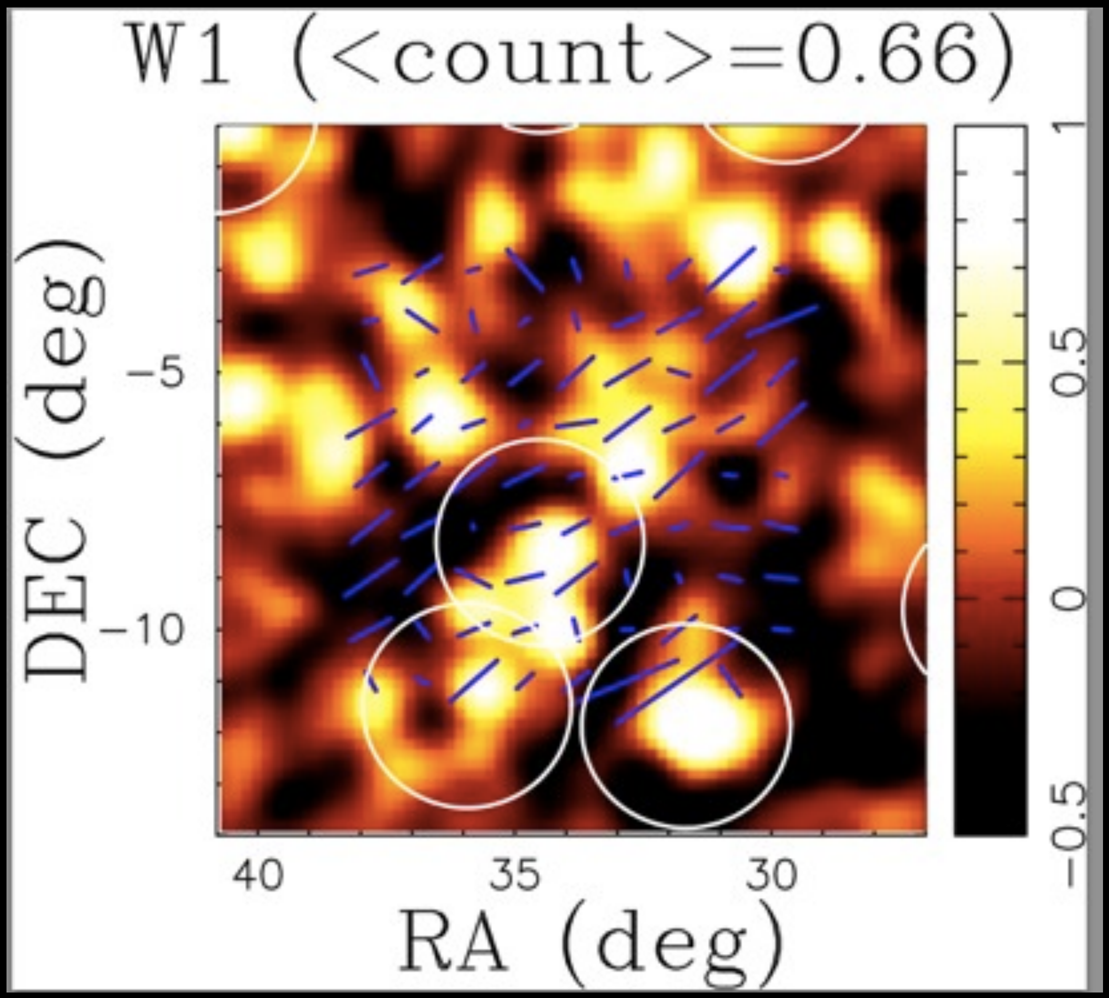
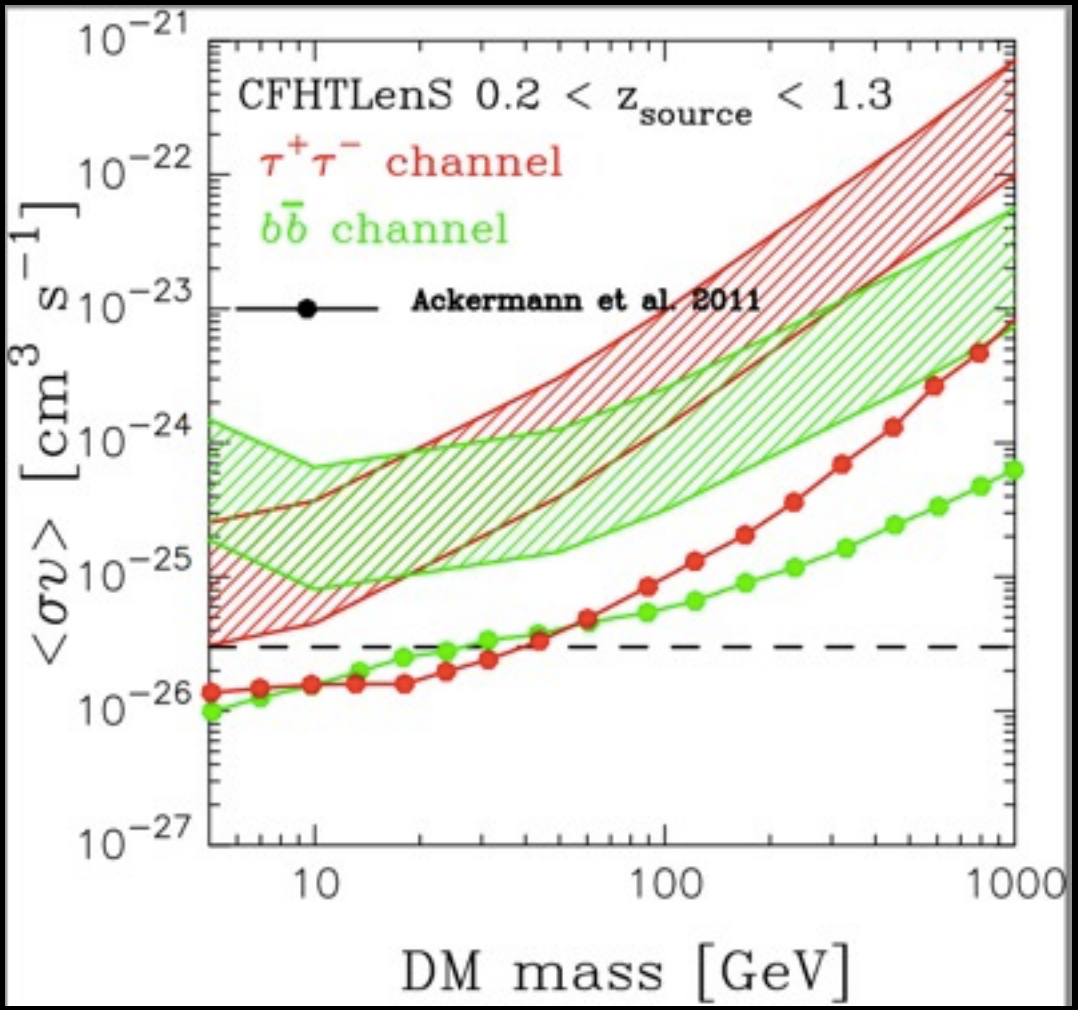
Dark Matter Annihilation Cross-section Constraints from Cross-Correlation of Cosmic Shear and Extragalactic Gamma-ray Background





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with Shunsaku Horiuchi (UCI), Naoki Yoshida (Univ. of Tokyo, IPMU)

Based on Shirasaki et al. 2014, PRD, 90, 063502 (arXiv:1404.5503)

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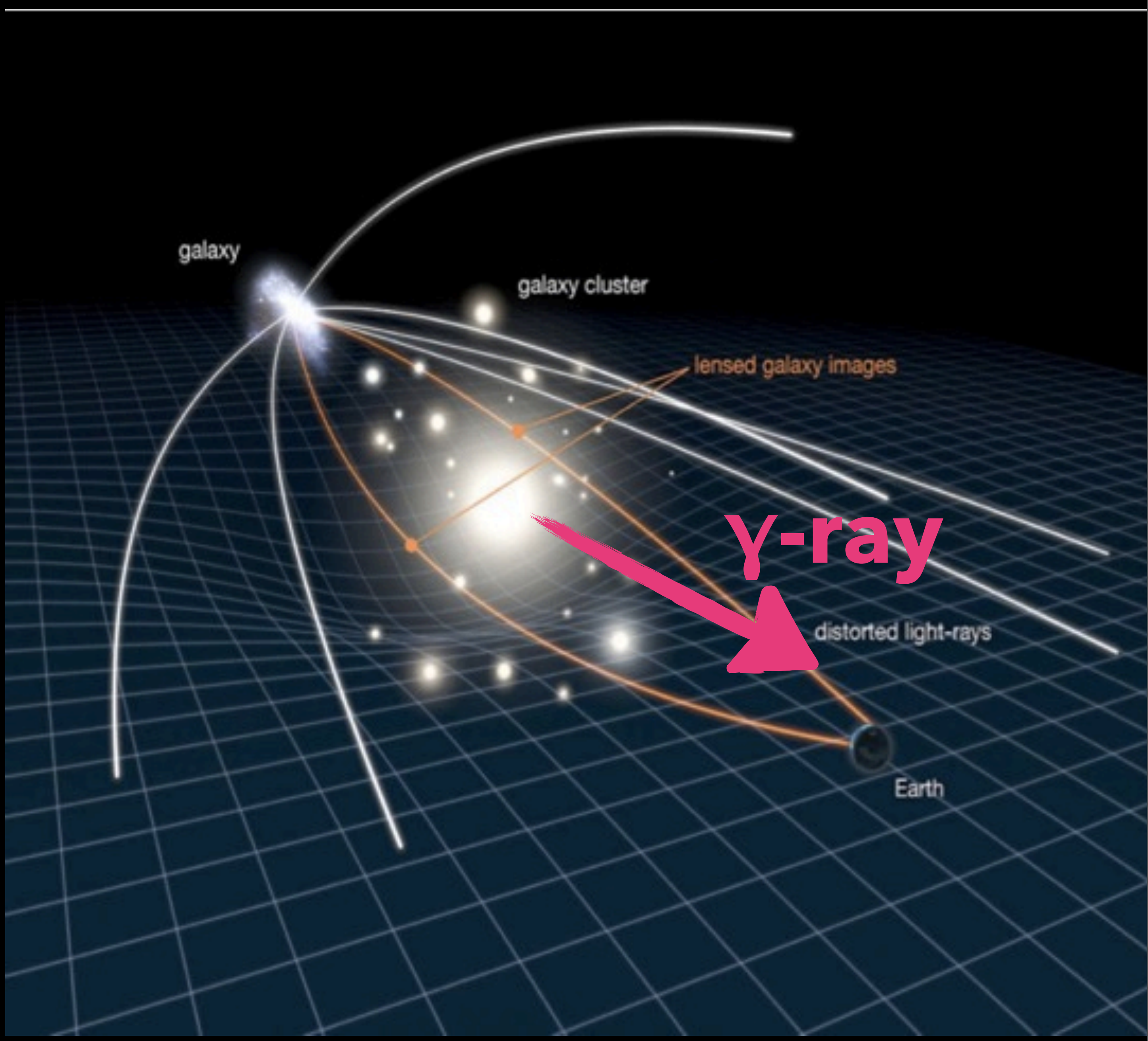
Exploring DM signal in Extragalactic Gamma-Ray Background

- Dark matter itself may be a source of gamma-ray through self-annihilation
- Observed EGB energy spectrum is well described by power low (index ~2.41)
- This suggests DM can not play a leading role in the range of 0.1 - 100 GeV because DM signal would have spectral feature
- To take a step forward, consider other observables, e.g. **anisotropy** of EGB!

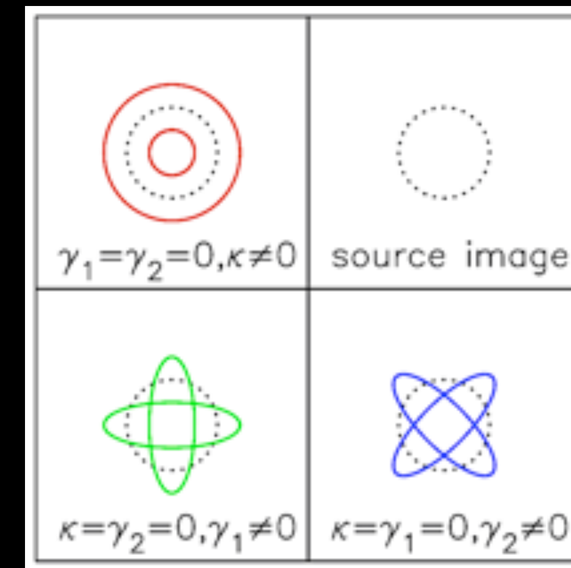
Cross-Correlation with Cosmic Shear

- The distortion of image of distant galaxies are produced by the matter distribution along the line of sight
- The lens object could be gamma-ray source due to
  - DM annihilation
  - Astrophysical sources, e.g. blazars and SFGs



Weak Lensing Basics

The distortion of image of a source object can be characterized by **convergence** and **shear**



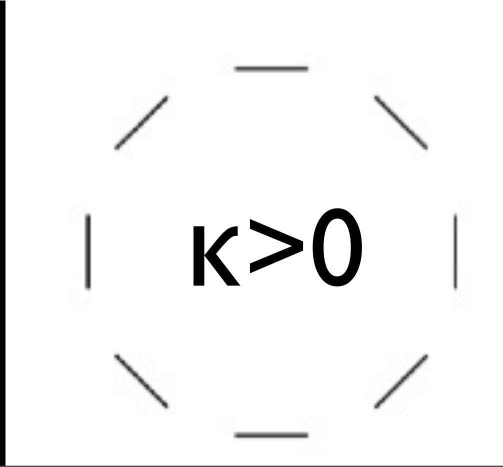
$$\kappa(\boldsymbol{\theta},\chi) = \int_0^{\chi_H} \mathrm{d}\chi\, W(\chi)\delta(r(\chi)\boldsymbol{\theta},\chi)$$

Convergence — $\kappa(\boldsymbol{\theta},\chi)$

matter overdensity — $\delta(r(\chi)\boldsymbol{\theta},\chi)$

$$W(\chi) = \frac{3}{2}\left(\frac{H_0}{c}\right)^2 \Omega_{\mathrm{m}0}\frac{r(\chi)}{a(\chi)}\int_\chi^{\chi_H} \mathrm{d}\chi' p(\chi')\frac{r(\chi'-\chi)}{r(\chi')},$$

a positive, radially symmetric κ leads to a **tangential** shear



Dark matter Annihilation

The number of EGB photon along the line of sight

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

Relevant field of γ-ray

In the case of DM annihilation,
g = overdensity squared

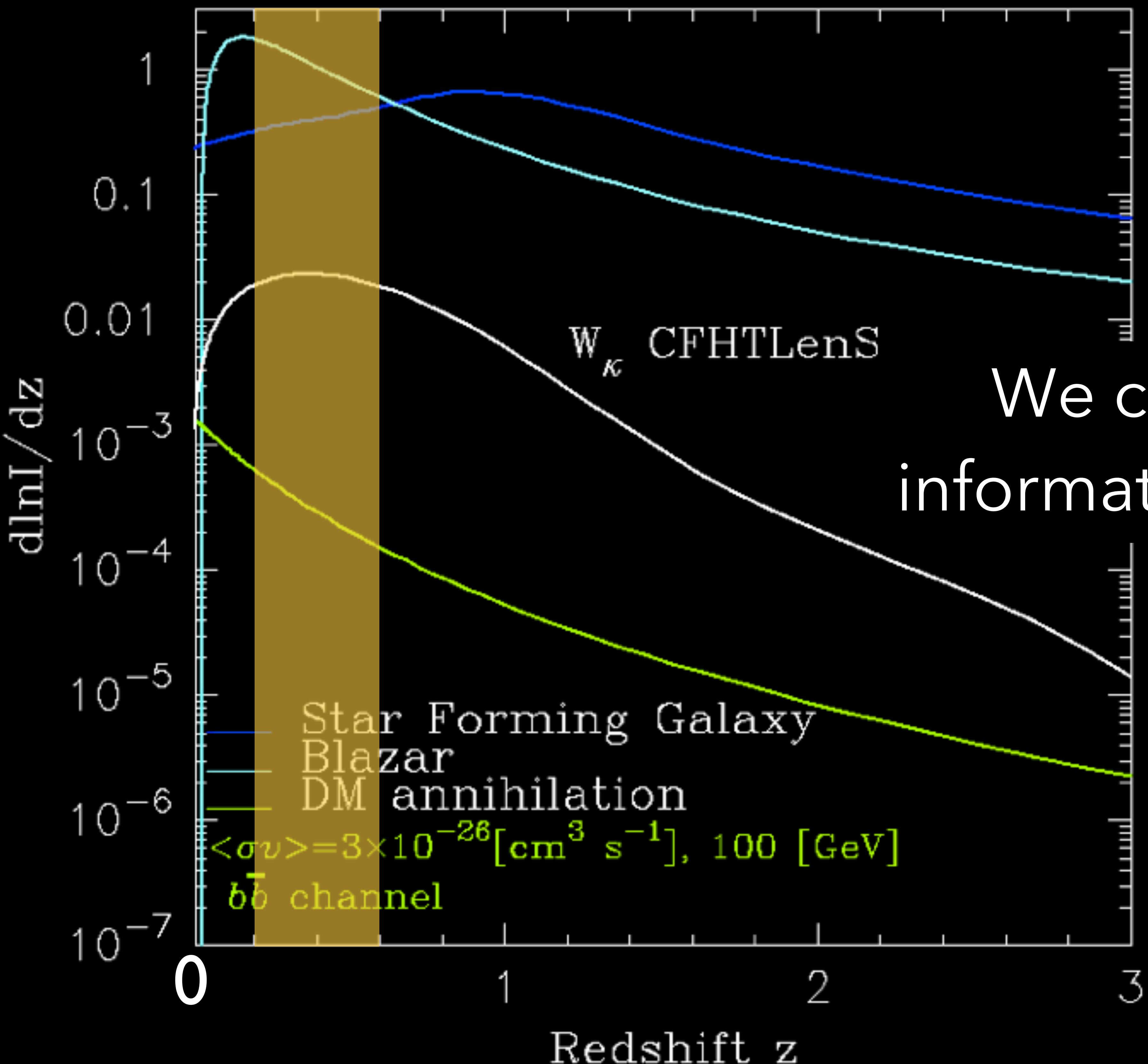
$$W_g(\chi) = \int_{E_{\gamma,\mathrm{min}}}^{E_{\gamma,\mathrm{max}}} \mathrm{d}E_\gamma \, \frac{\langle \sigma v \rangle}{8\pi} \left(\frac{\bar{\rho}_{\mathrm{dm},0}}{m_{\mathrm{dm}}}\right)^2 [1+z(\chi)]^3 \left.\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}\right|_{E'_\gamma} \exp\left[-\tau\left(E'_\gamma, \chi\right)\right] \eta(E_\gamma),$$

The particle properties of dark matter

Gamma-ray optical depth

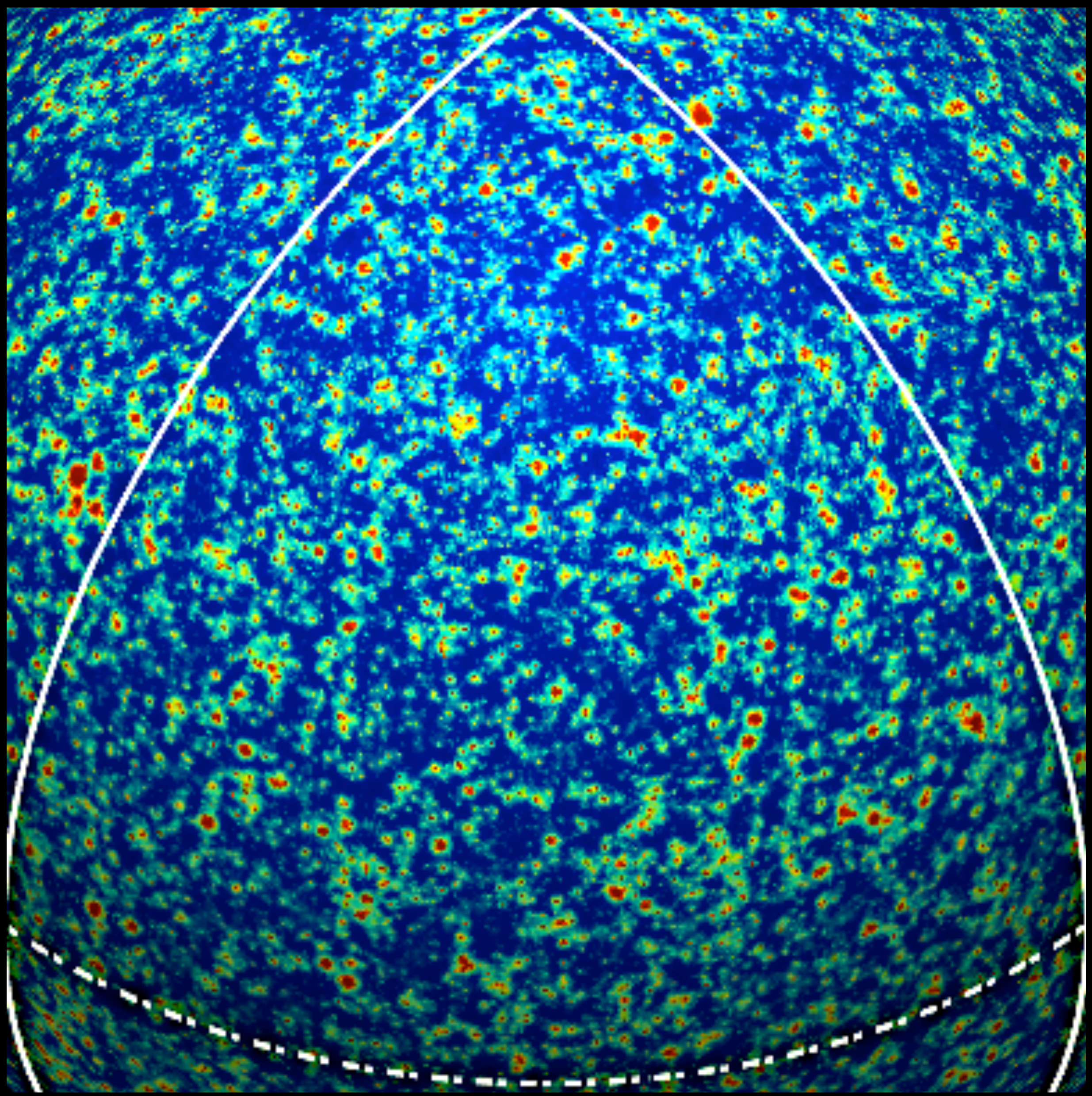
Exposure

Effective redshift in cross-correlation

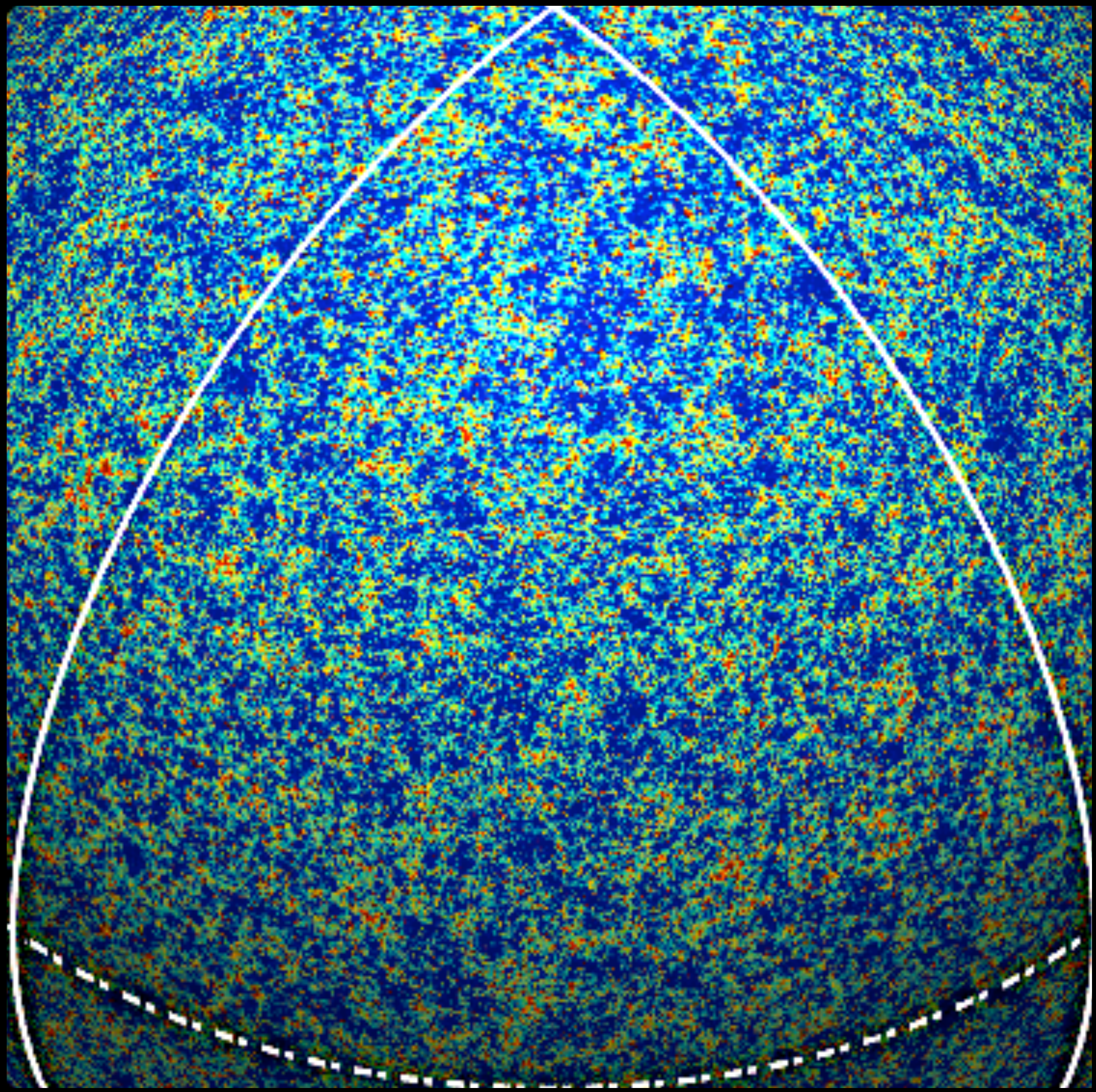


We can extract the information at z=**0.2-0.4**

Expected Cross-correlation

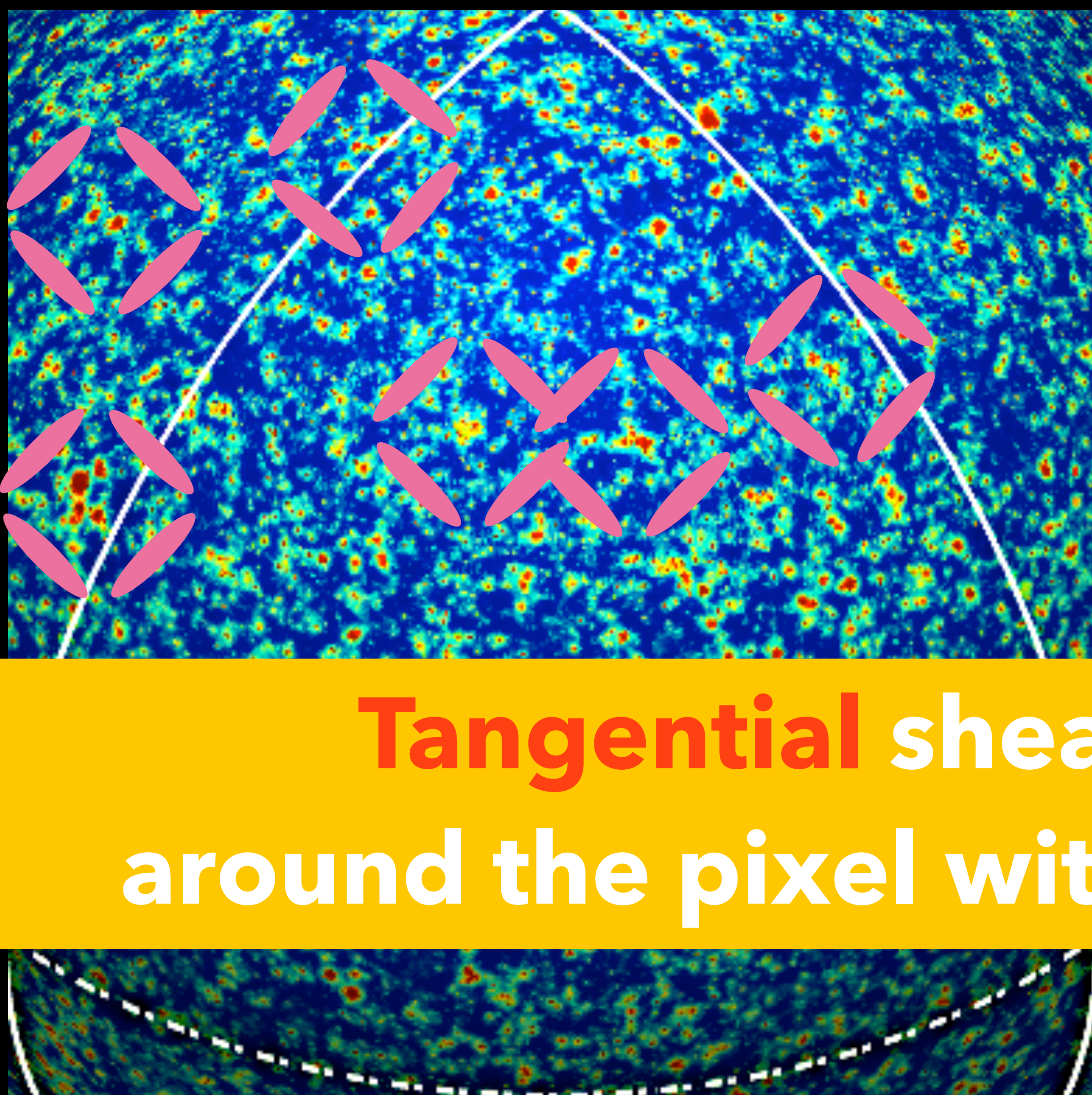


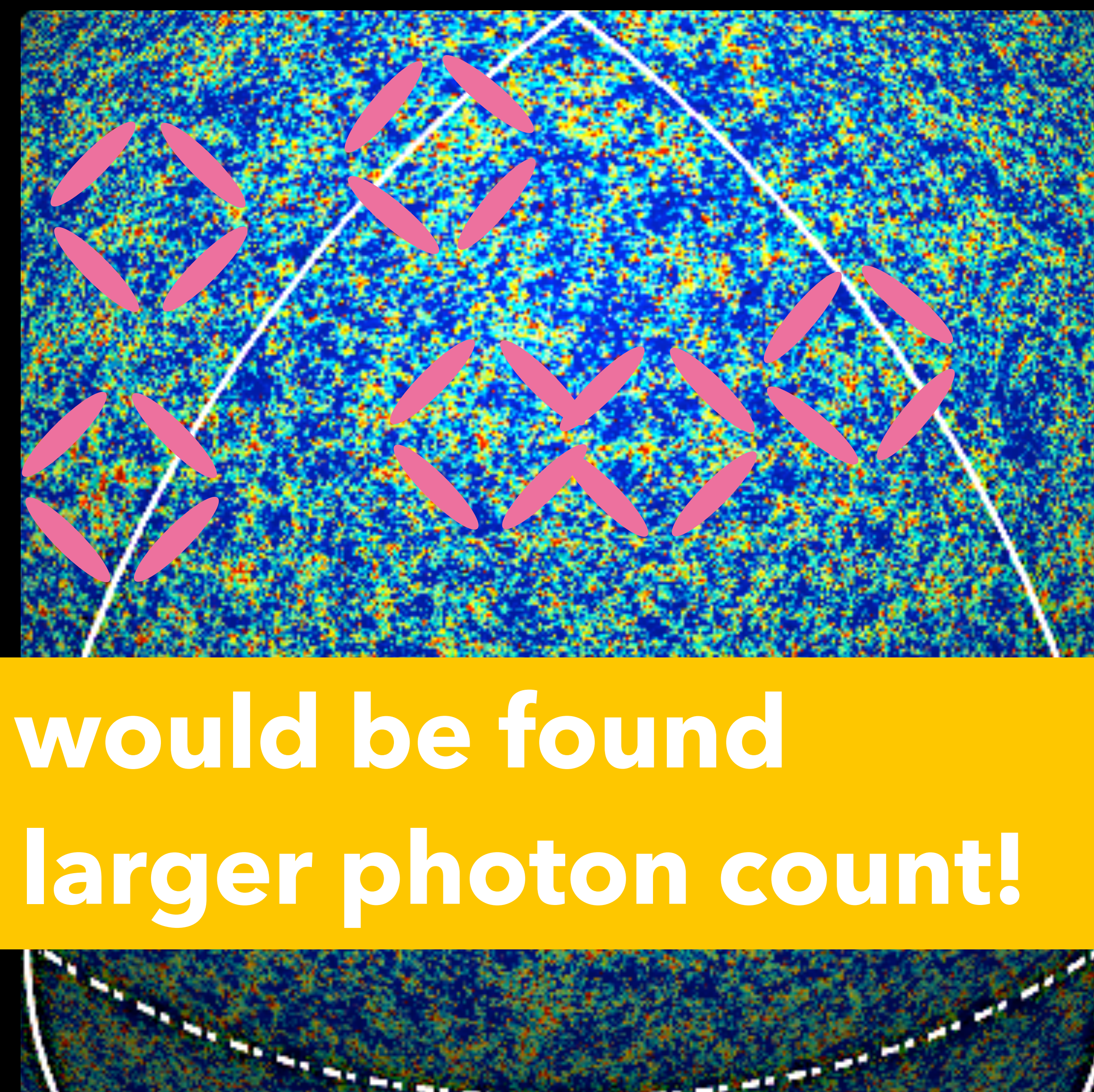
DM annihilation map
100GeV, 3×10^{-26} cc/s
bb channel



Lensing convergence
source galaxy locates at z=1

Expected Cross-correlation





Tangential shear would be found around the pixel with larger photon count!

DM annihilation map

100GeV, 3×10^{-26} cc/s

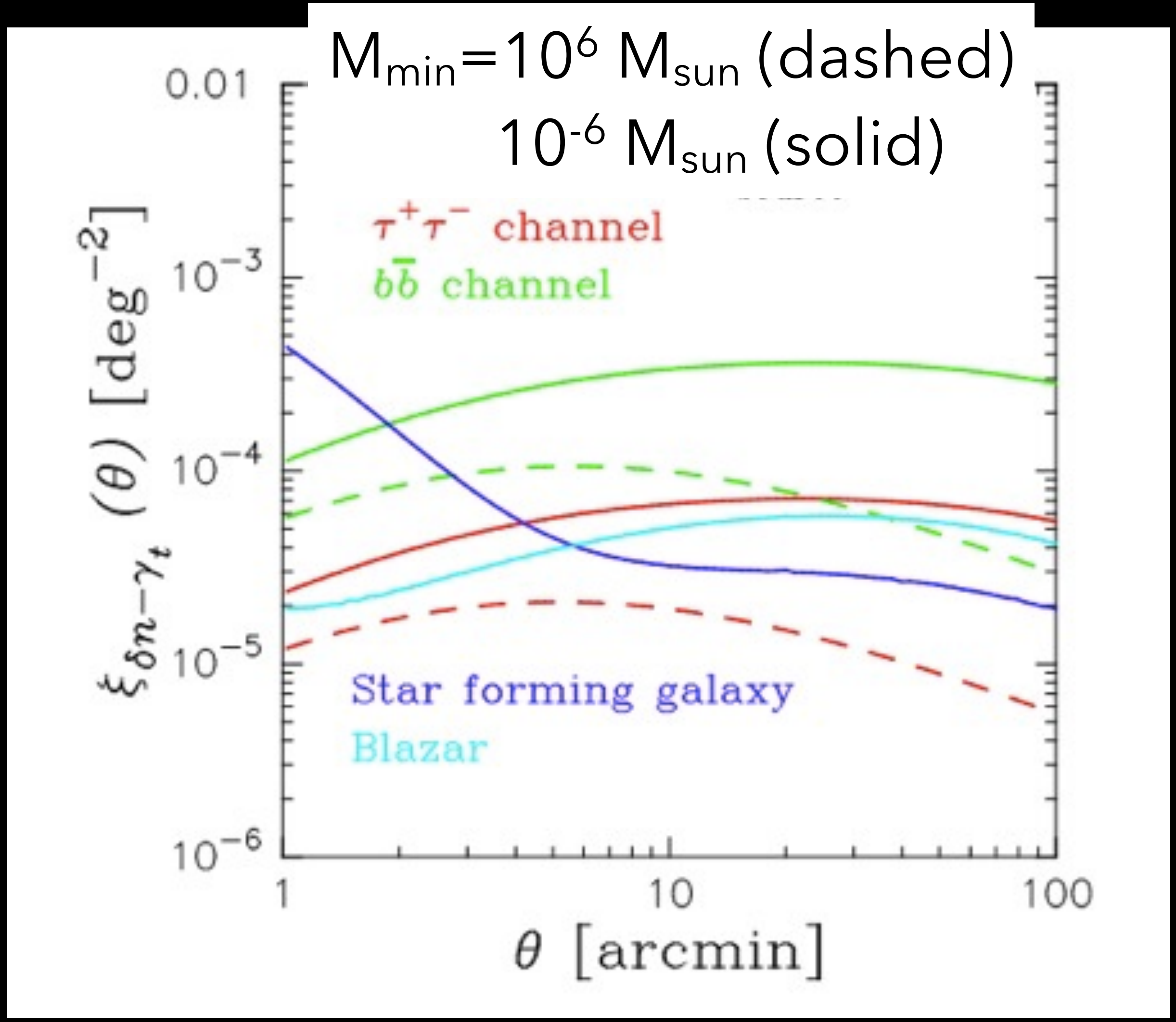
bb channel

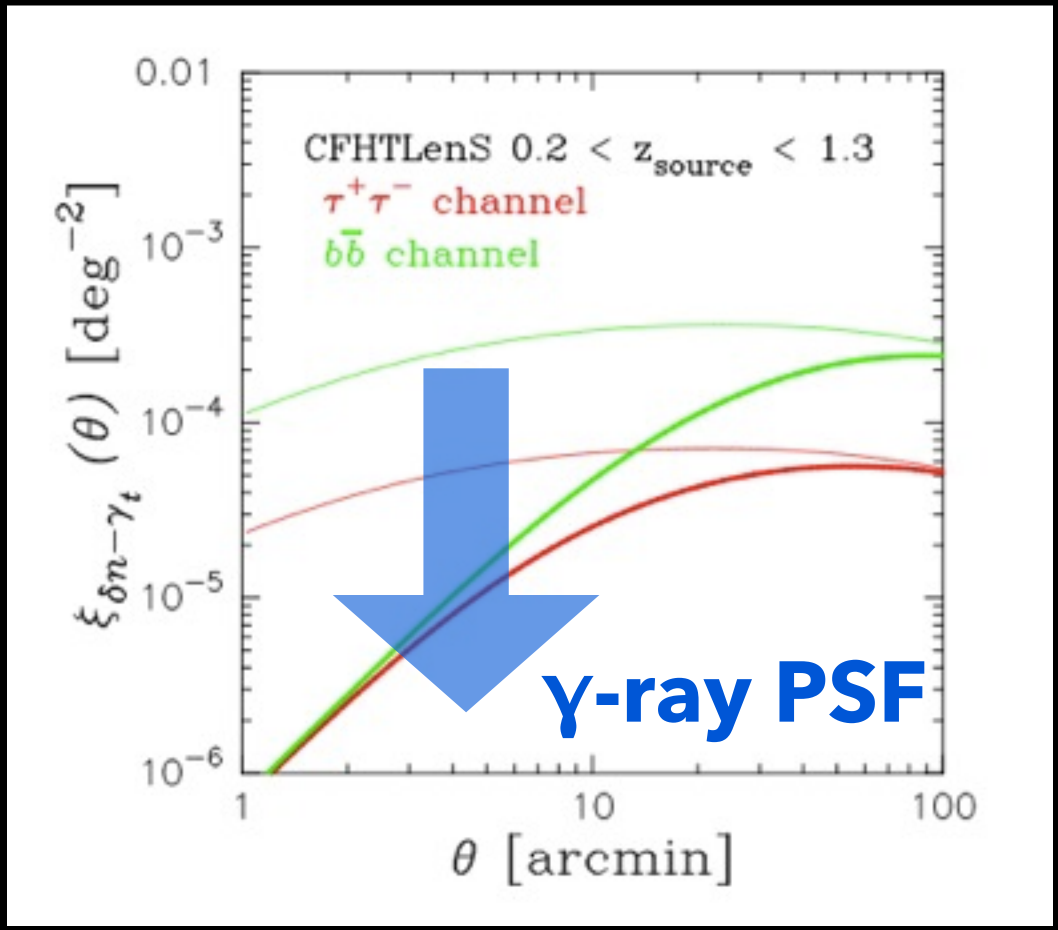
Lensing convergence

source galaxy locates at z=1

Our Benchmark model (m_{dm}=100GeV, <σv>=3×10^{-26} cc/s)

- *Halo-model approach* (e.g. Camera et al. 2013)
- DM signal would dominate at large angle scale
- consider Minimum halo mass as the effective model uncertainty
- two cases 10^{6} ,10^{-6} M_{sun}
- Gamma-Ray PSF would suppress any cross correlation signals at θ < 50 arcmin
- For constraints, we consider only DM signals at present (This is conservative)





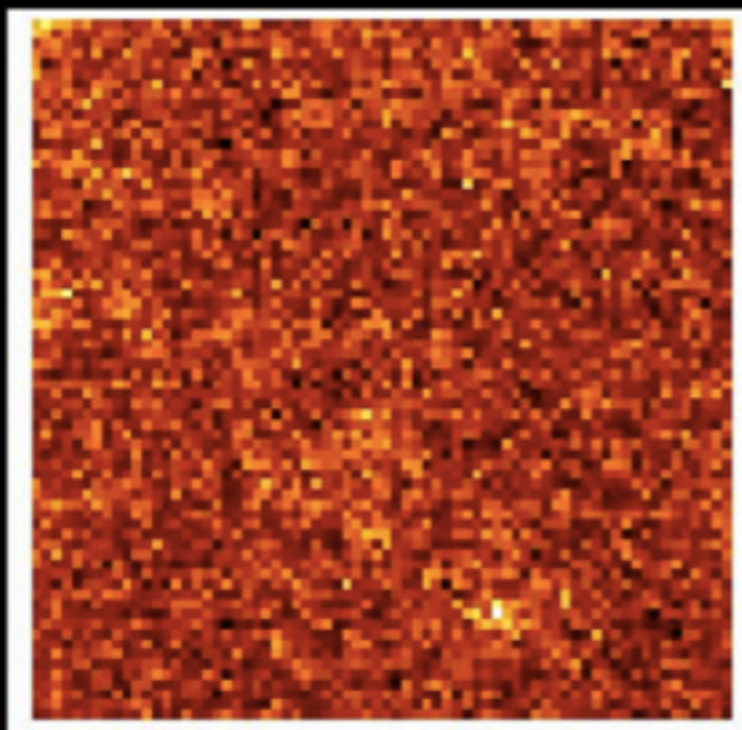
Application to Real Data

- CFHTLenS data (four patches ~154 deg^2)
  - The current largest cosmic shear data set
  - 11 resolved galaxies per 1 arcmin^2
  - median photo-z of 0.75 ($0.2 < z < 1.3$)
  - about 5.7 million galaxies are used for the correlation study

- Fermi LAT (All sky)
  - Pass7 reprocessed data taken from August 2008 to January 2014
  - Use 1-500 GeV ULTRACLEAN-class photons
  - CFHTLenS regions are far from the Fermi bubbles
  - point sources are masked
  - At present, the final results do not change significantly by the photon-selection and galactic diffuse model

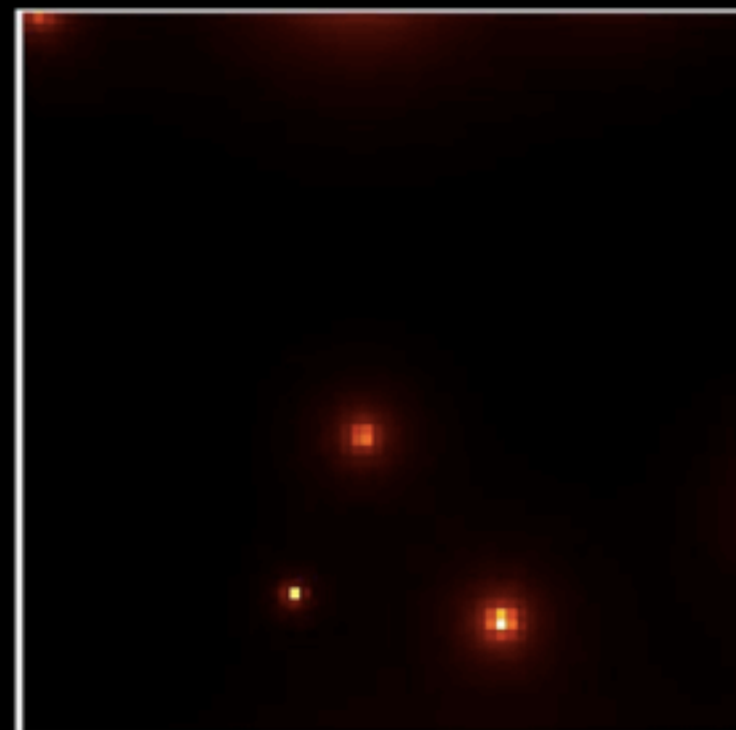
By S. Horiuchi

Gamma-Ray Data



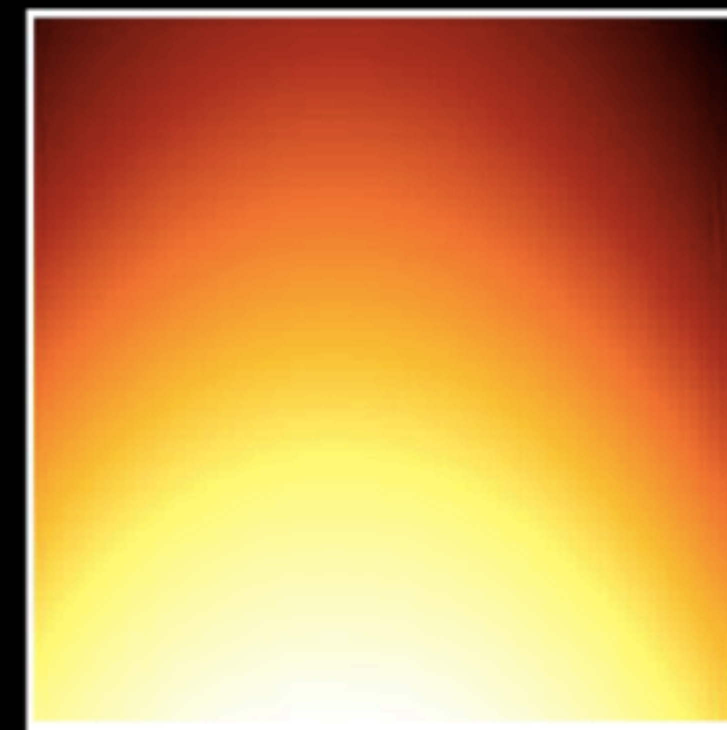
Data counts

=



Point source

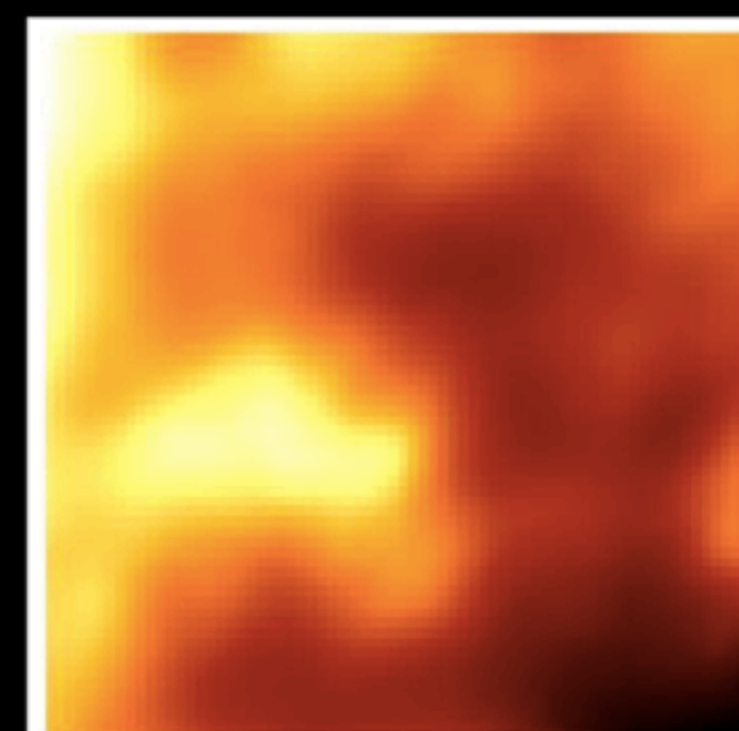
+



Isotropic diffuse

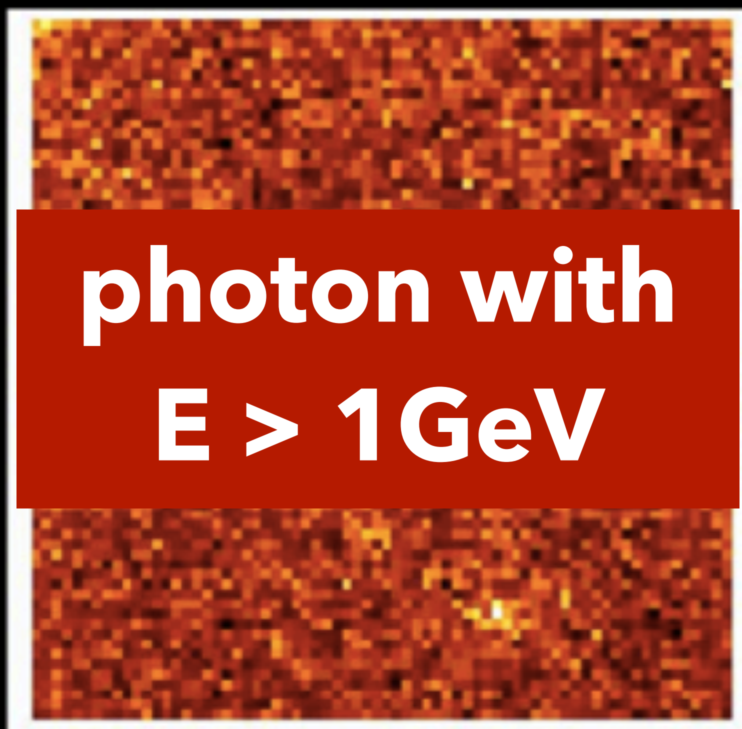
Modeling:
Point source spectra parameters and normalization, as well as diffuse normalizations (spectra and spatial morphology fixed by templates)

+



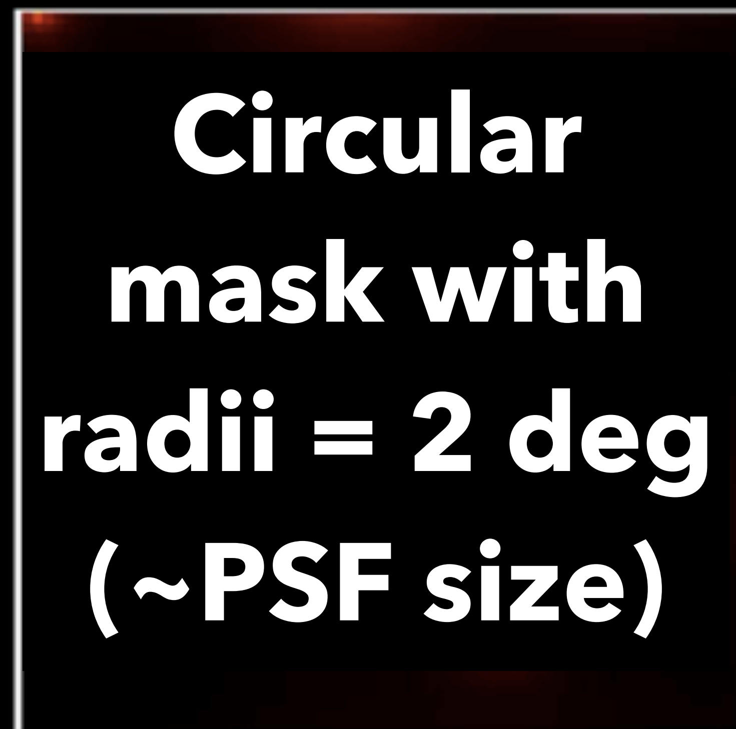
Galactic diffuse (foreground)

Gamma-Ray Data



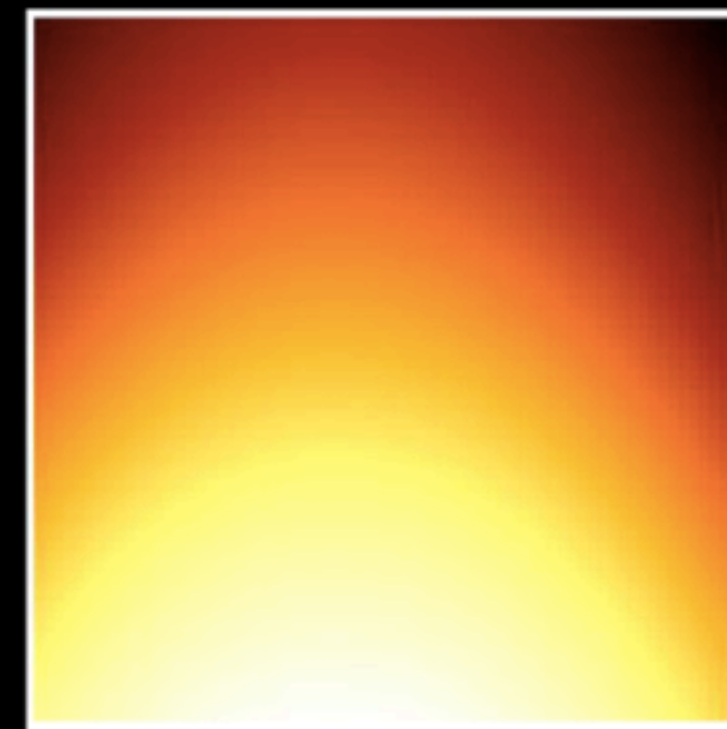
Data counts

=



Point source

+



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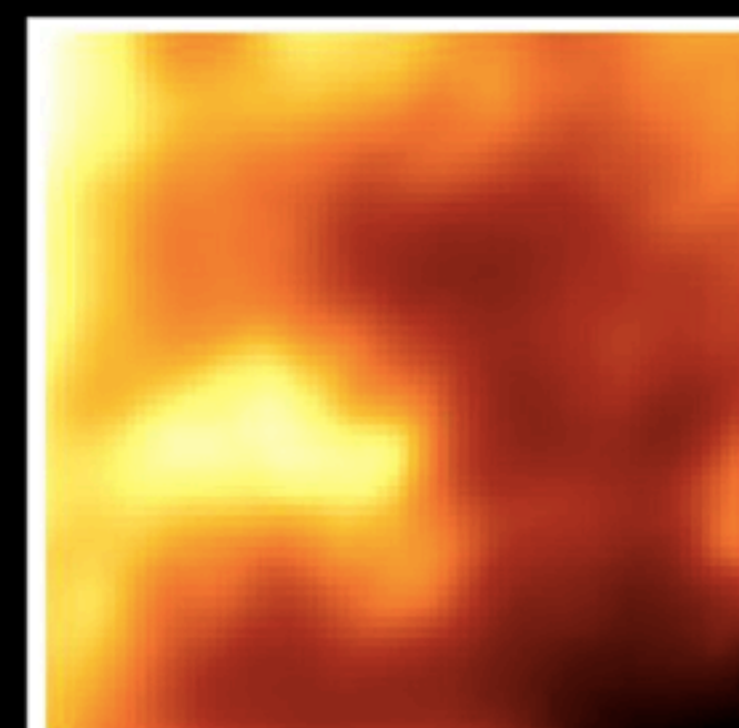
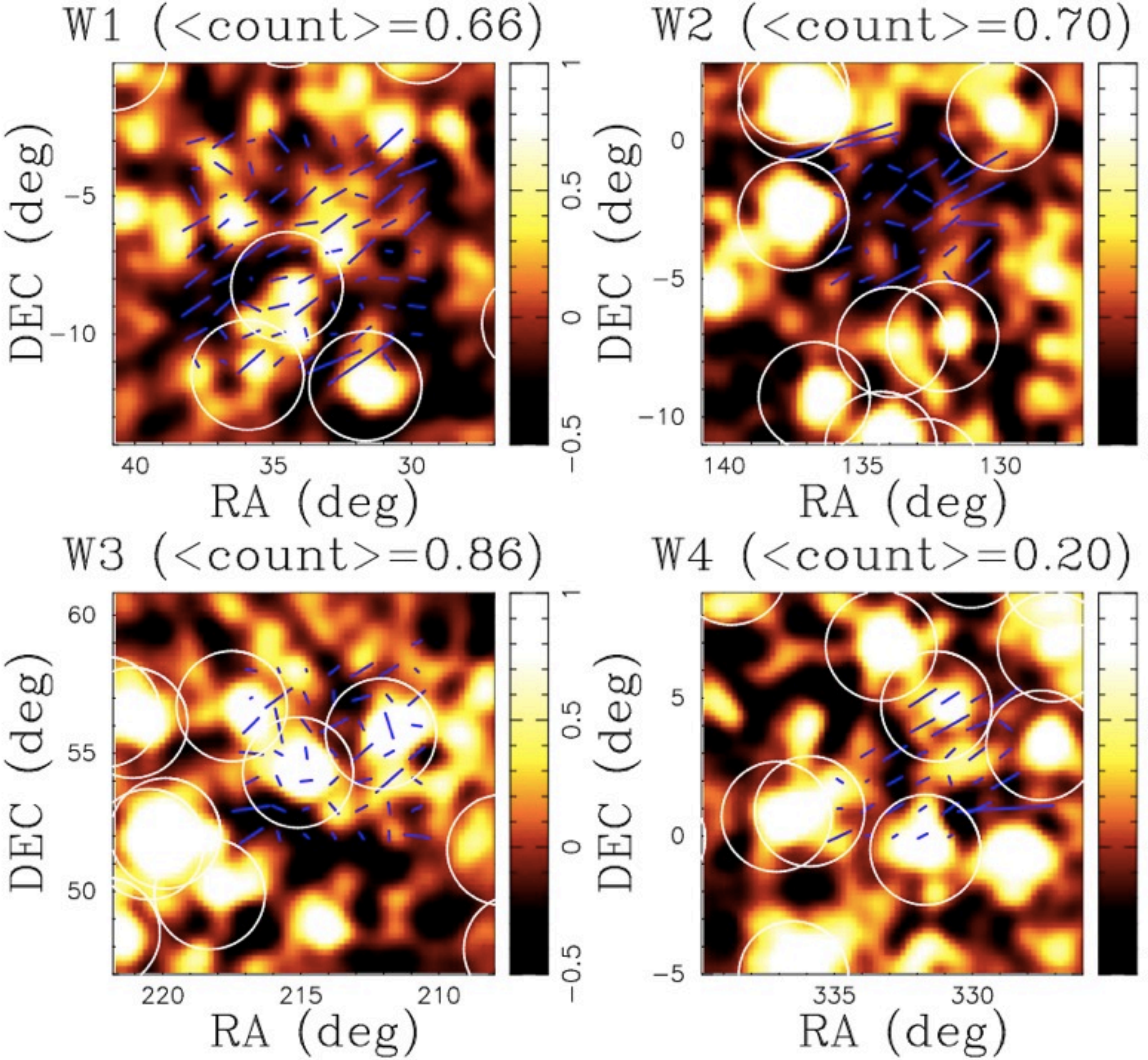
+

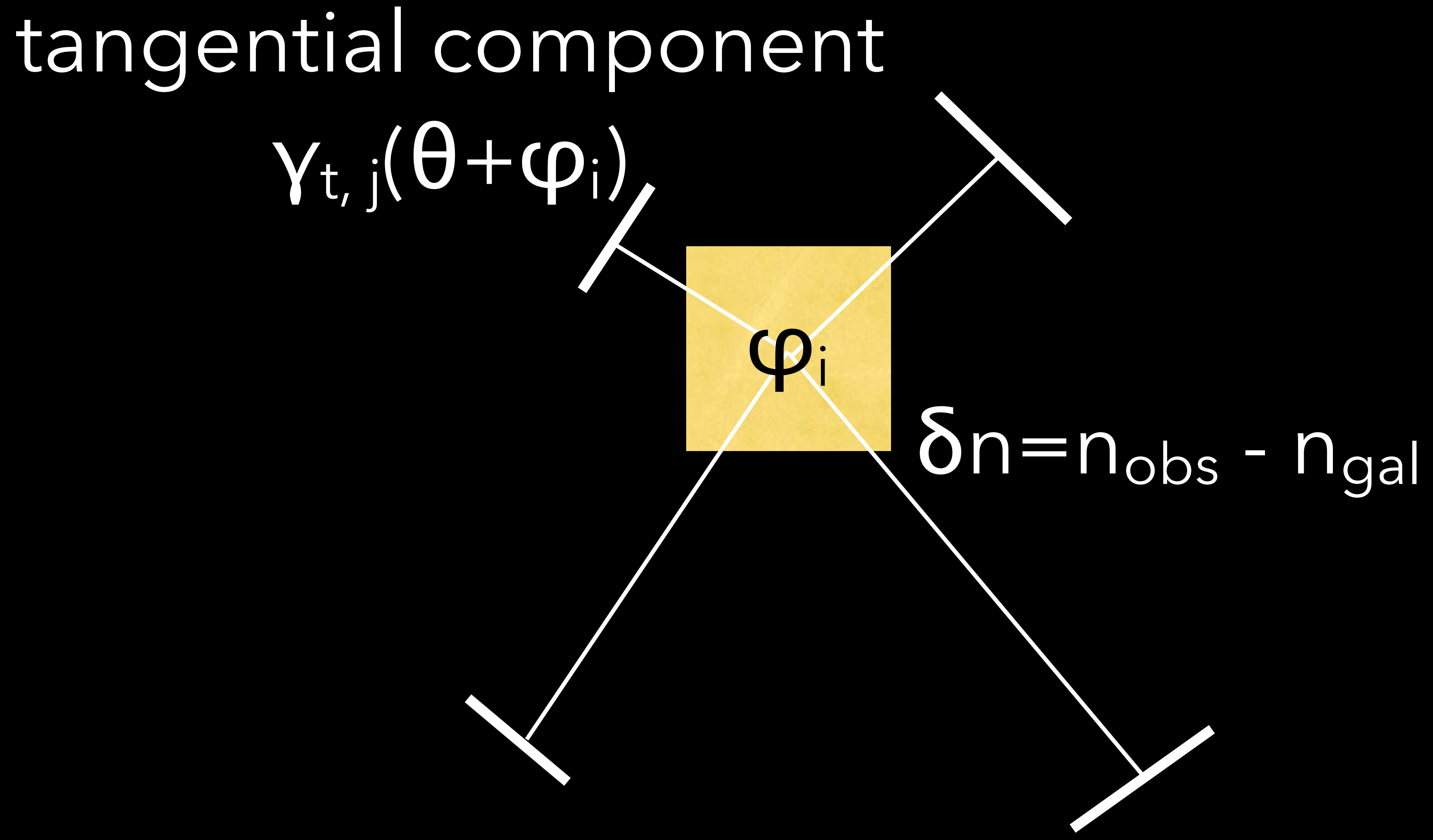


Galactic diffuse (foreground)



W1 (<count>=0.66)
W2 (<count>=0.70)
W3 (<count>=0.86)
W4 (<count>=0.20)
DEC (deg)
RA (deg)

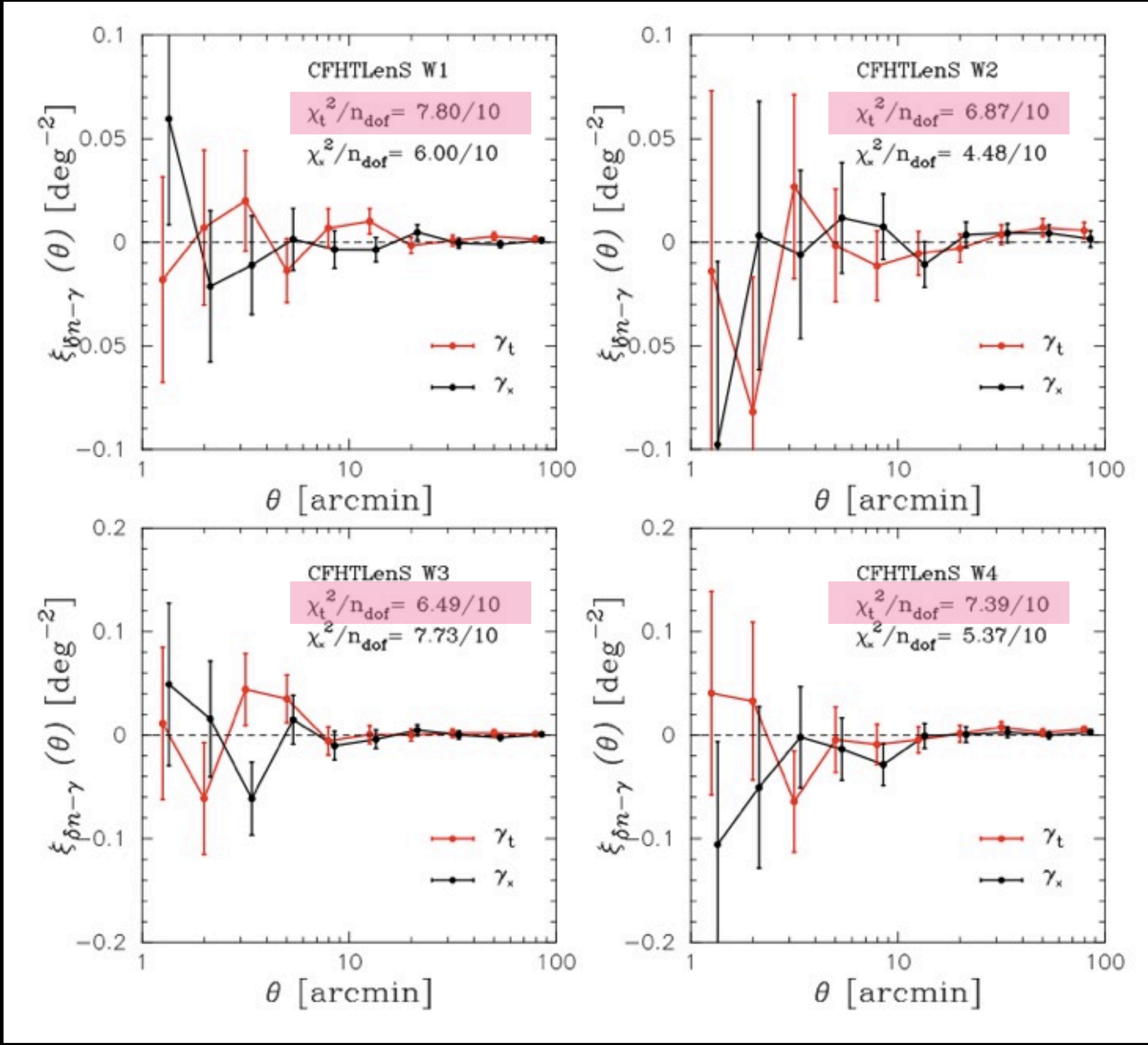
Correlation Analysis



calculate $\delta n(\varphi)\gamma_{t,j}(\theta+\varphi)$ for each bin of angular separation

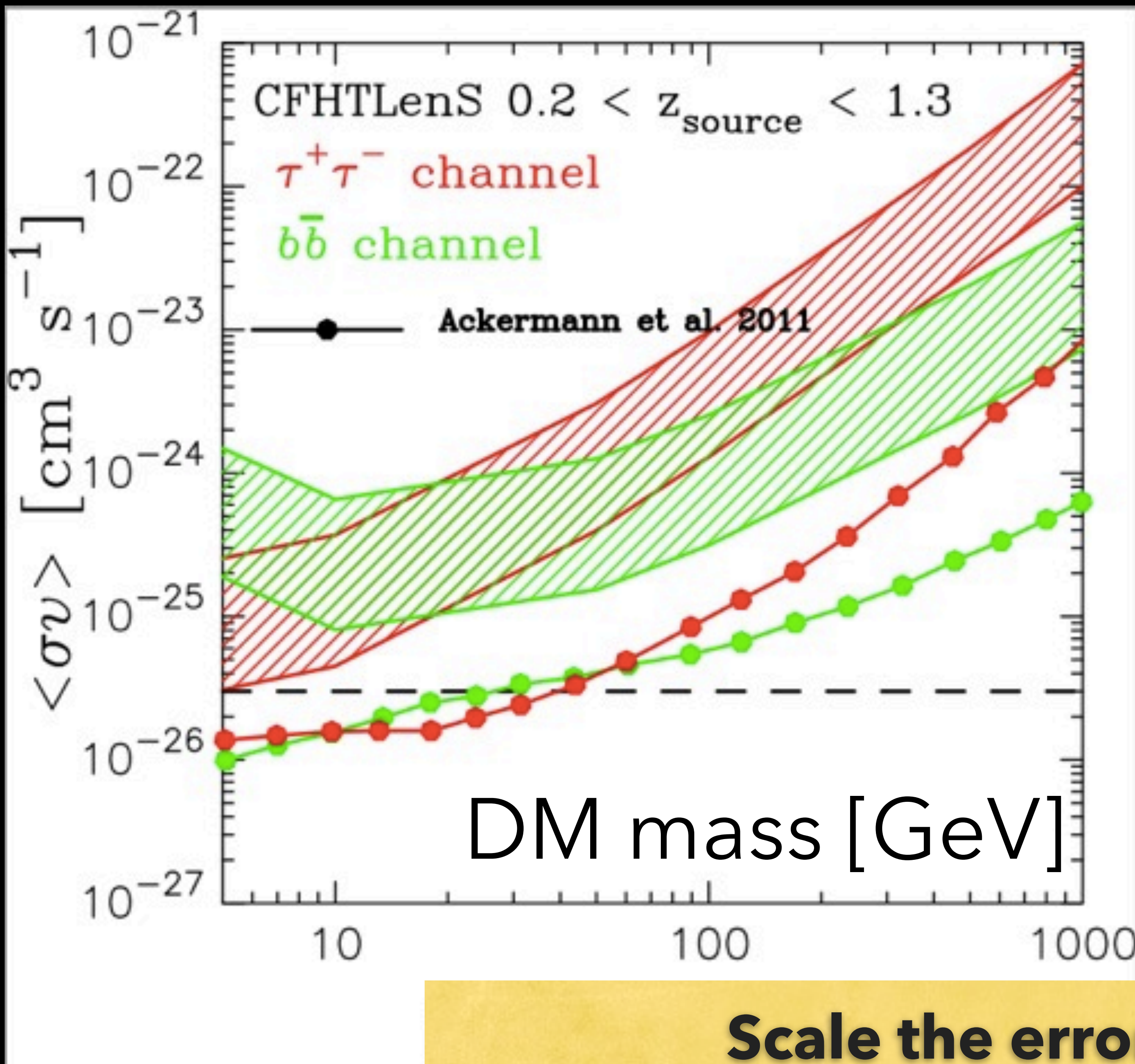
Do the same thing over all direction φ of interest

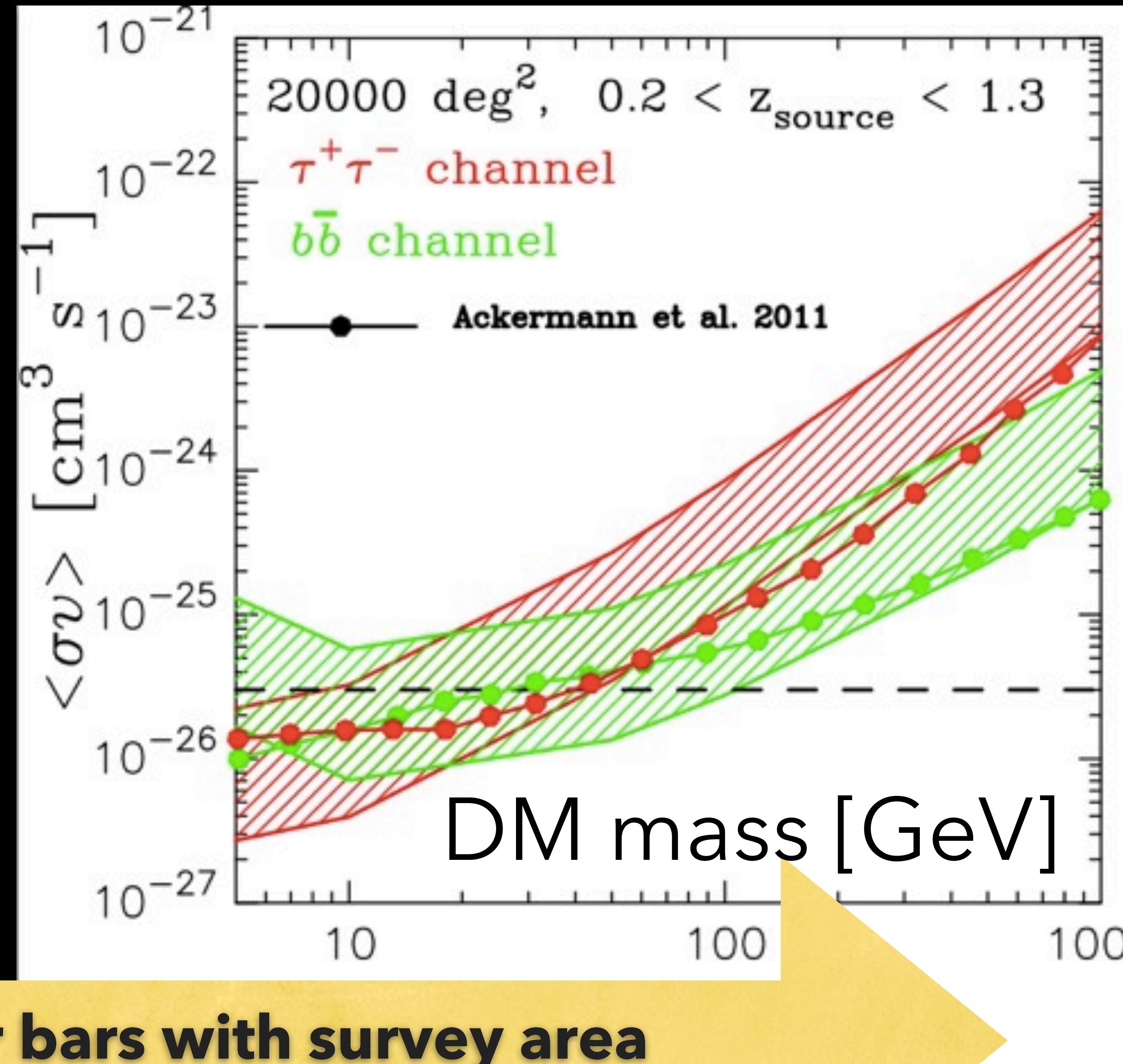
Estimate the statistical error with randomized shape catalogs and poisson random counts



All measurements are consistent with null signals

Constraints and Forecasts





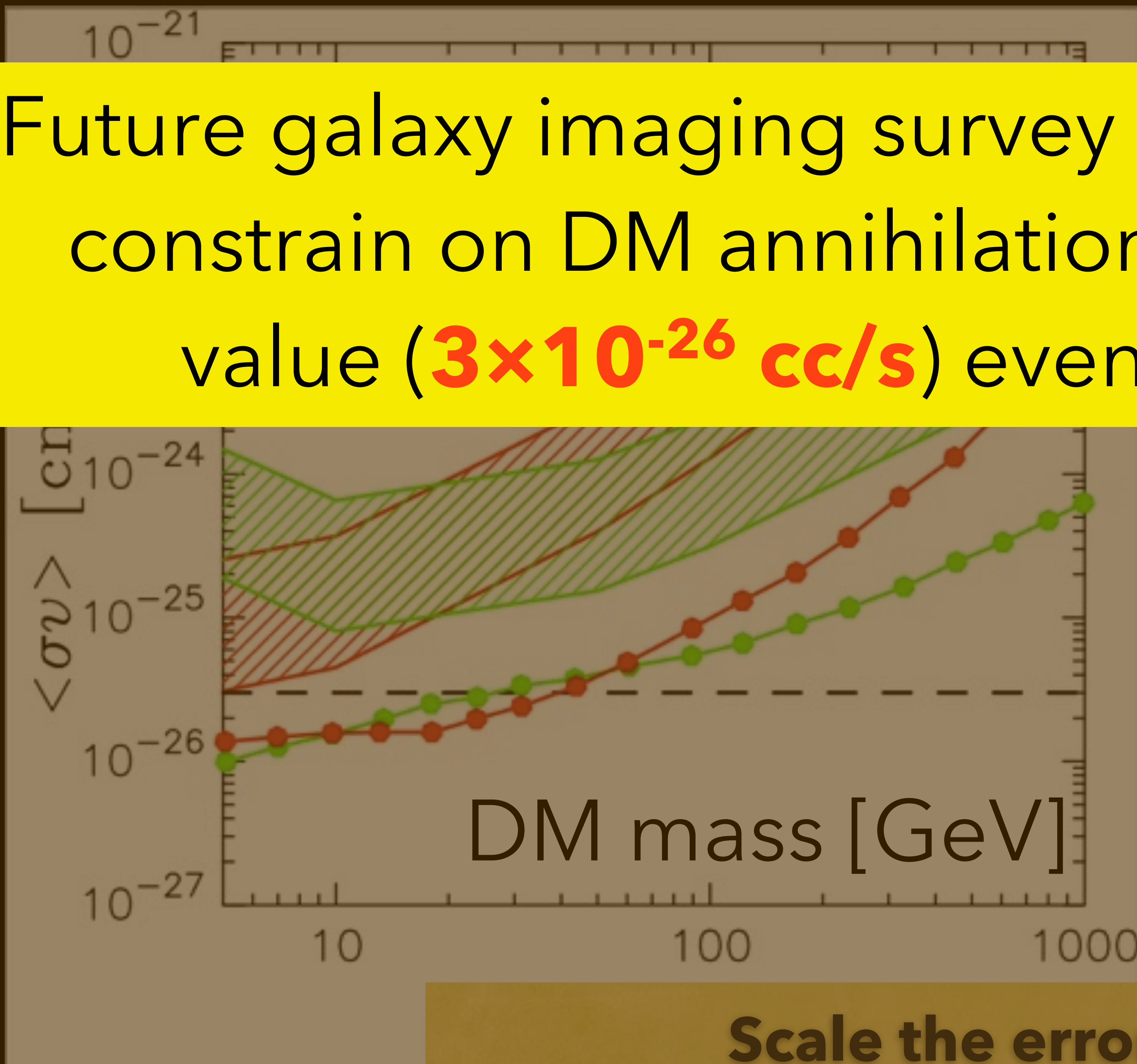
Scale the error bars with survey area

Current constraints by our measurements

Wide galaxy imaging survey like LSST

Constraints and Forecasts

Future galaxy imaging survey (e.g. LSST) would be helpful to constrain on DM annihilation with a level of the canonical value (**3×10^{-26} cc/s**) even for DM mass of **100 GeV**



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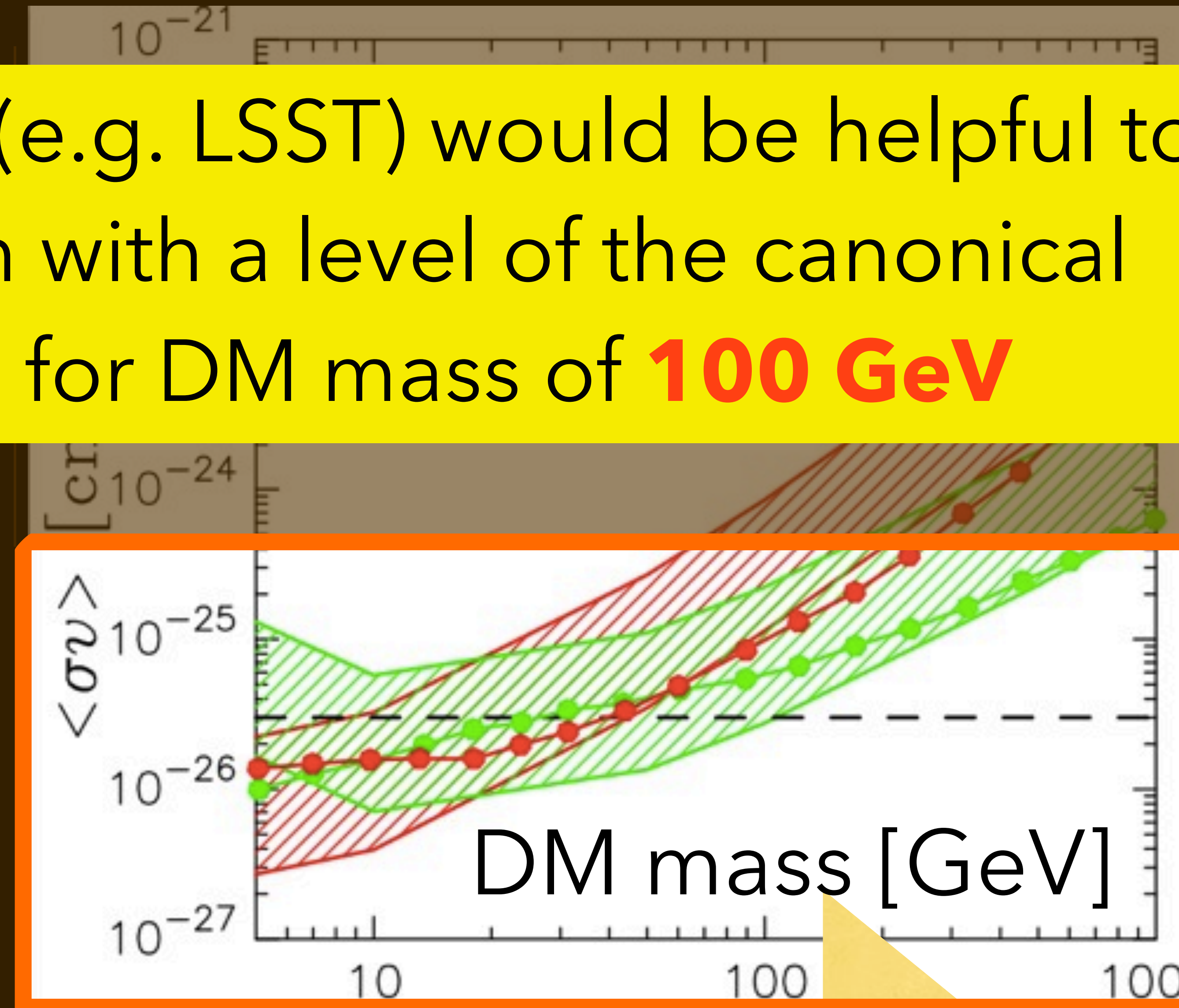

Wide galaxy imaging survey like LSST

Summary

- Origin of extragalactic gamma-ray background (EGB) is still unclear
- Cross correlation of EGB and cosmic shear is useful observable as the additional information of EGB
- Modeling based on *Halo model approach* has been developed
- We first measure the cross correlation of EGB and cosmic shear with CFHTLenS and Fermi LAT
- We can say there is **no correlation** for the current data set
- For upcoming surveys (e.g. **LSST**), we can put constraints on $\langle \sigma v \rangle \sim 3\times10^{-26}$ cc/s for the DM mass range of 1-100 GeV
- Our approach is based on **cosmological scale**, and is complementary to DM search in local galaxies

Backup Slides

Weak Lensing Basics

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

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

$\gamma_2 = \Phi_{12}$

$$\Phi_{ij} = \frac{2}{c^2}\int_0^{\chi} d\chi' g(\chi,\chi')\partial_i\partial_j\Phi(\chi'),$$

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

gravitational potential

The relation between convergence and shear in fourier space is given by

$$\begin{aligned}
\tilde{\gamma}(\boldsymbol{k}) &= \tilde{\gamma}_1(\boldsymbol{k}) + i\tilde{\gamma}_2(\boldsymbol{k}) \\
&= \frac{k_1^2 - k_2^2 + ik_1k_2}{k^2}\tilde{\kappa}(\boldsymbol{k}), \\
\tilde{\kappa}(\boldsymbol{k}) &= \tilde{\gamma}_1(\boldsymbol{k})\cos 2\phi + \tilde{\gamma}_2(\boldsymbol{k})\sin 2\phi,
\end{aligned}$$

$$\kappa(\boldsymbol{\theta}) = \frac{1}{\pi}\int d^2\theta' D(\boldsymbol{\theta}-\boldsymbol{\theta'})\gamma(\boldsymbol{\theta'}),$$

$$D(\boldsymbol{z}) = \frac{z_2^2 - z_1^2 + 2iz_1z_2}{z^4}.$$

Weak Lensing Basics

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

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

$\gamma_2 = \Phi_{12}$

$$\Phi_{ij} = \frac{2}{c^2} \int_0^{\chi} d\chi' g(\chi, \chi') \partial_i \partial_j \Phi(\chi'),$$

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gravitational potential

The relation between convergence and shear in fourier space is given by

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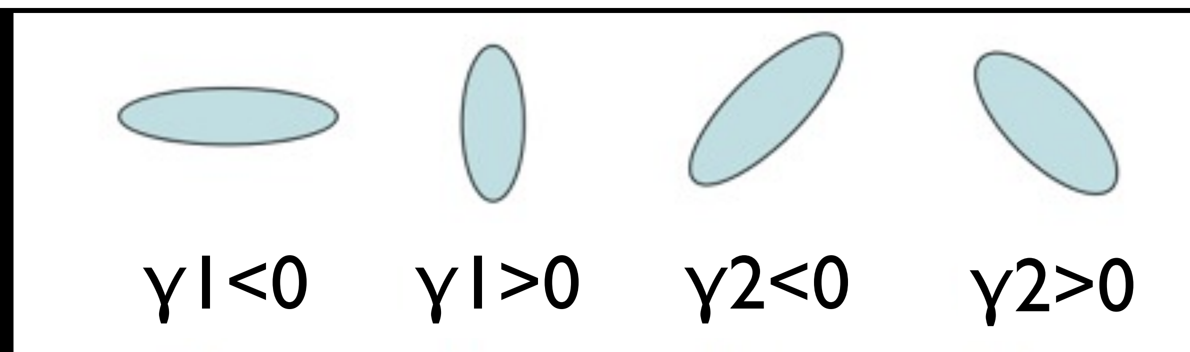
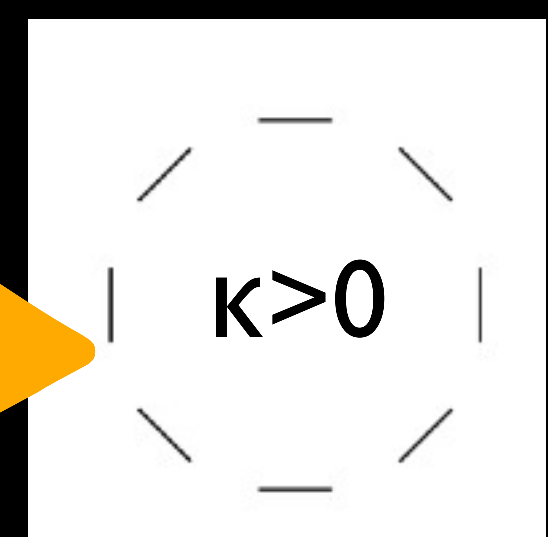


a positive, radially symmetric κ leads to a **tangential** shear

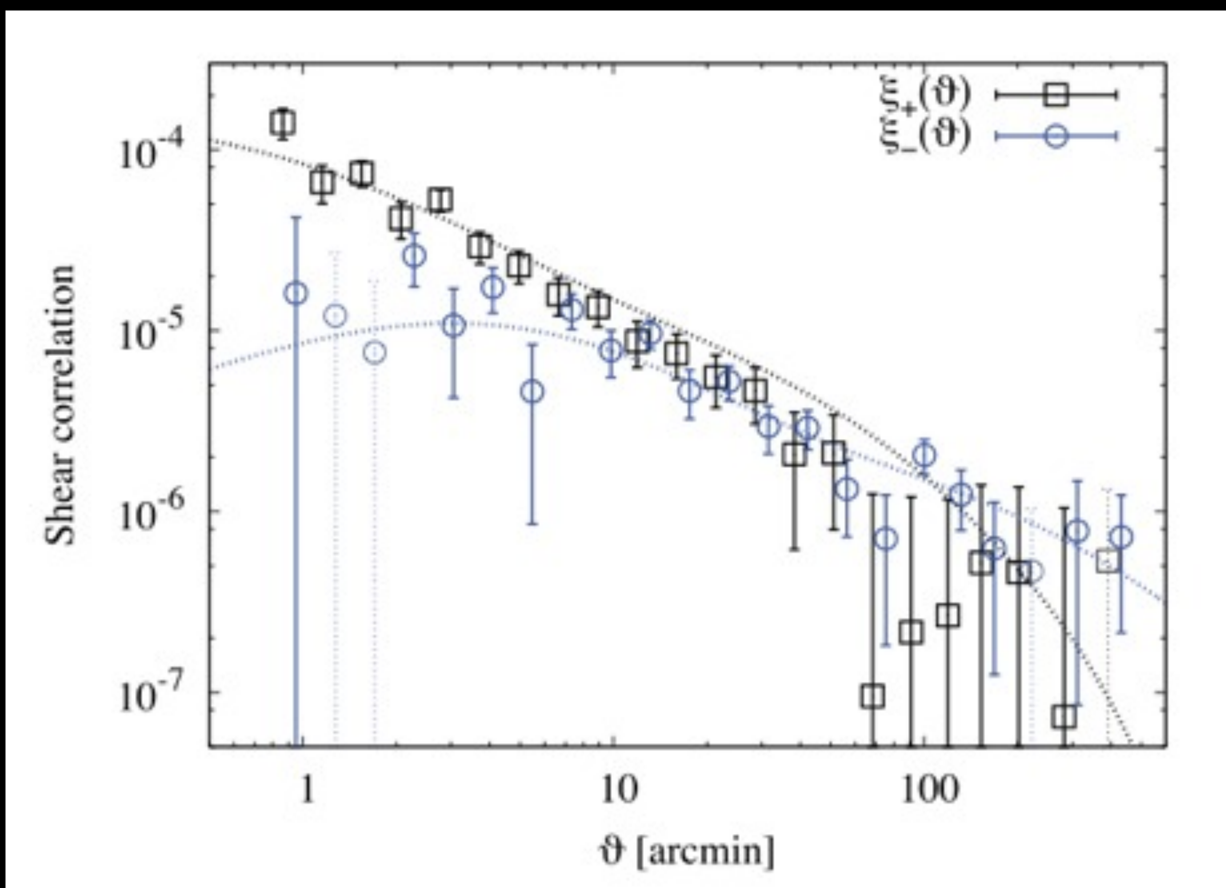
$\gamma_1 = \kappa \cos 2\varphi$

$\gamma_2 = \kappa \sin 2\varphi$



Typical value of Lensing

Cosmic shear
due to large-scale structure

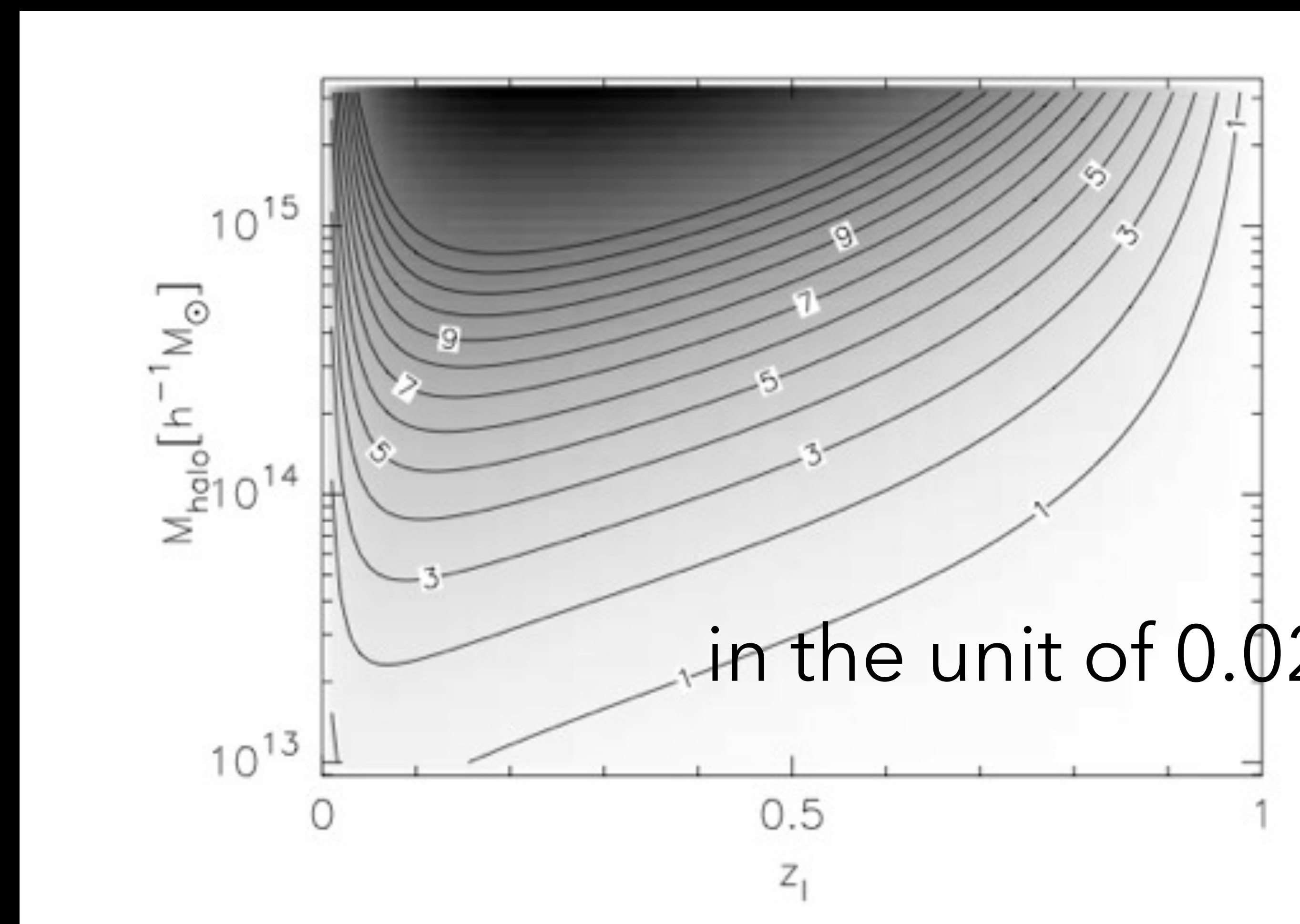


Kilbinger et al. 2013

→**Large-Scale Structure**

0.001-0.01

Smoothed convergence
of galaxy clusters



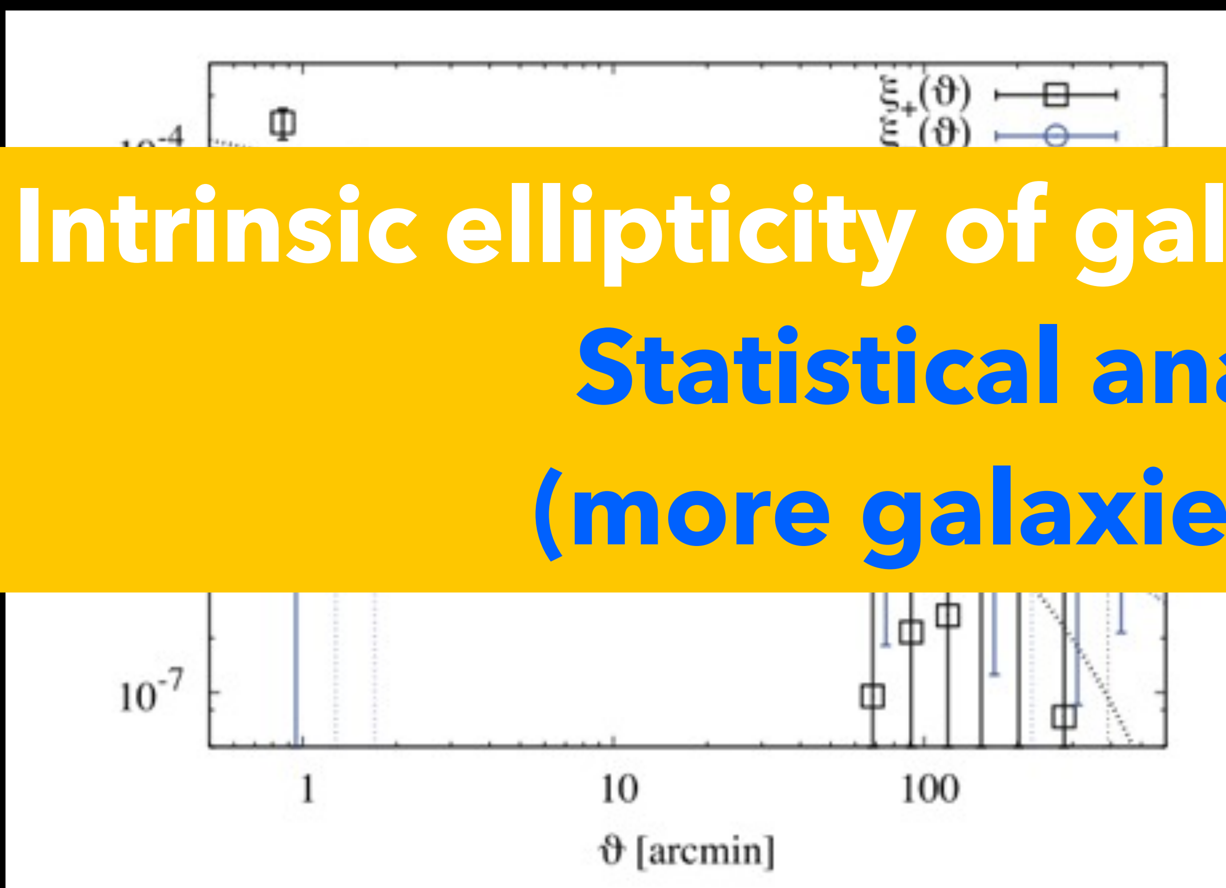
Hamana et al. 2004

→**Clusters ($10^{14}M_{sun}$@z=0.3)**

~0.1

Typical value of Lensing

Cosmic shear
due to large-scale structure



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Smoothed convergence
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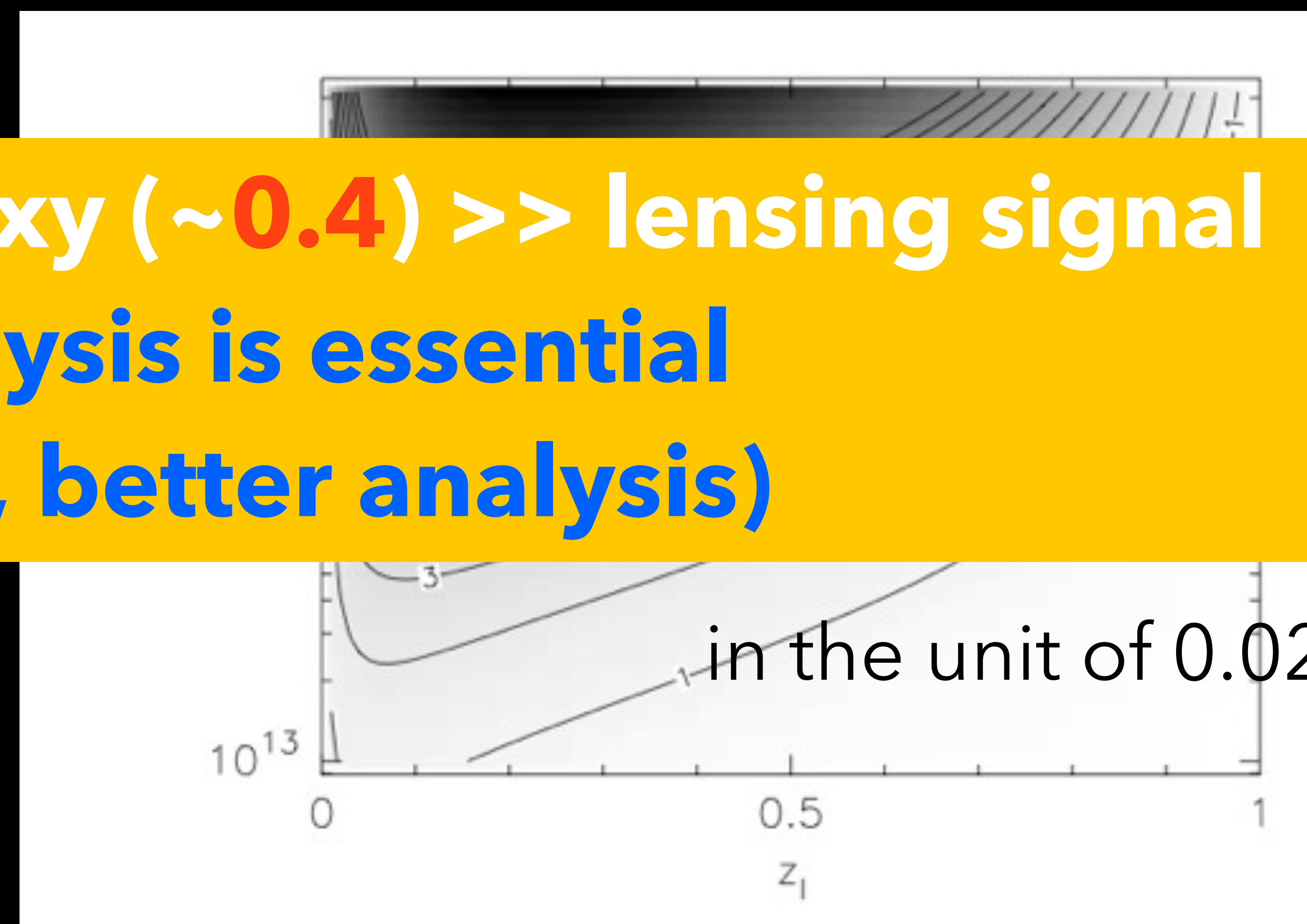


Hamana et al. 2004

→**Clusters ($10^{14}M_{sun}$@z=0.3)**

~0.1

Intrinsic ellipticity of galaxy (~0.4) >> lensing signal

Statistical analysis is essential

(more galaxies, better analysis)

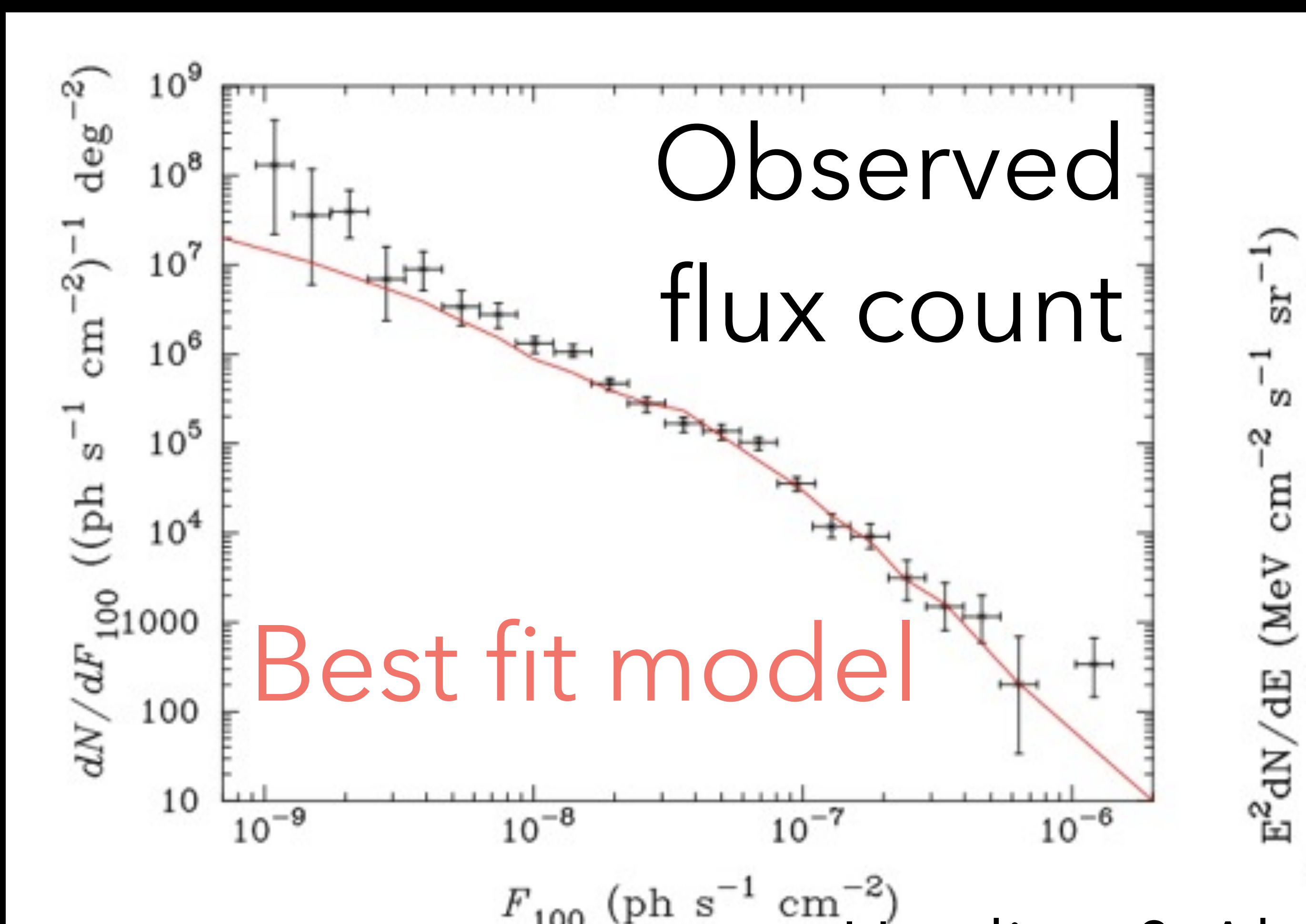
Contributor of EGB

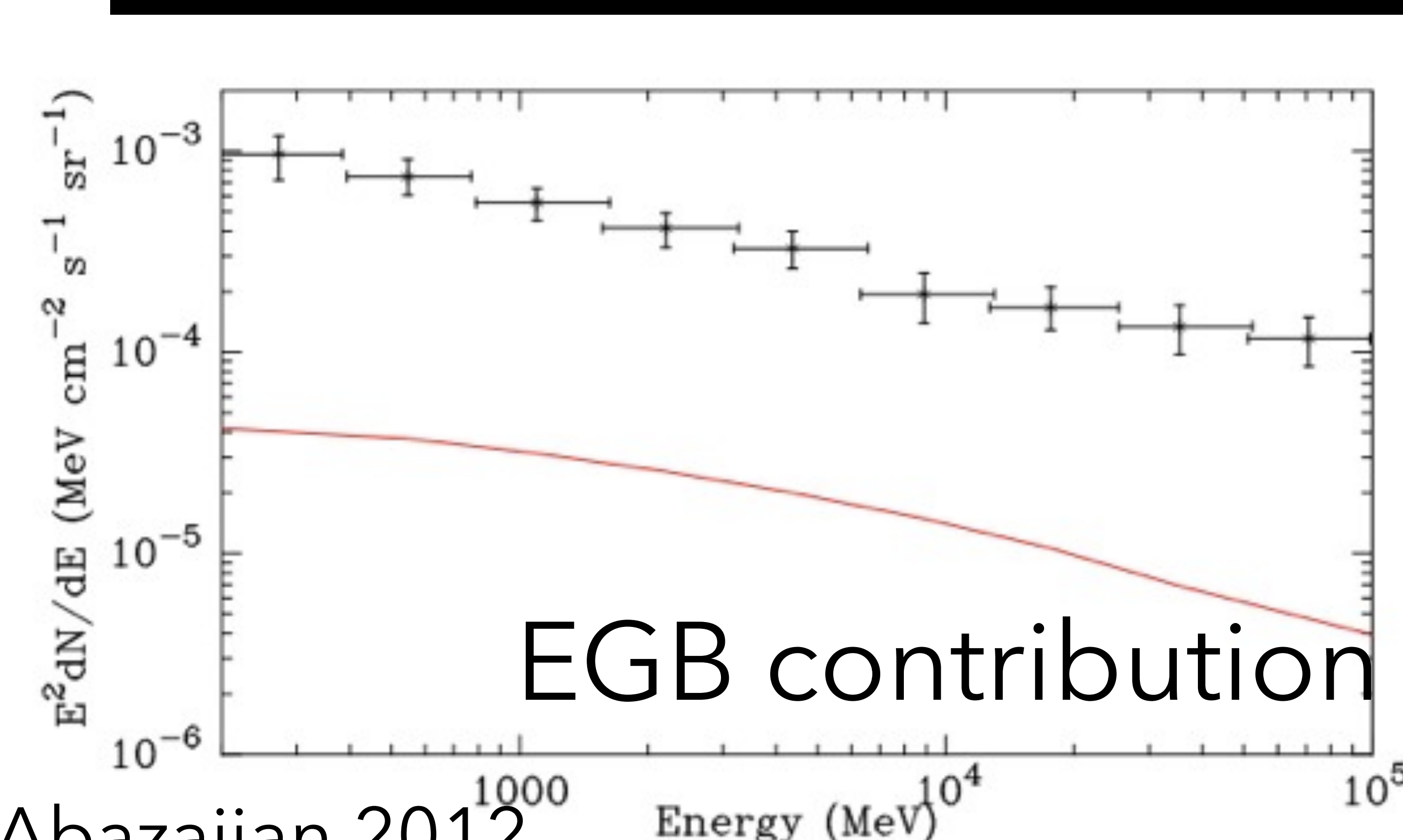
still unclear...

- Unresolved astrophysical sources
  - Blazar <30%?
    - Assuming the tight correlation of L_x and L_γ
    - X-ray Luminosity function
    - One can constrain on model parameters to reproduce the observed flux count and angular correlation function
  - Star Forming Galaxy 4-23%?
    - Observed Correlation of L_{IR} and L_γ (mainly for Nearby galaxies)
    - IR Luminosity Function
  - Galaxy Cluster We have **not** observed gamma-ray from clusters
    - collision between relativistic proton accelerated by shock waves and surrounding proton (--> neutral pion decay emission)
    - The inverse-Compton scattering of relativistic electron and CMB photon (This would emerge only the near the formation of shocks, i.e. when Clusters form)
- Dark Matter Annihilation and/or decay

Contributor of EGB (Blazar)

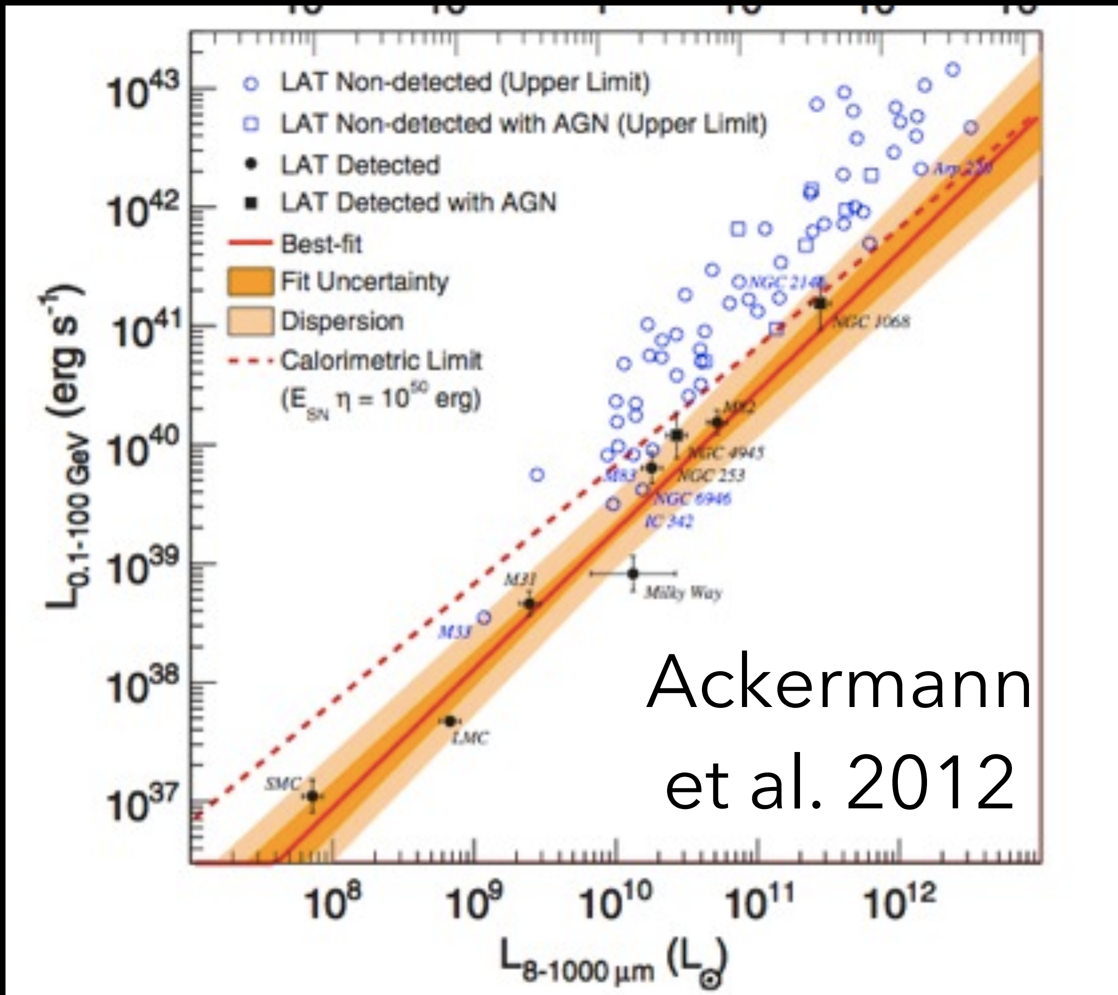
Blazar SED fitting formula
from radio to gamma ray band observation
+
3 parameters for Gamma-ray Luminosity Function
+
X-ray Luminosity Function (10 parameters fixed)



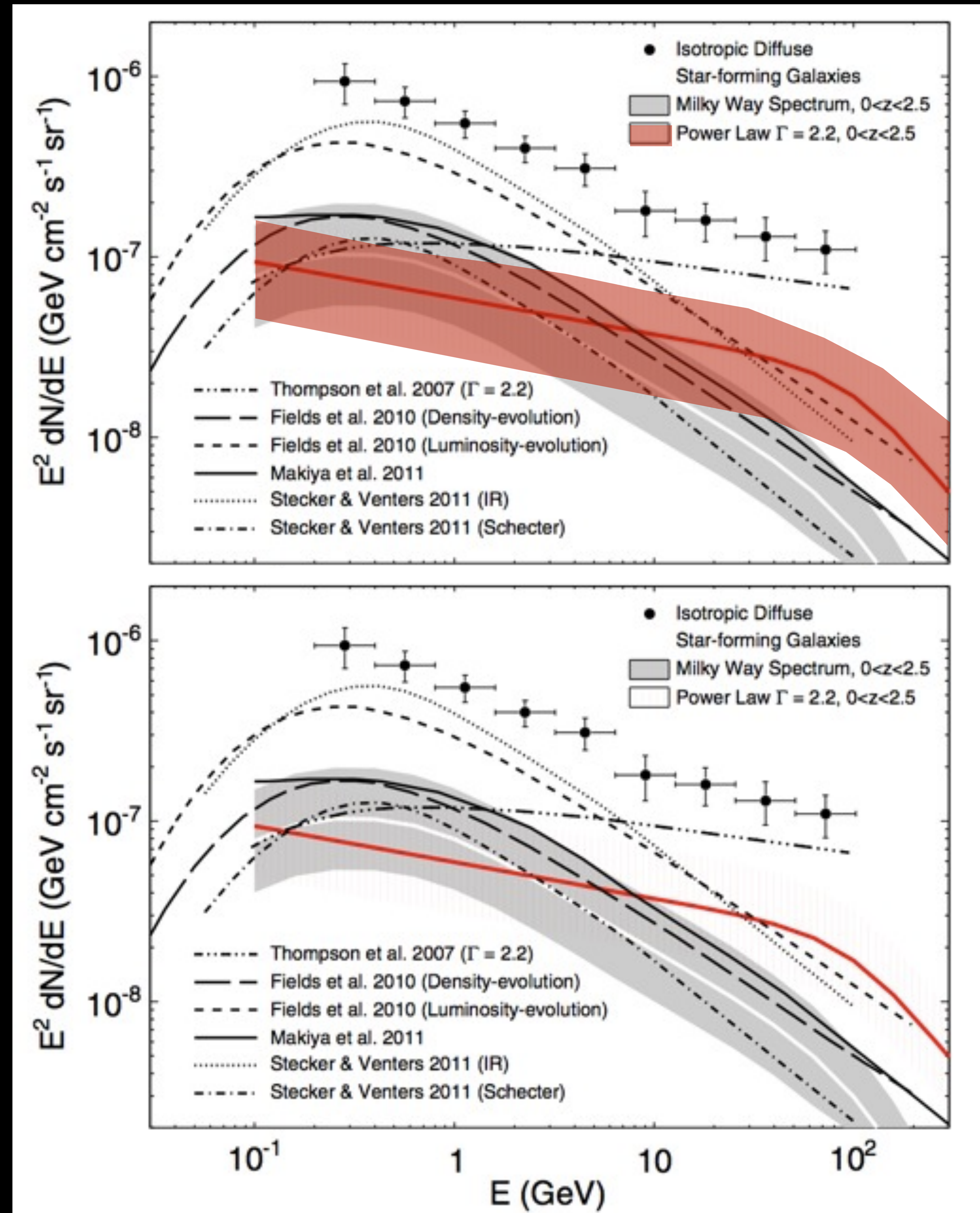


Harding & Abazajian 2012

Contributor of EGB (SFG)



+ IR Luminosity function (4 parameters fixed)



Astrophysical sources

The number of EGB photon along the line of sight

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

Relevant field of γ-ray

In the case of astrophysical sources,

g = Luminosity

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

Simple model

1. Blazar: α=2.4, Luminosity-dependent density evolution model
2. Star forming galaxy: α=2.7, Infrared luminosity function + correlation of luminosity at gamma-ray and infrared

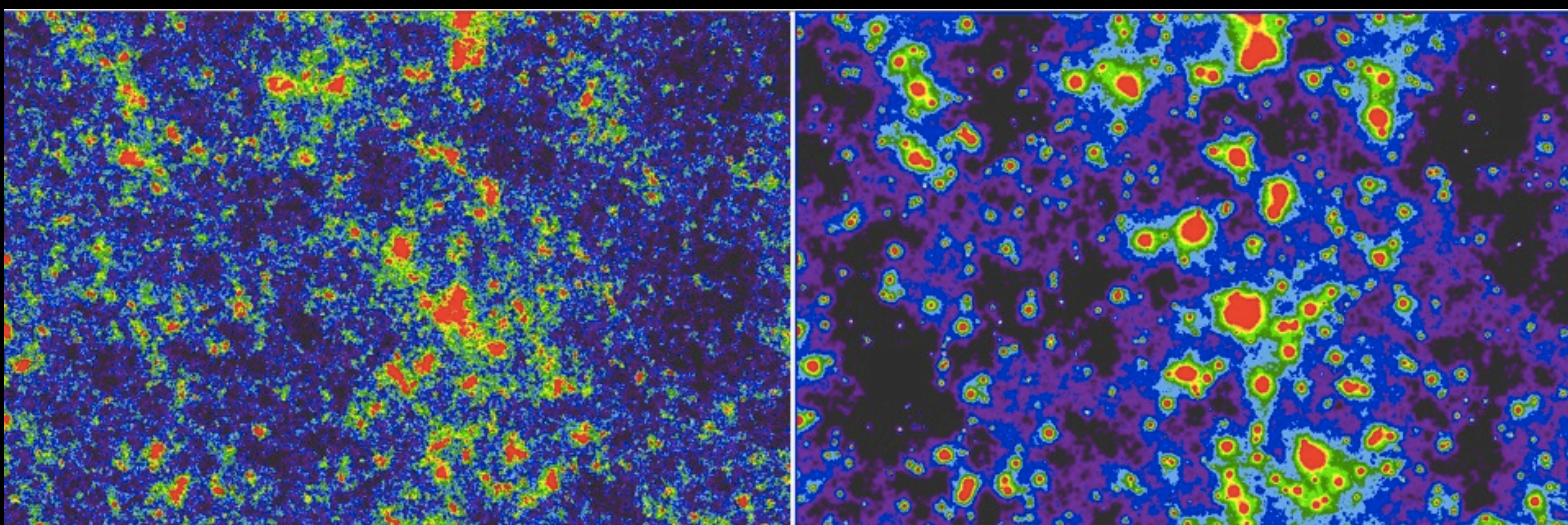
How to calculate the correlation signal

- Weak Lensing signal $\kappa = \int dz\, W_\kappa(z)\delta(z, \theta)$
- gamma-ray intensity (for DM annihilation)
  - $\delta n = \int dz\, W_g(z)\delta^2(z, \theta)$
  - $W_g \sim \langle\sigma v\rangle\, dN/dE\, (\Omega_{dm}\rho_{crit}/m_{dm})^2$
  - consider 100% branching ratio to bb/ττ final states
- cross-correlation in Fourier space is given by

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

We need 3D power spectrum of δ-δ²

- Based on *Halo-model approach*
- All components are hosted by a DM halo
- DM haloes have the universal density profile (= NFW profile) with some parameters as a function of redshift and Mass
- Use Halo mass function and Halo bias



from N-body simulation　　　based on Halo-model

For Astrophysical sources

- Consider blazar and Star Forming Galaxy
- gamma ray intensity $I = \int dz\, L(z, \theta) W(z)$
- Assuming blazars and SFGs are point sources with source Luminosity (emission profile = delta function)
- replace halo mass function with luminosity function
- assuming halo-Mass and Luminosity relation

Mass to Luminosity

- Suppose $M_h = A \times L_\gamma^B$
- For blazar, using the observed quasar bias

$$b_{Q,obs}(z) = \bar{b}_B(z) \equiv \frac{1}{\phi(z)} \int_{L_\gamma(F_{\gamma,\mathrm{lim}},z)}^{\infty} dL_\gamma \ \rho_\gamma(L_\gamma, z) b_B(L_\gamma, z), \quad (5)$$

$b_B(L_\gamma,z) = b_h(M_h = A \times L_\gamma^B, z)$

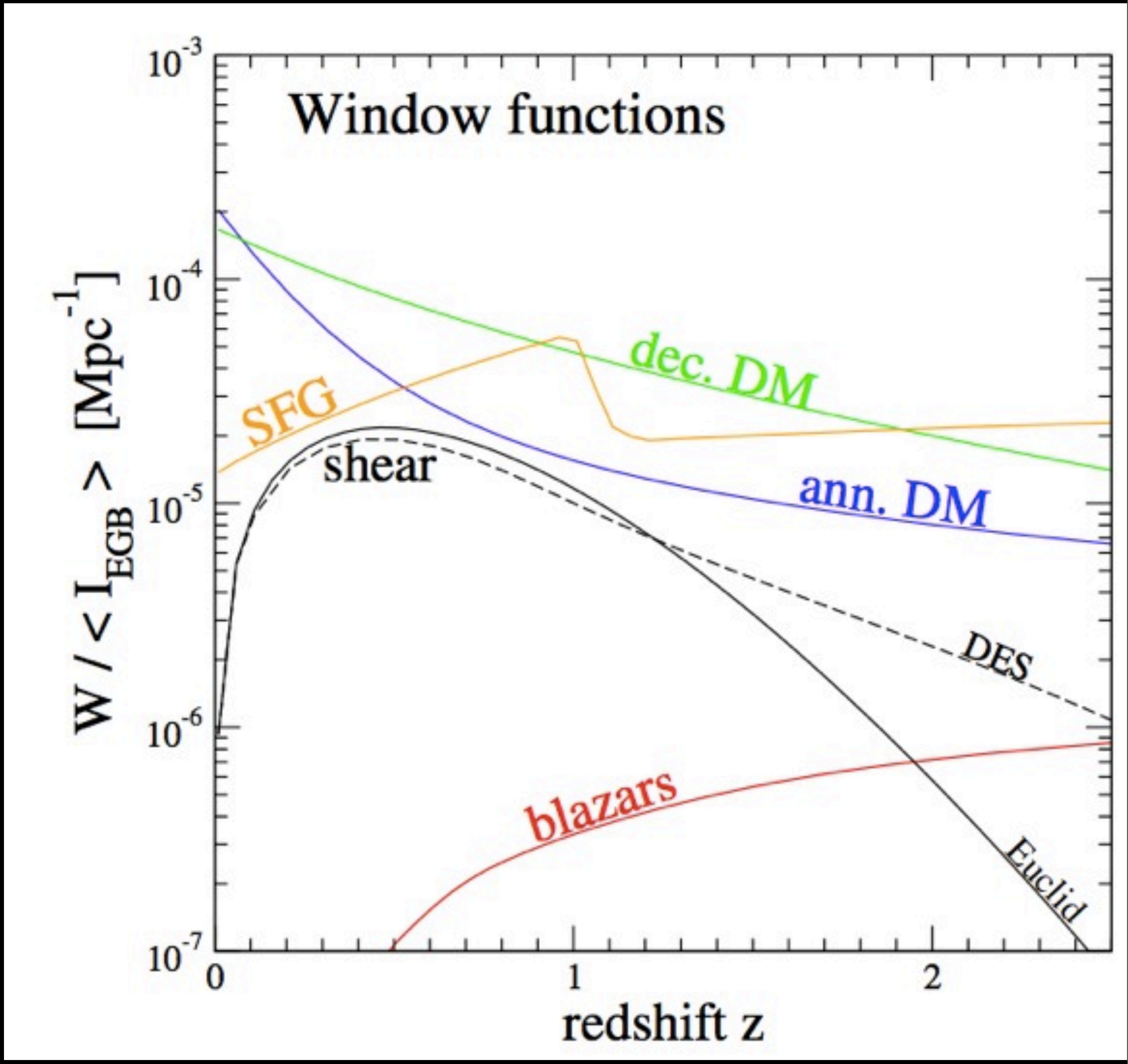
and $\phi(z)$ is the cumulative GLF of blazars, i.e., GLF integrated from a given minimum luminosity cut-off,

$$\phi(z) \equiv \int_{L_\gamma(F_{\gamma,\mathrm{lim}},z)}^{\infty} dL_\gamma \ \rho_\gamma(L_\gamma, z). \quad (6)$$

- For star forming galaxies,
  - Milky-way halo mass ~ 10^{12} M_{sun}/h
  - Maximum host halo ~ 10^{14} M_{sun}/h
  - Observed maximum luminosity ~ 10^{43} erg/s (estimated from IR luminosity)
  - These approximations leads to $M \sim L^{0.5}$

Advantage

- Cross-correlation signal would contain the information from z~0.1-1
- We can probe the DM signature at cosmological scale (1-1000 Mpc)
- Galaxy-EGB cross correlation is comprehensive. It would contain the information from z~0.1-0.5 in the case of SDSS



Camera et al. 2013

Correlation Analysis

Our estimator

$\Delta_\theta(\phi) = 1$ for $\theta - \Delta\theta/2 \leq \phi \leq \theta + \Delta\theta/2$ and zero otherwise

$$\hat{\xi}_{\delta n - \gamma_t}(\theta) = \frac{1}{N_{\rm p}(\theta)} \sum_i^{N_{\rm pixel}} \sum_j^{N_{\rm gal}} \delta n(\boldsymbol{\phi}_i) \epsilon_t(\boldsymbol{\phi}_j | \boldsymbol{\phi}_i) \Delta_\theta(\boldsymbol{\phi}_i - \boldsymbol{\phi}_j),$$

$$N_{\rm p}(\theta) = \sum_i^{N_{\rm pixel}} \sum_j^{N_{\rm gal}} \Delta_\theta(\boldsymbol{\phi}_i - \boldsymbol{\phi}_j),$$

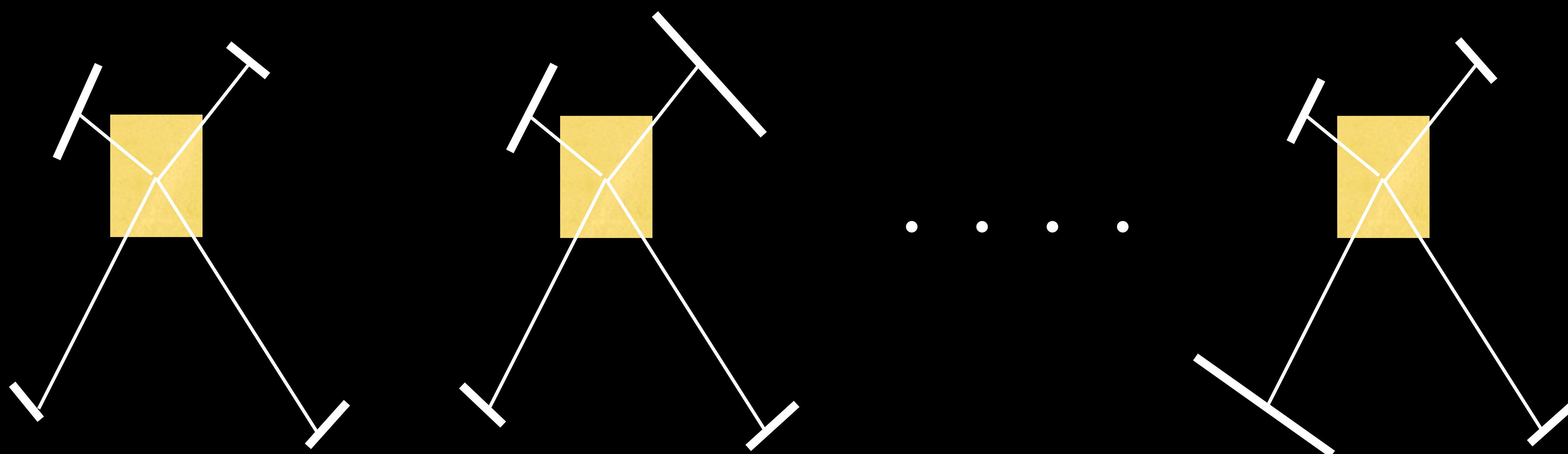
calculate $\delta n(\varphi)\gamma_{t,j}(\theta+\varphi)$ for each bin of angular separation

Do the same thing over all direction φ of interest

Estimate the statistical error with randomized shape catalogs and poisson random counts

Error Estimate (associated with shape measurement)

Rotate the ellipticity of each galaxy randomly



realization 1 <δn γt>

realization 2 <δn γt>

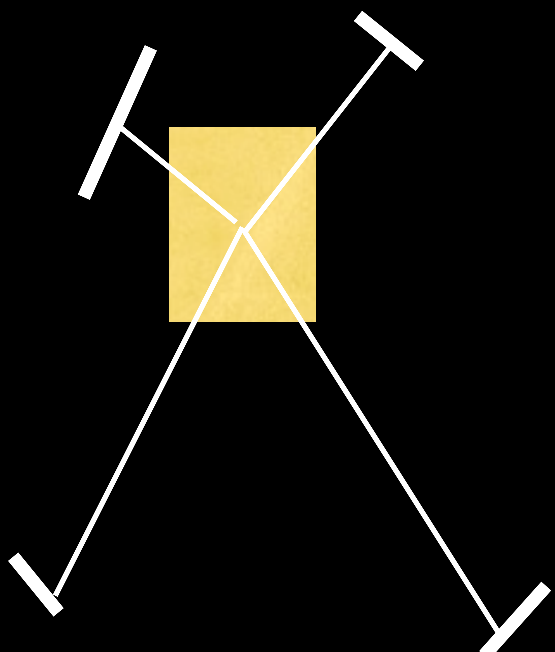
. . . .

realization 500 <δn γt>

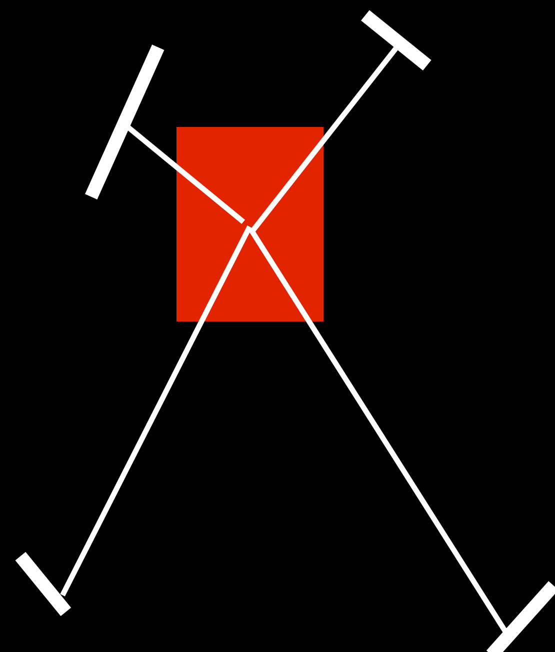
Estimate the error of <δn γt> by the standard deviation over 500 realizations

Error Estimate
(associated with EGB measurement)

Utilize random poisson distribution
and fix lensing data

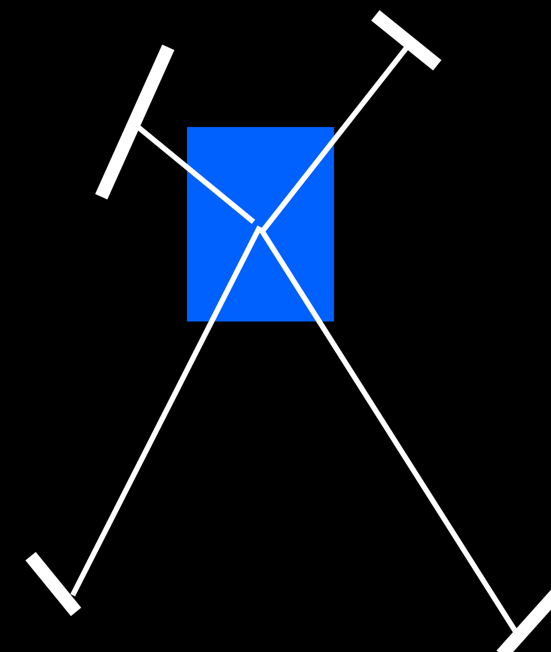


realization 1
<δn γt>



realization 2
<δn γt>

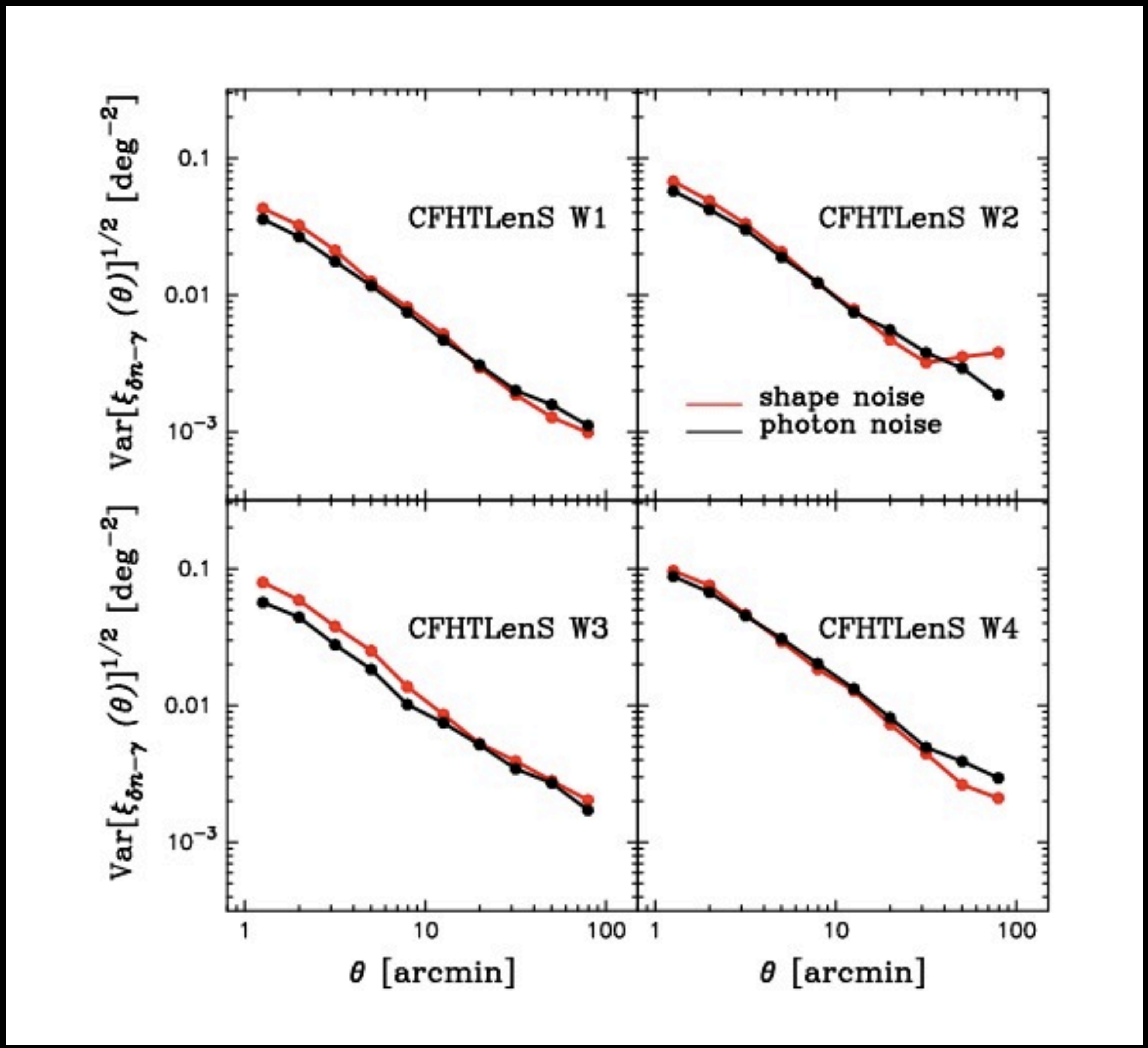
. . . .



realization 500
<δn γt>

Estimate the error of <δn γt> by the standard deviation over 500 realizations

Statistical Error in CFHTLenS patches



Dependence of Galactic templates and Event selection

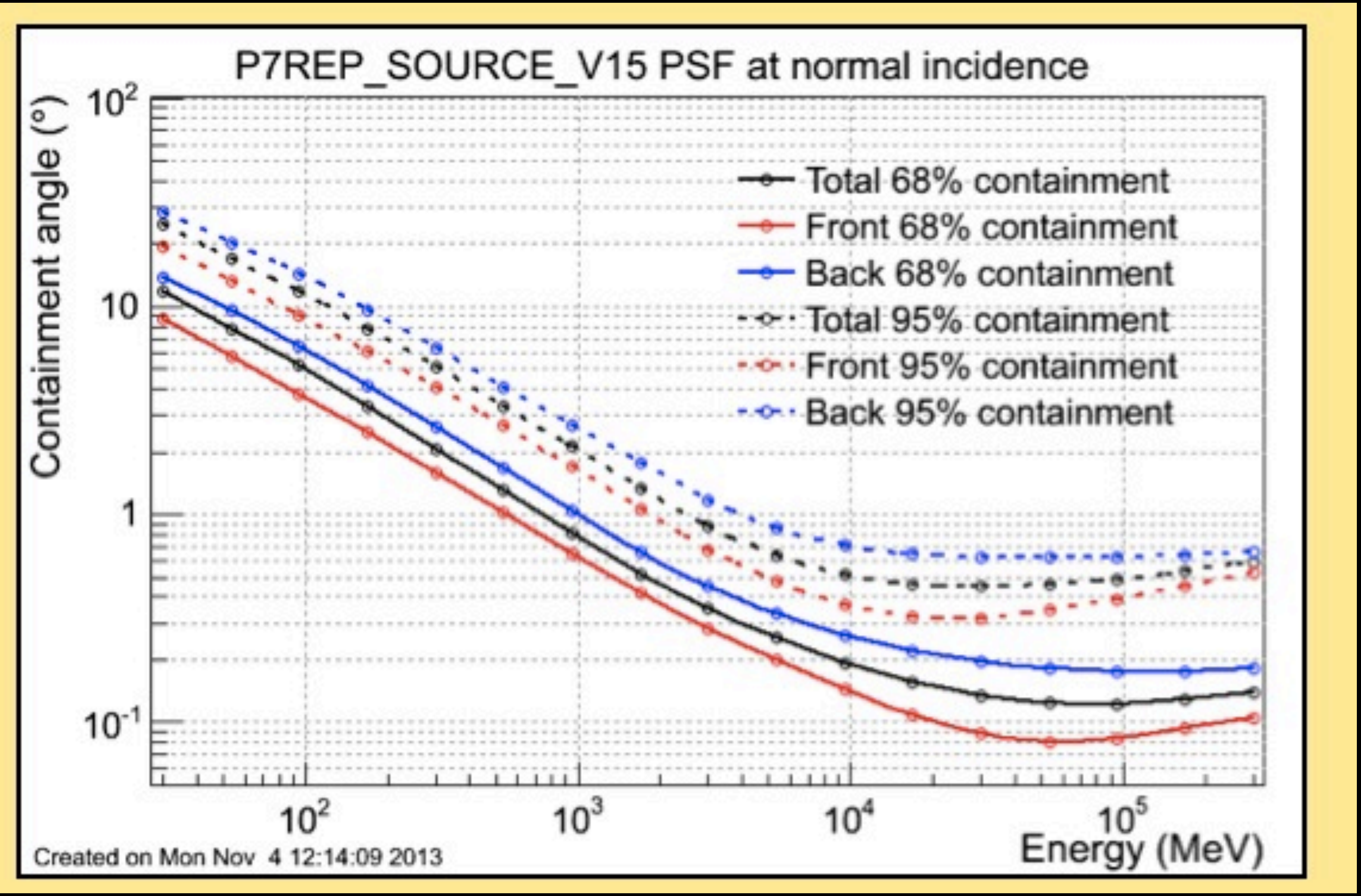
	ev2/P7V6	ev2/P7rep	ev4/P7V6	ev4/P7rep
W1	6.91/10	6.22/10	8.58/10	7.80/10
W2	12.26/10	12.32/10	6.98/10	6.87/10
W3	7.62/10	7.11/10	8.77/10	6.49/10
W4	12.88/10	12.95/10	7.57/10	7.39/10

P7V6:old template
P7rep: new template

ev2/ev4
Different photon
selection scheme

$\Delta\chi^2$ ~ **1-5**

Why 2 deg mask?



cf. http://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm

Current constraints on Dark matter annihilation by γ-ray from satellite galaxies

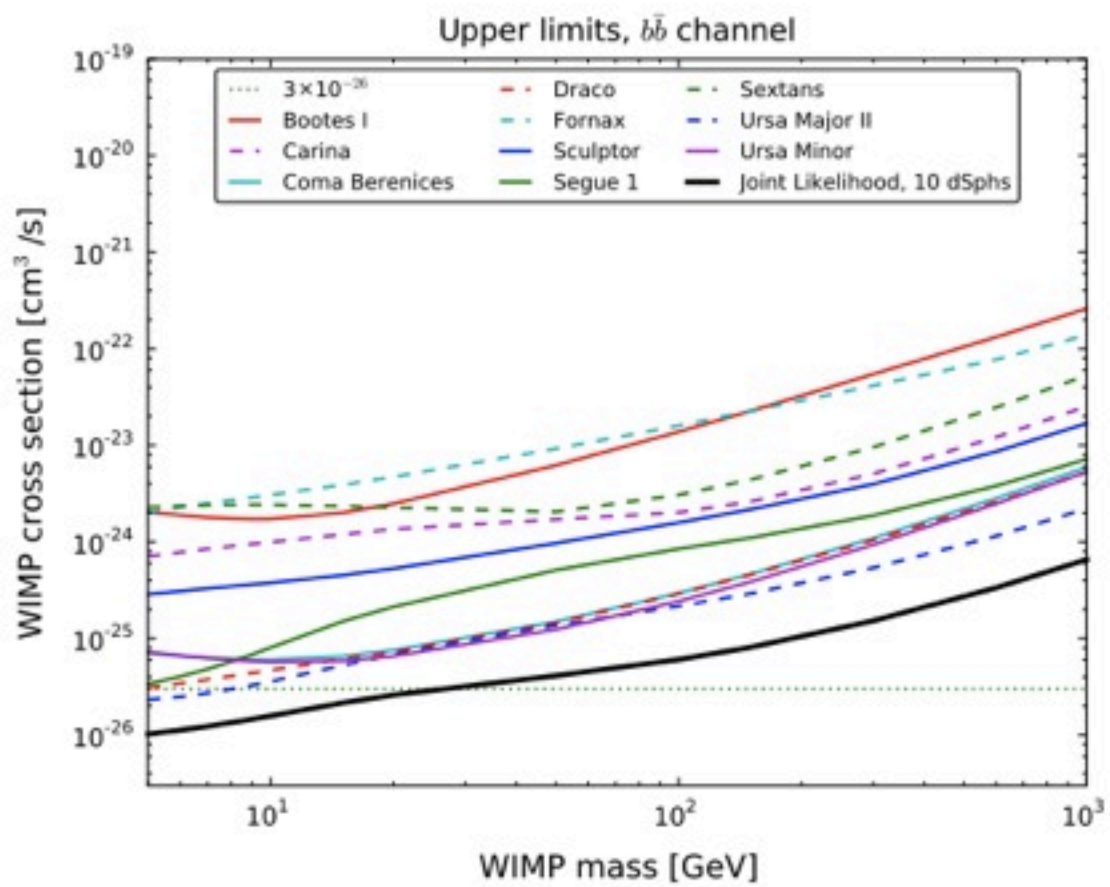


FIG. 1 (color online). Derived 95% C.L. upper limits on a WIMP annihilation cross section for all selected dSphs and for the joint likelihood analysis for annihilation into the $b\bar{b}$ final state. The most generic cross section ($\sim 3 \times 10^{-26}$ $cm^3\,s^{-1}$ for a purely s-wave cross section) is plotted as a reference. Uncertainties in the J factor are included.

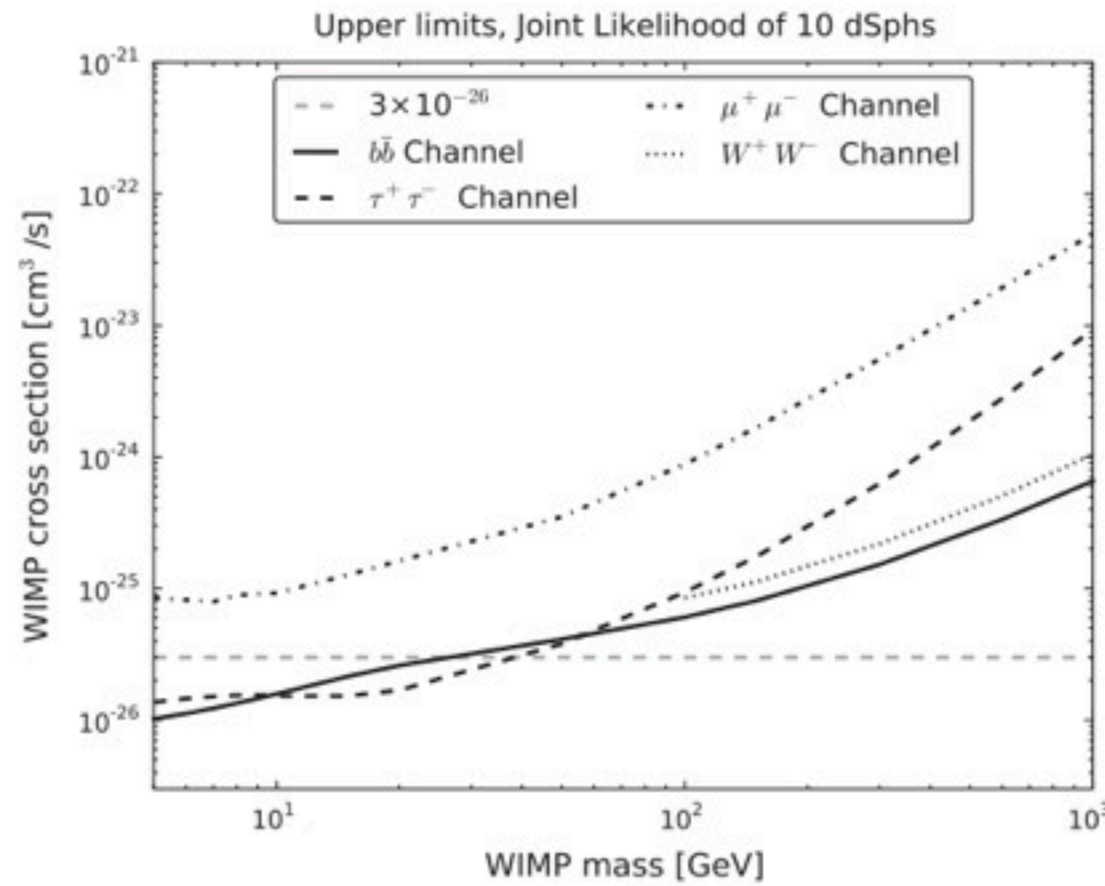


FIG. 2. Derived 95% C.L. upper limits on a WIMP annihilation cross section for the $b\bar{b}$ channel, the $\tau^+\tau^-$ channel, the $\mu^+\mu^-$ channel, and the W^+W^- channel. The most generic cross section ($\sim 3 \times 10^{-26}$ $cm^3\,s^{-1}$ for a purely s-wave cross section) is plotted as a reference. Uncertainties in the J factor are included.

Ackermann et al 2011

Parameter Space

Dark matter

mass

dN/dE

cross section

minimum halo mass

sub-structure

concentration

Astrophysical sources

blazar γ-ray LF

SFG γ-ray LF

L_γ - L_X, L_γ - L_{IR}

blazar L_γ - host halo mass

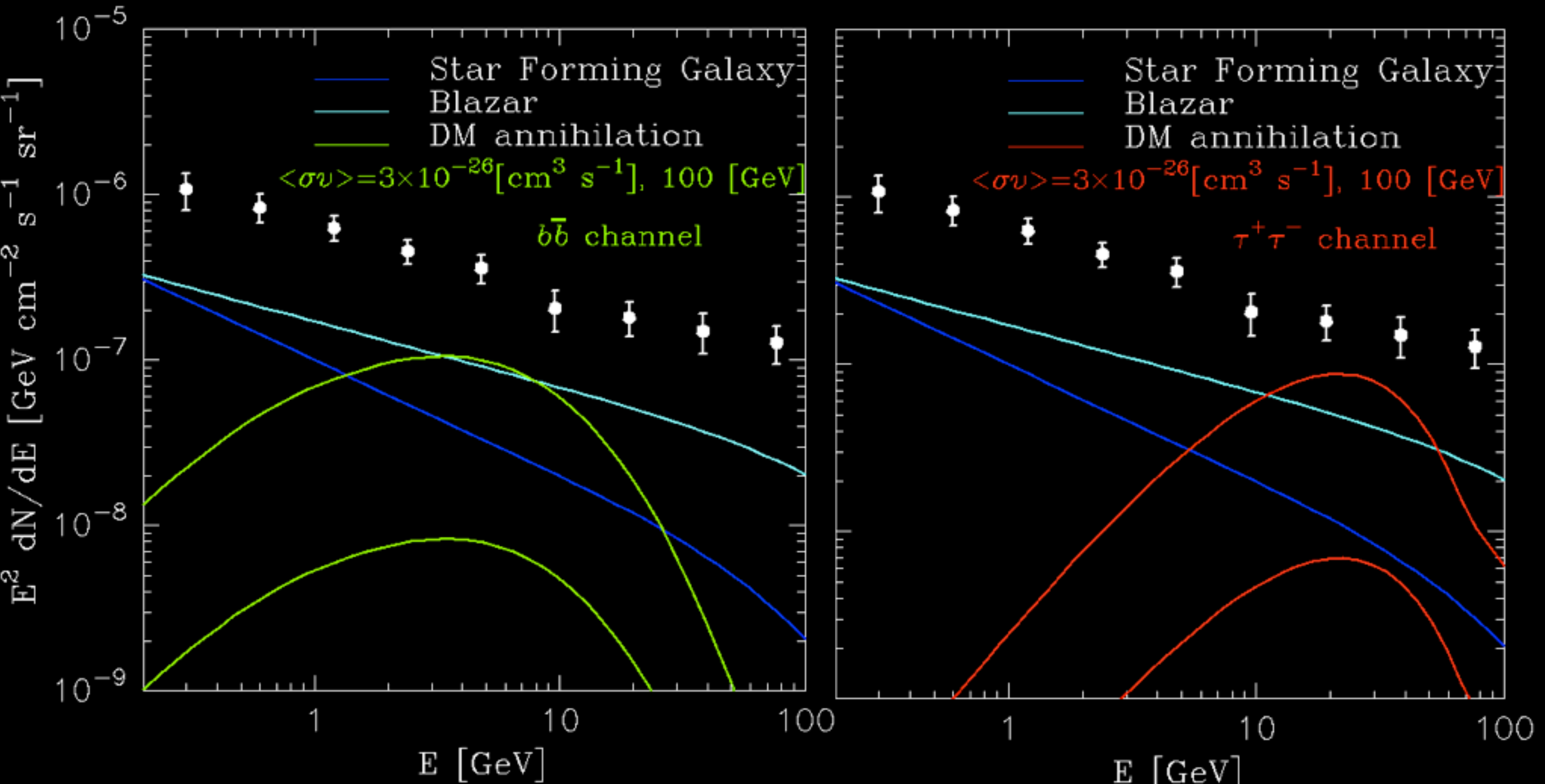
SFG L_γ - host halo mass

Other sources

Observable

- EGB intensity
- EGB power spectrum
- EGB-cosmic shear cross correlation
- EGB-galaxy cross correlation
- Others?

Mean Intensity in Our Model



Halo Model Formulation

What we want

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

Fourier space

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

Halo mass function

NFW profile (or its squared)

Halo model of $P_{\delta\delta2}$

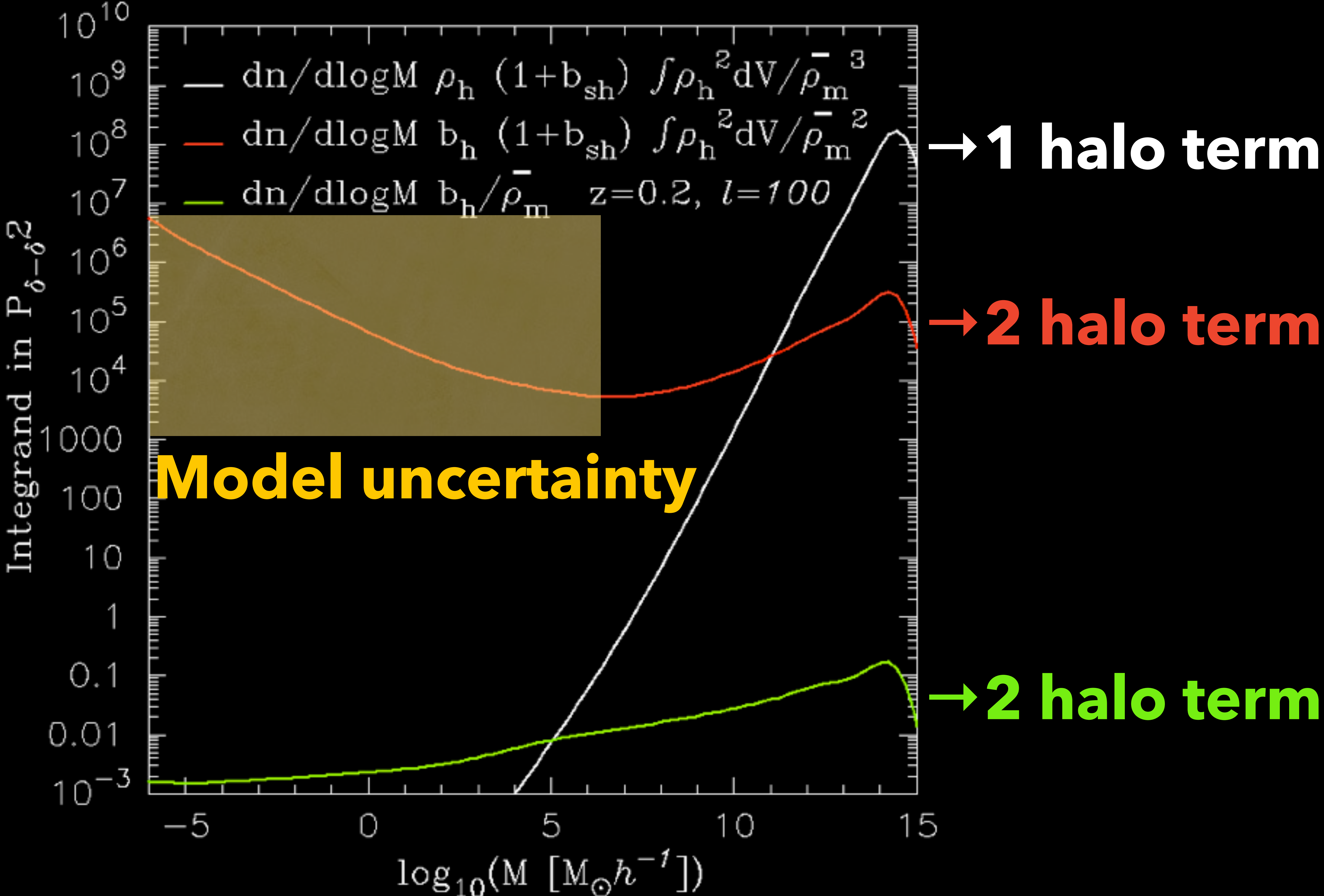
$$P^{1h}_{\delta-\delta^2}(k,z) = \left(\frac{1}{\bar{\rho}_m}\right)^3 \int_{M_{\min}} dM\, n(M,z) M\, u(k|M,z) \times (1 + b_{sh}(M)) v(k|M,z) \int dV \rho_h^2(r|M,z),$$

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

Halo bias

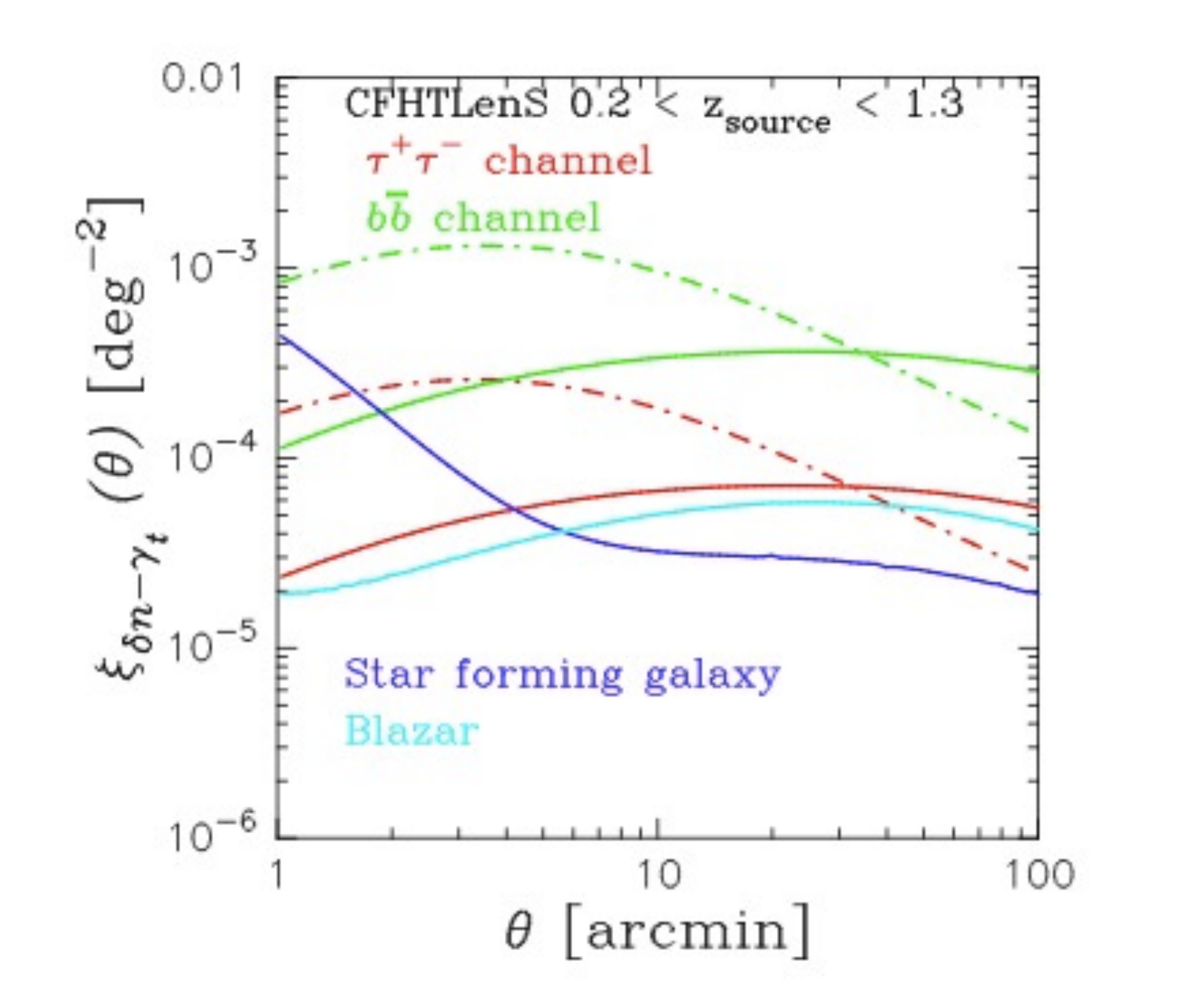
Boost factor

Halo model Integrand

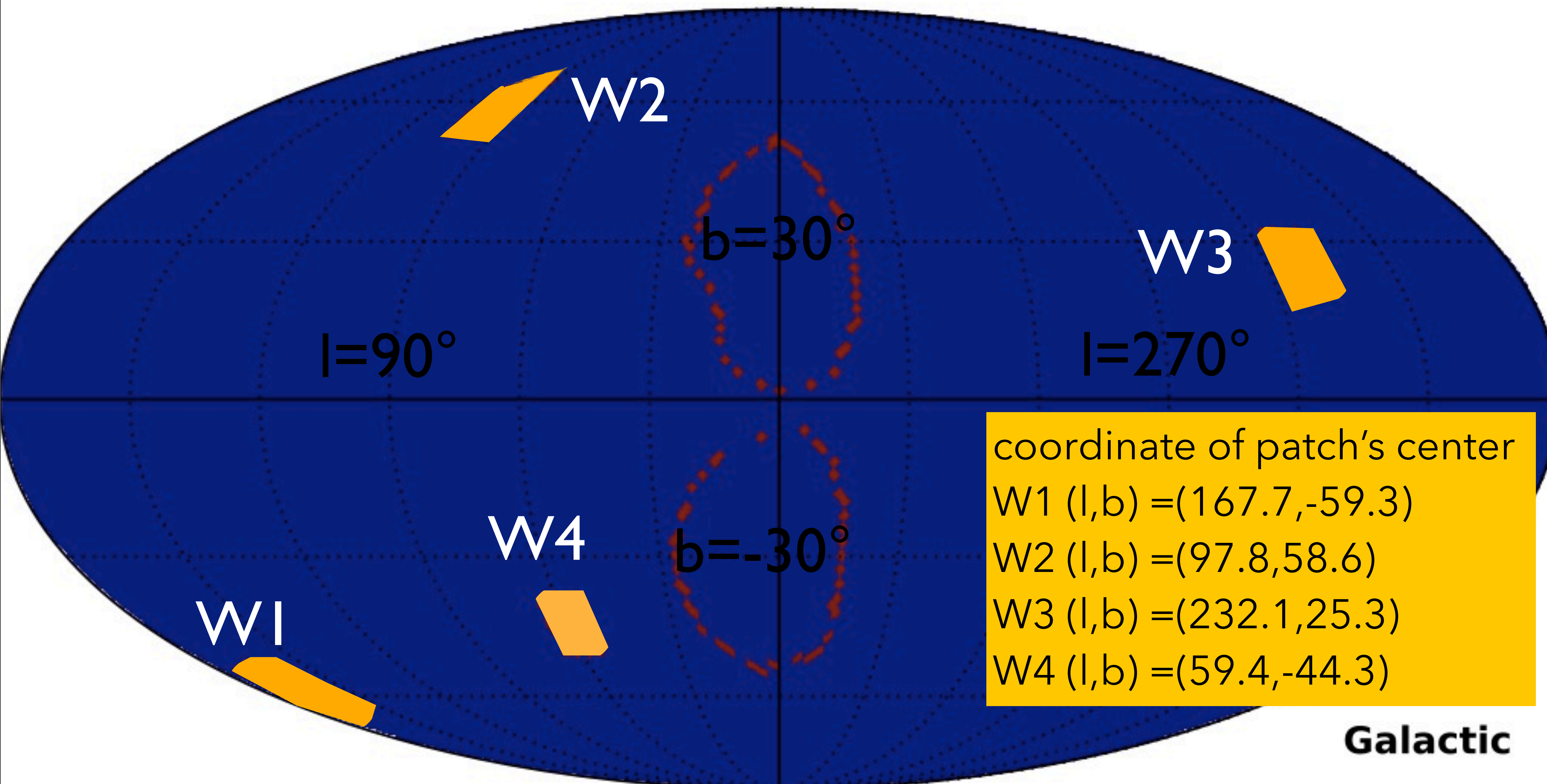


Impact of Concentration parameter model

- The difference of the monotonic c(z, M) and the non-monotonic model
- The final constraint changes with a level of 10 % for DM mass of 1-1000 GeV

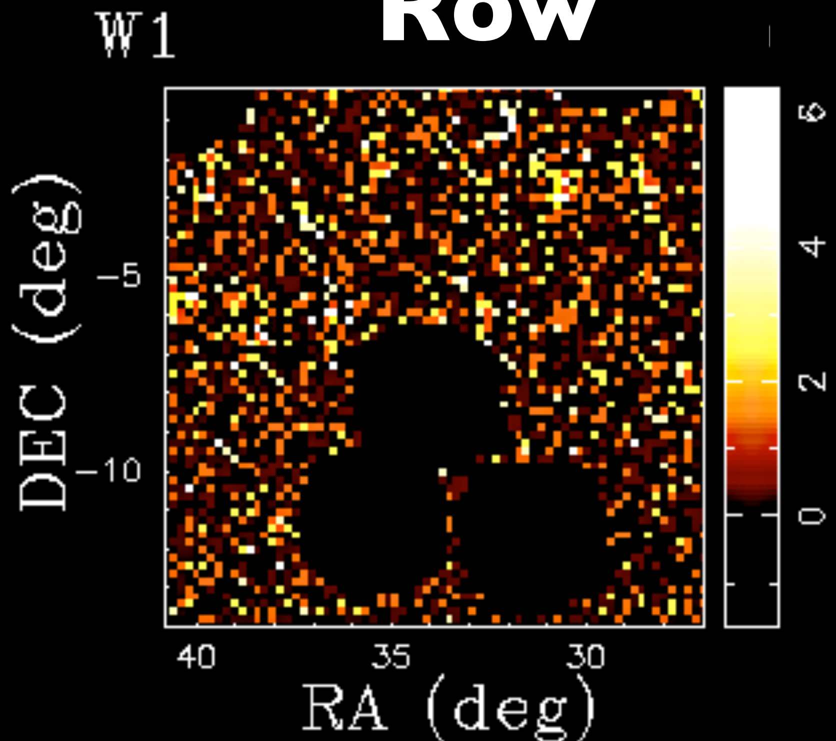


CFHTLenS region

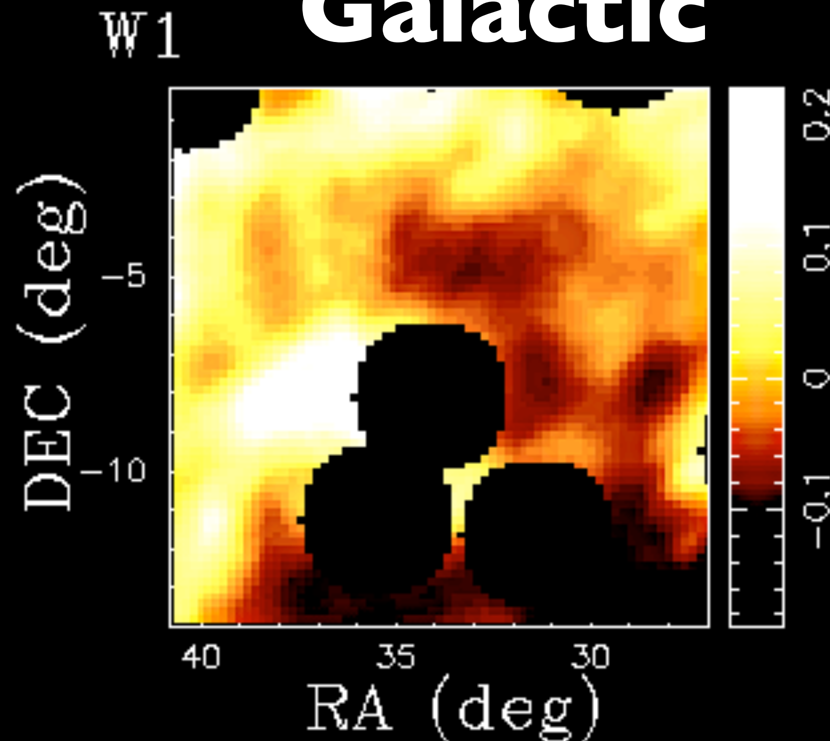


Map Decomposition

Row



Galactic

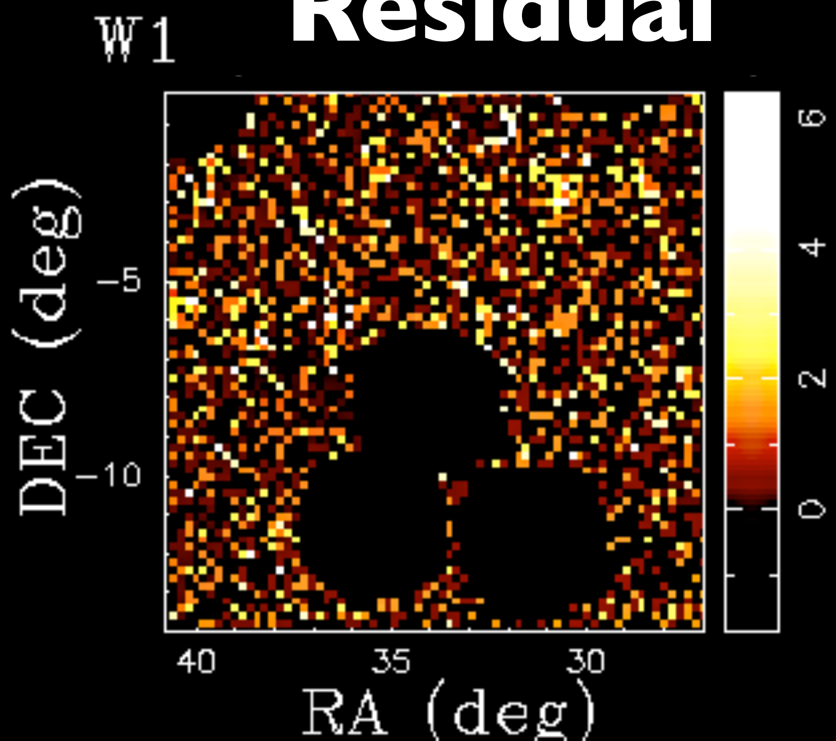


pixel size=0.2 deg

each panel show

count - mean count

Residual



mean photon count per pixel

	Row	Galactic	Residual
W1	1.65	0.98	0.66
W2	2.07	1.37	0.70
W3	1.91	1.05	0.86
W4	2.71	2.51	0.20