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Spectroscopy of Kerr Black Holes with Earth- and Space-Based Interferometers

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We estimate the potential of present and future interferometric gravitational-wave detectors to test the Kerr nature of black holes through "gravitational spectroscopy," i.e., the measurement of multiple quasinormal mode frequencies from the remnant of a black hole merger. Using population synthesis models of the formation and evolution of stellar-mass black hole binaries, we find that Voyager-class interferometers will be necessary to perform these tests. Gravitational spectroscopy in the local Universe may become routine with the Einstein Telescope, but a 40-km facility like Cosmic Explorer is necessary to go beyond $z \sim 3$. In contrast, detectors like eLISA (evolved Laser Interferometer Space Antenna) should carry out a few—or even hundreds—of these tests every year, depending on uncertainties in massive black hole formation models. Many space-based spectroscopical measurements will occur at high redshift, testing the strong gravity dynamics of Kerr black holes in domains where cosmological corrections to general relativity (if they occur in nature) must be significant.

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Introduction.—The first binary black hole (BH) merger signal detected by the LIGO Scientific Collaboration, GW150914 [1], had a surprisingly high combined signal-to-noise ratio (SNR) of 24 in the Hanford and Livingston detectors. The quasinormal mode signal ("ringdown") from the merger remnant is consistent with the predictions of general relativity (GR) for a Kerr BH, but it was observed with a relatively low SNR $\rho \sim 7$ [2]. The large masses of the binary components [3] have interesting implications for the astrophysics of binary BH formation [4]. This detection, together with a second detected BH merger [5], placed interesting constraints on the merger rates of BH binaries in the Universe [6–10].

LISA Pathfinder was successfully launched in December 2015, paving the way for a space-based detector such as eLISA (evolved Laser Interferometer Space Antenna) [11,12], which will observe mergers of massive BHs throughout the Universe with very large SNRs and test the Kerr nature of the merger remnants. The basic idea is that the dominant $\ell = m = 2$ resonant frequency and damping time can be used to determine the remnant's mass M and dimensionless spin $j = J/M^2$ (we adopt geometrical units $G = c = 1$ throughout this Letter.) In GR, all subdominant mode frequencies (e.g., the modes with $\ell = m = 3$ and $\ell = m = 4$ [13]) are then uniquely determined by M and j. The detection of subdominant modes requires high SNR, but each mode will provide one (or more) tests of the Kerr nature of the remnant [14]. As first pointed out by Detweiler in 1980, gravitational waves allow us to do BH spectroscopy: "After the advent of gravitational wave astronomy, the observation of these resonant frequencies might finally provide direct evidence of BHs with the same certainty as, say, the 21 cm line identifies interstellar hydrogen" [15].

Such high SNRs are known to be achievable with an eLISA-like detector [16]. The surprisingly high SNR of GW150914 raised the question whether current detectors at design sensitivity should routinely observe ringdown signals loud enough to perform gravitational spectroscopy. Leaving aside conceptual issues about ruling out exotic alternatives [17–19], here we use our current best understanding of the astrophysics of stellar-mass and supermassive BHs to compute the rates of events that would allow us to carry out spectroscopical tests.

Below we provide the details of our analysis, but the main conclusions can be understood relying on the noise power spectral densities (PSDs) $S_n(f)$ of present and future detectors, as shown and briefly reviewed in Fig. 1, and simple back-of-the-envelope estimates.

Ringdown SNR.—Consider the merger of two BHs with source-frame masses (m_1, m_2), spins $(\mathbf{j}_1, \mathbf{j}_2)$, total mass $M_{\rm tot} = m_1 + m_2$, mass ratio $q \equiv m_1/m_2 \geq 1$, and symmetric mass ratio $\eta = m_1 m_2 / M_{\rm tot}^2$. The remnant mass and dimensionless spin, M and $j = J/M^2$, can be computed

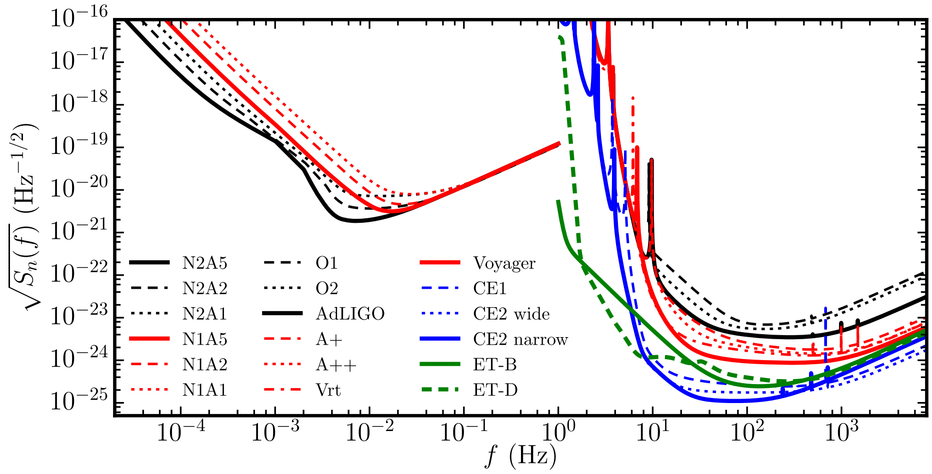

FIG. 1. Noise PSDs for various space-based and advanced Earth-based detector designs. “NiAk” refers to non-sky-averaged eLISA PSDs with pessimistic (N1) and optimistic (N2) acceleration noise and armlength $L = k$ Gm (cf. [20]). In the high-frequency regime, we show noise PSDs for (top to bottom): the first AdLIGO observing run (O1); the expected sensitivity for the second observing run (O2) and the advanced LIGO (AdLIGO) design sensitivity [21]; the pessimistic and optimistic ranges of AdLIGO designs with squeezing (A+, A++) [22]; Vrt and Voyager [23,24]; Cosmic Explorer (CE1), basically A+ in a 40-km facility [25]; CE2 wide and CE2 narrow, i.e., 40-km detectors with Voyager-type technology but different signal extraction tuning [24,26]; and two possible Einstein Telescope designs, namely, ET-B [27] and ET-D in the “xylophone” configuration [28].

using the fitting formulas in Refs. [29] and [30], respectively (see also Refs. [31,32]). The ringdown SNR ρ can be estimated by following Ref. [16]. Including redshift factors and substituting the Euclidean distance r by the luminosity distance D_L as appropriate, Eq. (3.16) of Ref. [16] implies that ρ is well approximated by

$$\rho = \frac{\delta_{\rm eq}}{D_L \mathcal{F}_{lmn}} \left[\frac{8}{5} \frac{M_z^3 \epsilon_{\rm rd}}{S_n(f_{lmn})}\right]^{1/2}, \tag{1}$$

where $M_z = M(1+z)$. Fits of the mass-independent dimensionless frequencies $\mathcal{F}_{lmn}(j) \equiv 2\pi M_z f_{lmn}$ are given in Eq. (E1) of Ref. [16]. The geometrical factor $\delta_{\rm eq} = 1$ for Michelson interferometers with orthogonal arms. For eLISA-like detectors the angle between the arms is 60°, so $\delta_{\rm eq} = \sqrt{3}/2$, and we use the *non-sky-averaged* noise PSD $S_n(f)$ [20,33]. The ringdown efficiency for nonspinning binaries is well approximated by the matched-filtering estimate of Eq. (4.17) in Ref. [13]: $\epsilon_{\rm rd} = 0.44\eta^2$. When using the best-fit parameters inferred for GW150914 [3], Eq. (1) yields a ringdown SNR $\rho \simeq 7.7$ in O1 (in agreement with Ref. [2]) and $\rho \simeq 16.2$ in AdLIGO.

Because of the orbital hang-up effect [34], spinning binaries with aligned (antialigned) spins radiate more (less) than their nonspinning counterparts. The dominant spin-induced correction to the radiated energy is proportional to a weighted sum of the components of the binary spins along the orbital angular momentum [29,35,36]. We estimate this correction by rescaling the radiated energy by the factor $E_{\rm rad}(m_1, m_2, \mathbf{j}_1, \mathbf{j}_2)/E_{\rm rad}(m_1, m_2, \mathbf{0}, \mathbf{0})$, where the total energy radiated in the merger $E_{\rm rad}$ is computed using Eq. (18) of Ref. [29]. We find that spin-dependent corrections change ρ by at most 50%.

It is now easy to understand why Einstein Telescope-class detectors are needed to match the SNR of eLISA-like detectors and to perform BH spectroscopy. The quantity $\mathcal{F}_{lmn}(j)$ is a number of order unity [14,16]. The physical frequency is $f_{lmn} \propto 1/M_z$: for example, an equal-mass merger of nonspinning BHs produces a remnant with $j \simeq 0.6864$ and fundamental ringdown frequency $f_{220} \simeq 170.2(10^2 M_\odot/M_z)$ Hz. So Earth-based detectors are most sensitive to the ringdown of BHs with $M_z \sim 10^2 M_\odot$, while space-based detectors are most sensitive to the ringdown of BHs with $M_z \sim 10^6 M_\odot$. The crucial point is that, according to Eq. (1), $\rho \sim M^{3/2}$ at fixed redshift and noise PSD. As shown in Fig. 1, the “bucket” of the N2A5 eLISA detector is at $S_{\rm N2A5}^{1/2} \sim 10^{-21}$ Hz$^{-1/2}$. This noise level is $\sim 10^2$ (10^3, 10^4) times larger than the best sensitivity of AdLIGO (Voyager, Einstein Telescope), respectively. However, eLISA BHs are $\sim 10^4$ times more massive, yielding signal amplitudes that are larger by a factor $\sim 10^6$. Astrophysical rate calculations are very different in the two frequency regimes, but these qualitative arguments explain why only Einstein Telescope-class detectors will achieve SNRs nearly comparable to eLISA.

Astrophysical models.—We estimate *ringdown* detection rates for Earth-based interferometers (detection rates for the full inspiral-merger-ringdown signal are higher) using three population synthesis models computed with the `Startrack` code: models M1, M3, and M10. Models M1 and M3 are the “standard” and “pessimistic” models described in Ref. [9]. The “standard model” M1 and model M10 predict very similar rates for AdLIGO at design sensitivity. In both of these models, compact objects receive natal kicks that decrease with the compact object mass,

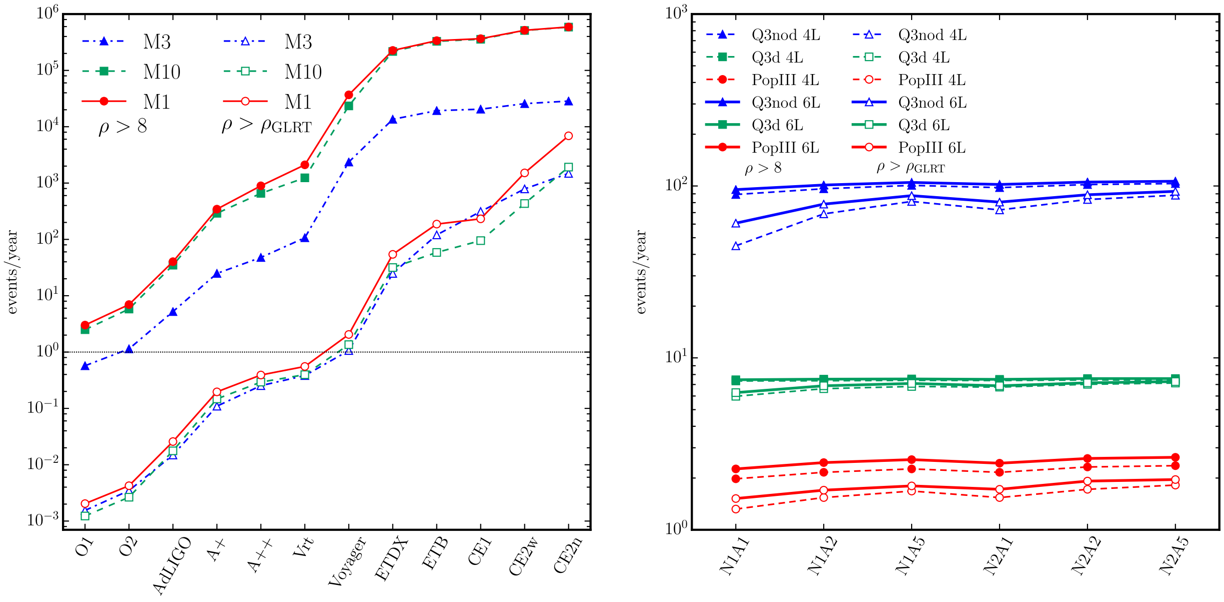

FIG. 2. Rates of binary BH mergers that yield detectable ringdown signals (filled symbols) and allow for spectroscopical tests (hollow symbols). Left panel: Rates per year for Earth-based detectors of increasing sensitivity. Right panel: Rates per year for six-link (solid) and four-link (dashed) eLISA configurations with varying armlength and acceleration noise.

with the most massive BHs receiving no natal kicks. This decreases the probability of massive BHs being ejected from the binary, increasing merger rates. Model M1 allows for BH masses as high as $\sim 100 M_\odot$. On the contrary, model M10 includes the effect of pair-instability mass loss, which sets an upper limit of $\sim 50 M_\odot$ on the mass of stellar origin BHs [37]. In model M3, all compact objects (including BHs) experience high natal kicks drawn from a Maxwellian with $\sigma = 265\ \mathrm{km\,s^{-1}}$ based on the natal kick distribution measured for single pulsars in our Galaxy [38]. The assumption of large natal kicks leads to a severe reduction of BH-BH merger rates, and therefore model M3 should be regarded as pessimistic [9]. In all of these models we set the BH spins to zero, an assumption consistent with estimates from GW150914 [4]. Even in the unrealistic scenario where all BHs in the Universe were maximally spinning, rates would increase by a factor $\lesssim 3$ (see Table 2 of Ref. [6]). Massive binaries with ringdowns detectable by Earth-based interferometers could also be produced by other mechanisms (see, e.g., Refs. [39–42]), and therefore our rates should be seen as lower bounds.

To estimate ringdown rates from massive BH mergers detectable by eLISA we consider the same three models (Pop III, Q3nod, and Q3d) used in Ref. [20] and produced with the semianalytical approach of Ref. [43] (with incremental improvements described in Refs. [44–46]). These models were chosen to span the major sources of uncertainty affecting eLISA rates, namely, (i) the nature of primordial BH seeds (light seeds coming from the collapse of Pop III stars in model Pop III; heavy seeds originating from protogalactic disks in models Q3d and Q3nod), and (ii) the delay between galaxy mergers and the merger of the BHs at galactic centers (model Q3d includes this delay; model Q3nod does not, and therefore yields higher detection rates). In all three models the BH spin evolution is followed self-consistently [43,44]. For each event in the catalog we compute ρ from Eq. (1), where $\epsilon_{\rm rd}$ is rescaled by a spin-dependent factor as necessary.

Detection rates.—The ringdown detection rates (events per year with $\rho > 8$ in a single detector) predicted by models M1, M3, M10 (for stellar-mass BH binaries) and Pop III, Q3d, Q3nod (for supermassive BH binaries) are shown in Fig. 2 with filled symbols. For example, models M1 (M10, M3) predict 3.0 (2.5, 0.57) events per year with detectable ringdown in O1; 7.0 (5.8, 1.1) in O2; and 40 (35, 5.2) in AdLIGO. Model Q3d (Q3nod, Pop III) predicts 38 (533, 13) events for a six-link N2A5 eLISA mission lasting five years, but in the plot we divided these numbers by five to facilitate a more fair comparison in terms of events *per year*.

BH spectroscopy.—Suppose that we know that a signal contains two (or possibly more) ringdown modes. We expect the weaker mode to be hard to resolve if its amplitude is low and/or if the detector's noise is large. The critical SNR for the second mode to be resolvable can be computed using the generalized likelihood ratio test (GLRT) [47] under the following assumptions: (i) using other criteria, we have already decided in favor of the presence of one ringdown signal; (ii) the ringdown frequencies and damping times, as well as the amplitude of the dominant mode, are known. Then the critical SNR $\rho_{\rm GLRT}$ to resolve a mode with either $\ell = m = 3$ or $\ell = m = 4$ from the dominant mode with $\ell = m = 2$ is well fitted, for nonspinning binary BH mergers, by

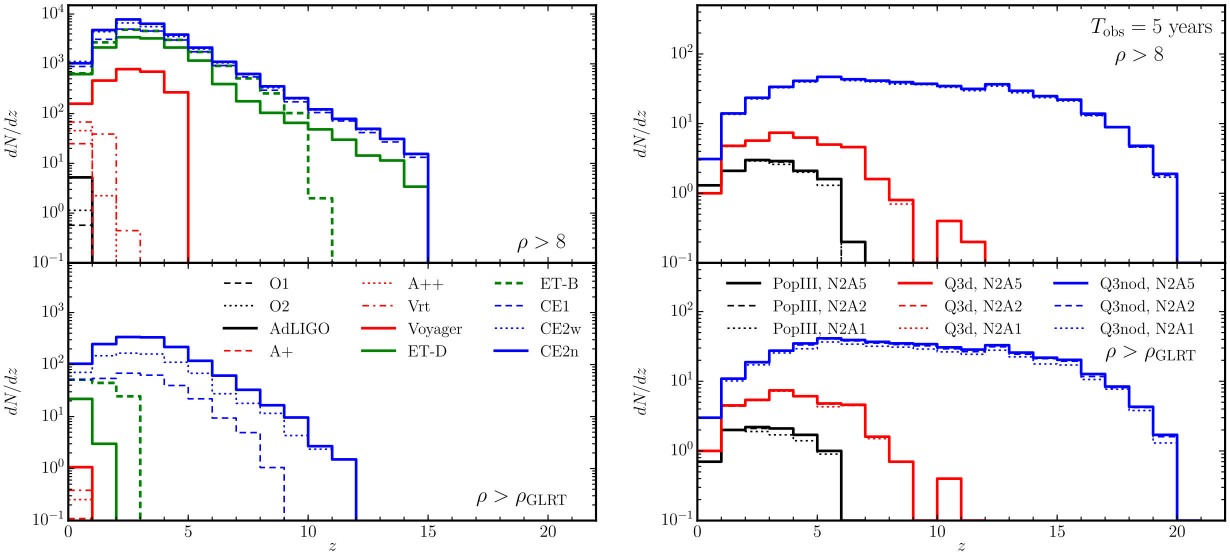

FIG. 3. Left: Redshift distribution of events with $\rho > 8$ (top) and $\rho > \rho_{\rm GLRT}$ (bottom) for model M1 and Earth-based detectors. In the bottom-left panel, the estimated AdLIGO rate ($\approx 2.6 \times 10^{-2}$ events/year) is too low to display. Right: Same for models Q3nod, Q3d, and Pop III. Different eLISA design choices have an almost irrelevant impact on the distributions.

$$\rho_{\rm GLRT}^{2,3} = 17.687 + \frac{15.4597}{q-1} - \frac{1.65242}{q}, \tag{2}$$

$$\rho_{\rm GLRT}^{2,4} = 37.9181 + \frac{83.5778}{q} + \frac{44.1125}{q^2} + \frac{50.1316}{q^3}. \tag{3}$$

These fits reproduce the numerical results in Fig. 9 of Ref. [47] within 0.3% when $q \in [1.01 - 100]$. Spectroscopical tests of the Kerr metric can be performed whenever either mode is resolvable, i.e., $\rho > \rho_{\rm GLRT} \equiv \min(\rho_{\rm GLRT}^{2,3}, \rho_{\rm GLRT}^{2,4})$. The $\ell = m = 3$ mode is usually easier to resolve than the $\ell = m = 4$ mode, but the situation is reversed in the comparable-mass limit $q \to 1$, where the amplitude of odd-m modes is suppressed [13,48]. Extreme mass-ratio calculations [49] and a preliminary analysis of numerical waveforms show that the ratio of mode amplitudes is, to a good accuracy, spin-independent, therefore this SNR threshold is adequate for our present purpose.

The rates of events with $\rho > \rho_{\rm GLRT}$ are shown in Fig. 2 by curves with hollow symbols. The key observation here is that, although ringdown *detections* should be routine already in AdLIGO, high-SNR events are exceedingly rare: reaching the threshold of ~1 event/year requires Voyager-class detectors, while sensitivities comparable to the Einstein Telescope are needed to carry out such tests routinely. This is not the case for space-based interferometers: typical ringdown detections have such high SNR that ≈50% or more of them can be used to do BH spectroscopy. The total number of eLISA detections and spectroscopic tests depends on the underlying BH formation model, but it is remarkably independent of detector design (although the N1A1 design would sensibly reduce rates in the most optimistic models).

Perhaps the most striking difference between Earth- and space-based detectors is that a very large fraction of the "spectroscopically significant" events will occur at cosmological redshift in eLISA, but not in the Einstein telescope. This is shown very clearly in Fig. 3, where we plot redshift histograms of detected events (top panel) and of events that allow for spectroscopy (bottom panel). eLISA can do spectroscopy out to $z \approx 5$ (10, or even 20) for Pop III (Q3d, Q3nod) models, while even the Einstein Telescope is limited to $z \lesssim 3$. Only 40-km detectors with cosmological reach, such as Cosmic Explorer [25,26], would be able to do spectroscopy at $z \approx 10$.

Conclusions.—Using our best understanding of the formation of field binaries, we predict that AdLIGO at design sensitivity should observe several ringdown events per year. However, routine spectroscopical tests of the dynamics of Kerr BHs will require the construction and operation of detectors such as the Einstein Telescope [50–52], and 40-km detectors [25,26] will be necessary to reach cosmological distances. Many of the mergers for which eLISA can do BH spectroscopy will be located at $z \gg 1$. These systems will test GR in qualitatively different regimes than any low-z observation by AdLIGO: BH spectroscopy with eLISA will test whether gravity behaves *locally* like GR even at the very early epochs of our Universe, possibly placing constraints on proposed extensions of Einstein's theory [53–56].

Given the time lines for the construction and operation of these detectors, it is likely that the first instances of BH spectroscopy will come from a space-based detector. This conclusion is based on the simple GLRT criterion introduced in Ref. [47], and it is possible that better data analysis techniques (such as the Bayesian methods advocated in

Refs. [51,52]) could improve our prospects for gravitational spectroscopy with Earth-based interferometers. We hope that our work will stimulate the development of these techniques and their use on actual data.

As shown in Fig. 2, differences in rates between models M1 and M10 become large enough to be detectable in A+. We estimate 34 (29) ringdown events per year for M1 (M10) in A+, and 89 (66) events per year in A++. Rate differences are even larger when we consider the complete signal. Therefore, while the implementation of squeezing in AdLIGO may not allow for routine BH spectroscopy, it could reveal the nature of the BH mass spectrum in the range $\sim[50\text{–}100]\ M_\odot$.

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