

INVITED REVIEWS

Past, present and future of the Resonant-Mass gravitational wave detectors

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Abstract Resonant-mass gravitational wave detectors are reviewed from the concept of gravitational waves and its mathematical derivation, using Einstein’s general relativity, to the present status of bars and spherical detectors, and their prospects for the future, which include dual detectors and spheres with non-resonant transducers. The review not only covers technical aspects of detectors and sciences that will be done, but also analyzes the subject in a historical perspective, covering the various detection efforts over four decades, starting from Weber’s pioneering work.

Key words: gravitation — gravitational waves — instrumentation: detectors

1 INTRODUCTION

The concept of gravitational waves goes back no more than three centuries in the history of mankind. Even after the publication of “Principia,” Newton refused to commit himself as to how gravitation was transmitted from body to body across the void. His words were: “I make no hypotheses.” Other scientists at that time, however, pictured gravitation as making its way through the *ether* as sound does (its way) through air (Asimov 1966). It is likely that the concept of gravitational field propagation had to wait around one century before evolving to the concept of gravitational waves. It seems that only after the experimental confirmation of the existence of electromagnetic waves by H. Hertz (1887), speculation was made about the possible existence of gravitational waves (GWs) (not only involving the gravitational field, but also the gravitomagnetic one). Heaviside (1893), Lorentz (1900), and Poincaré (1905) were examples of scientists making such speculations (Amaldi 1989). However, a mathematical derivation of gravitational waves was only possible after the formulation of the theory of General Relativity. Einstein himself derived them, using a weak field approximation, as an irradiative solution of the vacuum equations of general relativity in 1916 (Einstein 1916), and in a more detailed work two years later (Einstein 1918). A modified version of this derivation (Misner et al. 1973; Weber 1961) is summarized in the following section.

2 GENERAL RELATIVITY AND GRAVITATIONAL WAVES

The Einstein field equations are (neglecting the cosmological constant)

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = 8\pi\frac{G}{c^4}T_{\mu\nu}, \quad (1)$$

where $c = 2.99792458 \times 10^8 \text{ m s}^{-1}$, and $G = 6.67259(85) \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$. The left-hand side of these equations involves second order partial differential operations for the calculation of the components of the Riemann tensor. Because these equations are non-linear, the computation in GR theory is sometimes very complicated. This non-linearity of gravity also implies that the principle of superposition is no longer valid. Nevertheless, when the gravitational field is weak and sufficiently far from its source, many linearizations can be assumed. The spacetime curvature is nearly flat and the metric can be written as

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}, \quad (2)$$

where $\eta_{\mu\nu}$ is the Minkowski metric tensor and $h_{\mu\nu} \ll 1$. This simplifies the calculation of the Riemann tensor, which can now be expressed as

$$R_{\alpha\beta\mu\nu} = \frac{1}{2}(h_{\alpha\nu,\beta\mu} + h_{\beta\mu,\nu\alpha} - h_{\beta\nu,\alpha\mu} - h_{\alpha\mu,\beta\nu}), \quad (3)$$

where $h_{\alpha\beta,\mu\nu} = \frac{\partial^2 h_{\alpha\beta}}{\partial x^\mu \partial x^\nu}$ if terms of order h^2 are ignored. The Ricci tensor and Ricci scalar can now be computed and substituted into the field equations. Because the field equations contain the $g_{\mu\nu}/2$ term, we simplify them if we define

$$\bar{h}_{\mu\nu} \equiv h_{\mu\nu} - \frac{1}{2}\eta_{\mu\nu}h, \quad (4)$$

where $h = h^\alpha_\alpha = \eta^{\alpha\beta}h_{\alpha\beta}$. In addition to this, in order to obtain an even more compact form for the field equations, we choose a convenient gauge (the ‘‘Lorentz gauge’’) in which

$$\bar{h}_{,\alpha}^{\mu\alpha} = 0. \quad (5)$$

The field equations then assume the form

$$\square \bar{h}_{\mu\nu} \equiv -\frac{1}{c^2} \frac{\partial^2}{\partial t^2} + \nabla^2 \bar{h}_{\mu\nu} \equiv \bar{h}_{\mu\nu,\alpha\beta} \eta^{\alpha\beta} = -16\pi \frac{G}{c^4} T_{\mu\nu}. \quad (6)$$

In vacuum $T_{\mu\nu} = 0$, and we have a tensor wave equation with solutions of the form

$$\bar{h}_{\mu\nu} = A_{\mu\nu} e^{[ik(z-ct)]}, \quad (7)$$

which represents a monochromatic wave of spacetime geometry (Price 1982) propagating along the $+z$ direction with speed c (other theories of gravitation might predict a speed different from that of light) and frequency kc . These waves, ripples in the curvature of spacetime, are so called gravitational waves.

In an analogy with electromagnetic waves, which can be generated by accelerated charges, gravitational waves are produced by accelerated masses. However, there are some major differences between the two. The conservation of momentum, plus the fact that mass comes with only one sign, positive, prevents an oscillating (or accelerating) mass dipole from radiating gravitational waves (Forward 1961). Only an accelerated mass quadrupole or higher multipole moments can produce gravitational waves. Another difference is that the gravitational waves are very weak compared to the electromagnetic waves. This is a natural consequence of the weakness of gravitational forces compared to electromagnetic forces (36 orders of magnitude weaker for elementary particles such as a proton). $\frac{Gm_p^2}{4\pi\epsilon_0 e^2} \sim 10^{-36}$, where m_p is proton mass and e its charge.

This fact, together with the impossibility of the emission of dipole gravitational radiation, makes the generation of gravitational waves in nature only potentially significant for a very large total amount of mass in a coherent, fast, and strongly accelerating movement of particles. Therefore, only astrophysical and cosmological events are potentially detectable for the first set of successful gravitational wave detectors.

This weak coupling between mass and gravitational waves has reciprocal properties. Gravitational waves, as expected, also couple very weakly with matter. That is why the gravitons decoupled from matter when the Universe was only $\sim 10^{-43}$ s old (the Planck time). In one sense this is good: gravitational waves can bring information from dense cores of some astrophysical objects without being significantly attenuated by crossing the outside layers of matter, something that electromagnetic waves are unable to do. However, on the other hand it is bad: this weak coupling of GWs with matter makes it extremely difficult for experimentalists to detect them. Actually, since its mathematical prediction in 1916, no single gravitational radiation pulse has ever directly been detected. The only observational confirmation of the existence of such radiation comes from the observed decrease in the orbital period of a few compact binary systems such as the PSR 1913+16 system discovered by Hulse and Taylor (Taylor et al. 1976) in 1974 (some of the other ones are: PSR J0737–3039, PSR 2127+11C, PSR 1534+12, and J1141–6545). After ruling out other possible mechanisms to explain the observed change of orbital period, gravitational radiation damping was left as the only probable cause. The GR theory prediction for the orbital period decrease due to the loss of energy by gravitational waves in these systems agreed with observation within 0.2% (Will 1986). This discovery gave Taylor and Hulse the 1993 Nobel Prize in physics (Taylor 1994).

In order to understand the interaction with matter of a local plane gravitational wave in this linearized theory, we change the gauge, once more, to one that is transverse and traceless. In this gauge, only spatial components of $h_{\mu\nu}$ are nonzero ($h_{\mu\nu} = 0$), and they are transverse to the direction of propagation. Furthermore, these components are divergence-free ($h_{kj,j} = 0$) and trace-free ($h_{kk} = 0$). Since $h = h^\alpha_\alpha = h_{kk} = 0$, we can conclude that

$$\bar{h}_{\mu\nu} = h_{\mu\nu} = h_{\mu\nu}^{TT}. \quad (8)$$

This gauge is called a TT or transverse-traceless gauge (Einstein 1916). Here, the Riemann curvature tensor has the simple form

$$R_{j0k0} = -\frac{1}{2}h_{jk,00}^{TT}, \quad (9)$$

and in particular (Press & Thorne 1972)

$$R_{x0x0} = -R_{y0y0} = -\frac{1}{2}\ddot{h}_+ \left(t - \frac{z}{c}\right) \text{ and } R_{x0y0} = -R_{y0x0} = -\frac{1}{2}\ddot{h}_\times \left(t - \frac{z}{c}\right), \quad (10)$$

where (Thorne 1987)

$$h_+ \equiv h_{xx}^{TT} = -h_{yy}^{TT} = \Re\{A_+ e^{-i[\omega(t-z/c)+\phi_+]}\}, \quad (11)$$

and

$$h_\times \equiv h_{xy}^{TT} = -h_{yx}^{TT} = \Re\{A_\times e^{-i[\omega(t-z/c)+\phi_\times]}\}, \quad (12)$$

and A_+ together with A_\times are the amplitudes of the two independent modes of polarization (+ and \times). Then, the gravitational wave's driving force acting on each element of mass m_i of a material body can be derived as

$$F_j = \frac{1}{2}m_i \ddot{h}_{jk}^{TT} k, \quad \text{where } j, k = x \text{ or } y \quad (13)$$

and the total force ($= F_x e_x + F_y e_y$) becomes

$$\mathbf{F} = \frac{1}{2}m_i \{(\ddot{h}_+ x + \ddot{h}_\times y)e_x + (\ddot{h}_\times x - \ddot{h}_+ y)e_y\}, \quad (14)$$

From Equations (11) and (12): if $\phi_+ = \phi_\times$, the resultant force is linearly polarized; if $\phi_+ = \phi_\times \pm 90^\circ$ and the magnitudes A_+ and A_\times are equal, the resultant force is circularly polarized; otherwise it is elliptically polarized.

Forces induced by gravitational waves are strictly transverse, as in Figure 1, which shows the effect of pure h_+ or h_\times plane gravitational waves arriving perpendicularly to the plane of a circular array of test particles (the amplitudes are exaggerated). It is apparent that GWs not only change distances, but also angles. The orthogonality with h_+ or h_\times can be appreciated if we imagine deformations for very small amplitudes; a material segment forming an angle $\phi = 0^\circ, 90^\circ, 180^\circ,$ and 270° with the x axis will change length due to h_+ and rotate due to h_\times and vice versa if $\phi = 45^\circ, 135^\circ, 225^\circ,$ and 315° . It is the Principle of Equivalence that causes the acceleration (and the force) to be locally undetectable ($\xi_k=0$). Only the relative acceleration or the “relative force” can be observed.

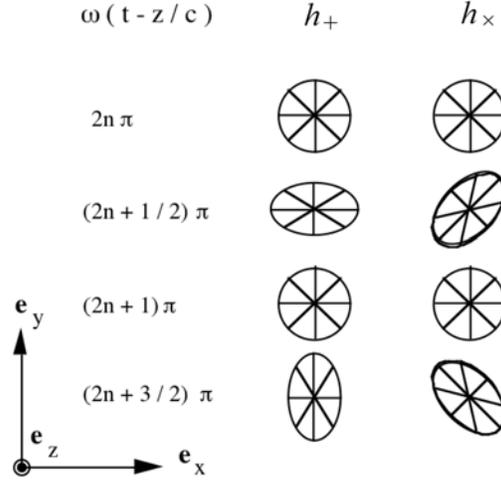


Fig. 1 Deformation of a circle due to forces induced by pure h_+ or h_\times waves.

The strain, $h = \sqrt{h_+^2 + h_\times^2}$, $h \equiv \Delta L/L$, is the dimensionless amplitude that can be measured by gravitational wave detectors. It is the composition of the two dimensionless polarization amplitudes h_+ and h_\times . However, a more useful quantity, which gives a better indication of the detector’s sensitivity, is the “strain spectral sensitivity,” in units of $\text{Hz}^{-1/2}$. This quantity takes into account the observable frequency bandwidth where the signal is present. Evidently, this means that burst events should be strong in order to be detected, in contrast with detectable monochromatic signals, which can be much fainter.

It is possible to envision various schemes of detection of gravitational waves (Misner et al. 1973; Peng 1990). The two most explored principles of detection are the monitoring of the distance between two or more points and the measurement of the oscillations driven on a solid “antenna” by stress¹. The first principle of detection can be performed with a laser interferometer (Vinet 2010), or a Doppler tracking array, or a pulsar timing array (Anderson 1971; Hellings 1981). The second principle can be carried out with a resonant-mass antenna coupled to an electromechanical transducer of some kind. Joseph Weber was the first one who proposed the feasibility of this method.

¹ Among other principles of operation which have not been pursued are direct interaction between GWs and electromagnetic waves, superfluid movements or superconductivity driven by GWs, sharp phase transitions induced by GWs, and plasma antennae.

3 THE FIRST GENERATION OF RESONANT-MASS GRAVITATIONAL WAVE DETECTORS: THE PIONEERING WORK OF JOSEPH WEBER AND MANY OTHERS

By the end of the 50s, after four decades of debate, it became possible “for a number of physicists to conclude that general relativity really does predict the existence of gravitational waves.” Also, thanks to the technological advances in the 40s and 50s, it became feasible to do some new gravitational experiments and to repeat the older ones in more precise ways. The man who was capable of making these two statements at that time was Joseph Weber (Weber 1961). He was, at the same time, a brilliant experimentalist and a competent theorist on general relativity. He almost invented the maser earlier in the 50s. On the other hand, he spent the 1955–1956 academic year as a fellow of the Institute for Advanced Study in Princeton, New Jersey, where he dipped himself in general relativity. This rare union between experiment and theory made him the only one with “vision to see that there were technological possibilities of ultimate success” (Thorne 1987). His major contribution to science was to start this experimental and exciting field of gravitational wave detection, by constructing the first resonant-mass antenna with electromechanical transducers and influencing Robert Forward (his former Ph.D. thesis student) to construct the first free-mass antenna with laser interferometry (Moss et al. 1971). The idea of a laser-interferometer gravitational-wave detector was independently proposed by Felix Pirani (1956), Gertsenshtein & Pustovoid (1962), Weber (1964), and Rainer Weiss (Thorne 1987). Let us now understand these two techniques.

The Equivalence Principle forbids that the accelerations produced by the passage of gravitational waves be felt locally. Any detector has to be an extensive one, because the accelerations are of the tidal type. This poses two possibilities: a free-mass detector or a non-free-mass detector. In the free-mass case, the experimentalist should monitor the distance between the two or more free-masses that compose the detector. No energy is absorbed from the gravitational wave in this case. Weber proposed to use laser interferometry to monitor the distances between these masses (actually this becomes an almost-free-mass case, because on the Earth it is impossible to have a complete free-mass situation).

In the case of non-free-mass, there is some sort of connection between the masses, such as the forces that connect the atoms in the crystalline structure of a body. This is the case of the so called resonant-mass detector. The atoms of a body try to follow the geodesic trajectories produced by the spacetime distortion (geodesic deviation) caused by the passage of the gravitational wave. However, the electrostatic connections between the body’s atoms prevent them from following these precise trajectories. This case is analyzed below.

Suppose we model the mechanical longitudinal oscillation of a cylindrical bar antenna by the oscillation of two point masses separated by the distance r and connected by a spring. For simplification, let us consider the detector to be perpendicular to the wave propagation direction, so that we can write the equation that describes the oscillation of the point masses as

$$\ddot{\zeta} + \frac{b}{m}\dot{\zeta} + \frac{k}{m}\zeta = \frac{1}{2}r\ddot{h}(t) + F_N, \quad (15)$$

(acceleration + dissipation force + restoring force = external force caused by the GW + external force caused by various noise sources), where f_o is the resonant frequency, $\omega_o = 2\pi f_o$, b is the dissipation factor, m is the mass of each point mass, k is the spring constant, $\omega_o^2 = \frac{k}{m}$, $Q = \frac{\omega_o m}{b}$ (the mechanical quality factor),

$$\ddot{h}(t) = \sqrt{[\ddot{h}_+(t)]^2 + [\ddot{h}_\times(t)]^2},$$

$$\ddot{h}_+(t) = -2c^2 R_{x0x0} = 2c^2 R_{y0y0},$$

and

$$\ddot{h}_\times(t) = -2c^2 R_{x0y0} = -2c^2 R_{y0x0}.$$

The Riemann tensor is the driving force in this harmonic oscillator equation. Making

$$h(t) = h_o \sin \omega t,$$

so that

$$\ddot{h}(t) = -h_o \omega^2 \sin \omega t,$$

we arrive at the following results²:

$$|\zeta(t_p)| \sim \frac{1}{4} r h_o \omega_o t_p, \quad \text{if } t_p \ll Q/\omega_o, \quad (16)$$

and

$$|\zeta(t_p)| \sim \frac{1}{2} r h_o Q, \quad \text{if } t_p \rightarrow \infty, \quad (17)$$

where t_p is the time duration of the pulse.

The problem with this scheme was noise, more specifically: thermal noise. The average amplitude of oscillation of a cylindrical bar due to thermal fluctuations (Brownian-noise forces or Langevin forces) was many orders of magnitude larger than the oscillation amplitudes induced by an expected gravitational wave. Weber envisaged a very clever solution to this problem. He had the idea of using a material with high mechanical quality factor ($Q = \omega \tau_E$, where τ_E is the energy relaxation time, $\tau_E = (\text{maximum stored energy})/(\text{power dissipated})$ and τ_A , the amplitude decay time, is $2\tau_E$). If one uses high Q materials for the antenna, the variations of amplitude due to thermal fluctuations will still be very large (the same as before), but they would occur in a time much longer than the gravitational wave period, so long that the short gravitational wave signal would still be detectable if a suitable digital filter is used (Weber 1960; Misner et al. 1973).

Weber's first large suspended bar antenna of high Q aluminum was constructed in the early 60's. It was a 1.2-ton aluminum cylinder of length ~ 1.5 m and diameter of ~ 61 cm suspended in a vacuum chamber on acoustic filters. Its first longitudinal mode was resonant at room temperature at 1657 Hz (Weber 1966). The transducer system, able to convert the mechanical strains to voltages, was a series of piezoelectric crystals (quartz strain gauges) mounted on its surface close to the central region as shown in Figure 2(a). It started operating with good sensitivity and isolation around 1965 January. Two years later, Weber reported the first possible gravitational wave signals (Weber 1967).

In 1968, he again reported possible events. This time, he used two aluminum cylinders tuned to ~ 1.66 kHz instead of just one. They were spaced about 2 km apart. He claimed that the number of coincident events had an extremely small probability to be statistically significant (Weber 1968). Finally, in 1969, Weber stated that coincidences had been observed on gravitational-radiation detectors over a base line of about 1000 km at Argonne National Laboratory and at the University of Maryland, and that the probability that all of these coincidences were accidental was incredibly small (Weber 1969). The output of each detector was put on a chart recorder like those used to record earthquakes. By 1973, he had claimed an excess of coincidences from the statistical average of about seven events per day, showing a peak in the direction of the galactic center (Weber 1970, 1972; Weber et al. 1973). These and subsequent observations by Weber were greeted with great excitement in the early 1970s; however, the strength implied by his signals was very much in excess of what was expected.

In the following years, various experimenters built more sensitive bars, including low-temperature bars, and looked for signals, but none of them confirmed Weber's findings. The first ones to find null results were Tyson at Bell Labs, Murray Hill, NJ, and Levine and Garwin at the IBM Thomas J. Watson Research Center, in Yorktown Heights, NY, both in 1973 (Tyson 1973; Levine & Garwin 1973; Garwin & Levine 1973). Both these experiments disagreed with Weber's results and suggested that the events he found were not gravitational wave events.

² Aguiar, O. D. 1991, INPE/AST-300, course notes



Fig. 2 *left*: Weber and one of his room temperature bars (60s) (courtesy of the LSU Gravity Allegro group); *middle left*: the LSU detector dewar arriving at the old lab (early 70s) (courtesy of the LSU Gravity Allegro group); *middle right*: the Explorer detector at CERN (early 80s) (courtesy of the LSU Gravity Allegro group); *right*: the earthquake damaged Stanford bar detector (picture taken in 1994) with the large 4.8 ton 6061 aluminum alloy antenna inside (author's private collection).

In any case, Weber's pioneering work was decisive for the initial growth of the gravitational wave community. Thanks to Weber's reported results in 1969 of having seen GW signals, about ten groups tried to repeat his results. Even though none could confirm Weber's findings, the basis of gravitational wave detection was definitely established.

The following 12 groups, which operated room temperature resonant-mass GW detectors in the 60s, 70s and 80s, were motivated by Weber's pioneering effort:

- **Moscow, in Russia**: two detectors 20 km apart composed of two 1.2 ton aluminum alloy bars, 150 cm long and ~ 60 cm in diameter, resonant at 1640 Hz, and equipped with capacitive transducers (Braginskii et al. 1974);
- **BTL (Bell Labs), New Jersey, USA**: one 3.7 ton aluminum alloy bar, 357 cm long, ~ 70 cm in diameter, resonant at 710 Hz, equipped with PZT-8 transducers (Tyson 1973);
- **Rochester, in Rochester (NY), USA**: another 3.7 ton aluminum alloy bar 420 km apart from the one above, 357 cm long, ~ 70 cm in diameter, resonant at 710 Hz, equipped with PZT-8 transducers (Douglass et al. 1975);
- **IBM, Yorktown Heights (NY), USA**: one 118 kg aluminum alloy bar, 150 cm long and 19 cm in diameter, resonant at 1695 Hz, equipped with PZT-4 transducers (Levine & Garwin 1973; Garwin & Levine 1973);
- **Bristol group, England**: two parallel split-bars in the same vacuum chamber composed of two aluminum half-bars. Each split-bar had its own transducer (made of lithium niobate piezoelectric material) and amplifier detector, but they shared a common vacuum chamber and vibration isolation system. The signals from the two split-bars were monitored separately and were also cross-correlated (Aplin 1972);
- **Glasgow, Scotland**: two split-bar detectors 50 m apart composed of two aluminum half-bars of 300 kg total mass and 155 cm total length, ~ 30 cm in diameter, cemented together via PZT transducers, resonant at 1020 and 1100 Hz (Drever et al. 1973);
- **Reading-Rutherford Lab, England**: two split-bar detectors 30 km apart composed of two aluminum alloy half-bars of 625 kg total mass and 150 cm total length, 46 cm in diameter, cemented together via PZT transducers, resonant at 1200 Hz (Allen & Christodoulides 1975);

- **Univ. Tokyo, Tokyo, Japan:** two 1.4 ton 165 cm×165 cm×19 cm square antennae made of an aluminum alloy, both in the Physics building, resonant at 145 Hz, equipped with dc-capacitive transducers (Hirakawa & Narihara 1975) (later, one of these antennae was mechanically tuned to 60.2 Hz in order to become CRAB II (Oide et al. 1979)), $h < 8.4 \times 10^{-21}$ for continuous waves, one 400 kg 110 cm×110 cm×12 cm square antenna made of an aluminum alloy, resonant at 60.2 Hz, equipped with dc-capacitive transducers (CRAB I) (Hirakawa et al. 1978), $h < 1.1 \times 10^{-19}$ for continuous waves, and some other small antennae ($M < 40$ kg) (Iso et al. 1984, 1985);
- **Munich-Frascati group:** two detectors ~700 km apart (later only 10 km, when the Frascati detector was moved to Garching) composed of two 1.2 ton 6061-O aluminum alloy bars, 154 cm long by 62.5 cm in diameter, resonant at 1654 Hz, equipped with piezoelectric transducers, and intended to reproduce the precision of the Weber experiment, with some sensitivity improvements (Billing et al. 1975; Billing & Winkler 1976; Bramanti & Maischberger 1972), set the lowest upper limits to the rates of gravitational wave pulses in the 70s (Kafka & Schnupp 1978). They took a piezoelectric material with better mechanical and electrical properties, and arranged the piezos differently (arranging strain and polarization parallel) thereby providing a better coupling. Because of the new topological arrangement of the piezos, they were able to manage an impedance matching between the “source” of the signal, the piezos, and the input of the amplifier. Thus, the detector was noticeably improved in comparison with Weber’s setup. In addition, the signal processing was performed with the two degrees of freedom in phase space, equivalent to amplitude and phase or the two independent quadrants, whereas in most cases Weber just used the energy of the bar (Winkler 2007, private communication);
- **Zhongshan Univ., Guangzhou, China:** one ~2 ton (1963 kg) aluminum alloy bar, 178 cm long, 71.4 cm in diameter, resonant at ~1.5 kHz, using PZT-4 transducers, and one 498 kg 200 cm² square antenna, resonant at 47.3 Hz, equipped with dc-capacitive transducers (Hu et al. 1986; Zhu et al. 1988);
- **Beijing Univ., Beijing, China:** one 1.3 ton aluminum alloy bar, 153 cm long, 62.5 cm in diameter, resonant at 1687 kHz, equipped with PZT transducers (Pizzella 1988b; Feng et al. 1983);
- **Meudon group, in France:** a conical antenna equipped with capacitive transducers (Bonazzola & Chevreton 1973).

Also six groups, Stanford and LSU in the USA, University of Rome, University of Western Australia (UWA) (Blair 1980), University of Regina (Canada) (Papini 1974; Barton et al. 1977), and the Legnaro group, were formed in the 60s, 70s and 80s. They decided to construct cryogenic resonant-mass (RM) GW detectors, instead of room temperature ones, starting a second and a third generation of RM detectors. At the same time, some other existing groups, such as the ones in Tokyo (in collaboration with KEK), Moscow (Rudenko et al. 1994), Rochester (Bocko et al. 1984), and Maryland (Davis & Richard 1980) were switching to cryogenics. “These groups made a number of significant improvements over Weber’s original design. One improvement was to lower the temperature of the bar to liquid helium temperatures (4 K). The second was a better suspension of the bar with increased vibration isolation. The third was the use of a resonant transducer and low noise amplifier to observe the motion of the bar.”³ Figure 2 shows some historical pictures⁴ and the author’s private archive.

Let us finish this section by mentioning the standard data analysis procedure used by the first and second generation detectors. This procedure was to produce a list of events above some arbitrary reasonable energy threshold for each detector and from these lists to produce time delay histograms for each pair combination of detectors. The time delay histograms would give the number of coincidences for each combination of time shift (delay or advance) of their detector event list time.

³ <http://sam.phys.lsu.edu/Overview/history.html>

⁴ <http://sam.phys.lsu.edu/ImageSets/ImageSets.php?whichpage=.%2FScanned+Slides>

The “zero time delay bin” would, then, give the number of coincidences between the two detectors without altering their event list times. Evidently, if no gravitational wave detection was made, all the histogram bins (including the zero delay bin) would have their counts fluctuating around an average number, which was related to the statistical probability of coincidence by chance. However, if some GW detections were made, the “zero time delay bin” would have additional counts. Consequently, if the “zero time delay bin” was significantly (statistically) above the average count, as Weber found many times in the late 60s and 70s, a suspicion of detection could be claimed.

In the 90s, the cryogenic bar detectors groups decided to make some changes in the way they were producing their event lists and the way they were comparing themselves with each other. They decided to improve the statistical results of this kind of analysis, decreasing the number of events in their detector lists by increasing the energy threshold. This threshold was chosen to produce only about 100 events h^{-1} for each detector. With this new procedure, the average number of coincidences by chance would drop and, consequently, the significance of a few real detections would statistically increase, standing out more clearly. Another procedure had to do with the way the groups exchanged data. They started to send four lists of events to the other groups in which only one of them had the correct time. The reason for that “protocol” was to avoid any analysis bias.

Evidently when three or more detectors find an event at the same time, a more strong case is made. Unfortunately, no triple or quadruple events were ever registered for the combinations of lists (with reasonably high thresholds). Part of the reason for this was because it is hard to coordinate the operation of individual bars in order to have them operate synchronously. In the 80s, there were only about 60 h of coordinated triple operation between three facilities (Stanford, LSU and Rome). In the 90s, Stanford was no longer active; Niobe only started in 1993 and Auriga in 1997. From 1997 January to 2003 June (a total of 78 months), triple coordinated operations were much more frequent, about two years ($\sim 30\%$ of the total time), and quadruple operations were possible for four months ($\sim 5\%$).

4 THE SECOND GENERATION RESONANT-MASS DETECTORS: THE ADVANTAGE OF COOLING THE MASS DOWN TO LOW TEMPERATURES

There are many advantages of cooling the antenna down to low temperatures: the thermal (Brownian) noise decreases, the antenna’s mechanical quality factor (Q_{mec}) increases (a fact discovered later) (Carelli et al. 1975), superconductor materials can be used for the transducer circuitry, which in turn increases the transducer electrical quality factor (Q_e), and very low noise cryogenic amplifiers can be used.

Basically, the second or third generation resonant-mass detector consists of a cryogenic resonant-mass antenna coupled to an electromechanical resonant (at the same frequency) transducer that has its electrical output signal pre-amplified by a very low noise cryogenic amplifier. This pre-amplified signal is recorded on magnetic tapes, after passing through an analog-digital converter, for later digital filtering and computational analysis. The cryogenic antenna, which is made of a high mechanical Q material, usually an aluminum alloy (the Australian Niobe antenna is one of the exceptions, because it is made of pure niobium), is kept in vacuum and at 4.2 K, the boiling point of liquid helium (the second generation) or at ~ 0.1 K if a dilution refrigerator is used (the third generation), and isolated as much as possible from floor or sound vibrations. The first transducer was composed of piezoelectric crystals during the first generation (room temperature) of antennae. They were replaced around the mid-seventies by electromechanical resonant transducers using superconducting circuits. The first one was a tunable-diaphragm with an inductive pick-up transducer, designed and constructed by Ho Jung Paik⁵. Compared to capacitive or inductive resonant transducers, piezo-

⁵ Paik, H. 1974, Analysis and Development of a Very Sensitive Low Temperature Gravitational Radiation Detector, Ph.D. dissertation, Stanford University, unpublished.

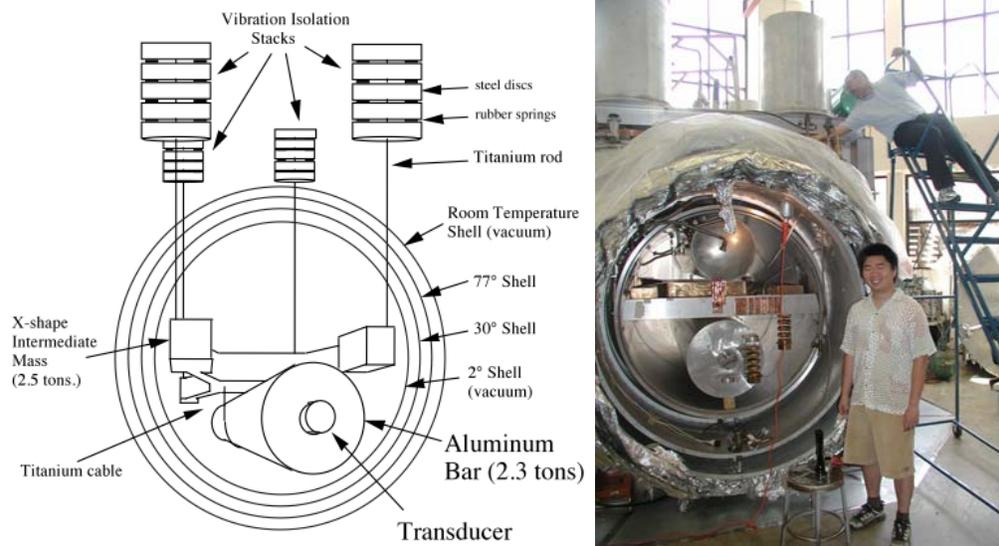


Fig. 3 LSU Cryogenic Antenna. *left*: Schematic view (the extra liquid helium cylindrical tank over the intermediate mass and the bar antenna was omitted for simplicity); *right*: Picture of the detector (without the end caps) in the new lab, with Warren Johnson (*top*) and Ik Siong Heng (courtesy of the LSU Gravity Allegro group).

electrical transducers did not have high mechanical quality factors, even at low temperatures, and electromechanical couplings were not as high.

Cryogenic mass-resonant antennae of the bar type have their first longitudinal vibrational mode, which is sensitive to a quadrupolar gravitational wave, around 900 Hz. The 5056 aluminum alloy (Mg 5.1%, Mn 0.12%, Cr 0.12%, balance Al) is the most used one, because it is known by the gravitational wave community as the aluminum alloy with the highest mechanical Q at cryogenic temperatures (Suzuki et al. 1978).

As an example of the second generation bar antenna, Figure 3 shows the schematic drawing of the LSU detector⁶ and a picture of the detector at the new lab⁷. The antenna is balanced on a titanium cable which is attached to the intermediate mass, an H-shape, 2.5-ton bronze casting supported by titanium rods that hang from vibration isolation stacks. These stacks are kept in vacuum chambers which are connected to the 2 K shell space. To avoid overloading the schematic, the aluminum frame and pneumatic air springs on which the stacks rest were omitted from the drawing. The transducer is bolted to one of the bar ends, and a calibrator capacitor is bolted to the other end. All the wiring attached to the transducer passes through small intermediate brass disks connected to each other by fine titanium wires. This array of disks is named a “Taber isolation” stack after its inventor, and its function is to guarantee vibration isolation for the antenna-transducer system. The bronze X mass, the vibration isolation on top, and the “Taber isolation” stack work together to reflect the external mechanical excitation by the principle of mechanical impedance mismatching.

The principle of detection is very simple. When gravitational waves strike the aluminum bar antenna, it is driven into oscillation. A major part of the energy received from the GWs is coupled

⁶ Aguiar, O. D. 1990, Parametric Motion Transducer for Gravitational Wave Detectors, Ph.D. dissertation, Louisiana State University, unpublished.

⁷ <http://sam.phys.lsu.edu/ImageSets/ImageSets.php?whichpage=.%2FOpen+ALLEGRO>

to the bar's first longitudinal mode which has a node about the titanium cable section and anti-nodes at both ends of the bar. The transducer attached to one of the ends is, therefore, set into oscillation. Because the transducer's mechanical resonance is at the same frequency f_o as the bar resonance frequency, there is a beating between the two oscillations with beat frequency equal to $f_o/2$ times the square root of the ratio: (transducer effective mass/antenna effective mass). The amplitude of the transducer's harmonic oscillator increases until almost all the energy from the bar's first longitudinal mode has been transferred to the transducer oscillation mode. This method obtains an amplitude gain equal to the square root of the inverse ratio mentioned above, and an increase in frequency bandwidth above noise level. The transducer then converts part of this energy into an electrical signal which is pre-amplified by a very low noise cryogenic amplifier. Finally, this amplified signal, as mentioned before, is recorded on magnetic tapes for later analysis.

As we have stated in Section 2, gravitational waves have a very weak interaction with matter. If we calculate the integrated cross section $\int_0^\infty \sigma_n(\nu)d\nu$ of a bar antenna of mass M , length L , radius R , and Poisson ratio σ , for a sinusoidal gravitational wave with optimum polarization, the result is (Paik & Wagoner 1976)

$$\int_0^\infty \sigma_n(\nu)d\nu = \left(\frac{8}{\pi}\right) \left(\frac{M}{n^2}\right) \left(\frac{G}{c}\right) \left(\frac{V}{c}\right)^2 \sin^4 \theta_i \left[1 + \frac{\sigma(1-2\sigma)}{2} \left(\frac{n\pi R}{L}\right)^2\right], \quad (18)$$

where n is the longitudinal mode number, V is the material sound speed, and θ_i is the angle the wave propagation vector forms with the bar axis. For the first longitudinal mode ($n = 1$) of the LSU antenna ($M = 2300$ kg, $L = 3$ m, $R = 0.6$ m, $V = 5.4$ km s⁻¹, and $\sigma = 0.345$) and $\theta_i = 90^\circ$, this equation gives 4×10^{-25} m² or 4 kbarn, which is 4.5×10^{24} times smaller than the bar's physical cross section area.

This equation tells us that we can increase the cross section if we use higher density materials or materials with a higher sound velocity. If we include a transducer which resonates at the same frequency as the bar antenna, the equation changes a little because the mechanical system is no longer a single harmonic oscillator, but now has two normal modes. However, the integrated cross section continues to be dependent on the first power of M and the second power of V . However, a more stringent equation is obtained if we take into account the noise involved in the process. We can define a noise temperature T_N which, when multiplied by the Boltzmann constant, is equal to the minimum energy deposited in the antenna by the GW pulse that can provide a signal to noise ratio equal to one after optimum filtering. The rms conventional gravitational wave strain amplitude for the bar antenna as a function of this noise temperature can be found to be, at $f \sim 900$ Hz for any of the current bar antennae, approximately equal to (Xu et al. 1989)

$$h = \frac{\pi}{4} \frac{1}{L} \sqrt{\frac{4k_B T_N}{M\omega^2}} \sim 10^{-18} \sqrt{\frac{T_N}{20 \text{ mK}}}. \quad (19)$$

This means that by decreasing the noise temperature or by increasing the mass one achieves a smaller h . More recently, resonant-masses have been using sensitivities \tilde{h} in units of Hz^{-1/2}. So, the dimensionless sensitivity h for bursts depends on \tilde{h} and on the bandwidth B . If \tilde{h} is a constant along the bandwidth B , for SNR = 1 and a 1 ms burst, h can be found using the following expression (Astone 2002):

$$h = \frac{\tilde{h}}{0.001} \sqrt{\frac{2}{\pi B}}, \quad (20)$$

(by the way, the expression which is valid for continuous monochromatic GW signals is completely different from the above one; there h becomes numerically much smaller than \tilde{h} , and the duration of the time that the data is accumulated is taken into account).

The noise temperature could be lowered by increasing the mechanical Q of the antenna, or by cooling the antenna with an He³-He⁴ dilution refrigerator down to 0.1-0.01 K together with the use

of less noisy transducers and amplifiers. A less noisy transducer can be obtained by increasing its mechanical and electrical Q 's, and a less noisy amplification can be achieved by the use of a D.C. SQUID preamplifier or HEMT amplifiers. The present state of the art SQUIDs can reach $\sim 2 \hbar$ of energy sensitivity (Awschalom et al. 1989) in units of J Hz^{-1} . The bandwidth can be expanded by the use of a transducer with more stages (Richard 1984) (bandwidth $= 2f_o\sqrt{\mu}$, where μ is the ratio between two consecutive masses). The mass can be increased by a factor of 15 by the use of a spherical antenna. This also has the advantage of being omnidirectional, of measuring all the GW polarizations, and of determining the direction from which the wave arrives (Forward 1971). Noise temperatures below the “standard Heisenberg quantum limit” for a 1 kHz resonant-mass bar detector ($T_N \approx \hbar\omega/k_B = 0.05 \mu\text{K}$) could be achieved by circumventing techniques that perform quantum non-demolition measurements (Thorne et al. 1979).

The first researcher to start proposing cryogenic detectors was William Fairbank from Stanford University, around the time of Weber’s first PRL paper (1966), Hamilton (2007, private communication). Fairbank discussed this idea with Bill Hamilton many times over the years. However, it was only when Weber strongly claimed evidences for the discovery of gravitational radiation (Weber 1969) that Fairbank proposed the construction of cryogenic detectors (Everitt et al. 1970). J. M. Reynolds, a professor at LSU, at that time suggested to Fairbank and Hamilton the use of a large available laboratory at the LSU physics building, initially constructed for a Van De Graaff accelerator, to house one of the bar detectors.

The experimental search for gravitational waves started in Italy at the University of Rome in 1970 September (the Frascati group of ESRIN, which took part in the Frascati-Munich collaboration, does not count as an Italian experiment, but rather as a European ESRO experiment). The group was formed initially by Edoardo Amaldi, Guido Pizzella and Massimo Cerdonio. Amaldi had attended lectures by Joe Weber in 1961 in Varenna and visited him at the University of Maryland in 1966. He was enthusiastic to start this experimental field in Italy, which became possible with the manifested interest of Pizzella and Cerdonio (Pizzella 2007, private communication).

In 1971 January Amaldi confidentially received the Stanford and Louisiana (Fairbank-Hamilton) proposal for a detector consisting of a 5 ton ultracryogenic (3 mK) aluminum bar antenna, equipped with a DC SQUID amplifier, and coupled to a resonant transducer by Remo Ruffini. This fact influenced the recently formed Italian group to collaborate in this effort. Pizzella, Cerdonio, Renzo Marconero, and Ivo Modena, with the help of Ruffini, visited Stanford, LSU, NASA, and Bell Labs to start collaboration on 1971 April 19 (Pizzella 2007, private communication).

A collaboration then started between Louisiana, Rome and Stanford for the construction of three 5-ton cryogenic detectors to be installed in the three locations (Pizzella 2007, private communication). The cryostats for the Stanford and Louisiana detectors were constructed at the Mississippi-NASA Test Facility Center in Louisiana (Boughn et al. 1974). The one in Rome was designed and constructed in Italy. However, at that time the technology for welding aluminum was not well known in Europe and the construction of a reliable big cryostat could not go fast. When the Rome group realized this they decided to suspend activities with the large cryostat and to continue the experiment through successive steps with smaller cryostats (Amaldi et al. 1978a) until the construction of ALTAIR ($M = 389 \text{ kg}$) (Amaldi et al. 1978b), Explorer ($M = 2.3 \text{ ton}$) at CERN (Fig. 4) and the ultracryogenic ($\sim 100 \text{ mK}$) Nautilus (initially $M = 2.3 \text{ ton}$, but now lighter for searching for the SN 1987A pulsar). The Rome group also constructed a bar, similar to Explorer, but which would operate at room temperature and was equipped with PZT and FET amplifiers. It was GEOGRAV, which was in operation by the time of SN 1987A (Aglietta et al. 1989; Pizzella 1988a). They also constructed the AGATA room temperature antenna. AGATA was installed in 1980 at CERN and in the beginning it was mainly used for tests. It later gathered data for long periods (Fafone 2007, private communication).

By 1976, both the groups in Stanford and Rome had already observed the mechanical Nyquist or Johnson (Brownian) noise at 4.2 K in their initial cryogenic gravitational-wave antennae (Boughn

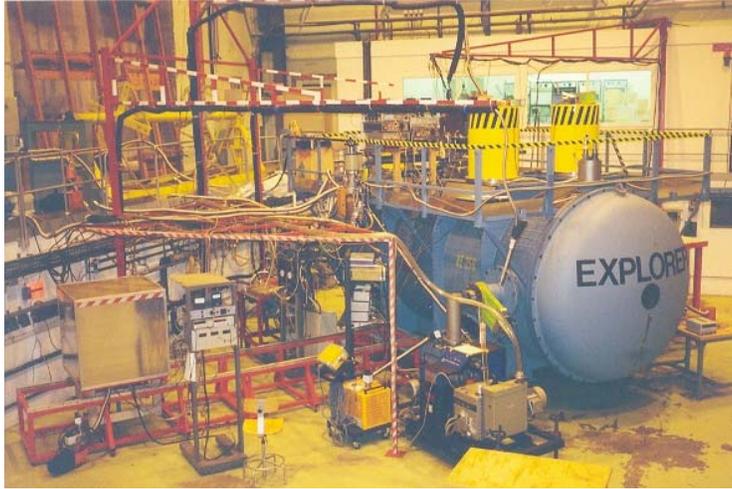


Fig. 4 Explorer detector at CERN (author's private collection).

et al. 1977; Amaldi et al. 1978a). The Stanford group was using a 680 kg aluminum alloy antenna, 0.4 m in diameter, 2 m long, covered with a 0.4-mm sheet of superconducting Nb-Ti, which was levitated by a magnetic field of 0.2 T. The antenna was resonant at 1315.3 Hz and presented an effective noise temperature of 0.39 K. On the other hand, the Italians used a small 30 kg bar, equipped with a large piezoelectric crystal and an FET electronic amplifier. The noise temperature obtained was ~ 10 K.

The Rome group achieved an important step by cooling and measuring the Brownian noise of an intermediate size antenna of ~ 400 kg (ALTAIR) (Amaldi et al. 1978b). Noise temperatures as low as 300 mK (0.3 K) were obtained (Amaldi et al. 1980). This showed the feasibility of cryogenic antennae. Seismic, acoustic and thermal disturbances were reasonably under control. The group felt ready to take the next step towards developing a large antenna again. Pizzella decided to install and operate it at CERN. An agreement was signed in which CERN would contribute with the buildings, cryogenic liquids and technical support. At the beginning of 1980 October, the Explorer cryostat started to be delivered at CERN (Pizzella 2007, private communication).

The Australian cryogenic Niobe project began in 1976 when David Blair came to the University of Western Australia (UWA). The UWA project was an informal collaboration with Stanford and LSU, initially led by Prof. Roy Rand, from SLAC, who came to UWA for 2 yr. LSU supplied a small 6 kg niobium bar which was made into a magnetically levitated system that achieved a noise temperature of 40 mK, a record in those days. The Australian group, then, developed a 1 m levitated niobium bar, which operated inside the Niobe dewar. They then went on to get the worlds biggest piece of niobium around 1982 and it took 10 yr to get cryostat, bar and suspension into working order. They had worked out that there was a maximum diameter that could be levitated (about 200 mm) and they abandoned magnetic levitation in favor of a multimode suspension. Around 1987, they demonstrated a Q factor of 240 million, a world record for any metal (Blair et al. 1977, Blair 2007, private communication).

The Tokyo University group, which was already a well established GW detection group operating room temperature detectors, constructed two cryogenic resonant-mass detectors for the search of low frequency continuous GW wave signals coming from the Crab pulsar, in collaboration with KEK (High Energy Accelerator Research Organization). They were

- CRAB III: 74 kg, 5056 aluminum alloy, 60 Hz torsion type antenna at 4.2 K, which reached a sensitivity of $h \sim 2 \times 10^{-21}$ for 1800 h of observation⁸;
- CRAB IV: 1200 kg, 5056 aluminum alloy, 60 Hz torsion type antenna at 4.2 K, which reached a sensitivity of $h \sim 2 \times 10^{-22}$ for 1900 h of observation (Suzuki 1995, Tsubono 2007, private communication).

The group at Moscow State University was working with a cryogenic very high Q ($\sim 2 \times 10^9$) silicon antennae with mass around 10 kg, and equipped with parametric transducers operating in the GHz region (Pizzella 1988b). There was another one in Rochester (USA), which was using a 1.2 m long and 0.3 m in diameter 5056 Al cylinder of 208 kg, resonant at 2302 Hz, and cooled to 1.6–4.2 K (Bocko et al. 1984), but they had discontinued operation by the mid 80s. The University of Maryland also built a cryogenic bar ($M = 1400$ kg, $L = 1.5$ m, 6061 Al, $f \sim 1700$ Hz) (Pizzella 1988b).

There was also a group in Regina (Canada). The antenna consisted of a single crystal of quartz with dimensions 30.5 cm by 2.5 cm by 1.9 cm and a rectangular cross section, 385 g of mass, resonant at 8846 Hz, with a mechanical $Q \sim 3.3 \times 10^7$ at $T = 1$ K. The crystal was gold plated at two opposite faces and soldered to the plates in the nodal plane were four headed wires from which the crystal was suspended and through which electrical contact was made. Because of the piezoelectric properties of quartz, the antenna was its own transducer. The crystal was cooled to a final temperature of 3×10^{-3} K in stages: liquid N, liquid He and three stages of adiabatic demagnetization. The detector was operated in the period 1979–1982 with a sensitivity of 2×10^7 erg cm⁻² Hz⁻¹ at a temperature $T \sim 1$ K, at which temperature the dominant noise was the noise temperature of the then available RF SQUID amplifier. Attempts to lower the RF SQUID noise temperature by constructing and adding a DC SQUID in front of the RF SQUID were not successful and the expected ultimate quantum limited sensitivity of $\sim 10^4$ cm⁻² Hz⁻¹ could not be reached. The experiment was abandoned shortly after (Davies 1980; Panini 2007, private communication).

The first bar antenna to reach a noise temperature below 50 mK was the one in Stanford in 1981 (Boughn et al. 1982). Perhaps one can say it was the first cryogenic resonant-mass antenna which was intended to be a gravitational wave detector to enter into operation. This antenna recorded data with an average noise temperature of 20 mK for about 74 d. However, this performance was never repeated in the following years. In 1986, for example, the noise temperature was around 50 mK.

Explorer began operation in 1985 November and the LSU antenna (later called ALLEGRO) started operation in 1986 (Pallottino 1987; Fairbank 1987).

Finally, after one and a half decades of development, involving resonant superconducting transducers, RF SQUIDS, and innovative vibration isolation systems, the first gravitational wave coincidence experiment between cryogenic resonant-mass detectors was finally achieved in 1986 (Amaldi et al. 1989). The groups involved were Louisiana, Rome, and Stanford. The bars were Explorer (at CERN, Geneva), the one later called Allegro (in Baton Rouge), and the 4800 kg Stanford bar (in Palo Alto). The data analyzed were collected during the period of 1986 April to July. Unfortunately, the three antennae were still far from the design sensitivity, they were also too vulnerable to non thermal noise, and the total time of triple simultaneous operations was only 55 h (60 h, according to my calculations, Aguiar et al. 1987). The Chinese group, with a room temperature detector in Guangzhou, also sent data to LSU to be analyzed together with the data from the three cryogenic detectors. No triple coincidences were found at all thresholds for the data exchanged and no zero time delay bins were above three standard deviations for any combination of two-detector data (among all four detectors). If real events were recorded in that period, they did not happen during those ~ 60 h (by the way, Guangzhou was not operating during this period) and they were not numerous enough to show up in the combinations of any pair of detector data. In spite of the null result, this coincidence experiment was a milestone in gravitational wave research.

⁸ Owa, S. 1987, Doctoral Thesis, University of Tokyo, unpublished.



Fig. 5 Stanford ultra-low temperature detector which was proposed in the late 60s by Fairbank, but never completed (picture taken during the Marcell Grossmann Meeting at Stanford, Palo Alto, in 1994) (author's private collection).

Paradoxically the successful 1986 coincidence experiment between the three cryogenic antennae was the reason why they were unprepared for the Supernova 1987A event in February of the following year. Well aware of the improvements the three groups should carry out on their detectors in order to increase their sensitivity, to diminish non-thermal noises (non-stationary or non-Gaussian noises), and to increase duty cycle (time operational/total time), they all decided to stop operation and implement the improvements. During the year of 1987, the LSU group, for example, completely redesigned the antenna support system, both in the low temperature region and on the outside of the dewar, in an attempt to minimize up-conversion (low frequency motion producing high frequency mechanical noise by non linear processes, such as friction) and to eliminate internal resonances near the antenna frequencies. They also stiffened the vibration isolation stacks, and redesigned the shape and dimensions of their composed masses. The previous loose support allowed large amplitude low frequency motions to be excited, which were believed to be the cause of non stationary noise in the data sets. A new antenna suspension system was introduced, now using a single 7 mm diameter titanium vanadium rod about the center of mass, which was attached at two points to a 2.4 ton bronze intermediate H-shaped mass to act as a stable mechanical ground for the antenna. They also added an extra liquid helium reservoir with capacity slightly under 600 liters, which increased the time required between helium transfers, and they introduced an aluminum mushroom shaped calibrator transducer. Finally, they also changed the antenna itself to the high Q 5056 Al alloy (Hamilton et al. 1987).

The 50 kpc away supernova SN 1987A event only had two room temperature bar antennae in operation: GEOGRAV (Rome) and Maryland. Although the expected sensitivity was not high enough for gravitational waves, a correlation was claimed between the two room temperature bars and the three neutrino detectors: Mont Blanc, Kamiokande and IMB around 2:40 U.T., five hours before the strong neutrino coincidence between Kamiokande and IMB (the famous 8+11 neutrinos) (Amaldi et al. 1987; Aglietta et al. 1989, 1991a,b; Dickson & Schutz 1995). Even if the correlation had something to do with SN 1987A, many questions have yet no answers. Which neutrinos were detected around 2:40 U.T.? Were they part of a pre-phase explosion? Did the bars detect gravitons from SN 1987A or some other particles that excited the bars by thermoelastic processes? In any case, we hope that another supernova will solve this problem.

Contrary to 1986, which was a great year for the second generation resonant-mass detectors, 1989 was a bad year: Amaldi and Fairbank died, and the Loma Prieto earthquake badly damaged the Stanford detector. These events were decisive for the future of the Stanford group. In the beginning they were unable to fix the 4.2 K detector, because the group was completely busy, involved in the construction of an ultracryogenic antenna at that time. Later, around 1994 or 1995, it became clear to NSF (the US National Science Foundation) that it would not make sense to support the construction of any resonant-mass detector in an earthquake area. This was a death sentence to the Stanford ultra-low temperature antenna (Fig. 5). Furthermore, it was too complicated to start a new ultracryogenic resonant-mass project (bar or sphere). A new world order was under way in the 90s (cold war had ended, among other things). This and other boundary conditions were pressing NSF in the direction of Big Science. The opening of other ultracryogenic resonant-mass projects, such as the LSU TIGA (Truncated Icosahedron Gravitational Antenna), would have to obtain, after a very well elaborated management plan, necessary agreements for operation of multiple facilities as a single experiment and to identify a strong and experienced project manager, as Richard Isaacson made clear in a Gravity Co-op meeting in Baton Rouge in 1995 April 7⁹. Furthermore, it would be very difficult for NSF at that time to approve two new big gravitational wave detection projects, such as LIGO and TIGA. The US physics and astronomy community would not accept that. So, only LIGO was approved, and new projects for ultracryogenic antennae would have to be done as isolated initiatives in other countries, but in close collaborations with each other.

5 THE THIRD RESONANT-MASS GENERATION AND THE REGULAR OPERATION OF THE BAR NETWORK IN THE 90s

Italy constructed the only two ultracryogenic bar antennae that ever went into operation: Nautilus and Auriga, shown in Figures 6 and 7, respectively. The construction was part of the original 1969 Fairbank plan to cool the bar to 3 mK (initially an American plan that the American groups could not ultimately accomplish). These two bars were “twins,” in the sense they were constructed from the same antenna and cryostat (dewar) design. Nautilus, named in honor of Jules Verne’s submarine ship, had its external shell painted green, and Auriga was painted yellow. Nautilus came first. Its initial tests at 4.2 K were performed at CERN during 1989, and in February 1991, the first ultra-low temperature (< 0.1 K) test of Nautilus of the Rome group was performed in the CERN laboratory (Astone et al. 1991). In 1992, Nautilus was moved to Frascati (Astone et al. 1995) and has stayed there ever since. Then, in July 1994, it was cooled again to ultra-low temperatures. On the other hand, Auriga’s lab was completed in 1992. The first cryogenic runs (using an FET amplifier instead of a SQUID) happened between mid 1995 to mid 1996, and the first ultra-cryogenic run began in February 1997 (scientific data started in May 1997) (Prodi & et al. 1998).

The 90s were the golden years for resonant-mass bar detectors already constructed. Most of the large baseline interferometers were under construction with one exception: TAMA300, which became operational at the beginning of 1999 (Arai & The Tama300 Project 2002), so most of the gravitational wave observations relied on the bar network of five state-of-the-art bars: Explorer (1990), Allegro (1991), Niobe (1993), Nautilus (December 1995), and Auriga (1997) (the year inside the parentheses is when the detector became operational for scientific runs) (Astone 2002; Fafone 2004).

Even though the situation was good for the operation of bars, it was not good for the proposal of new resonant-mass projects, in particular for sphere projects. There were already four project proposals (TIGA, GRAVITON, GRAIL, and SFERA) under way for the construction of truncated icosahedron and/or sphere antennae when the “Cryogenic Gravitational Wave Antennae: a Progress Workshop,” organized by Massimo Cerdonio, took place at the INFN in Legnaro (Padova) in 1993 June. However, none of them really became a reality before 2000 (de Waard & Frossati 2000).

⁹ Isaacson, R. 1995, overhead projector presentation



Fig. 6 Picture of the Nautilus detector (*open*) (courtesy of the ROG collaboration).

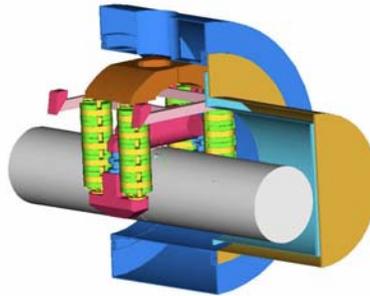


Fig. 7 *left*: Picture of the Auriga cryostat equipped with the room temperature commercial gas damper (*blue color*); *right*: Schematic of the Auriga detector partially sectioned. The toroidal liquid helium vessel is sky blue, the bar in gray and the column assembly of the cryogenic suspension is drawn in green and yellow (*courtesy of the Auriga collaboration*).

The major parameters for the five mentioned bar detectors are presented below^{10,11} (Astone et al. 2003):

EXPLORER: 2270 kg Al antenna, located at CERN (Geneva, Switzerland), cooled to 2.6 K, and equipped with a capacitive transducer and a SQUID amplifier;

ALLEGRO: 2296 kg Al antenna, located in Baton Rouge (Louisiana, USA), cooled to 4.2 K, and equipped with an inductive transducer and a SQUID amplifier;

NIOBE: 1500 kg Nb antenna, located in Perth (Western Australia, Australia), cooled to 5 K, and equipped with a parametric transducer and an FET amplifier;

NAUTILUS: 2260 kg Al antenna, located in Frascati (Rome, Italy), cooled to 130 mK with a liquid helium dilution refrigerator, and equipped with a capacitive transducer and a SQUID amplifier;

AURIGA: 2230 kg Al antenna, located in Legnaro (Padova, Italy), cooled to 200 mK, and equipped with a capacitive transducer and a SQUID amplifier.

¹⁰ <http://igec.lnl.infn.it/>

¹¹ http://arxiv.org/PS_cache/astro-ph/pdf/0302/0302482.pdf



Fig. 8 Locations of the five cryogenic bar detectors in the world which participated in the IGEC (International Gravitational Event Collaboration). All bars were usually kept oriented to the same direction in the sky. The way to do that was to keep them perpendicular to the Earth's great circle line shown in the map. This would optimize the GW signal correlation in energy, but would make them to lose the capability to determine the source direction (courtesy of the IGEC collaboration, <http://igec.lnl.infn.it/>).

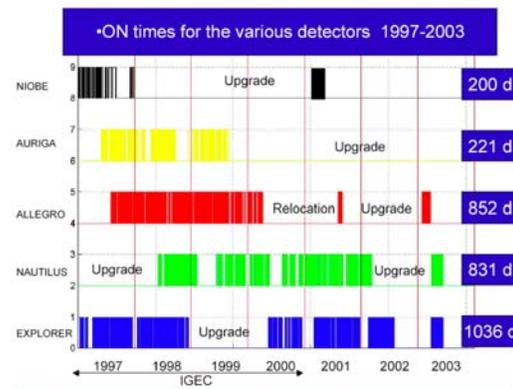


Fig. 9 Operational times of the network of detectors, from 1997 January to 2003 June (courtesy of the IGEC collaboration, <http://igec.lnl.infn.it/>).

Figure 8 shows the locations of the five bars, and the operational times of the network of detectors, from 1997 January to 2003 June, which can be seen in Figure 9. It is apparent that in that period of six and a half years (78 months) there were about two years of triple operation (three detectors on) and about four months of quadruple operation. Unfortunately, there was no period of the simultaneous operation of all five bar detectors. However, this figure demonstrated that the bar detectors achieved a reliable, high duty cycle and stable operation.

Today, the network¹² only has two detectors (Nautilus and Auriga). Niobe and Allegro are no longer in operation, and Explorer is being phased out to save money.

Niobe was a bar, which had good sensitivity from the beginning. In 1993, the Australian group achieved about a 4 mK noise temperature and was able to get the full parametric transducer system to operate reliably. Finally, on the last run in 2001, the group achieved about 600 microkelvin, but ran out of money and stopped operation. In that period, they determined the low interaction rate of cosmic rays with the bar (Blair 2007, private communication).

¹² <http://igec.lnl.infn.it/>

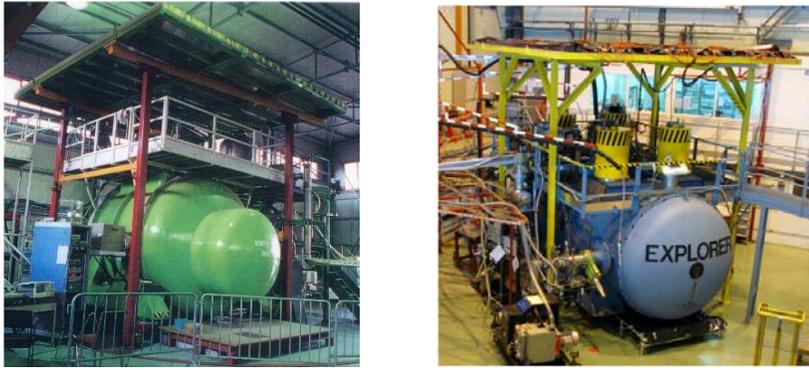


Fig. 10 Nautilus (*left*) and Explorer (*right*) detectors with streamer tubes placed above and below the cryostats for cosmic ray detection/veto (courtesy of the ROG collaboration).

Allegro has operated from 2004 February to 2006 with about a 96% duty cycle. It ceased operations in 2007 April 15, mainly because LIGO had surpassed its sensitivity around 900 Hz. However, LIGO will be upgraded to the advanced version in the period 2011–2013, so, perhaps Allegro should be put back into operation during this three-year period.

The Nautilus and Explorer detectors with streamer tubes placed above and below the cryostats for cosmic ray detection/veto are shown in Figure 10. The passage of cosmic rays has been observed to excite mechanical vibrations in resonant gravitational wave detectors with high sensibility (Astone et al. 2000), so these cosmic ray detections should be used for vetoing the times cosmic rays were registered.

6 THE PRESENT STATUS OF THE RESONANT-MASS GRAVITATIONAL WAVE DETECTORS

It was clear during the time that the interferometers were under construction or in their commissioning phase that the bar antennae should (if enough money was available) be kept in operation. After all, there was no other way to try to detect GWs. However, we are now in a situation where a network of highly sensitive interferometers is operational in scientific data collection mode. What will happen?

In order to answer this question, we should ask ourselves the following question: what have the bar detectors achieved? One of the major achievements made by the bar detectors was its high duty cycle and stable operation. As already mentioned, Allegro has operated from 2004 February to 2006 with about 96% of its duty cycle. Auriga has been operating with the same high duty cycle (96%) since 2005 May (it actually resumed operation in 2003 December). The duty cycles of Explorer and Nautilus were 87% and 86% in 2005, respectively, but in spite of that, in the period 2003–2004–2005, Explorer and Nautilus had an overlapping operation of 50% of the time on average (148.7 d, 218.5 d, and 182.1 d, respectively). Finally, Auriga-Explorer-Nautilus had a time period of triple overlapping operation in 2005 covering 130.7 d from May 20 to Nov 15 (180 d), or about 72% of the time during that period¹³(Giordano 2007, private communication). It will take some time before a network of interferometers reaches a similar performance.

What about sensitivity? Are they good enough for scientific runs? Figures 11, 12, and 13 present the sensitivity curves of the current four operational bar detectors. These noise curves are a composition of a few noise contributions, such as antenna and transducer thermal noises, amplifier noise, and

¹³ Second International Gravitational Event Collaboration (IGEC2)

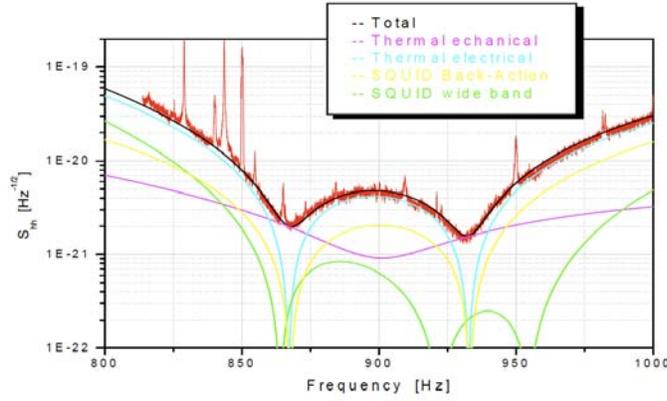


Fig. 11 Strain noise spectral density of the Auriga detector operating at 4.5 K, using a two stage low noise dc-SQUID amplifier. The agreement between the predicted value (*black curve*) and the experimental one (*red curve*) is quite good. The dominant noise source is the electrical resonator thermal noise (*sky blue curve*) except at resonances, where the antenna's thermal noise dominates (courtesy of the Auriga collaboration).

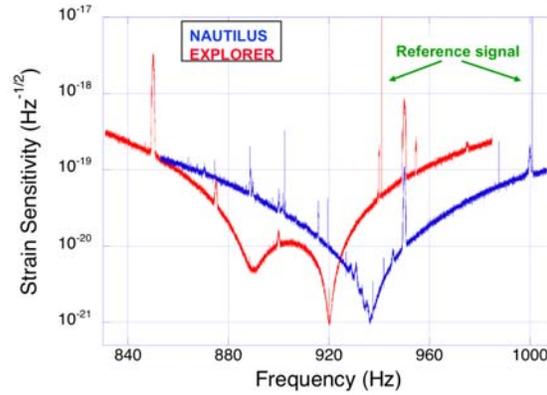
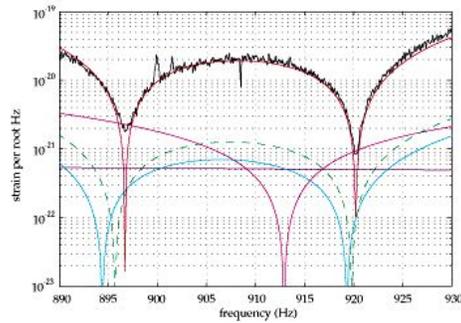


Fig. 12 Strain noise spectral density of Nautilus and Explorer detectors (courtesy of the ROG collaboration). The strain sensitivity is about $7 \times 10^{-22} \text{ Hz}^{-1/2}$ and the bandwidth is about 5 Hz. The sensitivity for 1 ms bursts is $h = 3 \times 10^{-19}$. The Nautilus antenna was machined in order to reach maximum sensitivity around the SN 1987A pulsar frequency.

back action noise; therefore the cooling of the antenna from 4.2 K to 100 mK does not necessarily improve the sensitivity curve if thermal noise, which is proportional to $\sqrt{T/Q_{\text{mec}}}$, is not the dominant one in the bandwidth. The initial results of the 2nd International Gravitational Event Collaboration (IGEC2) are shown in Figures 14, 15, 16, and 17. Some significant progress was achieved in bandwidth increase for all four detectors in the last few years, proving that resonant-mass detectors can be broadband detectors when better transducers and amplifiers are used. There was also a significant improvement in sensitivity from IGEC1 to IGEC2.

IGEC2 was the only GW observatory in operation from 2005 May 20 to November 15 (180 d) involving all four bar antennae, which were co-aligned (pointing to the same region in the sky). It

Measured Strain Noise Spectral Density of ALLEGRO



Measured strain noise spectral density of ALLEGRO and the various noise contributions which are predicted from the noise model of the detector.
 — Measured total noise, — antenna brownian, — transducer brownian,
 — transducer electrical loss, — SQUID white noise, — SQUID back action.

Fig. 13 Measured strain noise spectral density of the Allegro detector using a two stage low noise dc-SQUID amplifier (courtesy of the LSU Gravity Allegro group). The SQUID white noise is the dominant one for the whole bandwidth except at the resonances, where the transducer's Brownian noise dominates.

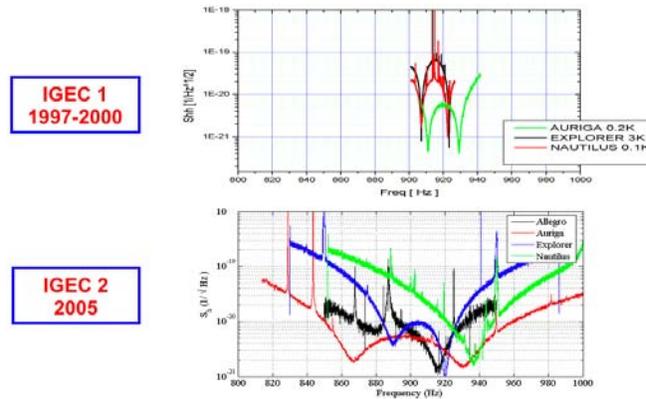


Fig. 14 From IGEC1 to IGEC2 (courtesy of the IGEC2 collaboration). Some significant progress was achieved in bandwidth increase for all four detectors in the last few years, proving that resonant-mass detectors can be broadband detectors with better transducers and amplifiers.

searched for a broader class of signals than IGEC1. Auriga, Explorer, and Nautilus exchanged data. The Allegro data were initially only available for a follow-up investigation, but they were added later. The search for GW burst signals was tuned to identify single candidates with high confidence. Only triple coincidences, which had a false alarm rate equal to 1/century, were searched. No candidates were found during the period. All four detectors presented high duty cycles and very low false alarms. Therefore, the identification of single candidates at low SNR was possible with very high confidence. The blind search (nobody knows the correct times of the event lists) in the statistical sense made the statistical interpretation non-controversial. IGEC2 also continued with four bars from 2005 November 6 until 2007 April 15, when Allegro ceased operation; the results, which appeared

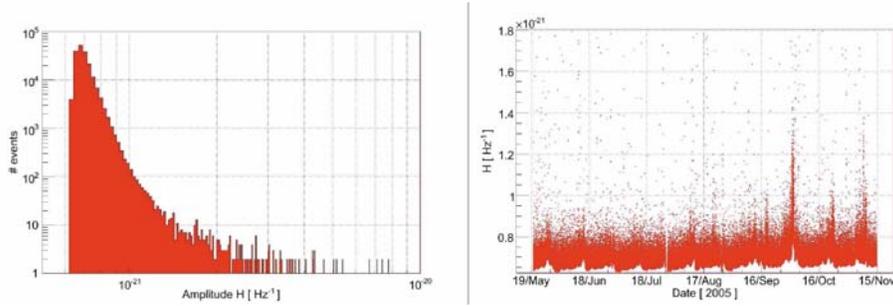


Fig. 15 *left*: Cumulative histogram for the search of impulsive events over 173 d (2005 May–November) of Auriga data. The threshold is $\text{SNR} = 4.5$ and the total number of events is 186 911; *right*: Strip chart of the Auriga candidate events during the same period. It becomes evident that the detector works in a very stable configuration with a small number of outliers above $\text{SNR} = 6$ (12 per day). The short breaks occurring every two weeks come from the ordinary cryogenic operations (liquid helium refill) (courtesy of the Auriga collaboration). Explorer and Nautilus, which have sensitivities about 2.5 times worse, present similar curves, but their curves are displaced to the right by a factor of 2.5, towards higher H s (strain in Hz^{-1} units).

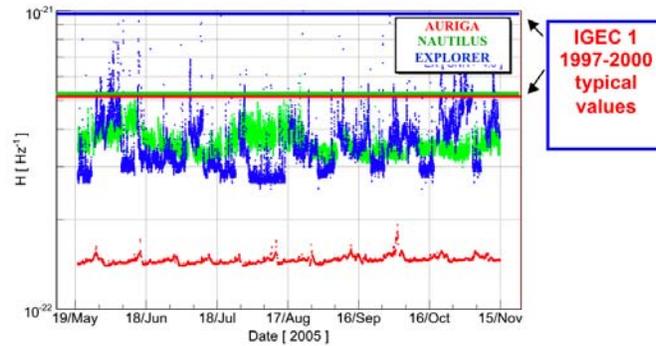


Fig. 16 Noise of the Detectors is plotted versus Time in terms of the Fourier component H (courtesy of the IGEC2 collaboration). There was also a significant improvement in sensitivity from IGEC1 to IGEC2. The data exchanged between detectors considered thresholds around $\text{SNR} > 4$ for Explorer and Nautilus and above 4.5 for Auriga.

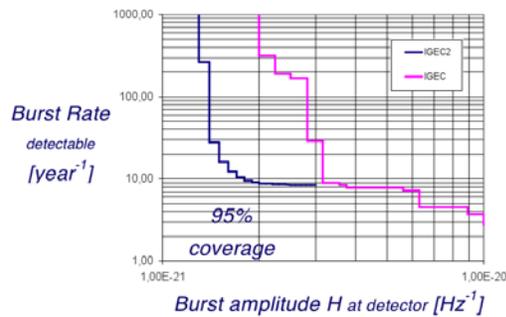


Fig. 17 Burst rate as a function of burst amplitude (in Hz^{-1}) (courtesy of the IGEC2 collaboration). Only the regions on the left or under the curves are not eliminated.

recently (Astone et al. 2010), span the longest ever period of time with four detectors in simultaneous operation about 300 d. No coincidences were found when tuning the search in a “detection mode” and allowing for less than 1 false alarm/century. IGEC 2 has been thereafter discontinued and the Italian bars performed their searches with the initial LIGO and Virgo interferometers (Acernese et al. 2008; Baggio et al. 2008). Since the laser interferometers LIGO and Virgo are due for a shut down by the end of 2010, for their upgrades to the advanced versions, Auriga and Nautilus (Explorer is being phased out to save money) will continue to be on the air for an “astrowatch” of Galactic Supernovae and of other strong signals until LIGO/VIRGO can resume operation (Massimo Cerdonio 2010, private communication).

In spite of the outstanding performance of the current bar detectors, if one compares these sensitivity curves with the ones presented by the best laser interferometers’ performances around 900 Hz, the bars have been surpassed. Overall, however, considering their stability and high duty cycles, they still should be kept operational, because a burst event related to GW detection can happen any-time. Therefore, continuous operation with high duty cycle is necessary. Furthermore, they would detect the wave using another physical principle: energy absorption from the wave, instead of direct geodetic deviation caused by its passage.

Can resonant-mass detectors do better in sensitivity? Can they reach the standard quantum limit?

The *standard quantum limit* (SQL) (Thorne et al. 1979) is the minimum level of noise which can be obtained *without* the use of squeezed states. When we are not able to “squeeze” the signal with the transducer (or to perform the measurement with uncertainties in amplitude and phase with different magnitudes), the smallest value of measurement that one can do is the SQL. A resonant-mass antenna (bar or sphere) is a harmonic oscillation whose amplitude and phase are sampled (measured) many times per second in order to detect the arrival of gravitational waves. If the transducer is of the passive type, such as used by all current bars, in which a DC voltage or a DC superconducting current is running in the circuit, there is no way to control the (*quantum*) *demolition* one measurement produces in the next immediate measurement of amplitude and phase. If, however, an active transducer is used, such as a parametric transducer in which an AC power biases the circuit, it is possible to do *quantum non-demolition* (QND) (Braginskii et al. 1980) or, if the classical noises are still dominant, to do *back-action evasion* (Speitz et al. 1984; Bocko 1986). Optical transducers (Conti et al. 2003a,b) or microwave parametric transducers (Speitz et al. 1984) can circumvent this *standard quantum limit* and do a measurement with arbitrary precision. The “only” problem is to decrease the classical noises to the level of the *standard quantum limit* and to implement this artifice keeping the same stability and high duty cycle that bar detectors have achieved using passive transducers. So, better transducers and better amplifiers should be built if one wants to reach the *standard quantum limit*, or even surpass it. This question has been addressed by the fourth generation of resonant-mass detectors: spheres and dual detectors, which will be presented in the next section.

7 THE SPHERICAL ANTENNAE AND OTHER RESONANT-MASS PROPOSALS FOR GW DETECTION, AND THEIR PROSPECTS FOR THE FUTURE

One can increase the sensitivity of a resonant-mass detector by maximizing signal-to-noise ratio. Maximization of the signal to noise ratio can go in two directions: the minimization of noise or the maximization of signal. If it is hard to decrease the noise, one can try to increase the signal. A GW antenna with a spherical shape (massive or hollow) seems to be the best solution for a given choice of frequency; because it maximizes the GW absorption (the transformation of gravitons into phonons) and is omnidirectional (it has equal sensitivity in any direction). Robert Forward, one of Weber’s former graduate students in the early 60s, was the first to realize this (Forward 1971). Almost nobody paid any attention to his idea at the time, as Weber had claimed in 1969 that coincidences had been observed. In 1971, all the groups involved in GW detection either had already started the construction of their bar antennae or had already submitted their proposals; in both cases they were willing

to repeat Weber's experiment as close as possible, using only bars. Only a few researchers (Neil Ashby, Joseph Dreitlein, Robert Wagoner, and Ho Jung Paik) (Ashby & Dreitlein 1975; Wagoner & Paik 1977) performed some theoretical speculations about this new shape for a GW resonant-mass antenna in the years that followed. Then, ten years passed before Warren Johnson, who had already moved to LSU (from Rochester), revived Forward's idea in 1988. In 1989, LSU presented it at GR12, in Boulder, Colorado (Hamilton 1990b,a). It would have been nice if NSF had supported a spherical antenna project at that time (1989). I personally talked to Richard Isaacson about this at the conference cocktail, who acknowledged that a GW spherical antenna was an old idea (I will never forget that he was wearing Bermudas, black shoes, and black socks). Unfortunately this was another brilliant American idea, along with Fairbank's ultra-low temperature bar, neither of which was ever implemented in USA.

In 1988, LSU started a solid line of research about spherical antennae, actually polyhedron antennae (in order to facilitate the transducer's attachment to the antenna surface). Norbert Solomonson and I were too busy being involved with our transducer development, so Warren and Bill Hamilton had to rely on the work of undergraduate students in the beginning. When Stephen Merkowitz, who graduated from the University of Colorado and who had attended GR12, joined LSU as a graduate student, things started getting better. Warren and Stephen discovered the minimum transducer arrangement, which would make the antenna omnidirectional, and called it TIGA: Truncated Icosahedron Gravitational Antenna. The arrangement was to place six transducers on six non-opposite pentagonal faces of a truncated icosahedron (Johnson & Merkowitz 1993). They demonstrated that TIGA could absorb 56 times more energy from a passing gravitational wave than the "equivalent" bar. Figure 18 shows the first room temperature TIGA constructed by LSU. Another twin TIGA went to the Rome University group. Both were machined from an old LSU 6063 aluminum bar. Their diameters were 84 cm¹⁴.

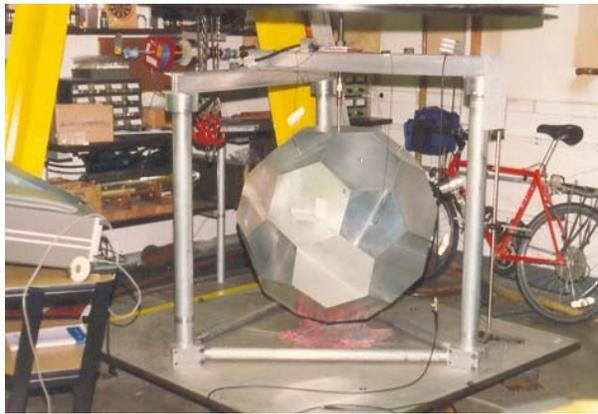


Fig. 18 LSU TIGA, with which Stephen Merkowitz did his thesis work (his bike gives an idea of the size of the antenna) (author's private collection).

Soon after finishing my Ph. D. program at LSU in 1990 December (I was officially on leave from the *Instituto Nacional de Pesquisas Espaciais* - Inpe (National Space Research Institute) since 1984 to develop such a program), I began talking about starting a gravitational wave detection project involving the construction of a spherical antenna in Brazil. Laser interferometers were too expensive

¹⁴ Merkowitz, S. 1995, Ph.D. Thesis, Louisiana State University, unpublished.

for the country, a fact I had already realized in the early 80s, when I received many letters from experimentalists using both techniques (bars and lasers) mentioning detector costs for construction. I received the green light from Inpe around March 1991 to get involved with this research activity. One of the first people I talked to about this project was Prof. José Antônio de Freitas Pacheco, who gave me a list of people involved with the Virgo laser interferometer collaboration in Brazil since October 1989. They were Mauro Cattani, Armando Turtelli, Nilton O. Santos, Carlos Escobar, and himself. He also gave me a longer list which included people that I could talk to about my idea, such as Jorge Horvath and José Carlos N. de Araujo. Pacheco and Escobar at that time had two doctoral students: Nadja S. Magalhães and Walter Velloso, who joined the Graviton group. Many others followed. The name Graviton, which is suitable for a detector whose principle of operation was to absorb quanta of energy from the GWs, came from a meeting at Mario Novello's house in Rio around 1991 February. Luis Alberto R. de Oliveira suggested this name.

Carlos Escobar, who is heavily involved in the Auger project nowadays, arranged a meeting between me and Giorgio Frossati in his office at the University of São Paulo (USP) in 1993 January. Giorgio, an expert in dilution refrigerator development and a respectable researcher in low temperature physics, who had lived in Brazil from 1947 to 1970, had been enthusiastic about gravitational waves since the publication of Weber's first papers. The cooling of a giant spherical antenna weighting dozens of tons was a challenge he relished facing and this was an opportunity for him to pursue this research in the Kammerlingh Onnes Laboratory, in the Netherlands. Five months later, he had already presented the proposal for the construction of Grail, a 30 ton, 2.6 m in diameter, aluminum alloy spherical antenna cooled to 10 mK (Boswell 1993; Frossati 1994, 1996, 1997a), at the Legnaro workshop (organized by Massimo Cerdonio). This had a cascade effect. The contacts he made before the workshop with the Rome group motivated it to submit a proposal for Sfera, a similar antenna, in Italy, which, in turn, stimulated LSU to propose TIGA to NSF in the US. The Graviton project, which had already been informed to the gravity community at the Marcel Grossmann Meeting in Kyoto in 1991 (by a letter of intention) and had been presented as a contributed paper (poster) at GR13, in 1992¹⁵, had to wait a few years in order to study the project viability (including a search for a site) and to form a group, before being submitted to the Ministry of Science and Technology (MCT) and FAPESP in Brazil in 1996 and 1998, respectively.

During the 90s, many studies regarding spherical and polyhedral shaped antennae were performed world-wide (Johnson & Merkowitz 1993; Frossati 1994; Coccia et al. 1995a; Magalhaes et al. 1995; Merkowitz & Johnson 1995; Lobo 1995; Coccia et al. 1995b, 1996; Lobo & Serrano 1996; Merkowitz & Johnson 1996; Harry et al. 1996; Magalhaes et al. 1997; Stevenson 1997; Merkowitz & Johnson 1997, 1998; Merkowitz 1998; Merkowitz et al. 1999). A detector with a spherical antenna can determine the wave polarization and localize its astrophysical source in the sky for all gravitational wave signals detected in any given gravitational theory (Forward 1971; Bianchi et al. 1996). Furthermore, it is never "blind" to any particular direction or polarization of the arriving wave (Merkowitz & Johnson 1995). Both these advantages of a spherical antenna are due to its omnidirectionality achieved by the use of six transducers placed in accordance with the truncated icosahedron configuration monitoring the quadrupole modes plus a transducer monitoring the monopole "breathing" mode (Johnson & Merkowitz 1993; Coccia & Lobo 1996). Another very important advantage of this kind of detector is precisely due to fact that it has many transducers monitoring many quadrupolar modes. It is like having many detectors operating together at the same time and site (Coccia et al. 1995b). So, you can perform real time data analysis looking for correlations between the signals of the transducers, which is impossible to do using detectors located at different sites.

The Dutch group, in collaboration with the Rome group, also made significant progress in finding a suitable material for the antenna with high density (8 g cm^{-3}), high mechanical Q ($\sim 2 \times 10^7$), and non-superconductivity at ultra-low temperatures ($\sim 15 \text{ mK}$). The group tested many

¹⁵ Aguiar, O. et al. 1992, in the Graviton Project, in Abstracts and Contributed Papers of the GR13 Conference, Universidad Nacional de Córdoba, Córdoba, ed. P. W. Lamberti & O. E. Ortiz, Universidad Nacional de Córdoba, Córdoba, 455.

small spheres at these temperatures (Coccia et al. 1996; Frossati 1997b). Some of them are shown in Figure 19.

The Grail project was rejected in the Netherlands, so the Dutch group, in collaboration with the Rome group and the Brazilian group, decided to build Mini-Grail. This became the first spherical antenna for gravitational waves when it started operation at ultra-low temperature (~ 80 mK) using three transducers, in 2004. The second spherical antenna to go into operation was Schenberg at 5 K from the Brazilian group, in September 2006, also with three transducers. Both detectors are now in the commissioning phase and are expected to soon begin their scientific operations.

The Dutch Mini-Grail detector is shown in Figure 20. It is composed of a cryogenic 68 cm in diameter spherical gravitational wave antenna made of CuAl (6%) alloy with a mass of 1400 kg, a resonance frequency of 2.9 kHz and a bandwidth around 230 Hz¹⁶(de Waard et al. 2005).

Figure 21 shows a schematic view of the Brazilian Mario Schenberg detector at the Physics Institute of the University of São Paulo, in São Paulo city (Aguiar et al. 2002). The Schenberg CuAl6% antenna has a diameter of 65 cm and weighs 1.15 tons. The mechanical Q (figure of merit) of the antenna is 2.7 million at $T = 2$ K, and it seems to follow the expression $Q = 4.9 \times 10^6 T^{-0.86}$ (Aguiar et al. 2004). It has nine little holes on its surface for up to nine transducers, six of which follow the TIGA configuration¹⁹. At the *standard quantum limit* sensitivity, it will have a strain noise spectral density of $\sim 10^{-22} \text{ Hz}^{-1/2}$ (Tobar et al. 2000). Further improvement can be made because parametric transducers are able to squeeze signal and surpass the *standard quantum limit*. The construction was fully supported by FAPESP (the São Paulo State Foundation for Research Support) and started around 2001.

Both spherical detectors will operate in coincidence with each other, along with some long baseline laser interferometer detectors (Aguiar et al. 2004), searching for high frequency events in the 2.7–3.4 kHz frequency bandwidth. For the GW signals that contribute with power in both bandwidths (~ 900 Hz and ~ 3 kHz), such as some types of bursts, the coincidence is even possible with the bar detectors.

Each one of the five quadrupole modes of the Schenberg sphere has an effective mass for a quadrupole oscillation of 287 kg. These five independent modes will be coupled to the modes of six transducers, which have oscillating masses of 53.6 g and 10 mg. All these modes are tuned to the ~ 3.2 kHz resonant frequency and the energy flowing from the sphere modes to the 10 mg transducer masses due to this coupling produces an amplitude gain of about $(287 \text{ kg } 10 \text{ mg}^{-1})^{1/2} \sim 5 \times 10^3$ (Richard 1984; Pang & Richard 1992). The 10 mg transducer mass is the effective mass of a membrane that closes the microwave klystron cavity and forms a 0.1 mm gap with the top of the cavity post. This membrane is made of pure silicon (Fig. 22) and is supposed to have high mechanical Q .

This kind of parametric transducer used by the Schenberg detector was studied and developed by both the Japanese (Fujisawa 1958; Tsubono et al. 1977, 1986) and the Australian (Blair & Mann 1981) groups. In the same way as the Australians were doing with Niobe, the signal is sent to and received from the transducers by pairs of microstrip antennae, so no wires or coaxial cables touch the spherical antenna (Fig. 23). The preamplifiers, which use HEMT technology, as the Australian group was planning to do with Niobe (Tobar 2000), have a noise temperature of 8–10 K, which corresponds to 12–14 \hbar in sensitivity at 10 GHz ($T_n = 9 \text{ K} \sim 13 \hbar \omega/k_B \ln 2$) (Heffner 1962). However, as described above, we have changed the mechanical design of this transducer (Aguiar et al. 2006).

We believe this mechanical *innovation* in the transducer design was a good decision in order to increase the antenna's sensitivity and to reach the *standard quantum limit* (Caves et al. 1980; Braginskii et al. 1980). The drastic change in the last mass of the antenna-transducer's resonant chain from the Niobe bending flap mass, which was around 0.43 kg, to just 10 mg (Ribeiro et al. 2002) gave

¹⁶ <http://www.minigrail.nl/>



Fig. 19 *left*: The Dutch setup (dilution refrigerator + sphere + hammer + PZT sensor) for measuring mechanical Q of small spheres (author's private collection); *right*: Some of the small spheres tested (author's private collection).



Fig. 20 Mini-Grail detector. *left*: Schematic view of the Mini-Grail detector. Six capacitive transducers distributed according to the truncated icosahedron (TIGA) arrangement proposed by Johnson and Merkwitz will monitor their fundamental modes of vibration; *middle*: The detector lifted by the hydraulic system (from left to right: José Carlos N. de Araujo, Arlette de Waard, Odyllo D. Aguiar, and Ho Jung Paik. Giorgio Frossati took the picture in 2004 July; *right*: Details of the Mini-Grail antenna equipped with a dilution refrigerator (courtesy of the Mini-Grail group, <http://www.minigrail.nl/>).

this kind of transducer many advantages. Firstly, the pump requirement of phase noise to achieve the standard quantum limit of sensitivity dropped from -180 dBc Hz^{-1} to only -145 dBc Hz^{-1} , which is a much more feasible goal. Secondly, a high electromechanical coupling can be accomplished with only a few nanowatts of pumping power, which is excellent news for one trying to cool the antenna down to the lowest thermodynamical temperature possible. Thirdly, the amplitude gain, which is related to the square root of the ratio between the last mass of the antenna-transducer's resonant chain and the antenna's effective mass, increases from ~ 26 to $\sim 5.4 \times 10^3$. Finally, the need for carrier suppression for maximum HEMT performance (they require less than -80 dBm at the input (Ivanov et al. 2000)) will also decrease, because the power injected in the cavity is smaller.

Figure 24 shows the predicted strain noise spectral density considering conservative parameters and the Schenberg antenna operating at 4.2 K . The various components of the noise curve of one mode channel can be seen. Far away from the optimum sensitivity, the electronic noise dom-

inates. At the optimum sensitivity, thermal noise dominates. The histogram of the optimal linear filter output for a short burst signal, using the best 12 h of the first commissioning run of Schenberg, is shown in Figure 25. It presented an absence of outliers outside the Gaussian noise distribution. However, its sensitivity is not as good as the outstanding sensitivity reached by Mini-Grail on its first commissioning run in 2004, which is shown in Figure 26.

The map with the locations of the bars, interferometers, and spheres is presented in Figure 27.

The expected sensitivity for a 2 m sphere, such as the SFERA detector (SFERA: Proposal for a Spherical Gravitational Wave Detector, 2005), involving a collaboration between Italy, Switzerland and the Netherlands, is shown in Figure 28. The curve represents the sensitivity that can be achieved with a read-out at the quantum limit. For a $20 \hbar$ SQUID, the sensitivity worsens by a factor of only



Fig. 21 Mario Schenberg detector. *left*: Schematic view of the Schenberg detector. Six parametric transducers distributed according to the truncated icosahedron arrangement proposed by Johnson and Merkwitz will monitor their fundamental modes of vibration; *middle*: The Schenberg detector lifted by the hydraulic system; *right*: Details of the antenna with three transducers installed. The three cryogenic HEMT amplifiers are on the top, just below the liquid helium reservoir.

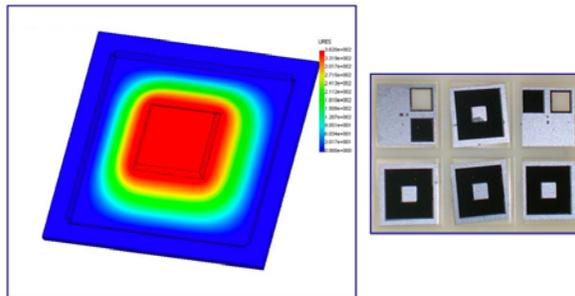


Fig. 22 Silicon membrane: *left*: Photolithograph membrane design and results of a numeric simulation for the fundamental mode using the software Cosmos. The amplitude scale, in microns (10^{-6} m), is shown on the right; *right*: Picture of the first membranes made. It is possible to produce them with a thickness of $20 \pm 1 \mu\text{m}$ and with an island in the middle to adjust the value of the effective mass.



Fig. 23 Details of the Schenberg pair of microstrip antennae positioned in front of each other. The microwave pump signal from the very low phase noise oscillator jumps from the antenna on the right to the antenna on the left. The later sends the signal to the klystron cavity. Then, the modulated signal jumps back and, thanks to a circulator (which is just above the right angle plug-plug SMA connector), is sent to a cryogenic HEMT preamplifier.

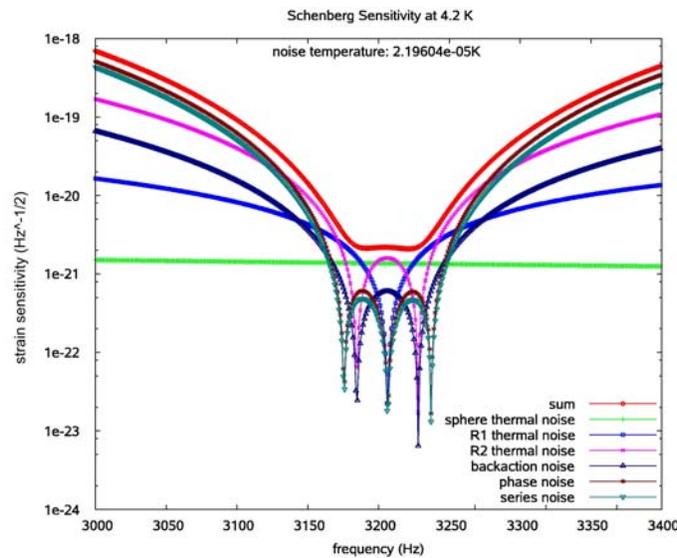


Fig. 24 Schenberg sensitivity curve at 4.2 K (*red line*) for a single quadrupole mode and the individual contributions of the noise sources.

4–5. On the other hand, by the use of parametric transducers and by squeezing the signal sensitivities, better than $10^{-23} \text{ Hz}^{-1/2}$ can be achieved.

Spherical self-gravitating bodies, such as the Earth, the Earth's moon and other moons (Mars e.g.) were also considered as gravitational wave antennae (Ashby & Dreitlein 1975; Johnson 1990; Paik 2004). If the deployment of sensors on these bodies is technologically and economically feasible, it would be a way to search for GWs below 10 Hz. Interesting science could be done in this frequency bandwidth such as pulsar search, the study of binary systems of many types, supermassive black holes, and cosmological background search (coming from the inflationary period or from a pre-big bang universe) (Thorne 1987; Gasperini & Veneziano 2003).

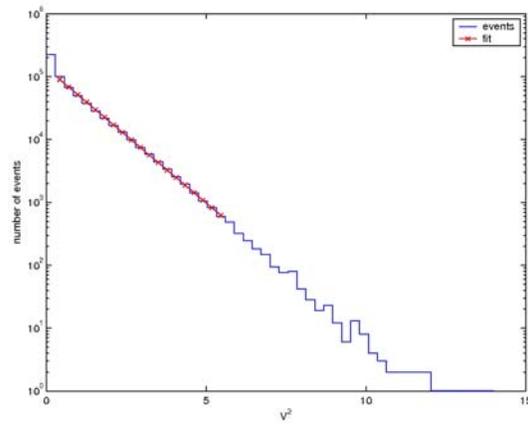


Fig. 25 Histogram of the optimal linear filter output for a short burst signal using the best 12 h of the first commissioning run of Schenberg. It presents an absence of outliers outside the Gaussian noise distribution.

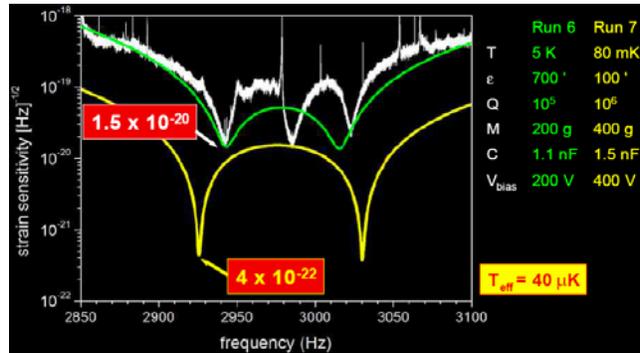


Fig. 26 Mini-Grail sensitivity (*white curve*) in the first commissioning run (6th overall cryogenic run) and the prospects for the next (7th) run (*yellow curve*) are shown (courtesy of the Mini-Grail group, <http://www.minigrail.nl/Presentations/LISA-GR17-2004.pdf>).

The present resonant-mass detectors do not have bandwidths as large as the ones laser interferometers have. The multi-mode solution proposed by Richard in 1984 (Richard 1984) or the more exotic Paik solution (Paik et al. 1996) have some practical limitations. An obvious way to circumvent this problem is by the use of a set of resonant-mass detectors, with each of them being tuned to a different frequency in such a way as to cover a large overall bandwidth. This is the so called “xylophone” solution (Johnson & Merkowitz 1993; Harry et al. 1996). Another approach is the Dual detector proposed by the Auriga group.

In a Dual detector, the relative motion between two massive bodies must be measured, avoiding noise contributions from the lighter resonant transducer. A Dual detector can be formed by two nested massive bodies whose quadrupolar modes (i.e. the modes sensitive to the GW signal) resonate at different frequencies. In reference (Cerdonio et al. 2001), the two resonators are two spheres, a full inner one and a hollow outer one. A dual cylinder configuration has also been evaluated (Bonaldi et al. 2003). These two configurations are shown in Figure 29. The signal is read in the gap between



Fig. 27 State of the art cryogenic resonant-mass detectors and interferometers around the world (courtesy of the ROG collaboration).

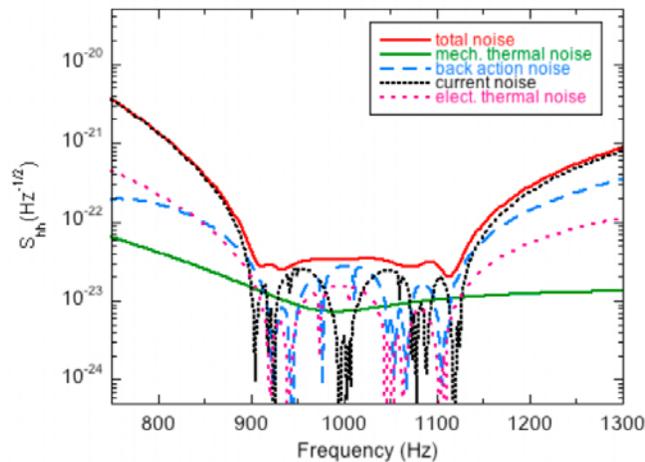


Fig. 28 Calculated strain noise spectrum for a 2 m in diameter CuAl sphere. The sphere is equipped with six transduction chains in the TIGA configuration, with noise at the quantum limit (SFERA proposal). For a $20 \hbar$ SQUID, the sensitivity worsens by a factor of only 4–5 (courtesy of the SFERA collaboration).

the two masses as their differential deformations: the centers of mass of the two bodies coincide and remain mutually at rest while the masses resonate, thus providing the rest frame of the measurement (Bonaldi, for the Auriga collaboration, 2007, private communication).

It can be shown that the response to GW excitation is preserved at any frequency between the resonances of the two test masses, while the response to the back action noise force, which acts out-of-phase with respect to the two resonators, tends to be reduced (because it acts with opposite sign on

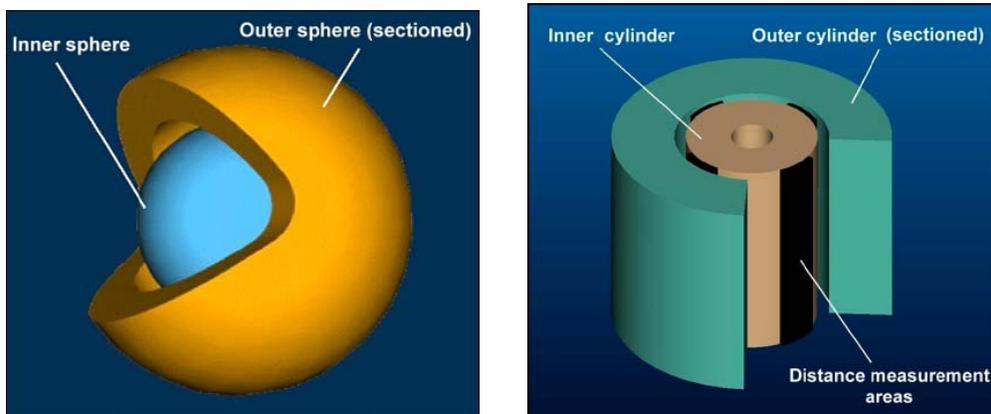


Fig. 29 Different Dual detector configurations are shown: *left*: the dual spheres; *right*: the dual cylinders (courtesy of the Auriga collaboration).

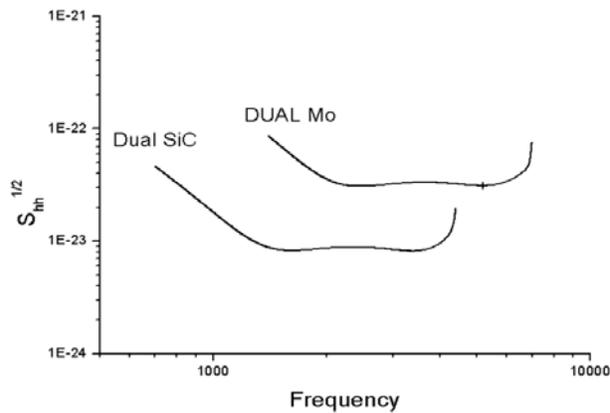


Fig. 30 Sensitivity curves for two dual detectors: Dual SiC detector (inner cylinder radius 0.82 m, outer cylinder internal-external radius 0.83–1.44 m, height 3 m, weight 20.5–41.7 ton, fundamental quadrupolar modes 3281 Hz and 596 Hz, amplifier noise $S_{xx} = 6 \times 10^{-46} \text{ m}^2 \text{ Hz}^{-1}$, $Q/T > 2 \times 10^8 \text{ K}^{-1}$) and Dual Mo dual detector (inner cylinder radius 0.25 m, outer cylinder internal-external radius 0.26–0.47 m, height 2.35 m, weight 4.8–11.6 ton, fundamental quadrupolar modes 5189 Hz and 1012 Hz, amplifier noise $S_{xx} = 10 \times 10^{-46} \text{ m}^2 \text{ Hz}^{-1}$, $Q/T > 2 \times 10^8 \text{ K}^{-1}$) (courtesy of the Auriga collaboration, in this case: M. Bonaldi, M. Cerdonio, L. Conti, M. Pinard, G. A. Prodi, L. Taffarello and J. P. Zendri) (Bonaldi et al. 2003).

the facing bodies). The sensitivity of the dual detector is predicted to be of interest in the frequency range between the first quadrupolar modes of the two masses. This can be as broad as a few kHz in the kHz range. Of course, the transducer system is required to be wide band and suitably adapted, i.e. to provide the optimal balance between the displacement noise and the back-action force noise (Bonaldi, for the Auriga collaboration, 2007, private communication).

In Figure 30, the sensitivity curves of two dual detectors can be seen. These curves could be considered as having the maximal sensitivity possible with these detectors. The possibility to reach

such results strongly depends on supportive researches, mainly on the material properties and on the readout sensitivity. Better sensitivities could only be obtained with larger detectors, which we consider to be hardly attainable with present technologies.

The limited bandwidth of traditional acoustic detectors is due to the usage of the resonant transducer, which is needed to reduce the effect of the noise of the amplifier. In this case, bandwidth enhancements can be obtained by the use of properly optimized readouts, but the thermal noise contribution of the resonant transducer limits the bandwidth to about 10% of the detector's central frequency (Bonaldi, for the Auriga collaboration, 2007, private communication). A revolutionary solution would be if one goes back to the old 70s idea of non-resonant transducers, but now using a “super transducer” with an ultra high sensitivity (ultra-high df/dx , for example) and very high electrical Q in order to decrease the influence of all the noises associated with the electrical and amplifier parts. In this case, the dominant noise would be the antenna's Brownian, which is white, and so the detector would be broadband (Tobar, 2004, private communication). This solution was impossible in the 70s, but it may soon become possible with nanotechnology.

Applying this idea, a xylophone of a few spheres was proposed to cover a very large bandwidth using only six non-resonant transducers each¹⁷. The array of spheres mentioned in previous works (Johnson & Merkwitz 1993; Harry et al. 1996) required a larger number of spheres than the present proposal, and each of them with a much larger number of resonant-transducers (a set of transducers for each order of quadrupole modes). In Figure 31, the sensitivity curve of an array of six spheres (in which the Schenberg is the larger one) is shown using six non-resonant transducers.

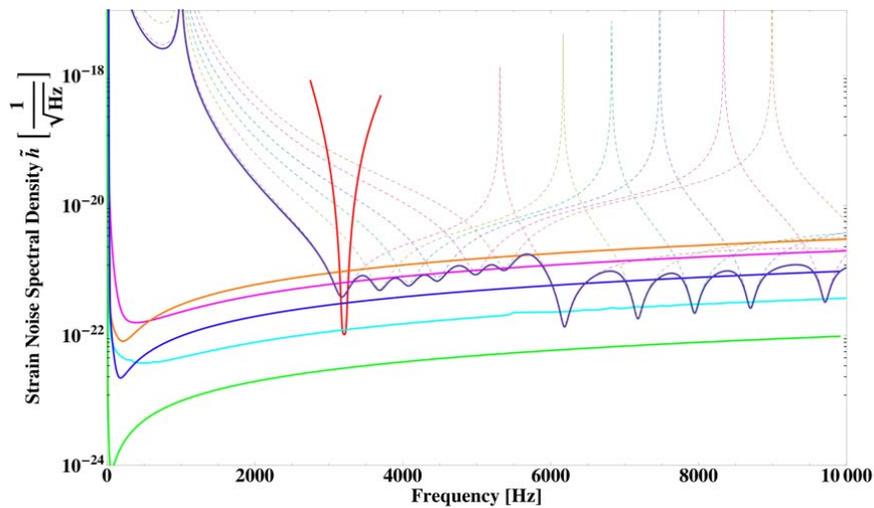


Fig. 31 Sensitivity curve for the Schenberg broadband detector using a nanogap klystron cavity non-resonant transducer. The dashed curves represent each of the six spheres we chose for the array (masses: 1150 kg (Schenberg), 744, 547, 414, 301 and 239 kg), with the lowest frequency being the Schenberg case. The V-shaped red curve is the Schenberg case with its usual configuration operating at dilution refrigerator temperatures (~ 10 mK). Interferometer curves are also plotted: advanced LIGO (*green*), LIGO (*blue*), TAMA300 (*pink*) and GEO600 (*orange*). All of these are projected curves, not actual data.

¹⁷ Aguiar, O. et al. 2009, Honorable Mention Award Essay by the Gravity Research Foundation

Spherical detectors, when fully operational at their designed sensitivities, will be very reliable instruments. The reason is because they are six-sensor detectors while the interferometers, like the bars, are only single sensor detectors. A gravitational wave burst signal arrives at the interferometers and to the bars at different times, therefore it is very difficult to confirm a burst signal if it comes close to the noise level. In these cases, a confirmation from the electromagnetic band is necessary, which gives valuable information about the wave direction and arrival time. On the other hand, being a six-sensor instrument, a spherical antenna always has robust information about a detected signal, which already helps to separate a real signal from ordinary noise with a high probability.

An array of six spheres, when placed close enough together (only a few meters apart) and sampled with the same A/D converter system, is an even more reliable system. They will form a coherent system able to provide the correct phase in various frequency bands, because the wave is a coherent source of energy in the various frequency bands of such a detecting system. Furthermore, detecting a wave with a different physical principle (absorption of the wave energy by the resonant-mass) will certainly contribute to our knowledge about it.

In conclusion, the future of resonant-mass detectors is still promising. New technological improvements will allow them to reach the standard quantum limit and beyond.

8 SCIENTIFIC OUTCOME OF GRAVITATIONAL WAVE ASTRONOMY

The first gravitational wave detection and the regular observation of gravitational waves are certainly among the most important scientific goals and technological challenges for the beginning of this millennium. They will open a new window for the observation of the universe.

Evidently, the first impact of gravitational wave detection will be in Gravitational Physics. The direct confirmation of the existence of these waves will be, in itself, a very important scientific milestone. However, it is probably in Astrophysics and Cosmology that the greatest scientific benefit will be found from this “window” of observation, because gravitational waves carry information that cannot be obtained from the detection of electromagnetic waves (radio, infrared, optical, ultraviolet, X- and gamma rays). The information provided by such waves is completely different when compared to that provided by electromagnetic waves. GWs carry detailed information on the coherent bulk motions of matter, such as in collapsing stellar cores or coherent vibrations of space–time curvature as produced, for example, by black holes. On the other hand, electromagnetic waves are usually an incoherent superposition of emissions from individual atoms, molecules and charged particles, and are unable to provide data from the dense core of some astrophysical objects. Gravitational Wave *telesensors* (Aguiar et al. 1991) rather than electromagnetic telescopes will “feel” the mass dynamics of a compact object’s interior. Therefore, the detection of gravitational waves will open a new window for the observation of the universe.

The speed and polarity of the oncoming GWs will be determined. Later on, as more detections are registered, aspects of gravitation never before observed will become apparent. Then, we will be able to put the General Theory of Relativity and other gravitation theories to the test (Bianchi et al. 1996; Eardley et al. 1973b,a). General Relativity, for example, predicts that the graviton, the fundamental particle associated with GWs, has zero mass, and spin 2; therefore gravitons travel at the speed of light, carry energy ($E = h\omega$) and momentum ($p = E/c$), and produce the tensorial forces on matter discussed at beginning of this chapter. General Relativity also predicts very non-linear gravity in the vicinities of high density matter (strong field), a phenomenon which could be confirmed by the detection of black hole coalescing binaries. Other theories of gravitation, either classical or quantum, including braneworld theories, may predict other polarizations, intensities, and speeds for the gravitational waves (Novello et al. 1997; Cardoso et al. 2003; Will 1993; Randall & Sundrum 1999; de Paula et al. 2004).

Because theoretical models estimate that collapsing and bouncing cores of supernovae, as well as corequakes and star collisions, produce large intensities of gravitational radiation in the vicinity

of 1–3 kHz, these events are likely to be observed by these resonant-mass detectors like those from the pioneering works in the 60s and 70s.

The strain expected to reach Earth coming from one of the burst sources mentioned above is highly uncertain. Thorne (Thorne 1987) gives the expression

$$h = 2.7 \times 10^{-20} \left[\frac{\Delta E_{\text{GW}}}{M_{\odot} c^2} \right]^{1/2} \left[\frac{1 \text{ kHz}}{f} \right]^{1/2} \left[\frac{10 \text{ Mpc}}{d} \right], \quad (21)$$

where ΔE_{GW} is the energy converted to GWs, M_{\odot} is the solar mass, f is the characteristic frequency of the burst, and d its distance from us ($\sim 14 \text{ Mpc}$, which is the distance to the center of the Virgo Cluster of galaxies for a Hubble constant of $70 \text{ km s}^{-1} \text{ Mpc}^{-1}$). The fraction of energy ($\Delta E_{\text{GW}}/M_{\odot} c^2$) converted to gravitational radiation depends on the asymmetry of the event. For perfectly symmetrical events this fraction is zero, since there is no variation of the quadrupole moment. A fairly optimistic value for supernova events is an energy fraction around 7×10^{-4} (Stark & Piran 1986, Proceedings of the 4th Marcel Grossmann Meeting on General Relativity, Elsevier, Amsterdam, page 327), which gives a strain close to $h \sim 10^{-18}$ if the supernova occurs in the center of our galaxy (8.5 kpc away). This strain has been in the detection range of the bar detectors since the early 90's (Hamilton & Paik 1993, Hamilton 1991, private communication). However, no supernova explosion in our galaxy able to produced neutrinos occurred in the past 20 yr, as the community of neutrino detectors states. Considering that the bars today have a sensitivity for detecting bursts around $h \sim 3 \times 10^{-19}$, they would be able to detect a supernova explosion, with the GW energy factor mentioned above, as far away as 25 kpc (hence, in our galaxy). Therefore, the time for this event to happen may come soon.

There is a host of possible astrophysical sources of gravitational waves: namely, supernovae, the collapse of a star or star cluster to form a black hole, inspiral and coalescence of compact binaries (de Freitas 2010), MACHOs as primordial black holes (PBHs), quark stars, boson stars, neutron star modes, the fall of stars and black holes into supermassive black holes, rotating neutron stars, ordinary binary stars, relics of the Big Bang, vibrations or collisions of monopoles, cosmic strings and cosmic bubbles, among others (Thorne 1987, 1995, 1997; Schutz 1996, 1999; de Araujo et al. 2004, 2005; Marranghello & de Araujo 2006). From a theoretical point of view, there has been a great effort to study which are the most promising sources of gravitational waves to be detected.

In particular, the waveforms, the characteristic frequencies and the number of sources per year that one expects to observe are questions that have been addressed (Thorne 1997; Schutz 1999; Grishchuk 2005). In a few years, starting from the observations (waveforms, amplitudes, polarizations, etc.), it will really be possible to understand how gravitational wave emission is generated by astrophysical sources.

It is quite probable that the Universe is pervaded by a background of gravitational waves, because of the fact that they are produced by a large variety of astrophysical sources and cosmological phenomena. A variety of binary stars (ordinary, compact or combinations of them), Population III stars, phase transitions in the early Universe and cosmic strings and a variety of binary stars are examples of sources that could produce such a putative background of gravitational waves (Thorne 1987; Blair & Ju 1996; Owen et al. 1998; Ferrari et al. 1999a,b; Schutz 1999; Giovannini 2000; Maggiore 2000; Schneider et al. 2000; de Araujo et al. 2002).

With a network of sufficiently sensitive gravitational wave detectors, important information could be obtained about (Thorne 1987):

- the existence of black holes;
- the position of nearby neutron stars and black holes, and their ratio (number of neutron stars) / (number of black holes);
- the formation rate of compact stars in our galaxy and neighboring galaxies and the fraction of supernovas that are not visible;

- the explosion mechanism, including the dynamics (rotation, radial movement, and timescale of collapse and rebound) of the nucleus' collapse, as well as the masses and angular momenta of supernovae occurring in our galaxy and in neighboring galaxies;
- the masses and viscosities of neutron stars (including their upper limit), and the masses of black holes (including their lower limit);
- the equation of state of neutron stars and quark (or strange) matter if it exists;
- the sources of gamma-ray bursts, if they are associated with compact binaries (Mosquera Cuesta et al. 1998);
- the hypothesis of occurrence of hydrodynamic instability in neutron stars by gain of angular momentum due to accretion of matter in binary systems (Houser et al. 1994);
- the amount of baryonic dark matter in the local universe;
- the determination of the Hubble constant with reasonable precision, checking the values of current observations (Chernoff & Finn 1993), which also includes the possible accelerated expansion of the Universe;
- the cosmological structure of the local Universe.

Gravitational wave astronomy may be very important for testing other theories of gravitation such as pre-Big Bang theories, brane-world theories, the existence of extra dimensions (Seahra et al. 2005), the holographic principle, and cosmological theories which try to explain the existence of dark matter and dark energy (Kobayashi & Tanaka 2006; Soares-Santos et al. 2005).

9 SUMMARY

The first experiment to detect gravitational waves was proposed and performed over 40 yr ago by Weber using a resonant-mass detector with a bar shape. Around 1965 January, the first high-frequency detector, designed and constructed by Weber, went into operation. Soon he started claiming coincidences between two operational detectors 1000 km apart. During the seventies and the years that followed, there were unsuccessful efforts worldwide to repeat Weber's claims even with higher sensitivity. To date there is no conclusive confirmation of such events, and theoretical estimates of local fluxes carried out so far also reinforce this position. However, Weber's pioneering work was decisive for the initial growth of the gravitational wave community. Thanks to Weber's results, more than a dozen gravitational wave detector groups worldwide were formed, and the basis of gravitational wave detection was established.

Today, resonant-mass bar detectors have achieved a record of superb stable operation. Some of them have very high sensitivity and high duty cycles above 95%. Simultaneous operation of four bar detectors for long periods of time is a technological possibility nowadays. Their sensitivity can also be improved if enough financial support is given. The standard quantum limit can be surpassed if state-of-the-art parametric transducers are used. New resonant-mass projects have been pursued over the last decade: spherical antennae promise a leap in sensitivity and capability. Direction and polarization will be determined by the use of a single spherical detector. Simultaneous operation of an array of such detectors may become a reality soon. If that is not enough, dual resonant-mass antennae will also provide resonant-mass detectors with a much larger bandwidth at very low cost, surpassing the xylophone (an array of detectors each of which is tuned to a specific frequency) proposal. A xylophone of spheres equipped with non-resonant transducers, on the other hand, may become the best solution for wideband gravitational wave detection, capable of finding a wave's direction and polarization with a single site instrument. A cubic array of spheres could even make directional detection by suitable computational analysis of the spheres' outputs possible.

The quest for gravitational wave detection has been one of the toughest technological challenges ever faced by experimental physicists and engineers. Despite the null results to date, after four decades of research, the community involved in this area is continuously growing. One of the main reasons for this is because the first gravitational wave detection and the regular observation of

gravitational waves are among the most important scientific goals for the beginning of this millennium. They will test one of the foundations of physics, Einstein's theory of General Relativity, and will open a new window for the observation of the universe, which will certainly cause a revolution in our knowledge of physics and astrophysics.

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