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FROM GALAXY PAIRS COUNT TO MASSIVE BLACK HOLE MERGERS: PROSPECTS FOR GRAVITATIONAL WAVES DETECTION

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Abstract. Our understanding of the seed and evolution of black holes over cosmic time will make a huge step forward in the next decades thanks to gravitational waves. However, predictions of the BH merger rate and detections by new experiments such as LISA are based so far on cosmological simulations only, which do not resolve yet the dwarf galaxies ($M_\star < 10^9 \mathrm{M}_\odot$) population. Thanks to the analysis of VLT/MUSE deep fields, we show that such predictions can now be based on measurements of the galaxy merger rate over 12.5 Gyrs of galaxy evolution and covering a broad range of galaxy stellar masses ($10^7 - 10^{11} \mathrm{M}_\odot$), thus extending into the low-mass dwarf galaxy regime.

Keywords: Galaxies: mergers – Galaxies: high-redshift – Galaxies: massive black holes – Gravitational waves – LISA

1 Introduction

Gravitational wave (GW) observations have opened a new way to observe and characterize compact objects throughout the Universe and at all cosmic epochs. The Laser Interferometer Space Antenna (LISA) should be able to detect black holes (BH) of masses in the range $M_{\mathrm{BH}} = 10^4 - 10^7$ M$_\odot$ through the last stages of inspiral and merger up to $z \sim 20$ (Amaro-Seoane et al. 2022). LISA will thus open a wide discovery space for massive black holes (MBH). Indeed, considering the current state-of-the-art, we still do not know how MBH form and evolve in the early Universe, how they assemble with time and become present in almost all the galaxies in the local Universe (see Volonteri et al. 2021, for a review). BH binaries that merge at the millihertz frequencies, where LISA is most sensitive, are typically hosted in the most common type of galaxies, namely dwarf and massive spiral galaxies.

In the hierarchical paradigm of galaxy formation, we expect central MBH to coalesce after the merger of their host galaxies. However, MBH will have to cross an impressive range of physical scales, from $\sim 10^3$ pc, when they are hosted in distinct galaxies, to 10^{-6} pc when they coalesce with each other. Currently, the predicted MBH merger rate, based so far on cosmological simulations only (eg. Salcido et al. 2016; Katz et al. 2020; Volonteri et al. 2020; Li et al. 2022), spans more than one order of magnitude, from a few LISA detections per year to tens. These predictions depend essentially on computational methods and on the modeling of the relevant physics. The exact number of detectable MBH mergers and their properties will depend on still poorly understood parameters, such as the low-mass end of the MBH mass function and their seeding mechanism, or the host galaxy type and environment.

This paper presents a first attempt to predict LISA detections of MBH mergers from observations, i.e. from the count of galaxy pairs up to redshift $z \sim 7$ as measured in VLT/MUSE deep fields. The methodology described in the next section has been developed during the Master internship of Rémi Delpech at IRAP and the results are still preliminary.

2 Methodology & Results

The different steps allowing to predict the GW detection rate of MBH mergers with LISA from galaxy pairs count are described in the following sub-sections and sketched in Fig. 1.

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2.1 From galaxy pairs to merger rate

A catalog of 261 close pairs of galaxies has been assembled from a total of 2137 galaxies up to $z \sim 7$ with accurate spectroscopic redshifts thanks to deep MUSE observations in four deep fields (Ventou et al. 2017, 2019). A redshift confidence level (secure vs. tentative) is assigned to each galaxy depending on the quality of the MUSE spectra. This flag is further used as a weight in the estimate of the galaxy merger fraction. Together with the accurate estimate of pair separation (projected distance & velocity), the stellar mass has been derived for each galaxies using standard SED fitting methods, making use of the extensive UV-to-NIR multi-band photometry available for the four fields. For the sake of completeness, we only keep galaxies with stellar masses in the range $10^7 - 10^{11}$ $M_\odot$ and mass ratios $\mu = M_1/M_2$ in the range $10 - 1$, where M_1 and M_2 is the stellar mass of the primary and companion galaxy of the pair, respectively. Thanks to the sensitivity of MUSE, we are thus able to start with a galaxy pairs sample extending over 4 dex in stellar masses, down to the dwarf galaxies population, and probing both the minor and major merger regimes.

The next step is to estimate the probability that these close pairs of galaxies will effectively merge by redshift zero. Ventou et al. (2019) made a first attempt using ILLUSTRIS simulations to define the merging probability as a function of the pair separation (projected distance & velocity). We further refined these probabilities taking into account the redshift dependence as introduced by O'Leary et al. (2021) in the EMERGE simulations. To estimate a merger fraction from the sample of close pairs for each redshift bin, the number of galaxy pairs is divided by the number of primary galaxies in the parent sample, and corrected for all selection effects. Indeed, observations are limited in volume and luminosity and this must be taken into account and corrected in the fraction estimates. The merger fraction is thus calculated following equation 5 of Ventou et al. (2019), the only difference being the weight associated to the merging probability which is now a function of the pair separation and redshift. The selection effects which are taken into account in the calculation are related to the spectroscopic redshift confidence and completeness, and the MUSE limited spatial resolution and field-of-view.

In order to compute the galaxy merger rate, defined as the merger fraction over the mean observability timescale of the pairs, we need to introduce two quantities: first the merging timescale and then the pair observability timescale. To estimate the first quantity we also make use of the EMERGE simulation predictions where O'Leary et al. (2021) give an expression to compute the merging timescale as a function of the pair separation and redshift, for a grid of primary galaxy masses and mass ratios. The second quantity, the pair observability timescale, is defined as the time during which we are able to observe the galaxy merger until the two galaxies are no longer discernible from each other. It depends on the limited spatial resolution of MUSE observations. The galaxy merger rate up to $z \sim 5$ is shown in Fig. 1. It reaches a maximum of nearly 0.2 Gyr^{-1} above $z \sim 1$, consistent with previous estimates (Ventou et al. 2017, 2019) and simulation predictions.

2.2 From galaxy to black hole mergers

Now that we have discussed how to compute the galaxy merger rate, we would like to use this relation in order to estimate the merger rate of MBH and then to predict their detection with LISA. We first need to estimate the MBH masses from the properties of their host galaxies. Since we only have the galaxy masses as reliable information, we have to rely on the scaling relation linking the mass of the MBH to the stellar mass of the host galaxy. To this end, we used the relation given by Greene et al. (2020) for late-type galaxies (their Figure 3 and parametrization in Table 5) as most of the galaxies probed by MUSE up to ~ 7 are star-forming galaxies. With a scatter of about 1 dex this relation implies a poorly-constrained BH mass, especially for low-mass galaxies, and thus a lot of uncertainty on the prediction of GW detection with LISA.

When two galaxies are merging, their respective black holes will not merge immediately, and sometimes never. They are wandering a while before they merge and emit GW, going through several mechanisms (dynamical friction, stellar hardening, gaseous torques, etc) over nine order of magnitude in physical scales (from $\sim 10^3$ to 10^{-6} pc). Constraining the MBH merging probability and timescale is a real challenge since we only have access to macroscopic observable from their host galaxies. Some analytical solutions exist, but only if we can measure the stellar velocity dispersion in the bulge (Katz & Larson 2019; Volonteri et al. 2020), which we cannot do with the MUSE sample, especially at high redshift. To estimate the merging probability of two MBH, we used the prediction from the two simulations HORIZON-AGN and NEW-HORIZON (Volonteri et al. 2020) when combined are well-suited for our purpose covering both a large volume for massive galaxies (HORIZON-AGN), but at the cost of low resolution, and a smaller volume but at a higher resolution (NEW-HORIZON) for the low-mass galaxies population probed with our MUSE sample. We thus use the prediction of these simulations to estimate the probability that a galaxy pair with a separation distance below 30 kpc will initiate their respective MBH

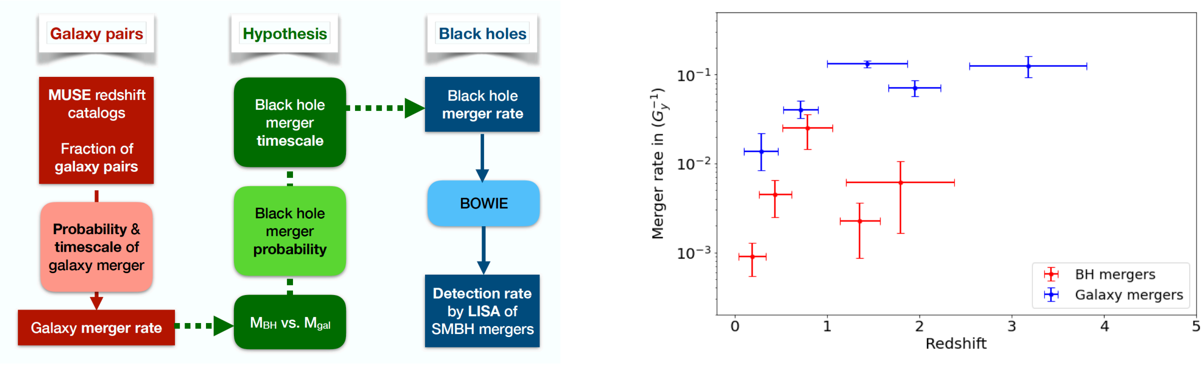

Fig. 1. Left: Summary of the various steps and hypotheses applied to predict LISA detections of MBH mergers from galaxy pairs observed with MUSE. **Right:** Cosmic evolution of the galaxies (red) and black holes (blue) merger rates.

merger phase within a characteristic timescale. To constrain the BH merging timescale, we use the probability distribution function from Chen et al. (2020) which gives an estimate of $T_{\rm delay}$ which represents the total BH merging timescale starting from the beginning of the dynamical friction stage until the end of the ringdown phase. Three probability distribution functions are proposed by Chen et al. (2020) depending on the galaxy shape distributions. We decided to use the axisymmetric galaxy configuration since most of the galaxies in the MUSE sample are disc galaxies, at least up to $z \sim 1.5$. The morphology/shape of higher redshift galaxies is not well constrained but they are probably mainly disc-like too. The BH merger timescale is of the order of a few Gyr, showing a strong dependence with the mass of the BH binary, being shorter for low-mass ones, and to a lesser extent with the binary mass ratio. Note, however, that recent N-body simulations at ultra-high resolution to study intermediate-mass BH dynamics in nucleated dwarf galaxies show that the merging timescale of binary BH could be as short as a few Myr (Khan & Holley-Bockelmann 2021).

Compining the galaxy merger rate computed in sect. 2.1, the probability that their MBH will merge by redshift zero with a timescale which depends on their total mass and mass ratios, we are able to estimate the MBH merger rate from the MUSE spectroscopic sample of galaxy pairs. As shown in Fig. 1, the BH merger rate increases steadily from redshift zero to $z \sim 0.8$ where it reaches a maximum of ~ 0.03 Gyr^{-1}. Minor BH binaries (ie. with high $\mu = M_1/M_2$) are not the main contributors to this total merger rate compared to major ones as their merging timescale is higher. Note that the redshift of the BH merger is reevaluated with respect to the galaxy merger event as it depends on the time delay $T_{\rm delay}$. It explains why the peak of the BH merger rate is shifted toward lower redshifts with respect to the peak of the galaxy merger rate.

2.3 *Prediction for LISA gravitational waves detection*

The final step is to estimate the GW signal of these MBH binary mergers and their detectability with LISA. For this purpose we use the GW analysis tool Bowie (Katz & Larson 2019) which provides a way to directly generate the signal-to-noise ratio (SNR) from the total strain applied on LISA arms during the GW perturbation event due to the merger of compact objects such as MBH. The SNR is calculated using the MBH masses (primary and companion of the binary), the redshift of the MBH pair when the GW is emitted, the remaining time at the beginning of the record and the remaining time at the end of the record before the end of the ringdown phase, assuming a nominal duration of 3 years for the LISA mission. GW waveforms are generated with the well-known PHENOMD tool for GW analysis (Khan et al. 2016).

To assess the LISA detectability, we follow the method proposed by Katz et al. (2020) using the relation of Berti et al. (2016). The MBH detection rate by LISA, based on our MUSE sample of galaxies, follows the same behaviour as in Fig. 1, with steadily increase from redshift zero to $z \sim 1$. The mass of binary BH mergers detected by LISA ranges from $\sim 10^3$ to 10^7 M$_\odot$ with a median mass of $\sim 10^5$ M$_\odot$. This is in rough agreement with the predictions made using Eagle simulations (Salcido et al. 2016) or semi-analytic models (Barausse et al. 2020) which both depend on supernovae feedback.

3 Conclusions and perspectives

This paper presents a first attempt to predict the detection of GW signal with LISA produced by MBH mergers, based on the characterization of galaxy close pairs identified up to ~ 7 in MUSE deep fields. Many improvements are planned in the coming years to refine these predictions. First on the observation side of galaxy pairs by increasing significantly the sample size by a factor of ~ 10, thanks to the analysis of additional MUSE-GTO and public deep fields that will reduce drastically the uncertainties in the derived galaxy merger rate, especially those due to cosmic variance. Second by improving our knowledge of BH in low-mass dwarf galaxies in terms of demography, including the BH occupation fraction, scaling relations (e.g. $M_{\rm BH}$ vs. $M_\star$) and BH merger timescale. And third on the side of the LISA data analysis and parameter estimation for the GW signal, much remain to be explored. In particular, asymmetric galaxy mergers might lead to high mass ratios binaries ($\sim 20 - 100$), a range where our theoretical understanding of waveforms is limited and where data analysis remains uncharted. In turn, depending on their accuracy, the measurements of the masses and spins of MBH systems by LISA will enrich our understanding of the formation of MBHs as well as their co-evolution with their host galaxies.

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