Virgo and Einstein Telescope status

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The IN2P3 Virgo groups: APC, IJCLab, IP2I, IPHC, LAPP

1 Overview

Between 2015 and 2017 the Virgo and the LIGO Collaborations performed 2 scientific data takings, O1 and O2. The first (from September 12th 2015 to January 19th 2016) with the two Advanced LIGO detectors and the second (from November 30th, 2016 to August 25th, 2017) including also Advanced Virgo. During O1 and O2, 11 sources were found. These observations, summarized in the first gravitational-wave transient catalog (GWTC-1[1]) and detailed in several publications of the LIGO and Virgo Collaborations[2], have several implications for astrophysics, cosmology, test of general relativity and nuclear physics.

After a series of detector upgrades, in April 2019 the Advanced Virgo/Advanced LIGO network started the O3 data taking, ended in March 2020, one month before the official date due to the COVID-19 pandemics. 56 candidates have been identified and 4 sources already published. The analysis is still ongoing.

In the next years, the network LIGO-Virgo has planned two new data takings (O4, planned for 2022 and O5, planned for 2025), alternated with detector upgrades, until $\sim$ 2027. During this period, the Advanced Virgo range will be increased by a factor $\sim 2.5 - 4$. The Japanese detector KAGRA will join the network during 04 and LIGO India will be operational for O5. Details about the GW network plans are contained in the "LIGO-Virgo-KAGRA observing scenario" [4], a document constantly updated.

After a preparatory phase, the installation of Advanced Virgo+ (or AdV+), the major upgrade of Advanced Virgo, started in July 2020, and it is organized in 2 phases: The phase-I detector, which will be operated during O4, and the the Phase-II detector, installed after 04 and be operated during 05. Upgrades are also planned for Advanced LIGO (advanced LIGO +, or aLIGO+).

Plans for the network after O5 (upgrades and data takings) are under study.

2 Advanced Virgo during O3

Between O2 and O3, several improvements allowed to increase the Advanced Virgo sensitivity. Among them, the injection of a squeezed vacuum source and the increase of the laser input power from 10 W to 26 W, both allowing the reduction of the shot noise and the replacement of the steel suspension wires with fused silica fibers, allowing the reduction of the suspension thermal noise. Moreover, several technical noises were also reduced. These upgrades,together with the subsequent commissioning work (including a break during the two segments of O3, in October 2019), enabled an increase of the sensitivity over the full detector bandwidth (see fig.2). The standard figure of merit is the binary neutron star range, shown in fig.2 for the three detectors Virgo, LIGO-Hanford and LIGO-livingston during O3b. The best range for Virgo improved from almost 30 Mpc (end of O2) to 60 Mpc (at the beginning of 2020).

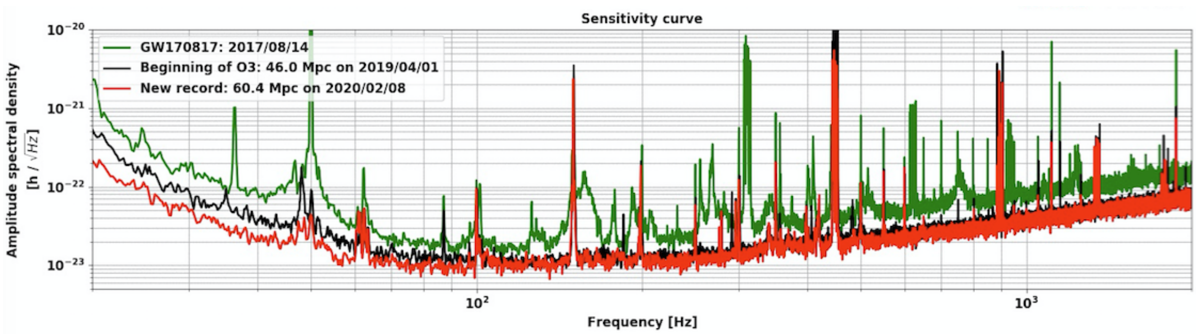

Figure 1: Improvement of the Advanced Virgo sensitivity curve between O2 and the end of O3

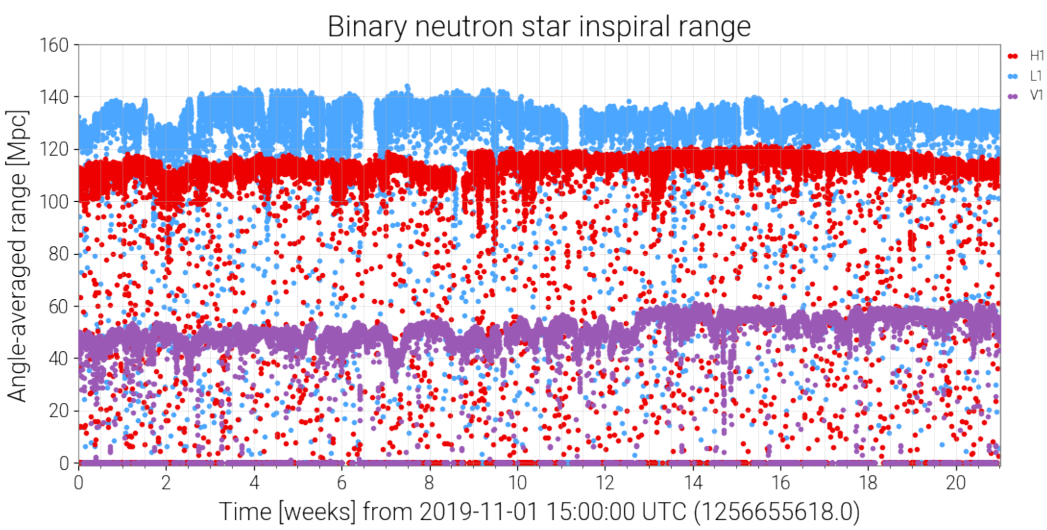

Figure 2: Trend of the binary neutron star inspiral range during O3b for Virgo, LIGO-Hanford and LIGO-Livingston

The duty cycle of Advanced Virgo during O3 was 76% (fraction of the time in which the detector was in science mode). For 47.4% of time, the LIGO-Virgo network was operated with all three detectors simultaneously in science mode; 36% of the time the network had two detectors online (sum of the three possible combinations), 13.4% of the time only one detector was in science mode.

3 03 scientific results

The data obtained during O3 are still being analysed, but we can summarize the science outcomes with the following numbers: 56 gravitational-waves candidates have been identified (in average one over 6 days, see fig.3)[3], 4 new types of astrophysical sources already published (detailed in the following), the maximum distance of a gravitational-wave source has increased by 60% with respect to 02 (from z=0.49 for GW170729 to z=0.82 for GW190521), and completely new tests of the general relativity have been performed.

The gravitational-wave sources already published are the following:

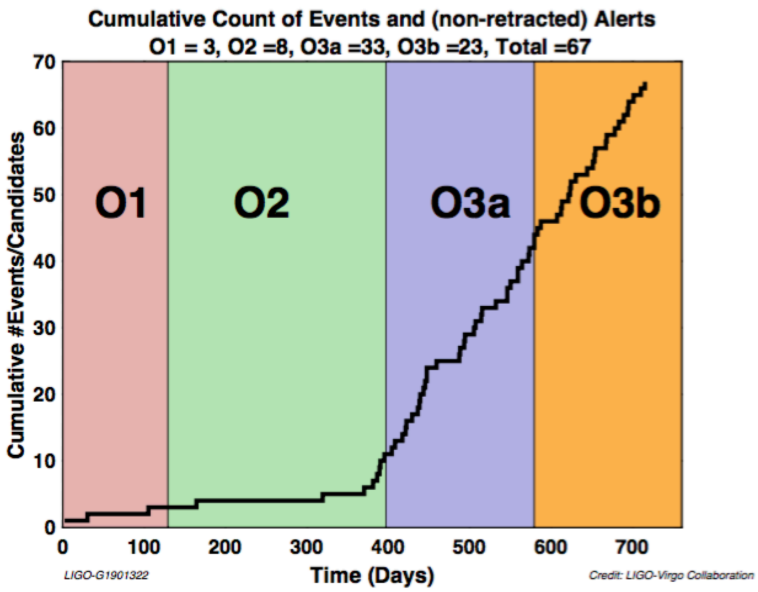

Figure 3: Improvement of the Advanced Virgo sensitivity curve between O2 and the end of O3. Top: equivalent gravitational-wave strain for O2 (green), beginning of O3 (black) and end of O3 (red), Bottom: detector range for binary neutron star as a function of time

- GW190412[5], a binary black-hole merger, with component masses of $\sim 8\mathrm{M}_\odot$ and $\sim 3\mathrm{M}_\odot$. This is the first system where the mass asymmetry is such that it allows to observe strong evidence for gravitational radiation beyond the leading quadrupolar order in the observed signal. The higher-order gravitational-wave emission allows to perform new tests of general relativity and to partially break the degeneracy between the luminosity distance of the source and its inclination with respect to the line of sight, allowing a better measurement of both quantities.

- GW190425[6], a binary neutron star system, with a total mass of $\sim 3.4\mathrm{M}_\odot$. This is the second binary neutron star merger detected by LIGO and Virgo, and its total mass is significantly larger than any of the other known binary neutron star systems. The detection of this source suggests the existence of a new population of more massive BNS systems not observed so far.

- GW190814[7], a merger of two compact objects with component masses of $\sim 23\mathrm{M}_\odot$ and $\sim 3\mathrm{M}_\odot$. The most massive object is a black-hole while the less massive can be the lightest black-hole or the heaviest neutron-star ever observed. The asymmetry in the mass provides further tests of the gravitational-wave emission at higher multipoles. Due to their mass asymmetry, both GW190412 and GW190814, are interesting for binary-black hole formation scenarios.

- GW190521[8, 9], a merger of two black-holes with component masses $\sim 66 M_{\odot}$ and $\sim 85 M_{\odot}$. This is the most massive source (total mass $\sim 150 M_{\odot}$ and most distant source observed by LIGO-Virgo (z=0.8). With a mass of 85 $M_{\odot}$ the primary black-hole is the first observed inside the pair-instability mass gap, challenging current formation models for this object. The final black-hole is the first intermediate mass black-hole observed by LIGO and Virgo.

LIGO and Virgo data are available on the gravitational-wave open science center (GWOSC) [10].

4 Advanced Virgo +

The Advanced Virgo+ major upgrade of Advanced Virgo aims to improve the Advanced Virgo sensitivity by a factor $\sim$ 2.5-4 in terms of binary neutron star range (see figure 4).

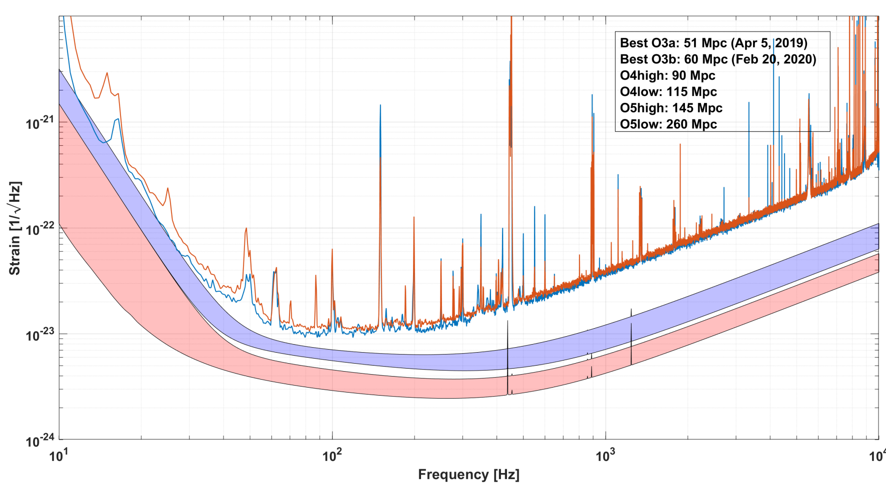

Figure 4: Advanced Virgo+ anticipated sensitivities for the two phases, with respect to the O3 sensitivities

- The goal of the phase-I is mainly the reduction of the quantum noise, obtained by the increase of the laser power, the use of the signal recycling technique, and of the quantum filter cavity (300-m long). The use of the signal recycling technique requires the installation of a new suspended mirror (the recycling mirror, between the beam-splitter and the interferometer output) and special auxiliary lasers, at a different frequencies, to bring the interferometer in the working condition. The filter cavity is a suspended 300-m Fabry-Perot cavity, between the squeezing source and the interferometer, requiring a new vacuum tube, new vacuum chamber and suspensions for the cavity optics.

- The aim of the phase-II is a further reduction of the quantum noise, with an increase of the laser power, but mainly the reduction of the effect of the thermal noise of the mirrors. The latter is obtained with an increase of the laser beam size on the end mirrors and, if possible, with a reduction of the mechanical losses in the mirror coatings. This phase requires bigger end cavity mirrors (x 1.6 in diameter, corresponding to a diameter of 55 cm and with a weight of 100 kg).

During the two phases, other improvements are planned, allowing the reduction of several technical noises and the subtraction of the gravity gradient noise (produced by the seismic induced gravity changes) by a network of seismometers around the interferometer's mirrors.

The installation of the phase-I started in July 2020, and the first milestone, the installation of the signal recycling mirror, was obtained in time. During the first semester 2021, it is planned the commissioning of the signal recycling and of the filter cavity. The 04 data taking is planned at the beginning of 2022, jointly with LIGO.

5 Einstein Telescope

Einstein Telescope (ET) aims to gain an order of magnitude in sensitivity with respect to Advanced Virgo and to enlarge the bandwidth of the detector down to 1-2 Hz (compared to $\sim$ 10 Hz for Virgo). In order to reach this goal, ET has 10 km long arms and it is located underground. Moreover, the detector is a *xylophone*, composed by two different sub-detectors working at different frequency bands, and merged together (similar to two electromagnetic telescopes sensitive to slightly different wavelengths). To fully resolve the two GW polarisations predicted by GR with a single detector, ET has a triangular shape leading to 3 independent Michelson interferometers [11]. The ET infrastructure will be able to accommodate future detector upgrades for the next few decades.

Two sites have been proposed for ET, the first in Sardinia (Italy) and the second in the Meuse–Rhine Euroregion, near Aachen, Mastricht and Liège (the vertex of the ET triangle will be in three different countries: Germany, Holland and Belgium. Campaigns of site seismic noise characterization, evaluation of the excavation costs and socio-economic impact of the ET site implantation are on going.

After the release of the conceptual design report 2011[11], ET went through few years of lower level activity, mainly due to the fact that the GW community was focused on the upgrades and operations of Virgo and LIGO. After the first GW detections, the ET project has re-gained momentum. The Einstein Telescope collaboration has been created in 2019. The ET steering committee has been formed, with $\sim$ 20 members (3 from France). Recently an "instrument science board" (ISB) has been created, with the goal of writing the ET technical design report.

An application to integrate the 2021 ESFRI roadmap has been submitted by the ET Consortium in September 2020 (including a revision of the conceptual design report). The outcome of the selection is expected in September 2021.

A possible timeline for the project is the following:

- 2021-2022 formalisation of the ET collaboration
- 2023: Technical design report (first phase: infrastructure related aspects)
- 2024 Selection of the hosting site

- 2026: Full technical design report
- 2027 Beginning of the excavation works
- 2032 Start of installations
- 2036 Data taking

ET will be mainly based on concepts and techniques developed and tested in the framework of Virgo and LIGO: a modified Michelson interferometer (Fabry-Perot dual recycled Michelson interferometer: Fabry-Perot Cavities in the arms, power recycling and signal recycling), use of frequency dependent squeezing (as planned for Advanced Virgo+ and Advanced LIGO+), complex seismic isolation systems (a combination of passive isolation based on chain of pendula and an active isolation). While the instrument concepts are well-established, the detailed implementation nonetheless requires an R&D program in order to reach the sensitivity targetted for ET. A key technology not yet present in Virgo and LIGO is cryogenics, which is being currently tested in the japanese projet KAGRA.

6 Science with ET

Thanks to a tenfold increase in sensitivity with respect to second generation detectors and the enlargement of the bandwidth down to a few Hz, Einstein telescope will increase the scientific reach of the present instrument in three different ways: 1) in-depth and complete survey of the source populations observed by the 2G detectors, namely larger number of sources, 2) sources detected with larger signal-to-noise ratios and, 3) possibility to detect new classes of sources, that are out-of-reach to the current detector generation. The ET science objectives are summarized in the document "Science case for the Einstein Telescope"[12].

A striking example of the potential of ET is given by the expected number and distances for binary black-hole (BBH) and binary neutron star (BNS) coalescences. The 2G network (Virgo and LIGO) will detect - at full sensitivity - BNS coalescences up to z$\sim$ 0.2 and BBH up tp z $\sim$1. Einstein Telescope will detect BNS up to z$\sim$ 2-3 and BBH up to $\sim$20 and beyond. This means that ET will detect 90% of all BBH mergers in the Universe, and cover the redshift range beyond star formation epoch. This allows to probe the entire evolution and demography of black-hole formation in the Universe, through the dark ages. A BBH merger detected at redshifts higher than 20 provide a strong case for the existence of primordial black holes.

Moreover, ET will detect BBH with masses up to a few thousands solar masses, accessing the region of the intermediate black-holes (the first example being GW190521), thus providing key information for the hierarchical formation scenarios for the super-massive black-holes at the center of galaxies.

In terms of number of detected events, Virgo and LIGO are currently detecting $\sim$1 candidate BBH per week in average. Einstein Telescope will detect 1 BBH every $\sim$ minutes. This represents a wealth of data to study the distribution and formation scenarios of these sources and also use them as cosmological probes.

Moreover, the BBH mergers detected today would be observed with SNR of a few hundreds, thus allowing the access to fine details (higher-order modes) in the gravitational-wave waveform, leading very precise tests of general relativity.

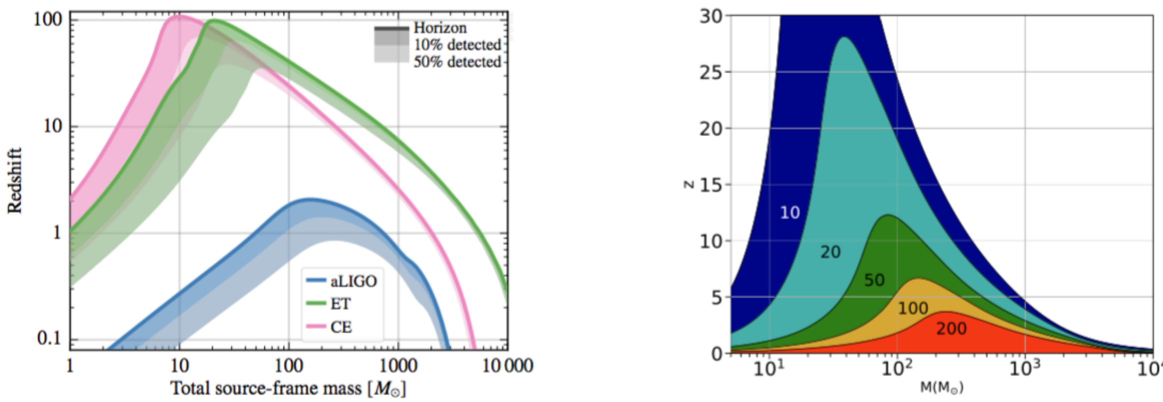

Figure 5: Left: observable distance for non spinning compact object for 2nd generation detectors and 3rd generation detectors (Einstein Telescope and Cosmic Explorer), versus the total mass of the system. Right: zones of constant signal-to-noise ratio versus total mass of the system and observable distance.

In addition to these sources, Einstein Telescope has also the potential to address other sources, as the core collapse supernovae, the rotating neutron stars, and to seek for a cosmological background of gravitational-waves.

7 The IN2P3 role

The IN2P3 is present in Virgo through 5 laboratories: APC, IJCLab, IPHC, IP2I/LMA, LAPP, for a total of 98 persons (including researchers, engineers, technicians, PhD students, post-docs), corresponding to 63.6 FTE. (among them, 56 persons are authors of the publications). Other french research units are Artemis (Nice), ILM (Lyon) and LKB (Paris), for a total of 39 persons and 23,4 FTE. The Virgo Collaboration counts today 13 countries, $\sim$ 600 members, $\sim$ 400 authors of the publications.

The IN2P3 has crucial activities and responsibilities at all level in the Virgo structure. Among them (not exhaustive list):

- IN2P3 members have top-level responsibilities of 3 over 4 of the LIGO-Virgo search groups (compact binary coalescences, bursts and stochastic searches) and of the detection characterization group. IN2P3 groups are involved in several activities related to the search of gravitational-waves produced by compact objects, stochastic background, test of general relativity, cosmology using gravitational-waves (measurement of the Hubble constant), multi-messenger astrophysics.

- On the Advanced Virgo+ side, IN2P3 members have top-level management responsibilities (project leader of AdV+, manager of the "interferometer" system, sub-system managers of the detection, data-acquisition, auxiliary laser, squeezing injection, mirrors and calibration sub-systems. IN2P3 groups are involved in the development, construction and commissioning of the detector, and in particular: mirrors and coatings, detection system, squeezing, vacuum, digital and analog electronics.

- Several IN2P3 members and groups are involved in research and development activities in fields as squeezing, mirrors and coatings, calibration, reduction of stray light, electronics.
- IN2P3 members are involved in top-level responsibilities in the Virgo Collaboration: chair of the Virgo organization committee, co-chair of the Virgo core program committee, member of the public data release committee, co-chair of the Virgo diversity committee, member of the AdV+ project supervising board.

About Einstein Telescope: 2 IN2P3 members are in the Einstein Telescope steering committee and 2 IN2P3 members are co-chairs of division of the Instrumental science board (ISB) of Einstein telescope. Other INP23 members are proposed for Work Packages leading roles. The experience of the IN2P3 groups in detector developments, commissioning and data-analysis represents a major resource for Einstein Telescope. Moreover, others IN2P3 groups not currently participating to Virgo, could greatly contribute to ET, in field of expertise of the Virgo groups, but also with new competences, as, for instance, cryogenics and underground operations.

References

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