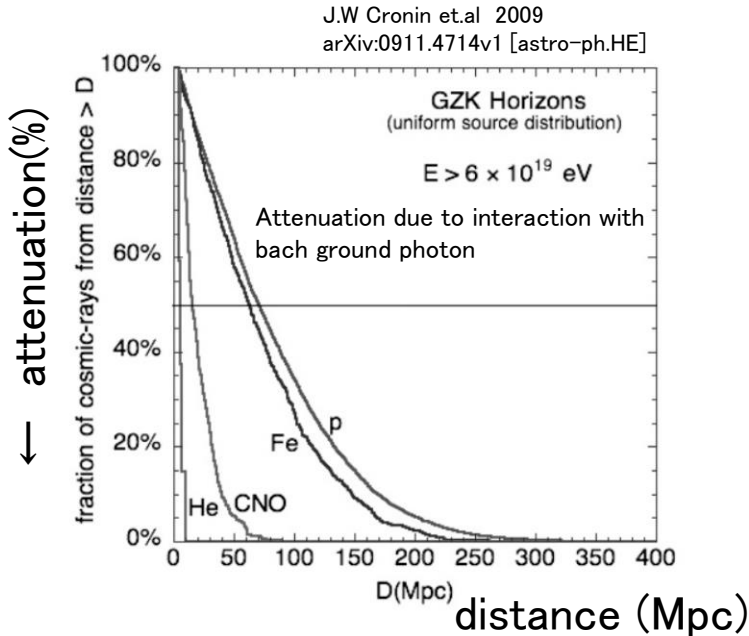


Anisotropy search in energy distribution using the Telescope Array surface detector data

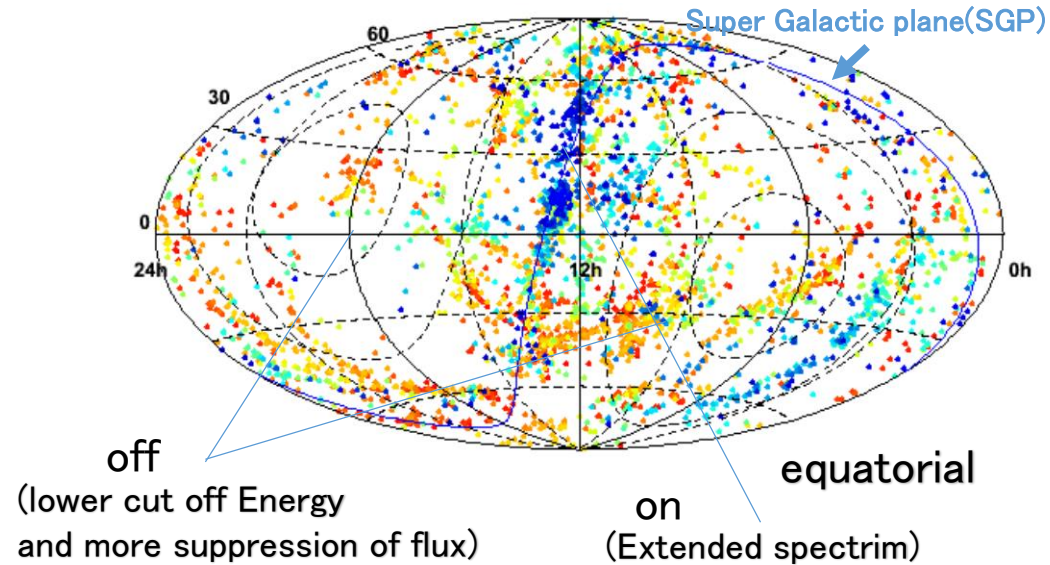
Toshiyuki Nonaka for Telescope Array Collaboration
Institute for Cosmic Ray Research
University of Tokyo ,

Background of study

- Matter distribution at near distance



Distribution of Galaxy within 75Mpc (2MRS)
Most of Galaxy concentrate near SGP direction



- UHECR attenuate while propagation.
- Matter distribution differ depending on directions
- Cosmic ray sources \propto matter distribution
- We can expect different spectrum



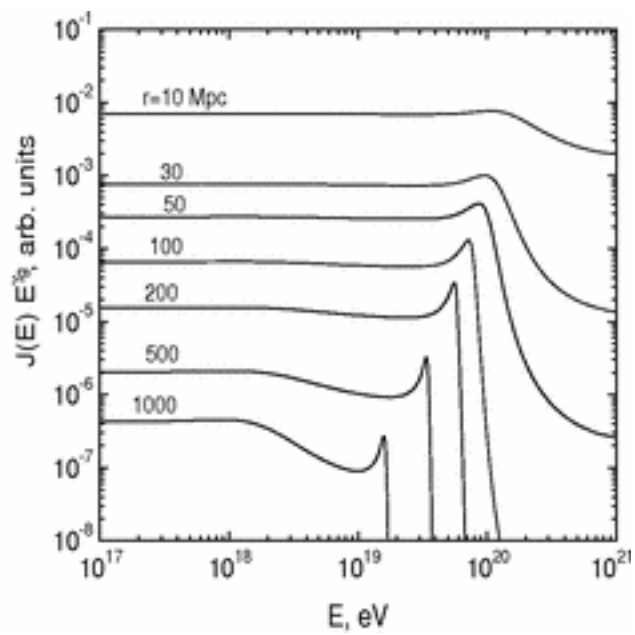
Spectrum Anisotropy

- How much it differ
- Compare theoretical expectation

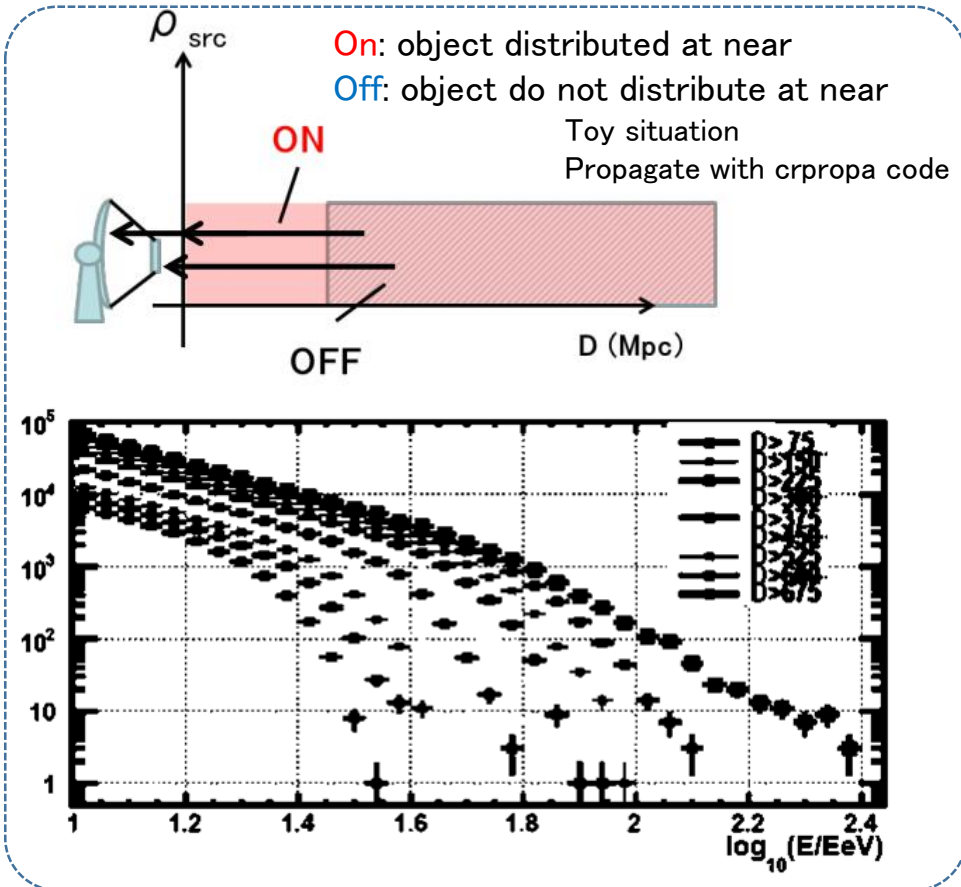
Background of study

- How the spectrum is expected to be differ
- Spectrum from single source at various distance (left)
- Simulation of how the spectrum tend to differ depending on direction (right side)

Modulated spectrum shape from single source at various distance



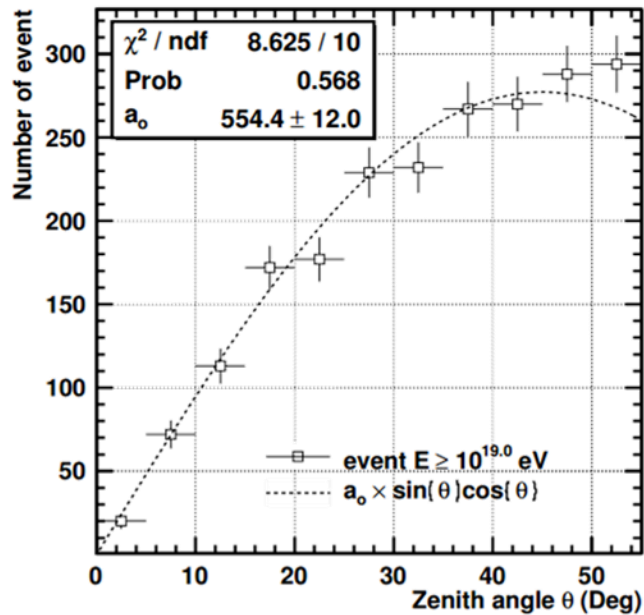
V.Berezinsky et.al Phys. Rev. D 74, 043005 (2006)



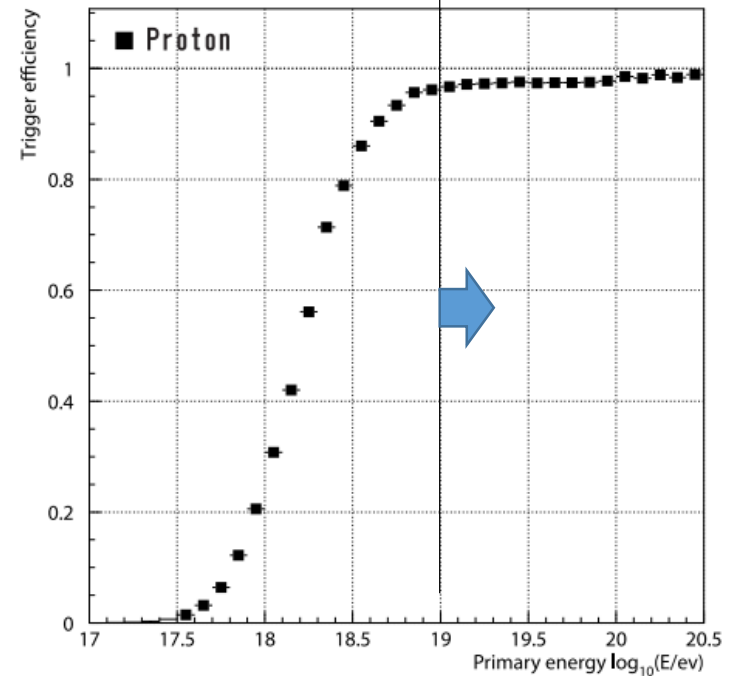
On : Extent spectrum / Off early break and steeper fall at higher energy

Data

- TA SD data
- Period : 2008/05/11 – 2013/05/11
 - 5 year data
- Energy $E > 10 \text{ EeV}$
 - Efficiency -- 100%
- Zenith angle $< 55^\circ$

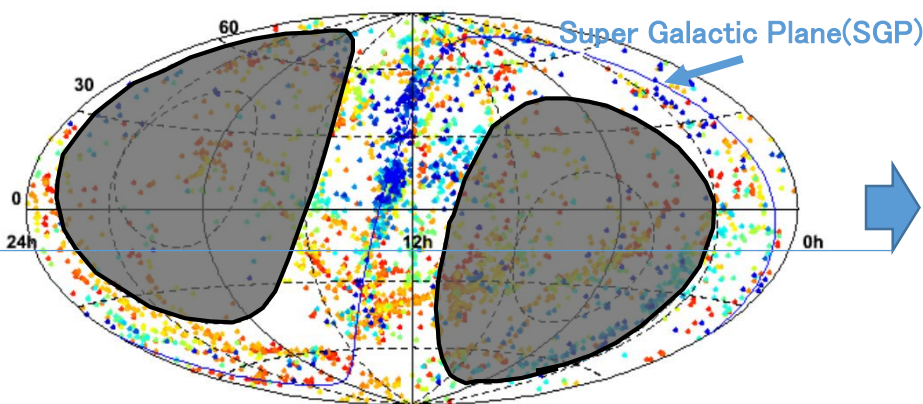


SD efficiency

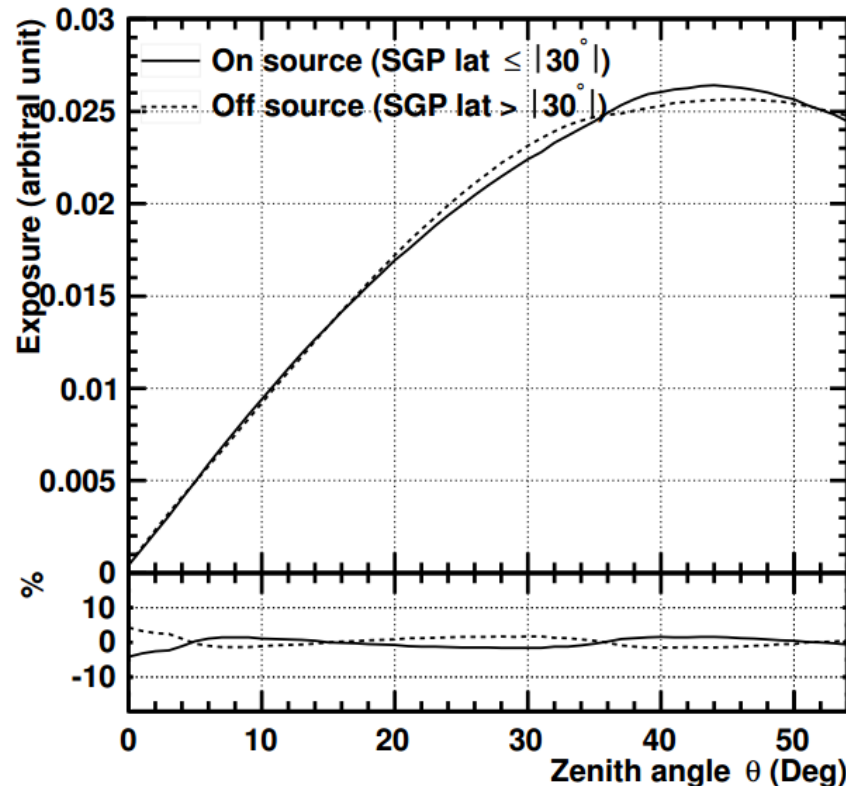


Dividing sky into two part

TAField of View (dec $> -15^\circ$)



Zenith angle distribution of Exposure

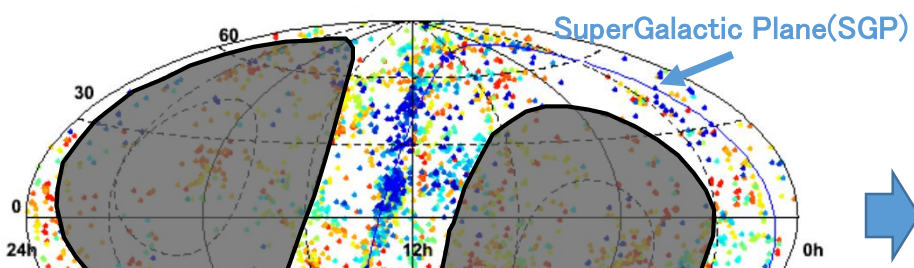


SGP latitude $< |30^\circ|$ (On source)
 SGP latitude $> |30^\circ|$ (Off source)
 Fraction in Exposure (52% vs 48%)

- As a first step using “Super Galactic Plane” as a target of sky division
- Simple shape of “On”/”Off” sky area.
- Condition of Observation is identical.

Energy distributions

TA Field of View (dec > -15°)



SGP latitude < |30°| (On source)
 SGP latitude > |30°| (Off source)
 Fraction in Exposure (52% vs 48%)

Evaluate shape of distribution with broke power low.

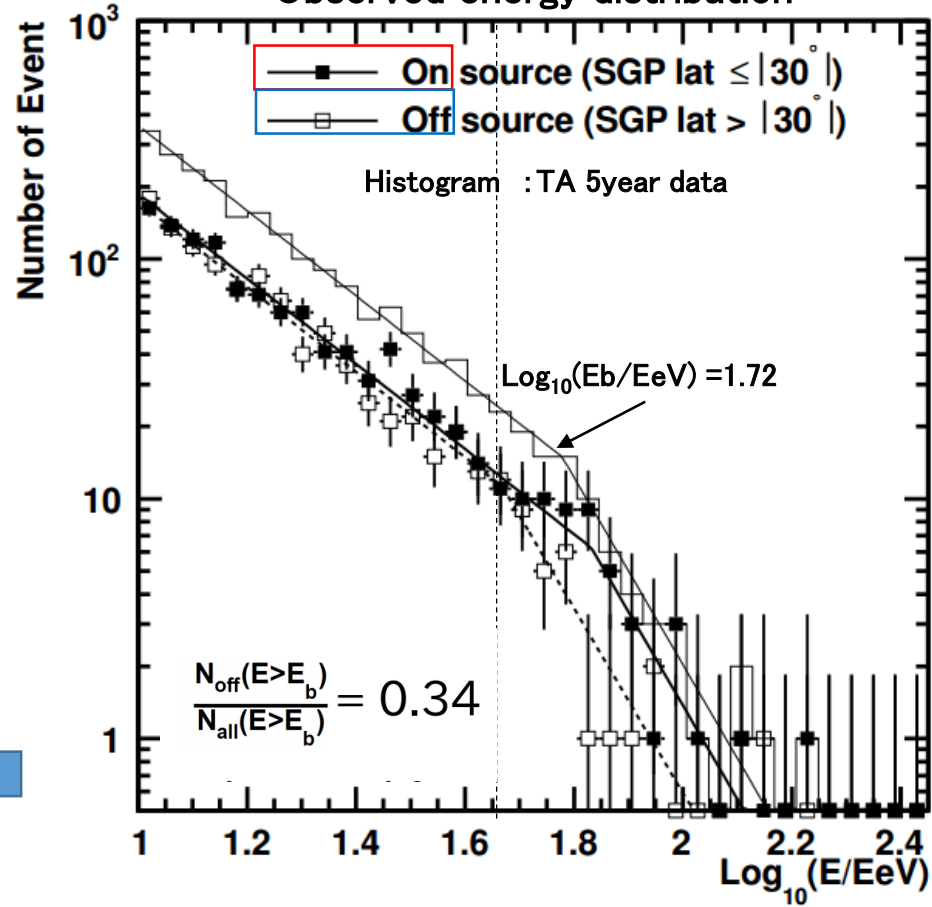
	$\text{Log}_{10}(E_b / \text{EeV})$	Fraction ($E > E_b$) _{off}
All	1.72	-
On	1.83 (1.72)	0.66 (0.52)
Off	1.67 (1.72)	0.34 (0.48)

() Expected from exposure

$$\text{Log}_{10}(E_b / \text{EeV}) = 1.67$$

$$\frac{N_{\text{off}}(E > E_b)}{N_{\text{all}}(E > E_b)} = 0.34$$

Observed energy distribution

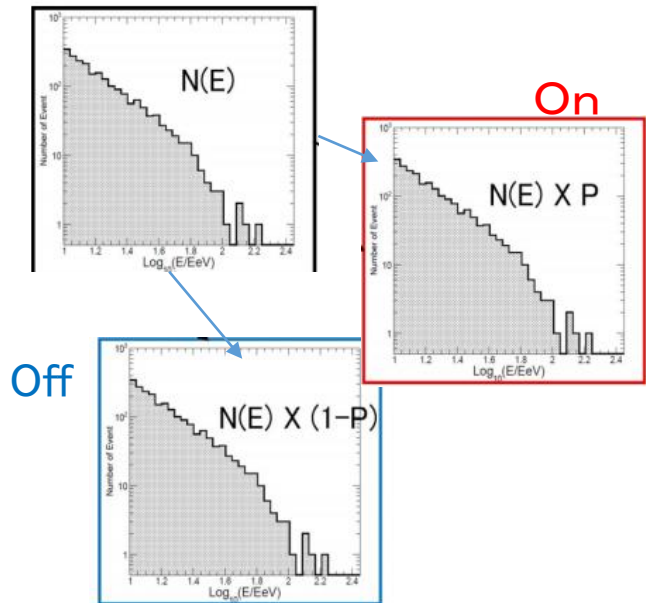


Lower break energy at off source
 Fraction of event is less than expectation

Chance Probability Estimation

Procedure of calculation

- Shuffle events to **On** source and **Off** source with binominal probability based on exposure fraction.

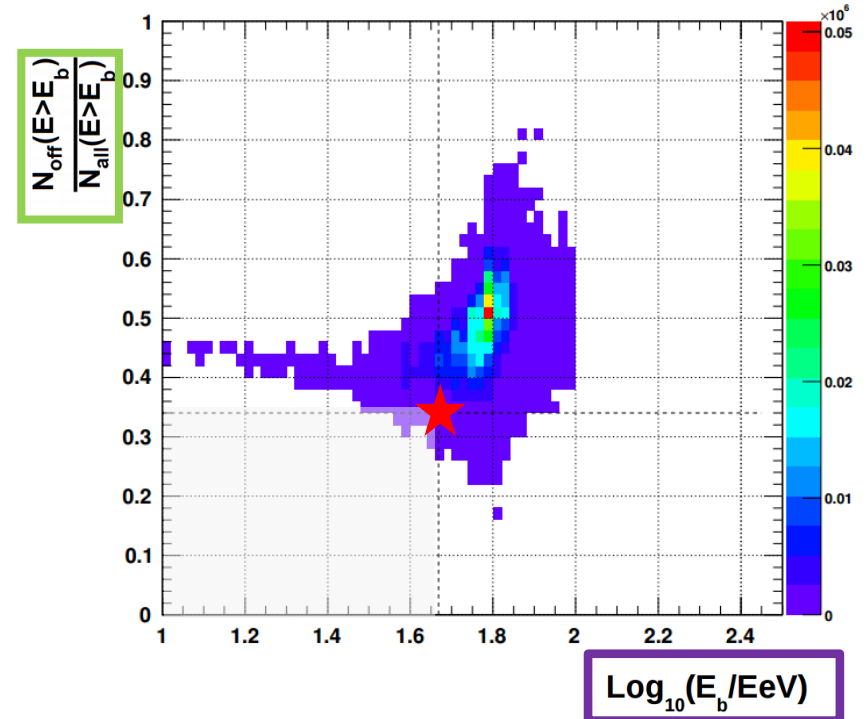


- Obtain $\text{Log}_{10}(E_b/E\text{eV})$ and $\frac{N_{\text{off}}(E>E_b)}{N_{\text{all}}(E>E_b)}$ with same procedure at each trial.
- Repeat and count how many times smaller $\frac{N_{\text{off}}(E>E_b)}{N_{\text{all}}(E>E_b)}$ is observed.

★ Data

$$\text{Log}_{10}(E_b/E\text{eV}) = 1.67$$

$$\frac{N_{\text{off}}(E>E_b)}{N_{\text{all}}(E>E_b)} = 0.34$$

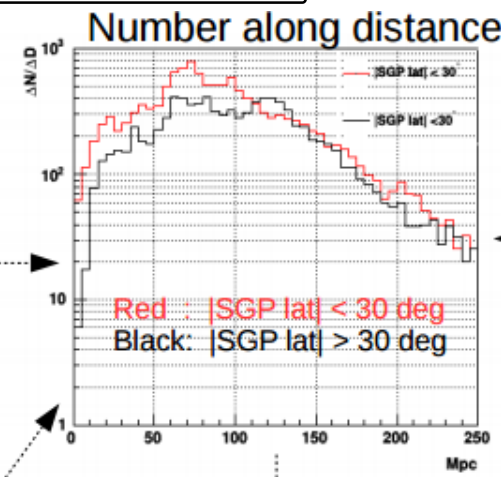
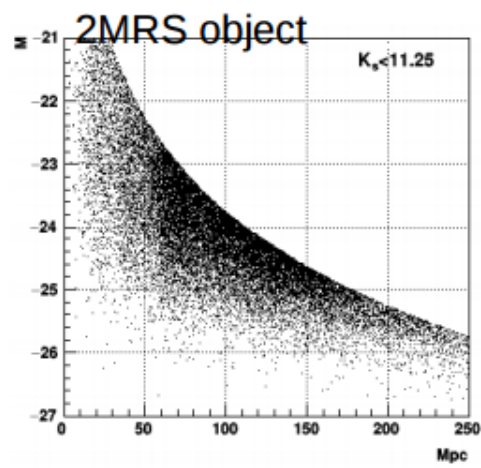


$$P = 6.2 \times 10^{-4} \quad (3.2 \sigma)$$

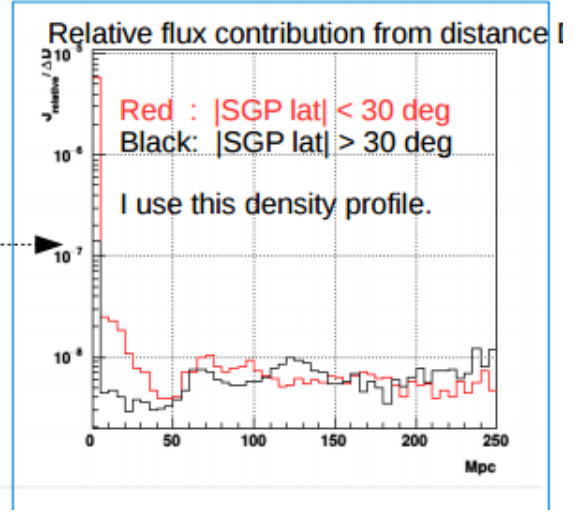
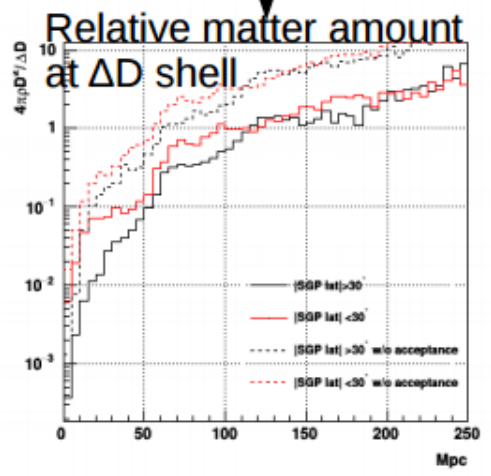
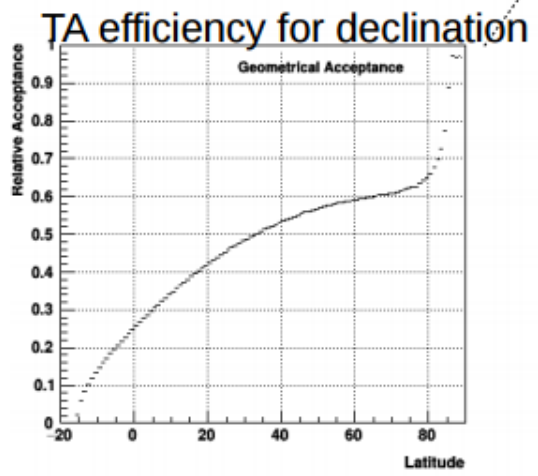
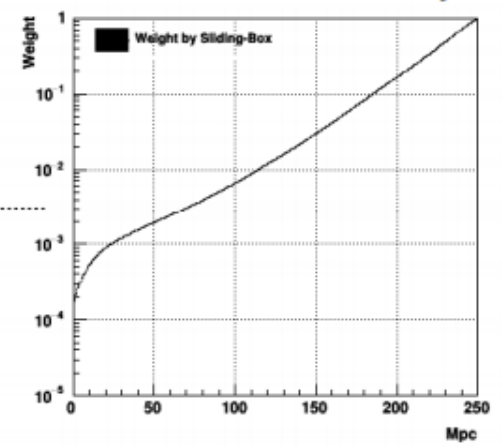
Comparison with simple model

Procedure of calculation

1. Extract matter distribution from 2mrs catalog for On/Off sky.



H. B. J. Koers and P. Tinyakov (2009)
 OBSERVATION EFFICIENCY.



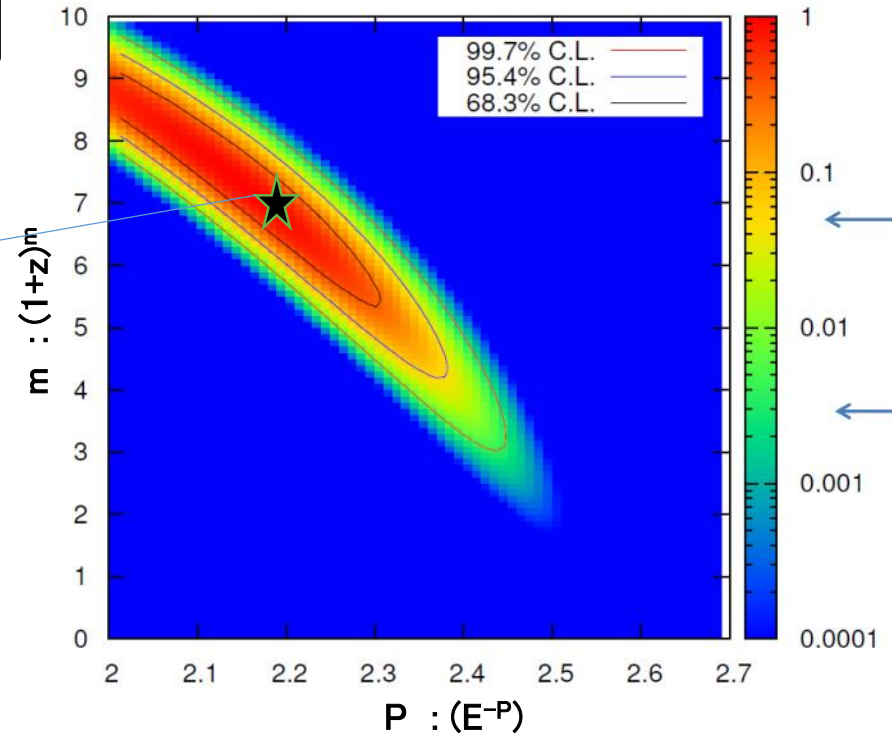
Comparison with simple model

Procedure of calculation

1. Extract matter distribution from 2mrs catalog for On/Off sky.
2. Propagate (proton) with injection spectrum -2.2 and source evolution 7 .
 1. TA all spectrum fit in uhecr2014
 2. CRPROPA code.

E.Kido et. al :
SD Spectrum Fit study
presented at UHECR2014

$\Delta \chi^2$ map for all spectrum



$(P, m) = (2.2, 7)$

Comparison with simple model

Procedure of calculation

1. Extract matter distribution from 2mrs catalog for On/Off sky.
2. Propagate (proton) with injection spectrum -2.2 and source evolution 7.
 1. TA all spectrum fit in uhecr2014
 2. CRPROPA code.
3. Obtain expected energy distribution for each part of sky. Result is shown in right.

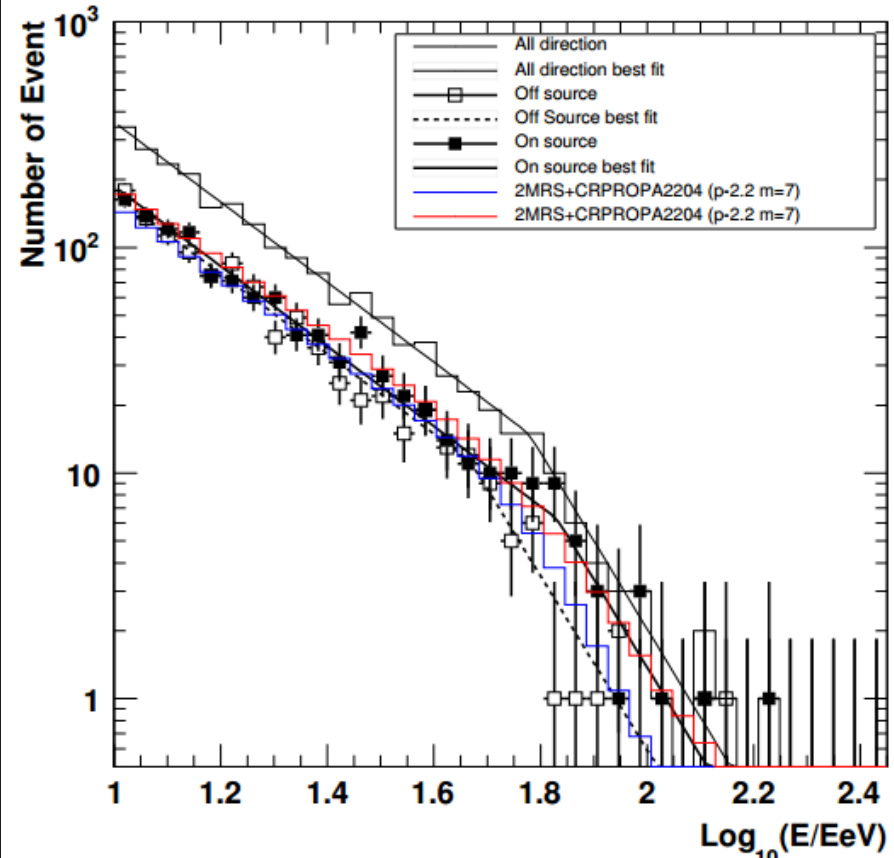
Red | SGP lat $< 30^\circ$ (On source)

Blue | SGP lat $> 30^\circ$ (Off source)

At $E > E_b = 10^{19.67} \text{ eV}$

MC $40(\pm 0.4\%)$ events at off source

Data 30 event $\rightarrow P \sim 6\%$

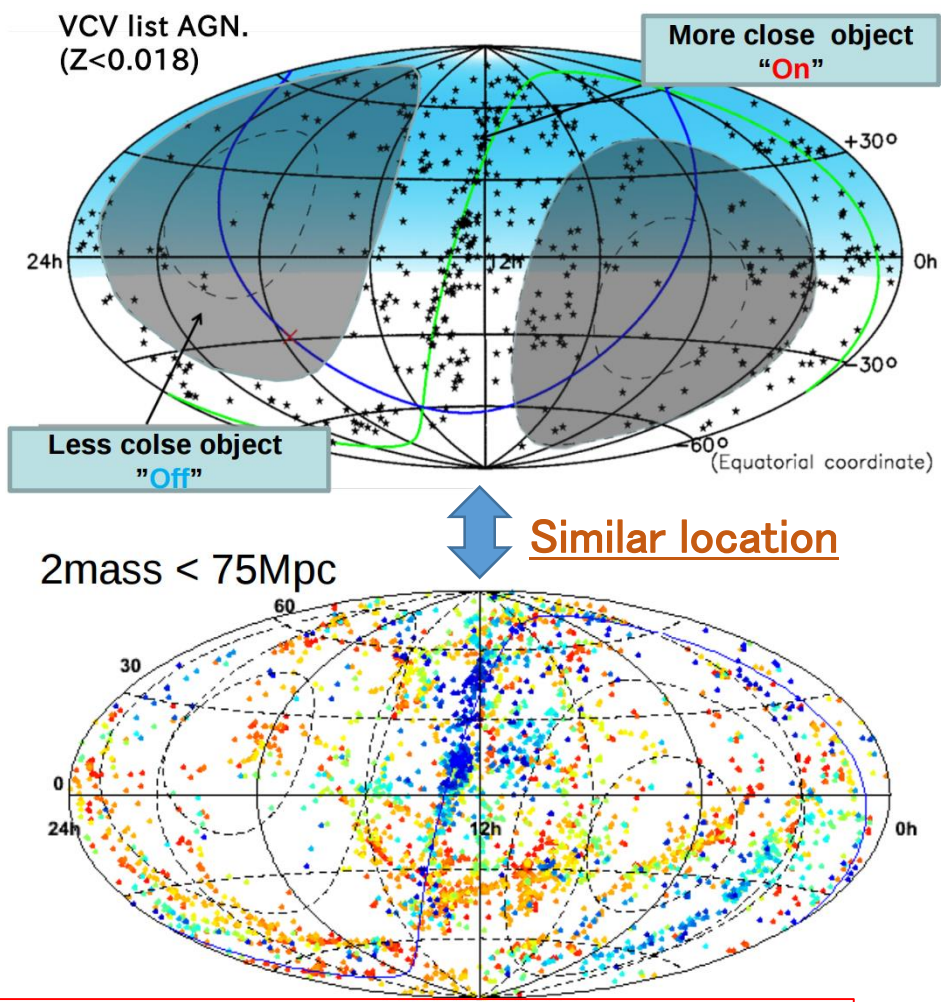


- Spectrum attenuation at off source is qualitatively reasonable.
- Data shows more attenuation than this simple expectation.

More realistic definition of Sky area

By using given AGN catalog we can set sky areas which have more largely different matter distribution.

- AGNs follow matter distribution

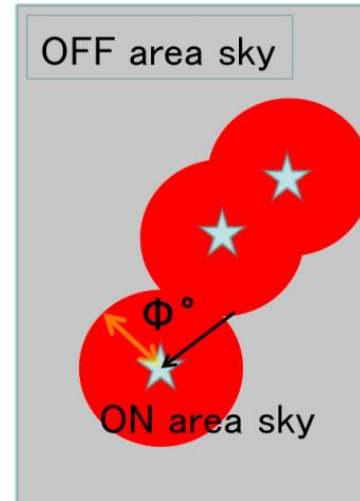
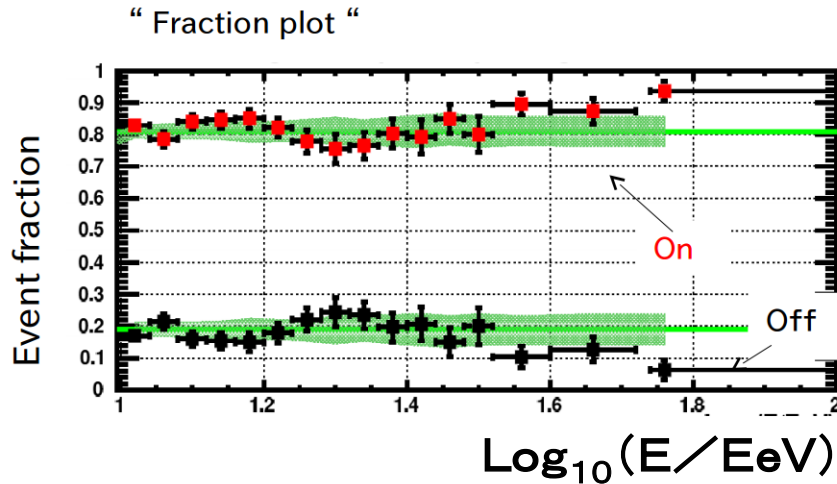


- Need to decide opening angle from AGN direction
- In this study, we decided opening angle from "data".

Deciding opening angle

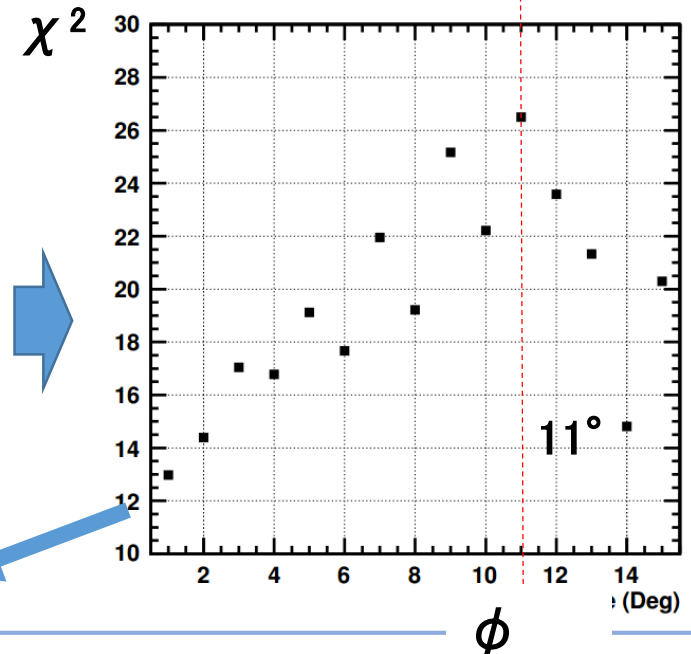
How Opening angle decided

- Number of event in On/Off area is expected as **Fraction of exposure**
- “Scan” data to find largest deviation from the expectation
- Used VCV agns $z < 0.018$. Change opening angle “ Φ ” from 1° to 15°

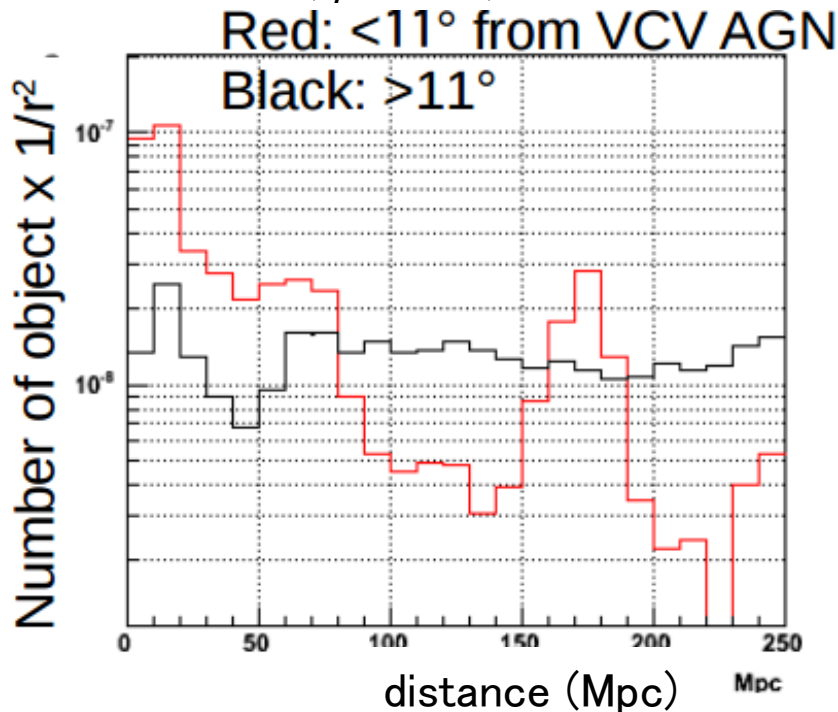


- Calculate binomial prob at each energy bin
- Convert the prob to σ
- Sum up σ^2 to obtain χ^2 for entire distribution

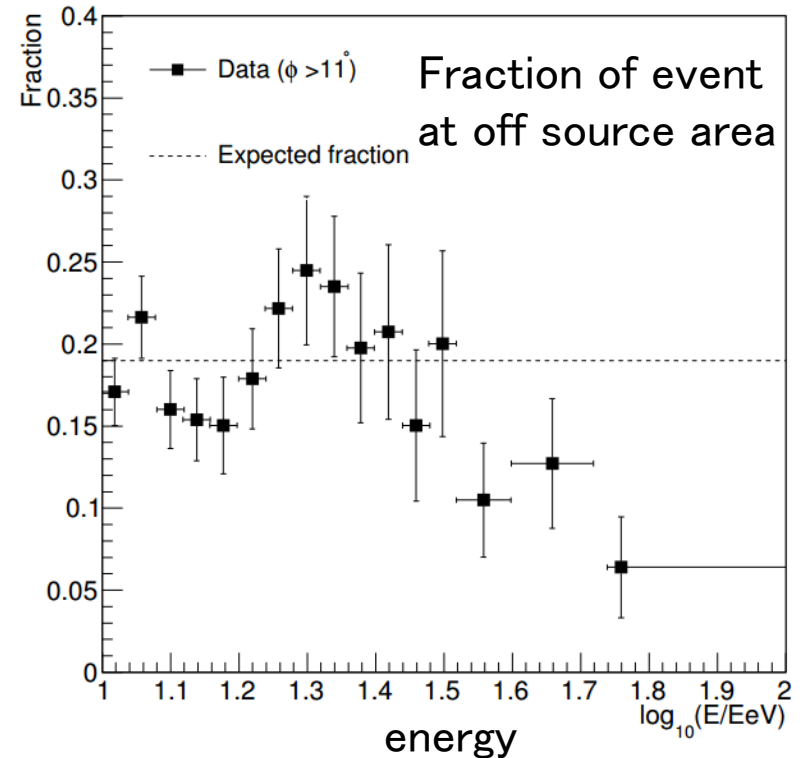
- Define ϕ which gives largest χ^2 as ϕ_{max}
- Used the ϕ_{max} to set On/Off sky area.



Comparison of matter distribution
Between AGN direction ($\phi < 11^\circ$)
and others ($\phi > 11^\circ$)

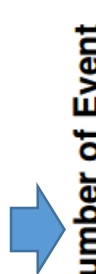
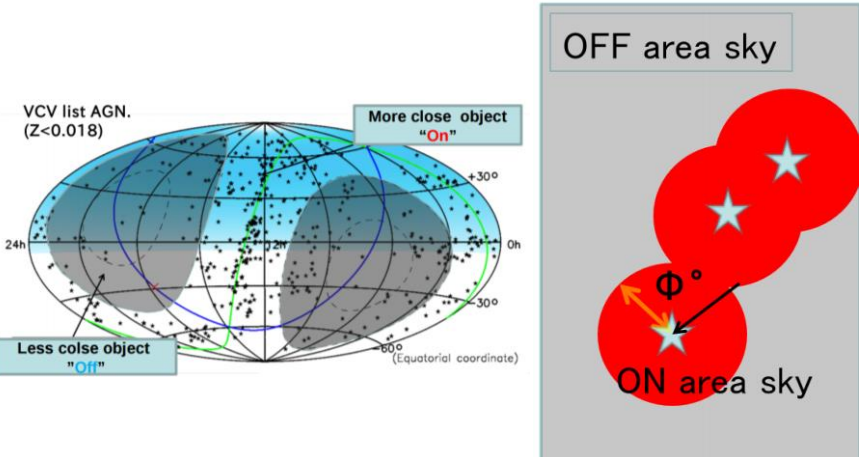


Fraction plot : $\Phi = 11^\circ$

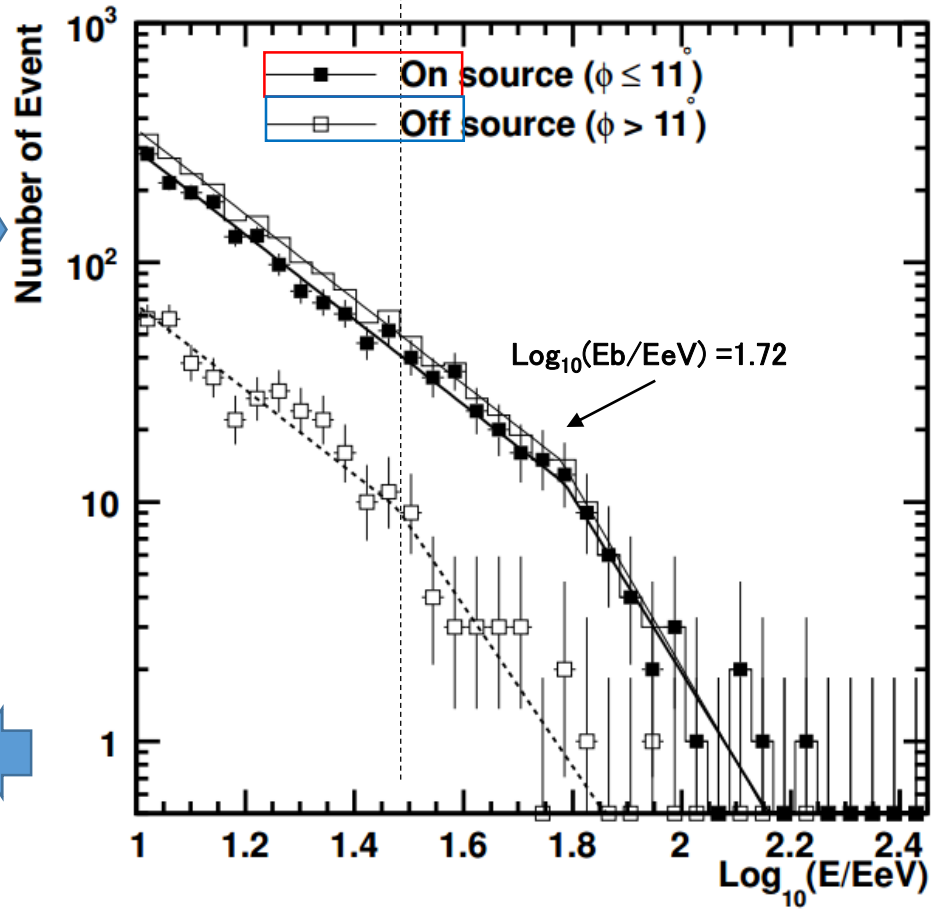


- Difference of Matter distribution at On source sky is more enhanced.
- Event fraction at **On/Off** area shows largest deviation from expectation at a case $\Phi = 11^\circ$.
- Exposure fraction for **On** and **Off** area is **81%** vs **19%**

Data



Observed energy distribution



Evaluate shape of distribution with broke power low.

	$\text{Log}_{10}(E_b / \text{EeV})$	Fraction ($E > E_b$) _{off}
All	1.72	-
On	1.78 (1.72)	0.88 (0.81)
Off	1.47 (1.72)	0.12 (0.19)

() Expected from exposure

$$\text{Log}_{10}(E_b / \text{EeV}) = 1.47$$

$$\frac{N_{\text{off}}(E > E_b)}{N_{\text{all}}(E > E_b)} = 0.12$$

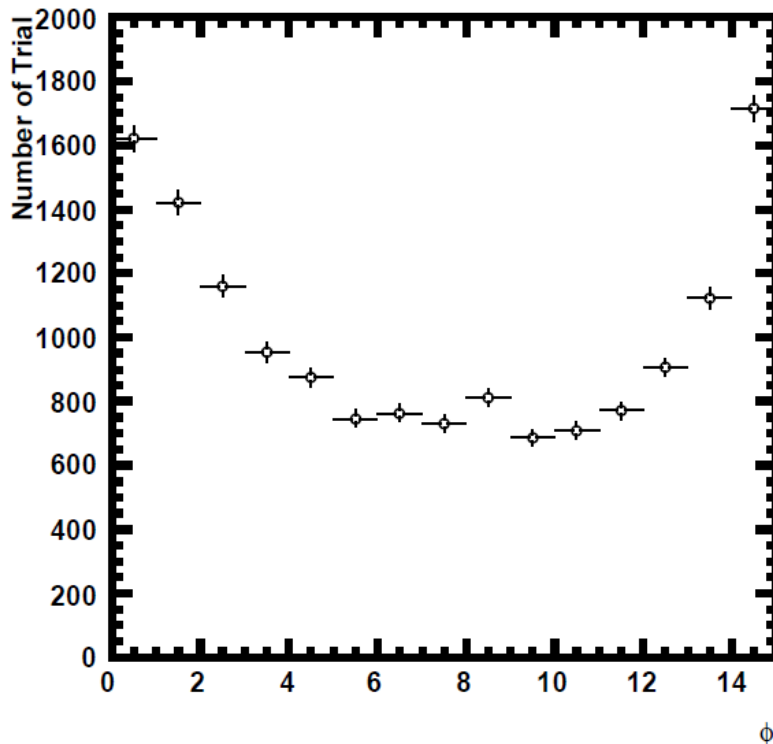
Lower break energy at off source
 Fraction of event is less than expectation



Scan penalty factor

Penalty factor by scanning Φ was calculated as following.

From Φ max's frequency at random simulation, The weight is estimated by assuming that "Penalty" is proportional to the frequency.



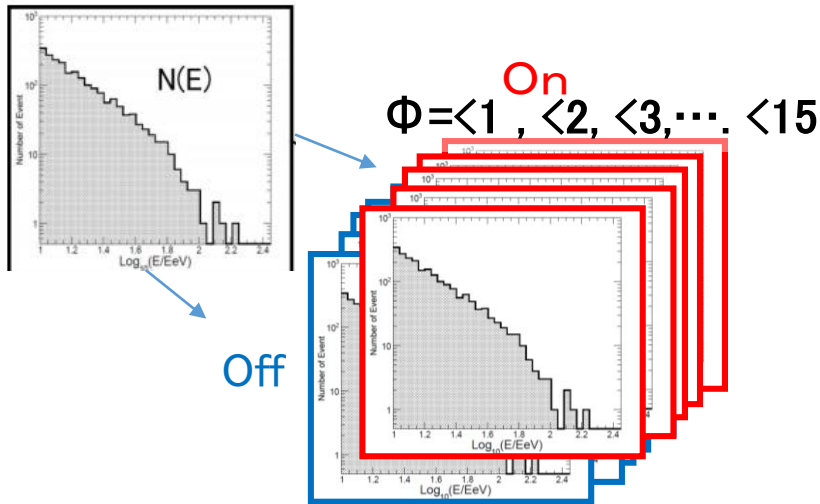
Φ max	N(times)	Relative frequency
<15	1714	1.000
<14	1122	0.655
<13	907	0.529
<12	771	0.450
<11	708	0.413
<10	687	0.401
<09	812	0.474
<08	731	0.426
<07	763	0.445
<06	746	0.435
<05	875	0.511
<04	953	0.556
<03	1159	0.676
<02	1421	0.829
<01	1621	0.946
SUM:	14990	8.7

Quoted
scan penalty : ~ 9

Chance Probability Estimation

Procedure of calculation

- Shuffle events to give opening angle with probability based on exposure fraction for each ϕ range.



- Pick up $\phi_{\max} = 11^\circ$ case and do following.

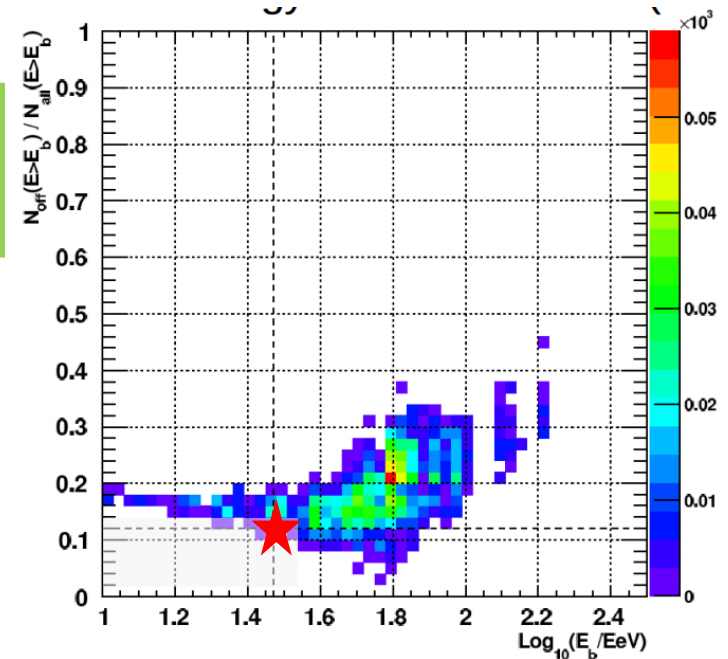
- Obtain $\text{Log}_{10}(E_b/E\text{eV})$ and $\frac{N_{\text{off}}(E>E_b)}{N_{\text{all}}(E>E_b)}$ with same procedure at each trial.
- Repeat and count how many times smaller $\text{Log}_{10}(E_b/E\text{eV})$ $\frac{N_{\text{off}}(E>E_b)}{N_{\text{all}}(E>E_b)}$ is observed.

★ Data

$$\text{Log}_{10}(E_b/E\text{eV}) = 1.47$$

$$\frac{N_{\text{off}}(E>E_b)}{N_{\text{all}}(E>E_b)} = 0.12$$

$$\frac{N_{\text{off}}(E>E_b)}{N_{\text{all}}(E>E_b)}$$



$$\text{Log}_{10}(E_b/E\text{eV})$$

$$P = 1.7 \times 10^{-3} \text{ (pretrial)} \times 9 \text{ (scan)} = 1.5 \times 10^{-2}$$

Summary

We searched anisotropy in spectrum shape at $E > 10 \text{ EeV}$ using TA SD 5 year data.

We proposed a different way of evaluation of anisotropy.

By dividing sky into 2 part (On and Off sky), we did following study.

- 1st dividing sky simply with 30° from SGP and other (exposure half), we see more early attenuation in observed energy distribution at Off sky.
 - The chance probability estimated is 3.2σ .
 - Using simple model, we compared the On/Off sky difference with numerical simulation. The result is qualitatively much.
- 2nd by selecting On/Off sky using near object, obtain more different matter distribution at each sky area.
 - The observed energy distribution had larger difference of break energy .
 - Estimated chance probability is 1.7×10^{-3} but by adding scan penalty factor, post trial probability is 1.5×10^{-2}