JAMES WEBB SPACE TELESCOPE CAN DETECT KILONOVAE IN GRAVITATIONAL WAVE FOLLOW-UP SEARCH

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ABSTRACT

Kilonovae represent an important electromagnetic counterpart for compact binary mergers, which could become the most commonly detected gravitational-wave (GW) source. Follow-up observations of kilonovae, triggered by GW events, are nevertheless difficult due to poor localization by GW detectors and due to their faint near-infrared peak emission, which has limited observational capability. We show that the Near-Infrared Camera (NIRCam) on the James Webb Space Telescope will be able to detect kilonovae within the relevant GW-detection range of \(\sim 200\) Mpc in short (\(\lesssim 12\)-s) exposure times for a week following the merger. Despite this sensitivity, a kilonova search fully covering a fiducial localized area of \(10\,\text{deg}^2\) will not be viable with NIRCam due to its limited field of view. However, targeted surveys may be developed to optimize the likelihood of discovering kilonovae efficiently within limited observing time. We estimate that a survey of \(10\,\text{deg}^2\) focused on galaxies within 200 Mpc would require about 13 hr, dominated by overhead times; a survey further focused on galaxies exhibiting high star formation rates would require \(\sim 5\) hr. The characteristic time may be reduced to as little as \(\sim 4\) hr, without compromising the likelihood of detecting kilonovae, by surveying sky areas associated with 50\%, rather than 90\%, confidence regions of 3 GW events, rather than a single event. Upon the detection and identification of a kilonova, a limited number of NIRCam follow-up observations could constrain the properties of matter ejected by the binary and the equation of state of dense nuclear matter.

Key words: gravitational waves – infrared: general – methods: observational

1. INTRODUCTION

Compact binary mergers are one of the most actively studied astrophysical phenomena. The mergers of neutron stars and stellar-mass black holes are promising targets for gravitational-astrophysical phenomena. The mergers of neutron stars and drive relativistic outflows, which powers the emission. Due to the large opacity at optical wavelengths of the formed r-process elements, kilonovae peak in the near-infrared, with expected luminosities of \(\sim 10^{40}–10^{41}\) erg s\(^{-1}\), and last for over a week (Barnes & Kasen 2013). Nevertheless, this standard theoretical estimate has important uncertainties that may affect detectability. There is a significant ongoing theoretical effort to obtain a more complete understanding of the emission process, which may inform observations in the future (e.g., Fernández et al. 2015; Kasen et al. 2015a).

Kilonovae are promising electromagnetic counterparts of binary mergers because (i) the emission is isotropic; therefore, the number of observable mergers is not limited by beaming; (ii) the week-long emission period allows sufficient time for follow-up observations; and (iii) once identified, source location can be accurately recovered, allowing for the identification of the host environment and the search for.
counterparts in other electromagnetic regimes. For comparison, some other electromagnetic counterparts, such as gamma-ray bursts and X-ray afterglows, are highly beamed, reducing the number of observable mergers. Optical and radio afterglows are also emitted off-axis; however, detection at large viewing angles is difficult (van Eerten & MacFadyen 2011). Gamma-ray and X-ray emission are also of short duration, which can also be a significant limitation, as it allows less time for follow-up observations. On the other hand, the observability of kilonovae is currently limited by the lack of sufficiently sensitive survey instruments in the near-infrared band that can provide coverage over tens of square degrees, the typical area within which GW events will be localized by the Advanced LIGO-Virgo network (LIGO Scientific Collaboration et al. 2013). The sole kilonova observation so far took advantage of the precisely reconstructed source direction (Berger et al. 2013; Tanvir et al. 2013).

The James Webb Space Telescope (JWST) is a planned, highly sensitive infrared space telescope with an expected launch in 2018. In this paper, we show that its Near-Infrared Camera (NIRCam; Horner & Rieke 2004), with a spectral range of 0.6–5 μm, is well-suited for quickly detecting kilonovae following GW triggers from Advanced LIGO-Virgo.

In Section 2, we determine the sensitivity of NIRCam to detecting kilonova emission within its field of view. In Section 3, we detail the need for observation strategies that target nearby galaxies to host kilonovae; in Section 4, we discuss examples of such targeted surveys to identify kilonovae. The possible role of other astrophysical sources being misidentified as kilonovae is presented in Section 5. In Section 6, we investigate how NIRCam could probe the kilonova emission model and source parameters. We summarize our findings in Section 7.

2. NIRCAM SENSITIVITY TO KILONOVAE

We first calculate the JWST/NIRCam sensitivity for detecting kilonovae. We determine which NIRCam filter is the most sensitive for the expected emission spectrum, and derive the integration time necessary for a 10σ detection. Only then may we develop viable observing strategies with the greatest likelihood of enabling kilonovae identification.

We adopt the kilonova emission model obtained by Barnes & Kasen (2013) using time-dependent, multi-wavelength radiative transport calculations. Barnes & Kasen (2013) simulated a range of emission parameters, particularly ejecta masses $\sim 10^{-3}$–$10^{-1} M_\odot$ and characteristic ejection velocities $\beta \equiv v/c \sim 0.1$–0.3. These ranges seem to cover the expected and observed kilonova emission parameters (Berger et al. 2013; Tanvir et al. 2013).

To determine the observed kilonova flux at Earth, we assume a source luminosity distance of 200 Mpc, which represents the average reach of the Advanced LIGO-Virgo network at design sensitivity to binary neutron star mergers. While some sources may occur even closer or as far as ~450 Mpc under the most favorable conditions, our choice of 200 Mpc provides a good estimate of the potential limitations of a follow-up search with NIRCam.

With kilonova spectra expected to peak in the near-infrared, we calculated the minimum integration time sufficient to detect a kilonova for each of NIRCam’s wideband filters. Preliminary

![Figure 1. Integration time for JWST NIRCam necessary to detect a kilonova ($10^{-2}M_\odot$, ejected mass, $\beta = 0.2$) with 10σ significance as a function of time after a binary merger at 200 Mpc, for different NIRCam filters. The results indicate that the F200W and F277W filters are well-suited to observe kilonovae, depending on how quickly the observations are obtained following the merger.](http://www.stsci.edu/jwst/instruments/nircam/instrumentdesign/filters)

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4 For each filter, the number in the filter name represents 100 times the central wavelength in microns. For example, the central wavelength of F356W is ~3.56 μm.

5 http://jwstetc.stsci.edu/etc/input/nircam/imaging/
minimum integration time of 10.6 s due to the readout time of the detectors in full-array mode; and (ii) the 5″ gaps between the four detectors of each module and the 50″ gap between the two modules, which necessitate positional shifts of less than half the 2/2 × 4/4 field of view for full coverage in the short wavelength channel in survey mode. These positional shifts would also serve to provide, for each point imaged, 2–3 dithered exposures, which may be used to remove image artifacts, such as bad pixels and cosmic rays. To uniformly cover a fiducial localized sky area of 10 deg² associated with a GW source, at a confidence level of 90%, these two factors would necessitate ~50 hr of total exposure time, not including overheads, making it unfeasible to cover the full region associated with a GW trigger event.

4. TARGETED SURVEYS

Several approaches may be used to develop a viable NIRCam survey, triggered by a GW source, to efficiently search for a kilonova, with the greatest chance of success. The survey should be triggered only by the most promising GW sources: those with high S/N and well-localized areas. While we consider a fiducial sky area of 10 deg², a substantial fraction of GW trigger events will have larger reconstructed sky areas (e.g., LIGO Scientific Collaboration et al. 2013; Singer et al. 2014) and will therefore require proportionally longer NIRCam observing times. In this section, we discuss approaches that yield targeted surveys in order to reduce the required NIRCam observing time.

Instead of covering the full 10 deg² area, one approach is to focus the follow-up search toward known galaxies (Kanner et al. 2008; Kopparapu et al. 2008; Nissanke et al. 2013; Hanna et al. 2014; Bartos et al. 2015) within ~200 Mpc, taking advantage of the expectation that binary mergers occur in or near galaxies (Fong et al. 2010). Following Nissanke et al. (2013), the number density of galaxies within 200 Mpc is estimated to be ~8 deg⁻²; therefore, one would need to follow-up ~80 galaxies for a fiducial GW sky area of 10 deg².

Since most galaxies can be covered well within a 400 × 400 pixel² (13″ × 13″) region (e.g., Fong et al. 2010), the NIRCam can be used in a subarray imaging mode (e.g., Beichman et al. 2014) for such a survey of galaxies. In this mode, exposure times as short as ~2 s are possible. In principle, this minimum exposure could be used with F277W for each of 3 dithered images in order to mitigate image artifacts of a galaxy, if observed within three days of the merger. For our purposes, we consider instead three dithered 4-s exposures, enabling the use of F200W for up to a week after the merger. For the 80 galaxies, assuming the most time-intensive case of only one galaxy present in a field, the total exposure time would be 16 minutes, not including overheads. While such an approach represents a significant improvement over full coverage of the GW event, the time associated with overheads is expected to be significant.

The overheads for such an NIRCam imaging survey may be attributed to a number of sources, summarized in Table 1 (Gordon et al. 2012). The most significant contributors to overhead time would be the time for JWST to slew and acquire guide stars. The standard assumption for slew time to a new field is 30 minutes, which we adopt for the slew to the first galaxy following a GW event. Slew times to subsequent galaxies associated with that event depend on the angular separation between the galaxies. While JWST slews at a nominal rate of at least 90″ per hour, the slew rates are nonlinear with distance due to inertia. Shorter slew distances are associated with slower effective rates. A survey of 80 galaxies over a 10 deg² region suggests an average separation of ~21″ between nearby galaxies. According to expectations for slew rates as a function of slew distance (Gardner et al. 2010),

| Table 1 | Targeted Surveys of GW Trigger Event |
|---------|-------------------------------------|
| **90% Confidence Region** | **50% Confidence Region** |
| **Fiducial sky area (deg²)** | 10 | 10 | 2 | 2 |
| **Number of Galaxies** | 80 | 30 | 16 | 6 |
| **Slew Time to First Galaxy (minute)** | 30.0 | 30.0 | 30.0 | 30.0 |
| **Slew Time to Each Subsequent Galaxy (minute)** | 3.6 | 4.5 | 3.6 | 4.5 |
| **Guide Star Acquisition Time for Each Galaxy (minute)** | 4.0 | 4.0 | 4.0 | 4.0 |
| **Dithering Time for Each Galaxy (minute)** | 1.0 | 1.0 | 1.0 | 1.0 |
| **Other Overhead Time (minute)** | 25.1 | 10.1 | 5.9 | 2.9 |
| **Total Overhead Time (hr)** | 12.3 | 5.3 | 8.5 | 4.3 |
| **Total Exposure Time (minute)** | 16.0 | 6.0 | 9.6 | 3.6 |

**Notes.**

a Two dither motions, each requiring 30 s, in order to obtain three dithered images for each galaxy.

b Includes 65 s for filter move and detector configuration, necessary only once, and an adopted detector deadtime of 18 s for each galaxy. The detector deadtime for our subarray observations was assumed to be 6 s, based on discussion in Gordon et al. (2012), for each of the three images of a galaxy.

c Total times listed for a targeted survey of 50% confidence regions are those associated with three GW trigger events for direct comparison to total times for a targeted survey of the 90% confidence region of a single event, yielding a similar likelihood of kilonova detection.
our typical slew time would be no more than $\sim 3.6$ minutes\(^6\) to point from one galaxy to the next. This typical slew is sufficiently large that each field will require a different guide star and 4 minutes for its acquisition. Accounting for the move to the first galaxy, moves to subsequent galaxies, and guide star acquisitions for all fields, the total overhead time associated with slewing and guide stars is 10.6 hr. The next most significant contributor to overhead times would be the time associated with the small (e.g., $< 2\, \text{yr}$) dithering, which totals 1.3 hr for all fields. Finally, other overheads include moving the filter wheel, detector configuration, and deadtime, which total only 0.4 hr. With the full overhead time of 12.3 hr, the total time for this targeted survey of 80 galaxies in 10 $\text{deg}^2$, associated with a GW trigger event, is 12.6 hr.

A second approach is to further focus the survey to target only those nearby galaxies most likely to host kilonovae. For example, the star formation rate is correlated with the rate of compact binary mergers (Leibler & Berger 2010); H\(\alpha\) is an indicator of the star formation rate and therefore may be used to optimize the probability of discovering kilonovae efficiently within a limited observing time. Specifically, H\(\alpha\) mapping may be used to identify those galaxies responsible for 90% of star formation and for 50% of the mass (Metzger et al. 2013; Bartos et al. 2015). Based on the galaxy stellar-mass function for the nearest galaxies (Baldry et al. 2012; Moustakas et al. 2013), with the component due to star-forming galaxies normalized such that they account for 60% of mass of the nearest galaxies (Metzger et al. 2013), these H\(\alpha\)-detected galaxies would represent about 40% of the total number of galaxies. Thus, with only $\sim 30$ galaxies most likely to host kilonovae within 200 Mpc over 10 $\text{deg}^2$, and typical separations of $\sim 35\, \text{arcmin}$, the total overhead associated with slewing and guide star acquisition is further decreased to no more than 4.7 hr. With the additional overheads, the total time for this targeted survey would be 5.4 hr.

We note that a focus on H\(\alpha\) serves to solve another problem: a comprehensive galaxy catalog complete to 200 Mpc may not be ready by 2019, when Advanced LIGO detectors will reach their design sensitivities. For reference, recent galaxy catalogs are estimated to be only $\sim 60\%$ complete to 100 Mpc (e.g., White et al. 2011). Bartos et al. (2015) suggested that on-the-fly H\(\alpha\) mapping may be used to generate catalogs of galaxies for kilonova searches triggered by GW events, and found that mapping a $\sim 10\, \text{deg}^2$ region to identify these galaxies within 200 Mpc can be done cost effectively and quickly, within a day, using a 1–2 m class telescope.

Finally, another approach for a targeted survey is to focus on the galaxies in the 50% (as opposed to 90%) confidence region of the localized sky area associated with a GW event. Such an approach can decrease the covered sky area by a factor of $\sim 5$ (Singer et al. 2014). In this case, if the targeted survey follows up three GW triggers instead of one, then a similar probability of success (90%) is achieved by covering 40% fewer galaxies than the survey of a single 90% confidence region. Such an approach, however, does not require 40% less time since the slew to the first galaxy following a GW trigger would occur three times. Targeted surveys of all nearest ($\leq 200$ Mpc) galaxies and only nearby H\(\alpha\) galaxies within 50% confidence regions of the localized areas of three optimal GW sources could be done with NIRCam within a total of 8.7 and 4.4 hr, respectively. Not only would such an approach require less time, but it would also result in fewer galaxies needing follow-up observations to confirm a kilonova identification.

JWST is not an efficient facility for a survey involving quick exposures of many fields. In these examples of targeted surveys, the overhead times are 50–70 times greater than the exposure times. Despite this inefficiency, by judiciously choosing the galaxies most likely to host kilonovae associated with GW events, the NIRCam observing time can be minimized to enable high-impact science that is not possible from other facilities.

5. IDENTIFICATION OF KILONOVAE

Kilonovae and supernovae are among the intrinsically brightest extragalactic compact sources, more than two orders of magnitude brighter than other, more typical sources at optical wavelengths (e.g., Rau et al. 2009; Kasliwal, 2013). In the near-infrared, kilonovae are even brighter (Barnes & Kasen 2013). A single-epoch NIRCam observation is therefore sufficient to identify any galaxy associated with a kilonova candidate, particularly a candidate identified within a week of and coincident with a GW trigger event.

Once a kilonova candidate is identified, one needs to distinguish it from the foreground (e.g., Milky Way stars and asteroids), background (e.g., distant galaxies), and unresolved (e.g., H\(\alpha\) regions) sources. For example, multiple background galaxies that are sufficiently bright may overlap a nearby (~200 Mpc) galaxy, resulting in a continuous quasi-point source with brightness comparable to kilonovae. Distinguishing between a bona fide kilonova and continuous sources requires a template to be obtained, either before or after the occurrence of the kilonova, or multiple NIRCam exposures to be obtained days apart. For the former, there is currently no suitable all-sky survey for this purpose, but it will be possible to carry out a survey selectively for the relevant galaxies, using other facilities to complement NIRCam observations. For the latter, NIRCam follow-up observations could be obtained on the galaxies. This approach may not be optimal since it requires double JWST time, but the advantage is that such observations would provide the template to distinguish a kilonova from continuous sources and enable characterization of its dimming.

Some transient sources (e.g., foreground asteroids and dwarf novae, background supernovae) could be mistaken as kilonovae, resulting in false positive transient events. To address this issue, we first recall the results of Kulkarni & Kasliwal (2009), who found that the background rate of supernovae, aligned by chance with a nearby galaxy, for Advanced LIGO-Virgo in a single snapshot within 12 $\text{deg}^2$ with $r$-band luminosity of $r < 24$ should be $\leq 0.1$. That study also finds the foreground rate of flares to be even less, $\leq 0.01$. These sources are expected to be the dominant source of false positive events. While these false positive events could, in principle, be different in NIRCam’s infrared wavelength range, they are unlikely to be significantly greater. We therefore expect that any survey focused on galaxies, and especially the targeted surveys discussed in Section 4, will render the number of false positive transient events practically negligible.

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\(6\) We discuss this slew time as an upper limit since it represents an extrapolation from 2.5 minutes for a 5\'\,slew and 3.3 minutes for a 17\'\,slew (Gardner et al. 2010). Since greater slews are more efficient, the actual slew time may be less than that extrapolated. Note that the 2.5 minutes for the 5\'\,slew with the 4 minutes for the guide star acquisition is comparable to mission requirement MR-180 (Bogenberger 2007), which is also reflected in the operations requirement M0-442 (Jordan 2014), which states that a 4/7\,slew, including guide star acquisition, be accomplished in 8 minutes or less.
6. PROBING THE KILONOVA EMISSION MODEL

The detection of kilonovae from a compact binary merger detected via GWs will help answer a number of important questions. Many of these questions may be addressed with the detailed observation of one kilonova, making even the limited observation time required for one detection valuable. If one determines the peak flux and the timescale for the kilonova to reach maximum light, one can deduce the quantity of r-process ejecta and its mean velocity (e.g., Metzger et al. 2010). For a statistical sample of such events, this information will address whether neutron star mergers are the dominant source for producing r-process elements in our Galaxy. When coupled with GW measurements of the parameters of the merging binary, the mass and velocity of the ejecta will also help constrain the equation of state of dense nuclear matter (e.g., Bauswein et al. 2013).

Determining the peak flux of a kilonova may nevertheless not be possible unless the light curve is observed multiple times during the emission period. In principle, such rapid follow-up observations are possible. The initial survey, executed as a target-of-opportunity, could occur within two days (operations requirement MO-210; Jordan 2014) of the GW event. With calibrated, processed NIRCam images then available within five days after downlink (e.g., operations requirement MO-41; Jordan 2014), follow-up NIRCam observations of a candidate or confirmed kilonova could then be executed as a target-of-opportunity again within two days. Thus, if an investigator develops data processing pipelines such that an appropriate GW event can be selected and NIRCam images can be searched in relatively short periods of time, two epochs of NIRCam observations separated by a week may be obtained for a kilonova within 9–10 days of the binary merger. This timeframe is likely sufficiently short to enable additional observations of the kilonova, providing information on its temporal evolution.

Triggered spectroscopic follow-up, either with JWST itself or a large ground-based near-infrared telescope (e.g., the Giant Magellan Telescope), could confirm the merger origin of the event by detecting the absorption lines of exotic r-process elements (e.g., Kasen et al. 2015b). The strength of individual lines, once identified, could in principle be used to determine the relative abundances of individual nuclei.

7. CONCLUSION

We showed that JWST/NIRCam can easily detect kilonovae out to distances relevant to GW observations of compact binary mergers. To efficiently survey the sky for kilonovae following a GW detection, NIRCam observations will need to be directed toward galaxies within the GW distance range. For a maximum source distance of 200 Mpc, which will be the typical distance of detected binaries with Advanced LIGO-Virgo at design sensitivity, the required NIRCam observation time for a fiducial 10 deg² GW-localized sky area would be about 13 hr, overwhelmingly dominated by slewing and guide star acquisition. This time can be significantly decreased, perhaps to about 4 hr, by focusing on (i) the galaxies with the highest star formation rates and (ii) especially those within the most probable GW sky area, enabling a survey of multiple GW detections in less time without compromising detection of a kilonova counterpart.

We find that the identification of kilonovae is unlikely to be limited by foreground or background transient events. With such detection capability, JWST/NIRCam will be able to (i) regularly survey GW event candidates for kilonova counterparts, therefore establishing a statistically significant sample size of kilonova emission parameters, and (ii) will be able to rapidly find kilonovae, enabling detailed study of their temporal and spectral evolution.

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REFERENCES

Aasi, J., Abadie, J., Abbott, B. P., et al. 2014, ApJS, 211, 7
Abadie, J., Abbott, B. P., Abbott, R., et al. 2010, CQGra, 27, 173001
Abadie, J., Abbott, B. P., Abbott, R., et al. 2012, AdA, 541, A155
Baldry, I. K., Driver, S. P., Loveday, J., et al. 2012, MNRAS, 421, 621
Barnes, J., & Kasen, D. 2013, ApJ, 775, 18
Bartos, I., Brady, P., & Márka, S. 2013, CQGra, 30, 123001
Bartos, I., Crotts, A. P. S., & Mrka, S. 2015, ApJ, 801, L1
Bartos, I., Veres, P., Nieto, D., et al. 2014, MNRAS, 443, 738
Bauswein, A., Goriely, S., & Janka, H.-T. 2013, ApJ, 773, 78
Beichman, C., Benneke, B., Knutson, H., et al. 2014, PASP, 126, 1134
Berger, E., Fong, W., & Chornock, R. 2013, ApJL, 774, L23
Bogenberger, B. 2007, James Webb Space Telescope Project Mission Requirements Document NASA, JWST-RQMT-000634 Rev P, http://spacese代孕grant.org/uploads/Requirements%20Conf/JWST%20Mission%20Requirements%20Document.pdf
Fernández, R., Kasen, D., Metzger, B. D., & Quataert, E. 2015, MNRAS, 446, 750
Fong, W., Berger, E., & Fox, D. B. 2010, ApJ, 708, 9
Gardner, J. P., Stiavelli, M., Mather, J. & the JWST Science Working Group 2010, James Webb Space Telescope Studies of Dark Energy, http://www.stsci.edu/jwst/doc-archive/white-papers/JWST_Dark_Energy.pdf
Gordon, K. D., Balzano, V., Blair, W., et al. 2012, Proc. SPIE, 8448, 1
Hanna, C., Mandel, I., & Vousten, W. 2014, ApJ, 784, 8
Harry, G. M. & LIGO Scientific Collaboration 2010, CQGra, 27, 084006
Horne, S. D., & Rieke, M. J. 2004, Proc. SPIE, 5487, 628
Iyer, B., Souradeep, T., Umnikrishnan, C., et al. 2011, LIGO-India, Proposal of the Consortium for Indian Initiative in Gravitational-wave Observations (IndIGO), Tech. rep., LIGO-M1100296
Jordan, M. 2014, James Webb Space Telescope Project JWST Mission Operations Concept Document, NASA, JWST-OPS-002018 Rev E, http://www.stsci.edu/jwst/doc-archive/technical-reports/JWST-MOCP.pdf
Kanner, J., Huard, T. L., Márka, S., et al. 2008, CQGra, 25, 184034
Kasen, D., Fernandez, R., & Metzger, B. D. 2015a, MNRAS, 450, 1777
Kasen, D., Fernandez, R., & Metzger, B. D. 2015b, MNRAS, 450, 1777
Kasliwal, M. M. 2013, in IAU Symp. 281, Binary Paths to Type Ia Supernovae Explosions, ed. R. Di Stefano, M. Orio, & M. Moe (Cambridge: Cambridge Univ. Press), 9
Kopparapu, R. K., Hanna, C., Kalogera, V., et al. 2008, ApJ, 675, 1459
Kulkarni, S., & Kasliwal, M. M. 2009, in Proc. RIKEN Symp., Astrophysics with All-Sky X-Ray Observations, ed. N. Kawai et al., 312 (http://cosmic.riken.dp.uni/mass/astros/proven-web/pdf/62-kulkarn.pdf)
Kulkarni, S. R. 2005, arXiv:astro-ph/0510256
Leibler, C. N., & Berger, E. 2010, ApJ, 725, 1202
Li, L.-X., & Paczyński, B. 1998, ApJL, 507, L59
LIGO Scientific Collaboration, Virgo Collaboration, Aasi, J., et al. 2013, arXiv:1304.0670
Metzger, B. D., & Berger, E. 2012, ApJ, 746, 48
Metzger, B. D., Kaplan, D. L., & Berger, E. 2013, ApJ, 764, 149
Metaizer, B. D., Martínez-Pinedo, G., Darbha, S., et al. 2010, MNRAS, 406, 2650
Moustakas, J., Coil, A. L., Aird, J., et al. 2013, ApJ, 767, 50
Nakar, E., & Piran, T. 2011, Natur, 478, 82
Nissanke, S., Kasliwal, M., & Georgieva, A. 2013, ApJ, 767, 124
Rau, A., Kulkarni, S. R., Law, N. M., et al. 2009, PASP, 121, 1334
Rosswog, S. 2005, ApJ, 634, 1202
Singer, L. P., Price, L. R., Farr, B., et al. 2014, ApJ, 795, 105

Smith, M. W. E., Fox, D. B., Cowen, D. F., et al. 2013, APh, 45, 56
Somiya, K. 2012, CQGra, 29, 124007
Tanvir, N. R., Levan, A. J., Fruchter, A. S., et al. 2013, Natur, 500, 547
The Virgo Collaboration, Advanced Virgo Baseline Design Tech. Rep, VIR-0128A-12 (http://www.nikhef.nl/pub/departments/mt/projects/virgo/ general/pub/TDR/AdV_TDR.pdf)
van Eerten, H. J., & MacFadyen, A. I. 2011, ApJL, 733, L37
White, D. J., Daw, E. J., & Dhillon, V. S. 2011, CQGra, 28, 085016