An astrophysically motivated ranking criterion for low-latency electromagnetic follow-up of gravitational wave events

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ABSTRACT
We investigate the properties of the host galaxies of compact binary mergers across cosmic time. To this end, we combine population synthesis simulations together with galaxy catalogues from the hydrodynamical cosmological simulation \textit{eagle} to derive the properties of the host galaxies of binary neutron star (BNS), black hole-neutron star (BHNS) and binary black hole (BBH) mergers. Within this framework, we derive the host galaxy probability, i.e., the probability that a galaxy hosts a compact binary coalescence as a function of its stellar mass, star formation rate, $K_s$ magnitude and $B$ magnitude. This quantity is particularly important for low-latency searches of gravitational wave (GW) sources as it provides a way to rank galaxies lying inside the credible region in the sky of a given GW detection, hence reducing the number of viable host candidates. Furthermore, even if no electromagnetic counterpart is detected, the proposed ranking criterion can still be used to classify the galaxies contained in the error box. Our results show that massive galaxies (or equivalently galaxies with a high luminosity in $K_s$ band) have a higher probability of hosting BNS, BHNS, and BBH mergers. We provide the probabilities in a suitable format to be implemented in future low-latency searches.

Key words: black hole physics – gravitational waves – methods: numerical – stars: black holes – stars: mass-loss – stars: neutron

1 INTRODUCTION
The number of gravitational wave (GW) detections is rapidly growing. The LIGO-Virgo collaboration (LVC) reported eleven compact binary mergers from their first two observing runs: ten merging binary black holes (BBHs) and one binary neutron star (BNS), black hole-neutron star (BHNS) and binary black hole (BBH) mergers. Within this framework, we derive the host galaxy probability, i.e., the probability that a galaxy hosts a compact binary coalescence as a function of its stellar mass, star formation rate, $K_s$ magnitude and $B$ magnitude. This quantity is particularly important for low-latency searches of gravitational wave (GW) sources as it provides a way to rank galaxies lying inside the credible region in the sky of a given GW detection, hence reducing the number of viable host candidates. Furthermore, even if no electromagnetic counterpart is detected, the proposed ranking criterion can still be used to classify the galaxies contained in the error box. Our results show that massive galaxies (or equivalently galaxies with a high luminosity in $K_s$ band) have a higher probability of hosting BNS, BHNS, and BBH mergers. We provide the probabilities in a suitable format to be implemented in future low-latency searches.

Key words: black hole physics – gravitational waves – methods: numerical – stars: black holes – stars: mass-loss – stars: neutron

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short gamma ray bursts and kilonovae. Moreover, with the improvement of GW interferometers, more multimessenger detections are expected in the near future. Nonetheless, finding the EM counterpart is a “needle in the haystack” problem, because the uncertainty on the sky localization for current GW detector network spans from tens to thousands of square degrees (Abbott et al. 2018).

The standard method for EM follow-up, uses the probability skymap error box reported by LIGO-Virgo for each GW source (Veitch et al. 2015; Singer et al. 2016). In order to improve the search process, one strategy is to first identify the galaxies contained within the credible regions given by the LVC using a complete galaxy catalogue such as GLADE (D’Alba et al. 2018), and then rank the galaxies according to their localisation probability (see e.g., Gehrels et al. 2016; Arcavi et al. 2017). Finding a criterion to predict the properties of the most likely host galaxies of a GW event might improve the overall ranking procedure in two ways. On the one hand, it can speed up low-latency searches for EM counterparts by prioritising observations of the most likely host galaxies. On the other hand, even if the counterpart is not detected, it can be used to weigh the candidate galaxies identified in the error box, facilitating some further analysis such as the measurement of the Hubble constant (Abbott et al. 2019a). Previous works propose to rank the most likely host galaxies according to their properties such as luminosity and distance (see e.g., Nuttall & Sutton 2010; Fan et al. 2014; Antolini & Heyl 2016). In particular, Ducoin et al. (2020) have recently shown that including a dependence on galaxy stellar mass in the probability density improves the galaxy ranking dramatically.

From a theoretical perspective, predicting the most likely host galaxies of compact binary mergers is a challenging task, due to the extreme physical scales involved. A possible approach to tackle this problem is to combine galaxy formation models with binary population synthesis simulations. This methodology has been implemented in several works using semi-analytic models or cosmological simulations together with population synthesis models (see e.g., O’Schaunessy et al. 2010, 2017; Dvorkin et al. 2016; Lamberts et al. 2016; Mapelli et al. 2017; Schneider et al. 2017; Cao et al. 2018; Mapelli et al. 2018; Mapelli & Giacobbo 2018; Artale et al. 2019, 2020; Marassi et al. 2019; Boco et al. 2019; Conselice et al. 2019; Eldridge et al. 2019; Mapelli et al. 2019; Toffano et al. 2019; Adhikari et al. 2020; Jiang et al. 2020).

In our previous studies (Artale et al. 2019, 2020), we found a strong correlation between the binary merger rate per galaxy, the stellar mass and the star formation rate (SFR) of the host galaxy. In particular, we showed that the correlation between merger rate per galaxy and stellar mass is the strongest one, is almost linear, holds for all different types of compact binaries (BBHs, BHNSs and BNSs) and for the entire redshift range considered, from z = 0 to z = 6. Moreover, the median stellar mass of host galaxies increases as redshift decreases, as a consequence of the cosmic assembly history of the galaxies, together with the delay time of merging compact binaries.

In this study, we make use of the simulations already presented in Artale et al. (2019) and Artale et al. (2020) to compute the density of mergers per galaxy as a function of its stellar mass and SFR at different redshifts (up to redshift z ∼ 6). From there, we use the density to build a probability-like quantity (host galaxy probability) that can be integrated as an additional ranking criterion in low-latency searches of EM counterparts, facilitating a prompt multi-messenger follow-up (Nissanke et al. 2013; Hanna et al. 2014; Gehrels et al. 2016; Mapelli & Giacobbo 2018; Del Pozzo et al. 2018). Alternatively, if the EM counterpart is not detected, our results can still be used to rank possible host galaxies in the LVC error box, hence providing useful information for measurements of the Hubble constant (e.g. Schutz 1986; Del Pozzo 2012; Abbott et al. 2017e; Chen et al. 2018; Vitale & Chen 2018; Fishbach et al. 2019; Soares-Santos et al. 2019; Del Pozzo et al. 2018; Abbott et al. 2019a).

This paper is organized as follows. Section 2 describes the methodology we implemented to seed the EAGLE cosmological simulation with a population of merging compact objects (BNSs, BHNSs, and BBHs), along with the approach we used to build our ranking criterion. We present our results in Section 3 and we compare them with previous work in Section 4. Our main conclusions are drawn in Section 5.

2 METHOD

2.1 Catalogues of binary mergers and their host galaxies

We adopt the methodology introduced by Mapelli et al. (2017) (also implemented in Mapelli et al. 2018; Mapelli & Giacobbo 2018; Mapelli et al. 2019; Artale et al. 2019, 2020) to produce a galaxy catalogue of merging compact objects. The main idea is to combine the simulated galaxies from the EAGLE simulation suite (Schaye et al. 2015) with merging compact object catalogues obtained with the population synthesis code MOBSE (Giacobbo et al. 2018). In this section we summarize the main details of the methodology; while a more exhaustive description can be found in the aforementioned papers.

The population synthesis code MOBSE (Giacobbo et al. 2018) is an upgrade of the BSE code (Hurley et al. 2000, 2002). MOBSE includes new prescriptions for metallicity dependent stellar winds (Vink et al. 2001; Vink & de Koter 2005; Chen et al. 2015), core collapse supernovae (SNe), following Fryer et al. (2012), and pair-instability and pulsational pair-instability SNe (Woosley 2017; Spera & Mapelli 2017).

In this work, we use the catalogues from the merging compact model CC1505 presented in Giacobbo & Mapelli (2018), which was already implemented in several previous works (Mapelli et al. 2018, 2019; Artale et al. 2019; Toffano et al. 2019; Artale et al. 2020). The run CC1505 is composed of 12 subsets of metallicities Z = 0.0002, 0.0004, 0.0008, 0.0012, 0.0016, 0.002, 0.004, 0.006, 0.008, 0.012, 0.016 and 0.02, where each subset was run initially with 10^7 stellar binaries making a total of 1.2 × 10^5 initial binary systems. For each metallicity we get a merging compact object catalogue for BNSs, BHNSs, and BBHs, containing properties such as delay times and masses of compact objects.

The EAGLE suite (Schaye et al. 2015; Crain et al. 2015) is a set of hydrodynamical cosmological simulations run with

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1 We refer to delay time as the time elapsed between the formation of the stellar progenitor to the merger of the binary compact object system.
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2 http://icc.dur.ac.uk/Eagle/, http://virgo.dur.ac.uk/.

In this work, we are interested in using the density of mergers per galaxy as a function of stellar mass, SFR and Z to build a probability-like quantity called \( p(M_*, \text{SFR}, Z) \), that we will refer to as host-galaxy probability. As shown later in this section, \( p(M_*, \text{SFR}, Z) \) can be used to derive the relative probability that a galaxy hosts a GW merger for a selected set of targeted galaxies, making this quantity particularly relevant for EM follow-up ranking procedure.

For each redshift bin, we approximate the values of the host galaxy probability as a piecewise constant function in bins of \((M_*, \text{SFR}, Z)\) with values

\[
p^X_{i,j,k} = \frac{N^X_{i,j,k}}{N_{\text{gal}, i,j,k}},
\]

where \(N^X_{i,j,k}\) is the sum of all events of kind \(X\) (where \(X = \text{BNS, BHNS or BBH}\) occurring in galaxies with masses in the \(i\)th bin (between \(M_* - \Delta M_*/2\) and \(M_* + \Delta M_*/2\)), SFR in the \(j\)th bin (between \(\text{SFR}_i - \Delta \text{SFR}/2\) and \(\text{SFR}_i + \Delta \text{SFR}/2\)) and \(Z\) in the \(k\)th bin (between \(Z_k - \Delta Z/2\) and \(Z_k + \Delta Z/2\))

\[Z_{\text{gal}, i,j,k}\]

while \(N_{\text{gal}, i,j,k}\) is the sum of all galaxies with \(M_*\) in the \(i\)th bin, \(\text{SFR} \) in the \(j\)th bin and \(Z\) in the \(k\)th bin. Finally, \(n_{\text{norm}}\) is a normalization factor chosen so that \(\sum_{i,j,k} n^X_{i,j,k} = 1\).

By marginalising over the metallicity, one can obtain the host galaxy probability \( p(M_*, \text{SFR}) \) taking values

\[
p^X_{i,j} = \sum_{k=1}^{N_Z} p^X_{i,j,k},
\]

where \(N_Z\) is the number of bins along the metallicity axis. Similarly, we can marginalise a second time over \(\text{SFR}\) and \(M_*\) to obtain respectively the host galaxy probabilities \(p(M_*)\) and \(p(\text{SFR})\).

Following a similar approach to Artalte et al. (2020), we use a grid of \(25 \times 25 \times 25\) points, with a range of \(\log(M_*/M_\odot) \in [7.0, 12.5]\), \(\log(\text{SFR}/M_\odot \text{yr}^{-1}) \in [-5.5, 2.5]\), and \(\log Z \in [-8, -0.7]\), in order to compute the elements of the host galaxy probability \(p(M_*, \text{SFR}, Z)\) in Eq. (2).

In practice, the host galaxy probability that we have constructed can be directly integrated inside ranking procedures used by EM follow-up searches. To illustrate this, let us take an example where a GW detection with \(N_G\) candidate galaxies identified and for which we have access to the stellar mass and SFR. If we take the very simplistic case where we both assume that all possible galaxies have been identified and have the same sky localisation probabilities, the relative probability that the \(k\)-th galaxy of our sample is the host of the merger is given by

\[
P^X(\text{galaxy } k) = \frac{p(M_*^k, \text{SFR}^k)}{\sum_{i=1}^{N^X} p(M_*^i, \text{SFR}^i)}
\]

where \((M_*^k, \text{SFR}^k)\) are the stellar mass and SFR of the \(k\)-th galaxy of our targeted search sample and \(p(M_*^k, \text{SFR}^k)\) is computed using Eq. (2) with the appropriate bin. If we now add the information coming from the sky localisation of the source, the relative probability that the \(k\)-th galaxy of our sample is the host of the merger is given by

\[
P^X(\text{galaxy } k) = \frac{P^X(\text{galaxy } k) \ p_{\text{loc}}(\text{galaxy } k)}{\sum_{k=1}^{N_G} P^X(\text{galaxy } k) \ p_{\text{loc}}(\text{galaxy } k)},
\]

where \(P^X(\text{galaxy } k)\) is the quantity defined in eq. 3 and \(P_{\text{loc}}(\text{galaxy } k)\) is the probability that the galaxy hosts the merger based on sky localisation and redshift probability. Furthermore, the previous equation can easily be updated in more complex analysis that takes into account other factors such as the integration of galaxies without mass information or the effect of the incompleteness of the galaxy catalogue used (e.g. Ducoin et al. 2020).

Using equation 4, we can assign a probability \(\tilde{P}(\text{galaxy } k)\) to each galaxy of our catalogue identified in the error box of a GW event. If the EM counterpart is not found, each
galaxy in the box is at least ranked by this probability. This prioritization can be used to give a different weight to each galaxy when, e.g., we want to estimate the Hubble constant $H_0$ from GW data. Namely, our probability can be folded in equation 5 of Abbott et al. (2019a) to refine our knowledge of the host galaxy distance.

Finally, we highlight that the host-galaxy probability defined in Eq. (1) is significantly different from the merger probability that was calculated in Eq. (4) of Artale et al. (2020). The merger probability discussed in Artale et al. (2020) accounts for two different ingredients: i) how common a galaxy with a given stellar mass and SFR at a given redshift in the Universe is (massive galaxies are way less numerous than low-mass galaxies); ii) the dependence of the number of compact-binary mergers on the stellar mass and SFR of the host galaxy. In contrast, the probability defined here in Eq. (1) accounts only for the second ingredient.

3 RESULTS

In Section 3.1, we discuss the marginalized host galaxy probability as a function of the stellar mass, $p(M_*)$, at redshift $z = 0.1, 1, 2$ and 6. The dependence on both SFR and $M_*$ is treated in Section 3.2.

3.1 Host-galaxy probability: stellar mass

Figure 1 shows the host galaxy probability as a function of stellar mass, $p(M_*)$, for merging BNSs, BHNSs, and BBHs, at redshifts $z = 0.1, 1, 2,$ and 6. In all cases, massive galaxies are more likely to host merging compact objects than low mass galaxies. In addition, the peak of the distributions shifts towards higher values of stellar mass for decreasing values of redshift, as expected from galaxy assembly history (i.e., galaxies accrete more mass and become more massive with time). Moreover, the host-galaxy probability for BBHs and BHNSs has a stronger dependence on redshift than for BNSs. These features are explained by the differences in the delay time distributions of the merging compact objects (see Mapelli et al. 2018, 2019). In fact, BNSs have a delay time distribution that approximately scales with $t^{-1}$ over the entire redshift range studied here, while merging BHNSs and BBHs tend to have a flatter delay time distribution at $z \leq 0.1$.

The host probability associated with the smallest galaxies ($M_* \lesssim 10^8 M_\odot$) is significantly higher at high redshift ($z = 6$). This is another effect of delay time, as compact binaries with a very short delay time merge by $z = 6$, because the Universe at $z \sim 6$ was younger than 1 Gyr and the first stars formed only few hundreds of Myr before. Hence, most of the compact binaries which merge at $z \sim 6$ form and merge in the same galaxy.

The host probability as a function of mass increases almost monotonically from $M_* = 10^8 M_\odot$ to $10^{10} M_\odot$, but then it shows a turn-over at $M_* \gtrsim 10^{10} M_\odot$. The turn-over point shifts toward higher masses as redshift decreases. Low-statistics effects affect our results at the high-mass tail: due to the size of the box of the EAGLE, $\lesssim 10$ galaxies have stellar mass $\log(M_*/M_\odot) \geq 11.69, 11.46,$ and $11.12$ at $z = 0.1, 1,$ and 2, respectively. The most evident effect of low-statistics is the oscillatory behaviour of the distribution for $\log(M_*/M_\odot) \gtrsim 11.7$ at $z = 0.1$.

So far, our analysis directly took the distributions predicted by our model without taking into account detectability effects. However, we know that the current and future GW detectors introduce a bias in the observed distributions of compact mergers that should directly impact the evaluation of the host galaxy probability. To account for this, we have created catalogues of observed compact binary mergers by filtering our original catalogue using the framework already presented in previous works (Finn & Chernoff 1993; Dominik et al. 2015; Chen et al. 2018; Gerosa et al. 2018), and summarised in Appendix A. We highlight here that, given the computational cost of this analysis and the high number of binaries contained in the original catalogue (for instance, we have more than $6 \times 10^4$ BNSs at $z = 1$), all the catalogues were downsampling in order to have a number of sources close to $10^7$. This number represents $\sim 1 - 20\%$ of the original intrinsic catalogues, and allows us to manageable computation time. To check the validity of our downsampling procedure, we compared the values for $p(M_*)$ obtained with the full set and the downsampled one. We found a maximal percentage error value close to $3\%$, indicating very little bias between the two sets.

Figure 2 shows the values of $p(M_*)$ inferred from the downsampling catalogues that include detectability effects, considering advanced LIGO-Virgo design sensitivity and Einstein Telescope (hereafter ET) at $z = 0.1$, and 1. BNS and BHNS sources are not detected by advanced LIGO at $z = 1$ due to the lack of sensitivity of the instrument at this redshift value.

At $z = 0.1$, including detectability effects does not change the general features of $p(M_*)$, that still favours galaxies with high mass. However, we do observe some bias introduced by detectability effects for advanced LIGO-Virgo, especially at high values of mass $M_* > 10^{11} M_\odot$. We find values of residuals as high as 0.25 for BNSs, while the maximum value of the residuals peaks at 0.15 and 0.02 for BHNSs and BBHs, respectively (see Figure 2). This trend is explained by the fact that BNSs at redshift $z \sim 0.1$ are already close to the instrumental horizon of advanced LIGO-Virgo, resulting in a loss of 77% of the sources after applying our filtering technique. For ET, we observe no differences between the two distributions and the residuals are almost always equal to zero. Once again, this is easily understood given that an ET-like detector can detect almost all compact binary mergers in our local Universe.

At $z = 1$, $p(M_*)$ does not change significantly when we consider the sensitivity of an ET-like observatory. The situation is very different for advanced LIGO-Virgo, since only BBHs can be detected at this redshift, with a loss of $\sim 88\%$ of the intrinsic number of sources, resulting in a maximum value for the residual close to 0.2.

3.2 Host-galaxy probability: stellar mass and SFR

SFR is another key ingredient that needs to be considered in the analysis. Several studies have shown that there is an intrinsic correlation between the stellar mass and the SFR of galaxies (see e.g., Furlong et al. 2015; Sparre et al. 2015; Trayford et al. 2019). Figures 3, 4 and 5 show the values of the host-galaxy probability as a function of stellar mass and
SFR, \( p(M_*, \text{SFR}) \), for merging BNSs, BHNSs, and BBHs, respectively, at \( z = 0.1, 1, 2, \) and 6. These figures also display the marginal probability \( p(\text{SFR}) \) depending on SFR only.

Galaxies with higher values of SFR have a higher probability \( p(\text{SFR}) \) to host a merger, regardless of the compact object type. If we now take a look at the probability \( p(M_*, \text{SFR}) \) as a function of both stellar mass and SFR, we see that galaxies with high values of both stellar mass and SFR have a higher probability of hosting a merger, for all type of compact objects and for all considered redshifts. The shape of the distributions also suggests that stellar mass is the main parameter influencing the host galaxy probability. In fact, for a fixed value of SFR, we observe more variation of the distribution than in the case where stellar mass is fixed. Quantitatively, we found that the ratio between the maximum and minimum (non-zero) value of the host galaxy probability is \( 10 \sim 100 \) higher when SFR is fixed, compared to the case where \( M_* \) is fixed. Hence, according to our model, the stellar mass of the host galaxies of compact binary mergers is more important than SFR to characterize the host galaxy probability.

3.3 Host galaxy probability: \( K_s \) and \( B \) magnitudes

Galaxy surveys used for the EM follow-up of GW sources (such as GLADE and CLU Dilya et al. 2018; Cook et al. 2019) do not include direct information on the stellar mass and SFR of galaxies. Rather, they contain \( B \)—band and \( K_s \)—band magnitudes as a proxy of SFR and stellar mass, respectively.

Hence, in order to facilitate the usage of our results in EM searches, we derive the host galaxy probability as a function of the rest-frame absolute magnitudes in \( B \)— and \( K_s \)—band, \( p(M_B) \) and \( p(M_{K_s}) \) respectively. To this purpose, we have extracted the rest frame absolute magnitudes provided in the EAGLE database. The magnitudes were computed for the galaxies with stellar mass above \( M_* \sim 1.81 \times 10^9 M_\odot \).
Figure 3. Host-galaxy probability as a function of $M_*$ and SFR for the hosts of BNS mergers at redshifts $z = 0.1, 1, 2$ and 6. The marginal histograms show the host galaxy probability as a function of SFR ($p(SFR)$, right) and stellar mass ($p(M_*)$, top). The white dotted line represents a specific SFR $= 10^{-10} \text{yr}^{-1}$.

and for the stellar emission including the effect of dust (see Trayford et al. 2019, for further details).

Figure 6 shows the host galaxy probability as a function of the rest-frame absolute magnitudes in $B-$ and $K_s-$band, $p(M_B)$ and $p(M_{K_s})$. The host galaxy probabilities are computed with the same methodology as explained in Section 2.2 and 3.1, but replacing the stellar mass of each galaxy with its rest-frame magnitude. Both $p(M_B)$ and $p(M_{K_s})$ grow as a function of $M_B$ and $M_{K_s}$, respectively.

The peak of the host galaxy probability as a function of the $K_s$ magnitude shifts to higher luminosities (i.e., more massive galaxies) as redshift decreases, following the same trend that we found for $p(M_*)$. This trend is stronger for the host galaxies of BHNSs and BBHs than for the host galaxies of BNSs.
In contrast, $p(M_{B})$ does not show significant variations with redshift in the range $z = 0.1 - 2$. Indeed, the lack of a trend with redshift is similar to what we found for the host galaxy probability as a function of the SFR $p(SFR)$. These results confirm that while the $K_s$ magnitude is a good proxy for stellar mass, the $B$ magnitude is affected by dust extinction, i.e., it is more a tracer of the SFR than a proxy for the stellar mass.

4 COMPARISON TO OTHER PRIORITIZATION STRATEGIES

Previous studies have developed prioritization strategies which include stellar mass (Ducoin et al. 2020) or $B$–magnitude (Arcavi et al. 2017). Our method is complementary to such strategies for the following reasons.

- Previous work assumes that the host-galaxy probability scales with the stellar mass (or with the $B$–band luminosity) based on heuristic arguments, such as the host-galaxy mass
distribution of short gamma ray bursts (Leibler & Berger 2010; Fong et al. 2013; Berger 2014), and on the results of previous theoretical studies (Artale et al. 2020; Toffano et al. 2019; Mapelli et al. 2018). Here, we directly compute a probability distribution from our astrophysical model. Hence, while our criterion is more model dependent than previous studies, it is also self-consistent and robustly motivated from an astrophysics point of view.

- In previous work, the host galaxy probability is assumed to scale linearly with stellar mass (excluding possible corrections, such as the correction for galaxies without mass measurement introduced by Ducoin et al. 2020). In contrast, we do not need to assume a linear scaling. Rather, we assign specific weights to each stellar mass bin (and/or SFR bin), which are uniquely determined by our model. We show that there is a correlation between the merger rate per galaxy and the stellar mass, and this correlation is not simply a linear relation. Weighting this correlation is important to quantify deviations with respect to a linear scaling. Future detections

Figure 5. The same as Figure 3, but for the host galaxies of BBHs.
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5 CONCLUSIONS

Understanding what are the properties of the most likely host galaxies of BNS, BHNS and BBH mergers is fundamental for the EM follow-up of GW detections. Here, we discussed the host galaxy probability, i.e. the probability that a galaxy hosts a merging compact object as a function of its stellar mass and SFR at redshifts $z = 0.1, 1, 2,$ and $6$. Our methodology combines the results from the population synthesis code MORSE (Giacobbo et al. 2018; Giacobbo & Mapelli 2018) together with galaxy catalogues from the cosmological simulation EAGLE (Schaye et al. 2015). With a Monte Carlo approach, we populate each galaxy in the EAGLE catalogue with BNSs, BHNSs and BBHs.

Our results show that there is a strong dependence of the host galaxy probability on the stellar mass, $p(M_*)$ for all types of compact binaries: massive galaxies are more likely to host a compact-binary merger than low-mass galaxies. Moreover, the distribution shifts towards massive hosts as redshift decreases (see Fig. 1), as a consequence of the cosmic galaxy assembly and the delay time distribution of compact binary sources.

We also find that galaxies with higher SFR have a higher probability of hosting compact object mergers. Nevertheless, as shown in Fig. 3, 4, and 5, the dependence on SFR is not as strong as the dependence on stellar mass. At a fixed stellar mass, $p(M_*, \text{SFR})$ shows less significant variation compared to the case where SFR is fixed. Overall, the peak of the host probability at high SFR is mainly due to massive galaxies which in turn are forming more stars.

Our conclusions depend on the population-synthesis model and on the cosmological simulation. On the other hand, it is remarkable that both BNSs and BBHs show the same trend: their preferred host galaxies are the most massive ones and possibly the most star forming. This result indicates that the dependence on a specific population-synthesis model is not particularly strong, if we consider that the merger efficiency of BNSs marginally depends on metallicity in our models, while the merger efficiency of BBHs and BHNSs
dramatically depends on progenitor’s metallicity. The key ingredient here is the delay time distribution, which is not strongly affected by model assumptions (Mapelli et al. 2019). Our results rely on the choice of the EAGLE simulation. In Artale et al. (2020), we have shown that our results are not significantly influenced by resolution, although we are not able to study galaxies with stellar mass $M_\star < 10^7 M_\odot$ and $> 10^{12} M_\odot$. The EAGLE appears to match some of the most important observables, such as the mass–metallicity relation of galaxies (De Rossi et al. 2017), the colour–magnitude diagram at $z = 0$ (Trayford et al. 2015), the evolution of the galaxy stellar mass function, and the cosmic SFR density evolution (Furlong et al. 2015; Trayford et al. 2019).

In the context of the EM follow-up of GW sources, our results can be implemented in ranking procedures applied for GW mergers detected by advanced LIGO-Virgo (Singer et al. 2016). The standard strategy consists in targeting galaxies within the sky domain provided by the LVC using a complete galaxy catalogue such as GLADE (Dálya et al. 2018). Then, the galaxies are ranked adopting a criterion generally based on the 2D localization region, distance, and $B$–band magnitude (see e.g., Arcavi et al. 2017; Coughlin et al. 2018; Rana & Mooley 2019). Recently, Ducoin et al. (2020) proposed to use the stellar mass instead of the $B$–band magnitude in the ranking procedure.

Here, we propose a new astrophysically motivated criterion to compute the relative probability that a galaxy inside the LVC uncertainty box hosts a GW detection. If we calculate this host galaxy probability as a function of stellar mass only ($p(M_\star)$), our results are in agreement with the analytic model from Ducoin et al. (2020), and we find that high mass galaxies are much more likely to host mergers than low mass galaxies.

In addition, we also investigate what is the impact of including the SFR in our ranking criterion, which to our knowledge was never done before. While we find that the effect of SFR is less important than stellar mass, we observe that the probability that a galaxy hosts a merger is higher for high values of both stellar mass and SFR.

Galaxy catalogues usually do not include direct information on stellar mass and SFR. Hence, to facilitate the usage of our ranking criterion, we calculate the host galaxy probabilities $p(M_\star)$ and $p(B)$ as a function of the $K_s$–band and $B$–band magnitudes. The former shows a similar trend to $p(M_\star)$, while the latter is reminiscent of $p(SFR)$, suggesting that $K_s$ and $B$ magnitudes are tracers of stellar mass and SFR, respectively.

Our host-galaxy probabilities can be implemented in future low-latency searches, providing a useful criterion to rank possible host galaxies within the sky localization map. The tables of the host-galaxy probabilities can be obtained online in table format.

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See Appendix B, or alternatively https://github.com/mcartale/HostGalaxyProbability

3 See Appendix B, or alternatively https://github.com/mcartale/HostGalaxyProbability
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APPENDIX A: JOINT PROBABILITY DISTRIBUTION ACCORDING TO THE DETECTABILITY OF GROUND BASED INTERFEROMETERS

To produce catalogues of sources as observed by either LIGO-Virgo or ET, we follow a similar approach as done in previous works (see e.g., Finn & Chernoff 1993; Dominik et al. 2015; Gerosa et al. 2018). Here, we briefly summarise the main details of this approach.

To assess if a source is detected or not, we look at the value of its signal-to-noise ratio (SNR) given by,

$$\rho = 4 \int_0^\infty \frac{\left| \tilde{h}(f) \right|^2}{S_n(f)} df,$$

where $\tilde{h}(f)$ is the gravitational waveform in the Fourier domain and $S_n(f)$ is the one-sided noise power spectral density of the detector. In this study, we have used the design sensitivity for advanced LIGO-Virgo and ET, as given in Abbott et al. (2018) and Abbott et al. (2017a), respectively.

For the waveform models, we adopted the IMRPhenomD model Khan et al. (2016) for BBH coalescence and TaylorF2 for BNS and BHNS coalescences, where we set the spins equal to 0. The waveforms and detector sensitivities were both generated by the package PyCBC (Dal Canton et al. 2014; Usman et al. 2016).

As our catalogues only provide values for the masses and the redshift, the dependence of the waveform on other parameters such as the position in the sky and inclination, is represented by the parameter $\omega$. The SNR is then expressed as $\rho = \omega \times \rho_{\omega}$, where $\rho_{\omega}$ is the optimal SNR when the
source is face-on and optimally oriented. The probability of detecting a source is then given by
\[
p_{\text{det}}(w) = 1 - F_\omega(\rho_{\text{thr}}/\rho_{\text{opt}}),
\] (A2)
where \( F_\omega \) is the cumulative distribution function of \( \omega \). This function can easily be approximated by Monte Carlo methods such as the ones implemented in the package we used (Gerosa 2019). For the SNR threshold, we take \( \rho_{\text{thr}} = 8 \), as it was shown to be a good proxy of more complex analysis involving a network of detectors.

In practice, we evaluate the optimal SNR \( \rho_{\text{opt}} \) for each source in our catalogue and then compute the detection probability as in eq. (A2). We then draw a random number \( \epsilon \sim U[0, 1] \) and add the source with probability \( p_{\text{det}} \) in our catalogues of detectable sources that are used to produce Fig. 2.

APPENDIX B: SUPPLEMENTARY MATERIAL: HOST-GALAXY PROBABILITY TABLES

The host-galaxy probabilities for BNSs, BHNSs, and BBHs at \( z = 0.1, 1, 2, \) and 6 presented in Fig. 3, 4, and 5 can be obtained in table format in the supplementary material online. Alternatively, the tables are also available on https://github.com/mcartale/HostGalaxyProbability. Our results can be directly implemented in low-latency searches of EM counterparts as described in Section 2.
Table B1. Table of the host galaxy probability as a function of $M_*$ and SFR, for BNSs at $z = 0.1$, corresponding to the results presented in Fig. 5. Stellar masses are in units of $M_\odot$, while SFR are in $\text{yr}^{-1} M_\odot$. Note: This table is presented in its entire version in [https://github.com/mcartale/HostGalaxyProbability](https://github.com/mcartale/HostGalaxyProbability). An abbreviated version is shown here for guidance.

| $\log(M_\text{min})$ | $\log(M_\text{max})$ | $\log(\text{SFR}_\text{min})$ | $\log(\text{SFR}_\text{max})$ | $p(M_*, \text{SFR})$ |
|----------------------|----------------------|----------------------|---------------------|-------------------|
| 7.0                  | 7.229                | -5.5                 | -5.167              | 0.0               |
| 7.0                  | 7.229                | -5.167               | -4.833              | 0.0               |
| 7.0                  | 7.229                | -4.833               | -4.5                | 0.0               |
| 7.0                  | 7.229                | -4.5                 | -4.167              | 0.0               |
| 7.0                  | 7.229                | -4.167               | -3.833              | 0.0               |
| 7.0                  | 7.229                | -3.833               | -3.5                | 0.0               |
| 7.0                  | 7.229                | -3.5                 | -3.167              | 1.830809731518871e-06 |
| 7.0                  | 7.229                | -3.167               | -2.833              | 3.876326253400243e-06 |
| 7.0                  | 7.229                | -2.833               | -2.5                | 6.905726150471546e-06 |
| 7.0                  | 7.229                | -2.5                 | -2.167              | 6.13113402365386e-06 |
| 7.0                  | 7.229                | -2.167               | -1.833              | 1.555843012065854e-05 |
| 7.0                  | 7.229                | -1.833               | -1.5                | 1.423655645772669e-05 |
| 7.0                  | 7.229                | -1.5                 | -1.167              | 3.24963287051857e-05 |
| 7.0                  | 7.229                | -1.167               | -0.833              | 2.3883921312230474e-05 |
| 7.0                  | 7.229                | -0.833               | -0.5                | 2.28021510139597e-05 |
| 7.0                  | 7.229                | -0.5                 | -0.167              | 8.486969225985846e-06 |
| 7.0                  | 7.229                | 0.0                  | 0.167               | 0.0               |
| 7.0                  | 7.229                | 0.167                | 0.5                 | 3.829732624985512e-07 |
| 7.0                  | 7.229                | 0.5                  | 0.833               | 0.0               |
| 7.0                  | 7.229                | 0.833                | 1.167               | 0.0               |
| 7.0                  | 7.229                | 1.167                | 1.5                 | 0.0               |
| 7.0                  | 7.229                | 1.5                  | 1.833               | 0.0               |
| 7.0                  | 7.229                | 1.833                | 2.167               | 0.0               |
| 7.0                  | 7.229                | 2.167                | 2.5                 | 0.0               |