Dark Matter Indirect Searches

- γ-rays/radio connection
- Angular cross-correlations

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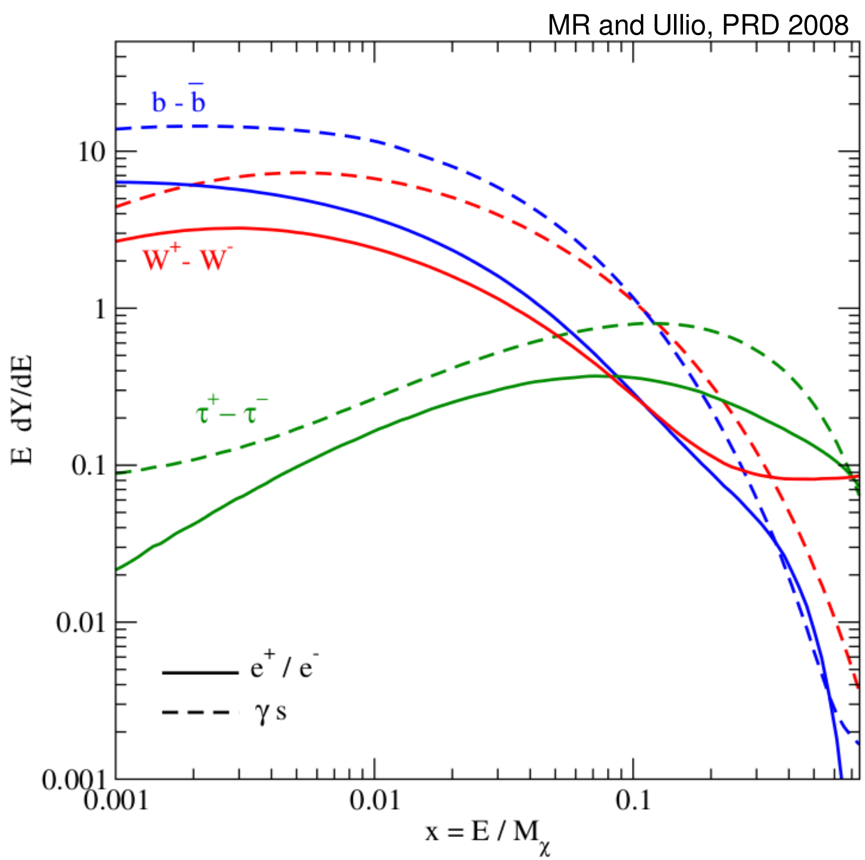
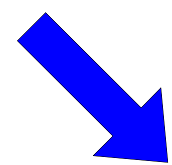
γ-rays/radio connection

Sizable production of gamma-rays typically comes with a comparable e^+-e^- yield





Comparable luminosities

for gamma-ray (prompt) and synchrotron emissions

(and also for IC on CMB in X- or γ-rays)

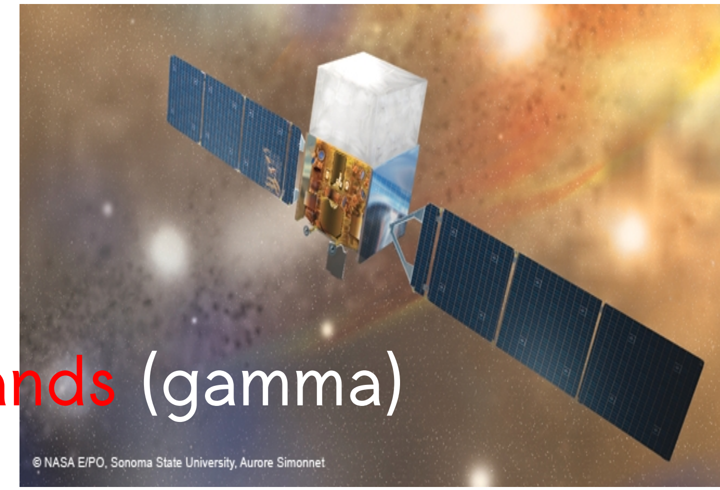
What to learn from radio frequencies ?

A simple comparison between radio and gamma astronomy:

Number of

known sources =

Few millions (radio) vs few thousands (gamma)

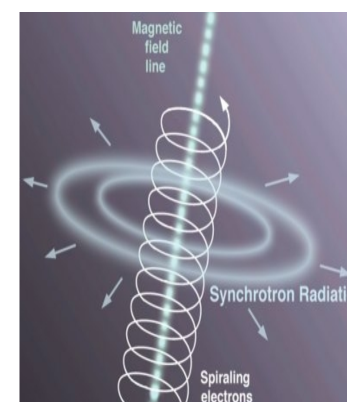


Generically speaking, for phenomena with connected radio-gamma production mechanisms, it is simpler to catch the source with radio telescopes due to superior sensitivity and angular resolution

BUT

Synchrotron radiation requires an additional player:

the magnetic field



Credit: Sky & Telescope / Gregg Dinderman

dwarf spheroidal galaxies - radio projects

Single-dish

"Fermi-like" images

Spekken, Mason, Aguirre, Natarajan et al.

(Green Bank Telescope)

Interferometry

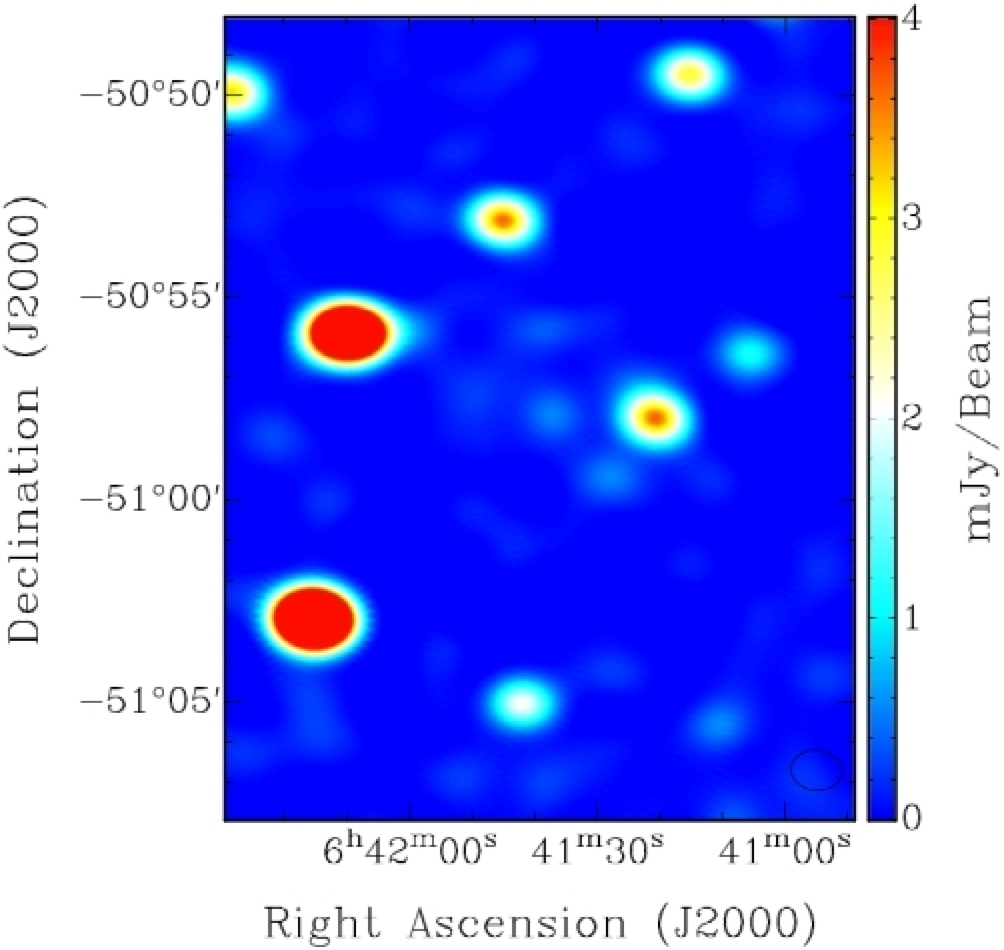
Higher sensitivity and angular resolution, no emission on very large scales

Regis, Richter, Colafrancesco, de Blok, Massardi, Profumo (ATCA)

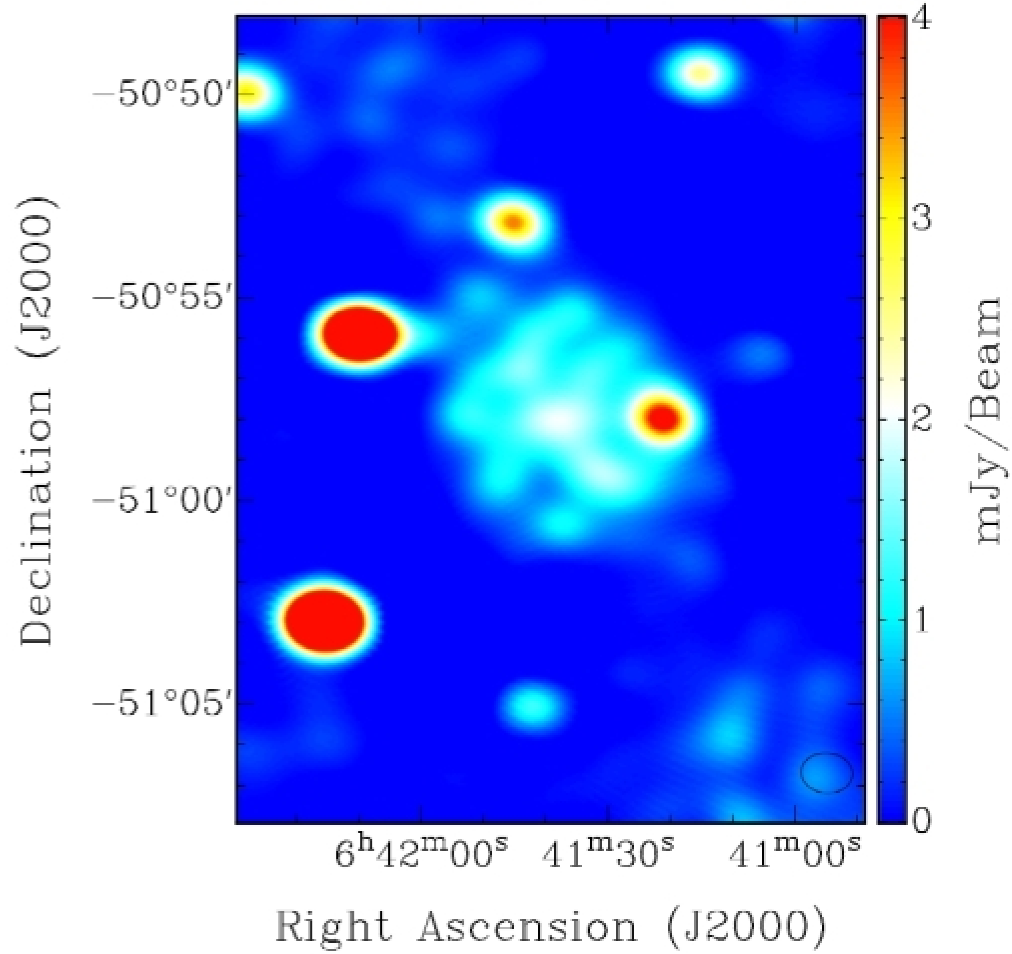
ATCA project

Observations of Carina, Fornax, Sculptor, BootesII, SegueII, Hercules with ~ 50 μJy sensitivity

Observed field

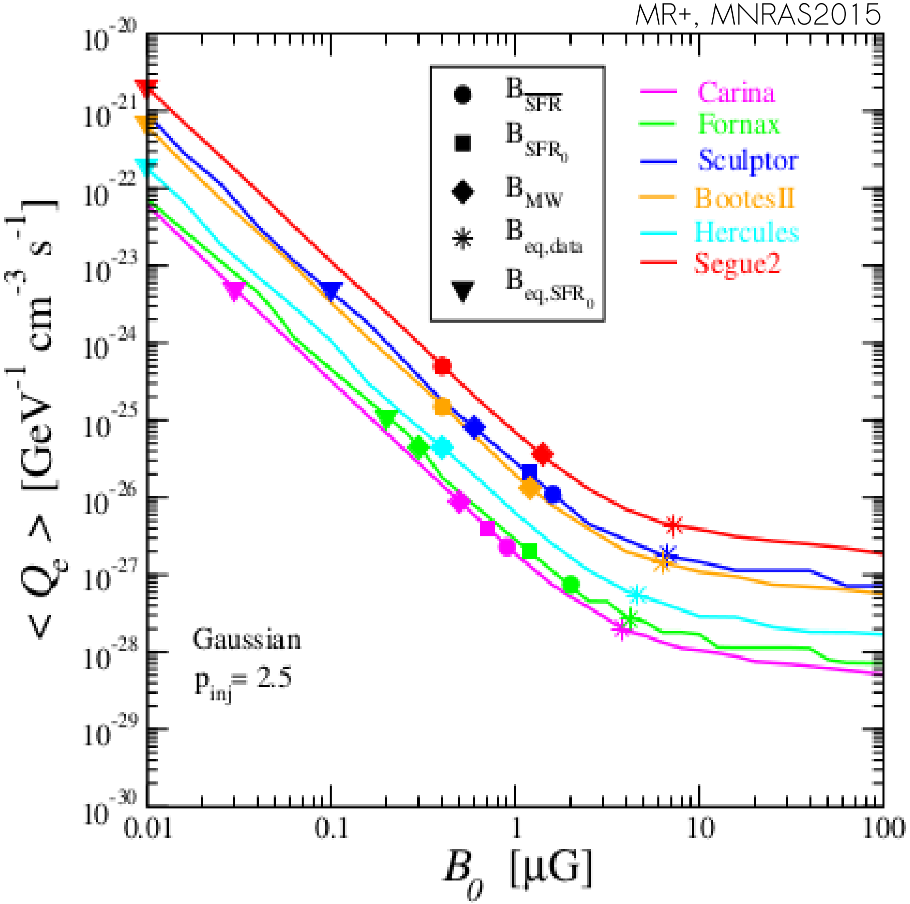


Observed field plus simulated dark matter

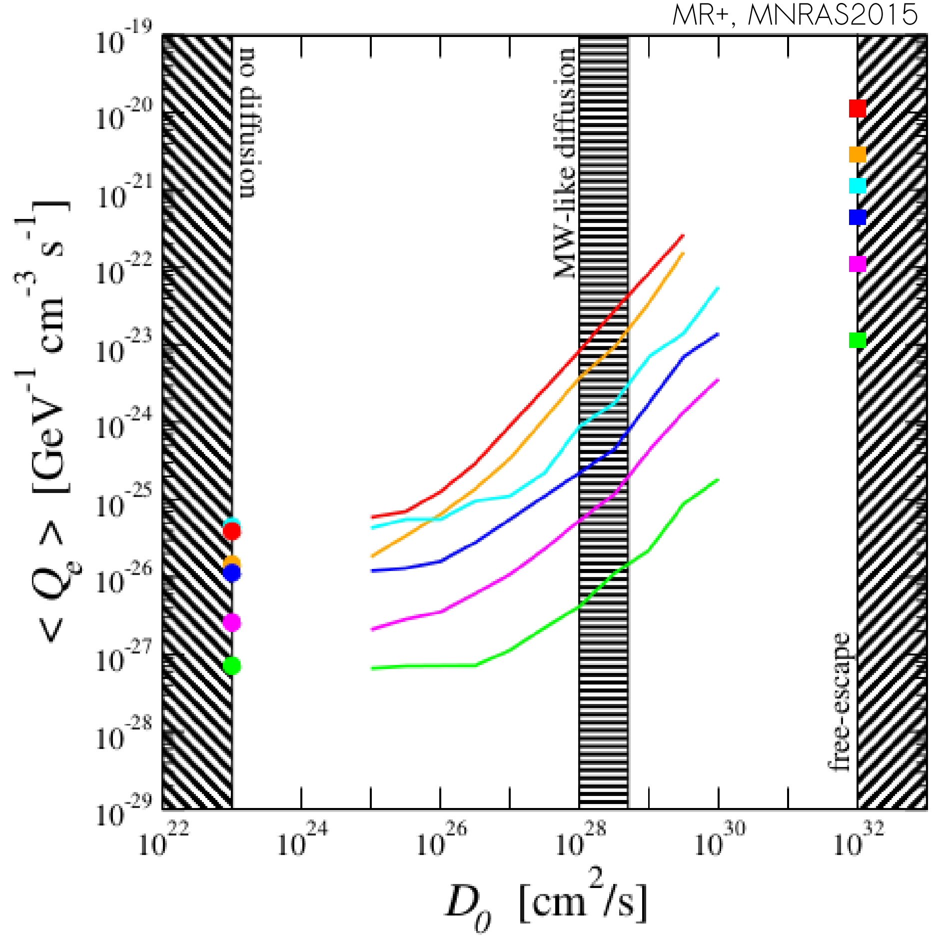


Magnetic field uncertainties

Magnetic field strength



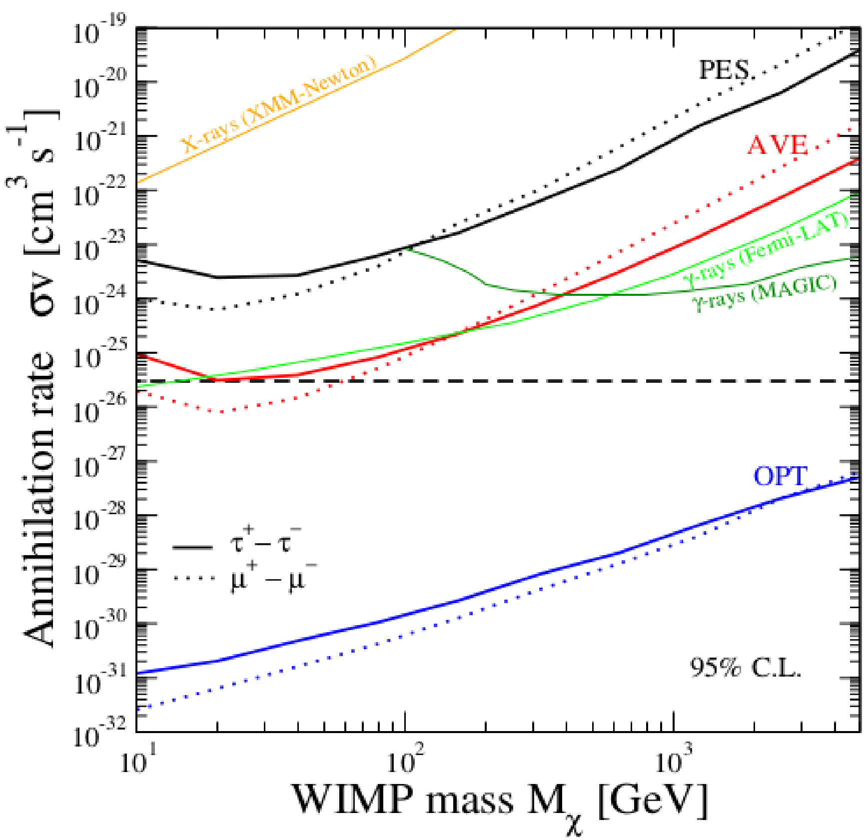
Spatial diffusion

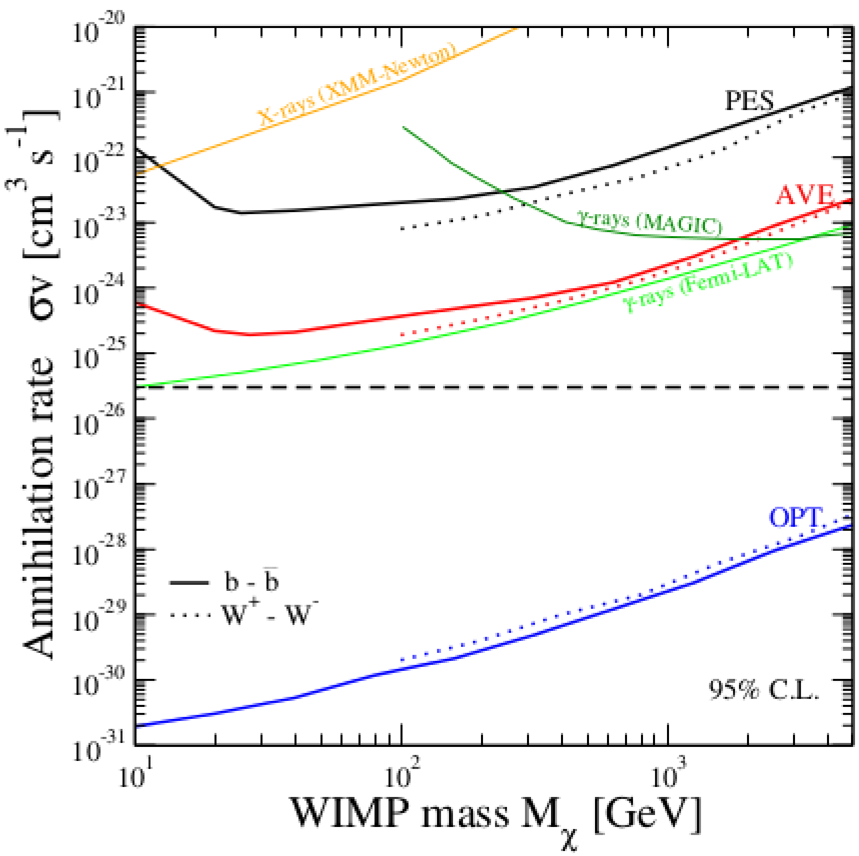


Bounds on WIMPs

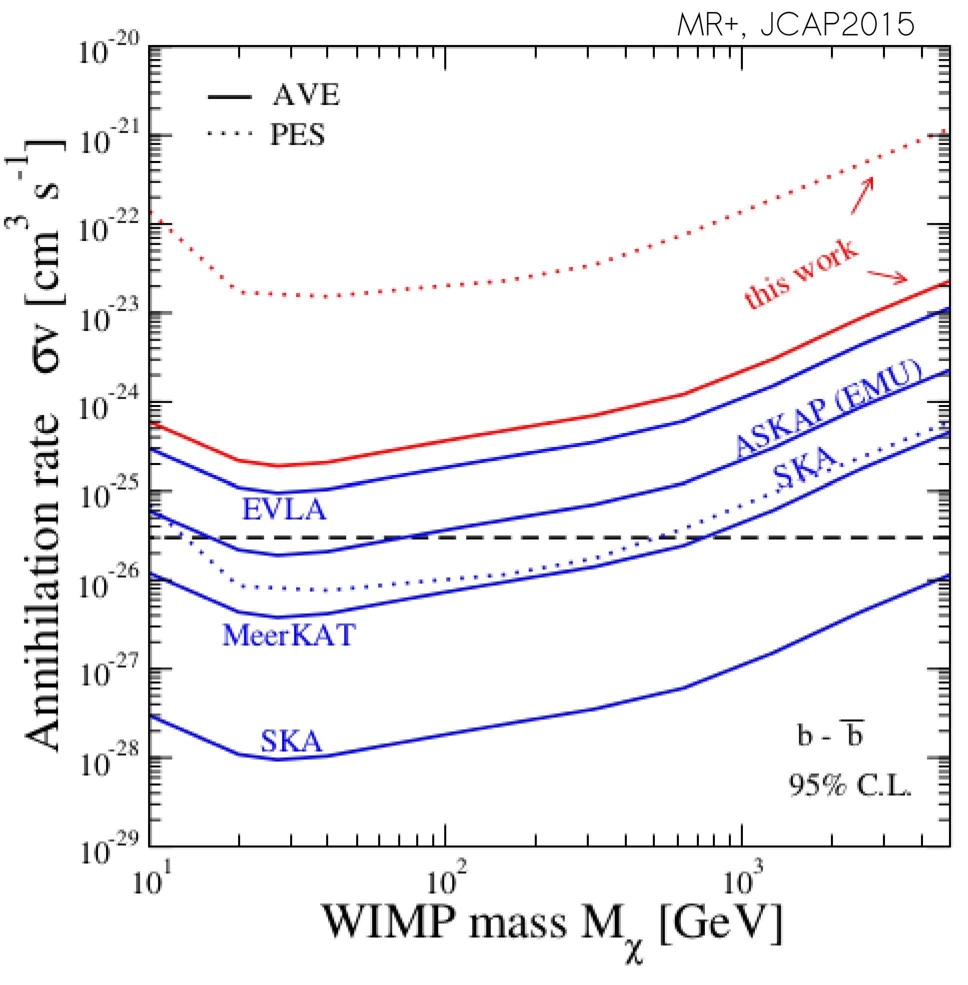
MR+, JCAP2015

Name	magnetic field	diffusion scheme	DM profile
OPT	B_{eq}^{obs}	loss-at-injection	Einasto
AVE	$\max(B_{\overline{SFR}}, 1\,\mu\mathrm{G})$	$D = 3 \cdot 10^{28}\,(E/\mathrm{GeV})^{0.3} \exp(r/r_*)\,\mathrm{cm}^2/\mathrm{s}$	NFW
PES	B_{SFR_0}	$D = 10^{30}\,(E/\mathrm{GeV})^{0.3} \exp(r/r_*)\,\mathrm{cm}^2/\mathrm{s}$	Burkert





Prospects



Future radio telescopes can progressively test WIMP models with **"thermal" annihilation rate**, for various astrophysical scenarios.

Can Fermi-LAT detect DM in dSphs?

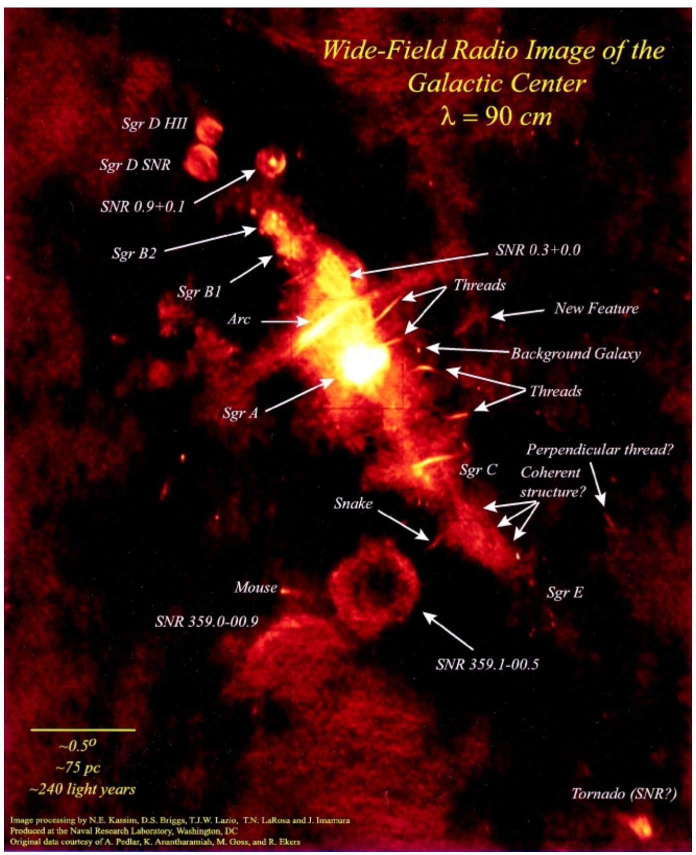
Given the current situation (no clear signal from dSphs),
the answer is probably NO.

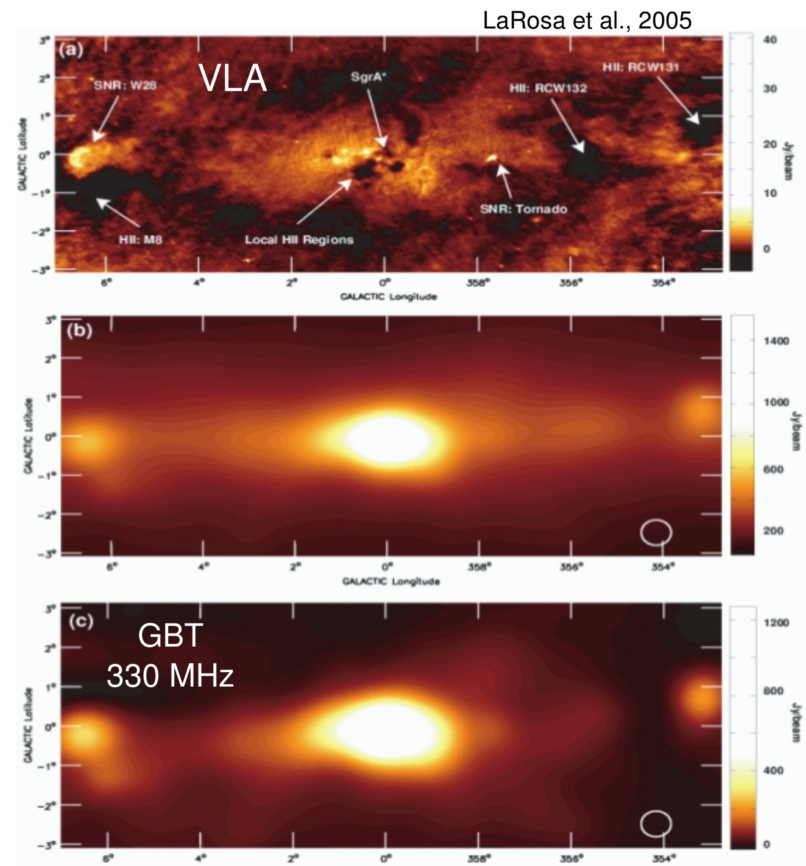
Possible issues:
- beam (to test DM extended emission against "point-like" background sources and astrophysical sources in the dSph)
- statistics (to get spectrum at high energy and for detection in different targets), unless massive dedicated observations..

For the next 5-8 years, **shall we bet instead on radio** (or X-rays) ?

Galactic Center

The **nucleus** of our Galaxy is a very rich system ("starburst-like"), with higher supernova rates, stronger magnetic fields, more intense radiation fields, and larger amounts of dense molecular gas than in the Galactic disk.

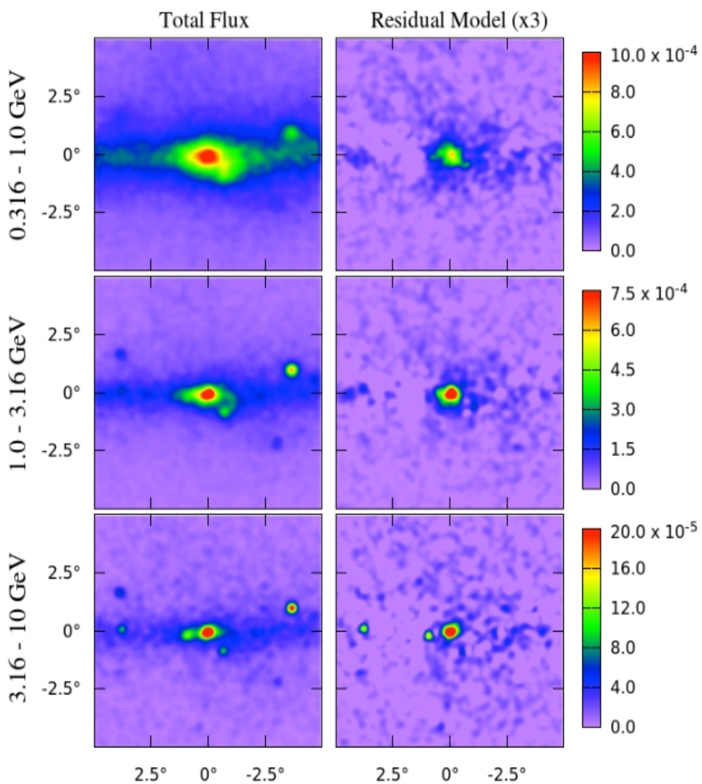


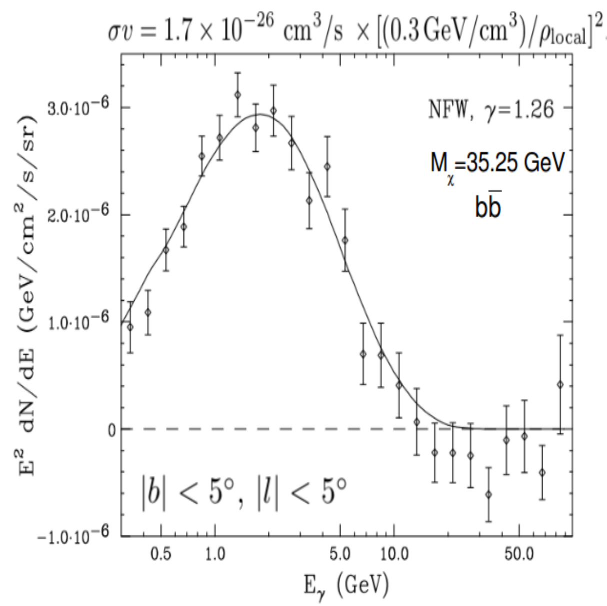


GC γ-ray "excess"

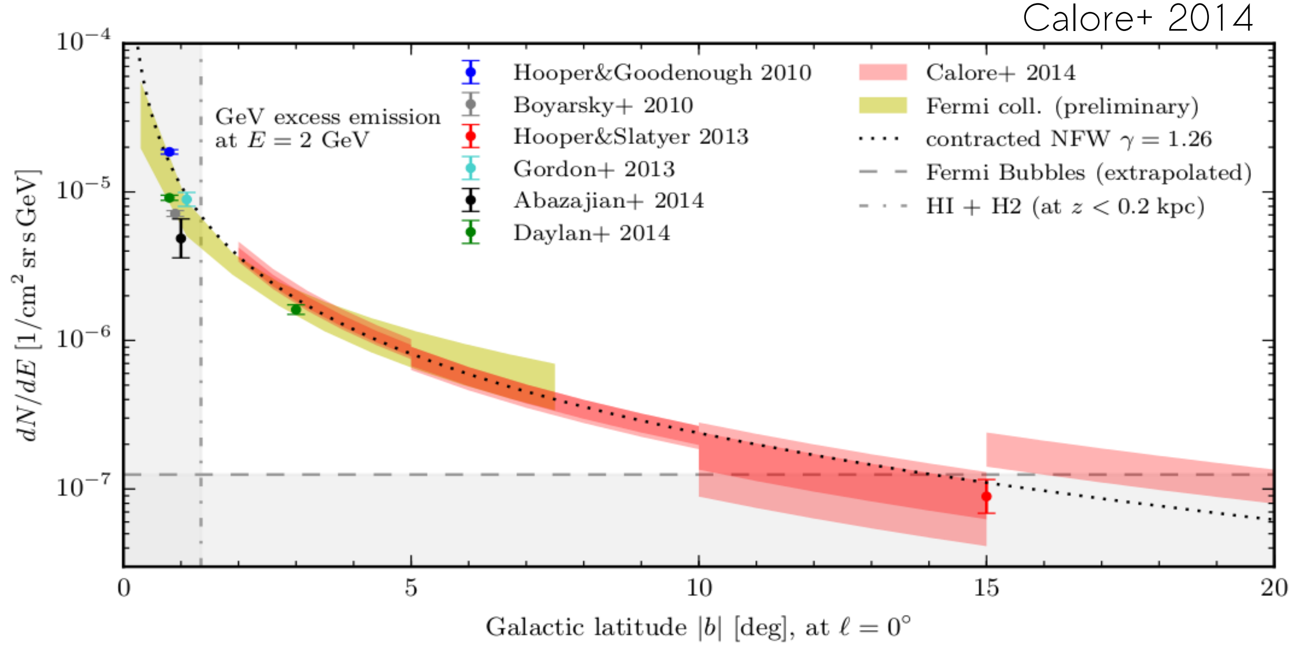
Mattia's talk

Daylan+ 2014



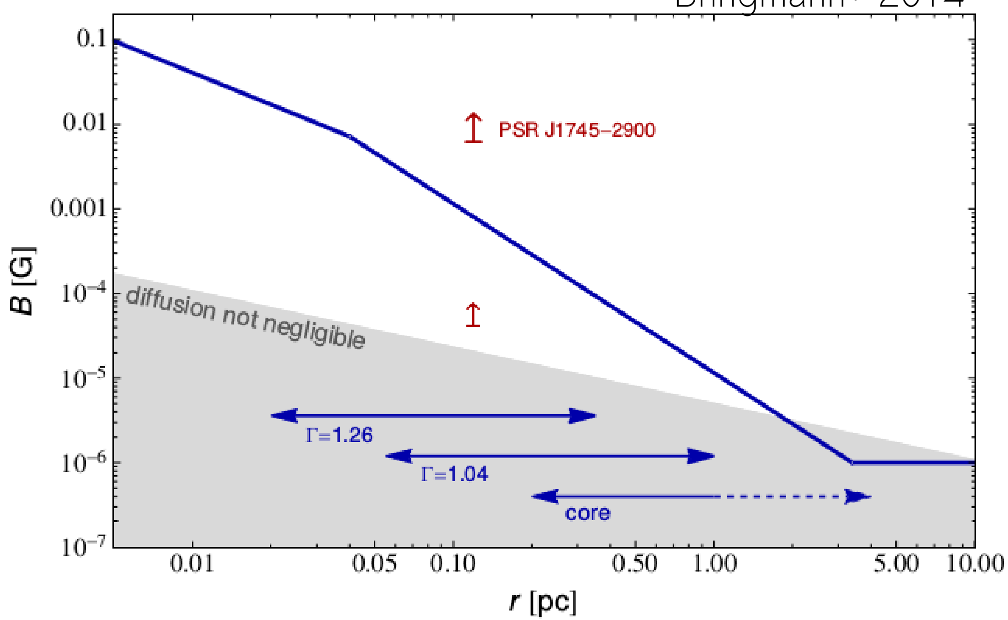


Calore+ 2014



Radio bounds on DM at GC

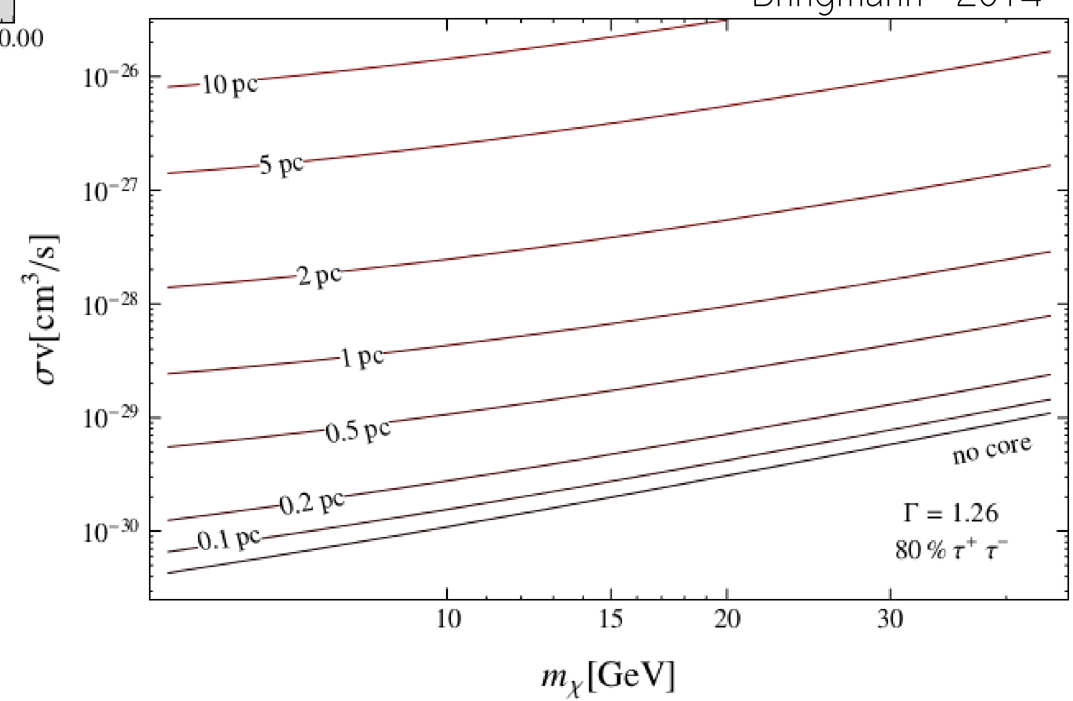
Bringmann+ 2014



Observations on **few arcsec** scales put the strongest radio constraints for DM cuspy profiles

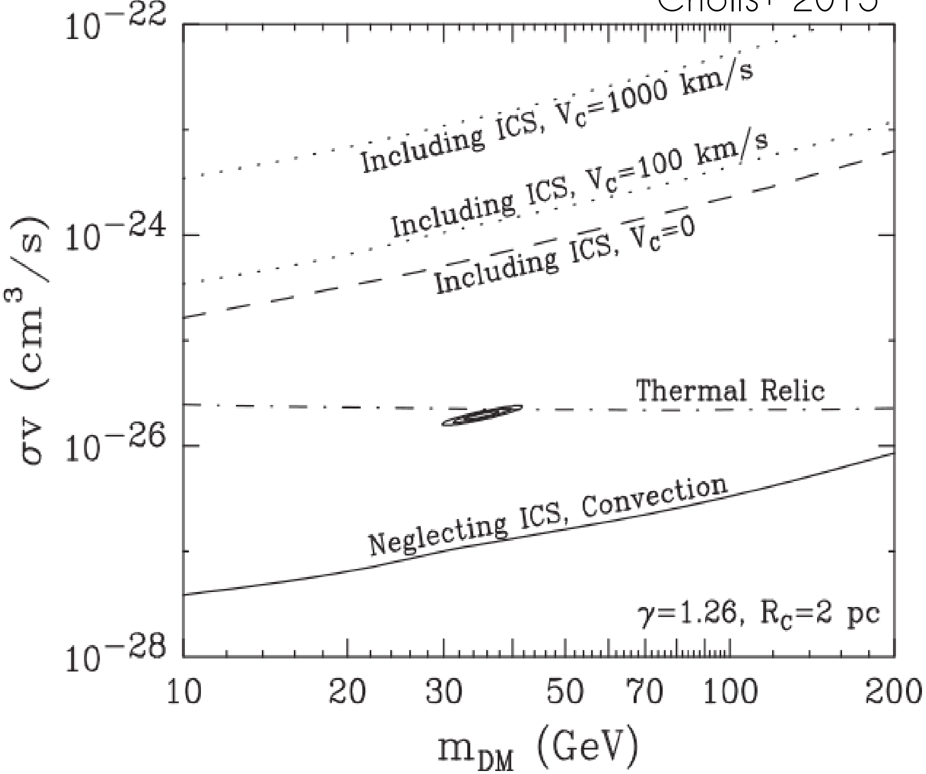
(Regis&Ullio 2008)

Bringmann+ 2014

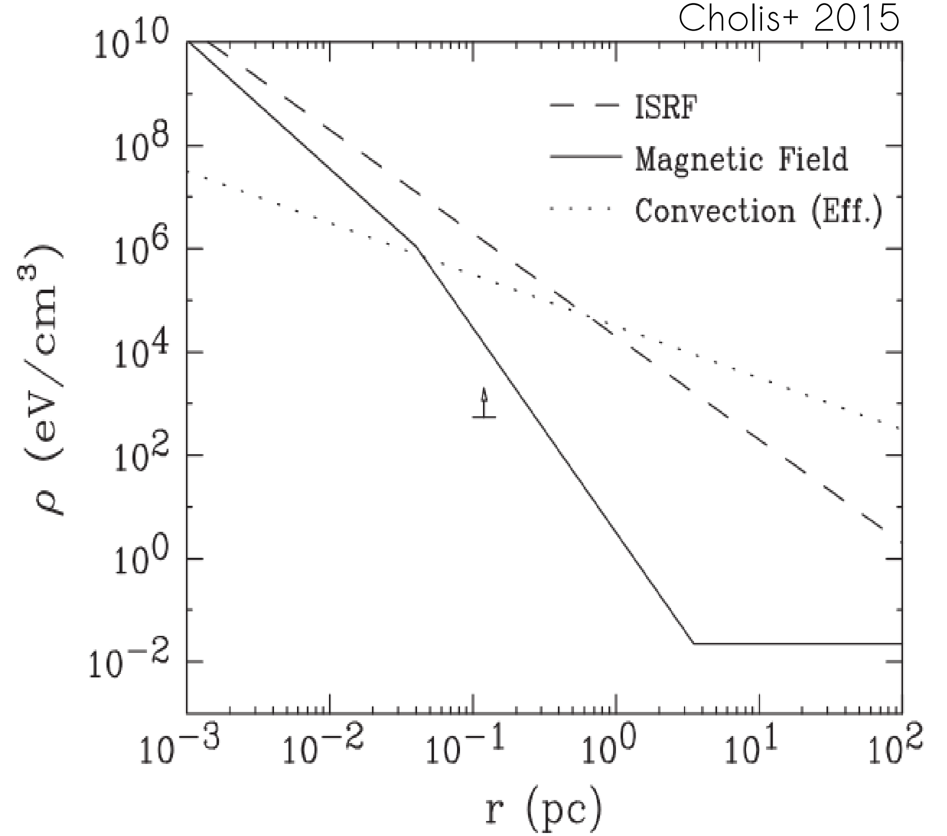


Uncertainties in the **magnetic field** and **DM spatial profile** in the innermost region of the Galaxy

Radio bounds on DM at GC



Uncertainties in the description of **ICS losses, winds and diffusion** in the innermost region of the Galaxy



Radio bounds on DM at GC

Assuming a **DM cuspy profile** down to the sub-pc region, robust bounds can be obtained if the ambient **magnetic field** will be found to be **strong** (B> mG in the innermost region < 1 pc)

SKA (and precursors) surveys of
magnetar population → rotation and dispersion measures → estimates of B

Could you think about a radio test for the GC excess??

Which radio counterpart we should look for? Diffuse? Point-sources?

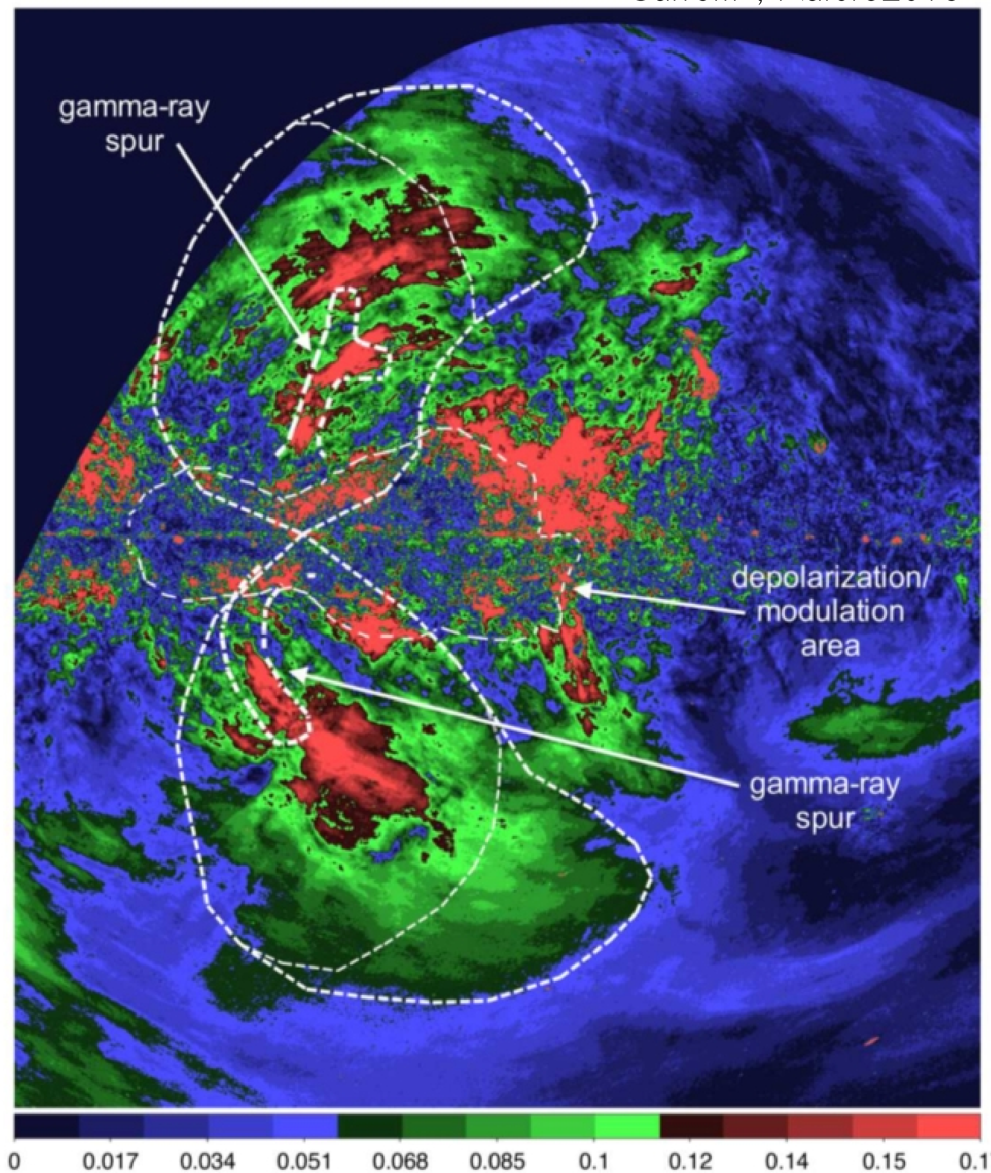
Interesting analogy: Fermi bubbles

Radio counterpart of Fermi bubbles

S-PASS

mapped the polarized radio emission of the entire southern sky with the Parkes Radio Telescope at a frequency of 2.3 GHz with 9' angular resolution.

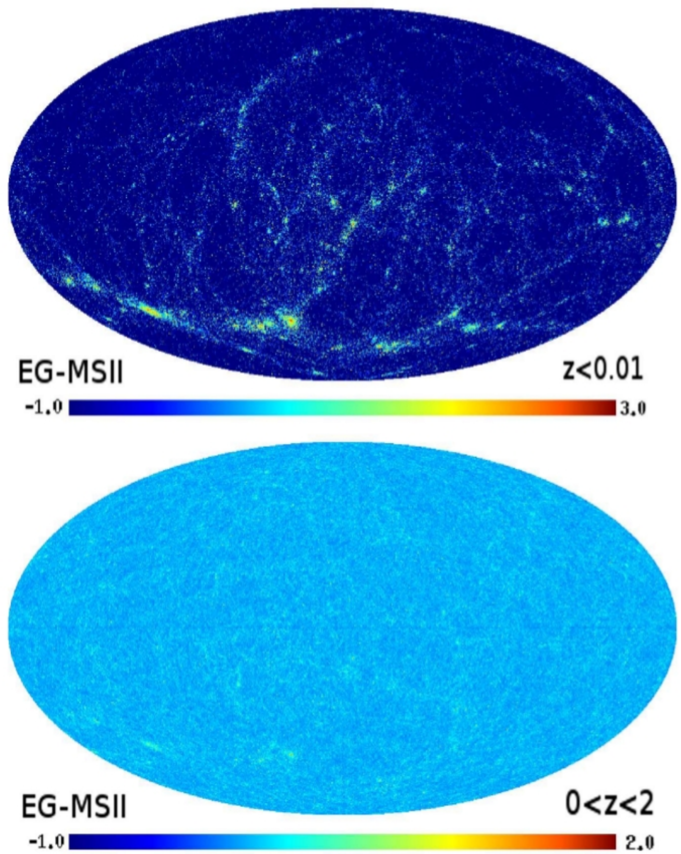
Carretti+, Nature2013



Angular cross-correlations

Angular correlations

Even if DM is too **faint** to detect the emission from an individual halo, it is the most **numerous** population in the Universe, which means that the **DM "cumulative" signal** or its **spatial coherence** might be observable.



from Fornasa et al., 2013

➡ Look at statistical correlations in the unresolved extragalactic sky

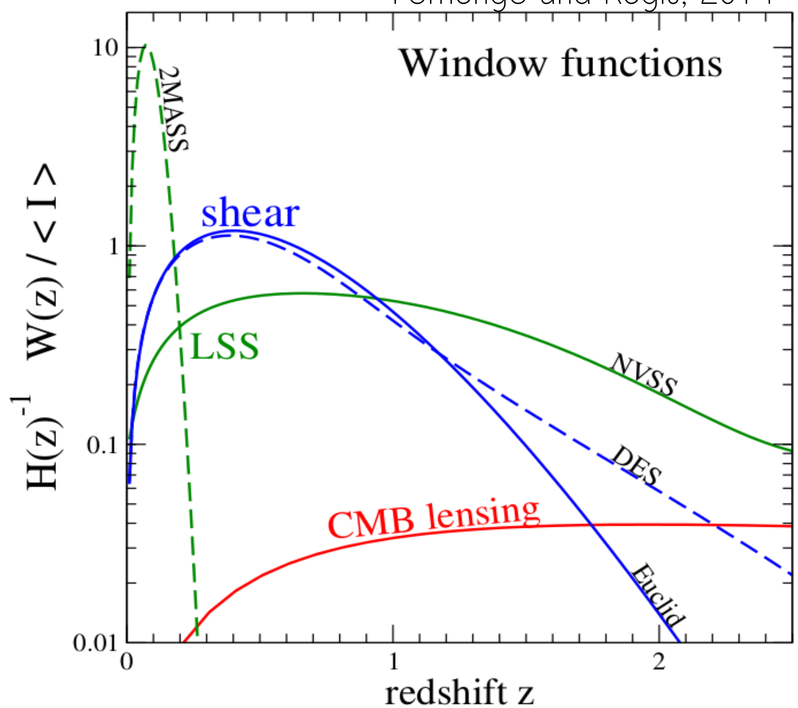
Cross correlation with DM gravitational tracers

Lensing potential or
number counts **of galaxies**
trace the DM density

↓

Correlation with the
WIMP non-gravitational signal

Fornengo and Regis, 2014



TOMOGRAPHIC
APPROACH

<u>Angular power spectrum</u>

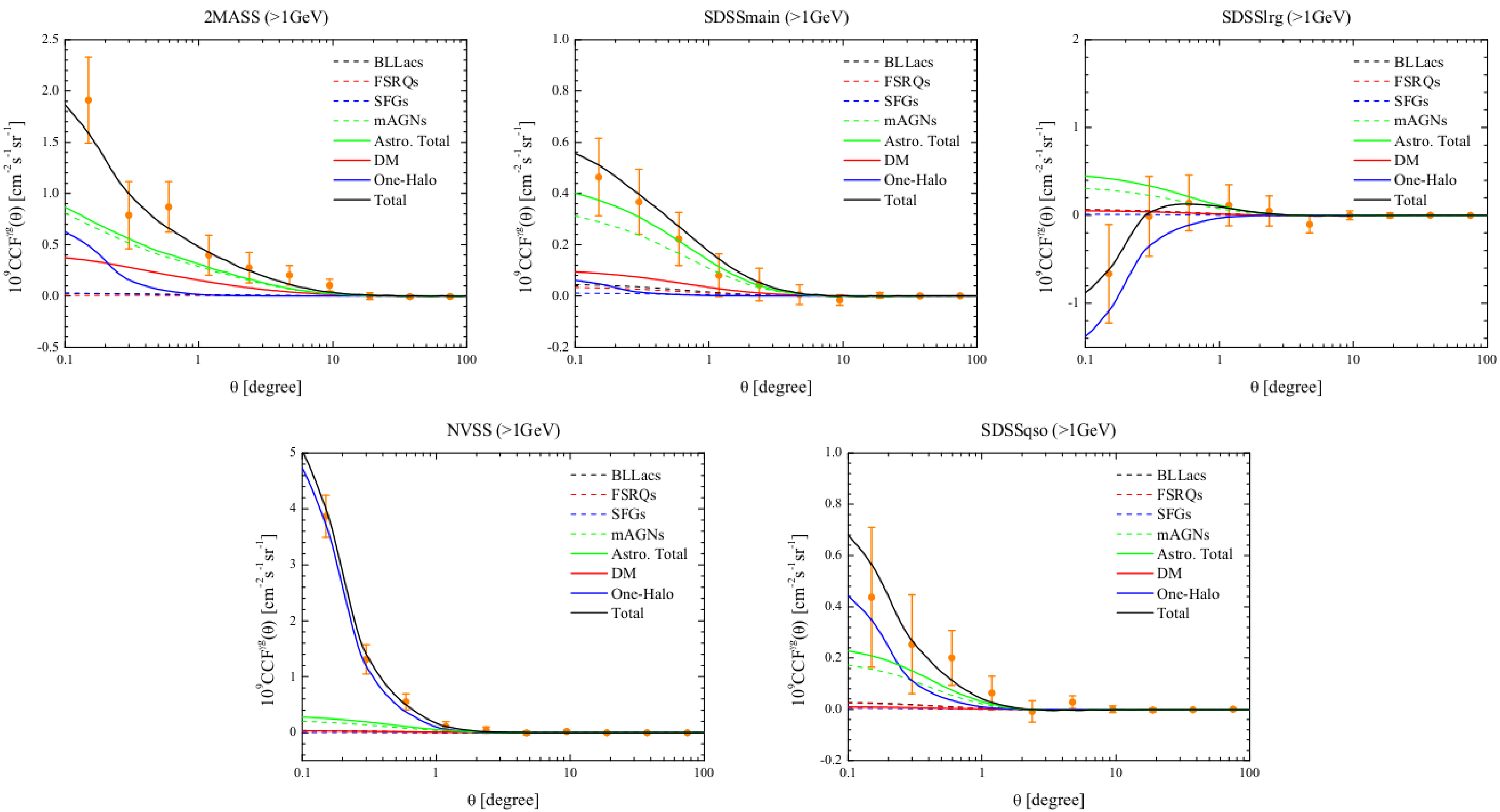
$$C_\ell^{(ij)} = \frac{1}{\langle I_i \rangle \langle I_j \rangle} \int \frac{d\chi}{\chi^2} W_i(\chi)\, W_j(\chi) P_{ij}(k = \ell/\chi, \chi)$$

<u>Correlation function</u>

$$\omega(\theta) = \frac{1}{4\pi} \sum_{\ell=1}^{\infty} (2\,\ell + 1)\, C_\ell\, P_\ell(\cos\theta)$$

Observations

Measurement of **cross-correlation** between the 5yr Fermi-LAT unresolved sky and 5 different galaxy catalogues (Xia, Cuoco, Branchini, Viel, 2015)



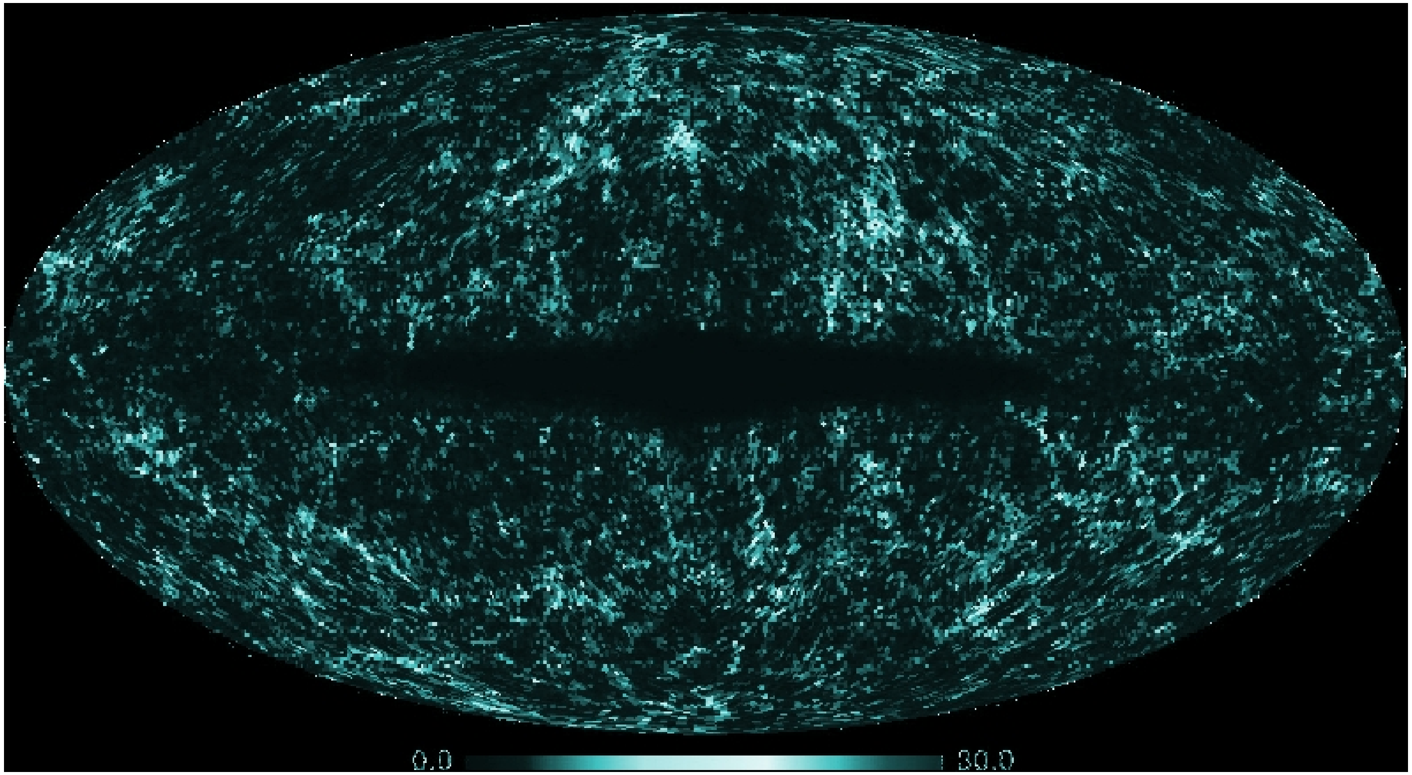
DM and cross correlation of Fermi-LAT with the 2MASS catalogue

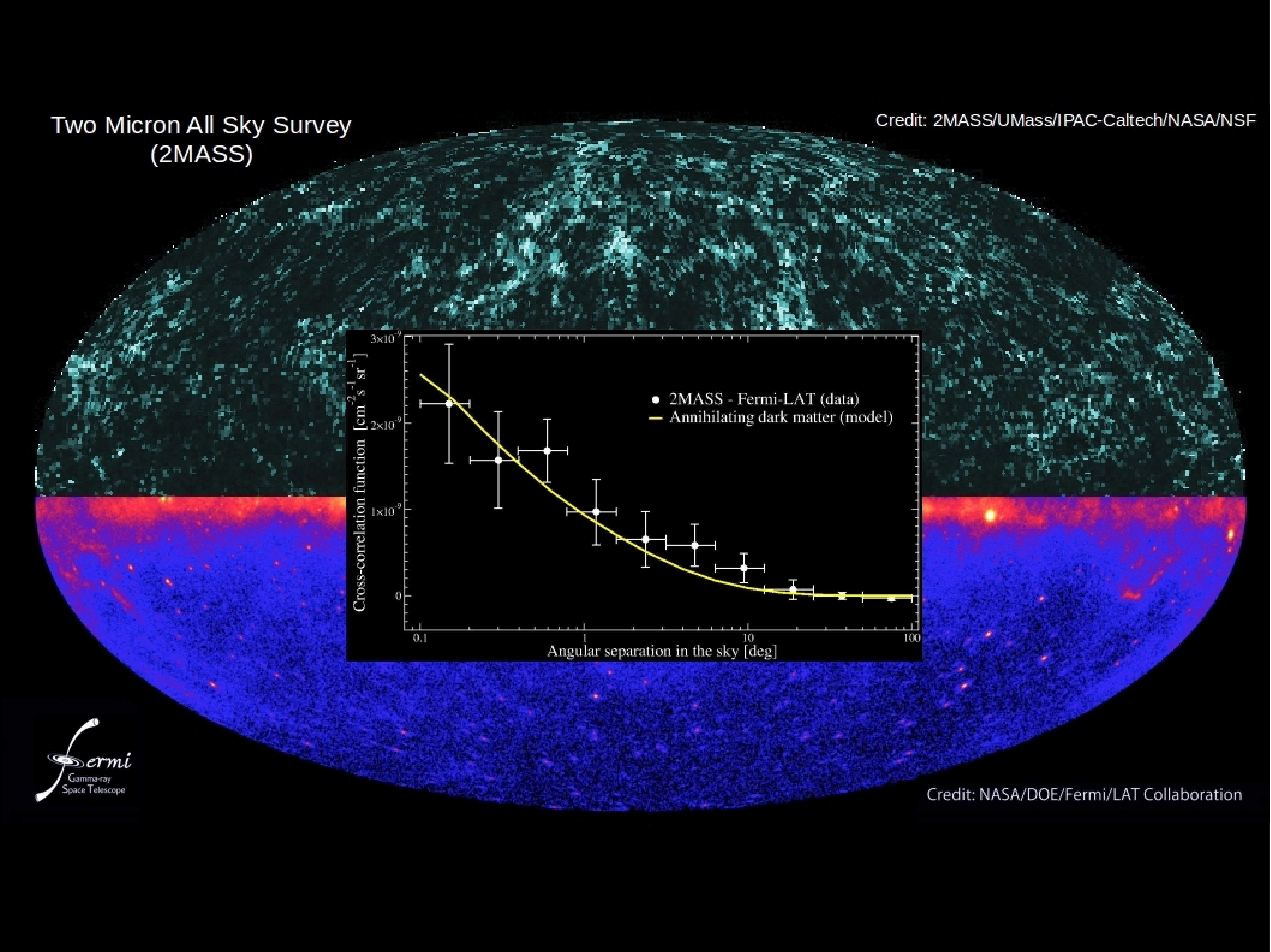
(Fornengo&Regis2013, Ando+2013, Ando2014, Regis+2015, Cuoco+2015)

2MASS

770000 galaxies with mean redshift z ~ 0.072

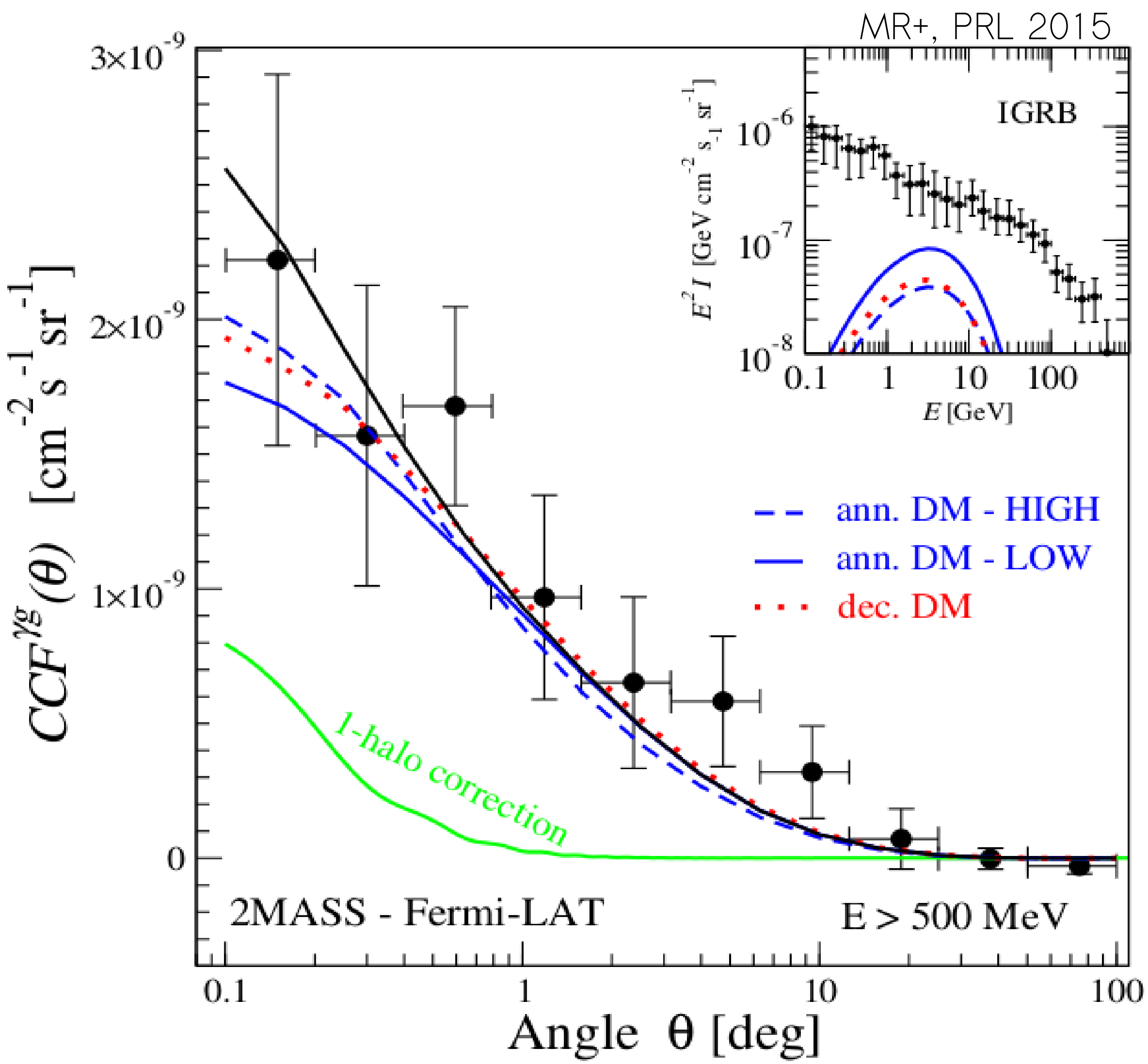
2MASS Redshift Survey "only" 43500 galaxies but spectroscopic redshift (see Ando 2014)





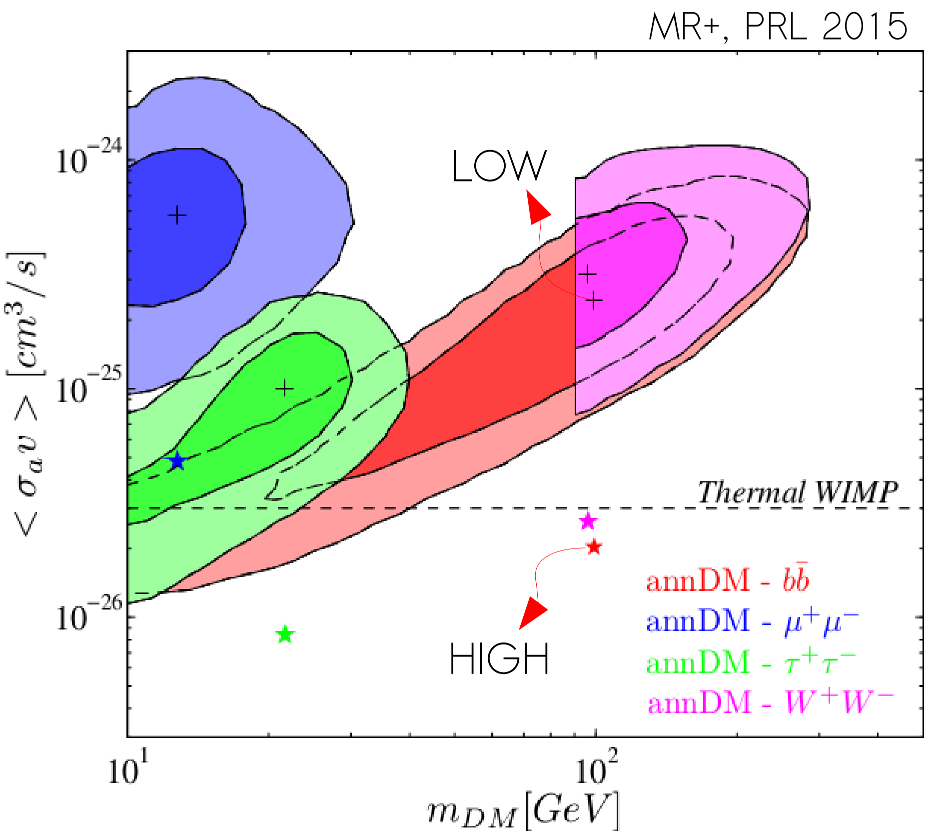
Two Micron All Sky Survey
(2MASS)
Credit: 2MASS/UMass/IPAC-Caltech/NASA/NSF
2MASS - Fermi-LAT (data)
Annihilating dark matter (model)
Cross-correlation function [cm⁻² s⁻¹ sr⁻¹]
Angular separation in the sky [deg]
3×10⁻⁹
2×10⁻⁹
1×10⁻⁹
0
0.1
1
10
100
Fermi
Gamma-ray Space Telescope
Credit: NASA/DOE/Fermi/LAT Collaboration

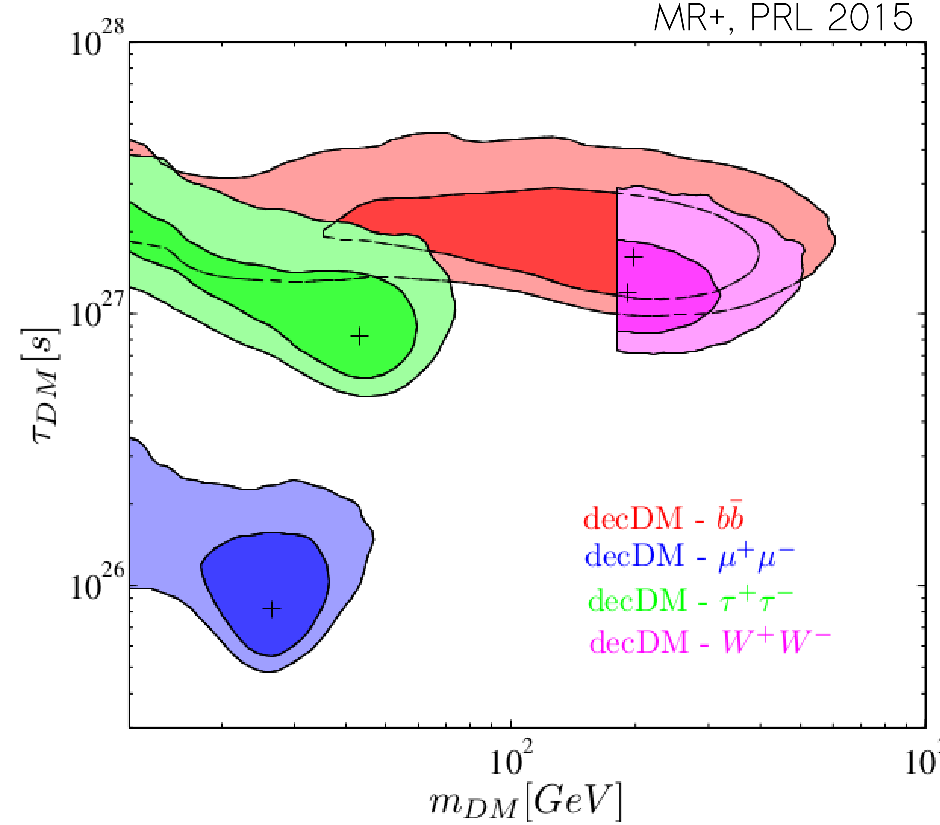
DM interpretation



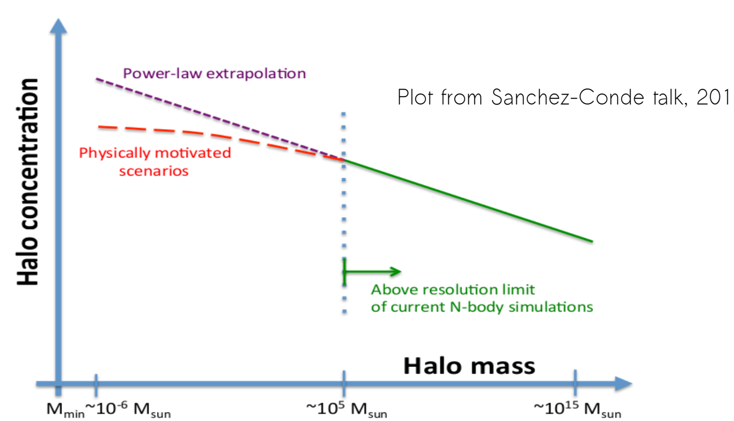
The particle DM signal **can fit** the measured cross-correlation between Fermi-LAT and 2MASS

DM interpretation





(about subhalos model



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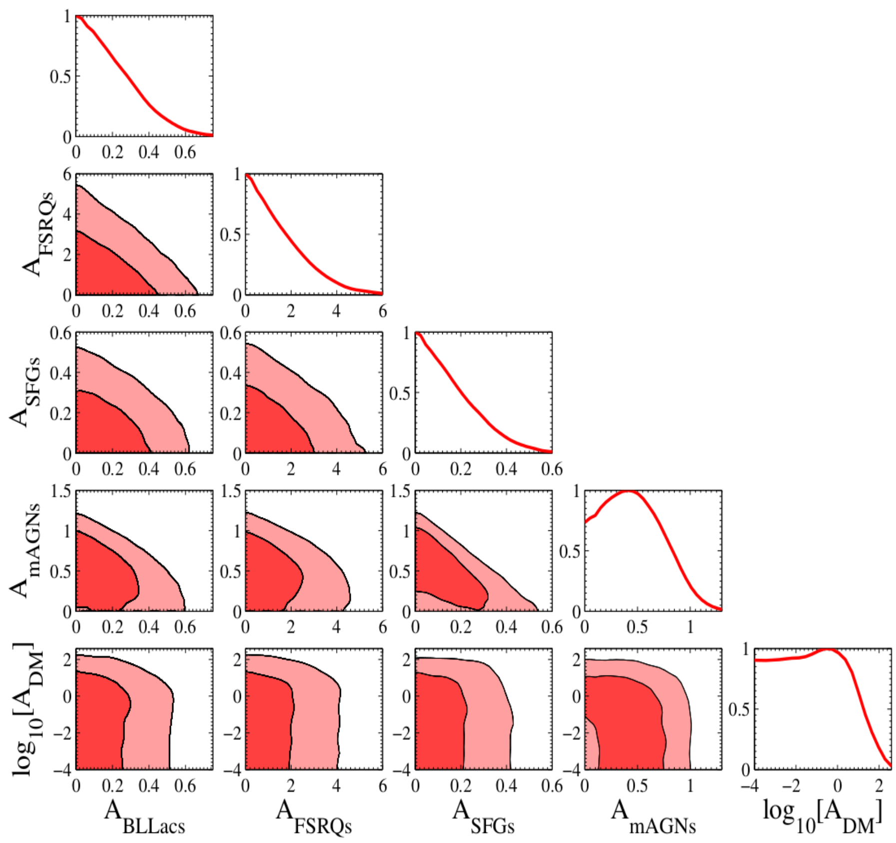
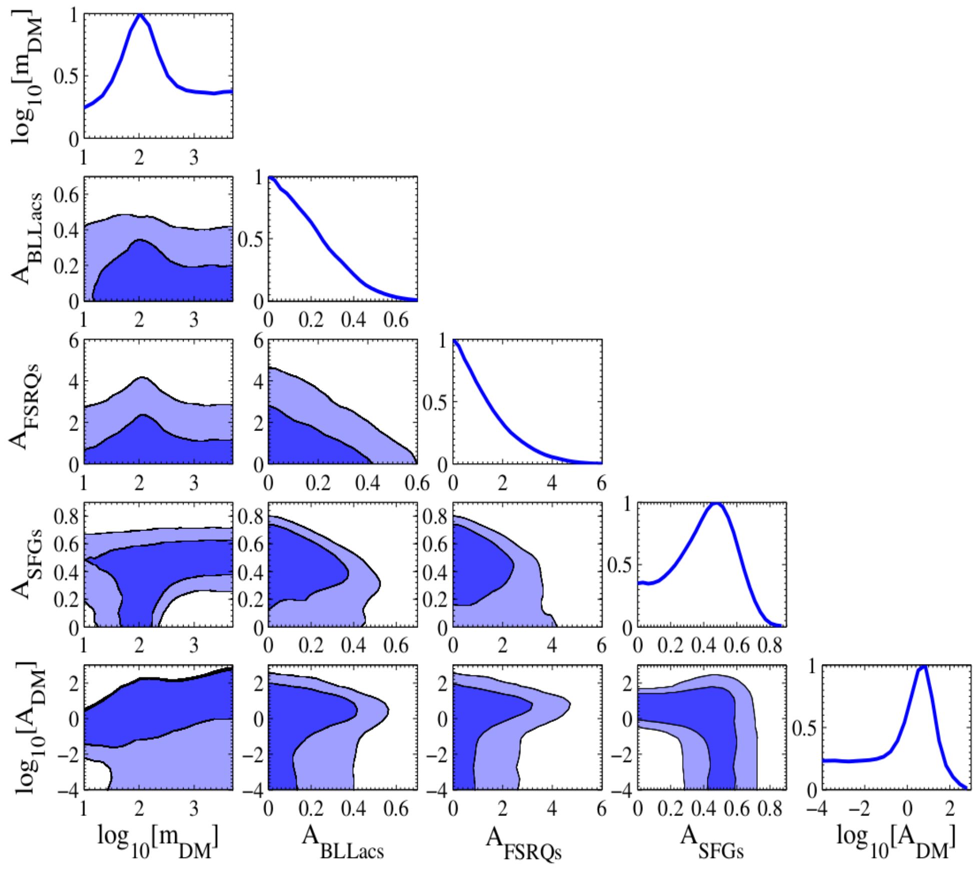
Disentanglement from astrophysical backgrounds



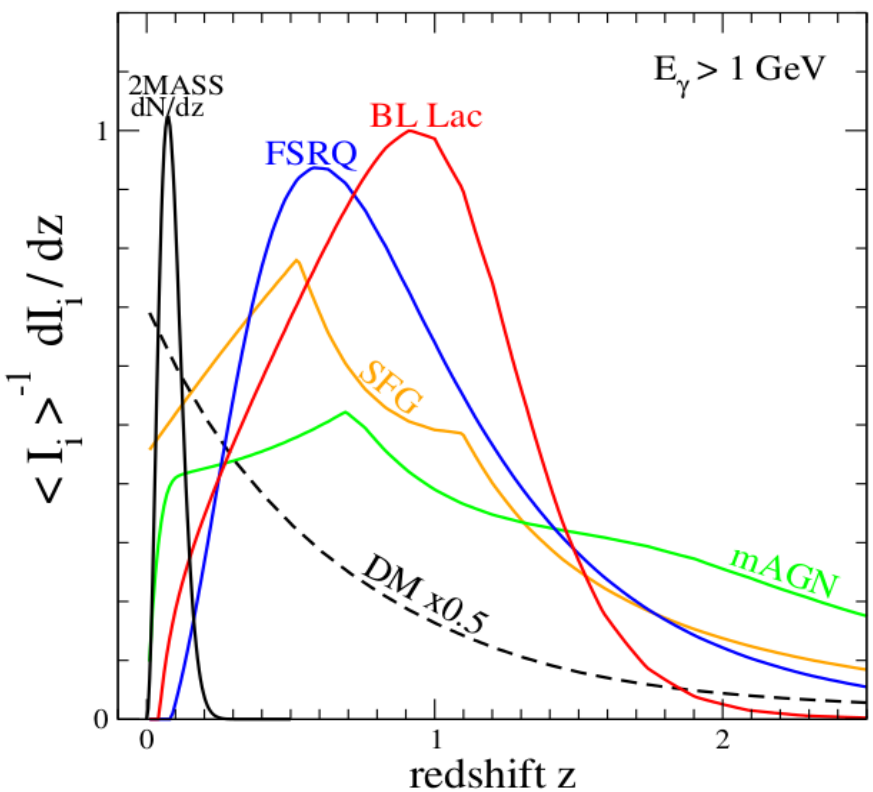


Xia, Cuoco, Regis, Branchini, Fornengo, Viel, 2015

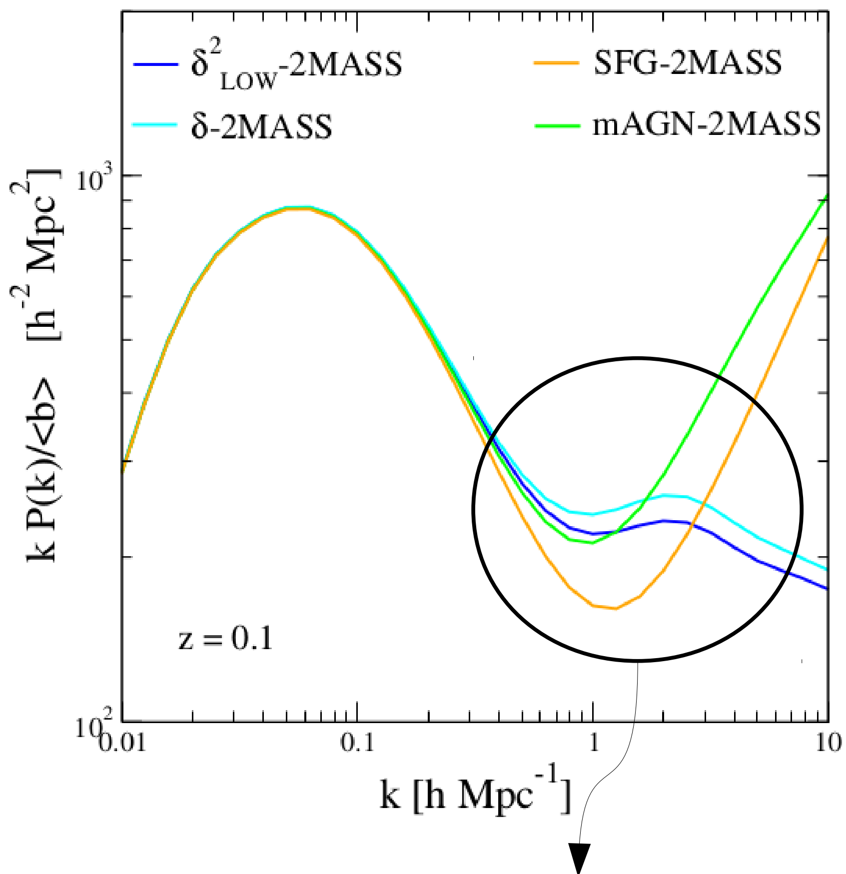
Disentanglement from astrophysical backgrounds

We can exploit predicted **differences** in:

Window functions



3D power spectra

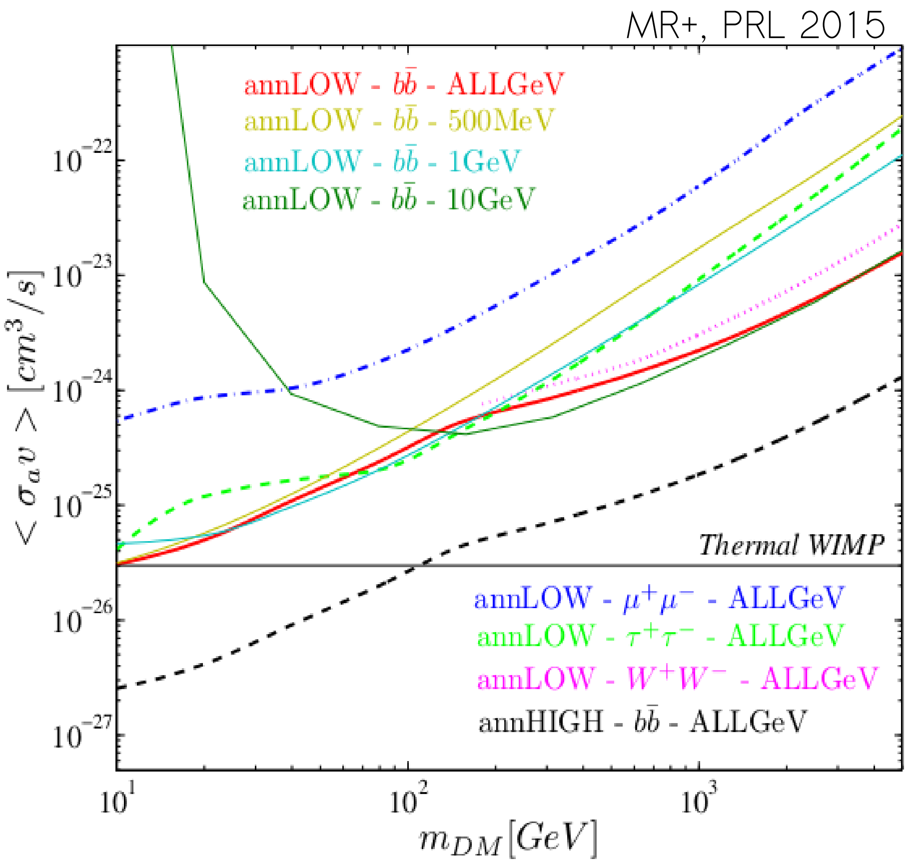


It is (roughly speaking) mapped in the multipole range 100 < l < 1000

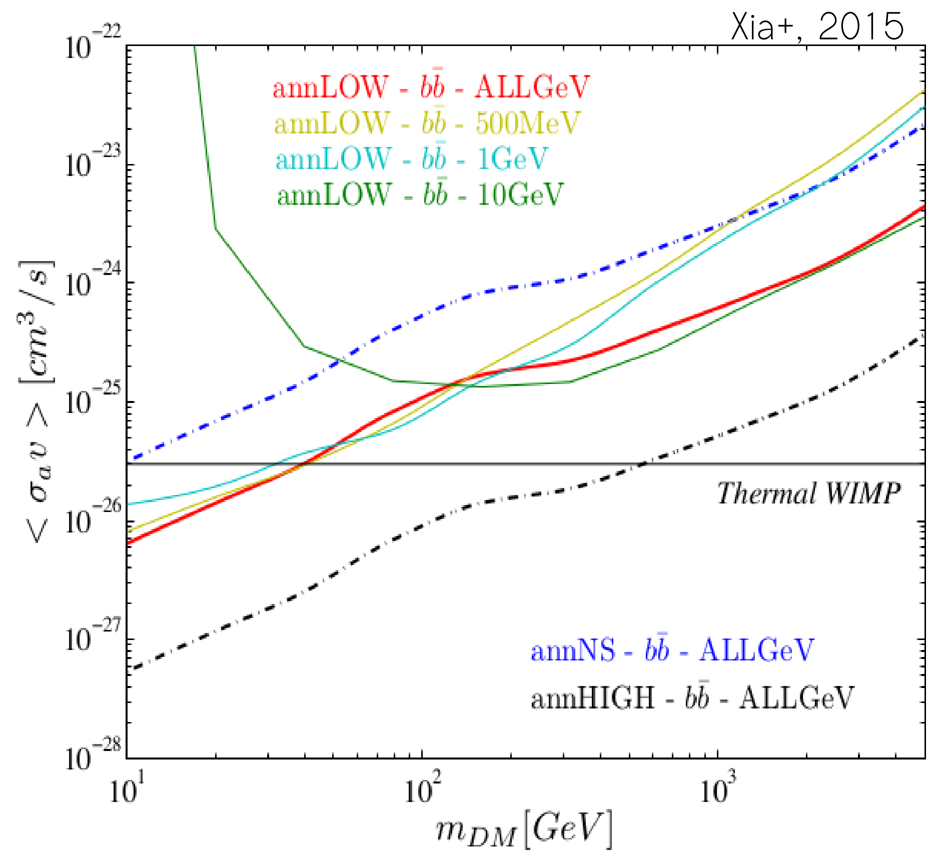
+ **energy spectrum** (in the usual way)

Bounds on WIMPs

DM-only



including astro sources



Future directions/questions

- **Energy** spectrum
- Low-z **tomography**
- **Smaller scales**
- Better knowledge of **astrophysical GLF at low z**
- **Lensing** surveys: cleaner test, larger non-linear term (Camera+ 2012, 2014)

Future directions/questions

- **Energy** spectrum
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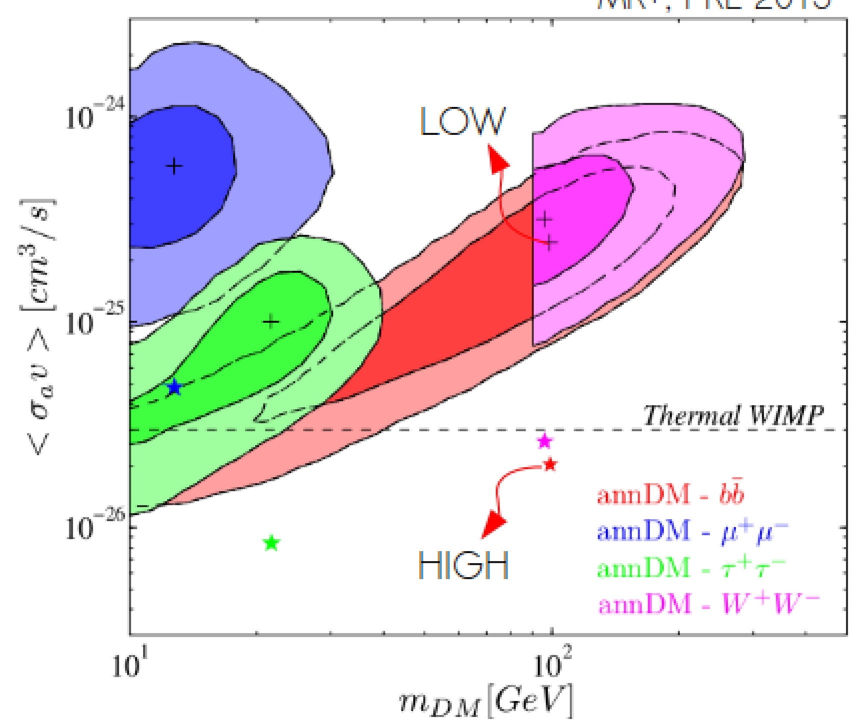
Is the DM interpretation viable?

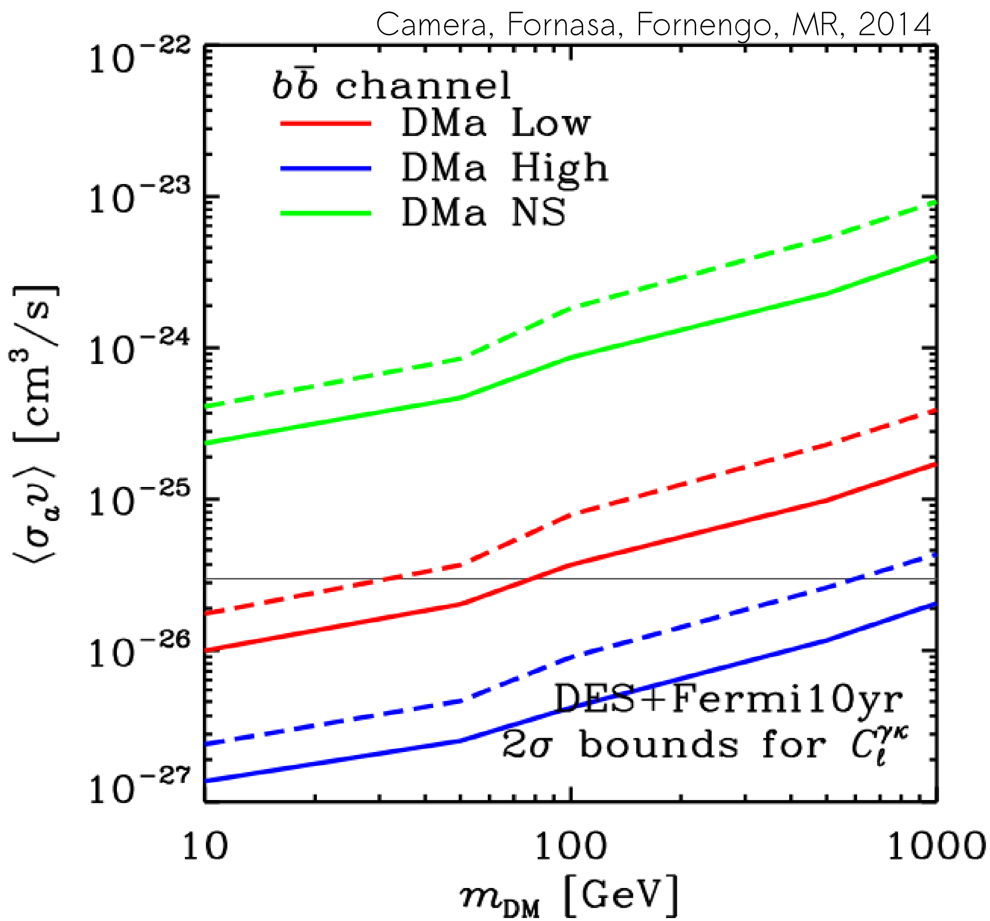
i.e. is it compatible with other bounds (like dSphs)?

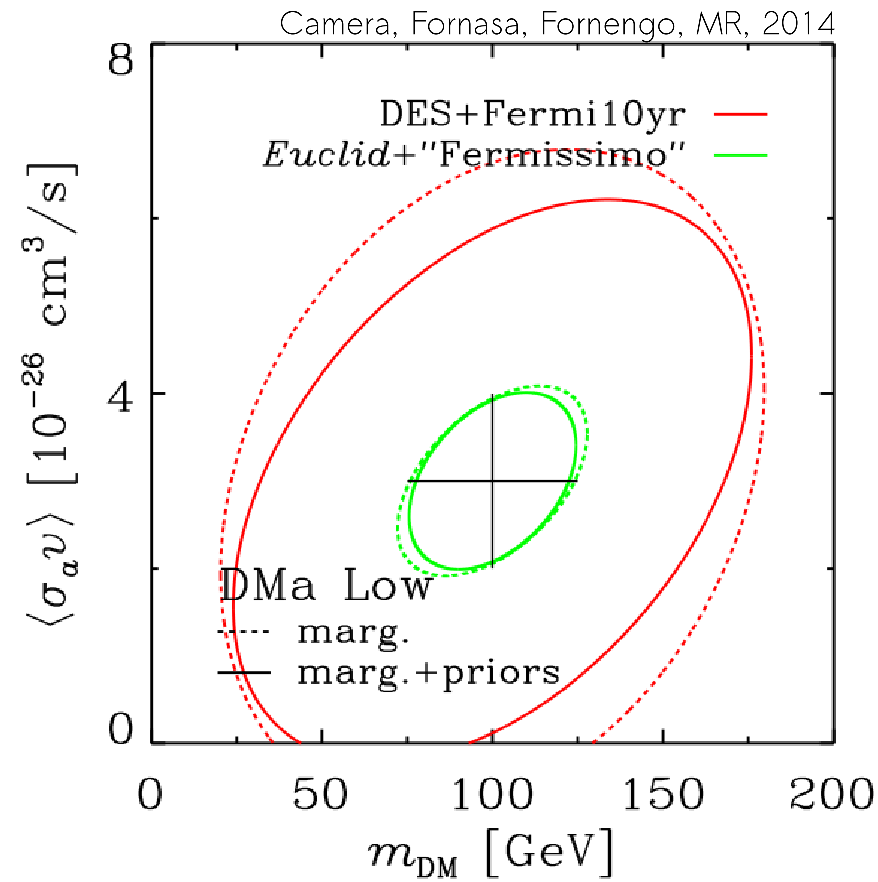
MR+, PRL 2015



Backup

Prospects for DM detection/bounds using cross-correlation with shear





First attempt of measurement

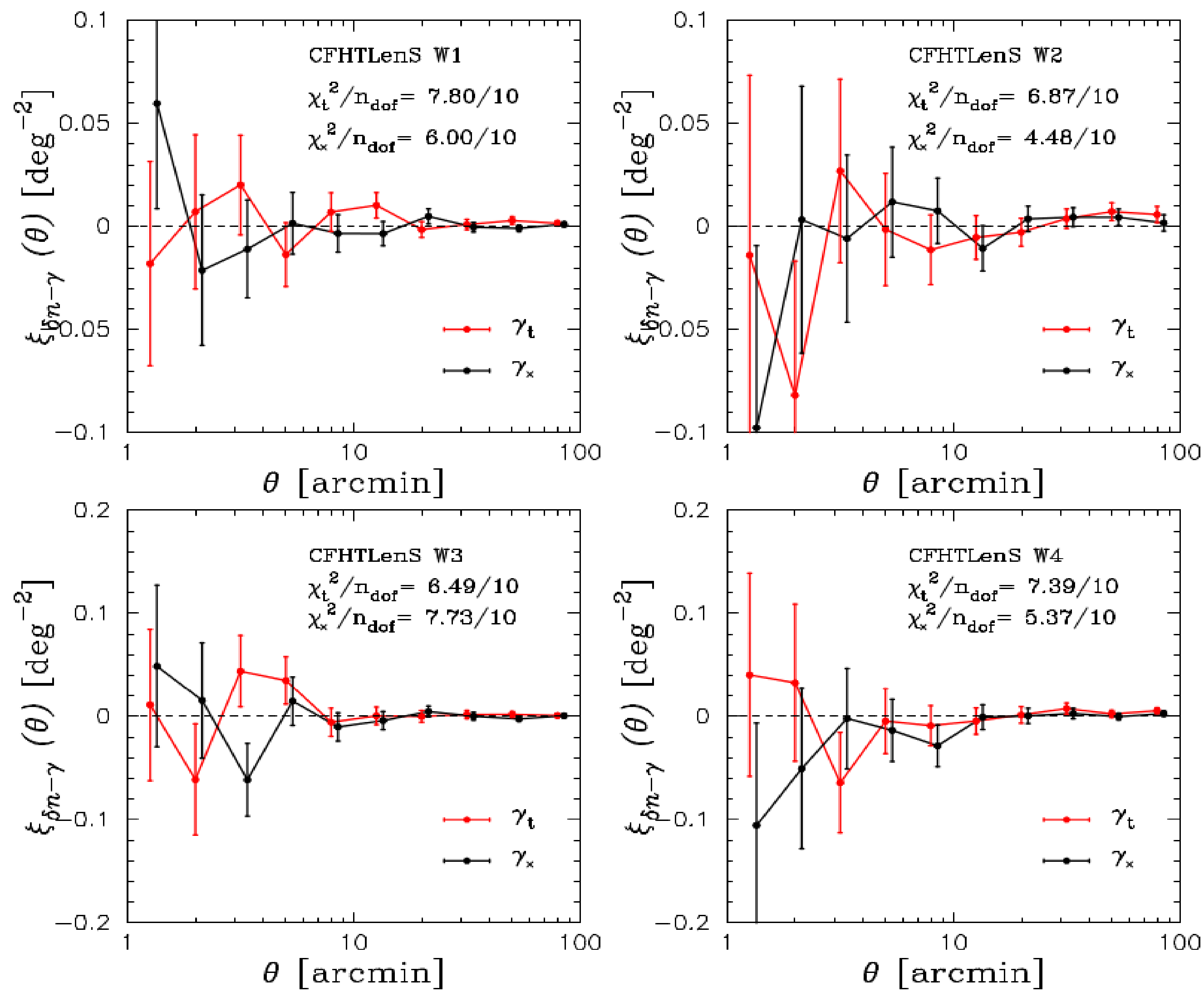
(of the cross-correlation between cosmic shear and the EGB)

Canada-France-Hawaii Lensing Survey (CFHTLenS) + 5yr Fermi LAT data

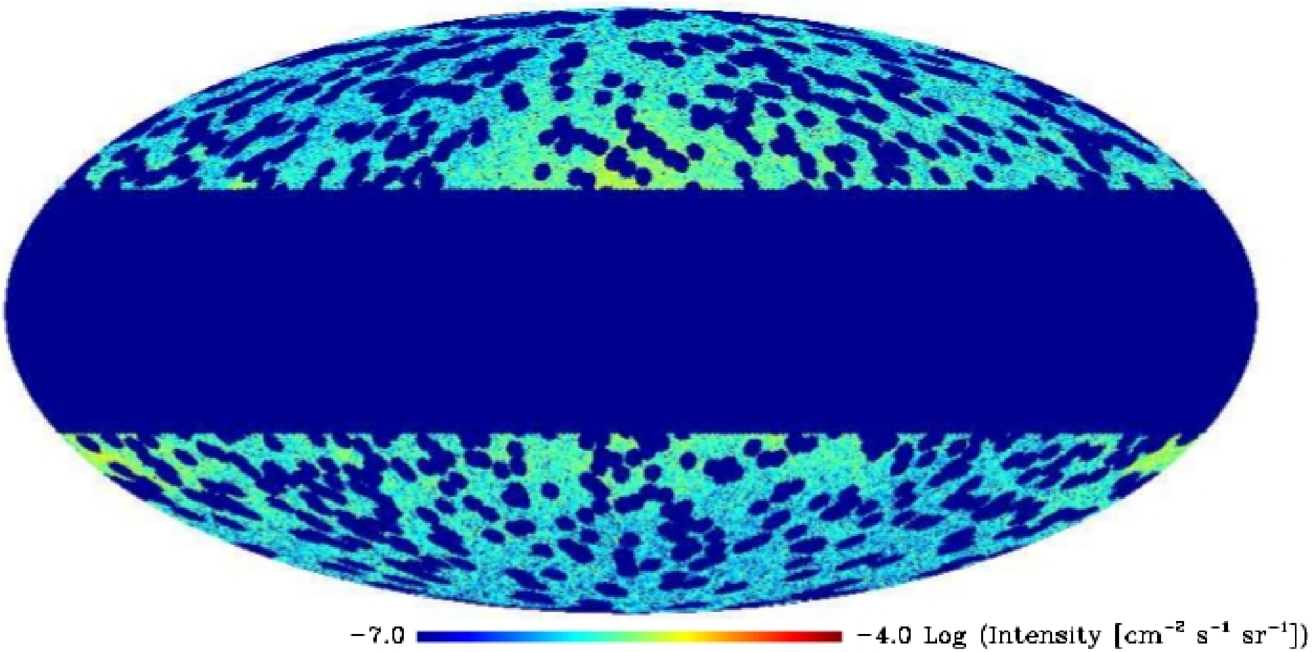
(Shirasaki, Horiuchi, Yoshida, 2014)

CFHTLenS
surveyed four
separated fields for a
total of
~150 sq. deg.
with
11 gal/arcmin^2

(DES → 5000 sq.deg.)

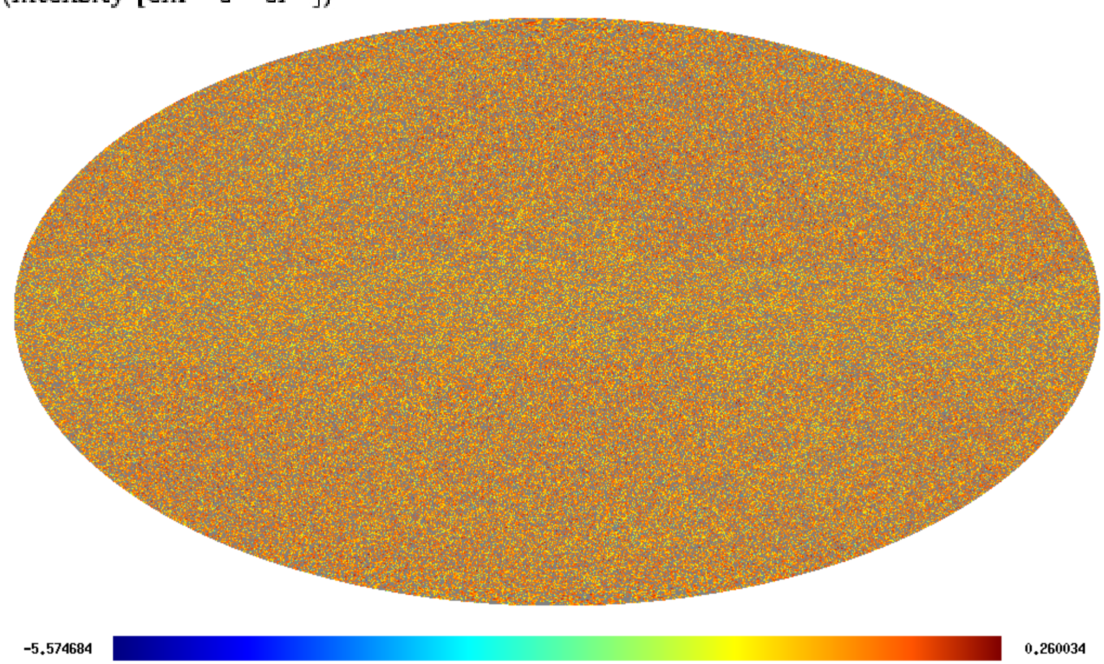


Cross correlation with CMB lensing

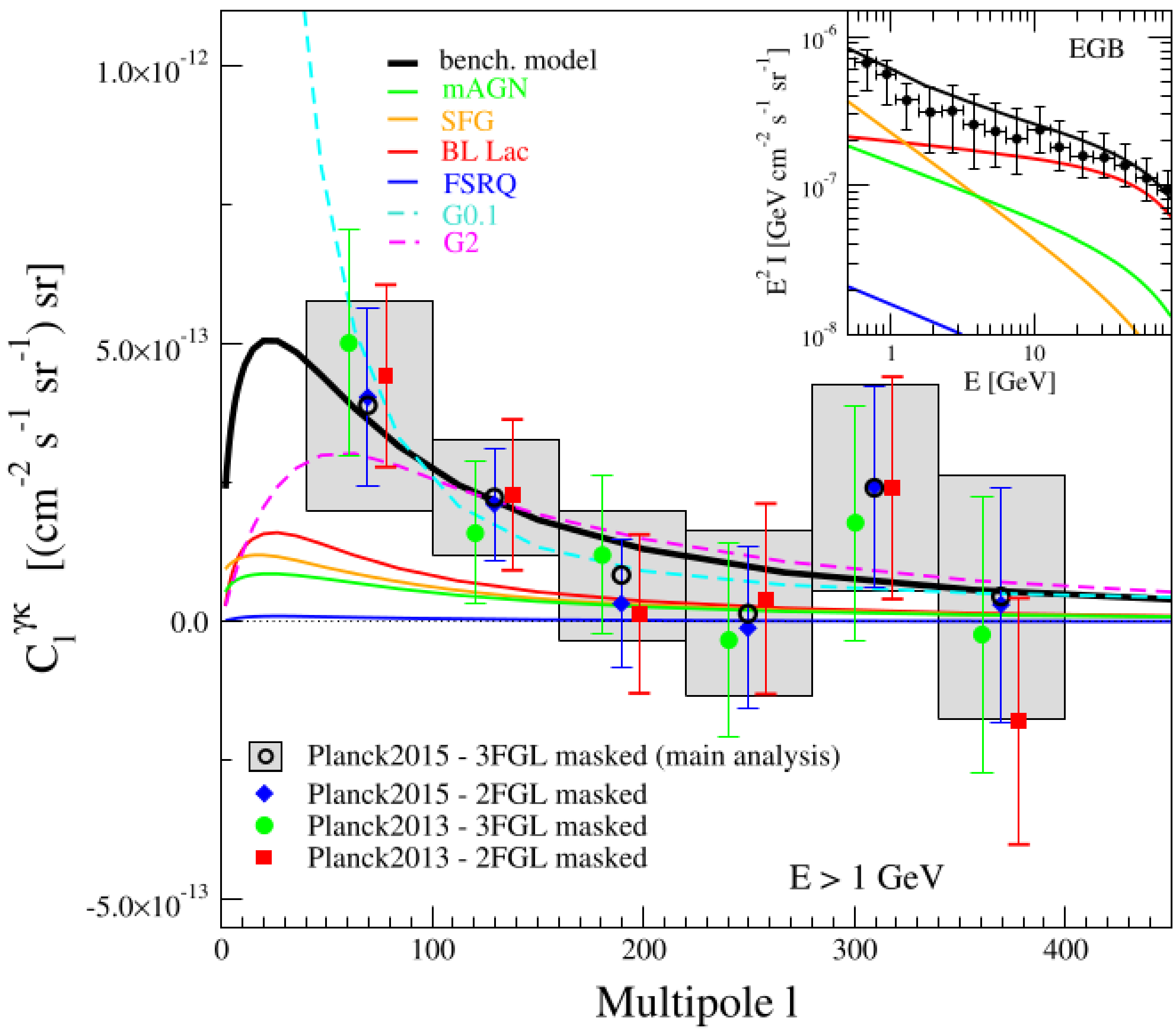


Fermi-LAT 6yr data

Planck 2015 data release



Cross correlation with CMB lensing



3σ evidence

Fornengo, Perotto, Regis, Camera
ApJ 2015

Direct evidence of the extragalactic origin of the diffuse γ-ray background

Future observations

Gamma: Fermi-LAT Pass-8, GAMMA-400, HERD, DAMPE

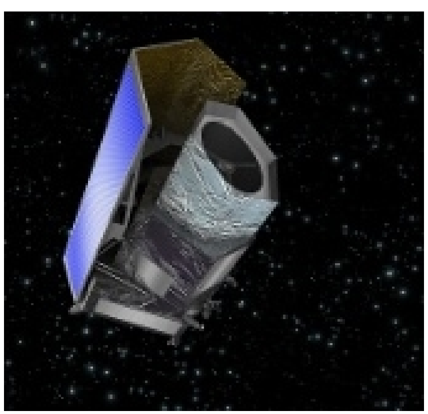
Radio: SKA and its precursors (LOFAR, ASKAP)

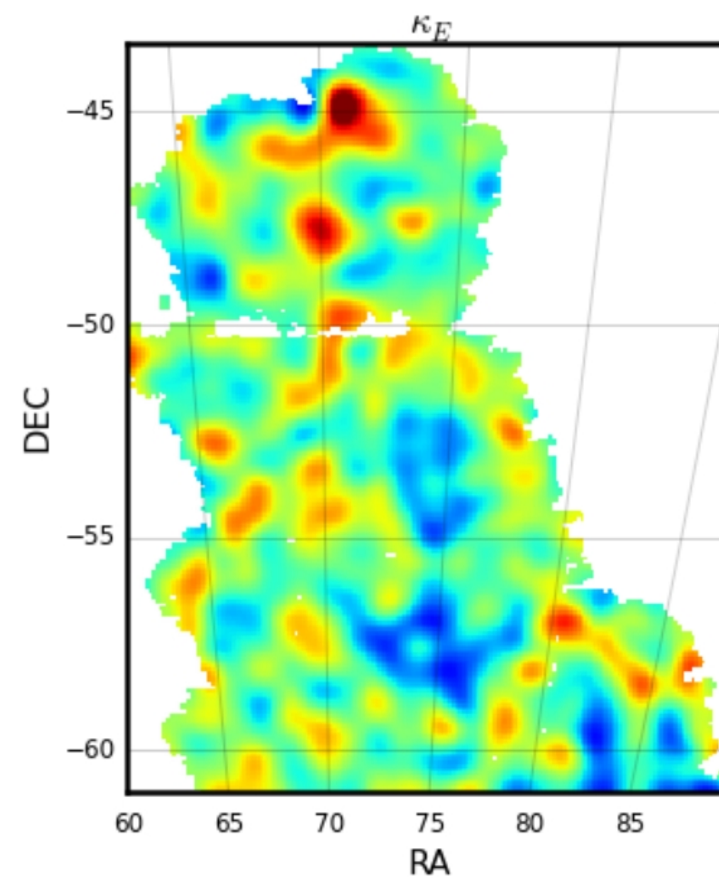
X-rays: eROSITA, ATHENA, ..

Vikram+, 2015 (DES)

Lensing and galaxy surveys:

HSC, DES, eBOSS, DESI, LSST, Euclid, ..

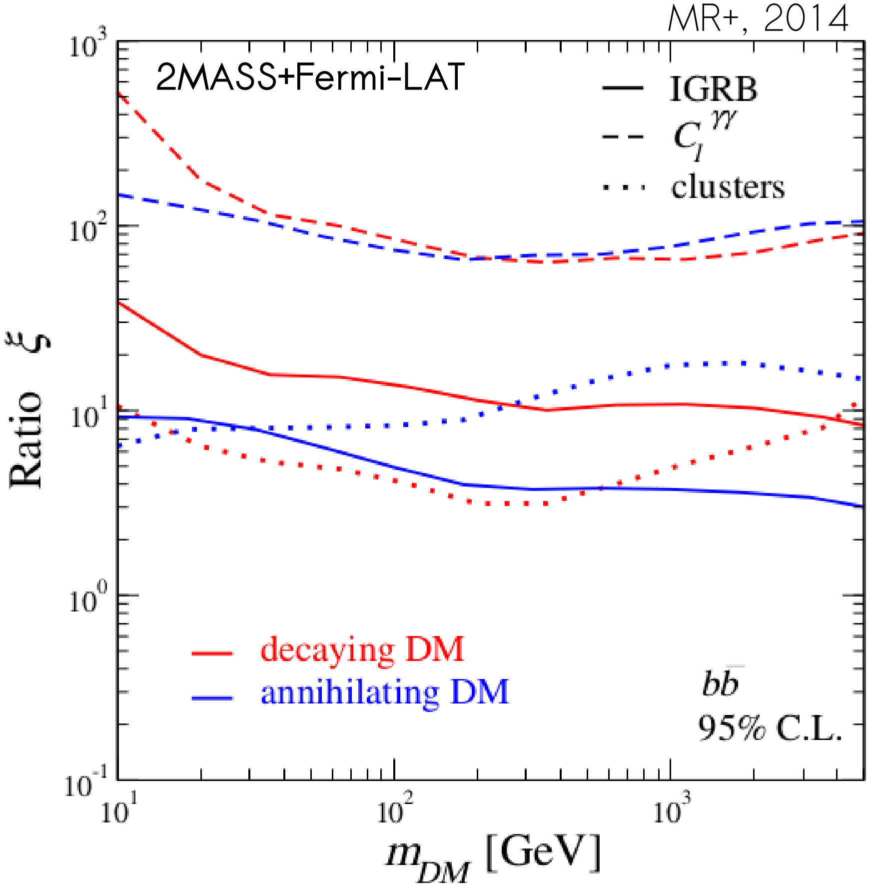




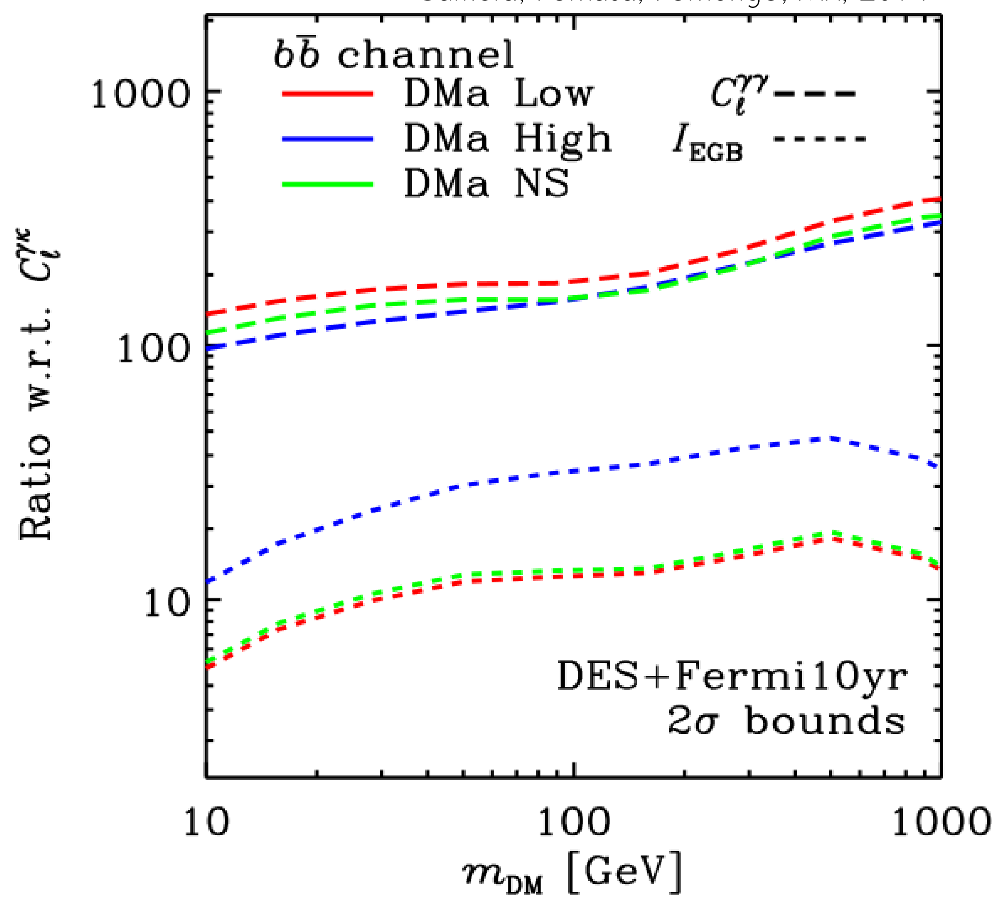
WTF?

(Where To Find dark matter?)

MR+, 2014

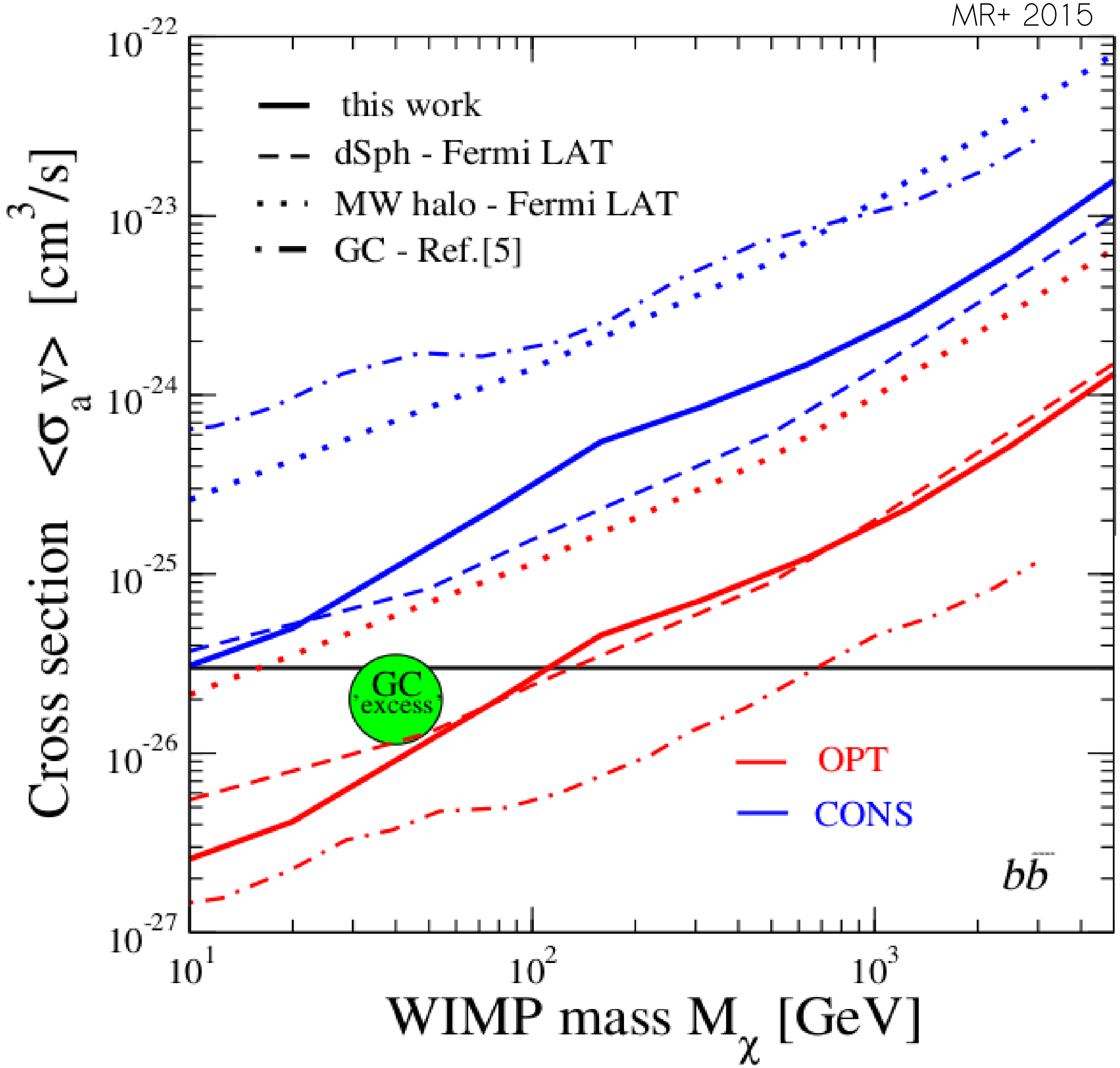


Camera, Fornasa, Fornengo, MR, 2014

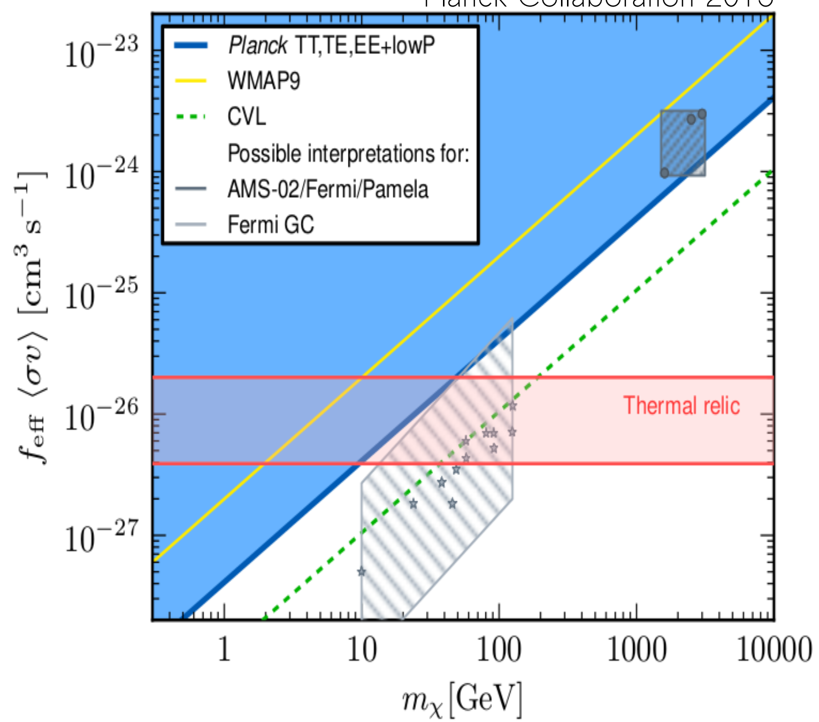


Comparison with other methods

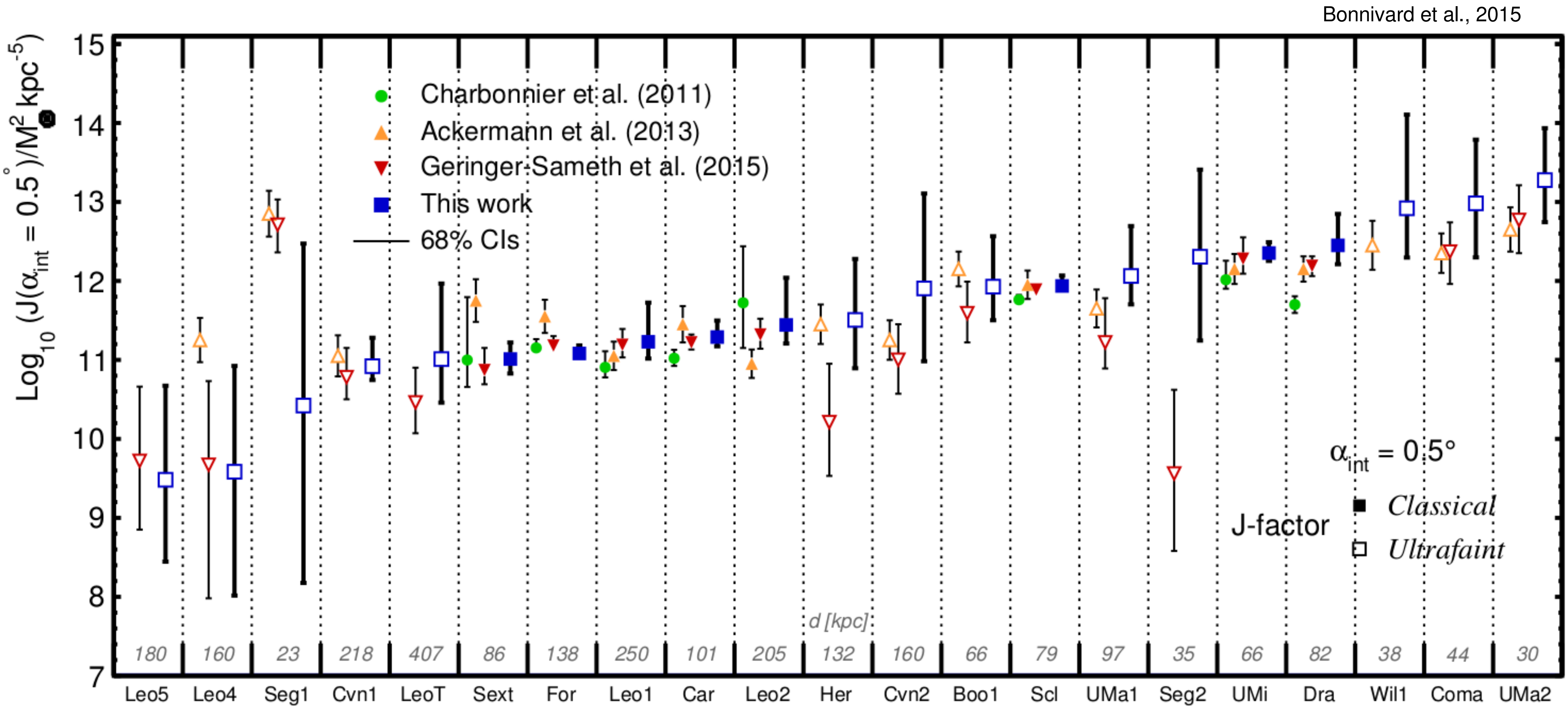
MR+ 2015



Planck Collaboration 2015



J-factor



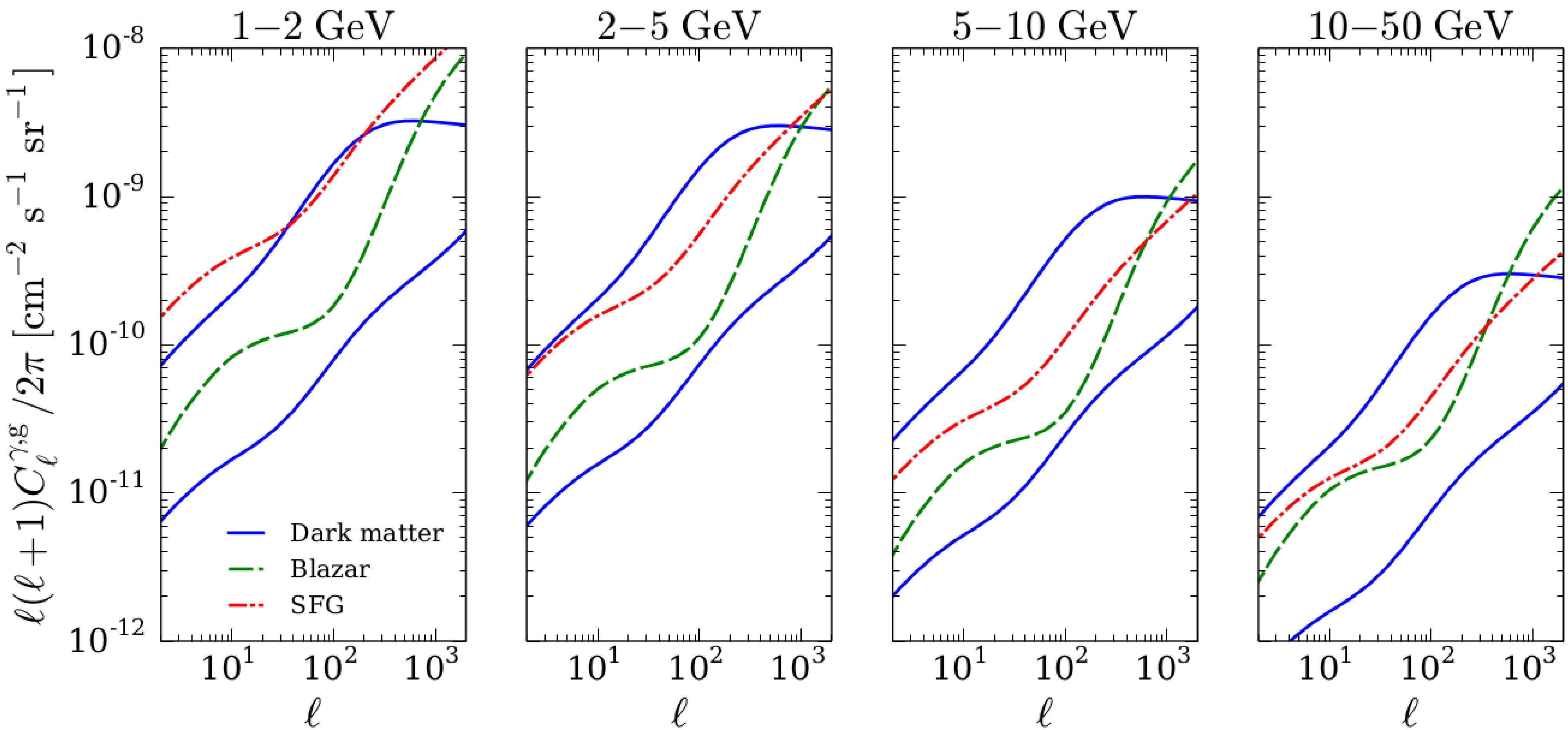
Bonnivard et al., 2015
Charbonnier et al. (2011)
Ackermann et al. (2013)
Geringer-Sameth et al. (2015)
This work
68% CIs
$Log_{10}(J(\alpha_{int} = 0.5^\circ)/M^2_\odot \, kpc^{-5})$
15
14
13
12
11
10
9
8
7
$\alpha_{int} = 0.5°$
J-factor
Classical
Ultrafaint
d [kpc]
180
160
23
218
407
86
138
250
101
205
132
160
66
79
97
35
66
82
38
44
30
Leo5
Leo4
Seg1
Cvn1
LeoT
Sext
For
Leo1
Car
Leo2
Her
Cvn2
Boo1
Scl
UMa1
Seg2
UMi
Dra
Wil1
Coma
UMa2

Cross correlation with 2MASS: predictions

$m_{\rm dm} = 100$ GeV, $\langle \sigma v \rangle = 3 \times 10^{-26}$ cm^3 s^{-1}

$b\bar{b}$ annihilation channel

Ando, 2014



Two-point statistics

Angular power spectrum of fluctuations

$$\delta I_g(\vec{n}) \equiv I_g(\vec{n}) - \langle I_g \rangle \qquad \delta I_g(\vec{n}) = \langle I_g \rangle \sum_{\ell m} a_{\ell m} Y_{\ell m}(\vec{n})$$

$$C_\ell^{(ij)} = \frac{1}{2\ell+1} \langle \sum_{m=-\ell}^{\ell} a_{\ell m}^{(i)} a_{\ell m}^{(j)*} \rangle$$

Correlation function

$$\omega(\theta) = \frac{1}{4\pi} \sum_{\ell=1}^{\infty} (2\,\ell+1)\, C_\ell\, P_\ell(\cos\theta)$$

Angular power spectrum

General expression for the angular power spectrum:

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

$$\langle I_g \rangle = \int d\chi \, W(\chi)$$

→ Window function

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

→ 3D power spectrum

FT of density field of the source

Cross correlation

The idea is to have an **accurate tracer of the DM distribution** (gravitational potential) in the Universe, to be used as a filter in order to separate the DM non-gravitational signal from other astrophysical emissions.

$$C_\ell^{(ij)} = \frac{1}{2\ell+1}\langle \sum_{m=-\ell}^{\ell} a_{\ell m}^{(i)} a_{\ell m}^{(j)*} \rangle$$

Gravitational tracer
("filter")

Gamma-ray sky
(or X-ray, radio, ... sky)

Window function

It **weights** the contribution at different redshifts.

<u>Gravitational</u>

W_κ lensing

W_g # of galaxies

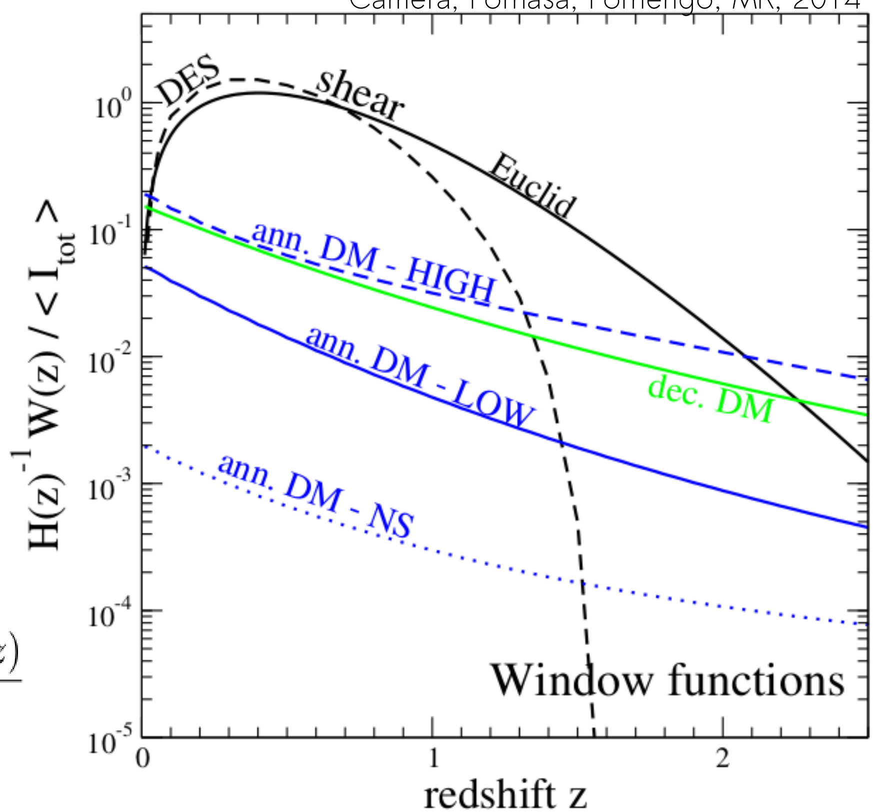
<u>Non-gravitational</u> (γ-rays, X-rays, radio)

W_{ann} annihilating DM

W_{dec} decaying DM

W_{astro} astrophysical non-thermal sources

Camera, Fornasa, Fornengo, MR, 2014



Annihilating DM

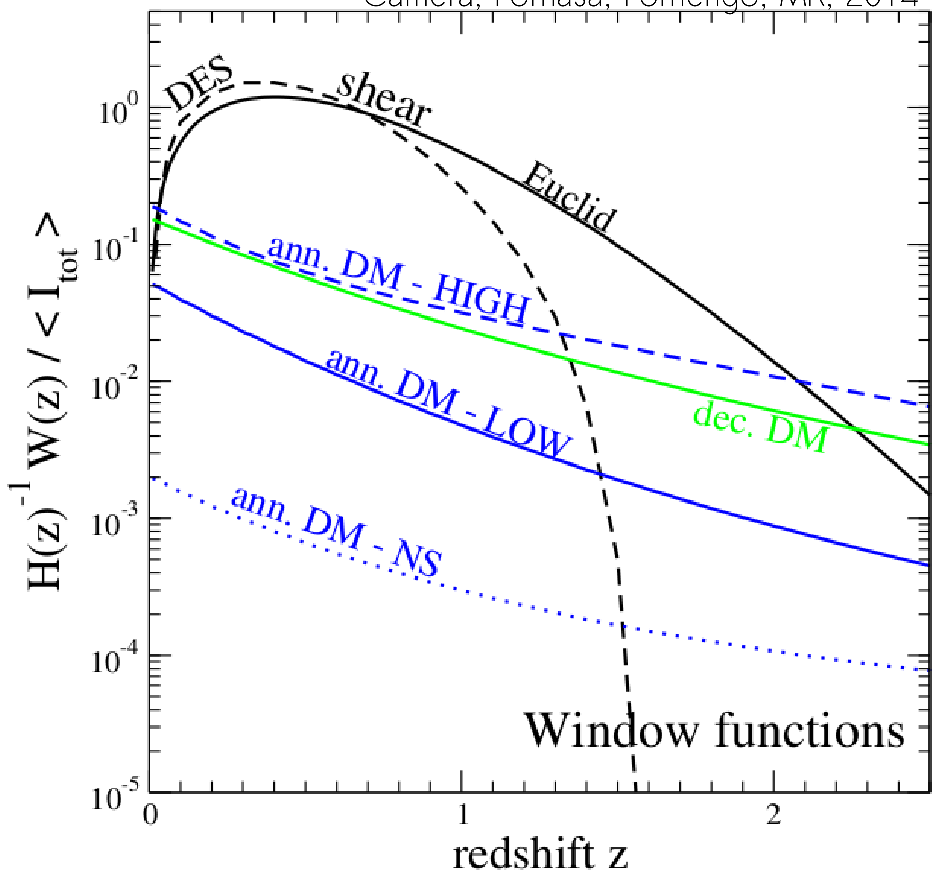
$$W(E,z) = \frac{(\Omega_{DM}\rho_c)^2}{4\pi}\frac{\langle\sigma_a v\rangle}{2m_\chi^2}(1+z)^3\,\Delta^2(z)\,\frac{dN_a[E(1+z)]}{dE}\,e^{-\tau[E(1+z),z]}$$

<u>Clumping factor</u> (or flux multiplier):

$$\Delta^2(z) \equiv \frac{\langle\rho_{\rm DM}^2\rangle}{\bar\rho_{\rm DM}^2} = \int_{M_{\rm min}}^{M_{\rm max}} {\rm d}M\,\frac{{\rm d}n}{{\rm d}M}(M,z)\,[1+b_{\rm sub}(M,z)]\int {\rm d}^3\mathbf{x}\,\frac{\rho_h^2(\mathbf{x}|M,z)}{\bar\rho_{\rm DM}^2}$$

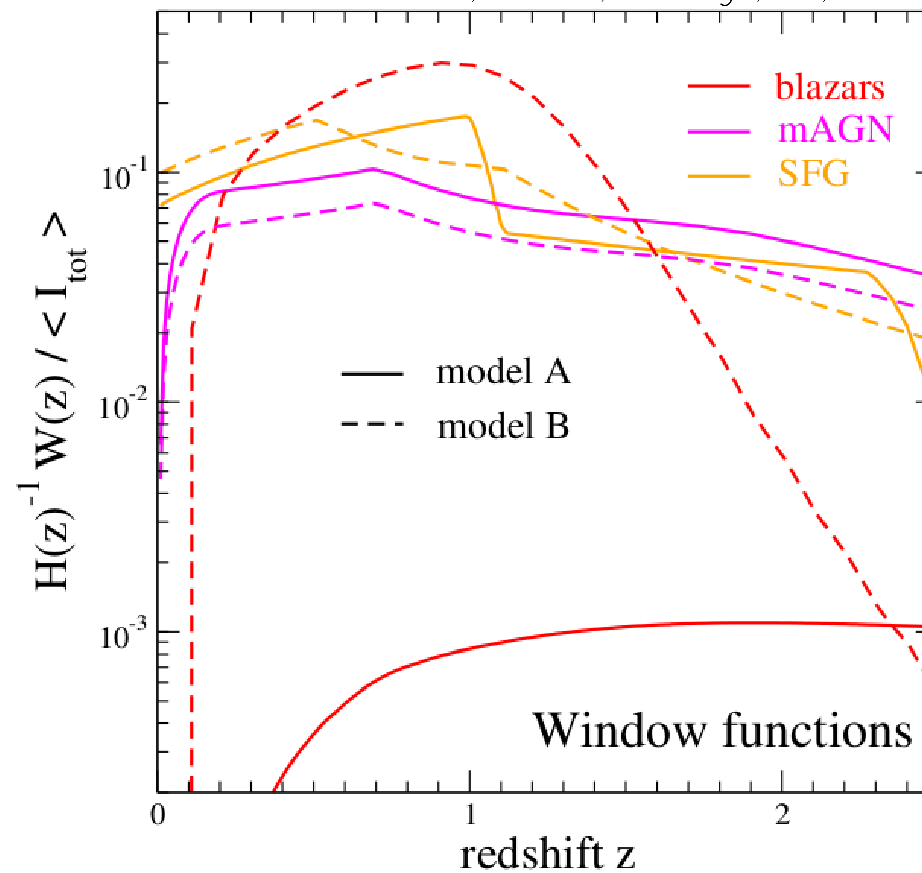
Window functions

Camera, Fornasa, Fornengo, MR, 2014



DM and lensing probes
peaked at low z

Camera, Fornasa, Fornengo, MR, 2014



Astrophysical sources
peaked at z > 0.5

3D power spectrum

It can be obtained from:

- **Simulations**
- **Halo model** approach

(- Squeezed bispectrum?)

Halo model

$$P_{ij}(k) = P_{ij}^{1h}(k) + P_{ij}^{2h}(k)$$

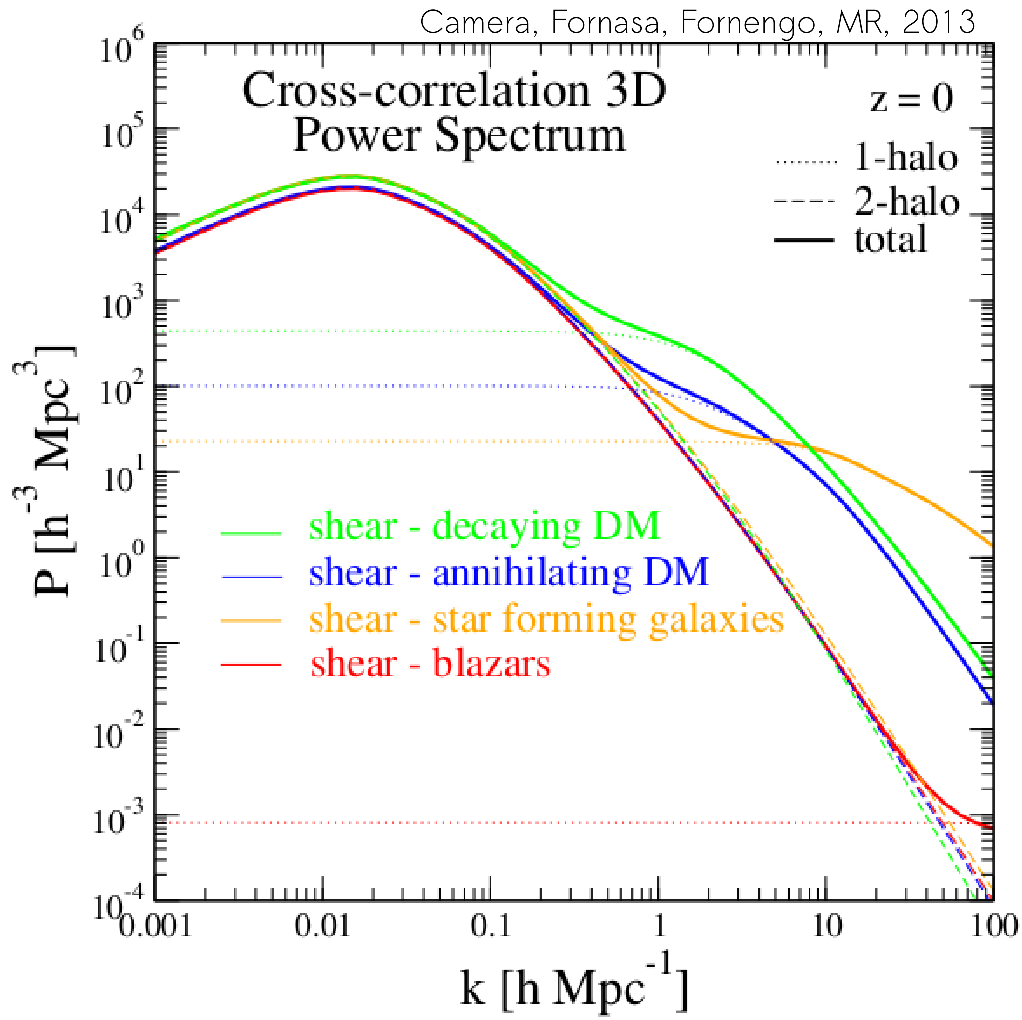
$$P_{ij}^{1h}(k) = \int dm \, \frac{dn}{dm} \hat{f}_i^*(k|m) \, \hat{f}_j(k|m)$$

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

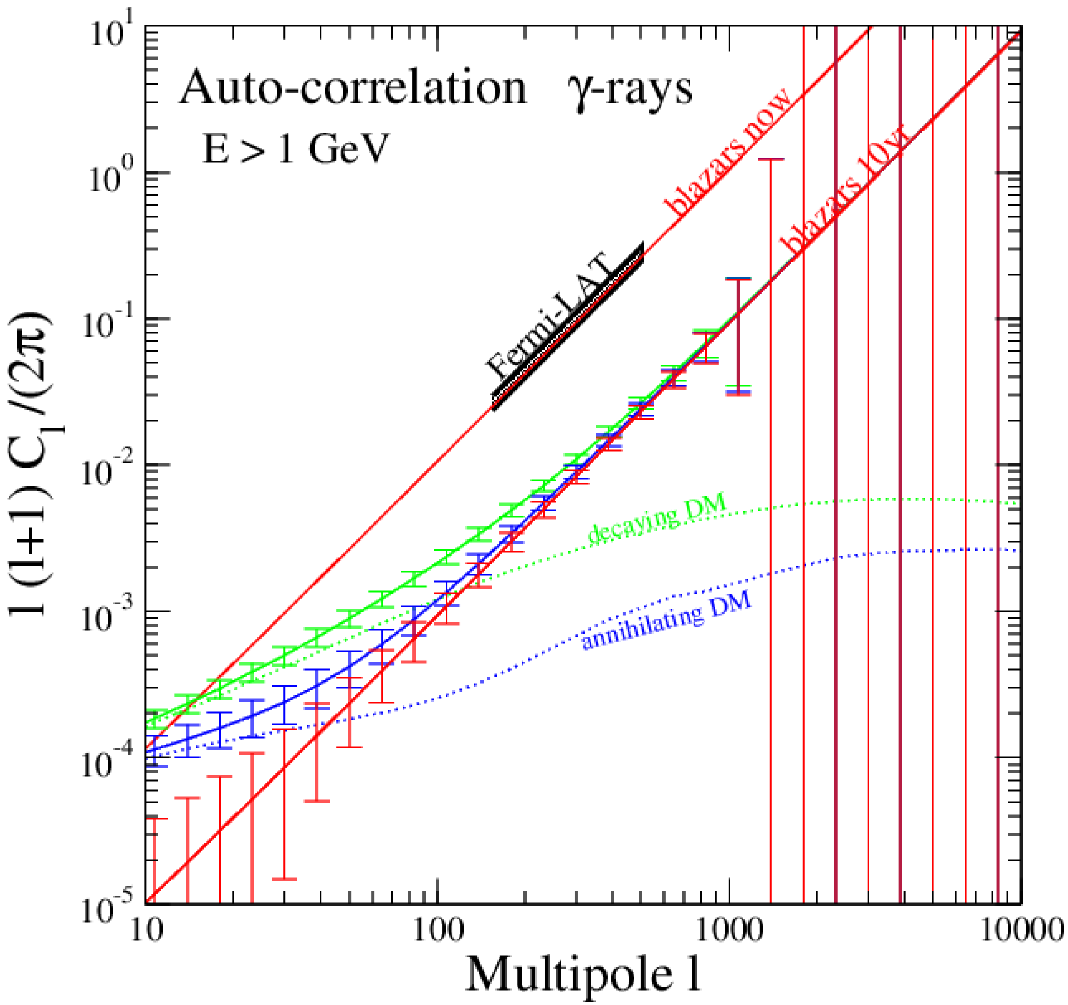
Required ingredients: Halo mass function dn/dm, Concentration of halos c(m), DM distribution in halos (NFW, Einasto, Burkert, ...) and the same for subhalos, or B(**x**,m,z)

Critical point: **extrapolation** from the resolution of numerical simulations down to m_{min}

3D power spectrum



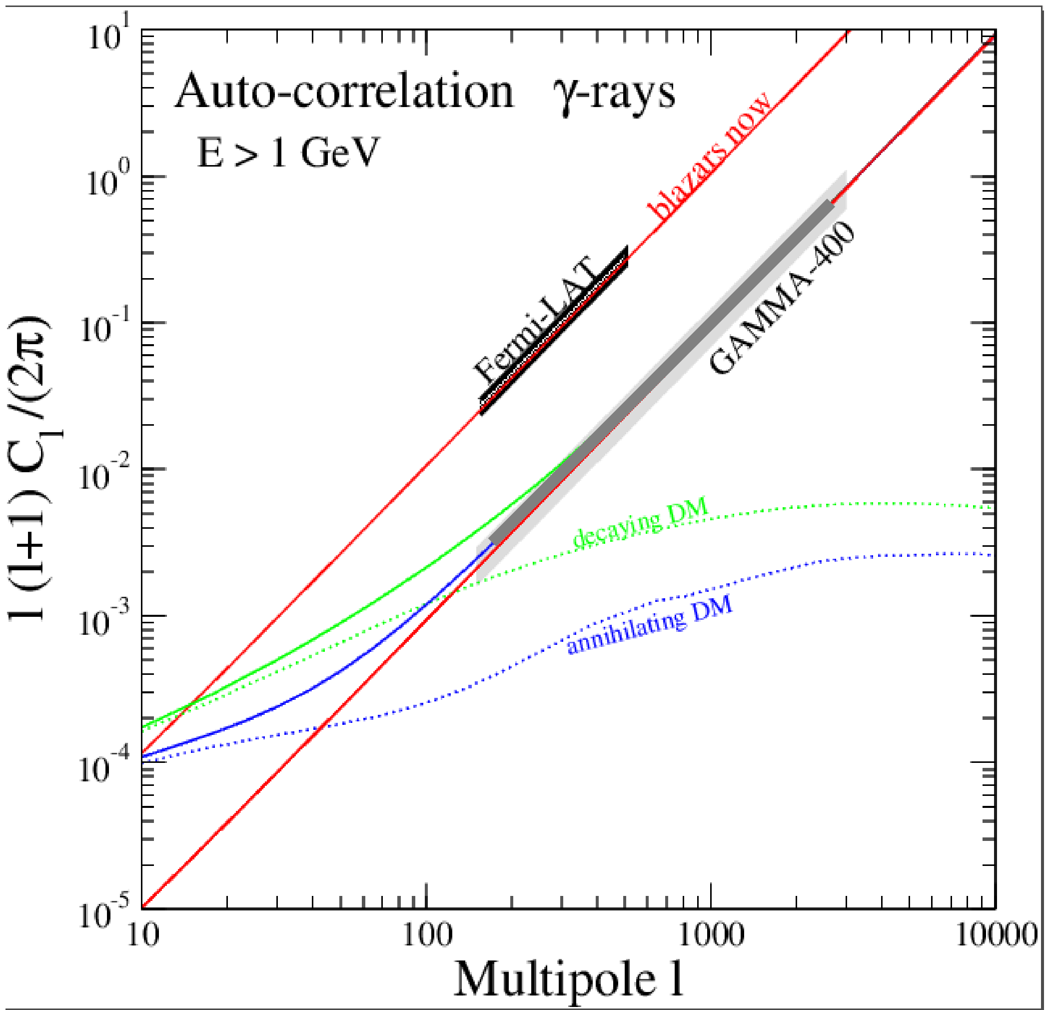
What's "wrong" with γ-rays alone?



NEAR FUTURE

Very difficult to extract a clear WIMP signature from the extragalactic gamma-ray background alone.

What's "wrong" with γ-rays alone?



NEAR FUTURE

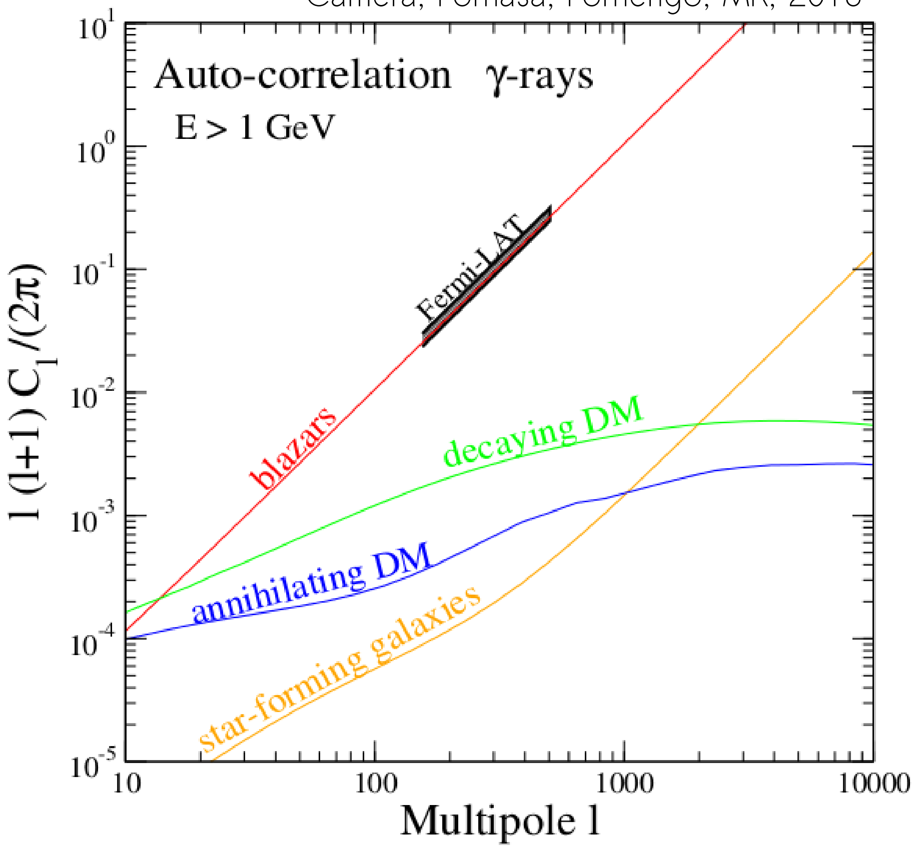
Very difficult to extract a clear WIMP signature from the extragalactic gamma-ray background alone.

Example

WIMP model with m_{DM}=100 GeV and $\langle\sigma_a v\rangle$ = 8×10^{-26} cm^3/s in $b\bar{b}$

(such that the EGB is saturated at few GeV)

Camera, Fornasa, Fornengo, MR, 2013



Camera, Fornasa, Fornengo, MR, 2013