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The Virgo experiment and the hunt for gravitational waves: status, recent results and prospects.

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Since the first discovery in 2015, the field of gravitational-wave searches has strongly developed, with a total of 90 confirmed detections during the first three observing runs of the Advanced LIGO/Virgo detectors. In this talk, I will present the current status of the Virgo detector and its contribution in the global network of Earth-based detectors. Then, I will discuss the various searches that are currently carried on, along with the recent findings and their scientific implications. Finally, I will discuss future upgrades of the detector and the prospects for the coming decades.

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1. Introduction: gravitational waves and detectors

Gravitational waves (GWs) are a perturbative solution of the Einstein field equations, which link the space-time metrics $g_{\mu\nu}$ with the stress-energy tensor of a system $T_{\mu\nu}$ as

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \tag{1}$$

where $G_{\mu\nu}$ is the Einstein tensor, a combination of the space-time tensor $g_{\mu\nu}$ and its first and second derivatives. GW solutions are obtained by expanding the Einstein equations around the flat-space metric $\eta_{\mu\nu}$, introducing a perturbation $h_{\mu\nu}$ in order to write

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \,, \qquad \left|h_{\mu\nu}\right| \ll 1 \tag{2}$$

In absence of matter, the stress-energy tensor vanishes, i.e. $T_{\mu\nu} = 0$. In this situation, the perturbation propagates under the wave equation

$$\Box\, h_{\mu\nu} = 0 \tag{3}$$

where the presence of the D'Alembert operator $\Box = -(1/c^2)\partial_t^2 + \nabla^2$ implies that GWs propagate at the speed of light in vacuum. By looking at the order of magnitude of the constant factor in Equation 1 that links the mass-energy content to the space-time curvature, $8\pi G/c^4 \simeq 2 \cdot 10^{-43} \mathrm{N}^{-1}$, we see that GWs are in general extremely faint. They need bulk motion of matter to be emitted, and we need huge concentrations of matter to have GWs strong enough to be observable at Earth.

There is a subset of astrophysical systems that meets this condition, which defines the possible sources that are target of present Earth-based detectors. We can mark GW signals as transient, if they stay in the detector sensitivity band for a limited time, or continuous, if they last for the entire observation time of the detector. We can moreover distinguish between modeled and unmodeled signals, depending on the understanding of the physical mechanisms that drive the emission. This first-level classification is reported in Table 1.

	Modeled	Unmodeled
Transient signals	Coalescence of compact binaries Postmerger neutron stars	Bursts Supernova explosions
Continuous signals	Periodic sources	Stochastic background

Table 1: Classification of GW signals between transient/continuous and modeled/unmodeled.

- **Coalescence of compact binaries.** They are the only sources detected so far. They are binary systems of compact objects, including black-hole pairs (BBH), neutron-star pairs (BNS) but also mixed neutron-star-black-hole pairs (NSBH). The configuration of two (or more) mutually orbiting bodies is among the most efficient GW emitters, since it strongly violates the cylindrical symmetry. In the first 3 LIGO/Virgo observing runs a total of 90 GWs from coalescences have been detected [1–4], including 86 BBHs, 2 BNS systems [5, 6] and 2 NSBH systems [7].

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- **Bursts.** They are short-duration, unmodeled transients that are for instance emitted by Supernovae explosions from stars at the end of their life cycle. Those sources are the first searched since the beginning, but unfortunately they have not yet been detected up to now. The reason is that these explosions do not emit engergetic GWs, so the search range is limited to our Galaxy, but these are very rare events, expected to happen once per century.

- **Periodic sources.** Periodic sources emit a nearly monochromatic signal, often called continuous wave (CW). These signals typically last for times much longer than the observing time of the detectors, so they are always present in the data. An intermediate case are the long-lasting transients, with typical duration that ranges from hours to days, even up to months. The most important sources are rapidly spinning neutron stars, that are thought to emit GWs if they are deformed from the axial symmetry. There are also more exotic possible sources of CWs, like the boson condensates around spinning black holes. The expected signal is, in general, several orders of magnitude weaker than signals from coalescences. These sources have not yet been detected, but improvements in detectors and longer observing periods increase the detection chances.

- **Stochastic background.** A stochastic background can be seen as a superposition of plane waves, with frequencies covering a given range, with amplitudes as random variables and therefore this process cannot be described through analytic waveforms. The stochastic background can originate from the superposition of many, unresolved astrophysical sources, revealing important information on the distribution of sources in the near and far universe. A stochastic background can originate also from cosmological phenomena. The detection of a cosmological GW background would have a strong impact on the cosmology research field, unveiling probes on the earliest stages of the Universe. Also in this case, stochastic GWs are not yet detected.

Currently, the network of GW detectors is composed by two LIGO detectors, placed at Hanford and Livingston [8], Virgo in Italy [9], KAGRA in Japan [10] and a smaller one, GEO600, in Germany [11]. They are currently in observing mode, at the middle of the fourth observing run in the Advanced configuration, named "O4".

The basic layout of a GW interferometer consists in a in-vacuum, suspended Michelson interferometer with Fabry-Perot cavities as arms. An infra-red laser is injected in the detector and then split in two beams into the two Frbry-Perot arms through a suspended beam-splitter. The Fabry-Perot cavities are delimited by so-called input mirrors at the entrance and test-mass mirrors at the end. The two laser beams on the output of the arms are recombined back together and sent to the read-out system. All the main optics are suspended to multi-stage seismic insulators, which in Virgo are the so-called superattenuators. The effect of a GW passing through the detector is the deformation of the optical path of the laser, producing a phase shift on the recombined beams that is formally equivalent to a change in the arms length, proportional to the GW strain amplitude. From the measured output laser power, we reconstruct the phase difference between the recombined laser beams and then produce the estimated time series of the GW strain, called $h(t)$.

The first generation (1G) of kilometer-scale GW interferometric detectors made a great jump with respect to the past. However, further substantial upgrades were necessary. The optics, which

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were first suspended through steel wires, have been suspended through monolithic silica wires, creating a unique monolithic suspension and reducing the associated thermal noise by many orders of magnitude. Two additional cavities have been added to the original optical layout: a power-recycling cavity between the laser input system and the beam-splitter, to increase the circulating power, and a signal-recycling cavity between the beam-splitter and the detection system, to enlarge the sensitivity bandwidth. A detector with these new cavities added is called dual-recycled. To manage the increased circulating power and further increase the power of the injected laser, high-power optomechanics have been installed. Moreover, squeezing techniques have been developed and applied to the laser to beat the quantum noise. The improvements listed above, although not exhaustive, led to the so-called second-generation (2G) detectors. The jump in the strain sensitivity between 1G and 2G detectors was of about one order of magnitude over the whole frequency bandwidth. This jump in sensitivity made possible the first GW detection during the first observing run in the Advanced configuration, O1 [12].

2. The O4 run and the status of Virgo

The first part of the fourth observing run, named O4a, started in May 2023 and lasted until January 2024. In that part the two LIGO detectors were observing, with KAGRA joining the run in the first month and then stopping to continue commissioning and improving its sensitivity with the perspective of join again the run in the last months. During that period the network was observing in the 83% of the time, with a 53% of double detector observing in coincidence. The second part of the run, named O4b, started in April 2024 with the plan to stop in January 2025, making a smooth transition to the third and last part (O4c) without any break. Virgo joined O4b since the beginning and is currently observing with a sensitivity range to binary neutron stars (BNS range) of 50-55 Mpc, while the two LIGO detectors are observing with a BNS range from 150 to 170 Mpc. Up to the 22th October 2024 the network was in observing mode for $\sim$ 90% of the time, with a 35% of time of triple detector. This percentage grows up to 45% if we exclude from the calculus the intentional break periods.

Virgo joined O4 in April 2024 with a sensitivity comparable with the one achieved during the O3 run, after a long commissioning period. The fact that in Advanced Virgo the two recycling cavities (nominally, the power-recycling and the signal-recycling) are in a marginally stable configuration makes the detector more sensitive to aberrations and thermal effects, with a negative impact on the complexity of the interferometer and on the power that can be injected. Moreover, since the Virgo detector achieved a stable and reliable lock, a new unmodeled noise showed up in the bucket, limiting the sensitivity. The current noise budget of Virgo is shown in Figure 1 and can be summarized as follows. At low frequencies (up to 60 Hz) the noise from local controls dominates over the fundamental noises like quantum radiation pressure and seismic noise. At intermediate frequencies (up to 200-300 Hz) the extra unmodeled noise adds to the fundamental noises, like the thermal noise of mirrors' coating and the optical quantum noise. At high frequencies (above 300 Hz), the leading contribution if from the quantum shot noise.

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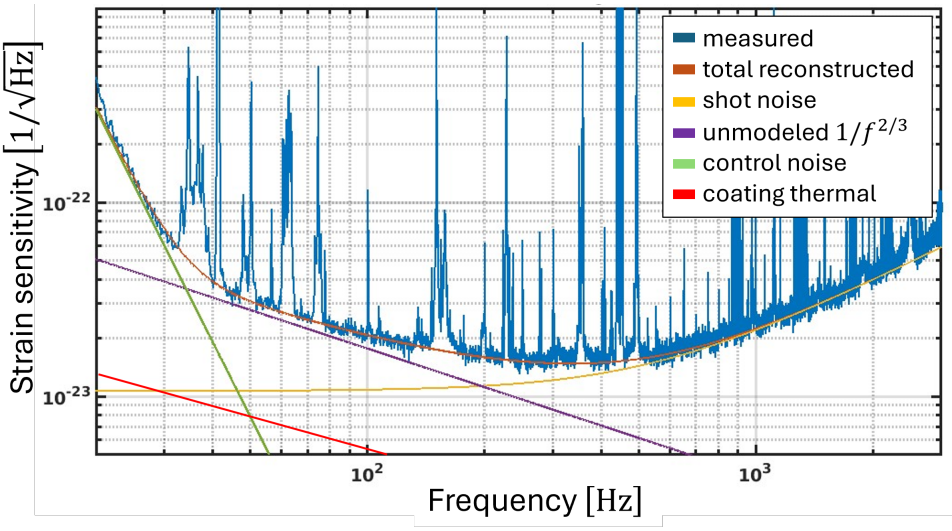

Figure 1: The noise budget of Virgo, measured during the commissioning for the O4 run. The blue line is the measured GW strain. The other curves are the projections of the main noise sources in terms of strain.

3. Observations during the O4 run

The first GW detection happened at the beginning of the O1 run, when the BNS range of the network of gravitational detectors was about 80 Mpc. That range was 135 Mpc during the last concluded run, O3, and is currently around 170 Mpc. So, the observing range has been more than doubled with respect to the first-detection period. As the sensitivity of the network increases, the volume of the inspected universe scales as the cubic power of the BNS range. This means that we are now exploring a portion of universe one order of magnitude bigger than at the time of the first detection, and twice as muche the universe as in O3. The rate of GW detections is growing accordingly, as can be seen in the plot at the left side in Figure 2 showing the cumulative GW observations as function of time across the various observing runs. In particular, the plot at the right side in Figure 2 shows that the number of alerts generated by the on-line search pipelines during the O3 and the O4 runs and the cumulative product between volume of inspected universe and observing time evolve with the same rate.

During the O3 run a total of 79 detections has been confirmed during an observing time of about 11 months. In the first part of the current observing run, O4a, 81 significant candidates have been selected in 9 months, and other 68 candidates have been selected in the next 8 months, during O4b, up to the 22th October 2024.

3.1 GW230529: filling the mass gap

In the 29th of May 2023, during O4a, the LIGO Livingston detector recorded an interesting GW event named GW230529 from the coalescence of two light compact objects [13]. The first one is likely a neutron star with mass $\simeq 1.4 M_{\text{sun}}$ while the second object, most likely a black hole, has mass $\simeq 3.6 M_{\text{sun}}$ falling within the so-called mass-gap, a range of masses between $3 M_{\text{sun}}$ and $5 M$sun for which stellar-evolution models do not predict the existence of compact objects. At the moment, GW230529 provides the best evidence of compact objects existing in that mass gap.

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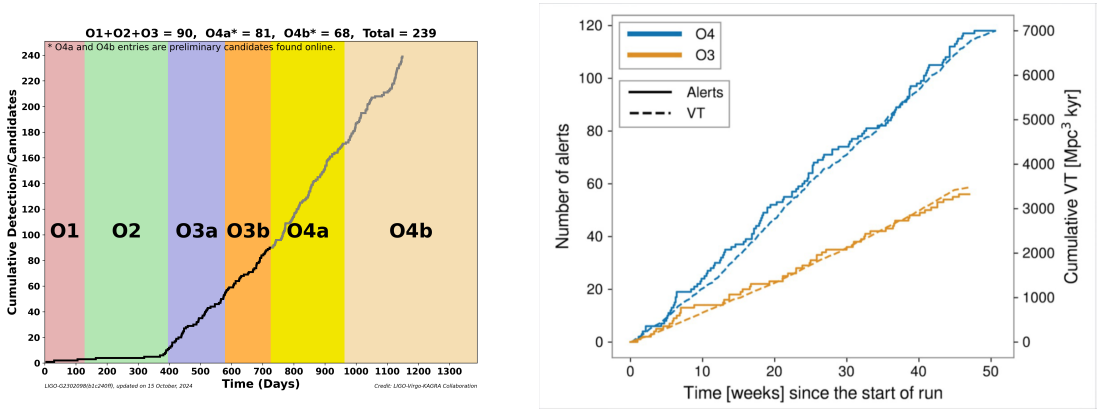

Figure 2: Left plot: cumulative GW detections, as function of effective observing time, since O1 up to the 22th October 2024. Right plot: detail of the GW alerts received during O3 and O4 (up to the 22th October 2024), compared to the cumulative Volume × Time product, as function of the time since the beginning of each run.

Unfortunately, the LIGO Hanford detector was not observing at that time, but the event was detected by all the active on-line pipelines with high significance, enough to confidently claim the detection. Consequently the event has a poor sky localization, with the 90% credible area $\sim 25000 deg^2$ wide, and no electromagnetic counterpart has been found. In any case, the observation of GW230529 has important astrophysical implications. If the merger is actually the outcome of the evolution of an isolated binary system, the existence of a mass-gap object is a hint that we have an incomplete understanding of core-collapse processes in massive stars. Another possibility for this merger is to be the outcome of a hierarchical merger between two neutron stars in a dense stellar environment, or a triple system. However, the expected rates of such mergers are estimated to be multiple orders-of-magnitude lower than isolated binary systems.

3.2 O4b and the impact of Virgo

The Virgo detector is observing with a BNS Range of 50-55 Mpc and a 80% observing time. Even if its sensitivity is approximately 1/3 of the two LIGO detectors, the contribution of Virgo is crucial to improve the sky localization of GW events through triangulation. In order to maximize triple-detector time, the Virgo down-times are synchronized with LIGO. Thanks to these efforts, the localization of GWs during O4b is greatly improved with respect to O4a. During O4a, with two observing detectors at most, only the 15% of the alerts had a 90% credible area in the sky tighter than 1000 deg^2, with the most localized event having an area 82 deg^2 wide. During O4b, at the 22th October 2024 the number of alerts with 90% credible area tighter than 1000 deg^2 is about a 50%, with the most localized event having ad area only 4 deg^2 wide. Thanks to this improvement in sky localization, multimessenger astronomy is possible.

Up to the 22th October 2024, there are 68 significant GW candidates reported by the on-line search pipelines. They are mostly BBH events, with 4 of them having a weak probability, about $10-30\%$, to come from mixed NSBH systems. There is one very interesting GW event, observed in the 22th April 2024, with strong probability $> 99\%$ to be a NSBH candidate [14]. It was detected by both LIGO and Virgo detectors, with a well-defined sky localization with a 90% credible area of

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259 deg^2 and a 50% credible area of 72 deg^2 and a distance of (188 ± 43)Mpc. Currently, further follow-up analyses are being carried on this candidate.

As already shown in this Section, the detection rate for GWs from BBH systems is growing according to the improvements in the sensitivity of the detectors network. What is actually missing during O4 are GW candidates from BNS systems. After the first BNS detection in O2, which also marked the beginning of the multimessenger astronomy [5], there has been only one other BNS detection during O3, made by only the LIGO Livingston detector [6]. Based on those two detections and on the cumulative volume of inspected universe and ovserving time up to O3, the rate of BNS mergers has been inferred to be between 10 and 1700 $\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$ [15]. However, for the whole O4a and during O4b up to the 22th October 2024, no GW candidate from BNS has been found. Consequently, the expectations on BNS rate are being revised. In particular, the inferred rate of BNS including the non-detections in O4a has to be corrected to $5 - 920\,\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$ [16] and will be further updated depending on the detections in O4b. In any case, this results tell us that further improvements in sensitivity are needed to make neutron-star physics. Thus, future upgrades on the detectors are crucial.

4. Future developments: O5 and post-O5

The current observing run O4 is planned to stop on the 7th October 2025. Then, after a two-year period of upgrades and commissioning of the detectors, the network will begin the next observing run, named O5. The O5 run is planned to start sometime during 2027 and to last for 3 years, with a nearly continuous data flow while progressively increasing the sensitivity [17].

In light of the inputs came during the commissioning period for O4, Virgo is considering to give priority to the installation of stable recycling cavities, as the current marginally stable configuration has been individuated as the most limiting factor for further upgrades. In parallel, a strategy for the so-called post-O5 period is under evaluation. In the mid-future next-generation GW detectors, like Einstein Telescope and Cosmic Explorer. Those third-generation (3G) will implement facilities to improve the design sensitivity of current detectors by one order of magnitude in the full bandwidth and, moreover, to extend the sensitivity window to lower frequencies down to 2 Hz. The range of the observed universe would be enlarged up to the Dark Age, at the $z = 100$ redshift. However, the path towards 3G detectors is still long and we don't expect they will produce observational science before the 2040. Moreover, there is a technological gap between currend 2G detectors to 3G detectors which represents a high risk: many facilities for 3G detectors will require technological improvements with respect to the current state of art. Thus, the scientific program of LIGO, Virgo and KAGRA detectors needs to be extended until the advent of 3G detectors, in order to both keep producing observational science and to keep the gravitational community together, forming a new generation of GW experts.

In Virgo a "Post-O5 study" committee has been set up, with the creation of the *Virgo_nEXT* project. The general intent is to improve on the Advanced Virgo design sensitivity maintaining the same infrastructure, the same wavelength of the laser and keeping the mirrors at room temperature. Some of the foreseen upgrades under evaluation include the possible increase of the inter-cavity power up to the order of MW, reaching a deeper level of squeezing, the installation of heavier test masses as well as the development of better coatings.

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5. Conclusions

The network of Earth-based GW detectors, composed by LIGO, Virgo and KAGRA, is currently carrying on the 4th scientific run in the "Adanced era", named O4. Virgo has joined O4 in the second part of the run, in April 2024, is currently taking data together with the two LIGO detectors and KAGRA will join the run towards the end, which is scheduled for the 7th October 2025. Joint LIGO-Virgo observations have shown that GW science has an enormous discovery potential both for fundamental physics, astrophysics and cosmology. So far, the contribution of Virgo in the network has proven to be fundamental for better localizing the sources in the sky and doing multimessenger astronomy. While completing the O4 observing run, Virgo is preparing the plan for O5 and is working on the long-term planning as well. The field of GW science is rapidly growing, but is just in its early phase and in the next 20 years it will develop its full potential.

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