Testing Quantum Gravity with LIGO and VIRGO

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We argue that if particularly powerful electromagnetic afterglows of the gravitational waves bursts detected by LIGO-VIRGO will be observed in the future, this could be used as a strong observational support for some suggested quantum alternatives for black holes (e.g., firewalls and gravastars). A universal absence of such powerful afterglows should be taken as a suggestive argument against such hypothetical quantum-gravity objects.

If there is no matter around, an inspiral-type coalescence (merger) of two uncharged black holes with masses M_1, M_2 into a single black hole with the mass M_3 results in emission of gravitational waves, but no electromagnetic radiation. The maximal amount of the gravitational wave energy $E/c^2 = (M_1 + M_2) - M_3$ that may be radiated from a merger was estimated by Hawking [1] from the condition that the total area of all black hole horizons cannot decrease. Because the horizon area is proportional to the square of the black hole mass, one has $M_3^2 > M_2^2 + M_1^2$. In the case of equal initial masses $M_1 = M_2 = M$, this yields [1],

$$\frac{E}{Mc^2} = \frac{1}{M}\left[(M_1 + M_2) - M_3\right] < \frac{1}{M}\left[2M - \sqrt{2M^2}\right] \approx 0.59. \tag{1}$$

From advanced numerical simulations (see, e.g., [2–4]) one gets, in the case of comparable initial masses, a much more stringent energy estimate,

$$\frac{E_{\mathrm{GRAV}}}{Mc^2} \approx 0.03; \text{ meaning that } E_{\mathrm{GRAV}} \approx 1.8 \times 10^{52}\left(\frac{M}{M_\odot}\right)[\mathrm{erg}]. \tag{2}$$

The estimate assumes validity of Einstein's general relativity.

Recently, the LIGO antennas detected a burst of gravitational radiation, emitted by a black hole merger, that lasted $\Delta\, t = 0.12$[sec] and emitted the energy of $3M_\odot c^2$, so its average luminosity was[5],

$$L_{\mathrm{GRAV}} = \frac{3\mathrm{M}_\odot c^2}{0.12[\mathrm{sec}]} = 1.7 \times 10^{55}[\mathrm{erg/sec}] = 0.5 \times 10^{-4}\left(\frac{c^5}{G}\right), \tag{3}$$

where $c^5/G = 3.6 \times 10^{59}$[erg/sec] is the Planck unit of power. The LIGO and VIRGO teams estimated [5] from a very detailed analysis of the waveform registered during the event that the initial (comparable) masses of the black holes were $M_1 = 29M_\odot$ and $M_2 = 36M_\odot$, and that the final mass was $M_3 = 62M_\odot$. The analysis was done assuming the validity of standard Einstein's general relativity in a fully dynamical context.

In binary systems consisting of a star which looses matter and a black hole which accretes this matter through a thin accretion disk, the mass of the disk cannot be much larger than,

$$m < 10^{-6}\, M. \tag{4}$$

In the double black hole system detected by LIGO, there is no matter source. If there was any matter there, its mass should be small in comparison to the final black hole mass $M = M_3$. Adopting a kind of a rough upper limit, derived from accretion disk theory (4), and assuming a high efficiency of converting mass to radiation, $\eta = 0.1$, one may say that the LIGO event may be accompanied by an "afterglow" in electromagnetic radiation with a luminosity not larger (and most probably much smaller) than[1],

$$L_{\mathrm{EM}} = \left(\frac{10^{-7}\, M\, c^2}{\Delta t}\right) = 6 \times 10^{43} \left(\frac{M}{M_\odot}\right) [\mathrm{erg/sec}] \approx 3.6 \times 10^{49} [\mathrm{erg/sec}]. \qquad (5)$$

This conclusion will be modified if the coalescence results in ultra relativistic outflows, like those in gamma ray bursts (GRBs). In this case the radiation will be strongly beamed in a cone with the width $1/\Gamma$, where Γ is the Lorentz factor of the outflow. The accelerated beams would then be observable only for favourable source orientation. However constraints on such beaming may be placed by statistics of the GRBs.

There were attempts to find such an afterglow in gamma rays by the satellite Fermi [6]. Results are not conclusive, however the GMB data revealed a flare above 50keV that started 0.4s after the gravitational wave burst. The false alarm probability of the association between the two phenomena is 0.0022, and thus the identification is not conclusive. Assuming that the two events come from the same source the luminosity of the gamma ray flare was $L_\gamma = 1.8 \times 10^{49}$[ergs/sec] in the band between 1 [keV] and 10 [MeV], so $L_\gamma / L_{\mathrm{GRAV}} \approx 2 \times 10^{-6}$.

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[1] In the case of stationary accretion a much lower limit - the Eddington luminosity would apply. For a $62 M_\odot$ black holes this limit would be $L_{\mathrm{Edd}} = 7.5 \times 10^{39}$[erg/sec]. However, the event is certainly not stationary, so the Eddington luminosity should be only considered as a reference.

We argue here that collisions of firewalls [7], gravastars [8], or other "quantum-gravity alternatives" to standard Einstein's black holes, may have luminosity of the gravitational wave afterglows 10^6 times larger than that expected in the standard scenario of Einstein's black hole merger (5), and that this is observationally testable. The reason is these "quantum" objects would be expected to have a mass content m comparable with the total mass, i.e. $m \approx M$. Below, we explain why.

Quantum entanglement of Hawking radiation leads to the the black hole information paradox. One of the suggested remedies for the paradox supposes the existence of a Planck density $\epsilon_{\rm P}$ "firewall" with a Planck thickness $\ell_{\rm P}$ near the black hole horizon [7]. One may estimate the firewall mass m neglecting the effect of backreaction on the Einstein field equations i.e. by assuming that the firewall mass $m = \epsilon_{\rm P}\ell^*_{\rm P}\mathcal{A}$ is much smaller than the black hole mass M. Here $\mathcal{A} = 16\pi M^2$ is the area of the black hole horizon and $\ell^*_{\rm P}$ is a "proper" Planck length in the Schwarzschild geometry. This simple calculation has been done in [9]. The result,

$$m = 4\pi M, \tag{6}$$

shows that the assumption $m \ll M$ is not correct. Therefore, one should calculate the back reaction of the mass of the firewall on the metric. In doing this, one must use some kind of field equations that link the matter distribution and geometry. This was carefully done in [9], where validity of the standard Einstein field equations was assumed (as there are no quantum gravity field equations known, associated with firewalls). The conclusion was that *Planck density firewalls are excluded by Einstein's equations for black holes of mass exceeding the Planck mass*[2]. Although

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[2] For different reasons, other authors have also criticized the firewall concept. Susskind's paper on firewalls [10]

for many physicists today arguments based on the standard Einstein equations are not decisive, everyone should accept the point that we present here: *independently* on whether Einstein's field equations are correct or not, *if the Planck density firewalls exist*, they should have masses comparable with masses of their host black holes, $m \approx M$.

Static, spherically symmetric gravastars models [8] are exact solutions of the standard Einstein field equations. A gravastar with the total mass M consists of a dark energy sphere, with a radius nearly equal to the gravitational radius $r_{\rm G} = 2MG/c^2$, surrounded by a Planck thickness shell of matter with the extreme equation of state $p = c^2\epsilon$. Outside the gravastar, $r > r_{\rm G}$, the metric is that of the standard vacuum Schwarzschild. Thus, obviously, for gravastars one has $m = M$.

When field equations of a particular quantum gravity theory are known, it is of course (in principle) possible to calculate, in a very detailed way, all observational consequences of collisions of "black holes" predicted in the theory. This is the case of Hořava's quantum gravity [11] (see a list of relevant references in [12]). Calculating Hořava's black hole ringdown may be particularly interesting in the view of the recent argument that the gravitational ringdown may not be a probe of the event horizon [13]. One of the arguments discussed in [13] in the context of the gravitational radiation, resembles what was pointed out in [14], namely that there is no observational proof possible for the existence of the event horizon, based on electromagnetic radiation. These observations may probe only the existence of the circular light ray (at $r = 1.5\, r_{\rm G}$ in the Schwarzschild spacetime) but not smaller radii.

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has been withdrawn with a comment "the author no longer believes the firewall argument was correct"

Our point that collisions of standard black holes (with “pure” horizons) are much dimmer in electromagnetic radiation than collisions of non-standard quantum black holes (with no horizon or with a “dirty” horizon), resembles arguments advocated by Lasota, Narayan and others [15], [16] that accreting black holes are much dimmer than similarly accreting neutron stars.

We wish to conclude that: (1) At present, most of the proposed quantum alternatives to the standard Einstein black holes, for example firewalls, do not follow from a consistent mathematical descriptions. (2) Nevertheless, these alternatives make qualitative predictions with observationally testable consequences. (3) A testable prediction of firewalls, for example, is that there could be powerful afterglows in electromagnetic radiation associated with the gravitational wave bursts emitted during firewall collisions. (4) Existence of such afterglows will be a strong observational support for several quantum alternatives for black holes, its universal absence will be an argument against.

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