INFN - LNF
November 22, 2010

NAUTILUS
Searching for Gravitational Waves at LNF

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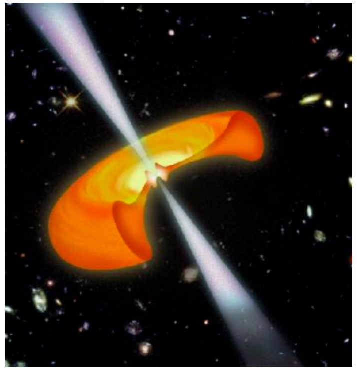
www.lnf.infn.it/esperimenti/rog

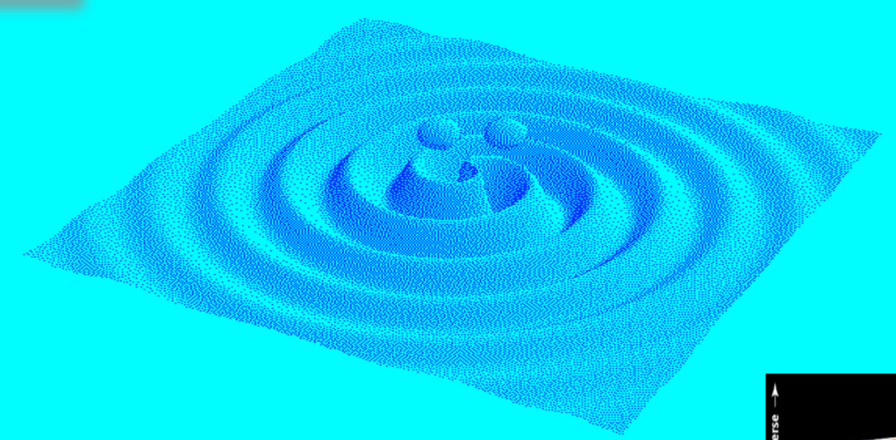
GW OBJECTIVES

FIRST DETECTION
test Einstein prediction

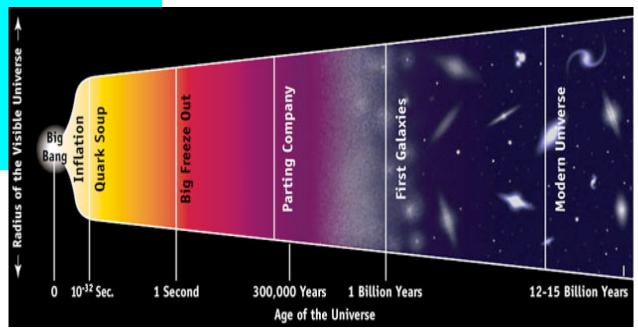
$$\mathbf{G} = \frac{8\pi G}{c^4}\mathbf{T}$$

ASTRONOMY & ASTROPHYSICS
look beyond the visible,
understand Black Holes,
Neutron Stars and supernovae
understand GRB



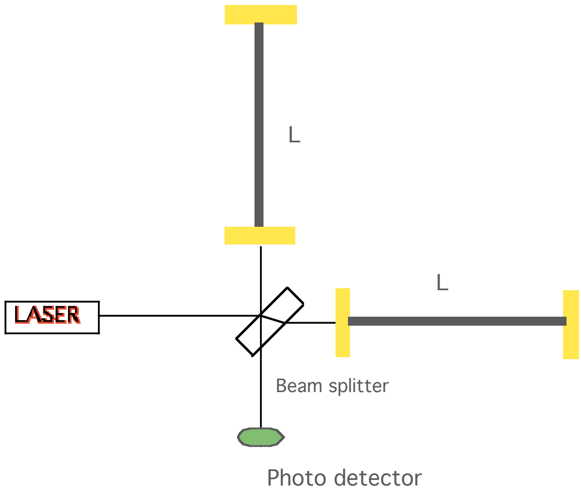


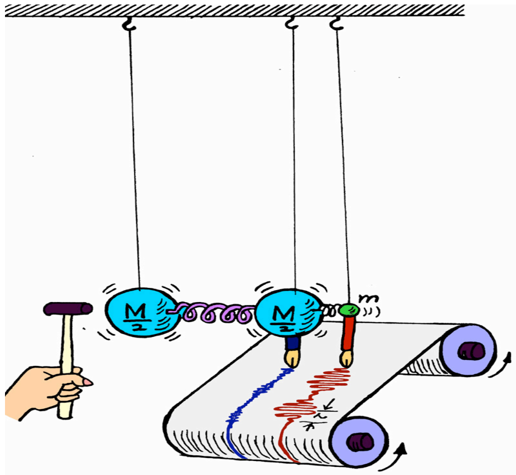
COSMOLOGY
the Planck time:
look as back in time as theorist can conceive



$$h = \frac{\Delta L}{L}$$

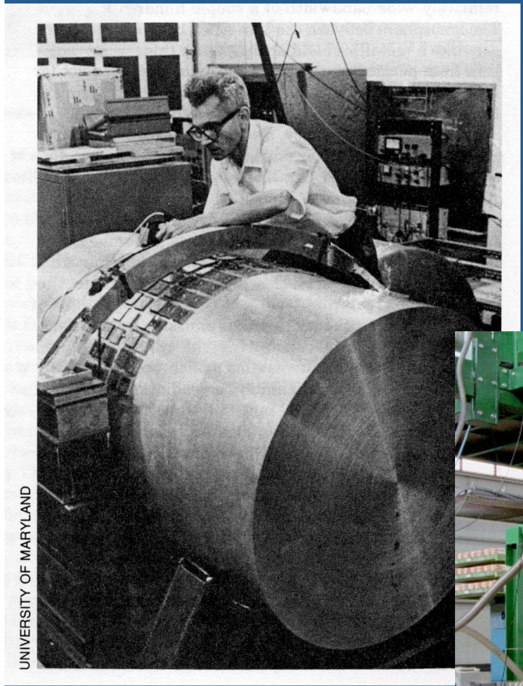
$$\ddot{x}(t) + \tau^{-1}\dot{x}(t) + \omega_0^2 x(t) = \frac{\ell}{2}\ddot{h}(t)$$



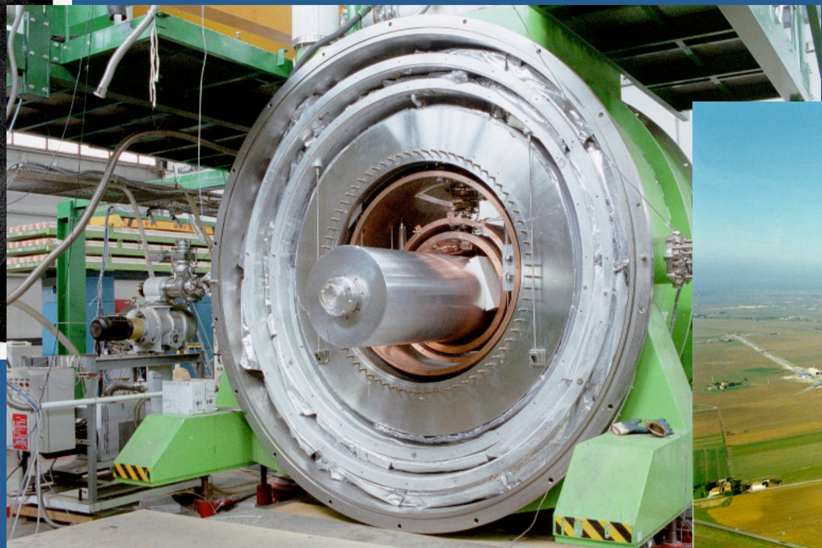


Some perspective: 40 years of attempts at detection:

Since the pioneering work of Joseph Weber in the '70, the search for Gravitational Waves has never stopped, with an increasing effort of manpower and ingenuity:



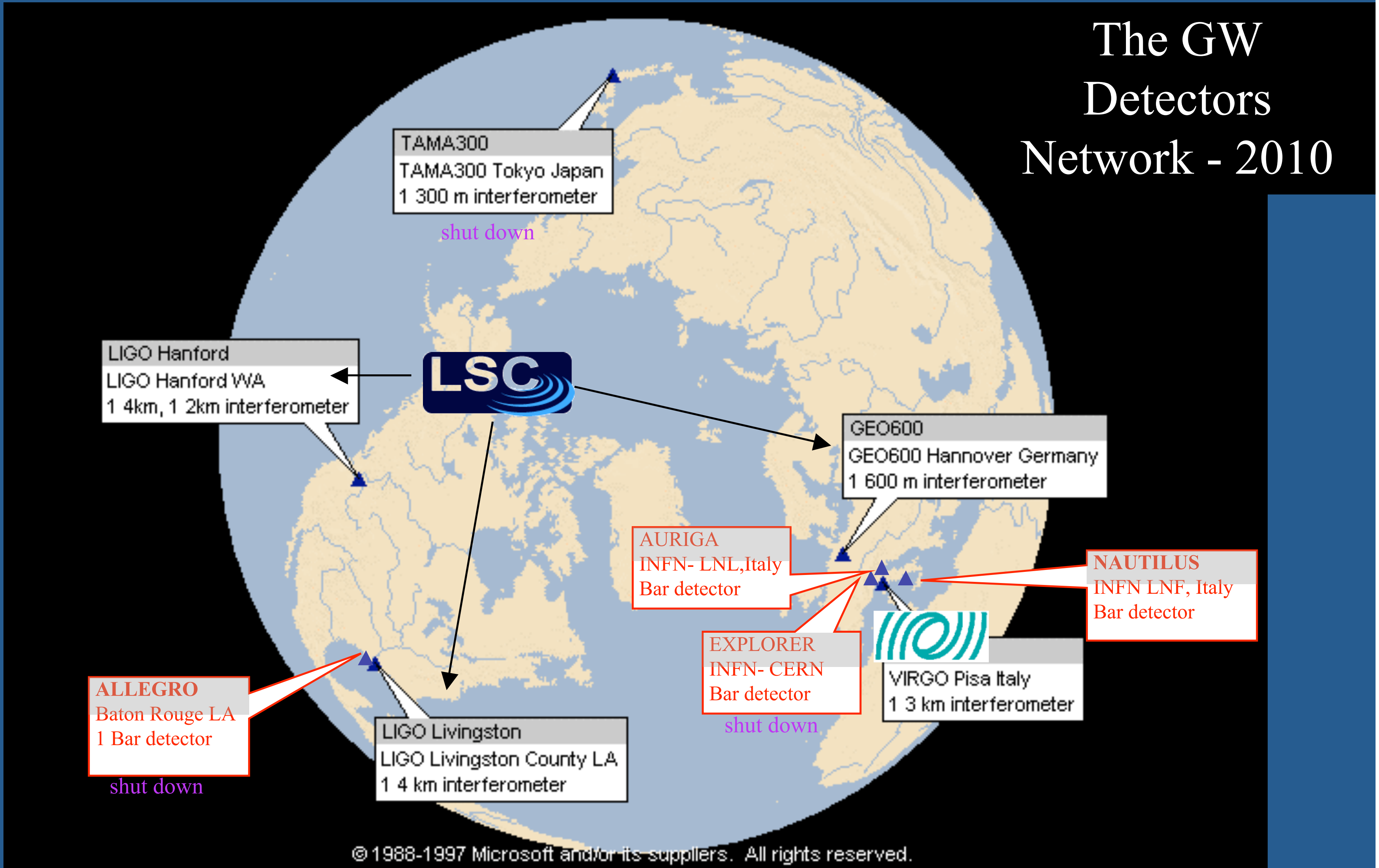
70': Joe Weber pioneering work



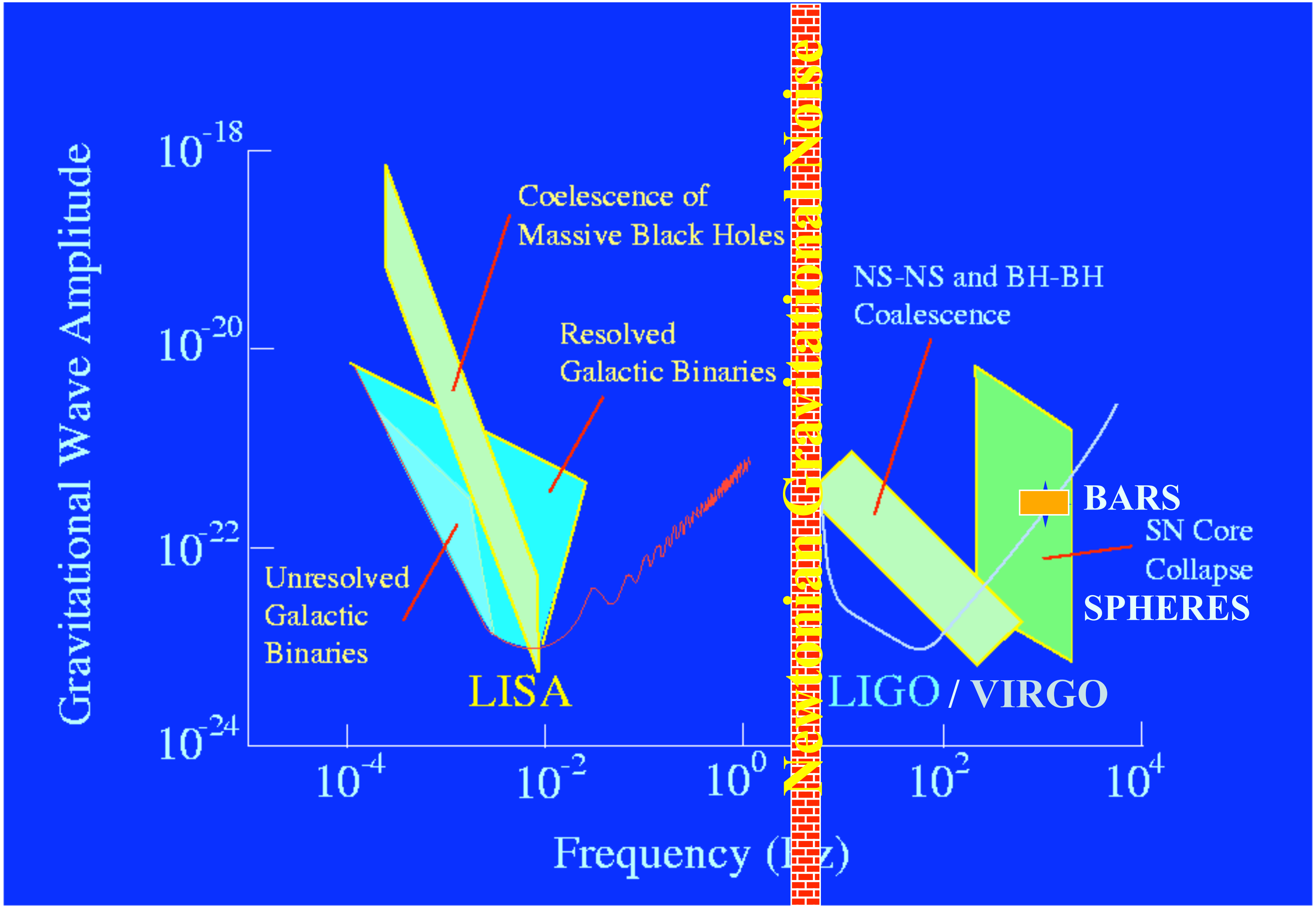
1990 - : Cryogenic Resonant Bars

2005 - : Large Interferometric Detectors

Over the years, techniques and sensitivities varied greatly, but since the start it has been clear that to detect gravitational waves we need a **NETWORK**



2010



Gravitational Wave Amplitude
10-18
10-20
10-22
10-24
Coelescence of
Massive Black Holes
Resolved
Galactic Binaries
Unresolved
Galactic
Binaries
LISA
Newtonian Gravitational Noise
NS-NS and BH-BH
Coalescence
BARS
SN Core
Collapse
SPHERES
LIGO / VIRGO
10-4
10-2
100
102
104
Frequency (Hz)

Frequency emitted by a dynamic system of density ρ :

$$f \sim \sqrt{G\rho}$$

kHz frequencies correspond to nuclear densities (10^{-15} g/cm^3)

Sources: compact objects

- gravitational collapse to form neutron star or black hole,
- last orbits of an inspiraling neutron star or black hole binary system, its merging, and its final ringdown,
- starquakes, phase transitions neutron to quark star

Bar detectors can reveal unique features of matter at extreme densities and strong gravitational fields

LNF: Giordano
Marini
Pizzella
Ronga

ROMA: Astone
Pallottino
Frasca

ROMA
Tor Vergata:
Bassan
Coccia
D'Antonio
Fafone
Minenkov
Modena
Moleti
Rocchi

INAF/IFSI:
Bonifazi
Terenzi
Visco

ricerca onde gravitazionali
gravitational wave research

ROG Collaboration 2010

Regular data exchange
Auriga and Allegro (IGEC)

MoUs and Agreements
CERN
LIGO, VIRGO, GEO, TAMA
LVD, Beppo-SAX

Bar Al 5056 M = 2270 kg

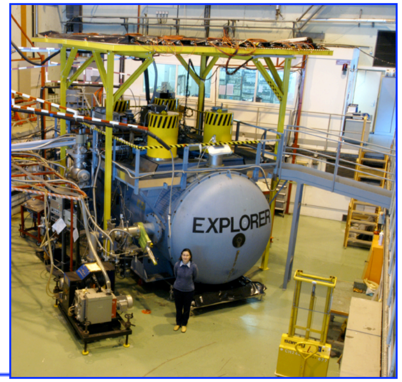
L = 2.91 m Ø = 0.6 m

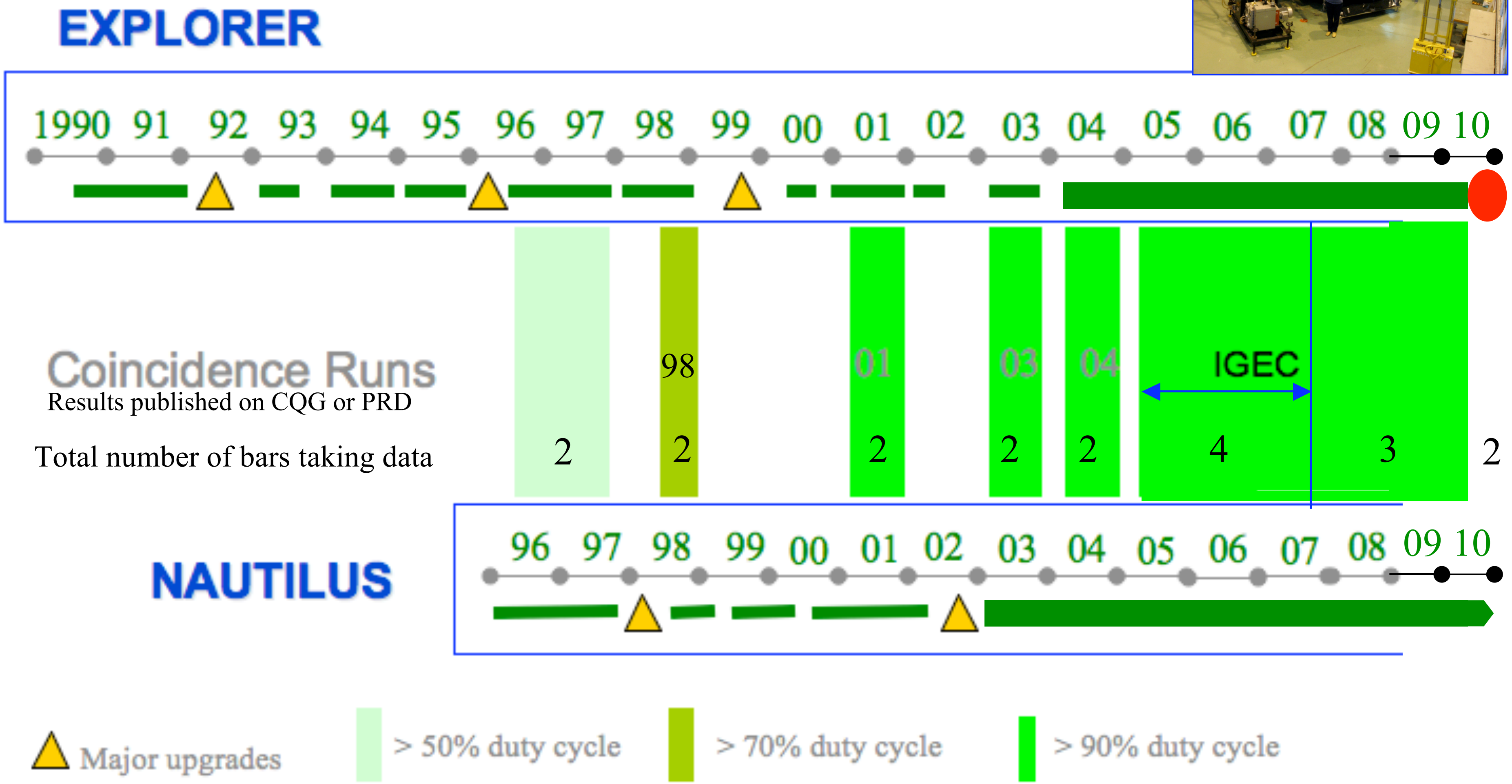
ν_A=935Hz @ T = 3 K

(T=130mK with dilution refrigerator)

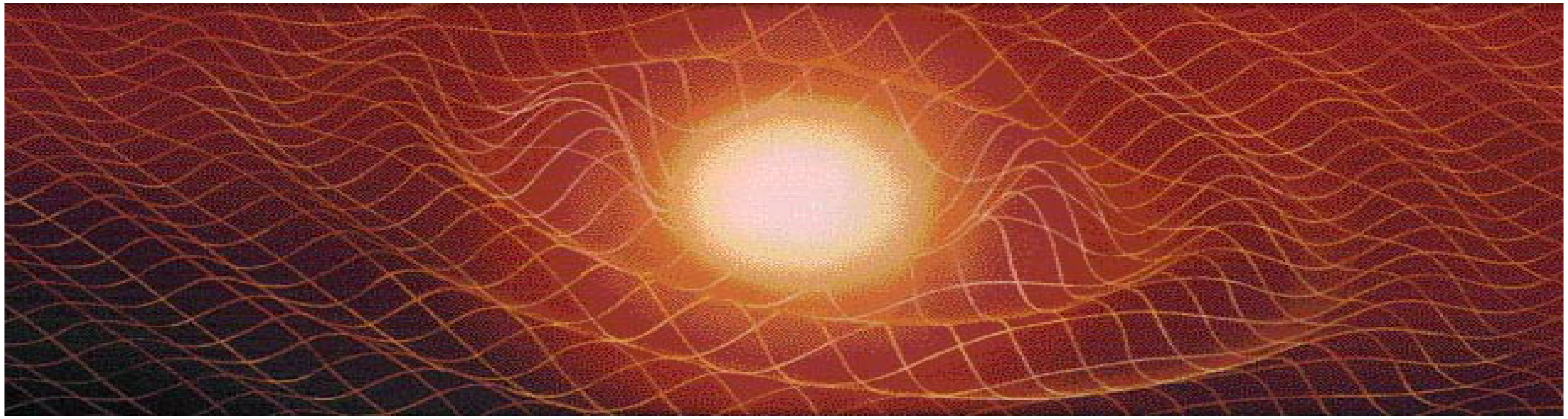
Cosmic ray detector

History of ROG DATA TAKING





GW amplitude due to the isotropic conversion of a mass M in GWs

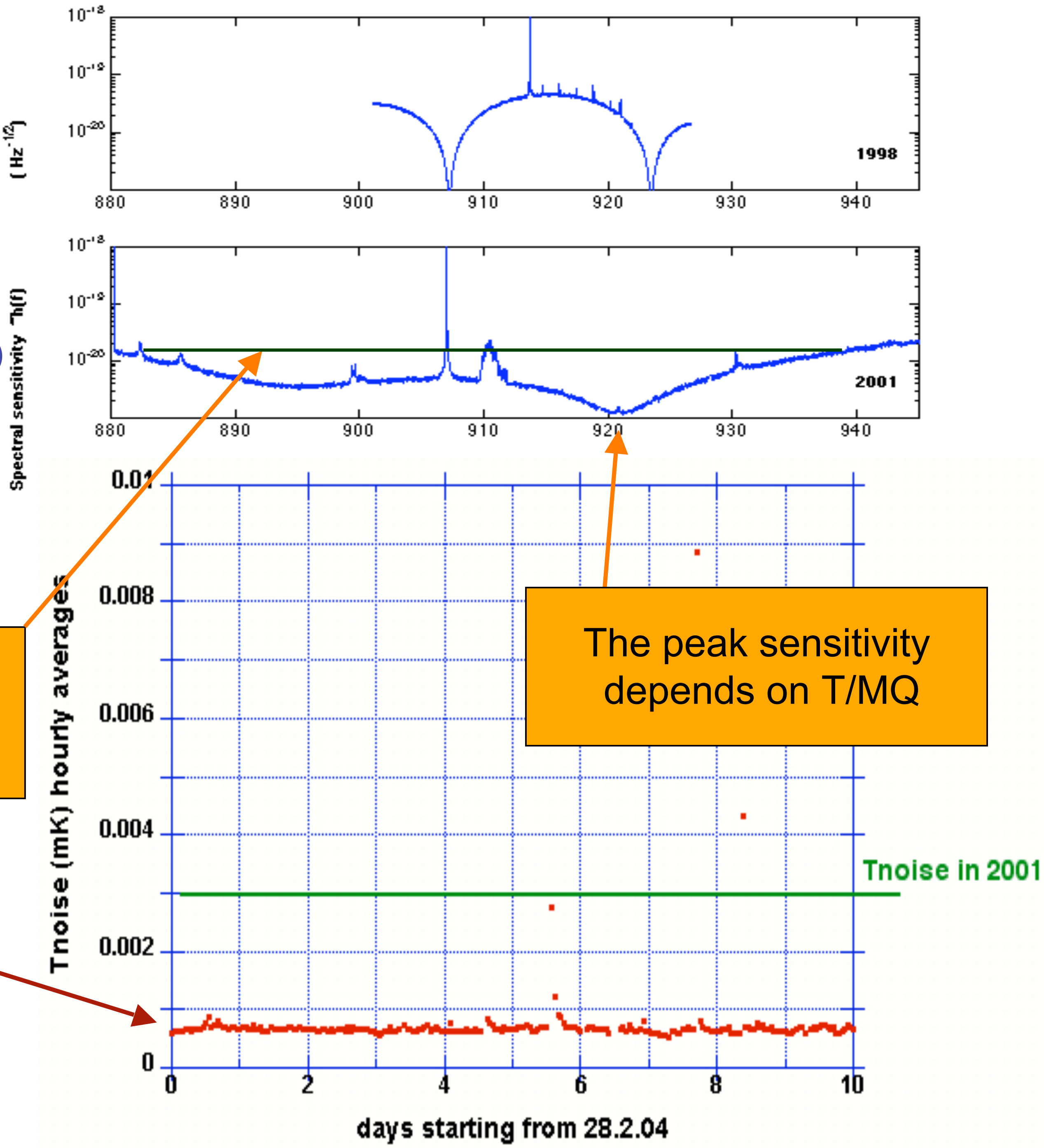


$$h = 2 \cdot 10^{-19} \left(\frac{8kpc}{r} \right) \sqrt{\frac{M_{GW}}{10^{-4} M_{\bullet}}}$$

$$r = 80\,pc \Rightarrow M_{GW} = 10^{-8} M_{\bullet}$$

NAUTILUS AND EXPLORER
Duty cycle = 90%

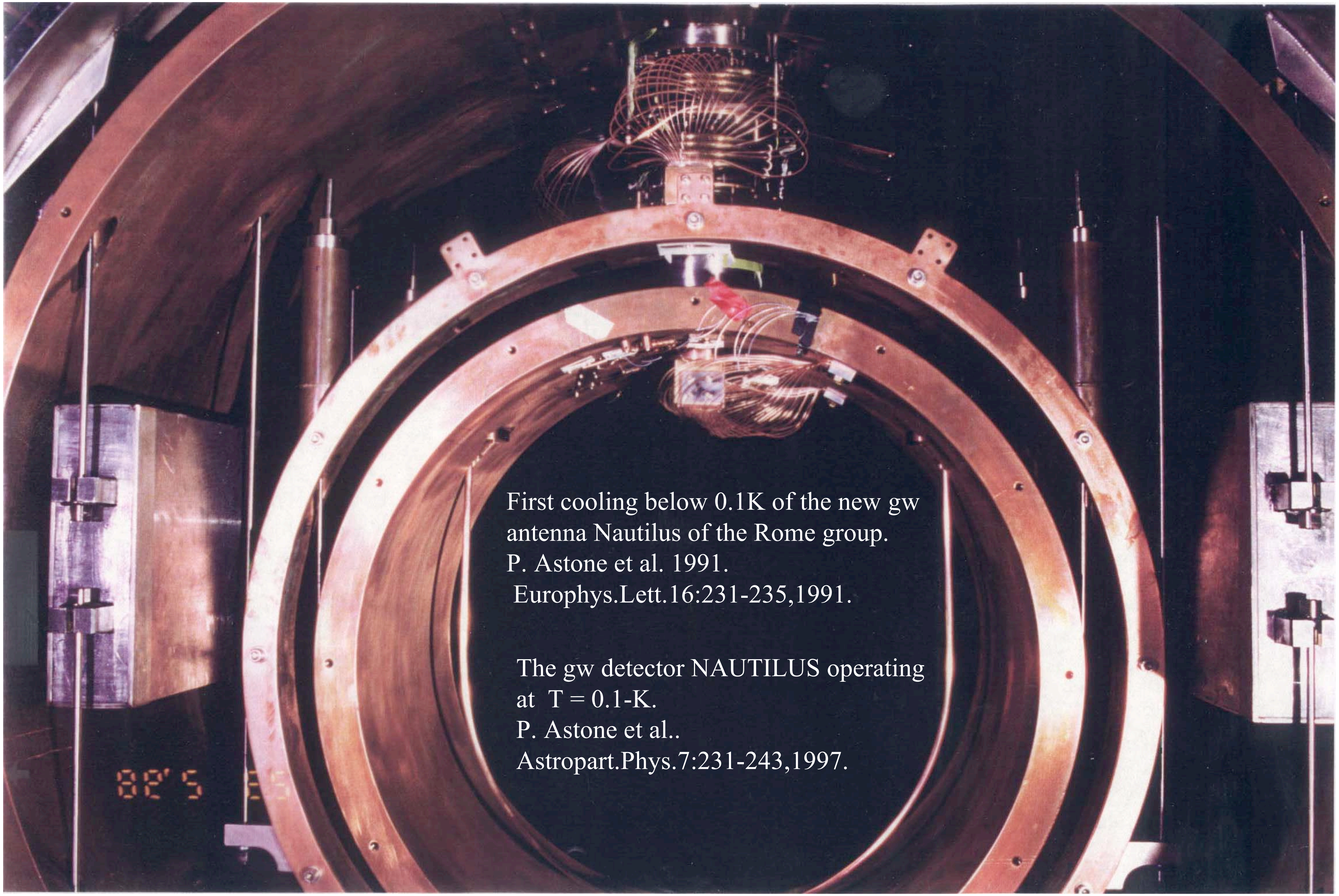
Astone et al.(ROG Collaboration)
Phys. Rev. Lett. 2003



The bandwidth depends mainly on the transducer and amplifier

The peak sensitivity depends on T/MQ

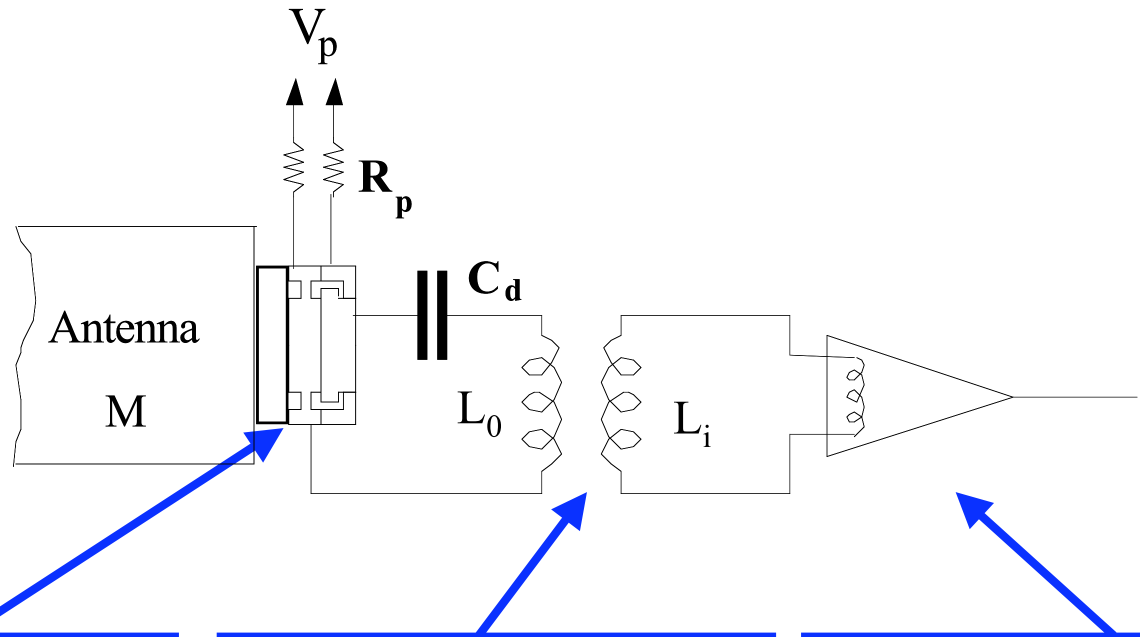
T noise = 690 μK



First cooling below 0.1K of the new gw antenna Nautilus of the Rome group.
P. Astone et al. 1991.
Europhys.Lett.16:231-235,1991.

The gw detector NAUTILUS operating at T = 0.1-K.
P. Astone et al..
Astropart.Phys.7:231-243,1997.

EXPERIMENTAL CONFIGURATION



Capacitive transducer

Al 5056

m_t = 0.75 kg

ν_t = 916 Hz

C_t = 11 nF

Superconducting Low-dissipation Transformer

Lo=2.86 H

Li=0.8μH

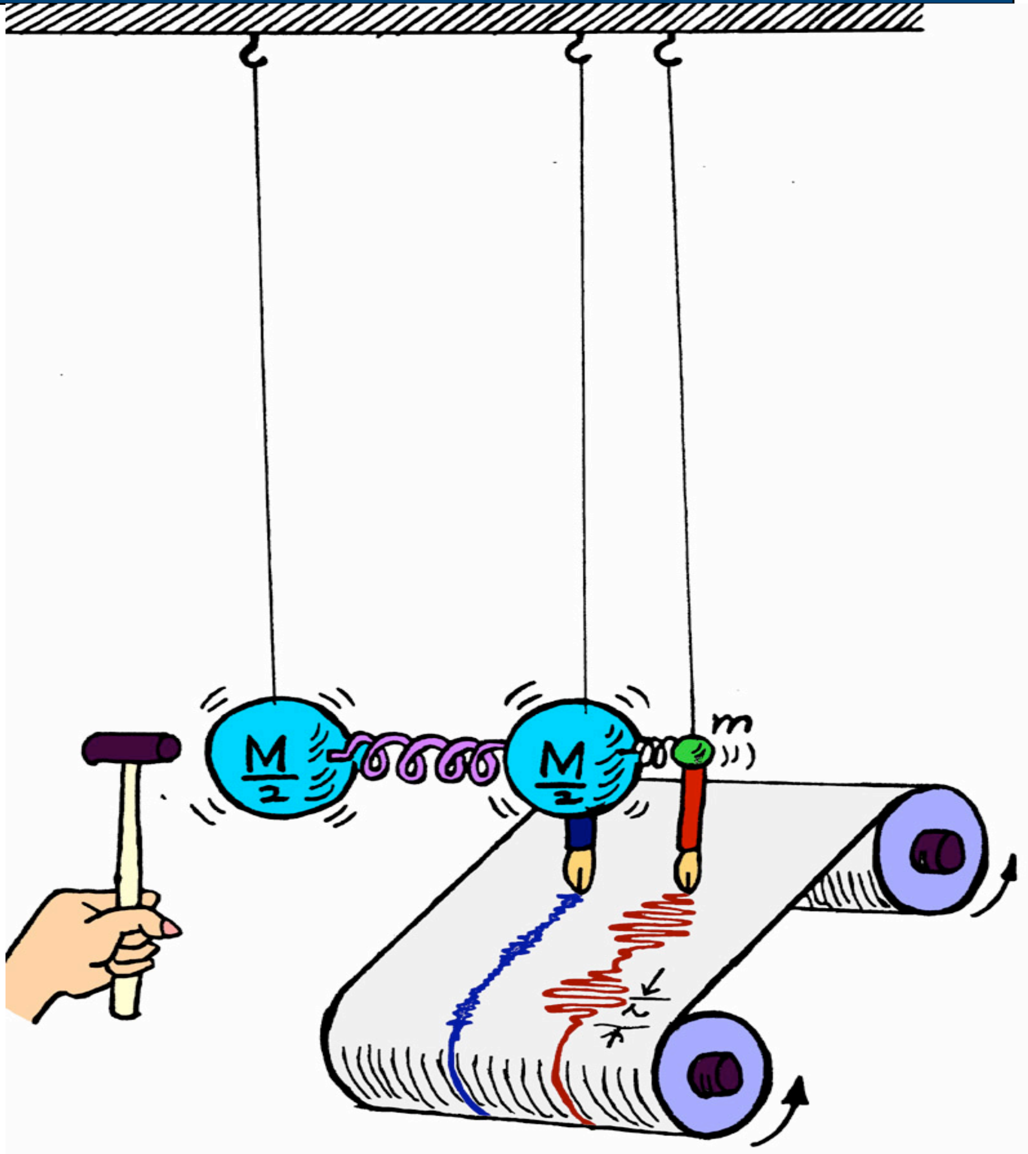
K=0.8

dc-SQUID

M_s = 10 nH

$\Phi_n = 3 \cdot 10^{-6}\ \Phi o/\sqrt{Hz}$

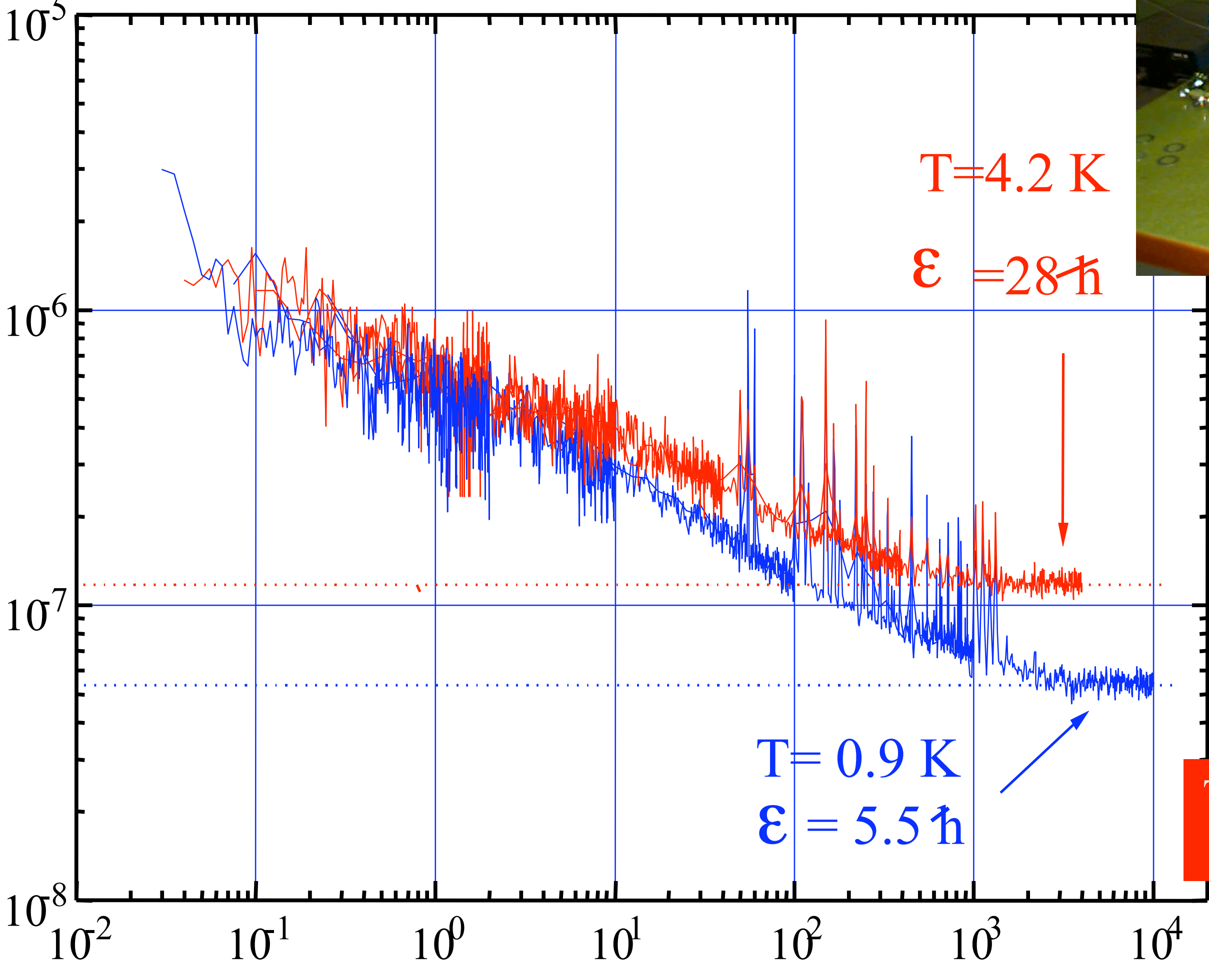
Principle of a Resonant Transducer

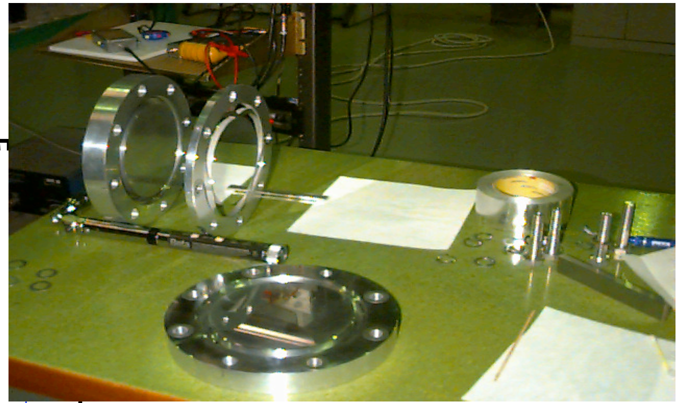


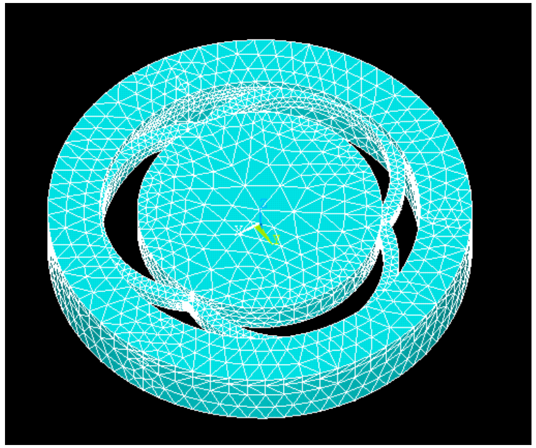
The displacement of the secondary oscillator modulates a dc electric or magnetic field or the frequency of a s.c. cavity

$$x_m = \sqrt{\frac{M}{m}} x_M$$

Experimental flux noise spectral density

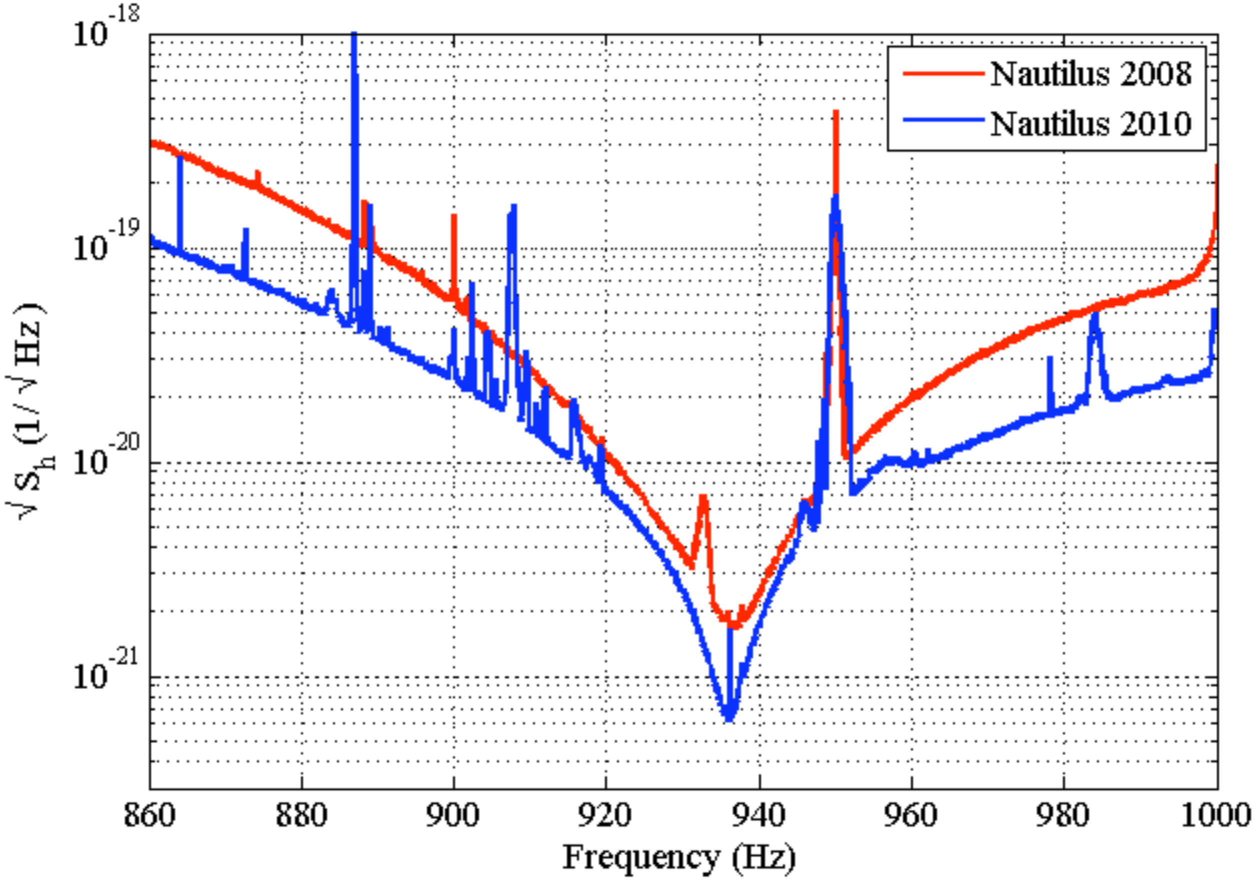






The rosette capacitive transducer
gap=9μm

Increasing the bandwidth of resonant gravitational antennas: The Case of Explorer.
P. Astone et al. (ROG Collaboration)
Phys.Rev.Lett.91:111101,2003.

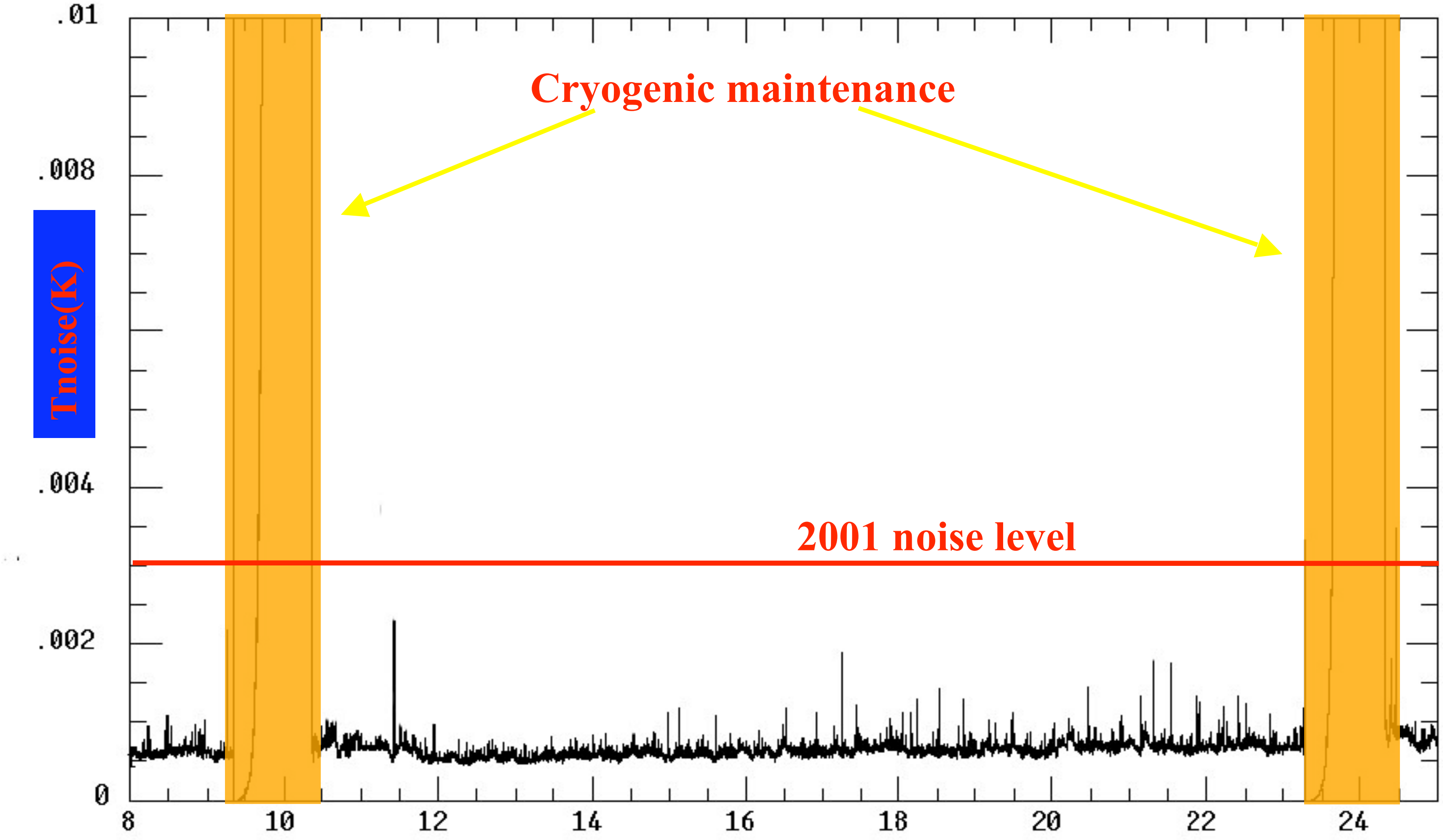


Peak sensitivity

$$6\times10^{-22}\ {}^{1}\!\big/\!\sqrt{Hz} \longrightarrow 7.2\times10^{-22}\ m\big/\sqrt{Hz}$$

strain displacement

World Record!

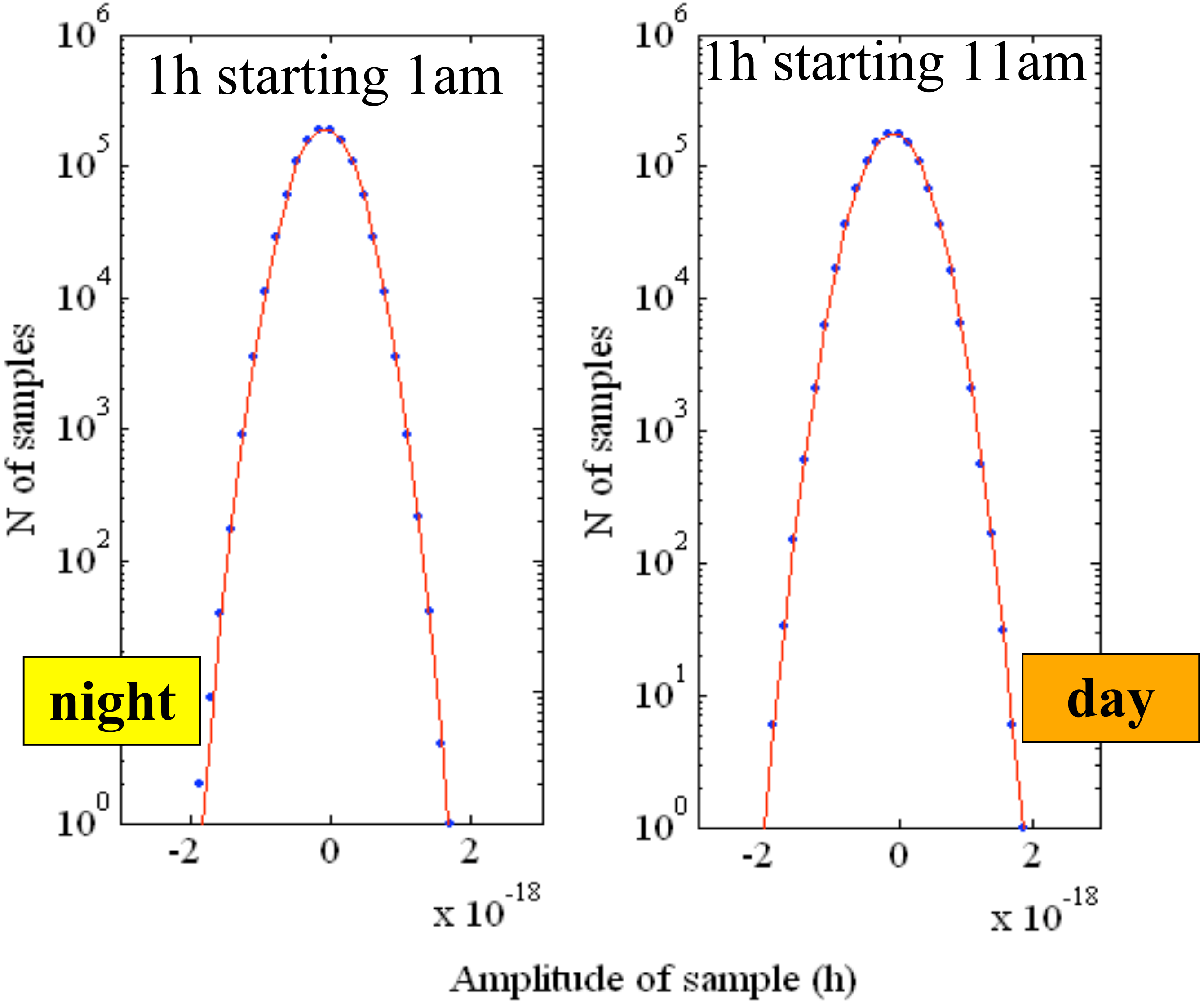


15 days in June 2010

High duty cycle

For ~ 80% of total time the sensitivity to short gw bursts is better than $h=2.1*10^{-19}$

NAUTILUS - 5 April 2010



Some Historical papers

Upper limit for a gravitational-wave stochastic background
with the EXPLORER and NAUTILUS resonant detectors
P. Astone et al. (ROG Collaboration)
Phys. Lett. B **385**, 421-424, 1996.

Upper limit for nuclearite flux from the Rome gravitational wave resonant detectors
P. Astone et al. (ROG Collaboration)
Phys.Rev.D47:4770-4773, 1993

Cosmic rays observed by the resonant gravitational wave detector NAUTILUS
P. Astone et al. (ROG Collaboration)
Phys.Rev.Lett.84:14-17, 2000.

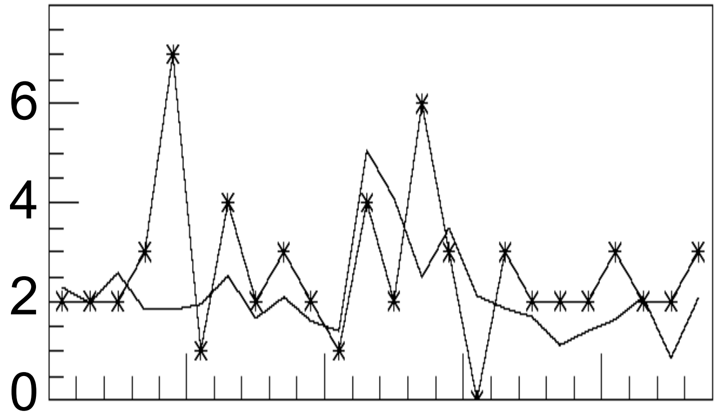
Search for correlation between GRB's detected by BeppoSAX and the gw detectors EXPLORER and NAUTILUS
P. Astone et al. (ROG Collaboration)
Phys.Rev.D66:102002, 2002.

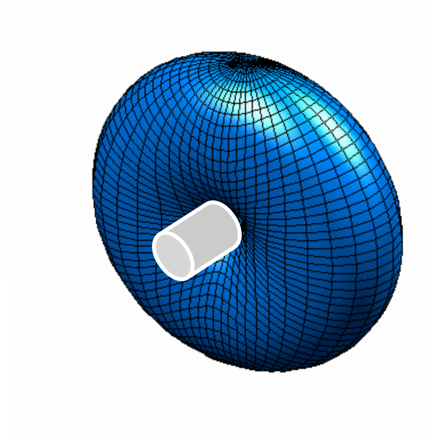
Study of coincidences between the GW detectors Explorer and Nautilus
P. Astone et al. (ROG Collaboration)
Class. Quantum Grav. *19, 5449, 2002.*

Intriguing coincidence excess

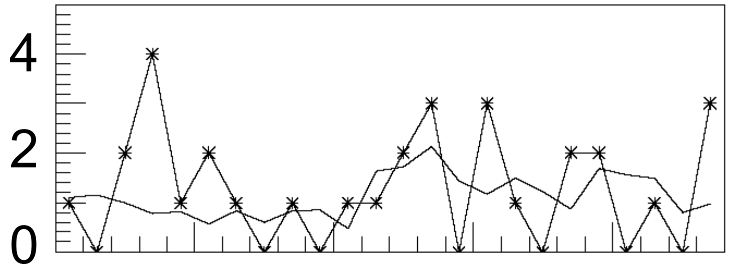
Increasing the bandwidth of resonant gravitational antennas
P. Astone et al. (ROG Collaboration)
Phys.Rev.Lett.91:111101, 2003.

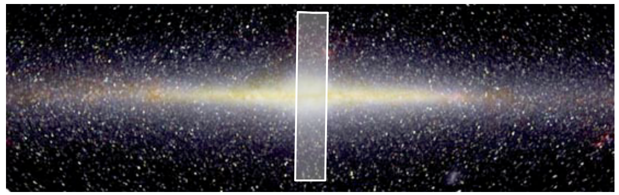
1998



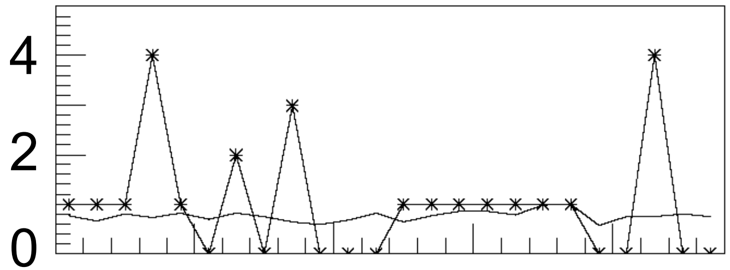


2001





2003



The EXPLORER/NAUTILUS SEARCH FOR SHORT GW BURSTS

1997- 2000 IGEC search *Phys. Rev. Lett. 85, 5046 (2000)*

1998 931 hours; *CQG 18, 43 (2001)*

2001 2156 hours; *CQG 19, 5449 (2002)*

2003 3677 hours; AMALDI 6, *CQG 23, S169 (2006)*

2004 5196 hours; AMALDI 7, *CQG* 25:114048 *(2008)*

2005 IGEC2 search, *Phys.Rev. D76:102001 (2007)*

2006-2007 IGEC2 search, *Phys.Rev. D76:102001 (2010)*

Results of the IGEC-2 search for gravitational wave bursts during 2005

P. Astone[1], D. Babusci[2], L.Baggio[3], M. Bassan[4,5], M. Bignotto[6,7], M. Bonaldi[8,9], M. Camarda[10] , P. Carelli[5,11], G. Cavallari[12], M. Cerdonio[6,7], A. Chincarini[13], E. Coccia[4,14], L. Conti[6,7], S. D'Antonio[5], M. De Rosa[15,16], M. di Paolo Emilio[11,14], M. Drago[6,7], F. Dubath[17], V. Fafone[4,5], P. Falferi[8,9], S. Foffa[17], P. Fortini[18], S. Frasca[1,19], G. Gemme[13], G. Giordano[2], G. Giusfredi[20], W.O. Hamilton[21], J. Hanson[21], M. Inguscio[16,22], W.W. Johnson[21], N. Liguori[6,7], S. Longo[23], M. Maggiore[17], F. Marin[16,22], A. Marini[2], M. P. McHugh[24], R. Mezzena[9,25], P. Miller[21], Y. Minenkov[14], A. Mion[9,25], G. Modestino[2], A. Moleti[4,5], D. Nettles[21], A. Ortolan[23], G.V. Pallottino[1,19], R. Parodi[13], G. Piano Mortari[11,14], S. Poggi[26], G.A. Prodi[*9,25], L. Quintieri[2], V. Re[9,25], A. Rocchi[4], F. Ronga[2], F. Salemi[9,25], G. Soranzo[7], R. Sturani[17], L. Taffarello[7], R. Terenzi[1,27], G. Torrioli[1,28], R. Vaccarone[13], G. Vandoni[12], G. Vedovato[7], A. Vinante[8,9], M. Visco[4,27], S. Vitale[9,25], J. Weaver[21], J.P. Zendri[7] and P. Zhang[21]
(IGEC-2 Collaboration)

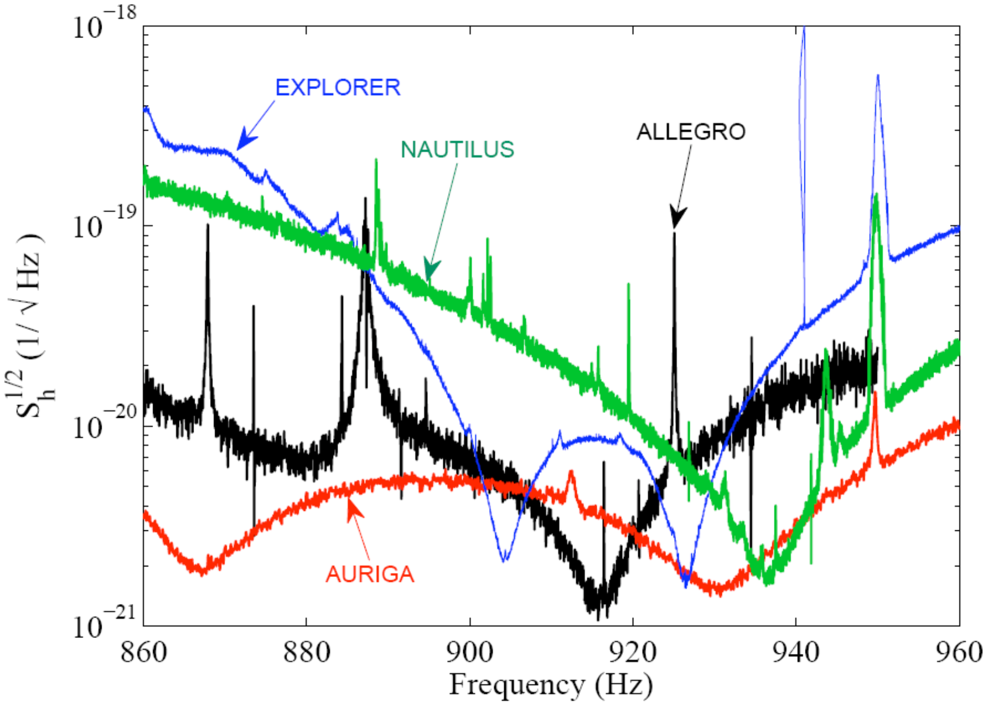
Phys.Rev.D**76** (2007) 102001
gr-qc 0705.0688

ALLEGRO (LSU) - AURIGA - EXPLORER - NAUTILUS

- First analysis in 2005:**180 days from May to November 2005.** Search for triple coincidences.

No coincidence found on a background of 1event/century

- Second analysis: **515 days from 16 November 2005 to 14 April 2007.** Search for triple and quadrupole coincidences. **No coincidence found on a background of 1event/century** (*http://arxiv1.library.cornell.edu/abs/1002.3515v1*, *Phys.Rev. D76:102001 (2010)*

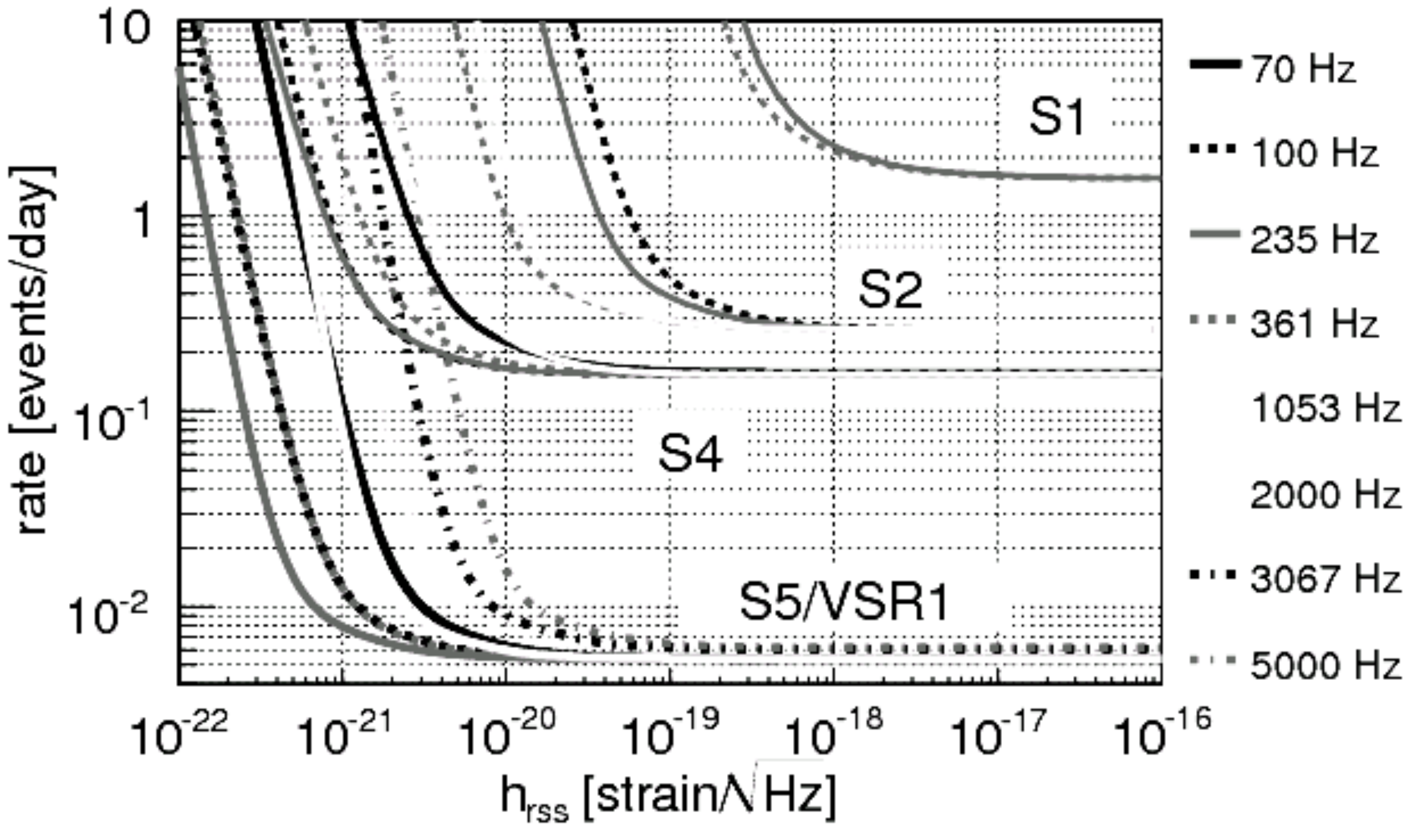


Complete coverage

Configuration	Time of operation (days)
0 detector	0
1 detectors	1.633
2 detectors	30.998
3 detectors	188.837
4 detectors	293.532

94% of the observation time

Burst search results: Upper limits



- Combined upper limits for the entire S5/VSR1 in the frequency range 50-6000

rate limit: 2 events/year

Comparison with IGEC:

1.5 events per year but with two orders lower strain sensitivity.

BURST SEARCH

Last two years

First joint Gravitational Waves search by the Auriga-Explorer-Nautilus-Virgo collaboration.
By AURIGA-EXPLORER-NAUTILUS-Virgo Collaboration (F. Acernese et al.). Oct 2007. 23pp.
Published in Class.Quant.Grav.25:2005007, 2008. e-Print: arXiv:0710.3752 [gr-qc]

Results of the IGEC-2 search for gravitational wave bursts during 2005.
By IGEC-2 Collaboration (P. Astone et al.). May 2007. 10pp.
Published in Phys.Rev.D76:102001, 2007. e-Print: arXiv:0705.0688 [gr-qc]

EXPLORER and NAUTILUS gravitational wave detectors: status report on recent analysis
P. Astone et al. 2008. 8pp.
Published in Class.Quant.Grav.25:114048, 2008.

CONTINUOUS SIGNALS SEARCH

All-sky search of NAUTILUS data.
P. Astone et al. Sep 2008. 12pp.
Published in Class.Quant.Grav.25:184012,2008. e-Print: arXiv:0809.0273 [gr-qc]

All-sky incoherent search for periodic signals with Explorer 2005 data.
P. Astone et al. Aug 2007. 9pp.
Published in Class.Quant.Grav.25:114028,2008. e-Print: arXiv:0708.4367 [gr-qc]

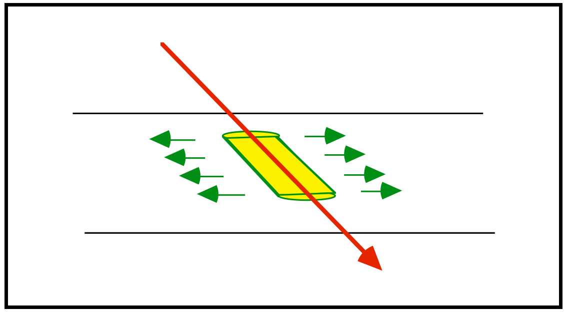
COSMIC RAYS DETECTION

Detection of high energy cosmic rays with the resonant gravitational wave detector NAUTILUS and EXPLORER.
P. Astone et al. Jun 2008. 21pp.
Published in Astropart.Phys.30:200-208,2008. e-Print: arXiv:0806.1335 [hep-ex]

Cosmic ray interaction in the bar

Thermo-Acoustic Model:

the ***energy deposited*** by the particle is converted in a ***local heating*** of the medium:



$$\delta T = \frac{\delta E}{\rho C V_0}$$

$$\delta p = \gamma \frac{\delta E}{V_0} \qquad \gamma = \frac{\alpha Y}{\rho C}$$

Excitation of the longitudinal modes of a cylindrical bar

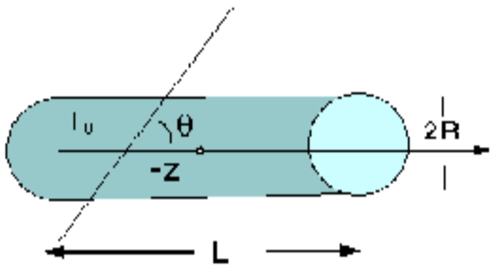
$$E_n = \frac{1}{2}\frac{l^2}{V}\frac{G_n^2}{\rho v^2}\gamma^2\left(\frac{dE}{dX}\right)^2$$

Allega A.M. & Cabibbo N. Lett Nuovo Cim 38 (1983) 263-

A. De Rujula & B. Lautrup, Nucl Phys. B242 (1984) 93-144

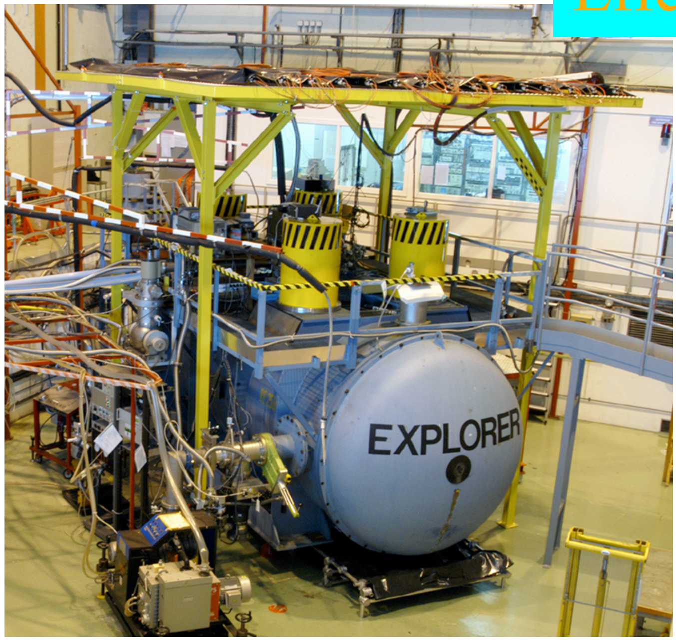
G_n form factor

A resonant gw detector used as a particle detector is different from any other particle detector



γ = Gruneisen “constant”

Effect of cosmic rays



EXPLORER is equipped with 3 layers (2 above the cryostat - area 13m^2 - and 1 below -area 6 m^2) **of Plastic Scintillators.**

NAUTILUS is equipped with 7 layers (3 above the cryostat - area 36m^2/each - and 4 below -area 16.5 m^2/each) **of Streamer tubes.**

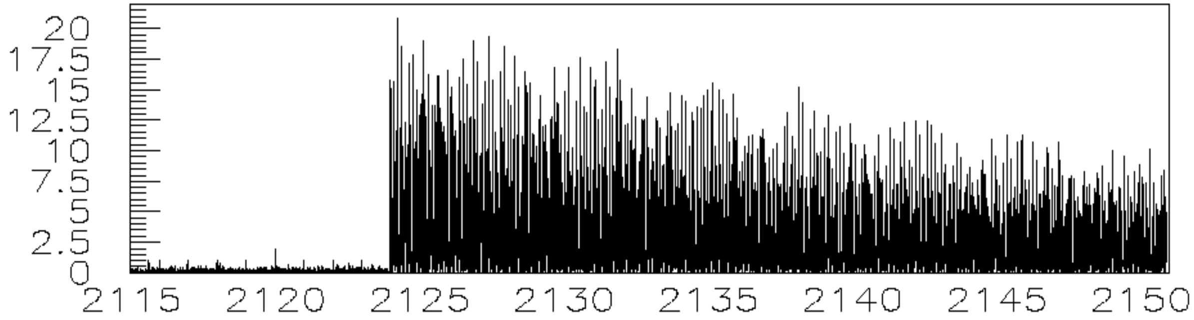
The cosmic ray effect on the bar is measured by an offline correlation, driven by the arrival time of the cosmic rays, between the observed multiplicity in the CR detector (saturation for $M \geq 10^3$ particles/m^2) and the data of the antenna, sampled each 4.54 ms and processed by a filter matched to δ signals

$\Delta E = 500\ \mu K = 75\ peV$

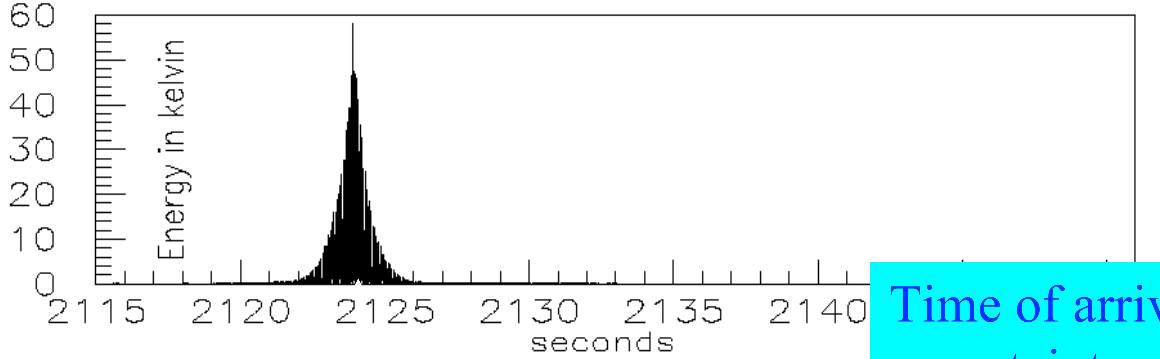
Burst event for a present bar: a millisecond pulse, a signal made by a few millisecond cycles, or a signal sweeping in frequency through the detector resonances. The burst search with bars is therefore sensitive to different kinds of gw sources such as a stellar gravitational collapse, the last stable orbits of an inspiraling NS or BH binary, its merging, and its final ringdown.

Real data: the arrival of a cosmic ray shower on NAUTILUS

Unfiltered signal



The signal after filtering (kelvin)



Time of arrival uncertainty ~ 1 ms

Physics News Update
The American Institute of Physics Bulletin of Physics News

Number 465 (Story #3), January 7, 2000 by Phillip F. Schewe and Ben Stein

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COSMIC RAYS OBSERVED BY GRAVITY-WAVE DETECTOR at the Frascati Laboratory in Italy consists of a 2300-kg aluminum cylinder cooled to a temperature of 0.1 K. The plan is that a passing gravitational wave (broadcast, say, by the collision of two neutron stars) would excite a noticeable vibration in the cylinder. NAUTILUS has not yet recorded any gravitational waves, but scientists have now witnessed the cylinder vibrated by energetic particle showers initiated when cosmic rays strike the atmosphere. The signal generated by the rays is believable because conventional cosmic-ray detectors surrounding the bar also lit up when they were struck by the particles. In effect the detector is able to discern a mechanical vibration as small as 10^{-18} meters, corresponding to an energy deposit as small as 10^{-6} eV. (Astone et al., *Physical Review Letters*, 3 January 2000; Select Article. Contact Giuseppina Modestino, modestino@lnf.infn.it, 011-39-694-032-756.)

Thermo-acoustic effect and Cosmic ray detection in Nautilus and Explorer "enhancement at T=0.14Kelvin"

- an "event" in the antenna language --> signal many sigma above noise (~10 mKelvin or more)
- adding the antenna output for many cosmic ray signals and subtracting the background out of time we have sensitivity for very small signals (~0.01 mKelvin)

In this plot you see directly the enhancement due to superconductive state.
The RAP experiment using a particle beam has confirmed the thermo-acoustic model for T>Tc.
For T<Tc RAP has measured an enhancement similar to Nautilus. This is due to superconductive effects

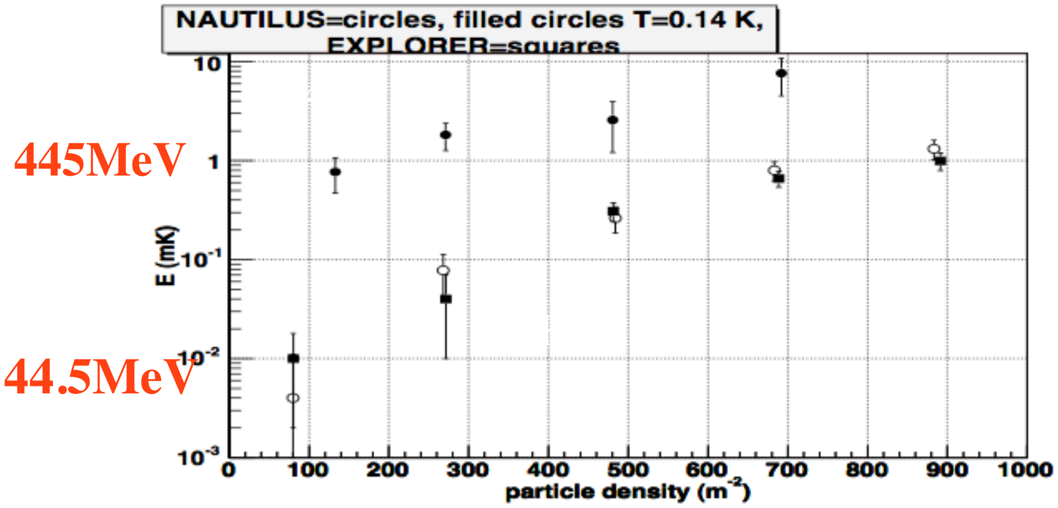


Fig. 3. Averages of signals with energy $E_{exp} \leq 0.1\ K$, grouping data in ranges of particle density Λ. Filled circles NAUTILUS at T = 0.14 K, open circles NAUTILUS at $T = 3\ K$, filled squares EXPLORER at $T = 3\ K$. The data gathered at $T = 0.14\ K$ are almost one order of magnitude larger than those collected at $T = 3\ K$.

In Nautilus T= 0.14 K >1 order of magnitude in energy

Thermo-acoustic effect: "exotics particles"

searches in anti- coincidence with the CR detector

we need very high energy release
candidates: (nuclearites= stable matter with s quark, qballs ecc..)

$$\frac{dE}{dx} = 480 \frac{\text{GeV}}{\text{cm}} \left[\frac{\beta\theta(m)}{10^{-3}} \right]^2 ,$$

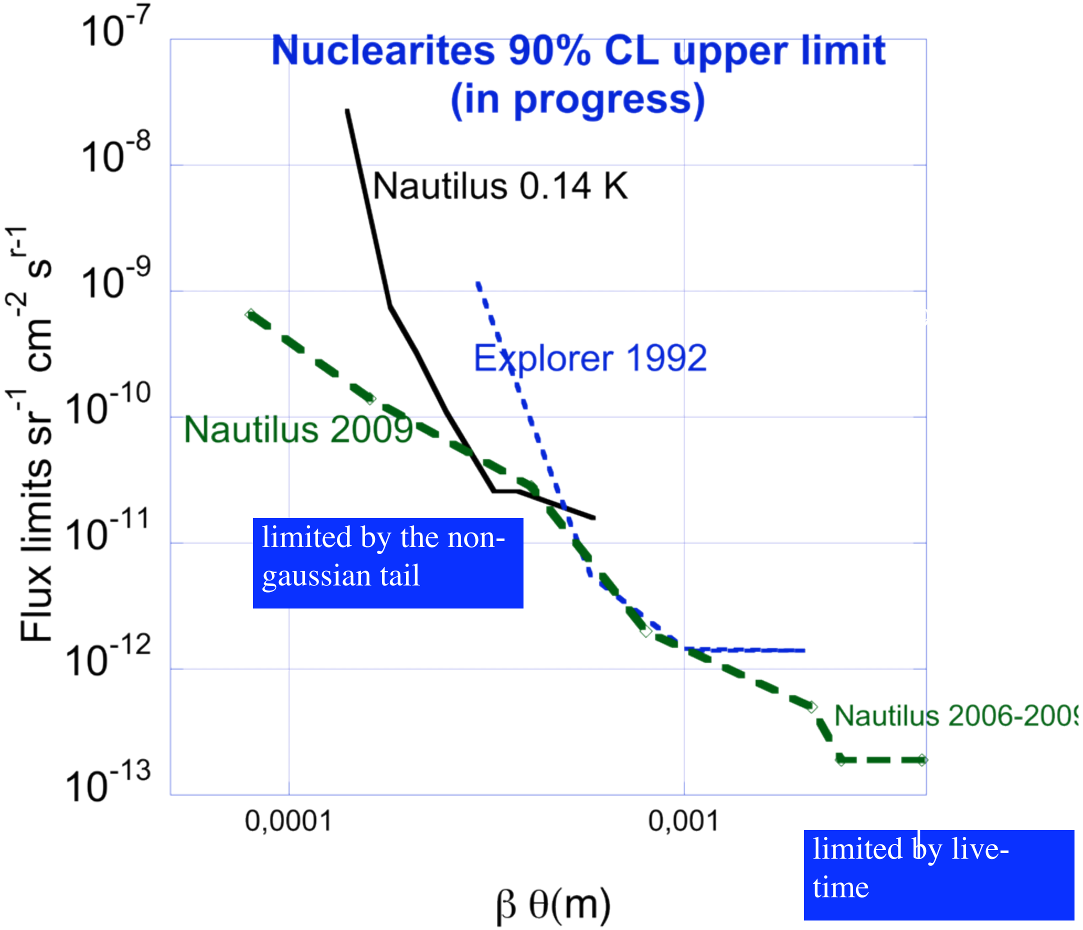
where the mass dependence is

$$\theta(m) = 1 \quad \text{if } m \leq 1.5 \text{ ng} ,$$

$$\theta(m) = \left[\frac{m}{1.5 \text{ ng}} \right]^{1/3} \quad \text{if } m \geq 1.5 \text{ ng} .$$

- limits are higher than the ones in other experiments (SLIM 1.4 10^{-15} MACRO 3 10^{-16})

- some interest because the detection mechanism is quite simple, no threshold in β "calorimetric measurement"

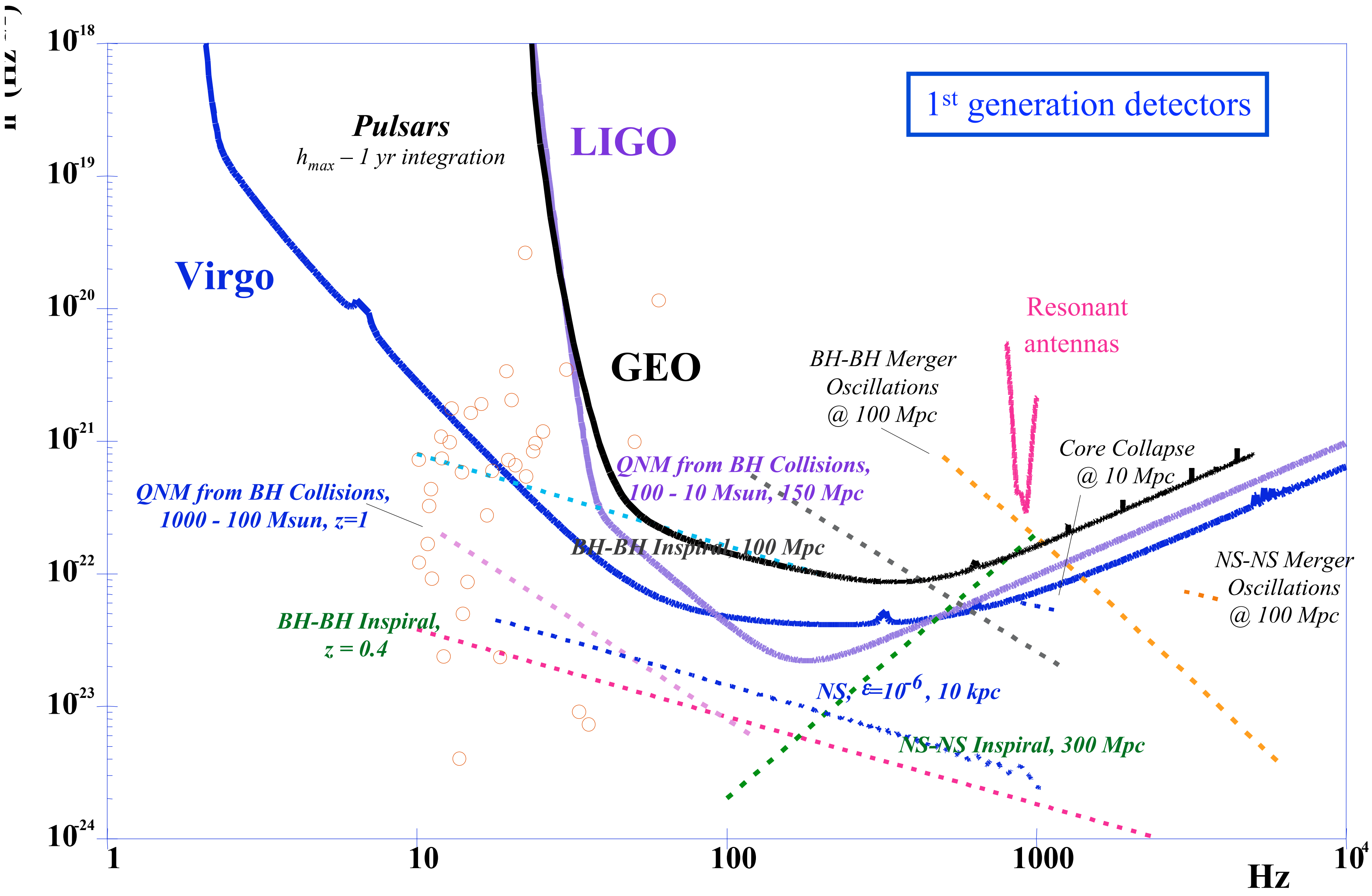


The phase change and the future

1960 - 2005
Given the uncharted territory that gravitational-wave detectors are probing unexpected sources may actually provide the first detection.

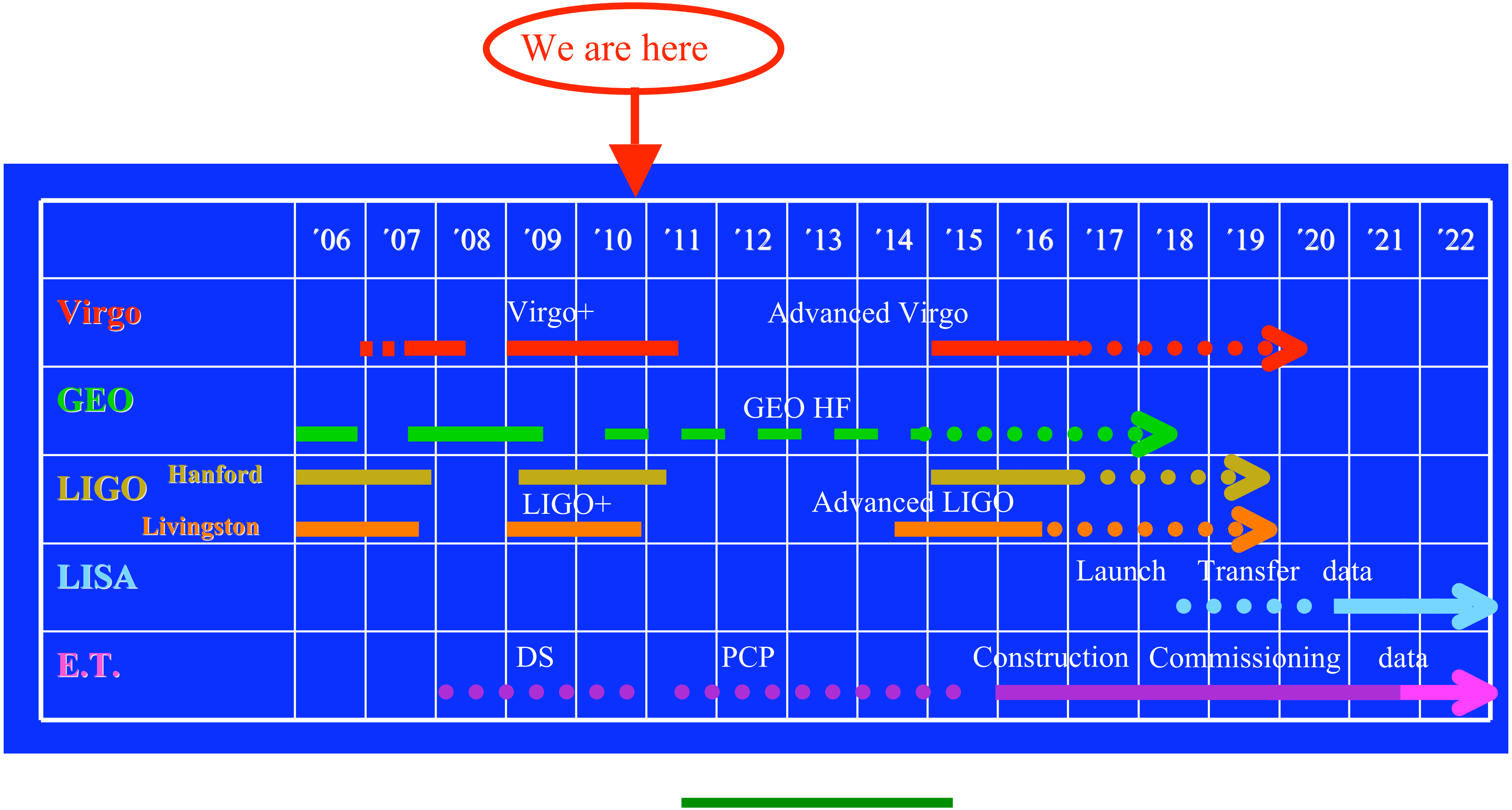
2005 -
Only new high sensitivity detectors can provide the first detection and open the GW astronomy

The contribution of Resonant Bars has been essential in establishing the field, giving interesting results and putting some important upper limits on the gravitational landscape around us, but now **the hope for guaranteed detection is in the Network of long arm interferometers.**



1st generation detectors
Pulsars
h_max – 1 yr integration
LIGO
Virgo
GEO
Resonant antennas
BH-BH Merger Oscillations @ 100 Mpc
Core Collapse @ 10 Mpc
QNM from BH Collisions, 100 - 10 Msun, 150 Mpc
QNM from BH Collisions, 1000 - 100 Msun, z=1
BH-BH Inspiral, 100 Mpc
NS-NS Merger Oscillations @ 100 Mpc
BH-BH Inspiral, z = 0.4
NS, ε=10^-6, 10 kpc
NS-NS Inspiral, 300 Mpc
10^-18
10^-19
10^-20
10^-21
10^-22
10^-23
10^-24
1
10
100
1000
10^4
Hz

Data Taking



Window of opportunity

Detectable signals today

BURSTS: Black Hole ($M \sim 10 M_O$) formation, $10^{-4} M_O$ into GW

$$SNR = 6 \times 10^3 \left(\frac{10kpc}{r}\right)^2 \left(\frac{10^{-44} Hz^{-1}}{\tilde{h}^2}\right)\left(\frac{\Delta f}{1Hz}\right)$$

SPINNING NEUTRON STARS: Non axisymmetric ($\varepsilon \sim 10^{-6}$) pulsar, $M \sim 1.4 M_O$

$$SNR \approx 30 \left(\frac{10kpc}{r}\right)^2 \left(\frac{10^{-44} Hz^{-1}}{\tilde{h}^2}\right)\left(\frac{\varepsilon}{10^{-6}}\right)\left(\frac{T_{obs}}{1y}\right)$$

COALESCING BINARIES: Inspiraling NS-NS system, $M \sim 1.4 M_O$

$$SNR \approx 10^3 \left(\frac{10kpc}{r}\right)^2 \left(\frac{10^{-44} Hz^{-1}}{\tilde{h}^2}\right)\left(\frac{\Delta f}{1Hz}\right)$$

STOCHASTIC BACKGROUND: 2 detectors, at distance $d << \lambda_{GW}$

$$\Omega_{GW} \approx 2 \times 10^{-3} \left(\frac{f}{900Hz}\right)^3 \left(\frac{\tilde{h}_{1,2}}{10^{-22} Hz^{-1/2}}\right)^2 \left(\frac{1Hz}{\Delta f}\right)^{1/2} \left(\frac{1y}{T_{obs}}\right)^{1/2}$$

Sn 1987a February 23, 1987

Conclusion

• NAUTILUS

- 95% duty cycle
- monitor of gw sources in the Galaxy
- data *validated* by cosmic ray acoustic effect
- study of coincidences in long runs

• NAUTILUS and AURIGA in continuous operation: continuous search for strong galactic sources during the long period not covered by long arm interferometers.