Appel à contributions pour l'exercice de prospective nationale “Technologies quantiques pour les deux infinis”

Quantum technologies and gravitational-wave detectors

Authors:

The Virgo groups of: APC, Artemis, IJCLab, IPHC, IP2I, LAPP, LKB, and the g-MAG Virgo group (ILM, INL,INSP, Navier)

Contact: Matteo Barsuglia (barsu@apc.in2p3.fr)

May 2021

Quantum technologies and gravitational-wave (GW) detectors have a long standing link: the need for gravitational-wave detectors to push more and more the limits of their performances was one of the drivers for the development of *squeezing* sources and *quantum non demolition* studies and techniques. After many years of R&D, GW detectors are today routinely using quantum technologies to improve their astrophysical reach.

1. Background

Quantum noise is one of the main limitations of current gravitational-wave detectors. It arises from vacuum fluctuations entering from the interferometer output “dark” port [1]. In Virgo and LIGO, squeezing techniques are used since the O3 data taking to reduce the shot noise (high-frequency component of the quantum noise), with a gain of ~ 3 dB [2,3] and a very good duty cycle, allowing an extension of the detection range up to ~ 25% for Virgo and ~ 50% for LIGO. This technique is referred to as *frequency independent squeezing*. The expected increase of the radiation pressure noise at low frequency, due to the use of this technique, is at present barely visible, because of the presence of other noise sources.

In the ongoing upgrades of Virgo and LIGO (AdvancedVirgo+ and aLIGO+) a frequency dependent squeezing source will be used to reduce the quantum noise in a much larger detection bandwidth, and especially below 100 Hz. This technique uses frequency-independent squeezing sources filtered by a suspended Fabry-Perot cavity, the so-called *filter cavity*, in order to rotate the squeezing ellipse before entering the interferometer. Frequency dependent squeezing is planned for the data taking O4 (2022) and it is currently under commissioning (see fig.1).

For the next data taking (O5), a further reduction of the quantum noise through a squeezing improvement is expected. This proceeds mainly through a reduction of the optical losses. Moreover, lessons learnt from Advanced Virgo+ phase I and from R&D activities will be also used to further improve the filter cavity control and the performances of the whole squeezing system. One possibility for Advance Virgo+, still under discussion, is to use for O5 an in-vacuum squeezed source (as it is done in LIGO), in order to reduce environmental noises and the impact of scattered light.

Virgo and LIGO *post-O5* plans (2027-2036) are still being drafted and a first assessment about possible upgrade scenarios will be released in early 2022 by the LIGO and Virgo Collaborations. Further incremental increases of the squeezing performances are an option, or – more ambitiously – the use of new squeezing techniques. As an example among others, the use of the EPR (Einstein-Podolsky-Rosen) squeezing [4] is currently under study.

While working on the Virgo upgrades, the CNRS researchers are contributing to the Einstein Telescope design. The project, submitted to the ESFRI roadmap [5], could be operated around 2035 and it will consist of a triangular underground detector with 10 km long arms. The goal of increasing the sensitivity by a factor ~10 with respect to 2nd generation detectors will require ~ 10 dB of quantum noise reduction and thus a further improvement of the squeezing techniques: multiple filter cavities in order to deal with more complex signal extraction techniques (due to detuned signal recycling) and squeezing at other wavelengths (1.5 micron or 2 micron, with respect to 1 micron used today).

Gravitational-wave detectors using atom interferometry (for instance MIGA or AION) are currently under study and they may benefit from squeezing technologies developed in the field of laser interferometric gravitational-wave detectors.

The use of these squeezing techniques stimulated the development of skills in CNRS laboratories which have been participating in several ways to simulation efforts, R&D experiments, developments of components for squeezing, and construction of squeezing hardware for Virgo.

The goal of this document is to describe: 1) the activities related to quantum technologies in which CNRS Virgo laboratories have developed expertises and in which they can contribute in the next decade, 2) the possible improvements of GW detectors using quantum technologies, 3) the possible spin-off toward other experiments or communities.

2. Quantum technologies activities

2.1. Simulations

While analytical models are useful for simple configurations, they present limits to simulate more complex GW interferometers with several coupled cavities and quantum-mechanical effects.

Several simulation packages exist in the field of GW interferometry, and some of them have been developed by CNRS-Virgo laboratories (for instance, OSCAR and darkF). Optical simulations based on modal expansion on the Hermitte Gauss base, like Finesse [6], can simulate accurately the shot noise limited sensitivity and in recent years, they have been updated for a full quantum treatment including radiation pressure, squeezed light sources and homodyne detection. With those tools it is also possible to simulate the squeezing angle rotation from the filtering cavity, including optical losses, mode mismatching and the most common imperfections.

2.2. Components for squeezing

In present GW experiments, squeezing is generated by parametric down conversion using an optical parametric oscillator (OPO). The OPO consists of a nonlinear crystal and a resonant optical cavity. In present GW detectors (using lasers with 1064 nm wavelength) high levels of squeezing, up to 15 dB have been reached [7]. This frequency-independent squeezed vacuum field is then shaped by a filter cavity (Fabry-Perot cavity) of a few 100 meters before being injected in the interferometer via the dark port. This field needs to be precisely matched to the interferometer beam using a mode matching telescope. Faraday isolators are also essential components in order to inject the squeezed field inside the interferometer. Faraday isolators also serve to isolate the squeezing system from spurious light arising from the dark port beam leaking into the squeezing system at the interface and which can be back-scattered into the interferometer inducing additional noise. All those elements are located on optical benches between the squeezing system and the main interferometer (in Virgo, those benches are developed by LAPP). On those optical benches, care has to be taken in order to keep the scattered light as low as possible while preserving low losses (using, for example, appropriate diaphragms). Once the squeezed field is injected into the interferometer and overlapped to the main beam the output beam is detected at the dark port by high quantum efficiency photodiodes after passing through a mode cleaner cavity (output mode cleaner). Fig. 1 shows a schematic of the Advanced Virgo+ optical layout with squeezing injection.

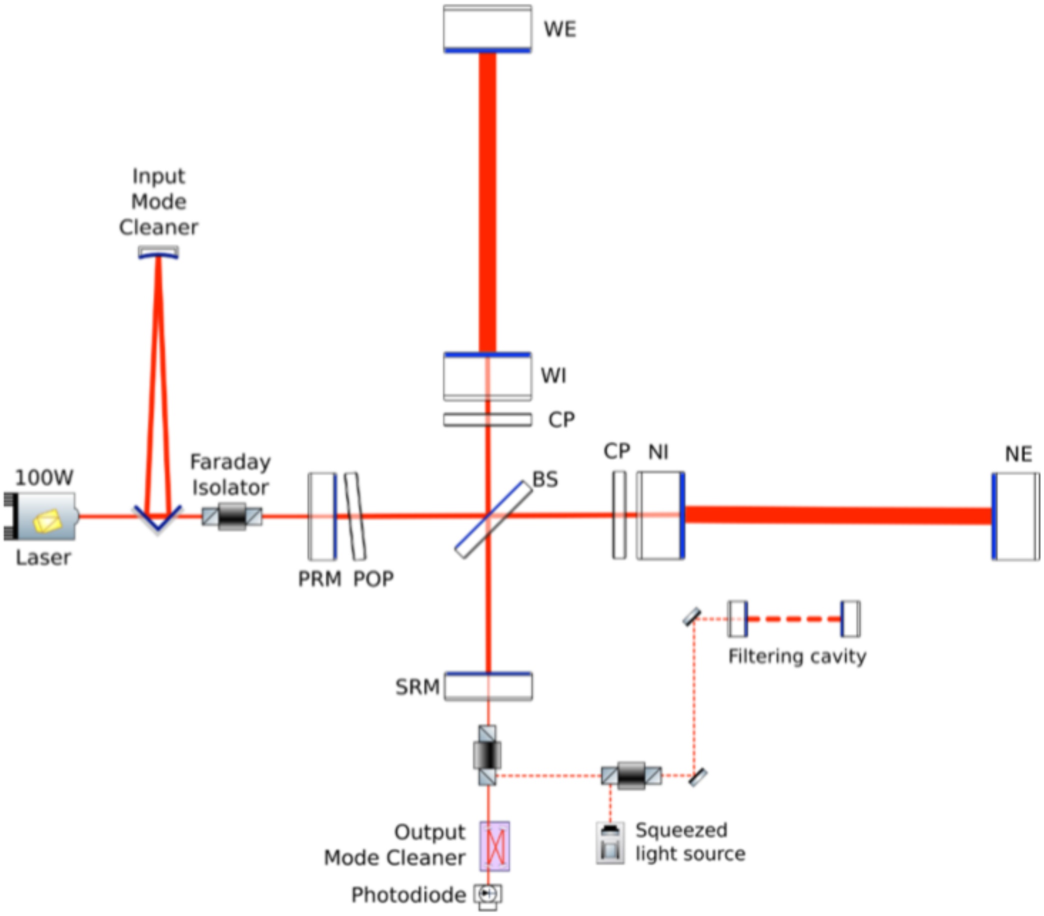

Fig 1: *schematic view of the Advanced Virgo+ interferometer with frequency dependent squeezing (from the Advanced Virgo+ technical design report)*

2.3. Table-top prototypes

Over the past years, the performances of squeezing sources at 1064 nm (the one needed for current GW detectors) have been largely improved and reached a very high squeezing level (>10 dB) starting from low frequencies (~10 Hz). Even though such performances are largely compliant with the needs of current (second generation) detectors, future detectors (Einstein Telescope, Cosmic Explorer) may require the development of different types of squeezing sources. Among the possibilities, there are sources at other wavelengths (i.e 1550nm, 2000 nm) that might be chosen to operate 3G detectors, and squeezing of higher order modes. Some table top experiments aiming to demonstrate the feasibility and performances these alternative squeezing sources have been performed or are in-going [8,9,10], but the optimization of various components (e.g. photodetectors, faraday isolators etc.) for different wavelengths and in general the improvement in the overall squeezing performances will be a research topic in the next years, requiring the development of specific table-top prototypes.

A squeezing independent source is currently hosted at IJCLab and used in the CALVA experiment (see next paragraph). CNRS researchers are also contributing to a R&D squeezing source, hosted at the European Gravitational Observatory, on the Virgo site [11].

2.4. Suspended and in-vacuum prototypes

In-vacuum and suspended ~ 10-100 m scale prototypes have been and are used in the GW community as an intermediate step before the implementation of technologies in gravitational-wave detectors. Not only are such configurations much closer to full scale detectors, but - thanks to the suspension system - they allow testing of opto-mechanical effects in the audio band (100 Hz). Moreover, the vacuum system allows performing noise studies and control studies in conditions similar to the real ones.

For several years, a platform, CALVA, has been developed at IJCLab with a suspended cavities system under vacuum. The first version included 2 coupled cavities (5+50m long) and was used to study lock acquisition techniques. With the support of ANR Exqueez (2015-2021), the instrument has been modified by removing the 5m long cavity and adding a squeezer with all the needed optics to perform a full scale frequency dependent squeezing experiment [24], which includes nonlinear optics and squeezing (LKB), suspended 50-m long filter cavity (IJCLAB), low loss optics (LMA) and Virgo standard electronics (LAPP). We are presently testing the production of squeezed light under vacuum and we will soon add the 50m long filtering cavity to produce frequency dependent squeezing. The squeezer is based on a design done in collaboration with ANU using a bow-tie configuration to reduce light scattering in the propagation of the squeezed light. The CALVA experiment uses the same electronics and software used in Virgo.

Some CNRS laboratories (APC, LAPP) are contributing to the development of an integrated prototype in the TAMA infrastructure, at NAOJ (Mitaka, Tokyo). This setup, a 300-m in-vacuum filter cavity with suspended optics and a squeezing source, has been used for the experimental demonstration (in 2020) of the frequency dependent squeezing rotation in the frequency region planned for current GW detectors [12], for measurements of squeezing losses in a full scale filter cavity [13], and it is still used to test filter cavity control strategies [14].

2.5. Quantum effects in Virgo and LIGO

As already mentioned, since O3, Virgo and LIGO are routinely using frequency-independent squeezing. The Virgo filter cavity is currently under commissioning and frequency-dependent squeezing is expected to be observed soon. The sensitivity and the characteristics of Virgo and LIGO allows the observation of optomechanical effects with kg scale objects, which is impossible in top-table and small prototypes. The recent observation of quantum backaction and quantum correlations between light and mirrors is one of these examples [14,15]. In the future Virgo, LIGO and KAGRA will continue to represent a powerful way to test quantum effects on macroscopic (kg scale) objects and acquire experience on quantum technologies and devices.

3. Possible applications of quantum technologies in future GW detectors

3.1 Squeezing vacuum source for Advanced Virgo+

Previous work has shown the importance of backscatter light pollution in squeezing degradation [16]. The introduction of the squeezer is a new possible source of backscattering light which may have an important contribution below 100 Hz (in the most Virgo sensitive region). There are several options to reduce such problems: moving the OPO on a bench which is seismically isolated, and then decreasing the possible motion of the OPO vs the rest of the interferometer; or reducing the level of spurious light reaching the OPO by working on better isolation with Faraday isolator (see next paragraph) or using a different geometry for the OPO cavity (like bow-tie).

For AdvancedVirgo+ phase II (to be operated in 2025, for the O5 LIGO-VIrgo-KAGRA data taking), IJCLab and KLB teams will study (in relation to the activity done at CALVA) the possibility of replacing the current squeezer hosted on an in-air table by a full system under vacuum on one of the suspended benches.

3.2 Low losses components

Optical losses are very detrimental to squeezed light as such light has to pass numerous components before reaching the final photodiode at the output of the interferometer. Any loss on the squeezed field corresponds in fact to re-injecting the equivalent amount of non-squeezed vacuum.

This is well illustrated by the currently observed squeezing level in operating GW detectors [2,3]: in Advanced Virgo, a reduction of quantum noise of 3 dB was routinely observed while injecting 13 to 14 dB of squeezed vacuum. Losses are due to mode mismatch, limited quantum efficiency of the photodiodes, optical absorption in Faraday isolators, mode cleaner cavity, optical losses in the filter cavity, and phase noise arising to the locking accuracy of the filter cavity. As an example, during the O3 run the total detection losses (photodiodes, output mode cleaner, Faraday isolator, mode matching,...) were of the order of 80%. In order to reach higher reduction of quantum noise, these losses have to be reduced for all optical components: we use low absorption crystals for Faraday isolators, high quantum efficiency photodiodes and associated very low noise electronics, low noise resonant optical cavities (mode cleaner and filter cavity), low loss mirrors (especially for the filter cavity), low aberration tunable mode matching telescopes. For the O4 run (starting in 2022), with the present state of the art technologies, all individual components should contribute to at most 1-2% loss each which, given the number of components turns into a total efficiency of 85-90%, leading to an achievable gain of 5-6dB (starting from a squeezing source of 14dB).

State of the art polishing and coating is required to limit excessive optical losses as well as a dust free environment. LMA has a long experience in producing low loss optical coatings and strives to continue to further improve the performances of these layers. One of the focuses now is to develop very low anti-reflective coatings, with a reflectivity below 50 ppm in a reliable way, on fused silica but also crystals in nonlinear cavity or Faraday isolators.

3.3. Alternative squeezing techniques: Einstein-Podolsky-Rosen squeezing

In 2016 Y.Ma et al. [4] proposed an alternative way to benefit from frequency dependent squeezing without the need of an additional long cavity. The main idea is to inject a pair of EPR-entangled beams from the ITF dark port. If one of the two beams is frequency detuned with respect to the carrier, it will see the reflection from the interferometer as that of a filter cavity, thus it will experience frequency dependent squeezing. Even though this configuration is more sensitive to optical losses, it might be advantageous for 3G detectors, such as the Einstein Telescope or Cosmic Explorer, as it would avoid the use of several filter cavities, which are currently included in the design. Recently, table top experiments have demonstrated the technique at high frequency and an additional experiment aiming to develop an EPR squeezing source to be tested in Virgo in on-going with the participation of researchers from APC.

3.4 Alternative squeezing techniques: Q-filter

Present filtering cavities for frequency dependent squeezing are designed for a specific configuration (corresponding to a given cut-off frequency) and cannot be changed without either changing the mirrors or the length of the cavity. The system is then optimized mainly for a given input power and any change in this value will modify the relative impact of the two parts of the quantum noise, so that the rotation of the noise ellipse will no longer be optimal. One possibility to tune the frequency cut-off is to use a coupled cavity system, made of an input cavity in the role of the input mirror, together with the usual end mirror. Such a system allows to tune the effective reflectivity of the equivalent input mirror (simply by controlling the resonance of the input cavity through the position of one mirror). With this technique, it is envisioned to tune the rotation frequency between 10Hz and 10 kHz. This technique will be tested in a second step on the CALVA platform after completing the work on-going with the in-vacuum squeezer. This project is funded by an international ANR project, QFilter, with Japan and includes LKB, IJCLab and LMA for the French part.

3.5 Plans for post-O5 and Einstein Telescope

The O5 data taking (corresponding to the Advanced Virgo+ phase 2) will end in 2027. The frequency dependent squeezing performances in Advanced Virgo+ are not known yet, as the system is just being commissioned. It will be characterized before the O4 run and some improvements could be planned for O5 (for instance the implementation of in vacuum OPO (see 3.1). However, it is clear that the present technology will not have reached its limits for O5 and further improvements are possible, especially in terms of losses. For the post-O5 era, incremental improvements of the current technologies are envisaged, but also alternative schemes (for instance 3.3, 3.4) are considered.

For the 3rd generation (3G) detectors, the baseline design includes the same technologies used today (squeezing sources + filter cavities), with improved projected performances. Any gain for the Post O5 era will therefore be useful for Einstein Telescope.

One of the ET challenges lies in the fact that the low frequency detector (ET-LF) will most probably not use 1064 nm wavelength but 1550 nm or even 2 um (while the high frequency detector, ET-HF, will still use 1064nm). Squeezing has never been demonstrated to a high level in the Hz-kHz bandwidth at these wavelengths and all the technology has to be developed, including: squeezed vacuum source, low loss filter cavities (of km scale), Faraday isolators, low loss output mode cleaner and high efficiency photodiodes and related low noise electronics. In addition, most of these components need to be vacuum compatible.

Other techniques to reduce quantum noise have been proposed and could be considered for Einstein Telescope if their will reach a significant level of maturity, as for instance *QND speed-meter interferometers*, *white light cavity* systems (using a negative dispersion medium), *intracavity signal amplification* or *coherent quantum noise amplification* (for a review, see [25]).

CNRS researchers are contributing to the studies for possible post-O5 upgrades, before the start of the 3rd generation detectors (Einstein Telescope and Cosmic Explorer). CNRS researchers are also contributing to the design of Einstein Telescope, with responsibilities also related to quantum technologies.

4.Spin-off of quantum technologies and skills developed in the context of laser GW detection towards other communities and projects

Gravitational-wave detection using atom interferometry

In 2016 [18], a ground-based gravitational wave detector based on atom interferometry was proposed. It consists in a specific spatial distribution of gradiometers allowing the average of Newtonian noise. This configuration extends the observation window of current detectors by a decade and fills the gap [0.1 Hz-10 Hz] between ground-based and space-based instruments. At high frequency [1 Hz-10 Hz], the proposed configuration is limited by the quantum projection noise which scales as the total number of atoms used in the whole detector. Currently, the quantum projection noise limits the state-of-the-art atom interferometers used as initial sensors at a level close to 1 mrad .Hz-½ . Three similar interferometers installed on a single 150m baseline and interrogated by the same lasers are being installed on the MIGA facility [19]. Hence, the MIGA project stands for a demonstrator to a future low frequency ground-based gravitational wave detector.

Quantum projection noise is called the standard quantum limit and is similar to shot noise in optical interferometry. In order for the gravitational wave detector to reach the required sensitivity, the shot noise level has to reach 0.1 μrad.Hz-½ [20]. Several squeezing techniques were proposed and validated to overcome this limit [21]. Techniques based on optical cavities, on which the expertise developed on ground based optical detectors, are of great interest here: 1) *Squeezing based on quantum nondemolition* (QND) [22]: The squeezing is due to the projective measurement of the atomic state upon detection of the light. The strength of the interaction between the light and the individual atoms is enhanced within an optical cavity, 2) *Entangled state preparation* [23]: Standard quantum limit in atomic interferometry can be overcome using entanglement. Resonant atom-light coupling in an optical cavity offers the possibility to create entangled states.

Although these techniques were tested on table top experiments, they need to be adapted for kilometer scale cavities and applied to several distant atomic clouds at the same time.

5. Summary

Quantum technologies and gravitational-wave detectors are tightly linked. Quantum noise is a main limitation of VIrgo and LIGO, and quantum-mechanical effects are observable in GW interferometers. Squeezed vacuum is currently used during observational runs, and more sophisticated quantum techniques are under development to further increase the sensitivity of GW detectors.

CNRS Virgo laboratories are at the forefront of this research, to which they contribute in several ways, ranging from simulation, table-top experiment, optical components, middle scale prototypes. CNRS Virgo laboratories are also strongly involved in the current and future Virgo upgrades related to squeezing and in the Einstein Telescope design.

This research is necessary for Virgo and GW astronomy, but Virgo also represents an instrument to test quantum optics effects on kg mirrors, and a way to develop skills and experience which are useful in other fields.

6. References

[1] C. M. Caves, *Quantum-mechanical noise in an interferometer*, Phys. Rev. D 2(Apr, 1981) 1693–1708

[2] M. Tse *et al., Quantum-Enhanced Advanced LIGO Detectors in the Era of Gravitational-Wave Astronomy*, Phys. Rev. Lett. 123, 231107 – 2019

[3] F. Arcenese, et al. (Virgo Collaboration), I*ncreasing the Astrophysical Reach of the Advanced Virgo Detector via the Application of Squeezed Vacuum States of Light*, Phys. Rev. Lett. 123, 231108 (2019).

[4] Y.Ma et al., *Proposal for gravitational-wave detection beyond the standard quantum limit through EPR entanglement*, Nature Physics vol. 13, pages 776–780 (2017)

[5] www.et-gw.eu

[6] https://git.ligo.org/finesse/finesse

[7] M Mehmet and H Vahlbruch, *High-efficiency squeezed light generation for gravitational wave detectors*, Classical and Quantum Gravity 36, 015014 (2018)

[8] M.Mehmet et al., *Squeezed light at 1550 nm with a quantum noise reduction of 12.3 dB*, Optics Express Vol. 19, Issue 25 (2011)

[9] G. L. Mansell, *Observation of Squeezed Light in the 2µm Region*, Phys. Rev. Lett. 120, 203603 (2018)

[10] J. Heinze et al., *Frequency-doubling of continuous laser light in the Laguerre–Gaussian modes LG00 and LG33*, Optics Letters Vol. 45, Issue 18 (2020)

[11] C.Nguyen et al., *Automated source of squeezed vacuum states driven by finite state machine based software*, Rev. Sci. Instrum. 92, 054504 (2021)

[12] Y.Zhao et al, *Frequency-Dependent Squeezed Vacuum Source for Broadband Quantum Noise Reduction in Advanced Gravitational-Wave Detectors*, Phys. Rev. Lett. 124, 171101 – Published 28 April 2020

[13] E.Capocasa et al., *Measurement of optical losses in a high-finesse 300 m filter cavity for broadband quantum noise reduction in gravitational-wave detectors*, Phys. Rev. D 98, 022010 – Published 31 July 2018

[14] N.Aritomi et al., *Control of a filter cavity with coherent control sidebands*, Phys. Rev. D 102, 042003

[15] F. Acernese *et al.* (The Virgo Collaboration), *Quantum Backaction on kg-Scale Mirrors: Observation of Radiation Pressure Noise in the Advanced Virgo Detector*, Phys. Rev. Lett. 125, 131101 – Published 22 September 2020

[16] H. Yu *et al.*, *Quantum correlations between light and the kilogram-mass mirrors of LIGO*, Nature 583,43 (2000)

[17] S.S.Y. Chua et al., *Impact of backscattered light in a squeezing-enhanced interferometric gravitational-wave detector,* Classical and Quantum Gravity 31, 035017 (2014).

[18] W. Chaibi *et. al*. *Low frequency gravitational wave detection with ground-based atom interferometer arrays,* Phys. Rev. D 93, 021101(R) (2016)

[19] B. Canuel *et. al., Exploring gravity with the MIGA large scale atom interferometer,* Scientific Reports volume 8, Article number:14064 (2018)

[20] B. Canuel *et.al. ELGAR — a European Laboratory for Gravitation and Atom-interferometric Research,* 2020 Class. Quantum Grav. 37 225017

[21] L. Pezzè *et al., Quantum metrology with nonclassical states of atomic ensembles,* Rev. Mod. Phys. 90, 035005

[22] O. Hosten *et al., Measurement noise 100 times lower than the quantum-projection limit using entangled atoms,* Nature volume 529, pages 505–508 (2016)

[23] F. Haas et al., *Entangled States of More Than 40 Atoms in an Optical Fiber Cavity,* Science 11 2014 Vol. 344, Issue 6180, pp. 180-183

[24] A. Lartaux, *Beating the Standard Quantum Limit for the gravitational wave detector Advanced Virgo*, thèse de l'Université Paris-Saclay, 2020

[25] *The Einstein Telescope design report, 2020 update,* https://apps.et-gw.eu/tds/?content=3&r=17245