Resonant mass detectors: present status

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Abstract

A review of the main features of resonant mass gravitational wave (g.w.) detectors is given. After a brief survey of their main characteristics, with a particular attention to the news on each of them, recent experimental results are presented.

1 Main characteristics of the detectors

Resonant mass detectors of g.w., " in operation", are cylindrical bars, whose end face vibrate when the bar is hit by a g.w.. The bar end face displacement ΔL is proportional to the dimensionless wave amplitude $h \approx \frac{\Delta L}{L}$, where L is the lenght of the bar. The measurement of the displacement is done by means of transducers, well coupled to the bar, that convert the displacement into an electric signal. Typically, resonant mass detectors have two resonance frequencies $\approx (10-30)$ Hz apart, where the sensitivity is at its best. The system parameters that determine the sensitivity are:

- the mass M of the bar. Given a material, the sensitivity improves with the mass;
- the bar temperature T. The sensitivity increases by cooling down the bar. In fact, the displacement of the bar due to the thermal noise depends on the square root of the temperature [1] ($\Delta L = 10^{-17}$ m at T= 3 K, $\Delta L = 3 \cdot 10^{-18}$ m at T= 300 mK);
- the merit factor Q of the bar-transducer system, proportional to the time the energy released by the signal remains into the bar. The higher the Q the better is the sensitivity.

Resonant bar g.w. detectors [2] are [1]:

Allegro: 2300 kg Al antenna, located in Baton Rouge (Louisiana, USA). Operational since the year 1991. Cooled at 4.2 K.

Auriga: 2230 kg Al antenna, located in Legnaro (Padova, Italy). Operational since the year 1997. Cooled at 200 mK, with a liquid helium dilution refrigerator.

Explorer: 2270 kg Al antenna, located at CERN (Geneve, CH). Operational since the year 1990. Cooled at 2.6 K.

Nautilus: 2260 kg Al antenna, located in Frascati (Roma, Italy). Operational since Dec. 1995. Cooled at 130 mK, with a liquid helium dilution refrigerator.

Niobe: 1500 kg Nb antenna, located in Perth (Western Australia). Operational since the year 1993. The bar material is Niobium, with high Q factor. It is cooled at 5K.

The sensitivity of the detectors to g.w. signals is determined by $\tilde{h}$, the **noise spectral amplitude** (or **strain sensitivity**), in units of $1/\sqrt{\mathrm{Hz}}$. Fig.1 shows the strain

[1] the cooling of the bar brings also other major advantages, such as the increasing of the merit factor and the possibility of using super-conducting, hence low-noise, devices.

[2] I will use lower case characters for the detector names, even if the name is an acronym.

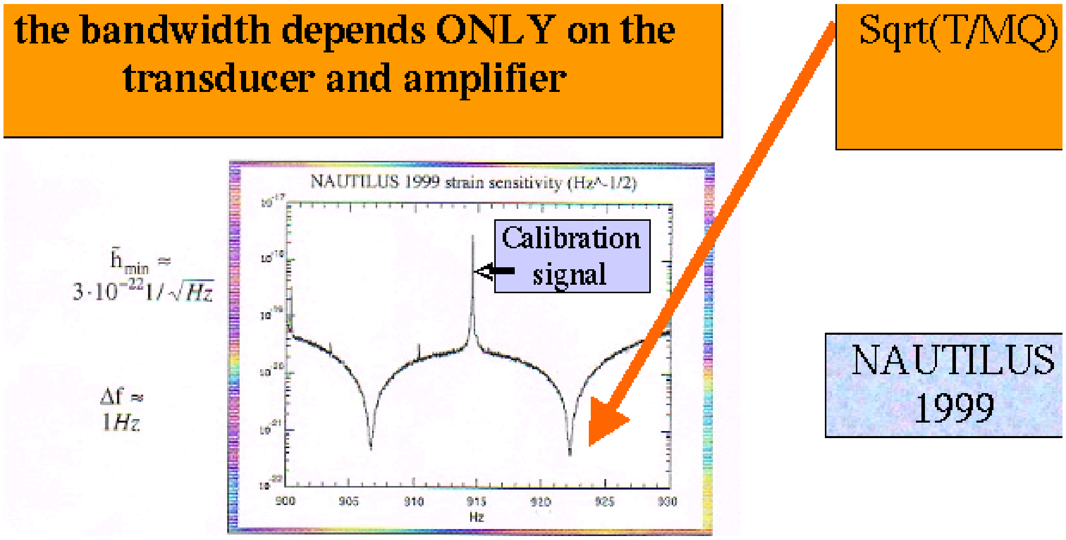

Figure 1: Nautilus strain sensitivity during the 1999 run. The x-axis is the frequency, in the range 900-930 Hz. The y-axis is in units of $1/\sqrt{Hz}$. The strain sensitivity at the two resonances is $\tilde{h} = 3 \cdot 10^{-22}/\sqrt{\mathrm{H}z}$

sensitivity of Nautilus in the 1999 run. At the resonances (and over a bandwidth of $\simeq 1$ Hz):

$$\tilde{h} \propto \sqrt{T/(MQ)} = 3 \cdot 10^{-22} \ /\sqrt{\mathrm{H}z} \qquad (1)$$

The bandwidth depends only on the transducer and amplifier. It can be increased by improving the coupling of the bar-transducer system and/or by reducing the noise temperature of the amplifier.

These detectors allow to investigate various classes of signals:

- **Bursts**, that are signals from Supernova explosion, fall of a body into a black hole, final merge of the coalescence of a binary system. The expected signals are short pulses (a few ms each). The sensitivity to bursts h depends on $\tilde{h}$ and on the bandwidth [3] B. The expected signal on Earth, if a Supernova explosion in the Galactic Center releases 1% of M_0 into g.w., is $h \approx 10^{-18}$. Optimum filters and coincidence analyses between the detectors are needed [2, 3].
- **Continuous waves**, that are signals from rotating neutron stars or stars in binary systems. The signal is expected to be always present during the observation time. The sensitivity h_c to continuous waves depends on $\tilde{h}$ and, at least ideally, on the square root of the observation time t_{obs}.
- **Stochastic background** (SB), produced by a high number of uncorrelated events. At least two detectors, properly located and oriented, are needed. The sensitivity depends on the noise spectral amplitudes of both the detectors and on the square root of the overlapping frequency bandwidth and observation time. A detailed discussion on SB (theory and experiments) is given in [4].

A new important activity is the development of spherical detectors. Groups in Brazil, in The Netherlands and in Italy are working to develop small spherical detectors [5, 6] (CuAl spheres, diameter=65 cm, mass=1.15 ton) that will exploit the high frequency range $\approx$ 3kHz.

[3] in the approximation of constant $\tilde{h}$, for SNR=1 and for a 1 ms burst, we get: $h = \frac{\tilde{h}}{0.001}\sqrt{\frac{2}{\pi B}}$.

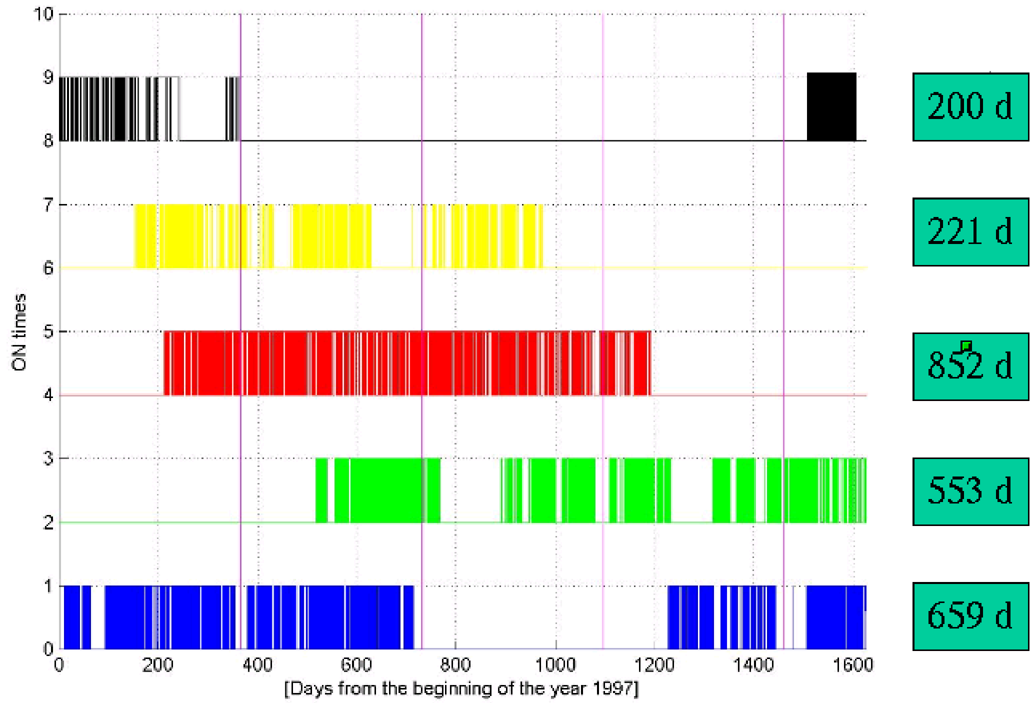

Figure 2: Operation times of the detectors, from Jan 1997 up to June 2001. The x-axis are days, from 1 Jan 1997. The numbers in the rectangular regions are the total number of days of observation T_{obs}, for each detector. From bottom to top: Explorer (T_{obs}=659 days), Nautilus (T_{obs}=553 days), Allegro (T_{obs}=852 days), Auriga (T_{obs}=221 days), Niobe (T_{obs}=200 days). The y-axis is different for the various detectors, e.g, for Allegro it ranges from 4 (detector off) to 5 (detector on).

2 News on the detectors

Resonant g.w. bar detectors have been operating since many years. Fig. 2 shows the operation times, from Jan 1997 up to June 2001. Allegro, which is also very stationary at a level of $h \simeq 1 \cdot 10^{-18}$, has reached the best duty cycle, with 852 days of operation from August 1997 up to March 2000. After the joint effort of taking as much data as possible during the years 1997-2000, to perform the coincidence analysis with the **IGEC observatory** [7], some apparatuses have been "switched off" and others are going to be switched off in order to make important improvements:

- **Allegro** has taken data until March 2000, then has been relocated. It is now going to be again on the air. The strain noise will be the same as in the 1997-2000 run: $\tilde{h} \simeq 2 \cdot 10^{-21}\ /\sqrt{Hz}$, over 1 Hz. One goal now is to run in coincidence with LIGO. Then, the bar will be equipped with a 2-mode transducer (originally designed by Solomonson, Geng, Johnson, Hamilton and developed in collaboration with the group of Paik, Maryland), and a Wellstood SQUID amplifier, expected to reach 300 $\hbar$. The new system will have a bandwidth of 60 Hz, at the level $\tilde{h} \simeq 1 \cdot 10^{-21}\ 1/\sqrt{Hz}$. Details are given in [8].
- **Auriga** has taken data until Aug 1999, with $\tilde{h} \simeq 4 \cdot 10^{-22}\ /\sqrt{Hz}$, over 2 Hz (that is, for bursts, $h \simeq 2.5 \cdot 10^{-19}$). A new readout (a new double stage DC SQUID amplifier and a new transducer) and new mechanical suspensions (with attenuation 360 db @1kHz) are being tested. The system will be operative before

the end of the year 2001. The expected strain noise is (Phase I, at T=1.5 K): $\tilde{h} \simeq 6 \cdot 10^{-22}$ $/\sqrt{Hz}$ at the resonances, and $\tilde{h} \leq 10^{-21}$ $/\sqrt{Hz}$ over 40 Hz; after 1 year (Phase II, at T=100 mK): $\tilde{h} \simeq 2 \cdot 10^{-22}$ $/\sqrt{Hz}$ at the resonances, and $\tilde{h} \leq 10^{-21}$ $/\sqrt{Hz}$ over 80 Hz. Details are given in [9].

- **Explorer**: the transducer and the SQUID have been replaced in the year 1999. The detector operates again since the beginning of the year 2000. Explorer is now working at the level $h \simeq 4 \cdot 10^{-19}$. There is some work to do to increase the Q of the transducer and to reduce extra noise acting on the SQUID, that increases the level of the electronic noise. The expected strain noise is [4]: $\tilde{h} \simeq 1 \cdot 10^{-21}$ $/\sqrt{Hz}$ at the resonances, and $\tilde{h} \leq 3 \cdot 10^{-21}$ $/\sqrt{Hz}$ over 30 Hz. Cosmic ray detectors will be installed around the bar. Details are given in [10].
- **Nautilus** is still operating, with $\tilde{h} \simeq 3 \cdot 10^{-22}$ $/\sqrt{Hz}$, over 1 Hz. (that is $h \simeq 2.5 \cdot 10^{-19}$). It will be turned off at the beginning of the year 2002 [5]. The bar will be changed, and the new system will work at 935 Hz, where we expect a pulsar, as remnant of the SN1987A [11]. A new transducer and a new SQUID amplifier (the same used for Explorer) will be used. The expected strain noise is: $\tilde{h} \simeq 6 \cdot 10^{-23}$ $/\sqrt{Hz}$ over a very small ($\leq$ 1 Hz) bandwidth. Details are given in [12].
- **Niobe** has taken data until the end of 1997. Then, the readout system has been improved, by using a new very low noise μwave amplifier. The μwave noise has been confirmed at about 10 times the quantum limit. Cosmic rays detectors, provided by the University of Adelaide, have been installed to test for the cosmic ray interactions, as observed by Nautilus. The bar has been cooled down again on Feb. 2001, and has worked at the level $h \simeq (4-5) \cdot 10^{-19}$ (that corresponds to the record noise temperature, after the filtering, of 500μK). It is still expected some improvement, working on the apparatus. Presently Niobe is not working due to a power failure (occurred on June, 18^{th}) that caused the failure of the thermal vacuum. Details are given in [13].

Fig.3 shows the previsions for Auriga, compared to the strain noise in the 1997-1999 run. An interesting work is also in progress in the Auriga group to test a new readout system, based on a Fabry-Perot cavity installed between bar and transducer. Details can be found in [14]. The actual strain noise of the Explorer detector is shown in fig.4, compared to the expectations.

Fig.5 shows the expectation for Nautilus, with the new bar and the new readout system.

3 Results and planned analyses

3.1 The IGEC analysis

The results of the first analysis with the 1997-1998 data of the five detectors of **IGEC**, International Gravitational Event Collaboration, have been published [15]: a new upper limit on the events in the Galaxy has been put, since no g.w. bursts above $h = 4 \cdot 10^{-18}$ have been detected. New data, that cover the period Jan 1997 - Dec 2000 have been exchanged. A new exchanging protocol has been followed, since we decided to exchange a much more detailed information on the events [6]. Preliminary results have been discussed by G. Prodi at this Conference [16]. It is interesting to

[4]these values have already been reached during the year 2000, but the SQUID working point was not stable enough, to guarantee a proper duty cycle of the apparatus.

[5]Explorer must be turned off during Christmas, since CERN closes, thus we want Nautilus to operate. In January Explorer will be again cooled down and then Nautilus will be warmed up for improvements.

[6]we have also added information on the status of the detectors with the time.

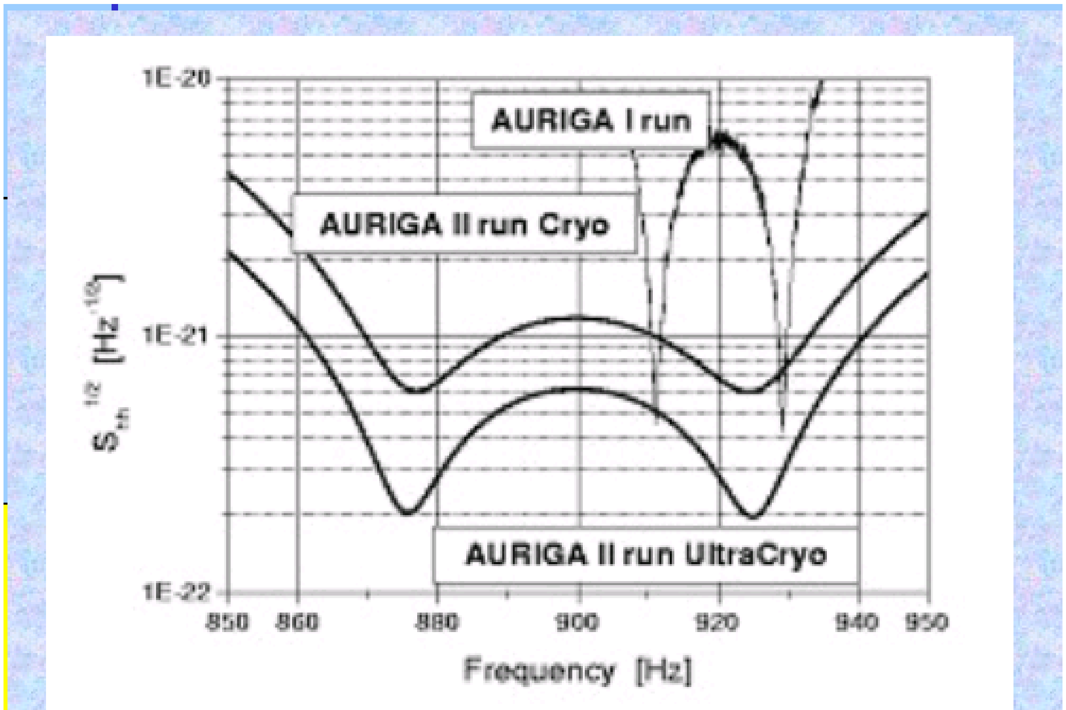

Figure 3: The Auriga expected strain noise, $1/\sqrt{\mathrm{H}z}$, with the new read-out system and suspensions. The figure shows also the strain in the 1997-1999 run: note the improvement on the bandwidth.

note that, over a total time of 1460 days (4 years), at least one detector was working for the 90% of the time (1322 days). Fig.6 shows the details.

3.2 The search for Continuous waves

Upper limits for signals in the GC and Tucanae have been put by the Allegro group, using three months of data in 1994 [17]. A procedure to search for periodic sources has been developed by the Rome group, and has been applied to the data of Explorer, searching for sources in the Galactic Center [18]: no signals with amplitude greater than $h_c = 2.9 \cdot 10^{-24}$, in the frequency range (921.32-921.38) Hz, were observed using data collected over a time period of 95.7 days, in 1991.

An overall sky search, based on a procedure developed by A. Krolak and collaborators [19] is now running on Explorer data. We are analysing two days of data and a bandwidth of 0.8 Hz. So far we have analyzed 1 million points of the parameter space, by choosing randomly spin-down parameter and position. We expect to put limits at the level $h_c = 3 \cdot 10^{-23}$ [20].

Incoherent analysis over the whole 1991 data of Explorer (see [21] for a description of the apparatus and data in 1991) is in progress, in collaboration with A. Krolak. A collaboration with Virgo has also been established, to apply to the Explorer and Nautilus data the Rome strategy for the pulsar search.

The decision of tuning Nautilus at the frequency 935 Hz of the neutron star in the SN1987A (thus giving up the increasing of the bandwidth) is justified by the fact that the estimation [11] of the signal on Earth gives the value $h_c \approx 10^{-26}$ that, with the expected strain $\tilde{h} = 6 \cdot 10^{-23}/\sqrt{Hz}$, can be reached even with a few months of observation. In fact, since all parameters of the source are known, we get (SNR=1,

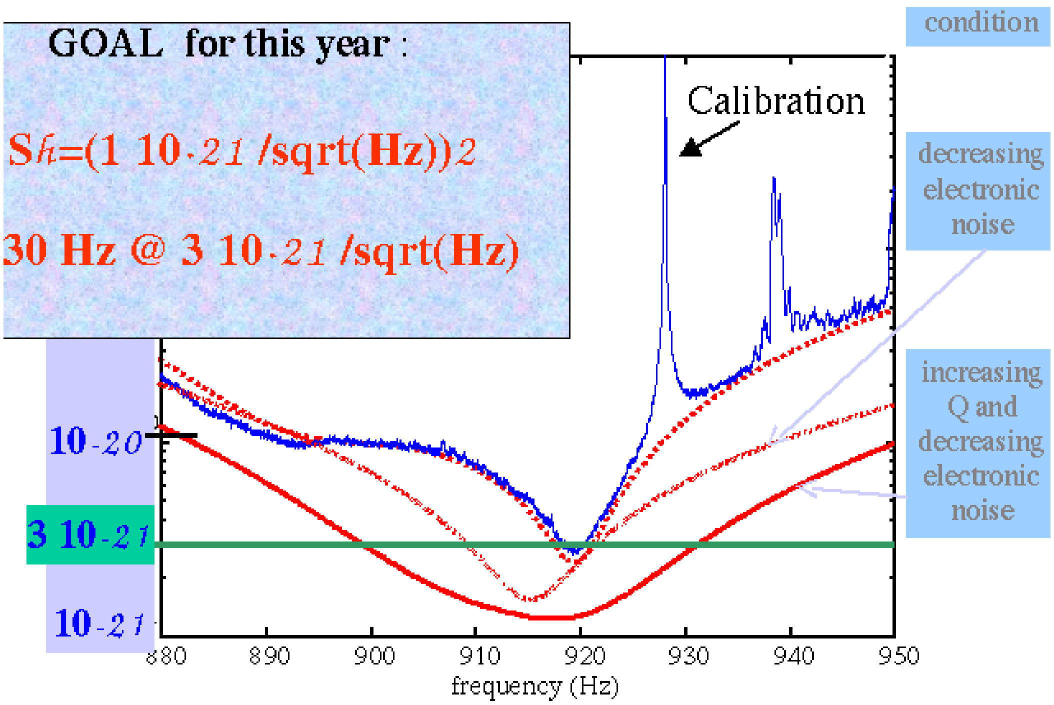

Figure 4: Explorer strain noise $1/\sqrt{\mathrm{H}z}$. The actual situation is represented in the top curve, with the calibration peak. The expectation with the actual parameters, including the extra-noise, is also represented (dotted curve). The other two curves (the first and the second curve from the bottom of the figure) represent the expectations with reduced noise and increased Q.

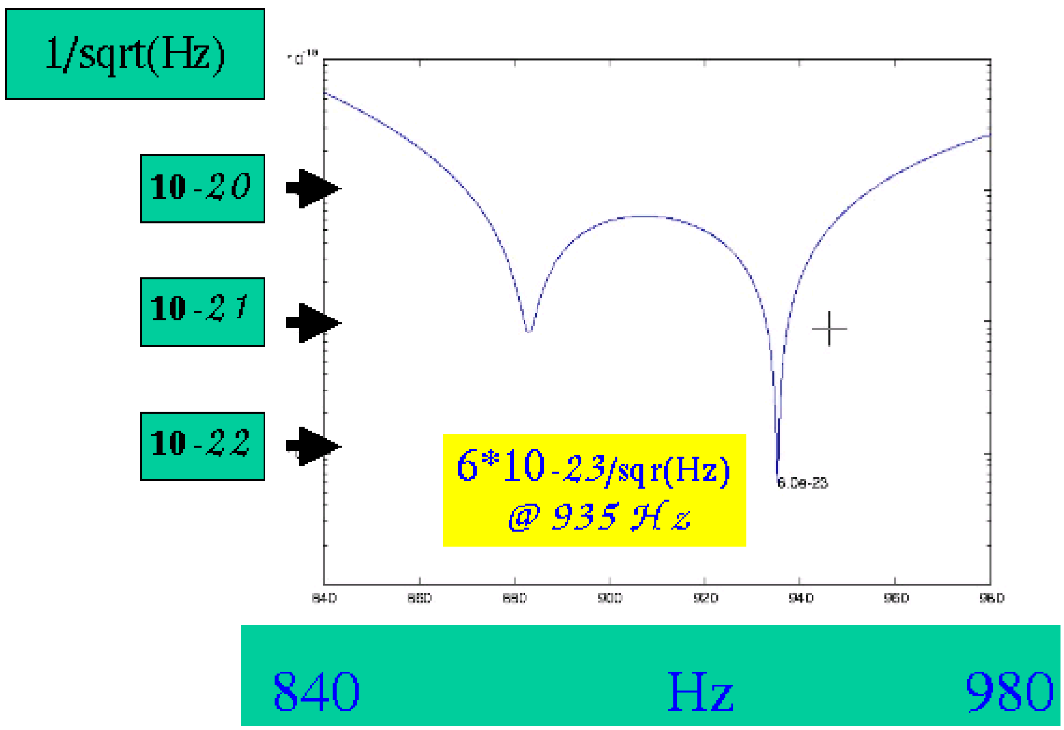

Figure 5: The Nautilus expected strain noise. The system will be very sensitive at 935 Hz, to look for the pulsar in the SN1987A.

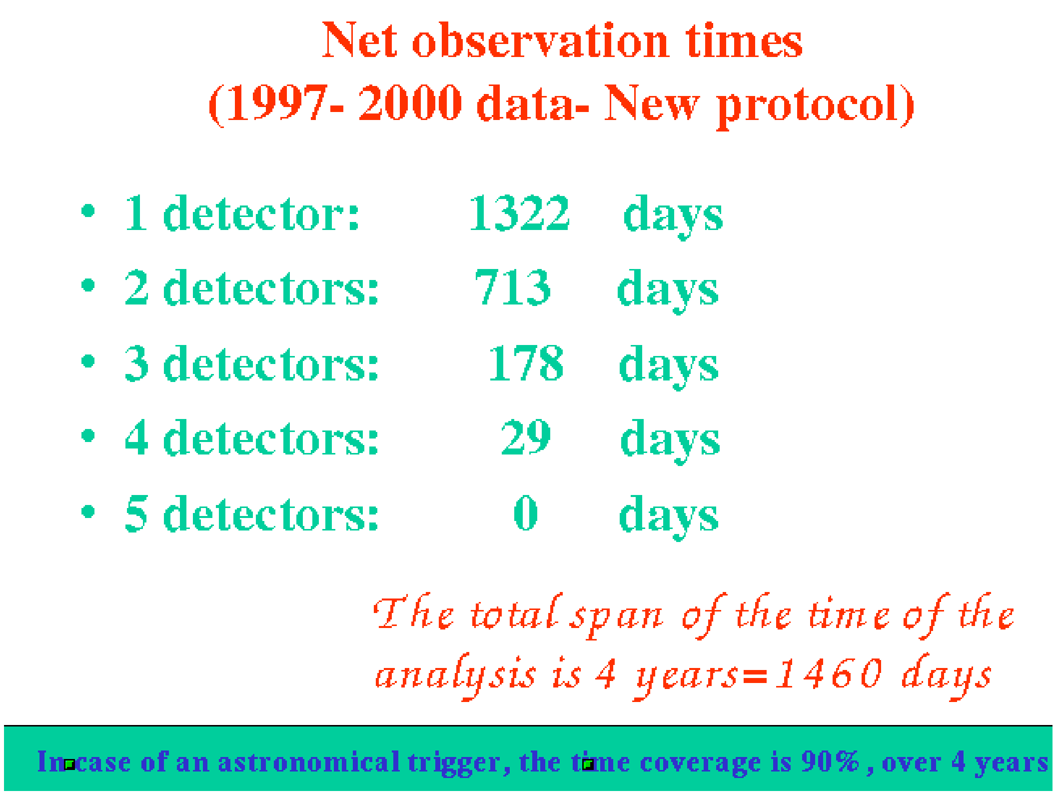

Figure 6: Net observation times, obtained with the 5 detectors of the IGEC collaboration.

$t_{obs} = 1$ year):

$$h_c = \tilde{h}(@935Hz)\sqrt{2/t_{obs}} \simeq 1.5 \cdot 10^{-26} \quad (2)$$

This search could also be done with the Auriga detector, if the decision to change the bar is taken.

3.3 The search for Stochastic Background

A limit ($\Omega_{gw} \leq 60$) has been put by cross-correlating few hours of Explorer and Nautilus data in the year 1997 [22]. Limits on Ω_{gw} less than the unity can be achieved cross-correlating data from a bar/bar couple or from a bar/interferometer couple:

- the cross-correlation of 4 months of Nautilus and Auriga data, at the sensitivity expected by the year 2002, would put the limit $\Omega_{gw} \leq 0.1$.
- joint analyses [23] with Virgo, Nautilus and Auriga may put limits at the level $\Omega_{gw} \leq 3 - 5 \cdot 10^{-3}$ (with 1 year of integration, the expectations for Nautilus and Auriga (Phase II), and $\tilde{h}(@900\ Hz) \simeq 10^{-22}\ /\sqrt{Hz}$ for Virgo).
- the two groups Ligo and Allegro, operating two detectors 40 km apart, have planned to do SB searches, as soon as both the detectors will be operative. Details can be found in [24]. Using Ligo I and the actual Allegro sensitivity [7], the limit that will be put is $\Omega_{gw} \leq 0.1$ (one year of data, analysed at pieces of 2-3 months [24]). With Ligo II and the improved Allegro this limit will be $\Omega_{gw} \leq 6 \cdot 10^{-4}$.

3.4 Cosmic rays

Nautilus is equipped with cosmic ray (c.r.) detectors. The first coincidence analysis between the c.r. events and the Nautilus data has shown, with a very significant correlation (more than 20 standard deviations), that the passage of c.r. excites, as expected, the first longitudinal mode of the bar [25]. A second analysis has shown very large coincident signals at a rate much larger than expected [26]. The largest signal corresponds to an energy release in the bar of 87 Tev. The two analyses do not contradict, since the first was done using such criteria to look **only** for signals corresponding to a very small energy release in the bar, as suggested by the theory. The second analysis started after the observation, by chance, of very large Nautilus events in coincidence with c.r. events. Several explanations are possible. A detailed discussion has been given at the Conference by F. Ronga [27].

Cosmic rays detectors will be put on Explorer, and the experiment will check if the anomalous observation is related to super-conductivity[8]. Cosmic rays detectors have been put near Niobe, and the coincidence experiment that is going to be done is very important, since it may check if the effect is related to the bar material.

References

[1] `Allegro`: http://gravity.phys.lsu.edu; `Auriga`: http://www.auriga.lnl.infn.it; `Explorer,Nautilus`: http://www.roma1.infn.it/rog (site under construction. Up to now we recommend to visit the Data analysis pages); `Niobe`: http://www.gravity.pd.uwa.edu.au

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[12] E. Coccia, in this Proceedings

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