Supplement: "Localization and Broadband Follow-up of the Gravitational-wave Transient GW150914" (2016, ApJL, 826, L13)

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

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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 (deg^2). 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 deg^2 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*–BAT[383]) 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 ~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 deg^2 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 deg^2) 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 deg^2. 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

[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.
[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 ($\approx$50 deg^2 with uniform sensitivity for the LOFAR observations carried out as part of this follow-up program; and up to 1200 deg^2 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 $\approx$25 deg^2 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 $\approx$7 to $\approx$14 days after the GW trigger, reaching rms sensitivities of 1–3 mJy beam^{-1}. LOFAR conducted three observations from $\approx$7 days to $\approx$3 months following the GW trigger, reaching a rms sensitivity of $\approx$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 $\approx$1 to $\approx$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 $\approx$6 GHz (primary beam FWHP of $\approx$9′, and synthesized beam FWHP of $\approx$12″). The rms sensitivity of these VLA observations was $\approx$8–10 μJy beam^{-1}.

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S. B. Coughlin[82], J.-P. Coulon[53], S. T. Countryman[40], P. Couvares[1], E. E. Cowan[64], D. M. Coward[51], M. J. Cowart[6],
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J. Hough[36], E. A. Houston[36], E. J. Howell[51], Y. M. Hu[36], S. Huang[73], E. A. Huerta[82,103], D. Huet[23], B. Hughey[97],
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T. G. F. Li[1], A. Libson[10], T. B. Littenberg[115], N. A. Lockerbie[105], J. Logue[36], A. L. Lombardi[101], J. E. Lord[35],
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Sequino[13,25], A. Sergeev[107], G. Serna[22], Y. Setyawati[9,52], A. Sevigny[37], D. A. Shaddock[20], S. Shah[9,52], M. S. Shahriar[82], M. Shaltev[8], Z. Shao[1], B. Shapiro[41], P. Shawhan[63], A. Sheperd[16], D. H. Shoemaker[10], D. M. Shoemaker[64], K. Siellez[53,64], X. Siemens[16], D. Sigg[37], A. D. Silva[11], D. Simakov[8], A. Singer[1], A. Singh[8,29], R. Singh[2], A. Singhal[12], A. M. Sintes[67], B. J. J. Slagmolen[20], J. R. Smith[22], N. D. Smith[1], R. J. E. Smith[1], E. J. Son[125], B. Sorazu[36], F. Sorrentino[47], T. Souradeep[14], A. K. Srivastava[95], A. Staley[40], M. Steinke[8], J. Steinlechner[36], S. Steinlechner[36], D. Steinmeyer[8,17], B. C. Stephens[16], R. Stone[85], K. A. Strain[36], N. Straniero[66], G. Stratta[57,58], N. A. Strauss[78], S. Strigin[49], R. Sturani[120], A. L. Stuver[6], T. Z. Summerscales[128], L. Sun[84], P. J. Sutton[91], B. L. Swinkels[34], M. J. Szczepańczyk[97], M. Tacca[30], D. Talukder[59], D. B. Tanner[5], M. Tápai[96], S. P. Tarabrin[8], A. Taracchini[29], R. Taylor[1], T. Theeg[8], M. P. Thirugnanasambandam[1], E. G. Thomas[45], M. Thomas[6], P. Thomas[37], K. A. Thorne[6], K. S. Thorne[76], E. Thrane[113], S. Tiwari[12], V. Tiwari[91], K. V. Tokmakov[105], C. Tomlinson[86], M. Tonelli[18,19], C. V. Torres[85], C. I. Torrie[1], D. Töyrä[45], F. Travasso[32,33], G. Traylor[6], D. Trifirò[21], M. C. Tringali[89,90], L. Trozzo[19,129], M. Tse[10], M. Turconi[53], D. Tuyenbayev[85], D. Ugolini[130], C. S. Unnikrishnan[99], A. L. Urban[16], S. A. Usman[35], H. Vahlbruch[17], G. Vajente[1], G. Valdes[85], N. van Bakel[9], M. van Beuzekom[9], J. F. J. van den Brand[9,62], C. Van Den Broeck[9], D. C. Vander-Hyde[22,35], L. van der Schaaf[9], J. V. van Heijningen[9], A. A. van Veggel[36], M. Vardaro[42,43], S. Vass[1], M. Vasúth[38], R. Vaulin[10], A. Vecchio[45], G. Vedovato[43], J. Veitch[45], P. J. Veitch[102], K. Venkateswara[131], D. Verkindt[7], F. Vetrano[57,58], A. Viceré[57,58], S. Vinciguerra[45], D. J. Vine[50], J.-Y. Vinet[53], S. Vitale[10], T. Vo[35], H. Vocca[32,33], C. Vorvick[37], D. Voss[5], W. D. Vousden[45], S. P. Vyatchanin[49], A. R. Wade[20], L. E. Wade[132], M. Wade[132], M. Walker[2], L. Wallace[1], S. Walsh[8,16,29], G. Wang[12], H. Wang[45], M. Wang[45], X. Wang[70], Y. Wang[51], R. L. Ward[20], J. Warner[37], M. Was[7], B. Weaver[37], L.-W. Wei[53], M. Weinert[8], A. J. Weinstein[1], R. Weiss[10], T. Welborn[6], L. Wen[51], P. Wessels[8], T. Westphal[8], K. Wette[8], J. T. Whelan[8,112], D. J. White[86], B. F. Whiting[5], R. D. Williams[1], A. R. Williamson[91], J. L. Willis[133], B. Willke[8,17], M. H. Wimmer[8,17], W. Winkler[8], C. C. Wipf[1], H. Wittel[8,17], G. Woan[36], J. Worden[37], J. L. Wright[36], G. Wu[6], J. Yablon[82], W. Yam[10], H. Yamamoto[1], C. C. Yancey[63], M. J. Yap[20], H. Yu[10], M. Yvert[7], A. Zadrożny[110], L. Zangrando[43], M. Zanolin[97], J.-P. Zendri[43], M. Zevin[82], F. Zhang[10], L. Zhang[1], M. Zhang[119], Y. Zhang[112], C. Zhao[51], M. Zhou[82], Z. Zhou[82], X. J. Zhu[51], M. E. Zucker[1,10], S. E. Zuraw[101], J. Zweizig[1]

(The LIGO Scientific Collaboration and the Virgo Collaboration),

J. Allison[134,135], K. Bannister[134,135], M. E. Bell[134,135], S. Chatterjee[136], A. P. Chippendale[134], P. G. Edwards[134], L. Harvey-Smith[134], Ian Heywood[134,137], A. Hotan[138], B. Indermuehle[134], J. Marvil[134], D. McConnell[134], T. Murphy[135,139], A. Popping[135,140], J. Reynolds[134], R. J. Sault[84,134], M. A. Voronkov[134], M. T. Whiting[134]
(The Australian Square Kilometer Array Pathfinder (ASKAP) Collaboration),

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(The BOOTES Collaboration),

T. M. C. Abbott[165], F. B. Abdalla[137,166], S. Allam[167], J. Annis[167], R. Armstrong[168], A. Benoit-Lévy[166,169,170], E. Berger[171], R. A. Bernstein[172], E. Bertin[169,170], D. Brout[173], E. Buckley-Geer[167], D. L. Burke[174,175], D. Capozzi[176], J. Carretero[177,178], F. J. Castander[177], R. Chornock[179], P. S. Cowperthwaite[171], M. Crocce[177], C. E. Cunha[174], C. B. D'Andrea[26,176], L. N. da Costa[180], S. Desai[181,182], H. T. Diehl[167], J. P. Dietrich[181,182], Z. Doctor[183], A. Drlica-Wagner[167], M. R. Drout[171], T. F. Eifler[173,184], J. Estrada[167], A. E. Evrard[98], E. Fernandez[178], D. A. Finley[167], B. Flaugher[167], R. J. Foley[185,186], W.-F. Fong[187], P. Fosalba[177], D. B. Fox[188], J. Frieman[167,183], C. L. Fryer[189], E. Gaztanaga[177], D. W. Gerdes[190], D. A. Goldstein[191,192], D. Gruen[174,175], R. A. Gruendl[185,193], G. Gutierrez[167], K. Herner[167], K. Honscheid[194,195], D. J. James[165], M. D. Johnson[193], M. W. G. Johnson[193], I. Karliner[186], D. Kasen[192,196], S. Kent[167], R. Kessler[183], A. G. Kim[192], M. C. Kind[185,193], K. Kuehn[197], N. Kuropatkin[167], O. Lahav[166], T. S. Li[198], M. Lima[180,199], H. Lin[167], M. A. G. Maia[180], R. Margutti[200], J. Marriner[167], P. Martini[194,201], T. Matheson[202], P. Melchior[168], B. D. Metzger[203], C. J. Miller[190,204], R. Miquel[178,205], E. Neilsen[167], R. C. Nichol[176], B. Nord[167], P. Nugent[192], R. Ogando[180], D. Petravick[193], A. A. Plazas[184], E. Quataert[206], N. Roe[192], A. K. Romer[207], A. Roodman[174,175], A. C. Rosell[180], E. S. Rykoff[174,175], M. Sako[173], E. Sanchez[208], V. Scarpine[167], R. Schindler[175], M. Schubnell[190], D. Scolnic[183], I. Sevilla-Noarbe[185,208], E. Sheldon[209], N. Smith[187], R. C. Smith[165], M. Soares-Santos[167], F. Sobreira[180], A. Stebbins[167], E. Suchyta[173], M. E. C. Swanson[193], G. Tarle[190], J. Thaler[186], D. Thomas[176], R. C. Thomas[192], D. L. Tucker[167], V. Vikram[210], A. R. Walker[165], R. H. Wechsler[41,174,175], W. Wester[167], B. Yanny[167], Y. Zhang[98], J. Zuntz[211]
(The Dark Energy Survey and the Dark Energy Camera GW-EM Collaborations),

V. Connaughton[212], E. Burns[213], A. Goldstein[214,378], M. S. Briggs[215], B.-B. Zhang[216,217], C. M. Hui[214], P. Jenke[216], C. A. Wilson-Hodge[214], P. N. Bhat[216], E. Bissaldi[218], W. Cleveland[212], G. Fitzpatrick[216], M. M. Giles[219], M. H. Gibby[219], J. Greiner[220], A. von Kienlin[220], R. M. Kippen[221], S. McBreen[222], B. Mailyan[216], C. A. Meegan[216], W. S. Paciesas[212], R. D. Preece[215], O. Roberts[222], L. Sparke[223], M. Stanbro[213], K. Toelge[220], P. Veres[216], H.-F. Yu[220,224], L. Blackburn[171]
(The Fermi GBM Collaboration),

M. Ackermann[225], M. Ajello[226], A. Albert[227], B. Anderson[228,229], W. B. Atwood[230], M. Axelsson[231,232], L. Baldini[227,233], G. Barbiellini[234,235], D. Bastieri[236,237], R. Bellazzini[238], E. Bissaldi[239], R. D. Blandford[227], E. D. Bloom[227], R. Bonino[240,241], E. Bottacini[227], T. J. Brandt[242], P. Bruel[243], S. Buson[242,244,245], G. A. Caliandro[227,246], R. A. Cameron[227], M. Caragiulo[239,247], P. A. Caraveo[248], E. Cavazzuti[249], E. Charles[227], A. Chekhtman[250], J. Chiang[227], G. Chiaro[237], S. Ciprini[249,251], J. Cohen-Tanugi[252], L. R. Cominsky[253], F. Costanza[239], A. Cuoco[240,241], F. D'Ammando[254,255], F. de Palma[239,256], R. Desiante[240,257], S. W. Digel[227], N. Di Lalla[238], M. Di Mauro[227], L. Di Venere[239,247], A. Domínguez[226], P. S. Drell[227], R. Dubois[227], C. Favuzzi[239,247], E. C. Ferrara[242], A. Franckowiak[227], Y. Fukazawa[258], S. Funk[259], P. Fusco[239,247], F. Gargano[239], D. Gasparrini[249,251], N. Giglietto[239,247], P. Giommi[249], F. Giordano[239,247], M. Giroletti[254], T. Glanzman[227], G. Godfrey[227], G. A. Gomez-Vargas[260,261], D. Green[242,262], I. A. Grenier[263], J. E. Grove[264], S. Guiriec[242,378], D. Hadasch[265], A. K. Harding[242], E. Hays[242], J. W. Hewitt[266], A. B. Hill[227,267], D. Horan[243], T. Jogler[227], G. Jóhannesson[268], A. S. Johnson[227], S. Kensei[258], D. Kocevski[242], M. Kuss[238], G. La Mura[237,265], S. Larsson[229,231], L. Latronico[240], J. Li[269], L. Li[229,231], F. Longo[234,235], F. Loparco[239,247], M. N. Lovellette[264], P. Lubrano[251], J. Magill[262], S. Maldera[240], A. Manfreda[238], M. Marelli[248], M. Mayer[225], M. N. Mazziotta[239], J. E. McEnery[242,262], M. Meyer[228,229], P. F. Michelson[227], N. Mirabal[242,378], T. Mizuno[270], A. A. Moiseev[245,262], M. E. Monzani[227], E. Moretti[271], A. Morselli[261], I. V. Moskalenko[227], M. Negro[240,241], E. Nuss[252], T. Ohsugi[270], N. Omodei[227], M. Orienti[254], E. Orlando[227], J. F. Ormes[272], D. Paneque[227,271], J. S. Perkins[242], M. Pesce-Rollins[227,238], F. Piron[252], G. Pivato[238], T. A. Porter[227], J. L. Racusin[242], S. Rainò[239,247], R. Rando[236,237], S. Razzaque[273], A. Reimer[227,265], O. Reimer[227,265], D. Salvetti[248], P. M. Saz Parkinson[230,274,275], C. Sgrò[238], D. Simone[239], E. J. Siskind[276], F. Spada[238], G. Spandre[238], P. Spinelli[239,247], D. J. Suson[277], H. Tajima[227,278], J. B. Thayer[227],

D. J. Thompson[242], L. Tibaldo[279], D. F. Torres[269,280], E. Troja[242,262], Y. Uchiyama[281], T. M. Venters[242], G. Vianello[227], K. S. Wood[264], M. Wood[227], S. Zhu[262], S. Zimmer[228,229]
(The Fermi LAT Collaboration),

E. Brocato[282], E. Cappellaro[283], S. Covino[284], A. Grado[285], L. Nicastro[286], E. Palazzi[286], E. Pian[286,287], L. Amati[286], L. A. Antonelli[282,288], M. Capaccioli[289], P. D'Avanzo[284], V. D'Elia[282,288], F. Getman[285], G. Giuffrida[282,288], G. Iannicola[282], L. Limatola[285], M. Lisi[282], S. Marinoni[282,288], P. Marrese[282,283], A. Melandri[284], S. Piranomonte[282], A. Possenti[290], L. Pulone[282], A. Rossi[286], A. Stamerra[287,291], L. Stella[282], V. Testa[282], L. Tomasella[283], S. Yang[283]
(The GRAvitational Wave Inaf TeAm (GRAWITA)),

A. Bazzano[292], E. Bozzo[293], S. Brandt[294], T. J.-L. Courvoisier[293], C. Ferrigno[293], L. Hanlon[295], E. Kuulkers[296], P. Laurent[297], S. Mereghetti[298], J. P. Roques[299], V. Savchenko[300], P. Ubertini[292]
(The INTEGRAL Collaboration),

M. M. Kasliwal[301], L. P. Singer[39,378], Y. Cao[301], G. Duggan[301], S. R. Kulkarni[301], V. Bhalerao[14], A. A. Miller[184,301,379], T. Barlow[301], E. Bellm[301], I. Manulis[302], J. Rana[14], R. Laher[303], F. Masci[303], J. Surace[303], U. Rebbapragada[184], D. Cook[301], A. Van Sistine[16], B. Sesar[304], D. Perley[305], R. Ferreti[306], T. Prince[301], R. Kendrick[307], A. Horesh[302]
(The Intermediate Palomar Transient Factory (iPTF) Collaboration),

K. Hurley[308], S. V. Golenetskii[309], R. L. Aptekar[309], D. D. Frederiks[309], D. S. Svinkin[309], A. Rau[220], A. von Kienlin[220], X. Zhang[220], D. M. Smith[230], T. Cline[39,380], H. Krimm[245,310]
(The InterPlanetary Network),

F. Abe[311], M. Doi[312], K. Fujisawa[313], K. S. Kawabata[314], T. Morokuma[312], K. Motohara[312], M. Tanaka[315], K. Ohta[316], K. Yanagisawa[317], M. Yoshida[314]
(The J-GEM Collaboration),

C. Baltay[318], D. Rabinowitz[318], N. Ellman[318], S. Rostami[318]
(The La Silla–QUEST Survey),

D. F. Bersier[319], M. F. Bode[319], C. A. Collins[319], C. M. Copperwheat[319], M. J. Darnley[319], D. K. Galloway[320,321], A. Gomboc[322,323], S. Kobayashi[319], P. Mazzali[319], C. G. Mundell[324], A. S. Piascik[319], Don Pollacco[325], I. A. Steele[319], K. Ulaczyk[325]
(The Liverpool Telescope Collaboration),

J. W. Broderick[326], R. P. Fender[327], P. G. Jonker[52,328], A. Rowlinson[135,326,329], B. W. Stappers[211], R. A. M. J. Wijers[329]
(The Low Frequency Array (LOFAR) Collaboration),

V. Lipunov[330], E. Gorbovskoy[330], N. Tyurina[330], V. Kornilov[330], P. Balanutsa[330], A. Kuznetsov[330], D. Buckley[331], R. Rebolo[332], M. Serra-Ricart[332], G. Israelian[332], N. M. Budnev[333], O. Gress[333], K. Ivanov[333], V. Poleshuk[333], A. Tlatov[334], V. Yurkov[335]
(The MASTER Collaboration),

N. Kawai[336], M. Serino[337], H. Negoro[338], S. Nakahira[339], T. Mihara[337], H. Tomida[340], S. Ueno[340], H. Tsunemi[341], M. Matsuoka[337]
(The MAXI Collaboration),

S. Croft[342,343], L. Feng[344], T. M. O. Franzen[345], B. M. Gaensler[135,139,346], M. Johnston-Hollitt[347], D. L. Kaplan[16], M. F. Morales[131], S. J. Tingay[135,345,348], R. B. Wayth[135,345], A. Williams[345]
(The Murchison Wide-field Array (MWA) Collaboration),

S. J. Smartt[349], K. C. Chambers[350], K. W. Smith[349], M. E. Huber[350], D. R. Young[349], D. E. Wright[349], A. Schultz[350], L. Denneau[350], H. Flewelling[350], E. A. Magnier[350], N. Primak[350], A. Rest[351], A. Sherstyuk[350], B. Stalder[350], C. W. Stubbs[352], J. Tonry[350], C. Waters[350], M. Willman[350]
(The Pan-STARRS Collaboration),

F. Olivares E.[353,354], H. Campbell[355], R. Kotak[349], J. Sollerman[306], M. Smith[26], M. Dennefeld[356], J. P. Anderson[357],

M. T. Botticella[285], T.-W. Chen[220], M. D. Valle[285], N. Elias-Rosa[283], M. Fraser[355], C. Inserra[349], E. Kankare[349], T. Kupfer[301], J. Harmanen[358], L. Galbany[353,359], L. Le Guillou[360,361], J. D. Lyman[325], K. Maguire[349], A. Mitra[361], M. Nicholl[171], A. Razza[353,359], G. Terreran[283,349], S. Valenti[362,363], A. Gal-Yam[364]
(The PESSTO Collaboration),

A. Ćwiek[110], M. Ćwiok[365], L. Mankiewicz[366], R. Opiela[366], M. Zaremba[365], A. F. Żarnecki[365]
(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. Evans[367], J. A. Kennea[72], D. N. Burrows[72], S. Campana[284], S. B. Cenko[39,368], P. Giommi[288], F. E. Marshall[39], J. Nousek[72], P. O'Brien[367], J. P. Osborne[367], D. Palmer[369], M. Perri[282,288], M. Siegel[72], G. Tagliaferri[284]
(The Swift Collaboration),

A. Klotz[370], D. Turpin[370], R. Laugier[53]
(The TAROT, Zadko, Algerian National Observatory, and C2PU Collaboration),
M. Beroiz[85,371], T. Peñuela[85,372], L. M. Macri[373], R. J. Oelkers[373], D. G. Lambas[374], R. Vrech[374], J. Cabral[374], C. Colazo[374], M. Dominguez[374], B. Sanchez[374], S. Gurovich[374], M. Lares[374], J. L. Marshall[373], D. L. DePoy[373], N. Padilla[375], N. A. Pereyra[85], M. Benacquista[85]
(The TOROS Collaboration),
and

N. R. Tanvir[367], K. Wiersema[367], A. J. Levan[325], D. Steeghs[325], J. Hjorth[305], J. P. U. Fynbo[305], D. Malesani[305], B. Milvang-Jensen[305], D. Watson[305], M. Irwin[355], C. G. Fernandez[355], R. G. McMahon[355], M. Banerji[355], E. Gonzalez-Solares[355], S. Schulze[353,375], A. de U. Postigo[305,376], C. C. Thoene[376], Z. Cano[377], and S. Rosswog[306]
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