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Letter

Dynamical descalarization with a jump during a black hole merger

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Black holes in scalar-Gauss-Bonnet gravity are prone to scalarization, that is a spontaneous development of scalar hair for strong enough spacetime curvature. Since large spacetime curvature is associated with smaller black hole masses, the merging of black holes can lead to dynamical descalarization. This is a spontaneous release of the scalar hair of the newly formed black hole in case its mass is above the scalarization threshold. Depending on the exact form of the Gauss-Bonnet coupling function, the stable scalarized solutions can be either continuously connected to the Schwarzschild black hole, or the transitions between the two can happen with a jump. By performing simulations of black hole head-on collisions in scalar-Gauss-Bonnet gravity prone to dynamical descalization we have demonstrated that such a jump can be clearly observed in the accumulated gravitational wave data of multiple merger events with different masses. The simulations were performed in the decoupling limit approximation, where the backreaction of the scalar field on the metric is neglected. This is a reasonable assumption for weak enough scalar fields. The distinct signature in the gravitational wave signal will share similarities with the effects expected from first order matter phase transitions happening during neutron star binary mergers.

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I. INTRODUCTION

The rapid advance of the gravitational wave detectors gives us hope that soon gravity will be better understood in the realm of large spacetime curvature. Among the best candidates in this respect are binary black hole mergers [1]. Due to their complexity, the numerical merger simulations in modified gravity were performed only in a handful of cases [2–7]. They demonstrated, though, the big potential in using merger events for constraining alternative theories of gravity.

A class of theories, offering a natural built-in screening mechanism [8,9] are the theories of gravity allowing for the so-called spontaneous scalarization [10]. It was recently shown that black holes can also scalarize in scalar-Gauss-Bonnet (sGB) gravity [11–13] that made them an interesting candidate for exploring astrophysical implications. Subsequently, the topic was largely developed to include different types of coupling [14–16], scalar field potential [17,18], rapid rotation [19,20]. The strongest constraints on these theories come from the binary pulsar observations [21] as well as the binary mergers [22]. It was also demonstrated that black holes can scalarize in a wider variety of extended scalar-tensor theories [23–29].

The dynamics of the scalar field within sGB gravity around isolated black holes was considered in [30–37]. Binary black hole merger in GB gravity was studied in the decoupling limit [7], i.e., when the scalar field backreaction on the metric is neglected. This is also the approach we adopt in the present paper. Dynamical descalarization, which is the spontaneous "release" of the scalar field, was observed after the merger when the mass of the newly formed black hole was beyond the scalarization window. The full problem without approximation was simulated in [6] where more light was shed on the loss of hyperbolicity for such systems.

All studies of black hole scalarization dynamics in sGB gravity until now considered the standard case when the stable scalarized black hole branch is continuously connected to the GR one. Allowing for a more general form of the coupling we can even have a region in the parameter space where both the Schwarzschild solution and the scalarized ones are linearly stable. The properties of such static black holes were considered in [36] and their stability was examined later in [38]. Similar behavior is observed also in other modified theories of gravity for charged black holes [39,40]. In the present paper we study their astrophysical implications by simulating the merger of two black holes in sGB gravity for a coupling function allowing for such a jump. Interestingly, the presence of a gap between two stable branches of solutions is also observed for neutron stars possessing first-order matter phase transition from confined hadronic to deconfined quark matter [41–44]. Even though we consider here quite distinct compact objects, the merger will possess certain clear similarities with [45–47].

II. SCALARIZED BLACK HOLES IN GAUSS-BONNET GRAVITY

The action in sGB gravity has the following form:

$$S = \frac{1}{16\pi}\int d^4x\sqrt{-g}[R - 2\nabla_\mu\varphi\nabla^\mu\varphi + \lambda^2 f(\varphi)\mathcal{R}^2_{GB}], \qquad (1)$$

where R is the Ricci scalar with respect to the spacetime metric $g_{\mu\nu}$, φ denotes the scalar field, $f(\varphi)$ is the coupling between the scalar field and the Gauss-Bonnet invariant, λ is the so-called Gauss-Bonnet coupling constant having dimension of *length* and $\mathcal{R}^2_{GB} = R^2 - 4R_{\mu\nu}R^{\mu\nu} + R_{\mu\nu\alpha\beta}R^{\mu\nu\alpha\beta}$.

In order to have spontaneous (de)scalarization we must require that $(df/d\varphi)(\varphi=0)=0$ and $(df^2/d\varphi^2)(\varphi=0)\neq 0$. The simplest function satisfying these conditions is $f(\varphi)=\varphi^2$. It leads, though, to unstable scalarized black hole solutions [48]. One can go one step further and add a quartic scalar field term to the coupling that can potentially stabilize the solutions [15,16]. From a numerical perspective, it has proven much more convenient to work with a coupling being an exponential function of the scalar field. A common choice is $f(\varphi)=\frac{1}{2\beta}(1-\exp(-\beta\varphi^2))$ [11] that leads to stable and well behaved solutions from a numerical point of view (see e.g., Refs. [14,19,38,49]).

Allowing for a bit more complex form of the coupling leads to the existence of a qualitatively different strong field effect: nonlinear scalarization. In this case, the GR black hole is linearly stable and for a certain range of parameters scalarized black holes exist as well. The latter can be formed by imposing a strong enough nonlinear perturbation onto the GR black hole. One of the simplest ways to achieve this is to introduce a quartic scalar field term in the exponent, namely

$$f(\varphi) = \frac{1}{2\beta}(1-\exp(-\beta(\varphi^2+\kappa\varphi^4))), \qquad (2)$$

with two independent parameters β and κ. For a small scalar field this coupling resembles the form $f(\varphi)=\beta\varphi^2+\eta\varphi^4$ considered in [15,16]. We find, though, the exponential function more convenient numerically and that is why we employ it. Our tests suggest, though, that the effects reported here are generic, qualitatively very similar for a much larger class of couplings, as long as a jump between the GR and sGB black hole branches is present.

The scalar charge as a function of the normalized parameter λ/M is shown in Fig. 1 for branches of scalarized static black holes with coupling (2), $\beta=6$ and two values

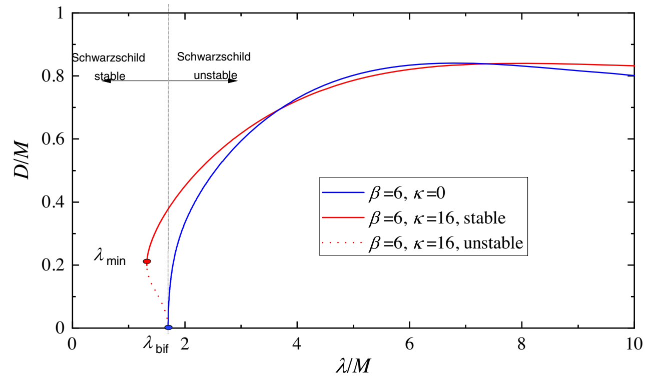

FIG. 1. The normalized scalar charge D/M as a function of the normalized GB coupling parameter λ/M for sequences of scalarized black holes with $\beta=6$ and two values of κ. The unstable part of the $\kappa=16$ branch is marked with a dotted line.

of κ. Here the scalar charge D is defined through the asymptotic $\varphi(r\to\infty)\sim D/r$. The Schwarzschild black hole in our case is always a solution of the field equations corresponding to the x axis with $D=0$. It destabilizes for λ/M larger than the point of bifurcation $\lambda_{\rm bif}$. The first choice $\kappa=0$ in the figure is the standard scalarization considered for the first time in [11] where we have the scalarized black holes branching out at a certain $\lambda_{\rm bif}$ with the scalar charge increasing as λ/M increases. If κ is sufficiently large, e.g., the case of $\kappa=16$ in Fig. 1, after the bifurcation point the branch first moves to the left and, after reaching a minimum $\lambda_{\rm min}$, it turns right. This small portion of the branch after the bifurcation is unstable [38] and thus the last stable scalarized solution is not continuously connected to Schwarzschild. Even more, there is a range of λ/M, namely $(\lambda_{\rm min},\lambda_{\rm bif})$, where both the scalarized solutions and the Schwarzschild black hole are linearly stable resembling closely the nonlinear black hole scalarization [36]. Thus the transition between the two classes of solutions will happen with a jump that will have a very interesting effect on the binary black hole mergers discussed below.

In Fig. 1, $\lambda_{\rm bif}=1.70\,M$ and $\lambda_{\rm min}=1.32\,M$. Note that if we vary β and κ, only $\lambda_{\rm min}$ changes while $\lambda_{\rm bif}$ remains the same. The quantities presented here are expressed in units of M. One can normalize to λ instead and then the point of bifurcation will be located at $M_{\rm bif}/\lambda=0.587$ and $\lambda_{\rm min}$ will correspond to a maximum mass for which $\kappa=16$ solutions exist, that is $M_{\rm max}/\lambda=0.756$.

III. 3 + 1 DECOMPOSITION AND NUMERICAL APPROACH

We will work with the $3+1$ decomposition of the field equations adopting Brown's covariant form [50] of the BSSN formalism [51–53] in curvilinear coordinates [54–57]. The general form of the spacetime metric in the $3+1$ formalism is

$$ds^2 = g_{\mu\nu}dx^\mu dx^\nu = -\alpha^2 dt^2 + \gamma_{ij}(dx^i + \beta^i dt)(dx^j + \beta^j dt), \tag{3}$$

where α is the lapse function, β^i is the shift vector, and γ_{ij} is the three-dimensional spacial metric. We introduce a conformally related spatial metric $\bar{\gamma}_{ij}$ via the relation $\bar{\gamma}_{ij} = e^{-4\phi}\gamma_{ij}$, where the conformal factor is $e^{-4\phi}$. In contrast to the original BSSN formulation, the determinant $\bar{\gamma}$ is not required to be unity, but instead, its time derivative vanishes.

In our simulations, we will adopt the decoupling limit approximation similar to [7]. It captures very well the scalar field dynamics and can be quantitatively quite accurate for relatively weak scalar fields [34]. Thus it can perfectly serve our purpose to study the qualitative effect of the presence of a jump in the solution space visible in Fig. 1. The pure GR BSSN formalism in spherical coordinates has been developed in a series of papers [50,54–57]. Since we neglect the scalar field contribution to metric field equations they remain unchanged and we will not comment on them in detail but instead refer the reader to [57,58]. Below we will discuss only the scalar field equation written within the considered formalism.

The $3+1$ decomposition of the scalar field equation, written with respect to the barred conformal metric is given by

$$(\partial_t - \beta^i\partial_i)\varphi = -\alpha K_\varphi, \tag{4}$$

$$(\partial_t - \beta^i\partial_i)K_\varphi = -e^{-4\phi}\bar{D}_i\alpha\bar{D}^i\alpha - \alpha\left[e^{-6\phi}\bar{D}_i(e^{2\phi}\bar{D}^i) - KK_\varphi + \frac{1}{4}\lambda^2\frac{df}{d\varphi}\mathcal{R}^2_{GB}\right], \tag{5}$$

where the covariant derivatives $\bar{D}$ are taken with respect of the conformal metric $\bar{\gamma}_{ij}$ and K is the trace of the extrinsic curvature. For the solution of the above equations on top of the GR evolution we have developed an extension of the NRPy + code [58].

In our calculations we have adopted a grid with resolution $400 \times 96 \times 2$ in the radial and the two angular directions. Taking only 2 points in the φ direction reduces the evolution to axial symmetry, suited to our simulations. The two black holes collide starting at rest from a separation of 5 M. Due to limitations of the grid construction in NRPy+, that was the maximum we could achieve assuming a reasonable computation time while being able to observe the physically interesting phenomena. In the Supplemental Material [59] we show that the dynamics after the merger is weakly affected and the qualitative conclusions remain unchanged for larger initial separation. We have used Kreiss-Oliger numerical dissipation [60] for the scalar field equations similar to [61], with a dissipation strength of 0.01.

The extension of the NRPy + code developed for the purpose of the present study was verified in the following way. First, we have confirmed that the scalar field has a 4th order convergence that is the same as for the evolution of the metric quantities. In addition, we have verified that the scalar charge of the newly formed black hole and the transition point from scalarized to GR solutions coincide within a few percent with the results from the scalar field evolution around isolated black holes [34].

IV. BLACK HOLE HEAD-ON COLLISION

We have considered the head-on collision of two equal mass black holes with mass $0.5M$ located at a distance of $5M$, adopting the decoupling limit approximation. As for the sGB theory, we have fixed $\beta = 6$ in the coupling (2). The time evolution of the scalar charge for $\kappa = 0$ (that is similar to [7]) is presented in Fig. 2 while the $\kappa = 16$ case is plotted in Fig. 3. In the lower panels of both figures the dominant $l = 2$, $m = 0$ mode of ψ_4 multiplied by the extraction radius is shown for comparison. The extraction radius is at $r_{\mathrm{ex}} = 12.5\ M$ and we have verified that at this distance the scalar charge is already saturated to a constant with a relatively good accuracy. All values of λ/M are chosen around λ_{min} and λ_{bif} (see Fig. 1) so that the two individual black holes with mass 0.5 M are well within the

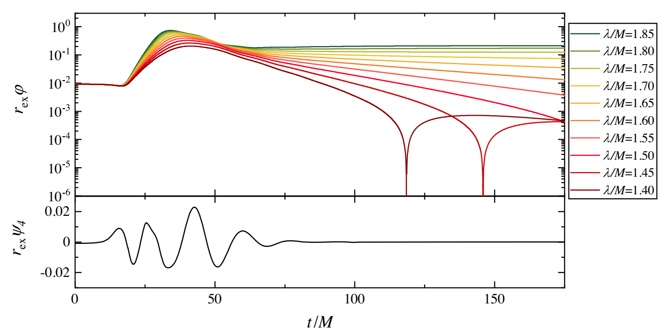

FIG. 2. (Top) The evolution of the scalar charge $r_{\mathrm{ex}}\varphi$ as the head-on collision proceeds for $\beta = 6$, $\kappa = 0$ and several λ/M close to the bifurcation point, where $r_{\mathrm{ex}} = 12.5\ M$. (Botton) Dominant ($l = 2$, $m = 0$) mode of ψ_4 times r_{ex} for a comparison, extracted at the same r_{ex}.

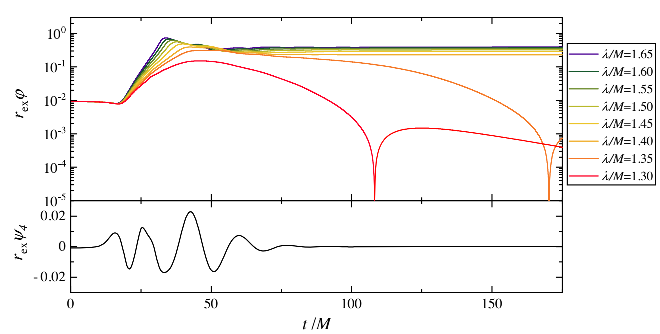

FIG. 3. Same as Fig. 2 but for $\kappa = 16$.

scalarization window, while the newly formed black hole after the merger is on the border of scalarization.

In our simulations we used Brill-Lindquist initial data for the metric quantities. The initial black hole momentum is zero, thus the black holes are initially at rest. The scalar field evolution starts from a small perturbation and as time proceeds, the two individual black holes quickly develop scalar hair. In both Figs. 2 and 3 one can observe the exponential growth of the scalar field at early times. After a certain point, this exponential growth starts saturating. However, it cannot reach proper equilibrium due to the short time until the merger that is a consequence of the limited initial separation between the black holes. The evolution after the merger differs qualitatively for $\kappa = 0$ and $\kappa = 16$.

Let us first focus on the $\kappa = 0$ case depicted in Fig. 2. As the black holes merge, the scalar field starts to decrease until it either reaches a new equilibrium for larger λ/M or it starts decreasing exponentially for smaller λ/M lower than $\lambda_{\rm bif}$. Close enough to the bifurcation point both the real and the imaginary parts of the scalar quasi-normal mode (QNM) frequency tend to zero and practically no oscillations can be observed in the case of descalarization and scalar field emission. Instead, one can see only a slow exponential decay for λ/M smaller but close to $\lambda_{\rm bif}$. The well-known form of the QNMs with oscillations and a subsequent tail is recovered only for λ/M sufficiently smaller than $\lambda_{\rm bif}$ (e.g., $\lambda/M < 1.5$ in Fig. 2).

It is clear that for $\kappa = 0$ the transition between the two regimes of scalarized and nonscalarized black hole remnant is continuous with the scalar field being decreasingly small as the bifurcation point is approached. In addition, the small damping/growth time of the scalar field close to that point will lead to a continuous and gradient effect on the overall evolution of the system in case the full coupled system of the metric and scalar field evolution is considered. Thus, it might be difficult to discriminate between these two regimes in the gravitational wave data.

The picture changes qualitatively for large enough κ. From the results resented in Fig. 3 one can easily see that there is an abrupt change of the scalar field evolution/emission as λ/M passes below the minimum one $\lambda_{\rm min}$ for which scalarized solutions exist. Note that this point is different from the point of bifurcation $\lambda_{\rm min} < \lambda_{\rm bif}$. The main differences with the $\kappa = 0$ case are the following. First, as λ/M decreases and passes through $\lambda_{\rm min}$, the scalar charge changes with a jump that can have a clear signature in the GW observations of the merger itself and the subsequent QNM ringing. Even more importantly, for any value of λ/M lower than $\lambda_{\rm min}$, the real and imaginary parts of the Schwarzschild scalar field QNM frequency are already substantially different from zero that results in a rapid descalarization of the new BH. If one considers the coupled evolution of the scalar field and the metric, then the rapid scalar field decrease that carries energy away to infinity will certainly have also influence on the emitted gravitational wave signal. Estimating this effect is beyond the scope of the present paper since we are considering the evolution in the decoupling limit approximation. If such information is available from full numerical simulations beyond the decoupling limit, though, and a large enough number of binary merging events are observed, one will be able to tell apart the different behavior of the system observed in Figs. 2 and 3. This will naturally lead to strong constraints on the parameter space of the theory and even more generally—it can potentially even completely discard certain types of couplings in sGB gravity.

Note that we have normalized all quantities with respect to M for convenience. One can normalize with respect to λ instead. Then the different simulations for different λ/M we have performed will be equivalent to simulations with a fixed λ but different initial black hole masses. For example, the range of explored λ/M in Figs. 2 and 3 can be translated to different initial masses of the merging black holes if the quantities are normalized with respect to λ. Taking into account that we have worked with $M_b = 0.5\ M$, the range of explored λ/M in Figs. 2 translates to a mass range from $M_{\rm b\ min}/\lambda = 0.270$ to $M_{\rm b\ max}/\lambda = 0.357$, while in Fig. 3: from $M_{\rm b\ min}/\lambda = 0.303$ to $M_{\rm b\ max}/\lambda = 0.385$. A fixed sGB theory means fixing the parameter λ and multiple gravitational wave observations will provide us with the opportunity to observe mergers with different black hole masses. In the discussion below we will consider exactly this scenario.

V. DISCUSSION AND OBSERVATIONAL PROSPECTS

We have performed simulations of black hole head-on collision of equal mass black holes in the decoupling limit approximation in sGB gravity observing the process of descalarization. This allows us to capture qualitatively the main features of descalarization and make predictions for the possible observational manifestations. In contrast to previous works, we have focused on the case when the coupling function has both quadratic and quartic terms in the scalar field. This changes the picture of scalarization not only quantitatively but also qualitatively. Namely, the branch of stable scalarized solutions is not continuously connected to Schwarzschild and there is a jump between both. In addition, there is a region of the parameter space where both the GR and the scalarized branches are linearly stable.

This property of the solutions leads to a very interesting phenomenology of the black hole mergers. In order to demonstrate it, we have considered a set of parameters for which the individual binary black holes are well within the scalarization window. The newly formed black hole, though, is on the border of scalarization. Namely, for a fixed coupling parameter λ and as the black hole mass is varied, we make a transition between the regimes where the resulting black hole with mass M_f is either scalarized or M_f

is large enough and only the GR solution exists. The limiting value of the mass dividing the two regimes is different for the case of standard scalarization with zero quartic term and $\kappa = 0$ (denoted by $M_{\rm bif}$ that coincides with the point of bifurcation of the scalarized branch from Schwarzschild) and the case when the quartic term is strong enough with $\kappa > 0$ (denoted by $M_{\rm max} > M_{\rm bif}$).

We clearly observed that for $\kappa = 0$ the scalar charge of the resulting black hole after the merger goes to zero continuously as M_f approaches $M_{\rm bif}$. If we thus observe a number of merger events with a dense distribution of their total mass, and take a series of such events with increasing total mass, we will observe the following. The newly formed black hole will slowly decrease its scalar charge as the mass M_f increases. At a certain point the initial binary masses will become such that M_f surpasses $M_{\rm bif}$ that will result in a descalarization after the merger. For M_f close to the bifurcation point $M_{\rm bif}$ the scalar charge is very weak and it will have a small influence on the black hole dynamics after the merger. Moreover, the damping time of the scalar field tends to zero at the bifurcation point leading to a slow emission of the remaining scalar field. Such a slow energy release is unlikely to have a strong influence on the binary dynamics and GW emission. That is why the transition between the two regimes before and after $M_{\rm bif}$ will not be easily seen in the GW signal. Of course, the presence of scalar charge of the individual merging black holes can be detected through other methods, especially in the inspiral phase of an actual merger (see e.g., Ref. [62]).

For a strong enough quartic term in the coupling with $\kappa > 0$ there is a jump between the last stable scalarized solution and Schwarzschild. That is why we observed that the scalar charge of the merger remnant saturates to a fixed value with the increase of the binary mass M_f until the threshold $M_{\rm max}$ is reached and it jumps to zero. More specifically, the observed merger remnants for a series of observations will be divided into two parts—merger remnants with a strong scalar field that clearly has a different ringdown compared to GR, and a GR merger remnant. There will be no continuous transition between both since there are no stable intermediate weak scalar field black holes. In addition, the Schwarzschild black hole with $M_{\rm max}$ is already stable and has a relatively short damping time of the scalar gravitational radiation resulting in a rapid emission of the scalar field that has developed before the merger. Thus, if one observes a large number of binary mergers with a sufficient density in the mass distribution, such a jump can be clearly observed in the GW signal.

The process described above has very interesting similarities with the first-order matter phase transition from confined hadronic to deconfined quark matter. In that case, as well it happens that if the initial mass of the merging neutron stars surpasses a given threshold, a phase transition can happen during the merger resulting in a newborn supramassive neutron star with a quark matter core. This process was first simulated in [45–47] demonstrating the abrupt change in the merger characteristics in the presence of such phase transition. The methodology developed for searching of such matter phase transitions in the GW signal can be readily applied for black hole mergers in sGB gravity since the process shares interesting similarities.

We should keep in mind that in the original sGB theory the scalar gravitational radiation is not directly coupled to the perturbations of the metric and is thus directly not observable with the gravitational wave detectors. The scalar waves carry away energy, though, that will leave clear imprints on the observed gravitational wave signal. For example, there will be a phase difference between a merger of GR black holes and the scalarized ones, with the latter ones merging faster because of the accelerated inspiral. In the case of dynamical descalarization, it might happen that such scalar wave energy loss is present during the inspiral but the newly formed black hole is just Schwarzschild that will clearly lead to specifics in the data analysis of both the inspiral and the ringdown phase. A rapid release of scalar energy during merger in the case of descalarization can also alter the dynamics of the actual merger if the backreaction of the scalar field on the spacetime dynamics is taken into account. Last but not least, the sGB gravity can be slightly modified to include such a direct coupling between the scalar and metric perturbations leading to the presence of potentially observable breathing modes.

Even though we stick to the sGB gravity in the present paper, we have all reason to believe that the conclusions we have made are not very sensitive on the particular coupling and the theory itself, as long as we have a black hole scalarization mechanism and a coupling allowing for a gap between the stable solutions. The observation of an abrupt change in the gravitational wave signature happening at a certain black hole mass will be a hint of the presence of the effect described above. On the other hand, if enough gravitational wave observations are accumulated without clear evidence for the presence of such a jump, a whole class of couplings can be excluded.

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