Pis'ma v ZhETF, vol. 103, iss. 10, pp. 708 – 710

On constraining the speed of gravitational waves following GW150914

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Submitted 12 April 2016

We point out that the observed time delay between the detection of the signal at the Hanford and Livingston LIGO sites from the gravitational wave event GW150914 places an upper bound on the speed of propagation of gravitational waves, $c_{gw} \lesssim 1.7$ in the units of speed of light. Combined with the lower bound from the absence of gravitational Cherenkov losses by cosmic rays that rules out most of subluminal velocities, this gives a model-independent double-sided constraint $1 \lesssim c_{gw} \lesssim 1.7$. We compare this result to model-specific constraints from pulsar timing and cosmology.

DOI: 10.7868/S0370274X16100039

I. Introduction. The recent discovery of gravitational waves (GWs) by the LIGO collaboration [1] opens a window for testing fundamental properties of gravitation [2–4]. In this short note, we point out that these results can be used to bound the speed of propagation of GWs in a model-independent manner, giving complementary, if weaker, constraints to model-specific ones already in the literature.

If one considers that GWs propagate as free waves, one can parameterize the dispersion relation of their frequency ω and momentum $k = |\mathbf{k}|$ by the generic formula (we restrict to theories where gravitational waves are described by equations with two time-derivatives and assume rotational invariance),

$$\omega^2 = m_{gw}^2 + c_{gw}^2 k^2 + \alpha_{(4)} \frac{k^4}{\Lambda^2} + ..., \qquad (1)$$

where we have introduced a mass m_{gw} term, the possibility of a speed of propagation c_{gw} different from[2)] 1 for modes $k \ll \Lambda$ and a high scale Λ beyond which dispersive effects become relevant. The modification of the velocity and the dispersion appear in some approaches to quantum gravity [5, 6]. The mass m_{gw} has already been constrained by the LIGO collaboration in [2]: $m_{gw} \leq 1.2 \times 10^{-22}$ eV by studying the arrival time of different frequency components of the signal that has traveled across ~ 400 Mpc.

We will assume that the high-energy scale Λ is much higher than the characteristic frequency of the signal ~ 100 Hz, and that m_{gw} satisfies the LIGO bound. LIGO Collaboration has not placed a constraint on c_{gw}: in [2], $c_{gw} = 1$ is assumed in order to allow for the localization of event GW150914 in the sky. In this note, we point out that independently of the degeneracy with the source direction, GW150914 can be used to place the first *model independent upper* bound on c_{gw}.

II. Existing bounds on c_{gw}. We first remind that the interesting region to constrain corresponds to

$$1 - c_{gw} \lesssim 10^{-15}. \qquad (2)$$

This is a conservative bound arising from the absence of gravitational Cherenkov radiation allowing for the unimpeded propagation of high-energy cosmic rays across our galaxy [7] (see [8] for an earlier study and also [9] for the study with generic dispersion relations). Note that another lower bound $1 - c_{gw} \lesssim 10^{-2}$ can be obtained from pulsar timing [10]. Though weaker, this bound directly constrains the speed of classical gravitational waves and is independent of the microscopic interactions of gravitons with high-energy particles.

Second, regarding upper bounds, let us note that for theories where Lorentz invariance is broken at the fundamental level, there is no theoretical argument (or pathology) against signals propagating faster than

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2) We work in the units where the speed of light is equal to 1.

light [6, 11]. Furthermore, these theories provide a set-up where gravity can be potentially quantized using the standard framework of quantum field theory in 4-dimensions [12, 13]. Thus, a measurement of c_{gw} is a concrete application of LIGO results to test the ideas of quantum gravity.

Upper bounds on c_{gw} can and have been obtained from various astrophysical and cosmological tests. However, these bounds are model dependent. For instance, in the case of Lorentz-violating theories, the bounds from radiation damping in binary systems imply $c_{gw} - 1 \lesssim 10^{-2}$ [14]. Similar constraints have been derived is scalar-tensor theories [15] and using cosmology[3] [18, 19]. Forecasts for different constraints using advanced detectors can be found in [20]. See also [21] for the constraints on the speed of cosmological gravitational waves with future CMB instruments.

III. Upper bounds from GW150914. There is clearly an interest in setting an upper bound on c_{gw}. Let us recall that in [1, 2] this was not done since it was assumed that $c_{gw} = 1$ and the difference in the time of arrival of the signal to the different interferometers of LIGO was used to localize the event.

One can also take a different view. We use the fact that the two LIGO sites at Livingston (L1) and Hanford (H1) separated by the distance of $d = 10$ ms light travel time have detected the signal with the time shift of $\Delta t = 6.9^{+0.5}_{-0.4}$ ms [1]. This time delay is equal to the projection $l_\perp$ of the intersite distance d on the direction perpendicular to the gravitational wavefront (see Fig. 1), divided by c_{gw},

$$\Delta t = l_\perp / c_{gw}. \quad (3)$$

Independently of the arrival direction of the GW, $l_\perp$ cannot be larger than the intersite distance d itself which gives the bound

$$c_{gw} \Delta t \leq d. \quad (4)$$

Substituting conservatively the minimal value of Δt within two-sigma deviation from the mean, we get,

$$c_{gw} < 1.7. \quad (5)$$

IV. Discussion. We have shown how our very naive reinterpretation of the analysis of the detection of GW150914 sets the first direct bound on the speed of propagation of GWs, Eq. (5). This bound complements the lower bound coming from observations of high-energy cosmic rays (2).

[3] In principle, one can use the fact that $c_{gw} \neq 1$ is related to the presence of gravitational slip to eventually produce stronger bounds from cosmology [16, 17].

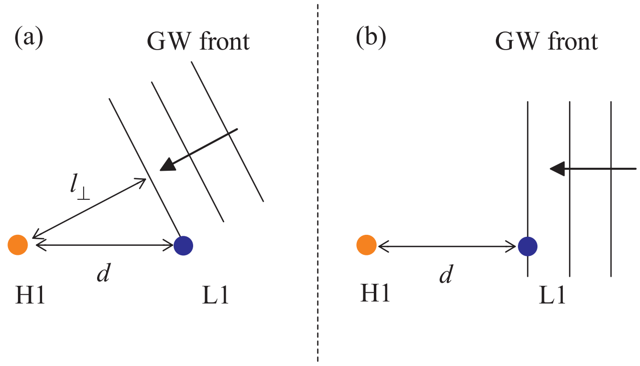

Fig. 1. (Color online) (a) – Incidence of GW from a generic direction. (b) – Orientation giving the maximal time delay

Our constraint is already interesting and yet very conservative. We believe it can be improved by considering other features of the event, such as orientations of the detectors and the resulting antenna patterns, the amplitudes of the waveforms measured at the two sites or more information about the position of the source in the sky.

We have made the assumption that the change in the emission process as a result of a modification of gravity would not affect the measurement of the time delay between the two waveforms significantly, even if it would affect the determination of the source parameters. One can envisage two approaches to relax this assumption. The first is to develop complete numerical simulations of compact binary coalescence in existing theories predicting deviations of c_{gw} from 1. Alternatively, one can focus just on the propagation of the GW and implement a data analysis that would disentangle the measurement of the time delay from the model of the GW emission.

We believe that the results obtained by pursuing both these directions will be of great value to fundamental physics.

This work was supported by the Swiss National Science Foundation (M. I. and S. S.), the RFBR grant 14-02-00894 (M. I.), and by the Maria Sklodowska-Curie Intra-European Fellowship Project "DRKFRCS" (I. S.).

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