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Gravitational waves: Perspectives of detection

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Summary. — With Giovanni Losurdo, the PI of Advanced Virgo, we recently dwelled on this subject in an invited review paper [1]. Here I first give a short introduction by answering in brief to a few basic and relevant questions, which I was often asked by colleagues not specifically working on gravitation. Then I highlight the main considerations discussed in [1], in a sort of guide for the reader, where more details and an extensive reference list can be found. For more complete info, I call the attention to a number of beautiful pictures, kindly provided by my colleagues, which I put on the IFAE website, but are not given here nor in [1]. After publication of [1], a few relevant developments occurred, especially in the long-term planning of experiments, on which I report here. To update the references would have resulted in adding some sort of ten percent more than those in [1], so I have added only a few, which I rate most recent and particularly relevant to the relative issue.

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1. – Questions and answers (Q&A)

–What are gravitational waves (GW)?
GW are vibrations *of* space-time. By contrast electromagnetic waves are vibrations of the EM field propagating *in* space-time.

–Can we detect them? (If space shrinks/stretches under the gravitational wave and the light does the same, maybe the effects compensate and nothing can be detected...)
Yes, we can. Nowadays the leading method consists in measuring phase shifts of light in Michelson-like interferometers. A formal answer is the following. In the weak field approximation of the Einstein equations, the Riemann tensor is gauge invariant and gives directly the second derivative of the phase shift, which is the invariant measurable

quantity. One calculates the GW-induced phase shifts in a convenient gauge, finds it non-zero and that is it. The experimentalist answer requires some more explanation. She/he may like to use the Fermi gauge. In such a "laboratory" gauge three gyroscopes sit in free fall at the origin, and give the three directions of the Cartesian coordinates. The Michelson interferometer has the arms on two of the axes and the beam splitter is at the origin. In the approximation —appropriate for both ground- and space-based detectors— in which the GW wavelength is much larger than the arm length, in turn much larger than the wavelength of the laser light, the picture is simple. The coordinate distance of the end mirror in each arm stretches and shrinks —in counter phase to the other arm— but light is not affected at lowest order. So the travel time of light and the corresponding phase shifts give a measure of the GW amplitude. Does such a "coordinate" description give the actual gauge-invariant physics? Yes, in fact the *coordinate* arm length approximates well the *proper* length and this oscillates as the Riemann GW tensor induces a "geodetic deviation" of the end mirror with respect to the front mirror. And, to double-check, one can use the so-called Transverse Traceless (TT) gauge, within which the approximation of "short" arms is not even needed, to get the same phase shift when recombining the light beams from the arms. Notice how the TT description is different: in TT the mirror coordinates do not change, while it is rather the light, which gets an oscillating GW-dependent effective "refractive index". Of course if one uses both the coordinate descriptions at the same time then one gets the (wrong) intuition given in the question above. Beyond the above, for a most illuminating, gauge-independent discussion of GW detection, see ref. [2].

–Did we have already detection?

Yes (somebody may say indirectly): Neutron stars (NS) in binary systems spiralize one onto the other, because of the energy loss due to the emission of gravitational waves. In some NS-NS binaries, one or even both are pulsars delivering their regular ticking to us. Thus the dynamics of the system can be recorded, with secular augmentation of the precision of the measured orbital features. The pulsar PSR $1913+16$ has been observed since 1974, and it gives unequivocally that it is part of a binary system of almost equal-mass neutron stars, which is losing energy and angular momentum due to GW emission. The GW emission is just that predicted by the classic 1916 Einstein quadrupole formula —R. A. Hulse and J. H. Taylor, Nobel Prize in Physics 1993.

–Should we wait for ground- and/or space-based detectors to be sure GW exist?

No, see previous Q&A.

–Should we wait for ground-based detectors to detect first, before deciding to launch a space mission like LISA? Would LISA be unnecessary, if a GW astronomy were in place with ground-based detectors?

No: The two kinds of instruments are totally complementary in the frequency band covered and therefore the physics to be discovered is much different (see below). It would be like stating that we do not need to detect and study the Universe in microwaves and far infrared, because we have already the astronomy in the visible! And in fact the decision for a LISA-like mission has been at last taken: "The Gravitational Universe has been selected, when on 28 November 2013 ESA decided on the next large missions in the time frame 2028–2034". In addition, as the PI Stefano Vitale has recently informed, the LISA Pathfinder, the precursor mission to demonstrate the LISA technology, will be definitively launched in September 2015.

–Why is it so difficult to detect GW?

A simple dimensional calculation gives the idea (see ref. [1]). The initial detectors, based on massive mechanical resonator —the "Weber bars"— targeted Supernovae as detectable sources, but, by the time the most sensitive cryogenic bars achieved the design performance, it became clear from theoretical astrophysics and numerical relativity that the SN signal would have been much weaker and rarer than predicted at the time the construction of cryogenic bar was decided. Thus the community switched to km-base laser interferometers and now the target source is the coalescence of a neutron star - neutron star binary system. After the Hulse & Taylor discovery, rates and amplitudes of putative signals are more confidently predicted and should be in reach of the "advanced" instruments now ready to start operation. For instance, a typical GW amplitude given by a NS-NS merger at 100 Mpc —a distance from which it is reasonable to expect a few events/y— would be of the order of $h \sim 10^{-22}$. The GW amplitude h is $h \sim \Delta L/L$, the differential shrinking/stretching of the arms of a Michelson interferometer. For Virgo with $L = 3\,\mathrm{km}$, this means $\Delta L \sim 3 \cdot 10^{-19}\,\mathrm{m}$. This is much less than the proton diameter, but no problem: this is the average position of a mirror of some 10 kg and of course corresponds to an average of the collective motion of a lot of atoms on the surface of the mirror. On the other hand, this is close to the quantum limit dictated by the Heisenberg principle in localizing an object of that mass.

–Why have GWs not yet been detected with the LIGO/VIRGO/GEO/TAMA "initial" instruments?

They stayed in observation at design sensitivity over $O(1\,\mathrm{y})$ times and gave only (astrophysical relevant) upper limits. The point is that the expected rate of NS-NS coalescences is about 10^{-4}/y for galaxies like ours, and the reach out for the NS-NS signals of the most sensitive interferometers —LIGO and Virgo— was only about to 100 galaxies. The Advanced LIGO/Virgo [3] and the cryogenic KAGRA [3] will reach out to the Local Supercluster of galaxies and thus the predicted rates go up to 10/y and possibly even more, if also (stellar) black hole-black hole and neutron star-black hole binaries will show up.

2. – Detectors in operation, under upgrade or approved for construction

In fact the detection scheme is just only one: measure the differential relative acceleration of test masses in free fall, using light to connect them [2].

On ground we have now the second —dubbed "advanced"— generation of km base Michelson interferometers, which will start operating by 2015–2016, to reach design performance before 2020: in the U.S. the Advanced LIGO [3] "observatory" —two instruments of 4 km arms, one at Livingstone, Louisiana and the other at Hanford, Washington State— in Italy Advanced Virgo [3], 3 km arms at Cascina (a French-Italian collaboration). The cryogenic mirror interferometer KAGRA [3], under the Kamioka mountain in Japan, has 3 km arms, and will start operation by $\sim$ 2017. An agreement is well in progress to install in India the 2 km arms interferometer originally together in the same vacuum with the LIGO Hanford 4 km —the INDIGO project.

As for now the 600 m arms GEO [3] in Hannover, an English-German collaboration, is in "astrowatch" for about 70% of the time, just in case a rare event, like a SN, would come in before the Advanced LIGO/Virgo go on the air. For the same purpose, the Italian cryogenic bars AURIGA at Legnaro and NAUTILUS at Frascati are on the air at 95% duty cycle in the AUNA coordination. By the end of 2015, as the Advanced detectors will start operation, AURIGA and NAUTILUS will be phased out, while GEO will stay on for the R&D towards a third generation on the horizon 2030 - ET, the Einstein Telescope, the feasibility and design of which is under study with EU funding: `http://www.et-gw.eu/`.

The four 3–4 km ifos will be in a network, operating in the band 10 Hz–10 kHz. They will reach out to 200 Mpc for NS-NS binaries and to 500 Mpc for (stellar mass) BH-BH binaries. In this respect the collaboration that LIGO/Virgo started with the IPN for "multimessenger" searches, to associate GRBs to GW is very relevant. (The Interplanetary Network, IPN, is a group of spacecraft used to localize Gamma Ray Bursts (GRBs) and soft gamma repeaters (SGRs, or magnetars). Nine spacecrafts contribute data: Wind, Mars Odyssey, MESSENGER, INTEGRAL, RHESSI, Swift, Suzaku, AGILE and Fermi). In the same spirit Virgo has recently launched a call for the follow-up of GW events. Already some 60 MOUs have been signed, involving 19 countries and 150 telescopes, which cover the EM spectrum from radio waves to hard gamma rays. The Italian INAF is actively participating with its observatories.

The ground-based interferometers, in relation to the sources they target, are "noise-dominated" instruments. Still notice that they are close to the "standard quantum limit" in measuring the differential displacement between the mirrors. So it is crucial to have on one side a quite accurate modelling of the expected signals and on the other side frontier methods of analysis to extract them out of the noise. Both these lines of research have enjoyed recently an enormous progress thanks to the development of supercomputers. The study of "templates" for the GW signals from processes in strong gravitational field had in recent years a breakthrough, after the failure in the last century of the so-called Grand Challenge collaboration failed. Now numerical relativity methods, aided by supercomputing, can solve the Einstein equations in the extremely strong field regime, to give the full dynamics and the GW energetic even of the coalescence of black holes.

In space we shall have eLISA flying by 2028 `https://www.elisascience.org/`. Three test masses, housed in "drag free" satellites 1 million km apart, will orbit the Sun, trailing the Earth. Laser light will link them to measure their relative velocities by Doppler shifts. Their residual spectral noise in relative acceleration will be below some $5 \cdot 10^{-14}$ m s^{-2} Hz$^{-1/2}$ in a band between 10^{-4} Hz and 1 Hz. The detector will be "signal dominated" and will have an "absolute" calibration, using astronomically well understood binary systems of white dwarfs, which will give calculated GW signals at levels SNR > 100. Actually it will be a full observatory, because, as it orbits around the Sun, it works as an aperture synthesis telescope. The main sources targeted are the coalescences of supermassive black holes —10^4 to 10^8 solar masses— when the galaxies, which have them at their center, make a dramatic encounter. This process will be seen at distances up to redshifts $z \sim 10$ (the farthest galaxy seen by Hubble in 2013 is at $z = 7.51$). Another process most relevant to fundamental physics is the fall of a stellar black hole in the supermassive black hole at the center of its galaxy. The GW signal will give a map of the horizon, the no-return surface limiting the black hole (see [1] for details of the eLISA science). The eLISA mission will be ESA led. Substantial collaboration with NASA is expected.

Pulsars are mechanical clocks of extreme stability. The study of the Time Of Arrival, TOA, of the radio pulses of a number of them isotropically distributed around us will allow the detection of GW at frequencies in the range 10^{-9}–10^{-7} Hz. Such GW are expected from primordial processes and from the coalescence of black holes even more massive —10^8 to 10^{10} solar masses— than those in reach of eLISA. The method consists in extracting the quadrupolar component of the relative variations of the TOAs among some 30 pulsars. Such a component is characteristic of GW and so can be disentangled from the TOA noises of each pulsar, which are uncorrelated, and from monopolar and dipolar correlations, coming from the uncertainty in the ephemeris in the solar system and the variations in the Earth time. The method is being developed fast, and is expected to produce detections in a few years.

All the projects for GW detection, which are being or have been approved for realization, are spontaneously coordinated in the Gravitational Wave International Committee (GWIC), current Chair Eugenio Coccia, `https://gwic.ligo.org/`. GWIC was formed in 1997 to facilitate international collaboration and cooperation in the construction, operation and use of the major gravitational-wave detection facilities worldwide. It is associated with the IUPAP as its Working Group WG11. Through this association, GWIC is connected with the International Society on General Relativity and Gravitation (IUPAP's Affiliated Commission AC.2), its Commission C19 (Astrophysics), and another Working Group, the AstroParticle Physics International Committee (APPIC). GWIC promotes international cooperation in all phases of construction and scientific exploitation of gravitational-wave detectors, coordinates and supports long-range planning for new instrument proposals, or proposals for instrument upgrades, promotes the development of gravitational-wave detection as an astronomical tool, exploiting especially the potential for multi-messenger astrophysics, organizes regular, world-inclusive meetings and workshops (note: the leading ones are the two series "AMALDI Conference" and "LISA Symposium", both biennial and alternating) for the study of problems related to the development and exploitation of new or enhanced gravitational-wave detectors, and foster research and development of new technology, represents the gravitational-wave detection community internationally, acting as its advocate, provides a forum for project leaders to regularly meet, discuss, and jointly plan the operations and direction of their detectors and experimental gravitational-wave physics generally.

3. – The physics

The menu is quite rich. To mention the most relevant searches: i) astronomy of white dwarfs, which are progenitors of SNIa and thus are of interest for stellar and galactic evolution and for the nature of GRB; ii) physics of matter in extreme conditions, in particular Equation Of State of nuclear matter, collapses and thermoinstabilities, and neutrino transport in SN explosions; iii) EOS of neutron star from the coalescence and merging of NS-NS and NS-BH binaries and from the setting down of newborn NS after SN events; iv) the astroseismology of "starquakes" in magnetars-NS with extreme magnetic fields; v) quarkstars —if they exist; vi) all the processes involving black holes (BH), *i.e.* coalescences, merging and ringdown in the final evolution of binary systems either of BH of stellar size, about 10 solar masses, and supermassive BH in the center of galaxies, from 10^4 to 10^{10} solar masses, and the fall of stellar BH into the supermassive BH in their galaxy center; last but not least vii) the search for a stochastic background of primordial GW.

As one can see, the expectations are for relevant contributions, not otherwise obtainable, in a number of physics sectors. Of particular interest to INFN are points ii) to v), as they touch upon frontier nuclear [4] and subnuclear physics. Also of interest for INFN is point vi), which touches on fundamental physics, in regard to gravity: direct tests of the predictions about black holes given by General Relativity, from the no-hair theorem to the area theorem, with its thermodynamic implications, and of the Kerr metric for spinning BH; then limits or detections of primordial GW may carry signatures of inflation, cosmic strings, and even pre Big Bang processes. In ref. [1] a more extensive discussion is given in relation to all classes of detectors.

Finally let me consider a matter I am particularly interested in, and that I find very well focused in the most recent ref. [5]. General Relativity, GR, has passed with flying colors all *local* tests, that is those in the Solar System and, via the observations on pulsars in NS binaries, farther in the Galaxy to some 10 kpc. Observations of strong gravitational lensing of quasars light by intervening galaxies and galaxy clusters give somewhat weaker test of GR farther away in the cosmos. But to use weak lensing to map the distribution of dark matter and even more to construct the standard cosmological model from the current "precision" cosmological observations, one need to *assume* GR to be accurately valid at scales, where we do not have any independent test of its validity. In principle there are still opportunities for theories alternative to GR, in some of which dark matter and/or dark energy are just absent. In fact the argument was turned around at the Warsaw General Relativity GR20 Conference in July 2013: the statement was that the success of current cosmology, the so-called standard ΛCDM model, *proves* that GR is good at cosmological scales at least back to red-shifts $z \sim 10^5$. Now the finding of ΛCDM that the curvature radius of the Universe is much larger than the Hubble radius is taken as a direct evidence for the inflationary paradigm, and one would like to have this feature model-independent. In ref. [5] a new approach on the data from precision cosmology has been used, which "... provides a new type of constraints on the curvature of space without assuming GR ...". The obtained constraints are quite close to those given by Planck. Also it has been "... found that GR is entirely consistent with existing data ... ". But this is achieved at the price of assuming that the dark energy EOS has $w = -1$, that is dark energy is vacuum energy/cosmological constant. With other w values, opportunities considerably reopen for theories alternative to standard GR.

With GW a crucial contribution can be given to this issue. The observation for a long time of the inspiral of a BH-BH binary, either stellar or supermassive —the behavior is mass invariant— gives a unique method to measure the luminosity distance of the system. The GW signal is a "chirp", an oscillation steadily and slowly increasing in frequency and amplitude. First the analysis of such a signal will provide accurate tests of GR. Then at any time one can measure both the period and the time derivative of the period, and use these data to eliminate the unknown mass of the system in favor of the luminosity distance. As the red-shift is needed to get proper distance from the luminosity distance, one needs to associate the event with the galaxy where it occurred—methods to achieve that are developing fast. Then one can construct the Hubble diagram in an absolute way, *without* recourse to the ladder of different standard rulers used currently, and in the context of a GR fully tested at the same scale. Ground-based detectors can do this up to $z \sim 1$ and eLISA could go as far as $z \sim 10$. Notice that, according to current cosmology, the acceleration in the expansion of the Universe started at about $z \sim 1$. So combining results from ground- and space-based GW detectors, we may get not only an *independent* test of GR at the cosmological scales relevant for the study of dark energy, but also new independent constraints to its equation of state —probably this would be the highest impact of GW searches on fundamental physics and cosmology.

4. – Conclusions

Gravity is the inner engine of the evolution of the Universe and GW are its direct messenger, which can reach us undisturbed even from the initial instants. We are still "deaf" to such "sounds" from the cosmos. Let me say that we have a duty and a right to start "listening".

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