

5<sup>th</sup> Edoardo Amaldi Conference on Gravitational Waves  
Green Park Resort - Tirrenia (Pisa)  
*July 6-11, 2003*

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# Resonant detectors: bars and spheres

Viviana Fafone  
INFN-LNF  
7 July 2003

LIGO-G030471-00-Z

# Gravitational Wave Detectors

- Interferometric
- Resonant-Mass

LISA

MINIGRAIL

GEO

AURIGA

EXPLORER

VIRGO

NAUTILUS

TAMA

LCGT

LIGO

ALLEGRO

LIGO

MARIO SCHENBERG

AIGO

NIOBE

# NEWS from the detectors

ALLEGRO:

AURIGA:

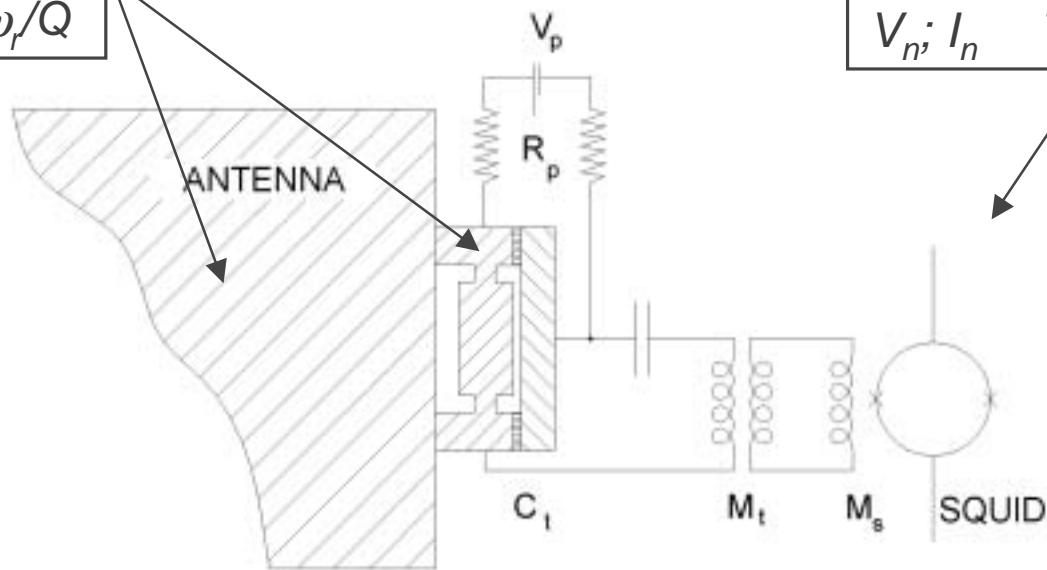
EXPLORER:

NAUTILUS:

New bar tuned at 935 Hz. New bar suspension cable.  
New transducer and SQUID (the same EXPLORER readout).  
Third run has started; the bar is at 3.5 K for the time being.  
The peak strain sensitivity is  $2 \times 10^{-21} \text{ Hz}^{-1/2}$   
and the bandwidth 30 Hz @  $10^{-20} \text{ Hz}^{-1/2}$

Thermal noise  
 $S_F = MkT\omega_r/Q$

Electronic noise  
 $V_n, I_n \quad T_n = \sqrt{V_n^2 I_n^2} / k$



**The mechanical oscillator**

Mass **M**  
 Speed of sound **v<sub>s</sub>**  
 Temperature **T**  
 Quality factor **Q**  
 Res. frequency **f<sub>r</sub>**

**The transducer**

Efficiency **β**

**The amplifier**

Noise temperature **T<sub>n</sub>**

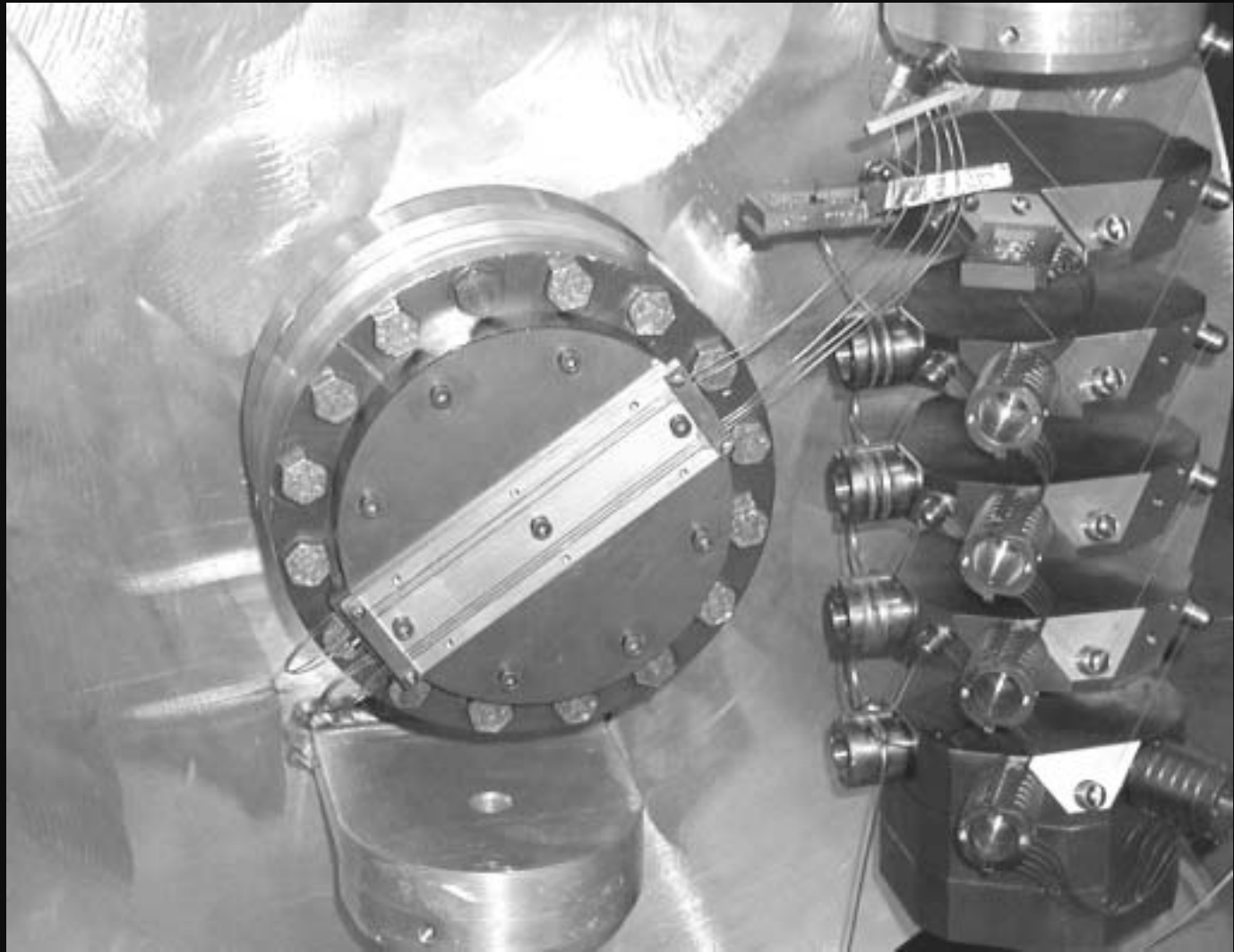
# ALLEGRO

After a run during the LIGO E7 run, the system was upgraded.

The old transducer had lost coupling on several previous cooldowns (persistent current had declined by half to 6 amps.)

An old Maryland transducer was adapted and installed, coupled to a QD dc SQUID.

- Sensor gap reduced from LSU transducer by factor of  $\sim 5$ , from  $\sim 125$  mm to  $\sim 25$  mm
- Current increased by 2.5, from 6 A to 16 A
- Doubled area (pickup coils on both sides)
- Improved coupling



- About one month of good data, covering the second half of S2.
- Data for three orientations during run.
  - At start (15 March) ~  $63^\circ$  W of N (~ parallel to IGEC)
  - Rotated to  $\sim 18^\circ$  W of N on 28 March (~ LLO y-axis)
  - Rotated to  $\sim 108^\circ$  W of N on 9 April (~LLO x-axis)

# Plans for the short term ...

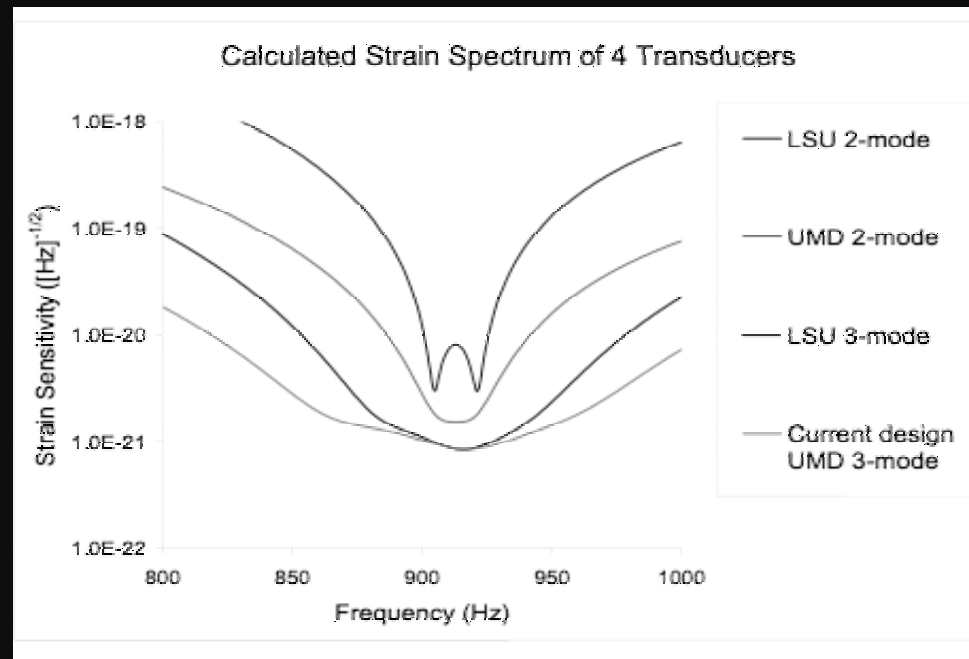
- Helium leak
- Mechanical Q. (low by factor of 3 or 4)
- Amplifier (noise high by factor of  $\sim 2$ )
- New calibrator (calibrator mode interfering with detection modes)

New run in october (S3)



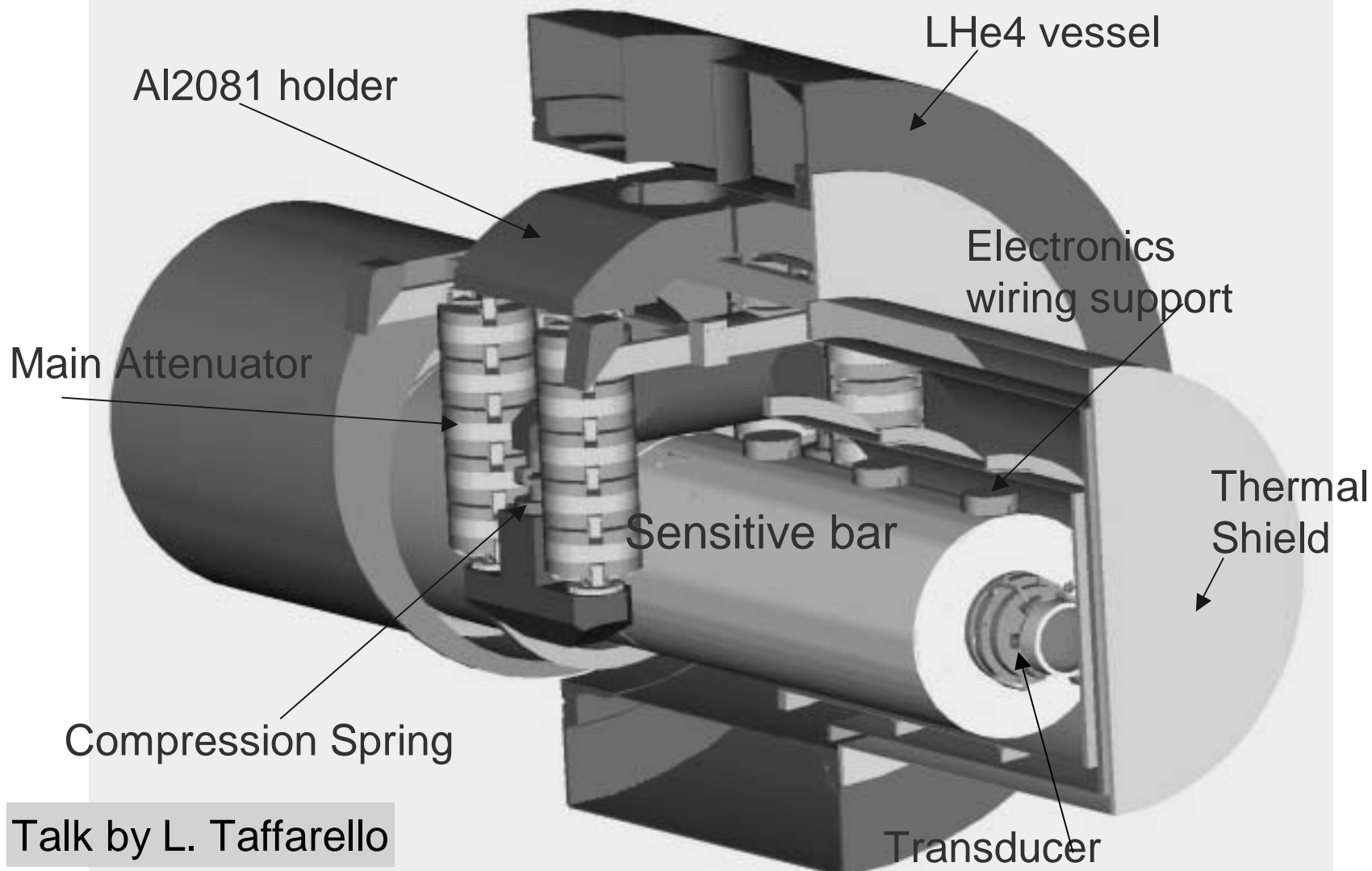
...and mid term (about 1 year)

- Design a two-mode transducer
- Integrate a 2-stage SQUID (AURIGA-QD design)





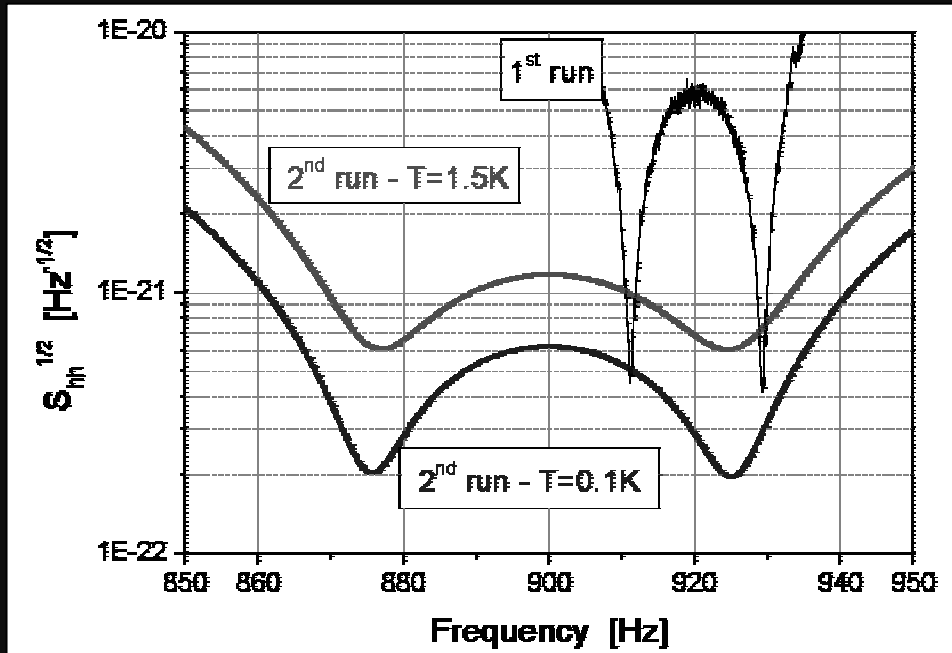
# AURIGA II run (mid 2003)



Talk by L. Taffarello



# AURIGA II run (mid 2003): upgrades



## new mechanical suspensions:

attenuation > 360 dB at 1 kHz

## new capacitive transducer and s.c. transformer

two-modes (1 mechanical+1 electrical)

## new amplifier:

double stage SQUID

## new data analysis:

C++ object oriented code

FEM modelled

optimized mass

200  $\hbar$  energy resolution

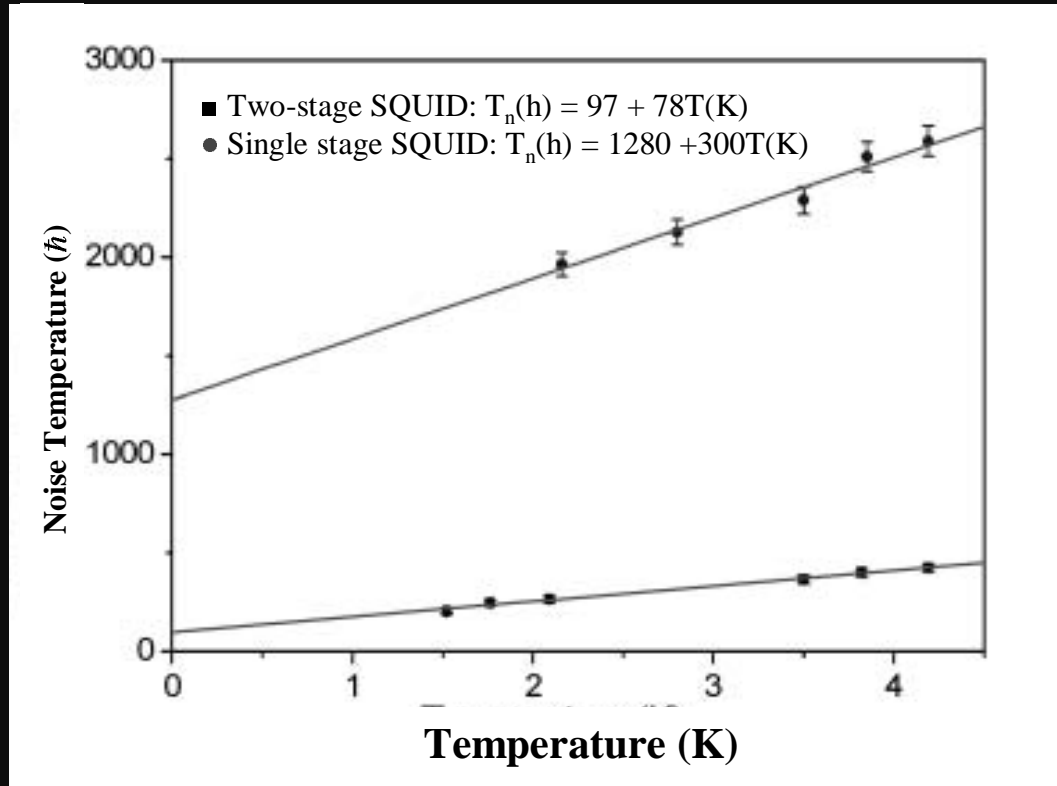
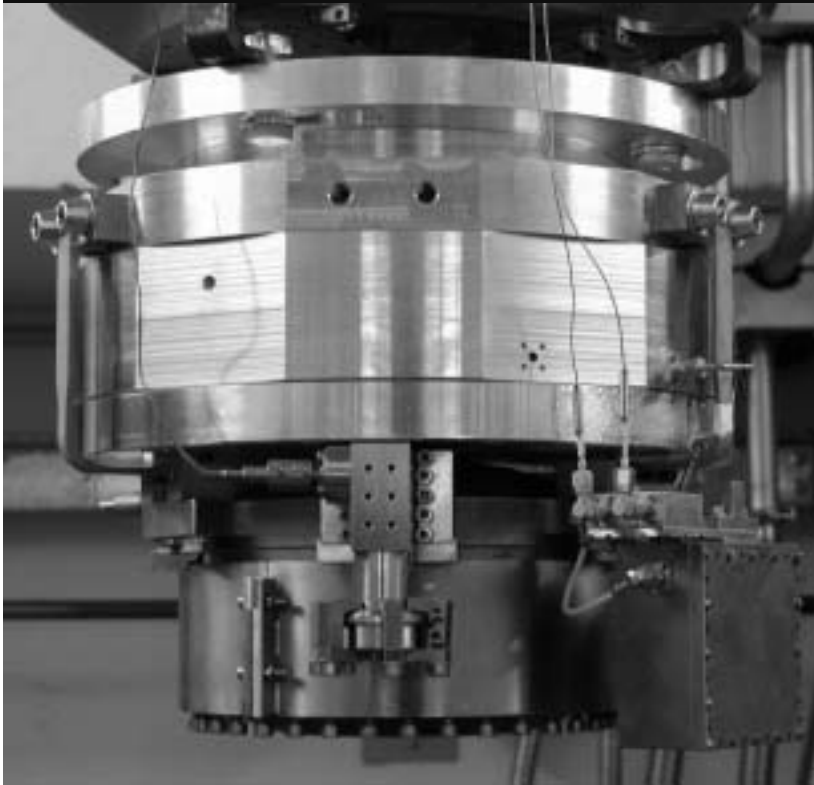
frame data format



# AURIGA II run (mid 2003): upgrades



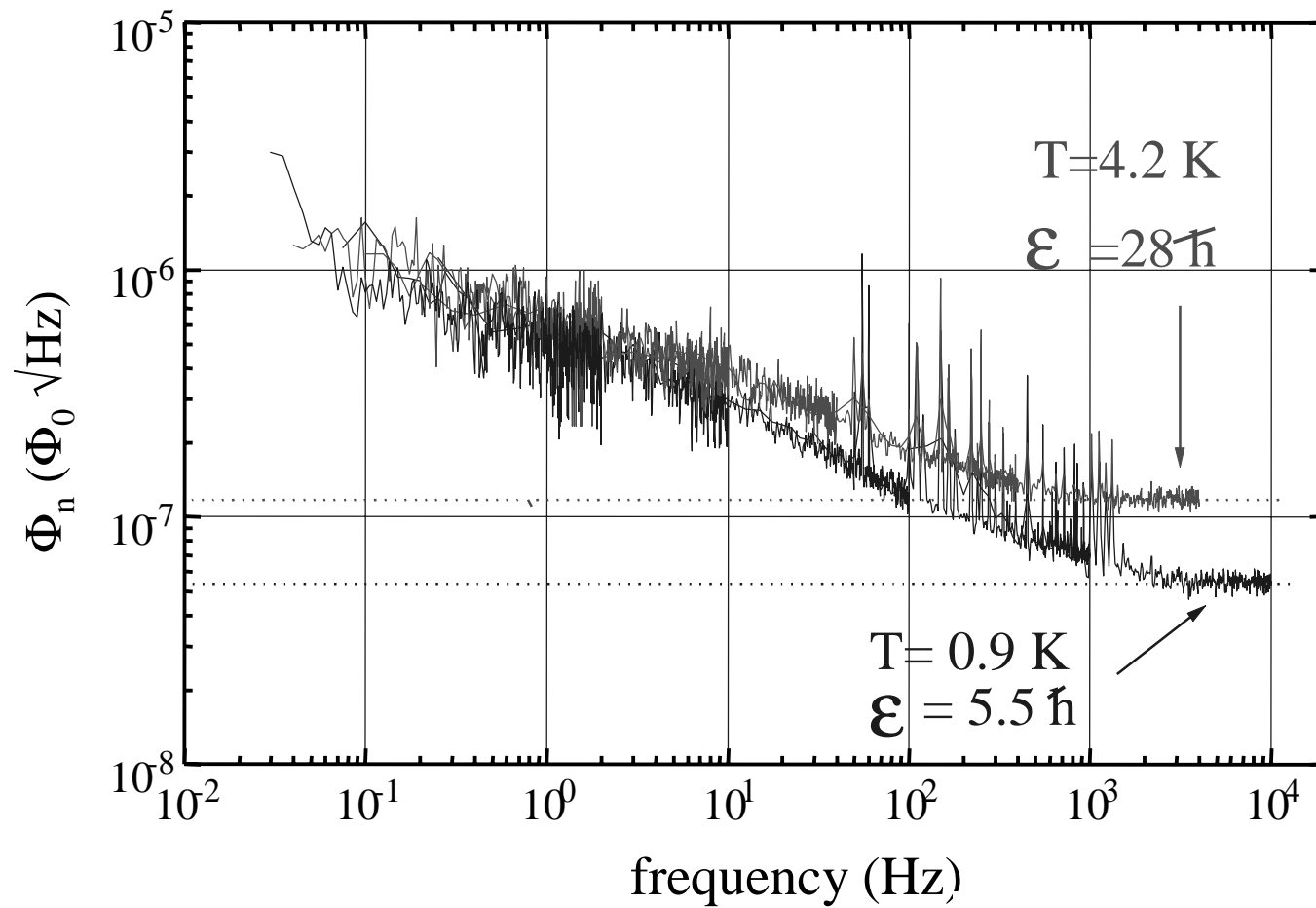
single \* double stage SQUID amplifier



achieved same performances of SQUID amplifier after integration with the capacitive transducer

Talk by J. Zendri

# Experimental flux noise spectral density



Carelli et al. ('98) ROG coll.

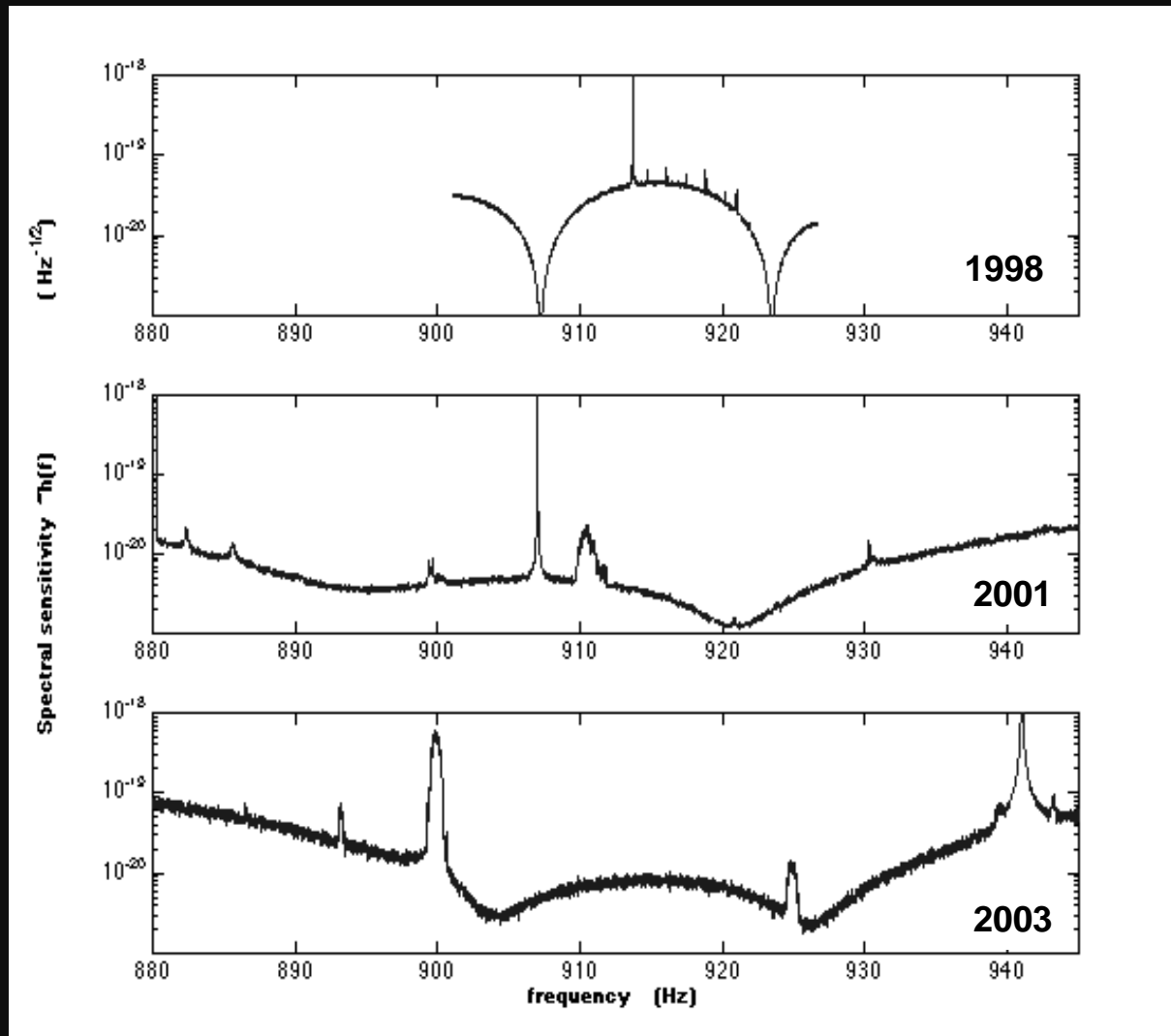
# EXPLORER

EXPLORER has been on the air since May 2000 with:

- new, 10  $\mu\text{m}$  gap transducer
- new, high coupling SQUID

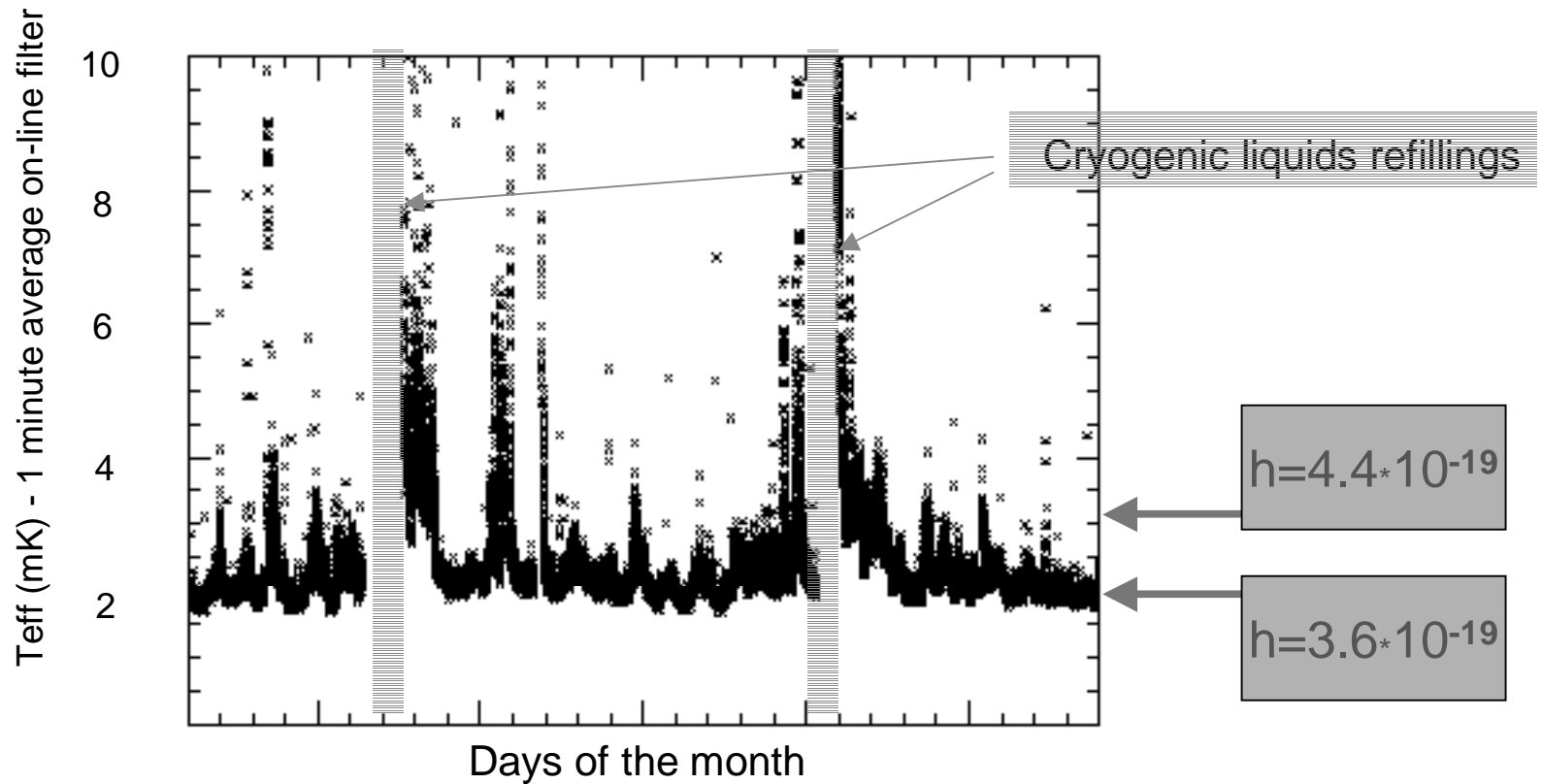
The noise temperature is  $< 3 \text{ mK}$  ( $h=4.4 \cdot 10^{-19}$ ) for 84% of the time.

Bandwidth: the detector has a sensitivity better than  $10^{-20} \text{ Hz}^{-1/2}$  on a band larger than 30 Hz



Talk by M. Visco

# EXPLORER June 2003



For ~ 80% of time the sensitivity to short gw bursts is better than  $h=4.4 \cdot 10^{-19}$

# NAUTILUS 2003

- $\nu_a = 935$  Hz
- new antenna suspension cable
- new capacitive transducer
- Quantum Design dc SQUID

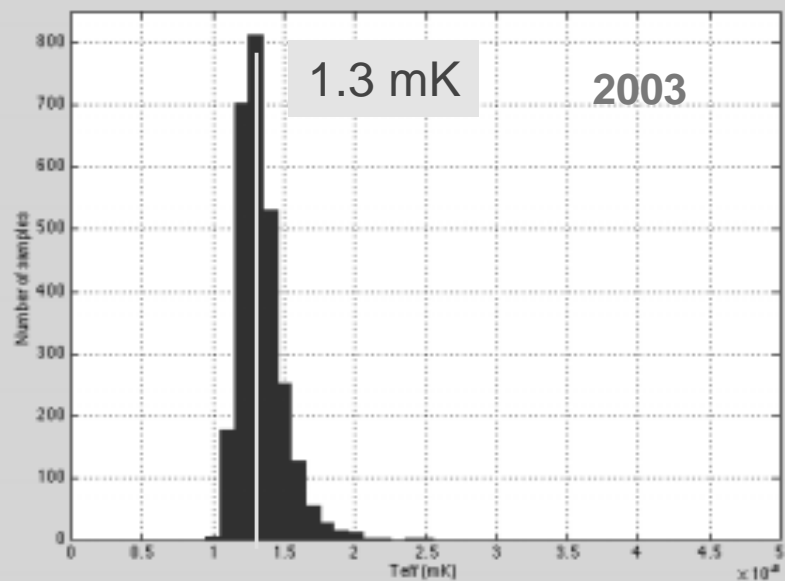
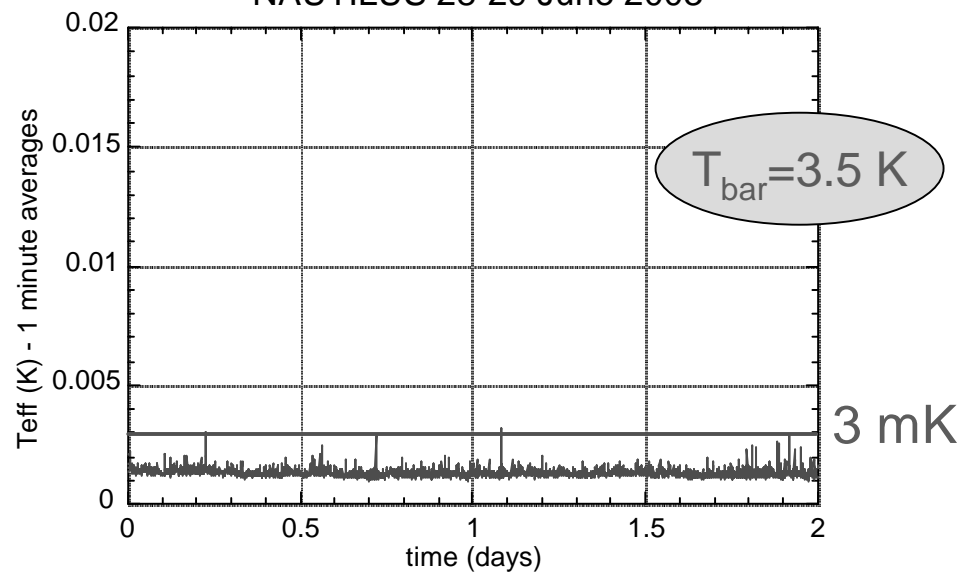
The bar was cooled down to 3.5 K in April. Data taking is under way. Performances can be improved with system optimization.



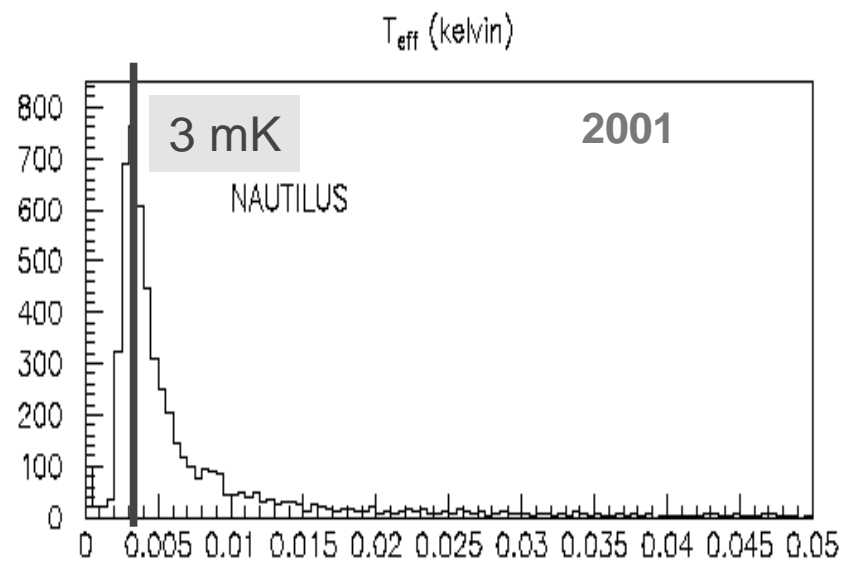
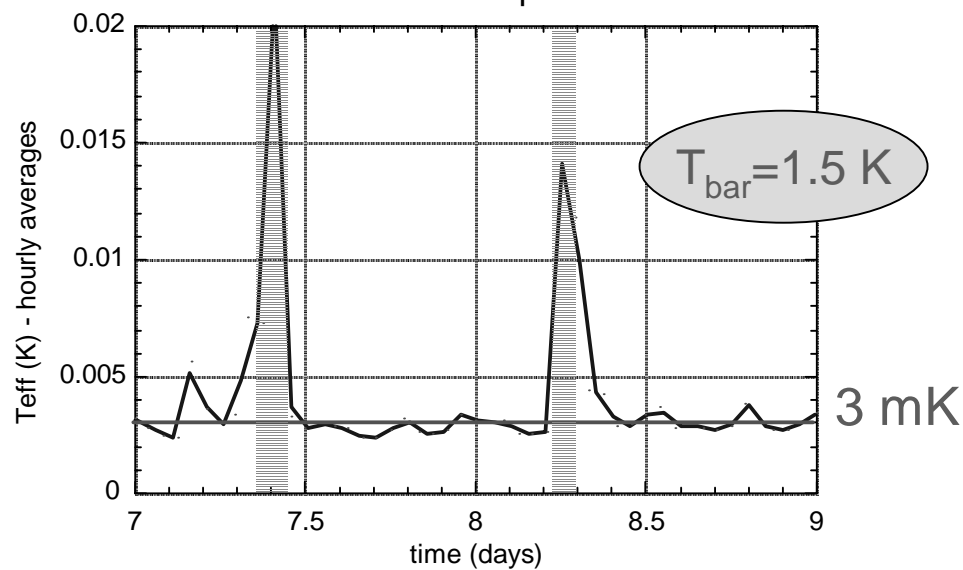
Talk by M. Visco



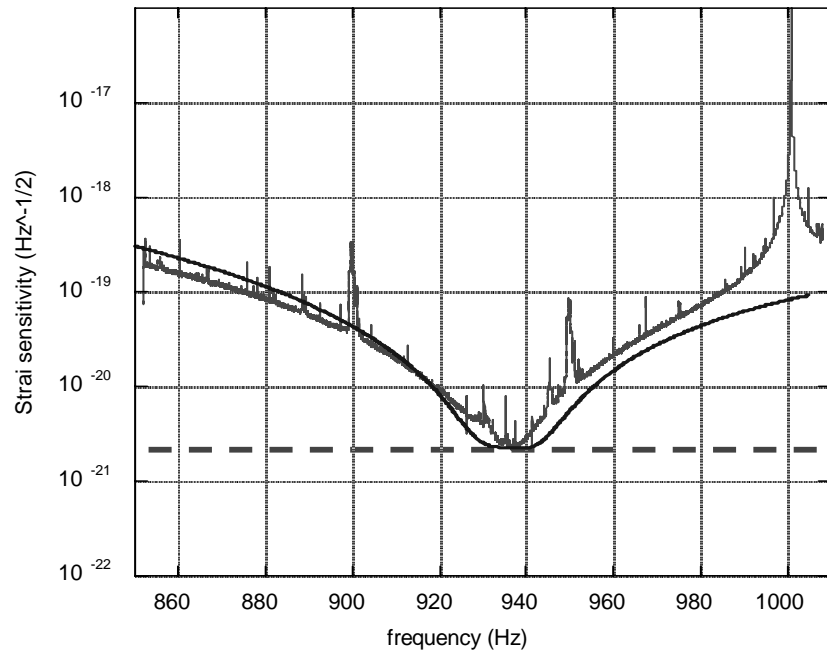
NAUTILUS 28-29 June 2003



NAUTILUS April 2001



# NAUTILUS spectral density at 3.5 K June 2003

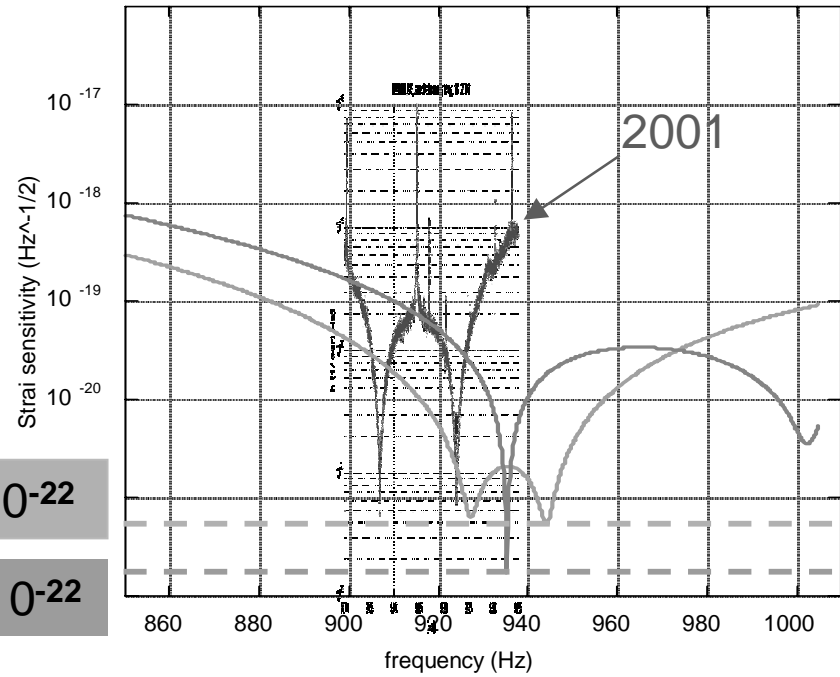


$2 \times 10^{-21}$

Expected spectral density at 0.15 K

$6 \times 10^{-22}$

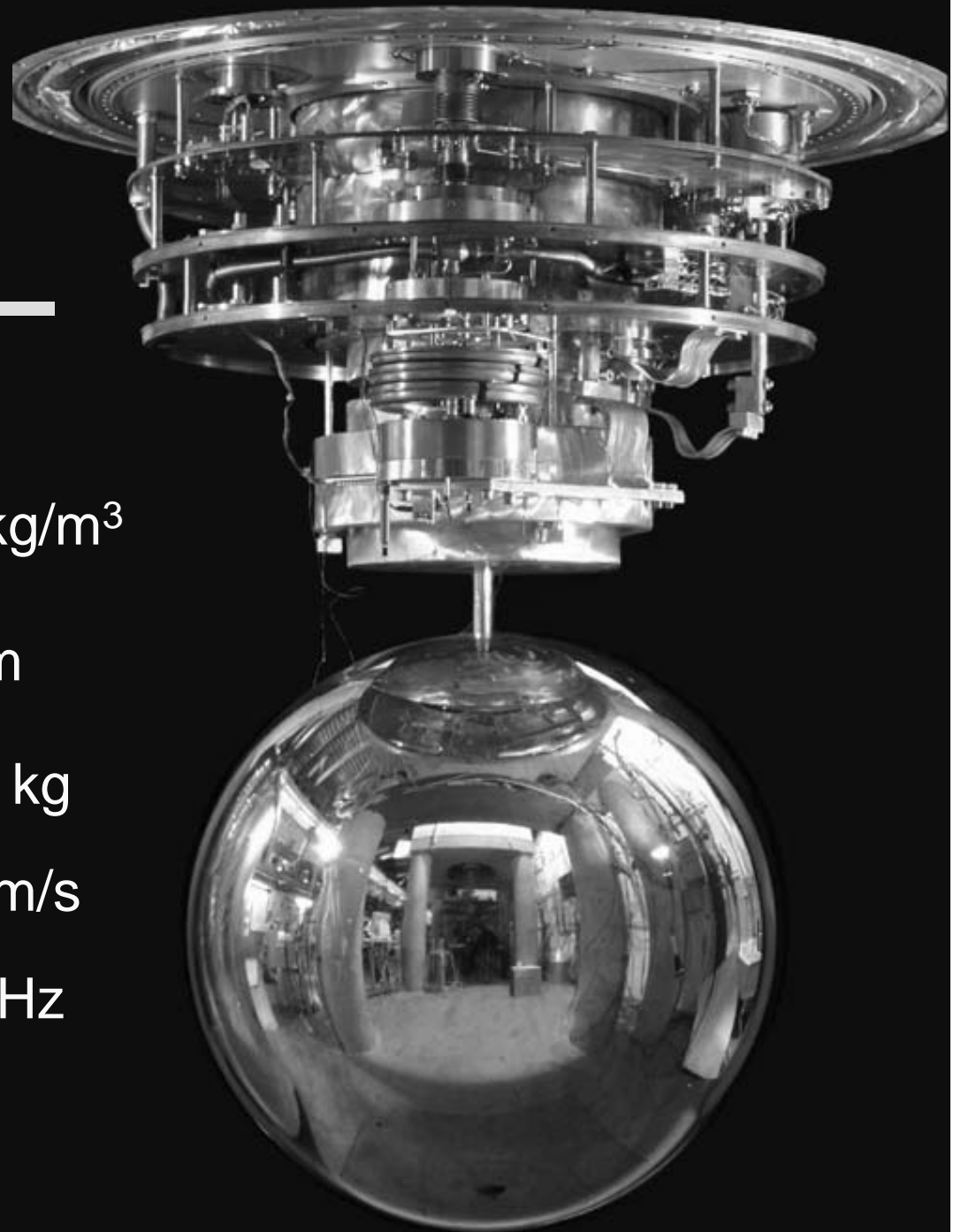
$1.6 \times 10^{-22}$



# Present Spherical Detectors Properties

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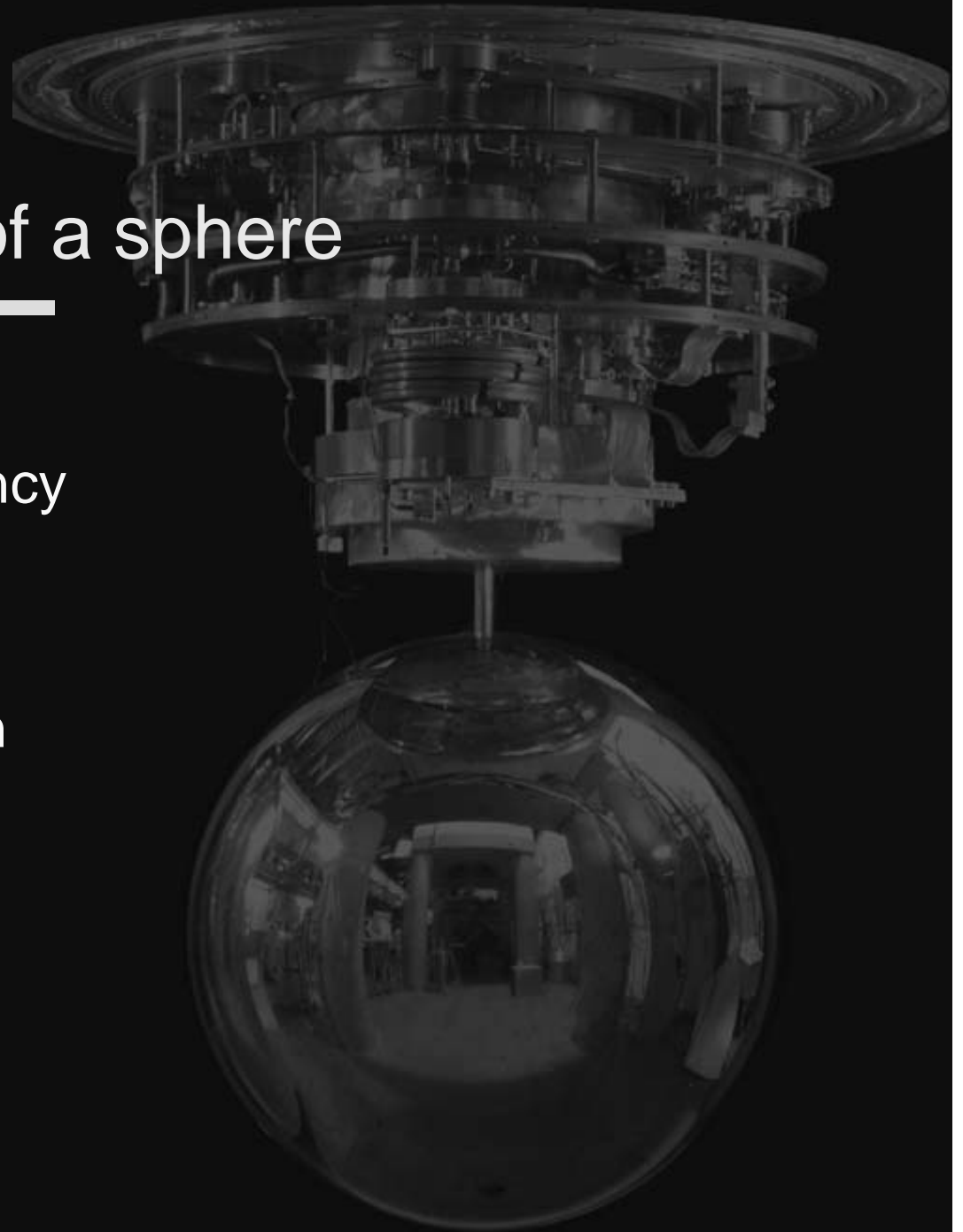
Material	CuAl6%
Density	$\rho = 8000 \text{ kg/m}^3$
Diameter	$\Phi = 0.65 \text{ m}$
Mass	$M = 1150 \text{ kg}$
Sound velocity	$v = 4000 \text{ m/s}$
Resonant freq.	$f = 3160 \text{ Hz}$
Short cool-down time	





## Advantages of a sphere

- Larger cross-section than a bar of the same frequency
- Omni-directional
- Determination of direction and polarization



# Schenberg

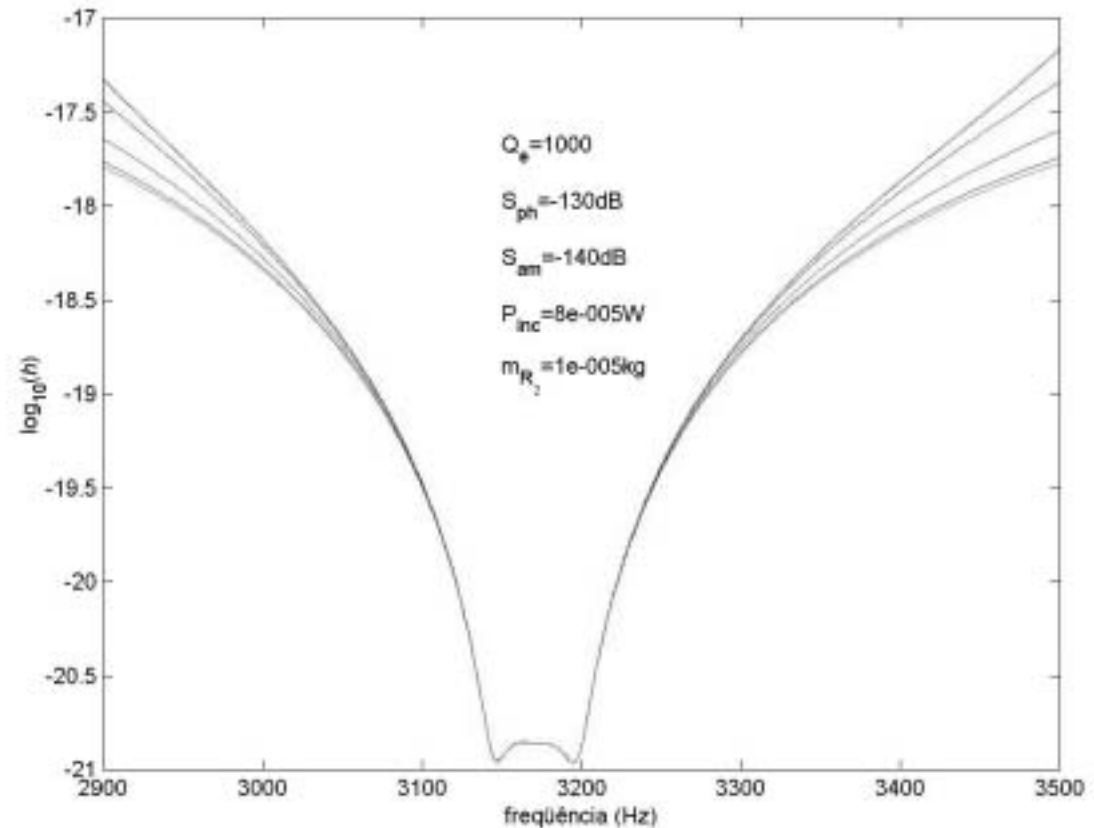
- All the "heavy" parts (cryogenic chambers, antenna vibration isolation system, and the antenna itself) are already assembled.
- A couple of weeks ago: first cool down to 4.2 K failed due to a leak.
- In the first cool the Q measurement of the antenna will be performed.



Talk by O. Aguiar

# Schenberg

Two-mode parametric transducer with an oscillator phase noise = -131dBc @ 3.2kHz from the 10.21 GHz carrier.  
electrical Q ~ 1k  
mechanical Q ~ 1M at the moment  
intermediate mass = 53 g  
last mass = 0.01g  
HEMT pre-amplifiers.  
Expected sensitivity with this system =  $10^{(-21)}$  Hz<sup>(-1/2)</sup> in a 50Hz bandwidth



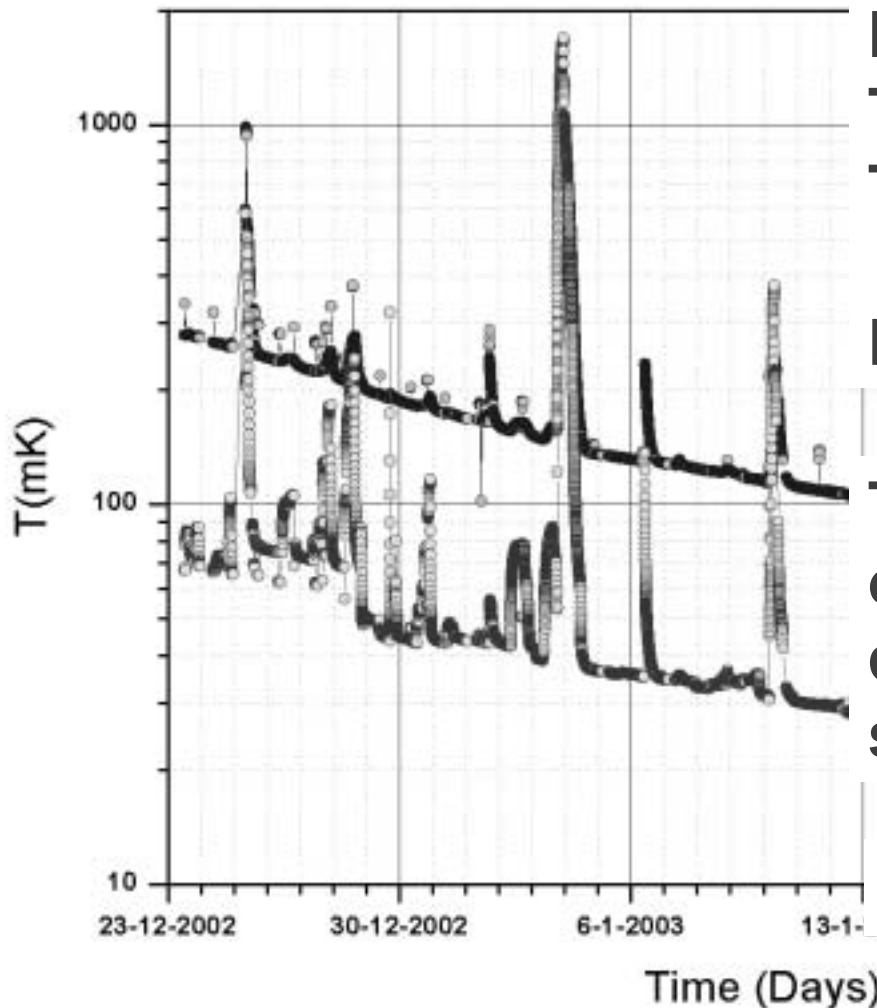


# MiniGRAIL

*Results on cool-down*

[www.minigrail.nl](http://www.minigrail.nl)

Talk by A. de Waard



**Minimum temperatures:**

$$T_{\text{sphere}} = 80 \text{ mK}$$

$$T_{\text{mc}} = 20 \text{ mK}$$

**Heat leak:  $45 \mu\text{W}$  from sphere**

**Time dependent heat leak due to ortho-para conversion of  $\text{H}_2$  confined in micro-bubbles in the sphere ( $\sim 50 \text{ ppm}$ )**

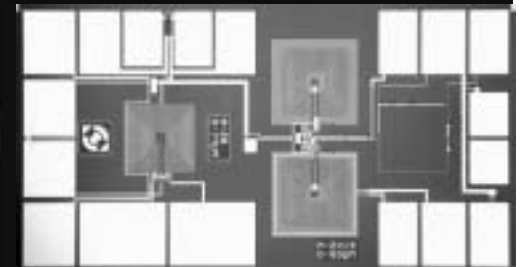
**Expected temperature  $\sim 20 \text{ mK}$**



[www.minigrail.nl](http://www.minigrail.nl)

Talk by L. Gottardi

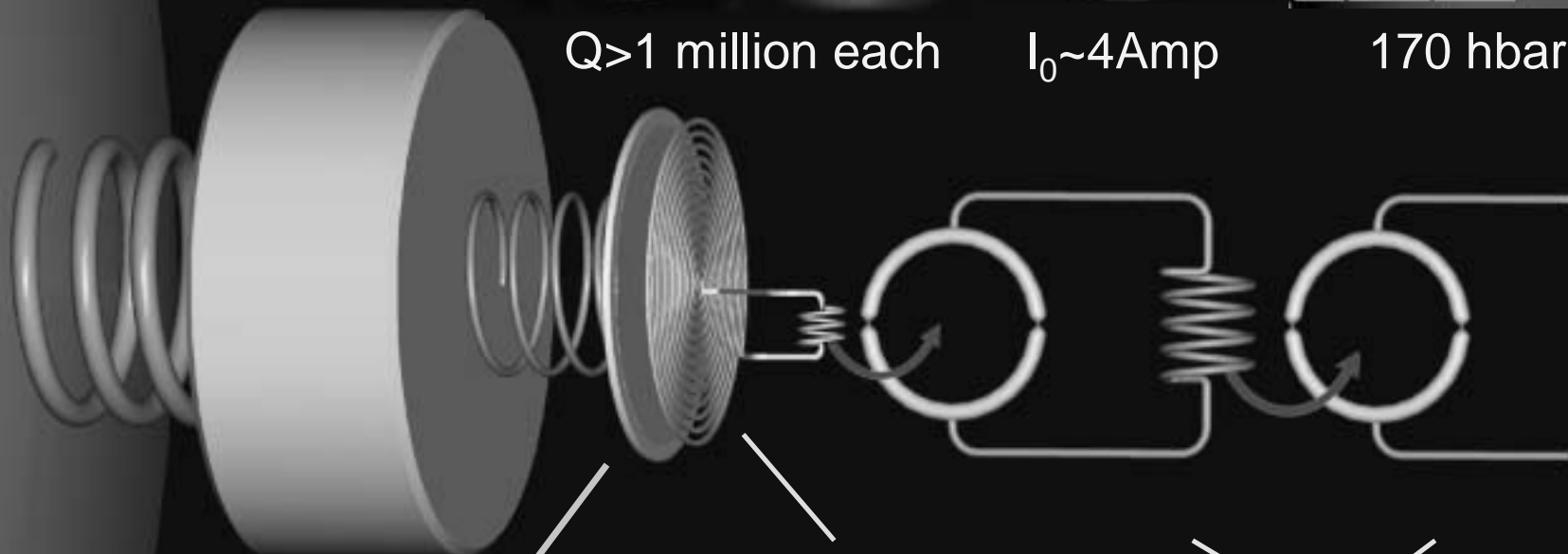
## 3-mode inductive transducer



$Q > 1$  million each

$I_0 \sim 4$  Amp

170 hbar @ 4K



3 mode system

flat, super  
conducting  
Niobium coil

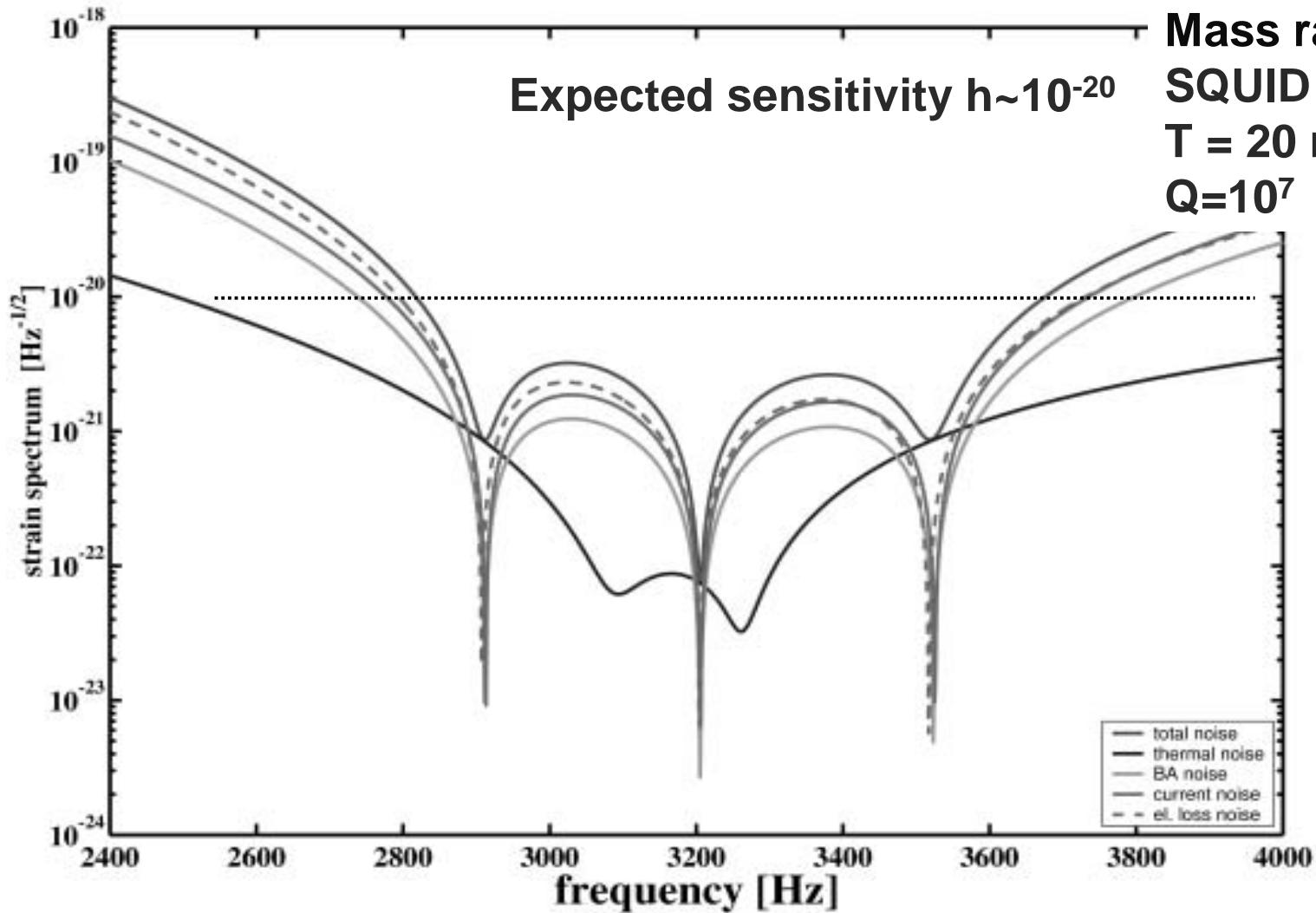
2 stage SQUID

In collaboration with Twente Univ.





# Sensitivity - 3 mode inductive transducer



Expected sensitivity  $h \sim 10^{-20}$

Mass ratio –  $10^{-3}$

SQUID - quantum limit

T = 20 mK

Q =  $10^7$

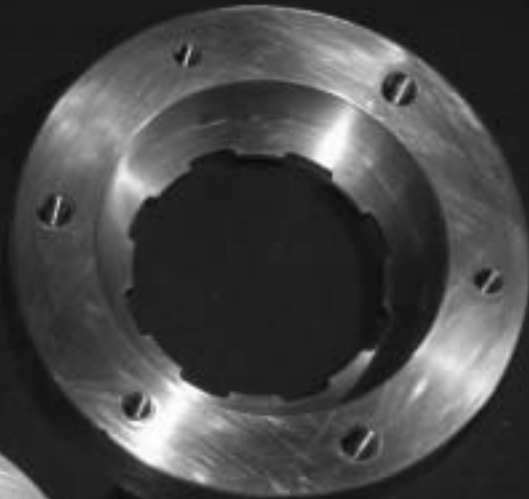




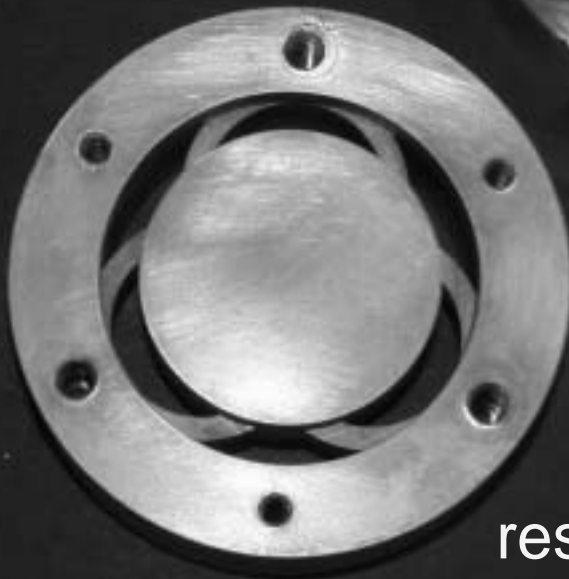
# capacitive transducer



electrode



electrode  
support

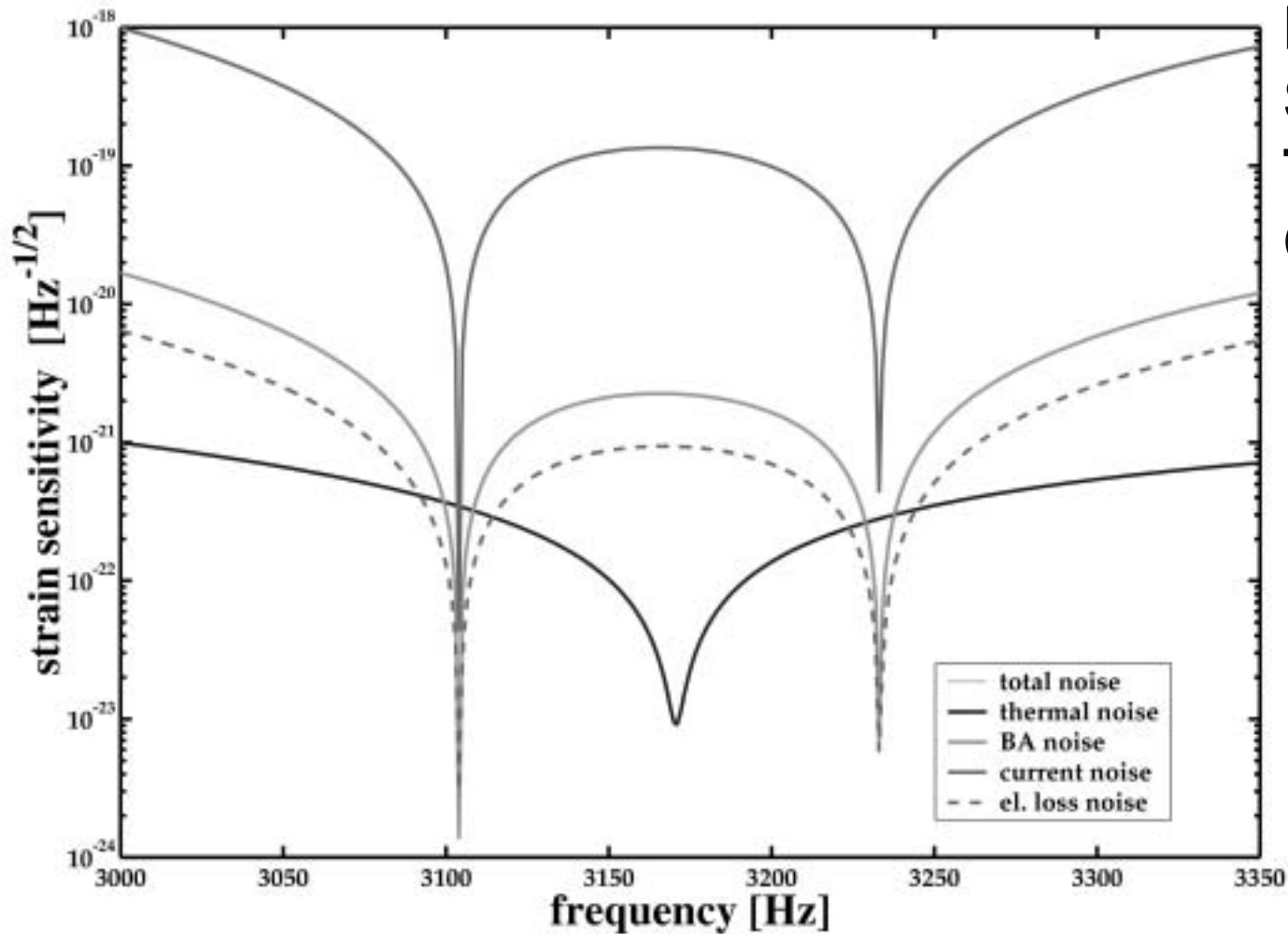


resonator

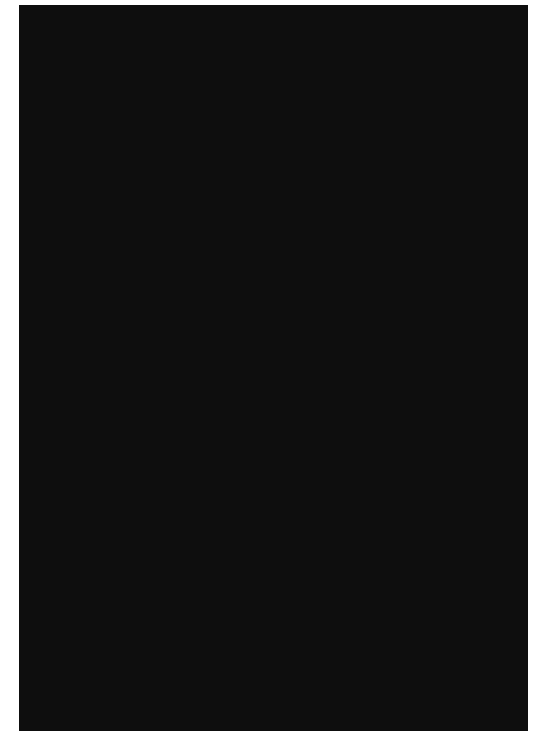




# capacitive transducer



Mass ratio –  $10^{-3}$   
SQUID - 700 hbar  
T = 20 mK  
Q =  $10^6$



## Bursts

*IGEC, Phys. Rev. Lett. 85, 5046 (2000)*  
*ROG Coll.: Class. Quant. Grav. 18, 243 (2001)*  
*ROG Coll.: Class. Quant. Grav. 19, 5449 (2002)*  
*IGEC: Phys. Rev. D in press, astro-ph 0302482*

## Continuous signals

*ALLEGRO Coll.: Proc. 2nd E. Amaldi Conference 1997*  
*ROG Coll: Phys. Rev. D 65, 022001(2002)*  
*A. Krolak et al and ROG Coll: CQG GWDAW2002 Proc. in press, gr-qc/0304107*

## Stochastic Background

*ROG Coll.:Astron. Astrophys. 351, 811 (1999)*

## *more*

### *Search for correlation with GRB's*

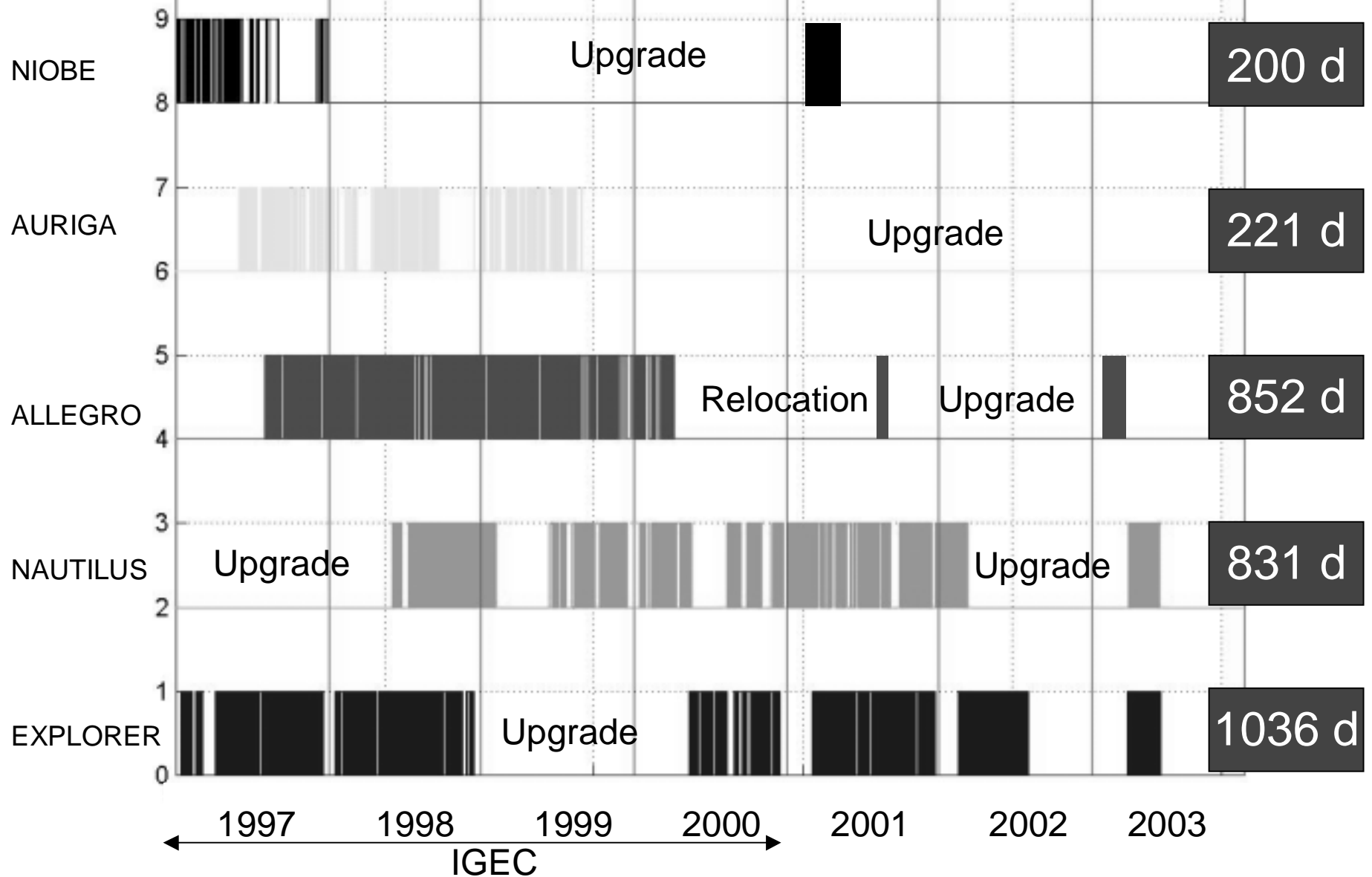
*ROG Coll.: Astron. Astrophys. Suppl. Ser. 138, 603 (1999).*  
*ROG Coll.: Astron. Astrophys. Suppl. Ser. 138, 605 (1999).*  
*AURIGA Coll.: Phys. Rev. D 63, 022005 (2001).*  
*ROG Coll.: Phys. Rev. D 66, 102202 (2002).*

## Talk by G Modestino

### *Effect of cosmic rays*

*ROG Coll.: Phys. Rev. Lett. 84 , 14 (2000)*  
*ROG Coll.: Phys. Lett. B 499, 16 (2001),*  
*ROG Coll.: Phys. Lett. B 540 (2002).*

•ON times for the various detectors 1997-2003

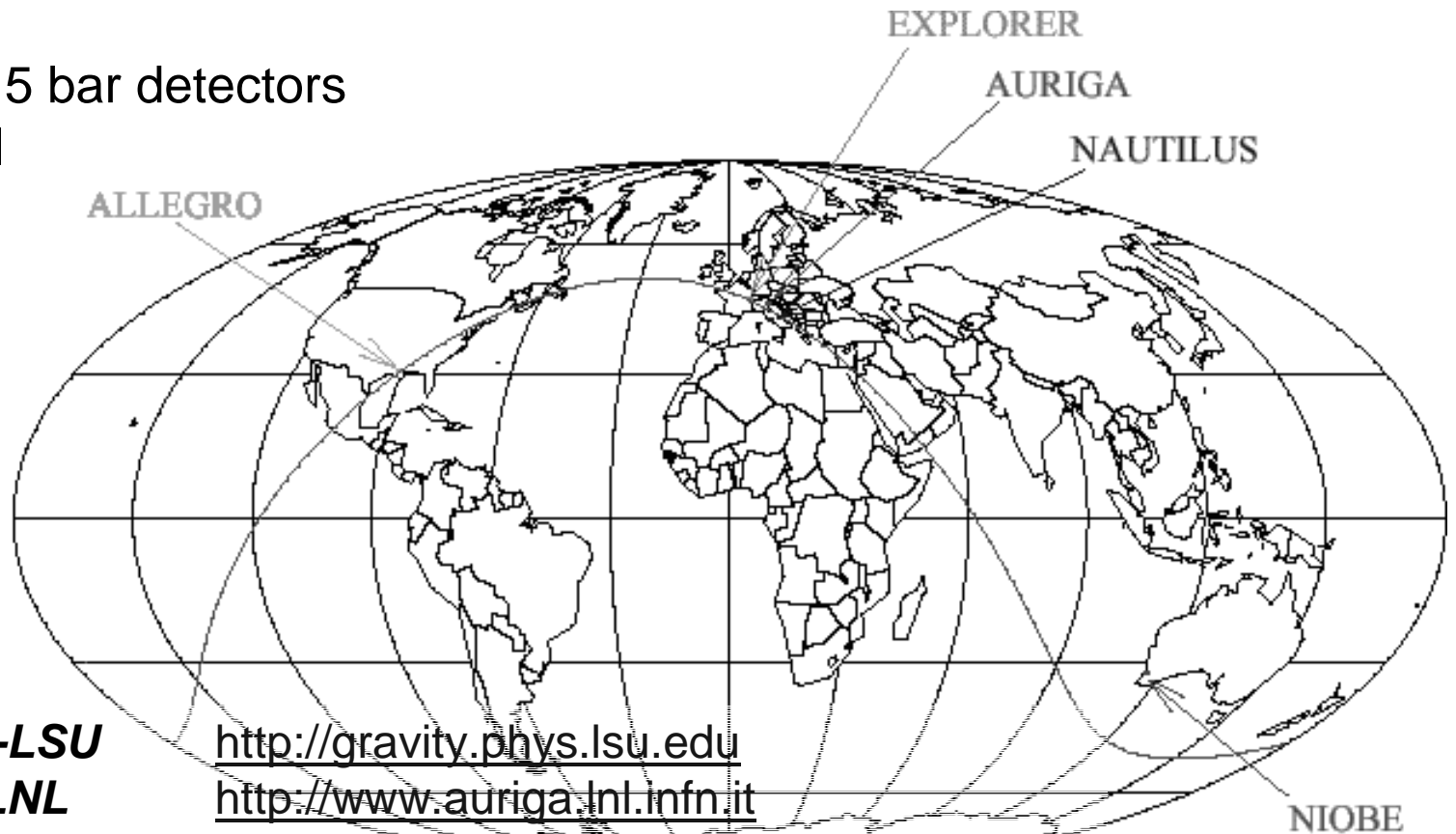


# IGEC

International Gravitational Event Collaboration  
<http://igec.lnl.infn.it>

## Results of the 1997-2000 Search for Burst Gw by IGEC PRD 68, n2 (2003) astro-ph/0302482

Network of the 5 bar detectors  
almost **parallel**



**ALLEGRO NFS-LSU**

<http://gravity.phys.lsu.edu>

**AURIGA INFN-LNL**

<http://www.auriga.lnl.infn.it>

**NIOBE ARC-UWA**

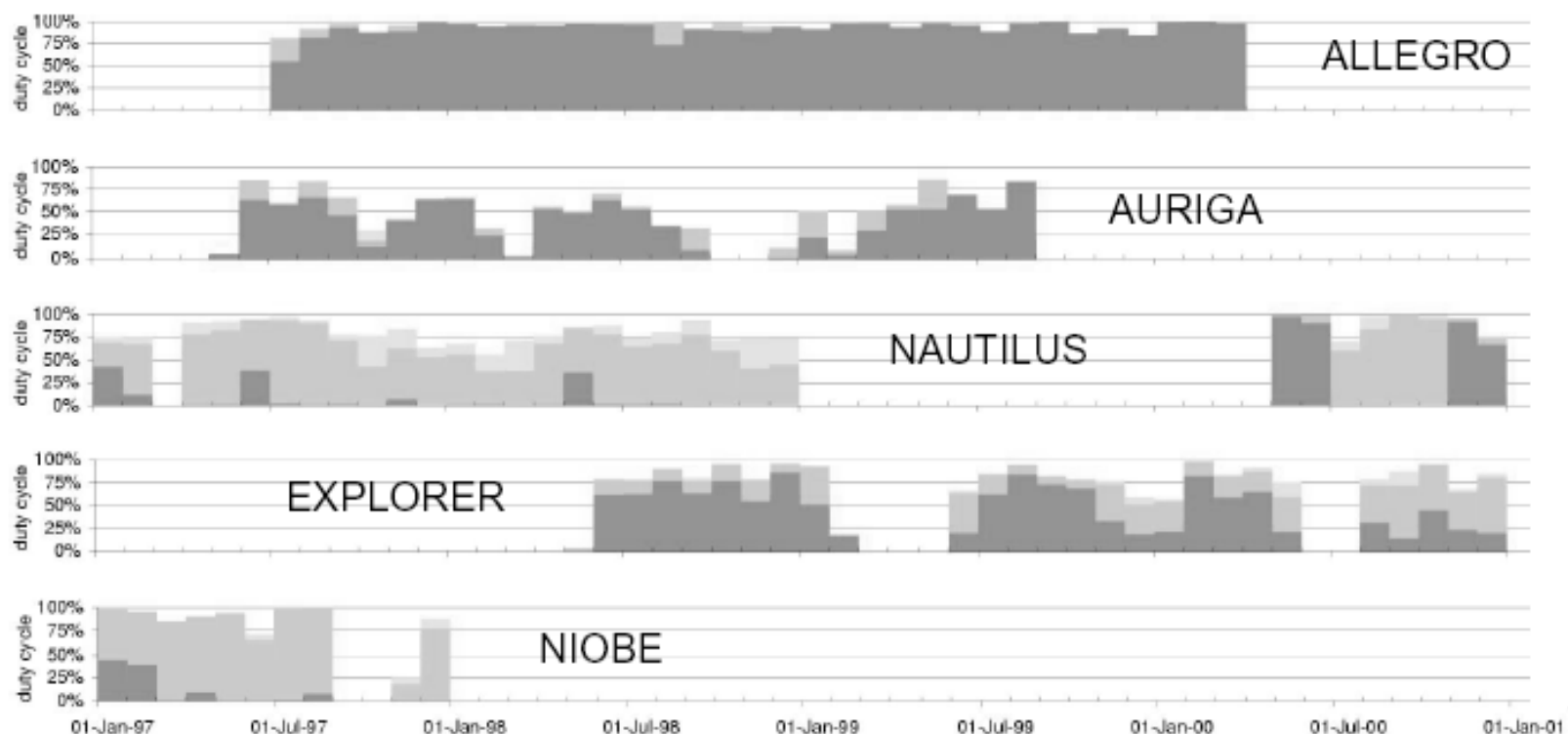
<http://www.gravity.pd.uwa.edu.au>

**EXPLORER INFN-CERN**

<http://www.roma1.infn.it/rog/rogmain.html>

**NAUTILUS INFN-LNF**

## EXCHANGED PERIODS of OBSERVATION 1997-2000



fraction of time in monthly bins

- exchange threshold
- $H > 6 \cdot 10^{-21} \text{ Hz}^{-1}$
  - $3 + 6 \cdot 10^{-21} \text{ Hz}^{-1}$
  - $H < 3 \cdot 10^{-21} \text{ Hz}^{-1}$

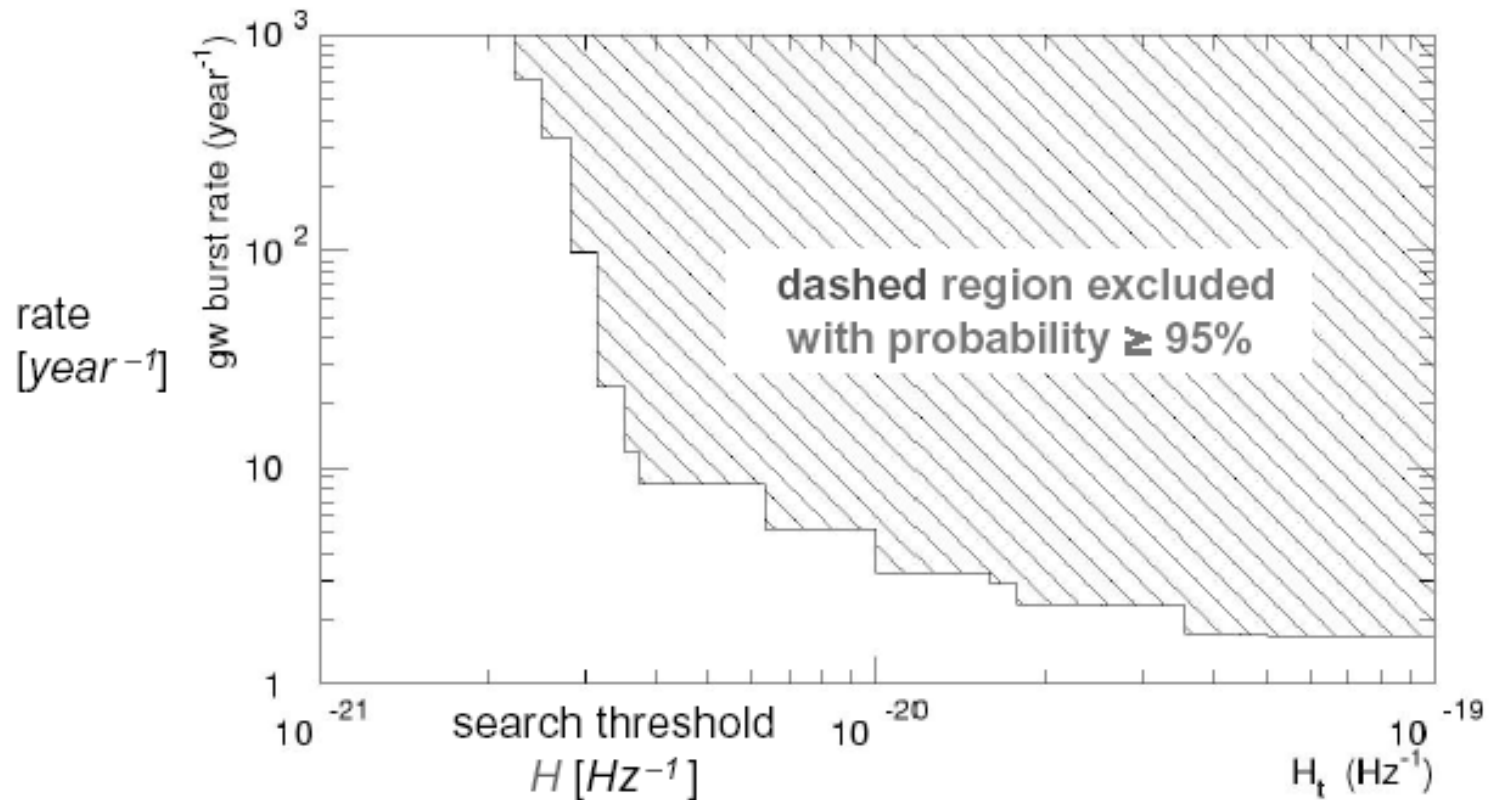
$H$  is *Fourier amplitude* of burst gw

$$h(t) = H \cdot \delta(t - t_0)$$

*arrival time*

UPPER LIMIT on the RATE of BURST GW  
from the GALACTIC CENTER DIRECTION

Talk by G.A. Prodi



Upper limit for burst GWs with random arrival time and measured amplitude  $\geq$  search threshold

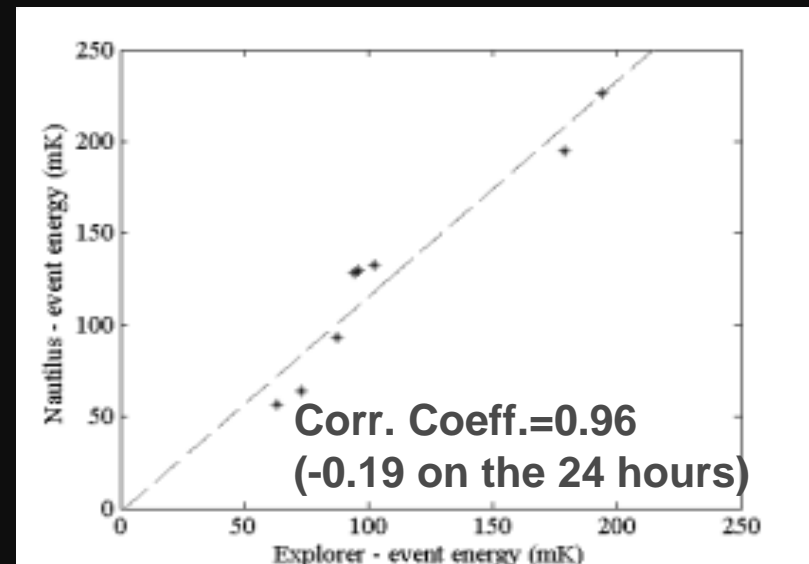
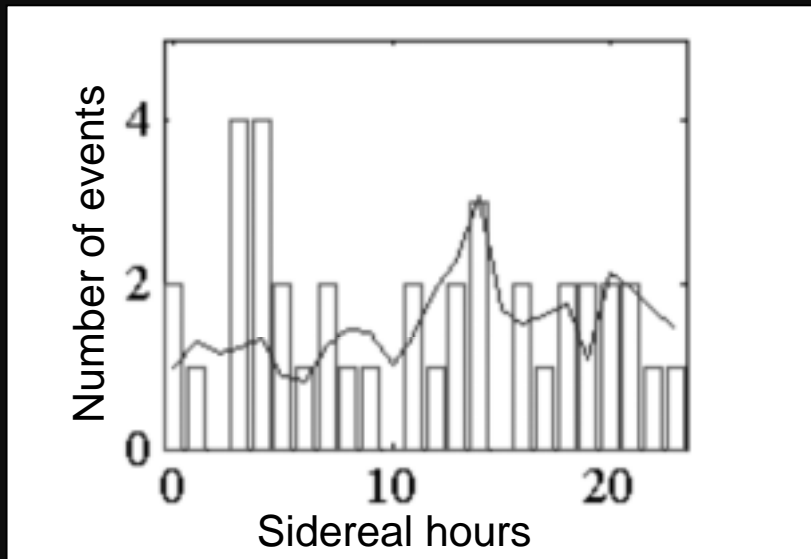
$$H \sim 2 \cdot 10^{-21} / \text{Hz} \leftrightarrow 0.02 M_{\odot} \text{ converted at Galactic Center}$$



# EXPLORER-NAUTILUS 2001 data analysis

During 2001 EXPLORER and NAUTILUS were the only two operating resonant detectors, with the best ever reached sensitivity.

A new algorithm based on energy compatibility of the event was applied to reduce the “background”



*ROG Coll.: CQG 19, 5449 (2002)*

*L.S.Finn: CQG 20, L37 (2003)*

*P.Astone, G.D'Agostini, S.D'Antonio: CQG Proc. Of GWDAW 2002, gr-qc/0304096*

*E. Coccia ROG Coll.:CQG Proc. Of GWDAW 2002*

*ROG Coll.: gr-qc/0304004*

Talk by M. Visco

New data are needed for further considerations

# STOCHASTIC BACKGROUND

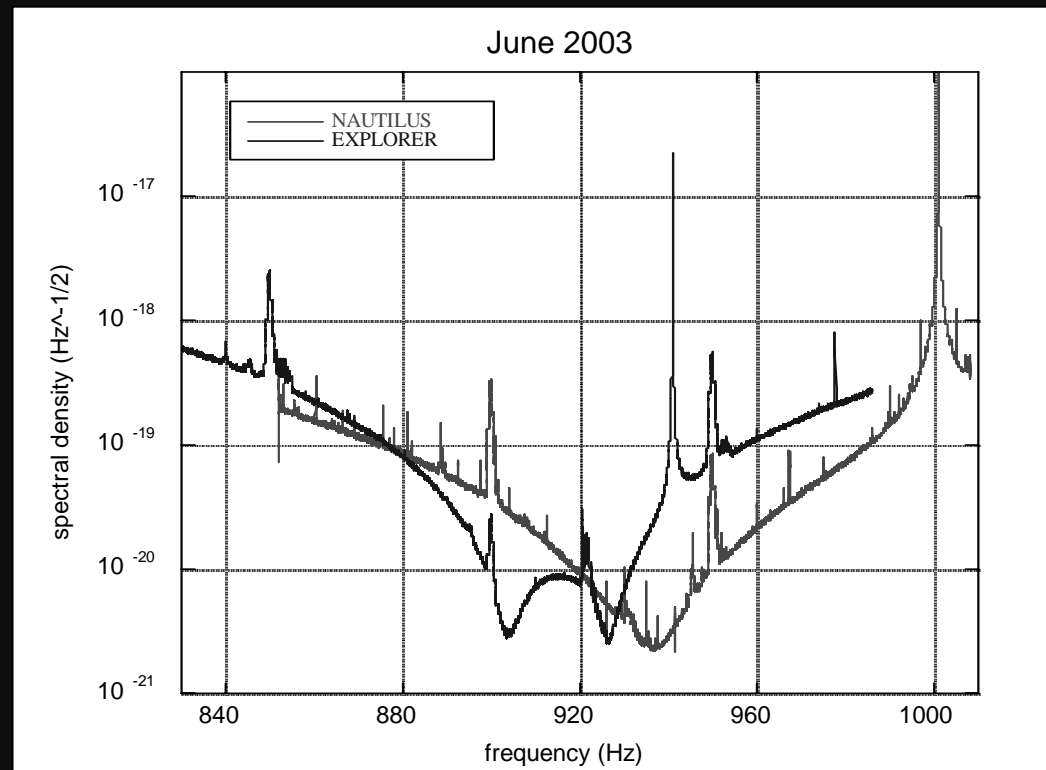
Previous result: *ROG Coll. Astron. Astrophys*, 351 (1999)

12 hours of data  $\Delta f = 0.1 \text{ Hz}$   $S_{12} < 1 \times 10^{-44} \text{ Hz}^{-1}$

$\Omega_{\text{GW}} (920.2 \text{ Hz}) < 60$

- Will optimize overlapping bandwidth by acting on the bias E field
- Potential common band is  $\sim 100 \times$  that exploited in '97.

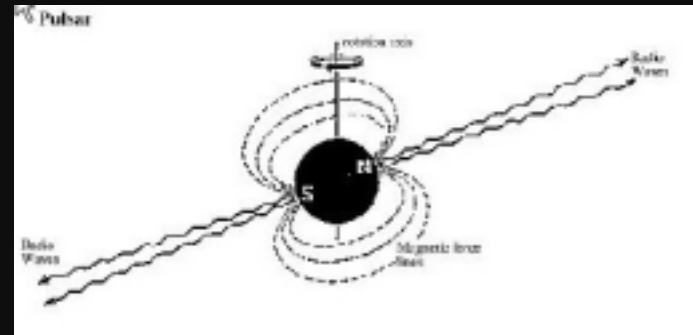
With Tobs of about 100 days, upper limit on  $\Omega_{\text{GW}}$  less than unity can be achieved



# Stochastic Background

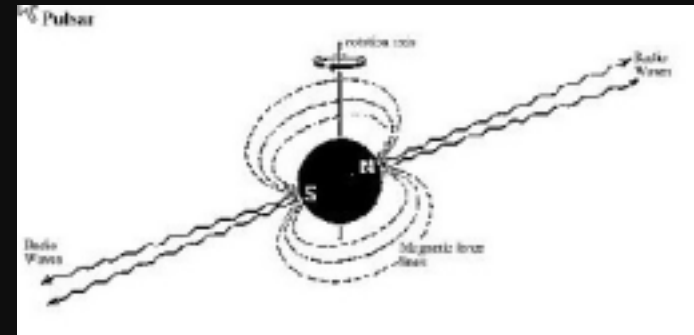
- The cross-correlation of 6 months of NAUTILUS and AURIGA phase I, would put the limit  $\Omega_{\text{gw}} \leq 0.1$  @ 935 Hz.
- Joint analyses with VIRGO - NAUTILUS and VIRGO - AURIGA II may put limits at the level  $\Omega_{\text{gw}} \leq 3-5 \cdot 10^{-3}$  (1y integration  $10^{-22} \text{ Hz}^{-1/2}$  @900 Hz for VIRGO)
- LIGO I ( $10^{-22} \text{ Hz}^{-1/2}$  @ 1 kHz) and ALLEGRO ( $2 \cdot 10^{-21} \text{ Hz}^{-1/2}$ ):  
 $\Omega_{\text{gw}} \leq 0.1$  (1y of data, analysed at periods of 2-3 months).
- LIGO II ( $10^{-23} \text{ Hz}^{-1/2}$  @ 1 kHz) and ALLEGRO ( $10^{-22} \text{ Hz}^{-1/2}$ ):  
 $\Omega_{\text{gw}} \leq 6 \cdot 10^{-4}$

# Continuous waves



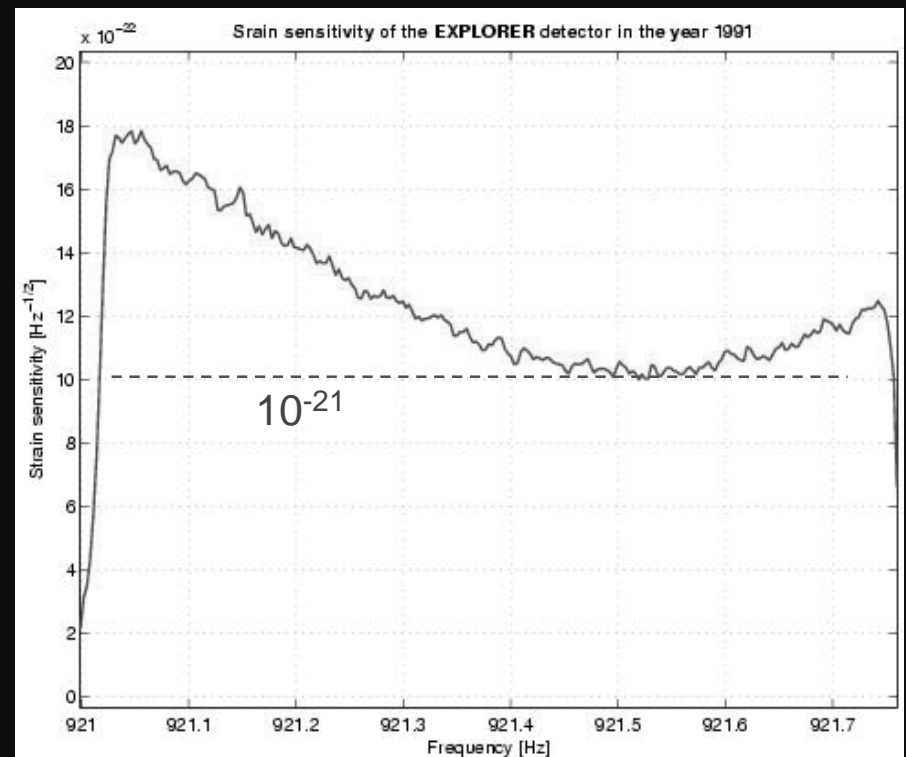
- ALLEGRO put upper limits ( $4 \cdot 10^{-23}$  over 1 Hz band) on signals from the GC and 47Tucanae using one month of data
- Limit for signals in the GC, using 95 days of EXPLORER data  $h_c = 3 \times 10^{-24}$ , in the range 921.32 - 921.38 Hz (ROG Coll.: *PRD*, 2002)

# Continuous waves

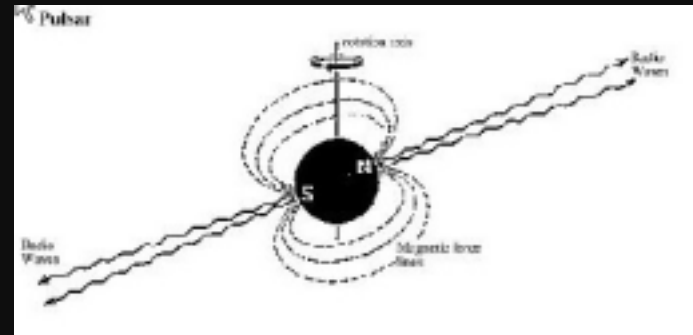


## Overall sky search

Phase I ended: 2 days of EXPLORER 1991 data analyzed in collaboration with A. Krolak & Collaborators put an upper limit of  $h_c = 2 \times 10^{-23}$ . (10<sup>8</sup> points, by choosing spin-down parameter and position randomly) - CQG, proc. GWDAW 2002



# Continuous waves



**Phase II ended:** collaboration with Krolak & C. and the Virgo Project Group in Rome. Two-day stretch of data disjoint from the two-day stretch analysed in the previous search.

Search done using the computers provided by the Virgo Project (March-May 2003). Number of candidates found: 29909.

Highest SNRS:

Northern Sky=8.15

Southern Sky=7.83

(99% confidence threshold is 8.3, none of the candidates exceeded this thr.)

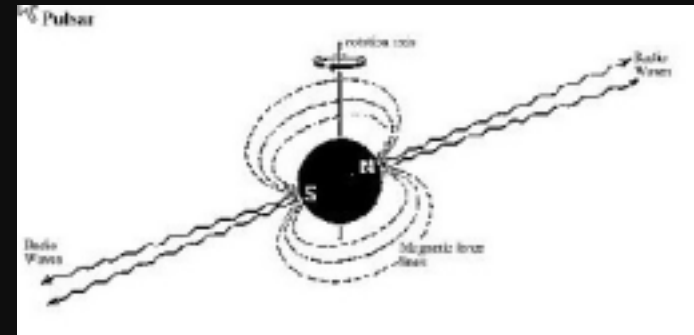
Comparison of candidates found in the two searches is now in progress.

The results of the search will be compared with those of an analysis done using the hierarchical search procedure, developed by the Virgo group of Rome, in collaboration with the ROG group (this work is now in progress). The aim is to analyze at least 1 year of data of EXPLORER and NAUTILUS.

**Phase III:** 2 more days of EXPLORER data is in progress.

[www.astro.uni.torun.pl/~kb/all-sky](http://www.astro.uni.torun.pl/~kb/all-sky) and [www.roma1.infn.it/rog](http://www.roma1.infn.it/rog)

# Continuous waves



Agreement between ROG and AEI Max Planck in Golm for the coherent analysis of data selected from 1 year of data of Nautilus 2001.

The data base of FFTs (17193 FFTs, 28 minutes each, in the format used by GEO/LIGO in their analysis) has been produced and is now in the cluster in Golm.

The procedures to veto the data is under studying.

Searches pointing at Globular Clusters, Galactic Plane..are in schedule.

# Effect of cosmic rays

$$h = 3 \times 10^{-22} \text{ Hz}^{1/2}$$

$$h_{\text{pulse}} = \Delta L/L = 4 \times 10^{-19}$$

$$\Delta E = 2 \text{ mK} = 0.3 \mu\text{eV}$$

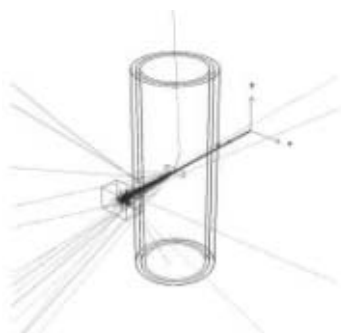
**Nautilus is equipped with 7 layers (3 above the cryostat - area 36m<sup>2</sup>/each - and 4 below -area 16.5 m<sup>2</sup>/each) of Streamer tubes.**



Period	NAUTILUS temperature (K)	Duration (hours)	nc	n	Rate(ev/day)
Sept-Dec 1998	0.14	2002	12	0.47	
Feb-July 2000	0.14	707	9	0.42	
total		2709	21	0.89	0.178
Aug -Dec 2000	1.1	118	0	0.03	
Mar-Sept 2001	1.5	2003	1	0.54	
total		2121	1	0.45	0.006



# Effect of cosmic rays



Talk by G. Mazzitelli





# DUAL: wideband high freq gw detector

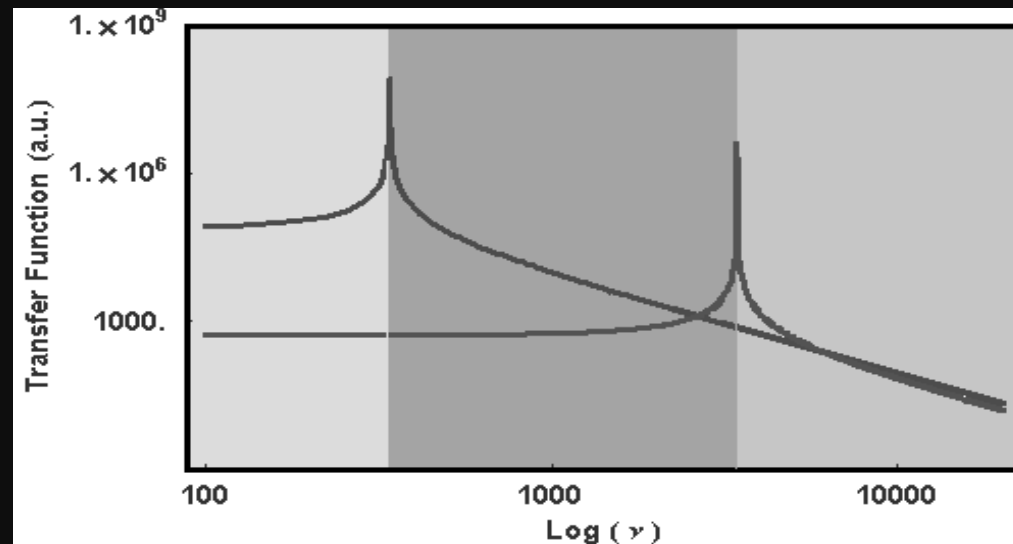
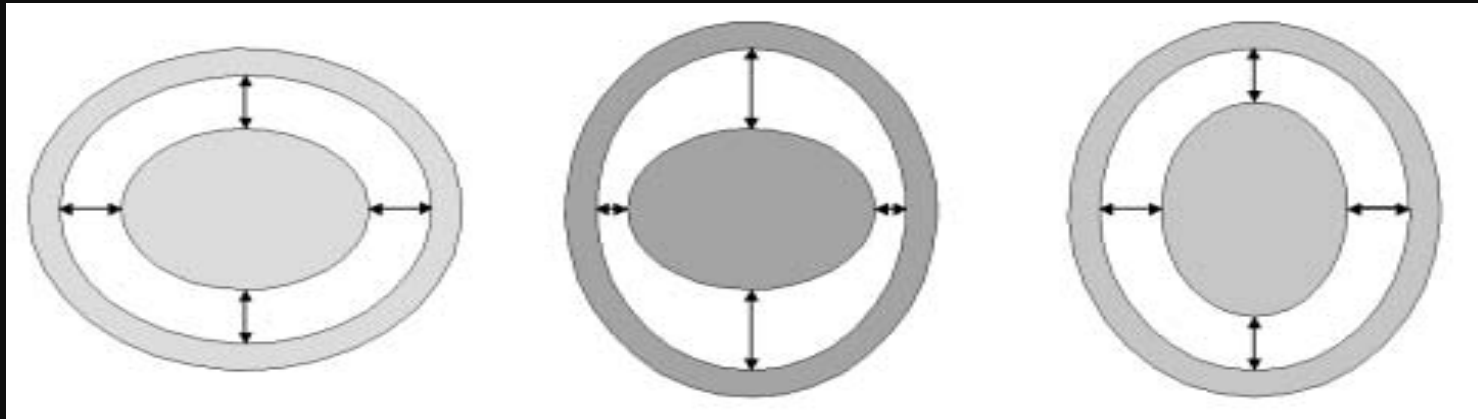
PRL 87 (2001) 031101

gr-qc/0302012



## 2 nested resonant masses

*measure the differential deformation between the lowest quadrupolar modes*



Talk by M. Bonaldi

- gw signals add
- back action noises subtract



# DUAL: wideband high freq gw detector

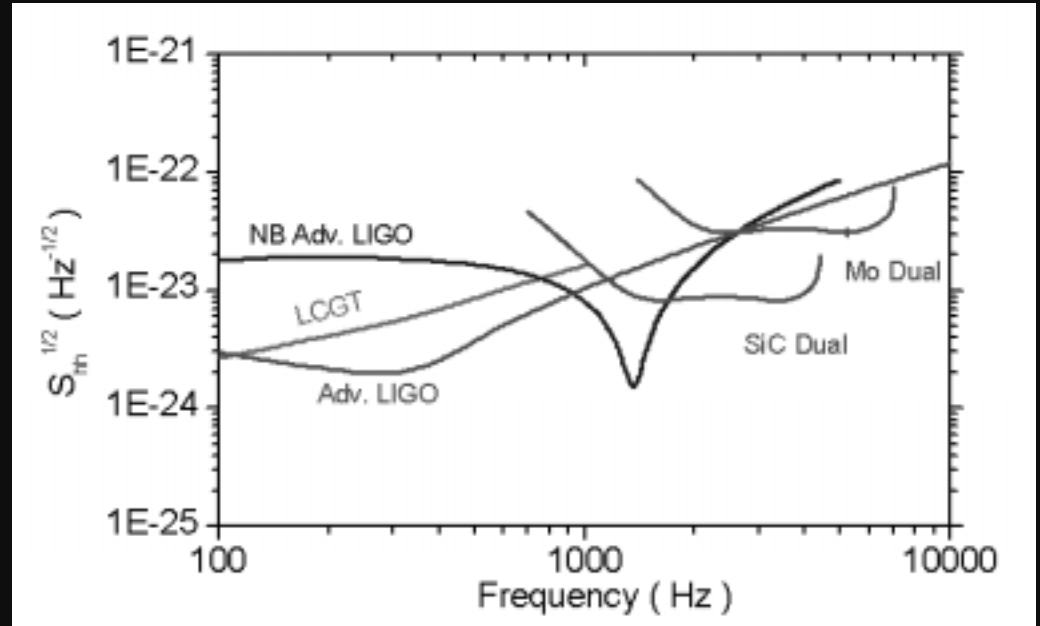
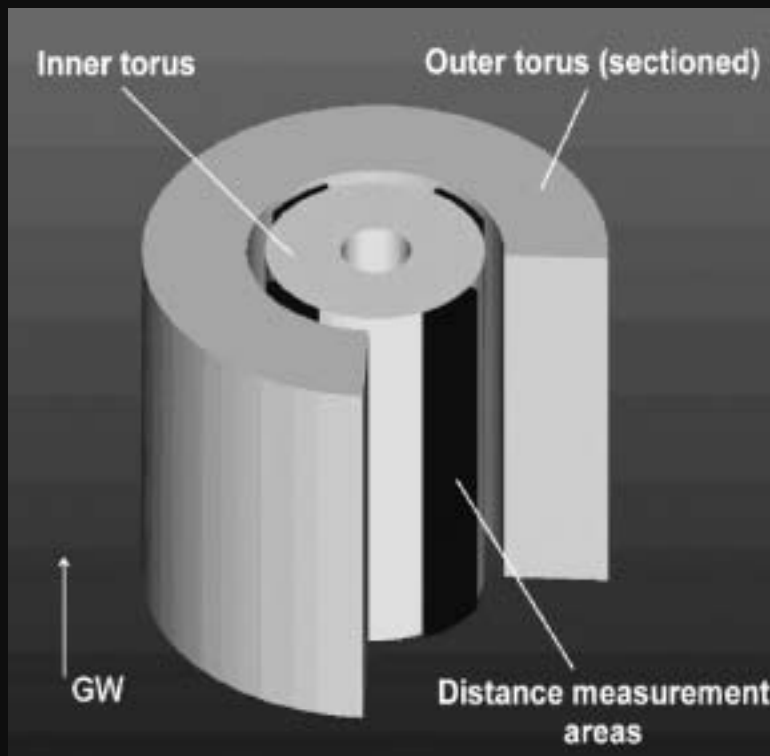
PRL 87 (2001) 031101

gr-qc/0302012



## 2 nested resonant masses

Sensitive in a kHz-wide frequency band



<b>Mo Dual</b>	16.4 ton	height 2.3 m	Ø 0.94m
<b>SiC Dual</b>	62.2 ton	height 3 m	Ø 2.9m

T~0.1 K , Standard Quantum Limit

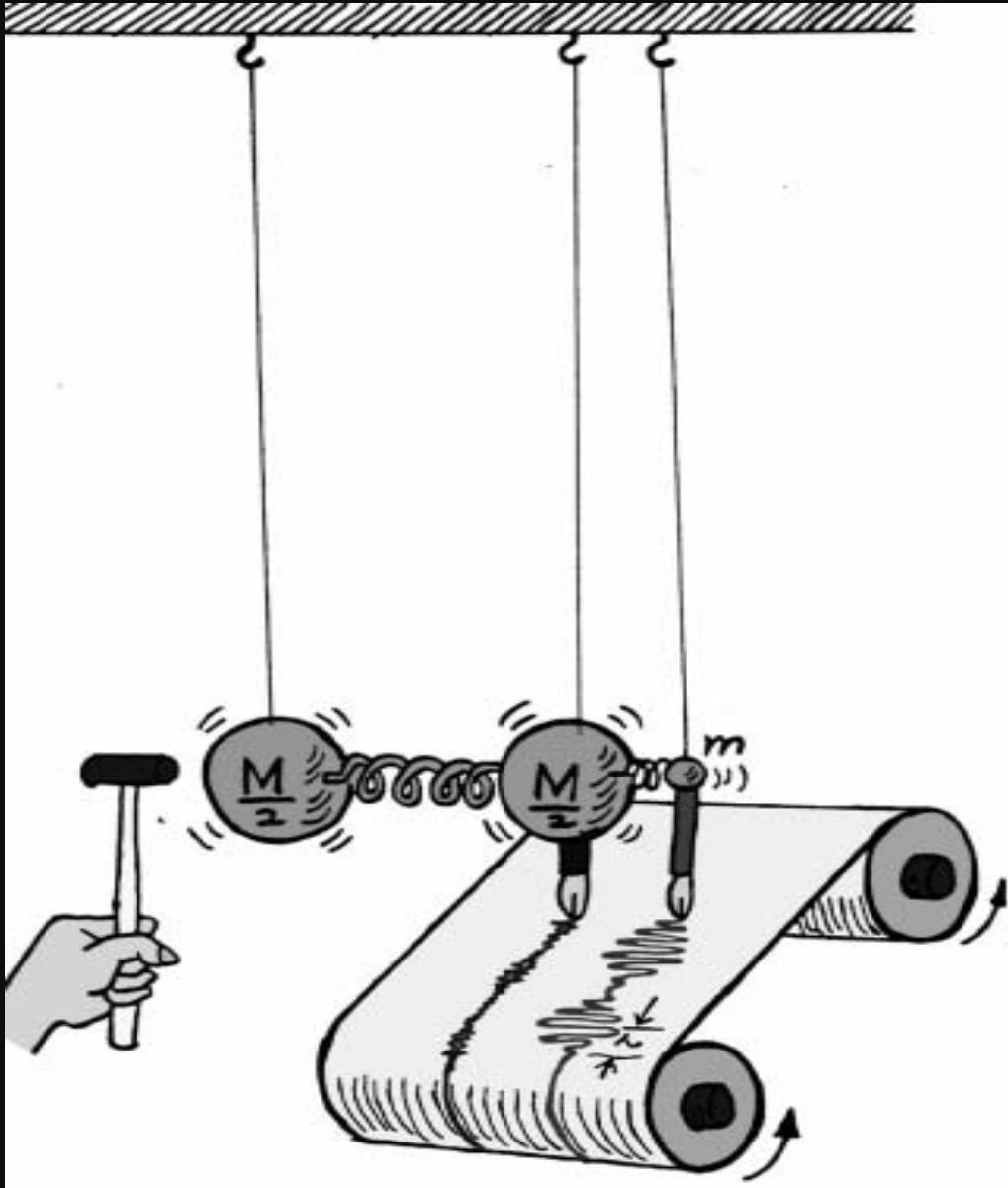
readout:

selects quadrupolar deformations  
averages over a wide area

⇒ **flat** sensitivity in a wide band

The End

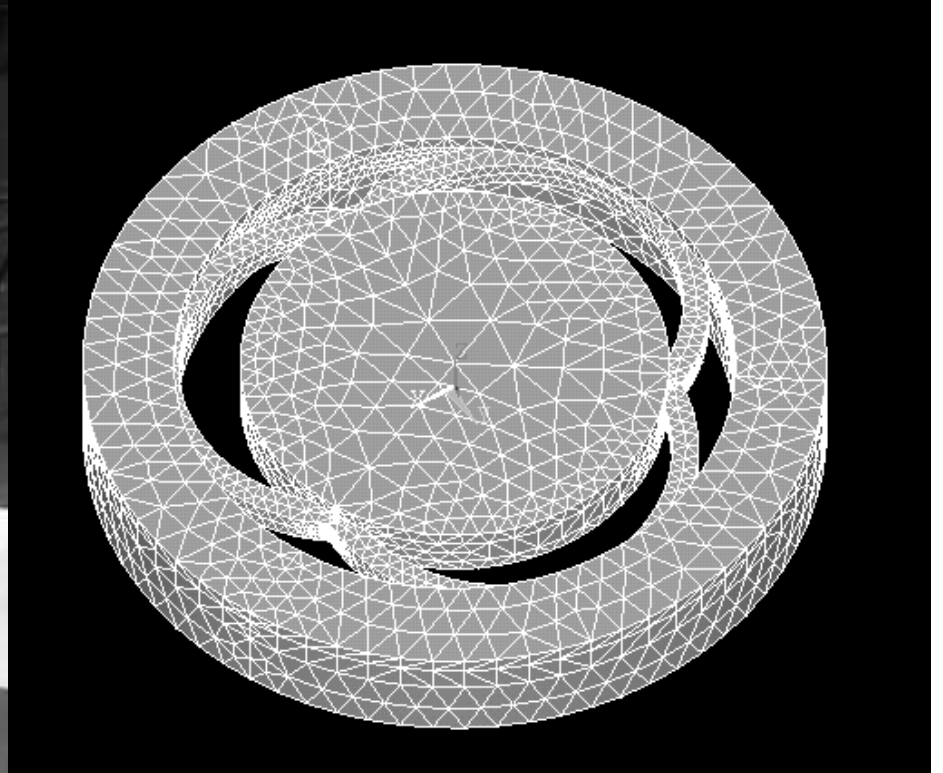
## Principle of a Resonant Transducer



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

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

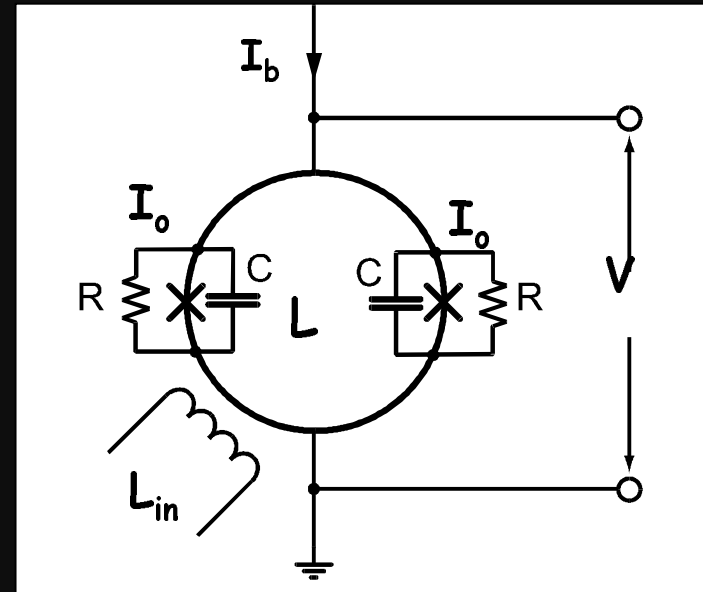
# MICROMECHANICS



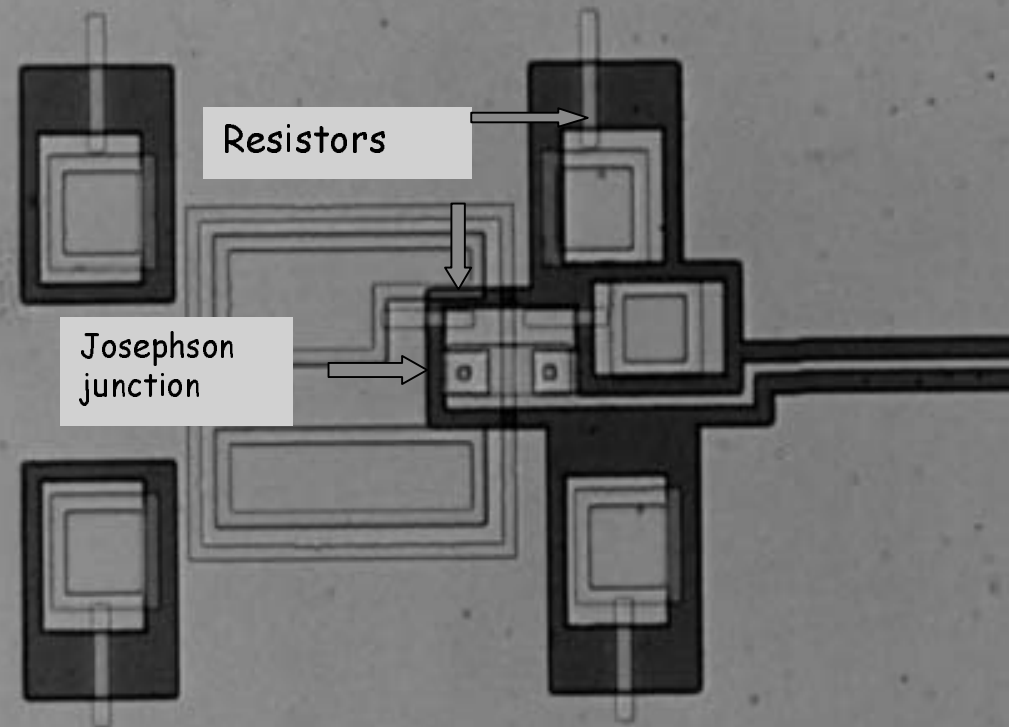
The ROG rosette capacitive transducer; gap= $9\mu\text{m}$

# Quantum technology

## dc-SQUID



- superconducting loop with inductance  $L$
- 2 Josephson junctions: critical current  $I_0$ , shunt resistance  $R$ , capacitance  $C$ ,
- Input inductance  $L_{in}$ , coupling  $\alpha$



# Eliminating the Vibrational Noise in Continuously Filled 1 K Pots

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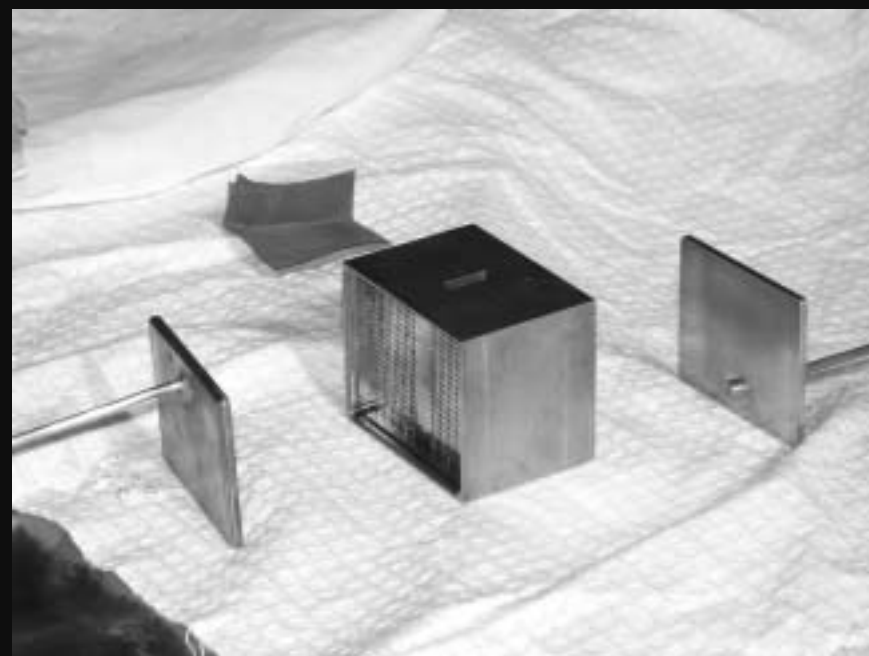
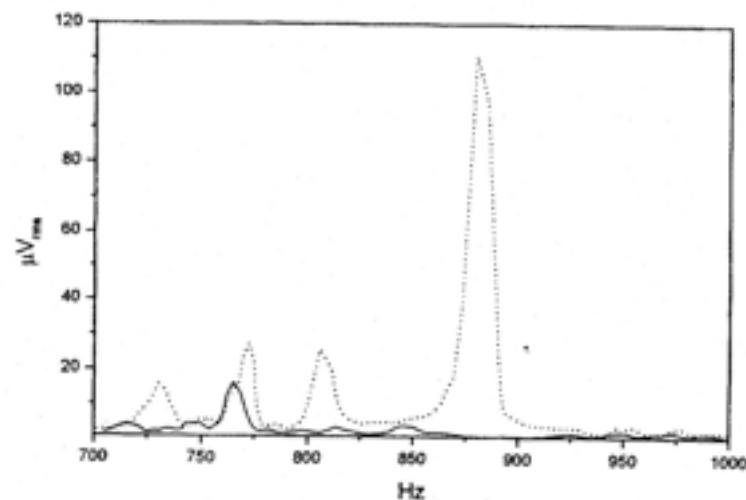
**Abstract.** We present a study on the origin of the vibrational noise originating from pumped helium chambers (1 K pots) that are continuously replenished from a main bath at 4.2 K. The vibrations can be eliminated by thermalizing the helium, coming from the main bath, to the pot temperature. Vibrations in 1 K pots are a source of excess noise in cryogenic detectors and therefore have detrimental consequences on their performance.

## INTRODUCTION

1 K pots are small pumped helium chambers continuously replenished from a main bath at 4.2 K through a flow impedance. 1 K pots are often a necessary cooling step in continuously operating  $^3\text{He}$ - $^4\text{He}$  dilution refrigerators, that are commonly used to cool many different kinds of sensitive detectors to temperatures of a few mK, e.g. gravitational-wave antennas [1], bolometers for far-infrared radiation or high-resolution energy particle detection [2].

It is known that continuously filled 1 K pots are the source of vibrations that can result in electrical, thermal and mechanical noise [3]. Suggested solutions to the problem of vibrational noise in the 1 K pot include: either mechanical decoupling [2] of the experiment, or regulating the helium flow from the main bath and adjusting the helium level inside the 1 K pot itself [4].

These methods provide only a partial attenuation of the noise and not the elimination of its origin; in some experiments this may not be a sufficient solution.



ROG implementation of Raccanelli scheme



# EXPLORER cosmic ray detector

## Plastic scintillators

2 layers of 13 m<sup>2</sup>

1 layer of 6 m<sup>2</sup>





## Transducer location (TIGA)

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