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The origin of progenitors in merging black hole binaries.

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Abstract

Are the stellar-mass merging binary black holes, recently detected by their gravitational wave signal, of stellar or primordial origin? Answering this question will have profound implications for our understanding of the Universe, including the nature of dark matter, the early Universe and stellar evolution. We develop the idea that the clustering properties of merging binary black holes can provide information about binary formation mechanisms and origin, in particular the cross-correlation of galaxy with gravitational wave catalogues carries information about whether black hole mergers trace more closely the distribution of dark matter – indicative of primordial origin – or that of stars harboured in luminous and massive galaxies – indicative of a stellar origin. We forecast the detectability of such signal for several forthcoming and future gravitational wave interferometers and galaxy surveys. Our results show that forthcoming experiments could allow us to test most of the parameter space of the still viable models investigated, and shed more light on the issue of binary black hole origin and evolution.

1 Introduction

The first detection of gravitational waves (GWs) emitted by the coalescence of two black holes (BHs) of approximately 30 $M_{\odot}$ [2] opened the era of gravitational waves astronomy, not only by confirming General Relativity predictions, but also establishing a new way to observe and analyse the cosmos. Even if some authors expected such massive progenitors to be the first sources to be detected [6], this fact was hailed by part of the community as unexpected and led some researchers to suggest that such events may not be uncommon. Indeed other GWs events followed and confirmed that apparently a significant fraction of the detected progenitors has masses between 20 and 40 $M_{\odot}$. Such large masses of the progenitors are not incompatible with classical stellar/binary evolution [5]. Nevertheless the possibility that BHs with an origin different from the standard end-point of stellar evolution and constituting a significant fraction of the dark matter regained interest [9].

Primordial Black Holes (PBHs) formed during radiation-dominated era because of the collapse of large density fluctuations in the primordial cosmic fluid that overcame pressure forces [15]. These results were later confirmed by the authors of Ref. [20], who were the first to provide general relativistic numerical computations of PBHs formation during the radiation-dominated era.

Given the high interest in PBHs as dark matter candidates, a remarkable amount of different observational constraints have been obtained, including constraints coming from gravitational lensing effects, dynamical effects and accretion effects (see e.g., Ref. [26] for a recent review). Even if these constraints cover the whole mass range and seem to disfavour PBHs as a significant fraction of the dark matter, these results are far from being conclusive due to the variety of assumptions involved, see e.g., Ref. [7]. Some mass "windows" still exist, for instance one around 10^{-12} $M_{\odot}$ and another 10 $M_{\odot}$, where the latter one can be probed by future GWs observatories as Advanced LIGO (aLIGO) [1], KAGRA [29], LIGO-India [31] or Einstein Telescope (ET) [27].

Despite the fact PBHs may not constitute the totality of the dark matter, it is valuable to explore different ways to determine if mergers progenitors' origin is stellar or primordial. In this work we focus on developing further the cross-correlation approach suggested by the authors of Ref. [24], who show that the statistical properties of the type of galaxy (or halo) hosting a GWs event can provide information about the system origin (stellar or primordial). In fact, in more massive halos the typical velocities are higher than those in the less massive ones. As a consequence, it is much more probable that two PBHs form a gravitationally bound binary through GWs emission in low-mass halos, since the cross section of such process is inversely proportional to some power of the relative velocity of the progenitors. The higher velocity dispersion of high-mass halos make this process for PBHs less likely to happen. In addition, low-mass halos tend to be less luminous than high-mass ones and trace more closely the dark matter distribution than high-mass halos. On the other hand the merger probability for stellar black holes is more likely to correlate with galaxies' (or halos') stellar mass, hence stellar black holes mergers tend to happen in more luminous and massive halos. Recall that star formation efficiency increases with halo mass for halo of masses below $10^{12} M_{\odot}$. It decrease for higher mass-halos but these are very rare and more closely associated to galaxy clusters rather than galaxies [14]. The clustering properties of these two halos populations are different, in particular low-mass halos are less strongly clustered than high (stellar) mass galaxies: they have different *bias* parameters. The bias parameter governs the ratio of clustering amplitude of the selected tracer to that of the dark matter.

At the moment too few GWs events have been detected to measure the auto and cross correlation of maps of GWs events and galaxies, but during next LIGO's runs, thousands of events are likely to be detected due to the improved sensitivity. On the other hand, during the next decade a large volume of the Universe at high redshift will be surveyed thanks to several surveys, as EMU [22], DESI [4] or SKA [18], which we consider in the rest of the paper.

In this brief communication we report just a small fraction of the framework we have developed and analysed. The interested reader can find more details and a broader discussion in the complete work in Ref. [28].

2 Methodology

Since BH-BH mergers do not have an electromagnetic counterpart, the identification of their host object is impossible even if the event is measured by more than three detectors. Because of the poor localisation in the sky of the GWs events, the GWs maps are typically very "low resolution". For this reason we approach the problem in a statistical way, by using measurements and statistical properties of their number counts. In particular, we work in harmonic space and we consider the number counts angular power spectrum, C_ℓ, where only low multipoles ℓ are considered because of the maps' low angular resolution. The maximum multipole $\ell_{\max}$ is determined by the angular resolution θ that can be achieved: $\ell_{\max} \sim 180^o/\theta$. For the aLIGO+Virgo network $\ell_{\max} = 20$, once also LIGO-India and KAGRA are included, we improve the spatial resolution up to $\ell_{\max} = 50$ and finally with the futuristic Einstein Telescope, $\ell_{\max} = 100$ will be reached [21].

In the following we assume to have (tomographic) maps of GWs events and of galaxies (i.e., the *tracers*). The observed harmonic coefficients used to compute the angular power spectra are given by $a^X_{\ell m}(z_i) = s^X_{\ell m}(z_i) + n^X_{\ell m}(z_i)$, where $s^X_{\ell m}$ and $n^X_{\ell m}$ are the partial wave coefficients of the signal and of the noise for tracer X. We consider the noise angular power spectrum to be given only by a shot noise term $\mathcal{N}^X_\ell(z_i)$ and we assume that the noise terms from different experiments and different redshift bins are uncorrelated. The expectation value of the signal gives the $C^{XY}_\ell(z_i, z_j)$ [23], while the signal-cross-noise expectation value is zero since we assume signal and noise to be statistically independent. In general the observed number count fluctuation receives contributions from density, velocity, lensing and gravity effects [12]. Even if the bias parameter b_X of the tracer X enters only in the density contribution, we cannot overlook the effect of the other terms on the signal-to-noise, as sometimes done in the literature. The reader interested in a more in general discussion on the importance of a correct modelling of an observable can check Ref. [8]. We extend the public code `CLASS` [10, 13] to include the possibility to have different tracers ($X \neq Y$). We present this new version of `CLASS`, called `Multi_CLASS`, in Ref. [8].

We estimate the capability of future GWs observatories and large scale structure surveys to determine BHs mergers progenitors' origin in a way close to an actual data analysis. We assume that we can model well enough some properties of the tracers that are currently still uncertain and that cosmological parameters are known. We perform what can be seen as a null hypothesis testing, comparing two models, one in which progenitors origin is stellar, the other in which is primordial. We assume one model as fiducial and we check if the alternative model can be differentiated from the fiducial one by computing a Signal-to-Noise ratio S/N. The null hypothesis is that the model is indistinguishable from the fiducial, which happens for low values of the Signal-to-Noise ratio ($S/N \lesssim 1$). We quantify the distance of an alternative model from the fiducial using a $\Delta\chi^2$ statistics. In our case the $\Delta\chi^2$ is given by the logarithm of a likelihood, in particular we assume a likelihood quadratic in the angular power spectra. The resulting $\Delta\chi^2$ statistics reads as

$$\left(\frac{S}{N}\right)^2_{\sqrt{\Delta\chi^2}} \sim \Delta\chi^2 := f_{\rm sky} \sum_2^{\ell_{\rm max}} (2\ell+1)(\mathbf{C}_\ell^{\rm Alternative} - \mathbf{C}_\ell^{\rm Fiducial})^T {\rm Cov}_\ell^{-1} (\mathbf{C}_\ell^{\rm Alternative} - \mathbf{C}_\ell^{\rm Fiducial}), \tag{1}$$

where $\mathbf{C}_\ell^T = \left(C_\ell^{\rm gg}(z_1, z_1), \cdots, C_\ell^{\rm gGW}(z_1, z_1), \cdots, C_\ell^{\rm GWGW}(z_1, z_1), \cdots\right)$, $f_{\rm sky}$ is the observed fraction of the sky and ${\rm Cov}_\ell$ is a covariance matrix, computed from angular power spectra of the fiducial model as explained in Ref. [8]. Notice that the ability to distinguish between two scenarios can differ according to which model is the alternative model and which one is the fiducial, since the covariance matrix and thus the errors depend (sometimes strongly) on the fiducial model adopted.

3 Tracers

In this section we describe the two tracers we consider in this work, galaxies and GWs. For cosmological purposes, each of these tracers is characterised by a source number density per redshift bin and square degree $d^2N_X/dzd\Omega$, bias $b_X(z)$ and magnification bias $s_X(z)$ parameters. Even if some of these quantities are uncertain at the moment, we exploit their evolution in redshift to maximize the differences between the two models.

3.1 Galaxies

Depending on the experimental set up under consideration, we choose as luminous tracers emission-line galaxies in the redshift range $[0.6 - 1.7]$, targeted by DESI, or star-forming galaxies, targeted by EMU and SKA in the redshift range $[0.0 - 5.0]$. For DESI galaxies we use data in Ref. [4], while for EMU and SKA we use the Tiered Radio Extragalactic Continuum Simulation (T-RECS) [11] catalogue with different detection threshold (100 μJy for EMU and 5 μJy for SKA). We report in the top left panel of figure 1 the three normalized number densities $d^2N_{\rm g}/dzd\Omega$.

The bias $b_{\rm g}(z)$ for emission-line galaxies is taken from Ref. [4], while the bias for EMU and SKA star-forming galaxies is modelled as in Ref. [25]. We show the bias redshift dependence in the bottom left panel of figure 1.

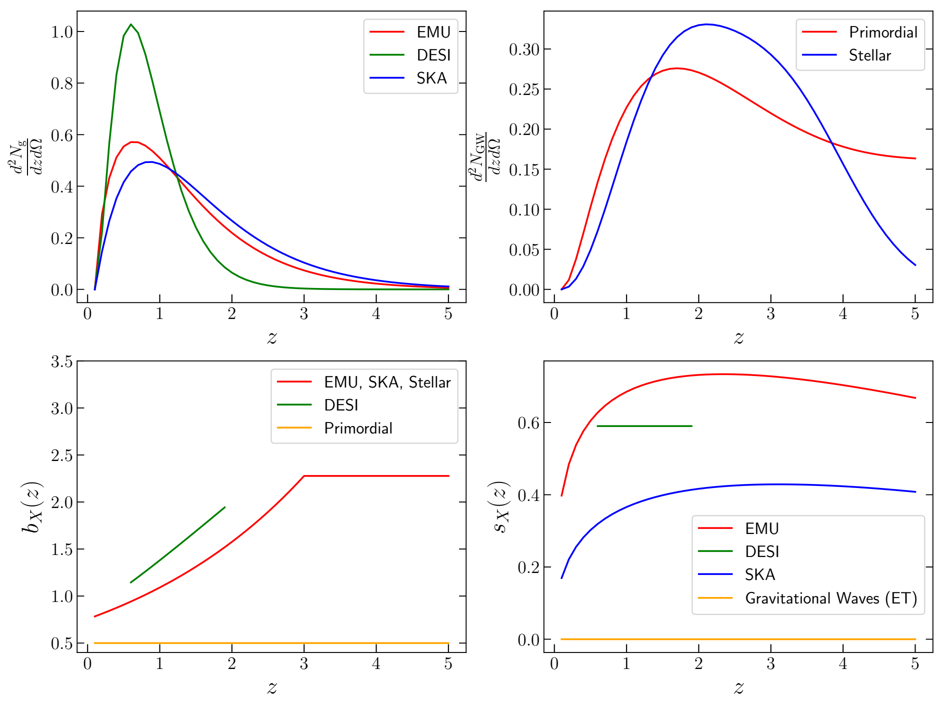

Figure 1: *Top panels*: normalized number density distribution per redshift bin per square degree $d^2N_X/dzd\Omega$ for galaxies (*top left*) and GWs (*top right*). *Bottom panels*: bias $b_X(z)$ (*bottom left*) and magnification bias parameter $s_X(z)$ (*bottom right*) for galaxies and GWs. We report the GWs magnification bias parameter associated to a BHs population with monochromatic mass distribution detected by an interferometer with characteristics similar to those of ET.

Gravitational lensing changes the sources surface density on the sky in two competing ways [30], by increasing the area, which in turn decreases the projected number density, but also by magnifying individual sources and promoting faint objects above the magnitude limit. The change in the number of observed sources depends on the magnification bias $s_{\rm g}(z)$, the value of the slope of the faint-end of the luminosity function [16]. For DESI we use the magnification bias reported in Ref. [4], while for EMU and SKA we use the T-RECS catalogue [11] to compute it. We report the magnification bias parameter $s_{\rm g}(z)$ in the bottom right panel of figure 1.

3.2 Gravitational Waves

The number density of detected GWs events per redshift bin per square degree $d^2N_{\rm GW}/dzd\Omega$ is proportional to the total comoving merger rate $\mathcal{R}_{\rm tot}(z)$, which in turn depends on the progenitors origin. The uncertainty in the total merger rate is of orders of magnitude, however what enters in the calculation of the angular power spectra C_ℓ^{XY} (i.e., the signal) is the shape of $d^2N_{\rm GW}/dzd\Omega$, not the global amplitude. On the other hand, the merger rate (and its normalisation) affects the signal-to-noise ratio (i.e., the error-bars): a larger number density will decrease the shot noise, improving the constraints on the cosmological parameters of interest. We report in the top right panel of figure 1 the normalized number densities corresponding to the stellar and primordial scenarios.

If the progenitors have primordial origin and merge according to the scenario proposed in Ref. [9], then the merger events trace low-velocity dispersion low-mass halos ($M_{\rm halo} < 10^6 M_\odot$). The bias of these halos is given by $b_{\rm lmh}(z) \simeq 0.5$ [19], independently on redshift. On the other hand, when progenitors of a merging event have stellar origin, they are more likely correlated with higher-mass halos that had a higher star-formation rate, therefore their bias will be the same of the galaxies under consideration, i.e. $b_{\rm GW}(z) = b_{\rm g}(z)$. We show the bias redshift dependence in the bottom left panel of figure 1.

We calculate for the first time the magnification bias for GWs [28], finding that for common BHs mass distribution and for future GWs observatories it stays close to zero at every redshift considered. We show the magnification bias for GWs in the bottom right panel of figure 1.

4 Results

In this section we provide forecasts for specific combinations of GWs observatories and large scale structure surveys.

Merger rates are poorly known, both on the observational and theoretical side, spanning several orders of magnitude and affecting the overall expected number of GWs events. After the first run of LIGO, the observational merger rate today is estimated to be $\mathcal{R}^{\rm LIGO}_{\rm today} \simeq 9 - 240~{\rm Gpc}^{-3}{\rm yr}^{-1}$ [3], while the theoretically predicted merger rates for the stellar and primordial scenario are $\mathcal{R}^{\rm Stellar}_{\rm today} \simeq 150~{\rm Gpc}^{-3}{\rm yr}^{-1}$ [17] and $\mathcal{R}^{\rm Primordial}_{\rm today} \simeq 4~{\rm Gpc}^{-3}{\rm yr}^{-1}$ [9]. We parametrize the uncertainty on the number of GWs events by introducing a new parameter r constant in redshift, in which we include every uncertainty in the modelling. The values $r^{\rm Stellar,\,Primordial} = 1$ correspond to the merger rates reported above. To account for several theoretical uncertainties that can influence the merger rates, we provide results for a range $r^{\rm Stellar,\,Primordial} \in [10^{-1}, 10]$.

We report the Signal-to-Noise forecasts in figure 2 (stellar as fiducial model) and figure 3 (primordial as fiducial model). In each of these figures we show two panels: in the left panels we show bar charts obtained for different values of the parameter r at fixed maximum multipole $\ell_{\rm max}$ (50 for aLIGO and 100 for ET), while in the right panels we report the scaling of the Signal-to-Noise for different values of the maximum angular resolution when $r^{\rm Stellar,\,Primordial} = 1$.

We explicitly show that surveys covering a bigger volume (or redshift range) can discriminate better between different models, i.e. have higher Signal-to-Noise ratios, as expected from surveys with smaller shot noise. Notice that in the cases of stellar as fiducial, we have better Signal-to-Noise ratio than in the primordial scenario, due to higher merger rates, thus higher number of detected sources and lower shot noise. Achieving high angular resolutions is fundamental to discriminate between the two models. In general we can conclude that future

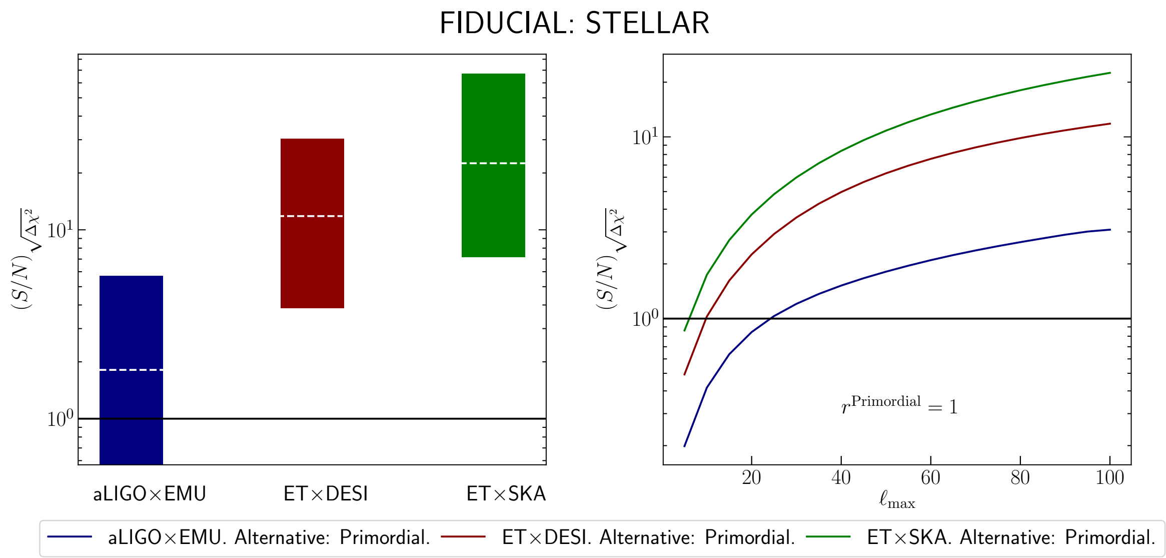

Figure 2: Signal-to-Noise S/N estimates for specific surveys combinations. *Left panel:* Signal-to-Noise S/N estimates as a function of r, assuming a fixed $\ell_{\max}$. The horizontal dashed white lines refer to the $r = 1$ case. *Right panel:* Signal-to-Noise S/N estimates as a function of $\ell_{\max}$ for the fiducial merger rate case $r = 1$.

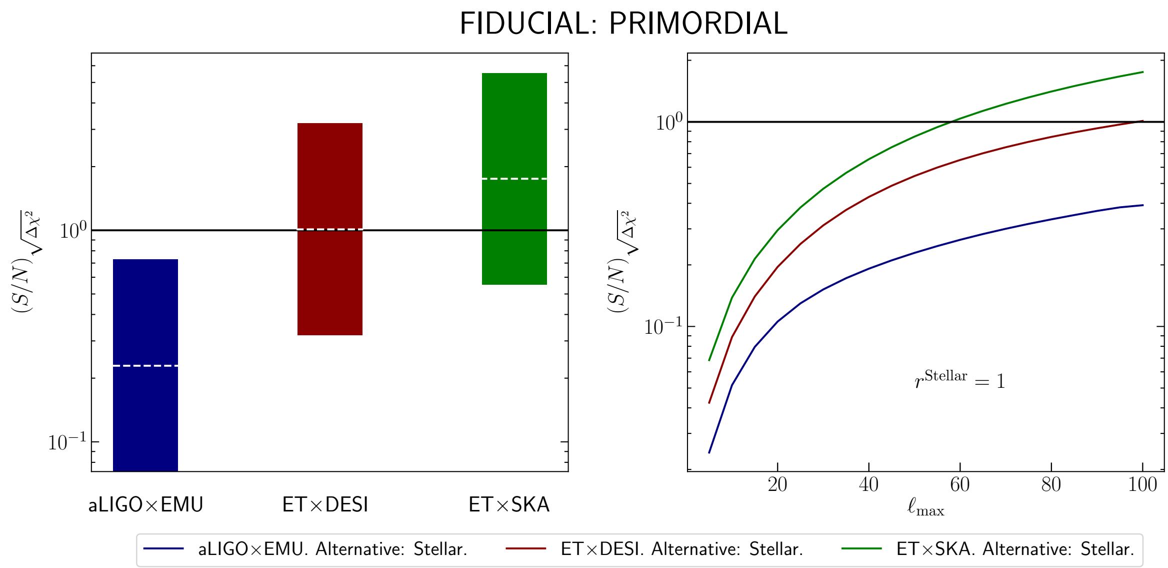

Figure 3: Signal-to-Noise S/N estimates for specific surveys combinations. *Left panel:* Signal-to-Noise S/N estimates as a function of r, assuming a fixed $\ell_{\max}$. The horizontal dashed white lines refer to the $r = 1$ case. *Right panel:* Signal-to-Noise S/N estimates as a function of $\ell_{\max}$ for the fiducial merger rate case $r = 1$. The horizontal dashed white lines refer to $r = 1$.

surveys will enable us to address questions about binary BHs mergers given enough observation time (here assumed to be 10 years) and angular resolution. One caveat is that this does not always happen for the aLIGO$\times$EMU combination, which will have a Signal-to-Noise lower or very close to unity in some cases (especially if mergers come from the primordial formation mechanism). This is due to the fact that this combination of GWs observatory and large scale structure survey can only cover a low redshift range, where the biases are very similar (see e.g., the bottom left panel of Figure 1) and we have an higher shot noise due to the scarce number of detected objects.

5 Conclusions

The renewed interest in primordial black holes has highlighted their importance not only as a possible constituent of the dark matter but also because their existence (if confirmed) would have profound implications about the physics of the early Universe. It is therefore essential to explore new ways to discriminate between primordial or stellar origin of the black holes which mergers have been observed with laser interferometers. Beyond the standard ways to constrain the existence of stellar mass primordial black holes through lensing or the effect on cosmic backgrounds, a complementary approach is to assess whether the GWs signal from merging binary BHs we detect are produced by objects of primordial origin or not.

Here we build on the idea that the cross-correlation of galaxy catalogues with GWs (from the merger of binary BHs) maps is a powerful tool to statistically study the origin of the progenitors of BHs mergers [24]. This will be possible once the next generation of GWs detectors will provide localization of enough events to make low resolution maps. Galaxy catalogues covering a significant fraction of the sky and an overlapping redshift range are also under construction or at an advanced planning stage. Then, by measuring the bias of the halos hosting the binary BHs mergers we can infer the clustering properties of the progenitors of the binary BHs. Clustering properties matching those of luminous, high velocity-dispersion, high stellar-mass galaxies, would indicate a stellar origin, while clustering properties more similar to those of low-mass galaxies preferentially populating the filamentary structure of large-scale structures indicate a primordial origin.

In complete work in Ref. [28] we have also considered different models for the binary BHs formation, accretion mechanism, merger rate, mass distribution and clustering properties, both for the stellar and primordial nature of the BHs. We generalized similar studies on the cross-correlation between galaxy and gravitational wave maps by performing a full multi-tracer analysis that accounts for different redshift distributions, galaxy bias evolution, magnification bias of luminous sources as well as GWs, and relativistic projection effects. Even including all these uncertainties we found quite general results that can be still used once some of such quantities will be better understood. Our results show that forthcoming experiments could allow us to test most of the parameter space of the still viable models investigated, and shed more light on the issue of binary black hole origin and evolution. We firmly believe that the present work can contribute to further develop the new avenue of GW-LSS synergies, and that the vast range of parameters and models explored here make our results general enough to provide a realistic forecast of what this can teach us on the nature of binary BHs progenitors in the next decade.

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