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Precessing supermassive black hole binaries and dark energy measurements with LISA

Adamantios Stavridis,[1,*] K. G. Arun,[1,†] and Clifford M. Will[1,2,‡]

[1]*McDonnell Center for the Space Sciences, Department of Physics, Washington University, St. Louis, Missouri 63130, USA*
[2]*GReCO, Institut d'Astrophysique de Paris, CNRS, Université Pierre et Marie Curie, 98 bis Boulevard Arago, 75014 Paris, France*
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Spin induced precessional modulations of gravitational wave signals from supermassive black hole binaries can improve the estimation of luminosity distance to the source by space based gravitational wave missions like the Laser Interferometer Space Antenna (LISA). We study how this impacts the ability of LISA to do cosmology, specifically, to measure the dark energy equation of state (EOS) parameter w. Using the ΛCDM model of cosmology, we show that observations of precessing binaries with mass ratio 10:1 by LISA, combined with a redshift measurement, can improve the determination of w up to an order of magnitude with respect to the nonprecessing case depending on the total mass and the redshift.

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I. INTRODUCTION

When the proposed orbiting Laser Interferometer Space Antenna (LISA) detects an inspiralling compact binary system, it can not only localize the source on the sky but can also measure its luminosity distance independent of astronomical distance ladder calibrations. If an electromagnetic (EM) counterpart associated with this gravitational wave (GW) event provides the redshift to the source, then the combination of these observations can have profound cosmological implications [1], such as precise determinations of Hubble's constant [1–7] and measurements of the dark energy equation of state parameter w [8–10].

Spin effects may also help to improve cosmological measurements using gravitational waves. If the compact binary components have nonaligned spins, then the modulations induced by precession [11,12] can break degeneracies between various parameters being estimated and improve accuracy, especially of the sky location and luminosity distance [13–15]. Recently we have developed a code to carry out parameter estimation for precessing inspiralling massive binary black holes, using the Fisher matrix formalism, in order to consider the impact of spin precession on LISA's ability to distinguish a general class of massive theories of graviton from general relativity [16] (see also a similar work by [17]). In this report, we use a variant of this code to study the cosmological implications of the improved distance measurements possible with spinning massive black hole binaries.

Vecchio [13] first pointed out the possible improvements in precision provided by precessions induced by a subset of spin-orbit couplings. Lang and Hughes [14,15] generalized this to the full panoply of spin-orbit as well as spin-spin effects. Reference [14] focused on the improvement in the estimation of masses and spins of the binary and briefly discussed improvements in distance measurements. Their follow-up paper [15] showed that precessing binaries would offer much better angular localization by LISA and discussed how electromagnetic follow-ups could be used effectively to identify the host galaxy and obtain the redshift (see also Ref. [18]).

In this paper, we show explicitly that improved distance measurements with precessing binaries combined with a redshift to the source could lead to precise measurements of w; the results are summarized in Fig. 1. For example, for a binary system of $(1 + 10) \times 10^6 M_\odot$ at redshift $z = 1.5$, the median 1σ error in measuring w, over an ensemble of 10^4 binaries distributed randomly in spins, orbital orientations, and sky locations is about 2%.

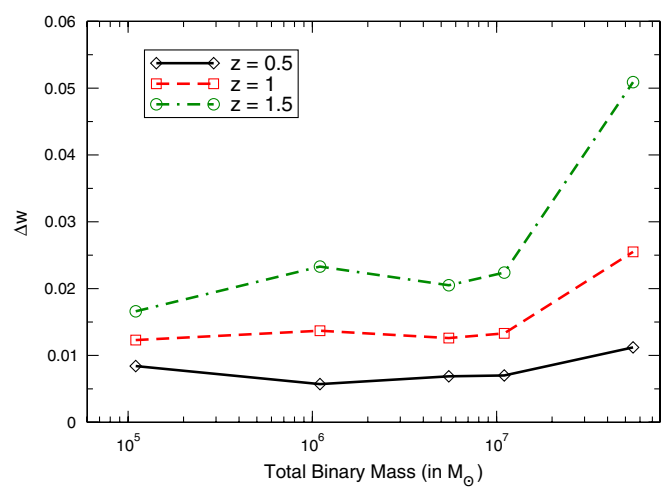

FIG. 1 (color online). 1σ errors in the dark energy EOS parameter w as a function of the total binary black hole mass at redshifts of 0.5, 1 and 1.5. Binaries are all assumed to have precession and contain black holes of mass $(1, 10) \times 10^4$, $(1, 10) \times 10^5$, $(5, 50) \times 10^5$, $(1, 10) \times 10^6$, $(5, 50) \times 10^6 M_\odot$. The data points are medians of 10^4 runs for each mass and redshift, and ignore the effect of weak lensing.

*astavrid@physics.wustl.edu
†arun@physics.wustl.edu
‡cmw@wuphys.wustl.edu

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II. MODELS AND ASSUMPTIONS

Our waveform model is described in detail in [16]. We use second-post-Newtonian (2PN) accurate "restricted" waveforms (RWF) for binaries on quasicircular orbits and include the precession effects of spin-orbit and spin-spin coupling. The stationary phase approximation is used for computing the Fourier transform of the signal. Though spin contributions at 2.5PN [19] and nonspinning terms up to 3.5PN order [20] are available for the RWF, we assume that they induce only corrections to the leading effects studied here. However, incorporation of spin dependent higher harmonics [12,21] could have some influence on the results [22]. We follow Cutler [23] in our model of the LISA satellite and its orbital motion. The noise characteristics of LISA that we assume and use are the same as in Ref. [24] and used by Lang and Hughes [15]. We have taken into account the effect of precession on the antenna pattern functions of LISA.

We use a Fisher matrix analysis to estimate the errors in estimating the 15 parameters that characterize the system: two masses, two dimensionless spin magnitudes (which vary from 0 to 1), the time and phase of coalescence, four sets of two angles each specifying the location of the binary, the initial angular momentum direction and the two initial spin directions of the binary's members (eight in total), and finally the luminosity distance. All the angles used are with respect to the solar system barycenter. In the specific case that the individual spin vectors of the black holes are aligned, (a rather optimistic case astrophysically) the two extra sets of angles (four parameters) for the individual spins are not needed since the binaries do not precess [24]. We also assume that LISA provides two independent signal outputs with uncorrelated noises. Finally, we assume that the sources are observed for 1 yr prior to coalescence.

For a given choice of the physical masses of the two black holes and of the redshift or luminosity distance, we distribute 10^4 sources randomly in the sky with random values of the remaining 10 parameters (we choose coalescence time and phase to be 1 yr and zero, respectively, in all cases). For each of the realizations, we solve numerically the precessing equations during the inspiral phase of the system, compute the output signals h^{I}, h^{II}, and the Fisher information matrix defined as

$$\Gamma_{ab} \equiv \left(\frac{\partial h^{\mathrm{I}}}{\partial \theta^a} \middle| \frac{\partial h^{\mathrm{I}}}{\partial \theta^b}\right) + \left(\frac{\partial h^{\mathrm{II}}}{\partial \theta^a} \middle| \frac{\partial h^{\mathrm{II}}}{\partial \theta^b}\right), \tag{2.1}$$

where the inner product is

$$(h_1|h_2) \equiv 4\,\mathrm{Re}\int_0^\infty df\,\frac{\tilde{h}_1^*(f)\tilde{h}_2(f)}{S_n(f)}, \tag{2.2}$$

where $\tilde{h}(f)$ denotes the Fourier transform of the gravitational waveform $h(t, \theta^a)$, star denotes complex conjugate, $S_n(f)$ is the noise spectral density of the detector, and $\partial h/\partial\theta^a$ denotes the partial derivative with respect to the parameter θ^a being estimated. The superscripts I and II denote the two LISA outputs. The signal-to-noise ratio (SNR) for a given signal $h(t, \theta^a)$ is then given by, $\rho[h] \equiv (\tilde{h}|\tilde{h})^{1/2}$. We then invert the Fisher matrix to obtain the covariance matrix Σ^{ab}, and the corresponding root mean square errors from the square roots of the diagonal entries, as follows,

$$\Delta\theta^a = \sqrt{\Sigma^{aa}}, \qquad \Sigma = \Gamma^{-1}. \tag{2.3}$$

We focus on systems with a mass ratio of 10:1 since these are astrophysically interesting and exhibit stronger effects of spin precession.

Figure 2 shows the histogram of the relative errors in the luminosity distance for a system with masses $(10^5, 10^6)M_\odot$ at a redshift of $z = 1$. Precession of the binary has a significant impact on the distribution as the peak of the distribution shifts to the left (improves) almost by an order of magnitude with respect to the case where all systems in the population are nonprecessing. This is in reasonable agreement with the results of Lang and Hughes [15] (see, e.g., Fig. 7 of their paper).

However, to do cosmology, we need the redshift of an electromagnetic signal associated with an observed LISA event or with its host galaxy. To date there is no clear understanding of the astrophysical mechanisms that could produce an electromagnetic afterglow (or a precursor) to a binary black hole merger, although a number of possibilities have been discussed [10]. Whether LISA can localize the source on the sky so that extensive electromagnetic follow-up missions can be launched has been addressed in many recent works. Of particular interest here are the estimates of Lang and Hughes [15], showing that typically

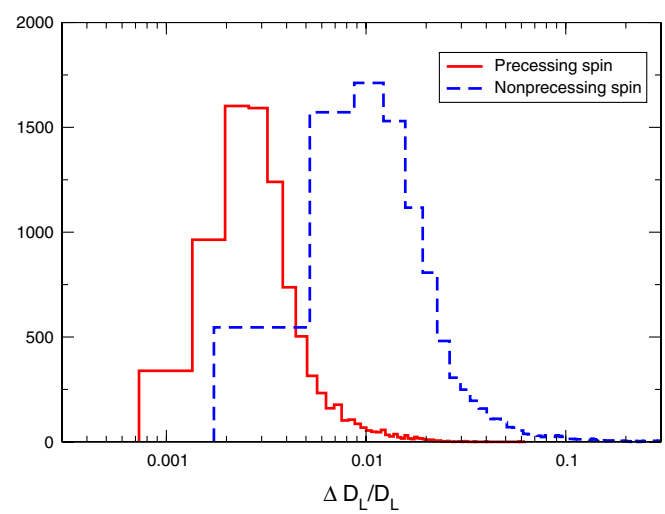

FIG. 2 (color online). Distribution of the 1σ errors in luminosity distance measurement based on 10^4 random realizations. The mass of the binary system is $(10^5 + 10^6)M_\odot$ at a redshift of $z = 1$. Solid (red) histogram is for precessing systems; dashed (blue) histogram is for systems with spins aligned.

for a $z = 1$ source of total mass $10^6 M_\odot$, the angular resolution taking precession into account is about 0.3–3 square degrees 1 d prior to merger (see Table 5 of [15] for example). Kocsis *et al.* [25] argued that finding EM counterparts associated with LISA sources will be difficult, but may be achievable with the advent of various wide field telescopes which would be operational by the time LISA flies (see Table I of Ref. [25] for details). Further, some authors have argued [8,10] that the number of candidate galaxies associated with a LISA event can be reduced by 2–3 orders of magnitude by looking for the source within a 3D error volume, combining the angular resolution of LISA and the approximate luminosity distance LISA would provide in advance. For this reason (rather optimistically) we have not rejected any distance estimate in the 10^4 realizations based on the size of the angular error box or the detectability of an EM counterpart.

To translate distance errors into errors in the dark energy EOS parameter w, we work with the standard cosmological model with a flat universe and the nominal parameters $H_0 = 75\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$, matter density $\Omega_M = 0.25$, dark energy density $\Omega_\Lambda = 0.75$, and $w = -1$. The luminosity distance of a source at a redshift z is given by

$$D_L = (1 + z) \int_0^z \frac{dz'}{H(z')}, \tag{2.4}$$

where $H(z)$ is given by

$$H(z) = H_0 \sqrt{\Omega_M (1 + z)^3 + \Omega_\Lambda (1 + z)^{3(1+w)}}. \tag{2.5}$$

In order to illustrate directly the effect of precession, we assume that errors in H_0, Ω_M, Ω_Λ, and z are negligible, so that the error in w is related directly to the error in D_L by [26]

$$\Delta w = D_L \left| \frac{\partial D_L}{\partial w} \right|^{-1} \frac{\Delta D_L}{D_L}. \tag{2.6}$$

The value of $\partial D_L / \partial w$ can be calculated using (2.4) and (2.5) for the different values of the redshift used.

Finally, we have neglected the effect of weak lensing on the estimation of the luminosity distance. This is a serious caveat, especially at redshifts above 1. However, mechanisms have been proposed which might help to reduce the weak lensing error in the future. These include "corrected lenses" [27], the accurate measurement of the weak lensing power spectrum with radio observations [28], and combining optical and infrared observations of foreground galaxies [29]. See [30] for a recent discussion.

III. RESULTS AND DISCUSSION

The inclusion of spin precession and its attendant modulation of the GW waveform has a significant impact on the accuracy of measurements of the dark energy parameter, which in turn is due to improved estimation of the luminosity distance, as shown in Fig. 2. Figure 1 depicts how the estimation of w varies with the total mass of the binary. We show the median errors from various runs corresponding to different masses and redshifts. It is interesting to note that for masses between 10^5–$10^7 M_\odot$, $\Delta w \leq 3\%$ for redshifts up to 1.5. The left panel of Fig. 3 shows that the errors in the measurement of w go down by a factor of approximately 10 when the spins of the binaries are not aligned compared to the aligned, nonprecessing case. Note that all our histograms, except the cumulative plots in the insets, are *unnormalized*, so that the histograms show the number of realizations in each bin. The dependence of the

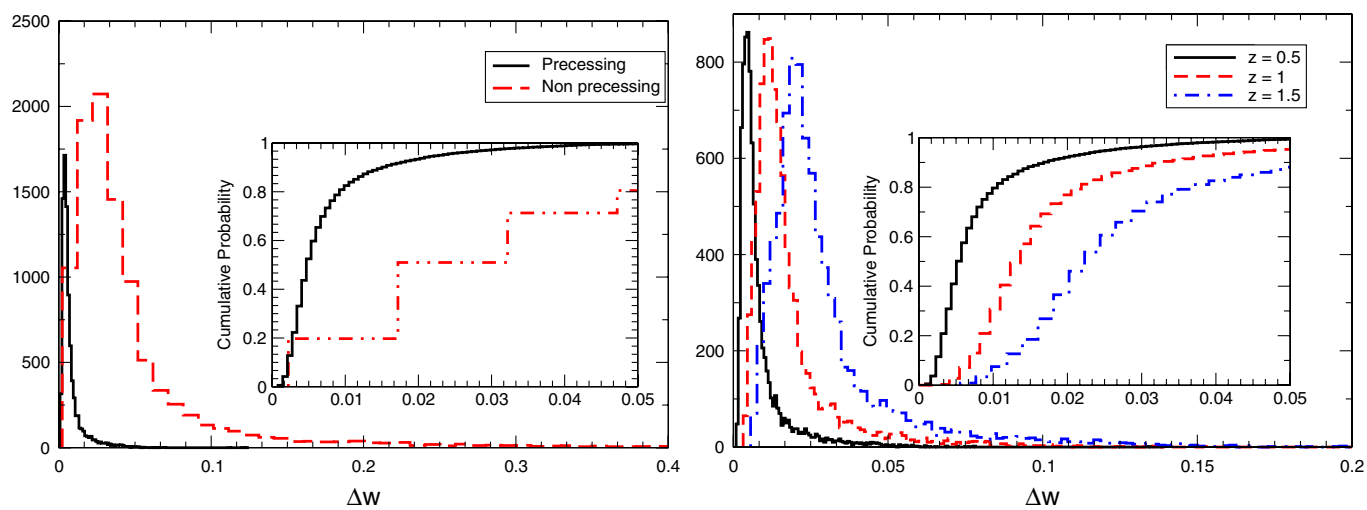

FIG. 3 (color online). Distributions of 1σ errors in w for various values of redshifts and spin configurations. Left panel: Distribution of the errors in the dark energy EOS parameter w for a binary system of masses $10^5 + 10^6 M_\odot$ at redshift $z = 1$, and for the precessing and nonprecessing cases. The inset frame shows a zoom of the corresponding cumulative histograms. Right panel: Distribution of errors in w for the same binary system with masses $10^5 + 10^6 M_\odot$ in the precessing case for three different redshifts. The inset frame shows a zoom of the corresponding cumulative histograms.

errors on the redshift z is shown in the right panel of Fig. 3. As is expected the errors get worse with increasing redshift (distance), but the degradation of errors is not dramatic. Even for $z = 1.5$, a significant fraction of the 10^4 randomly distributed sources permit measurement of w to better than 5% accuracy. However, for larger redshifts, more galaxies will be found in the LISA error volume and it will be more difficult to obtain a redshift.

Van den Broeck *et al.* [31] have recently revisited the measurement accuracy of the dark energy EOS parameter w, using a GW signal without precession but including higher harmonics. Though higher harmonics and precession are completely different effects, it is interesting to note that both improve the estimation of w significantly and to comparable orders. This further motivates the attempt to incorporate the effect of higher harmonics in the presence of spin precession (see [22] for a recent analysis). We have ignored any possible effect of orbital eccentricity in the waveforms (see, e.g. [32] and references therein). These are topics for future consideration.

ACKNOWLEDGMENTS

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