3rd Anisotropic Universe meets BAM

Barolo Astroparticle Meeting

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Cross-correlations of gamma-rays with galaxy, cluster and lensing surveys

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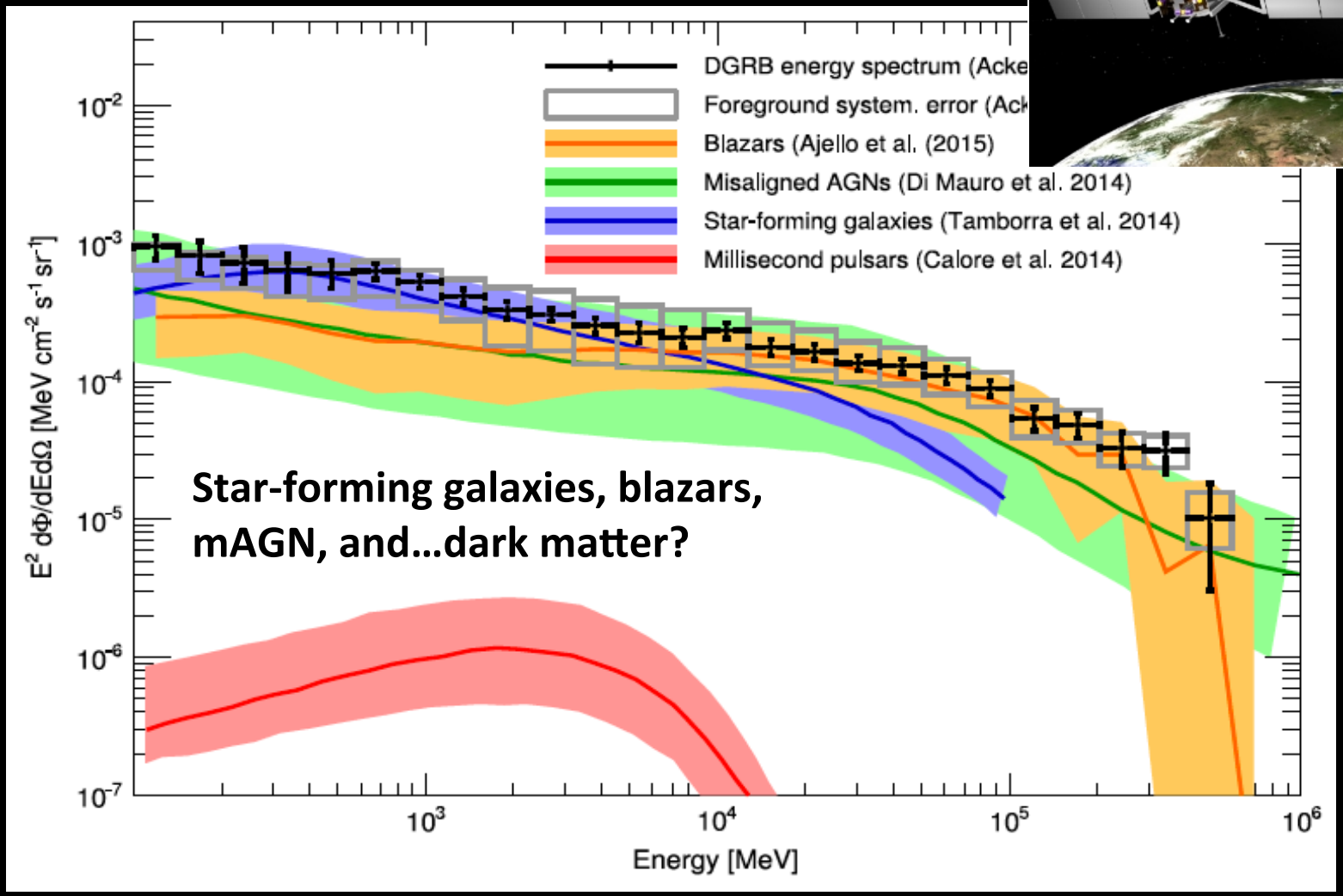
Fermi-LAT data, 5 years

Unresolved gamma-ray background

Contributors: AGNs, blazars, galaxies, pulsars, … and others (CR?)
Dark matter: spectrally distinct, if there subdominant

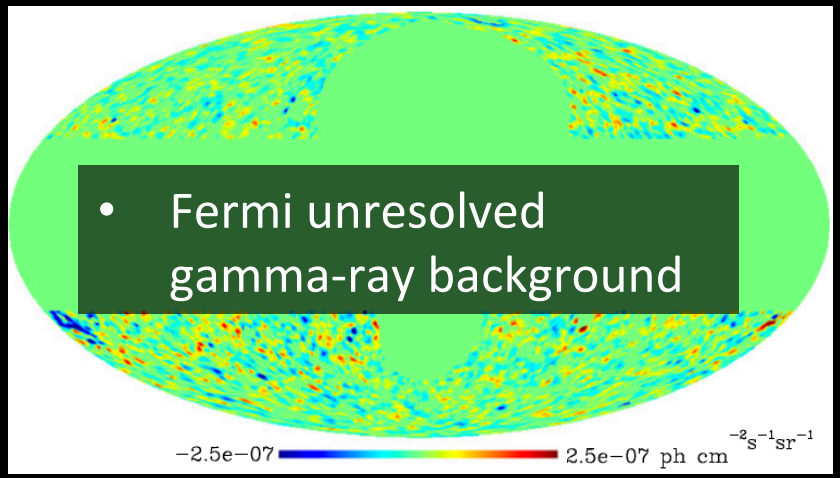


Fornasa & Sanchez-Conde (2015)

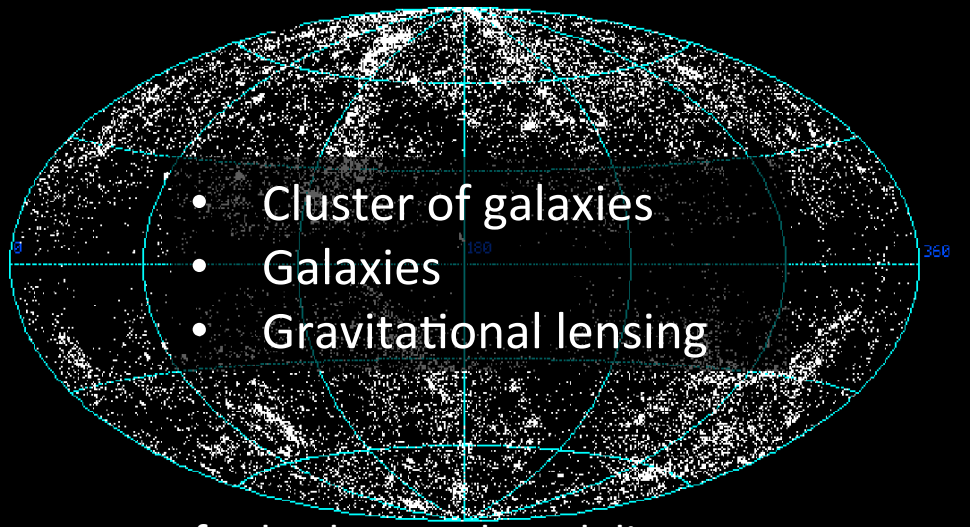
Angular cross correlation

Use anisotropy of the unresolved gamma-ray background 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 background modeling

2PCF ξ: 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), Ando (2014), …

CORRELATION WITH GALAXY CLUSTERS

Correlation with galaxy clusters

Why galaxy clusters?

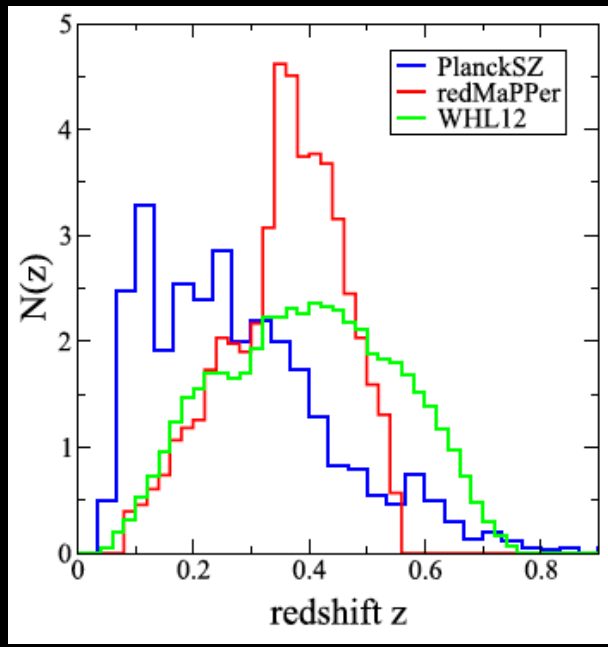
- Contains potential sources, e.g., AGNs, galaxies, DM
- ICM should emit gamma-rays from CR interactions
  - but have not yet been unambiguously detected

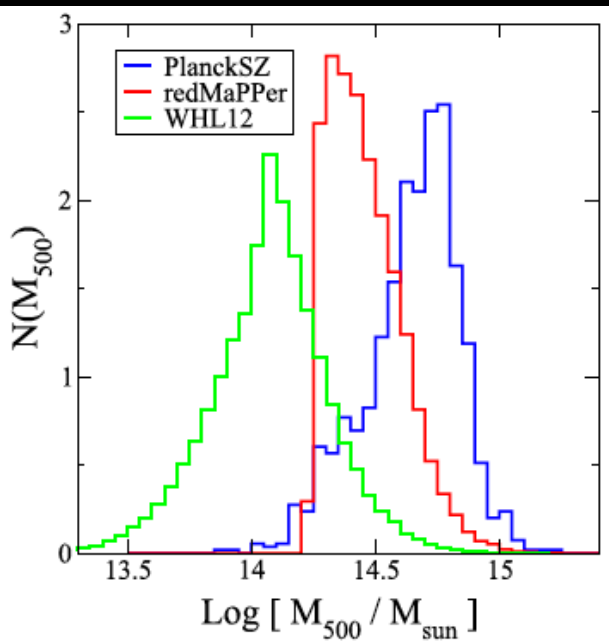
e.g., Colafrancesco & Blasi (1998), Pinzke & Pfrommer (2010)

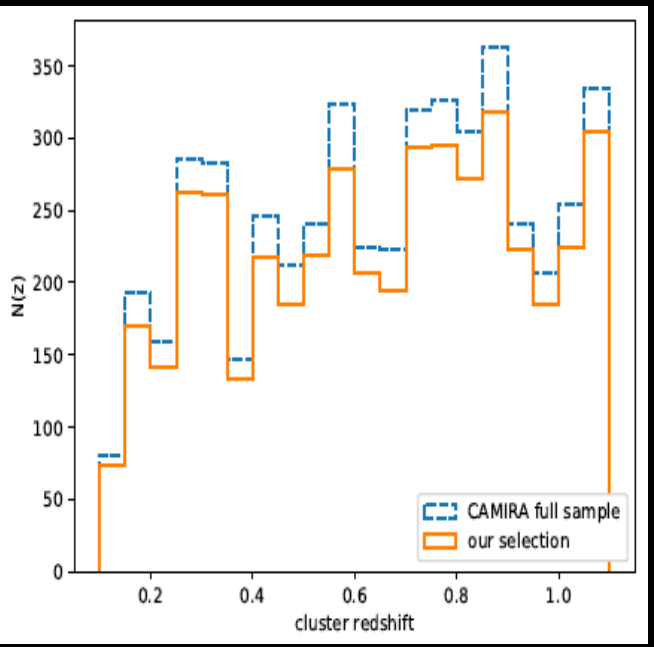
e.g., Dutson et al (2013), Zandanel & Ando (2014), Fermi (2011,2014,2015,2016)

Catalogs of clusters been correlated:

1. WHL12 (158,103 clusters)
2. redMaPPer (26,350 clusters)
3. PlanckSZ (1,653 clusters)
4. HSC CAMIRA (4,948 clusters)



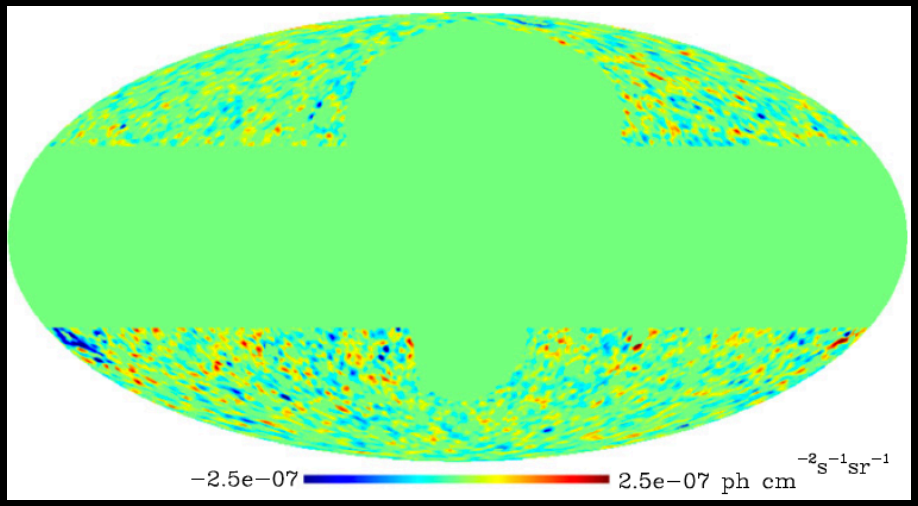


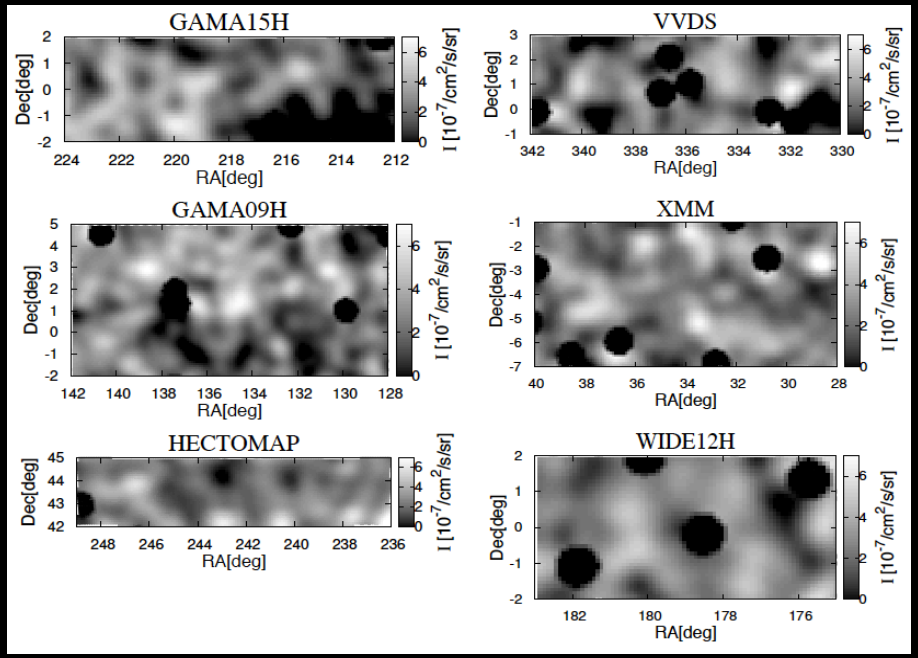


Branchini et al (2017)

Hashimoto et al (2018)

Datasets





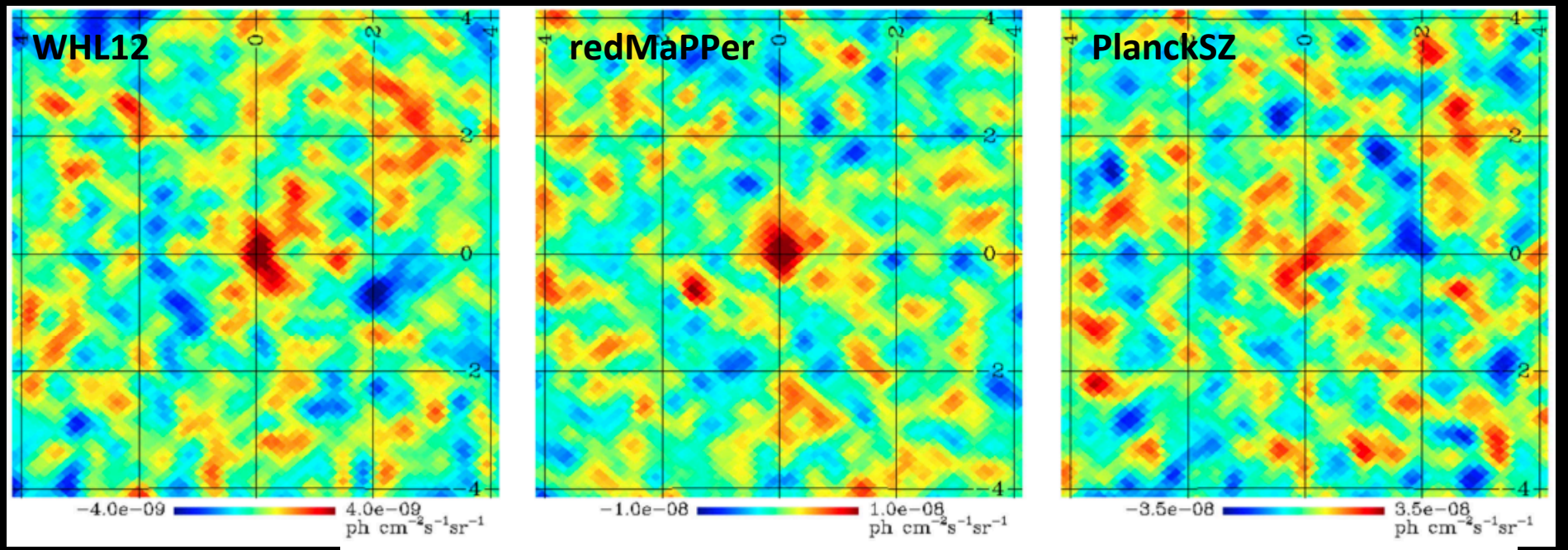
Gamma rays

- Fermi P8, ~6-7 yrs
- Energies 500 MeV or 1 GeV and above
  **balance of PSF & statistics*
- Fit & remove Galactic emission
  **not a big problem since they don't correlate with the LSS maps*
- Mask point sources, accommodating for the energy dependent PSF
- Masks for large diffuse structures: Galactic disk, Fermi bubbles, loop I

← High latitude sky, or in patches

(similar procedures for most cross correlation analyses)

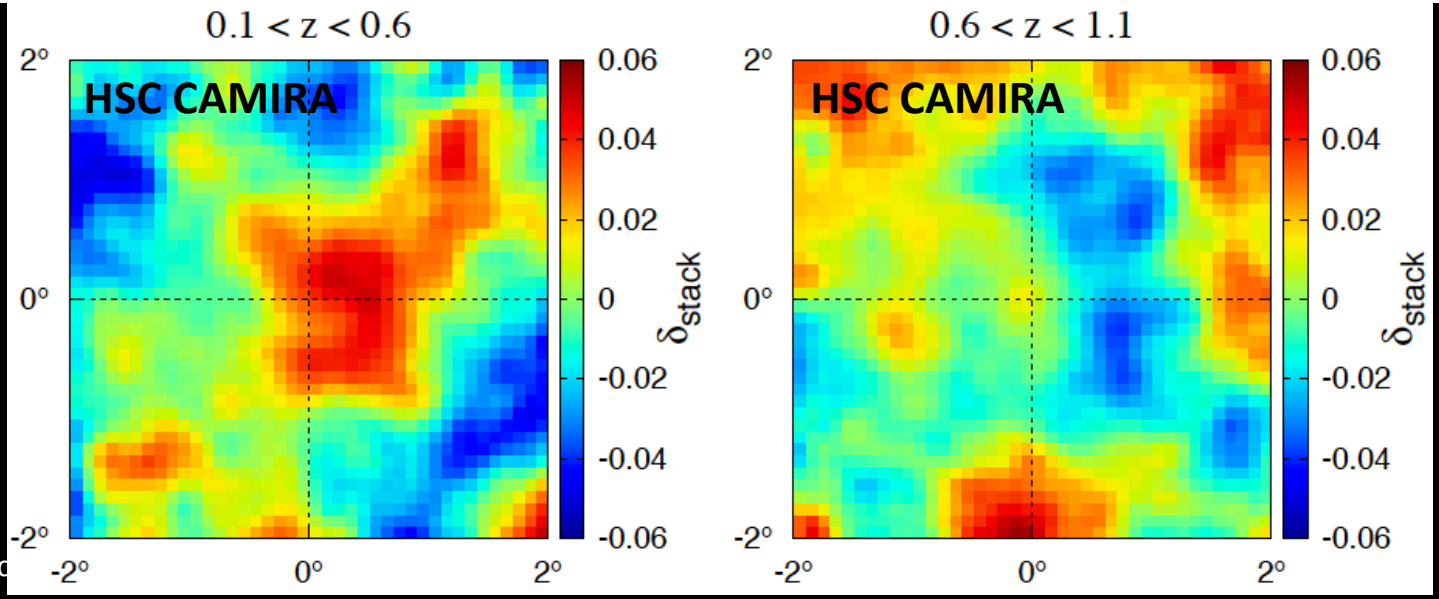
Stacked measurements



Branchini et al (2017)

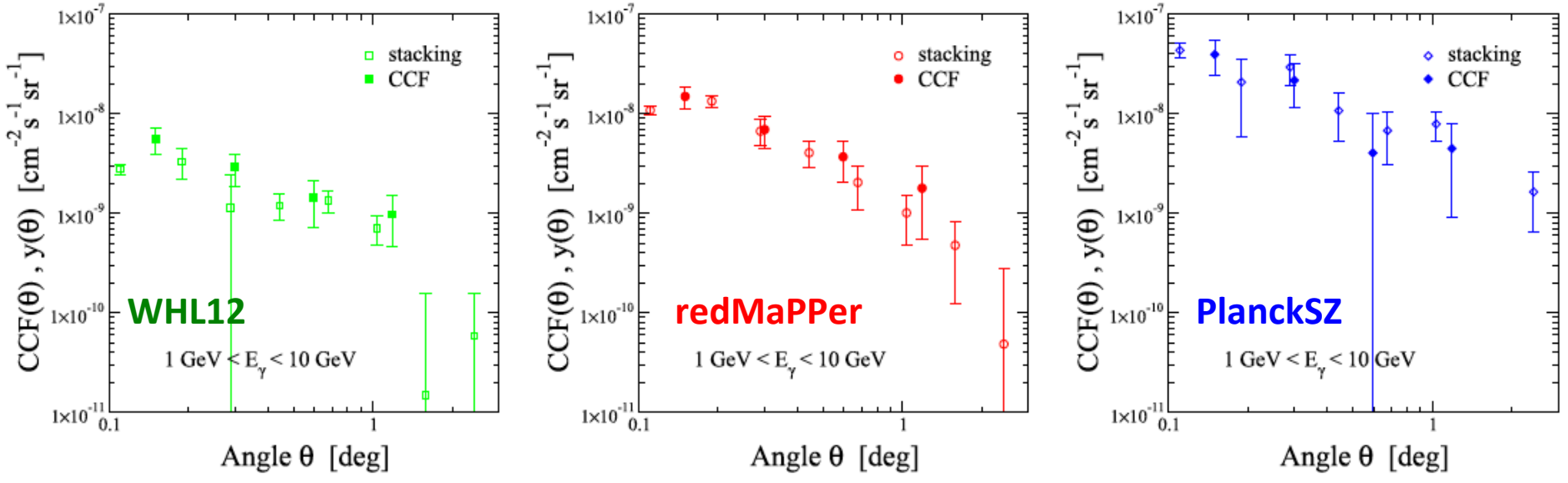
Hotspots!
(except high-z HSC CAMIRA sample)

Note: images correlations



Hashimoto et al (2018)

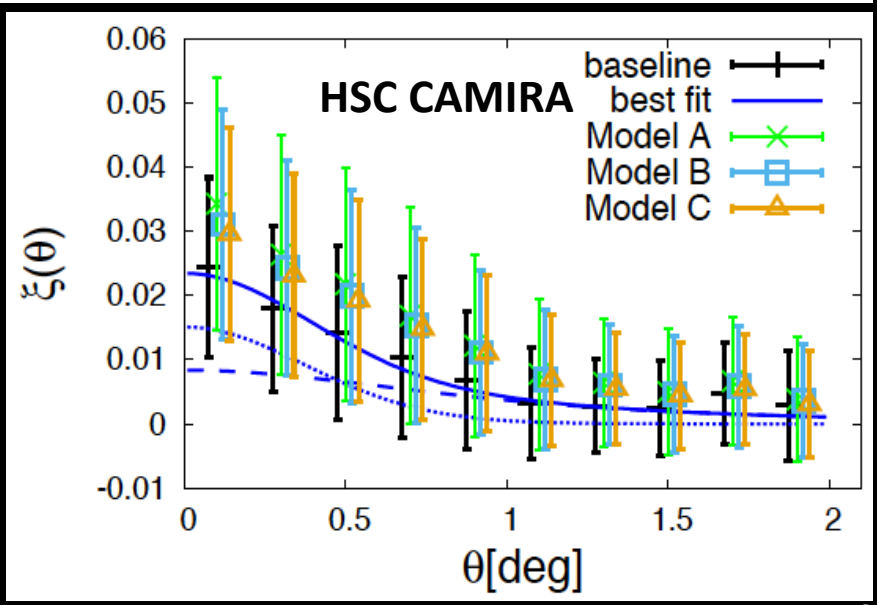
Cross correlation measurements



Branchini et al (2017)

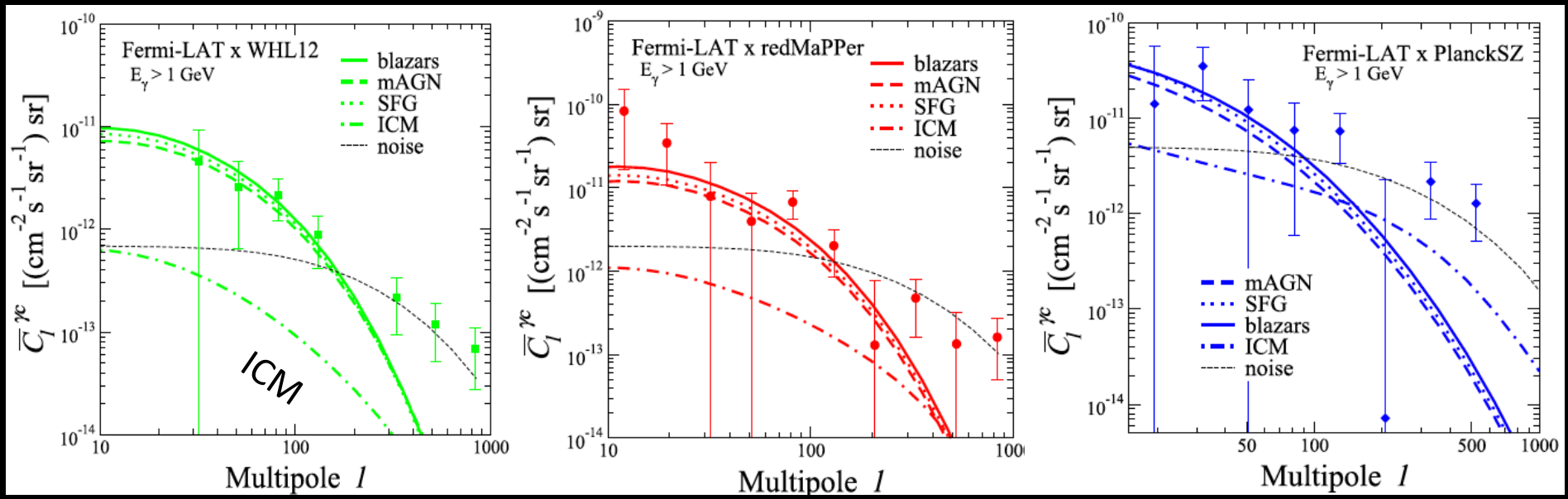
Positive correlations

- All except high-z subsample of HSC CAMIRA
- Correlations consistent with stacked profiles
- Angular extent: > 1 degree (> 10 Mpc)
  - Suggestive of not the ICM, but rather, emission from the AGNs along the LSS the cluster positions probe



Hashimoto et al (2018)

CAPS measurements & interpretations

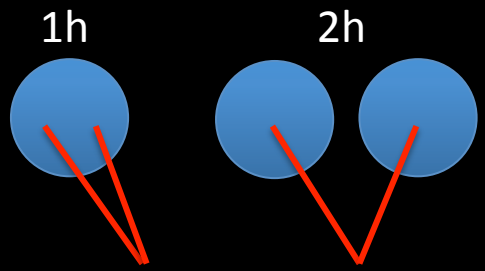


Branchini et al (2017)

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

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

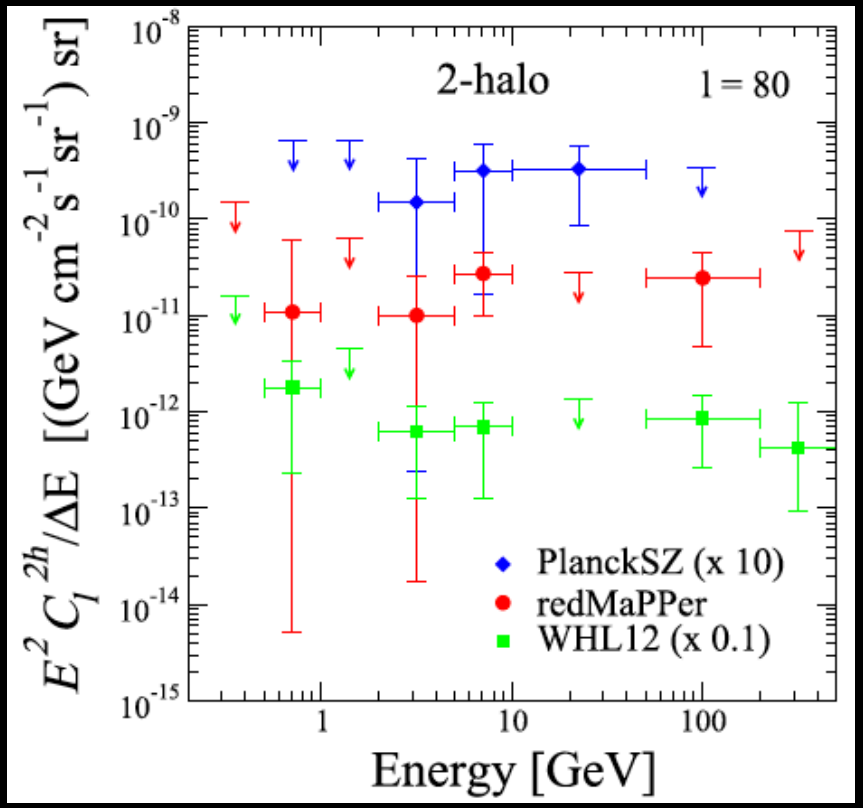
Decompose: $P(k) = P^{1h}(k) + P^{2h}(k)$

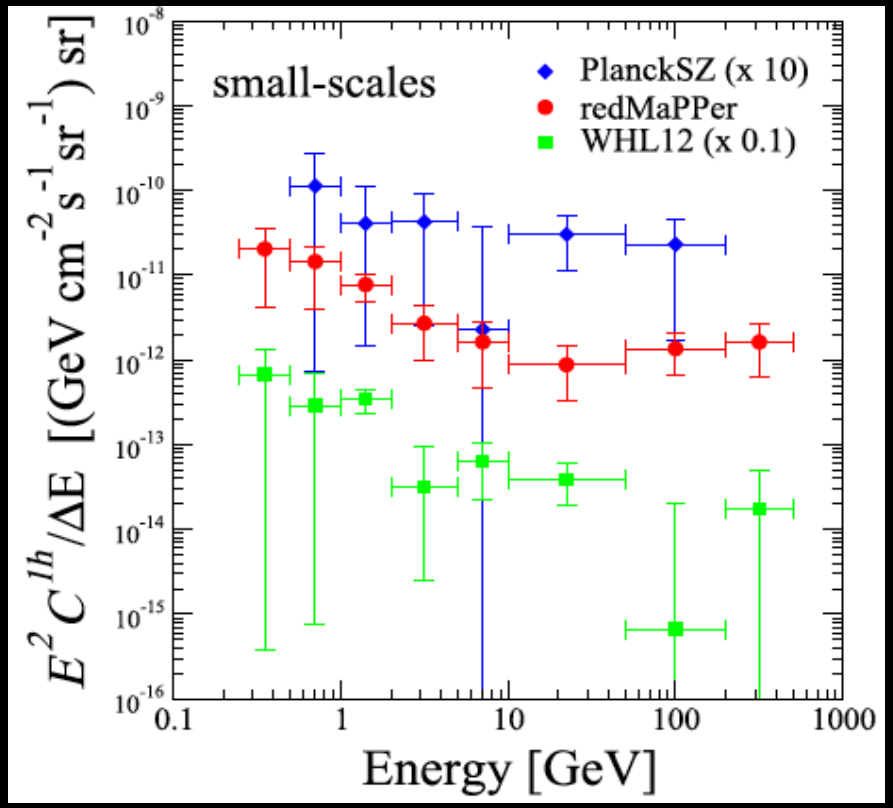


- Small-scale correlation needs additional power
  - ICM? Constrained by nearby clusters
  - Correction for inaccuracies in 1h term? (due to discrete gamma-ray sources)

cf Ando (2014)

Hints from energy spectrum





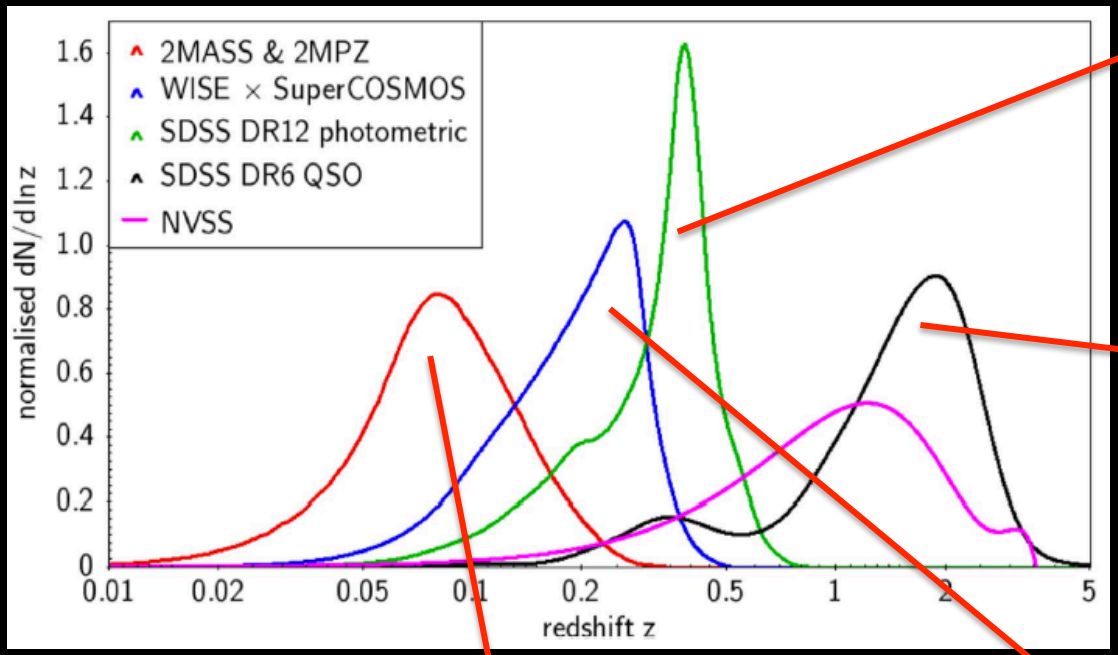
Branchini et al (2017)

- 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?

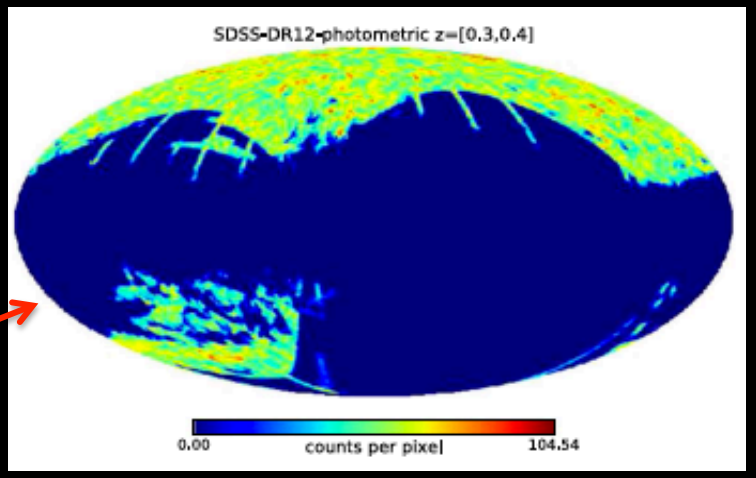
CORRELATION WITH GALAXIES

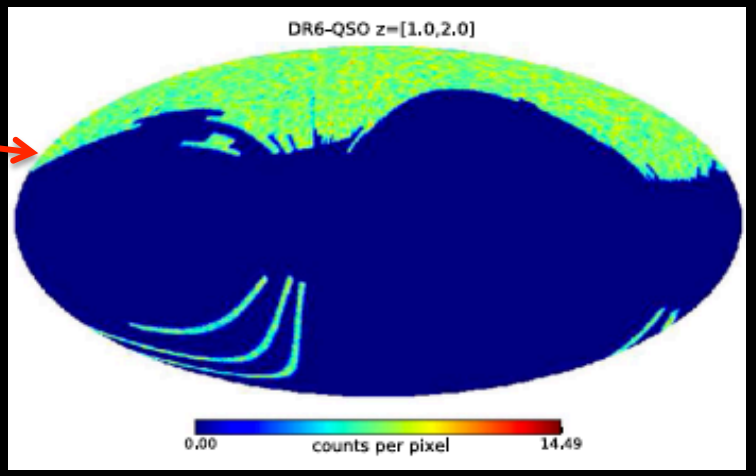
Galaxy catalogs

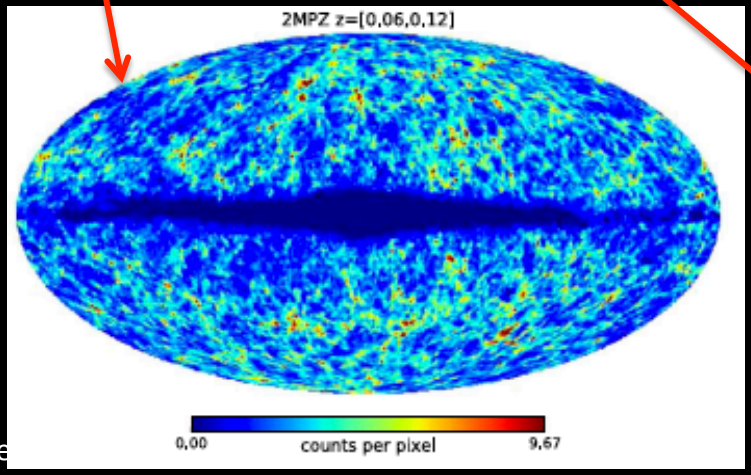
Galaxy catalogs studied:

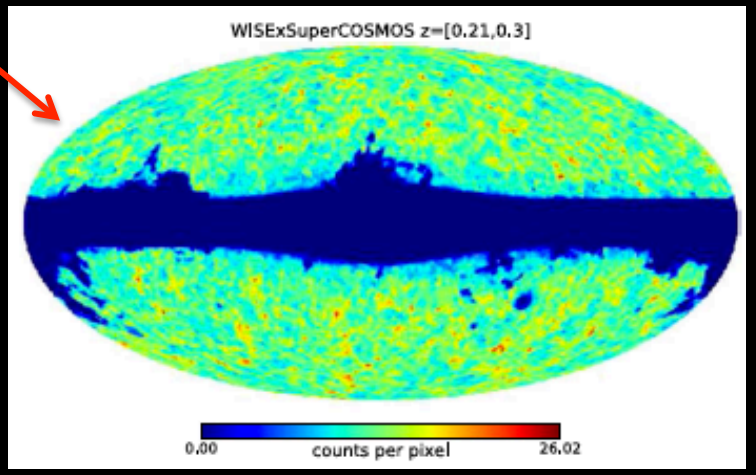


Cuoco et al (2017)



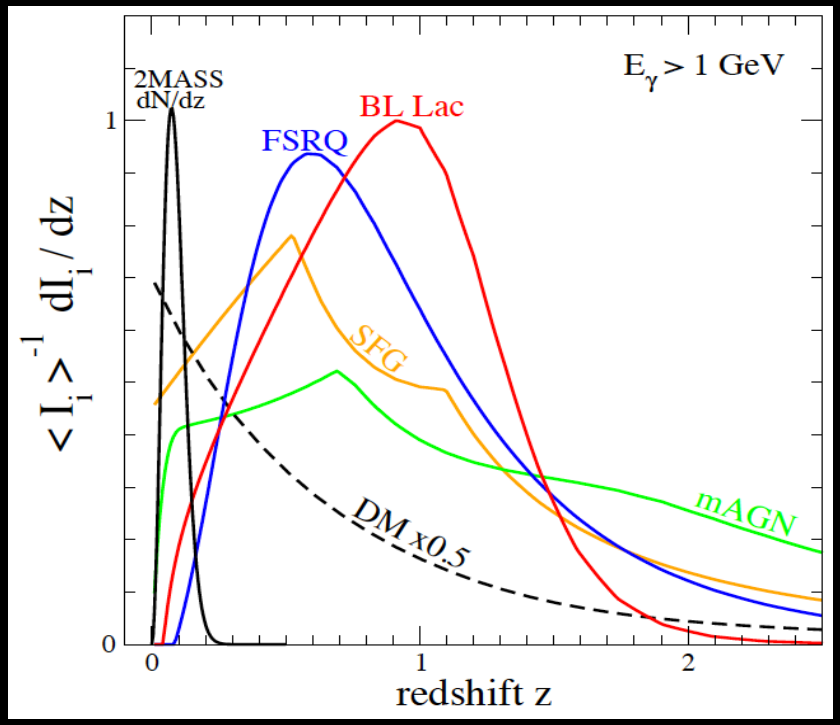






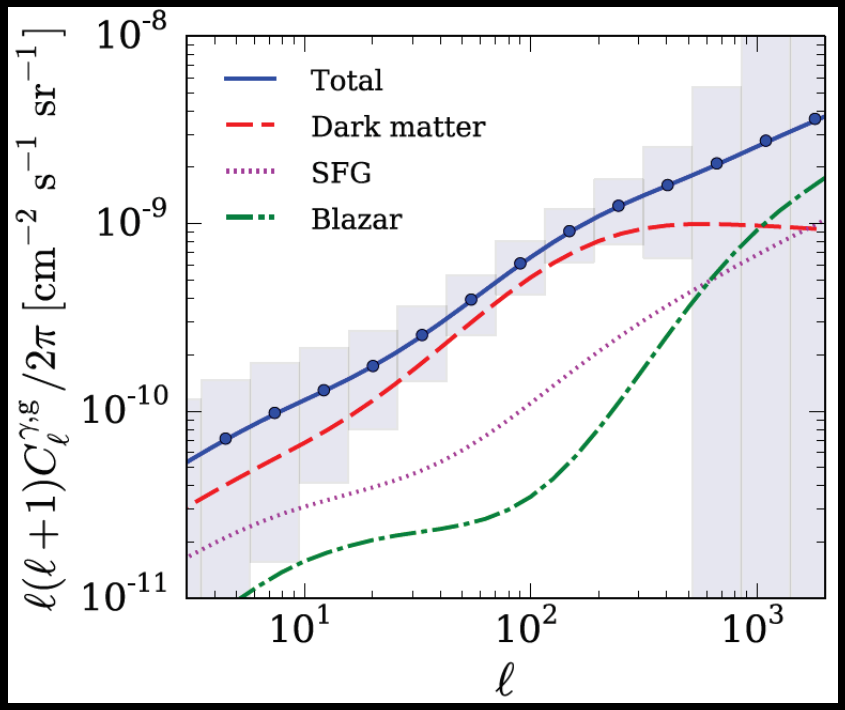
Tomography

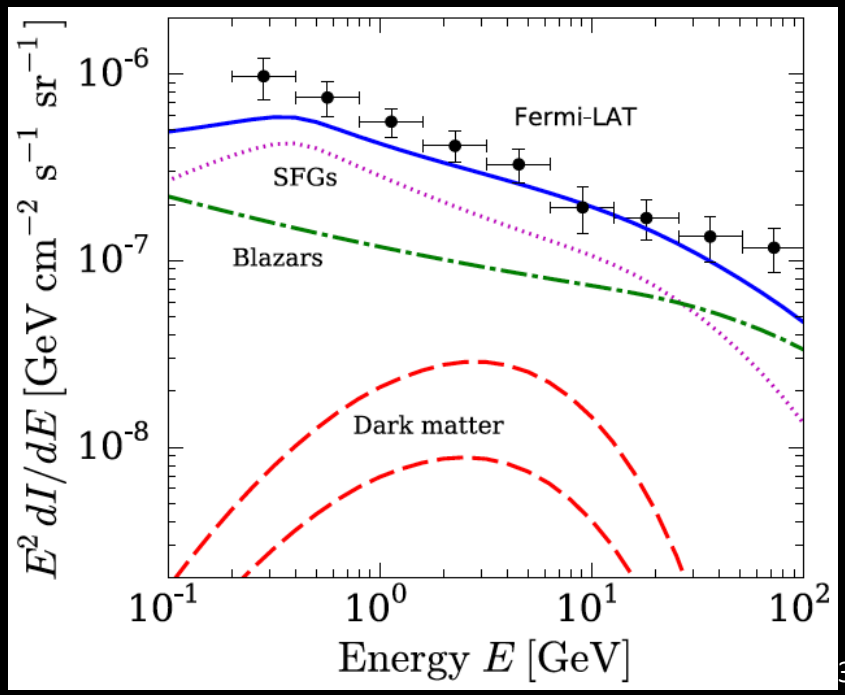
Multiple galaxy catalogs will provide tomographic information to help unravel contributors.



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

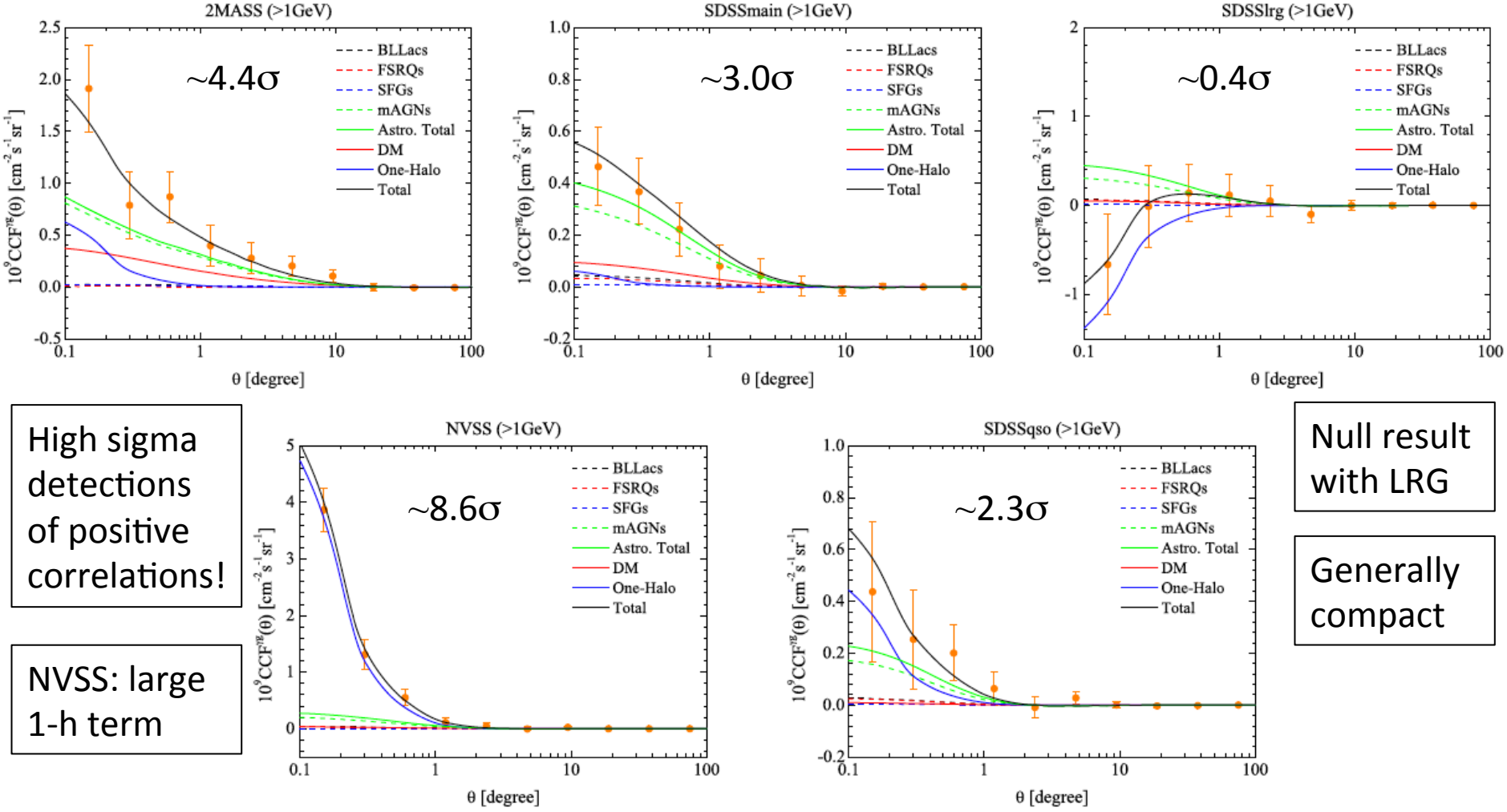
Ando 2014





First detection of the cross correlation

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



High sigma detections of positive correlations!

NVSS: large 1-h term

Null result with LRG

Generally compact

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

Interpretations of CCF

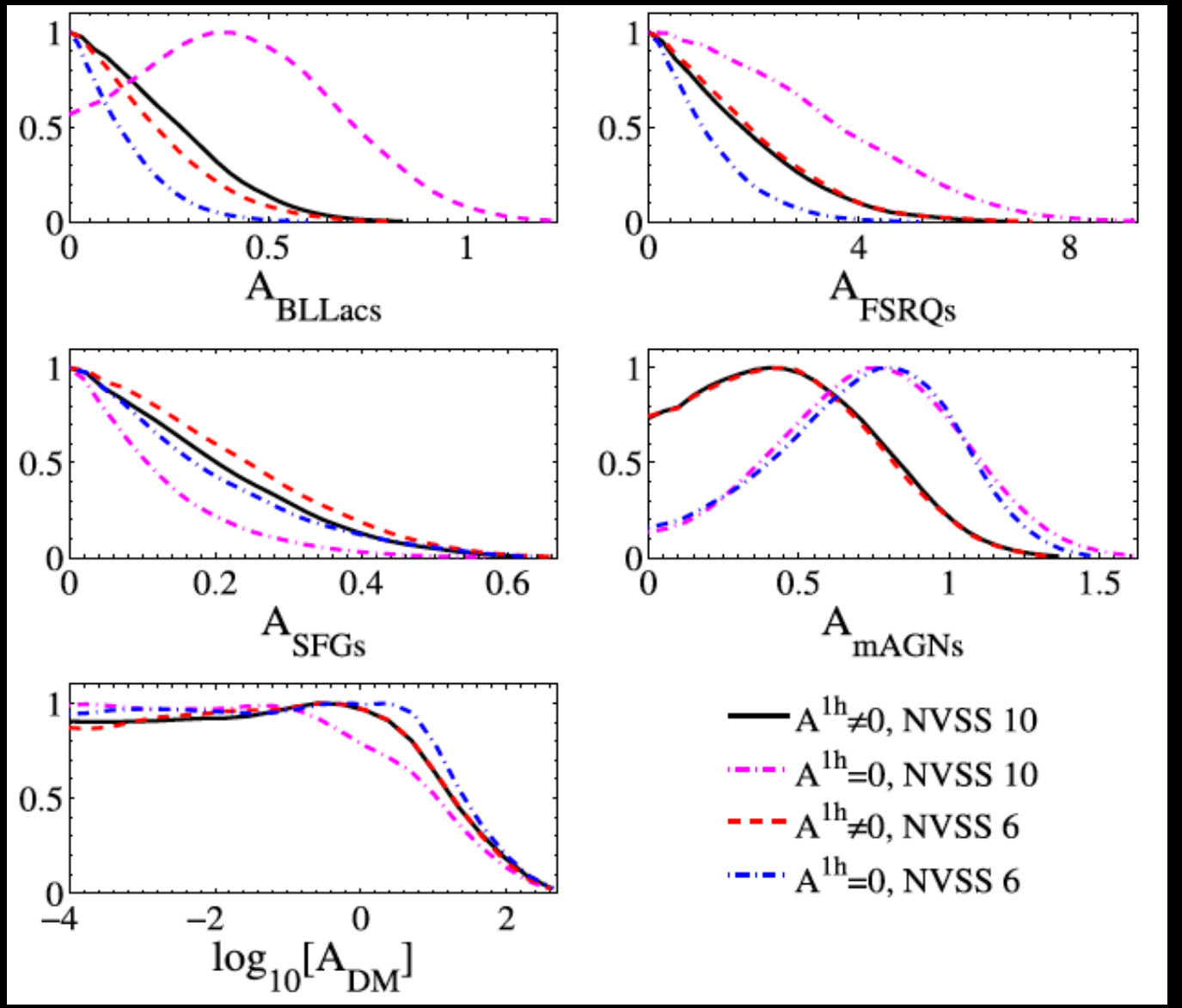
Global fit: 5 sources,
5 catalogs, in 3 energies

Marginalized posterior distributions

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

Considerable degeneracy exist between sources

Some effect due to treatment of 1h correction term



Cuoco et al (2015)

(+6 parameters)

New correlation analyses

- More data (6.5 yrs P8 >0.25 GeV), more galaxies, ad
- Redshift tomography results in significant detection

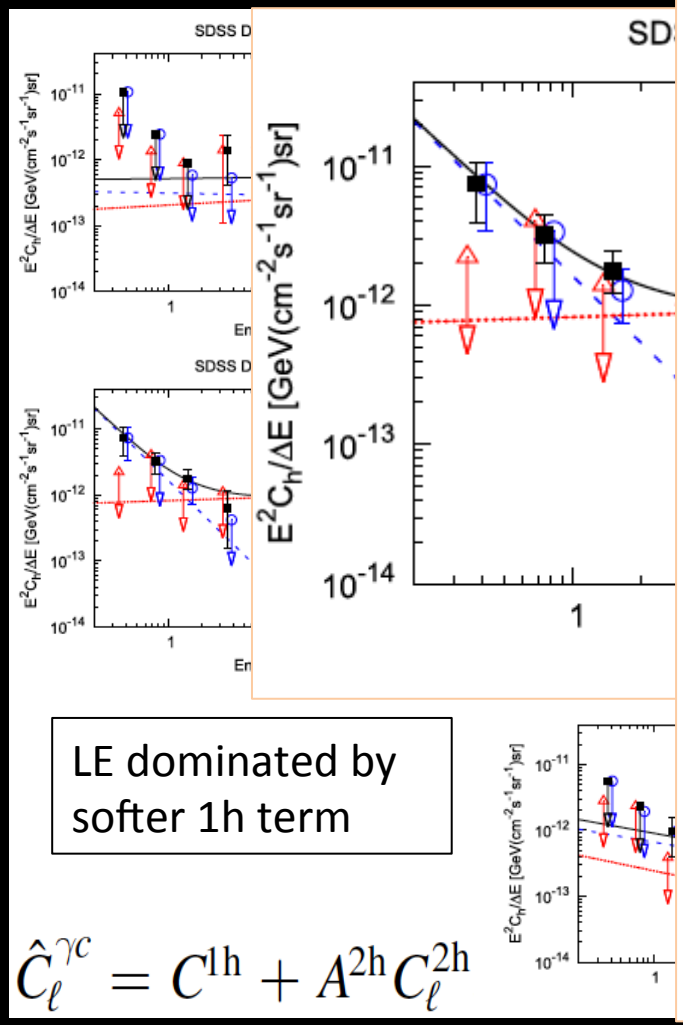
- Spectrum shows hints of break

- CC signal varies by catalog, redshift, and energy range

→ sources with different properties contribute differently to UGRB

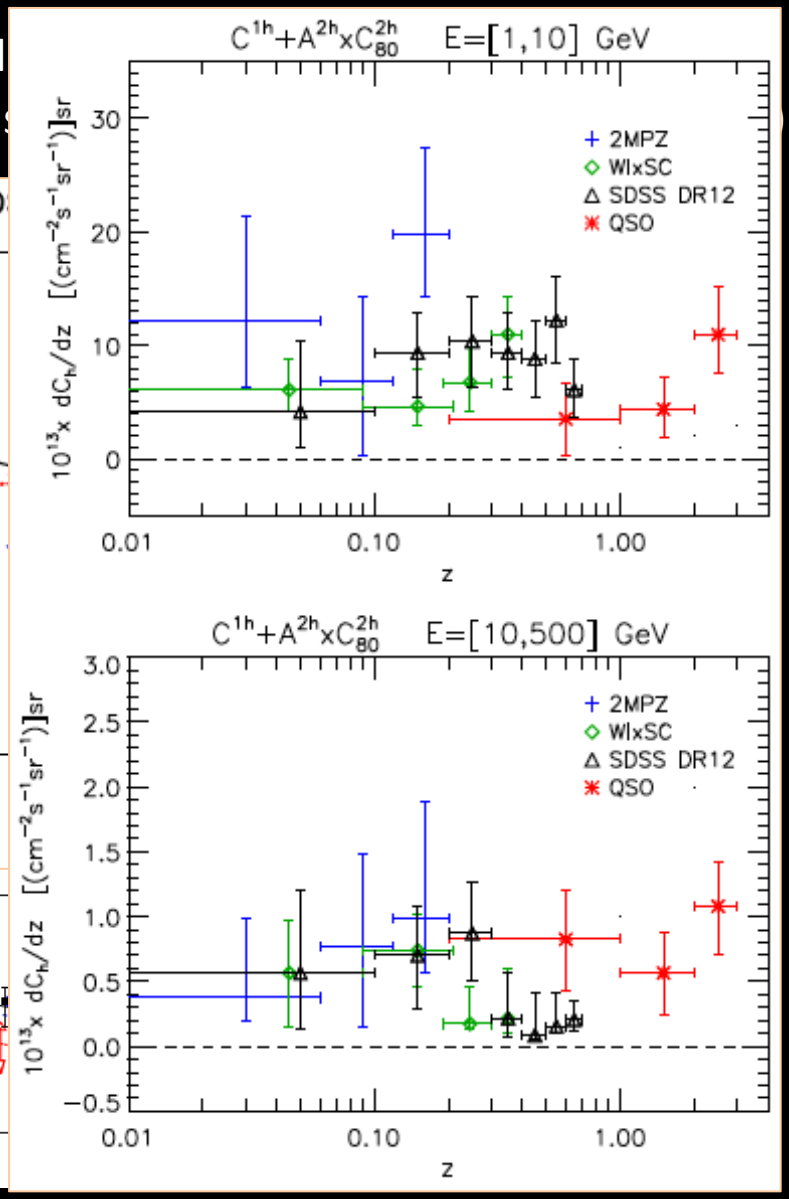
Stay tuned…

Future goal…



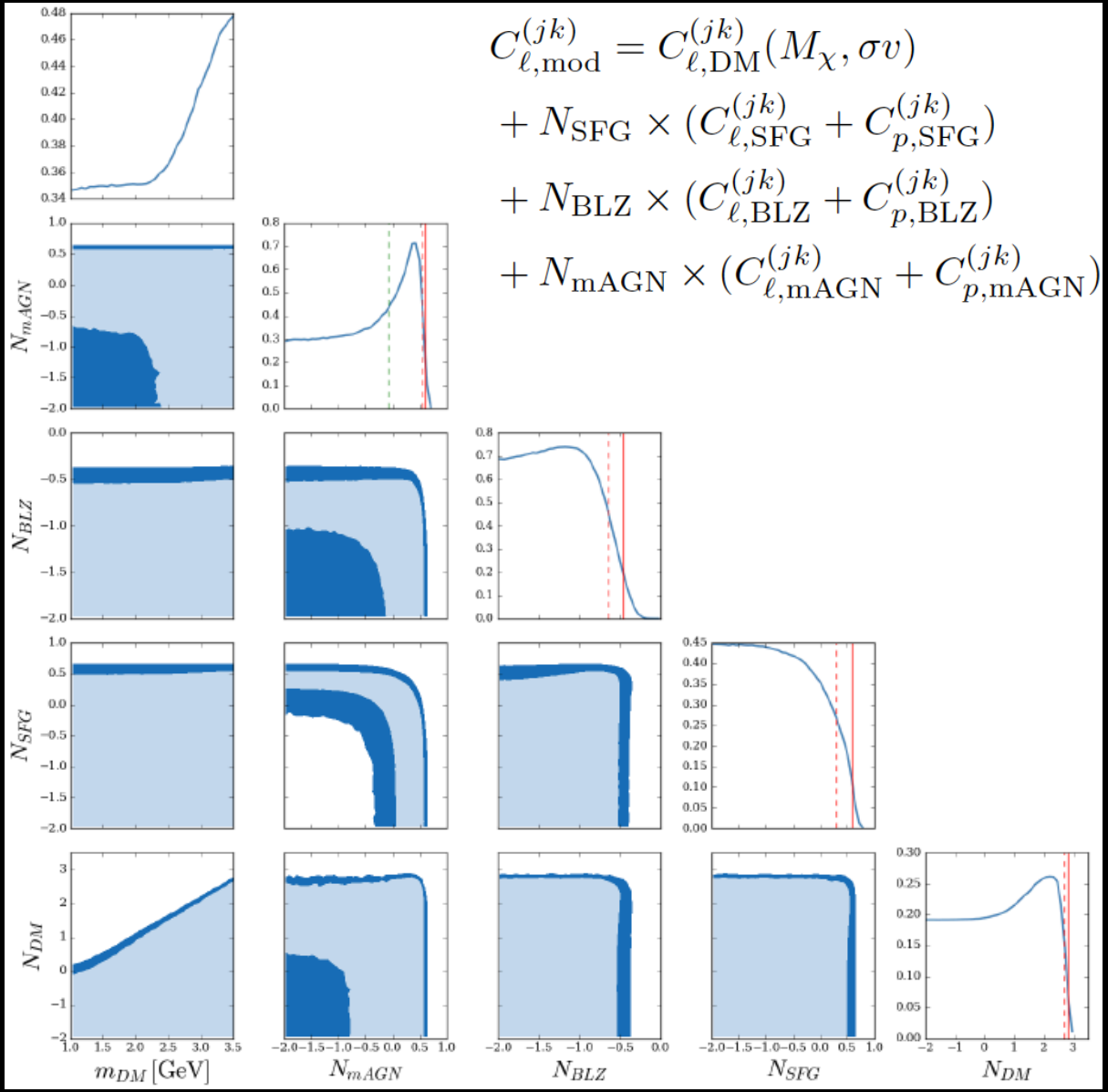
LE dominated by softer 1h term

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



Cuoco et al (2017)

Focus on the 2MASS (2MPZ)



Focus on 2MPZ

- 9 yrs of P8 Fermi-LAT data
- 2MPZ: 2MASS with 8 bands multi-wavelength data.
- Further split into redshift, B-band, and K-band bins

Fit results:

- Correlation consistent with arising mostly from mAGN
- SFG and blazars appear subdominant
- Situation can change at higher redshifts

Ammazzalorso et al (2018)

Shot-noise term

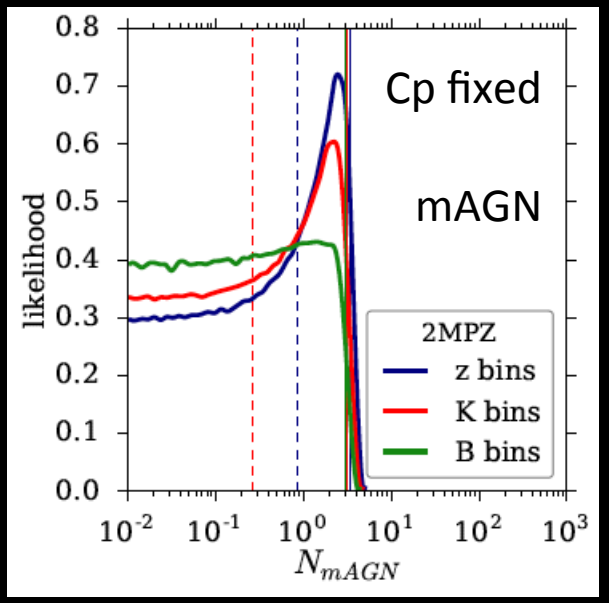
With 2MPZ, shot-noise can be estimated more directly:

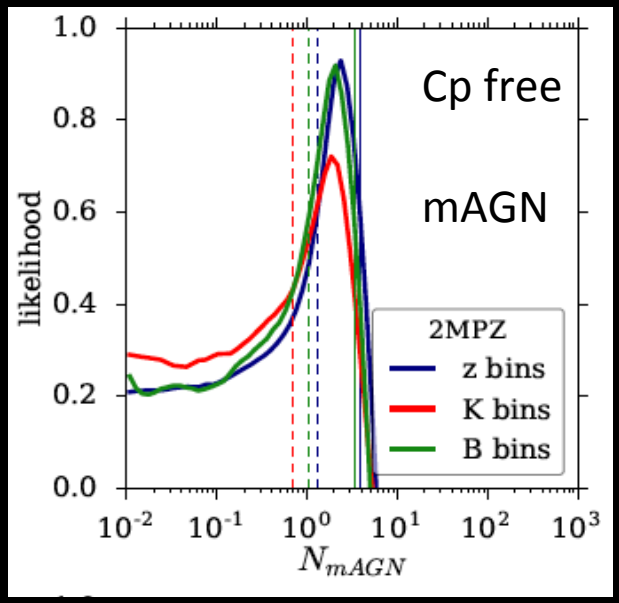
- Based on IR colors, can identify mAGN and blazars candidates in the 2MPZ
- Using scaling relations, can estimate the gamma

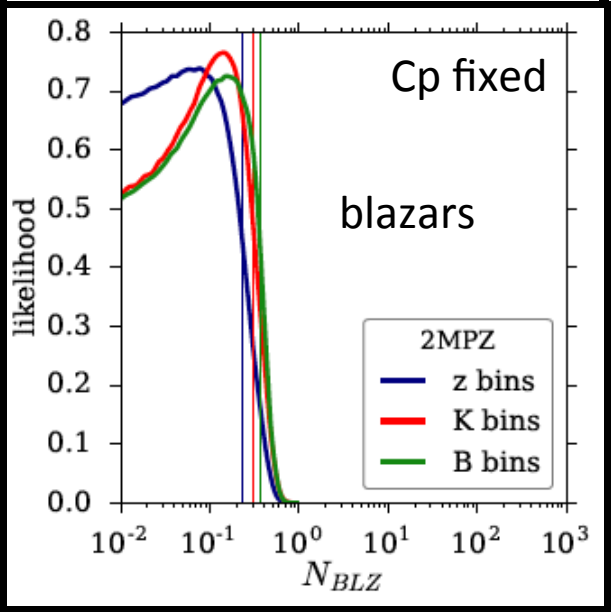
Effect of free shot-noise term?

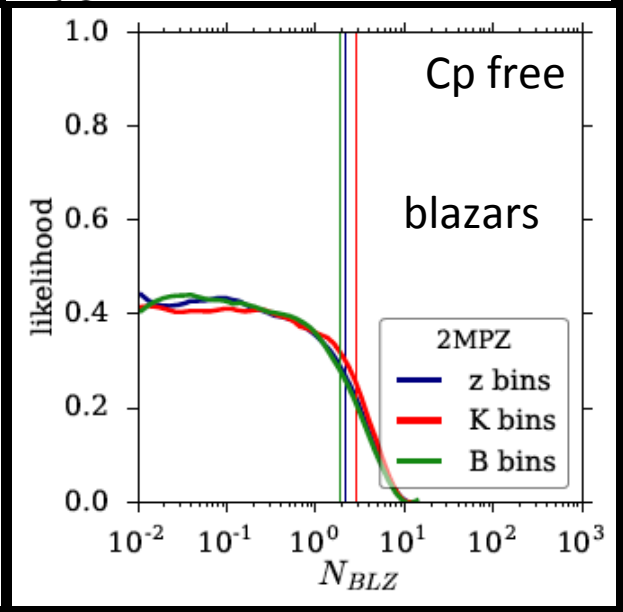
- mAGN remains non-zero
- E.g., blazar goes from subdominant to weakly constrained

Ammazzalorso et al (2018)





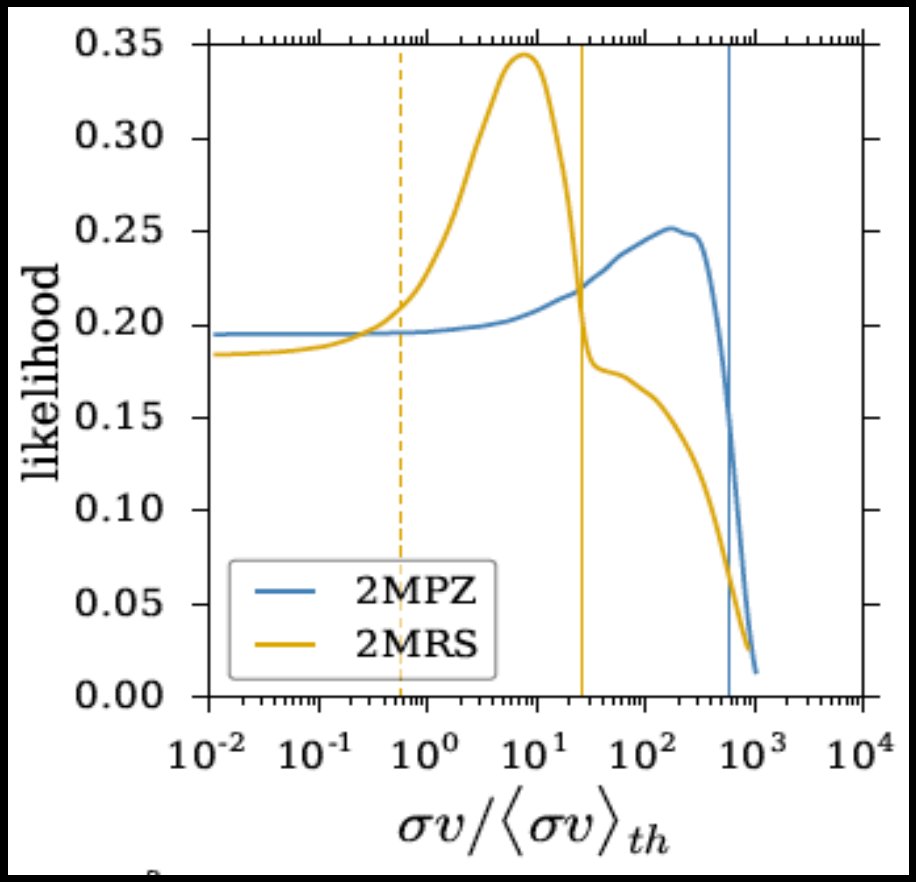


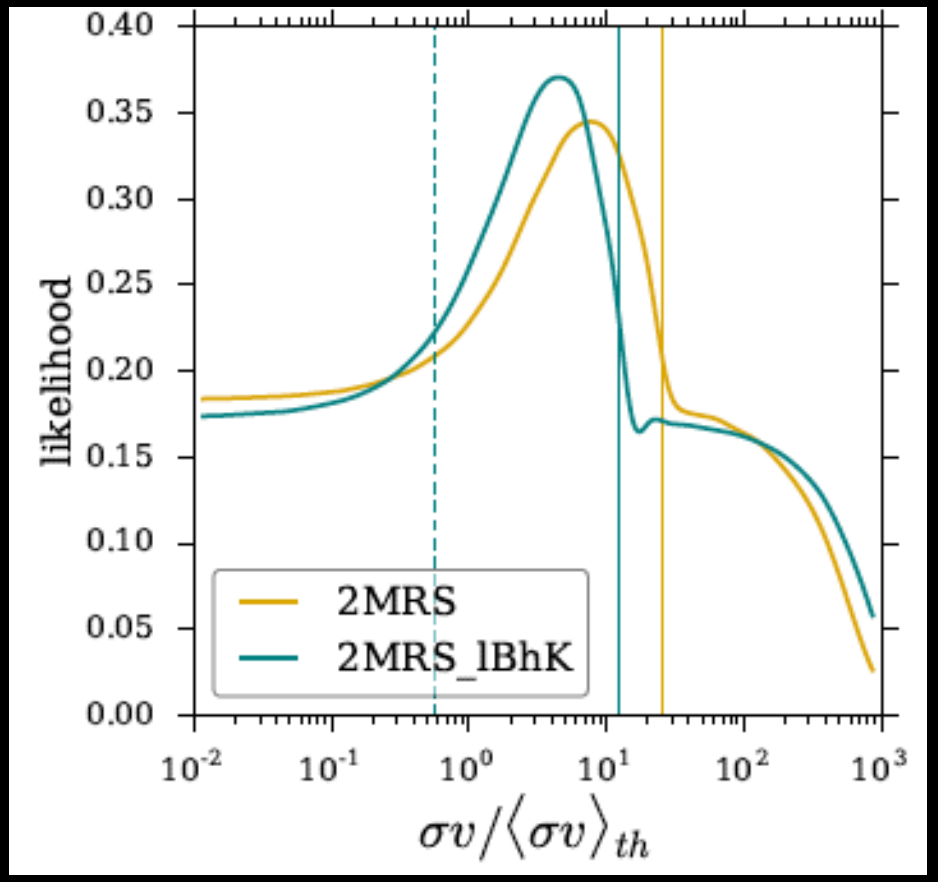


Implications for dark matter

Dark matter? Trends consistent with DM expectations:

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



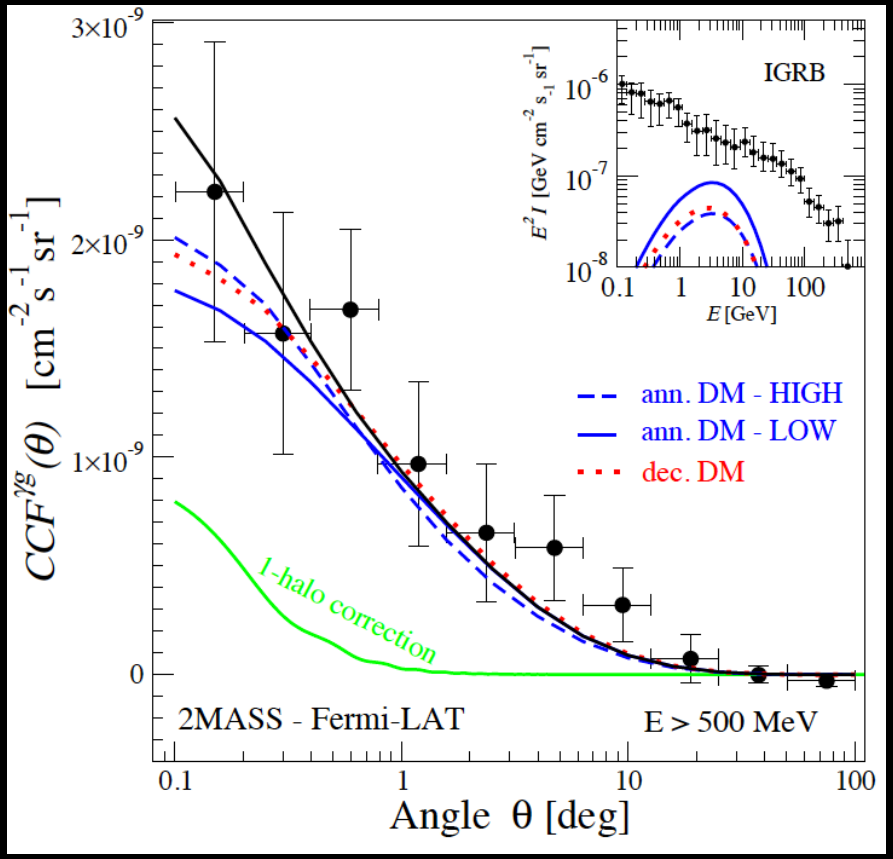


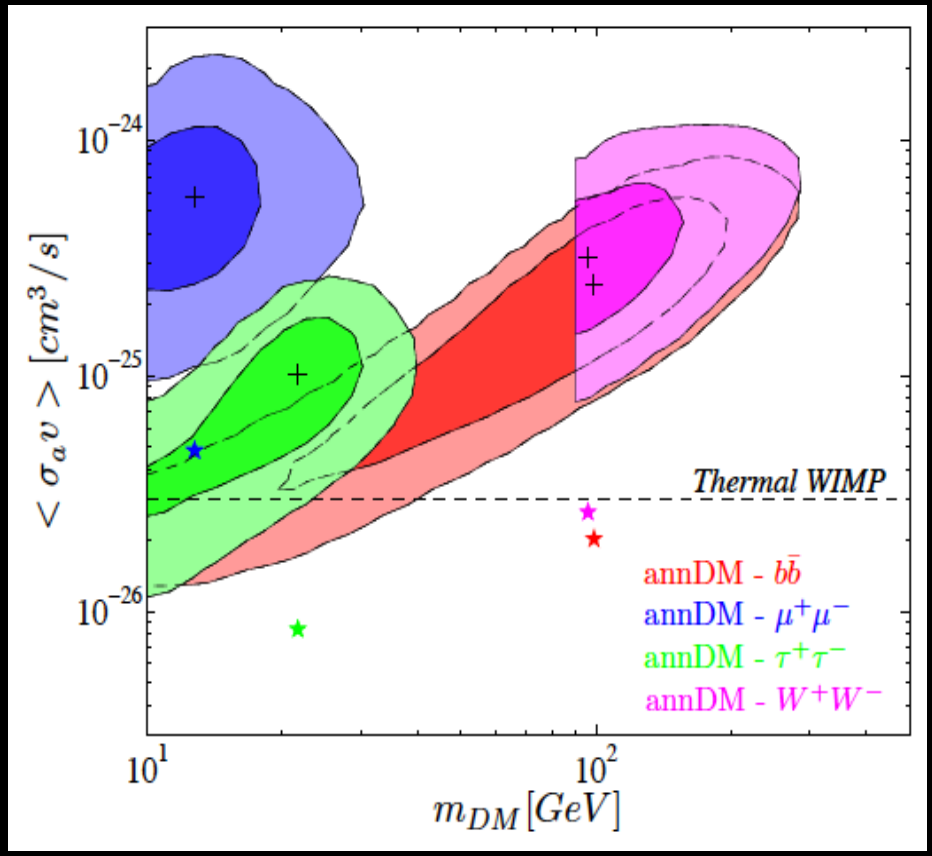
Ammazzalorso et al (2018)

Implications for dark matter

Fit with only dark matter

No astrophysics assumed (conservative for limits). Both the shape and intensity can be satisfied by dark matter.





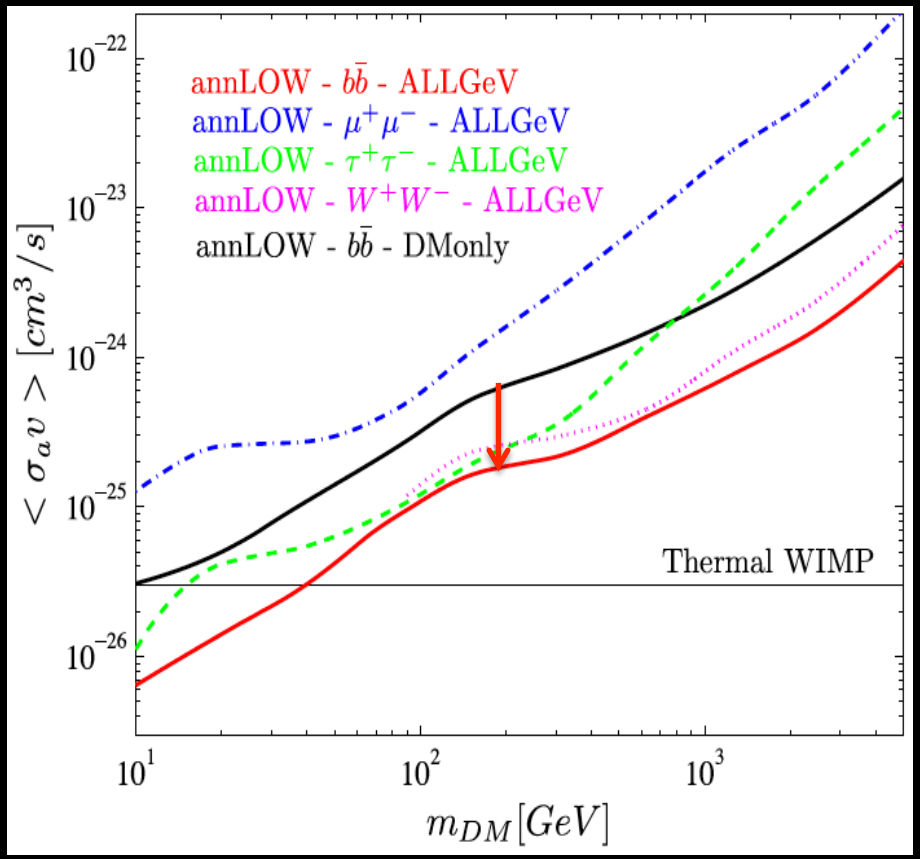
Fermi-LAT – 2MASS cross-correlation

Regis et al (2015)

Limits on dark matter

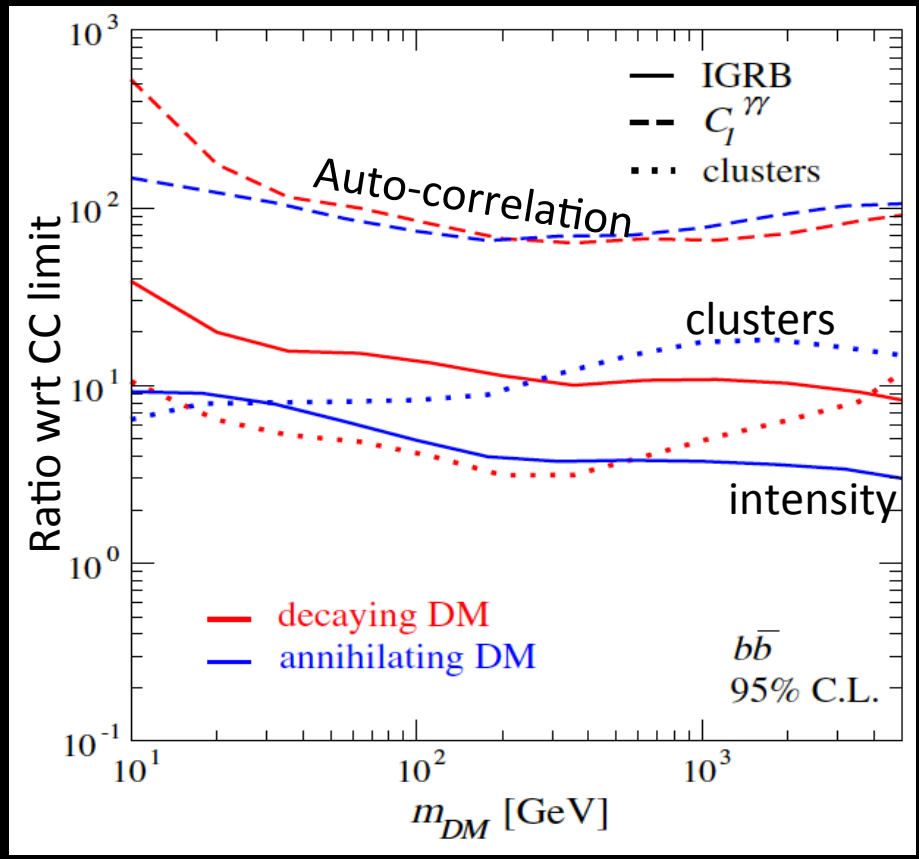
Fit with astrophysics

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



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

Sensitivity from cross-correlation can be better than other EGB methods



Regis et al (2015)

CORRELATION WITH LENSING MAPS

Correlation with lensing maps

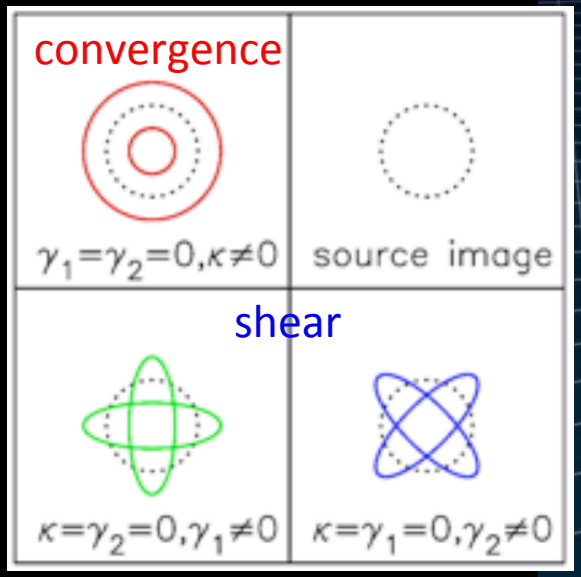
Images of distant galaxies are distorted by matter along the line of sight

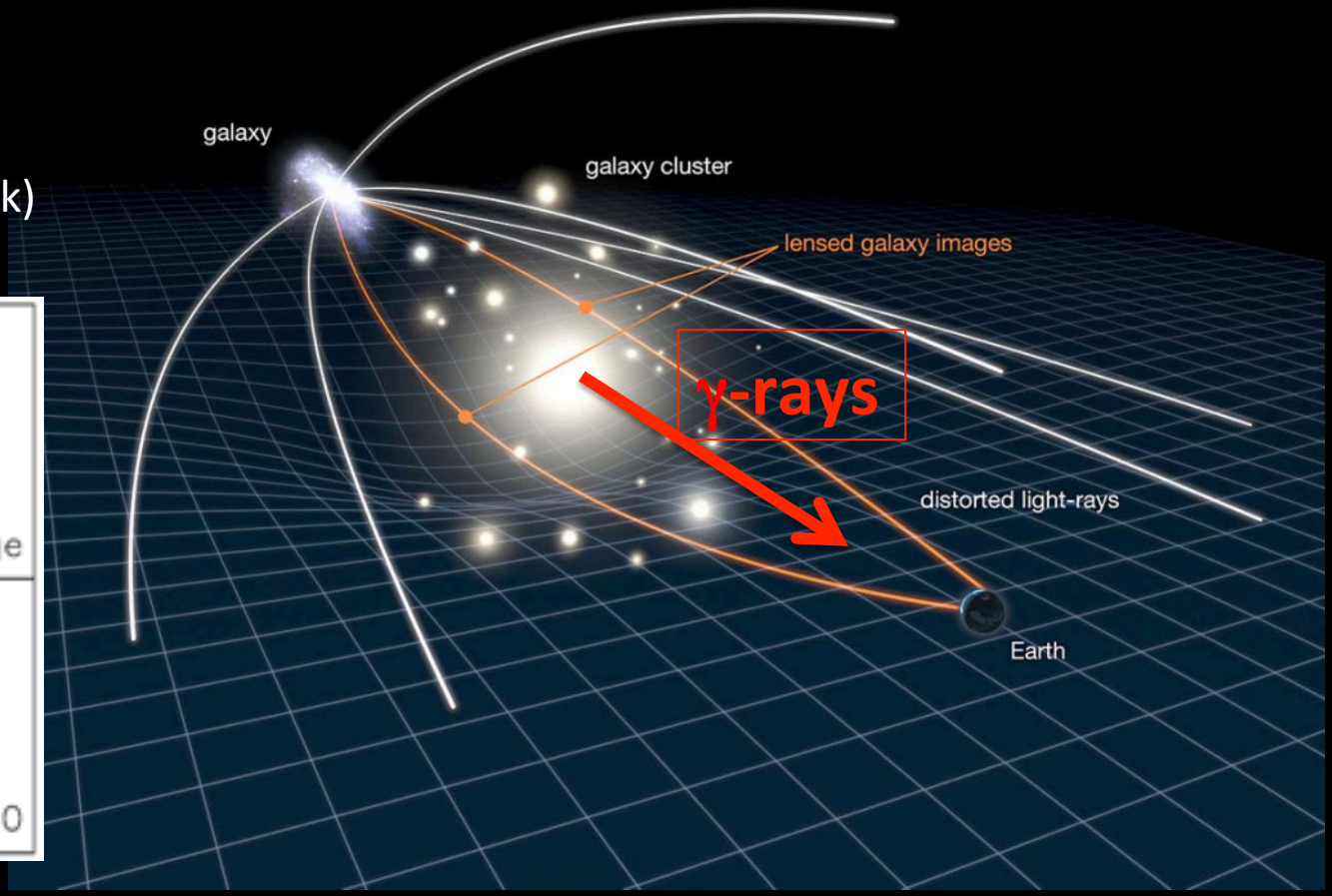
The lens object is also a gamma-ray source, due to astrophysical and potential dark matter physics

→ Probe this connection with cross-correlation

→ Shirasaki-san's talk

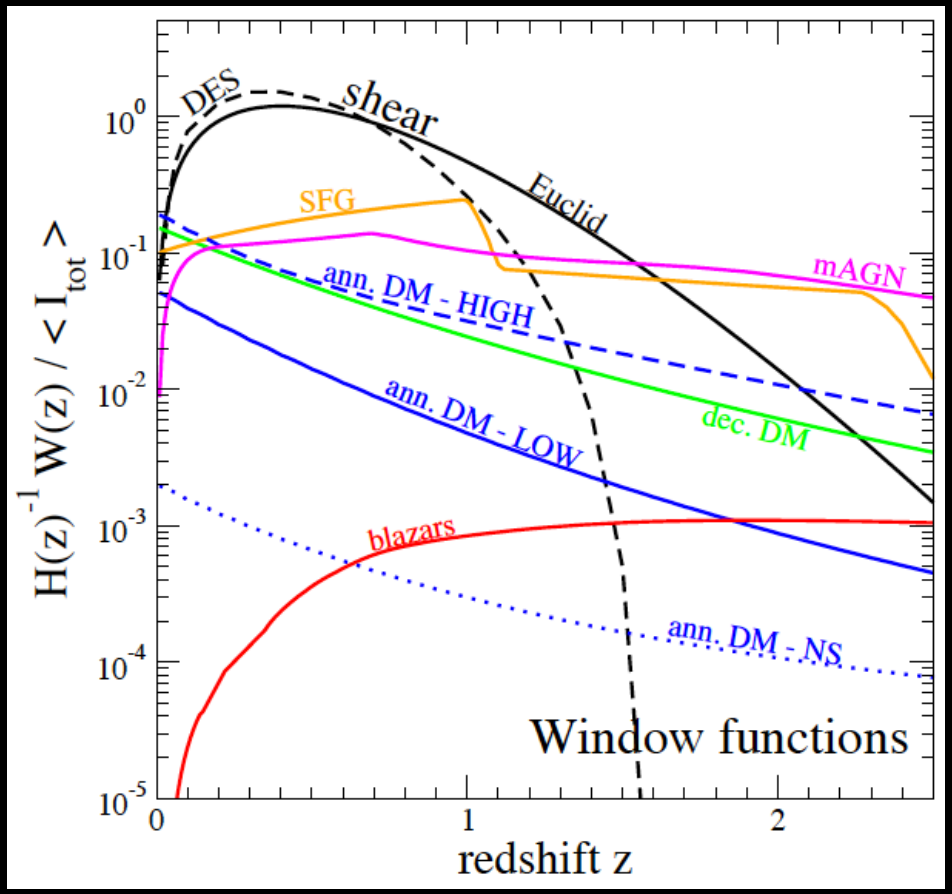
Distortions: convergence (k) and shear (γ)





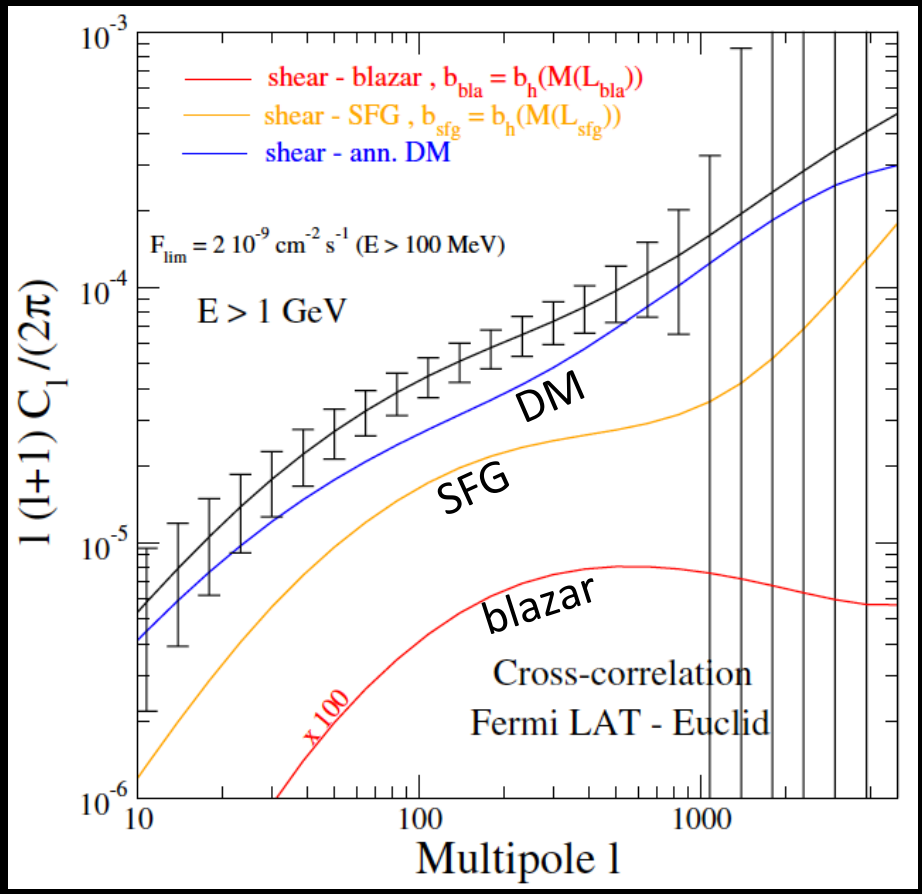
Early studies & predictions

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



Camera et al (2013,2014)

The blazar contribution is lower and dark matter can be disentangled



(Fermi-LAT & Euclid)

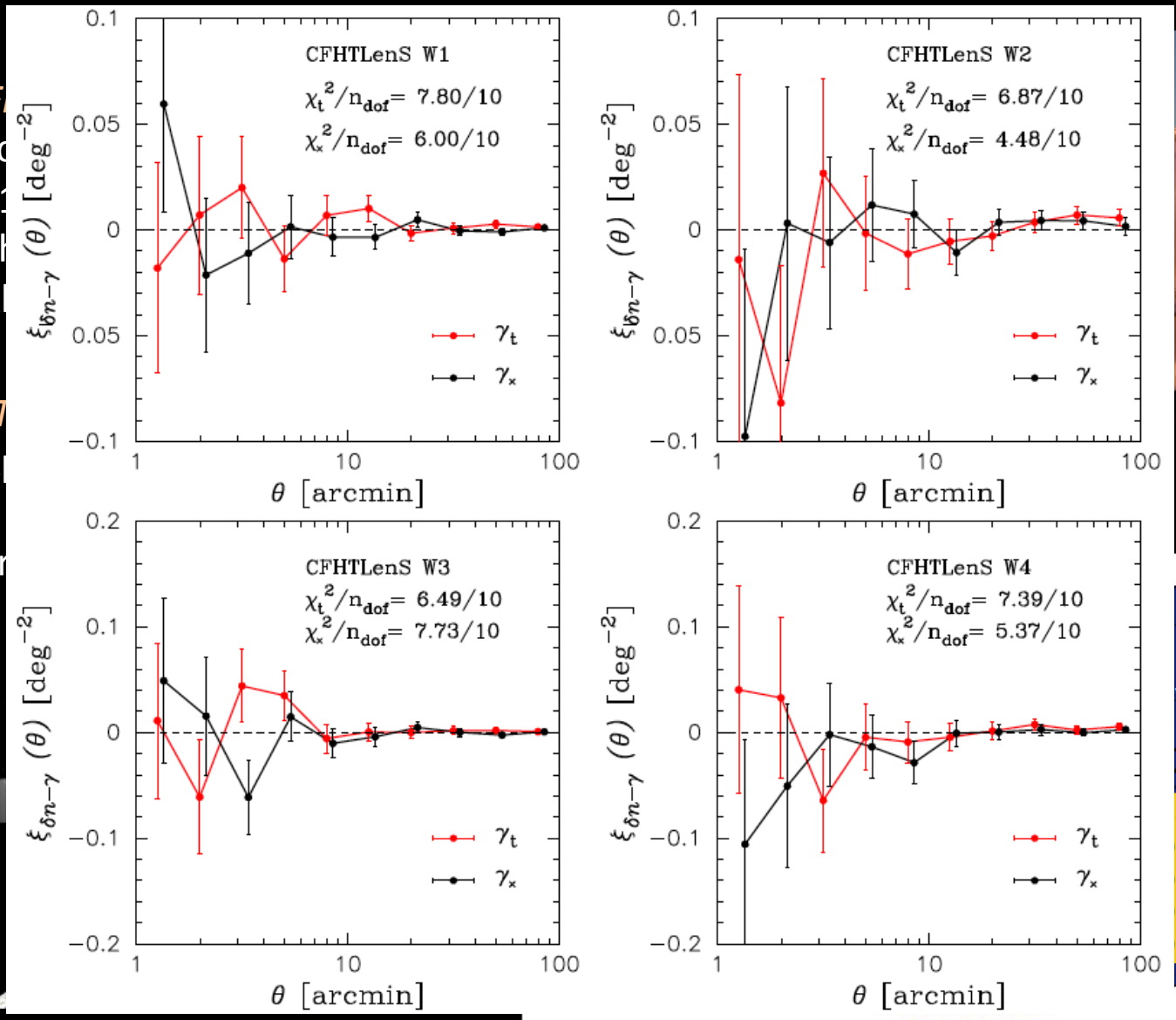
Analysis with real data

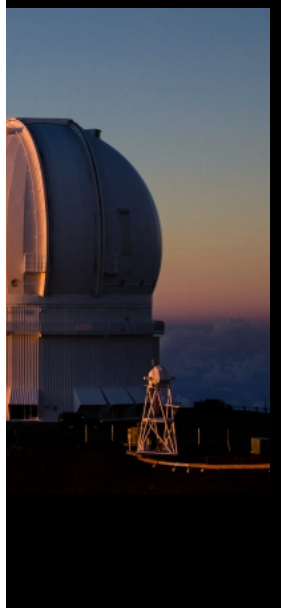
Canada-F

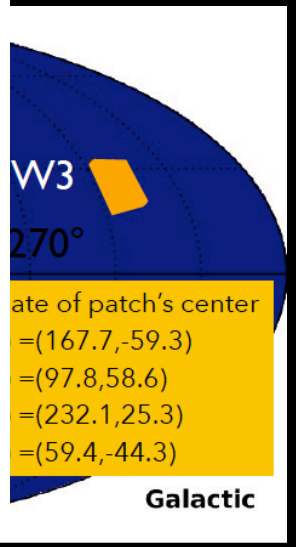
- Fo
- 11
- Ph
- Al

Fermi-LAT

- Ap
- 1
- Tr







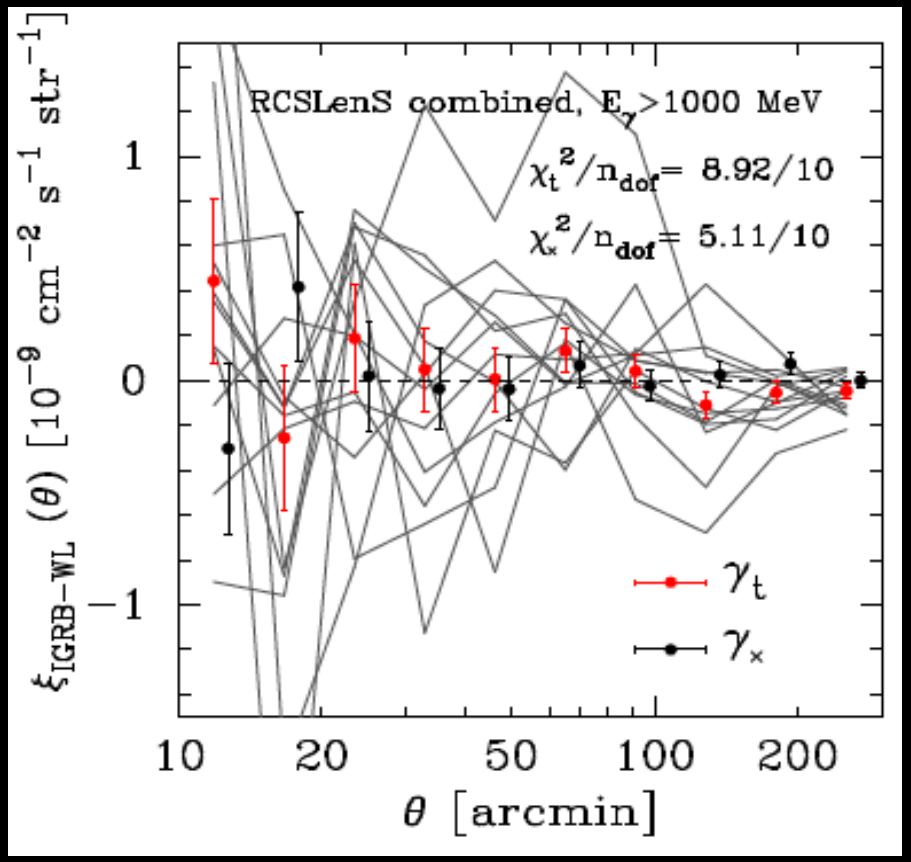
Shirasaki et al (2014)

More attempts

(CFHTLenS + RCSLenS) x 7 yrs Fermi P8

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

→ Null detection

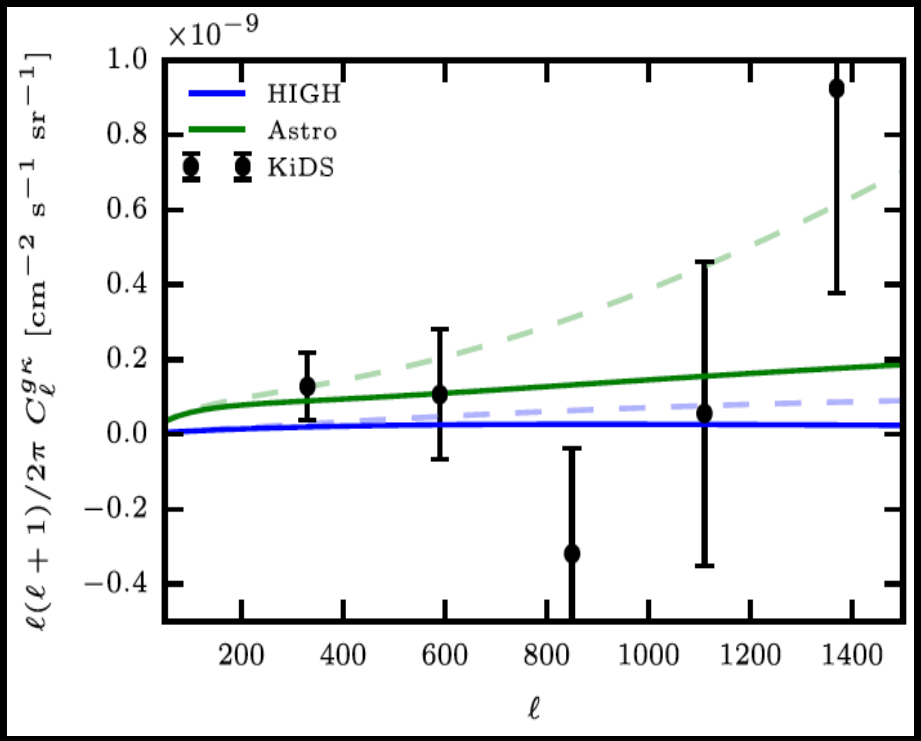


Shirasaki, Macias et al (2016)

(CFHTLenS + RCSLenS + KIDS) x 7 yrs Fermi P8

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

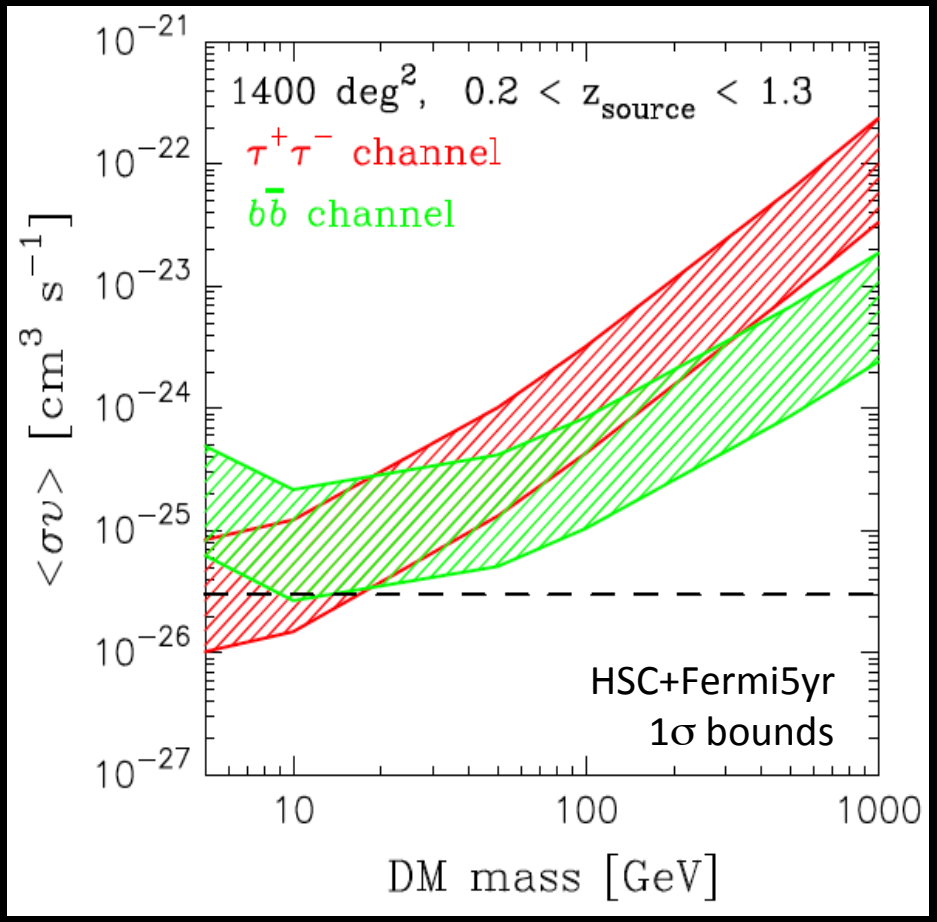
→ Null detection



Troster et al (2017)

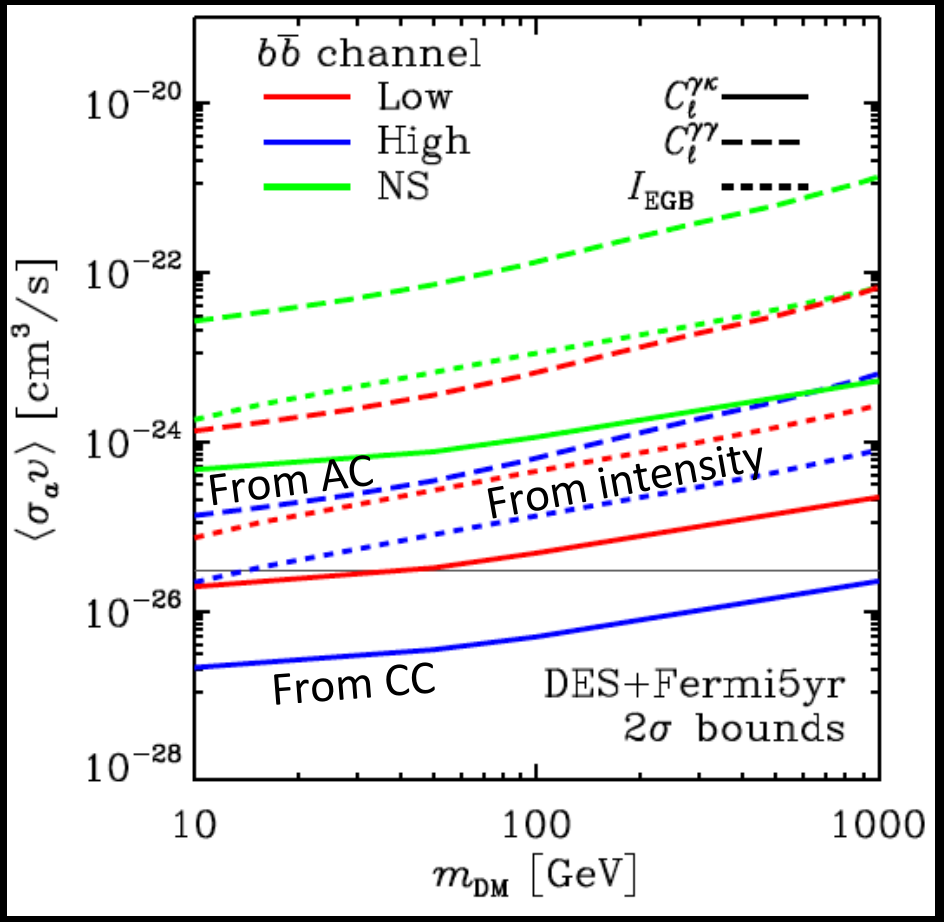
Ongoing & future surveys

Hyper-Suprime Cam: ~1,400 deg^2
Limits scaled by (survey area)$^{1/2}$



Shirasaki et al (2014)

Dark Energy Survey: ~5,000 deg^2
(2σ bounds)



Camera et al (2014)

More with LSST, Euclid!

Summary

The unresolved gamma-ray background contains a wealth of knowledge.

- Guaranteed sources, new sources like dark matter and/or surprises
- These can be probed by exploiting cross-correlation techniques

Amazing progress already, future prospects are high

- Correlation with clusters: significant. More clusters to test/refute ICM origin versus other sources
- Correlation with galaxies: highly significant. Rich prospects with multiple catalogs, galaxy subsamples, redshift tomography, etc.
- Correlation with gravitational lensing: not significant (so far), but advances guaranteed with upcoming surveys (DES, LSST, Euclid)
- Synergies: with each other, but also with other anisotropy probes

Thank you!