PROCEEDINGS OF SCIENCE

Gravitational waves propagation as a probe of new fundamental physics

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The direct detection of gravitational waves opened an unprecedented channel to probe fundamental physics. Several alternative theories of gravitation have been proposed with various motivations, including accounting for the accelerated expansion of the Universe and the unification of fundamental forces. The study of gravitational waves propagation enables putting several predictions from those proposed theories to test, with the advantages of presenting deviations that are source-independent and tractable over the complete waveform signal. This proceeding presents an overview of the recent searches for anomalous propagation effects using the events detected by the LIGO-Virgo-KAGRA collaboration during the three observational runs. Several proposals, such as massive gravity and unified theories, predict a frequency-dependent dispersion of the gravitational waves breaking local CPT and/or Lorentz symmetry. Constraints on the dispersion coefficients are obtained from the analysis of the gravitational waveform signals using an effective field theory framework. Using inferred wave and source properties from candidate multimessenger events, constraints are independently obtained on the speed of gravity, the presence of large extra dimensions and scalar-tensor gravitation theories parameterizations.

41st International Conference on High Energy physics - ICHEP2022
6-13 July, 2022
Bologna, Italy

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[*] Speaker

PoS(ICHEP2022)076

1. Introduction: status of gravitational waves detections

The three first observing runs of the LIGO-Virgo-KAGRA (LVK) collaboration led to the detection of 90 gravitational-waves (GW) events. All the events originate from the coalescence of binary systems of black holes and/or neutron stars, and are reported in the following Gravitational-Wave Transient Catalogs (GWTC):

- GWTC-1: 11 GW events detected during the first and second observing runs [1]
- GWTC-2.1: 44 GW events detected during the first half of the third observing run [2]
- GWTC-3: 35 GW events detected during the second half of the third observing run [3]

The sources have masses comprised between 1.17 and 105.5 $M_\odot$ and luminosity distances between 0.04 and 8.28 Gpc. A variety of tests have been performed to test the agreement of the detected signals with predictions from General Relativity (GR) [4]. Those tests include residual tests, consistency tests between different part of the waveform, parameterized tests including deviations across several waveform frequencies, searches for extra GW polarizations and tests of GW propagation. Modified GW propagation is the focus of this proceeding, as it presents the advantage of probing source-independent deviations enabling to perform joint analyses with several types of GW emitters. The effects may also be cumulative, potentially leading to an amplification of small-scale deviations, particularly for sources located at large distances where the spacetime regime is notably dynamical due to the accelerated expansion of the Universe. This proceeding reviews the constraints obtained with various propagation tests, on the graviton mass, speed of gravity, scalar-tensor theories, and provides a specific focus on new results concerning spacetime symmetry breaking tests.

2. Gravitational waves propagation

A general formula for modified GW equation of motion during propagation is given by:

$$h''_{ij} \ + \ (2+\nu)\, H\, h_{ij} + (c_{GW}^2 k^2 \ + \ a^2\mu^2)\, h_{ij} \ = \ a^2\, \Gamma\, \gamma_{ij} \tag{1}$$

where ν is the Planck mass run rate, H the Hubble constant, c_{GW} the GW velocity, a the cosmological scale factor, μ the graviton mass, and $\Gamma\, \gamma_{ij}$ due to anisotropic stress [5]. This equation corresponds to the GR case when $\nu = \mu = \Gamma = 0$ and $c_{GW} = c_{EM}$.

A non-zero value of ν can lead to GW friction, i.e. a frequency-independent dispersion impacting only the amplitude of the signal. In such case, the luminosity distance inferred from the GW amplitude would differ from the distance obtained from the redshift of the electromagnetic (EM) waves emitted by a multimessenger source. With the binary neutron star merger event GW170817 / GRB170817A located 40 Mpc away, constraints on friction due to a running Planck mass have been obtained with a joint estimation of the cosmological parameters [6]. Studying the sensitivity given by a multimessenger event located at a luminosity distance of $\sim$ 5 Gpc such as GW190521, large extra dimensions and scalar-tensor theories of gravity proposals have been put under tests as well.

When multimessenger events emit GW and EM radiation coincidentally, the arrival time of the signals can be compared to measure the speed of gravity. From the simultaneous detection of GW170817 and GRB170817A, deviation from the speed of light has been constrained to be less than $O(10^{-15}\text{m/s})$ [7].

In the case of a modified dispersion of GW that is frequency-dependent, the waveform morphology is distorted and can be studied with GW signals only, without relying on complementary emissions. Such dispersion can be parameterized by adding an extra term to the energy relation [8]:

$$E^2 = p^2c^2 + m_g^2c^4 + \mathbb{A}p^\alpha c^\alpha \tag{2}$$

where $\mathbb{A}$ and α are extra parameters inducing Lorentz invariance violation, leading to a frequency-dependent, polarisation-independent, isotropic dispersion. Selecting 45 significant events (with false alarm rate $\leq 10^{-3}\text{yr}^{-1}$), constraints on the order of $O(10^{-20}\text{m/s})$ have been obtained on the $\mathbb{A}$ parameter for semi-integer values of α between [0;4] [4]. The case where $\alpha = 0$, $\mathbb{A} > 0$ corresponds to a GW dispersion due to a massive graviton, enabling to constrain the mass of the graviton to $m_g < 1.27 \cdot 10^{-23}$ eV/c^2.

3. Spacetime symmetry breaking

An effective field theory framework, referred to as the Standard Model Extension (SME), has been designed with the purpose of deriving phenomenological consequences of spontaneous spacetime symmetry breaking [9]. The addition of new terms in the linearised GR Lagrangian:

$$\mathcal{L}_{SME} = \mathcal{L}_{GR} + \frac{1}{4} h_{\mu\nu} \left(\hat{s}^{\,\mu\nu\rho\sigma} + \hat{q}^{\,\mu\nu\rho\sigma} + \hat{k}^{\,\mu\nu\rho\sigma}\right) h_{\rho\sigma} \tag{3}$$

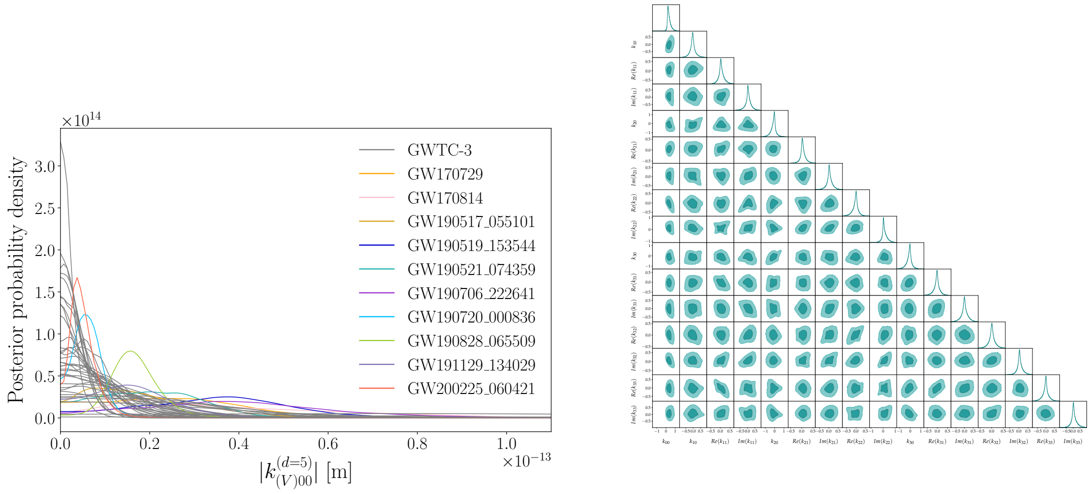
leads to a modified GW dispersion with different observables according to the mass dimensions of the extra fields.

At mass dimensions $d = 4$, corresponding to nine Lorentz-violating $\hat{s}$ operators, the dispersion is frequency-independent, leading to a modification of the speed of gravity. Constraints on the order of $O(10^{-5})$ (for the first operator $s_{00}^{(d=4)}$) and $O(10^{-14})$ (for the other operators $s_{lm}^{(d=4)}$) have been obtained from the measurement of the GW velocity described on Section 2 [7].

At mass dimension $d = 5$, both Lorentz invariance and CPT symmetry breaking occur, and the dispersion is frequency and polarization-dependent as shown by the modified strain [10]:

$$h_{+,\times}^{SME} = \cos\beta\, h_{+,\times}^{GR} \mp \sin\beta\, h_{\times,+}^{GR} \tag{4}$$

where $h_{+,\times}$ are the GW polarizations, $\beta = \omega\tau \left| \sum_{lm} Y_{lm}(\theta,\phi)\, k_{(V),lm}^{(d=5)} \right|$ is the mass dimension 5 correction factor with ω the frequency, $Y_{lm}(\theta,\phi)$ the spherical harmonics and $\tau = \int_0^z \frac{(1+z)^{d-4}}{H(z)} dz$ a cosmological term. Sixteen $\hat{k}$ operators are responsible for the dispersion, the first operator $k_{(V),00}^{(d=5)}$ inducing isotropic dispersion while the other $k_{(V),lm}^{(d=5)}$ lead to anisotropic, i.e., sky location-dependent, dispersion [11]. The $k_{(V),00}^{(d=5)}$ coefficient has been inferred jointly with the source parameters for the same sample of 45 events as described on Section 2 [12]. As shown on Figure 1a, each event lead to a constraint of $O(10^{-13})$ m, and 10 of the 45 events have a 68.3% credible interval (CI)



(a) **(b)**

Figure 1: **(a)** : Posterior probability on the isotropic dispersion coefficient $k^{(d=5)}_{(V),00}$ from 45 GWTC-3 events. Coloured lines are the distribution where the 68.3% CI is not compatible with GR, while the events in grey are compatible. **(b)** : Posterior probability of the $k^{(d=5)}_{(V),lm}$ coefficients (in 10^{-12} m). Dark cyan surfaces correspond to 68.3% CI and light cyan to 90% CI.

not compatible with the GR case of $k^{(d=5)}_{(V),00} = 0$. A reanalysis of several events, using different models to simulate the GW signals templates on which the dispersion correction is applied, shows that three events result in posteriors compatible with GR when higher harmonics are added to the model, or a different description of the binary dynamics is relied on. Additionally, eight of the ten events presenting deviations have shown pathological behavior in other types of GR tests, including residual, consistency or parameterized tests. [4]. When combining the posteriors of Figure 1a, the constraint on the $k^{(d=5)}_{(V),00}$ coefficient becomes $5.62 \cdot 10^{-16} < |k^{(d=5)}_{(V),00}| < 2.81 \cdot 10^{-15}$ m at 68.3% CI, and $|k^{(d=5)}_{(V),00}| < 3.19 \cdot 10^{-15}$ m at 90% CI. The deviation at 68.3% CI is alleviated when removing the events GW190720_000836, GW190828_065509 and GW200225_060421.

The measurements of the isotropic dispersion coefficient $k^{(d=5)}_{(V),00}$ from several events can be combined to extract joint bounds on the anisotropic coefficients $k^{(d=5)}_{(V),lm}$. The results are shown on Figure 1b, where the bias is still present for the first coefficient but not displayed by the others. The global bounds on the sixteen dispersion coefficients are on the order of $O(10^{-13})$ m [12].

4. Conclusion

GW astrophysics is a nascent field, yet the existing detections have already enabled to put several alternative theories of gravitation to test, including massive gravity and scalar-tensor theories. Propagation tests have been shown to be a powerful tool as they provide both agnostic tests as well as parameterizations that can be mapped to proposed models, and benefit from the ability of combining several events to extract constraints. As events showing deviations in other type of tests (residuals, consistency, additional degrees of freedom) also present biases in propagation tests, the latter are shown to be sensitive to a lack of physics in the waveform description. The results shown on Section 3 yet indicate that tests of GR are strongly dependent on the underlying waveform model, and outliers may indicate a lack of accuracy of the template used to model the GR signals rather than the presence of new physics. The GW community is therefore putting scrutiny to establish robust tests and study the impact of waveform models and transient noise on the results obtained, notably following the measurement of deviations from GR in some tests.

Such accuracy is primordial as those tests will become more precise in the following years. The improvement of the LVK interferometers will result in a higher detection rate for the fourth observing run, scheduled to start in Spring 2023. The next generation of GW interferometers, such as the Einstein Telescope, Cosmic Explorer or LISA, will access events at redshifts up to $z = 100$, providing the ability to reach a strongly dynamical regime and larger amplitude for cumulative deviations [13]. Therefore, the results shown in this proceeding are expected to become more precise thanks to the improved information from numerous detections and better detectors, but also with the improvement of the underlying components of those analyses.

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