PROCEEDINGS OF SCIENCE

Tests of anomalous correlations between ultra-high-energy cosmic rays and BL Lac type objects with the Telescope Array data

Maria Kudenko,[a,b,*] **M. Kuznetsov,**[a] **G. Rubtsov**[a] **and S. Troitsky**[a,b] **on behalf of the Telescope Array Collaboration**

E-mail: kudenko.ma19@physics.msu.ru

PoS(ICRC2025)311

Observations made by the High Resolution Fly's Eye detector in stereoscopic fluorescent mode revealed correlations between arrival directions of ultra-high-energy cosmic rays and positions of distant BL Lac type objects ([1], [2]). They implied the existence of non-deflected particles traveling for cosmological distances, which was hard to explain within standard physics and astrophysics. These correlations have not been conclusively tested with independent data. Here we present preliminary results of such tests performed with the use of two different methods and Telescope Array data.

39th International Cosmic Ray Conference (ICRC2025)
15–24 July 2025
Geneva, Switzerland

ICRC 2025
The Astroparticle Physics Conference
Geneva July 15-24, 2025

*Speaker

1. Introduction

Two decades ago, puzzling correlations between arrival directions of ultra-high-energy cosmic rays, detected by the High Resolution Fly's Eye experiment (HiRes) in stereo mode, and the BL Lac type objects (BL Lacs) were discovered [1], [2]. HiRes is a detector of ultra-high-energy cosmic rays which was located in Utah and operated from 1997 to 2006. These BL Lacs, which constitute a subclass of blazars, are active galactic nuclei with jets pointing to the observer, and are located at cosmological distances. Though they are plausible sites of cosmic-ray acceleration, charged nuclei would be deflected by cosmic magnetic fields, while the angular distances between arrival directions of HiRes events and these sources were significantly smaller than the expected deflections.

The effect was initially discovered in 2004 during the analysis of cosmic rays with energies greater than 10 EeV with the use of a method which was named as "pair counting method". The main idea of this method would be described in sec. 2. The results of this analysis have shown that most of the correlating cosmic-rays have arrival directions within $0.8°$ from BL Lac type objects when HiRes angular resolution in stereo mode is $0.6°$.

Later in 2006, the HiRes collaboration, using a larger set of cosmic rays with energies greater than 1 EeV and the same set of 156 BL Lacs, confirmed the earlier result of correlations using the maximum likelihood method, which takes into account the individual angular resolution of each cosmic ray [2], [3], [4].

The absence of deflection of charged particles of cosmic rays under the influence of astrophysical magnetic fields indicates the presence of neutral particles included in the emission of blazars. However, the Standard Model does not contain neutral particles that could explain this phenomenon. This effect was called anomalous correlations.

There are three important components in the analysis of anomalous correlations of cosmic rays and BL Lacs: a set of BL Lacs, a set of cosmic rays and a research method (pair counting or the maximum likelihood method). Anomalous correlations have not been tested with independent data on cosmic-ray before. Here preliminary results of such tests performed with the use of both pair-counting and likelihood methods and Telescope Array Surface Detectors (TA SD) data are presented. For this analysis of TA SD data the same set of 156 BL Lacs [5] as in previous analysis of HiRes data was used.

2. Pair counting method

The main idea of the pair counting method is to calculate amount of pairs «BL Lac – cosmic-ray arrival direction» separated by the angle $\leq \theta$ using real data, where θ is fixed beforehand. Then the same procedure is repeated for a large number of simulated sets of arrival directions, and the p-value measuring how often this or larger number of pairs can be observed by chance, is determined. Here $0.1° \leq \theta \leq 3.0°$ in steps $0.1°$ was considered.

For this analysis 6712 cosmic-rays with $E \geq 10$ EeV collected during 16 years of TA SD operation were used. The result of this part of the analysis is presented in fig. 1 together with the 2004 result for HiRes from [1].

The lowest pre-trial p-value is 3×10^{-3}. Post-trial p-value in this case is 3×10^{-2}. Here correlating cosmic-rays are within angular distance $\theta = 1.4°$ from BL Lac type objects. This

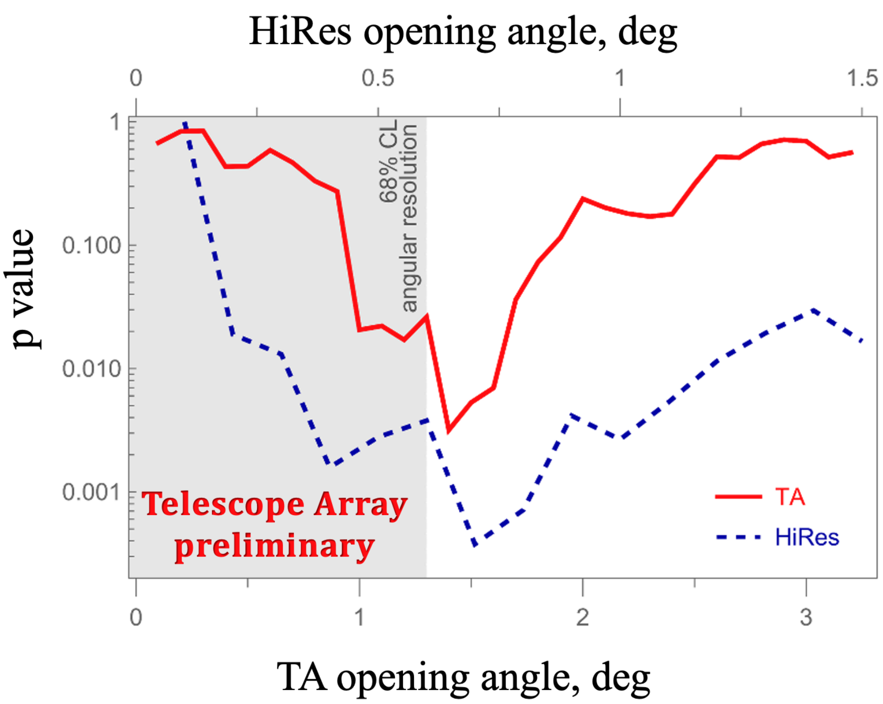

Figure 1: Pre-trial p-value dependence on angular separation distance θ for TA SD and HiRes data on the same plot for comparison. Light gray shading – detector's angular resolution.

deflection couldn't be explained by magnetic field and it is important to mention that TA SD angular resolution is 1.3°.

It is possible to see from fig. 1 that results of HiRes and TA SD data analyses are consistent, but for TA SD data signal is not so strong.

3. Maximum Likelihood Method

In 2006 in order to confirm previous result on correlations HiRes collaboration applied an unbinned maximum likelihood method in the search for point sources of ultra–high-energy cosmic rays [2]. Two important advantages of this method are the ability to accommodate events with different errors, and to give weighted sensitivity to angular separations – avoiding the loss of information that follows from choosing an angular separation cut-off.

Here the same maximum likleihood method was used as in [2]. The premise involved in the maximum likelihood analysis is that the data sample of N events consists of n_s source events which came from some source position(s) in the sky, and $N - n_s$ background events. A background event arrives according to the probability distribution given by the detector exposure to the sky, $R(\mathbf{x}, \mathrm{E})$, where $\mathbf{x}$ are equatorial or local coordinates of the event and E is an energy of the event in EeV. The true arrival direction of a source event is the location of the source $\mathbf{s}$, but the event is observed somewhere near $\mathbf{s}$ according to the probability distribution $Q(\mathbf{x}_i, \mathbf{s}, E_i)$, where $Q(\mathbf{x}_i, \mathbf{s}, E_i)$ is a point spread function.

$$P_i(\mathbf{x}_i, \mathrm{E}_i) = \frac{n_s}{N} Q(\mathbf{x}_i, \mathrm{E}_i) + \frac{N - n_s}{N} R(\mathbf{x}_i, \mathrm{E}_i) \tag{1}$$

$$Q_i^{tot}(\mathbf{x}_i, \mathrm{E}_i) = \sum_{j=1}^{M} R(\mathbf{s}_j, \mathrm{E}_i) Q(\mathbf{x}_i, \mathbf{s}_j, \mathrm{E}_i) / \sum_{k=1}^{M} R(\mathbf{s}_k, \mathrm{E}_i) \tag{2}$$

$$P_i(\mathbf{x}_i, \mathrm{E}_i) = \frac{n_s}{N} Q_i^{tot}(\mathbf{x}_i, \mathrm{E}_i) + \frac{N - n_s}{N} R(\mathbf{x}_i, \mathrm{E}_i) \tag{3}$$

$$\mathcal{L}(n_s) = \prod_{i=1}^{N} P_i(\mathbf{x}_i, \mathrm{E}_i) \tag{4}$$

$$\mathcal{R}(n_s) = \frac{\mathcal{L}(n_s)}{\mathcal{L}(0)} = \prod_{i=1}^{N} \left(\frac{n_s}{N} \left(\frac{Q_i^{tot}(\mathbf{x}_i, \mathrm{E}_i)}{R(\mathbf{x}_i, \mathrm{E}_i)} - 1 \right) + 1 \right) \tag{5}$$

The idea is to maximize $\ln\mathcal{R}(n_s)$ by changing n_s. This calculation could be performed for real data and then the same procedure is repeated for a large number of simulated sets of arrival directions, and the p-value measuring how often this or larger maximized $\ln\mathcal{R}$ can be observed by chance, is determined.

To perform this analysis it is necessary to know point spread function for each event $Q(\mathbf{x}_i, \mathbf{s}, E_i)$ and exposure $R(\mathbf{x}_i, \mathrm{E}_i)$.

3.1 Point Spread Function

It was shown that point spread function $Q_i(\mathbf{x}_i, \mathbf{s}, E_i)$ for TA depends not only on angular distance δ between $\mathbf{x}_i$ and $\mathbf{s}$, but also on energy E and zenith angle θ of the event [6]. In order to construct such function 14 years of proton Monte Carlo were used. All MC events were separated into different bins based on reconstructed energy and zenith angle and then inside each bin a distribution fit was performed. After that, all fit parameters were fitted as functions of reconstructed energy and zenith angle. The resulting point spread function looks like this:

$$Q(\mathbf{x}_i, \mathbf{s}, \mathrm{E}_i) = Q(\delta, \mathrm{E}_i, \theta_i) = N \left(1 + \frac{\delta^2}{2\sigma_1^2} \right)^{-\sigma_2} \tag{6}$$

$$\sigma_1\,(\mathrm{E}, \theta) = \sum_{i=1}^{3} a_i \log_{10} \left(\frac{\mathrm{E}}{\mathrm{EeV}} \right)^i \cdot \theta + \sum_{i=1}^{3} b_i \log_{10} \left(\frac{\mathrm{E}}{\mathrm{EeV}} \right)^i \tag{7}$$

$$\sigma_1\,(\mathrm{E}, \theta) = \sum_{i=1}^{2} c_i \log_{10} \left(\frac{\mathrm{E}}{\mathrm{EeV}} \right)^i \cdot \theta + \sum_{i=1}^{2} d_i \log_{10} \left(\frac{\mathrm{E}}{\mathrm{EeV}} \right)^i, \tag{8}$$

where N – normalization constant which is defined from eq. 9.

$$\int_1^{10^{2.6}} \int_0^{\pi/4} \int_0^{\pi} Q(\delta, \mathrm{E}, \theta) \sin(\delta) d\mathrm{E} d\theta d\delta = 1 \tag{9}$$

PoS(ICRC2025)311

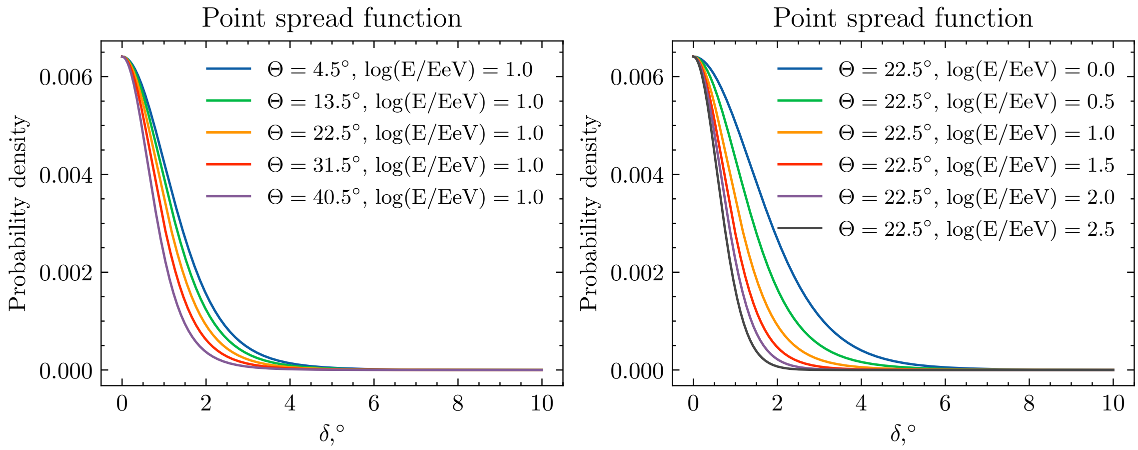

Figure 2: Point spread function $Q(\delta, \mathrm{E}_i, \theta_i)$ for different energies E and zenith angles θ.

3.2 Exposure

TA SD operates during the whole year, that is why, its exposure is independent of right ascension, but still depends on the declination and the energy of the event. To get a grip of exposure function all real data for 14 years of observation was divided into different bins based on energy and then declination distribution fit was performed. After that the resulting fit parameters were fitted as a function of energy. Thus, such exposure function was obtained:

$$R(\mathbf{x}_i, \mathrm{E}_i) = R(\mathrm{DEC}_i, \mathrm{E}_i) = N\alpha\,(\mathrm{E}) \cdot \sum_{i=0}^{3} \sigma_i \sin^i(\mathrm{DEC}) \tag{10}$$

$$\alpha\,(\mathrm{E}) = a_0 \tanh\left(-b_0 \log_{10}\left(\frac{\mathrm{E}}{\mathrm{EeV}}\right) + c_0\right) + d_0 \tanh\left(f_0 \log_{10}\left(\frac{\mathrm{E}}{\mathrm{EeV}}\right) + g_0\right) + h_0 \tag{11}$$

$$\sigma_1\,(\mathrm{E}) = a_1 \tanh\left(-b_1 \log_{10}\left(\frac{\mathrm{E}}{\mathrm{EeV}}\right) + c_1\right) + d_1 \tanh\left(f_1 \log_{10}\left(\frac{\mathrm{E}}{\mathrm{EeV}}\right) + g_1\right) + h_1 \tag{12}$$

$$\sigma_2\,(\mathrm{E}) = a_2 \tanh\left(-b_2 \log_{10}\left(\frac{\mathrm{E}}{\mathrm{EeV}}\right) + c_2\right) + h_2 \tag{13}$$

$$\sigma_3\,(\mathrm{E}) = a_3 \tanh\left(-b_3 \log_{10}\left(\frac{\mathrm{E}}{\mathrm{EeV}}\right) + c_3\right) + h_3, \tag{14}$$

where DEC – declination, N – normalization constant which is defined from:

$$\int_1^{10^{2.6}} \int_0^{2\pi} \int_{-5.6\frac{\pi}{180}}^{84.3\frac{\pi}{180}} R(\mathrm{DEC}, \mathrm{E}) \cos(\mathrm{DEC}) d\mathrm{E} d\mathrm{RA} d\mathrm{DEC} = 1 \tag{15}$$

3.3 Preliminary results

With the usage of exposure function and point spread function constructed as described above it is possible to perform necessary calculations of maximum logarithm of likelihood ratio $\ln\mathcal{R}$.

For 14 years of events detected with TA SD with E $\geq$ 1.0 EeV and from 10000 simulated datasets of cosmic-rays it was established that p-value to obtain this or higher value than $\ln\mathcal{R}$ is 2.4×10^{-3}. And for the events with energies E $\geq$ 10.0 EeV p-value = 3.0×10^{-3}.

In 2006 analysis p-value calculated with the use of maximum likelihood method was $\sim 4\times10^{-4}$ [2].

4. Conclusion

It can be seen that the preliminary results of TA SD data analysis obtained with both pair counting (post-trial p-value = 3×10^{-2} for events with E $\geq$ 10 EeV) and likelihood method (p-value = 3.0×10^{-3} for events with E $\geq$ 10 EeV and p-value = 2.4×10^{-3} for events with all energies) are consistent with each other and with previous results on correlations with HiRes data. But signal is weaker for TA SD. This effect may be due to the smaller fraction of events from BL Lac type objects detected in TA SD than it was in HiRes.

Acknowledgments

The Telescope Array experiment is supported by the Japan Society for the Promotion of Science(JSPS) through Grants-in-Aid for Priority Area 431, for Specially Promoted Research JP21000002, for Scientific Research (S) JP19104006, for Specially Promoted Research JP15H05693, for Scientific Research (S) JP19H05607, for Scientific Research (S) JP15H05741, for Science Research (A) JP18H03705, for Young Scientists (A) JPH26707011, for Transformative Research Areas (A) JP25H01294, for International Collaborative Research 24KK0064, and for Fostering Joint International Research (B) JP19KK0074, by the joint research program of the Institute for Cosmic Ray Research (ICRR), The University of Tokyo; by the Pioneering Program of RIKEN for the Evolution of Matter in the Universe (r-EMU); by the U.S. National Science Foundation awards PHY-1806797, PHY-2012934, PHY-2112904, PHY-2209583, PHY-2209584, and PHY-2310163, as well as AGS-1613260, AGS-1844306, and AGS-2112709; by the National Research Foundation of Korea (2017K1A4A3015188, 2020R1A2C1008230, and RS-2025-00556637) ; by the Russian Science Foundation project 22-12-00253-P, by the Ministry of Science and Higher Education of the Russian Federation under the contract 075-15-2024-541, IISN project No. 4.4501.18, by the Belgian Science Policy under IUAP VII/37 (ULB), by National Science Centre in Poland grant 2020/37/B/ST9/01821, by the European Union and Czech Ministry of Education, Youth and Sports through the FORTE project No. CZ.02.01.01/00/22_008/0004632, and by the Simons Foundation (MP-SCMPS-00001470, NG). This work was partially supported by the grants of the joint research program of the Institute for Space-Earth Environmental Research, Nagoya University and Inter-University Research Program of the Institute for Cosmic Ray Research of University of Tokyo. The foundations of Dr. Ezekiel R. and Edna Wattis Dumke, Willard L. Eccles, and George S. and Dolores Doré Eccles all helped with generous donations. The State of Utah supported the project through its Economic Development Board, and the University of Utah through the Office of the Vice President for Research. The experimental site became available through the cooperation of the Utah School and Institutional Trust Lands Administration (SITLA), U.S. Bureau of Land Management (BLM), and the U.S. Air Force. We appreciate the assistance of the State of Utah and

Fillmore offices of the BLM in crafting the Plan of Development for the site. We thank Patrick A. Shea who assisted the collaboration with much valuable advice and provided support for the collaboration™s efforts. The people and the officials of Millard County, Utah have been a source of steadfast and warm support for our work which we greatly appreciate. We are indebted to the Millard County Road Department for their efforts to maintain and clear the roads which get us to our sites. We gratefully acknowledge the contribution from the technical staffs of our home institutions. An allocation of computing resources from the Center for High Performance Computing at the University of Utah as well as the Academia Sinica Grid Computing Center (ASGC) is gratefully acknowledged.

References

[1] D.S. Gorbunov, P.G. Tinyakov, I.I. Tkachev and S.V. Troitsky, *Testing the correlations between ultra-high-energy cosmic rays and BL Lac type objects with HiRes stereoscopic data*, *JETP Lett.* **80** (2004) 145 [astro-ph/0406654].

[2] R.U. Abbasi, T. Abu-Zayyad, J.F. Amann, G. Archbold, K. Belov, J.W. Belz et al., *Search for Cross-Correlations of Ultrahigh-Energy Cosmic Rays with BL Lacertae Objects*, **636** (2006) 680 [astro-ph/0507120].

[3] J. Braun, J. Dumm, F. De Palma, C. Finley, A. Karle and T. Montaruli, *Methods for point source analysis in high energy neutrino telescopes*, *Astropart. Phys.* **29** (2008) 299 [0801.1604].

[4] R. Jansson and G.R. Farrar, *Maximum Likelihood Method for Cross Correlations with Astrophysical Sources*, *JCAP* **06** (2008) 017 [0711.0177].

[5] M.P. Veron-Cetty and P. Veron, “VizieR Online Data Catalog: Quasars and Active Galactic Nuclei (9th Ed.) (Veron+ 2000).” VizieR On-line Data Catalog: VII/215. Originally published in: 2000ESOSR..19....1V, Mar., 2000.

[6] Telescope Array collaboration, *A Northern Sky Survey for Point-Like Sources of EeV Neutral Particles with the Telescope Array Experiment*, *Astrophys. J.* **804** (2015) 133 [1407.6145].

Full Authors List: The Telescope Array Collaboration

R.U. Abbasi[1], T. Abu-Zayyad[1,2], M. Allen[2], J.W. Belz[2], D.R. Bergman[2], F. Bradfield[3], I. Buckland[2], W. Campbell[2], B.G. Cheon[4], K. Endo[3], A. Fedynitch[5,6], T. Fujii[3,7], K. Fujisue[5,6], K. Fujita[5], M. Fukushima[5], G. Furlich[2], A. Gálvez Ureña[8], Z. Gerber[2], N. Globus[9], T. Hanaoka[10], W. Hanlon[2], N. Hayashida[11], H. He[12*], K. Hibino[11], R. Higuchi[12], D. Ikeda[11], D. Ivanov[2], S. Jeong[13], C.C.H. Jui[2], K. Kadota[14], F. Kakimoto[11], O. Kalashev[15], K. Kasahara[16], Y. Kawachi[3], K. Kawata[5], I. Kharuk[15], E. Kido[5], H.B. Kim[4], J.H. Kim[2], J.H. Kim[2†], S.W. Kim[13‡], R. Kobo[3], I. Komae[3], K. Komatsu[17], K. Komori[10], A. Korochkin[18], C. Koyama[5], M. Kudenko[15], M. Kuroiwa[17], Y. Kusumori[10], M. Kuznetsov[15], Y.J. Kwon[19], K.H. Lee[4], M.J. Lee[13], B. Lubsandorzhiev[15], J.P. Lundquist[2,20], H. Matsushita[3], A. Matsuzawa[17], J.A. Matthews[2], J.N. Matthews[2], K. Mizuno[17], M. Mori[10], S. Nagataki[12], K. Nakagawa[3], M. Nakahara[3], H. Nakamura[10], T. Nakamura[21], T. Nakayama[17], Y. Nakayama[10], K. Nakazawa[10], T. Nonaka[5], S. Ogio[5], H. Ohoka[5], N. Okazaki[5], M. Onishi[5], A. Oshima[22], H. Oshima[5], S. Ozawa[23], I.H. Park[13], K.Y. Park[4], M. Potts[2], M. Przybylak[24], M.S. Pshirkov[15,25], J. Remington[2§], C. Rott[2], G.I. Rubtsov[15], D. Ryu[26], H. Sagawa[5], N. Sakaki[5], R. Sakamoto[10], T. Sako[5], N. Sakurai[5], S. Sakurai[3], D. Sato[17], K. Sekino[5], T. Shibata[5], J. Shikita[3], H. Shimodaira[5], H.S. Shin[3,7], K. Shinozaki[27], J.D. Smith[2], P. Sokolsky[2], B.T. Stokes[2], T.A. Stroman[2], H. Tachibana[3], K. Takahashi[5], M. Takeda[5], R. Takeishi[5], A. Taketa[28], M. Takita[5], Y. Tameda[10], K. Tanaka[29], M. Tanaka[30], M. Teramoto[10], S.B. Thomas[2], G.B. Thomson[2], P. Tinyakov[15,18], I. Tkachev[15], T. Tomida[17], S. Troitsky[15], Y. Tsunesada[3,7], S. Udo[11], F.R. Urban[8], M. Vrábel[27], D. Warren[12], K. Yamazaki[22], Y. Zhezher[5,15], Z. Zundel[2], and J. Zvirzdin[2]

[1] *Department of Physics, Loyola University-Chicago, Chicago, Illinois 60660, USA*
[2] *High Energy Astrophysics Institute and Department of Physics and Astronomy, University of Utah, Salt Lake City, Utah 84112-0830, USA*
[3] *Graduate School of Science, Osaka Metropolitan University, Sugimoto, Sumiyoshi, Osaka 558-8585, Japan*
[4] *Department of Physics and The Research Institute of Natural Science, Hanyang University, Seongdong-gu, Seoul 426-791, Korea*
[5] *Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba 277-8582, Japan*
[6] *Institute of Physics, Academia Sinica, Taipei City 115201, Taiwan*
[7] *Nambu Yoichiro Institute of Theoretical and Experimental Physics, Osaka Metropolitan University, Sugimoto, Sumiyoshi, Osaka 558-8585, Japan*
[8] *CEICO, Institute of Physics, Czech Academy of Sciences, Prague 182 21, Czech Republic*
[9] *Institute of Astronomy, National Autonomous University of Mexico Ensenada Campus, Ensenada, BC 22860, Mexico*
[10] *Graduate School of Engineering, Osaka Electro-Communication University, Neyagawa-shi, Osaka 572-8530, Japan*
[11] *Faculty of Engineering, Kanagawa University, Yokohama, Kanagawa 221-8686, Japan*
[12] *Astrophysical Big Bang Laboratory, RIKEN, Wako, Saitama 351-0198, Japan*
[13] *Department of Physics, Sungkyunkwan University, Jang-an-gu, Suwon 16419, Korea*
[14] *Department of Physics, Tokyo City University, Setagaya-ku, Tokyo 158-8557, Japan*
[15] *Institute for Nuclear Research of the Russian Academy of Sciences, Moscow 117312, Russia*
[16] *Faculty of Systems Engineering and Science, Shibaura Institute of Technology, Minumaku, Tokyo 337-8570, Japan*
[17] *Academic Assembly School of Science and Technology Institute of Engineering, Shinshu University, Nagano, Nagano 380-8554, Japan*
[18] *Service de Physique Th©orique, Universit© Libre de Bruxelles, Brussels 1050, Belgium*
[19] *Department of Physics, Yonsei University, Seodaemun-gu, Seoul 120-749, Korea*
[20] *Center for Astrophysics and Cosmology, University of Nova Gorica, Nova Gorica 5297, Slovenia*
[21] *Faculty of Science, Kochi University, Kochi, Kochi 780-8520, Japan*
[22] *College of Science and Engineering, Chubu University, Kasugai, Aichi 487-8501, Japan*
[23] *Quantum ICT Advanced Development Center, National Institute for Information and Communications Technology,*

Koganei, Tokyo 184-8795, Japan
[24] *Doctoral School of Exact and Natural Sciences, University of Lodz, Lodz, Lodz 90-237, Poland*
[25] *Sternberg Astronomical Institute, Moscow M.V. Lomonosov State University, Moscow 119991, Russia*
[26] *Department of Physics, School of Natural Sciences, Ulsan National Institute of Science and Technology, UNIST-gil, Ulsan 689-798, Korea*
[27] *Astrophysics Division, National Centre for Nuclear Research, Warsaw 02-093, Poland*
[28] *Earthquake Research Institute, University of Tokyo, Bunkyo-ku, Tokyo 277-8582, Japan*
[29] *Graduate School of Information Sciences, Hiroshima City University, Hiroshima, Hiroshima 731-3194, Japan*
[30] *Institute of Particle and Nuclear Studies, KEK, Tsukuba, Ibaraki 305-0801, Japan*

[*] Presently at: Purple Mountain Observatory, Nanjing 210023, China
[†] Presently at: Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA
[‡] Presently at: Korea Institute of Geoscience and Mineral Resources, Daejeon, 34132, Korea
[§] Presently at: NASA Marshall Space Flight Center, Huntsville, Alabama 35812, USA