Research Plan

Abstract

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2.1 Parameter estimation for coalescing massive binary black holes with LISA including effects due to the eccentricity of the orbits

Gravitational waves emitted by binary systems are known to carry a non-trivial structure. In addition to that, spinning binaries experience a precession of the orbital angular momentum and of the individual spins. It is thought that BHs have a non-negligible spin which in a general relativistic theory will couple with other spins or angular momenta. This spin-spin and spin-orbit interactions let the binary's spins and angular momentum precess, inducing a modulation into the emitted GWs [**?**]. This modulation makes detection harder, since additional parameters have been added to the problem. On the other hand, precession creates further structure in the GW signal which will improve the decorrelation of certain parameters once the signal has been detected. Before our efforts in the last four years, all studies of the measurement accuracy of gravitational wave experiments for comparable-mass binary systems have considered either spinless binaries, or spinning binaries without the full gravitational wave structure. We studied the measurement accuracy for the parameters describing spinning supermassive black hole binaries as expected to be observed with (original) LISA, taking into account the full 2PN waveform as well as spin-precession effects. We found that for binaries with a total mass in the range $10^5 M_\odot < M < 10^7 M_\odot$ at a redshift of 1, a factor ~ 1.5 is in general gained in accuracy, with the notable exception of the determination of the individual masses in equal-mass systems, for which a factor ~ 5 can be gained. We also found that using the full waveform helps increasing the upper mass limit for detection, which can be as high as $M = 10^8 M_\odot$ at a redshift of 1, as well as the redshift limit where some information can be extracted from a system, which is roughly $z \geq 10$ for $M \leq 10^7 M_\odot$, 1.5 - 5 times higher than with the waveform used in previous studies. We found that the full waveform allows to use supermassive black hole binaries to determine the Hubble diagram with high accuracy up to a redshift of $z \approx 1.6$, about 0.4 larger than what previous studies allowed [**?**]. Moreover, we computed the spin-orbit and spin-spin couplings needed for an accurate computation of the phasing of gravitational waves emitted by comparable-mass binaries on eccentric orbits at the second post-Newtonian (PN) order. We used a quasi-Keplerian parametrization of the orbit free of divergences in the zero eccentricity limit. We found that spin-spin couplings induce a residual eccentricity for coalescing binaries at 2PN, of the order of 10^{-4}-10^{-3} for supermassive black hole binaries in the LISA band. Spin-orbit precession also induces a non-trivial pattern in the evolution of the eccentricity, which could help to reduce the errors on the determination of the eccentricity and spins in a gravitational wave measurement [**?**]. We used these results to study the influence of the eccentricity on the parameter estimation for coalescing massive binary black holes with LISA. We are currently completing the numerical simulations and writing up the paper with the results.

We also invested a lot of time in the study of the impact on our results when assuming for original LISA a shorter arm length, of about 1 million km instead of 5 millions km. This happened in the framework of the effort to redesign a cheaper eLISA mission, affordable by ESA only.

3 Own Recent and Ongoing Work (updated)

3.1 Gravitational waves from intermediate-mass black holes in young clusters

Massive young clusters (YCs) are expected to host intermediate-mass black holes (IMBHs) with mass ranges between $\sim 10^2 - 10^4$ that are born via runaway collapse. These IMBHs are likely in binaries and can undergo mergers with other compact objects, such as stellar mass black holes (BHs) and neutron stars (NSs). Together with Michela Mapelli, we derived the occurence of such mergers starting from information available in the local universe; in particular, we assumed that a fraction ($\sim$0.75) of all the YCs more massive than $10^5 M_\odot$ might host one IMBH, as suggested by a statistical analysis of the properties of YCs in the Milky Way and in the Antennae. Mergers of IMBHNS and IMBHBH binaries are sources of gravitational waves (GWs), which might allow us to reveal the presence of IMBHs. We examined the detectability of such binaries by current and future GW observatories, both ground- and space-based. In particular, as representatives of different classes of instruments, we considered the Initial and Advanced LIGO, the proposed *Einstein gravitational-wave Telescope* (ET) and the original LISA. We found that IMBH mergers are unlikely to be detected with instruments operating at the sensitivity of initial LIGO (which was operating at the time of the conception of the paper). LISA detections are disfavored by the mass range of IMBHNS and IMBHBH binaries: less than one event per year is expected to be observed by such an instrument. Advanced LIGO is expected to observe a few merger events involving IMBH binaries in a oneyear long observation. Advanced LIGO is particularly suited for mergers of relatively light IMBHs ($\sim 10^2 M_\odot$) with stellar mass BHs. The number of mergers detectable with ET is much larger: tens (hundreds) of IMBHNS (IMBHBH) mergers might be observed per year, according to the runaway collapse scenario for the formation of IMBHs. This work has been published in the Astrophysical Journal in 2010 [**?**].

3.2 Including effects of alternative gravity theories into parameter estimation

To expand the considerations in [**?**] (section 2.1), I studied the impact of alternative general relativistic theories on the parameter estimation for coalescing supermassive black holes as could be measured by LISA [**?**]. I introduced correction parameters that account for modified gravity into the second post-Newtonian gravitational wave phase for circular black hole binaries with precessing spins and took into account the full gravitational wave structure instead of the restriction to only the second harmonic used so far by previous works. Such a correction scheme allows to map the infinite range of alternative theories to a certain set of alternative theory parameters (six in our case), considering those as an addition to the existing binary parameter set. In order to find LISA's measurement accuracy for physical parameters of such a binary as well as for alternative theory corrections, I used the Fisher matrix approach [**?**] which gives a rough approximation for the parameter estimation error and carried out Monte Carlo simulations for large sets of several supermassive black hole binary mass combinations. This led to overall expected error distributions. Many studies use only the *restricted waveform* (RWF) for the gravitational wave for their calculations, which only considers the dominant harmonic of the signal. This removes parts of the complicated structure from the signal in favor of reducing the computational costs for applying the templates. On the other hand, removing structure results in the loss of information and hence in more correlation among the different parameters, effectively losing measurement accuracy. I have used the *full waveform* (FWF) which is taking into account higher harmonics and will therefore lead to higher accuracy. For GW science a crucial point is to find an optimal combination of measurement accuracy and computational cost. An important question to ask is therefore how much accuracy is lost by only using the RWF instead of the FWF, because if it is only a factor of a few, we can save a lot of time and still estimate the alternative theory parameters with reasonable accuracy.

I found that for low-mass supermassive black hole binaries ($10^5 M_\odot < M < 10^7 M_\odot$), the errors on the alternative theory parameters improve only by a factor of up to three while to two orders of magnitude can be gained for high-mass binaries ($10^7 M_\odot < M < 10^8 M_\odot$) when using the FWF instead of the RWF. Due to the dilution of the available information, the accuracy of the original binary parameters is reduced by factors of a few. It is therefore reasonable to use the RWF for the detection of low-mass SMBHBs to save template production time. However, for high-mass binaries, the FWF has to be used to retain a sensible measurement accuracy. To compare our results with on-going research, I computed an optimal lower bound on the Compton wavelength of the graviton [**?** **?**] which can be improved by a factor of 1.5 to $\lambda_g > 7.6 \times 10^{21}$ cm when using the full waveforms.

The results of this study have been published 2012 in Physical Review D [**?**].

3.3 Creating an MCMC signal injection and alternative theory recovery framework

Previous studies on the measurement of deviations from GR concentrated on estimating the errors on so-called alternative theory parameters for eLISA using either Fisher matrix [**?**] or *Markov Chain Monte Carlo* (MCMC, see e.g. [**?** **?**]) simulations. Instead of relying on such theoretical predictions, I recently started (in collaboration with Ed Porter, APC Paris) to work on an MCMC framework which tests eLISA's ability to actually recover the theory parameters of a gravitational wave signal injected into the expected background. This will allow us to see whether in practice eLISA (the reduced variant of LISA) will be able to distinguish the underlying theory from GR at all or whether some other spacecraft configuration is more favorable.

4 Planned Research (updated)

As one of the main scientific objectives of eLISA is to probe new physics, the primary goal for my PhD thesis is to continue my studies on the recovery of alternative theory parameters from supermassive black hole binary mergers. I will try to enhance our alternative theory framework presented in [**?**] by also looking at amplitude corrections in the waveform instead of only taking into account the (dominant) phase corrections. In addition I intend to consider the effects of eccentric orbits which add further structure and therefore further information to the gravitational waveform and make our model much more realistic. Since I studied a search for modifications of different post-Newtonian orders at the same time, I plan to use this work to investigate how the use of next-to-leading order modifications to GR could affect the determination of alternative theory parameters. Currently, I am only considering the inspiral phase of the binary, but not the merger and ringdown. Recent studies have shown that including the latter two processes into the calculation by creating so called *hybrid* waveforms can increase the measurement accuracy by a factor of ten [**?**]. It would therefore be a great improvement for eLISA to expand our framework with merger/ringdown waveforms. Also, the observation of not one single black hole binary but several of them could further increase accuracy [**?**].

As a secondary objective, I wish to try to answer a question which arose during the conception of [**?**]. When the two constituents of the SMBHB come very close to a few Schwarzschild radii (R_{S}), they generate a GW signal which is much stronger than at orbital separations of tens of R_{S}. This means that the last few stable orbits of the binary contribute the strongest to the signal-to-noise ratio measured by the detector. At the same time our modeling of the expected signal (which we need for matched filtering) is at the brink of failing, since usually one is assuming that a) the orbital decay is adiabatic, b) the post-Newtonian approximation still holds, c) the orbit-averaged precession differential equations [**?**] are valid and d) the stationary phase approximation [**? ?**] can be applied for the spinning black holes. It is therefore of utmost importance to find a good point to stop our integrations, i.e. when the our model is still reasonably accurate to allow to account for such a strong signal. Preliminary results are available, but not yet ready for a publication.

In the previous work I concentrated on the effect of alternative theories on the orbital dynamics of black hole binaries, introducing spin precession due to general relativistic frame-dragging as an overall modulation of the waveform. I plan to take a closer look on gravitomagnetic effects and how spin precession behaves for departures from GR and how this could create a bias in our models. I hope to accomplish this project with a Master's student in theoretical physics.

So far the effects of extra gravitational wave polarizations (such as longitudinal modes) caused by alternative gravity theories [**?**] have not been accounted for in parameter estimation simulations. It is known that other metric theories could produce up to four polarizations in addition to the existing two predicted by GR. The existence of such extra polarizations would immediately put GR into question and favor proposed alternatives. However, eLISA is not capable of directly detecting extra polarizations since it lacks enough independent detectors (yet it could be possible with pulsar timing arrays mentioned in the introduction), but for compact binary inspirals, such additional degrees lead to faster energy loss through gravitational radiation and hence they leave their imprints in the orbital evolution. I plan to extend our framework to account for such effects in parameter estimation, recently more closely investigated by [**?**].

5 Resources and Timing

Until June 30, 2013, I am supported by the Candoc Forschungskredit No. 57181802. Office space is already provided by the Institute for Theoretical Physics. I need the grant for the final year of my PhD, from July 2013 until approximately July 2014, to account for my living (see separate budget) and an appropriate amount of conference and travel fees. Within this one-year period I expect to closer investigate the research problems listed in section 4.

6 Scientific Relevance of Expected Results

The main problems addressed in my thesis deal with tests of General Relativity and possible alternative theories as well as gravitational waves. These topics are at the very center of the contemporary astrophysics and cosmology research and are thus very important. Clearly in such highly competitive fields already small advancements are of great value and are also relevant for planning new observations. Given my supervisor's involvement in LISA-Pathfinder and eLISA some of our projects are directly relevant for the planning and definition of the science objectives of eLISA and of the subsequent interpretation of the data, since possible improvements in the process of signal search and parameter estimation could decrease the cost and increase the accuracy of the results for eLISA.

References

[1] É. É. Flanagan and S. A. Hughes. New Journal of Physics **7** (2005)