Measurement of redshift dependent cross-correlation of HSC clusters and Fermi gamma-ray

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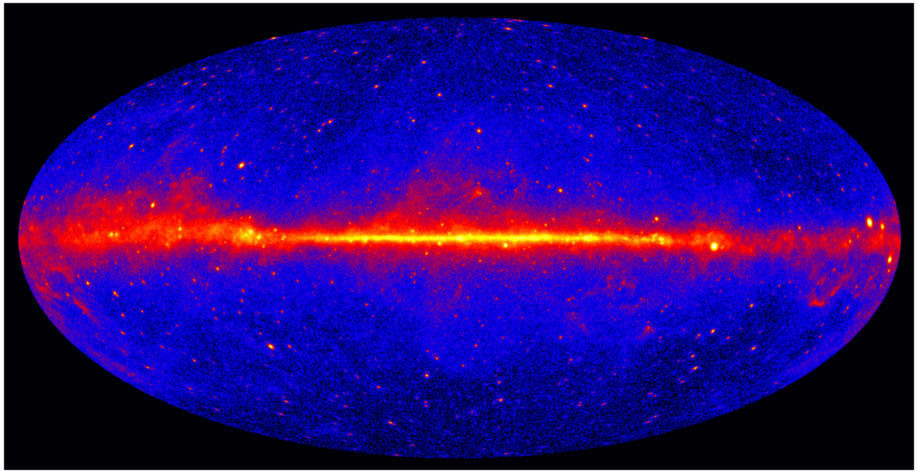
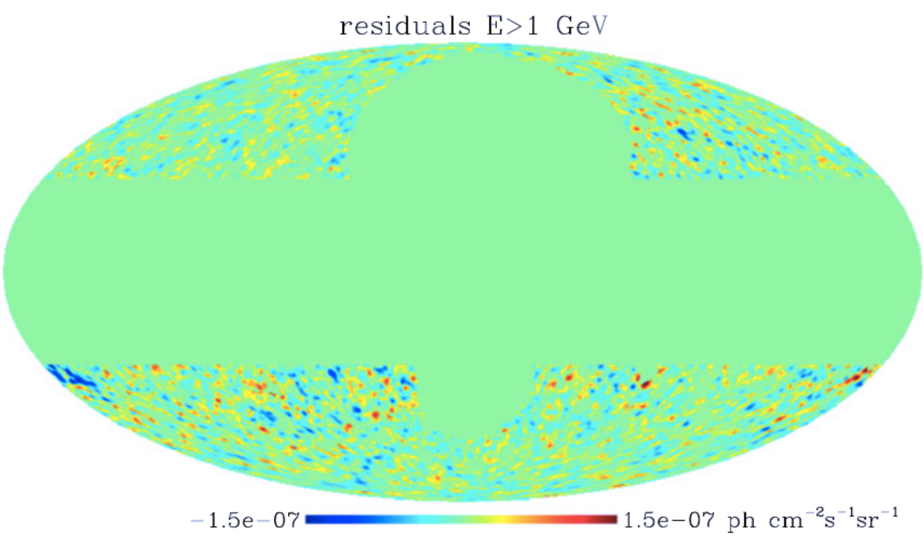
Unresolved Gamma-Ray Background (UGRB)



← Fermi gamma-ray sky

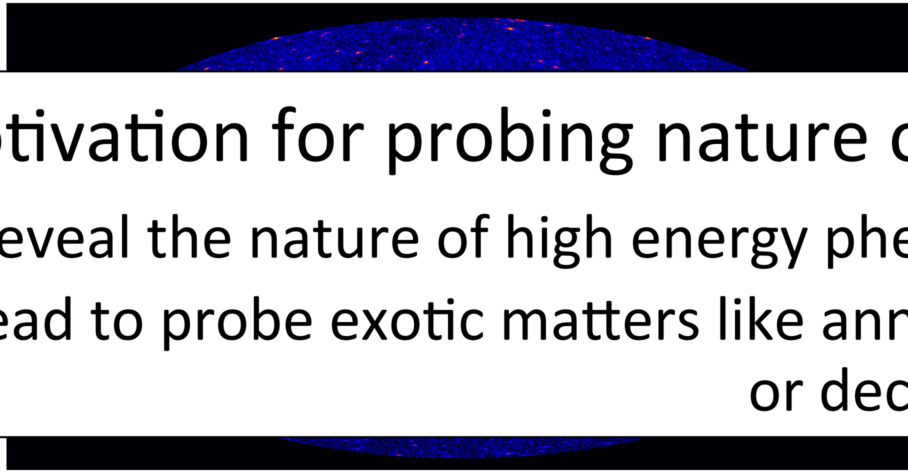
Image Credit: NASA/DOE/Fermi LAT Collaboration



← Unresolved gamma-ray background (UGRB): Extragalactic gamma-ray from unknown sources

Xia et al. 2015

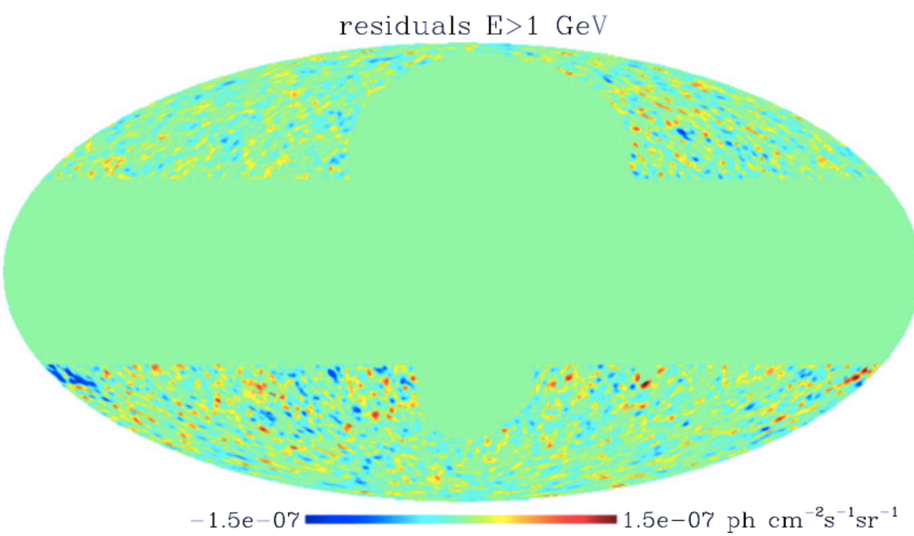
Unresolved Gamma-Ray Background (UGRB)



Motivation for probing nature or origins of UGRB :

- reveal the nature of high energy phenomena like AGN
- lead to probe exotic matters like annihilating or decaying dark matter

Image Credit: NASA/DOE/Fermi LAT Collaboration



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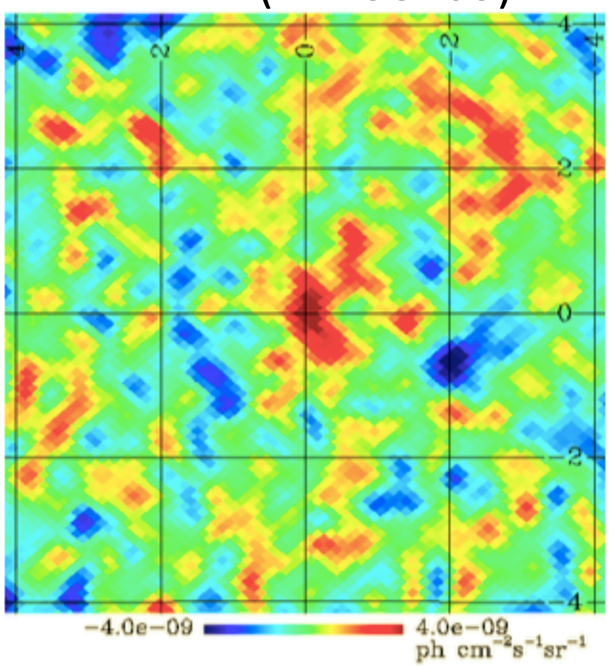
Xia et al. 2015

Previous Work *Branchini et al.(2017)*

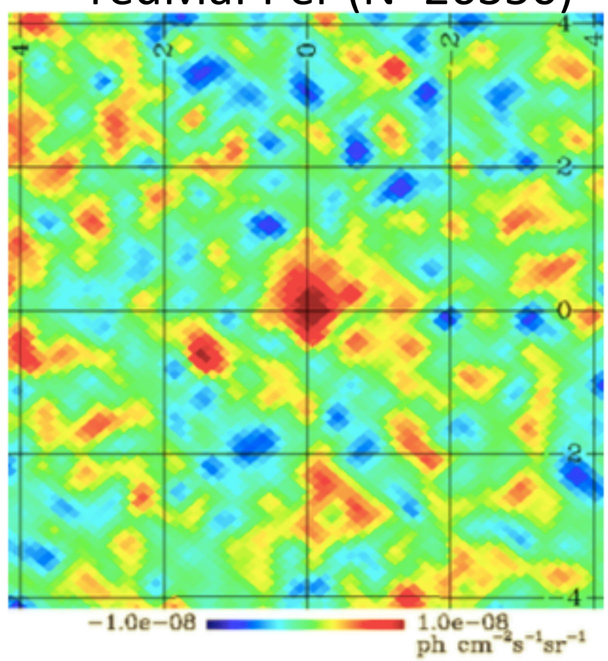
Stacking Analysis & Cross-Correlation Analysis
of UGRB with 3 galaxy cluster catalogs

Stacked Image

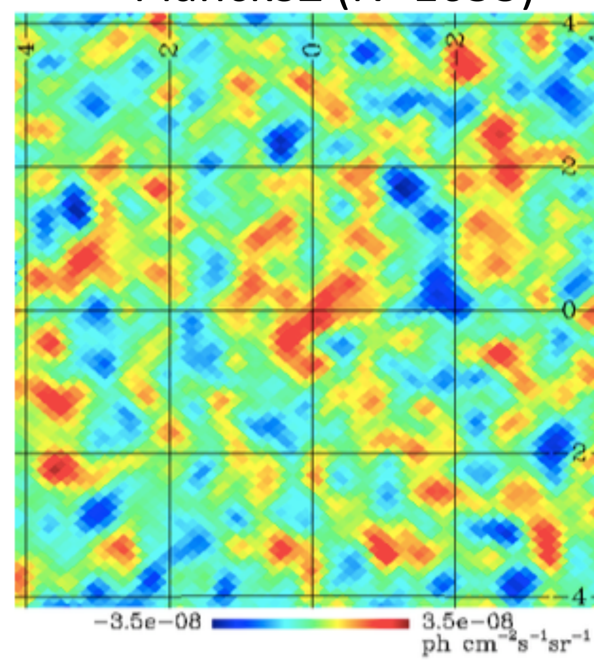
WHL12 (N=158103)



redMaPPer (N=26350)



PlanckSZ (N=1653)



gamma-ray energy : 1-10GeV

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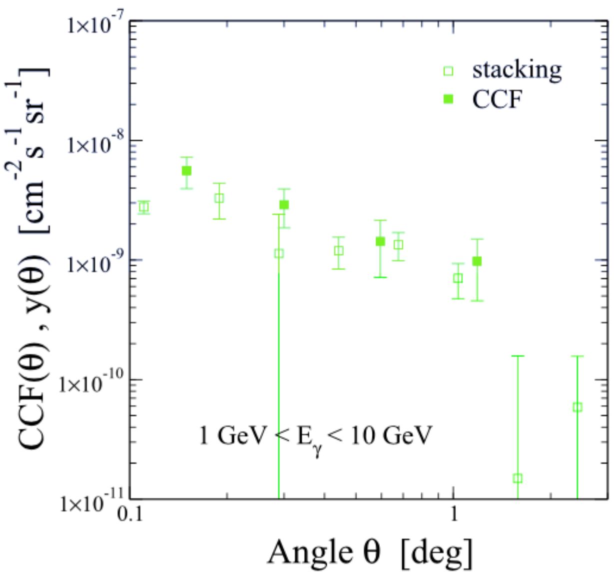
Radial Profile for Stacking & Cross-Correlation Analysis

WHL12 (N=158103)



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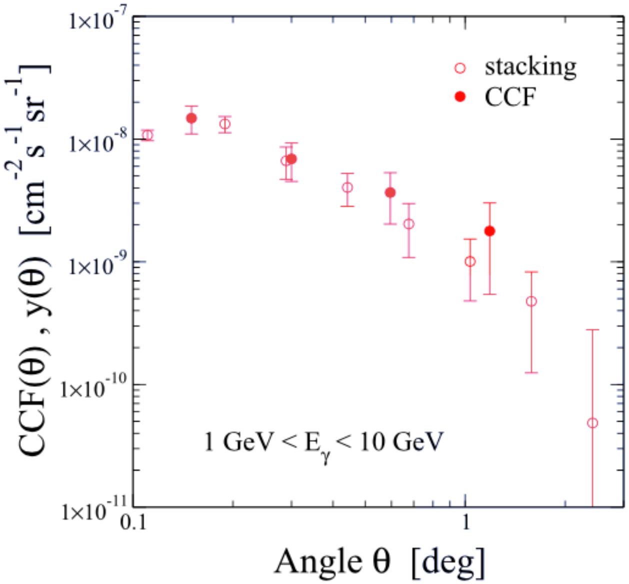

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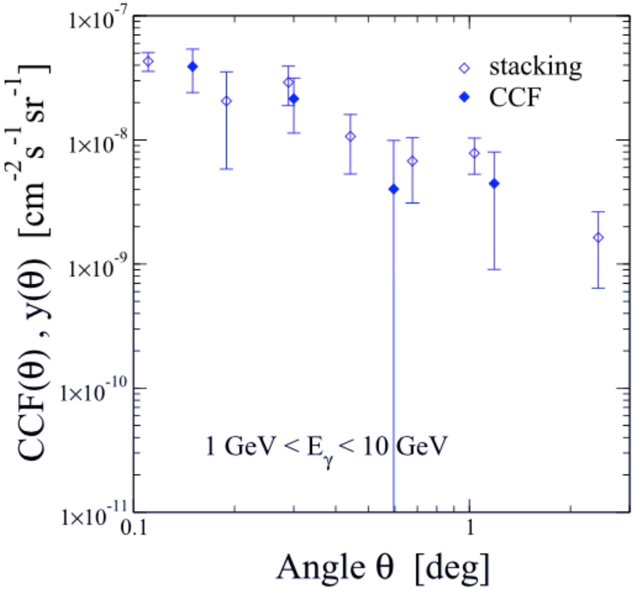


gamma-ray energy : 1-10GeV

In this work...

Data set : *HSC cluster catalog (CAMIRA)*
UGRB by Fermi-LAT

To detect the correlation signal

Analysis : *Stacking Analysis*
Cross-Correlation Analysis

+ Additional study

Data : HSC cluster & UGRB map

- HSC cluster catalog (*CAMIRA* catalog)

  Number of clusters : ~4000

  Area size : ~200 deg^2

  Redshift range : $0.1 < z < 1.1$

- UGRB map (*Fermi*-LAT)

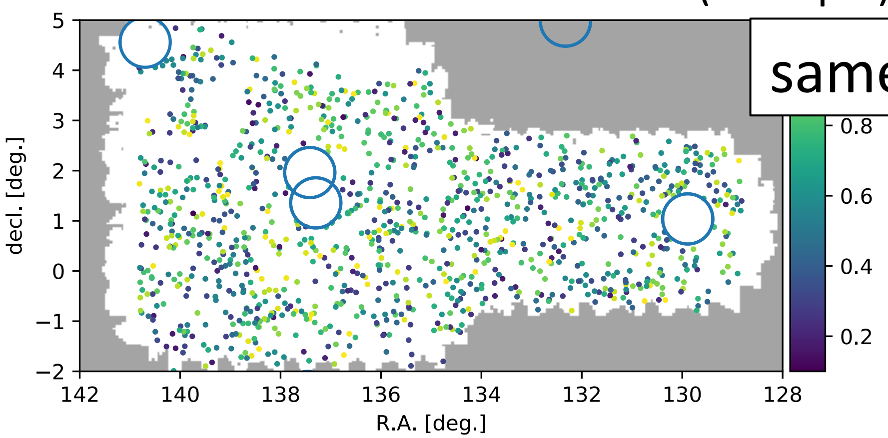
  Energy range : 1-100 GeV

  Fermi-PSF :

  <1.0 deg (1GeV < E < 10 GeV)

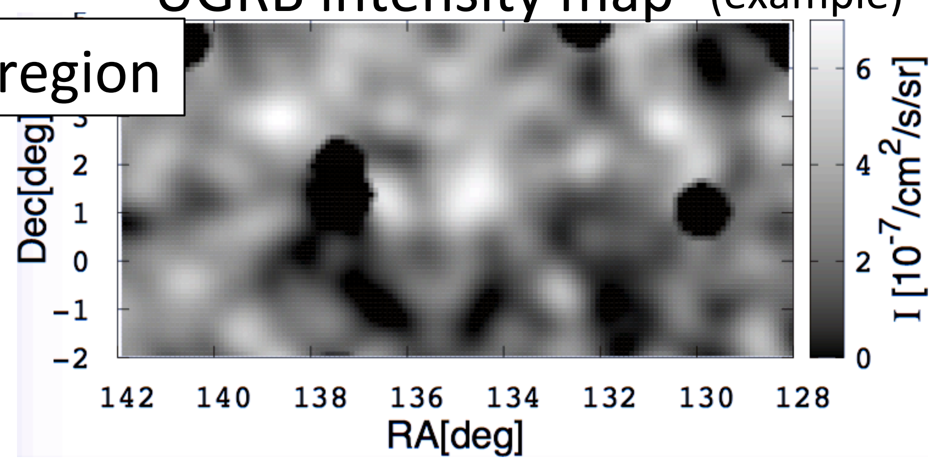
  ~0.2 deg (E > 10 GeV)

HSC-cluster distribution (example)



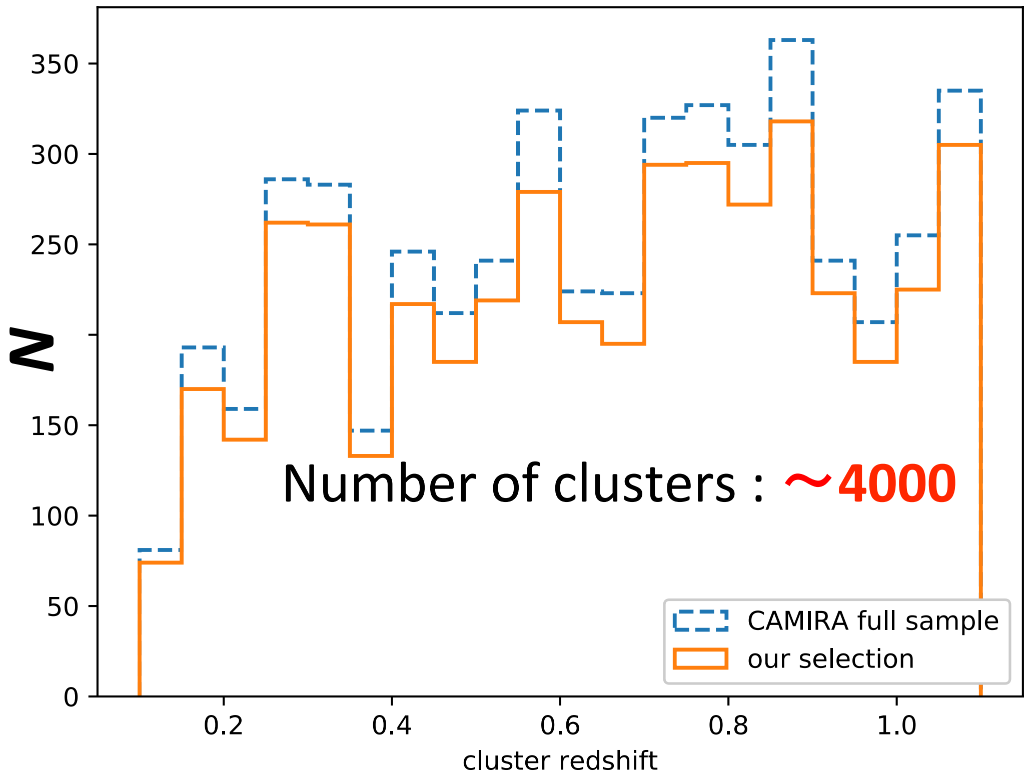
same region

UGRB intensity map (example)

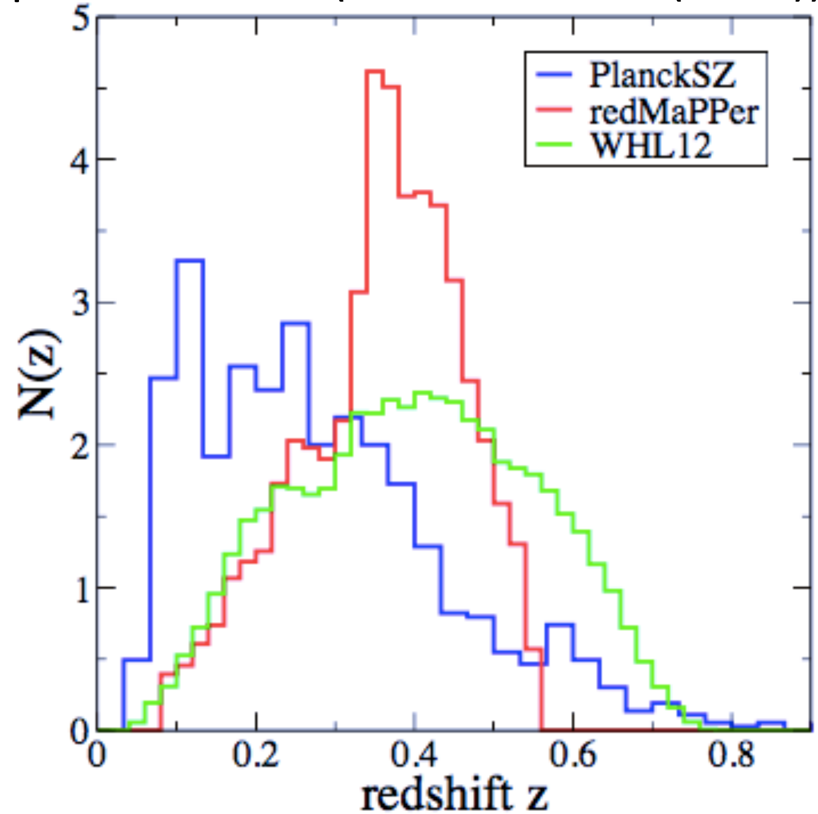


Redshift Distribution

HSC cluster catalog



previous work (Branchini et al.(2017))



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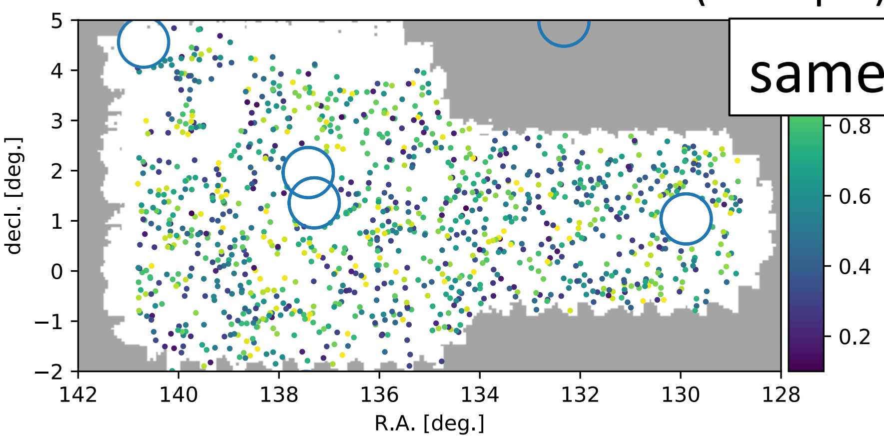
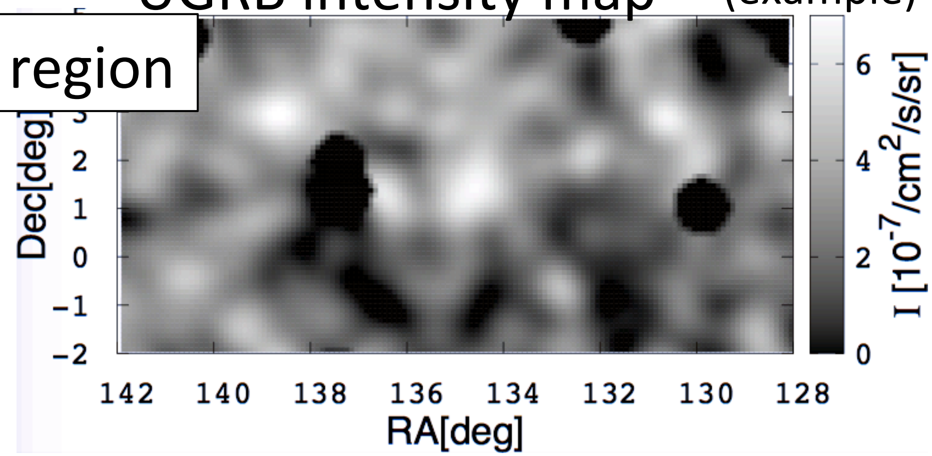
HSC-cluster distribution (example)

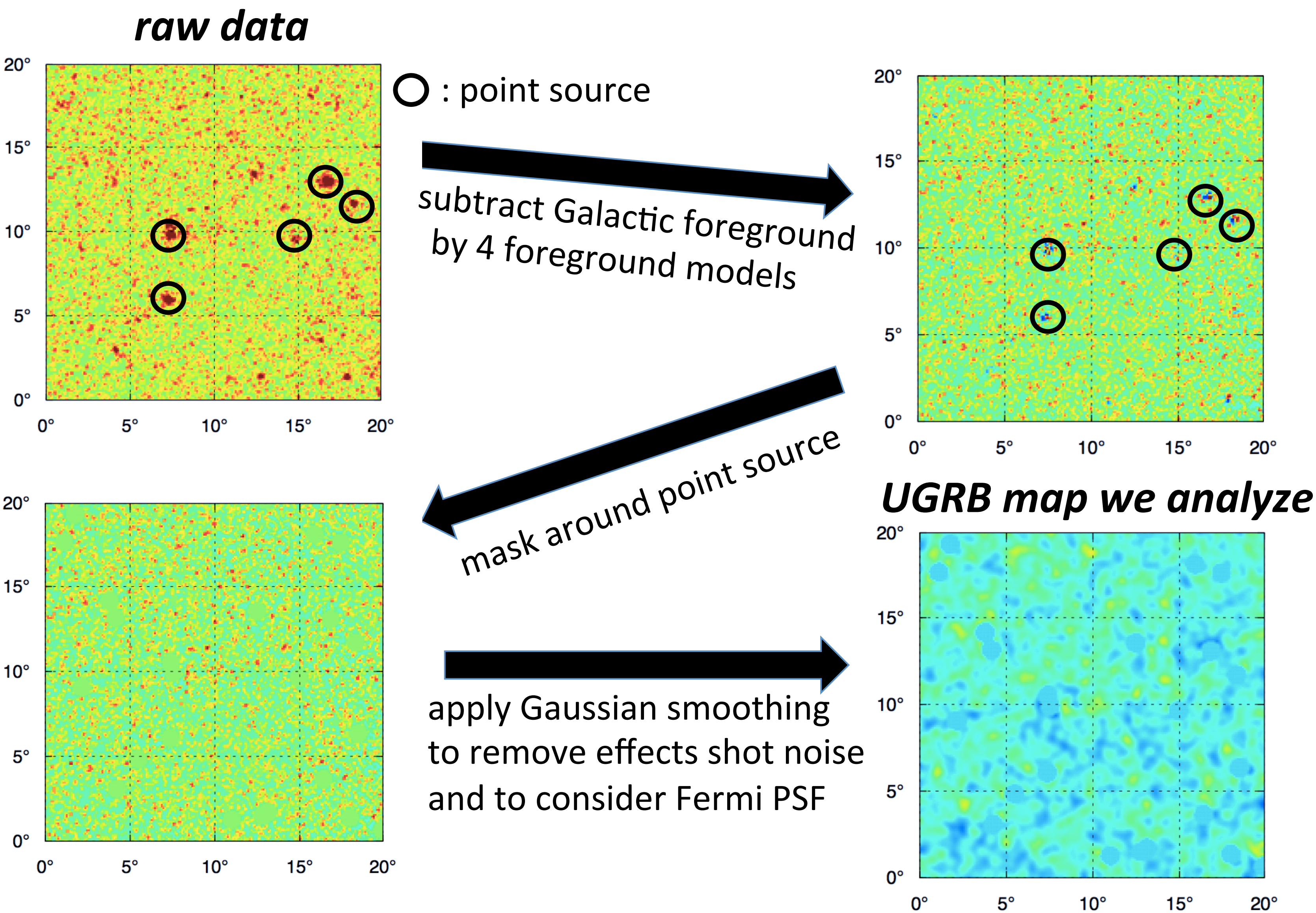


same region

UGRB intensity map (example)

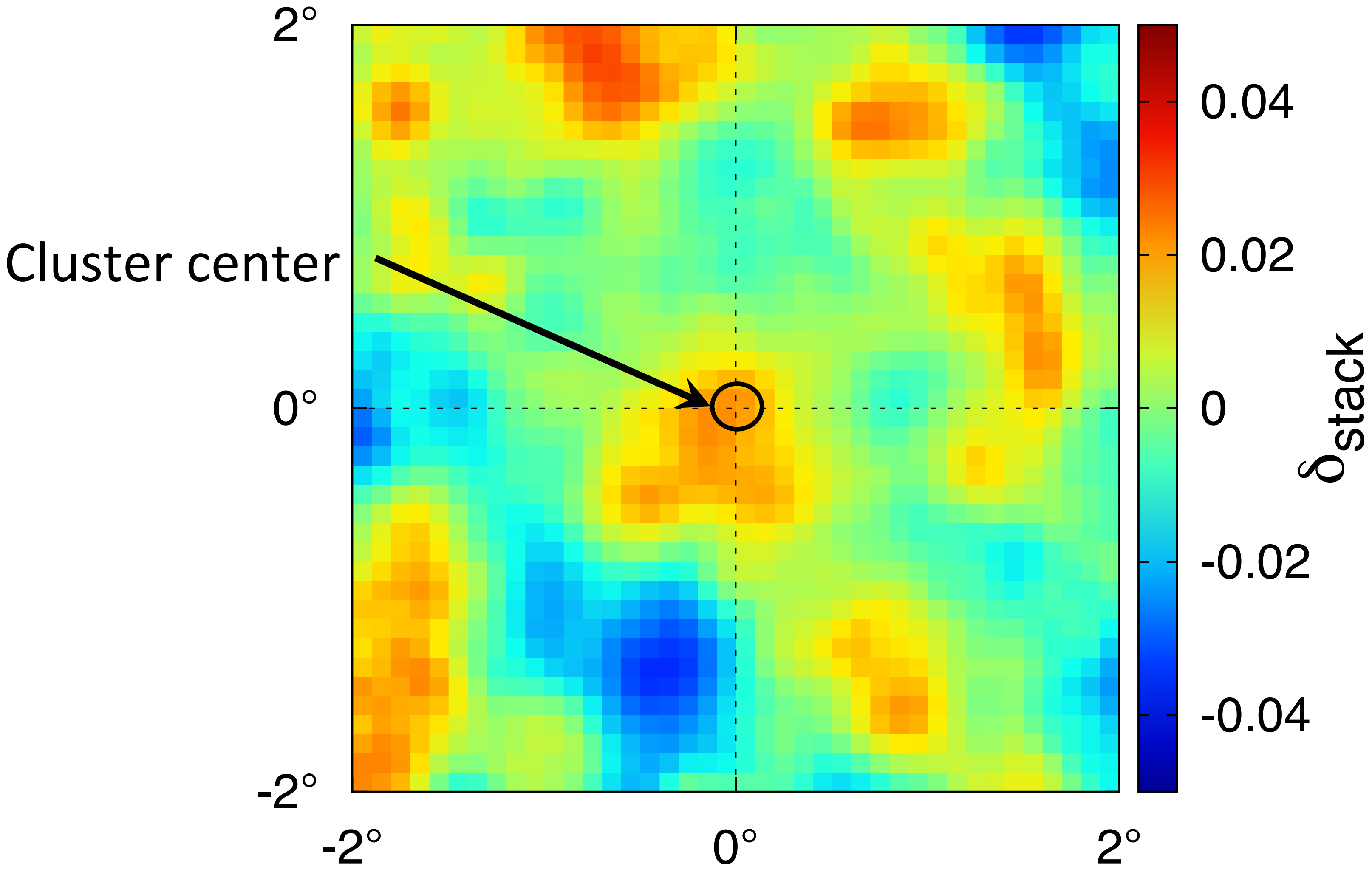


Construction of UGRB Map



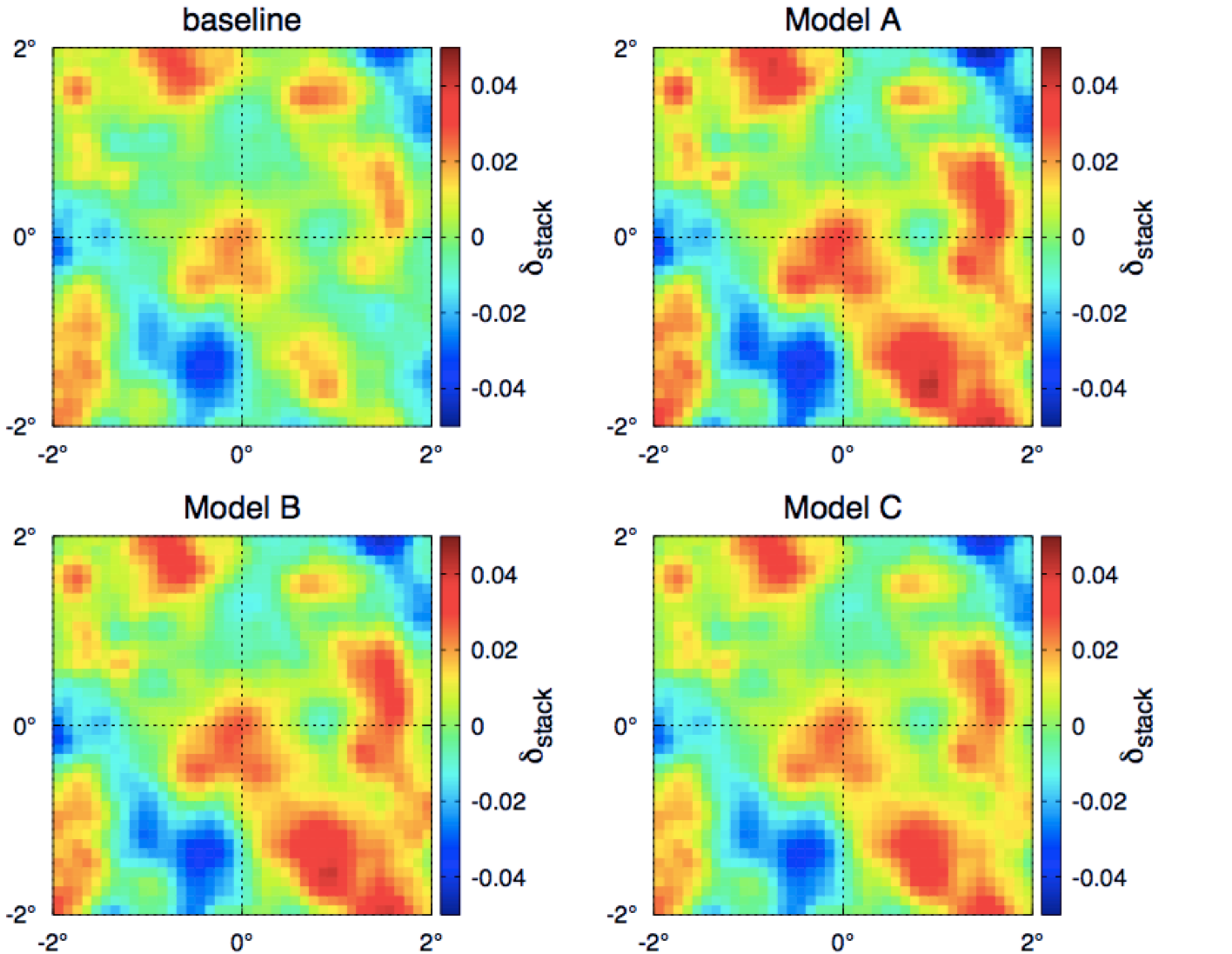
Stacking Analysis

Fluctuation field of UGRB around cluster position



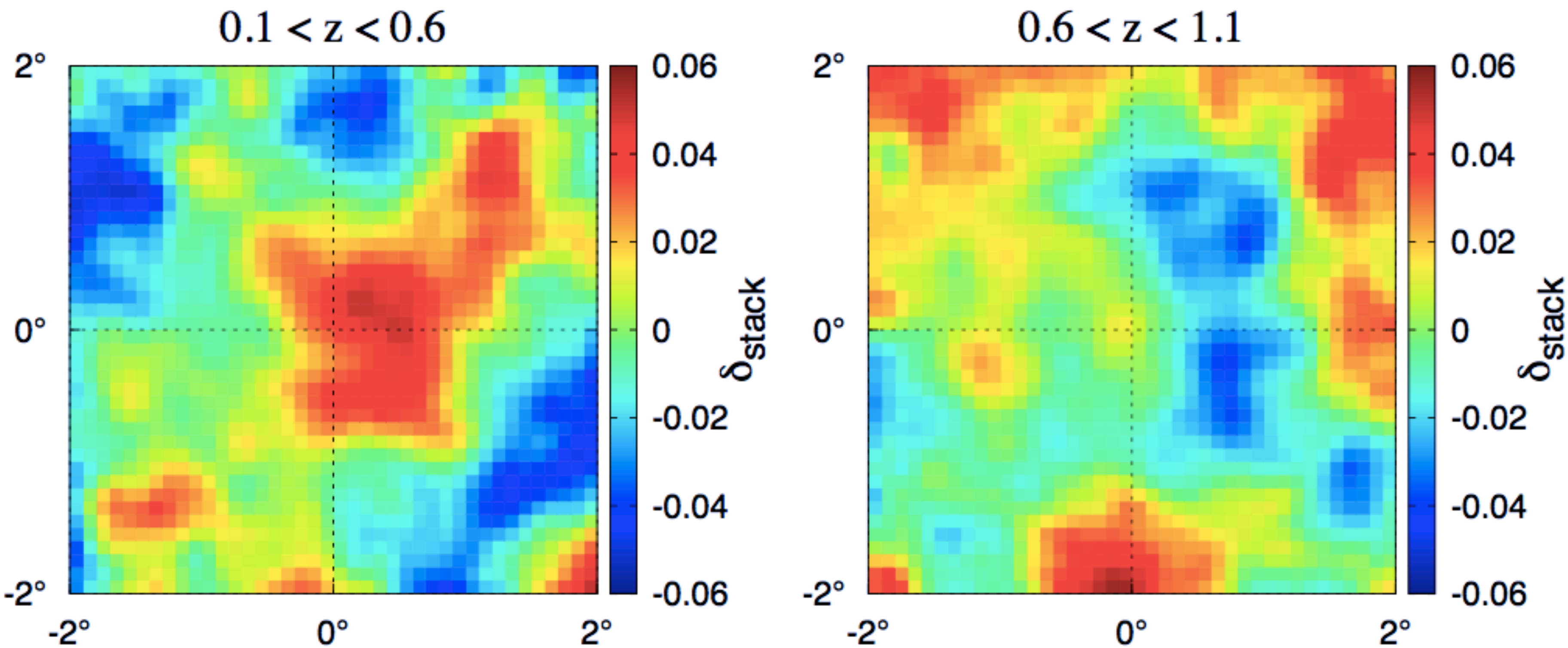
Stacking Analysis

Fluctuation field of UGRB using different Galactic foreground models



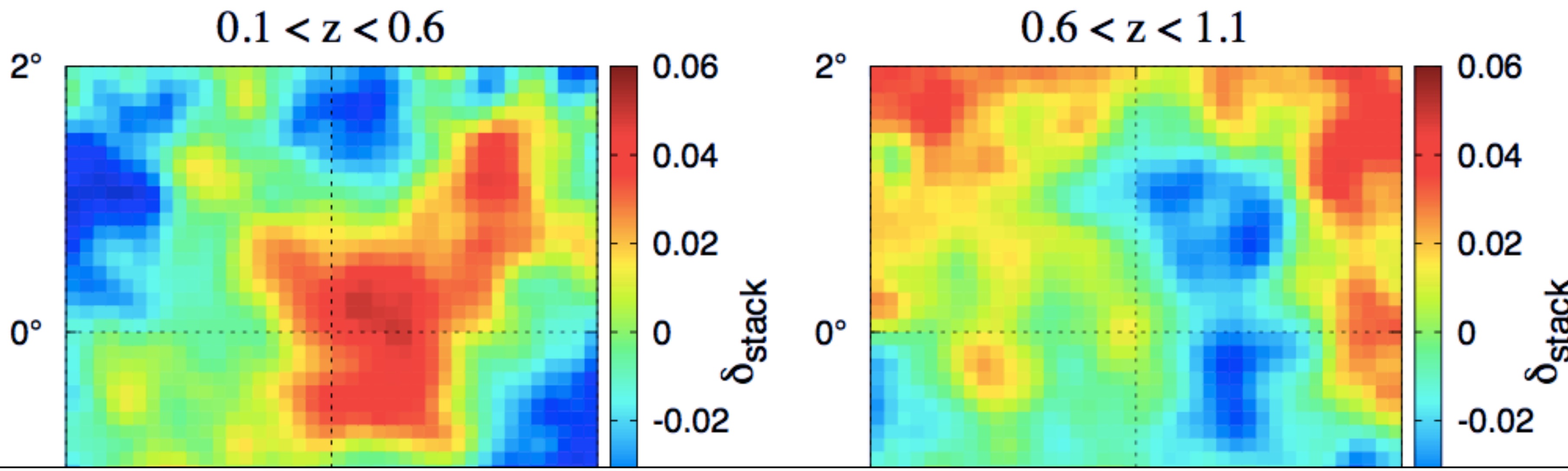
Stacking Analysis

Fluctuation field of UGRB using low-z clusters and high-z clusters



Stacking Analysis

Fluctuation field of UGRB using low-z clusters and high-z clusters



The average separation of the CAMIRA clusters is ~0.2 degrees.

It is much smaller than the image size of 4 degrees.

→ Some photons appear multiple times at different positions in the stacked image.

So we NOT perform quantitative analysis using this result.

Cross-Correlation Analysis

2-point angular cross-correlation function: $\xi(\theta)$

$\xi(\theta)$: Correlation of UGRB intensity with cluster position
with separation angle θ from cluster center

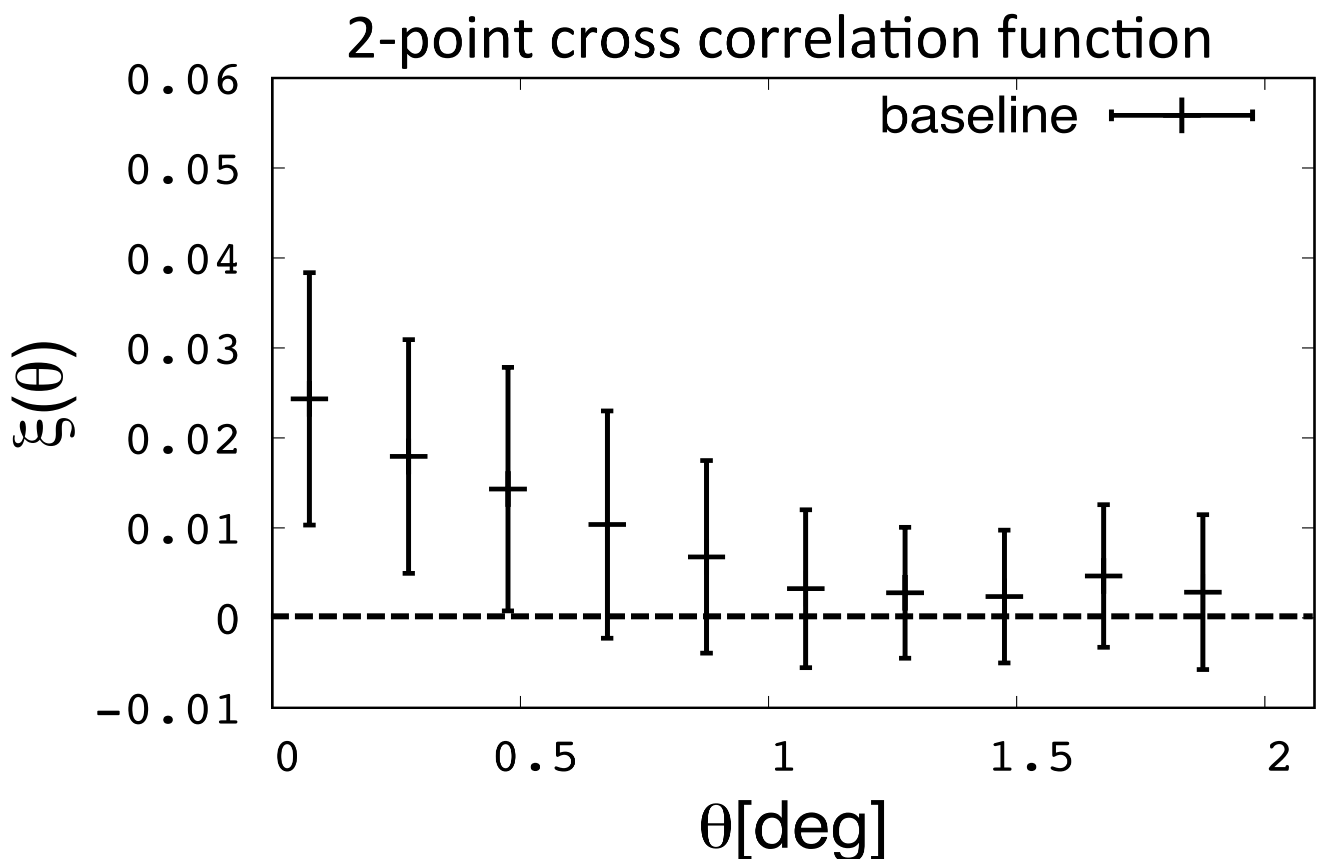
$$\xi(\theta) = \langle n_{clu}(0)\delta_\gamma(\theta)\rangle$$

$n_{clu}(0)$: number density of clusters at θ=0 ($\because n_{\rm clu}(0) = 1$)

$$\delta_\gamma(\theta) = \frac{I(\theta) - \bar{I}}{\bar{I}}$$

* We use the Landy-Szalay estimator to compute the correlation function, the Jackknife method to estimate statistical errors

Cross-Correlation Analysis

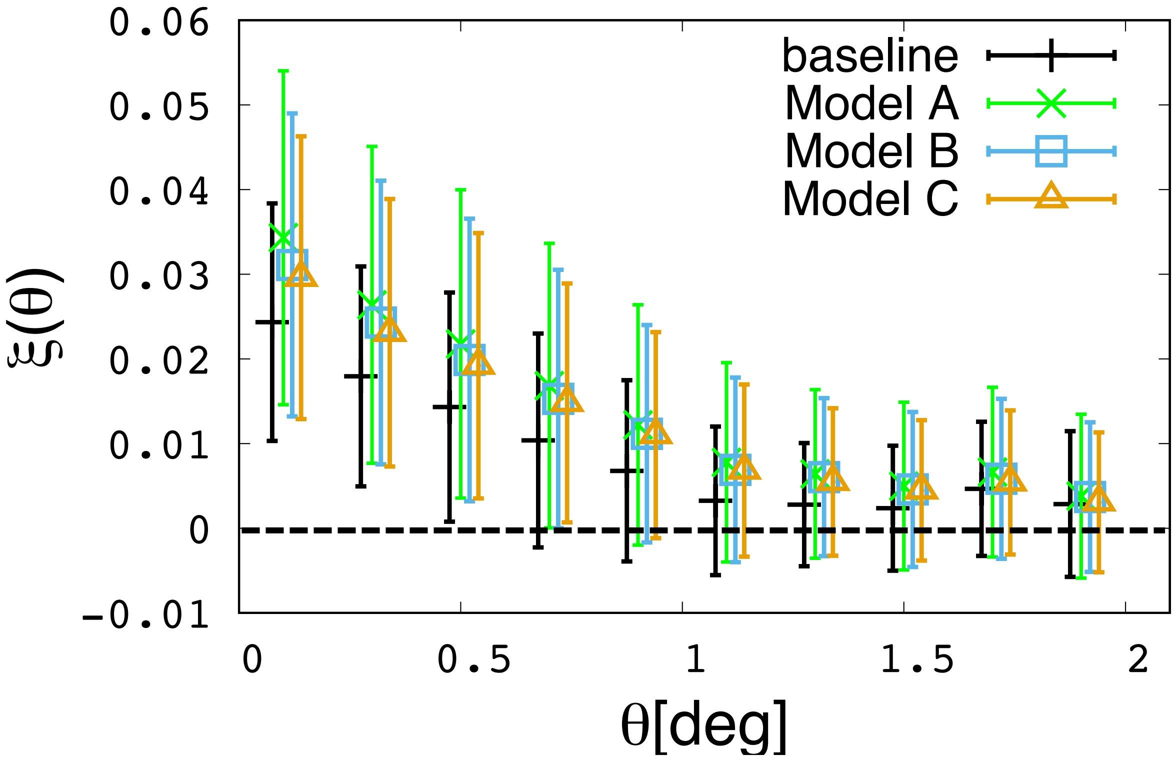


Statistical significance

redshift range	baseline	Model A	Model B	Model C
$0.1 < z < 1.1$	2.2	2.0	2.0	2.0
$0.1 < z < 0.6$	2.2	2.1	2.1	2.3
$0.6 < z < 1.1$	1.9	1.6	1.6	1.6

Cross-Correlation Analysis

Cross-correlation function using different Galactic foreground models



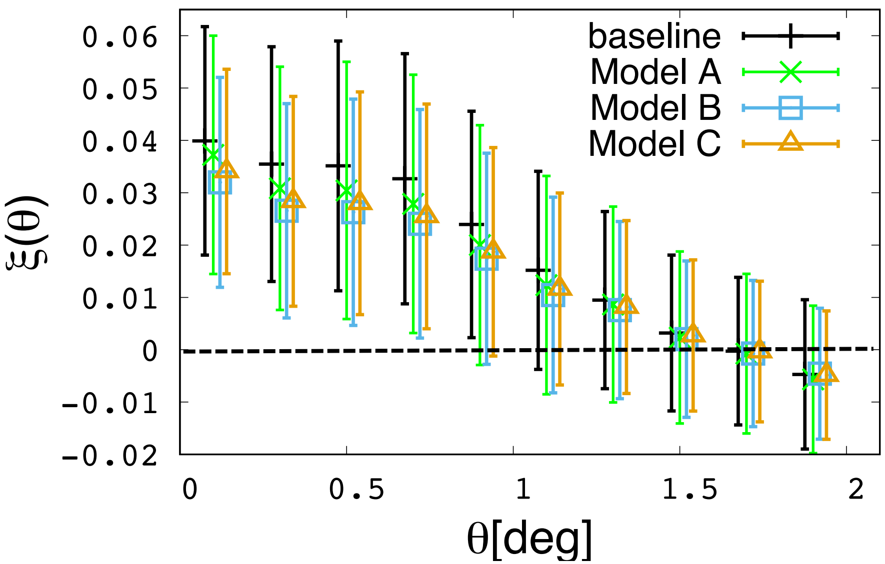
Statistical significance

redshift range	baseline	Model A	Model B	Model C
$0.1 < z < 1.1$	2.2	2.0	2.0	2.0
$0.1 < z < 0.6$	2.2	2.1	2.1	2.3
$0.6 < z < 1.1$	1.9	1.6	1.6	1.6

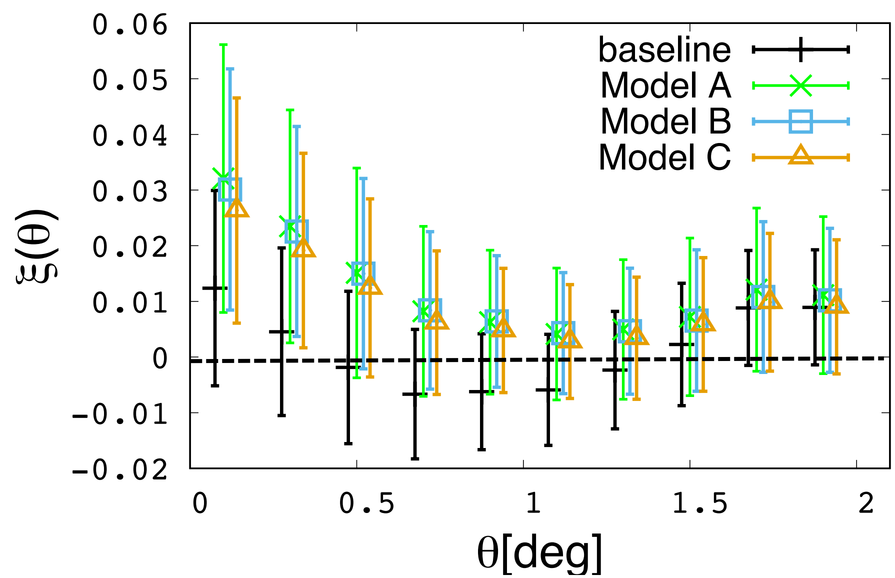
Cross-Correlation Analysis

Cross-correlation function using low-z clusters and high-z clusters

low-z (0.1 < z < 0.6)



high-z (0.6 < z < 1.1)



Statistical significance

redshift range	baseline	Model A	Model B	Model C
$0.1 < z < 1.1$	2.2	2.0	2.0	2.0
$0.1 < z < 0.6$	2.2	2.1	2.1	2.3
$0.6 < z < 1.1$	1.9	1.6	1.6	1.6

Implication

What are the components of the cross-correlation signal ?

Possible gamma-ray emitters :

Blazar, Star-forming Galaxy, Radio galaxy

$$P_{c\gamma}(\ell) = \sum_X \int \frac{\mathrm{d}\chi}{r(\chi)^2} W_{\gamma,X}(\chi)\, W_{\mathrm{clu}}(\chi)\, P_{\mathrm{h}X}^{(3\mathrm{D})}\left(\frac{\ell}{r(\chi)}, z(\chi)\right)$$

$W_{\mathrm{clu}}(\chi)$: the effective window function for CAMIRA clusters

$W_{\gamma,X}(\chi)$: the window function for population X

$P_{\mathrm{h}X}^{(3\mathrm{D})}$: three dimensional cross power spectrum between cluster and population X

$$\xi(\theta) = \frac{1}{\langle n_{\mathrm{clu}}\rangle \langle I_\gamma\rangle} \int \frac{\mathrm{d}^2\ell}{(2\pi)^2} \exp\left[i\boldsymbol{\ell}\cdot\boldsymbol{\theta}\right] P_{c\gamma}(\ell)\hat{W}(\ell, \theta_G)$$

$\hat{W}(\ell, \theta_G)$: Gaussian smoothing

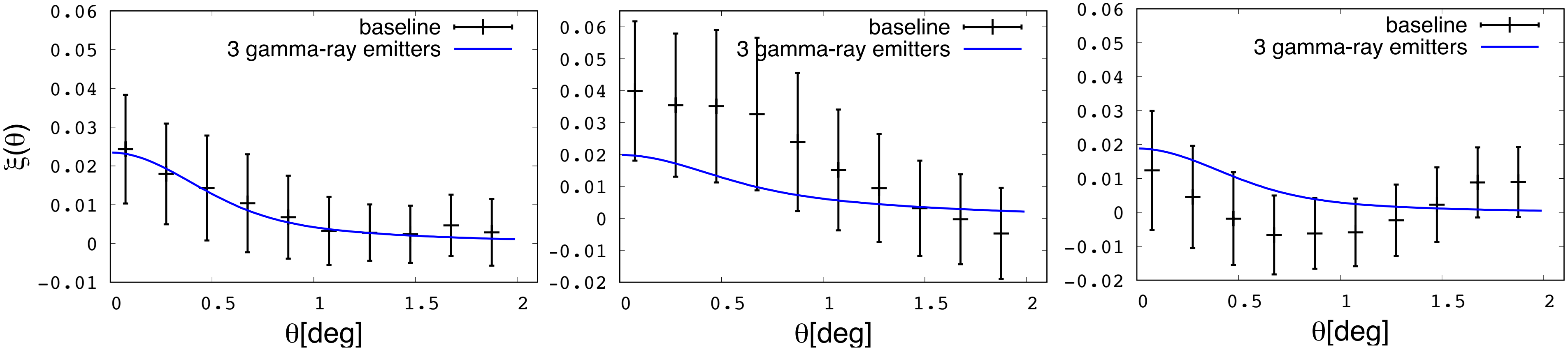
Shirasaki et al. Phys. Rev. D,97,123015 (2018)

Implication

0.1 < z < 1.1

0.1 < z < 0.6

0.6 < z < 1.1



This simple model for 3 gamma-ray emitters
can explain the signal in this work.

Summary

Probe cross correlation of UGRB intensity map with HSC clusters position :

✔ Cross-correlation signal

- Find evidence of the cross-correlation signal (2.0-2.3σ) with clusters in all-redshift and lower redshift ranges ($0.1 < z < 1.1$ and $0.1 < z < 0.6$).
- With higher redshift range ($0.6 < z < 1.1$), lower statistical significance is found (1.6-1.9σ).
- Confirm the consistency of the cross-correlation analysis with the stacking analysis.

✔ Implication for the signal

- Assume three gamma-ray emitter (*blazar, star-forming galaxy, radio galaxy*) to model cross-correlation signal.
- It seems that the detected signal is fairly consistent with the theoretically predicted model.

✔ In the future ...

- HSC observation area will increase by at least three times, statistical error can be reduced by a factor of $1/\sqrt{3}$.
- This leads to the further probe of the gamma-ray emitter or exotic matters such a annihilating or decaying dark matter.

Cross-Correlation Analysis

How to estimate two point cross-correlation

Calculate the cross-correlation functions $\xi(\theta)$ in sub regions

by using the Landy-Szalay estimator

$$\xi(\theta) = \frac{D_{\rm cluster}(0)D_\gamma(\theta) - D_{\rm cluster}(0)R_\gamma(\theta) - R_{\rm cluster}(0)D_\gamma(\theta) + R_{\rm cluster}(0)R_\gamma(\theta)}{R_{\rm cluster}(0)R_\gamma(\theta)}$$

$D_{\rm cluster}(0)$: count of CAMIRA cluster's numbers in the cluster's position, so $D_{\rm cluster}(0)$ = 1 at all time

$R_{\rm cluster}(0)$: count of cluster's numbers in random clusters catalog in the cluster's position, so $R_{\rm cluster}(0)$ = 1 at all time

$D_\gamma(\theta)$: count of photon numbers in Fermi map separation θ from cluster

$R_\gamma(\theta)$: count of photon numbers in random map separation θ from cluster

Cross-Correlation Analysis

How to compute statistical significance

- Covariance matrix $C^{\rm JK}_{\theta\theta'}$

$$C^{\rm JK}_{\theta\theta'} = \frac{M-1}{M}\sum_{k=1}^{M}[\xi^{\rm obs}_k(\theta) - \xi^{\rm mean}(\theta)] \times [\xi^{\rm obs}_k(\theta') - \xi^{\rm mean}(\theta')]$$

Scranton & Johnston (2002)

M : number of jackknife-subsumples

$\xi^{\rm obs}_k(\theta)$: correlation function in k-th subsumple

$\xi^{\rm mean}(\theta)$: averaged correlation function over all $\xi^{\rm obs}_k(\theta)$

- χ^2

$$\chi^2 = \sum_{i,j}(\xi^{mean}(\theta_i) - m_i)C^{-1}_{ij}(\xi^{mean}(\theta_j) - m_j)$$

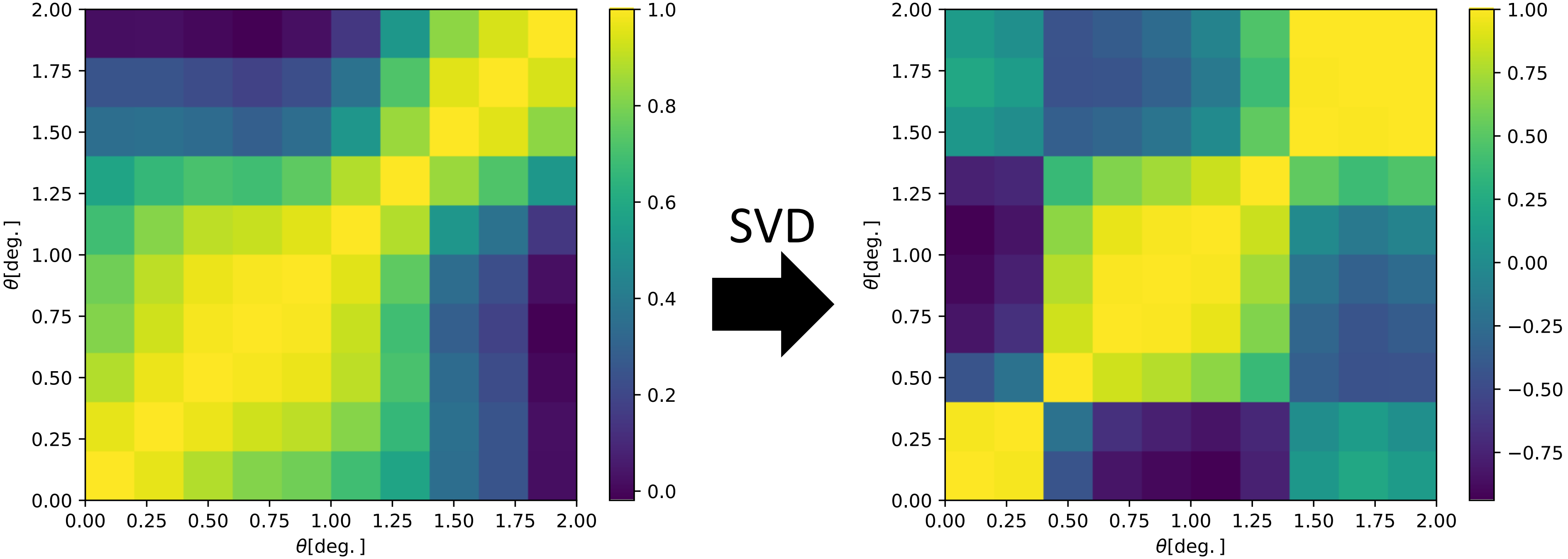
m_i : correlation with certain model (null correlation→ $m_i = 0$)

→ the significance σ is represented by χ

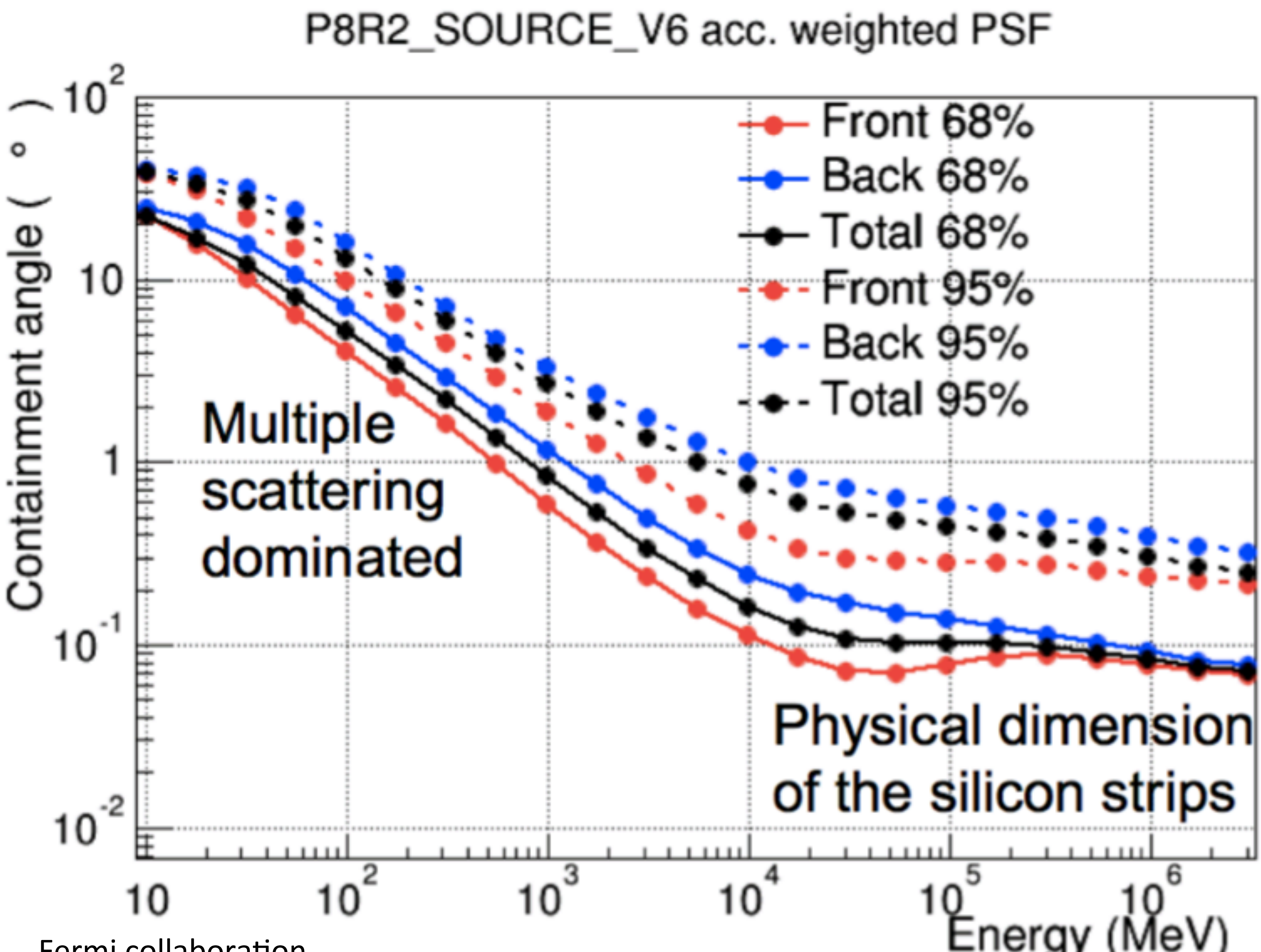
Covariance Matrix

Number of eigen value : 10

Number of eigen value : 4

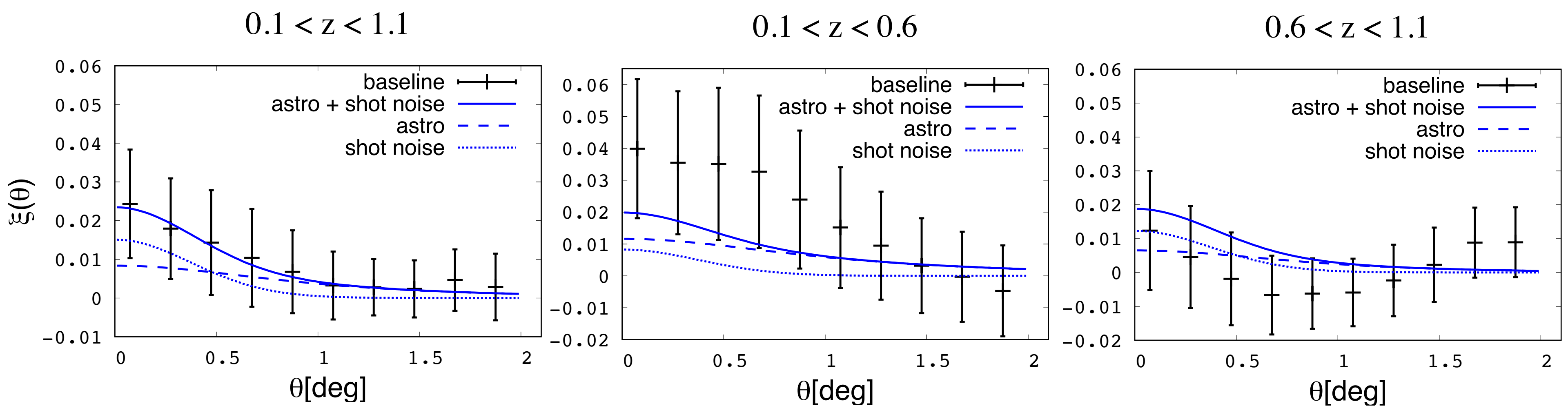


↑Angular bins has a strong correlation with other bins.



Fermi collaboration

Implication



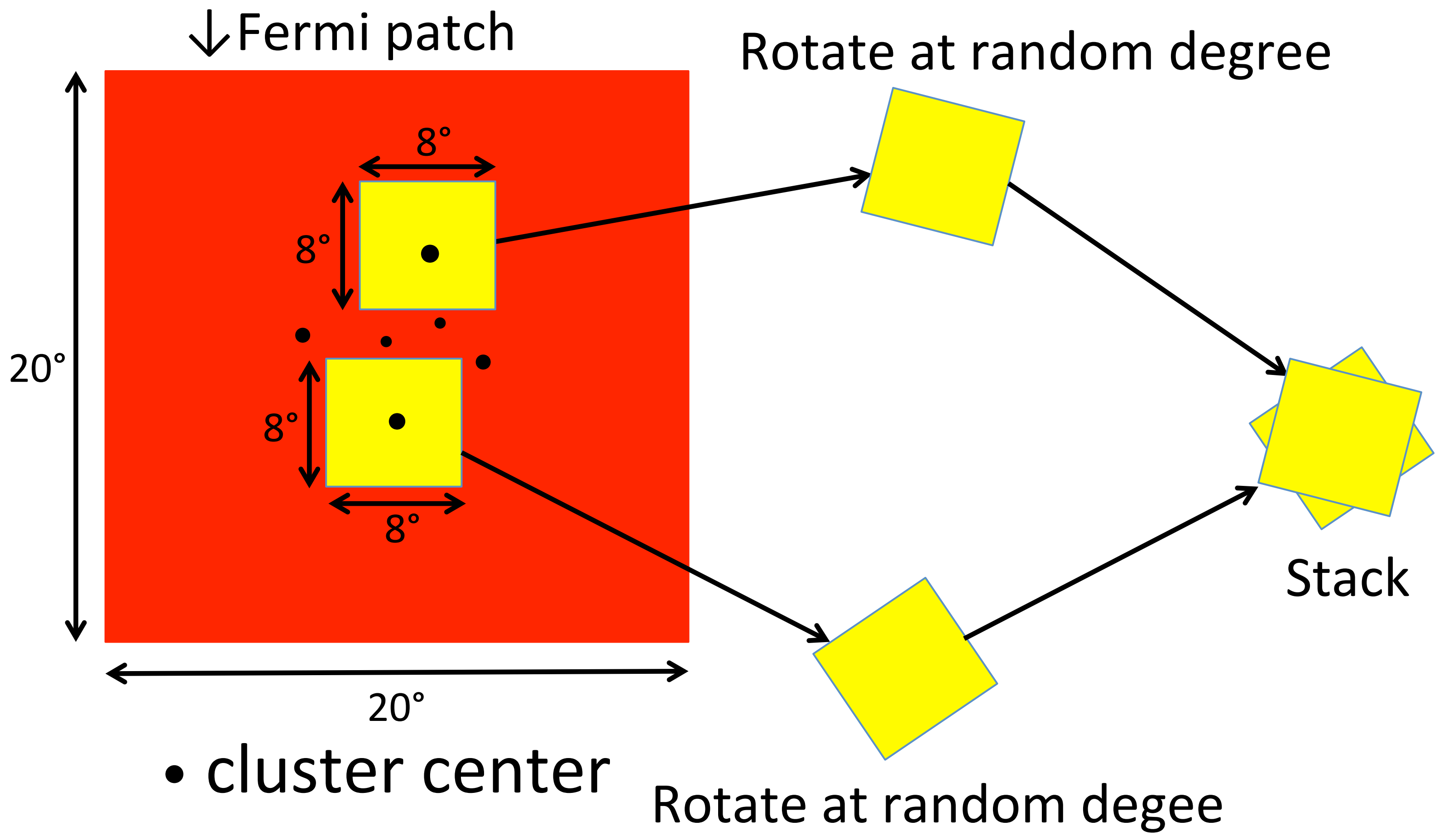
$\chi^2_{\rm clu} - \chi^2_{\rm mod}$ (degree of freedom = 3)

redshift range	Baseline	Model A	Model B	Model C
$0.1 < z < 1.1$	0.30	0.29	0.28	0.27
$0.1 < z < 0.6$	2.2	1.9	1.8	2.2
$0.6 < z < 1.1$	2.5	0.79	0.76	0.78

Shot-noise amplitude ($10^{-9}{\rm cm}^{-2}{\rm s}^{-1}{\rm sr}^{-1}$)

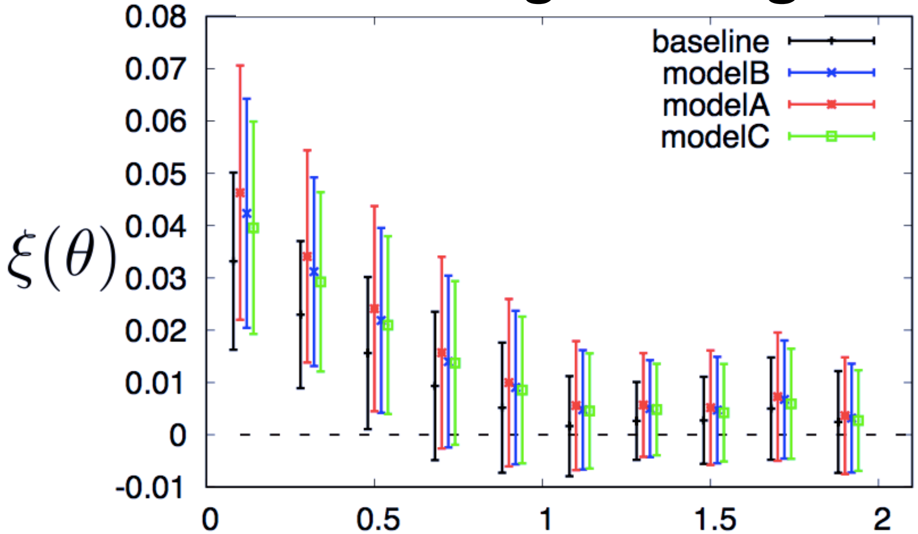
redshift range	Baseline	Model A	Model B	Model C
$0.1 < z < 1.1$	5.1	6.3	5.6	5.2
$0.1 < z < 0.6$	2.8	4.4	3.6	3.6
$0.6 < z < 1.1$	4.2	6.9	6.3	5.6

Stacking Method

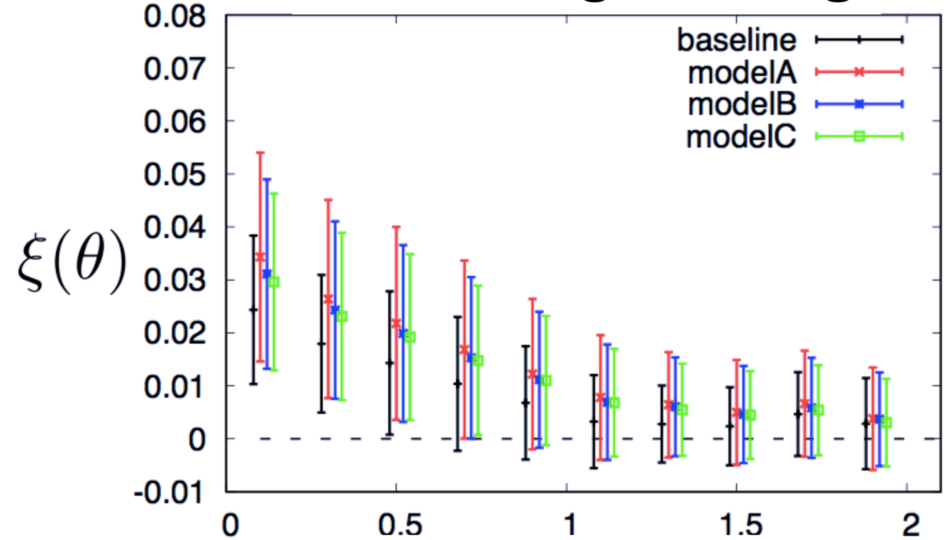


Cross-Correlation Analysis

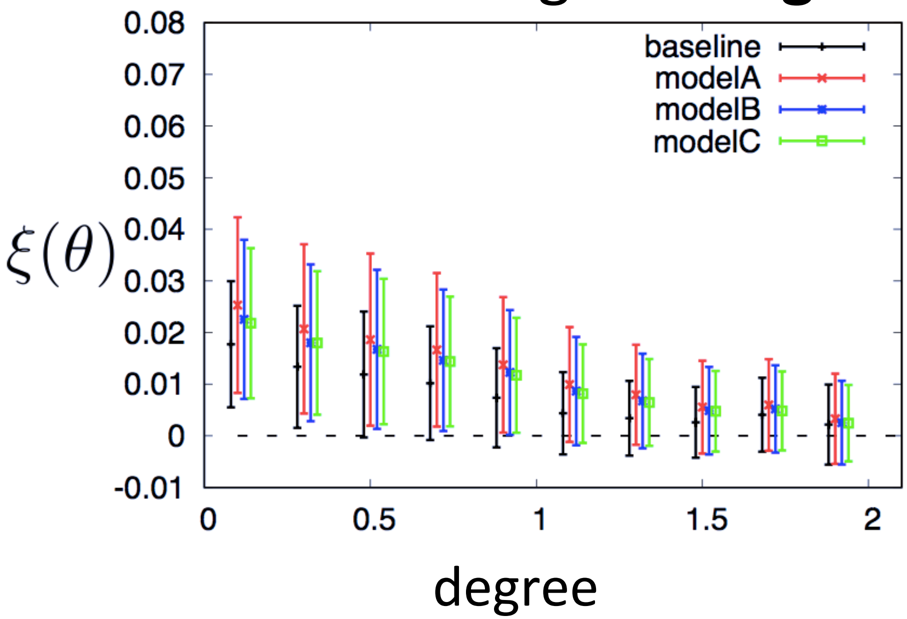
smoothing : **0.3deg**



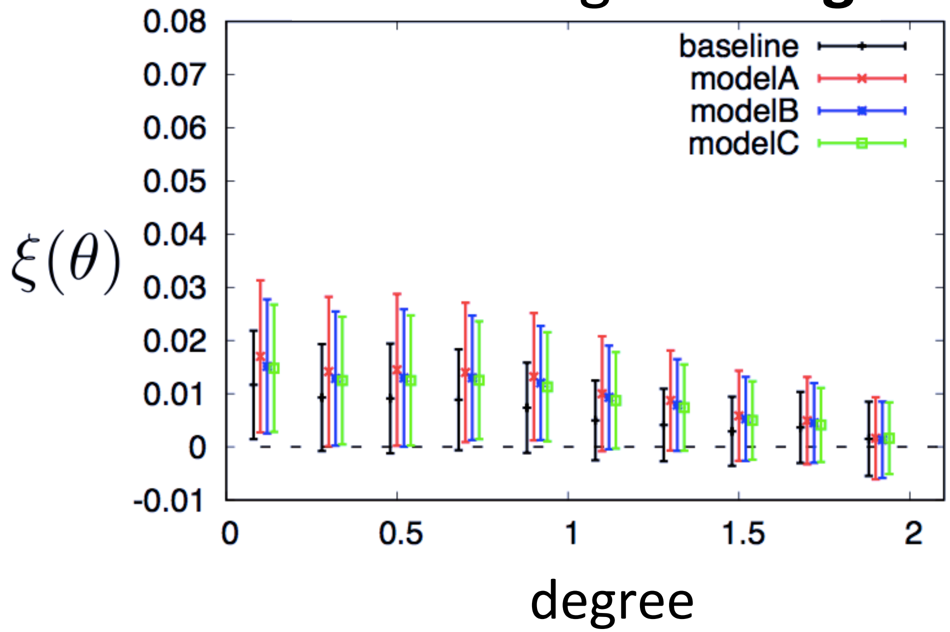
smoothing : **0.5deg**



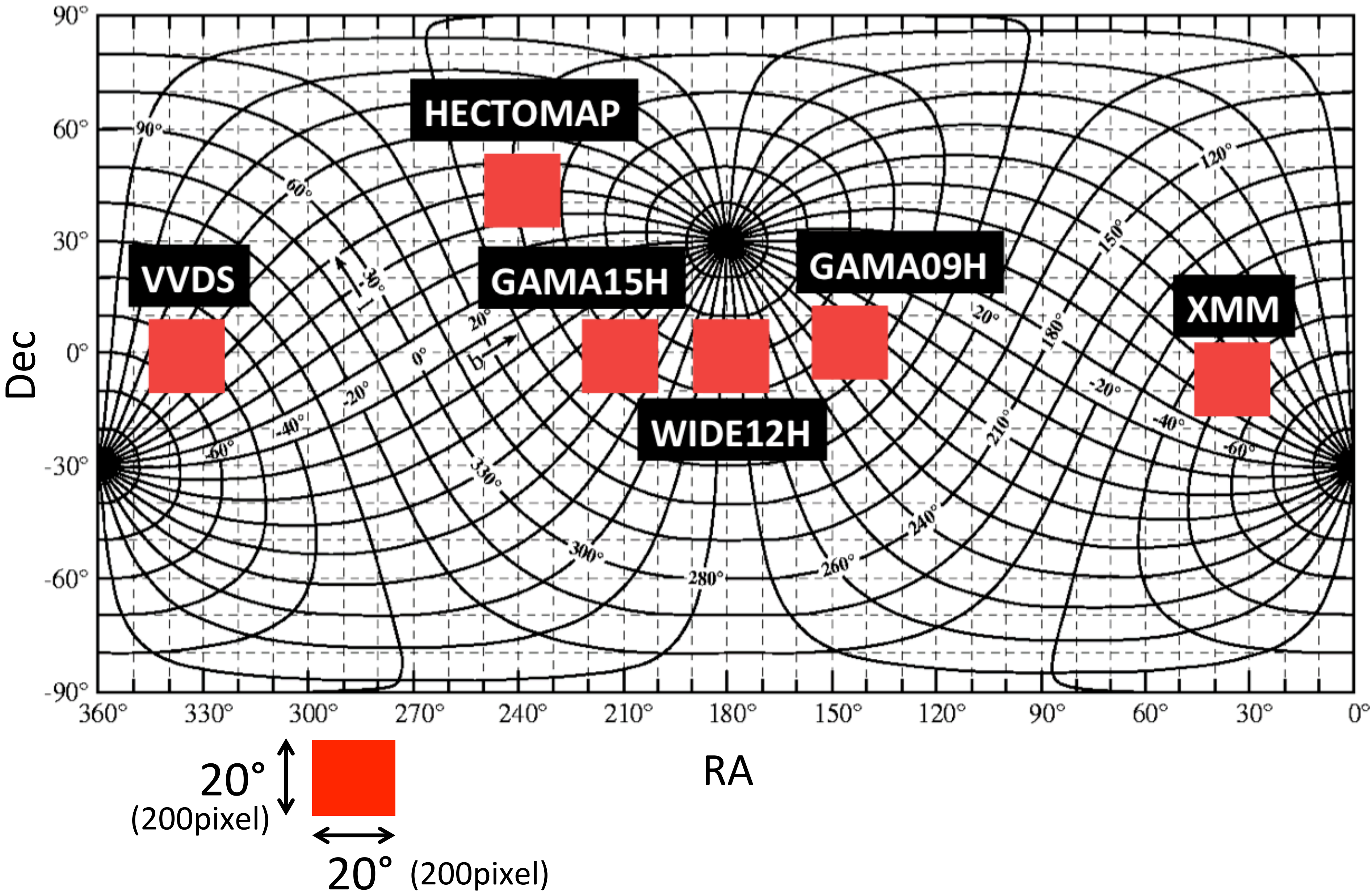
smoothing : **0.7deg**



smoothing : **1.0deg**

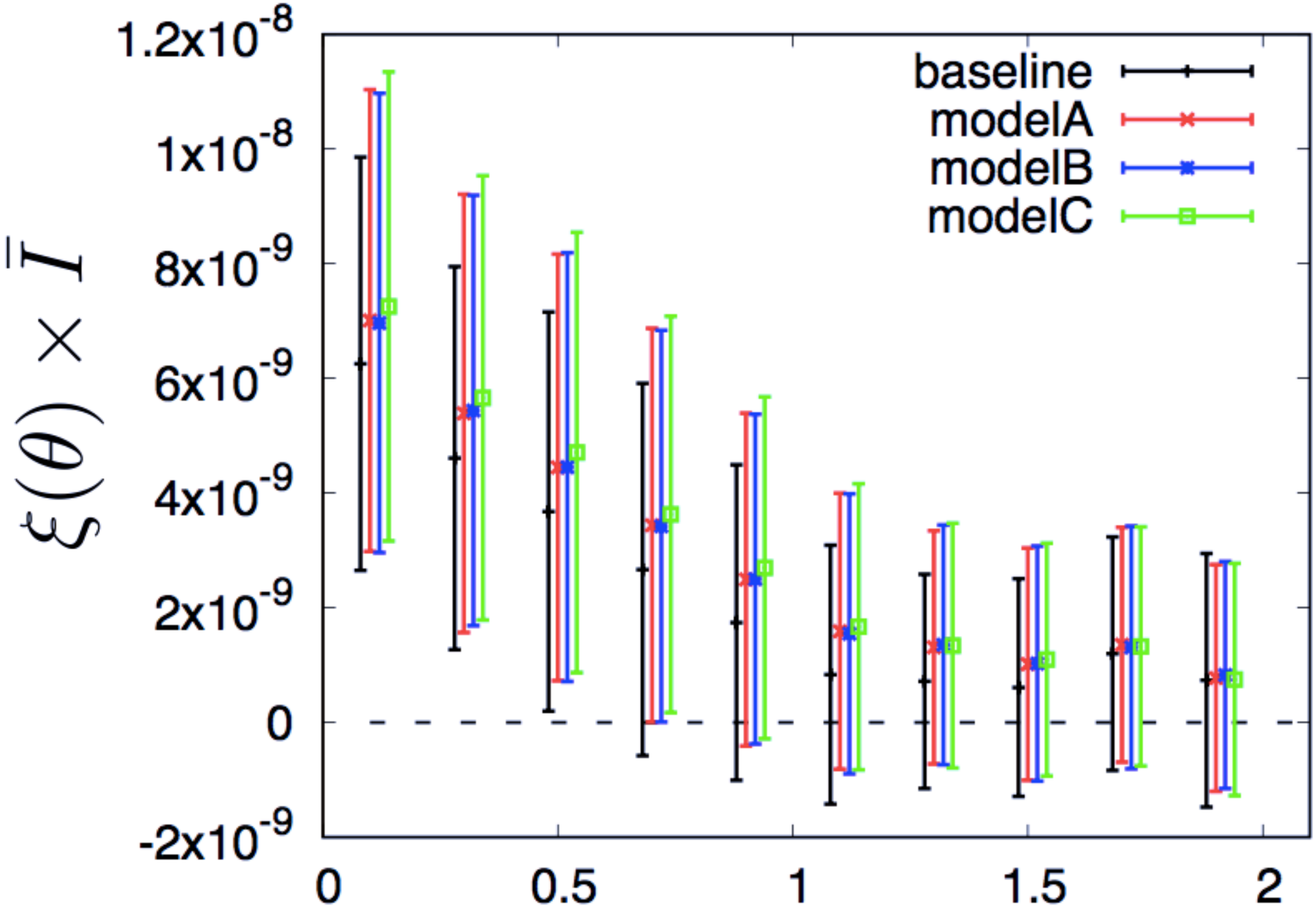


Distribution of Fermi observation area we use



Cross-Correlation Analysis

Cross-correlation function × mean intensity of gamma-rays



degree