In preparation. Target journal: ApJL
Preprint typeset using LaTeX style AASTeX6 v. 1.0

LOCALIZATION AND BROADBAND FOLLOW-UP OF THE GRAVITATIONAL-WAVE TRANSIENT GW150914

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ABSTRACT

A gravitational-wave transient was identified in data recorded by the Advanced LIGO detectors on 2015 September 14. The event, initially designated G184098 and later given the name GW150914, is described in detail elsewhere. By prior arrangement, preliminary estimates of the time, significance, and sky location of the event were shared with 63 teams of observers covering radio, optical, near-infrared, X-ray, and gamma-ray wavelengths with ground- and space-based facilities. In this Letter we describe the low-latency analysis of the gravitational wave data and present the sky localization of the first observed compact binary merger. We summarize the follow-up observations reported by 25 teams via private Gamma-ray Coordinates Network Circulars, giving an overview of the participating facilities, the gravitational wave sky localization coverage, the timeline and depth of the observations. As this event turned out to be a binary black hole merger, there is little expectation of a detectable electromagnetic signature. Nevertheless, this first broadband campaign to search for a counterpart of an Advanced LIGO source represents a milestone and highlights the broad capabilities of the transient astronomy community and the observing strategies that have been developed to pursue neutron star binary merger events. Detailed investigations of the electromagnetic data and results of the electromagnetic follow-up campaign will be disseminated in the papers of the individual teams.

Keywords: gravitational waves; methods: observational

1. INTRODUCTION

A new generation of gravitational wave (GW) detectors is now enabling deeper searches for GW events, with the Advanced Laser Interferometer Gravitational-wave Observatory (LIGO; Aasi et al. 2015) operational and Advanced Virgo (Acernese et al. 2015) expected to join in the next months (Abbott et al. 2016f). Some of the most readily detectable GW signals are linked to systems that are known or inferred to produce broadband electromagnetic (EM) emission as well as neutrinos. This includes, for example, core-collapse supernova (SNe) and stellar-mass compact binary coalescences (CBCs).

In a CBC event, a tight binary comprised of two neutron stars (NSs), two black holes (BHs), or a NS and a BH experiences a runaway orbital decay due to gravitational radiation. In a NS binary—a binary neutron star (BNS) or neutron star–black hole (NSBH) system—we expect EM signatures due to energetic outflows at different timescales and wavelengths. If a relativistic jet forms, we may observe a prompt short gamma-ray burst (SGRB) lasting on the order of one second or less, followed by X-ray, optical and radio afterglows of hours-days duration (e.g., Eichler et al. 1989; Narayan et al. 1992; Nakar 2007; Berger 2014a; Fong et al. 2015). Rapid neutron capture in the sub-relativistic ejecta (e.g., Lattimer & Schramm 1976) is hypothesized to produce a kilonova (KN) or macronova, an optical–near infrared signal lasting hours–weeks (e.g., Li & Paczyński 1998). Eventually, we may observe a radio blast wave from this sub-relativistic outflow, detectable for months–years (e.g., Nakar & Piran 2011). Furthermore, several seconds prior to or tens of minutes after merger, we may see a coherent radio burst lasting milliseconds (e.g., Hansen & Lyutikov 2001; Zhang 2014). In short, a NS binary can produce EM radiation over a wide range of wavelengths and time scales. On the other hand, in the case of a stellar-mass binary black hole (BBH), the current consensus is that no significant EM counterpart emission is expected, except for those in highly improbable environments pervaded by large ambient magnetic fields or baryon densities.

The first GW-triggered EM observations were carried out during the 2009–2010 science run of the initial LIGO and Virgo detectors (Abadie et al. 2012), featuring real-time searches for un-modeled GW bursts and CBCs. 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.

In preparing for Advanced detector operations, LIGO and Virgo worked with the broader astronomy community to set up an evolved and greatly expanded EM follow-up program.[1] Seventy-four groups with access to ground- and space-based facilities joined, of which 63 were operational during Advanced LIGO's first observing run (O1). 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 a 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 Notices on the Gamma-ray Coordinates Network (GCN)[2], 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.

After years of construction and commissioning, the Advanced LIGO detectors at Livingston, Louisiana, and Hanford, Washington, began observing in 2015 September with about 3.5 times the distance reach (> 40 times the sensitive volume) of the earlier detectors. A strong GW event was identified shortly after the pre-run calibration process was completed. Deep analysis of this event, initially called G184098 and later given the name GW150914, is discussed in detail in Abbott et al. (2016a) and companion papers referenced therein. In this paper we describe the initial low-latency analysis and event candidate selection (§2), rapid determination of likely sky localization (§3), and the follow-up EM observations carried out by partner facilities (§4, §5). For analyses of those observations, we refer the reader to the now-public GCN Circulars[3] and forthcoming publications. We end with a brief discussion of EM counterpart detection prospects for this and future events.

2. DATA ANALYSIS AND DISCOVERY

As configured for O1, four low-latency pipelines continually search for transient signals that are coincident in the two detectors within the 10 ms light travel time separating them. Coherent WaveBurst (cWB; Klimenko et al. 2015) and Omicron+LALInference Burst (oLIB; Lynch et al. 2015) both search for un-modeled GW bursts (Abbott et al. 2016d) and produce sky position probability maps. GSTLAL (its name derived from GStreamer and LAL, the LIGO Algorithm Library; Cannon et al. 2012; Messick et al. 2016) and Multi-Band Template Analysis (MBTA; Adams et al. 2015) search specifically for NS binary mergers using matched filtering. Since CBC waveforms can be precisely computed from general relativity, GSTLAL and MBTA are more sensitive to CBC signals than the burst search pipelines are. The BAYESTAR algorithm (Singer & Price 2016) calculates sky maps for all CBC candidates. All four detection pipelines report candidates within a few minutes of data acquisition.

LIGO conducted a series of engineering runs throughout Advanced LIGO's construction and commissioning to prepare to collect and analyze data in a stable configuration. The eighth engineering run (ER8) began on 2015 August 17 at 15:00[4] and critical software was frozen by August 30. The rest of ER8 was to be used to calibrate the detectors, to carry out diagnostic studies, to practice maintaining a high coincident duty cycle, and to train and tune the data analysis pipelines. Calibration was complete by September 12 and O1 was scheduled to begin on September 18. On 2015 September 14, cWB reported a burst candidate to have occurred at 09:50:45 with a network signal-to-noise ratio (S/N) of 23.45 and an estimated false alarm rate (FAR) < 0.371 yr^{-1} based on the available (limited at that time) data statistics. Also, oLIB reported a candidate with consistent timing and S/N. No candidates were reported at this time by the low-latency GSTLAL and MBTA pipelines, ruling out a BNS or NSBH merger.

Although the candidate occurred before O1 officially began, the LIGO and Virgo collaborations decided to send an alert to partner facilites because the preliminary FAR estimate satisfied our planned alert threshold of 1 month^{-1}. Though we had not planned to disseminate real-time GCN Notices before the formal start of O1, most of the computing infrastructure was in place. Basic data quality checks were done within hours of GW150914; both interferometers were stable and the data stream was free of artifacts (Abbott et al. 2016b). A cWB sky map was available 17 min after the data were recorded, and a LALInference Burst (LIB) sky map after 14 hr. After extra data integrity checks and an update to the GCN server software, these two sky maps were communicated to observing partners in a GCN Circular nearly two days after the event occurred (GCN 18330). Mass estimates were not released in this initial Circular, and observers may have assumed the event was associated with a BNS system or a GW burst (e.g., from a nearby core-collapse SN). The knowledge that GW150914 was consistent with a BBH inspiral and merger was only shared later, on October 3 (GCN 18388). The chronology of the GW detection alerts and follow-up observations is shown in Fig. 1.

The data were re-analyzed offline with two independent

[1] See program description at http://www.ligo.org/scientists/GWEMalerts.php.
[2] http://gcn.gsfc.nasa.gov
[3] All Circulars related to GW150914 are collected at http://gcn.gsfc.nasa.gov/other/GW150914.gcn3
[4] All dates and times are in UT.

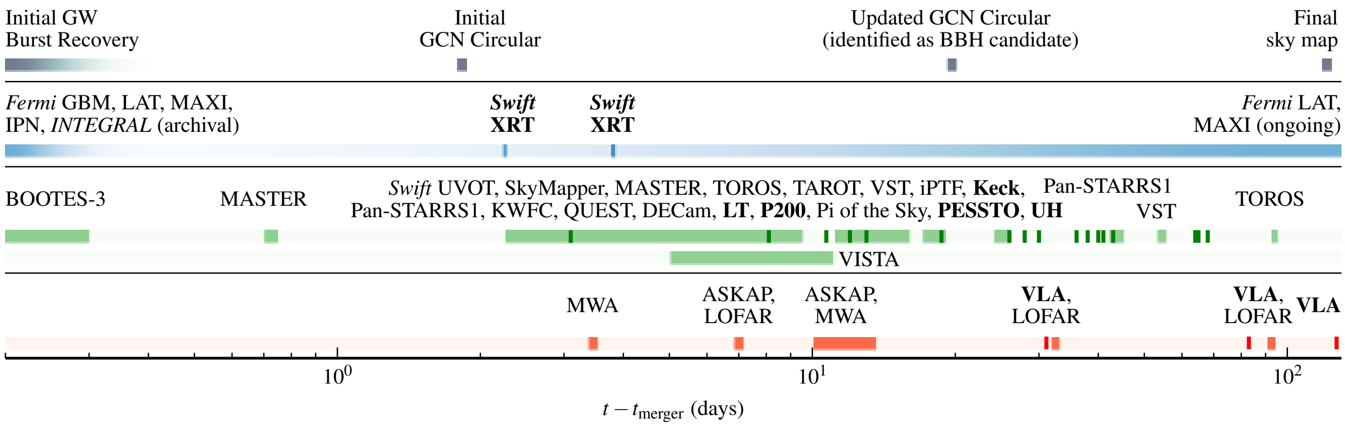

Figure 1. Timeline of observations of GW150914, separated by band and relative to the time of the GW trigger. The top row shows GW information releases. The bottom four rows show high-energy, optical, near-infrared, and radio observations respectively. Optical spectroscopy and narrow-field radio observations are indicated with darker tick marks and boldface text. More detailed information on the timeline of observations is reported in Table 2.

matched-filter searches using a template bank which includes both NS binary and BBH mergers. The waveform was confirmed to be consistent with a BBH merger and this information was shared with observers about 3 weeks after the event (GCN 18388). The FAR was evaluated with the data collected through 20 October, reported to be less than 1 in 100 years (GCN 18851; Abbott et al. 2016c), and ultimately determined to be much lower. The final results of the offline search are reported in Abbott et al. (2016a).

3. SKY MAPS

We produce and disseminate probability sky maps using a sequence of algorithms with increasing accuracy and computational cost. Here, we compare four location estimates: the prompt cWB and LIB localizations that were initially shared with observing partners plus the rapid BAYESTAR localization and the final localization from LALInference. All four are shown in Fig. 2.

cWB performs a constrained maximum likelihood (ML) estimate of the reconstructed signal on a sky grid (Klimenko et al. 2015) weighted by the detectors' antenna patterns (Essick et al. 2015) and makes minimal assumptions about the waveform morphology. With two detectors, this amounts to restricting the signal to only one of two orthogonal GW polarizations throughout most of the sky. LIB performs Bayesian inference assuming the signal is a sinusoidally modulated Gaussian (Lynch et al. 2015). While this assumption may not perfectly match the data, it is flexible enough to produce reliable localizations for a wide variety of waveforms, including BBH inspiral-merger-ringdown signals (Essick et al. 2015). BAYESTAR produces sky maps by triangulating the times, amplitudes, and phases on arrival supplied by the CBC pipelines (Singer & Price 2016). BAYESTAR was not available promptly because the low-latency CBC searches were not configured for BBHs; the localization presented here is derived from the offline CBC search. LALInference performs full forward modeling of the data using a parameterized CBC waveform which allows for BH spins and detector calibration uncertainties (Veitch et al. 2015). It is the most accurate method for CBC signals but takes the most time due to the high dimensionality. We present the same LALInference map as Abbott et al. (2016e), with a spline interpolation procedure to include the potential effects of calibration uncertainties. The BAYESTAR and LALInference maps were shared with observers on 2016 January 13 (GCN 18858), at the conclusion of the O1 run. Since GW150914 is a CBC event, we consider the LALInference map to be the most accurate, authoritative, and *final* localization for this event.

All of the sky maps agree qualitatively, favoring a broad, long section of arc in the Southern hemisphere and to a lesser extent a shorter section of nearly the same arc near the equator. While the majority of LIB's probability is concentrated in the Southern hemisphere, a non-trivial fraction of the 90% confidence region extends into the Northern hemisphere. The LALInference shows much less support in the Northern hemisphere which is likely associated with the stronger constraints available with full CBC waveforms. The cWB localization also supports an isolated hot spot near $\alpha \sim 9^{\rm h}, \delta \sim 5°$. While all algorithms assume elliptical polarization throughout most of the sky, cWB's assumptions are relaxed near this island where the detector responses make it possible to distinguish other polarizations.

Table 1 shows that the size of confidence regions varies between the algorithms. For this event, cWB produces smaller confidence regions than the other algorithms. While cWB produces reasonably accurate maps for typical BBH signals, it can systematically misestimate the sizes of large confidence

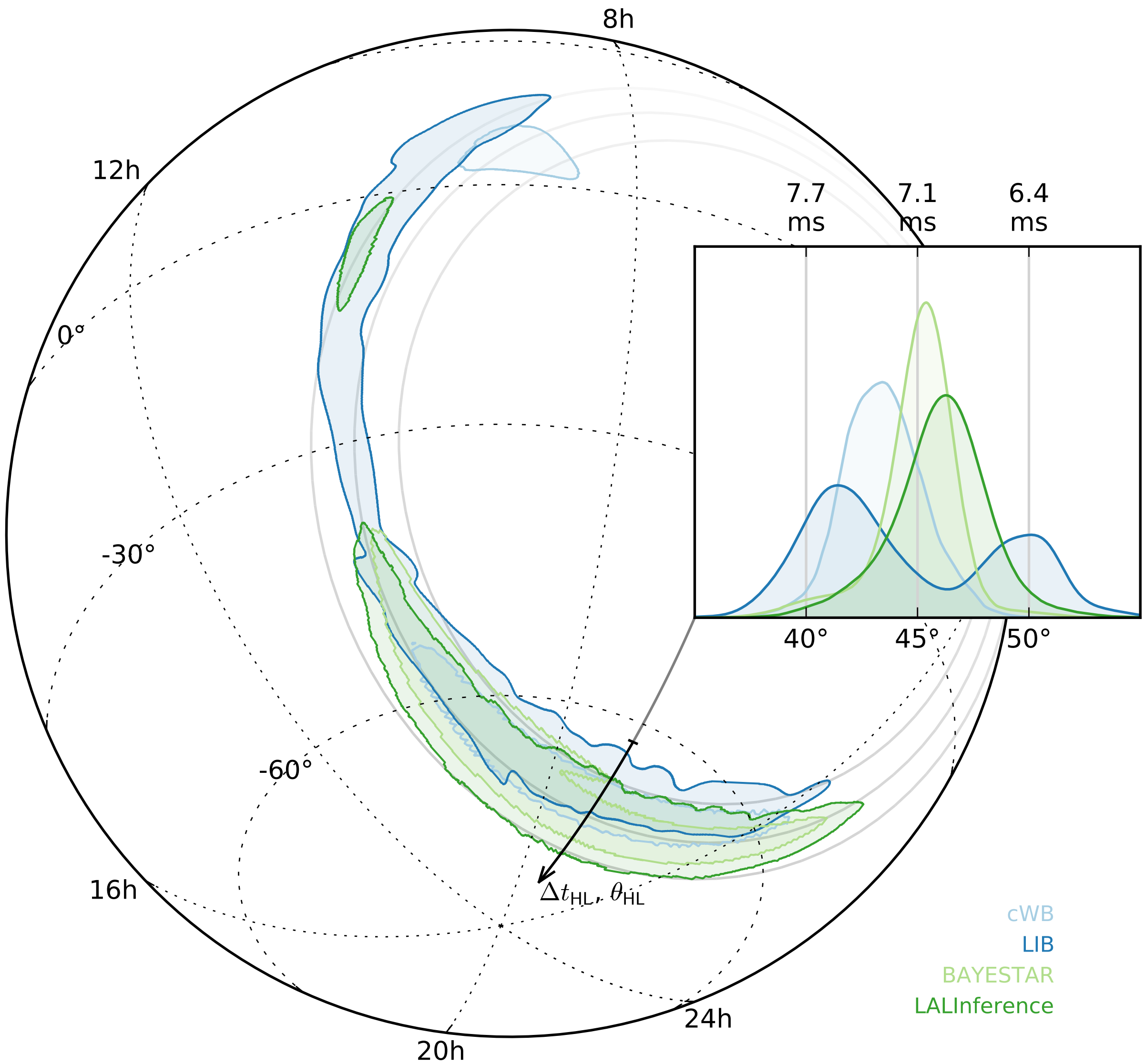

Figure 2. Comparison of different GW sky maps, showing the 90% credible level contours for each algorithm. This is an orthographic projection centered on the centroid of the LIB localization. The inset shows the distribution of the polar angle θ_{HL} (equivalently, the arrival time difference Δt_{HL}).

regions (Essick et al. 2015). The other algorithms are more self-consistent 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.

The main feature in all of the maps is an annulus with polar angle θ_{HL} determined by the arrival time difference Δt_{HL} between the two detectors. However, refinements are possible due to phase as well as amplitude consistency and the mildly directional antenna patterns of the LIGO detectors (Kasliwal & Nissanke 2014; Singer et al. 2014). In particular, the detectors' antenna patterns dominate the modulation around the ring for unmodelled reconstructions through a correlation

Table 1. Description of Sky Maps

	Area[a]			$\theta_{\rm HL}$[b]	Comparison[c]			
	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	270
BSTR	10	90	400	45^{+2}_{-2}	0.64	0.56	—	350
LALInf	20	150	620	46^{+3}_{-3}	0.59	0.55	0.90	—

[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. (2016e) due to minor differences in sampling and interpolation.

[b] Mean and 10% and 90% percentiles of polar angle in degrees.

[c] Fidelity (below diagonal) and the intersection in deg^2 of the 90% confidence regions (above diagonal).

with the inferred distance of the source (Essick et al. 2015). As shown in Table 1 and Fig. 2, the algorithms all infer polar angles that are consistent at the 1σ level. Table 1 also shows the intersections of the 90% confidence regions as well as the fidelity $F(p, q) = \int \sqrt{pq}\,\mathrm{d}\Omega \in [0, 1]$ between two maps p and q. All these measures show that 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 $\theta_{\rm HL}$ distribution (Fig. 2 inset), which is associated with a degeneracy in the signal's chirality (or equivalently the binary's inclination) at different points around the ring. Similar features were noted for BNS systems as well (Singer et al. 2014).

4. FOLLOW-UP OBSERVATIONS

Twenty-five teams of observers participating in the EM follow-up program responded to the GW candidate alert. The EM observations involved satellites and ground-based telescopes around the globe spanning 19 orders of magnitude in frequency across the EM spectrum. Fig. 1 shows the different facilities and the timeline of the observations.

The search for EM counterpart candidates started shortly after the candidate was announced, two days after the event was recorded, and included both archival analysis and targeted observations. Portions of the cWB and LIB sky maps were covered by wide-field facilities based on the GW sky map and instrument visibility. Some groups, considering the possibility of a NS merger or core-collapse SN, selected fields based on the areal density of nearby galaxies or pointed at the Large Magellanic Cloud (LMC) (e.g. Annis et al. 2016). Had the BBH nature of the signal been promptly available, most groups would not have favored local galaxies because LIGO's range for BBH mergers is many times larger than for BNSs. Fig. 3 displays the footprints of all reported observations. The campaign is summarized below and in Table 2 in terms of depth, time and sky coverage.

4.1. *Gamma-ray/X-ray*

The *Fermi* Gamma-ray Burst Monitor (GBM; Meegan et al. 2009), instruments onboard *INTEGRAL* (Winkler et al. 2003), and the InterPlanetary Network (IPN; Hurley et al. 2010) were used to search for prompt high-energy emission temporally coincident with the GW event. Although no GRB trigger was reported by any instrument in coincidence with GW150914, an off-line analysis of the Fermi-GBM (8 keV–40MeV) data revealed a weak transient with duration of $\sim$ 1 s (Connaughton et al. 2016). A similar analysis was performed for the instruments onboard *INTEGRAL* (Winkler et al. 2003) among which the most effective for this purpose is the anti-coincidence shield of the spectrometer (SPI–ACS, von Kienlin et al. 2003, 75 keV–1 MeV) [5] (GCN 18354). No significant signals were detected by *INTEGRAL*, which set the upper limits on the hard X-ray fluence at the time of the event reported in Table 2 (Savchenko et al. 2016). See Savchenko et al. (2016) and Connaughton et al. (2016) for details on how the *INTEGRAL* SPI-ACS upper limit compares with the *Fermi*-GBM result. Data from the six-spacecraft, all-sky, full-time monitor IPN, (*Odyssey- HEND*, *Wind- Konus*, *RHESSI*, *INTEGRAL- SPIACS*, and *Swift - BAT*[6] were analyzed. Apart from the weak GBM signal, no bursts were detected around the time of GW150914. A more complete description of the IPN search is in preparation.

The *Fermi* LAT, MAXI and *Swift* searched for high-energy afterglow emission. The LIGO localization first entered the *Fermi* LAT field of view (FOV) at 4200 s after the GW trigger and was subsequently observed in its entirety over the next 3 hr and every 3 hr thereafter searching 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 (GSC; Matsuoka et al. 2009) aboard the International Space Station (ISS) from 86 to 77 min before the GW trigger and was re-observed during each subsequent $\sim$ 92 min orbit. 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 5 tiles containing 8 nearby galaxies for a total $\sim$0.3 deg^2 area in the 0.3–10 keV energy range. A further series of 37-point tiled observations was taken the day after on a portion of the LMC. *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).

4.2. *Optical/Near-IR*

Searches in the optical and near infrared were performed in stages, with wide-field (1–10 deg^2) telescopes concentrating their observations during the first week to identify candidate

[5] NTEGRAL instruments, including the coded-mask imager (IBIS, Ubertini et al. 2003, 20–200 keV) were pointed far outside the interesting region for the GW trigger.

[6] *Swift* Burst Alert Telescope did not intersect the GW localization at the time of the trigger

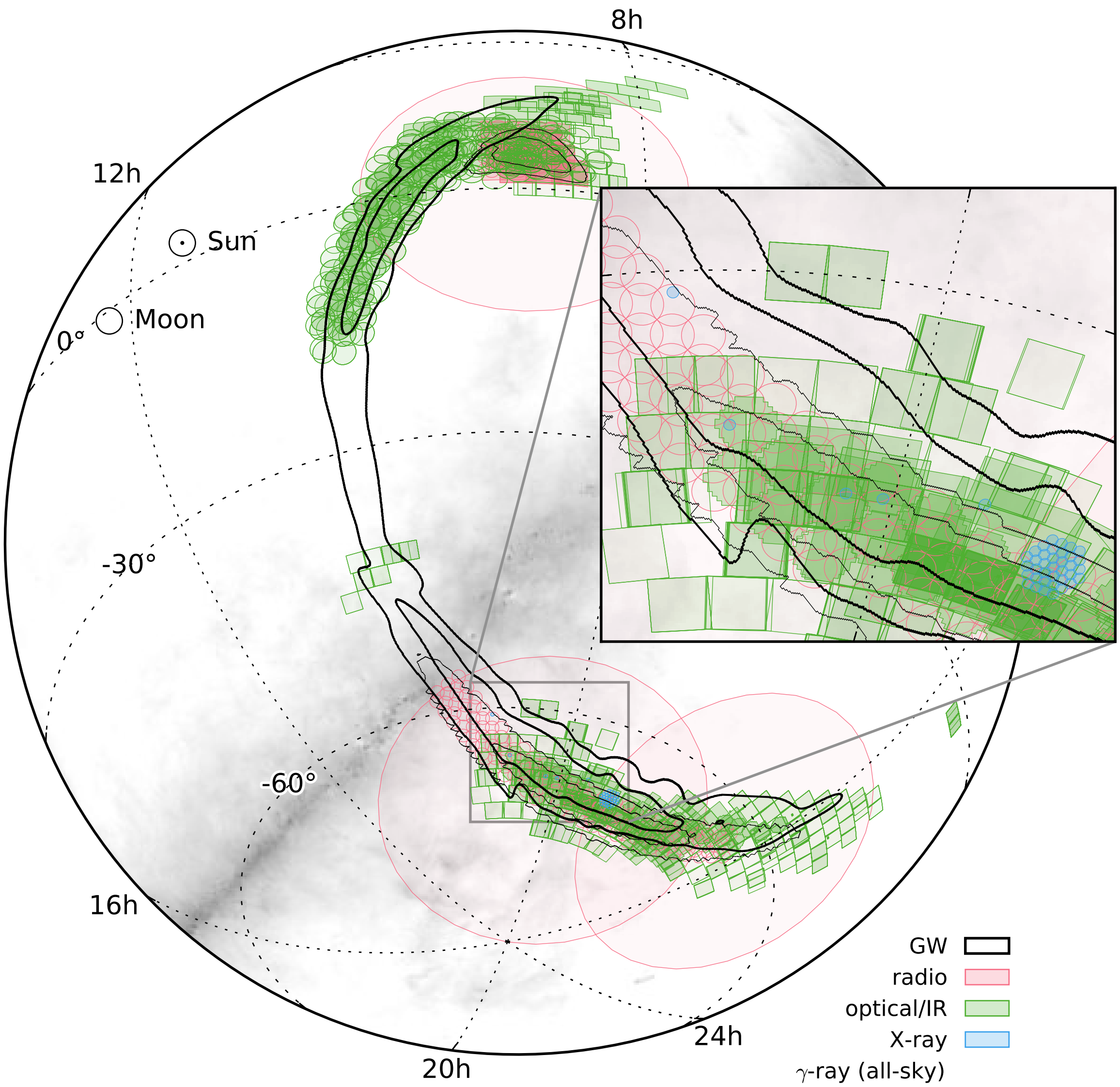

Figure 3. Footprints of observations in comparison with the 50% and 90% credible levels of the initially distributed GW localization maps. Radio fields are shaded red, optical/infrared fields are green, and XRT fields are blue circles. The all-sky *Fermi* GBM, LAT, *INTEGRAL* SPI-ACS, and MAXI observations are not shown. Where fields overlap, the shading is darker. The initial cWB localization is shown as thin black contour lines and the refined LIB localization as thick black lines. The inset highlights the *Swift* observations consisting of a hexagonal grid and a selection of the *a posteriori* most highly ranked galaxies. The Schlegel et al. (1998) reddening map is shown in the background to represent the Galactic plane. The projection is the same as in Fig. 2.

counterparts, and then with larger telescopes (with narrower FOVs) to obtain classification. The operating wide-field facilities were the DECam on the CTIO Blanco telescope Blanco (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), MASTER-SAAO twin robotic telescope of 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, Brocato et al. 2016 in preparation)[7] in the optical band, and the Visible and Infrared Survey Telescope (VISTA@ESO; Emerson et al. 2006)[8] in the near infrared. They represent different classes of instruments ranging from diameters of 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 70–430 $\deg^2$. 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 prep.), also participated in the optical coverage of the GW sky maps. *Swift* UVOT ultraviolet and optical simultaneously with XRT, giving a broadband coverage of 80% of the *Swift* XRT FOV.

A few tens of candidate counterparts were identified by the wide-field telescope surveys and followed by larger telescopes, including the 10 m Keck II telescope (DEIMOS; 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,

Bright optical transients were searched also using archival data of 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 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 to find slowly fading transients brighter than $R < 11.5$ mag (GCN 19034).

[7] ESO proposal ID:095.D-0195,095.D-0079
[8] ESO proposal ID:095.D-0771

4.3. *Radio*

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 2–3). The Low Frequency Array (LOFAR; van Haarlem et al. 2013) and the Murchison Widefield 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 Murchison Widefield Array). The Australian Square Kilometer Array Pathfinder (ASKAP; Hotan et al. 2014) is an interferometric array composed of thirty-six 12 m-diameter dish antennas. The Karl G. Jansky Very Large Array (VLA; Perley et al. 2009) is a twenty-seven antenna array, with dishes of 25 m diameter. Both Australian Square Kilometer Array Pathfinder and the VLA are sensitive from centimeter to decimeter wavelengths.

MWA started observing 3 d after the GW trigger with a 30 MHz bandwidth around a central frequency of 118 MHz and reached a root mean square (RMS) noise level of about 40 mJy/beam. The ASKAP observations used the five-element Boolardy Engineering Test Array (BETA; Schinckel et al. 2012), which has a 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 ≈ 7 to ≈ 14 d after the GW trigger, reaching RMS sensitivities of $1 - 3$ mJy/beam. LOFAR conducted three observations from ≈ 7 d to ≈ 3 months following the GW trigger, reaching a RMS sensitivity of ≈ 2.5 mJy/beam 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 month to ≈ 4 months after the GW trigger[9], 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 $\approx 8 - 10\mu$Jy/beam.

5. COVERAGE

Using the GW data by itself, we can only constrain the position of the source on the sky to an area of $590\,\deg^2$ (90% confidence), a redshift of $z = 0.09^{+0.03}_{-0.04}$, corresponding to a luminosity distance of 410^{+160}_{-180} Mpc (Abbott et al. 2016e).

Table 2 lists the area tiled by each facility and the probability contained within those tiles, calculated with respect to the localization methods described in §3.

[9] VLA/15A-339, PI: A. Corsi

By far the most complete coverage of the area is at the highest energies. The *INTEGRAL* SPI–ACS provided the largest effective area in the 75 keV–1 MeV range, albeit with significantly different detection efficiency. Owing to its nearly omnidirectional response, it had a full coverage of the GW probability map (GCN 18354; Savchenko et al. 2016). *Fermi* GBM captured 75% of the localization at the time of the GW trigger and the entire area by 25 min after (GCN 18339). *Fermi* LAT observations started 4200 s after the trigger and the entire localization continued to be observed every three hours.

Coverage in X-rays is complete down to 10^{-9} erg cm^{-2} s^{-1} with the MAXI observations, but relatively sparse at fainter flux, with the *Swift* XRT tiles spanning about 5 deg^2 and enclosing a probability of $\sim$0.3% in the energy range 0.3–10 keV to a depth of 10^{-13}–10^{-11} erg cm^{-2} s^{-1} (GCN 18346).

Optical facilities together tiled about 870 deg^2 and captured a containment probability of 57% of the initial LIB sky map, though only 36% of the refined LALInference sky map that was available only after the observations were completed. The depth varies widely among these facilities. The covered area is dominated by MASTER (unfiltered magnitude $<$ 19.9 mag; GCNs 18333, 18390, and 18903), Pan-STARRS ($i < 19.2 - 20.8$), and iPTF ($R <$ 20.4 mag; GCN 18337), while the contained probability is dominated by MASTER, DECam ($i <$ 22.5 mag; Soares-Santos et al. 2016), Pan-STARRS, VST@ESO ($r <$ 22.4 mag; GCNs 18336 and 18397) for the initial sky maps, and MASTER, DECam, VST@ESO for the updated sky maps. Relatively small area and contained probability were covered by facilities that targeted nearby galaxies. The only near infrared facility VISTA@ESO covered 70 deg^2 and captured a containment probability of 8% of the refined LALInference sky map.

The radio coverage is also extensive, with the contained probability of 86%, dominated by MWA in the 118 MHz band (GCN 18345).

Table 3 summarizes the follow-up of candidate optical counterparts by large telescope spectrographs and a radio facility. Deep photometry, broadband observations and spectroscopy identified the majority of the candidates to be normal population type Ia and type II SNe, a few dwarf novae and active galactic nuclei (AGNs), all very likely unrelated to GW150914. Candidate classification, comparison of redshift with the GW distance, and use of source age are crucial constraints to rule candidates in and out. A detailed discussion of candidate selection, spectroscopic and broadband follow-up will be presented in forthcoming survey-specific publications: iPTF (Kasliwal et al., 2016, in prep), Pan-STARRS and PESSTO (Smartt et al. 2016) and other papers by individual teams.

6. SENSITIVITY

In the third column of Table 2 we summarize the depth of the follow-up program. We provide limiting flux, flux density, or magnitude for the different facilties. We emphasize that these limits only apply to the fraction of the sky contours that have been followed up. For example, the MWA fields have an 86% chance of containing the source's sky location, and provide no constraints on the remaining 14% of the possible sky locations.

Since the follow-up program was primarily designed to search for counterparts to BNS and NSBH systems, it is interesting to note that the observational campaign would have provided powerful constraints. If GW150914 had an associated short GRB, it would easily have been detectable within the actual distance of GW150914 (Berger 2014b). For a BNS coalescence at $\sim$ 70 Mpc, the average distance at which it could have been detected during O1[10], might produce a short gamma-ray burst X-ray afterglow 11 hours after the burst with isotropic-equivalent flux of 2×10^{-11} to 6×10^{-8} erg cm^{-2} s^{-1} (Berger 2014b). A BNS at that distance might also produce a kilonova (e.g., Metzger et al. 2010; Barnes & Kasen 2013; Tanaka & Hotokezaka 2013; Grossman et al. 2014) within a few days after merger with apparent magnitude in the range 17–24. This range lies within the depth reached in the optical band but also in the near IR where observations (Tanvir et al. 2013; Berger et al. 2013) suggest the bulk of the emission. Finally, this BNS system might have produced radio afterglows in the range of 0.1–15 mJy (e.g., Hotokezaka & Piran 2015). We note that many of these possible counterparts could have been detected by the EM follow-up effort associated with GW150914. Tables 2–3 show that the radio observations from wide field facilities were sensitive to the bright counterparts at low frequencies while the VLA to fainter counterparts at frequencies above a few GHz.

7. CONCLUSIONS

GW150914 is consistent with the inspiral and merger of two BHs of masses 36^{+5}_{-4} and $29^{+4}_{-4}\,M_\odot$ respectively, resulting in the formation of a final BH of mass $62^{+4}_{-4}\,M_\odot$ (Abbott et al. 2016a). In classical general relativity, a *vacuum* BBH merger does not produce any EM or particle emission whatsoever. Whereas supermassive BBHs in galactic centers may appear as dual AGNs or have other distinctive EM signatures due to interactions with gas or magnetic fields, stellar BBH systems are not expected to possess detectable EM counterparts. The background gas densities and magnetic field strengths should therefore be typical of the interstellar medium, which are many orders of magnitude smaller than the environments of EM bright supermassive BBHs. Although GW150914 is loud in GWs and expected to be absent in all EM bands, thorough follow-up observations were pursued to check for EM emission. Future EM follow-ups of GW sources will shed light on the presence or absence of firm EM counterparts and

[10] https://dcc.ligo.org/LIGO-G1501223/public

Table 2. Summary of Tiled Observations

Instrument	Band[a]	Depth[b]	Time[c]	Area (deg^2)	Contained probability (%) cWB	LIB	BSTR.	LALInf.	GCN
				Gamma-ray					
Fermi LAT	20 MeV–300 GeV	1.7×10^{-9}	(every 3 hr)	—	100	100	100	100	18709
Fermi GBM	8 keV–40 MeV	0.7–5 $\times 10^{-7}$ (0.1–1 MeV)	(archival)	—	100	100	100	100	18339
INTEGRAL	75 keV–1 MeV	1.3×10^{-7}	(archival)	—	100	100	100	100	18354
IPN	15 keV–10 MeV	1×10^{-9}	(archival)	—	100	100	100	100	—
				X-ray					
MAXI/GSC	2–20 keV	1×10^{-9}	(archival)	17900	95	89	92	84	19013
Swift XRT	0.3–10 keV	5×10^{-13} (gal.)	2.3, 1, 1	0.6	0.03	0.18	0.04	0.05	18331
		2–4 $\times 10^{-12}$ (LMC)	3.4, 1, 1	4.1	1.2	1.9	0.16	0.26	18346
				Optical					
DECam	i, z	$i < 22.5$, $z < 21.5$	3.9, 5, 22	100	38	14	14	11	18344, 18350
iPTF	R	$R < 20.4$	3.1, 3, 1	140	3.1	2.9	0.0	0.2	18337
KWFC	i	$i < 18.8$	3.4, 1, 1	24	0.0	1.2	0.0	0.1	18361
MASTER	C	< 19.9	-1.1, 7, 7	590	56	35	55	49	18333, 18390, 18903, 19021
Pan-STARRS1	i	$i < 19.2 - 20.8$	3.2, 21, 42	430	28	29	2.0	4.2	18335, 18343, 18362, 18394
La Silla–QUEST	g, r	$r < 21$	3.8, 5, 0.1	80	23	16	6.2	5.7	18347
SkyMapper	i, v	$i < 19.1$, $v < 17.1$	2.4, 2, 3	30	9.1	7.9	1.5	1.9	18349
Swift UVOT	u	$u < 19.8$ (gal.)	2.3, 1, 1	3	0.7	1.0	0.1	0.1	18331
	u	$u < 18.8$ (LMC)	3.4, 1, 1						18346
TAROT	C	$R < 18$	2.8, 5, 14	30	15	3.5	1.6	1.9	18332, 18348
TOROS	C	$r < 21$	2.5, 7, 90	0.6	0.03	0.0	0.0	0.0	18338
VST	r	$r < 22.4$	2.9, 6, 50	90	29	10	14	10	18336, 18397
				Near Infrared					
VISTA	Y, J, K_S	$J < 20.7$	4.8, 1, 7	70	15	6.4	10	8.0	18353
				Radio					
ASKAP	863.5 MHz	5–15 mJy	7.5, 2, 6	270	82	28	44	27	18363, 18655
LOFAR	145 MHz	12.5 mJy	6.8, 3, 90	100	27	1.3	0.0	0.1	18364, 18424, 18690
MWA	118 MHz	200 mJy	3.5, 2, 8	2800	97	72	86	86	18345

[a] Band: photon energy, optical or near-infrared filter (or C for clear, unfiltered light), wavelength range, or central frequency

[b] Depth: gamma/X-ray limiting flux in erg cm^{-2} s^{-1}; 5σ optical/IR limiting magnitude (AB); and 5σ radio limiting spectral flux density in mJy. The reported values correspond to the faintest flux/magnitude of detectable sources in the images.

[c] Elapsed time in days between start of observations and the time of GW150914 (2015 September 14 09:50:45), number of repeated observations of the same area, total observation period in days

astrophysical processes that may trigger EM emission from these systems.

The EM campaign following GW150914 successfully demonstrates the capability of the observing partners to cover large swaths of the sky localization area, to identify candidates, and to activate larger telescopes for photometric and spectroscopic characterization within a few days of an event. We note that the information about the source's BBH nature and updated sky maps were sent out twenty days and four months after the event, respectively. This resulted in some instruments covering much less of the probability region or to the required depth of GW150914 than they may have planned for. We expect future alerts to be issued within tens of minutes, and more rapid updates of the maps. The follow-up efforts would have been sensitive to a wide range of emission expected from BNS or NSBH mergers, however the widely

Table 3. Summary of Follow-up Observations

Spectroscopic follow-up						
Instr.	n. of cand.	Disc. Survey	Epochs	λ (Å)	$\Delta\lambda^{a}$ (Å)	GCN
KeckII+DEIMOS	8	iPTF	1	$4650-9600$	3.5	18337, 18341
LT+SPRAT	1	Pan-STARRS1	1	$4500-7500$	18	18370, 18371
PESSTO	10	QUEST/Pan-STARRS1	1	$3650-9250$	18	18359, 18395
P200+DBSP	1	Pan-STARRS1	1	$3200-9000$	$4-8$	18372
UH2.2m+SNIFS	9	Pan-STARRS1	1	$3200-10000$	$4-6$	—
Radio follow-up						
Instr.	n. of cand.	Disc. Survey	Epochs	Freq. (GHz)	Lim. Flux[b] (uJy)	GCN
VLA	1	iPTF	3	6	$\lesssim 50$	18420, 18474, 18914

[a]FWHM resolution

[b] 5σ, 2 GHz nominal bandwidth, ≈ 20 min on-source

variable sensitivity reached across the sky localization area continues to be a challenge for an EM counterpart search.

The number of galaxies (with luminosities $L \geq 0.1L^{\star}$; Blanton et al. 2003) within the comoving volume of 10^{-2} Gpc^3 corresponding to the 90% credible area of the LALInference sky map and within the 90% confidence interval distance is $\sim 10^5$. Such a number makes it impossible to identify the host galaxy in the absence of an EM counterpart detection. The presence of a third GW detector such as Virgo would have improved the sky localization of GW150914 to a few tens of square degrees both for the un-modeled and CBC searches. The future addition of more GW detectors to the global network (Abbott et al. 2016f) will significantly improve the efficiency of searches for EM counterparts.

In summary, we have described the EM follow-up program carried out for the first GW source detected by Advanced LIGO. Within two days of the initial tentative detection of GW150914 a GCN circular was sent to EM follow-up partners alerting them to the event and providing them with initial sky maps. Twenty-five EM observing teams mobilized their resources, and over the ensuing three months observations were performed with a diverse array of facilities over a broad wavelength range (from radio to γ-ray). Findings from those observations will be disseminated in other papers. The localization and broadband follow-up of this GW event constitutes an important first step in a new era of gravitational wave multi-messenger astronomy.

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, Cultura 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. 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.

AJCT 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 U.S. Department of Energy, the U.S. 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.

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 works exploited data by INTEGRAL, an ESA project with instruments and science data centre 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 U.S. under NASA Grant NNX15AU74G.

This work is partly based on observations obtained with the Samuel Oschin Telescope 48-inch and the 60-inch 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. MMK and YC acknowledge funding from the National Science Foundation PIRE program grant 1545949. AAM acknowledges support from the Hubble Fellowship HST-HF-51325.01.

J-GEM is financially supported by KAKENHI Grant No. 24103003, 15H00774 and 15H00788 of MEXT Japan, 15H02069 and 15H02075 of JSPS, and "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 Astrofisica 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, that 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.

We thank JAXA and RIKEN for providing MAXI data, KAKENHI Grant No. 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 programs188.D-3003, 191.D-0935.

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

SJS acknowledges funding from the European Research Council under the European Union's Seventh Framework Programme (FP7/2007-2013)/ERC Grant agreement n^{o} [291222] and STFC grants ST/I001123/1 and ST/L000709/1. MF is supported by the European Union FP7 programme through ERC grant number 320360. KM acknowledges support from the STFC through an Ernest Rutherford Fellowship

FOE 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 number 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 Cientificas 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-P1500227-v9.

Software: Astropy (Robitaille et al. 2013)

Software: HEALPix (Górski et al. 2005)

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