Gravitational Waves Detectors

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Abstract. The search for direct detection of Gravitational Wave made a huge step forward in the years between 2015-2017. After the first detection signals from the coalescence of binary black hole systems, we had both the great success of the LISA pathfinder mission and the detection of the first event due to a neutron star - neutron star merger tagged as the birth of the multi messenger astronomy. A new era is now opened where the GW events are detected routinely by the triangular network of LIGO and Virgo that in the nearest future will be enlarged by including KAGRA, the fourth detector in Japan. Here we review the evolution of the existing detectors focusing our attention essentially on the middle and long-term evolution of those on the Earth.

1. The Gravitational Wave observation effort

On September 14th, 2015 the first unequivocal signal of Gravitational Wave (GW) was detected using the two LIGO detectors installed in USA: the era of the GW astronomy is started by detecting signals in the audio bandwidth[1]. In the December of the same year we had another crucial event regarding the advancement of the GW astronomy. The ESA mission LISA Pathfinder was launched from the Guyana space center, paving the way for future missions by testing in flight the very concept of gravitational wave detection in the space. Two test masses were set in a near-perfect gravitational free-fall state and their motion have been measured in the frequency bandwidth from 10^{-1} Hz down to 10^{-4} Hz with unprecedented accuracy[2]. The inertial sensors, the laser metrology system, the drag-free control system and the ultra-precise micro-propulsion system performed so well to support the assessment that the GW detector LISA will become a reality in the next decade.

In parallel to that other kind of instruments are used for detecting GWs in different frequency ranges. The International Pulsar Timing Array [3] looks at the signals in the range of $10^{-9} - 10^{-6}$ Hz emitted by massive black hole binaries in the centres of merging galaxies, where tens of millions of solar masses are in orbit with a period between months and a few years. The driving idea is to analyse the time noise of the radio signals emitted by the most stable pulsars (around twenty of them) looking for a correlated contribution due to GWs. This technique have not a stringent sky location of the sources, ranging the incertitude around of 100 square degrees at the best. Thus, the main goal will be to measure the amplitude of background gravitational waves caused by the overlap of GWs by the supermassive black hole mergers and infer from that the history of galaxies formation.

In addition to all of that, we have to note the progress in the measurements of the Cosmic Microwave Background polarisation. GWs from inflation can source B-mode polarisation, so a

B-mode search allows us to target the signal of inflation, the Universe expansion by an extreme large factor during a tiny fraction of a second at the time of the Big Bang. In this sense the joint analysis of the BIPCEP-2 and Planck satellite data [4] represents the start of a new era in the progress toward the detection of the GW signature in the CMB.

In the following section we will focus our attention to the evolution of the ground base detectors reporting their main technical improvements. At present GW signals are collected by the LIGO-Virgo network, which operates in observing mode. The new data taking started on April 2019 and will end after one year. Before the end of this period, we expect to have an increase in the number of network nodes thanks to the KAGRA detector in Japan that should end its first period of commissioning and enter in Science mode phase. Then, we will report on the middle and long term plans characterised by the smooth transition from the present generation of detectors to a new one with a significant gain in the GW strain sensitivity.

2. From the second to the third observing run of GW detector network on the Earth

The time interval between the observation run n.2 (O2) of LIGO and Virgo and the following one (O3) was fully devoted to cure the detectors failures and increase their sensitivity. In LIGO the time was mainly devoted to install an laser of higher power, replace five of eight test masses with better optical quality, new baffles to mitigate scattered light and improve the various controls systems. The Virgo collaboration operated in a similar way, by mounting a more powerful laser, new faraday isolator and photodiodes and replacing the wires of the last stage suspension of the mirror to reduce the thermal noise. In all the network sites, a system to inject in the interferometer a vacuum squeezed state of the light via the output port of the interferometer has been added, with the aim to reduce the shot noise contribution which affects the high sensitivity range of the detector bandwidth. In the figure we effect of the squeezing bench on the detector sensitivity in the Virgo case. A similar gain have been observed also in the two LIGO interferometers .

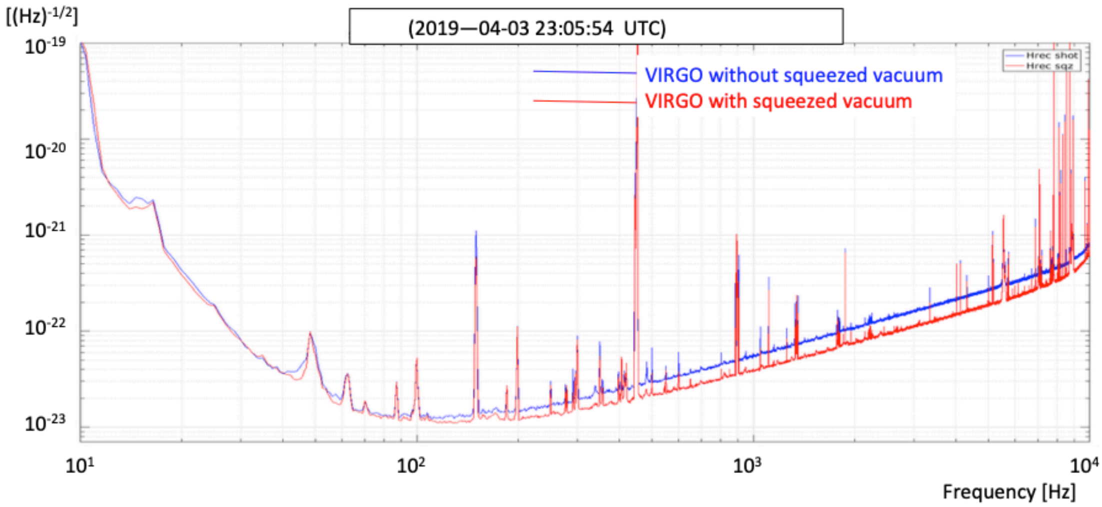

Figure 1. The impact of the vacuum squeezing bench on the interferometer sensitivity once installed on Virgo.

These changes caused a significant improvements on the detector performances and the run started on April 1^{st}, as planned, following a well coordinated schedule of the detector operations

to maximise the observation time of the three interferometer. At present, up to September 26^{th}, 2019, we can claim to have a triple coincidence time higher than the 44.5 % of the total run period, a double coincidence up to the 81.9 % and only 3.2 % of the time without any interferometer in observation mode. Advanced Virgo is still less sensitive than the two LIGOs but it has the highest duty cycle . This latter fact, combined with its distance from and different orientation with respect to, the two Advanced LIGO interferometers, increases the capabilities of the detector network to localise GW sources in the sky and to fully understand the characteristics of the GW signals.
Several new events have been detected, which have been communicated to the scientific community almost in time, by publishing the news via *GCN* circulars, that can be found in the web site *https://gracedb.ligo.org/latest/*.
The rapid communication concerning the GW event includes sky maps, statistical significance, distance and event ID. The circular is followed up with subsequent information (e.g., refined false alarm thresholds) when available or, in some case, with announcement of the GW trigger withdrawal.

Until the end of the Spring 2020, the data collection will continue fully exploiting the scientific potentialities of the network at the present sensitivities. Then, a long-term stop is scheduled to permit new implementations targeting to increase the astrophysical richness of the GW Observatories.

KAGRA, formerly the Large Scale Cryogenic Gravitational Wave Telescope (LCGT), is the first major gravitational wave observatory in Asia. Located at the site of the Kamioka mine, it is built underground and it makes use of cryogenic mirrors to reduce the thermal noise and to limit the thermal deformation of the mirrors. Because of these peculiar characteristics KAGRA can be classified as a 2.5 generation detector, pioneering the solutions to be adopted in the next generation of GW interferometers. During the days of the conference we received the news of the first lock of the Michelson interferometer equipped with Fabry-Perot (FP) arms, a great step forward in the path to join the LIGO-Virgo observation run. Then, on October 4^{th}, 2019 KAGRA celebrated the completion of its work to build the underground detector, a milestone in the international effort to advance gravitational-wave astronomy and significantly deepen our understanding of the universe. Later in the day, the memorandum of agreement on a research collaboration between KAGRA, LIGO and Virgo was formally signed.

KAGRA was installed in the underground site beating records on the installation time. The almost 7 km of galleries were drilled and the 6 km of ultra vacuum tubes have been mounted in less than two years. The complete optical and cryogenic installation ended in April 2019 and then the commissioning of the full interferometer, equipped with the Sapphire mirrors cooled at low temperature, started. At present the KAGRA collaboration is fully committed in trying to solve the experimental problems, which are mainly due to their innovative set-up to respect of LIGO and Virgo. At the time I am writing this article, the main current problem seems to be the unbalanced features of reflected light by the the input mirrors probably due to non-uniform birefringence of the FP input mirrors: currently the detector groups are discussing how to solve this problem.

3. From the second to the third generation of GW detectors on the Earth

A continuous improvement in the sensitivity is a must for the entire GW community. It produces an increase of the event horizon and as a consequence a cubic expansion of the explored universe. In addition, the increased SNRs for a given population of events brings new and original informations on the astrophysics of the sources. Thus, further enhancements in sensitivity, thanks to the technological advancements and to more performant detection strategies must be pursued for the future upgrades of the interferometers.
Detailed program of upgrades both for the LIGO interferometers named A+, and for Virgo

named AdVirgo+ have been presented to the community.

The A+ design improves the sensitivity in all frequency bands. At the heart of A+ are frequency-dependent squeezing[28] and improved test mass coatings. Squeezed light will be used to reduce the quantum noise at low frequencies through the reduction of radiation pressure on the test masses and at high frequencies ($> 500\ Hz$) through the reduction of shot noise. Improvements at low and midle frequencies also rely on a reduction of coating thermal noise by a factor of two over the current Advanced LIGO mirror coatings. Balanced homodyne detection is planned, to provide lower loss and higher fidelity readout of the gravitational wave channel over DC readout.

Virgo is also looking at AdVirgo+ upgrade, implementing frequency squeezing and other technologies. In particular the Virgo collaboration is trying to explore two different approaches: the increase of the mirror masses and their reflective surface to decrease further the contribution of the thermal and radiation pressure noise. In addition there is an attempt to deploy a seismic sensor array around the test masses with the aim to subtract the Newtonian noise contribution affecting the detector sensitivity in the low frequency range.

In the case of KAGRA it is too early to define a detailed plan for upgrades; however discussions have already started to define the future improvements of this detector.

In conclusion, in the middle term the implementation of the new technologies will be scheduled in between long data taking phases of the network, improving progressively the detection horizon and the Signal to Noise Ratio (SNR) of events due to emitters located in the volume of the Universe that we are already able to explore. This implies that we will also improve our capability to localise the source. In fact, the effective time accuracy of each detector $\sigma_t = (2\pi\rho\sigma_f)^{-1}$ depends on the SNR ρ t by and on the effective bandwidth of the signal σ_f and in the future conditions we should expect a median 90 % credible region containing neutron star - neutron star coalescent events between $50 - 83 \times 10^3\ Mpc^3$ [5].

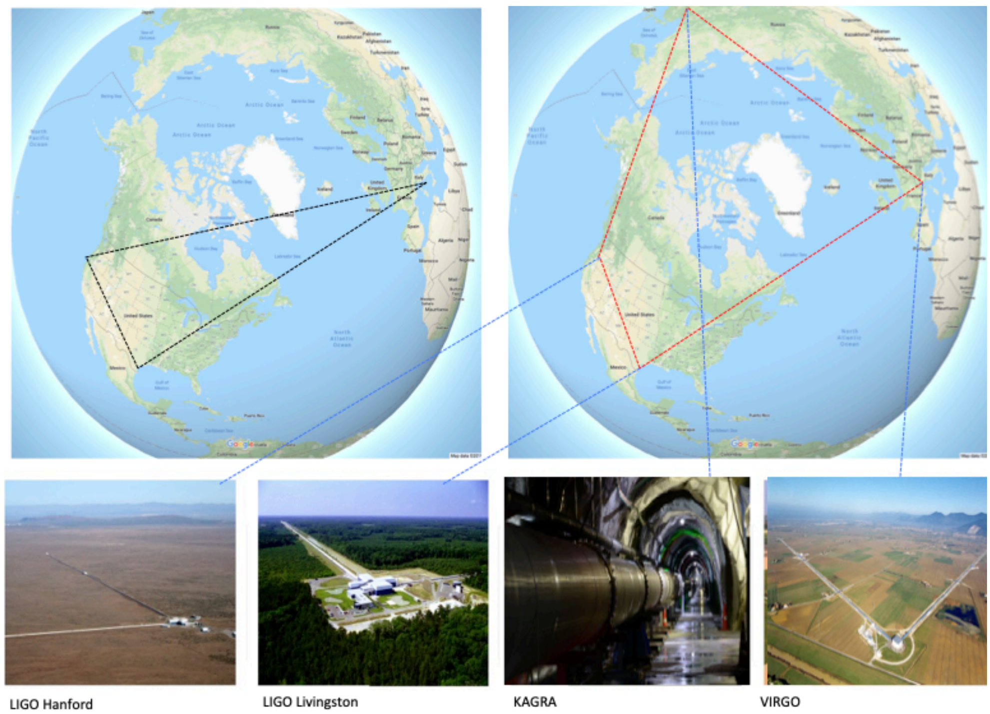

Figure 2. A pictorial view of the enlargement of the network baseline with the addition of the KAGRA detector.

In conclusion, during the next decade LIGO, Virgo and KAGRA will be in observing mode making frequent detections while, in the mean time IndIGO [6] , the new GW interferometer under construction in Inda, will become operational adding a fifth actor to this network.

4. New instruments for a new GW science

The first observation of a GW signal was achieved at the beginning of the Advanced detectors era, a second generation of interferometers born thanks to the upgrade of LIGO and Virgo. The GW detection and the beginning of the multimessenger astronomy stimulated a world wide acceleration toward a third generation (3G) GW observatories. The Einstein Telescope project is supported since 2010. At the beginning it took advantage of the support of an ILIAS Grant of the 6th Framework Programme, 2004-2008 of the European Union (EU) [1]. The goal was to promote infrastructure development among the astroparticle and gravitational-wave communities. Discussions among the ILIAS member groups led to the focus by the EU GW community, mainly by not only members of the Virgo and GEO collaborations, on a cryogenic and underground 3G facility. Scientists from USA, India, and Japan participated in the study, which continued still thanks to the EU support with the conceptual study of the Einstein Telescope (ET) facility [7], [8]. This happened well before 2015 and now the process has got momentum in Europe. The call for the formation of the Einstein Telescope collaboration has been launched and more than 700 physicists and engineers have expressed their interest to be part of it. The next step for 2020 is the submission of an ET project proposal to the ESFRI [2] roadmap.

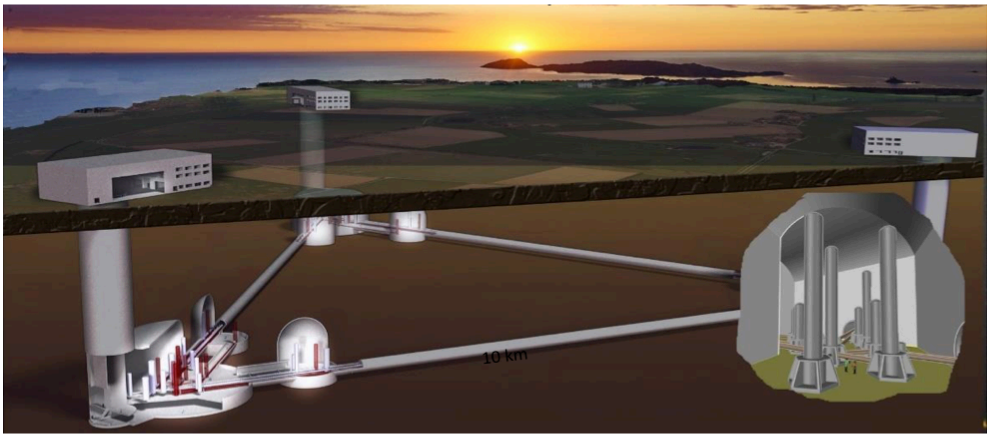

Figure 3. A rendering of the Einstein Telescope, the new underground detector under study in Europe. It is an equilateral triangle of a perimeter of 30 km: it should include six interferometers, three of them with mirrors at cryogenic temperature and the other three at room temperature to run with stored laser light at higher level.

In USA the idea of a giant 40 km detector, named Cosmic Explorer [9], is now born and supported, as Conceptual Design Study, by the National Science Foundation. In this scenario the Gravitational Wave International Committee (GWIC) decided to set up a global coordination committee named GWIC-3G that is attempting to harmonise the efforts and to find synergies[10]. The Physics of Gravitational Waves carried on with the kilometre scale interferometers anchored on the surface of our planet, relies on the detection of the tiny signals due to the GW plane wavefronts and, as it was well synthesised as first by Gary Sanders during a 3G meeting held

[1] ILIAS is the acronym for Integrated Large Infrastructures for Astroparticle Science
[2] ESFRI is the acronym for European Strategy Forum on Research Infrastructures

in Europe, *our detection platform is the entire Earth.* For this reason, the international GW community should converge toward a global vision for the 3rd generation network of detectors and present it to the government funding agencies supported by its strong scientific motivation. The 3G-GWIC group sponsored a deep study on the potentialities of the new detectors. Their increased sensitivities will permit to explore almost the entire Universe in the case of the BH-BH merger events. Population studies can achieve such a high precision to reveal the secrets of the galaxies formation [12]. In addition they will permit to acquire data in extreme gravity and will contribute to answer the questions concerning the nature of dynamical spacetimes, the nature of dark matter and the nature of compact objects. The emission of gravitational waves by ultra-compact objects can be qualitatively different depending on the presence or absence of an event horizon quantum modifications of GR black holes. The spectral difference of their internal oscillation modes will be the smoking gun [13] permitting to discover extremely compact objects such as boson stars, strange stars, gravstars and worm holes, if they exist. In order to carry on these future studies 3G detectors, operating at higher signal to noise ratio, are needed.

5. Conclusion

The new run O3 with LIGO and Virgo is started on April 1st and it will last for one year with the hope of KAGRA joining the network before the end of the run. New GW signals have been already collected and public alerts have launched to trigger multimessenger observations of the events.

In the mean time, we are preparing plans for future upgrades A+ and AdV+ paving the way for the construction of the new 3G detectors.

Acknowledgments

I wish to thank R. Passaquieti for the critical reading of the manuscript. This work is supported by the Grant Ateneo Sapienza 2017 and by the AMALDI Research Center of the Department of Physics of the University of Rome *Sapienza*

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