

Deep Search for Joint Sources of Gravitational Waves and High-Energy Neutrinos with IceCube During the Third Observing Run of LIGO and Virgo

R. ABBASI,¹ M. ACKERMANN,² J. ADAMS,³ S. K. AGARWALLA,^{4,*} J. A. AGUILAR,⁵ M. AHLERS,⁶ J.M. ALAMEDDINE,⁷ S. ALI,⁸ N. M. AMIN,⁹ K. ANDEEN,¹⁰ C. ARGÜELLES,¹¹ Y. ASHIDA,¹² S. ATHANASIADOU,² S. N. AXANI,⁹ R. BABU,¹³ X. BAI,¹⁴ J. BAINES-HOLMES,⁴ A. BALAGOPAL V.,^{4,9} S. W. BARWICK,¹⁵ S. BASH,¹⁶ V. BASU,¹² R. BAY,¹⁷ J. J. BEATTY,^{18,19} J. BECKER TJUS,^{20,†} P. BEHRENS,²¹ J. BEISE,²² C. BELLENGHI,¹⁶ S. BENKEL,² S. BENZVI,²³ D. BERLEY,²⁴ E. BERNARDINI,^{25,‡} D. Z. BESSON,⁸ E. BLAUFUSS,²⁴ L. BLOOM,²⁶ S. BLOT,² I. BODO,⁴ F. BONTEMPO,²⁷ J. Y. BOOK MOTZKIN,¹¹ C. BOSCOLO MENEGUOLO,^{25,‡} S. BÖSER,²⁸ O. BOTNER,²² J. BÖTTCHER,²¹ J. BRAUN,⁴ B. BRINSON,²⁹ Z. BRISSON-TSAVOUSSIS,³⁰ R. T. BURLEY,³¹ D. BUTTERFIELD,⁴ M. A. CAMPANA,³² K. CARLONI,¹¹ J. CARPIO,^{33,34} S. CHATTOPADHYAY,^{4,*} N. CHAU,⁵ Z. CHEN,³⁵ D. CHIRKIN,⁴ S. CHOI,¹² B. A. CLARK,²⁴ A. COLEMAN,²² P. COLEMAN,²¹ G. H. COLLIN,³⁶ D. A. COLOMA BORJA,²⁵ A. CONNOLLY,^{18,19} J. M. CONRAD,³⁶ S. T. COUNTRYMAN,³⁷ D. F. COWEN,⁴ C. 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D. PESIOS,³³⁸ S. PETRACCA,²³⁰ C. PETRILLO,¹⁴⁸ H. P. PFEIFFER,⁶⁴ H. PHAM,¹²⁵ K. A. PHAM,¹⁵⁶ K. S. PHUKON,^{174,96,293}
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F. SORRENTINO,¹¹⁷ N. SORRENTINO,^{146,147} H. SOTANI,³⁵⁴ R. SOULARD,¹¹⁰ A. SOUTHGATE,⁸¹ V. SPAGNUOLO,^{95,96}
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L. M. THOMAS,⁶⁵ M. THOMAS,¹²⁵ P. THOMAS,⁶⁶ J. E. THOMPSON,²¹⁰ S. R. THONDAPU,¹⁶⁰ K. A. THORNE,¹²⁵
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K. TOLAND,⁸⁹ A. E. TOLLEY,¹⁸⁷ T. TOMARU,⁸⁴ K. TOMITA,²⁵⁶ T. TOMURA,¹¹¹ C. TONG-YU,²⁰⁴ A. TORIYAMA,²⁸⁵
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G. TROIAN,²⁴⁵ L. TROIANO,^{364,170} A. TROVATO,^{245,108} L. TROZZO,⁶⁸ R. J. TRUDEAU,⁶⁵ T. T. L. TSANG,⁸¹ R. TSO,^{210,††}
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V. UNDHEIM,³²⁷ T. USHIBA,¹¹¹ M. VACATELLO,^{147,146} H. VAHLBRUCH,^{103,104} N. VAIDYA,⁶⁵ G. VAJENTE,⁶⁵ A. VAJPEYI,²¹³
G. VALDES,¹⁹² J. VALENCIA,¹⁵⁸ M. VALENTINI,^{164,96} S. A. VALLEJO-PEÑA,³⁴³ S. VALLERO,⁸⁶ V. VALSAN,⁷¹ N. VAN BAKEL,⁹⁶

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J. J. VARGHESE,¹²⁹ V. VARMA,¹⁹⁷ M. VASÚTH,^{143,†} A. VECCHIO,¹⁷⁴ G. VEDOVATO,¹⁵¹ J. VEITCH,⁸⁹ P. J. VEITCH,¹⁷¹
S. VENIKOUDIS,⁷³ J. VENNEBERG,^{103,104} M. VEREECKEN,^{153,73} P. VERDIER,¹⁷⁷ D. VERKINDT,⁹¹ B. VERMA,¹⁹⁷ P. VERMA,²³⁵
Y. VERMA,¹⁶⁰ S. M. VERMEULEN,⁶⁵ F. VETRANO,¹²³ A. VEUTRO,^{126,127} A. M. VIBHUTE,⁶⁶ A. VICERÉ,^{123,124} S. VIDYANT,¹³⁹
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A. VIRTUOSO,^{245,108} S. VITALE,⁹⁴ A. VIVES,¹³⁸ H. VOCCA,^{148,112} D. VOIGT,¹⁴⁵ E. R. G. VON REIS,⁶⁶
J. S. A. VON WRANGEL,^{103,104} S. P. VYATCHANIN,¹⁶⁵ L. E. WADE,¹³⁵ M. WADE,¹³⁵ K. J. WAGNER,²⁵⁸ A. WAJID,^{117,118}
M. WALKER,¹⁸¹ G. S. WALLACE,¹⁵⁷ L. WALLACE,⁶⁵ H. WANG,¹⁰⁰ J. Z. WANG,¹⁴⁹ W. H. WANG,²²² Z. WANG,²⁰⁴
G. WARATKAR,²⁶² J. WARNER,⁶⁶ M. WAS,⁹¹ T. WASHIMI,⁸⁴ N. Y. WASHINGTON,⁶⁵ D. WATARAI,¹⁰⁰ K. E. WAYT,¹³⁵
B. R. WEAVER,⁸¹ B. WEAVER,⁶⁶ C. R. WEAVING,¹⁸⁷ S. A. WEBSTER,⁸⁹ M. WEINERT,^{103,104} A. J. WEINSTEIN,⁶⁵
R. WEISS,⁹⁴ F. WELLMANN,^{103,104} L. WEN,⁹⁰ P. WESSELS,^{103,104} K. WETTE,⁹³ J. T. WHELAN,²⁵⁸ B. F. WHITING,¹⁰⁶
C. WHITTLE,⁶⁵ J. B. WILDBERGER,⁶⁴ O. S. WILK,¹³⁵ D. WILKEN,^{103,104,104} A. T. WILKIN,²⁶⁴ D. J. WILLADSEN,¹⁴⁴
K. WILLETTS,⁸¹ D. WILLIAMS,⁸⁹ M. J. WILLIAMS,¹⁸⁷ N. S. WILLIAMS,¹⁷⁴ J. L. WILLIS,⁶⁵ B. WILKE,^{104,103,104} M. WILS,¹⁶⁶
J. WINTERFLOOD,⁹⁰ C. C. WIPF,⁶⁵ G. WOAN,⁸⁹ J. WOHLER,^{95,96} J. K. WOFFORD,²⁵⁸ N. E. WOLFE,⁹⁴ H. T. WONG,²⁰⁴
H. W. Y. WONG,²⁷¹ I. C. F. WONG,²⁷¹ J. L. WRIGHT,⁹³ M. WRIGHT,⁸⁹ C. WU,²⁰³ D. S. WU,^{103,104} H. WU,²⁰³
E. WUCHNER,¹¹⁵ D. M. WYSOCKI,⁷¹ V. A. XU,⁹⁴ Y. XU,²⁶⁰ N. YADAV,¹⁵⁴ H. YAMAMOTO,⁶⁵ K. YAMAMOTO,²³⁹
T. S. YAMAMOTO,³⁰⁶ T. YAMAMOTO,¹¹¹ S. YAMAMURA,²⁵⁵ R. YAMAZAKI,²⁸⁵ S. YAN,⁷⁸ T. YAN,¹⁷⁴ F. W. YANG,²⁵²
K. Z. YANG,¹⁵⁶ Y. YANG,²⁰⁷ Z. YARBROUGH,⁷² H. YASUI,¹¹¹ S.-W. YEH,²⁰³ A. B. YELIKAR,²⁵⁸ X. YIN,⁹⁴
J. YOKOYAMA,^{368,100} T. YOKOZAWA,¹¹¹ J. YOO,²¹¹ H. YU,²¹⁰ S. YUAN,⁹⁰ H. YUZURIHARA,¹¹¹ A. ZADROŻNY,²³⁵
M. ZANOLIN,¹²⁹ M. ZEESHAN,²⁵⁸ T. ZELENKOVA,¹¹⁹ J.-P. ZENDRI,¹⁵¹ M. ZEOLI,^{176,73} M. ZERRAD,⁹⁸ M. ZEVI,¹⁴⁰ L. ZHANG,⁶⁵
R. ZHANG,¹⁰⁶ T. ZHANG,¹⁷⁴ Y. ZHANG,⁹³ C. ZHAO,⁹⁰ YUE ZHAO,²⁵² YUHANG ZHAO,¹³¹ Y. ZHENG,¹⁶² H. ZHONG,¹⁵⁶
R. ZHOU,²⁷⁶ X.-J. ZHU,³⁶⁹ Z.-H. ZHU,^{369,263} A. B. ZIMMERMAN,²⁰⁹ M. E. ZUCKER,^{94,65} AND J. ZWEIZIG⁶⁵

THE LIGO SCIENTIFIC COLLABORATION, THE VIRGO COLLABORATION, AND THE KAGRA COLLABORATION

¹Department of Physics, Loyola University Chicago, Chicago, IL 60660, USA

²Deutsches Elektronen-Synchrotron DESY, Platanenallee 6, D-15738 Zeuthen, Germany

³Dept. of Physics and Astronomy, University of Canterbury, Private Bag 4800, Christchurch, New Zealand

⁴Dept. of Physics and Wisconsin IceCube Particle Astrophysics Center, University of Wisconsin—Madison, Madison, WI 53706, USA

⁵Université Libre de Bruxelles, Science Faculty CP230, B-1050 Brussels, Belgium

⁶Niels Bohr Institute, University of Copenhagen, DK-2100 Copenhagen, Denmark

⁷Dept. of Physics, TU Dortmund University, D-44221 Dortmund, Germany

⁸Dept. of Physics and Astronomy, University of Kansas, Lawrence, KS 66045, USA

⁹Bartol Research Institute and Dept. of Physics and Astronomy, University of Delaware, Newark, DE 19716, USA

¹⁰Department of Physics, Marquette University, Milwaukee, WI 53201, USA

¹¹Department of Physics and Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA 02138, USA

¹²Department of Physics and Astronomy, University of Utah, Salt Lake City, UT 84112, USA

¹³Dept. of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA

¹⁴Physics Department, South Dakota School of Mines and Technology, Rapid City, SD 57701, USA

¹⁵Dept. of Physics and Astronomy, University of California, Irvine, CA 92697, USA

¹⁶Physik-department, Technische Universität München, D-85748 Garching, Germany

¹⁷Dept. of Physics, University of California, Berkeley, CA 94720, USA

¹⁸Dept. of Astronomy, Ohio State University, Columbus, OH 43210, USA

¹⁹Dept. of Physics and Center for Cosmology and Astro-Particle Physics, Ohio State University, Columbus, OH 43210, USA

²⁰Fakultät für Physik & Astronomie, Ruhr-Universität Bochum, D-44780 Bochum, Germany

²¹III. Physikalisches Institut, RWTH Aachen University, D-52056 Aachen, Germany

²²Dept. of Physics and Astronomy, Uppsala University, Box 516, SE-75120 Uppsala, Sweden

²³Dept. of Physics and Astronomy, University of Rochester, Rochester, NY 14627, USA

²⁴Dept. of Physics, University of Maryland, College Park, MD 20742, USA

²⁵Dipartimento di Fisica e Astronomia Galileo Galilei, Università Degli Studi di Padova, I-35122 Padova PD, Italy

²⁶Dept. of Physics and Astronomy, University of Alabama, Tuscaloosa, AL 35487, USA

²⁷Karlsruhe Institute of Technology, Institute for Astroparticle Physics, D-76021 Karlsruhe, Germany

²⁸Institute of Physics, University of Mainz, Staudinger Weg 7, D-55099 Mainz, Germany

²⁹School of Physics and Center for Relativistic Astrophysics, Georgia Institute of Technology, Atlanta, GA 30332, USA

³⁰Dept. of Physics, Engineering Physics, and Astronomy, Queen's University, Kingston, ON K7L 3N6, Canada

³¹Department of Physics, University of Adelaide, Adelaide, 5005, Australia

- ³²Dept. of Physics, Drexel University, 3141 Chestnut Street, Philadelphia, PA 19104, USA
- ³³Department of Physics & Astronomy, University of Nevada, Las Vegas, NV 89154, USA
- ³⁴Nevada Center for Astrophysics, University of Nevada, Las Vegas, NV 89154, USA
- ³⁵Dept. of Physics and Astronomy, Stony Brook University, Stony Brook, NY 11794-3800, USA
- ³⁶Dept. of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
- ³⁷Columbia Astrophysics and Nevis Laboratories, Columbia University, New York, NY 10027, USA
- ³⁸Dept. of Astronomy and Astrophysics, Pennsylvania State University, University Park, PA 16802, USA
- ³⁹Dept. of Physics, Pennsylvania State University, University Park, PA 16802, USA
- ⁴⁰Vrije Universiteit Brussel (VUB), Dienst ELEM, B-1050 Brussels, Belgium
- ⁴¹Centre for Cosmology, Particle Physics and Phenomenology - CP3, Université catholique de Louvain, Louvain-la-Neuve, Belgium
- ⁴²Institut für Kernphysik, Universität Münster, D-48149 Münster, Germany
- ⁴³Erlangen Centre for Astroparticle Physics, Friedrich-Alexander-Universität Erlangen-Nürnberg, D-91058 Erlangen, Germany
- ⁴⁴Dept. of Physics, University of Alberta, Edmonton, Alberta, T6G 2E1, Canada
- ⁴⁵Dept. of Physics and Astronomy, University of Gent, B-9000 Gent, Belgium
- ⁴⁶Dept. of Physics, University of Wuppertal, D-42119 Wuppertal, Germany
- ⁴⁷Karlsruhe Institute of Technology, Institute of Experimental Particle Physics, D-76021 Karlsruhe, Germany
- ⁴⁸Dept. of Physics and The International Center for Hadron Astrophysics, Chiba University, Chiba 263-8522, Japan
- ⁴⁹Dept. of Physics, Southern University, Baton Rouge, LA 70813, USA
- ⁵⁰Institute of Physics, Academia Sinica, Taipei, 11529, Taiwan
- ⁵¹Institut für Physik, Humboldt-Universität zu Berlin, D-12489 Berlin, Germany
- ⁵²Oskar Klein Centre and Dept. of Physics, Stockholm University, SE-10691 Stockholm, Sweden
- ⁵³Dept. of Astronomy, University of Wisconsin—Madison, Madison, WI 53706, USA
- ⁵⁴Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
- ⁵⁵Dept. of Physics, Simon Fraser University, Burnaby, BC V5A 1S6, Canada
- ⁵⁶Dept. of Physics, Chung-Ang University, Seoul 06974, Republic of Korea
- ⁵⁷Département de physique nucléaire et corpusculaire, Université de Genève, CH-1211 Genève, Switzerland
- ⁵⁸Dept. of Physics, Yale University, New Haven, CT 06520, USA
- ⁵⁹Department of Physics, Mercer University, Macon, GA 31207-0001, USA
- ⁶⁰Dept. of Physics and Astronomy, University of Alaska Anchorage, 3211 Providence Dr., Anchorage, AK 99508, USA
- ⁶¹Dept. of Physics, Sungkyunkwan University, Suwon 16419, Republic of Korea
- ⁶²Dept. of Physics, University of Oxford, Parks Road, Oxford OX1 3PU, United Kingdom
- ⁶³Dept. of Physics, University of Wisconsin, River Falls, WI 54022, USA
- ⁶⁴Max Planck Institute for Gravitational Physics (Albert Einstein Institute), D-14476 Potsdam, Germany
- ⁶⁵LIGO Laboratory, California Institute of Technology, Pasadena, CA 91125, USA
- ⁶⁶LIGO Hanford Observatory, Richland, WA 99352, USA
- ⁶⁷Dipartimento di Farmacia, Università di Salerno, I-84084 Fisciano, Salerno, Italy
- ⁶⁸INFN, Sezione di Napoli, I-80126 Napoli, Italy
- ⁶⁹University of Warwick, Coventry CV4 7AL, United Kingdom
- ⁷⁰The Pennsylvania State University, University Park, PA 16802, USA
- ⁷¹University of Wisconsin-Milwaukee, Milwaukee, WI 53201, USA
- ⁷²Louisiana State University, Baton Rouge, LA 70803, USA
- ⁷³Université catholique de Louvain, B-1348 Louvain-la-Neuve, Belgium
- ⁷⁴Inter-University Centre for Astronomy and Astrophysics, Pune 411007, India
- ⁷⁵Queen Mary University of London, London E1 4NS, United Kingdom
- ⁷⁶Department of Physics and Astronomy, Sejong University, 209 Neungdong-ro, Gwangjin-gu, Seoul 143-747, Republic of Korea
- ⁷⁷Instituto Nacional de Pesquisas Espaciais, 12227-010 São José dos Campos, São Paulo, Brazil
- ⁷⁸Stanford University, Stanford, CA 94305, USA
- ⁷⁹Università di Roma Tor Vergata, I-00133 Roma, Italy
- ⁸⁰INFN, Sezione di Roma Tor Vergata, I-00133 Roma, Italy
- ⁸¹Cardiff University, Cardiff CF24 3AA, United Kingdom
- ⁸²Universiteit Antwerpen, 2000 Antwerpen, Belgium
- ⁸³International Centre for Theoretical Sciences, Tata Institute of Fundamental Research, Bengaluru 560089, India
- ⁸⁴Gravitational Wave Science Project, National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka City, Tokyo 181-8588, Japan
- ⁸⁵Advanced Technology Center, National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka City, Tokyo 181-8588, Japan
- ⁸⁶INFN Sezione di Torino, I-10125 Torino, Italy
- ⁸⁷Theoretisch-Physikalisches Institut, Friedrich-Schiller-Universität Jena, D-07743 Jena, Germany
- ⁸⁸Dipartimento di Fisica, Università degli Studi di Torino, I-10125 Torino, Italy

- ⁸⁹*SUPA, University of Glasgow, Glasgow G12 8QQ, United Kingdom*
- ⁹⁰*OzGrav, University of Western Australia, Crawley, Western Australia 6009, Australia*
- ⁹¹*Univ. Savoie Mont Blanc, CNRS, Laboratoire d'Annecy de Physique des Particules - IN2P3, F-74000 Annecy, France*
- ⁹²*Università di Napoli "Federico II", I-80126 Napoli, Italy*
- ⁹³*OzGrav, Australian National University, Canberra, Australian Capital Territory 0200, Australia*
- ⁹⁴*LIGO Laboratory, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
- ⁹⁵*Maastricht University, 6200 MD Maastricht, Netherlands*
- ⁹⁶*Nikhef, 1098 XG Amsterdam, Netherlands*
- ⁹⁷*Université Libre de Bruxelles, Brussels 1050, Belgium*
- ⁹⁸*Aix Marseille Univ, CNRS, Centrale Med, Institut Fresnel, F-13013 Marseille, France*
- ⁹⁹*Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France*
- ¹⁰⁰*University of Tokyo, Tokyo, 113-0033, Japan.*
- ¹⁰¹*Institut de Ciències del Cosmos (ICCUB), Universitat de Barcelona (UB), c. Martí i Franquès, 1, 08028 Barcelona, Spain*
- ¹⁰²*Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Campus UAB, E-08193 Bellaterra (Barcelona), Spain*
- ¹⁰³*Max Planck Institute for Gravitational Physics (Albert Einstein Institute), D-30167 Hannover, Germany*
- ¹⁰⁴*Leibniz Universität Hannover, D-30167 Hannover, Germany*
- ¹⁰⁵*Gran Sasso Science Institute (GSSI), I-67100 L'Aquila, Italy*
- ¹⁰⁶*University of Florida, Gainesville, FL 32611, USA*
- ¹⁰⁷*Dipartimento di Scienze Matematiche, Informatiche e Fisiche, Università di Udine, I-33100 Udine, Italy*
- ¹⁰⁸*INFN, Sezione di Trieste, I-34127 Trieste, Italy*
- ¹⁰⁹*Tecnológico de Monterrey Campus Guadalajara, 45201 Zapopan, Jalisco, Mexico*
- ¹¹⁰*Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Artemis, F-06304 Nice, France*
- ¹¹¹*Institute for Cosmic Ray Research, KAGRA Observatory, The University of Tokyo, 238 Higashi-Mozumi, Kamioka-cho, Hida City, Gifu 506-1205, Japan*
- ¹¹²*INFN, Sezione di Perugia, I-06123 Perugia, Italy*
- ¹¹³*Università di Camerino, I-62032 Camerino, Italy*
- ¹¹⁴*University of Washington, Seattle, WA 98195, USA*
- ¹¹⁵*California State University Fullerton, Fullerton, CA 92831, USA*
- ¹¹⁶*Villanova University, Villanova, PA 19085, USA*
- ¹¹⁷*INFN, Sezione di Genova, I-16146 Genova, Italy*
- ¹¹⁸*Dipartimento di Fisica, Università degli Studi di Genova, I-16146 Genova, Italy*
- ¹¹⁹*European Gravitational Observatory (EGO), I-56021 Cascina, Pisa, Italy*
- ¹²⁰*Georgia Institute of Technology, Atlanta, GA 30332, USA*
- ¹²¹*Royal Holloway, University of London, London TW20 0EX, United Kingdom*
- ¹²²*Astronomical course, The Graduate University for Advanced Studies (SOKENDAI), 2-21-1 Osawa, Mitaka City, Tokyo 181-8588, Japan*
- ¹²³*Università degli Studi di Urbino "Carlo Bo", I-61029 Urbino, Italy*
- ¹²⁴*INFN, Sezione di Firenze, I-50019 Sesto Fiorentino, Firenze, Italy*
- ¹²⁵*LIGO Livingston Observatory, Livingston, LA 70754, USA*
- ¹²⁶*INFN, Sezione di Roma, I-00185 Roma, Italy*
- ¹²⁷*Università di Roma "La Sapienza", I-00185 Roma, Italy*
- ¹²⁸*Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France*
- ¹²⁹*Embry-Riddle Aeronautical University, Prescott, AZ 86301, USA*
- ¹³⁰*Dipartimento di Fisica "E.R. Caianiello", Università di Salerno, I-84084 Fisciano, Salerno, Italy*
- ¹³¹*Université Paris Cité, CNRS, Astroparticule et Cosmologie, F-75013 Paris, France*
- ¹³²*King's College London, University of London, London WC2R 2LS, United Kingdom*
- ¹³³*Korea Institute of Science and Technology Information, Daejeon 34141, Republic of Korea*
- ¹³⁴*Université libre de Bruxelles, 1050 Bruxelles, Belgium*
- ¹³⁵*Kenyon College, Gambier, OH 43022, USA*
- ¹³⁶*International College, Osaka University, 1-1 Machikaneyama-cho, Toyonaka City, Osaka 560-0043, Japan*
- ¹³⁷*Institute for Gravitational and Subatomic Physics (GRASP), Utrecht University, 3584 CC Utrecht, Netherlands*
- ¹³⁸*University of Oregon, Eugene, OR 97403, USA*
- ¹³⁹*Syracuse University, Syracuse, NY 13244, USA*
- ¹⁴⁰*Northwestern University, Evanston, IL 60208, USA*
- ¹⁴¹*Departament de Física Quàntica i Astrofísica (FQA), Universitat de Barcelona (UB), c. Martí i Franquès, 1, 08028 Barcelona, Spain*

- ¹⁴² *Dipartimento di Medicina, Chirurgia e Odontoiatria "Scuola Medica Salernitana", Università di Salerno, I-84081 Baronissi, Salerno, Italy*
- ¹⁴³ *HUN-REN Wigner Research Centre for Physics, H-1121 Budapest, Hungary*
- ¹⁴⁴ *Concordia University Wisconsin, Mequon, WI 53097, USA*
- ¹⁴⁵ *Universität Hamburg, D-22761 Hamburg, Germany*
- ¹⁴⁶ *Università di Pisa, I-56127 Pisa, Italy*
- ¹⁴⁷ *INFN, Sezione di Pisa, I-56127 Pisa, Italy*
- ¹⁴⁸ *Università di Perugia, I-06123 Perugia, Italy*
- ¹⁴⁹ *University of Michigan, Ann Arbor, MI 48109, USA*
- ¹⁵⁰ *Università di Padova, Dipartimento di Fisica e Astronomia, I-35131 Padova, Italy*
- ¹⁵¹ *INFN, Sezione di Padova, I-35131 Padova, Italy*
- ¹⁵² *Institute for Plasma Research, Bhat, Gandhinagar 382428, India*
- ¹⁵³ *Universiteit Gent, B-9000 Gent, Belgium*
- ¹⁵⁴ *Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, 00-716, Warsaw, Poland*
- ¹⁵⁵ *Dipartimento di Ingegneria, Università del Sannio, I-82100 Benevento, Italy*
- ¹⁵⁶ *University of Minnesota, Minneapolis, MN 55455, USA*
- ¹⁵⁷ *SUPA, University of Strathclyde, Glasgow G1 1XQ, United Kingdom*
- ¹⁵⁸ *IAC3-IEEC, Universitat de les Illes Balears, E-07122 Palma de Mallorca, Spain*
- ¹⁵⁹ *Departamento de Matemáticas, Universitat Autònoma de Barcelona, 08193 Bellaterra (Barcelona), Spain*
- ¹⁶⁰ *RRCAT, Indore, Madhya Pradesh 452013, India*
- ¹⁶¹ *GRAPPA, Anton Pannekoek Institute for Astronomy and Institute for High-Energy Physics, University of Amsterdam, 1098 XH Amsterdam, Netherlands*
- ¹⁶² *Missouri University of Science and Technology, Rolla, MO 65409, USA*
- ¹⁶³ *Colorado State University, Fort Collins, CO 80523, USA*
- ¹⁶⁴ *Department of Physics and Astronomy, Vrije Universiteit Amsterdam, 1081 HV Amsterdam, Netherlands*
- ¹⁶⁵ *Lomonosov Moscow State University, Moscow 119991, Russia*
- ¹⁶⁶ *Katholieke Universiteit Leuven, Oude Markt 13, 3000 Leuven, Belgium*
- ¹⁶⁷ *Università di Trento, Dipartimento di Fisica, I-38123 Povo, Trento, Italy*
- ¹⁶⁸ *INFN, Trento Institute for Fundamental Physics and Applications, I-38123 Povo, Trento, Italy*
- ¹⁶⁹ *Bar-Ilan University, Ramat Gan, 5290002, Israel*
- ¹⁷⁰ *INFN, Sezione di Napoli, Gruppo Collegato di Salerno, I-80126 Napoli, Italy*
- ¹⁷¹ *OzGrav, University of Adelaide, Adelaide, South Australia 5005, Australia*
- ¹⁷² *Centre national de la recherche scientifique, 75016 Paris, France*
- ¹⁷³ *Univ Rennes, CNRS, Institut FOTON - UMR 6082, F-35000 Rennes, France*
- ¹⁷⁴ *University of Birmingham, Birmingham B15 2TT, United Kingdom*
- ¹⁷⁵ *Washington State University, Pullman, WA 99164, USA*
- ¹⁷⁶ *Université de Liège, B-4000 Liège, Belgium*
- ¹⁷⁷ *Université Claude Bernard Lyon 1, CNRS, IP2I Lyon / IN2P3, UMR 5822, F-69622 Villeurbanne, France*
- ¹⁷⁸ *Instituto de Fisica Teorica UAM-CSIC, Universidad Autonoma de Madrid, 28049 Madrid, Spain*
- ¹⁷⁹ *INFN, Laboratori Nazionali del Gran Sasso, I-67100 Assergi, Italy*
- ¹⁸⁰ *Laboratoire Kastler Brossel, Sorbonne Université, CNRS, ENS-Université PSL, Collège de France, F-75005 Paris, France*
- ¹⁸¹ *Christopher Newport University, Newport News, VA 23606, USA*
- ¹⁸² *Astronomical Observatory Warsaw University, 00-478 Warsaw, Poland*
- ¹⁸³ *University of Maryland, College Park, MD 20742, USA*
- ¹⁸⁴ *Università degli Studi di Milano-Bicocca, I-20126 Milano, Italy*
- ¹⁸⁵ *INFN, Sezione di Milano-Bicocca, I-20126 Milano, Italy*
- ¹⁸⁶ *L2IT, Laboratoire des 2 Infinis - Toulouse, Université de Toulouse, CNRS/IN2P3, UPS, F-31062 Toulouse Cedex 9, France*
- ¹⁸⁷ *University of Portsmouth, Portsmouth, PO1 3FX, United Kingdom*
- ¹⁸⁸ *Université de Lyon, Université Claude Bernard Lyon 1, CNRS, Institut Lumière Matière, F-69622 Villeurbanne, France*
- ¹⁸⁹ *IGFAE, Universidade de Santiago de Compostela, 15782 Spain*
- ¹⁹⁰ *University of Chicago, Chicago, IL 60637, USA*
- ¹⁹¹ *NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA*
- ¹⁹² *Texas A&M University, College Station, TX 77843, USA*
- ¹⁹³ *OzGrav, University of Melbourne, Parkville, Victoria 3010, Australia*
- ¹⁹⁴ *INFN, Laboratori Nazionali del Sud, I-95125 Catania, Italy*
- ¹⁹⁵ *Niels Bohr Institute, Copenhagen University, 2100 København, Denmark*
- ¹⁹⁶ *Istituto di Astrofisica e Planetologia Spaziali di Roma, 00133 Roma, Italy*

- ¹⁹⁷ *University of Massachusetts Dartmouth, North Dartmouth, MA 02747, USA*
- ¹⁹⁸ *Departamento de Astronomía y Astrofísica, Universitat de València, E-46100 Burjassot, València, Spain*
- ¹⁹⁹ *Observatori Astronòmic, Universitat de València, E-46980 Paterna, València, Spain*
- ²⁰⁰ *Niels Bohr Institute, University of Copenhagen, 2100 København, Denmark*
- ²⁰¹ *University of British Columbia, Vancouver, BC V6T 1Z4, Canada*
- ²⁰² *Department of Physics, National Cheng Kung University, No.1, University Road, Tainan City 701, Taiwan*
- ²⁰³ *National Tsing Hua University, Hsinchu City 30013, Taiwan*
- ²⁰⁴ *National Central University, Taoyuan City 320317, Taiwan*
- ²⁰⁵ *OzGrav, Charles Sturt University, Wagga Wagga, New South Wales 2678, Australia*
- ²⁰⁶ *Vanderbilt University, Nashville, TN 37235, USA*
- ²⁰⁷ *Department of Electrophysics, National Yang Ming Chiao Tung University, 101 Univ. Street, Hsinchu, Taiwan*
- ²⁰⁸ *Kamioka Branch, National Astronomical Observatory of Japan, 238 Higashi-Mozumi, Kamioka-cho, Hida City, Gifu 506-1205, Japan*
- ²⁰⁹ *University of Texas, Austin, TX 78712, USA*
- ²¹⁰ *CaRT, California Institute of Technology, Pasadena, CA 91125, USA*
- ²¹¹ *Cornell University, Ithaca, NY 14850, USA*
- ²¹² *Northeastern University, Boston, MA 02115, USA*
- ²¹³ *OzGrav, School of Physics & Astronomy, Monash University, Clayton 3800, Victoria, Australia*
- ²¹⁴ *Dipartimento di Ingegneria Industriale (DIIN), Università di Salerno, I-84084 Fisciano, Salerno, Italy*
- ²¹⁵ *INAF, Osservatorio Astronomico di Padova, I-35122 Padova, Italy*
- ²¹⁶ *OzGrav, Swinburne University of Technology, Hawthorn VIC 3122, Australia*
- ²¹⁷ *INAF, Osservatorio Astronomico di Brera sede di Merate, I-23807 Merate, Lecco, Italy*
- ²¹⁸ *Departamento de Matemáticas, Universitat de València, E-46100 Burjassot, València, Spain*
- ²¹⁹ *Montana State University, Bozeman, MT 59717, USA*
- ²²⁰ *Texas Tech University, Lubbock, TX 79409, USA*
- ²²¹ *University of Rhode Island, Kingston, RI 02881, USA*
- ²²² *The University of Texas Rio Grande Valley, Brownsville, TX 78520, USA*
- ²²³ *Chennai Mathematical Institute, Chennai 603103, India*
- ²²⁴ *Università degli Studi di Sassari, I-07100 Sassari, Italy*
- ²²⁵ *Université de Normandie, ENSICAEN, UNICAEN, CNRS/IN2P3, LPC Caen, F-14000 Caen, France*
- ²²⁶ *Laboratoire de Physique Corpusculaire Caen, 6 boulevard du maréchal Juin, F-14050 Caen, France*
- ²²⁷ *Université Claude Bernard Lyon 1, CNRS, Laboratoire des Matériaux Avancés (LMA), IP2I Lyon / IN2P3, UMR 5822, F-69622 Villeurbanne, France*
- ²²⁸ *Dipartimento di Scienze Matematiche, Fisiche e Informatiche, Università di Parma, I-43124 Parma, Italy*
- ²²⁹ *INFN, Sezione di Milano Bicocca, Gruppo Collegato di Parma, I-43124 Parma, Italy*
- ²³⁰ *University of Sannio at Benevento, I-82100 Benevento, Italy and INFN, Sezione di Napoli, I-80100 Napoli, Italy*
- ²³¹ *Perimeter Institute, Waterloo, ON N2L 2Y5, Canada*
- ²³² *Corps des Mines, Mines Paris, Université PSL, 60 Bd Saint-Michel, 75272 Paris, France*
- ²³³ *Indian Institute of Technology Madras, Chennai 600036, India*
- ²³⁴ *Graduate School of Science, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8551, Japan*
- ²³⁵ *National Center for Nuclear Research, 05-400 Świerk-Otwock, Poland*
- ²³⁶ *Institut d'Astrophysique de Paris, Sorbonne Université, CNRS, UMR 7095, 75014 Paris, France*
- ²³⁷ *Vrije Universiteit Brussel, 1050 Brussel, Belgium*
- ²³⁸ *Carleton College, Northfield, MN 55057, USA*
- ²³⁹ *Faculty of Science, University of Toyama, 3190 Gofuku, Toyama City, Toyama 930-8555, Japan*
- ²⁴⁰ *Canadian Institute for Theoretical Astrophysics, University of Toronto, Toronto, ON M5S 3H8, Canada*
- ²⁴¹ *University of Cambridge, Cambridge CB2 1TN, United Kingdom*
- ²⁴² *Stony Brook University, Stony Brook, NY 11794, USA*
- ²⁴³ *Center for Computational Astrophysics, Flatiron Institute, New York, NY 10010, USA*
- ²⁴⁴ *Montclair State University, Montclair, NJ 07043, USA*
- ²⁴⁵ *Dipartimento di Fisica, Università di Trieste, I-34127 Trieste, Italy*
- ²⁴⁶ *HUN-REN Institute for Nuclear Research, H-4026 Debrecen, Hungary*
- ²⁴⁷ *Centre de Physique des Particules de Marseille, 163, avenue de Luminy, 13288 Marseille cedex 09, France*
- ²⁴⁸ *CNR-SPIN, I-84084 Fisciano, Salerno, Italy*
- ²⁴⁹ *Scuola di Ingegneria, Università della Basilicata, I-85100 Potenza, Italy*
- ²⁵⁰ *Western Washington University, Bellingham, WA 98225, USA*
- ²⁵¹ *SUPA, University of the West of Scotland, Paisley PA1 2BE, United Kingdom*
- ²⁵² *The University of Utah, Salt Lake City, UT 84112, USA*

- ²⁵³ *Eötvös University, Budapest 1117, Hungary*
- ²⁵⁴ *Centro de Física das Universidades do Minho e do Porto, Universidade do Minho, PT-4710-057 Braga, Portugal*
- ²⁵⁵ *Institute for Cosmic Ray Research, KAGRA Observatory, The University of Tokyo, 5-1-5 Kashiwa-no-Ha, Kashiwa City, Chiba 277-8582, Japan*
- ²⁵⁶ *Department of Physics, Graduate School of Science, Osaka Metropolitan University, 3-3-138 Sugimoto-cho, Sumiyoshi-ku, Osaka City, Osaka 558-8585, Japan*
- ²⁵⁷ *Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Lagrange, F-06304 Nice, France*
- ²⁵⁸ *Rochester Institute of Technology, Rochester, NY 14623, USA*
- ²⁵⁹ *California State University, Los Angeles, Los Angeles, CA 90032, USA*
- ²⁶⁰ *University of Zurich, Winterthurerstrasse 190, 8057 Zurich, Switzerland*
- ²⁶¹ *University of Szeged, Dóm tér 9, Szeged 6720, Hungary*
- ²⁶² *Indian Institute of Technology Bombay, Powai, Mumbai 400 076, India*
- ²⁶³ *School of Physics and Technology, Wuhan University, Bayi Road 299, Wuchang District, Wuhan, Hubei, 430072, China*
- ²⁶⁴ *University of California, Riverside, Riverside, CA 92521, USA*
- ²⁶⁵ *INAF, Osservatorio Astronomico di Capodimonte, I-80131 Napoli, Italy*
- ²⁶⁶ *University of Nottingham NG7 2RD, UK*
- ²⁶⁷ *Ariel University, Ramat HaGolan St 65, Ari'el, Israel*
- ²⁶⁸ *The University of Mississippi, University, MS 38677, USA*
- ²⁶⁹ *Institute of Physics, Academia Sinica, 128 Sec. 2, Academia Rd., Nankang, Taipei 11529, Taiwan*
- ²⁷⁰ *Shanghai Astronomical Observatory, Chinese Academy of Sciences, 80 Nandan Road, Shanghai 200030, China*
- ²⁷¹ *The Chinese University of Hong Kong, Shatin, NT, Hong Kong*
- ²⁷² *Marquette University, Milwaukee, WI 53233, USA*
- ²⁷³ *American University, Washington, DC 20016, USA*
- ²⁷⁴ *University of Nevada, Las Vegas, Las Vegas, NV 89154, USA*
- ²⁷⁵ *Department of Applied Physics, Fukuoka University, 8-19-1 Nanakuma, Jonan, Fukuoka City, Fukuoka 814-0180, Japan*
- ²⁷⁶ *University of California, Berkeley, CA 94720, USA*
- ²⁷⁷ *University of Lancaster, Lancaster LA1 4YW, United Kingdom*
- ²⁷⁸ *College of Industrial Technology, Nihon University, 1-2-1 Izumi, Narashino City, Chiba 275-8575, Japan*
- ²⁷⁹ *Faculty of Engineering, Niigata University, 8050 Ikarashi-2-no-cho, Nishi-ku, Niigata City, Niigata 950-2181, Japan*
- ²⁸⁰ *Department of Physics, Tamkang University, No. 151, Yingzhuan Rd., Danshui Dist., New Taipei City 25137, Taiwan*
- ²⁸¹ *Rutherford Appleton Laboratory, Didcot OX11 0DE, United Kingdom*
- ²⁸² *Department of Astronomy and Space Science, Chungnam National University, 9 Daehak-ro, Yuseong-gu, Daejeon 34134, Republic of Korea*
- ²⁸³ *Scuola Normale Superiore, I-56126 Pisa, Italy*
- ²⁸⁴ *Kavli Institute for Astronomy and Astrophysics, Peking University, Yiheyuan Road 5, Haidian District, Beijing 100871, China*
- ²⁸⁵ *Department of Physical Sciences, Aoyama Gakuin University, 5-10-1 Fuchinobe, Sagamihara City, Kanagawa 252-5258, Japan*
- ²⁸⁶ *Nambu Yoichiro Institute of Theoretical and Experimental Physics (NITEP), Osaka Metropolitan University, 3-3-138 Sugimoto-cho, Sumiyoshi-ku, Osaka City, Osaka 558-8585, Japan*
- ²⁸⁷ *Directorate of Construction, Services & Estate Management, Mumbai 400094, India*
- ²⁸⁸ *University of Białystok, 15-424 Białystok, Poland*
- ²⁸⁹ *Astronomical Observatory, Jagiellonian University, 31-007 Cracow, Poland*
- ²⁹⁰ *University of Southampton, Southampton SO17 1BJ, United Kingdom*
- ²⁹¹ *Department of Physics, Ulsan National Institute of Science and Technology (UNIST), 50 UNIST-gil, Ulju-gun, Ulsan 44919, Republic of Korea*
- ²⁹² *Institute for Cosmic Ray Research, The University of Tokyo, 5-1-5 Kashiwa-no-Ha, Kashiwa City, Chiba 277-8582, Japan*
- ²⁹³ *Institute for High-Energy Physics, University of Amsterdam, 1098 XH Amsterdam, Netherlands*
- ²⁹⁴ *Chung-Ang University, Seoul 06974, Republic of Korea*
- ²⁹⁵ *University of Washington Bothell, Bothell, WA 98011, USA*
- ²⁹⁶ *Aix Marseille Université, Jardin du Pharo, 58 Boulevard Charles Livon, 13007 Marseille, France*
- ²⁹⁷ *Laboratoire de Physique et de Chimie de l'Environnement, Université Joseph KI-ZERBO, 9GH2+3V5, Ouagadougou, Burkina Faso*
- ²⁹⁸ *Ewha Womans University, Seoul 03760, Republic of Korea*
- ²⁹⁹ *Seoul National University, Seoul 08826, Republic of Korea*
- ³⁰⁰ *Korea Astronomy and Space Science Institute, Daejeon 34055, Republic of Korea*
- ³⁰¹ *Sungkyunkwan University, Seoul 03063, Republic of Korea*
- ³⁰² *Institute of Particle and Nuclear Studies (IPNS), High Energy Accelerator Research Organization (KEK), 1-1 Oho, Tsukuba City, Ibaraki 305-0801, Japan*
- ³⁰³ *Division of Science, National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka City, Tokyo 181-8588, Japan*
- ³⁰⁴ *Bard College, Annandale-On-Hudson, NY 12504, USA*

- ³⁰⁵ *Institute of Mathematics, Polish Academy of Sciences, 00656 Warsaw, Poland*
- ³⁰⁶ *Department of Physics, Nagoya University, ES building, Furocho, Chikusa-ku, Nagoya, Aichi 464-8602, Japan*
- ³⁰⁷ *Université de Montréal/Polytechnique, Montreal, Quebec H3T 1J4, Canada*
- ³⁰⁸ *Indian Institute of Science Education and Research, Kolkata, Mohanpur, West Bengal 741252, India*
- ³⁰⁹ *Inje University Gimhae, South Gyeongsang 50834, Republic of Korea*
- ³¹⁰ *NAVIER, École des Ponts, Univ Gustave Eiffel, CNRS, Marne-la-Vallée, France*
- ³¹¹ *Università di Firenze, Sesto Fiorentino I-50019, Italy*
- ³¹² *National Center for High-performance Computing, National Applied Research Laboratories, No. 7, R&D 6th Rd., Hsinchu Science Park, Hsinchu City 30076, Taiwan*
- ³¹³ *NASA Marshall Space Flight Center, Huntsville, AL 35811, USA*
- ³¹⁴ *West Virginia University, Morgantown, WV 26506, USA*
- ³¹⁵ *Institut fuer Theoretische Astrophysik, Zentrum fuer Astronomie Heidelberg, Universitaet Heidelberg, Albert Ueberle Str. 2, 69120 Heidelberg, Germany*
- ³¹⁶ *School of Physics Science and Engineering, Tongji University, Shanghai 200092, China*
- ³¹⁷ *Institut d'Estudis Espacials de Catalunya, c. Gran Capità, 2-4, 08034 Barcelona, Spain*
- ³¹⁸ *Institucio Catalana de Recerca i Estudis Avançats (ICREA), Passeig de Lluís Companys, 23, 08010 Barcelona, Spain*
- ³¹⁹ *Tsinghua University, Beijing 100084, China*
- ³²⁰ *INFN Cagliari, Physics Department, Università degli Studi di Cagliari, Cagliari 09042, Italy*
- ³²¹ *Saha Institute of Nuclear Physics, Bidhannagar, West Bengal 700064, India*
- ³²² *Tata Institute of Fundamental Research, Mumbai 400005, India*
- ³²³ *Hobart and William Smith Colleges, Geneva, NY 14456, USA*
- ³²⁴ *Institut des Hautes Etudes Scientifiques, F-91440 Bures-sur-Yvette, France*
- ³²⁵ *Faculty of Law, Ryukoku University, 67 Fukakusa Tsukamoto-cho, Fushimi-ku, Kyoto City, Kyoto 612-8577, Japan*
- ³²⁶ *Department of Physics and Astronomy, University of Notre Dame, 225 Nieuwland Science Hall, Notre Dame, IN 46556, USA*
- ³²⁷ *University of Stavanger, 4021 Stavanger, Norway*
- ³²⁸ *Physics Program, Graduate School of Advanced Science and Engineering, Hiroshima University, 1-3-1 Kagamiyama, Higashihiroshima City, Hiroshima 903-0213, Japan*
- ³²⁹ *Laboratoire Univers et Théories, Observatoire de Paris, 92190 Meudon, France*
- ³³⁰ *Observatoire de Paris, 75014 Paris, France*
- ³³¹ *Université PSL, 75006 Paris, France*
- ³³² *Université de Paris Cité, 75006 Paris, France*
- ³³³ *National Institute for Mathematical Sciences, Daejeon 34047, Republic of Korea*
- ³³⁴ *Graduate School of Science and Technology, Niigata University, 8050 Ikarashi-2-no-cho, Nishi-ku, Niigata City, Niigata 950-2181, Japan*
- ³³⁵ *Niigata Study Center, The Open University of Japan, 754 Ichibancho, Asahimachi-dori, Chuo-ku, Niigata City, Niigata 951-8122, Japan*
- ³³⁶ *CSIR-Central Glass and Ceramic Research Institute, Kolkata, West Bengal 700032, India*
- ³³⁷ *Consiglio Nazionale delle Ricerche - Istituto dei Sistemi Complessi, I-00185 Roma, Italy*
- ³³⁸ *Department of Physics, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece*
- ³³⁹ *Department of Astronomy, Yonsei University, 50 Yonsei-Ro, Seodaemun-Gu, Seoul 03722, Republic of Korea*
- ³⁴⁰ *Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi", I-00184 Roma, Italy*
- ³⁴¹ *Dipartimento di Ingegneria Industriale, Eletttronica e Meccanica, Università degli Studi Roma Tre, I-00146 Roma, Italy*
- ³⁴² *Subatech, CNRS/IN2P3 - IMT Atlantique - Nantes Université, 4 rue Alfred Kastler BP 20722 44307 Nantes CÉDEX 03, France*
- ³⁴³ *Universidad de Antioquia, Medellín, Colombia*
- ³⁴⁴ *Departamento de Física - ETSIDI, Universidad Politécnica de Madrid, 28012 Madrid, Spain*
- ³⁴⁵ *Department of Electronic Control Engineering, National Institute of Technology, Nagaoka College, 888 Nishikatahai, Nagaoka City, Niigata 940-8532, Japan*
- ³⁴⁶ *Università Degli Studi Di Ferrara, Via Savonarola, 9, 44121 Ferrara FE, Italy*
- ³⁴⁷ *Faculty of Science, Toho University, 2-2-1 Miyama, Funabashi City, Chiba 274-8510, Japan*
- ³⁴⁸ *Indian Institute of Technology, Palaj, Gandhinagar, Gujarat 382355, India*
- ³⁴⁹ *Laboratoire MSME, Cité Descartes, 5 Boulevard Descartes, Champs-sur-Marne, 77454 Marne-la-Vallée Cedex 2, France*
- ³⁵⁰ *Institute of Systems and Information Engineering, University of Tsukuba, 1-1-1, Tennodai, Tsukuba, Ibaraki 305-8573, Japan*
- ³⁵¹ *Institute for Quantum Studies, Chapman University, 1 University Dr., Orange, CA 92866, USA*
- ³⁵² *Faculty of Information Science and Technology, Osaka Institute of Technology, 1-79-1 Kitayama, Hirakata City, Osaka 573-0196, Japan*
- ³⁵³ *INAF, Osservatorio Astrofisico di Arcetri, I-50125 Firenze, Italy*
- ³⁵⁴ *iTHEMS (Interdisciplinary Theoretical and Mathematical Sciences Program), RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*
- ³⁵⁵ *Scuola Internazionale Superiore di Studi Avanzati, Via Bonomea, 265, I-34136, Trieste TS, Italy*

- ³⁵⁶*Institut für Theoretische Physik, Johann Wolfgang Goethe-Universität, Max-von-Laue-Str. 1, 60438 Frankfurt am Main, Germany*
- ³⁵⁷*INAF, Osservatorio di Astrofisica e Scienza dello Spazio, I-40129 Bologna, Italy*
- ³⁵⁸*Universidade Estadual Paulista, 01140-070 São Paulo, Brazil*
- ³⁵⁹*Faculty of Physics, University of Warsaw, Ludwika Pasteura 5, 02-093 Warszawa, Poland*
- ³⁶⁰*Research Center for Space Science, Advanced Research Laboratories, Tokyo City University, 3-3-1 Ushikubo-Nishi, Tsuzuki-Ku, Yokohama, Kanagawa 224-8551, Japan*
- ³⁶¹*Department of Physics, Kyoto University, Kita-Shirakawa Oiwake-cho, Sakyou-ku, Kyoto City, Kyoto 606-8502, Japan*
- ³⁶²*Yukawa Institute for Theoretical Physics (YITP), Kyoto University, Kita-Shirakawa Oiwake-cho, Sakyou-ku, Kyoto City, Kyoto 606-8502, Japan*
- ³⁶³*University of Catania, Department of Physics and Astronomy, Via S. Sofia, 64, 95123 Catania CT, Italy*
- ³⁶⁴*Dipartimento di Scienze Aziendali - Management and Innovation Systems (DISA-MIS), Università di Salerno, I-84084 Fisciano, Salerno, Italy*
- ³⁶⁵*National Institute of Technology, Fukui College, Geshi-cho, Sabae-shi, Fukui 916-8507, Japan*
- ³⁶⁶*Department of Communications Engineering, National Defense Academy of Japan, 1-10-20 Hashirimizu, Yokosuka City, Kanagawa 239-8686, Japan*
- ³⁶⁷*Eindhoven University of Technology, 5600 MB Eindhoven, Netherlands*
- ³⁶⁸*Kavli Institute for the Physics and Mathematics of the Universe, WPI, The University of Tokyo, 5-1-5 Kashiwa-no-Ha, Kashiwa City, Chiba 277-8583, Japan*
- ³⁶⁹*Department of Astronomy, Beijing Normal University, Xijiekouwai Street 19, Haidian District, Beijing 100875, China*

ABSTRACT

The discovery of joint sources of high-energy neutrinos and gravitational waves has been a primary target for the LIGO, Virgo, KAGRA, and IceCube observatories. The joint detection of high-energy neutrinos and gravitational waves would provide insight into cosmic processes, from the dynamics of compact object mergers and stellar collapses to the mechanisms driving relativistic outflows. The joint detection of multiple cosmic messengers can also elevate the significance of the common observation even when some or all of the constituent messengers are *sub-threshold*, i.e. not significant enough to declare their detection individually. Using data from the LIGO, Virgo, and IceCube observatories, including sub-threshold events, we searched for common sources of gravitational waves and high-energy neutrinos during the third observing run of Advanced LIGO and Advanced Virgo detectors. Our search did not identify significant joint sources. We derive constraints on the rate densities of joint sources. Our results constrain the isotropic neutrino emission from gravitational-wave sources for very high values of the total energy emitted in neutrinos ($> 10^{52}$ – 10^{54} erg).

1. INTRODUCTION

With the discoveries of new cosmic messengers, multimessenger astrophysics has become a reality. Astrophysical high-energy ($\gtrsim$ TeV) neutrinos (HENs) were discovered in 2013 (IceCube Collaboration 2013; Aartsen et al. 2014a) by the IceCube Neutrino Observatory (Aartsen et al. 2017, 2024)(IceCube in the following). Multimessenger science matured with the gravitational-

wave (GW) discoveries by Advanced LIGO (Aasi et al. 2015) and Advanced Virgo (Acernese et al. 2015), including the detection of binary black hole (BBH) coalescences (Abbott et al. 2016; Abbott et al. 2016, 2017a,b) and a binary neutron star coalescence (BNS) in their first two observing runs (Abbott et al. 2017c, 2019a). IceCube has been taking data in its full 86-string configuration continuously since 2011 (Aartsen et al. 2017) overlapping with the LIGO Scientific, Virgo, and KAGRA (LVK) Collaboration (Abbott et al. 2019b, 2021a, 2024; Abbott et al. 2023a; The LIGO Scientific Collaboration et al. 2025a) observing runs, which have included the discovery of 218 probable cosmic compact binary sources. The multimessenger observation of the merging BNS system GW170817 (Abbott et al. 2017c) established connections between GW sources and emissions in the electromagnetic spectrum from gamma-rays to radio (Abbott et al. 2017d).

What was missing from the observed multimessenger repertoire of GW170817 were HENs which were ex-

* also at Institute of Physics, Sachivalaya Marg, Sainik School Post, Bhubaneswar 751005, India

† also at Department of Space, Earth and Environment, Chalmers University of Technology, 412 96 Gothenburg, Sweden

‡ also at INFN Padova, I-35131 Padova, Italy

§ also at Earthquake Research Institute, University of Tokyo, Bunkyo, Tokyo 113-0032, Japan

¶ now at INFN Padova, I-35131 Padova, Italy

** Deceased, September 2024

†† Deceased, July 2023

‡‡ Deceased, February 2024

pected but not observed (Albert et al. 2017a; Murase & Bartos 2019; Ando et al. 2013). HENs are predicted to be emitted from the jets forming after the time of GW emission. These jets are expected to accelerate charged particles, leading to the production of mesons, and the subsequent decay of these mesons should result in the emission of detectable HENs (Ando et al. 2013; Fang & Metzger 2017; Kimura et al. 2018). Consequently detection of HENs will carry information about the hadronic processes consequent to GW emissions. Short gamma-ray bursts (GRBs) have also been expected from such jets which was observationally confirmed with GW170817. However, despite this expected connection between GRBs and HENs, the searches for HENs coincident with GRBs have not yielded any significant detection. The searches constrained the HEN emission from GRBs, with stricter constraints for long GRBs (Aartsen et al. 2017; Abbasi et al. 2022a, 2024a,b). The searches for HENs coincident with GWs can also illuminate the GRB-HEN relation better, thanks to the observed connection between BNS mergers and short GRBs.

The large overlap between the LVK observation schedules and the nearly-continuous operation of IceCube allows searches for common sources of HENs and GWs. Consequently, multiple searches have been executed, including some before the discovery of astrophysical GWs (Adrián-Martínez et al. 2013; Aartsen et al. 2014b; Adrián-Martínez et al. 2016; Albert et al. 2017a,b; Keivani et al. 2019; De Wasseige et al. 2019; Albert et al. 2019, 2020; Aartsen et al. 2020; Veske et al. 2022; Abbasi et al. 2023a,b). IceCube (Abbasi et al. 2021), Super-Kamiokande (Abe et al. 2016, 2018; Abe et al. 2021a), KamLAND (Abe et al. 2021b), and Borexino (Agostini et al. 2017) also searched for coincident low-energy neutrinos. While the successive searches have produced better and better constraints on source populations, the improving quality and growing size of the data did not result in a confident multimessenger discovery with neutrinos and GWs together.

With the growing interest in such searches (Ando et al. 2013) and their results (Keivani et al. 2021); methodology (Aso et al. 2008; van Elewyck et al. 2009; Bartos et al. 2011; Baret et al. 2012; Bartos et al. 2019; Countryman et al. 2019; Veske et al. 2020; Veske et al. 2021; Marka et al. 2022) and theory have progressed (Kimura et al. 2018; Fang et al. 2019; de Bruijn et al. 2020; Guetta et al. 2020), forming a firm foundation for the comprehensive search for common sources of GWs and high-energy neutrinos we describe in this paper.

Cosmic phenomena accompanied by accretion can cause acceleration of hadrons. HENs can provide information about the acceleration mechanisms and their

environments (Halzen & Hooper 2002; Razzaque et al. 2003; Bartos et al. 2012; Loeb & Waxman 2006). Indeed, IceCube observed neutrinos from a range of origins, including a diffuse flux potentially with unresolved point sources (Aartsen et al. 2013; IceCube Collaboration 2013), the blazar TXS 0506+056 (IceCube Collaboration et al. 2018; Keivani et al. 2018; Albert et al. 2018), the active galaxy NGC 1068 (Abbasi et al. 2022b) and from the Milky Way (Abbasi et al. 2023). However, the majority of observed IceCube cosmic neutrinos are not associated with any identified source. This motivates studies which focus on neutrino emission from observable and well-characterizable sources, such as gravitational-waves sources.

Discovery and observation of joint sources of HENs and GWs will have a multifold impact, including a better understanding of emitter physics, source localization, and messenger characterization (Ando et al. 2013; Fang & Metzger 2017; Kimura et al. 2018). A coincident detection with a GW event can shed light on the jet physics involved. For example, a coincidence without a gamma-ray counterpart in a binary neutron star merger can indicate presence of a choked jet. In addition there are different estimations for the jet energetics. Searches for joint emissions constrain possible jet characteristics with or without detections. HEN observations can also significantly constrain the sky localization of joint events, greatly decreasing the cost of follow-up searches with narrow field-of-view instruments. For example, IceCube sky location reconstruction for charged current ν_μ interactions typically has an angular uncertainty $\lesssim 1^\circ$ (Aartsen et al. 2020), much smaller than tens to hundreds, or even thousands, of square degrees that are normal for GW sky localizations (Abbott et al. 2020). Consequently, joint multimessenger observations can constrict the sky localization of the observed events, making further follow-ups much more feasible.

The current wealth of multimessenger data provides the opportunity for statistically refined searches (Veske et al. 2021) aimed at identifying common cosmic sources of GWs and HENs. In this article, we describe a comprehensive archival search for HEN emission from GW candidates observed during the entirety of the Advanced LIGO and Advanced Virgo detectors’ third observing run (O3), including sub-threshold event candidates, i.e. candidate events with higher false alarm rates than in catalogs. This search complements the previous searches and represents the most sensitive offline search done for joint emission of HEN and GW events, using a more extended dataset including data from a more sensitive run of the GW detectors. Having summarized the state of the field, we continue in Section 2 where we de-

scribe the IceCube detector and the specific neutrino data that is used in our analysis. In Section 3, we describe the GW detectors and the GW data. In Section 4, we present the core concepts and distinctive aspects of our search methodology, implemented through the Low-Latency Algorithm for Multimessenger Astrophysics (LLAMA) analysis software (Countryman et al. 2019), while also pointing to more intricate methodological discussions in previous works (e.g., Bartos et al. (2019); Aartsen et al. (2020); Veske et al. (2021)). Section 5 presents the outcomes of our search. Finally, in Section 6, we contextualize our findings and offer perspectives on future directions in this field.

2. THE ICECUBE HEN DETECTOR AND ITS DATA

IceCube is positioned at the geographic South Pole in Antarctica, utilizing a cubic kilometer of clear ice for its detection medium (Aartsen et al. 2017). The IceCube Collaboration has deployed 5160 optical modules distributed across 86 vertical strings, to observe the depths of Antarctic ice between 1500 and 2500 meters. The main sensors within the optical modules are photomultiplier tubes designed to capture Cherenkov light emissions resulting from the interactions of neutrinos within the ice.

IceCube neutrino events can be broadly categorized as *tracks* and *cascades*. *Tracks* are events where muons or anti-muons traverse a linear trajectory, leaving a trail of detected Cherenkov light in their path. Atmospheric muons and atmospheric muon neutrinos are the major sources of background contamination for the set of astrophysical neutrino induced tracks events. *Cascades* refer to showers occurring in the ice, originating from charged-current interactions of electron neutrinos or neutral-current interactions. These event topologies have different relevance for multimessenger searches depending on their different directional accuracy on the sky. For tracks, the typical reconstruction accuracy is $\lesssim 1^\circ$ (Aartsen et al. 2020), whereas for cascades it is $\gtrsim 10^\circ$. In this search, we use tracks-based neutrino triggers due to their better localization which is crucial for multimessenger astronomy.

IceCube maintains a duty cycle exceeding 99% and can observe neutrinos from the entire sky (Pizzuto et al. 2021). IceCube data based on muon tracks consist primarily of background signals from muons and neutrinos originating in the Earth’s atmosphere. The background in the Northern Hemisphere primarily comprises atmospheric neutrinos, while in the Southern Hemisphere, atmospheric muons predominate. As a result, the detector has less background in the Northern Hemisphere

and the energy threshold for the detection of tracks in the Northern Hemisphere can be kept significantly lower ($\mathcal{O}(1)$ TeV) than that in the Southern Hemisphere ($\mathcal{O}(100)$ TeV).

The data analysis presented here relies on a low-latency (~ 30 s) event reconstruction, facilitating timely multimessenger follow-up endeavors to IceCube events, known as the Gamma-ray Follow-Up (GFU) data stream (IceCube Collaboration et al. 2016; Kintscher, T. for the IceCube Collaboration 2016; Blaufuss et al. 2019). GFU events are well-reconstructed tracks, which enable precise sky localization essential for effective collaborative astrophysics with electromagnetic observatories. Although the low-latency property is not relevant for this article, the LLAMA pipeline has also been used in real-time searches for coincident GW and HEN events, and in that case the low latency is crucial (Keivani et al. 2019).

The analysis presented is based on a considerably larger number of candidate cosmic HEN events compared to the number of GW candidates, in average ~ 6.4 neutrinos in the search time window of each candidate GW event.

3. GW DETECTORS AND THEIR DATA

The LIGO and Virgo detectors (Aasi et al. 2015; Acernese et al. 2015) are Michelson-type interferometers spanning multiple kilometers. LIGO has two nearly identical detectors, separated by 3000 km, situated in Hanford, Washington and in Livingston, Louisiana within the United States. Virgo operates a single detector located in Cascina, Italy.

On April 1, 2019, the LIGO and Virgo detectors commenced their third observing run O3, which was divided into two periods. The initial part (O3a) encompassed the period from April to September 2019, while the second part (O3b) spanned November 2019 to March 2020. Over the course of O3, the GW detectors amassed datasets of unprecedented size and quality at the time (Buikema et al. 2020; Abbott et al. 2021a; Abbott et al. 2023a; Acernese et al. 2023), with the GW strain data now being publicly accessible (Abbott et al. 2023b).

Not every IceCube GFU candidate coincided with GW detector observations as their duty factors were lower during O3 than IceCube’s. For the first half of O3 they were 71% for Hanford, 76% for Livingston, and 76% for Virgo; in the second half of the run 79%, 79%, and 76% respectively (Davis et al. 2021). The cosmic reach of the Hanford, Livingston, and Virgo detectors remained comparable during the first and second parts of the third observing run: 108 Mpc, 135 Mpc, and 45 Mpc of BNS

inspiral range (Finn & Chernoff 1993; Chen et al. 2021) versus 115 Mpc, 133 Mpc, and 51 Mpc, respectively (Abbott et al. 2023b).

The optimal joint treatment of events from IceCube, LIGO, and Virgo in the analysis relies on the localizations of both neutrinos and GWs detected by the network. Given the better accuracy of neutrino localization compared to GW localization, this approach significantly enhances the sky-localization potential for joint multimessenger candidates to $\mathcal{O}(1) \text{ deg}^2$, beyond the localization capabilities of the GW network alone ($\mathcal{O}(10\text{--}1000) \text{ deg}^2$), presenting new opportunities for electromagnetic observations in low-latency or using archival data.

The analysis presented relies on GW candidates, having a false alarm rate below two per day from GWTC-2.1 (LIGO Scientific Collaboration et al. 2021a) and GWTC-3.0 (LIGO Scientific Collaboration et al. 2021b). Most of these events are *sub-threshold* compared to the conventional thresholds for confident detections, such as having an estimated probability of astrophysical origin (p_{astro}) greater than 0.5 (Abbott et al. 2024; Abbott et al. 2023a).

We consider events from three template-based searches using compact binary coalescence (CBC) waveforms (Abbott et al. 2023a) commonly used by the LVK: GstLAL (Messick et al. 2017; Sachdev et al. 2019; Hanna et al. 2020; Cannon et al. 2021), Multi-Band Template Analysis (MBTA; Adams et al. 2016; Aubin et al. 2021), and PyCBC (Allen et al. 2012; Allen 2005; Dal Canton et al. 2014; Usman et al. 2016; Nitz et al. 2017; Davies et al. 2020). The latter was implemented in two versions, PyCBC-broad and PyCBC-BBH.

A total of 2210 GW candidates from CBC searches are used here in the joint GW+HEN analysis. This set includes the 79 CBC candidates confidently identified by at least one of the template-based searches with a p_{astro} greater than 0.5; of which 10–15% may be contamination from triggers of terrestrial origin (Abbott et al. 2023a). When a CBC trigger appeared in the candidate lists of multiple pipelines, the metadata (localization, p_{astro} , etc.) associated with the pipeline having the highest probability of astrophysical origin was used in the joint analysis.

A total of 481 non-public candidates from the all-sky search for generic GW bursts from O3 (Abbott et al. 2021b) were also selected for joint analyses. The selected triggers were produced by the coherent Wave Burst (cWB) search pipeline (Klimenko et al. 2016; Drago et al. 2021) specifically designed to find candidates without explicit model prediction. The cWB pipeline, even in its generic all-sky mode, is capable of finding some

of the CBC triggers (Abbott et al. 2021b; Abbott et al. 2023a). We are using cWB-allsky triggers with selection criteria based on the correlation coefficient (Klimenko et al. 2016), which quantifies the relative proportion of the coherent energy in the detector network’s data, requiring it to be greater than 0.8 for Hanford–Livingston detections and greater than 0.5 for Hanford–Virgo and Livingston–Virgo detections (Abbott et al. 2021b). For the cases of selected Hanford–Livingston candidates where Virgo data were also available, we produced the three-detector localizations dedicated for the analysis presented here, as source localization overlap is a deciding factor in multimessenger searches.

4. METHODOLOGY

Our analysis has two parts. First, we analyze the GW triggers one by one and find the HEN coincidence significance for each of them. Second, we evaluate them collectively to learn about the astrophysical population of jointly GW and HEN emitting sources.

4.1. Analysis of individual events

Previous studies of joint sources of GWs and HENs using sub-threshold trigger sets from both types of messengers during the initial GW detectors era and the first observing run of Advanced LIGO (Aso et al. 2008; van Elewyck et al. 2009; Bartos et al. 2011; Baret et al. 2012; Adrián-Martínez et al. 2013; Ando et al. 2013; Aartsen et al. 2014b; Albert et al. 2019) employed likelihood methods. The analysis presented here employs the LLAMA pipeline (Countryman et al. 2019), which was previously used for neutrino follow-up of *confident* GW candidates (Aartsen et al. 2020; Veske et al. 2022; Abbasi et al. 2023a). The LLAMA pipeline uses an optimal model-dependent method (Bartos et al. 2019) for GW+HEN searches. LLAMA uses prior probabilities informed by astrophysics and detector characteristics to combine several hypotheses optimally for a physical model and reduces the problem to a simple test of two hypotheses. The odds ratio of having a multimessenger detection or not becomes the optimal test statistic for the physically motivated model.

Our priors are on the distribution of the source parameters $\theta = \{D_L, \Omega_s, t_s, E_{\text{GW}}, E_\nu\}$, which are the luminosity distance of the source D_L ($\propto D_L^2$ prior distribution up to the GW detection range), its sky position Ω_s (uniform prior distribution over the sky), the reference time for the astrophysical event t_s (uniform distribution in the observing period), the isotropic equivalent emission energies in GWs E_{GW} and in HENs E_ν . Beyond solving the optimal testing problem, the use of assumed emission energies also allows the use of the distance information from GW triggers optimally which further increases

the statistical power of the search (Bartos et al. 2019). For GWs, the emission energies (log uniform distribution in $[10^{-1}, 10^1] M_\odot c^2$) were chosen by considering the released energies in CBCs that have a total mass between $2 M_\odot$ and $200 M_\odot$.

Short GRBs produced in BNS mergers are the most promising known high-energy emission mechanism for coincident GW and HEN detection, where the energy emitted in HENs is expected to be comparable with the energy emitted in gamma-rays (Kimura et al. 2017; Biehl et al. 2018; Murase & Bartos 2019). Consequently, the HEN emission energies (log uniform distribution in $[10^{46}, 10^{51}]$ erg) were chosen according to an empirical distribution of short GRB photon emission energies (Berger 2014). We assume the differential number density of the neutrino emission energy spectrum is a power law with exponent -2 which is expected for the neutrinos from cosmic rays accelerated by Fermi acceleration (Drury 1983; Kurahashi et al. 2022).

Although the searches for HENs coincident with GRBs have not yielded any detection (Ando et al. 2013; Fang & Metzger 2017; Kimura et al. 2018), a potential correlation between gravitational waves and high-energy neutrinos may still be explained through the GRB connection. As neutrino emission is less confined by beaming or opacity, a neutrino observed in coincidence with a neutron star merger would indicate off-axis, electromagnetically obscured, or failed GRB source.

Our observational inputs ($\mathbf{x}$) from the GW side are the localization, candidate event detection time, signal-to-noise ratio (ρ), and for template-based searches source

distance information and p_{astro} . From the neutrino detector side, the inputs are the reconstructed time of arrival, energy proxy (related to the energy deposited in the detector), direction, and angular uncertainty of the HENs.

The standard prompt search time window is ± 500 s and was established on the assumption of a GRB source model (Baret et al. 2011). Our signal likelihood is maximum when there is no time difference between the neutrino and the GW candidate, and it decreases to zero linearly as the time difference approaches ± 500 s. We evaluate all of the neutrino candidates coincident with the GW trigger within this time window together.

Our analysis is based on testing a signal hypothesis H_s : the GW and at least one HEN come from the same astrophysical source, against multiple background hypotheses: both the GW and HENs are noise originated (H_n), the GW is astrophysical while all HENs are noise originated (H_c^{GW}), i.e. atmospheric muons or neutrinos, and finally the GW is noise originated and a HEN is astrophysical (H_c^ν). Other very low probability occurrences (about 2 orders of magnitude less probable than the aforementioned cases) which include more than one astrophysical but unrelated messengers (i.e. a GW coming from an astrophysical event and a neutrino coming from a separate astrophysical event) are ignored. In the case of HENs, noise refers to atmospheric muons or neutrinos. We combine the background hypotheses by using their prior probabilities which were calculated using our assumed source parameters and detector characteristics. Our test statistic (TS) is

$$\text{TS}(\mathbf{x}) = \frac{P(\mathbf{x}|H_s)P(H_s)}{P(\mathbf{x}|H_n)P(H_n) + P(\mathbf{x}|H_c^{\text{GW}})P(H_c^{\text{GW}}) + P(\mathbf{x}|H_c^\nu)P(H_c^\nu)}. \quad (1)$$

The prior probability of H_s is an overall constant in the TS and does not affect any of our results.

The analysis presented here differs from previous analyses with LLAMA (Aartsen et al. 2020; Veske et al. 2022; Abbasi et al. 2023a) where we used only confident detections of GWs (e.g., $p_{\text{astro}} > 0.5$) and thus the first and third terms in the denominator of Eq. (1) were taken as zero. The original analysis method in Bartos

et al. (2019) is suitable for the analyses with confident or sub-threshold GW triggers, where only ρ was used to estimate the signalness of the GW candidates. Here we improve it for the triggers of the template-based searches by using an additional input: $p_{\text{terr}} = 1 - p_{\text{astro}}$ which is the estimated probability of terrestrial origin for the GW triggers. For these triggers, we modify the way we calculate the joint probability density of noise origin for GWs and signal-to-noise ratio as

$$P(\rho, \text{GW noise}) = P(\rho)P(\text{GW noise}|\rho) = \left[\frac{P(\rho|\text{GW noise})R_{\text{bgGW}} + 3\rho_{\text{min}}^3/\rho^4(4\pi D_{\text{L-max}}^3 \dot{n}_{\text{GW}\nu}/3)}{R_{\text{bgGW}} + 4\pi D_{\text{L-max}}^3 \dot{n}_{\text{GW}\nu}/3} \right] \times p_{\text{terr}}. \quad (2)$$

Here we used $P(\text{GW noise}|\rho) = p_{\text{terr}}$. The expression in the square brackets is $P(\rho)$. Here R_{bgGW} is the rate of GW background triggers, $\dot{n}_{\text{GW}\nu}$ is the rate density of astrophysical multimessenger emitting events and $D_{\text{L-max}}$ is the horizon distance of the GW detectors for the minimum signal-to-noise ratio in our dataset $\rho_{\text{min}} \approx 5.6$. We take $\dot{n}_{\text{GW}\nu}$ constant as $23.9 \text{ Gpc}^{-3}\text{yr}^{-1}$, which is the most recent estimate of the local rate density of BBH mergers (Abbott et al. 2023c) that make up the most of the detections. For this calculation only, we ignore the cosmological expansion for simplicity, which may have a minuscule negative effect on the statistical power of the search; but does not have a direct effect on our physical inferences otherwise. The probability $P(\rho)$ is estimated by using the conditional distributions of ρ when the GW candidate is of noise and astrophysical origin; and the two scenarios' expected relative frequencies. The conditional distributions are $P(\rho|\text{GW noise})$ and $3\rho_{\text{min}}^3\rho^{-4}$ respectively for noise and astrophysical origins. While the former is estimated empirically, the latter can be derived assuming homogeneously distributed sources that are detected according to a ρ threshold (Schutz 2011). The relative frequencies are proportional to R_{bgGW} and $(4/3)\pi D_{\text{L-max}}^3 \dot{n}_{\text{GW}\nu}$.

In order to evaluate the significance of each joint candidate, we use the Bayesian odds ratio in Eq. (1) as a test statistic. We find the frequentist significance by comparing the odds ratio for each event to a distribution built empirically using background data and simulations. Coincidences are simulated by randomly matching neutrinos from the GFU stream and the GW trigger events we analyze at the detection rate of the GFU stream (6.4 neutrino triggers per GW trigger on average in 1000 s of search window). We use different background distributions for CBC and cWB triggers.

4.2. Population analysis

The individual analysis described above can uncover individual events that become high-significance once GW and neutrino information is combined. We carried out a separate population analysis that combines significances from multiple events and aims to find an excess significance from the whole dataset to examine the presence of a joint emission from *any* of the events. In this case, even if no individual event is sufficiently significant to claim a discovery, we can statistically infer the presence of a signal by finding that the significance distribution shows an excess of high-significance events compared to what would be expected from background.

For our population study we constructed a new test statistic TS_{pop} (Eq. (3)); because the new question we would like to answer now is whether there are any de-

tections in the dataset or not. When the *a priori* expected number of multimessenger events in the dataset is low, the optimal test statistic is equivalent to the *sum* of the individual test statistics from the individual observations. Hence, we construct TS_{pop} as the sum of the test statistics of the analyzed events. Here, a single event should be understood as the combination of neutrinos within the search time window with a GW candidate. The sum is over all such combinations in the whole observation run

$$\text{TS}_{\text{pop}} = \sum_i \text{TS}(\mathbf{x}_i). \quad (3)$$

While such a population study does not identify specific joint events as significant, it has more power to test whether there *are* such events in the dataset. It can be thought of as a more efficient trials correction which uses all the information in the whole dataset.

The p -value of this analysis was found by constructing an appropriate background distribution. This was done by repeatedly sampling events from our previously generated background events as many as the analyzed events (2210 for CBC and 481 for cWB) and summing their TSs.

In order to constrain the rate density of joint GW+HEN emitters, we need to characterize the behaviour of the new test statistic when there are different numbers of multimessenger events in the dataset. For this, we injected simulated multimessenger signals to the background event set and created TS_{pop} distributions with different number of (0, 1, 2, ...) simulated multimessenger events. These essentially differ from the 0 multimessenger event case by the individual TS of the extra multimessenger events. In order to create such multimessenger events we artificially injected a GW signal and a neutrino from the same source location. For this we simulate GW events and combine them with neutrinos.

The additional sub-threshold GW events were generated by injection simulations using BAYESTAR (Singer & Price 2016; Singer et al. 2016). We simulated GW events using the properties of the LIGO and Virgo detectors and taking into account the properties of the observed populations for each detector combination during O3 (Abbott et al. 2023a). For each source type of BNS, neutron star-black hole binaries (NSBH), and BBH, we performed randomized injections for the corresponding source populations' parameter (mass, spin, sky position, inclination, distance) distributions, calculated the signal-to-noise ratio, and generated the corresponding localizations considering a network of at least two detectors. The POWERLAW+PEAK model (Talbot & Thrane 2018) with the median estimations of

the parameters from the analysis of GWTC-3.0 (Abbott et al. 2023c) was used for the mass distribution of the injected BBH mergers. For neutron stars, we used $1.4 M_\odot$. With the insufficient observational preference for the mass distribution of NSBH, we simply drew the black hole masses from the primary mass distribution of the BBH mergers and the neutron star masses as $1.4 M_\odot$. For the simulated GW events we assigned p_{astro} values by using the public injection set for GW detection pipelines (LIGO Scientific Collaboration et al. 2023). We found the injection in that dataset that has the most similar parameters to the parameters of our injections, for each of our injections, and assigned the same p_{astro} value. This is done by defining a unitless statistic which quantifies the similarity of the events based on the product of the differences in the parameters (χ_{eff} spin parameter, chirp mass, luminosity distance, and the sky position in the detector frame) scaled by the expected measurement uncertainties.

The background neutrinos for each injected GW signal are drawn from the scrambled GFU sample. The 90%

central energy range of the GFU sample ranges from 500 GeV–50 PeV, assuming a source with ϵ^{-2} spectrum. This simple spectrum can be viewed as a nominal spectrum without the complicated different structures predicted in theoretical studies, and we generate signal neutrinos assuming this spectrum for the differential number density. We inject one Monte Carlo generated signal neutrino corresponding to the injection sky localization position of the signal GW event.

The population upper limit at a confidence level CL then can be found by the standard Neyman’s construction (Neyman 1937) by requiring the probability of having TS_{pop} for the same sample size containing injected multimessenger signal(s) being higher than the observed TS_{pop} to be CL or higher.

The upper limit on the multimessenger (MM) rate density $\dot{n}_{\text{GW}\nu}$, depending on the neutrino emission energy E_ν and the GW source type ($\mathcal{S}$, e.g., BNS, NSBH, BBH) can be calculated as

$$P(\text{TS}_{\text{pop}} > \text{TS}_{\text{pop}}^{\text{observed}} | E_\nu, \mathcal{S}, \dot{n}_{\text{GW}\nu}) = \sum_{\#_{\text{MM}}=0}^{\text{No. of obs. GW events}} P(\text{TS}_{\text{pop}} > \text{TS}_{\text{pop}}^{\text{observed}} | \mathcal{S}, \#_{\text{MM}}) P(\#_{\text{MM}} | E_\nu, \mathcal{S}, \dot{n}_{\text{GW}\nu}) = CL, \quad (4)$$

where the sum is over the MM event count in the dataset ($\#_{\text{MM}}$) whose occurrence probability is

$$P(\#_{\text{MM}} | E_\nu, \mathcal{S}, \dot{n}_{\text{GW}\nu}) = \text{Poisson} \left(\#_{\text{MM}}, \text{Mean} = \dot{n}_{\text{GW}\nu} \times T_{\text{obs}} \int 2\pi f(D_L, z) p_{\text{det}}^\nu(E_\nu, D_L, \delta) p_{\text{det}}^{\text{GW}}(\mathcal{S}, D_L) \cos \delta d\delta dD_L \right), \quad (5)$$

where $p_{\text{det}}^\nu(E_\nu, D_L, \delta)$ and $p_{\text{det}}^{\text{GW}}(\mathcal{S}, D_L)$ are the detection probabilities of neutrinos and GWs respectively from an event with total neutrino emission energy E_ν and the specific GW event type $\mathcal{S}$, as a function of luminosity distance D_L , and declination (δ). The total observation time is represented by T_{obs} , $\text{Poisson}(a, \text{Mean} = b) = b^a e^{-b}/a!$ is the probability of a Poisson point process for a happened events with mean b , while $f(D_L, z)$ gives the distribution of MM events as a function of distance and redshift z . Considering the cosmological expansion,

$$f(D_L, z) = (1+z)^{-1} \frac{dV_c}{dD_L} = \frac{c}{(1+z)^3 H_0 \sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}} \frac{dz}{dD_L} D_L^2, \quad (6)$$

assuming a constant rate in comoving volume V_c where c is the speed of light, $H_0 = 67.9 \text{ km s}^{-1} \text{ Mpc}^{-1}$ is the Hubble constant, $\Omega_m = 0.3065$ and $\Omega_\Lambda = 0.6935$ are the energy densities of matter and cosmological constant (Planck Collaboration et al. 2016). We find $p_{\text{det}}^{\text{GW}}(\mathcal{S}, D_L)$ by calculating the detection fraction of our injected GW events as a function of their distance for different source types, averaged over their remaining properties including their sky positions. The sky averaging is a sensible approximation as the GW detection probability would have a mild dependency on the sky location after averaging only over the Earth’s rotational motion. On the other hand, the detection probability of neutrinos has a strong dependency on the declination after being averaged only over the Earth’s rotational motion. Therefore its declination dependent form was used,

which is the Poisson probability of observing at least one neutrino. The mean number of detected neutrinos for this Poisson probability is expressible in terms of the effective area of the detector A_{eff} and the isotropically equivalent emitted energy in neutrinos (E_{iso}) as

$$\langle n_{\nu} \rangle(E_{\text{iso}}, D_L, \delta) = \frac{1}{3} \frac{E_{\text{iso}}}{4\pi D_L^2 \ln(\epsilon_{\text{max}}/\epsilon_{\text{min}})} \int \frac{A_{\text{eff}}(\epsilon, \delta)}{\epsilon^2} d\epsilon, \quad (7)$$

where the ratio of the limits of the relevant energy range is $\epsilon_{\text{max}}/\epsilon_{\text{min}} \approx 10^6$, the factor $1/3$ accounts for the fact that only a third of the astrophysical HEN are expected to be muon neutrinos (Athar et al. 2006; Pakvasa et al. 2008) and we assumed an ϵ^{-2} spectrum for the emitted neutrino number density (see also Eq. 3 in Aartsen et al. 2020). For isotropic emissions, isotropically equivalent emission energy is equal to the total emitted energy: $E_{\text{iso}} = E_{\nu}$. For beamed emissions with beaming factor f_{beam} , $E_{\text{iso}} = f_{\text{beam}} E_{\nu}$ within the emission cone and zero outside. With these we can write the probability of detecting neutrinos as

$$p_{\text{det}}^{\nu}(E_{\nu}, D_L, \delta) = 1 - \exp(-\langle n_{\nu} \rangle(E_{\nu}, D_L, \delta)). \quad (8)$$

5. RESULTS

5.1. Individual p -values

There are on average 6.4 GFU track neutrinos within any 1000 s time segment in our data. Of the 2210 CBC candidate events, 5 did not have coincident neutrinos within the ± 500 s search time window around the GW trigger time, resulting in individual p -values of 1 for each of these events. Altogether 14491 time coincident neutrino tracks were identified and analyzed under a joint source hypothesis; none of them had a sufficiently high significance to claim a detection considering the number of analyzed GW triggers.

The lowest p -value candidate, presented in Fig. 1, has an individual p -value of 3.8×10^{-4} (0.84 post-trials after multiplying by the number of analyzed events). The GW trigger is a BNS candidate; but it is much more likely to be of terrestrial origin ($p_{\text{terr}} = 0.997$). The coincident neutrino number 6, which produces most of the significance, has a reconstructed energy of 2.4 TeV. Its sky position is right above the equator, corresponding to the high sensitivity declination region of the IceCube detector, while its energy is not particularly outstanding from the expected background. The reconstructed mean localization distance for the GW candidate's source is 295 Mpc. The GW trigger occurred 222 s after the arrival time of neutrino number 6.

The cumulative distribution of all of the p -values for CBC candidates is shown in Fig. 2. It is consistent with a uniform p -value distribution, which is expected

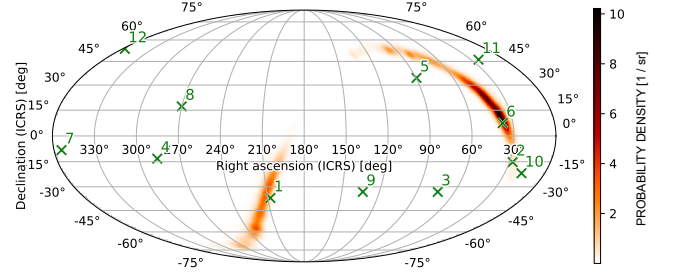


Figure 1. Joint sky localization showing all neutrino candidates coincident with GW BNS candidate at GPS time = 1262142545.615. Neutrino #6 gives the dominant contribution to the significance.

in the absence of any joint emission. The Kolmogorov–Smirnov test p -value when comparing to a uniform distribution is 0.05, which is consistent with the expectation from background.

For cWB events, we similarly did not have a sufficiently high-significance case to claim a joint detection considering the number of analyzed triggers. The lowest p -value candidate, with an individual p -value of 4.3×10^{-4} (0.21 post-trials after multiplying by the number of analyzed events), is shown in Fig. 3. The coincident neutrino number 3, which produces most of the significance, has a reconstructed energy of 2.3 TeV. It was detected 154 s after the GW trigger.

The cumulative distribution of all of the p -values of the cWB part of the analysis is shown in Fig. 4. It is consistent with a uniform p -value distribution with a discrete behaviour at high p -values. This discrete behaviour is caused by cWB sky localizations not containing low probability densities below a certain threshold, which causes non-smooth distributions. The Kolmogorov–Smirnov test p -value is 0.67 in comparison with a uniform distribution with a similar discrete behaviour.

We provide the properties of the neutrino triggers that produce individual p -values of 0.01 or less in Table 1 in the Appendix.

5.2. Population Constraints

When the whole dataset was analyzed collectively, we obtained a p -value of 0.22 for CBC triggers and 0.18 for cWB triggers. Consequently, we conclude that there is no significant sign of joint detection of GW and HEN in our dataset. We obtained frequentist 90% upper limits for the rate density of multimessenger events related to CBC triggers, assuming a homogeneous distribution in comoving volume. HEN emission from CBC sources is expected to be beamed. We calculate different limits assuming an isotropic neutrino emission and a beamed emission with a beaming factor of $f_{\text{beam}} \sim 100$ (Fong

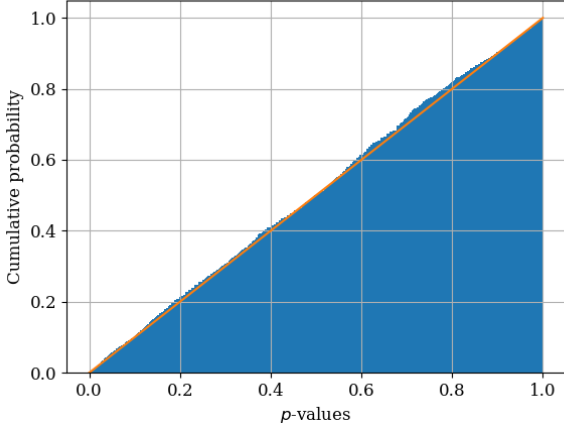


Figure 2. Cumulative distribution of the p -values from the CBC part of the analysis. The orange line is a reference for uniform distribution.

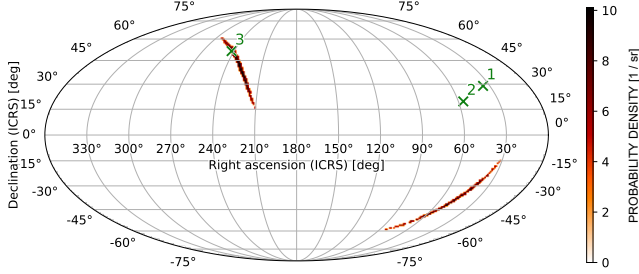


Figure 3. Joint sky localization showing all neutrino candidates coincident with GW burst candidate at GPS time = 1241247887.938. Neutrino #3 gives the dominant contribution to the significance.

et al. 2015). We find the limits for different time integrated bolometric neutrino emission luminosities (total E_ν) which are assumed to be the same for all GW events. For the beamed emission we assume the total energy to be concentrated in a solid angle of $4\pi/f_{\text{beam}}$, directed isotropically without considering correlations with the GW emission geometry. This is a conservative assumption as the beamed jets are predicted to be directed along the orbital axis of the binaries along which the GW emission is also more powerful.

The limits on GW+HEN source population are shown in Fig. 5 together with the estimated 90% credible intervals of the rate densities of different CBC sources (Abbott et al. 2023c). We show the BBH rate density at $z = 0.2$, based on a model in which the BBH rate density evolves as $(1+z)^\kappa$ with an estimated $\kappa = 2.9^{+1.7}_{-1.8}$. For any of our GWHEN limits we do not assume such a redshift evolution. Since the observed sources are all below $z \lesssim 1$, this modeling difference can bring at most $\mathcal{O}(1)$

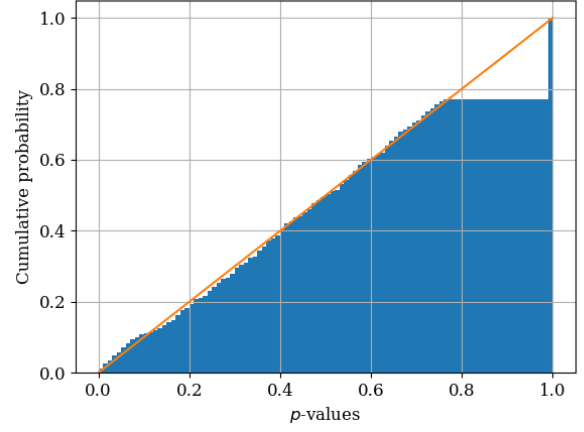


Figure 4. Cumulative distribution of the p -values from the cWB part of the analysis. The orange line is a reference for uniform distribution. The discrete behavior at the right side is due to cWB sky localizations not having smooth probability distributions, most of the sky possessing exactly zero probability.

variations to the compared BBH rate, which would not change our conclusions substantially. We can constrain any HEN emission from a GW source if our derived upper limits lie below the estimated rate density of GW sources. However, the upper limits at 90% confidence level and the 90% credible intervals can only be compared with the caveat that one is a frequentist concept and the other a Bayesian one. The 90% confidence level population upper limits assume neutrino emission with an ϵ^{-2} spectrum between 100 GeV and 100 PeV. The energy bounds of the spectrum were chosen according to the sensitivity of IceCube to track events as in previous analyses (Aartsen et al. 2020; Abbasi et al. 2023a). Although these bounds can vary from model to model, the multimessenger upper limits weakly depend on these bounds as they enter the calculation only logarithmically (Eq. (7)) for an ϵ^{-2} spectrum.

Even our most stringent joint source population upper limit shows that neutrino emission from GW sources can only be constrained at very high neutrino emission energies (time integrated bolometric luminosity $> 10^{52} - 10^{54}$ erg) with isotropic emission. These energies can be compared with the beaming-corrected most energetic short GRB energies of $\sim 10^{51}$ erg (Berger 2014). For beamed neutrino emissions or lower total neutrino emission energies, which correspond to typical GRB emission characteristics, the upper limits on the joint source rate densities lie above the estimated rate densities of GW sources; hence they do not constrain the joint emission from GW sources. The limits of beamed emissions remain higher compared to isotropic emission at high neu-

trino emission energies as the fact that there is a limited solid angle of emission also bounds the chance of neutrino observation independent of the emission strength. The values 90% upper limits converge to at the higher end of neutrino emission energies are set by the detection capabilities of GW detectors; since a sufficiently high number of neutrinos can be detected from such energetic emissions and neutrino detection from a joint emission would not be constraining. That is also mostly the reason why limits for BBH mergers reaches lower values compared to BNS and NSBH mergers, as BBH mergers are detected by LIGO and Virgo much more easily due to the higher amplitude of emitted GW waves in the detectors' sensitive frequency band. On the other hand, for lower neutrino emission energies, the upper limits are set by the neutrino detection capabilities. These upper limits present the first constraints on the high-energy neutrino emission from the population of CBCs. Previous constraints have been put using only the candidate GW bursts which were from the first observing run of Advanced LIGO (Albert et al. 2019).

In the context of the short GRB source population, we note that the rate of observable (on-axis) GRBs is estimated to be around 1% of the O3 BNS rate shown on Fig. 5. While no high-energy neutrinos were observed in coincidence with a detected GRB, there is still room for observable neutrino emission from neutron star containing binary mergers through off-axis emission or from electromagnetically opaque environments. The GW+HEN population limits presented here started to chart that territory.

6. CONCLUSION AND OUTLOOK

The discovery and multimessenger observation of cosmic sources involving HENs and GWs hold the potential to shed light on the origin of the highest energy neutrinos and cosmic rays, reveal high-energy emission from GW engines, enable more effective electromagnetic follow-up efforts, and enhance our understanding of source dynamics. A detailed examination of the O3 data and coincident IceCube event candidates has significantly expanded the analyzed dataset, thereby facilitating a new search.

The LLAMA analysis, employing a model-dependent statistically optimal approach, was applied to all sub-threshold GW candidates within the O3 catalogs and all time-coincident IceCube event candidates. We searched for neutrino emission within a ± 500 s time window centered around the GW merger time. No significant neutrino emission was observed during the search for individual GW candidates. The intersections of the coinciding sky localizations showed the potential effectiveness of

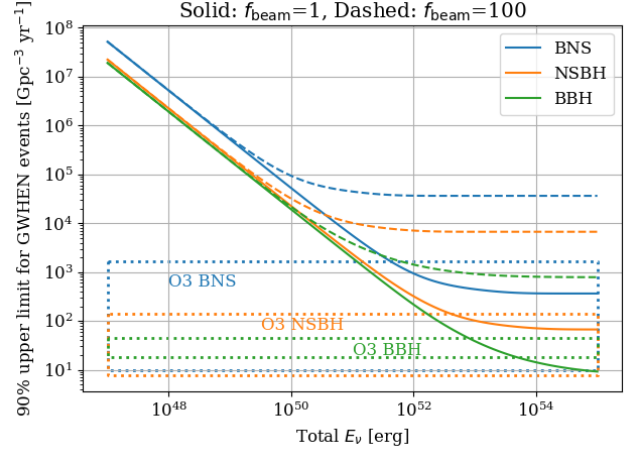


Figure 5. 90% upper limits on GW+HEN source population for different CBC source types as a function of the total neutrino emission energy from each source. We assume identical neutrino emission characteristics for sources with an ϵ^{-2} spectrum. The GW related properties are according to the injections which were guided by the O3 inferences (Abbott et al. 2023c). The upper limits are shown for isotropic neutrino emission with solid lines and for a beamed emission with a beaming factor of 100 with the dashed lines. The rectangular regions described by dotted lines correspond to the estimated rate densities of the corresponding GW sources after O3 with 90% credibility (Abbott et al. 2023c).

multimessenger searches in guiding the observing strategies of electromagnetic observatories by significantly reducing the area that needs to be scanned by telescopes.

The absence of a GWHEN definitive detection resulted in constraints on the population of cosmic multimessenger sources, involving both GWs and neutrinos. These limits can constrain the fraction of HEN emitting GW sources only at very high neutrino emission energies and for isotropic emission. This implies that the joint detection of GW and HEN is mainly limited by the neutrino detection capabilities, providing additional motivations for the next generation of neutrino detectors. We expect enhanced chances for the joint detection of GW and HEN, and improvements for such analyses with the development of next generation neutrino detectors.

The fourth observing run of LVK (O4) is ongoing, with an improved sensitivity (Soni et al. 2025; Virgo Collaboration 2025). Beyond the confirmed 128 CBC mergers identified with $p_{\text{astro}} \geq 0.5$ and thousands of sub-threshold candidates from the first portion of O4 (The LIGO Scientific Collaboration et al. 2025a), there are already additional hundreds of significant mergers and subthreshold candidates to investigate for joint emission with neutrinos that were identified in low-latency (LIGO Scientific, Virgo, and KAGRA Collaborations 2025; The

LIGO Scientific Collaboration et al. 2025a). Real-time multimessenger searches involving HENs and GWs are currently operational on both confident and sub-threshold GW candidates collected during the fourth observing run. The successful operation of O4 (The LIGO Scientific Collaboration et al. 2025b) showcases improved performance, consequently expanding the scope of investigated compact object mergers. The growing network of gravitational-wave detectors will give rise to a heightened rate of GW exploration and more confined source localizations, which in turn will provide more opportunities for conducting multimessenger studies, increasing the likelihood of discovering common sources of neutrinos and GWs.

Next-generation ground-based GW detectors Einstein Telescope and Cosmic Explorer are currently in their design phase, with the goal of significantly expanding the cosmic volume reach by orders of magnitude (Reitze et al. 2019; Sathyaprakash et al. 2011; ET Design 2020; Kalogera et al. 2019). The planned space-based GW detectors LISA (Danzmann 2000; Amaro-Seoane et al. 2017), TianQin (Luo et al. 2016) and Taiji (Ruan et al. 2020) will probe the millihertz frequency regimes. Simultaneously, the neutrino detectors are poised to increase their instrumented volumes with the next generation detector projects IceCube-Gen2 and KM3NeT (Aartsen et al. 2021; Biagi & the KM3NeT consortium 2012). Anticipating a substantial increase in both the rate and quality of observations from these future detectors, we look forward to heightened chances and excitement surrounding future multimessenger discoveries (Ando et al. 2013; Bartos & Kowalski 2017; Márka et al. 2010; Murase & Bartos 2019; Márka 2012; Mészáros et al. 2019).

DATA AVAILABILITY

Supplementing data to this article can be found at <https://dataverse.harvard.edu/dataverse/icecube>.

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REFERENCES

- Aartsen, M., Ackermann, M., Adams, J., et al. 2017, *Journal of Instrumentation*, 12, P03012, doi: [10.1088/1748-0221/12/03/P03012](https://doi.org/10.1088/1748-0221/12/03/P03012)
- . 2024, *Journal of Instrumentation*, 19, E05001, doi: [10.1088/1748-0221/19/05/E05001](https://doi.org/10.1088/1748-0221/19/05/E05001)
- Aartsen, M. G., Abbasi, R., Abdou, Y., et al. 2013, *Physical Review Letters*, 111, 021103, doi: [10.1103/PhysRevLett.111.021103](https://doi.org/10.1103/PhysRevLett.111.021103)
- Aartsen, M. G., Ackermann, M., Adams, J., et al. 2014a, *Physical Review Letters*, 113, 101101, doi: [10.1103/PhysRevLett.113.101101](https://doi.org/10.1103/PhysRevLett.113.101101)
- . 2014b, *Physical Review D*, 90, 102002, doi: [10.1103/PhysRevD.90.102002](https://doi.org/10.1103/PhysRevD.90.102002)
- . 2017, *Journal of Instrumentation*, 12, P03012, doi: [10.1088/1748-0221/12/03/P03012](https://doi.org/10.1088/1748-0221/12/03/P03012)
- Aartsen, M. G., Ackermann, M., Adams, J., et al. 2017, *The Astrophysical Journal*, 843, 112, doi: [10.3847/1538-4357/aa7569](https://doi.org/10.3847/1538-4357/aa7569)
- Aartsen, M. G., Ackermann, M., Adams, J., et al. 2020, *The Astrophysical Journal Letters*, 898, L10, doi: [10.3847/2041-8213/ab9d24](https://doi.org/10.3847/2041-8213/ab9d24)

- Aartsen, M. G., Ackermann, M., Adams, J., et al. 2020, *Physical Review Letters*, 124, 051103, doi: [10.1103/PhysRevLett.124.051103](https://doi.org/10.1103/PhysRevLett.124.051103)
- Aartsen, M. G., Abbasi, R., Ackermann, M., et al. 2021, *Journal of Physics G Nuclear Physics*, 48, 060501, doi: [10.1088/1361-6471/abbd48](https://doi.org/10.1088/1361-6471/abbd48)
- Aasi, J., Abbott, B. P., Abbott, R., et al. 2015, *Classical and Quantum Gravity*, 32, 074001, doi: [10.1088/0264-9381/32/7/074001](https://doi.org/10.1088/0264-9381/32/7/074001)
- Abbasi, R., Ackermann, M., Adams, J., et al. 2021, arXiv e-prints, arXiv:2105.13160, doi: [10.48550/arXiv.2105.13160](https://doi.org/10.48550/arXiv.2105.13160)
- Abbasi, R., Ackermann, M., Adams, J., et al. 2022a, *The Astrophysical Journal*, 939, 116, doi: [10.3847/1538-4357/ac9785](https://doi.org/10.3847/1538-4357/ac9785)
- . 2022b, *Science*, 378, 538–543, doi: [10.1126/science.abg3395](https://doi.org/10.1126/science.abg3395)
- Abbasi, R., Ackermann, M., Adams, J., et al. 2023a, *The Astrophysical Journal*, 944, 80, doi: [10.3847/1538-4357/aca5fc](https://doi.org/10.3847/1538-4357/aca5fc)
- . 2023b, *The Astrophysical Journal*, 959, 96, doi: [10.3847/1538-4357/aceefc](https://doi.org/10.3847/1538-4357/aceefc)
- Abbasi, R., Ackermann, M., Adams, J., et al. 2023, *Science*, 380, 1338–1343, doi: [10.1126/science.adc9818](https://doi.org/10.1126/science.adc9818)
- . 2024a, *The Astrophysical Journal*, 964, 126, doi: [10.3847/1538-4357/ad220b](https://doi.org/10.3847/1538-4357/ad220b)
- . 2024b, *The Astrophysical Journal*, 971, 193, doi: [10.3847/1538-4357/ad683e](https://doi.org/10.3847/1538-4357/ad683e)
- Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2016, *Physical Review Letters*, 116, doi: [10.1103/physrevlett.116.061102](https://doi.org/10.1103/physrevlett.116.061102)
- Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2016, *Physical Review X*, 6, 041015, doi: [10.1103/PhysRevX.6.041015](https://doi.org/10.1103/PhysRevX.6.041015)
- . 2017a, *Physical Review Letters*, 118, 221101, doi: [10.1103/PhysRevLett.118.221101](https://doi.org/10.1103/PhysRevLett.118.221101)
- . 2017b, *Physical Review Letters*, 119, 141101, doi: [10.1103/PhysRevLett.119.141101](https://doi.org/10.1103/PhysRevLett.119.141101)
- . 2017c, *Physical Review Letters*, 119, 161101, doi: [10.1103/PhysRevLett.119.161101](https://doi.org/10.1103/PhysRevLett.119.161101)
- . 2017d, *The Astrophysical Journal Letters*, 848, L12, doi: [10.3847/2041-8213/aa91c9](https://doi.org/10.3847/2041-8213/aa91c9)
- . 2019a, *Physical Review X*, 9, 011001, doi: [10.1103/PhysRevX.9.011001](https://doi.org/10.1103/PhysRevX.9.011001)
- . 2019b, *Physical Review X*, 9, 031040, doi: [10.1103/PhysRevX.9.031040](https://doi.org/10.1103/PhysRevX.9.031040)
- Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2020, *Living Reviews in Relativity*, 23, doi: [10.1007/s41114-020-00026-9](https://doi.org/10.1007/s41114-020-00026-9)
- Abbott, R., Abbott, T. D., Abraham, S., et al. 2021a, *Physical Review X*, 11, 021053, doi: [10.1103/PhysRevX.11.021053](https://doi.org/10.1103/PhysRevX.11.021053)
- Abbott, R., Abbott, T. D., Acernese, F., et al. 2021b, *Physical Review D*, 104, 122004, doi: [10.1103/PhysRevD.104.122004](https://doi.org/10.1103/PhysRevD.104.122004)
- Abbott, R., Abbott, T. D., Acernese, F., et al. 2023a, *Physical Review X*, 13, 041039, doi: [10.1103/PhysRevX.13.041039](https://doi.org/10.1103/PhysRevX.13.041039)
- Abbott, R., Abe, H., Acernese, F., et al. 2023b, *The Astrophysical Journal*, 267, 29, doi: [10.3847/1538-4365/acdc9f](https://doi.org/10.3847/1538-4365/acdc9f)
- Abbott, R., Abbott, T. D., Acernese, F., et al. 2023c, *Physical Review X*, 13, 011048, doi: [10.1103/PhysRevX.13.011048](https://doi.org/10.1103/PhysRevX.13.011048)
- Abbott, R., Abbott, T. D., Acernese, F., et al. 2024, *Physical Review D*, 109, 022001, doi: [10.1103/PhysRevD.109.022001](https://doi.org/10.1103/PhysRevD.109.022001)
- Abe, K., Haga, K., Hayato, Y., et al. 2016, *The Astrophysical Journal Letters*, 830, L11, doi: [10.3847/2041-8205/830/1/L11](https://doi.org/10.3847/2041-8205/830/1/L11)
- Abe, K., Bronner, C., Hayato, Y., et al. 2018, *The Astrophysical Journal Letters*, 857, L4, doi: [10.3847/2041-8213/aabaca](https://doi.org/10.3847/2041-8213/aabaca)
- Abe, K., Bronner, C., Hayato, Y., et al. 2021a, *The Astrophysical Journal*, 918, 78, doi: [10.3847/1538-4357/ac0d5a](https://doi.org/10.3847/1538-4357/ac0d5a)
- Abe, S., Asami, S., Gando, A., et al. 2021b, *The Astrophysical Journal*, 909, 116, doi: [10.3847/1538-4357/abd5bc](https://doi.org/10.3847/1538-4357/abd5bc)
- Acernese, F., Agathos, M., Agatsuma, K., et al. 2015, *Classical and Quantum Gravity*, 32, 024001, doi: [10.1088/0264-9381/32/2/024001](https://doi.org/10.1088/0264-9381/32/2/024001)
- Acernese, F., Agathos, M., Ain, A., et al. 2023, *Classical and Quantum Gravity*, 40, 185006, doi: [10.1088/1361-6382/acd92d](https://doi.org/10.1088/1361-6382/acd92d)
- Adams, T., Buskulic, D., Germain, V., et al. 2016, *Classical and Quantum Gravity*, 33, 175012, doi: [10.1088/0264-9381/33/17/175012](https://doi.org/10.1088/0264-9381/33/17/175012)
- Adrián-Martínez, S., Samarai, I. A., Albert, A., et al. 2013, *JCAP*, 6, 8, doi: [10.1088/1475-7516/2013/06/008](https://doi.org/10.1088/1475-7516/2013/06/008)
- Adrián-Martínez, S., Albert, A., André, M., et al. 2016, *Physical Review D*, 93, 122010, doi: [10.1103/PhysRevD.93.122010](https://doi.org/10.1103/PhysRevD.93.122010)
- Agostini, M., Altenmüller, K., Appel, S., et al. 2017, *The Astrophysical Journal*, 850, 21, doi: [10.3847/1538-4357/aa9521](https://doi.org/10.3847/1538-4357/aa9521)
- Albert, A., André, M., Anghinolfi, M., et al. 2017a, *The Astrophysical Journal Letters*, 850, L35, doi: [10.3847/2041-8213/aa9aed](https://doi.org/10.3847/2041-8213/aa9aed)

- . 2017b, *Physical Review D*, 96, 022005, doi: [10.1103/PhysRevD.96.022005](https://doi.org/10.1103/PhysRevD.96.022005)
- . 2018, *The Astrophysical Journal Letters*, 863, L30, doi: [10.3847/2041-8213/aad8c0](https://doi.org/10.3847/2041-8213/aad8c0)
- . 2019, *The Astrophysical Journal*, 870, 134, doi: [10.3847/1538-4357/aaf21d](https://doi.org/10.3847/1538-4357/aaf21d)
- . 2020, *European Physical Journal C*, 80, 487, doi: [10.1140/epjc/s10052-020-8015-6](https://doi.org/10.1140/epjc/s10052-020-8015-6)
- Allen, B. 2005, *Physical Review D*, 71, 062001, doi: [10.1103/PhysRevD.71.062001](https://doi.org/10.1103/PhysRevD.71.062001)
- Allen, B., Anderson, W. G., Brady, P. R., Brown, D. A., & Creighton, J. D. E. 2012, *Physical Review D*, 85, 122006, doi: [10.1103/PhysRevD.85.122006](https://doi.org/10.1103/PhysRevD.85.122006)
- Amaro-Seoane, P., Audley, H., Babak, S., et al. 2017, *Laser Interferometer Space Antenna*. <https://arxiv.org/abs/1702.00786>
- Ando, S., Baret, B., Bartos, I., et al. 2013, *Reviews of Modern Physics*, 85, 1401, doi: [10.1103/RevModPhys.85.1401](https://doi.org/10.1103/RevModPhys.85.1401)
- Aso, Y., Márka, Z., Finley, C., et al. 2008, *Classical and Quantum Gravity*, 25, 114039, doi: [10.1088/0264-9381/25/11/114039](https://doi.org/10.1088/0264-9381/25/11/114039)
- Athar, H., Kim, C. S., & Lee, J. 2006, *Modern Physics Letters A*, 21, 1049–1065, doi: [10.1142/s021773230602038x](https://doi.org/10.1142/s021773230602038x)
- Aubin, F., Brighenti, F., Chierici, R., et al. 2021, *Classical and Quantum Gravity*, 38, 095004, doi: [10.1088/1361-6382/abe913](https://doi.org/10.1088/1361-6382/abe913)
- Baret, B., Bartos, I., Bouhou, B., et al. 2011, *Astroparticle Physics*, 35, 1, doi: [10.1016/j.astropartphys.2011.04.001](https://doi.org/10.1016/j.astropartphys.2011.04.001)
- . 2012, *Physical Review D*, 85, 103004, doi: [10.1103/PhysRevD.85.103004](https://doi.org/10.1103/PhysRevD.85.103004)
- Bartos, I., Dasgupta, B., & Márka, S. 2012, *Physical Review D*, 86, 083007, doi: [10.1103/PhysRevD.86.083007](https://doi.org/10.1103/PhysRevD.86.083007)
- Bartos, I., Finley, C., Corsi, A., & Márka, S. 2011, *Physical Review Letters*, 107, 251101, doi: [10.1103/PhysRevLett.107.251101](https://doi.org/10.1103/PhysRevLett.107.251101)
- Bartos, I., & Kowalski, M. 2017, *Multimessenger Astronomy* (Springer), doi: [10.1088/978-0-7503-1369-8](https://doi.org/10.1088/978-0-7503-1369-8)
- Bartos, I., Veske, D., Keivani, A., et al. 2019, *Physical Review D*, 100, 083017, doi: [10.1103/PhysRevD.100.083017](https://doi.org/10.1103/PhysRevD.100.083017)
- Berger, E. 2014, *ARA&A*, 52, 43, doi: [10.1146/annurev-astro-081913-035926](https://doi.org/10.1146/annurev-astro-081913-035926)
- Biagi, S., & the KM3NeT consortium. 2012, *Journal of Physics: Conference Series*, 375, 052036, doi: [10.1088/1742-6596/375/1/052036](https://doi.org/10.1088/1742-6596/375/1/052036)
- Biehl, D., Heinze, J., & Winter, W. 2018, *Monthly Notices of the Royal Astronomical Society*, 476, 1191, doi: [10.1093/mnras/sty285](https://doi.org/10.1093/mnras/sty285)
- Blaufuss, E., Kintscher, T., Lu, L., & Tung, C. F. 2019, in *International Cosmic Ray Conference*, Vol. 36, 36th International Cosmic Ray Conference (ICRC2019), 1021, doi: [10.22323/1.358.1021](https://doi.org/10.22323/1.358.1021)
- Buikema, A., Cahillane, C., Mansell, G. L., et al. 2020, *Physical Review D*, 102, 062003, doi: [10.1103/PhysRevD.102.062003](https://doi.org/10.1103/PhysRevD.102.062003)
- Cannon, K., Caudill, S., Chan, C., et al. 2021, *SoftwareX*, 14, 100680, doi: [10.1016/j.softx.2021.100680](https://doi.org/10.1016/j.softx.2021.100680)
- Chen, H.-Y., Holz, D. E., Miller, J., et al. 2021, *Classical and Quantum Gravity*, 38, 055010, doi: [10.1088/1361-6382/abd594](https://doi.org/10.1088/1361-6382/abd594)
- Collaboration, T. A., Price-Whelan, A. M., Lim, P. L., et al. 2022, *The Astrophysical Journal*, 935, 167, doi: [10.3847/1538-4357/ac7c74](https://doi.org/10.3847/1538-4357/ac7c74)
- Countryman, S., Keivani, A., Bartos, I., et al. 2019, *arXiv e-prints*, arXiv:1901.05486, doi: [10.48550/arXiv.1901.05486](https://doi.org/10.48550/arXiv.1901.05486)
- Dal Canton, T., Nitz, A. H., Lundgren, A. P., et al. 2014, *Physical Review D*, 90, 082004, doi: [10.1103/PhysRevD.90.082004](https://doi.org/10.1103/PhysRevD.90.082004)
- Danzmann, K. 2000, *Advances in Space Research*, 25, 1129, doi: [https://doi.org/10.1016/S0273-1177\(99\)00973-4](https://doi.org/10.1016/S0273-1177(99)00973-4)
- Davies, G. S., Dent, T., Tápai, M., et al. 2020, *Physical Review D*, 102, 022004, doi: [10.1103/PhysRevD.102.022004](https://doi.org/10.1103/PhysRevD.102.022004)
- Davis, D., Areeda, J. S., Berger, B. K., et al. 2021, *Classical and Quantum Gravity*, 38, 135014, doi: [10.1088/1361-6382/abfd85](https://doi.org/10.1088/1361-6382/abfd85)
- de Bruijn, O., Bartos, I., Biermann, P. L., & Tjus, J. B. 2020, *The Astrophysical Journal Letters*, 905, L13, doi: [10.3847/2041-8213/abc950](https://doi.org/10.3847/2041-8213/abc950)
- De Wasseige, G., Bartos, I., de Vries, K., & O’Sullivan, E. 2019, in *International Cosmic Ray Conference*, Vol. 36, 36th International Cosmic Ray Conference (ICRC2019), 865, doi: [10.22323/1.358.0865](https://doi.org/10.22323/1.358.0865)
- Drago, M., Klimenko, S., Lazzaro, C., et al. 2021, *SoftwareX*, 14, 100678, doi: <https://doi.org/10.1016/j.softx.2021.100678>
- Drury, L. O. 1983, *Reports on Progress in Physics*, 46, 973, doi: [10.1088/0034-4885/46/8/002](https://doi.org/10.1088/0034-4885/46/8/002)
- ET Design. 2020, *Einstein Telescope Design Study 2020* https://gwic.ligo.org/3Gsubcomm/docs/ET-0007B-20_ETDesignReportUpdate2020.pdf
- Fang, K., & Metzger, B. D. 2017, *The Astrophysical Journal*, 849, 153, doi: [10.3847/1538-4357/aa8b6a](https://doi.org/10.3847/1538-4357/aa8b6a)
- Fang, K., Metzger, B. D., Murase, K., Bartos, I., & Kotera, K. 2019, *The Astrophysical Journal*, 878, 34, doi: [10.3847/1538-4357/ab1b72](https://doi.org/10.3847/1538-4357/ab1b72)

- Finn, L. S., & Chernoff, D. F. 1993, *Physical Review D*, 47, 2198, doi: [10.1103/PhysRevD.47.2198](https://doi.org/10.1103/PhysRevD.47.2198)
- Fong, W., Berger, E., Margutti, R., & Zauderer, B. A. 2015, *The Astrophysical Journal*, 815, 102, doi: [10.1088/0004-637X/815/2/102](https://doi.org/10.1088/0004-637X/815/2/102)
- Guetta, D., Rahin, R., Bartos, I., & Della Valle, M. 2020, *MNRAS*, 492, 843, doi: [10.1093/mnras/stz3245](https://doi.org/10.1093/mnras/stz3245)
- Halzen, F., & Hooper, D. 2002, *Reports on Progress in Physics*, 65, 1025, doi: [10.1088/0034-4885/65/7/201](https://doi.org/10.1088/0034-4885/65/7/201)
- Hanna, C., Caudill, S., Messick, C., et al. 2020, *Physical Review D*, 101, 022003, doi: [10.1103/PhysRevD.101.022003](https://doi.org/10.1103/PhysRevD.101.022003)
- Harris, C. R., Millman, K. J., van der Walt, S. J., et al. 2020, *Nature*, 585, 357, doi: [10.1038/s41586-020-2649-2](https://doi.org/10.1038/s41586-020-2649-2)
- Hunter, J. D. 2007, *Computing in Science & Engineering*, 9, 90, doi: [10.1109/MCSE.2007.55](https://doi.org/10.1109/MCSE.2007.55)
- IceCube Collaboration. 2013, *Science*, 342, 1242856, doi: [10.1126/science.1242856](https://doi.org/10.1126/science.1242856)
- IceCube Collaboration, Aartsen, M. G., Abraham, K., et al. 2016, *Journal of Instrumentation*, 11, P11009, doi: [10.1088/1748-0221/11/11/P11009](https://doi.org/10.1088/1748-0221/11/11/P11009)
- IceCube Collaboration, Aartsen, M. G., Ackermann, M., et al. 2018, *Science*, 361, eaat1378, doi: [10.1126/science.aat1378](https://doi.org/10.1126/science.aat1378)
- Kalogera, V., Bizouard, M.-A., Burrows, A., et al. 2019, *BAAS*, 51, 239, doi: [10.48550/arXiv.1903.09224](https://doi.org/10.48550/arXiv.1903.09224)
- Keivani, A., Veske, D., Countryman, S., et al. 2019, in *International Cosmic Ray Conference*, Vol. 36, 36th International Cosmic Ray Conference (ICRC2019), 930, doi: [10.22323/1.358.0930](https://doi.org/10.22323/1.358.0930)
- Keivani, A., Murase, K., Petropoulou, M., et al. 2018, *The Astrophysical Journal*, 864, 84, doi: [10.3847/1538-4357/aad59a](https://doi.org/10.3847/1538-4357/aad59a)
- Keivani, A., Kennea, J. A., Evans, P. A., et al. 2021, *The Astrophysical Journal*, 909, 126, doi: [10.3847/1538-4357/abdab4](https://doi.org/10.3847/1538-4357/abdab4)
- Kimura, S. S., Murase, K., Bartos, I., et al. 2018, *Physical Review D*, 98, 043020, doi: [10.1103/PhysRevD.98.043020](https://doi.org/10.1103/PhysRevD.98.043020)
- Kimura, S. S., Murase, K., Mészáros, P., & Kiuchi, K. 2017, *The Astrophysical Journal Letters*, 848, L4, doi: [10.3847/2041-8213/aa8d14](https://doi.org/10.3847/2041-8213/aa8d14)
- Kintscher, T. for the IceCube Collaboration. 2016, *Journal of Physics: Conference Series*, 718, 062029, doi: [10.1088/1742-6596/718/6/062029](https://doi.org/10.1088/1742-6596/718/6/062029)
- Klimenko, S., Vedovato, G., Drago, M., et al. 2016, *Physical Review D*, 93, 042004, doi: [10.1103/PhysRevD.93.042004](https://doi.org/10.1103/PhysRevD.93.042004)
- Kurahashi, N., Murase, K., & Santander, M. 2022, *Annual Review of Nuclear and Particle Science*, 72, 365–387, doi: [10.1146/annurev-nucl-011122-061547](https://doi.org/10.1146/annurev-nucl-011122-061547)
- LIGO Scientific Collaboration, Virgo Collaboration, & KAGRA Collaboration. 2021a. <https://zenodo.org/records/5759108>
- . 2021b. <https://zenodo.org/records/5546665>
- . 2023. <https://zenodo.org/records/7890437>
- LIGO Scientific, Virgo, and KAGRA Collaborations. 2025, *Gravitational-Wave Candidate Event Database (GraceDB)*, (Accessed June 25, 2025). <https://gracedb.ligo.org/latest/>
- Loeb, A., & Waxman, E. 2006, *JCAP*, 2006, 003, doi: [10.1088/1475-7516/2006/05/003](https://doi.org/10.1088/1475-7516/2006/05/003)
- Luo, J., Chen, L.-S., Duan, H.-Z., et al. 2016, *Classical and Quantum Gravity*, 33, 035010, doi: [10.1088/0264-9381/33/3/035010](https://doi.org/10.1088/0264-9381/33/3/035010)
- Márka, S., LIGO Scientific Collaboration, & Virgo Collaboration. 2010, in *Journal of Physics Conference Series*, Vol. 243, *Journal of Physics Conference Series*, 012001, doi: [10.1088/1742-6596/243/1/012001](https://doi.org/10.1088/1742-6596/243/1/012001)
- Marka, Z., Oliveira, A. C., Veske, D., et al. 2022, in *APS Meeting Abstracts*, Vol. 2022, *APS April Meeting Abstracts*, K14.005
- Messick, C., Blackburn, K., Brady, P., et al. 2017, *Physical Review D*, 95, 042001, doi: [10.1103/PhysRevD.95.042001](https://doi.org/10.1103/PhysRevD.95.042001)
- Mészáros, P., Fox, D. B., Hanna, C., & Murase, K. 2019, *Nature Reviews Physics*, 1, 585, doi: [10.1038/s42254-019-0101-z](https://doi.org/10.1038/s42254-019-0101-z)
- Murase, K., & Bartos, I. 2019, *Annual Review of Nuclear and Particle Science*, 69, 477, doi: [10.1146/annurev-nucl-101918-023510](https://doi.org/10.1146/annurev-nucl-101918-023510)
- Márka, S. 2012, *Annals of the New York Academy of Sciences*, 1260, 55, doi: <https://doi.org/10.1111/j.1749-6632.2011.06414.x>
- Neyman, J. 1937, *Phil. Trans. Roy. Soc. Lond. A*, 236, 333, doi: [10.1098/rsta.1937.0005](https://doi.org/10.1098/rsta.1937.0005)
- Nitz, A. H., Dent, T., Dal Canton, T., Fairhurst, S., & Brown, D. A. 2017, *The Astrophysical Journal*, 849, 118, doi: [10.3847/1538-4357/aa8f50](https://doi.org/10.3847/1538-4357/aa8f50)
- Pakvasa, S., Rodejohann, W., & Weiler, T. J. 2008, *Journal of High Energy Physics*, 2008, 005–005, doi: [10.1088/1126-6708/2008/02/005](https://doi.org/10.1088/1126-6708/2008/02/005)
- Pérez, F., & Granger, B. E. 2007, *Computing in Science & Engineering*, 9, 21, doi: [10.1109/MCSE.2007.53](https://doi.org/10.1109/MCSE.2007.53)
- Pizzuto, A., Abbasi, R., Ackermann, M., et al. 2021, in *Proceedings of 37th International Cosmic Ray Conference — PoS(ICRC2021)*, Vol. 395, 952, doi: [10.22323/1.395.0952](https://doi.org/10.22323/1.395.0952)
- Planck Collaboration, Ade, P. A. R., Aghanim, N., et al. 2016, *A&A*, 594, A13, doi: [10.1051/0004-6361/201525830](https://doi.org/10.1051/0004-6361/201525830)

- Python Software Foundation. 2024, Python Language Reference, version 3.x, <https://www.python.org/>, doi: [10.5281/zenodo.8247853](https://doi.org/10.5281/zenodo.8247853)
- Razzaque, S., Mészáros, P., & Waxman, E. 2003, Physical Review D, 68, 083001, doi: [10.1103/PhysRevD.68.083001](https://doi.org/10.1103/PhysRevD.68.083001)
- Reitze, D., Adhikari, R. X., Ballmer, S., et al. 2019, in Bulletin of the American Astronomical Society, Vol. 51, 35, doi: [10.48550/arXiv.1907.04833](https://doi.org/10.48550/arXiv.1907.04833)
- Ruan, W.-H., Guo, Z.-K., Cai, R.-G., & Zhang, Y.-Z. 2020, International Journal of Modern Physics A, 35, 2050075, doi: [10.1142/s0217751x2050075x](https://doi.org/10.1142/s0217751x2050075x)
- Sachdev, S., Caudill, S., Fong, H., et al. 2019, arXiv e-prints, arXiv:1901.08580, doi: [10.48550/arXiv.1901.08580](https://doi.org/10.48550/arXiv.1901.08580)
- Sathyaprakash, B., Abernathy, M., Acernese, F., et al. 2011, arXiv e-prints, arXiv:1108.1423, doi: [10.48550/arXiv.1108.1423](https://doi.org/10.48550/arXiv.1108.1423)
- Schutz, B. F. 2011, Classical and Quantum Gravity, 28, 125023, doi: [10.1088/0264-9381/28/12/125023](https://doi.org/10.1088/0264-9381/28/12/125023)
- Singer, L. P., & Price, L. R. 2016, Physical Review D, 93, 024013, doi: [10.1103/PhysRevD.93.024013](https://doi.org/10.1103/PhysRevD.93.024013)
- Singer, L. P., Chen, H.-Y., Holz, D. E., et al. 2016, The Astrophysical Journal Letters, 829, L15, doi: [10.3847/2041-8205/829/1/L15](https://doi.org/10.3847/2041-8205/829/1/L15)
- Soni, S., Berger, B. K., Davis, D., et al. 2025, Classical and Quantum Gravity, 42, 085016, doi: [10.1088/1361-6382/adc4b6](https://doi.org/10.1088/1361-6382/adc4b6)
- Talbot, C., & Thrane, E. 2018, The Astrophysical Journal, 856, 173, doi: [10.3847/1538-4357/aab34c](https://doi.org/10.3847/1538-4357/aab34c)
- The LIGO Scientific Collaboration, the Virgo Collaboration, the KAGRA Collaboration, et al. 2025a, arXiv e-prints, arXiv:2508.18082, doi: [10.48550/arXiv.2508.18082](https://doi.org/10.48550/arXiv.2508.18082)
- . 2025b, arXiv e-prints, arXiv:2508.18080, doi: [10.48550/arXiv.2508.18080](https://doi.org/10.48550/arXiv.2508.18080)
- Usman, S. A., Nitz, A. H., Harry, I. W., et al. 2016, Classical and Quantum Gravity, 33, 215004, doi: [10.1088/0264-9381/33/21/215004](https://doi.org/10.1088/0264-9381/33/21/215004)
- van Elewyck, V., Ando, S., Aso, Y., et al. 2009, International Journal of Modern Physics D, 18, 1655, doi: [10.1142/S0218271809015655](https://doi.org/10.1142/S0218271809015655)
- Veske, D., Márka, Z., Bartos, I., & Márka, S. 2021, The Astrophysical Journal, 908, 216, doi: [10.3847/1538-4357/abd542](https://doi.org/10.3847/1538-4357/abd542)
- Veske, D., Márka, Z., Bartos, I., & Márka, S. 2020, Journal of Cosmology and Astroparticle Physics, 2020, 016–016, doi: [10.1088/1475-7516/2020/05/016](https://doi.org/10.1088/1475-7516/2020/05/016)
- Veske, D., IceCube, Abbasi, R., et al. 2022, in 37th International Cosmic Ray Conference, 950, doi: [10.22323/1.395.0950](https://doi.org/10.22323/1.395.0950)
- Virgo Collaboration. 2025, ApOpt, 64, 4710, doi: [10.1364/AO.555312](https://doi.org/10.1364/AO.555312)
- Virtanen, P., Gommers, R., Oliphant, T. E., et al. 2020, Nature Methods, 17, 261, doi: [10.1038/s41592-019-0686-2](https://doi.org/10.1038/s41592-019-0686-2)

APPENDIX

GW event GPS Time	p -value [10^{-3}]	Energy [GeV]	R.A. [deg]	Dec. [deg]	90% containment radius [deg]	Δt [s]
CBC Events						
1262142545.615	0.38	2416	37.31	7.46	2.62	-222
1258769976.671	0.52	2553	213.01	24.91	2.40	-232
1260567236.512	0.52	890	323.19	4.53	4.08	-43
1264693411.565	0.83	1045	138.52	14.12	1.59	-59
1261317209.144	1.1	4260	11.03	53.31	5.23	412
1240986884.531	1.3	1222	161.03	39.41	3.41	3
1248922975.872	1.7	1099	11.80	43.66	0.86	-79
1251996593.946	1.9	6656	341.15	3.53	0.43	85
1261395060.713	2.0	1227	7.32	25.41	2.17	55
1242369559.803	2.3	4938	67.79	80.85	6.24	-148
1245646385.592	2.6	2615	181.93	-5.55	1.07	-131
1259556411.479	3.5	921	342.74	51.25	2.98	-309
1257878102.660	3.8	1549	78.01	15.62	2.17	-286
1262800092.537	5.6	702	289.72	0.23	1.22	85
1257317013.751	5.7	1264	91.41	35.29	3.07	-209
1248959867.938	5.8	2090	62.89	29.51	2.60	25
1239281492.824	6.1	1385	60.72	19.89	1.03	49
1246655423.219	7.9	16865	277.26	-7.61	0.43	295
1258085887.274	8.3	1708	23.33	17.38	2.29	3
1238533707.234	8.3	2344	299.04	22.97	1.37	23
1249072561.974	9.3	1986	125.07	31.54	4.65	296
1262751997.732	9.6	1448	81.07	55.20	1.27	-46
cWB Events						
1241247887.938	0.43	2268	242.35	51.34	3.20	154
1259085330.234	1.1	1960	197.90	25.78	3.13	6
1266181040.000	1.3	2636	144.50	7.87	1.27	389
1258325594.125	4.3	330	7.44	19.58	4.03	171
1250185147.797	8.9	710	131.95	11.31	2.04	-19

Table 1. Properties of the coincident neutrinos that produce a p -value of 0.01 or less. Sky coordinates are in right ascension (R.A.) and declination (Dec.). The time difference Δt is neutrino detection time minus GW event time.