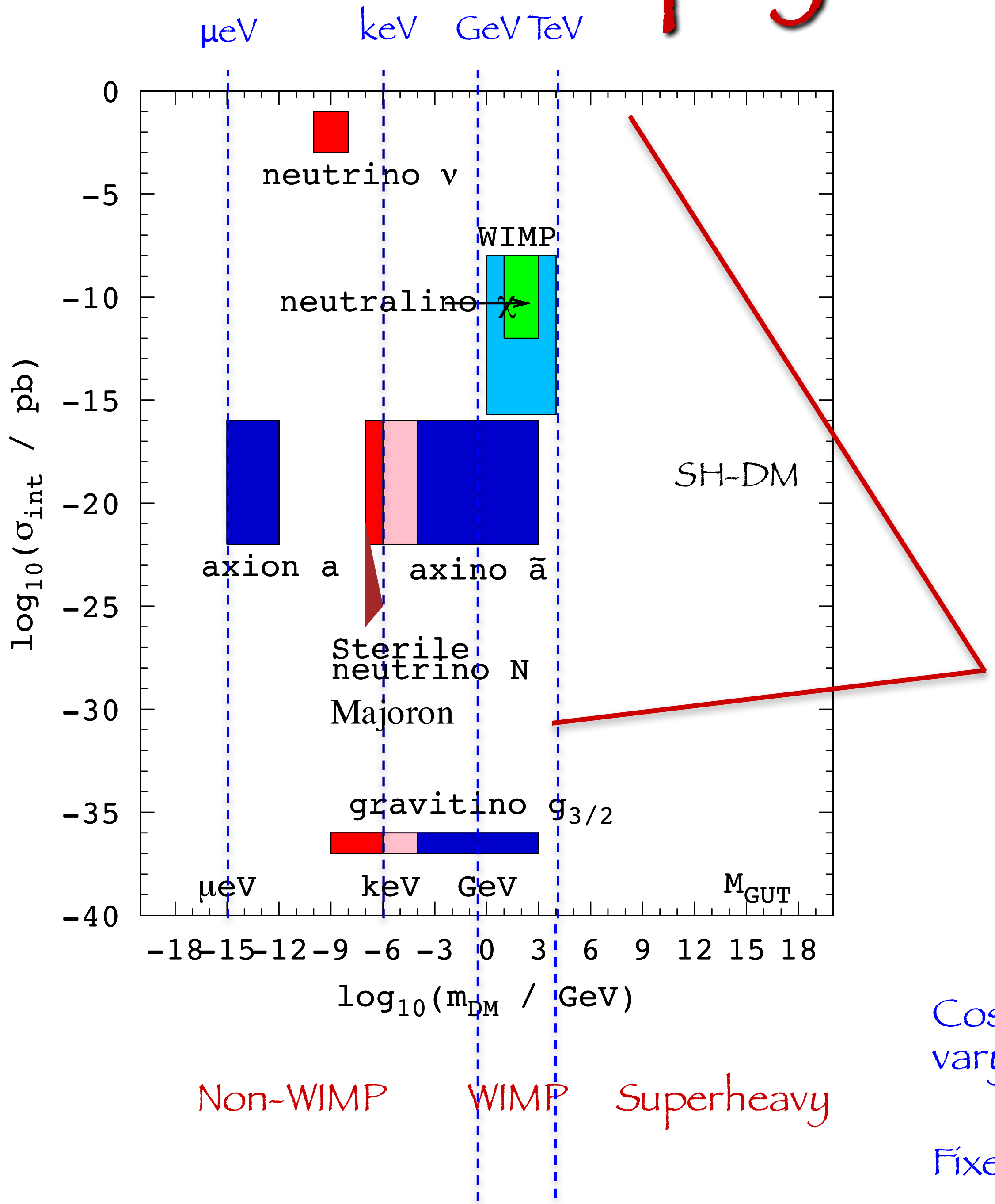
Dark Matter

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

If DM is a new particle, a non-gravitational signal (due to it's particle physics nature) is expected

Particle physics scales



"Strong (-ish)"

- Self-interacting
- Technicolor DM
- ...

"EM (-ish)"

- Millicharged DM
- E/M dipole
- Dark photons
- ...

Weak

- WIMP

Gravitational

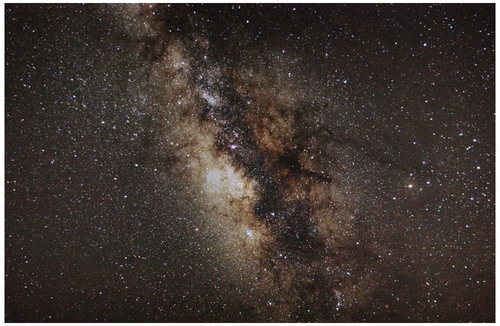
Cosmological production mechanism vary for different candidates

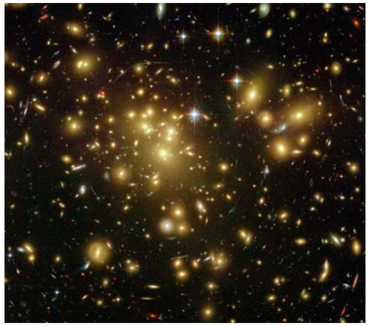
Fixed points: $\Omega_{DM} \approx 25\%$ + correct LSS

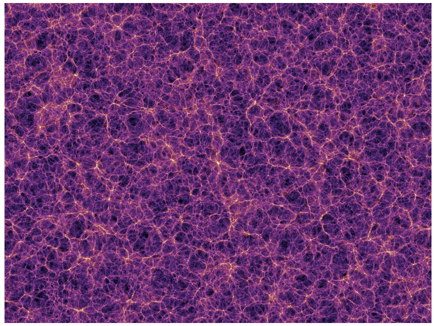
Where to search for a signal

DM is present in:

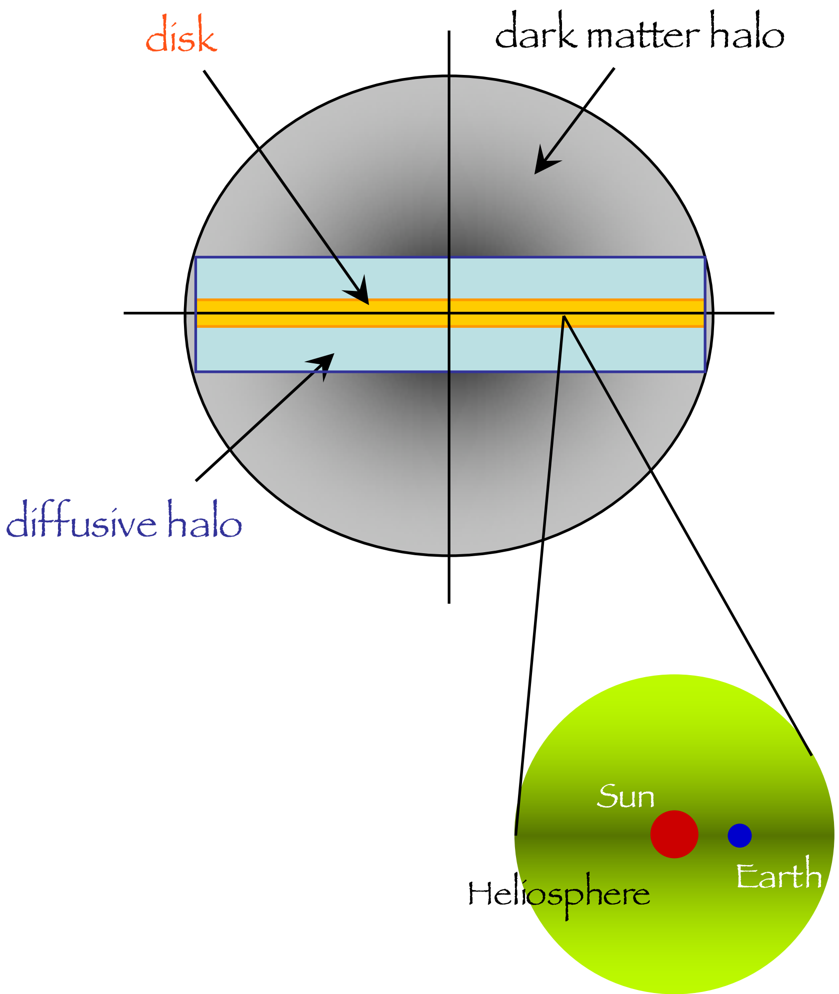
- Our Galaxy
  - smooth component
  - subhalos
- Satellite galaxies (dwarfs)
- Galaxy clusters
  - smooth component
  - individual galaxies
  - galaxies subhalos
- "Cosmic web"







Galactic dark matter signals



Halo signals

(*) Charged CR ($e^{\pm}$, antip, antiD)

(*) 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

(*) Neutrinos

Local signals

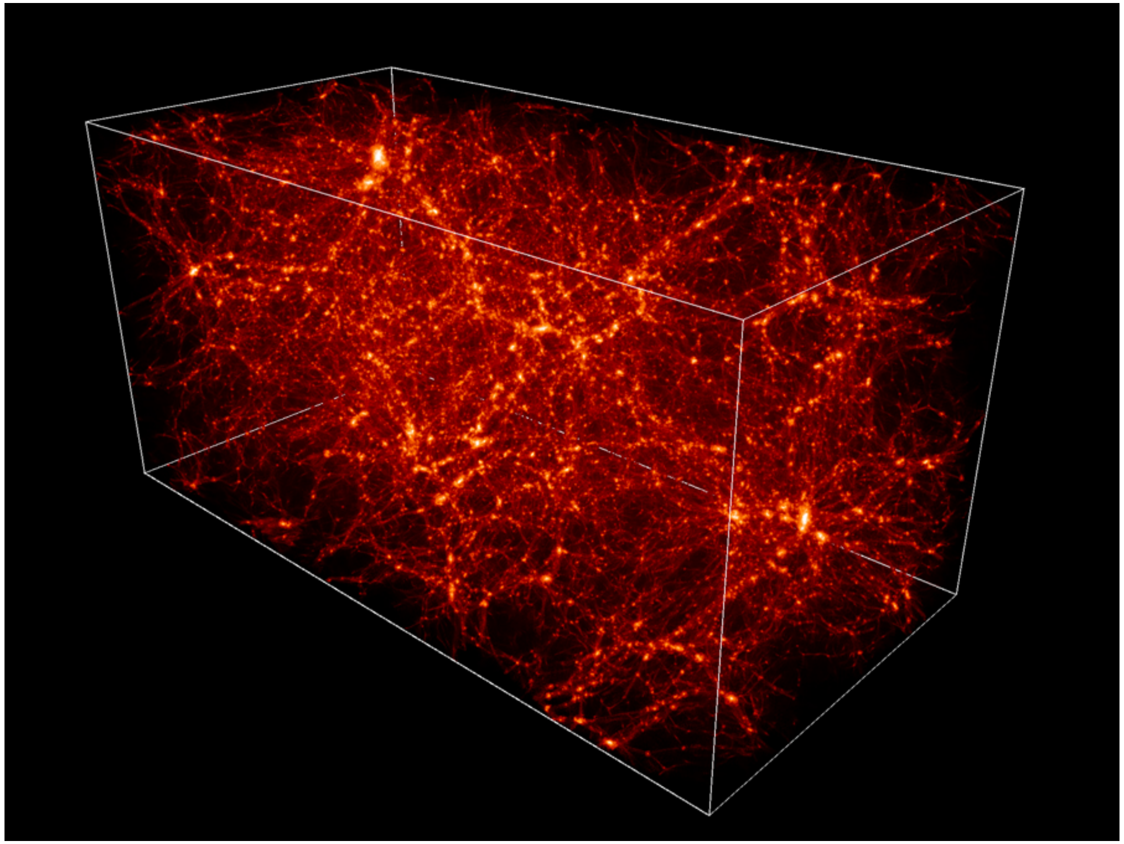
(+) Direct detection

(+*) Neutrinos from Earth and Sun

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

(+) $\chi + \mathcal{N}/e^- \longrightarrow \chi + \mathcal{N}/e^-$

Extragalactic/cosmological signals



Extragalactic signals

Photons: gamma, X, radio

Neutrinos

Sunyaev-Zeldovich effect on CMB

Optical depth of the Universe

Stellar physics

Effects on stellar physics

Neutron stars

Multi: messenger/wavelength/technique

	radio	X	gamma
	WIMP non WIMP	WIMP non WIMP	WIMP

Photons

Cosmic rays	electrons/positrons	WIMP, non WIMP
	antiprotons, antideuterium, antinuclei	WIMP
Neutrinos		WIMP, non WIMP

Direct detection	WIMP, non WIMP
Accelerator searches for New Physics	WIMP, non WIMP

General dependencies of the signals

Annihilating DM

$$S \sim \left(\frac{\rho_{\rm DM}}{m_{\rm DM}}\right)^2 \langle \sigma_{\rm ann} v \rangle \; I(E)$$

astrophysics

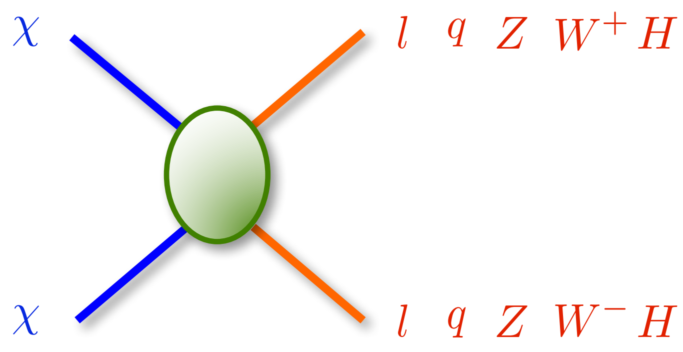
particle physics

Decaying DM

$$S \sim \frac{\rho_{\rm DM}}{m_{\rm DM}} \frac{1}{\tau_{\rm dec}} I(E)$$

+ additional astrophysical dependence on the propagation of the signal from the source to us

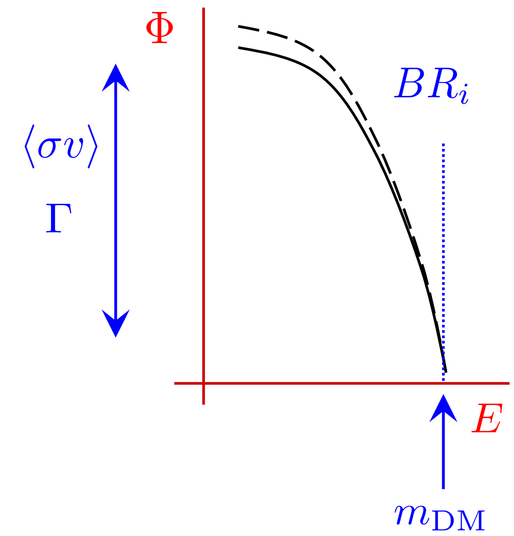
General dependencies of the signals



Annihilation (or decay)

Relevant particle physics properties:

1. Annihilation cross section (*) (or decay rate)
2. Mass of the DM particle
3. BR in the different final states



1 + 2 : Size of the signal
2 + 3 : Spectral features

(*) Determines also the cosmological relic abundance (for a thermal WIMP)

$$\Omega h^2 = 0.11 \quad \longleftrightarrow \quad \langle \sigma_{\rm ann} v \rangle = 2.3 \times 10^{-26}\ {\rm cm^3\ s^{-1}}$$

Charged messengers

- Tranport in the galactic environment
  - Diffusion largely affects directionality + spectral distortion
  - Energy losses spectral distortion

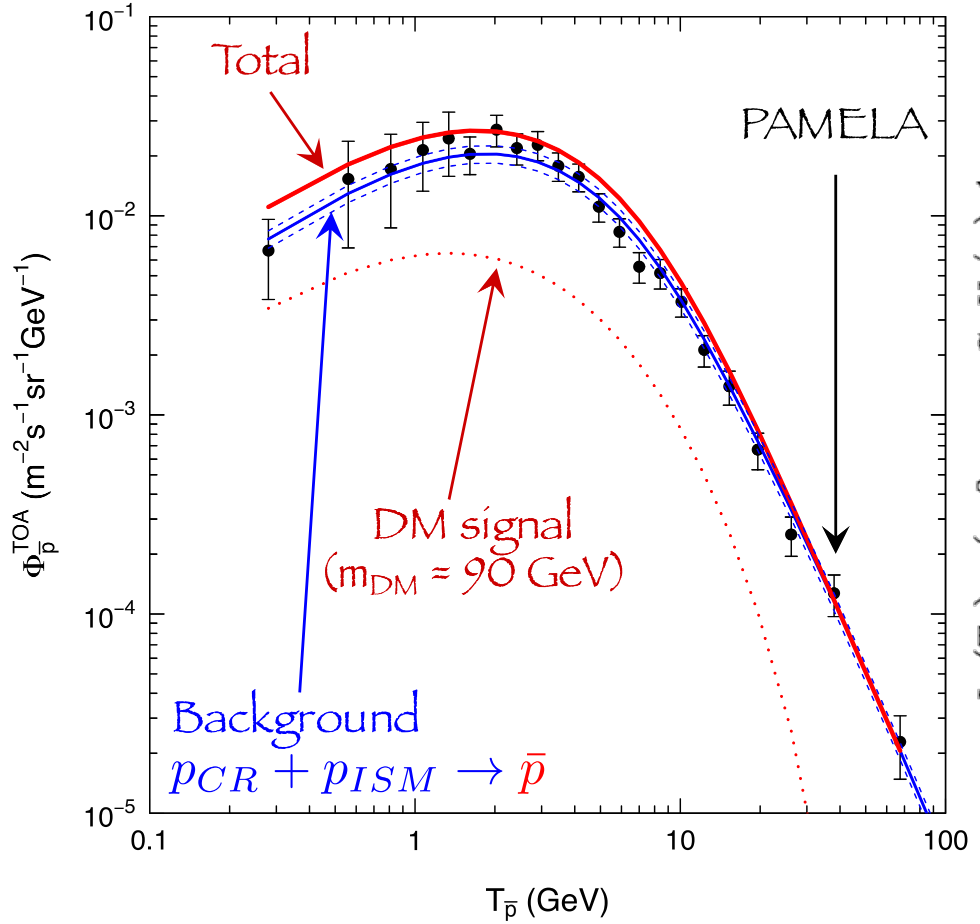
- Transport in the heliosphere
  - Affects rigidities below 10-50 GeV/n spectral distortion

Antiprotons vs. Antideuterons

Donato, NF, Salati, PRD 62 (2000) 043003

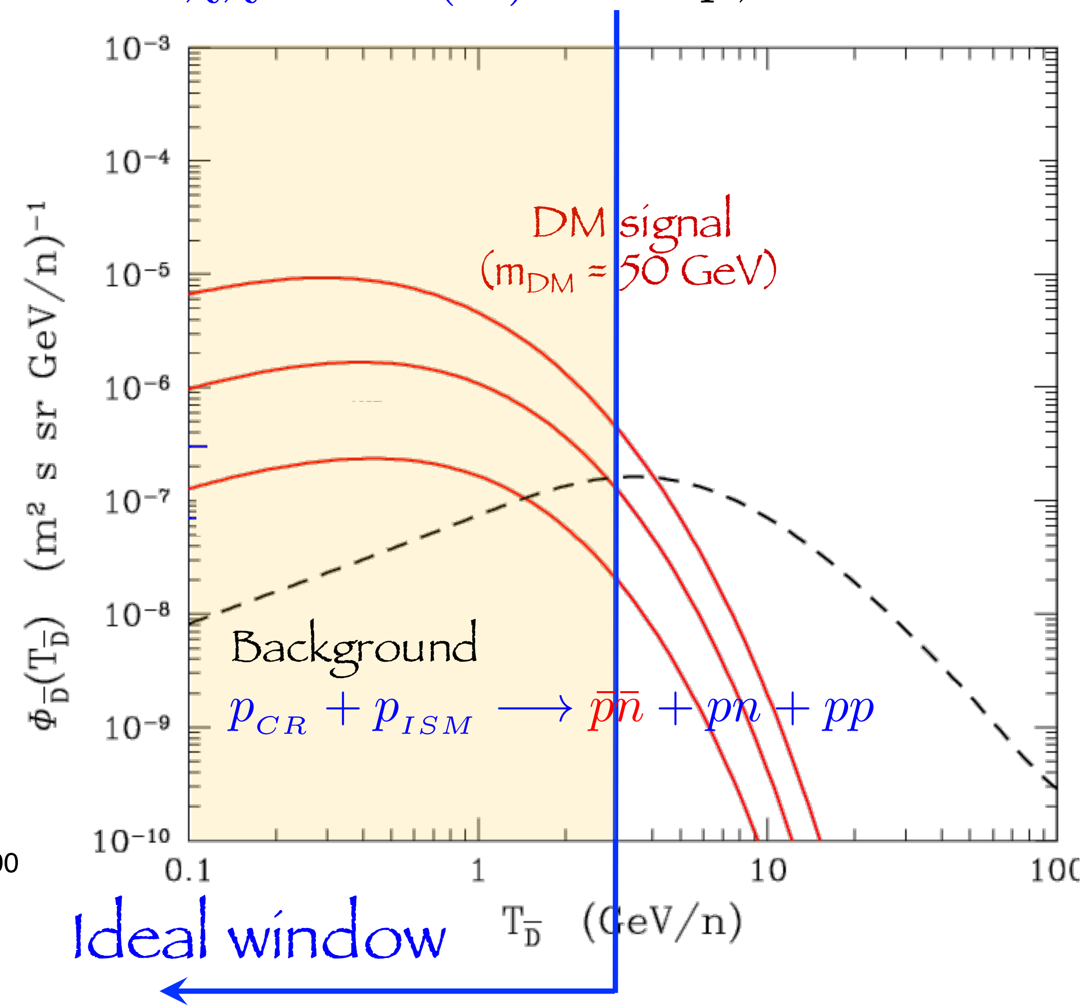
AntiProtons

$$\chi\chi \longrightarrow (\ldots) \longrightarrow \bar{p}$$



AntiDeuterons

$$\chi\chi \longrightarrow (\ldots) \longrightarrow \bar{p}, \bar{n} \longrightarrow \bar{D}$$

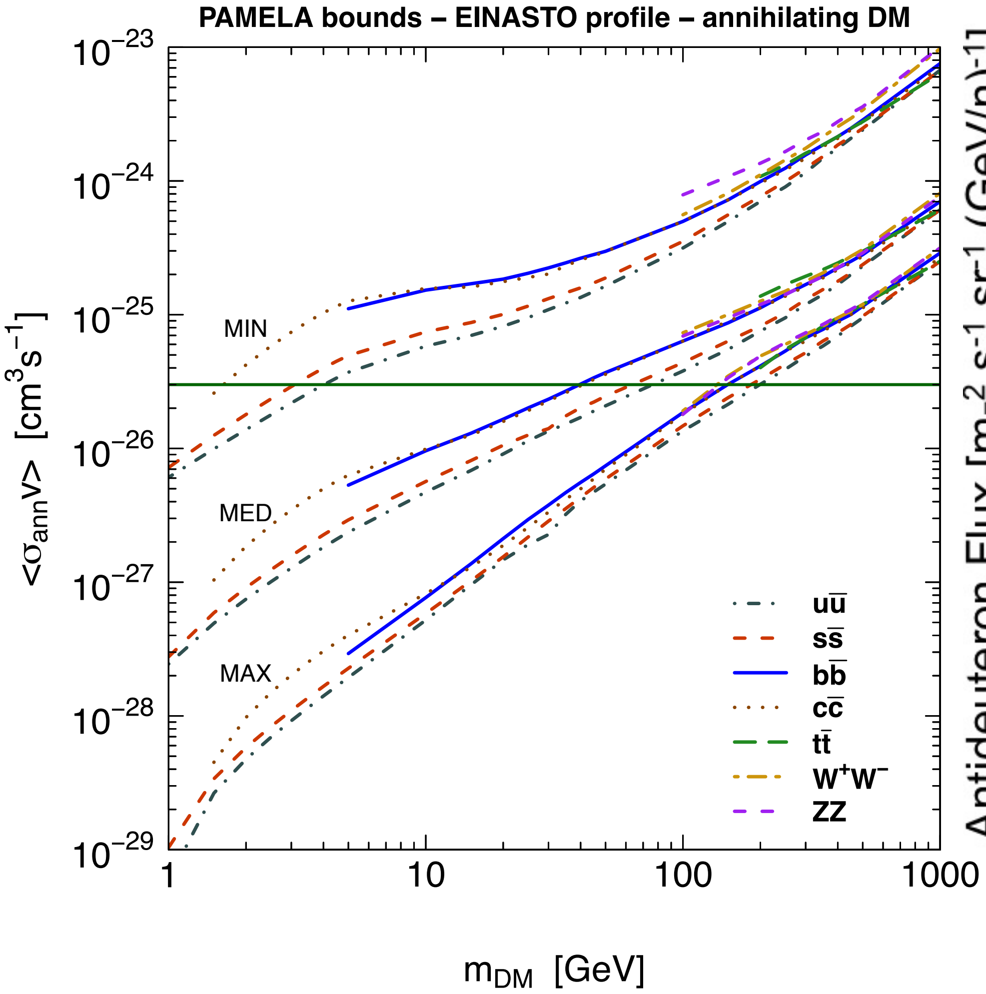


Donato, NF, Maurin, PRD 78 (2008) 0403506

Bounds and prospects

AntiProtons

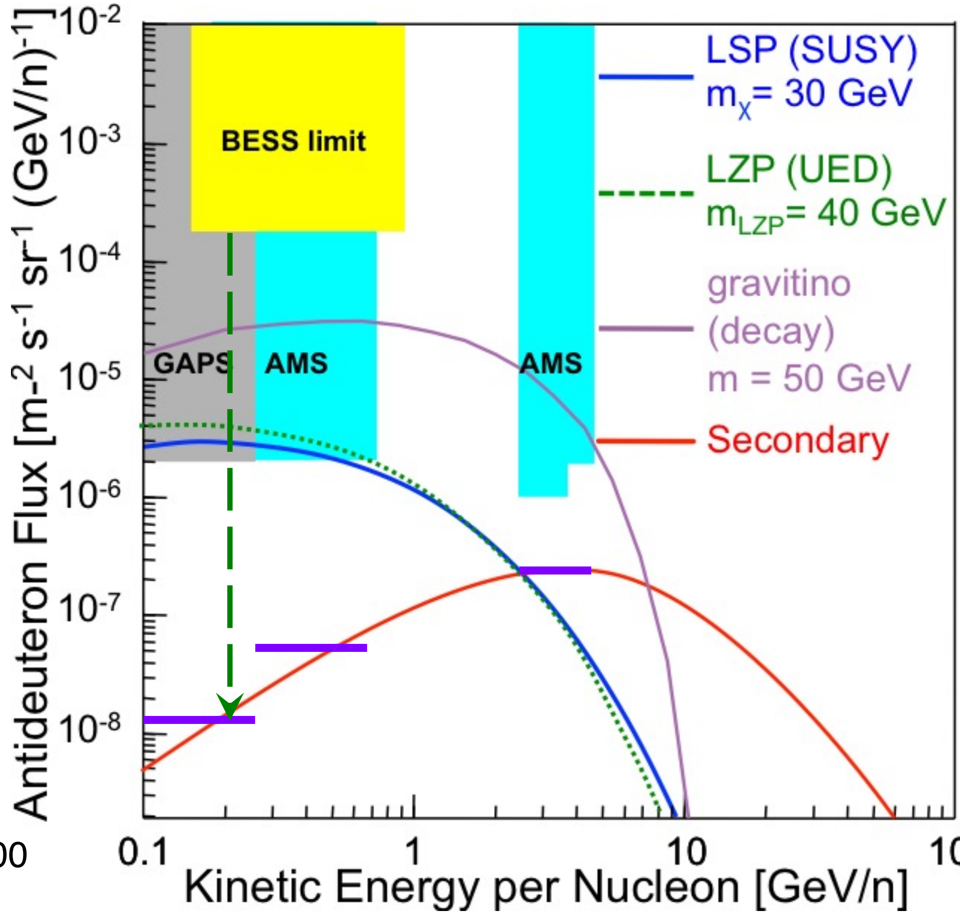
NF, Maccione, Vittino, JCAP 1404 (2014) 003



Bounds from PAMELA

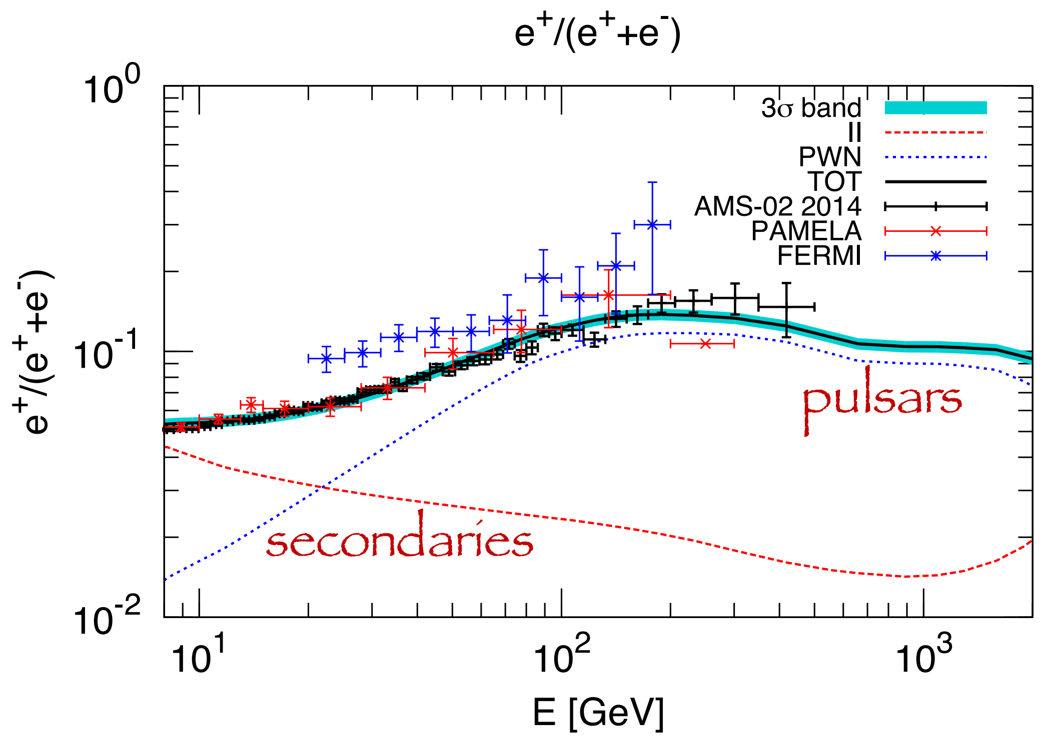
AntiDeuterons

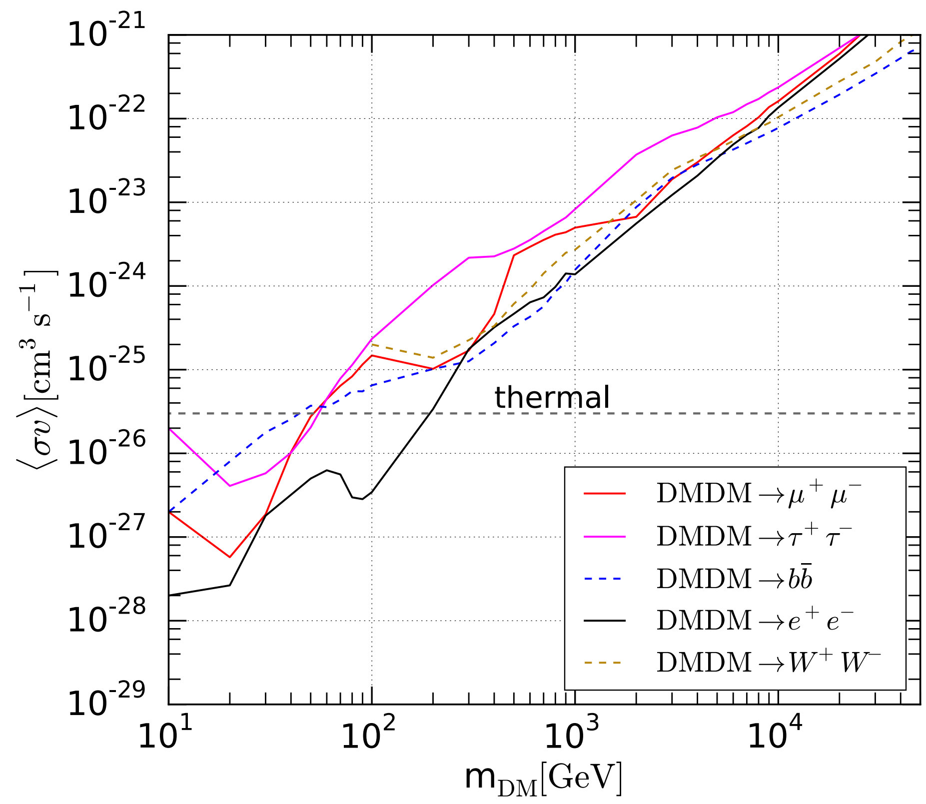
Aramaki, Donato, NF, Vittino et al, Phys. Rep. 618 (2016) 1



Best window: below 1 GeV/n - optimal at 100 MeV
Kinematics: largely favours signal over background
Opportunity: "0-back" over 3/4 orders of magnitude
Even a "single antiD": smoking gun for exotics

Electrons/positrons





Astrophysical interpretation

Bounds on DM

Di Mauro, Donato, NF, Vittino, arXiv:1507.07001 (to appear in JCAP)

Charged cosmic rays - Outlook

Antiprotons

- Provide strong bounds
- Theoretical uncertainties are the limiting factor (nuclear cross-sections and transport in the Galaxy)
- Even though affected by solar modulation, it might be important to approach the low-energy window (GAPS? ALADINO?)

Antideuterons

- Best "discovery" channel at low energies ($E < 3$ GeV)
- Prospects for AMS-02 and GAPS

Electrons/positrons above $E > 10$ GeV

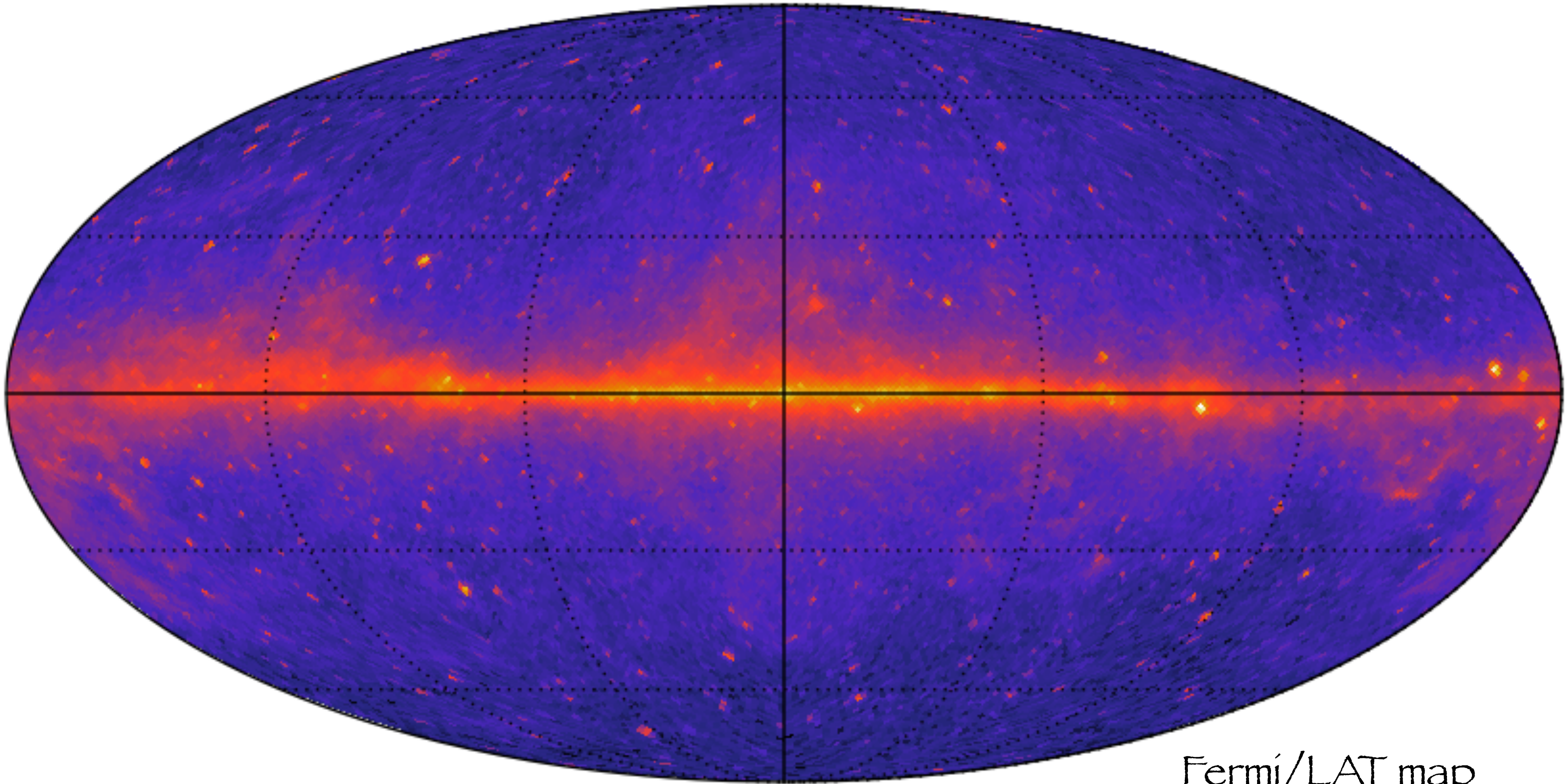
- Local source: DM or pulsars?
- Difficult to separate astro from DM emission
- Important to see higher energies, it migh not be decisive though

Neutral messengers

- Gamma-rays and neutrinos
  - Trace (more) directly the source
  - Energy losses only at very large energies
  - Angular and energy resolution good but not exceptional

- Radio
  - Produced through electrons: source somehow blurred
  - Depend on local magnetic field, which are largely uncertain
  - Great energy and angular resolution

Gamma-ray sky



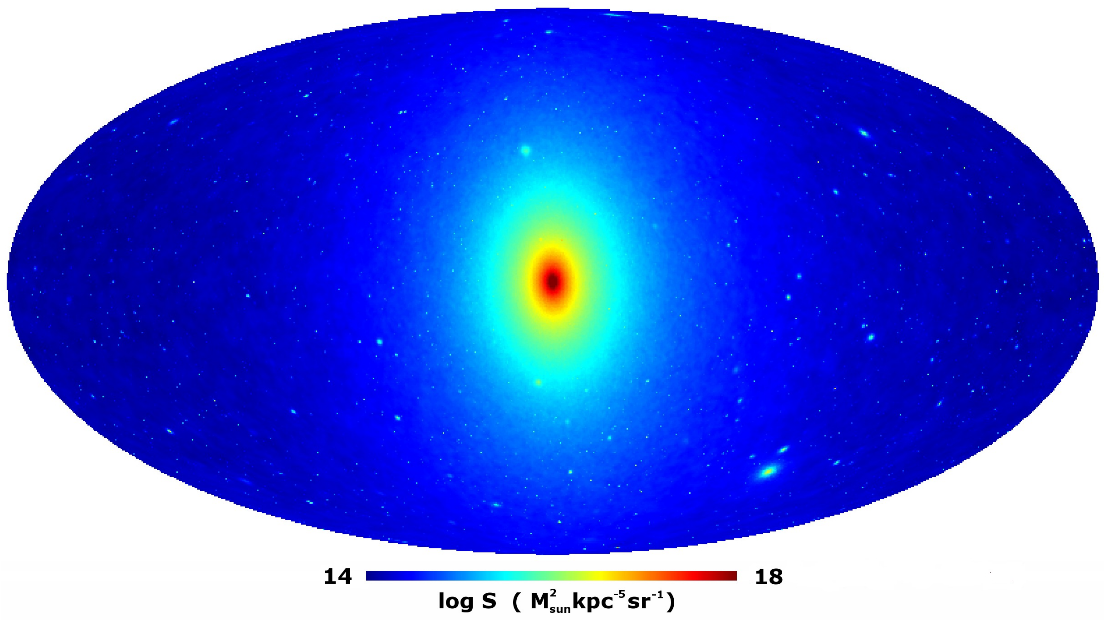
Fermi/LAT map

Galactic foreground emission

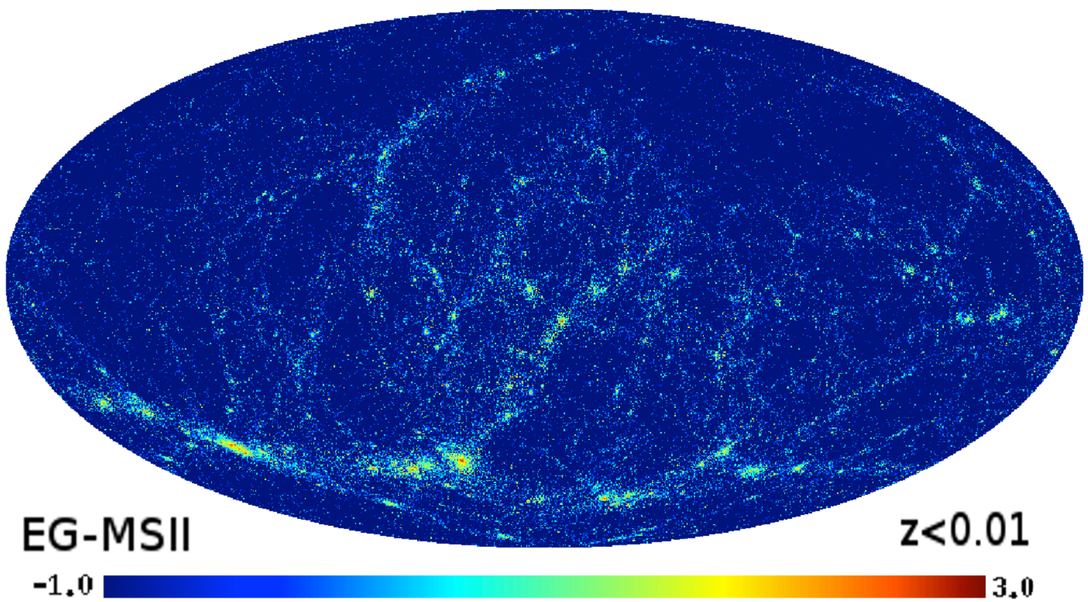
Resolved sources

Diffuse Gamma-Ray Backgound (DGRB)

Gamma-ray sky and DM



Galactic emission



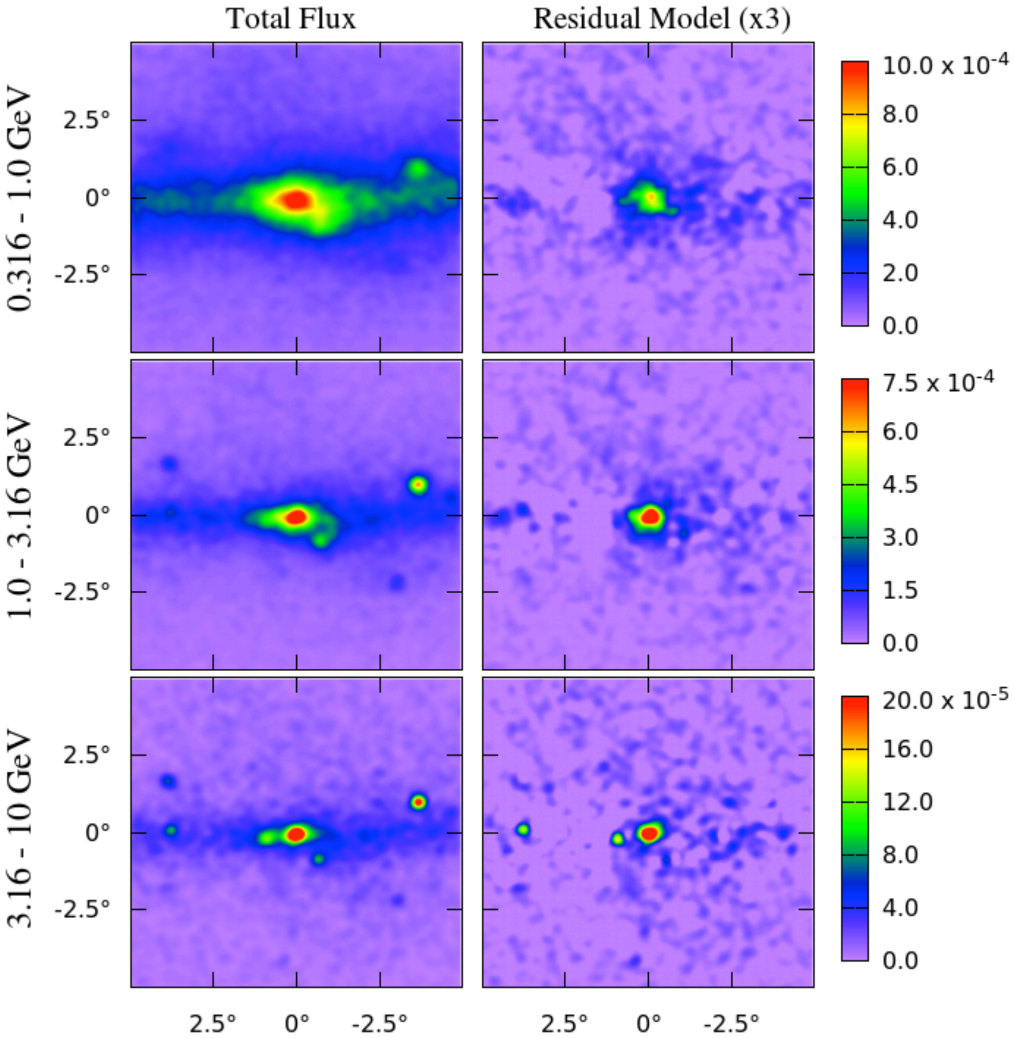
Extra galactic emission

Galactic center: an "excess" ?

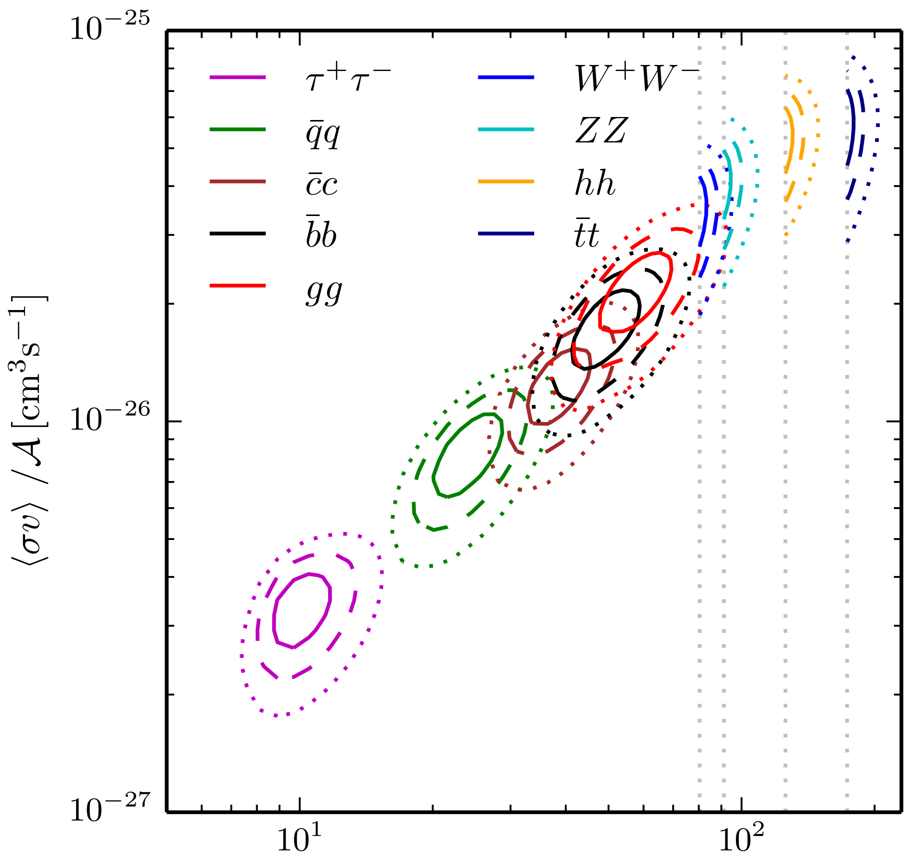
Hooper, Goodenough, PLB (2011) 697 (2011)
Hooper, Linden, PRD 84 (2011) 123005
Boyarsky et al., PLB (2011) 705
Daylan et al., arXiv:1402.6703
Abazajian et al., arXiv 1402.4090
Lacroix, Boehm, Silk, arXiv: 1403.1987

Fermi/LAT excess(es) at the galactic center

DM or pulsars or bursts?

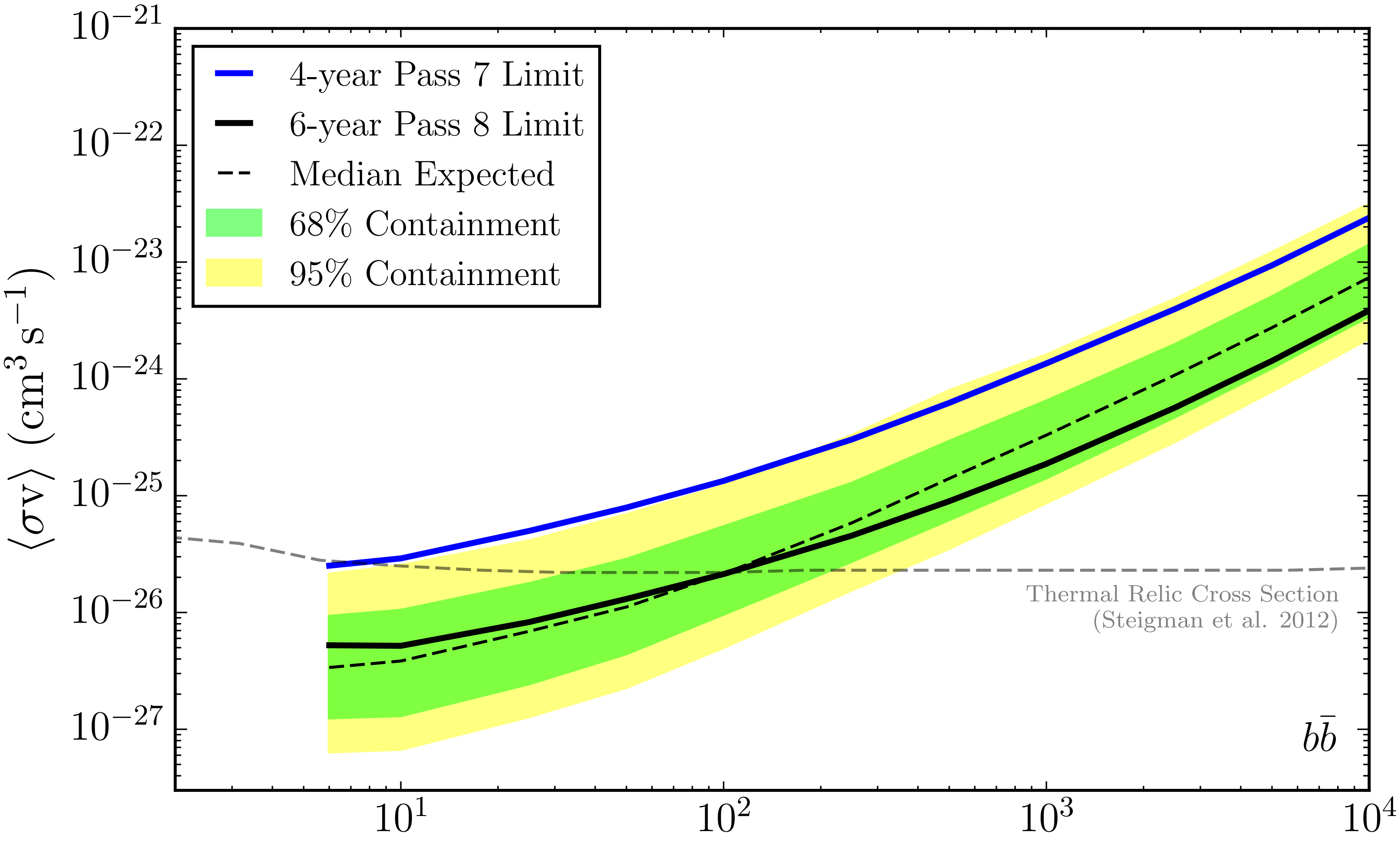


Daylan et al., arXiv:1402.6703



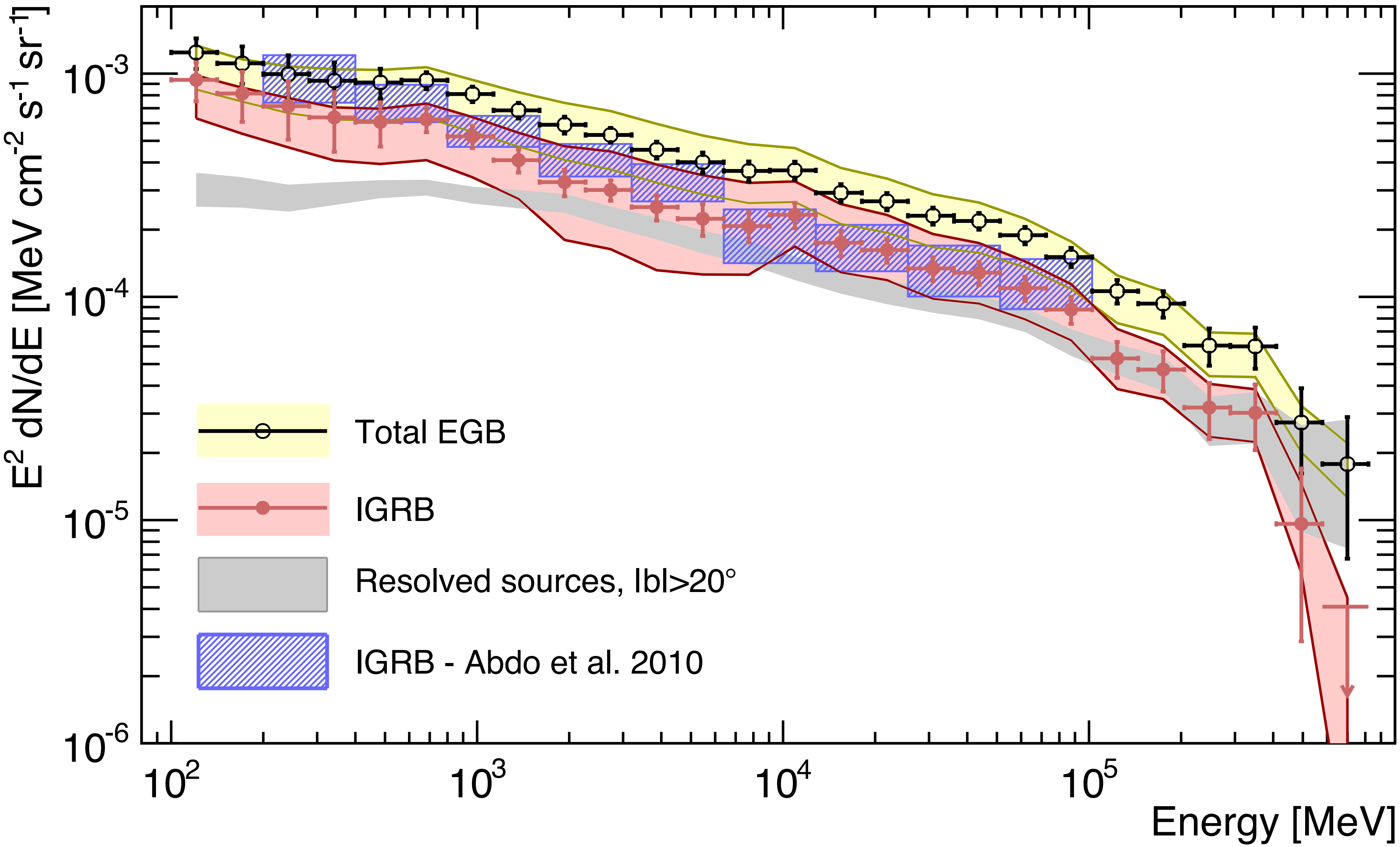
Calore et al. PRD 91 (2015) 063003

Dwarf galaxies



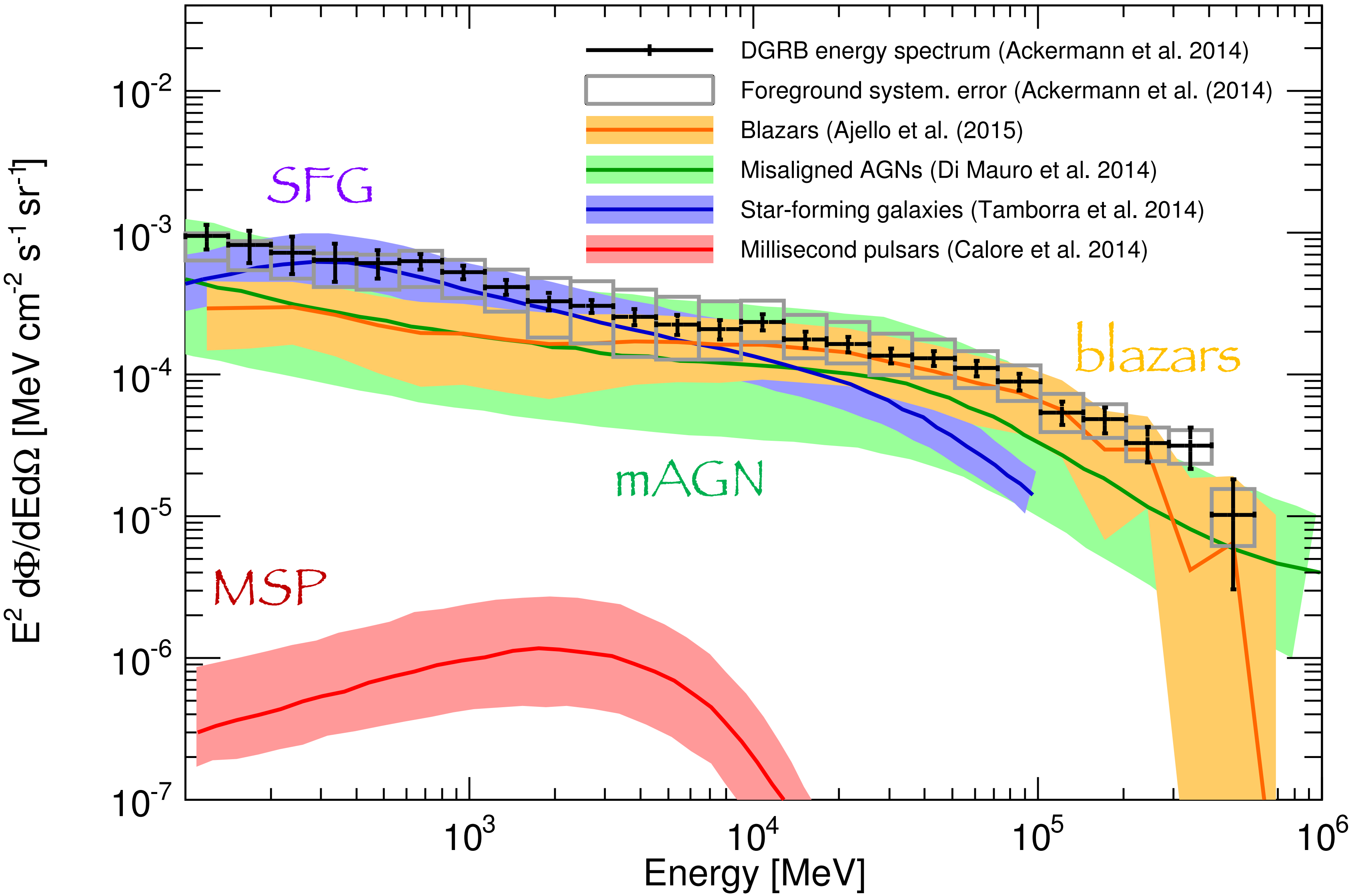
Ackermann et al. (Fermi Collab.), arXiv:1503.02641

DGRB Intensity



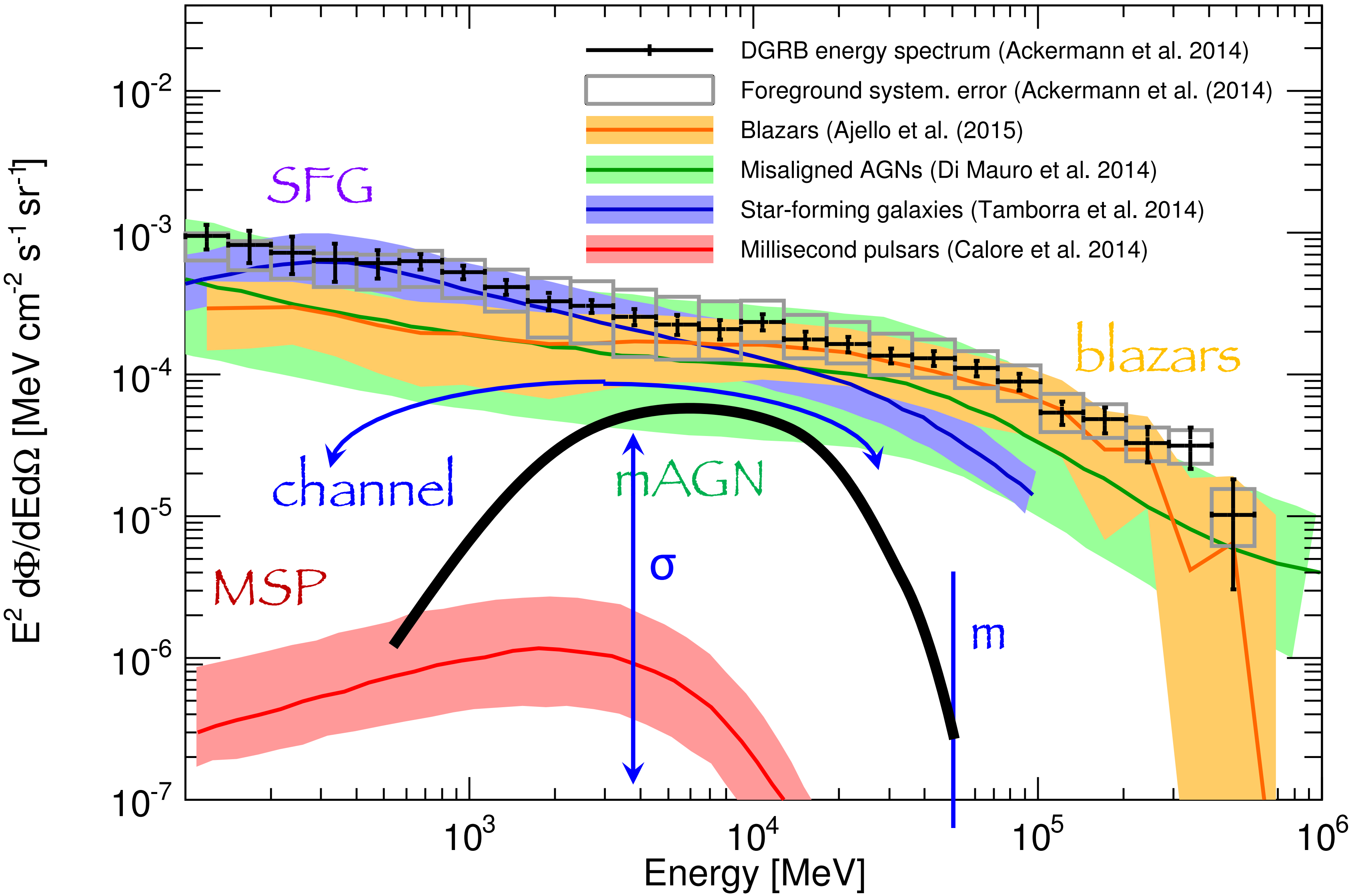
Ackerman et al. (Fermi Collab.) Ap. J. 799 (2015) 86

DGRB Intensity

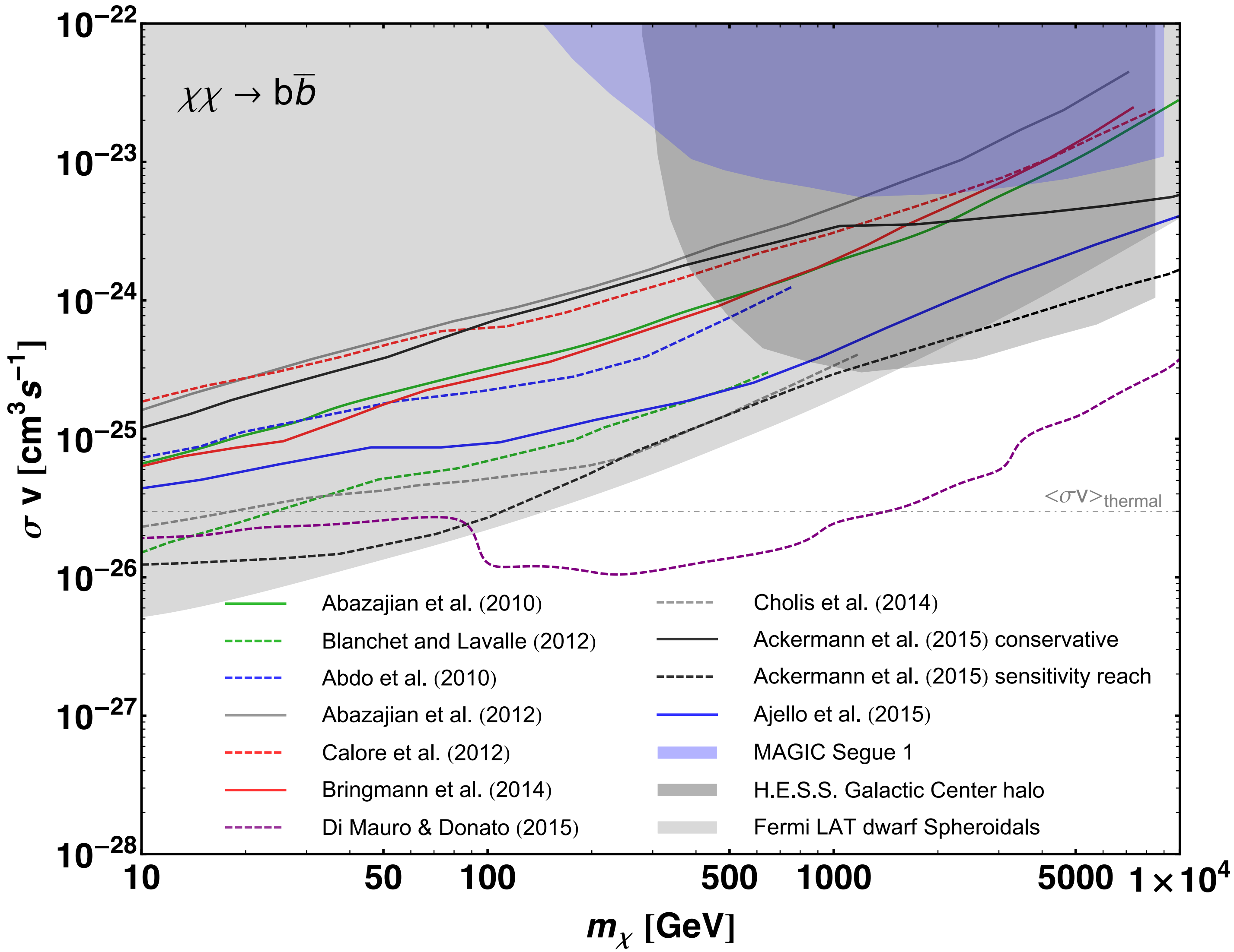


Fornasa, Sanchez-Conde, Phys. Rep. 598 (2015) 1

DGRB Intensity



DGRB intensity bounds on DM



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

Gamma rays - Outlook

Galactic center

Very interesting target, but difficult

Potential hints, under hot discussion

Isotropic gamma-ray background

Relevant for extragalactic DM

Complex to seperate a DM signal from astrophysical sources

Dwarf galaxies

One of the best targets (DM dominated)

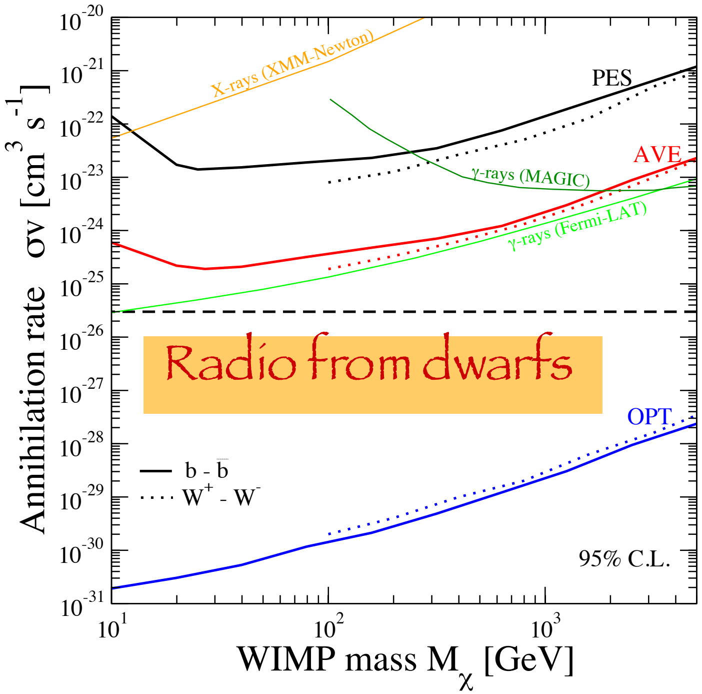
Recently, new dwarfs have been discovered (DES): great potentiality

Lower frequencies

Radio emission

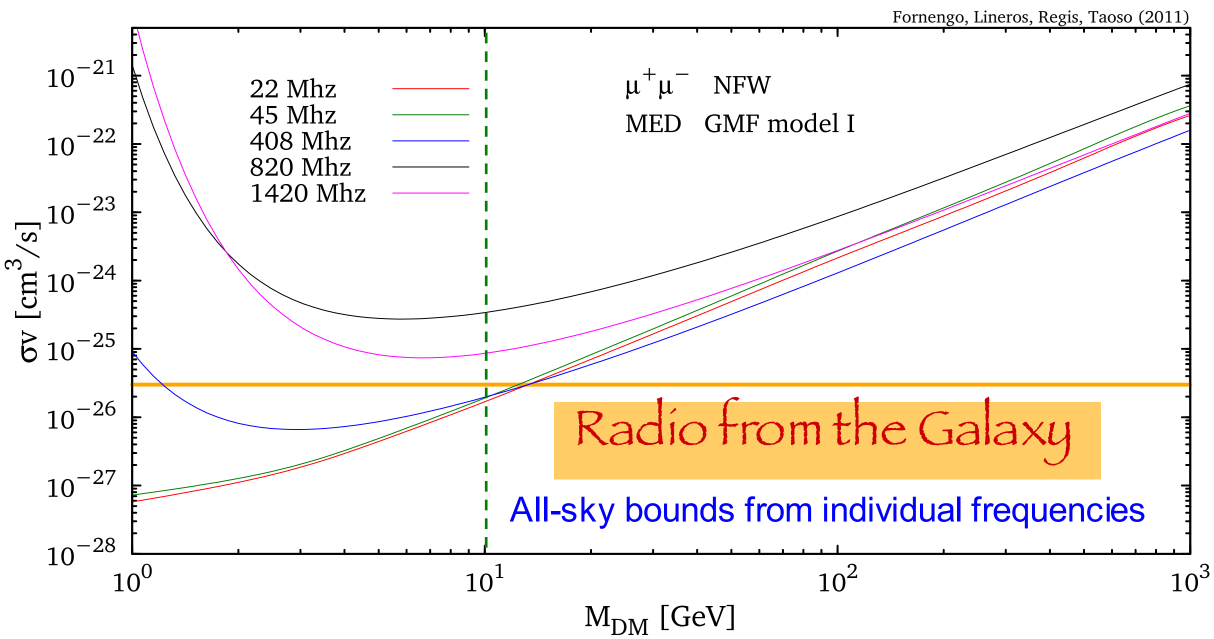
$$E \sim 15\sqrt{\nu_{\rm GHz}/B_{\mu \rm G}}\ \ \text{GeV}$$

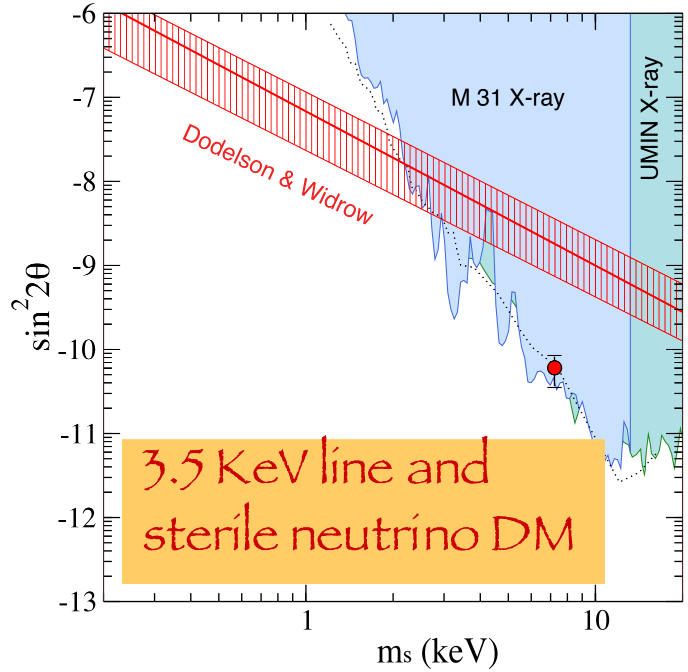
Galactic center
Galactic and extragalactic diffuse emission
Dwarf galaxies
Larger undertainties, but promising for discovery



X-rays

Opportunity for non-WIMP DM






Going
beyond

Based on:

Camera, Fornasa, NF, Regis, *Ap. J. 771 (2013) L5* — gamma + cosmic shear
Camera, Fornasa, NF, Regis, *JCAP 1506 (2015) 029* — gamma + cosmic shear

NF, Regis, *Front. Physics 2 (2014) 6* — general theory

NF, Regis, Perotto, Camera, *Ap.J. 802 (2015) L1* — gamma + CMB lensing

Regis, Xia, Cuoco, NF, Branchini, Viel, *PRL 114 (2015) 241301* — gamma + LSS
Cuoco, Xia, Regis, NF, Branchini, Viel, Ap. J. Suppl. 221 (2015) 29 — gamma + LSS

Zechlin, Cuoco, Donato, NF, Vittino, arXiv:1512.07190 — gamma 1pPDF
Zechlin, Cuoco, Donato, NF, Regis, arXiv:1605.02456 — gamma 1pPDF

Indirect dark matter signals

- Indirect detection signals are intrinsically anisotropic

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

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

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

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

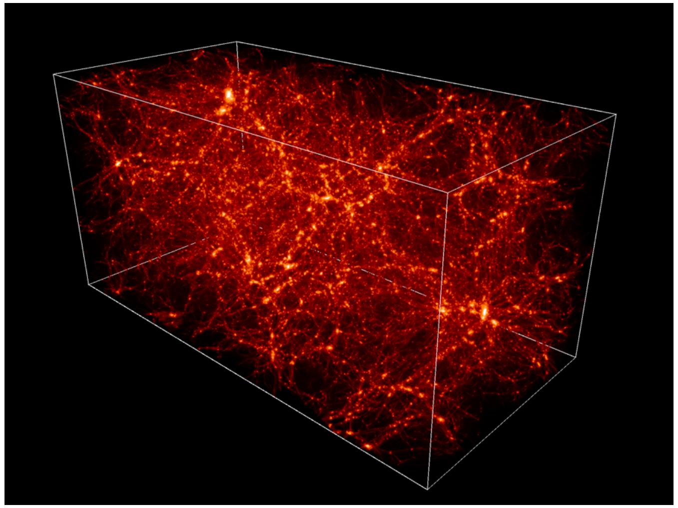
      at a deeper level anisotropic

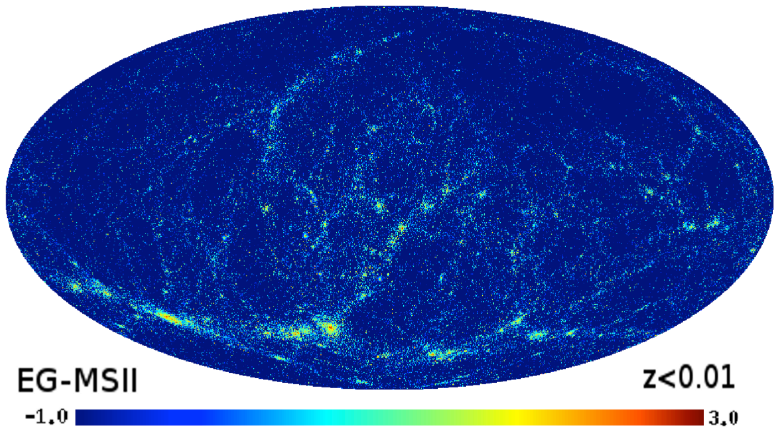
DGRB: not quite isotropic ...

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

To first approximation: isotropic

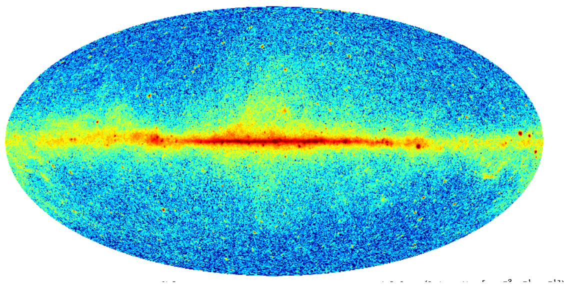
At a deeper level: anisotropies are present





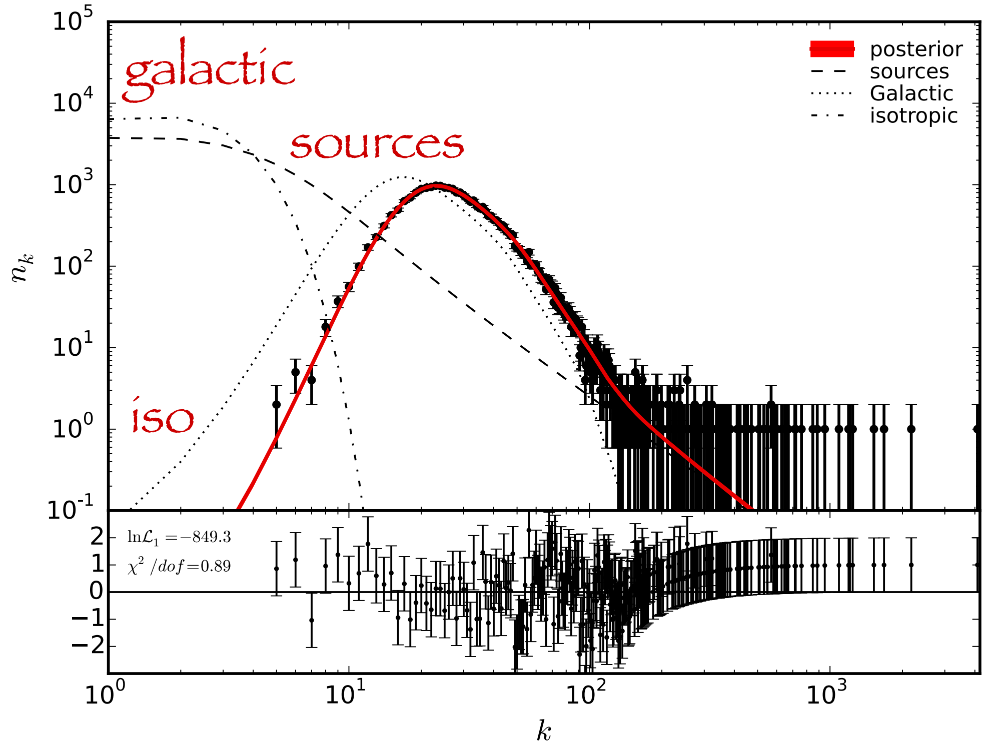
Even though sources are too dim to be individually resolved, they can affect the statistics of photons across the sky

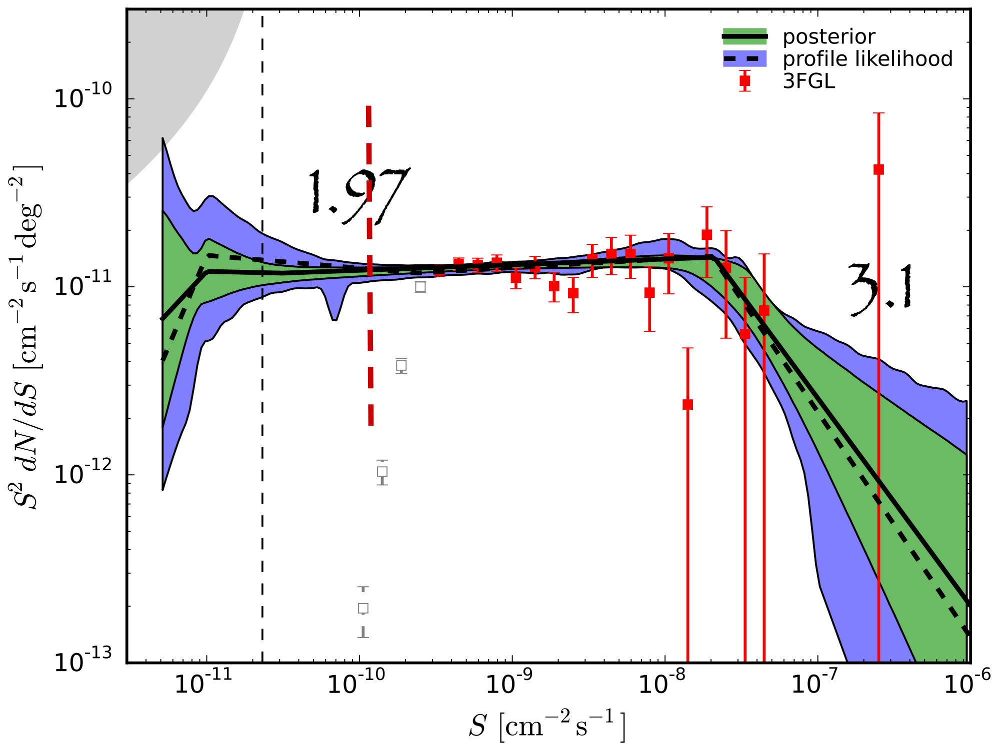
Photon statistics



Photon pixel counts (1 point PDF)

Source count number dN/dS below detection threshold



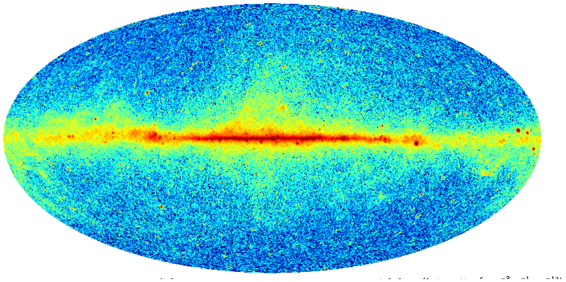


Zechlin, Cuoco, Donato, NF, Vittino, arXiv:1512.07190

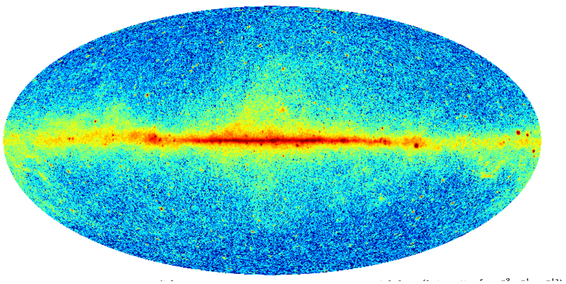
Malyshev, Hogg, Astrophys. J. 738 (2011) 181
Zechlin, Cuoco, Donato, NF, Regis, 1605.04253
Zechlin+

Energy dependence
DM implications

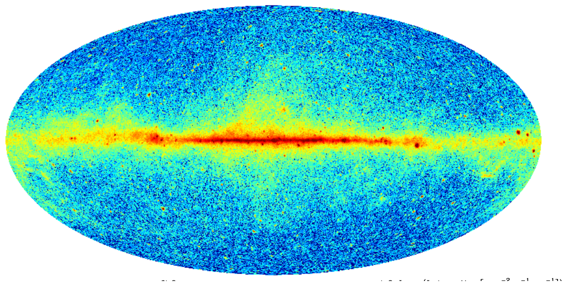
Photon statistics



Photon pixel counts (1 point PDF)



×



2 point correlator
angular power spectrum

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

Auto Correlation

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

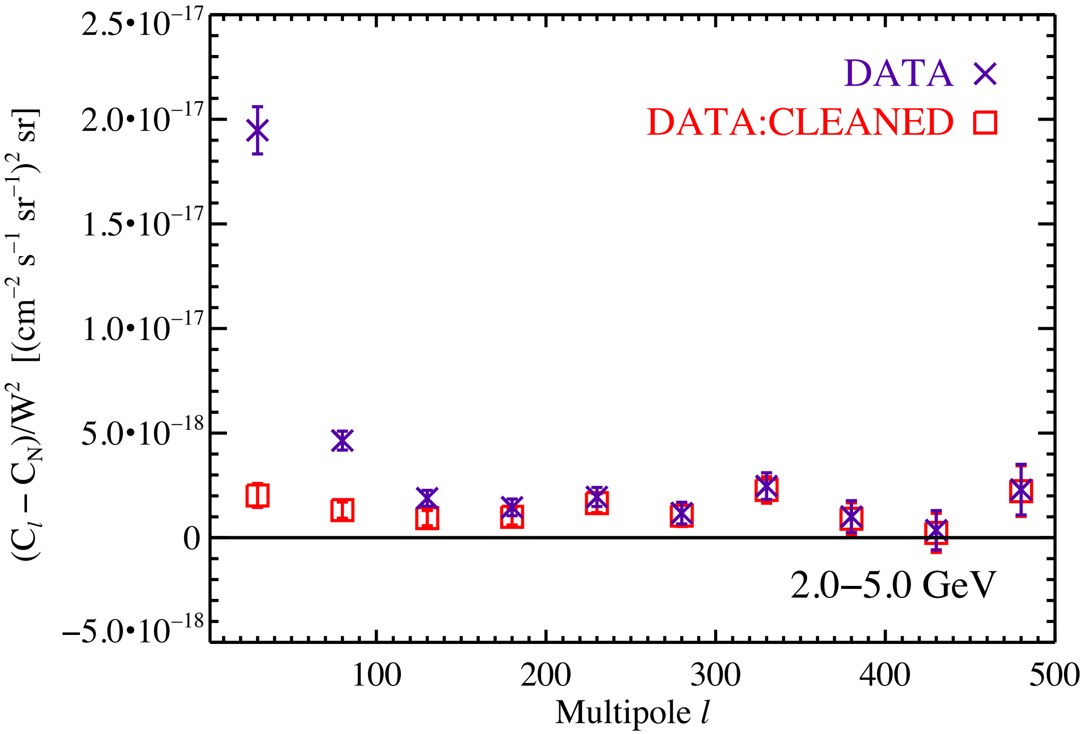
window function
how the signal is distributed in redshift

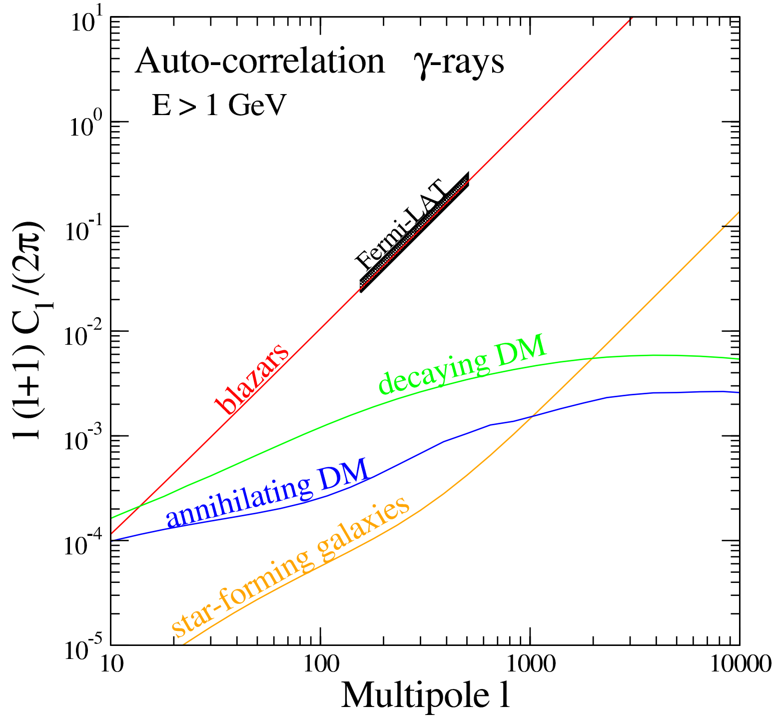
power spectrum
how the signal clusters

Observationally:

Energy dependence is available
Redshift dependence is not available

Gamma rays auto-correlation





Fermi/LAT (22 months)

4 energy bins in 1-50 GeV

Overall significance: 9σ

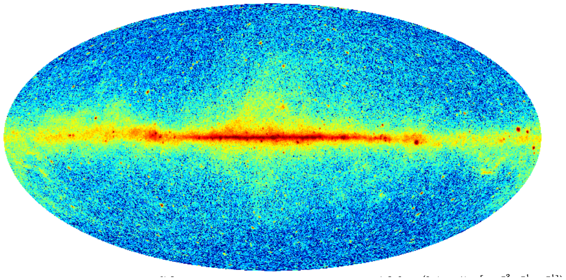
Compatible with being dominated by blazars

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

Cuoco et al PRD 86 (2012) 063004

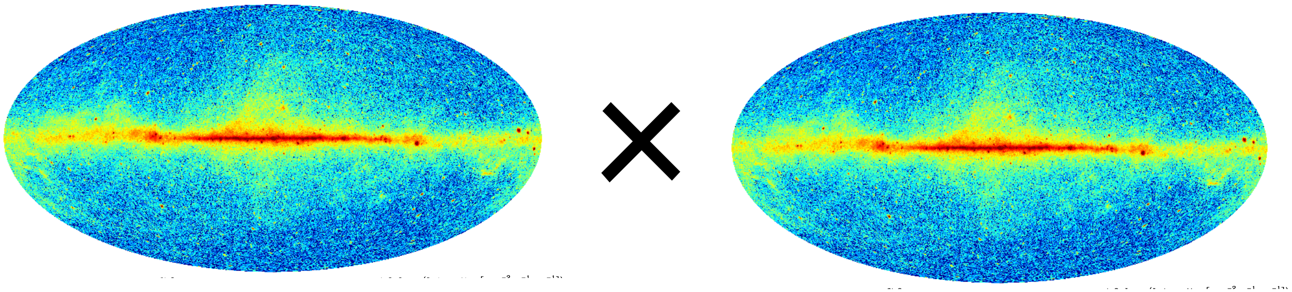
Harding, Abazajian JCAP 1211 (2012) 026

Di Mauro et al JCAP 1411 (2014) 012



Photon pixel counts (1 point PDF)

Source count number dN/dS below detection threshold



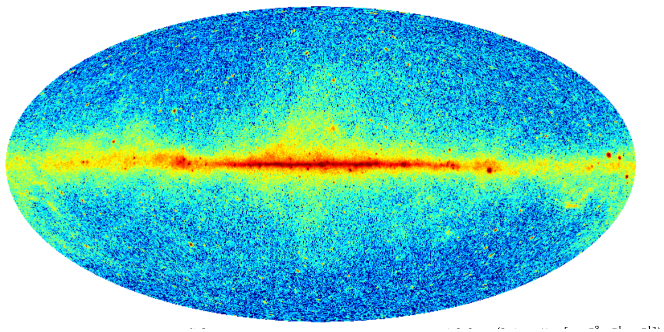
2 point correlator

angular power spectrum

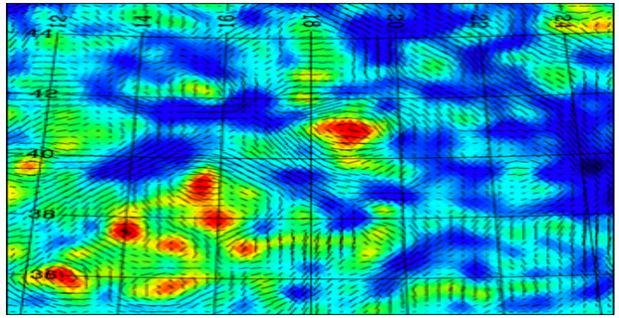
$$\langle I(\vec{n}_1) I(\vec{n}_2) \rangle \longrightarrow C(\theta) \longrightarrow C_l$$

Can we do more ?

Fold two pieces of information



×



Cross-correlation of EM signal with gravitational tracer of DM

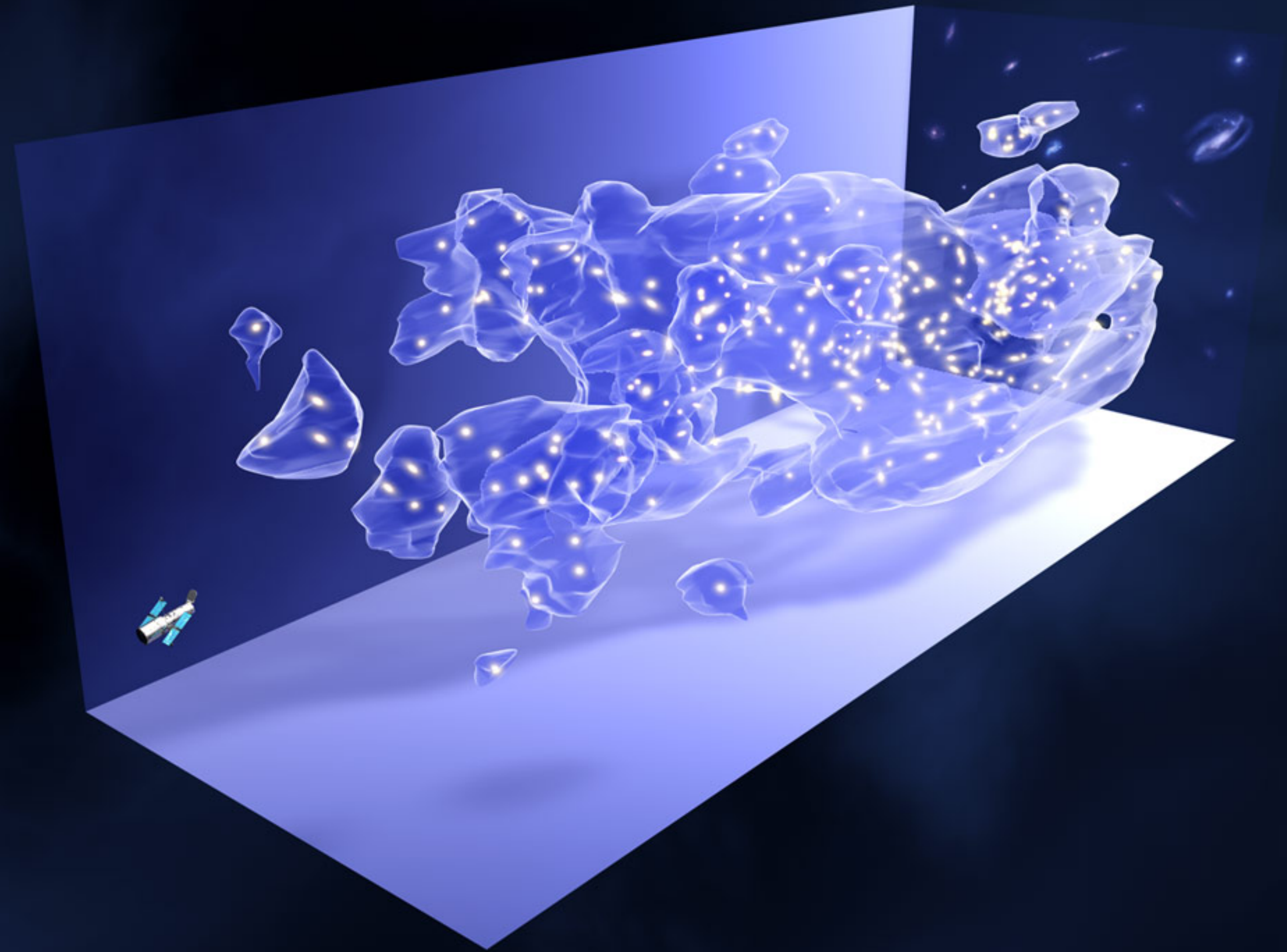
It exploits two distinctive features of particle DM:

- Electromagnetic signal: manifestation of the particle nature of DM
- Gravitational tracer: 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 as a particle

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

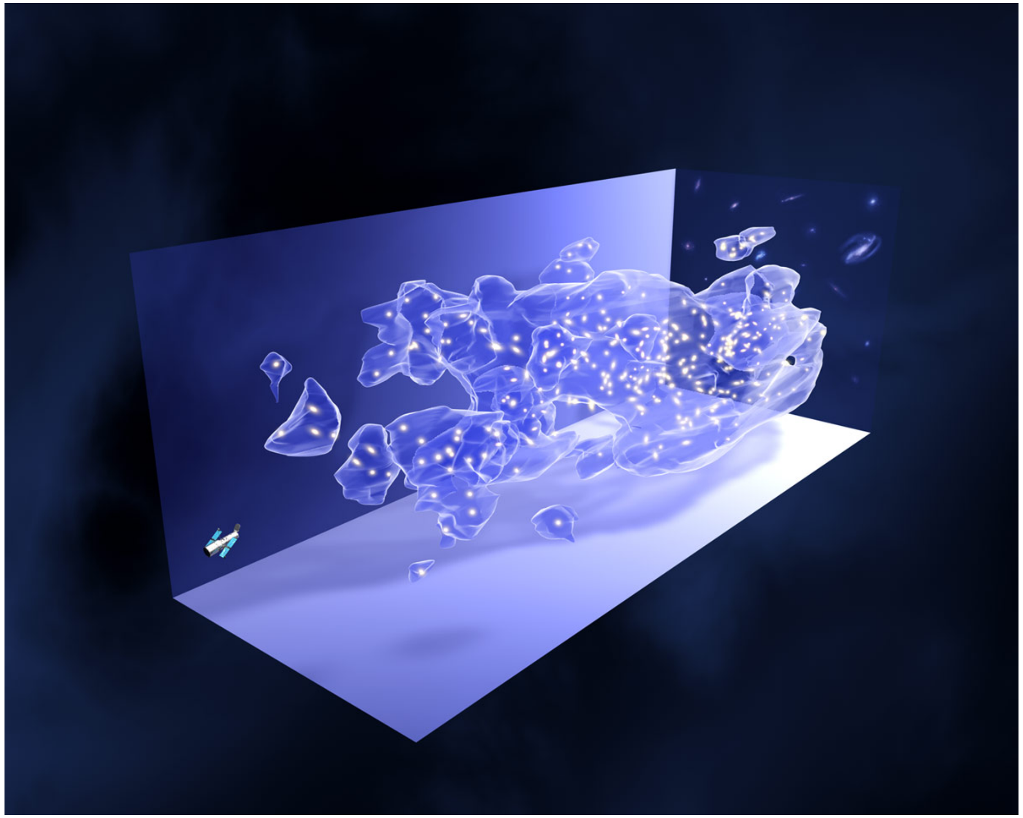
Weak gravitational lensing



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”

Cross angular power spectrum

$$\langle I_\gamma(\vec{n}_1) I_\phi(\vec{n}_2)\rangle \longrightarrow C_l^{\gamma\phi}$$

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

window functions

overlap between the two signal is necessary

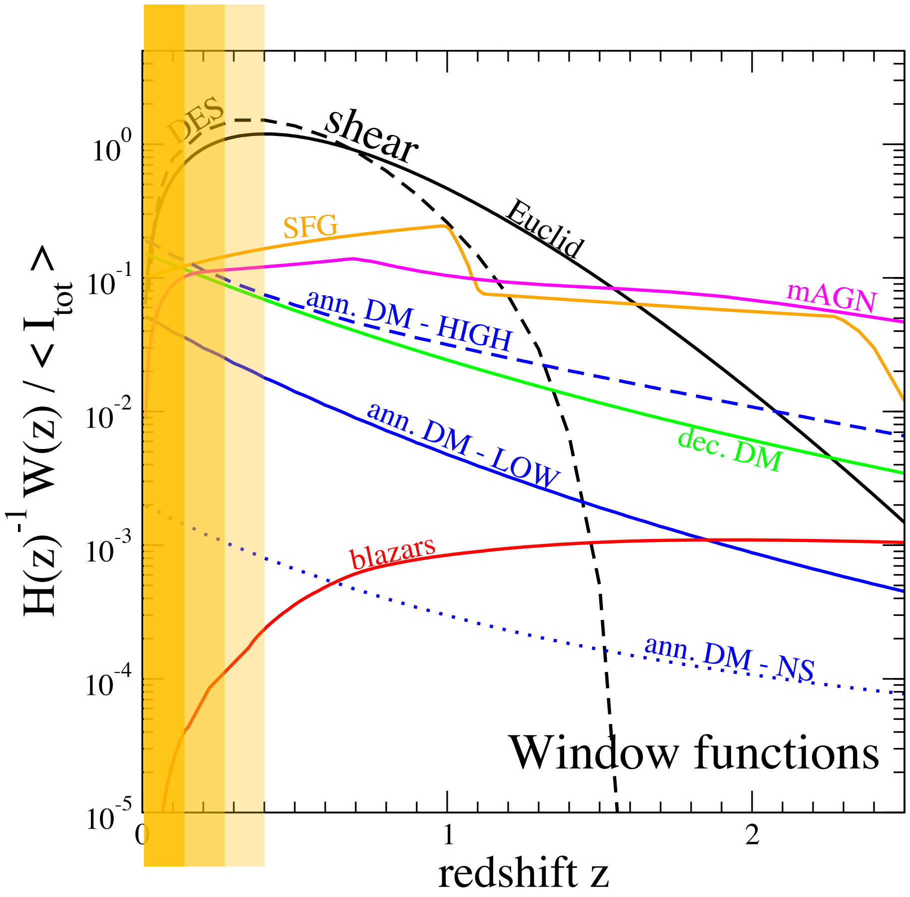
power spectrum

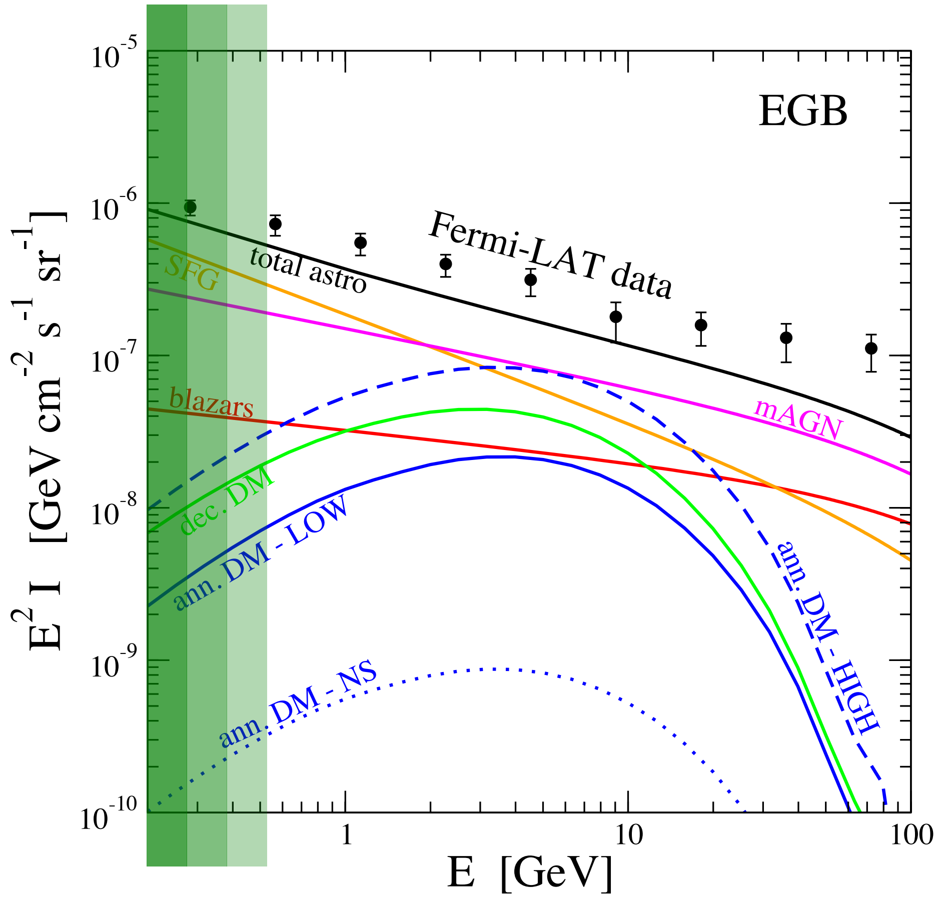
Redshift dependence

Energy dependence

Camera, Fornasa, NF, Regis, Ap. J. Lett. 771 (2013) L5
Camera, Fornasa, NF, Regis, JCAP 1506 (2015) 029
NF, Regis, Front. Physics 2 (2014) 6

Tomographic-spectral approach





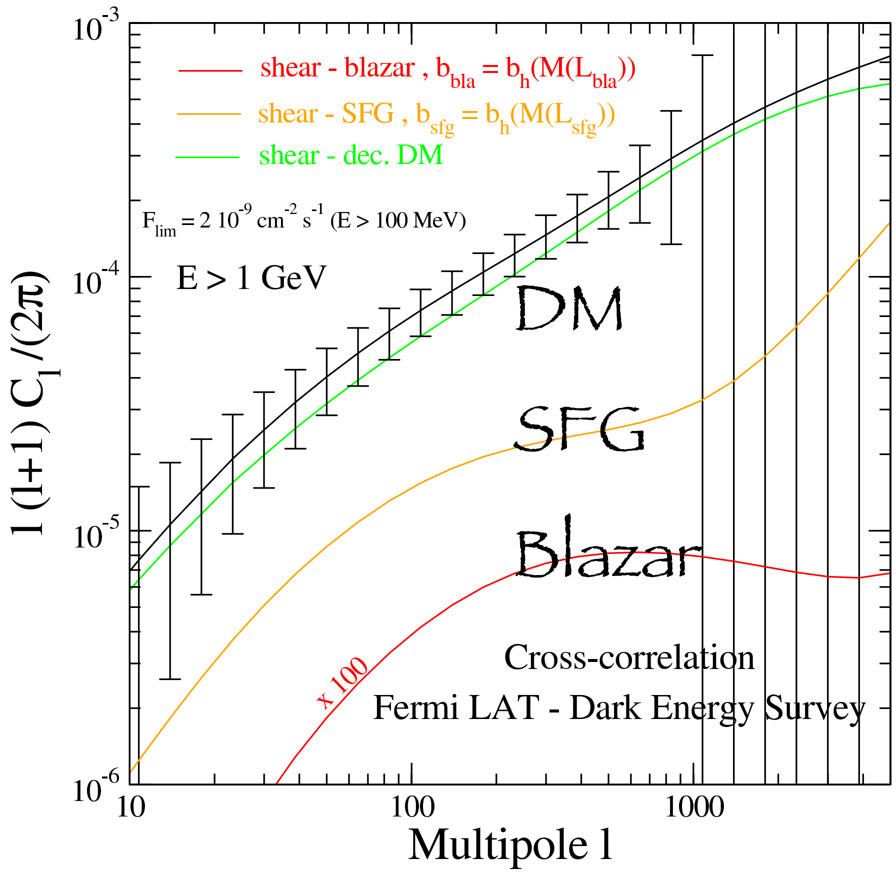
Reshift information in shear can help in "filtering" signal sources

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

Camera, Fornasa, NF, Regis, JCAP 1506 (2015) 029

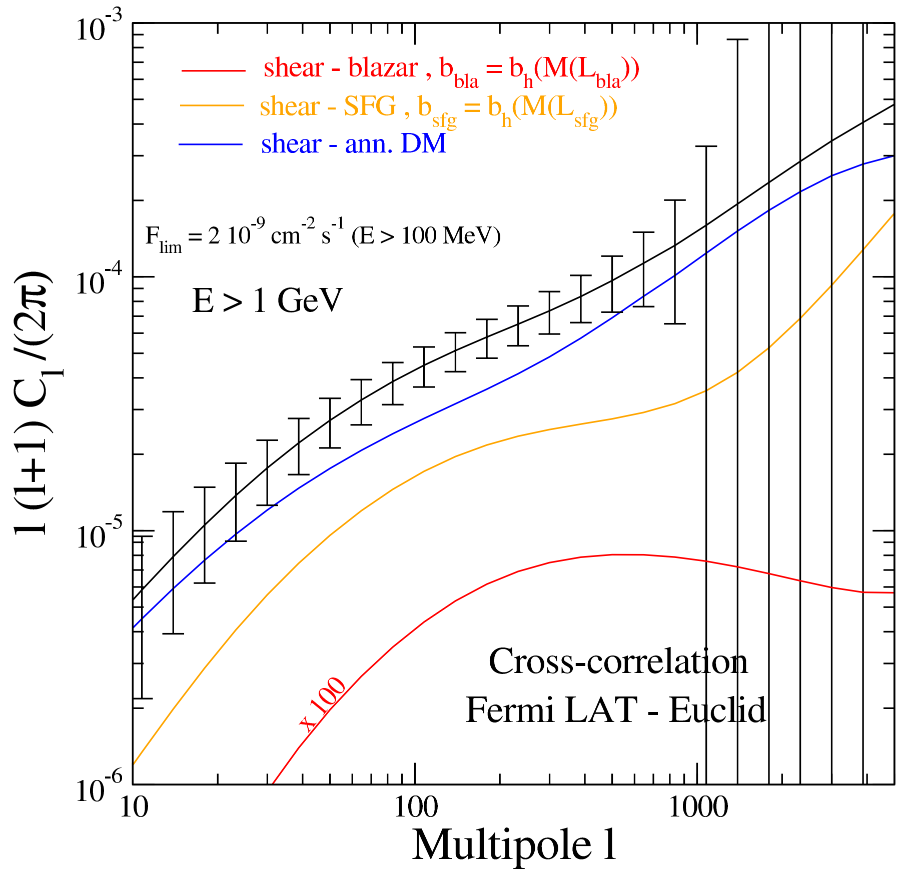
Proof of concept

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

Further advantages

Observationally:

- Auto correlation feels:
  - Detector noise (auto correlates with itself)
  - Galactic foregound (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

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

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

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

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

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

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

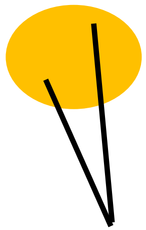
1-halo term $$P^{1h}_{ij}(k) = \int dm \, \frac{dn}{dm} \hat{f}^*_i(k|m)\, \hat{f}_j(k|m)$$

Linear matter PS

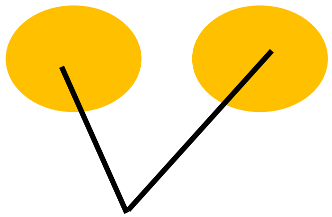
2-halo term $$P^{2h}_{ij}(k) = \left[\int dm_1 \frac{dn}{dm_1} b_i(m_1)\hat{f}^*_i(k|m_1)\right]\left[\int dm_2 \frac{dn}{dm_2} b_j(m_2)\hat{f}_j(k|m_2)\right] P^{\rm lin}(k)$$

Linear bias

1 halo



2 halo



depens 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 for DM: M_{min}

subhalo boost

Window functions for annihilating DM

Clumping factor : a measure of the clustering

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

DM photon "emissivity"

Halo mass function   Halo profile

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

Subhalo boost

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

Uncertainties from:

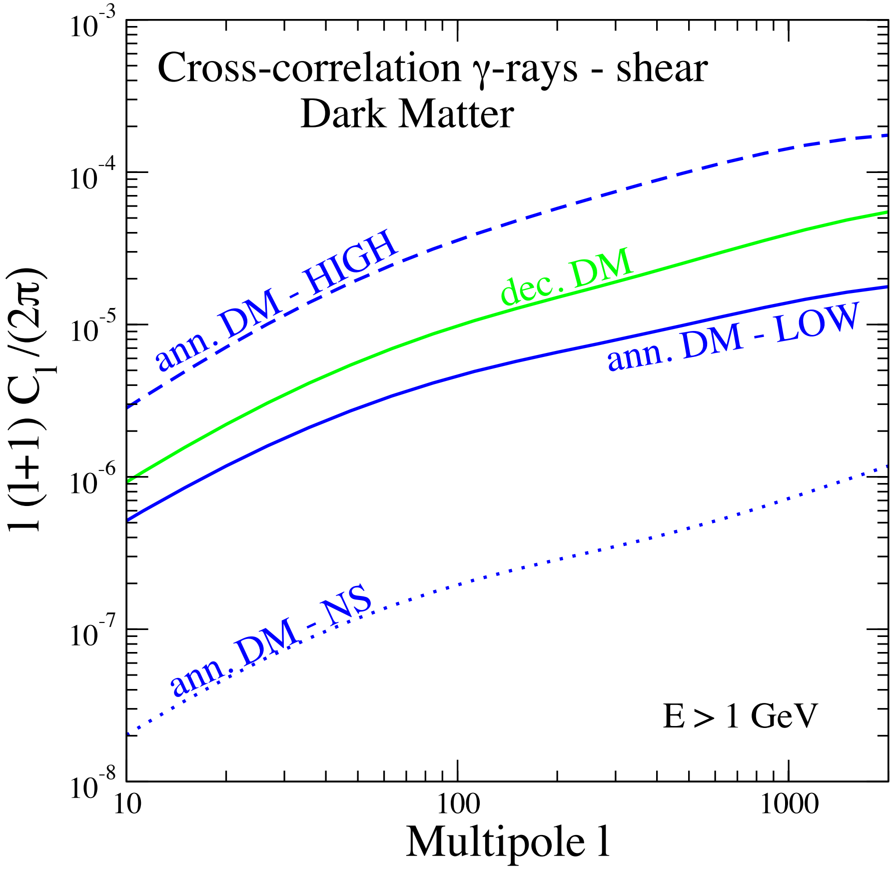
- Minimal halo mass M_{min}
- Halo concentration c(M)

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

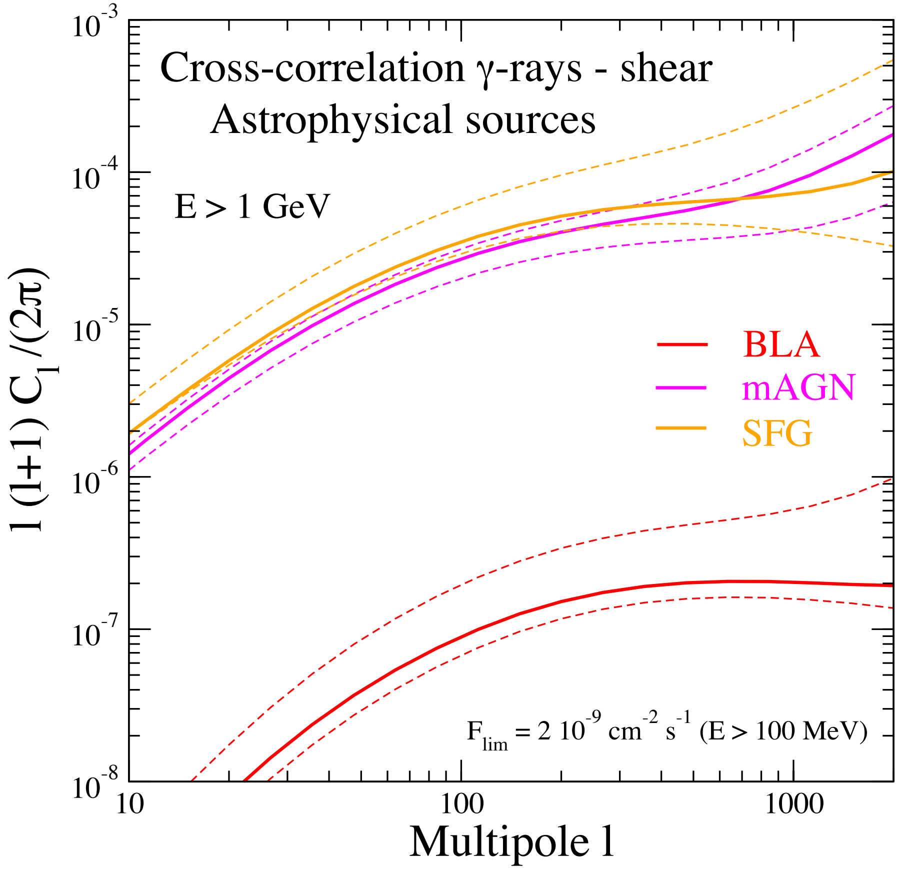
Gamma-rays are also emitted by astrophysical sources, each of which has a specific window function

Angular power spectra

Dark Matter APS

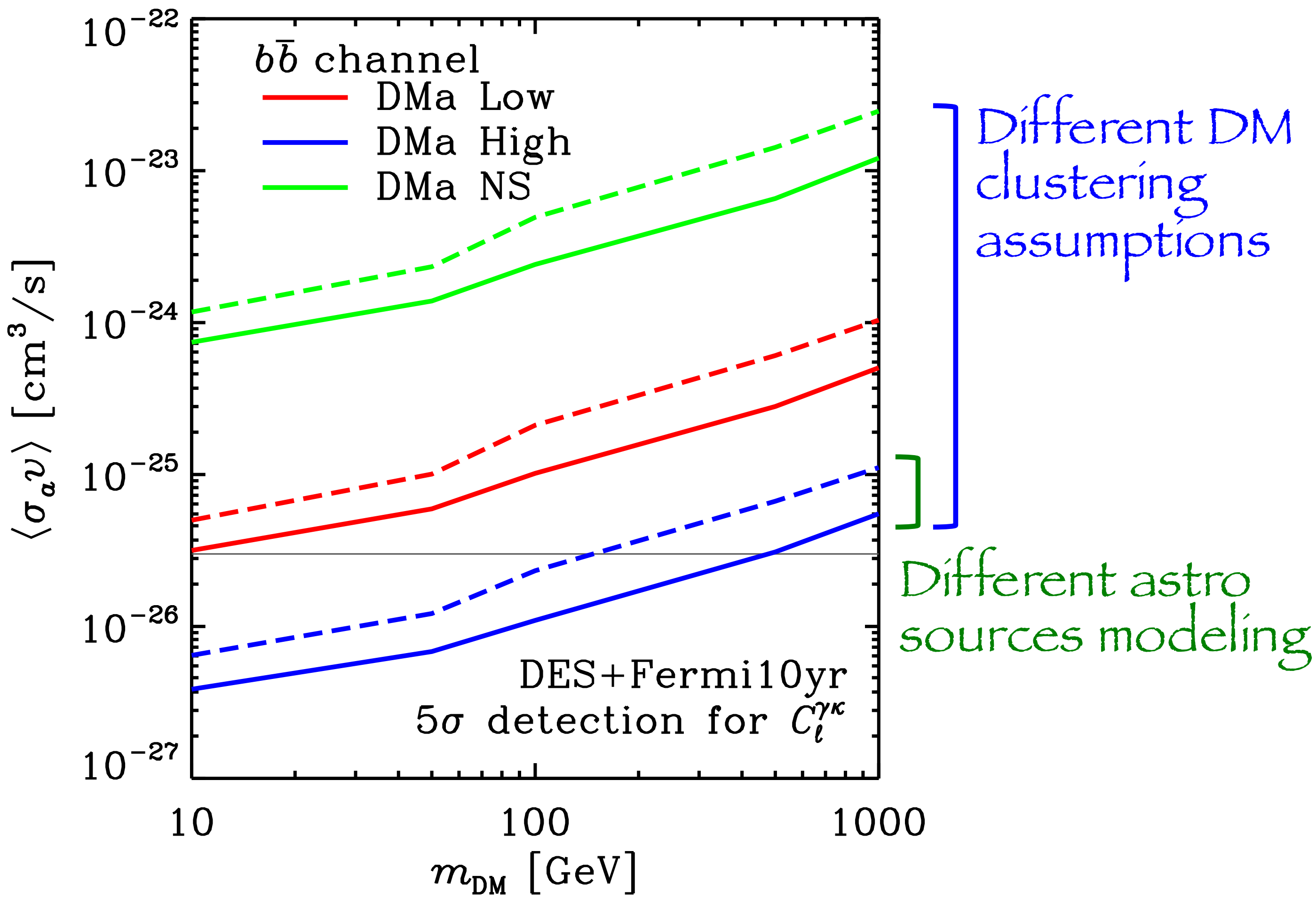


Astrophysical sources APS



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

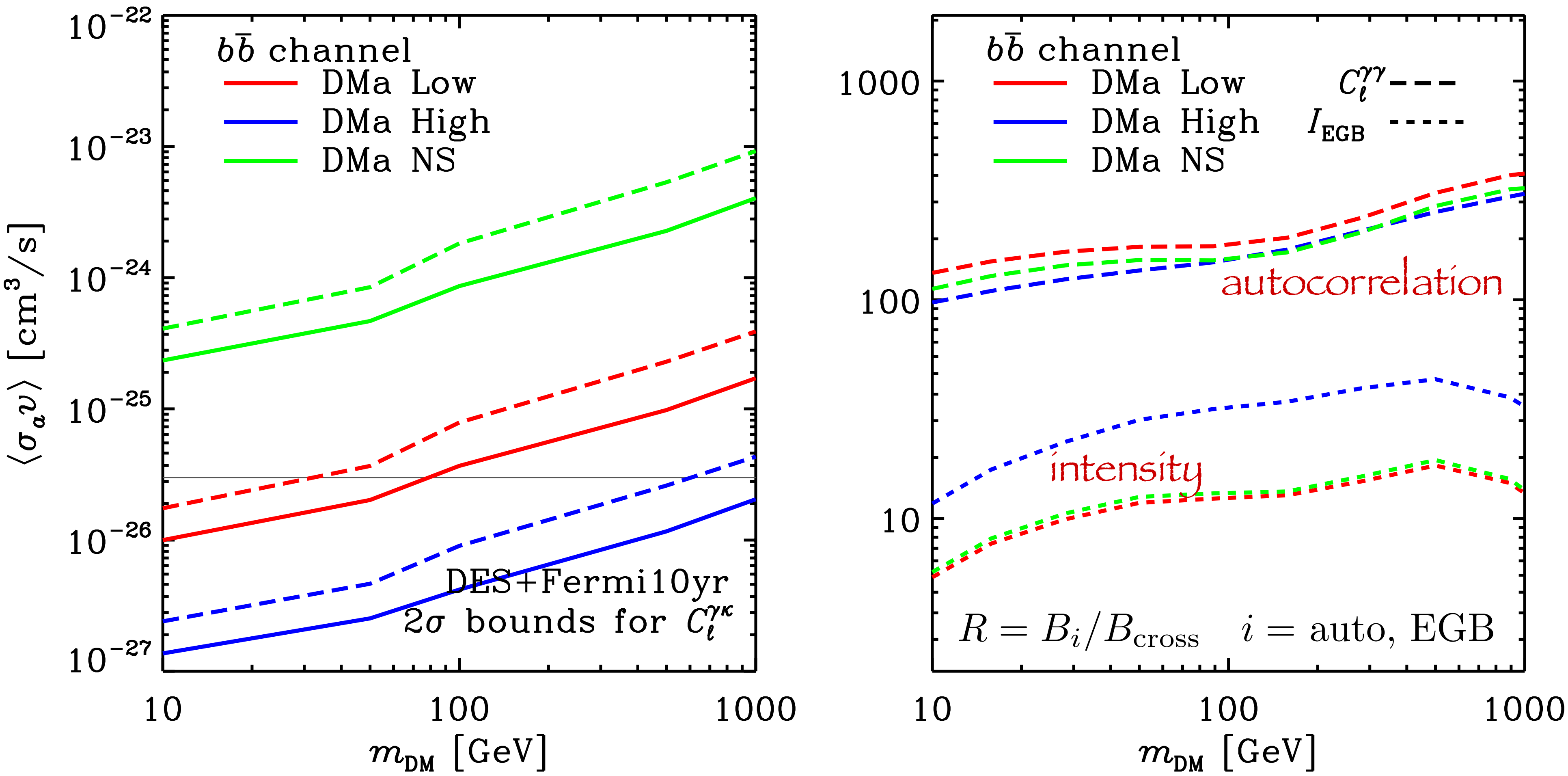
Detection forecasts



5σ detection for DES + Fermi 10yr

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

Sensitivity limits forecast

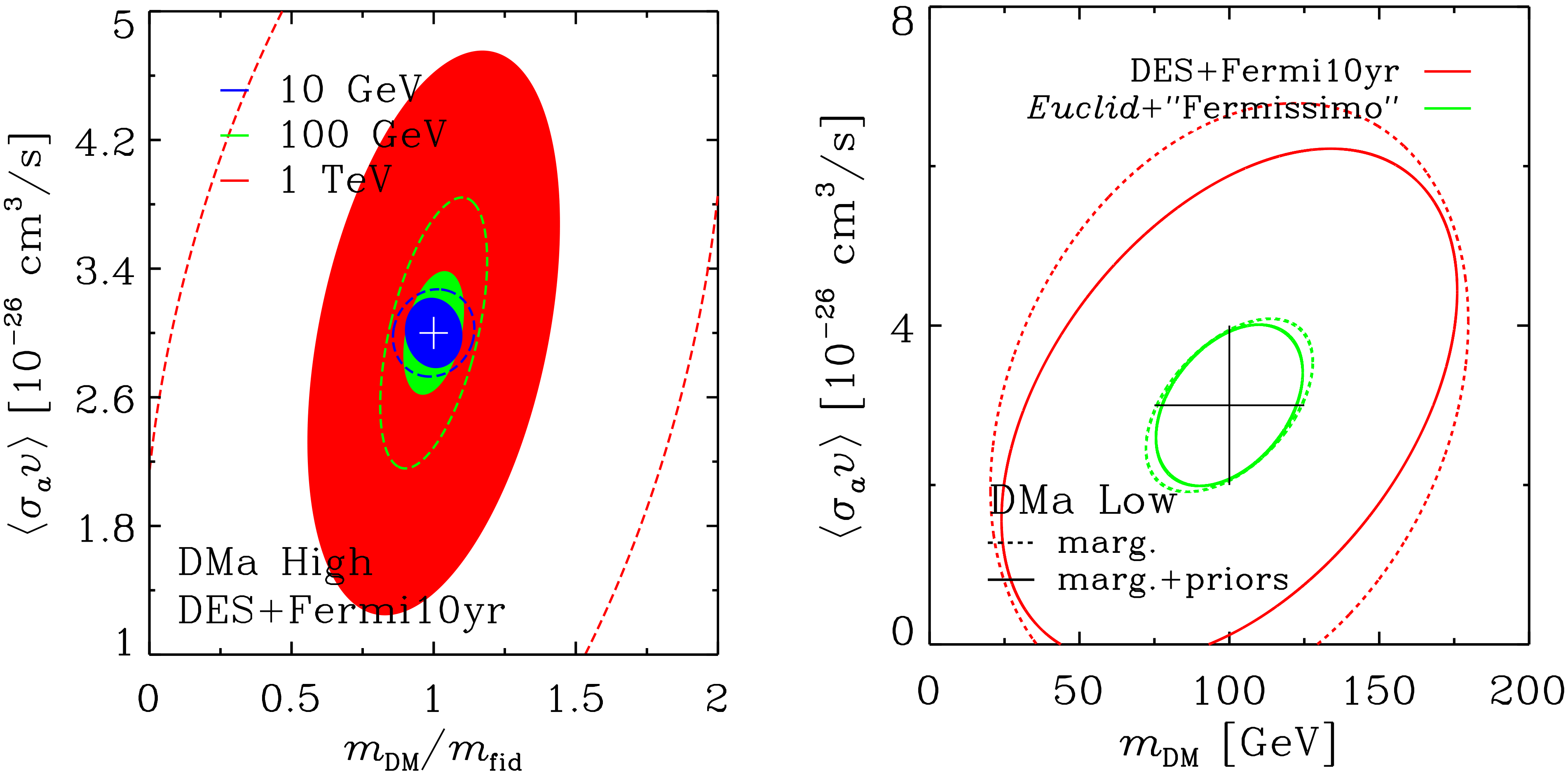


2σ bounds
DES + Fermi 10yr

Comparison

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

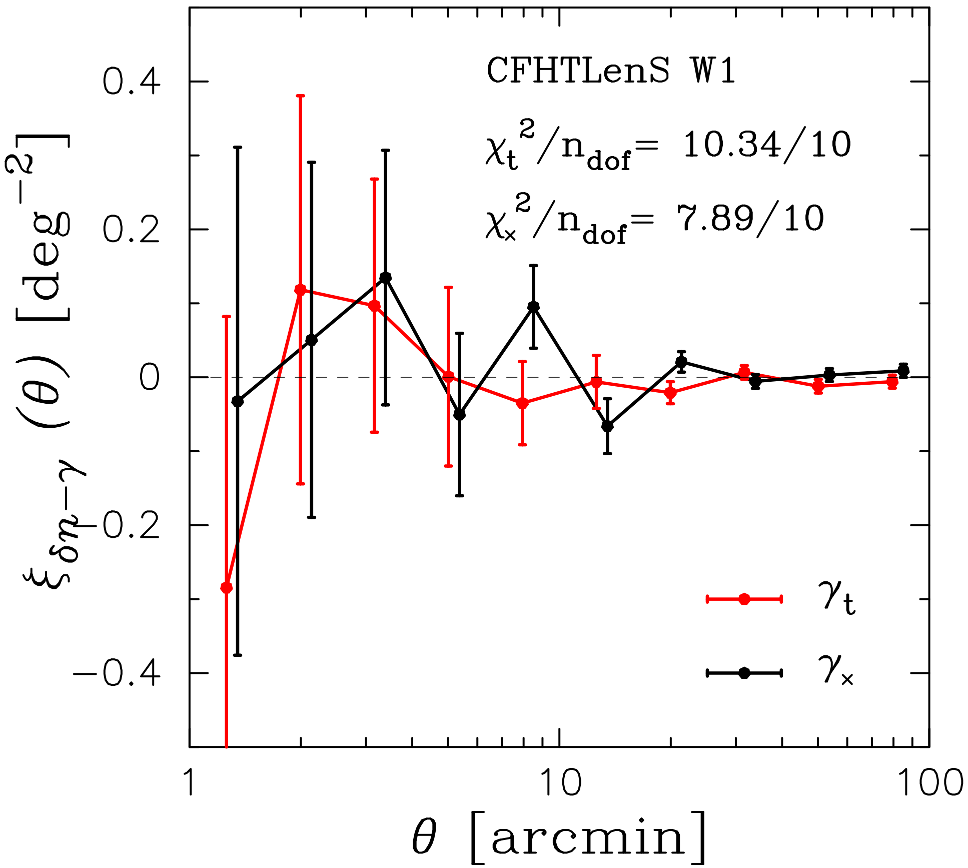
Sensitivity on DM parameters

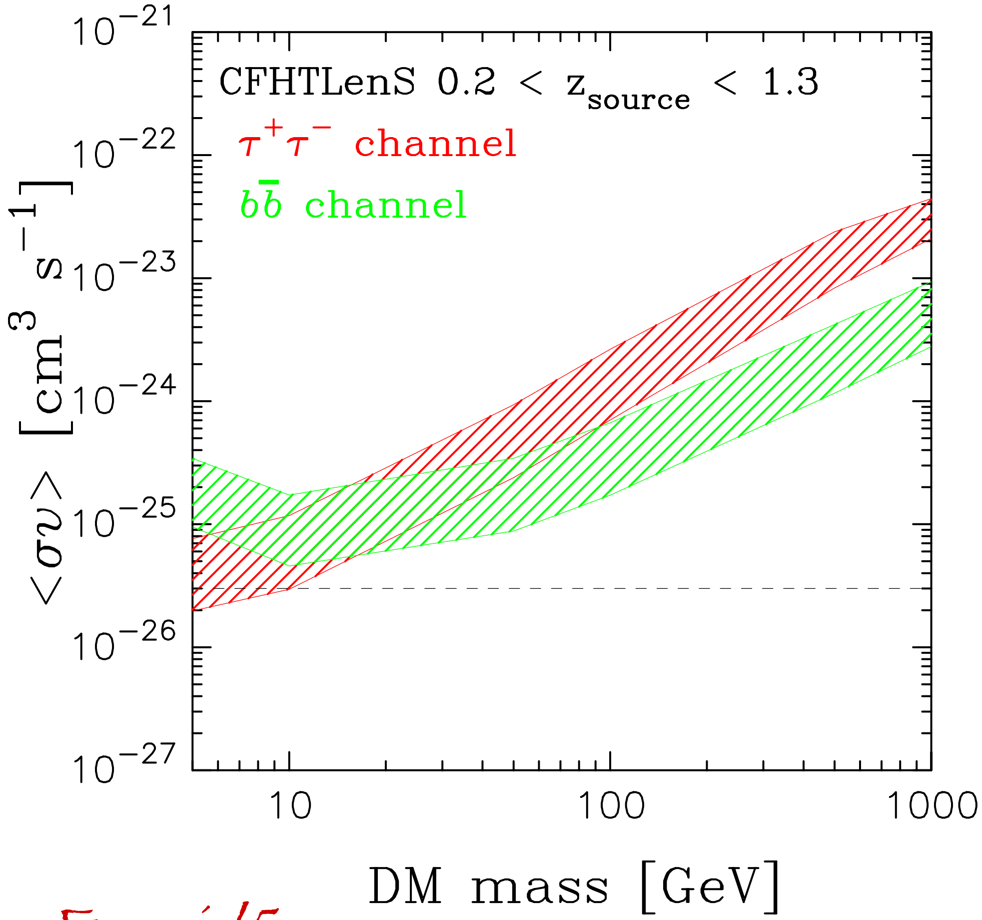


Camera, Fornasa, NF, Regis, JCAP 06 (2015) 029

First analysis on data

Patch W1: 72 sq. deg



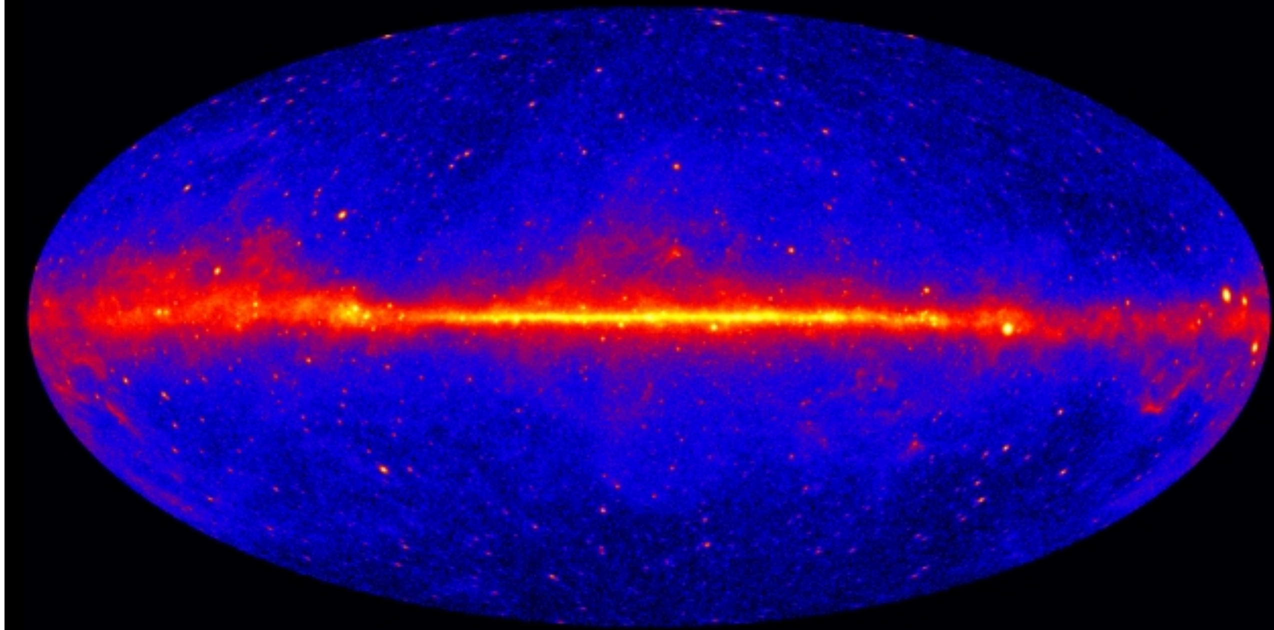


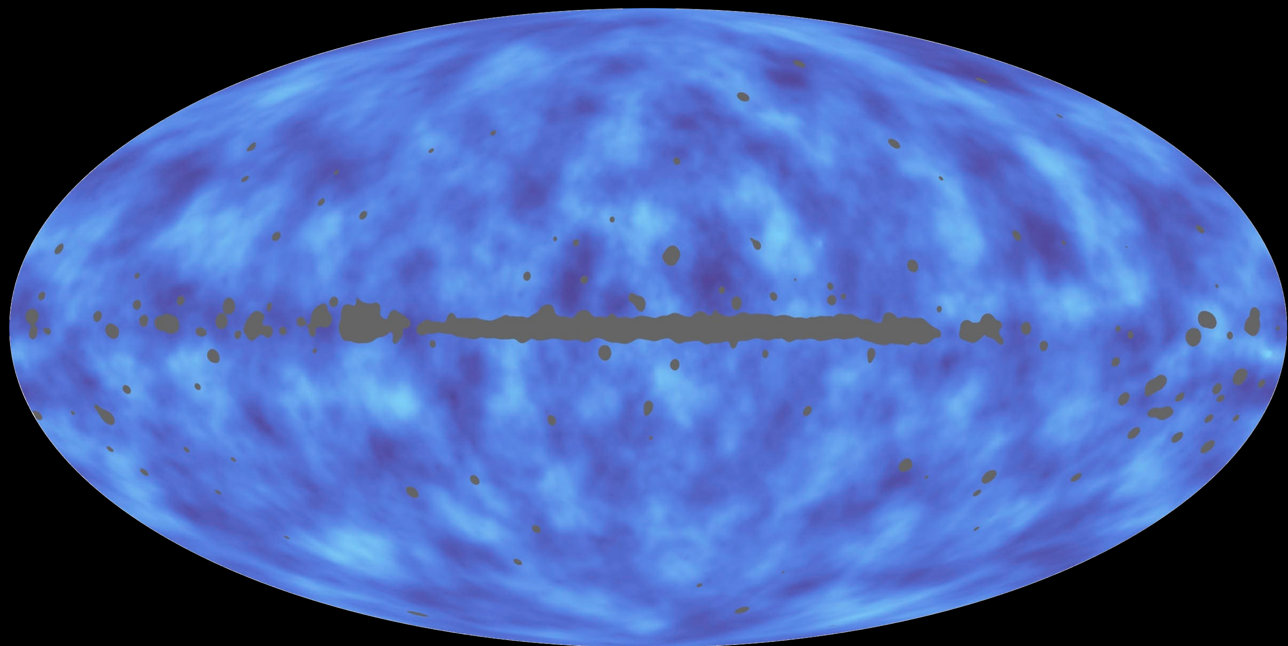
CFHTLens + Fermi/5yr

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

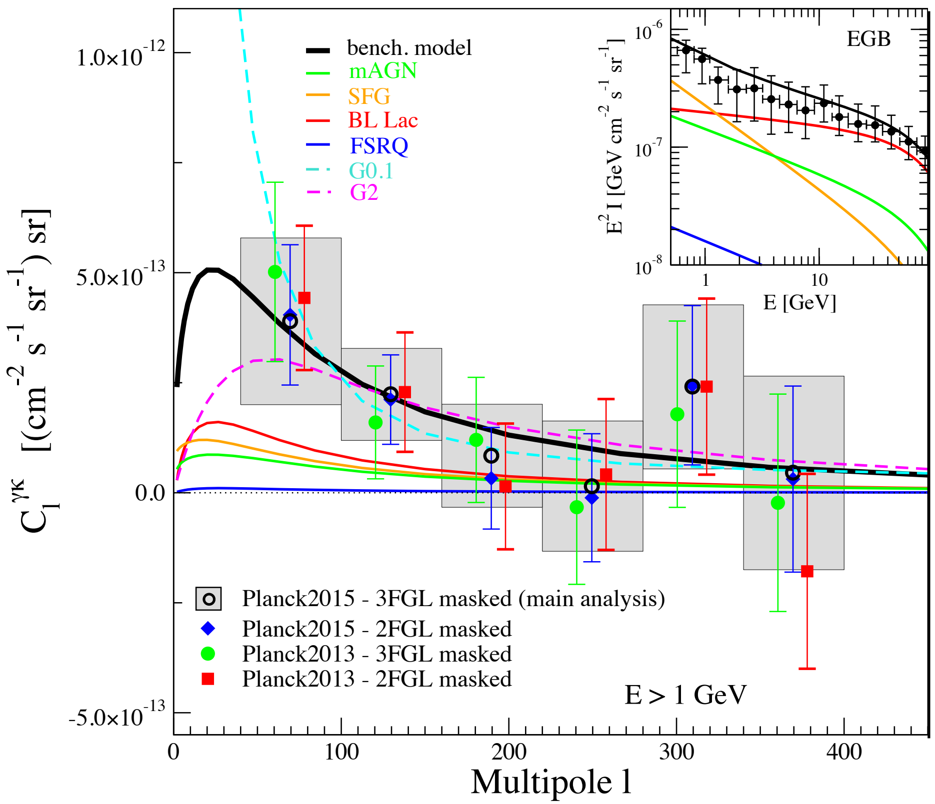
Troester, Camera, Fornasa, Regis, Ando, NF, Van Vaerbecke +, to appear
Analysis under way on CFTHLenS + RCSLenS + KiDS
150 (14) / 500 (5.5) / 450 (8.8) deg2 (arcmin-2)

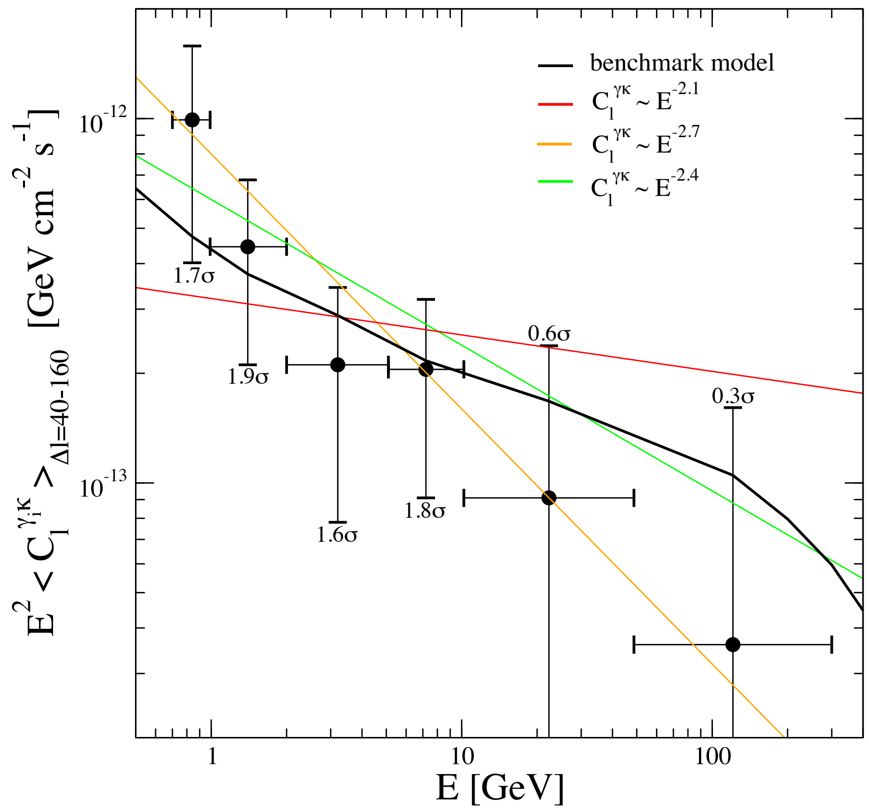
Fermi/gamma + Planck/CMB lensing





Fermi/gamma + Planck/CMB lensing





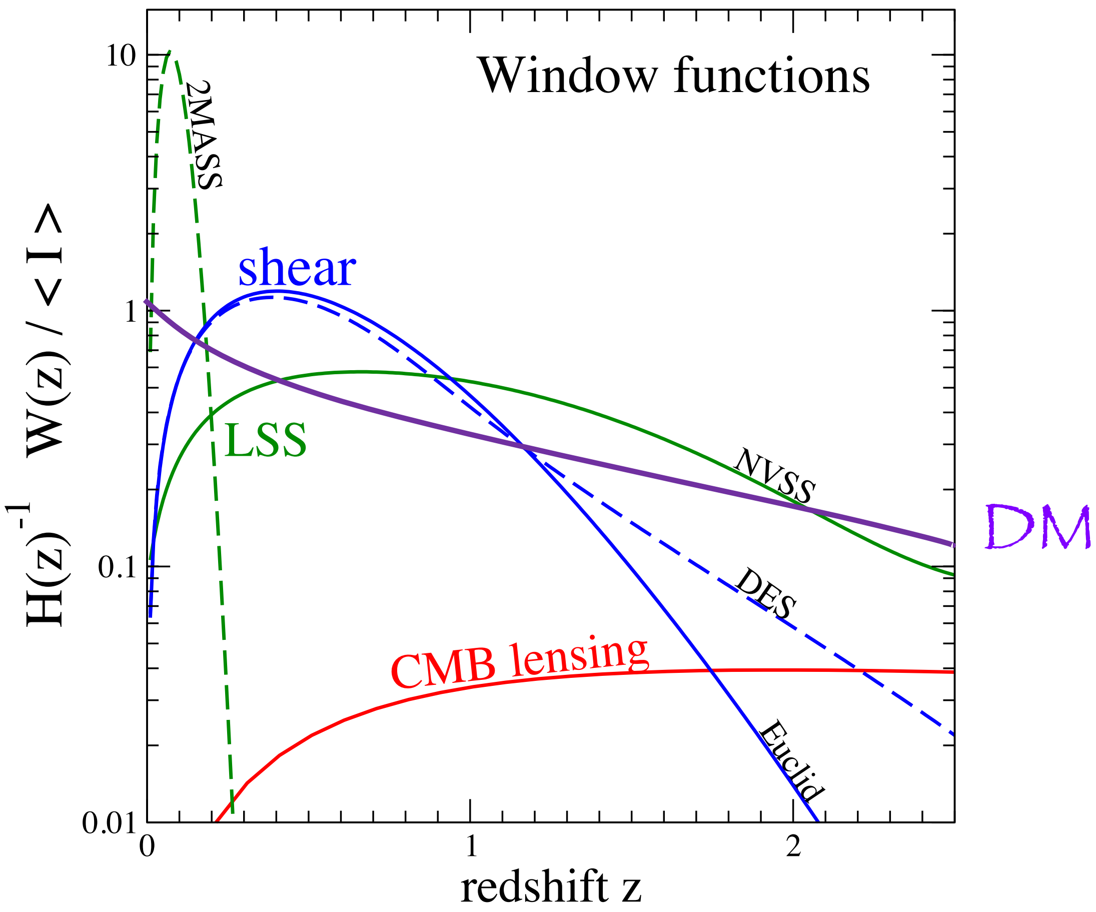
Cross-correlation: 3.0σ evidence

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

Window functions: DM x CMBlensing

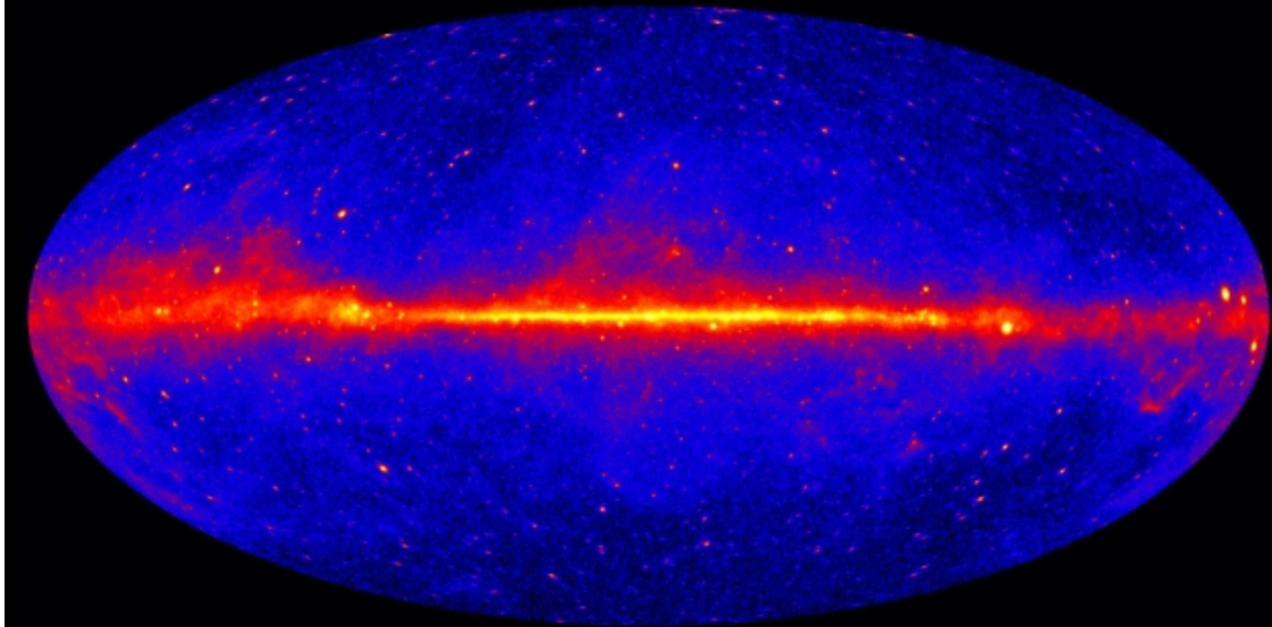


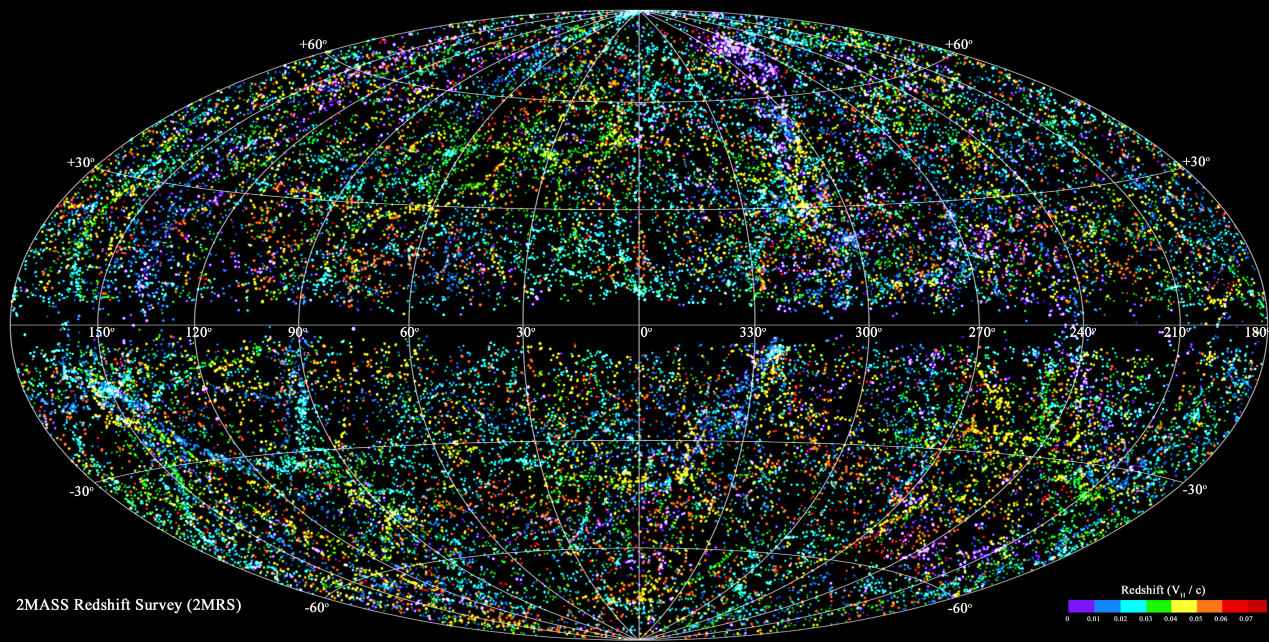
CMB lensing is not the best observable for DM

Instead it can hopefully help in constraining astrophysical sources

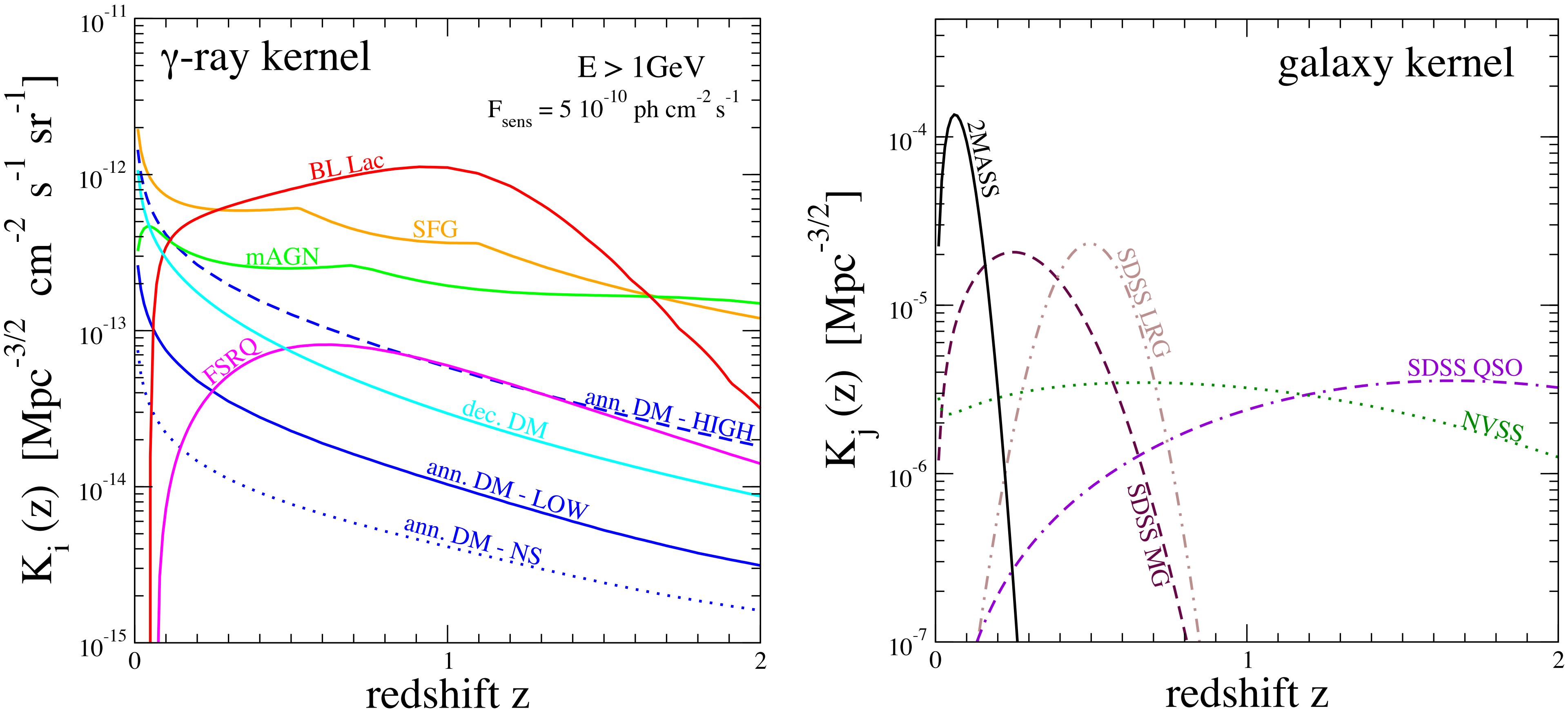
NF, Regis, Front. Physics 2 (2014) 6

Fermi/gamma x Galaxy catalogs





Window functions: DM x LSS



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

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

NF, Regis, Front. Physics 2 (2014) 6
Ando, Benoit-Levy, Komatsu, PRD 90 (2014) 023514
Ando, JCAP 1410 (2014) 061

Cross correlation with galaxy catalogs

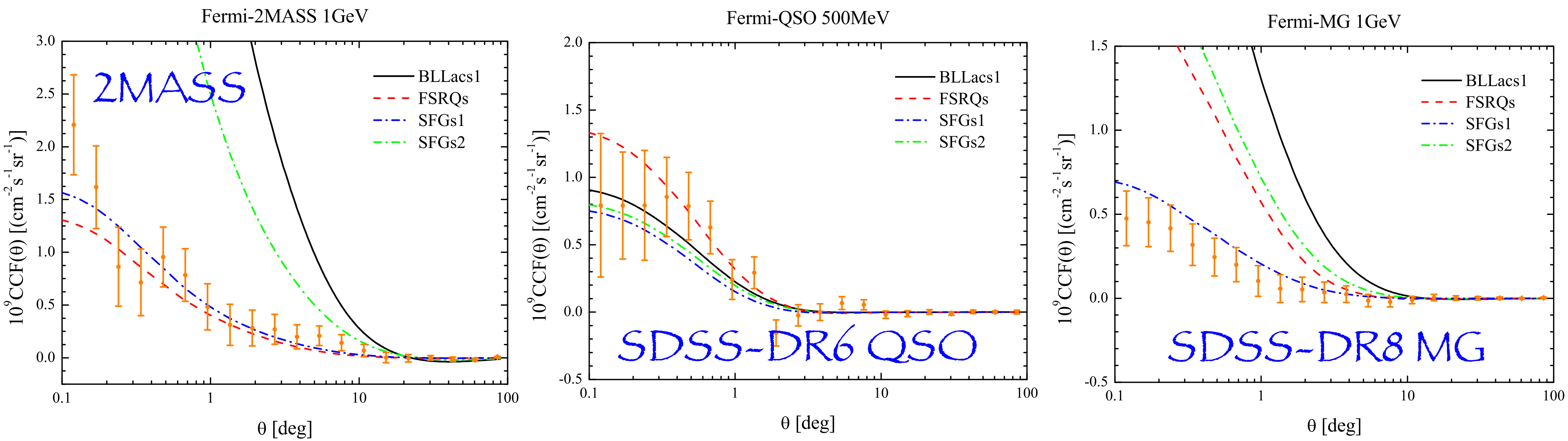
Cuoco, Brandbyge, Hannestad, Haugbolle, Miele, PRD 77 (2008)123518 th

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

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

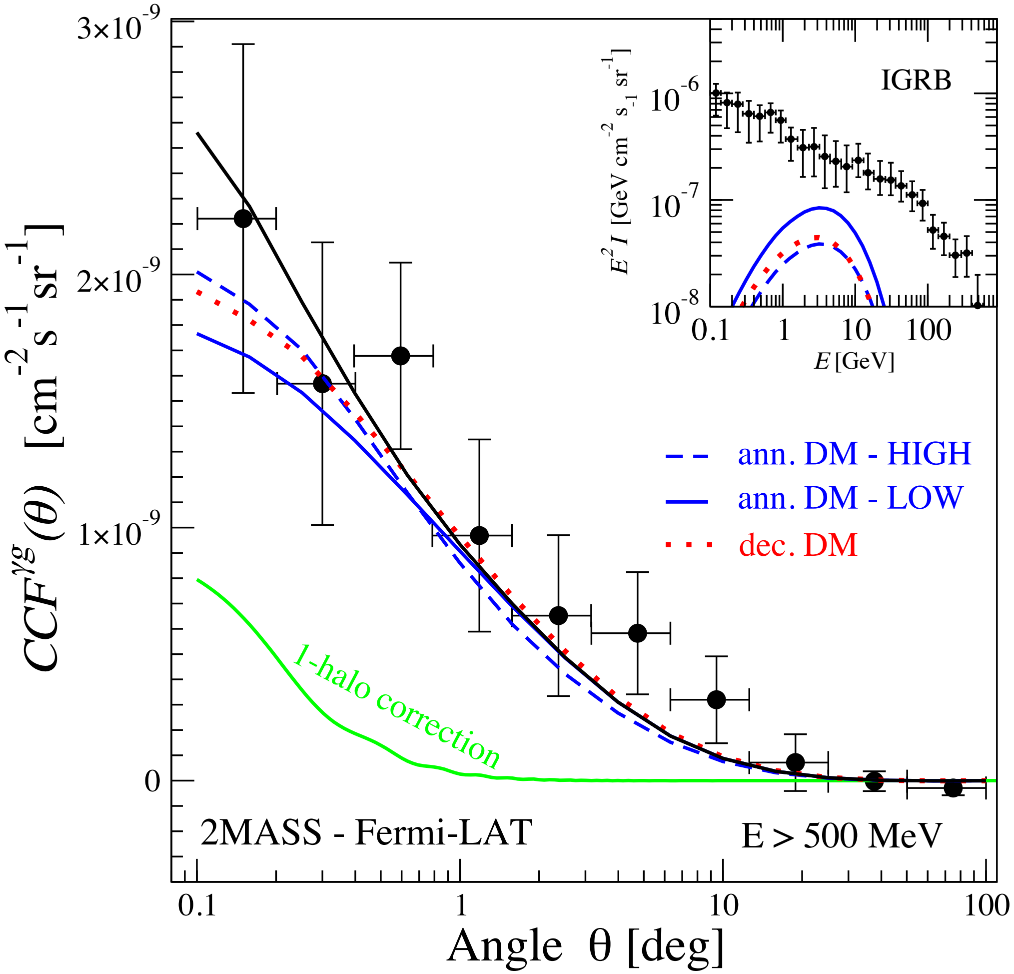
Xia, Cuoco, Branchini, Viel, APJS 217 (2015) 15

SDSS 6 QSO, SDSS 8 MGS, SDSS LRG, 2MASS, NVSS
x Fermi 60 months signal



correlation observed at the degree scale

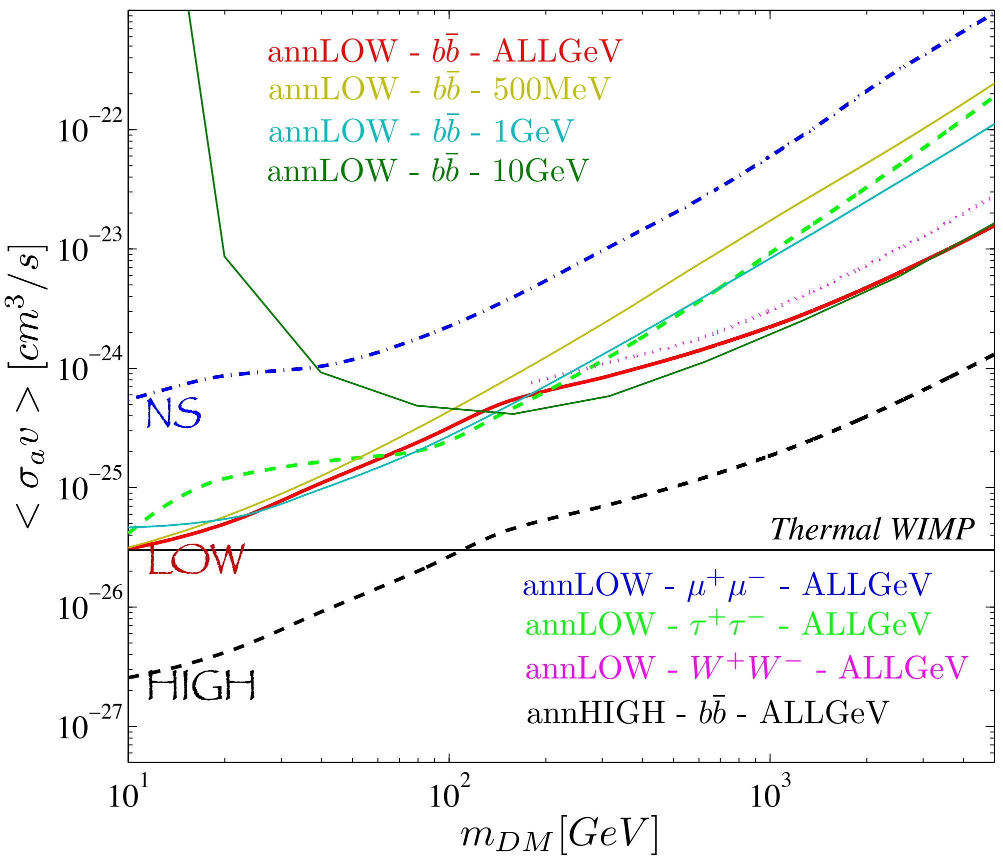
Fermi + 2MASS



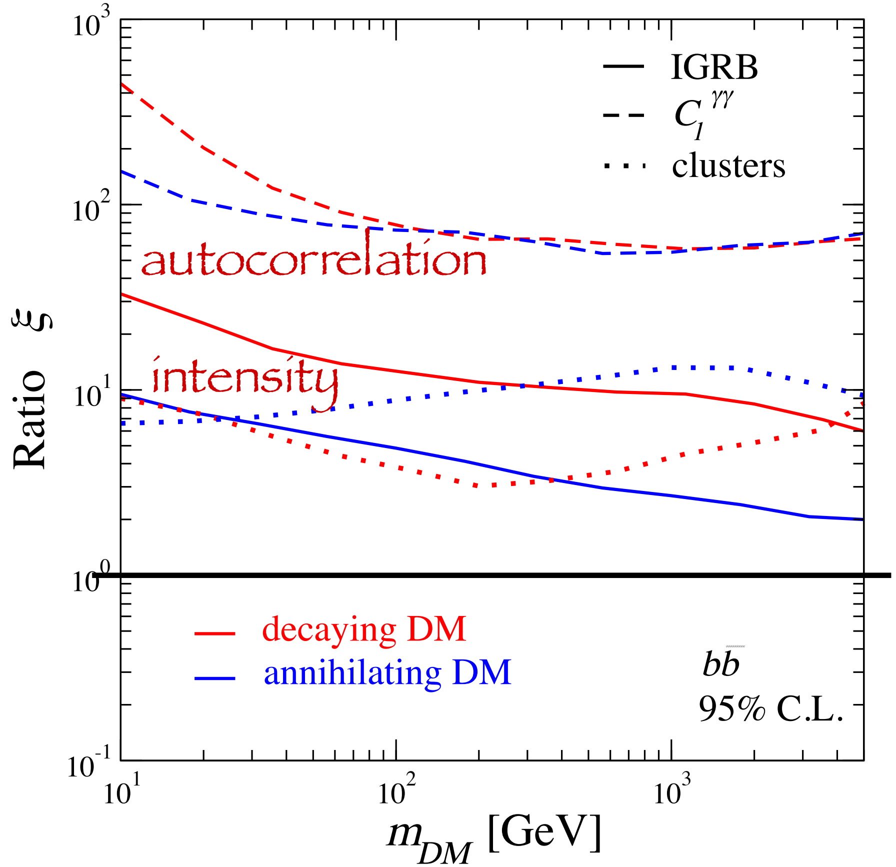
The observed cross-correlation(*) can be reproduced (both in shape and size) by a DM contribution that is largely subdominant in the total intensity

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

Fermi + 2MASS



Bound from cross correlation



Bounds ratios
Correlation technique is stronger

Regis, Xia, 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

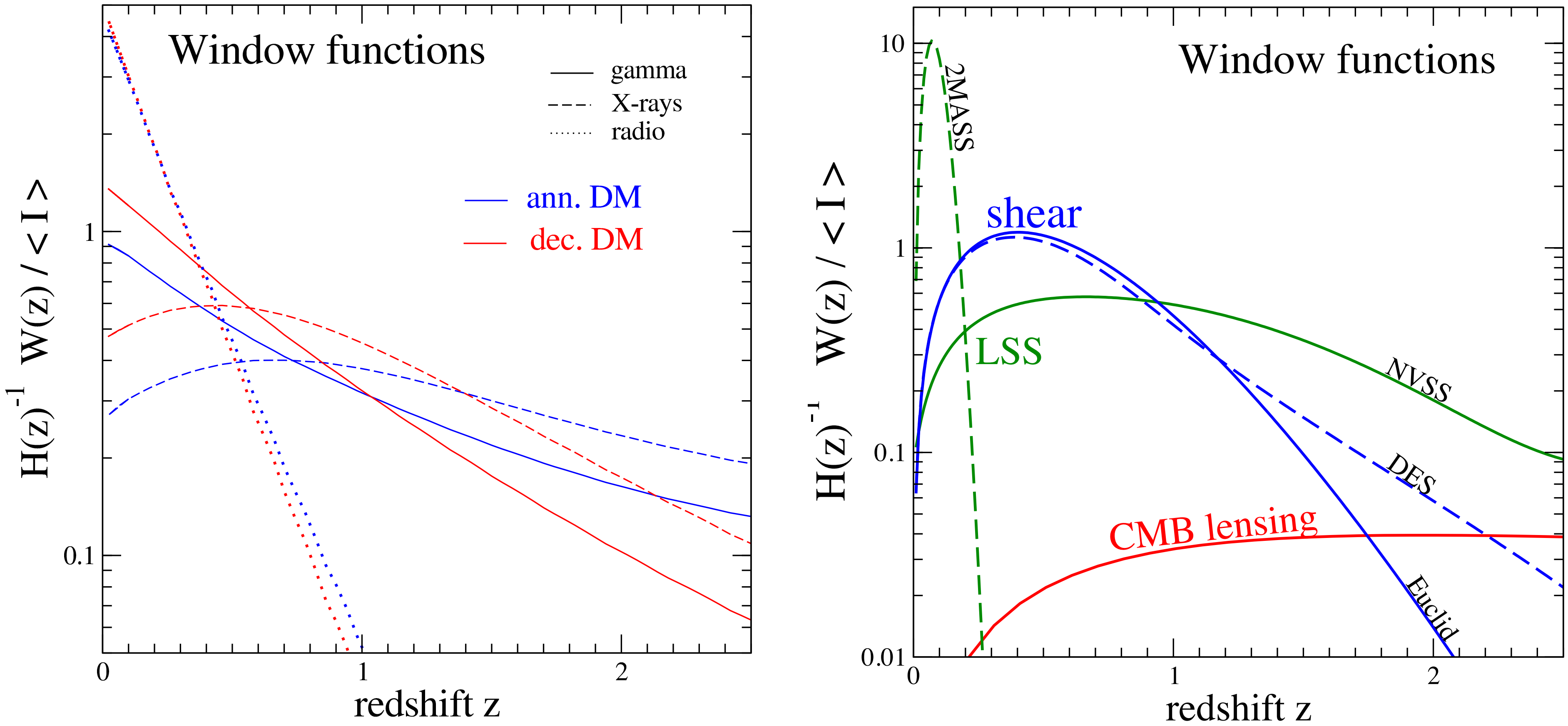
- Gravitational tracers: G_i
  - Weak lensing surveys (cosmic shear) — traces the whole DM
  - CMB lensing
  - LSS surveys — traces light -> bias

- Electromagnetic signals: E_a
  - Radio
  - X
  - Gamma

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

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

Additional cross correlations channels



Multiwavelength signals

&

LSS tracers and gravitational probes

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

Cross-correlations - Outlook

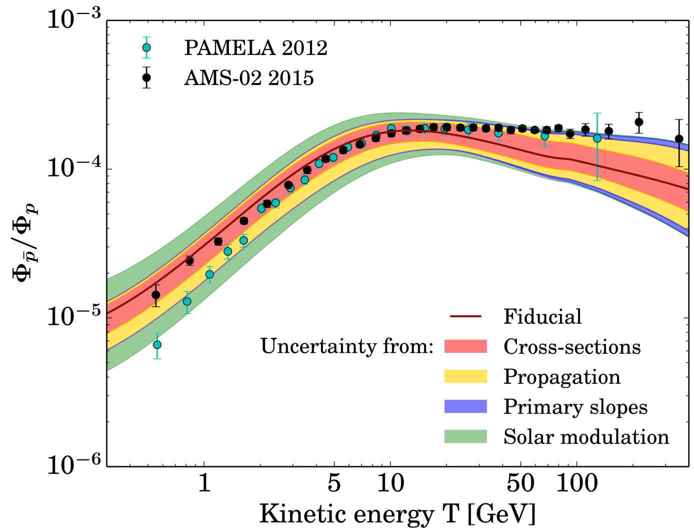
- In order to separate a DM non-gravitational signal from other astrophysical emissions, a filter based on the DM properties (i.e. the associated gravitational potential) appears to be very promising
- Cross-correlations offer an emerging opportunity:
  - DM particle signal: multiwavelenght emission (radio, X, gamma)
  - DM gravitational tracers: cosmic-shear, LSS surveys, CMB lensing
- Gamma rays + cosmic shear: cleanest possibility, appears quite powerful
- First relevant observational opportunity hopefully soon years with DES
- High-sensitivity will require Euclid together with the total accumulated Fermi statistics (plus possible novel gamma-ray detectors)
- 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)


Exciting times ahead and …
… a lot of fun expected!

Backup slides

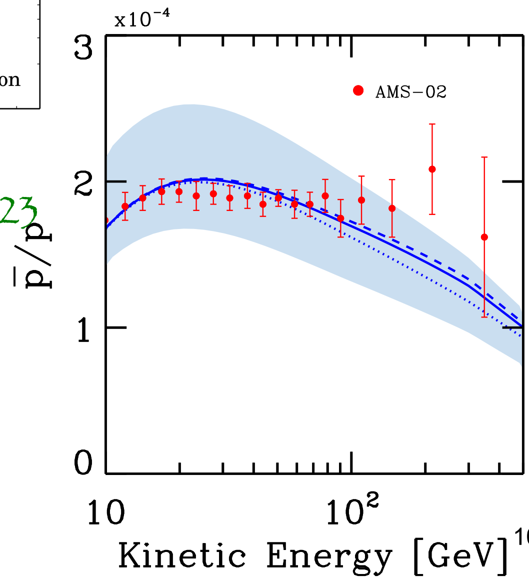
AMS-02 pbar/p

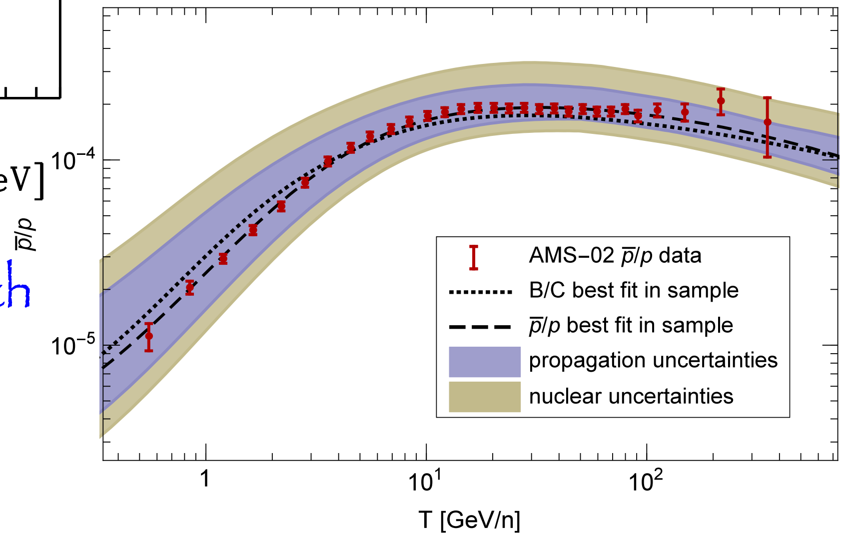
Kounine, "AMS days" at CERN, April 2015



Giesen et al., JCAP 1509 (2015) 023

Evoli, Gaggero, Grasso, arXiv:1504.05175





Kappl, Reinert, Winkler, JCAP 1510 (2015) 034

In addition AMS is bringing very detailed information on cosmic rays nuclei (e.g. B/C) which will allow shaping the CR transport models (DRAGON, Galprop, Usine, non public codes)

This is relevant for both DM signals and its backgrounds

1pPDF

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

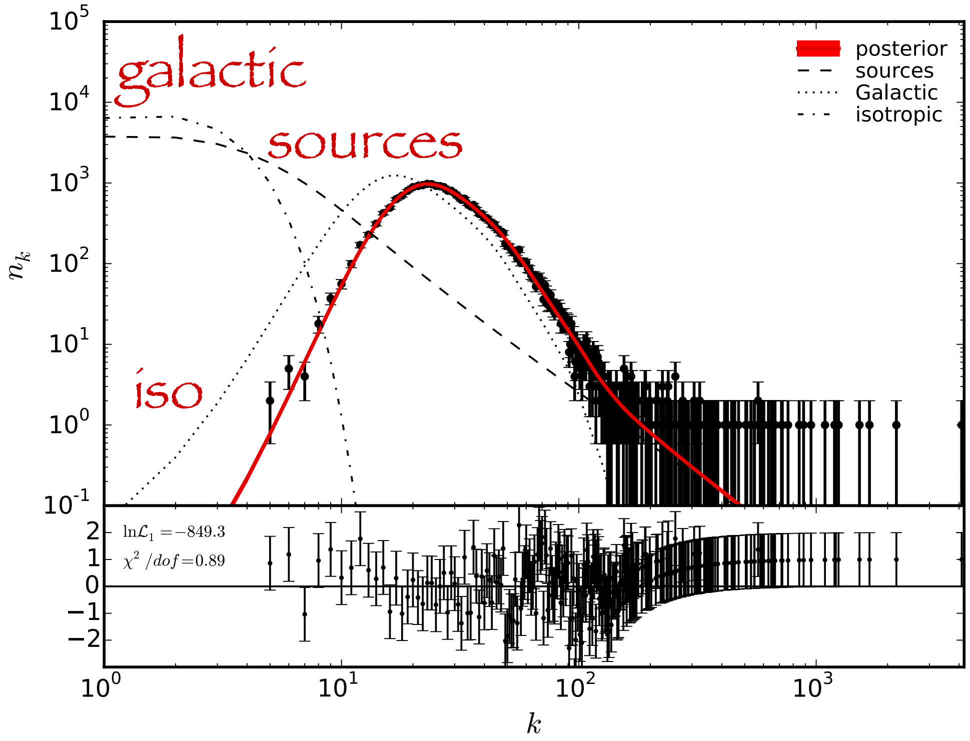
Radio P(D)

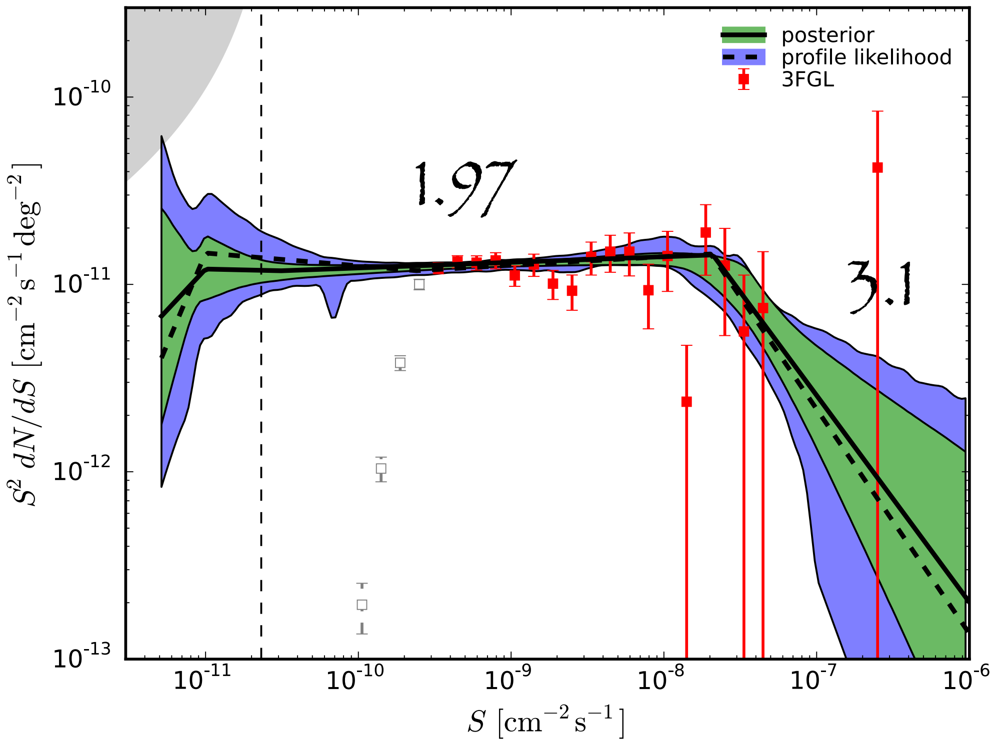
Scheuer, PCPS 53 (1957) 764
Condon, ApJ 188 (1974) 279
Venstrom, Scott, Wall, MNRAS 440 (2014) 2781
Vernstrom, Norris, Scott, Wall, MNRAS 447 (2015) 2243

X rays

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

Photon counts



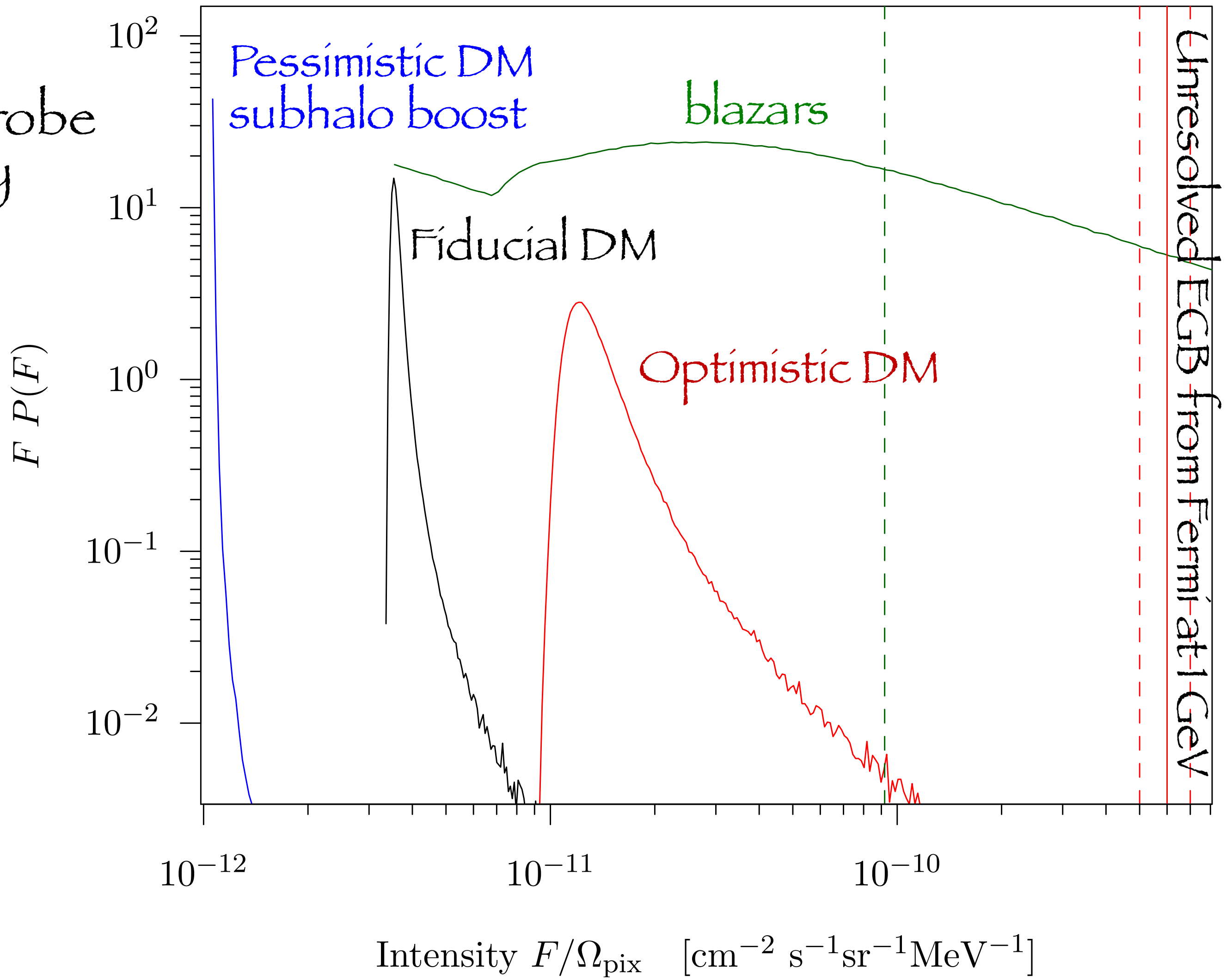


Point sources	25%	6 years Fermi data
Galactic foreground	69%	$\vert b\vert > 30$ deg
Diffuse isotropic	6%	Energy range: (1-10) GeV

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

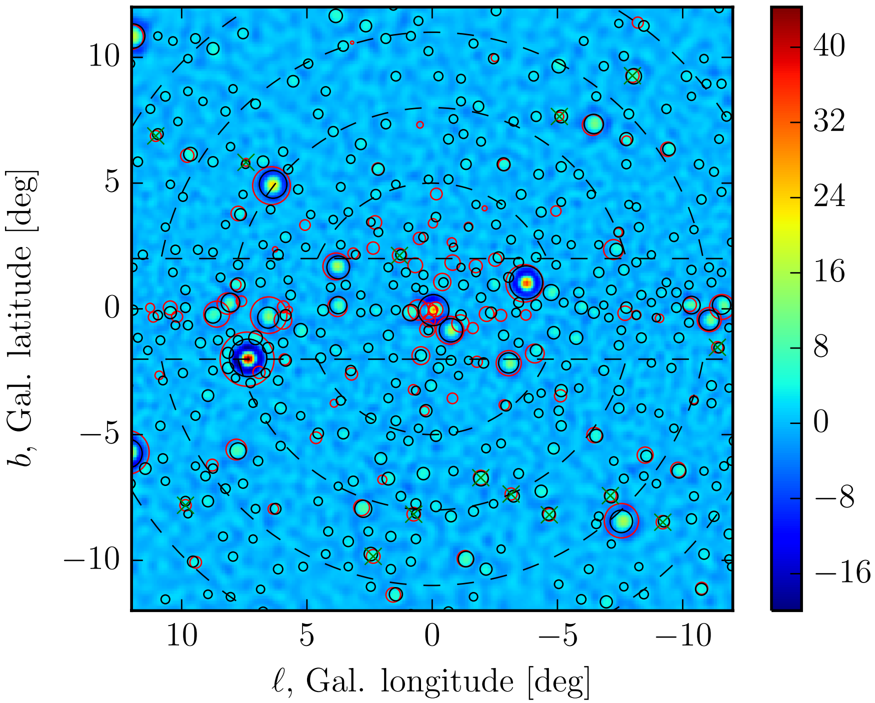
Flux PDF

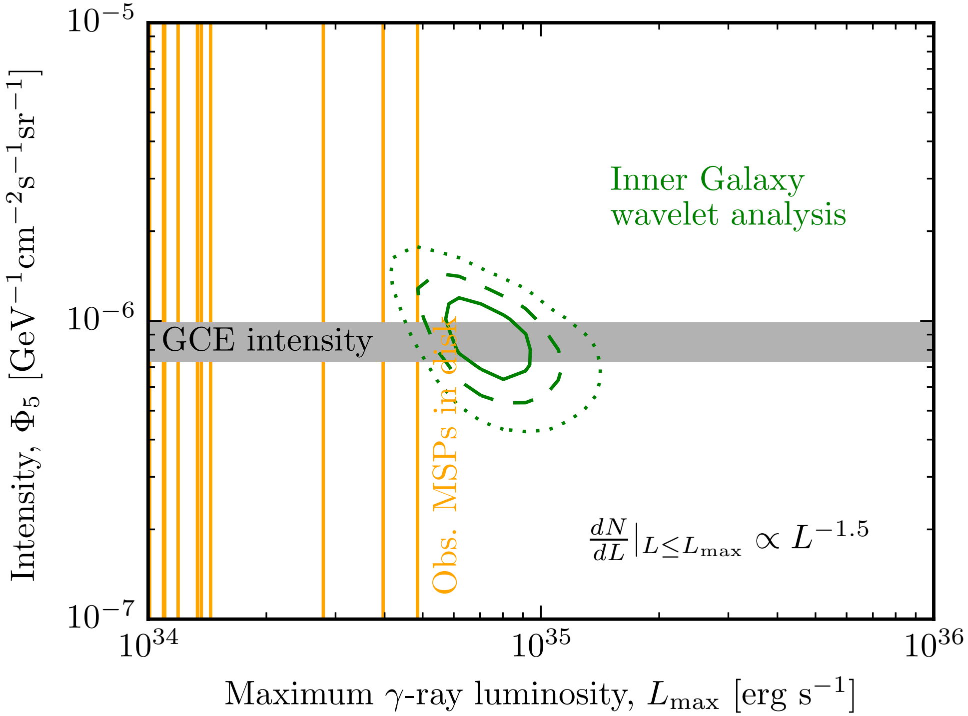
Flux PDF: probe of luminosity function



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

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

Gamma rays autocorrelation

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, Sellerholm, 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

Gamma rays autocorrelation

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) 1074S	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

Auto Correlation

Density field: DM density contrast(²)

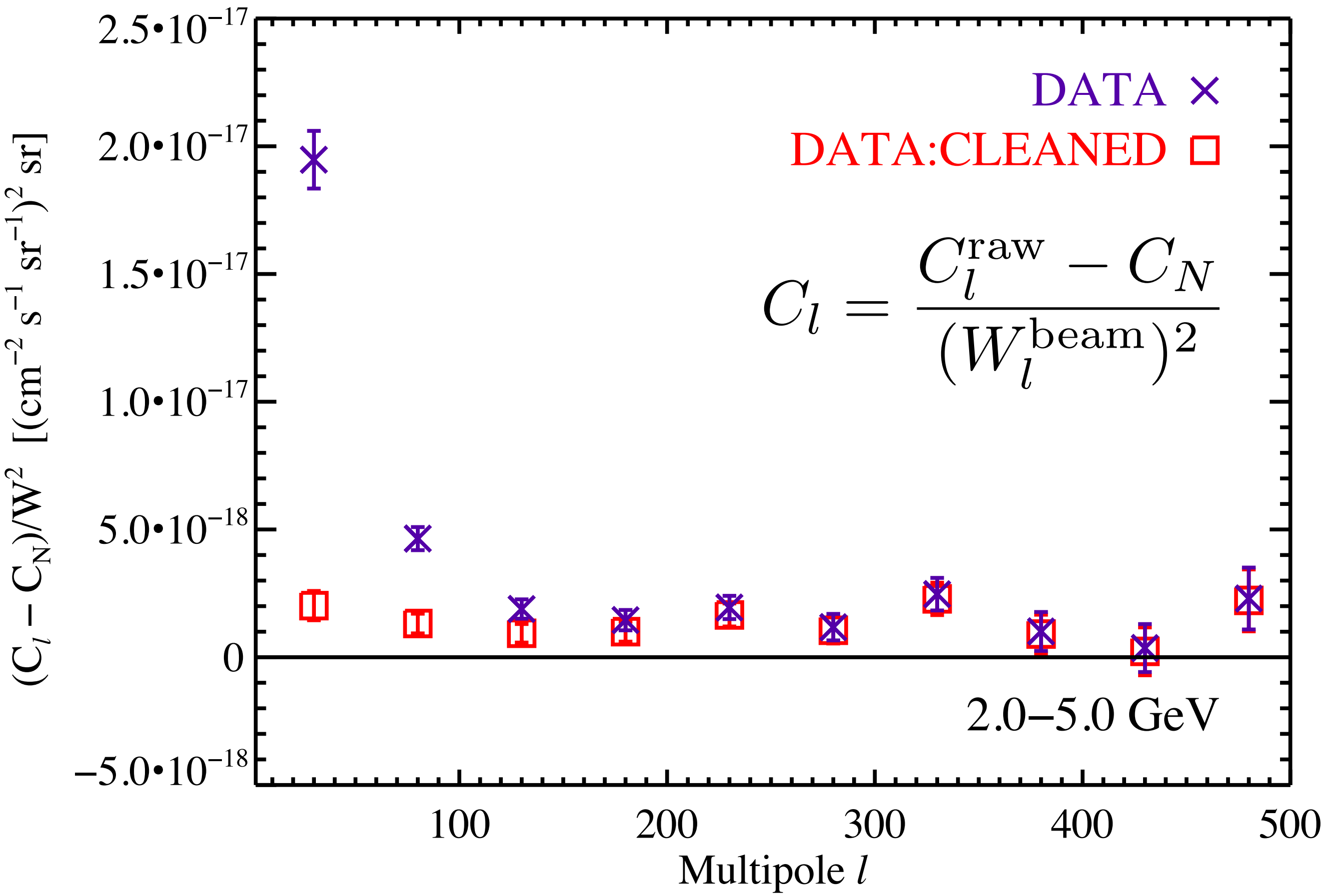
δ annihilating DM

δ^2 decaying DM

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

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

Gamma rays auto correlation

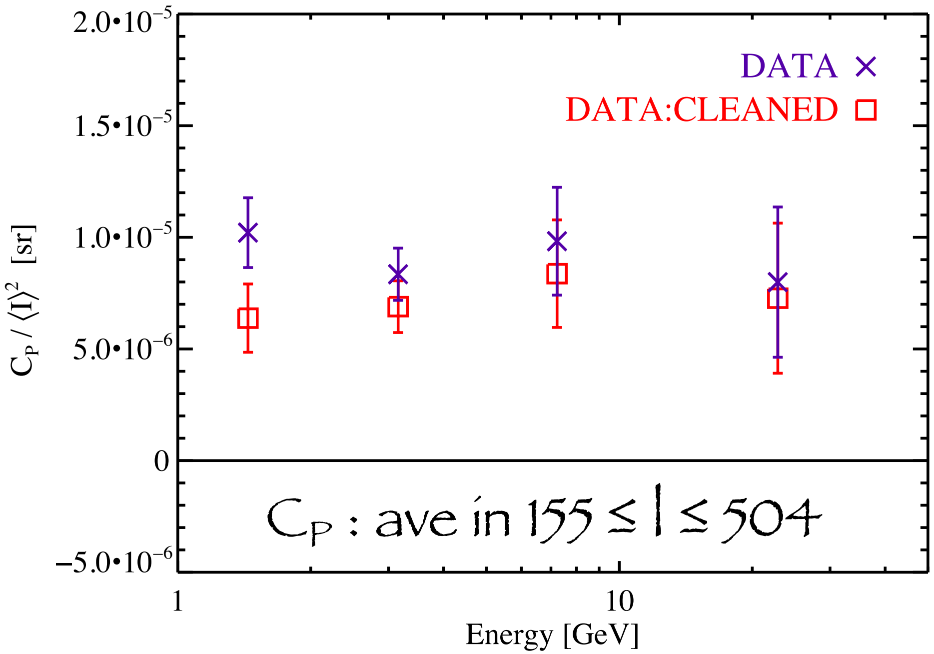


Fermi/LAT (22 months), 4 bins in 1-50 GeV

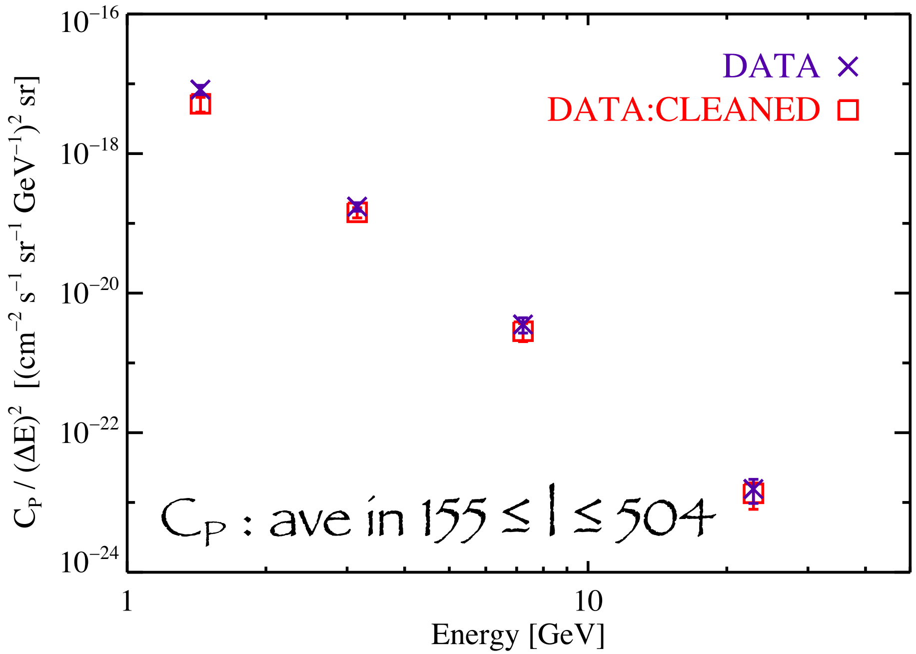
Overall significance: 9σ

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

Energy dependence



Fluctuation anisotropy spectrum



Differential anisotropy spectrum

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

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

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

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

$$I_g(\vec{n}) \longrightarrow a^g_{lm}$$

$$I_k(\vec{n}) \longrightarrow a^k_{lm}$$

$$\longrightarrow \quad C_l^{gk} = \frac{1}{2l+1} \sum_{m=-l}^{l} a^{g*}_{lm} a^k_{lm}$$

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

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

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

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

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

$\hat{f}_g$: Fourier tranform

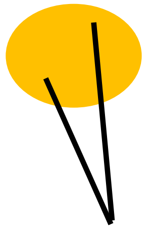
1-halo term $$P_{ij}^{1h}(k) = \int dm \, \frac{dn}{dm} \hat{f}_i^*(k|m) \, \hat{f}_j(k|m)$$

Linear matter PS

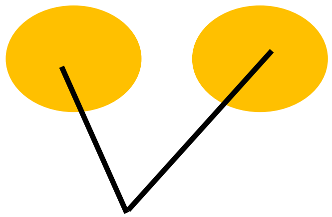
2-halo term $$P_{ij}^{2h}(k) = \left[\int dm_1 \frac{dn}{dm_1} b_i(m_1) \hat{f}_i^*(k|m_1) \right] \left[\int dm_2 \frac{dn}{dm_2} b_j(m_2) \hat{f}_j(k|m_2) \right] P^{\mathrm{lin}}(k)$$

Linear bias

1 halo



2 halo



depens 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

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

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

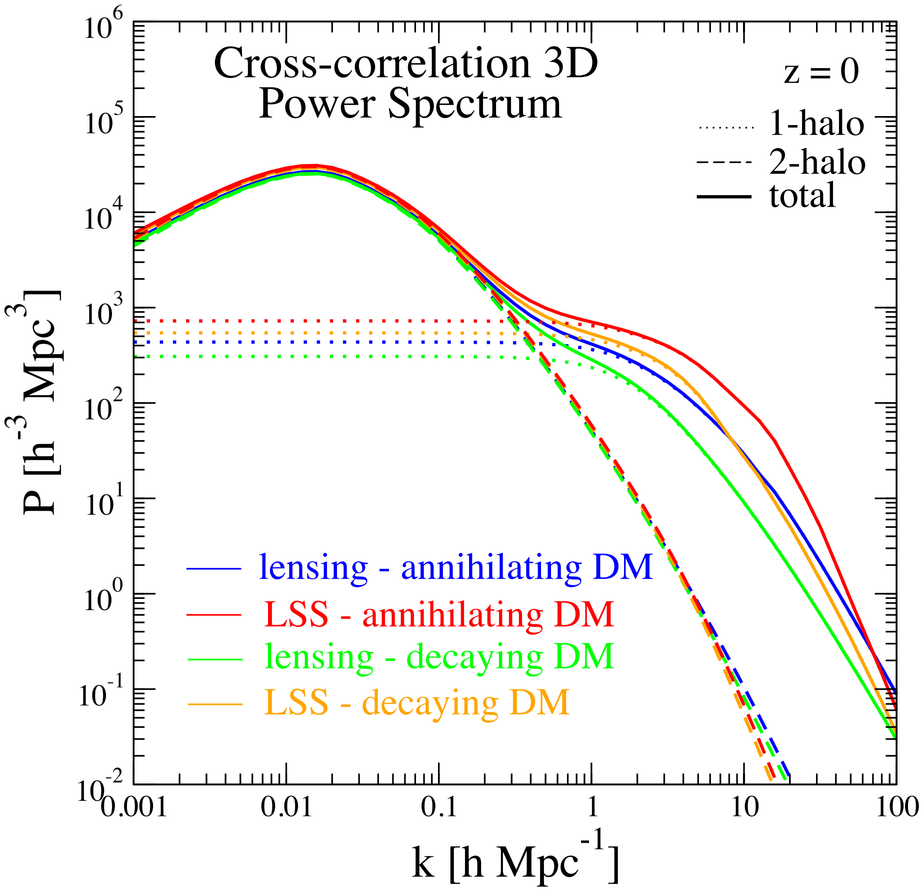
Decaying DM

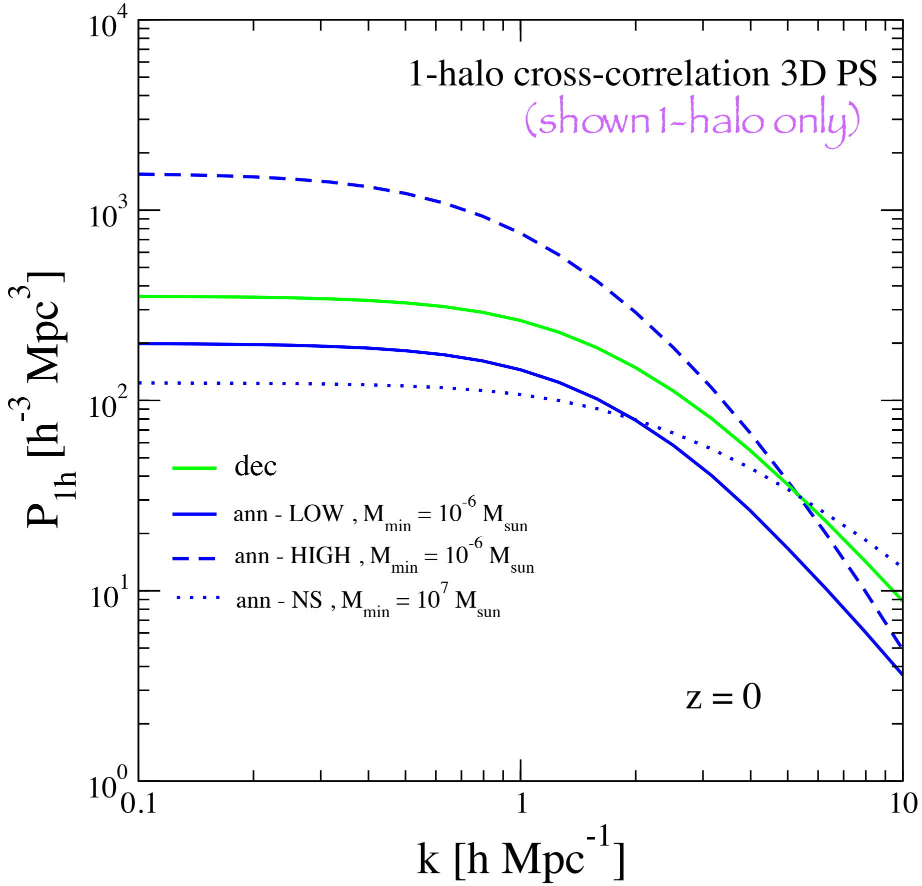
$$P_{1h}^{\delta\delta}(k,z) = \int_{M_{\rm min}}^{M_{\rm max}} dM \frac{dn}{dM} \tilde{v}^2(k|M)$$

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

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

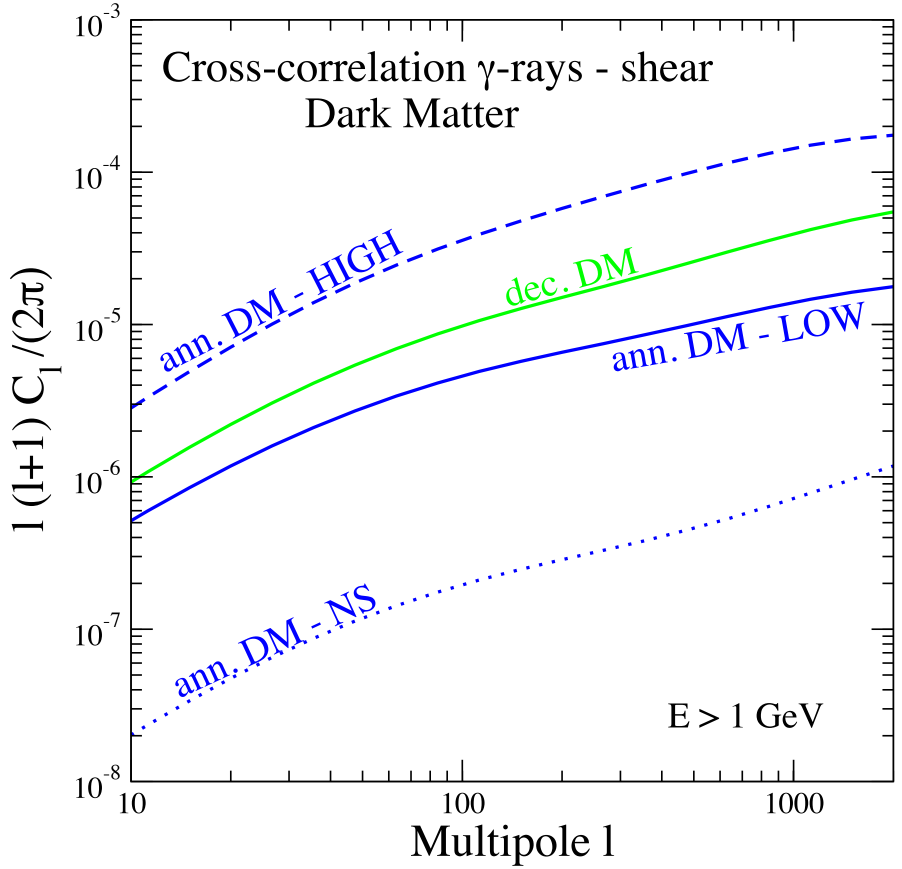




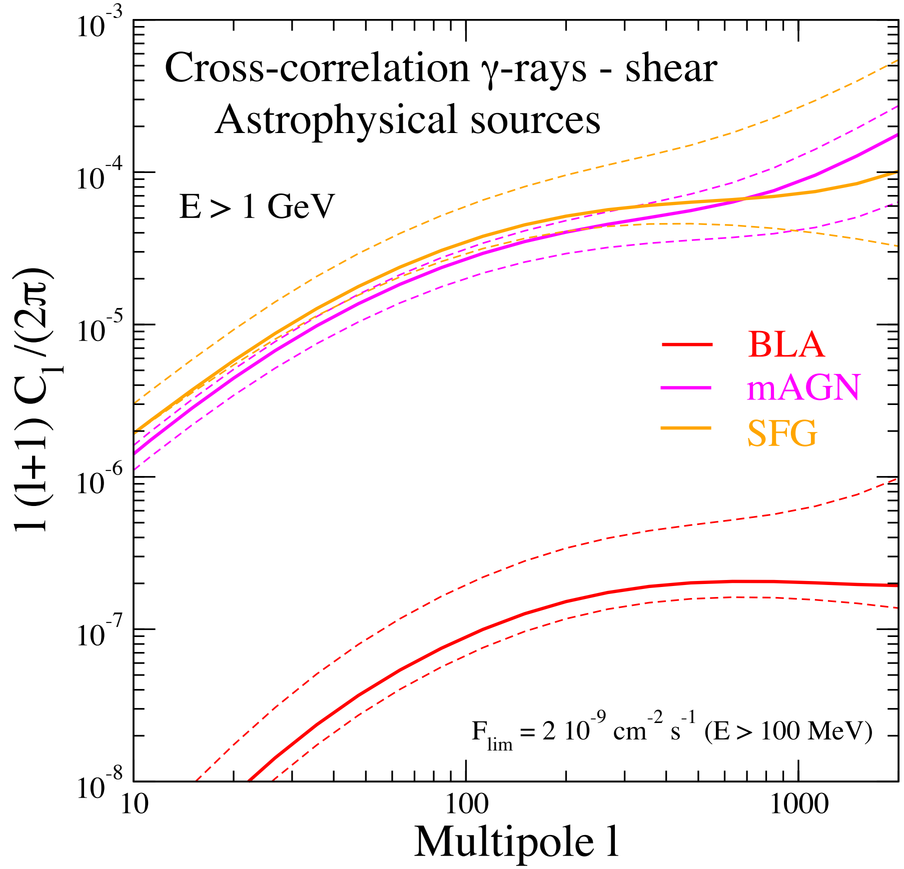
NF, Regis, Front. Physics 2 (2014) 6

Angular power spectra

Dark Matter APS



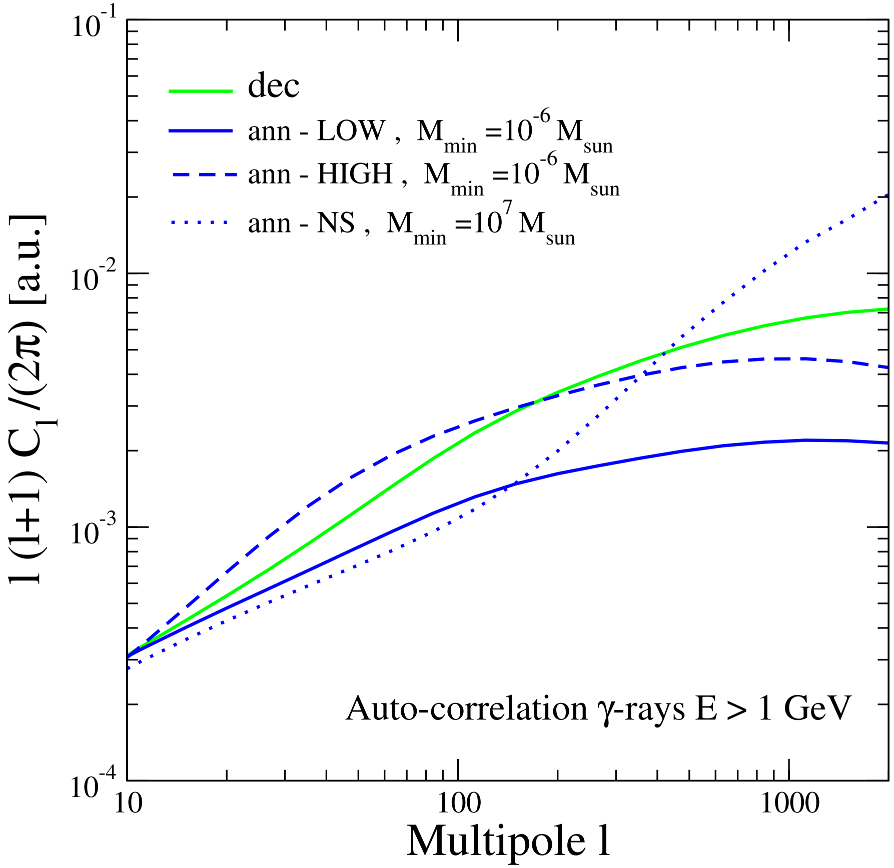
Astrophysical sources APS



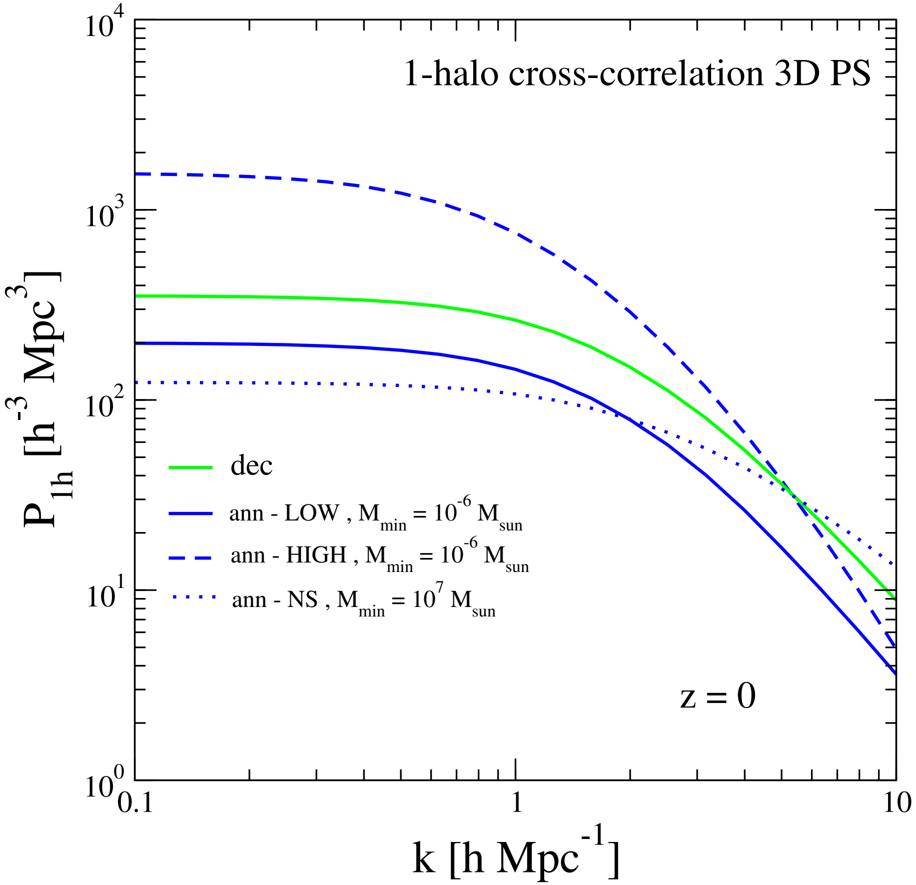
$$C_l^{(i,j)} \longleftarrow W_i(\chi)\, W_j(z)\, P_{ij}(k = l/\chi, \chi)$$

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

Auto correlation



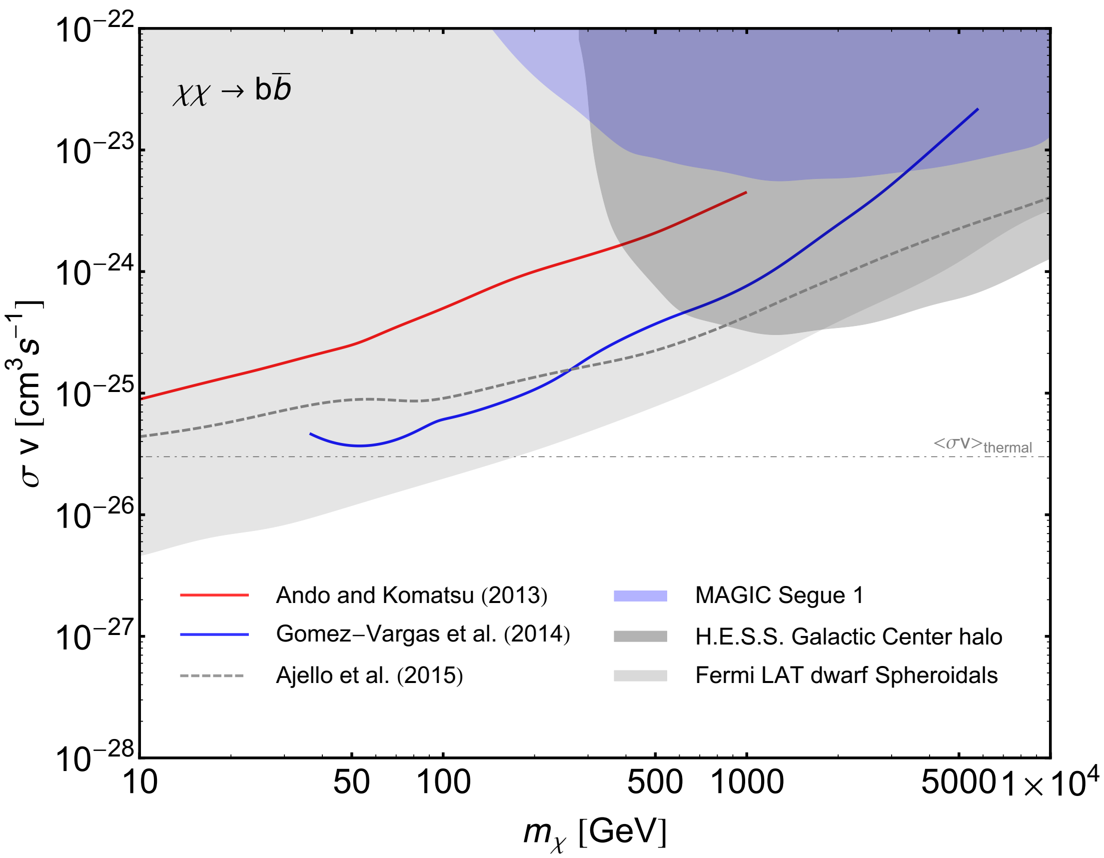
Angular power spectrum



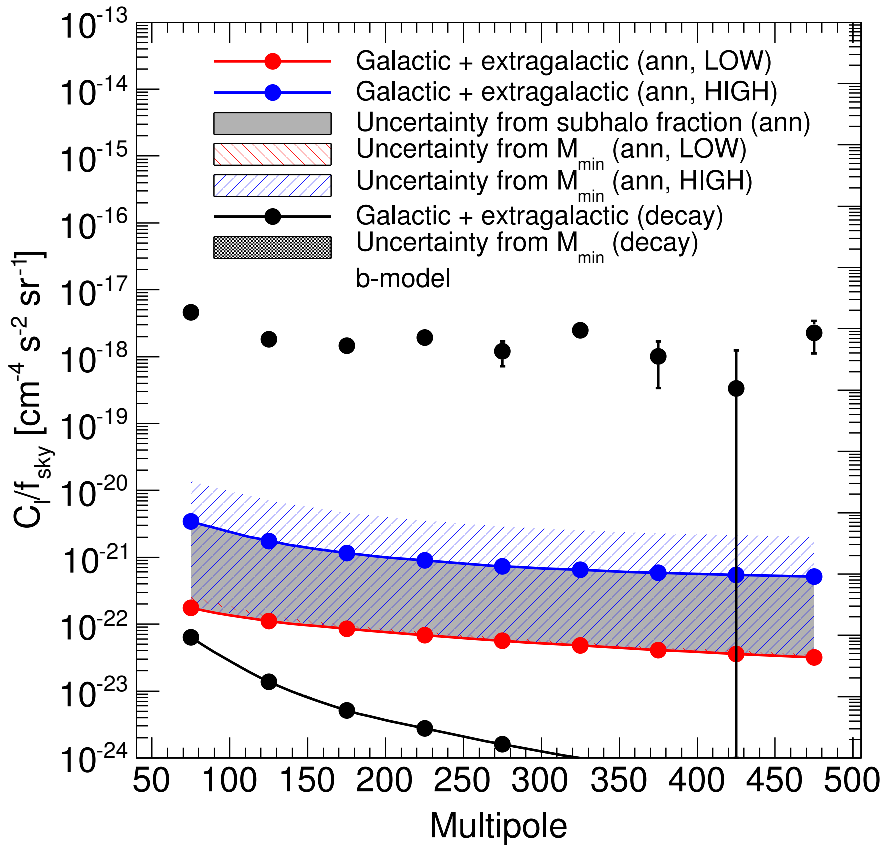
3D power spectrum

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

DM & Auto Correlation



Bounds



Uncertainties

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

Fornasa, et al., MNRAS 429 (2012) 1529

Cross Correlation

Density field: DM density contrast$^{(2)}$

δ annihilating DM, lensing, LSS

δ^2 decaying DM

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

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

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) 1 15
    Regis, Xia, Cuoco, Branchini, NF, Viel, PRL 114 (2015) 24 241301
    Cuoco, Xia, Regis, Branchini, NF, Viel, ApJS 221 (2015) 29

Detectors and configurations

Parameter	Description	DES	Euclid
f_{sky}	Surveyed sky fraction	0.12	0.36
$\bar{N}_g$ [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

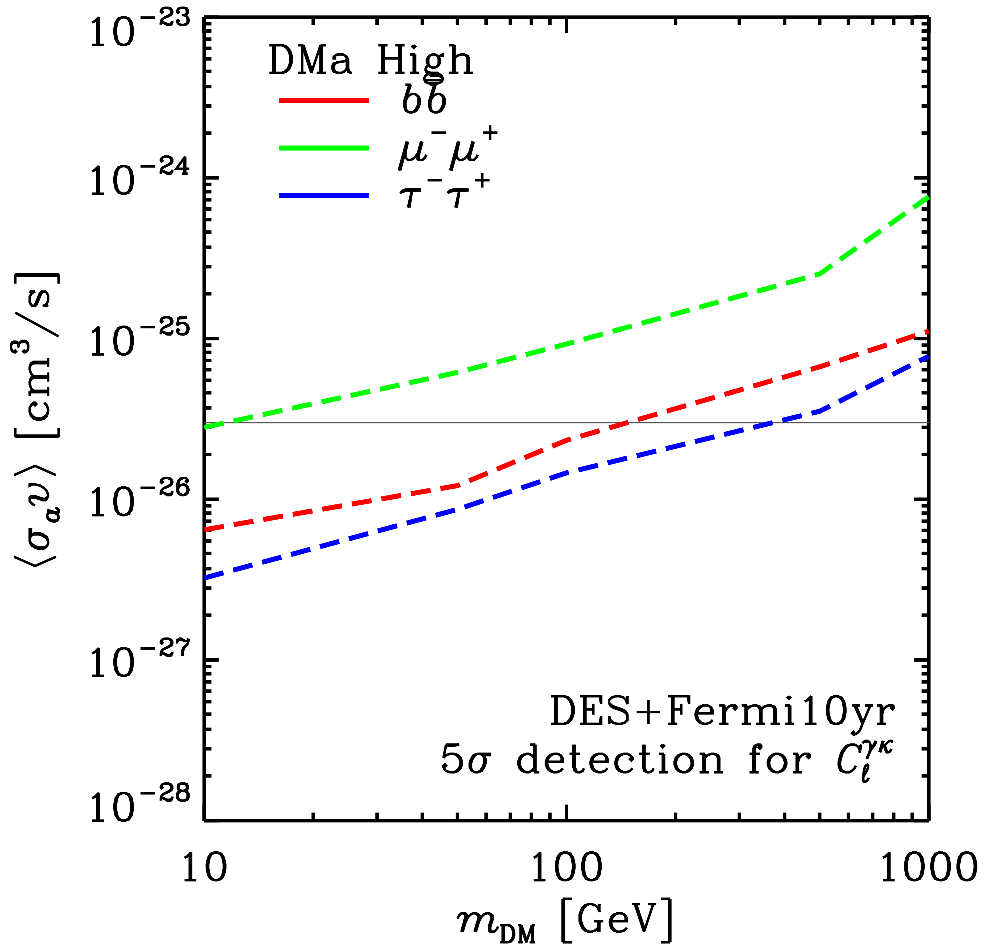
Parameter	Description	Fermi-10yr	Fermissimo
f_{sky}	Surveyed sky fraction	1	1
$E_{\text{min}} - E_{\text{max}}$ [GeV]	Energy range	1 – 300	0.3 – 1000
N_E	Number of bins	6	8
ε [cm^2 s]	Exposure	3.2×10^{12}	4.2×10^{12}
$\langle \sigma_b \rangle$ [deg]	Average beam size	0.18	0.027

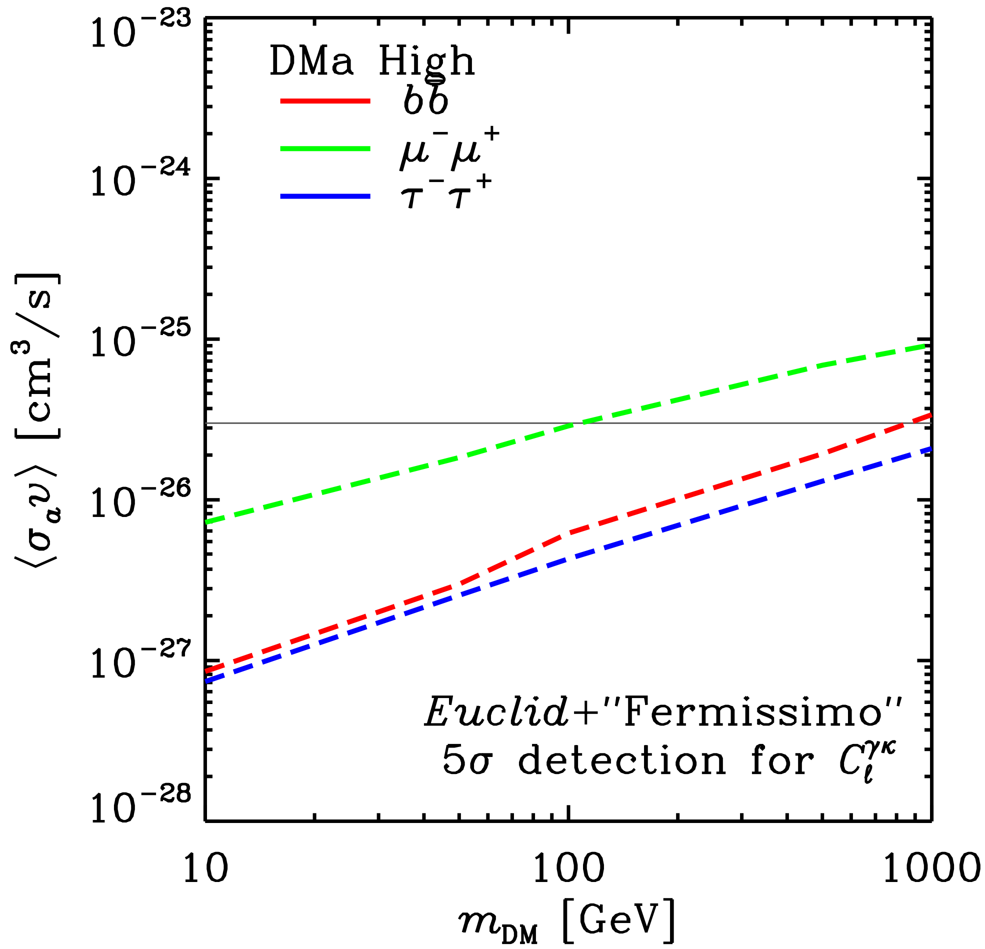
Combinations:

DES + Fermi 10 yr

Euclid + “Fermissimo”

Detection forecasts



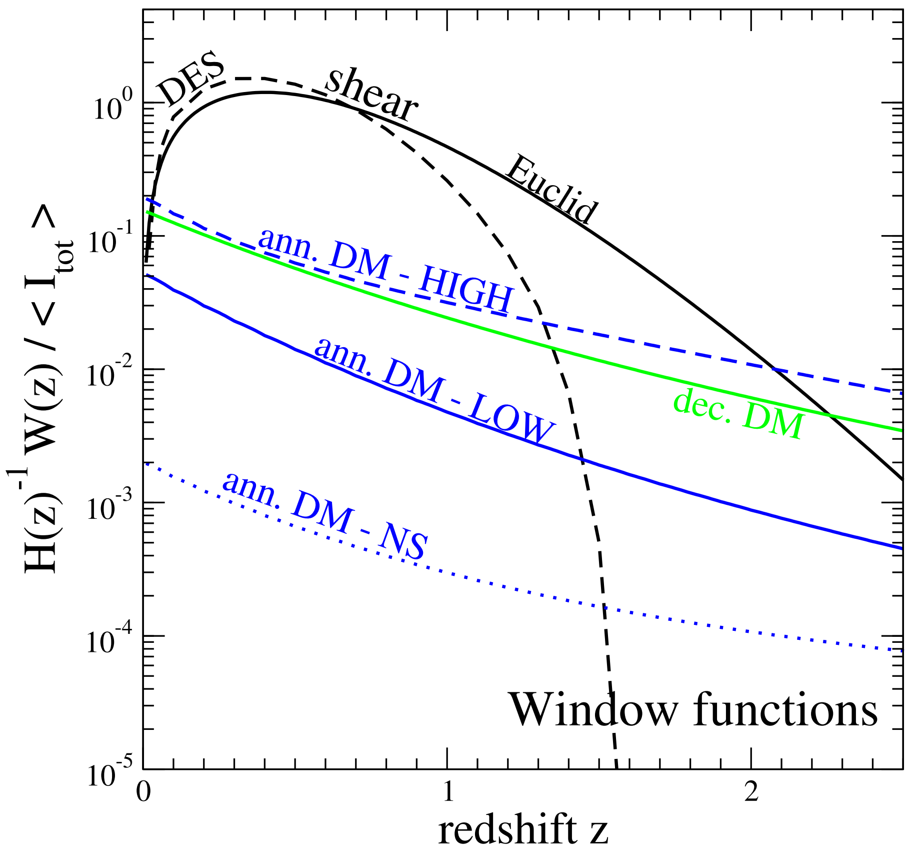


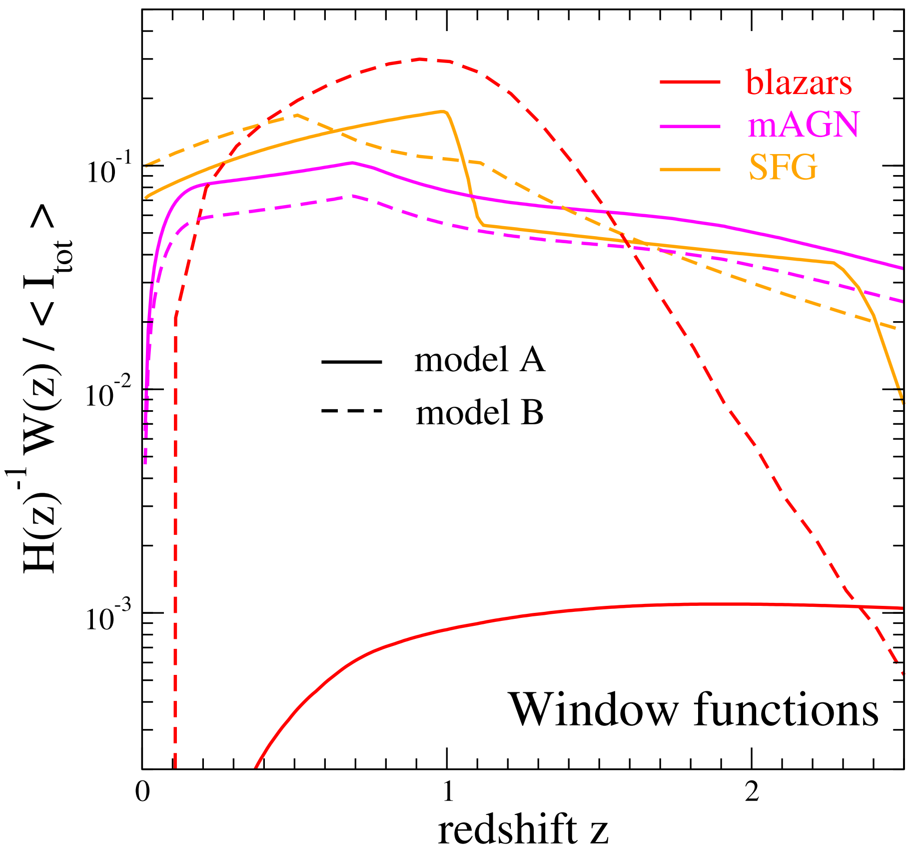
DES + Fermi 10yr

Euclid + "Fermissimo"

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

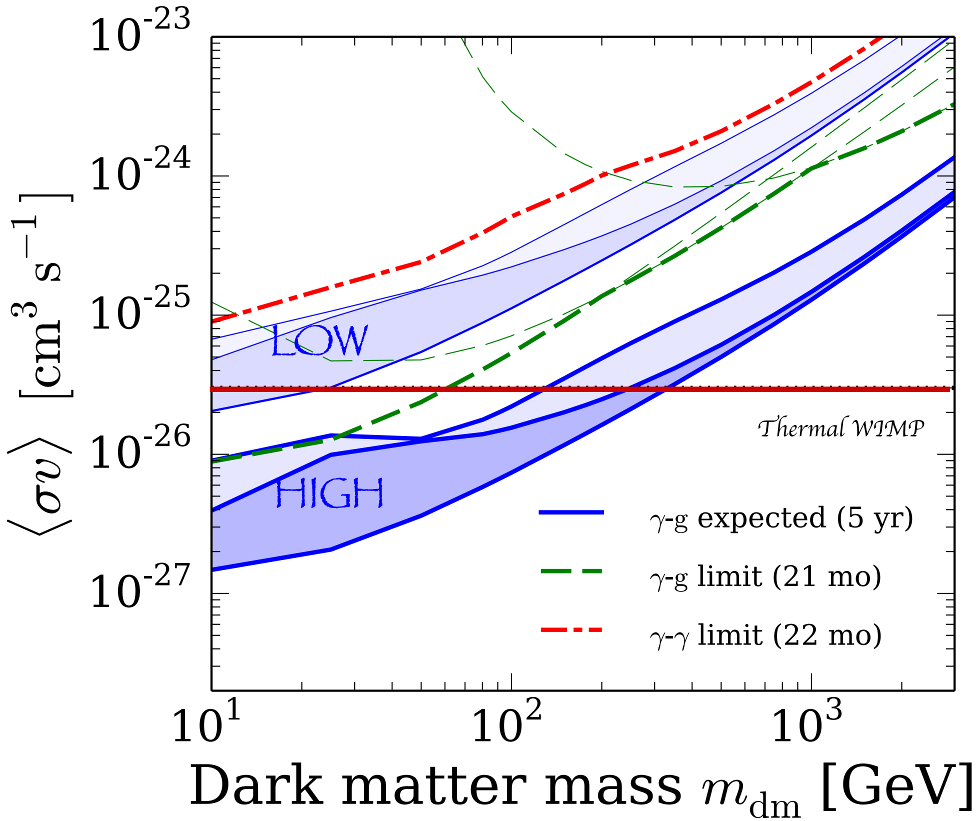
Window functions

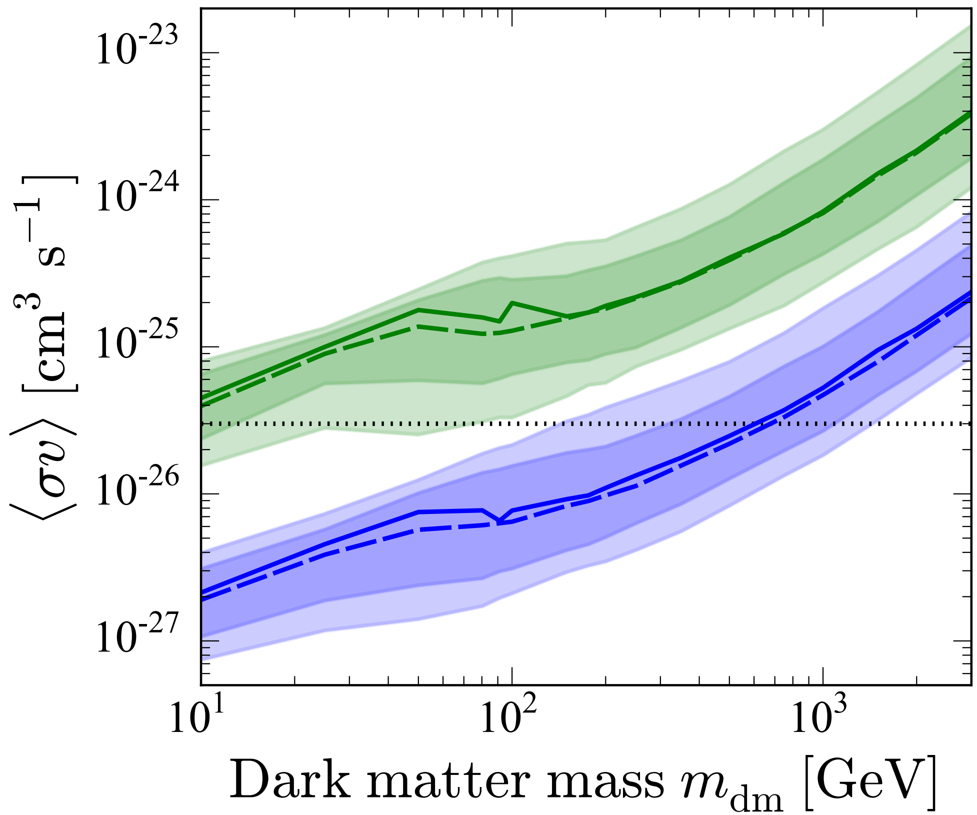




Camera, Fornasa, NF, Regis, JCAP 06 (2015) 029

Fermi x 2MASS





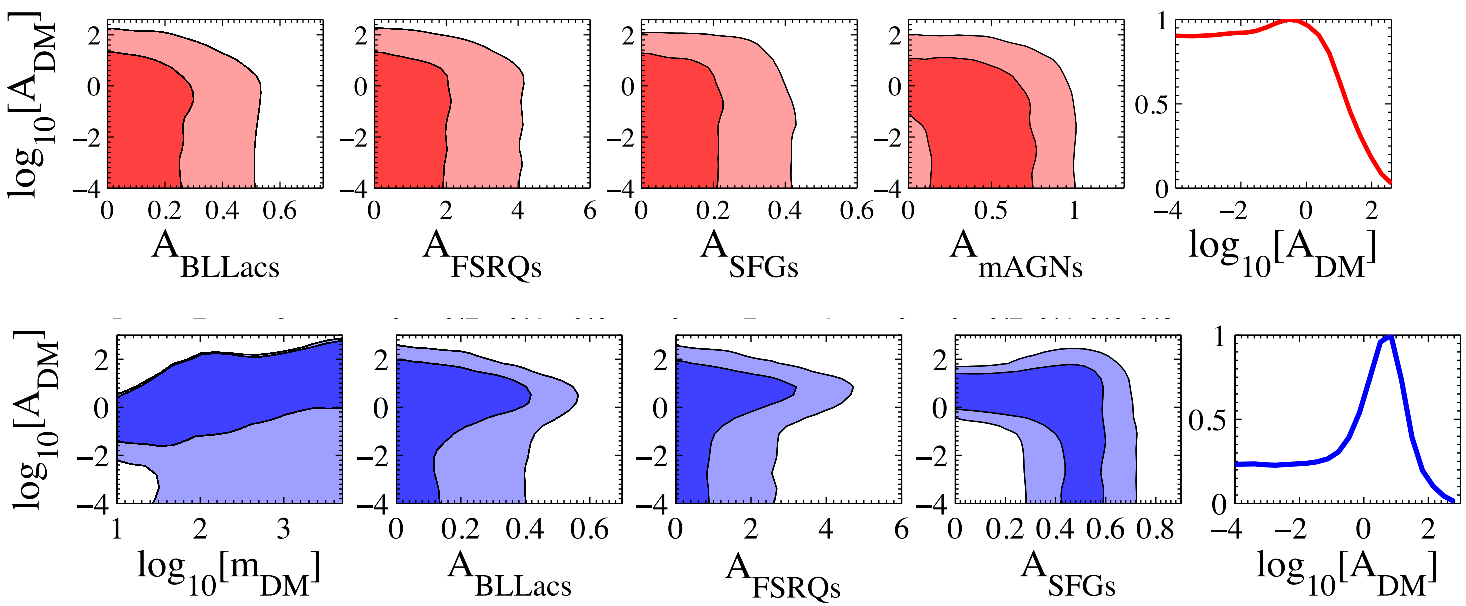
Bounds based on non-observation of correlation in (*)

Forecasts includes tomography

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

Ando, JCAP 1410 (2014) 061

Fermi + LSS catalogs: DM + astro sources



(*)

(*)

LOW

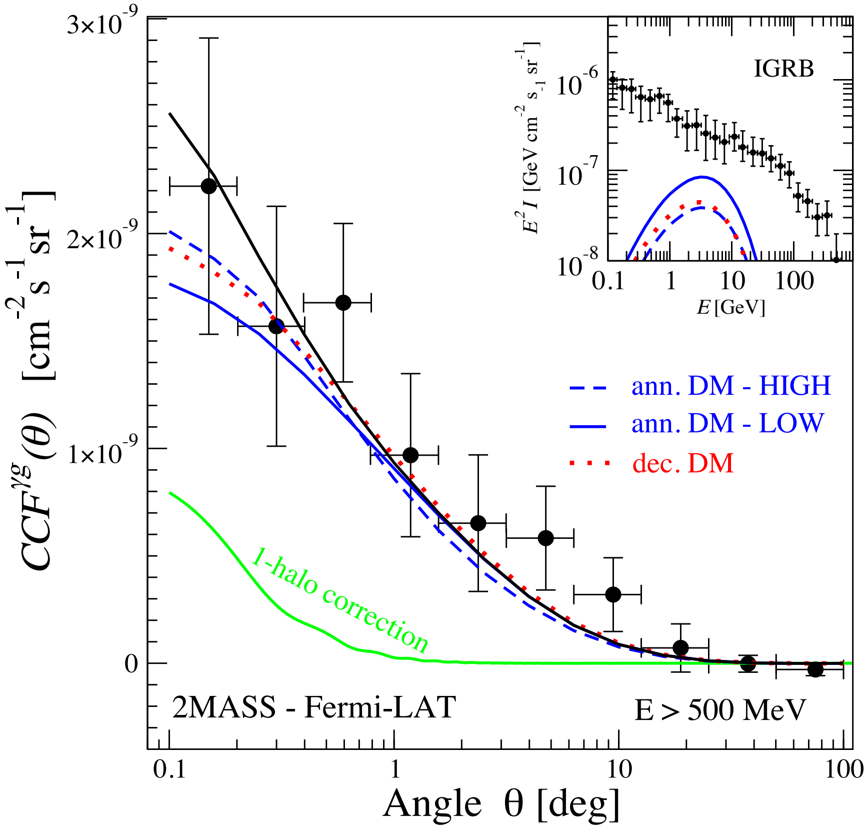
Degeneracy between DM and mAGN:

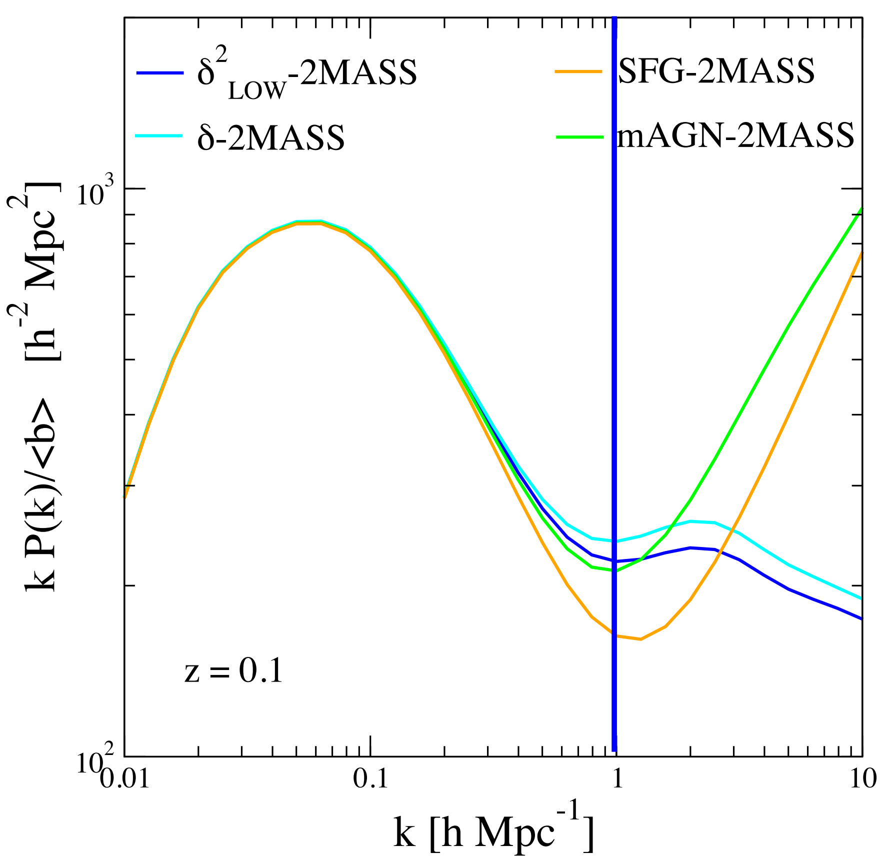
(*) Enhanced mAGN contribution

(*) Suppressed mAGN contribution

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

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 gamma ray angular resolution

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

Fermi/gamma + Planck/CMB lensing

Analysis:

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

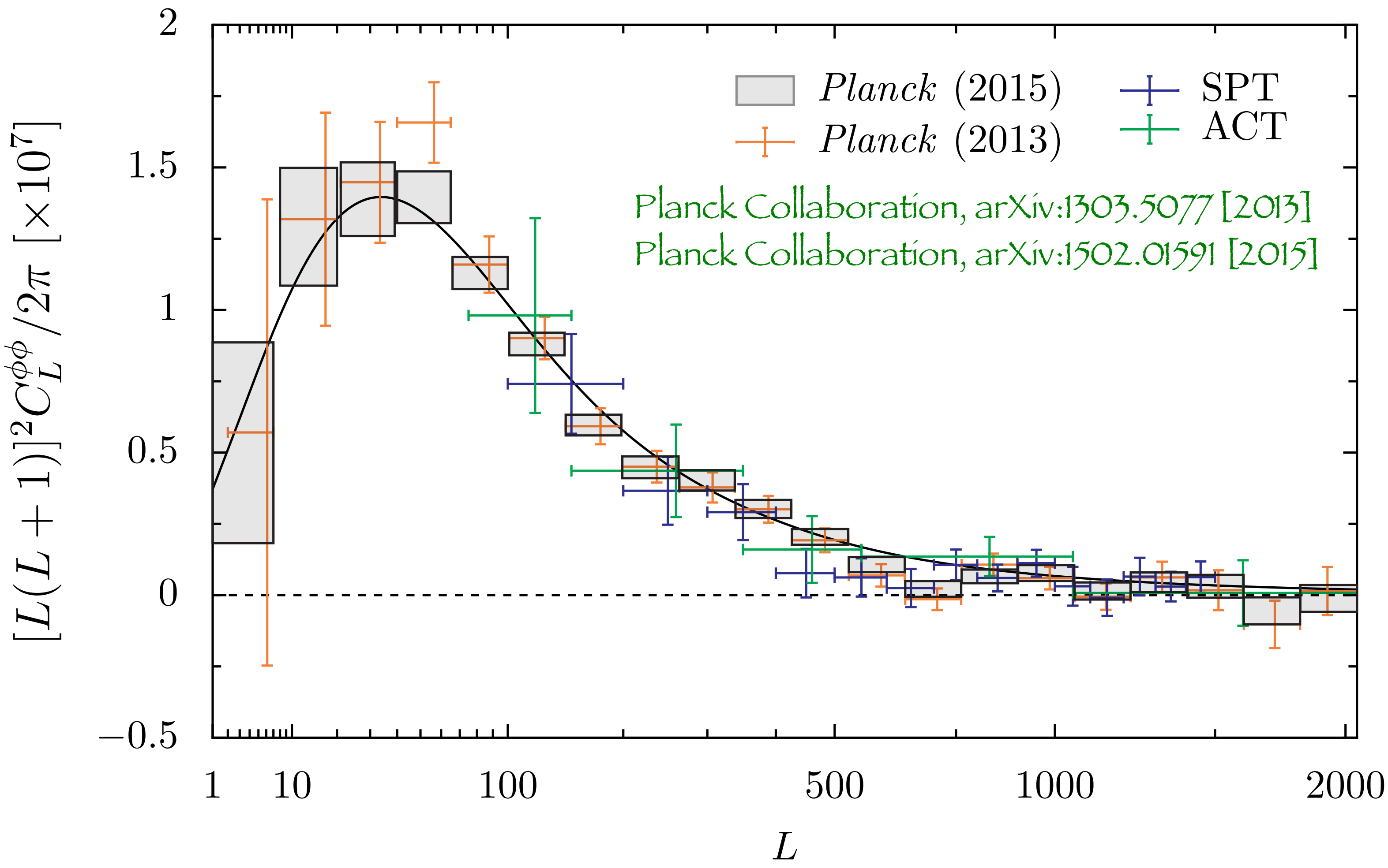
- Galactic emission subtracted
- Masks for CMB lensing:
  - Planck official masks (available sky fraction 70%)
  - 5 deg apodized
- Masks for gamma rays:
  - Planck masks + |b| < 25 deg cut
  - 1 deg cut around 2FGL (3FGL) Fermi source catalogs apodized 3 deg/2 deg

    sky fraction 24% (23%)

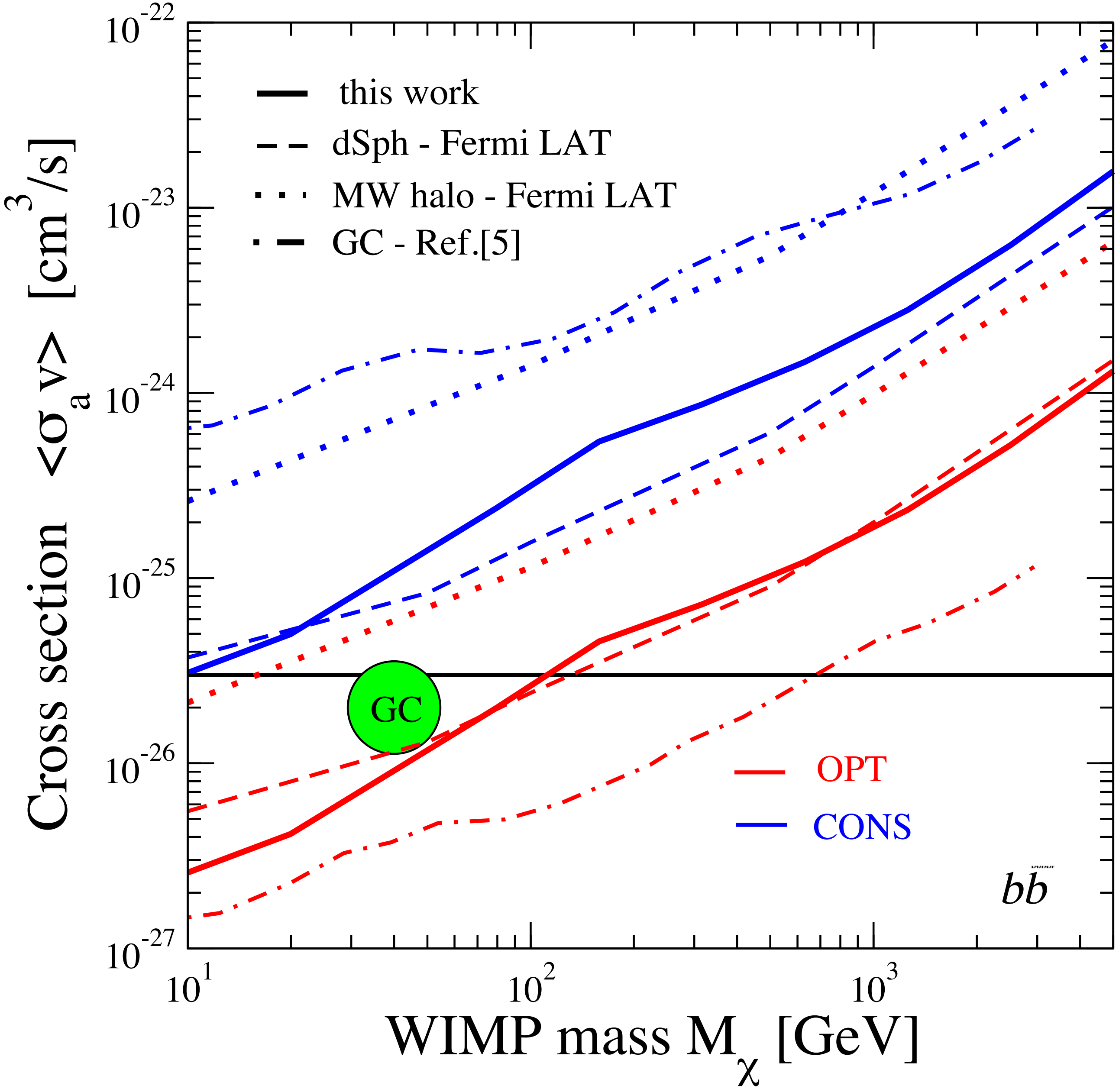
Results stable for different sets of apodization and galactic masks, including Fermi bubble mask

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

Planck CMB lensing

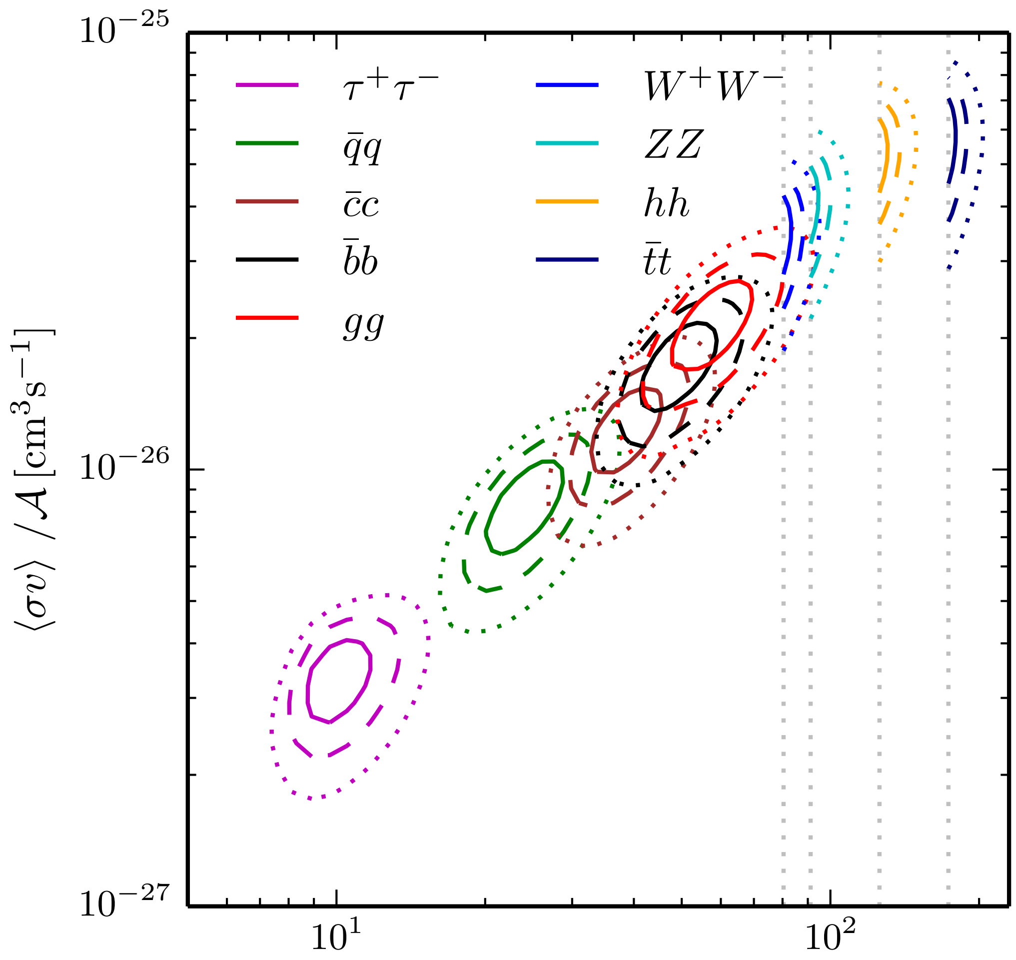


- CMB-lensing autocorrelation is measured: 40σ significance
- CMB-lensing: integrated measure of DM distribution up to last scattering
- It might exhibit correlation with gamma-rays emitted in DM structures



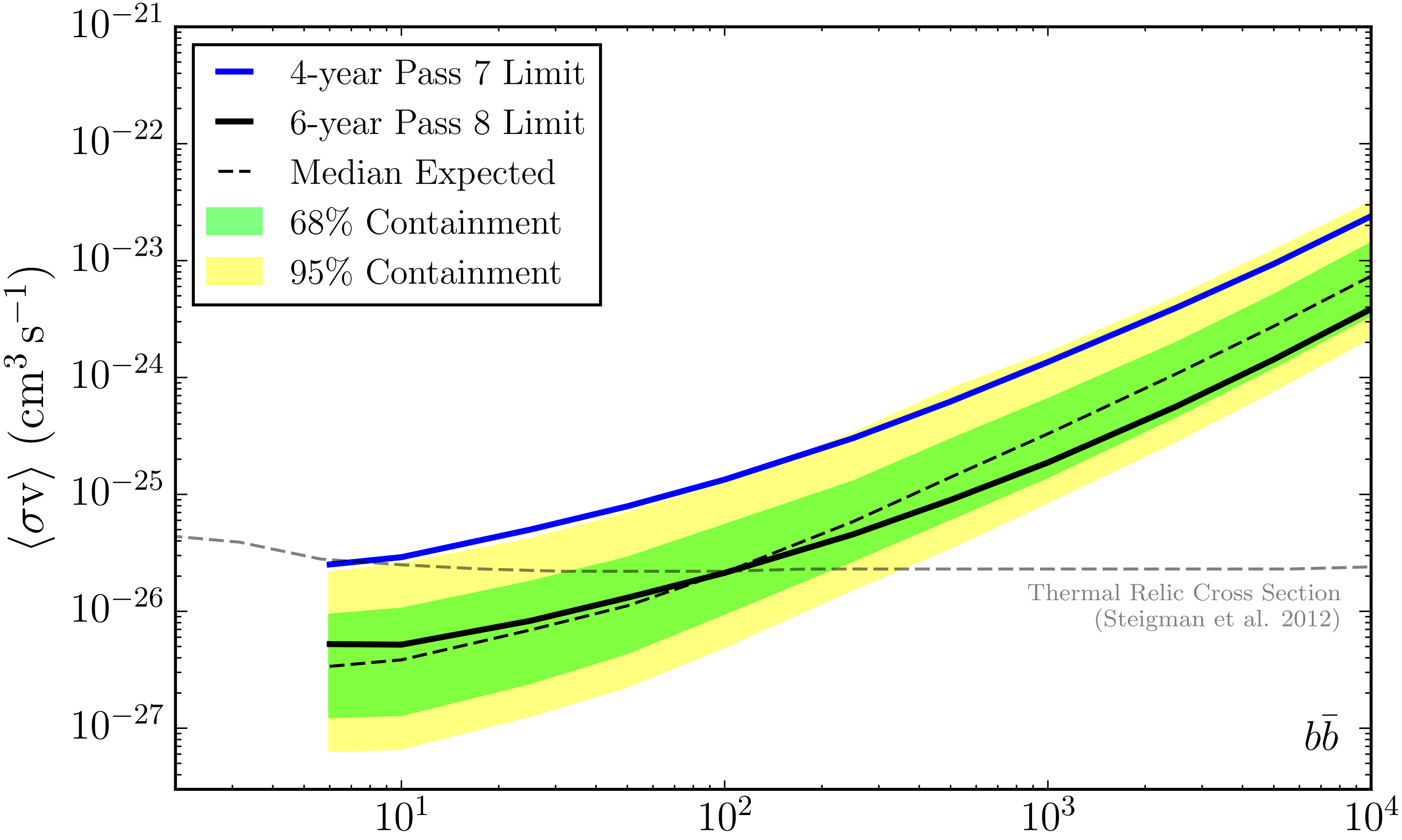
this work
dSph - Fermi LAT
MW halo - Fermi LAT
GC - Ref.[5]
GC
OPT
CONS
$b\bar{b}$
Cross section $<\sigma_a v>$ [cm^3/s]
WIMP mass M_χ [GeV]
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^1
10^2
10^3

Galactic center



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

Dwarf galaxies



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