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

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Supermassive binaries detectable by the future space gravitational-wave interferometer LISA might allow to distinguish black holes from ultracompact horizonless objects, even when the latter are motivated by quantum-gravity considerations. We show that a measurement of very small tidal Love numbers at the level of 10% accuracy (as achievable with “golden binaries”) may also allow 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 modeling. Our analysis uses only coordinate-independent quantities related to the proper radial distance and the total mass of the object.

Introduction. Gravitational-wave (GW) measurements of the tidal deformability of neutron stars (NSs) provide the most accurate tool so far to probe the microphysics of the NS interior well above the nuclear saturation density. Two NSs with similar mass and radius can have a TLN that differs by as much as 100%, if the two stars are described by equations of state (EoS) with different stiffness. 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 npeµ matter, or hyperons, pion condensates, quarks, strange matter, etc.

It has been realized that GW measurements of the TLNs can also be used to distinguish black holes (BHs) from other ultracompact objects. The TLNs of a BH are identically zero, whereas those of exotic compact objects (ECOs) are small but finite. 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.

Certain models of ECOs (all belonging to the ClePhO category introduced in Ref. [26, 27]) 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 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, even for those models of ECOs which are motivated by quantum-gravity scenarios, in which case one expects r0 ≈ 2M + δP (in a coordinate-independent way to be specified below; here δP ≈ 1.6 × 10^{-33} cm is the Planck length). In particular, it was pointed out that for highly-spinning supermassive binaries detectable by the future space interferometer LISA 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.

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?

ECO model selection through TLNs. In order to investigate the above question, we consider some specific examples of ECO models with TLNs vanishing logarithmically in the BH limit. All previous studies on the TLNs of ECOs have used the quantity δ = r0 − 2M as a measure of how “close” the surface of the ECO is relative to the Schwarzschild radius. Since this quantity does not have any physical (i.e., coordinate-independent) meaning, it is more useful to adopt the proper distance ∆ between the radius of the object and the would-be horizon,

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

where the last step is valid to leading order when r0 ≈
2M. We shall use \( \Delta \to 0 \) as a coordinate-independent limit to the BH case.

The TLNs of three toy models of ultracompact objects which can be arbitrarily close to the compactness of a BH were computed in Ref. [12] by solving linearized Einstein’s equations coupled to exotic matter fields, and with suitable boundary or junction conditions. In terms of the proper distance \( \Delta \), the (electric, quadrupolar) TLNs of these models in the limit \( \Delta \ll 2M \) read

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

where \( a = (10, \frac{5(23-\log 64)}{16}, \frac{35}{16}) \), \( b = (15, \frac{45}{16}, \frac{15}{2}) \) for wormholes, gravastars, and perfectly reflective objects, respectively.

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 [38]. In Fig. 1 we show that this is the case, and 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. This plot – inspired by standard analysis to discriminate among NS EoS [5, 40] – shows the tidal deformability \( \lambda = \frac{2}{3} M^2 |k_2| \) as a function of the object mass for the three different toy models above. Crucially, in all cases we assume the emergence of a Planckian fundamental scale and set the proper distance \( \Delta = \ell_p \).

A putative measurement of \( k_2 \approx 10^{-3} - 10^{-2} \) at the level of 10% (as achievable for highly spinning LISA binaries up to luminosity distance of 2 Gpc [12] and with other planned GW detectors such as BBO [41]) would allow to distinguish among all three models. 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.

Furthermore, in Fig. 1 we have also included the intrinsic error coming from the quantum uncertainty principle as proposed in Ref. [38]. The quantum uncertainty principle implies an intrinsic uncertainty on length scales at the level of \( \ell_p \) only 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 be negligible. This is confirmed by Fig. 1 in which each curve is actually a very narrow band obtained by considering \( \Delta = \ell_p \pm \ell_p/2 \), i.e. we included an intrinsic uncertainty \( \pm \ell_p/2 \) [38]. As clear from Fig. 1 this effect is negligible compared to the statistical errors on \( \lambda \). This is consistent also with Fig. 1 in Ref. [38] and with the fact that the wavelengths relevant for this system are of the order of the orbital separation of the binary, \( d \gg O(M) \sim O(10^{45}) \left( \frac{M}{10^8 M_\odot} \right) \ell_p \) at least.

**Probing quantum structures at the horizon?** Our results confirm and extend the analysis of Ref. [12], suggesting that not only it should 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 the GW measurement of the TLNs in NS binaries. 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 [38]. 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 ef-
fects in compact stars is provided by Chandrasekhar’s mass limit \[ M_{\text{Ch}} \sim \frac{M_P^2}{m_H}, \] 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 \( M_{\text{Ch}} \propto \hbar^{3/2} \) 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, we do not disagree with the motivation for the analysis of Ref. [23]. However, as we argue here 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 [6, 13, 45], 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 uncertain event rates and on the ability of building accurate waveforms.

Finally, we conclude by reminding that probing near-horizon corrections as small as Planckian would only be possible if ECO models displaying logarithmic corrections exist [13, 20, 27]. Other models (such as the one studied in Ref. [40]) might display a power-law behavior, \( k_2 \sim (\Delta/M)^n \), in which case an analysis similar to what shown in Fig. 1 can be done for models in which \( \Delta \gg \ell_P \). For example, if \( k_2 \sim \Delta/(2M) \) and \( M \approx 10^7 M_\odot \), models with \( \Delta = 10^9 \) km would have the same TLN of the models discussed above with \( \Delta = \ell_P \), and in such case a GW measurement of the TLN would not probe any quantum scale.

For models that do not show a logarithmic behavior, the measurement of the tidal heating (i.e., absorption by a putative horizon which modifies the binary dynamics) might allow for more stringent corrections than those coming from measuring the TLNs, since tidal heating enters at lower post-Newtonian order in the inspiral phase [12]. Indeed, in certain models the TLNs might be too small to be measurable, but the absence of tidal heating would provide a sharper smoking gun for quantum corrections at the horizon scale.

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