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Telescope Array anisotropy summary

T. Fujii,[1] D. Ivanov,[2] C.C.H. Jui,[2] K. Kawata,[3] J.H. Kim,[2] M.Yu. Kuznetsov,[4,5] T. Nonaka,[3] S. Ogio,[6,7] G.I. Rubtsov,[4] H. Sagawa,[3] G.B. Thomson,[2] P.G. Tinyakov,[4,5] I. Tkachev[4,*] and S. Troitsky[4] on behalf of the Telescope Array Collaboration
(a complete list of authors can be found at the end of the proceedings)

[1] *The Hakubi Center for Advanced Research and Graduate School of Science, Kyoto University, Kitashirakawa-Oiwakecho, Sakyo-ku, Kyoto, Japan*
[2] *High Energy Astrophysics Institute and Department of Physics and Astronomy, University of Utah, Salt Lake City, Utah, USA*
[3] *Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba, Japan*
[4] *Institute for Nuclear Research of the Russian Academy of Sciences, 60th October Anniversary Prospect 7a, 117312 Moscow, Russia*
[5] *Service de Physique Theorique, Universite Libre de Bruxelles, Boulevard du Triomphe CP225, 1050 Brussels, Belgium*
[6] *Graduate School of Science, Osaka City University, Osaka, Osaka, Japan*
[7] *Nambu Yoichiro Institute of Theoretical and Experimental Physics, Osaka City University, Osaka, Osaka, Japan*

E-mail: tkachev@inr.ru

In this talk, we summarise the results of recent anisotropy studies conducted by the Telescope Array (TA) collaboration. At largest scales we test the TA data for the presence of a dipole. On smaller scales, an update on the excess of events in the direction of Ursa Major previously found in the TA data will be presented. These flux variations may trace the distribution of UHECR sources. We will examine the data for correlations with large-scale structures in the nearby Universe, and as a result, hints for the chemical composition of primaries will be provided. We also discuss a related anisotropy of the UHECR spectrum.

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1. Introduction and data used

Introduction. The origin of ultra-high energy cosmic rays (UHECR) is still unknown after decades of experimental efforts. Small number of events at the highest energies and poorly known deflections of primary particles in cosmic magnetic fields make the problem of source identification particularly difficult. In such a situation, the search for sources should be based on statistical methods, in particular on the search for anisotropies. In general, the following approaches exist.

CR clustering (Sec. 2). Within this approach, we study CR autocorrelations, search for statistically significant CR doublets, clusters, hot and cold spots. Here we are also looking for a deviation from uniformity at the largest angular scales, which in the most basic approach is described by the multipole expansion of the CR flux.

Correlations with putative sources (Sec. 3). If clusters are significant, the CR sources should be behind. In addition to the possible connection with specific structures in the distribution of matter, such spots can reflect several nearby bright sources together with large magnetic deflections of cosmic ray primaries. If sources are numerous and faint they have to follow the spatial matter distribution in the local Universe and can be revealed in the cross-correlation analysis of CR flux with the Large Scale Structure (LSS) in the local Universe.

Spectral and compositional reflections of anisotropy (Sec. 4). These will include searches for direction-dependent patterns in the energy spectrum and composition-dependent features of the UHECR anisotropy. This helps us understand the physical reasons for possible deviations from isotropy found in the distribution of arrival directions and even to restrict the composition itself.

Data. In this talk, we report on the results of anisotropy studies conducted by the Telescope Array (TA) collaboration using surface detector (SD) data collected up to 12 years of operation (May 2008 – May 2020). TA is a hybrid UHECR detector located in the Northern hemisphere in Utah, USA (39°17′48″ N, 112°54′31″ W). The SD array consists of 507 scintillator detectors covering the area of approximately 700 km^2 (for details see [1]). The atmosphere over the surface array is viewed by 38 fluorescence telescopes arranged in 3 stations [2]. In this analysis we use the SD event set as the one having by far the largest statistics and a simple (geometrical) exposure.

A special data set is prepared for anisotropy studies. Compared to the SD data sets used for the spectrum and composition studies, this “anisotropy set” has relaxed cuts on the zenith angle (55° versus 45°) and on the distance of the reconstructed shower core position from the array border (all events with the core inside the array boundary are included, compared to the 1.2 km distance cut in other sets). We tested that relaxing the cuts in this way does not lead to a significant loss of the data quality. By comparing the thrown and reconstructed arrival directions of the simulated data sets, the angular resolution of TA events with $E > 10$ EeV was found to be approximately 1.5°. Events with zenith angles between 45° and 55° have even better angular resolution. The energy resolution of the TA surface detector at $E > 10$ EeV is close to 20% [3]. Relaxing the cuts results in a considerable increase of the exposure.

In the anisotropy studies the crucial role is played by the exposure function. The exposure of the TA SD detector was calculated by the Monte-Carlo (MC) technique with the full simulation of the detector. It follows from these MC simulations that above 10 EeV the efficiency of the TA SD is 100%.

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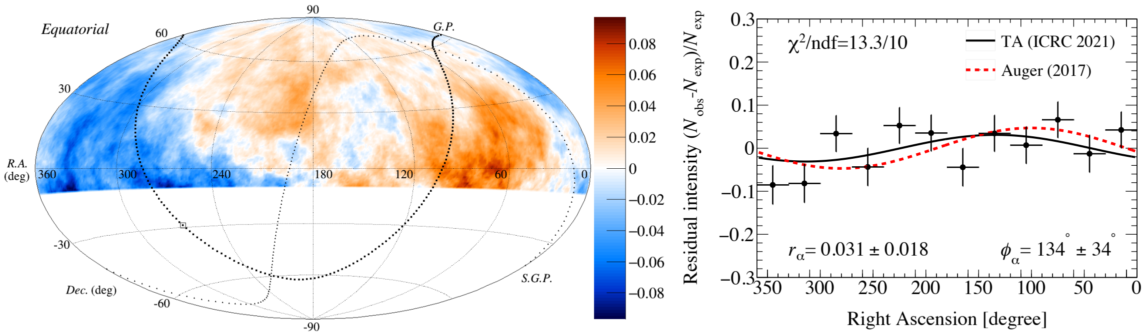

Figure 1: Left panel: The sky map of the UHECR excess and deficit with respect to the isotropic background is shown in equatorial coordinates. The Galactic plane and the super-galactic plane are shown by thick and thin dotted curves, respectively, the empty square indicates the center of the Galaxy. Right panel: Residual intensities of UHECRs as a function of right ascension. The black curve is the TA best fit to dipole while the red dashed curve is the dipole reported by Auger.

2. CR clustering

Dipole. In 2017 the Pierre Auger Collaboration reported the observation of a dipole structure in the arrival directions of cosmic rays above 8 EeV [4] which has an amplitude of 4.7% with a phase of 100°. Similar dipole structure had been found with an amplitude of 3.3±1.9% and a phase of 131° ± 33° in the TA dataset for 11 years [5]. However, the TA result for 11 years is consistent with both the isotropic distribution and the dipole structure described by Auger. Here we update the dipole using TA data recorded over 12 years from May 2008 to May 2020. As in [5] we use an *a priori* energy threshold of 8.8 EeV, equivalent to 8 EeV used by Auger, taking into account the 10% energy scale difference between TA and Auger [6]. There are 6518 events surviving this energy cut with zenith angles below 55° and the same quality cuts as used in the TA spectrum analysis [3]. In this dataset, TA SD is capable of measuring UHECRs in a declination band from −15° to 90°.

Figure 1 shows preliminary resulting residual intensity, defined as $(N_{obs} - N_{exp})/N_{exp}$. Here N_{obs} and N_{exp} correspond to 12 years of TA SD data above 8.8 EeV and isotropic expectation calculated from the MC simulations, respectively. The left panel of this figure shows the residual-intensity as a sky map in equatorial coordinates, while the right panel displays it as a function of right ascension. The residual intensity is fitted to $r_\alpha \cos(x - \phi_\alpha)$, where r_α is the amplitude of the dipole and ϕ_α is the phase. The obtained dipole structure has an amplitude of 3.1±1.8% with a phase of 134° ± 34°. In this figure, the TA SD result is also compared to the dipole reported by Auger. Although they are similar, with the current statistics the obtained TA SD result is still consistent with a fluctuation in the isotropic distribution, for more details see contribution by T. Fujii at this conference.

The TA hot spot. In the highest energy set with $E > 57$ EeV collected during the first 5 years of the TA operation, a concentration of events has been observed in the circle of radius 20° around the direction RA= 147°, DEC= 43° [7]. The number of observed events in this "hot spot" was found to be 19 out of 72 total (for the description of the data set used in the hot spot analysis see Ref. [7]), while 4.5 were expected in the case of a uniform background. The post-trial significance of this excess was evaluated to be 3.7×10^{-4} (3.4σ). In the 12-year TA SD data set in the hot spot we

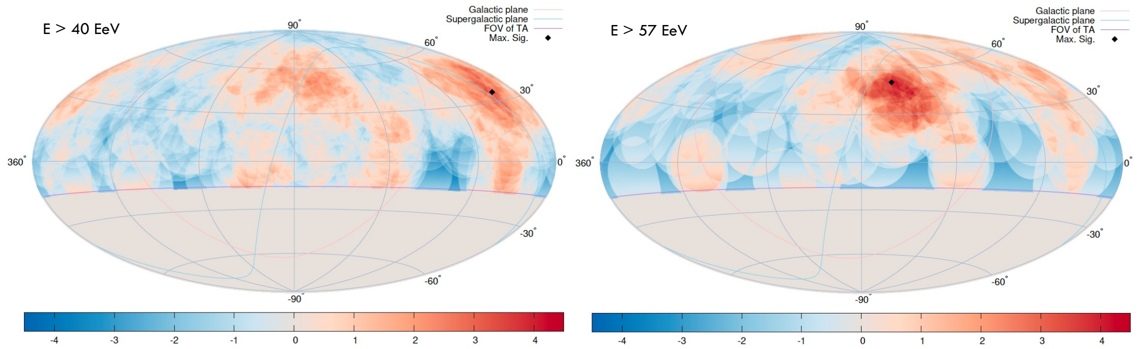

Figure 2: The skymap representing direction-dependent excesses and deficit with respect to the isotropic background, based on 11 years of TA data for $E > 40$ EeV (left panel) and $E > 57$ EeV (right panel).

observe 40 events while 14.6 events is expected for the isotropic distribution with the same cuts as in Ref. [7]. Post-trial significance has dropped to 3.2σ, but the increase rate of the events inside the hotspot circle is consistent with the linear increase within 1σ, for details see report by J.H. Kim at this conference.

In Figure 2 we show residual intensities as a sky map in equatorial coordinates above $E >$ 40 EeV (left panel) and $E > 57$ EeV (right panel). We see that that the overall pattern at both energy threshold is similar and resembles also the dipole structure shown in Fig. 1 with CR deficit in the left hemisphere and excess in the right. On the dependence of the dipole on energy, see the reports by T. Fuji and P. Tinyakov at this conference. Also, by eye, the excess of CR in Fig. 2 traces the supergalactic plain. A quantitative description of the correlation of CR fluxes with LSS is given in the next section.

3. Correlations with putative sources

Correlation with starburst galaxies. An update on the correlations of combined Auger and TA surface-detector 11 yr. data with a sample of nearby starburst galaxies is given in the report by A. di Matteo at this conference. A correlation has been found between the arrival directions of $11.8\%^{+5.0\%}_{-3.1\%}$ of cosmic rays detected with $E > 38$ EeV by Auger or with $E > 49$ EeV by TA and positions of nearby starburst galaxies on a $15.5^{\circ}{}^{+5.3^{\circ}}_{-3.2^{\circ}}$ angular scale, with a 4.3σ post-trial significance, as well as a somewhat weaker correlation, at about 3σ, with the overall galaxy distribution from the 2MASS catalog.

Correlation with LSS. The UHECR sources, regardless of their nature, are expected to trace the matter distribution. In the limit when the density of sources is sufficiently high so that they can be treated statistically, the resulting expected UHECR flux can be calculated, as a function of energy, with essentially one free parameter, the typical deflection angle θ which encodes uncertainties and unknowns of Galactic and extragalactic magnetic fields and of chemical composition. The predicted flux can be compared with observations to derive θ. The analysis of this type has been previously performed using the HiRes [8], the PAO [9, 10] and the TA [11] data.

We have examined the 11 year TA SD dataset for correlation with LSS using the procedure developed in [12], which is more advanced than previous approaches, for more details see contribu-

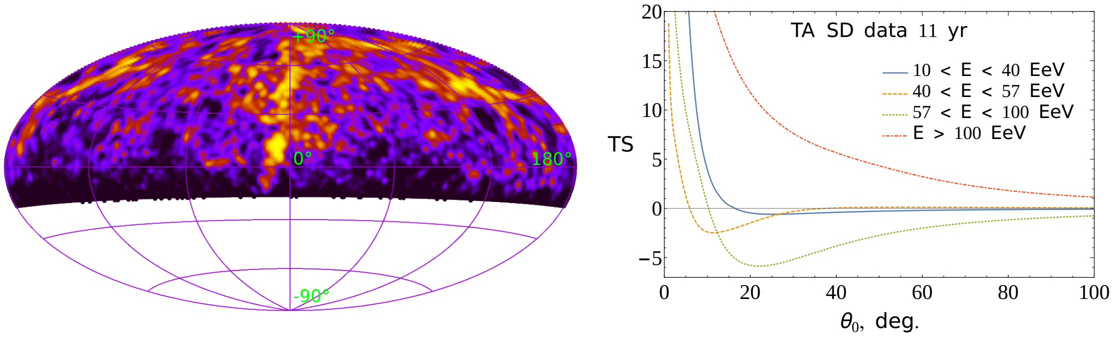

Figure 3: Left panel: example of the UHECR flux model map Φ_k for $\theta_0 = 1°$ and $E_k = 57$ EeV. Right panel: the resulting $TS(\theta_0)$ for the three datasets defined in the legend.

tion by M. Kuznetsov at this conference. The mass distribution in the Universe was inferred from the 2MASS Galaxy Redshift Catalog (XSCz) that is derived from the 2MASS Extended Source Catalog (XSC). We use a sample corrected for the incompleteness of the catalog and remove sources that are closer to us than 5 Mpc. We have assumed that sources follow the matter distribution, and propagated UHECRs from sources to the Earth taking full account of the energy attenuation processes under the assumption that the primary particles are protons with $E^{-2.5}$ injection spectrum. Accounting for the energy dependence does not introduce additional parameters as the deflection angles are inversely proportional to event energies and can be expressed in terms of a single parameter θ_0 – the deflection at a reference energy $E_0 = 100$ EeV. We bin the energies in log-uniform intervals with lower boundaries E_k (ten bins per energy decade with the highest bin an open interval $E > 180$ EeV) and neglect the energy dependence within each bin. The arrival directions then are smeared with the spherical Gaussian function (von Mises–Fisher distribution) with the opening angle $\theta = \theta(E, \theta_0)$ containing $\sim 63\%$ of probability.

For a given smearing parameter θ_0 and given energy bin we construct the sky map of the expected flux making use of the source distribution in space and the exposure of the experiment. We normalize a flux map $\Phi_k(\theta_0, \mathbf{n})$ obtained in this way to a unit integral over the sphere so that it can be interpreted as a probability density to observe an event from the direction $\mathbf{n}$. An example of such map is shown in Fig. 3, left panel. Finally, we define our test statistics $TS(\theta_0)$ as follows:

$$TS(\theta_0) = -2 \sum_k \left(\sum_i \ln \frac{\Phi_k(\theta_0, \mathbf{n}_i)}{\Phi_{\text{iso}}(\mathbf{n}_i)} \right), \qquad (1)$$

where the internal sum runs over the events observed in the energy bin k and the normalization factor $\Phi_{\text{iso}}(\mathbf{n}_i)$ corresponds to the isotropic distribution of sources — a uniform flux modulated by the exposure function. In the limit of a large number of events, this test statistics is distributed around its minimum according to χ^2-distribution with one degree of freedom. The procedure is described in detail in Ref. [12].

We calculate $TS(\theta_0)$ for data divided into four already customary energy ranges (in EeV): $10 < E < 40$, $40 < E < 57$, $57 < E < 100$, and $E > 100$. In three lowest energy intervals $TS(\theta_0)$ has minima, see Fig. 3, right panel. This indicates that UHECR do correlate with LSS (isotropic distribution is excluded at 2.4σ level according to the deepest minimum). Position of the minimum gives estimate for the most probable θ_0. The estimate for θ_0 is rather large, $\sim 20°$. However, this is compatible with a proton fraction of 90%, while it does not favour a 50/50 or heavier mixture of protons and iron at $E < 100$ EeV, see Sec. 4.

4. Spectral and compositional reflections of anisotropy

Additional information can be extracted from the arrival direction studies, which may help to better understand the origin and location of UHCR accelerators, and even to restrict chemical composition. It includes spectral anisotropies as well as the energy and composition dependence of anisotropy features.

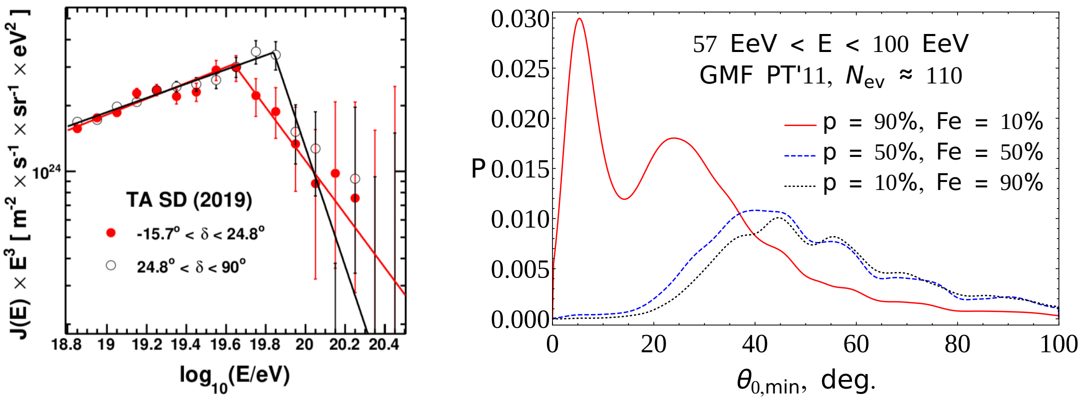

Figure 4: Left panel: TA SD spectrum measured in two declination bands. Right panel: distributions of TS minima (see, Sec 3) in composition dependent Monte Carlo. GMF model of Ref. [13] had been used.

Spectral anisotropies. After correcting the 10% energy scale mismatch [6], the difference in the spectra of the Telescope Array and Pierre Auger still remains above about 10 EeV, and particularly in the location of the high-energy cutoff as was established by the common working group [**?**]. To try to understand the remaining difference the working group examined the two experiments spectra in the band of declination covered by both experiments, $-15.7° < \delta < 24.8°$. Although the result is not complete agreement between the spectra, the energy of the cutoff was found to agree well in the common declination band. This result prompted the TA collaboration to measure the spectrum in the northern part of the sky outside of the common declination band. When the data are divided into two declination bands, above and below 24.8°, the cutoff appears at 3.9 (7.1) EeV in the lower (higher) band, an energy difference of 82%, see Fig. 4, left panel. In the 11 years of TA data, the global significance of the difference is 4.3 standard deviations. A comprehensive search for an instrumental effect to explain the difference has failed to find one, and both the TA collaboration and the joint TA-Auger working group studying the spectrum of ultrahigh energy cosmic rays have concluded that the variation of the cutoff energy with declination is an astrophysical effect.

Constraint on CR composition. The procedure described in Sec. 3 can be repeated many times in Monte Carlo simulations with different chemical compositions of synthetic cosmic ray datasets to find the distribution of θ_0 where TS happens to be minimal, see Fig. 3. The resulting distributions are shown in Fig. 4 for three particular composition models. In 11 yr TA data the most

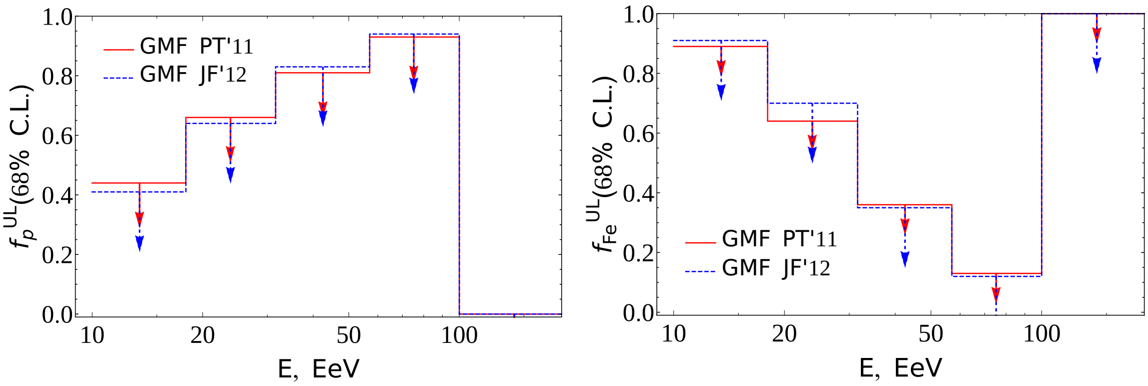

Figure 5: Upper limits on proton (left panel) and iron (right panel) fractions as functions of energy derived from correlation with LSS. Solid and dashed lines correspond to two different GMF models, [13] and [14].

significant minimum of TS is at $\theta_{0,\min} = 20°$. Smaller values for $\theta_{0,\min}$ in the same energy range 57 EeV $< E <$ 100 EeV occur only in 1.3% of realisations for 50/50 proton/iron composition and are even more rare for heavier 10/90 composition. Therefore, such compositions are disfavoured. On the other hand, the 90% fraction of protons at 57 EeV $< E <$ 100 EeV is compatible with the TA observation. The limits at 68% C.L. on the proton and iron fractions obtained in this approach for the p+Fe composition model are shown in Fig. 5, for details see report by M. Kuznetsov at this conference.

5. Conclusions

We have summarised the results of recent anisotropy studies conducted by the Telescope Array (TA) collaboration. At largest angular scales and smallest energies we see indication for the dipole contribution in the distribution of arrival directions. At largest energies, 40 EeV $< E <$ 100 EeV, we detect correlations with LSS of the Universe, and derive constraint on the chemical composition based on the angular scale of correlations. At these energies, we also see spectral anisotropy, which is an astrophysical effect related to the properties and distribution of sources.

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Full Authors List: Telescope Array Collaboration

R.U. Abbasi[1,2], T. Abu-Zayyad[1,2], M. Allen[2], Y. Arai[3], R. Arimura[3], E. Barcikowski[2], J.W. Belz[2], D.R. Bergman[2], S.A. Blake[2], I. Buckland[2], R. Cady[2], B.G. Cheon[4], J. Chiba[5], M. Chikawa[6], T. Fujii[7], K. Fujisue[6], K. Fujita[3], R. Fujiwara[3], M. Fukushima[6], R. Fukushima[3], G. Furlich[2], R. Gonzalez[2], W. Hanlon[2], M. Hayashi[8], N. Hayashida[9], K. Hibino[9], R. Higuchi[6], K. Honda[10], D. Ikeda[9], T. Inadomi[11], N. Inoue[12], T. Ishii[10], H. Ito[13], D. Ivanov[2], H. Iwakura[11], A. Iwasaki[3], H.M. Jeong[14], S. Jeong[14], C.C.H. Jui[2], K. Kadota[15], F. Kakimoto[9], O. Kalashev[16], K. Kasahara[17], S. Kasami[18], H. Kawai[19], S. Kawakami[3], S. Kawana[12], K. Kawata[6], I. Kharuk[16], E. Kido[13], H.B. Kim[4], J.H. Kim[2], J.H. Kim[2], M.H. Kim[14], S.W. Kim[14], Y. Kimura[3], S. Kishigami[3], Y. Kubota[11], S. Kurisu[11], M. Kuznetsov[16,20], Y.J. Kwon[21], K.H. Lee[14], B. Lubsandorzhiev[16], J.P. Lundquist[2,22], K. Machida[10], H. Matsumiya[3], T. Matsuyama[3], J.N. Matthews[2], R. Mayta[3], M. Minamino[3], K. Mukai[10], I. Myers[2], S. Nagataki[13], K. Nakai[3], R. Nakamura[11], T. Nakamura[23], T. Nakamura[11], Y. Nakamura[11], A. Nakazawa[11], E. Nishio[18], T. Nonaka[6], H. Oda[3], S. Ogio[3,24], M. Ohnishi[6], H. Ohoka[6], Y. Oku[18], T. Okuda[25], Y. Omura[3], M. Ono[13], R. Onogi[3], A. Oshima[3], S. Ozawa[26], I.H. Park[14], M. Potts[2], M.S. Pshirkov[16,27], J. Remington[2], D.C. Rodriguez[2], G.I. Rubtsov[16], D. Ryu[28], H. Sagawa[6], R. Sahara[3], Y. Saito[11], N. Sakaki[6], T. Sako[6], N. Sakurai[3], K. Sano[11], K. Sato[3], T. Seki[11], K. Sekino[6], P.D. Shah[2], Y. Shibasaki[11], F. Shibata[10], N. Shibata[18], T. Shibata[6], H. Shimodaira[6], B.K. Shin[28], H.S. Shin[6], D. Shinto[18], J.D. Smith[2], P. Sokolsky[2], N. Sone[11], B.T. Stokes[2], T.A. Stroman[2], Y. Takagi[3], Y. Takahashi[3], M. Takamura[5], M. Takeda[6], R. Takeishi[6], A. Taketa[29], M. Takita[6], Y. Tameda[18], H. Tanaka[3], K. Tanaka[30], M. Tanaka[31], Y. Tanoue[3], S.B. Thomas[2], G.B. Thomson[2], P. Tinyakov[16,20], I. Tkachev[16], H. Tokuno[32], T. Tomida[11], S. Troitsky[16], R. Tsuda[3], Y. Tsunesada[3,24], Y. Uchihori[33], S. Udo[9], T. Uehama[11], F. Urban[34], T. Wong[2], K. Yada[6], M. Yamamoto[11], K. Yamazaki[9], J. Yang[35], K. Yashiro[5], F. Yoshida[18], Y. Yoshioka[11], Y. Zhezher[6,16], and Z. Zundel[2]

[1] Department of Physics, Loyola University Chicago, Chicago, Illinois, USA
[2] High Energy Astrophysics Institute and Department of Physics and Astronomy, University of Utah, Salt Lake City, Utah, USA
[3] Graduate School of Science, Osaka City University, Osaka, Osaka, Japan
[4] Department of Physics and The Research Institute of Natural Science, Hanyang University, Seongdong-gu, Seoul, Korea
[5] Department of Physics, Tokyo University of Science, Noda, Chiba, Japan
[6] Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba, Japan
[7] The Hakubi Center for Advanced Research and Graduate School of Science, Kyoto University, Kitashirakawa-Oiwakecho, Sakyo-ku, Kyoto, Japan
[8] Information Engineering Graduate School of Science and Technology, Shinshu University, Nagano, Nagano, Japan
[9] Faculty of Engineering, Kanagawa University, Yokohama, Kanagawa, Japan
[10] Interdisciplinary Graduate School of Medicine and Engineering, University of Yamanashi, Kofu, Yamanashi, Japan
[11] Academic Assembly School of Science and Technology Institute of Engineering, Shinshu University, Nagano, Nagano, Japan
[12] The Graduate School of Science and Engineering, Saitama University, Saitama, Saitama, Japan
[13] Astrophysical Big Bang Laboratory, RIKEN, Wako, Saitama, Japan
[14] Department of Physics, SungKyunKwan University, Jang-an-gu, Suwon, Korea
[15] Department of Physics, Tokyo City University, Setagaya-ku, Tokyo, Japan
[16] Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia
[17] Faculty of Systems Engineering and Science, Shibaura Institute of Technology, Minato-ku, Tokyo, Japan
[18] Department of Engineering Science, Faculty of Engineering, Osaka Electro-Communication University, Neyagawa-shi, Osaka, Japan
[19] Department of Physics, Chiba University, Chiba, Chiba, Japan
[20] Service de Physique ThÃ©orique, UniversitÃ© Libre de Bruxelles, Brussels, Belgium
[21] Department of Physics, Yonsei University, Seodaemun-gu, Seoul, Korea
[22] Center for Astrophysics and Cosmology, University of Nova Gorica, Nova Gorica, Slovenia
[23] Faculty of Science, Kochi University, Kochi, Kochi, Japan
[24] Nambu Yoichiro Institute of Theoretical and Experimental Physics, Osaka City University, Osaka, Osaka, Japan
[25] Department of Physical Sciences, Ritsumeikan University, Kusatsu, Shiga, Japan
[26] Quantum ICT Advanced Development Center, National Institute for Information and Communications Technology, Koganei, Tokyo, Japan
[27] Sternberg Astronomical Institute, Moscow M.V. Lomonosov State University, Moscow, Russia
[28] Department of Physics, School of Natural Sciences, Ulsan National Institute of Science and Technology, UNIST-gil, Ulsan, Korea
[29] Earthquake Research Institute, University of Tokyo, Bunkyo-ku, Tokyo, Japan
[30] Graduate School of Information Sciences, Hiroshima City University, Hiroshima, Hiroshima, Japan
[31] Institute of Particle and Nuclear Studies, KEK, Tsukuba, Ibaraki, Japan
[32] Graduate School of Science and Engineering, Tokyo Institute of Technology, Meguro, Tokyo, Japan
[33] Department of Research Planning and Promotion, Quantum Medical Science Directorate, National Institutes for Quantum and Radiological Science and Technology, Chiba, Chiba, Japan
[34] CEICO, Institute of Physics, Czech Academy of Sciences, Prague, Czech Republic
[35] Department of Physics and Institute for the Early Universe, Ewha Womans University, Seodaaemun-gu, Seoul, Korea