Constraints on Lorentz Invariance Violations from Gravitational Wave Observations

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Using a deformed dispersion relation for gravitational waves, Advanced LIGO and Advanced Virgo have been able to place constraints on violations of local Lorentz invariance as well as the mass of the graviton. We summarise the method to obtain the current bounds from the 10 significant binary black hole detections made during the first and second observing runs of the above detectors.

1. Introduction

The year 2015 saw the advent of gravitational wave (GW) astronomy with GW150914\(^1\), the first directly detected GW signal from a binary black hole (BBH) merger. Ref. 2 performed tests on strong-field gravity in the highly dynamical regime of general relativity (GR), finding no statistically significant violations of GR. Since then, 10 significant BBH signals have been detected, in addition to a binary neutron star (BNS) signal\(^4\). The first constraints on local Lorentz invariance violation (LIV) using real GW data were reported in Ref. 3. These bounds have been revised recently and reported in Ref. 7. These bounds, however, rely on the propagation effects and therefore do not directly probe the dynamical regime of gravity.

In this proceedings, we give a brief overview of the method to constrain LIV in Sec. 2 and summarise the results with some concluding remarks in Sec. 3.

2. Method

GWs propagating in GR are non-dispersive and travel with the speed of light. Following Refs. 5, 6, we adopt the generic dispersion relation

\[
E^2 = p^2 c^2 + A_{\alpha} p^\alpha c^\alpha. \tag{1}
\]
This is a Lorentz violating dispersion relation for $\alpha > 0$, the LIV parameter is characterised by $A_\alpha$. $\alpha = 0$ is a special case where we may parameterise the additional term in Eqn. 1 as $A_\alpha = m_g^2 c^4$, $m_g$ being the mass of the graviton. Examples of Lorentz violating theories for specific forms of Eqn. 1 include Doubly Special Relativity for $\alpha = 3$ and Ho\v{r}ava-Lifshitz theory for $\alpha = 4$, cf. Refs. 3, 7 for more examples and corresponding references.

As noted in Ref. 3, a combination of values of $\alpha$ and the sign of $A_\alpha$ can indicate whether the speed of GWs is subluminal or superluminal.

In the presence of dispersion, the low (high)-frequency components of a GW signal travel slower (faster) and result in an overall offset in arrival times at the detector, leading to a frequency-dependent shift in the phasing. In frequency domain (FD), the total phase is then given by

$$\Psi(f) = \Psi_{GR}(f) + \Psi_\alpha(f).$$

$\Psi_{GR}(f)$ is the phasing obtained from GR predictions and $\Psi_\alpha(f)$ denotes the phase shift following from the dispersion. The waveform model in FD used in our analyses is constructed by

$$\tilde{h}(f) = A(f) e^{-i\Psi_\alpha(f)}.$$ 

In the above equation, $M$ is the detector-frame chirp mass of the binary system, a combination of component masses given by $M = (m_1 m_2)^{3/5} / (m_1 + m_2)^{1/5}$, $m_1$ and $m_2$ being the component masses. $f$ is the frequency component and $Z$ denotes the redshift to the source. $D_\alpha$ is a cosmological distance, see Refs. 5, 7 for more details.

The analyses carried out in the following section is based on a Bayesian framework which incorporates the Bayes’ theorem

$$p(\theta \mid d) = \frac{p(d \mid \theta) p(\theta)}{p(d)},$$

where $\theta$ refers to a parameter set, $d$ refers to the data, $p(\theta \mid d)$ refers to the posterior probability density obtained on $\theta$ from the likelihood calculated from the data $p(d \mid \theta)$ and the a priori probability density given by $p(\theta)$. $p(d)$ is a normalisation constant. The information learnt from the data is folded in the likelihood which takes the following form

$$p(d \mid \theta) \propto \exp \left[ -\frac{1}{2} (d - h|d - h) \right].$$

In the presence of a GW signal, the data output from the detector is $d = h(t) + n(t)$, where $h(t)$ is the GW signal and $n(t)$ is the noise. For our
analyses, the likelihood integral is computed in FD by including the LIV-deformed phase in the model waveform. For a value of $\alpha$, this enables us to obtain a posterior probability density function on the parameter $A_\alpha$, leading to a constraint on LIV.

3. Results

Being a propagation effect, the strongest constraints come from events located at larger luminosity distances. The bounds obtained from the catalogue of 10 sources are presented in Fig. 1. The current bounds obtained from combining all sources lead to an improvement in previously reported bounds$^3$ by factors up to 2.4 as reported in Ref. 7.

![Fig. 1. 90% credible upper bounds on $A_\alpha$ from the BBH detections GW150914, GW151226 and GW170104 (triangles) and those from combining all 10 significant BBH detections (diamonds) in O1 and O2 as given in Ref. 7. Same as Fig.5 of Ref. 7 but grayscaled.](image)

From combining these sources, the mass of the graviton has been constrained to $m_g \leq 5.0 \times 10^{-23}$ eV/c$^2$ at 90% confidence.
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