**5th EDOARDO AMALDI CONFERENCE**
**ON GRAVITATIONAL WAVES**
July 6 - 11, 2003
Green Park Resort
Tirrenia (Pisa) - Italy

# THE NEW RUN OF EXPLORER AND NAUTILUS


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***Università degli Studi di Roma "Tor Vergata"***
***Università degli Studi de L'Aquila***
***CERN - European Organization for Nuclear Research***



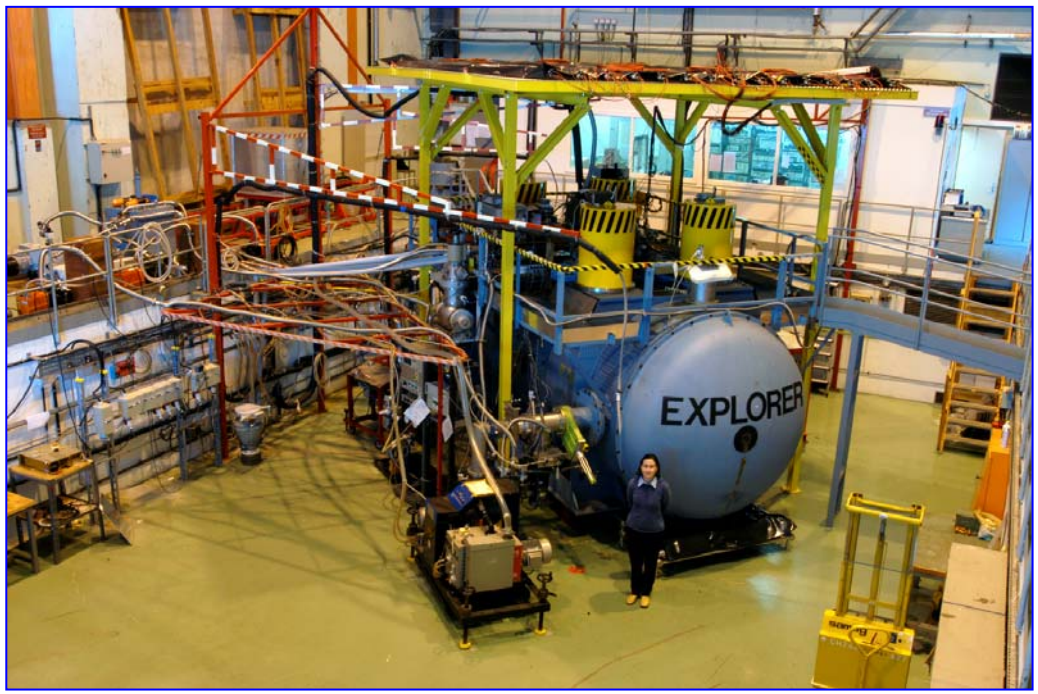

# OUTLINE OF THE TALK

- Description of NAUTILUS and EXPLORER
- Past and present performances
- Results of searches for different kind of signals:
  - –Continuous waves
  - –Stochastic background
  - –Search for burst



# G.W. ANTENNA EXPLORER

## CERN - GINEVRA




Bar Al 5056 M = 2270 kg

L = 2.97 m Ø = 0.6 m

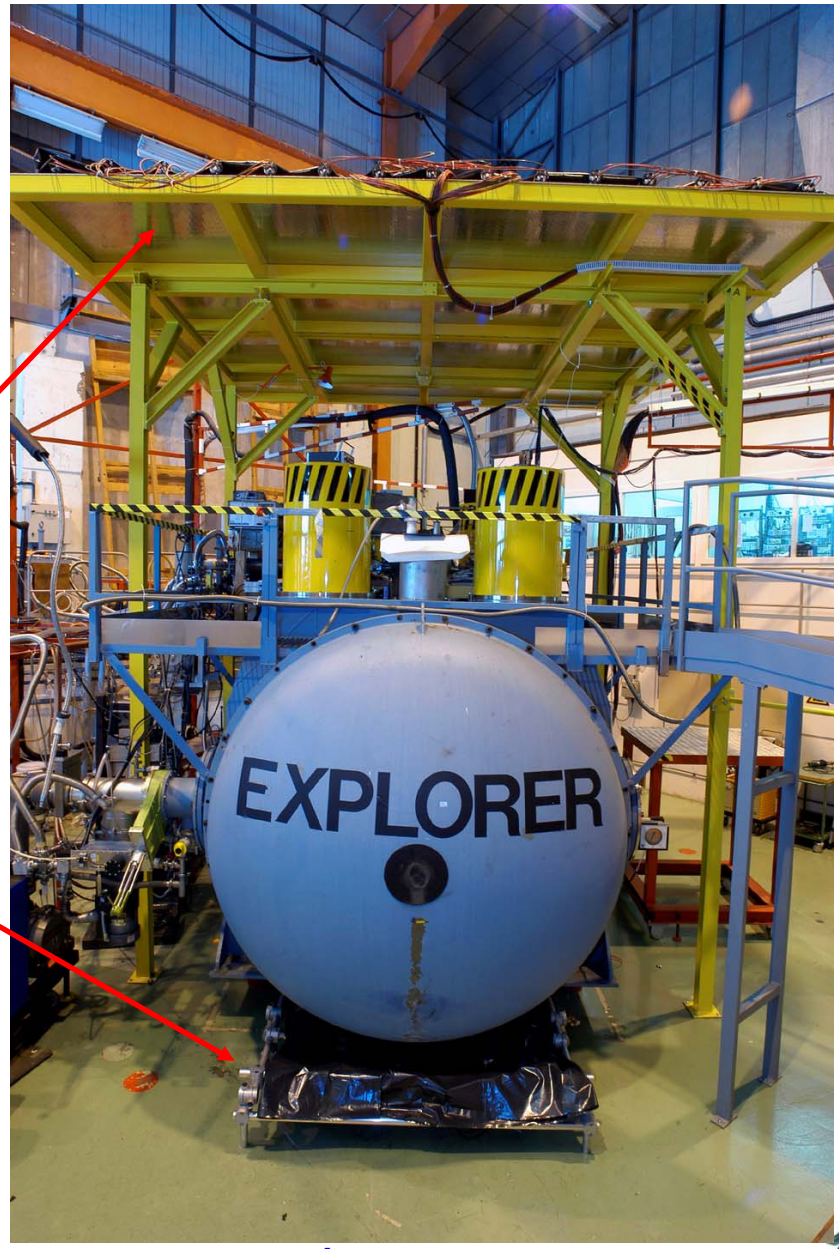
$\nu_A$= 915 Hz @ T = 2.5 K

Cosmic ray detector (recently completed)

## Plastic scintillators

2 layers of 13 $m^2$

1 layer of 6 $m^2$



# G.W. ANTENNA NAUTILUS
## LNF - FRASCATI

Al 5056 bar  M = 2270 kg

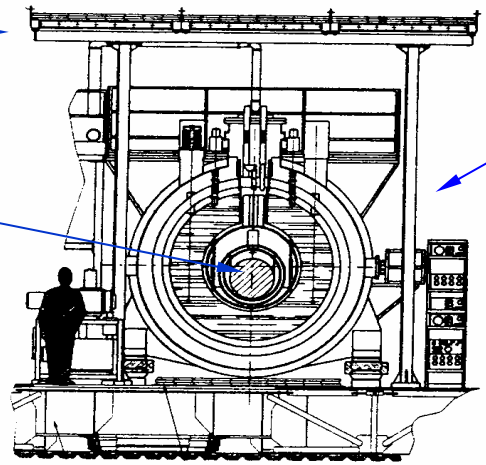
L = 2.97 m  Ø = 0.6 m

$\nu_A$= 935 Hz

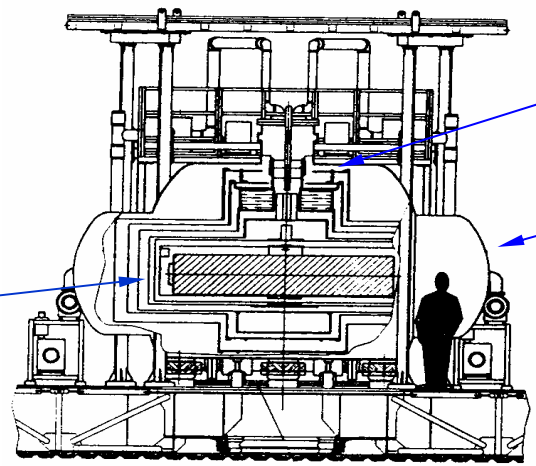
Cooled by a dilution refrigerator T=130 mK

Cosmic ray telescope

# NAUTILUS CRYOSTAT



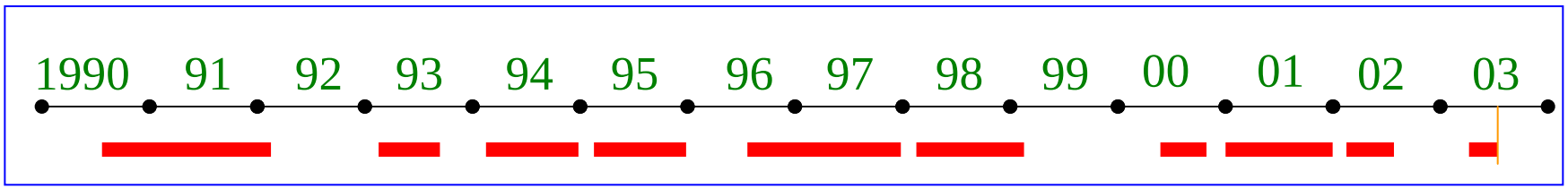

FRONT VIEW




SIDE VIEW

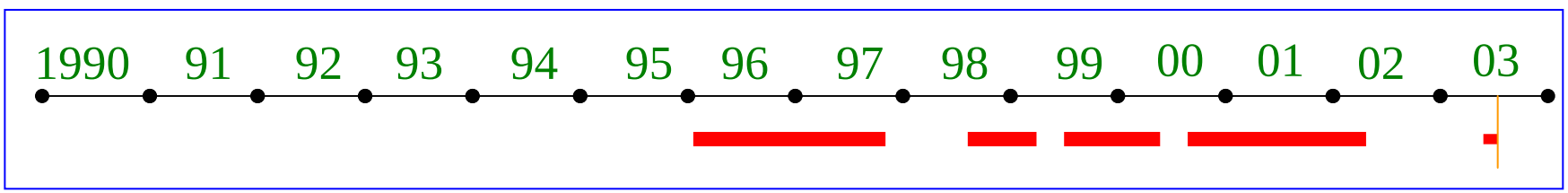
# DATA TAKING DURING THE LAST 10 YEARS

## EXPLORER



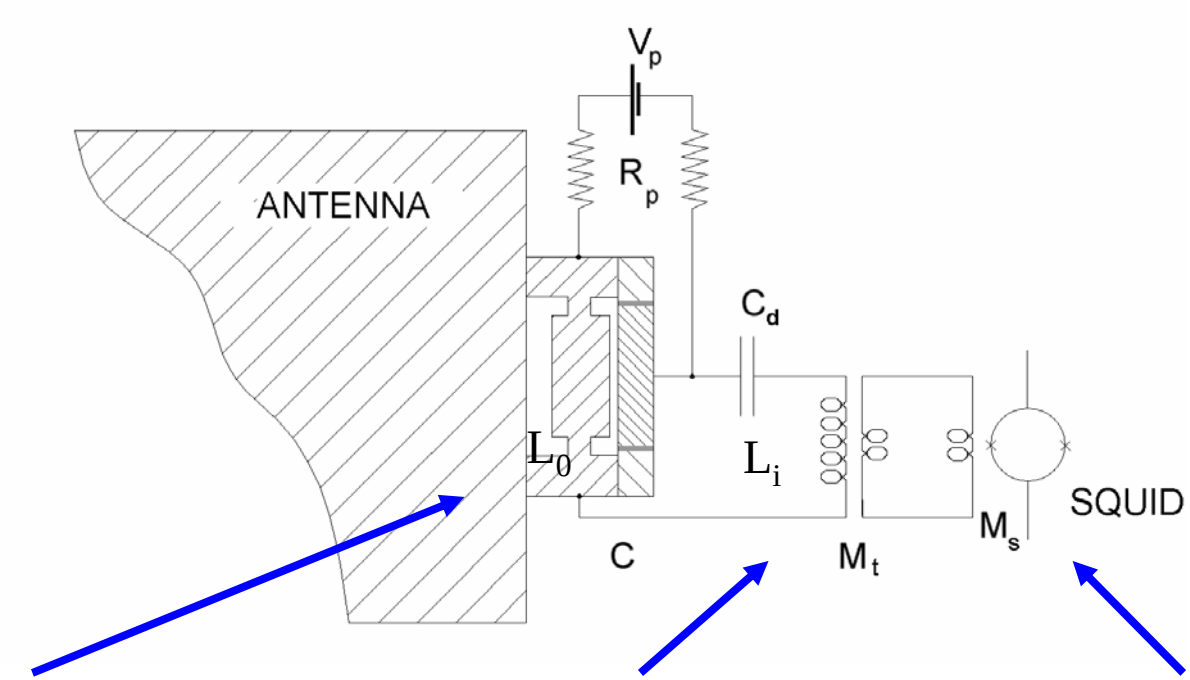

h from $10^{-18}$ to $3 \cdot 10^{-19}$

## NAUTILUS




h from $10^{-18}$ to $3 \cdot 10^{-19}$

# EXPERIMENTAL CONFIGURATION




**Small gap capacitive transducer**

Al 5056
$m_t$ = 0.75 kg
$\nu_t$= 916 Hz
$C_t$ = 11 nF

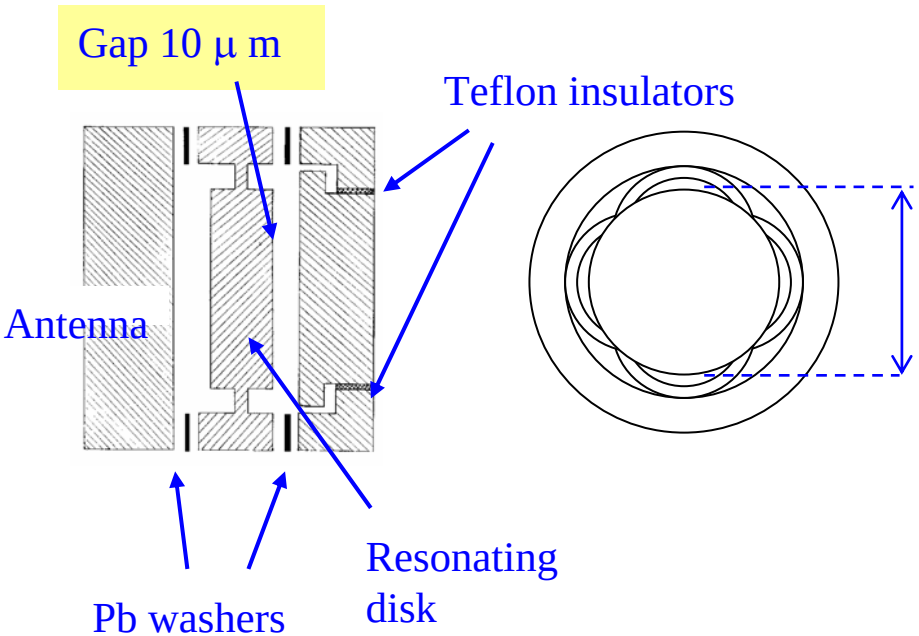
**Superconducting matching transformer**

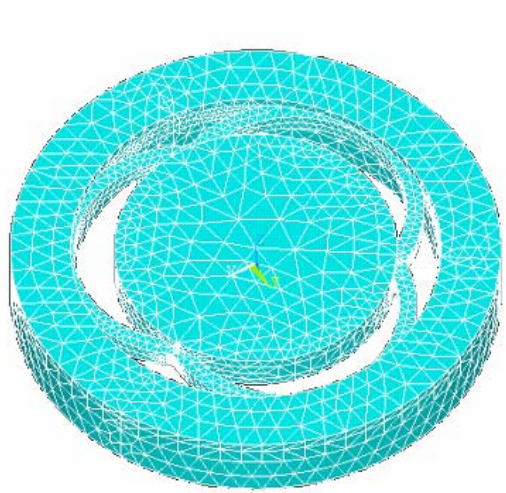
Lo=2.86 H
Li=0.8μH
K=0.8

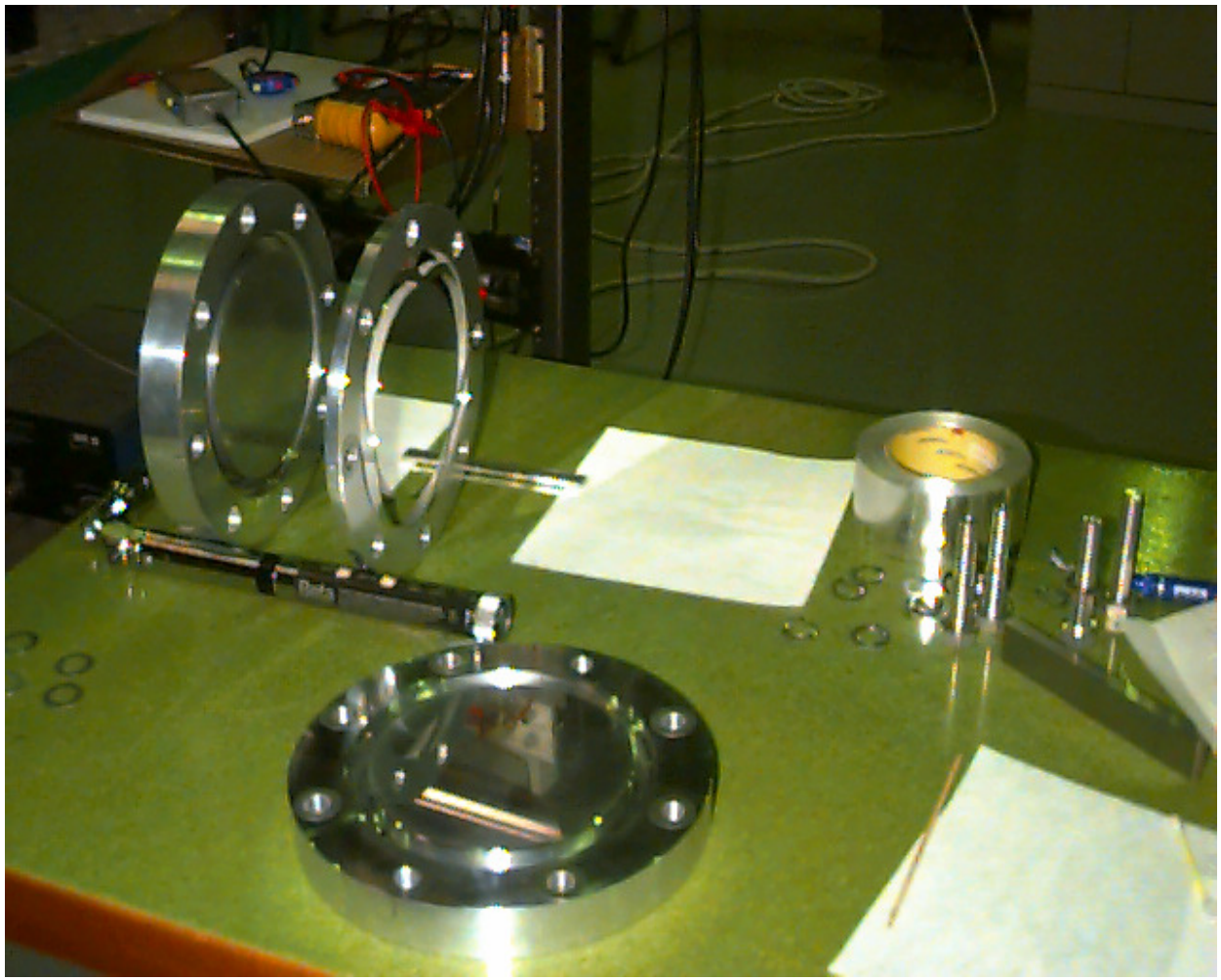
**High coupling dc-SQUID**

$M_s$ = 10 nH
$\phi_n$= 3 ·$10^{-6}$ Φo/√Hz

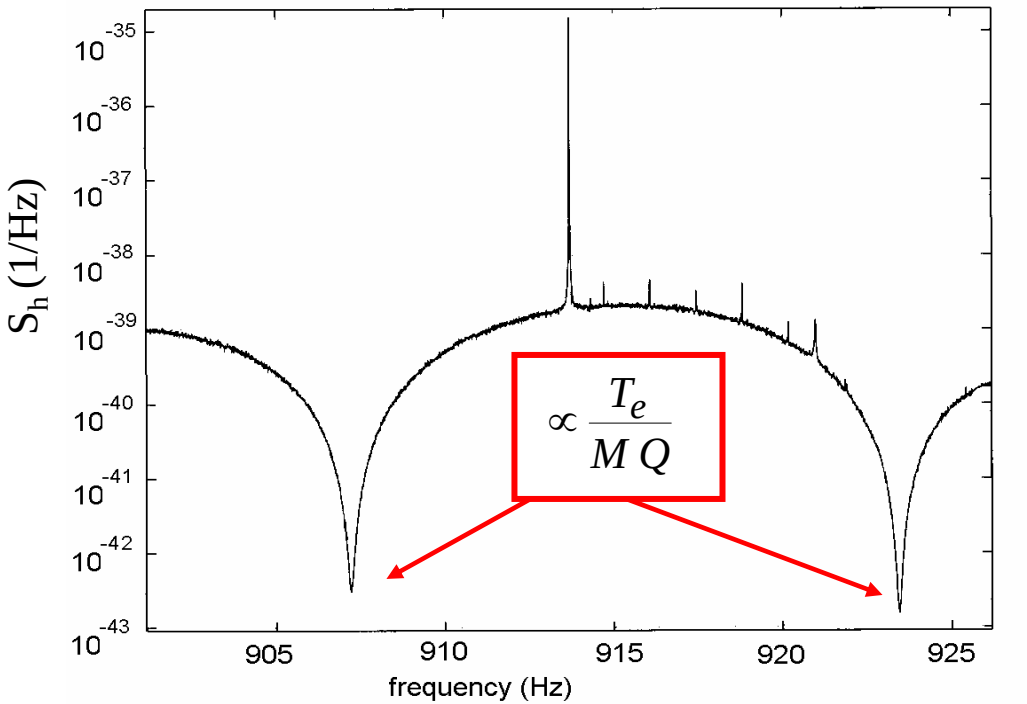
# ROME GROUP TRANSDUCER





# SENSITIVITY OF BAR DETECTORS

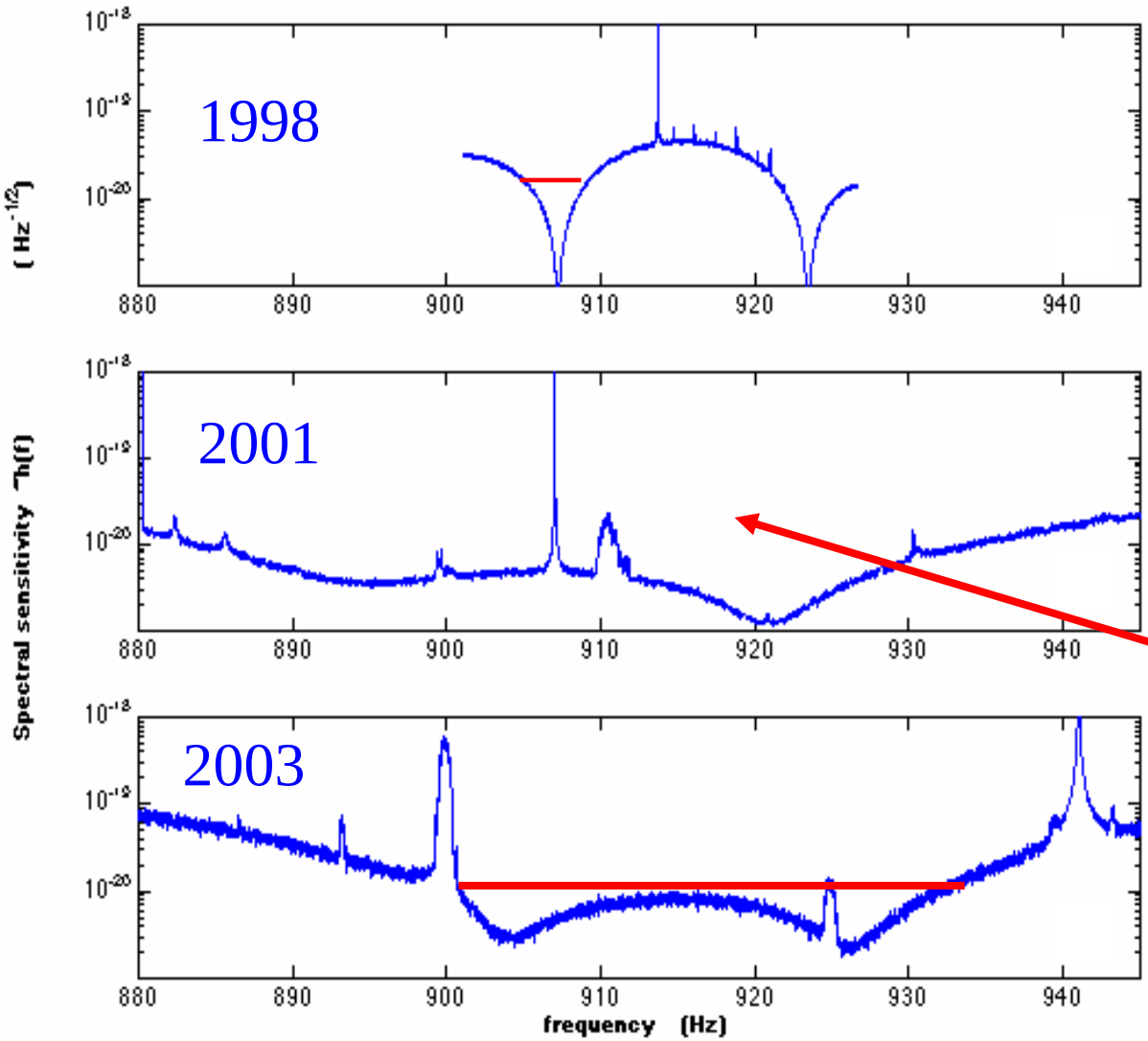



- The sensitivity of a detector is usually given in terms of the noise spectral density referred to the input of the antenna

- The "peak" sensitivity depends on "physical" parameters (T,M,Q). To increase the overall sensitivity a larger bandwidth is required. It can be obtained decreasing the electronics noise contribution and increasing the energy transfer



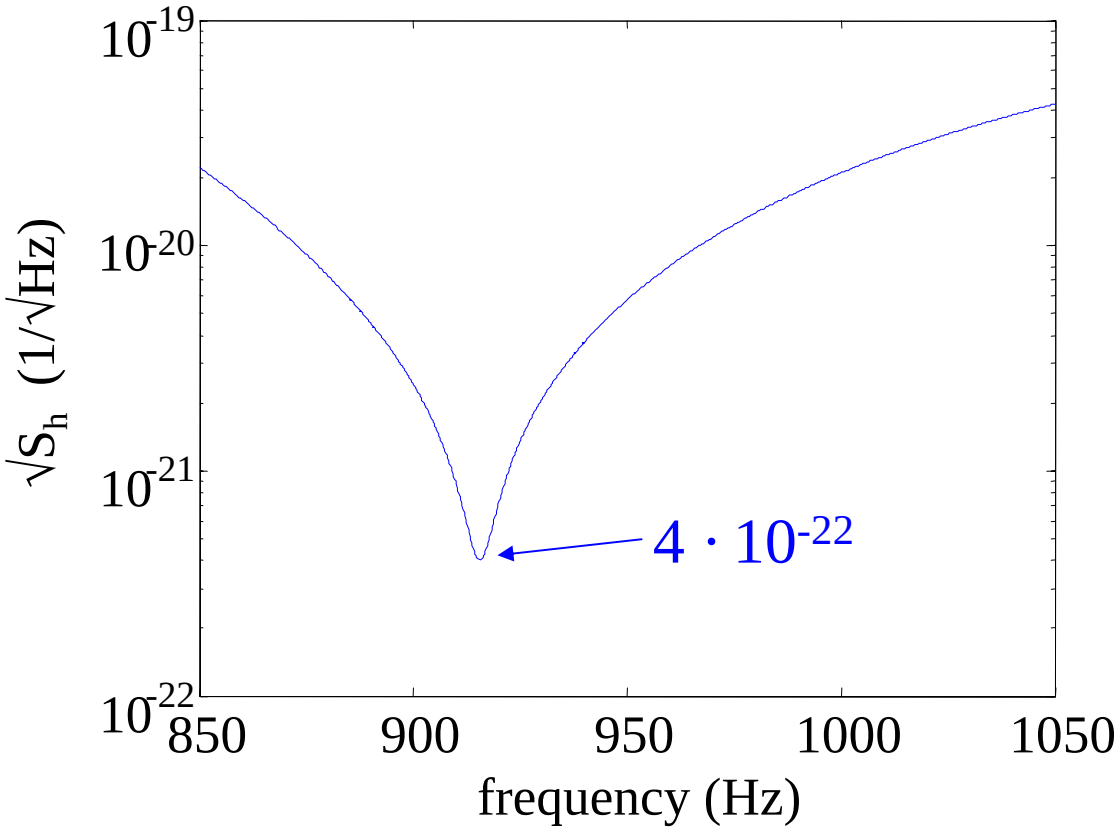
# WIDENING THE BAND IN EXPLORER




$< 10^{-20}$ Hz$^{-1/2}$
on 40 Hz

# TARGET SENSITIVITY OF EXPLORER

- EXPLORER can reach a sensitivity of $T_{eff}$=150 μK
  $h = 1 \cdot 10^{-19}$ -bandA




- New transducer double gap
- New transformer higher elect. Q
- New SQUID lower noise



# EXPLORER STATUS

- EXPLORER was upgraded in 1999. After a tune-up period, it has been on the air since 2000 with a duty cycle close to 84% excluding six months in 2002 and the yearly stop for CERN winter

- The apparatus is now equipped with a cosmic ray detector consisting of plastic scintillators:1 layer of 6 $m^2$ under the cryostat and 2 layers of 13 $m^2$ over it the cryostat



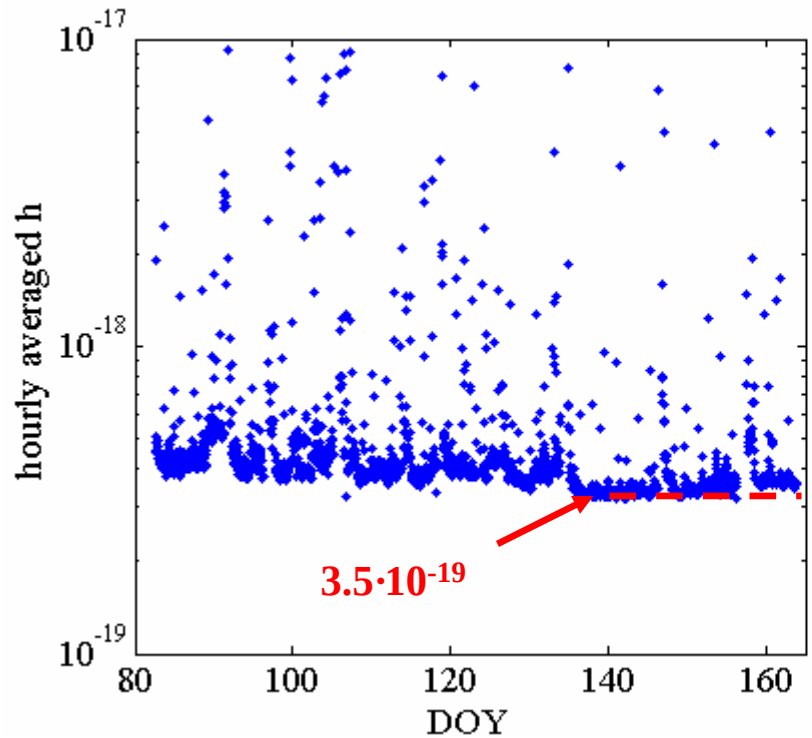
# NAUTILUS STATUS

- It has worked from 1999 to March 2002 with a duty-cycle xxxx greater then 80% and an effective temperature smaller then 5 mK corresponding to $h = 6 \cdot 10^{-19}$
- NAUTILUS operations has been stopped on March 2002 for an upgrade, restarted March 2003
- The apparatus is approaching optimum performance

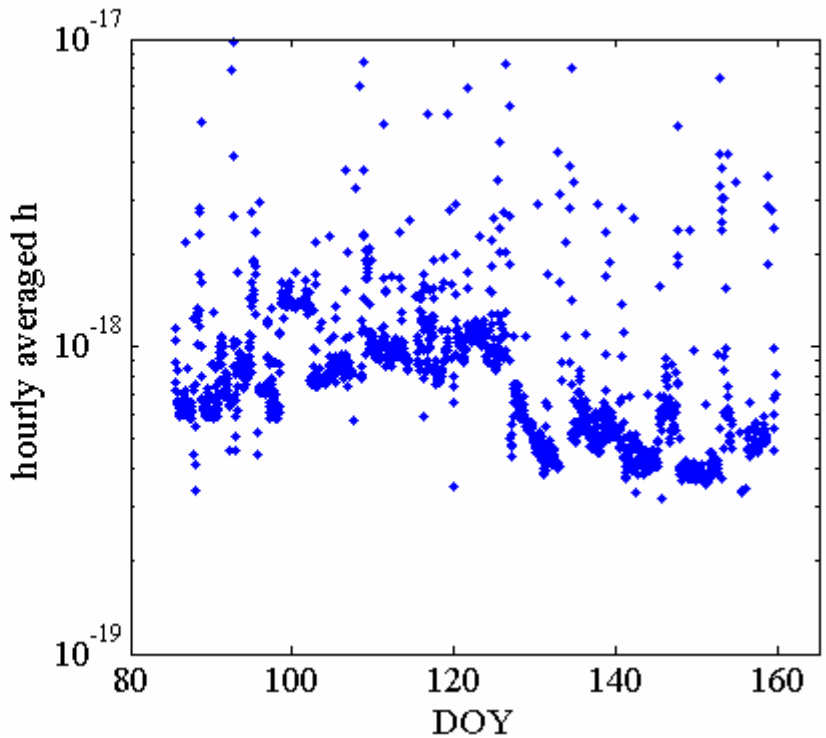


# OPERATIONS DURING 2003

EXPLORER

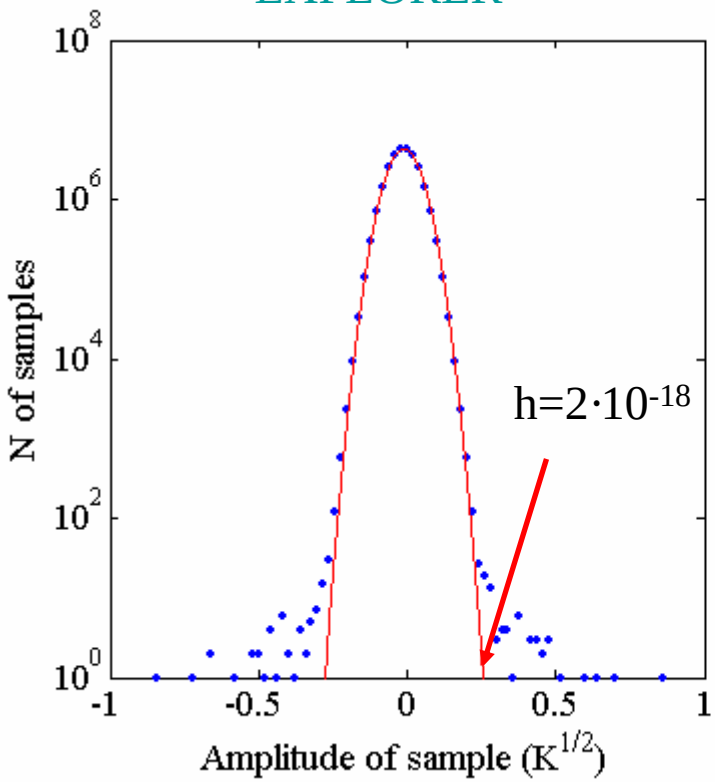



NAUTILUS

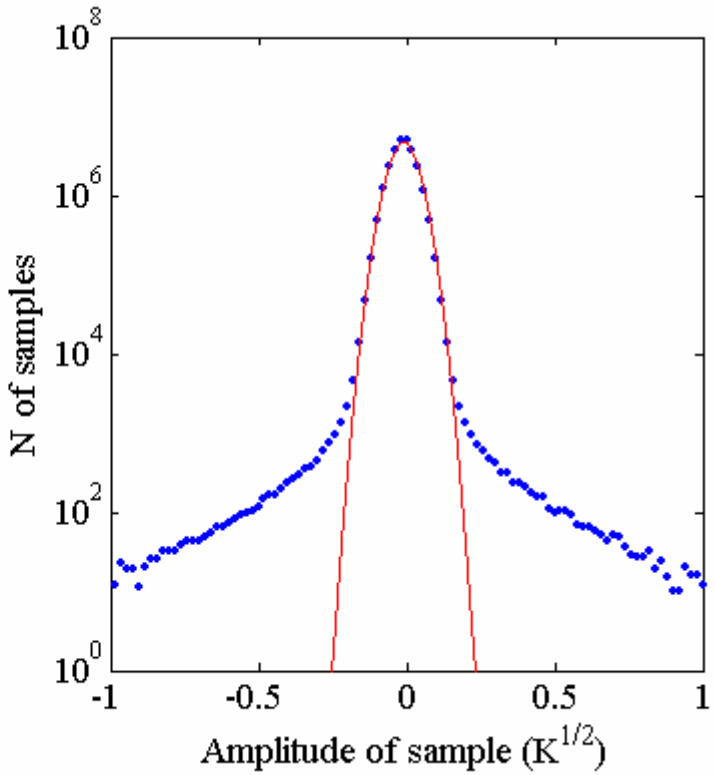


# GAUSSIANITY

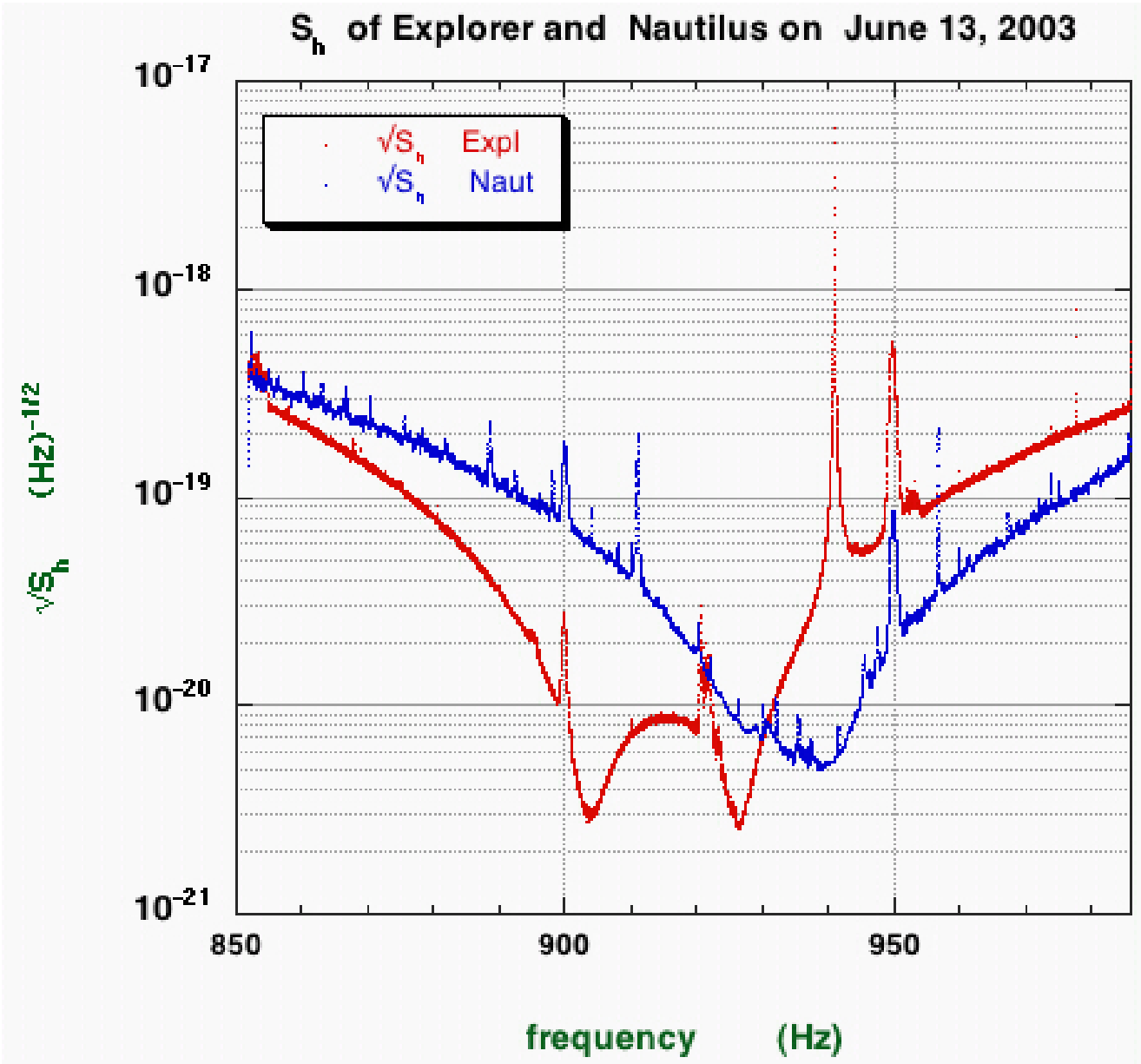
EXPLORER




NAUTILUS




1 day of data on june 2003




The overlap can be optimized to reach a common band-width of ~ 30 Hz

(300 times larger than that of 1997)



# SIGNAL DETECTABLE TODAY

- STOCHASTIC SOURCES:

  fluctuation in the density of early universe

$$\Omega_{GW} \approx 2\times10^{-3}\left(\frac{f}{900Hz}\right)^3\left(\frac{\tilde{h}^2}{10^{-22}\,Hz^{-1/2}}\right)^2\sqrt{\frac{1Hz}{\Delta f}}\sqrt{\frac{1y}{T_{obs}}}$$

- CONTINUOUS:

  spinning neutron stars ($M\sim1.4\ M_o$ $\varepsilon\sim10^{-6}$)

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

- BURST SIGNAL:

  Black hole ($M\sim10M_o$) $\sim10^{-4}\ M_o$ into GW

$$SNR = 6\times10^3\left(\frac{10kpc}{d}\right)^2\left(\frac{10^{-44}\,Hz^{-1}}{\tilde{h}^2}\right)\left(\frac{\Delta f}{1Hz}\right)$$

  Coaleshing binaries NS-NS $M\sim1.4\ M_o$

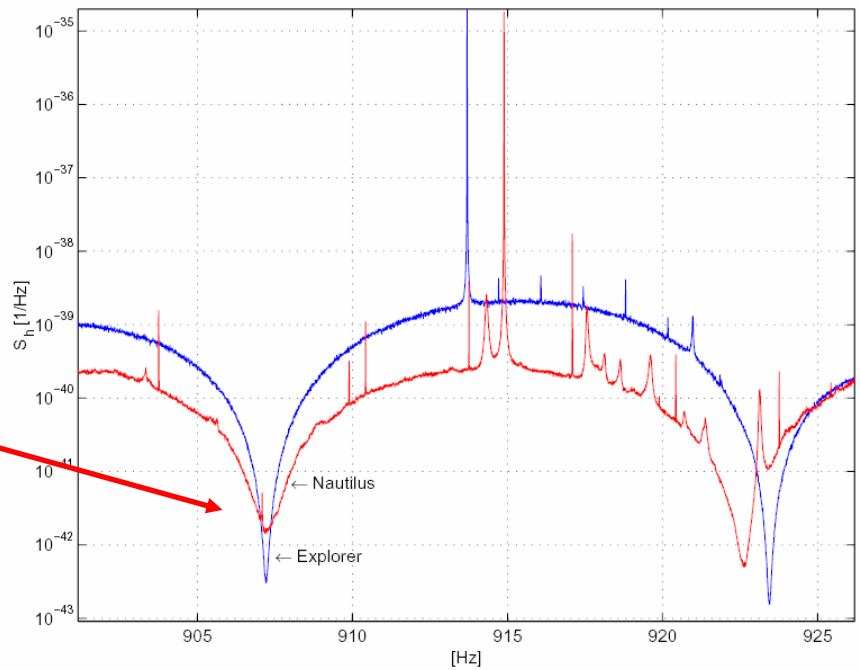
$$SNR = 10^3\left(\frac{10kpc}{d}\right)^2\left(\frac{10^{-44}\,Hz^{-1}}{\tilde{h}^2}\right)\left(\frac{\Delta f}{1Hz}\right)$$



# SEARCH FOR STOCHASTIC BACKGROUND

- Crosscorrelation of EXPLORER and NAUTILUS data over 10 hours in a band of 0.1Hz in 1997

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




P.Astone, et al. : "*Crosscorrelation measurement of stochastic gravitational waves with two resonant gravitational wave detectors*", Astron. and Astrophys**,** 351, 811-814, (1999).)

# SEARCH FOR CONTINUOUS WAVES

**Amplitude of the wave**

**Observation time**

$$SNR = \frac{\bar{h} \cdot t_{obs}}{2 S_h(\bar{\nu})}$$

**Spectral noise density of the detector**

Upper limits:

- From the GC, using 95.7 days of EXPLORER data $\mathbf{h_c = 3 \cdot 10^{-24}}$ in the frequency interval 921.32 ÷ 921.38 Hz
(P.Astone et al. *"Search for periodic gravitational wave sources with the Explorer detector"* Phys. Rev. D 65, 022001,2002 )

- From all the Sky, using 2 days of EXPLORER data $\mathbf{h_c = 2 \cdot 10^{-23}}$ in the frequency interval 921.00 ÷ 921.76 Hz
(P.Astone et al. *"All-Sky upper limit for gravitational radiation from spinning neutron stars"* , proceedings GWDAW 2002 – collab with KrolaK et alii)



# SEARCH FOR BURST SIGNALS

• The search for burst signals with a single detector is of not interest. It is almost impossible to distinguish the candidate events from the back-ground of noise. The “coincidence analysis” between the event candidates of different detectors strongly decrease the false alarm probability.

$$\lambda = N \frac{(\Delta t)^{N-1}}{T_{obs}^{N}} \prod_{i=1}^{N} n_i$$

**Rate of accidental coincidences**

**Number of detectors**

**Common observation time**

**Coincidence window**

**Number of events**



# BURST SIGNALS

- International Gravitationl Event Collaboration: *"First Search for Gravitational Wave Burst with a Network of Detectors"*, Physical Review Letters, 85, 5046-5050, (2000).

P.Astone et al.: *"Study of coincidence between resonant gravitational wave detectors"*, Classical and Quantum Gravity, 18, 243-251, (2001).

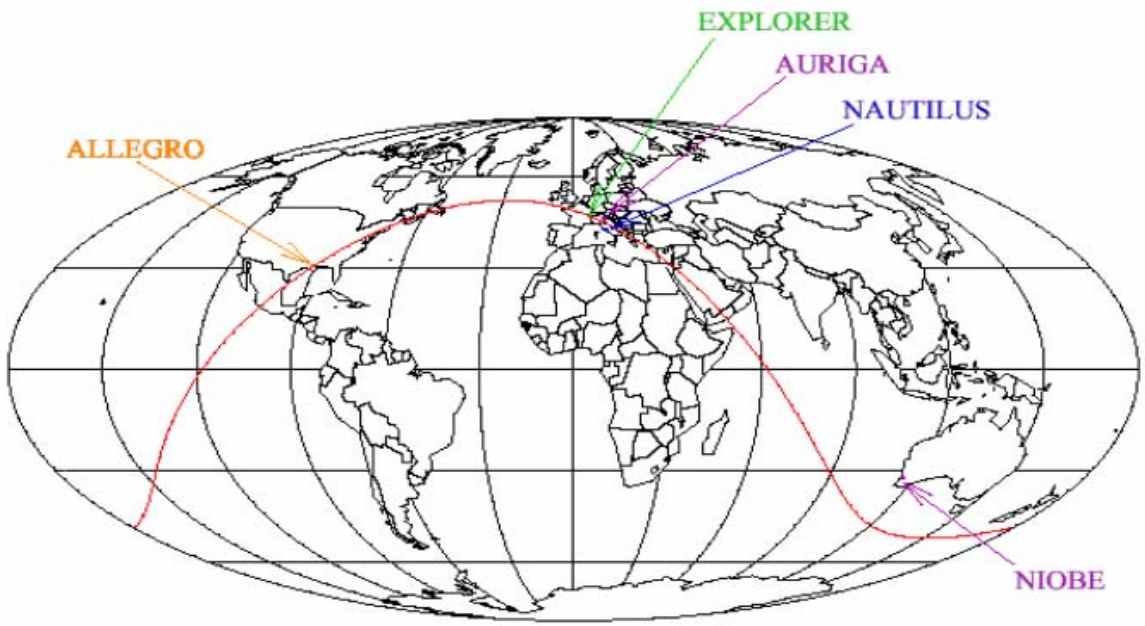
P.Astone et al.: *"Study of the coincidences between the gravitational wave detectors EXPLORER and NAUTILUS in 2001"*, Classical and Quantum Gravity 19, 5449-5463 (2002).

P. Astone et al.: *"Search for correlation between GRB's detected by BeppoSAX and gravitational wave detectors EXPLORER and NAUTILUS"*, Physical Review D, 66, 2002 102002



IGEC

International Gravitational Event Collaboration




- Collaboration for data exchange between the five resonant detector operating world wide

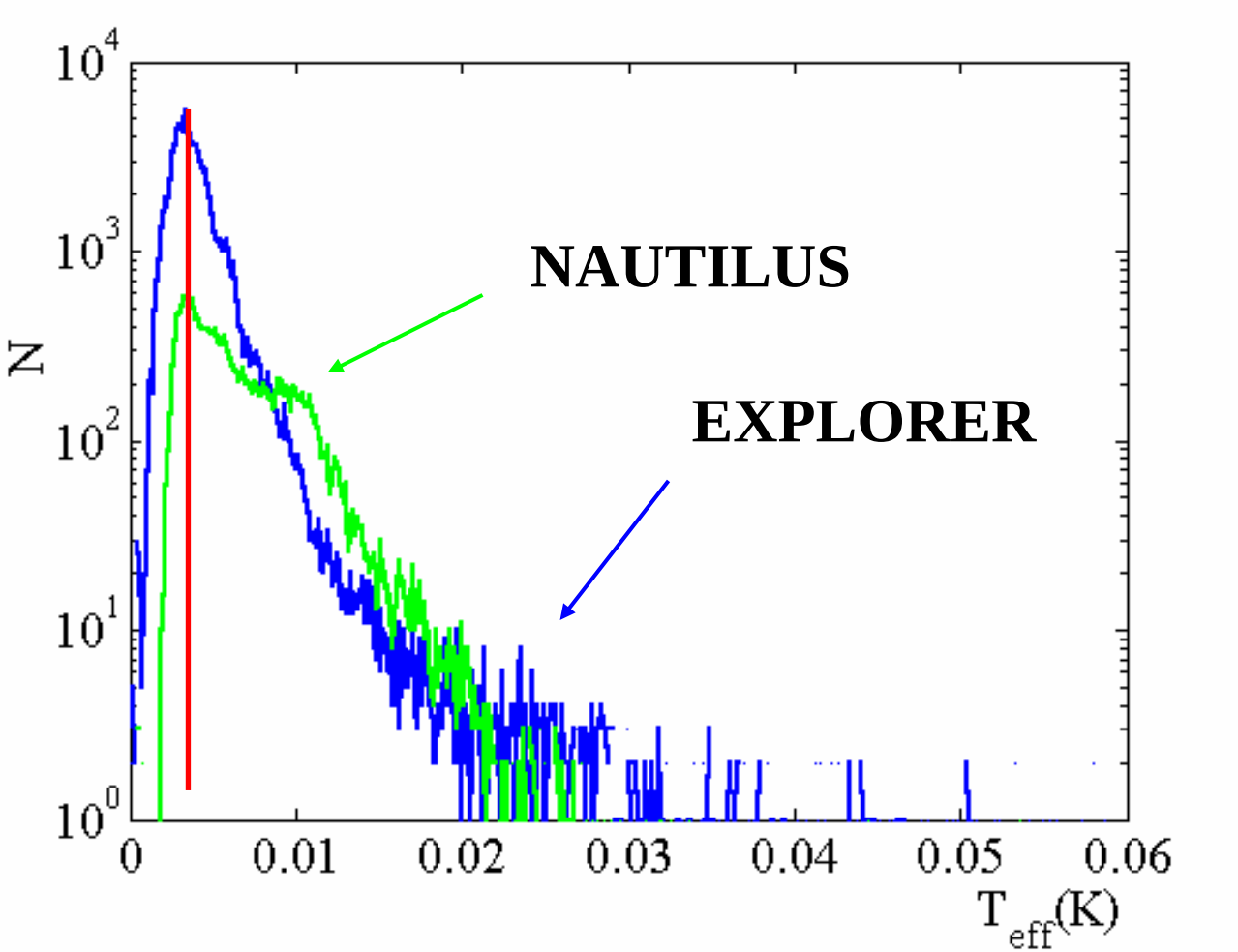
# 2001 DATA ANALYSIS

- During 2001 EXPLORER and NAUTILUS were the only two operating resonant detectors.
- Never before two detectors operated with such sensitivity
- A new algorithm based on energy compatibility of the event was applied to reduce the “background”

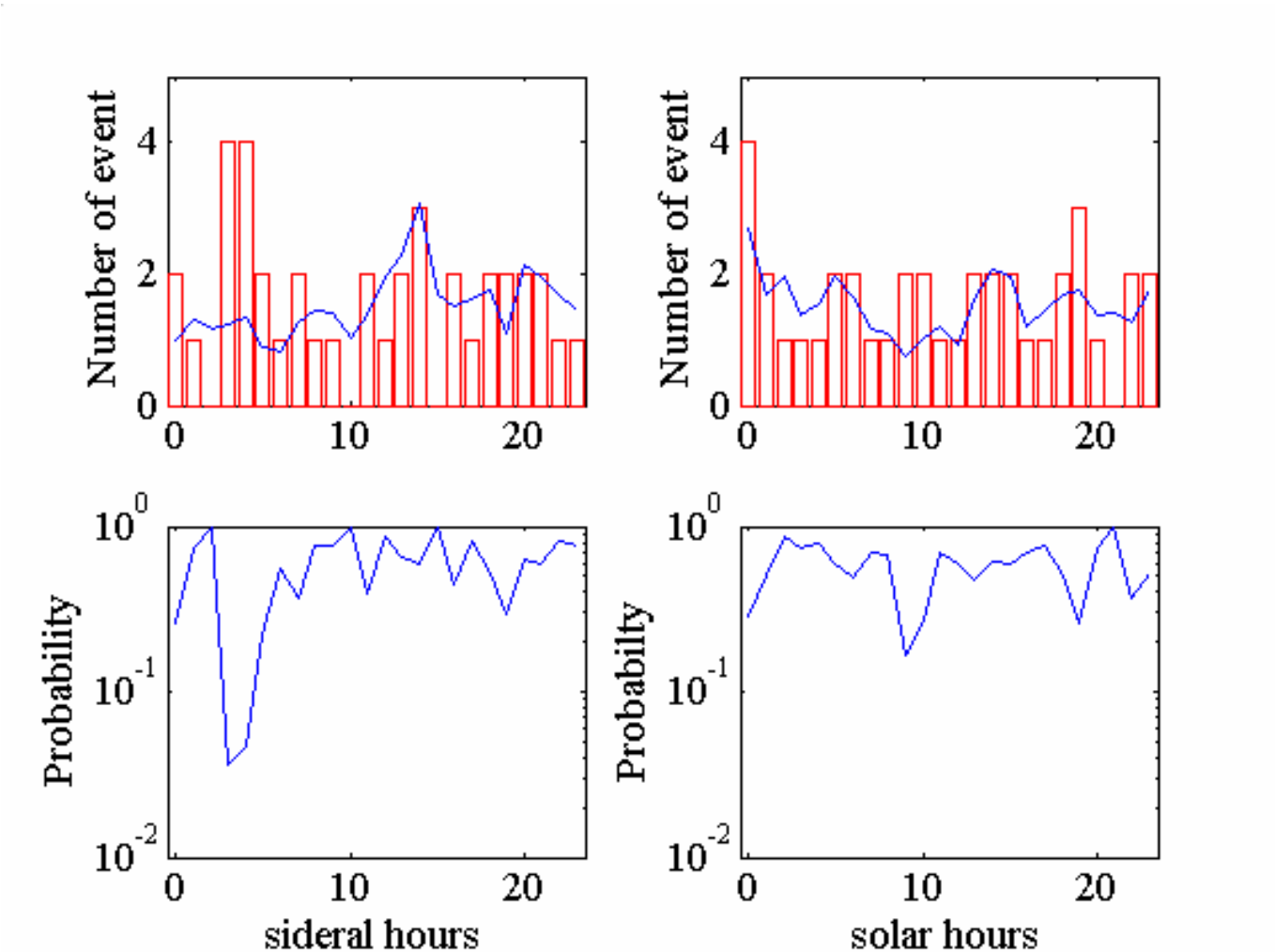


# EFFECTIVE TEMPERATURE OF THE EVENTS

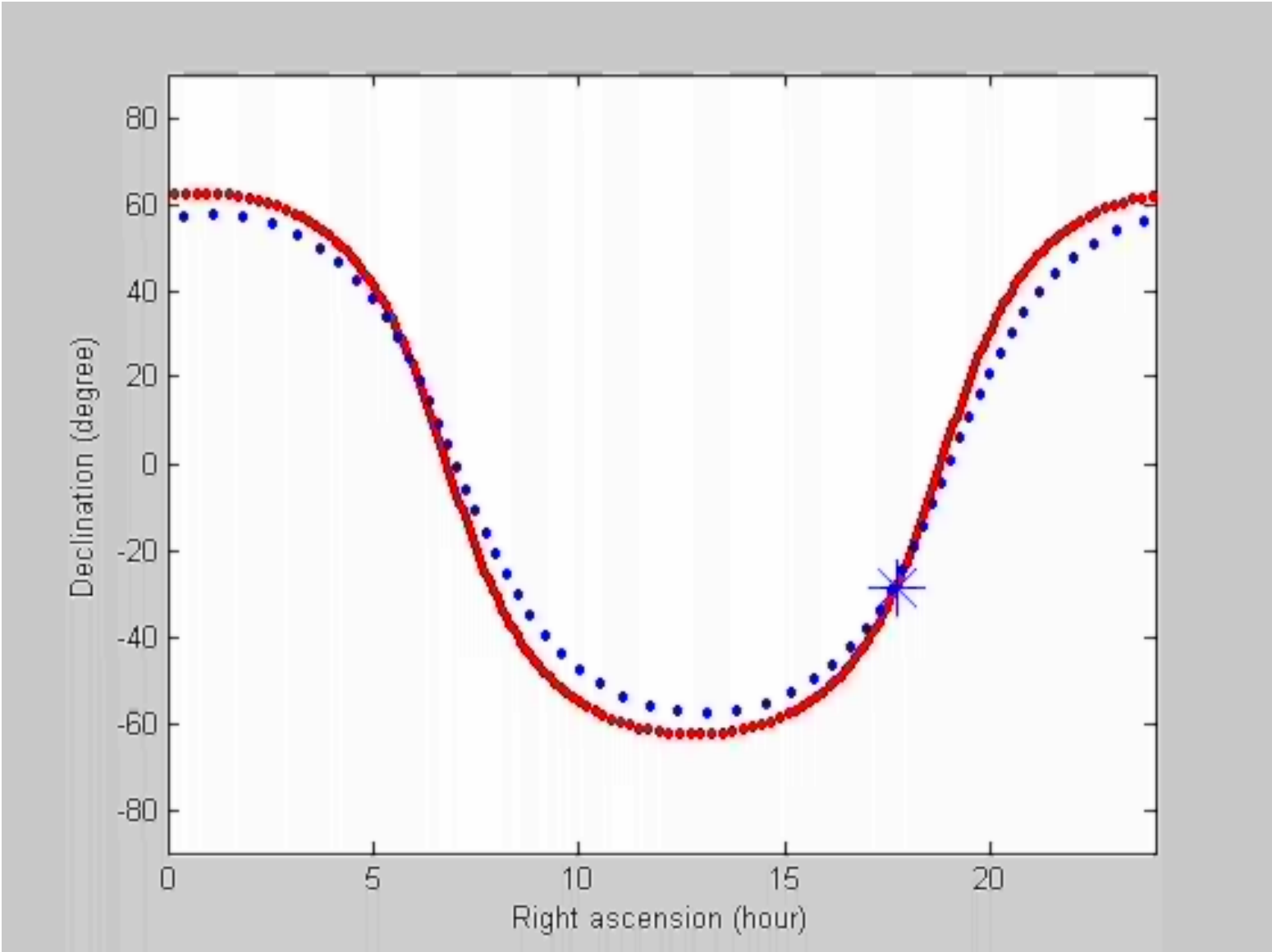
## Best performances ever obtained by two detectors



# RESULT OF THE ANALYSIS

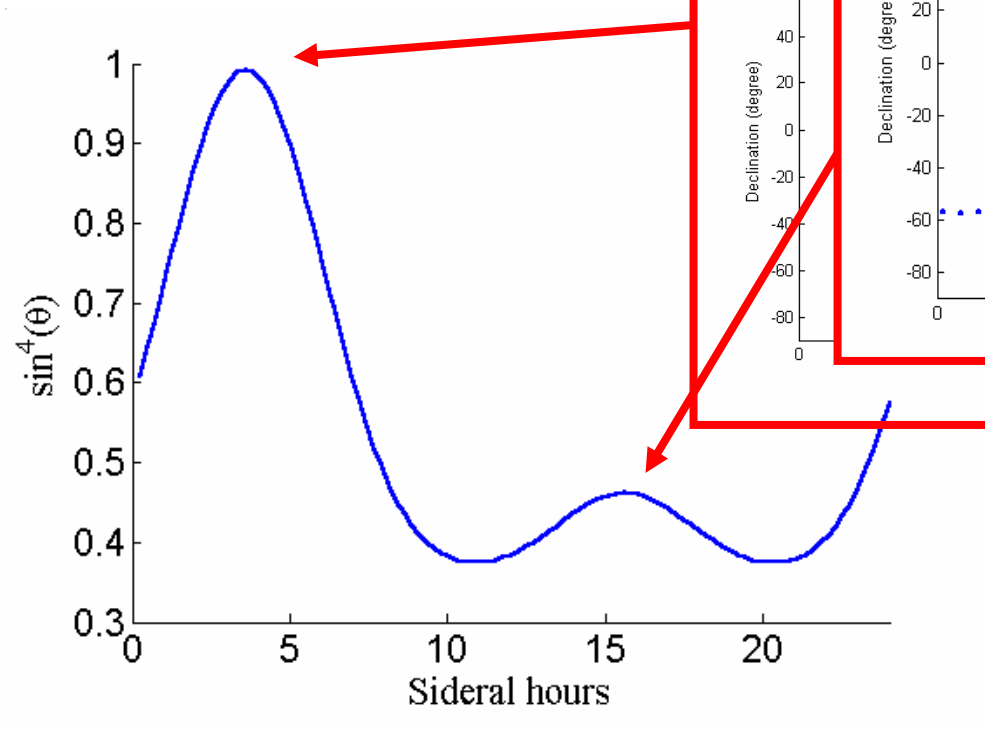


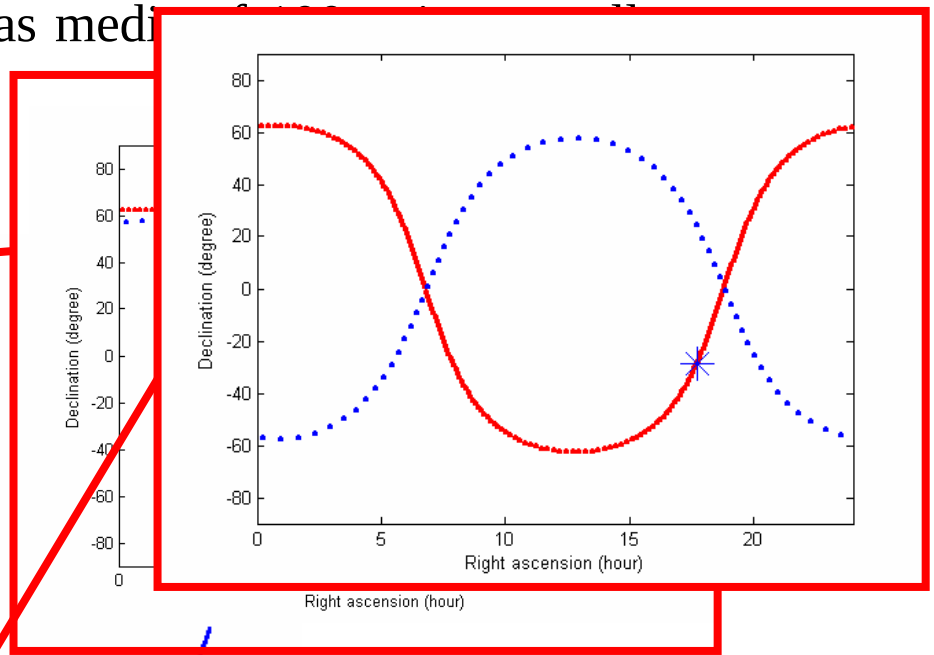

In the interval


Declination (degree)
80
60
40
20
0
-20
-40
-60
-80
0
5
10
15
20
Right ascension (hour)

# AVERAGED ANGLES VS SIDERAL HOURS

- Value of $\sin^4(\theta)$ calculated as medi
  spaced over the galaxy disk

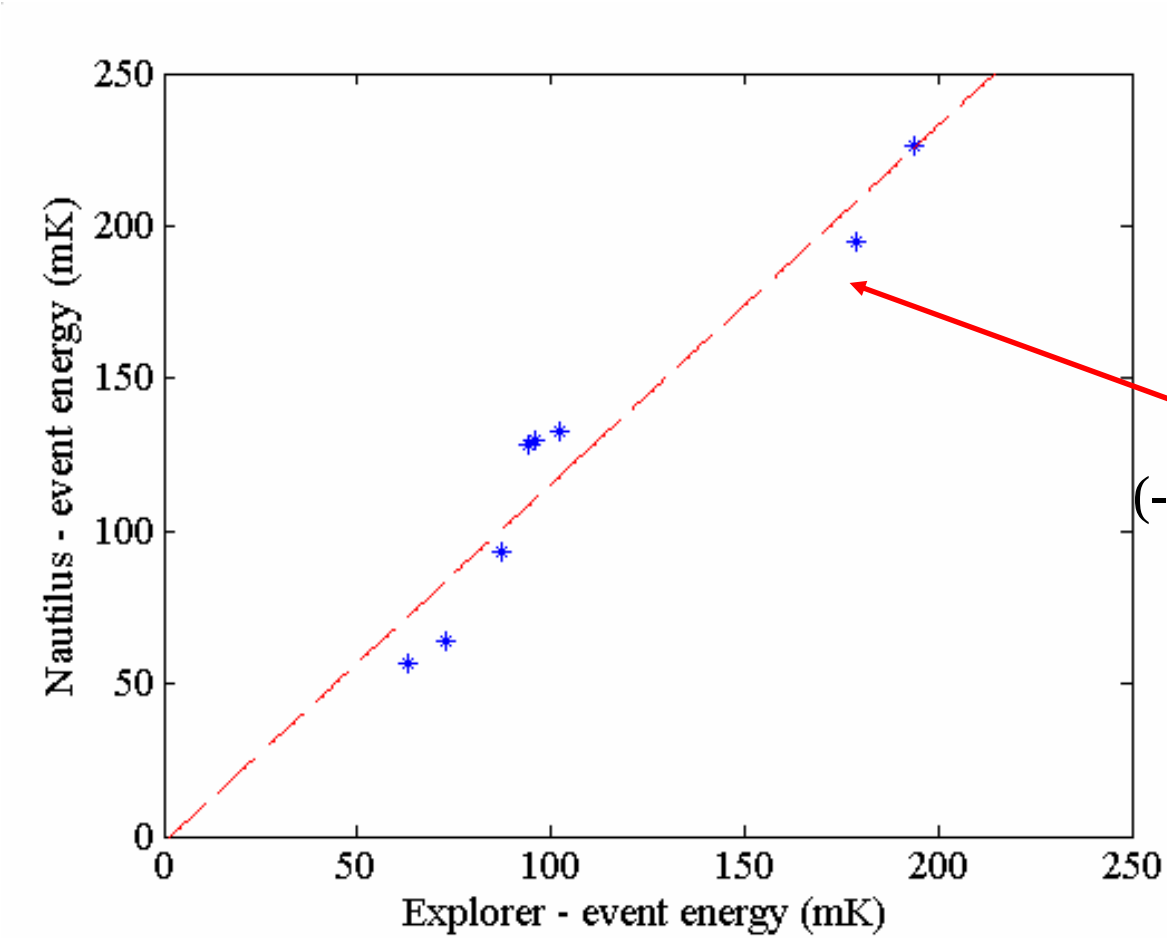





# CORRELATION BETWEEN EVENTS

## SIDERAL HOURS 3-5




Corr coeff **0.96**

(**-0.19** on the 24 hours)

# DOES THE EXCESS SEEN MAKE ANY SENSE?

- The “interesting coincidences” have an energy around 100 mK corresponding to a conventional burst amplitude $h \sim 2 \cdot 10^{-18}$
- The energy is equivalent to a conversion of $4 \cdot 10^{-3}$ solar masses in galactic center (8 kpc)
- New data are needed for further considerations



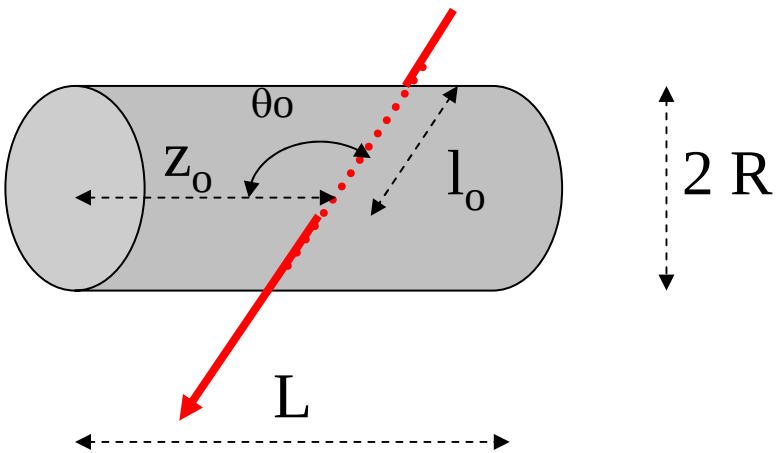
# EFFECT OF COSMIC RAYS ON A RESONANT DETECTOR

**Grüneisen coefficient** — **Energy lost**

$$E = \frac{4}{9\pi}\frac{\gamma^2}{\rho L v^2}\left(\frac{dW}{dx}\right)^2\left(\sin\left(\frac{\pi z_o}{L}\right)\frac{\sin(\pi l_o \cos(\theta_o)/2L)}{\pi R\cos(\theta_o)/L}\right)^2 = 7.64\,x10^{-9}\,W^2\,f\left[\frac{K}{GeV^2}\right]$$

**density** — **sound velocity**

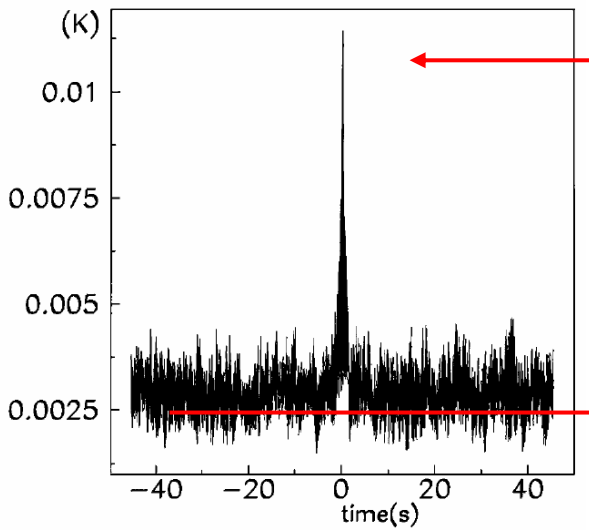
**Calculation for Nautilus**




The longitudinal mode of vibration of the antenna is excited by the thermal expansion due to the energy lost by the particles

- The first analysis confirmed the calculation made by several authors.

P.Astone et al.: *"Cosmic rays observed by the Resonant Gravitational wave detector Nautilus"* Physical Review Letter, **84**, (2000)14-17



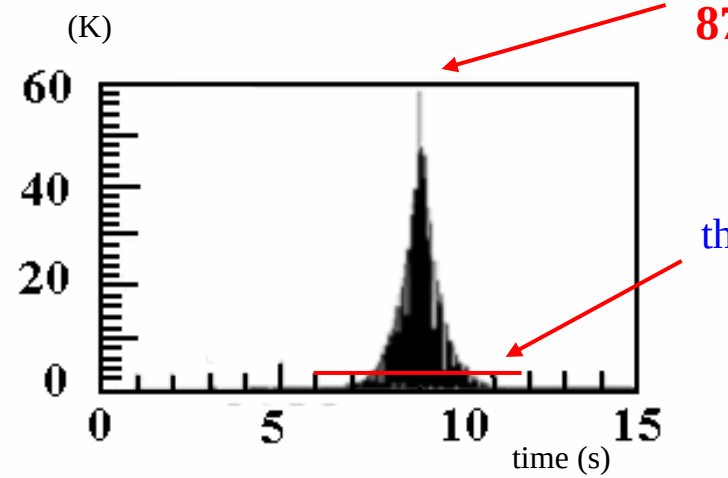

**Maximum 11.5 mK**

Average

- Detection of very large unexpected events.

P.Astone et al.: *"Energetic Cosmic Rays observed by the resonant gravitational wave detector NAUTILUS"* , Phys. Letters B 499, Feb 2001 16-22

**58 K**
**87 TeV**




threshold

# RESULTS WITH NAUTILUS BAR NOT SUPERCONDUCTOR

| 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 |

- Superconductivity is presently considered as the origin of the anomalous events

P.Astone et alii: *"Effect of cosmic rays on the resonant g.w. detector Nautilus at temperature T=1.5K"* Physics Letters B 540 179-184 (2002)).



# COINCIDENCE EXPLORER-COSMIC RAY

2002

| Noise | Tempo | Min density | Coincidence ±0.1 s | Background | Ev/day |
|---|---|---|---|---|---|
| 5 mk | 71.6 days | 1000 | 7 | 1.5 | 0.08 |

No event E > 1 Kelvin

2003

| Noise | Tempo | Min density | Coincidence ±0.1 s | Background | Ev/day |
|---|---|---|---|---|---|
| 10 mK | 24.8 days | 1000 | 4 | 0.45 | 0.14 |
| 100 mk | 30.5 days | 1000 | 16 | 8 | 0.25 |

4event E > 1 Kelvin



# THE END