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P. Abbott, B.; Abbott, R.; Abbott, T. D. ; R. Abernathy, M.; Acernese, F.; Ackley, K.; Adams, C.; Adams, T. ; Addesso, P.; X. Adhikari, R.

Total number of authors:
18

Published in:
Astrophysical Journal Supplement Series

Link to article, DOI:
[10.3847/0067-0049/225/1/8](https://doi.org/10.3847/0067-0049/225/1/8)

Publication date:
2016

Document Version
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

Citation (APA):

P. Abbott, B., Abbott, R., Abbott, T. D., R. Abernathy, M., Acernese, F., Ackley, K., Adams, C., Adams, T., Addesso, P., X. Adhikari, R., Brandt, S., Perley, D., Hjorth, J., Fynbo, J. P. U., Malesani, D., Milvang-Jensen, B., Watson, D., & Ugarte Postigo, A. D. (2016). Supplement: “Localization And Broadband Follow-Up of the Gravitational-Wave Transient GW150914” (2016, Apjl, 826, L13). *Astrophysical Journal Supplement Series*, 225(1). <https://doi.org/10.3847/0067-0049/225/1/8>

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SUPPLEMENT: “LOCALIZATION AND BROADBAND FOLLOW-UP OF THE GRAVITATIONAL-WAVE TRANSIENT GW150914” (2016, ApJL, 826, L13)

THE LIGO SCIENTIFIC COLLABORATION AND THE VIRGO COLLABORATION, THE AUSTRALIAN SQUARE KILOMETER ARRAY PATHFINDER (ASKAP) COLLABORATION, THE BOOTES COLLABORATION, THE DARK ENERGY SURVEY AND THE DARK ENERGY CAMERA GW-EM COLLABORATIONS, THE FERMI GBM COLLABORATION, THE FERMI LAT COLLABORATION, THE GRAVITATIONAL WAVE INAF TEAM (GRAWITA), THE INTEGRAL COLLABORATION, THE INTERMEDIATE PALOMAR TRANSIENT FACTORY (IPTF) COLLABORATION, THE INTERPLANETARY NETWORK, THE J-GEM COLLABORATION, THE LA SILLA-QUEST SURVEY, THE LIVERPOOL TELESCOPE COLLABORATION, THE LOW FREQUENCY ARRAY (LOFAR) COLLABORATION, THE MASTER COLLABORATION, THE MAXI COLLABORATION, THE MURCHISON WIDE-FIELD ARRAY (MWA) COLLABORATION, THE PAN-STARRS COLLABORATION, THE PESSTO COLLABORATION, THE PI OF THE SKY COLLABORATION, THE SKYMAPPER COLLABORATION, THE SWIFT COLLABORATION, THE TAROT, ZADKO, ALGERIAN NATIONAL OBSERVATORY, AND C2PU COLLABORATION, THE TOROS COLLABORATION, AND THE VISTA COLLABORATION

(See the end matter for the full list of authors.)

Received 2016 April 27; accepted 2016 May 4; published 2016 July 20

ABSTRACT

This Supplement provides supporting material for Abbott et al. (2016a). We briefly summarize past electromagnetic (EM) follow-up efforts as well as the organization and policy of the current EM follow-up program. We compare the four probability sky maps produced for the gravitational-wave transient GW150914, and provide additional details of the EM follow-up observations that were performed in the different bands.

Key words: gravitational waves – methods: observational

1. PAST AND PRESENT FOLLOW-UP PROGRAM

The first gravitational-wave (GW)-triggered electromagnetic (EM) observations were carried out during the 2009–2010 science run of the initial LIGO and Virgo detectors (Abadie et al. 2012b), featuring real-time searches for unmodeled GW bursts and compact binary coalescences (CBCs; Abadie et al. 2012a, 2012b). GW candidates were identified—typically within 30 minutes—and their inferred sky locations were used to plan follow-up observations with over a dozen optical and radio telescopes on the ground plus the *Swift* satellite (Gehrels et al. 2004). Tiles were assigned to individual facilities to target known galaxies that were consistent with the GW localizations and that were within the 50 Mpc nominal BNS detectability horizon. Eight GW candidates were followed up. Though none of the GW candidates were significant enough to constitute detections and the EM candidates found were judged to be merely serendipitous sources (Evans et al. 2012; Aasi et al. 2014), the program demonstrated the feasibility of searching in real time for GW transients, triggering follow-up, and analyzing GW and EM observations jointly.

The present program of follow-up of GW candidates involves a large number of facilities and observer teams. Instead of centrally planning the assignment of tiles to facilities, we have set up a common EM bulletin board for facilities and observers to announce, coordinate, and visualize the footprints and wavelength coverage of their observations. The new program builds on the Gamma-ray Coordinates Network (GCN)³⁸¹ system that has long been established for broadband follow-up of gamma-ray bursts (GRBs). We distribute times and sky positions of event candidates via machine-readable GCN Notices, and participating facilities communicate the results of observations via short bulletins,

GCN Circulars. A key difference is that GRB Notices and Circulars are instantly public, whereas GW alert Notices and follow up Circulars currently are restricted to participating groups until the event candidate in question has been published. After four high-confidence GW events have been published, further high-confidence GW event candidates will be promptly released to the public.

2. COMPARISON OF GRAVITATIONAL-WAVE SKY MAPS

In the main Letter (Abbott et al. 2016a), we introduced four GW sky maps produced with different methods: cWB (Klimenko et al. 2016), LIB (Lynch et al. 2015), BAYESTAR (Singer & Price 2016), and LALInference (Veitch et al. 2015). cWB and LIB treat the GW signal as an unmodeled burst; BAYESTAR and LALInference assume that the source is a CBC. The LALInference sky map should be regarded as the authoritative one for this event. Table 1 shows that the areas of the 10%, 50%, and 90% confidence regions vary between the algorithms. For this event, cWB produces smaller confidence regions than the other algorithms. While cWB produces reasonably accurate maps for typical binary black hole (BBH) signals, it can systematically misestimate the sizes of large confidence regions (Essick et al. 2015). The other algorithms are self-consistent even in this regime. Only the LALInference results account for calibration uncertainty (systematic errors in the conversion of the photocurrent into the GW strain signal). Because systematic errors in the calibration phase affect the measured arrival times at the detectors, the main effect is to broaden the position uncertainty relative to the other sky maps.

Table 1 also shows the intersections of the 90% confidence regions as well as the fidelity $F(p, q) = \int \sqrt{pq} d\Omega \in [0, 1]$ between the two maps p and q . All these measures show that

³⁸¹ <http://gcn.gsfc.nasa.gov>

Table 1
Description of Sky Maps

	Area ^a			θ_{HL} ^c	Comparison ^b			
	10%	50%	90%		cWB	LIB	BSTR	LALInf
cWB	10	100	310	43^{+2}_{-2}	...	190	180	230
LIB	30	210	750	45^{+6}_{-5}	0.55	...	220	300
BSTR	10	90	400	45^{+2}_{-2}	0.64	0.56	...	360
LALInf	20	150	630	46^{+3}_{-3}	0.60	0.57	0.90	...

Notes.

^a Area of credible level (deg²). Note that the LALInference area is consistent with but not equal to the number reported in Abbott et al. (2016b) due to minor differences in sampling and interpolation.

^b Fidelity (below diagonal) and the intersection in deg² of the 90% confidence regions (above diagonal).

^c Mean and 10% and 90% percentiles of polar angle in degrees.

the sky maps are similar but not identical. Typically, this level of quantitative disagreement is distinguishable by eye and has been observed in large simulation campaigns (Singer et al. 2014; Berry et al. 2015; Essick et al. 2015) for approximately 10%–20% of the simulated signals. This even includes the bi-modality of LIB’s θ_{HL} distribution (see the inset of Figure 2 of the main paper), which is associated with a degeneracy between sky location and the handedness of the binary orbit projected on the plane of the sky. Similar features were noted for BNS systems as well (Singer et al. 2014).

3. GAMMA-RAY AND X-RAY OBSERVATIONS

The *Fermi* Gamma-ray Burst Monitor (GBM; Meegan et al. 2009), *INTEGRAL* (Winkler et al. 2003), and the Inter Planetary Network (IPN; Hurley et al. 2010) searched for prompt high-energy emission temporally coincident with the GW event. Although no GRB in coincidence with GW150914 was reported, an offline analysis of the *Fermi* GBM (8 keV–40 MeV) data revealed a weak transient with a duration of ~ 1 s (Connaughton et al. 2016). A similar analysis was performed for the instruments on board *INTEGRAL* (Winkler et al. 2003), particularly the spectrometer’s anticoincidence shield (SPI-ACS; von Kienlin et al. 2003, 75 keV–1 MeV)³⁸². No significant signals were detected, setting upper limits on the hard X-ray fluence at the time of the event (Savchenko et al. 2016). Data from the six-spacecraft, all-sky, full-time monitor IPN, (*Odyssey*–HEND, *Wind*–Konus, *RHESSI*, *INTEGRAL*–SPI-ACS, and *Swift*–BAT³⁸³) revealed no bursts around the time of GW150914 apart from the weak GBM signal (K. Hurley et al. 2016, in preparation).

The *Fermi* Large Area Telescope (LAT), MAXI, and *Swift* searched for high-energy afterglow emission. The LIGO localization first entered the *Fermi* LAT field of view (FOV) at 4200s after the GW trigger and was subsequently observed in its entirety over the next 3 hr and every 3 hr thereafter at GeV energies (Fermi-LAT Collaboration 2016). The entire region was also imaged in the 2–20 keV X-ray band by the MAXI Gas Slit Camera (Matsuoka et al. 2009) aboard the International Space Station from 86 to 77 minutes before the GW trigger and was re-observed during each subsequent

³⁸² *INTEGRAL*’s coded-mask imager (IBIS, Ubertini et al. 2003, 20–200 keV) was pointed far outside the GW localization region.

³⁸³ The *Swift* Burst Alert Telescope did not intersect the GW localization at the time of the trigger.

~ 92 minute orbit (N. Kawai et al. 2016, in preparation). The *Swift* X-ray Telescope (XRT; Burrows et al. 2005) followed up the GW event starting 2.25 days after the GW event, and covered five tiles containing eight nearby galaxies for a total ~ 0.3 deg² area in the 0.3–10 keV energy range. A 37 point tiled observation of the Large Magellanic Cloud was executed a day later. The *Swift* UV/Optical Telescope (UVOT) provided simultaneous ultraviolet and optical observations, giving a broadband coverage of 80% of the *Swift* XRT FOV. Details of these observations are given in Evans et al. (2016).

4. OPTICAL AND NEAR-IR OBSERVATIONS

The optical and near-infrared observations fell into roughly two stages. During the first week, wide FOV (1–10 deg²) telescopes tiled large areas to identify transient candidates, and then larger but narrower FOV telescopes obtained classification spectroscopy and further photometry. The wide FOV instruments included DECam on the CTIO Blanco telescope (Flaugher et al. 2015; Dark Energy Survey Collaboration et al. 2016), the Kiso Wide Field Camera (KWFC, J-GEM; Sako et al. 2012), La Silla QUEST (Baltay et al. 2007), the Global MASTER Robotic Net (Lipunov et al. 2010), the Palomar 48 inch Oschin telescope (P48) as part of the intermediate Palomar Transient Factory (iPTF; Law et al. 2009), Pan-STARRS1 (Kaiser et al. 2010), SkyMapper (Keller et al. 2007), TAROT-La Silla (Boër et al. 1999, node of the TAROT-Zadko-Algerian National Observatory–C2PU Collaboration), and the VLT Survey Telescope (VST@ESO; Capaccioli & Schipani 2011, GRAvitational Wave Inaf TeAm, E. Brocato et al. 2016, in preparation)³⁸⁴ in the optical band, and the Visible and Infrared Survey Telescope (VISTA@ESO; Emerson et al. 2006)³⁸⁵ in the near-infrared. They represent different classes of instruments ranging in diameter from 0.25 to 4 m and reaching apparent magnitudes from 18 to 22.5. About one-third of these facilities followed a galaxy-targeted observational strategy, while the others tiled portions of the GW sky maps covering 70–590 deg². A narrow (arcminute) FOV facility, the 1.5 m EABA telescope in Bosque Alegre operated by the TOROS Collaboration (M. Diaz et al. 2016, in preparation), also participated in the optical coverage of the GW sky maps. *Swift* UVOT observed simultaneously with XRT, giving a broadband coverage of 80% of the *Swift* XRT FOV.

A few tens of transient candidates identified by the wide-field telescopes were followed up on the 10 m Keck II telescope (using the DEIMOS instrument; Faber et al. 2003), the 2 m Liverpool Telescope (LT; Steele et al. 2004), the Palomar 200 inch Hale telescope (P200; Bracher 1998), the 3.6 m ESO New Technology Telescope (within the Public ESO Spectroscopic Survey of Transient Objects, PESSTO; Smartt et al. 2015), and the University of Hawaii 2.2 m telescope (SuperNovae Integral Field Spectrograph, SNIFS). The follow-up observations of the candidate counterparts are summarized in Table 3 of the main paper.

An archival search for bright optical transients was conducted in the CASANDRA-3 all-sky camera database of BOOTES-3 (Castro-Tirado et al. 2012) and the all-sky survey of the Pi of the Sky telescope (Mankiewicz et al. 2014), both covering the entire southern sky map. The BOOTES-3 images

³⁸⁴ ESO proposal ID:095.D-0195,095.D-0079.

³⁸⁵ ESO proposal ID:095.D-0771.

are the only observations simultaneous to GW150914 available to search for prompt/early optical emission. They reached a limiting magnitude of 5 due to poor weather conditions (GCN 19022). The Pi of the Sky telescope images were taken 12 days after GW150914 and searched for transients brighter than $R < 11.5$ mag (GCN 19034).

5. RADIO OBSERVATIONS

The radio telescopes involved in the EM follow-up program have the capability to observe a wide range of frequencies with different levels of sensitivity, and a range of FOVs covering both the northern and southern skies (Tables 2 and 3 of the main paper). The Low Frequency Array (LOFAR; van Haarlem et al. 2013) and the Murchison Wide-field Array (MWA; Tingay et al. 2013) are phased array dipole antennas sensitive to meter wavelengths with large FOVs (≈ 50 deg² with uniform sensitivity for the LOFAR observations carried out as part of this follow-up program; and up to 1200 deg² for MWA). The Australian Square Kilometer Array Pathfinder (ASKAP; Schinckel et al. 2012) is an interferometric array composed of 36 12 m diameter dish antennas. The Karl G. Jansky Very Large Array (VLA; Perley et al. 2009) is a 27 antenna array, with dishes of 25 m diameter. Both ASKAP and VLA are sensitive from centimeter to decimeter wavelengths.

MWA started observing 3 days after the GW trigger with a 30 MHz bandwidth around a central frequency of 118 MHz and reached an rms noise level of about 40 mJy beam⁻¹ in a synthesized beam of about 3'. The ASKAP observations used the five-element Boolardy Engineering Test Array (BETA; Hotan et al. 2014), which has an FOV of ≈ 25 deg² and FWHM synthesized beam of 1'–3'. These observations were performed with a 300 MHz bandwidth around a central frequency of 863.5 MHz, from ≈ 7 to ≈ 14 days after the GW trigger, reaching rms sensitivities of 1–3 mJy beam⁻¹. LOFAR conducted three observations from ≈ 7 days to ≈ 3 months following the GW trigger, reaching a rms sensitivity of ≈ 2.5 mJy beam⁻¹ at 145 MHz, with a bandwidth of 11.9 MHz and a spatial resolution of $\approx 50''$. ASKAP, LOFAR, and MWA all performed tiled observations aimed at covering a large area of the GW region.

The VLA performed follow-up observations of GW150914 from ≈ 1 to ≈ 4 months after the GW trigger,³⁸⁶ and targeted selected candidate optical counterparts detected by IPTF. VLA observations were carried out in the most compact array configuration (D configuration) at a central frequency of ≈ 6 GHz (primary beam FWHP of $\approx 9'$, and synthesized beam FWHP of $\approx 12''$). The rms sensitivity of these VLA observations was ≈ 8 – 10 μ Jy beam⁻¹.

The authors gratefully acknowledge the support of the United States National Science Foundation (NSF) for the construction and operation of the LIGO Laboratory and Advanced LIGO as well as the Science and Technology Facilities Council (STFC) of the United Kingdom, the Max-Planck Society (MPS), and the State of Niedersachsen/Germany for support of the construction of Advanced LIGO and construction and operation of the GEO 600 detector. Additional support for Advanced LIGO was provided by the Australian Research Council. The authors gratefully acknowledge the Italian Istituto Nazionale di Fisica Nucleare (INFN),

the French Centre National de la Recherche Scientifique (CNRS), and the Foundation for Fundamental Research on Matter supported by the Netherlands Organisation for Scientific Research, for the construction and operation of the Virgo detector, and the creation and support of the EGO consortium. The authors also gratefully acknowledge research support from these agencies as well as by the Council of Scientific and Industrial Research of India, Department of Science and Technology, India, Science & Engineering Research Board (SERB), India, Ministry of Human Resource Development, India, the Spanish Ministerio de Economía y Competitividad, the Conselleria d'Economia i Competitivitat and Conselleria d'Educació Cultural i Universitats of the Govern de les Illes Balears, the National Science Centre of Poland, the European Commission, the Royal Society, the Scottish Funding Council, the Scottish Universities Physics Alliance, the Hungarian Scientific Research Fund (OTKA), the Lyon Institute of Origins (LIO), the National Research Foundation of Korea, Industry Canada and the Province of Ontario through the Ministry of Economic Development and Innovation, the National Science and Engineering Research Council Canada, Canadian Institute for Advanced Research, the Brazilian Ministry of Science, Technology, and Innovation, Russian Foundation for Basic Research, the Leverhulme Trust, the Research Corporation, Ministry of Science and Technology (MOST), Taiwan, and the Kavli Foundation. The authors gratefully acknowledge the support of the NSF, STFC, MPS, INFN, CNRS, and the State of Niedersachsen/Germany for provision of computational resources.

The Australian SKA Pathfinder is part of the Australia Telescope National Facility which is managed by CSIRO. The operation of ASKAP is funded by the Australian Government with support from the National Collaborative Research Infrastructure Strategy. Establishment of the Murchison Radio-astronomy Observatory was funded by the Australian Government and the Government of Western Australia. ASKAP uses advanced supercomputing resources at the Pawsey Supercomputing Centre. We acknowledge the Wajarri Yamatji people as the traditional owners of the Observatory site.

A.J.C.T. acknowledges support from the Junta de Andalucía (Project P07-TIC-03094) and Univ. of Auckland and NIWA for installing of the Spanish BOOTES-3 station in New Zealand, and support from the Spanish Ministry Projects AYA2012-39727-C03-01 and 2015-71718R.

Funding for the DES Projects has been provided by the United States Department of Energy, the United States National Science Foundation, the Ministry of Science and Education of Spain, the Science and Technology Facilities Council of the United Kingdom, the Higher Education Funding Council for England, the National Center for Supercomputing Applications at the University of Illinois at Urbana-Champaign, the Kavli Institute of Cosmological Physics at the University of Chicago, the Center for Cosmology and Astro-Particle Physics at the Ohio State University, the Mitchell Institute for Fundamental Physics and Astronomy at Texas A&M University, Financiadora de Estudos e Projetos, Fundação Carlos Chagas Filho de Amparo à Pesquisa do Estado do Rio de Janeiro, Conselho Nacional de Desenvolvimento Científico e Tecnológico and the Ministério da Ciência, Tecnologia e Inovação, the Deutsche Forschungsgemeinschaft, and the Collaborating Institutions in the Dark Energy Survey.

³⁸⁶ VLA/15A-339, PI: A. Corsi.

The Collaborating Institutions are Argonne National Laboratory, the University of California at Santa Cruz, the University of Cambridge, Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas-Madrid, the University of Chicago, University College London, the DES-Brazil Consortium, the University of Edinburgh, the Eidgenössische Technische Hochschule (ETH) Zürich, Fermi National Accelerator Laboratory, the University of Illinois at Urbana-Champaign, the Institut de Ciències de l'Espai (IEEC/CSIC), the Institut de Física d'Altes Energies, Lawrence Berkeley National Laboratory, the Ludwig-Maximilians Universität München and the associated Excellence Cluster universe, the University of Michigan, the National Optical Astronomy Observatory, the University of Nottingham, The Ohio State University, the University of Pennsylvania, the University of Portsmouth, SLAC National Accelerator Laboratory, Stanford University, the University of Sussex, and Texas A&M University.

The DES data management system is supported by the National Science Foundation under Grant Number AST-1138766. The DES participants from Spanish institutions are partially supported by MINECO under grants AYA2012-39559, ESP2013-48274, FPA2013-47986, and Centro de Excelencia Severo Ochoa SEV-2012-0234. Research leading to these results has received funding from the European Research Council under the European Union's Seventh Framework Programme (FP7/2007-2013) including ERC grant agreements 240672, 291329, and 306478.

The *Fermi* LAT Collaboration acknowledges support for LAT development, operation, and data analysis from NASA and DOE (United States), CEA/Irfu and IN2P3/CNRS (France), ASI and INFN (Italy), MEXT, KEK, and JAXA (Japan), and the K.A. Wallenberg Foundation, the Swedish Research Council and the National Space Board (Sweden). Science analysis support in the operations phase from INAF (Italy) and CNES (France) is also gratefully acknowledged. The *Fermi* GBM Collaboration acknowledges the support of NASA in the United States and DRL in Germany.

GRAWITA acknowledges the support of INAF for the project "Gravitational Wave Astronomy with the first detections of adLIGO and adVIRGO experiments."

This work exploited data by *INTEGRAL*, an ESA project with instruments and science data center funded by ESA member states (especially the PI countries: Denmark, France, Germany, Italy, Switzerland, Spain), and with the participation of Russia and the USA. The SPI ACS detector system has been provided by MPE Garching/Germany. We acknowledge the German *INTEGRAL* support through DLR grant 50 OG 1101.

IPN work is supported in the US under NASA Grant NNX15AU74G.

This work is partly based on observations obtained with the Samuel Oschin 48 in Telescope and the 60 in Telescope at the Palomar Observatory as part of the Intermediate Palomar Transient Factory (iPTF) project, a scientific collaboration among the California Institute of Technology, Los Alamos National Laboratory, the University of Wisconsin, Milwaukee, the Oskar Klein Center, the Weizmann Institute of Science, the TANGO Program of the University System of Taiwan, and the Kavli Institute for the Physics and Mathematics of the universe. M.M.K. and Y.C. acknowledge funding from the National Science Foundation PIRE program grant 1545949. A.A.M. acknowledges support from the Hubble Fellowship HST-HF-

51325.01. Part of the research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA.

J-GEM is financially supported by KAKENHI Grant No. 24103003, 15H00774, and 15H00788 of MEXT Japan, 15H02069 and 15H02075 of JSPS, and the "Optical and Near-Infrared Astronomy Inter-University Cooperation Program" supported by MEXT.

The Liverpool Telescope is operated on the island of La Palma by Liverpool John Moores University in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias with financial support from the UK Science and Technology Facilities Council.

LOFAR, the Low Frequency Array designed and constructed by ASTRON, has facilities in several countries, which are owned by various parties (each with their own funding sources), and that are collectively operated by the International LOFAR Telescope (ILT) foundation under a joint scientific policy. R. Fender acknowledges support from ERC Advanced Investigator Grant 267697.

MASTER Global Robotic Net is supported in parts by Lomonosov Moscow State University Development program, Moscow Union OPTICA, Russian Science Foundation 16-12-00085, RFBR15-02-07875, National Research Foundation of South Africa.

We thank JAXA and RIKEN for providing MAXI data. The MAXI team is partially supported by KAKENHI grant Nos. 24103002, 24540239, 24740186, and 23000004 of MEXT, Japan.

This work uses the Murchison Radio-astronomy Observatory, operated by CSIRO. We acknowledge the Wajarri Yamatji people as the traditional owners of the observatory site. Support for the operation of the MWA is provided by the Australian Government Department of Industry and Science and Department of Education (National Collaborative Research Infrastructure Strategy: NCRIS), under a contract to Curtin University administered by Astronomy Australia Limited. The MWA acknowledges the iVEC Petabyte Data Store and the Initiative in Innovative Computing and the CUDA Center for Excellence sponsored by NVIDIA at Harvard University.

Pan-STARRS is supported by the University of Hawaii and the National Aeronautics and Space Administration's Planetary Defense Office under grant No. NNX14AM74G. The Pan-STARRS-LIGO effort is in collaboration with the LIGO Consortium and supported by Queen's University Belfast. The Pan-STARRS1 Sky Surveys have been made possible through contributions by the Institute for Astronomy, the University of Hawaii, the Pan-STARRS Project Office, the Max Planck Society and its participating institutes, the Max Planck Institute for Astronomy, Heidelberg, and the Max Planck Institute for Extraterrestrial Physics, Garching, The Johns Hopkins University, Durham University, the University of Edinburgh, the Queen's University Belfast, the Harvard-Smithsonian Center for Astrophysics, the Las Cumbres Observatory Global Telescope Network Incorporated, the National Central University of Taiwan, the Space Telescope Science Institute, and the National Aeronautics and Space Administration under grant No. NNX08AR22G issued through the Planetary Science Division of the NASA Science Mission Directorate, the National Science Foundation grant No. AST-1238877, the University of Maryland, Eotvos Lorand University (ELTE), and the Los Alamos National Laboratory. This work is based

(in part) on observations collected at the European Organisation for Astronomical Research in the Southern Hemisphere, Chile as part of PESSTO, (the Public ESO Spectroscopic Survey for Transient Objects Survey) ESO programs 188.D-3003, 191.D-0935.

Some of the data presented herein were obtained at the Palomar Observatory, California Institute of Technology.

S.J.S. acknowledges funding from the European Research Council under the European Union's Seventh Framework Programme (FP7/2007-2013)/ERC Grant agreement No. [291222] and STFC grants ST/I001123/1 and ST/L000709/1. M.F. is supported by the European Union FP7 programme through ERC grant No. 320360. K.M. acknowledges support from the STFC through an Ernest Rutherford Fellowship.

F.O.E. acknowledges support from FONDECYT through postdoctoral grant 3140326.

Parts of this research were conducted by the Australian Research Council Centre of Excellence for All-sky Astrophysics (CAASTRO), through project No. CE110001020.

Funding for *Swift* is provided by NASA in the US, by the UK Space Agency in the UK, and by the Agenzia Spaziale Italiana (ASI) in Italy. This work made use of data supplied by the UK *Swift* Science Data Centre at the University of Leicester. We acknowledge the use of public data from the *Swift* data archive.

The TOROS Collaboration acknowledges support from Ministerio de Ciencia y Tecnología (MinCyT) and Consejo Nacional de Investigaciones Científicas y Tecnológicas (CONICET) from Argentina and grants from the USA NSF PHYS 1156600 and NSF HRD 1242090.

The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

VST and VISTA observations were performed at the European Southern Observatory, Paranal, Chile. We acknowledge ESO personnel for their assistance during the observing runs.

This is LIGO document LIGO-P1600137-v2.

Software: Astropy (Robitaille et al. 2013), HEALPix (Górski et al. 2005).

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AUTHORS

B. P. ABBOTT¹, R. ABBOTT¹, T. D. ABBOTT², M. R. ABERNATHY¹, F. ACERNESE^{3,4}, K. ACKLEY⁵, C. ADAMS⁶, T. ADAMS⁷, P. ADDESSO³, R. X. ADHIKARI¹, V. B. ADYA⁸, C. AFFELDT⁸, M. AGATHOS⁹, K. AGATSUMA⁹, N. AGGARWAL¹⁰, O. D. AGUIAR¹¹, L. AIELLO^{12,13}, A. AIN¹⁴, P. AJITH¹⁵, B. ALLEN^{8,16,17}, A. ALLOCCA^{18,19}, P. A. ALTIN²⁰, S. B. ANDERSON¹, W. G. ANDERSON¹⁶, K. ARAI¹, M. C. ARAYA¹, C. C. ARCENEUX²¹, J. S. AREEDA²², N. ARNAUD²³, K. G. ARUN²⁴, S. ASCENZI^{13,25}, G. ASHTON²⁶, M. AST²⁷, S. M. ASTON⁶, P. ASTONE²⁸, P. AUFMUTH⁸, C. AULBERT⁸, S. BABAK²⁹, P. BACON³⁰, M. K. M. BADER⁹, P. T. BAKER³¹, F. BALDACCINI^{32,33}, G. BALLARDIN³⁴, S. W. BALLMER³⁵, J. C. BARAYOGA¹, S. E. BARCLAY³⁶, B. C. BARISH¹, D. BARKER³⁷, F. BARONE^{3,4}, B. BARR³⁶, L. BARSOTTI¹⁰, M. BARSUGLIA³⁰, D. BARTA³⁸, S. BARTHELMY³⁹, J. BARTLETT³⁷, I. BARTOS⁴⁰, R. BASSIRI⁴¹, A. BASTI^{18,19}, J. C. BATCH³⁷, C. BAUNE⁸, V. BAVIGADDA³⁴, M. BAZZAN^{42,43}, B. BEHNKE²⁹, M. BEJGER⁴⁴, A. S. BELL³⁶, C. J. BELL³⁶, B. K. BERGER¹, J. BERGMAN³⁷, G. BERGMANN⁸, C. P. L. BERRY⁴⁵, D. BERSANETTI^{46,47}, A. BERTOLINI⁹, J. BETZWIESER⁶, S. BHAGWAT³⁵, R. BHANDARE⁴⁸, I. A. BILENKO⁴⁹, G. BILLINGSLEY¹, J. BIRCH⁶, R. BIRNEY⁵⁰, S. BISCANS¹⁰, A. BISHT^{8,17}, M. BITOSSI³⁴, C. BIWER³⁵, M. A. BIZOUARD²³, J. K. BLACKBURN¹, C. D. BLAIR⁵¹, D. G. BLAIR⁵¹, R. M. BLAIR³⁷,

S. BLOEMEN⁵², O. BOCK⁸, T. P. BODIYA¹⁰, M. BOER⁵³, G. BOGAERT⁵³, C. BOGAN⁸, A. BOHE²⁹, P. BOJTOŠ⁵⁴, C. BOND⁴⁵,
 F. BONDU⁵⁵, R. BONNAND⁷, B. A. BOOM⁹, R. BORK¹, V. BOSCHI^{18,19}, S. BOSE^{14,56}, Y. BOUFFANAIS³⁰, A. BOZZI³⁴,
 C. BRADASCHIA¹⁹, P. R. BRADY¹⁶, V. B. BRAGINSKY⁴⁹, M. BRANCHESI^{57,58}, J. E. BRAU⁵⁹, T. BRIANT⁶⁰, A. BRILLET⁵³,
 M. BRINKMANN⁸, V. BRISSON²³, P. BROCKILL¹⁶, A. F. BROOKS¹, D. A. BROWN³⁵, D. D. BROWN⁴⁵, N. M. BROWN¹⁰,
 C. C. BUCHANAN², A. BUIKEMA¹⁰, T. BULIK⁶¹, H. J. BULTEN^{9,62}, A. BUONANNO^{29,63}, D. BUSKULIC⁷, C. BUY³⁰, R. L. BYER⁴¹,
 L. CADONATI⁶⁴, G. CAGNOLI^{65,66}, C. CAHILLANE¹, J. C. BUSTILLO^{64,67}, T. CALLISTER¹, E. CALLONI^{4,68}, J. B. CAMP³⁹,
 K. C. CANNON⁶⁹, J. CAO⁷⁰, C. D. CAPANO⁸, E. CAPOCASA³⁰, F. CARBOGNANI³⁴, S. CARIDE⁷¹, J. C. DIAZ²³, C. CASENTINI^{13,25},
 S. CAUDILL¹⁶, M. CAVAGLIÀ²¹, F. CAVALIER²³, R. CAVALIERI³⁴, G. CELLA¹⁹, C. B. CEPEDA¹, L. C. BAIARDI^{57,58}, G. CERRETANI^{18,19},
 E. CESARINI^{13,25}, R. CHAKRABORTY¹, T. CHALERMSONGSAK¹, S. J. CHAMBERLIN⁷², M. CHAN³⁶, S. CHAO⁷³, P. CHARLTON⁷⁴,
 E. CHASSANDE-MOTTIN³⁰, H. Y. CHEN⁷⁵, Y. CHEN⁷⁶, C. CHENG⁷³, A. CHINCARINI⁴⁷, A. CHIUMMO³⁴, H. S. CHO⁷⁷, M. CHO⁶³,
 J. H. CHOW²⁰, N. CHRISTENSEN⁷⁸, Q. CHU⁵¹, S. CHUA⁶⁰, S. CHUNG⁵¹, G. CIANI⁵, F. CLARA³⁷, J. A. CLARK⁶⁴, F. CLEVA⁵³,
 E. COCCIA^{12,13,25}, P.-F. COHADON⁶⁰, A. COLLA^{28,79}, C. G. COLLETTE⁸⁰, L. COMINSKY⁸¹, M. CONSTANCIO, JR.¹¹, A. CONTE^{28,79},
 L. CONTI⁴³, D. COOK³⁷, T. R. CORBITT², N. CORNISH³¹, A. CORSI⁷¹, S. CORTESE³⁴, C. A. COSTA¹¹, M. W. COUGHLIN⁷⁸,
 S. B. COUGHLIN⁸², J.-P. COULON⁵³, S. T. COUNTRYMAN⁴⁰, P. COUVARES¹, E. E. COWAN⁶⁴, D. M. COWARD⁵¹, M. J. COWART⁶,
 D. C. COYNE¹, R. COYNE⁷¹, K. CRAIG³⁶, J. D. E. CREIGHTON¹⁶, J. CRIPE², S. G. CROWDER⁸³, A. CUMMING³⁶, L. CUNNINGHAM³⁶,
 E. CUOCO³⁴, T. DAL CANTON⁸, S. L. DANILISHIN³⁶, S. D'ANTONIO¹³, K. DANZMANN^{8,17}, N. S. DARMAN⁸⁴, V. DATTILO³⁴,
 I. DAVE⁴⁸, H. P. DAVELOZA⁸⁵, M. DAVIER²³, G. S. DAVIES³⁶, E. J. DAW⁸⁶, R. DAY³⁴, D. DEBRA⁴¹, G. DEBRECZENI³⁸,
 J. DEGALLAIX⁶⁶, M. DE LAURENTIS^{4,68}, S. DELÉGLISE⁶⁰, W. DEL POZZO⁴⁵, T. DENKER^{8,17}, T. DENT⁸, H. DERELI⁵³, V. DERGACHEV¹,
 R. T. DEROSA⁶, R. DE ROSA^{4,68}, R. DESALVO⁸⁷, S. DHURANDHAR¹⁴, M. C. DÍAZ⁸⁵, L. DI FIORE⁴, M. DI GIOVANNI^{28,79},
 A. DI LIETO^{18,19}, S. DI PACE^{28,79}, I. DI PALMA^{8,29}, A. DI VIRGILIO¹⁹, G. DOJCINOSKI⁸⁸, V. DOLIQUE⁶⁶, F. DONOVAN¹⁰,
 K. L. DOOLEY²¹, S. DORAVARI^{6,8}, R. DOUGLAS³⁶, T. P. DOWNES¹⁶, M. DRAGO^{8,89,90}, R. W. P. DREVER¹, J. C. DRIGGERS³⁷, Z. DU⁷⁰,
 M. DUCROT⁷, S. E. DWYER³⁷, T. B. EDO⁸⁶, M. C. EDWARDS⁷⁸, A. EFFLER⁶, H.-B. EGGENSTEIN⁸, P. EHRENS¹, J. EICHHOLZ⁵,
 S. S. EIKENBERRY⁵, W. ENGELS⁷⁶, R. C. ESSICK¹⁰, T. ETZEL¹, M. EVANS¹⁰, T. M. EVANS⁶, R. EVERETT⁷², M. FACTOUROVICH⁴⁰,
 V. FAFONE^{12,13,25}, H. FAIR³⁵, S. FAIRHURST⁹¹, X. FAN⁷⁰, Q. FANG⁵¹, S. FARINON⁴⁷, B. FARR⁷⁵, W. M. FARR⁴⁵, M. FAVATA⁸⁸,
 M. FAYS⁹¹, H. FEHRMANN⁸, M. M. FEJER⁴¹, I. FERRANTE^{18,19}, E. C. FERREIRA¹¹, F. FERRINI³⁴, F. FIDECARO^{18,19}, I. FIORI³⁴,
 D. FIORUCCI³⁰, R. P. FISHER³⁵, R. FLAMINIO^{66,92}, M. FLETCHER³⁶, J.-D. FOURNIER⁵³, S. FRANCO²³, S. FRASCA^{28,79}, F. FRASCONI¹⁹,
 Z. FREI⁵⁴, A. FREISE⁴⁵, R. FREY⁵⁹, V. FREY²³, T. T. FRICKE⁸, P. FRITSCHEL¹⁰, V. V. FROLOV⁶, P. FULDA⁵, M. FYFFE⁶,
 H. A. G. GABBARD²¹, J. R. GAIR⁹³, L. GAMMAITONI^{32,33}, S. G. GAONKAR¹⁴, F. GARUFI^{4,68}, A. GATTO³⁰, G. GAUR^{94,95},
 N. GEHRELS³⁹, G. GEMME⁴⁷, B. GENDRE⁵³, E. GENIN³⁴, A. GENNAI¹⁹, J. GEORGE⁴⁸, L. GERGELY⁹⁶, V. GERMAIN⁷, A. GHOSH¹⁵,
 S. GHOSH^{9,52}, J. A. GIAIME^{2,6}, K. D. GIARDINA⁶, A. GIAZOTTO¹⁹, K. GILL⁹⁷, A. GLAEFKE³⁶, E. GOETZ⁹⁸, R. GOETZ⁵, L. GONDAN⁵⁴,
 G. GONZÁLEZ², J. M. G. CASTRO^{18,19}, A. GOPAKUMAR⁹⁹, N. A. GORDON³⁶, M. L. GORODETSKY⁴⁹, S. E. GOSSAN¹, M. GOSSELIN³⁴,
 R. GOUATY⁷, C. GRAEF³⁶, P. B. GRAFF⁶³, M. GRANATA⁶⁶, A. GRANT³⁶, S. GRAS¹⁰, C. GRAY³⁷, G. GRECO^{57,58}, A. C. GREEN⁴⁵,
 P. GROOT⁵², H. GROTE⁸, S. GRUNEWALD²⁹, G. M. GUIDI^{57,58}, X. GUO⁷⁰, A. GUPTA¹⁴, M. K. GUPTA⁹⁵, K. E. GUSHWA¹,
 E. K. GUSTAFSON¹, R. GUSTAFSON⁹⁸, J. J. HACKER²², B. R. HALL⁵⁶, E. D. HALL¹, G. HAMMOND³⁶, M. HANEY⁹⁹, M. M. HANKE⁸,
 J. HANKS³⁷, C. HANNA⁷², M. D. HANNAM⁹¹, J. HANSON⁶, T. HARDWICK², K. HARIS¹⁰⁶, J. HARMS^{57,58}, G. M. HARRY¹⁰⁰,
 I. W. HARRY²⁹, M. J. HART³⁶, M. T. HARTMAN⁵, C.-J. HASTER⁴⁵, K. HAUGHIAN³⁶, A. HEIDMANN⁶⁰, M. C. HEINTZE^{5,6},
 H. HEITMANN⁵³, P. HELLO²³, G. HEMMING³⁴, M. HENDRY³⁶, I. S. HENG³⁶, J. HENNIG³⁶, A. W. HEPTONSTALL¹, M. HEURS^{8,17},
 S. HILD³⁶, D. HOAK¹⁰¹, K. A. HODGE¹, D. HOFMAN⁶⁶, S. E. HOLLITT¹⁰², K. HOLT⁶, D. E. HOLZ⁷⁵, P. HOPKINS⁹¹, D. J. HOSKEN¹⁰²,
 J. HOUGH³⁶, E. A. HOUSTON³⁶, E. J. HOWELL⁵¹, Y. M. HU³⁶, S. HUANG⁷³, E. A. HUERTA^{82,103}, D. HUET²³, B. HUGHEY⁹⁷,
 S. HUSA⁶⁷, S. H. HUTTNER³⁶, T. HUYNH-DINH⁶, A. IDRISY⁷², N. INDIK⁸, D. R. INGRAM³⁷, R. INTA⁷¹, H. N. ISA³⁶, J.-M. ISAC⁶⁰,
 M. ISI¹, G. ISLAS²², T. ISOGAI¹⁰, B. R. IYER¹⁵, K. IZUMI³⁷, T. JACQMIN⁶⁰, H. JANG⁷⁷, K. JANI⁶⁴, P. JARANOWSKI¹⁰⁴, S. JAWAHAR¹⁰⁵,
 F. JIMÉNEZ-FORTEZA⁶⁷, W. W. JOHNSON², D. I. JONES²⁶, R. JONES³⁶, R. J. G. JONKER⁹, L. JU⁵¹, C. V. KALAGHATGI^{24,91},
 V. KALOGERA⁸², S. KANDHASAMY²¹, G. KANG⁷⁷, J. B. KANNER¹, S. KARKI⁵⁹, M. KASPRZACK^{2,23,34}, E. KATSAVOUNIDIS¹⁰,
 W. KATZMAN⁶, S. KAUFER¹⁷, T. KAUR⁵¹, K. KAWABE³⁷, F. KAWAZOE^{8,17}, F. KÉFÉLIAN⁵³, M. S. KEHL⁶⁹, D. KEITEL^{8,67},
 D. B. KELLEY³⁵, W. KELLS¹, R. KENNEDY⁸⁶, J. S. KEY⁸⁵, A. KHALAIDOVSKI⁸, F. Y. KHALILI⁴⁹, I. KHAN¹², S. KHAN⁹¹, Z. KHAN⁹⁵,
 E. A. KHAZANOV¹⁰⁷, N. KIJBUNCHOO³⁷, C. KIM⁷⁷, J. KIM¹⁰⁸, K. KIM¹⁰⁹, N. KIM⁷⁷, N. KIM⁴¹, Y.-M. KIM¹⁰⁸, E. J. KING¹⁰²,
 P. J. KING³⁷, D. L. KINZEL⁶, J. S. KISSEL³⁷, L. KLEYBOLTE²⁷, S. KLIMENKO⁵, S. M. KOEHLLENBECK⁸, K. KOKEYAMA², S. KOLEY⁹,
 V. KONDRASHOV¹, A. KONTOS¹⁰, M. KOROBKO²⁷, W. Z. KORTH¹, I. KOWALSKA⁶¹, D. B. KOZAK¹, V. KRINGEL⁸, A. KRÓLAK^{110,111},
 C. KRUEGER¹⁷, G. KUEHN⁸, P. KUMAR⁶⁹, L. KUO⁷³, A. KUTYNIA¹¹⁰, B. D. LACKEY³⁵, M. LANDRY³⁷, J. LANGE¹¹², B. LANTZ⁴¹,
 P. D. LASKY¹¹³, A. LAZZARINI¹, C. LAZZARO^{43,64}, P. LEACI^{28,29,79}, S. LEAVEY³⁶, E. O. LEBIGOT^{30,70}, C. H. LEE¹⁰⁸, H. K. LEE¹⁰⁹,
 H. M. LEE¹¹⁴, K. LEE³⁶, A. LENON³⁵, M. LEONARDI^{89,90}, J. R. LEONG⁸, N. LEROY²³, N. LETENDRE⁷, Y. LEVIN¹¹³, B. M. LEVINE³⁷,
 T. G. F. LI¹, A. LIBSON¹⁰, T. B. LITTENBERG¹¹⁵, N. A. LOCKERBIE¹⁰⁵, J. LOGUE³⁶, A. L. LOMBARDI¹⁰¹, J. E. LORD³⁵,
 M. LORENZINI^{12,13}, V. LORIETTE¹¹⁶, M. LORMAND⁶, G. LOSURDO⁵⁸, J. D. LOUGH^{8,17}, H. LÜCK^{8,17}, A. P. LUNDGREN⁸, J. LUO⁷⁸,
 R. LYNCH¹⁰, Y. MA⁵¹, T. MACDONALD⁴¹, B. MACHENSCHALK⁸, M. MACINNIS¹⁰, D. M. MACLEOD², F. MAGAÑA-SANDOVAL³⁵,
 R. M. MAGEE⁵⁶, M. MAGESWARAN¹, E. MAJORANA²⁸, I. MAKSIMOVIC¹¹⁶, V. MALVEZZI^{13,25}, N. MAN⁵³, I. MANDEL⁴⁵, V. MANDIC⁸³,
 V. MANGANO³⁶, G. L. MANSSELL²⁰, M. MANSKE¹⁶, M. MANTOVANI³⁴, F. MARCHESONI^{33,117}, F. MARION⁷, S. MÁRKA⁴⁰, Z. MÁRKA⁴⁰,
 A. S. MARKOSYAN⁴¹, E. MAROS¹, F. MARTELLI^{57,58}, L. MARTELLINI⁵³, I. W. MARTIN³⁶, R. M. MARTIN⁵, D. V. MARTYNOV¹,

J. N. MARX¹, K. MASON¹⁰, A. MASSEROT⁷, T. J. MASSINGER³⁵, M. MASSO-REID³⁶, F. MATICHARD¹⁰, L. MATONE⁴⁰,
 N. MAVALVALA¹⁰, N. MAZUMDER⁵⁶, G. MAZZOLO⁸, R. MCCARTHY³⁷, D. E. MCCLELLAND²⁰, S. MCCORMICK⁶, S. C. MCGUIRE¹¹⁸,
 G. MCINTYRE¹, J. MCIVER¹, D. J. MCMANUS²⁰, S. T. MCWILLIAMS¹⁰³, D. MEACHER⁷², G. D. MEADORS^{8,29}, J. MEIDAM⁹,
 A. MELATOS⁸⁴, G. MENDELL³⁷, D. MENDOZA-GANDARA⁸, R. A. MERCER¹⁶, E. MERILH³⁷, M. MERZOUGUI⁵³, S. MESHKOV¹,
 C. MESSENGER³⁶, C. MESSICK⁷², P. M. MEYERS⁸³, F. MEZZANI^{28,79}, H. MIAO⁴⁵, C. MICHEL⁶⁶, H. MIDDLETON⁴⁵,
 E. E. MIKHAILOV¹¹⁹, L. MILANO^{4,68}, J. MILLER¹⁰, M. MILLHOUSE³¹, Y. MINENKOV¹³, J. MING^{8,29}, S. MIRSHEKARI¹²⁰, C. MISHRA¹⁵,
 S. MITRA¹⁴, V. P. MITROFANOV⁴⁹, G. MITSELMAKHER⁵, R. MITTMAN¹⁰, A. MOGGI¹⁹, M. MOHAN³⁴, S. R. P. MOHAPATRA¹⁰,
 M. MONTANI^{57,58}, B. C. MOORE⁸⁸, C. J. MOORE¹²¹, D. MORARU³⁷, G. MORENO³⁷, S. R. MORRIS⁸⁵, K. MOSSAVI⁸, B. MOURS⁷,
 C. M. MOW-LOWRY⁴⁵, C. L. MUELLER⁵, G. MUELLER⁵, A. W. MUIR⁹¹, A. MUKHERJEE¹⁵, D. MUKHERJEE¹⁶, S. MUKHERJEE⁸⁵,
 N. MUKUND¹⁴, A. MULLAVEY⁶, J. MUNCH¹⁰², D. J. MURPHY⁴⁰, P. G. MURRAY³⁶, A. MYTIDIS⁵, I. NARDECCHIA^{13,25},
 L. NATICCHIONI^{28,79}, R. K. NAYAK¹²², V. NECULA⁵, K. NEDKOVA¹⁰¹, G. NELEMANS^{9,52}, M. NERI^{46,47}, A. NEUNZERT⁹⁸,
 G. NEWTON³⁶, T. T. NGUYEN²⁰, A. B. NIELSEN⁸, S. NISSANKE^{9,52}, A. NITZ⁸, F. NOCERA³⁴, D. NOLTING⁶, M. E. N. NORMANDIN⁸⁵,
 L. K. NUTTALL³⁵, J. OBERLING³⁷, E. OCHSNER¹⁶, J. O'DELL¹²³, E. OELKER¹⁰, G. H. OGIN¹²⁴, J. J. OH¹²⁵, S. H. OH¹²⁵, F. OHME⁹¹,
 M. OLIVER⁶⁷, P. OPPERMANN⁸, R. J. ORAM⁶, B. O'REILLY⁶, R. O'SHAUGHNESSY¹¹², D. J. OTTAWAY¹⁰², R. S. OTTENS⁵,
 H. OVERMIER⁶, B. J. OWEN⁷¹, A. PAI¹⁰⁶, S. A. PAI⁴⁸, J. R. PALAMOS⁵⁹, O. PALASHOV¹⁰⁷, N. PALLIYAGURU⁷¹, C. PALOMBA²⁸,
 A. PAL-SINGH²⁷, H. PAN⁷³, C. PANKOW⁸², F. PANNARALE⁹¹, B. C. PANT⁴⁸, F. PAOLETTI^{19,34}, A. PAOLI³⁴, M. A. PAPA^{8,16,29},
 H. R. PARIS⁴¹, W. PARKER⁶, D. PASCUCCI³⁶, A. PASQUALETTI³⁴, R. PASSAQUIETI^{18,19}, D. PASSUELLO¹⁹, B. PATRICELLI^{18,19},
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X. ZHANG²²⁰, D. M. SMITH²³⁰, T. CLINE^{39,380}, H. KRIMM^{245,310}
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- F. ABE³¹¹, M. DOI³¹², K. FUJISAWA³¹³, K. S. KAWABATA³¹⁴, T. MOROKUMA³¹², K. MOTOHARA³¹², M. TANAKA³¹⁵, K. OHTA³¹⁶,
K. YANAGISAWA³¹⁷, M. YOSHIDA³¹⁴
(THE J-GEM COLLABORATION),
- C. BALTAY³¹⁸, D. RABINOWITZ³¹⁸, N. ELLMAN³¹⁸, S. ROSTAMI³¹⁸
(THE LA SILLA-QUEST SURVEY),
- D. F. BERSIER³¹⁹, M. F. BODE³¹⁹, C. A. COLLINS³¹⁹, C. M. COPPERWHEAT³¹⁹, M. J. DARNLEY³¹⁹, D. K. GALLOWAY^{320,321},
A. GOMBOC^{322,323}, S. KOBAYASHI³¹⁹, P. MAZZALI³¹⁹, C. G. MUNDELL³²⁴, A. S. PIASCIK³¹⁹, DON POLLACCO³²⁵, I. A. STEELE³¹⁹,
K. ULACZYK³²⁵
(THE LIVERPOOL TELESCOPE COLLABORATION),
- J. W. BRODERICK³²⁶, R. P. FENDER³²⁷, P. G. JONKER^{52,328}, A. ROWLINSON^{135,326,329}, B. W. STAPPERS²¹¹, R. A. M. J. WIJERS³²⁹
(THE LOW FREQUENCY ARRAY (LOFAR) COLLABORATION),
- V. LIPUNOV³³⁰, E. GORBOVSKOY³³⁰, N. TYURINA³³⁰, V. KORNILOV³³⁰, P. BALANUTSA³³⁰, A. KUZNETSOV³³⁰, D. BUCKLEY³³¹,
R. REBOLO³³², M. SERRA-RICART³³², G. ISRAELIAN³³², N. M. BUDNEV³³³, O. GRESS³³³, K. IVANOV³³³, V. POLESHUK³³³,
A. TLATOV³³⁴, V. YURKOV³³⁵
(THE MASTER COLLABORATION),
- N. KAWAI³³⁶, M. SERINO³³⁷, H. NEGORO³³⁸, S. NAKAHIRA³³⁹, T. MIHARA³³⁷, H. TOMIDA³⁴⁰, S. UENO³⁴⁰, H. TSUNEMI³⁴¹,
M. MATSUOKA³³⁷
(THE MAXI COLLABORATION),
- S. CROFT^{342,343}, L. FENG³⁴⁴, T. M. O. FRANZEN³⁴⁵, B. M. GAENSLER^{135,139,346}, M. JOHNSTON-HOLLITT³⁴⁷, D. L. KAPLAN¹⁶,
M. F. MORALES¹³¹, S. J. TINGAY^{135,345,348}, R. B. WAYTH^{135,345}, A. WILLIAMS³⁴⁵
(THE MURCHISON WIDE-FIELD ARRAY (MWA) COLLABORATION),
- S. J. SMARTT³⁴⁹, K. C. CHAMBERS³⁵⁰, K. W. SMITH³⁴⁹, M. E. HUBER³⁵⁰, D. R. YOUNG³⁴⁹, D. E. WRIGHT³⁴⁹, A. SCHULTZ³⁵⁰,
L. DENNEAU³⁵⁰, H. FLEWELLING³⁵⁰, E. A. MAGNIER³⁵⁰, N. PRIMAK³⁵⁰, A. REST³⁵¹, A. SHERSTYUK³⁵⁰, B. STALDER³⁵⁰,
C. W. STUBBS³⁵², J. TONRY³⁵⁰, C. WATERS³⁵⁰, M. WILLMAN³⁵⁰
(THE PAN-STARRS COLLABORATION),
- F. OLIVARES E.^{353,354}, H. CAMPBELL³⁵⁵, R. KOTAK³⁴⁹, J. SOLLERMAN³⁰⁶, M. SMITH²⁶, M. DENNEFELD³⁵⁶, J. P. ANDERSON³⁵⁷,

M. T. BOTTICELLA²⁸⁵, T.-W. CHEN²²⁰, M. D. VALLE²⁸⁵, N. ELIAS-ROSA²⁸³, M. FRASER³⁵⁵, C. INSERRA³⁴⁹, E. KANKARE³⁴⁹,
 T. KUPFER³⁰¹, J. HARMANEN³⁵⁸, L. GALBANY^{353,359}, L. LE GUILLOU^{360,361}, J. D. LYMAN³²⁵, K. MAGUIRE³⁴⁹, A. MITRA³⁶¹,
 M. NICHOLL¹⁷¹, A. RAZZA^{353,359}, G. TERRERAN^{283,349}, S. VALENTI^{362,363}, A. GAL-YAM³⁶⁴
 (THE PESSTO COLLABORATION),

A. WIEK¹¹⁰, M. WIOK³⁶⁵, L. MANKIEWICZ³⁶⁶, R. OPIELA³⁶⁶, M. ZAREMBA³⁶⁵, A. F. ARNECKI³⁶⁵
 (THE PI OF THE SKY COLLABORATION),

C. A. ONKEN^{20,135}, R. A. SCALZO^{20,135}, B. P. SCHMIDT^{20,135}, C. WOLF^{20,135}, F. YUAN^{20,135}
 (THE SKYMAPPER COLLABORATION),

P. A. EVANS³⁶⁷, J. A. KENNEA⁷², D. N. BURROWS⁷², S. CAMPANA²⁸⁴, S. B. CENKO^{39,368}, P. GIOMMI²⁸⁸, F. E. MARSHALL³⁹,
 J. NOUSEK⁷², P. O'BRIEN³⁶⁷, J. P. OSBORNE³⁶⁷, D. PALMER³⁶⁹, M. PERRI^{282,288}, M. SIEGEL⁷², G. TAGLIAFERRI²⁸⁴
 (THE SWIFT COLLABORATION),

A. KLOTZ³⁷⁰, D. TURPIN³⁷⁰, R. LAUGIER⁵³
 (THE TAROT, ZADKO, ALGERIAN NATIONAL OBSERVATORY, AND C2PU COLLABORATION),
 M. BEROIZ^{85,371}, T. PEUELA^{85,372}, L. M. MACRI³⁷³, R. J. OELKERS³⁷³, D. G. LAMBAS³⁷⁴, R. VRECH³⁷⁴, J. CABRAL³⁷⁴,
 C. COLAZO³⁷⁴, M. DOMINGUEZ³⁷⁴, B. SANCHEZ³⁷⁴, S. GUROVICH³⁷⁴, M. LARES³⁷⁴, J. L. MARSHALL³⁷³, D. L. DEPOY³⁷³,
 N. PADILLA³⁷⁵, N. A. PEREYRA⁸⁵, M. BENACQUISTA⁸⁵
 (THE TOROS COLLABORATION),

AND

N. R. TANVIR³⁶⁷, K. WIERSEMA³⁶⁷, A. J. LEVAN³²⁵, D. STEEGHS³²⁵, J. HJORTH³⁰⁵, J. P. U. FYNBO³⁰⁵, D. MALESANI³⁰⁵,
 B. MILVANG-JENSEN³⁰⁵, D. WATSON³⁰⁵, M. IRWIN³⁵⁵, C. G. FERNANDEZ³⁵⁵, R. G. MCMAHON³⁵⁵, M. BANERJI³⁵⁵,
 E. GONZALEZ-SOLARES³⁵⁵, S. SCHULZE^{353,375}, A. DE U. POSTIGO^{305,376}, C. C. THOENE³⁷⁶, Z. CANO³⁷⁷, AND S. ROSSWOG³⁰⁶
 (THE VISTA COLLABORATION)

¹ LIGO, California Institute of Technology, Pasadena, CA 91125, USA; lsc-spokesperson@ligo.org, virgo-spokesperson@ego-gw.eu

² Louisiana State University, Baton Rouge, LA 70803, USA

³ Universit di Salerno, Fisciano, I-84084 Salerno, Italy

⁴ INFN, Sezione di Napoli, Complesso Universitario di Monte S. Angelo, I-80126 Napoli, Italy

⁵ University of Florida, Gainesville, FL 32611, USA

⁶ LIGO Livingston Observatory, Livingston, LA 70754, USA

⁷ Laboratoire d'Annecy-le-Vieux de Physique des Particules (LAPP), Universit Savoie Mont Blanc, CNRS/IN2P3, F-74941 Annecy-le-Vieux, France

⁸ Albert-Einstein-Institut, Max-Planck-Institut fr Gravitationsphysik, D-30167 Hannover, Germany

⁹ Nikhef, Science Park, 1098 XG Amsterdam, The Netherlands

¹⁰ LIGO, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

¹¹ Instituto Nacional de Pesquisas Espaciais, 12227-010 So Jos dos Campos, SP, Brazil

¹² INFN, Gran Sasso Science Institute, I-67100 L'Aquila, Italy

¹³ INFN, Sezione di Roma Tor Vergata, I-00133 Roma, Italy

¹⁴ Inter-University Centre for Astronomy and Astrophysics, Pune 411007, India

¹⁵ International Centre for Theoretical Sciences, Tata Institute of Fundamental Research, Bangalore 560012, India

¹⁶ University of Wisconsin-Milwaukee, Milwaukee, WI 53201, USA

¹⁷ Leibniz Universitt Hannover, D-30167 Hannover, Germany

¹⁸ Universit di Pisa, I-56127 Pisa, Italy

¹⁹ INFN, Sezione di Pisa, I-56127 Pisa, Italy

²⁰ Australian National University, Canberra, Australian Capital Territory 0200, Australia

²¹ The University of Mississippi, University, MS 38677, USA

²² California State University Fullerton, Fullerton, CA 92831, USA

²³ LAL, Univ. Paris-Sud, CNRS/IN2P3, Universit Paris-Saclay, Orsay, France

²⁴ Chennai Mathematical Institute, Chennai, India

²⁵ Universit di Roma Tor Vergata, I-00133 Roma, Italy

²⁶ School of Physics and Astronomy, University of Southampton, Southampton, SO17 1BJ, UK

²⁷ Universitt Hamburg, D-22761 Hamburg, Germany

²⁸ INFN, Sezione di Roma, I-00185 Roma, Italy

²⁹ Albert-Einstein-Institut, Max-Planck-Institut fr Gravitationsphysik, D-14476 Potsdam-Golm, Germany

³⁰ APC, AstroParticule et Cosmologie, Universit Paris Diderot, CNRS/IN2P3, CEA/Irfu, Observatoire de Paris, Sorbonne Paris Cit,
 F-75205 Paris Cedex 13, France

³¹ Montana State University, Bozeman, MT 59717, USA

³² Universit di Perugia, I-06123 Perugia, Italy

³³ INFN, Sezione di Perugia, I-06123 Perugia, Italy

³⁴ European Gravitational Observatory (EGO), I-56021 Cascina, Pisa, Italy

³⁵ Syracuse University, Syracuse, NY 13244, USA

³⁶ SUPA, University of Glasgow, Glasgow G12 8QQ, UK

³⁷ LIGO Hanford Observatory, Richland, WA 99352, USA

³⁸ Wigner RCP, RMKI, H-1121 Budapest, Konkoly Thege Mikls t 29-33, Hungary

³⁹ NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA

⁴⁰ Columbia University, New York, NY 10027, USA

- ⁴¹ Stanford University, Stanford, CA 94305, USA
- ⁴² Università di Padova, Dipartimento di Fisica e Astronomia, I-35131 Padova, Italy
- ⁴³ INFN, Sezione di Padova, I-35131 Padova, Italy
- ⁴⁴ CAMK-PAN, 00-716 Warsaw, Poland
- ⁴⁵ University of Birmingham, Birmingham B15 2TT, UK
- ⁴⁶ Università degli Studi di Genova, I-16146 Genova, Italy
- ⁴⁷ INFN, Sezione di Genova, I-16146 Genova, Italy
- ⁴⁸ RRCAT, Indore MP 452013, India
- ⁴⁹ Faculty of Physics, Lomonosov Moscow State University, Moscow 119991, Russia
- ⁵⁰ SUPA, University of the West of Scotland, Paisley PA1 2BE, UK
- ⁵¹ University of Western Australia, Crawley, Western Australia 6009, Australia
- ⁵² Department of Astrophysics/IMAPP, Radboud University Nijmegen, P.O. Box 9010, 6500 GL Nijmegen, The Netherlands
- ⁵³ Artemis, Université Côte d'Azur, CNRS, Observatoire Côte d'Azur, CS 34229, Nice cedex 4, France
- ⁵⁴ MTA Eötvös University, "Lendulet" Astrophysics Research Group, Budapest 1117, Hungary
- ⁵⁵ Institut de Physique de Rennes, CNRS, Université de Rennes 1, F-35042 Rennes, France
- ⁵⁶ Washington State University, Pullman, WA 99164, USA
- ⁵⁷ Università degli Studi di Urbino "Carlo Bo", I-61029 Urbino, Italy
- ⁵⁸ INFN, Sezione di Firenze, I-50019 Sesto Fiorentino, Firenze, Italy
- ⁵⁹ University of Oregon, Eugene, OR 97403, USA
- ⁶⁰ Laboratoire Kastler Brossel, UPMC-Sorbonne Universités, CNRS, ENS-PSL Research University, Collège de France, F-75005 Paris, France
- ⁶¹ Astronomical Observatory Warsaw University, 00-478 Warsaw, Poland
- ⁶² VU University Amsterdam, 1081 HV Amsterdam, The Netherlands
- ⁶³ University of Maryland, College Park, MD 20742, USA
- ⁶⁴ Center for Relativistic Astrophysics and School of Physics, Georgia Institute of Technology, Atlanta, GA 30332, USA
- ⁶⁵ Institut Lumière Matière, Université de Lyon, Université Claude Bernard Lyon 1, UMR CNRS 5306, F-69622 Villeurbanne, France
- ⁶⁶ Laboratoire des Matériaux Avancés (LMA), IN2P3/CNRS, Université de Lyon, F-69622 Villeurbanne, Lyon, France
- ⁶⁷ Universitat de les Illes Balears, IAC3—IEEC, E-07122 Palma de Mallorca, Spain
- ⁶⁸ Università di Napoli 'Federico II', Complesso Universitario di Monte S. Angelo, I-80126 Napoli, Italy
- ⁶⁹ Canadian Institute for Theoretical Astrophysics, University of Toronto, Toronto, Ontario M5S 3H8, Canada
- ⁷⁰ Tsinghua University, Beijing 100084, China
- ⁷¹ Texas Tech University, Lubbock, TX 79409, USA
- ⁷² The Pennsylvania State University, University Park, PA 16802, USA
- ⁷³ National Tsing Hua University, Hsinchu City, 30013, Taiwan R.O.C.
- ⁷⁴ Charles Sturt University, Wagga Wagga, New South Wales 2678, Australia
- ⁷⁵ University of Chicago, Chicago, IL 60637, USA
- ⁷⁶ Caltech CaRT, Pasadena, CA 91125, USA
- ⁷⁷ Korea Institute of Science and Technology Information, Daejeon 305-806, Korea
- ⁷⁸ Carleton College, Northfield, MN 55057, USA
- ⁷⁹ Università di Roma "La Sapienza", I-00185 Roma, Italy
- ⁸⁰ University of Brussels, Brussels B-1050, Belgium
- ⁸¹ Sonoma State University, Rohnert Park, CA 94928, USA
- ⁸² Northwestern University, Evanston, IL 60208, USA
- ⁸³ University of Minnesota, Minneapolis, MN 55455, USA
- ⁸⁴ The University of Melbourne, Parkville, Victoria 3010, Australia
- ⁸⁵ The University of Texas Rio Grande Valley, Brownsville, TX 78520, USA
- ⁸⁶ The University of Sheffield, Sheffield S10 2TN, UK
- ⁸⁷ University of Sannio at Benevento, I-82100 Benevento, Italy and INFN, Sezione di Napoli, I-80100 Napoli, Italy
- ⁸⁸ Montclair State University, Montclair, NJ 07043, USA
- ⁸⁹ Università di Trento, Dipartimento di Fisica, I-38123 Povo, Trento, Italy
- ⁹⁰ INFN, Trento Institute for Fundamental Physics and Applications, I-38123 Povo, Trento, Italy
- ⁹¹ Cardiff University, Cardiff CF24 3AA, UK
- ⁹² National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan
- ⁹³ School of Mathematics, University of Edinburgh, Edinburgh EH9 3FD, UK
- ⁹⁴ Indian Institute of Technology, Gandhinagar, Ahmedabad, Gujarat 382424, India
- ⁹⁵ Institute for Plasma Research, Bhat, Gandhinagar 382428, India
- ⁹⁶ University of Szeged, Dóm tér 9, Szeged 6720, Hungary
- ⁹⁷ Embry-Riddle Aeronautical University, Prescott, AZ 86301, USA
- ⁹⁸ University of Michigan, Ann Arbor, MI 48109, USA
- ⁹⁹ Tata Institute of Fundamental Research, Mumbai 400005, India
- ¹⁰⁰ American University, Washington, D.C. 20016, USA
- ¹⁰¹ University of Massachusetts-Amherst, Amherst, MA 01003, USA
- ¹⁰² University of Adelaide, Adelaide, South Australia 5005, Australia
- ¹⁰³ West Virginia University, Morgantown, WV 26506, USA
- ¹⁰⁴ University of Białystok, 15-424 Białystok, Poland
- ¹⁰⁵ SUPA, University of Strathclyde, Glasgow G1 1XQ, UK
- ¹⁰⁶ IISER-TVM, CET Campus, Trivandrum Kerala 695016, India
- ¹⁰⁷ Institute of Applied Physics, Nizhny Novgorod, 603950, Russia
- ¹⁰⁸ Pusan National University, Busan 609-735, Korea
- ¹⁰⁹ Hanyang University, Seoul 133-791, Korea
- ¹¹⁰ NCBJ, 05-400 Świerk-Otwock, Poland
- ¹¹¹ IM-PAN, 00-956 Warsaw, Poland
- ¹¹² Rochester Institute of Technology, Rochester, NY 14623, USA
- ¹¹³ Monash University, Victoria 3800, Australia
- ¹¹⁴ Seoul National University, Seoul 151-742, Korea
- ¹¹⁵ University of Alabama in Huntsville, Huntsville, AL 35899, USA
- ¹¹⁶ ESPCI, CNRS, F-75005 Paris, France

- ¹¹⁷ Università di Camerino, Dipartimento di Fisica, I-62032 Camerino, Italy
- ¹¹⁸ Southern University and A&M College, Baton Rouge, LA 70813, USA
- ¹¹⁹ College of William and Mary, Williamsburg, VA 23187, USA
- ¹²⁰ Instituto de Física Teórica, University Estadual Paulista/ICTP South American Institute for Fundamental Research, São Paulo SP 01140-070, Brazil
- ¹²¹ University of Cambridge, Cambridge CB2 1TN, UK
- ¹²² IISER-Kolkata, Mohanpur, West Bengal 741252, India
- ¹²³ Rutherford Appleton Laboratory, HSIC, Chilton, Didcot, Oxon OX11 0QX, UK
- ¹²⁴ Whitman College, 345 Boyer Ave, Walla Walla, WA 99362 USA
- ¹²⁵ National Institute for Mathematical Sciences, Daejeon 305-390, Korea
- ¹²⁶ Hobart and William Smith Colleges, Geneva, NY 14456, USA
- ¹²⁷ Janusz Gil Institute of Astronomy, University of Zielona Góra, 65-265 Zielona Góra, Poland
- ¹²⁸ Andrews University, Berrien Springs, MI 49104, USA
- ¹²⁹ Università di Siena, I-53100 Siena, Italy
- ¹³⁰ Trinity University, San Antonio, TX 78212, USA
- ¹³¹ University of Washington, Seattle, WA 98195, USA
- ¹³² Kenyon College, Gambier, OH 43022, USA
- ¹³³ Abilene Christian University, Abilene, TX 79699, USA
- ¹³⁴ CSIRO Astronomy and Space Science, PO Box 76, Epping NSW 1710, Australia
- ¹³⁵ ARC Centre of Excellence for All-sky Astrophysics (CAASTRO)
- ¹³⁶ Cornell Center for Astrophysics and Planetary Science, Ithaca, NY 14853, USA
- ¹³⁷ Department of Physics and Electronics, Rhodes University, PO Box 94, Grahamstown, 6140, South Africa
- ¹³⁸ CSIRO Astronomy and Space Science, 26 Dick Perry Avenue, Technology Park, Kensington WA 6151, Australia
- ¹³⁹ Sydney Institute for Astronomy, School of Physics, The University of Sydney, NSW 2006, Australia
- ¹⁴⁰ International Centre for Radio Astronomy Research (ICRAR), The University of Western Australia, M468, 35 Stirling Highway, Crawley, Perth, WA, 6009, Australia
- ¹⁴¹ Instituto de Astrofísica de Andalucía (IAA-CSIC), P.O. Box 03004, E-18080 Granada, Spain
- ¹⁴² Departamento de Ingeniería de Sistemas y Automática, Escuela de Ingenierías, Universidad de Málaga, Unidad Asociada al CSIC, Dr. Pedro Ortiz Ramos, E-29071 Málaga, Spain
- ¹⁴³ Astronomical Institute, Academy of Sciences of the Czech Republic 251 65 Ondřejov, Czech Republic
- ¹⁴⁴ Institute of Physics of the Czech Academy of Sciences, Na Slovance 1999/2, 182 21 Praha 8, Czech Republic
- ¹⁴⁵ Nikolaev National University, Nikolska str. 24, 54030 Nikolaev, Ukraine
- ¹⁴⁶ Facultad de Ciencias, Universidad de Málaga, Boulevard Louis Pasteur, E-29010 Málaga, Spain
- ¹⁴⁷ Enseñanza Virtual y Laboratorios Tecnológicos, Universidad de Málaga, Jiménez Fraud 10, E-29071 Málaga, Spain
- ¹⁴⁸ ISDEFE for the SMOS FOS (ESA-ESAC), E-28692 Villanueva de la Cañada (Madrid), Spain
- ¹⁴⁹ Czech Technical University, Faculty of Electrical Engineering, Dep. of Radioelectronics, Technická 2 166 27 Praha, Czech Republic
- ¹⁵⁰ Astronomical Institute of the Academy of Sciences, Boční II 1401, CZ-14100 Praha 4, Czech Republic
- ¹⁵¹ Estación de Sondeos Atmosféricos (ESAt) de El Arenosillo (CEDEA-INTA), E-21130 Mazagón, Huelva, Spain
- ¹⁵² Departamento de Ingeniería Electrónica, Sistemas Informáticos y Automática, Universidad de Huelva, E.T.S.I. de La Rábida, E-21819 Palos de la Frontera (Huelva), Spain
- ¹⁵³ Instituto de Hortofruticultura Subtropical y Mediterránea La Mayora (IHSM/UMA-CSIC), E-29750 Algarrobo Costa (Málaga), Spain
- ¹⁵⁴ Department of Physics, University of Auckland, Private Bag 92019, New Zealand
- ¹⁵⁵ Vintage Lane Observatory, RD3, 7273 Blenheim, New Zealand
- ¹⁵⁶ National Institute of Water and Atmospheric Research (NIWA), Lauder, New Zealand
- ¹⁵⁷ Department of Physics, Sungkyunkwan University (SKKU), Suwon, Korea
- ¹⁵⁸ Yunnan Astronomical Observatory, CAS, Kunming 650011, Yunnan, China
- ¹⁵⁹ National Astronomical Observatory, Chinese Academy of Sciences, Beijing 100012, China
- ¹⁶⁰ Instituto de Astronomía, Universidad Nacional Autónoma de México, 22800 Ensenada, Baja California, México
- ¹⁶¹ Instituto de Astronomía, Universidad Nacional Autónoma de México, Apdo Postal 70-264, Cd. Universitaria, 04510 México DF, México
- ¹⁶² Aryabhata Research Institute of Observational Sciences, Manora Peak, Nainital-263 002, India
- ¹⁶³ Escuela Politécnica Superior, Universidad de Cádiz, Avda. Ramón Puyol, E-11202 Algeciras (Cádiz), Spain
- ¹⁶⁴ División de Ciencias del Espacio, Instituto Nacional de Técnica Aeroespacial (INTA), E-28850 Torrejón de Ardoz (Madrid), Spain
- ¹⁶⁵ Cerro Tololo Inter-American Observatory, National Optical Astronomy Observatory, Casilla 603, La Serena, Chile
- ¹⁶⁶ Department of Physics & Astronomy, University College London, Gower Street, London, WC1E 6BT, UK
- ¹⁶⁷ Fermi National Accelerator Laboratory, P. O. Box 500, Batavia, IL 60510, USA
- ¹⁶⁸ Department of Astrophysical Sciences, Princeton University, Peyton Hall, Princeton, NJ 08544, USA
- ¹⁶⁹ CNRS, UMR 7095, Institut d'Astrophysique de Paris, F-75014, Paris, France
- ¹⁷⁰ Sorbonne Universités, UPMC Univ Paris 06, UMR 7095, Institut d'Astrophysique de Paris, F-75014, Paris, France
- ¹⁷¹ Harvard-Smithsonian Center for Astrophysics, 60 Garden St, Cambridge, MA 02138, USA
- ¹⁷² Carnegie Observatories, 813 Santa Barbara St., Pasadena, CA 91101, USA
- ¹⁷³ Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, PA 19104, USA
- ¹⁷⁴ Kavli Institute for Particle Astrophysics & Cosmology, P. O. Box 2450, Stanford University, Stanford, CA 94305, USA
- ¹⁷⁵ SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA
- ¹⁷⁶ Institute of Cosmology & Gravitation, University of Portsmouth, Portsmouth, PO1 3FX, UK
- ¹⁷⁷ Institut de Ciències de l'Espai, IEEC-CSIC, Campus UAB, Carrer de Can Magrans, s/n, E-08193 Bellaterra, Barcelona, Spain
- ¹⁷⁸ Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Campus UAB, E-08193 Bellaterra (Barcelona) Spain
- ¹⁷⁹ Astrophysical Institute, Department of Physics and Astronomy, 251B Clippinger Lab, Ohio University, Athens, OH 45701, USA
- ¹⁸⁰ Laboratório Interinstitucional de e-Astronomia—LIneA, Rua Gal. José Cristino 77, Rio de Janeiro, RJ-20921-400, Brazil
- ¹⁸¹ Excellence Cluster Universe, Boltzmannstr. 2, D-85748 Garching, Germany
- ¹⁸² Faculty of Physics, Ludwig-Maximilians-Universität, Scheinerstr. 1, D-81679 Munich, Germany
- ¹⁸³ Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL 60637, USA
- ¹⁸⁴ Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA
- ¹⁸⁵ Department of Astronomy, University of Illinois, 1002 W. Green Street, Urbana, IL 61801, USA
- ¹⁸⁶ Department of Physics, University of Illinois, 1110 W. Green St., Urbana, IL 61801, USA
- ¹⁸⁷ University of Arizona, Steward Observatory, University of Arizona, 933 N. Cherry Avenue, Tucson, AZ 85721, USA
- ¹⁸⁸ Department of Astronomy & Astrophysics, Center for Particle & Gravitational Astrophysics, and Center for Theoretical & Observational Cosmology, Pennsylvania State University, University Park, PA 16802, USA

- ¹⁸⁹ CCS Division, Los Alamos National Laboratory, Los Alamos, NM 87545, USA
- ¹⁹⁰ Department of Physics, University of Michigan, Ann Arbor, MI 48109, USA
- ¹⁹¹ Department of Astronomy, University of California, Berkeley, 501 Campbell Hall, Berkeley, CA 94720, USA
- ¹⁹² Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720, USA
- ¹⁹³ National Center for Supercomputing Applications, 1205 West Clark St., Urbana, IL 61801, USA
- ¹⁹⁴ Center for Cosmology and Astro-Particle Physics, The Ohio State University, Columbus, OH 43210, USA
- ¹⁹⁵ Department of Physics, The Ohio State University, Columbus, OH 43210, USA
- ¹⁹⁶ Departments of Physics and Astronomy, University of California, Berkeley, CA, USA
- ¹⁹⁷ Australian Astronomical Observatory, North Ryde, NSW 2113, Australia
- ¹⁹⁸ George P. and Cynthia Woods Mitchell Institute for Fundamental Physics and Astronomy, and Department of Physics and Astronomy, Texas A&M University, College Station, TX 77843, USA
- ¹⁹⁹ Departamento de Física Matemática, Instituto de Física, Universidade de São Paulo, CP 66318, CEP 05314-970, São Paulo, SP, Brazil
- ²⁰⁰ Center for Cosmology and Particle Physics, New York University, 4 Washington Place, New York, NY 10003, USA
- ²⁰¹ Department of Astronomy, The Ohio State University, Columbus, OH 43210, USA
- ²⁰² National Optical Astronomy Observatory, 950 North Cherry Avenue, Tucson, AZ 85719, USA
- ²⁰³ Columbia Astrophysics Laboratory, Pupin Hall, New York, NY, 10027, USA
- ²⁰⁴ Department of Astronomy, University of Michigan, Ann Arbor, MI 48109, USA
- ²⁰⁵ Institució Catalana de Recerca i Estudis Avançats, E-08010 Barcelona, Spain
- ²⁰⁶ Department of Astronomy & Theoretical Astrophysics Center, University of California, Berkeley, CA 94720-3411, USA
- ²⁰⁷ Department of Physics and Astronomy, Pevensey Building, University of Sussex, Brighton, BN1 9QH, UK
- ²⁰⁸ Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
- ²⁰⁹ Brookhaven National Laboratory, Bldg 510, Upton, NY 11973, USA
- ²¹⁰ Argonne National Laboratory, 9700 South Cass Avenue, Lemont, IL 60439, USA
- ²¹¹ Jodrell Bank Center for Astrophysics, School of Physics and Astronomy, University of Manchester, Oxford Road, Manchester, M13 9PL, UK
- ²¹² Universities Space Research Association, 320 Sparkman Dr. Huntsville, AL 35806, USA
- ²¹³ Physics Dept, University of Alabama in Huntsville, 320 Sparkman Dr., Huntsville, AL 35899, USA
- ²¹⁴ Astrophysics Office, ZP12, NASA/Marshall Space Flight Center, Huntsville, AL 35812, USA
- ²¹⁵ Dept. of Space Science, University of Alabama in Huntsville, 320 Sparkman Dr., Huntsville, AL 35899, USA
- ²¹⁶ CSPAR, University of Alabama in Huntsville, 320 Sparkman Dr., Huntsville, AL 35899, USA
- ²¹⁷ Instituto de Astrofísica de Andalucía (IAA-CSIC), P.O. Box 03004, E-18080 Granada, Spain
- ²¹⁸ Istituto Nazionale di Fisica Nucleare, Sezione di Bari, I-70126 Bari, Italy
- ²¹⁹ Jacobs Technology, Inc., Huntsville, AL, USA
- ²²⁰ Max-Planck-Institut für Extraterrestrische Physik, Giessenbachstraße 1, D-85748, Garching, Germany
- ²²¹ Los Alamos National Laboratory, NM 87545, USA
- ²²² School of Physics, University College Dublin, Belfield, Stillorgan Road, Dublin 4, Ireland
- ²²³ NASA Headquarters, Washington DC, USA
- ²²⁴ Excellence Cluster Universe, Technische Universität München, Boltzmannstr. 2, D-85748, Garching, Germany
- ²²⁵ Deutsches Elektronen Synchrotron DESY, D-15738 Zeuthen, Germany
- ²²⁶ Department of Physics and Astronomy, Clemson University, Kinard Lab of Physics, Clemson, SC 29634-0978, USA
- ²²⁷ W. W. Hansen Experimental Physics Laboratory, Kavli Institute for Particle Astrophysics and Cosmology, Department of Physics and SLAC National Accelerator Laboratory, Stanford University, Stanford, CA 94305, USA
- ²²⁸ Department of Physics, Stockholm University, AlbaNova, SE-106 91 Stockholm, Sweden
- ²²⁹ The Oskar Klein Centre for Cosmoparticle Physics, AlbaNova, SE-106 91 Stockholm, Sweden
- ²³⁰ Santa Cruz Institute for Particle Physics, Department of Physics and Department of Astronomy and Astrophysics, University of California at Santa Cruz, Santa Cruz, CA 95064, USA
- ²³¹ Department of Physics, KTH Royal Institute of Technology, AlbaNova, SE-106 91 Stockholm, Sweden
- ²³² Tokyo Metropolitan University, Department of Physics, Minami-osawa 1-1, Hachioji, Tokyo 192-0397, Japan
- ²³³ Università di Pisa and Istituto Nazionale di Fisica Nucleare, Sezione di Pisa I-56127 Pisa, Italy
- ²³⁴ Istituto Nazionale di Fisica Nucleare, Sezione di Trieste, I-34127 Trieste, Italy
- ²³⁵ Dipartimento di Fisica, Università di Trieste, I-34127 Trieste, Italy
- ²³⁶ Istituto Nazionale di Fisica Nucleare, Sezione di Padova, I-35131 Padova, Italy
- ²³⁷ Dipartimento di Fisica e Astronomia “G. Galilei”, Università di Padova, I-35131 Padova, Italy
- ²³⁸ Istituto Nazionale di Fisica Nucleare, Sezione di Pisa, I-56127 Pisa, Italy
- ²³⁹ Istituto Nazionale di Fisica Nucleare, Sezione di Bari, I-70126 Bari, Italy
- ²⁴⁰ Istituto Nazionale di Fisica Nucleare, Sezione di Torino, I-10125 Torino, Italy
- ²⁴¹ Dipartimento di Fisica Generale “Amadeo Avogadro”, Università degli Studi di Torino, I-10125 Torino, Italy
- ²⁴² NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA; Julie.E.McEnery@nasa.gov
- ²⁴³ Laboratoire Leprince-Ringuet, École polytechnique, CNRS/IN2P3, Palaiseau, France
- ²⁴⁴ Department of Physics and Center for Space Sciences and Technology, University of Maryland Baltimore County, Baltimore, MD 21250, USA
- ²⁴⁵ Center for Research and Exploration in Space Science and Technology (CRESTT) and NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
- ²⁴⁶ Consorzio Interuniversitario per la Fisica Spaziale (CIFS), I-10133 Torino, Italy
- ²⁴⁷ Dipartimento di Fisica “M. Merlin” dell’Università e del Politecnico di Bari, I-70126 Bari, Italy
- ²⁴⁸ INFN-Istituto di Astrofisica Spaziale e Fisica Cosmica, I-20133 Milano, Italy
- ²⁴⁹ Agenzia Spaziale Italiana (ASI) Science Data Center, I-00133 Roma, Italy
- ²⁵⁰ College of Science, George Mason University, Fairfax, VA 22030, resident at Naval Research Laboratory, Washington, DC 20375, USA
- ²⁵¹ Istituto Nazionale di Fisica Nucleare, Sezione di Perugia, I-06123 Perugia, Italy
- ²⁵² Laboratoire Univers et Particules de Montpellier, Université Montpellier, CNRS/IN2P3, Montpellier, France
- ²⁵³ Department of Physics and Astronomy, Sonoma State University, Rohnert Park, CA 94928-3609, USA
- ²⁵⁴ INFN Istituto di Radioastronomia, I-40129 Bologna, Italy
- ²⁵⁵ Dipartimento di Astronomia, Università di Bologna, I-40127 Bologna, Italy
- ²⁵⁶ Università Telematica Pegaso, Piazza Trieste e Trento, 48, I-80132 Napoli, Italy
- ²⁵⁷ Università di Udine, I-33100 Udine, Italy
- ²⁵⁸ Department of Physical Sciences, Hiroshima University, Higashi-Hiroshima, Hiroshima 739-8526, Japan
- ²⁵⁹ Erlangen Centre for Astroparticle Physics, D-91058 Erlangen, Germany
- ²⁶⁰ Instituto de Astrofísica, Facultad de Física, Pontificia Universidad Católica de Chile, Casilla 306, Santiago 22, Chile
- ²⁶¹ Istituto Nazionale di Fisica Nucleare, Sezione di Roma “Tor Vergata”, I-00133 Roma, Italy

- ²⁶² Department of Physics and Department of Astronomy, University of Maryland, College Park, MD 20742, USA
- ²⁶³ Laboratoire AIM, CEA-IRFU/CNRS/Université Paris Diderot, Service d'Astrophysique, CEA Saclay, F-91191 Gif sur Yvette, France
- ²⁶⁴ Space Science Division, Naval Research Laboratory, Washington, DC 20375-5352, USA
- ²⁶⁵ Institut für Astro- und Teilchenphysik and Institut für Theoretische Physik, Leopold-Franzens-Universität Innsbruck, A-6020 Innsbruck, Austria
- ²⁶⁶ University of North Florida, Department of Physics, 1 UNF Drive, Jacksonville, FL 32224, USA
- ²⁶⁷ School of Physics and Astronomy, University of Southampton, Highfield, Southampton, SO17 1BJ, UK
- ²⁶⁸ Science Institute, University of Iceland, IS-107 Reykjavik, Iceland
- ²⁶⁹ Institute of Space Sciences (IEEC-CSIC), Campus UAB, E-08193 Barcelona, Spain
- ²⁷⁰ Hiroshima Astrophysical Science Center, Hiroshima University, Higashi-Hiroshima, Hiroshima 739-8526, Japan
- ²⁷¹ Max-Planck-Institut für Physik, D-80805 München, Germany
- ²⁷² Department of Physics and Astronomy, University of Denver, Denver, CO 80208, USA
- ²⁷³ Department of Physics, University of Johannesburg, PO Box 524, Auckland Park 2006, South Africa
- ²⁷⁴ Department of Physics, The University of Hong Kong, Pokfulam Road, Hong Kong, China
- ²⁷⁵ The University of Hong Kong, Laboratory for Space Research, Hong Kong, China
- ²⁷⁶ NYCB Real-Time Computing Inc., Lattingtown, NY 11560-1025, USA
- ²⁷⁷ Department of Chemistry and Physics, Purdue University Calumet, Hammond, IN 46323-2094, USA
- ²⁷⁸ Solar-Terrestrial Environment Laboratory, Nagoya University, Nagoya 464-8601, Japan
- ²⁷⁹ Max-Planck-Institut für Kernphysik, D-69029 Heidelberg, Germany
- ²⁸⁰ Institutió Catalana de Recerca i Estudis Avançats (ICREA), Barcelona, Spain
- ²⁸¹ Department of Physics, 3-34-1 Nishi-Ikebukuro, Toshima-ku, Tokyo 171-8501, Japan
- ²⁸² INAF - Osservatorio Astronomico di Roma, via Frascati 33, I-00078 Monte Porzio Catone (RM), Italy
- ²⁸³ INAF - Osservatorio Astronomico di Padova, Vicolo Osservatorio 5, I-35122 Padova, Italy
- ²⁸⁴ INAF - Osservatorio Astronomico di Brera, via E. Bianchi 46, I-23807 Merate, Italy
- ²⁸⁵ INAF - Osservatorio Astronomico di Capodimonte, salita Moiriello 16, I-80131 Napoli, Italy
- ²⁸⁶ INAF - Istituto di Astrofisica Spaziale e Fisica Cosmica di Bologna, via Gobetti 101, I-40129 Bologna, Italy
- ²⁸⁷ Scuola Normale Superiore, Piazza dei Cavalieri, 7, I-56126 Pisa, Italy
- ²⁸⁸ ASI-Science Data Center, via dl Politecnico s.n.c., I-00133 Roma, Italy
- ²⁸⁹ Dip. di Fisica Ettore Pancini, University of Naples "Federico II", C.U. Monte Sant'Angelo, Via Cinthia, I-80126, Napoli, Italy
- ²⁹⁰ INAF—ORA—Osservatorio Astronomico di Cagliari, Via della Scienza n. 5, I-09047 Selargius (CA), Italy
- ²⁹¹ INAF—Osservatorio Astronomico di Torino, Strada Osservatorio 20, I-10025, Pino Torinese (To), Italy
- ²⁹² INAF-Institute for Space Astrophysics and Planetology, Via Fosso del Cavaliere 100, I-00133 Rome, Italy
- ²⁹³ ISDC, Department of astronomy, University of Geneva, chemin d'Écogia, 16 CH-1290 Versoix, Switzerland
- ²⁹⁴ DTU Space—National Space Institute Elektrovej—Building 327 DK-2800 Kongens Lyngby Denmark
- ²⁹⁵ Space Science Group, School of Physics, University College Dublin, Belfield, Dublin 4, Ireland
- ²⁹⁶ European Space Astronomy Centre (ESA/ESAC), Science Operations Department, E-28691, Villanueva de la Cañada, Madrid, Spain
- ²⁹⁷ APC, AstroParticule et Cosmologie, Université Paris Diderot, CNRS/IN2P3, CEA/Irfu, Observatoire de Paris, Sorbonne Paris Cité, 10 rue Alice Domont et Léonie Duquet, F-75205 Paris Cedex 13, France
- ²⁹⁸ INAF, IASF-Milano, via E. Bassini 15, I-20133 Milano, Italy
- ²⁹⁹ Université Toulouse; UPS-OMP; CNRS; IRAP; 9 Av. Roche, BP 44346, F-31028 Toulouse, France
- ³⁰⁰ François Arago Centre, APC, Université Paris Diderot, CNRS/IN2P3, CEA/Irfu, Observatoire de Paris, Sorbonne Paris Cité, 10 rue Alice Domon et Léonie Duquet, F-75205 Paris Cedex 13, France
- ³⁰¹ Cahill Center for Astrophysics, California Institute of Technology, Pasadena, CA 91125, USA
- ³⁰² Department of Particle Physics and Astrophysics, Weizmann Institute of Science, 76100 Rehovot, Israel
- ³⁰³ Infrared Processing and Analysis Center, California Institute of Technology, Pasadena, CA 91125, USA
- ³⁰⁴ Max Planck Institute for Astronomy, Königstuhl 17, D-69117 Heidelberg, Germany
- ³⁰⁵ Dark Cosmology Centre, Niels Bohr Institute, Juliane Maries Vej 30, Copenhagen Ø, DK-2100, Denmark
- ³⁰⁶ Department of Astronomy and the Oskar Klein Centre, Stockholm University, AlbaNova, SE-106 91 Stockholm, Sweden
- ³⁰⁷ Lockheed Martin Space Systems Company, Palo Alto, CA 94304
- ³⁰⁸ University of California, Berkeley, Space Sciences Laboratory, 7 Gauss Way, Berkeley, CA 94720-7450, USA
- ³⁰⁹ Ioffe Physical Technical Institute, Politekhnicheskaya 26, St. Petersburg, 194021, Russia
- ³¹⁰ Universities Space Research Association, 7178 Columbia Gateway Drive, Columbia, MD 21046 USA
- ³¹¹ Institute for Space-Earth Environmental Research, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8601, Japan
- ³¹² Institute of Astronomy, Graduate School of Science, The University of Tokyo, Mitaka, Tokyo 181-0015, Japan
- ³¹³ The Research Institute for Time Studies, Yamaguchi University, Yamaguchi, Yamaguchi 753-8511, Japan
- ³¹⁴ Hiroshima Astrophysical Science Center, Hiroshima University, Higashi-Hiroshima, Hiroshima 739-8526, Japan
- ³¹⁵ Division of Theoretical Astronomy, National Astronomical Observatory of Japan, Mitaka, Tokyo 181-8588, Japan
- ³¹⁶ Department of Astronomy, Kyoto University, Kyoto, Kyoto 606-8502, Japan
- ³¹⁷ Okayama Astrophysical Observatory, National Astronomical Observatory of Japan, Asakuchi, Okayama 719-0232, Japan
- ³¹⁸ Physics Department, Yale University, New Haven, CT 06520, USA
- ³¹⁹ Astrophysics Research Institute, Liverpool JMU, Liverpool L3 5RF, UK
- ³²⁰ Monash Centre for Astrophysics (MoCA), Monash University, Clayton VIC 3800, Australia
- ³²¹ School of Physics & Astronomy, Monash University, Clayton VIC 3800, Australia
- ³²² University of Nova Gorica, Vipavska 13, 5000 Nova Gorica, Slovenia
- ³²³ Faculty of Mathematics and Physics, University of Ljubljana, Jadranska 19, 1000 Ljubljana, Slovenia
- ³²⁴ Department of Physics, University of Bath, BA2 7AY, UK
- ³²⁵ University of Warwick, Department of Physics, Gibbet Hill Road, Coventry, CV4 7AL, UK
- ³²⁶ ASTRON, The Netherlands Institute for Radio Astronomy, Postbus 2, 7990 AA, Dwingeloo, The Netherlands
- ³²⁷ Astrophysics, Department of Physics, University of Oxford, Keble Road, Oxford OX1 3RH, UK
- ³²⁸ SRON Netherlands Institute for Space Research, Sorbonnelaan 2, 3584 CA Utrecht, the Netherlands
- ³²⁹ Anton Pannekoek Institute for Astronomy, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, The Netherlands
- ³³⁰ Lomonosov Moscow State University, Sternberg Astronomical Institute, 13, Universitetskiy prospekt, Moscow, 119234, Russia
- ³³¹ South African Astronomical Observatory, PO Box 9, 7935 Observatory, Cape Town, South Africa
- ³³² The Instituto de Astrofísica de Canarias, Calle Via Lactea, s/n, E-38200 La Laguna, Tenerife, Spain
- ³³³ Applied Physics Institute, Irkutsk State University, 20, Gagarin blvd., Irkutsk, 664003, Russia
- ³³⁴ Kislovodsk Solar Station of the Main (Pulkovo) Observatory RAS, P.O.Box 45, ul. Gagarina 100, Kislovodsk, 357700, Russia
- ³³⁵ Blagoveschensk State Pedagogical University, Lenin str., 104, Amur Region, Blagoveschensk, 675000, Russia

- ³³⁶ Department of Physics, Tokyo Institute of Technology, Meguro-ku, Tokyo 152-8851, Japan
- ³³⁷ MAXI team, RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan
- ³³⁸ Department of Physics, Nihon University, 1-8-14 Kanda-Surugadai, Chiyoda-ku, Tokyo 101-8308, Japan
- ³³⁹ JEM Mission Operations and Integration Center, Human Spaceflight Technology Directorate, Japan Aerospace Exploration Agency, 2-1-1 Sengen, Tsukuba, Ibaraki 305-8505, Japan
- ³⁴⁰ Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA), 3-1-1 Yoshinodai, Chuo, Sagami, Kanagawa 252-5210, Japan
- ³⁴¹ Department of Earth and Space Science, Osaka University, 1-1 Machikaneyama, Toyonaka, Osaka 560-0043, Japan
- ³⁴² University of California, Berkeley, Astronomy Dept., 501 Campbell Hall #3411, Berkeley, CA 94720, USA
- ³⁴³ Eureka Scientific, Inc., 2452 Delmer Street Suite 100, Oakland, CA 94602, USA
- ³⁴⁴ Kavli Institute for Astrophysics and Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
- ³⁴⁵ International Centre for Radio Astronomy Research, Curtin University, Bentley, WA 6102, Australia
- ³⁴⁶ Dunlap Institute for Astronomy and Astrophysics, University of Toronto, Toronto, ON M5S 3H4, Canada
- ³⁴⁷ School of Chemical & Physical Sciences, Victoria University of Wellington, PO Box 600, Wellington 6140, New Zealand
- ³⁴⁸ Osservatorio di Radio Astronomia, Istituto Nazionale di Astrofisica, Bologna, I-40123, Italy
- ³⁴⁹ Astrophysics Research Centre, School of Mathematics and Physics, Queens University Belfast, Belfast BT7 1NN, UK
- ³⁵⁰ Institute for Astronomy, University of Hawaii at Manoa, Honolulu, HI 96822, USA
- ³⁵¹ Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
- ³⁵² Department of Physics, Harvard University, Cambridge, MA 02138, USA
- ³⁵³ Millennium Institute of Astrophysics, Casilla 36-D, Santiago, Chile
- ³⁵⁴ Departamento de Ciencias Físicas, Universidad Andrés Bello, Avda. Republica 252, Santiago, Chile
- ³⁵⁵ Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK
- ³⁵⁶ Institut d'Astrophysique de Paris, CNRS, and Université Pierre et Marie Curie, 98 bis Boulevard Arago, F-75014, Paris, France
- ³⁵⁷ European Southern Observatory, Alonso de Cordova 3107, Vitacura, Santiago, Chile
- ³⁵⁸ Tuorla Observatory, Department of Physics and Astronomy, University of Turku, Väiäläntie 20, FI-21500 Piikkiö, Finland
- ³⁵⁹ Departamento de Astronomía, Universidad de Chile, Camino El Observatorio 1515, Las Condes, Santiago, Chile
- ³⁶⁰ Sorbonne Universités, UPMC Univ. Paris 06, UMR 7585, LPNHE, F-75005, Paris, France
- ³⁶¹ CNRS, UMR 7585, Laboratoire de Physique Nucleaire et des Hautes Energies, 4 place Jussieu, F-75005 Paris, France
- ³⁶² Las Cumbres Observatory Global Telescope Network, 6740 Cortona Dr., Suite 102, Goleta, CA 93117, USA
- ³⁶³ Department of Physics, University of California Santa Barbara, Santa Barbara, CA 93106, USA
- ³⁶⁴ Benozziyo Center for Astrophysics, Weizmann Institute of Science, 76100 Rehovot, Israel
- ³⁶⁵ Faculty of Physics, University of Warsaw, 02-093 Warszawa, Poland
- ³⁶⁶ Center for Theoretical Physics of the Polish Academy of Sciences, 02-668 Warszawa, Poland
- ³⁶⁷ Department of Physics and Astronomy, University of Leicester, Leicester, LE1 7RH, UK
- ³⁶⁸ Joint Space-Science Institute, University of Maryland, College Park, MD 20742, USA
- ³⁶⁹ Los Alamos National Laboratory, B244, Los Alamos, NM, 87545, USA
- ³⁷⁰ L'Institut de Recherche en Astrophysique et Planétologie, CNRS UMR 5277/UPS, 14 avenue Edouard Belin, F-31400 Toulouse, France
- ³⁷¹ University of Texas at San Antonio, San Antonio, TX, USA
- ³⁷² Ludwig Maximilian Universität Munich, Faculty of Physics, Schellingstrasse 4, D-80799 Munich, Germany
- ³⁷³ Mitchell Institute for Fundamental Physics and Astronomy, Department of Physics and Astronomy, Texas A&M University, 4242 TAMU, College Station, TX 77843, USA
- ³⁷⁴ Universidad Nacional de Córdoba, IATE, Laprida 854, Córdoba, Argentina
- ³⁷⁵ Instituto de Astrofísica, Pontificia Universidad Católica de Chile, Av. Vicuña Mackenna 4860, Santiago, Chile
- ³⁷⁶ Instituto de Astrofísica de Andalucía, Consejo Superior de Investigaciones Científicas, Glorieta de la Astronomía s/n, E-18008 Granada, Spain
- ³⁷⁷ Centre for Astrophysics and Cosmology, Science Institute, University of Iceland, 107 Reykjavik, Iceland
- ³⁷⁸ NASA Postdoctoral Program Fellow, USA
- ³⁷⁹ Hubble Fellow
- ³⁸⁰ Emeritus