SEARCHING FOR NEW PHYSICS DURING GRAVITATIONAL WAVE PROPAGATION

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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 to put several predictions from those proposed theories to test. 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 events detecting by the LIGO-Virgo-KAGRA collaboration during their three first observational runs. The speed of gravity, presence of extra dimensions and predictions from scalar-tensor theories are constrained using multimessenger events such as GW170817/GRB170817A.

1 Introduction

Following its third observational run, the LIGO-Virgo-KAGRA (LVK) collaboration reported the detection of a total of 90 gravitational-wave events, all originating from the coalescence of compact binary systems of black holes and/or neutron stars [1]. The gravitational waves signals can be analysed to infer the properties of the sources, but also to perform searches for new physics. A large panel of tests of general relativity have been performed with the LVK detections, including testing the consistency of the signal, probing the nature of black holes by searching anomalous features, and searching for additional polarisations of the waves [2]. This document describes searches for new fundamental physics affecting the propagation of gravitational waves, and is the proceeding of the presentation given at the *Rencontres de Blois on particle physics and cosmology* in 2021, available at this link: `https://indico.cern.ch/event/997281/contributions/4574361/attachments/2332476/3977182/01_Haegel.pdf`.

The existence of new physics coupling with gravitation can modify gravitational waves as they travel through spacetime. Probing new physics that occur during their propagation presents numerous advantages: on the observational side, small deformations may accumulate during the propagation and amplify Planck-scale effects, providing a way to probe the existence of a unified theory. On the phenomenological side, contrarily to test of gravitational waves generation, the deviation can be computed as an overall effect on the signal and is independent of the nature of the source, enabling to probe the large signal-to-noise ratio of the merger and to combine a large set of events [3]. The LVK detections, located up to ~ 8 Gpc away from Earth (corresponding to a redshift of $z = 1.14$), provide a new channel to probe new physics in the gravitational sector.

2 Theoretical framework

In the general relativity case, gravitational waves propagate as in the equation:

$$h''_{ij} \ + 2 \ H \ h_{ij} + c^2 \ k^2 \ h_{ij} \ = \ 0 \tag{1}$$

where h_{ij} is the gravitational-wave strain, H is the Hubble constant, c is the speed of light and k is the wavenumber. A general formulation of modified gravitational waves propagation is given by [4]:

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

where a is the cosmic scale factor, ν is the Planck mass run rate, c_T is the gravitational waves velocity, μ is the graviton mass and $\Gamma\gamma_{ij}$ is the anisotropic stress source term.

A massive graviton can lead to gravitational waves being dispersed, while the existence of anisotropic stress can be probed in the context of effective field theory designed to search for the existence of spacetime symmetry breaking. In both cases, the gravitational wave signal is deformed, and the corresponding physics can be probed with the LIGO and Virgo detections as described on Section 3. A non-0 Planck mass run rate can impact the gravitational wave amplitude, while the signal will reach Earth at a different time than predicted by general relativity if their velocity is sub or supraluminal ($c_T \neq c$). Both of those effects can be probed with multimessenger events where the coincident detection of gravitational waves and electromagnetic radiation or astroparticles can provide independent information on the timing and/or distance of the event as described on Section 4.

3 Tests with gravitational-waves events

3.1 Graviton mass and modified dispersion relation

Several alternative theories of gravitation assume that Lorentz invariance is violated. An observational consequence of this change of paradigm is the possible dispersion of gravitational waves, that can be parameterised by adding a term to the equation of the conservation of energy as in the modified dispersion relation [5]:

$$E^2 = p^2c^2 + m_g^2c^4 + \mathbb{A}p^\alpha c^\alpha \tag{3}$$

The extra term $\mathbb{A}p^\alpha c^\alpha$ leads to a frequency-dependent, polarisation-independent, isotropic dispersion of the gravitational wave that can be observed as a modification of the strain detected by the LIGO and Virgo detectors. By analysing the signals recorded by the interferometers, the LVK collaboration constrains the value of $\mathbb{A}$ for discrete values of $\alpha \in [0, 4]$ with steps of 0.5 (at the exception of $\alpha = 2$ that is degenerate with the coalescence time) [2]. Only the most significant events, with false-alarm rate $\leq 10^{-3}$/year, are included, as less significant events are unlikely to bring strong constraints but may induce biases due to non-Gaussian noise features. The upper limit on the $\mathbb{A}$ coefficient is shown on Figure 1 left. Several values of α can be put in correspondance with alternative theories of gravitation, and and upper limit on the graviton mass can be derived from the constraint on the positive values of $\mathbb{A}$ when $\alpha = 0$, it is found to be $m_g \leq 1.27 \cdot 10^{-23} eV/c^2$. Constraints on $\alpha = 2.5$ corresponds to prediction from multi-fractal spacetime, $\alpha = 3$ from Doubly Special Relativity, and $\alpha = 4$ from Hořava-Lifshitz and extra dimensional theories.

3.2 Spacetime symmetry breaking

It has been postulated that a unified theory of gravitation and quantum physics may break fundamental symmetries, and a program of effective field theories has been developed to systematically probe for the phenomenology they could induce. In this effective field theory, additional fields

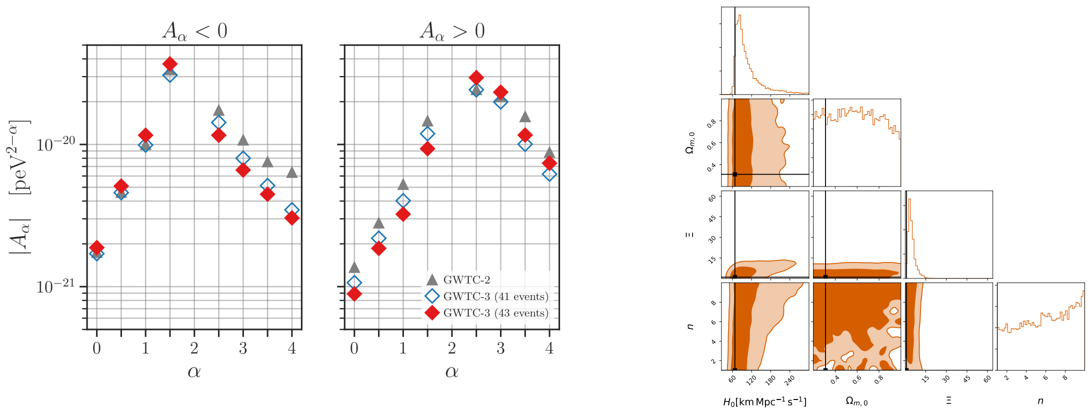

Figure 1 – *Left*: Upper limit on the Lorentz-violating coefficients $\mathbb{A}_\alpha$ as described on Section 3.1 [2]. *Right*: Constraints on the friction parameters Ξ and n as described on Section 4.2 [10].

are added to the linearised general relativity Lagrangian, and the observable manifestations are derived assuming gauge invariance [6]:

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

The operators $\hat{s}$ and $\hat{k}$ correspond to even values of mass dimensions, starting from $d = 4$ and $d = 6$ respectively, and are Lorentz-violating but CPT-conserving. The operator $\hat{q}$ corresponds to odd values of mass dimensions starting from $d = 5$ and is both Lorentz- and CPT-violating. Starting from $d = 5$, the additional fields lead to frequency-dependent, polarisation-dependent, anisotropic dispersion of the gravitational waves. Sensitivity analyses show that individual LVK detections can constrain the spacetime symmetry breaking $\hat{q}$ coefficients at the order of $\mathcal{O}(10^{-13})$ when analysing directly the LVK strain [7].

4 Tests with multimessenger events

4.1 Speed of gravity

The coincident detection of gravitational and electromagnetic radiation from the GW170817/GRB170817A event, corresponding to the coalescence of a binary system of neutron stars, provided complementary signals enabling to test the speed of gravity [8]. By comparing the difference in the arrival time of the two signals, and accounting for a delay of up to 10s delay due to astrophysical processes occurring during the coalescence, the difference between the gravitational waves velocity v_{GW} and the electromagnetic waves velocity v_{EM} has been bounded to $\mathcal{O}(10^{-15})$:

$$-3 \cdot 10^{-15} \leq \frac{v_{GW} - v_{EM}}{v_{EM}} \leq 7 \cdot 10^{-16} \tag{5}$$

In the effective field theory described on Section 3.2, the mass dimension 4 operator affects the gravitational waves velocity. Constraints on the $\hat{s}$ coefficients of Equation 4 can therefore be extracted from the limits in Equation 5, and have been found to be $\mathcal{O}(10^{-14})$.

4.2 Gravitational waves friction

Gravitational waves friction refers to a dispersion impacting the amplitude of the waveform but not its frequency, leading to misreconstruct the distance of the event if general relativity is assumed. Using the information of the multimessenger event described on Section 4.1, friction parameters can be measured by comparing the luminosity distance of GW170817 with the distance inferred from the redshift of the associated event GRB170817A. The presence of large extra dimensions, predicted by DGP and quantum gravity proposals, has been constrained for several values of distance screening scales [9]. Several alternative theories of gravity aim at explaining the accelerated expansion of the Universe, parameterising the friction term to depends on the ratio of dark energy content at different redshift modulo an extra parameter c_M. The c_M parameter has been measured jointly with the Hubble constant in an independent analysis, and is consistent with the general relativity value of $c_M = 0$ [10].

Scalar-tensor theories are a class of gravitation theories where a scalar is added to the tensorial formulation of general relativity, such as Brans-Dicke, (beyond-)Horndeski, DHOST and $f(R)$ theories. They induce a modification of the reconstructed luminosity distance, that is different for each theory but can be parameterised with a single equation including two new parameters Ξ and n with different values according to the proposed theory [11]:

$$d_L^{GW}(z) \; = \; d_L^{EM}(z) \left[\Xi \; + \; \frac{1 - \Xi}{(1+z)^n} \right] \tag{6}$$

Due to the presence of two free parameters, information from two multimessenger events are required to measure them. Studies show that the detection of a multimessenger event located at $z = 0.44$, such as GW190521, enable to constrain Ξ but offer weak determination of the n parameter as shown on Figure 1.

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