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RESONANT DETECTORS FOR GRAVITATIONAL WAVES

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ABSTRACT

For the first time a number of cryogenic resonant bar detectors of gravitational waves - ALLEGRO, AURIGA, EXPLORER, NAUTILUS, NIOBE - are on the air, in a continuous search for impulsive events. We present their capabilities, the foreseen upgrades and their role in a future global network with interferometric detectors..

INTRODUCTION

The drive to cool to mK temperatures the resonating bar gravitational wave detector, invented by J.Weber (Weber, 1960) came from W.F. Fairbank and W.O Hamilton some 30 years ago (Hamilton, 1988). After Weber's pioneering experimental work with a bar operated at room temperature, it was apparent that to reach out to the nearest predicted sources, e.g. supernovae in the Local Group, a substantial enhancement in sensitivity was needed. Low temperature technologies appeared to help in a natural way to get such an enhancement. The fascinating idea was actually to put a resonant mass of tons so quiet as to make one able to detect exchanges of energies with the external world of the order of a few quanta of vibration. By 1969 W.F.Fairbank at Stanford, W.O.Hamilton at Baton Rouge and E.Amaldi and G.Pizzella in Rome started projects to set up cryogenic bar detectors to be part of a network operating in coincidence. Later D.Blair started another detector at Perth. One of the authors, M.C., had joined from the very start the Rome group, from which two groups have evolved. Regretfully, the Stanford detector eventually terminated operation. Presently 3 resonant bar detectors are operating at liquid helium temperatures ALLEGRO (Mauceli *et al.*, 1996) at Baton Rouge, EXPLORER (Astone *et al.*, 1993) at CERN and NIOBE (Blair *et al.*, 1995) at Perth and 2 more are operating at temperatures of about 100 mK- AURIGA (Prodi *et al.*, 1997) at Legnaro and NAUTILUS (Astone *et al.*, 1997) at Frascati.

PRINCIPLES OF OPERATION

Figure 1 gives a self-explaining schematic of a cryogenic "bar" detector of gravitational waves. The metric perturbation h carried by the wave, with polarization angle ϕ, impinges at angle θ with the bar axis and drives the longitudinal resonant modes of the bar through the tidal force $F_G=(ML/\pi^2)\, d^2h/dt^2\, f(\theta,\phi)$, where M and L are the effective mass and length of the relevant bar mode. Notice that the antenna pattern factor $f(\theta,\phi)=\sin^2\theta \cos 2\phi$, effectively modulates the response of the detector when, say, it is in relative motion in respect to a potential source and this fact can be advantageously used in dedicated searches (see insert Figure 1).
The bar is suspended, typically with a cascade of intermediate masses and pendula, to attain the largest insulation from seismic, ambient and other vibrational noises particularly in the vicinities of the frequency of

the mode chosen for the detector operation. Odd longitudinal modes of order n respond to gravitational waves as $1/n^2$, even order modes are insensitive. While this is in principle of interest to get a signature of gravitational waves absorption, for practical reasons all operating detectors work on the lowest longitudinal mode of frequency ν, with masses M tons, L meters and ν kHz; the vibrational insulation at such mode typically exceeds 300 db and operators may climb on the cryostat without disturbing the detector. A resonant electromechanical transducer is tuned to the bar mode to maximize the transfer of vibrational energy of the bar to the readout electronics, so that the detector becomes a system of two mechanical modes. The transducer, for instance, can be made up of a capacitor charged up to electric fields just below breakdown, 10^7 V/m, one plate of which is solid with one bar end face, while the other plate is free to vibrate at a frequency very close to that of the bar mode; the currents, which so originate, are coupled and transformed in magnetic fluxes via superconducting circuitry to a final amplifier, which currently is a superconducting quantum interference device, SQUID. The efficiency in transferring the vibrational energy of the bar into electromagnetic energy in the final amplifier is typically 10^{-4}-10^{-2} and the SQUID energy resolution at the modes frequencies is currently of the order of 10^{-30} Joule/Hz. This last figures translates in about $10^4\ \hbar$, the Planck constant. One says that the SQUID has an energy resolution $\varepsilon=10^4\ \hbar$ and that, as an amplifier, it is not so far from the "quantum limit" $\varepsilon=\hbar/\ln 2$ (Heffner, 1962).

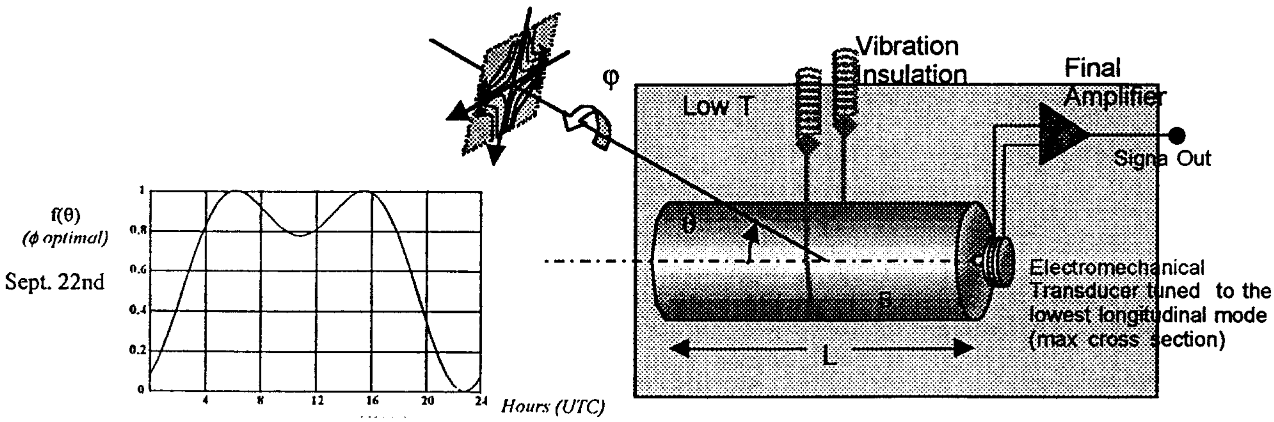

Fig. 1 Scheme of a cryogenic bar detector. The insert show the dependence on day Sept. 22^{nd} of the antenna pattern $f(\vartheta,\ \varphi)$ for optimal φ in searching for sources at the Galactic Center.

One may see how simple is (in principle...) a cryogenic bar detector. Once the external vibrations are successfully shielded, only two sources of noise must be taken in consideration. One is the noise introduced by the readout amplifier, which enters the transduction chain at the output port. The other is the noise in the two mechanical resonant modes, which enters the detector at the input port, the same as the gravitational waves signal. The detector performance – spectral sensitivity, impulsive sensitivity and effective bandwidth – are all governed by the interplay of these two kinds of noises. The final amplifier noise has an intrinsic limit: in "classical" measurements the energy resolution cannot be smaller than the quantum limit quoted above. The noise in the modes is made of three contributions: the (predictable) thermal "brownian" noise in the two modes, which is represented at input by the white fluctuating force of frequency independent spectral density $S_F=\pi k_B TM\nu/Q$, the (predictable) "back-action" of the final amplifier, which heats up the modes back through the transduction chain and depends on the energy transfer efficiency, and an (unmodeled – we shall comment about below) "background", which is invariably found in all operating detectors. The noise on the modes gets in at the same port as the signal, so this contribution to the signal to noise ratio, SNR, would be frequency independent. Would it be all, the detector would be quite wide band! But, to see anything, signal+noise from the modes must pop out of the amplifier noise, which directly adds up at the output port, where they appear as peaked resonances, the narrower the larger the mechanical quality factor Q of the modes: so it is the ratio between the modes noise, which at output appears "narrow band", S_{nb}, and the "wide band" noise of the final amplifier, S_{wb}, which determines the actual useful bandwidth Δν of the detector. Currently one has Δν=1Hz, to be compared to the bandwidth of the modes, which with a typical $Q=10^6$, is of the order of 10^{-3} Hz. To characterize the sensitivity of a detector, it is convenient to use the square root of the power spectral density of noise at input $S_{hh}^{1/2}$ expressed as equivalent metric perturbation. Figure 2a) gives as an example the actual data for a detector in operation, AURIGA. The shape of the spectrum reflects the combination of the narrow band contribution, peaked at the resonances of the two mechanical modes with the flat wide band contribution from the final amplifier. The minima, which correspond to the maximal sensitivity of the detector, scale according to the relation $S_{hh}^{1/2}=(\pi/16)^{1/2}(k_BT/MQv^3L^2)^{1/2}$ the bandwidth, as discussed above, is $\Delta v=(v/Q)(S_{nb}/S_{wb})^{1/2}$ and the impulsive sensitivity h_{min} to a pulse of duration τ_g, according to Wiener-Kolmogorov optimal filtering, is $h_{min}=\tau_g(S_{hh}/2\Delta v)^{1/2}$. For an extended recent review giving the above relations see ref. (Coccia, et al. 1997)

a)

b)

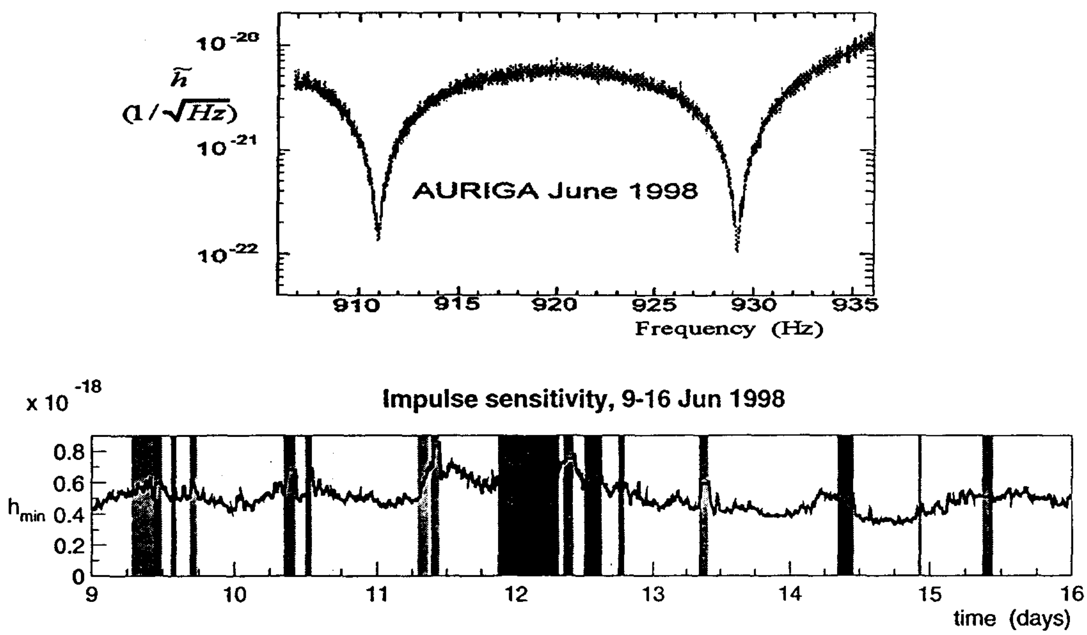

Fig. 2 **a)** Square root of the spectral density of noise at input $(S_{hh})^{1/2}$ versus frequency , epressed as equivalent metric perturbation, of AURIGA (one hour average). **b)** The impulsive sensitivity h_{min} of Auriga over one week; the dark regions indicate interruption due to cryogenic maintenance (refill 1 Kpot of the He^3-He^4 refrigerator, refill of the main bath, etc).

Given mass and length, dictated by practical reasons as availability of materials, overall size and weight of a cryogenic system, etc, and by going to very low temperatures one may get quite a few crucial benefits in one effort: at lower T, the ratio T/Q gets smaller not only for the decrease in T, but also because Q gets larger; in addition amplifiers as SQUIDs gets less noisy, actually closer to their quantum limit. In fact it appeared from the beginning that it would have been feasible to set up an ultracryogenic bar detector – Fairbank's goal was 5 mK – which, for impulsive signals, would be actually limited by the quantum noise of the final amplifier, what is called the standard quantum limit, SQL, for the detector. The criterion for approaching the SQL is $k_BT/Q \cong h\Delta v$, when the "thermal" and "quantum" actions over the detection time are comparable.

PERFORMANCES, SHORT TERM UPGRADES AND CAPABILITIES AS "SUPERNOVA WATCH"

The five detectors in operation differ in many relevant details, from materials and working temperature to type of electromechanical transducer, but their performances are presently quite similar in almost all respects; Table 1 gives a summary.

One notices that the so called ultracryogenic ones, that is AURIGA and NAUTILUS working at He^3-He^4 refrigerator temperatures, show a somewhat better spectral sensitivity at resonance, while on the other hand the burst sensitivity is close to the others: the reason is that ultracryogenic operation is not yet fully exploited, since the final amplifier, the SQUID, is still too "hot", with $\varepsilon > 10^4\ \hbar$. Short term upgrades concern the integration of SQUIDs with $\varepsilon < 100\ \hbar$ (Carelli *et al.*, 1998) (Jin *et al.*, 1997) and should also bring along a wider bandwidth of some 50 Hz. Similar performances are expected with parametric systems (Tobar *et al.*, 1997) and with optical readouts, which use interferometric methods at low temperatures (Conti *et al.*, 1998).

The duty cycle given in Table 1 concerns strictly that allowed by ordinary operations of cryogenic maintenance (see Fig. 2b) during the same cool down, not that due to major maintenances which require warm up of the system, with consequent interruption of operation for a few months. The daily SNR>5 rate for impulsive events is a factor 3-5 larger than expected from a gaussian statistics and this is the unmodeled background mentioned above. With ALLEGRO it has been reduced, by enhancing the insulation against microseismicity and electrical disturbances (Heng *et al.*, 1996). With AURIGA attempts are made to use χ^2-tests on the output to select against spuria (Vitale *et al.*, 1997), under the assumption that energy absorptions not originating in the bar, will propagate differently along the transduction chain. Of course such a background is presently the actual limitation in the searches of rare impulsive events, which can be overcome only by having as many as possible detectors in coincidence.

Table 1

• *ALLEGRO* • *EXPLORER* • *NAUTILUS* • *AURIGA*	*material* *Al* 5056 *mass* 2.3 *ton* $L = 3m, Diam = 0.6m$ *frequencie s* 895 ÷ 930 *Hz*	*NIOBE*	*material* *Nb* *mass* 1.5 *ton* $L = 2.75\,m$ *frequencie s* 694 ,713 *Hz*

	ALLEGRO	EXPLORER	NIOBE	NAUTILUS	AURIGA
Bar Working Temperature [K]	4.2	2.6	5	0.1	0.2
Mech. Quality Factor Q	1.5×10^6	2×10^6	20×10^6	0.5×10^6	3×10^6
S_{hh} at resonance [$Hz^{-1/2}$]	10×10^{-22}	6×10^{-22}	8×10^{-22}	3×10^{-22}	2×10^{-22}
Effective. Bandwidth [Hz]	≈ 1	≈ 0.2	≈ 1	≈ 0.6	≈ 0.5
Burst Sensitivity h_{min}	8×10^{-19}	8×10^{-19}	1×10^{-18}	4×10^{-19}	4×10^{-19}
Duty Cycle	97%	50%	75%	60%	66%
SNR > 5 event rate [day^{-1}]	100	150	75	150	200

The data acquisition and analysis have recently evolved under the pressure of the peculiarities of the actual data outcome, in particular the non-stationarity of the noise parameters. With AURIGA it has been introduced (Ortolan *et al.*, 1997) (Vitale *et al.*, 1994) a fast, 5 kHz, A/D conversion of the signal from the final amplifier, synchronized within 1μs with UTC time, which allows on one hand a full storage of the raw data and on the other hand a fully numerical analysis, with online adaptive filters. Presently the search and reconstruction of impulsive events gives amplitude, time of arrival (Crivelli Visconti *et al.*, 1998) and χ^2-test vetos (Vitale *et al.*, 1997). The nature of the noise appears to be that of a quasi-stationary gaussian process, with the parameters expected from the thermal noise acting on the bar-transducer system and the amplifier noise, plus the background noise.

To maximize the probability of coincidental detection, the 5 detectors in operation have been oriented with their bar axis roughly parallel each other and all orthogonal to the earth great circle close to which they happen to stay. The bars in operation, working in collaboration under the IGEC agreement (IGEC) are already searching for impulsive events in coincidence and will extend the searches to continuous sources from specific astronomical objects. The network is sensitive to the upper range of predictions for gravitational waves emission from, say, rapidly rotating neutron stars with asymmetries and supernova events in the Galaxy.

In the time span until about 2002, with the fast analysis and with the enhancements in sensitivity to $h_{min}=3*10^{-20}$ and in bandwidth $\Delta\nu=50$ Hz, they will keep a "Galactic supernova watch" with the following characteristics: 16hours/day of coverage of the Galactic luminous mass; detect down to $2*10^{-5}$ M_* converted in gravitational waves at the Galactic Center; background $<3*10^{-7}$ fourfold coincidences/year (one detector will be under maintenance at any time); arrival time with < 1ms of resolution; source position in the sky within degs; test of c-velocity propagation.

APPROACHING THE SQL

Let us discuss how close/far current ultracryogenic detectors are from the SQL. To find what is the optimal detection bandwidth $\Delta\nu$ for impulsive event, using for instance a Wiener-Kolmogorov optimal off-line filtering of the data, it takes some effort with numerical calculations on exact electromechanical models of the detector. The result for the transduction chain described above (Cerdonio *et al.*, 1994) is $\Delta\nu=50$ Hz; the intrinsic mechanical quality factor of the materials used for the current bars, Niobium and Al5056, are $Q>5*10^7$ at

T<100 mK, so current bars would fulfill the SQL condition working at T=10 mK. NAUTILUS has been occasionally cooled at 60 mK; AURIGA has a refrigerator of similar power: the technology for making possible SQL measurements with ultracyogenic bars as AURIGA and NAUTILUS is available. NIOBE could also approach the SQL conditions, even working at T=5 K, because of the larger Niobium intrinsic Q (Tobar *et al.*, 1997). To get the SQL, one needs also the other ingredient: a final amplifier with noise at the quantum limit. Here the progress has been slower: SQUIDs, which in bench tests approach substantially their quantum limit, when integrated in a detector show instead much poorer performance, with $\varepsilon > 10^4\hbar$. All efforts ongoing as short term upgrades quoted above are in fact intended to bring ultimately to the SQL, in the conviction that the problem is solvable with available technology. An impulsive SQL detection would then be at the level of amplitude of metric perturbation $h=2*10^{-21}$; this would mean that Galactic supernovae would be detectable, even if of very poor efficiency $<10^{-6}$ M_O in gravitational waves conversion, and that large efficiency supernovae and neutron stars and black-hole mergers in the Virgo Cluster would also be detectable. In the SQL conditions the bandwidth would be appreciably open to allow searches of stochastic background by correlating the outputs of nearby detectors, as just AURIGA and NAUTILUS are (Vitale *et al.*, 1997) and to allow searches of continuous sources giving spectral metric perturbations amplitudes at the detectors $S_{hh}^{1/2}=10^{-23}$ $Hz^{-1/2}$, that is amplitudes $h>5*10^{-27}$ over 100 days integration time, in some 100 Hz around 1kHz. This gives an idea why low temperature methods have been found attractive and still are.

PERSPECTIVES: A GLOBAL GRAVITATIONAL WAVES OBSERVATORY

Even if in a narrow band around about 900 Hz, still AURIGA and NAUTILUS already show the spectral sensitivity that the interferometric gravitational waves detectors under construction promise to achieve in the same band. Upgrades are foreseen to enhance the sensitivity to approach the SQL and considerably expand the usable frequency band. One may have noticed that the SQL condition does not contain the mass M of the detector. The integrated cross section Σ, which for narrow band detector links the energy E absorbed by the resonator in an impulsive event with the spectral flux at the frequency of resonance of incoming gravitational waves $f(\nu)$, $E=\Sigma f(\nu)$, depends instead linearly on M. Also the spectral sensitivity maximum, improves with increasing M. So for all gravitational waves signals - impulsive, continuous and stochastic – the SNR gets enhanced, if the mass of the detector increases. Long ago it had been proposed (Forward, 1971) that a spherical mechanical resonator, when the response of its five quadrupolar modes is suitably correlated, would give an omnidirectional gravitational waves detector, actually able to identify the direction of propagation of the wave. Recently the idea has been revived (Merkowitz and Johnson, 1997) and the study of materials and cooling methods has led to the notion that it would be feasible (Frossati *et al.*, 1997) to cool at 10 mK a Cu-Al sphere of 3 m diameter, weighting some 100 tons. So, in addition to the all-sky coverage, one would get a significant increase in cross section of almost two orders of magnitude, pushing the impulsive sensitivity close to $h_{min}=10^{-22}$ and all other sensitivity numbers accordingly. Possibly, at these levels of sensitivity, high energy cosmic rays may become a problem (Oberski *et al.*, 1997), which would be overcome by locating the detector in an underground laboratory, as for instance the Gran Sasso INFN Natl. Lab. in Italy.Ultracryogenic mechanical resonators may stay the most sensitive, though only in a band of some 50 Hz around 1 kHz, in a complementary way to interferometers.

One may ask what would be the role of ultracryogenic mechanical resonators, when, on a such longer time scale, “advanced” interferometric detectors will be on the air. For any detection, it would be quite convincing if the signal would be seen by detectors based on different principles of operation and different construction technologies. It is natural to propose that all the upcoming interferometric detectors - LIGO, VIRGO, GEO and TAMA – may collaborate, from “initial” to “advanced” operation, for correlated signal searches, in sort of a global network, together with the most sensitive cryogenic resonant mass detectors, the bars now, the sphere afterwards. With such a network for instance it could be possible to solve the so called inverse problem, for searches of impulsive signals, by a straightforward extension of the exercise done for a “6 bars” network (Cerdonio *et al.*, 1993).A spherical detector could enter the network, as “advanced” detector in place of the bars, contributing in a similar way to the solution of the inverse problem. These solutions give also signatures of symmetries of the gravitational waves Riemann tensor, as tracelessness and trasversality, which could be used as vetos against spuria. As interferometers are intrinsically insensitive to the trace of the gravitational waves Riemann tensor, again resonant detectors are crucially complementary in the global network. Given impulsive sensitivities $h_{min}=10^{-21}$–10^{-22}, as expected when enhancing performance beyond the “initial” for all detectors, such a global network would detect gravitational wavesbursts of 0.1 M_O out to 100-1000 Mpc, having full sky coverage, allowing reconstruction of polarization and direction of propagation, giving the arrival time to less than 1 ms, together with tests on the velocity of the waves and on the Riemann symmetries quoted above.

Undoubtedly solutions of the inverse problem with similar merits, using such a global network, can be worked out for other kind of searches, as emissions from continuous sources and "chirps" from coalescing binaries (the effect of such a signal on a spherical detector has already been worked out (Coccia and Fafone, 1996).

As a final touch of optimism, let us notice that the enhancements in sensitivity both of resonant mass and of interferometric detectors are in principle boundless. As the interaction of gravitational waves with a SQL detector is expected to be that of a classic wave packet with a quantum system, the SQL is only a limit for the use of "classical" measurement methods, not an intrinsic limit for the ultimate sensitivity (Braginsky *et al.*, 1975) (Thorne *et al.*, 1978).

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