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Implications of the search for optical counterparts during the second part of the Advanced LIGO’s and Advanced Virgo’s third observing run: lessons learned for future follow-up observations

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ABSTRACT
Joint multimessenger observations with gravitational waves and electromagnetic (EM) data offer new insights into the astrophysical studies of compact objects. The third Advanced LIGO and Advanced Virgo observing run began on 2019 April 1; during the 11 months of observation, there have been 14 compact binary systems candidates for which at least one component is potentially a neutron star. Although intensive follow-up campaigns involving tens of ground and space-based observatories searched for counterparts, no EM counterpart has been detected. Following on a previous study of the first six months of the campaign, we present in this paper the next five months of the campaign from 2019 October to 2020 March. We highlight two neutron star–black hole candidates (S191205ah and S200105ae), two binary neutron star candidates (S191213g and S200213t), and a binary merger with a possible neutron star and a ‘MassGap’ component, S200115j. Assuming that the gravitational-wave (GW) candidates are of astrophysical origin and their location was covered by optical telescopes, we derive possible constraints on the matter ejected during the events based on the non-detection of counterparts. We find that the follow-up observations during the second half of the third observing run did not meet the necessary sensitivity to constrain the source properties of the potential GW candidate. Consequently, we suggest that different strategies have to be used to allow a better usage of the available telescope time. We examine different choices for follow-up surveys to optimize sky localization coverage versus observational depth to understand the likelihood of counterpart detection.

Key words: gravitational waves – methods: statistical.

1 INTRODUCTION
The observational campaigns of Advanced LIGO (Abbott et al. 2015) and Advanced Virgo (Acernese et al. 2015) revealed the existence of a diverse population of compact binary systems. Due to the continuous upgrades of the detectors from the first observing run (O1) over the second observing run (O2) up to the recent third observational campaign (O3), the gain in sensitivity leads to an increasing number of compact binary merger candidates: 16 alerts of gravitational-wave (GW) candidates were sent to the astronomical community during O1 and O2, covering a total of 398 d (Abbott et al. 2019d), compared to 80 alerts for O3a and O3b, covering a total of 330 d. Some of the candidates found during the online searches were retracted after further analysis, e.g. only 10 out of the 16 alerts were confirmed as candidates during the O1 and O2 runs (Abbott et al. 2019b, d). Additional compact binary systems were found during the systematic offline analysis performed with re-calibrated data, e.g. Abbott et al. (2019b), resulting in 11 confirmed GW events. During O3a and O3b, 24 of 80 alerts have already been retracted due to data quality issues, e.g. LIGO Scientific Collaboration & Virgo Collaboration (2019m, 2020c).
GW detections improve our understanding of binary populations in the nearby Universe (distances less than \( \sim 2 \) Gpc), and cover a large range of masses; these cover from \( \sim 1 \) to 2.3 solar masses (e.g. Lattimer 2012; Özel & Freire 2016; Margalit & Metzger 2017; Rezzolla, Most & Weiβ 2018; Abbott et al. 2020a) for binary neutron stars (BNSs) to \( \sim 100 \) solar masses for the most massive black hole (BH) remnants. They may also potentially constrain BH spins (LIGO Scientific Collaboration & Virgo Collaboration 2019a).

For mergers including NSs, electromagnetic (EM) observations provide a complementary view, providing precise localizations of the event, required for redshift measurements that are important for cosmological constraints (Schutz 1986); these observations may last for years at wavelengths outside the optical spectrum; for instance, X-ray photons were detected almost 1000 days post-merger in the case of GW170817 (Troja et al. 2020).

The success of joint GW and EM observations to explore the compact binaries systems has been demonstrated by the success of GW170817, AT2017gfo, and GRB170817A (e.g. Tanvir et al. 2013; Abbott et al. 2017b, d; Arcavi et al. 2017; Coulter et al. 2017; Lipunov et al. 2017; Mooley et al. 2017; Savchenko et al. 2017; Soares-Santos et al. 2017; Troja et al. 2017; Valenti et al. 2017). GRB170817A, a short \( \gamma \)-ray burst (sGRB; Eichler et al. 1989; Paczynski 1991; Narayan, Paczynski & Piran 1992; Mochkovitch et al. 1993; Lee & Ramirez-Ruiz 2007; Nakar 2007), and AT2017gfo, the associated kilonova (Li & Paczynski 1998; Sari, Piran & Narayan 1998; Metzger et al. 2010; Roberts et al. 2011; Kasen et al. 2017), were the EM counterparts of GW170817. Overall, this multimessenger event has been of interest for many reasons: to place constraints on the supranuclear equation of state describing the NS interior (e.g. Bauswein et al. 2017; Margalit & Metzger 2017; Coughlin et al. 2018b; Radice et al. 2018; Rezzolla et al. 2018; Abbott et al. 2019a; Coughlin et al. 2019b; Radice & Dai 2019; Capano et al. 2020; Dietrich et al. 2020), to determine the expansion rate of the Universe (Abbott et al. 2017a; Dhawan et al. 2020; Hotokezaka et al. 2019; Coughlin et al. 2020; Dietrich et al. 2020), to provide tests for alternative theories of gravity (Baker et al. 2017; Creminelli & Vernizzi 2017; Ezquiaga & Zumalacarregui 2017; Abbott et al. 2019c), to set bounds on the speed of GWs (Abbott et al. 2017b), and to prove BNS mergers to be a production site for heavy elements (e.g. Pian et al. 2017; Watson et al. 2019a).

Numerical-relativity studies reveal that not all BNS and BH–NS (BHNS) collisions will eject a sufficient amount of material to create bright EM signals (e.g. Bauswein, Baumgarte & Janka 2013; Hotokezaka et al. 2013; Kawamura et al. 2016; Abbott et al. 2017c; Dietrich & Ujevic 2017; Foucart, Hinderer & Nissanke 2018; Agathos et al. 2020; Köppel, Bovard & Rezzolla 2019; Krüger & Foucart 2020). For example, there will be no bright EM signal if a BH forms directly after merger of an almost equal-mass BNS, neutrinos, cosmic rays, and the EM spectrum; about half of the participating groups are in the optical. In total, GW follow-up represented \( \sim 50 \) per cent of the GCN service traffic (Gamma-ray Coordinates Network) with 1558 circulars. The first half of the third observation run (O3a) brought 10 compact binary merger candidates that were expected to have low-mass components, including GW190425 (LIGO Scientific Collaboration & Virgo Collaboration 2019b, c), S190426c (LIGO Scientific Collaboration & Virgo Collaboration 2019d, f), S190510g (LIGO Scientific Collaboration & Virgo Collaboration 2019e), GW190814 (Abbott et al. 2020b), S190901ap (LIGO Scientific Collaboration & Virgo Collaboration 2019g), S190910h (LIGO Scientific Collaboration & Virgo Collaboration 2019i), S190910d (LIGO Scientific Collaboration & Virgo Collaboration 2019h), S190923y (LIGO Scientific Collaboration & Virgo Collaboration 2019j), and S190930t (LIGO-Virgo collaboration 2019k). The follow-up campaigns of these candidates have been

The second half of the third observation run (O3b) has brought 23 new publicly announced compact binary merger candidates for which observational facilities performed follow-up searches, including two new BNS candidates, S191213g (LIGO Scientific Collaboration & Virgo Collaboration 2019) and S200213t (LIGO Scientific Collaboration & Virgo Collaboration 2020d) and two new BHNS candidates, S191205ah (LIGO Scientific Collaboration & Virgo Collaboration 2019k) and S200105ae (LIGO Scientific Collaboration & Virgo Collaboration 2020a, d). S200115j is special for having one NS component and one component object likely falling in the ‘MassGap’ regime, indicating it is between 3 and 5 \( M_\odot \) (LIGO Scientific Collaboration & Virgo Collaboration 2020e). After the second half of this intensive campaign, no significant counterpart (either GRB or kilonovae) was found. While this might be caused by the fact that the GW triggers have not been accompanied by bright EM counterparts, a likely reason for this lack of success in finding optical counterparts is the limited coordination of global EM follow-up surveys and the limited depth of the individual observations.

In this article, we build on our summary of the O3a observations (Coughlin et al. 2019c) to explore constraints on potential counterparts based on the wide field-of-view telescope observations during O3b, and provide analyses summarizing how we may improve existing strategies with respect to the fourth observational run of advanced LIGO and advanced Virgo (O4). In Section 2, we review the optical follow-up campaigns for these sources. In Section 3, we summarize parameter constraints that are possible to achieve based on these follow-ups assuming that the candidate location was covered during the observations. In Section 4, we use the results of these analyses and others to inform future observational strategies trying to determine the optimal balance between coverage and exposure time. Finally, in Section 5, we summarize our findings.
deep limits from a number of teams. As a point of reference, we include the apparent magnitude of an object with an absolute magnitude of $-16$ with distances ($\pm 1 \sigma$ error bars) consistent with the respective events. As a more physical visualization of the coordinated efforts that go into the follow-up process, we provide Fig. 3; this representation displays the tiles observed by various telescopes for the BNS merger candidate S200213t, along with a plot of the integrated probability and sky area that was covered over time by each of the telescopes. The black line is the combination of observations made by the telescopes indicated in the caption. These plots are also reminiscent of public, online visualization tools such as GWSky,\(^2\) the Transient Name Server (TNS),\(^3\) and the Gravitational Wave Treasure Map (Wyatt et al. 2020).

2.1 S191205ah

LIGO/Virgo S191205ah was identified by the LIGO Hanford Observatory (H1), LIGO Livingston Observatory (L1), and Virgo Observatory (V1) at 2019-12-05 21:52:08 UTC (LIGO Scientific Collaboration & Virgo Collaboration 2019k) with a false alarm rate of one in 2 yr. It has been so far categorized as a BHNS signal (77 per cent) with a moderate probability of being terrestrial (23 per cent), as well as a note that scattered light glitches in the LIGO detectors may have affected the estimated significance and sky position of the event. As expected for BNS candidates, the distance is more nearby (initially $195 \pm 59$ Mpc, later updated to $201 \pm 81$ Mpc with the LALInference map, LIGO Scientific Collaboration & Virgo Collaboration 2019n). The updated map covered $\sim 4500$ deg\(^2\). Since the updated skymap was released $\sim 1$ d after trigger time, much of the observations made in the first night used the initial BAYESTAR map.

While it was the first BNS alert during the second half of the O3 campaign, the response to this alert was relatively tepid, likely due to the scattered light contamination. However, 53 report circulars have been distributed for this event due to the presence of an interesting transient found by the Pan-STARRS Collaboration PS19hg/g/AT2019wxt, finally classified as supernovae IIb due to the photometry evolution and spectroscopy characterization (McBrien et al. 2019b; Valley 2019; Antier et al. 2020b). In total, three neutrinos, one VHE, eight $\gamma$-rays, two X-rays, 19 optical, and one radio groups participated to the S191205ah campaign (see the list of GCNs for S191205ah). No significant neutrino, VHE, and $\gamma$-ray GW counterpart was found in the archival data. A moderate fraction of the localization area was covered using a tiling approach (GRANDMA, Master-Network, ZTF) (see Table A1). The MASTER-network covered $\approx 41$ per cent within 144 h down to 19 in clear (Lipunov et al. 2019), and the Zwicky Transient Facility covered $\approx 28$ per cent down to 20.4 in $g$ and $r$ band (Andreoni et al. 2019c; Stein et al. 2019c; Kasliwal et al. 2020a). The search yielded 19 candidates of interest from ZTF, as well as the transient counterpart AT2019wxt from the Pan-STARRS Collaboration (McBrien et al. 2019b). It was shown that all ZTF candidates were in fact unrelated with the GW candidate S191205ah (Andreoni et al. 2019d; Brennan et al. 2019; Perley & Copperwheat 2019).

In addition to searches by wide field of view telescopes, there was also galaxy-targeted follow-up performed by the J-GEM collaboration, observing 57 galaxies (Onozato et al. 2019), and the GRANDMA citizen science program, observing 16 galaxies (Ducoin et al. 2019) within the localization of S191205ah.

2.2 S191213g

LIGO/Virgo S191213g was identified by H1, L1, and V1 at 2019-12-13 04:34:08 UTC (LIGO Scientific Collaboration & Virgo Collaboration 2019f). It has been so far categorized as a BNS signal (77 per cent) with a moderate probability of being terrestrial (23 per cent), although none displayed particularly interesting characteristics encouraging further follow-up; all of the candidates for which spectra were obtained were ultimately ruled out as unrelated to S191205ah (Castro-Tirado et al. 2019a, b, c).

2.3 S200105ae

LIGO/Virgo S200105ae was identified by L1 (with V1 also observing) at 2020-01-05 16:24:26 UTC as a subthreshold event with a false alarm rate of 24 per year; if it is astrophysical, it is most consistent with being a BHNS. However, its significance is likely underestimated due to it being a single-instrument event. This candidate was most interesting due to the presence of chrip-like structure in the spectrograms (LIGO Scientific Collaboration & Virgo Collaboration 2020a, b). The first public notice was delivered 27.2 h
after the GW trigger impacting significantly the follow-up campaign of the event. In addition, the most updated localization was very coarse, spanning \( \approx 7400 \, \text{deg}^2 \) with a distance of \( 283 \pm 74 \, \text{Mpc} \) (LIGO Scientific Collaboration & Virgo Collaboration 2020d).

S200105ae follow-up activity was comparable to S191205ah’s: 25 circular reports were associated with the S200105ae in the GCN service with the search of counterpart engaged by two neutrinos, one VHE, seven \( \gamma \)-ray, one X-ray, and five optical groups (see the list of GCNs for S200105ae). No significant neutrino, VHE, and \( \gamma \)-ray GW counterpart was found in the archival analysis. Various groups participated to the search of optical counterpart with ground-based observatories: GRANDMA, Master-Network, and the Zwicky Transient Facility (see Table A1). The alert system for Gaia was also activated (Kostrzewa-Rutkowska et al. 2020). The MASTER-network covered \( \approx 43 \) per cent down to 19.5 in clear and within 144 h (Lipunov et al. 2020a). The telescope network was already observing at the time of the trigger and because its routine observations were compatible with the sky localization of S200105ae, the delay was limited to 3 h. GRANDMA-TCA telescope was triggered as soon as the notice comes out, and the full GRANDMA network finalized 12.5 per cent of the full LALInference sky map down to 17 mag in clear and within 60 h (Antier et al. 2020b). The Zwicky Transient Facility covered \( \approx 52 \) per cent of the LALInference sky map down to 20.2 in both \( g \) and \( r \) bands (Stein et al. 2020; Kasiwal et al. 2020a) and with a delay of 10 h. There were 23 candidate transients reported by ZTF, as well as one candidate from the Gaia Alerts team (Kostrzewa-Rutkowska et al. 2020) out of which ZTF20aaaerivo and ZTF20aaertpj were both quite interesting due to their red colours (\( g - r = 0.66 \) and 0.35, respectively), and absolute magnitudes (\( -16.4 \) and \( -15.9 \), respectively) (Stein et al. 2020). ZTF20aaaerivo was soon classified as an SN IIp \( \sim 3 \) d after maximum, and ZTF20aaertpj as an SN Ib close to maximum (Castro-Tirado et al. 2020a, b).

### 2.4 S200115j

LIGO/Virgo S200115j, a MassGap signal (99 per cent) with a very high probability (99 per cent) of containing an NS as well, was identified by H1, L1, and V1 at 2020-01-15 04:23:09.742 UTC (LIGO Scientific Collaboration & Virgo Collaboration 2020e). As discussed before, it can be considered as a BHNS candidate. Due to its discovery by multiple detectors, the sky location is well-constrained; the most updated map spans \( \approx 765 \, \text{deg}^2 \), with most of the probability shifting towards the southern lobe in comparison to the initial localization, and has a distance of \( 340 \pm 79 \, \text{Mpc} \).

With a very high \( P_{\text{prompt}} > 99 \) per cent (LIGO Scientific Collaboration & Virgo Collaboration 2020f) and good localization, many space and ground instruments/telescopes followed up this signal: 33 circular reports were associated with the event in the GCN service with the search of counterpart engaged by two neutrinos, three VHE, five \( \gamma \)-ray, two X-ray, and eight optical groups (see the list of GCNs for S200115j). INTEGRAL was not active during the time of the event (Ferrigno et al. 2020) and so was unable to report any prompt short GRB emission. No significant neutrino, VHE, and \( \gamma \)-ray GW counterpart was found in the archival analysis. Swift satellite was also pointed towards the best localization region for finding X-ray and UVOT counterpart. Some candidates were reported: one of them was detected in the optical by Swift/UVOT and the Zwicky Transient Facility, but was concluded to likely be due to active galactic nucleus activity (Andreoni et al. 2020b; Oates et al. 2020).

Various groups participated to the search of optical counterpart with ground observatories: GOTO, GRANDMA, Master-Network, Pan-Starrs, SVOM-GWAC, and the Zwicky Transient Facility (see Table A1). GOTO (Steeghs et al. 2020) covered \( \approx 50 \) per cent down to 19.5 in \( g \) band, starting almost immediately the observations, while the SVOM-GWAC team covered \( \approx 40 \) per cent of the LALInference sky localization down to 16 in \( R \) band using the SVOM-GWAC only 16 h after the trigger time (Han et al. 2020).

In addition, a list of 20 possible host galaxies for the trigger was produced by convolving the GW localization with the 2MPZ galaxy catalogue (Bilicki et al. 2014; Evans et al. 2020a); 12 of these galaxies were observed by GRAWITA (Savaglio et al. 2020) in the \( r \)-\text{sdxs} filter.

### 2.5 S200213t

S200213t was identified by H1, L1, and V1 at 2020-02-13 at 04:10:40 UTC (LIGO Scientific Collaboration & Virgo Collaboration 2020g).
Figure 3. Coverage of the BHNS candidate S200115j (left column) and BNS candidate S200213t (right column) within 12 (top row), 24 (middle row), and 48 h (bottom row) after the GW trigger time by ZTF (Bhalerao et al. 2020; Kasliwal et al. 2020b) and GRANDMA, including the TAROT (TCA, TCH, and TRE) network and OAJ (Antier et al. 2020b). The LALInference localization probabilities are shown in shaded red. S200115j was detected at 2020-01-15 04:23:09.742 UTC, enabling immediate follow-up observations in South and North America (TCH and ZTF). S200213t was detected at 2020-02-13 at 04:10 UTC, offering only a few hours of observation for the European telescopes, such as for TCA, but a full night of observations with ZTF. OAJ could have begun observing immediately post-merger, but technical issues required human intervention and so the observations began only a few hours post-merger. We plot the integrated probability covered in the 2D skymap with solid lines. We show all telescopes combined in the black lines. The full list of observations is reported in Table A1.
It has been categorized as a BNS signal (63 per cent) with a moderate probability of being terrestrial (37 per cent). The LALInference localization spanned $\sim 2326$ deg$^2$, with a distance of $201 \pm 80$ Mpc (LIGO Scientific Collaboration & Virgo Collaboration 2020h). A total of 51 circular reports were associated with this event including two neutrinos, two VHE, eight $\gamma$-rays, two X-ray, and 11 optical groups (see the list of GCNs for S200213t). \textit{Fermi} and \textit{Swift} were both transiting the South Atlantic Anomaly at the time of event, and so were unable to observe and report any GRBs coincident with S200213t (Lien et al. 2020; Veres et al. 2020). No significant counterpart candidate was found during archival analysis: IceCube detected muon neutrino events, but it was shown that they have not originated from the GW source (Hussain 2020).

With a very high $p_{\text{remnant}} > 99$ per cent and probable BNS classification, many telescopes followed-up this signal: DDOTI/OAN, GOTO, GRANDMA, MASTER, and ZTF. DDOTI/OAN covered $\approx 26$ h down to 18 mag in clear (TCA) and down to 21 mag in $R$ band (OAN). GOTO covered $\approx 54$ per cent of bayestar skymap down to 18.4 in $G$ band (Cutter et al. 2020). 15 candidate transients were reported by ZTF (Andreoni et al. 2020c; Kasliwal et al. 2020b; Reusch et al. 2020), as well as one by the MASTER-network (Lipunov et al. 2020a). All were ultimately ruled out as possible counterparts to S200213t through either spectroscopy or due to pre-discovery detections (Andreoni et al. 2020d; Castro-Tirado et al. 2020c; d; Ho et al. 2020; Mroz et al. 2020; Srivastav & Smartt 2020). Galaxy targeted observations were conducted by several observatories: examples include KAIT, which observed 108 galaxies (Zheng et al. 2020), Nanshan-0.6m, which observed a total of 120 galaxies (Xu et al. 2020), in addition to many other teams (Gregory 2020; Onozato et al. 2020).

### 3 KILONOVA MODELLING AND POSSIBLE EJECTA MASS LIMITS

Following Coughlin et al. (2019c), we will compare the upper limits described in Section 2 to different kilonova models. We seek to measure `representative constraints,’ limited by the lack of field and time-dependent limits. To do so, we approximate the upper limits in a given passband as one-sided Gaussian distributions. To include the uncertainty in distance, we sample from a Gaussian distribution. We take time-dependent limits. To do so, we approximate the upper limits in a given passband as one-sided Gaussian distributions. We take time-dependent limits. We will show limits as a function of one parameter for each model chosen to maximize its impact on the predicted kilonova brightness and colour, marginalizing out the other parameters when performing the sampling. For the models based on Kasen et al. (2017) and Bulla (2019), as grid-based models, we interpolate these models by creating a surrogate model using a singular value decomposition (SVD) and Gaussian Process Regression (GPR) based interpolation (Doctor et al. 2017) that allows us to create light curves for arbitrary ejecta properties within the parameter space of the model (Coughlin et al. 2018b, 2019b). We refer the reader to Coughlin et al. (2019c) for more details about the models, but we will also briefly describe them in the following for completeness.

Model I (Kasen et al. 2017) depends on the ejecta mass $M_{ej}$, the mass fraction of lanthanides $X_{lan}$, and the ejecta velocity $v_{ej}$. We allow the sampling to vary within $-3 \leq \log_{10}(M_{ej}/M_{\odot}) \leq 0$ and $0 \leq v_{ej} \leq 0.3$, while restricting the lanthanide fraction to $X_{lan} = [10^{-9}, 10^{-5}, 10^{-4}, 10^{-3}, 10^{-2}, 10^{-1}]$.

Model II (Bulla 2019) assumes an axisymmetric geometry with two ejecta components, one component representing the dynamical ejecta and one the post-merger wind ejecta. Model II depends on four parameters: the dynamical ejecta mass $M_{ej, dyn}$, the post-merger wind ejecta mass $M_{ej, pm}$, the half-opening angle of the lanthanide-rich dynamical-ejecta component $\phi$, and the inclination angle $\theta_{\text{obs}}$ (with $\cos \theta_{\text{obs}} = 0$ and $\cos \theta_{\text{obs}} = 1$ corresponding to a system viewed edge-on and face-on, respectively). We refer the reader to Dietrich et al. (2020) for a more detailed discussion of the ejecta geometry. In this study, we fix the dynamical ejecta mass to the best-fitting value from Dietrich et al. (2020), $M_{ej, dyn} = 0.005 M_{\odot}$, and allow the sampling to vary within $-3 \leq \log_{10}(M_{ej, pm}/M_{\odot}) \leq 0$ and $0 \leq \phi \leq 90^\circ$, while restricting the inclination angle to $\theta_{\text{obs}} = [0^\circ, 30^\circ, 60^\circ, 90^\circ]$. To facilitate comparison with the other models, we will provide constraints on the total ejecta mass $M_{ej} = M_{ej, dyn} + M_{ej, pm}$ for Model II. We note that the model adopted here is more tailored to BNS than BHNS mergers given the relatively low dynamical ejecta mass, $M_{ej, dyn} = 0.005 M_{\odot}$. However, for a given $M_{ej, pm}$, the larger values of $M_{ej, dyn}$ predicted in BHNS are expected to produce longer lasting kilonovae more easily detectable. Therefore, the ejecta mass upper limits derived below for BHNS systems should be considered conservative.

Model III (Hotokezaka & Nakar 2020) depends on the ejecta mass $M_{ej}$, the dividing velocity between the inner and outer component $v_{ej}$, the lower and upper limit of the velocity distribution $v_{\text{min}}$ and $v_{\text{max}}$, and the opacity of the two components, $\kappa_{\text{low}}$ and $\kappa_{\text{high}}$. We allow the sampling to vary within $-3 \leq \log_{10}(M_{ej}/M_{\odot}) \leq 0$, $0 \leq v_{ej} \leq 0.3$, $0.1 \leq v_{\text{min}}/v_{ej} \leq 1.0$, and $0 \leq v_{\text{max}}/v_{ej} \leq 2.0$. We restrict $\kappa_{\text{low}}$ and $\kappa_{\text{high}}$ to a set of representative values in the analysis, i.e. $0.15$ and $1.5$, $0.2$ and $2.0$, $0.3$ and $3.0$, $0.4$ and $4.0$, $0.5$ and $5.0$, and $1.0$ and $10 \text{ cm}^2 \text{ g}^{-1}$.

Figure 4 shows the ejecta mass constraints for BNS events, S191213g and S200213t, while Figure 5 shows them for NSBH events, S191205ah and S200213t, while Fig. 5 shows them for NSBH events, S191205ah and S200213t. We mark each 90 per cent confidence with a horizontal dashed line. As a brief reminder, given that the entire localization region is not covered for these limits, and the limits implicitly assume that the region containing the counterpart was imaged, these should be interpreted as optimistic scenarios. It is also simplified to assume that the light curve cannot exceed the stated limit at any point in time. Similar to what was found during the analysis of O3a (Coughlin et al. 2019c), the constraints are not particularly strong, predominantly due to the large distances for many of the candidate events. Given the focus of these systems on the bluer optical bands, the constraints for the bluer kilonova models (low $X_{lan}$, low $\theta_{\text{obs}}$, and low $\kappa_{\text{low}}$/$\kappa_{\text{high}}$) tend to be stronger.

#### 3.1 S191205ah

The left column of Fig. 5 shows the ejecta mass constraints for S191205ah based on observations from ZTF (left, Andreoni et al. 2019b) and SAGUARO (right, Paterson et al. 2019). For all models we basically recover our prior, i.e. no constraint on the ejecta mass can be given.

#### 3.2 S191213g

The middle column of Fig. 4 shows the ejecta mass constraints for S191213g based on the observations from ZTF (Andreoni et al. 2019c; Stein et al. 2019c) and the MASTER-Network (Lipunov et al. 2019j). Interestingly, Model II allows us for small values of
Figure 4. Probability density for the total ejecta mass for the BNS events, S191213g and S200213t, and employed light-curve models. From the left to the right, we show constraints as a function of lanthanide fraction for the Kasen et al. (2017) Model, as a function of inclination angle (from a polar orientation, system viewed face-on) for the Bulla (2019) Model, and as a function of the opacity of the two components, $\kappa_{\text{low}}$ and $\kappa_{\text{high}}$, for the Hotokezaka & Nakar (2020) Model. The dashed lines are the upper limits that contain 90 percent of the probability density. For S191213g, we use ZTF (Andreoni et al. 2019c; Stein et al. 2019c) and the MASTER-Network (Lipunov et al. 2019j). For S200213t, we use ZTF (Kasliwal et al. 2020b) and GOTO (Cutter et al. 2020). See Table A1 for further details.
Figure 5. Probability density for the total ejecta mass for the NSBH events, S191205ah, S200105ae, and S200115j, and employed light-curve models. From the left to the right, we show constraints as a function of lanthanide fraction for the Kasen et al. (2017) Model, as a function of inclination angle (from a polar orientation, system viewed face-on) for the Bulla (2019) Model, and as a function of the opacity of the two components, $\kappa_{\text{low}}$ and $\kappa_{\text{high}}$, for the Hotokezaka & Nakar (2020) Model. The dashed lines are the upper limits that contain 90 percent of the probability density. For S191205ah, we use ZTF (left, Andreoni et al. 2019b) and SAGUARO (right, Paterson et al. 2019). For S200105ae, we use ZTF (Stein et al. 2020) and the MASTER-network (Lipunov et al. 2020a). For S200115j, we use ZTF (Bhalerao et al. 2020) and GOTO (Steeghs et al. 2020). See Table A1 for further details.
The right column of Fig. 5 shows the ejecta mass constraints for S200105ae based on observations from ZTF (Bhalerao et al. 2020) and the MASTER-network (Lipunov et al. 2020a). As for S191205ah, our analysis recovers basically the prior and no additional information can be extracted.

The left column of Fig. 5 shows the ejecta mass constraints for S200115j based on observations from ZTF (Bhalerao et al. 2020) and GOTO (Steehgs et al. 2020). Model II allows us for small values of $\theta_{\text{obs}}$ (brighter kilonovae) to constrain ejecta masses above $\sim 0.1\, M_\odot$, however for larger angles, no constraint can be made; similar constraints (ejecta masses below 0.15 $M_\odot$) are also obtained with Model III. As for S191213g, the obtained bounds are not strong enough to reveal interesting properties about the source properties.

The right column of Fig. 4 shows the ejecta mass constraints for S200213t based on observations from ZTF (Kasliwal et al. 2020b) and GOTO (Cutter et al. 2020). As for S191205ah and S191213g, our analysis recovers basically the prior and no additional information can be extracted for Model I and Model II. Model III allows us to rule out large ejecta masses $>0.15\, M_\odot$ for low opacities.

In conclusion, we find that for the follow-up surveys to the important triggers of O3b, the derived constraints on the ejecta mass are too weak to extract any information about the sources as it was possible for GW190425 (Coughlin et al. 2019c). This is likely due to a number of different circumstances: a reduction number of observations from O3a to O3b, e.g. three GW events out of five were happening around 4 h UTC, leading to an important delay of observations for all facilities located in Asia and Europe. Furthermore, the distance to most of the events was quite far (around 200 Mpc) and there was the possibility that in many cases a non-astrophysical origin caused the GW alert. Also, the weather was particularly problematic for a number of the promising events (see above). Unfortunately, we also observed that some groups were less rigorous in their report compared to O3a and did not report all observations publicly, which clearly hinders the analysis outlined above. Overall, some of the observational strategies were not optimal and motivates a more detailed discussion in Section 4.

While these analyses do not evaluate the joint constraints possible based on multiple systems, under the assumption that different telescopes observed the same portion of the sky in different bands (or at different times), it makes sense that improved constraints on physical parameters are possible. To demonstrate this, in Fig. 6, we show the ejecta mass constraints for GW190425 based on observations from ZTF (left, Kasliwal et al. 2019a) and PS1 (right, Smith et al. 2019) and the combination of the two. While the constraints for the low lanthanide fractions are stronger than available for the ‘red kilonovae’ for all examples, the combination of $g$- and $r$-band observations from ZTF and $i$ band from PS1 yield stronger constraints across the board.

**4 Using the Kilonova Models to Inform Observational Strategies**

Given the relatively poor limits on the ejecta masses, we are interested in understanding how optimized scheduling strategies can aid in obtaining higher detection efficiencies of kilonova counterparts. Similar but slightly stronger constraints were obtained during the analysis of the first six months of O3 (Coughlin et al. 2019c), where we advocated for longer observations at the cost of a smaller sky coverage.

For our investigation, we use the codebase GWEMOPT\(^5\) (Gravitational-Wave ElectroMagnetic OPTimization; Coughlin et al. 2018a), which has been developed to schedule Target of Opportunity (ToO) telescope observations after the detection of possible multi-messenger signals, including neutrinos, GWs, and $y$-ray bursts. There are three main aspects to this scheduling: tiling, time allocation, and scheduling of the requested observations. Multitelescope, network-level observations (Coughlin et al. 2019a) and improvements for scheduling in the case of multi-lobed maps (Almualla et al. 2020) are the most recent developments in these areas. We note that GWEMOPT naturally accounts for slew and read out times based on telescope-specific configuration parameters, which are important to account for inefficiencies in either long slews or when requesting short exposure times.

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\(^4\)While the 90 percent indicates that the prior is recovered, the shape of the posterior distributions suggest that the parameter space is somewhat constrained, disfavouring the high ejecta masses somewhat, but not enough to affect the limits.

\(^5\)https://github.com/mcoughlin/gwemopt
We now perform a study employing these latest scheduling improvements to explore realistic schedules, analysing them with respect to exposure time in order to determine the time-scales required to make kilonova detections. We will use four different types of light-curve models to explore this effect. The first is based on a ‘top hat’ model, where a specific absolute magnitude is taken as constant over the course of the observations; in this paper, we take an absolute magnitude (in all bands) of −16, which is roughly the peak magnitude of AT2017gfo (Arcavi et al. 2017). The second is similar: a base absolute magnitude of −16 is taken at the start of observation, but the magnitude decays linearly over time at a decay rate of 0.5 mag per day. These agnostic models depend only on the intrinsic luminosity and luminosity evolution of the source. The third and fourth model types are derived from our Model II (Bulla 2019). We use two different values of the post-merger wind ejecta component to explore the dependence on the amount of ejecta, one with dynamical ejecta $M_{\text{ej,dyn}} = 0.005 M_\odot$ and post-merger wind ejecta $M_{\text{ej,pm}} = 0.01 M_\odot$ and the other with $M_{\text{ej,dyn}} = 0.005 M_\odot$ and $M_{\text{ej,pm}} = 0.05 M_\odot$, similar to that found for AT2017gfo (Dietrich et al. 2020). As mentioned in Section 3, dynamical ejecta masses of $M_{\text{ej,dyn}} = 0.005 M_\odot$ are more typical for BNS than BHNS mergers, and therefore we restrict our analysis to a BNS event (see below).

Fig. 7 shows the efficiency of transient discovery for these models as a function of exposure time for a BNS event occurring at a distance similar to that of S200213t, 224 ± 90 Mpc. We inject kilonovae according to the 3D probability distribution in the final LALInference localization of S200213t and generate a set of tilings for each telescope (with fixed exposure times) through scheduling algorithms. Here, the detection efficiency corresponds to the total number of detected kilonovae divided by the total number of simulated kilonovae, which is a proxy for the probability that the telescope covered the correct sky location during observations to a depth sufficient to detect the transient.

We show the total integrated probability that the event was part of the covered sky area as a black line, and the probabilities for all four different light-curve models as coloured lines.6 For our study, we use OAJ (top left), PS1 (top right), and ZTF (bottom left), and a network consisting of all three telescopes. As expected, there is a trade-off between exposure time and the ability to effectively cover a large sky area. Both of these contribute to the overall detection efficiency, given that the depths required for discovery are quite significant. In order to rule out moving objects (e.g. asteroids) during the transient-filtering process, it is important to have at least 30 min gaps between multi-epoch observations; opting for longer exposure times can render this close to impossible, and hinder achieving coverage of the 90 per cent credible region during the first 24 h, especially for larger localizations. There are also observational difficulties, as field star-based guiding is not available on all telescopes, so some systems are not able to exceed exposure durations of a few minutes without sacrificing image quality. Therefore, we are interested in pinpointing the approximate peaks in efficiency so as to find a balance between the depth and coverage attained, and ultimately increase the possibility of a kilonova detection. It is important to note that the comparatively

6For intuition purposes: a tourist observing the full night sky at Mauna Kea in Hawaii would have reached 70 per cent for the integrated probability, but a detection efficiency of 0 per cent (since the typical depth reached by the human eye is about 7 mag), whereas a ~1 arcmin field observed by Keck, a 10 m class telescope on the mountain near to them, would have reached the necessary sensitivity but covered close to 0 per cent of the integrated probability.
Figure 7. Efficiency of recoveries for S200213t (focusing on g- and r-band observations). We include a model with a constant absolute magnitude of $-16$ with 0 mag per day decay, a model with a base absolute magnitude of $-16$ and decay rate of 0.5 mag per day, and two kilonova models (Bulla 2019), one with dynamical ejecta of $M_{\text{ej, dyn}} = 0.005 \, M_\odot$ and post-merger wind ejecta $M_{\text{ej, pm}} = 0.01 \, M_\odot$ and the other one with $M_{\text{ej, dyn}} = 0.005 \, M_\odot$ and $M_{\text{ej, pm}} = 0.05 \, M_\odot$. We show the integrated probability of the most updated sky localization area of S200213t covered by observations made within 72 h of the event in a solid black line; we note that this is the same integrated probability for the schedule in all four models, and the detection efficiency and integrated probability should converge to the same values in cases where all kilonovae within a specific portion of the 2D localization are detectable. The maximum coverage reachable for the three sites is 65 per cent for OAJ, 78 per cent for ZTF, 57 per cent for PS1, and 88 per cent for the network. We also show the nominal survey exposure times in vertical dashed lines (for OAJ, we show a grey band indicating the range of survey times employed, which changes based on atmospheric and moon conditions) and range of ToO observation exposure times (120–300 s) for comparison. We include analyses using OAJ (top left), PS1 (top right), ZTF (bottom left) individually, and a joint analysis of the three.

Figure 8. Efficiency of recoveries for S200213t for a model with a constant absolute magnitude of $-16$ (Tophat), a model with a base absolute magnitude of $-16$ and decay rate of 0.5 mag per day (Tophat), and two kilonova models (Bulla 2019), one with dynamical ejecta $M_{\text{ej, dyn}} = 0.005 \, M_\odot$ and post-merger wind ejecta $M_{\text{ej, pm}} = 0.01 \, M_\odot$ and the other one with $M_{\text{ej, dyn}} = 0.005 \, M_\odot$ and $M_{\text{ej, pm}} = 0.05 \, M_\odot$, similar to that found for AT2017gfo (Dietrich et al. 2020). We also show the nominal ZTF survey exposure time (30 s) and range of ToO observation exposure times (120–300 s) for comparison. On the left is for a limiting magnitude of 20.5, corresponding to 16th percentile night, while on the right, the limiting magnitude is 19.5, corresponding to a 84th percentile night.
especially optimal towards the upper end of the 120–300 s range. For relatively poor conditions (right-hand panel), longer exposure times are required, which is now possible due to the significant work that has gone into improving ZTF references to adequate depths for these deeper observations. One more point of consideration is the distance information for the event; a kilonova with twice the luminosity distance will produce four times less flux, and this will affect the depth required to possibly detect the transient. This aspect of the analysis does not overshadow the importance of prioritizing longer exposure times (in particular under bad observational conditions). We note that the quoted limits for S200213t are $\sim 0.7$ mag in 120 s from ZTF (Kasliwal et al. 2020b); this corresponds to $\sim 19.2$ expected for 30 s exposures, and therefore suboptimal conditions.

5 SUMMARY

In this paper, we have presented a summary of the searches for EM counterparts during the second half of the third observing run of Advanced LIGO and Advanced Virgo; we focus on the GW event candidates that are likely to be the coalescence of compact binaries with at least one NS component. We used three different, independent kilonova models Kasen et al. (2017), Bulla (2019), Hotokoezaka & Nakar (2020) to explore potential ejecta mass limits based on the non-detection of kilonova counterparts of the five potential GW events S191205ah, S191213, S200105ae, S200115j, and S200213t by comparing apparent magnitude limits from optical survey systems to the GW distances. While the models differ in their radiative transfer treatment, our results show that the publicly available observations do not provide any strong constraints on the quantity of mass ejected during the possible events, assuming the source was covered by those observations. The most constraining measurement is obtained for S200115j due to the observations of ZTF and GOTO; the model of Bulla (2019) excludes an ejecta of more than 0.1 $M_\odot$ for some viewing angles. In general, the reduced number of observations between O3a and O3b, the delay of observations, the shallower depth of observations, and large distances of the candidates, which yield faint kilonovae, explain the minimal constraints for the compact binary candidates. However, it shows the benefit of a systematic diagnostic about quantity of ejecta due to the observations, as was done in the analysis of O3a (Coughlin et al. 2019c). Although the strategy of follow-up employed by the various teams and their instrument capabilities did not evolve significantly in the eleven months of O3, it is clear that a global coordination of the observations would yield expected gains in efficiency, both in terms of coverage and sensitivity.

Given the uninformative constraints, we explored the depths that would be required to improve the detection efficiencies at the cost of coverage of the sky location areas for both single telescopes and network level observations. We find that exposure times of $\sim 3$–10 min would be useful for ZTF to maximize its sensitivity for the events discussed here, depending on the model and atmospheric conditions, which is a factor of 6–20 $\times$ longer than survey observations, and up to a factor of 2 $\times$ longer than for current ToO observations; the result is similar for OAJ. For PS1, on the other hand, its larger aperture leads to the conclusion that its natural survey exposure time is about right for events in the BNS distance range. Our results also highlight the advantages of telescope networks in increasing coverage of the localization and thereby allowing for longer exposure times to be used, thus leading to a corresponding increase in detection efficiencies.

It is also important to connect our results to conclusions drawn in other works: Carracedo et al. (2020) showed that detections of a AT2017gfo-like light curve at 200 Mpc requires observations down to limiting magnitudes of 23 mag for lanthanide-rich viewing angles and 22 mag for lanthanide-free viewing angles. The authors point out that because the optical light curves of kilonovae become red in a matter of few days, observing in red filters, such as inclusion of r-band observations, results in almost double the detections as compared to observations in g and r band only. They propose that observations of rapid decay in blue bands, followed by longer observations in redder bands is therefore an ideal strategy for searching for kilonovae. This strategy can be combined with the exposure time measurements here to create more optimized schedules. Kasliwal et al. (2020a) also demonstrate that under the assumption that the GW events are astrophysical, strong constraints on kilonova luminosity functions are possible by taking multiple events and considering them together, even when the probabilities and depths covered on individual events are not always strong. This motivates future work where ejecta mass constraints can be made on a population basis by considering the joint constraints over all events.

Building in field-dependent exposure times will be critical for improving the searches for counterparts. While our estimates are clearly model dependent (e.g. by assuming an absolute magnitude, a decay rate for candidate counterparts, and a particular kilonova model), it is clear that deeper observations are required, especially with the future upgrades of the GW detectors, to improve detection efficiencies when the localization area and telescope configuration allow for it. Telescope upgrades alone do not guarantee success, as detecting more marginal events at further distances will not necessarily yield better covered skymaps. Smaller localizations from highly significant, nearby events are key, perhaps with the inclusion of more information to differentiate those most likely to contain counterpart, such as the chirp mass (Margalit & Metzger 2019), to support the follow-up.

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DATA AVAILABILITY

The data underlying this article are derived from public code found here: https://github.com/mcoughlin/gwemlightcurves. The simulations resulting will be shared on reasonable request to the corresponding author.

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Table A1. Reports of the observations by various teams of the sky localization area of gravitational-wave alerts of possible BNS candidates S191213g and S200213t, and BHNS candidates S191205ah, S200105ae, and S200115j. For ease of comparison to limits, assuming an absolute magnitude of $-16$ mag, the median distances correspond to apparent magnitudes of 20.5, 20.5, 21.9, 21.3, and 21.7 mag, respectively. Teams that employed ‘galaxy targeting’ during their follow-up or with less than 1 percent coverage of the sky localization area are not mentioned here. In the case where numbers were not reported or provided upon request in order to calculate the total coverage based on the most updated sky localization area, we recomputed some of them; if this was not possible, we add $\ldots$.

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