

GRAVITATIONAL WAVES WITH THE INTERFEROMETER DETECTORS ON THE EARTH

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Abstract

We present the plans for upgrading the Gravitational Wave detectors on the Earth in view of the next observation run O4 planned to start in 2023. Then, we highlight the main results obtained during the previous three observation runs. We conclude focusing on the future evolution of these detectors in the next decades.

1 Introduction

To detect gravitational waves emitted by stellar compact objects, large-scale laser interferometers are organised to compose a global network of advanced detectors. Two LIGO interferometers in USA are located, the first in Livingstone (Louisiana) and the second in Hanford (Washington state); Virgo is in Cascina, near Pisa in Italy and KAGRA is the new Japanese detector, which

started to be operative in 2015. KAGRA is installed in two orthogonal galleries, 3 km long, excavated near Kamioka in the Gifu prefecture. The KAGRA location is near the caverns hosting the neutrino detectors Super-Kamiokande and Hyper-Kamiokande, the first in operation in the Kamioka mine and the second under construction in the Tohibora mine.

The network of GW interferometers has the advantages to better define the location of the sources emitting transient GW signal, to disentangle the polarisation components of the GW signal and increase further the event detection rate by improving the network duty cycle. In 2015, the first gravitational-wave signals were detected by the two US Advanced LIGO instruments, and two years later the network LIGO-Virgo permitted to pinpoint in the sky the binary neutron star coalescence, then observed across the whole electromagnetic spectrum by a impressive numbers of astronomical detectors on the Earth and in the space, opening the era of the multi-messenger astronomy. At present, the catalog of events detected by the network accounts for 90 signals that, as we will see in the next section, have already a significant impact on several fronts in fundamental physics and astrophysics. The advanced GW interferometers alternate periods of time devoted to observation to upgrade phases for improving the detector sensitivity. A gain of a factor 2 on the minimum detectable value of GW strain expands the explored volume of the Universe of a factor 8, and as consequence, increases the detection rate of the GW signals. At the time of writing this article, all the detectors are preparing the new observation run O4 that will start in 2023 and in the following section we highlight the most significant changes of the experimental set-ups for LIGO, Virgo and KAGRA .

2 LIGO, Virgo and KAGRA Upgrades

In general, the planned hardware changes are different for LIGO, Virgo and KAGRA. However, some strategic choices are in common as the injection through the output port of the interferometer an electromagnetic (e.m.) vacuum with a frequency dependent squeezing. During the last run O3 ended in 2020, a *phase* quadrature squeezed vacuum was successfully utilised in LIGO and Virgo, allowing for a 3 dB quantum noise reduction above ~ 100 Hz. However, at the same time, the low frequency quantum noise originating from *amplitude* quadrature vacuum fluctuation was increased due to the Heisenberg uncertainty principle, potentially spoiling the limit of the low frequency noise budget. To

have a reduction of the optical noise on the entire detection bandwidth, the use of frequency dependent squeezed vacuum is required. It will allow to preserve the low-frequency sensitivity even when the light power stored in the cavity will be increased, a standard approach to gain in sensitivity at high frequencies (see fig 1). Preserving the low-frequency sensitivity will guarantee the possibility to observe binary black holes (BBHs) with higher masses and collect signals emitted in the far Universe.

The frequency dependency is obtained by reflecting the squeezed vacuum (generated outside the main GW interferometer) from a Fabry-Perot filter cavity having low optical losses. The rotation of the ellipse representing the combined phase and amplitude fluctuations of e.m. field in the quadrature space, was obtained for the first time in the MHz region in 2005 ¹⁾ and then it has been observed in the kHz region in the LIGO laboratory of the Massachusetts Institute of Technology ²⁾. At present both LIGO and Virgo are implementing this technique in their detectors. The task is not simple: the interface between the squeezing system and the interferometer requires optical junction benches, both to inject the beam into the cavity and send it to the bench hosting the detection photodiodes. Losses and stray light in the filter cavity as in the whole optical set-up must be limited.

Moreover, the list of the other planned upgrades for all the detectors is long: here we will present for each detector just an incomplete list.

2.1 LIGO

LIGO has set for O4 the sensitivity goal for the two US interferometer to achieve an horizon range of 160 to 190 Mpc for the detection 1.4-1.4 coalescent binary neutron stars (BNS). To fulfil this goal it is needed to:

- reduce or even eliminate inhomogeneous coating absorption in the mirrors acting as test masses, by replacing one of them in the interferometer installed in Hanford and all the test masses in Louisiana;
- change the pre-stabilised lasers in the two LIGO detectors. The new light sources will provide 140 W output into the interferometer;
- achieve a value of 400 kW for the light power stored in the arm cavities;
- deploy many baffles to minimise stray light;

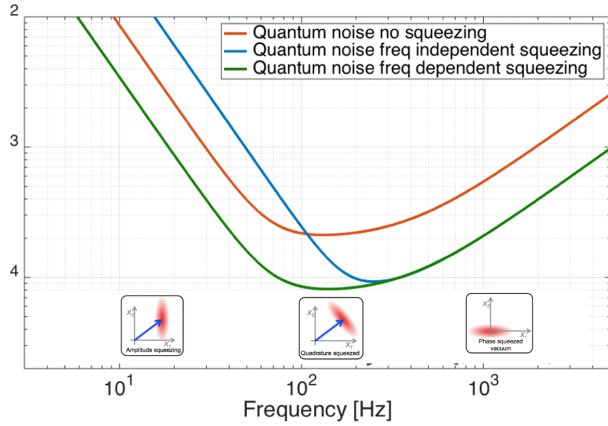


Figure 1: Comparison of the sensitivity gain of the interferometer in the three configurations: without squeezing (red curves), with frequency independent squeezing (blue curve) and with an optimised frequency dependent squeezing (green curve).

- install a new Faraday isolator for reducing the optical loss at the output port of the interferometer;
- implement adjustably deformable mirrors in the output port to tune up and maximise the matching of the beams in the output mode cleaner and in the filter cavity of the squeezing system.

The installation of the new hardware is completed; the following step is the commissioning of the detector and the noise hunting.

2.2 Virgo

The Virgo sensitivity goal is to achieve a horizon range of 80 - 110 Mpc, for the detection 1.4-1.4 coalescent binary neutron stars (BNS). The main innovation for Virgo is the installation of the signal recycling at the interferometer output. This is a significant change in the optical configuration: it implies a deep review of the control strategy of the whole interferometer. The signal recycling allows

the resonance of the whole interferometer to boost the detector sensitivity in the desired frequency interval. The reflectivity chosen for the signal recycling mirror determines the sharpness of the tuning: the present choice concerns the detection of signals from coalescing BBH and BNS. As for LIGO, the list of the other upgrades is long and here we report just few of them:

- a new output mode cleaner is installed with reduced optical loss;
- the payload of the input mode is new and it is equipped with instrumented baffles to mitigate and monitor the stray light;
- the thermal compensation system has been reviewed and upgraded;
- an array of several velocimeters has been deployed close to the vacuum chambers hosting the end test masses of the interferometer. The scientific target is to develop a method to subtract the Newtonian noise arising from terrestrial gravity fluctuations from the interferometer data. The Newtonian noise is affecting the detector bandwidth below 20 Hz. The success of this method will increase the chance to detect the continuous GW signals emitted by rotating NS and to increase the detection rate of BBH at higher masses.

2.3 KAGRA

The O4 goal is less ambitious than LIGO and Virgo: KAGRA started the first operation in 2015 and it is improving progressively the detector sensitivity. The detector has been designed to include new technological features: KAGRA is located in an underground environment to reduce the seismic noise and it makes use of cryogenic techniques to cool the mirrors in the range of 20 K. They have installed a 30 W laser at the input of the interferometer and they plan to start the run having replaced the signal recycling mirror and with the Fabry-Perot mirrors (acting as test masses of the space-time metric) at room temperature. In the second part of the run they plan to cool down the mirrors to improve the sensitivity in the low frequency region and even increase the power laser. As for LIGO and Virgo, KAGRA has a dedicated plan for deploying several baffles to minimise the stray light.

Table 1: *Table 1: Estimated ranges of the merge rates for BBH, NSBH and BNS ⁴⁾*

BBH	17.9 – 44	$\text{Gpc}^{-3} \text{ yr}^{-1}$
NSBH	7.8 – 140	$\text{Gpc}^{-3} \text{ yr}^{-1}$
BNS	10 – 1700	$\text{Gpc}^{-3} \text{ yr}^{-1}$

3 The Gravitational Wave Observations

The GW events detected in the previous run of the network are collected in the catalog GWTC-3 ³⁾. It contains a total of 90 signals: 11 events from the first and second observing runs (O1 and O2), 44 from the first part of O3 and 35 from the second part. It includes BBH events plus two BNS events, 3 coalescences of neutron star - black hole (NSBH) and 1 event with the companion mass to be classified in between neutron star (NS) and black hole (BH). These observations are used to predict both the extrinsic and intrinsic properties of the GW sources. Extrinsic properties describe how we observed the event from Earth, i.e. the location of the source on the sky, its distance from the Earth, and the orientation of the plane in which the two compact objects orbit around one another. The extrinsic parameters and the intrinsic ones (as masses, spins and deformability of the compact objects), are derived on statistical basis (mainly via a Bayesian approach) by defining the 90% region where the inferred values of the source parameters are compatible with the data. In the following subsections, we will highlight some of the results obtained by analysing these data. They are related to studies on the population of compact objects, fundamental physics and search for primordial black holes.

3.1 Populations Studies

In the table 1 we report the merger rates for the three categories of compact objects as derived on the base of the actual observations reported in the catalog GWTC-3 and published in ⁴⁾. The intervals of the BNS and NSBH merger rates are estimated with a large uncertainty because of the poor number of events available: here it was assumed a constant rate density versus co-moving volume and it was taken the union of 90% credible intervals for all the methods

used in this analysis. For the BBH merger, the rate interval is computed at a redshift $z = 0.2$, accounting for the evolution of the merger rate to with redshift z , while it changes slightly as $\sim (1+z)^{2.7}$.

A large fraction of the BBH events are related to binary systems with mass ratio q near 1. Indeed, two events, GW190412 and GW190814, have $q = 0.28_{0.06}^{+0.12}$ and $q = 0.112_{-0.009}^{+0.008}$ respectively. In addition, the secondary mass of the system emitting the GW198014 results to be $M_2 = 2.59_{-0.09}^{+0.08} M_\odot$: a BH mass value is much lower than those of the galactic X-ray binary population or a NS mass too high asking for a significantly high spin to be compatible with the NS hypothesis.

The study of the spin distribution should help to discriminate among the various formation scenarios of these binary systems. For example, the dynamical formation of BBHs requires a dense stellar environments where the original binary system interacts with a third body, which replaces one of the binary components. Simulations show that the dynamical exchange involved in this process, is compatible with a random distribution of the spin directions for the final states. The BBH formation in isolation, a scenario complicated by several different processes occurring during the evolution of the system, pushes toward the observation of binary systems with spins well aligned to the orbital angular momentum and nearly zero orbital eccentricity.

The spin distribution of the BBH population is obtained by marginalising (in a statical sense) over the joint estimate of the mass and spin distribution $P(m_1, m_2, \chi_1, \chi_2)$, where m_i , $i = 1, 2$ are the masses and χ_i , $i = 1, 2$ the adimensional spins of the two compact objects. We have to note also that the inference of the spin population is affected by a selection bias, because BBHs with high, aligned spins can be observed at greater distances (at fixed distance and equal masses, the spin aligned events can be detected at higher signal to noise ratio). What we can conclude on the base of the present data, is that the spin distribution seems to advocate for a multiple formation scenario.

3.2 Fundamental Physics

Another interesting aspect one can probe are GW polarisations. In GR, there are only two tensor polarisation modes, which are typically decomposed as plus and cross modes (see fig. 2).

In theories beyond GR, two scalar polarisation modes (breathing and longi-

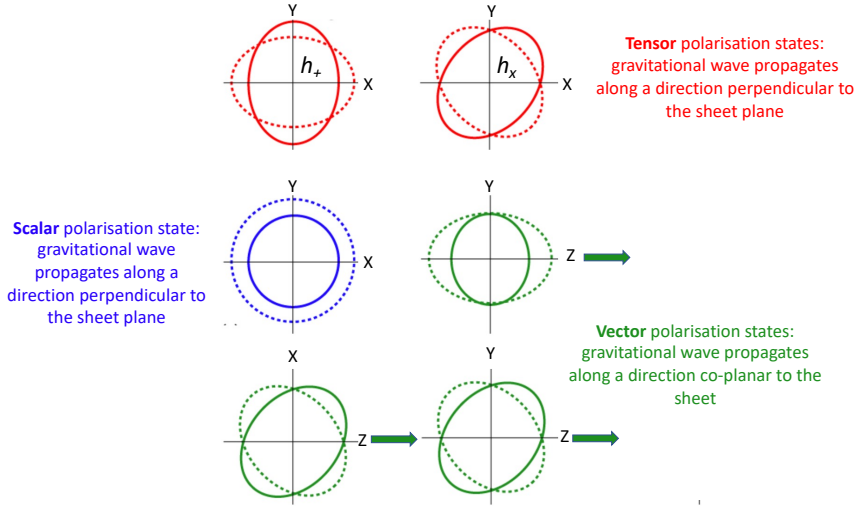


Figure 2: *General Relativity predicts the existence of two fundamental states of polarisation, the tensor modes h_+ and h_\times . Other theories of gravitation include four extra modes, scalar and vector ones* ⁵⁾.

tudinal) and two vector modes can exist in addition. Examples of breathing modes are reported in blue in the fig. 2. The LVC has used GW170817 and carried out a model selection analysis among three different models: tensor only, vector only, and scalar only models. It was found ⁶⁾ that a fully tensor wave was significantly preferred from the data over the other two hypothesis, consistent with the GR prediction. KAGRA has recently joined the collaboration and started its operation. This additional detector will help to further test additional polarisations. For example, one will be able to compare the tensor-only model against tensor + scalar model, the most popular hypothesis among the alternative theories of gravity.

The speed of gravitational waves in the general theory of relativity is equal to c , the light speed in a vacuum. In alternative theories of gravity often the dispersion relation is not as simple and a difference between c and the GW

propagation velocity v_{GW} should appear at some orders of the measurement accuracy.

In August 2017, the LIGO and Virgo detectors received the GW170817 signal. Data have been interpreted as due to the coalescence of two neutron stars located at a distance between 26 to 49 Mpc from Earth. Later the location was confirmed in the shell of the elliptical galaxy NGC 4993. The chirp mass of the system was extracted from the data resulting to be $1.188^{+0.004}_{-0.002} M_{\odot}$. The masses of the component stars have greater uncertainty. The larger (has a 90% chance of being between 1.36 and 2.26 M_{\odot} , and the smaller has a 90% chance of being between 0.86 and 1.36 M_{\odot} . 1.7 seconds after the GW merger signal, a short (2 seconds duration) gamma-ray burst, designated GRB 170817A, was detected by the Fermi and INTEGRAL spacecrafts: the gamma ray detection confirmed roughly that the e.m. burst was coming from the same patch of the sky pointed by the LIGO-Virgo network.

The delay between the e.m. and GW signals and the large distance between the Earth and the galaxy NGC 4993, provided the strong limit on the difference between the speed of light and that of gravity:

$$-3 \cdot 10^{-15} < \frac{v_{GW} - c}{c} < +7 \cdot 10^{-16}$$

Later , this results was revisited 7) to give the upper limit on the graviton mass:

$$m_g < 1.76 \cdot 10^{-23}$$

3.3 Primordial Black Holes

Apparently there is no mechanism for the formation of ultracompact objects with masses $< 1 M_{\odot}$ within the standard model of particle physics and the Λ CDM cosmological model or at least this is a controversial point. A possibility to have black holes with masses accessible to ground based interferometers is that they could have formed deep in the radiation era of the Universe from the prompt collapse of large primordial over-densities on the scale of the early time Hubble volume 9) 10). In addition, it has been argued, on the base of micro-lensing observations, that the primordial black holes (PBH) outside the mass range of $0.05 M_{\odot} \lesssim M \lesssim 0.45 M_{\odot}$ cannot contribute significantly to explain the dark matter mystery 8). Other constraints have been set on the PBH existence. PBHs lighter than $\sim 10^{15}$ g , which have not evaporated yet

or are in the final state of evaporation by the Hawking radiation, leave some signals from which an upper limit on their PBH abundance can be placed. They can change the abundance of the light elements produced by the big bang nucleosynthesis ($10^9 g < M_{PBH} < 10^{13} g$), extragalactic photon background ($10^{14} g < M_{PBH} < 10^{15} g$), and damping of the CMB temperature anisotropies on small scales by modifying the cosmic ionisation history ($10^{13} g < M_{PBH} < 10^{14} g$). By comparing these effects with observations, upper limits on the PBH fraction for various PBH mass can be obtained (under specific assumptions of their mass function) ^{11), 12)}. Except for the constraints from the entropy production and the primordial helium abundance, these limits are severe in the sense that they allow only a tiny fraction of PBHs in dark matter at any cosmic time before the PBHs evaporate.

Nevertheless, the search of PBH as dark matter contributors gained attention ¹⁴⁾ and, since the detections of gravitational waves is a novel tool to observationally search for PBHs complementary to the electromagnetic waves, we expect to make significant progresses even on this domain (for a comprehensive review of this topic see ¹³⁾). The existence of sub-solar-mass black holes would be considered to be a definitive proof that they were produced in the primordial Universe, as stellar evolution cannot produce black holes below about $3 M_{\odot}$.

To date, searches have been performed for sub-solar-mass black holes, but no detection has been made so far, leading to some of the best upper limits on the fraction of dark matter in black holes of mass $0.2 - 1.0 M_{\odot}$ ¹⁵⁾. In ¹⁵⁾, assuming a particular primordial black hole (PBH) formation model, it has concluded that a population of merging $0.2 M_{\odot}$ black holes can account for less than 16% of the dark matter density and a population of merging $1.0 M_{\odot}$ BHs can account for less than 2% of the dark matter density.

4 Future plans

Using as figure of merit the horizon of standard coalescent BNS events at a signal to noise ratio equal to 8, the final goal is to go from 60 Mpc achieved in O3 to 260 Mpc target for O5. Moreover, we must say that the present GW facilities have the potentiality to get a further increase in sensitivity for an extra factor 2 in amplitude. The instrumental set-up in a post O5 run can include larger light beams impinging on the Fabry-Perot mirrors acting as

test masses of the space-time geometry. These mirrors will have heavier masses with monolithic suspensions and better low-loss coatings. The combination of these actions, with a robust campaign to reduce the technical noises mainly affecting the sensitivity at low frequency, will permit to reduce the intrinsic limit due to the thermal noise. In addition higher light power can be stored in the arm cavities and improvements can be implemented on the readout scheme, detection benches seismically isolated and under vacuum. Newtonian noise subtraction will be implemented, improving further the low frequency region.

This sensitivity increment will permit to discover and characterise thousands of BBH events per year such to increase our understanding of the black hole population in the Universe and achieve new fundamental physics results.

Despite the amount of scientific results produced with GW170817, this event remains the only conclusive multimessenger observation with GWs to date. The increase in the detector sensitivity will multiply the chance to observe this category of events, enhancing our understanding of the inner core of neutron stars. Another class of multimessenger observation, reach of physics information, will be the detection of GWs in connection with e.m. and neutrino emissions from a core collapse supernova. Although the event rate is low for an observation limited to the local group of galaxies, even the joint detection of one event, will be a huge boost in our understanding of the explosion mechanism. In fact, despite the huge theoretical effort done in the simulation domain, the supernova explosion is far to be fully understood: the only direct measurement, guiding in a sense the simulation efforts of the core engine of the explosion, comes from SN 1987A. Neutrinos and GWs leave the core around the time of collapse and a joint detection of the two messengers will probe directly the inner dynamics of the SN process: neutrinos will allow us to probe mainly the thermodynamics of the collapse and from the GW data we will infer the matter dynamics.

The post-O5 plans are under preparation: they are conceived for extending the life of the network of the advanced detectors at least up to 2040. At that time the network will include also the LIGO-India detector, which is now under construction. The GW observations of the Earth based interferometers will continue to produce results, paving the way of the future detectors as Einstein Telescope and Cosmic Explorer, able to explore the whole Universe.

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