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Detection of gravitational waves from black holes: Is there a window for alternative theories?

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ABSTRACT

Recently the LIGO and VIRGO Collaborations reported the observation of gravitational-wave signal corresponding to the inspiral and merger of two black holes, resulting into formation of the final black hole. It was shown that the observations are consistent with the Einstein theory of gravity with high accuracy, limited mainly by the statistical error. Angular momentum and mass of the final black hole were determined with rather large allowance of tens of percents. Here we shall show that this indeterminacy in the range of the black-hole parameters allows for some non-negligible deformations of the Kerr spacetime leading to the same frequencies of the black-hole ringing. This means that at the current precision of the experiment there remains some possibility for alternative theories of gravity.

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1. Introduction

A century after the formulation of General Relativity the LIGO and VIRGO Collaborations [1,2] detected gravitational waves from a pair of merging black holes and answer thereby a number of appealing questions related to our understanding of astrophysics, black holes, and gravitation. Interaction of two black holes can be conditionally divided into the four stages:

1. Newtonian stage, when the distance between two black holes is much larger than their sizes; it includes rotation of the black holes around each other in close orbit, *inspiral* [3,4];
2. the merger of two black holes into a single one which ends up with;
3. the ringdown phase characterized by the *quasinormal modes* [5] of the resultant black hole.

The last stages of formation of a single black hole and the consequent quasinormal ringing, corresponding to the regime of a strong gravitational field, cannot be described in terms of the post-Newtonian approximation. These last stages represent essential intrinsic characteristics of a theory of gravity.

Indeed, there is a number of alternative theories of gravity which produce the same black-hole behavior at a far distance from its surface, i.e. in the asymptotic region, but lead to qualitatively different features near the event horizon. One of the aims of detection of gravitational waves from black holes is testing the black-hole near-horizon geometry and distinguishing Kerr spacetime [6] from, possibly, another black-hole geometry corresponding to some alternative theory of gravity.[1]

Comparison of numerical simulations of the gravitational-wave signal, made within the Einstein gravity, with the observations (fig. 1 in [1]) shows very good agreement up to a few percents. However, there is a rather large range of possible values of mass and angular momentum of the black hole (see fig. 3 in [2]) leading to the same gravitational-wave signal within the achieved accuracy. *This range of allowed values of the black-hole parameters could naturally be imagined as opportunity for deviation from the Kerr spacetime instead of deviation from given values of black-hole parameters within the same Kerr geometry.* This intuitive thought is supported by understanding that the quasinormal frequencies strongly depend on mass and angular momentum of a black hole, so that two black holes with different masses and momenta in two different theories of gravity may produce very close dominant quasinormal frequencies. If it is so, agreement of the observed gravitational wave signal with the one predicted by General Relativity (GR) for the Kerr spacetime would rule out all alternatives only if parameters of the final black hole were determined with high accuracy

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[1] In some cases the Kerr metric can also be a solution of non-Einsteinian theories of gravity, for example, of some $f(R)$ theories, though the perturbations equations and, thereby, the ringdown profile will be different from the Einsteinian one [7,8].

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(and, preferably, independently on the supposition of the validity of GR) and shown to be equal to the Kerr's ones. At the moment this is not the case, though the precision of the experiment will be increasing in the near future, what should, one way or the other, give us more constrained range of the black-hole parameters.

Here we shall show that the current indeterminacy in the values of the black-hole parameters allows for non-negligible deviations from the Kerr spacetime which leads to essentially the same quasinormal ringing. This may mean that not only the Einsteinian theory of gravity is consistent with the latest observations of gravitational waves, but also some deviations from it do not contradict the ringdown picture.

For this purpose in Sec. 2 we shall "prepare" a rather arbitrary deformation of the Kerr spacetime, which preserves asymptotic properties of the Kerr metric, such as its post-Newtonian expansion coefficients, relation between quadrupole momentum and mass, but drastically changes its near-horizon behavior. For simplicity, the deformation is described by only one parameter, which is also fully justified by purely illustrative aim of our note. Then, we shall show that the large indeterminacy in a and M of such a deformed black hole allows for a wide range of values of the deformation parameter. In Sec. 3 we shall give another example: the Kerr black hole with a fixed angular momentum will be shown to produce quasinormal modes which are close to those of the Sen black hole with different value of the angular momentum and a nonzero dilaton.

2. Kerr vs deformed Kerr space-time

For convenience, we shall consider the line element of an arbitrary axially symmetric black hole in the following form [9]

$$\begin{aligned} ds^2 = &-\frac{N^2(r,\theta)-W^2(r,\theta)\sin^2\theta}{K^2(r,\theta)}dt^2 \\ &-2W(r,\theta)r\sin^2\theta dt d\phi + K^2(r,\theta)r^2\sin^2\theta d\phi^2 \\ &+\Sigma(r,\theta)\left(\frac{B^2(r,\theta)}{N^2(r,\theta)}dr^2 + r^2 d\theta^2\right), \end{aligned} \tag{1}$$

where the Kerr metric is given as

$$\begin{aligned} N^2(r,\theta) &= \frac{r^2-2Mr+a^2}{r^2}, \\ B(r,\theta) &= 1, \\ \Sigma(r,\theta) &= \frac{r^2+a^2\cos^2\theta}{r^2}, \\ K^2(r,\theta) &= \frac{(r^2+a^2)^2-a^2\sin^2\theta(r^2-2Mr+a^2)}{r^2(r^2+a^2\cos^2\theta)}, \\ W(r,\theta) &= \frac{2Ma}{r^2+a^2\cos^2\theta}, \end{aligned} \tag{2}$$

where M is the mass and a is the rotation parameter.

Now, we shall deform the above Kerr spacetime by adding a static deformation which changes the relation between the black-hole mass and position of the event horizon, but preserves asymptotic properties of the Kerr spacetime. Namely, the substitution

$$M \to M + \frac{\eta}{2r^2}, \tag{3}$$

once it is used in (2), modifies the Kerr metric as follows

$$\begin{aligned} N^2(r,\theta) &= \frac{r^2-2Mr+a^2}{r^2} - \frac{\eta}{r^3}, \\ B(r,\theta) &= 1, \\ \Sigma(r,\theta) &= \frac{r^2+a^2\cos^2\theta}{r^2}, \\ K^2(r,\theta) &= \frac{(r^2+a^2)^2-a^2\sin^2\theta(r^2-2Mr+a^2)}{r^2(r^2+a^2\cos^2\theta)} \\ &\quad + \frac{a^2\eta\sin^2\theta}{r^3(r^2+a^2\cos^2\theta)} \\ W(r,\theta) &= \frac{2Ma}{r^2+a^2\cos^2\theta} + \frac{\eta a}{r^2(r^2+a^2\cos^2\theta)}, \end{aligned} \tag{4}$$

where M is the ADM mass and $a = J/M$ is the rotation parameter.

The above constructed spacetime of the deformed black hole possesses the following important for us properties:

1. it allows for the separation of radial and angular variables in the field equation, what allows us to reduce the perturbation problem to a radial, master wave-like equation,
2. it has the same post-Newtonian asymptotic ($\beta = \gamma = 1$) as the Kerr metric,
3. the quadrupole momentum of such a deformed spacetime obeys the same relation $Q = -Ma^2$ as the Kerr black hole,
4. the deformed metric has quite different (from Kerr) near-horizon geometry, expressed, in particular, in a different position of the spherical event horizon.

Similarly to the Kerr black hole, the Killing horizon obeys the following relation,

$$g^{rr} \equiv \frac{N^2(r,\theta)}{B^2(r,\theta)} = \frac{r^2-2Mr+a^2}{r^2} - \frac{\eta}{r^3} = 0, \tag{5}$$

and coincides with the event horizon.

It is convenient to parametrize the considered family of metrics with an additional parameter r_0, so that

$$\eta = r_0(r_0^2 - 2Mr_0 + a^2).$$

We shall use the parameter δr measuring deviation of the position of the event horizon from the Kerr one r_{Kerr},

$$r_0 = r_{\text{Kerr}} + \delta r = M + \sqrt{M^2 - a^2} + \delta r,$$

so that $\delta r = 0$ implies $\eta = 0$ and corresponds to the Kerr metric. Although δr is a coordinate dependent measure of deviation from the Kerr geometry, the coordinates (4) are indistinguishable from the Boyer–Lindquist coordinates at infinity, so that different distant stationary observers should in principle agree on what is accepted as "large deviation from Kerr".

As our aim is only to *evaluate the order of an allowed range of the deformation parameter* δr at a given relatively small allowance for the quasinormal frequency (a few percents), we do not need to be tied to a particular theory, type of perturbation or even fixed value of the quasinormal frequency. Therefore, we shall consider a test scalar field in the deformed background (2) and use simple semi-classical WKB estimates. Such a test-field approach will not distinguish the Kerr space-time as a solution of the Einstein field equations from the same Kerr space-time as solution of some non-Einsteinian gravity mentioned above [7,8]. However, our aim here is not to include all the possible alternative theories into consideration, but to show that at least *some deviations* from the Einstein gravity are still allowed by the observations. Analysis of gravitational perturbations would obviously constrain the possible alternatives better.

A massless minimally-coupled scalar field obeys the equation

$$\Phi^{;\mu}_{;\mu} = \frac{1}{\sqrt{-g}}\partial_\mu\left(\sqrt{-g}g^{\mu\nu}\partial_\nu\Phi\right) = 0. \tag{6}$$

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