Eighth International Fermi Symposium, Baltimore, October 14-19th 2018

Dark matter through gamma-ray cross-correlations with gravitational tracers

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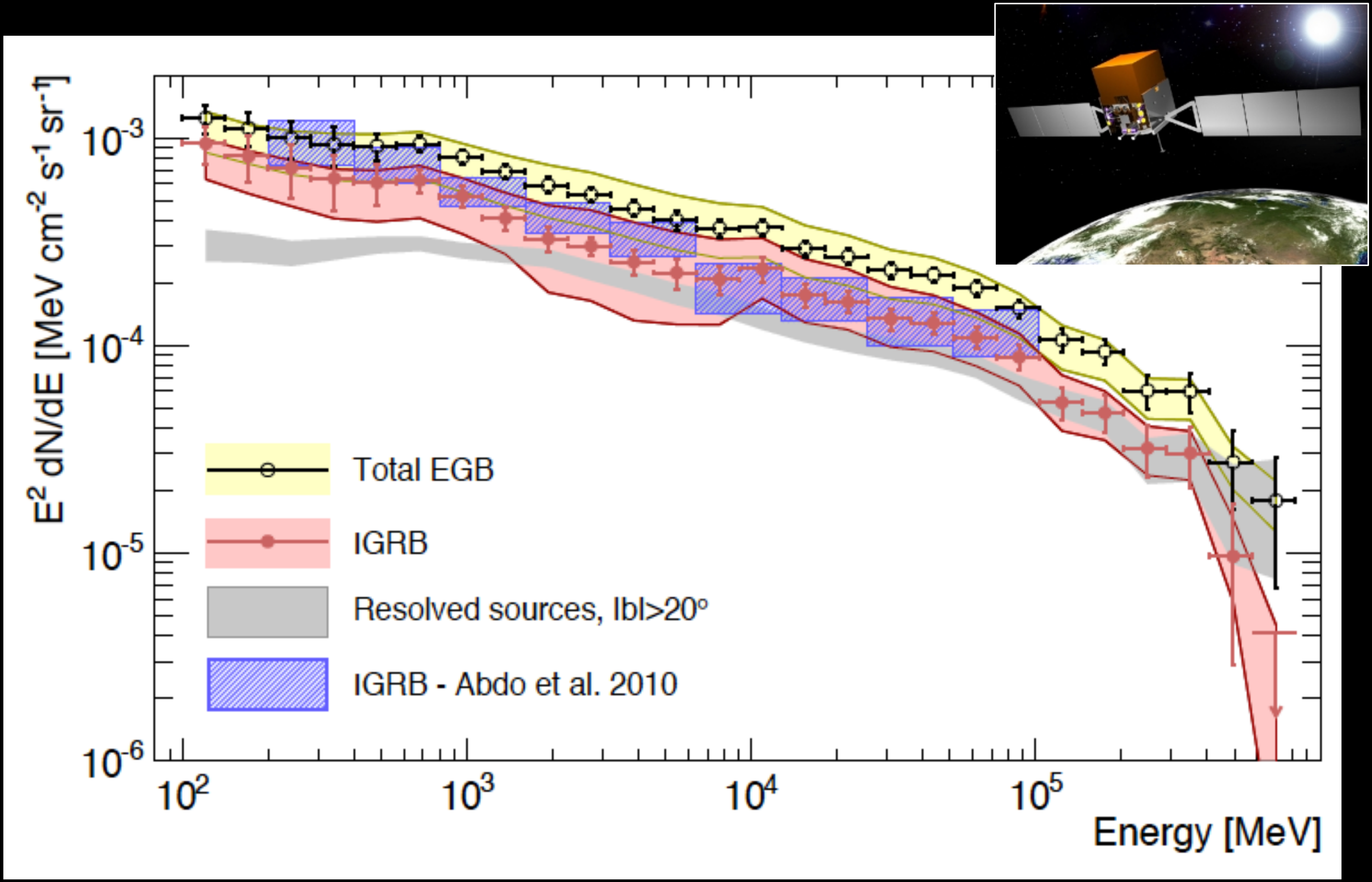
Fermi-LAT 5 years

Extragalactic gamma-ray background

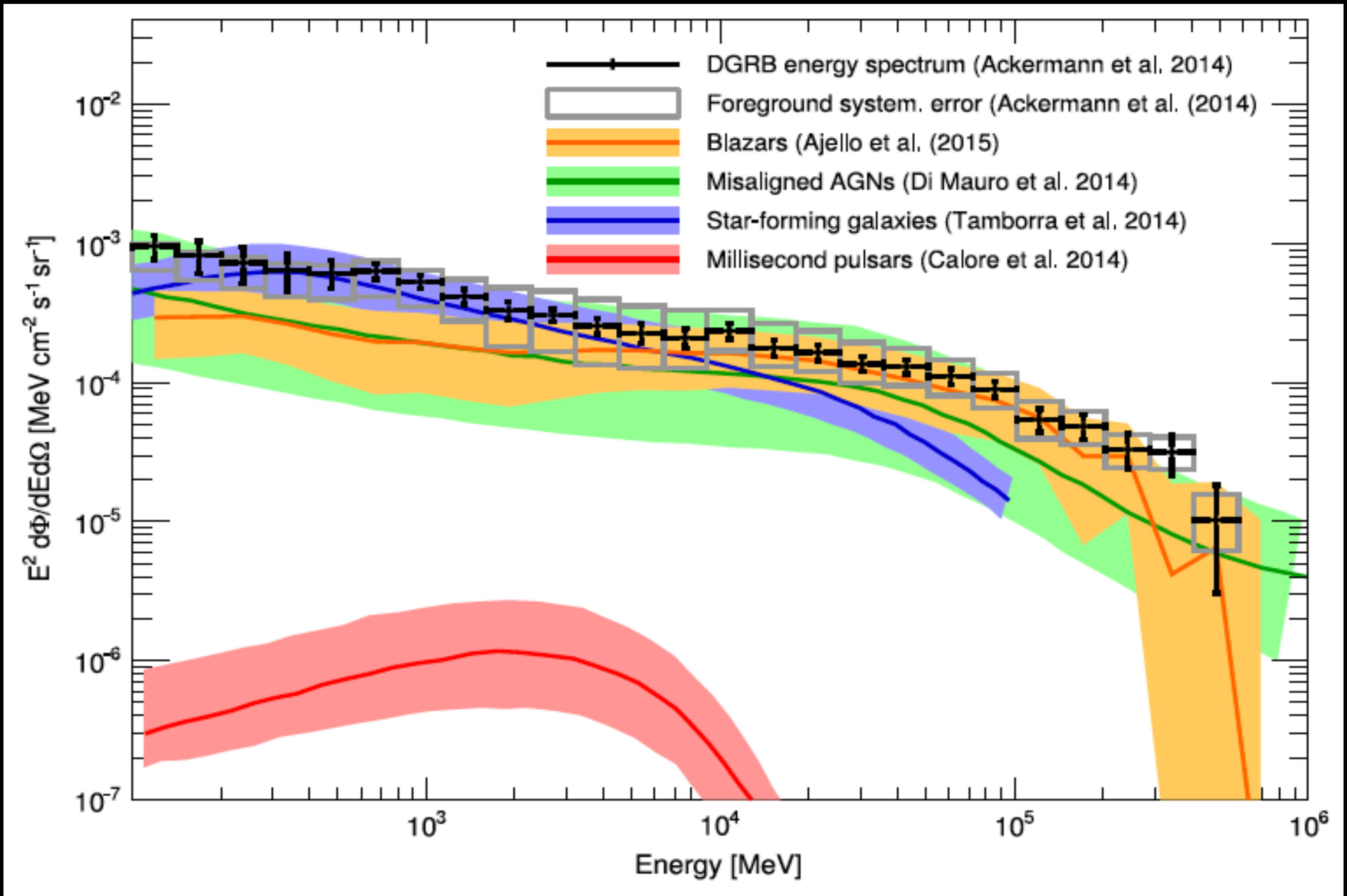


Fermi collaboration (2015)

Unresolved gamma-ray background

Contributors

FSRQ, BL Lacs, galaxies, pulsars, UHECR, … and dark matter?

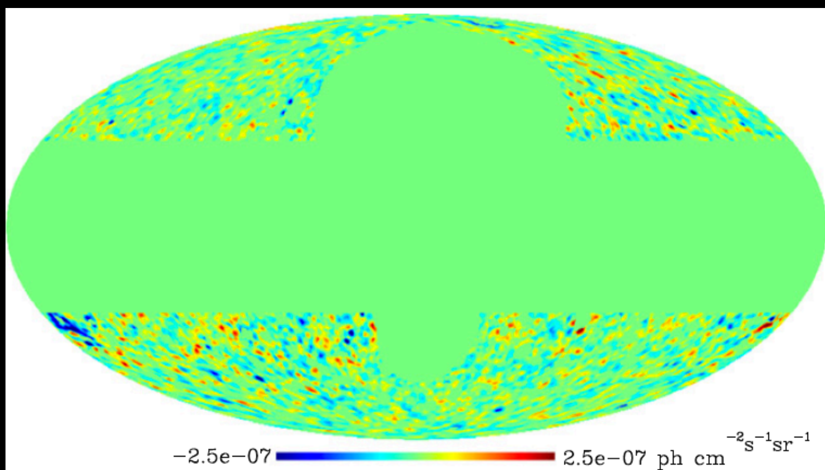


Fornasa & Sanchez-Conde (2015)

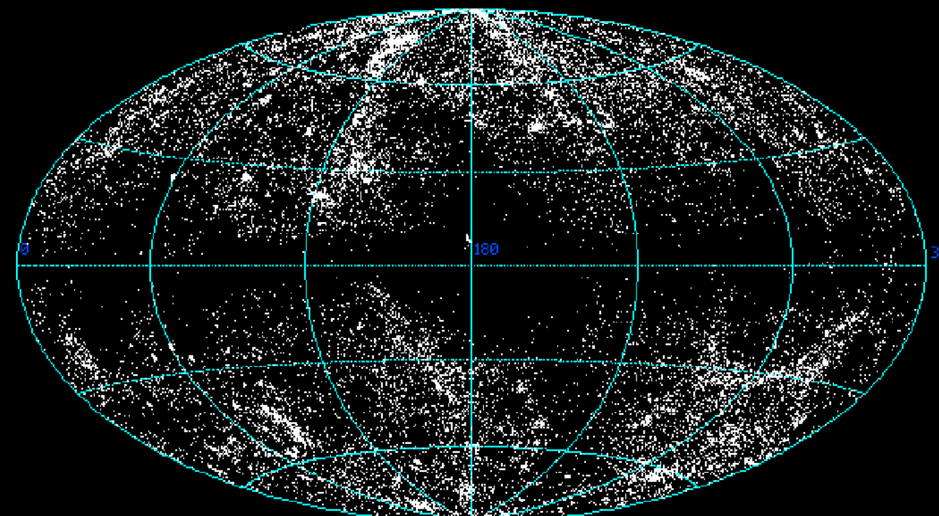
Angular cross correlation

Use anisotropy to help probe contributions

We'd like to test the origins of the noise-dominated unresolved gamma-ray data:



…we can get help by using signal-dominated datasets that trace source populations



Advantage: will also largely negate concerns for foreground modeling

2PCF: excess probability (of finding a pair of objects i and j at a certain scale) above what is expected from unclustered random distributions

$$\langle \delta_i(\theta_1)\delta_j(\theta_2)\rangle \rightarrow \mathrm{CCF}^{ij}(|\theta_1 - \theta_2|) \rightarrow C_l^{ij}$$

(physical) *(harmonic)*

Cuoco et al (2008), Ando & Pavlidou (2009), Camera et al (2013), …

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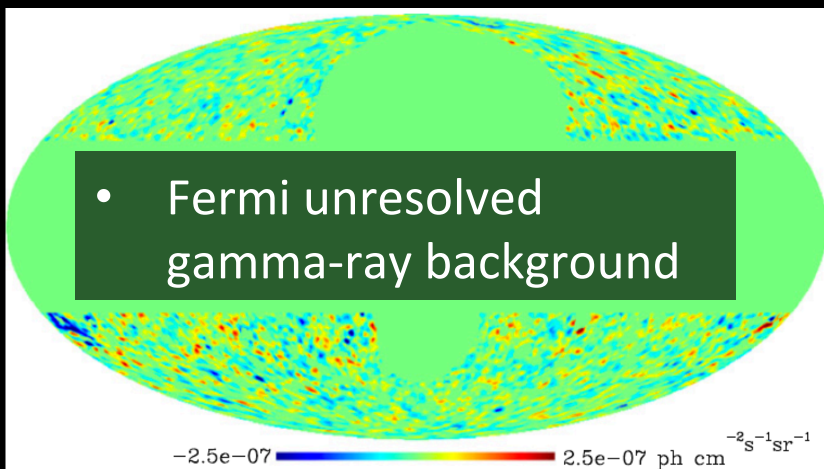

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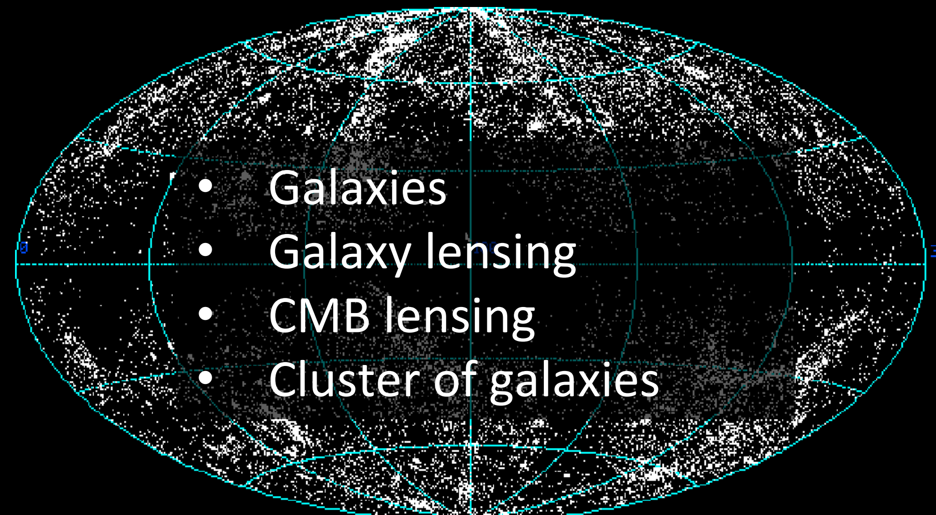

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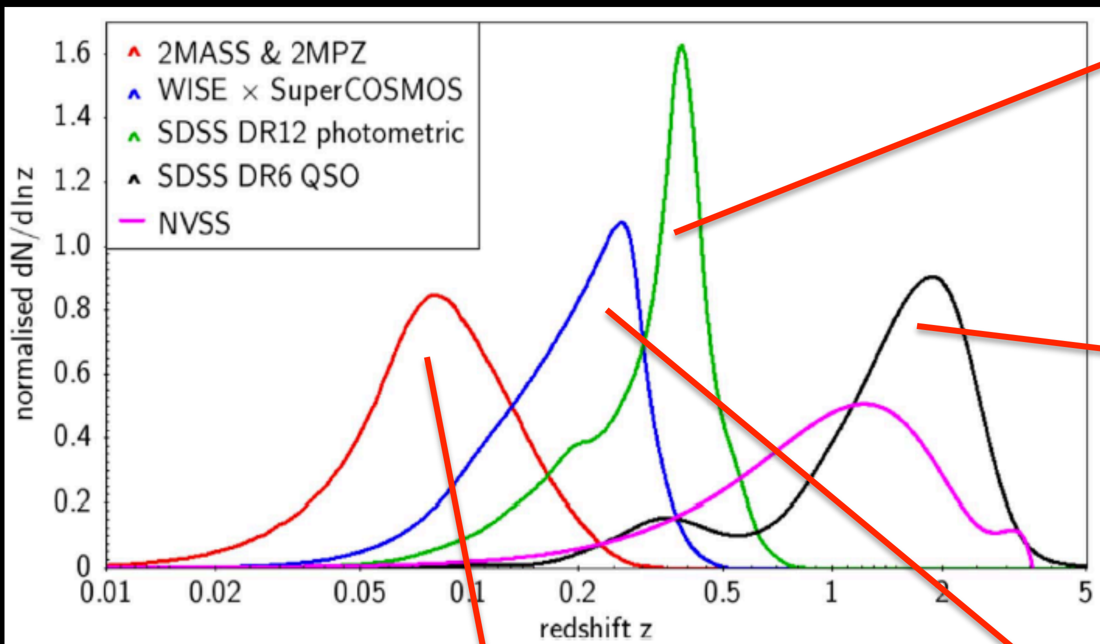
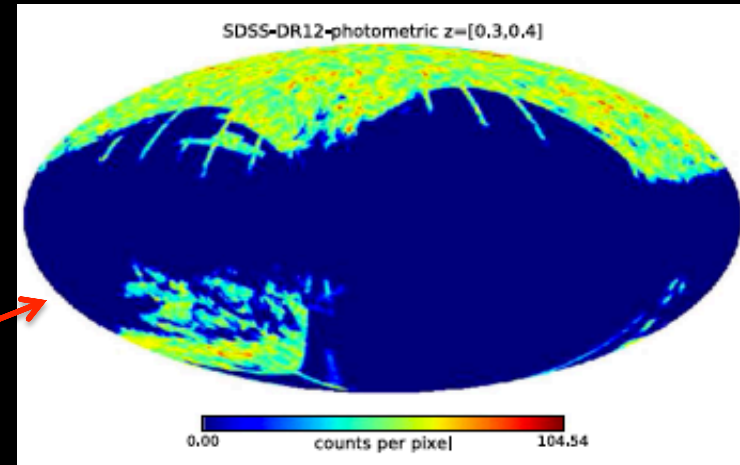
CORRELATION WITH GALAXIES

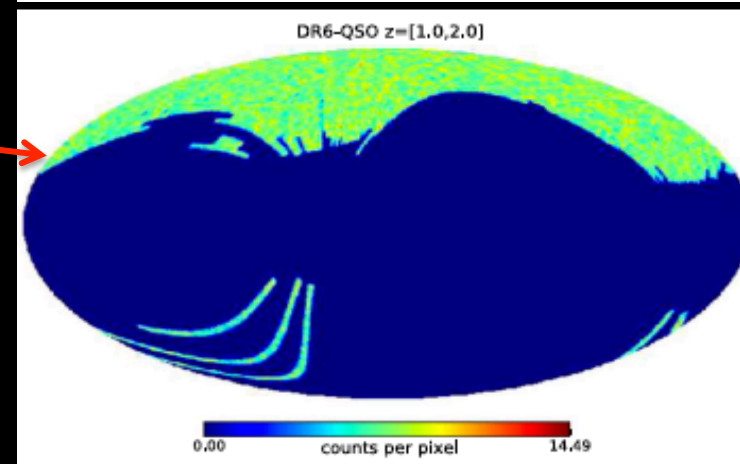
Galaxy catalogs

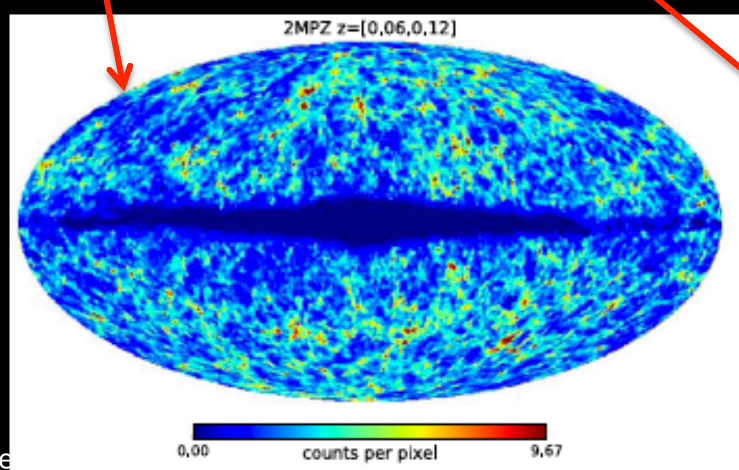
Many galaxy catalogs:

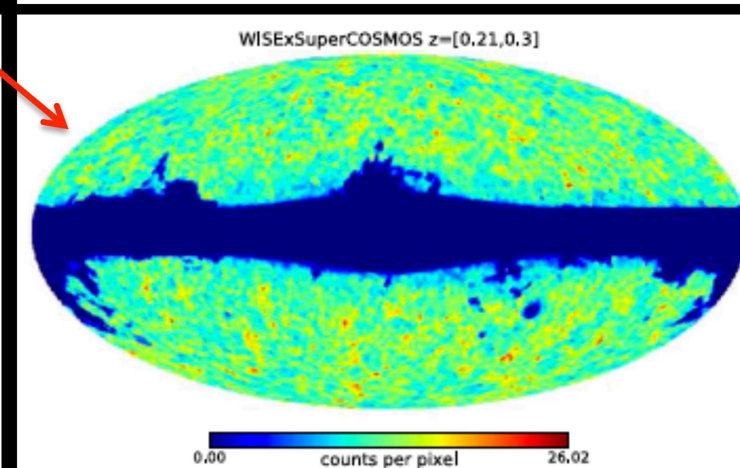


Cuoco et al (2017)



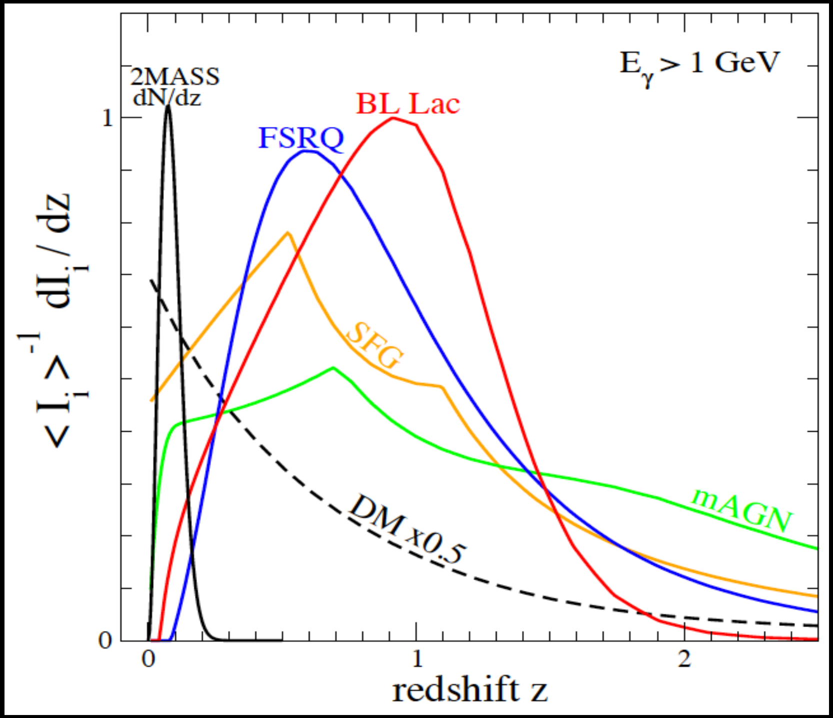


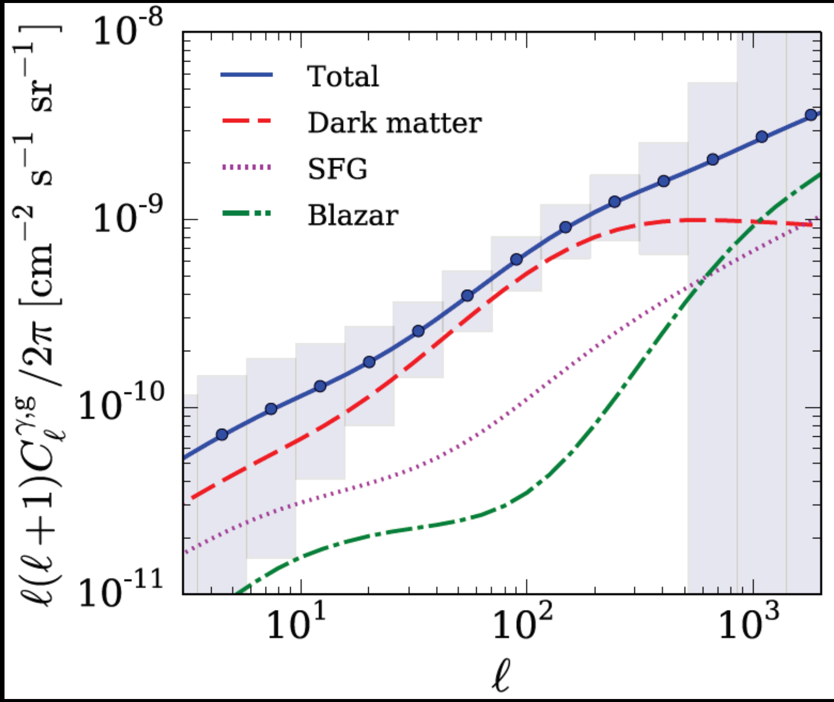




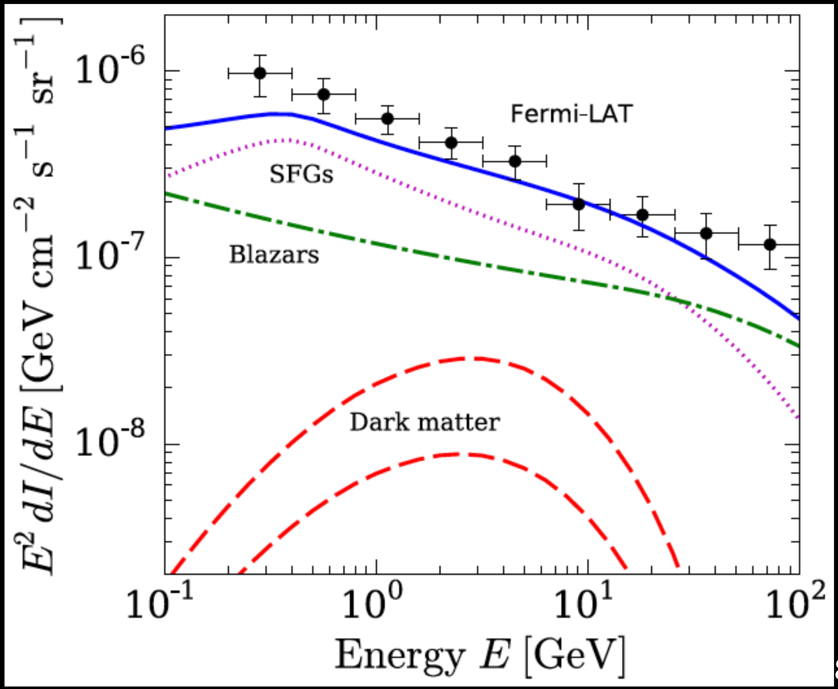
Tomography

Multiple galaxy catalogs will provide tomographic information to help unravel contributors.



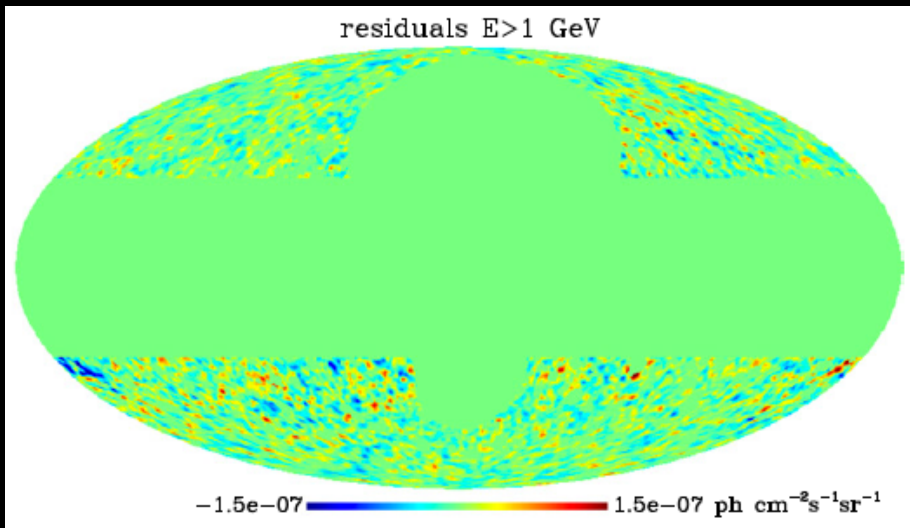


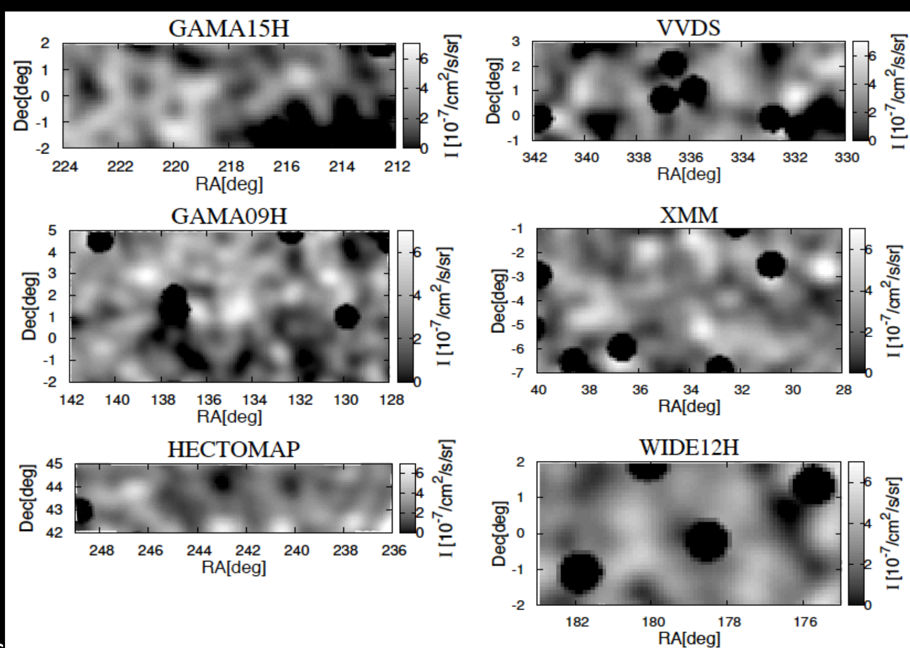
e.g., 2MASS overlaps nicely with DM, predicting strong correlation, despite small contribution to total intensity



Ando 2014

Datasets





Gamma rays

- Energies 500 MeV or 1 GeV and above

  **balance of PSF & statistics*

- Fit & remove Galactic emission

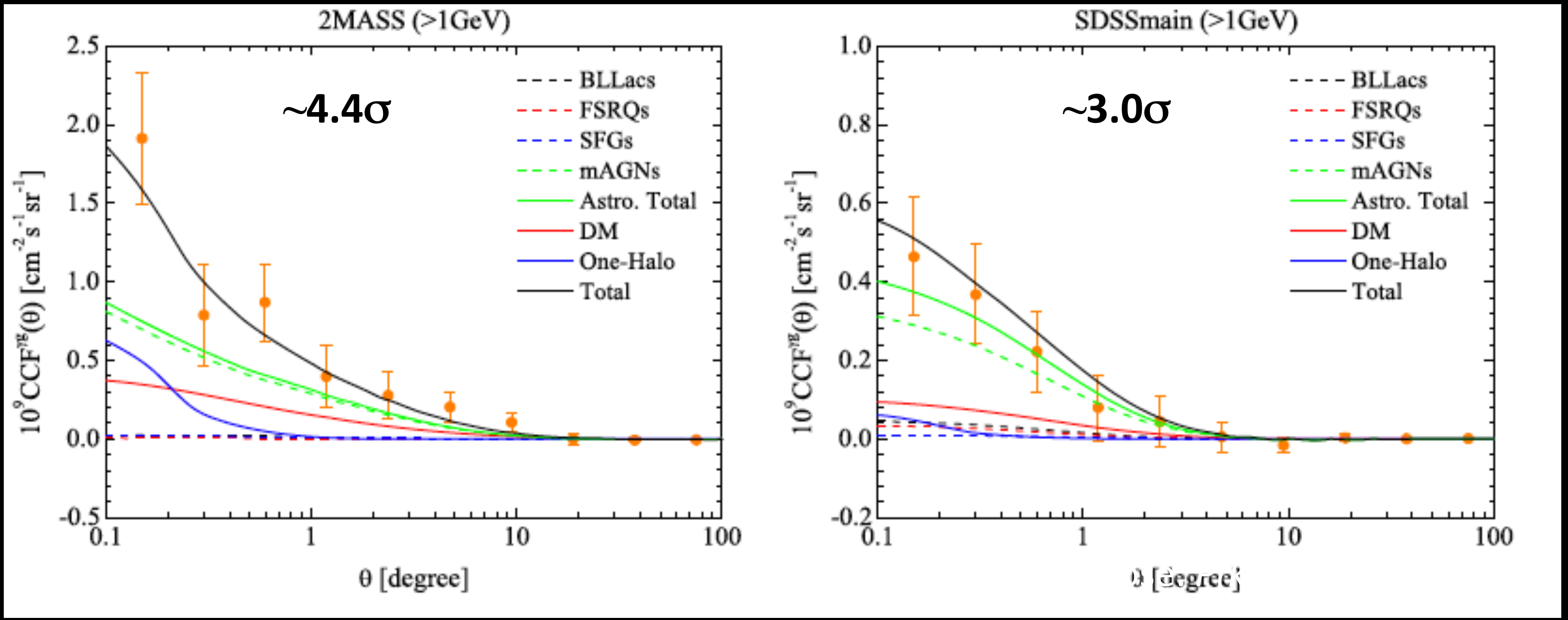
  **foregrounds not expected to correlate with LSS maps*

- Mask point sources
- Mask large diffuse structures: Galactic disk, Fermi bubbles, loop I

(similar procedures for most cross correlation analyses)

First detection of cross correlation

- Use 5 galaxy catalogs, 5 yrs Fermi P7REP from 500 MeV to 100 GeV
- Many sanity checks: estimator, Galactic diffuse, null detection in mock realizations



Xia et al (2015), interpretation in Cuoco et al (2015)

- 2MASS, NVSS, SDSS-MG, -LRG, -QSO
- Astrophysical sources modeled under the halo model can explain the correlations (except NVSS which needs additional shot noise term)

$$C_l^{(ij)} = \int \frac{d\chi}{\chi^2} W_i(\chi) W_j(\chi) P_{ij}(k = l/\chi, \chi)$$

i: galaxy catalog, j: astrophysical source

New correlation analyses

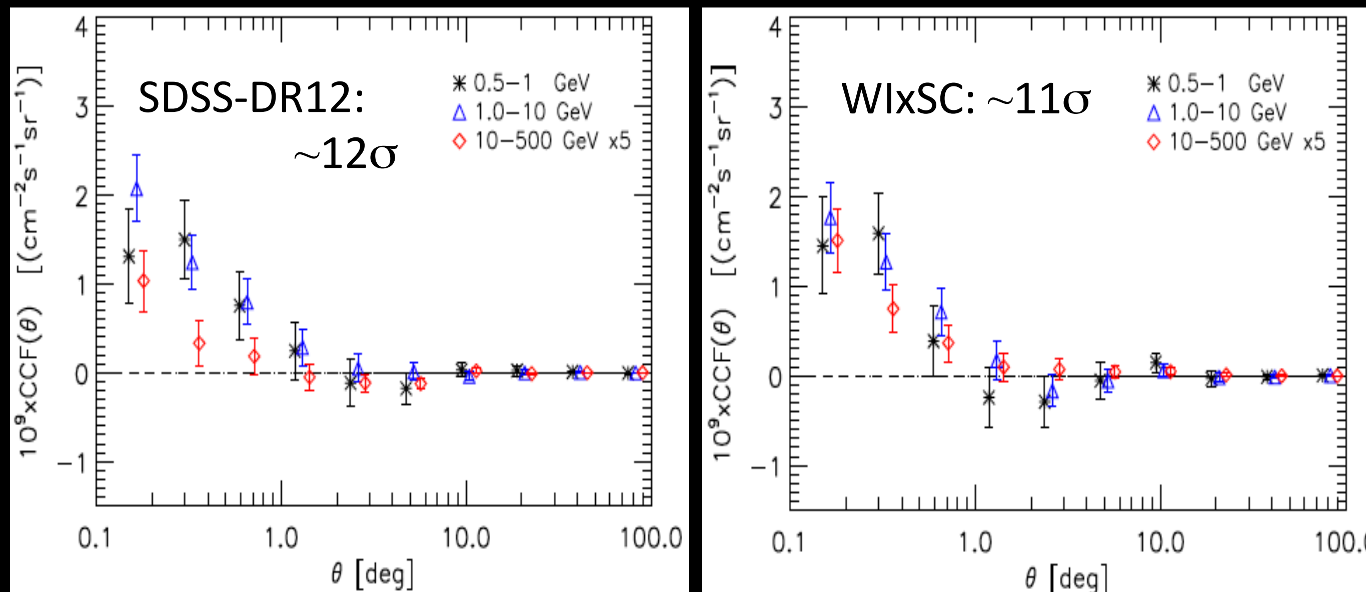
- More data (6.5 yrs P8 >0.25 GeV), more galaxies, additional redshift tomography

→ Higher detection significances (e.g., $\sim 12\sigma$ for SDSS-DR12, $\sim 11\sigma$ for WIxSC)

- CC varies by catalog, energy range, and redshift

→ sources with different properties contribute differently to UGRB

Stay tuned…



Cuoco et al (2017)

New correlation analyses

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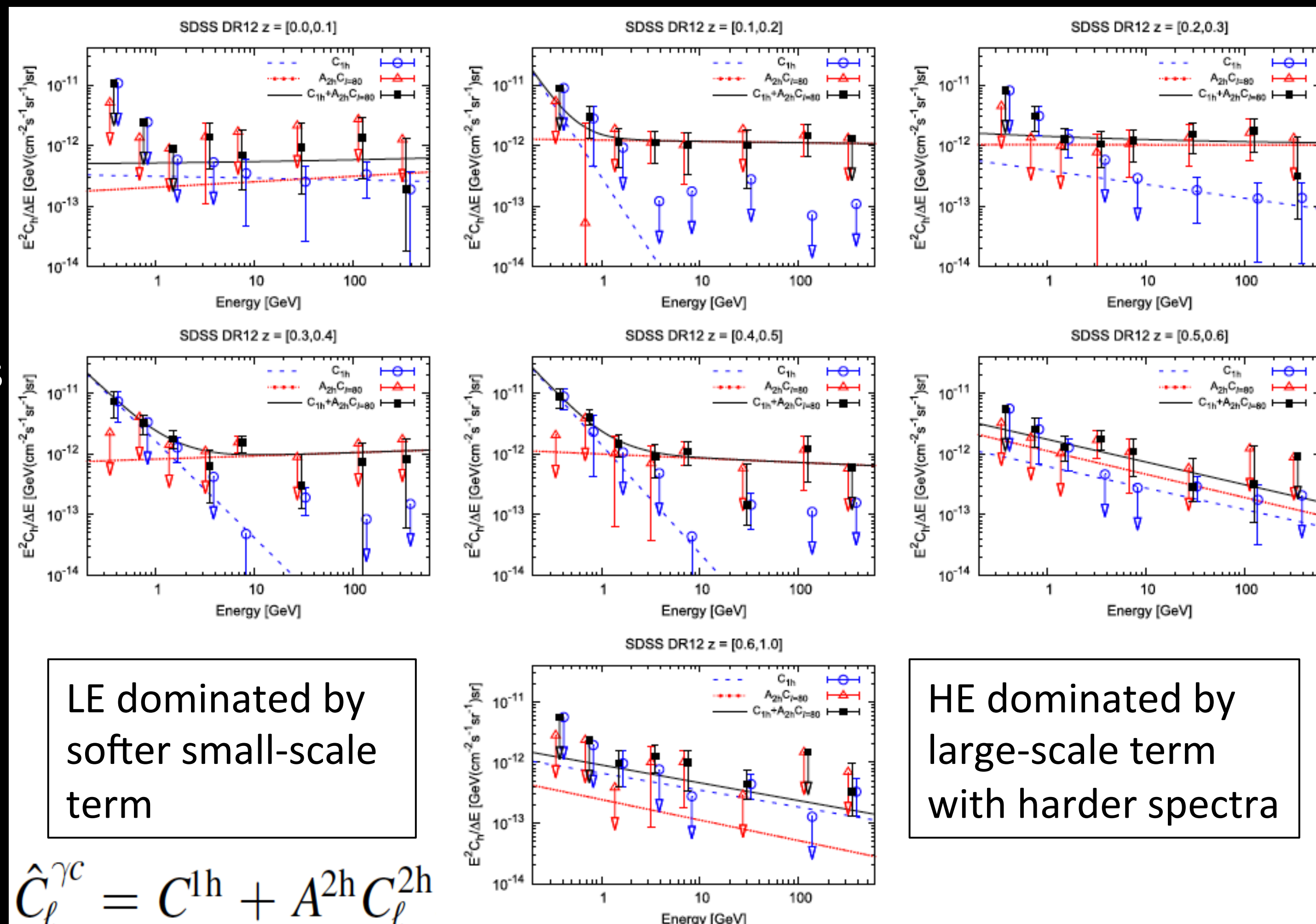
Stay tuned…

- Spectrum shows hints of an energy break



LE dominated by softer small-scale term

HE dominated by large-scale term with harder spectra

$$\hat{C}_\ell^{\gamma c} = C^{1h} + A^{2h} C_\ell^{2h}$$

New correlation analyses

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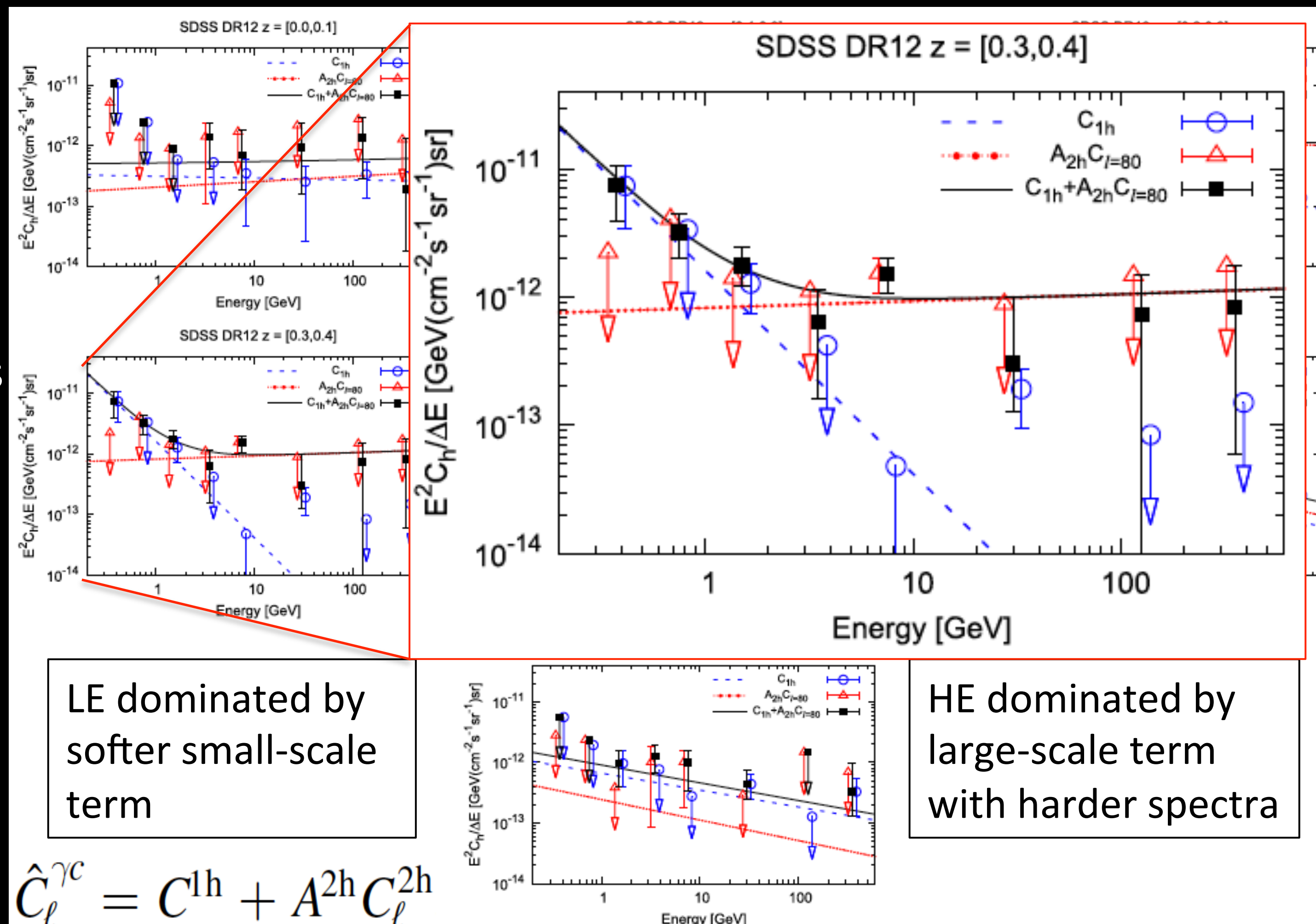

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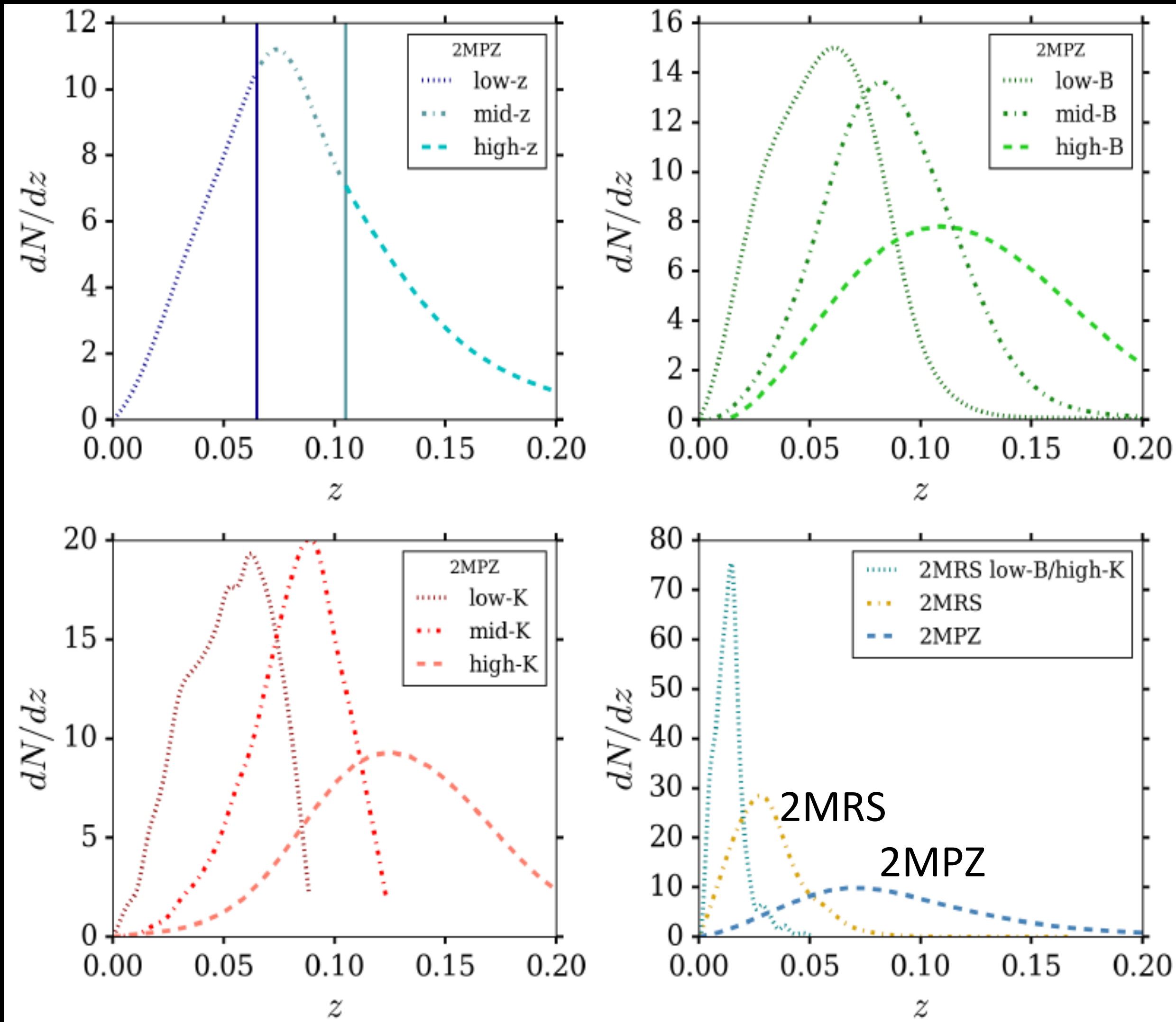
Focus on the 2MASS (2MPZ)

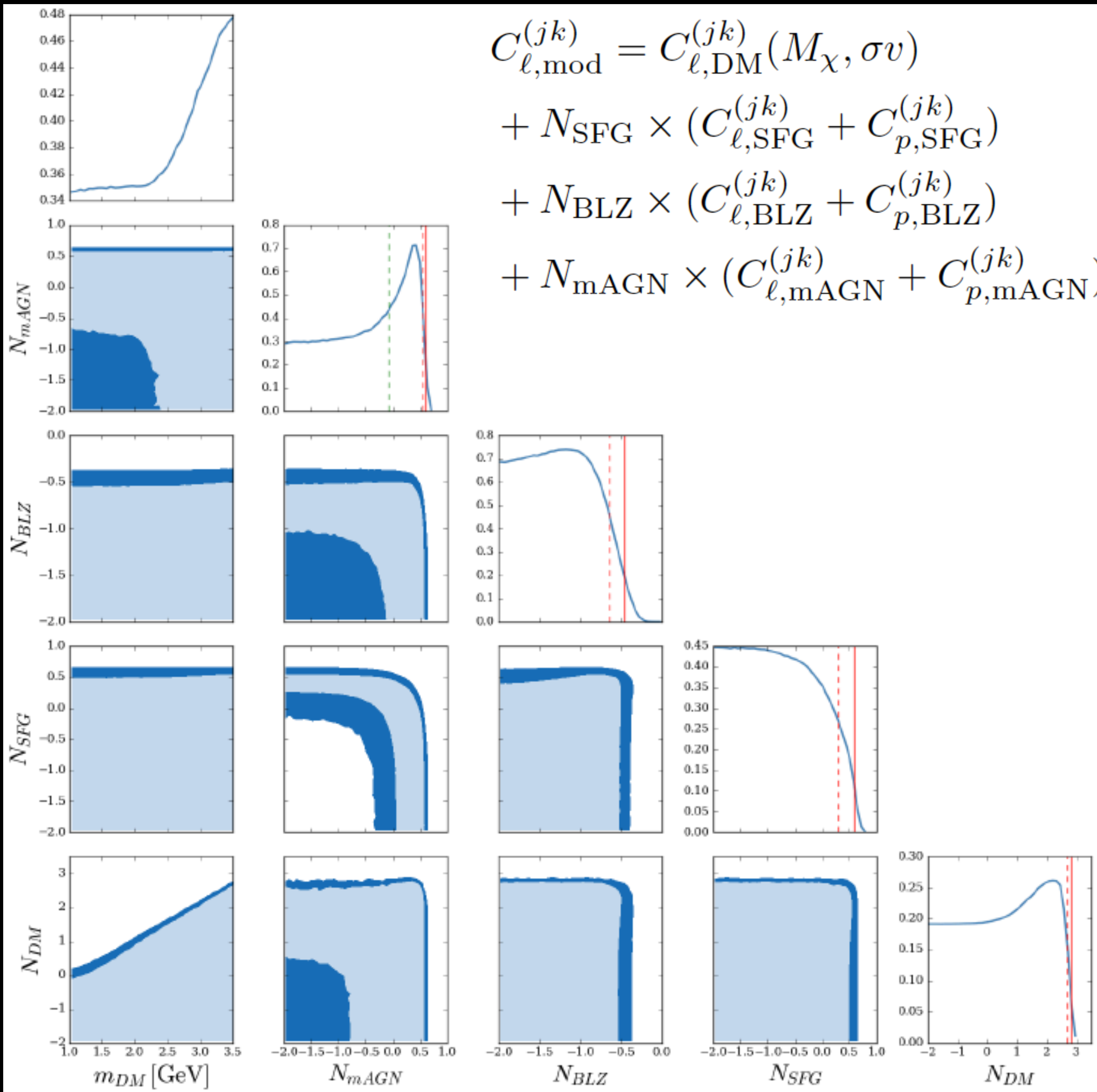


Ammazzalorso et al (2018)

Focus on 2MPZ

- 2MPZ: 2MASS with 8 multi-wavelength data.
- 2MRS: subset of 2MPZ with spec-z
- Further split into redshift, B-band, and K-band samples
- Correlate with 9 yrs of P8 Fermi-LAT data

Focus on the 2MASS (2MPZ)



$$
\begin{aligned}
C_{\ell,\mathrm{mod}}^{(jk)} &= C_{\ell,\mathrm{DM}}^{(jk)}(M_\chi, \sigma v) \\
&+ N_{\mathrm{SFG}} \times (C_{\ell,\mathrm{SFG}}^{(jk)} + C_{p,\mathrm{SFG}}^{(jk)}) \\
&+ N_{\mathrm{BLZ}} \times (C_{\ell,\mathrm{BLZ}}^{(jk)} + C_{p,\mathrm{BLZ}}^{(jk)}) \\
&+ N_{\mathrm{mAGN}} \times (C_{\ell,\mathrm{mAGN}}^{(jk)} + C_{p,\mathrm{mAGN}}^{(jk)})
\end{aligned}
$$

Marginalized posterior distributions

- Correlation consistent with arising mostly from mAGN
- SFG and blazars appear subdominant
- 2MPZ probes local 10% of γ-rays; situation can change at higher redshifts

NB: shot-noise

With 2MPZ, can be estimated more directly:

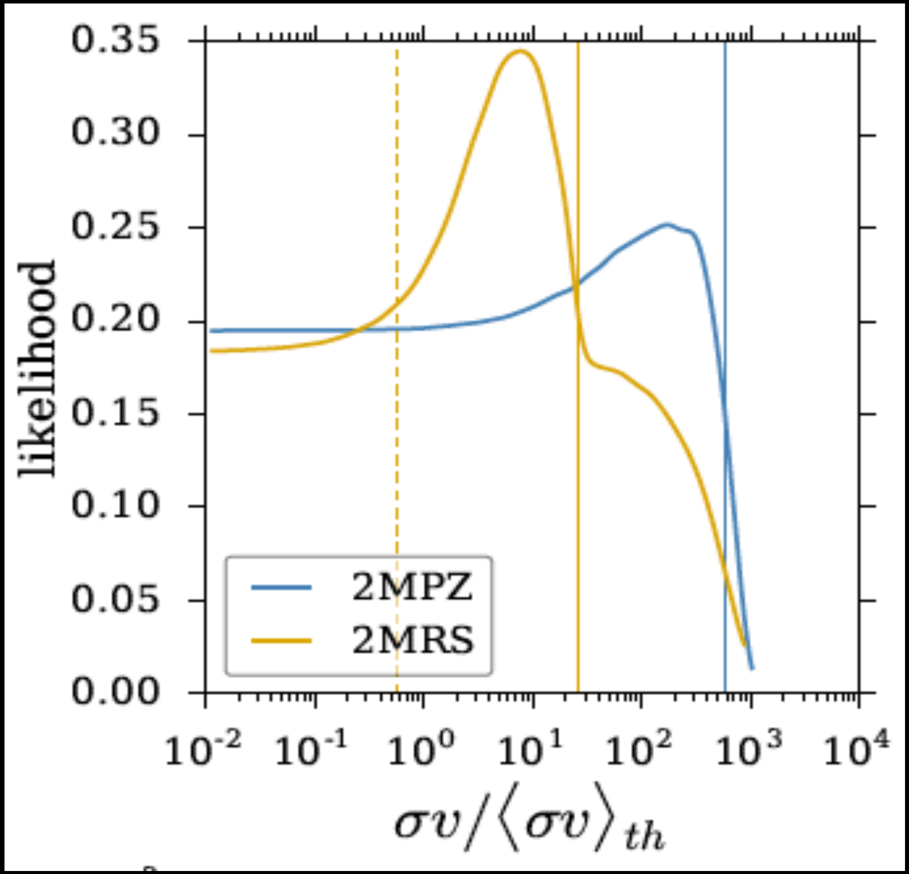
- Identify mAGN and blazars candidates
- Using scaling relations, estimate the γ rays

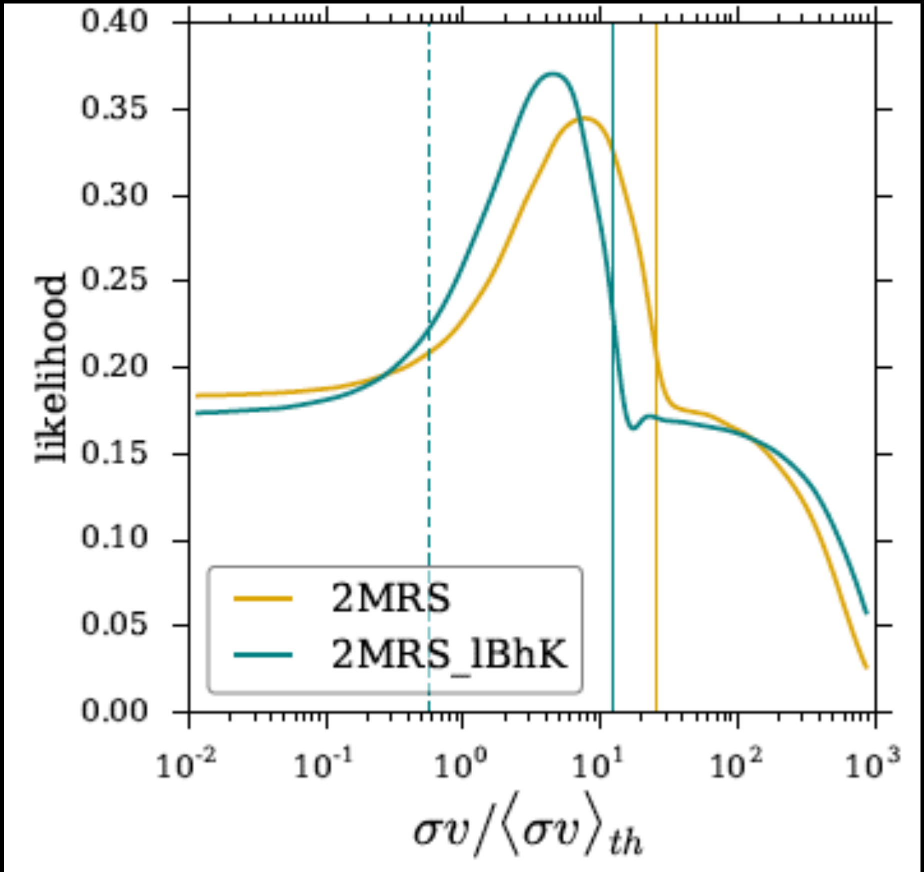
Ammazzalorso et al (2018)

Implications for dark matter

Dark matter: peaks consistent with expectations

- Small peak in inferred annihilation cross section in 2MPZ
- 2MRS (lower-*z*) shows more prominent peak than 2MPZ
- Low-B / high-K (low-astro / large-DM) sample shows slightly more prominent peak



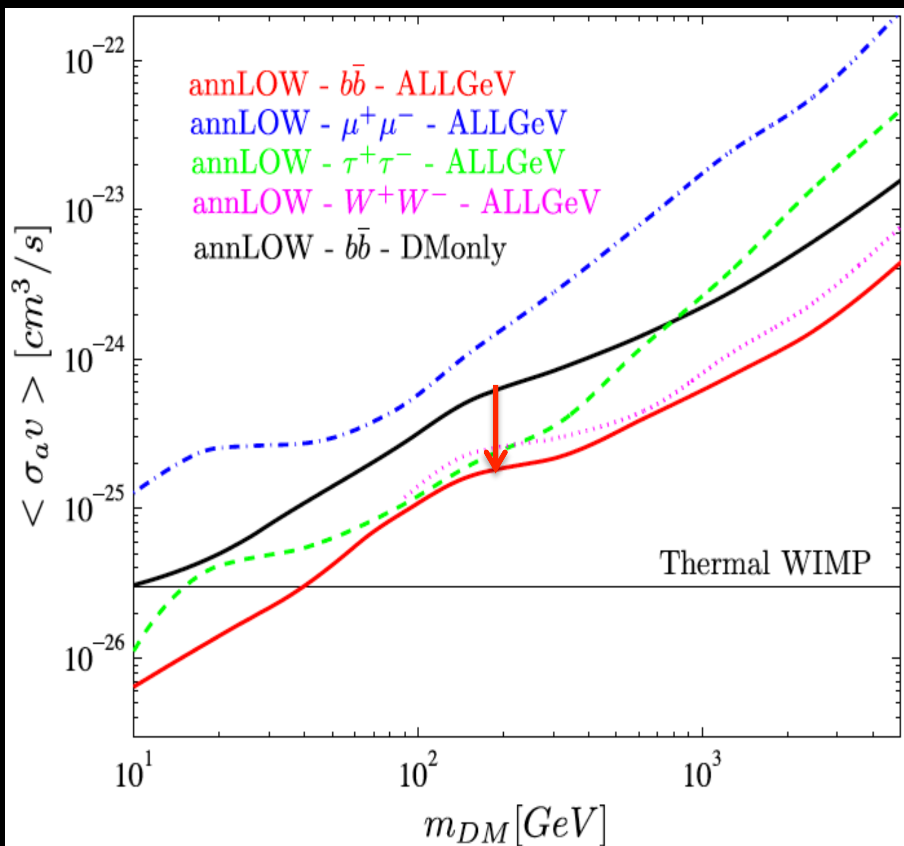


Ammazzalorso et al (2018)

Limits on dark matter

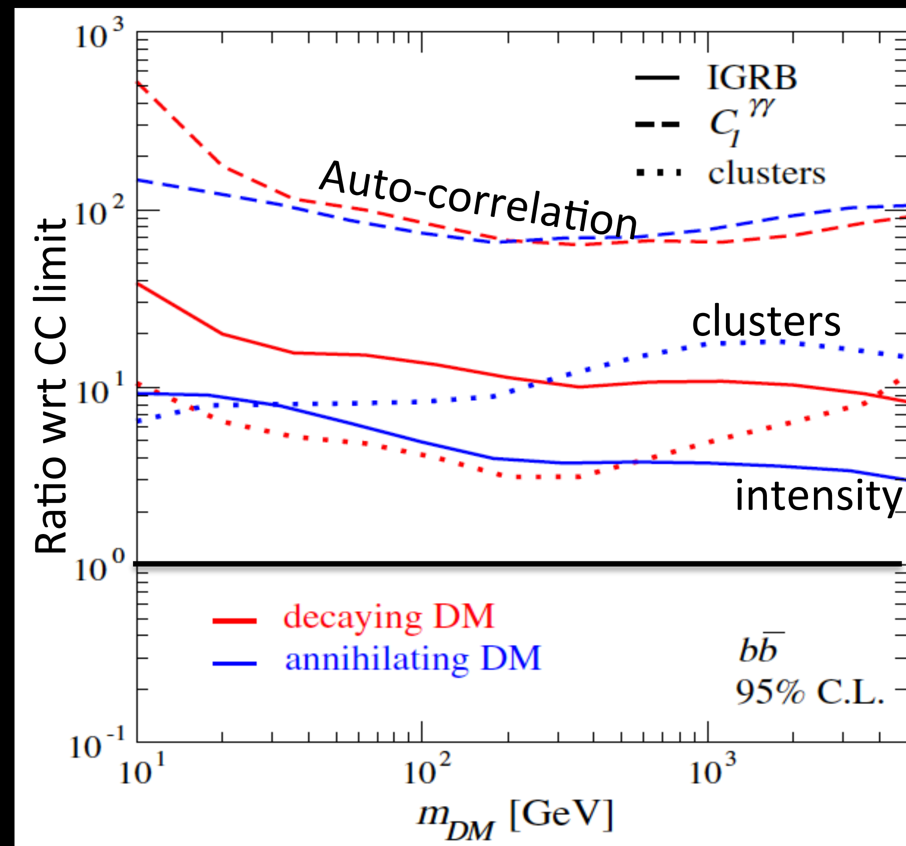
Fit including astrophysics

Limits on improve by factor of ~4 when concurrently modeling astrophysics



Regis et al (2015), Cuoco et al (2015)

Sensitivity from cross-correlation better than other EGB methods



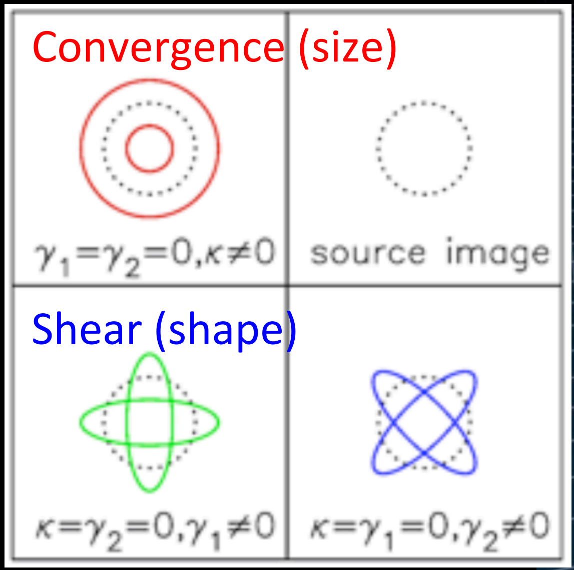
Regis et al (2015)

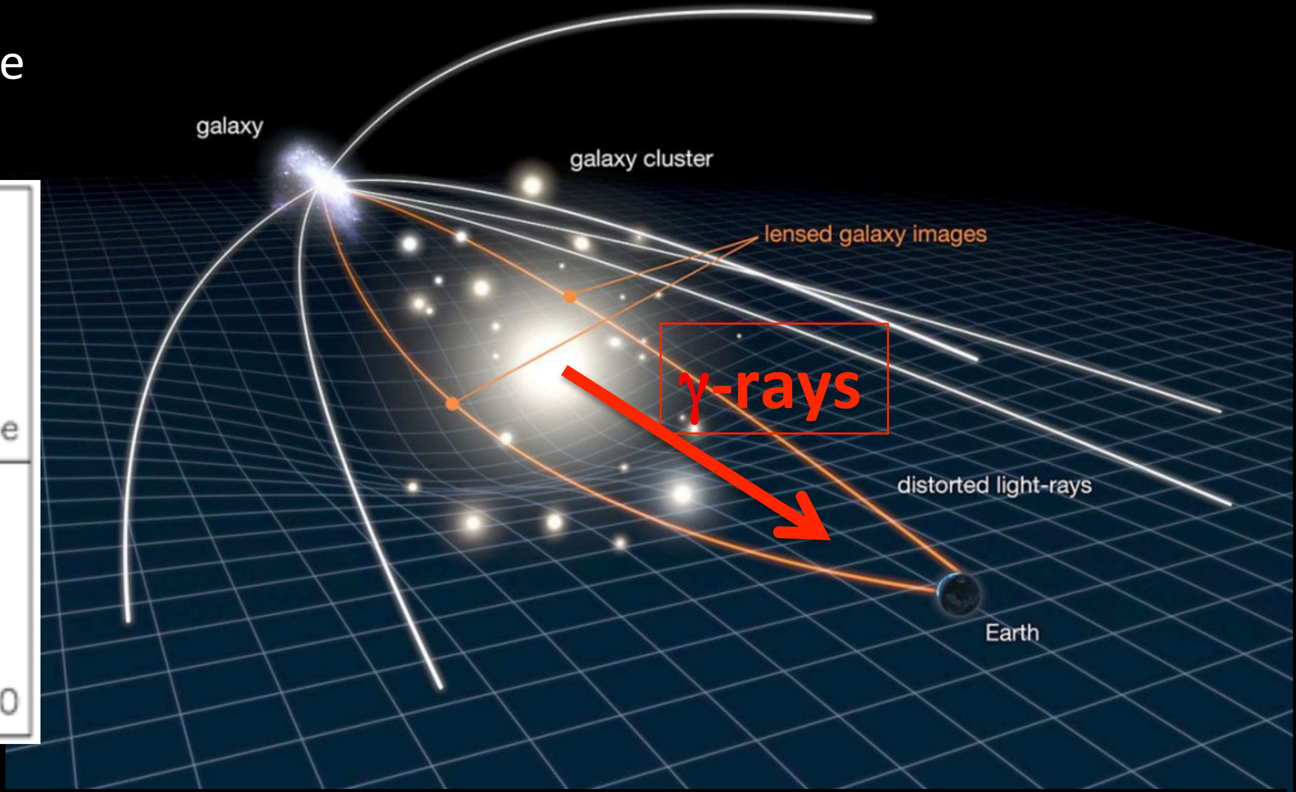
CORRELATION WITH LENSING MAPS

Correlation with lensing maps

Images of distant galaxies are distorted by matter along the line of sight

Distortions: convergence (k) and shear (γ)

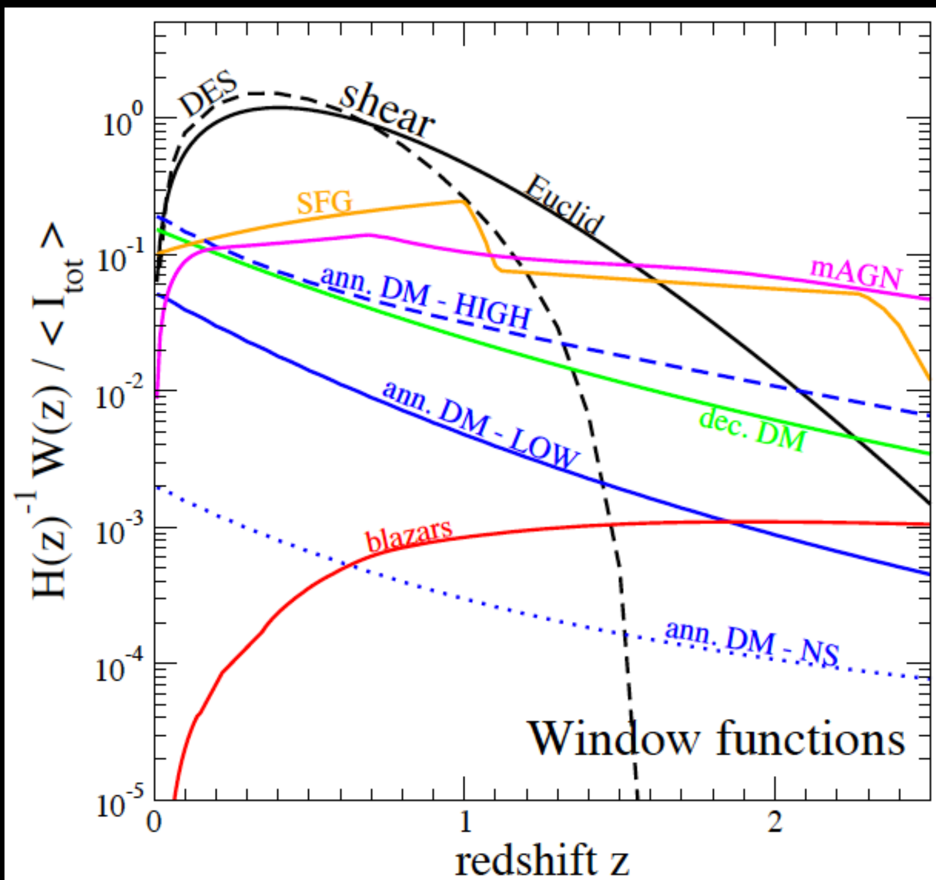




- The lens object is also a gamma-ray source (astrophysical and potential dark matter physics)
- Probe this connection with cross-correlation

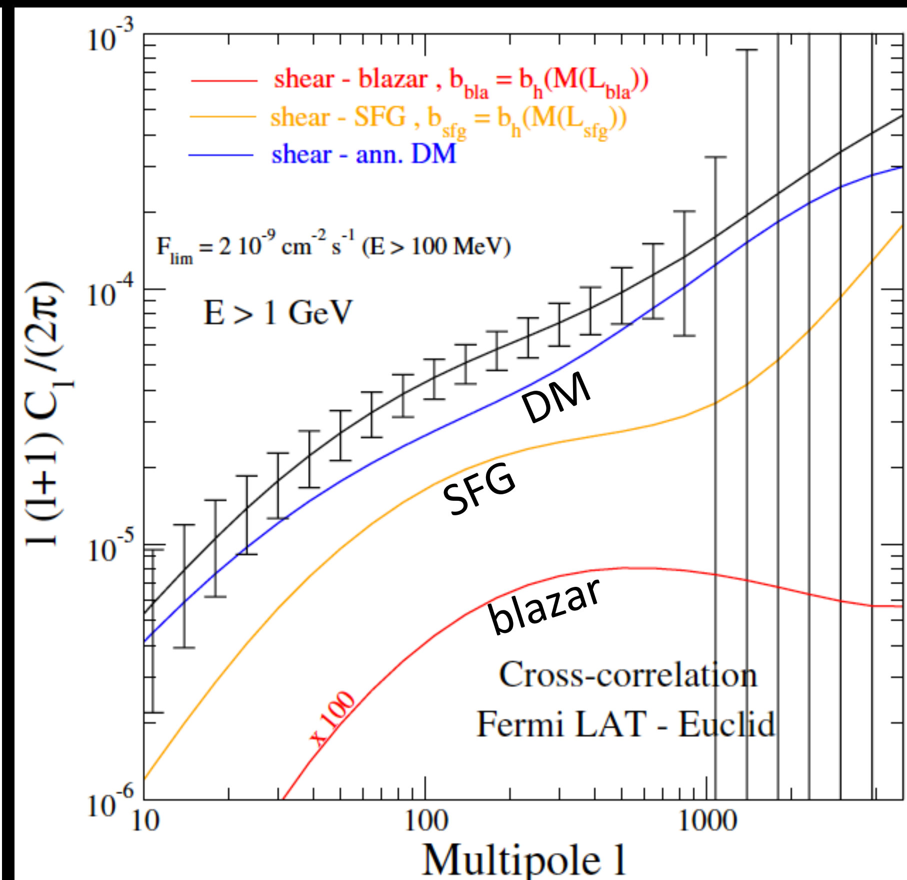
First studies & predictions

Shear probes a broad redshift range that overlaps nicely with major sources



Camera et al (2013,2014)

With future surveys, dark matter can be disentangled from astrophysics



(Fermi-LAT & Euclid)

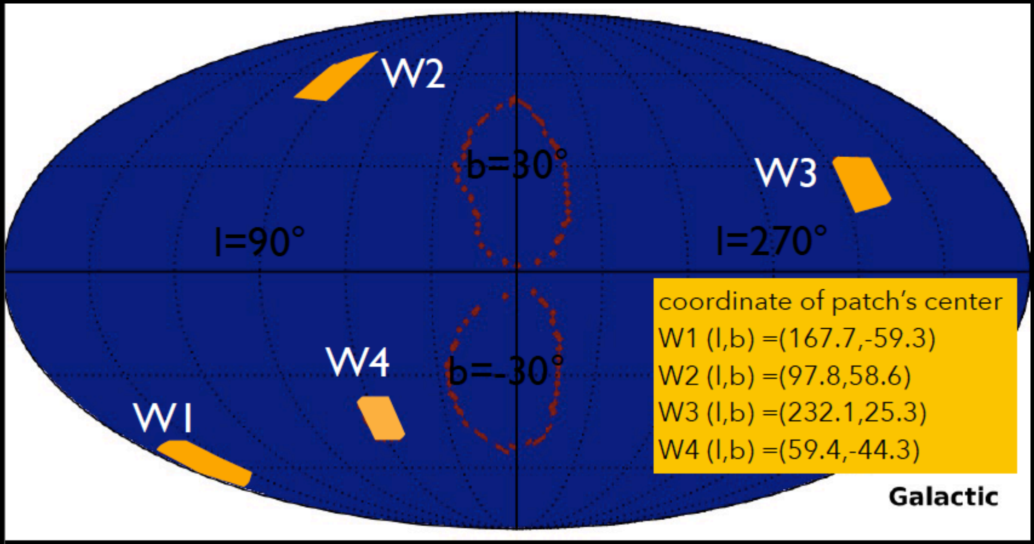
Analysis with real data

Canada-France-Hawaii Lensing Survey (CFHTLenS)

- Four patches, total ~154 deg^2
- 11 resolved galaxies per $arcmin^2$
- Photo-z between $0.2 < z < 1.3$ (median 0.75)
- About 5.7 million galaxies

Fermi-LAT

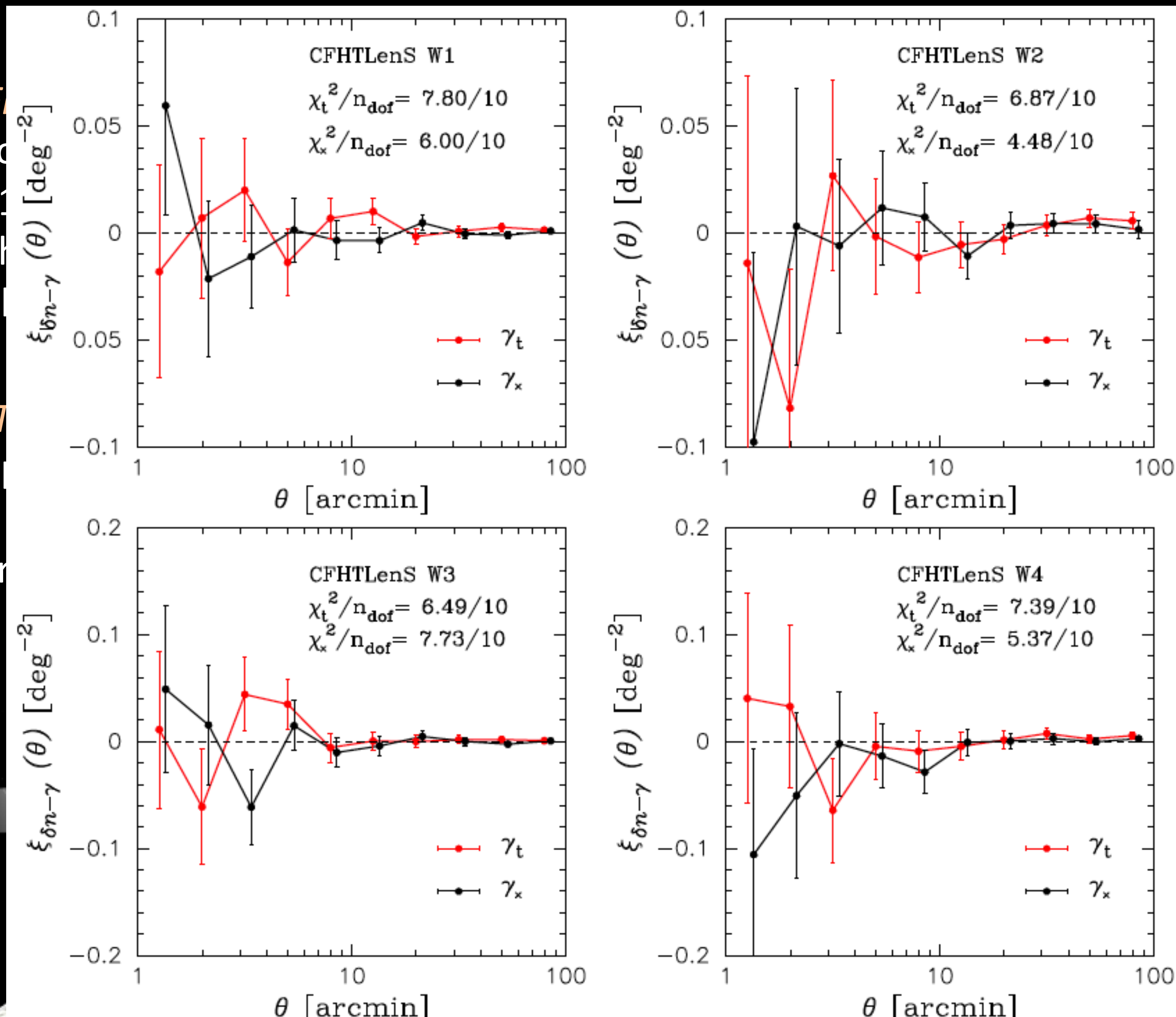
- Approx 5 yrs of Pass 7REP data
- 1 – 500 GeV ULTRACLEAN photons
- Treat patches independently

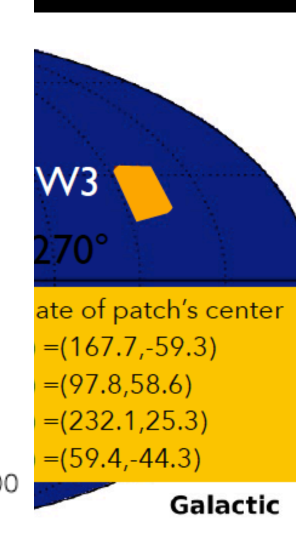


Analysis with real data

Canada-F
- Fo
- 11
- Ph
- Al

Fermi-LAT
- Ap
- 1
- Tr





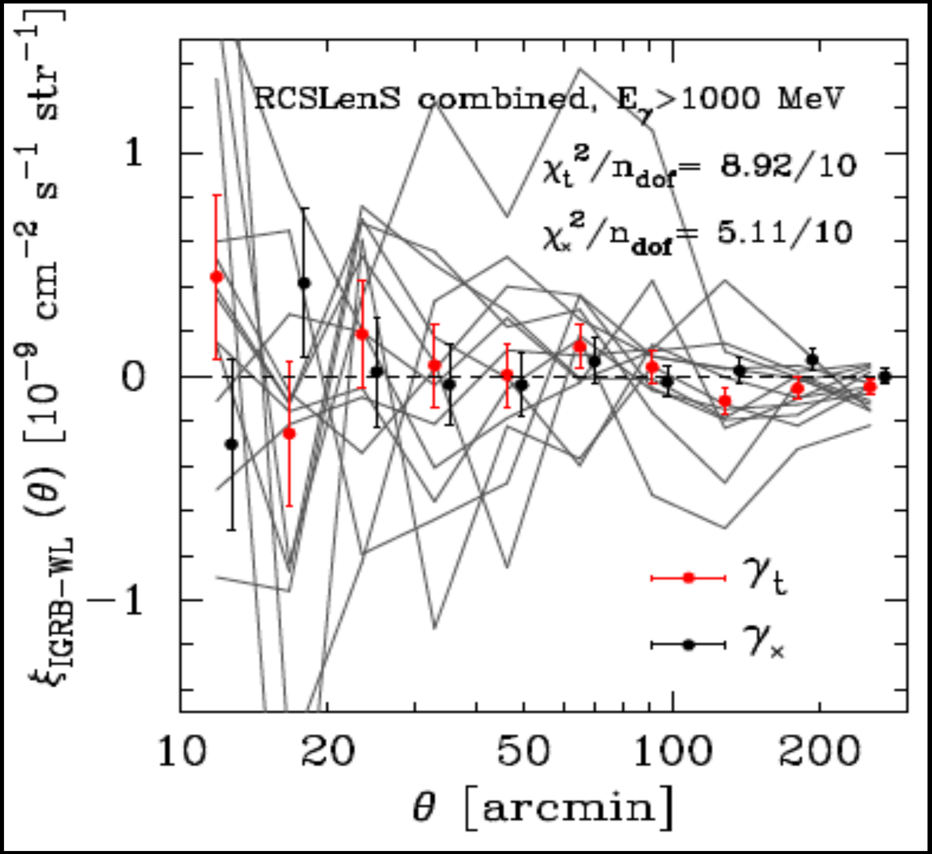
Shirasaki et al (2014)

More attempts

<u>(CFHTLenS + RCSLenS) x 7 yrs Fermi P8</u>

RCSLenS: adds 785 deg2 (~5.8 gal/arcmin2)

→ **Null detection**

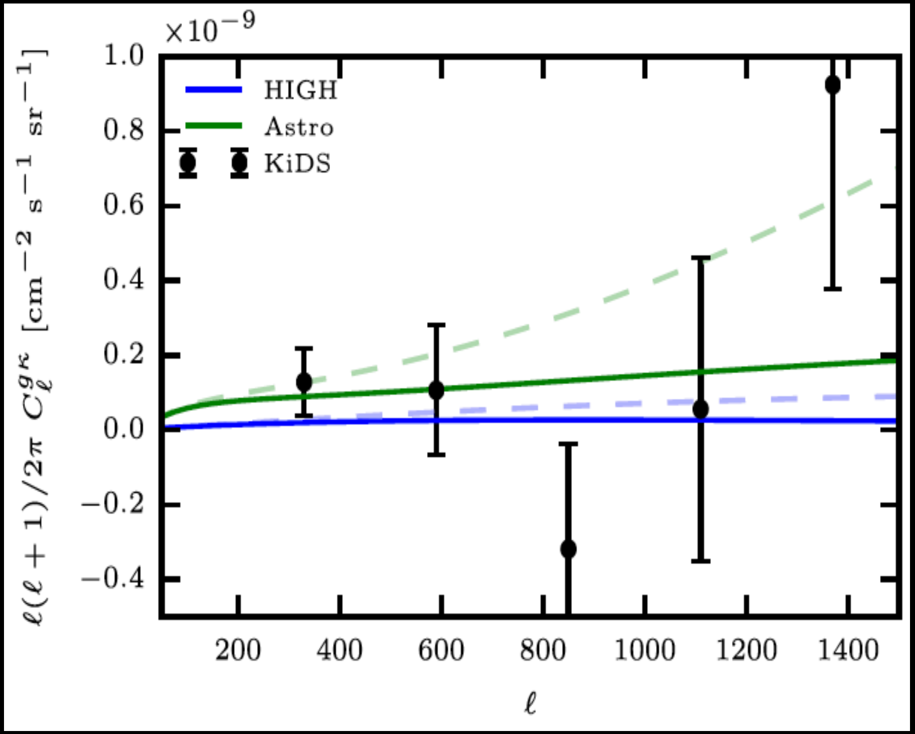


Shirasaki et al (2016)

<u>(CFHTLenS + RCSLenS + KIDS) x 7 yrs Fermi P8</u>

KIDS: adds 450 deg2 (~8 gal/arcmin2)

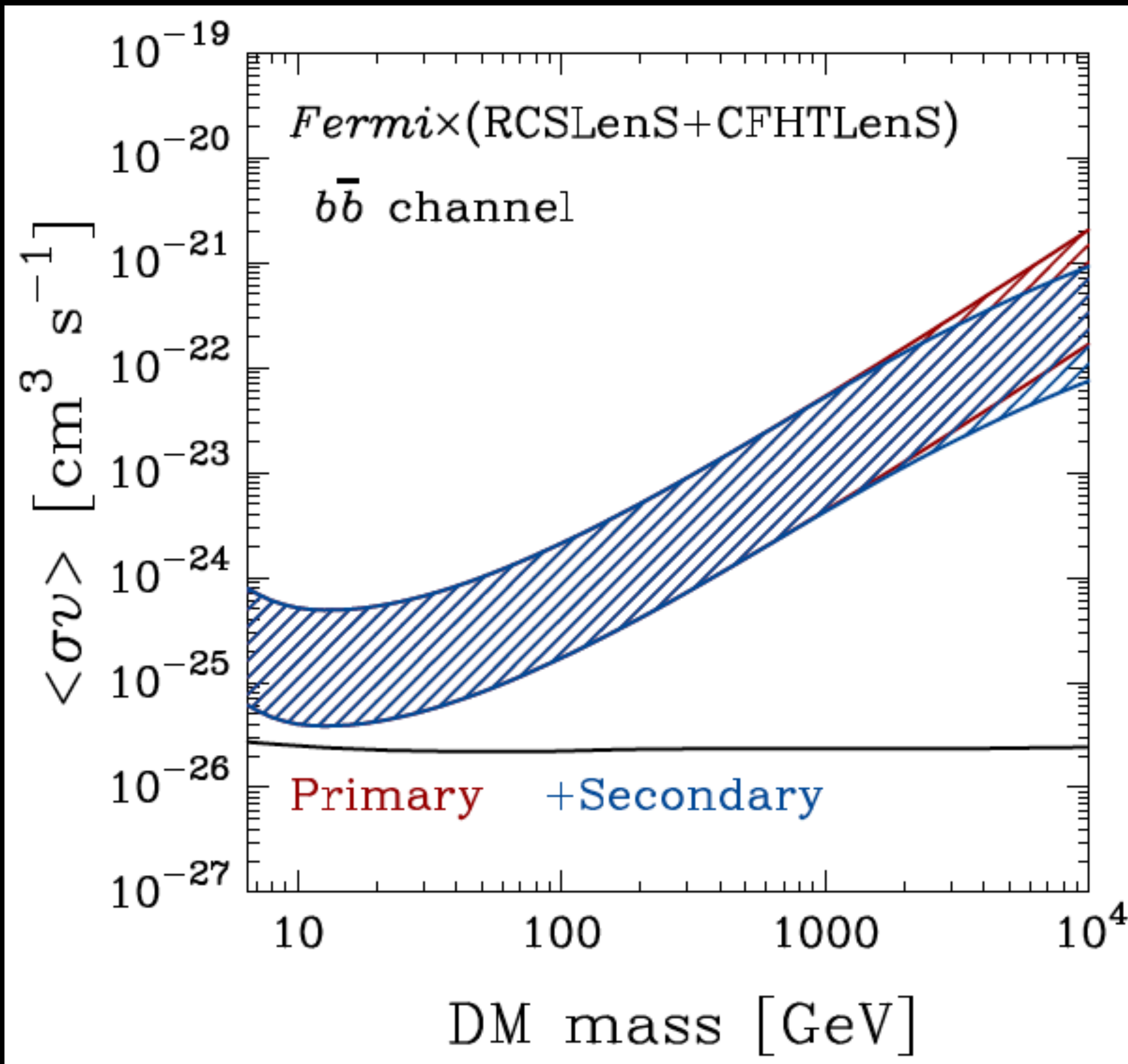
→ **Null detection**



Troster et al (2017)

Dark matter limits

From null observations



Shirasaki et al (2016)

Based on a total of 660 deg^2 (about 1.5% of the full sky)

Boost factor

Factor of ~10 between optimistic & conservative subhalo boost factors

Gao et al (2012)
Sanchez-Conde & Prada (2013)

Recent calibrated analytic methods providing useful guidance: predicts factor ~2 more than conservative

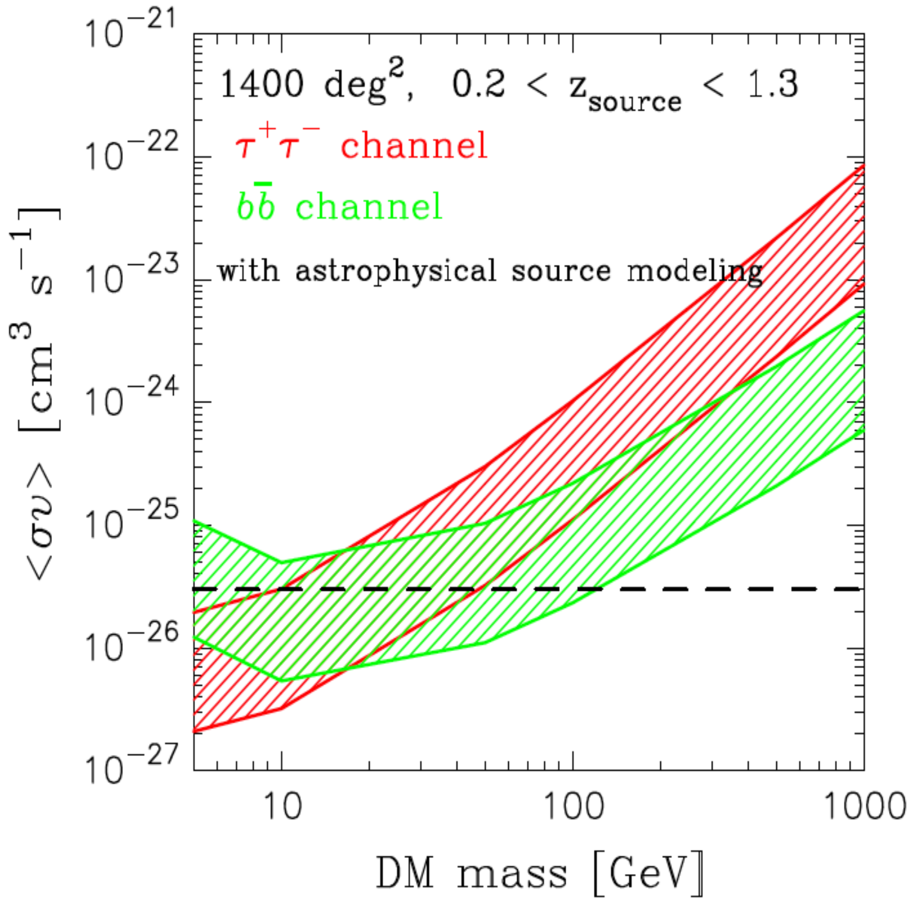
e.g., Hiroshima et al (2018)

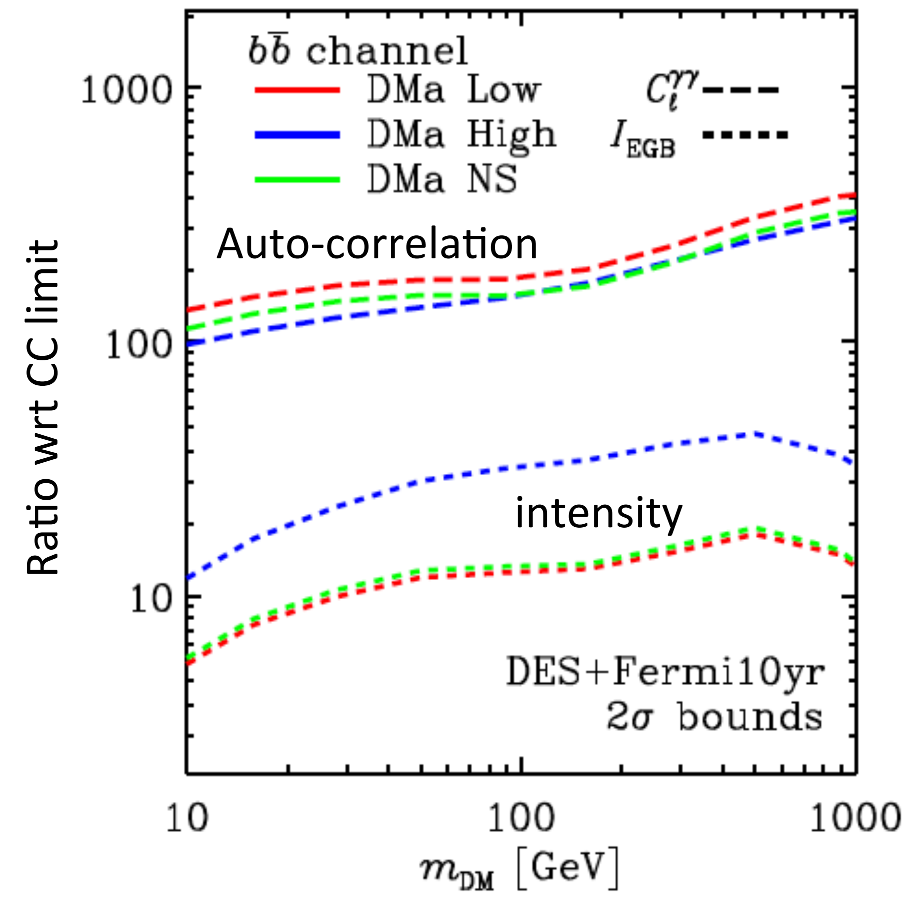
Ongoing & future developments

1. Significant increase in shear map coverage

Hyper-Suprime Cam: ~1,400 deg^2
Dark Energy Survey: ~5,000 deg^2

Euclid: ~15,000 deg^2 (2021-)
LSST: ~20,000 deg^2 (2023-)





Shirasaki et al (2014)

Camera et al (2014)

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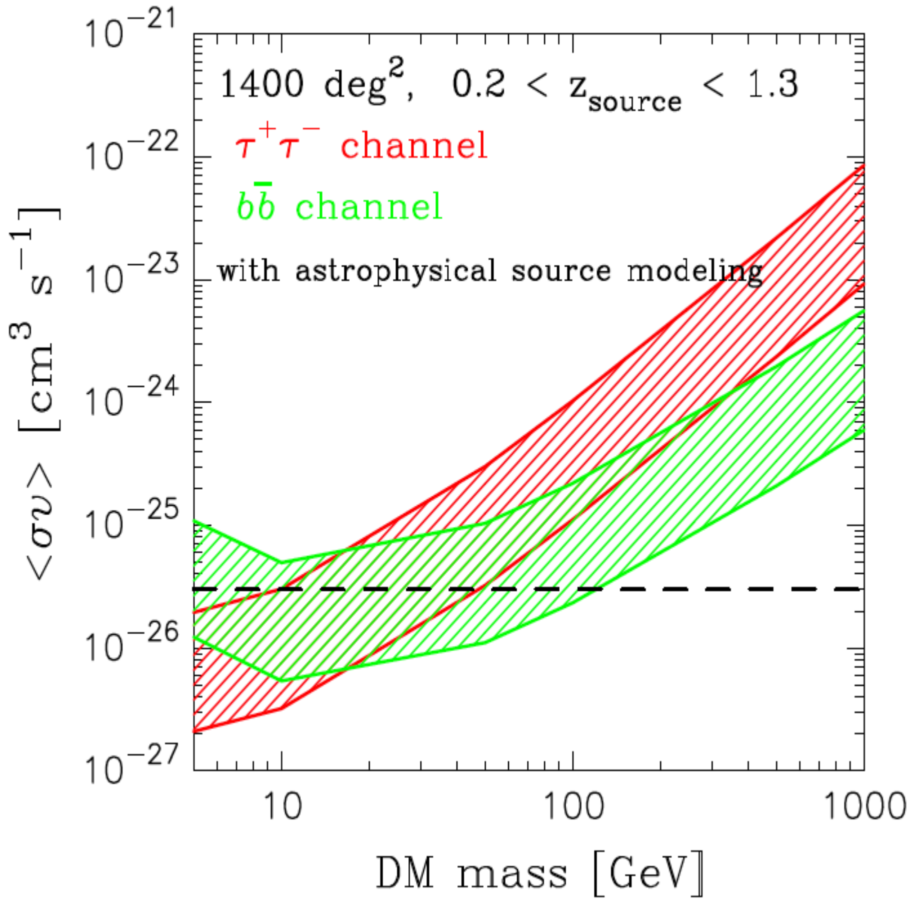
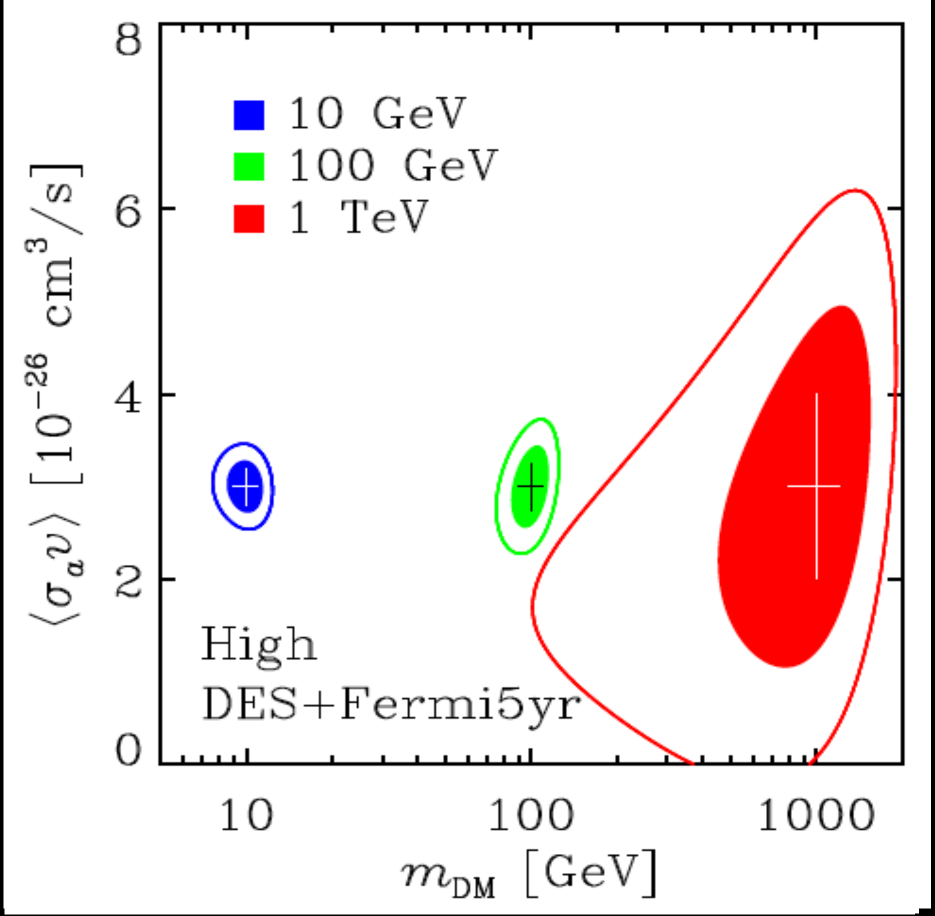


Shirasaki et al (2014)

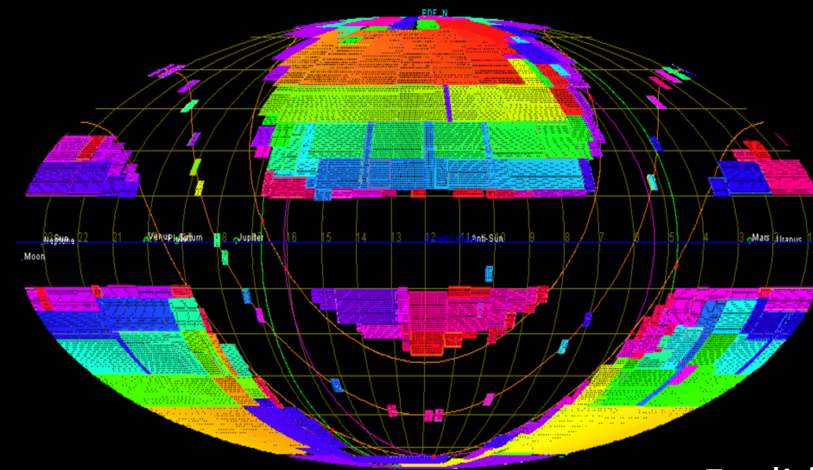


Camera et al (2014)

Ongoing & future developments

2. Significant increase in catalogs

e.g., especially in the Southern hemisphere, increasing the use of the γ-ray data
e.g., new sources such as cosmic voids



Euclid

3. Exploit multi-wavelength information

e.g., tomography in halo mass, SFR
e.g., improved estimates of shot noise
e.g., tomography with gravitational lensing

4. Various anisotropy studies

Complementary; help break degeneracies ← See Michela Negro's talk!

5. Fermi-LAT will have more data

e.g., statistics & PSF improvement expected to be impactful.

Together, will be able to make much more detailed studies of the Fermi data!

Concluding remarks

The ***unresolved gamma-ray background*** *measurement by Fermi contains a wealth of knowledge.*

– Guaranteed sources, and potentially new sources like dark matter
– These can be probed by exploiting cross-correlation techniques

Great progress already. Future prospects are high

– **Correlation with galaxies:** highly significant already. Rich prospects with multiple catalogs, subsamples, tomography, etc.
– **Correlation with gravitational lensing:** not significant (so far), but advances guaranteed with upcoming surveys (HSC, DES, LSST, Euclid)
– **Other correlations:** cluster and CMB lensing (significant). More clusters to test/refute ICM origin versus other sources.
– **Synergies:** by combining anisotropy probes

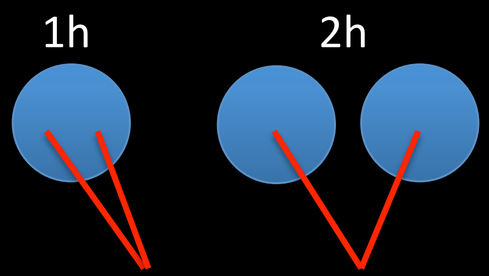
Stay tuned!

BACKUP

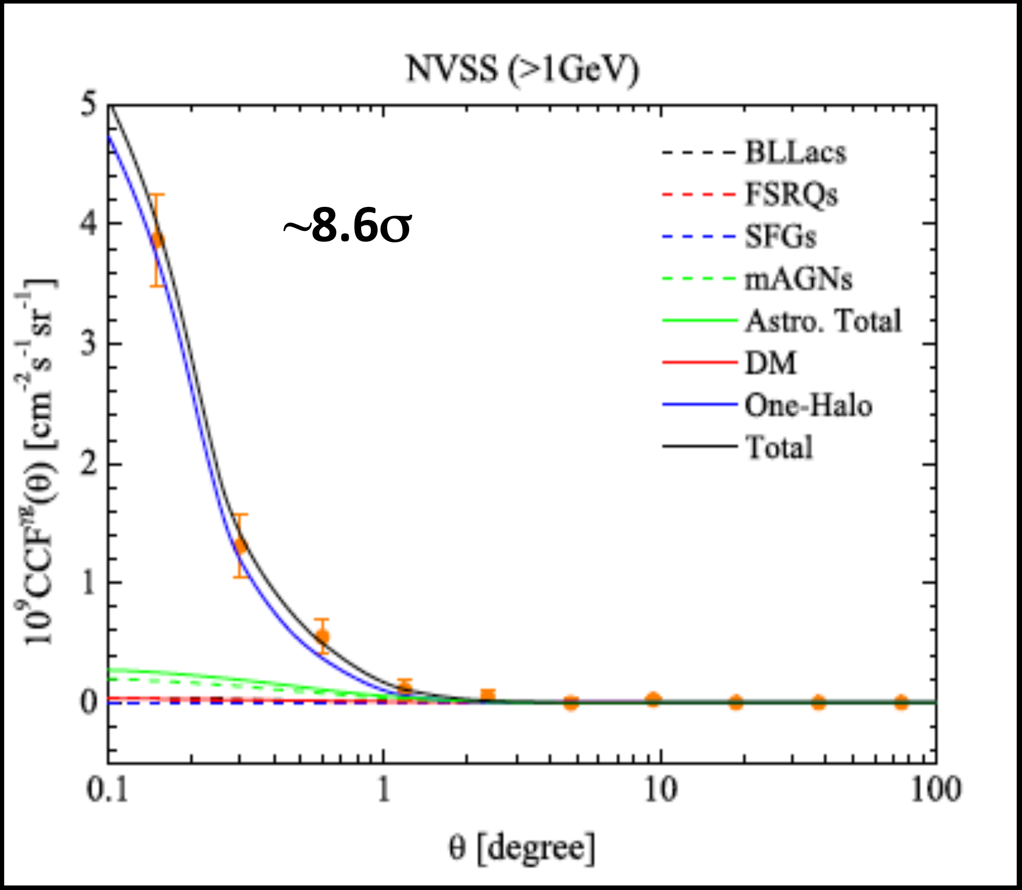
First detection of cross correlation

- Use 5 galaxy catalogs and 5 yrs Fermi P7REP from 500 MeV to 100 GeV
- Many sanity checks: estimator, Galactic diffuse, null detection in mock realizations

- NVSS consistent with additional small-scale (1halo-like) term:
  - Correction for inaccuracies in 1h term (due to discrete gamma-ray sources within in the galaxy catalog, causing shot-noise)



- NVSS correlation also shows narrowing with energy



Xia et al (2015), interpretation in Cuoco et al (2015)

Interpretations of CCF

Global fit: 5 sources, 5 catalogs, 3 energies

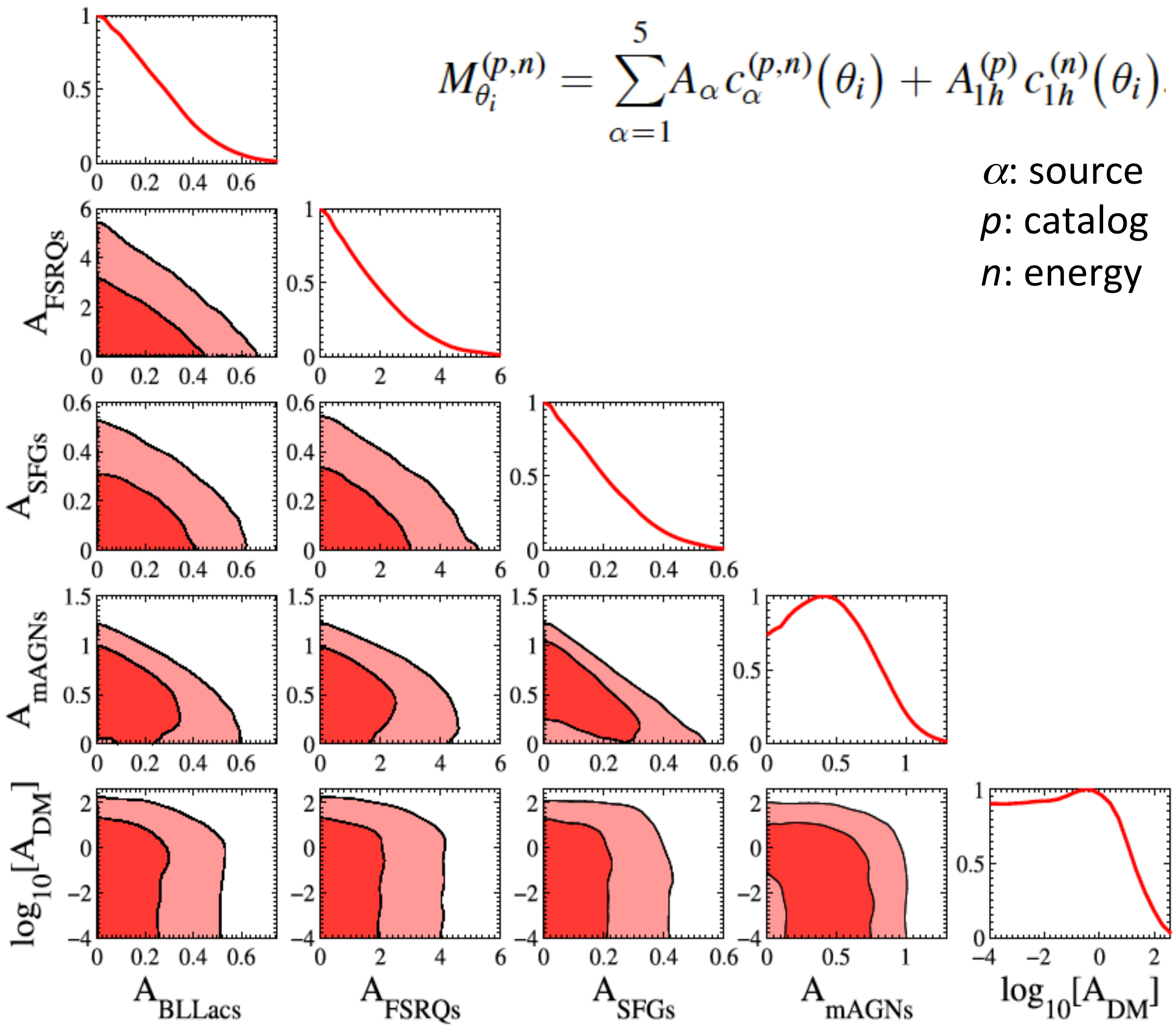
Marginalized posterior distributions

Hard to pin-point unique source; mAGN shows hint of a peak.

Considerable degeneracy exist between sources

$$M_{\theta_i}^{(p,n)} = \sum_{\alpha=1}^{5} A_\alpha c_\alpha^{(p,n)}(\theta_i) + A_{1h}^{(p)} c_{1h}^{(n)}(\theta_i)$$

α: source
p: catalog
n: energy



Cuoco et al (2015)

(+6 parameters)

Shot-noise term

With 2MPZ, shot-noise can be estimated more directly:

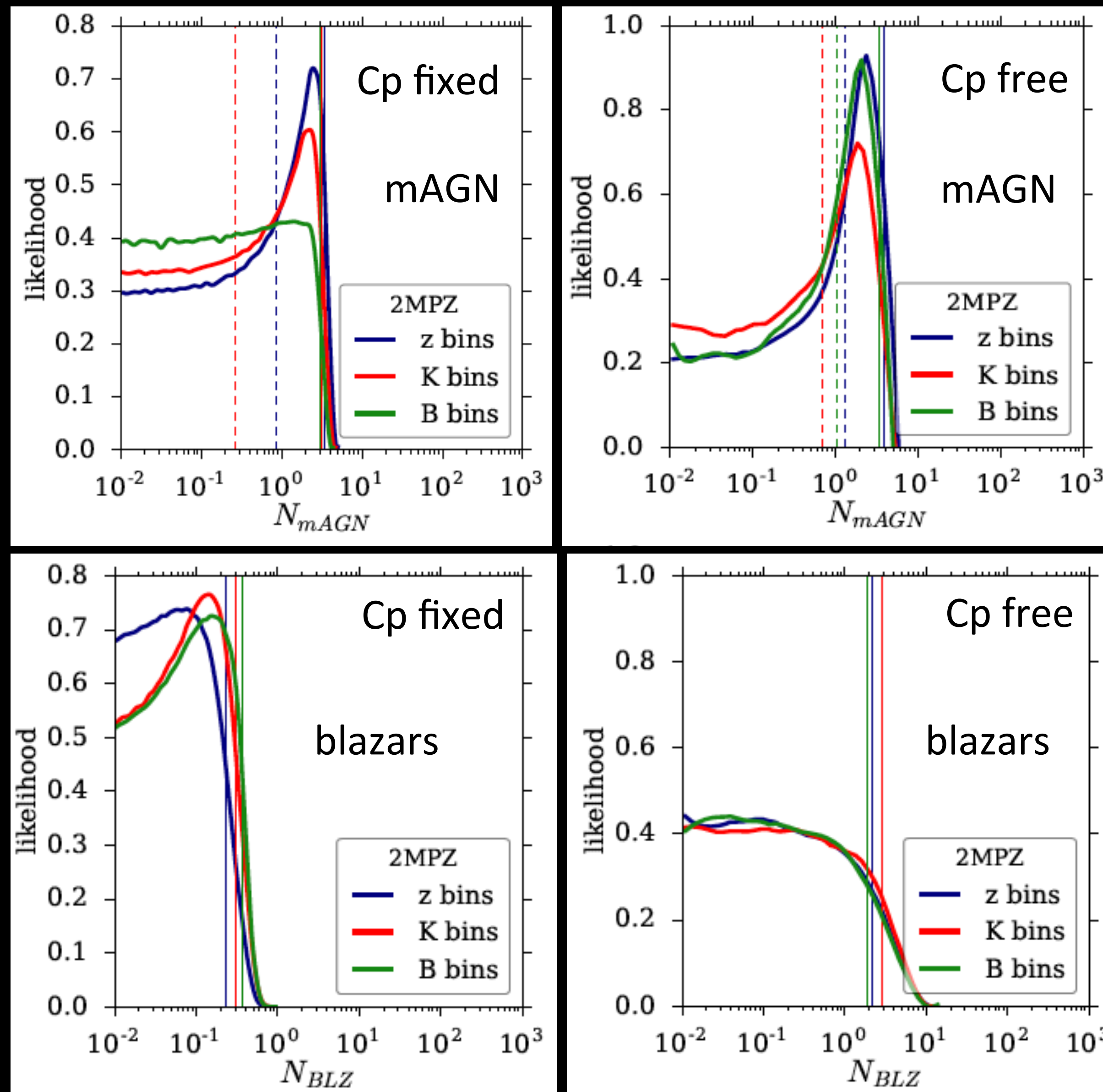
- Based on IR colors, can identify mAGN and blazars candidates
- Using scaling relations, can estimate the γ rays

Massaro & Abrusco (2016)
Mingo et al (2016)

NB: free shot-noise term

- mAGN remains non-zero
- Blazar goes from subdominant to weakly constrained

Ammazzalorso et al (2018)

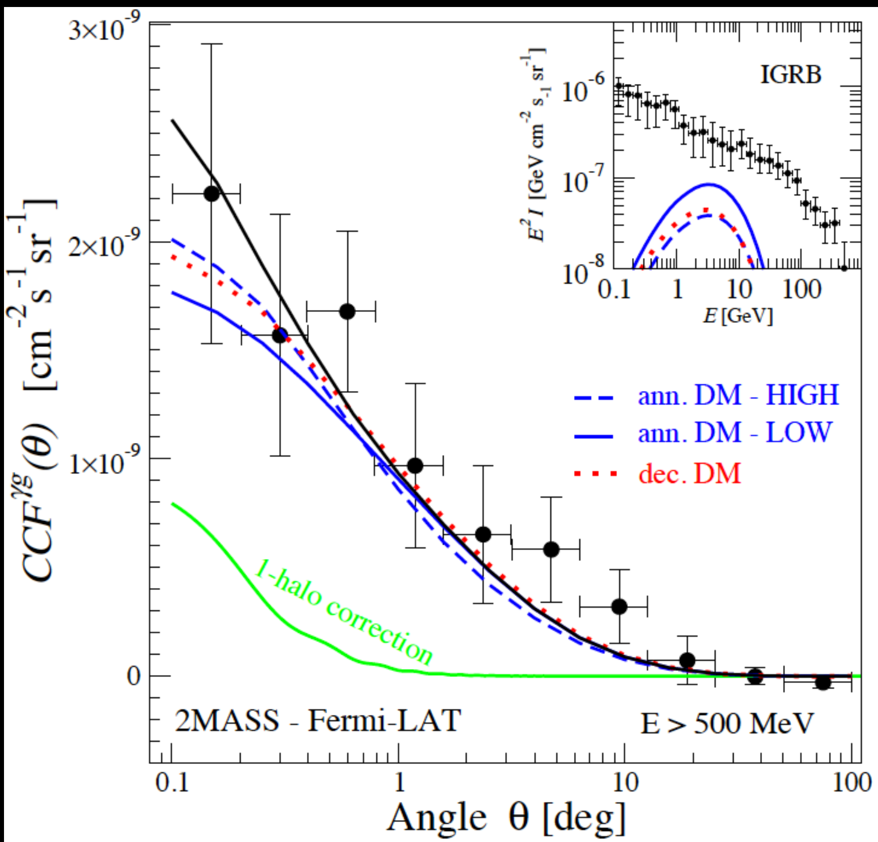


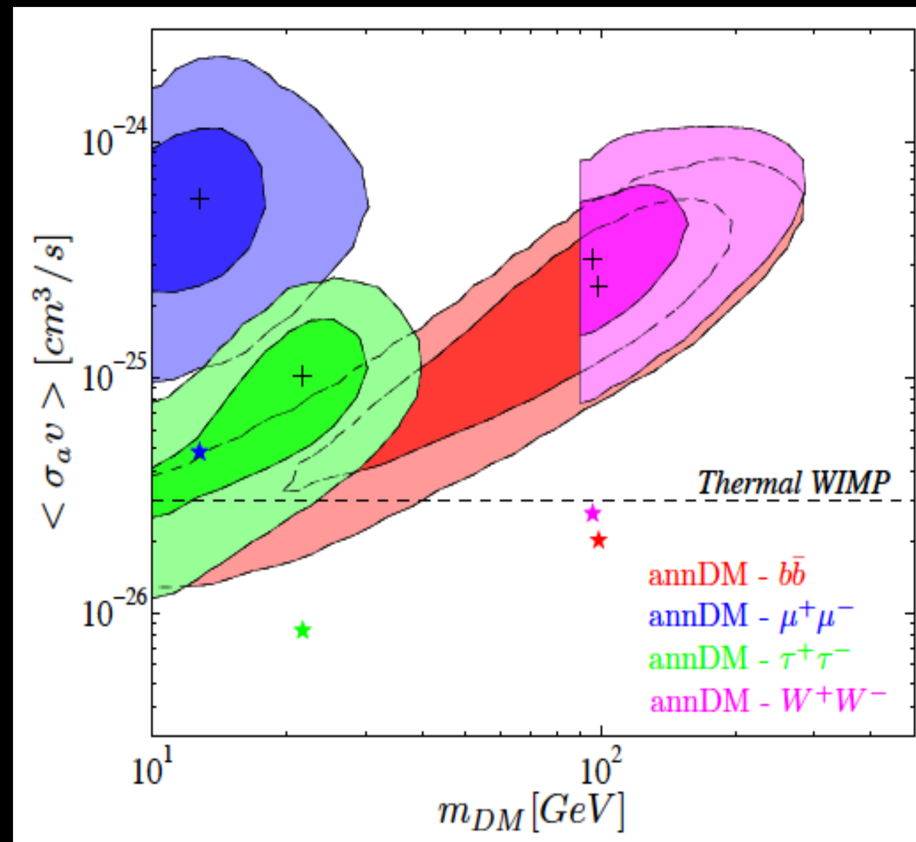
Pure dark matter interpretation

Fit with only dark matter

Both the shape and intensity can be satisfied by dark matter.

Not excluded since high 2MASS—DM correlation does not much affect high *z*'s





(Fermi– 2MASS cross-correlation)

Regis et al (2015)

Correlation functions

Source intensity — Source density field — Window function

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

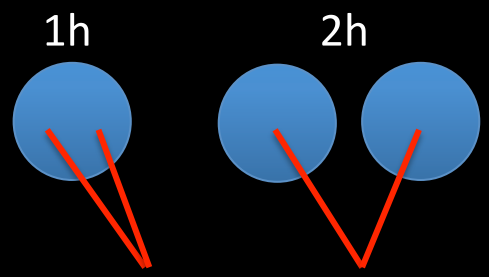
W(z): e.g., for annihilation — DM particle properties — DM distribution — Gamma-ray optical depth

$$W_\gamma^a(z) = \frac{(\Omega_{\rm DM}\rho_c)^2 \langle\sigma_a v\rangle}{8\pi m_{\rm DM}{}^2}(1+z)^3 \Delta^2(z) \frac{dN_a}{dE_\gamma} e^{-\tau[z,E_\gamma(z)]}$$

Cross correlation APS: — Cross 3D power spectrum

$$C_l^{(ij)} = \int \frac{d\chi}{\chi^2} W_i(\chi) W_j(\chi) P_{ij}(k = l/\chi, \chi)$$

Decompose: $P(k) = P^{1h}(k) + P^{2h}(k)$



Halo model: gamma-ray emitters confined to DM halos.

Halo mass function — FT of source density field

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

See e.g., Fornengo & Regis (2014)

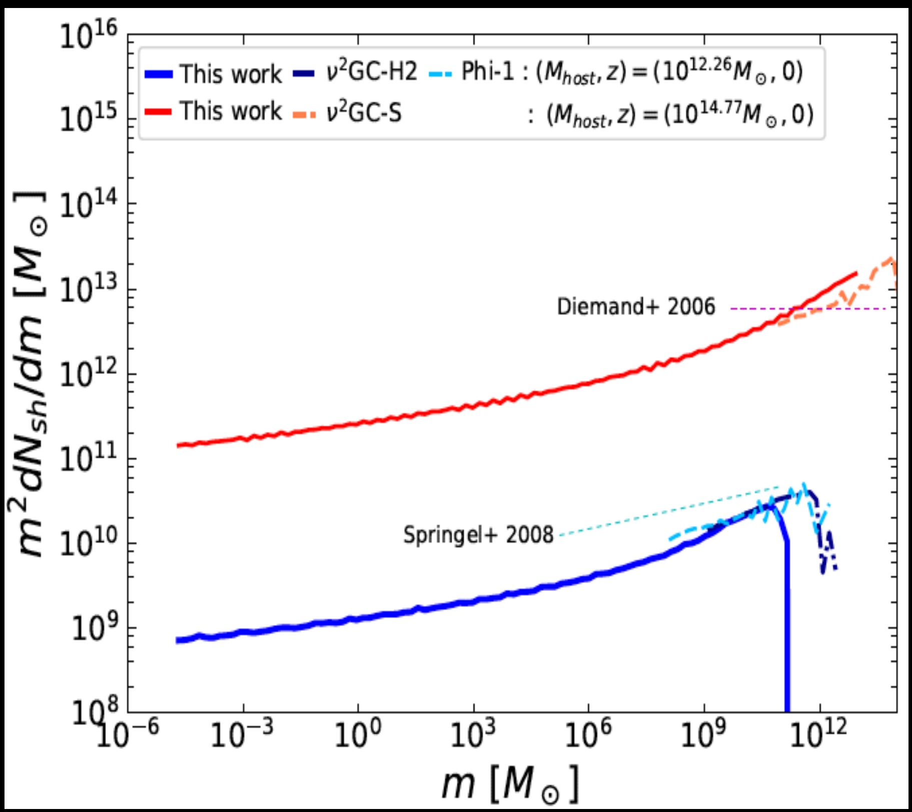
$$P_{ij}^{2h}(k) = \left[\int dm_1 \frac{dn}{dm_1} b_i(m_1) \hat{f}_i^*(k|m_1)\right] \left[\int dm_2 \frac{dn}{dm_2} b_j(m_2) \hat{f}_j(k|m_2)\right] P^{\rm lin}(k)$$

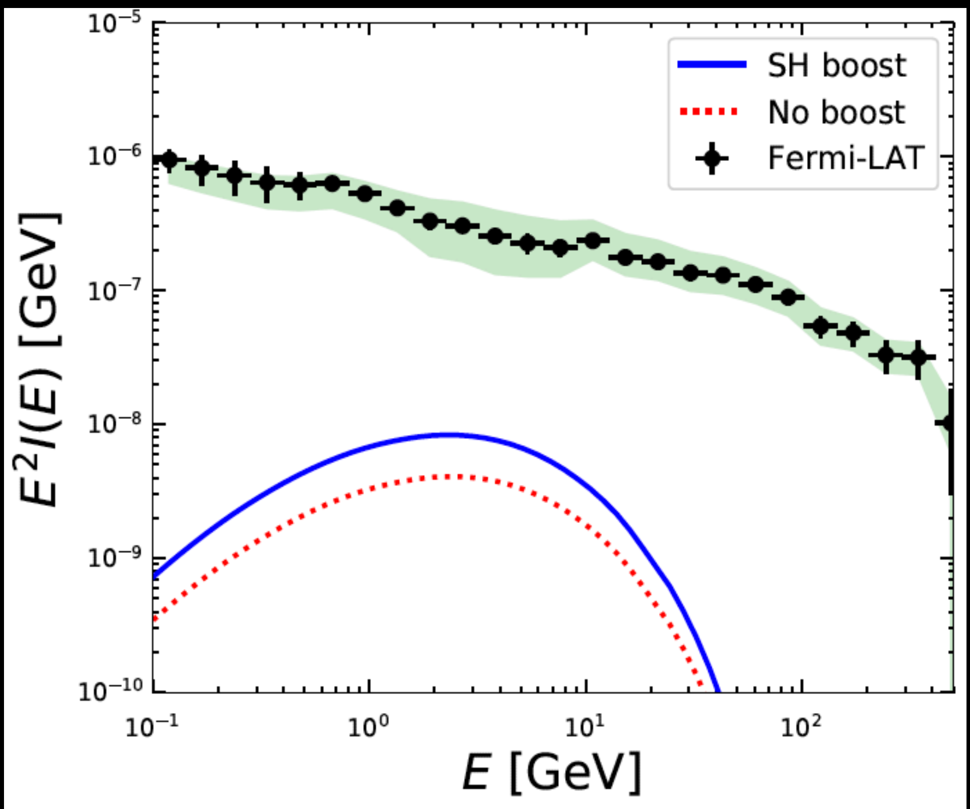
Linear bias — Linear matter power spectrum

Boost factor uncertainties

Analytic subhalo model

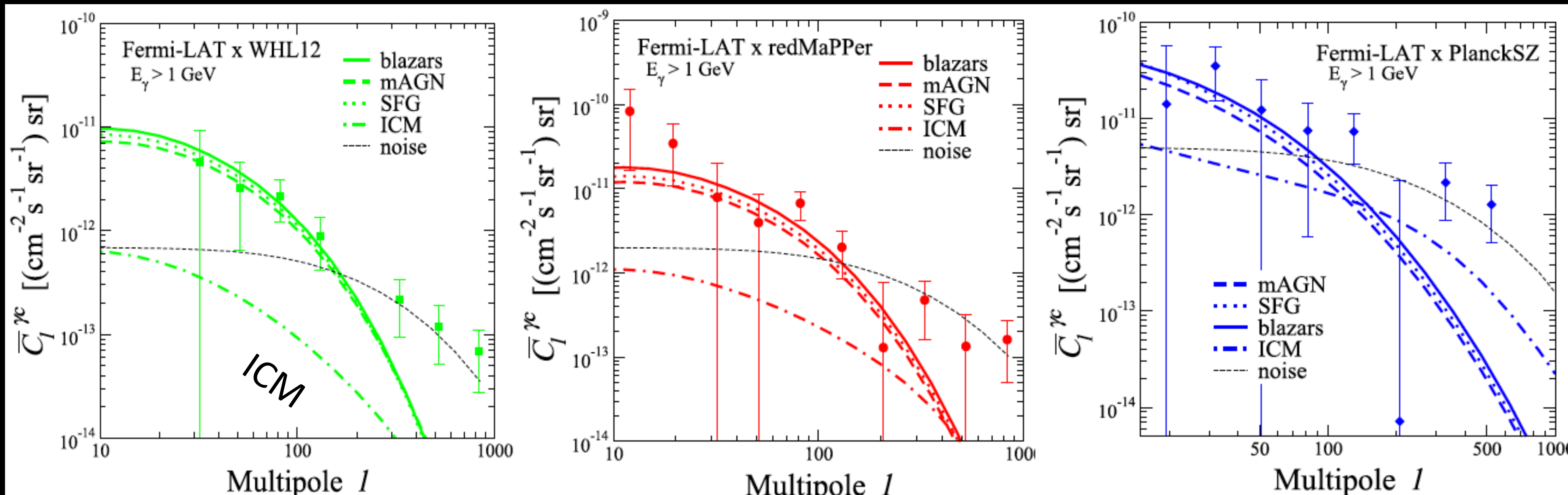
- Complementary to simulations
- Tested against simulations at resolved scales
- Physics-based extrapolation (extended Press-Schechter formalism + prescriptions for tidal stripping and mass loss) beyond simulations





Hiroshima et al (2018)

CAPS measurements & interpretations

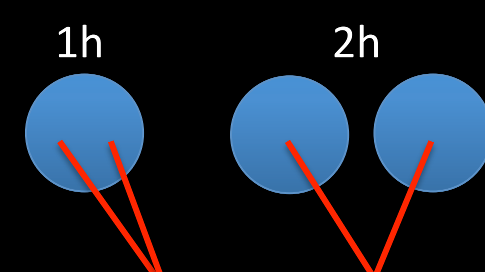


Branchini et al (2017)

- Positive CAPS: > 5σ for redMaPPer and WHL12, > 3σ for PlanckSZ
- Can be explained by either blazars, mAGN, or SFG, providing 100% of the UGRB

$$C_l^{(ij)} = \int \frac{d\chi}{\chi^2} W_i(\chi) W_j(\chi) P_{ij}(k = l/\chi, \chi)$$

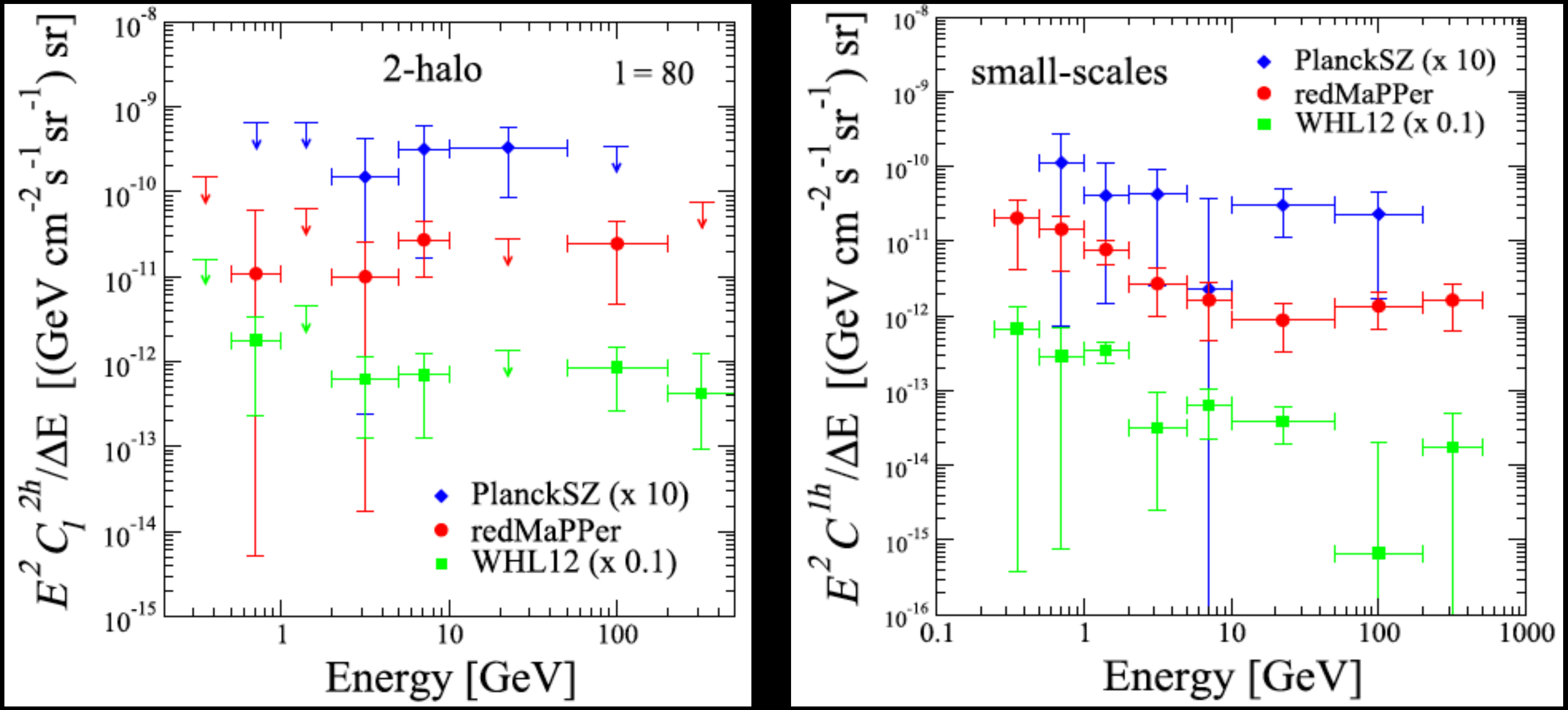
Decompose: $P(k) = P^{1h}(k) + P^{2h}(k)$



- Small-scale correlation needs additional power
  - ICM? Constrained by nearby clusters
  - Correction for inaccuracies in 1h term? (due to discrete gamma-ray sources)

cf Ando (2014)

Hints from energy spectrum



Branchini et al (2017)

- Fit to CAPS derived in 8 energy bins
- Large scales: single power-law (hard) → BL Lacs?
- Small scales: two power-laws preferred over a single power-law
  - High-energy spectrum consistent with large scale → BL Lacs?
  - Spectrum is softer at low energies → SFG? ICM? Others?