Virgo_nEXT

June 7, 2023

The IN2P3 Virgo laboratories and researchers [1]

Abstract

In the last years, LIGO and Virgo have made significant progress in the field of gravitational-wave (GW) science, detecting numerous signals from merging binary compact objects. These observations have provided valuable insights into general relativity, astrophysics, and cosmology. This document presents Virgo_nEXT, a major upgrade to the Virgo detector to be operated in the early 2030's, aimed at bridging the gap between the current phase and the future Einstein Telescope. Virgo_nEXT encompasses the following key objectives: continuing Virgo's science program in the LIGO-Virgo-Kagra (LVK) gravitational-wave detector network, pushing the potential of the existing infrastructure to its limits, testing the technologies used in the Einstein Telescope, filling a potential gap of a decade between the end of the current phase and the first Einstein Telescope design sensitivity, keeping and developing the expertise of the experimental and data analysis community. This document provides an overview of the scientific potential of Virgo_nEXT, the detector concept, project history and schedule, international context, expertises and potential contributions from IN2P3 groups, and synergies with the Einstein Telescope.

1 INTRODUCTION AND CONTEXT

In the last seven years, through three observational campaigns, LIGO and Virgo have started in the era of gravitational-wave (GW) astronomy, detecting about 90 signals produced by the merging of binary compact objects: black-holes binary systems (BBH), but also binary systems formed by two neutron stars (BNS) and mixed neutron star/black-hole binary systems (NS-BH) [2].

These observations have provided a wealth of scientific results, ranging from general relativity to astrophysics and cosmology. Just to give a few examples, thanks to the GW observations it has been possible to discover a population of very massive stellar black holes (M> 20 $M_{\odot}$), never observed before. The properties of this population (such as mass, spin, and the rate of observed events) already provide some clues to distinguish

[1] Editor: Matteo Barsuglia, barsu@apc.in2p3.fr

between different mechanisms of formation and evolution of these binary systems. GW allowed also testing, for the first time, general relativity (GR) in the strong field regime, confirming that the measured wave-forms are in agreement with the predictions of the theory. The first detection of gravitational waves from a BNS merger (GW170817) [6] demonstrates with great precision that gravitational waves travel at the speed of light (as predicted by GR) and that this type of event is connected to (at least some) short GRBs and kilonova. The precise GW170817 localization provided by the LIGO-Virgo network allowed the identification of counterpart in almost the whole electromagnetic spectrum, which also led to the identification of the host galaxy and the redshift measurement. Since the properties of GW emitted by a binary coalescence allow the measurement of the source luminosity distance, the combination of this measurement with the redshift made possible a new measurement of the Hubble constant, independent of those obtained from supernovae and the cosmic microwave background [7].

After these three data taking campaigns (called O1, O2 and O3), the gravitational wave detector network (2 LIGOs, Virgo and the Japanese detector KAGRA), will continue its scientific program alternating observations and upgrades. Two data taking periods are currently planned: O4, starting in 2023 and O5, expected in 2026 (see Fig. 1). Concerning Virgo, after the phase called *Advanced Virgo*, corresponding to the data takings O2 and O3, the detector has been upgraded to *Advanced Virgo+* (whose phase-1 will be operated during O4 and phase-2 will be operated during O5). With respect to Advanced Virgo, the phase-1 aims mainly at a reduction of the quantum noise and the phase-2, a further reduction of the mirror thermal noise[2].

In parallel with the Virgo development and operation, a new European gravitational-wave observatory, *Einstein Telescope* (or ET[3]) is under study since 10 years (for details see the Einstein Telescope report for the IN2P3 Scientific Council). ET aims to increase the sensitivity of current detectors by an order of magnitude and enlarge the bandwidth towards lower frequencies (1-2 Hz, compared to 10-20 Hz today). Similarly to Virgo, LIGO and KAGRA, ET is a dual recycled Michelson interferometer with Fabry-Perot cavities in the arms, but it will be composed of two separate detectors: a 'warm' detector (ET-HF), more sensitive at high frequencies, and a 'cold' detector (ET-LF), operating at cryogenic temperatures and more sensitive at low frequencies. Moreover, ET will have 10 km arms and it will be placed in an underground facility. The ET "first light" is expected in the second half of 2030's decade. According to the experience of current GW detectors, the ET design sensitivity could be reached after a few years of commissioning activity.

In this context, Virgo_nEXT is a next major Virgo upgrade, whose purpose is to fill the gap between the current phase (Advanced Virgo+) and Einstein Telescope. More specifically, the aims of Virgo_nEXT are:

---

[2] As explained in the following, a re-definition of the Advanced Virgo+ phase 2 maybe be necessary after the difficulties encountered during commissioning of phase-1, which led to a delay in entering in the data taking O4.

[3] Einstein Telescope is considered a third generation, or 3G, detector. Initial Virgo and initial LIGO correspond to the first generation, Advanced Virgo and Advanced LIGO — including the upgraded versions Advanced Virgo+ and Advanced LIGO+ — are the second generation. The 3G (Einstein Telescope, Cosmic Explorer) will be in new infrastructures.

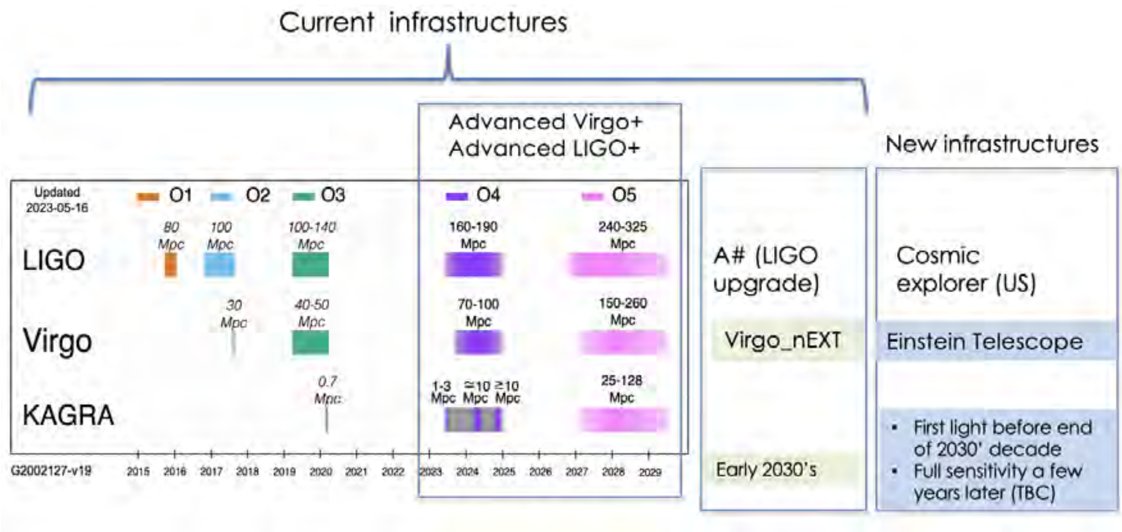

Figure 1: Timeline of ground-based detectors upgrades and of the past and future observing runs.

- Continue Virgo's science programme in the LVK gravitational-wave detector network
- Push the potential of the existing infrastructure to its limits
- Test the technologies used in the ET avoiding design mistakes and accelerating commissioning
- Fill a potential gap of a decade between the end of O5 and the first ET design sensitivity
- Keep and develop the expertise of the experimental and data analysis community
- Ensure smooth generational transition and training of new leaders

Virgo_nEXT is planned to be built in the Virgo infrastructure (vacuum system, building, main suspension systems), at the European Gravitational Observatory, the French-Italian-Dutch consortium operating the Virgo detector. The goal is to extend the Advanced Virgo+ goal sensitivity up to a factor ∼2, then placing the detector at half-way between Virgo and Einstein Telescope (see 2). This will be obtained reducing the main instrumental noises (quantum, thermal, technical noises), by pushing the current detector technologies (the squeezing level, the power in the arms, the mechanical losses of the mirrors) to their technological limits. The sensitivity of Virgo_nEXT is discussed in the following chapters (and shown in Fig. 7).

As Virgo is inserted today in the global LVK network, we make the hypothesis that Virgo_nEXT will be inserted in a "post-O5" network, formed by upgrades of LIGO and KAGRA. For instance, a LIGO upgrade (A#) is under discussion within the LIGO community and with the NSF, with a similar objective: doubling LIGO horizon, bringing

LIGO technologies to its limits. Similarly as for Virgo_nEXT, A# is considered a testbench for Cosmic Explorer (CE), the next generation detector under discussion in the US.

> This document focuses on the scientific opportunity, concept design of Virgo_nEXT, and synergies with ET (Einstein Telescope). Since the Virgo_nEXT Technical Design Report (TDR) has not been finalized and a Work Breakdown Structure (WBS) does not exist yet, we are unable to provide detailed information regarding the final involvement of IN2P3 groups and researchers in Virgo_nEXT. However, we will provide a comprehensive description of the current areas of expertise and responsibilities of IN2P3 in Advanced Virgo+

The structure of the document is the following: first we will give an overview of the Virgo_nEXT scientific potential (chapter: 2), followed by the detector concept (chapter 3), an history and schedule of the project (chapter 4), the international context (chapter 5), the IN2P3 and CNRS contributions (chapter 6), and finally the synergies with Einstein Telescope (chapter 7).

The results and plots presented in this document are based on the work of the "post-O5" working groups and in general of the whole Virgo Collaboration.

2 VIRGO_NEXT SCIENTIFIC GOALS

As already mentioned, the science that can be explored with a GW detector covers many areas of astrophysics, cosmology and fundamental physics. In this section, we discuss several scientific targets at the frontier of current research in GW astronomy, and how Virgo_nEXT will contribute to them.

2.1 *Main hypotheses and figures of merit*

> Virgo_nEXT is expected to operate as part of a worldwide network of GW detectors, including A# (LIGO Hanford, LIGO Livingston and LIGO India) and KAGRA

Although a single detector can in principle detect and characterise astrophysical signals on its own, in practice a worldwide network of detectors is extremely beneficial for a confident detection of any signal and for maximising the observing time. Moreover, for signals lasting less than a few hours, a geographically distributed network is required to localise the source in space [1]. The figure 2 shows the sensitivities of LIGO (A#), KAGRA and Virgo_nEXT (as well as ET), as main hypothesis for the following work.

Thanks to the GW observations performed since 2015, we know that such a network will primarily observe signals from the inspirals and mergers of stellar-mass black holes

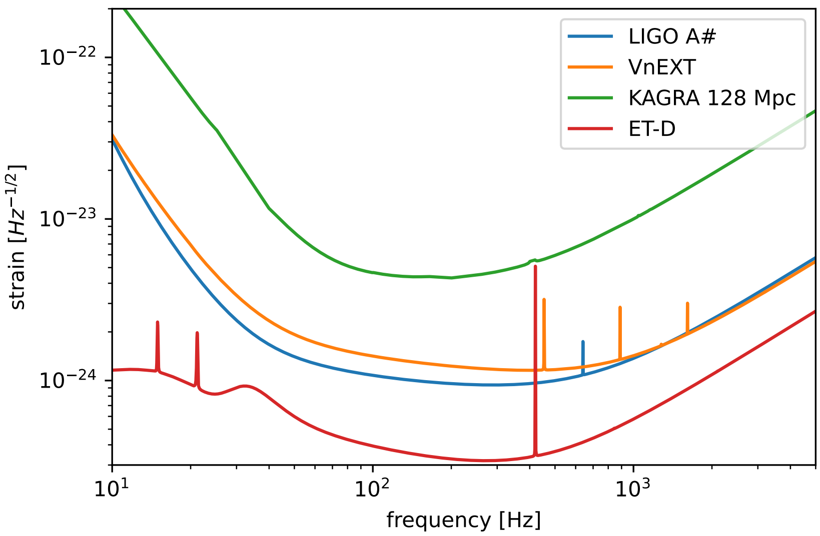

Figure 2: Sensitivity curves for LIGO A#, VnEXT, and KAGRA during the post-O5 era used in the simulations in this section. The curves for LIGO A# and Virgo_nEXT correspond to the best predicted performances (see https://git.ligo.org/post-o5/sensitivity-curves and https://gitlab.et-gw.eu/et/isb/interferometer/adv_noisebudget.git respectively). The curve for KAGRA may turn out to be an underestimate as it is based on the O5 sensitivity curve given in [1]; it has been used here because studies are still underway for the post O5 era. In the following, the LIGO A# sensitivity curve has been applied to LIGO-Livingston, LIGO-Hanford and LIGO-India, assuming that all three observatories shall be able to achieve the best expected performances. For a comparison with next generation observatories, the predicted sensitivity curve for the Einstein Telescope is also shown (from https://dcc.ligo.org/DocDB/0126/P1600143/018/).

and neutron stars. The population of these objects is gradually being uncovered thanks to the current observations, and in our evaluation of Virgo_nEXT's performance, we assume population properties consistent with the Gravitational Wave Transient Catalog produced by LIGO, Virgo and KAGRA [2].

Given the existing observations, a large part of Virgo_nEXT's scientific case revolves around compact binary mergers, and some of the most relevant figures of merit to evaluate Virgo_nEXT's performance are directly related to their signals. In particular, we discuss the maximum distance (or redshift) at which Virgo_nEXT can observe compact binary mergers, Virgo_nEXT's impact on the rate of compact binary mergers detected by the worldwide network of detectors, and its impact on the ability of the network to localize compact binary mergers in space. Present cosmological constraints and tests of general relativity derived from gravitational wave observations also rely on compact binary merger events [3, 4], and we discuss how Virgo_nEXT will improve those areas as well.

One of the major open questions in gravitational wave astronomy is what kind of signal can be realistically detected *apart* from the compact binary merger signals that are routinely observed at present. Major expectations include short bursts from core collapse supernovae, long lived quasi-monochromatic signals from neutron stars, and a persistent stochastic foreground arising from the incoherent superposition of many signals from individual compact binary systems. We present a few highlights showing how Virgo_nEXT will improve our searches for such signals. More details can be found in the Virgo_nEXT concept study [34].

2.2 *Astrophysics of compact objects*

Roughly 90 mergers of compact objects have been detected and characterised so far by LIGO and Virgo, including a handful of events involving neutron stars [2]. We are starting to probe their population, in particular tracing their mass distribution, however much remains to be done due to the relatively limited sample [5]. The primary task to be achieved in order to learn more about these objects is to significantly increase the number of confident observations, and the only way to do this in any useful time is to observe the universe at larger and larger distances, or equivalently, larger redshifts.

To this end, one of the simplest figures of merit to evaluate Virgo_nEXT is the maximum redshift at which a compact binary merger can be identified in the detector noise with a useful confidence. Most LIGO/Virgo/KAGRA signals are consistent with quasicircular mergers of nearly equal mass compact objects, so we focus on the same kind of source here. The result is shown in Fig. 3, which also includes the Virgo configuration in the O3 run, a prediction for Einstein Telescope, the redshift at which the star formation history peaks and a few milestone compact binary merger discoveries. We can immediately see that Virgo_nEXT will greatly extend Virgo's reach, placing it between the present capability and Einstein Telescope, and allowing us to study the black hole population around the peak of the star formation history.

The second figure of merit we discuss is the rate of detections of compact objects assuming our present knowledge of their population, in particular their mass distribution and the space-time density at which they merge. To this end, we simulate a worldwide network of detectors including LIGO Hanford, LIGO Livingston, LIGO India, KAGRA and Virgo_nEXT, and a population of compact binary mergers consistent with observations from the O3 run.

> With the "post-O5" network we obtain a yearly detection rate of approximately 10^4 binary black hole mergers, and approximately 10^3 binary neutron star mergers. This is orders of magnitudes larger than what is possible with present detectors.

The majority of these events would be detected by at least four detectors, making them extremely robust discoveries with precisely measured masses and spatial locations (typically tens of square degrees for the sky location).

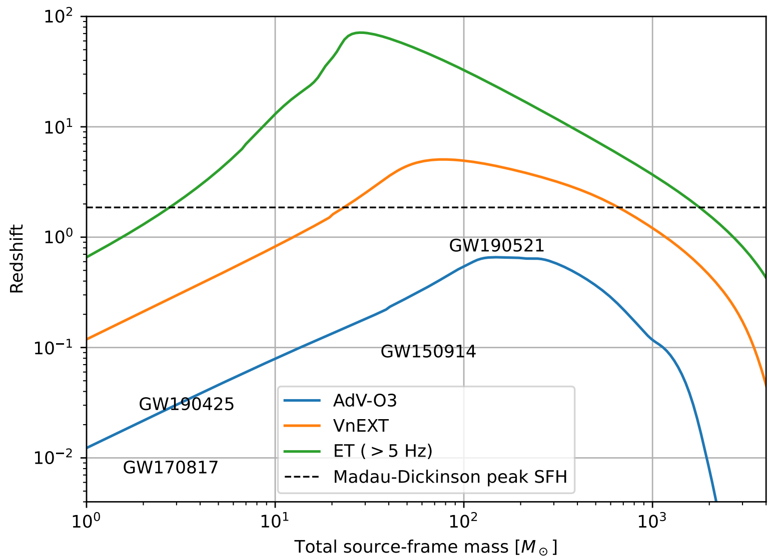

Figure 3: Maximum redshift at which a quasicircular merger of two compact objects can be detected. The objects are taken to have the same mass, and their total mass is shown in the horizontal axis. The lower curve shows the Virgo configuration during the second half of the O3 run; the middle curve shows Virgo_nEXT; the upper curve shows an estimate for the Einstein Telescope. The approximate locations of a few milestone GW events are included for reference. The black dashed line indicates the redshift at which the star formation rate peaks.

> After only a few years of such observations, we will know the mass and spin distribution of black holes and neutron stars to a precision far greater than we do at present. In particular, we will most likely know the detailed shape of the mass gaps that may exist between neutron stars and black holes masses, and around ∼70 solar masses for black holes. The measurements of structures in the black-hole mass distribution will be also crucial for the cosmology with GW signals only (methods of the "dark sirens" see below).

Moreover, the accurate interpretation of thousands of large amplitude signals will require significant theoretical development to produce reliable physical models of the signals, maintaining the theory and data analysis communities active during the next decade and ready for the 3G era.

In addition to signals from merging neutron stars and black holes, we expect to detect long-lived, quasi-monochromatic gravitational waves (commonly called continuous waves) from neutron stars, under a variety of emission models related to the structure of neutron stars or the properties of their environment. One such model is an isolated, rotating and non-accreting neutron star, typically one of the known millisecond pulsars, exhibiting some degree of asymmetry with respect to its rotation axis, and slowly losing angular momentum due to gravitational or electromagnetic radiation. A similar model is a non-axisymmetric neutron star which is accreting material from a companion star, typically in a low-mass X-ray binary such as Scorpius X-1, balancing the angular momentum gain from accretion with its loss due to gravitational radiation. Other scenarios predict the emission of day-long signals from newly born magnetars, possibly after the mergers of neutron star binaries. Although none of these signals have been observed yet, upper limits related to some of these scenarios have been set using present detectors, and more stringent limits from Virgo_nEXT will tighten the constraints on these models.

> Notably, one year of observations with Virgo_nEXT would double the number of millisecond pulsars for which we can exclude gravitational radiation as the cause of the loss of angular momentum. Virgo_nEXT would also increase by $\sim$5 times the sample of galactic neutron stars for which we can set a given ellipticity upper limit. Moreover, we could strongly constrain gravitational-wave emission as the cause of angular momentum loss in Scorpius X-1, and approach the same constraint for a few more systems. Apart from setting constraints, some arguments predict that at Virgo_nEXT sensitivities we have a plausible chance of making a first discovery of a continuous gravitational wave.

Finally, the birth of a compact object from a core-collapse supernova is expected to be associated with a short-duration burst of gravitational waves. Such a signal is yet to be observed, mainly due to the rare occurrence of supernovae, their relatively small luminosity in gravitational waves, and the complicated shape of the waveform. Observing such a signal would allow us to probe the bulk motion of the matter inside the collapsing core and provide the precise time of the collapse to at least a few seconds.

> Virgo_nEXT will allow us to extend the observable range for supernova bursts by a factor of $\sim$2, and increase our chance of having gravitational-wave observations in case one of these rare events occurs in our galaxy.

2.3 *Cosmology*

GW cosmology is a new research field which is currently undergoing rapid expansion on both theoretical and observational sides, notably since the detection of GW170817 which provided the first GW measurement of the Hubble constant [24]. Virgo_nEXT is expected to play a principal role in a network of GW detectors which will provide unprecedented cosmological information, possibly leading to unique insights on some of the current mysteries surrounding cosmology, in particular the Hubble tension and the nature of dark energy.

As a central pillar in a larger GW network, Virgo_nEXT will provide percent constraints on the Hubble constant, playing a fundamental role in solving the Hubble tension, and will deliver unprecedented tests on the nature of dark energy and of gravity at the largest scales.

The Hubble tension. Measuring the actual value of the Hubble constant H_0, which defines the current expansion rate of the Universe, is one of the main task in cosmology since Hubble first discovered the cosmic expansion in 1929. Various techniques have provided a large number of different measurements, eventually converging on two possible values for H_0. Early-universe, model-dependent (i.e. depending on the assumed cosmological model) observations provide values around 67 km s^{-1} Mpc^{-1}, and are mainly represented by the latest CMB data collected by the *Planck* mission which yields 66.93±0.62 km s^{-1} Mpc^{-1}. On the other hand, late-universe, model-independent observations provide values around 73 km s^{-1} Mpc^{-1}, and are mainly represented by Supernovae type-Ia (known as standard candles) data which yields 73.5±1.4 km s^{-1} Mpc^{-1}. The two measurements are in disagreement with a statistical significance which goes beyond 4σ, and cannot be explained neither by obvious systematic effects in one of the two experimental methods nor by obvious physical effects beyond-ΛCDM, the current standard cosmological model. This is the origin and essence of the so-called *Hubble tension*, and at present it is considered one of the major problem to be solved by contemporary cosmology, possibly leading to new physics beyond the decades-old ΛCDM model.

GW observations enter the stage by opening a new way to probe the expansion of the Universe, and in particular to measure the Hubble constant. GW data from compact binary coalescences such as BBHs and BNSs, provide a direct measurement of the luminosity distance to the source. If coupled with a redshift estimate for the same source, such distance measurements can then be employed to constrain the expansion of the Universe, similarly to how standard candles are used. As an analogy GW signals from compact binary coalescences are usually referred to as *standard sirens*, although contrary to supernovae type-Ia they do not rely on calibration through the *cosmic distance ladder* yielding instead absolute, i.e. self-calibrated, measurements of cosmological distances. For this reason standard sirens are somehow regarded as a new independent late-universe probe of the cosmic expansion as they would not be affected by would-be systematic originating by calibration through the cosmic distance ladder. The main difficulty with standard sirens is to obtain a redshift estimate associated to the GW source. There are two main techniques developed so far, distinguished by the availability (*bright sirens*) or not (*dark sirens*) of an EM counterpart to the GW event. Let us see what they can do with Virgo_nEXT.

The single bright siren from the multi-messenger observation of GW17087 offers so far the bulk of GW information available on the Hubble constant, delivering $H_0 = 70.0^{+12.0}_{-8.0}$ km s^{-1} Mpc^{-1} [24]. The forthcoming O4 and O5 observational runs are expected to improve upon this results, but not to reach the few % measurement needed to *solve* the Hubble tension, i.e. to discern between early- and late-universe measurements of

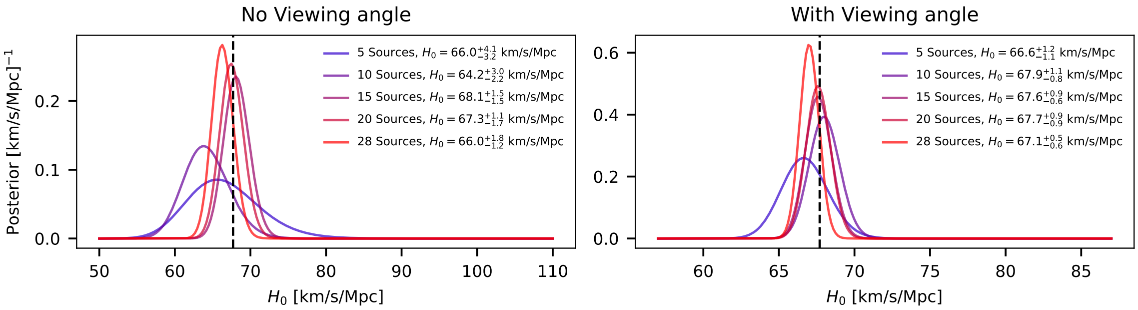

Figure 4: Simulated Ho posterior BNS sources expected to be detected by Virgo_nEXT with EM counterpart. The legend indicates the number of sources considered and the 1σ credible intervals of the Ho posterior. The left (right) panel assumes that additional information on the binary viewing angle is not (is) available from EM observations. Figure taken by [34]

.

H_0. Virgo_nEXT on the other hand, by working in concert with a network of at least 4 or 5 GW detectors, and by assuming the Vera C. Rubin Observatory's Legacy Survey of Space and Time (LSST) or another similar EM telescope will be available to observe EM counterparts of BNSs, can reach measurements of order few % in one single year of bright siren observations (cf Fig. 4). Such a result will definitely help solving the Hubble tension, notably if additional observational time beyond one year is factored in.

On the other hand, if no EM counterparts are detected, GW events can still be used to extract cosmological information, either by cross-correlating their sky-localisation with catalogs of galaxies and/or by exploiting features in the mass distribution of the GW sources themselves. Such dark siren techniques are routinely applied to current GW data, but do not yields strong constraints by themselves yet but offer a significant improvement (credible interval reduced by 44%) if combined with GW170817 results.

Nevertheless they have the advantage to rely on the availability of a larger number of sources since they do not require EM counterparts and can thus be applied to BBHs as well which have the additional advantage of being detectable at higher distances. By considering the number and characteristics of BBH detections expected from a network of 4-5 GW detectors including Virgo_nEXT, a few % constraint on H_0 is attained in one year of observation [34], sufficient again to solve the Hubble tension.

Two different techniques, bright and dark sirens, will thus separately allow Virgo_nEXT to reach % constraints on H_0 (always in the working hypothesis that observations are taken in concert with a network of GW detectors, and also that that an absolute calibration of the GW signal is available for reliable percent), and they can deliver better constraints if combined together, measurements. These results and the duplication of methods to obtain them, provide a solid argument for Virgo_nEXT to play an important role in the solution to the Hubble tension.

Dark energy and modified GW propagation. Another of the major unsolved problem of cosmology consist in identifying the nature of the accelerated expansion of the Universe, usually attributed to an unknown cosmic entity called *dark energy*. In the ΛCDM model dark energy is described by the *cosmological constant*, but such a simple solution suffer from different theoretical issues although it is still well in agreement with observational data. Alternatives to the cosmological constant description abound in the literature, and usually either introduce additional yet unobserved cosmological fields/particles or outright change the dynamics of the gravitational interaction by modifying Einstein's theory of general relativity at cosmic scales. GW brings a new way to probe possible effects of dark energy and of modified gravity. In fact many dark energy and modified gravity theories used to explain the acceleration of the Universe, predicts deviations in the way GW propagates leading to new tests which can only be performed with GW data. The strongest example of such tests is the constraint on the GW speed of propagation obtained from GW170817 [25], which set this speed to be the speed of light within a fraction of 10^{-15} and excluded several dark energy theories. Other still viable theories predict an additional damping of the amplitude of GWs, which can again be tested by comparing a GW and EM distance measurement of the same source. Such an effect can barely be constrained by current GW detectors neither with bright sirens [26] nor with dark sirens [27] due to technological limitations. However by extrapolating on those results, we expect constraints on an anomalous amplitude damping in the GW propagation to reach an interesting level of accuracy using few years of observations from a multi-detector GW network including Virgo_nEXT. This will allow us to effectively start probing dark energy and modified gravity theories which provides strong deviations in the propagation of GWs, an effect that cannot be tested by standard EM observations.

2.4 *Dark Matter*

Although the existence of dark matter (DM) has been known for decades, no direct detection has been achieved and its precise nature is one of the central questions we face in our quest to understand the Universe. Theoretical speculations predict a variety of DM candidates, from ultralight elementary particles to black holes with a mass similar to the sun. Ground-based gravitational waves detectors participate to the characterisation of DM in several ways, as summarised below.

GW signals from coalescence of primordial black holes or exotic compact objects. Primordial black holes (PBHs) are of high theoretical interest as they are candidates to form at least a fraction of the Universe DM. According to different models (see [8] and references therein), PBHs can arise from several processes in the early Universe, such as large primordial fluctuations at small scales during inflation, or collapse of overdensities created by bubble nucleation or cosmic string loops. Alternative mechanisms can produce compact objects rich in DM in the late Universe, it is the case of BHs from dissipative DM and boson stars or neutron stars collapsing into BHs via DM accretion. LIGO/Virgo/KAGRA data have been used to search for GW signals from coalescences of compact objects involving at least one component below one solar mass (and down to 0.1 solar masses) since the first observing run within the collaboration [9, 10, 11] and independently using public data [12, 13]. In the absence of a significant detection, these results improve the constraints on DM models. These searches exploit the standard data analysis techniques of compact binary coalesces searches, whose success is responsible for the many observations of

LIGO and Virgo. The existence of lighter, planetary-mass primordial black holes [14], or the gravitational waves emission from boson clouds around known black holes [15] can also be tested using continuous waves analysis techniques. Other models predict the existence of exotic compact objects, as neutron stars composed of a mixture of ordinary and dark matter [16] or boson dark stars [17]. The quantity and nature of DM composing these compact objects would affect their properties and hence modify the gravitational wave signal emitted by their coalescence, providing a clear experimental signature. The increased sensitivity of Virgo_nEXT might allow the scientific community to witness the first detection of such a signal or, in the absence of experimental evidence, would drastically improve the constraints on theoretical DM models.

Probing dark matter through gravitational lensing. Depending on the hypotheses, the fraction of GW signals from compact binary coalescences affected by strong gravitational lensing can lie in the region 10^{-4}—10^{-3} [20]. With the expected number of observations, future observing runs with Virgo_nEXT and an improved-sensitvity worldwide network might well bring the first gravitational waves lensing detections. Strongly lensed gravitational waves signals, arising from the binary systems mergers LIGO and Virgo have already started observing, can probe the spatial distribution of DM [18] . Alternative DM models, as self-interacting DM or warm DM, can be probed by observations of signals diffractively lensed by mini-halos of DM [19].

Gravitational Waves interferometers as dark matter detectors. Beyond gravitational waves, present and future interferometers can also be used directly as DM detectors. As an example, direct searches for DM dark photons coupling to the Advanced LIGO and Virgo interferometers [21] provide stringent limits on the coupling of dark photons to baryons, over a large mass range, with performance comparable to the ones of dedicated experiments.

> Gravitational waves observations can constrain Dark Matter. For compact objects composed (even partly) of dark matter, the chances to get a first observation or - in the absence of it - the possible constraints on the merger rate scale with the volume probed by the interferometers network. With the expected increase in sensitivity, after one year of running with LIGO Hanford, LIGO Livingston, LIGO India, KAGRA and Virgo nEXT, the probed volume will be $\sim$ 100 times the one of O3. Thanks to the expected number of observations of mergers involving standard compact objects, we might be able to detect lensed GW signals from compact binary coalescences, that can help in probing large-scale distribution of dark matter. Finally, the upgraded detectors will also have improved sensitivity for direct dark matter searches.

2.5 *Nuclear physics and the QCD phase diagram*

The GWs radiated by the inspiral of a compact binary are, to a certain approximation, insensitive to the composition and structure of the compact objects due to the strong equivalence principle. However, the internal properties of the objects do become im-

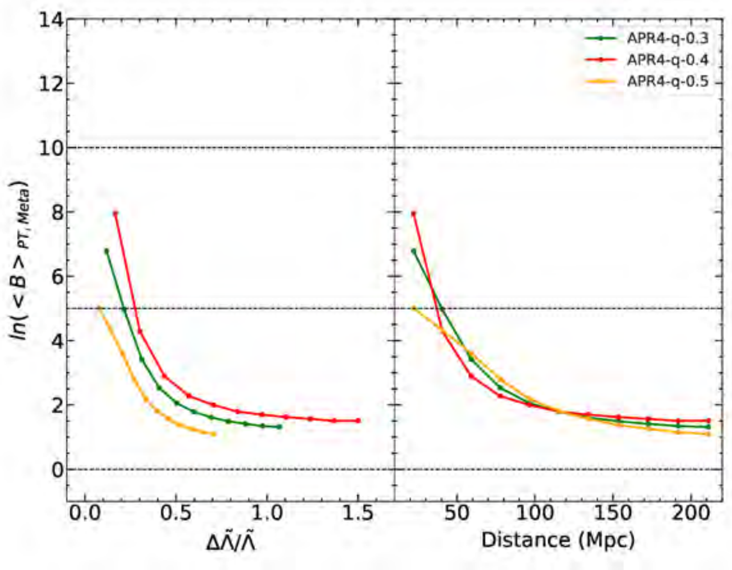

Figure 5: Average Bayes factor as a function of luminosity distance $\mathcal{D}_L$ for different injection models, averaged over the respective class of hybrid metamodels using eq.(1). The different model classes are labeled by the density value assumed for the phase transition to occur (see text). The distributions come from the variation assumed in q and $\mathcal{M}_c$, that we took consistent with the GW170817 event, as well as from the uncertainty in the respective EoS models.

portant during the last few orbits of the inspiral. Before the merger, the tidal field of an object induces a small deformation on the companion. The deformation transfers orbital energy into the structure of the objects, accelerating the rate of the inspiral and therefore slightly affecting the GW phase. This effect is commonly quantified via the tidal deformability parameter $\tilde{\Lambda}$, which can be inferred from the GW signal and, in the case of NSs, can be directly related to the equation of state (EoS) of matter at (supra)nuclear densities. If the tidal deformation in the late inspiral is generally a weak effect, the dynamics of the merger and the emitted radiation depend dramatically on the nature and structure of the compact objects. A particular interesting question in this context is the possible presence of a first-order phase transition (PT) to degenerate quark matter in the core of the neutron star, and the formation of so-called hybrid stars. This transition is theoretically expected in the low-temperature, non-zero chemical potential part of the QCD phase diagram, but it cannot be accessed by terrestrial experiments. In principle, such a phase transition should soften the matter EoS and therefore leave an imprint in the tidal deformability of the star. Given a signal from the late inspiral of a binary neutron star (BNS) coalescence, assessing the presence of such a phase transition depends on the precision that can be attained in the determination of the tidal deformability parameter, as well as on the model used to describe the hybrid star EoS. For the latter, it is important to employ a modelling that largely spans the parameter space associated with both the low density phase and the quark high density phase, and that is compatible with current experimental and astrophysical constraints [22]. In order to assess the uncertainty in the parameter estimation associated with future observations of GWs from the coalescence of BNSs, we make use of the publicly available tool gwbench [23], which implements the Fisher information paradigm. We use a Bayesian framework to quantify the compatibility of a simulated observation between a purely nucleonic and a hybrid (nucleons+quarks) neutron star core. Figure 5 shows an example of the expected performance of GW detectors with a post-O5 configuration. We consider a reference system consistent with GW170817, but placed at a variety of luminosity distances up to 210 Mpc. We also assume a purely nucleonic equation-of-state and compare it to a hybrid star model which contains a first-order phase transition to deconfined matter in the core of the star; the baryonic density at which the transition happens is a variable parameter of the hybrid model. This comparison is quantified via the average Bayes factor defined as :

$$\log\langle B\rangle = \int d\tilde{\Lambda}\; p_{GW}(\tilde{\Lambda}) \log\left[\frac{p_{PT}(\tilde{\Lambda})}{p_{nuc}(\tilde{\Lambda})}\right]. \tag{1}$$

Here, p_{GW} is the observed distribution in a hypothetical BNS coalescing event, assuming that the phase transition takes place at a given baryonic density, that we choose among three representative possibilities $n_t = 0.3\ \text{fm}^{-3}$ (q-03), $n_t = 0.4\ \text{fm}^{-3}$ (q-04), $n_t = 0.5\ \text{fm}^{-3}$ (q-05). In this same equation, p_{PT} is the distribution predicted under the hypothesis that the phase transition takes place, while p_{nuc} assumes that no deconfinement occurs. The injection model at low density, before the phase transition, is APR4.

From the results shown in Fig. 5 we can see that for a $\tilde{\Lambda}$ uncertainty around 30%, corresponding to a merger at a distance comparable to GW170817, a phase transition can be detected if it happens at a baryonic density that can be found in the star core. This shows that a single loud BNS event detected with Virgo_nEXT, together with LIGO and KAGRA, might be sufficient to infer the presence of a phase transition to deconfined matter in the neutron star core.

> Together with LIGO and KAGRA, VnEXT will enable powerful constraints on the structure and composition of neutron stars. For instance, observing another merger like GW170817 may allow us to detect the presence of phase transitions to deconfined matter in the cores of the neutron stars.

2.6 *Multi-messenger astrophysics*

One of the major endeavours in current astronomy is the simultaneous observation of a source through different "messengers" (namely electromagnetic waves, gravitational waves, neutrinos and cosmic rays). The idea behind this *multimessenger* astronomy is that different messengers are emitted by different physical processes at the source, and therefore complement the information that we can acquire. Classic cases of successful multimessenger astronomy are the supernova SN 1987A, observed in neutrino observatories and electromagnetic telescopes, and the neutron star merger GW170817, observed in gravitational waves and in the entire electromagnetic spectrum. Having a confident gravitational-wave signal associated with a gamma-ray or optical transient event immediately identifies the astrophysical engine at the origin of the electromagnetic signal. This can, for example, immediately resolve the ambiguous distinction between short-hard and long-soft gamma-ray bursts. On the other hand, identifying an optical transient pinpoints the host galaxy of a gravitational-wave source, enabling a measurement of the redshift and therefore the measurement of the Hubble constant, as discussed earlier.

Multimessenger astronomy with gravitational waves greatly benefits from a rapid and precise measurement of the sky location of the gravitational-wave source, since a counterpart in other messengers may not last more than a few hours after the discovery of the gravitational wave, and can often only be detected by instruments with a field of view smaller than a few square degrees. On the other hand, sky localisation of gravitational wave signals lasting less than one hour requires a geographically distributed network of detectors operating simultaneously with comparable sensitivity. The present LIGO/Virgo/KAGRA network does occasionally lead to remarkably precise localisations, but multimessenger astronomy with gravitational waves is a challenge with present observatories.

> Virgo_nEXT will be a necessary component of the post-O5 network in order to guarantee continuous monitoring of the gravitational-wave sky and sufficiently precise localisations for future multimessenger astronomy. Specifically, using the simulations described in Sec. 2.2, we estimate that a global network including Virgo_nEXT will detect thousands of binary neutron star mergers per year, most of which will be localised to an area in the sky smaller than 100 square degrees. Hundreds of those mergers per year will in fact be localised to an area smaller than the field of view of the Vera Rubin Observatory.

2.7 *Tests of general relativity*

Theories of gravity alternative to general relativity are in principle testable in several ways through gravitational-wave observations. Here we describe the prospects of Virgo_nEXT in the context of two of these tests.

Any theory of gravity that can describe the evolution of a binary system throughout its merger can in principle be used to derive the corresponding gravitational waveform, and therefore undergo model comparison against general relativity. However, alternative theories of gravity have not yet reached sufficient maturity to accurately predict the corresponding waveforms. Therefore, a popular test consists in perturbing the phase of a compact binary inspiral through the introduction of a series of parameters, whose values are zero if general relativity is the correct description of the dynamics. Using a Bayesian formalism, one can then infer the posterior distribution for these deviation parameters from a collection of compact binary merger observations, and detect any deviation from general relativity as a deviation of one of the distributions from zero. Given the expected improvement in signal-to-noise ratio that Virgo_nEXT would bring for a given binary black hole merger (roughly one order of magnitude) and considering that the uncertainty in the distributions of the perturbation parameters typically scales with the inverse signal-to-noise-ratio, we can expect Virgo_nEXT to substantially improve the constraints on parametric test from individual binary black hole detections.

Gravitational wave signals are also able to probe the no-hair theorem for black holes formed by a coalescence, that implies that the postmerger (or ringdown) signal is represented by a superposition of quasi-normal modes whose spectrum is entirely determined by the mass and spin of the remnant black hole. With the detection of several of these quasi-normal modes in the ringdown part of the signal, we would be able to test the General Relativity prediction for the structure of black holes and eliminate proposed alternatives for the nature of compact objects. Current detectors already perform more indirect tests of consistency between the pre-merger and post-merger signals, but the unambiguous detection of subdominant modes in the ringdown-only part of the signal is difficult and requires a high signal-to-noise (claims of detection for certain systems are currently debated). The improved sensitivity of Virgo_nEXT would significantly better the prospects for such a detection and test, and potentially enable it for a handful of signals.

Another common test is related to the tensorial structure of gravitational radiation in general relativity. Some alternative theories predict scalar or vector modes in addition to tensor modes. This hypothesis can be tested by observing bright gravitational-wave signals with at least three sensitive detectors, which is presently challenging due to the small number of detectors operating with comparable sensitivity. As discussed in Sec. 2.2, Virgo_nEXT will provide several thousand binary black hole merger detections per year observed by at least four detectors, providing plenty of data for such tests.

> Virgo_nEXT will substantially improve the present constraints on parametric tests for deviations from general relativity, and potentially enable tests of the nature of black holes from the spectrum of their ringdown signals. In conjunction with the other detectors, it will also greatly facilitate constraining scalar and vector modes of gravitational radiation.

3 DETECTOR CONFIGURATION

3.1 *Introduction, planned sensitivity*

The baseline optical layout of Virgo_nEXT is shown in Fig. 6. It is a dual recycling Michelson interferometer with Fabry-Perot arm cavities (same as Advanced Virgo+, A+ and KAGRA). The beam size in the arm cavities of the interferometer will be the same as the one used in the Advanced Virgo+ phase 2 (higher by ∼66% with respect to Advanced Virgo+ Phase 1) and also the Fabry-Perot geometry. The central part will be modified in order in have stable recycling cavities instead of the marginally stable cavities, used in the present configuration. The squeezing system configuration will be the same of the Advanced Virgo+ one. The change of optical configuration in the central part is motivated by the difficulties encountered during the commissioning for the O4 run and will be explained in Sec. 3.2.

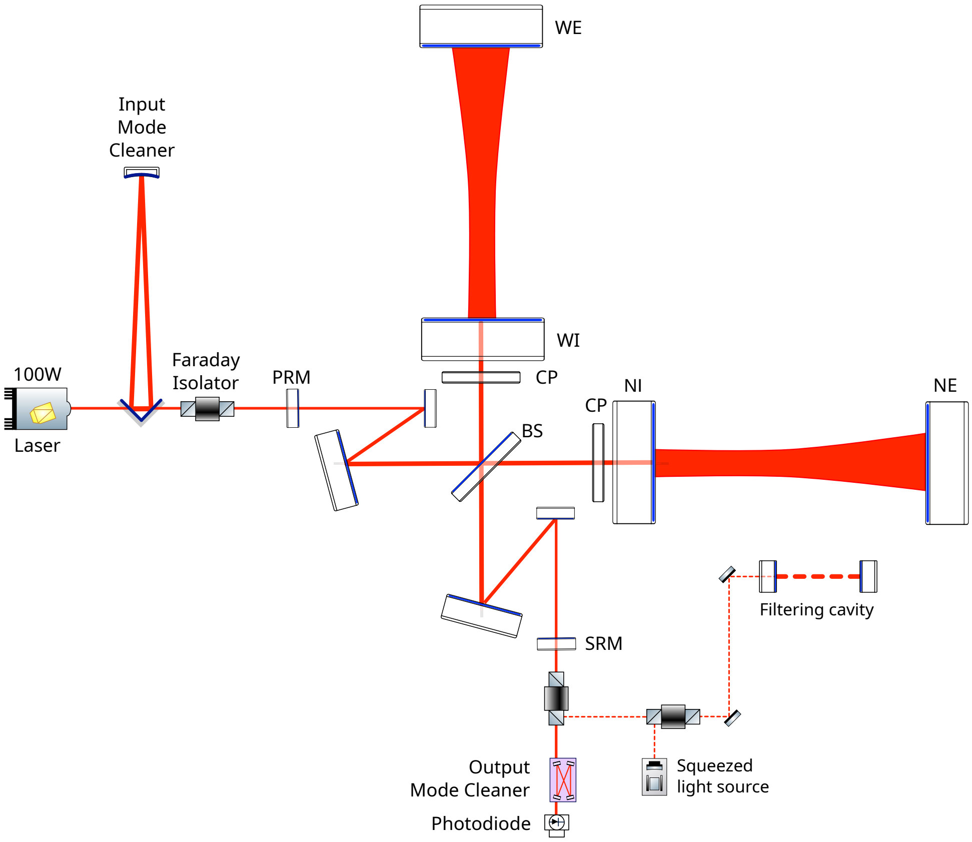

Figure 6: Virgo_nEXT design

In the following sections, a description of the proposed upgrades for Virgo_nEXT is given, both in terms of reduction of fundamental and technical noises, and of detector robustness.

The proposed actions for the reduction of the fundamental noises are the following:

- **Quantum noise**: the quantum noise is limiting the sensitivity of GW detectors in the whole frequency band, as *shot noise* in the high frequency region ($\gtrapprox$ 100 Hz) and *radiation pressure noise* in the low frequency region. In order to reduce the quantum noise it is foreseen to act in two ways: increase the laser input power (lowering the shot noise) and improve the performance of the frequency dependent squeezing technique (allowing to lower the quantum noise in the whole frequency band, see Sec 3.3.1).

- **Thermal noise**: the dominant source of thermal noise comes from the thermal noise of the coatings, limiting the sensitivity in the intermediate region, around 100 Hz. Lowering this thermal noise will require new materials and improved manufacturing processes for the coating of the mirrors, see Sec 3.4.2. At lower frequencies (few tens of Hz), the mirror's suspension thermal noise might become a limitation. In order to lower this noise the lower stage of the suspension will be redesigned (see Sec. 3.4.3).

In addition to the fundamental noises, the sensitivity of GW detectors is limited by technical noises from the laser source (*laser noises*), for the signal detection (electronic noises) and from the signals used to keep the interferometer at the needed operating point (*control noises*). In order to obtain a sensitivity limited by the fundamental noises, those technical noises need to be reduced through upgrades of the instrumentation composing the interferometer, see Sec. 3.5. In the following chapters we will describe the issues related to stable recycling cavities and the strategies to reduce the main noises. The following box summarizes the main features of Virgo_nEXT.

- 1 MWatt stored in the arms to reduce the quantum noise (at high frequency)
  - High power stabilized lasers
  - Thermal compensation system
  - Reduction of the point defects on mirrors
- 10 dB squeezing to reduce the quantum noise (whole spectrum)
  - Reduction of optical losses
  - Improvement of controls (filter cavity, phase noise)
- New coatings to reduce thermal noise
- Reduction of technical noises
  - Improvement of laser stabilisation
  - Improvement of output and auxiliary optics to reduce scattering
  - Improvement of interferometer controls (better electronics, machine learning techniques)
  - Reduction of HVAC (heating, ventilation and air conditioning) system noise
- Use of stable recycling cavities

3.2 *Stable recycling cavities*

The present optical configuration of Advanced Virgo+ is based on the use of two *marginally stable* recycling cavities: a power recycling and a signal recycling cavities, which together with the 3 km arm-cavities, form a system of coupled resonant cavities. These cavities allow for the coexistence of the laser beam's higher order modes with the main TEM00 mode[4]. However, when there is an imperfection in the cavity (such as misalignment, mirror surface imperfections, or thermal deformation caused by laser beam heating), high-order modes are generated and can resonate simultaneously with the main mode. This leads to various undesirable effects, making it extremely challenging to control the interferometer, as was demonstrated during the O4 commissioning phase

- The HOMs resonant in the recycling cavities create optical offsets on the error signals used to control the interferometer. As a consequence, they change the working point of the interferometer itself and increase the coupling of some technical noises. In other terms, the zero of the error signals is not corresponding anymore to the correct working point of the interferometer. These offsets can also vary in time due to thermal effects.
- The different degrees of freedom are more coupled, which increases the complexity of the controls and reduce the stability margins.
- The quantity of the HOMs changes during a thermal transient just after the lock of the interferometer (when the light inside the detector's arms increase suddenly to $\sim$100 kW, or more in the future). Keeping the control of the interferometer during the thermal transient is extremely challenging and requires dynamically changing several parameters of the feedback systems.
- The HOMs present on the output port of the detector are amplified in the signal recycling cavity, which degrade the contrast defect of the interferometer and increases some technical noises, such as scattered light noise and the laser amplitude noise.
- The losses due to the HOMs create optical losses and degrade the squeezing performances.
- The simulations are also more complex and less reliable as many HOMs (in general more than 10) need to be included to properly reproduce the correct behaviour of the interferometer. This makes the simulations slowing converging and sometimes difficult to interpret. This compromises the reliability of simulations in accurately modeling the behavior of the interferometer.

In conclusion, the use of marginally stable cavities has therefore two large drawbacks: the interferometer control is much less robust and more sensitive to small variations (thermal effects,...) and the coupling of technical noises is larger.

Following the O4 commissioning experience and previous and new simulations, in the Virgo Collaboration we reached the conclusion that the marginally stable cavities are not compatible with the planned power increase for Virgo_nEXT and increased requirements on squeezing (15 times more power stored inside the interferometer than today, and 10 dB of squeezing with respect to the 3 dB already obtained during O3).

---

4 The reason is that the current Virgo recycling cavities are too short to allow the beam to acquire a non-negligible Gouy phase during its propagation. The Gouy phase being different for TEM00 and high-order modes, it and make different the resonant frequencies of these modes

The alternative to marginally stable are the *stable recycling cavities*, where the HOM are not close to the resonance of the fundamental mode. This solution was studied during the transition between LIGO and Advanced LIGO and successfully implemented in the US detector. During the same period (around 2009-2011) this solution was also studied during the transition between Virgo and Advanced Virgo and discarded for budget and planning reason[5].

At present, the Virgo Collaboration is re-examinating two main possibilities for the implementation of stable cavities in Virgo: the first one is an *external* (or long cavities) solution, requiring additional buildings and vacuum systems as mentioned above, the second one is an *internal* solution, using medium-length cavities, with additional focusing optical elements (curved mirrors) which could be hosted inside the central building but require new small suspension systems, or a modification of the present superattenuators, to accommodate more mirrors. These two solutions will be explored in terms of technical feasibility, interferometer controllability and cost in the coming months and one of them, if possible, will be implemented before Virgo_nEXT. Otherwise, stable cavities will be in the Virgo_nEXT design.

> Following the problems observed in the commissioning activities in view of O4 and to be able to operate the detector with much higher input powers, Virgo_nEXT will have stable recycling cavities.

3.3 *Quantum noise*

The quantum noise will be reduced by increasing the laser power and by improving the frequency dependent squeezing technique, already prepared for Advanced Virgo+. With the increased laser power, thermal effects will highly increase, which requires an upgrade of the current thermal compensation system.

3.3.1 *Frequency dependent squeezing*

Quantum noise in a gravitational-wave interferometric detector is caused by vacuum fluctuations entering in the detector through the anti-symmetric port (aka *dark port*). In the 1980s, C. Caves proposed to reduce quantum noise replacing the ordinary vacuum entering the anti-symmetric port with a squeezed vacuum or *squeezing*. This technique has been tested in various prototypes and successfully implemented in Virgo and LIGO during the O3 data taking, allowing a reduction of quantum noise of 3 dB at high frequency and a corresponding increase up to 25% in the detection rate for Virgo. While such technology can only reduce quantum noise at high frequency, a more sophisticated version, known as *frequency-dependent squeezing*, will be used for O4 in both LIGO and

[5] The proposed solution at that time required the realization of two new buildings to accommodate new mirrors and the vacuum pipes, approximately 100 m long, to connect the new buildings to the central hall.

Virgo and will be able to bring a quantum noise reduction at all frequencies[6]. In order to produce frequency-independent squeezing, Virgo_nEXT will use the configuration currently installed for Advanced Virgo+: the squeezed states are generated by an optical parametric oscillator (OPO) and reflected by a 285-meter Fabry-Perot cavity (called the *filter cavity*), to impress the frequency dependence to the squeezing ellipse[7]. A basic scheme of the setup is shown in Fig. 6.

The ultimate quantum noise reduction target forVirgo_nEXT is 10 dB. It is well known that squeezed states are easily degraded in the presence of losses and phase noise of the squeezed field. A useful rule of thumb that gives the achievable squeezing (in dB) as a function of the optical losses Λ and the phase noise $\theta_{\rm rms}$ is: $10 \log_{10}(\Lambda + 2\theta_{\rm rms})$. This shows that for reaching the 10 dB target we need to achieve an overall optical losses below 8% and a phase noise level below 10 mrad.

In table 3 of the appendix B, the main parameters for frequency-dependent squeezing in Virgo_nEXT are shown and compared to those expected for O5. The corresponding achievable quantum noise reduction is also shown in fig. 11 of appendix B, where all the degradation contributions are plotted. Reaching such a low loss level will require several actions. The most relevant are reported below:

- Improve the quality of all the optics of the squeezing system, to reduce the scattering mainly due to point defects generated during the coating phase (see Sec 3.4.2). This will be particularly relevant for the filter cavity mirrors, as the round trip losses are expected to be particularly detrimental, given the large finesse of the cavity.
- Reduce the propagation losses, in particular improving the performances of the most lossy optical components (such as Faraday isolators).
- Minimize the mode mismatching between the squeezed beam and the multiple cavities composing the system. This will require correcting not only curvature mismatch but also astigmatism and higher-order aberrations. To this purpose, dedicated sensors and actuators are being studied. Moreover, the interplay of very high power and squeezing has to be considered: optical path length distortion in the input test masses will generate higher-order mismatches between the arms and the signal recycling cavities, which will need an extremely performative compensation system.
- Study the possibility to reduce the power picked off for the control purposes.
- Reduce the losses in the readout chain, particularly replacing the current monolithic output mode cleaner cavity with an open cavity or a hollow cavity to remove absorption losses and Rayleigh scattering losses inside the cavity medium.

[6] Frequency independent squeezing has been already injected in LIGO and increases significantly the detector horizon, see for instance: https://agenda.infn.it/event/32907/contributions/200465/

[7] In the jargon: "The filter cavity allows to rotage the squeezing ellipse as a function of the frequency"

Moreover, we are considering the possibility to put the OPO under vacuum as it is currently done in LIGO. This decision will be taken based on the performances of the current in-air OPO during Advanced Virgo+ operation.

It is important to remark that the 10 dB squeezing is also the target for LIGO post-O5 upgrades and for 3rd generation detectors (Einstein telescope and Cosmic Explorer), which will also rely on the same frequency-dependent squeezing technology. Therefore, we envisage a strong synergy in the related R&D activity, and we expect that the experience of Virgo_nEXT will be crucial for achieving 3G detectors' sensitivity goal.

3.3.2 *Laser power increase*

Virgo's sensitivity is limited at high frequency by the shot noise (the high frequency component of the quantum noise), which is inversely proportional to the square root of the laser power.

In order to increase the injected power into the interferometer we need at first to provide a laser source able to provide the necessary power while satisfying requirements in terms of relative intensity noise (RIN), polarization purity and frequency noise. Moreover, optical components compatible with the higher power such as electro-optics modulators, acousto-optic modulators and Faraday isolators also have to be improved and developed. For Advanced Virgo+, the Virgo laser beam will be provided by a fiber amplifier which was tested at 130 W. This laser was produced by Azur Light Systems (ALS, Bordeaux, France). ALS has worked with CNRS laboratories LP2N (Bordeaux) and ARTEMIS (Nice) on the development of fiber laser amplifiers. Fiber laser amplifiers were demonstrated to provide up to 350 W of light power while responding to gravitational wave detectors requirements and no fundamental limitations are foreseen to reach an output power of 500 W [40]. Regarding the present technological limitations and the foreseen improvements, the maximum power realistically reachable at the interferometer input is around 300 W hence fulfilling the Virgo_nEXT requirements.

No breakthrough on the fiber technologies is required to reach 300 W. However, the robustness of high fiber amplifiers at such high power is to be proved. This implies, as for the AdV+ system, a development of adapted cooling systems, of high power low noise power supplies, control electronics and security systems. The aim of this development is to insure the robustness of the system towards the long term operation required in the frame of a GW detector. Up to now, the critical point has been the Mode Field Adaptor (MFA) which injects the signal and the pumps beam into the high power fiber. We propose to use a free space system in order to control all degrees of freedom and study their effect on the output beam characteristics.

Further increase of the power using the same technology is likely to be limited by nonlinear effects like the Stimulated Brillouin Scattering (SBS) and Transverse Mode Instabilities (TMI). Coherent Beam Combination (CBC) is the ultimate technique to be used since it does not suffer from any technological limitation [41].

Increasing the power is one way to improve sensitivity, but at the expenses to increase thermal effects and parametric opto-mechanical effect (for instance, parametric instabilities), which can make difficult controlling of the interferometer and strongly affect its performances. Therefore, in parallel with the development and test of an high-power laser, it is required to develop mitigation strategy for thermal effects and parametric instabilities.

3.3.3 *Parametric instabilities*

At present a 2D detection system able to move a 4 W beam in 50 ns has been built [39]. The rapidity does not depend on the distance between two consecutive positions and it is important for damping mechanical modes up to few hundreds of kHz. The beam diameter size at the mirror surface would be of one sixth of its diameter. Further experimental investigations are needed to determine the most efficient way to apply the radiation pressure force, and to define the way to implement the feedback loop. Tests and prototypes will be realized on table top experiments before the integration design can be initiated in collaboration with other subsystems having hardware at the ETM transmission. The implementation of this PI mitigation system represents a substantial modification of the both vacuum and optical systems around the test masses. The next step is to conduct the required R&D to validate the principle of radiation pressure based mitigation of PIs. An ANR funded research program (project SPINA, PI: Margherita Turconi) exists in the context of developing active methods for damping parametric instabilities for Virgo_nEXT and the Einstein Telescope.

3.4 *Thermal noise*

In order to reduce the thermal noises the mirrors will need to be replaced and coated with improved coatings. The mirror's suspensions will also be upgraded.

3.4.1 *Mirror substrates*

Virgo_nEXT will have large mirrors both for input and end test masses of the Fabry-Perot cavities (550 mm diameter, 20 mm thickness and 105 kg). Large mirrors are already in preparation for O5 for the end test masses. The mirrors and their coatings need to have extremely low absorption (about < 0.3 ppm/cm for the substrate, < 1ppm for the coating) in order to limit as much as possible the thermal effects. Indeed, in addition to optical losses, the optical absorption causes thermal lensing which affects the interferometer stability, its contrast defect and degrades its sensitivity. The mirrors also need to have very low point defects as these can induce either local thermal defects or high losses due to their induced light scattering. Operation of the detector at high laser power requires test masses without any point defects in their central area. Some improvements have already been made to the LMA's equipment and to the coating deposition procedure for the production of O5 test masses but it is likely that further improvements will be needed for Virgo_nEXT. The mirror substrates will be made of the same fused silica already used in Advanced Virgo and they will be polished by external companies. The coating deposition will be done at LMA, as well as the final characterisation in terms of optical properties (optical properties, surface quality and point defects).

3.4.2 *Mirror coatings*

The mirror thermal noise is due to the mirror surface vibration driven by its temperature. The dominant source of thermal noise is due to the thin coating (few microns thick) deposited on the substrate to provide the desired reflectivity. This coating is composed of Bragg structure made of a stack of doublets with each doublet composed of a lower index of refraction layer and a higher index of refraction layer. In order to decrease the effect of the thermal noise it is necessary to increase as much as possible the mirror mechanical quality factor, or equivalently decrease its mechanical losses. As mentioned above the coating should also have very low absorption ($<$ 1ppm) and low scattering. These two considerations limit the materials which can be used in the coating layers.

All the main mirrors of GW detectors have been coated by LMA. The present coatings are based on amorphous materials and consist of silica (SiO_2) for the lower index layers and a mixture of titania and tantala for the high index layer. The coating mechanical losses are limited by the high index layer (2 to 4 10^{-4}). New coatings are being developed for O5 with the aim to lower the mechanical losses down to 8×10^{-5}. The aim for Virgo_nEXT is to further lower these losses down to 6×10^{-6}, which is a big challenge and will require extensive R&D. This requires progress towards two main directions: identifying new materials with improved intrinsic physical properties; and in parallel, gaining scientific understanding about how technological fabrication processes impact the deposited material and its final properties, as the deposition process can change the material properties.

In this context, intensive R&D is being pursued concerning amorphous coatings which are used in present detectors. Other materials with lower losses have being found but the coatings based on these materials don't achieve yet the required optical properties. An alternative to amorphous coatings are crystalline coatings, based on single crystals. Such coatings have been developed based on stacks of AlAs and GaAs layers, resulting in the so-called AlGaAs mirrors. Small mirrors have been produced and characterised showing that it is possible to decrease the coating mechanical losses by one order of magnitude. These coatings also show very good optical properties.

The coating R&D is therefore pursuing two directions: the improvement of amorphous coatings (as the coating already used in Virgo) and the development of crystalline coatings.

Amorphous coatings. The research in amorphous material regards mostly the high index material, as it is the main source of mechanical losses. Several class of materials are already or will be investigated like nitrides, amorphous semi-conductors, oxide mixtures such as germania-titania (Geo2-TiO2), silica-titania (SiO2-TiO2) and hafnia-tantala (HfO2-Ta2O5). For all coatings materials, the optimal deposition parameters need to be clearly identified. Indeed, the deposition process and the post-deposition treatments (the coatings must go through an annealing process) may strongly affect the resulting coatings properties. Furthermore, several multi-material coating designs are being considered, in order to get a Bragg reflector with the lowest optical and mechanical losses possible. A roadmap for R&D on amorphous coatings has already been established [37], and research is already ongoing within the Virgo Coating R&D (VCR&D) collaboration.

Crystalline coatings. The crystalline coatings are very promising but very challenging. Very good properties have been obtained on small mirrors and the technology needs to be developed for the large GW mirrors. In order to produce those coatings, these have to be grown on a substrate having the same lattice constant as the crystal. This limits the choice of materials that can be grown. AlGaAs coatings can therefore not be grown on the silica substrates. They are grown on a thin wafer of GaAs (or Germanium) through molecular beam epitaxy (MBE) and then transfered to the silica substrate. The entire process has been developed allowing the production of the first 10 cm diameter AlGaAs multi-layer coating deposited on a silica wafer. In order to upscale this technology, several steps are needed: the availability of larger wafers, the development of the deposition technology on these wafers and the development of the technique for the transfer to the large mirror substrate. Other possible materials are crystalline oxides which have the advantage that they can directly be grown on a sapphire for which large wafers are available. This development is however less advanced as no sample has been produced yet and there is therefore no measurement of thermal noise nor optical properties.

3.4.3 *Mirror suspensions*

The mirrors are suspended to a chain of pendulum in order to isolate them from the seismic noise. The lower stages of the suspension also bring thermal noise which is the fundamental noise limiting the sensitivity in the low frequency region. In the present detectors silica fibers are used, instead of steel wires, to suspend the mirror from the last stage of the suspension called the Marionette (this is the so-called monolithic suspension). This allows to reduce the suspension thermal noise . This thermal noise could be further reduced by upgrading the last stage of the suspension, either by changing the material used to suspend the Marionette or by adding an intermediate mass between the mirror and the Marionnette, suspended with silica fibers. This last option would have a big impact on the whole suspension as additional space would be needed for the intermediate stage. Detailed studies and R&D will be pursued in order to decide on the option [8]

3.5 *Technical noises*

Once the interferometer is controlled at its desired working point (i.e. the length of the optical cavities are tuned for the right resonance conditions) most of the commissioning effort concerns the reduction of the technical noises which pollute the interferometer's sensitivity in the whole frequency band. Those technical noises arise from the necessary instrumentation which is used in order to monitor and control the interferometer

[8] Though the suspended optical benches themselves are among the area of expertise of CNRS groups, the suspension systems are not historically developed by CNRS.

and stabilize the input laser beam, typically: optical benches (optics, photo-detectors and associated readout electronics), real-time control loops, and mirror actuators and associated electronics. The mirrors' position is controlled via small magnets which are attached on the mirror surface. The interferometer output laser beam measured at several pick-off locations by dedicated photosensors is used to extract the error signal. These error signals are sensitive to the cavities length and are used, after proper filtering, to control the mirrors positions. The input laser beam also carries frequency and intensity noises which pollute the gravitational wave signal. Many technical noises can enter the interferometer through this control process:

- Input beam frequency, intensity and jitter noise. This noise is reduced with dedicated sensors and actuators which themselves can introduce noises
- The controls are necessary to keep the interferometer's working point at low frequencies but these can introduce displacement noise in the detection bandwidth. These noises may arise from: the photosensors electronics noise (analog and digital), the shot noise, the actuators electronic noise (typically the DACs) and from environmental electromagnetic noise picked up through the control process.
- The elements (optics, photodiodes, beam dumps, Faraday isolators) located on the optical benches scatter a small fraction of the incident light which can recombine with the main beam of the interferometer. As the diffusing element is moving with respect to the interferometer this spurious light generates phase and radiation pressure noises which can mimic a gravitational wave signal. In order to be less sensitive to scattered light noise the optical benches are located under vacuum and seismically isolated.
- The electromagnetic noise generated by the instrumentation (air conditioning, vacuum system, electric lines, lightnings...) can also introduce noise by coupling directly to the magnets attached to the mirrors.

Most of these noises affect the frequency region < 100 Hz. Several improvements will already be performed for the O4 and O5 run as the sensitivity improves. Several possible actions have already being identified and some will need the upgrade of part of the instrumentation. As an example the scattered light noise can be reduced with:

- Installation of absorbing fence around the critical optical benches in order to avoid spurious light from reaching the walls of the vacuum enclosure
- Use of higher quality beam dumps
- Installation of Faraday isolators in front of the critical photosensors to avoid their back-reflection
- Replacement of photosensors with lower diffusion ones
- Use of a new type of output mode cleaner cavity (see Sec. 3.3.1).

- Reduction of the relative displacement between the optical benches and the interferometer with improved tracking technique

Upgrades of the HVAC (Heating, Ventilation and Air Conditioning) system are also planned in order to reduce the environmental (acousic and seismic) and electromagnetic noise that it generates, either with a less noisy system or by a better isolation with respect to the interferometer and its instrumentation.

3.6 *Sensitivity*

Table 1 summarizes all the Virgo_nEXT parameters and compares with the O4 and O5 configurations. fig.7 shows the O3 (measured), O4, O5 and Virgo_nEXT planned sensitivities.

Table 1: Foreseen Virgo_nEXT interferometer parameters compared to O4 and O5 configurations. Here "high" and "low" refer to the assumptions on technical noises: high (resp. low) amplitude of technical noise is added to the fundamental noises. This is reflected by the bands in the fig.7

Parameter	O4 high	O4 low	O5 high	O5 low	VnEXT low
Power injected (W)	23 W	40 W	60 W	80 W	277 W
Arm power	120 kW	190 kW	290 kW	390 kW	1.5 MW
PR gain	34	34	35	3S	39
Finesse	446	446	446	446	446
Signal recycling	Yes	Yes	Yes	Yes	Yes
Squeezing type	FIS	FDS	FDS	FDS	FDS
Squeezing (db)	3	4.5	4.5	6	10.5
Payload type	AdV	AdV	AdV	AdV	Triple
ITM mass (kg)	42	42	42	42	105
ETM mass (kg)	42	42	103	103	103
ITM beam radius (mm)	49	49	49	49	49
ETM beam radius (mm)	58	38	91	91	91
Coating losses ETM	2.37e-4	2.37e-4	2.37e-4	7.90e-5	6.2e-6
Coating losses ITM	1.63e-4	1.63e-4	1.63e-4	5.40e-5	6.2e-6
Reduction NN	None	1/3	1/3	1/5	1/5
Technical noise	"high"	"low"	"low"	None	None
BNS range (Mpc)	90	115	145	260	500

4 PROJECT HISTORY AND SCHEDULE

The Virgo Collaboration initiated the Virgo_nEXT project in March 2021 with the objective of identifying a new upgrade for Virgo scheduled for the "post-O5" era. Two "post-O" ' committees have been formed, the first focusing on the project's scientific potential and the second on the detector design.

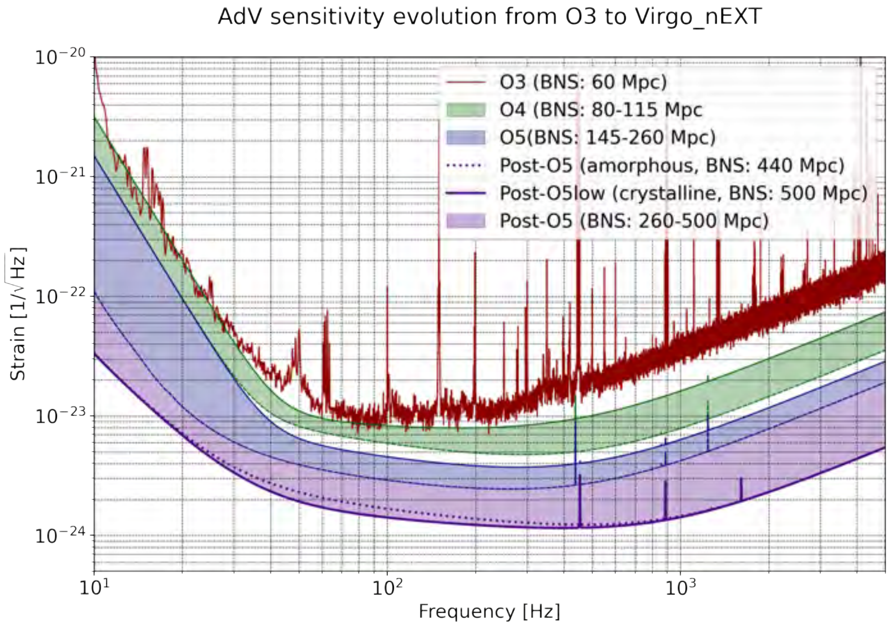

Figure 7: The purple band shows the range of sensitivities achievable by Virgo_nEXT. For comparison the sensitivity of Advanced Virgo in O3 and the design sensitivity of AdV+ in O4 and O5 also shown. The dotted curve in the purple band shows the best sensitivity achievable by Virgo_nEXT with improved amorphous coatings.

The committees produced a study summarized in a 140-pages document, known as the *Virgo_nEXT concept study [34]* (published as an internal note of the Virgo Collaboration). This document was extensively reviewed and discussed within the Virgo Collaboration and presented to the EGO council in June 2022. During the spring of 2022, the project was officially named "Virgo_nEXT".

After the publication of the concept design study, two critical aspects remained unresolved: the choice of coating and the optical configuration of the detector (marginally stable or stable recycling cavities). About the coating, the Collaboration released an extensive roadmap to study the various coating options [37].

In 2023, due to increasing commissioning difficulties associated with marginally stable cavities, the decision was made for the Virgo_nEXT to adopt stable cavities (which were initially identified as a risk reduction option in the 2022 concept study). A dedicated committee was appointed to provide a detailed motivation for the need of stable recycling cavities and to summarize it in an internal note of the Virgo Collaboration [36][9].

[9] As already mentioned, there is a possibility that stable cavities may be implemented prior to Virgo_nEXT as part of the Advanced Virgo+ phase 2. The Virgo Collaboration is currently evaluating various possibilities and is expected to present its conclusions to the EGO council in December 2023

At present, the Collaboration is working on a plan for the R&D activities for Virgo_nEXT. This effort includes informal discussions with the LIGO post-O5 group and colleagues from KAGRA.

Regarding the schedule: The years 2024-2029 will be used to develop the Virgo_nEXT components. The Technical design report is expected in December 2024. O5 is expected to end in 2029. Due to uncertainties surrounding the Advanced Virgo+ phase 2 upgrade, it is challenging to provide an exact date for the first Virgo_nEXT data-taking. Tentatively, the downtime is estimated to be around 2-3 years, bringing the first Virgo_nEXT data-taking in 2022-2023. The following box summarize the main steps of the project:

- March 2021: Virgo_nEXT study initiated
- Two committees formed:
  - Committee 1: Scientific potential
  - Committee 2: Detector design
- March 2022: Virgo_nEXT Concept study released (140 pages document)
- June 2022: Virgo_nEXT presented to EGO council and French Research Ministry
- January 2023: Virgo_nEXT coordinator appointed
- January 2023: 2 committees formed to address two main points:
  - Coating options
  - Need of stable recycling cavities
- July 2023: Finalizing preliminary plan for R&D
- December 2024: Expected Virgo_nEXT Technical Design report
- 2024-2029: Virgo_nEXT R&D and components development
- 2029: end of O5 LVK data taking
- 2032-2033: Possible Virgo_nEXT first data taking

5 INTERNATIONAL CONTEXT

Figure 8 shows the ground-based gravitational-wave network detector. LIGO and Virgo signed an MoU for the exchanges of data and joint publications in 2006 (renewed since then), and in 2020 the MoU included KAGRA. Today there are 4 running detectors (5 if we also consider GEO, which has a much lower sensitivity but it is used in "astrowatch" mode, in case of a nearby supernova event). The community has a joint observation scenario (regularly updated [1]), common searching groups, common (LVK) meetings (twice per years) and regular management meetings.

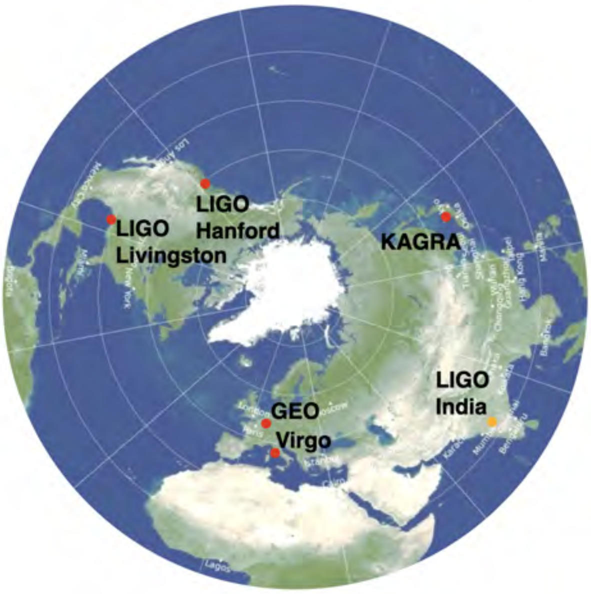

Figure 8: The gravitational-wave detector network

The LIGO detectors have always been approximately four years ahead of Virgo in terms of development. The sensitivity level achieved by LIGO in 2015, measured in terms of Binary Neutron Star (BNS) range, was only reached by Virgo in 2019-2020. This time gap can be attributed to several factors. Firstly, LIGO had earlier experience with this type of detector dating back to the 1970s. Secondly, LIGO received funding earlier than Virgo, giving them a head start. Lastly, LIGO's choice of using 4 km arms instead of 3 km allows for higher strain sensitivity, contributing to their technological advantage.

Currently, there is a growing sensitivity gap between LIGO and Virgo, primarily due to the limitations caused by marginally stable cavities in Virgo (not installed during its transition from Virgo to Advanced Virgo, as mentioned earlier). This widening gap diminishes the importance of Virgo within the network, particularly with the inclusion of new partners like KAGRA and LIGO India.

KAGRA still has significantly lower sensitivity compared to Virgo, comparable to what Virgo had in 2006. It also employs challenging techniques such as cryogenics. Although LIGO India has not been constructed yet, there has been a recent agreement by the Indian government [33]. It is reasonable to expect that the detector will be ready around the same time as Virgo Next and A#. Despite utilizing similar technologies to LIGO, the process of starting from scratch and the necessity of building local expertise for LIGO India may slow down the integration and commissioning activities.

Virgo has played and will continue to play a crucial role in the network of gravitational wave detectors, even with the addition of KAGRA and LIGO India. However, this is contingent upon preventing further widening of the gap between LIGO and Virgo.

6 IN2P3 ROLE: CONTRIBUTIONS AND RESOURCES AT IN2P3

6.1 *Laboratories involved, responsibilities and personnel*

IN2P3 contributes to Virgo with 81 FTE (139 persons), divided in 8 IN2P3 labs having IN2P3 as the first affiliation (APC, IJCLab, IPHC, LAPP, LPC/Ganil, IP2I, L2IT, Subatech) and ARTEMIS, formally an INSIS laboratory, but having IN2P3 as second affiliation. Among them, 8 laboratories (APC, ARTEMIS, IJCLab, IPHC, LAPP, IP2I, L2IT) are independent groups of the Virgo Collaboration and they are represented at the Virgo Steering Committee. LPC/Ganil is represented at the Virgo Steering Committee as a joint group with LUTH-Observatoire de Paris (around the common main interest of the physics of the neutron stars). Subatech is not represented for the moment at the Virgo Steering Committee (still below critical mass to form a group), and its members are associated to APC. In the future LPC/Ganil could become independent groups of the Virgo Collaboration (LPC/Ganil is already above the critical mass).

Table 2: Details of Virgo personpower in IN2P3 groups. The column "researchers" includes phd students,post-docs and staff researchers, the column "Eng/Tech" includes engineers and technicians. Personpower on Einstein Telescope are not included in this table

Lab	**FTE Eng/Tech**	**FTE Res/doc/post-doc**	**FTE total**	**persons**
APC (Paris)	2	6.95	8.95	18
ARTEMIS (Nice)	1.35	6.65	8	28
IJCLab (Orsay)	1	8.7	9.7	14
IPHC (Strasbourg)	2	5.6	7.6	12
LAPP (Annecy)	7	13	20	27
LPC/Ganil (Caen)	1	3.1	4.1	8
IP2I (Lyon)	10.4	7.4	17.8	23
L2IT (Toulouse)	0.7	1.95	2.65	6
Subatech (Nantes)	0.7	0.9	1.6	3
Total	26.15	53.55	80.7	139

CNRS is also formally contributing with laboratories belonging to INSIS/INP/INSU institutes: 2 INSIS laboratories (Institut Fresnel in Marseille and ARTEMIS in Nice, mentioned above, which have second affiliations with INP/INSU/IN2P3), 2 INP laboratories (ILM in Lyon and LKB in Paris) and one INSU laboratory (the already mentioned LUTH-Observatoire de Paris, associated with LPC/Ganil in the Virgo Collaboration). In total, there are 11 CNRS groups represented at the Virgo Steering Committee. Details of IN2P3 laboratoires are shown in the table 2. The CNRS groups and researchers are part of the Virgo Collaboration, counting $\sim$ 450 authors, dsitributed in 35 groups represented at the Virgo Steering Committee.

IN2P3 has crucial activities and responsibilities at all levels in the Virgo structure. Among them:

- IN2P3 members have various management responsibilities in LVK search groups

- several IN2P3 members are members of the Virgo executive committee (VEC).
- within Advanced Virgo+, IN2P3 members have top-level management and technical responsibilities.

Details of those responsibilities can be found in the Virgo organization chart [38].

Moreover, IN2P3 members are involved in R&D activities related with the above mentioned technical responsibilities.

IN2P3 in Virgo in 2023

- 9 laboratories (8 first affiliation and 1 second affiliation)
- APC, ARTEMIS (2nd affiliation), IJCLab, IPHC, LAPP, IP2I, L2IT, LPC/Ganil and Subatech
- 81 FTE, 139 persons

Remark: Although IN2P3 has a significant impact on many Virgo technologies and areas of expertise (as detailed below), the community that has designed, built, and operated Virgo and Advanced Virgo is aging, and a massive reinforcement of hiring is necessary, especially as experts in gravitational wave detectors, to maintain the institute's responsibilities and role in the era of Virgo_nEXT.

6.2 *Technological developments*

Since the beginning of Virgo, IN2P3 members have always been strongly involved in the development, construction, installation and commissioning of the detector and they will go along this line for Virgo_nEXT. Many parts of the detector will need to be upgraded in order to reach the Virgo_nEXT foreseen sensitivity (see Sec. 3) and many of the needed technological developments will be then under the responsibility of IN2P3 laboratories.

IN2P3 laboratories and researchers have developed strong expertise in mirror coatings and associated metrology, vacuum chambers, optical benches (telescopes, mode cleaner cavities, low loss systems, low scattering systems), squeezing techniques, low noise analog and digital electronics and interferometer calibration. All these technologies will be further improved for Virgo_nEXT following the aims of reducing the mirrors thermal noise, reducing the optical losses, reducing the technical noises such as scattered light and electronic noise and improving the precision of the signal reconstruction. In order to pursue this aim some R&D activities have already been initiated with ANR and local funds (answers for new ANR calls are expected early July 2023) and concern: improved squeezing techniques, improved coatings, scattered light reduction, improved digitisation electronics, improved calibration, mirrors metrology.

In addition, to these responsibilities, the ARTEMIS laboratory is responsible for the laser source and related R&D activities for the increase of power. It is also involved in developments for the control of parametric instabilities.

IN2P3 members have also been involved in the design studies for the implementation of stable recycling cavities during the Advanced Virgo project, so it is natural for them to be involved in Virgo_nEXT as well. The technical developments needed for this implementation is however too early to be described here as the design is not yet ready. These could involve developments in vacuum enclosures/tubes, optical benches and others sub-systems.

The following box summarizes the main IN2P3 R&D activities and technological development topics:

- Mirrors coatings: reduced thermal noise, defect free, low anti-reflective coatings
- Mirrors improved metrology
- Output mode cleaner cavity: lower losses and scattering
- Squeezing source: under vacuum
- Squeezing technology: low loss, frequency dependence
- Mode matching telescopes and associated sensing: new technology for lower losses
- Photodiodes: low noise electronics
- Optical elements and associated mechanics: low loss and scattering, characterisation
- Digital electronics: lower noise
- Real time software evolution
- Calibration: increased precision

6.2.1 *Mirrors*

As explained in Sec. 3.4.2 the quality of the mirrors and their coatings is primordial in order to achieve the foreseen sensitivity. The leading laboratory for amorphous coating R&D and production on large optics is the LMA/IP2I. This facility has benefited from large investment from EGO and IN2P3 for the new O5 large mirrors and has secured fundings for a new very large coating machine for the next generation of detectors. The aim is to stay competitive at the world level and hopefully be able to coat the most critical mirrors for the Japanese and American projects too. Amorphous coating deposited by IBS is 'relatively easily' scalable in size and is the only envisioned technology for low loss coating on diameter superior to 450 mm. Crystalline coatings have been investigated at LMA and more recently at LAPP in collaboration with other laboratories at CNRS and at CEA. Another CNRS laboratory, the iLM in Lyon, is also contributing to the coating R&D with structural characterisation and mechanical loss measurement.

One limiting factor to increase the circulating power in the arm cavity was the presence of few point absorbers in the coating. Those points were metallic particles coming likely from the coating chamber itself and embedded during the coating process. After a joint research with LIGO, this problem has been mitigated and the latest mirrors coated in 2022 have no large absorbing point as measured in Caltech. For the large mirrors for O5 and Virgo_nEXT, a new bench able to characterise the presence of absorbing point will be essential to validate the mirrors before installation. Such a bench is currently under design at LMA and should handle larger mirrors than the Caltech setup.

Another current research line to improve the amorphous coating deals with the reduction of scattering points, the dominant source of optical loss. Through structural analysis, optical characterisation and tuning of the deposition parameters we aim to understand better the creation process of such defects and be able to reduce their density. A project has been submitted to the ANR to start this year.

As underlined in Sec. 3.3.1, the improvement of squeezing performances requires the reduction of the losses inside the interferometer, due to the anti-reflective (AR) coatings deposited on one side of the main mirrors or on the pick-off/compensation plates. LMA will investigate the possibilities to reduce the AR reflectivities thanks to the improvement in the control of the coating layer thickness in the Grand Coater at LMA.

Concerning the reduction of thermal noise, several R&D are needed are two different fronts (see Sec 3.4.2): new or improved amorphous coatings and the realisation of crystalline coatings (up to 30 cm diameter). The search for new amorphous materials and their characterisation is mainly done by CNRS (LMA and iLM) and the INFN laboratories. The LMA is currently the main source of coatings for the Virgo collaboration and has dedicated a chamber for R&D in the framework of the CMO IN2P3 Master Project. Depending on the selected material, the LMA Grand Coater might need to be updated and the deposition process will need to be optimised for the lowest optical and mechanical losses and later to achieve the best uniformity.
On the crystalline coatings front, a collaboration between LAPP, LMA, the lab CNRS/LAAS (Toulouse) and CEA-LETI (Grenoble), developed in the context of a co-directed PhD thesis, allowed producing the first 10 cm diameter AlGaAs multilayer coating deposited on a silica wafer. In order to progress in this development a close collaboration between industry and research laboratories is being put in place and and a project submitted to the ANR.

6.2.2 *Squeezing and quantum technologies*

To mitigate the losses that limit the squeezing performances several upgrades of the squeezing and detection systems are required, as described in Sec 3.3.1. Those upgrades involve new technologies that require specific R&D to reach sufficient maturity. Several IN2P3 laboratories (APC, IJCLab, L2IT, LAPP, IP2I/LMA) are involved in these upgrades:

- The filter cavity losses can be reduced with a better quality of the mirror coatings (see Sec 6.2.1)
- The losses due to mode mismatch can be reduced with the development of new mode matching telescope based on adaptive optics. This development includes sensing, adequate optics and mechanics for the telescopes and its actuation (see also paragraph 6.2.3).
- The squeezing source might need to be placed under vacuum and/or the geometry of the OPO cavity might be changed in order to reduce back-scattered light. An R&D is on-going to demonstrate the feasibility of an in-vacuum squeezing source and its necessary air/vacuum interface. Two ANR grants have been obtained on this subject (Exsqueez and Qfilter).
- In order to test new frequency-dependent squeezing configurations, improved control systems, and low-loss optics, an ANR has been submitted to develop a new squeezing source.
- A new type of output mode cleaner cavity (open or hollow instead of monolithic) must be developed as the present technology has reached its limits. This new technology will allow to eliminate absorption losses and to lower the amount of scattering.

6.2.3 *Auxiliary optics: suspended benches and mode-matching telescopes*

IN2P3 has a strong expertise in the development of the auxiliary optics (including suspended benches and mode-matching telescopes), with LAPP, APC and L2IT labs. LAPP is in charge of the mechanics of the suspended optical benches. All the instrumentation described in Sec. 6.2.2 is located in optical benches located under vacuum and seismically isolated via a suspension system. The new instrumentation will require additional space (longer telescopes, squeezer under vacuum, new output mode cleaner) and some of the benches will have to be upgraded and/or their size increased. New optical benches will also be needed for the new pick-off beams which will be extracted inside the stable recycling cavities.
Several optical elements of the benches will also be improved in order to reduce the scattered light and losses. To this purpose an R&D platform is being developed. This platform consists of an optical suspended bench which will be used to perform and validate several developments which require to be located under vacuum. An ANR (MILDOG) has being obtained in 2022 to fund part of this platform but a non negligible fraction is still missing.

Optical telescopes at various ports of the interferometer should be upgraded in Virgo_nEXT to account for the implementation of the stable recycling cavity. This requires a re-design of the telescopes, and - for input and output telescopes- also requires incorporating an adaptative optics system to optimize the matching. As APC, L2IT and LAPP are already in charge of telescopes for Advanced Virgo+, they are in the best position to continue this activity for Virgo_nEXT.

6.2.4 *Electronics and data-acquisition*

IN2P3 has strong historic involvement and expertise in the development of analog and digital electronics and of the real-time data treatment and acquisition system, with expertise at LAPP and IPHC. In order to increase the detection efficiency the photodiodes and associated analog electronics used for the measurement of the gravitational wave signal will be replaced. This improvement requires the development of lower noise electronics boards. Some of the new instrumentation which will be installed for Virgo_nEXT will require additional electronic boards for the data acquisition and control system (ADCs, DACs and real-time data treatment) for which new developments will be done.

In addition, an R&D has been started in order to improve the flexibility and the performances of the whole photodiodes readout chain, which is limited by the fact that it is nowadays located under the optical benches, inside the vacuum enclosures. This new architecture will also be tested on the R&D platform mentioned in Sec. 6.2.3.

All the real-time software (data transfer and exchange, slow control) will be upgraded for improved performances.

6.2.5 *Calibration and h(t) reconstruction*

The hardware used for the calibration will need to be improved for the needs of a more precise calibration. The IN2P3 laboratories in charge of the Virgo calibration are IPHC and LAPP. They will define the needs for the two calibration systems they are in charge of (newtonian calibrator or NCAL and photon calibrator or PCAL) depending on the performances obtained for the O4 and O5 runs, and to perform the needed developments. One can already anticipate the improvement of the measurement of the auxiliary laser power (PCAL): more precise and stable powermeters, lower electronic noise, improvement of the optical benches. It might also be needed to install power meters under vacuum. The NCal system, that is providing the best absolute calibration but in a limited frequency band will also be improved on the experience gained during the O4 and O5 runs. Several upgrades can be anticipated: improved isolation between the rotors and the interferometer (to avoid direct seismic disturbance), upgraded rotors (faster, with improved geometry,...).

The IN2P3 groups who develop the hardware for the calibration also use them to calibrate the detector (mirror actuators, photodiode readout, ...). and they are also responsible for the software processing the h(t) reconstruction. Towards Virgo_nEXT, with higher detection rate and high probability for multimessenger detections, some developments can be anticipated as automatisation of calibration software tools and monitoring, or developing a new method for h(t) reconstruction to divide by 10 the latency, important for the alert generation.

6.2.6 *Simulations*

Gravitational wave detectors are based on major technological challenges: the use of very high powers, adaptive optics with heated mirrors, very large optics with very low losses, quantum technology with squeezing, etc. A fundamental aspect of detector design is based on optical simulations. It is necessary to develop reliable, robust and scalable simulations of the detector as a whole in order to understand the behaviour of the interferometer, and to anticipate some delicate technical aspects: to understand the coupling of noises on the sensitivity of the interferometer, the electromagnetic field distributions at the output of the detector and at different locations of the interferometer, propagation of higher order modes in the cavities, etc. The optical characterization of the interferometer is crucial to understand how to refine its settings and thus obtain a better sensitivity, and this topic will be a major improvement for Virgo_nEXT. Several IN2P3 laboratories are involved in simulation development or use.

6.3 *Data analysis*

The LIGO/Virgo/KAGRA physics program has implications on many fields of physics and covers several different possible sources of GW signals. These are typically divided in two broad categories, the transient (limited in time) and persistent signals. Transient signals can be modelled, as it is the case of Compact Binary Coalescences (CBC), for which we have a reasonably good theoretical understanding of the astrophysical process, and we are able to faithfully predict the signal waveform that we would detect. All the LVK detections achieved until now are associated with CBC events, where the considered compact objects are either black holes or neutron stars. In other cases of transient GW signals, for example the GW emission from a supernova explosion, the modelling of the signal is not so well determined. The LVK also searches for persistent GW emission from pulsars, any deviation from a symmetric shape in these highly rotating neutron stars would cause some energy in the form of GW emission: these searches are a way to constrain the inner structure of neutron stars. Finally, the LVK data are also searched for the presence of a persistent component called stochastic gravitational waves background, arising from the superposition of many sources, too far away to be detectable individually. The stochastic GW background might contain a component from the relic gravitational waves from the early evolution of the Universe.

In the context of the LIGO/Virgo/KAGRA collaboration - and this will likely remain true for future networks of interferometers - the data analysis is mostly a transversal activity, organised in LVK-wide working groups where collaborators from different experiments work together. These working groups are: *Burst* (unmodelled transient sources), *CBC* (Compact Binary Coalescences), *CW* (continuous wave emission from pulsars) and *Stochastic* (Stochastic GW background). An exception to this paradigm is the working group dedicated to the characterisation of the detector and understanding of the noise sources and their impact on data analysis (*Detchar*): each experiment has its own dedicated *Detchar* group, even though all of them share information, expertise and common tools.

The IN2P3 (and more generally the French) Virgo groups are deeply involved in data analysis: their contribution to this topic has been historically very important since the beginning of LIGO and Virgo science runs. The number of involved groups and FTEs devoted to data analysis has been increasing in time, together with the variety of covered subjects.

As detailed in the following, the French Virgo community is very active on detector characterisation, transient signal detection (both modelled and non-modelled), stochastic gravitational waves background, cosmology with gravitational waves, constraints on the structure and nature of neutron stars thanks to GW observations, as well as playing an important role in the process of making GW data public and easily accessible. It is reasonable to think this activity shall continue to grow for the future observing runs and in view of Virgo_nEXT, ensuring a rich scientific return, and sustaining an active community, visible and recognised at the international level.

The data analysis activities rely heavily on French national resources, as the IN2P3 computing center CCIN2P3 and the online cluster at the Virgo site, participating to their international visibility. The recognition and involvement of the french community in data analysis can be measured by the number of responsibilities undertaken by its members within the LVK, involving the convenership of the Burst and CBC groups, the CBC subgroups dedicated to detection techniques and cosmology, the DetChar group. The GW data analysis community is largely composed of early-career scientists and french groups are very active in forming the next generation of GW astronomers.

6.3.1 *Detector characterization*

The Virgo Detchar group operates at the interface of Virgo detector activities and LVK data analysis, with the scope of understanding, characterising and - whenever possible - mitigating the detector noise and its impact on physics analyses. The IN2P3 teams of IJCLab and LAPP are pillars of the Virgo Detchar group, with internationally recognised unique expertise, responsibility of widely-used tools, and their members have been leading the working group for years. More recently, the IP2I group has also joined this effort, bringing new personpower and ideas, and now hosts the leadership of the LVK group dedicated to the inspection and confirmation of alerts sent during O4, from a Virgo detchar point of view.

6.3.2 *Searches for transient GW signals*

The IN2P3 Virgo community is heavily involved in the searches for transient signals, with a high visibility and a strong impact within the LVK. The IJCLab and ARTEMIS teams are involved in searches for poorly modelled sources (aka 'burst'), being directly involved in the development and running of specific pipelines (X-pipeline, Cosmic String and PySTAMPAS) and also in the general coordination, with the responsibility of the Burst LVK working group. The IJCLab group also hosts an expertise on modelled searches, being very active in the development and running of the PyCBC pipeline, and with the leadership of the LVK working group dedicated to the detection of CBC events. The IPHC, and LAPP teams, more recently joined by the IP2I, work together on the detection of CBC signals, being the main developers of the MBTA pipeline and exploiting it to search for standard sources (BBH, BNS, NSBH) as well as coalescences involving at least one sub-solar mass compact object. The IP2I team also hosts the leadership of the LVK CBC working group. The APC group is involved in CBC searches, within the LVK and ET, with a strong expertise on waveform models, an interest on the acceleration of parameter estimation algorithms and tests of modified gravity with the final ringdown part of the merger signal. APC hosted the leadership of the CBC working group during the period of the O2 and O3a science runs. The APC group also pursues a range of method development projects related to the characterization of the GW polarization contents (ANR RICOCHET project) and to the use of machine learning approaches as alternative search techniques. The ARTEMIS group is also strongly involved in the development of parameter estimation methods for both CBC and non-modelled sources (especially core collapse supernova) and the use of machine learning techniques to improve the nonmodeled signal search pipeline PySTAMPAS.

6.3.3 *Searches for stochastic GW background*

The ARTEMIS and LAPP groups are involved in LVK searches for stochastic GW background, isotropic and anisotropic, with a role of working group leadership until recently. In parallel to its contribution to the LVK science, the two groups are also actively developing searches for stochastic GW background in view of ET. The APC team is involved in this activity through the collaborators at IAP with a specific focus on astrophysical backgrounds from BBH population.

6.3.4 *Constraints on extremely dense matter*

The LUTH/LPC/Ganil team has brought to the Virgo collaboration an additional expertise in terms of nuclear physics, very valuable for the activities aiming to better understand the extremely dense matter inside the neutron stars involved in the coalescences observed by the LVK. The team is very visible in the LVK dedicated working group, and actively encourages new interfaces with the astronuclear community. The IP2I team is also active on the subject, in close contact with a local theory community.

6.3.5 *Cosmology*

The observation of GW170817 and more generally, the collection of many CBC detections have boosted the field of GW cosmology. The interest and allocated person-power of the French GW community has increased in the last years, making it a structuring topic for the Virgo community at IN2P3. The L2IT team is heavily involved in cosmology studies with GW both on the analysis techniques and on the theory and phenomenology, within the LVK and in preparation for ET, and with close contacts with the LISA community. L2IT hosts the leadership of the LVK working group dedicated to cosmology with CBC. The APC team is also very active on this topic with a strong expertise on theory. The team has been involved in the development of the Icarogw pipeline at the very early stages. The development activities have been recently developing at the cross-roads between cosmology and the tests of general relativity, with potential application to test of the ΛCDM model. The IP2I team is also working on cosmology with GW, with activities on the development of the Icarogw pipeline within the LVK, and in contact with the international theory community on phenomenological studies.

6.3.6 *Multi-messenger astronomy*

The French Virgo teams, beside their above mentioned contributions to the transient GW searches that provided public alerts, are active in the field of multimessenger astronomy with GW, especially with the IJCLab, LAPP and ARTEMIS working on joint observations of GW signals and GRBs or FRBs, and electromagnetic followup of GW alerts. The IPHC team is working on associated detections of GW and high-energy neutrinos, exploiting the local expertise and KM3NET activity.

6.3.7 *Open science*

After a proprietary period, the GW LVK data are made public in order to maximise their scientific impact. A dedicated working group within the LVK is responsible for this important effort. The Gravitational-Wave Open Science Center located at http://gwosc.org distributes the data and software tools to the scientific community and to the general public. The GWOSC also organizes regular workshops and online courses to educate the wider community on GW science. The APC group had a leading role in the release process, both from the technical and scientific viewpoints. The IJCLab team is involved in the development of the PyCBC pipeline, widely used outside the LVK for GW analyses.

7 SYNERGIES WITH EINSTEIN TELESCOPE

The synergies between Virgo_nEXT and the Einstein Telescope develop along four different axes, as described below. It can be seen that the development of Virgo_nEXT will significantly accelerate the implementation timeline of the Einstein Telescope, including the development of necessary technologies, their integration into the detector, and the commissioning process to achieve the design sensitivity.

> Virgo_nEXT will accelerate the development and commissioning of Einstein Telescope by:
>
> - Testing technologies for ET-HF (i.e. squeezing sources, high power lasers, coatings)
> - Testing complex physical effects, not testable in prototypes (Parametric instabilities, high-power effects, etc)
> - Testing and reducing technical noises for ET-LF
> - Using the detector to train experts for ET

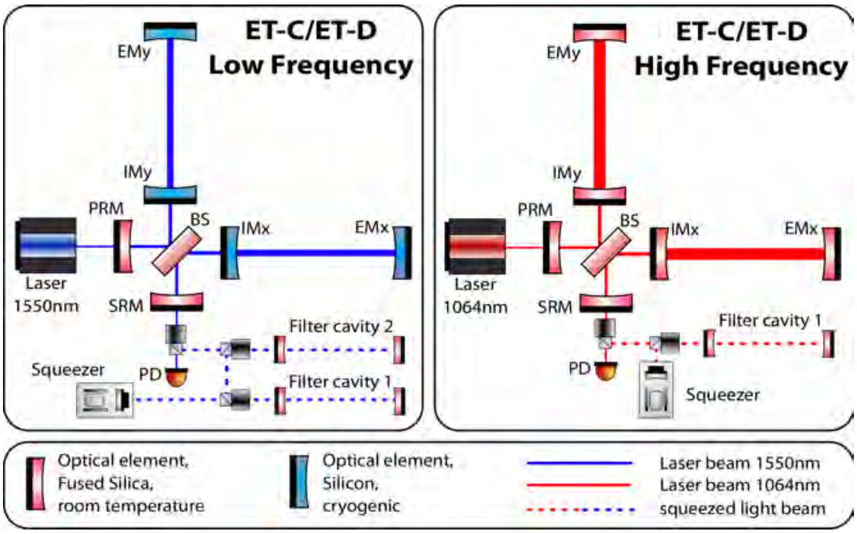

Figure 9: The two Einstein Telescope instruments: ET-HF hot (right, in red) and ET-LF cold (left, in blue). Virgo_nEXT can test all the technologies of ET-HF

.

7.1 *Virgo_nEXT and technologies for Einstein Telescope HF*

The technologies developed for Virgo_nEXT will be fully utilized in ET-HF. In other words, the main difference between Virgo_nEXT and ET-HF will be the arm-length. The parameters of Virgo_nEXT regarding arm-cavity power, coating thermal noise, and squeezing level are the same as those of ET. The research and development carried out in the context of Virgo_nEXT can be fully applied to ET and can be incrementally tested, allowing for effective retrofitting in case of issues. A detailed list of synergies between Virgo_nEXT and Einstein Telescope is in appendix A.

7.2 *Virgo_nEXT as test complex physical effects, not testable in prototypes*

The operation and performance of technologies developed for the Einstein Telescope HF can be effectively studied only in an experiment like Virgo_nEXT. This is primarily because some of the effects that may limit the sensitivity of ET, such as thermal effects or parametric instabilities (see Sec 3.3.2), are triggered only with similar arm powers (hundreds of kW) and beam widths comparable to the real ones (cm) with full-scale mirrors (kg). It is extremely challenging to verify such effects in small prototypes where large beams and powers similar to Virgo_nEXT are impossible to achieve. Additionally, sophisticated seismic suspensions and vacuum instrumentation are required to study second-order noises and effects (such as those related to scattered light from rough surfaces modulated by the relative motion between the central interferometer and auxiliary optical benches). Implementing these requirements in a prototype is difficult, whereas Virgo_nEXT serves as an almost-real-scale ideal prototype. Moreover, ET will require even more demanding detector calibration techniques for Hubble constant measurement or test of general relativity with signal having SNR up to a few thousand. Virgo_nEXT, with its unprecedent sensitivity, will offer a unique place for the development and long term validation of these techniques

7.3 *Virgo_nEXT as a prototype for studying noises in the 10 Hz region*

One of the strategic objectives of the Einstein Telescope is to extend the instrument's bandwidth below 10 Hz, down to 1-2 Hz. This is achieved through a room-temperature instrument (ET-HF) using a wavelength of 1 micron for the high frequency region, while a cryogenic instrument (ET-LF) will use a different wavelength and materials for the low frequency region. The development of the ET-LF instrument is complex and utilizes technologies that cannot be tested in Virgo_nEXT. However, to achieve the sensitivity of ET-LF, it is necessary to reduce all technical noises (control noises, laser source noises, environmental noises, and scattered light noises) that currently limit the sensitivity of Virgo and LIGO, which are orders of magnitude higher than fundamental noises (quantum and thermal noise) and higher than the ET design sensitivity (see Fig. 10. Although the impact of these noises will be reduced due to the elongation of the arm length of ET with respect to Virgo and the underground placement of the Einstein Telescope, there are still significant gains to be made . Virgo_nEXT will contribute to optimizing control methods and reducing environmental noises (such as Newtonian noise subtraction, magnetic noise, and reducing the noise from air conditioning machinery and vacuum pumps), thus accelerating the commissioning timeline of ET.

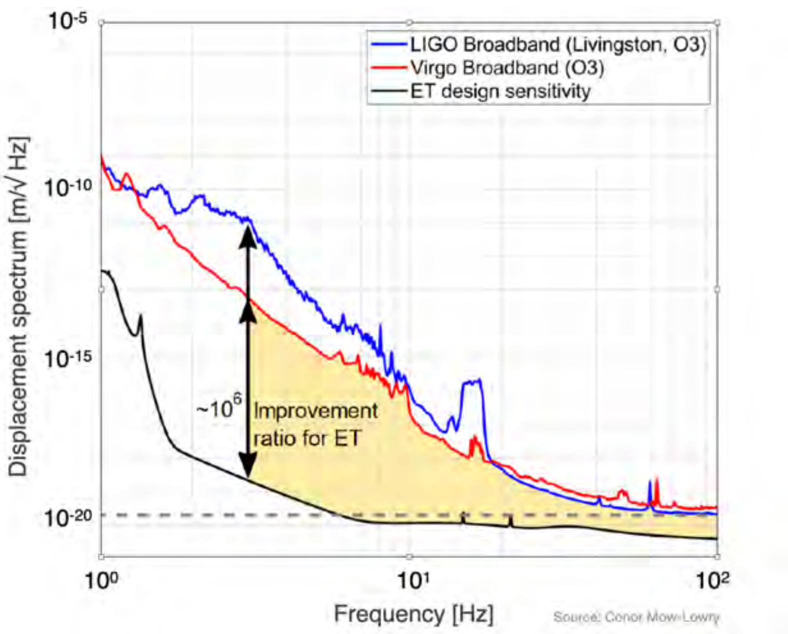

Figure 10: Low frequency sensitivity of Virgo and LIGO compared to ET. There is a factor 10^6 between Virgo sensitivity during O3 and ET sensitivity at 3 Hz (credit: Connor Mow-Lowry

.

7.4 *Development of an integrated detector simulation and testing during Virgo_nEXT*

Currently, it is possible to simulate a nearly-perfect detector, accounting for first-order defects such as small misalignments and low-order mirror defects. For ET, it is crucial to develop an integrated (end-to-end) simulation of the detector, which needs to be validated, tested, and iteratively improved using a similar detector prototype (at least for the HF part, which is likely to be implemented first). Therefore, Virgo_nEXT also serves as a test-bench for providing a reliable simulation for the Einstein Telescope, considering all the complex effects that can be fine-tuned and modeled using a real experiment.

7.5 *Training of detector experts*

The construction, commissioning and data-analysis of a detector like Virgo involves a unique combination of Fabry-Perot cavity optics, Gaussian beam optics, electronics, mechanics, signal processing, automatic controls, and the study of various noises. Training phd students, post-docs researchers and leaders in this field requires practical experience in commissioning and data-analysis with an existing interferometer. Virgo_nEXT can provide this type of training ground for students and researchers, even during the construction of Einstein Telescope. These students and researchers can later assume leadership roles in ET. Without Virgo_nEXT, the likely absence of three cycles of doctoral thesis and the gradual retirement of senior researchers would be disastrous for maintaining continuity and preserving this kind of experts.

ACKNOWLEDGMENTS

This report is based on the work of the whole Virgo Collaboration. We also acknowledge colleagues of LIGO, GEO, KAGRA, ET and CE for useful exchanges.

REFERENCES

[1] B. Abbott et al. (LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration), Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO, Advanced Virgo and KAGRA, Living Rev Relativ 23, 3 (2020)

[2] The LIGO Scientific Collaboration, the Virgo Collaboration, the KAGRA Collaboration, "GWTC-3: Compact Binary Coalescences Observed by LIGO and Virgo During the Second Part of the Third Observing Run" arXiv:2111.03606.

[3] The LIGO Scientific Collaboration, the Virgo Collaboration, the KAGRA Collaboration, Constraints on the cosmic expansion history from GWTC-3, arXiv:2111.03604

[4] The LIGO Scientific Collaboration, the Virgo Collaboration, the KAGRA Collaboration, Tests of General Relativity with GWTC-3, arXiv:2112.06861

[5] R. Abbott et al. (LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration), Population of Merging Compact Binaries Inferred Using Gravitational Waves through GWTC-3, Phys. Rev. X 13, 011048 – Published 29 March 2023

[6] The LIGO Scientific Collaboration and Virgo collaboration, "GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral" Phys. Rev. Lett. 119, 161101 (2017).

[7] The LIGO Scientific Collaboration and The Virgo Collaboration, The 1M2H Collaboration, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, The Las Cumbres Observatory Collaboration, The VINROUGE Collaboration , "A gravitational-wave standard siren measurement of the Hubble constant" Nature 551, pages 85–88 (2017) [arXiv:1710.05835]

[8] R. Abbott *et al.* [LIGO Scientific, VIRGO and KAGRA], "Search for subsolar-mass black hole binaries in the second part of Advanced LIGO's and Advanced Virgo's third observing run," Monthly Notices of the Royal Astronomical Society, stad588

[9] B. P. Abbott *et al.* [LIGO Scientific and Virgo], "Search for Subsolar-Mass Ultracompact Binaries in Advanced LIGO's First Observing Run," Phys. Rev. Lett. **121** (2018) no.23, 231103 doi:10.1103/PhysRevLett.121.231103

[10] B. P. Abbott *et al.* [LIGO Scientific and Virgo], "Search for Subsolar Mass Ultracompact Binaries in Advanced LIGO's Second Observing Run," Phys. Rev. Lett. **123** (2019) no.16, 161102 doi:10.1103/PhysRevLett.123.161102

[11] R. Abbott *et al.* [LIGO Scientific, VIRGO and KAGRA], "Search for Subsolar-Mass Binaries in the First Half of Advanced LIGO's and Advanced Virgo's Third Observing Run," Phys. Rev. Lett. **129** (2022) no.6, 061104 doi:10.1103/PhysRevLett.129.061104

[12] A. H. Nitz and Y. F. Wang, "Search for Gravitational Waves from the Coalescence of Subsolar-Mass Binaries in the First Half of Advanced LIGO and Virgo's Third Observing Run," Phys. Rev. Lett. **127** (2021) no.15, 151101 doi:10.1103/PhysRevLett.127.151101

[13] A. H. Nitz and Y. F. Wang, "Broad search for gravitational waves from subsolar-mass binaries through LIGO and Virgo's third observing run," Phys. Rev. D **106** (2022) no.2, 023024 doi:10.1103/PhysRevD.106.023024

[14] A. L. Miller, N. Aggarwal, S. Clesse and F. De Lillo, "Constraints on planetary and asteroid-mass primordial black holes from continuous gravitational-wave searches," Phys. Rev. D **105** (2022) no.6, 062008 doi:10.1103/PhysRevD.105.062008

[15] M. Isi, L. Sun, R. Brito and A. Melatos, "Directed searches for gravitational waves from ultralight bosons," Phys. Rev. D **99** (2019) no.8, 084042 [erratum: Phys. Rev. D **102** (2020) no.4, 049901] doi:10.1103/PhysRevD.99.084042

[16] R. Ciancarella, F. Pannarale, A. Addazi and A. Marciano, "Constraining mirror dark matter inside neutron stars," Phys. Dark Univ. **32** (2021), 100796 doi:10.1016/j.dark.2021.100796

[17] M. Bezares and C. Palenzuela, "Gravitational Waves from Dark Boson Star binary mergers," Class. Quant. Grav. **35** (2018) no.23, 234002 doi:10.1088/1361-6382/aae87c

[18] S. Cao, J. Qi, Z. Cao, M. Biesiada, W. Cheng and Z. H. Zhu, "Direct measurement of the distribution of dark matter with strongly lensed gravitational waves," Astron. Astrophys. **659** (2022), L5 doi:10.1051/0004-6361/202142694

[19] X. Guo and Y. Lu, "Probing the nature of dark matter via gravitational waves lensed by small dark matter halos," Phys. Rev. D **106** (2022) no.2, 023018 doi:10.1103/PhysRevD.106.023018

[20] R. Abbott *et al.* [LIGO Scientific, VIRGO and KAGRA], "Search for gravitational-lensing signatures in the full third observing run of the LIGO-Virgo network,"

[21] R. Abbott *et al.* [LIGO Scientific, KAGRA and Virgo], "Constraints on dark photon dark matter using data from LIGO's and Virgo's third observing run," Phys. Rev. D **105** (2022) no.6, 063030 doi:10.1103/PhysRevD.105.063030

[22] C.Mondal, M.Antonelli, F.Gulminelli, M.Mancini, J.Novak, M.Oertel, "Detectability of a phase transition in neutron star matter with third-generation gravitational wave interferometers", doi10.48550/arXiv.2305.05999

[23] S.Borhanian, "GWBENCH: a novel Fisher information package for gravitational-wave benchmarking", Classical and Quantum Gravity, Volume 38, Issue 17, id.175014, 28 pp, doi:10.1088/1361-6382/ac1618

[24] B. P. Abbott *et al.* [LIGO Scientific, Virgo, 1M2H, Dark Energy Camera GW-E, DES, DLT40, Las Cumbres Observatory, VINROUGE and MASTER], "A gravitational-wave standard siren measurement of the Hubble constant," Nature **551** (2017) no.7678, 85-88, DOI:10.1038/nature24471

[25] B. P. Abbott *et al.* [LIGO Scientific, Virgo, Fermi-GBM and INTEGRAL], "Gravitational Waves and Gamma-rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A," Astrophys. J. Lett. **848** (2017) no.2, L13 DOI:10.3847/2041-8213/aa920c

[26] E. Belgacem, Y. Dirian, S. Foffa, E. J. Howell, M. Maggiore and T. Regimbau, "Cosmology and dark energy from joint gravitational wave-GRB observations," JCAP **08** (2019), 015, DOI:10.1088/1475-7516/2019/08/015

[27] K. Leyde, S. Mastrogiovanni, D. A. Steer, E. Chassande-Mottin and C. Karathanasis, "Current and future constraints on cosmology and modified gravitational wave friction from binary black holes," JCAP **09** (2022), 012, DOI:10.1088/1475-7516/2022/09/012

[28] Flaminio R. (2014) Thermal Noise in Laser Interferometer Gravitational Wave Detectors. In: Bassan M. (eds) Advanced Interferometers and the Search for Gravitational Waves. Astrophysics and Space Science Library, vol 404. Springer, Cham.

[29] Pinard L. et al, Mirrors used in the LIGO interferometers for first detection of gravitational waves, Applied Optics, 56 (4), C11-C15 (2017)

[30] B. Cimma et al., 'Ion beam sputtering coatings on large substrates: toward an improvement of the mechanical and optical performances', Applied Optics 45 7 1436 (2006)

[31] Cole G. et al. Tenfold reduction of Brownian noise in high-reflectivity optical coatings. Nature Photon 7, 644–650 (2013)

[32] V. Hui et al, Transfer of an AlGaAs/GaAs crystalline Bragg mirror from a GaAs substrate to a fused silica substrate by direct bonding, Proceedings Volume 12137, Optics and Photonics for Advanced Dimensional Metrology II; 121370D (2022)

[33] https://www.ligo.caltech.edu/news/ligo20230417

[34] The Virgo Collaboration, Virgo_nEXT, beyond the AdV+ project; A concept study, Virgo internal note VIR-0497D-22, also available on: https://indico.in2p3.fr/event/30210/

[35] M.Evans et al, Observation of Parametric Instability in Advanced LIGO, https://arxiv.org/abs/1502.06058

[36] The need of stable cavities for Virgo_nEXT, Internal document of the Virgo Collaboration, also available on: https://indico.in2p3.fr/event/30210/

[37] Virgo_nEXT Concept Study - Update of the Coating Thermal Noise section, Virgo internal note, also available on: https://indico.in2p3.fr/event/30210/

[38] The current Virgo Collaboration organigram is available at the site https://indico.in2p3.fr/event/30210/

[39] T. Harder et al, High speed, high power 2D beam steering for mitigation of optomechanical parametric instability in gravitational wave detectors, Opt. Express Vol. 31, pp 1486 (2023), https://doi=10.1364/OE.454387

[40] C. Dixneuf et al, Ultra-low intensity noise, all fiber 365 W linearly polarized single frequency laser at 1064 nm , Optics Express, Vol. 28, Issue 8, pp. 10960–10969, (2020) https://doi.org/10.1364/OE.385095

[41] L. Wei et al, Coherently combined master oscillator fiber power amplifiers for Advanced Virgo, Optics Letters Vol. 41, Issue 24, pp. 5817-5820 (2016) https://doi.org/10.1364/OL.41.005817

APPENDIX A

List of possible technological synergies between Einstein Telescope and Virgo_nEXT

- Increased optical power; resulting in similar radiation pressure dynamics as in ET-HF because in Virgo_nEXT the ratio of optical power to testmass weight (1.5 MW to 105 kg) will be roughly identical to ET-HF (3 MW and 200 kg).
- High power lasers systems delivering several 100 W at a wavelength of 1064 nm and in a HG_{00} mode.
- Optical components (e.g. electro-optic modulators, Faraday isolators etc), in particular in the injection and input optics path, that can withstand the increased laser power.
- Development of mitigation strategies for parametric instabilities (PI), including passive dampers as well as active damping using spatially modulated auxiliary lasers.
- Improved thermal compensation systems (TCS). This includes e.g. higher power ringheaters, higher order mode actuators and improved wavefront sensing techniques.
- Improved coatings with a reduced point defect and point absorber density. Improved metrology for detection of point absorbers.
- Squeezed light sources with increased squeezing level (in air and in vacuum, TBD) based on reduced OPO losses.
- Optical components with reduced optical loss, in particular improved low-loss Faraday Isolators, low-loss free-space output modecleaners, etc.
- Development of improved mode matching sensors and actuators, both to reduce the losses inside the main interferometer, but also in the squeezed light injection path.
- Reduced phase noise on the squeezing ellipse via improved control strategies for the length and alignment sensing of the filter cavity.
- New coatings with lower mechanical loss and lower absorption. Amorphous coatings with new or optimized materials, deposition and heat treatment. Crystalline coatings of sufficient size and optical quality, plus relevant transfer and bonding technologies.
- Payloads with reduced suspension thermal noise based on triple stage payload with a fully monolith final stage consisting of the penulitimate mass and the test mass.

- Enhanced seismic isolation techniques: Compact, passive seismic isolation chains; Test of inertial platform in a real operation environment.
- Seismic Newtonian noise subtraction techniques based seismometer arrays and noise subtraction via e.g. Wiener filters.
- Scattered light mitigation, including scattered light tracing and detection methods, scattered light simulation tools, improved baffle materials etc.
- Improved sensors and control techniques for interferometric sensing and control, i.e. relevant alignment and longitudinal degrees of freedom.
- Digital-to-analog (DAC) converters with improved range, lower noise digitisation electronics, higher performance real-time data treatment.
- Improved environmental noise monitoring, i.e. for infrasound.
- Increased laser stabilization, i.e. reduced relative intensity noise (RIN) and jitter noise of the main laser and the input optics, as well as laser used for the photon calibrators (Pcal).
- Many technical noises need to be reduced, some 2 orders of magnitude with respect to O3, in order to reach the best possible Virgo_nEXT sensitivity. In order to achieve this goal significant R&D will have to be performed and one can anticipate also that new strategies and noise decoupling techniques will have to be developed for the controls. All these developments will pave the way for ET which is aiming at an even better sensitivity and pushing the low frequency wall towards lower frequencies.

APPENDIX B

The table 3 shows the main squeezing parameters for O5, a possible Virgo_nEXT initial phase of and the ultimate Virgo_nEXT goal.

The figure 11 shows the measured squeezing level for Virgo_nEXT as a function of the squeezing degradation sources.

Parameter	O5	Initial Virgo_nEXT	Virgo_nEXT
Injected squeezing	12 dB	12 dB	15 dB
Injection losses	6.5%	5.5%	1.8%
Filter cavity round-trip losses	30 ppm	30 ppm	20 ppm
Readout losses	6%	4.5%	2.5 %
Arm-cavity round-trip losses	75 ppm	75 ppm	75 ppm
Signal extraction cavity (SEC) round-trip losses	1000 ppm	1000 ppm	500 ppm
Phase noise	25 mrad	15 mrad	10 mrad
Mismatching squeezing - filter cavity	0.5%	0.5%	0.25%
Mismatching squeezing - interferometer	2%	1%	0.5%
Measured squeezing at high-frequency	5.5 dB	7.5 dB	10 dB

Table 3: Main frequency dependent squeezing parameters for "O5", "initial post-O5" and Virgo_nEXT.

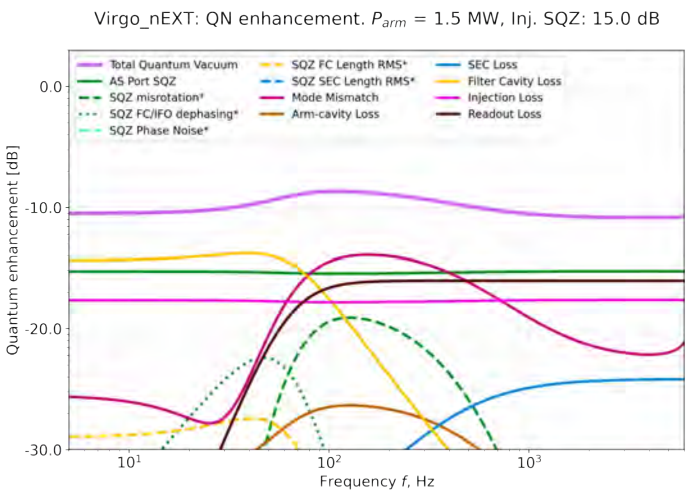

Figure 11: Measured squeezing level as a function of the frequency, computed as the ratio between power spectral density of the strain sensitivity (quantum noise limited) with and without squeezing, for Virgo_nEXT

.