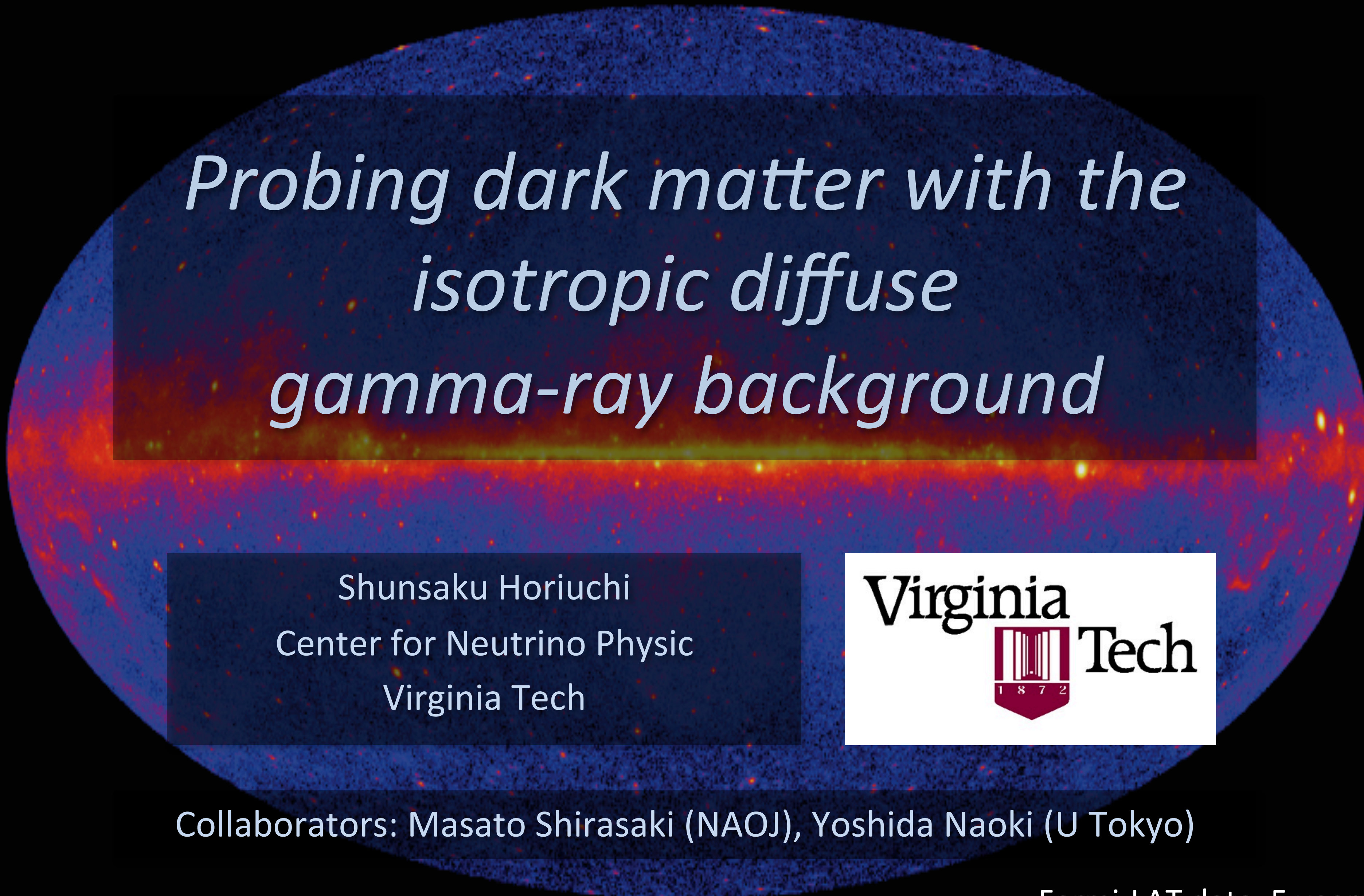
Gamma rays and Dark Matter, December 2015

Probing dark matter with the isotropic diffuse gamma-ray background

Shunsaku Horiuchi
Center for Neutrino Physic
Virginia Tech

Collaborators: Masato Shirasaki (NAOJ), Yoshida Naoki (U Tokyo)



Fermi-LAT data, 5 years

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Probing dark matter with the unresolved extragalactic gamma-ray background

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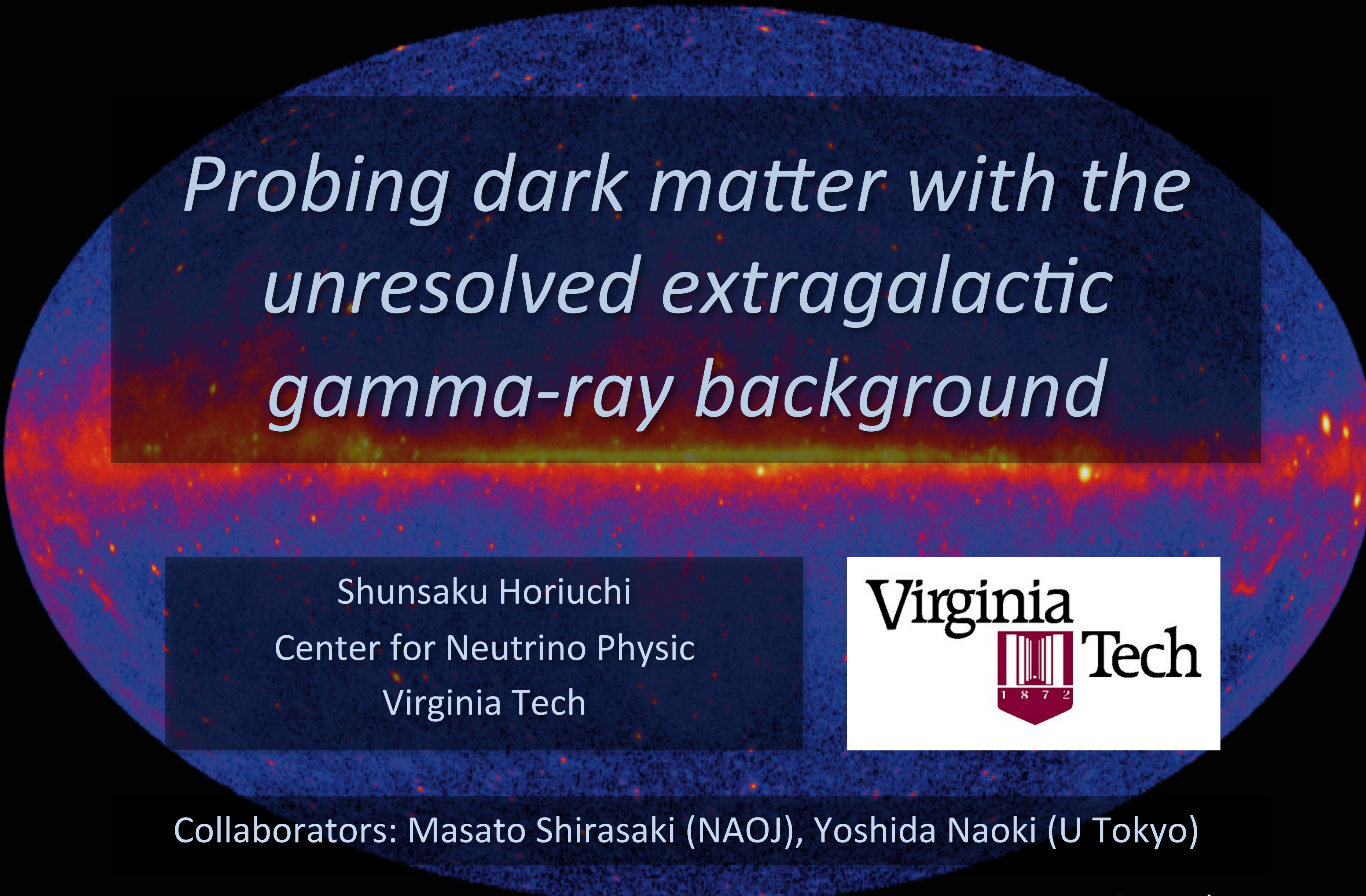
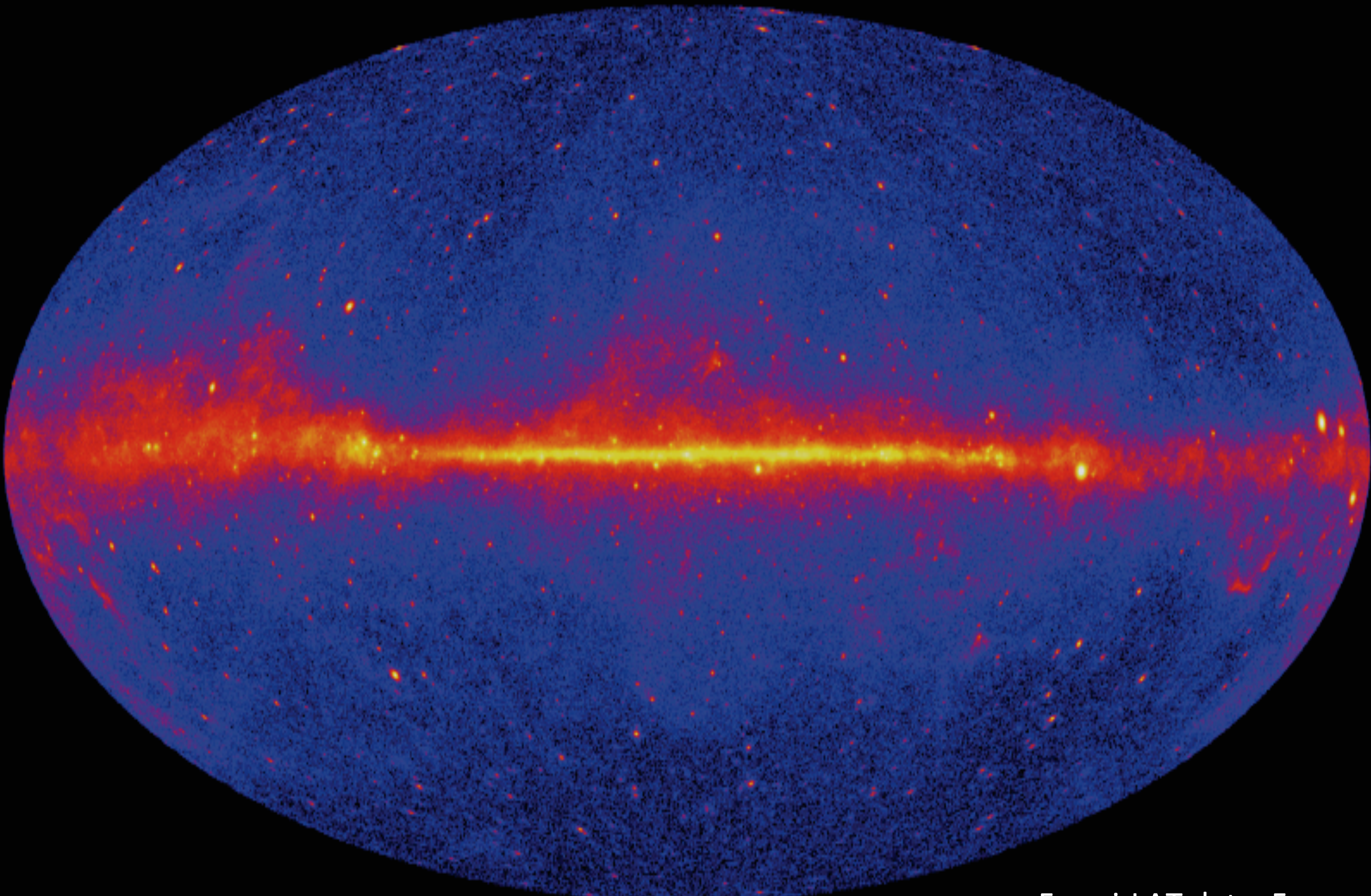


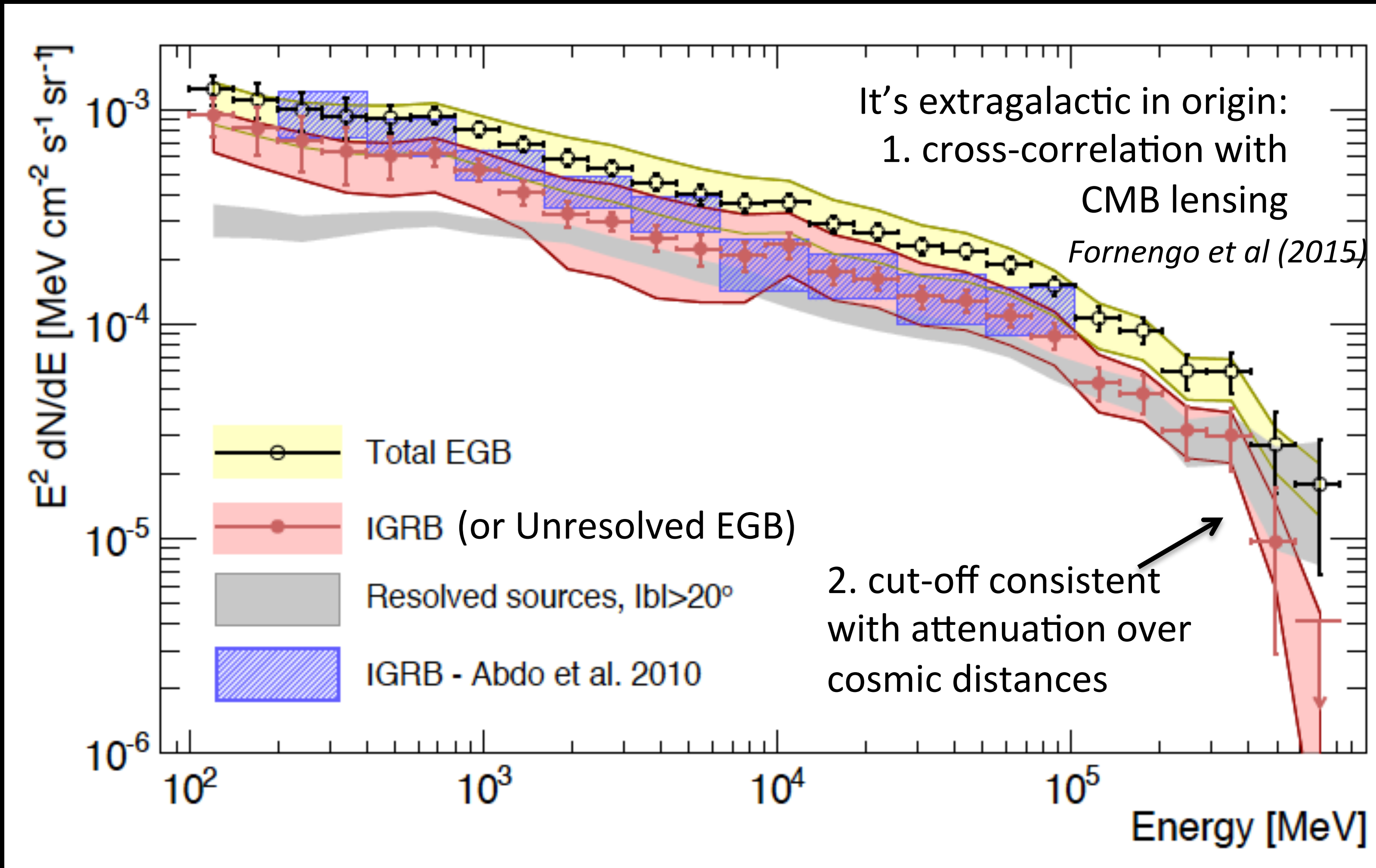
Fermi-LAT data, 5 years



Fermi-LAT data, 5 years

Isotropic Gamma-ray background

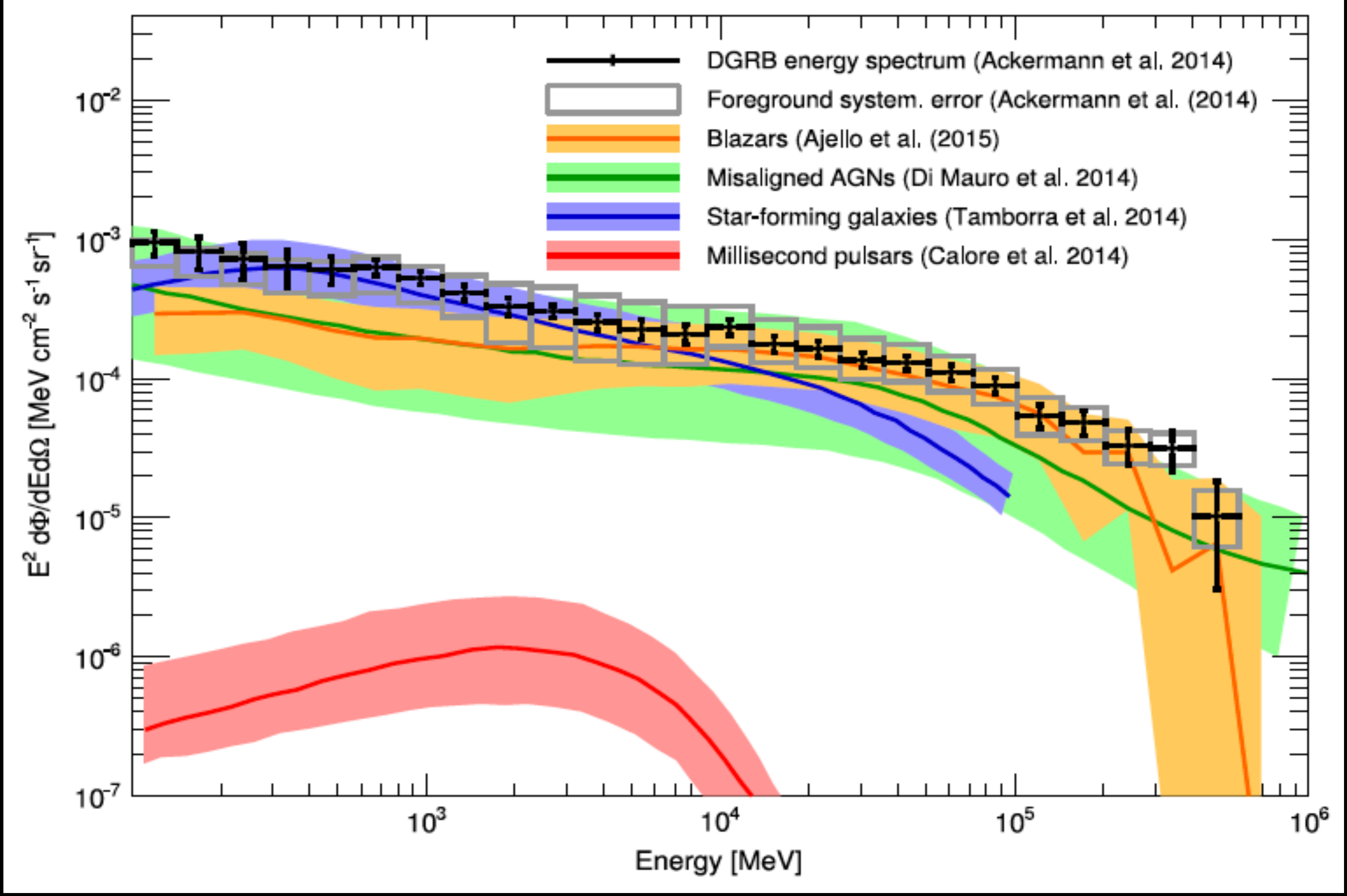
About ~50% of extragalactic gamma-rays resolved



Fermi collaboration (2014)

Explaining the intensity spectrum

Dark matter is a subdominant component



Fornengo & Sanchez-Conde (2015)

Cosmological dark matter annihilation

Number of photons along a line of sight θ:

$$\delta n(\boldsymbol{\theta}) = \int \mathrm{d}\chi\, g(\chi, \boldsymbol{\theta}) W_g(\chi)$$

Source field (g) for dark matter: mass overdensity squared, or "intensity multiplier"

$$\langle \delta^2 \rangle = \left(\frac{1}{\Omega_m \rho_c}\right)^2 \int_{M_{min}} dM \frac{dn(M,z)}{dM} [1 + b_{\mathrm{sh}}(M)] \int dV \rho^2_{\mathrm{host}}(r|M),$$

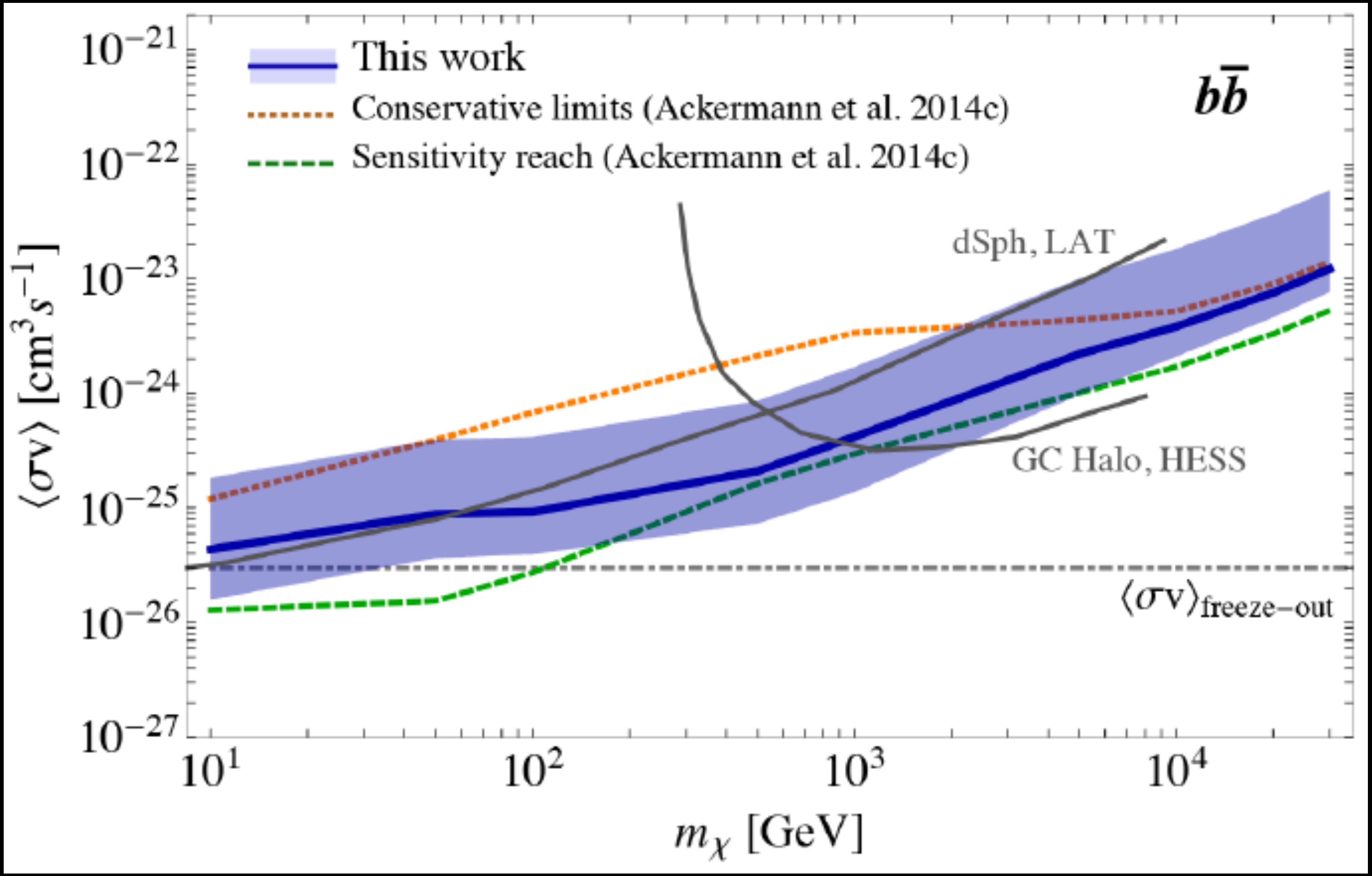
Halo mass function Subhalo boost factor Halo profile

Window function (W_g) for dark matter:

$$W(E,z) = \frac{\langle \sigma v \rangle}{8\pi} \left(\frac{\Omega_{\mathrm{dm}} \rho_c}{m_{\mathrm{dm}}}\right)^2 (1+z)^3 \frac{dN_{\gamma,\mathrm{ann}}}{dE} e^{-\tau(E,z)}$$

Dark matter particle properties Gamma-ray optical depth

Intensity analysis

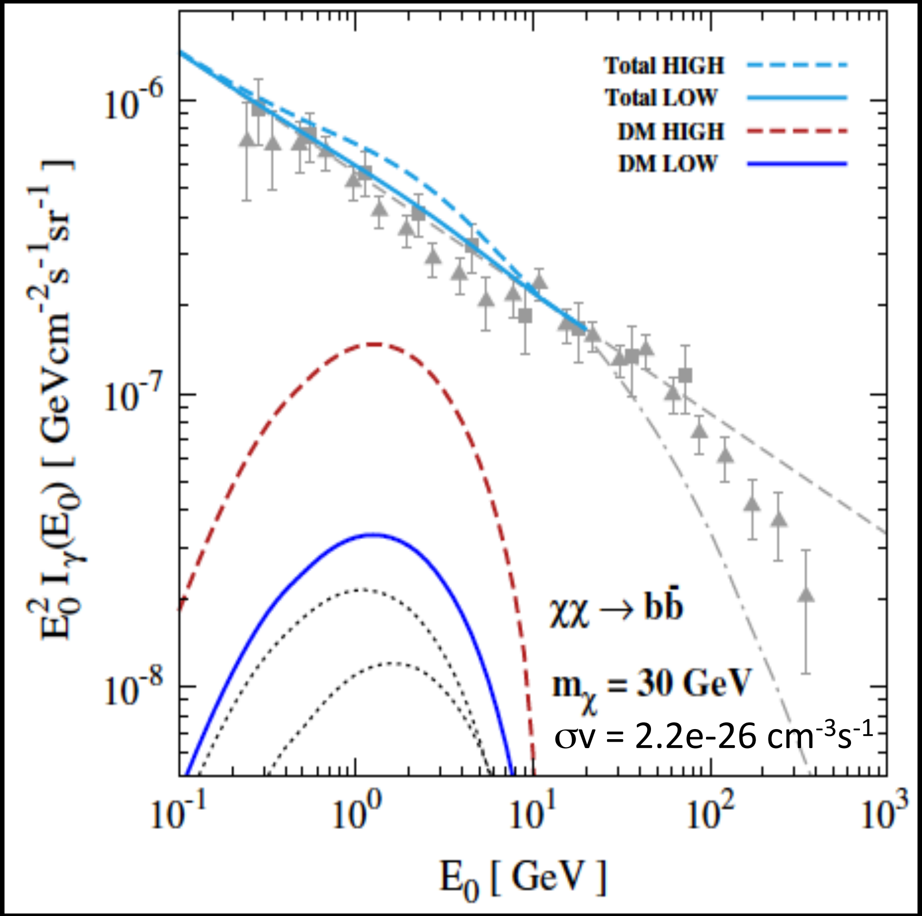


Ajello et al 2015

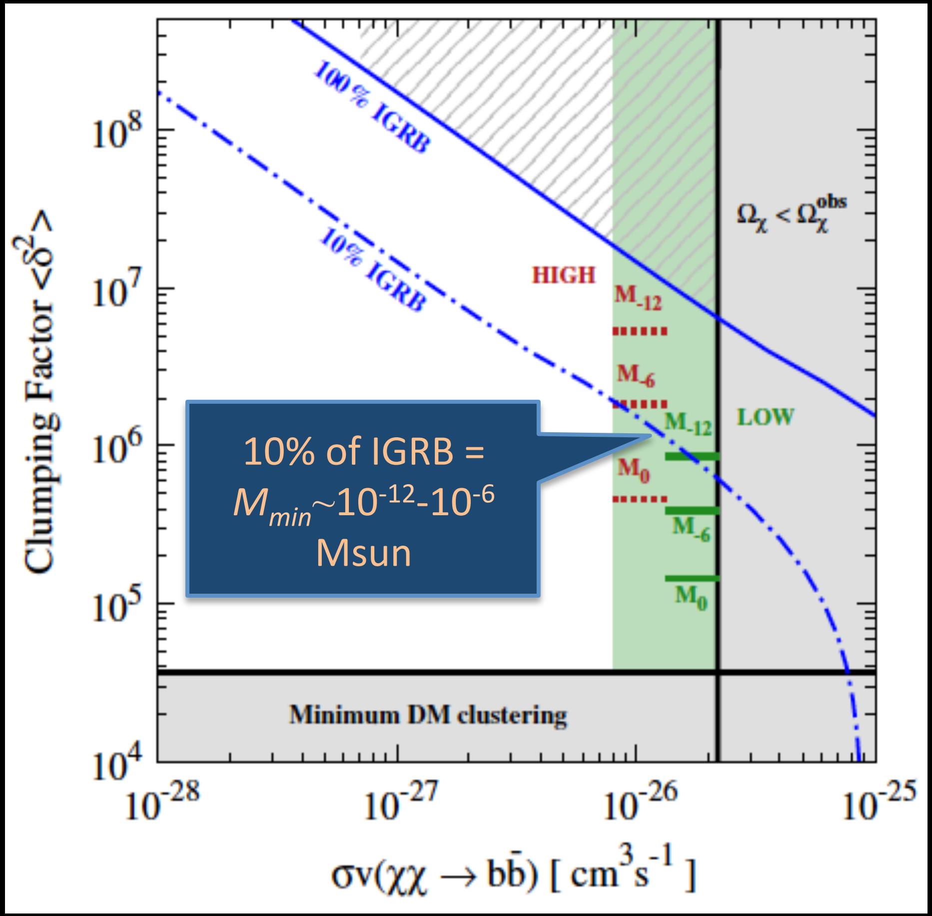
Also, Calore et al (2012), Cholis et al (2014), Bringmann et al (2014), Di Mauro & Donato (2015)

Probing the minimum halo mass

Contribution from dark matter motivated by the Galactic Center Excess



Connection to the minimum halo mass



Ng et al (2014)

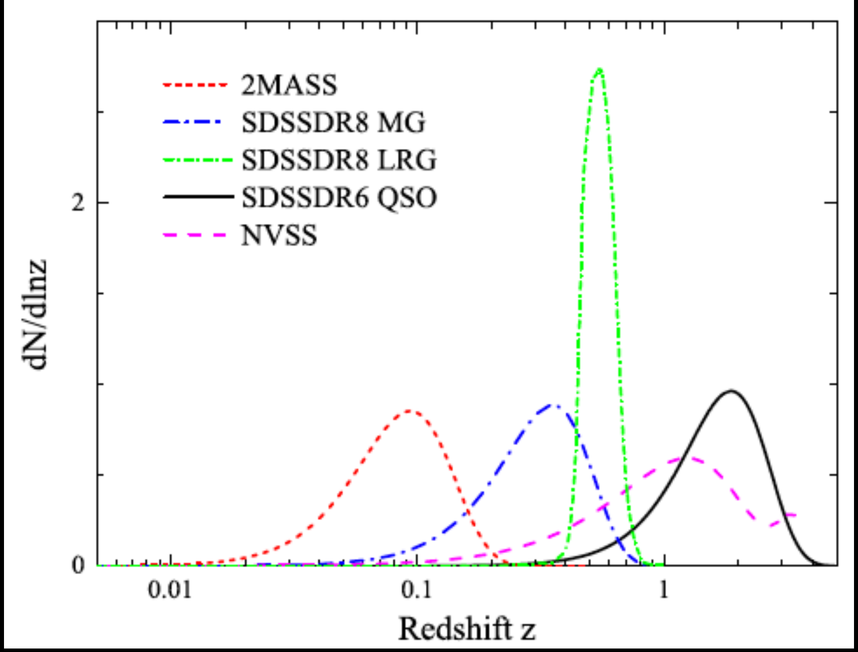
Cross-correlation analysis

The dark matter distribution is linked to:

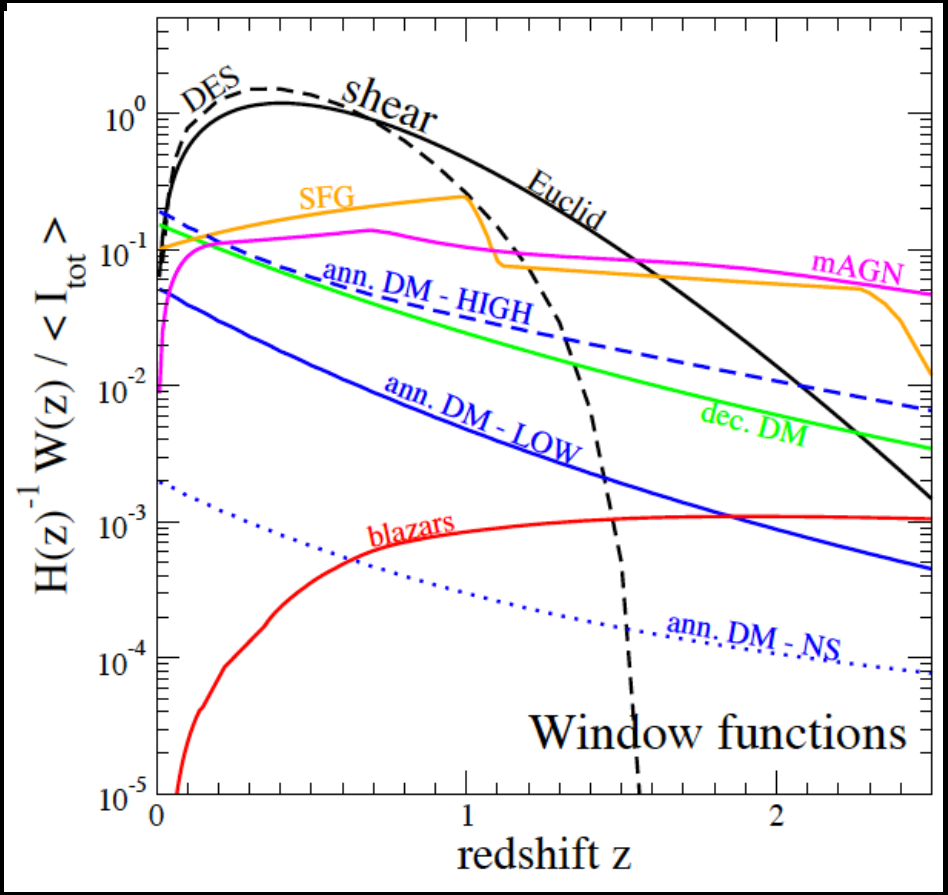
- Gamma-ray emission via annihilation or decay
- Large-scale structure (galaxies)
- Distortions of images of distant galaxies (weak gravitational lensing)

→ Exploit these connections with cross-correlation

→ Cosmic shear window function has a nice overlap with dark matter signals.



Xia et al 2014



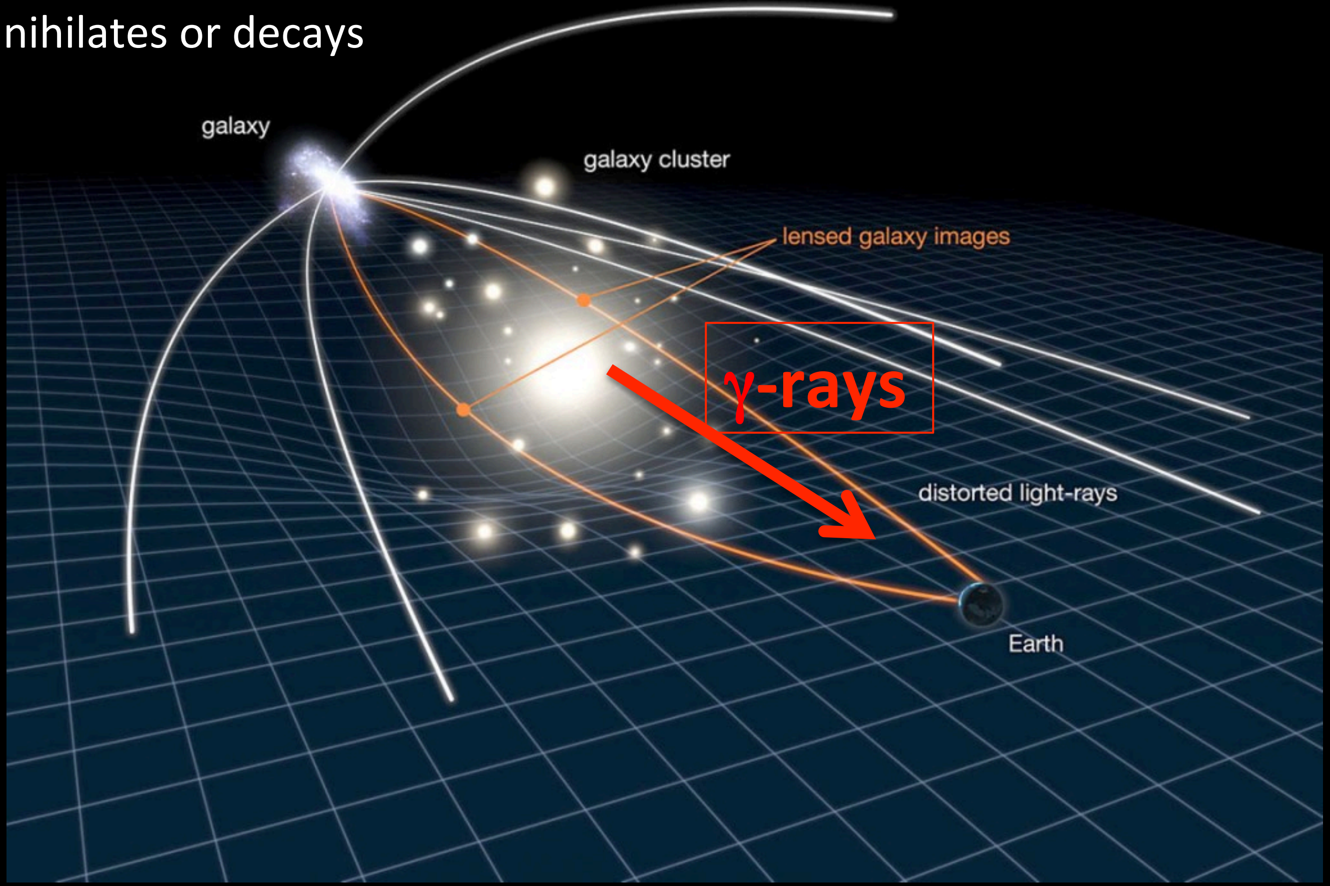
Camera et al 2014

Weak gravitational lensing

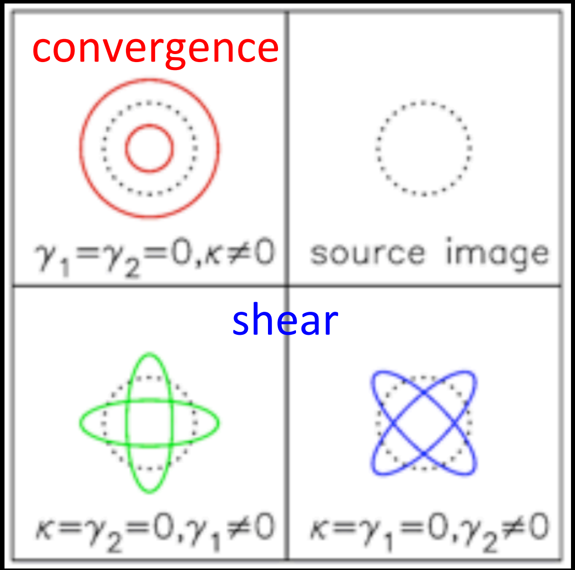
Images of distant galaxies are distorted by matter along the line of sight

The lens object is also a gamma-ray source due to
- Astrophysical processes
- Dark matter annihilates or decays

Exploit this connection with cross-correlation.



Cross-correlation with shear



The distortion of images of distant galaxies can be characterized by convergence (k) and shear (γ)

For weak lensing, the signal intensity can be written

$$\kappa(\boldsymbol{\theta}) = \int \mathrm{d}\chi W_\kappa(\chi)\delta(\boldsymbol{\theta}, \chi)$$

← Source field is the matter overdensity

with the window function

$$\langle g_\kappa(\chi)\rangle W_\kappa(\chi) = \frac{3}{2} H_0^2 \Omega_m [1 + z(\chi)]\, \chi \int_\chi^\infty d\chi' \frac{\chi' - \chi}{\chi'} \frac{dN_g(\chi')}{d\chi'}$$

galaxy redshift distribution

The cross-correlation APS is then

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

where i = convergence and j = the source (e.g., dark matter)

The 3D power spectrum of fluctuations P_{ij} can again be computed in the halo model.

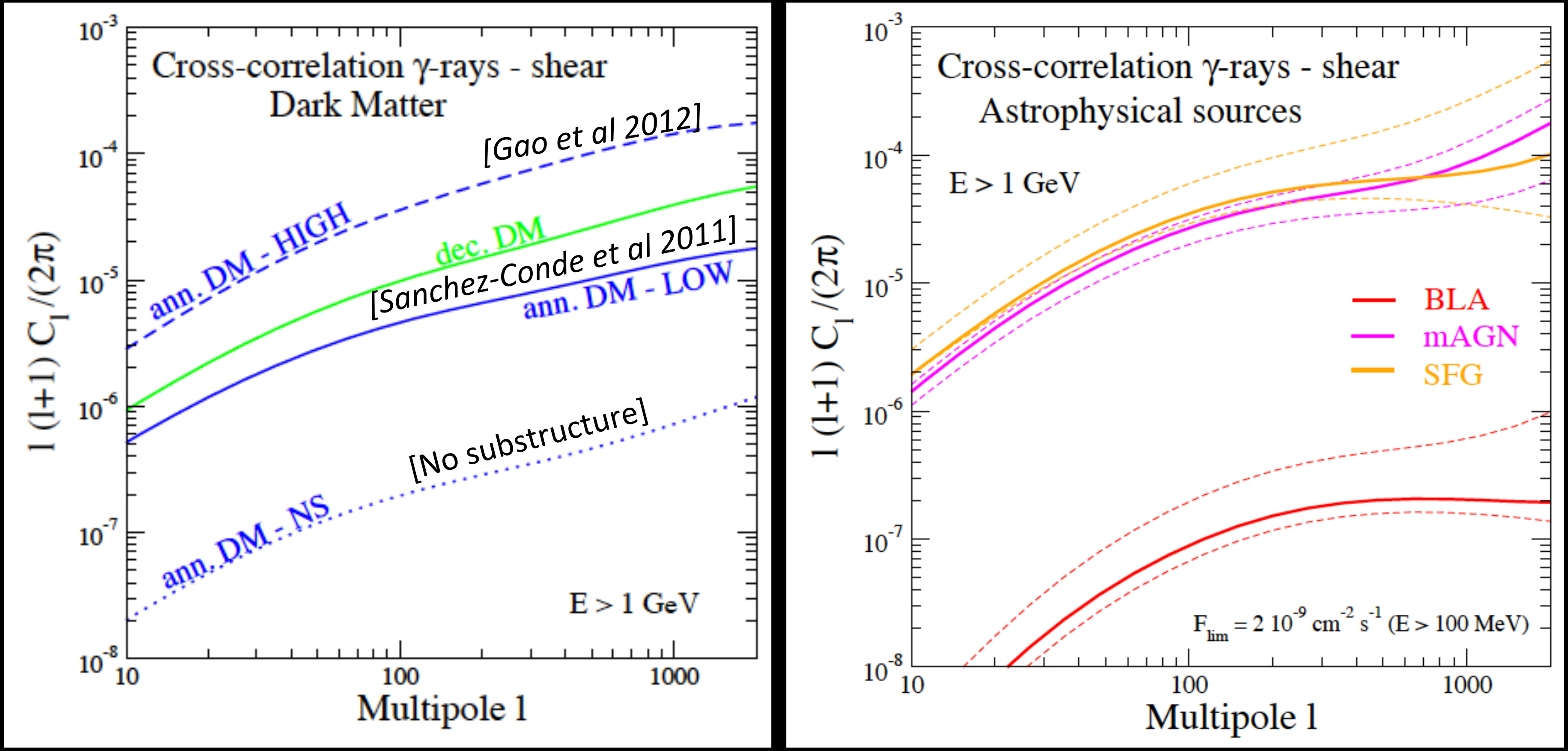
e.g., Ando & Komatsu 2006, Fornengo & Regis (2014)

See, *Camera et al 2013, 2014*

Cross correlation with shear map

Cross-correlation APS

Expected signal from astrophysical sources and dark matter, including uncertainties



Camera et al (2014)

→ Cross-correlation with dark matter can be comparable to those with astrophysical sources

Application to real data

Canada-France-Hawaii Lensing Survey (CFHTLenS)

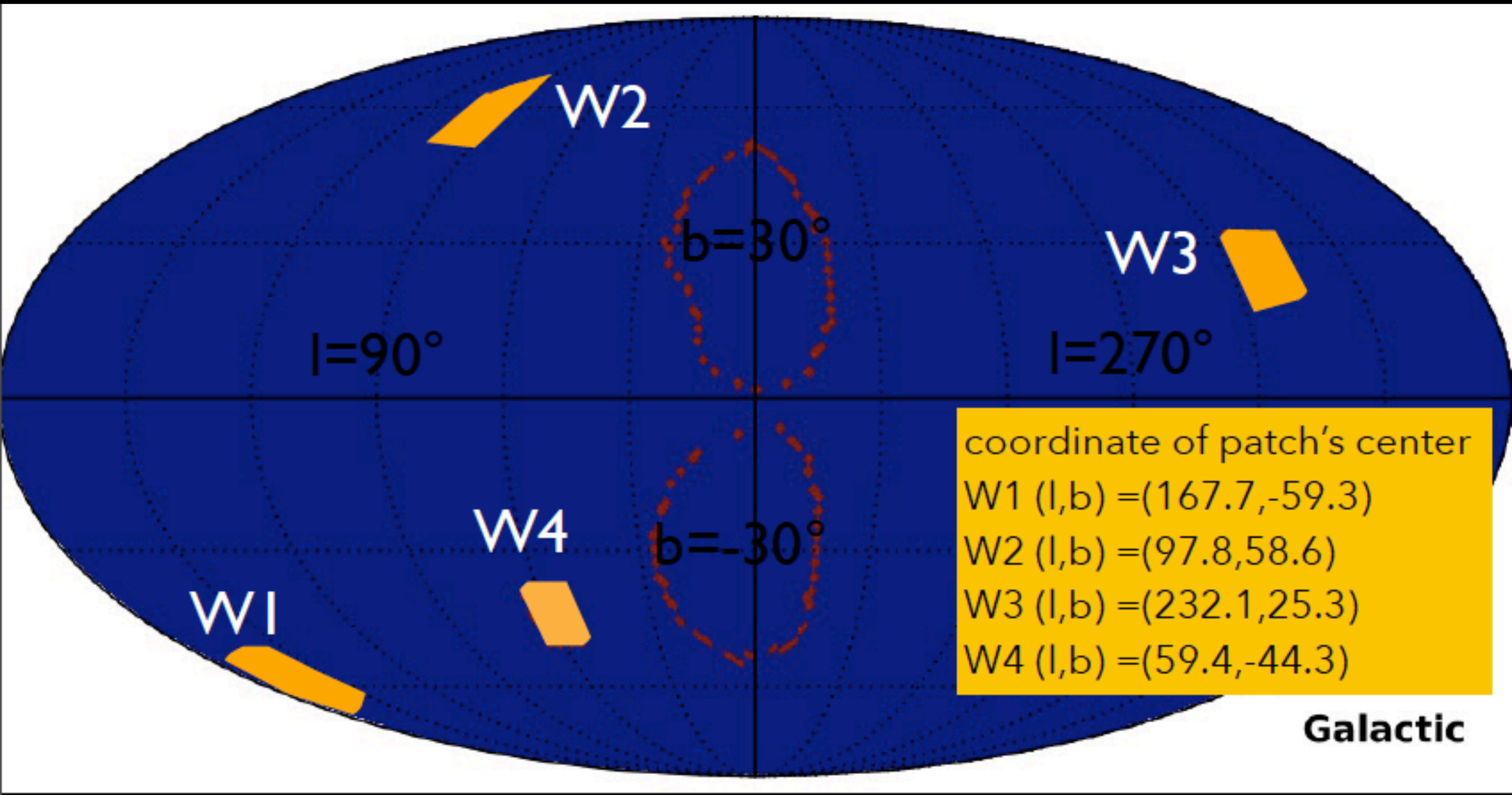
- Four patches, total ~154 deg^2
- Currently largest cosmic shear data set
- 11 resolved galaxies per 1 $arcmin^2$
- Photo-z between $0.2 < z < 1.3$ (median 0.75)
- About 5.7 million galaxies

Fermi-LAT

- 65 months of Pass7 reprocessed data
- 1 – 500 GeV ULTRACLEAN photons
- Each patch treated independently

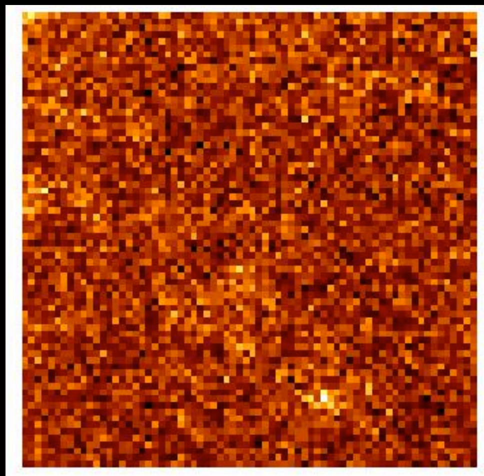
CFHTLenS fields

Away from known large extended foregrounds



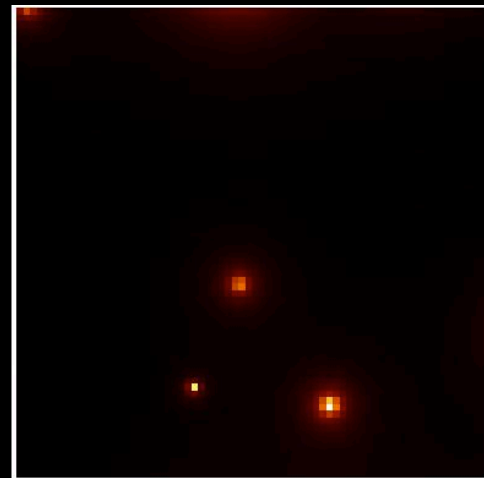
coordinate of patch's center
W1 (l,b) =(167.7,-59.3)
W2 (l,b) =(97.8,58.6)
W3 (l,b) =(232.1,25.3)
W4 (l,b) =(59.4,-44.3)

Fermi data analysis



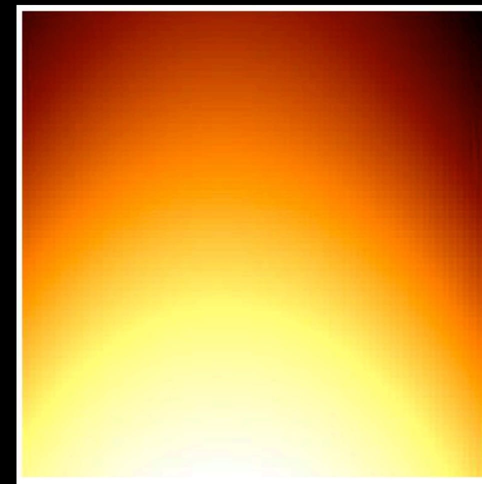
Data counts

=



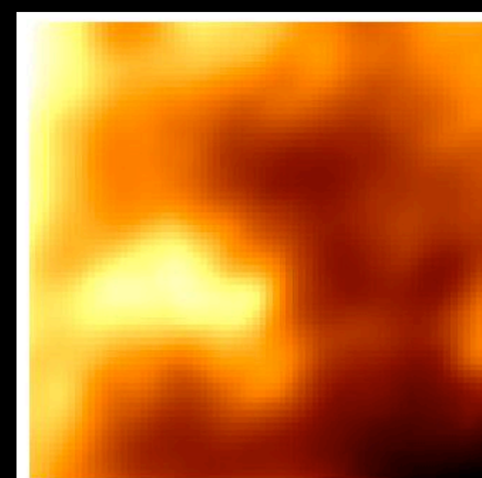
Point source

+



Isotropic diffuse

+



Galactic diffuse (foreground)

Modeling:

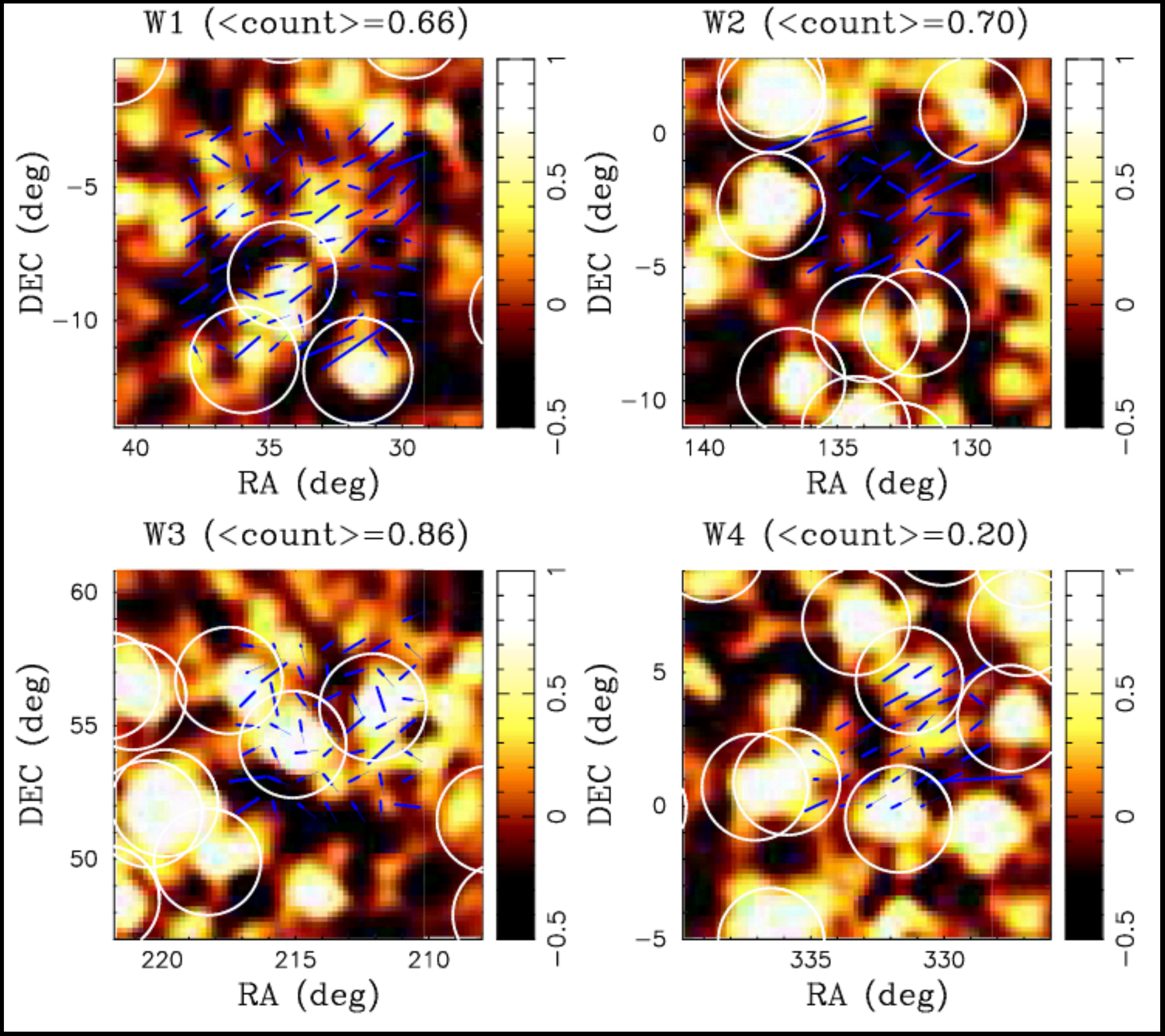
- Point source spectral parameters and normalization
- Extended source normalizations (spectra and spatial morphology fixed by templates)

(raw – Galactic diffuse) maps

Showing the +/- deviation wrt the ROI mean counts.

Circle: fiducial 2 deg mask

Lines: average ellipticities of source galaxies over 1 deg^2 regions from the CFHTLenS



Shirasaki, Horiuchi, Yoshida (2014)

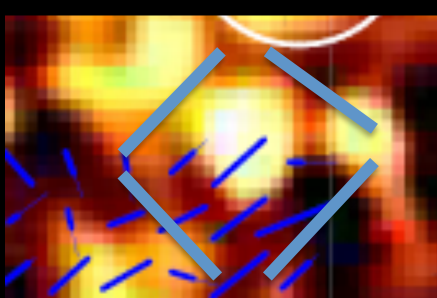
Residual counts maps

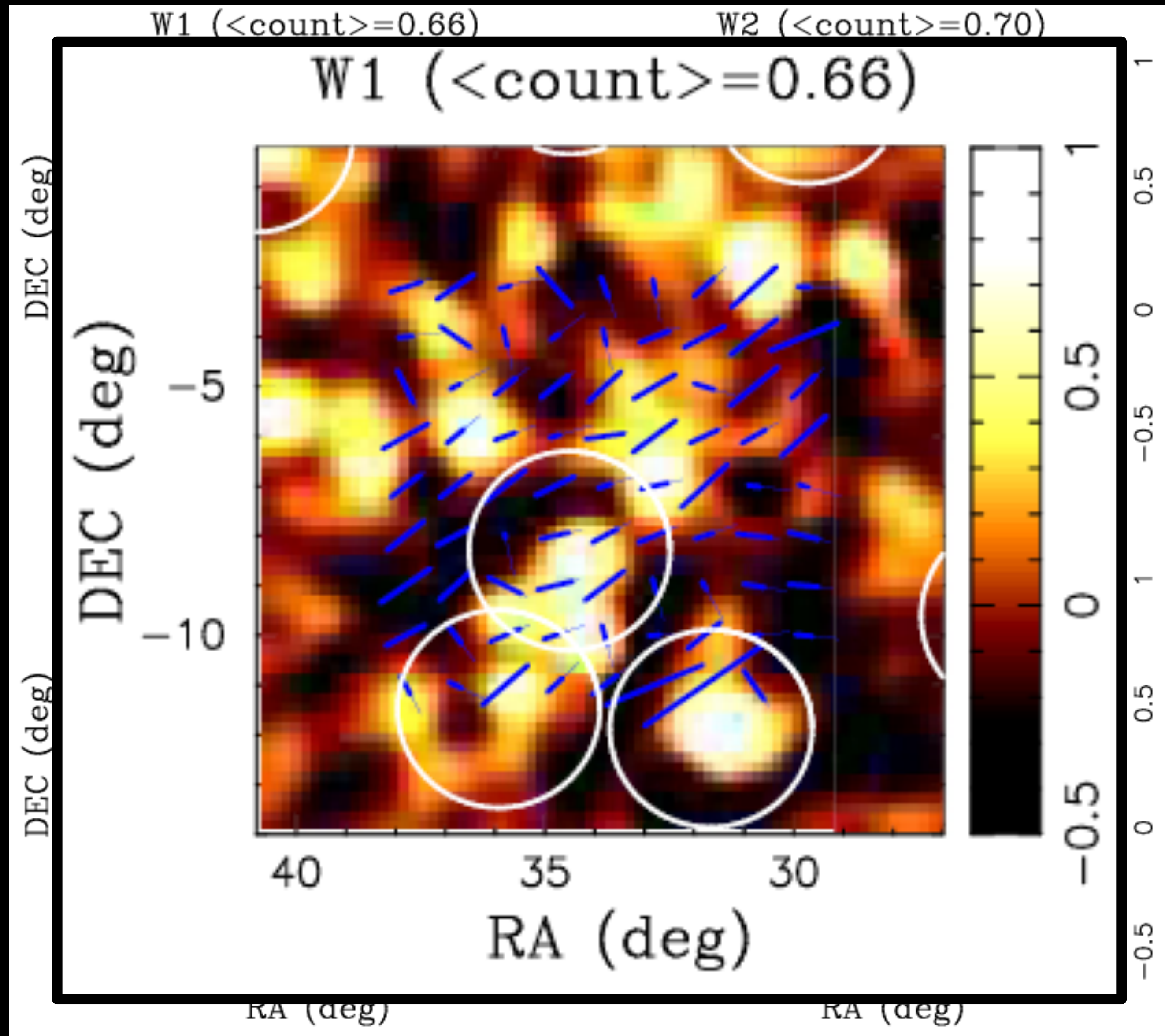
Showing the +/- deviation wrt the ROI mean counts.

Circle: fiducial 2 deg mask

Lines: average ellipticities of source galaxies over 1 deg^2 regions from the CFHTLenS

A positive correlation will appear as tangential ellipticities around pixels with high photon counts

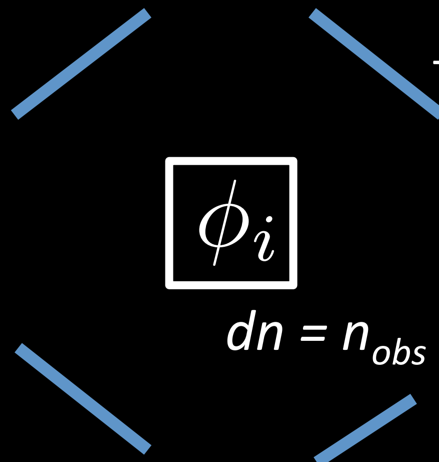




Shirasaki, Horiuchi, Yoshida (2014)

Cross-correlation signal

Estimator ξ :



Tangential component:

$$\gamma_{t,j}(\theta + \phi_i)$$

dn = n$_{obs}$ - n$_{GDE}$

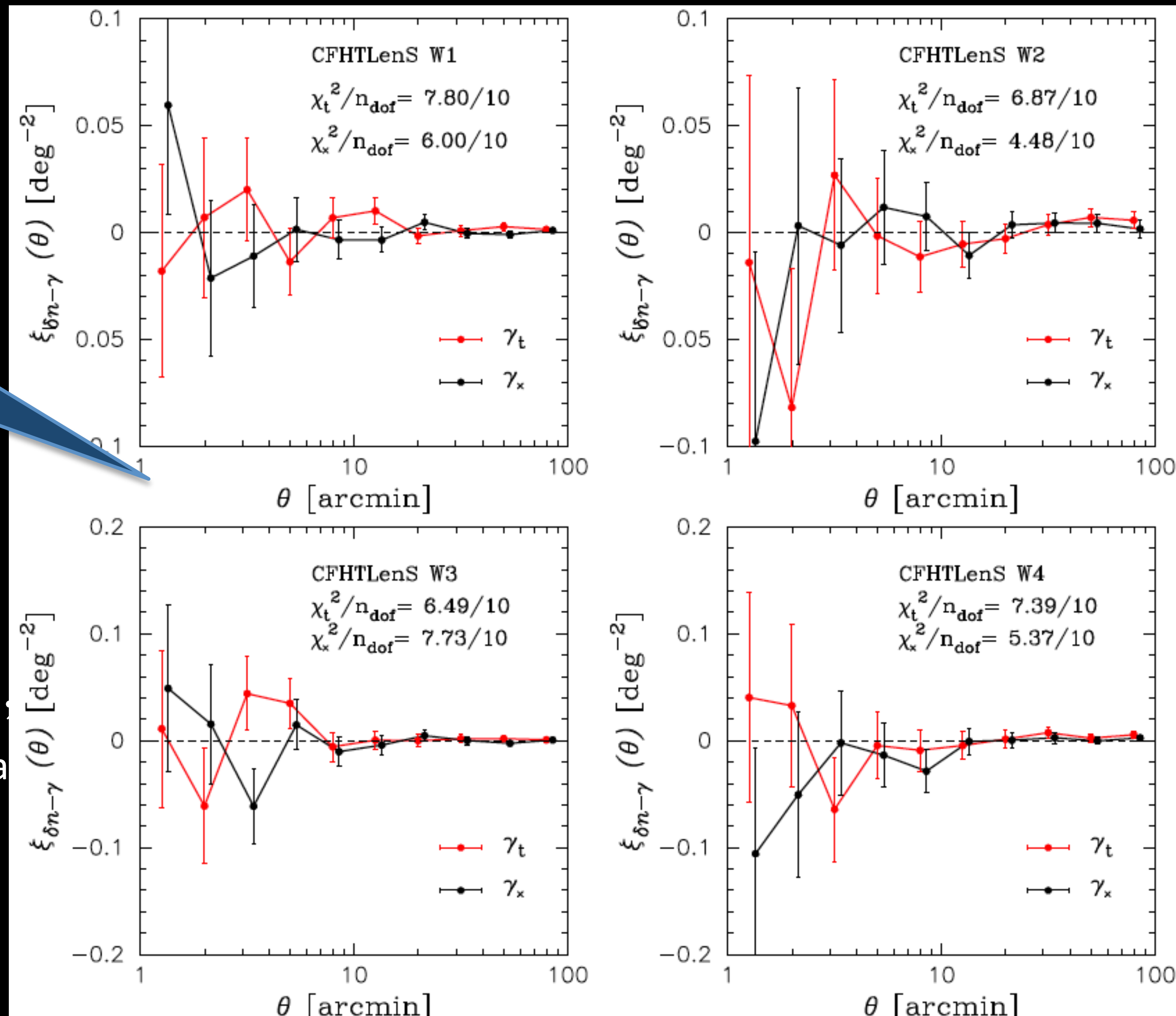
Calculate the product

$$dn(\phi_i)\gamma_{t,j}(\theta + \phi_i)$$

in bins of angular separation θ, then repeat over all directions ϕ_i of interest

Cross-correlation signal

Estimator ξ :



All consistent with null signals

Calculate the product

$$dn(\phi_i)\gamma_{t,}$$

in bins of angular separa

Shirasaki, Horiuchi, Yoshida (2014)

Statistical error estimates

Shape noise:
due to intrinsic variance in the shape measurements
→ Create 500 randomized shear catalogs (randomized directions, fixed amplitudes), calculate the CCF estimator for each, and calculate the covariance

$$C_{ij} = \frac{1}{N_{\rm re}-1}\sum_r (\xi^r_{\delta n-\gamma_t}(\theta_i) - \bar{\xi}_{\delta n-\gamma_t}(\theta_i))(\xi^r_{\delta n-\gamma_t}(\theta_j) - \bar{\xi}_{\delta n-\gamma_t}(\theta_j))$$

$$\bar{\xi}_{\delta n-\gamma_t}(\theta_i) = \frac{1}{N_{\rm re}}\sum_r \xi^r_{\delta n-\gamma_t}(\theta_i)$$

r-th realization for i-th angular bin

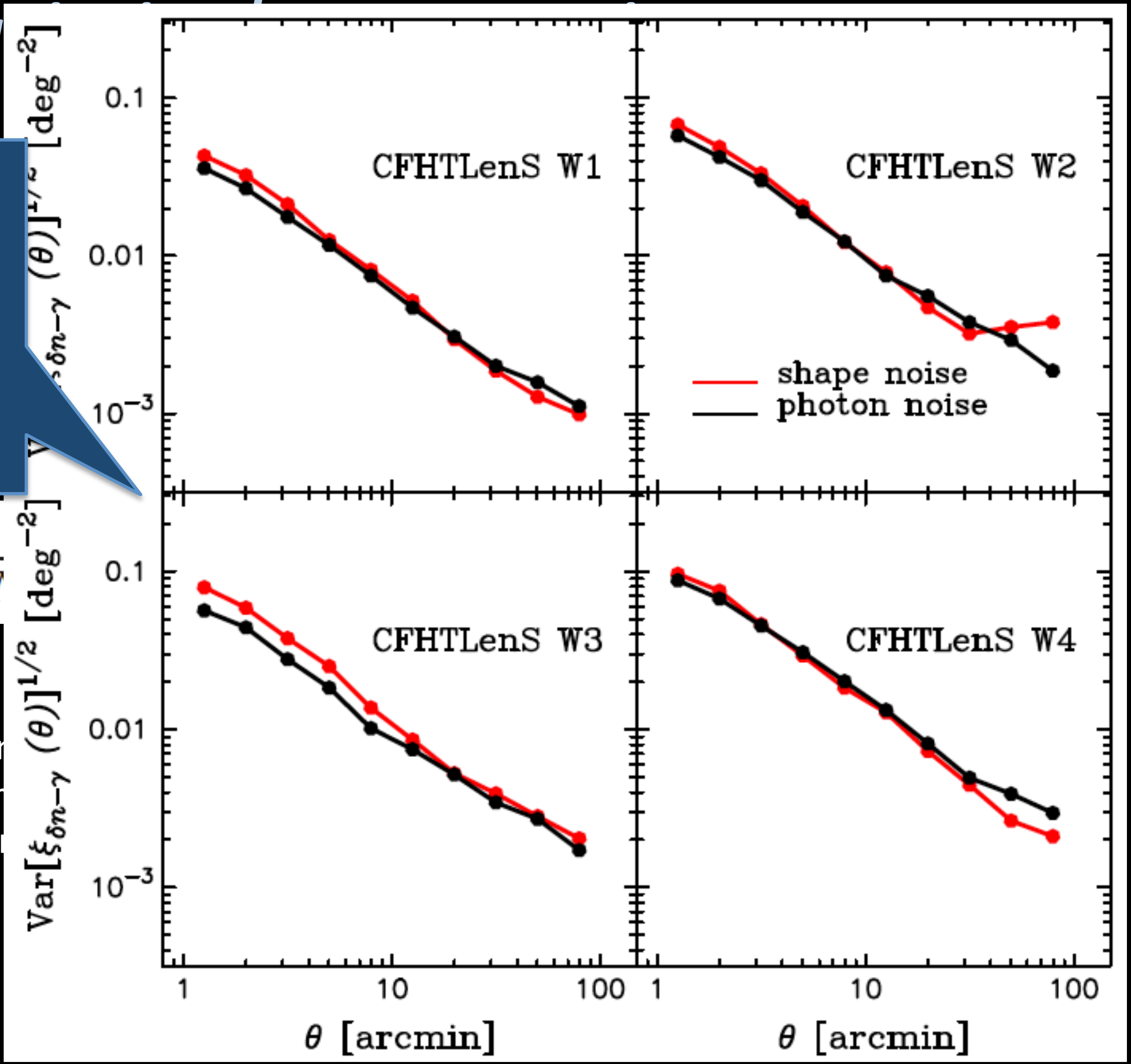
Photon noise:
due to limited photon statistics
→ Create 500 randomized photon count maps (Poisson distributed), calculate the CCF estimator for each, and similarly calculate the covariance.

Sta

Shape & photo noise are ~comparable.

Sigma is < 0.01 in angles of interest (above > 6 arcmin).

$$\bar{\xi}_{\delta n-\gamma_t}(\theta_i) = \frac{}{l}$$



Photon noise:

due to limited photon

→ Create 500 randon

estimator for each, a

Cross-correlation signal

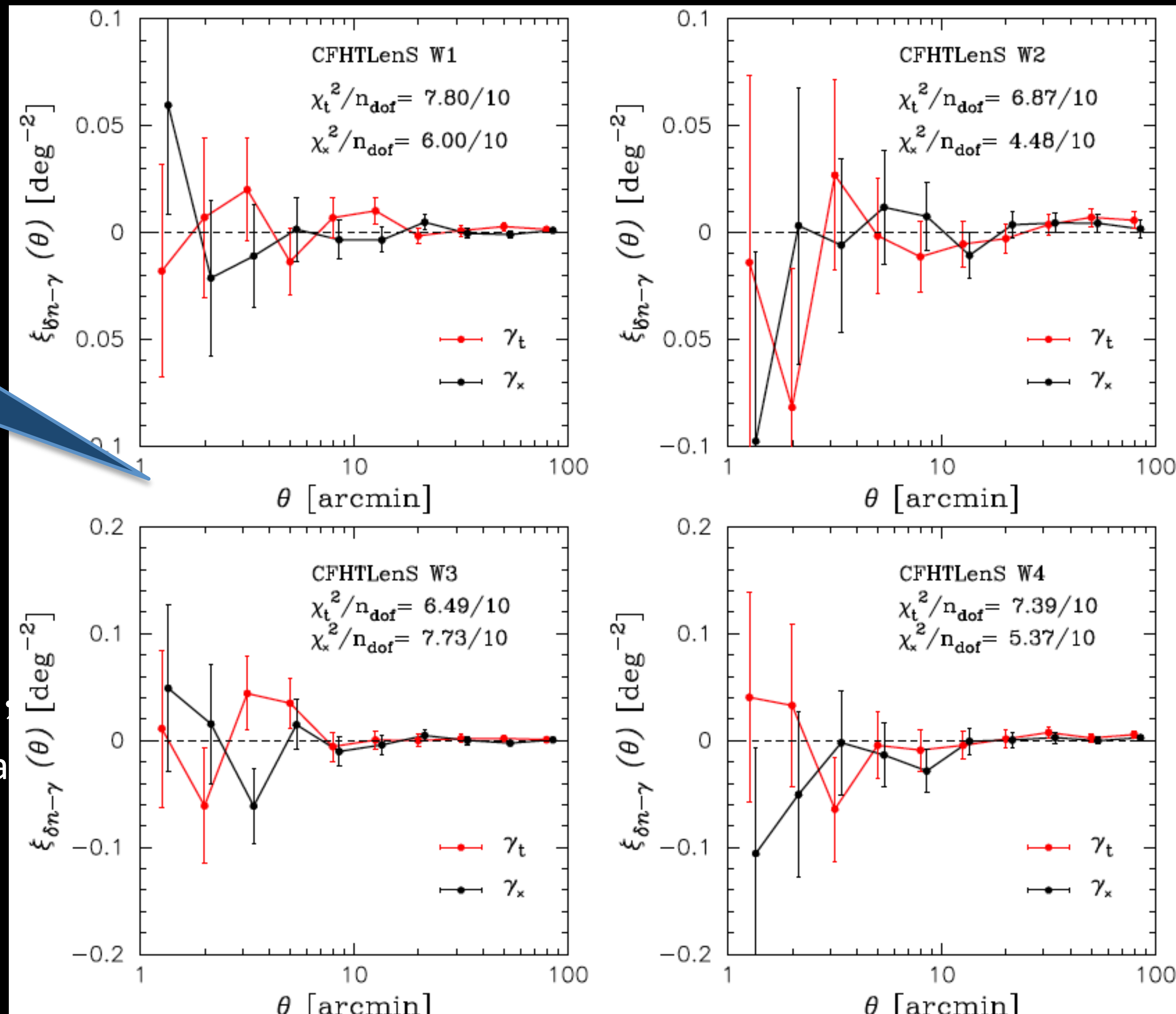
Estimator ξ :

All consistent with null signals

Calculate the product

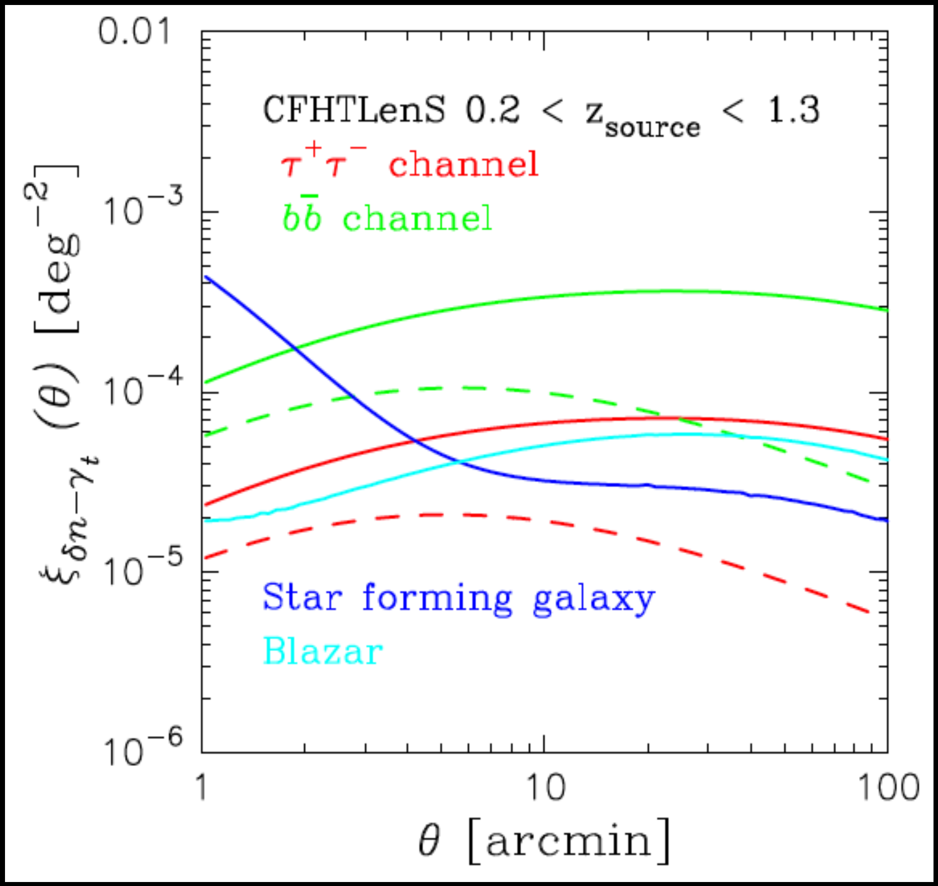
$$dn(\phi_i)\gamma_{t,}$$

in bins of angular separa



Shirasaki, Horiuchi, Yoshida (2014)

Predicted cross-correlation signal



Shirasaki, Horiuchi, Yoshida (2014)

Expected 2-point cross-correlation between shear (κ) and gamma rays (*dn*) is:

$$\xi_{\delta n-\gamma_t}(\theta) = \int \frac{d\ell\,\ell}{2\pi} P_{\delta n-\kappa}(\ell) J_2(\ell\theta)$$

Use the Halo-model approach

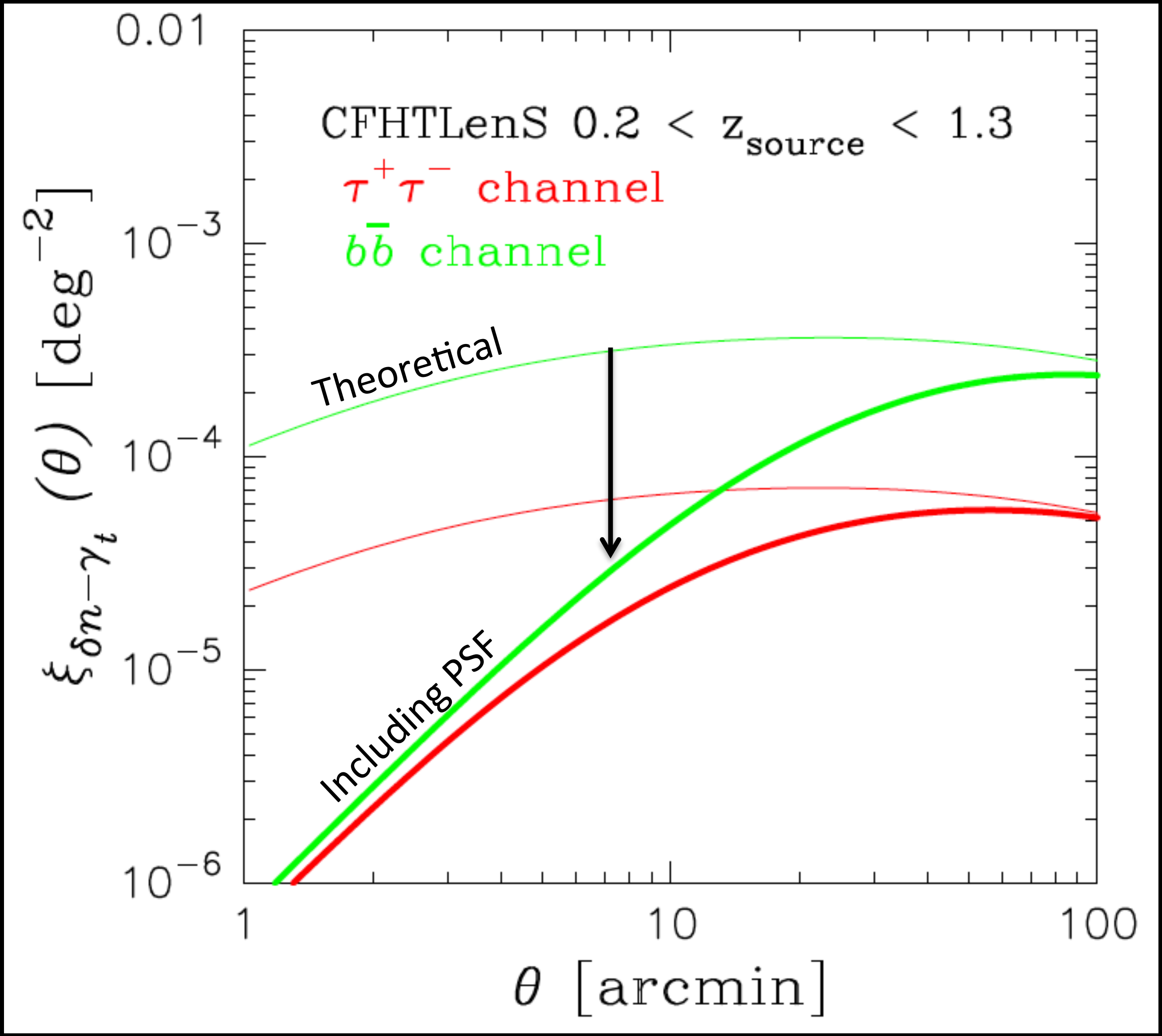
[e.g., Ando & Komatsu 2006, Camera et al 2013]

- DM annihilation: b-bbar & τ+τ- channels
  - Shown for 100 GeV, thermal σv
  - Two assumptions of M_{min}: 10^{-6} Msun (solid) and 10^{6} Msun (dashed)
- Astrophysics: assume as point sources with
  - Blazars: fixed spectra, luminosity-dependent density evolution model
  - SFG: fixed spectra, evolved as the IR luminosity function

→ Dark matter dominates at larger angular scales (2-halo term important)

Effect of Fermi's PSF

In fact, the PSF of Fermi-LAT further limits the probe of the two-point angular cross-correlation below a few arcmin angular scales:



We include the PSF effect in the CCF model.

Shirasaki, Horiuchi, Yoshida (2014)

Limits on dark matter contribution

Maximum likelihood method:

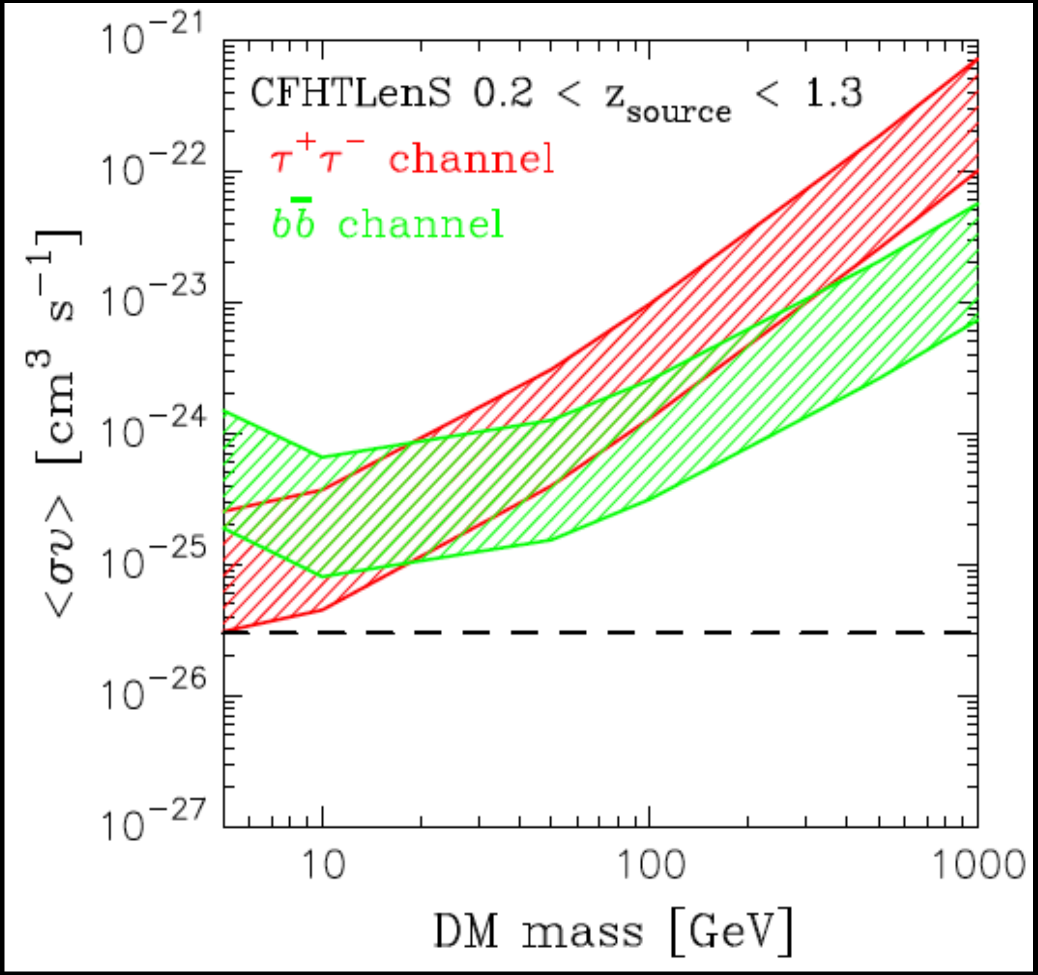
$$\chi^2(\boldsymbol{p}) = \sum_{i,j} (D_i - \mu_i(\boldsymbol{p})) C_{ij}^{-1} (D_j - \mu_j(\boldsymbol{p}))$$

- ***D***: measured cross-correlation
- μ: theoretical model
- ***p***: parameters of interest (mc, sv)
- ***C***: covariance matrix

Assume the fields are independent, so total χ^2 is simply the sum of the fields.

Obtain limits by (1σ):

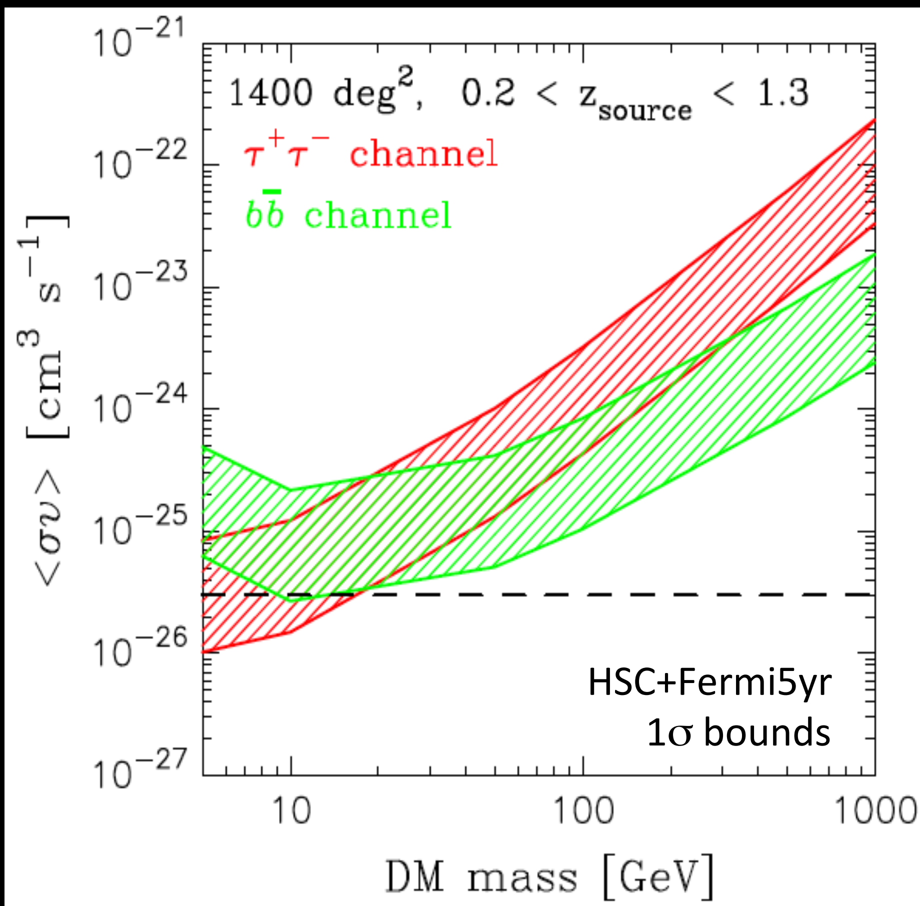
$$\Delta\chi^2(\boldsymbol{p}) = \chi^2(\boldsymbol{p}) - \chi^2(\boldsymbol{\mu} = 0) = 2.30$$



Shirasaki, Horiuchi, Yoshida (2014)

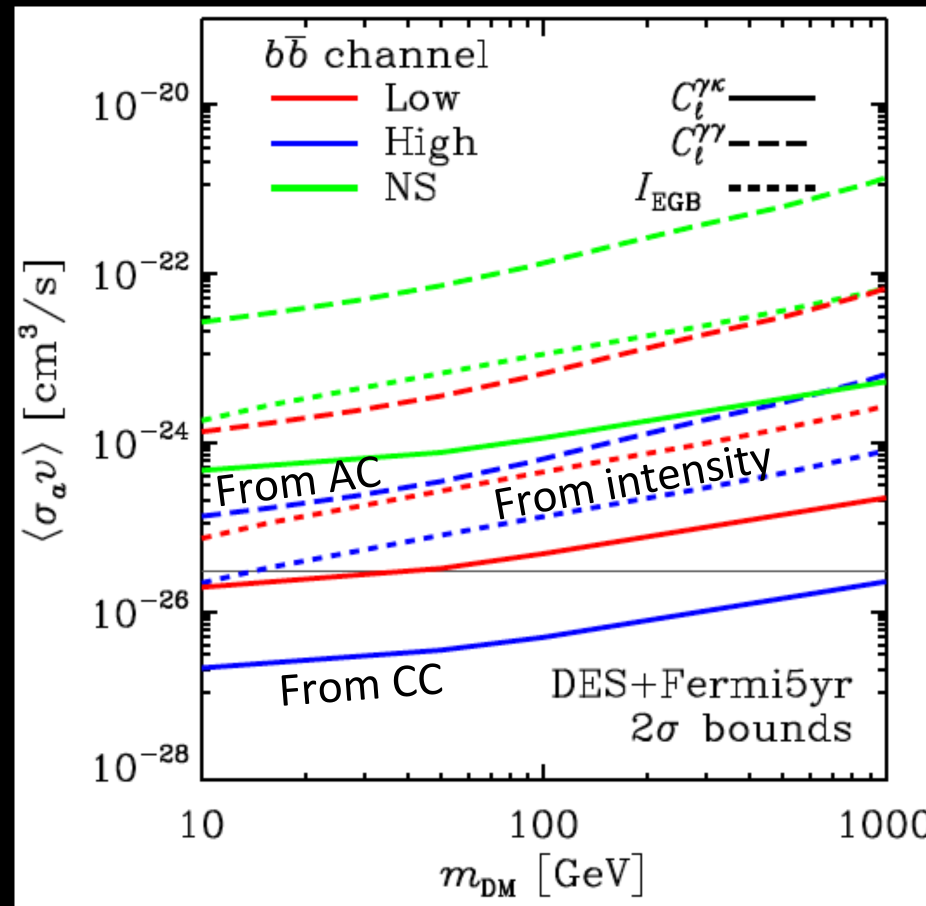
Ongoing surveys

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



Shirasaki, Horiuchi, Yoshida (2014)

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



Camera et al (2014)

Ongoing surveys

Hyper-Suprime Cam: ~1,400 deg^2
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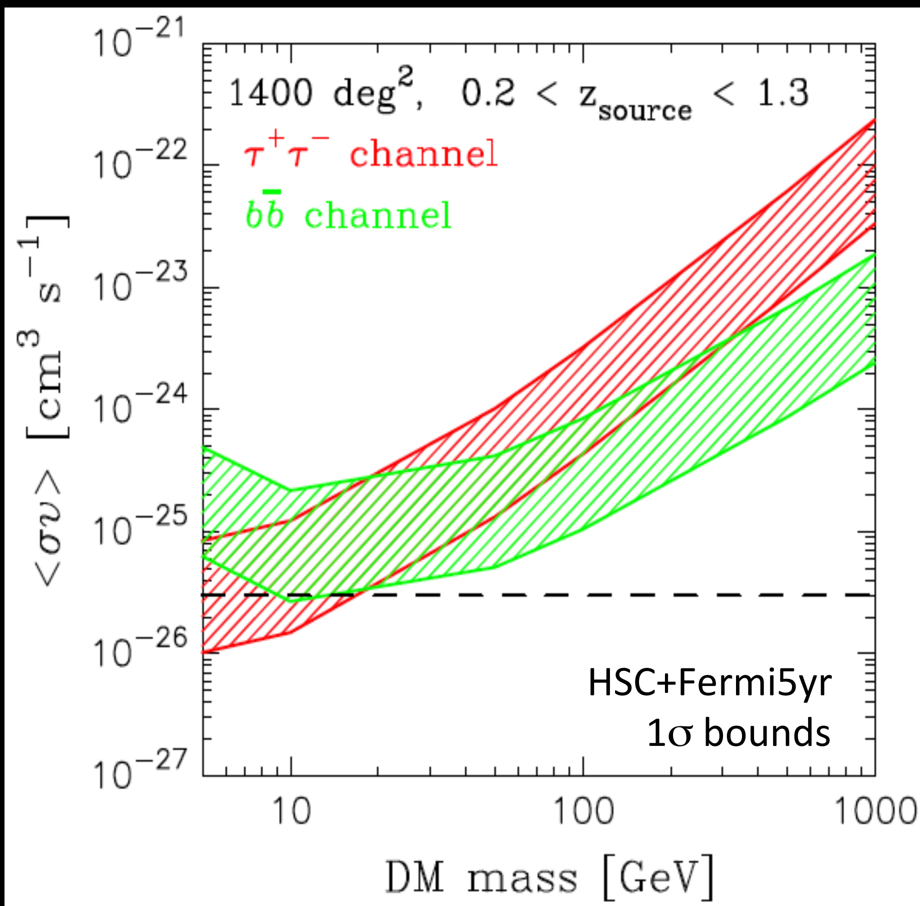

Shirasaki, Horiuchi, Yoshida (2014)

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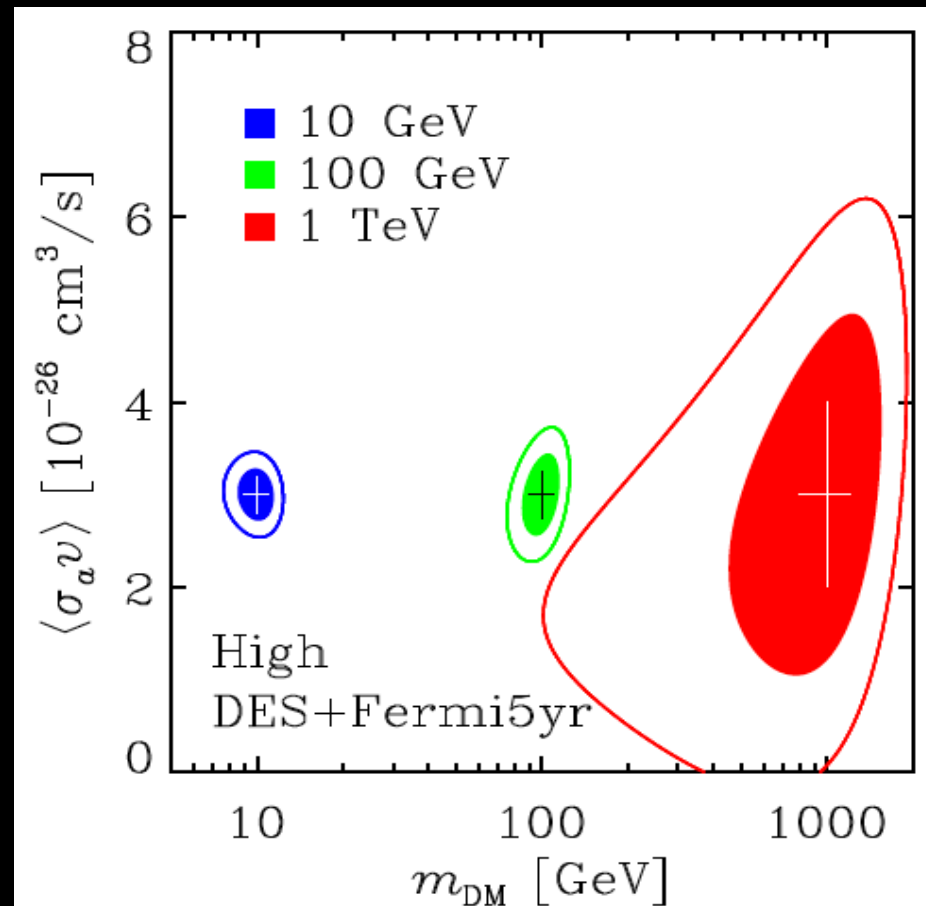


Camera et al (2014)

Early data

Hyper-Suprime-Cam early data release (Nov 2015)

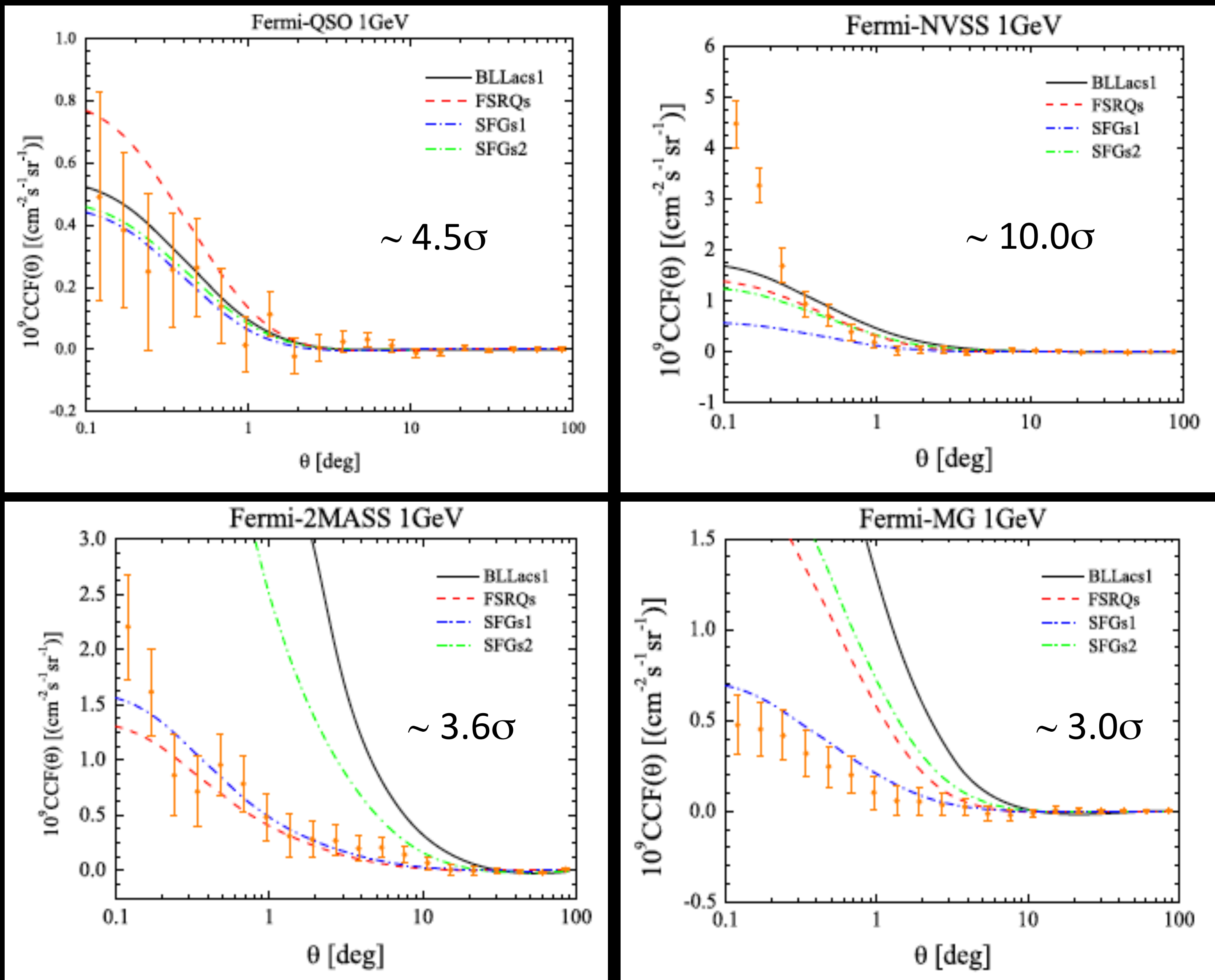
Early galaxy shape catalog

- Based on 5 band photometry
- Excellent seeing ~0.5 arcsec
- ~99 deg2 coverage
- Photo-z in preparation, expected z~1 and probing mass at z~0.5

Work in progress with Fermi pass8 data.

Stay tuned!

Cross-correlation with galaxies



> 3σ in cross-correlation with multiple galaxy catalogs

(NB: the signal with NVSS shows PSF-like energy dependence)

All models (BL Lacs, FSRQs, SFG) assume 100% contribution to the IGRB intensity, and not fitted to the CCF.

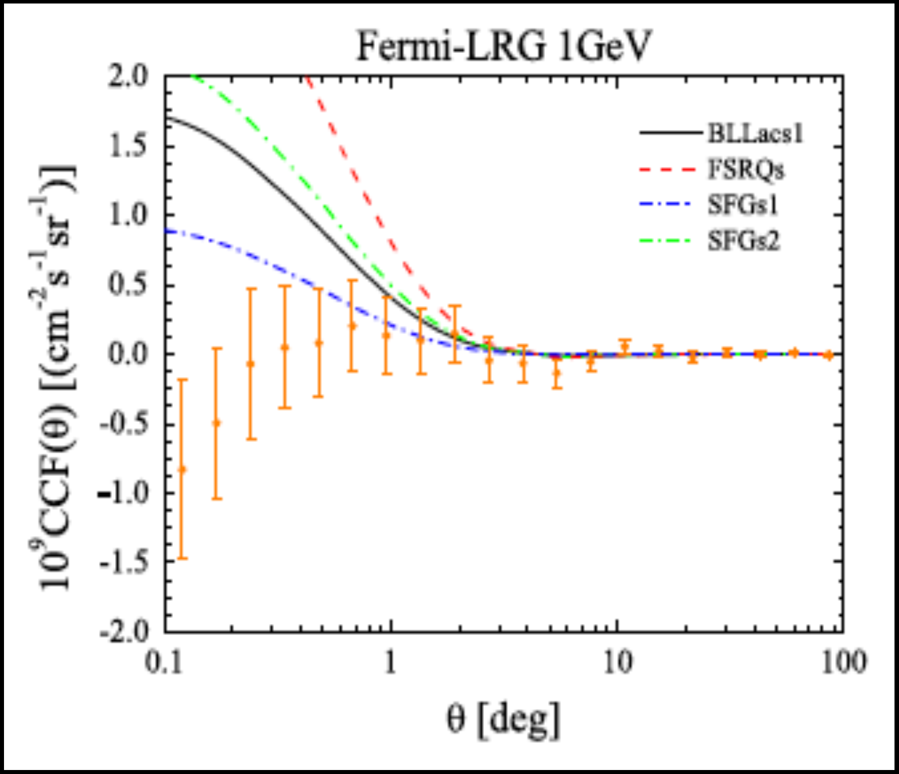
Dark matter interpretations

Regis et al (2015)

Xia et al (2015)

Luminous red galaxies (LRG)

No significant cross-correlation was observed with LRGs



Xia et al (2015)

Actually, LRGs are excellent targets for studying dark matter:

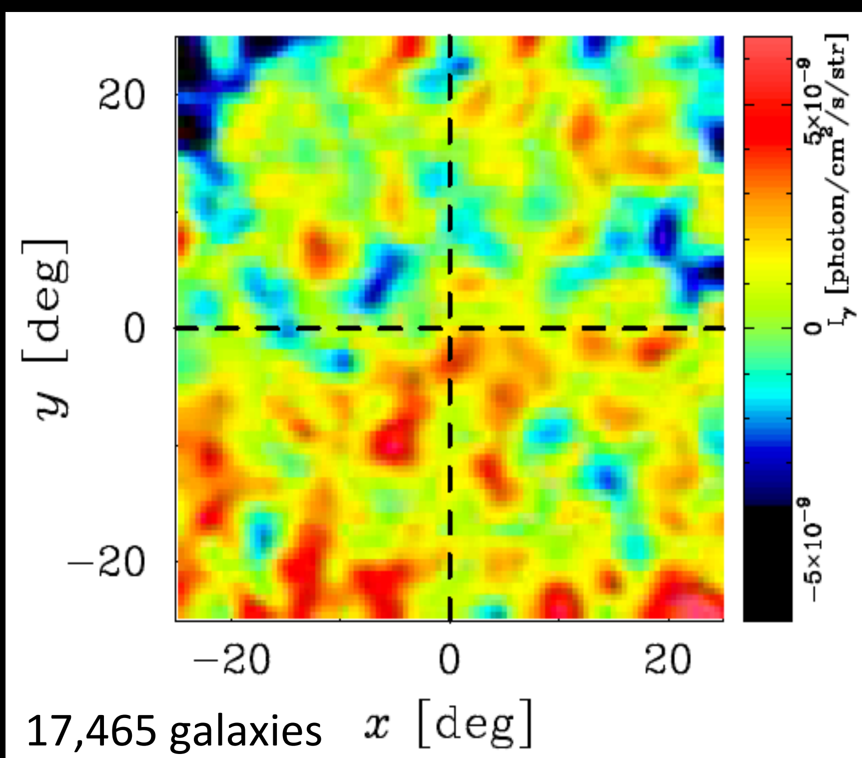
- Low astrophysical contamination
  → signal interpretation easier
- Good, complete catalogs exist, with good spec-z
  → well-defined target
- The dark matter halo properties can be observationally measured
  → well-defined signal

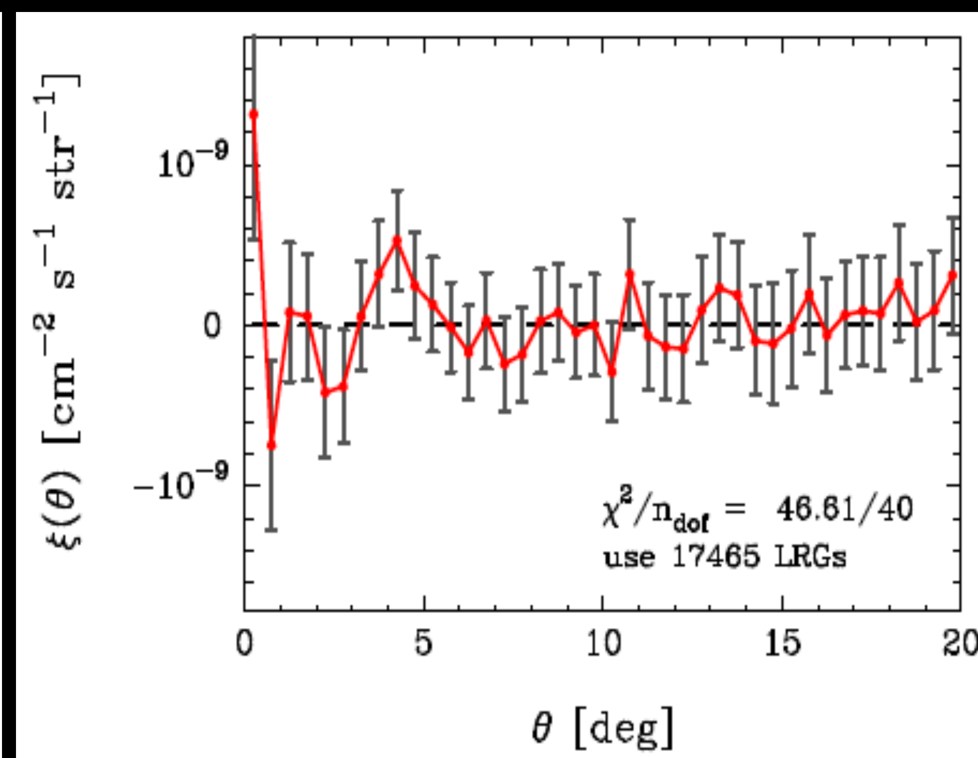
Bit like ‘dwarfs’ in the IGRB.

Investigate the cross-correlation with LRG in more detail to capture these advantages (e.g., the Xia et al (2014) sample was a large photo-z sample).

Luminous red galaxies (LRG)

- Sample: use 17,465 galaxies in SDSS DR7 all with spec-z
  → lower redshift (0.16–0.44) than photo-z sample in *Xia et al 2015* (0.4–0.8)
- Interpretation: relation to their host DM halos has been extensively investigated (2-point correlation function studied in *Kazin et al 2010*)
- Uncertainty: There exists a large number of mock catalogs
  → use for error



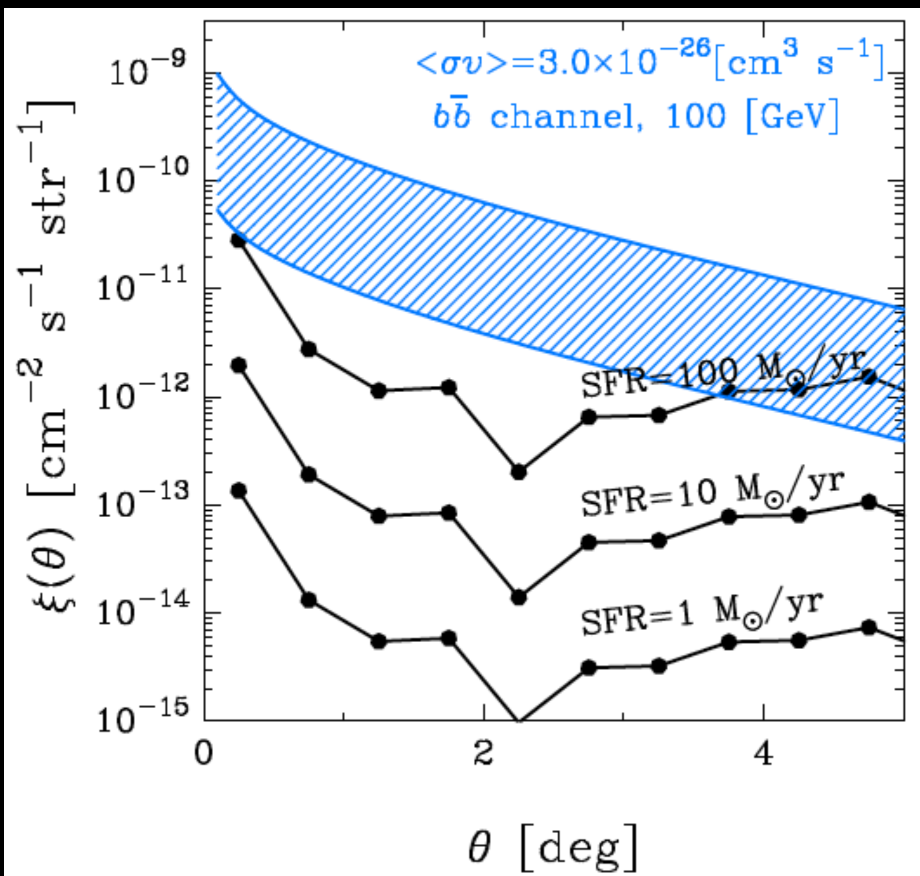


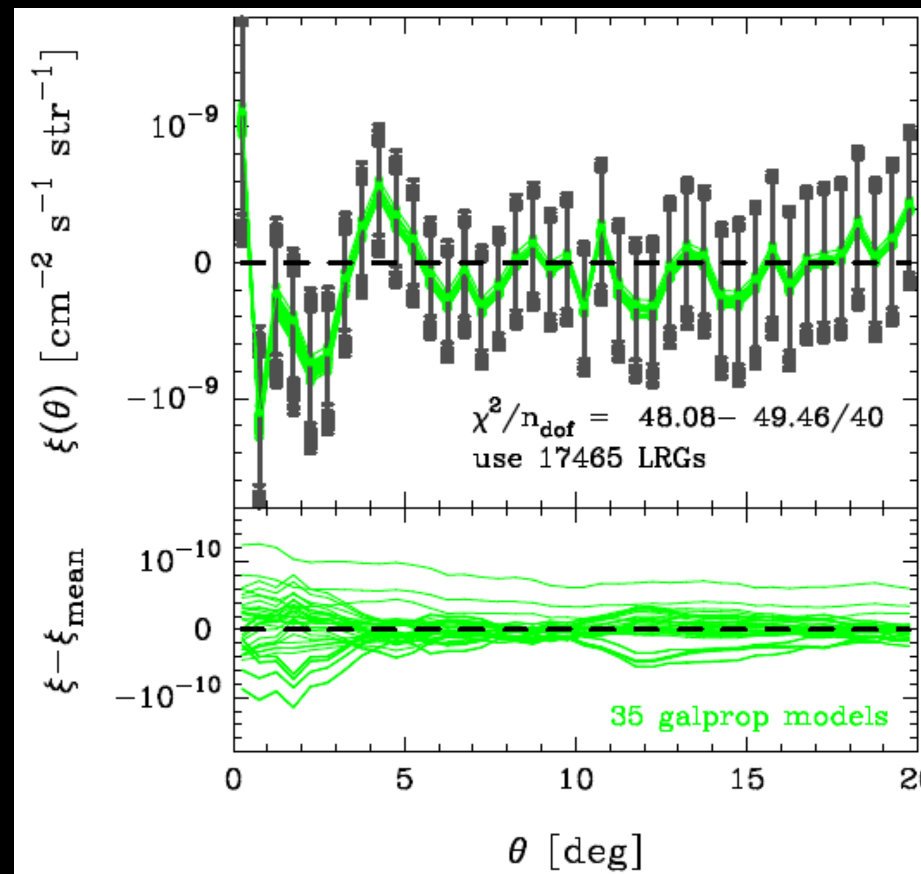
Shirasaki, Horiuchi, Yoshida (2015)

Systematics investigation

1. Low astrophysical contamination: estimated from the typical SFR of LRGs (0.1 – 1 Msun/yr) and using the L_γ–SFR scaling relation of Ackermann et al (2010)
2. Low uncertainty due to Galactic Diffuse Emission: redo cross-correlation analysis using 35 Galactic Diffuse Emission models of Ackermann et al (2012)

→ Confirmation that LRGs are good targets for dark matter.





Shirasaki, Horiuchi, Yoshida (2015)

Conclusions

- *The isotropic gamma-ray background contains a wealth of knowledge.*
  - Guaranteed sources, new sources like dark matter, or surprises
  - Can be exploited by cross-correlation analyses

- *For dark matter:*
  - Cross-correlation with weak lensing:
    - No correlation detection yet
    - But theoretical prospects remain high
    - Ongoing surveys will increase the expected sensitivity by factors of several in the next years. → stay tuned!
  - Cross-correlation with galaxies:
    - Positive signals already reported with various galaxies
    - Nothing yet from Luminous red galaxies (LRG); these are good targets for dark matter detection (small astrophysical contaminations)

Thank you!

BACKUP

Varying the gamma-ray foreground

Vary the photon class and the Galactic Diffuse template makes $\Delta\chi^2 \sim 1 - 5$

	ev2/P7V6	ev2/P7rep	ev4/P7V6	ev4/P7rep
W1	6.91/10	6.22/10	8.58/10	7.80/10
W2	12.26/10	12.32/10	6.98/10	6.87/10
W3	7.62/10	7.11/10	8.77/10	6.49/10
W4	12.88/10	12.95/10	7.57/10	7.39/10

Impact of concentration extrapolation

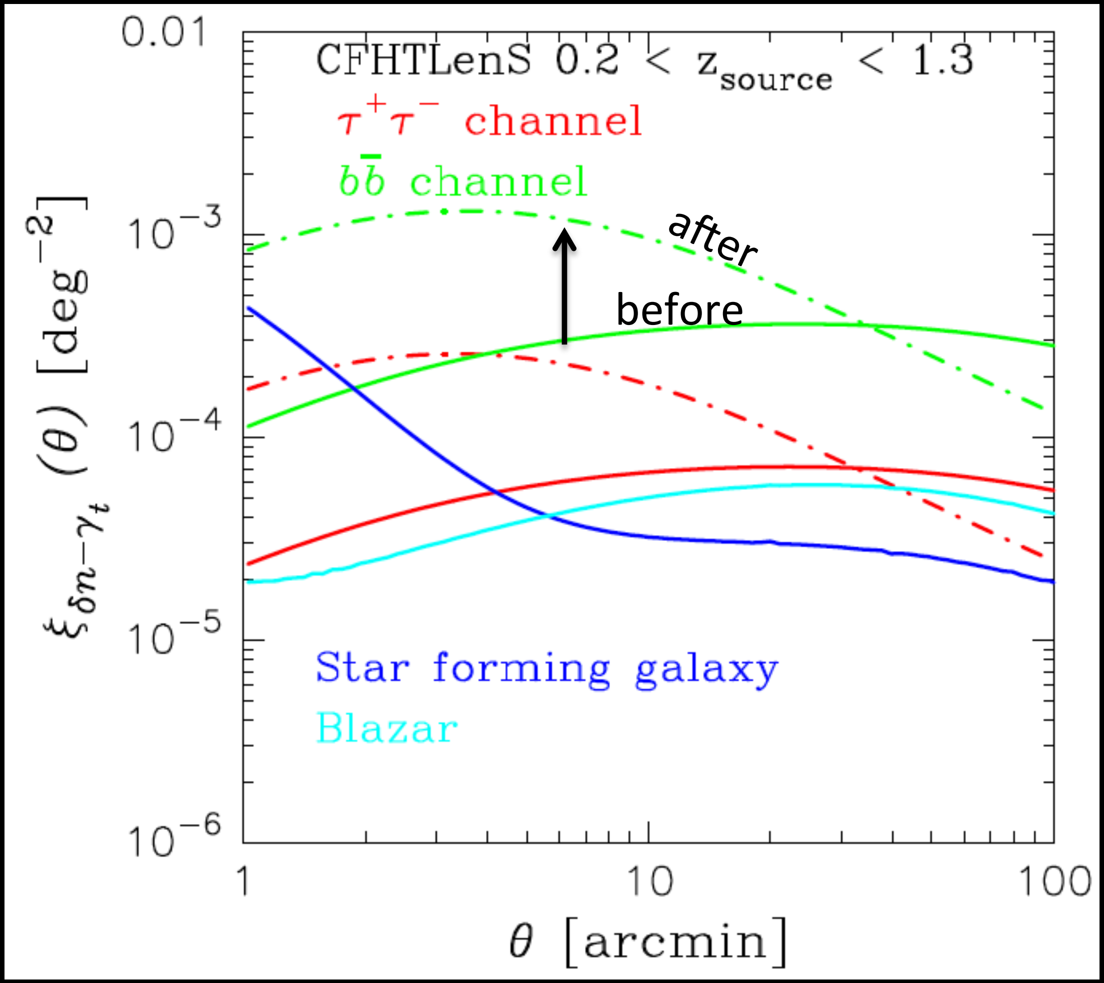
The extrapolation of the concentration parameter to small scales is not entirely monotonic. It is flatter [e.g., Prada et al 2012].

Update cross-correlation signal:

- Monotonic (solid)
- Non-monotonic (dot-dashed)

Due to the relatively higher concentration of large halos, the one-halo term dominates and the signal < 10 arcmin is some x10 larger.

However, the ultimate limits on dark matter reduces only at the 10% level, since most of the constraint comes from > 10 arcmin.



Weak lensing basics

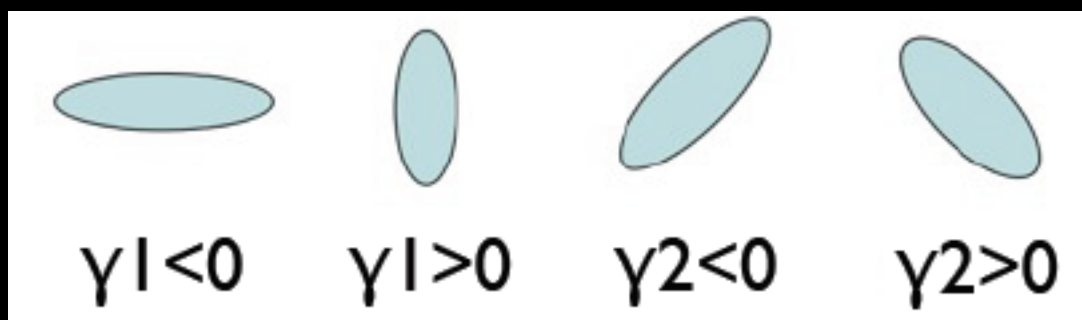
$$\Phi_{ij} = \frac{2}{c^2}\int_0^{\chi} \mathrm{d}\chi' f(\chi,\chi')\,\frac{\partial^2}{\partial x_i \partial x_j}\Phi[r(\chi')\boldsymbol{\theta},\chi'],$$

$$f(\chi,\chi') = \frac{r(\chi-\chi')\,r(\chi')}{r(\chi)},$$

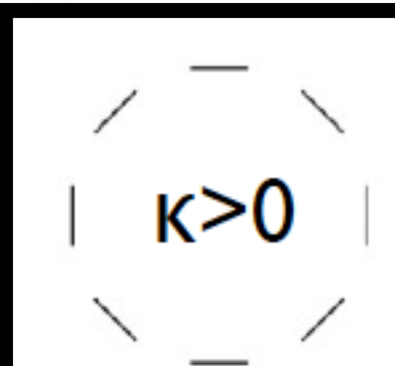
$$\kappa = (\Phi_{11}+\Phi_{22})/2$$

$$\gamma_1 = (\Phi_{11}-\Phi_{22})/2$$

$$\gamma_2 = \Phi_{12}$$



A positive radially symmetric k leads to a tangential shear



Astrophysical sources

Number of photons along a line of sight θ:

$$\delta n(\boldsymbol{\theta}) = \int \mathrm{d}\chi\, g(\chi, \boldsymbol{\theta}) W_g(\chi)$$

Source field (g): gamma-ray luminosity

Window function (W):

$$W_{g,\mathrm{ast}}(\chi) = \int_{E_{\min}}^{E_{\max}} \frac{\mathrm{d}E_\gamma}{4\pi} N_0(\chi) \left(\frac{E'_\gamma}{E_0}\right)^{-\alpha} \exp\left[-\tau\left(E'_\gamma, \chi\right)\right] \eta(E_\gamma)$$

Source properties — Gamma-ray optical depth — Exposure

- For blazars: a = 2.4 and luminosity-dependent density evolution model
- For star-forming galaxies: a = 2.7 and use the IR-gamma correlation with the IR luminosity function

Calculation of the correlation signal

The distortion of images of distant galaxies can be characterized by convergence (k) and shear (g)

The 2-point cross-correlation signal is

$$\xi_{\delta n-\gamma_t}(\theta) = \int \frac{d\ell\,\ell}{2\pi} P_{\delta n-\kappa}(\ell) J_2(\ell\theta)$$

where the cross-correlation APS is (for dark matter and astro sources):

$$P_{\delta n-\kappa}(\ell) = \int \frac{d\chi}{\chi^2} W_g(\chi) W_\kappa(\chi) P_{\delta-\delta^2}(\ell/\chi, z(\chi))$$

$$P_{\delta n-\kappa}(\ell) = \int \frac{d\chi}{\chi^2} W_{g,\mathrm{ast}}(\chi) W_\kappa(\chi) P_{\delta-L}(\ell/\chi, z(\chi))$$

(cross-correlation APS decomposed into spherical harmonics, $C_l^{(ij)}$)

The integrands are calculated by the halo-model approach.

Calculation of the correlation signal

Boost factor

DM profile

Halo bias

Halo mass function

$$P^{1h}_{\delta-\delta^2}(k,z) = \left(\frac{1}{\bar{\rho}_m}\right)^3 \int_{M_{\min}} \mathrm{d}M\, n(M,z) M\, u(k|M,z) \times (1 + b_{sh}(M)) v(k|M,z) \int \mathrm{d}V \rho_h^2(r|M,z),$$

$$P^{2h}_{\delta-\delta^2}(k,z) = P^{\mathrm{lin}}(k,z) \left(\frac{1}{\bar{\rho}_m}\right)^3 \left[\int_{M_{\min}} \mathrm{d}M\, n(M,z) b_h(M,z) M\, u(k|M,z)\right] \times \left[\int_{M_{\min}} \mathrm{d}M\, n(M,z) b_h(M,z)(1 + b_{sh}(M)) v(k|M,z) \int \mathrm{d}V \rho_h^2(r|M,z)\right]$$

Where n(M) is the mass function, u(k|M) and v(k|M) are the FT of rho(r) and rho(r)2

$$P^{1h}_{\delta-L}(k,z) = \frac{1}{\bar{\rho}_m \langle L \rangle} \int_{L_{\min}(z)}^{L_{\max}(z)} \mathrm{d}L\, \Phi(L,z) L\, u(k|M(L),z)$$

$$P^{2h}_{\delta-L}(k,z) = P^{\mathrm{lin}}(k,z) \left(\frac{1}{\bar{\rho}_m \langle L \rangle}\right) \left[\int_{M_{\min}} \mathrm{d}M\, n(M,z) b_h(M,z) u(k|M,z)\right] \times \int_{L_{\min}(z)}^{L_{\max}(z)} \mathrm{d}L\, \Phi(L,z) L\, b_h(M(L),z),$$

Where Phi(L) is the luminosity function, M(L) is the mass-luminosity relation

Astrophysical sources

For each source population, we need Phi(L), M(L), and the spectrum $N_0(\chi)\left(\frac{E'_\gamma}{E_0}\right)^{-\alpha}$

For blazars

- Fixed a = 2.4 [of resolved blazars]
- Luminosity-dependent density evolution model
  - Lower cutoff of 1042 erg/s
- Mass relation: power-law of mass, use observe quasar bias

Ando et al (2007)
Ando & Komatsu (2013)

For star-forming galaxies:

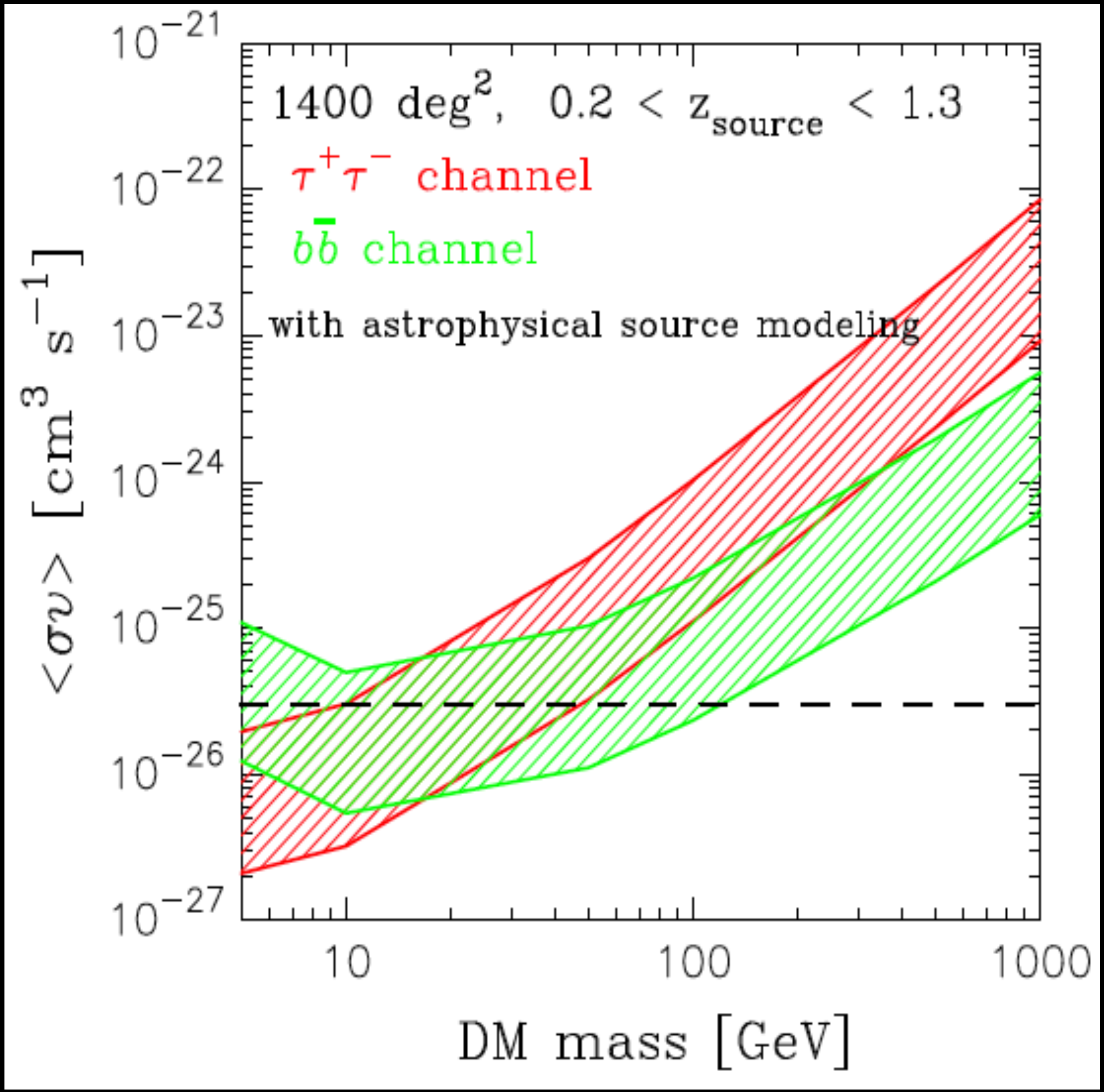
- Fixed a = 2.7
- Use the IR luminosity function and the IR-gamma correlation
  - Lower cutoff of 1030 erg/s
- Mass relation: power-law of mass, calibrated using the Milky Way:

$$M(L) = 10^{12} M_\odot (L/10^{39}\ \mathrm{erg\,s^{-1}})^{0.5}$$

Camera et al (2013)

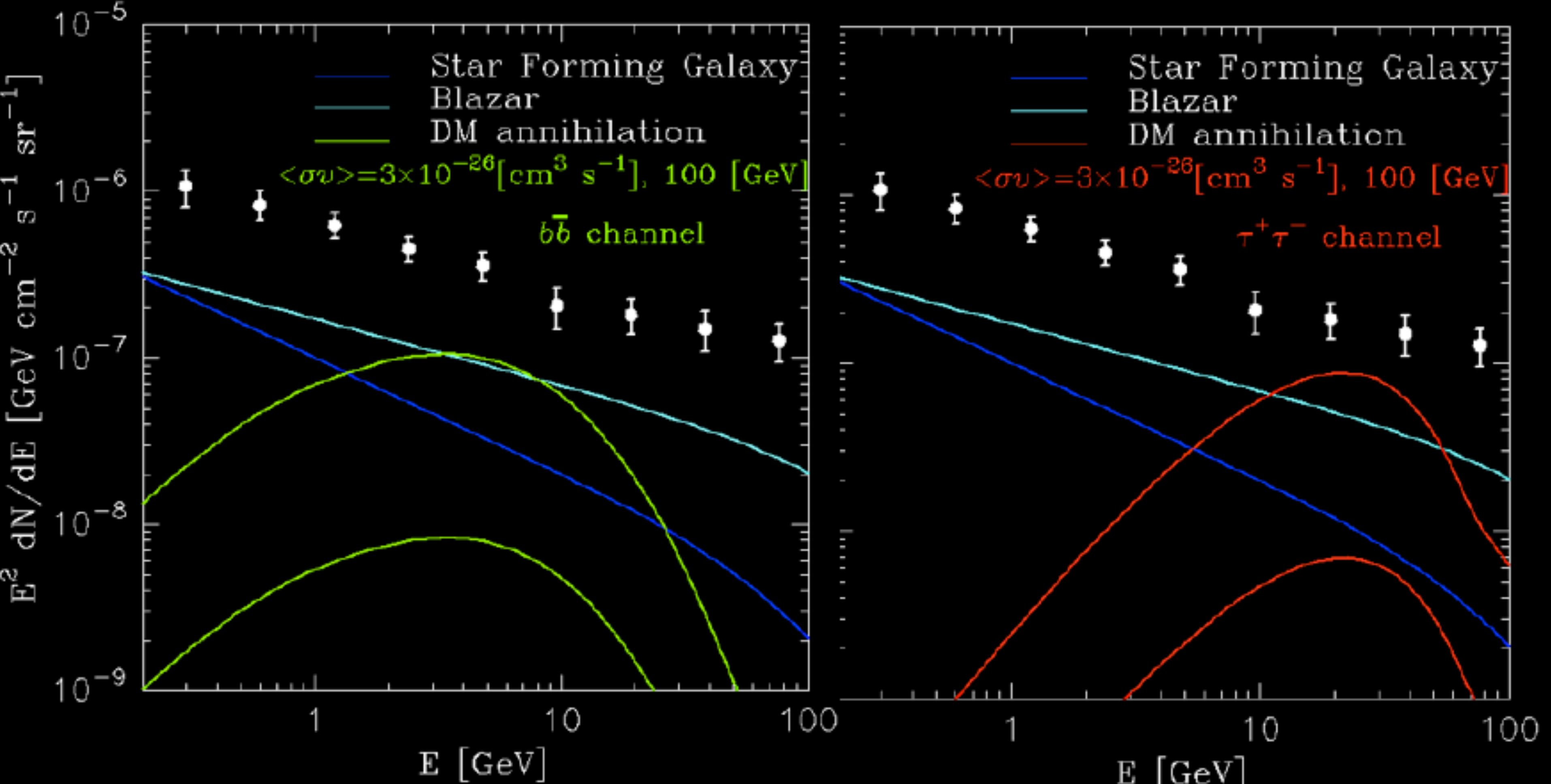
Ongoing surveys

Hyper-Suprime Cam: 1σ bounds with positive CC measurement and astro modeling

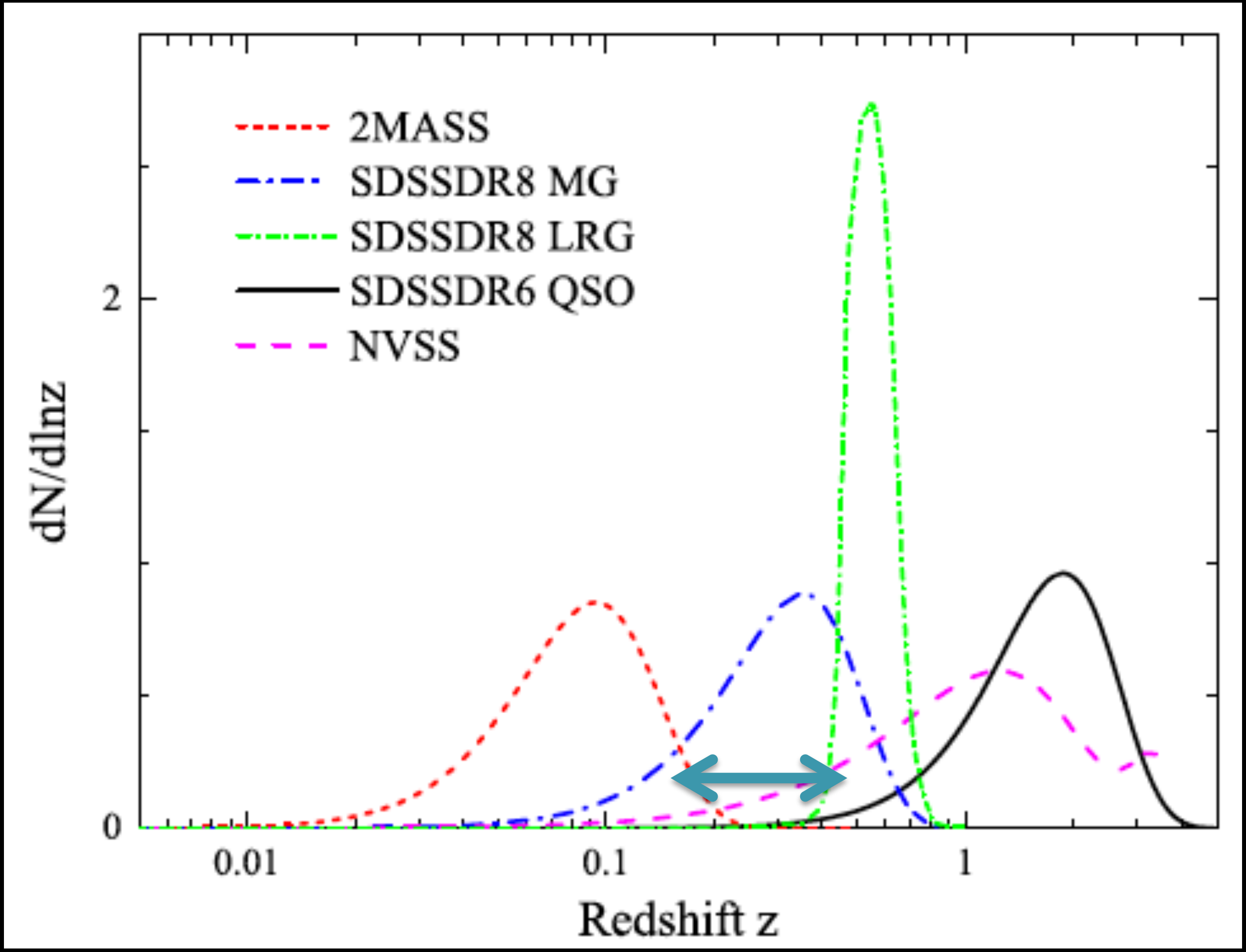


Shirasaki, Horiuchi, Yoshida (2014)

Mean Intensity in Our Model

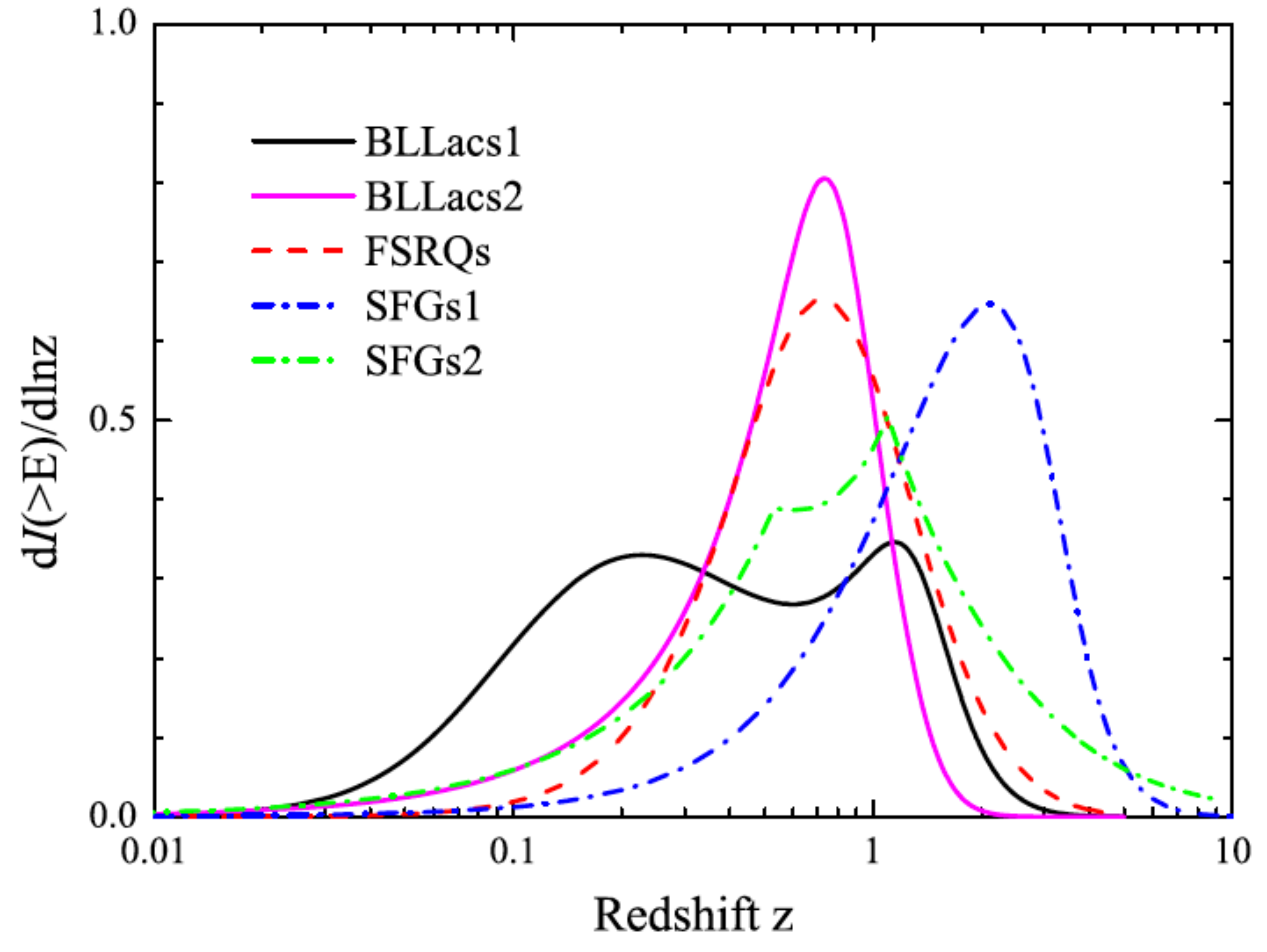


Cross-correlation with galaxies



Xia et al (2015)

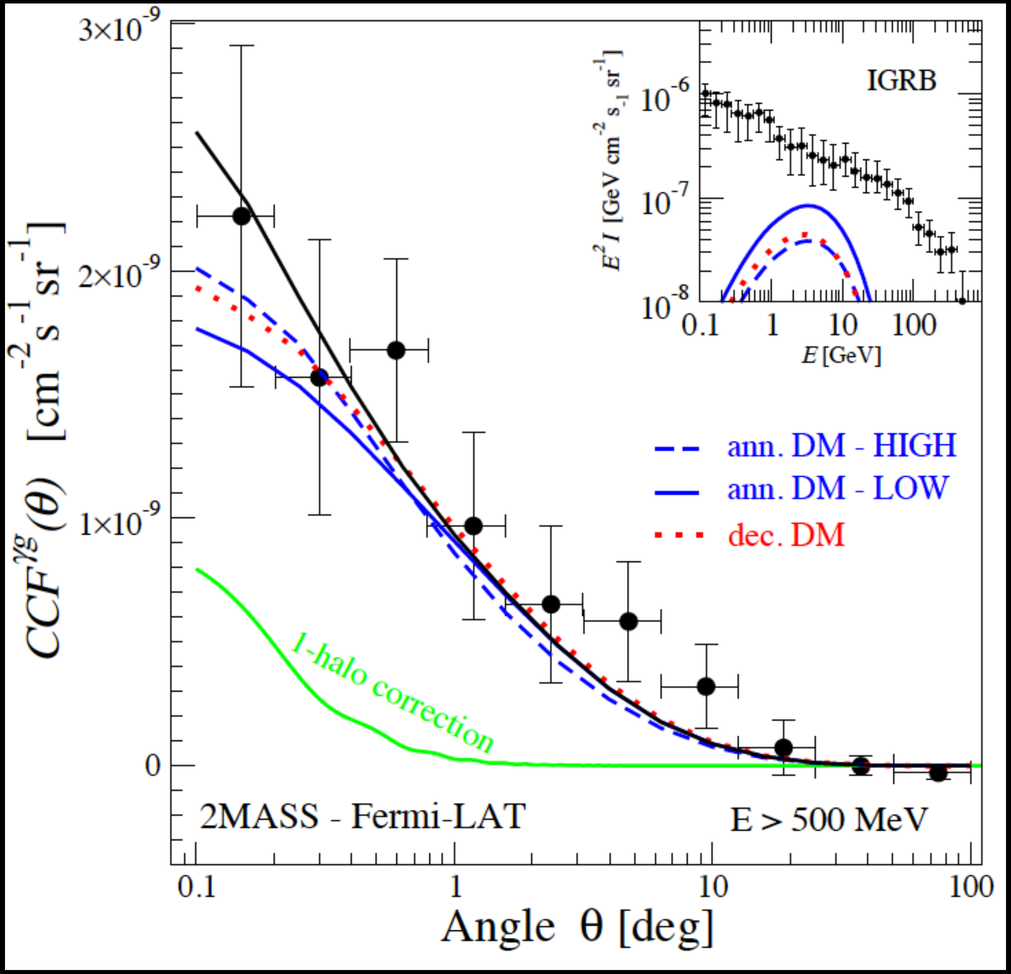
Cross-correlation with galaxies: models



Xia et al (2015)

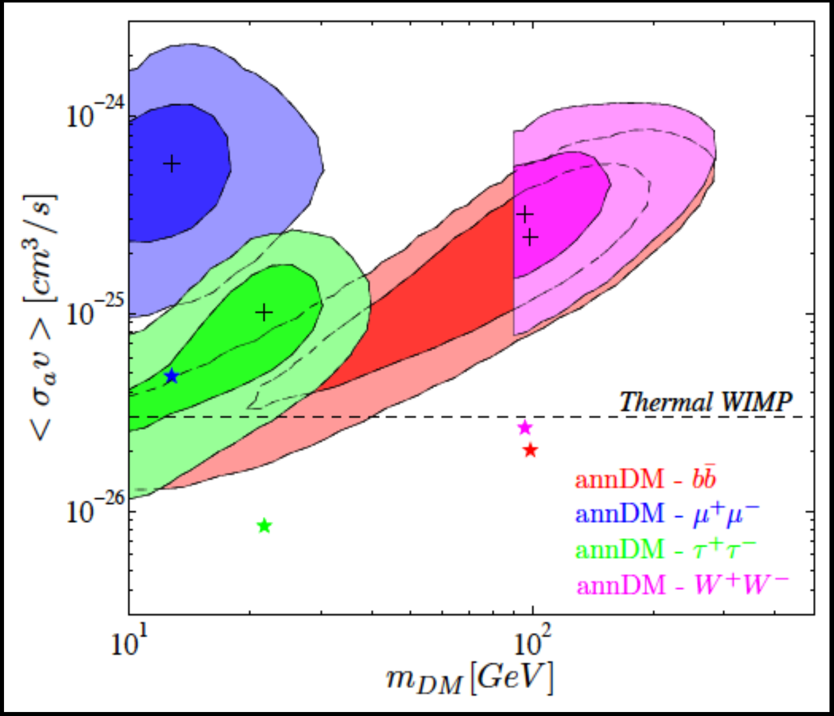
Explanations with dark matter

Fermi-LAT – 2MASS cross-correlation



Both the shape and intensity can be described by ~thermal dark matter.

No astrophysics assumed.



Regis et al (2015)