Present performance of resonant mass detectors for Gravitational Waves

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• Introduction to gravitational waves resonant detectors
• IGEC2 collaboration: status of 2005 data analysis
• Effects of cosmic rays on gravitational wave resonant detectors
• Future resonant detectors
# The search for gravitational waves

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>( \lambda )</th>
<th>RESEARCH TECHNIQUE</th>
<th>SOURCES</th>
</tr>
</thead>
<tbody>
<tr>
<td>10(^{-16})</td>
<td>10(^9) ly</td>
<td>Anisotropy of CBR</td>
<td>- Primordial</td>
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<tr>
<td>10(^{-9})</td>
<td>10 ly</td>
<td>Timing of ms pulsars</td>
<td>- Primordial</td>
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<td></td>
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<td></td>
<td>- Cosmic strings</td>
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<tr>
<td>10(^{-4}) - 10(^{-1})</td>
<td>0.01 - 10 AU</td>
<td>Doppler Tracking of spacecraft</td>
<td>- Binary stars</td>
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<td></td>
<td></td>
<td>Laser interferometers in space <strong>LISA</strong></td>
<td>- Supermassive BH (10(^3) -10(^7) M(_o)) formation, coalescence, inspiral</td>
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<tr>
<td>10 - 10(^3)</td>
<td>300 - 30000 km</td>
<td>Laser interferometers on Earth <strong>LIGO, VIRGO, GEO, TAMA</strong></td>
<td>- Inspiral of NS and BH binaries (1-1000 M(_o))</td>
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<td></td>
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<td>- Supernovae</td>
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<td></td>
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<td></td>
<td>- Pulsars</td>
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<tr>
<td>10(^3)</td>
<td>300 km</td>
<td>Cryogenic resonant detectors <strong>ALLEGRO, AURIGA, EXPLORER, NAUTILUS</strong></td>
<td>- NS and BH binary coalescence</td>
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<tr>
<td></td>
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<td></td>
<td>- Supernovae</td>
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<tr>
<td></td>
<td></td>
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<td>- ms pulsars</td>
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\[
\frac{\Delta L}{L} = h
\]

**RESONANT DETECTORS**

- Transducer
- Amplifier
- Data

- Mechanical vibration
- Electrical signal

- Seismic noise
- Thermal noise
- Cosmic ray noise
- Electronics noise

- Mechanical filters
- Low and ultralow temperature
- Veto
- Low noise amplifier (SQUID)
The “oldest” resonant detector EXPLORER has started operations about 16 years ago.

This kind of detector has reached, since several years, a high level of reliability.

The duty factor is higher than 90%.
EXPERIMENTAL RESULTS

• CONTINUOUS:
  – From the GC, 95.7 days EXPLORER $h_{\text{c}} = 3 \cdot 10^{-24}$ - frequency interval $921.32 \div 921.38$ Hz
  – From all the Sky, 2 days EXPLORER $h_{\text{c}} = 2 \cdot 10^{-23}$ - frequency interval $921.00 \div 921.76$ Hz
    (P.Astone et al., proceedings GWDAW 2002 – ROG – A. Krolak and collab.)

• STOCHASTIC SOURCES:
  – Crosscorrelation of EXPLORER and NAUTILUS data over 10 hours in a band of 0.1Hz in 1997 - $\Omega_{\text{GW}}(920.2$ Hz) $< 60$. (P.Astone, et al., Astron. and Astrophys, 351, 811-814, (1999).)
  – ALLEGRO Stochastic Search in collaboration with LLO- results are expected soon.
• **BURST SIGNALS:**

**GW detectors**

- IGEC collaboration: no GW bursts above $h \sim 2 \cdot 10^{-18}$ corresponding to $0.01M_\odot$ in the GC - IGEC Coll., Phys. Rev. D 68, 022001 (2003).

**GW - γ ray detectors**

- Analysis over 120 GRB (BATSE): no signals with $h > 1.5 \cdot 10^{-18}$ for a time delay within $\pm 5$ s - AURIGA Coll., Phys. Rev. D, 63, 082002 (2001).
- Analysis over 47 GRB (BeppoSAX): no signals with $h > 6.5 \cdot 10^{-19}$ for a time delay within $\pm 5$ s, and with $h > 1.2 \cdot 10^{-18}$ for a time delay within $\pm 400$ s, - ROG Coll., Phys. Rev. D, 66, 102002 (2002).
- Analysis of 387 GRB (BeppoSAX and BATSE) upper bound of $h = 2.5 \cdot 10^{-19}$ in a time window of $10$s - ROG Coll., Phys. Rev. D 71, 042001 (2005)

**GW – cosmic ray detectors**

IGEC 2

International Gravitational Events Collaboration

ALLEGRO– AURIGA – ROG (EXPLORER-NAUTILUS)
THE NEW IGEC

• **IGEC 1997-2000** - First experience of extended search of multiple coincidence using data of 5 resonant detectors: ALLEGRO, AURIGA, EXPLORER NAUTILUS and NIOBE.

• **IGEC2 2004 May → …** A new agreement for a joint search for gravitational waves, now 4 detectors, NIOBE ended its activity.
The four antennas receive an identical signal, independently from the source.
DATA ANALYSIS METHODOLOGY

• The analysis is based on lists of candidate events obtained selecting, with an adaptive threshold, data produced by a filter matched to a delta

• The search parameters are tuned with a blind analysis

• The analysis must be oriented to the detection as we expect from LIGO after S5 an upper limit far from present resonant detectors sensitivity.
SENSITIVITY OF PRESENT DETECTORS

The graph plots the sensitivity of different detectors as a function of frequency. The detectors include Allegro, Auriga, Explorer, and Nautilus. The sensitivity is measured in units of $\sqrt{S_h (1/\sqrt{Hz})}$. The x-axis represents frequency in Hz, ranging from 800 to 1000 Hz, while the y-axis represents the sensitivity on a logarithmic scale from $10^{-21}$ to $10^{-18}$. The sensitivity curves for each detector show variations and peaks at different frequencies.
FROM IGEC1 TO IGEC2

IGEC 1
1997-2000

IGEC 2
2004 - ....
OPERATION TIME – MAY 20 – NOV 15, 2005
(Preliminary AURIGA- EXPLORER- NAUTILUS)

Data from ALLEGRO to be added
• no detector 0.6 days
• Single 3.6 days
• Double 45.0 days
• Triple 130.8 days

days of operation

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<thead>
<tr>
<th>AL</th>
<th>AU</th>
<th>EX</th>
<th>NA</th>
</tr>
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<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>172.9</td>
<td>151.8</td>
<td>150.2</td>
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<tr>
<td>0</td>
<td>158.0</td>
<td>135.3</td>
<td>155.0</td>
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N of detectors

HIGH DUTY FACTOR

180 days

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TRIPLE COINCIDENCE DISTRIBUTION
AU-EX-NA (PRELIMINARY)

ADAPTIVE THRESHOLD: AURIGA SNR>4.5 – EXPLORER and NAUTILUS SNR>4

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<thead>
<tr>
<th>Poisson Fit (Black : Data - Green : Fit)</th>
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<tr>
<th>hstat</th>
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<tbody>
<tr>
<td>Entries</td>
</tr>
<tr>
<td>Mean</td>
</tr>
<tr>
<td>RMS</td>
</tr>
<tr>
<td>$\chi^2 / \text{ndf}$</td>
</tr>
<tr>
<td>$p_0$</td>
</tr>
<tr>
<td>$p_1$</td>
</tr>
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</table>
FALSE ALARM RATE vs DETECTION THRESHOLD
(AU-EX-NA PRELIMINARY)

Background estimate of triple coincidence on the common observation time (130 days) by $10^7$ time shifts

With a detection threshold of 5.5 stdev on AURIGA the FA rate goes down to 1 per century
IGEC2 PROGRAM FOR NEAR FUTURE

• Include Allegro data in the analysis.

• Complete estimation of false alarm probability and tuning of the coincidence analysis pipeline.

• Exchange true times to look for candidate GW events (if any) or set up upper limits.
EFFECT OF COSMIC RAYS ON RESONANT DETECTORS
EFFECT OF COSMIC RAYS ON A RESONANT DETECTOR

\[ E = \frac{4}{9\pi} \frac{\gamma^2}{\rho v^2} \left( \frac{dW}{dx} \right)^2 \left( \sin \left( \frac{\pi z_o}{L} \right) \frac{\sin(\pi l_o \cos(\theta_o)/2L)}{\pi R \cos(\theta_o)/L} \right)^2 = 7.64 \times 10^{-9} W^2 f \left[ \frac{K}{GeV^2} \right] \]

\[ \text{Calculation for Nautilus} \]

The longitudinal mode of vibration of the antenna is excited by the thermal expansion due to the energy lost by the particles.
EXPLORER is equipped with 3 layers (2 above the cryostat - area 13m² - and 1 below - area 6 m²) of Plastic Scintillators. NAUTILUS is equipped with 7 layers (3 above the cryostat - 36m²/each - and 4 below -16.5 m²/each) of Streamer tubes. The cosmic ray effect on the bar is measured by an offline correlation, driven by the arrival time of the cosmic rays, between the observed multiplicity in the CR detector (saturation for $M \geq 10^3$ particles/m²) and the data of the antenna, sampled each 4.54 ms and processed by a filter matched to $\delta$ signals.

$\Delta E = 1 \text{ mK} = 0.15 \text{ meV}$
• When the detector is superconductor there is an evident disagreement of the experimental data respect to the model.

Madison, August 30, 2006
COINCIDENCES BETWEEN COSMIC RAYS AND ANTENNA SIGNALS

- Measurements at distinct temperatures in different detectors show that there is a large disagreement when the detector is in superconducting state.

- The other discrepancies can be explained with CR model approximations.
Measurements with 5056 Aluminum alloy:
• results show agreement with the thermo-acoustic model in the 4-300 K range
• measurements below 1K (superconductive state) are expected in short time

Measurements with Niobium:
• results show agreement with the thermo-acoustic model in the 10-300 K range.
• superconducting niobium measurements show that an additional effect must be taken in account. Is likely to find something similar for Aluminum
FUTURE RESONANT DETECTORS
A spherical detector can measure all the 5 parameters describing a GW:

- $h_+ h_x$ - amplitude of the 2 polarization states
- $\alpha \delta$ - source direction
- $h_s$ - scalar component

It has a larger cross section respect a bar once the frequency is chosen.

$M = 1-200$ tons; $f = 100$Hz- 4kHz
Sensitivity: $10^{-23} - 10^{-24}$ Hz$^{-1/2}$
$h \sim 10^{-21} - 10^{-22}$

MINIGRAIL
Ø 68 cm - 1.4 ton 3kHz
Sensitivity predicted for next run

\[ 3 \times 10^{-22} \]
DUAL MAIN CONCEPT


- Read the differential deformations of two nested resonators
- GW signals are added - back action noises are subtracted
- Sensitive in a band of a few KHz
2012 - 2018 NETWORK

- slide from INFN roadmap