F Ronga

Anomalous signals due to cosmic rays in the Nautilus Gravitational Wave Detector

ROG Group :L'Aquila Frascati Rome1 Rome 2 CNR

Summary

• The Nautilus 100 mKelvin resonant bar gravitational wave detector in Frascati

• Cosmic rays and the thermo-acoustical model of interactions of cosmic rays with a bar detector. First quantitative evaluation:
E. Amaldi G. Pizzella Nuovo Cimento 9C 1986

• The "**expected**" low amplitude signals : the results of the October 1998 January 1999 data (Ph.Rev.Lett. 84 Jan 2000).

• The "**unexpected**" high amplitude signals (Ph.Lett. B 499 Jan 2001 in press)

• **Conclusions**

Gravitational Wave Sources

• Gravitational waves are predicted from the theory of **general relativity** : needed acceleration of big masses with at least a quadrupole asymmetry. Small signals. No possibilities to produce gravitational waves in **laboratory** .

• Astrophysical sources (stellar collapse, coalescent binary systems, black holes....) **Indirect evidence (1993 Taylor-Hulse Nobel prize PSR 1913 +13)**

• the sensitivity is generally measured as perturbation h_{ik} of the metric tensor g_{ik} for very short signals and for ratio signal/noise=1

• **expected $h = 3 \times 10^{-18}$** for a stellar collapse in the center of the galaxy and 1% of the energy in gravitational waves

•**running bar detectors:**

Antenna	h*min*	
Explorer (Cern)	$3x10^{-19}$	Dec 2000 world wide record
Allegro (USA)	$6x10^{-19}$	
Niobe (Australia)	$6x10^{-19}$	
NAUTILUS (Frascati)	$4x10^{-19}$	
AURIGA(Legnaro)	$4x10^{-19}$	

• The bar detectors in operation are sensitive to **galactic** supernovae only, rate ≈1 ev/30 years

==>> Virgo cluster (increase of sensitivity ($h_{min} \approx 10^{-21}$)

The Nautilus Gravitational Wave bar Detector

• **Al 5056 cylindrical bar** 2300 Kg (3.0 m and 0.6 m diameter) cooled to a temperature of 100 mKelvin and equipped with a resonant capacitive transducer and a DC SQUID amplifier

(see Astrop .Physics ***7*** *231 (1997))*

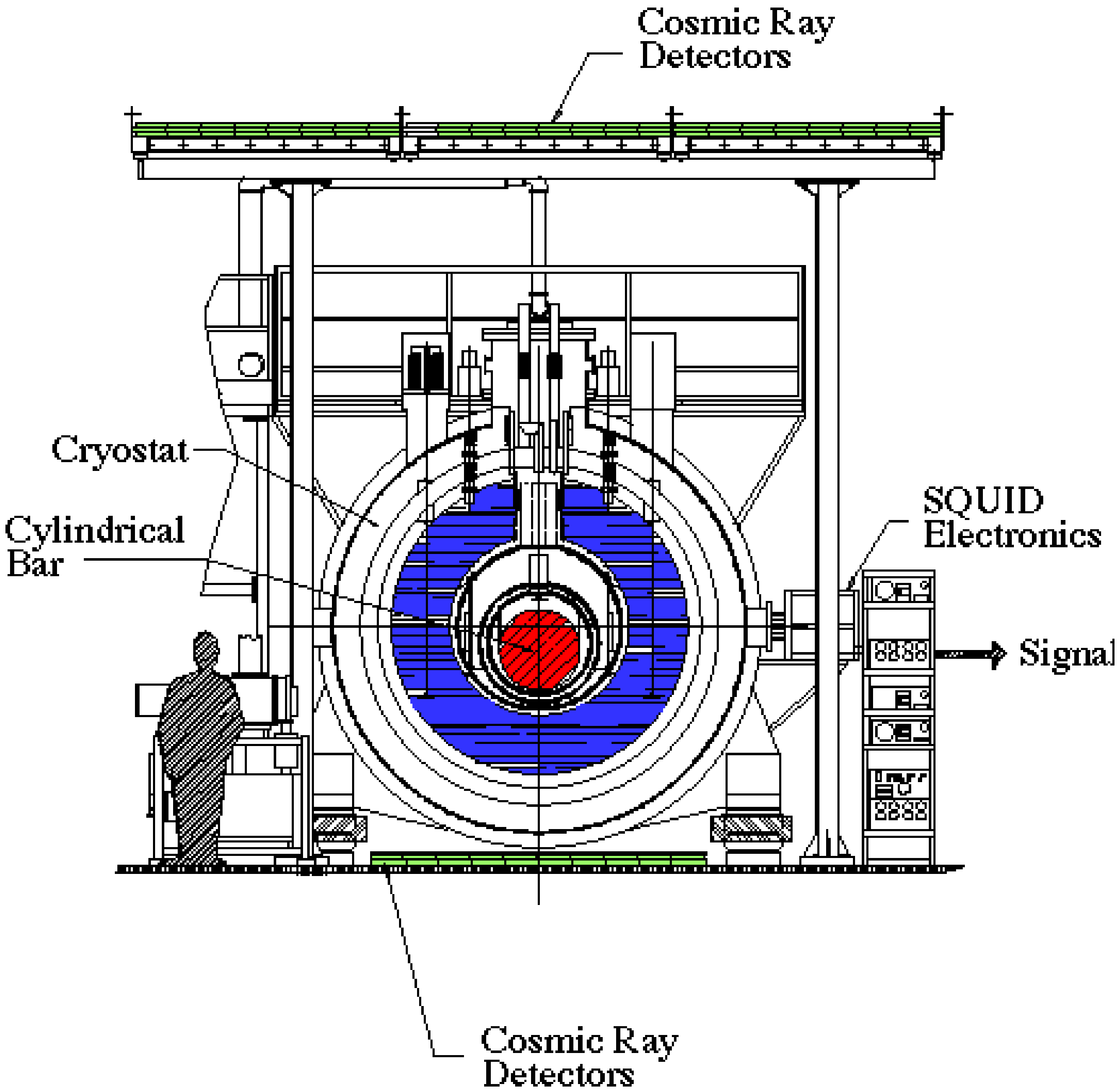
• **Central section** : two aluminium alloy shields cooled by helium gas, stainless liquid helium reservoir (2000 l), 3 copper rings, ^{3}He ^{4}He diluition refrigerator

• **Mechanical isolation :** shields are suspended one from the other forming a cascade of low pass mechanical filters; bar final suspension : U-shaped copper cable. 260 db at the bar resonant frequency (≈900 Hz)

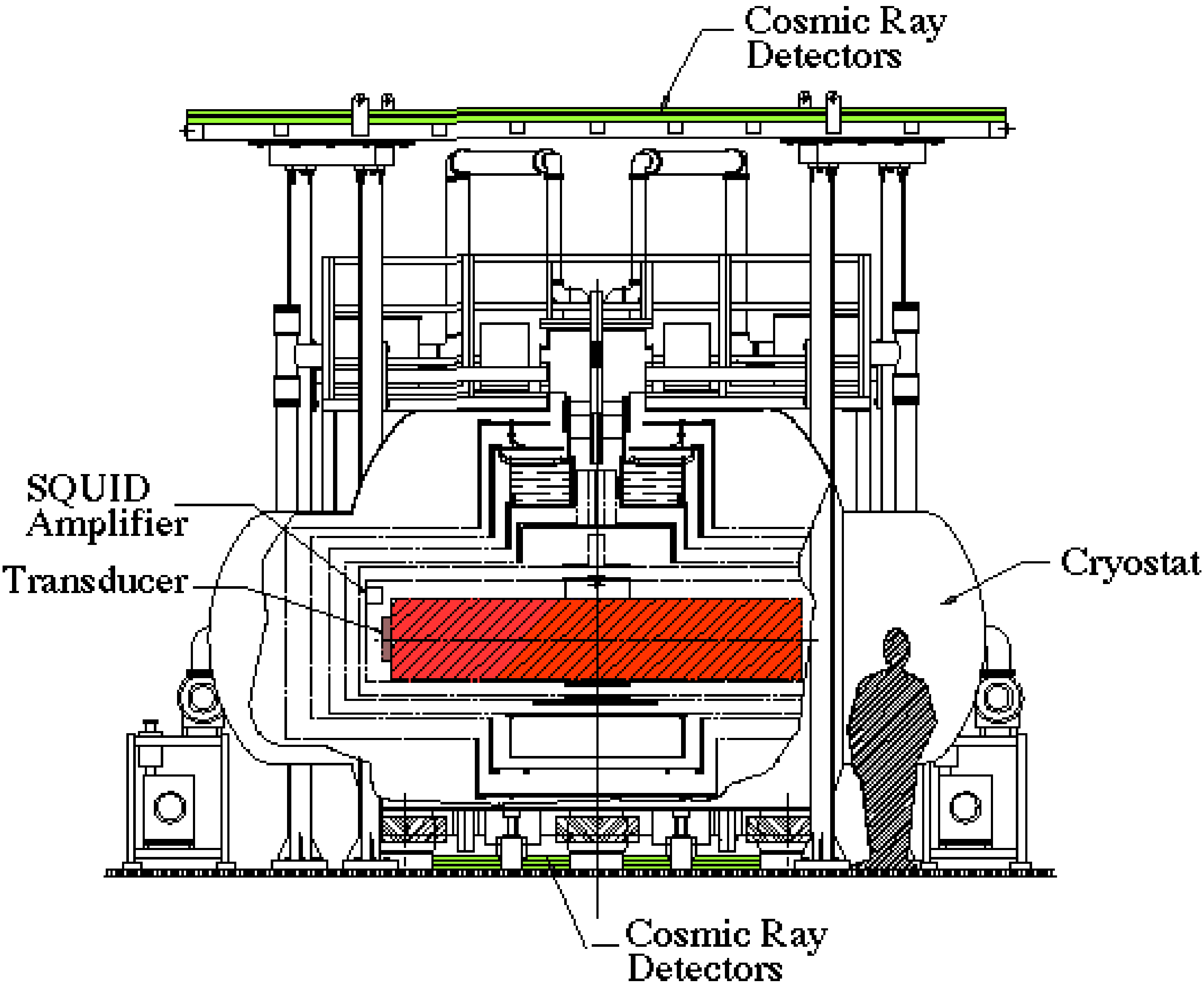
• **First run : 1994,**
several improvements done in 1997-1998 to reduce the mechanical noise. **==>>Nautilus 2** (started June 1998)

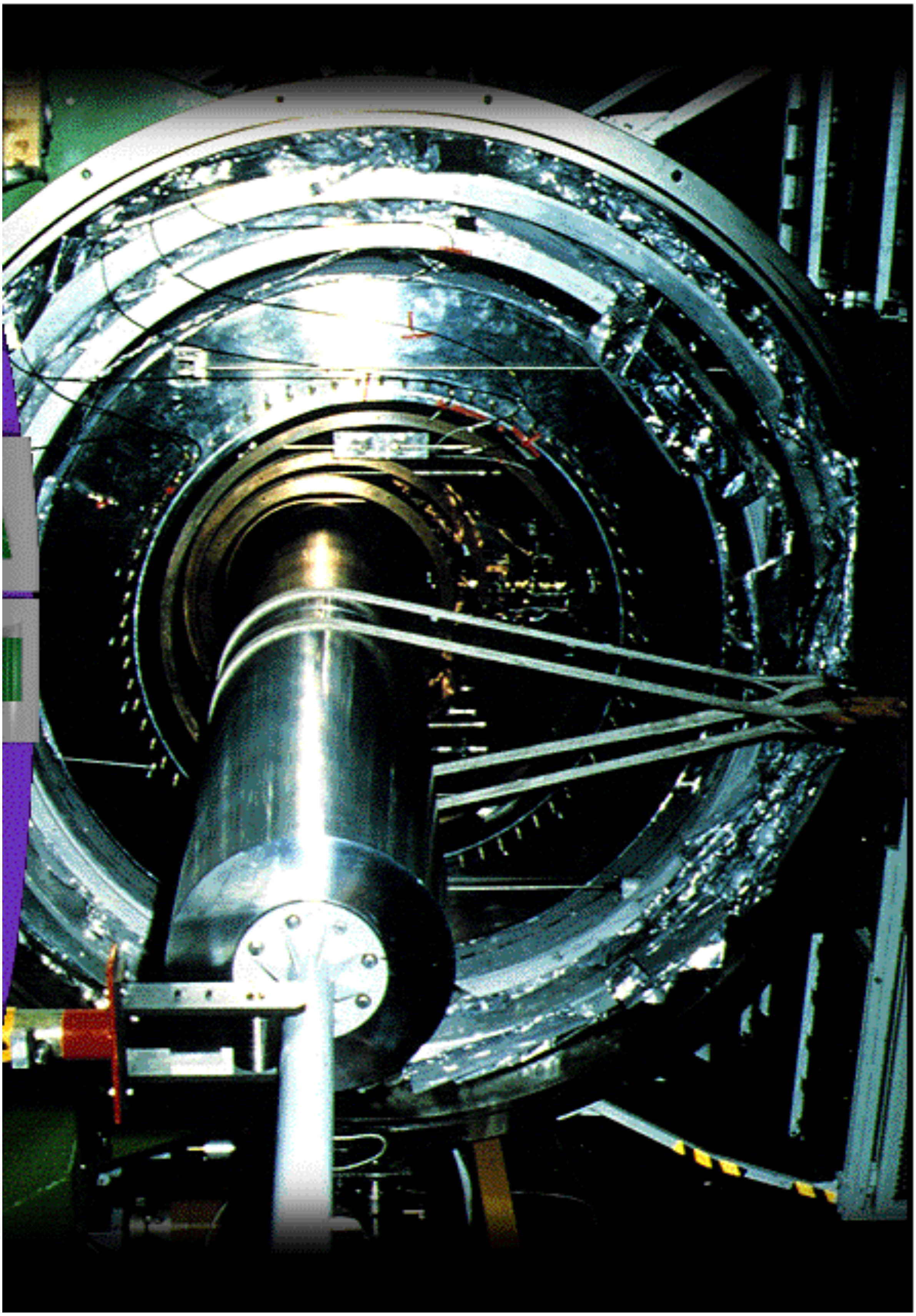
- Similar detector in Legnaro (Italy) **Auriga**

Nautilus
Front View



Nautilus
Side View





Nautilus Cooling

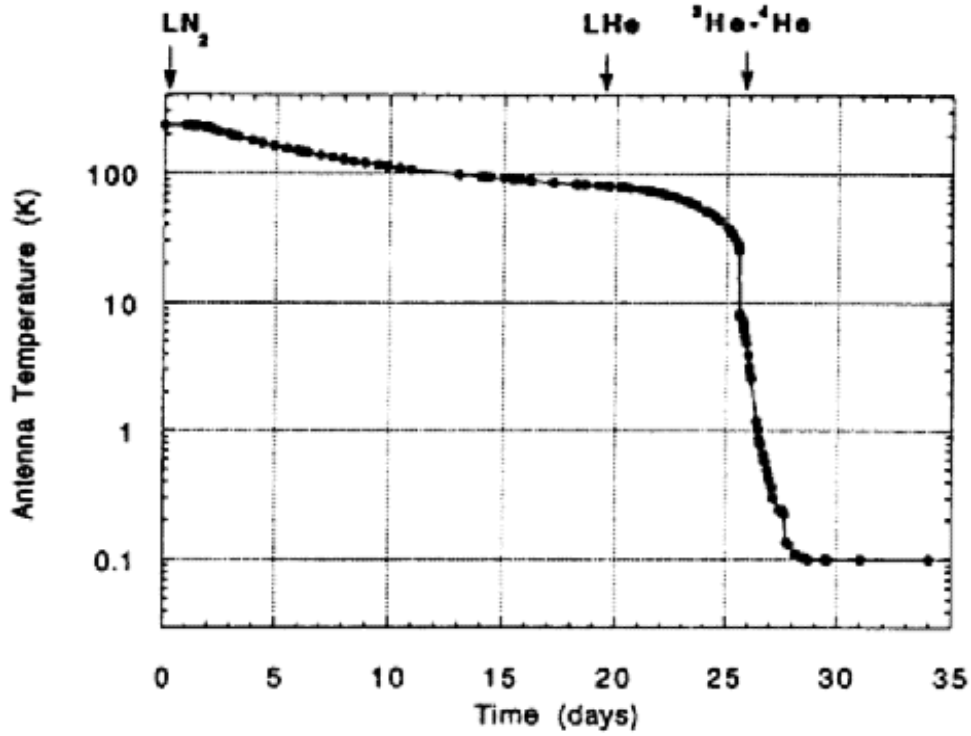


FIG. 4 – Temperature of the cylindrical bar versus time during the cooldown. The arrows indicate the main cryogenic operations, described in the text.

•

8000 liters of liquid Nitrogen +
5000 liters of liquid Helium

Nautilus Readout

- **Capacitive transducer** resonating at the antenna frequency. Gap : 49 micron (Explorer 10 micron). Voltage ≈ 300 Volt. Mode splitting :

$$\Delta f = f_a \sqrt{\mu}$$

where μ is the ratio between the effective masses of transducer disk and the bar.

$$f_a = 915.8\,Hz$$

$$f_- = 906.96$$

$$f_+ = 922.46$$

- Superconductive transformer to match the impedance transducer- SQUID .

$$f_{electric} = 1780\,Hz$$

Gain monitored by means of a known injected flux

$$f_{calibration} = 916.15$$

Nautilus Readout

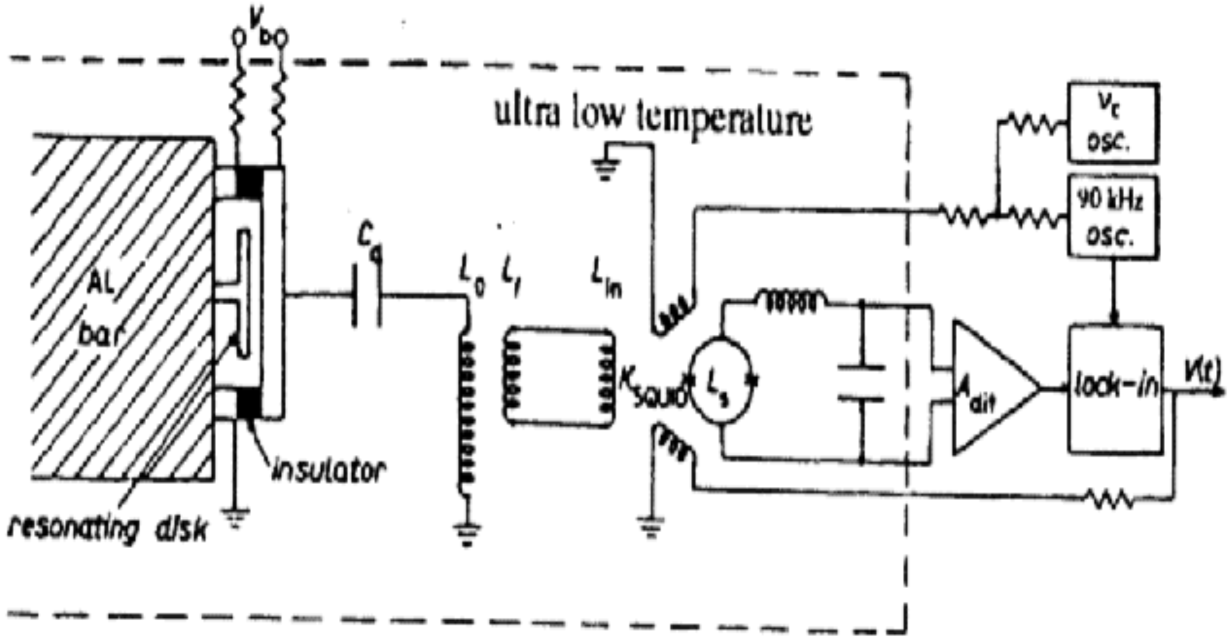


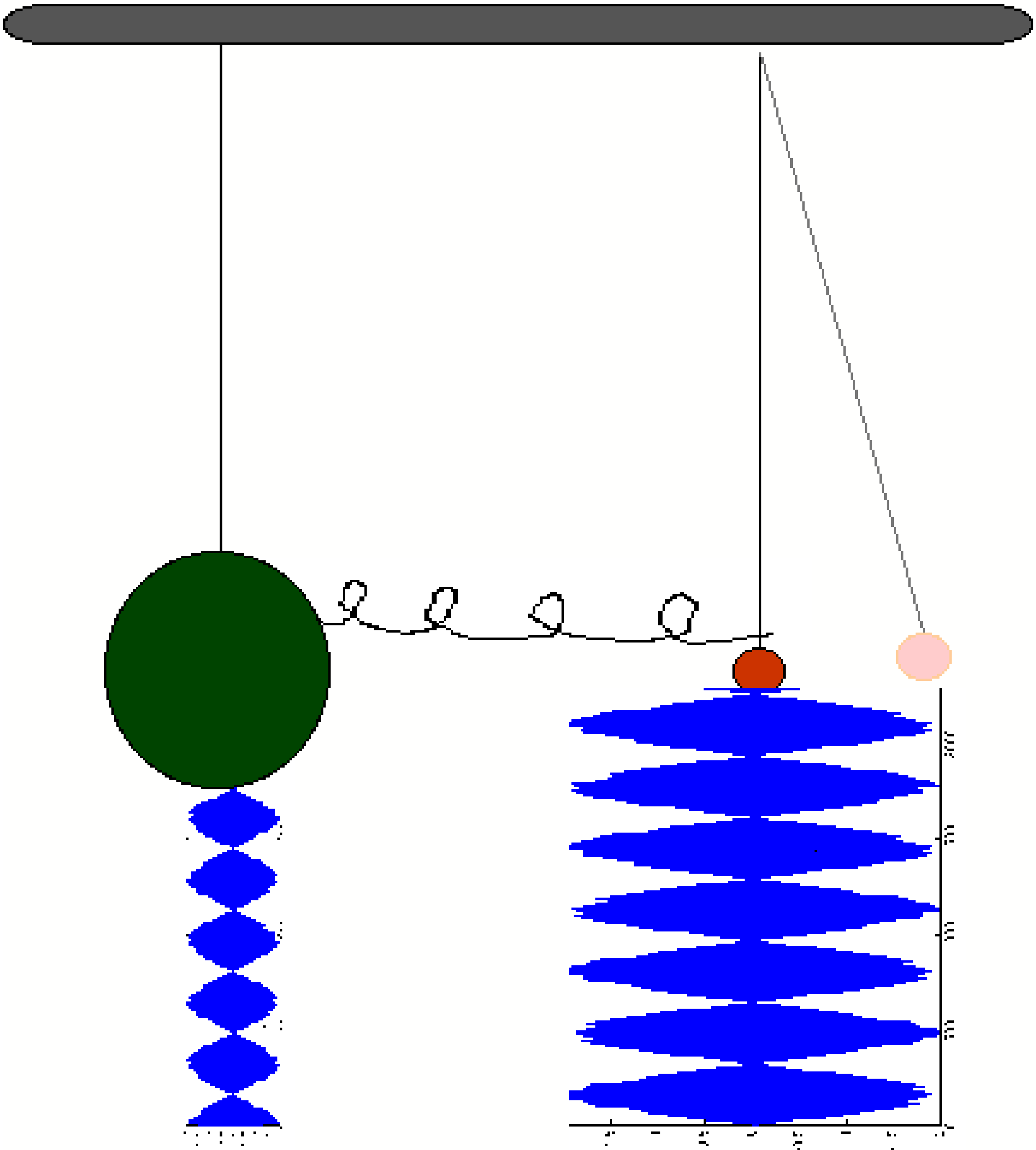
FIG. 6 – Schematic of the electronics of the experimental apparatus. The vibrations of the bar are converted into electrical signals by a resonant capacitive transducer and applied to the SQUID amplifier by a superconducting transformer. The output signals from the SQUID instrumentation contain information on the vibrational state of the antenna and can be properly processed.

• Calibration : two methods :

1)a second capacitive transducer mounted at the opposite end of the bar

2) piezoelectric ceramic glued on the bar near the central section

Antenna and transducer as coupled pendolus



• **Beats** due to the two resonating frequencies

• the first maximum on the transducer should have a **delay ≈33 msec respect to a delta like excitation**

Nautilus Signal Acquisition And Filtering

• the signal is read using an ADC sampled at 220 Hz (fast channel)(**5KHz from Feb 2000**).
Using aliasing is possible to study the signal in the 900 Hz region.
We use mainly the **"adaptive matched filter"**
(P Astone et al. Nuovo Cim 20 C 1997)
to extract a delta-like signal from the noise
The optimum filter parameters are computed from the noise distribution in a time interval ± 1 h.

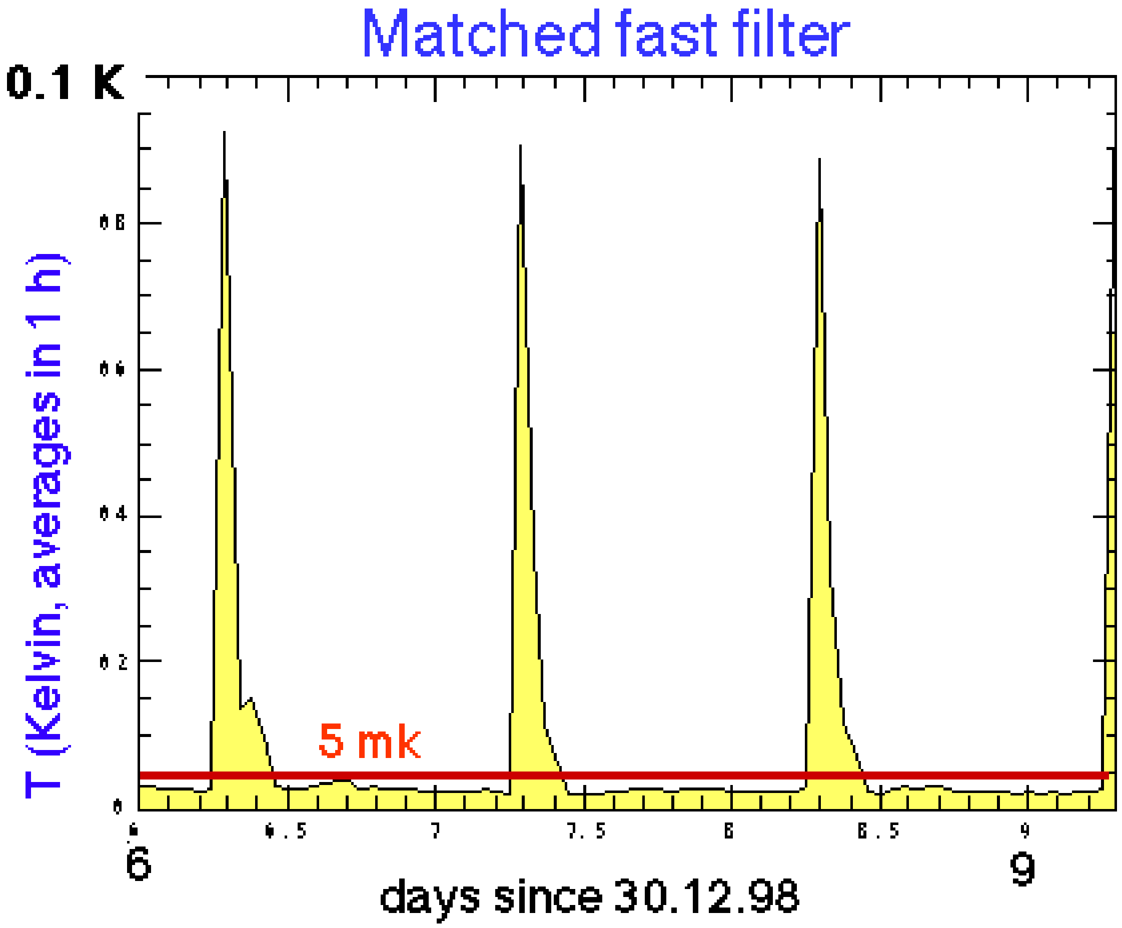
• GPS and Radio clocks used for timing

• The are also **lock-ins** to extract directly the Fourier components at the mode frequencies. The readout is every 0.29 sec.

Nautilus 2(June 1998)

- **Modifications** to the mechanical structure and to the final thermal connections ("spaghetti" Cu connections instead of soft multi-wire copper braids)
Spaghetti solution already used from the Auriga group in Legnaro (Italy)

- **Remarkable improvements** on the stability of the detector. Noise level constant without **jumps.**
Residual periodical jumps due mainly to the periodical filling of a chamber with He



Matched fast filter
0.1 K
T (Kelvin, averages in 1 h)
5 mk
6
9
days since 30.12.98

Nautilus Spectral Amplitude Sensitivity

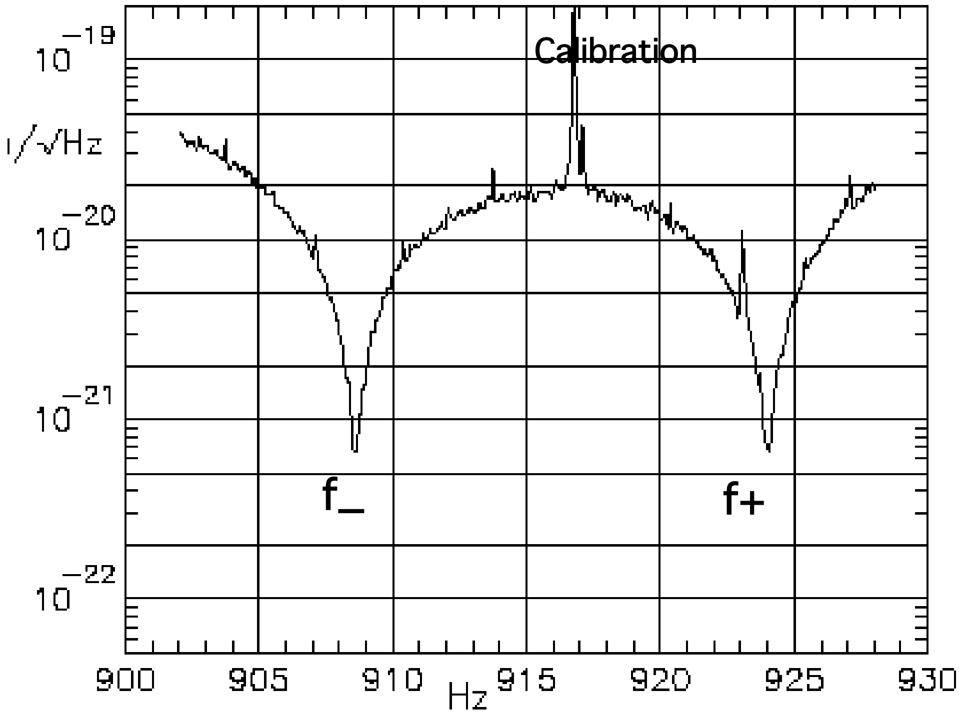


Figure 1: NAUTILUS experimental spectral amplitude sensitivity at 0.1 K.

- Gravitational wave stochastic background limits on Phys Lett B 385 (1996). Limits based on the cross correlation with Explorer in Astr. Astroph 1999.

Nautilus Brownian noise measurement

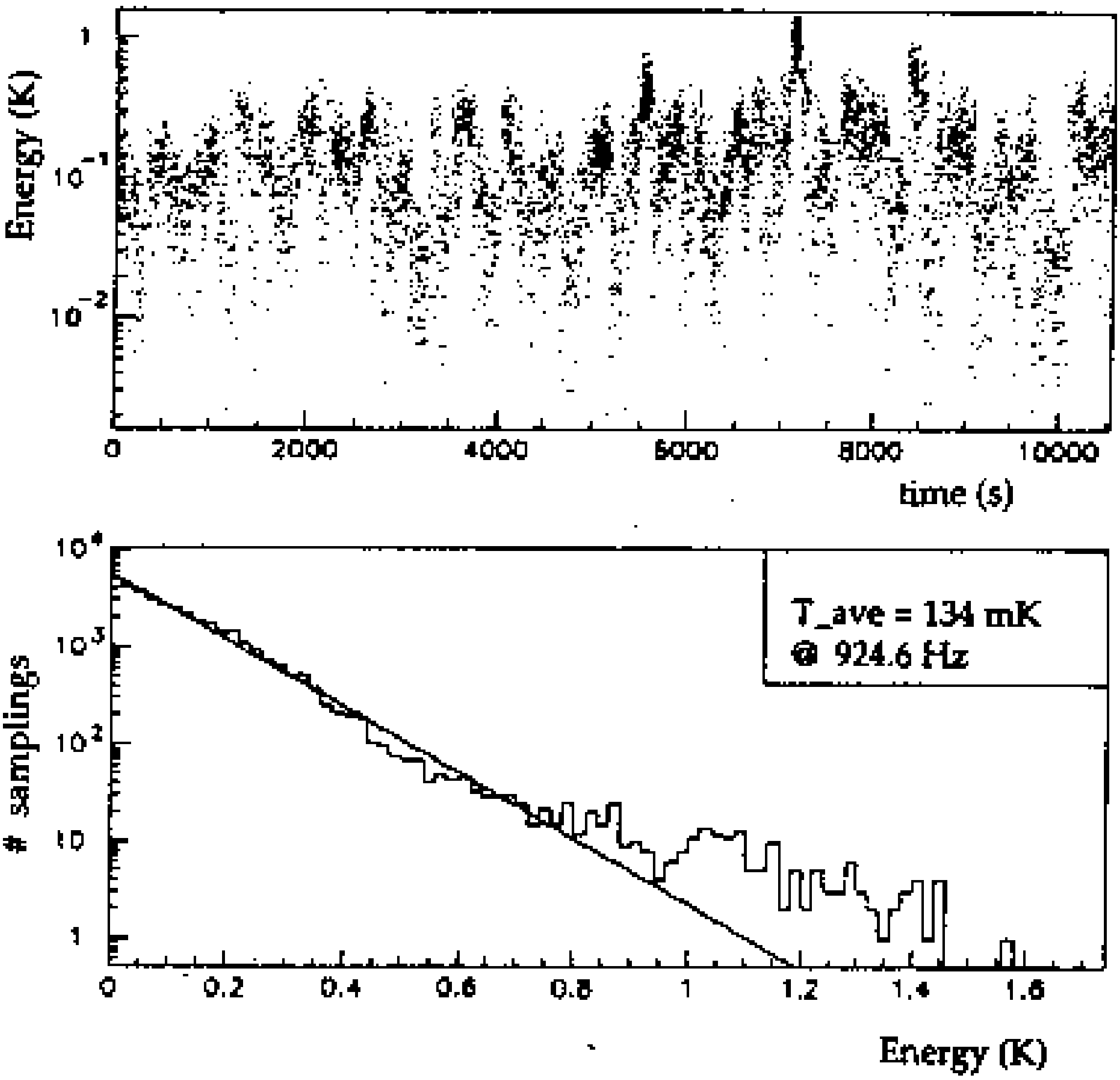


FIG. 9 – Measurement of the Browniian noise: a) history and b) distribution c vibration energy of the + mode in a three hours period. The average energy agreement with the thermodynamic temperature of the bar.

Nautilus noise measurement

- **Note the units : meters!!!!!**

(distance between the two faces)

- Filter optimized for very short signals

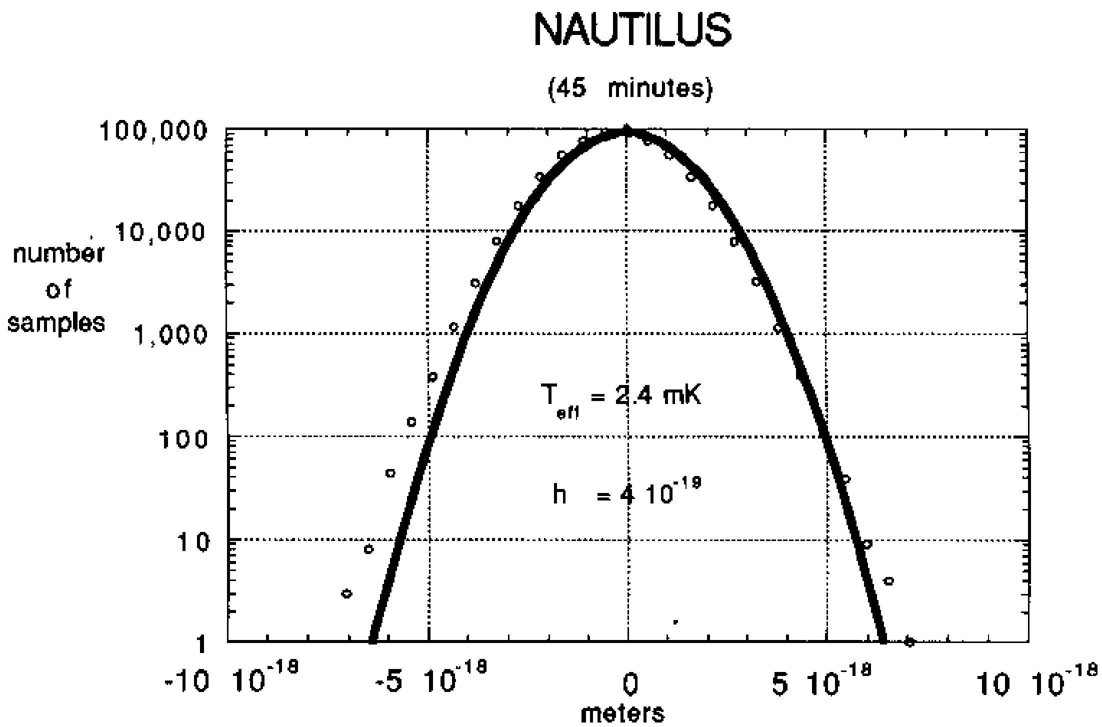
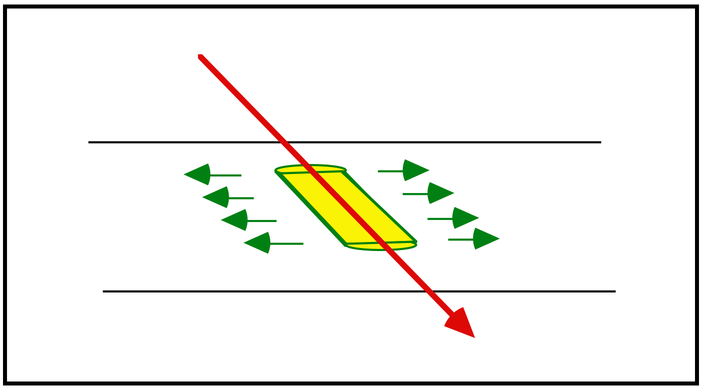


Fig.1
The noise distribution after optimum filtering. The continuos line is a gaussian fit.
T_{eff} = 2.4 mK for h=4 10^{-19}

Cosmic ray in the bar:

Thermo Acoustical Conversion

• under the hypothesis that all the ***deposited energy***, is converted in a ***local*** heating of the medium:



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

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

γ is the Gruneisen "constant"

Y =Young module, C= specific heat, α thermal expansion coefficient

Cosmic ray in the bar:

Thermo Acoustical Conversion

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

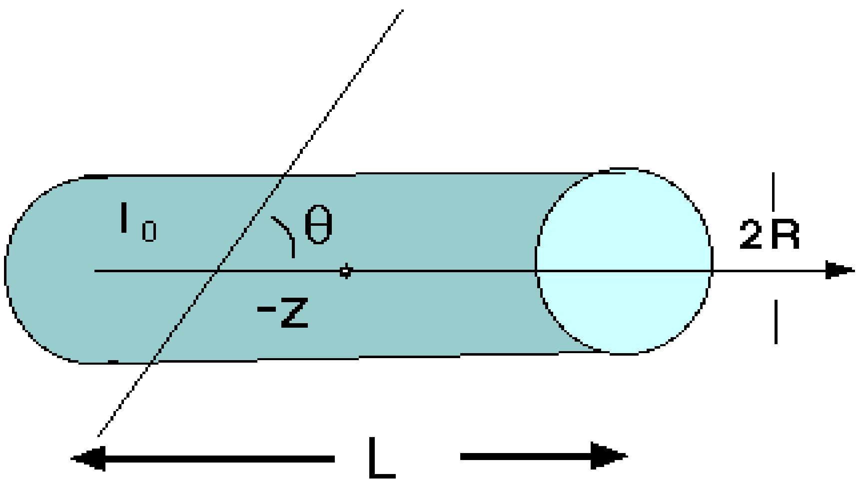
Allega A.M. & Cabibbo N. Lett Nuovo Cim 38 (1983) 263-

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

G_n form factor

- in the case of a cylinder and at the first order in R/L (Barish-Liu Phys Rev Lett 61 1988)

$$T_{eff} = 2.75*10^{-9}\left(\frac{dE}{dX}\right)^2\left(\sin\left(\frac{\pi z}{L}\right)\frac{\sin\left(\frac{\pi l_0\cos\theta}{2L}\right)}{\frac{\pi R\cos\theta}{L}}\right)^2$$



- verified without the R/L<<1 condition and for non axial tracks by Babusci,Quintieri, Raffone with analytic and numerical methods (ANSYS)

Cosmic ray in the bar:

Thermo Acoustical Conversion

- Pioneer work

Beron Hofstander piezoelectric disk on electron beam (Ph.Rev.Let. 23 184 (1969)

- The model with the bar has been roughly checked in 3experiments on a beam

1)Grassi Strini Tagliaferri (J. Appl Phys 51 1980)

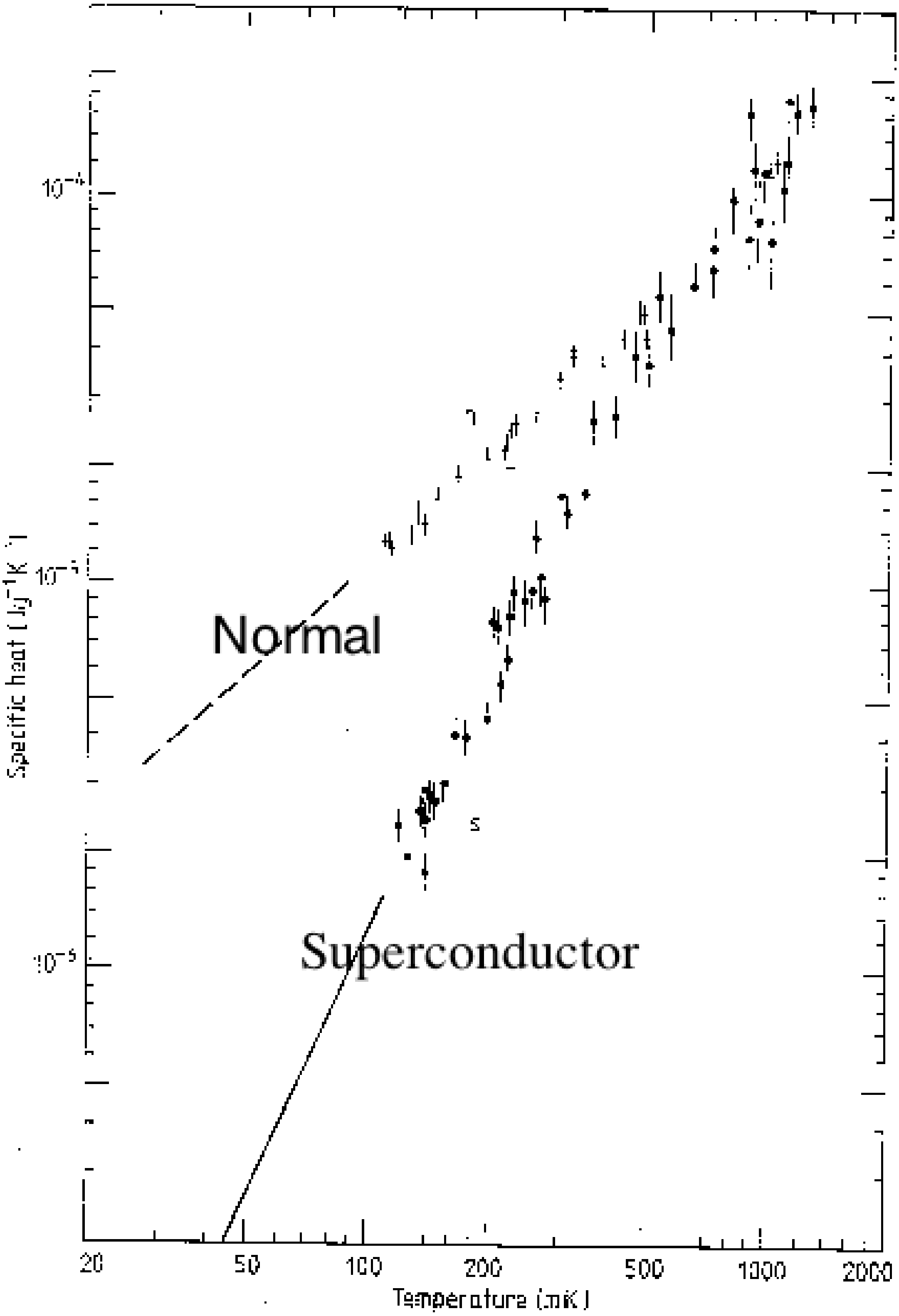
2).Jona Oberski et al (Nikehf, Rev Sci Instr 2000)
measured conversion factor 7.4 ±1.4(nm/J)
theoretical 10.0

3)Bressi Carugno Conti Onofrio : no signal

- Open question: is the Grunesein "constant" really constant ? (C==>>0) in superconductor Al

- Local heating due to the ionization? Transition superconductor Al to normal?

Specific heat at low temperatures for the bar



•The passage of a particle **should destroy the Cooper pairs** (0.34 meV binding energy in Al). Transition to normal state.

Thermo Acoustical Conversion: The Nikhef experiment

- 0.76 GeV electron beam 0.01 Joules/burst

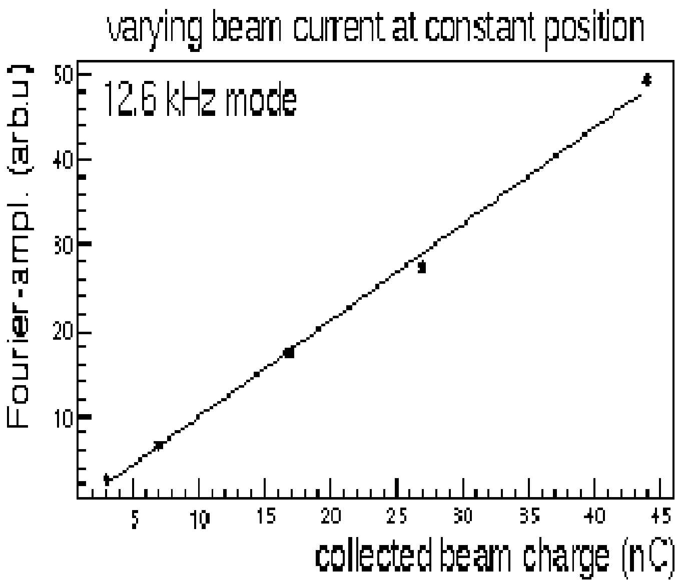


Figure 7: Correlation between the Fourier amplitude of the 12.6 kHz vibrational mode and the beam charge. Data points (*) and straight line fit.

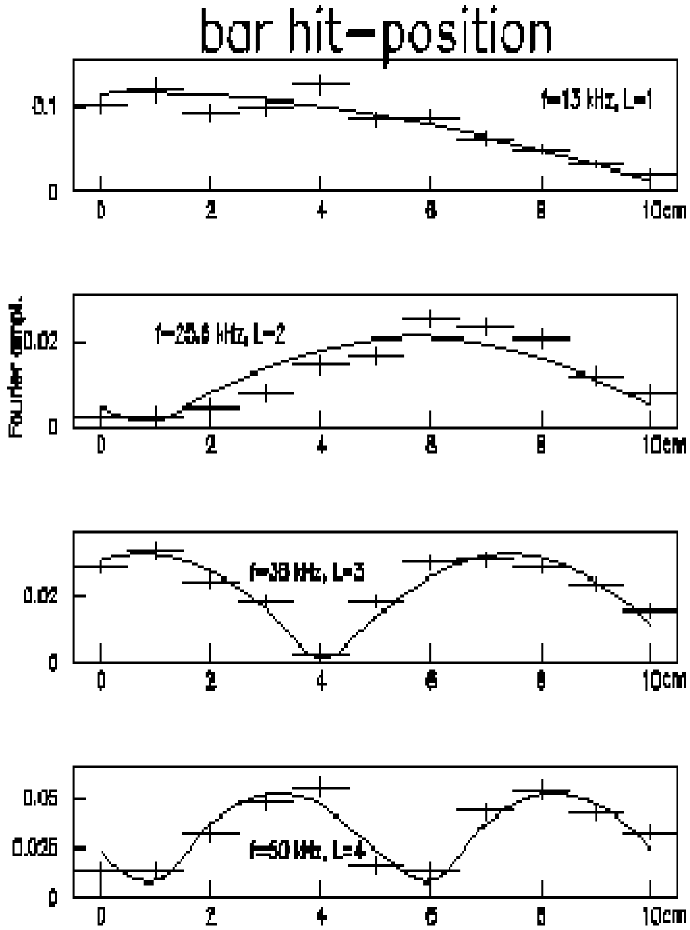


Figure 8: The measured, unnormalised Fourier amplitudes (+) and model calculations (–) as a function of the beam hit position along the cylinder axis for the four lowest longitudinal modes of bar BC.

Cosmic rays:
a few remarks

• **Cosmic Rays at Sea Level** are due to particles produced in the interactions of a Primary (Proton or Nuclei) in the Atmosphere

• **Energy Spectra** (of Primaries) in the range of energies up to 10^{20} eV

$$\frac{df}{dE} = 1.7E^{-2.67} cm^{-2} \sec^{-1} sr^{-1} GeV^{-1}$$

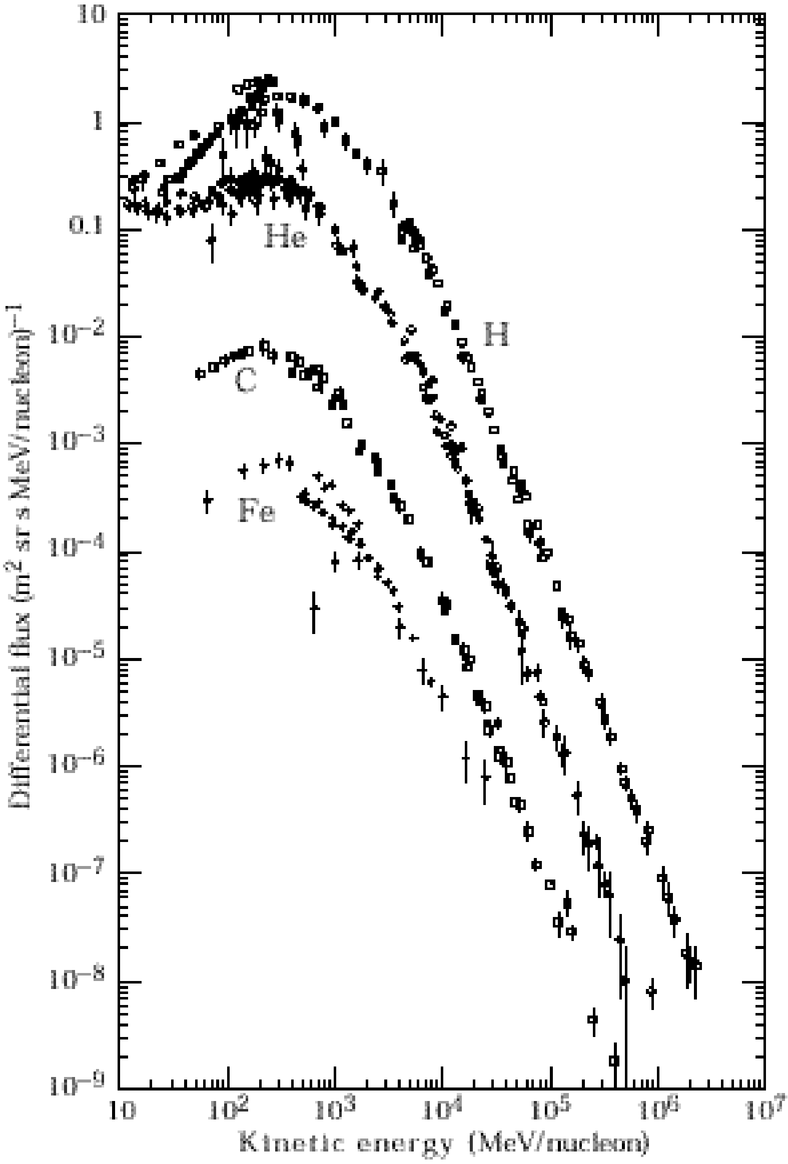
$E<10^{15}$ eV

• The Cascade is a **Complex Phenomena** not fully understood .
Complicated Montecarlo Calculations are in a continuos Development. The detailed Simulation of the Cascade is **Difficult.**

• At the sea level three main components : electrons (+ photons), muons, hadrons.

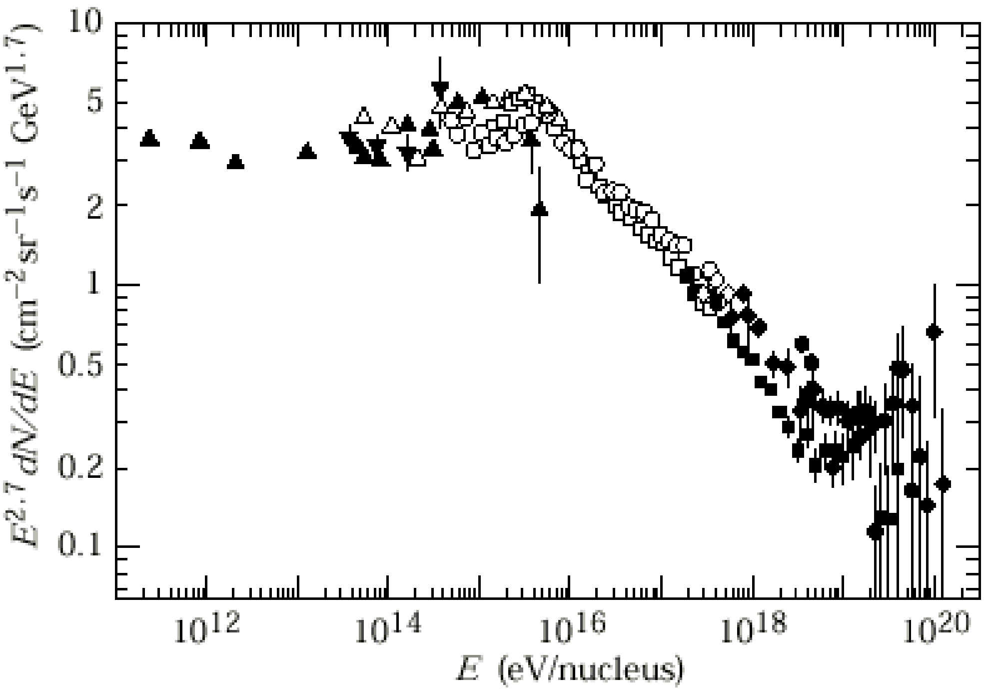
• At energies < 10^{15} eV the cosmic ray are probably due to supernovae.

Cosmic rays: composition (low energies)



Differential flux (m^2 sr s MeV/nucleon)$^{-1}$
Kinetic energy (MeV/nucleon)
H
He
C
Fe
10
1
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}

Cosmic rays: the knee



• **The knee is not explained,** several hypothesis:
1) change of composition
2) different production respect to low energy
3) unexpected phenomena

• Most of the cosmic ray events in Nautilus are **coming from the knee region**

Cosmic rays:
rate of events in the bar

• The three components (muons,hadrons,EAS) arrive together. But for purpose of simplicity the three components have been treated separately in the calculation for the effects on a resonant bar antenna.

• The **maximum energy flow** is in the core of the shower, near the direction of the primary.

• the calculations up to now are done for **single components**
large uncertainty for events having many particles (for example multi-hadrons) due to incertitude in the experimental measurements and in the simulations

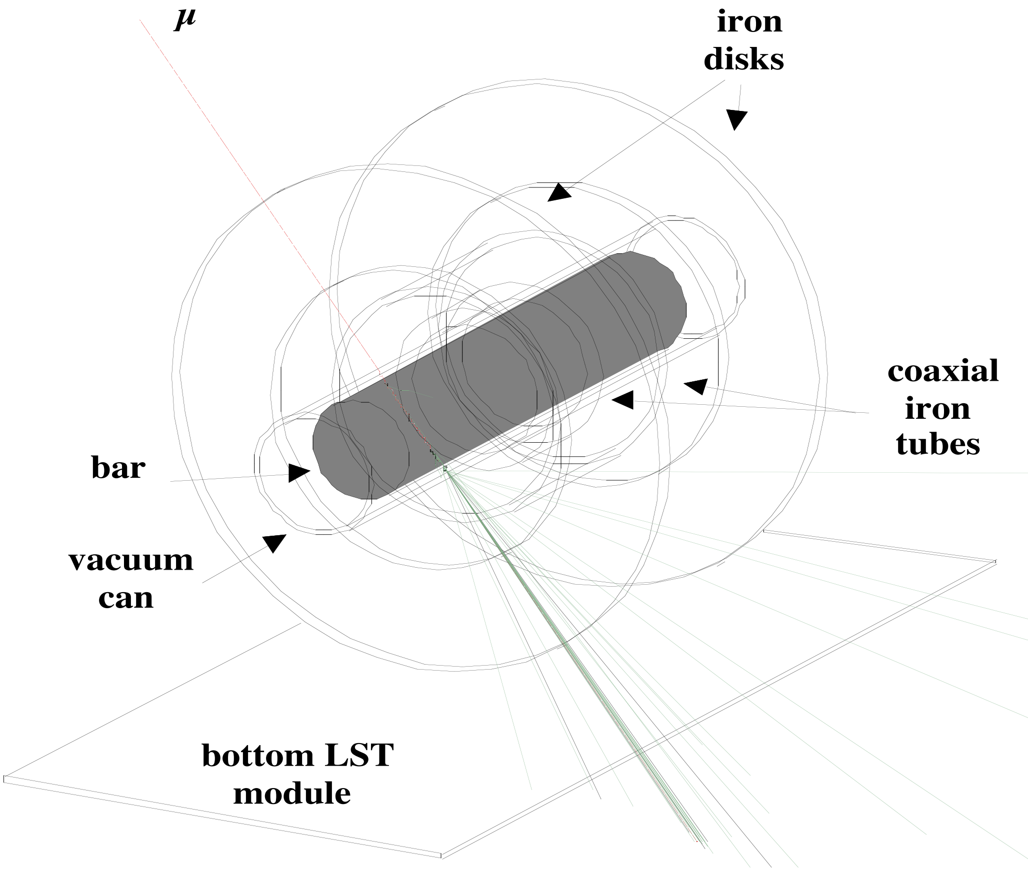
• Calculations

E Amaldi G Pizzella **Nuovo Cimento 9C 1986** ***(analytic)***
F Ricci **NIM A 260 491 (1991)** ***(Montecarlo -muons)***
J. Chiang et al (Stanford group) **NIM A 311 (1992)**
(MC muons - single hadrons)
E. Coccia et al (Nautilus group) **NIM A 355 (1995)**
(MC muons -single hadrons, multi-hadrons, EAS)

• recently we have done a full calculation using the Corsika Monte-Carlo+Geant (***single hadrons,multi-hadrons)***

Cosmic ray : rates in the bar

• Cern GEANT package to simulate the muon-hadron interactions in the bar with the full geometry



Cosmic ray : rates in the bar (events/day)

E kelvin	muon	EAS	Hadrons	Total
10^{-7}	1540	1890	-	8630
10^{-6}	155	323	-	941
10^{-5}	12.7	50	24.2	87
10^{-4}	1.2	7	3.0	11.2
10^{-3}	0.18	0.8	0.33	1.3
10^{-2}	0.002	0.1	0.05	0.15

Cosmic ray : rates in the bar (EAS)

• **particularly important** (we see now this signal!)

• Analytic rate calculation based on the following assumption:

1) $f(N > N_0) = 0.41 N_0^{-1.32 - 0.038 Log(N_0)}$ ev/sec-1 (Cocconi, 1961), in ≈ agreement with our data
N_0= number of particles /m2

2)**No particle absorption** in the bar (radiation length much less than the radiation length of the atmosphere). Actually we see a small increase in the number of particles (critical energy in Aluminium smaller than in air)

Cosmic ray :
rates in the bar (EAS)

3) dE/dX =2.2 MeV gr^{-1} cm^2 (electrons having energy equal to the critical energy in Al)

4) **Barish-Liu formula** adding the contribution from the different particles.
This formula is for local heating at the t=0 time
But for **EAS uniform heating at t=0**.
For a very thin bar this effect gives a -20% correction

==>> All the calculations for EAS are with a very large uncertainty

Cosmic ray : signal amplitude in the bar (EAS)

- average EAS signal computed using

$$< T >= \frac{\int_{N\min}^{N\max} \frac{df}{dN} N^2 T_1 dN}{\int_{N\min}^{N\max} \frac{df}{dN} dN} = 8 mKelvin$$

$$N_{\min} = 600$$

$$N_{\max} = \infty$$

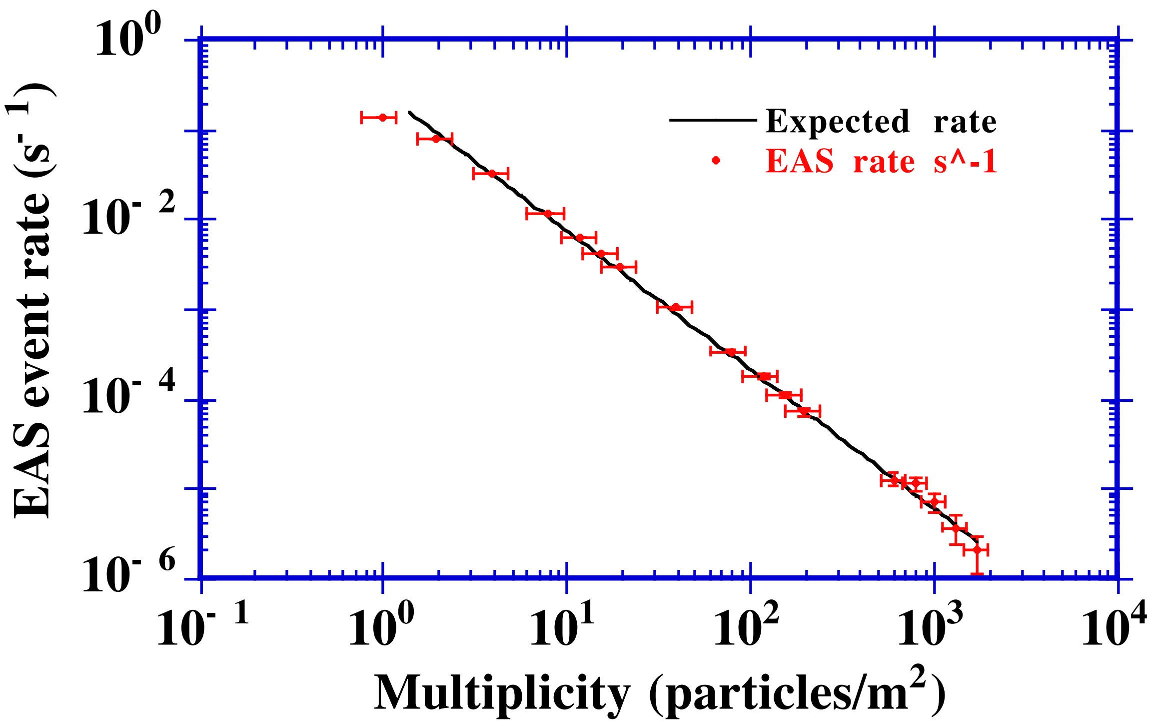
- where T_1 is the signal (in temperature) of a single average particle $T_1 \approx 4.7 * 10^{-10}$ Kelvin

The Nautilus Cosmic Ray Detector

- 116 3 cm^2 streamer tube chambers of the MACRO type 3 layers on the top 4 on the bottom. Only analogic readout (1 channel/tube).

One ADC /tube - Saturation at about 500 particles

To increase the maximum measured multiplicity in 15 chambers there is a second ADC with an attenuated signal (1/10)

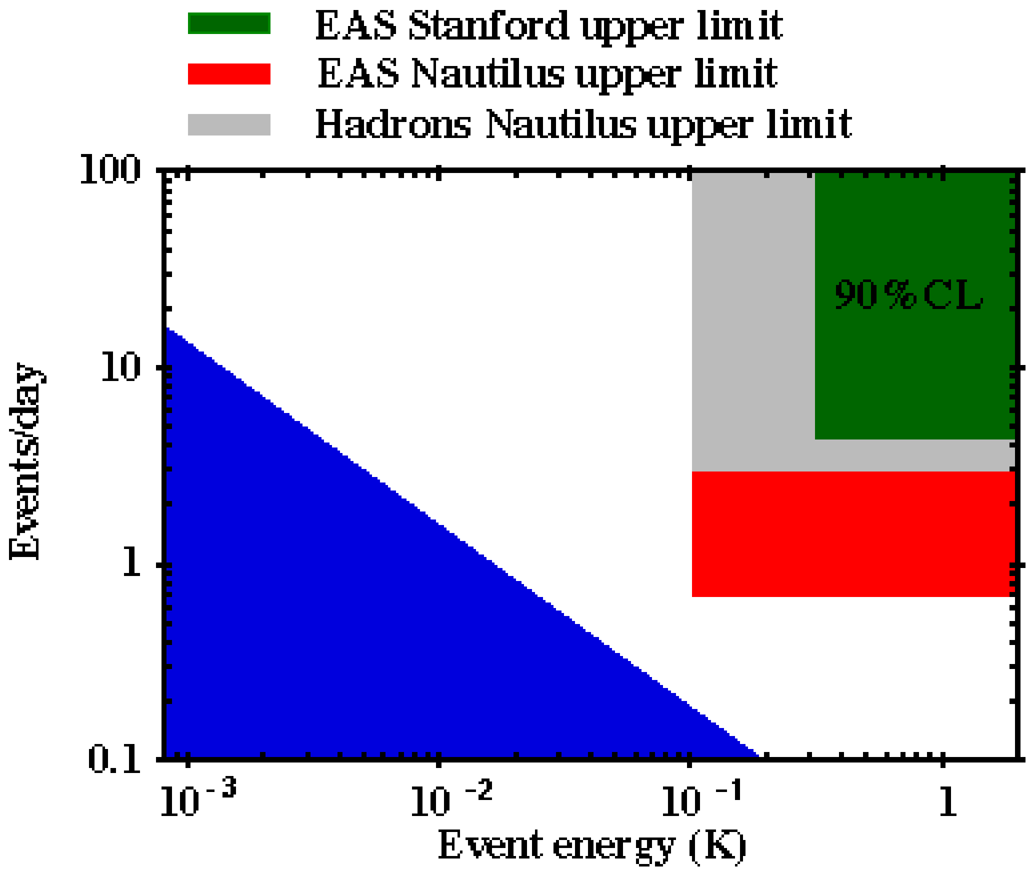


Previous Searches

- usually done looking for events in coincidence
- Gravitational wave event ==>> threshold

(50 mkelvin or more)

- low expected rates



A. Marini et Al. OMNI-1 Proceeding, Brazil 1996

Other Experiments:

Ezrow , Wall, Weber, Yodh **Phys Rev Lett 24 945 (1970)**

Moskowitz : **Grosmann meeting on General Rel. (1986)**

Zero-Threshold Search for low amplitude signals:

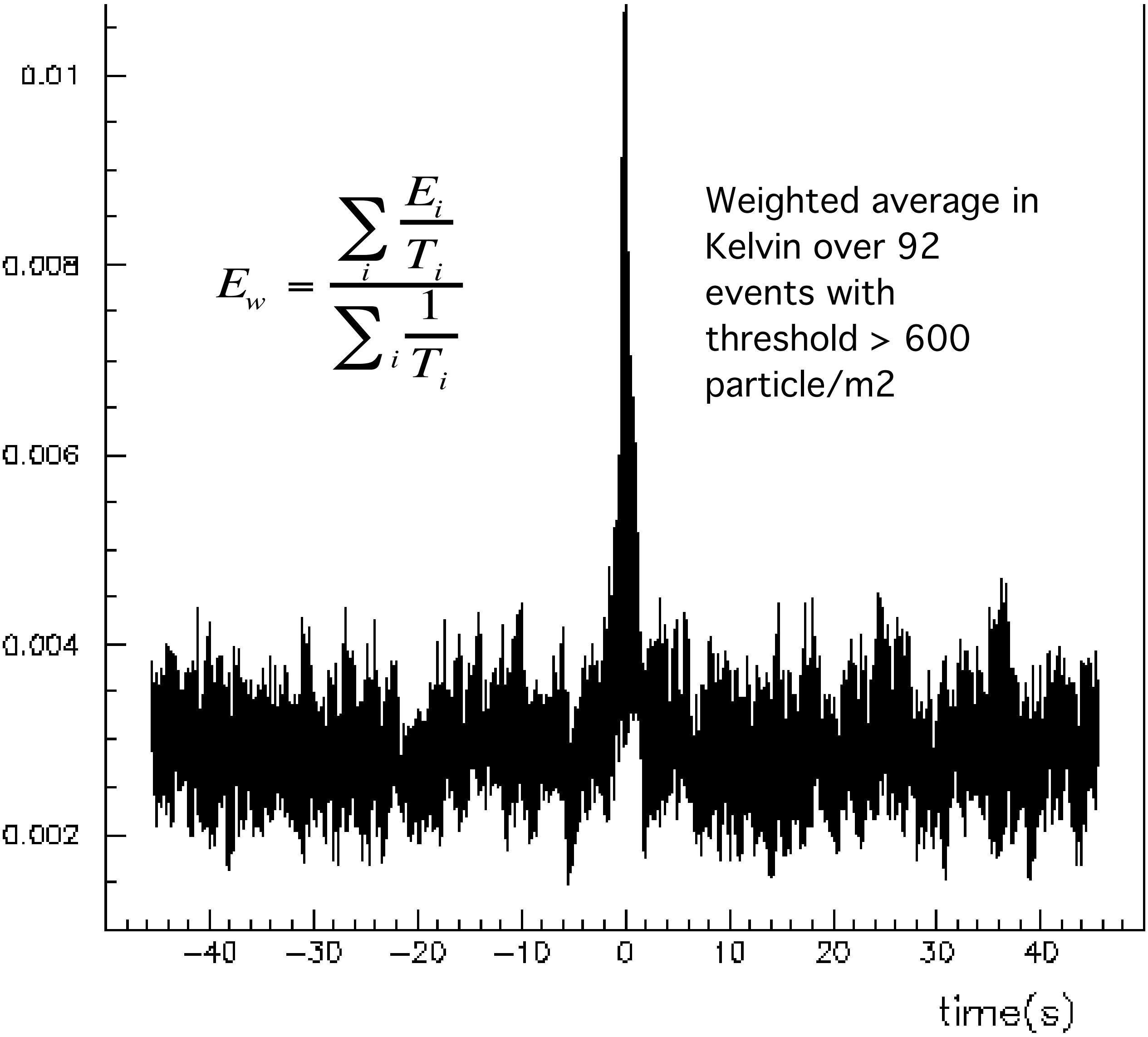
• Selection of high multiplicity events >600 part/m^2

• Average of all the signals respect to the cosmic arrival time (we use the output of the fast matched filter with 0 threshold, 220 samples/sec)

• It is possible to shows that this method has better sensitivity than the "event" method for the expected "small" signals.

• **cuts was decided before data analysis**

Zero-Threshold Search Results

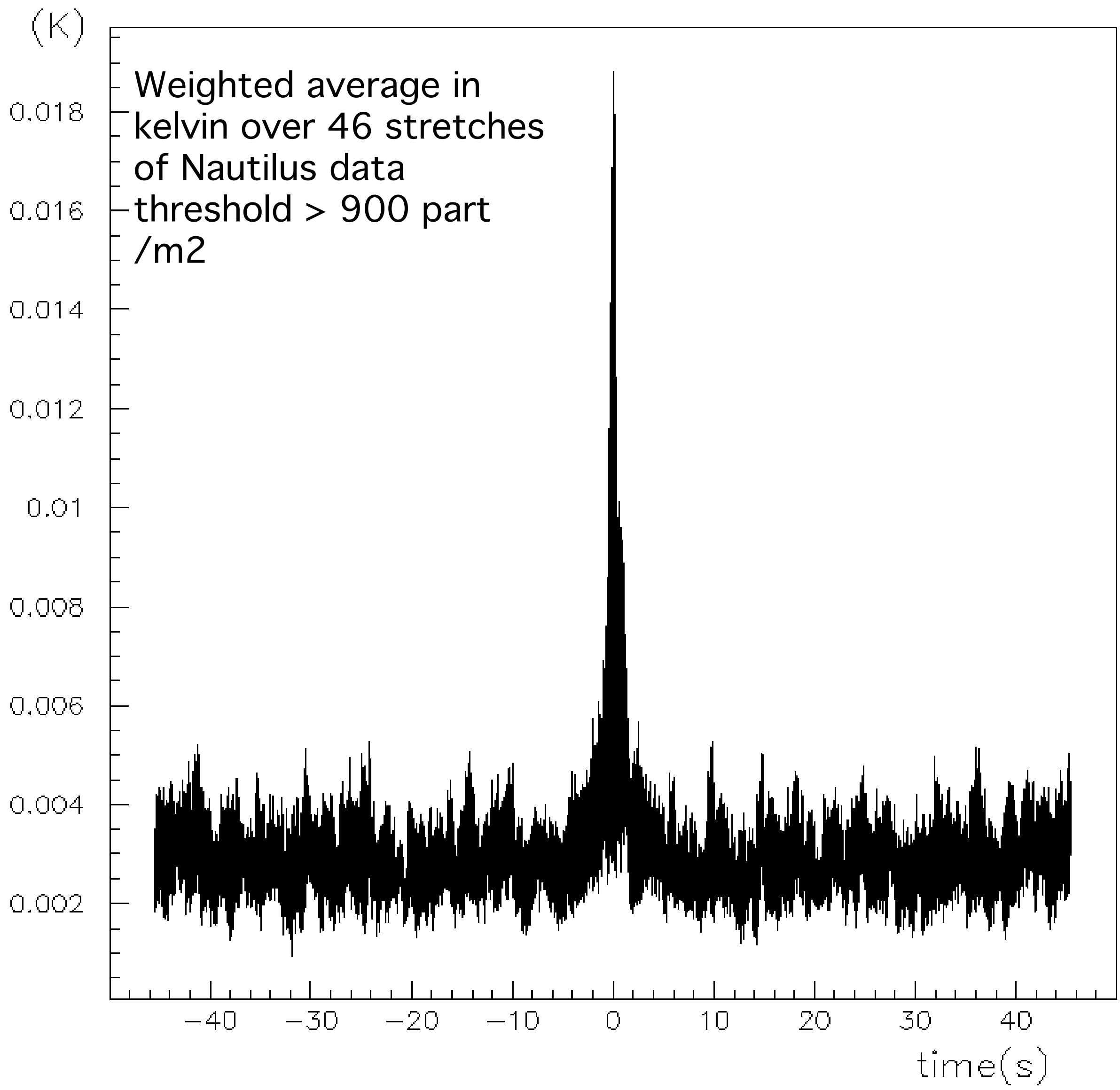


$$E_w = \frac{\sum_i \frac{E_i}{T_i}}{\sum_i \frac{1}{T_i}}$$

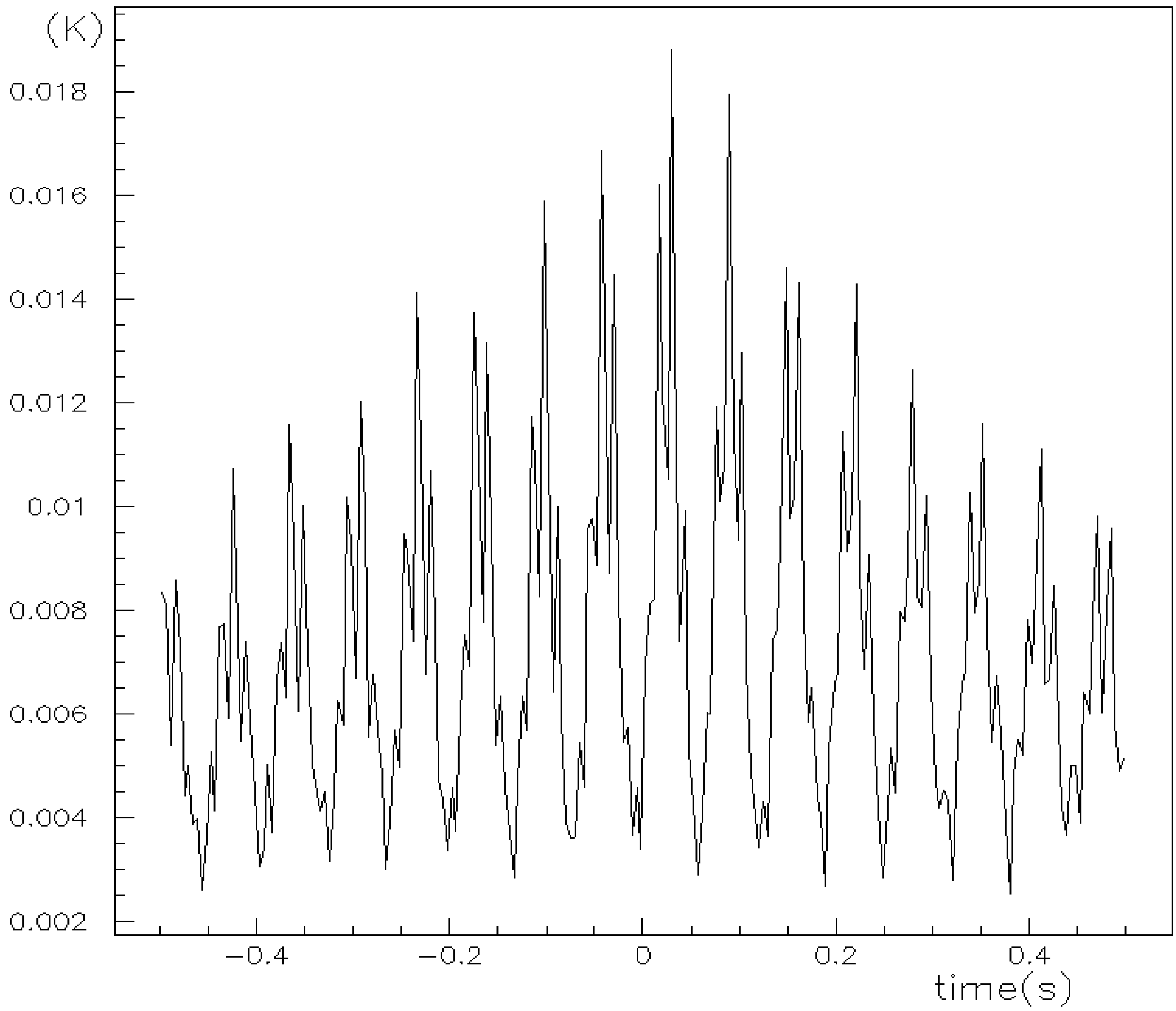
- Ti is the noise temperature around the cosmic ray events. **Cut Ti < 5 mK==>> 47.7 days**

- **Similar results** with the other filters :ZOP-Wiener, but less sensitivity

Zero-Threshold Search >900 part/m²



Zero-Threshold - Zoom



- **The periodicity** is in ***good agreement*** with the beat period due to the two resonance modes (64 msec)
- From the theory of the filter the envelope depends on the time as

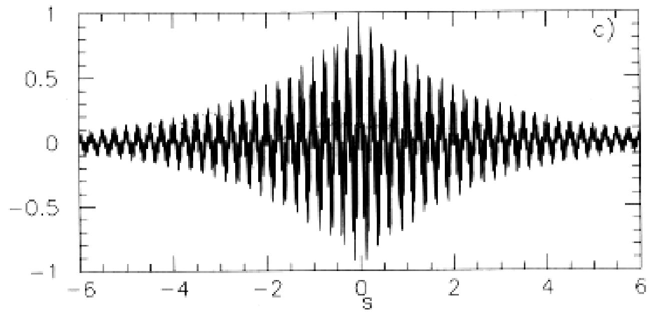
$$E(t) = E_0 e^{-2\beta_3 t}$$

$$\beta_3 = \pi \Delta f$$

Δf is the detector frequency bandwidth (0.24,0.30) to be compared with $\Delta f = 0.27 \pm 0.03$ (from β_3)

The theoretical response for a delta input signal

• See P Astone et al Nuovo Cim 20 C 9 (1997)
fast matched filter

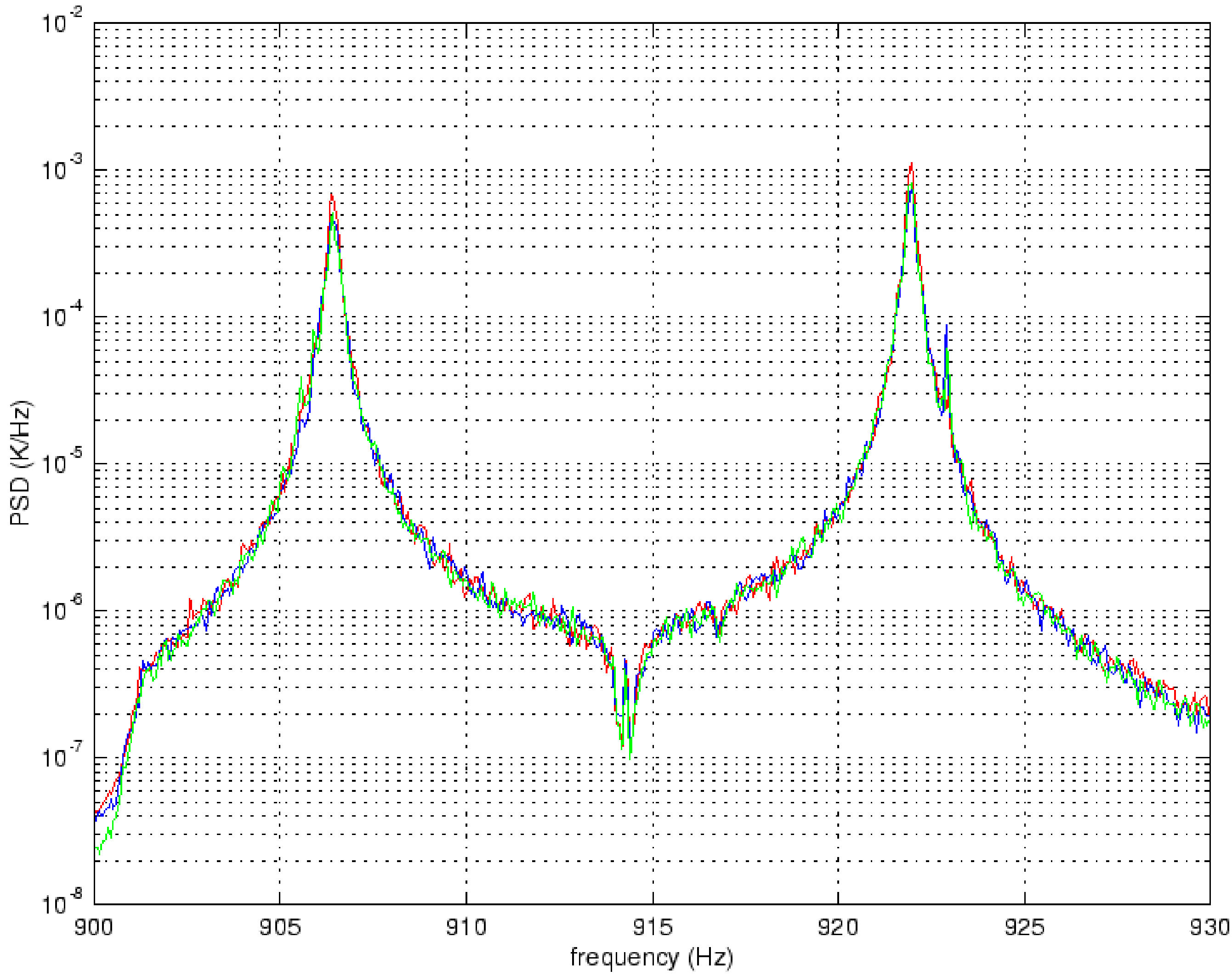


• The response is computed using a model for the antenna, transducer and the electrical circuit.

Some parameters (for example the resonant frequencies) could modify the results

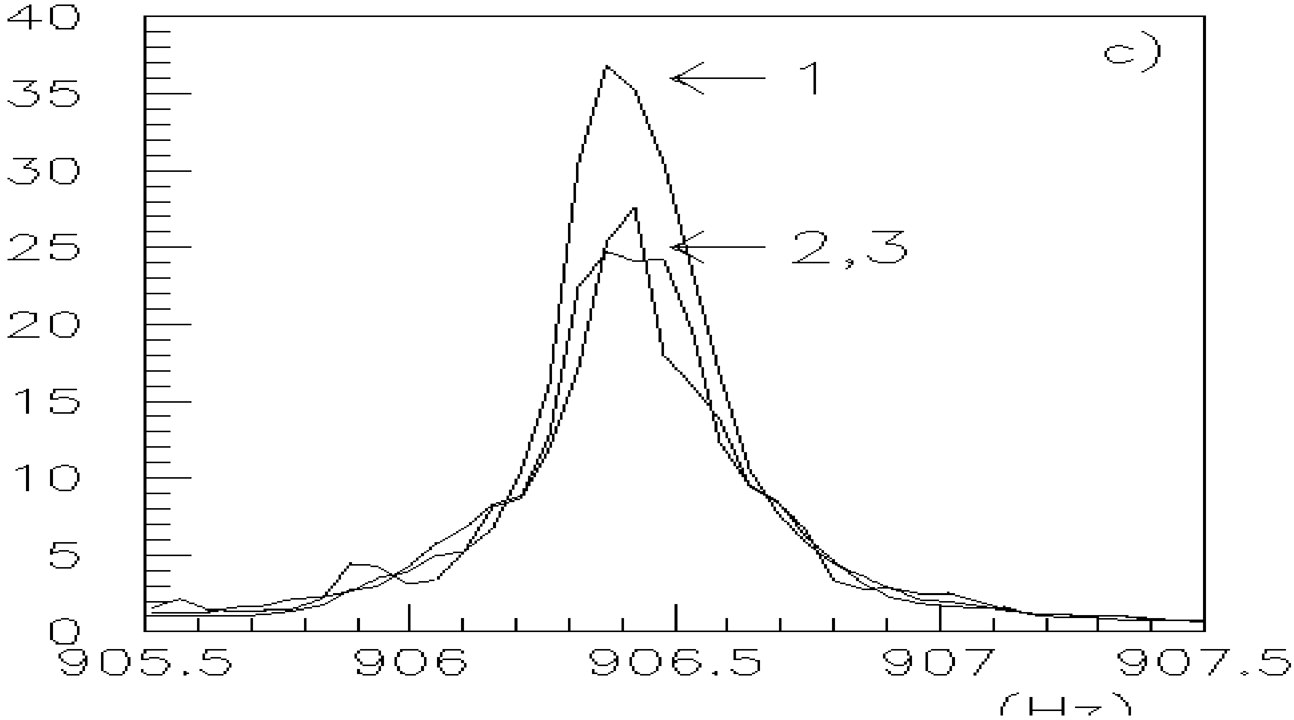
The Power Spectra

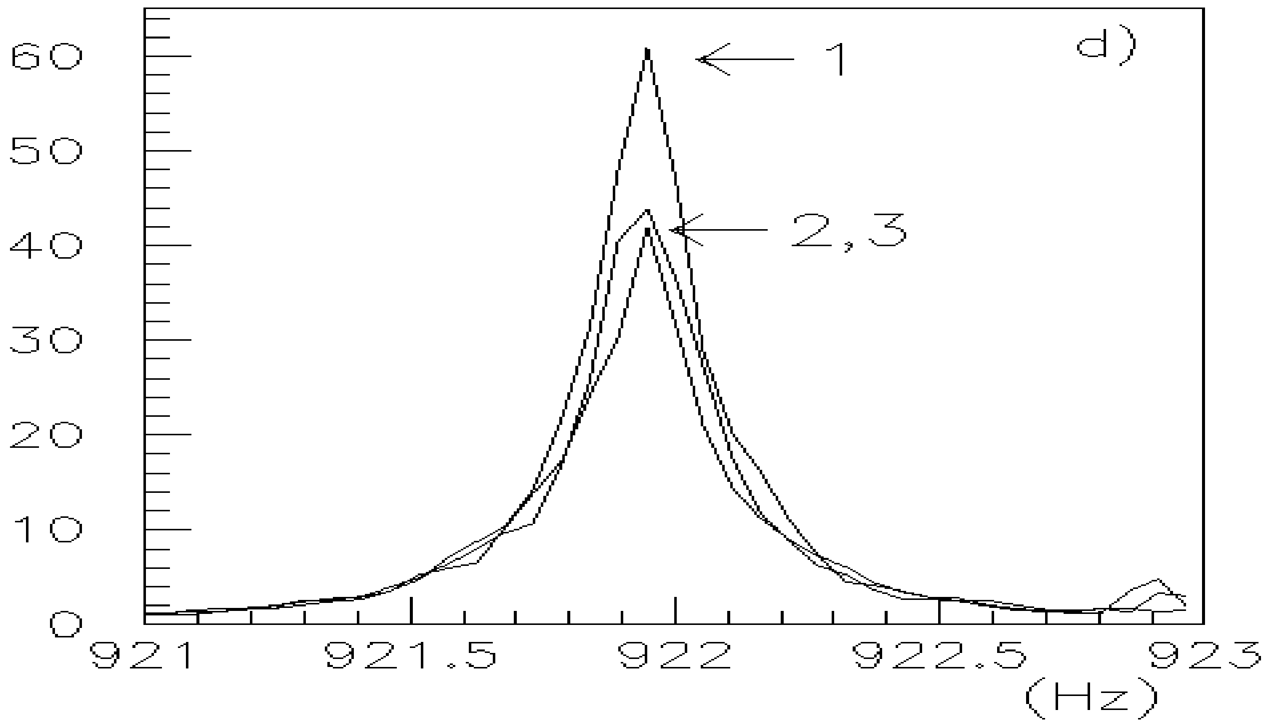
• As a check of the mechanical excitation (and not electrical) of the bar we have done the power spectra **in time (red)** , before the cosmic rays (-45 -26.8 sec) and after (26.8 45.4)



• The excitation is only at the resonant frequencies and not outside . The dip is due to the calibration signal

The Power Spectra Zoom

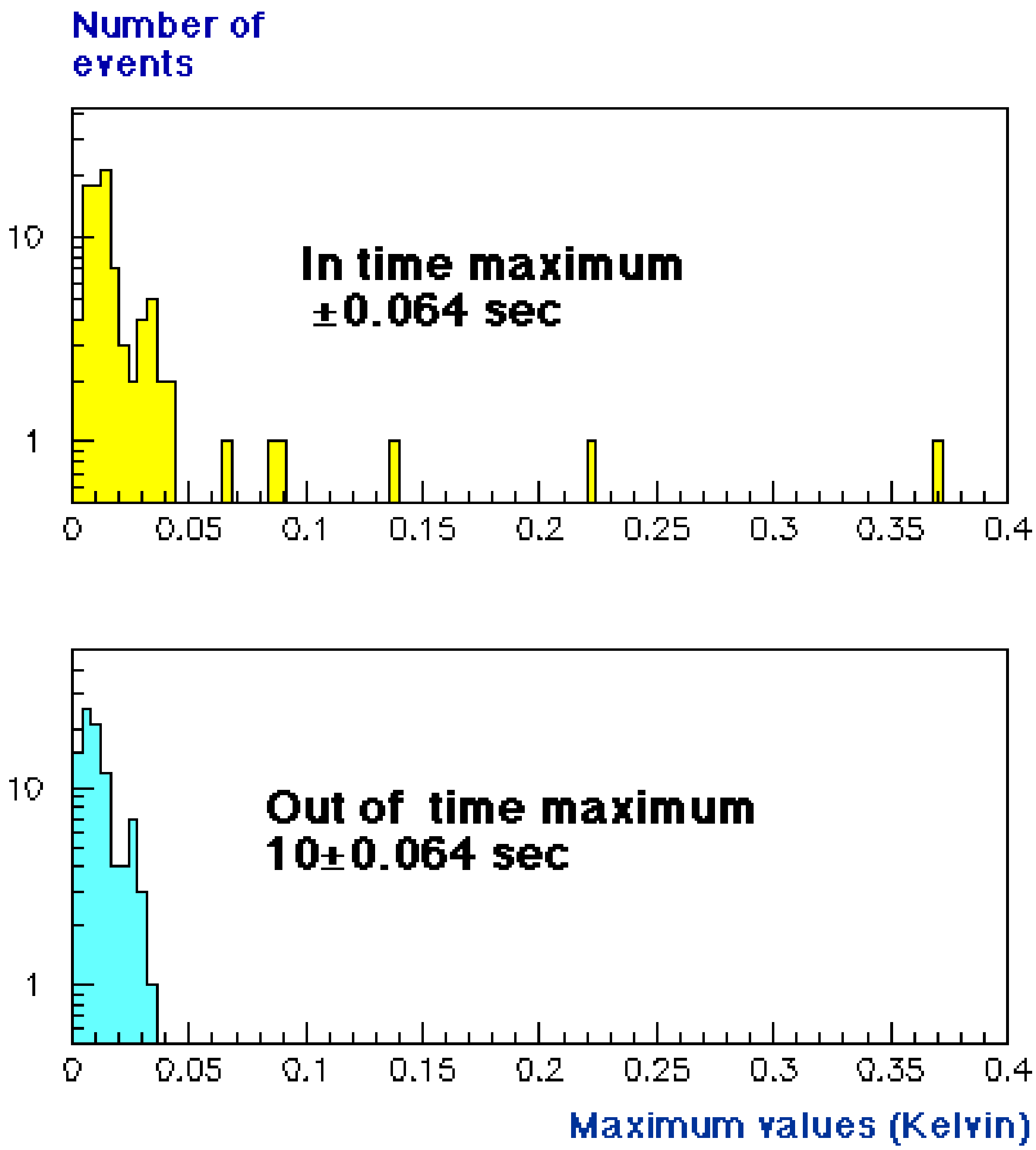




1= in time, 2 before, 3 after the cosmic ray

The Energy Distribution

• The signal is due **to several events** (not just one big event)



The Statistical Significance

• The statistical significance is computed from the RMS of the signals out of time

Threshold	noise mk	σ noise	excess mk	**σ in excess**
600 part/m2	2.89	0.43	8.6	**20**
900 part/m2	2.89	0.57	15.9	**28**

• eliminating the two largest events
==>> > 10 **σ in excess**

The Comparison with the expectations

- Large uncertainty due to :

1) **particle multiplicity** measurement ±30%
2) ADC and streamer tube **saturation** at high multiplicity
3) we can not measure the multiplicity **inside** the bar but only before or after
4) **hadrons** not taken into account

5) the procedure to add the **signal in phase** could suffer of the limited time precision (≈10 msec)

6) statistical fluctuations

Threshold	**excess mk**	**using the measured multiplicity**	**EAS theoretical calculation**
600±200 part/m2	**8.6-21**	**2.3**	**2.4-16**
900±300 part/m2	**16-31**		**8-26**

Electrical noise signal?

• **The signal is a mechanical signal in the bar**

• But an electric signal could induce a mechanical signal in the bar (via transducer) **"back-action"**

• For a single particle in a streamer tube we have typically 50 mV/ 50 ohm for 100 nsec

$$W = 5 * 10^{-12} \text{ joules}$$

for n=10000 particles and 7 layers:

$$W = 35 * 10^{-8} \text{ joules}$$

• It is a **very small** number compared to other possible sources of electrical noise around the antenna (pumps, lamps, various electronic devices..).

• We have done **tests using sparks** with energy E≈1 joule (>6 order of magnitude larger than the signal with 10000 particles)**==> No induced signal**

==>>All the test that we have done are **consistent with a mechanical signal only** :

Fourier spectra
Signal shape

Other possible sources of spurious signal

1) **SQUID sensitivity to charged particles**
Measured at the PSI (Muhfelder,Carelli et al) with electrons/proton beams. Protons : 54-280 MeV
Signals in the SQUID are seen starting at 10^3 protons/mm^2/sec
Squid loop area ≈ 1mm^2
==>> Interactions of EAS particles with the Squid should **not be a problem** (10^{-2} particles mm^2)

2) **Interactions of particles with the transducer**
(≈ 140 cm^2) gap = 49 μ E≈60 KV/cm
In principle the transducer could work as a spark chamber. But there is **vacuum!**

- **Recently we have found very big signals. The timing is good enough to exclude electric signal or a signal in the transducer (see later)**

The simplest way to explain the signal is just the one of the thermo-acustical model

But…….

But.......February 2000

• detection of the first very big event (10 kelvin)

• **then an analysis to search for *big signals*** using the event list that was posted for the IGEC (Internation Gravitational Collaboration)

• **Surprise**! In the 1998 data there was a **58 Kelvin** event!. This event was missed! The reason was due to the cut on the analysis requiring an average value of noise less than 5 mKelvin (this was done including the event).
There was also saturation of some electronics channels of the acquisition at 0.29 Hz.

• The livetime in this analysis is bigger (less restrictive cuts on the antenna noise)

The "big" event (1998)
(58 Kelvin ==> 87 TeV)

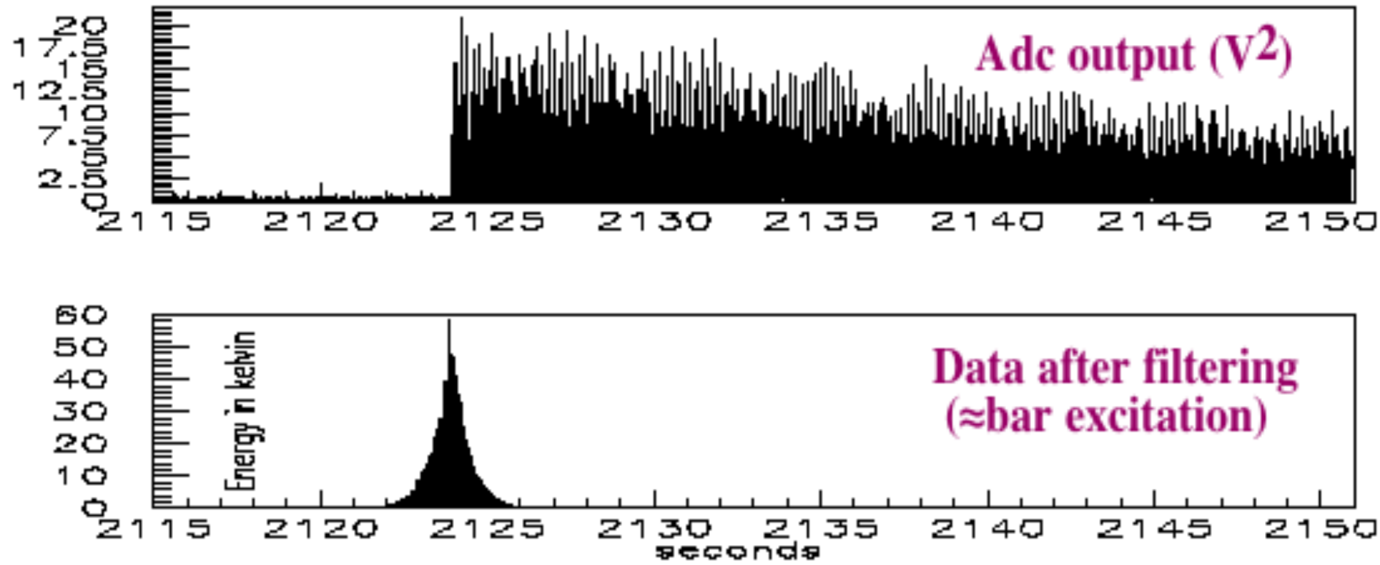
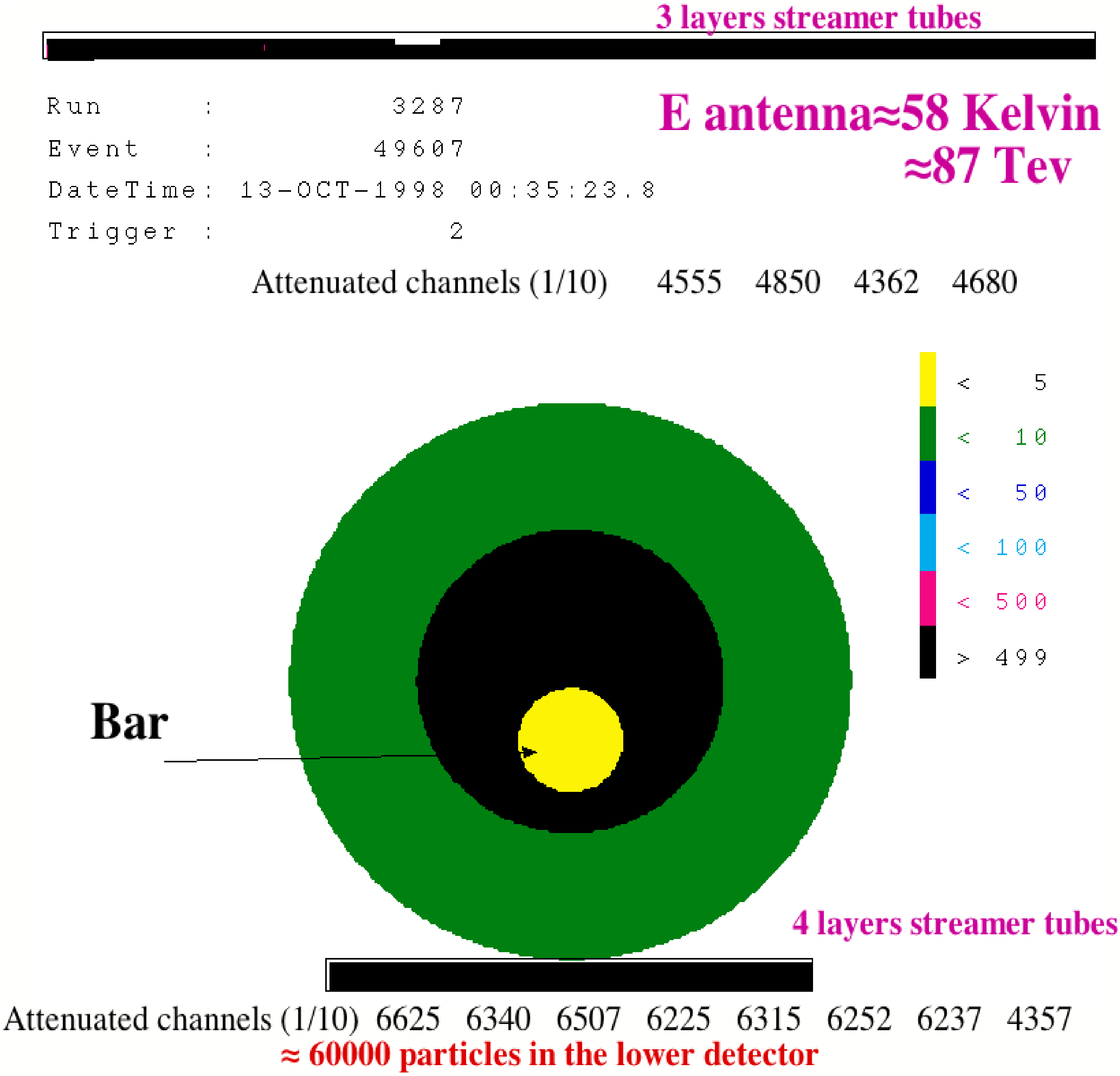


Figure 4: Time behavior of the largest NAUTILUS event in coincidence with an extens
air shower detected by the cosmic ray detector. The particle density in the extensive
shower is 3500 $particles/m^2$. In the upper figure we show the NAUTILUS signal (v
squared) before optimum filtering versus the UT time expressed in seconds, from
preceding midnight. From the decay we evaluate the merit factor of the apparatus, Q=
105. The lower plot shows the data after filtering, in units of kelvin.

The "big" event (1998)

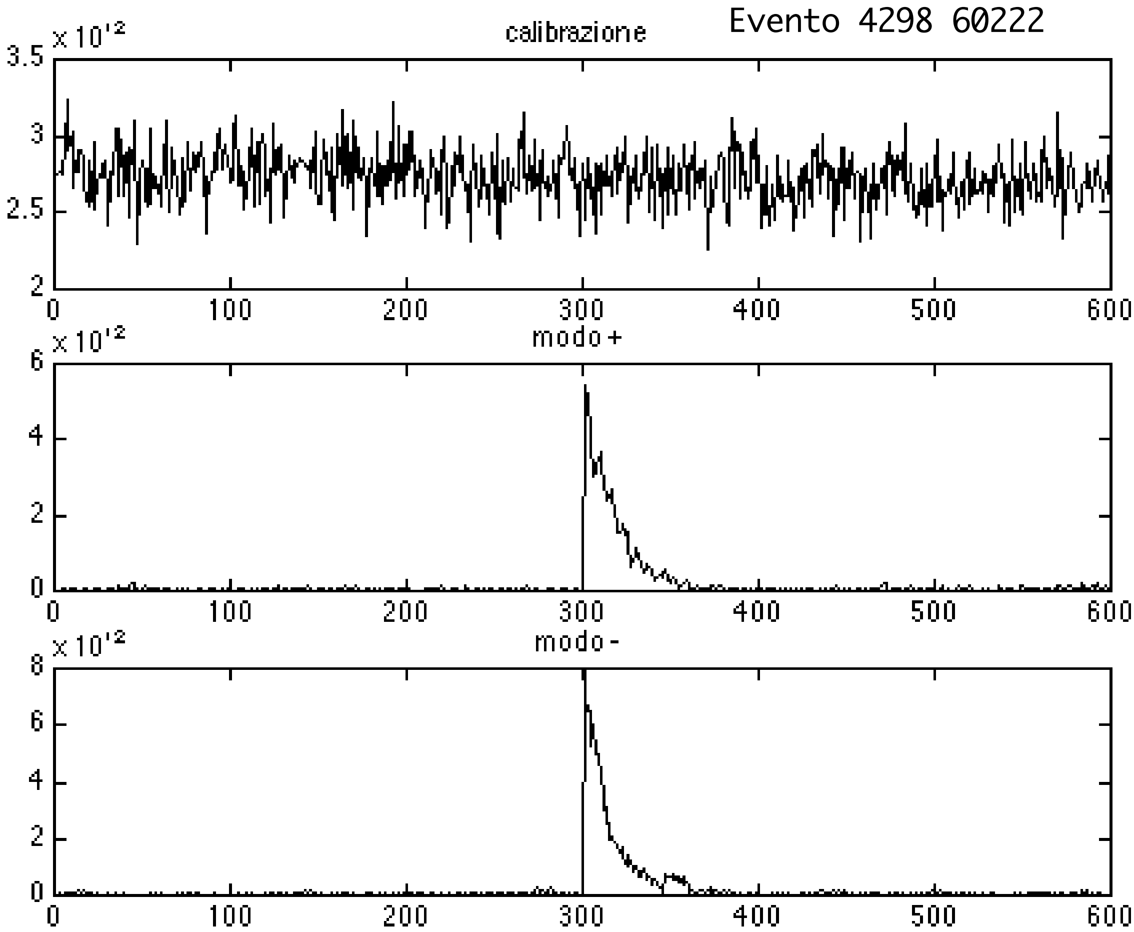


One of the largest events with the 5 kHz acquisition

≈9 Kelvin (June 2000)

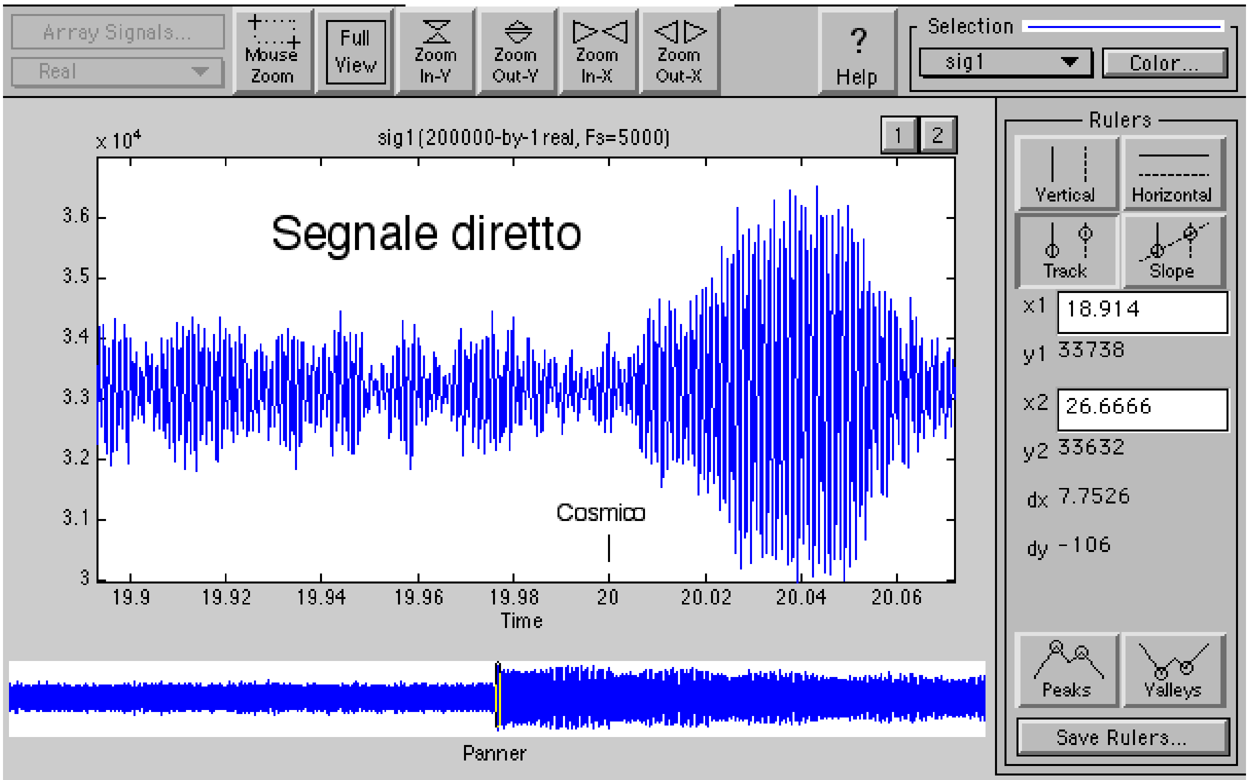
- GPS timing : 200μsec precision

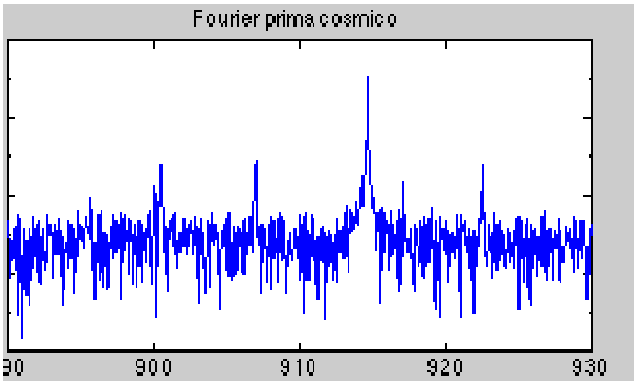
- The event is so big that no sophisticated filtering is necessary

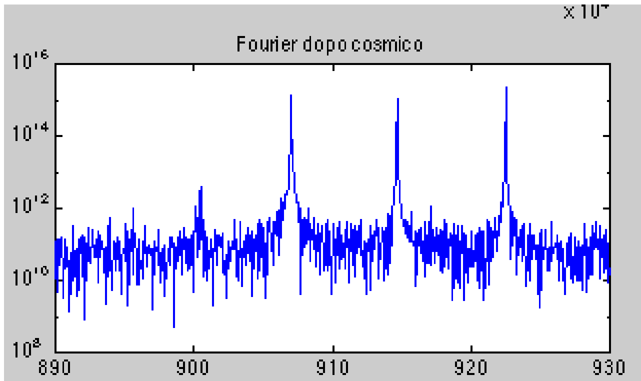


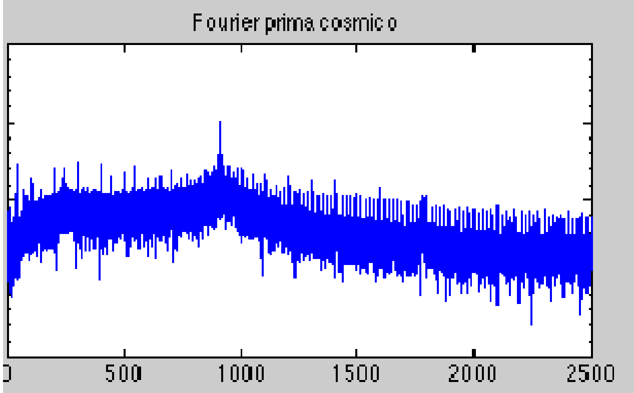
Time (seconds). The cosmic ray is at T=300 sec

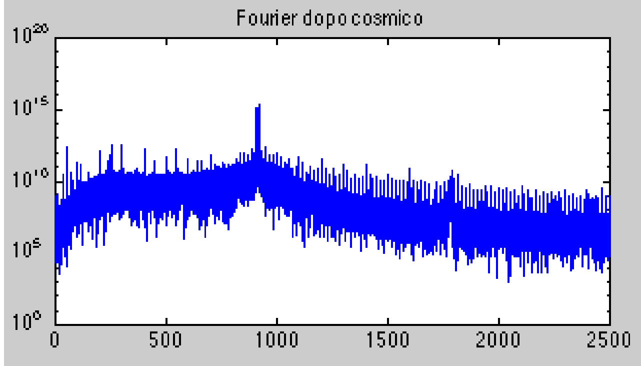
Evento 4298 60222 Giugno 2000











The search for coincidences (1998 data)

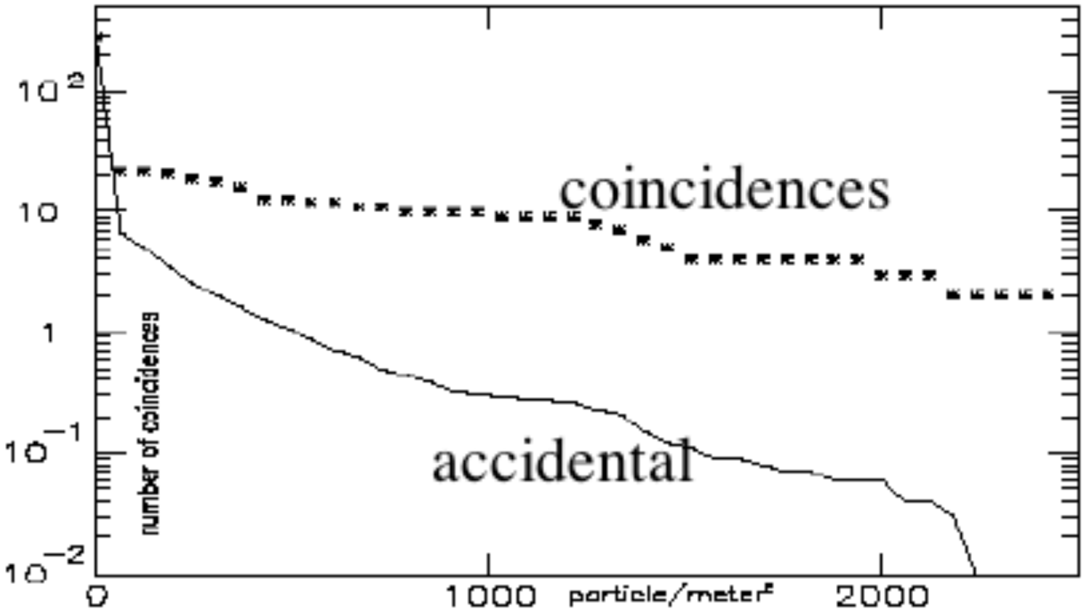


Fig. 1: Coincidences between the g.w. detector NAUTILUS and the c.r. detector. The asterisks show the integral num
observed coincidences versus the particle density observed by the c.r. counters located under the NAUTILUS cryostat
continuous line shows the estimated number of accidental coincidences.

Table 1: List of eighteen coincidences between NAUTILUS and the c.r. detector

day	hour	min	s	energy of the event $[K]$	noise of the g.w.detector T_{eff} in mK	up particle density $[m^{-2}]$	down particle density $[m^{-2}]$
262	23	11	29.581	2.28	0.003	37	312
277	22	26	35.771	0.04	0.002	118	405
285	17	23	14.9779	0.06	0.002	1238	2494
286	0	35	23.9222	57.89	0.004	2442	3556
295	21	0	34.3376	0.07	0.003	235	536
297	21	38	49.9765	0.37	0.011	547	1374
303	10	38	36.5147	0.42	0.016	227	360
306	8	19	59.5765	0.12	0.006	629	1409
311	15	24	27.1148	0.12	0.003	751	390
311	15	26	21.0289	0.14	0.004	148	623
311	23	22	8.4868	0.45	0.021	223	407
324	14	14	47.3926	1.14	0.044	258	785
350	20	56	18.6130	0.22	0.004	392	1323
354	23	54	19.2230	0.37	0.004	1064	1972
356	3	17	35.7440	0.09	0.004	434	2169
358	0	19	21.9564	0.04	0.002	286	1234
361	12	49	13.9211	0.09	0.003	258	983
365	12	35	40.6593	0.32	0.007	324	1490

Correlation with the particle density (1998 data)

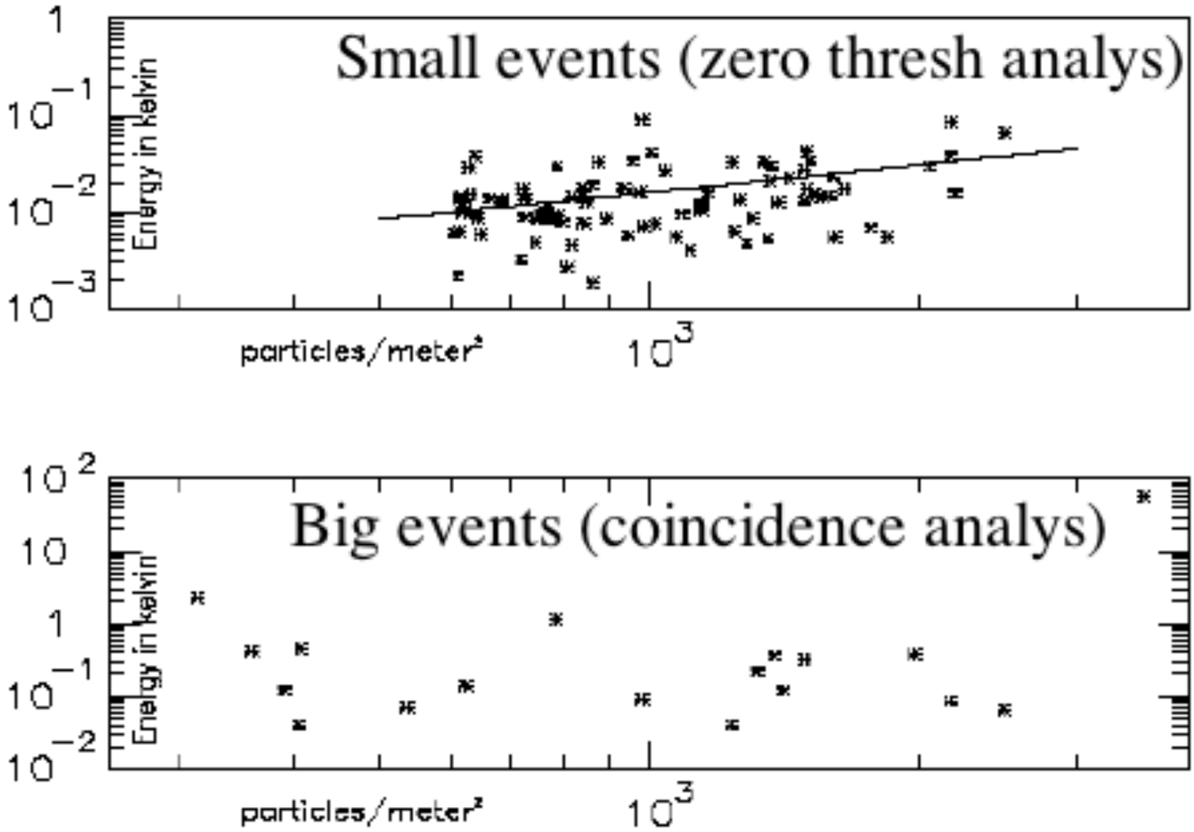


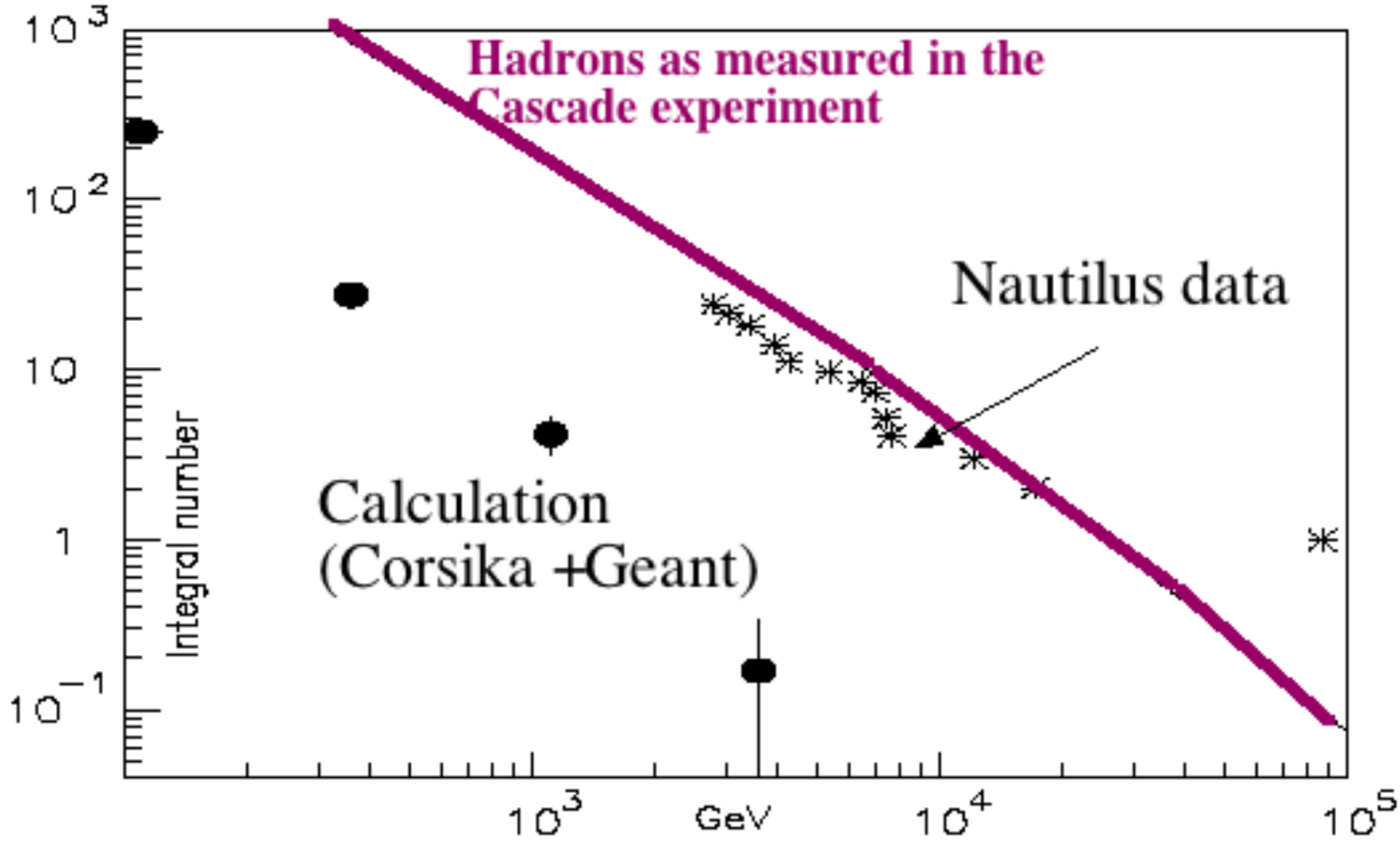
Fig. 3: Correlation between the NAUTILUS signals and the c.r. particle density. The upper graph shows the correlation of the NAUTILUS energy at zero delay (respect to the c.r. events) versus the corresponding c.r. lower particle density, for the 92 data points considered in the previous analysis. The correlation coefficient is 0.30, with a probability to be accidental of less than 1%. If we eliminate the three largest data points with energy greater than 100 mK, which belong also to the family of events of Table 1, the correlation coefficient increases to 0.42 with 89 data points, with a probability smaller than 10^{-4} for the correlation to be accidental. Instead the lower plot shows no correlation between the energy of the NAUTILUS coincident events analysed in this paper and the corresponding c.r. particle density.

- **For big events no correlation with the particle density (excluding the Big One)**

- **E.A.S. showers and thermo-acustical model unable to explain data**

Hadrons in the core of EAS?

Integral Distribution as function of energy calculated with the themo-acustical model



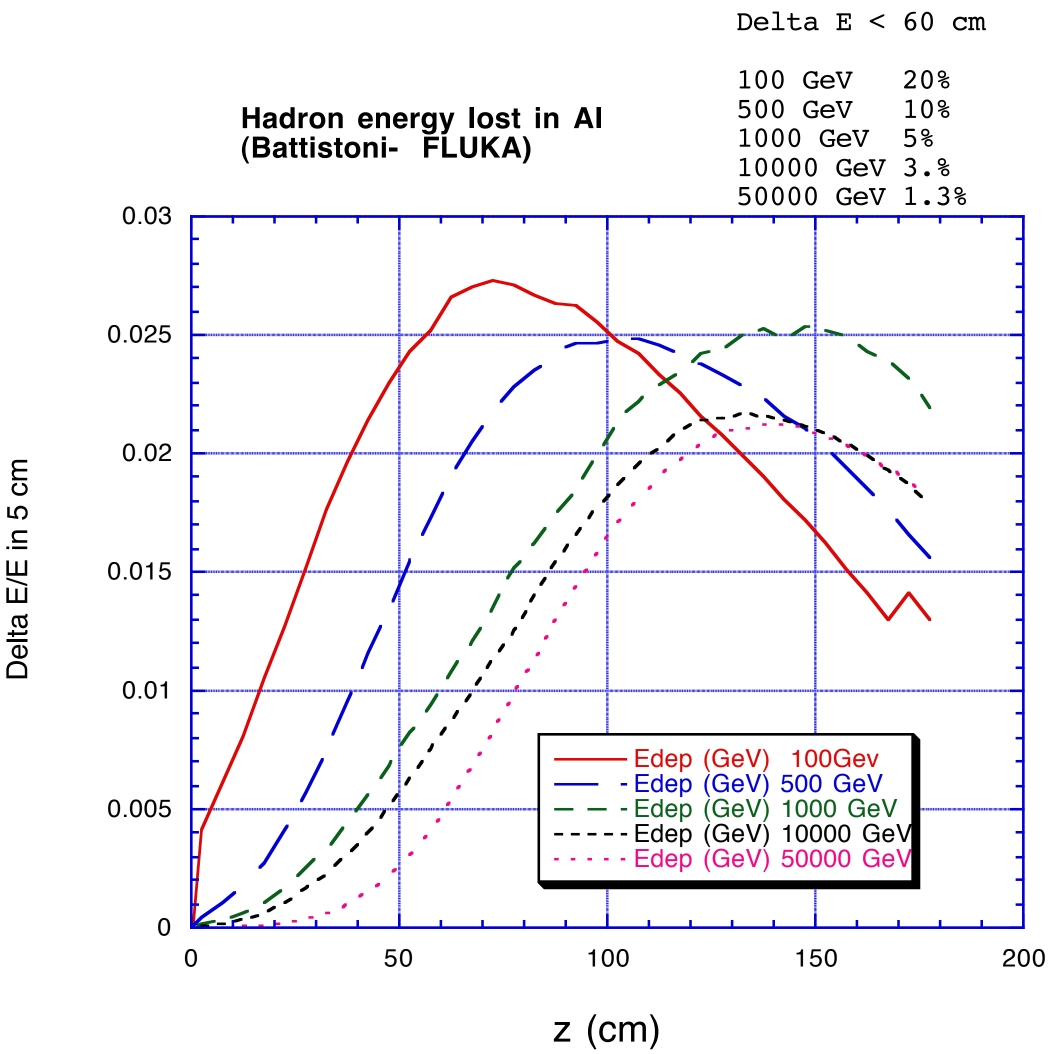
• Our calculation is in agreement with the direct measurement (Cascade experiment) taking into account the small energy contaiment in the antenna (a few percent at the energy of interest)==>>

a)Event Rate ≈2 order of magnitude higher than expected or

b) Energy ≈2 order of magnitude higher than the one computed with the thermo-acustical model

- **Hadrons + thermo-acustical model unable to explain the data**

Fraction of energy deposited in Aluminium



Possibilities to explain data

1) **Wrong calculations**,
 we are confident no mistake at a level of 2 order of magnitude

2) **Exotics** in the cosmic rays at the energy of interest (energies in the region of the knee of the cosmic ray)

3) **Detector (Nautilus) dependent effect** :

a)the cosmic rays could trigger a release **of non elastic audiofrequency modes**

b) **effects related to the superconductivity**:

the normal assumption is that the passage of a particle destroys the Cooper pairs (0.34 meV binding energy in Al).
Therefore in the thermo-acustical model is assumed normal Alluminium, but there are no experimental data for this model

or

the cosmic rays trigger some sort of metastable state due to the superconductivity

1)The cosmic ray possibility to explain data

• as was pointed by Barish-Liu acustical detectors are different from normal particle detector based on ionization.
In a gas detector for example you need to excite some atomic level==>> threshold in velocity (around $\beta \approx 10^{-3}$)

In acoustical detectors no threshold

• several kind of massive slow particles proposed in the past (monopoles, nuclearites..etc)

• very good limits (for example MACRO) for underground experiments but not for experiment at sea level

• the energy of interest is in the region of the cosmic ray knee where we know that something should happen

But

- the exotic particle should come together with a shower. This is not impossible but it is unlikely.

Nuclearites and Bar Detectors

The principal energy-loss mechanism for a nuclearite passing through matter is via atomic collisions. According to Refs. [2–4] when a nuclearite of mass m and velocity βc goes through an aluminum body, the rate of energy loss is

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

where the mass dependence is

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

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

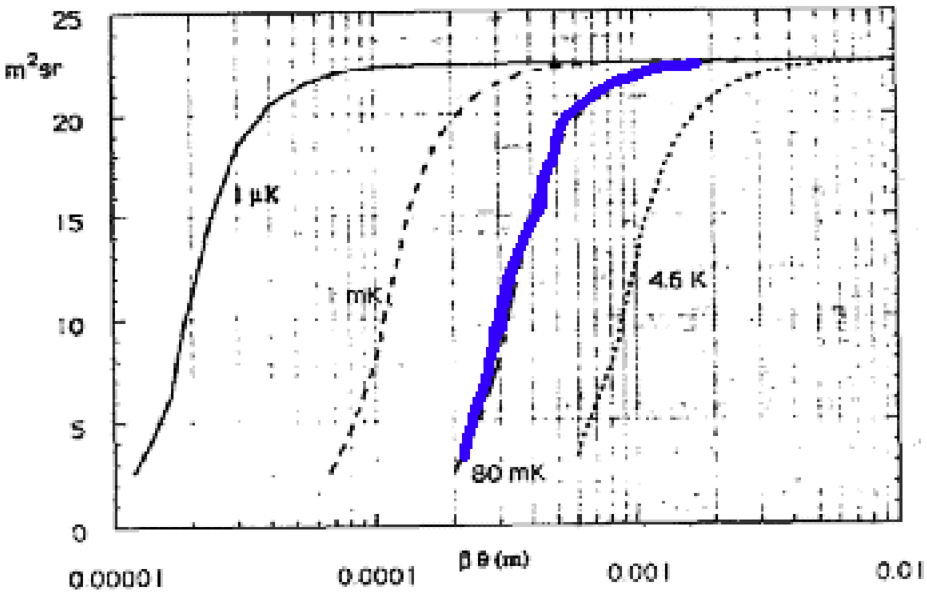


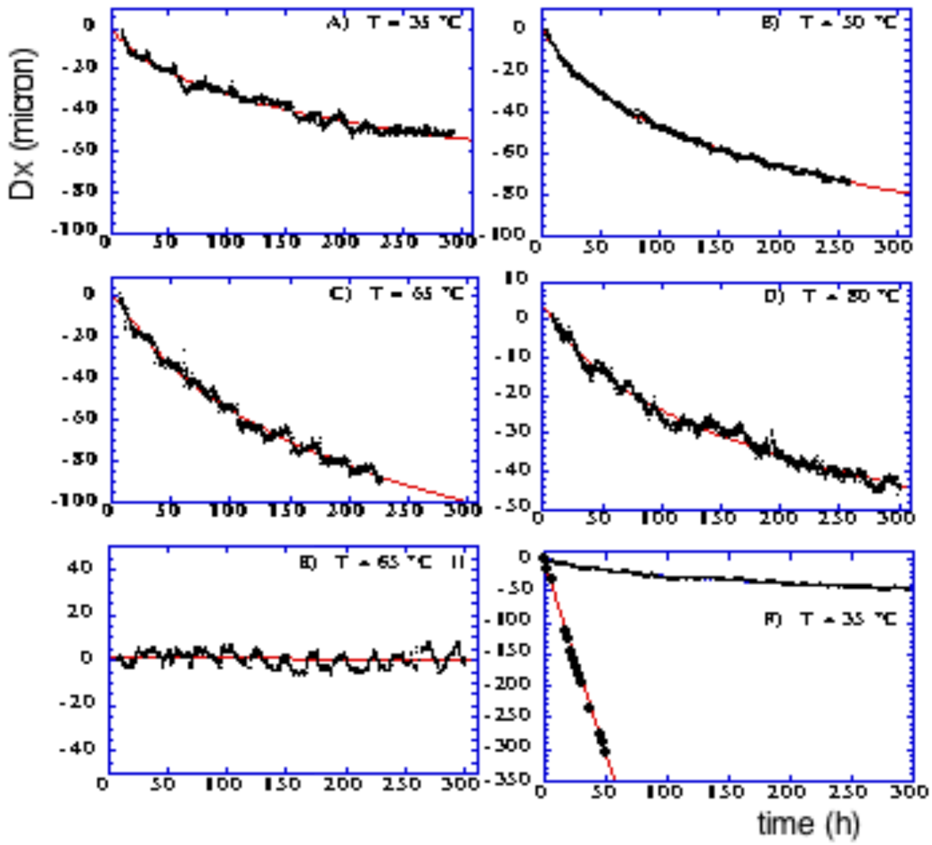
FIG. 2. Acceptance of the gravitational wave detector at the energy thresholds $\Delta T = 1\ \mu$K, 1 mK, 0.08 K, and 4.6 K. The vertical axis has to be divided by 2 if $m < 0.1$ g (nuclearites that cannot penetrate the Earth).

Explorer 1993 PRD 47 4770

2)Non elastic energy release

• the possibility to have non elastic energy release triggered by gravitational waves (or cosmic rays) was suggested by *Fitzgerald,E.R., Nature, 252, 638 (1974)*
It will be very nice because **this means an higher sensitivity.**

• It is a well know noise widely studied for example in Virgo, depending from temperature, history of the material, stress etc... typically ≈10^{-9} joules ≈10GeV.



3)Superconductivity

• It is the preferred explanation at the time of this talk.
After August 2000 Nautilus is working at a temperature > 1 Kelvin: normal state for Aluminium
Apparently no more big events.
Warning the analysis is preliminary! (on-line data)

Feb-July 2000 (T≈100 mKelvin)

Emin	Segn/noise	Noise max	Tempo vivo	Casuali	Eventi
0.1	20	0.05	69	2.5±0.5	12
0	20	1	79	2.8±0.5	14

Aug- January 12 2001 (T>≈1.1 Kelvin)

Emin	Segn/noise	Noise max	Tempo vivo	Casuali	Eventi
0.1	20	0.05	66.3	4.1±0.6	6
0	20	1	75	10±1	11

• So at the moment it seems that the **effect depends from the temperature (≈2 standard deviation)**.

•Why two category of events one with normal signal and another with large signals?

• The interaction of a particle with a superconductor is an interesting problem. Theoretician are working.

Summary 1

• We have found **for the first time** the cosmic rays induced signal in a resonant cryogenic detector. Very nice technical result ($\Delta x \approx 10^{-17}$ meters!)

• Several checks show that we have indeed a **mechanical excitation of the bar**.

• The **thermo-acustical model** is ≈ correct for most of the events. But for a fraction ≈ 20% of the showers we have signals much larger (2 order of magnitude) than expected.

• Interesting problem involving **gravitational waves, cosmic rays, particle detection and low temperature physics**

• Perhaps no more large signals for **non-superconductor Aluminium**...but not yet firm conclusion (≈2 standard deviation)

Summary 2

The understanding of this phenomena is important for :

- **Sensitivity for gravitational waves** (the amplification effect could exist also for gravitational waves)

- **Applications to exotic particle searches** with bar detectors with geometry optimized for particle detectors.
Calorimetry for very high energy particles / beams.

- **Study of analysis techniques.**
For example to search small signals with repetition:
(gamma-burst)

- Study of the limitations due to the cosmic rays in **future detectors** of improved sensitivity

Future

• **Data in different operating conditions are important to understand the physical mechanism.**

• **Nautilus :** after the shutdown in the spring (new transducer, change of resonant frequency for a new pulsar at ≈ 935 Hz....)
we will have a Iron/RPC sampling calorimeter (Monolith) to understand if the events giving big signals have anomalies in the hadronic or muonic components.

• **Explorer** (CERN) : currently is the best antenna in the world. The Aluminum is not superconductor. We will use scintillator counters from Cosmo-Aleph to set a cosmic ray detector (thanks to Mannocchi and Bechini)

• **Niobe** (Australia). They plan to implement a cosmic ray detector.

- **OMNI** (Brasil) they plan to implement a cosmic ray detetctor using the MACRO streamer tubes.

- Experiment on a particle beam?

Cosmic rays: the calculation

• for muons we have used the flux parametrization of DARR (Phys Rev Lett 51 (1983))

• For the hadrons of high energy we have used the charged hadron flux measured by Siohan et al. (J. Phys. G. Nucl. Pys vol 3 pag 1157 , 1977)

$$= (1 \pm .15) * 10^{-10} * (E/300)^{-2.6}$$

$$(cm^{-2}\ sec^{-1}\ sr.^{-1})$$

$$300 < E < 1700\ GEV$$

extrapolating the data to different zenith angles and with a correction to include neutral hadrons

$$\text{Correction} = 1.25 * e^{(-h+hz)/Lcoll}$$

$hz = 1030$ gr./cm^2

$h = hz/\cos(q)$

q : angle with the zenith

$Lcoll = 140$ gr./cm^2

• for $E < 300$ GEV we have used the flux reported in Lumme et al (J Phys G pag 683 (1984)) corrected for the same factor as function of q .

• at energy higher than 1700 GeV the contribution of multiple hadrons becomes important. We have done a very crude evaluation based on the Montecarlo calculation of Arvela et al (J. Phys G Nucl Phys 10 (1984))

Event with 375 mKelvin

3 layers of streamer tubes

attenuated signals 2420 2630 2550 2770

Run : 3432

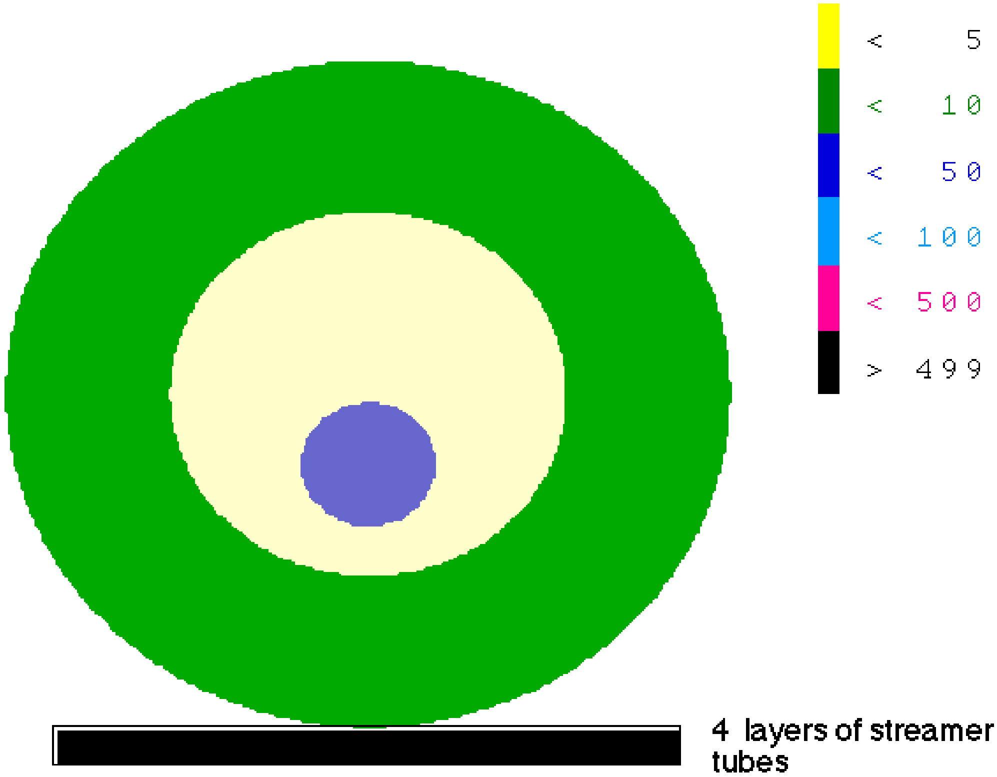
Event : 30341

DateTime: 20-DEC-1998 23:54:19.1

Trigger : 2

LARGEST SIGNAL EVENT

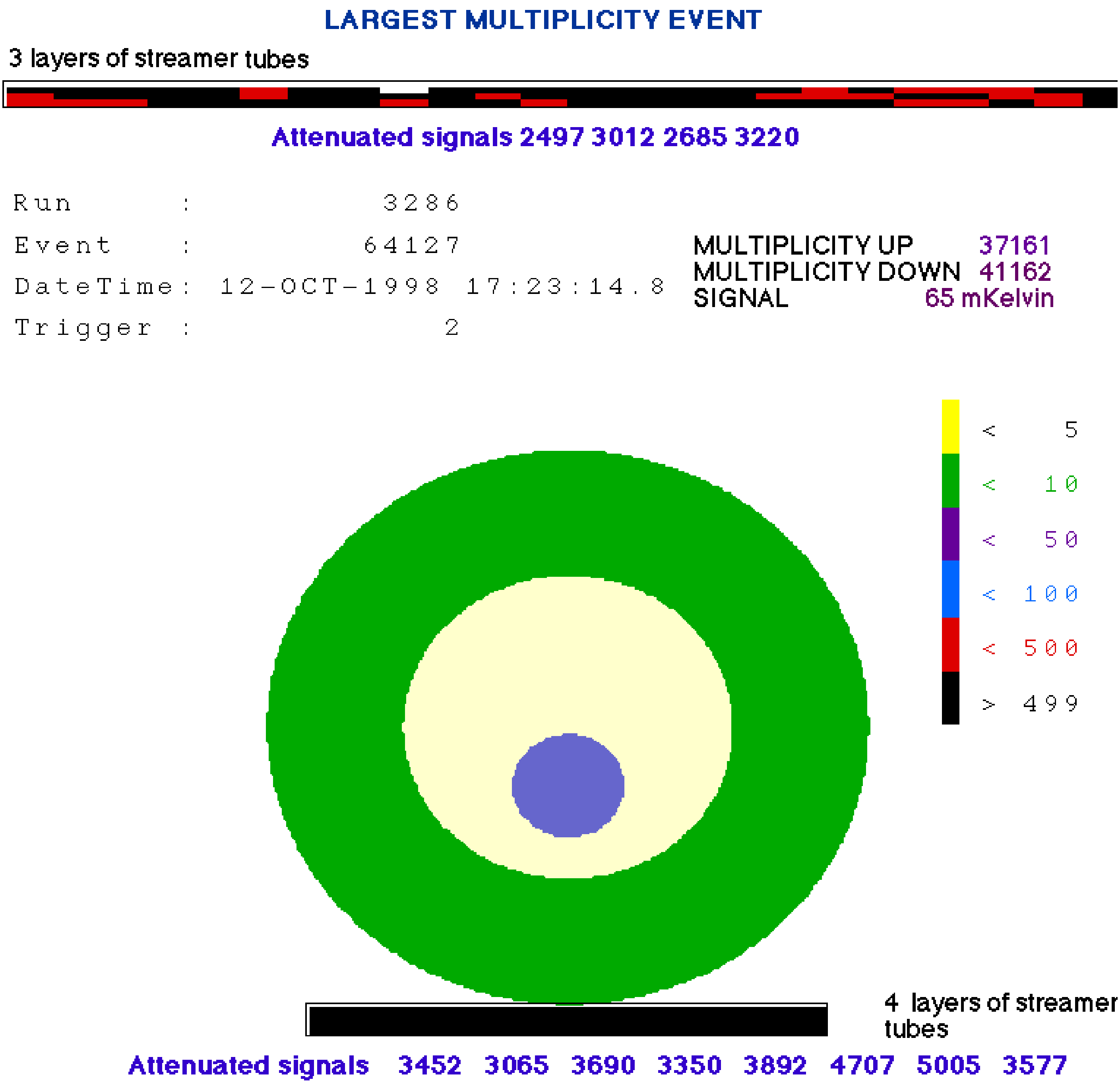
MULTIPLICITY UP 31955
MULTIPLICITY DOWN 32571
SIGNAL 370 mKelvin

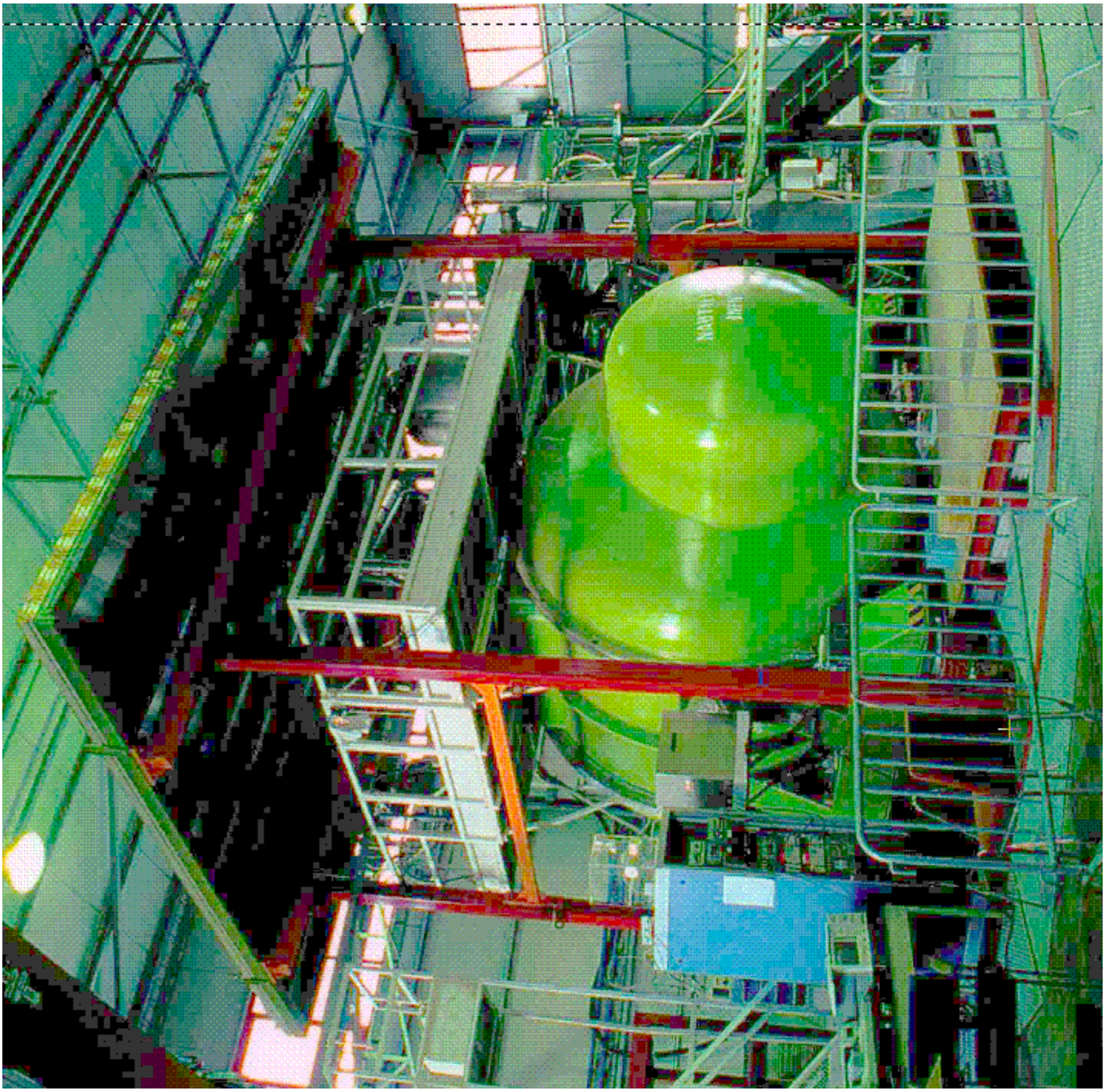


4 layers of streamer tubes

attenuated signals 4185 3627 3387 3120 2600 3087 3002 2215

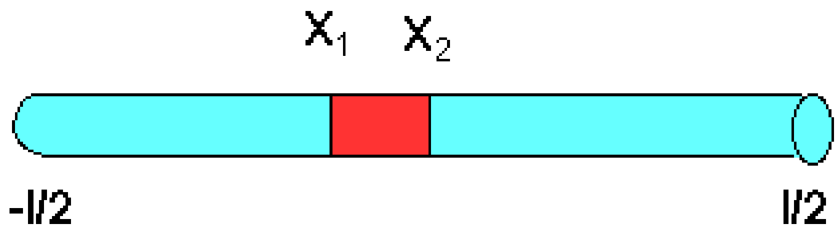
Event with 41000 particles (in the bottom)





Thermo Acoustical Model (simplified approach 1)

• In a very simplified approach the antenna can be considered as **a thin bar**
The vibrations are produced by thermal expansion due to uniform heat in a region x_1-x_2



usual wave equation

$$\frac{\partial^2 \Phi(x,t)}{\partial t^2} = c^2 \frac{\partial^2 \Phi(x,t)}{\partial x^2}$$

Boundary conditions at x=-l/2, x=l/2

$$\frac{\partial \Phi(x,t)}{\partial x} = 0$$

General solution :

$$\Phi(x,t) = \sum_{n=1}^{\infty} A_n \cos\left(\frac{2n\pi x}{l}\right)\cos\left(\frac{2n\pi ct}{l}\right) + \sum_{n=1}^{\infty} B_n \sin\left(\frac{(2n+1)\pi x}{2l}\right)\cos\left(\frac{(2n+1)ct}{2l}\right)$$

Simplified approach (2)

- **Initial conditions**

$$\frac{\partial\ \Phi(x,t=0^+)}{\partial x} = \frac{\alpha W}{C\rho A(x_1 - x_2)}$$

For $x \in [x_1, x_2]$ otherwise =0

W: Energy deposited between x1 and x2
α : thermal expansion coefficient
ρ : density   A : cross-sectional area

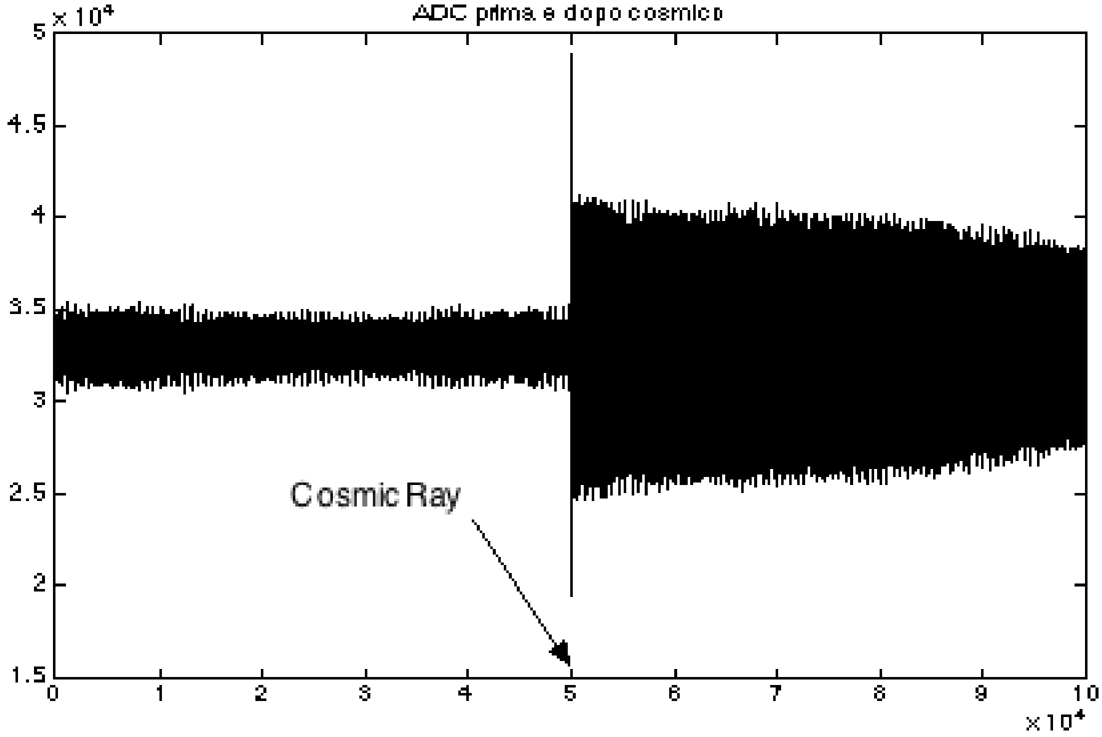
- fundamental mode **single particle**:

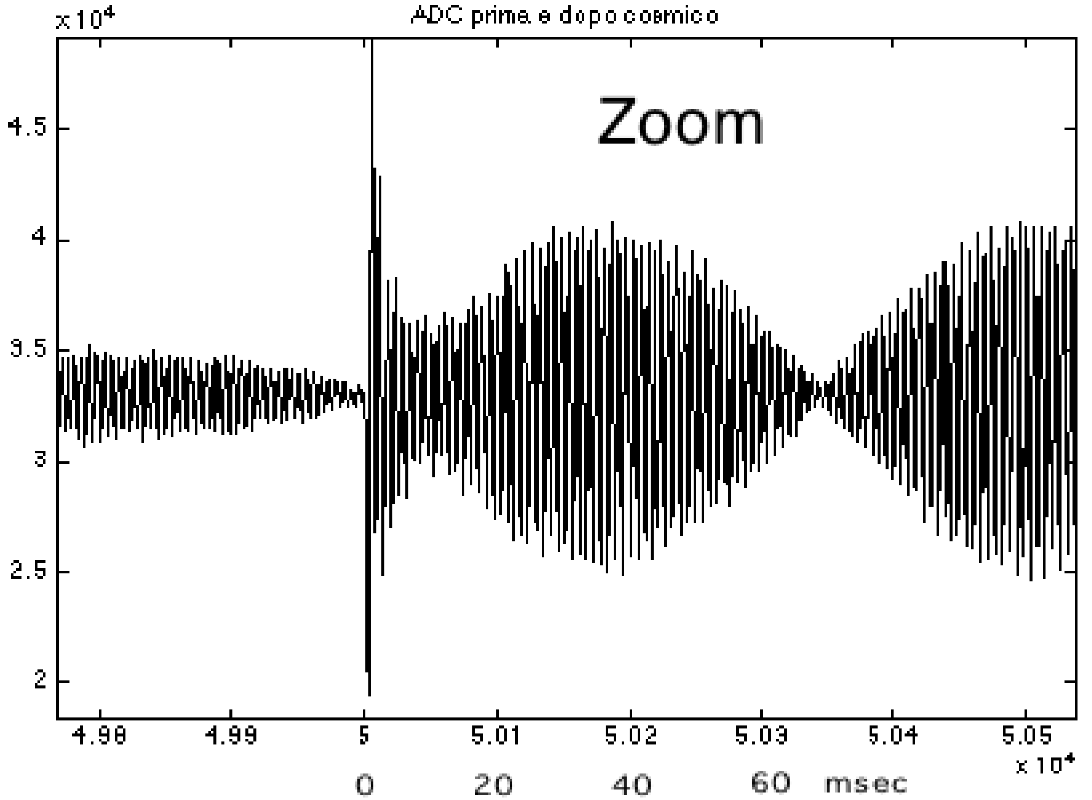
$$B_0 = \frac{2\alpha W l}{\pi C M} \cos\left(\frac{\pi\left(\frac{x_1 + x_2}{2}\right)}{l}\right)\left(\frac{\sin \pi \frac{x_1 - x_2}{2l}}{\pi \frac{x_1 - x_2}{2l}}\right)$$

- **Extensive Air Showers with uniform distribution(different boundary conditions):**

$$B_0 = \frac{2\alpha W l}{\pi C M} \cos\left(\frac{\pi\left(\frac{x_1 + x_2}{2}\right)}{l}\right)$$

Cosmic ray with 440 Kelvin in the bar ≈61000 particles in the lower detector





Cosmic ray with 440 Kelvin in the bar
≈61000 particles in the lower detector

The highest multiplicity detected up to now

UT time 23-FEB-2001 08:33:57

UP

attenuated chann 1/10

7465 8095 7595 7637

DOWN

atten channels (1/10)

7892 7682 8252 8142 9510 9635 9390 6192

Antenna was at 1.5 Kelvin (no superconductivity)