From micro to macro and back: probing near-horizon quantum structures with gravitational waves

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Abstract. Supermassive binaries detectable by the planned space gravitational-wave interferometer LISA might allow us to distinguish black holes from ultracompact horizonless objects, even for certain models motivated by quantum-gravity considerations. We show that a measurement of a very small tidal Love number with $\approx 10\%$ accuracy (as achievable by detecting "golden binaries") may also allow us to distinguish between different models of these exotic compact objects, even when taking into account an intrinsic uncertainty in the object radius putatively due to quantum mechanics. We argue that there is no conceptual obstacle in performing these measurements, the main challenge remains the detectability of small tidal effects and an accurate waveform modelling.

1. Introduction

Gravitational-wave (GW) measurements of the tidal deformability of neutron stars (NSs) [1, 2] – through the so-called tidal Love numbers (TLNs) [3] – provide the most accurate tool so far to probe the microphysics of the NS interior well above the nuclear saturation density [4, 5, 6, 7, 8, 9]. The TLNs encode the deformation properties of a compact object, and describe how its multipole moments change in response to the external tidal field. The dominant contribution among the TLNs is given by the apsidal constant k_2, which characterizes quadrupolar deformations. Two NSs with similar mass and radius – but described by equations of state (EoS) with different stiffness – can have a TLN that differs by as much as 100% [5]. The macroscopic difference in the TLNs acts as a *magnifying glass* to probe the fundamental interactions within the NS core, for example to understand if the latter is made of normal $npe\mu$ matter, or hyperons, pion condensates, quarks, strange matter, etc [10].

It has been realized that GW measurements of the TLNs can also be used to distinguish black holes (BHs) from other ultracompact objects [11, 12, 13, 14]. The TLNs of a BH are identically zero [15, 16, 17, 18, 19, 20, 21, 20], whereas those of exotic compact objects (ECOs) are small but finite [22, 23, 24, 11]. Therefore, measuring a nonvanishing TLN with measurements errors small enough to exclude the null case would provide a smoking gun for the existence of new species of ultracompact massive objects [11, 12, 14, 25].

Certain models of ECOs (all belonging to the ClePhO category introduced in Refs. [26, 27], see below) are characterized by a TLN that vanishes as the logarithm of the (proper) distance (see Eq. (2) below) in the BH limit (i.e., when their radius r_0 tends to the Schwarzschild radius $2M$ in the $G = c = 1$ units adopted hereafter). Owing to this logarithmic behavior‡, the TLNs of ultracompact objects are still large enough to be measurable in the future [11, 12], even for those models of ECOs which are motivated by quantum-gravity scenarios [32, 33, 34, 35, 36, 37], in which case one expects $r_0 \approx 2M + \ell_P$ (in a coordinate-independent way to be specified below; here $\ell_P \approx 1.6 \times 10^{-33}\,\mathrm{cm}$ is the Planck length). In particular, it was pointed out that for highly-spinning supermassive binaries detectable by the future space interferometer LISA [38] the signal-to-noise ratio might be high enough to distinguish BHs from ECOs even if the latter display Planckian corrections at the horizon scale [12].

The next most natural question, that we explore here, is the following: *assuming such ECOs exist, would a future detection be able to distinguish among different models, possibly allowing for model selection of different quantum-gravity scenarios?*

‡ This logarithmic behavior appears in various models of ECOs and it is related to the emergence of the "scrambling" time [28, 29]. Similar logarithmic behaviors have been reported for other observables, e.g. GW echoes [30, 31, 26, 27] and for the corrections to the multipole moments of certain ECO models relative to a Kerr BH [22, 23].

2. ECO model selection through TLNs

In order to investigate the above question, we consider exotic, nonspinning objects with surface r_0 very close to the Schwarzschild radius. We parametrize such objects with a quantity§ δ, such that $r_0 = 2M + \delta$. One could also adopt the *proper distance* Δ between the radius of the object and the would-be horizon [39],

$$\Delta = \int_{2M}^{r_0} \frac{dr}{\sqrt{1-2M/r}} \approx \sqrt{8M\delta}\,, \tag{1}$$

where the last step is valid to leading order when $r_0 \approx 2M$. We shall use $\Delta \to 0$ as a coordinate-independent limit to the BH case. As we shall discuss, owing to the logarithmic dependence of the TLNs the distinction between Δ and δ is negligible.

The TLNs of three toy models of ultracompact objects which can be arbitrarily close to the compactness of a BH were computed in Ref. [11] by solving linearized Einstein's equations coupled to exotic matter fields, and with suitable boundary or junction conditions. For these classes of ECOs, k_2 scales logarithmically with the radius' shift δ, namely $k_2 \sim 1/|\log(\delta/M)|$. In terms of the proper distance Δ, the (electric, quadrupolar) TLNs of these models in the limit $\Delta \ll 2M$ read

$$k_2 \sim \left(a + b\log\left(\frac{\Delta}{4M}\right)\right)^{-1}, \tag{2}$$

where $a = (10, \frac{5(23-\log 64)}{16}, \frac{35}{8})$, $b = (\frac{15}{2}, \frac{45}{8}, \frac{15}{4})$ for wormholes, gravastars, and perfectly reflective objects, respectively. We consider these models as ECO prototypes for which the TLNs are known analytically. Indeed, the above logarithmic scaling is actually a rather general property. Extending the analysis of Ref. [11], it is easy to show that the logarithmic scaling holds for any ECO whose exterior is Schwarzschild, and when generic Robin-type boundary conditions, namely $A\Psi + B\frac{d\Psi}{dr_*} = C$, are applied to the Zerilli function Ψ at the surface (here r_* is the standard tortoise coordinate). In this case, in the $\Delta \to 0$ limit one gets

$$k_2 \sim \frac{8A-6C}{15A}\log^{-1}\left(\frac{\Delta}{4M}\right), \tag{3}$$

the only exception concerns the zero-measure case $A = \frac{3}{4}C$, for which $k \sim \Delta^2/\log(\Delta/(4M))$. However, no ECO models described by these fine-tuned boundary conditions are known. Note that, since $\Delta \sim \sqrt{\delta}$ and k_2 depends logarithmically on it, the distinction between Δ and δ only accounts for a factor of 2 in the TLN.

It has been recently argued that the exponential dependence of $\delta(k)$ and of its errors (see bands in Fig. 1 of Ref. [12]) and the quantum uncertainty principle might prevent probing Planckian corrections at the horizon scale [40]. We disagree with this conclusion. Figure 1 – inspired by standard analysis to discriminate among NS equations

§ For the class of ClePhOs considered in this work – i.e., those objects which feature a "clean" photon-sphere – the radius' shift is smaller than a certain threshold, namely $\delta/(2M) \lesssim 0.0165$ [26, 27].

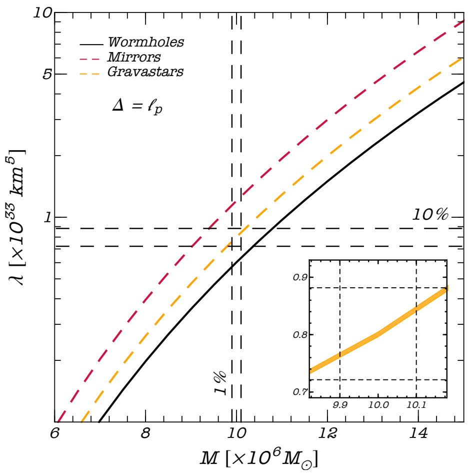

Figure 1. Tidal deformability λ as a function of the mass for three different models of ECOs. For all models, the surface is at Planckian proper distance, $\Delta = \ell_P$, from the Schwarzschild radius. The dashed lines refer to a putative measurement of the TLN at the level of 10% for an object with $M = 10^7 M_\odot$, which would allow to distinguish among different models. Although unnoticeable in the plot, each curve is actually a band of width ℓ_P to account for the intrinsic error due to the quantum uncertainty principle [40] (the thickness is resolved only in the zoomed inset).

of state (EoS) [5, 41] – shows the tidal deformability $\lambda = \frac{2}{3}M^5|k_2|$ as a function of the object mass for the different models presented above. Crucially, in all cases we assume the emergence of a Planckian fundamental scale and set the proper distance $\Delta = \ell_P$ (our results would be qualitatively the same if we consider $\delta = \ell_P$). This plots proves that the detectability of near-horizon quantum structures is not biased by any fundamental problem beside the observational challenge posed by extracting small TLNs from the GW signal. A putative measurement of $k_2 \approx 10^{-3} - 10^{-2}$ with 10% errors, as achievable for highly spinning LISA binaries up to luminosity distance of 2 Gpc [12], would allow to distinguish among all three models at more than 90% confidence level.‖ Thus, even though the microscopic scale of the correction, $\Delta = \ell_P$, is the same for all models, the TLNs (i.e., the macroscopic quantities that really enter the waveform) are different enough to allow for discrimination.

In Fig. 1 we have also included the intrinsic error coming from the quantum uncertainty principle as proposed in Ref. [40]. This implies an intrinsic uncertainty on length scales at the level of ℓ_P for energies of the order of the Planck mass. Since the latter is enormously smaller than the mass M of these objects, one would expect that the effect of the quantum uncertainty principle is negligible. This is confirmed by Fig. 1, where each curve is actually a very narrow band obtained by considering $\delta = \ell_P \pm \ell_P/2$, i.e. with an intrinsic uncertainty $\pm\ell_P/2$ [40]. This effect is negligible compared to the statistical errors on λ. This result is also consistent with Fig. 1 in Ref. [40] and with the fact that the wavelengths relevant for this system are of the order of the orbital

‖ We refer the reader to [12] for a detailed analysis on the statistical errors and on the systematics related to the TLN's measurements by GW interferometers.

separation of the binary, $d \gtrsim \mathcal{O}(M) \sim \mathcal{O}(10^{45}) \left(\frac{M}{10^7 M_\odot}\right) \ell_p$ at least.

3. Probing quantum structures at the horizon?

Our results confirm and extend the analysis of Ref. [12], suggesting that not only should it be possible to use future GW measurements of the TLNs to distinguish between BHs and ECOs (even for those ECO models in which $\Delta = \ell_P$), but also that – with a slightly higher signal-to-noise ratio – it might be possible to distinguish between different ECO models all with $\Delta = \ell_P$ but with different TLNs. This might allow to perform ECO model selections and possibly rule out certain scenarios that predict a particular ECO rather than another.

This tantalizing possibility should not come as a surprise, since this is precisely the same strategy used to constrain the NS EoS from GW measurements of the TLNs [4, 5, 6, 7, 8, 9]. One might argue that, since different EoS differ by the microscopic interactions occurring above the QCD scale – roughly 200 MeV or 1 fm – one would need a "gravitational microscope" with such length resolution [40]. If correct, this line of reasoning would prevent any constraint on the NS EoS through the TLNs, since the resolution on the wavelength of the GW signal from compact binaries is not even microscopic. The key point is that *microscopic* effects acting at small scales lead to different *macroscopic* TLNs; the latter are the quantities effectively entering the waveform and therefore measurable.

Another example of the magnification of quantum effects in compact stars is provided by Chandrasekhar's mass limit [42],

$$M_{\rm Ch} \sim \frac{M_P^3}{m_H^2}\,, \tag{4}$$

where $M_P = \ell_P c^2/G$ and m_H are the Planck mass and the mass of the proton, respectively. Since $\ell_P = \sqrt{\hbar G/c}$, a hypothetical change of the fundamental quantum scale governing the microphysics of the object would affect the Chandrasekhar mass *macroscopically*. For the sake of the argument, if (say) $\hbar \to 2\hbar$, then $M_{\rm Ch} \propto \hbar^{3/2}$ would change roughly by a factor of 3. Likewise, a putative intrinsic error $\ell_P \pm \ell_P/2$ would affect the Chandrasekhar limit at the level of kilometers.

Thus, at variance with Ref. [40], we argue that there is no fundamental or conceptual obstacle in probing Planckian corrections at the horizon scale ¶.

The real challenge is on the detectability side and parameter estimation, due to the smallness of the tidal deformability for these ECO models [12], the systematics of the waveform modeling [43, 44, 45, 6], and the requirement to reach a *resolution in the TLNs* small enough to distinguish two ECO models with $\Delta \approx \ell_P$. Future detectors seem on the verge to be able to detect this effect, the final answer will depend on the

¶ We remark that for ECOs which do not feature Planckian corrections (such as boson stars, which have a maximum compactness $M/r_0 \sim 0.3$), the TLNs are much bigger and easier to measure. In such case LISA would be able to measure TLNs from GW observations at the level of 1% and below [11].

uncertain event rates and on the ability of building accurate waveforms.

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