Echoes of compact objects: new physics near the surface and matter at a distance

R. A. Konoplya, Z. Stuchlík and A. Zhidenko

1 Institute of Physics and Research Centre of Theoretical Physics and Astrophysics, Faculty of Philosophy and Science, Silesian University in Opava, CZ-746 01 Opava, Czech Republic
2 Peoples Friendship University of Russia (RUDN University), 6 Miklukho-Maklaya Street, Moscow 117198, Russian Federation
3 Centro de Matemática, Computação e Cognição (CMCC), Universidade Federal do ABC (UFABC), Rua Abolição, CEP: 09210-180, Santo André, SP, Brazil

It is well known that a hypothetical compact object which looks like the Einsteinian (Schwarzschild or Kerr) black hole everywhere except a small region near its surface should have the ringdown profile predicted by the Einstein theory at early and intermediate times, but modified by the so called echoes at late times. A similar phenomenon appears when one considers the Einsteinian black hole and a shell of matter placed at a distance from it, so that the astrophysical estimates could be done for the allowed mass of the black hole environment. While echoes for both systems have been extensively studied recently, no such analysis was done for a system that has both phenomena simultaneously, that is, echoes due to new physics near the surface event horizon and echoes due to some matter at a distance from the black hole. Here, following [9, 11], we consider a traversable wormhole, obtained by identifying two Schwarzschild metrics with the same mass \( M \) at the throat, which is near the Schwarzschild radius, and add a non-thin shell of matter at a distance. This let us understand how the echoes of surface of the compact object are affected by the astrophysical environment at a distance. The straightforward calculations for the time-domain profiles of such system support expectations that if the echoes are observed, they should most probably be ascribed to some new physics near the event horizon rather than to some “environmental” effect.

PACS numbers: 04.50.Kd, 04.70.Bw, 04.30.-w, 04.80.Cc

I. INTRODUCTION

Recent observations of black holes in the gravitational [1, 2] and electromagnetic [3, 4] spectra give opportunity to test strong gravity regime via black holes. The data of the purely gravitational spectrum at the ring-down phase still allow for large deviations from Kerr geometry due to a huge uncertainty in the determination of the angular momentum and mass of the resultant black hole [1, 5]. Nevertheless, further constraints on the parameters of alternative theories of gravity are expected [6]. While there remains a possibility of significantly non-Kerr black-hole geometry owing to a non-Einsteinian gravitational theory, there may be also a more subtle situation, when the black hole is Einsteinian (given by the Schwarzschild or Kerr geometry) in the whole space except for a tiny region near the event horizon. In this case quasinormal ringing of a black hole (or even of a more exotic compact object, such as gravastar [7, 8] or wormhole [9]), mimics that of the Schwarzschild/Kerr black hole very well [1, 10], possibly except for the very late period, which will be modified by the so-called echoes [11, 12]. The effective potential for the master equation describing perturbations of Schwarzschild spacetime has the form of potential barrier and the quasinormal modes are poles of the reflection coefficient for that barrier. The echoes appear owing to the second scattering from the other peak of the effective potential near the event horizon and have been extensively studied recently for various compact objects and gravitational theories [11–21]. The second peak appears in a number of different circumstances, such as different equation of state and boundary conditions on the surface of the ultra-compact object (see fig. 3 in [11]) or due to a cloud of matter near the surface/horizon. At the same time, the large astrophysical-scale black holes are not believed to be free from the influence of their environment, be it accreting disks, other companion compact objects, active galactic nuclei or clouds of normal and/or phantom matter. This brought into consideration the concept of a “dirty black hole” [22–25]. The effective potential in the above cases can have an additional peak (for phantom matter) or gap (for normal matter) in the far region, farther than the main “Schwarzschild peak”. Therefore, it would be natural to expect echoes from scattering near the far peaks as well [26]. In other words, once the echoes are observed, it will be crucial to understand whether the effect should be ascribed to new physical effects near the surface of a compact object or to some, possibly even unseen, matter at some distance from it.

From theoretical point of view, any particular compact object, gravitational theory and model of the surrounding matter would give us various detailed answers to the above question on how to distinguish the both echoes, but a general qualitative understanding whether the both echoes produce equivalent effects or one of them could suppress the other should come in the first place. By now, two kinds of papers considered echoes. One is devoted to echoes from compact objects due to modi-
fection to Schwarzschild/Kerr geometry near the horizon/surface [15][21] and was initiated in [11], while the other group of works considered echoes from the astrophysical environment by posing a massive shell at some distance from the Schwarzschild black hole [26]. There was considered a shell of matter, which is not infinitely thin and can have either positive or negative energy, representing thereby either normal or phantom matter. It was shown that the thickness of the shell does not change estimates essentially. This generalized the approach of [27] based on the infinitely thin shell. The astrophysical estimations made in [26] showed that the deviation from Schwarzschild ringdown is relatively small, unless the mass of the shell is large enough, so that for most part of astrophysical factors the effect should be relatively small. Nevertheless, possible configuration of dark matter around black holes would leave some parametric freedom for echoes as well [26].

Here we shall consider both factors leading to echoes simultaneously: the modification of the Schwarzschild geometry near the surface and the non-thin shell of matter at a distance from it. This is a straightforward way to realize how the echoes owing to new physics near the surface would be affected by some matter at a distance. We shall consider the traversable wormhole obtained by identifying two Schwarzschild metrics [9, 12] and add a non-thin shell of matter at some distance from its throat. The echoes of the wormhole alone were studied in [12].

The paper is organized as follows. Sec. II gives essential information on construction of our configuration: the traversable wormhole obtained by surgery at the throat and another massive shell built with the help of infinitely thin shell. At a distance representing the astrophysical environment by posing a massive shell at some distance from its throat and another massive shell built with the help of infinitely thin shell.

We also add to the wormhole a shell of the mass $\Delta M$ located between $r_s > r_0$ and $r_s + \Delta r_s$ such that the mass function is defined as

$$m(r) = \begin{cases} 
M, & r < r_s; \\
M + \Delta M \left(3 - 2 \frac{r - r_s}{\Delta r_s} \left(\frac{r - r_s}{\Delta r_s}\right)^2\right), & r_s \leq r \leq r_s + \Delta r_s; \\
\Delta M, & r_s + \Delta r_s < r;
\end{cases}$$

and

$$f(r) = 1 - \frac{2m(r)}{r}.$$ 

This way $m(r)$ and $m'(r)$ are continuous functions (see Fig. 1). Here $\Delta M > 0$ ($\Delta M < 0$) corresponds to positive (negative) energy density of matter.

### III. The Wave Equation and Time-Domain Integration

For our qualitative consideration we need only to estimate the orders of the effects produced by both echoes, so that it is sufficient to be limited by a test field response to the initial perturbation. Even though perturbations of fields of other spin produce different quasinormal spectra, the dominant frequencies are, as a rule, of the same order [28]. We shall consider the Klein-Gordon equation for a massless scalar field, which can be reduced to the wave-like form

$$\left(\frac{\partial^2}{\partial t^2} - \frac{\partial^2}{\partial r_s^2} + V(r)\right)\Psi(t, r_s) = 0,$$
where $r_*$ is the tortoise coordinate in the observer’s universe,
\[
dr_* = \pm \frac{dr}{f(r)}.
\]
Here the signs ± refer to the two different universes connected at the throat $r_0$, and the effective potential is given by
\[
V(r) = f(r) \left( \frac{\ell(\ell+1)}{r^2} + \frac{f'(r)}{r} \right),
\]
where $\ell = 0, 1, 2, \ldots$ are the multipole numbers.

The whole space lays between two “infinities” connecting two distant regions or universes. Quasinormal modes of wormholes are solutions of the wave equation satisfying the following boundary conditions: requiring of purely incoming waves at $-\infty$ and purely outgoing waves at $+\infty$ [29, 30]. This means that no waves coming from either left or right infinity are allowed. This way, the boundary conditions for a wormhole is essentially the same as those for the black hole and our conclusions are expected to be qualitatively the same if, for example, one considers a black hole which is modified near its event horizon, instead of a wormhole.

Positive peak (fig. 2) corresponds to the phantom matter ($\Delta M < 0$). For the shell of positive mass the peak is replaced by a gap.

The ringdown phase for the spherically symmetric perturbations ($\ell = 0$) is relatively short. Although the results in this case are qualitatively similar, we shall represent here higher $\ell$ as better illustrations. Also $\ell = 0$ is not a dynamical degree of freedom for the gauge fields.

In order to produce the time-domain profiles, we integrate the wave-like equation (4) rewritten in terms of the light-cone variables $u = t - r_*$ and $v = t + r_*$. The discretization scheme [31] has the following form:
\[
\Psi(N) = \Psi(W) + \Psi(E) - \Psi(S) + \frac{-\Delta^2 V(W)\Psi(W) + V(E)\Psi(E)}{8} + O(\Delta^4),
\]
where we have used the following definitions for the points: $N = (u+\Delta, v+\Delta)$, $W = (u+\Delta, v)$, $E = (u, v+\Delta)$ and $S = (u, v)$. The initial data are specified on the two null surfaces $u = u_0$ and $v = v_0$. This method was tested in a great number of papers (see, for example, recent works [32, 33] and references therein) and showed good convergence and agreement with accurate calculations done by other approaches [28].

**IV. ECHOES**

As our configuration contains two shells, one is infinitely thin at the throat and the other is the distant shell representing matter, from here and on, when mentioning a “shell”, we will mean the non-thin shell posed on the shell configuration around the Schwarzschild black hole.

The position of the shell does not affect the intensity of echoes so much as it changes the time at which the echoes begin [34]. For the shell representing matter around a black hole, the minimal distance, at which such a quasi-stationary configuration of matter is still justified, is determined by the innermost stable circular orbit (ISCO)
V. CONCLUSIONS

Recently there have been broad discussions of the phenomenon of echoes, which are deviations of the quasinormal ringing from its General Relativity profiles at sufficiently late times. This phenomenon takes place in two different situations: when there is modification of the black-hole geometry only in a small region near its horizon or surface or if some distribution of matter exists at a distance from the compact object. Here we have considered the traversable Schwarzschild-like wormhole of [11] and added a massive non-thin shell of matter which models possible astrophysical environment of the compact object. We have shown that a distant shell, whose mass is much smaller than the wormhole, is unlikely to produce measurable effect on echoes from the throat. The shell representing the surrounding astrophysical environment must be extraordinary heavy (comparable to the mass of the compact object) to produce noticeable effect on the “main” echoes. Such large masses are normally not expected for the usual visible astrophysical environment of compact objects and if they existed, this would drastically change the inspiral phase. Thus, we argue that if echoes are observed after the purely Einsteinian inspiral, merger and early ringdown phases, then such echoes must be ascribed to a potentially new physics near the surface of the compact object, rather than to any astrophysical environment. It is also worth of mentioning that even when the mass of the shell is of the same order or larger than the mass of the wormhole, the echoes remain unaffected at sufficiently late times.

at $r = 3$. The most influential factor of the model is the mass of the shell.

The shell of normal or phantom mass can cause an echo-type signal. However, in order to produce a distinct second pulse the mass of the shell has to be of the same order as the black-hole mass. Apparently, the usual visible astrophysical environment, such as stars, accreting disks, clouds of gas etc. should be many orders lighter than the black hole and is unlikely to produce measurable distortion of the echoes from the surface. Nevertheless, this may not be so for the dark matter/energy whose interaction with the black hole is largely unknown and may lead to qualitatively new phenomena [24, 26, 35].

Moreover, if the matter of such enormous mass was indeed spread in a region around colliding black holes, it would lead to a significant change of the signal during the inspiral phase, which is much more sensitive to the external matter comparing to the ringdown phase. This way, the signal would be distinctively non-Schwarzschild one even at the stages which could be described by the post-Newtonian approximation.

Even a large mass of matter at a distance from a black hole leads to a small correction to the effective potential, comparing to the near-horizon geometry. For the Schwarzschild-like wormhole we observe that the echo signal due to reflection from the additional peak, formed by modifications near the surface/throat (see fig. 5), has a larger amplitude and dominate over echo due to the shell of matter at a distance (see figs. 4 and 5).

Supposing that instead of the Schwarzschild-like wormhole we deal with the pure Schwarzschild black hole, the power-law asymptotic tails would dominate in the signal at late times. Once one adds a shell of massive matter at a distance, the situation changes drastically: asymptotic tails appear at even later times, while immediately after the period of quasinormal oscillations significant echoes from a distant massive shell appear instead. Thus, a massive shell at a distance could be distinguished from the purely Schwarzschild evolution of perturbations. This is not so when we have a new physics near the surface of compact object, such as a wormhole. In this case the strong echoes of the surface dominate over the echoes of the distant shell and only an extraordinary large mass of the matter, located sufficiently close to the wormhole, would lead to relatively small, but noticeable changes in the main echoes of the surface.

REFERENCES

1. M. Shibata and Y. Taniguchi, Phys. Rev. D 81, 024018 (2010).
2. T. Tanaka and M. Shibata, Phys. Rev. D 82, 084043 (2010).
3. M. Shibata, Phys. Rev. D 84, 084020 (2011).
4. T. Tanaka, M. Shibata, and Y. Taniguchi, Phys. Rev. D 82, 024038 (2010).
ACKNOWLEDGMENTS

R. K. acknowledges support of the International Mobility Project CZ.02.2.69/0.0/0.0/16_027/0008521 and hospitality of the Silesian University in Opava. A. Z. acknowledges support of the Research Centre for Theoretical Physics and Astrophysics, Faculty of Philosophy and Science of Silesian University at Opava.

[1] B. P. Abbott et al. [LIGO Scientific and Virgo Collaborations], Phys. Rev. Lett. 116, no. 6, 061102 (2016) [arXiv:1602.03837 [gr-qc]]; Phys. Rev. Lett. 116, no. 22, 221101 (2016) [arXiv:1602.03841 [gr-qc]]; Phys. Rev. Lett. 116, no. 24, 241103 (2016) [arXiv:1606.04855 [gr-qc]].

[2] C. Goddi et al., Int. J. Mod. Phys. D 26, no. 02, 1730001 (2016) [arXiv:1606.08879 [astro-ph.HE]].

[3] C. Bambi, Rev. Mod. Phys. 89, no. 2, 025001 (2017) [arXiv:1509.03844 [gr-qc]].

[4] R. Konoplya and A. Zhidenko, Phys. Lett. B 756, 350 (2016) [arXiv:1602.04738 [gr-qc]].

[5] N. Yunes, K. Yagi and F. Preto, Phys. Rev. D 94, no. 8, 084002 (2016) [arXiv:1603.08955 [gr-qc]].

[6] E. Berti, K. Yagi, H. Yang and N. Yunes, Gen. Rel. Grav. 50, no. 5, 49 (2018) [arXiv:1801.03587 [gr-qc]].

[7] M. Visser and D. L. Wiltshire, Class. Quant. Grav. 21, 1135 (2004) [arXiv:0310107 [gr-qc]].

[8] C. B. M. H. Chirenti and L. Rezzolla, Class. Quant. Grav. 24, 4191 (2007) [arXiv:0706.1513 [gr-qc]].

[9] T. Damour and S. N. Solodukhin, Phys. Rev. D 76, 024016 (2007) [arXiv:0704.2667 [gr-qc]].

[10] R. A. Konoplya and A. Zhidenko, JCAP 1612, no. 12, 043 (2016) [arXiv:1606.05017 [gr-qc]].

[11] V. Cardoso, E. Franzin and P. Pani, Phys. Rev. Lett. 116, no. 17, 171101 (2016) Erratum: [Phys. Rev. Lett. 117, no. 8, 089902 (2016)] [arXiv:1602.07309 [gr-qc]].

[12] V. Cardoso, S. Hopper, C. F. B. Macedo, C. Palenzuela and P. Pani, Phys. Rev. D 94, no. 8, 084031 (2016) [arXiv:1608.08637 [gr-qc]].

[13] V. Cardoso and P. Pani, Nat. Astron. 1, no. 9, 586 (2017) [arXiv:1709.01525 [gr-qc]].

[14] K. W. Tsang et al., Phys. Rev. D 98, no. 2, 024023 (2018) [arXiv:1804.04877 [gr-qc]].

[15] C. Barceló, R. Carballo-Rubio and L. J. Garay, JHEP 1705, 054 (2017) [arXiv:1701.09156 [gr-qc]].

[16] R. Carballo-Rubio, F. Di Filippo, S. Liberati and M. Visser, arXiv:1809.08238 [gr-qc].

[17] H. Nakano, N. Sago, H. Tagoshi and T. Tanaka, PTEP 2017, no. 7, 071E01 (2017) [arXiv:1704.07175 [gr-qc]].

[18] A. Testa and P. Pani, Phys. Rev. D 98, no. 4, 044018 (2018) [arXiv:1806.01253 [gr-qc]].

[19] Y. T. Wang, Z. P. Li, J. Zhang, S. Y. Zhou and Y. S. Piao, Eur. Phys. J. C 78, no. 6, 482 (2018) [arXiv:1802.02003 [gr-qc]].

[20] P. Bueno, P. A. Cano, F. Goelen, T. Hertog and B. Verneilcke, Phys. Rev. D 97, no. 2, 024040 (2018) [arXiv:1711.00391 [gr-qc]].

[21] A. Maselli, S. H. Vollkel and K. D. Kokkotas, Phys. Rev. D 96, no. 6, 064045 (2017) [arXiv:1708.02217 [gr-qc]].

[22] M. Visser, Phys. Rev. D 46, 2445 (1992) hep-th/9203057; Phys. Rev. D 48, 583 (1993) hep-th/9303029; Phys. Rev. D 48, 5697 (1993) hep-th/9307194.

[23] L. M. Krauss, H. Liu and J. Heo, Phys. Rev. Lett. 77, 5164 (1996) hep-th/9610135.

[24] E. Babichev, V. Dokuchaev and Y. Eroshenko, Phys. Rev. Lett. 93, 021102 (2004) [gr-qc/0402089].

[25] C. F. B. Macedo, L. C. S. Leite and L. B. Crispino, Phys. Rev. D 93, no. 2, 024027 (2016) [arXiv:1511.08781 [gr-qc]].

[26] E. Barausse, V. Cardoso and P. Pani, Phys. Rev. D 89, no. 10, 104059 (2014) [arXiv:1404.7149 [gr-qc]]; J. Phys. Conf. Ser. 610, no. 1, 012044 (2015) [arXiv:1404.7140 [astro-ph.CO]].

[27] P. T. Leung, Y. T. Liu, W. M. Suen, C. Y. Tam and K. Young, Phys. Rev. Lett. 78, 2894 (1997) gr-qc/9703031.

[28] R. A. Konoplya and A. Zhidenko, Rev. Mod. Phys. 83, 793 (2011) [arXiv:1102.4014 [gr-qc]]; E. Berti, V. Cardoso and A. O. Starinets, Class. Quant. Grav. 26, 163001 (2009) [arXiv:0905.2975 [gr-qc]]; K. D. Kokkotas and B. G. Schmidt, Living Rev. Rel. 2, 2 (1999) [arXiv:gr-qc/9909058].

[29] R. A. Konoplya and C. Molina, Phys. Rev. D 71, 124009 (2005) [arXiv:gr-qc/0504139].

[30] R. A. Konoplya and A. Zhidenko, Phys. Rev. D 81, 124036 (2010) [arXiv:1004.1284 [hep-th]].

[31] C. Gundlach, R. H. Price and J. Pullin, Phys. Rev. D 49, 883 (1994) [hep-th/9307194].

[32] R. A. Konoplya, Z. Stuchlík and A. Zhidenko, arXiv:1808.03340 [gr-qc].

[33] C. F. B. Macedo, arXiv:1809.08691 [gr-qc].

[34] M. Mirbabayi, arXiv:1807.04843 [gr-qc].

[35] M. Raidal, S. Solodukhin, V. Vaskonen and H. Veermäe, arXiv:1808.07728 [astro-ph.CO]].