Descope of the ALIA mission

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Abstract. The present work reports on a feasibility study commissioned by the Chinese Academy of Sciences of China to explore various possible mission options to detect gravitational waves in space alternative to that of the eLISA/LISA mission concept. Based on the relative merits assigned to science and technological viability, a few representative mission options descoped from the ALIA mission are considered. A semi-analytic Monte Carlo simulation is carried out to understand the cosmic black hole merger histories starting from intermediate mass black holes at high redshift as well as the possible scientific merits of the mission options considered in probing the light seed black holes and their coevolution with galaxies in early Universe. The study indicates that, by choosing the armlength of the interferometer to be three million kilometers and shifting the sensitivity floor to around one-hundredth Hz, together with a very moderate improvement on the position noise budget, there are certain mission options capable of exploring light seed, intermediate mass black hole binaries at high redshift that are not readily accessible to eLISA/LISA, and yet the technological requirements seem to within reach in the next few decades for China.

1. Introduction

The present work originated from a recently completed second phase of the feasibility study commissioned by National Space Science Center, Chinese Academy of Sciences of China to explore various possible mission options to detect gravitational waves in space alternative to that of (e)LISA mission concept. At the beginning of the study dating back to more than three years ago, the ALIA (Advanced Laser Interferometer Antenna) mission concept first proposed by Peter Bender [1, 2] was chosen as the starting point. It is conceivably in many ways the simplest adaptation of the LISA mission concept to a measurement band centered around a few hundredth Hz. A more detailed study [3] of the possible sciences of the mission further indicates that, apart from the known LISA sources, the mission also holds the promise in mapping out the mass and spin distribution of intermediate mass black holes (IMBHs) possibly present in dense star clusters at low redshift as well as in shedding important light on the structure formation in the early Universe. However, when the key technologies of the mission is further looked at, the sub-picometer interferometry requirement in the laser metrology part poses a major obstacle on the technological side of the mission. With a view that China will have a reasonable chance to realise the mission in the next few decades and to minimise possible risks in future R&D of the key technologies, the task of mission descope is inevitably forced upon us.

Upon further evaluation of the relative merits between science and technological viability of a few representative descope options descended from the ALIA mission, it emerges that there exists certain class of mission design that is technologically viable within the next few decades for China, and yet it contains significant science that goes beyond eLISA/LISA. The principal aim of this report is to outline this set of mission design parameters and briefly sketch the scientific case study.

The outline of the present work may be described as follows. In Section 2, we will state the mission design parameters, display the corresponding sensitivity curves and the detection ranges with respect to black hole binaries with various mass ratios. In Section 3, a semi-analytic Monte-Carlo simulation is carried out to understand the scientific potential of the prospective missions in probing the structure formation in early Universe.

2. Mission descope

After some careful considerations, the following set of baseline design parameters will be chosen for future study and development.

Table 1.

Armlength (m)	Telescope diameter (m)	Laser power(W)	1-way position noise ($\frac{\mathrm{pm}}{\sqrt{\mathrm{Hz}}}$)	Acceleration ($\frac{\mathrm{m\ s^{-2}}}{\sqrt{\mathrm{Hz}}}$)
3×10^9	0.45-0.6	2	5-8	$3 \times 10^{-15} (> 0.1\mathrm{mHz})$
5×10^8 (ALIA)	1.0	30	0.1	$3 \times 10^{-16} (> 1\mathrm{mHz})$
5×10^9 (LISA)	0.4	2	18	$3 \times 10^{-15} (> 0.1\mathrm{mHz})$
1×10^9 (eLISA)	0.2	2	11	$3 \times 10^{-15} (> 0.1\mathrm{mHz})$

For reference purpose, the baseline design parameters of ALIA, LISA/eLISA are also given in Table 1. The relevant sensitivity curves are displayed in Figure 1. Apart from the instrumental noises, confusion noise generated by both galactic and extra-galactic compact binaries are also taken into consideration. Relevant confusion levels are converted from estimations by Hils and Bender [4] and Farmer and Phinney [5].

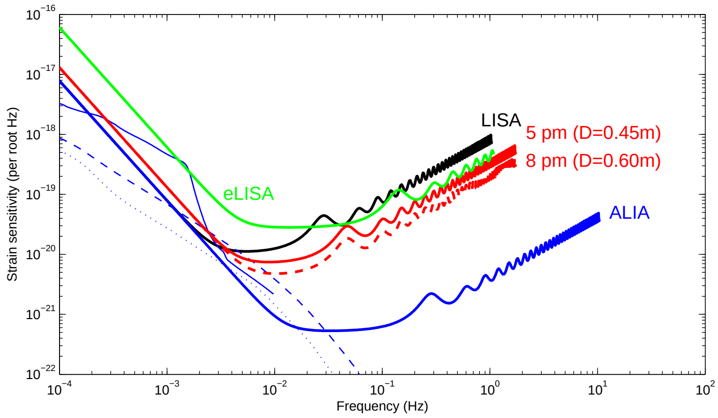

Figure 1.

For black hole binaries with mass ratio 1 : 4, typical of what one would expect from hierarchical black hole growth at high redshift, the all angle averaged detection range are plotted in Figure 2. Apart from galactic confusion noise [4], upper level (dashed curve) and lower level (dotted dashed curve) of confusion noise generated by extragalactic compact binaries as those estimated by [5] are also taken into account.

In calculating the averaged SNR, we have used hybrid waveforms in the frequency domain with black hole spin not taken into account [6, 7]. For one year of observation before merger, the contributions in SNR due to large spin is indeed negligible according to our calculations. Spin is relevant only in the parameter estimation stage, which will not be discussed in the present work. As may be seen from Figure 2, for a given redshift, the proposed mission concept is capable of detecting lighter black hole binaries in comparsion with eLISA/LISA and thereby provides better understanding of the hierarchical assembling process in early Universe.

Apart from IMBH binaries at high redshift, the designed sensitivity at around 0.01Hz measurement band means that the instrument is also capable of detecting IMRIs (Intermediate Mass Ratio Inspirals) harboured at globular clusters or dense young star clusters at low redshift

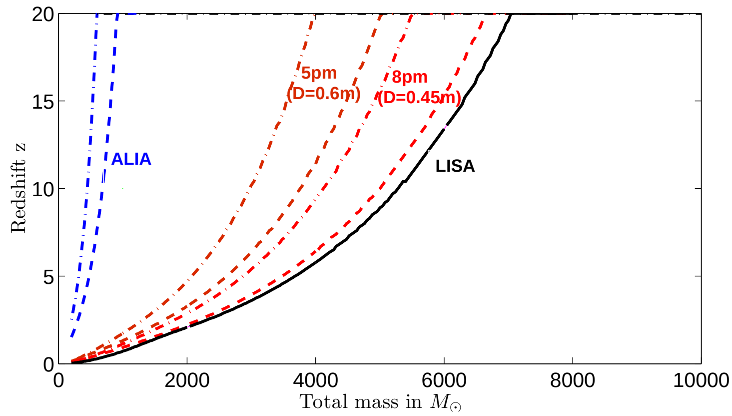

Figure 2. All-angle averaged detection range under a single Michelson threshold SNR of 7 for 1:4 mass ratio IMBH-IMBH binaries, one year observation prior to merger. For each mission option, both upper and lower confusion noise levels (represented by the dashed curve and dotted dashed curve respectively) due to extragalactic compact binaries are considered.

($z < 0.6$). See [8] for a further discussion of the capture dynamics of an IMRI in dense star clusters. Displayed in Fig 3 are the detection ranges of IMRIs with different mass ratios one year prior to merger. The stellar black hole inspiral into an IMBH is fixed to be $10M_{\odot}$, while the mass of the IMBH is subject to variation to generate different mass ratios in the figure.

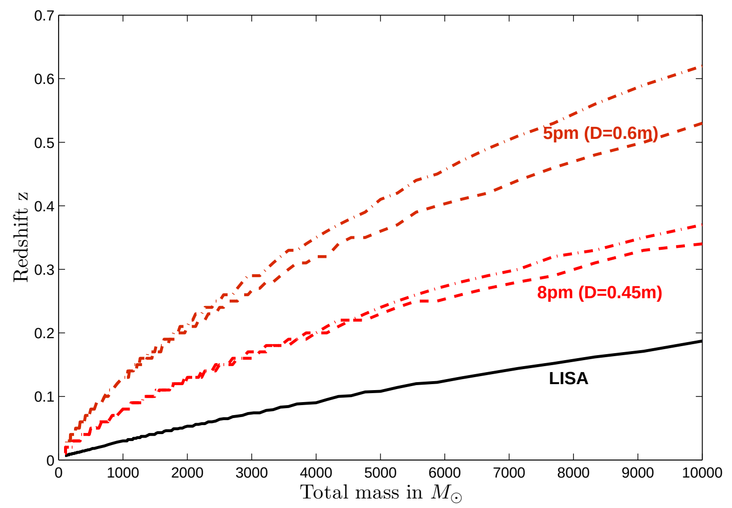

Figure 3. All-angle averaged detection range under a single Michelson threshold SNR of 7 for a stellar mass black hole spiralling into IMBHs with reduced masses of $10M_{\odot}$, one year observation prior to merger. For each mission option, both upper and lower confusion noise levels (represented by the dashed curve and dotted dashed curve respectively) due to extragalactic compact binaries are considered.

3. Scientific case study

The primary science driver of the ALIA mission is to make direct detection of IMBH binaries at high redshift descended from the heavy Pop III stars [3, 9, 10] and thereby provide insight into the physics of the structural formation processes at early Universe. It would be of interest to find out to what extent this science objective is compromised in the descoped mission. For this purpose, we carry out a simple Monte Carlo simulation of black hole merger histories based on the realizations of EPS formalism and semi-analytical dynamics, in accordance with the prescription given in [11, 12, 13].

Pop III remnant black holes of $150M_{\odot}$ are placed in 3.5σ biased halos at z=20 with initial spins of the seeds generated randomly. By prescribing VHM-type dynamics [11, 12], we trace downwards the black hole merging history. The halo mass ratio criteria for major merger is set to be > 0.1. Both the prolonged accretion and the chaotic accretion scenario are considered. Black hole spins coherently evolve through both mergers and accretions processes and their magnitudes influence strongly the mass-to-energy conversion efficiency. We assume efficient gaseous alignment of the black holes so that the hardening time is short and only moderate gravitational radiation recoils take place. Numerical simulations [14] suggest that the hardening and merging times scales remain short even in gas free environment. In calculations relevant to GW observations, we assume a threshold SNR of 7 for detection in the sense of single Michelson interferometer and one year observation prior to merger. The results are schematically given in Figure 4 and Figure 5.

We assess our simulations by fitting the black hole mass functions and luminosity functions at six almost equally divided successive redshift intervals ranging from z=0.4 to 2.1. In the prolonged accretion scenario, the results deviate from the observational constrains given by Soltan type argument when going up to redshift $z > 1.5$. It may therefore underestimate the black holes growth rate and perhaps also the coalescence rate. Observationally the existence of very high redshift ($z > 6$) AGNs implies that feed back mechanisms may be very different at early epoch so that fast growth of the seed black hole could be possible.

In terms of coalescence rate, our result displayed in Figure 4 is in overall agreement with the results given by Sesana et al [13, 16] and Arun et al [17], though the coalescence counts given by their simulations are about two or three times higher. It is likely due to various numerical discrepancies in the simulations. Overall, our black hole mass growth is slower, particularly in the prolonged accretion scenario. At $z = 15$, the total mass of the black hole binaries typically are still less than $600M_{\odot}$ in the prolonged model and this may lead to a smaller counts in detectable sources. We expect our results yields a very conservative (pessimistic) estimate of black hole binaries merger event rate.

The astrophysics encapsulated in our simulation represents the state of art understanding of structural formation after the dark age. Due to our poor understanding of the evolution of the Universe at this epoch, it is likely that the simulation overlooks many details of the physical processes involved. The event rate count should be looked upon in a cautious way. Instead of reading into the precise numbers, it serves as an indication what spaceborne gravitational wave detector is capable of and in our case, the advantage of setting the most sensitive regime of the measurement band from a few mHz to 0.01Hz.

Globular cluster harbored IMRIs

Before we conclude, let us also briefly estimate the detection capability for IMRIs in dense star clusters. The calculations and underlying hypotheses are identical to that in [3](see also [19, 18]). The results are given in Table 2.

The above event rate estimate is subject to many uncertainties and perhaps we should not attach too much importance to the precise numbers. Instead, the calculations serves as an indication of the detection potential of the mission concept as far as IMRIs at low redshift are

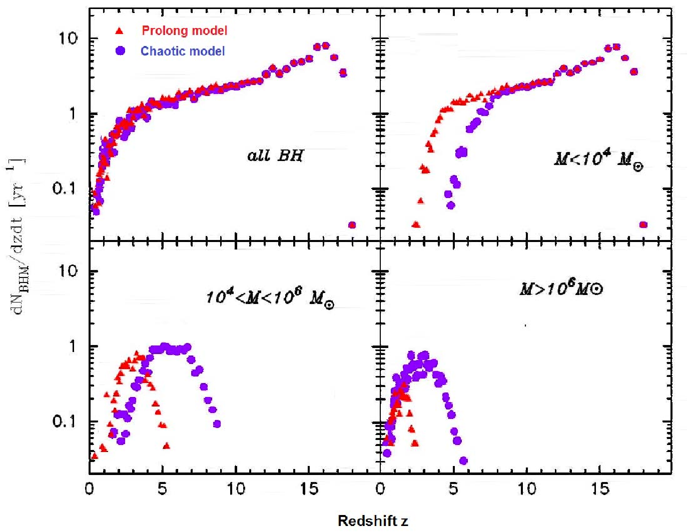

Figure 4. Coalescence rate predicted by the realized simulations.

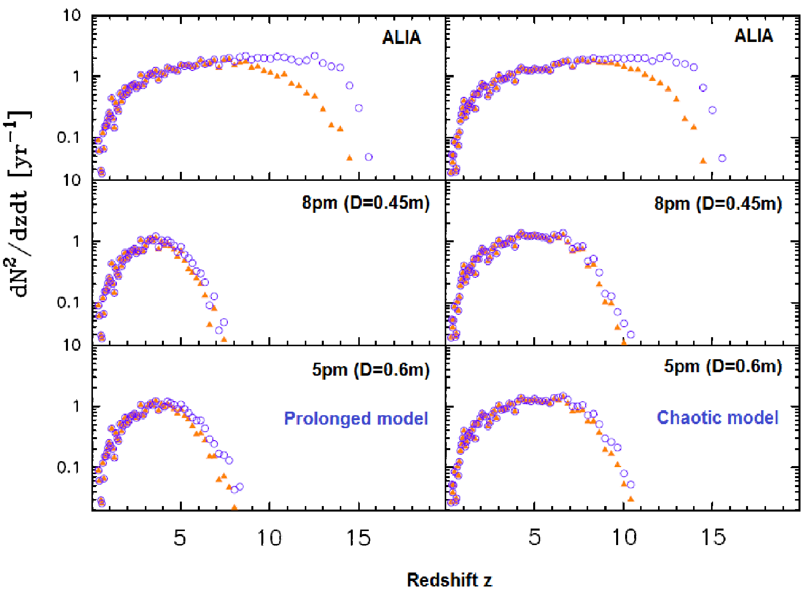

Figure 5. Event rates for descoped options.

concerned. Further, as event rate goes up as the cubic of the improvement in sensitivity, it also brings out the advantage of shifting slightly the most sensitive region of the measurement band to a few hundredth Hz, as far as detection of IMRIs is concerned. It should also be remarked that collision of dense star clusters [20] constitutes a possible IMBH gravitational wave sources, while the inspiral of massive black holes ($\sim 10^3 M_\odot$ to $\sim 10^4 M_\odot$) into the supermassive black hole at the center of a galaxy is also a promising IMRI source [21, 22]. However, the corresponding event rates would be difficult to estimate.

Table 2. Prospective detection rate for IMRIs in globular clusters.

Mission option	Upper level of confusion	Lower level of confusion
ALIA	$z_c = 5$: ~ 8000 $z_c = 3$: ~ 6000	~ 12000 ~ 7000
5pm (D=0.6m)	~ 90	~ 130
8pm (D=0.45m)	~ 26	~ 32
LISA	~ 3	

4. Concluding remarks

With the second phase of the feasibility study of gravitational wave detection in space coming to a close, a preliminary mission design deemed suitable as blue print for future development of the project in the Chinese Academy of Sciences is put forward. Together with the roadmap to advance the project step by step, the mission design will serve as a guide for future developments on both the theoretical as well as technological fronts. We hope to report upon further progress of the project on various areas soon.

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