Did GW150914 produce a rotating gravastar?

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The interferometric LIGO detectors have recently measured the first direct gravitational-wave signal from what has been interpreted as the inspiral, merger and ringdown of a binary system of black holes. The signal-to-noise ratio of the measured signal is large enough to leave little doubt that it does refer to the inspiral of two massive and ultracompact objects, whose merger yields a rotating black hole. Yet, the quality of the data is such that some room is left for alternative interpretations that do not involve black holes, but other objects that, within classical general relativity, can be equally massive and compact, namely, gravastars. We here consider the hypothesis that the merging objects were indeed gravastars and explore whether the merged object could therefore be not a black hole but a rotating gravastar. After comparing the real and imaginary parts of the ringdown signal of GW150914 with the corresponding quantities for a variety of gravastars, and notwithstanding the very limited knowledge of the perturbative response of rotating gravastars, we conclude it is not possible to model the measured ringdown of GW150914 as due to a rotating gravastar.

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Introduction. Gravastars were proposed in 2004 by Mazur and Mottola [1] as an ingenious alternative to the end state of stellar evolution for very massive stars, that is, as an alternative to black holes. The name gravastar comes from “gravitational vacuum condensate star” and it was proposed to be almost as compact as a black hole, but without an event horizon or a central singularity. This object would be formed as gravitational collapse brought the stellar radius very close to its Schwarzschild radius and as a phase transition would form a de Sitter core. This “repulsive” core stabilises the collapse, while the baryonic mass ends as a shell of stiff matter surrounding the core. Despite their uncertain and rather exotic origin, gravastars are perfectly acceptable solutions of the Einstein equations within classical general relativity.

Considerable effort has been dedicated to study gravastars, for instance exploring different possibilities for its structure [2, 3], generalising the solution [4–6] and investigating possible observational signatures [7–9]. As alternatives almost indistinguishable from a black hole in terms of electromagnetic radiation, gravastars have attracted the attention of those who wished for a spacetime solution without the issues brought by the existence of singularities and event horizons. Work was also done in order to assess its viability, in particular looking for instabilities in the solutions. Hence, there have been studies on the stability against radial oscillations [2, 10] and axial and polar gravitational perturbations [11–13]. For slowly rotating gravastars, scalar perturbations in the context of the ergoregion instability were also studied [14, 15]. None of these works has pointed out to a response that would allow one to discard gravastars as plausible solutions of general relativity.

In their original model, Mazur and Mottola [1] proposed a gravastar with infinitesimal but nonzero thickness as this allowed them to derive the most salient properties of the model analytically [16] (the thickness of the shell is effectively zero in the gravastar model of [2]). In any astrophysically realistic configuration, however, the gravastar is expected to have a finite thickness, so that the parameter space for nonrotating gravastar solutions has effectively three degrees of freedom: the total (gravitational) mass $M$, the inner radius of the shell $r_1$, and the outer one $r_2$, which is also the radius of the gravastar [2, 3, 12]. As a result, gravastar solutions are normally classified in terms of $\mu \equiv M/r_2$, and of the thickness of the shell $\delta \equiv r_2 - r_1$; within this parameter space it is always possible to find stable solutions. Because of the freedom in choosing $\delta$, it is in principle possible to build gravastars with $\delta/M \ll 1$ and radius that is only infinitesimally larger than the Schwarzschild radius, thus making these objects frustratingly hard to distinguish from black holes when using electromagnetic emission. However, as pointed out almost a decade ago [12], it is possible to distinguish a gravastar from a black hole if sufficiently strong gravitational radiation is detected; with the recent observation of GW150914 [17], we can now start to do so.

In this Letter we consider the possibility that the event GW150914 was produced by the merger of two gravastars, creating then a more massive and rotating gravastar as a result of the merger. Given the strength of the detected signal, the inspiral part of the signal could be reproduced by two compact objects that are not necessarily black holes, and could well be very compact gravastars or other exotic compact objects.\textsuperscript{1} The ringdown, however, presents a characteristic signature of the final compact object. After performing a quasi-normal mode analysis of slowly rotating gravastars, based on the rotational corrections of the oscillation frequencies of compact stars, we have investigated whether the resulting object from the binary merger in GW150914 could be a gravastar. We show here that, within the possible accuracy of our results, that object ringing down in GW150914 could not be a gravastar.

Results. In its essential simplicity, the merger of a black-

\textsuperscript{1} The compactness argument presented in [18] shows that the inspiralling bodies in GW150914 must have had radii smaller than 175 km, otherwise they would have touched before reaching the observed gravitational wave frequency of 150 Hz, therefore placing a lower bound of $\mu > G/c^2(35\, M_\odot)/(175\, \text{km}) \sim 0.3$ on the compactness.
hole binary system will lead to the formation of a new, rotating black hole [19–21] (a Schwarzschild black hole can in principle also be produced in a binary black-hole merger [22], but this is rather unlikely). The new Kerr black hole will be initially highly perturbed and hence emit gravitational waves by oscillating in its quasi-normal modes (QNMs); this is the characteristic ringdown signal of a perturbed black hole. A large bulk of work has been produced to extract information from the ringdown produced by the merger, including the main properties of the newly formed black hole (e.g., mass and spin) [23, 24], but also the recoil direction and magnitude [25–28].

The real and imaginary parts, \( \sigma_\ell \) and \( \sigma_i \), of the lowest order \( \ell = 2 = m \) QNM of a Kerr black hole have been studied in great detail by a number of authors within perturbation theory already in the 90’s (see, e.g., Ref. [29] for one of the initial analyses and Ref. [30] for a comprehensive review). In particular, for a rotating black hole with mass \( M \), angular momentum \( J \) and dimensionless spin parameter \( a \equiv J/M^2 \), these frequencies have been shown to be very well approximated by simple expressions [24]. Using perturbative analyses and numerical-relativity simulations, the ringdown signal from the observations of GW150914 was associated to the lowest QNM of a Kerr black hole with dimensionless spin \( a = 0.68^{+0.05}_{-0.06} \) and mass \( M = 62.2^{+3.4}_{-3.3} M_\odot \) [17, 31].

The vast literature on the perturbations of rotating black holes is in stark contrast with the very limited knowledge of perturbed rotating gravastars. Indeed, essentially all of the work carried out so far on the QNMs of gravastars has concentrated on nonrotating models and gravitational perturbations (axial and polar) [11–13]. An example of the perturbative response of a gravastar is reported in Fig. 1, which shows the evolution of the \( \ell = 2 = m \) axial perturbation \( \psi(t) \) for a Schwarzschild black hole (black dashed line) and for three different gravastars (coloured solid lines) with decreasing thickness, i.e., with \( \delta/M = 0.01, 0.005 \) and 0.0025; in all cases the gravastars have the same compactness \( \mu = 0.48 \).

Figure 1 is also useful to clarify a point that may otherwise be a source of confusion. Ref. [32] has recently discussed that an early-time decay of a gravitational-wave signal induced by a perturbation of an ultra-compact object is similar to that of a black hole, irrespective of the differences in the QNM spectrum. We obviously agree with this conclusion but also note that whether or not one is able to distinguish the very early-time signal (assuming this is all that is observed) from the putative horizon position \( \delta/M = 0.0025 \), \( \mu = 0.48 \) whose surface is only 4% (in radius) outside of the event horizon, even the very early part of the ringdown can be distinguished from the corresponding one for a Schwarzschild black hole, while the late part of the ringdown will be considerably different (as it should be in order to yield different QNMs). This conclusion holds true for any realistic gravastar independently of the internal structure and as long as the surface is not at an infinitesimal distance away from the putative horizon position \( 2M \) (see also the discussion in Ref. [33]). This is because at the gravastar’s surface, where the fields are strong and dynamical, the two spacetimes will be different, as will be boundary conditions of the corresponding perturbative problem. The timescale over which this difference can be probed via a perturbation is given by the crossing time between the peak of the scattering potential and the surface of the star; this timescale is comparable but smaller than the dynamical timescale of the gravastar’s response and so the difference is clearly detectable on such a timescale (cf. Fig. 1).

The real and imaginary parts of the \( \ell = 2 = m \) eigenfrequencies for axial gravitational perturbations are reported in Fig. 2, for a variety of nonrotating gravastars [12]. Lines of different colours refer to sequences of gravastars with constant compactness \( \mu \), but varying thickness \( \delta/r_2 \), which is marked by the various points on the curves and that ranges from \( \delta/r_2 = 5 \times 10^{-4} \) to \( \delta/r_2 = 0.3 \). The various \( \mu = \text{const.} \) curves essentially overlap in the \((\sigma_r, \sigma_i)\) plane, with “thick” gravastars yielding low oscillation frequencies and long damping times, while “thin” gravastars show instead high oscillation frequencies and short damping times. Such a behavior is rather natural since thick (nonrotating) gravastars tend to be increasingly similar to a (nonrotating) black hole, whose eigenfrequencies are shown with a red circle. Yet, independently of the compactness and thickness considered, the eigenfrequencies of nonrotating gravastars differ from the corresponding eigenfrequencies of a nonrotating black hole [12].

The analysis of the QNMs of rotating gravastars is effectively limited to scalar perturbations in the context of the ergoregion instability [14, 15, 34]. To make some progress despite the scarce present knowledge we have exploited the considerable experience that has been built in modelling the eigenfrequencies of rotating stars from the knowledge of the
To the average “density” of the star, as a function of the stellar structure, but is quite robustly related to the Keplerian frequency $\Omega$ when normalised to the maximum rotation frequency, i.e., the $\Omega_{K}$, proportional to the angular frequency of the star.

The latter is in general a complex expression (i.e., $\chi_{m}\epsilon_{\sigma}$), where $\chi_{m}\epsilon_{\sigma}$ are the real (imaginary) parts of the $f$ mode eigenfrequencies for the corresponding nonrotating star.

Expressions (1)–(2) contain two corrections to the nonrotating eigenfrequencies, namely, $\epsilon$ and $\sigma_{r,i}$. The first one accounts for the corrections due to rotation and is therefore proportional to the angular frequency of the stellar structure, but is quite robustly related to the average “density” of the star, as $\sqrt{\langle \rho \rangle} \sim \sqrt{M_{0}/R^{3}} \sim \sqrt{M/R^{5}}$, where $M_{0}$ and $M$ are the rest-mass and gravitational mass of the star. As customary, we express $\epsilon$ as

$$\epsilon \equiv \frac{\Omega}{\Omega_{K}} \approx \frac{J/(MR^{2})}{\Omega_{K}} \approx \chi \sqrt{\mu},$$

where $J$ is the angular momentum of the star and $\chi \equiv J/M^{2}$.

The second corrections in (1)–(2) are instead given by the modifications in the eigenfrequencies due to changes in compactness, i.e., $\sigma_{r,i}' = \sigma_{r,i}(\mu)$. In principle, these corrections should be obtained after performing a complete perturbative analysis of rotating gravastars, in analogy with what has already been done for relativistic stars [36, 37]. Because so little is known about the perturbative response of rotating gravastars, we exploit all of the understanding of the perturbative response of rotating compact stars to make progress in the phase space of rotating gravastars.

Given the extreme equation of state and the even more bizarre de Sitter interior, it is natural to ask how closely does the perturbative response of a gravastar resemble that of a compact star. Answering this question is not simple since gravastars have the thickness as an additional degree of freedom given when compared to compact stars. However, what is relevant here is that gravastars are essentially ultracompact stars with a de-Sitter core exhibiting a behaviour that correlates closely with the global properties such as the mass, the compactness or the effective average densities [12]. Such correlations are not surprising since gravastars ultimately have trapping potentials that are very similar to those already encountered in ordinary ultracompact stars, where QNMs can be trapped [34, 38] (cf. left panel of Fig. 6 in Ref. [12]).

Since the similarities discussed above suggest that it is not unreasonable to use knowledge on compact stars also in the context of gravastars, and lacking any alternative approach at present, we have used the expressions for $\sigma_{r,i}' = \sigma_{r,i}(\mu)$ derived for neutron stars [36] and have extrapolated their functional dependence on compactness from the typical range relative to neutron stars, i.e., $\mu \in [0.10, 0.24]$, over to the typical values of compactness that are relevant for gravastars, i.e., $\mu \in [0.4, 0.5]$. We note that the lower limit of this range of compactness is already rather small and that although gravastars with lower compactness can be constructed, they would not represent black-hole mimickers. Finally, although this represents a reasonable first approximation, especially since similar expressions have been shown to be valid for $\epsilon \lesssim 1$ [37] and to be only mildly dependent on the equation of state [37], it is nevertheless an extrapolation and a perturbative analysis of rotating gravastars is needed to validate that the extrapolation is accurate.

We report in Fig. 3 the real and imaginary parts of the axial-mode eigenfrequencies relative to rotating gravastars as obtained after computing the rotational and compactness corrections to the eigenfrequencies for axial QNMs of spherical gravastars [12]. In principle, polar modes would be the most relevant for gravitational-wave emission since they excite fluid motions [30]. However, for thin-shell gravastars, $\ell = 2$ axial and polar modes are almost isospectral for $\mu > 0.4$ [13]. The solid lines of different colours in Fig. 3 represent sequences of constant-compactness rotating gravastars with dimensionless spin $\chi = 0.68$, which is a reasonable prior given that gravastars are expected to have an orbital dynamics similar to that of black holes (stable gravastars with large spin, $\chi \lesssim 1.2$, are possible [14]). Because gravastars will have (slightly) larger sizes than black holes, the merger will effectively take place a bit earlier in the inspiral (as it happens for neutron stars) so that the effective final spin will be slightly larger than the one assumed here [39]. This is a rather crucial assumption, which is however rooted in the understanding built over the last 10 years when modelling the final spin.
FIG. 3. The same as Fig. 2 but including now also eigenfrequencies of rotating gravastars, as well as the eigenfrequencies of rotating black holes (red dashed line). Because of rotation the sequences of constant compactness no longer overlap and shaded area bounds the space of eigenfrequencies span by rotating gravastars compatible with GW150914. This region does not overlap by the range span by the eigenfrequencies of a Kerr black hole with dimensionless spin $a = 0.68 \pm 0.06$.

Also in Fig. 3, symbols mark gravastars with different thickness, which decreases when moving upwards along the curves. Note that these sequences are no longer overlapping as rotation acts differentially on gravastars of various compactness. In particular, comparatively less compact gravastars will have smaller real eigenfrequencies (light-blue solid line) than gravastars with larger compactness (blue solid line). In addition, because the real part of the eigenfrequencies increases with the rotation rate, the whole set of curves moves to the right with $\epsilon$. Hence, the space of eigenfrequencies spanned by rotating gravastars (shaded area) is effectively bounded by the sequence with smallest compactness and rotation rate within the measurements of GW150914, i.e., $\mu = 0.40$ and $\chi = 0.68 \pm 0.06$ (light-blue thick dashed line), and by the sequence with largest compactness and rotation rate, i.e., $\mu = 0.48$ and $\chi = 0.68 + 0.05$ (dark-blue thick dashed line).

This space of eigenfrequencies between the two thick-dashed lines should be compared with those relative to a rotating black hole and that is marked with a dashed red line in Fig. 3, where the spin obviously increases when moving from the left to the right along the curve. Also marked with a square on the dashed line is the position of the eigenfrequencies of a Kerr black hole with dimensionless spin $a = 0.68$. From binary black holes in quasi-circular orbits; such a spin is ultimately determined by the combination of the initial spins of the black holes and of the angular momentum that is not radiated when the binary merges [40–42]. As we discuss below, taking a value $\chi = 0.68$ is actually a conservative choice.

In Fig. 4 we compare our results to the GW150914 ringdown frequencies that were obtained by a direct damped-sinusoid fit to the ringdown data in [18]. The different 90% confidence regions shown in Fig. 4 correspond to different starting times after the merger time, while the solid black line corresponds to the 90% confidence region obtained with the complete inspiral-merger-ringdown (IMR) signal. In spite of the larger errors present, there is no overlap between the GW150914 ringdown frequencies and the eigenfrequencies of rotating gravastars, thus further strengthening our conclusions. These results, notwithstanding the approximations employed here, lead us to the conclusion that it is not possible to model the measured ringdown of GW150914 as due to a rotating gravastar.

Finally, the red and thick solid portion of the dashed line refers to eigenfrequencies with $a \in [0.68 - 0.06, 0.68 + 0.05]$ [17, 31]. Clearly, the range spanned by the rotating-gravastars eigenfrequencies is distinct from the one spanned when associating GW150914 to the ringdown of a rotating black hole. Finally, considering a (slightly) larger value of $\chi$ on the assumption that gravastars merge earlier than black holes, would just move all the curves to the right, making the overlap even harder.

Lastly, we should comment on the parameters of the final merged object. We used in our analysis the values presented by the LIGO team [17, 31], which were obtained from an analysis of the full GW150914 waveform (inspiral-merger-ringdown). If less restrictive constraints on the parameters were to be considered, by taking the 90% confidence interval
for the final mass and spin using data only from the inspiral [18], our conclusions would still hold. The larger uncertainties in the parameters only place a more strict constraint on the compactness of the gravastar, but still well within astrophysically relevant values (gravastars with $\mu > 0.48$ already show no overlap with the ringdown confidence regions shown in Fig. 4).

Conclusions. The measurement of the first direct gravitational-wave signal GW150914 has provided the first strong evidence for the existence of binary stellar-mass black hole systems. However, as remarked in Ref. [18], it is not yet possible to set tight constraints on different interpretations of GW150914 and, in particular, on alternative theories to general relativity or on the idea that the signal involves compact-object binaries composed of more exotic objects such as boson stars [43] or gravastars [1]. Hence, we have here considered the hypothesis that the merging objects were indeed gravastars. Because the constraints coming from GW150914 on the compactness of the merging objects are fully compatible with the intrinsically large compactness that can be associated with gravastars, it is presently difficult to exclude gravastars as being responsible for the inspiral signal. In view of this, we have concentrated on determining whether the merged object could be interpreted as a rotating gravastar. To do this we have made use of the numerous results available on the perturbations of nonrotating gravastars and of rotating compact stars. In particular, we have modelled the perturbative response of rotating gravastars as a correction to the corresponding response of nonrotating gravastars; this approach is not novel in rapid rotation and within the Cowling approximation [37]. Using this approach and comparing the real and imaginary parts of the ringdown signal with the corresponding quantities for gravastars, we find that the range spanned by the rotating-gravastars eigenfrequencies is well distinct from the one spanned when associating the measured GW150914 signal to the ringdown of a rotating black hole. Hence we conclude it is not possible to model the measured ringdown of GW150914 as due to a rotating gravastar. While our analysis has considered gravastars of compactness $\mu \leq 0.48$, the behaviour of the QNM spectrum is such that our conclusions extend also to larger compactnesses.

We conclude with two final remarks. First, there is no contradiction between our results and those of Ref. [32] as our conclusions refer to gravastars that are thick and have a surface at a small but not infinitesimal distance from the putative event horizon. Second, we stress again that our conclusion is based on a technique that has been developed and employed robustly for rotating compact stars and extended here to gravastars. This aspect of our analysis calls for the development of a proper perturbative analysis of rotating gravastars. Until such a framework is fully developed over the coming years, our results can be used to provide an “educated” answer to the question in the title.

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[1] P. O. Mazur and E. Mottola, Proc. Nat. Acad. Sci. 101, 9545 (2004)
[2] M. Visser and D. L. Wiltshire, Class. Quantum Grav. 21, 1135 (2004)
[3] C. Cattoen, T. Faber, and M. Visser, Class. Quant. Grav. 22, 4189 (2005)
[4] D. Horvat, S. Ilijic, and A. Marunovic, Class. Quant. Grav. 26, 025003 (2009)
[5] B. V. Turimov, B. J. Ahmedov, and A. A. Abdubjabbarov, Mod. Phys. Lett. A24, 733 (2009)
[6] N. Uchikata and S. Yoshida, Class. Quant. Grav. 33, 025005 (2016)
[7] A. E. Broderick and R. Narayan, Class. Quantum Grav. 24, 659 (2007)
[8] N. Sakai, H. Saida, and T. Tamaki, Phys. Rev. D 90, 104013 (2014)
[9] P. Pani, Phys. Rev. D 92, 124030 (2015)
[10] D. Horvat, S. Ilijić, and A. Marunovič, Class. Quantum Grav. 28, 195008 (2011)
[11] A. DeBenedictis, D. Horvat, S. Ilijic, S. Kloster, and K. Viswanathan, Class.Quant.Grav. 23, 2303 (2006)
[12] C. B. M. H. Chirenti and L. Rezzolla, Class. Quantum Grav. 24, 4191 (2007)
[13] P. Pani, E. Berti, V. Cardoso, Y. Chen, and R. Norte, Phys. Rev. D 80, 124047 (2009)
[14] C. B. M. H. Chirenti and L. Rezzolla, Phys. Rev. D 78, 084011 (2008)
[15] V. Cardoso, P. Pani, M. Cadoni, and M. Cavaglia, Physical Review D 77, 14 (2007)
[16] L. Rezzolla and O. Zanotti, Relativistic Hydrodynamics (Oxford University Press, Oxford, UK, 2013)
[17] The LIGO Scientific Collaboration and the Virgo Collaboration, Phys. Rev. Lett. 116, 061102 (2016)
[18] The LIGO Scientific Collaboration and the Virgo Collaboration, Phys. Rev. Lett. 116, 221101 (2016)
[19] F. Pretorius, Phys. Rev. Lett. 95, 121101 (2005)
[20] M. Campanelli, C. O. Lousto, P. Marronetti, and Y. Zlochower, Phys. Rev. Lett. 96, 111101 (2006)
[21] J. G. Baker, J. Centrella, D.-I. Choi, M. Koppitz, and J. van Meter, Phys. Rev. Lett. 96, 111102 (2006)
[22] L. Rezzolla, P. Diener, E. N. Dorband, D. Pollney, C. O. Lousto, P. Marronetti, and Y. Zlochower, Phys. Rev. Lett. 96, 111101 (2006)
[23] E. Berti, V. Cardoso, J. A. Gonzalez, U. Sperhake, M. Hannam, S. Husa, and B. Brügmann, Phys. Rev. D 78, 064034 (2008)
[24] E. Berti, V. Cardoso, and C. M. Will, Phys. Rev. D 73, 064030 (2006)
[25] J. D. Schnittman, A. Buonanno, J. R. van Meter, J. G. Baker, W. D. Boggs, J. Centrella, B. J. Kelly, and S. T. McWilliams,
