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The search for gravitational waves

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Summary. — In this paper we briefly review the status and the perspectives of the experimental search of gravitational waves, focusing on the ground based interferometers. The current status of the running detectors and the plans to upgrade them are discussed.

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1. – Introduction

Interferometric detectors of gravitational waves (GW) have taken the baton passed by the resonant bars (a type of detector greatly contributed by E. Amaldi [1]), continuing the effort towards the GW discovery and the start of a GW astronomy. Today a world-wide network of interferometers is operating:

- LIGO [2]: the US LIGO project is made of three interferometers. Two of them are co-located in the same facility at Hanford, WA, and are 4 km and 2 km long, respectively. The third one, 4 km arm length, is in Livingston, LA.
- Virgo [3]: the French-Italian detector Virgo, 3 km arm length, is in Cascina, near Pisa.
- GEO600 [4]: a smaller detector (600 m arm length) has been realized near Hannover by Germany and UK.

The LIGO Scientific Collaboration (including the LIGO and GEO600 detectors) and Virgo have signed a Memorandum of Understanding for joint data taking and analysis. They operate as a "single machine", thus enhancing the chances of detection.

2. – Status

After years of commissioning the most sensitive detectors of the network (LIGO and Virgo) have achieved two remarkable results: they have reached the design sensitivity almost on the entire frequency range together with a level of robustness that allows a duty cycle close to 90%. Such results have demonstrated the interferometer technology and confirmed they are the right instruments for chasing the elusive GW. A joint science run, lasting more than 4 months, has been held in 2009. The network of interferometers has pushed the upper limits on gravitational wave amplitude emitted by several astrophysical sources to the lowest level ever reached [5-9].

With respect to the original design Virgo has undergone a set of upgrades aimed to further improve its sensitivity and stability (given the importance of such upgrades the detector is now called Virgo+):

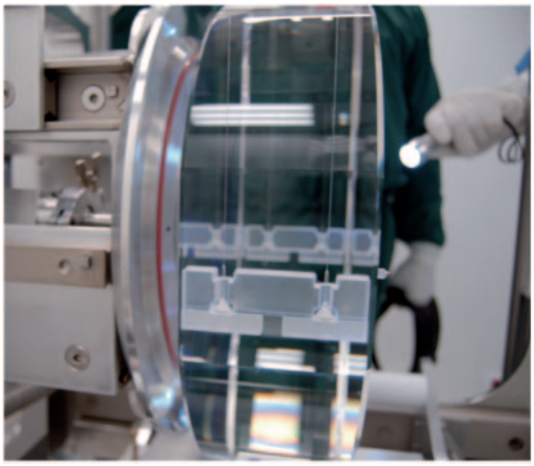

Fig. 1. – The Virgo+ monolithic payload: the 21 kg test mass is suspended through fused silica fibers.

- The laser power has been increased to reduce the shot noise that limits the sensitivity in the high-frequency range.
- In parallel, to cope with thermal aberrations induced by laser heating of the mirrors, it has been necessary to install a thermal compensation system, based on a CO_2 laser that heats the borders of the mirror, reducing the thermal lens created by the main laser.
- In October 2009 Virgo was shut down to be upgraded with an important piece of technology: the monolithic payloads (see fig. 1). New test masses have been suspended by fused silica fibers instead of the usual steel wires [10], allowing to reduce considerably the suspension thermal noise, one of the main limiting noise source in the low-frequency range. Though silica fibers are already used in GEO600, it is the first time ever that such an heavy mirror (21 kg) is suspended using that technology, with the possibility of improving the low-frequency sensitivity beating the Virgo suspension thermal noise limit.
- The new test masses form Fabry-Pérot cavities with higher finesse (150 instead of 50), enhancing the sensitivity in the mid-frequency range.

3. – The case for better detectors: the second generation

Despite the excellent sensitivity achieved, the detection of a gravitational wave event, even if possible, remains unlikely [11]. In order to enhance the detection probability to a level where several tens of events per year are expected, the sensitivity of the interferometers needs to be improved by one order of magnitude. Such an improvement will increase by a factor of a ~ 1000 the number of galaxies explored. As a consequence the rate of events of coalescence of binary neutron stars detected is expected to be in the range of 40/year. This number is affected by an uncertainty of plus or minus one order of magnitude since it is based on the relatively small number of binary neutron stars observed in our Galaxy.

The coalescence of binary black holes is expected to be a powerful generator of gravitational waves. In this case the number of events is based on purely theoretical models. According to the models the number of events per galaxy is smaller but, thanks to their larger masses, these events are visible to larger distances making the final statistics comparable. The observation of the gravitational wave emitted by the final oscillating black holes will provide the first direct observation of a signal generated by a black-hole gravity field.

Besides the search of coalescing binaries, the second generation detectors will target several other gravitational waves sources both galactic and extragalactic: these include periodic waves from rotating neutron stars, as well as impulsive events from supernovae and soft-gamma-ray repeaters. Electromagnetic counterparts are expected for several sources. For this reason the advanced gravitational wave detectors will be able to produce alerts and to share data with other kind of observatories such as gamma ray observatories or optical telescopes.

The advanced detectors will also search for the gravitational wave background produced at the epoch of the Big Bang. Initial LIGO has already bounded the energy density of such stochastic background (normalized by the critical energy density of the Universe), in the frequency band around 100 Hz, to be $\Omega < 6.9 \cdot 10^{-6}$ [6]. The advanced detectors will be able to push this limit down to $\sim 10^{-9}$, thus exploring several Big Bang scenarios among which those based on cosmic strings.

Second generation detectors are getting real: the upgrades of LIGO and Virgo to second generation detectors (Advanced LIGO and Advanced Virgo) have been funded and the two projects are in construction phase.

4. – Advanced Virgo

Advanced Virgo has been approved by INFN and CNRS at the end of 2009. Beside the Virgo funding agencies, Advanced Virgo will be contributed by the Dutch laboratory NIKHEF. The order for the first large procurement, consisting of all the mirror substrates was placed immediately after the approval. The description of the Advanced Virgo baseline design can be found in [12]. The reference sensitivity for Advanced Virgo is shown in fig. 2.

The sensitivity below 50 Hz is limited by a combination of suspension thermal noise and radiation pressure noise. The first is minimized by suspending the large mirrors (42 kg mass) with fused silica fibers similarly to what has been done for Virgo+. Around 100 Hz the main limitation to the sensitivity is due to the thermal noise in the mirror coatings. The sensitivity shown in the figure assumes current coating technology. So, any further improvements from the ongoing R&D will have a direct positive impact on the detector sensitivity. The effect of coating thermal noise is minimized running the Fabry-Pérot cavities near the co-focal configuration thus maximizing the beam size on the mirrors.

In order to increase the interferometer sensitivity at higher frequencies the laser input power will be around 200 W (with 125 W injected into the interferometer). The baseline design foresees the use of a solid state laser composed by a stabilized master laser followed by two stages of amplification. A possible alternative, currently being developed, is a fiber laser amplifier. The first tests have shown that very good frequency and power stabilities can be achieved. To cope with the larger radiation pressure effects due to the larger power injected heavier test masses (42 kg) will be used, and as in Virgo+, will be suspended through fused silica fibers. To this extent, the experience done with the new Virgo+

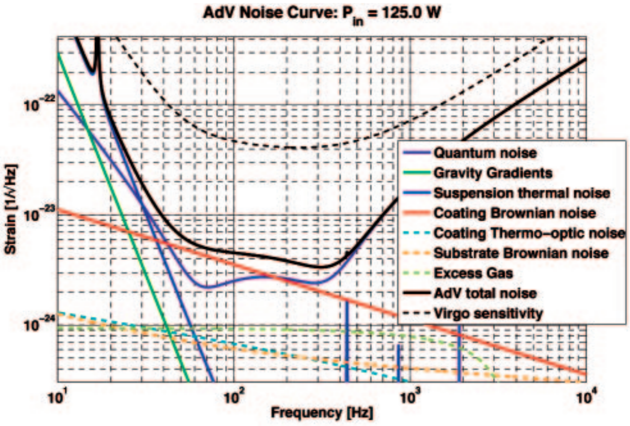

Fig. 2. – The reference Advanced Virgo sensitivity (solid black line) compared with the Virgo design sensitivity (dashed black line). The main noise contributions are also shown.

payloads will be precious to understand all the features of this technology, improve it further and reduce the risk for the advanced detectors.

The optical scheme is modified by the introduction of a signal recycling cavity. The use of signal recycling and of the resonant sideband extraction scheme allows widening the detector bandwidth thus extending the sensitivity into the kHz region. The sensitivity shown in fig. 2 assumes that the signal recycling is detuned by 0.15 rad such to have the best sensitivity to binary neutron stars coalescences. In this case the coalescences of binary neutron stars will be visible up to distances of 144 Mpc. Other tunings are possible and can be used to target other sources. Also the finesse of the 3 km Fabry-Pérot cavities will be larger (~ 900 in the baseline). A DC detection scheme will be adopted to reduce some technical noises.

The vacuum system and the infrastructures will be also upgraded to improve the sensitivity in the low and mid frequency range. Large cryotraps will be installed at the extremes of the 3 km vacuum pipes to isolate them from the rest of the vacuum system. This, combined with the baking of the tubes, will allow reducing the residual gas pressure to the target of 10^{-9} mbar. To reduce the risk of acoustic couplings, the air conditioning machines as well as several other sources of acoustic noise will be moved out of the central experimental hall.

According to the present planning in mid 2011 Virgo+ will be shut down and the installation of Advanced Virgo will start. The commissioning of the interferometer will start in 2014 with the goal of having the first data taking at low laser power in 2015.

5. – Conclusive remarks

Interferometric detectors of GW have proved to be able to reach the promised sensitivity and to be robust and reliable detectors. The current technology allows to increase their sensitivity by ~ 10, thus increasing the detection rate by ~ 1000. Advanced detectors are now in construction and are expected to be taking data in 2015. Discovering the GW could be a fantastic way to celebrate the centennial of the 1916-18 Einstein papers [13, 14] predicting their existence.

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