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1. Introduction

As we know from cosmology, most of the matter in the universe interacts only through the gravitational field. On the other hand, gravitational interaction is still the less known fundamental force of nature. In the near future, the detection of gravitational waves will be a powerful tool to integrate our e.m. view of the universe, providing a unique way to observe the behaviour of matter and gravitational fields at energies and densities unreachable by any laboratory experiment, that will probably open up the way to the inclusion of gravity within a unified theory of all interactions.

1.1 The Spectrum of Gravitational Waves

The first attempt at detecting gravitational waves dates back at the beginning of 1960’s, when Joseph Weber started the field. Weber's detectors had their peak sensitivity at frequencies around 1 kHz, with a bandwidth of only a fraction of Hz. Today, as we shall see in the following, large interferometric antennas have sensitivities
many orders of magnitude better, and a bandwidth of several kHz starting from 10 Hz.

Moreover, the importance of the scientific goal was such that many different experiments and detectors have been conceived over the years and are being proposed today to cover almost the entire gravitational wave spectrum, much as it has happened for e.m. radiation. This is shown in Table 1, where we resume some expected sources of gravitational waves from the lowest to the highest frequency range, with the related detectors and an indicative reference.

Table 1 The gravitational wave spectrum

<table>
<thead>
<tr>
<th>Freq. Range (Hz)</th>
<th>Source</th>
<th>Detector</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\approx 10^{-16}$</td>
<td>Quantum fluctuations of very early universe</td>
<td>Polarization map of CMB</td>
<td>[1]</td>
</tr>
<tr>
<td>$10^{-9} - 10^{-7}$</td>
<td>Binary Supermassive BH in galactic nuclei (SMBH)</td>
<td>Precision timing of millisecond pulsars</td>
<td>[2]</td>
</tr>
<tr>
<td>$10^{-4} - 10^{-2}$</td>
<td>Black Holes, Compact Stars captured by SMBH</td>
<td>Laser tracking spacecraft array (LISA)</td>
<td>[3] [4]</td>
</tr>
<tr>
<td>$10^{-2} - 10$</td>
<td>Binary stars in the galaxy and beyond</td>
<td>Big Bang Observer, DECIGO space detectors, atomic interferometers</td>
<td>[5] [6] [7]</td>
</tr>
<tr>
<td>$10 - \approx 10^4$</td>
<td>Merging Binary NS, BH, fast pulsars</td>
<td>Resonant Bars, Large Interferometric Detectors</td>
<td></td>
</tr>
</tbody>
</table>

[5] Corbin, V. and Cornish, N.J. Class. Quantum Grav. 23 2006 2435

1.2 The GWIC Roadmap

Since the start of this field with the pioneering work of Weber, the importance of having multiple detectors operating in coincidence has been evident. This concept has remained and has grown in depth and scope as the field progressed, and has helped in overcoming the natural difficulties in collaborating between different experimental groups. With time, this attitude has led to the GWIC, Gravitational Wave International Commitee, established in 1997, "to facilitate international collaboration and
Today, all major experiments for the detection of gravitational waves have members in the GWIC, that it is now a reference point for assessing the strategies for the development of the field.

As the sensitivity of the detectors improved, and the probability of a first detection increased, in July 2007 the GWIC

"...initiated the development of a strategic roadmap for the field of gravitational wave science with a 30-year horizon. The Roadmap Committee was made up primarily of members of GWIC with representation from the ground and space-based experimental gravitational wave communities, the gravitational wave theory and numerical relativity communities, the astrophysics components of the gravitational wave community and major projects and regions participating in the field worldwide. The committee sought and received advice from many experienced practitioners in the field, as well as a number of highly regarded scientists outside the field. Input was also sought from the many funding agencies that support research and projects related to gravitational wave science around the world."

This document relies heavily on the last version of the GWIC Roadmap, which is updated every few months, and can be found at:

http://gwic.ligo.org/roadmap/

2. The Medium (2011 - 2020) and Long (2020 - 2030) Term Roadmaps for Gravitational Waves

2.1 Detectors on Ground

2.1.1 Medium Term Roadmap (2011-2020):

The Advanced Detectors Network (LIGO - Virgo, GEO-HF, LCGT)

Fig.1 shows the current network of large interferometers: in the US, the Laser Interferometer Gravitational-wave Observatory (LIGO) consists of three multi-kilometer scale interferometers, two in Hanford, Washington, and one in Livingston, Louisiana. In Europe, Virgo is a multi-kilometer scale interferometer located near Pisa, Italy, and GEO600, a kilometer-scale interferometer, is located near Hannover, Germany. The TAMA detector, located near Tokyo, Japan, is half the size of GEO600. Two of the resonant antennas, that were in operation since 90’s, Nautilus and Auriga, are still taking data to cover the periods of shutdown of the Network of Interferometers.

The three LIGO detectors started to operate in 2002, and reached their initial goal sensitivity in 2007. The construction of Virgo ended in 2003, and its design sensitivity was reached in 2009.

Currently, these interferometers are in the enhanced stage (Enhanced LIGO and Virgo +MS), and construction has started for the next step in the evolution of the network: the Advanced stage.
The Advanced Detectors will have a sensitivity about ten times better than in the initial stage. The technologies at the base of this upgrade are currently being tested in GEO600 (monolithic suspensions, signal recycling and squeezed light) and also in Virgo: the Virgo+MS upgrade [F. Acernese et al. 01], started in January 2010, has tested for the first time the suspension of large mirrors with monolithic fused silica fibers in a km-size interferometer, and is currently under commissioning, with the aim to decrease the thermal noise almost at the level needed for Advanced Virgo.

At the same time, LIGO has done an intermediate upgrade, Enhanced LIGO [J. R. Smith 01], testing some Advanced LIGO technologies, mainly related to the injection and detection systems.

<table>
<thead>
<tr>
<th>IFO</th>
<th>Source</th>
<th>(dN/ dt)\textsubscript{low}/yr</th>
<th>(dN/ dt)\textsubscript{re}/yr</th>
<th>(dN/ dt)\textsubscript{high}/yr</th>
<th>(dN/ dt)\textsubscript{max}/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>NS-NS</td>
<td>2 × 10^{-4}</td>
<td>0.02</td>
<td>0.2</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>NS-BH</td>
<td>7 × 10^{-5}</td>
<td>0.004</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BH-BH</td>
<td>2 × 10^{-4}</td>
<td>0.007</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>IMRI into IMBH</td>
<td>&lt;0.001</td>
<td></td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Advance</td>
<td>IMBH-IMBH</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>NS-NS</td>
<td>0.4</td>
<td>40</td>
<td>400</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>NS-BH</td>
<td>0.2</td>
<td>10</td>
<td>300</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BH-BH</td>
<td>0.4</td>
<td>20</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>IMRI into IMBH</td>
<td>10</td>
<td></td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>IMBH-IMBH</td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2 Expected detection rates for Coalescing Compact Binaries [J. Abadie et al. 01].


Enhanced LIGO and Virgo+MS have run in coincidence from July to September 2010.

After the end of the run in 2010, LIGO has started its upgrade to Advanced [D. Sigg 01], which is progressing as expected. Virgo will start its upgrade by the end of 2011 [F. Acernese 02].

In a similar way, the GEO collaboration is upgrading their detector to the GEO-HF phase [B. Willke et al. 01], which will use signal recycling technology to reach sensitivities at high frequencies that would not be accessible to the advance detectors.

The first run of the new Network of Advanced Interferometers should start in 2014. Two years later, in 2016, the first extended run of interferometers with a sensitivity approaching the goal of the Advanced stage will start. At that time, as shown in Table 2, the rate of detection, at least for bursts coming from inspirals of binary massive objects, should be of the order of several events per year, and allow, with a high probability, the
first detection of a gravitational wave.

Of course, any addition to Advanced LIGO - Advanced Virgo - GEO-HF will be of great importance to improve the efficiency of the Network. According to the GWIC Roadmap:

"To capitalize fully on this important scientific opportunity, a true global array of gravitational wave antennae separated by intercontinental distances is needed to pinpoint the sources on the sky and to extract all the information about each source's behavior encoded in the gravitational wave signal. In the medium term this means the first priority for ground-based gravitational wave detector development is to expand the network, adding further detectors with appropriately chosen intercontinental baselines and orientations to maximize the ability to extract source information.

Figure 2 The Advanced Detectors Network

The most advanced plans along these lines are with the Japanese Large-scale Cryogenic Gravitational-wave Telescope (LCGT) [K. Kuroda 01] and the Australian International Gravitational Observatory (AIGO) [P. Barriga et al. 01]. Possibilities for a detector in India (INDIGO) are also being studied. An intercontinental scale net-work made up of advanced interferometers in the US, Europe, Asia and Australia would provide an all-sky array that could detect, decode and point to the sky-position of gravitational wave sources in the audio bandwidth where many of the most interesting sources are located."

Unfortunately, the good news of the approval of the LCGT project by Japan Government have been countered by the tremendous disaster that recently has devastated Japan territory. At this moment, there is no clear prediction of what the evolution of the LCGT project could be.

On the other side, the project to install the third LIGO interferometer in Australia is still progressing, also with a possible help from India.

2.1.2 Long Term Roadmap (2020-2030):
Third Generation Ground Detectors (ET & Others)

After these fundamental steps, the beginning of a systematic studies of astrophysical sources will require an improvement in detector sensitivities by another factor ten. Conceptual studies of such machines are beginning right now: recently the EU, in the frame of FP7, approved a three year program for a Design Study of a third generation gravitational wave detector: the Einstein Telescope (ET) project [P. Amaro-Seoane et al. 01]. ET will be located underground to reduce seismic noise, and will use cryogenic technology to cool down the suspended mirrors and reduce thermal noise. The limits given by shot noise will be overcome by a further increase in laser power and by using squeezed states of the injected light. The underground location will be essential also to overcome another fundamental noise limiting the sensitivity at frequencies around 1 Hz: the Newtonian noise, due to the motion of ground and air around the test masses. Citing again the GWIC Roadmap:

"There is a great opportunity to evolve the capabilities of this ground-based network in roughly the next 15 years by developing large underground observatories with greatly improved sensitivity, particularly at low frequency. Such underground facilities would operate together with
Advanced LIGO, Advanced Virgo, LCGT and AIGO as the capabilities of these advanced instruments are further enhanced. Successful deployment of third generation, underground gravitational wave observatories will require development of a number of new technologies by the gravitational wave community. Many of the necessary R&D programs are undertaken in a limited number of places, but with a growing level of coordination and communication. It is important that these developments are shared with the rest of the community and that the additional efforts required take place in all regions of the world so that a full range of robust technologies are ready when required for the third-generation facilities.

The most advanced concept for an underground low frequency detector is the Einstein Telescope (ET) project. A conceptual design study for ET was funded by the European Commission, within the Seventh Framework Programme (FP7), beginning in 2008 to assess the feasibility of a 3rd generation GW observatory, with a largely improved sensitivity, especially below 10 Hz due to an underground location. The realization of the ET research infrastructure, allowing operations for many decades, will be triggered by the first GW detection with the start of the site preparation beginning as early as 2017 and with scientific data being available in the first half of the following decade. Similarly, there is the possibility for a high-sensitivity large-bandwidth observatory to be built in the US, potentially in the Deep Underground Science and Engineering Laboratory (DUSEL).

Relevant Sites

References


[F. Acernese 02] F. Acernese et al. Class. Quantum Grav. 25 (2008) 184001


[K. Kuroda 01] Kauzaki Kuroda and the LCGT Collaboration Class. Quantum Grav. 23 2006 S215


[D. Sigg 01] Sigg, D. (for the LIGO Scientific Collaboration) Class. Quantum Grav. 25 (2008) 114041


[B. Willke et al. 01] Willke, B. et al. Class. Quantum Grav. 23 (2006) S207

2.2 LISA Pathfinder and LISA

LISA (Laser Interferometer Space Antenna) is a space-based interferometer, made of a constellation of three satellites 5 millions kilometers apart, funded by ESA and NASA, that
LISA Pathfinder is currently in an advanced implementation state for a launch in 2012.

However, recently, there are news (Nature vol 469, January 20th 2011, pag.280) of technical difficulties in the caging mechanics, that should release the test masses after launch. These difficulties are delaying the launch date to 2013 "and possibly later", as stated in the article on Nature.

2.2.2 Long Term Roadmap (2020-2030): LISA and LISA Follow-on Missions

According to GWIC, "LISA is a project in NASA’s Physics of the Cosmos Program, and the National Academy’s Astro2010 decadal review of astronomy and astrophysics will prioritize LISA relative to other large astrophysics missions. LISA is the gravitational wave community’s highest priority for a space-based mission."

Indeed, the Astro2010 decadal review has assumed a launch date in 2025. However this date could be delayed, as a consequence of the current difficulties of LPF. On the other hand, it is rightly argued that solving these difficulties on LPF will save time and avoid errors in the design of LISA.

Another major difficulty that LISA could encounter comes form the financial restrictions
that the present world-wide economic crisis is forcing on all countries. We hope that these restrictions will not impact on the science that LISA could produce.

When LISA will be launched, sometime around 2025, will start the observation of gravitational waves in the low frequency window up to 0.1 Hz, being the natural complement of ground-based instruments, in the same way that, for instance, optical and X-ray astronomy have provided different informations about different types of astrophysical objects and phenomena.

However, also the band between 0.1 and 1 Hz, which is not covered by LISA and ground interferometers, is of great scientific interest, for instance for the stochastic background measurements. This region of frequency, which currently is out of technological reach, could be covered by the DEci-hertz Interferometer Gravitational wave Observatory (DECIGO), a space gravitational wave antenna proposed in Japan, aiming for launch several years after LISA. The concept will be demonstrated with the DECIGO pathfinder mission that could be launched in around five years time. This frequency range is also a target for the US-based ALIA mission concept, and for the possible future atomic interferometers (see 2.5).

In the longer time frame, the Big Bang Observer is conceived as a LISA follow-on mission targeted at detecting the gravitational waves produced in the big bang and other phenomena in the early Universe.

2.3 Pulsar Timing (PPTA, EPTA, NanoGrav)

Pulsar Timing Experiments aim at the detection of gravitational waves in the nHz region. The detection principle is based on the extreme precision of the signal coming from millisecond pulsars: if a gravitational wave passes over the Earth and the pulsars, it modulates the received pulsar period. As a consequence, the observer on Earth measures a slight variation of the frequency of the pulsar. However, this kind of measurements are affected by many sources of noise, and observation of one or a small number of pulsars can be used only to set an upper limit on the amplitude of a gravitational signal. Thus, to detect gravitational waves, a large array of pulsars must be considered. In such a way, the common noise sources, coming for instance from planetary ephemeris errors, or from errors in Earth velocity, can be separated from the signals coming from many pulsars widely distributed in the sky, which have each its own different spatial correlation. However, the weakness of the signals results in a small contribution to residuals, and so long-term observations are needed. Nevertheless, the most stringent upper limit to date on the amplitude of a gravitational wave background in the nHz region has been set using these methods. Expressed in terms of gravitational wave energy density relative to the closure density of the Universe, is \( \Omega_{GW} \sim 10^{-8} \).

The GWIC Roadmap document resumes in a clear way the status and evolution of Pulsar Timing Experiments:

"The direct detection of gravitational waves is the main goal of the European Pulsar Timing Array (EPTA), the North American Nanohertz Observatory of Gravitational Waves (NANOGrav), and the Parkes Pulsar Timing Array (PPTA) projects. These three collaborations aim to observe a sample of 20 MSPs with a timing precision of 100 ns over more than five years and have joined forces in the International Pulsar Timing Array (IPTA)."
The European Pulsar Timing Array (EPTA) collects pulsar data on a large sample of pulsars using a combination of 100-m class radio telescopes at Jodrell Bank (UK), Effelsberg (D), Nancay (F), Westerbork (NL) and (later) Cagliari (I). The North American project, NANOGrav, has more than 20 years of data on the 305-m Arecibo and 100-m Green Bank Radio telescopes. The PPTA project is using the 64-m radio telescope in Parkes, Australia (350 km from Sydney), operated by the Australian Telescope National Facility (ATNF).

Looking ahead, the EVLA will provide another highly sensitive telescope in the Northern Hemisphere on a timescale of two years, and the proposed Allen Telescope Array 350-dish build out (USA) would add a similarly sensitive telescope within five years. The proposed Square Kilometer Array (SKA) will have very high sensitivity and is expected to observe 100 millisecond pulsars with rms residuals of the order of 50 ns for observing periods of 10 years, pushing the detection limit for the stochastic background at 3 nHz to $\Omega\nu \sim 10^{-13}$. The site of the SKA is not yet chosen but it is planned that it will be operational by the year 2020. Given the importance of the IPTA’s science, the community may seriously consider building a dedicated pulsar timing facility."

2.4 CMB Polarization and Gravitational Waves
(by Paolo de Bernardis and Silvia Masi)

2.4.1 The connection

Inflationary theory offers the most satisfying and plausible explanation for the initial conditions of the universe. Inflation is a phase of superluminal expansion of space itself, within $10^{-35}$ s of the Big Bang, during which quantum fluctuations are stretched to cosmological scales. Results from Cosmic Microwave Background (CMB) experiments, in particular the space missions COBE, BOOMERanG and WMAP, have established that the universe is almost spatially flat, with a nearly Gaussian, scale-invariant spectrum of primordial adiabatic perturbations. These characteristics are all consistent with the simplest models of inflation.

By providing accurate measurements of the E-mode (gradient component) polarization of the CMB, the ESA mission Planck will offer more stringent tests of the inflationary paradigm. Nevertheless, even with such an accurate characterization of the scalar perturbations, a decisive confirmation of inflation will be lacking, and large uncertainties in the allowed inflationary potentials will persist.

Inflation predicts the existence of primordial gravitational waves on cosmological scales. Their detection would establish firmly the existence of a period of inflationary expansion in the early universe, and confirm the quantum origin of cosmological fluctuations that led to the large scale structure observed today. The search for primordial B-mode (curl component) polarization of the CMB provides the only opportunity to detect in the foreseeable future the imprint of these gravitational waves (see e.g. Dodelson et al. astro-ph/0902.3796).

Measuring the amplitude of these tensor perturbations at one length scale would fix the energy scale of inflation and its potential. Measuring their amplitude at more than one length scale would provide a powerful consistency check of a broad class of inflationary models. If, as suggested by recent CMB and large scale galaxy surveys, the power spectrum of primordial perturbations is not exactly scale invariant, then in a wide class of inflationary models the level of gravitational waves will be within the range accessible to third-generation CMB polarization experiments.
A confirmation of inflation and determination of the inflationary potential would have profound implications for fundamental physics by providing new experimental data on the physics near the Planck scale. This is indispensable for model building in string and M theory. The energy scales probed by future CMB polarization experiments lie many orders of magnitude beyond any conceivable accelerator experiment. Consequently, the quest for primordial gravitational waves from inflation constitutes a unique window for constraining the new physics near the Planck scale, which will help understand how quantum gravity is unified with the other three fundamental interactions.

2.4.2 Medium term perspective (2011-2020)

In this decade the technology to measure CMB polarization and to extract it from the local polarized foreground emission at the same mm wavelengths will be developed and established, by means of ground-based and balloon-borne experiments. Three issues are in order:

a) The sensitivity of the experiments. With respect to Planck (using 60 detectors), the plan is to boost the sensitivity of CMB polarization surveys by a factor 10-100, using large detector arrays. In fact, the bolometric detectors in Planck are already limited by radiation noise from the natural background in space, so the final sensitivity of the survey can only improve by increasing the mapping speed. Cryogenic bolometers (TES technology) and Kinetic Inductance Detectors (KIDs) offer the best technology to replicate mm-wave detectors in arrays of several thousand pixels. Both technologies have been developed also in Italy in the framework of INFN group 5 activities and ASI technology programs. Currently planned balloon surveys, like the SPIDER [Crill et al, Proceedings of SPIE 7010, (2008), astro-ph/ 0807.1548], EBEX [Reichborn-Kjennerud et al, astro-ph/ 1007.3672 (2010)] and LSPE [de Bernardis et al., il Nuovo Cimento B 122, 1327 (2007)] experiments, will use large arrays of mm-wave detectors and validate the performance of this approach.

b) Systematic effects in the measurements. Subtle systematic effects in the experiments (beam mismatch, detector efficiency asymmetry, spectral mismatch etc.) can mask easily the faint B-mode polarization signal. The main improvement with respect to Planck and current experiments is the introduction of polarization modulators, like rotating half-wave plates or equivalent devices. The only recipe to find and remove systematic effects is to experiment, possibly measuring the same regions of the sky with completely independent experiments, based on orthogonal technologies.

c) Polarized emission of our galaxy and of extragalactic sources. This must be measured with such a detail that it can be removed with high confidence from future primordial B-modes measurements. The key to do this is to use the different spectral signatures of the foreground emission (synchrotron, free-free, dust) to separate them. Multi-band experiments are mandatory in this respect.

In the best case, these experiments will reach a sensitivity in the parameter $r$ (ratio of tensor to scalar fluctuations) of the order of $r = T/S =0.01$.

2.4.3 Long term perspective (2020-2030)

After validation of the methods by means of a decade of ground-based and balloon borne experiments, the final measurement of B-modes will be carried out from
space. Both NASA and ESA have already received proposals for such a mission [see e.g. Bock et al. astro-ph/0805.4207 (2008); de Bernardis et al., Exper.Astron.23:5-16, (2009); The COrE Collaboration, astro-ph/ 1102.2181 (2011)], which will be limited only by the accuracy in the removal of local foregrounds. The final sensitivity for scalar-to-tensor ratio $r=T/S$ ranges from 0.001 (optimistic foregrounds) to 0.005 (pessimistic foregrounds). Compared to the ESA mission Planck, this is an improvement in sensitivity to $T/S$ by two orders of magnitude.

2.5 New Ideas: R&D on Atomic Interferometers
(by Fiodor Sorrentino, Guglielmo Tino, Flavio Vetrano)

In the last twenty years cold-atom optics and interferometry underwent a dramatically fast development, leading to applications in a number of fields, whose success can be exemplified by the development of quantum sensors already competitive with other state-of-the-art measurement strategies, like inertial and rotational sensors [Gustavson00, Peters01]. Such sensors have already been applied in gravitational physics and more generally for gravimetric measurements; atom interferometers were also exploited to measure the gravitational red-shift with an accuracy improved by several orders of magnitudes, and to test the equivalence principle; proposals exist also to exploit atom interferometry to test for deviations from the Newtonian inverse square law at short distances (see [Sorrentino10] and references therein).

Recently, atom interferometry has been proposed for the possible detection of gravitational waves [Vetrano04, Tino-Vetrano07, Tino-Vetrano10, Dimopoulos09, AGIS-LEO]. In 2009 an international workshop was organized in Florence to discuss the application of atom interferometry sensors to the detection of gravitational waves [Special Issue on "Gravitational Waves Detection with Atom Interferometry" G.M. Tino, F. Vetrano, and C. Laemmerzahl Eds. To be published in General Relativity and Gravitation].

Motivations to study the possibility to apply AI for GW detection are summarized as follows:

- Atoms in free fall can be greatly isolated from environmental disturbances;
- “Differential configuration” allows for common-mode rejection of vibrations:
  - Super-attenuators are not required;
  - Low frequency sensitivity can be greatly enhanced with respect to terrestrial optical interferometers;
- The action of laser on the atoms is inherent part of the operation:
  - no thermal noise is expected to limit the low-frequency sensitivity;
- The possible choice of different internal/external quantum states, as well as of different isotopic species, provides “knobs” to isolate, model and minimize several possible noise sources;
- AI detectors can be sensitive in the frequency band around 1 Hz, which is
complementary to terrestrial (LIGO, Virgo, etc.) and space (LISA) optical interferometers;
- The size and cost of AI detectors can be smaller with respect to the optical counterparts, thus opening interesting perspectives in terms of multiplexing capabilities;
- Such technology is far from being mature, and major developments are foreseen in the near future.

In the time frame of twenty years it is conceivable to develop atom interferometers for the detection of gravitational waves, which could be competitive with current detectors like LIGO and Virgo, and their advanced versions, in terms of flexibility and operational cost, and complementary to terrestrial and space optical interferometers in terms of detection band.

2.5.1 Medium Term Roadmap (2011÷2020)

In the time frame of ten years, the research communities of GW detectors and AI sensors should collaborate to establish this technology on existing atom interferometry facility and to develop medium-scale demonstrators. This can be done along different parallel lines.

Development of conceptual design for the detection scheme (2011÷2014). Though different alternatives have already been considered in literature, the most convincing scheme so far consists in operating two simultaneous atomic fountains with vertical separation, probed in differential mode in order to reject some of the noise sources which would otherwise strongly limit the sensitivity. In the scheme discussed in [Dimopoulos09], the GW is detected through its effect on the propagation of a laser field. Two atom interferometers, acting as atomic clocks, are employed to read out such changes of the propagation length. In such configuration the leading term of the quantum projection noise (QPN) limited sensitivity function to GW induced strain reads

\[(1)\]

where 2nk is the momentum transferred to the atoms in the beam-splitting process, L is the vertical separation of atomic samples, T is the time interval between beam splitter processes and \(\lambda\) is the flux of detected atoms. High sensitivities at low frequencies entail large size set-ups, both through the separation L and the interaction time T.

Optimization and test of atom optics tools. Technologies providing sensitivity enhancement in the given detection scheme can be developed already on existing, small scale (~1 m) AI setups, i.e. the MAGIA experiment (see picture below). These include the production of high-flux atomic sources (in the range of 1012 at/s), the realization of LMT beam-splitters for the atomic wave-packet (up to hundreds of photon recoils), the development of advanced detection systems for large numbers of atoms.

Development of medium-scale (~10 m) demonstrators (2012÷2016). Implementation
of the above mentioned technological solutions on a medium scale apparatus will enable to directly test theoretical models of the detection scheme, as well as to carry on experimental studies of noise sources. Testing the sensitivity function of a medium-scale demonstrator, although not enough to detect a true GW signal, will provide a constraint to the GW stochastic background at the 10-16/√Hz level in the frequency range around 0.5 Hz.

Theoretical and experimental study of noise sources other than QPN (2011÷2020). In comparison with the noise budget studies carried out for optical GW detectors, and amply tested experimentally, our current understanding of the noise sources affecting a GW atomic detector is still preliminary, and it needs significant refinements. A detailed study of the influence of instrumental effects (cold atomic collisions, wave-front distortions, timing and phase errors, ...), environmental effects (high frequency vibrations and rotation noise, gradient of gravity ...) as well as more fundamental effects like possible back-action (thermal noise) on the performances of highly sensitive atom interferometry sensors is to be carried out both theoretically and experimentally.

Study of advanced schemes (2011÷2020). Scalability to larger size and or detectors based on simultaneous multiple AI must be studied in detail. This stage should include investigation of the potential of coherent atomic sources for matter-wave quantum sensors: optimal coherent source design, construction of a coherent atomic source, performance study of coherent atom source interferometers and study and test of optimal detection strategy. New detection schemes can be studied and possibly implemented, such as the use of entanglement or squeezing of atomic wave packets to beat the shot noise limit, along the lines discussed in [Gross10]. In this frame, theoretical and experimental work can be dedicated to the analysis of advanced detection methods based on the use of a BEC as a source for the atom interferometer.

Operation of a first generation (~100 m size) detector (2017÷2020). The previous activities will allow to develop and test the key elements of an AI detector of GW waves; results obtained may be used to project what could be the sensitivity of a full scale instrument implementing the solutions found, and their reasonable evolution. This will enable to estimate the requirements in terms of facilities and experimental environment for a full scale instrument. QPN limited sensitivity of a 100 m size detector should reach $10^{-18}/\sqrt{\text{Hz}}$ around 200 mHz.

The first part of this roadmap represents in fact the program of the INFN MAGIA R&D, a continuation of the MAGIA experiment after the measurement of G, which will result from a joint effort between researchers from the Virgo experiment and the MAGIA experiment.

2.5.2 Long Term Roadmap (2020÷2030)

In the time frame of twenty years, the realization of a full-scale atom interferometry GW detector is theoretically feasible. Although the most suited experimental scheme for a second-generation detector can only result from the previous studies on the configuration and noise budget, some reasonable extrapolation of expected
performance can be done using the model of [Dimopoulos09], where QPN limited sensitivity is given by eq. (1). For a km sized detector, sensitivities in the range of $10^{-20}/\sqrt{\text{Hz}}$ around 50 mHz are expected. In this simplified model the sensitivity is solely determined by QPN, i.e. it does not account for other noise sources, nor for sub-shot noise detection. Of course the real performance of such detector will be determined on one side by the presence of additional noise sources, and on the other side by the possible application of more advanced detection schemes.

Fig. 4 shows the expected QPN sensitivity given by eq. (1) in the different situations discussed here (assuming $k=1/780$ nm$^{-1}$ as for Rb).

Detection schemes with a set of atom interferometers in low terrestrial orbit have also been proposed [AGIS-LEO]. The advantage of operating atom interferometers in microgravity is represented by the much longer interaction times virtually available, where the sensitivity of light-pulse AI sensors scales as the square of interaction time. Although the possible realization of such kind of detectors is beyond the time scale of twenty years, small-scale demonstrators (for instance on the ISS) might be foreseen.

References


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3. Conclusions
3.1 From the GWIC Roadmap: The Gravitational Waves Opportunities Matrix

As a summary, in Figure 5 we report a very effective table from the GWIC Roadmap document, which shows at a glance the present time and future evolution of the complex landscape of detectors, sources, and scientific opportunities in gravitational wave physics.

Figure 5 Matrix of scientific opportunities in gravitational wave science.

3.2 Final Comments

Today, the gravitational wave community appears more and more organized. The necessity to exchange data and work together to be able to detect signal or set meaningful upper limits, has brought to an increasing integration of ground detectors. This attitude is now extending also to experiments covering other regions of the spectrum, with detectors in space or using CMB or Pulsars observations.

On the other hand, the future evolution of the fields appears also well defined: The network of large interferometers will begin to operate in the Advanced configuration around 2015. This Network should be able to achieve the first direct detection of a gravitational wave, probably sometime between 2015 and 2020.

The direct evolution of the Advanced Detectors on ground are the large Third Generation Interferometers. The most advanced project of this type is ET, the Einstein Telescope Design Study, funded by the FP7 Program of the European Union: it is important to maintain the current leadership of Europe in this area. In any case, it is clear that a first detection of gravitational waves by the Advanced Detectors Network would give a great impulse to the ET project.

On the other side, the LISA space interferometers should fly sometime in 2025, complementing the ground observatories in operation at that time. The science within reach of LISA is of the greatest importance. After years of efforts to find a few gravitational signals in a sea of noise, LISA could provide the first example of a gravitational observatory blindered by the background of gravitational wave sources. The GWIC roadmap document is very clear in supporting very strongly LISA, with its precursor mission, LISA Pathfinder. It would be a real miss for science if present or future constraints in budget will bring to a downgrading or a delay of this mission.

After 2020, we hope that the field of gravitational wave astronomy will be well established. That will be the time to study possible follow-on of LISA, like DeciGO, or Big Bang Observer. At that time also a detector based on Atomic Interferometry could be mature enough to be built. This new technology is now at the initial stage: however, it appears to have a great potential of further evolution and it is important that a serious R&D effort be started, also with the involvement of the community working on ground detectors.

Finally, the connections of the field with CMB and Pulsar Timing experiments should become deeper and more extended. Bringing together different expertises and views will be a great advantage to gain a deeper understanding of the phenomena that the new gravitational wave astronomy will find.