Report of the cross-correlation study of the gamma-ray background with HSC clusters

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高エネルギー物理学研究会2018 @東京大学

Introduction for Gamma-ray Background

Fermi Gamma-ray Space Telescope

(launched in 2008)

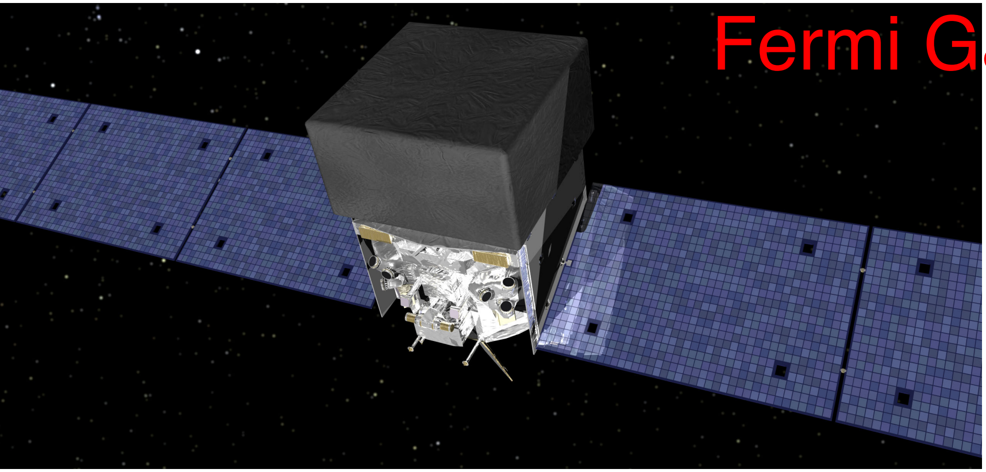


Image Credit: NASA

Fermi gamma-ray sky
by Fermi-LAT

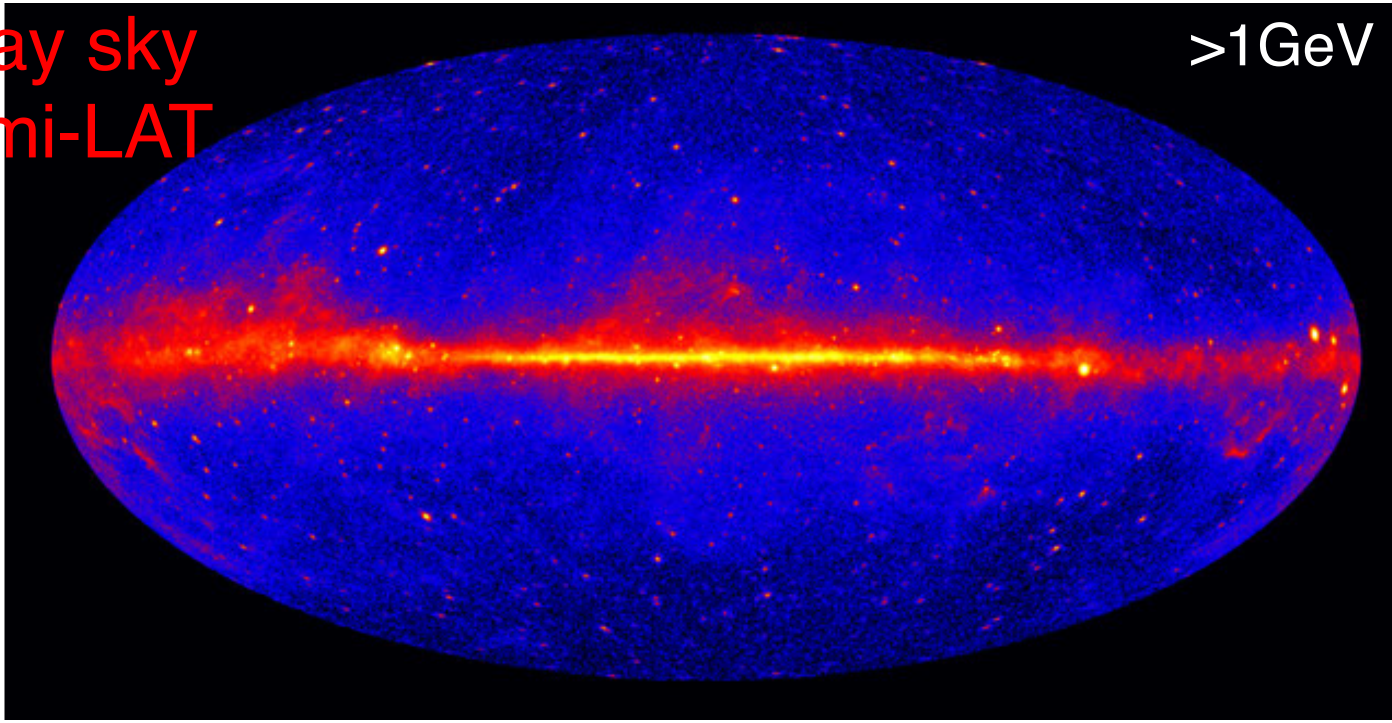


Image Credit: NASA/DOE/Fermi LAT Collaboration

Introduction for Gamma-ray Background

Fermi Gamma-ray Space Telescope

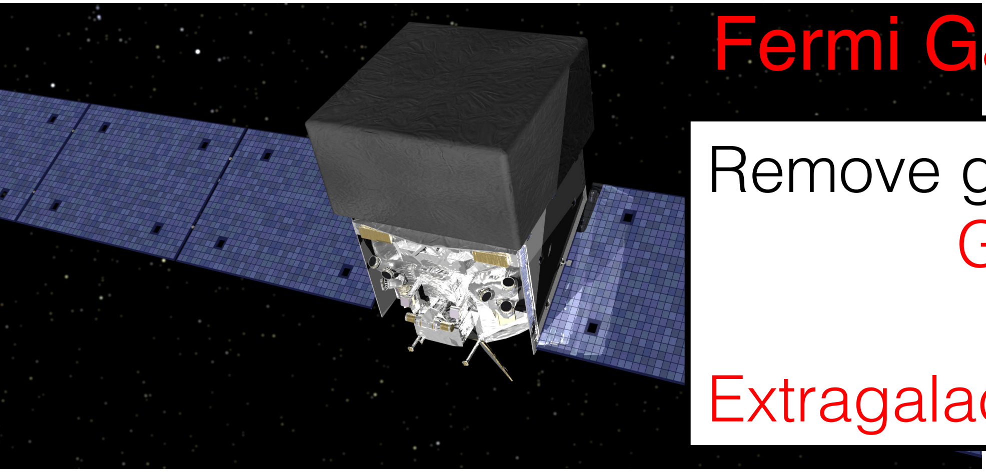


Image Credit: NASA

Remove gamma-ray emission from
Galactic medium
&
Extragalactic resolved point sources

Fermi gamma-ray sky
by Fermi-LAT

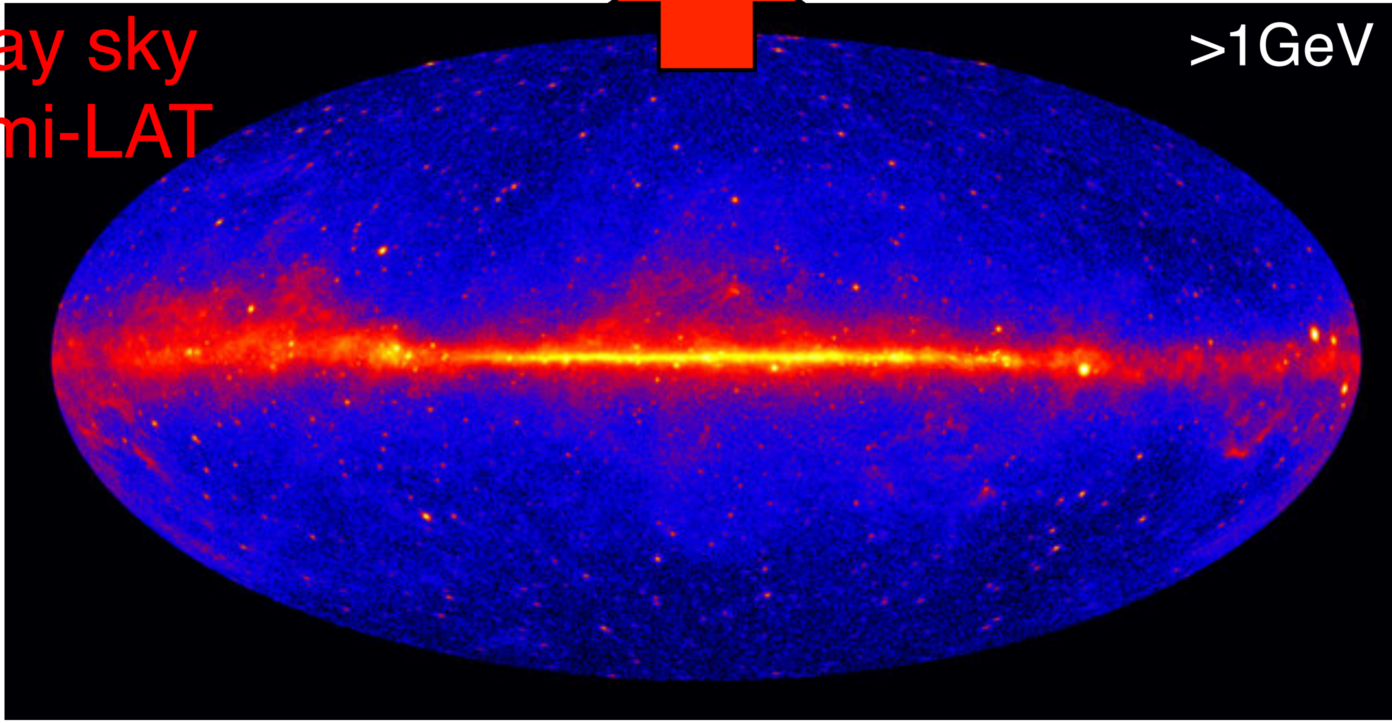
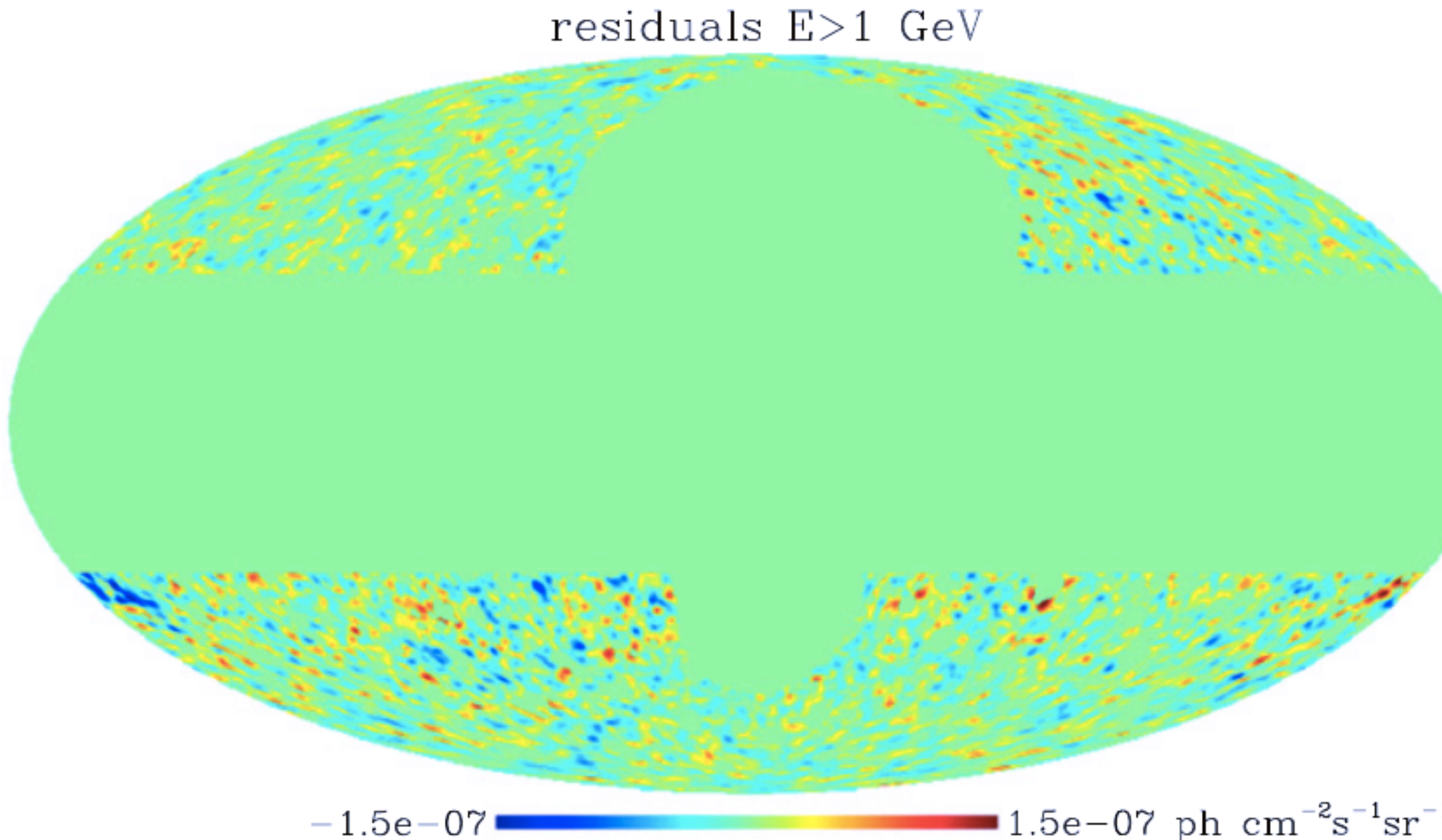


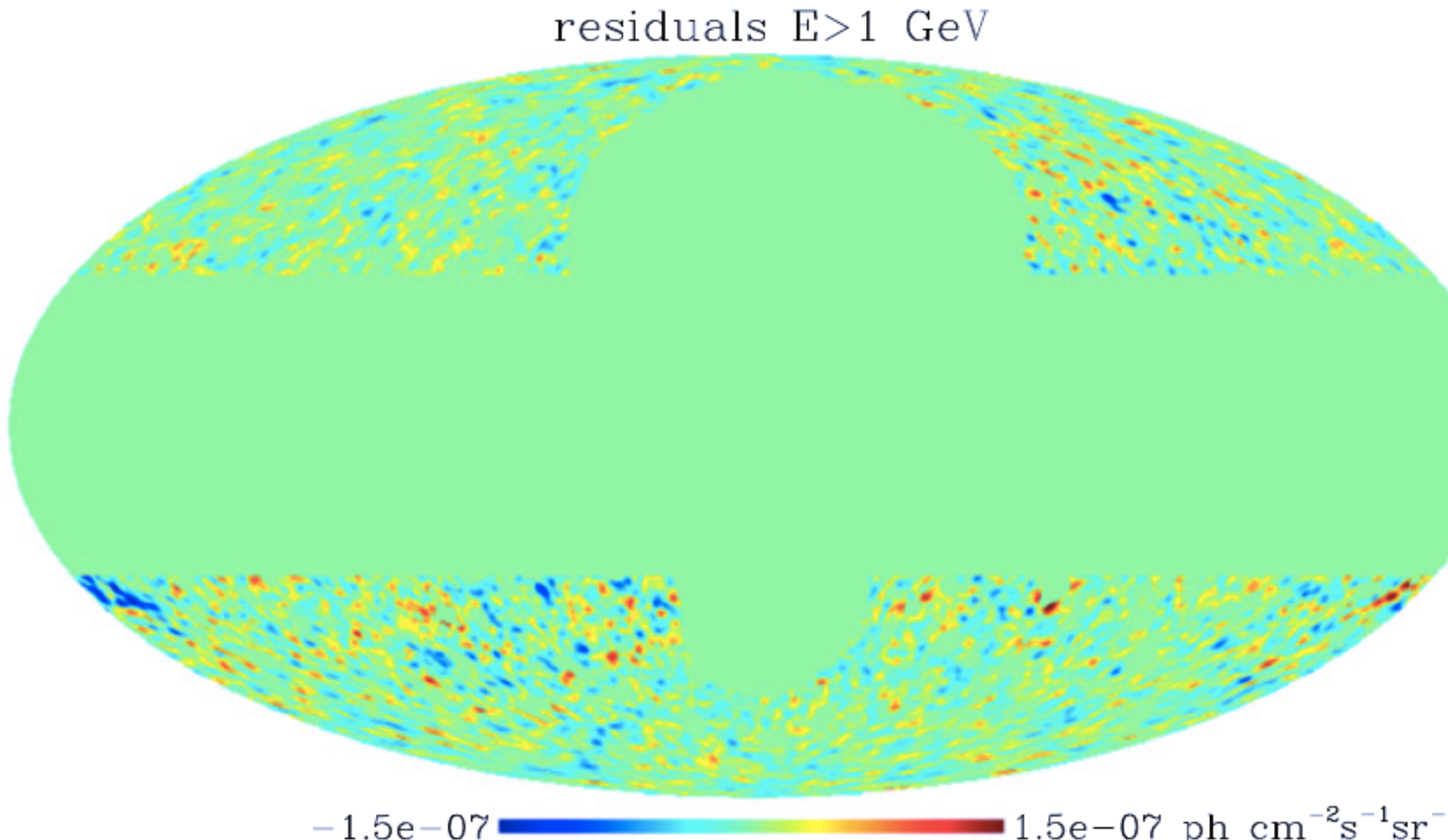
Image Credit: NASA/DOE/Fermi LAT Collaboration

Introduction for Gamma-ray Background



Xia et al. 2015

Introduction for Gamma-ray Background

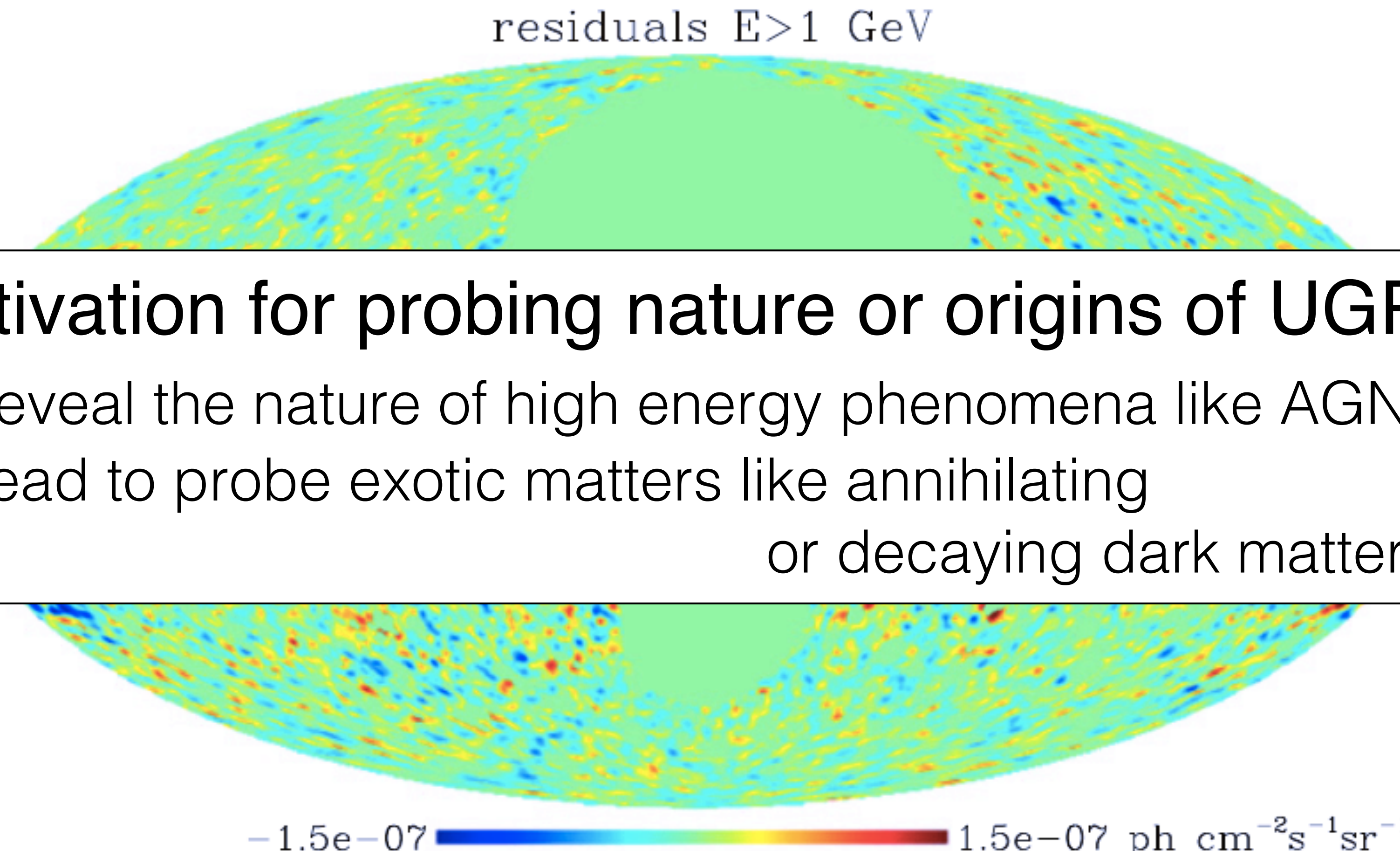


Xia et al. 2015

Unresolved Gamma-ray Background (UGRB)

...Extragalactic emission from unresolved sources containing astronomical or unknown objects

Introduction for Gamma-ray Background



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

Xia et al. 2015

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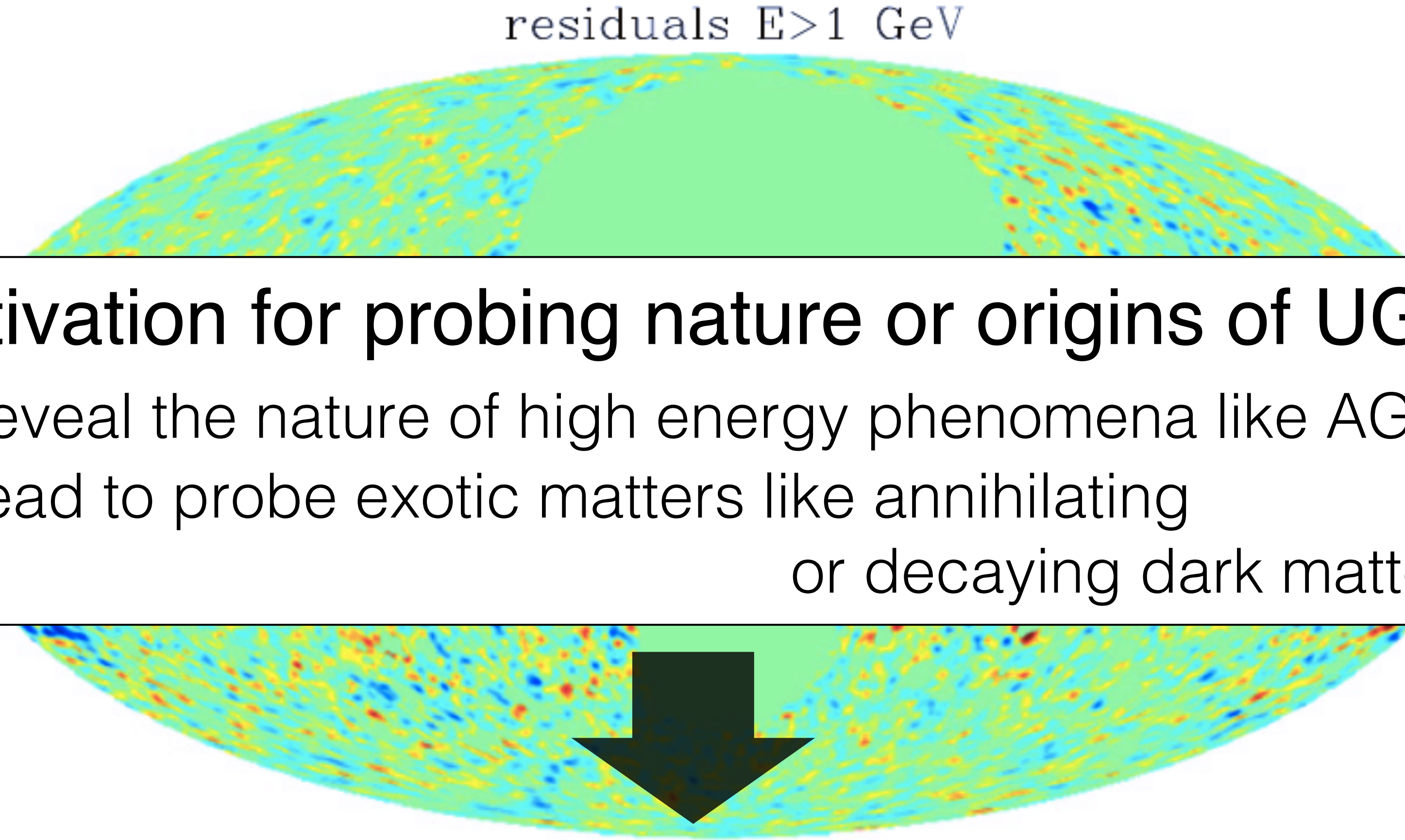

Motivation for probing nature or origins of UGRB:

- reveal the nature of high energy phenomena like AGN
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What is associated with UGRB ?

- large scale structure, galaxy cluster or galaxy

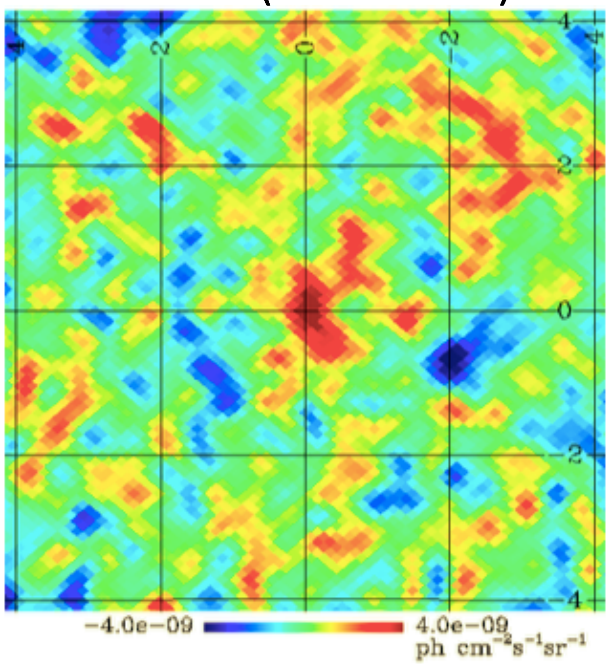
Previous Work

Branchini et al.(2017)

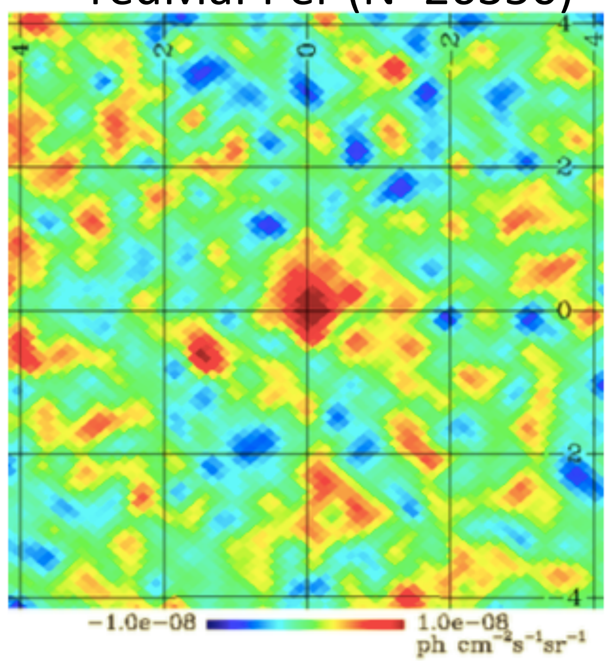
Stacking Analysis & **Cross-Correlation Analysis** of UGRB with 3 galaxy cluster catalogs

Stacked Image

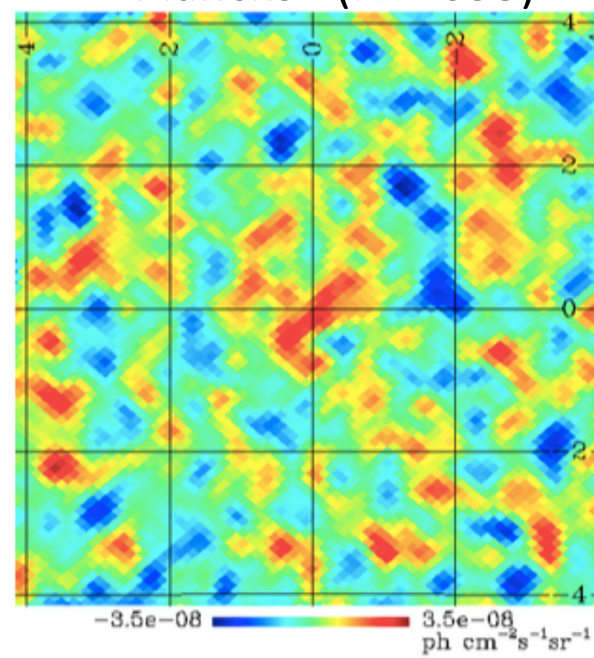
WHL12 (N=158103)



redMaPPer (N=26350)



PlanckSZ (N=1653)



gamma-ray energy : 1-10GeV

Previous Work *Branchini et al.(2017)*

Stacking Analysis & Cross-Correlation Analysis
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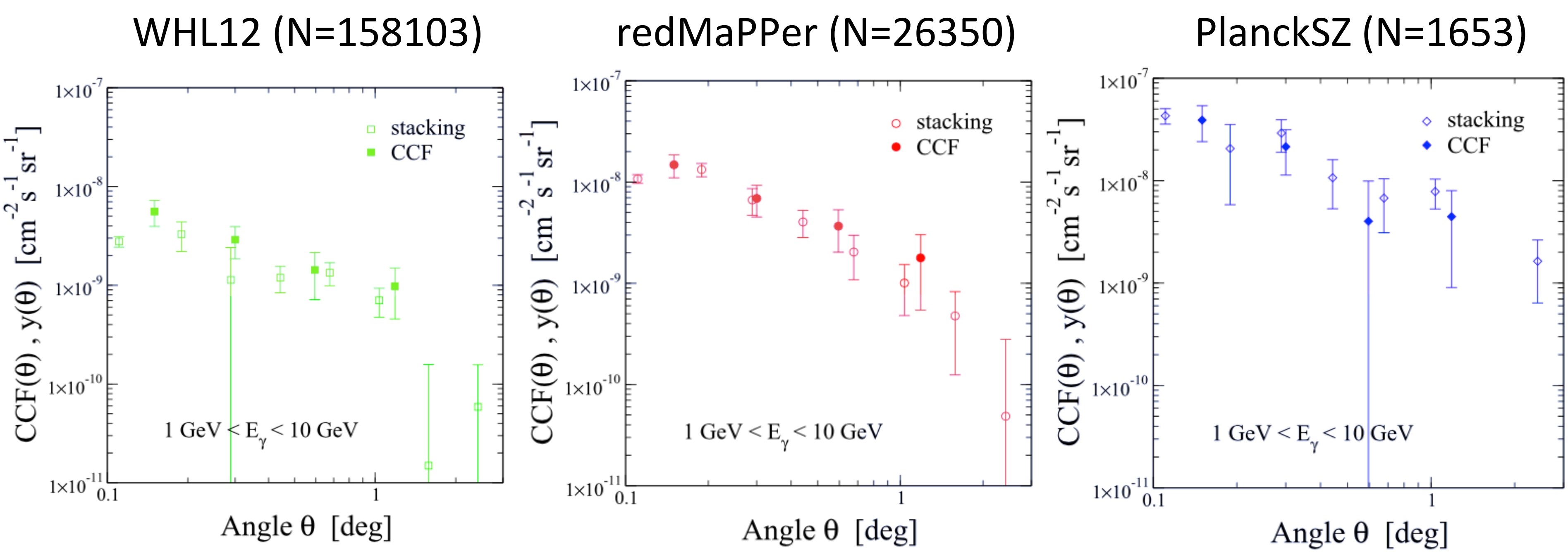
Cross-Correlation Analysis



gamma-ray energy : 1-10GeV

This Work

Probe association of UGRB with galaxy clusters

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)**

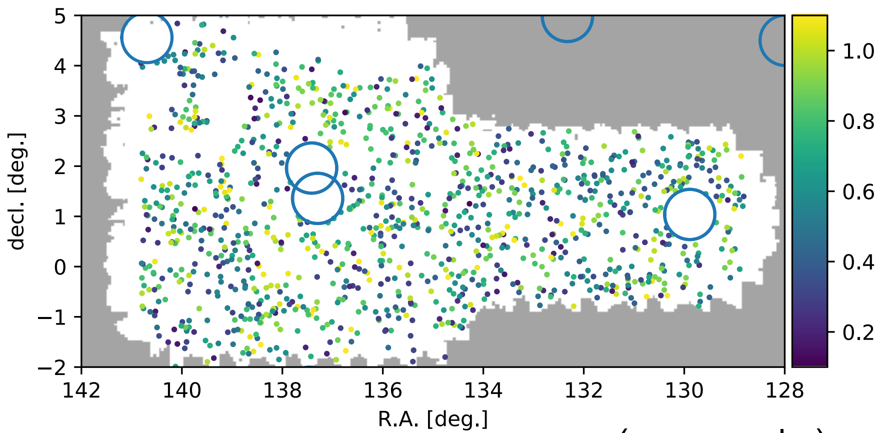
  Energy range : 1-100 GeV

  Fermi-PSF :

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

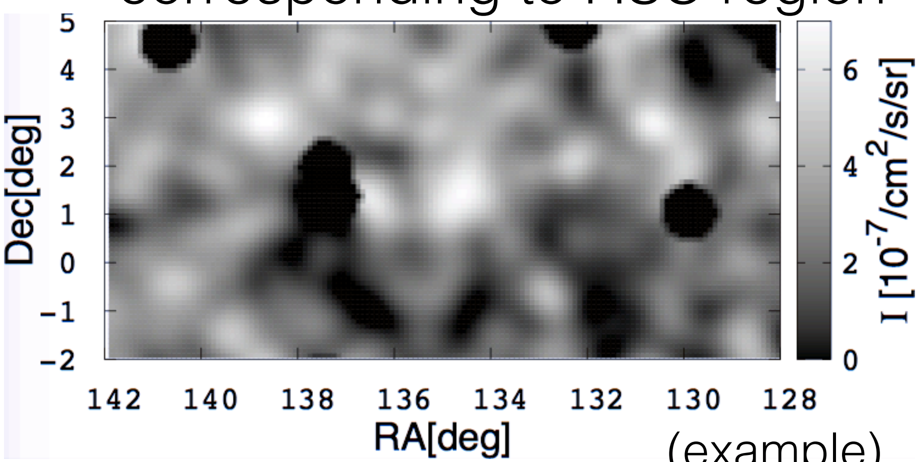
  ~0.2 deg (E > 10 GeV)

HSC-cluster distribution



(example)

UGRB intensity map corresponding to HSC region

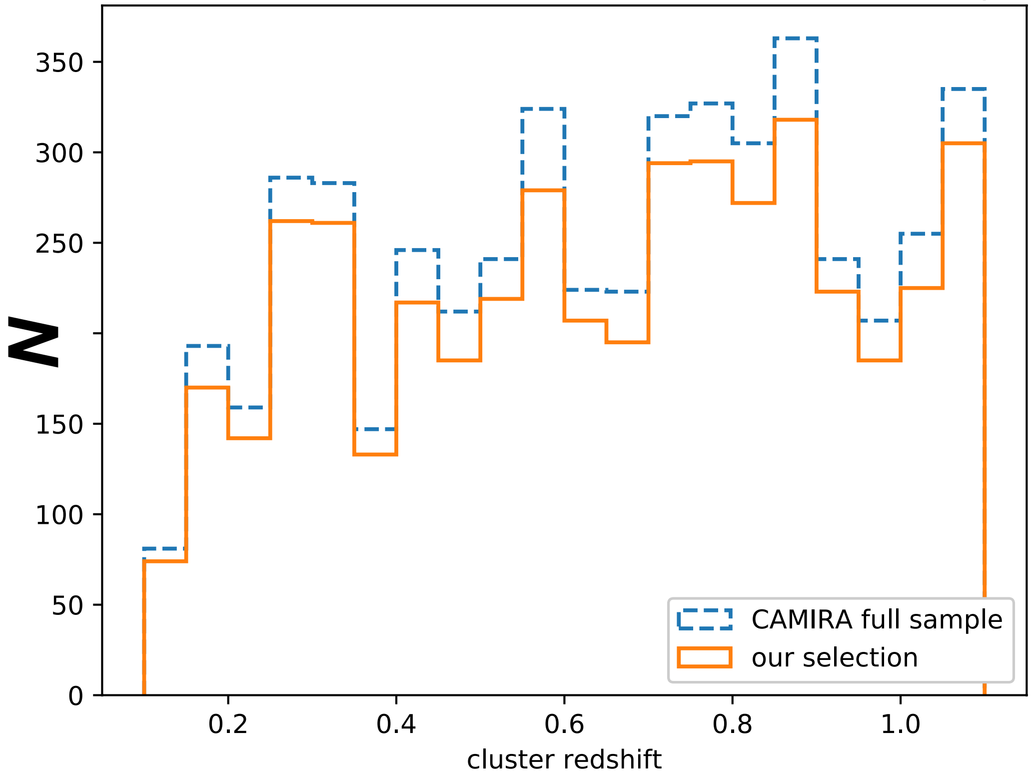


(example)

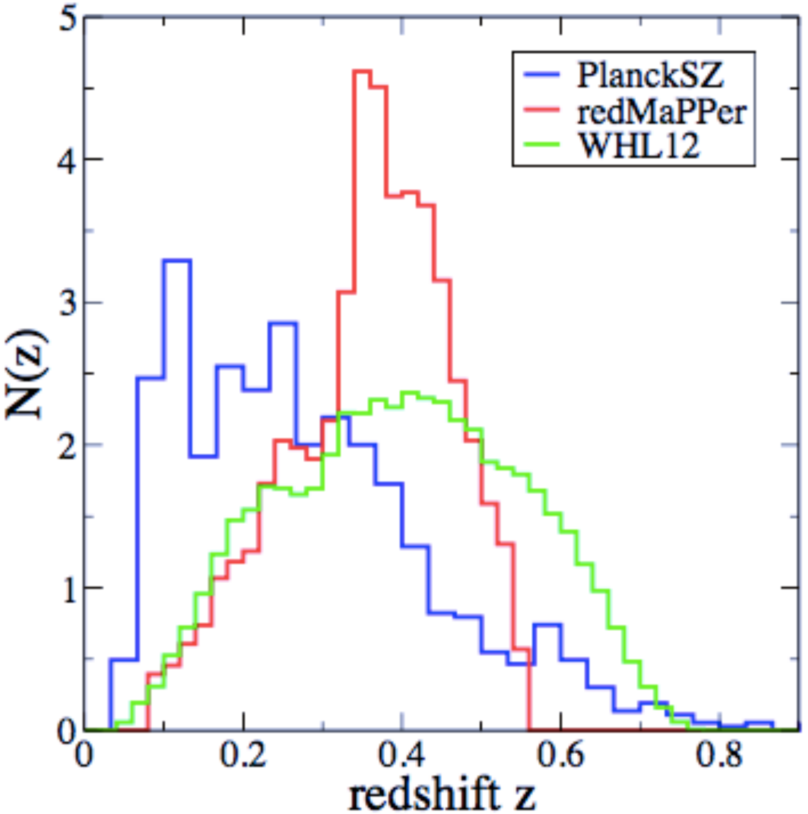
Data: HSC cluster & UGRB map

Redshift Distribution

This work (HSC cluster catalog)



previous work (Branchini et al.(2017))



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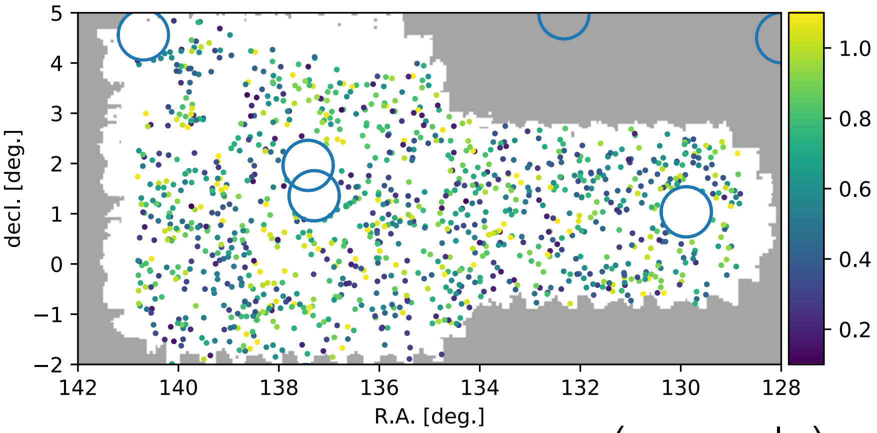
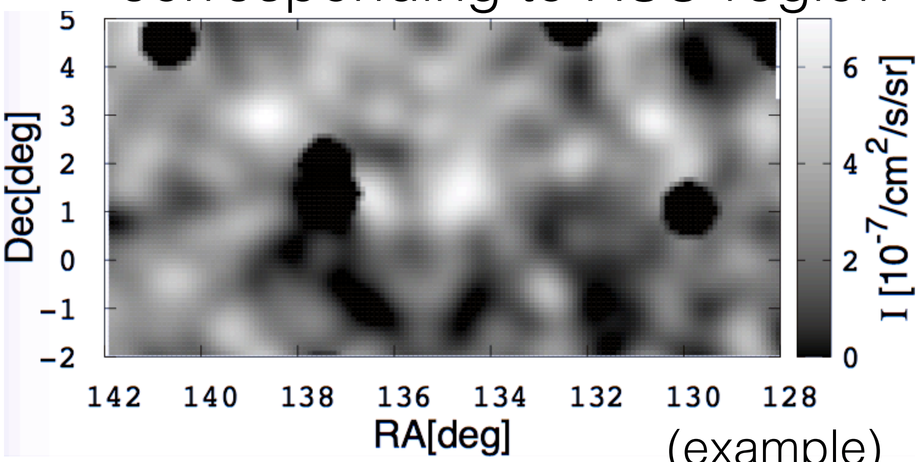


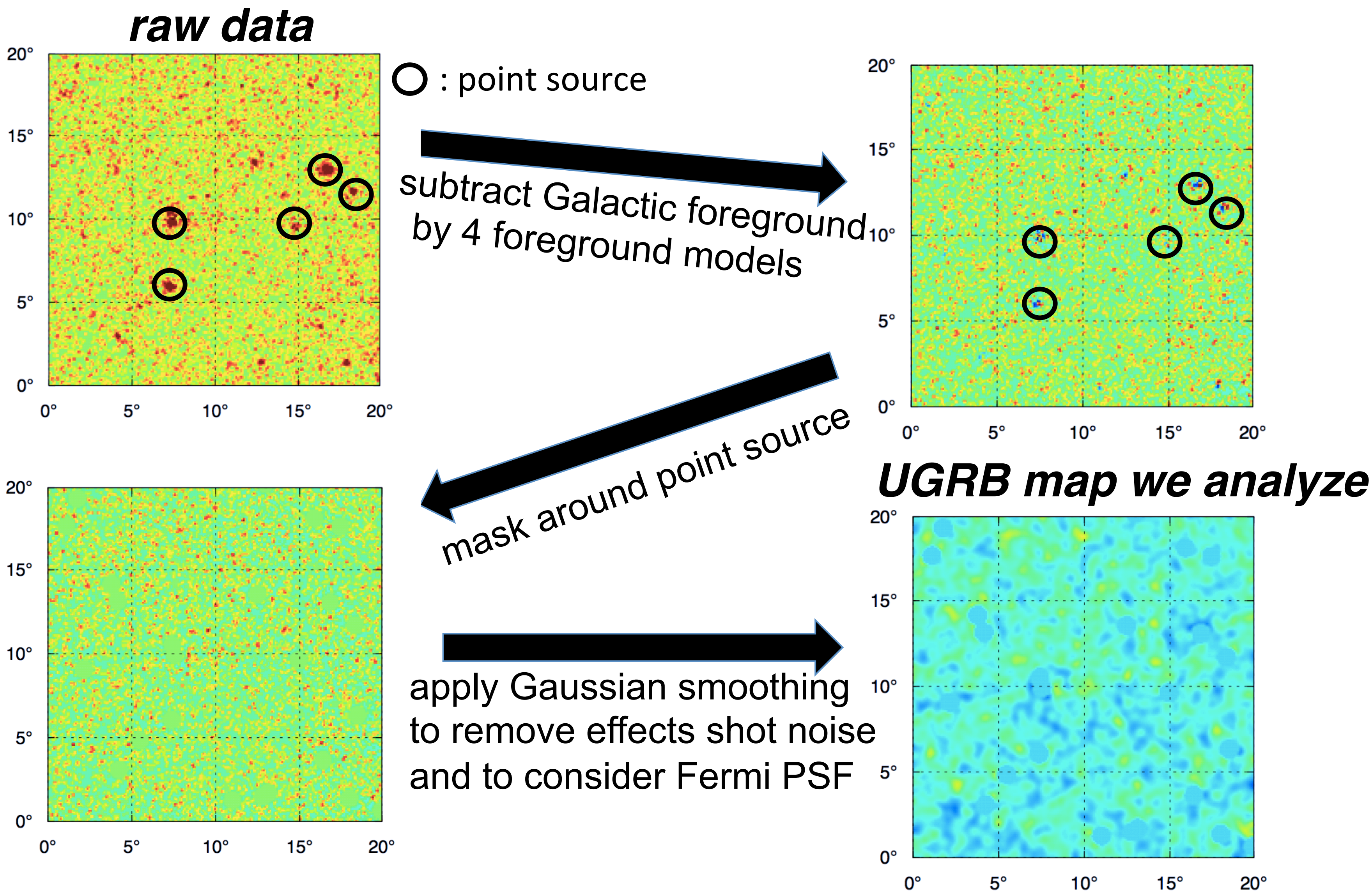
(example)

UGRB intensity map corresponding to HSC-region



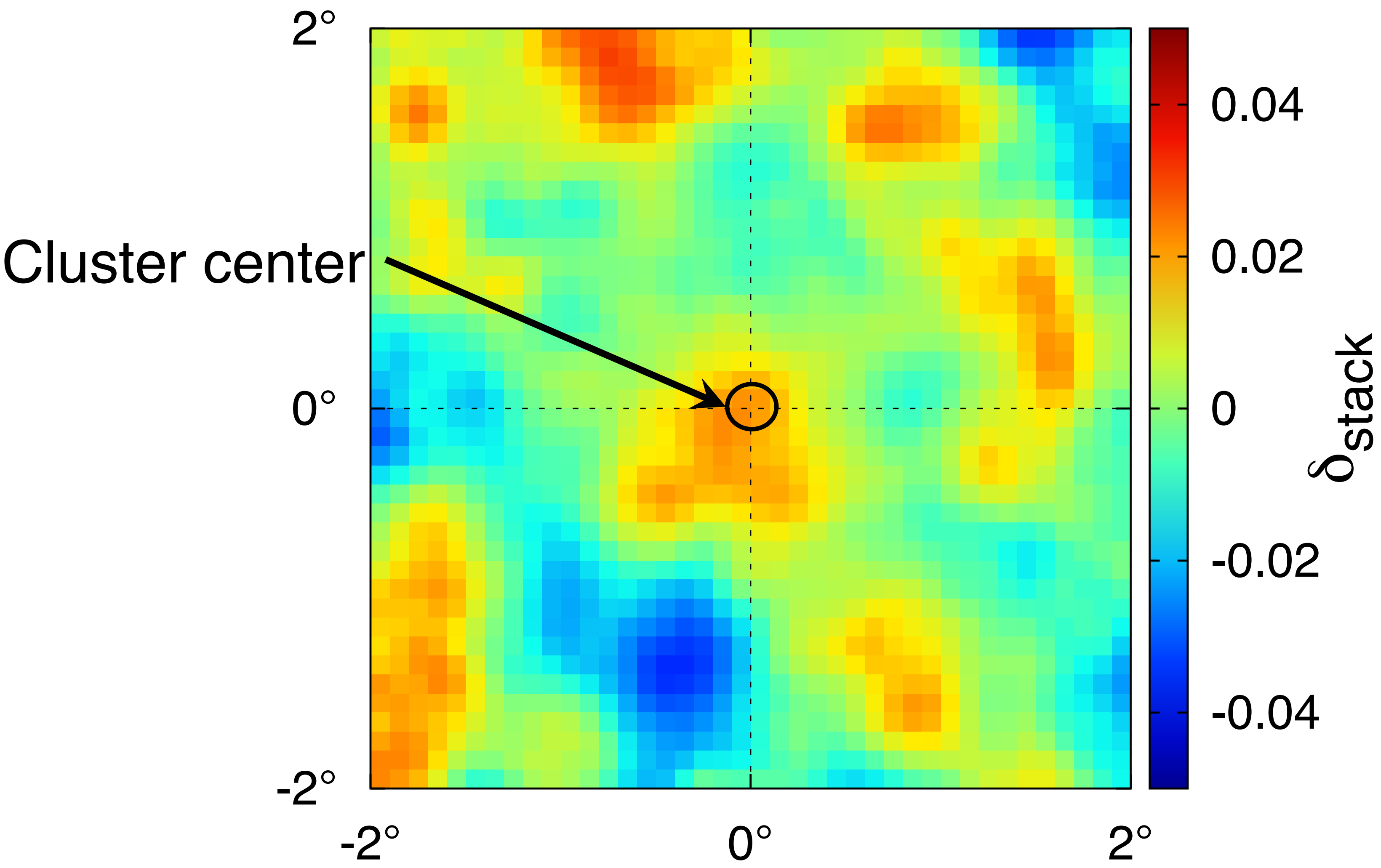
(example)

Construction of UGRB Map



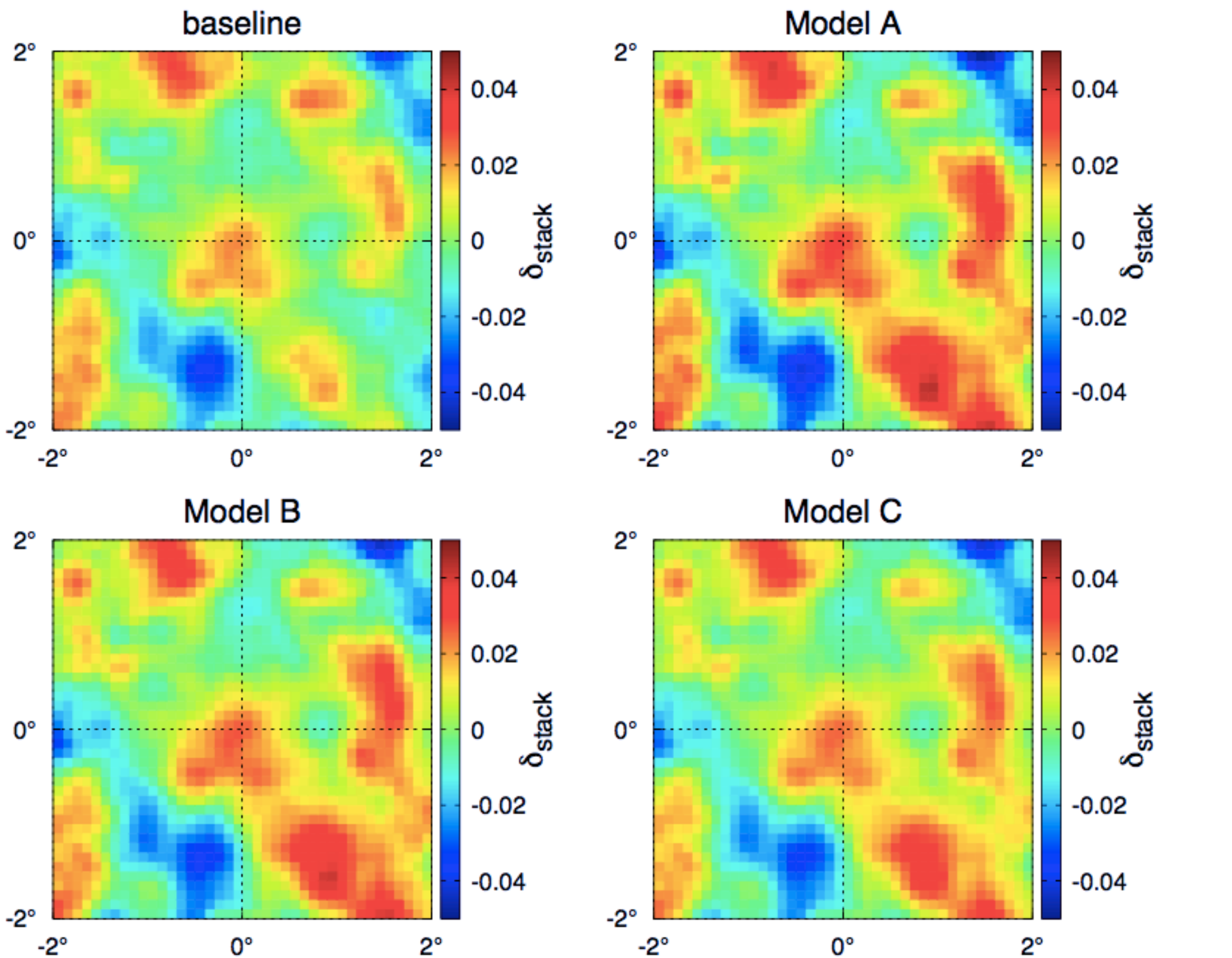
Stacking Analysis

Fluctuation field of UGRB around cluster position



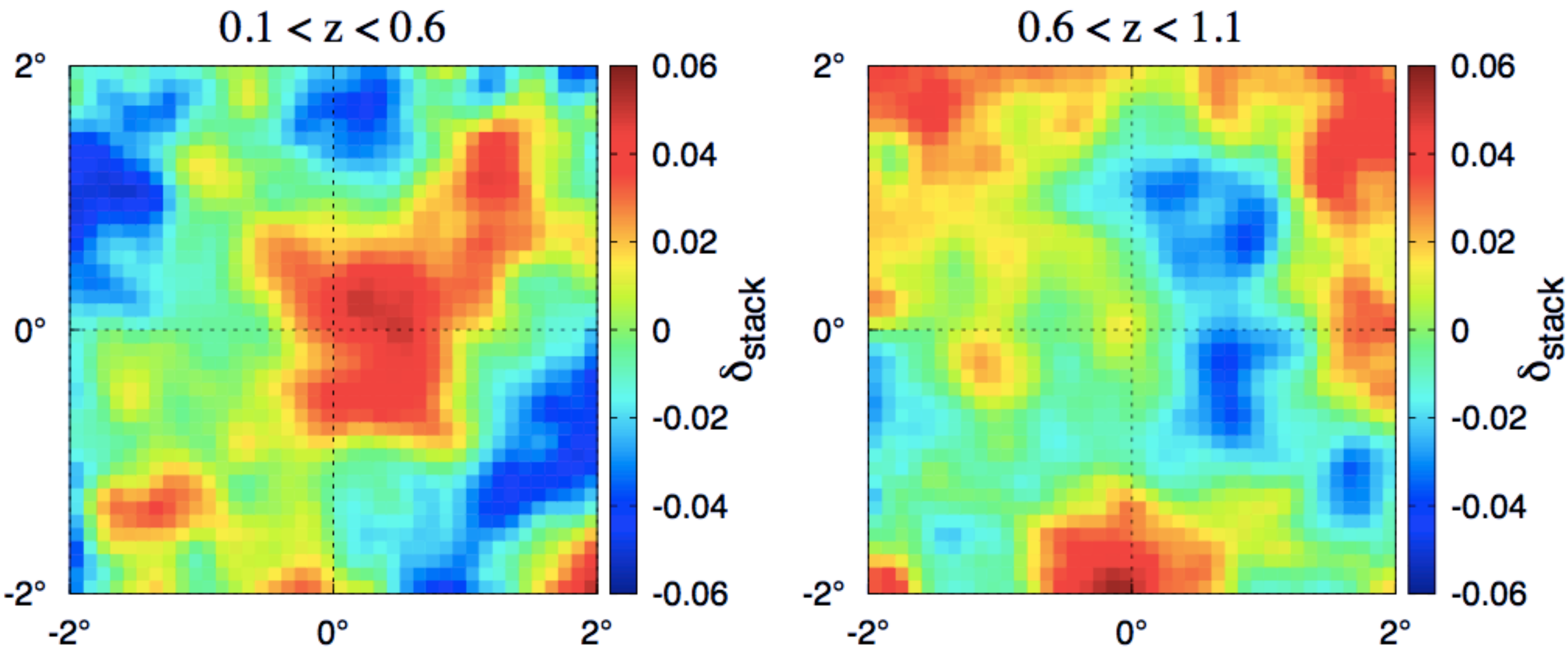
Stacking Analysis

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

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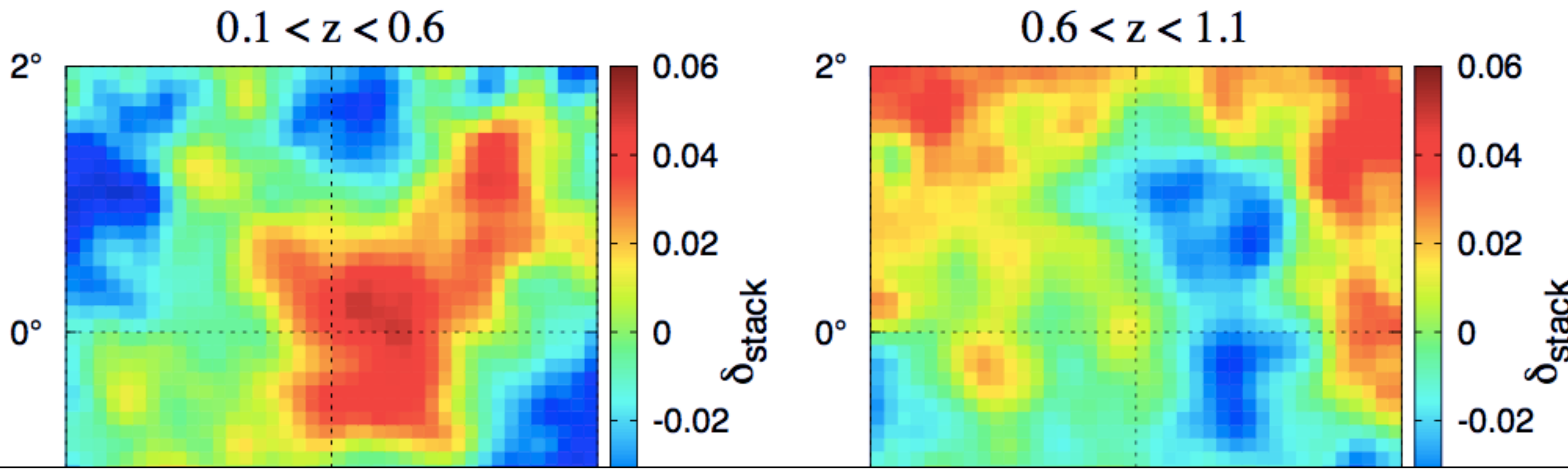


The average separation of the CAMIRA clusters is ~0.2 degrees.

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

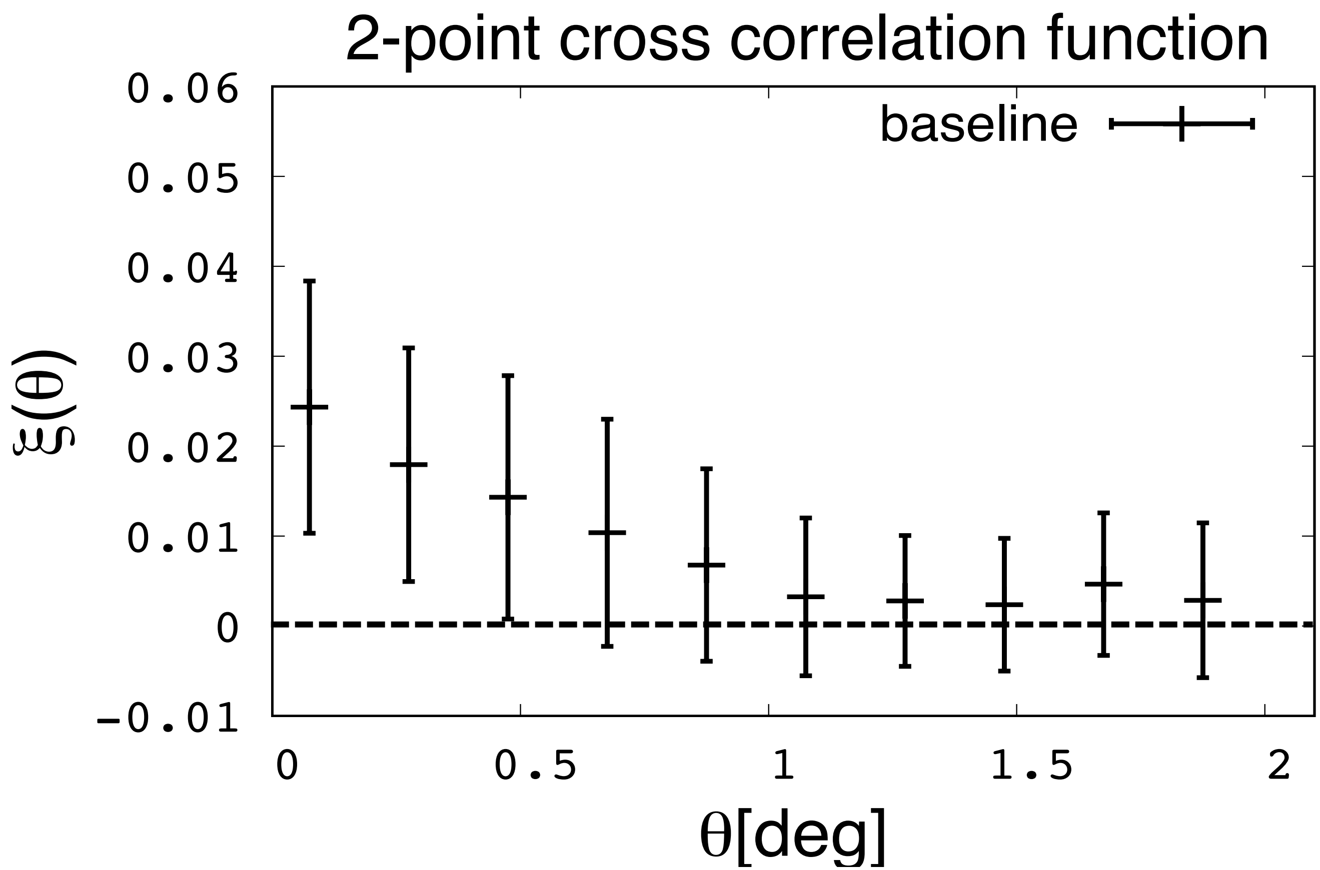
$$\xi(\theta) = \langle n_{clu}(0)\delta_\gamma(\theta)\rangle$$

$n_{clu}(0)$: 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 $\xi(\theta)$,
the Jackknife method to estimate statistical errors

Cross-Correlation Analysis

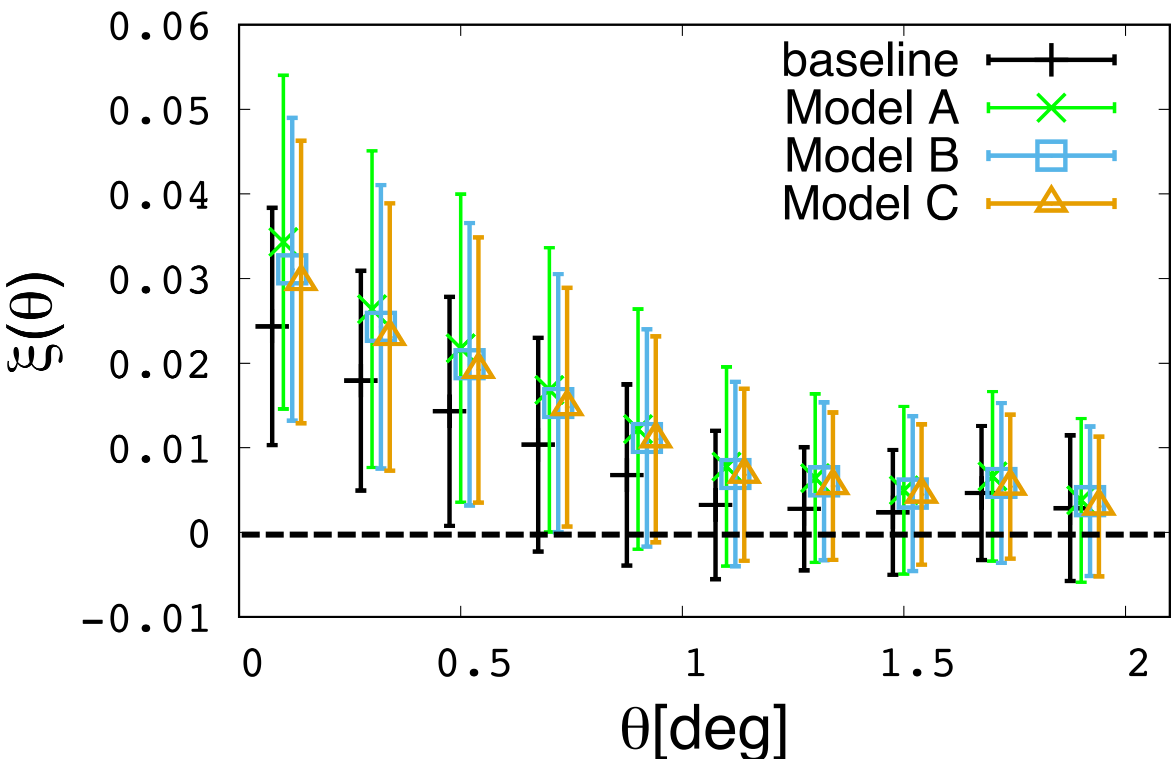


Statistical significance

redshift range	baseline	Model A	Model B	Model C
$0.1 < z < 1.1$	2.2	[redacted]		
[redacted]				

Cross-Correlation Analysis

Cross-correlation function using different Galactic foreground models



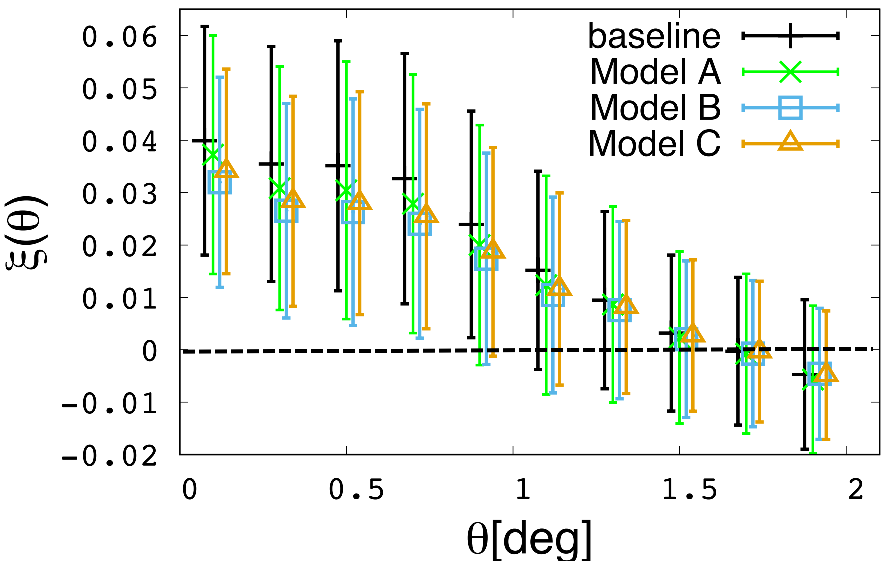
Statistical significance

redshift range	baseline	Model A	Model B	Model C
$0.1 < z < 1.1$	2.2	2.0	2.0	2.0
[redacted]				

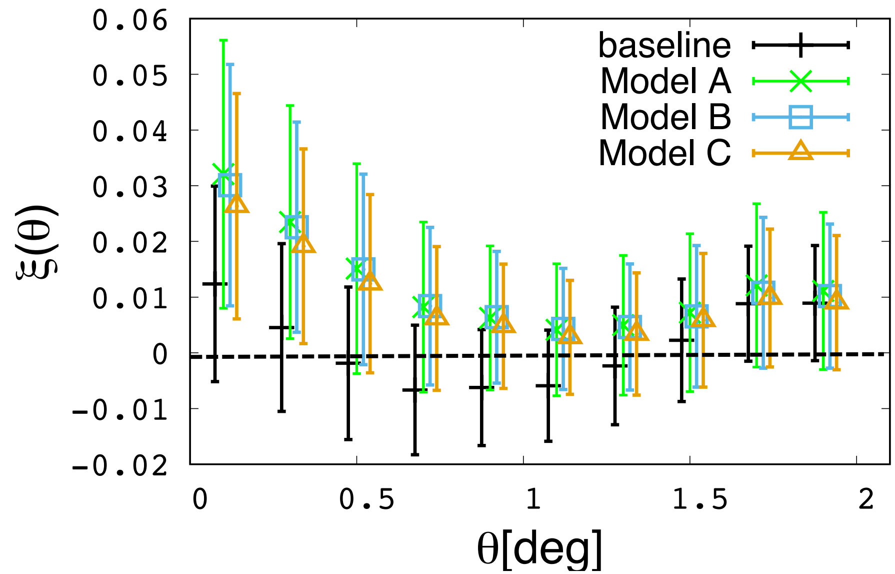
Cross-Correlation Analysis

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
[redacted]				
$0.1 < z < 0.6$	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

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

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

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

$P^{(3D)}_{hX}$: three dimensional cross power spectrum between cluster and X

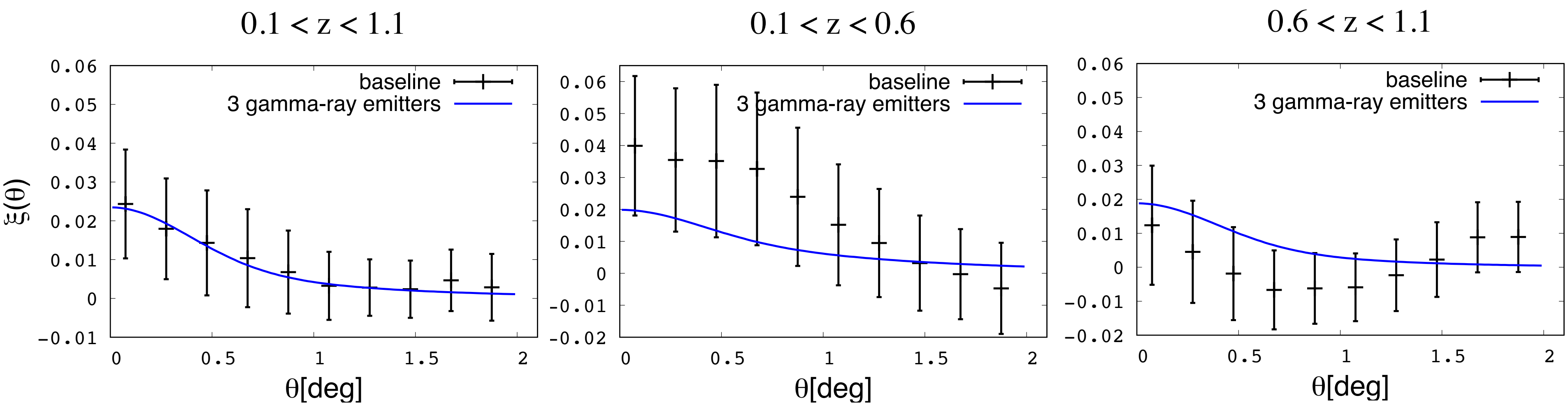
$$\xi(\theta) = \frac{1}{\langle n_{\rm clu}\rangle \langle I_\gamma \rangle} \int \frac{d^2\ell}{(2\pi)^2} \exp\left[i\boldsymbol{\ell}\cdot\boldsymbol{\theta}\right] P_{c\gamma}(\ell) \hat{W}(\ell, \theta_G)$$

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

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

Implication

Cross-correlation signals using Baseline foreground model and model predictions with 3 gamma-ray emitters



This simple model for 3 gamma-ray emitters can explain the signal so far.

Summary

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

✔ Cross-correlation signal

- Significance level : $0.1 < z < 1.1$ and $0.1 < z < 0.6$: **2.0-2.3 σ**,
  $0.6 < z < 1.1$: **1.6-1.9 σ**.
- Confirm the consistency for correlation signal between:
  Cross-Correlation Analysis & *Stacking Analysis*.

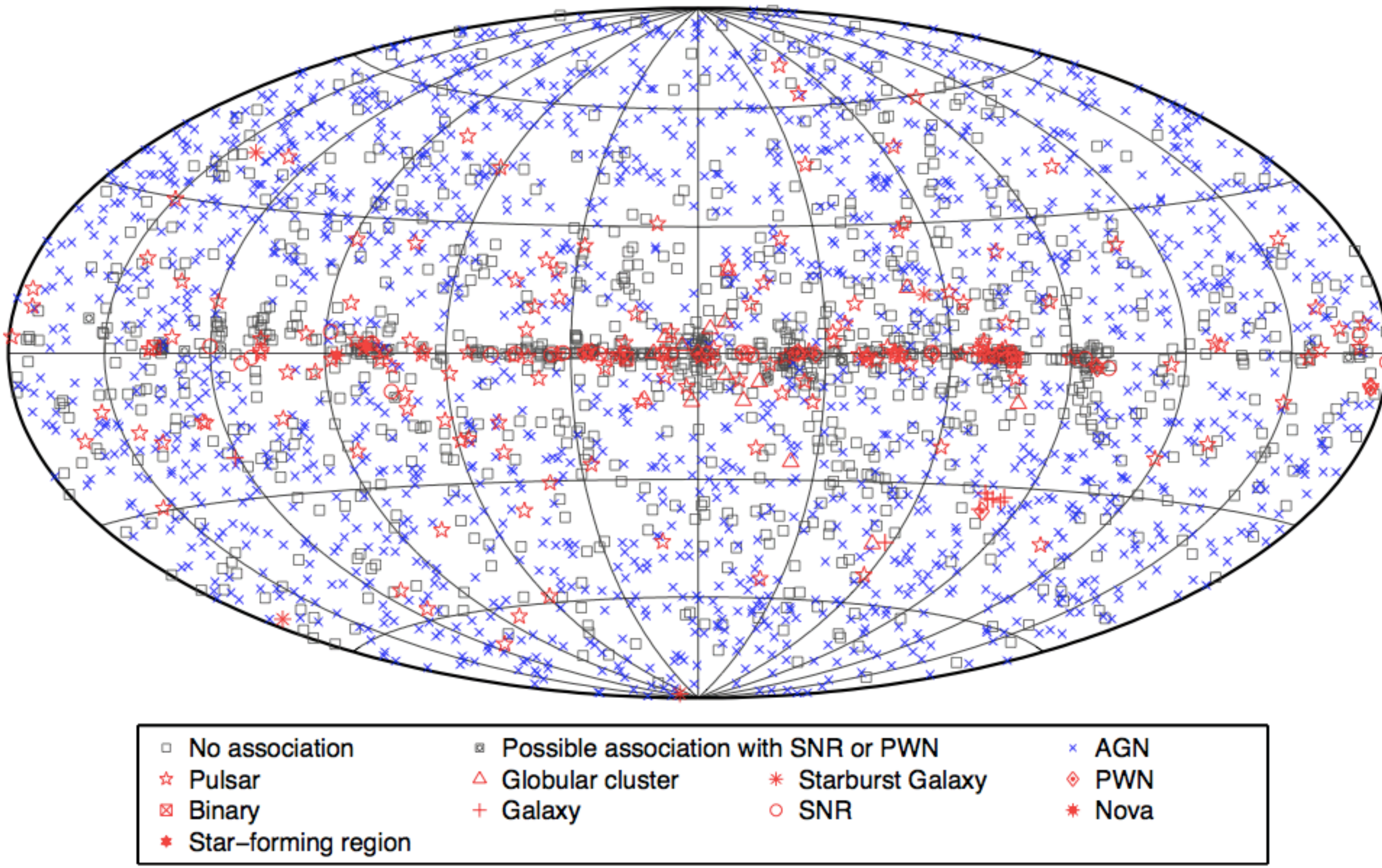
✔ Implication for the signal

- Assume 3 gamma-ray emitters to model cross-correlation signal:
  Blazar, Star-Forming Galaxy, Radio Galaxy.
- The detected signal is
  consistent with the theoretically predicted model.

✔ In the future ...

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

Gamma-ray Point Source



Acero, F. et al. (2015)

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**

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

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

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

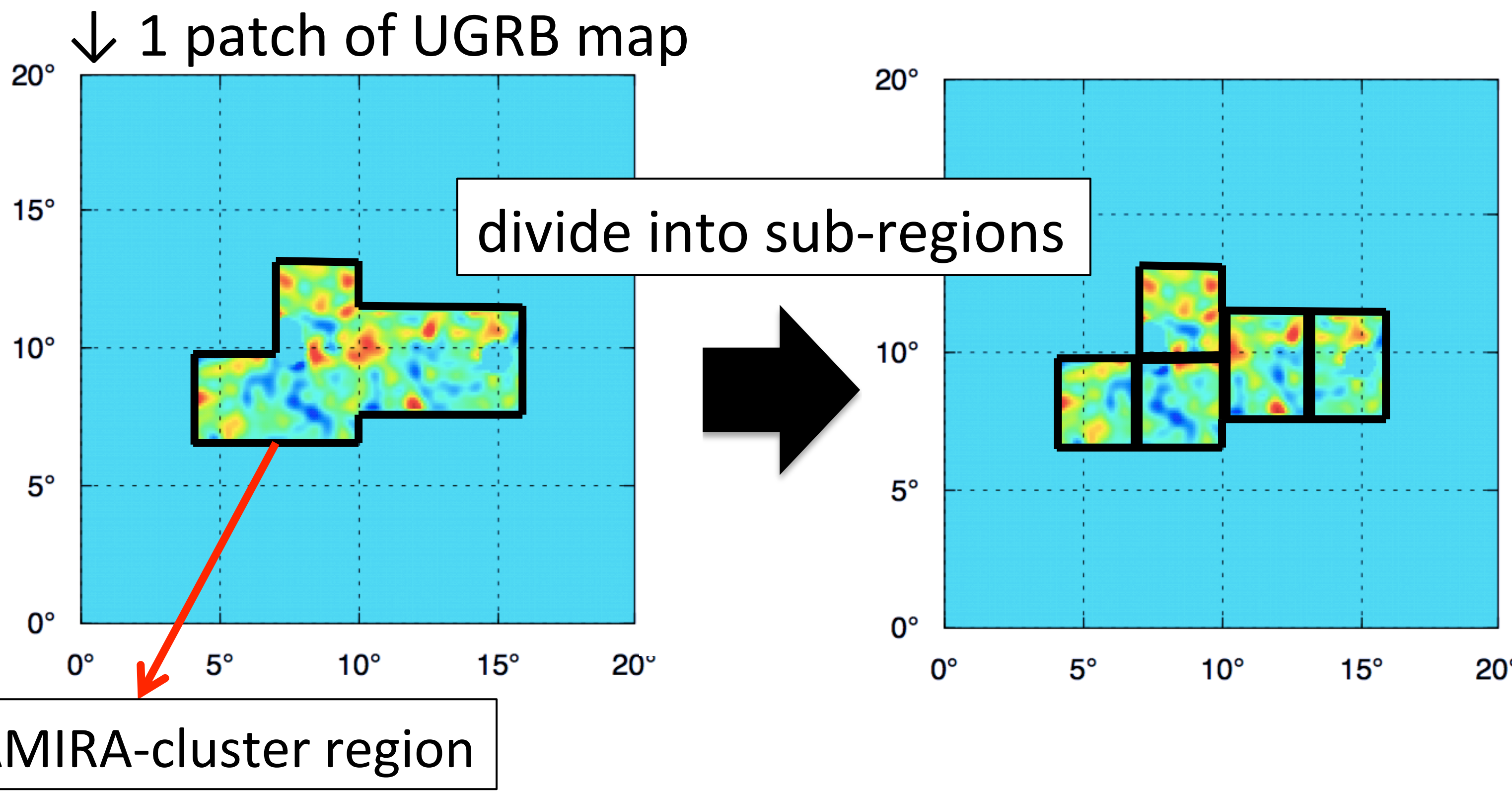
$D_{\gamma}(\theta)$: count of photon numbers in Fermi map separation θ from cluster

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

Cross-Correlation Analysis

How to estimate statistical error

- We use the Jackknife method to estimate the error:



(actually, all cluster regions are divided into 21 regions.)

Cross-Correlation Analysis

How to compute statistical significance

- Covariance matrix $C_{\theta\theta'}^{\mathrm{JK}}$

$$C_{\theta\theta'}^{\mathrm{JK}} = \frac{M-1}{M}\sum_{k=1}^{M}[\xi_k^{\mathrm{obs}}(\theta) - \xi^{\mathrm{mean}}(\theta)] \times [\xi_k^{\mathrm{obs}}(\theta') - \xi^{\mathrm{mean}}(\theta')]$$

Scranton & Johnston (2002)

M : number of jackknife-subsumples

$\xi_k^{\mathrm{obs}}(\theta)$: correlation function in k-th subsumple

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

- χ^2

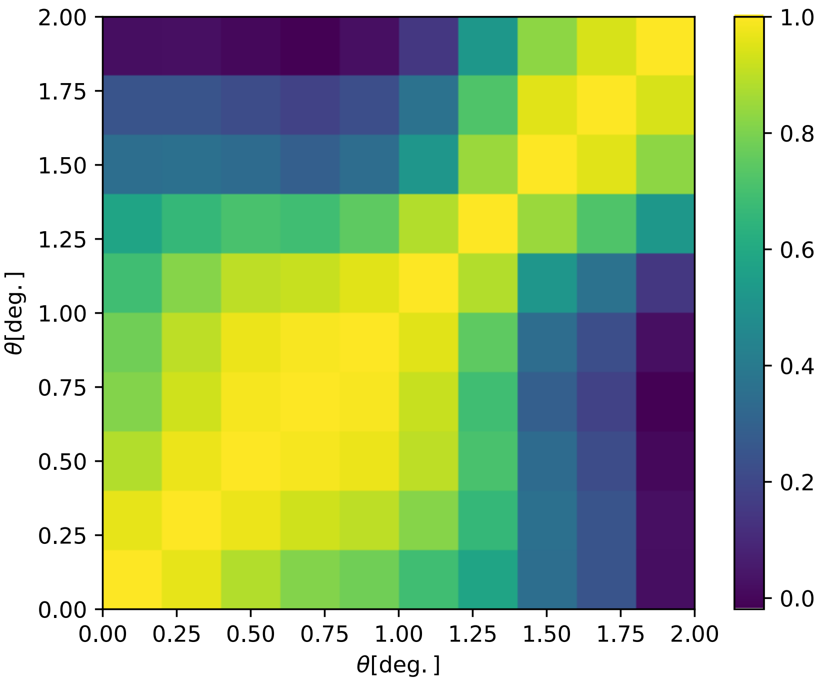
$$\chi^2 = \sum_{i,j}(\xi^{mean}(\theta_i) - m_i)C_{ij}^{-1}(\xi^{mean}(\theta_j) - m_j)$$

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

→ the significance σ is represented by χ

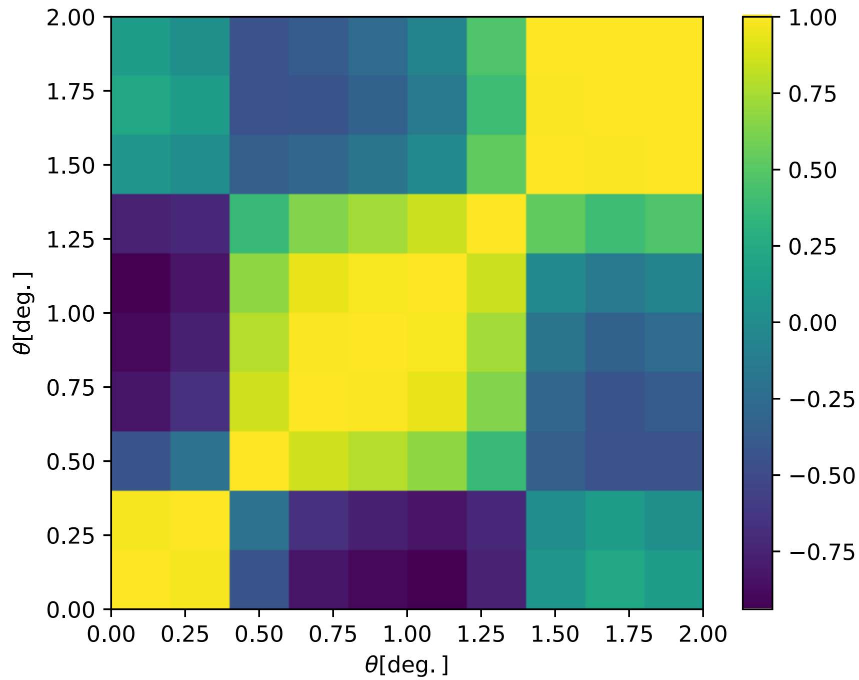
Covariance Matrix

Number of eigen value : 10

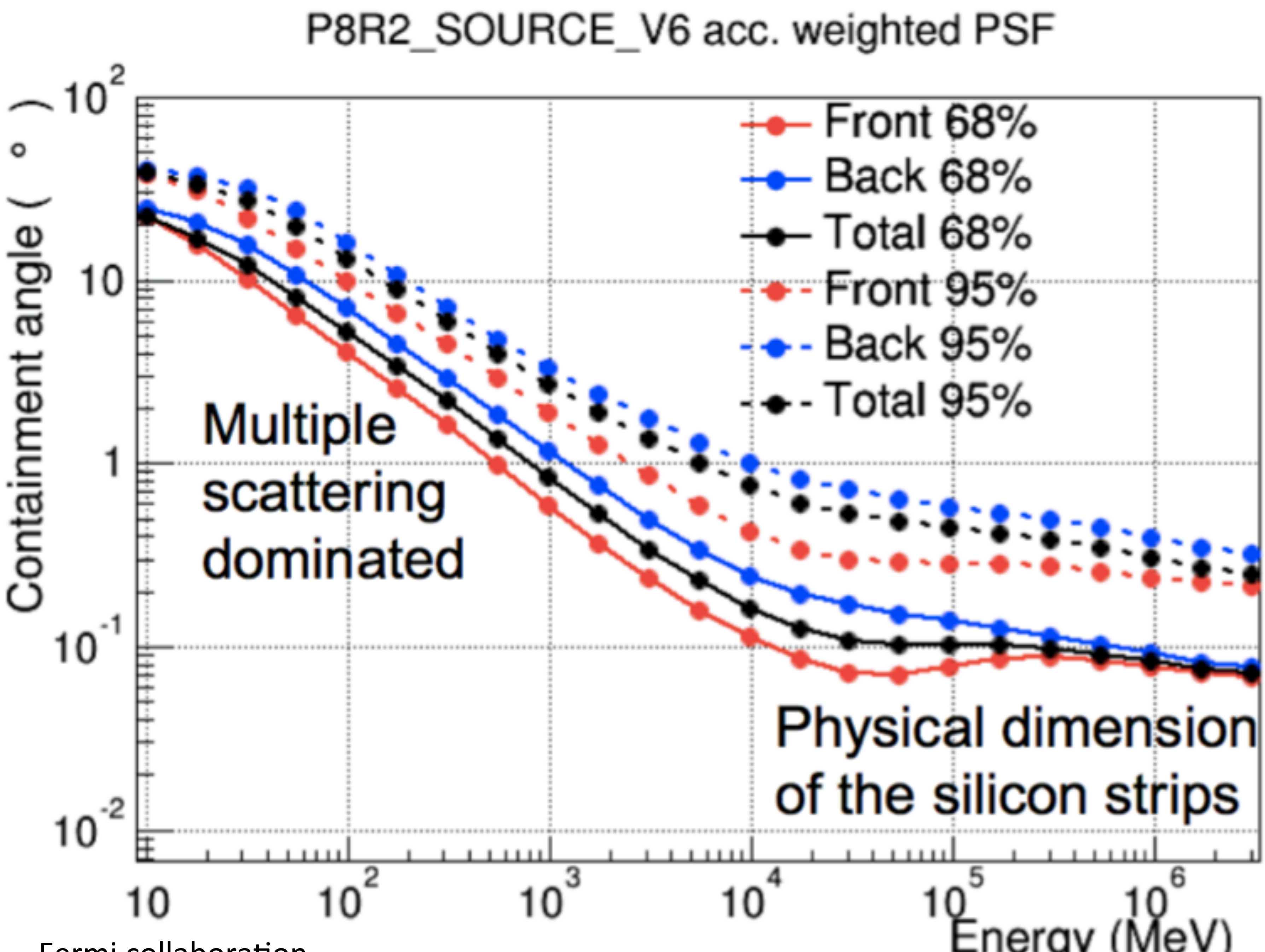


SVD

Number of eigen value : 4

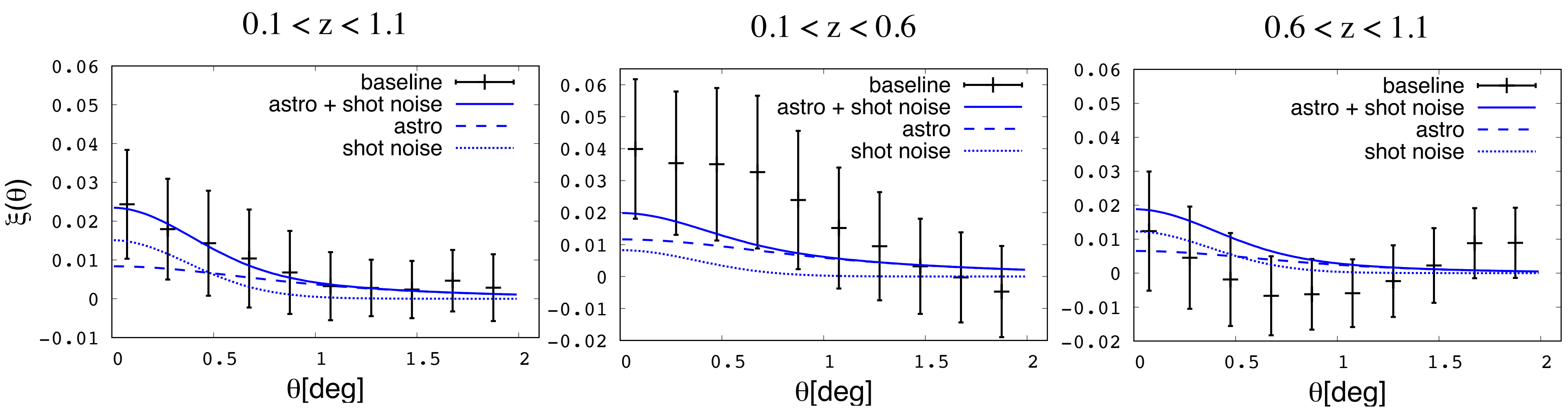


↑Angular bins has a strong correlation with other bins.



Fermi collaboration

Implication



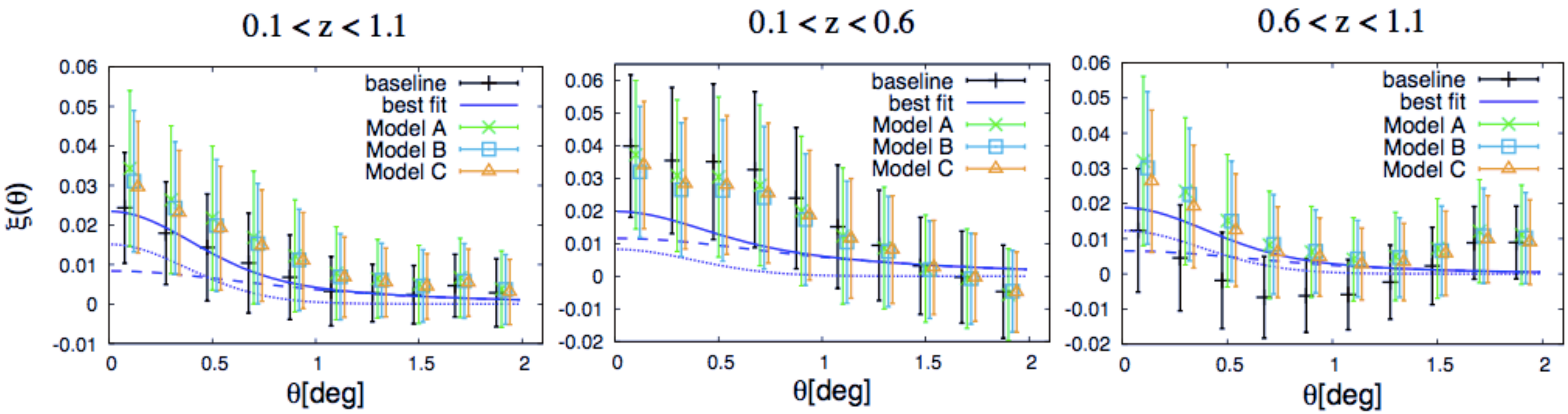
$\chi^2_{\rm clu} - \chi^2_{\rm mod}$ (degree of freedom = 3)

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

Implication



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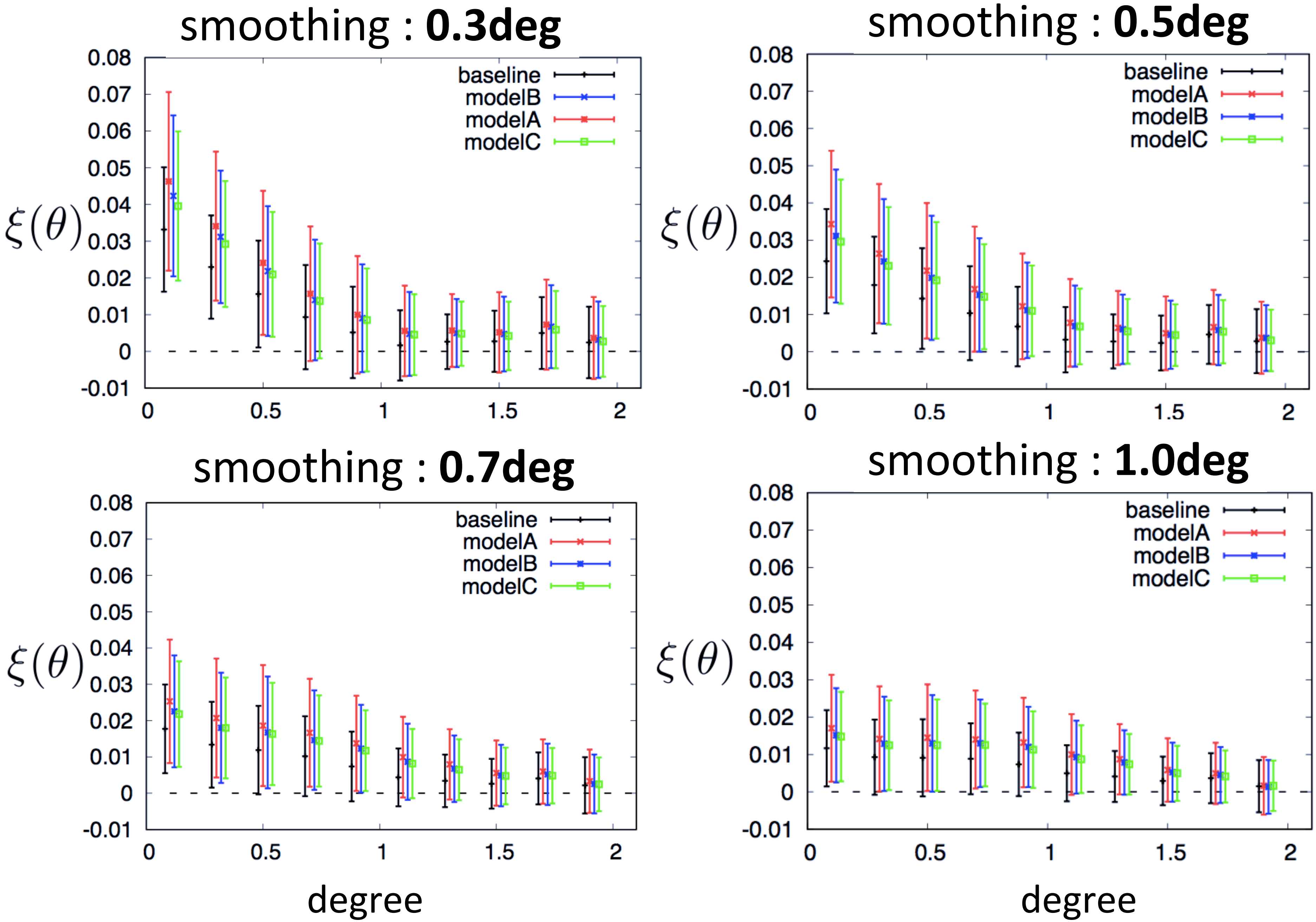
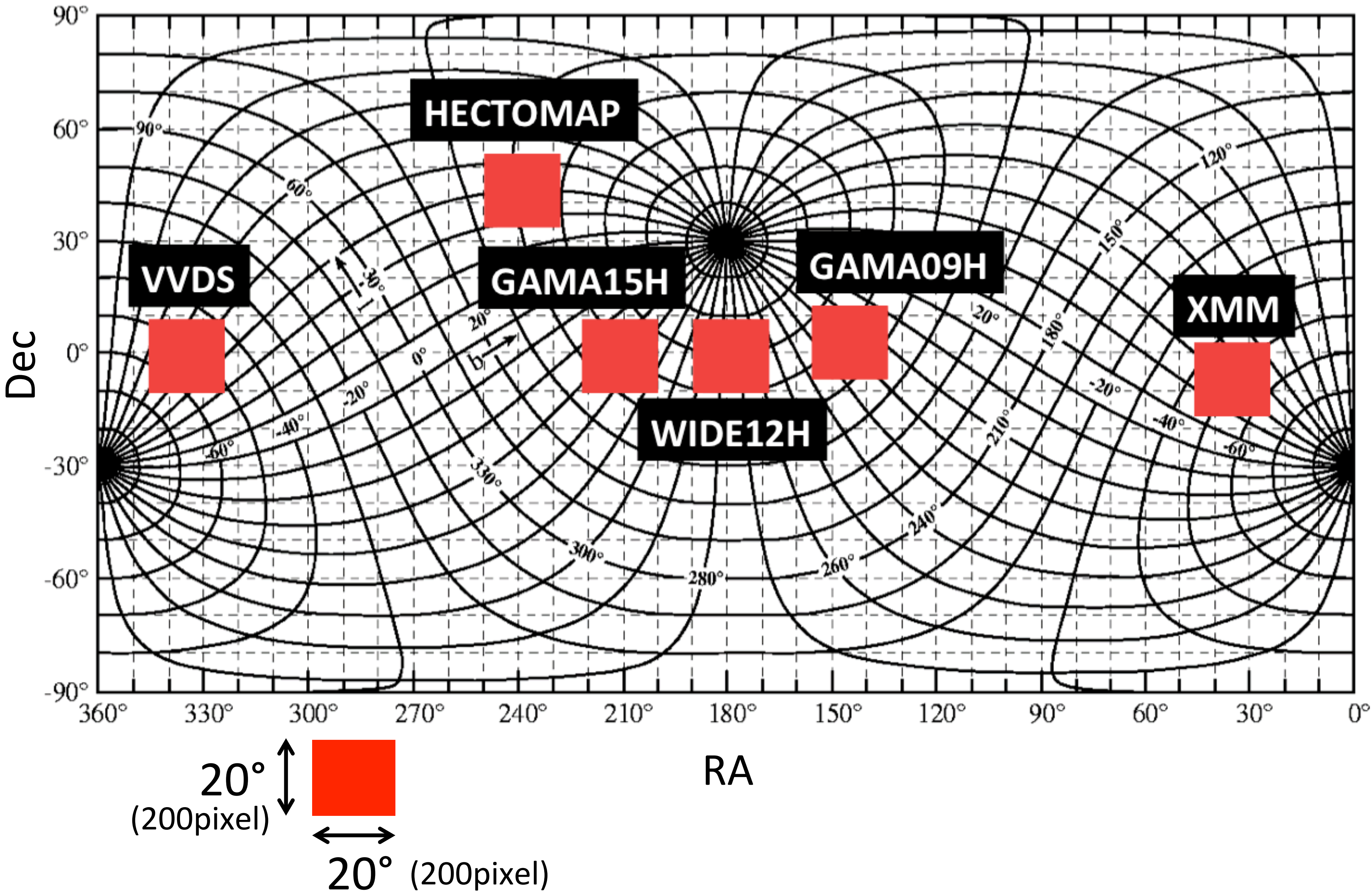
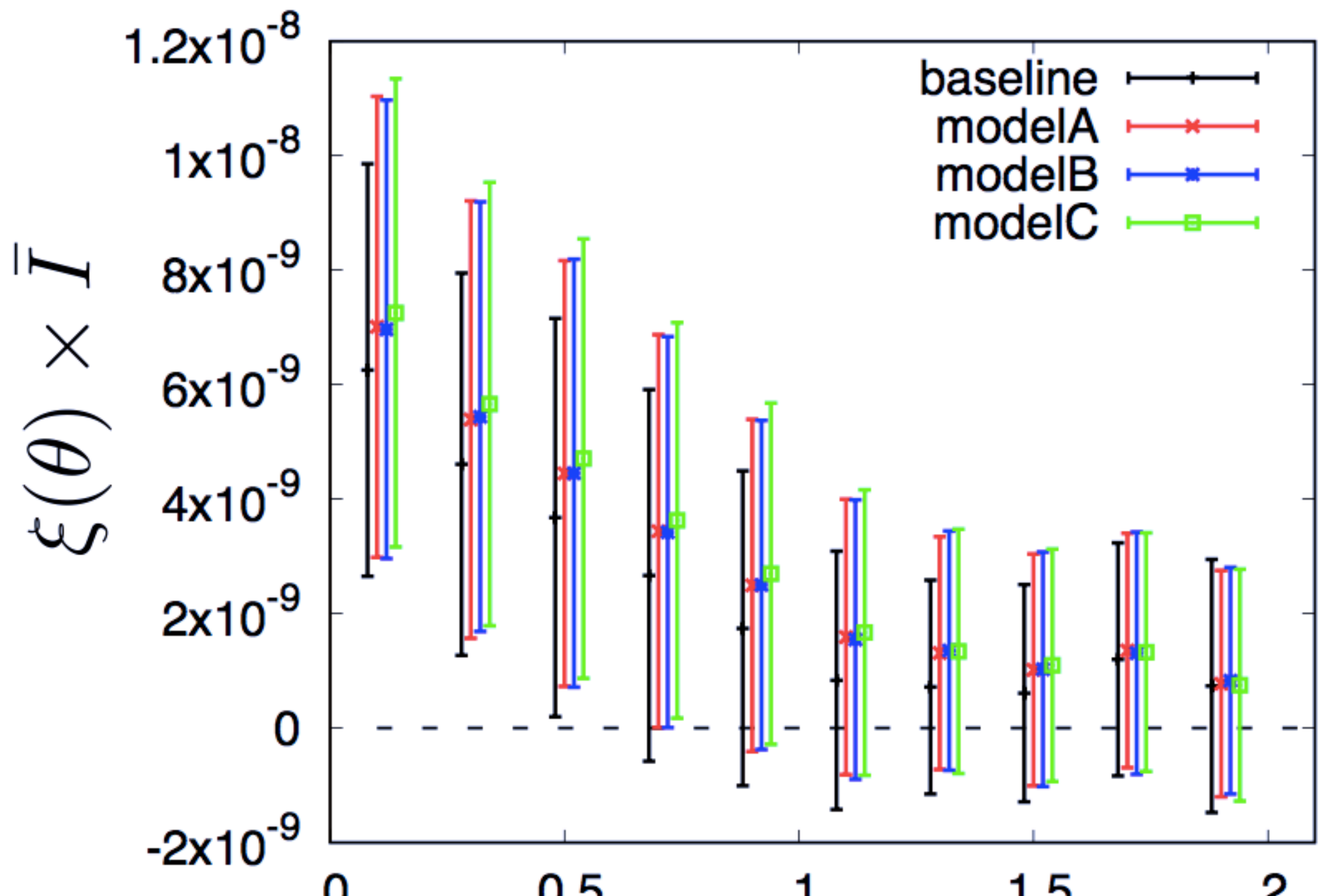


Distribution of Fermi observation area we use



Cross-Correlation Analysis

Cross-correlation function × mean intensity of gamma-rays



degree