UTILITY OF GALAXY CATALOGS FOR FOLLOWING UP GRAVITATIONAL WAVES FROM BINARY NEUTRON STAR MERGERS WITH WIDE-FIELD TELESCOPES

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ABSTRACT

The first detections of gravitational waves from binary neutron star mergers with advanced LIGO and Virgo observatories are anticipated in the next five years. These detections could pave the way for multi-messenger gravitational-wave (GW) and electromagnetic (EM) astronomy if GW triggers are successfully followed up with targeted EM observations. However, GW sky localization is relatively poor, with expected localization areas of ∼10–100 deg²; this presents a challenge for following up GW signals from compact binary mergers. Even for wide-field instruments, tens of hundreds of pointings may be required. Prioritizing pointings based on the relative probability of successful imaging is important since it may not be possible to tile the entire gravitational-wave localization region in a timely fashion. Galaxy catalogs were effective at narrowing down regions of the sky to search in initial attempts at joint GW/EM observations. The relatively limited range of initial GW instruments meant that few galaxies were present per pointing and galaxy catalogs were complete within the search volume. The next generation of GW detectors will have a 10-fold increase in range thereby increasing the expected number of galaxies per unit solid angle by a factor of ∼1000. As an additional complication, catalogs will be highly incomplete. Nevertheless, galaxy catalogs can still play an important role in prioritizing pointings for the next era of GW searches. We show how to quantify the advantages of using galaxy catalogs to prioritize wide-field follow-ups as a function of only two parameters: the three-dimensional volume within the field of view of a telescope after accounting for the GW distance measurement uncertainty, and the fraction of the GW sky localization uncertainty region that can be covered with telescope pointings. We find that the use of galaxy catalogs can improve the probability of successful imaging by ∼10% to ∼300% relative to follow-up strategies that do not utilize such catalogs for the scenarios we considered. We determine that catalogs with a 75% completeness perform comparably to complete catalogs in most cases, while 33%-complete catalogs can lead to lower follow-up success rates than complete catalogs for small fields of view, though still providing an advantage over strategies that do not use a catalog at all.

Key words: binaries: close – catalogs – gravitational waves – stars: neutron

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1. INTRODUCTION

Abadie et al. (2012a, 2012b) present the first low-latency searches for gravitational waves (GWs) that triggered electromagnetic (EM) follow-up observations with a ∼30 minute response time.4 No gravitational waves were detected, but several GW candidate events consistent with noise were followed up with telescopes at a variety of wavelengths (Evans et al. 2012; Asui et al. 2013). Later this decade, a network of advanced gravitational-wave (GW) detectors including LIGO and Virgo (Harry & the LIGO Scientific Collaboration 2010; Virgo Collaboration 2009) may detect tens of binary neutron star (BNS) mergers per year once at full sensitivity. Several of these detections may be accompanied by EM counterparts (e.g., Metzger & Berger 2012; Kelley et al. 2013; Bloom et al. 2009) summarized below.5 Several nearly “instantaneous” search methods for GWs from BNS mergers have been proposed, introducing the possibility of transmitting information about the candidate to EM telescope partners within tens of seconds of a binary merger (Cannon et al. 2012; Luan et al. 2012). BNS mergers are thought to generate several distinct EM counterparts spanning most of the EM spectrum; Figure 1 of Metzger & Berger (2012) illustrates the counterpart emission mechanisms. Short, hard gamma ray bursts occur on timescales of ∼2 s (Nakar et al. 2006) and are strongly beamed. Afterglow from shock waves produced when the emitted jet encounters the interstellar medium span the spectrum from X-rays to radio waves (e.g., van Eerten & MacFadyen 2011; Berger 2010; Perley et al. 2009; Nakar & Piran 2011). Thermal emission from r-process nucleosynthesis in the merger ejecta has been predicted to peak in the infrared (Kasen et al. 2013); the first hint of such a kilonova signal has been recently observed (Tanvir et al. 2013).

Several transient telescope networks exist with wide-field coverage and it is important to understand what is the best way to tile pointings within the GW localization region using wide-field instruments. This question has been addressed partly by Singer et al. (2012), who present a framework for allocating telescope resources to optimally cover the available sky localization region. In this work we consider the situation in which only a fraction of this area can be surveyed in a timely fashion,
where it is important to choose the tiles that represent the most likely source location first. Both Singer et al. (2012) and Fairhurst (2009) focus on the assumption of a uniform-on-the-celestial-sphere prior on the GW source location. However, given the broad GW localization region, pointing might be strongly influenced by a sharply peaked prior expectation for the signal location. Fairhurst (2009) mentions that a galaxy catalog could serve as a better prior and, indeed, Abadie et al. (2012a, 2012b) demonstrate that the use of a galaxy catalog (White et al. 2011) greatly increases the chance of imaging an EM counterpart in simulations for the initial GW detectors with $\lesssim 20$ Mpc range for GWs from merging BNSs. At this range, nature provides few galaxies as potential hosts for the merger, corresponding to sharp peaks in the prior probability.

The same angular scale will encompass many more galaxies in the advanced GW detector era and the usefulness of a galaxy catalog prior comes into question. Metzger & Berger (2012) suggest that the number of bright galaxies in the localization region will be too large to improve the prospects of imaging the EM counterpart. For example, GW detections in the advanced detector era will occur at a median distance of $\sim 200$ Mpc. A source at this distance may be optimistically localized to a sky area of $20\,\text{deg}^2$ and a fractional distance error of $\sim 30\%$ by GW measurements alone (Fairhurst 2009; LIGO Scientific Collaboration et al. 2013a; Veitch et al. 2012; Nissanke et al. 2011; Rodriguez et al. 2014) with a network of three or more GWs detectors. The volume defined by this solid angle and distance range will contain more than 500 galaxies brighter than $0.1\,L^*$ (see Section 3)—more than can realistically be imaged individually on short timescales.

If wide-field instruments are used to tile the GW localization region and the requirements on the speed and depth of the search make it impossible to follow up the entire localization region, the question arises of how to prioritize which tiles should be observed. Nuttall & Sutton (2010) partly address this problem by simulating follow-up searches within $100\,\text{Mpc}$ in the advanced detector era using the Gravitational Wave Galaxy Catalog (GWGC) of White et al. (2011). Individual galaxies are targeted on the basis of a ranking algorithm that accounts for luminosity and distance to putative host galaxies. Meanwhile, Nissanke et al. (2013) provide case studies for the process of detecting a GW event and locating and identifying its EM counterpart, using galaxy catalogs to eliminate false-positive EM signals. Both studies find that catalogs can be useful both for locating and identifying an EM counterpart when there are insufficient resources to point individually at each galaxy.

In this work, we revisit the utility of a galaxy catalog in the regime where there are too many galaxies in the GW localization region to be followed up individually, and observational constraints on the speed and depth of the search prevent complete coverage with wide-field instrument pointings. We quantify the utility of a galaxy catalog as a function of the three-dimensional volume within the field-of-view (FOV) of the follow-up telescope (after accounting for the distance measurement uncertainty from GW measurements) and of the fraction of the GW localization region that can be covered. We consider realistic catalogs, which are likely to be significantly incomplete within the large volumes in which advanced detectors are sensitive.

We find that even in the advanced-detector era, galaxy catalogs can still confer benefits through the inherent fluctuations in luminosity density on the sky. Galaxy luminosity and count fluctuations will help to prioritize tiles and increase the relative probability of imaging a GW EM counterpart. In particular, we will show that catalogs are most relevant for narrow and shallow follow-up searches (that is, smaller FOVs and shorter range) and that improving the completeness and range of existing catalogs is important for EM follow-up efforts.

This work is organized as follows. In Section 2 we define our condition for a “successful” follow-up and describe the algorithm we use to select tiles for pointing, given a galaxy catalog. In Section 3 we discuss the characteristics of the galaxy luminosity distribution and show that there can be significant variations in luminosity between tiles. Sections 4 and 5 present the results of simulated follow-up searches for several detection and observation scenarios and discuss the effects of incompleteness of the galaxy catalog on the results. Section 6 concludes with a brief discussion of our results and additional suggestions for future work.

2. PROBLEM STATEMENT

In this work we are not concerned specifically with identifying host galaxies, but rather with choosing the most probable sky regions commensurate with a given FOV by using galaxy catalog information. We neglect many of the practicalities considered by Nissanke et al. (2013) and Singer et al. (2012) (e.g., telescope slew time, limiting depth, day/night observation time, etc.) to isolate the utility of galaxy catalogs on their own merits. We do, however, assess the effect of incompleteness of galaxy catalogs in our method.

Throughout this work we will use a blue-band galaxy catalog as a proxy for merger rate density. This assumes that the rate of BNS mergers is proportional to the instantaneous massive star formation rate (with negligible time delays between formation and merger) and is therefore tracked by blue-light luminosity (Phinney 1991). On the contrary, observational evidence indicates that a quarter of short gamma ray bursts occur in elliptical galaxies with no signs of ongoing star formation (Fong et al. 2013). However, the choice of color is not critical for the modeling below; it is sufficient to assume that we have a catalog that is an accurate tracer of merger rate density. We discuss the validity of this assumption in Section 6.

To model the effect of using galaxy catalogs to assist in EM followup we begin by dividing the GW localization area, $A$, into $\mathcal{N}$ tiles (assumed to be non-overlapping for simplicity), each representing a telescope FOV $P$, where $\mathcal{N} = \lfloor A/P \rfloor$.

We define a successful follow-up as a GW-triggered EM transient search in which one of the tiles selected for imaging contains the GW source. For simplicity, we require only that the source reside in one of the tiles, and not that the expected EM counterpart is actually detectable by a given follow-up instrument or distinguishable from background events. We therefore assume the transient search to be limited in range only by the capabilities of the GW detector network and not by the depth of the follow-up instrument. Considering the above assumptions, the probability of success is 1 if all tiles in the sky are searched, regardless of whether the correct transient is identified.

In practice, sky localization from GW data will yield regions of non-uniform probability on the sky; in the high

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6 With significantly larger uncertainties expected for a two-detector network for the early runs of Advanced LIGO alone (LIGO Scientific Collaboration et al. 2013a; Kasliwal & Nissanke 2013).

7 In fact, the depth to which the available telescopes can detect an EM transient may influence the optimal choice of follow-up target. For example, there is little point in targeting galaxies that are so distant that the transients they might contain would not be detectable by a given telescope.
signal-to-noise ratio (S/N) limit, the probability distribution on the sky will have a Gaussian shape. The probability density function on the sky will be computed through coherent parameter estimation on GW detector data (LIGO Scientific Collaboration et al. 2013b). Here, we treat the event localization area $A$ as a suitable “effective” area, and consider the GW localization probability to be uniform over $A$.

We define the success fraction $f$ as the fraction of GW events that are expected to be successfully followed up for a given follow-up strategy according to the definition above. If one ignores the galaxy distribution, the relative probability that a GW is in a given tile is uniform amongst the tiles. The success fraction is

$$f = \frac{N}{N} = \frac{1}{N},$$

where $N$ is the number of telescope pointings compatible with search speed and depth requirements, and $f$ is simply the fraction of the GW localization area that is followed up. $f = N(P/A)$.

This should be compared to the case where each tile has a relative probability of containing the GW event proportional to its blue light luminosity $L_i$, and a greedy pointing algorithm is used whereby the brightest tiles are pointed at first, $L_i > L_{i+1}$ for all $i$:

$$f = \frac{L}{\sum_i L_i} = \frac{N}{N} = f,$$

where $L = \sum_i L_i$. With the greedy strategy, $f > f$; in other words, if GW sources are distributed according to blue luminosity then using that information never hurts the success fraction.

The GW amplitude depends on the inclination and orientation of the source relative to the line of sight, with the highest detector response for face-on sources. This allows us to compute the probability that a source in a given galaxy at a known distance and sky location would pass a signal-to-noise-ratio detection threshold under the assumption that the binary’s inclination and orientation are isotropically distributed. This probability decreases from $\approx 1$ for a very nearby galaxy to $0$ for a galaxy at the maximum distance for a given sky location and detector network configuration (where only face-on sources would be detectable); the decrease is roughly linear in the distance to the source (cf. the ad hoc (Nuttall & Sutton 2010) weighting of galaxies in the catalog by one over distance or one over distance squared). In principle, this detection probability should be included in the prior weighting of galaxies in the catalog, giving each galaxy an effective luminosity that is the product of its actual luminosity and the probability that a source in this galaxy would be detectable in a GW search with the given detector network.

However, in practice, the analysis of GW data will yield (strongly correlated) constraints on distance and inclination, so this prior probability should not be assigned independently of the detector data. As discussed in Section 6, the correct approach would be to include the galaxy catalog directly in coherent Bayesian parameter estimation as a prior, which would allow for a self-consistent application of all information, rather than attempting an a posteriori correction as we are doing here. However, for the purposes of estimating the utility of a galaxy catalog, we take the simplified approach of considering only galaxies in a range of distances consistent with the distance measurement accuracy expected for multi-detector networks: $\sim 30\%$ in fractional distance uncertainty for an event at the detection threshold (Veitch et al. 2012). Within this range, we will neglect the detection probability in the galaxy prior, and consider only priors proportional to blue-light luminosity. We expect this to be conservative, since the effective galaxy luminosity with the detection probability included would have had greater fluctuations than the absolute luminosity, and, as we will see below, luminosity fluctuations increase the utility of galaxy catalogs.

We will thus assume that the detector network is able to localize a source at distance $D$ to within a range $[D_{\text{min}}, D_{\text{max}}]$, with $D_{\text{min}} = 0.7D$ and $D_{\text{max}} = 1.3D$. Combining the solid angle $P$ of a telescope pointing with this range, we can define the pointing volume, i.e., the volume of each pointing within the measured distance range, as $V = (4/3)\pi (D_{\text{max}}^3 - D_{\text{min}}^3) P / \Omega$ where $\Omega \approx 41,000\,\text{deg}^2$ is the solid angle of the whole sky. The average luminosity per pointing volume is then given by $\langle L_i \rangle = V \rho_L$, where $\rho_L$ is the average spatial density of luminosity. We will use a luminosity density $\rho_L = 0.02\,L_{10}\,\text{Mpc}^{-3}$, where $L_{10}$ is defined as $10^{10}$ times the solar blue-light luminosity $L_{\odot}$ (Kopparapu et al. 2008; Abadie et al. 2010).

3. LUMINOSITY FLUCTUATIONS

In this section, we incorporate the distribution of intrinsic galaxy luminosity and the counting fluctuations in the number of galaxies in different pointings into the expected distribution of $L_i$. We neglect spatial correlations of galaxies (e.g., due to the presence of galaxy clusters—a conservative assumption since greater clustering improves the utility of galaxy catalogs, as we shall see shortly) and assume they are homogeneously distributed in volume. We model the distribution of galaxies in blue luminosity and volume as a Schechter function (Schechter 1976)

$$n(x) dx \propto x^\alpha e^{-x} \, dx,$$  

where $x \equiv L/L^*$ and $n(x) \, dx$ is the expected number of galaxies per Mpc$^3$ in the interval $[x, x + dx]$. We use the GWGC (White et al. 2011) within $20\,\text{Mpc}$, where it is complete, to estimate $\alpha = -1.1$ and $L^* = 2.2\,L_{10}$, slightly brighter than the Milky Way’s blue-band luminosity of $\sim 1.7\,L_{10}$.

8 Normalizing the luminosity function to yield $\rho_L = 0.02\,L_{10}\,\text{Mpc}^{-3}$ on the interval $L \in [0.001, 20]\,L_{10}$ (Kopparapu et al. 2008). All following results are based on this Schechter luminosity distribution. Figure 1 shows the luminosity function of the GWGC within $20\,\text{Mpc}$ as well as the Schechter model.

If we assume that a pointing tile has volume $V$, containing a random integer sample of galaxies taken from the distribution in Equation (3), then the resulting luminosity $L_i$ in that volume can be described by a random variable of mean $V \rho_L$. The results of a direct Monte Carlo simulation of Equation (3) for $100\,\text{Mpc}^3$ and $1000\,\text{Mpc}^3$ are shown in Figure 2. To understand these results, one can crudely approximate the Schechter galaxy population as a Poisson scattering of identical galaxies of “typical” luminosity $L^*$. In this case, the luminosity in a volume $V$ is simply $L = n L^*$, where $n$ is drawn from a Poisson distribution of mean $V \rho_L / L^*$. For $100\,\text{Mpc}^3$ and $1000\,\text{Mpc}^3$ pointing volumes, for example, we should expect $0.9 \pm 0.95$ and $9 \pm 3$ galaxies per pointing volume, with corresponding luminosities of $2.0 \pm 2.1\,L_{10}$ and $20 \pm 6.6\,L_{10}$, respectively. This closely matches the fluctuations of $2.0 \pm 2.0\,L_{10}$ and $20 \pm 6.3\,L_{10}$, respectively, measured via a Monte Carlo simulation of the actual Schechter distribution.
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Figure 1. GWGC luminosity function within 20 Mpc compared to a fit of Equation (3) with $L^* = 2.2 \, L_{10}$ and $\alpha = -1.1$. GWGC luminosities are divided into 50 logarithmically spaced bins covering the interval $[0.001, 20] \, L_{10}$; the fit is normalized to match the catalog luminosity density of $\sim 0.027 \, L_{10} \, \text{Mpc}^{-3}$ within 20 Mpc.

(A color version of this figure is available in the online journal.)

Figure 2. Distribution of luminosity drawn from Equation (3) for fixed volumes of 100 Mpc$^3$ and 1000 Mpc$^3$. The means are $2.0 \, L_{10}$ and $20.0 \, L_{10}$ and the standard deviations are $2.0 \, L_{10}$ and $6.3 \, L_{10}$, respectively. These values correspond approximately to a Poisson scattering of galaxies of “typical” luminosity $L^*$.

(A color version of this figure is available in the online journal.)

The large variations in tile luminosity—$2 \pm 2 \, L_{10}$ for the 100 Mpc$^3$ volume—suggest that there can be substantial advantage to following up the brightest tiles first in a survey with limited pointings. For lower pointing volumes, the distribution becomes increasingly non-Gaussian, and its skewness amplifies the advantage of luminosity-directed surveys.

4. RESULTS: COMPLETE GALAXY CATALOG

We show the success fraction $\mathcal{F}$ when using a complete, ideal galaxy catalog as a function of pointing volume in Figure 3, for four choices of the fraction $f \in \{0.01, 0.05, 0.10, 0.50\}$ of the GW localization region being followed up. Recall from Section 3 that in the case where no galaxy catalog is used we would expect on average that $\mathcal{F} = f$. We find in Figure 3 that in all cases when using the galaxy catalog $\mathcal{F} > f$ as we would expect, with the advantage of the catalog being more pronounced for smaller pointing volumes where the variation of luminosity per pointing is larger.

It is useful to apply the results of Figure 3 to a few potential scenarios in order to understand the impact that an ideal galaxy catalog would have. The distance at which a single advanced LIGO detector is capable of detecting an optimally oriented and located BNS merger at an $\text{S/N}$ of 8—known as the horizon distance—is $\sim 450$ Mpc (Abadie et al. 2010). However, averaging over sky locations and orientations, we expect 75% of detections to come from within $\sim 250$ Mpc, or 50% from within $\sim 200$ Mpc. For early versions of the advanced LIGO/Virgo network, this could be reduced to as little as $D \sim 100$ Mpc for the 50% percentile (LIGO Scientific Collaboration et al. 2013a). We therefore consider the median distance of 200 Mpc as a typical distance to a detection with the advanced detector network operating at design sensitivity in cases 1 and 2. Meanwhile, case 3 represents the scenario of a closer source at an estimated distance of 100 Mpc.

1. Consider a 10 deg$^2$ FOV telescope following up with a single pointing a GW source estimated to be at a distance of 200 Mpc, with a 100 deg$^2$ localization region. The pointing volume to this source, assuming GW observations constrain the distance to be $\in [140, 260]$ Mpc, is 15,000 Mpc$^3$. (For comparison, a 1 deg$^2$ conical FOV contains a volume of $\sim 100$ Mpc$^3$ out to a distance of 100 Mpc.) Without a galaxy catalog we would expect that the success fraction $\mathcal{F} = f = 10\%$. However, Figure 3 shows that using a galaxy catalog we might expect to have a $\sim 11\%$ success fraction.

2. Consider the same GW source as case 1 but with a 1 deg$^2$ FOV follow-up instrument having 10 pointings. While the overall coverage is still $f = 10\%$, the pointing volume is reduced to 1500 Mpc$^3$, so the fluctuations in luminosity between tiles are more significant. As a result, the success fraction improves to $\sim 16\%$.

3. Finally, consider a loud GW signal with a 100 Mpc distance estimate being followed up by a single pointing of a 1 deg$^2$ FOV instrument. The sky-localization and distance measurement accuracy improve for high S/N GW detections. We therefore consider a 10 deg$^2$ localization region and a reduced distance uncertainty range $\in [90, 110]$ Mpc. In this case, the pointing volume is only 60 Mpc$^3$, and the success fraction is $\sim 40\%$, a fourfold improvement over the nominal $\mathcal{F} = f = 10\%$ success fraction in the absence of a galaxy catalog.

These cases are meant as illustrations only. Distances to optimally located and oriented sources may range to 450 Mpc for advanced detectors at design sensitivity. Meanwhile, sources in the early phases of advanced detector commissioning, when detectors are sensitive within a smaller range, may resemble
case 3 in typical distance estimates, but with poorer sky localization and distance measurements.

While the overall fraction $f$ of the GW localization region is 10% for each of the above cases, the pointing volumes are respectively $\sim 15,000 \text{ Mpc}^3$, $\sim 1500 \text{ Mpc}^3$, and $\sim 60 \text{ Mpc}^3$. The progressively larger success fractions for each case illustrates how the utility of the catalog depends on pointing volume.

The effectiveness of a given follow-up telescope, as characterized by its FOV $P$ and the number of pointings $N$ that can be taken within the allotted time while observing to a sufficient depth, may be influenced by the sensitivity of the GW search and the distance estimate it yields. For case 3, an instrument with a larger FOV might be chosen at the expense of depth, since the EM signal is expected to be louder. Similarly, the greater imaging depth required to detect transients at 200 Mpc might mean that fewer pointings are available for the more distant sources in cases 1 and 2.

5. THE EFFECT OF GALAXY CATALOG COMPLETENESS

The previous discussion assumed that an ideal, complete galaxy catalog was available; however, GWGC (White et al. 2011), is incomplete beyond $\sim 30 \text{ Mpc}$, and there are limitations to how complete catalogs become at $\sim 200 \text{ Mpc}$ distances (Metzger et al. 2013). In practice, catalogs may comprise many different surveys with different characteristics and selection criteria, and will be influenced by spatially dependent factors such as extinction in the Galactic plane. However, the simplest model, and the one we consider here, is incompleteness from a flux-limited survey. As a simple example, we considered an extremely flux-limited survey that does not resolve galaxies fainter than apparent magnitude $m_B = 15.5$ in the blue band, which is a rough approximation to the GWGC. The resulting luminosity function of this hypothetical survey, for galaxies within 200 Mpc, is shown in Figure 4. The catalog is only 33% complete within this volume (i.e., contains 33% of the total absolute luminosity) compared to the model presented in Figure 1. However, it contains most of the rare bright galaxies, whose distribution on the sky shows significant fluctuations, making them most useful for informing pointing strategy, while missing common dim galaxies which are nearly homogenous on the sky and are therefore less useful for pointing.

The shape of the luminosity function for a flux-limited catalog is sensitive only to the overall completeness of the catalog, not the specific range and cut-off magnitude. Therefore, in order to express the follow-up success probability for a flux-limited catalog in terms of pointing volume, which incorporates FOV and depth in a single variable, we fix the completeness of the catalog, rather than the cut-off magnitude. This success probability is plotted in Figure 5 for three choices of completeness: 33%, 75%, and 100%.

In our flux-limited survey model for incompleteness, the catalog luminosity function agrees with a hypothetical complete luminosity function for the most luminous galaxies. It is therefore not surprising that incompleteness in a catalog has little effect on the scenarios where only a small fraction of the sky uncertainty region will be followed up, since both complete and incomplete catalogs will tend to agree on the most luminous tiles, which are the only ones that will be pointed at for small follow-up fractions. For example, in Figure 5, the line corresponding to a follow-up fraction of $f = 0.01$ is virtually unchanged from the corresponding line for a complete catalog.

When the follow-up fraction is large, incomplete catalogs still yield similar success fractions to complete catalogs as long as the pointing volume is also sufficiently large. Of course, at very large pointing volumes, $F$ asymptotes to $f$, as the fields of view become increasingly uniform due to the very large number of galaxies they contain, and a galaxy catalog ceases to be useful even when complete. Even at moderate pointing volumes and moderate follow-up fractions, catalog incompleteness is not necessarily a concern if it only leads to missing the many dim galaxies which are nearly homogeneously distributed on the sky. A few bright galaxies can still dominate the prior and since these are included even in incomplete flux-limited catalogs, the success fraction is still relatively insensitive to completeness. When pointing volumes are small, even the dimmest galaxies, which are missed out in incomplete catalogs, contribute to the variability between different fields of view. When follow-up fractions are large at small pointing volumes, the success probability asymptotes to the maximum possible success fraction $F \rightarrow \lambda + f(1 - \lambda)$, where $\lambda$ is the catalog completeness, and incompleteness limits catalog utility. This happens for a 33%-complete catalog when the pointing volume is $V \lesssim 100 \text{ Mpc}^3$ and the follow-up fraction

Consider a situation in which the number of bright galaxies that enter the catalog is sufficiently small that all of them can be followed up with a negligible number of pointings; the remaining allowed pointings will capture a fraction $f$ of the other fields of view, which have no galaxies in the incomplete catalog and have a uniform prior density $1 - \lambda$ painted across them.
is $f \gtrsim 10\%$. Nevertheless, even for larger follow-up fractions, $F$ is significantly larger than $f$ for a large range of pointing volumes, suggesting that even a moderately complete (33% complete) catalog is still useful for pointing at the sky region hosting the source of a GW transient.

As discussed above, an incomplete catalog is most useful when it contains a high fraction of intrinsically luminous galaxies at the expense of missing galaxies with low absolute magnitudes. Therefore, a simple flux limit is an optimistic model of a catalog’s incompleteness. If a catalog instead has a more gradual cut-off with apparent magnitude, its utility for a given completeness fraction $\lambda$ could be lower than estimated here. For example, for $f = 10\%$, the largest discrepancy between a 33%-complete flux-limited catalog and GWGC is at $V \sim 20$ Mpc$^3$, where they yield success fractions of $F \sim 63\%$ and $F \sim 60\%$, respectively. The difference drops to 1% for a pointing volume of 100 Mpc$^3$ and is below the statistical error of the simulation for $V = 1000$ Mpc$^3$.

6. CONCLUSION AND FUTURE WORK

EM follow-up prospects in the advanced GW detector era can be aided by the use of galaxy catalogs to direct follow-up surveys. The relevance of catalog-directed wide-field follow-ups is limited mostly by the modest spatial fluctuations of luminosity on the sky for the large three-dimensional localization uncertainty volumes of the advanced-detector network.

We have shown in Figures 3 and 5 that the utility of a catalog depends on the volume of individual telescope pointings and on the fractional coverage of the GW localization area. Catalogs are therefore most relevant for shallow and narrow follow-up searches, although narrow-field instruments are unlikely to follow up a sufficient fraction $f$ of the GW localization region for a successful follow-up to be realistic (with the possible exception of short-range observations, where individual galaxies could be followed up). Loud, nearby GW triggers are an obvious scenario where catalogs will be particularly useful. It is possible, for example, that they confer as much as a fourfold increase in success fraction over a follow-up that does not use a catalog; cf. case 3 in Section 3. Similarly, follow-ups from shallower GW searches—during the early commissioning phases of advanced detectors, for example—will also benefit from the use of catalogs.

However, even for sources located at the median 200 Mpc distance expected for detections with advanced-detector networks, we have shown that catalogs are still relevant for sufficiently small telescope fields of view. For example, a catalog might confer as much as a 70% increase in the probability of imaging the EM counterpart relative to a follow-up without the benefit of a catalog, as in case 2 of Section 5.

Realistic, incomplete galaxy catalogs are likely adequate for most follow-up campaigns. Metzger et al. (2013) propose that a catalog complete to $\sim 75\%$ with respect to $B$-band luminosity should be achievable. At $f = 10\%$, a hypothetical flux-limited catalog of this completeness conceives a fraction $<1\%$ of the success fraction from a complete catalog for both 100 Mpc$^3$ and 1000 Mpc$^3$ pointing volumes. Metzger et al. (2013) suggest that it will be difficult to construct a galaxy of more than $\sim 33\%$ completeness with respect to $K$-band luminosity, a tracer of total mass. Even in this case, the fractional loss of success fraction relative to a search with a complete catalog is small: 7.5% and 5% respectively for 100 Mpc$^3$ and 1000 Mpc$^3$ pointings.

6.1. Imaging versus Identifying of the Counterpart

Our study focuses on the probability of imaging the EM counterpart to a detected GW signal—i.e., pointing a telescope so that the EM counterpart is within the field of view—but not on the probability of detecting and identifying it among background sources. In reality, some telescopes may have trouble observing weak, distant EM counterparts (Aasi et al. 2013).

For example, Metzger & Berger (2012) suggest that the orphan optical afterglow expected to accompany a BNS merger at 200 Mpc will have a peak optical brightness as faint as $\sim 23$ mag when viewed slightly off-axis: beyond the limiting flux of many telescopes. Even if they are detected, contamination from background events may make it difficult to pick out the correct transient. Identification of GW EM counterparts among false positives is addressed by Nissanke et al. (2013). The detectability of EM counterparts could be further investigated by considering the capabilities of specific telescopes given the observing requirements of particular sources (for example, their peak luminosities, light-curve evolution, etc.).

6.2. Astrophysical Assumptions

We have made a number of assumptions about the astrophysics underlying BNS merger signals:

1. $B$-band luminosity of the host galaxy—which traces its star formation rate—is a proxy for the merger rate. In fact, if there are long time delays between star formation and binary merger, the total mass of the host galaxy, traced by $K$-band luminosity, might be the more relevant indicator of merger rate. For example, population synthesis modeling suggests that half of all BNS mergers may take place in elliptical galaxies with little ongoing star formation (de Freitas Pacheco et al. 2006; O’Shaughnessy et al. 2010). Meanwhile, observational evidence on short gamma ray bursts indicates that about a quarter of them occur in elliptical galaxies (Fong et al. 2013), though selection effects associated with the detection of afterglows that allow the host to be identified could influence this fraction.

2. The completeness of the galaxy catalog is known precisely. In practice, the completeness of the catalog is estimated from the expected spatial luminosity density in the local universe ($\sim 0.02 L_{10}$ Mpc$^{-3}$ for blue luminosity). Inaccuracy in the estimated completeness may lead to a less-than-optimal ranking of tiles on the sky. We can account for the incompleteness of a catalog by changing the weighting we give to individual galaxies; if the catalog completeness fraction is $\lambda$, then the catalogued luminosity of a given pixel, $L_\lambda$, is multiplied by $\lambda$ when computing the prior, with a prior fraction $1 - \lambda$ painted uniformly over the entire GW sky uncertainty region to account for the galaxies missed in the catalog.

3. Mergers are spatially coincident with host galaxies on the celestial sphere. Natal kicks accompanying supernovae that give birth to the neutron-star components of a binary (up to hundreds of km s$^{-1}$; Fryer & Kalogera 1997) can combine to give a significant velocity to the binary as a whole. As a result, mergers are distributed at larger distances from the galactic center than typical stellar concentrations (Fong & Berger 2013), and galaxies should properly be treated as extended objects rather than point sources. However, for telescope fields of view of order a square degree or more and typical source distances of 100–200 Mpc, treating galaxy sizes $\lesssim 100$ kpc as point sources will not affect our results.
On the other hand, binaries may be completely ejected from their host galaxies (e.g., Kelley et al. 2010), and some fraction of the “no-host” short gamma ray bursts (Berger 2010; Tunnicliffe et al. 2014) may provide evidence for this population of merging ejected binaries, which may be separated by more than a Mpc from their host galaxy (but see discussion in Kanner et al. 2012 and references therein).

We suggest a future study of the importance of these effects—given our ignorance—as parameterized priors. One would allow nature to choose a true value of a given parameter (e.g., the relative contribution of blue and red luminosity tracers to merger rates) and attempt to image counterparts from the resulting GW events by ranking tiles according to an assumed parameter value representing our own knowledge. The effects of our ignorance of the true values of each parameter could thus be described by a matrix in which one dimension represents nature’s choice of prior, and the other our assumed knowledge.

6.3. Coherent Use of Galaxy Catalogs

Finally, we have investigated the utility of a galaxy catalog when applied to the sky location posterior obtained from a parameter estimation pipeline. In practice, if a galaxy catalog were to be used for follow-up, it should be applied as a prior during coherent Bayesian parameter estimation (LIGO Scientific Collaboration et al. 2013b). Doing so would make it possible to consistently account for the probability that a given galaxy hosts the GW source, which depends not only on the galaxy luminosity but also on the distance to the galaxy and the inclination and orientation of the binary, which must yield a GW signal amplitude consistent with observations. This is particularly important when considering the correlations between the recovered GW signal parameters such as inclination and distance. Moreover, using coherent Bayesian parameter estimation would allow complex sky location posteriors could be accurately accounted for.

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