Constraining Lorentz invariance violation using gravitational wave observations

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in collaboration with

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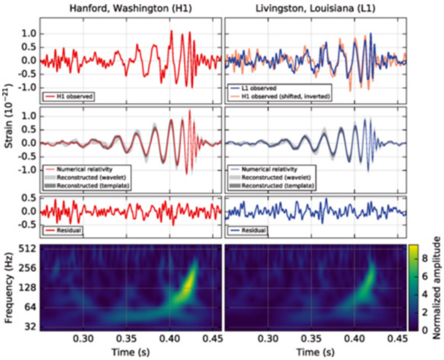
- The first GW signal GW150914 constrained the graviton mass m_g and its Compton wavelength λ_g to $m_g <= 1.2 \times 10^{-22}$ eV/c^2 and $\lambda_g > 10^{13}$ km [1].
- This was done by adding a mass-dependent term in the dispersion relation without invoking a specific massive-gravity model.
- We introduce a more generic dispersion relation which is Lorentz violating.



B.P.Abbott et al. 2016
The LIGO and VIRGO Scientific Collaborations

[1] B.P.Abbott et al. 2016, The LIGO and VIRGO Scientific Collaborations

Overview of the idea

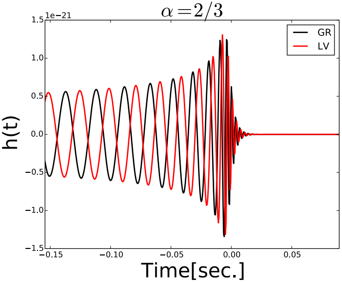
- With a modified dispersion, GWs emitted at different frequencies will be travelling at different speeds ⇒ Difference in times of arrival.
- Offset in arrival times lead to dephasing of waveform w.r.t GR predictions.
- Constraints on phasing used to constrain the magnitude of dispersion.
- Model independent way of testing LV by invoking a modified dispersion relation.
- We use effects only due to GW propagation ignoring generation of Lorentz violating GWs.

- Generic dispersion relation:

$$E^2 = p^2c^2 + \mathbb{A}p^\alpha c^\alpha$$

Mirshekari et al., 2012

$\mathbb{A}$, α: Lorentz violating parameters.



Propagation effects

- Define length scale $\lambda_{\mathbb{A}} = hc\,\mathbb{A}^{\frac{1}{(\alpha-2)}}$.
- $\alpha = 0, \mathbb{A} > 0;\ \lambda_{\mathbb{A}} \equiv \lambda_g\ (\lambda_g = \frac{h}{m_g c})$.
- $D_\alpha = \int_0^z \frac{(1+z')^{\alpha-2}}{\sqrt{\Omega_m(1+z')^3+\Omega_\Lambda}}$.
- $\frac{v_g}{c} = 1 + \frac{(\alpha-1)}{2}\mathbb{A}E^{\alpha-2}$.

- $\mathbb{A} > 0, \alpha > 1$ **or** $\mathbb{A} < 0, \alpha < 1 \Rightarrow v_g > c$ (superluminal).
- $\mathbb{A} < 0, \alpha > 1$ **or** $\mathbb{A} > 0, \alpha < 1 \Rightarrow v_g < c$ (subluminal).
- $\alpha = 1 \Rightarrow v_g = c$.

$$\Delta t_a = (1+z)\left[\Delta t_e + \frac{D_\alpha}{2\lambda_{\mathbb{A}}^{2-\alpha}}\left(\frac{1}{f_e^{2-\alpha}} - \frac{1}{f_e'^{2-\alpha}}\right)\right]$$

Method

- Frequency domain phase: $\Psi(f) = \Psi_{GR}(f) + \delta\Psi_{\alpha}(f)$.

- $\delta\Psi_{\alpha\neq 1} = -\frac{\pi}{1-\alpha}\frac{\mathbb{A}D_{\alpha}}{(hc)^{2-\alpha}}\left[\frac{(1+z)f}{c}\right]^{\alpha-1}$
- $\delta\Psi_{\alpha=1} = \frac{\pi\mathbb{A}D_1}{hc}\ln(\frac{\pi G\mathcal{M}f}{c^3})$.

- $\delta\Psi_{\alpha\neq 1} = -\text{sign}(\mathbb{A})\frac{\pi}{1-\alpha}\frac{D_{\alpha}}{|\lambda_{\mathbb{A}}|^{2-\alpha}}\left[\frac{(1+z)f}{c}\right]^{\alpha-1}$
- $\delta\Psi_{\alpha=1} = \text{sign}(\mathbb{A})\frac{\pi D_1}{|\lambda_{\mathbb{A}}|}\ln(\frac{\pi G\mathcal{M}f}{c^3})$.

Mirshekari et al., 2012

- GW observations directly estimate luminosity distance D_L; redshift z inferred from D_L assuming ΛCDM cosmology.
- We developed an analysis scheme within Bayesian inference to carry out the proposed test of GW dispersion.

Constraining the wavelength scale of dispersion

- We simulate waveforms conforming to GR and use Lorentz violating waveforms as templates.

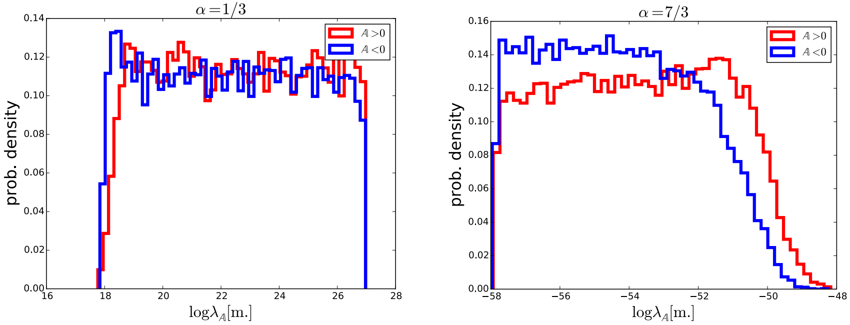


Figure : For $40 + 33\ M_{\odot}$ binary at 500 Mpc; using O1-like sensitivity.

Simulation Results

$$\boxed{\lambda_{\mathbb{A}} = hc\ \mathbb{A}^{\frac{1}{(\alpha-2)}}}$$

Table : Estimated bounds from a simulated $40 + 33\ M_{\odot}$ binary at $D_L = 500$ Mpc.:

α	$\mathbb{A} > 0[\mathrm{eV}^{2-\alpha}]$	$\lambda_{\mathbb{A}>0}[\mathrm{m.}]$	$\mathbb{A} < 0[\mathrm{eV}^{2-\alpha}]$	$\lambda_{\mathbb{A}<0}[\mathrm{m.}]$
0.0	$< 7.19 \times 10^{-45}$	$> 1.46 \times 10^{16}$	$< 1.49 \times 10^{-44}$	$> 1.02 \times 10^{15}$
$\frac{1}{3}$	$< 2.00 \times 10^{-40}$	$> 8.18 \times 10^{17}$	$< 2.02 \times 10^{-40}$	$> 8.13 \times 10^{17}$
$\frac{7}{3}$	$< 3.40 \times 10^{-15}$	$< 4.88 \times 10^{-50}$	$< 2.12 \times 10^{-15}$	$< 1.18 \times 10^{-50}$

Detecting possible GW dispersion

- $\lambda_{\mathit{eff}} = \left[\left(\frac{D_L}{D_\alpha} \right)^{\frac{1}{2-\alpha}} (1+z)^{\frac{1-\alpha}{2-\alpha}} \right] \lambda_{\mathbb{A}}.$
- $B^{LV}_{GR} = \frac{\mathrm{p(data|LV)}}{\mathrm{p(data|GR)}}.$

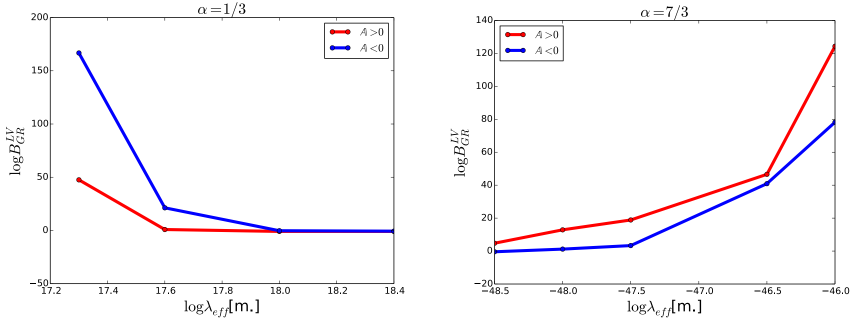


Figure : For $40 + 33\ M_\odot$ binary at 500 Mpc; using O1-like sensitivity.

Conclusions

- Developed a Bayesian parameter estimation method to constrain Lorentz violations using GW observations.
- Results from simulations indicate GW observations can put first ever constraints on Lorentz invariance violations from the purely gravitational sector.