Anisotropy search in the Ultra High Energy Cosmic Ray Spectrum in the Northern Hemisphere using the Telescope Array surface detector

T. Nonaka*[a], R. Cady[b], M. Fukushima[ac], D. Ivanov[b], K. Kawata[a], E. Kido[a],J.N. Matthews[b], S. Nagataki[d], T. Okuda[e], H. Sagawa[a], N. Sakurai[f], B.T. Stokes[b],M. Takeda[a],A. Taketa[g] for The Telescope Array Collaboration

a : *Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba, Japan* / **b:** *High Energy Astrophysics Institute and Department of Physics and Astronomy, University of Utah, Salt Lake City, Utah, USA*
c : *Kavli Institute for the Physics and Mathematics of the Universe (WPI), Todai Institutes for Advanced Study, the University of Tokyo, Kashiwa, Chiba, Japan* / **d:** *Astrophysical Big Bang Laboratory, RIKEN, Wako, Saitama, Japan*
e : *Department of Physical Sciences, Ritsumeikan University, Kusatsu, Shiga, Japan* / **f:** *Graduate School of Science, Osaka City University, Osaka, Osaka, Japan*
g : *Earthquake Research Institute, University of Tokyo, Bunkyo-ku, Tokyo, Japan*

Correspondence nonaka@icrr.u-tokyo.ac.jp Abstruct ID: 1004 Proceedings PoS(ICRC2015)384

Abstract: In the region of highest energies, the shape of cosmic ray energy spectrum may contain information on the source density distribution and chemical composition. In this study, using observed event with Telescope Array surface detector, we **search for directional differences in the shape of energy spectrum**. Observed cosmic ray energy spectras are **compared between sky areas that have larger density of nearby objects, such as the super-galactic plane, and others that do not.** The distributions differ. We found the chance probability to obtain the difference in statistically equivalent distributions is estimated as 6.2×10^{-4} (3.2σ). Similarly, observed energy distributions of events within 11° from VCV AGNs and out of this region were compared. Chance probability to obtain observed difference in statistically equivalent distributions is estimated as 1.5×10^{-2} after considering penalty factor. **The observed distributions were compared with the result from numerical propagation simulation expecting model parameter which obtained in the previous study and source density profile from 2MRS catalogue.** Qualitatively the observed difference is reasonably consistent with the expectation from the simulation.

Analysis for super galactic plane (SGP)

○ 5year data of TA surface detector (zenith angle <55° E >10^{19}eV)
○ Define SGP Latitude <30° as "On source" , SGP Latitude >30° as "Off source"
○ Exposure fractions for On/Off areas become ½ vs ½ . (52% vs 48%)

Fig.1 shows observed energy distributions from all sky , On and Off source sky. The black line shows the best fit broken power law expressed by the function

$$\frac{\Delta N(E)}{\Delta \log_{10}\left(\frac{E}{E_o}\right)} = C_0\left(\varepsilon(E,E_b)\left(\frac{E}{E_o}\right)^{-\alpha_1} + (1-\varepsilon(E,E_b))\left(\frac{E}{E_o}\right)^{-\alpha_2}\right)$$

$$\varepsilon(E,E_b) = \{1:(E<E_b),0:(E>E_b) \qquad (E_o = 1\ \mathrm{EeV}).$$

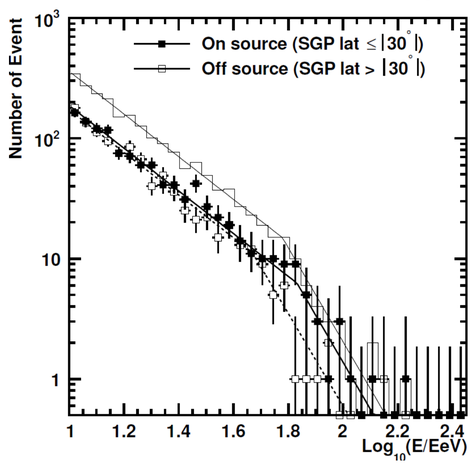

Fig. 1: The energy distributions of observed events for the On/Off areas using SGP.

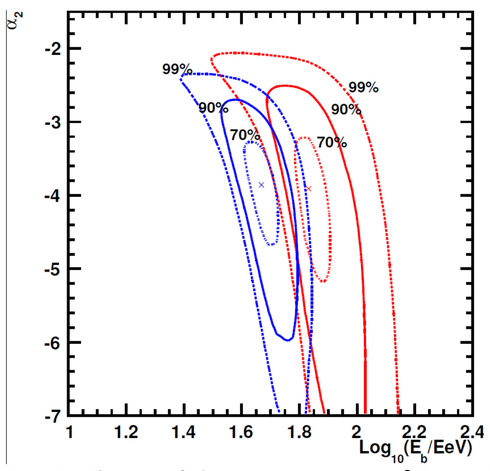

Fig. 2: The confidence contours of E_b and α_2. Red and blue colors denote CL for the On/Off regions respectively.

Table 1: Parameters of the best fit broken power law in the SGP case.

Region	C_o	α_1	$\log_{10}(E_b/EeV)$	α_2
All	$2.141^{+0.343}_{-0.298}\times10^{+4}$	$-1.775^{+0.053}_{-0.053}$	$1.778^{+0.040}_{-0.068}$	$-3.910^{+0.643}_{-0.660}$
On source	$(1.1128\times10^{+4})$	(-1.775)	$1.832^{+0.069}_{-0.041}$	$-3.910^{+0.696}_{-1.260}$
Off source	$(1.0286\times10^{+4})$	(-1.775)	$1.668^{+0.052}_{-0.053}$	$-3.858^{+0.582}_{-0.818}$

Summary of On/Off difference of distribution:
The difference of break energy , $\Delta\log_{10}(E_b/E_o)$, is 0.16.
The fraction of events in the Off source area above the break energy, $(N_{off}(E>E_b)/N_{all}(E>E_b))$, was 0.34 instead of 0.48 which is expected from the exposure ratio.

Chance probability estimation:
With a simulation which assumes that both distributions are statistically equivalent with the entire exposure. Namely, in each energy bin the events have been shuffled to On and Off source distributions accordingly to the corresponding fraction of the exposure, binomially. Fig.3 shows frequency distribution of the difference parameter. The observed value corresponds to a probability **6.2×10^{-4} (3.2σ).**
After considering 5% of anti-sidereal amplitude as remaining systematic effect which does not canceled out, still the chance probability does not change much.(6.9×10^{-4})

Condition	N	Fraction
$E_b > 10^{1.668} EeV, \frac{N_{off}(E>E_b)}{N_{all}(E>E_b)} > 0.34$	41580	0.83177
$E_b > 10^{1.668} EeV, \frac{N_{off}(E>E_b)}{N_{all}(E>E_b)} < 0.34$	7996	0.15996
$E_b < 10^{1.668} EeV, \frac{N_{off}(E>E_b)}{N_{all}(E>E_b)} < 0.34$	31	0.00062
$E_b < 10^{1.668} EeV, \frac{N_{off}(E>E_b)}{N_{all}(E>E_b)} > 0.34$	383	0.007662

Table 2: The number of occurrences with stated conditions in the SGP case. The estimated chance probability to obtain larger deviation is 6.2×10^{-4}.

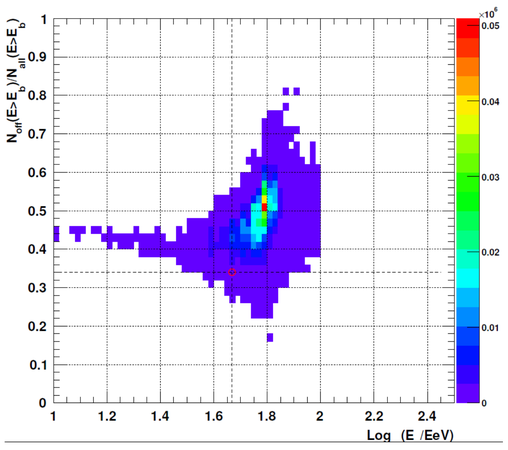

Fig. 3: $(N_{off}(E>E_b)/N_{all}(E>E_b))$, versus E_b Obtained in Monte Carlo simulations. Red marker represents observed value

Analysis for the known object list (VCV list)

With AGNs from Veron-Cetty& Veron 12 catalogue with cut on redshift z<0.018 [1]. The opening angle of the On and Off source areas was adjusted to maximize the signal (1°-15° 1° step).
For a given opening angle and given energy bin in the Off/On source area we calculate the ratio of the observed number of events to the expected number, based on the exposure ratio. Then deviation of this quantity from the expectation was calculated and sum it over all bins. In data, the largest deviations were seen for the opening angle 11°. Fig.4 is the fraction plot of Off source region at the opening angle 11°.
Same analysis with SGP case are repeated for energy distributions from On/Off area.

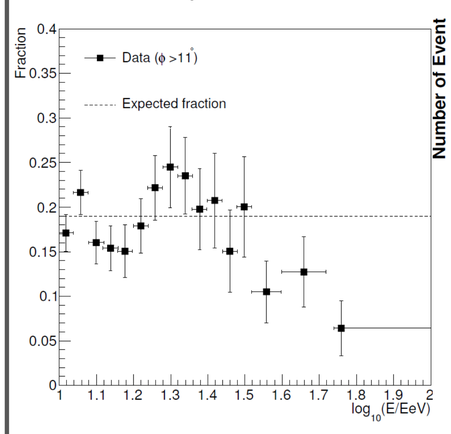

Fig. 4: Fraction of number of events in the Off source area to the expected number. ("fraction plot")

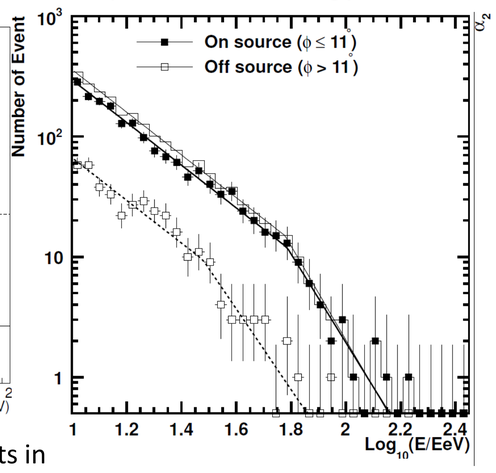

Fig. 5: The energy distributions of observed events for the On/Off areas using VCV AGNs.

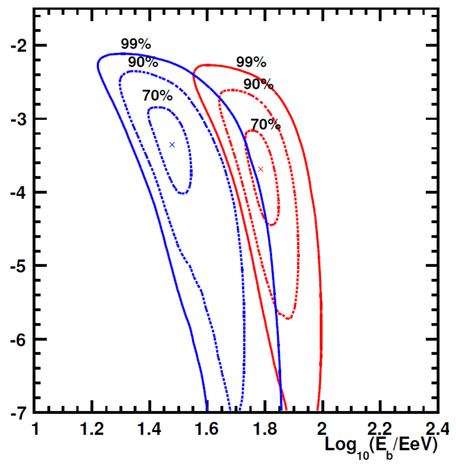

Fig. 6: The confidence contours of E_b and α_2. Red and blue correspond On/Off regions respectively.

Table 3: Parameters of the best fit broken power law in the AGN case.

Region	C_o	α_1	$\log_{10}(E_b/EeV)$	α_2
All	$2.141^{+0.343}_{-0.298}\times10^{+4}$	$-1.775^{+0.053}_{-0.053}$	$1.778^{+0.040}_{-0.068}$	$-3.910^{+0.643}_{-0.660}$
On source	$(1.7336\times10^{+4})$	(-1.775)	$1.786^{+0.058}_{-0.046}$	$-3.663^{+0.515}_{-0.784}$
Off source	$(4.0782\times10^{+4})$	(-1.775)	$1.470^{+0.061}_{-0.084}$	$-3.352^{+0.529}_{-0.673}$

Summary On/Off difference of distribution:
The difference of break energy , $\Delta\log_{10}(E_b/E_o)$, is 0.31.
The fraction of events in the Off source area above the break energy, $(N_{off}(E>E_b)/N_{all}(E>E_b))$, was 0.12 instead of 0.19 which is expected from the exposure ratio.

Chance probability estimation:
In each energy bin the events has been shuffled to On and Off source distributions accordingly to the corresponding fraction of exposure of each opening angle step binomially. Fig. 7 shows frequency distribution of the difference parameter in simulations. The distribution was sampled only from cases Φ =11° gave maximum deviation in a simulation. A penalty factor which accounts for the opening angle tuning was calculated by counting number of case giving maximum deviation for each opening angle in the simulations. Estimated penalty factor is 9.
The observed value correspond to a probability 1.5x10^{-2}

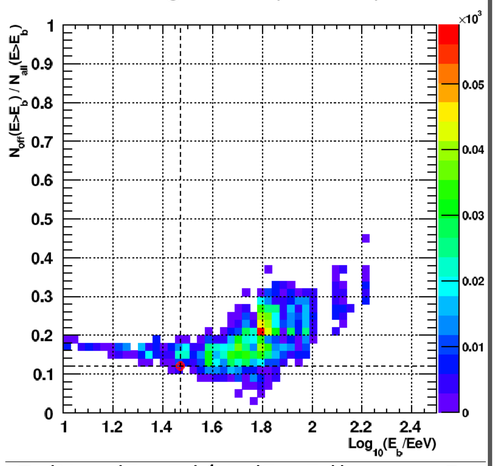

Fig. 7: $(N_{off}(E>E_b)/N_{all}(E>E_b))$, versus E_b. Obtained in Monte Carlo simulations. The distribution was sampled only from cases Φmax =11° in MC.

Condition	N	Fraction
$E_b > 10^{1.470} EeV, \frac{N_{off}(E>E_b)}{N_{all}(E>E_b)} > 0.12$	2004	0.845
$E_b > 10^{1.470} EeV, \frac{N_{off}(E>E_b)}{N_{all}(E>E_b)} < 0.12$	213	0.090
$E_b < 10^{1.470} EeV, \frac{N_{off}(E>E_b)}{N_{all}(E>E_b)} < 0.12$	4	1.7×10^{-3}
$E_b < 10^{1.470} EeV, \frac{N_{off}(E>E_b)}{N_{all}(E>E_b)} > 0.12$	152	0.0064

Table 4: The number of occurrences with stated conditions in the AGN case. Chance probability to obtain larger deviation is $\sim 1.5\times10^{-2}$ after considering penalty factor for the scan in the opening angle.

Comparison with propagation simulation using density profile from 2MRS catalogue for On/Off area.

we performed simulations using a propagation code CRPropa2.2.0.4 [2] and the source distribution from the 2MRS catalogue [3] using the density profile calculation described in [4]. The calculations were done for sky area with the definition of On source as |SGP lat| <30°, and Off source as |SGP lat|>30° . Fig. 8 and Fig. 9 display results of proton primary. Injection and evolution parameters were set to -2.2 and 7 respectively based on previous study [5]. Simulated flux is scaled with the number of events in data avove 10^{19} eV.

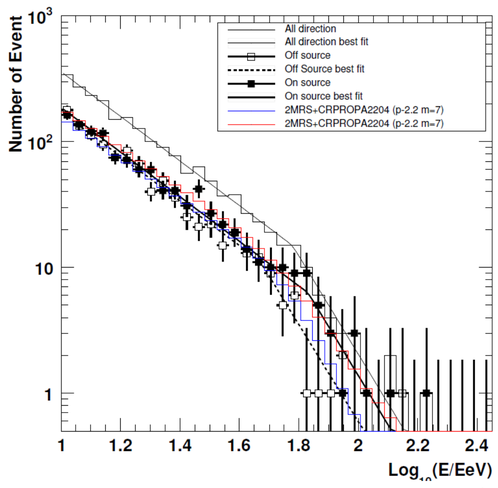

Fig .8 : Data and energy distributions On/Off area expected for protons arriving from the sources with 2MRS density profile.

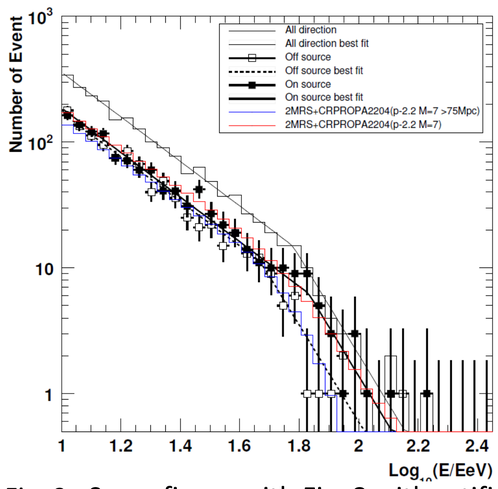

Fig .9 : Same figure with Fig. 8 with artificial cut on source distribution at Off source side distance <75Mpc.

Qualitatively, the difference of observed energy distributions between the On source and Off source regions was consistent with this simulation.
However, more statistics is needed to infer detail of composition.

Summary

- ☐ **A different way of evaluation of anisotropy of cosmic ray was tried.**
  → **The approach is complementary to the usual anisotropy studies.**
- ☐ **Energy distributions within 30° from SGP and out of this were compared.**
  → **Chance probability to obtain the observed difference is 6.2×10^{-4} (3.2σ).**
- ☐ **Same analysis for within 11° from AGNs as On source are done.**
  → **The chance probability for the observed difference is 1.5×10^{-2}**
- ☐ **The observed distributions were compared with simulation with source density profile from 2MRS catalogue.**
  → **The observed feature of difference in the flux attenuation at high energy end is consistent with its dependence on the distances of sources which is predicted with numerical simulation. We believe that the approach developed here will help to reveal cosmic ray sources and their chemical composition.**

References :

[1] M.-P. Véron-Cetty and P. Véron, Astronomy and Astrophysics 455 (Aug., 2006) 773– 777.
[2] K.-H. Kampert, et.al, Astroparticle Physics 42 (2013), no. 0 41 – 51.
[3] J. P. Huchra et.al, The Astrophysical Journal Supplement Series 199 (2012), no. 2 26.
[4] H. B. J. Koers and P. Tinyakov, Monthly Notices of the Royal Astronomical Society 399 (2009), no. 2 1005–1011,
[5] E.Kido et al, Proceedings of UHECR2014 conference (2014).