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Using the 2-MASS Photometric Redshift Survey to optimize LIGO Follow-Up Observations

Elisa Antolini[1], Jeremy S. Heyl⋆[2]
[1] *Dipartimento di Fisica e Geologia, Università degli Studi di Perugia, I-06123 Perugia, Italia*
[2] *Department of Physics and Astronomy, University of British Columbia, 6224 Agricultural Road, Vancouver, BC V6T 1Z1, Canada*

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ABSTRACT

The initial discovery of LIGO on 14 September 2015 was the in-spiral merger and ring-down of the black hole binary at a distance of about 500 Mpc or a redshift of about 0.1. The search for electromagnetic counterparts for such sources is impeded by poor initial source localizations and a lack of a compelling model for the counterpart Because astrophysical sources of gravitational radiation are likely to reside in galaxies, it would make sense to search first in regions where the LIGO-Virgo probability is large and where the density of galaxies is large as well. Under the Bayesian prior assumption that the probability of a gravitational-wave event from a given region of space is proportional to the density of galaxies within the probed volume, one can calculate an improved localization of the position of the source simply by multiplying the LIGO-Virgo skymap by the density of galaxies in the range of redshifts. We propose using the 2-MASS Photometric Redshift Galaxy Catalogue for this purpose and demonstrate that using it can dramtically reduce the search region for electromagnetic counterparts.

1 INTRODUCTION

LIGO has recently begun to detect gravitational wave events from the local Universe (Abbott et al. 2016). During these initial years of gravitational astronomy, the localization of the candidate events on the sky is poor with the ninety-percent confidence regions covering hundreds or even thousands of square degrees. Finding an electromagnetic counterpart to these candidate graviational-wave events will be crucial to understanding what produces them, interpretation of the signal and to provide tests of general relativity. The ideas of how the the electromagnetic counterparts would appear are varied and uncertain. There has been substantial speculation on the electromagnetic transients associated with the mergers of binaries that include a neutron star (e.g. East et al. 2016; Kawaguchi et al. 2016; D'Orazio et al. 2016; Fernández & Metzger 2015; Mingarelli et al. 2015; Kyutoku et al. 2015; Siegel & Ciolfi 2015b,a) However,the first discovered gravitational wave event appears to be the merger of binary black holes, so the appearance and duration of the electromagnetic counterparts are especially uncertain with only a few models (e.g. Gerosa et al. 2015; Margalit & Piran 2015; Cerioli et al. 2016; Yang & Zhang 2016) Consequently, rapid electromagnetic follow-up of a large portion of the probable region would increase the chance of success in finding a counterpart. Over the large search regions and over the span of days or weeks, many electromagnetic transients typically occur, and with the wide variety of models it will be difficult to associate unambigously a particular electromagnetic event with a candidate gravitational-wave event.

The purpose of this letter is to present a strategy to alleviate both of these issues; that is, to reduce both the search region and the time required to plan and begin observations. We follow the spirit of Gehrels et al. (2015) to develop a galaxy catalogue to guide the observational plan. However, our goal here is to develop a nearly complete catalogue at the expense of having less accurate estimates of the redshifts of the galaxies within the catalogue. The accuracy of the galaxy distances needs to be only as good as the distance estmates of the gravitational-wave events. Additionally we will outline a straightforward and rapid technique to generate a nearly optimal observing plan to follow up the events rapidly (i.e. within a few seconds of the trigger).

2 BAYESIAN APPROACH TO FOLLOW-UP

Because we will be interested in the rapid follow-up of candidate gravitational-wave events, we will focussed on the rapid Bayesian reconsruction outlined by Singer & Price (2015), BAYESTAR. At the most basic level, BAYESTAR yields a probability map on the sky in the form of a HEALPpix map (Górski et al. 2005) where each pixel contains the probability $P(d|m)$ that a particular model (i.e. position on the sky) will yield the data (i.e. the observed strains on the LIGO and Virgo interferometers). To plan an observing strategy one would like the probability of a particular model (i.e. position on the sky) given the data. We have from Bayes's theorem

$$P(\text{position}|\text{data}) = \frac{P(\text{position})P(\text{data}|\text{position})}{P(\text{data})}. \quad (1)$$

If we make the additional mild assumption that gravitational-waves originate from nearby galaxies, the probability of a given position on the sky naturally is proportional to the density (or perhaps the luminosity density) of galaxies in that direction integrated over distance range determined from the modelling of the gravitational waveform. Of course, these distance estimates will usually have large uncertainities so the distance range over which to integrate the galaxy density distribution will also be large, so highly accurate redshift information is not needed to construct P(position).

Furthermore, because we will ultimately be interested in which fields to observe (not which particular galaxies), accurate positions are not required in the construction of P(position). It is natural to sample P(position) also as a HEALPix grid with each pixel covering about the same solid angle as the field of view of the telescope of interest or the BAYESTAR map (a HEALPix level of 512 or about 50 square arcminutes per pixel), so positions no more accurate than arcminutes are required. The key to generate the observing plan rapidly is to calculate the required galaxy density maps beforehand in principle at the desired resolution (this optimization only speeds the process up slightly) for the distance ranges of interest. With the arrival of an alert, all that is required is to calculate Eq. (1) using the HEALPix maps, resample to the scale of the telescope, renormalize the probability, sort the pixels from most likely to least and output the positions to cover a given amount of cumulative probability (this entire process takes typically less than one second).

3 GALAXY CATALOGUES

To gain a picture of the local Universe, our focus will be the completness of the data rather than the accuracy of the distances and positions. Gehrels et al. (2015) combine several redshift surveys (e.g. Norberg et al. 2002; Liske et al. 2003; Driver et al. 2005; Huchra et al. 2012) that cover a large portion of the sky, but at various depths and attempt to increasing the completeness of the sample by using only the galaxies near the upper-end of the luminosity function (*i.e.* $L \sim L_*$) and ; the discovery that binary black holes with large masses (!) dominate the initial detections indicates that focussing the search on massive galaxies might not be the best strategy. After all such large black holes have not been found so far in our approximately L_*-galaxy, the Milky Way, or our neighbour, Andromeda. In fact theoretical arguments indicate that the production of such massive black holes results from the evolution of massive stars in low metallicity galaxies which are typically small in the local Universe. Our goal is to have a nearly complete survey that attempts to be unbiased with respect to the mass of the galaxy.

We follow in spirit the work of Jarrett (2004) who used The Two Micron All Sky Survey extended source catalogue (2MASS XSC, Jarrett et al. 2000b; Skrutskie et al. 2006), and the assuption that all galaxies have the same K_s-band luminosity of around L_* to estimate distances to each galaxy and create sky maps of the local Universe. A substantial fraction of 2MASS has measured redshifts (e.g Huchra et al. 2012). Bilicki et al. (2014) combined the photometric data from 2MASS XSC with additional photometry the mid-infrared from WISE (Wright et al. 2010) and the optical from SuperCOSMOS (Hambly et al. 2001a,b,c). Using this multiband photometry, they trained neural networks using measured spectroscopic redshifts from SDSS (Ahn et al. 2012, 2014), 2dF (Colless et al. 2001, 2003), 6dF (Jones et al. 2004, 2009) and other catalogues to determine photometric redshifts. They also extend the photometric redshift catalogue beyond the 2MASS XSC building a three-dimensional map of the sky out to a redshift of nearly 0.2 well into the realm of the first gravitational wave event. The 2MASS Photometric Redshift (2MPZ) catalogue contains over one million galaxies with a median redshift of 0.1 with a typical scatter between the photometric and spectroscopic redshifts (where both are known) of $\sigma_z = 0.015$.

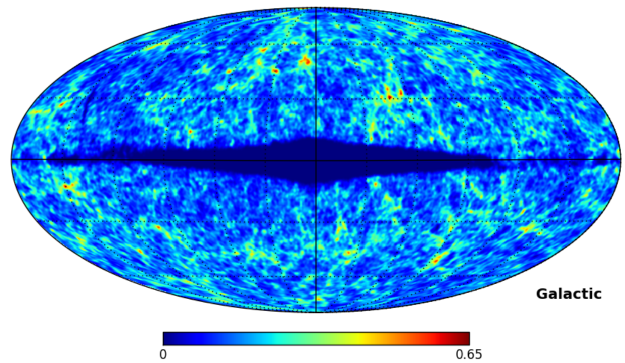

Figure 1. The relative surface density of galaxies in the 2-MASS Photometric Redshift Survey with photometric redshifts between 0.01 and 0.1, smoothed with a Gaussian of 0.6 degrees (0.01 radian).

Except for the most local sources, the estimate distances from the gravitational wave data itself have comparable errors to this, so this catalogue is sufficiently accurate to calculate the surface density of galaxies with the expected redshift range of a particular gravitational-wave detection. Furthermore, for the nearest sources, there are nearly uniform all-sky redshift surveys which would be more appropriate for this task (Saunders et al. 2000; Huchra et al. 2012, e.g). Of course, all of the techniques outlined here can be applied to these more nearby catalogues to produce sky maps of even more nearby galaxies. Here we will focus on galaxies with photometric redshifts between 0.01 and 0.1 from the 2MPZ as depicted in Fig. 1. For closer galaxies the redshift error is significant, and the outer end of the range is both the median redshift of the catalogue and the typical distances of the binary-black-hole sources.

To produce this map we divided the sky into 3,145,728 regions (each of about 45 square arcminutes, four ACS fields) using a HEALPix (Górski et al. 2005) tesselation with `NSIDE` $= 512$. Each cell of the map simply contains the number of galaxies in the 2MPZ catalogue within the range of photometric redshift that lie within that portion of sky. We have subsequently smoothed the map with a Gaussian with $\sigma = 0.01$ radian. Typically no HEALPix pixel contains more than one galaxy from the catalogue. After smoothing we notice the large-scale structure even when we have averaged over distance. This demonstrates the potential optimization in the observing strategy by observing fields with nearby galaxies. Depending on whether one believes that the sources are associated with the visible portion of galaxies or may travel some distance from the galaxy itself before the gravitational-wave event, one would use either the raw galaxy counts or the smoothed map.

Furthermore, our choice of weighting the fields simply by the number of galaxies within each field is perhaps the most simple one. Given the type of event, one could use a map that gives small, low-metallicity galaxies more weight or weigh the galaxies by their mass or luminosity. Of course, all of these possibilities would be informed by one's prior knownledge of the source inspired by theoretical models and the hints from the waveform itself and give a better estimate of P(position). The key is to calculate these maps beforehand.

There is a further structure apparent in the map, and this is of course the zone of avoidance imposed by the disk and bulge of our Galaxy. One can attempt to probe the zone of avoidance (e.g Jarrett et al. 2000a) and future 21-cm surveys like CHIME (Vanderlinde & Chime Collaboration 2014) will also probe the large-scale structure beyond the Galactic plane.

4 RESULTS

5 CONCLUSIONS

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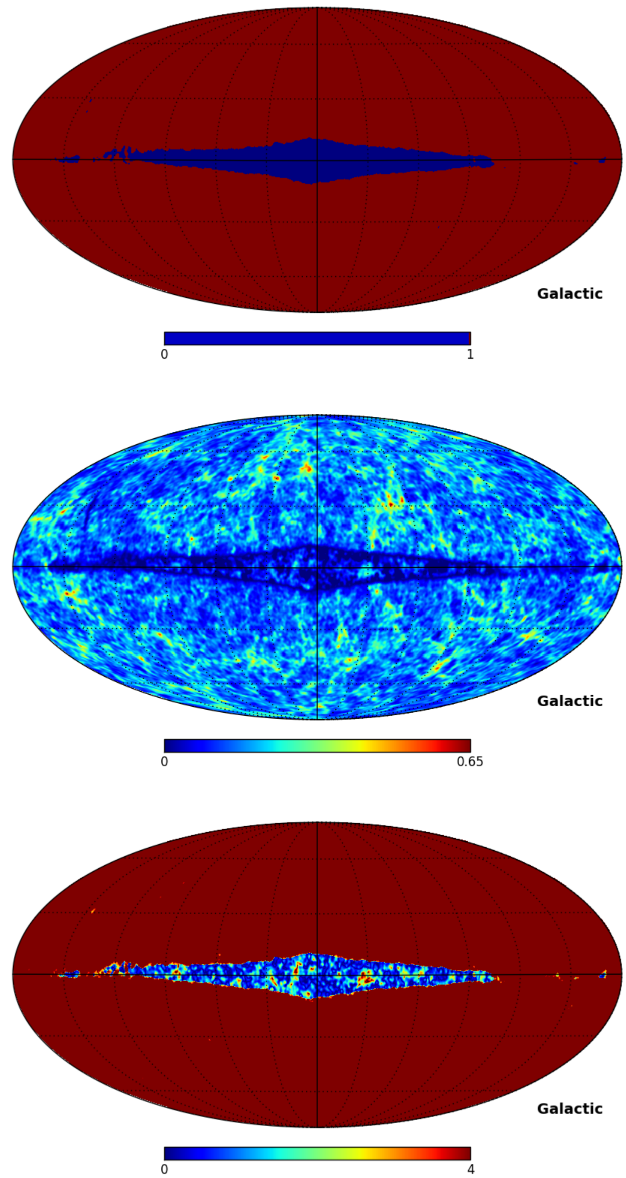

Figure 2. Upper: the mask used for the infilling procedure obtained by determining the regions where the galaxy density is less than one tenth of the mean. Middle: the infilled galaxy distribution. Lower: The signal-to-noise of the infilled map obtained by bootstrapping the galaxy catalogue.

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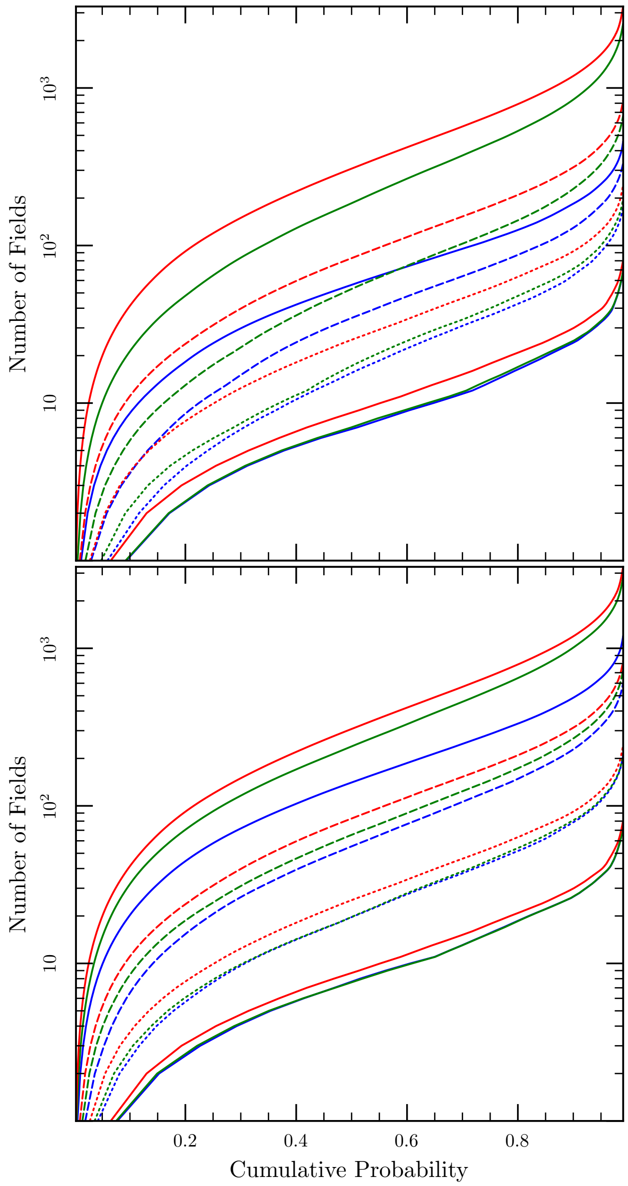

Figure 3. The number of fields required to cover the given fraction of the probablity region for a simulated LIGO detection (red curves without the galaxy map, green curves with a smoothed galaxy, blue curves with a raw galaxy map). The upper solid curves use a healpix map with about 200,000 cells, the dashed curves have about 50,000 cells, the dotted curves have about 12,000 cells and lower solid curves have about 3,000 cells, corresponding 0.2, 0.8, 3.2 and 13 square-degree fields of view. The redshift range of the galaxy map in the upper panel is $0.03 < z < 0.04$ and $0.01 < z < 0.05$ in the lowel panel.

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