Prospective IN2P3
Einstein Telescope

October 21, 2019

Principal author: M. Barsuglia (APC)

Co-authors: the Virgo groups of APC, IPHC, LAL, LAPP, LMA-IP2I
and the gravitation and theory groups of APC

1 Context

The first LIGO and Virgo detections, between 2015 and 2017 (corresponding to the data takings 01 and 02), [1] have shown the scientific potential of the gravitational-wave science. These results have implications in a wide range of fields including astrophysics, fundamental physics, cosmology and nuclear physics:

- GW allowed to perform tests of general relativity in strong field regime and demonstrated the consistency of gravitational wave observations with GR: GW waveforms fit the GR prediction, GW propagate at the speed of light with a precision of 1 in 10^{15} and GW polarizations are compatible with GR [2].

- GW demonstrated the existence of binary black-hole systems and that they can coalesce within the Hubble time. GW observations also allowed to obtain first hints about the properties of this BH population. [3].

- GW demonstrated the existence of a class of stellar mass BHs with masses higher than 20 solar masses, never observed before with standard telescopes and started to determined the properties of this BH population. [4].

- GW detection demonstrated the link between (at least some of) short GRB and the BNS mergers [5].

- GW detection demonstrated the link between the kilonovae and the BNS mergers, and the fact that the BNS mergers are the production site of some heavy chemical elements [6].

- GW allowed to perform a new measurement of $H0$, using GW emitted by compact objects as distance rulers [7].
- GW170817 imposed constraints on the equation of state of the neutron stars and on their radii, thus starting to probe the ultra-dense nuclear matter in a completely new way [8].

Moreover, as shown in the case of GW170817, gravitational-wave alerts were essential to trigger key observations leading to the discovery of a new type of electromagnetic transients [9], thus opening a new era of multi-messenger astronomy.

After the 10(BBH)+1(BNS)= 11 detections obtained in 01 and 02, and after a period of detector upgrades, LIGO and Virgo are currently observing (03 run, from April 2019 to April 2020). GW candidates are currently obtained with an average rate of $\sim$ 1 per week and open alerts are sent to the astronomical community (releasing the position, distance and probability of class of candidate [10]). Since the beginning of the data taking 03, 33 candidates of compact object coalescence have been identified and they are currently being analysed by the LIGO/Virgo Collaboration.

For the next decade, the scientific program of the network LIGO-Virgo foresees two more data taking periods (04 and 05), alternated with periods of detector upgrades (see figure 1, until $\sim$ 2026-2027. During this period, the sensitivity will increase up to a factor $\sim 3-5$ for Virgo and $\sim$ 3 for LIGO. The Japanese detector KAGRA will join the network in 2019 and LIGO India will be operational around 2024 [13].

Concrete plans are not yet settled after 2027. It is however likely that LIGO, Virgo and KAGRA (5 detectors) will operate till the end of the decade.

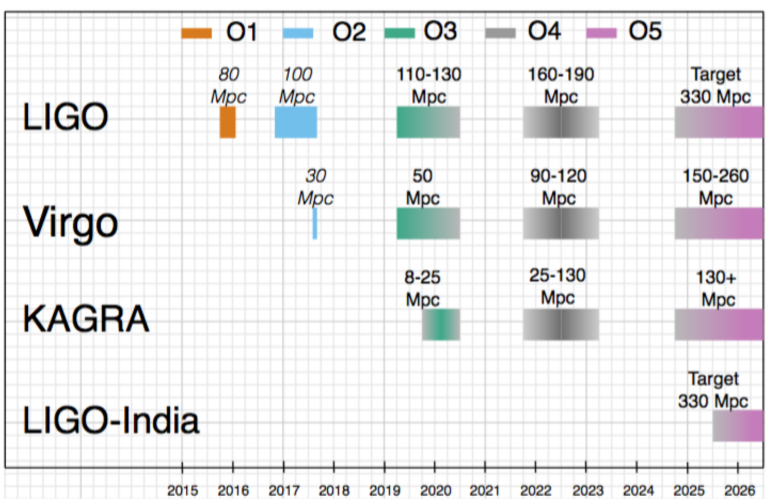

Figure 1: Virgo-LIGO-KAGRA past and future data takings and detector upgrades periods. The numbers indicate the averaged detection ranges for BNS coalescences [13].

2 Overview of Einstein Telescope

Initial Virgo and LIGO are considered the first generation (1G) of GW detectors. Advanced Virgo and Advanced LIGO are 2G detectors. Einstein Telescope will be a 3G detector.

At the end of the 20's current infrastructures won't allow further sensitivity progression and a new generation of Earth-based detectors is thus necessary.

The idea of Einstein Telescope (ET) was developed in the context of the EU programmes FP6 and FP7. In particular, a conceptual design was supported by FP7 with a 3Meuro funding, that led to a conceptual design study (CDR), published in 2011 [11].

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

After the release of the conceptual design report in 2011, ET faced a few years of lower level activity, mainly due to the fact that the GW community was focused on the upgrades and operations of Virgo and LIGO. After the first GW detections, the ET project has re-gained momentum.

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

The Einstein Telescope collaboration has been created in 2019, with 730 persons (68 from France) having signed the ET letter of intent [14]. A ET steering committee has been created, with 17 members, and 3 from France. A possible timeline for the project is the following one:

- 2019-2020: Possible application for the ESFRI roadmap.
- 2022: Site selection
- 2023: Technical design report
- 2025: Beginning of excavation operations
- 2030-2031: End of the infrastructure works. Beginning of the detector installation
- 2032+: Installation, commissioning and operation

Another 3G detector, called Cosmic Explorer, has been proposed by US and it is led by researcher of LIGO group at MIT [15]. Two detectors or more will help to get a accurate sky localization of the source, although some localization is possible with a single detector, thanks to Doppler effect on the signal due to the Earth rotation. Note that some of the advanced 2G detector that may still be in operation post 2030 may also help with the closest sources. A global coordination of US and EU detectors design and efforts is is important and currently performed by the GWIC (gravitational-wave international committee) and, in particular, by the 3G-GWIC subcommittee [16].

3 Science with ET

See also specific contributions about the science with ET

Thanks to a tenfold increase in sensitivity with respect to 2G detectors and the enlargement of the bandwidth down to a few Hz, Einstein telescope will increase the scientific reach of the present instrument three different ways: in-depth and complete survey of the source populations observed by the 2G detectors, namely larger number of sources, detected with larger signal-to-noise ratios. There is also the possibility to detect new classes of sources, that are out-of-reach to the current detector generation.

A striking example of the potential of ET is given by the expected number and distances for BBH and BNS coalescences.

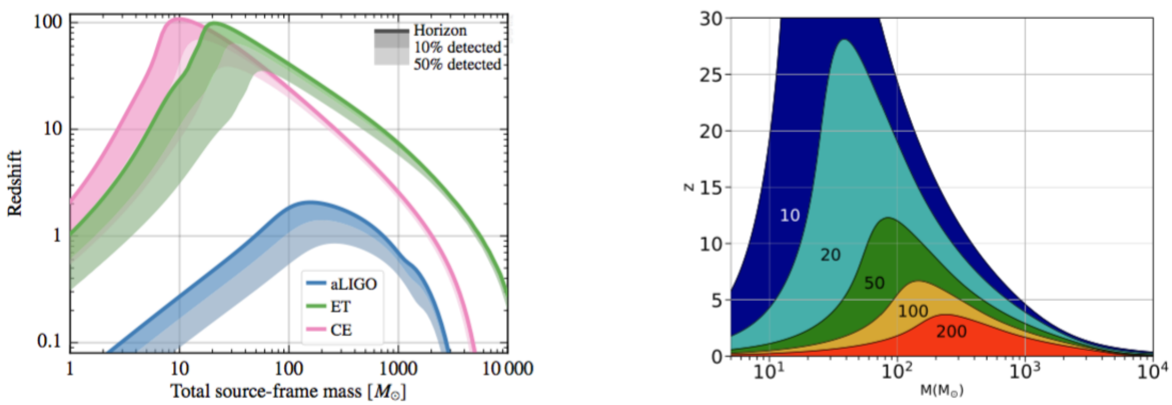

Figure 2: Left: observable distance for non spinning compact object for 2nd generation detectors and 3rd generation detectors (Einstein Telescope and Cosmic Explorer, versus the total mass of the system. Right: zones of constant signal-to-noise ratio versus total mass of the system and observable distance [17]

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

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

In terms of number of detected events, as already mentioned, today Virgo and LIGO are detecting $\sim$1 candidate per week in average. Einstein Telescope will detect 1 BBH every $\sim$30 seconds and 1 BNS every $\sim$5 minutes. This represent a wealth of data to study the distribution and formation scenarios of these sources and also used them as cosmological probes.

Moreover, the BBH mergers detected today would observed with SNR of a few hundreds (see fig 2 right), thus allowing the access to fine details (higher-order modes) in the GW waveform leading exquisite tests of GR.

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

In the following we develop 4 examples of physics that ET can address.

3.1 Tests of gravitation and the nature of black-holes

Virgo and LIGO observations allows test of gravity in strong field regime, never explored so far (see fig.3). The properties of GW correspond so far to the ones predicted by GR (speed, polarization, waveform)[2]. With the increase of the number of events and SNR, Einstein Telescope can highly increase the precision of these tests. Figure 3 shows the region where gravity can be tested by ground-based GW detectors and other current and planned experiments (in terms of gravitational potential on the x axis and curvature on the y axis) compared by other experiments. For binary sources, the gravitation potential is related to v^2/c^2 (the speed of the source compared with the speed of light).

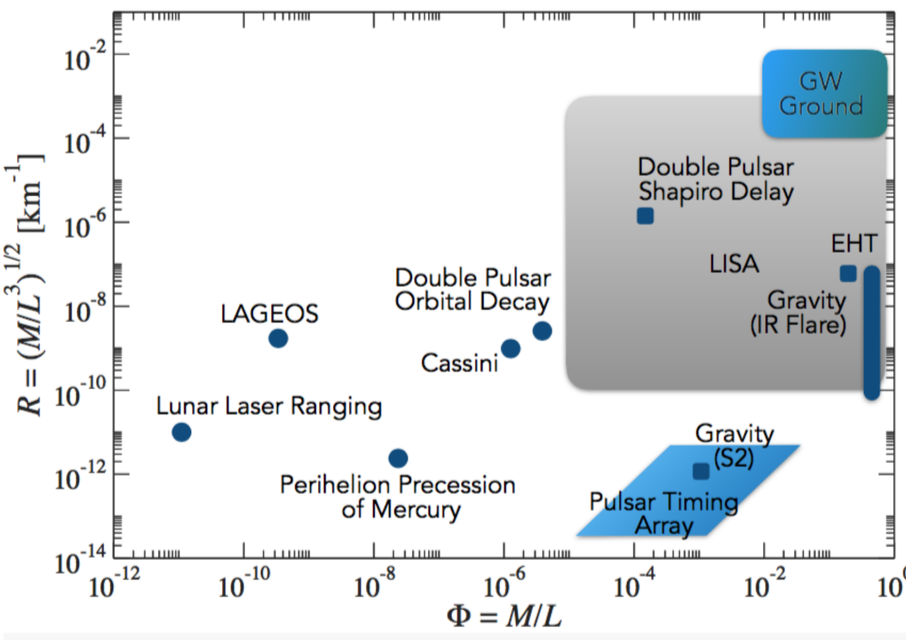

Figure 3: Tesf of GR by past, present and future experiments, as a function of the gravitional potential (x axis) and curvature (y axis). For coalescing binaries, the gravitational potential is related to the quantity v^2/c^2 [17]

ET can probe the true GR nature of black-holes. In GR black holes satisfy the no-hair theorem (the BH is only characterized by its mass and spin). After a merger, the newly formed BH continues to radiate GW through quasi-normal modes till it reaches stationary equilibrium (Kerr metric). The frequencies and damping factors of the quasi-normal modes depend only by the mass and spin of the BH. Measuring 2 normal-mode frequencies and one damping factor, it's then possible to test the no-hair theorem. The figure 4 shows the progression that can be achieve with ET compared to the current situation.

Moreover, ET can search for deviation from GR in the merger or post-merger signals, testing the presence of a "black-hole mimicker" (boson star, gravastar and others), and also searching

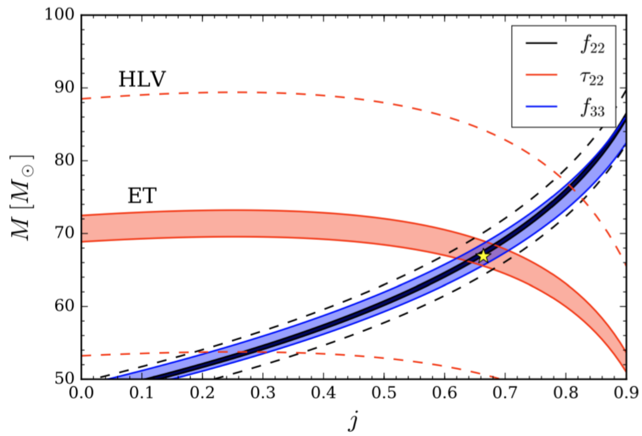

Figure 4: Test of the no-hair theorem by LIGO-Virgo (dashed lines) and by Einstein Telescope (solid lines). The star indicates the real mass and spin of the remnant black-hole after a coalescence. The lines indicates the measurements of mass and spin obtained with the quasi-normal modes. LIGo-Virgo (dashed lines) and Einstein Telescope (solid lines) [17].

for echoes, after the merger, sign of quantum gravity effects.

3.2 Cosmology, the nature of dark energy and alternative theories of gravity

The detection of GW170817 represented the first attempt to perform a new type of cosmology using gravitational-waves produced during coalescences of compact objects.

GR predicts the full GW waveform emitted during a binary merger. The GW amplitude scales inversely with the luminosity distance. By comparing the data with the theoretical model it is possible to measure the latter parameter, with no cosmic ladder. The measurement of the luminosity distance can be combined with the one of the redshift (if the host galaxy is identified, as for GW170817), to extract the cosmological parameters.

Alternatively, when there are no electromagnetic counterpart, it is possible to do the same measurement through a statistical method using galaxy catalogs. Cosmological parameters e.g., H0 can be computed for all possible host galaxies in the sky region identified by GW observations, thus leading to a distribution rather than the exact value. By repeating this measurement for a large number of sources, it is possible to reduce the statistical uncertainty and infer the value of the cosmological parameters[18].

Virgo and LIGO will probe redshifts up to 0.2 for BNS and BBH to z$\sim$ 1. As a consequence, Virgo and LIGO will mainly be able to measure $H0$. These measurements will be very interesting to better understand the current tension between the local universe measurement (supernovea) and the CMB measurements (early Universe), and in particular if this tension is the signature of a new physics. ET will start probing higher redshifts and then the dark energy sector. In particular ET can constraints the dark energy equation of state in a completely different way and can improve the future limits given by SN1A, CMB and BAO (see fig.5).

Moreover, ET can test alternative theories of gravity motivated by the dark energy. Some of those theories have already been excluded by the measurement of the GW speed (at 10^{15} precision level) obtained with GW170817. Theories assuming a speed of GW equal of speed

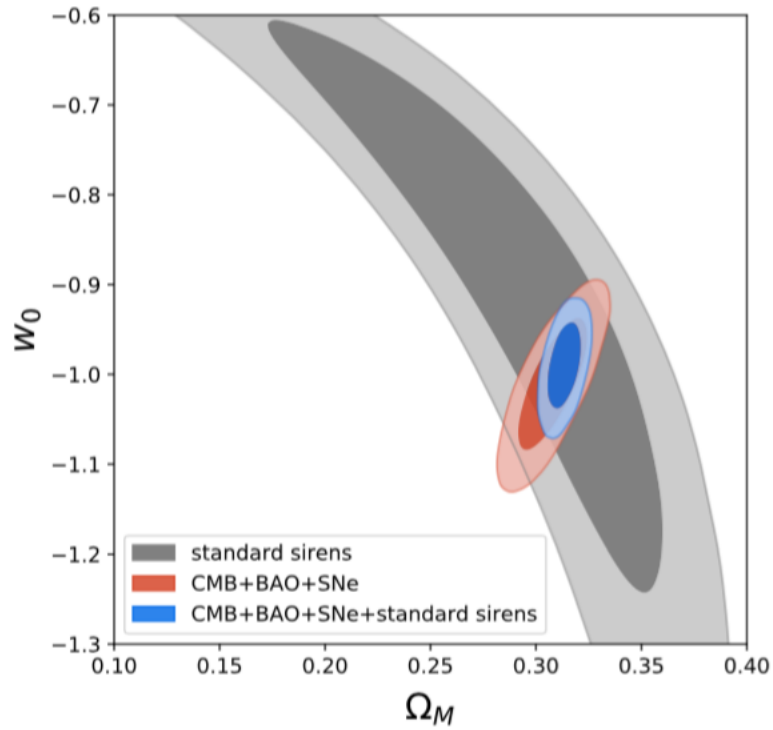

Figure 5: Probing the dark sector with standard sirens (a 3G detector as ET) and other cosmlological probes. Constraints in the plane $omega_M$ W_0, [17]

of light exist, but where the luminosity distance of GW is different from the electromagnetic luminosity distance [17].

Moreover, ET can also test the primordial Universe, searching for gravitational-waves generated by inflation, phase transitions and cosmic strings.

3.3 Supernovae physics: GW and neutrinos

According to most of the models, core collapse supernovae emit a very small amount of energy in gravitational-waves ($\sim 10^{-9}$ solar masses), since the collapse is expected highly symmetric. These events are not detectable with Virgo and LIGO, but a galactic supernova is in the reach of ET. Even if rare (1/30 years) a single event can shed light on the physics of the collapse (not yet understood). Even if the shape of these signals are not known, a GW coming from a supernova will be quasi-coincident with the neutrinos and this will allow to ease its detection and open interesting possibilities in multi-messenger studies of these sources.

3.4 GW and nuclear physics: the nature of matter at highest densities

During a BNS merger, GW waveform contains the imprint of the NS deformations due to tidal forces. This imprint gives access to the neutron star tidal deformability and details of their interior. Using GW170817, constraints on the equation of state of the nuclear matter have been put and some of the soft equations of state were discarded. This demonstrates that BNS mergers are laboratories for the study of matter at the extreme densities, a study that is not possible on Earth. 3G detectors such as ET can improve the current measurement of NS deformability by an order of magnitude, allowing to pinpoint the properties of NS nuclear matter.

Figure 6 shows the capability to determine the mass and radius of 8 NS stars (using 4 BNS). The circle represent the inferred parameters and the crosses the simulated ones.

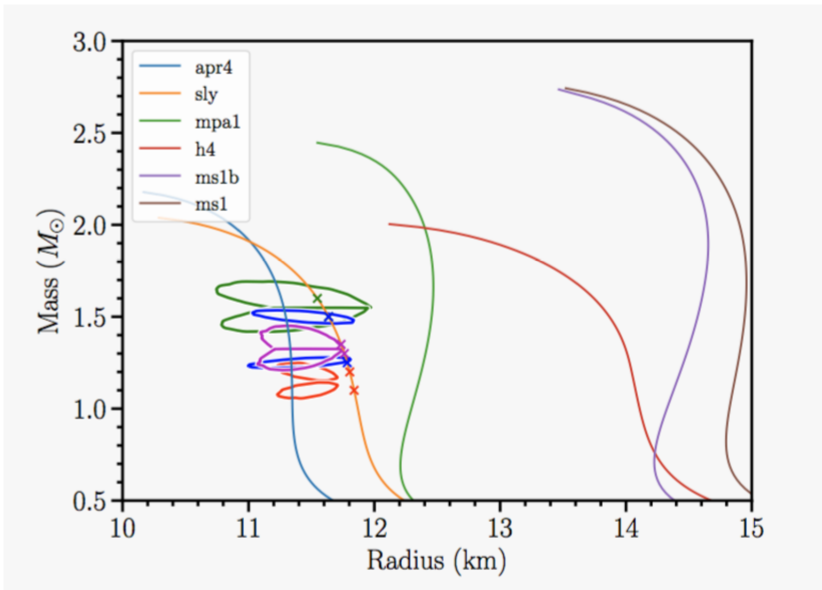

Figure 6: Determination of radius and mass of a NS with a 3G detector

These are only a few examples of the richness of the physics addressed by ET. Of course, ET, combined with cosmic explorer, will continue to be able to send alerts to the electromagnetic observatoires, allowing to address physics of compact objects, GRB physics and the study of the kilonovae.

4 Instrument design and technology

See also specific contributions about technological developments for ET

ET will be mainly based on technologies developed and demonstrated in the framework of Virgo and LIGO: a modified Michelson interferometer (Fabry-Perot dual recycled Michelson interferometer: Fabry-Perot Cavities in the arms, power recycling and signal recycling), use of frequency dependent squeezing (as planned for Advanced Virgo+ and Advanced LIGO+), complex seismic isolation systems (a combination of passive isolation based on chain of pendula and an active isolation). A key technology not yet present in Virgo and LIGO is cryogenics, which will be tested in the japanese projet KAGRA.

As already mentioned, according to the conceptual design documents, Key ET design concepts are:

- *Underground operation.* In order reduce the impact of seismic noise and gravity gradient noise induced by seismic waves and motion of air, ET will be underground. The underground operation will allow to extend the frequency band of the detector down to a few Hz. Underground operation requires a careful studies of (large) tunnels and caverns.

- *10 km.* ET arms will be 10 km long, in order to increase the signal produced by the GW and reduce then the impact of most of the noises. The gain will be at least 3 with respect to Virgo (3 km long) or more for some of the noises.

- *Triangle.* ET will be composed by 3 different Michelson interferometer in a triangle configuration, on the same (10 km) tunnels (see fig.[**?**]). This configuration will allow to resolve alone the GW polarisations.

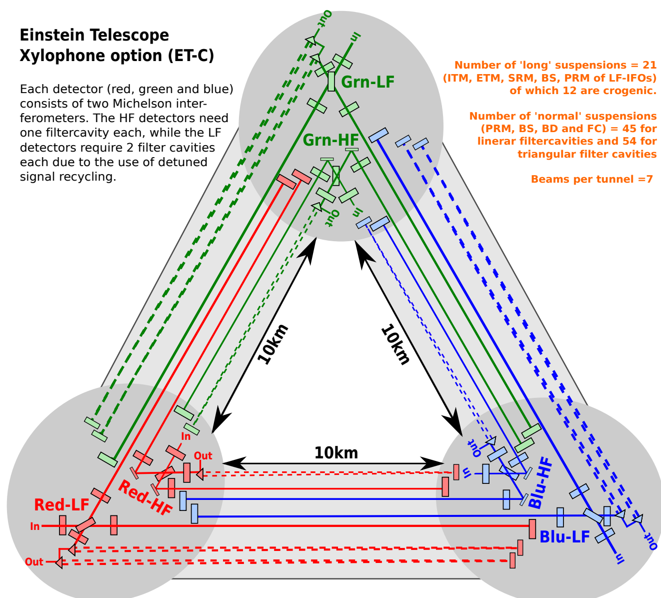

Figure 7: Scheme of the ET detector (arms are not in scale) [11].

- *Xylophone.* ET will be composed by two different detectors, the first with an high sensitivity at low frequencies and the second with high sensitivity at high frequency. The reason is to overcome problems related to the use of cryogenic techniques (needed to reduce the Brownian thermal noise of suspensions and mirrors), together with high power stored in the arms (needed to reduce the photon shot noise). The cryogenic and low power (cold) detector will work at low frequency and the high-power (hot) detector will work at high power.

If ET is based on technologies already used in Virgo and LIGO, a research and development program is needed to reach the level of maturity needed for ET. We give a non exhaustive list of these technologies:

- Cryogenics: a cold detector ($\sim$ 4 K, in the ET Conceptual Design Document) is needed to reduce the Brownian noise of mirrors and suspensions. Development of low noise cryocoolings are necessary to ET. Even if the experience gained with the KAGRA japanese detector will be crucial for ET, an in-house experience on how to operate a cryogenic detector is necessary.

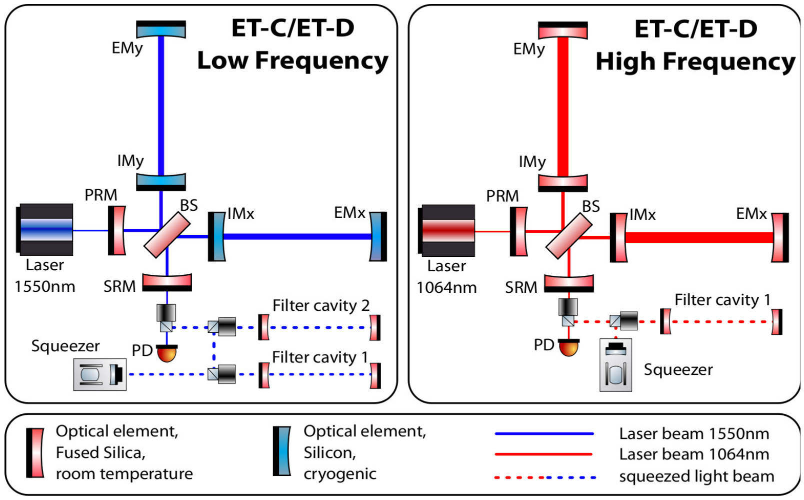

Figure 8: Main features of the cold and hot ET detectors [11].

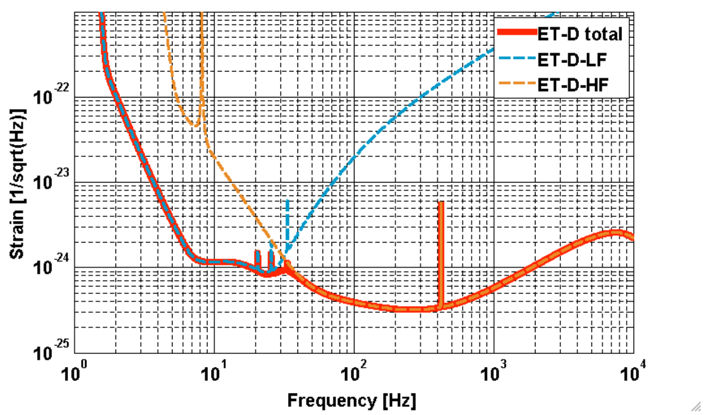

Figure 9: Sensitivities of the hot and cold ET detectors combined in the xylophone configuration [11].

- New material for test masses: cryogenics temperatures require to replace the fused silica test masses with new materials as silicon or sapphire.
- Large test masses: the reduction of Brownian thermal noise and radiation pressure (back-action) noise require the development of larger test masses with very high mechanical and optical properties. Larger test masses require the development of technologies for their production, polishing and coating.
- New coatings: coating thermal noise is currently the major limitation of the detector sensitivity in the 100 Hz region. New coating with better mechanical properties are necessary for ET.
- New laser wavelengths: The use of silicon require new laser wavelength transparent for this material.

- Seismic suspensions: better seismic isolators are required to enlarge the ET bandwidth down to a few Hz (compared to 10 Hz of Virgo).
- Frequency dependent squeezing: losses are the main enemy of squeezing. Low losses optical components are necessary to increase the squeezing levels.
- High power lasers: kW power lasers are required to reduce the quantum noise at high frequencies. Combined with frequency dependent squeezing techniques, high power will decrease the quantum noise over the complete ET bandwidth.
- Thermal compensation techniques: In ET powers of the order of MW will circulate in the arms. Even with a very low absorption components, the power absorbed will deform the wavefront. Advanced thermal compensation techniques, based on CO2 lasers and heaters elements will be necessary to maintain high quality beam profile inside the interferometer.
- Accurate calibration: with some signals having an SNR larger than one thousand, new calibration techniques will have to be developed to match the ET needs.

5 IN2P3 and CNRS role

Given its science potential, Einstein Telescope fits perfectly the IN2P3 missions. It also allows to develop unique synergies with other experiments in cosmology, nuclear physics, neutrino physics and astroparticle physics in general.

France is a founding and a leading country in Virgo and in the field of gravitational-waves. France is co-financing (with Italy) since more than 20 years EGO (European Gravitational Observatory, the French-Italian consortium responsible for the operation of the Virgo instrument). Einstein Telescope is a natural continuation of the Virgo experience, of the investments in EGO and of the leading role of CNRS in this endeavor.

IN2P3 grousp (APC, LAL, LAPP, LMA-IP2I Lyon and the newly formed group at IPHC) have contributed to Virgo in several ways:

- To the Virgo design and construction, especially in the fields of laser interferometry, suspended optical benches, auxiliary optics and telescopes, mirror coating and metrology, analog and digital electronics, data-acquisition, squeezing vacuum states, vacuum and pumping systems, mitigation of scattered light, calibration systems. IN2P3 is currently strongly involved in the next Virgo upgrade (Advanced Virgo+).
- To the commissioning and operation of Virgo the detector: controls, noise hunting, calibration.
- To the analysis of the Virgo/LIGO data, to the development and operation of new analysis algorithm and data processing techniques, data quality techniques, data handling, open data infrastructures. Moreover IN2P3 groups have contributed (and are contributing) to the scientific exploitation of the Virgo/LIGO data.

This experience represent a major resource for Einstein Telescope. Of course others IN2P3 groups not currently participating to Virgo, could greatly contribute to ET, in field of expertise of the Virgo groups, but also with new competences, as cryogenics, underground operations and others.

At the CNRS level, other institutes and laboratories are also currently involved in Virgo. The Artemis laboratory played a key contribution in Virgo, with the development of high-power stabilized lasers, optical metrology and interferometric techniques. This experience will be also crucial for ET. The LKB laboratory is also part of the Virgo Collaboration, contributing to the development of squeezing techniques.

ET needs a broader community to be developed and operated, going beyond the Virgo community. CNRS groups can contribute with an important role in ET in the fields of gravitational-wave waveforms, exploitation of the scientific data in the field of cosmology, nuclear physics, tests of gravity and astrophysics. Discussions about the role of CNRS are ongoing in the GdR ondes gravitationnelles and through a newly created mailing list "ET-France". This list will be used to share information and to coordinate national actions and relationships with other European partners. The creation of a ET-France collaboration is on going.

6 Concluding remarks

Virgo and LIGO have demonstrated the scientific potential of gravitational-waves. The current scientific program of Virgo/LIGO/KAGRA foresees data takings and upgrades up to 2026-2027, and probably up to the end of the decade 2020. After that period, a new detector, hosted in a new infrastructure, is necessary. Virgo and LIGO took $\sim$15 years to be built and put in operation. If we want to operate ET at the horizon 2035, the project should start now.

Einstein Telescope has the potential to address some of the most important scientific questions in modern physics (tests of gravitation), cosmology (about nature of dark energy and dark matter), nuclear physics (nature of ultra-dense matter), astrophysics (supernovae and gamma-ray bursts) and many others. The science accessible to ET is unique and complementary to LISA.

IN2P3 and CNRS can continue to play a crucial role in the gravitational-wave science with Einstein Telescope thanks to the experience accumulated and investments made in the last 30 years.

References

[1] EGWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs, B.P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), Phys. Rev. X 9, 031040 – Published 4 September 2019

[2] Tests of General Relativity with the Binary Black Hole Signals from the LIGO-Virgo Catalog GWTC-1, B.P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), arXiv:1903.04467

[3] Observation of Gravitational Waves from a Binary Black Hole Merger, B.P. Abbott et al., Phys. Rev. Lett., Vol. 116, 061102, 2016.

[4] Binary Black Hole Population Properties Inferred from the First and Second Observing Runs of Advanced LIGO and Advanced Virgo, B.P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), arXiv:1811.12940

[5] Gravitational Waves and Gamma-Rays from a Binary Neutron Star Merger: GW170817 and GRB170817A, B.P.Abbott, Astrophys. J. Lett. 848, L13 (2017)

[6] Estimating the Contribution of Dynamical Ejecta in the Kilonova Associated with GW170817, B.P. Abbott et al, ApJL 850:L39 (2017)

[7] A gravitational-wave standard siren measurement of the Hubble constant, B.P. Abbott et al, Nature 551, 85–88 (2017)

[8] Properties of the Binary Neutron Star Merger GW170817, B.P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), Phys. Rev. X 9, 011001 (2019)

[9] Multi-Messenger Observations of a Binary Neutron Star Merger, B.P.Abbott et al., Astrophys. J. Lett. 848, L12 (2017)

[10] https://gracedb.ligo.org

[11] Einstein Telescope conceptual design document. http://www.et-gw.eu/index.php/etdsdocument

[12] Einstein Telescope science case (under release)

[13] Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO, Advanced Virgo and KAGRA, The LIGO Scientific Collaboration, the Virgo Collaboration and the KAGRA Collaboration, arXiv:1304.0670

[14] http://www.et-gw.eu/index.php/letter-of-intent

[15] https://cosmicexplorer.org

[16] hhttps://gwic.ligo.org/3Gsubcomm/

[17] GWIC 3G subcommittee science case. https://gwic.ligo.org/3Gsubcomm/subcomm-science-case.shtml

[18] A Standard Siren Measurement of the Hubble Constant from GW170817 without the Electromagnetic Counterpart, authours from the Virgo and LIGO Collaborations, The Astrophysical Journal Letters, 871:L13