UHECR arrival directions in the latest data from the original Auger and TA surface detectors and nearby galaxies

Armando di Matteo,∗ Luis Anchordoqui, Teresa Bister, Jonathan Biteau, Lorenzo Caccianiga, Rogério de Almeida, Olivier Deligny, Ugo Giaccari, Diego Harari, Jihyun Kim, Mikhail Kuznetsov, Ioana Maris, Grigory Rubtsov, Peter Tinyakov, Sergey Troitsky and Federico Urban on behalf of the Pierre Auger Collaboration

(a complete list of authors can be found at the end of the proceedings)

∗Istituto Nazionale di Fisica Nucleare (INFN), sezione di Torino, Via Pietro Giuria 1, 10125 Torino, Italy
bObservatorio Pierre Auger, Av. San Martín Norte 304, 5613 Malargüe, Argentina
cTelescope Array Project, 201 James Fletcher Bldg, 115 S. 1400 East, Salt Lake City, UT 84112-0830, USA
E-mail: spokespersons@auger.org, ta-icrc@cosmic.utah.edu

The distribution of ultra-high-energy cosmic-ray arrival directions appears to be nearly isotropic except for a dipole moment of order $6 \times (E/10 \text{ EeV})$ per cent. Nonetheless, at the highest energies, as the number of possible candidate sources within the propagation horizon and the magnetic deflections both shrink, smaller-scale anisotropies might be expected to emerge. On the other hand, the flux suppression reduces the statistics available for searching for such anisotropies. In this work, we consider two different lists of candidate sources: a sample of nearby starburst galaxies and the 2MRS catalog tracing stellar mass within 250 Mpc. We combine surface-detector data collected at the Pierre Auger Observatory until 2020 and the Telescope Array until 2019, and use them to test models in which UHECRs comprise an isotropic background and a foreground originating from the candidate sources and randomly deflected by magnetic fields. The free parameters of these models are the energy threshold, the signal fraction, and the search angular scale. We find a correlation between the arrival directions of $11.8\% \pm 5.0\%$ of cosmic rays detected with $E \geq 38 \text{ EeV}$ by Auger or with $E \geq 49 \text{ EeV}$ by TA and the position of nearby starburst galaxies on a $15.5^\circ \pm 5.3^\circ \pm 3.2^\circ$ angular scale, with a $4.2\sigma$ post-trial significance, as well as a weaker correlation with the overall galaxy distribution.

37th International Cosmic Ray Conference (ICRC 2021)
July 12th – 23rd, 2021
Online – Berlin, Germany

*Presenter
1. Introduction

Ultra-high-energy cosmic rays (UHECRs) are particles from outer space with energies greater than $1 \text{ EeV} = 10^{18} \text{ EeV} \approx 0.16 \text{ J}$. They are electrically charged (protons and other atomic nuclei), so they are deflected by intergalactic and Galactic magnetic fields (typically by a few tens of degrees), meaning that, unlike with photons and other neutral messengers, the position of their sources cannot be directly reconstructed from their arrival directions.

Nowadays, arrays of particle detectors such as the Pierre Auger Observatory (Auger) [1] and the Telescope Array (TA) [2] cover areas of hundreds of square kilometers and detect thousands of events every year; nevertheless, over 60 years after the discovery of UHECRs, their origin remains unknown. Still, certain possibilities can be ruled out. The lack of anisotropies aligned with the Galactic plane excludes a sizable contribution of protons from within our Galaxy [3, 4], and mass estimates exclude a composition dominated by heavier nuclei [5, 6], hence most such particles must originate from outside our Galaxy. The lack of neutral particles such as neutrinos and gamma rays at these energies [7–10] excludes “top-down” mechanisms, e.g. the decay of super-heavy dark matter particles or topological defects, as a dominant origin (except possibly at $E \gtrsim 100 \text{ EeV}$). Therefore, UHECRs are widely believed to be ordinary matter accelerated to extreme energies by extragalactic astrophysical phenomena. Various possibilities that have been hypothesized [11, 12] include active galactic nuclei (AGNs), starburst galaxies (SBGs), gamma-ray bursts (GRBs) and tidal disruption events (TDEs).

A possible avenue to search for imprints of the distribution of UHECR sources in spite of magnetic deflections is to harness the huge statistics gathered by last-generation detector arrays to search for large-scale (dipolar and quadrupolar) anisotropies, which are the ones the least affected by a given amount of magnetic deflections. Another way is to focus on the highest-energy part of the UHECR spectrum, where magnetic deflections are expected to be smaller and the number of potential sources decreases, at the cost of the reduced statistics. A large-scale anisotropy has been reported in Auger data [13] whose statistical significance has now reached $6.6\sigma$ [14], but the lack of full-sky coverage impedes its interpretation in terms of dipole and quadrupole moments unless higher-order multipoles are assumed to vanish. Conversely, no medium- or small-scale anisotropy has been conclusively established so far, but a few indications have been reported (see the introduction of Ref. [15] for a review). In order to follow up on these indications using full-sky data, a working group has been established with members from both the Auger and TA collaborations. Our most recent results of searches for large-scale anisotropies are presented in Ref. [16], and those of searches for medium-scale anisotropies at the highest energies are presented here.

2. The datasets

In this work, we use the same data as in Ref. [16], namely those detected by the Pierre Auger Observatory from 2004 Jan 01 to 2020 Dec 31 and those detected by the Telescope Array from 2008 May 11 to 2019 May 10, but restricted to the highest-energy bin (above 32 EeV for Auger, above 40.8 EeV for TA), and using looser selection criteria for Auger events [17] resulting in 7% more events. The dataset comprises 2 625 Auger events and 315 TA events.
Figure 1: The directional exposure of the datasets we used. The yellow area in the left panel is the fiducial declination band used for the cross-calibration of energies [16].

Figure 2: The flux distribution from our dataset above two selected energy thresholds, in equatorial coordinates

The geometrical exposure is 95 700 km² yr sr for Auger vertical events (zenith angles $\theta < 60^\circ$) and 26 300 km² yr sr for Auger inclined events ($60^\circ \leq \theta < 80^\circ$). Taking into account the energy resolution effects, the effective exposure is 96 600 km² yr sr for Auger vertical events, 26 600 km² yr sr for Auger inclined events, and 13 700 km² yr sr for TA events. This represents a 33% increase from the last Auger–TA joint searches for medium-scale anisotropies [15]. The declination dependence of the directional exposure is computed in the approximation of 100% detector efficiency [18] and shown in Figure 1.

Following Ref. [16], we apply the conversion

$$E_{\text{TA}} \rightarrow E_{\text{Auger}} = 8.57 (E_{\text{TA}}/10 \text{ EeV})^{0.937} \text{ EeV}$$

(1)

to TA event energies in order to correct them for the mismatch in the energy scales of the two experiments, which has been estimated by comparing their data in a common declination band in the intersection of their fields of view. The distribution of arrival directions of the events above two selected energy thresholds, averaged over $20^\circ$-radius top-hat windows, is shown in Figure 2.

3. The analysis

In this work, we present the result of a likelihood ratio test between flux models including a contribution from nearby galaxies and the isotropic null hypothesis, similar to Refs. [17, 19, 20].
We define the test statistic
\[
TS(\psi, f, E_{\text{min}}) = 2 \ln \frac{L(\psi, f, E_{\text{min}})}{L(\psi, 0, E_{\text{min}})}, \quad L(\psi, f, E_{\text{min}}) = \prod_{E_i \geq E_{\text{min}}} \frac{\Phi(\hat{n}_i; \psi, f) \omega(\hat{n}_i)}{\int_{4\pi} \Phi(\hat{n}; \psi, f) \omega(\hat{n}) \, d\Omega},
\]
where \(\omega(\hat{n})\) is the combined directional exposure of the dataset, and the flux model is
\[
\Phi(\hat{n}; \psi, f) = f \Phi_{\text{signal}}(\hat{n}; \psi) + (1 - f) \Phi_{\text{background}},
\]
where the contribution of each source is a von Mises–Fisher distribution:
\[
\Phi_{\text{signal}}(\hat{n}; \psi) = \frac{1}{\sum_j w_j} \sum_j w_j \frac{\psi^{-2}}{4\pi \sinh \psi^{-2}} \exp \left( \psi^{-2} \hat{n}_s \cdot \hat{n} \right); \quad \Phi_{\text{background}} = \frac{1}{4\pi},
\]
where \(E_i\) and \(\hat{n}_i\) are the energy and arrival direction of the \(i\)-th event; \(w_s\) and \(\hat{n}_s\) are the weight and position of the \(s\)-th source candidate as defined in subsection 3.1; and \(\psi\) is the root-mean-square deflection per transverse dimension (i.e. the total r.m.s. deflection is \(\sqrt{2x} \times \psi\)).\(^1\) The von Mises–Fisher distribution is the analog of a Gaussian on a 2-sphere, centered on the position of each source. In reality, magnetic deflections include both regular and turbulent parts, but the directions of the former are not sufficiently well known to be used in a log-likelihood ratio test. In a future work, we plan to investigate using simulations how much realistic amounts of regular magnetic deflections can affect the result of an analysis which does not explicitly model them.

Since the null hypothesis (isotropy) is a special case of the model (obtained for \(f = 0\)) and for a fixed \(E_{\text{min}}\) the TS is a smooth function of \(\psi\) and \(f\), according to Wilks’ theorem [22] \(\max_{\psi, f} TS\) is \(\chi^2\)-distributed with two degrees of freedom.

The analysis is repeated using energy thresholds of 32 EeV, 33 EeV, \ldots, 80 EeV on the Auger scale, corresponding to 40.8 EeV, 42.2 EeV, \ldots, 108.6 EeV on the TA scale.

### 3.1 The galaxy catalogs

In this work, we use two different lists of candidate sources. The first is a list of 44,113 galaxies of all types at distances 1 Mpc \(\leq D < 250\) Mpc, based on the 2MASS catalog with distances from HyperLEDA, with weights assumed proportional to the near-infrared flux in the \(K\)-band (2.2 \(\mu\)m). The second is a list of 44 starburst galaxies at distances 1 Mpc \(\leq D < 130\) Mpc, taken from Ref. [23] except that we removed the SMC and LMC (which are dwarf irregular galaxies, not starburst galaxies, as evidenced by their infrared-to-radio flux ratio much lower than all other objects of the list), and added the Circinus galaxy with data from the Parkes telescope (\(\alpha = 213.29^\circ, \delta = -65.34^\circ, D = 4.21, S_{1.4\ GHz} = 1.50\) Jy); these galaxies were assigned weights proportional to their radio flux at 1.4 GHz. More details about these selections are found in Ref. [17].

In this work, we neglect the energy losses undergone by cosmic rays, hence the distant objects are assigned a larger weight than if energy losses were taken into account. Given the distance distributions of the objects we are considering, the effect of energy losses on the results can be presumed to be relatively small in the case of galaxies of all types and negligible in the case of starburst galaxies, though the precise rates depend on the mass composition of UHECRs. Also, like in previous studies [17, 19, 20], we do not attempt to correct for the fact that the catalogs are
\[\psi = 1.59\psi [21].\]
limited in flux rather than in intrinsic luminosity, meaning that distant objects can be excluded even if otherwise-identical objects would be included if closer to us. An estimate of the size of the effects of this limitation on the results is left for future works.

4. Results

Using the list of starburst galaxies, we find a maximum test statistic of $\text{TS} = 27.2$ with an energy threshold of $E_{\text{min}} = 38 \text{ EeV}$ on the Auger scale (49 EeV on the TA scale), an angular scale $\psi = 15.5^{+5.3}_{-3.2}$, and a signal fraction $f = 11.8^{+5.0}_{-3.1}$. Using the list of all types of galaxies, we find a maximum $\text{TS} = 16.2$ with $E_{\text{min}} = 41 \text{ EeV}$ on the Auger scale (53 EeV on the TA scale), $\psi = 24^{+13}_{-8}$, and $f = 38^{+28}_{-14}$. The TS as a function of the parameters for the two catalogs is shown in Figure 3. The best-fit flux models are shown in Figure 4. Using both catalogs, there

---

2Equivalent top-hat radius: $\Psi = 24.6^{+8.4}_{-5.0}$.
3Equivalent top-hat radius: $\Psi = 38^{+21}_{-13}$.

---
Figure 4: The best-fit flux models for the two catalogs we used

Figure 5: Same as in Figure 3 bottom, but with a higher energy threshold

also is a local maximum at $E_{\text{min}} = 59$ EeV on the Auger scale (78 EeV on the TA scale); the TS as a function of $\psi$ and $f$ at this threshold is shown in Figure 5.

According to Wilks’ theorem [22], when accounting for the scan over $\psi$ and $f$ (but not $E_{\text{min}}$) these test statistics correspond to local statistical significances of $4.7\sigma$ and $3.4\sigma$ respectively. Wilks’ theorem is not applicable to $E_{\text{min}}$ because the likelihood is not a smooth function of it, so we computed the post-trial significances accounting for all three free parameters using simulations in each of which the number and energies of events are the same as in the real data, but the arrival directions are randomly generated according to the combined directional exposure of the two arrays. The resulting distribution of test statistics is shown in Figure 6. We find that for the starburst galaxy model $\text{TS} = 27.2$ corresponds to a $4.2\sigma$ post-trial significance, and for the all-galaxy model $\text{TS} = 16.2$ corresponds to a $2.9\sigma$ post-trial significance.

4.1 Effect of the uncertainty in the energy cross calibration

As explained in Ref. [16], the statistical uncertainty in the cross calibration of energies can be treated as a $\pm 6.4\%$ uncertainty on the ratio between “effective” exposures, but we find that such an uncertainty has a negligible effect on the current study: if we increase the TA exposure by $\pm 6.4\%$, the maximum TS changes by $\pm 0.4$ and $\pm 0.1$, for the starburst galaxy model and the all-galaxy model respectively, with changes in $\psi$ and $f$ of less than $1^\circ$ and $1\%$ respectively. The reason for this is that neither hemisphere dominates the anisotropic component of either model, so the fit to the data cannot be substantially improved or worsened just by rescaling the flux in one or the other hemisphere.
5. Conclusion

Our combined dataset hints at an association between the arrival directions of around 12% of cosmic rays detected with $E \geq 38$ EeV by Auger or with $E \geq 49$ EeV by TA and the position of nearby starburst galaxies on an angular scale of around $16^\circ$, with a stronger significance than the Auger-only data [17] but still short of the discovery level, as well as a weaker association with the overall galaxy distribution. The astrophysical interpretation of this association is complicated by our incomplete knowledge about intergalactic and Galactic magnetic fields and the UHECR mass composition. Therefore we leave the possible interpretations of these results for future studies.

In the coming years, the upgraded arrays AugerPrime [24] and TA×4 [25] will gather more exposure, allowing us to probe flux models with more statistical sensitivity. It will be interesting to see if the new data will be able to confirm or dispute this finding. Furthermore, improved mass estimation from new analysis techniques (such as ones involving machine learning [26, 27]) and from the new detectors of Auger [24] will allow us to select high-rigidity event samples, which are expected to undergo smaller magnetic deflections.

References

\[13\] A. Aab et al. [Pierre Auger collab.], *Science* 357 (2017) 1266 [1709.07321].
\[14\] R. Menezes [for the Pierre Auger collab.], these proceedings.
\[16\] P. Tinyakov et al. [for the Pierre Auger and Telescope Array collabs.], these proceedings.
\[17\] J. Biteau [for the Pierre Auger collab.], these proceedings.
\[24\] A. Aab et al. [Pierre Auger collab.], arXiv:1604.03637 (2016); G. Cataldi [for the Pierre Auger collab.], these proceedings.
\[27\] A. Aab et al. [Pierre Auger collab.], *J. Instrum.* 16 (2021) P07019 [2101.02946].
The Pierre Auger Collaboration


1 Centro Atómico Bariloche and Instituto Balseiro (CNEA-UNCuyo-CONICET), San Carlos de Bariloche, Argentina
2 Centro de Investigaciones en Láseres y Aplicaciones, CITEDEF and CONICET, Villa Martelli, Argentina
3 Departamento de Física and Departamento de Ciencias de la Atmósfera y los Oceanos, FCEyN, Universidad de Buenos Aires and CONICET, Buenos Aires, Argentina
4 IFLP, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
5 Instituto de Astronomía y Física del Espacio (IAFE, CONICET-UBA), Buenos Aires, Argentina
6 Instituto de Física de Rosario (IFIR) – CONICET/U.N.R. and Facultad de Ciencias Bioquímicas y Farmacéuticas U.N.R., Rosario, Argentina
7 Instituto de Tecnologías en Detección y Astropartículas (CNEA, CONICET, UNSAM), and Universidad Tecnológica Nacional – Facultad Regional Mendoza (CONICET/CNEA), Mendoza, Argentina
8 Instituto de Tecnologías en Detección y Astropartículas (CNEA, CONICET, UNSAM), Buenos Aires, Argentina
9 International Center of Advanced Studies and Instituto de Ciencias Físicas, ECyt-UNSAM and CONICET, Campus Migulete – San Martín, Buenos Aires, Argentina
10 Observatorio Pierre AugerMalargüé, Argentina
11 Observatorio Pierre Auger and Comisión Nacional de Energía Atómica, Malargüé, Argentina
12 Universidad Tecnológica Nacional – Facultad Regional Buenos Aires, Buenos Aires, Argentina
13 University of Adelaide, Adelaide, S.A., Australia
14 Université Libre de Bruxelles (ULB), Brussels, Belgium
15 Vrije Universiteit Brussel, Brussels, Belgium
16 Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, RJ, Brazil
17 Centro Federal de Educação Tecnológica Celso Suckow da Fonseca, Nova Friburgo, Brazil
18 Instituto Federal de Educação, Ciência e Tecnologia do Rio de Janeiro (IFRJ), Brazil
19 Universidade de São Paulo, Escola de Engenharia de Lorena, Lorena, SP, Brazil
20 Universidade de São Paulo, Instituto de Física, São Paulo, SP, Brazil
21 Universidade de São Paulo, Instituto de Física, São Carlos, SP, Brazil
22 Universidade Estadual de Campinas, IFGW, Campinas, SP, Brazil
23 Universidade Estadual de Feira de Santana, Feira de Santana, Brazil
24 Universidade Federal do ABC, Santo André, SP, Brazil
25 Universidade Federal do Paraná, Setor Palotina, Palotina, Brazil
26 Universidade Federal do Rio de Janeiro, Instituto de Física, Rio de Janeiro, RJ, Brazil
27 Universidade Federal do Rio de Janeiro (UFRJ), Observatório do Valongo, Rio de Janeiro, RJ, Brazil
28 Universidade Federal Fluminense, EEMVR, Volta Redonda, RJ, Brazil
29 Universidad de Medellín, Medellín, Colombia
30 Universidad Industrial de Santander, Bucaramanga, Colombia
31 Charles University, Faculty of Mathematics and Physics, Institute of Particle and Nuclear Physics, Prague, Czech Republic
32 Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic
UHECR arrival directions and nearby galaxies

Armando di Matteo

33 Palacky University, RCPTM, Olomouc, Czech Republic
34 CNRS/IN2P3, IJCLab, Université Paris-Saclay, Orsay, France
35 Laboratoire de Physique Nucléaire et de Hautes Energies (LPNHE), Sorbonne Université, Université de Paris, CNRS-IN2P3, Paris, France
36 Univ. Grenoble Alpes, CNRS, Grenoble Institute of Engineering Univ. Grenoble Alpes, LPSC-IN2P3, 38000 Grenoble, France
37 Université Paris-Saclay, CNRS/IN2P3, IJCLab, Orsay, France
38 Bergische Universität Wuppertal, Department of Physics, Wuppertal, Germany
39 Karlsruhe Institute of Technology (KIT), Institute for Experimental Particle Physics, Karlsruhe, Germany
40 Karlsruhe Institute of Technology (KIT), Institut für Prozessdatenverarbeitung und Elektronik, Karlsruhe, Germany
41 Karlsruhe Institute of Technology (KIT), Institute for Astroparticle Physics, Karlsruhe, Germany
42 RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
43 Universität Hamburg, II. Institut für Theoretische Physik, Hamburg, Germany
44 Universität Siegen, Department Physik – Experimentelle Teilchenphysik, Siegen, Germany
45 Gran Sasso Science Institute, L’Aquila, Italy
46 INFN Laboratori Nazionali del Gran Sasso, Assergi (L’Aquila), Italy
47 INFN, Sezione di Catania, Catania, Italy
48 INFN, Sezione di Lecce, Lecce, Italy
49 INFN, Sezione di Milano, Milano, Italy
50 INFN, Sezione di Napoli, Napoli, Italy
51 INFN, Sezione di Roma “Tor Vergata”, Roma, Italy
52 INFN, Sezione di Torino, Torino, Italy
53 Istituto di Astrofisica Spaziale e Fisica Cosmica di Palermo (INAF), Palermo, Italy
54 Osservatorio Astrofisico di Torino (INAF), Torino, Italy
55 Politecnico di Milano, Dipartimento di Scienze e Tecnologie Aerospaziali, Milano, Italy
56 Università del Salento, Dipartimento di Matematica e Fisica “E. De Giorgi”, Lecce, Italy
57 Università dell’Aquila, Dipartimento di Scienze Fisiche e Chimiche, L’Aquila, Italy
58 Università di Catania, Dipartimento di Fisica e Astronomia, Catania, Italy
59 Università di Milano, Dipartimento di Fisica, Milano, Italy
60 Università di Napoli “Federico II”, Dipartimento di Fisica “Ettore Pancini”, Napoli, Italy
61 Università di Palermo, Dipartimento di Fisica e Chimica “E. Segrè”, Palermo, Italy
62 Università di Roma “Tor Vergata”, Dipartimento di Fisica, Roma, Italy
63 Università Torino, Dipartimento di Fisica, Torino, Italy
64 Benemérita Universidad Autónoma de Puebla, Puebla, México
65 Unidad Profesional Interdisciplinaria en Ingeniería y Tecnologías Avanzadas del Instituto Politécnico Nacional (UPITI-IPN), México, D.F., México
66 Universidad Autónoma de Chiapas, Tuxtla Gutiérrez, Chiapas, México
67 Universidad Michoacana de San Nicolás de Hidalgo, Morelia, Michoacán, México
68 Universidad Nacional Autónoma de México, México, D.F., México
69 Universidad Nacional de San Agustín de Arequipa, Facultad de Ciencias Naturales y Formales, Arequipa, Peru
70 Institute of Nuclear Physics PAN, Krakow, Poland
71 University of Łódź, Faculty of High-Energy Astrophysics, Łódź, Poland
72 Laboratório de Instrumentação e Física Experimental de Partículas – LIP and Instituto Superior Técnico – IST, Universidade de Lisboa – UL, Lisboa, Portugal
73 “Horia Hulubei” National Institute for Physics and Nuclear Engineering, Bucharest-Magurele, Romania
74 Institute of Space Science, Bucharest-Magurele, Romania
75 University Politecnica of Bucharest, Bucharest, Romania
76 Center for Astrophysics and Cosmology (CAC), University of Nova Gorica, Nova Gorica, Slovenia
77 Experimental Particle Physics Department, J. Stefan Institute, Ljubljana, Slovenia
78 Universidad de Granada and C.A.F.E.P., Granada, Spain
79 Instituto Galego de Física de Altas Enxéñases (IGFAE), Universidade de Santiago de Compostela, Santiago de Compostela, Spain
The Telescope Array Collaboration

UHECR arrival directions and nearby galaxies

Armando di Matteo

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 Théorique, Université 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, Seodaemun-gu, Seoul, Korea