Looking to Dark Matter through Gamma-Ray Anisotropies

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Pisa − 27.04.2017

Based on:

Camera, Fornasa, NF, Regis, *ApJ 771 (2013) L5*	gamma + cosmic shear
Camera, Fornasa, NF, Regis, *JCAP 1506 (2015) 029*	gamma + cosmic shear
Troester et al., *MNRAS* 467 (2016) 2706	gamma + cosmic shear
NF, Regis, *Front. Physics 2 (2014) 6*	general theory
NF, Regis, Perotto, Camera, *ApJ 802 (2015) L1*	gamma + CMB lensing
Regis, Xia, Cuoco, NF, Branchini, Viel, *PRL 114 (2015) 241301*	gamma + LSS
Cuoco, Xia, Regis, NF, Branchini, Viel, *ApJS 221 (2015) 29*	gamma + LSS
Zechlin, Cuoco, Donato, NF, Vittino, *ApJS 225 (2016) 18*	gamma 1pPDF
Zechlin, Cuoco, Donato, NF, Regis, *ApJL 826 (2016) L31*	gamma 1pPDF
Ando, Fornasa, NF, Regis, Zechlin, *arXiv:0701.06988*	gamma autocorrelation
Branchini, Camera, Cuoco, NF, Regis, Viel, Xia, *ApJS 228 (2017) 8*	gamma + clusters

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

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

Modified gravity?

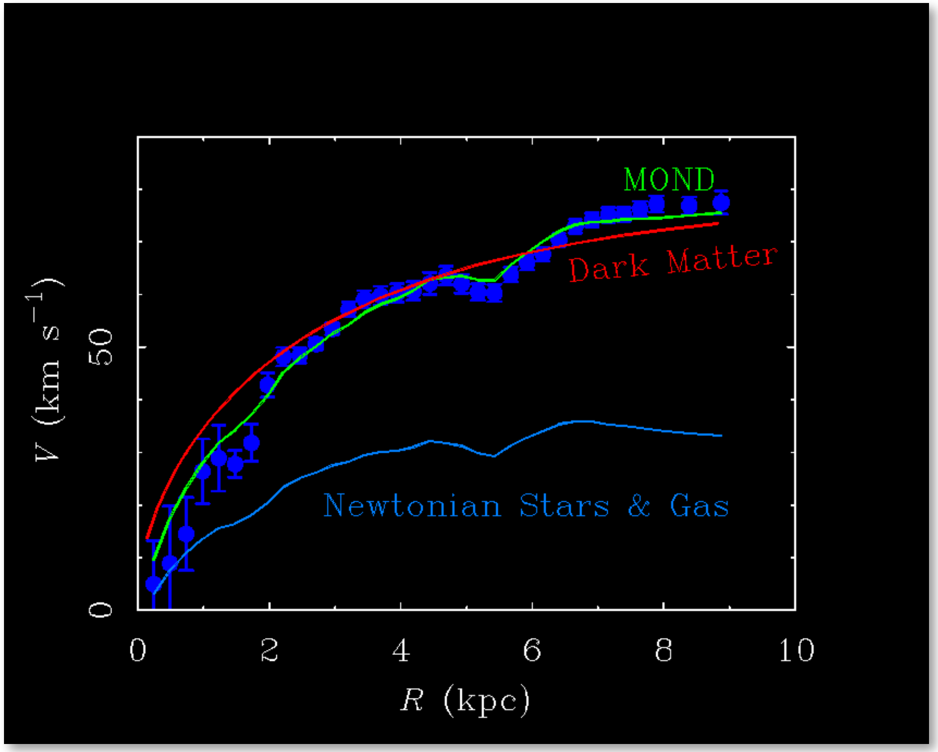
One possibility is that gravity behaves differently than GR

One example: MOND [Milgrom]

$$\vec{F} = m\vec{a}\,\mu(a/a_0)$$

$$\mu(x) = 1 \quad \text{for} \quad |x| \gg 1$$
$$\mu(x) = x \quad \text{for} \quad |x| \ll 1$$

$a_0 \approx 1.2 \times 10^{-10}\ \mathrm{ms^{-2}}$



[Bekenstein]

Non-covariant theory: can be a limit of TeVeS (or others)

What about cluster scales, lensing, structure formation?

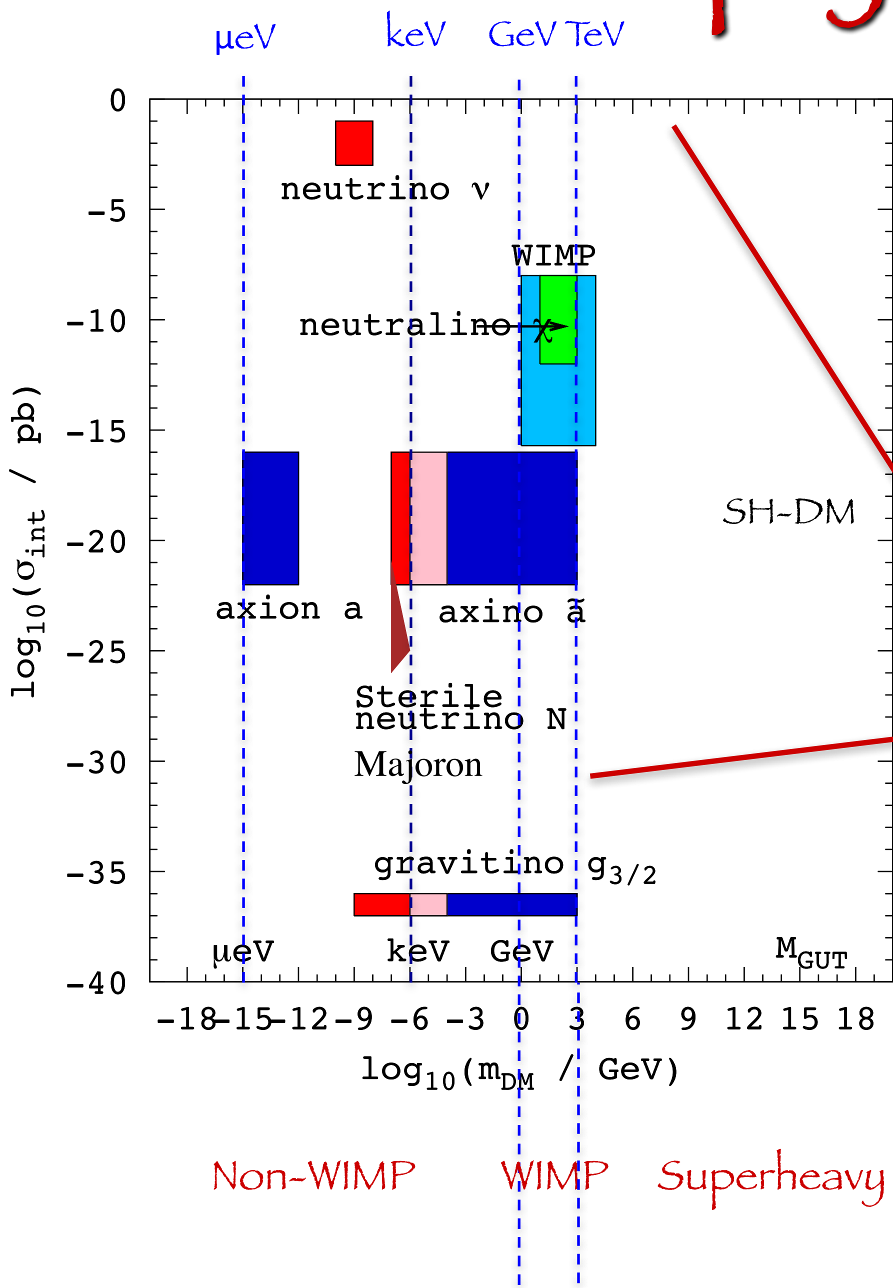
Dark Matter as a particle?

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

A natural solution is that DM is a new particle, relic from the early Universe

Particle physics scales



"Strong (-ish)"

Self-interacting

Technicolor DM

...

"EM (-ish)"

Millicharged DM

Electric/magnetic dipole

...

Weak

WIMP

Gravitational

Relic from the early Universe

- Thermal
- Non thermal

Dynamically: non relativistic (cold) collisionless

Dark Matter as a particle

DM evidence purely gravitational

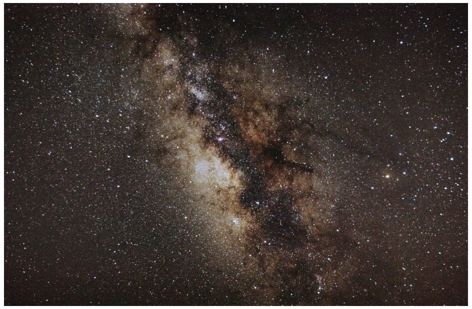
- Galaxy clusters dynamics
- Rotational curves of spiral galaxies
- Gravitational lensing
- Hydrodynamical equilibrium of hot gas in galaxy clusters
- Energy budget of the Universe
- The same theory of structure formation

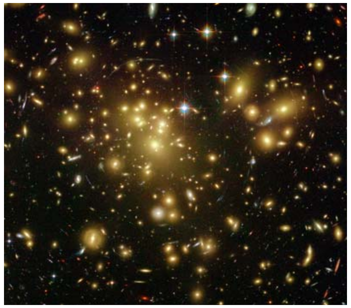
If DM is a new particle, a non-gravitational signal (due to it's particle physics nature) is expected

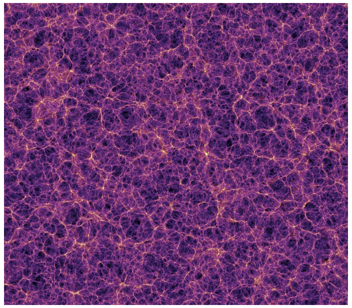
Where to search for a signal …

We can exploit every structure where DM is present …

- Our Galaxy
  - Smooth component
  - Subhalos
- Satellite galaxies (dwarfs)
- Galaxy clusters
  - Smooth component
  - Individual galaxies
  - Galaxies subhalos
- "Cosmic web"







... and what

...and we have a large number of messengers at disposal

- Our Galaxy
  - Smooth component
  - Subhalos
- Satellite galaxies (dwarfs)
- Galaxy clusters
  - Smooth component
  - Individual galaxies
  - Galaxies subhalos
- "Cosmic web"

A

Charged CR ($e^{\pm}$, antip, antiD) [G]

Neutrinos [G,E]

Photons [G,E]

- 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

B

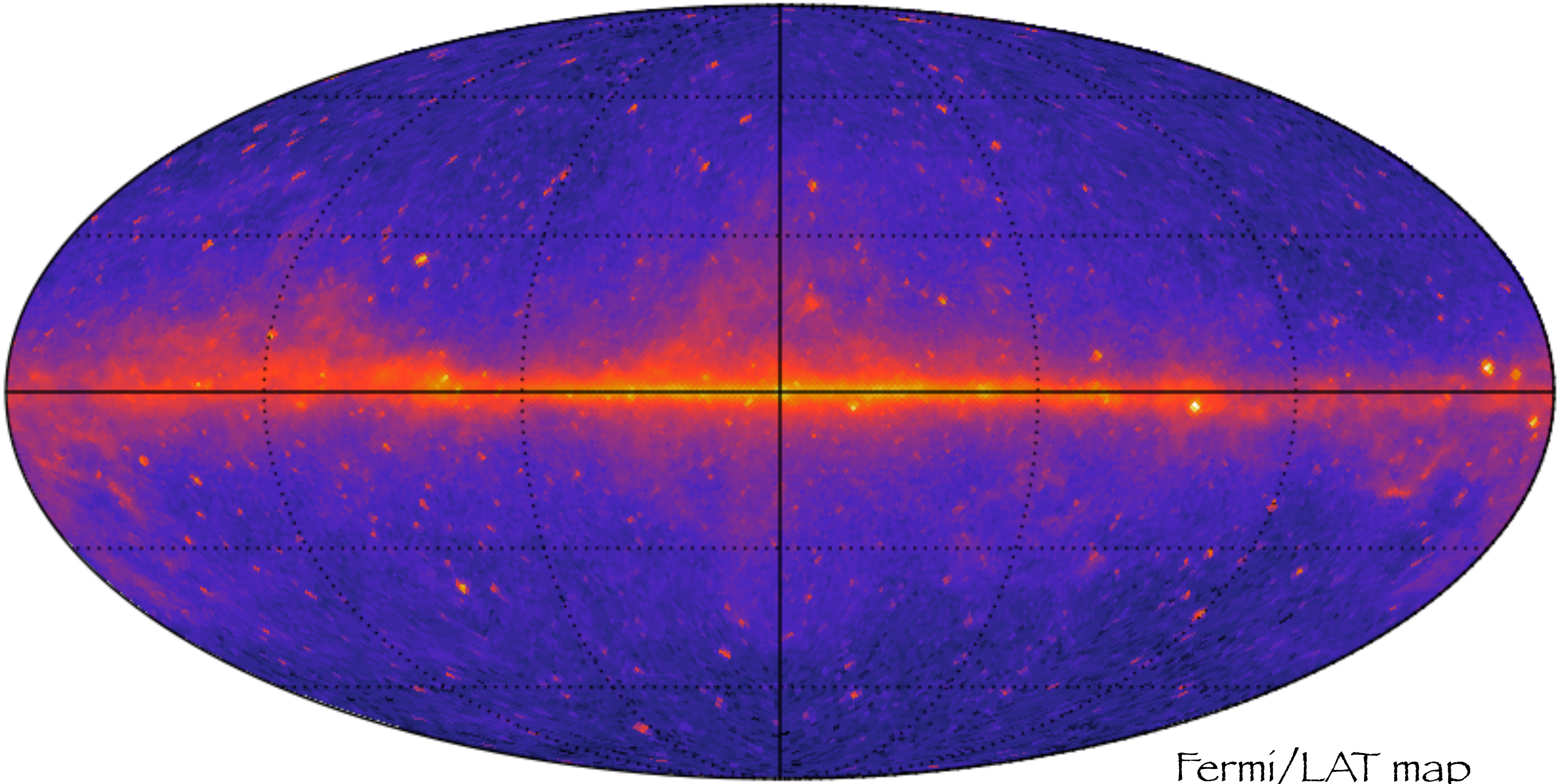
Direct detection [L]

A: $\mathrm{DM} + \mathrm{DM} \longrightarrow (...) \longrightarrow \mathrm{signal}$

B: $\mathrm{DM} + \mathcal{N} \longrightarrow \mathrm{DM} + \mathcal{N}$

Local [L] - Galactic [G] - Extragalactic [E]

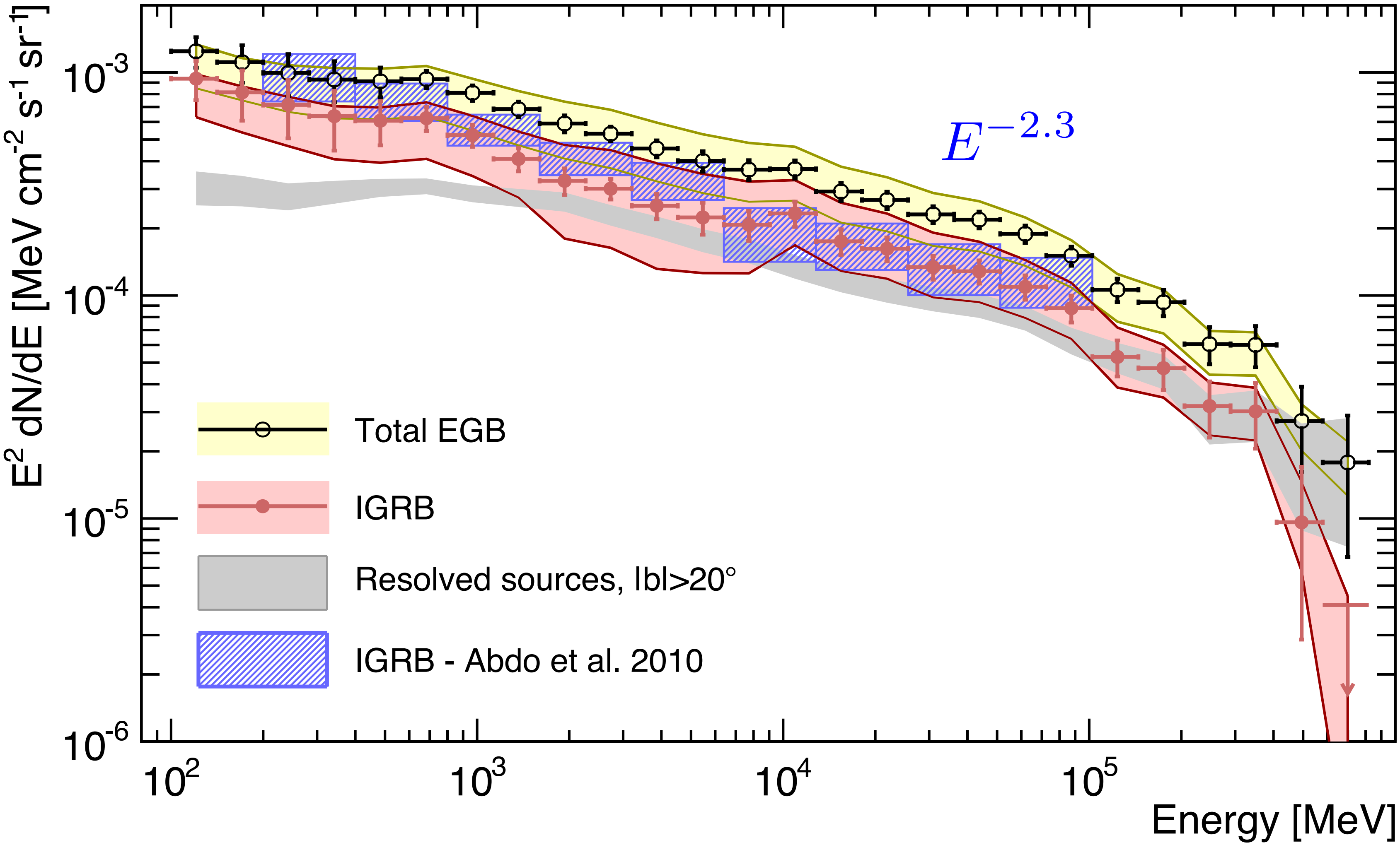
Gamma ray sky



Fermi/LAT map

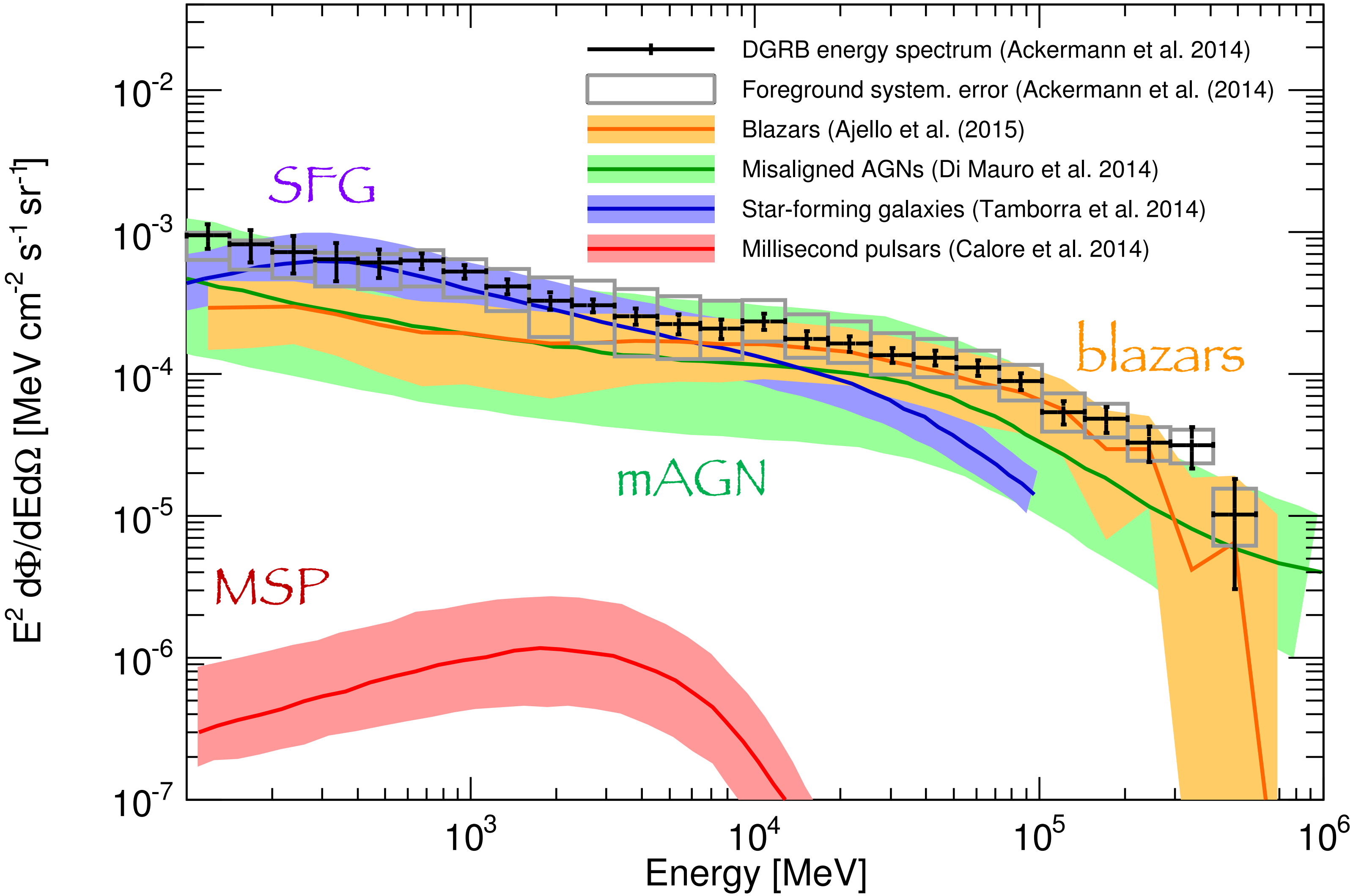
Galactic foreground emission
Resolved sources
Diffuse Gamma Rays Backgound (DGRB)

DGRB Intensity



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

DGRB Intensity

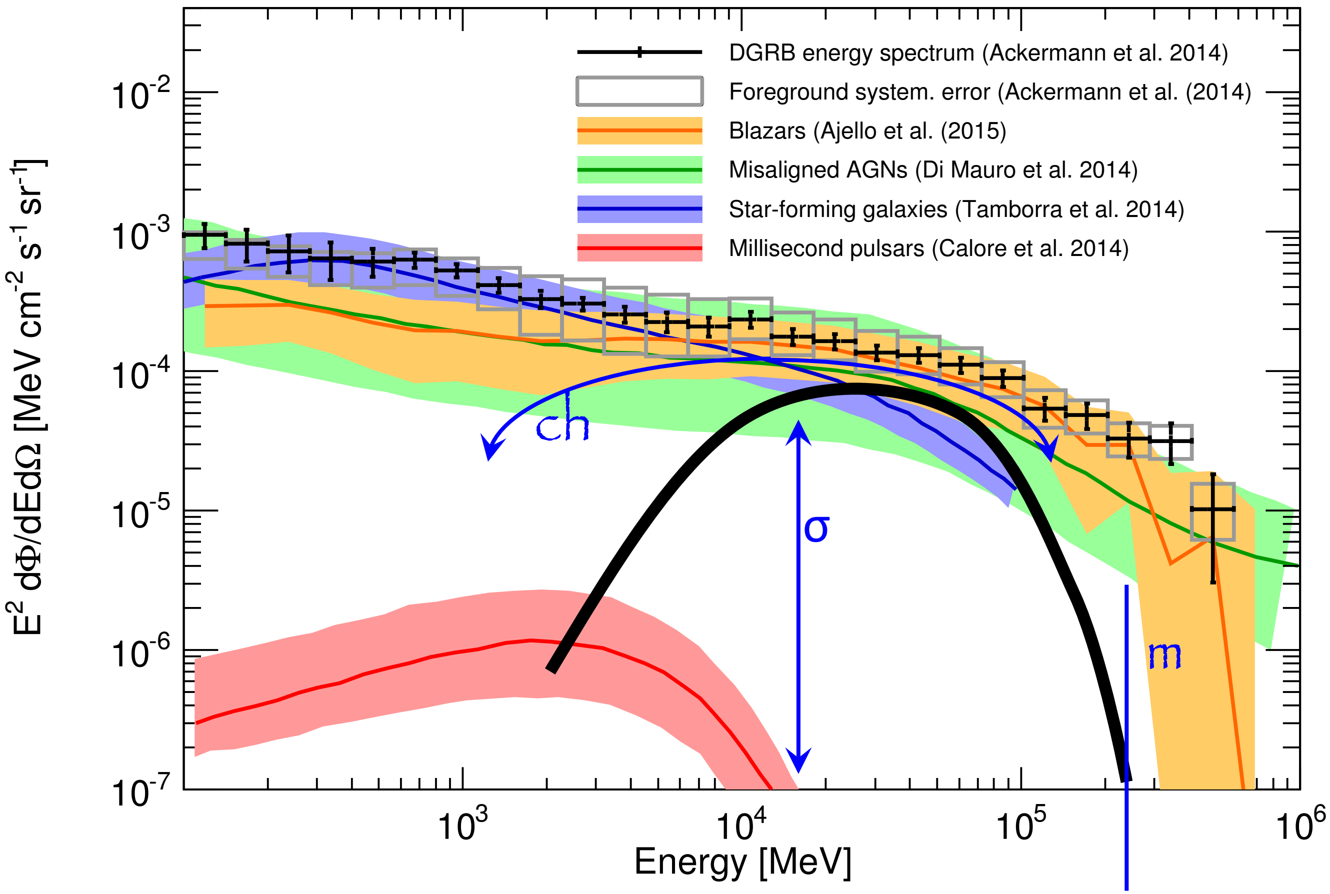


Fornasa, Sanchez-Conde, Phys. Rep. 598 (2015) 1

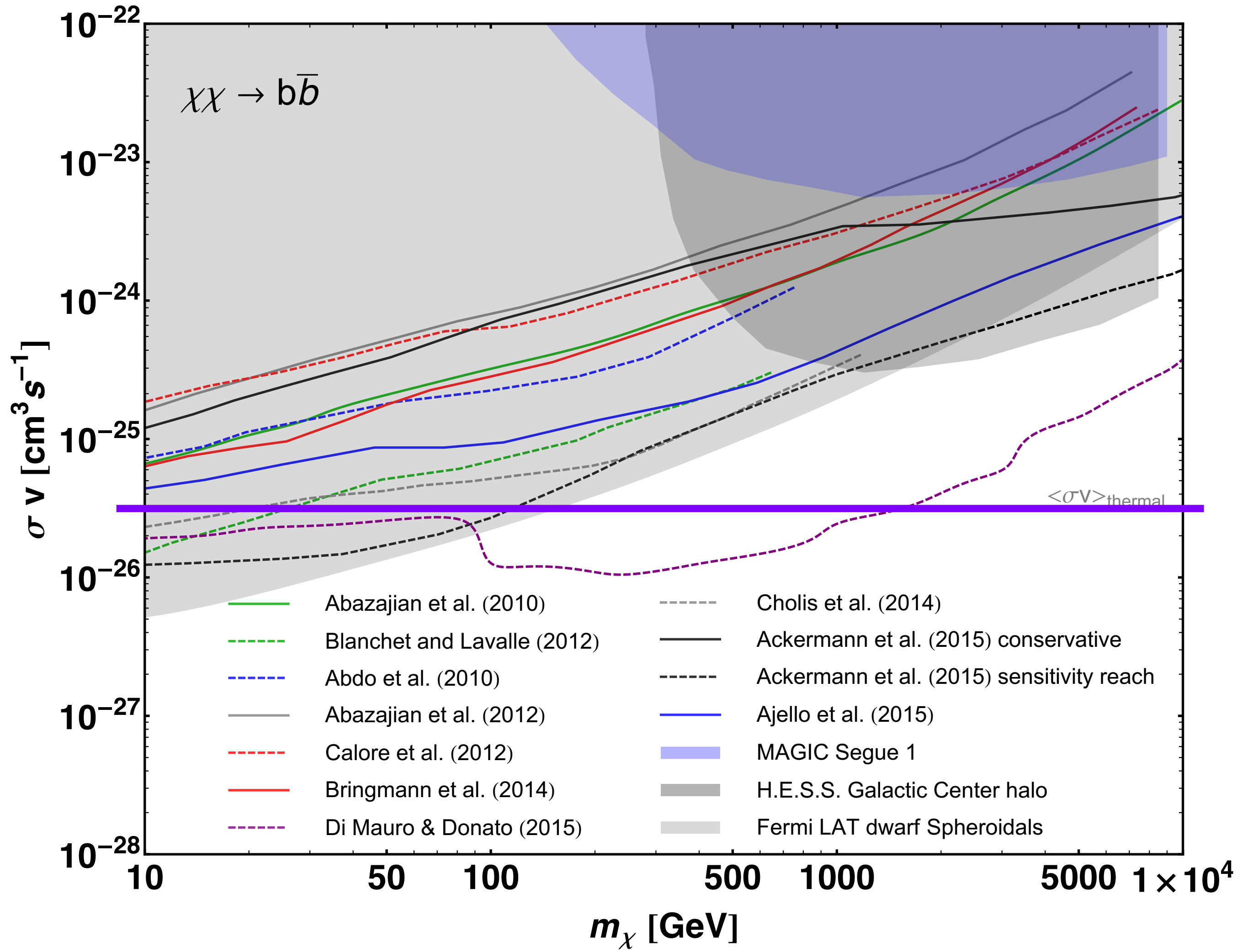
DGRB and Dark Matter

The Good: Spectral behaviour different from astro sources: (σ, m, ch)

The Bad: Can be quite subdominant in intensity

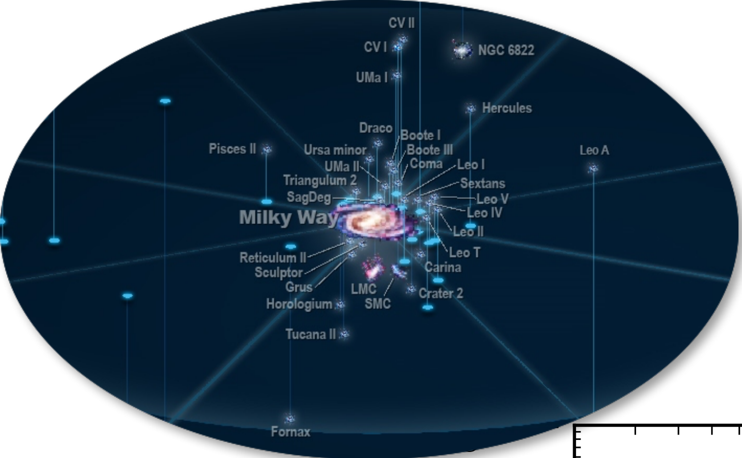


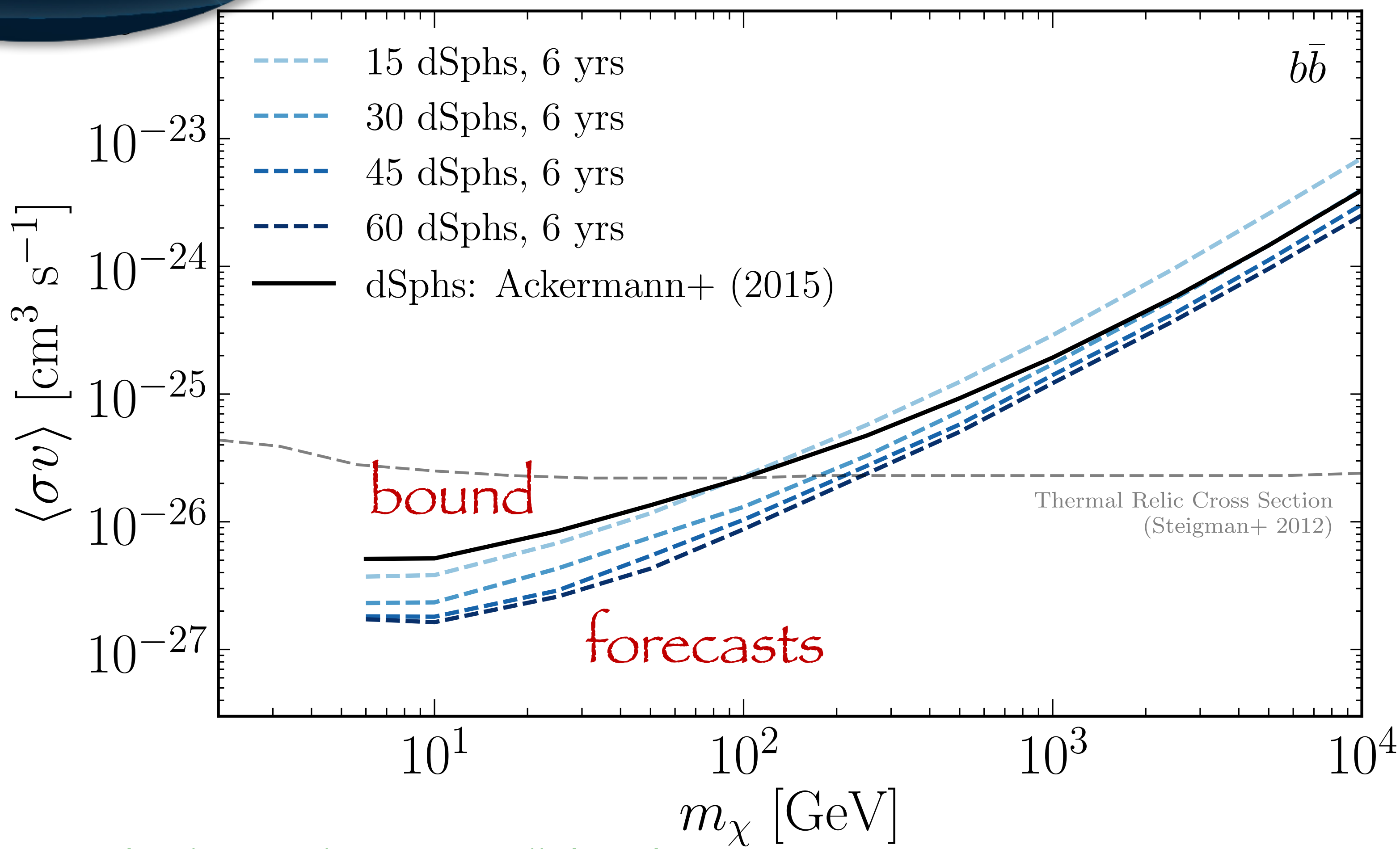
DGRB intensity bounds on DM



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

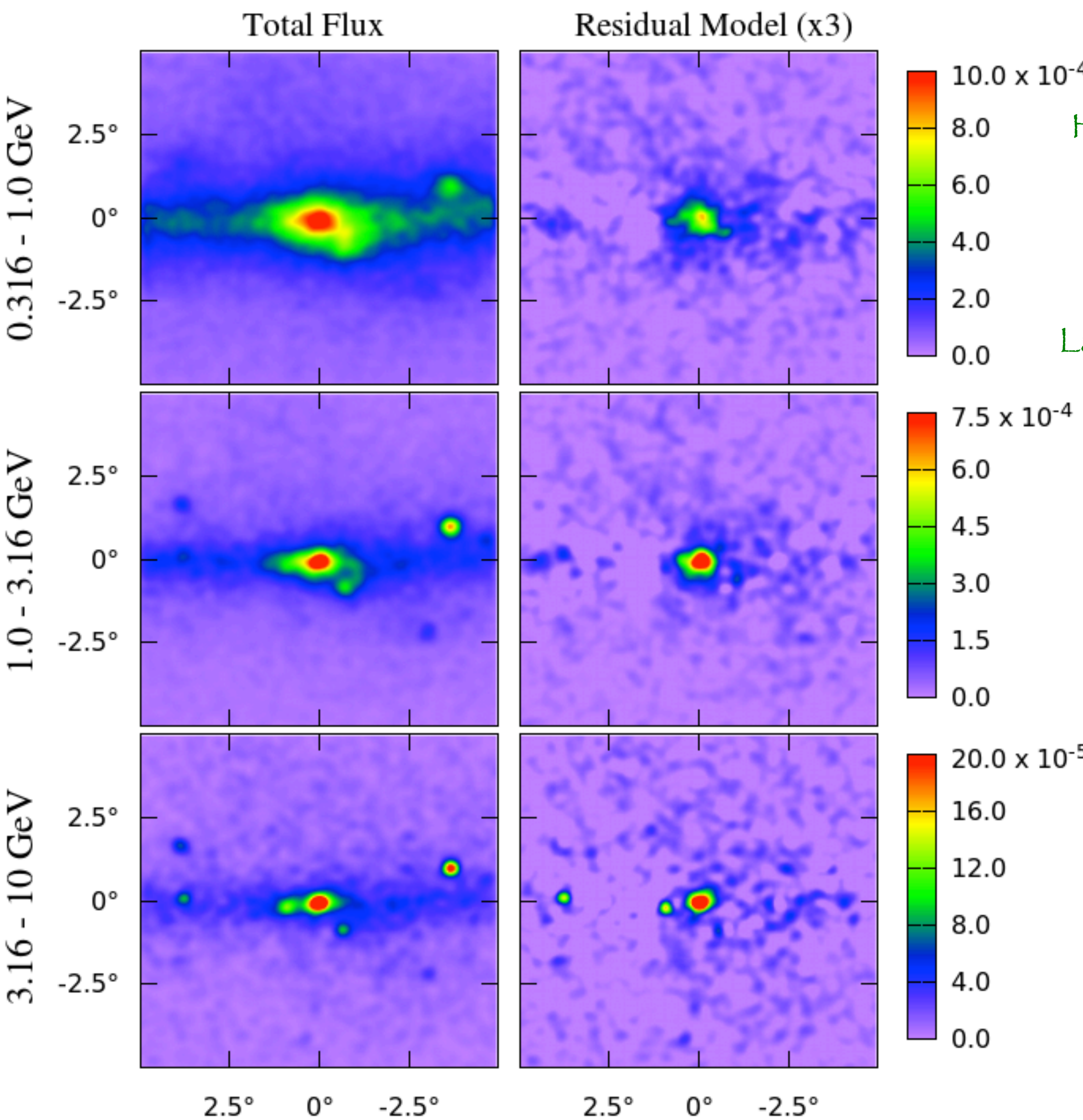
Dwarf galaxies





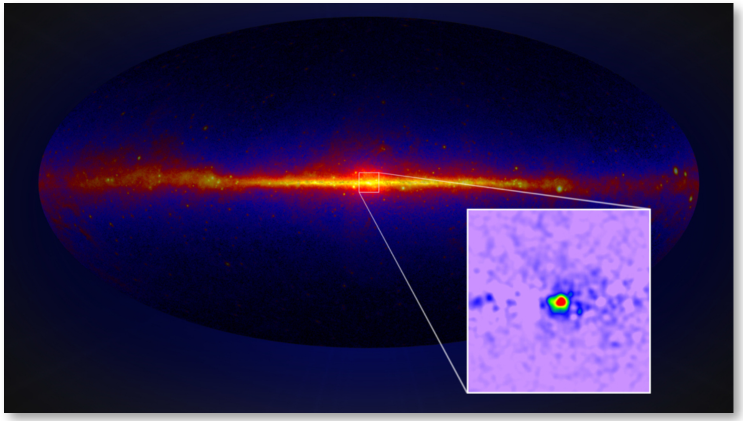
Charles et al (Fermi Collab) Phys Rep 636 (2016) 1

Galactic center: an “excess” ?

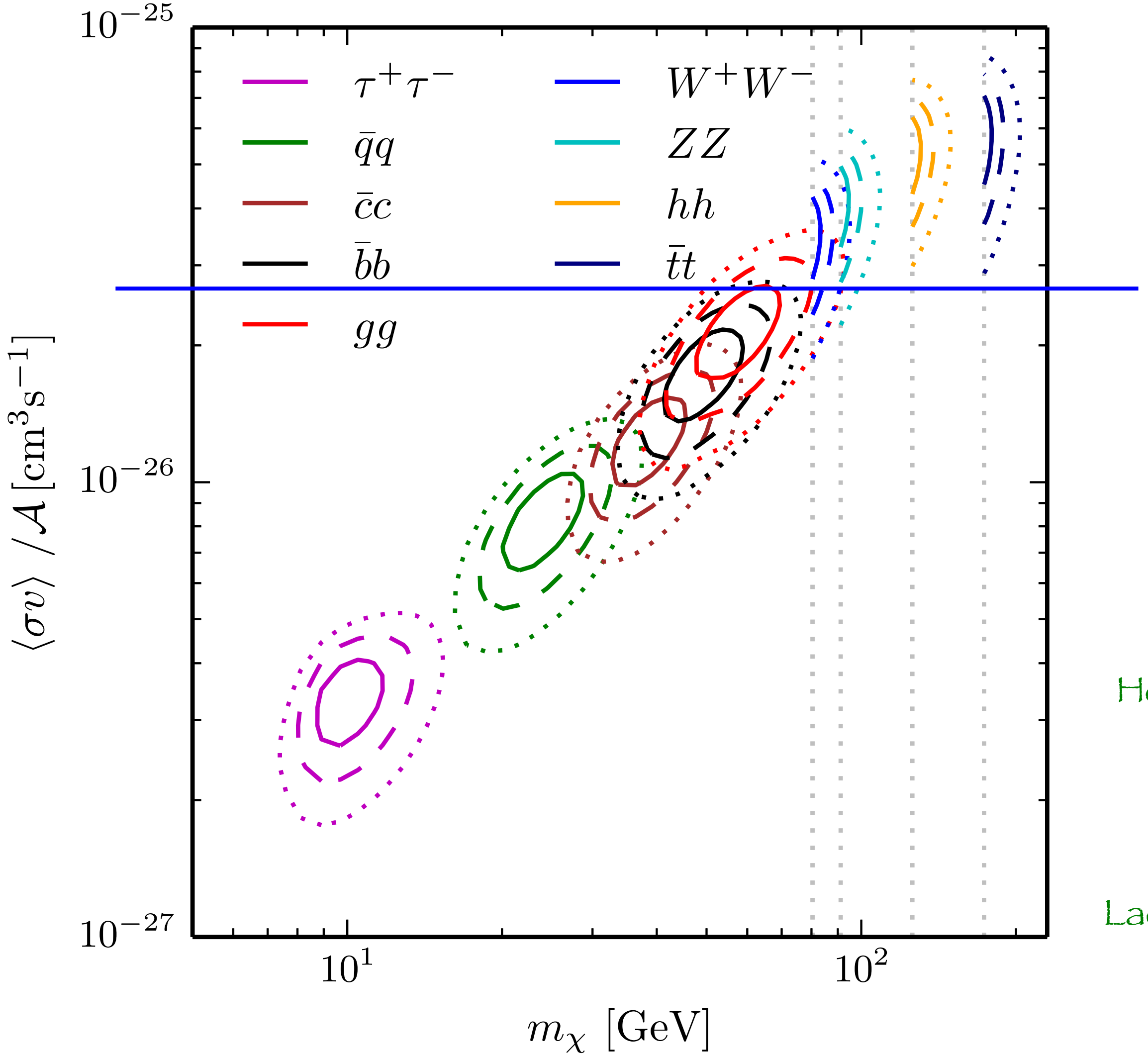


Daylan et al, Phys Dark Univ 12 (2016) 1

Hooper, Goodenough, PLB (2011) 697 (2011)
Hooper, Linden, PRD 84 (2011) 123005
Boyarsky et al., PLB (2011) 705
Daylan et al., Phy Dark Univ 12 (2016) 1
Abazajian et al, PRD 90 (2014) 023526
Lacroix, Boehm, Silk, PRD 90 (2014) 043508



DM interpretation



Calore et al, PRD 91 (2015) 063003

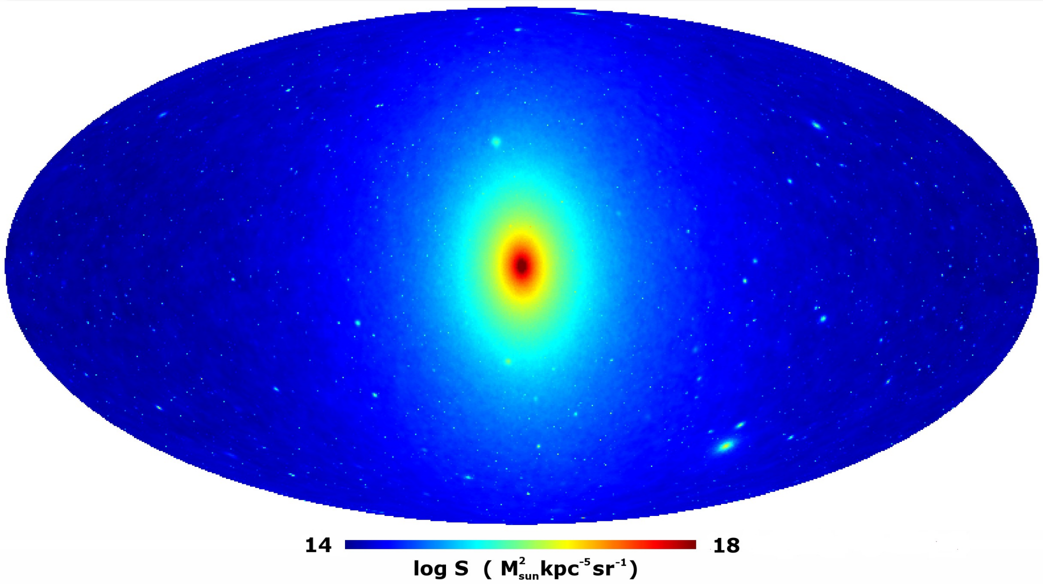
Hooper, Goodenough, PLB (2011) 697 (2011)
Hooper, Linden, PRD 84 (2011) 123005
Boyarsky et al., PLB (2011) 705
Daylan et al., Phy Dark Univ 12 (2016) 1
Abazajian et al, PRD 90 (2014) 023526
Lacroix, Boehm, Silk, PRD 90 (2014) 043508

Indirect dark matter signals

- Indirect detection signals are intrinsically anisotropic
  (being produced by DM structures, present at any scale)

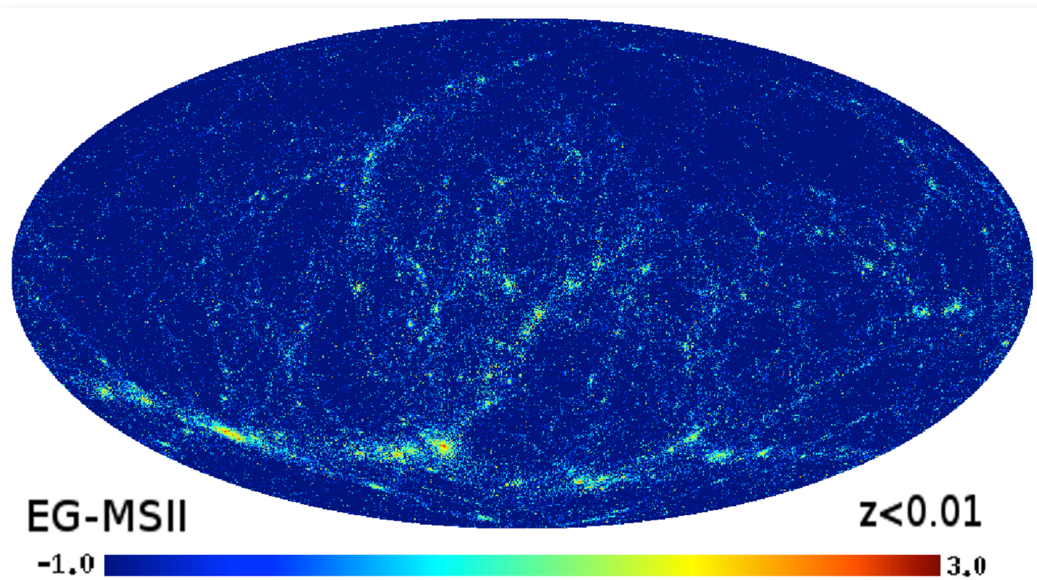
- EM signals (and neutrinos) more directly trace the underlying DM distribution: they need to exhibit some level of anisotropy
  - "Bright" DM objects: would appear as *resolved* sources
    - e.g: gamma or radio halo around clusters, dwarf galaxies or even subhalos
  - Faint DM objects: would be *unresolved* (i.e. below detector sensitivity)
    - Diffuse flux: at first level isotropic
      at a deeper level anisotropic

Gamma rays and Dark Matter



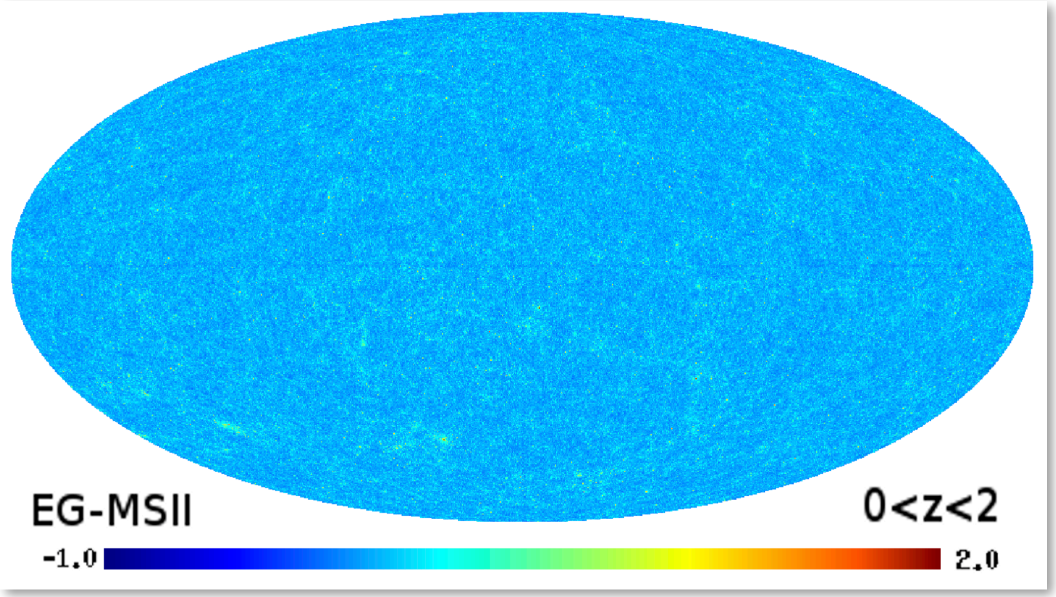
Galactic emission

(simulated maps)

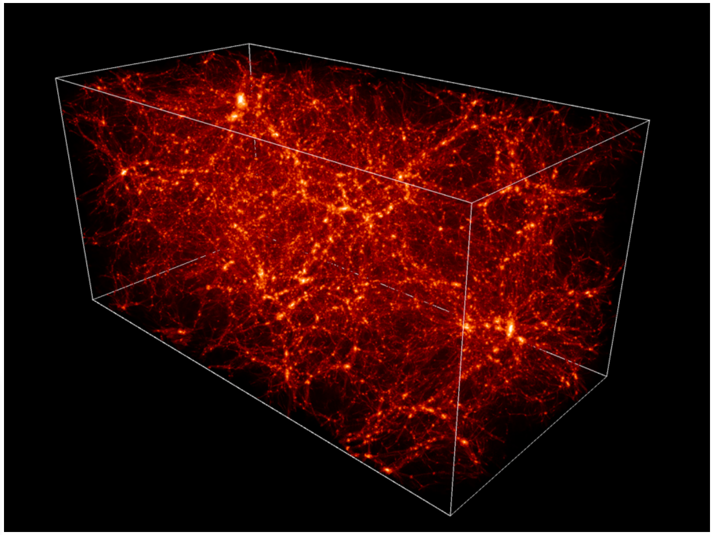


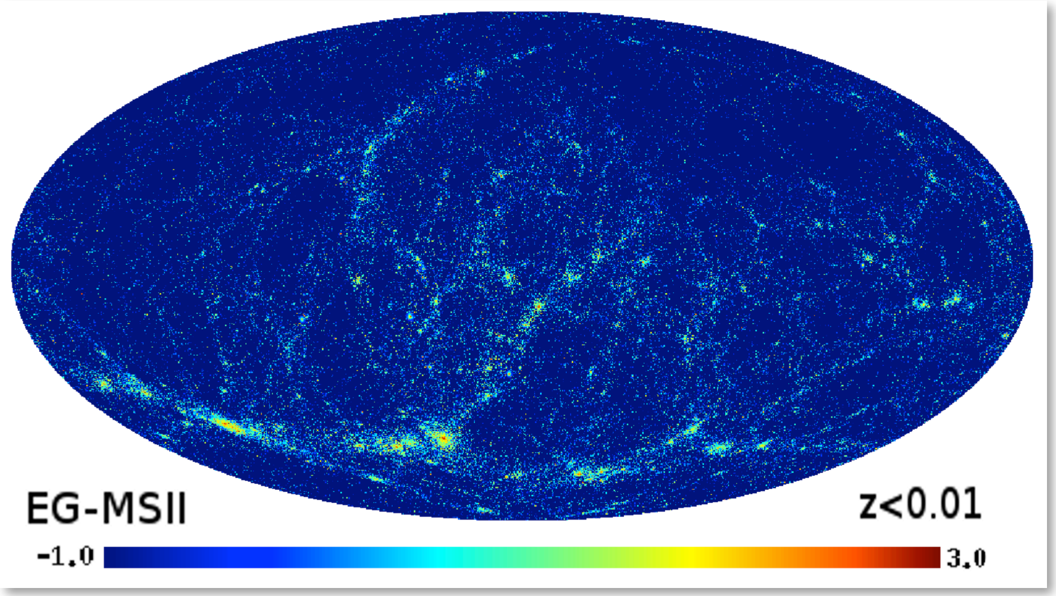
Extra galactic emission

Gamma rays and Dark Matter



Extra galactic emission
Higher redshift





Extra galactic emission
Lower redshift

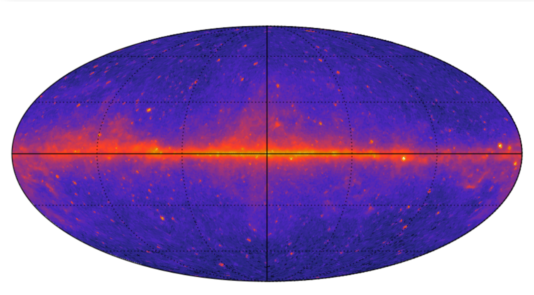
Anisotropic emission

Even though sources are too dim to be individually resolved, they can affect the

statistics of photons

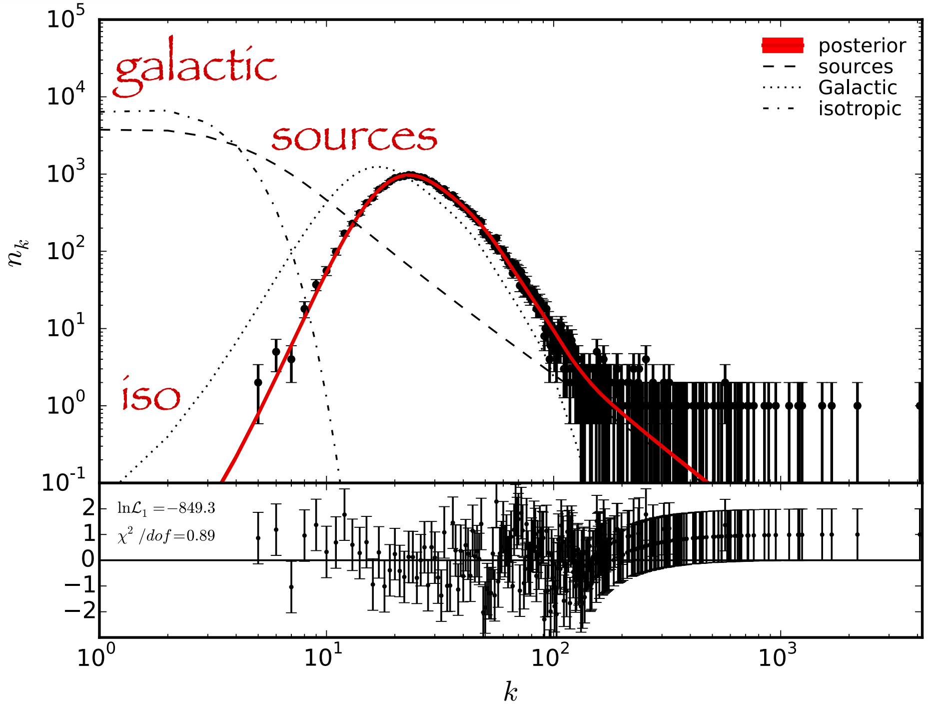
across the sky

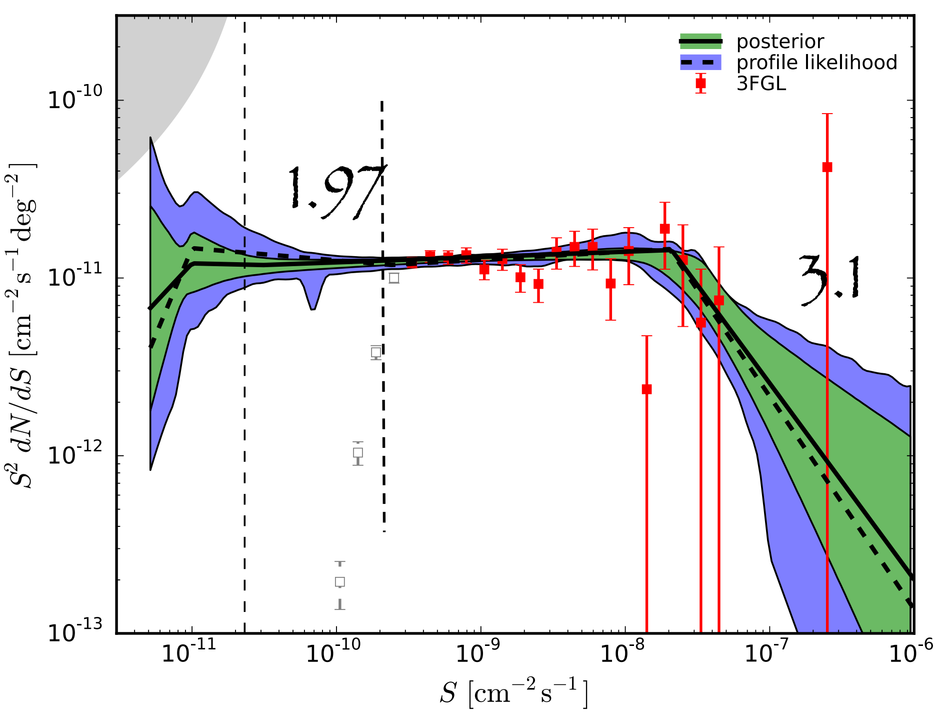
Photon statistics



Photon pixel counts (1 point PDF)

Source count number dN/dS below detection threshold





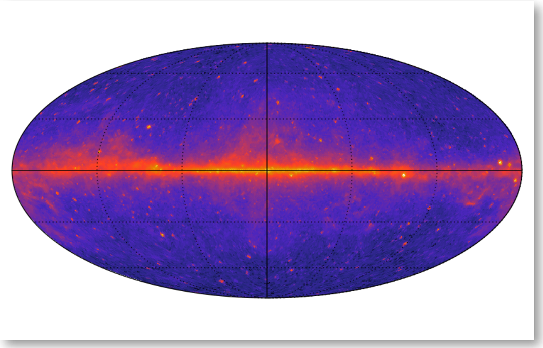
Zechlin, Cuoco, Donato, NF, Vittino, ApJS 225 (2015) 039

Zechlin, Cuoco, Donato, NF, Regis, ApJL 826 (2016) 831

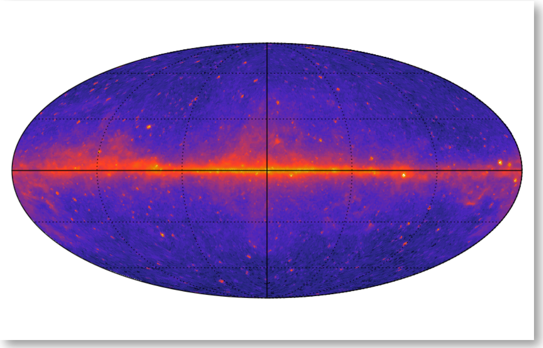
See also: Malyshev, Hogg, Astrophys. J. 738 (2011) 181

Lisanti et al, 1606.0401

Photon statistics



Photon pixel counts (1 point PDF)



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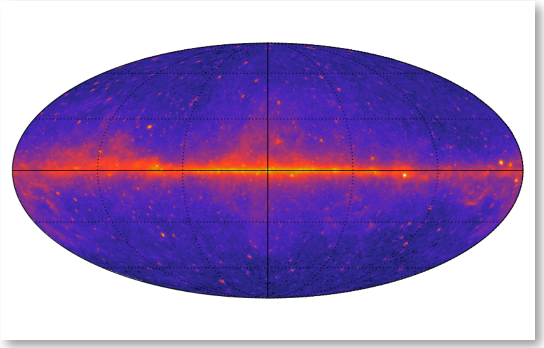
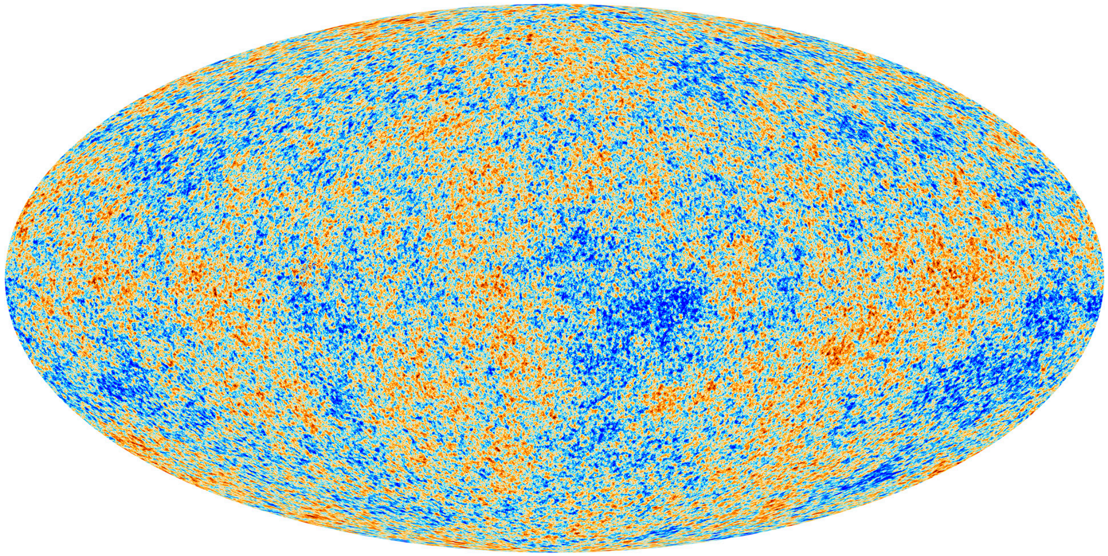
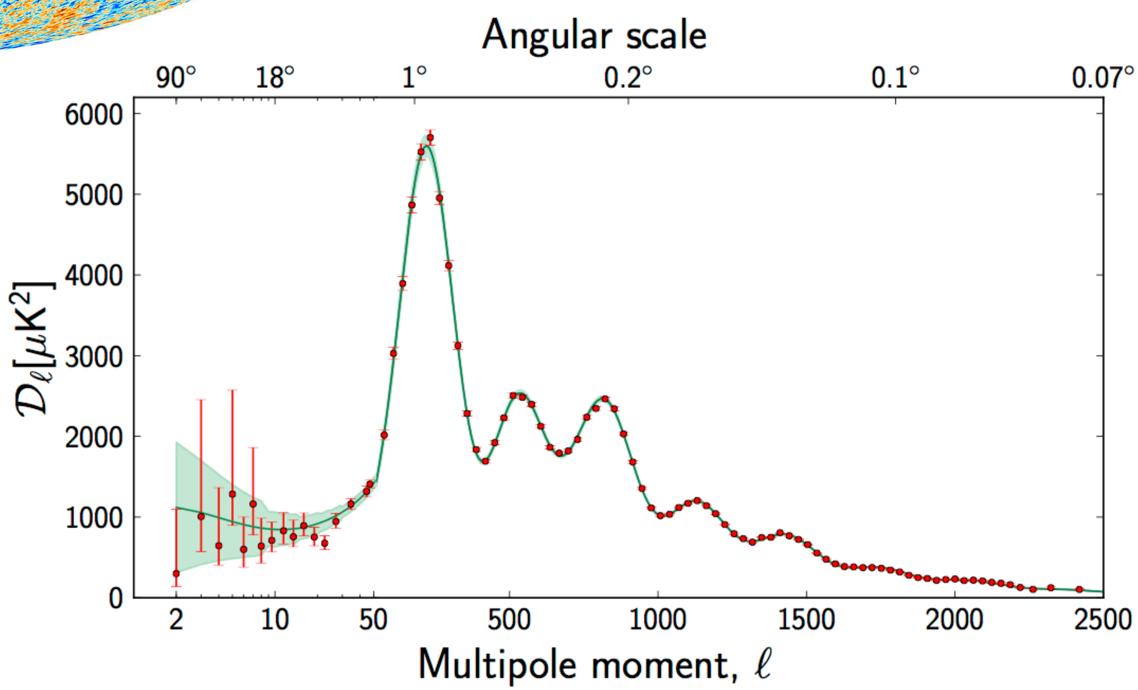


2 point correlator
angular power spectrum

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

Like for CMB temperature anisotropies





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 +
distribution of sources

$$I_g(\vec{n}) \longrightarrow a^g_{lm} \longrightarrow C^{gg}_l = \frac{1}{2l+1}\sum_{l=-m}^{m} |a^g_{lm}|^2$$

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

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

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

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

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

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

Window functions for annihilating DM

Clumping factor : a measure of the clustering

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

DM photon "emissivity"

Halo mass function *Halo profile*

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

Subhalo boost

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

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

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)

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

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

$\hat{f}_g$: Fourier tranform

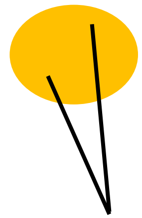
1-halo term $$P_{ij}^{1h}(k) = \int dm \, \frac{dn}{dm} \hat{f}_i^*(k|m) \, \hat{f}_j(k|m)$$

Linear matter PS

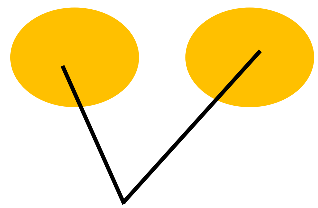
2-halo term $$P_{ij}^{2h}(k) = \left[\int dm_1 \, \frac{dn}{dm_1} b_i(m_1) \hat{f}_i^*(k|m_1) \right] \left[\int dm_2 \, \frac{dn}{dm_2} b_j(m_2) \hat{f}_j(k|m_2) \right] P^{\rm lin}(k)$$

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:

M_{min}

subhalo boost

Auto Correlation

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

window function

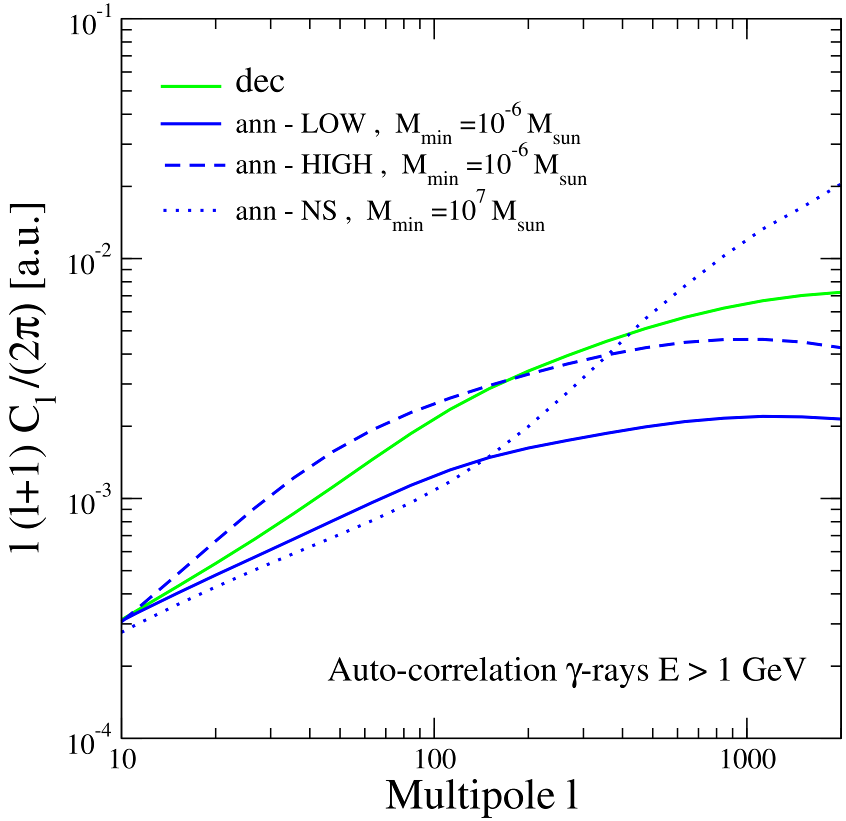
power spectrum

Observationally:

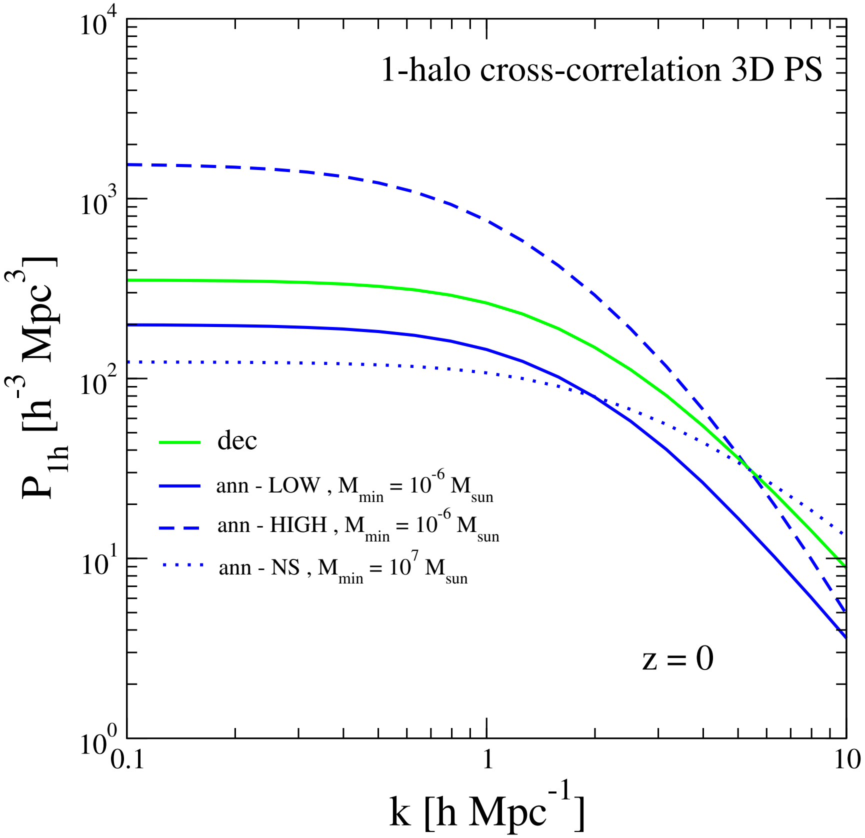
Energy dependence is available

Redshift dependence is not available

Auto Correlation



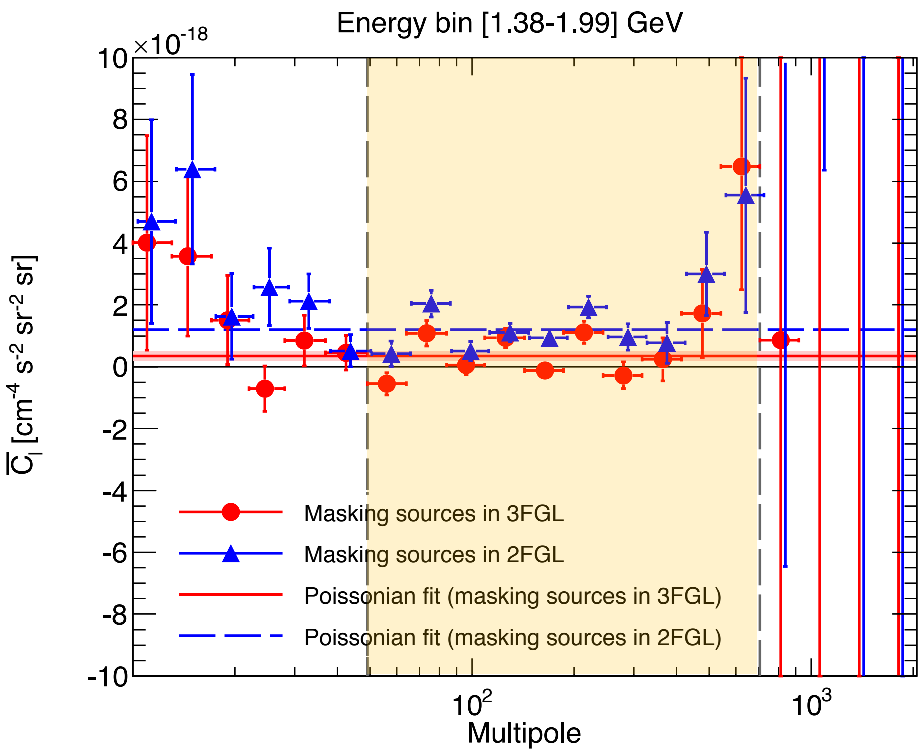
Angular power spectrum

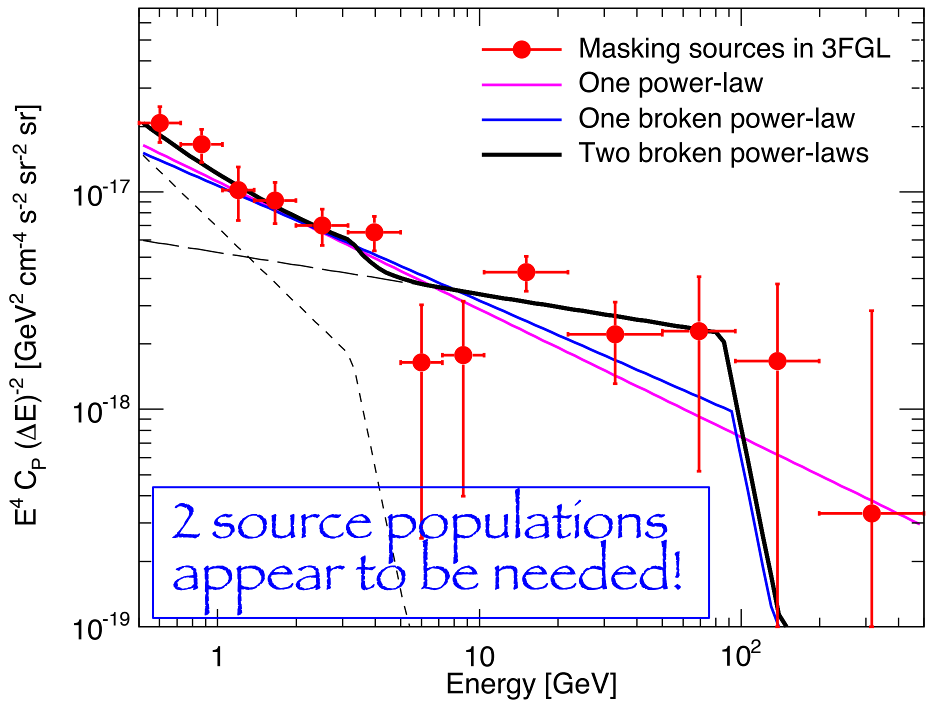


3D power spectrum

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

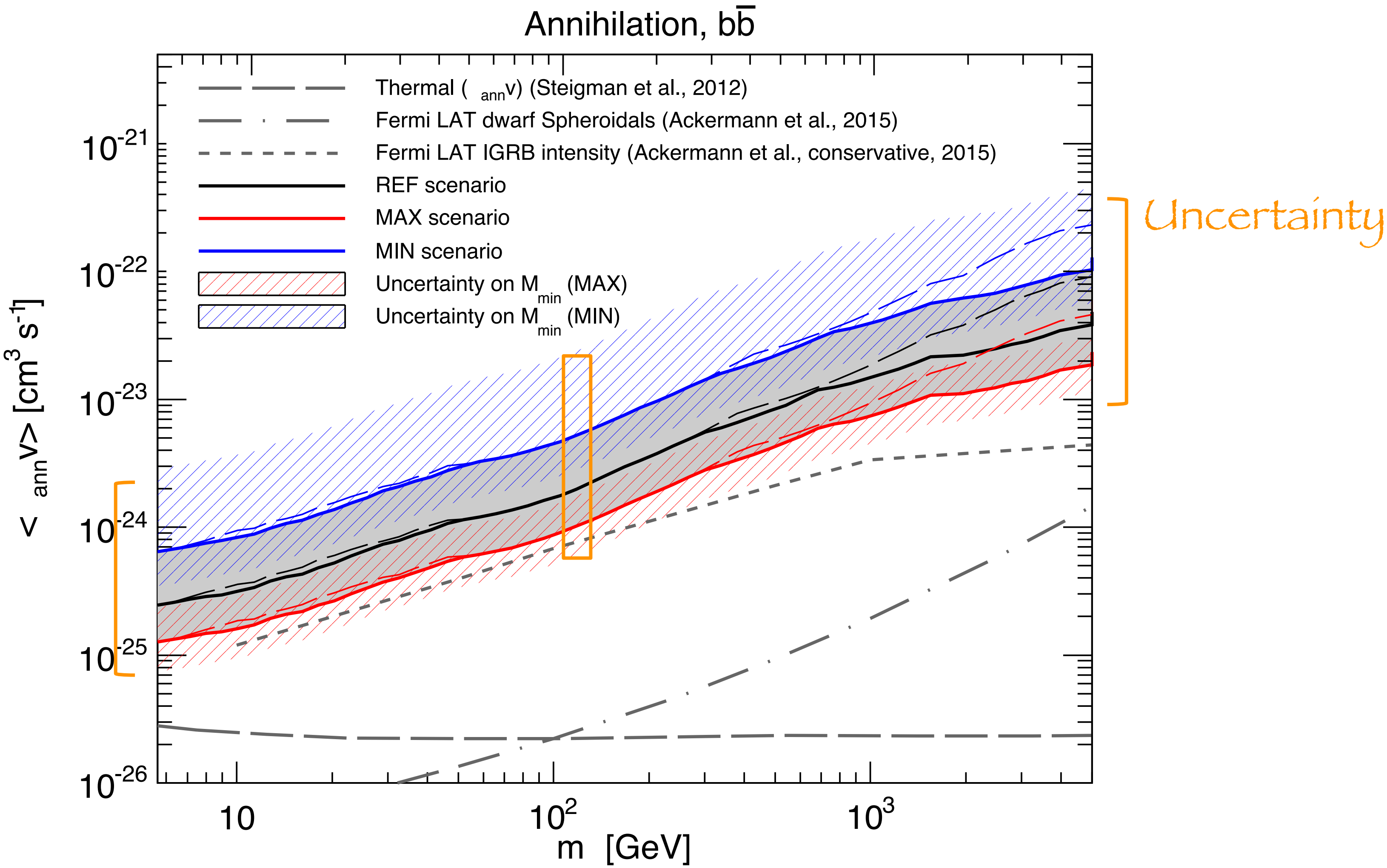
Gamma rays auto-correlation





Fornasa, Cuoco et al, PRD 94 (2016) 123005
Ando, Fornasa, NF, Regis, Zechlin, 1701.06988 (interpretation)
See also: Ackerman et al (Fermi Collab) PRD 85 (2012) 083007 (first detection)

Bounds from Auto Correlation



Fornasa, Cuoco et al, 1608.07289

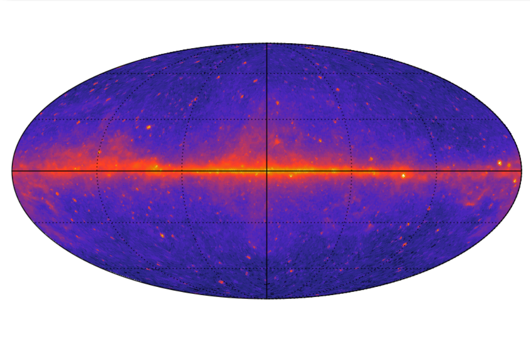
Gamma-ray auto-correlation

Features of the signal point toward interpretation in terms of blazars

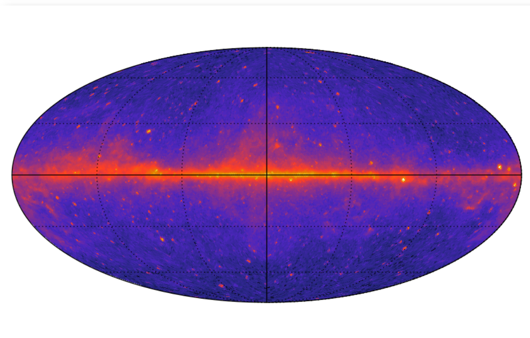
DM likely plays a subdominant role (as for total intensity)

Difficult to extract a clear DM signature from the EGB alone, while relevant to constrain the level of astro sources

Photon statistics



Photon pixel counts (1 point PDF)



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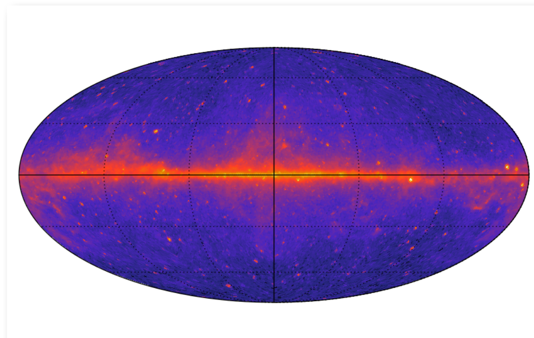
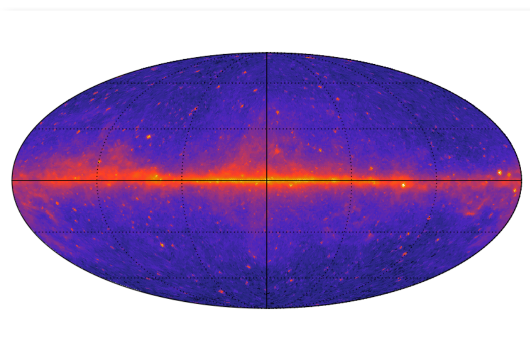


2 point correlator
angular power spectrum



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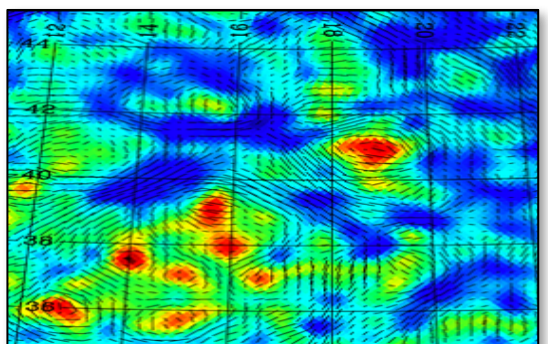
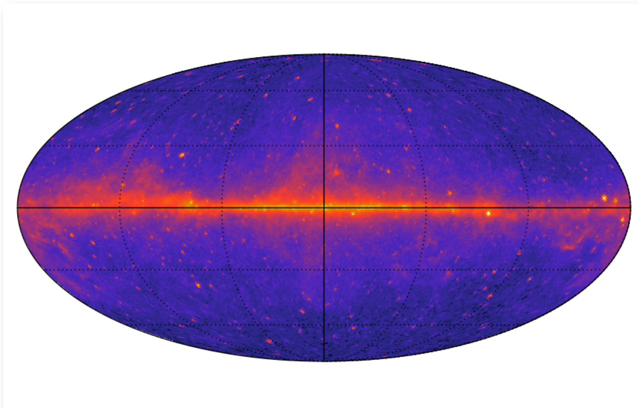


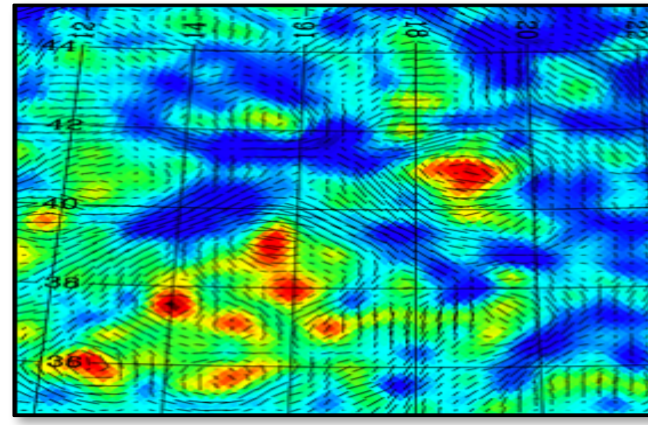
2 point correlator
angular power spectrum

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

Cross Correlations



×



Cross-correlation of EM signal with gravitational tracer of DM

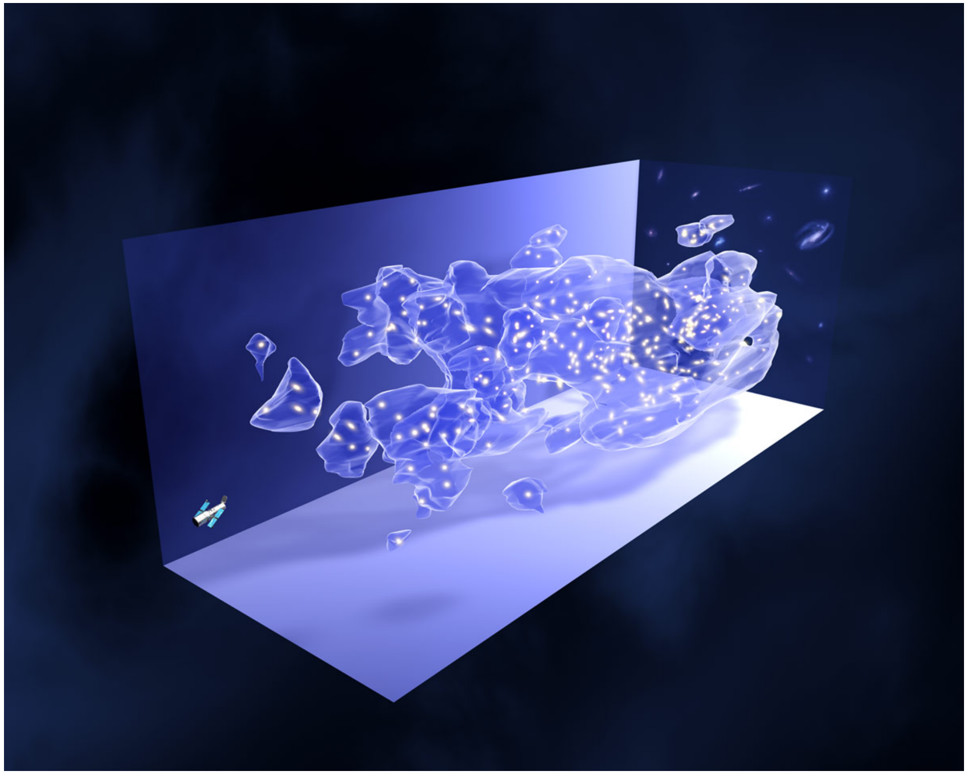
It exploits two distinctive features of particle DM:

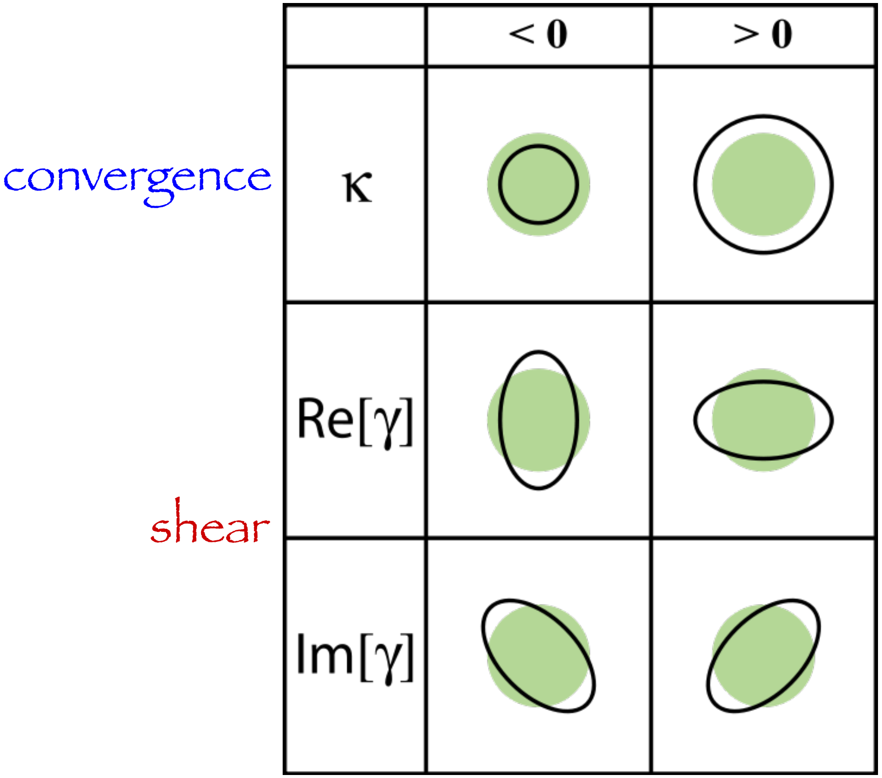
- An electromagnetic signal, manifestation of the particle nature of DM
- A gravitational probe of the existence of DM

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

Weak gravitational lensing

- Weak lensing: small distortions of images of distant galaxies, produced by the distribution of matter located between background galaxies and the observer
- Powerful probe of dark matter distribution in the Universe

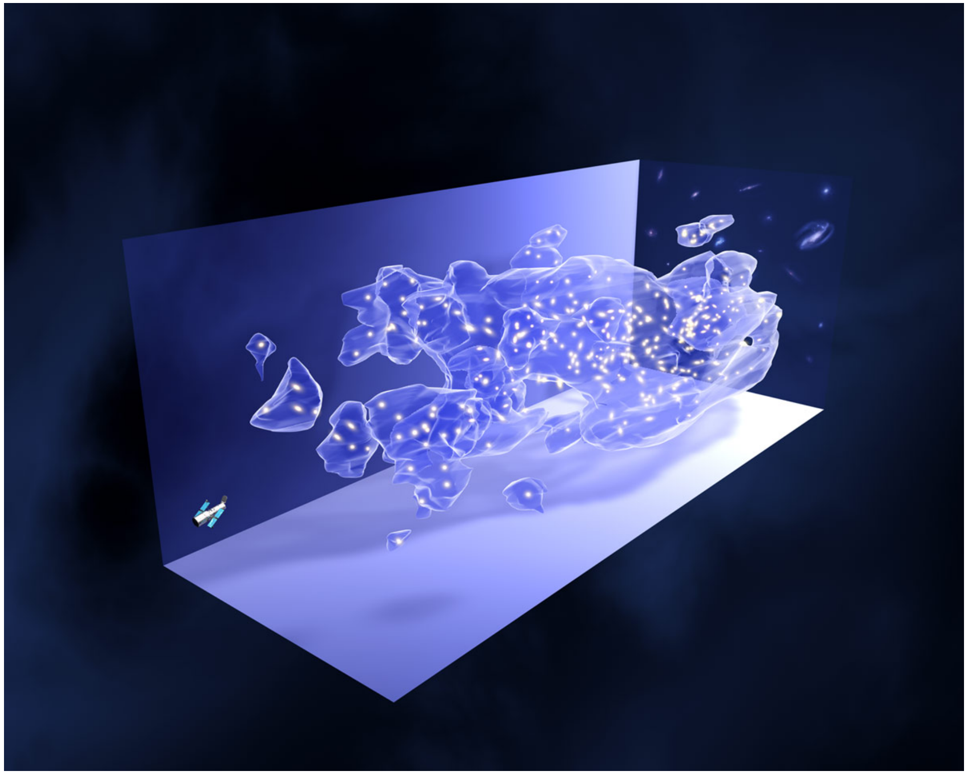




Cosmic structures and gamma-rays

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

- From 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)

Cross Correlations

- Lensing observables
  - Cosmic shear: directly traces the whole DM distribution
  - CMB lensing: traces DM imprints on CMB anisotropies
- Large scale structure
  - Galaxy catalogs: trace DM by tracing light

Furhter 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 (gravitational tracers 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

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

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

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

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

Cross angular power spectrum

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

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

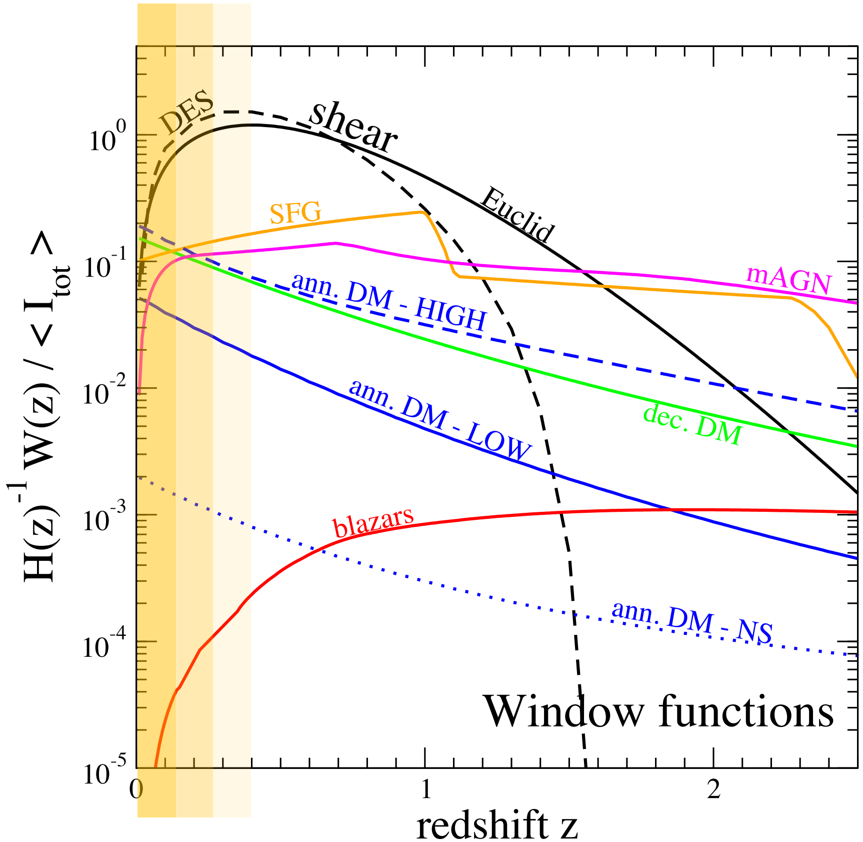
window functions

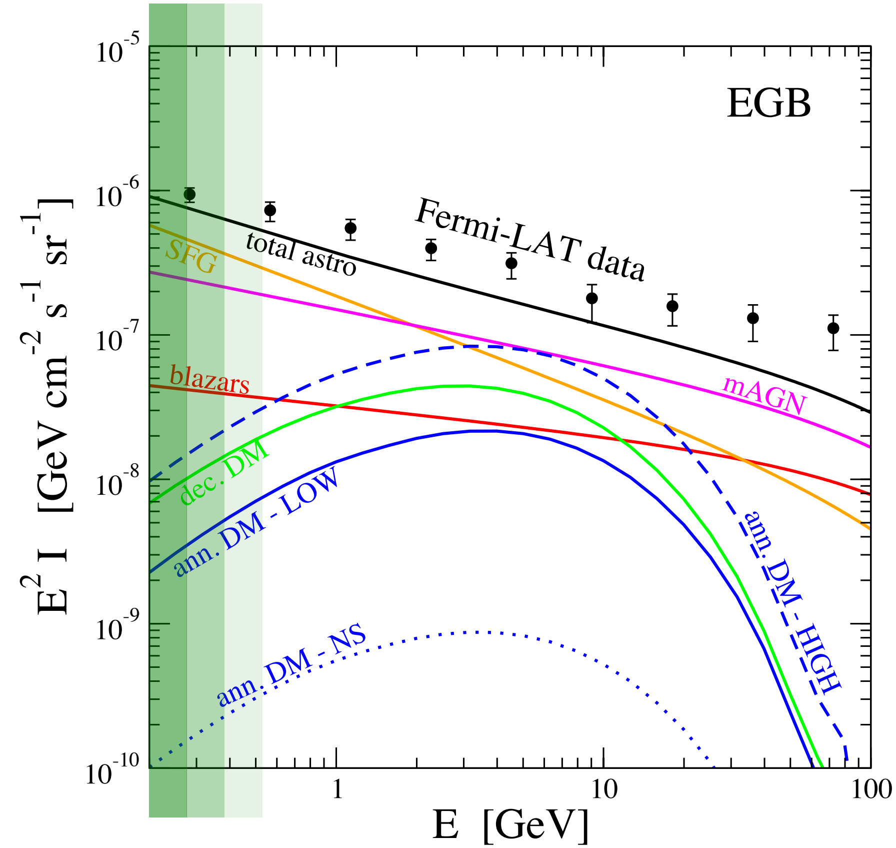
power spectrum

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





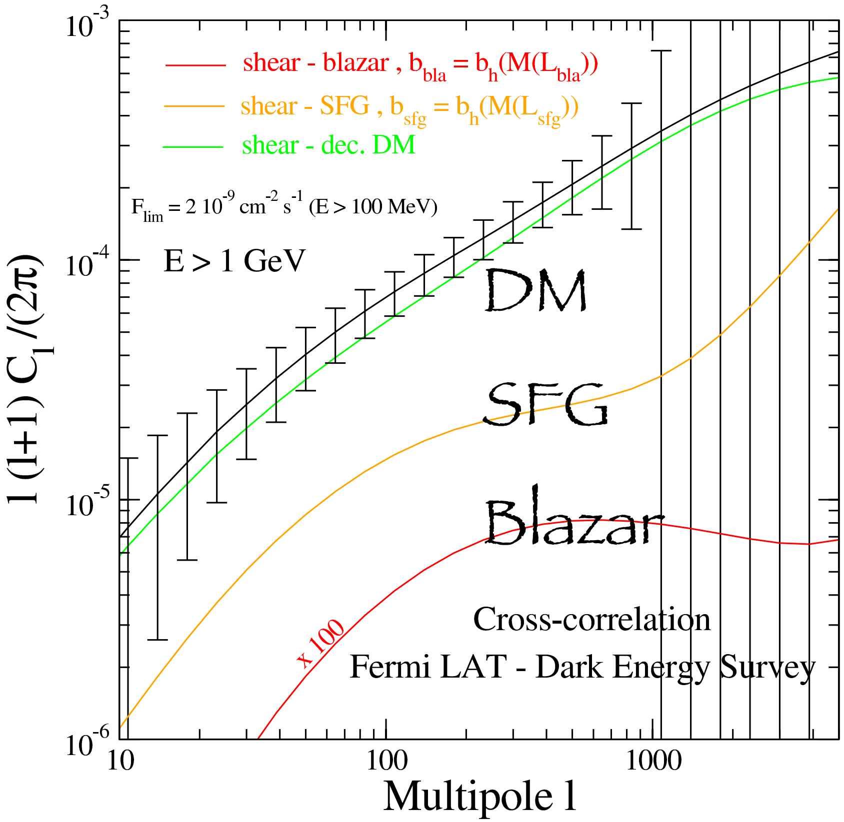
Reshift information in shear can help in "filtering" signal sources

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

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

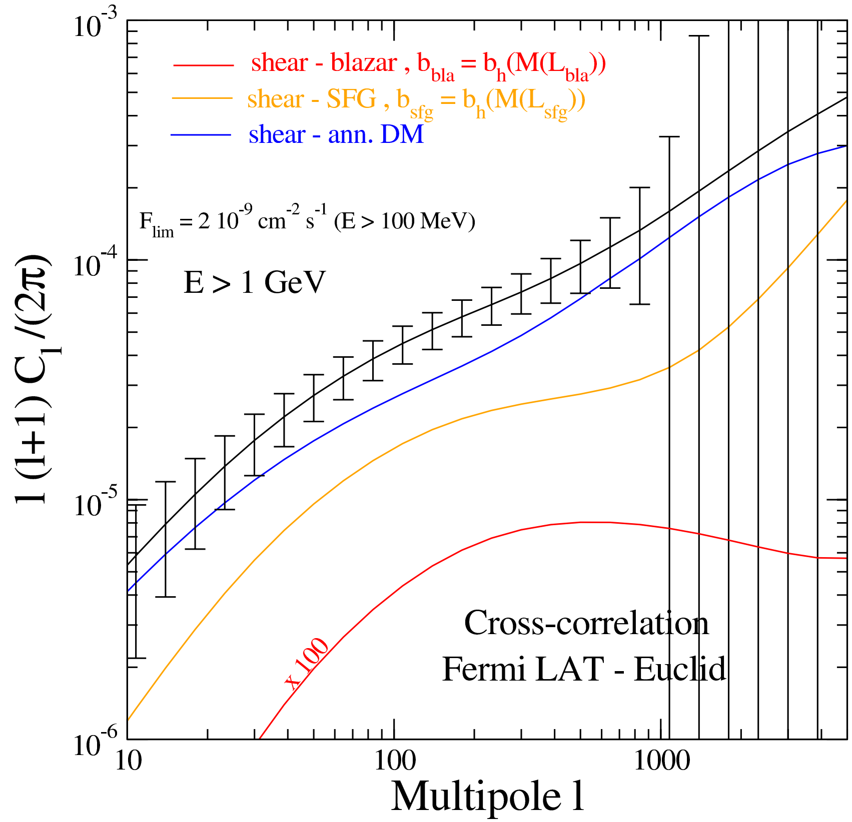
Proof of concept

Decaying DM



Fermi-LAT/5-yr with DES

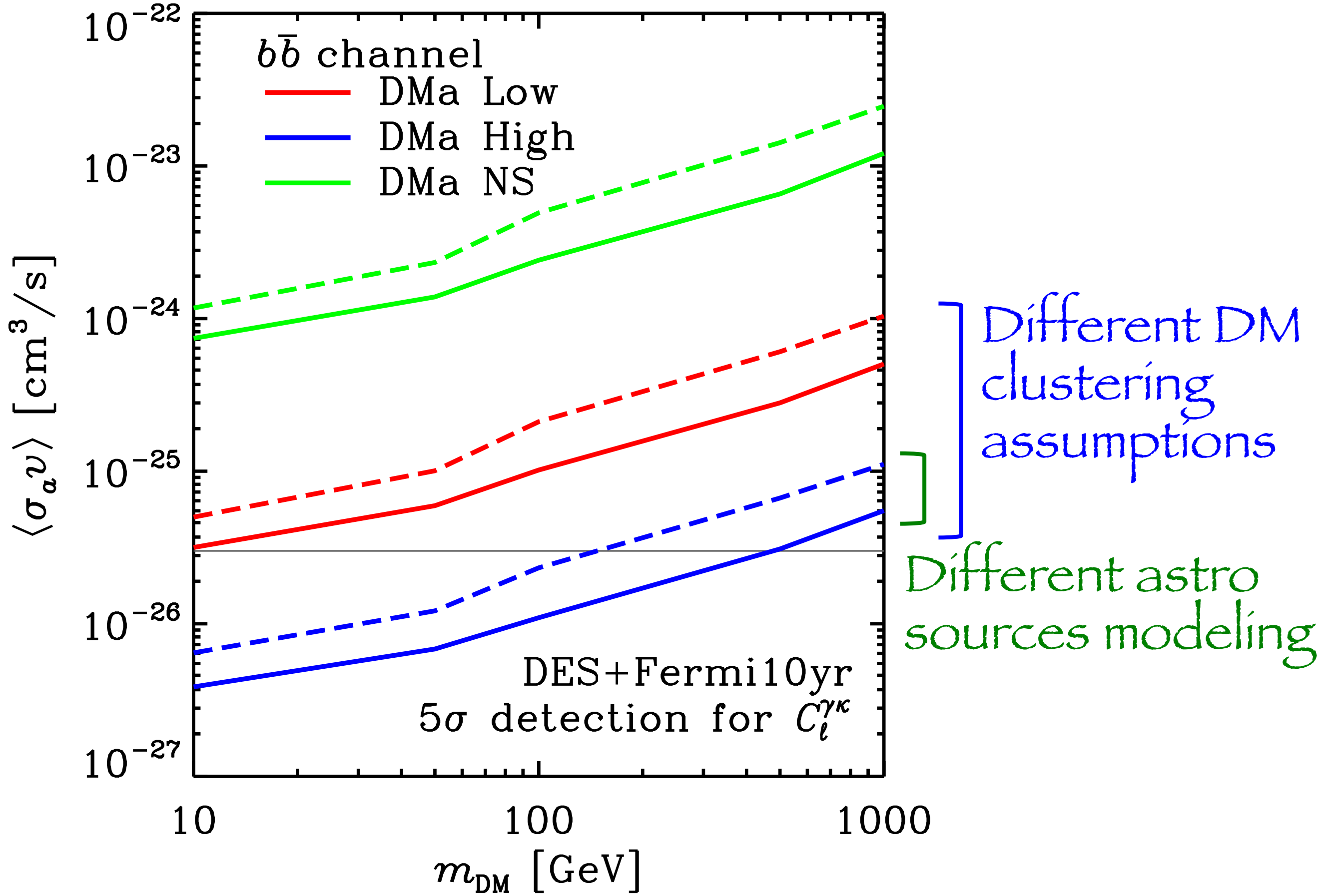
Annihilating DM



Fermi-LAT/5-yr with Euclid

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

Detection forecasts

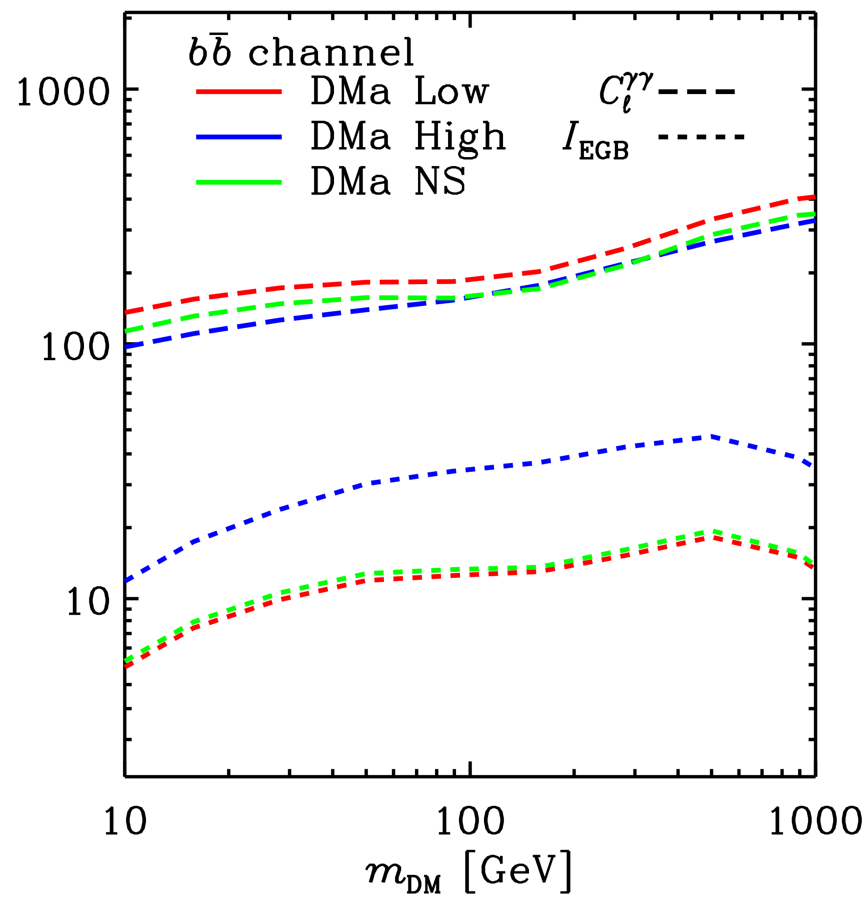


5σ detection for DES + Fermi 10yr

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

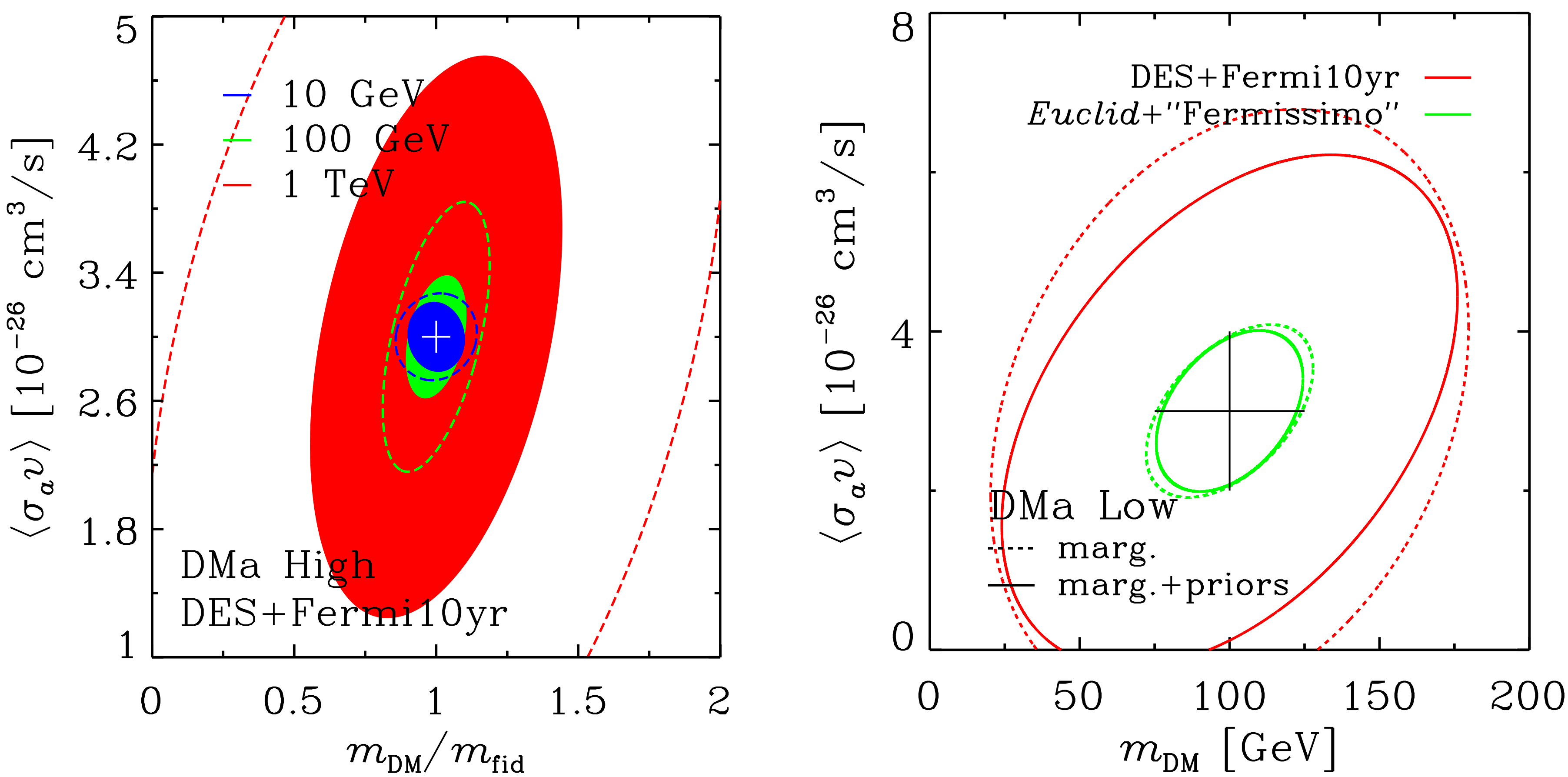
Comparison

$$R = B_i / B_{\rm cross} \quad i = \text{auto, EGB}$$



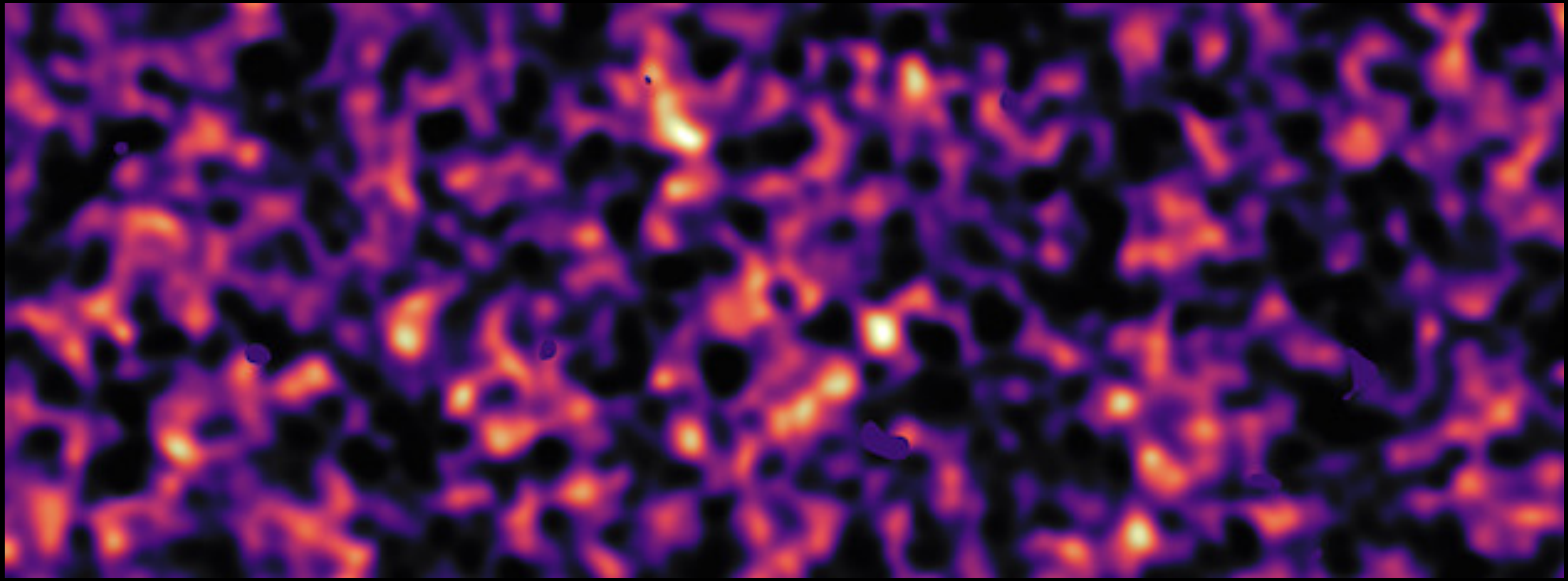
Camera, Fornasa, NF, Regis, JCAP 06 (2015) 029

Sensitivity on DM parameters



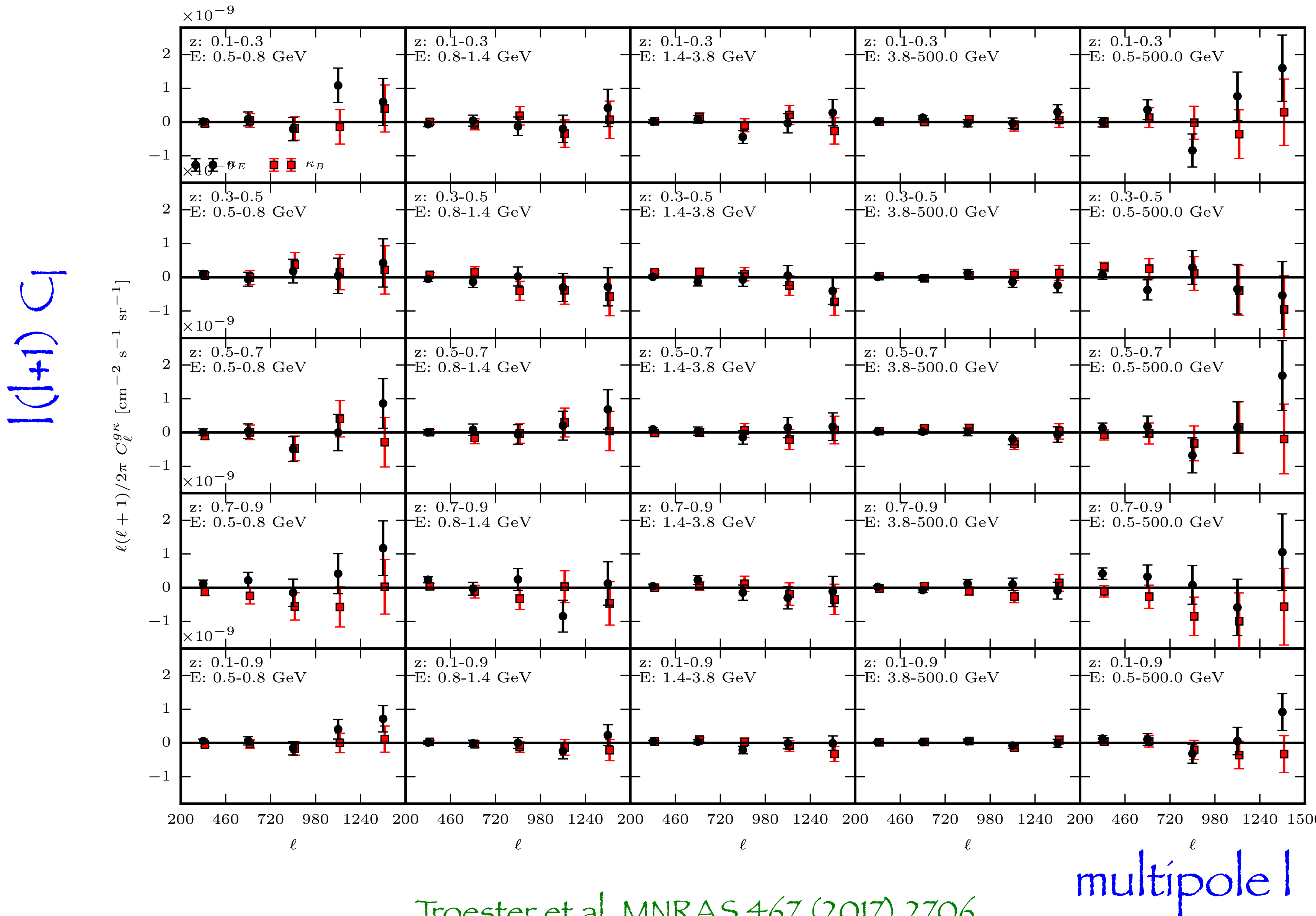
Camera, Fornasa, NF, Regis, JCAP 06 (2015) 029

We start having data



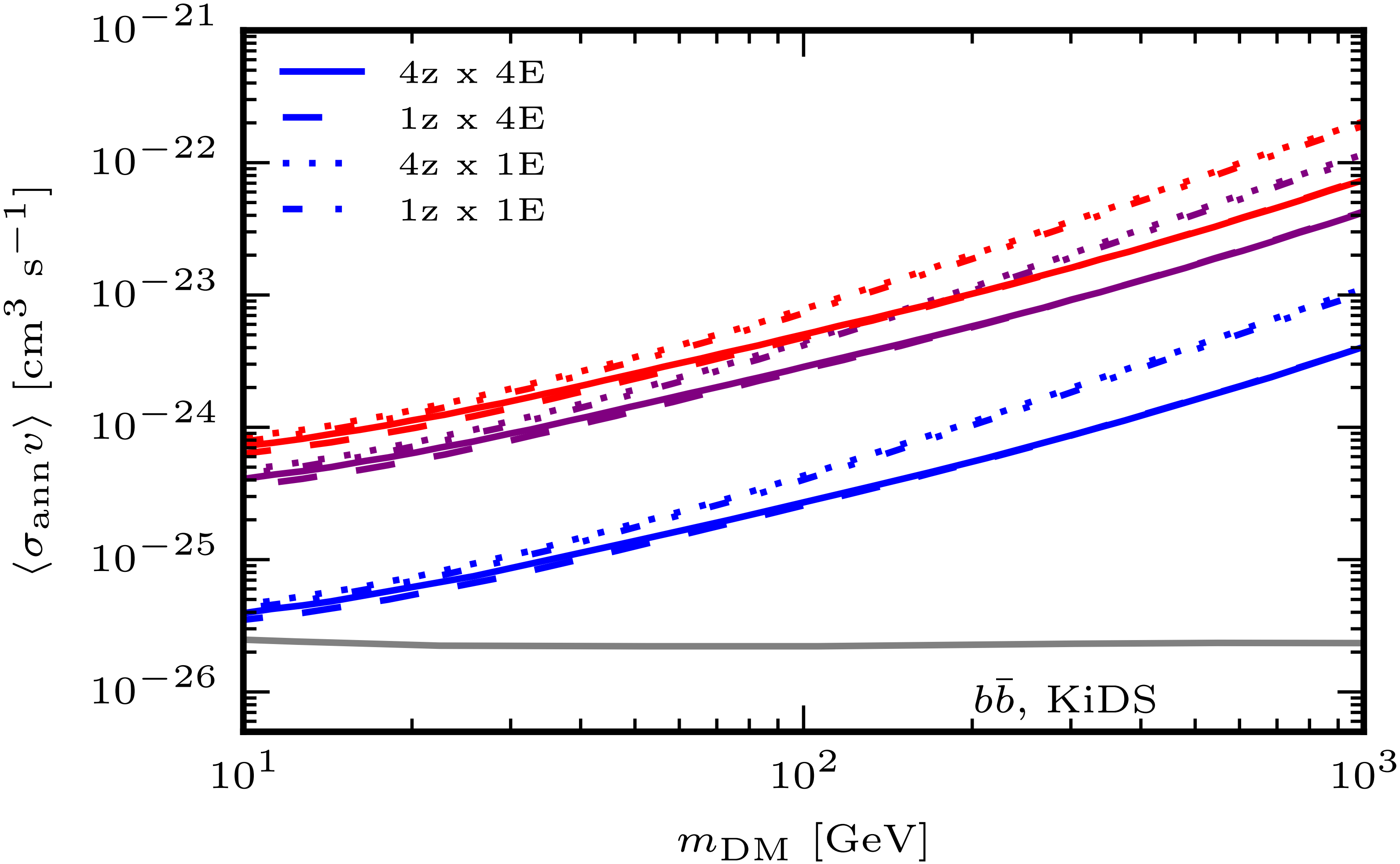
DM maps from KiDS analysis on weak lensing

Fermi x KiDS+RCSLens+CFTHLens



Troester et al, MNRAS 467 (2017) 2706

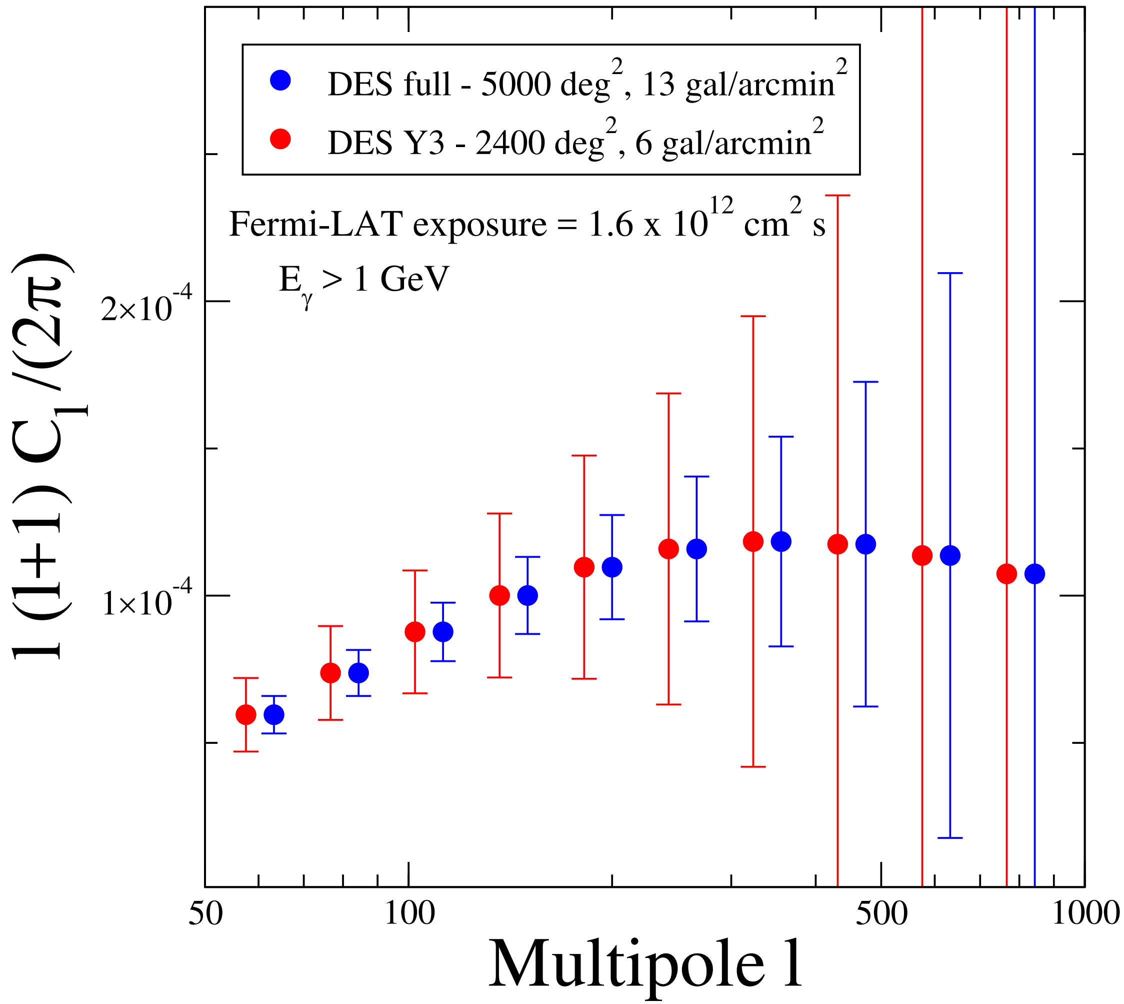
Fermi x KiDS+RCSLens+CFTHLens



Troester et al, MNRAS 467 (2017) 2706

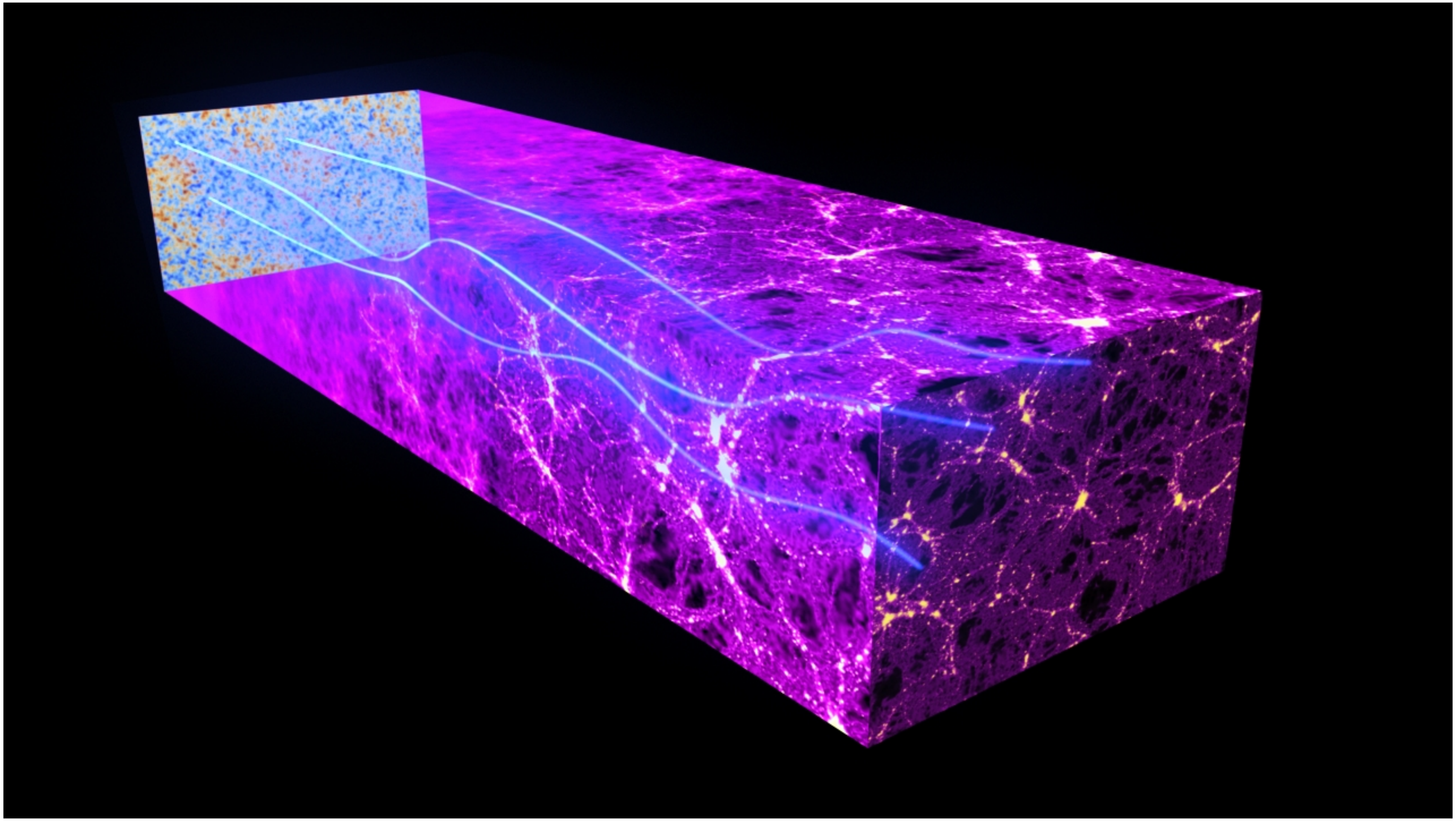
See also: Shirasaki, Horiuchi, Yoshida, PRD 90 (2014) 063502
Shirasaki, Marcias, Horiuchi, Shirai, Yoshida, PRD 94(2016) 063522

Forecast for DES

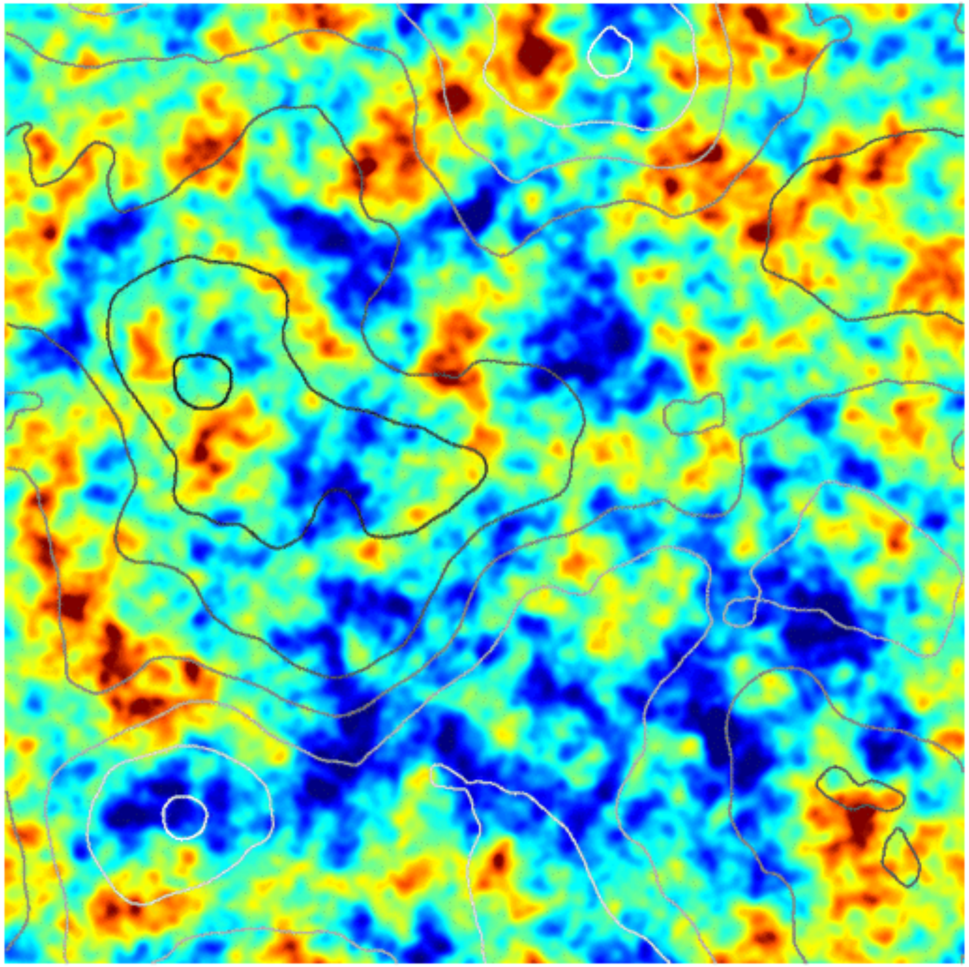


ANG population accounting for the measured DGRB

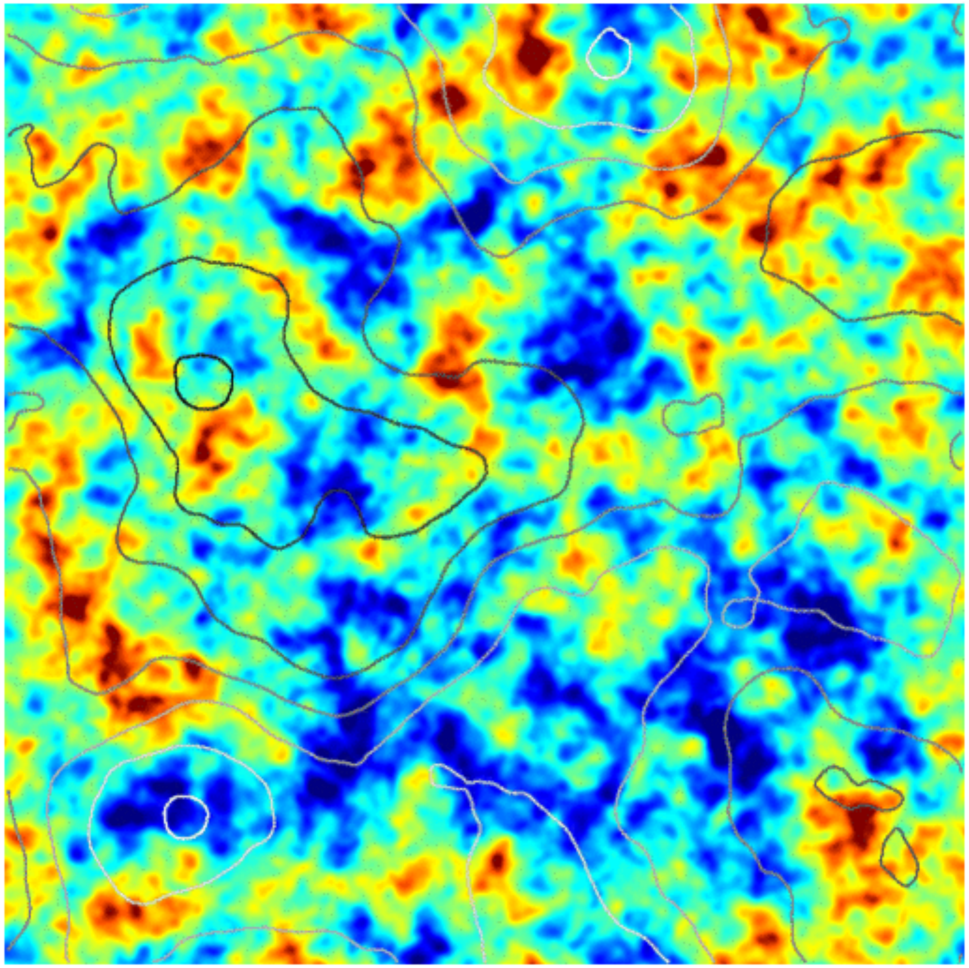
CMB Lensing



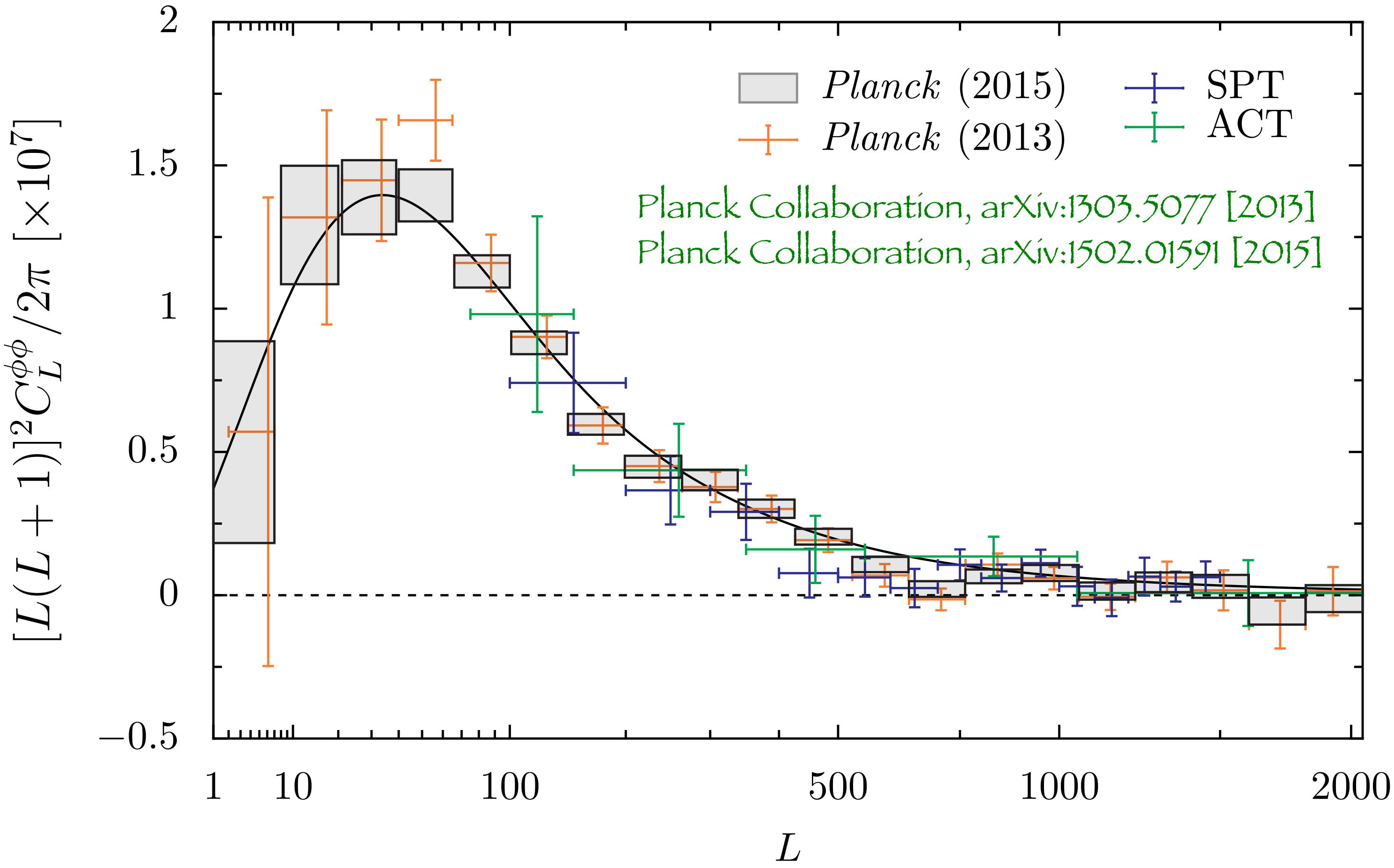
Unlensed CMB + Lensing potential



Lensed CMB

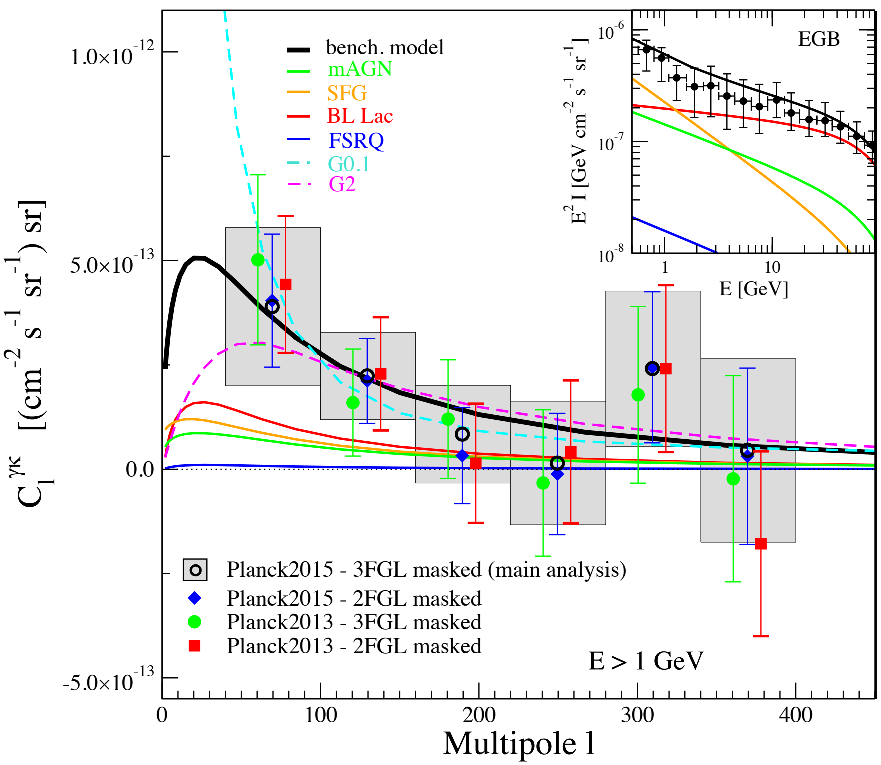


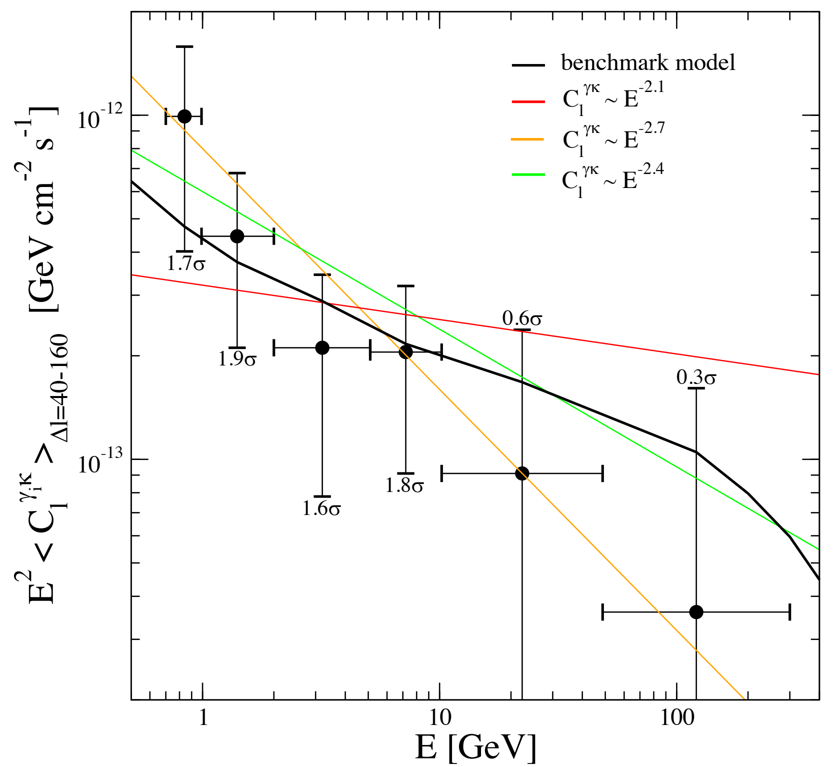
Planck CMB lensing



- 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





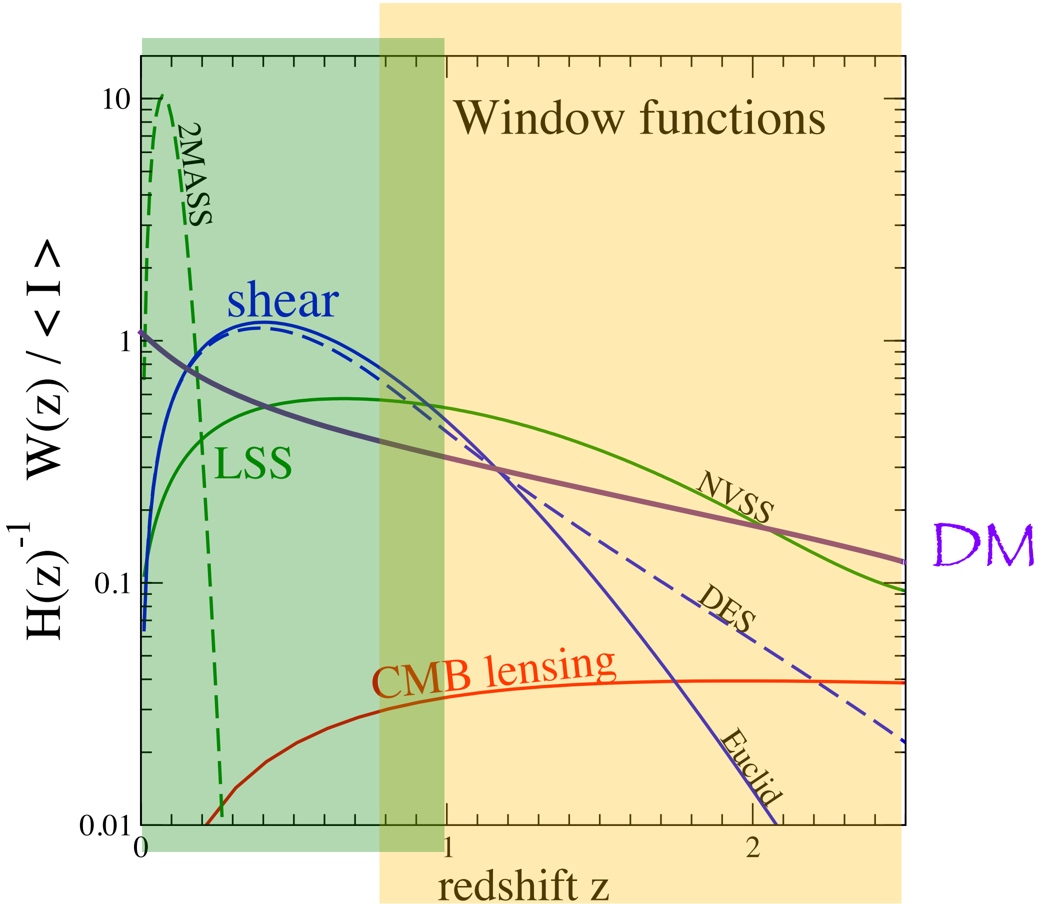
Cross-correlation: deviates 3.0σ from null signal

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 CMB lensing

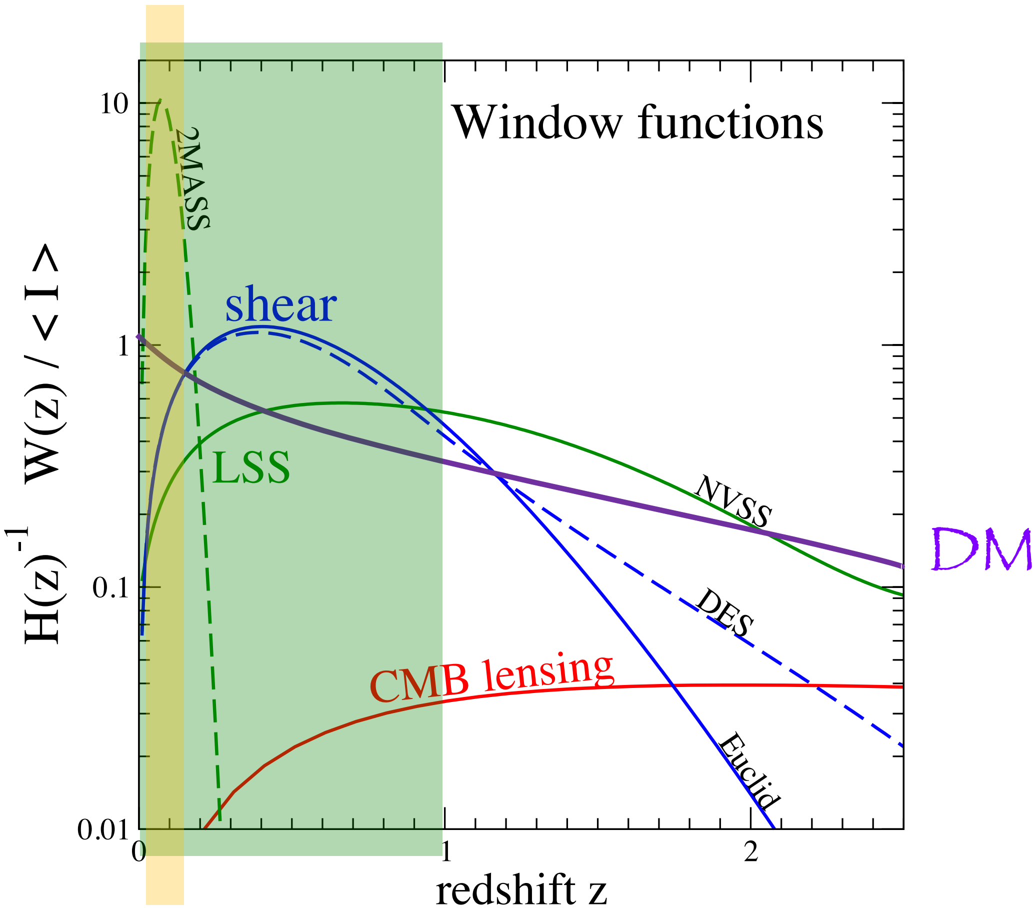


CMB lensing is likely not the best observable for DM

Instead it can hopefully help in constraining astrophysical sources

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

Window functions: DM x LSS

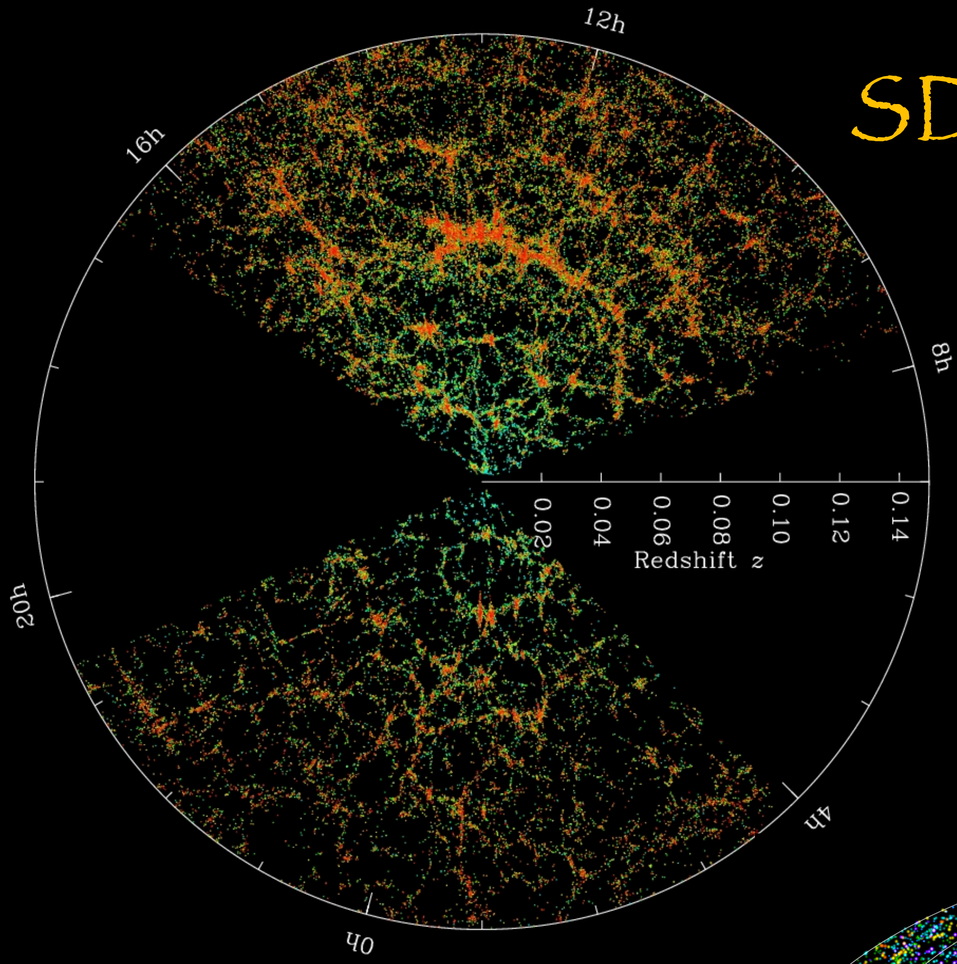


Galaxy catalogs (expecially low-z ones) can have good overlap with DM

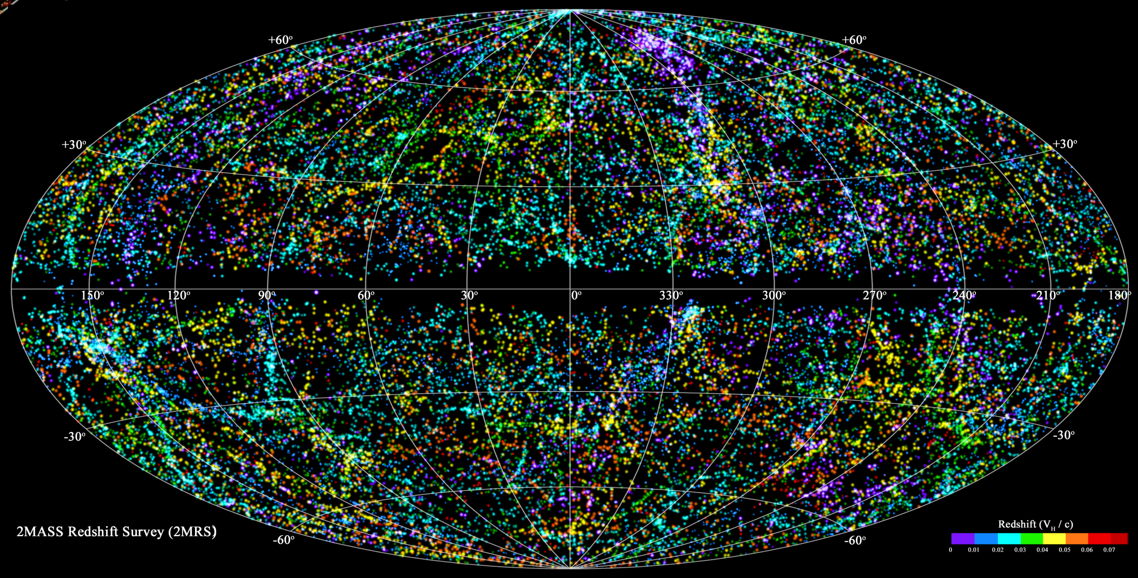
They trace light (while shear directly traces DM), but great potential

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

SDSS


12h
16h
8h
20h
4h
0h
0.02
0.04
0.06
0.08
0.10
0.12
0.14
Redshift z

2MASS


+60°
+30°
-30°
-60°
150°
120°
90°
60°
30°
0°
330°
300°
270°
240°
210°
180°
2MASS Redshift Survey (2MRS)
Redshift (V_H / c)

Cross correlation with galaxy catalogs

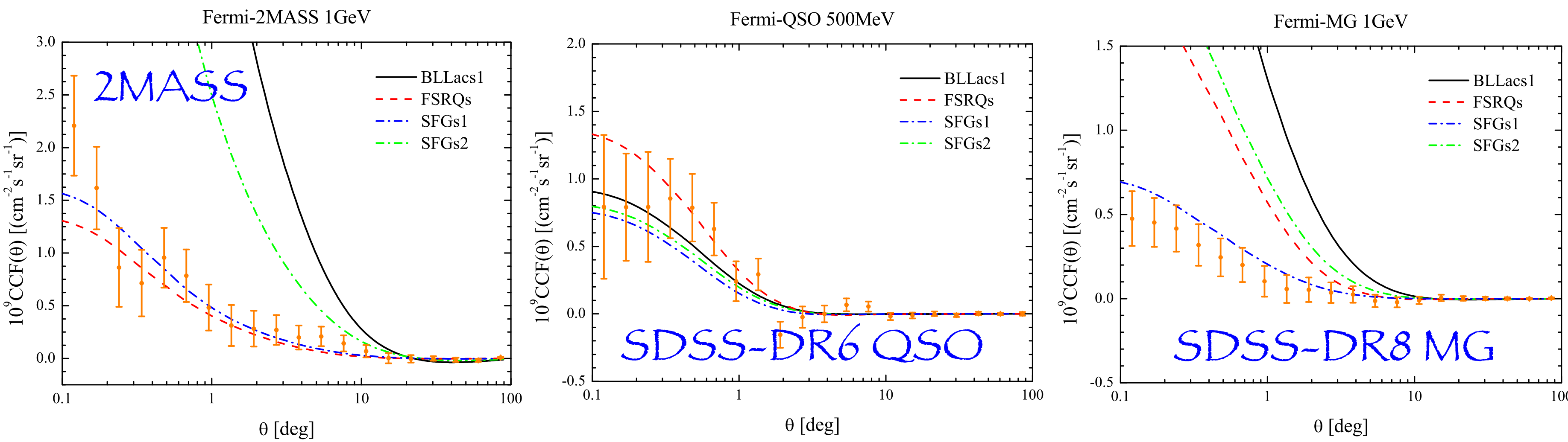
Cuoco, Brandbyge, Hannestad, Haugbolle, Miele, PRD 77 (2008)123518

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

SDSS 6, 2MASS, NVSS, SDSS 8 LRG <u>x</u> Fermi 21 months — no signal

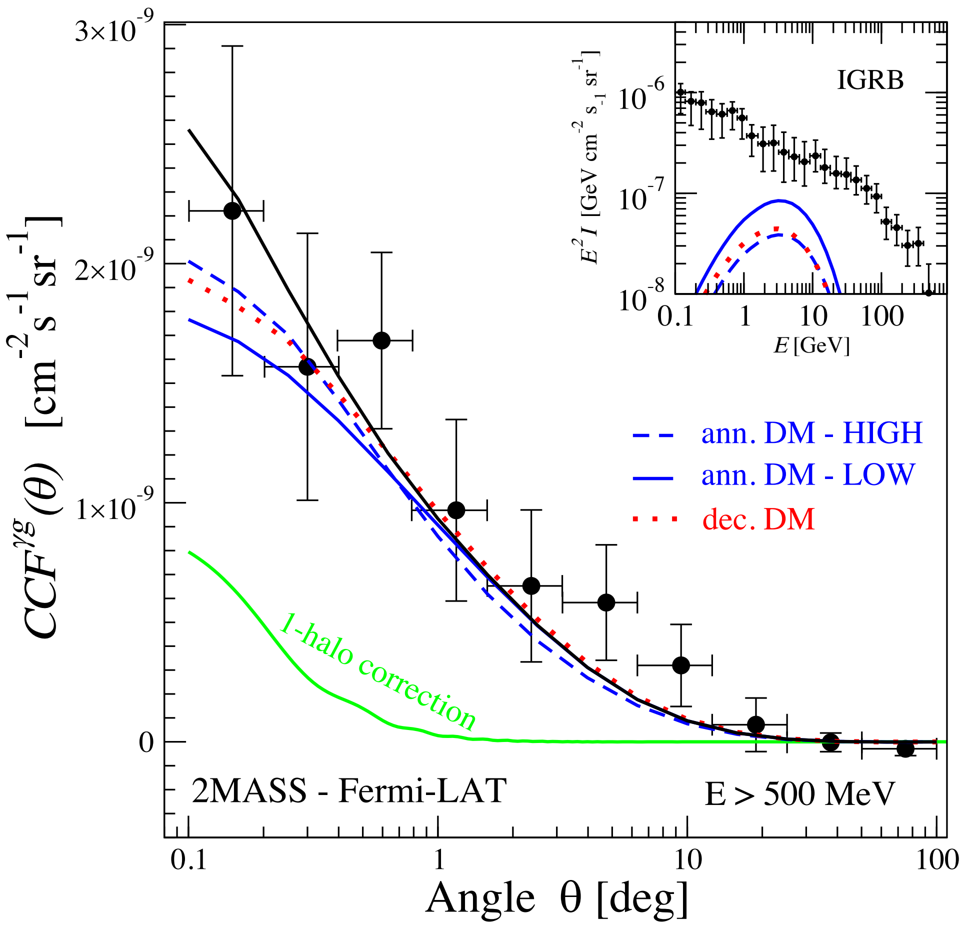
Xia, Cuoco, Branchini, Viel, APJS 217 (2015) 15

SDSS 6 QSO, SDSS 8 MGS, SDSS LRG, 2MASS, NVSS
<u>x</u> Fermi 60 months — <u>signal</u>



correlation at the degree scale

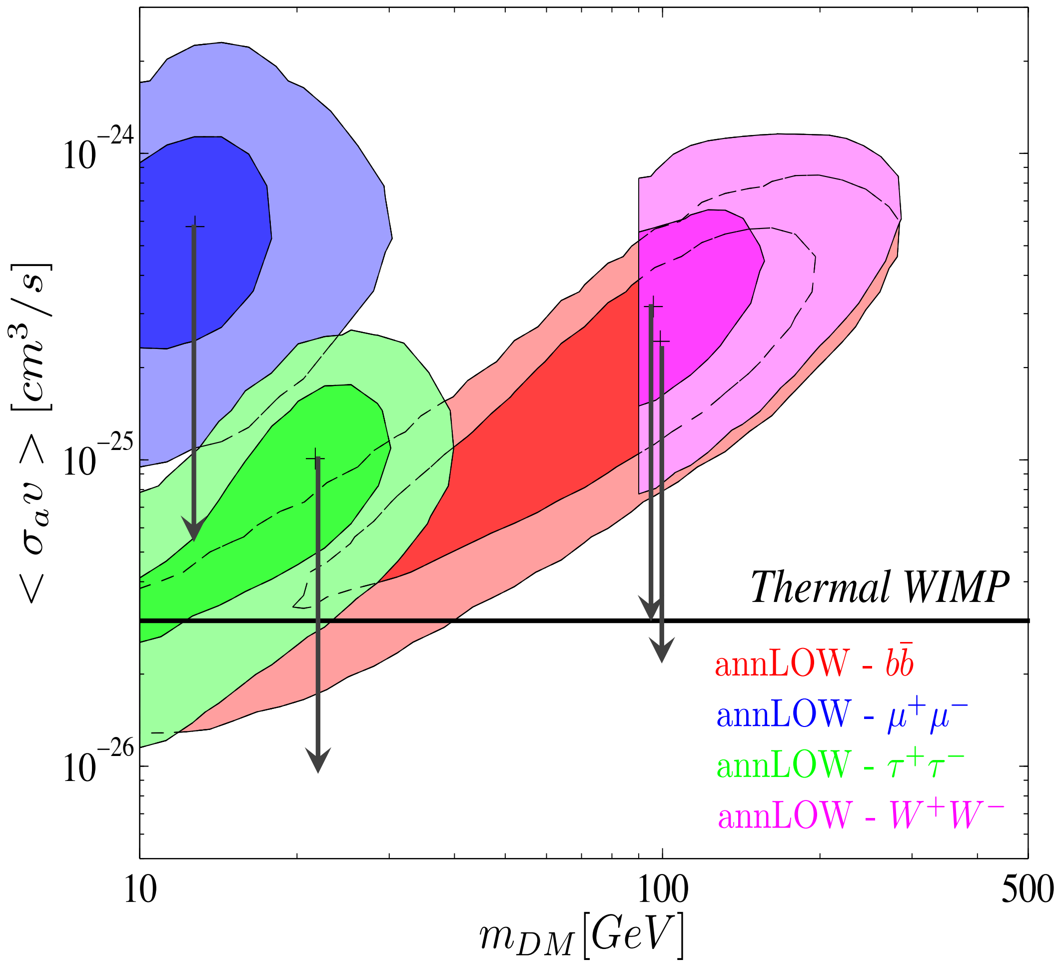
Fermi x 2MASS



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

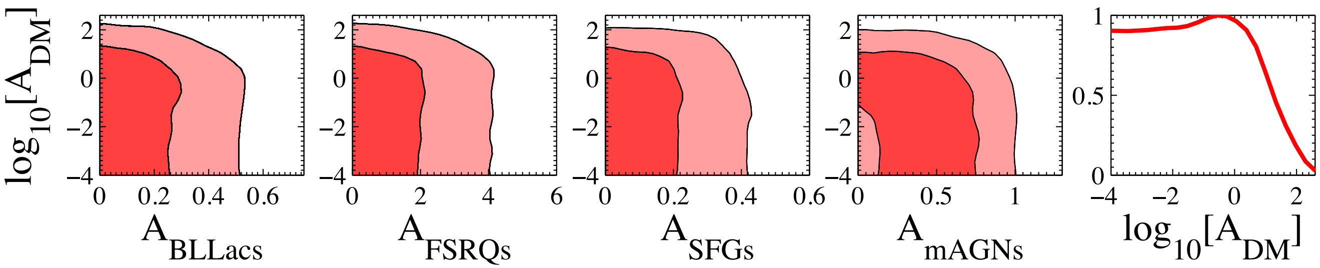
Fermi x 2MASS



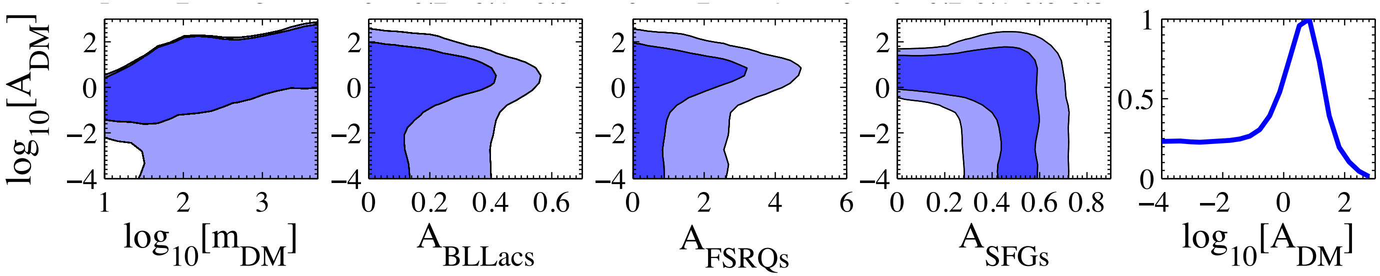
Just in case it's a DM signal ...

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

Fermi + LSS catalogs: DM + astro sources



(*)



(*)

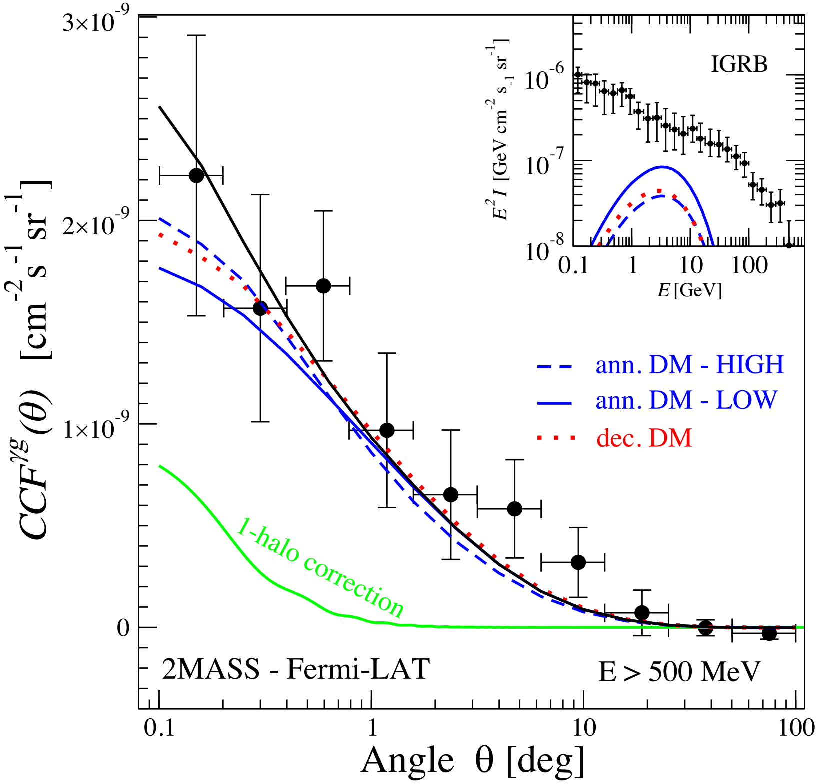
LOW

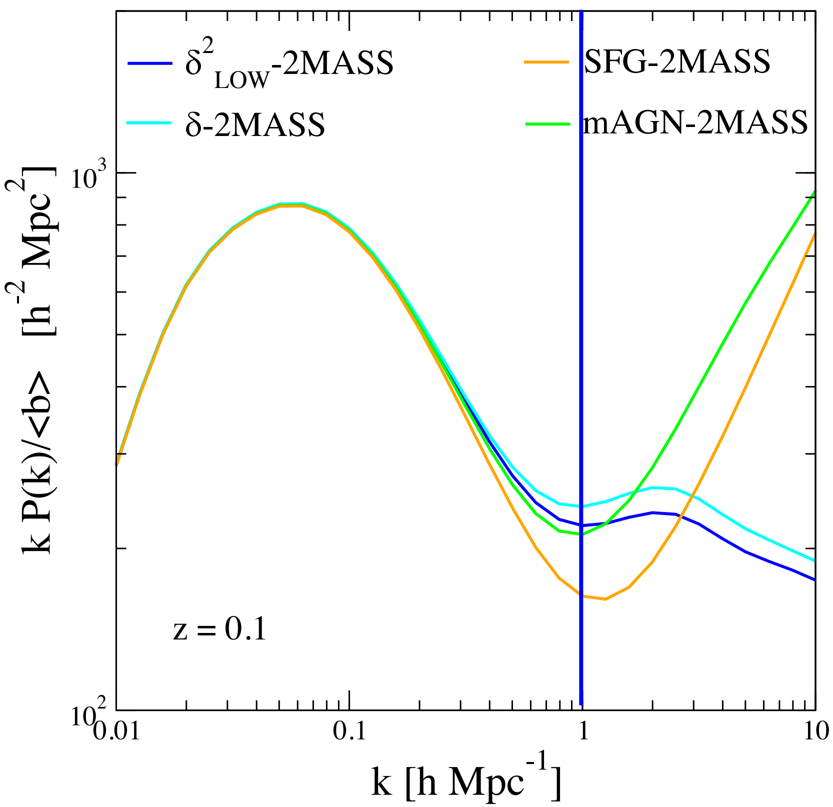
Degeneracy between DM and mAGN:

- (*) Enhanced mAGN contribution
- (*) Suppressed mAGN contribution

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

Measured power and scales





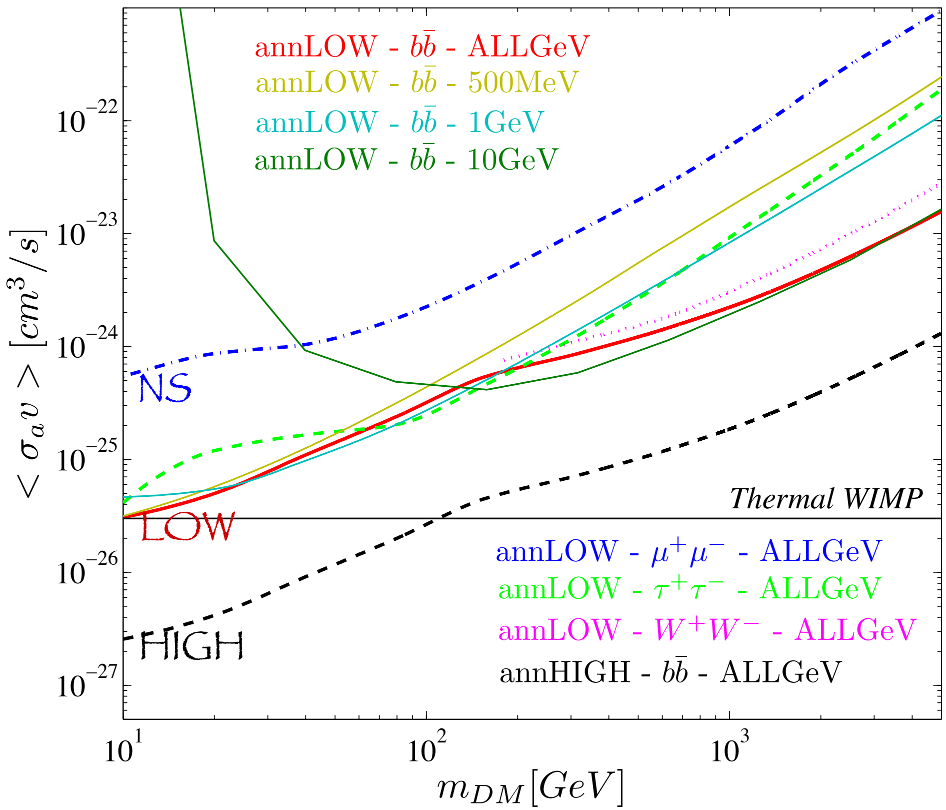
Data show power at the sub-degree scale

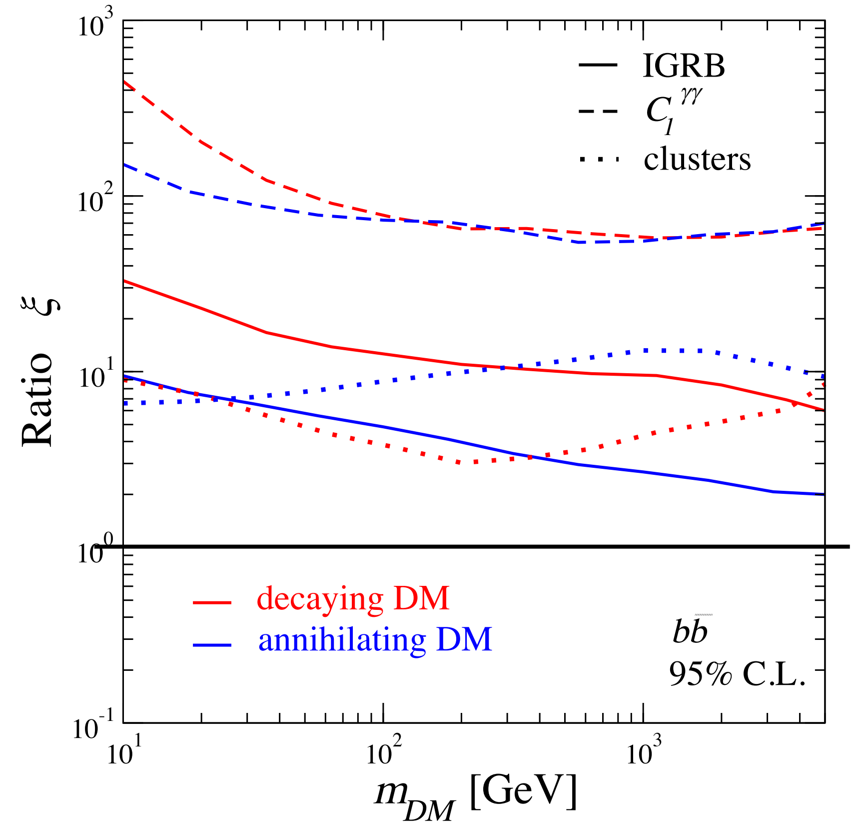
At the 2MASS redshift, sub-deg corresponds to Mpc scales, which are more compatible with DM or mAGN, rahter than SFG

Clear separation requires improved gamma ray angular resolution

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

Fermi x 2MASS





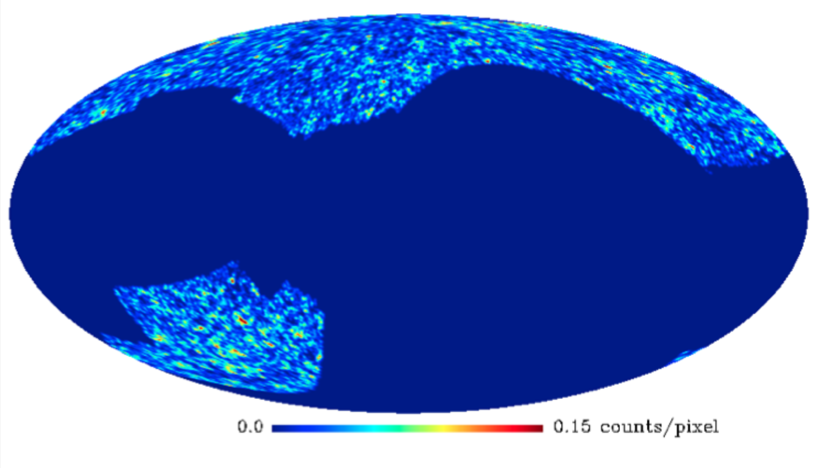
Bound from cross correlation

Bounds ratios
Correlation technique stronger

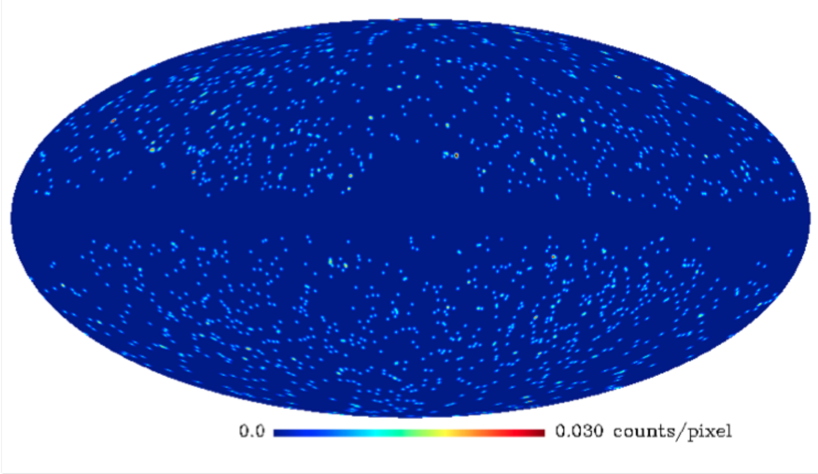
Regis, Xia, Cuoco, Branchini, NF, Viel, ApJS 221 (2015) 29
See also: Shirasaki, Horiuchi, Yoshida, PRD 90 (2014) 063502
Shirasaki, Horiuchi , Yoshida, PRD 92 (2015) 123540

Galaxy clusters

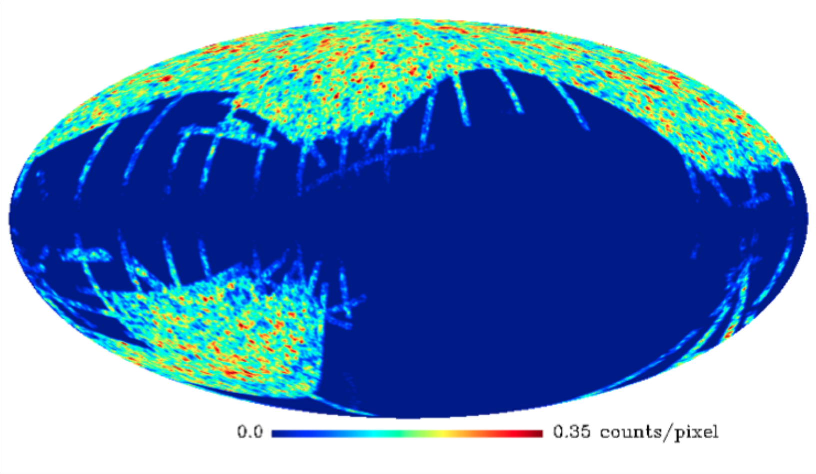
redMaPPer



Planck SZ

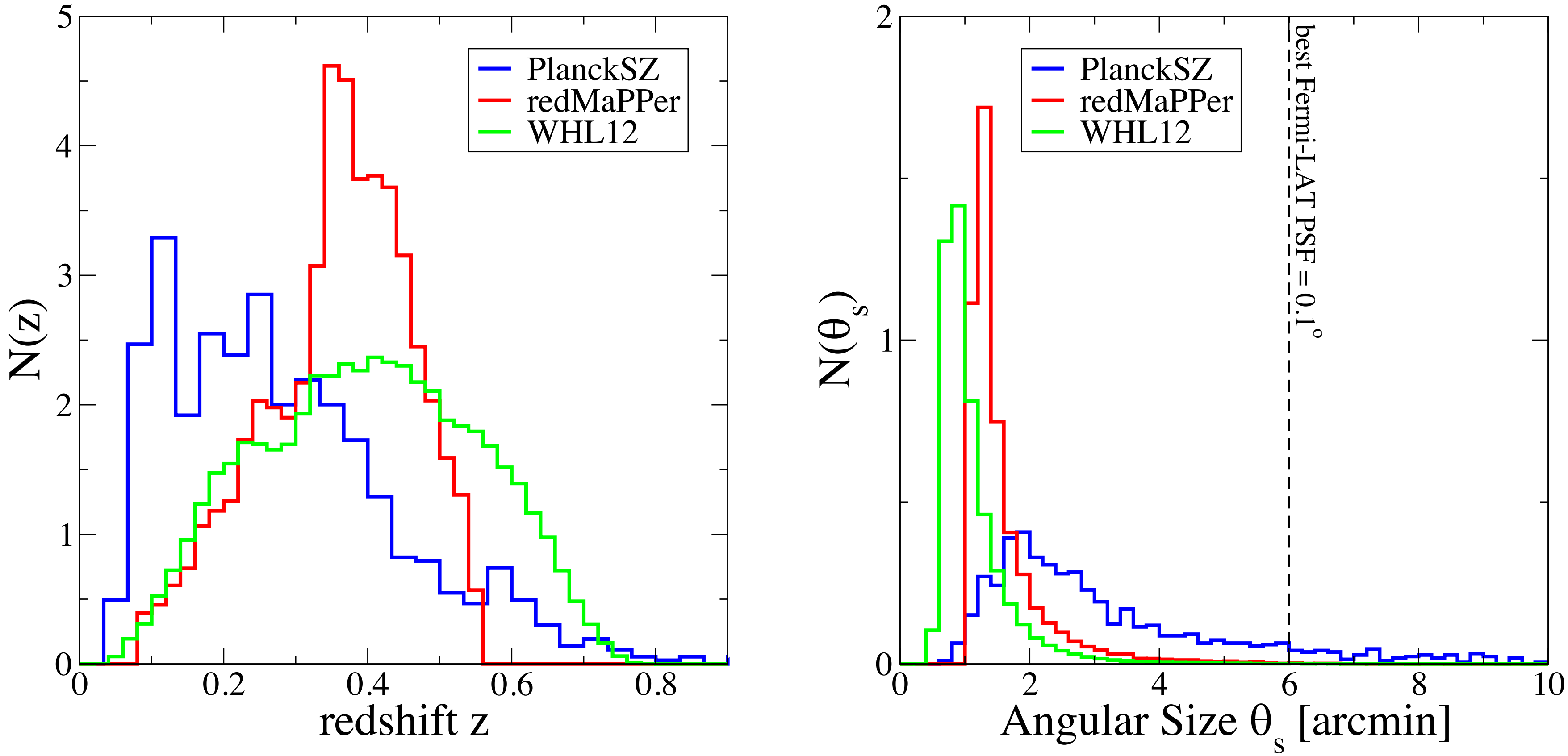


WHL12



Catalog	Objects
redMaPPer	26 350
WHL12	39 668
Planck SZ	1 653

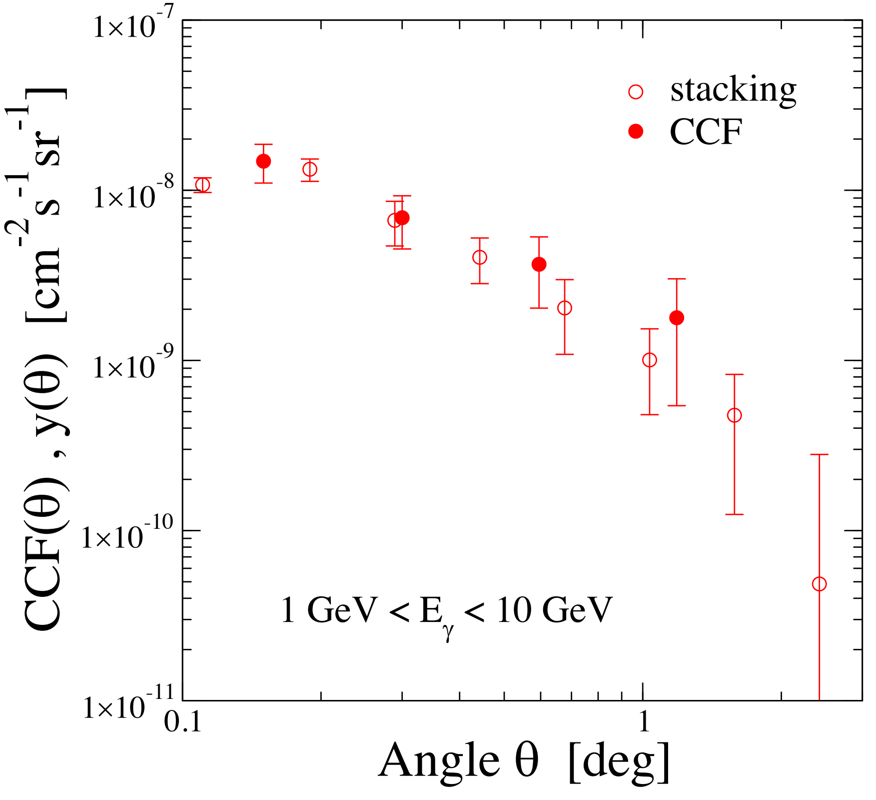
Catalogs

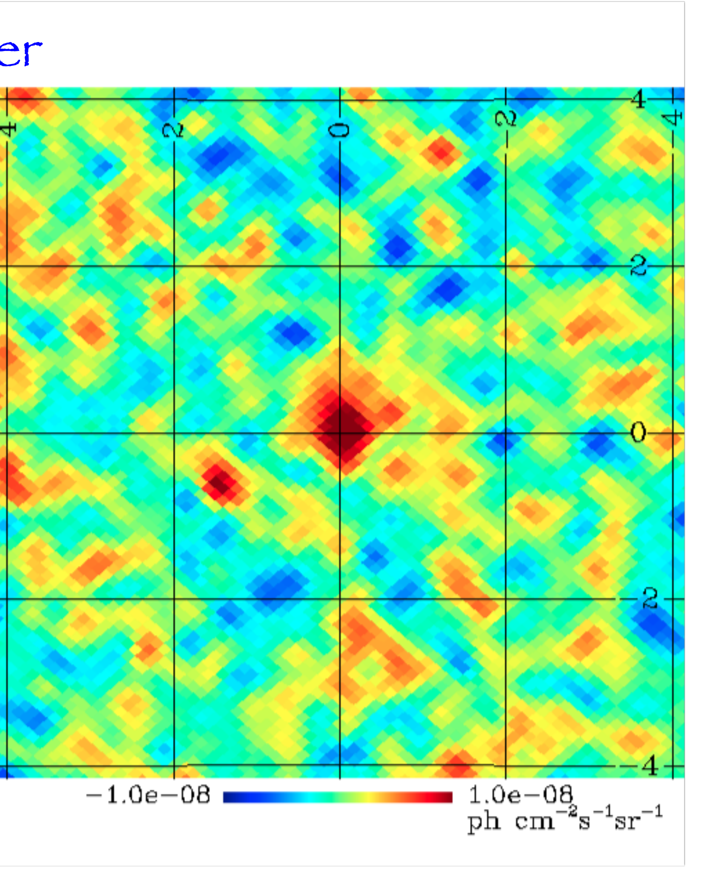


5
4
3
2
1
0
N(z)
0
0.2
0.4
0.6
0.8
redshift z
PlanckSZ
redMaPPer
WHL12
2
1
0
$N(\theta_s)$
0
2
4
6
8
10
Angular Size θ_s [arcmin]
best Fermi-LAT PSF = 0.1°

Cross correlation with gamma rays

redMaPPer





Correlation function and stacking profile

Gamma ray stacking

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

- A cross correlation signal is significantly detected out to 1 degree (beyond the Fermi PSF extension)

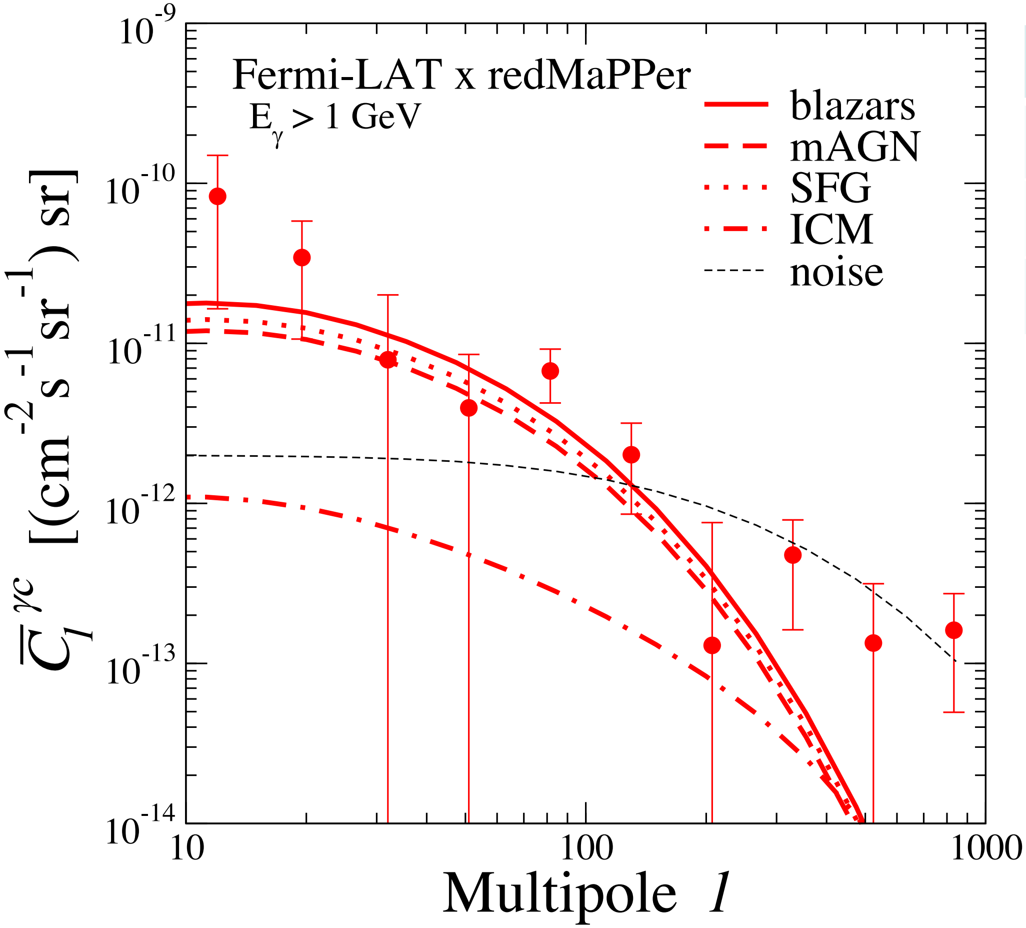
- The cross-correlation measurement confirms that the unresolved EGB observed by Fermi correlates with the large scale clustering of matter in the Universe (here traced by clusters)

- At the typical redshifts of the clusters in these catalogs, one degree corresponds to a linear scale of 10 Mpc

- This means that a (large?) fraction of the correlation signal seems to be not physically associated to the clusters

- Instead, it can be produced by AGNs or SFGs residing in the larger scale structures that surround the high density peaks where clusters reside

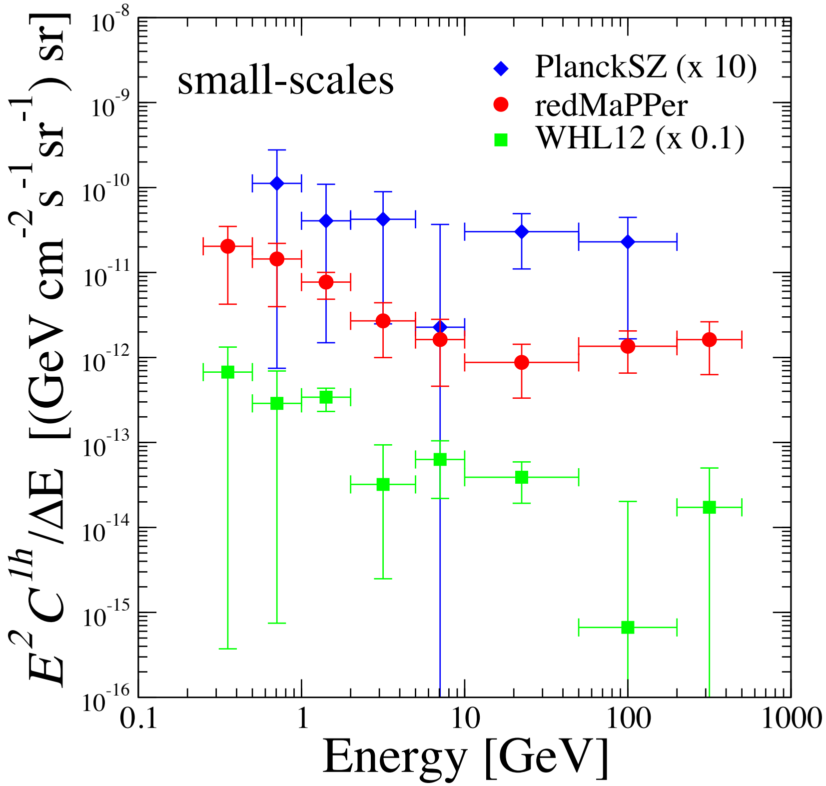
Angular power spectrum



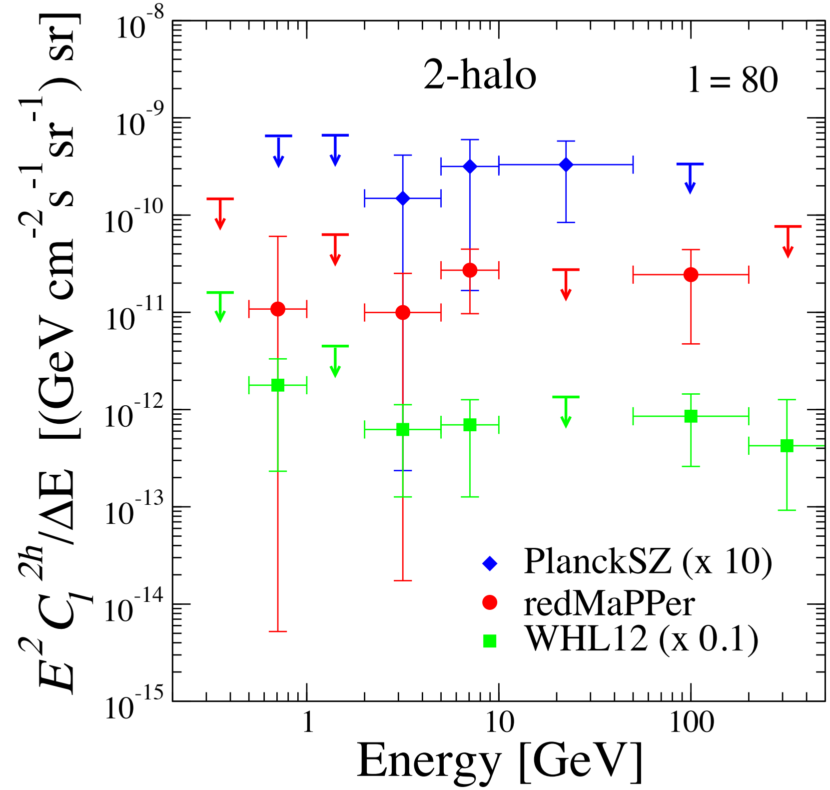
	1 halo	2 halo
redMaPPer	4.7 σ	2.1 σ
WHL12	3.9 σ	2.6 σ
Planck SZ	2.3 σ	1.8 σ

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

Energy dependence



Constant 1 halo term



2 halo term at l = 80

Branchini, Camera, Cuoco, NF, Regis, Viel, Xia, 1612.05788

Energy dependence

- Large scales (2-halo dominates): the signal is contributed by sources with hard energy spectra, consistent with that of the BL Lacs

- Small scales (1-halo dominates): signal could be contributed by different types of sources
  - At high (E > 10 GeV) energies the dominant sources have hard spectra (probably the same BL Lac population)
  - At smaller energies, the correlation signal shows a hint of contribution by sources with softer spectra. These can be non-BL LacAGNs, SFGs and/or the ICM (or DM)

Conclusions

- In order to separate a DM non-gravitational signal from other astrophysical emissions, a filter based on the DM properties (i.e. the associated gravitational potential) appears to be very promising

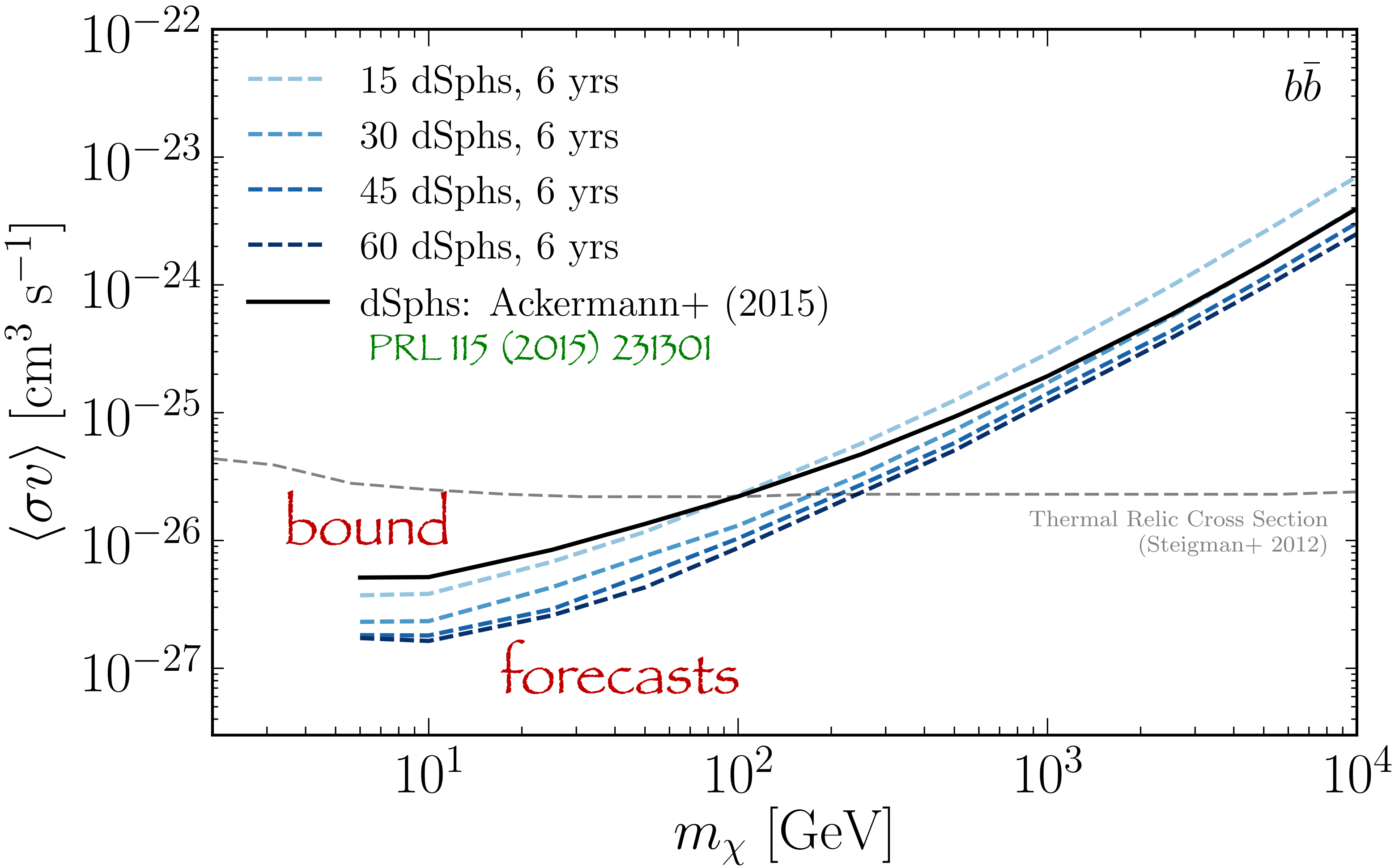
- Cross-correlations offer an emerging opportunity:
  - DM particle signal: multiwavelenght emission
  - DM gravitational tracers: cosmic-shear, LSS surveys

- Gamma rays x cosmic shear is the cleanest possibility and it appears to be powerful

Conclusions

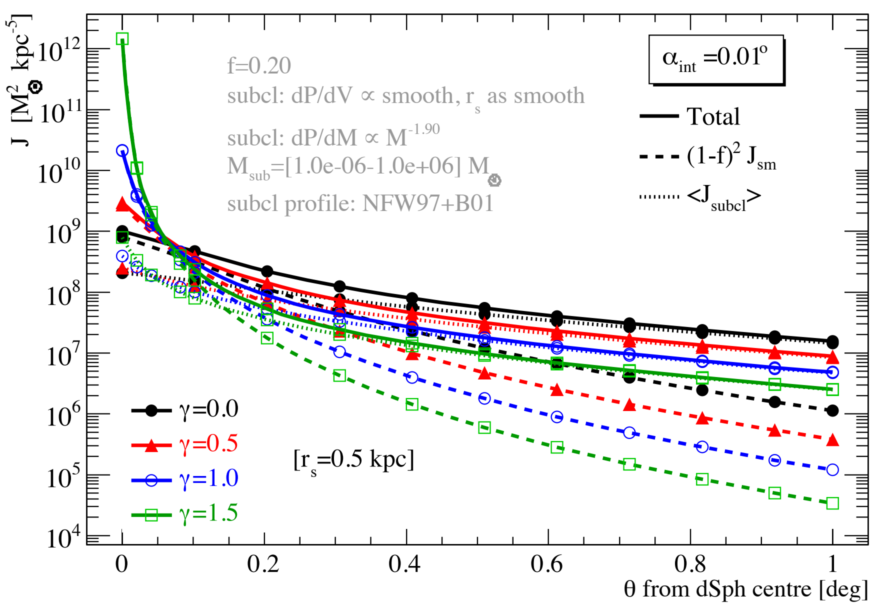
- Gamma-rays/gravity-tracers correlations start to emerge:
  - Cross-correlation with galaxy catalogs (3.5σ)
  - Cross-correlation with CMB-lensing (3.0σ)
  - Cross-correlation with cluster catalogs (4.7σ)
- For cosmic shear, first relevant observational opportunity soon with DES
- High-sensitivity will require Euclid/LSST, coupled with the total accumulated Fermi statistics (opportunity for CTA?)

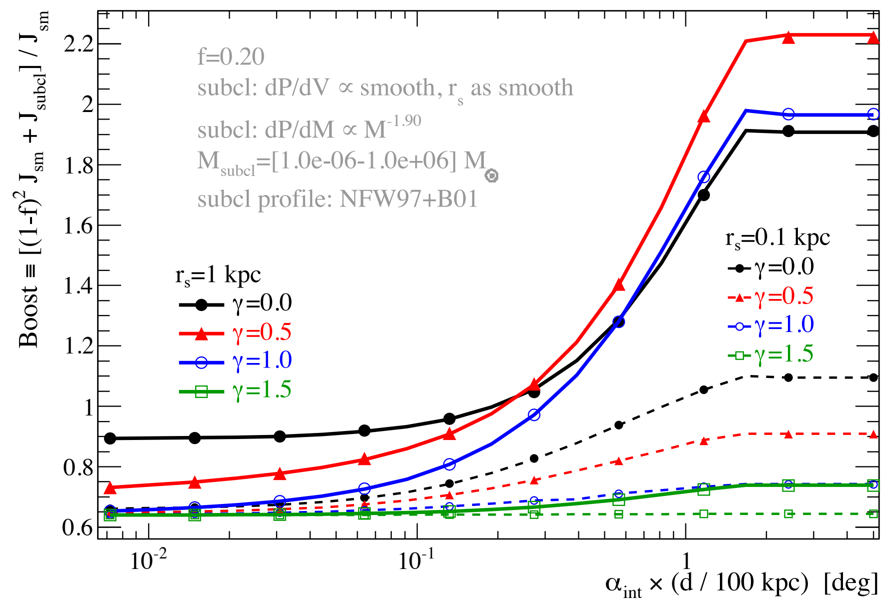
Dwarf galaxies



Charles et al (Fermi Collab) Phys Rep 636 (2016) 1

Astrophysical factors





J factor

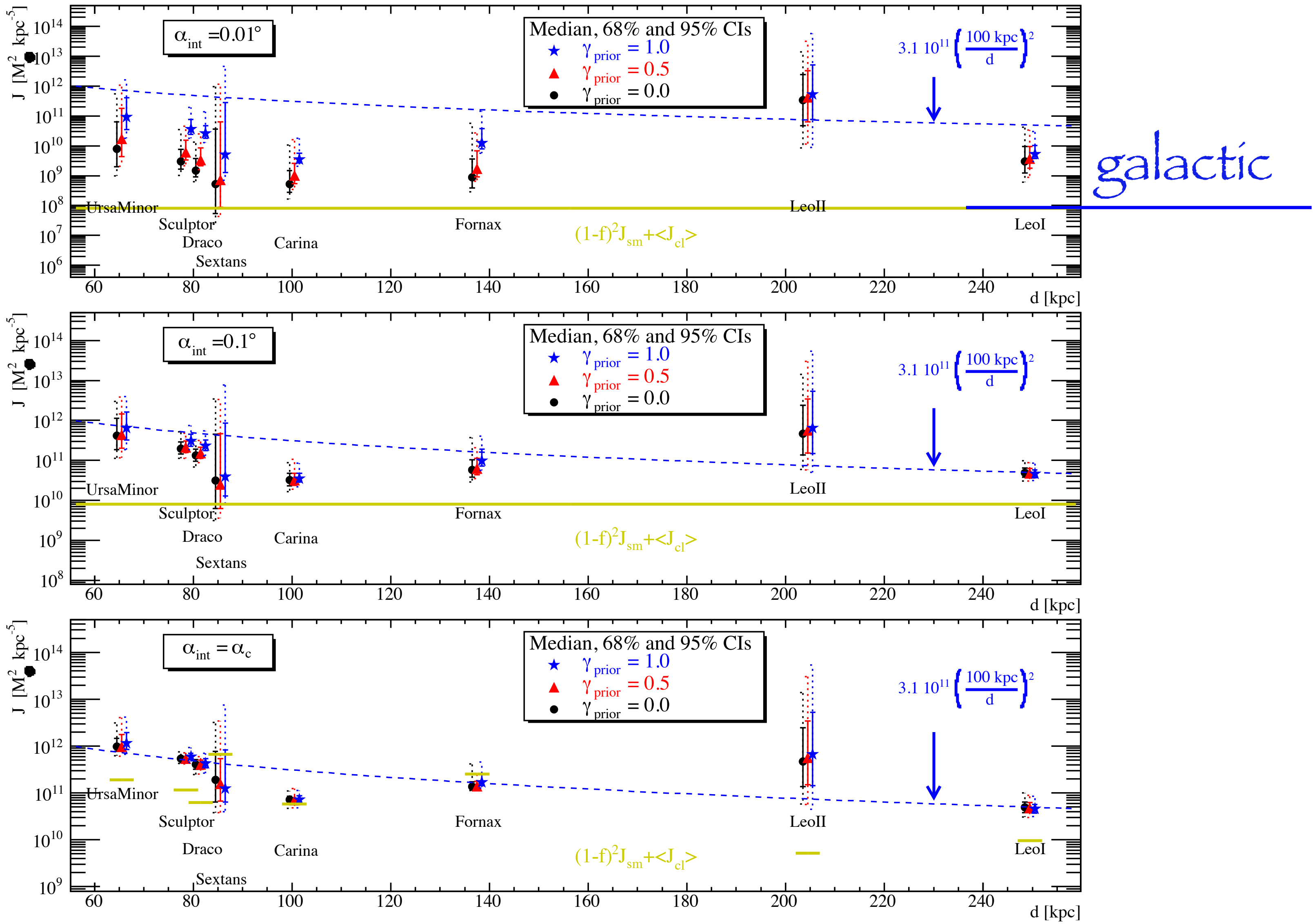
$$J(\Delta\Omega) = \int_{\Delta\Omega} \int \rho^2_{\rm DM}(l,\Omega)\, dl d\Omega.$$

Boost factor

due to substructures

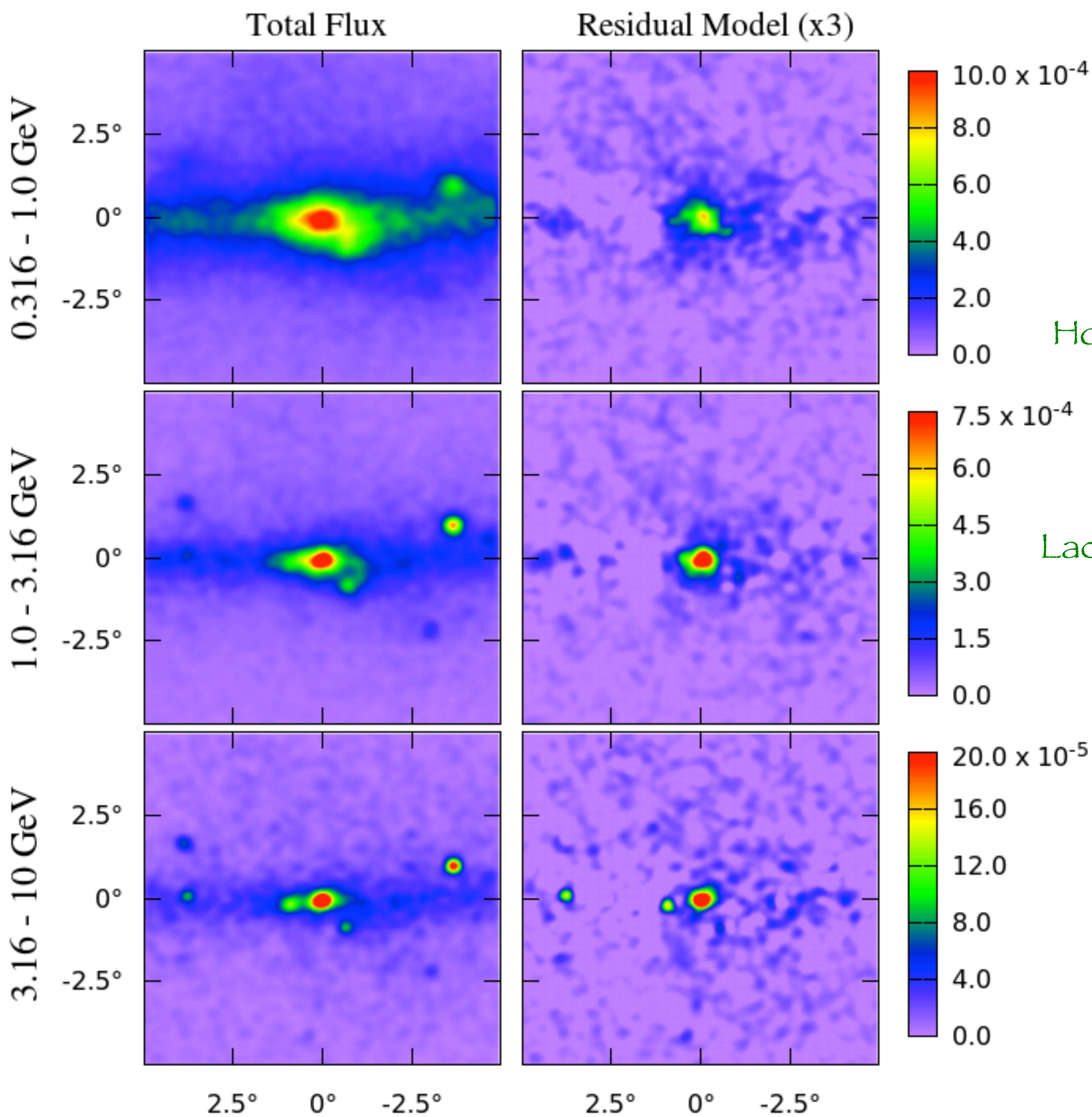
Charbonnier et al, MNRAS 418 (2011) 1526

J factor



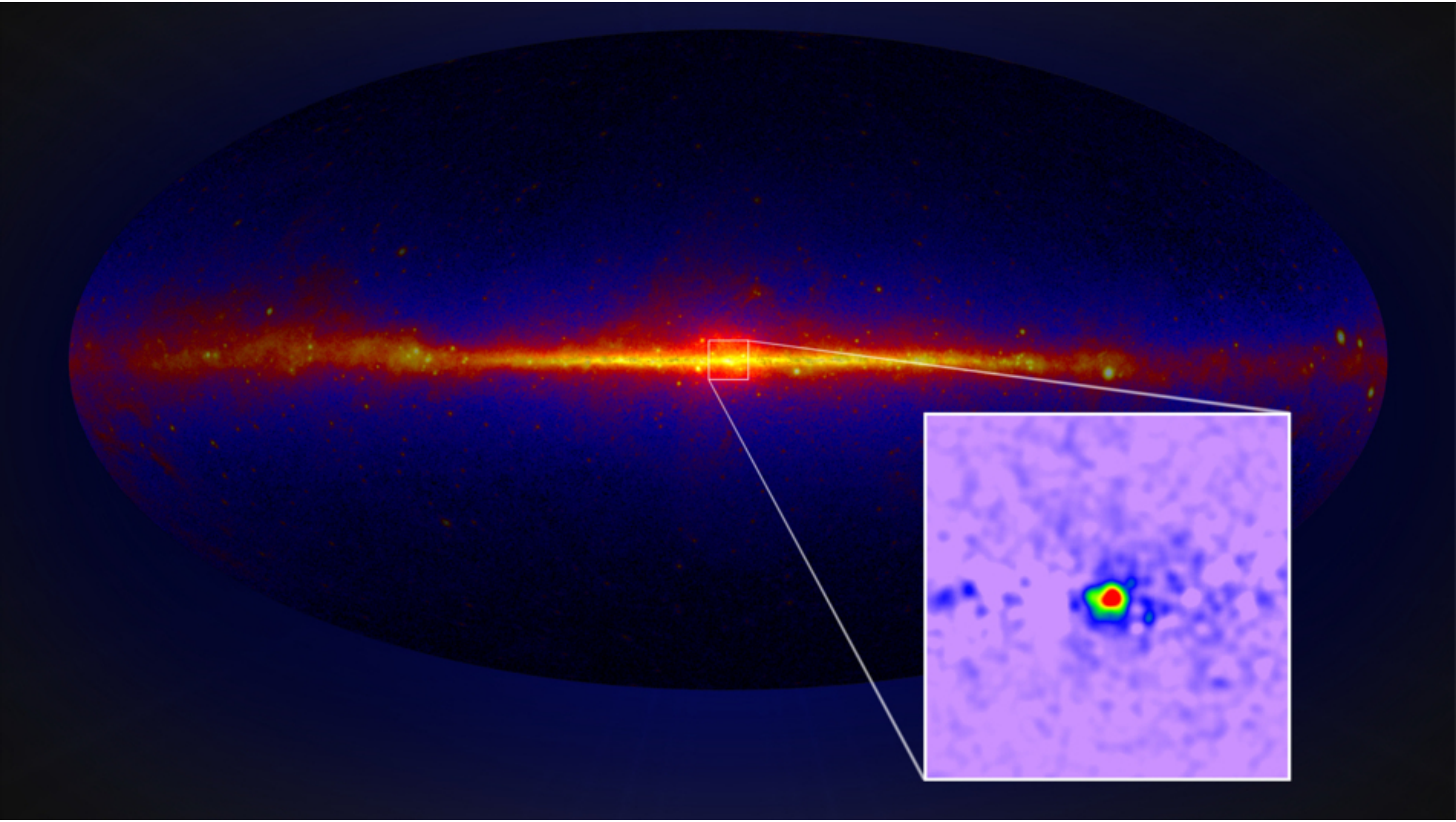
Charbonnier et al, MNRAS 418 (2011) 1526

Galactic center: an "excess" ?

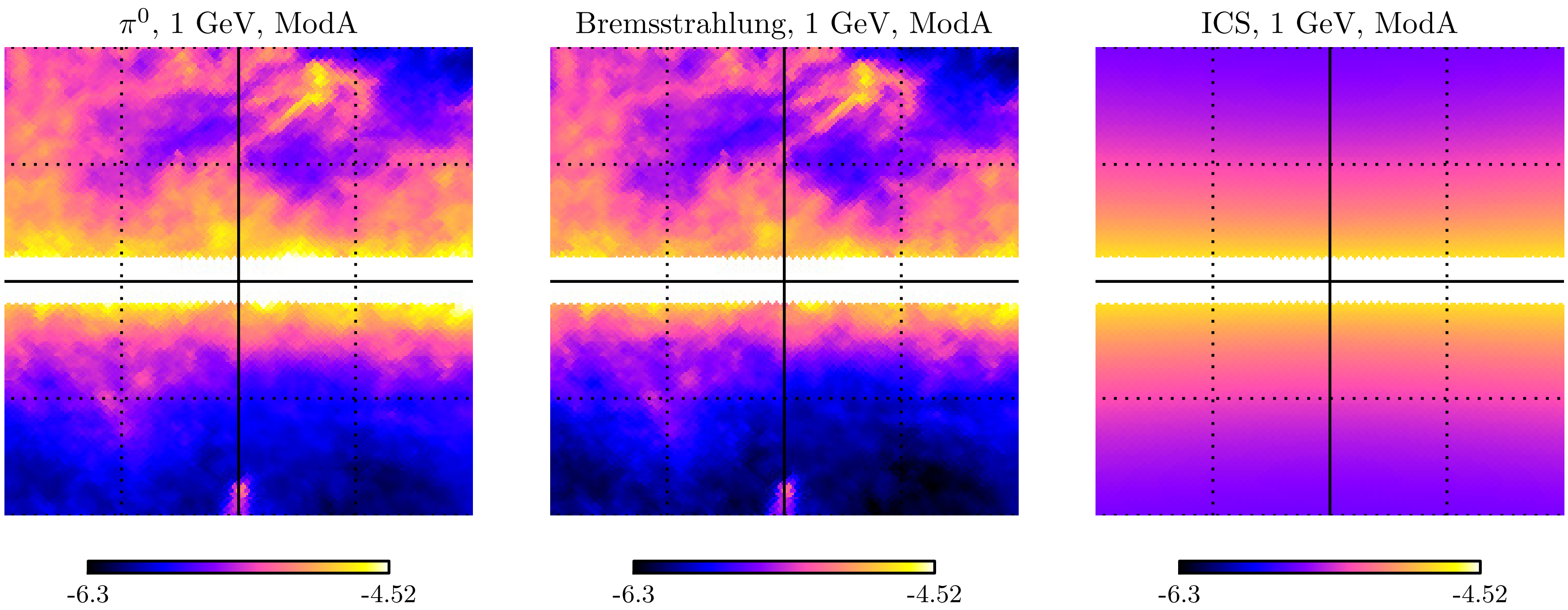


Daylan et al, Phys Dark Univ 12 (2016) 1

Hooper, Goodenough, PLB (2011) 697 (2011)
Hooper, Linden, PRD 84 (2011) 123005
Boyarsky et al., PLB (2011) 705
Daylan et al., Phy Dark Univ 12 (2016) 1
Abazajian et al, PRD 90 (2014) 023526
Lacroix, Boehm, Silk, PRD 90 (2014) 043508

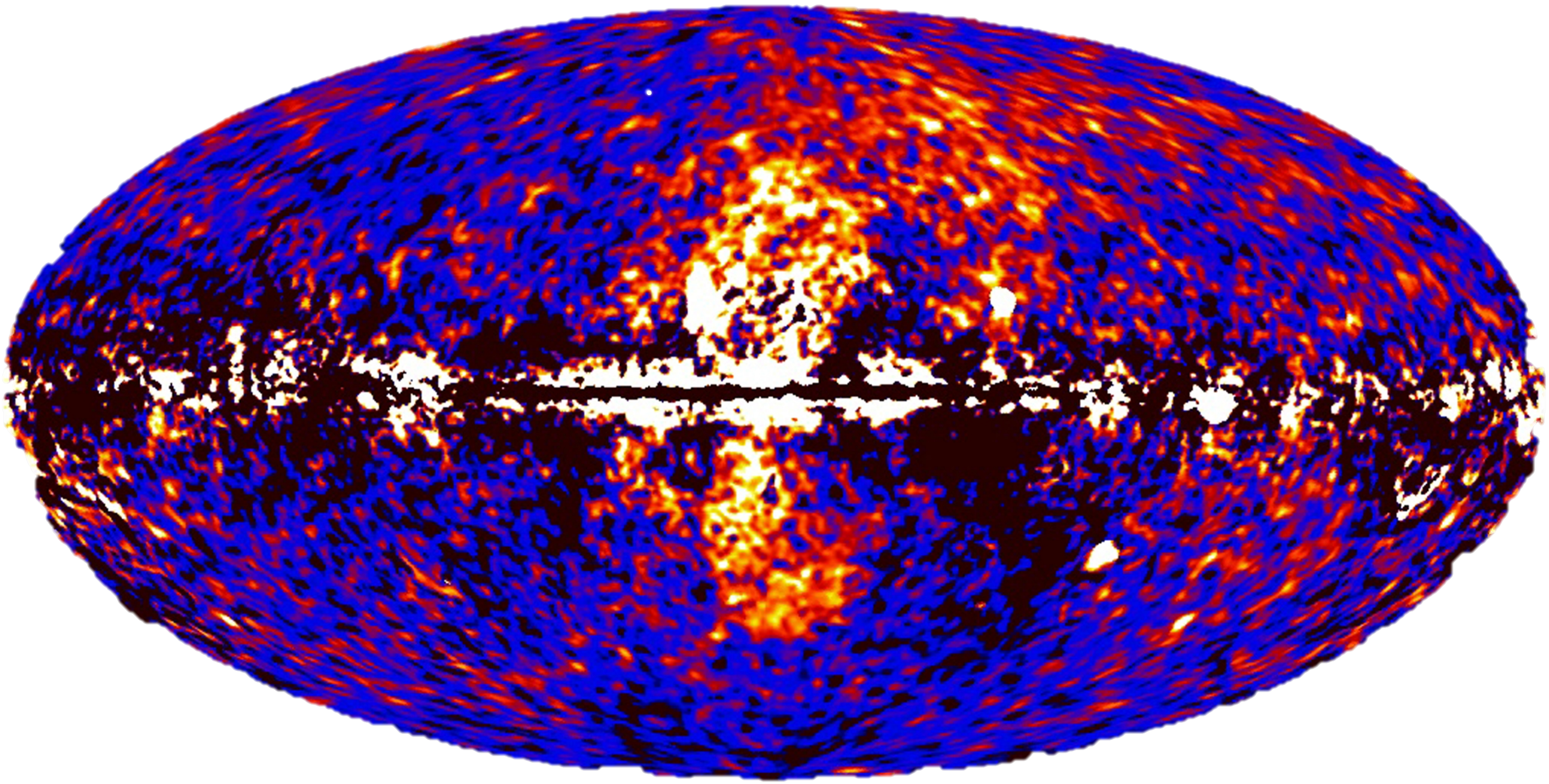


Galactic components: modeling

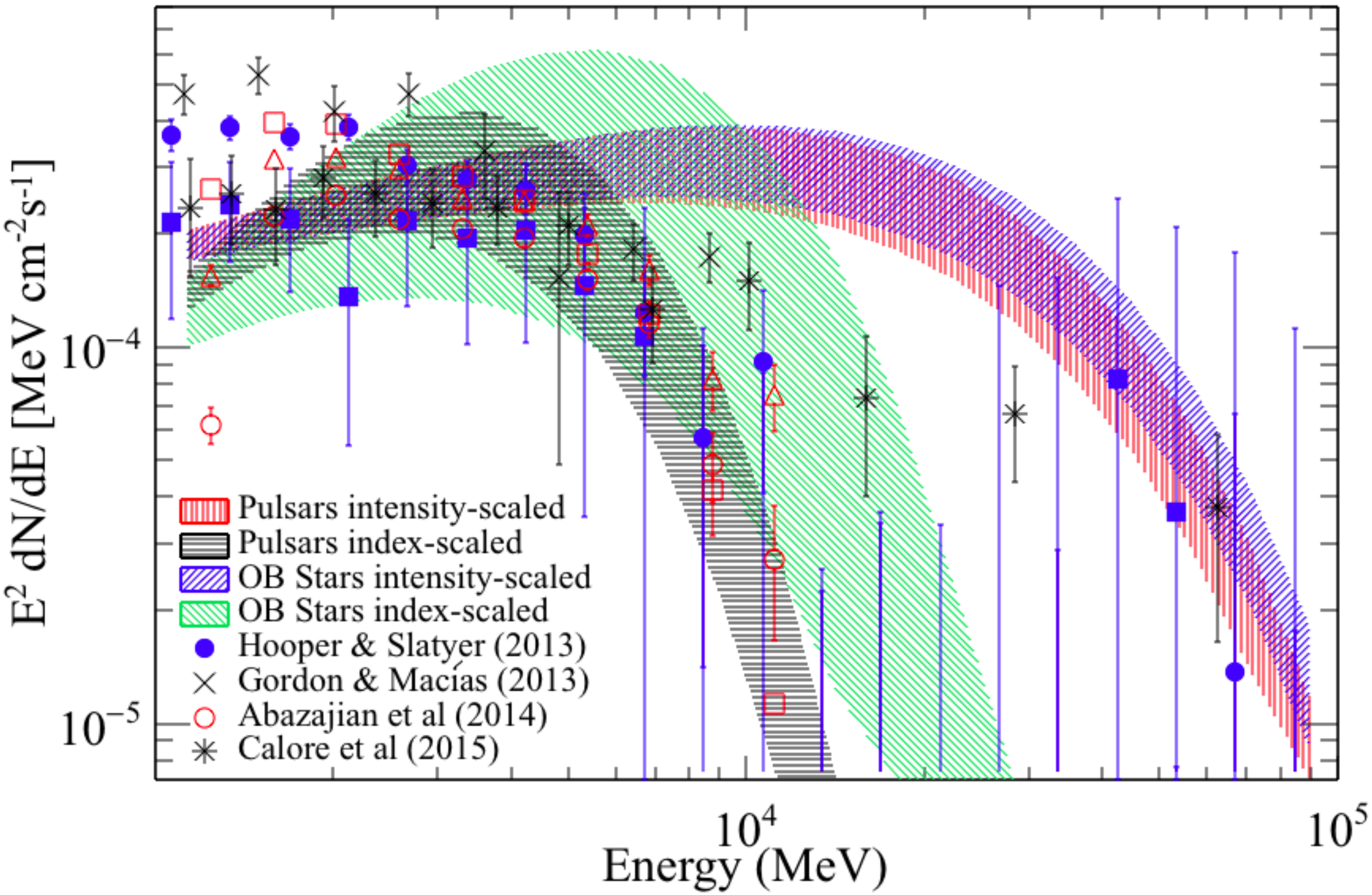


Calore, Cholis, Weniger, JCAP 03 (2015) 038

FERMI "bubbles"

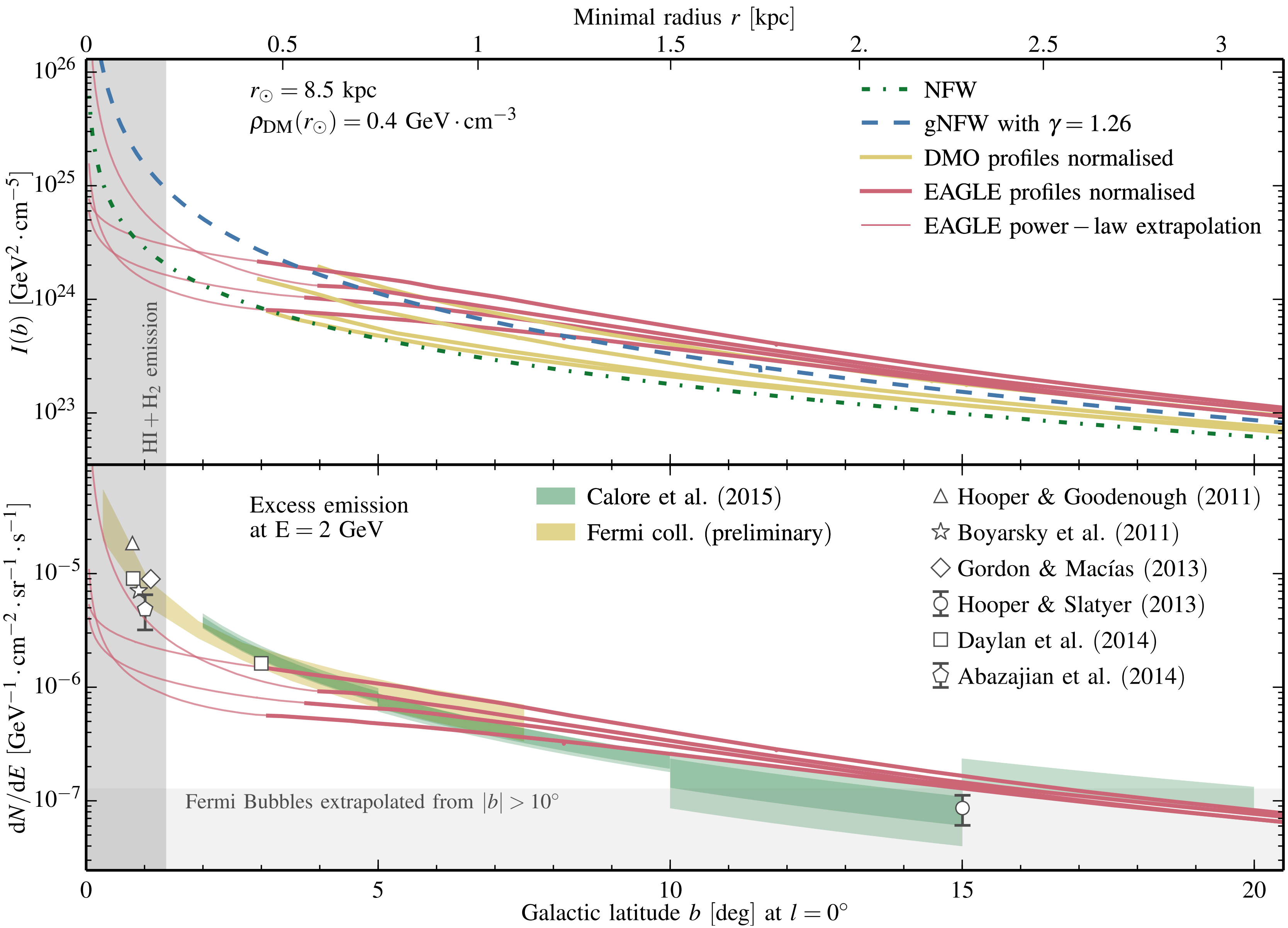


Spectrum of the excess



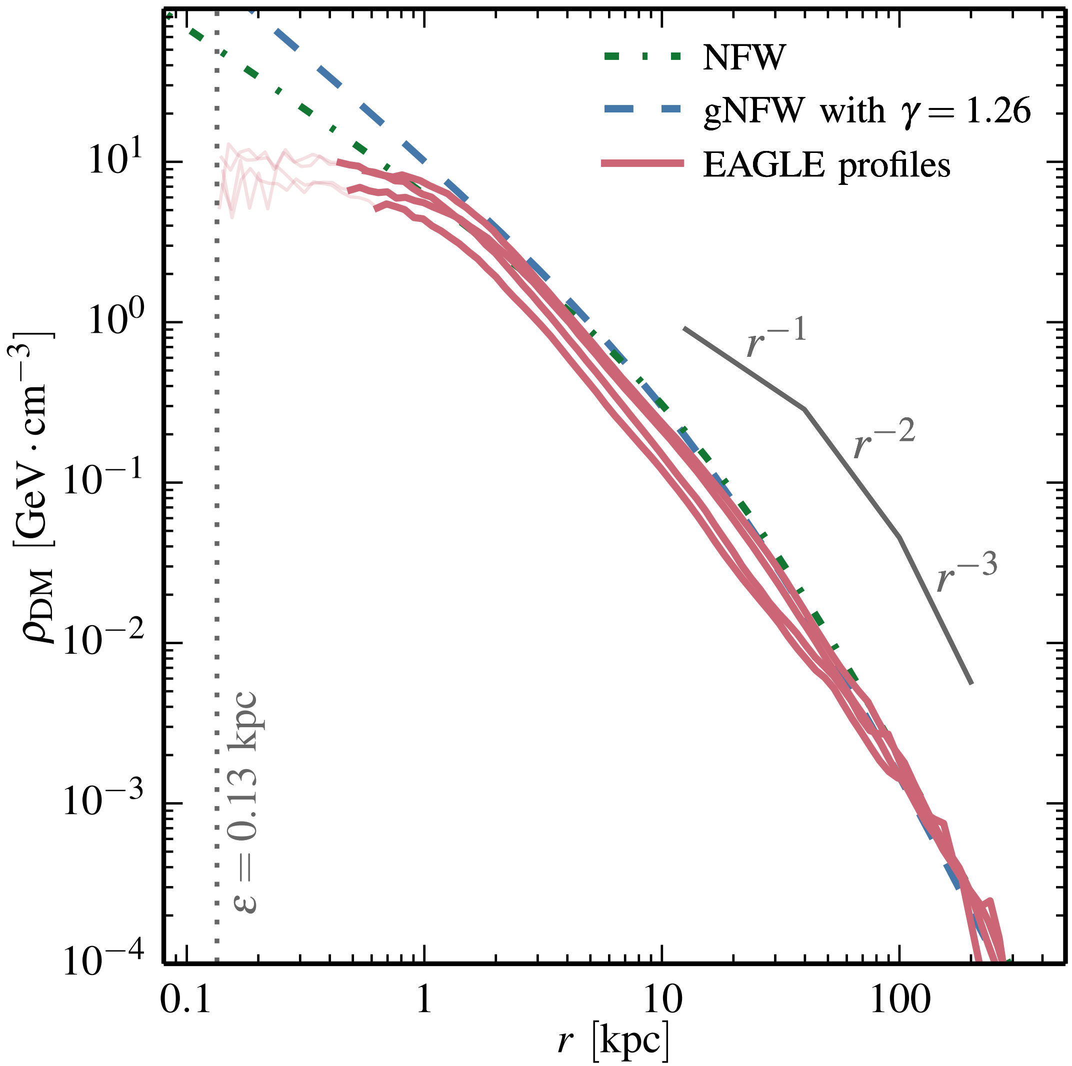
Ajello et al, ApJ 819 (2016) 44

Radial profile of the excess



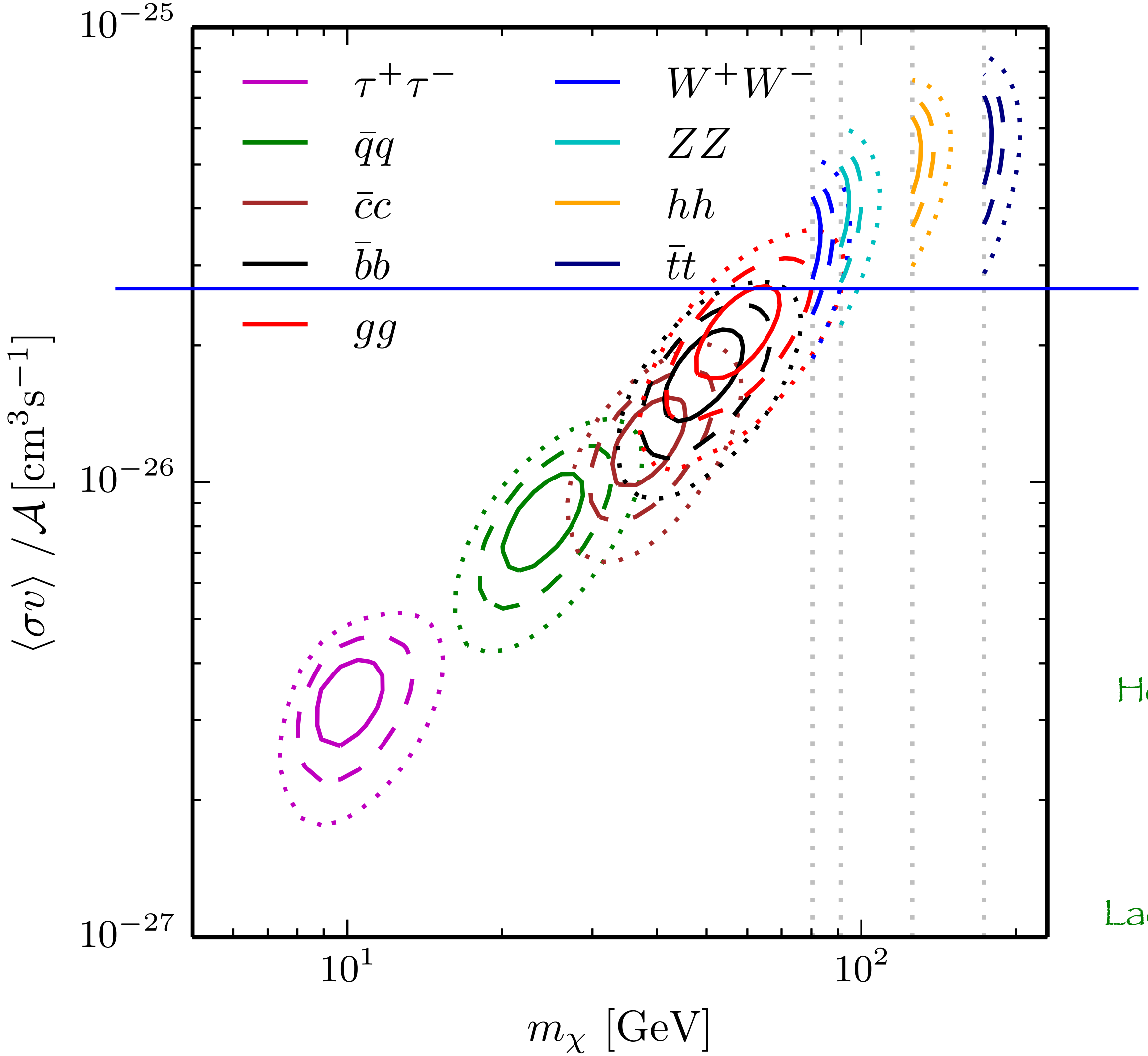
Schaller et al, MNRAS 455 (2016) 4442

DM density profiles



Schaller et al, MNRAS 455 (2016) 4442

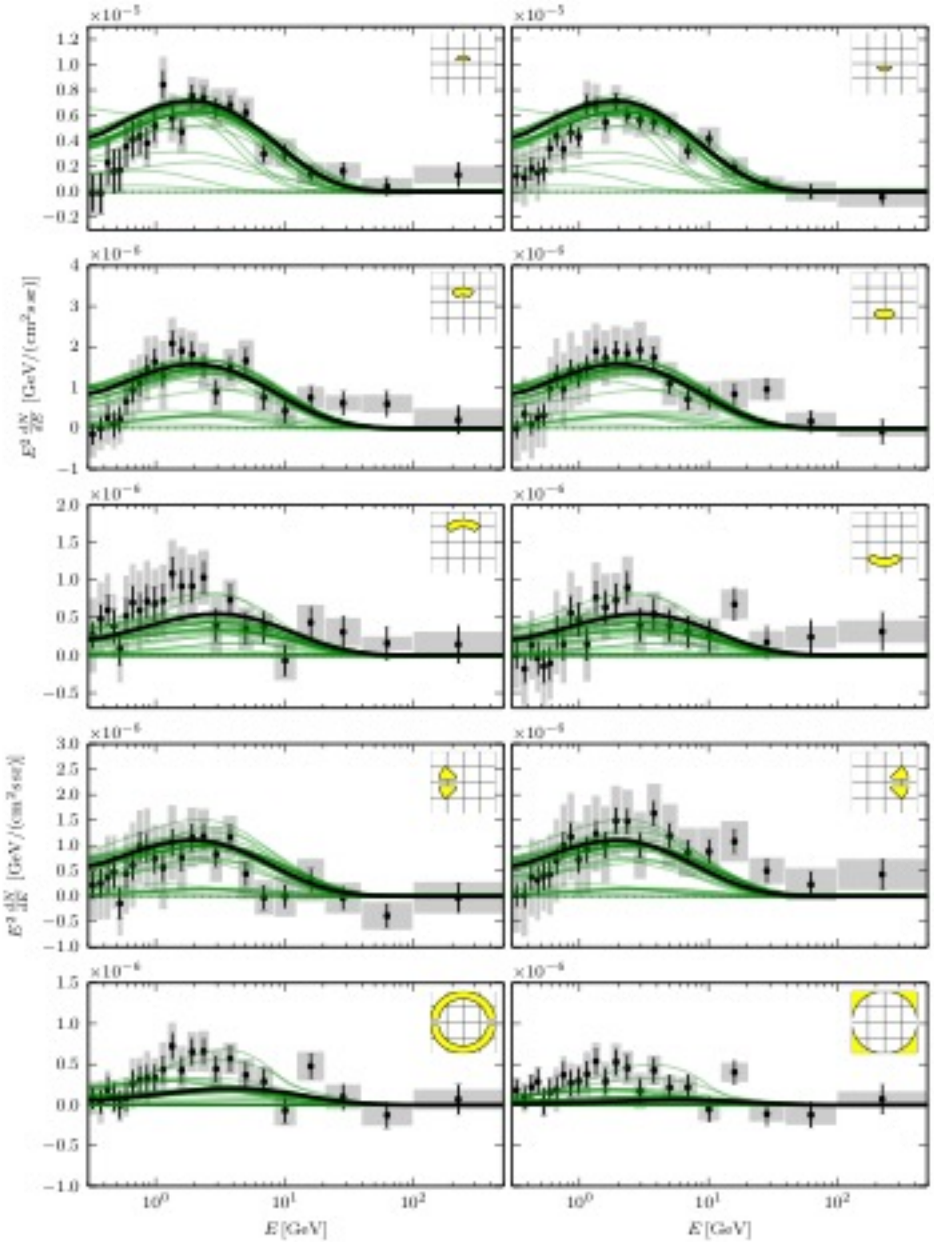
DM interpretation



Calore et al, PRD 91 (2015) 063003

Hooper, Goodenough, PLB (2011) 697 (2011)
Hooper, Linden, PRD 84 (2011) 123005
Boyarsky et al., PLB (2011) 705
Daylan et al., Phy Dark Univ 12 (2016) 1
Abazajian et al, PRD 90 (2014) 023526
Lacroix, Boehm, Silk, PRD 90 (2014) 043508

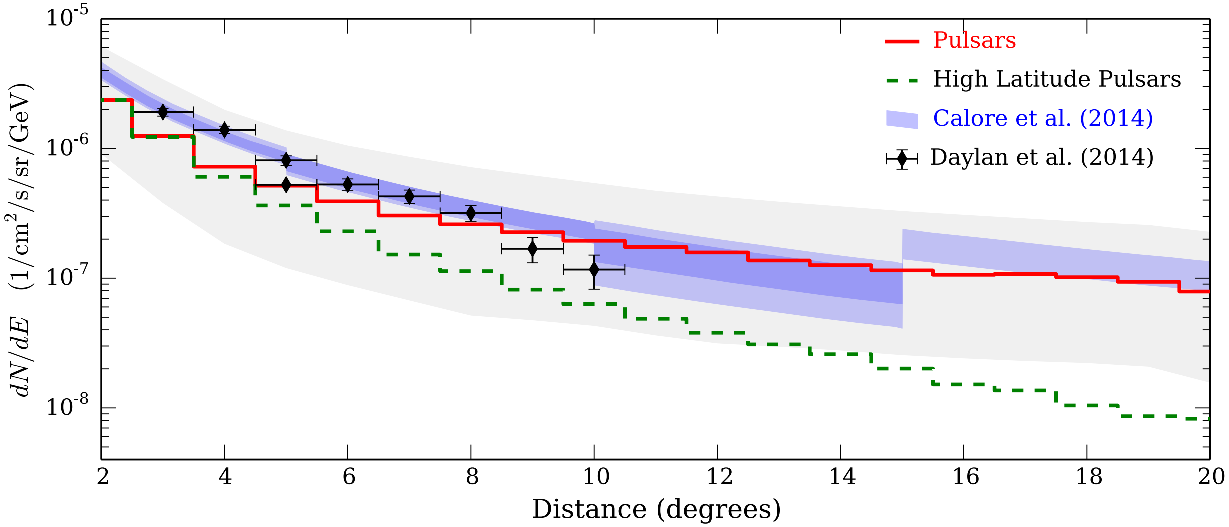
Leptonic cosmic ray outbursts

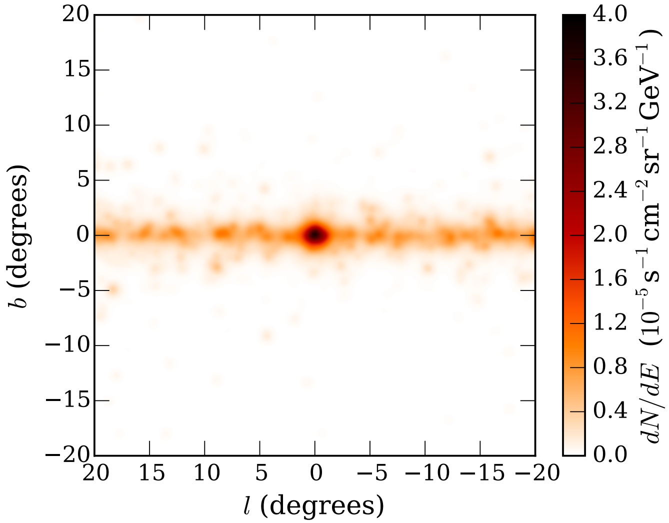


Models with 2 burts events

Cholis et al, JCAP 1512 (2015) 12

Unresolved pulsars



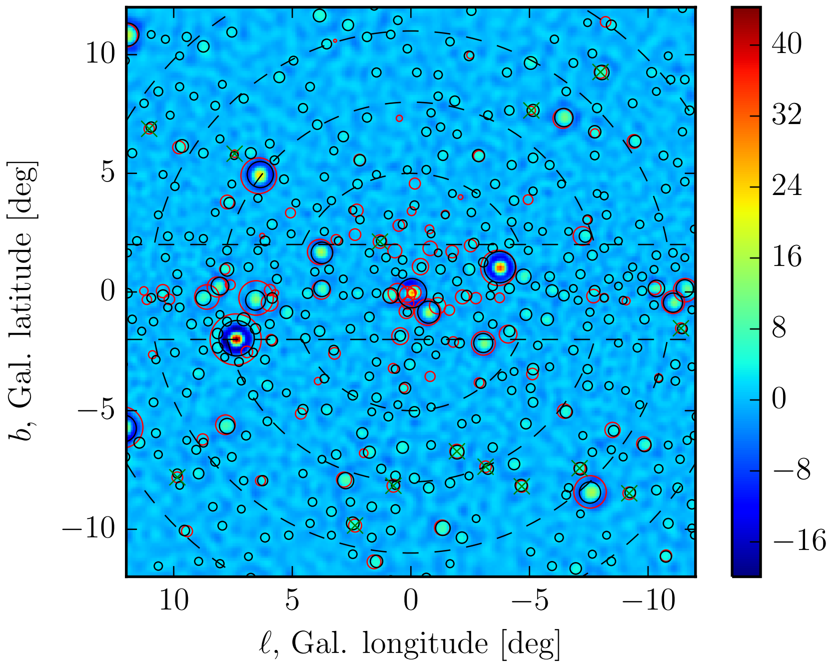


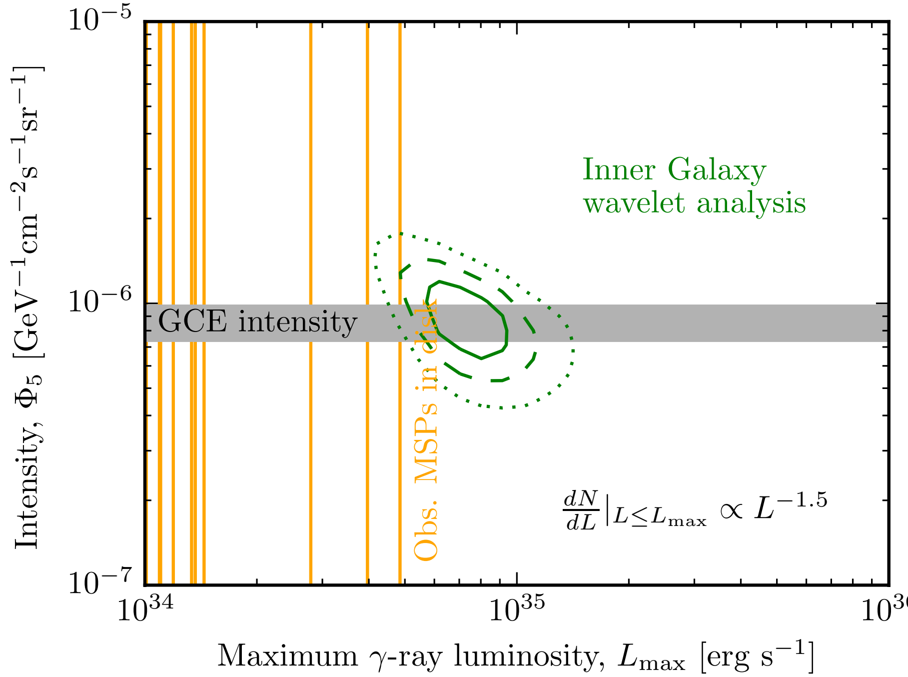
O'Leary et al, 1504.02477

Petrovic et al, 1411.2980

Conclusions strongly depend on MSP assumptions

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