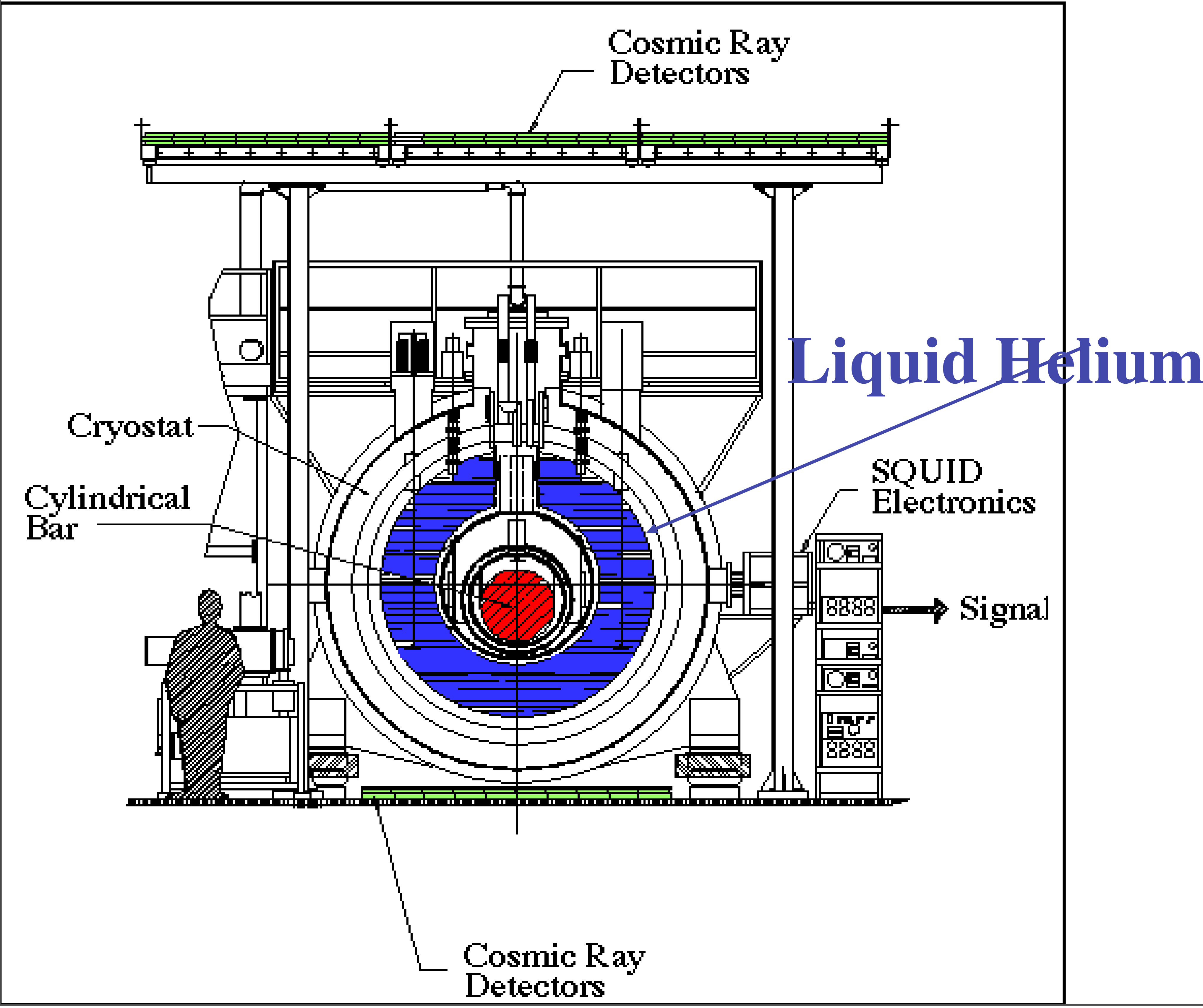
Detection of high energy cosmic rays with resonant gravitational wave detectors

- The NAUTILUS (Frascati) and EXPLORER (CERN) gravitational bar detectors (ROG collaboration)
- The cosmic ray detectors in NAUTILUS and EXPLORER
- The interaction of the cosmic rays with a bar and the thermoacustical model
- The detection of cosmic rays in NAUTILUS **and the surprise due to large amplitude events at very low temperature**
- Measurements on the Frascati linac to verify the thermoacustical model at low temperature (RAP experiment)
- Conclusions and "exotics" in cosmic rays

e-Print: arXiv:0806.1335 [hep-ex]

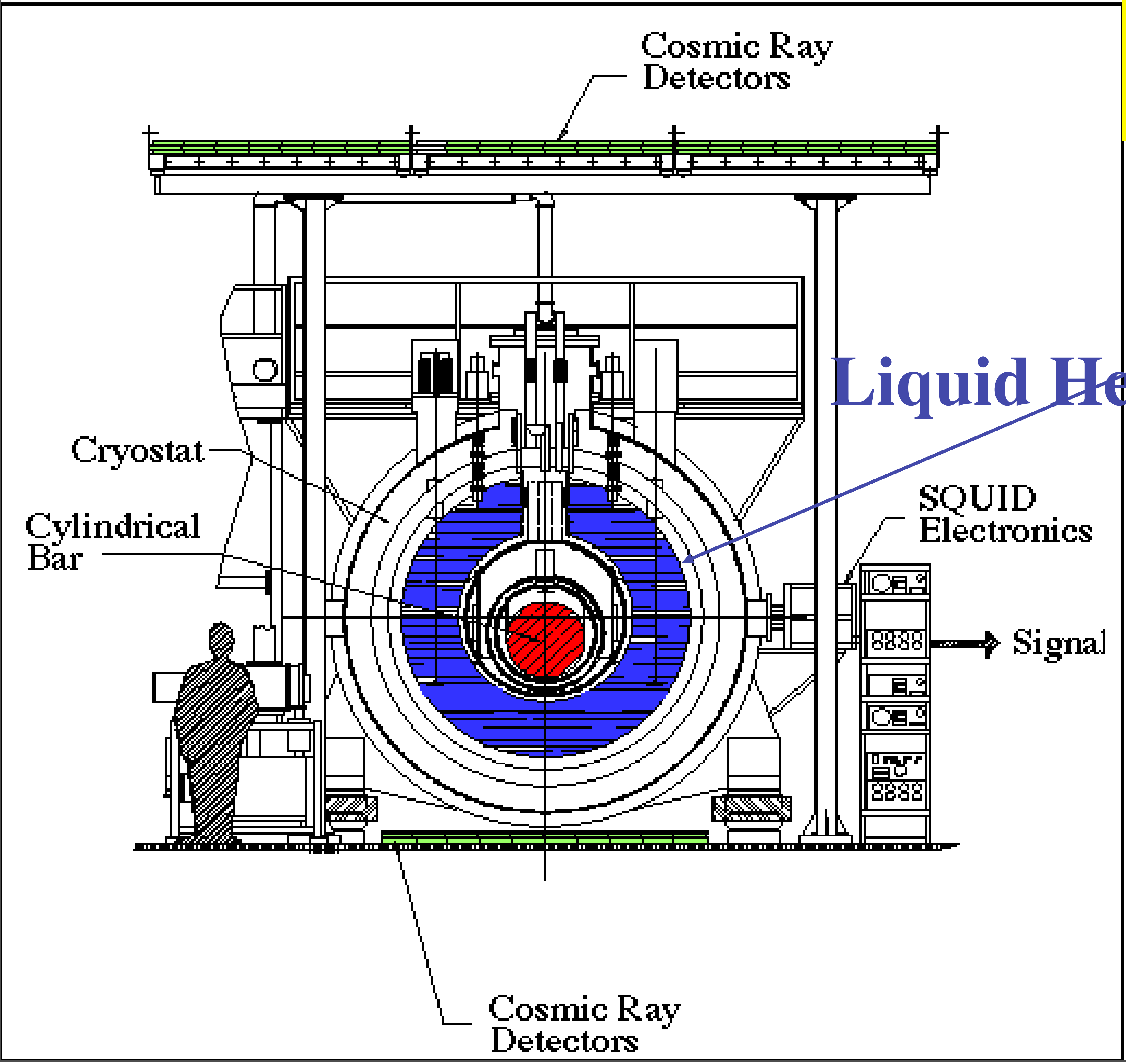
Example of a cylindrical resonant detector: Nautilus (the first cooled at 100 mK in 1998)



F Ronga INFN LNF CRIS2008

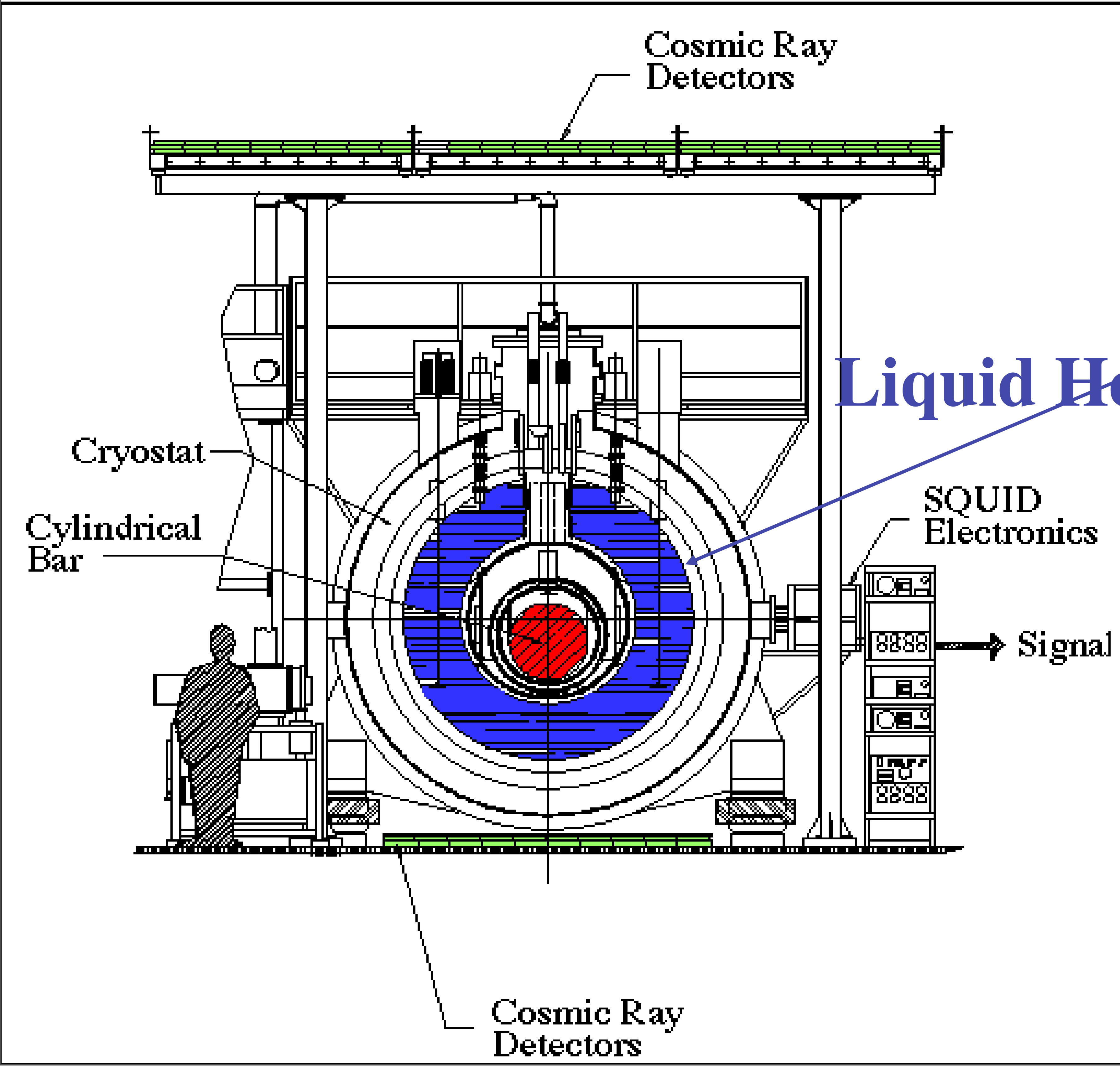
Example of a cylindrical resonant detector: Nautilus (the first cooled at 100 mK in 1998)

Al 2036 bar 2300 Kg L=3 m r=0.3m



F Ronga INFN LNF CRIS2008

Example of a cylindrical resonant detector: Nautilus (the first cooled at 100 mK in 1998)

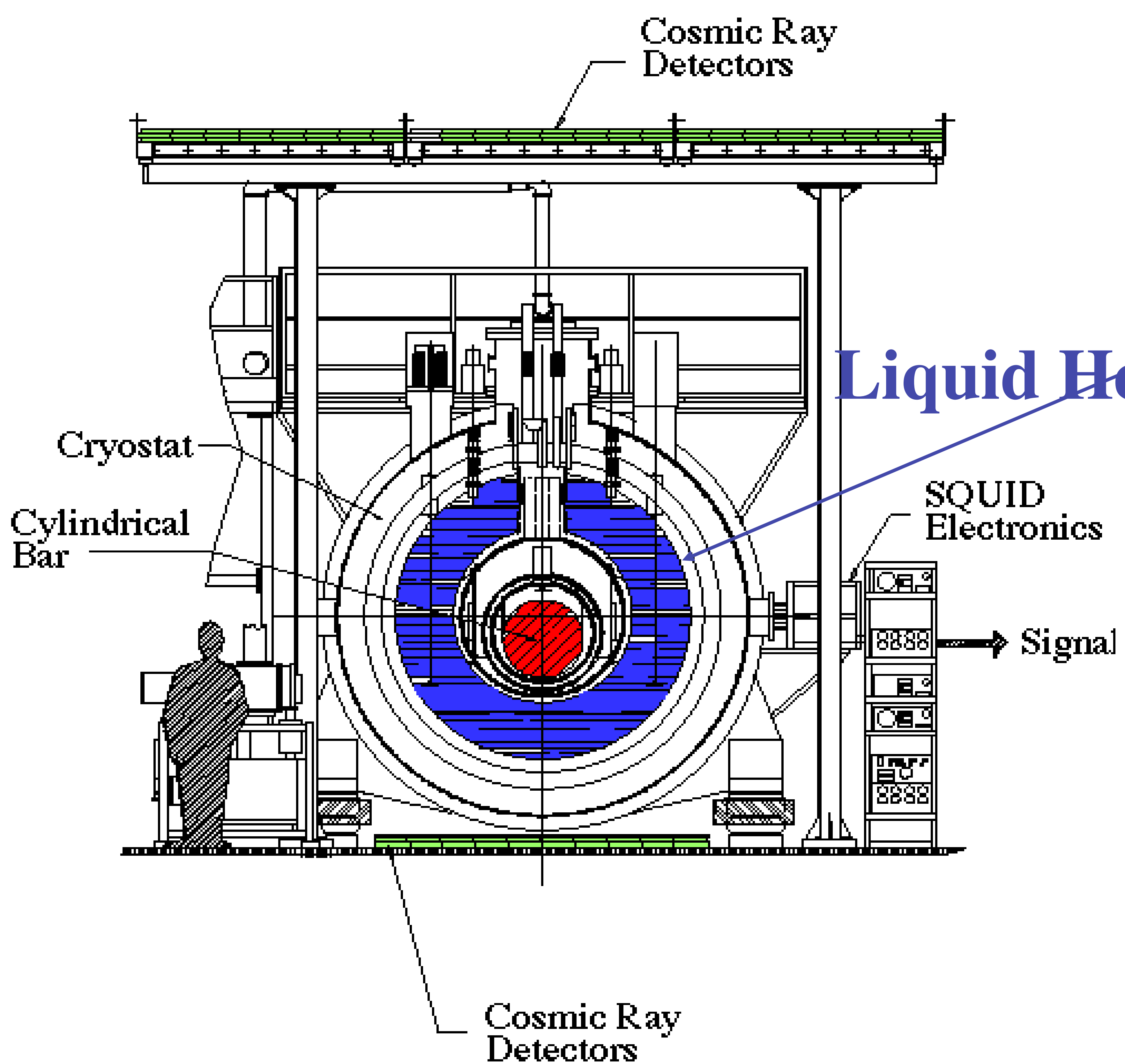


Al 2036 bar 2300

Cross section : 2 aluminum shields, container for helium **2000 liters**, dilution refrigerator with ^3He ^4He mixture

F Ronga INFN LNF CRIS2008

Example of a cylindrical resonant detector: Nautilus (the first cooled at 100 mK in 1998)



Al 2036 bar 2300

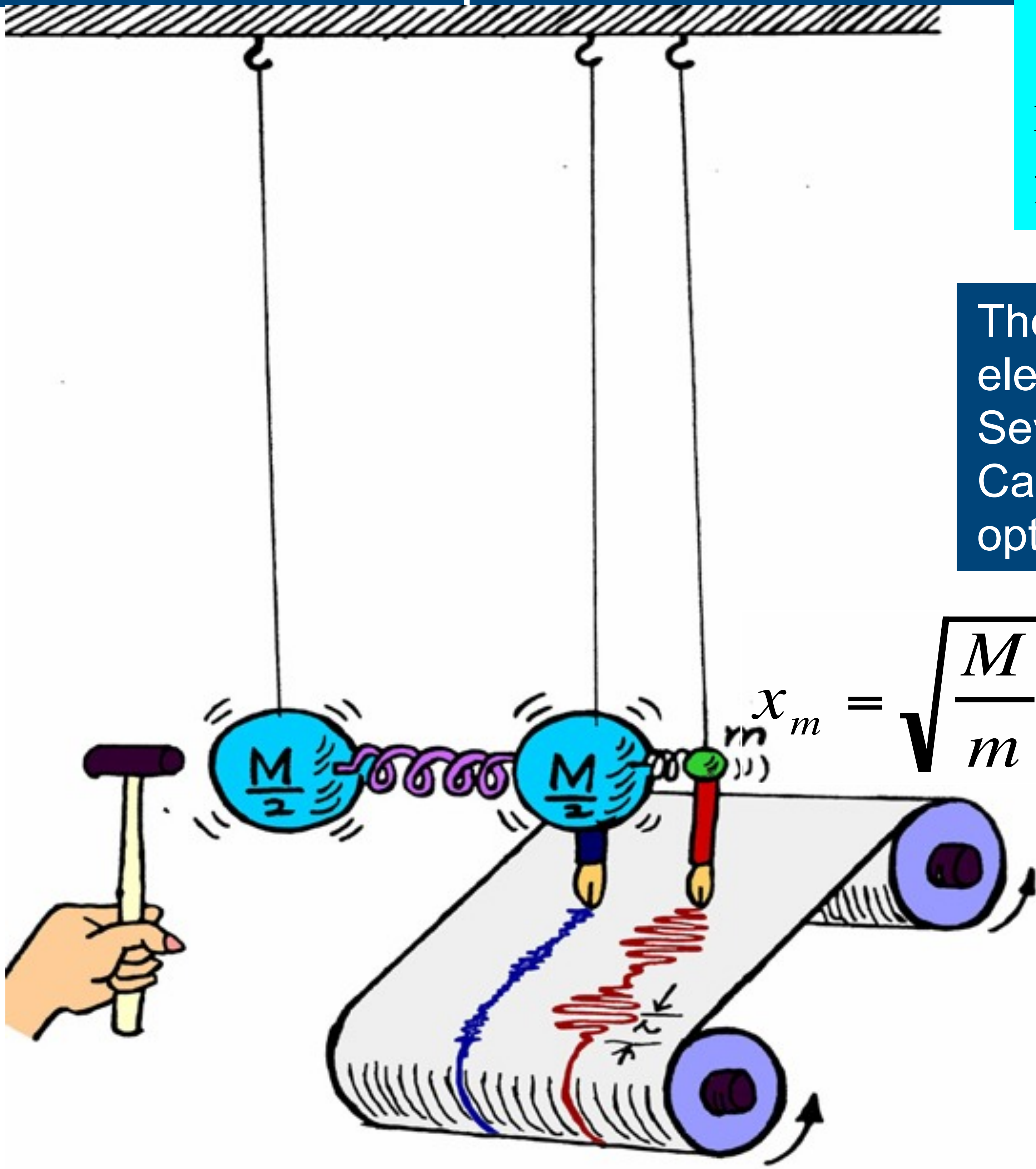
Cross section : 2 aluminum shields, container for helium **2000 liters**, dilution

Mechanical suspension: shields are suspended in a chains and copper wire around the bar 260 db @ 1 Khz

Resonant transducer as a mechanical amplifier

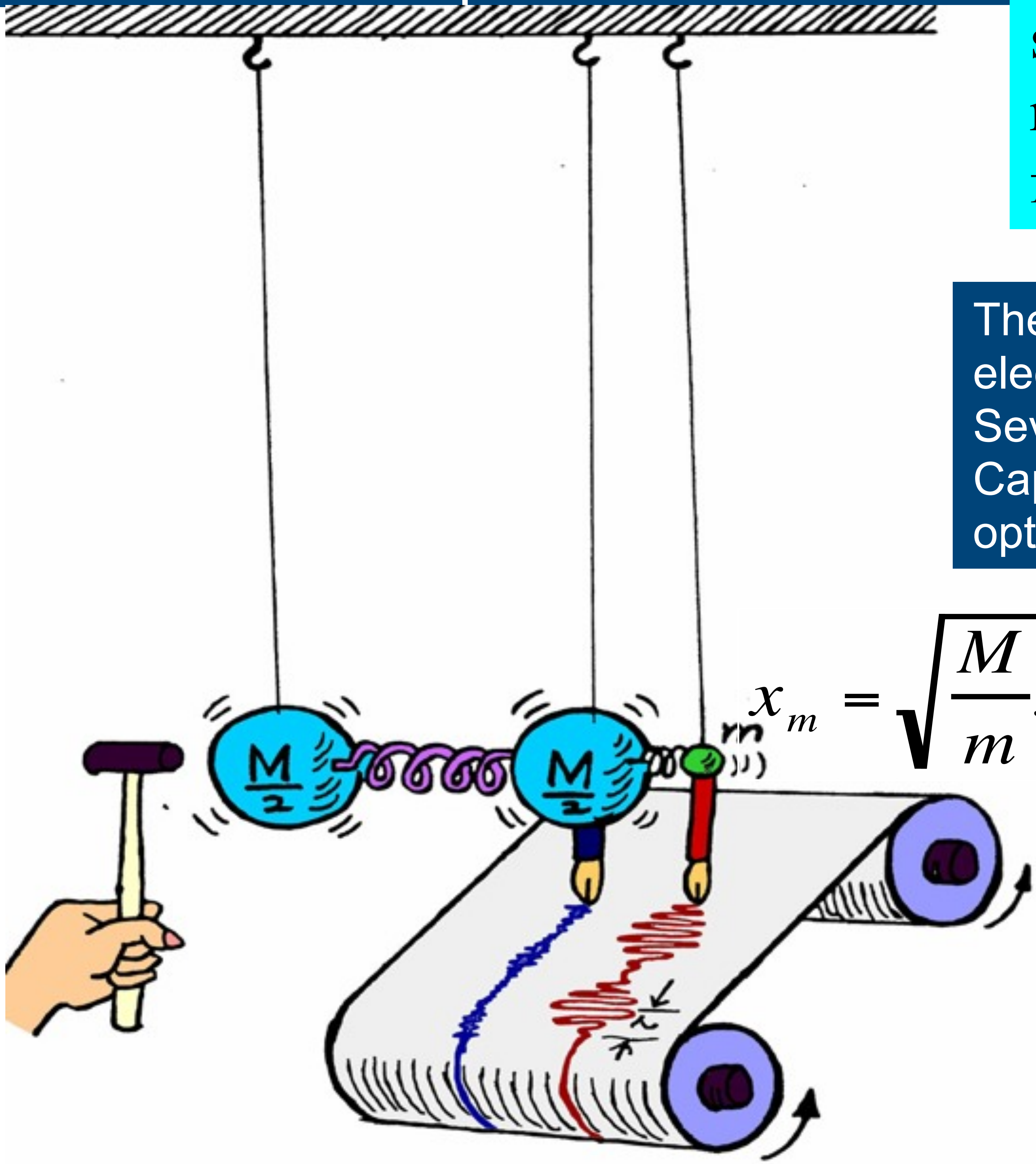
Coupled two oscillator system: splitting of the main fundamental resonance in two resonant frequencies

The displacement of m is converted in electrical signal:
Several systems:
Capacitor with electrical potential , RF or optical cavity ecc



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

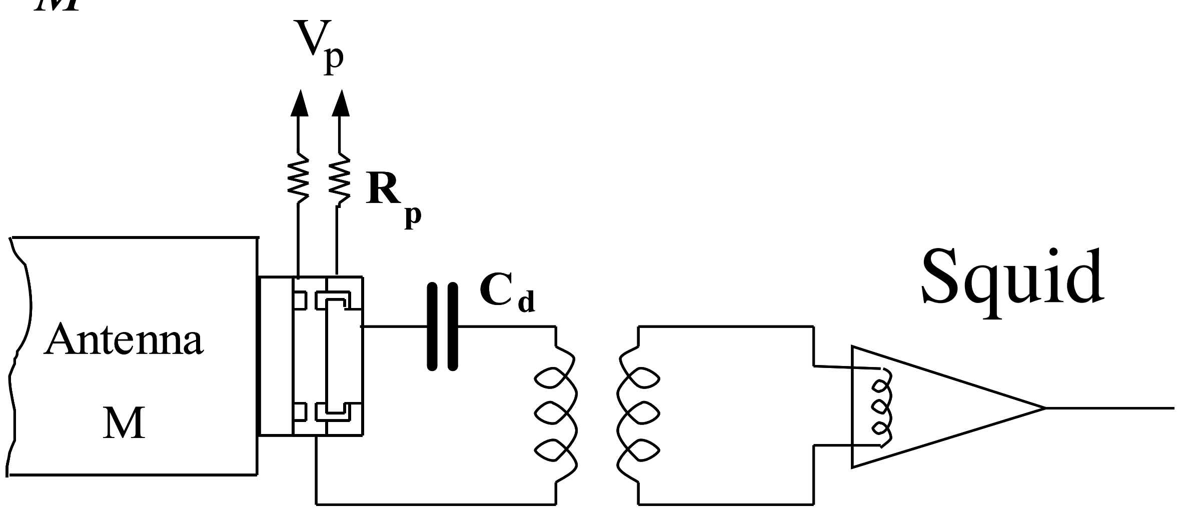
Resonant transducer as a mechanical amplifier



Coupled two oscillator system: splitting of the main fundamental resonance in two resonant frequencies

The displacement of m is converted in electrical signal:
Several systems:
Capacitor with electrical potential , RF or optical cavity ecc

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



Auriga Explorer Nautilus

Antenna acquisition and filtering

• The signal is read using a 16 bit ADC sampled at **5KHz.**

• Using aliasing the signal is studied normally in the 900 Hz region “the sensible 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

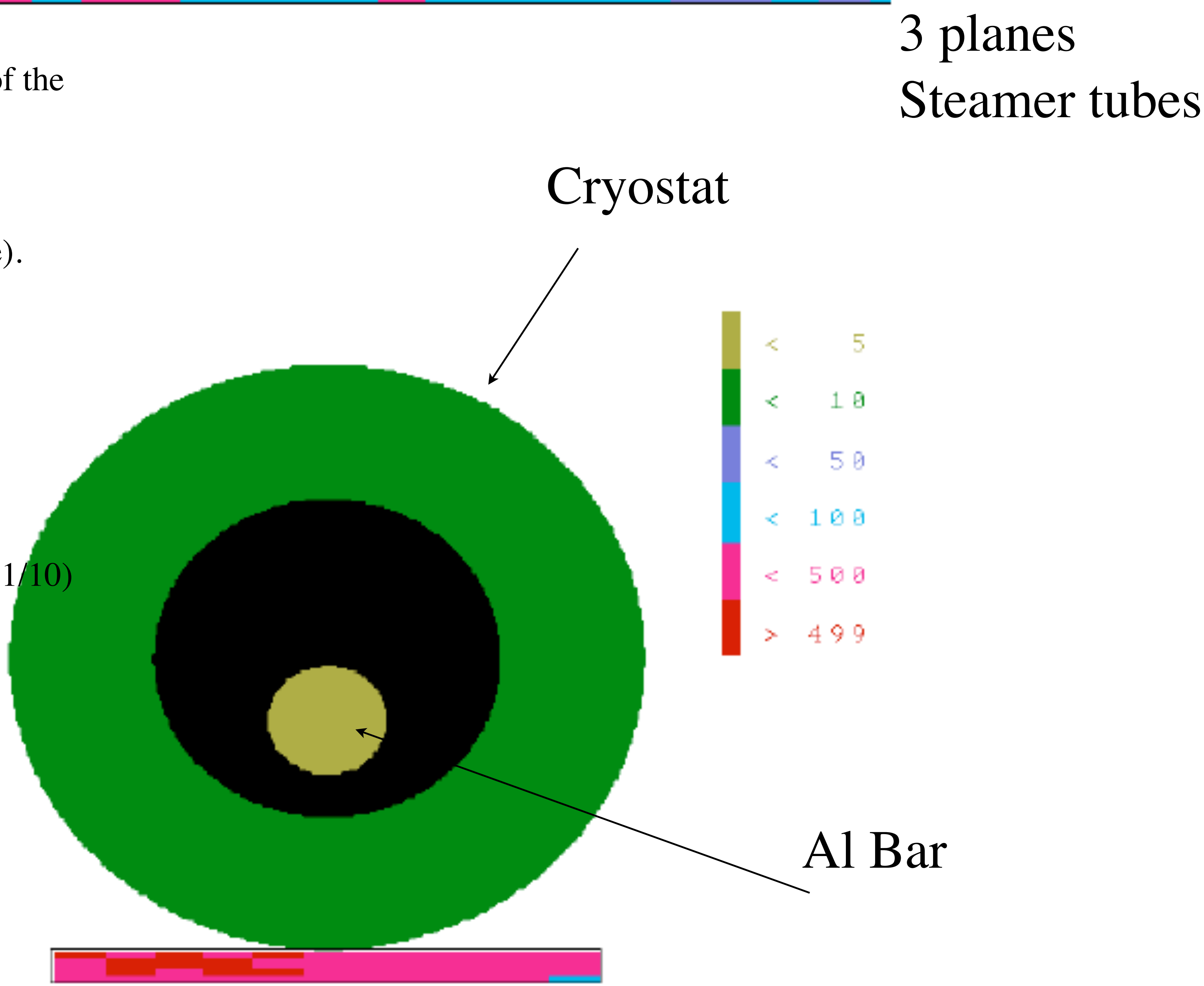
• The optimum filter parameters are computed from the noise distribution in a time interval ± 1 h.

• In the bar antenna jargon the **energy is measured in Kelvin**; the typical noise is less than 0.005 K (much lower than the thermodynamical temperature), due to the matched filter

• GPS clocks used for timing and to synchronize antenna and cosmic rays acquisition

Cosmic ray detector in NAUTILUS : streamer gas detector with charge readout

- 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)

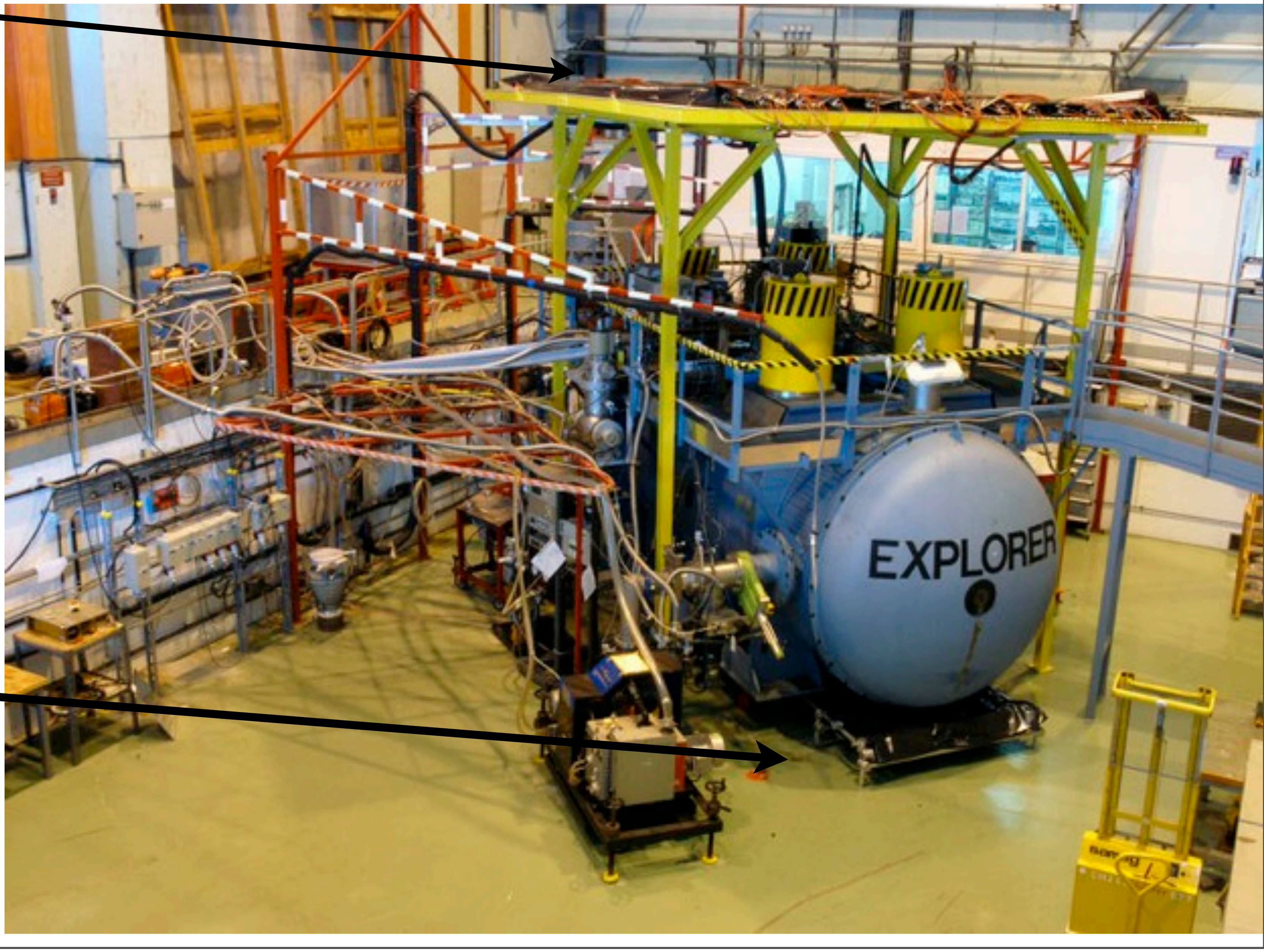


EXPLORER (CERN) in 2003 added scintillators

"cosmic ALEPH" LEP dismissed equipment

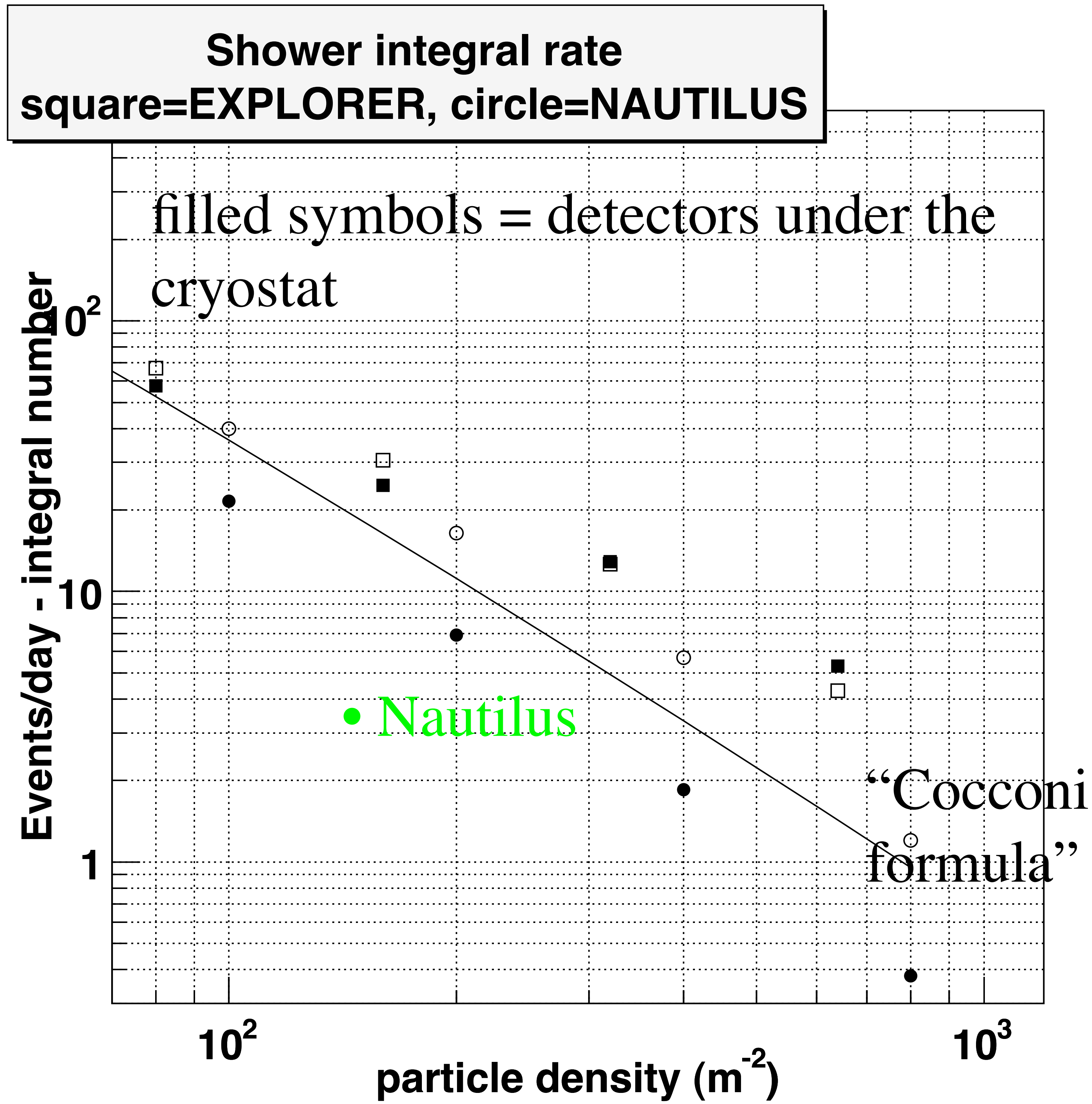
11 scintillators in 1 layer
anode and dynode charge readout
from the two sides
saturation ~ 2000 part/m^2

2 scintillators in 2 layers



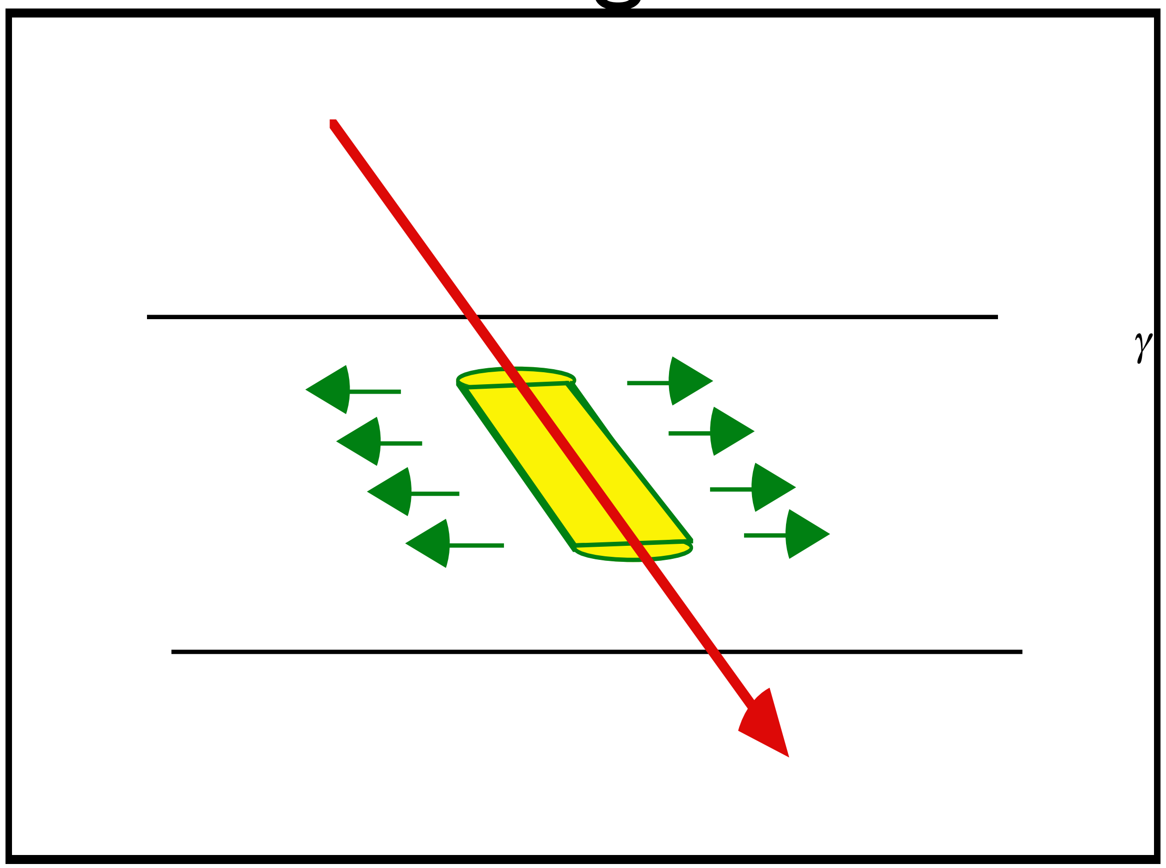
EAS rates in measured in NAUTILUS (Frascati) and EXPLORER (CERN)

- “calibration” done using muons
- rates are different in the upper and in the lower detectors (cryostat effect)
- rates are different because CERN and Frascati are at different heights and have different roofs in the building
- the rate in Explorer (detector under the cryostat) is ~ 2.8 higher than the one in NAUTILUS



Interaction of a particle with a bar: Thermo-Acustical model

Ionization energy lost is converted in thermal heating and therefore pressure wave



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

$$\delta p = \gamma \frac{\delta E}{V_0} \qquad \gamma = \frac{3\alpha}{\rho\, k C_v}$$

$$k = 3 * (1 - 2 * pois) / Y$$

γ Grunesein parameter

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

pois=Poisson module

Thermal acoustical conversion (General case for a single particle)

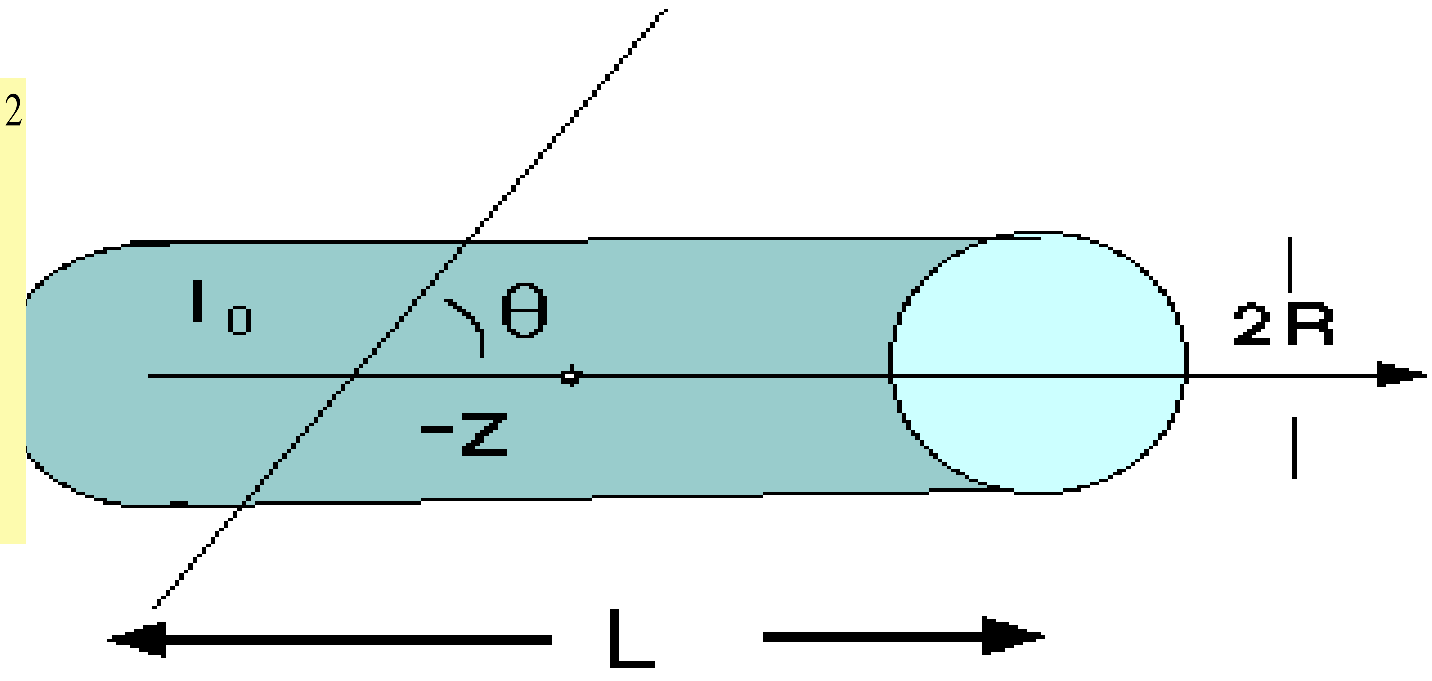
$$E_n = \frac{1}{2}\frac{l^2}{V}\frac{G_n^2}{\rho v^2}\gamma^2\left(\frac{dE}{dX}\right)^2$$

Allega A.M. & Cabibbo N. Lett Nuovo Cim 38 (1983) 263-
A. De Rujula & B. Lautrup, Nucl Phys. B242 (1984) 93-144

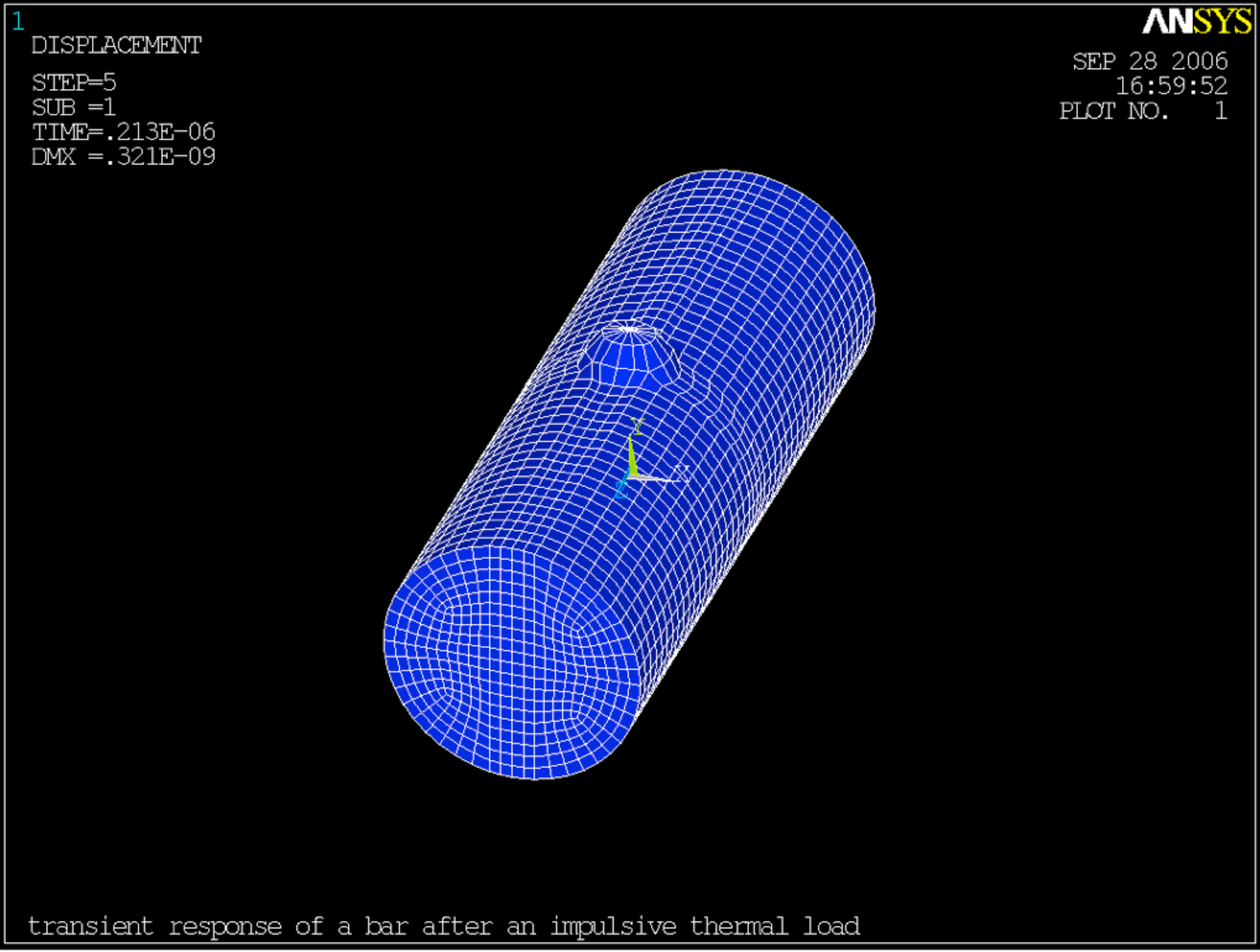
G_n cylinder form factor, first order in R/L

(Barish-Liu Phys Rev Lett 61 1988)

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



F Ronga INFN LNF CRIS2008



giovedì 13 settembre 2012

Thermal acoustical effects:

applications in several sectors

Thermal acoustical effects:

applications in several sectors

Dosimetry and beam monitoring:

Kalinichenko et al

Thermal acoustical effects:

applications in several sectors

Dosimetry and beam monitoring:

Kalinichenko et al

Proceedings of the 2003 Particle Accelerator Conference

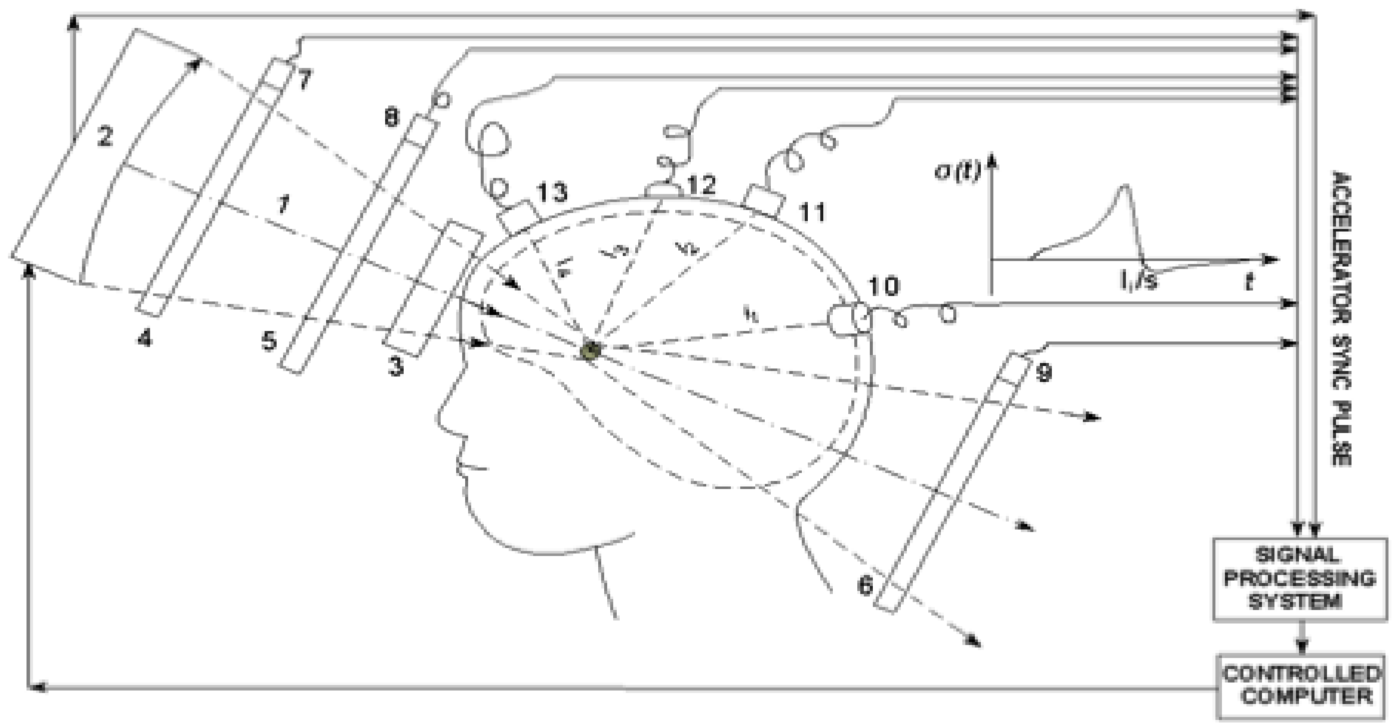


Figure 1: Scheme of radiation- acoustic monitoring of therapeutic beam in patient's body-

F Ronga INFN LNF CRIS2008

Thermal acoustical effects:

applications in several sectors

Dosimetry and beam monitoring:

Kalinichenko et al

Very high energy neutrinos under=sea

Saund , NEMO, ANTARES...

Proceedings of the 2003 Particle Accelerator Conference

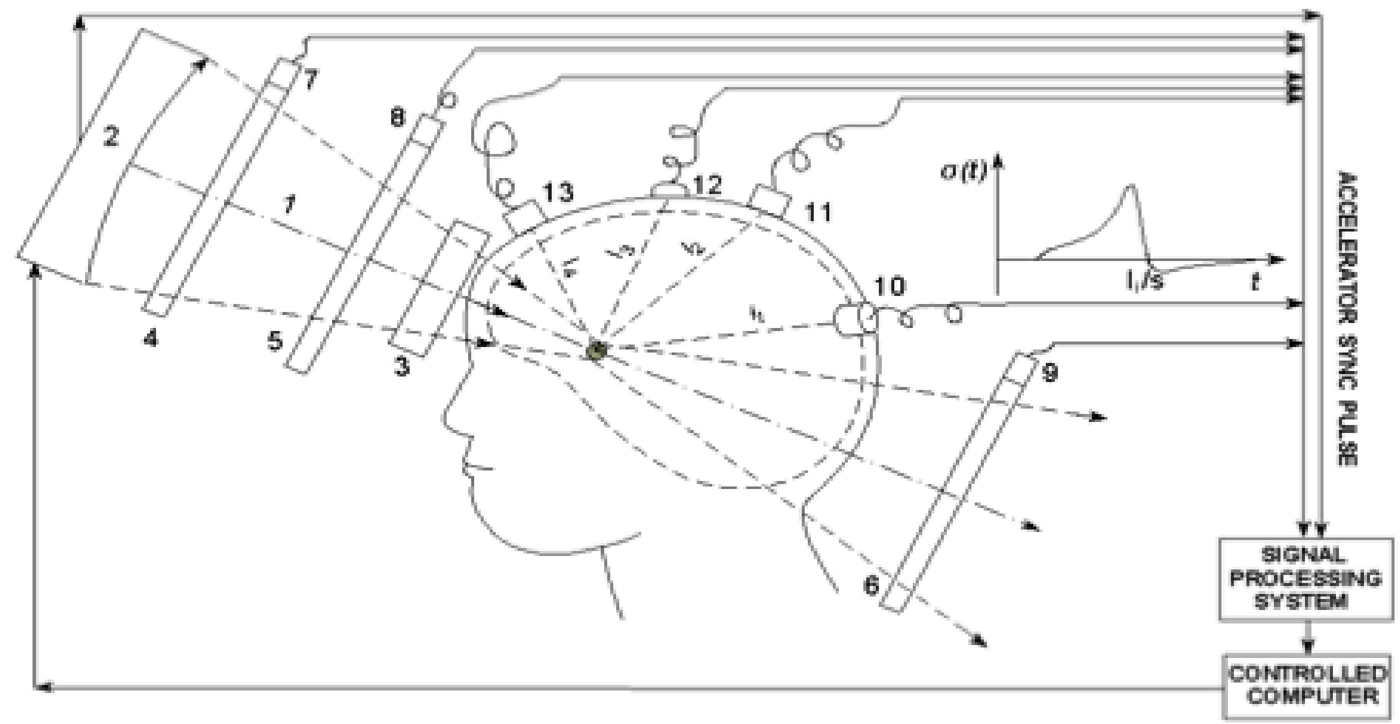


Figure 1: Scheme of radiation- acoustic monitoring of therapeutic beam in patient's body-

F Ronga INFN LNF CRIS2008

Thermal acoustical effects:

applications in several sectors

Dosimetry and beam monitoring:

Kalinichenko et al

Very high energy neutrinos under=sea

Saund , NEMO, ANTARES...

Proceedings of the 2003 Particle Accelerator Conference

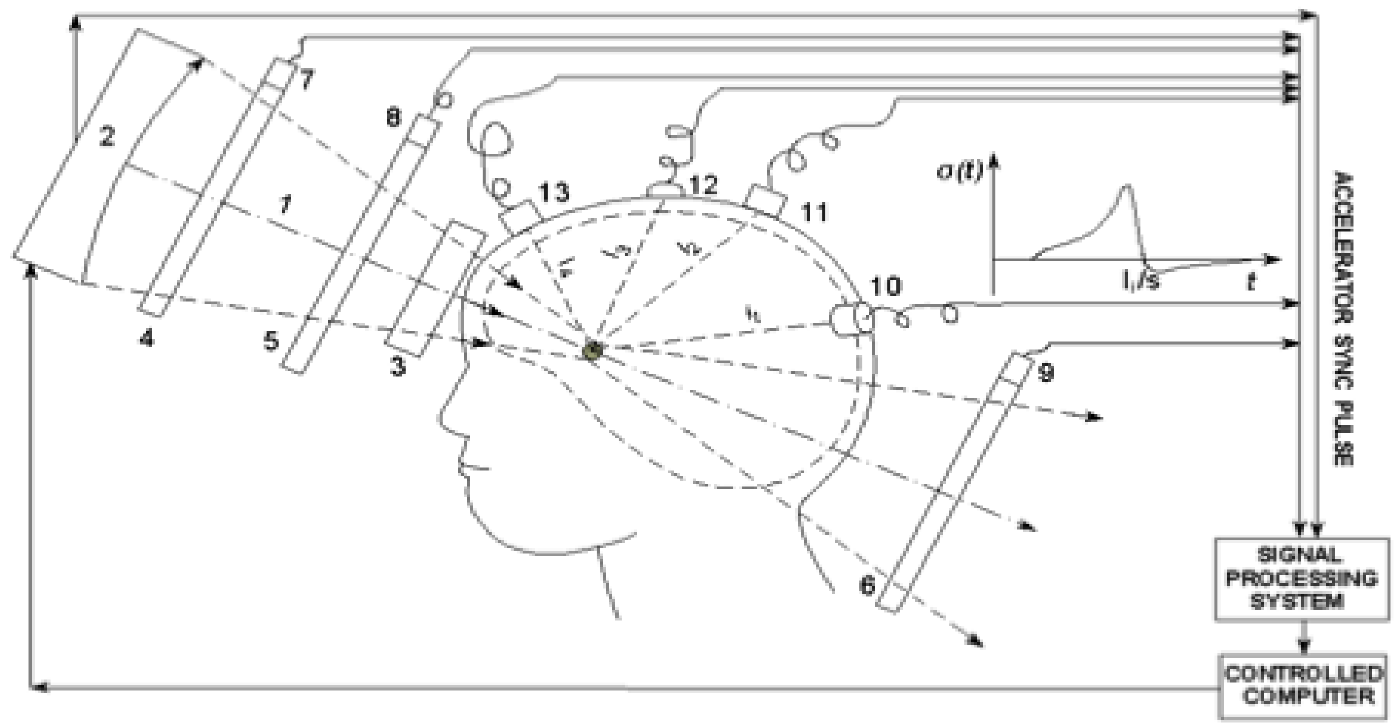


Figure 1: Scheme of radiation- acoustic monitoring of therapeutic beam in patient's body-

Thermal acoustical effects:

applications in several sectors

Proceedings of the 2003 Particle Accelerator Conference

Dosimetry and beam monitoring:

Kalinichenko et al

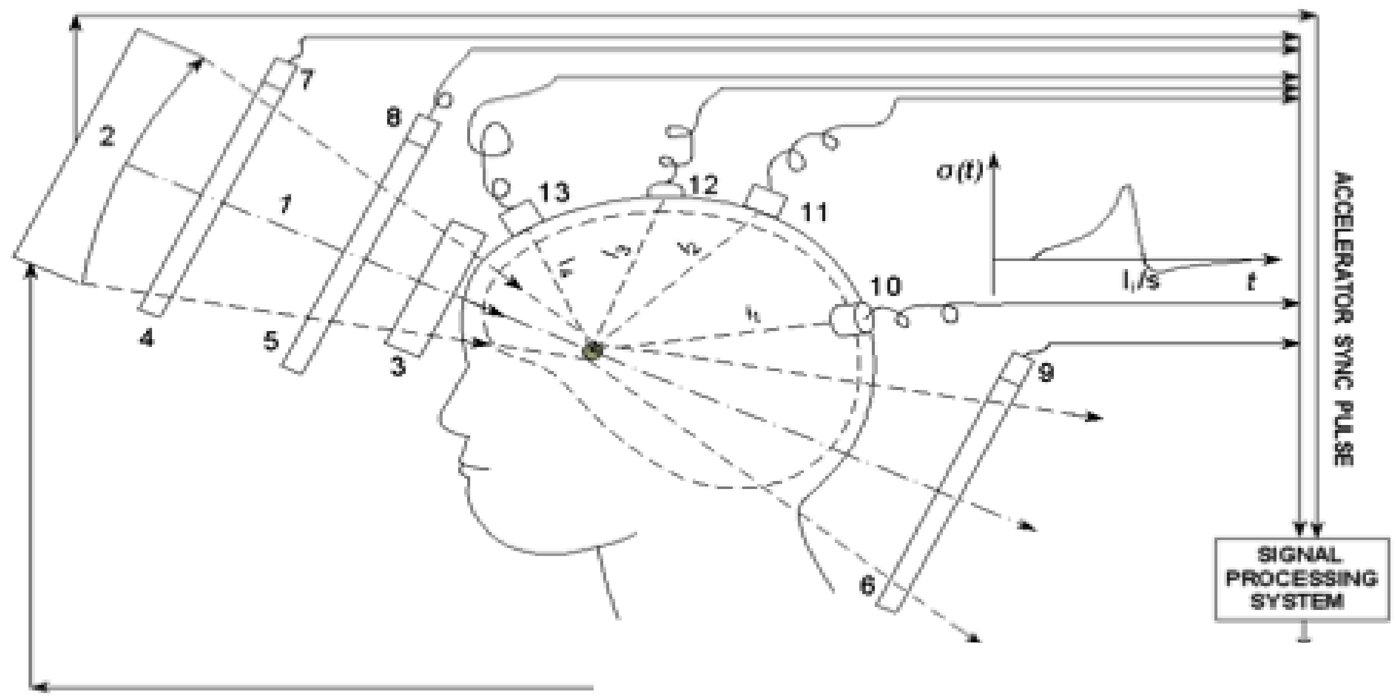
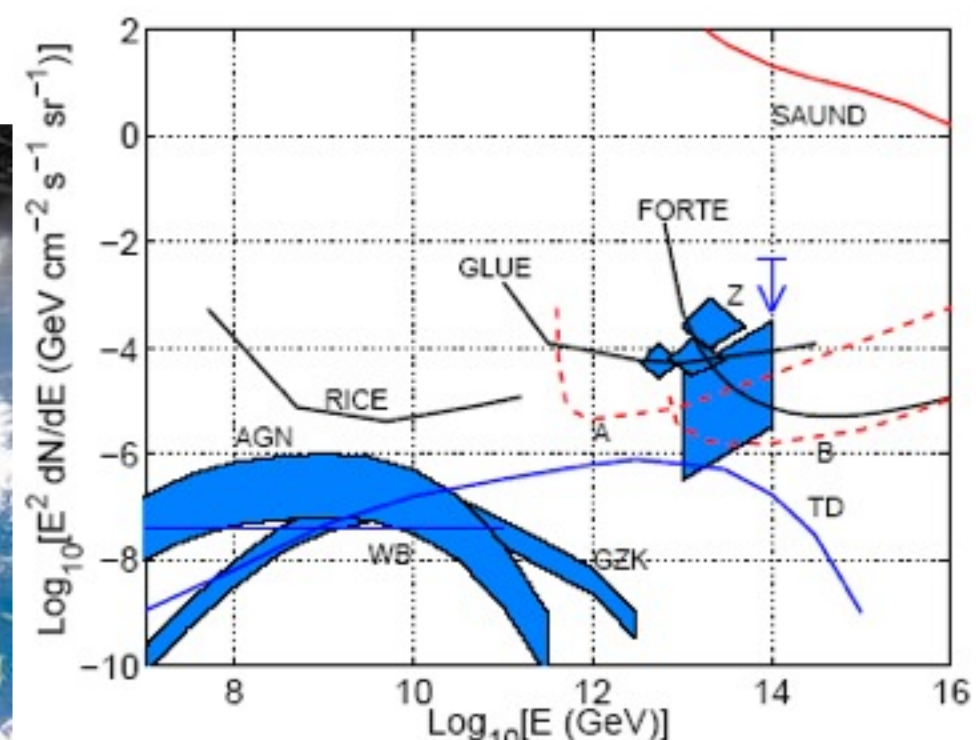


Figure 1: Scheme of radiation- acoustic monitorin;

Very high energy neutrinos under=sea

Saund , NEMO, ANTARES...



F Ronga INFN LNF CRIS2008

Thermal acoustical effects:

applications in several sectors

Dosimetry and beam monitoring:

Kalinichenko et al

Very high energy neutrinos under=sea

Saund , NEMO, ANTARES

dark matter (Picasso experiment)

Proceedings of the 2003 Particle Accelerator Conference

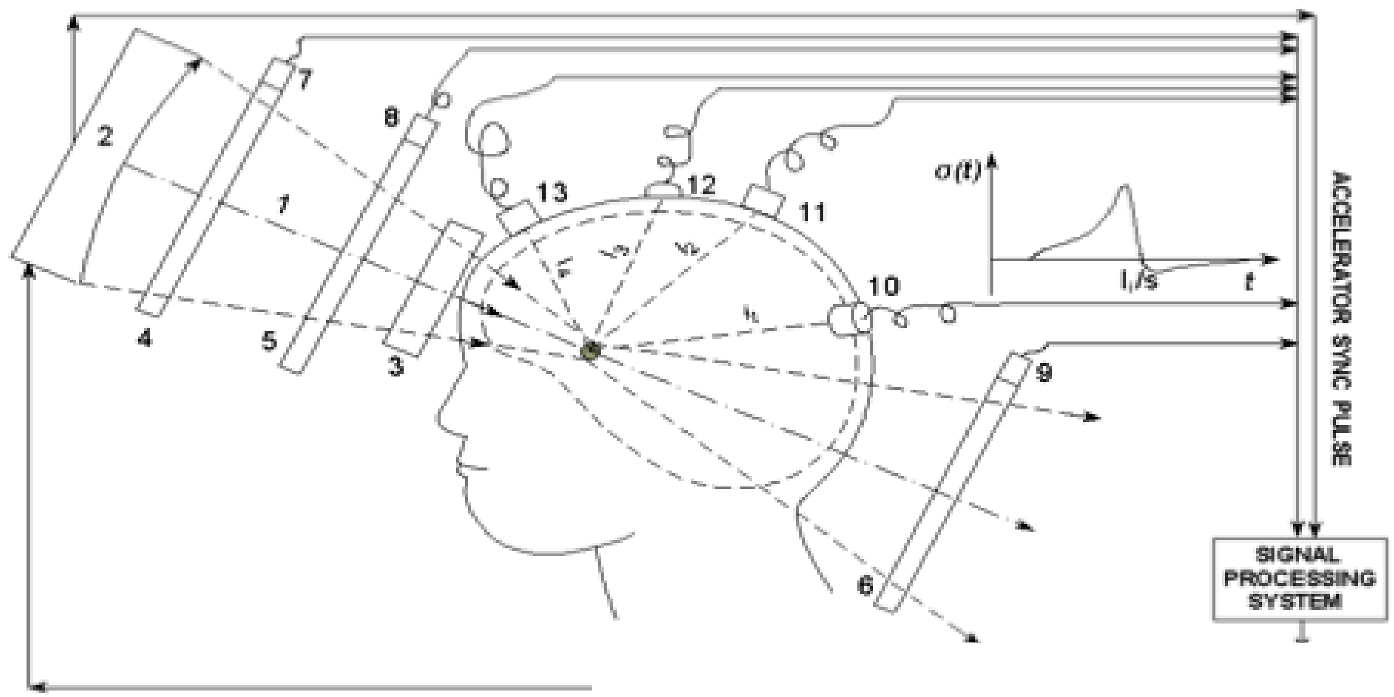
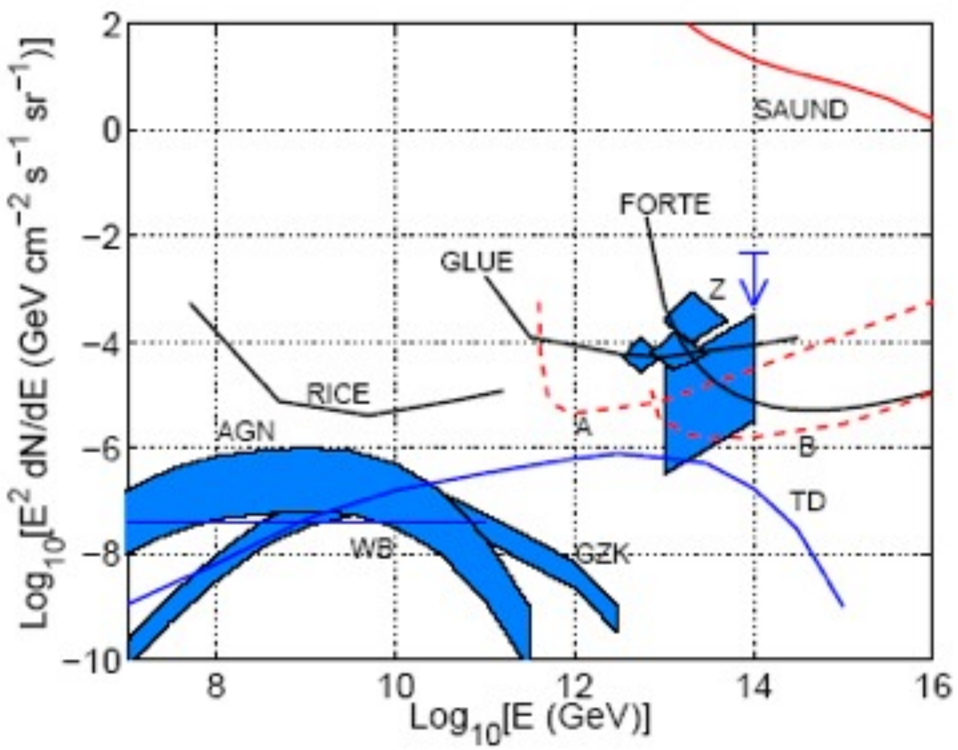


Figure 1: Scheme of radiation- acoustic monitoring



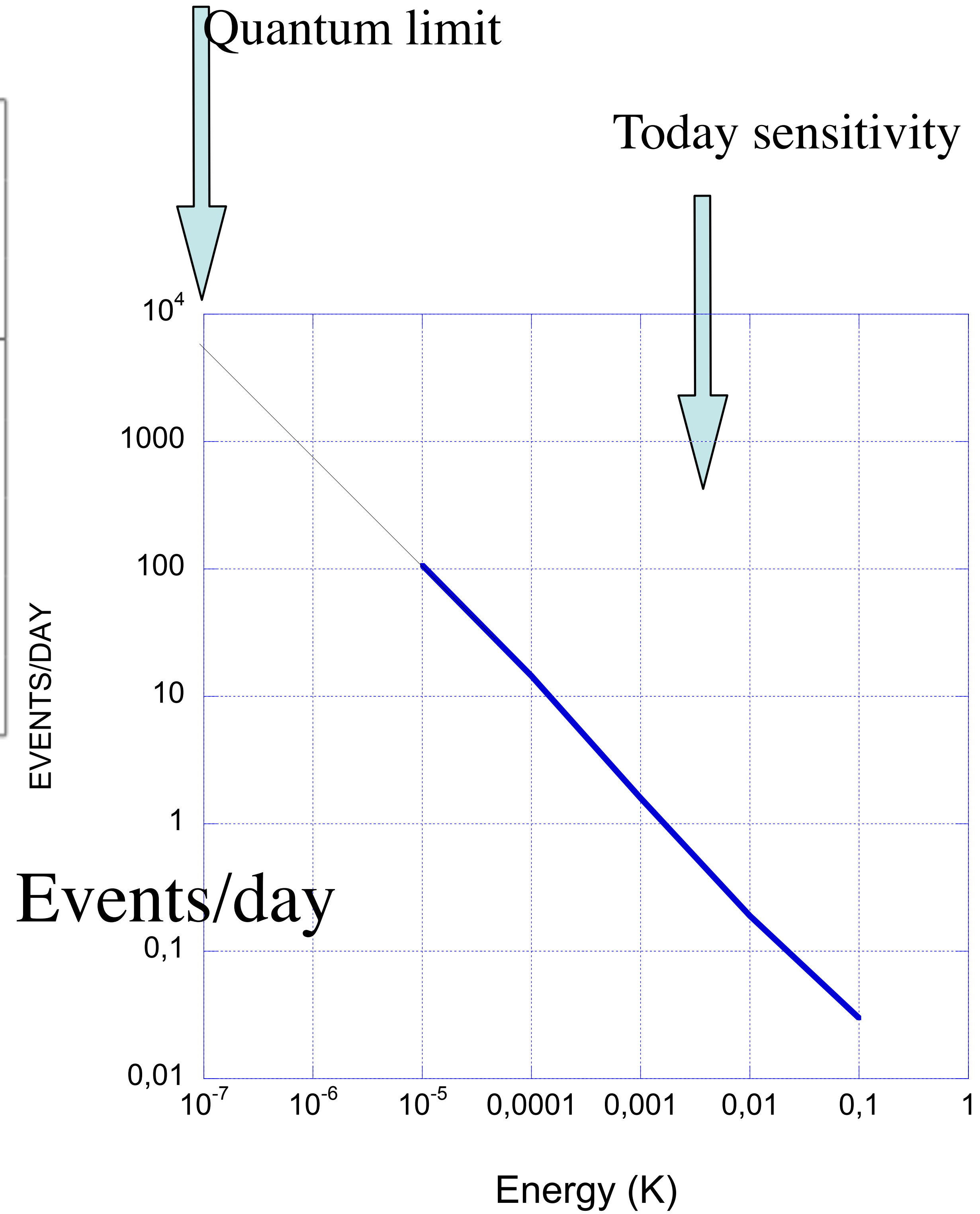
F Ronga INFN LNF CRIS2008

Cosmic rays rates in the bar - computed

Vibrational Energy E (K)	Deposited Energy W (GeV)	Muons	Ext Air Showers	Hadrons	Total (events/day)
$\geq 10^{-5}$	≥ 44.5	15.7	62	29.2	107
$\geq 10^{-4}$	≥ 141	1.6	8.9	4	14.5
$\geq 10^{-3}$	≥ 445	0.2	1	0.4	1.6
$\geq 10^{-2}$	≥ 1410	0.003	0.13	0.06	0.19
$\geq 10^{-1}$	≥ 4450				0.03

Table 1

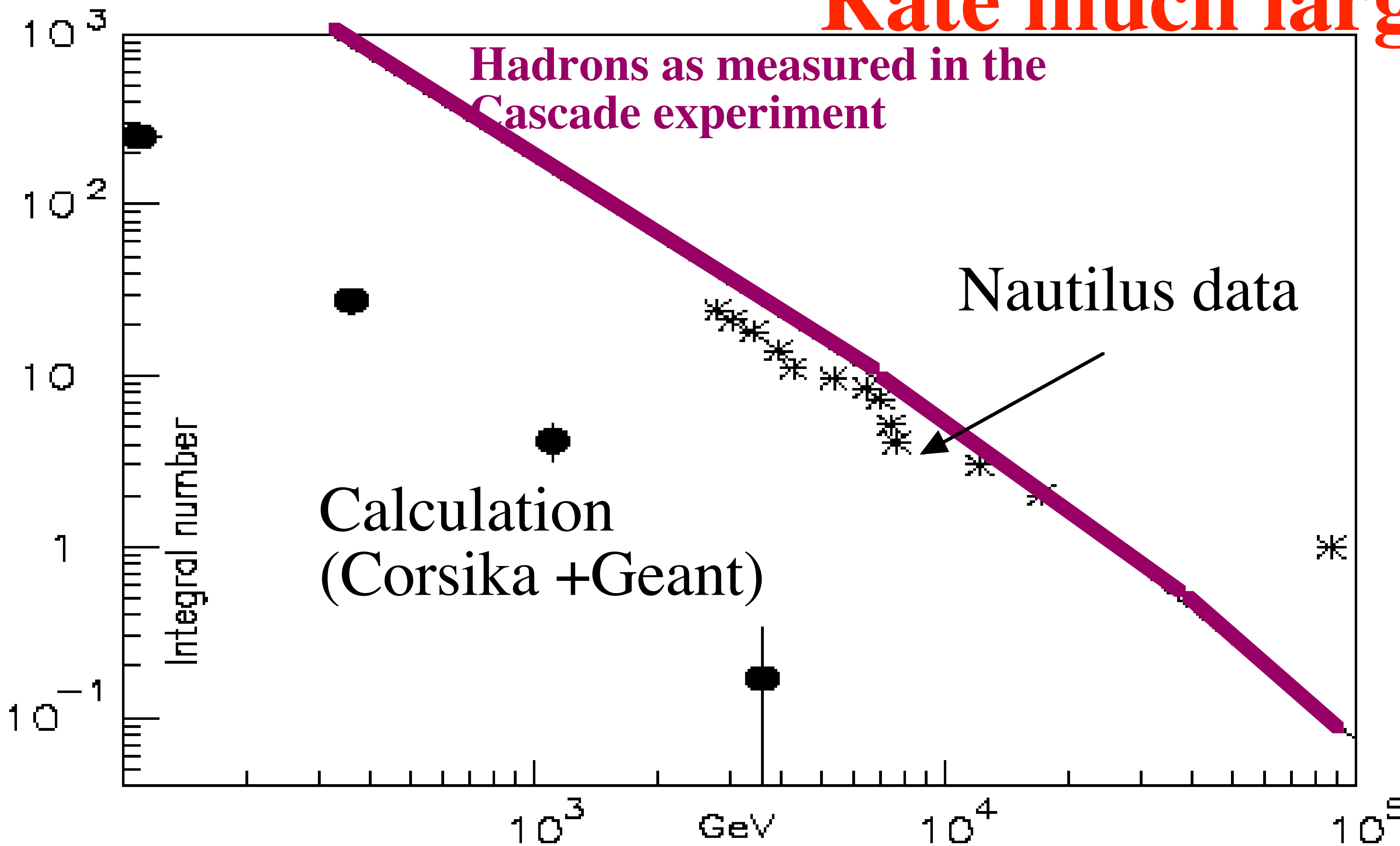
With the today bar sensitivity events are due mainly to cosmic rays with a primary of energy >**~10^{14} eV**



But a big surprise in 1998!!!

(Nautilus first detection of cosmic rays in a GW detector)

Rate much larger !!



The hadrons measured by Cascade should be and upper limit, because

the bar should contain only ~a few percent of the adronic energy

The unexpected result in 1998 :

- **more than 1 order of magnitude** difference in the rates (or in the energy measured by the antenna)
- the thermo-acustical detection is quite different from the conventional (no threshold in β.. see later....)
- 1) possibility of "exotics" in the interaction or in the particles (cross sections, nuclearites..ecc.)
- 2).... or an effect increasing the sensitivity of the detector ..for example due to the superconductivity
- we decided to proceed with a **dedicated experiment** (RAP rivelazione acustica di particelle) and in the meantime to implement a cosmic ray detector in EXPLORER

Nautilus Explorer and small signals:

enhancement at T=0.14K! 4 years of data

- an "event" in the antenna language should have a 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 : **quantitatively this enhancement is ~ the same observed in RAP (see next slides)**

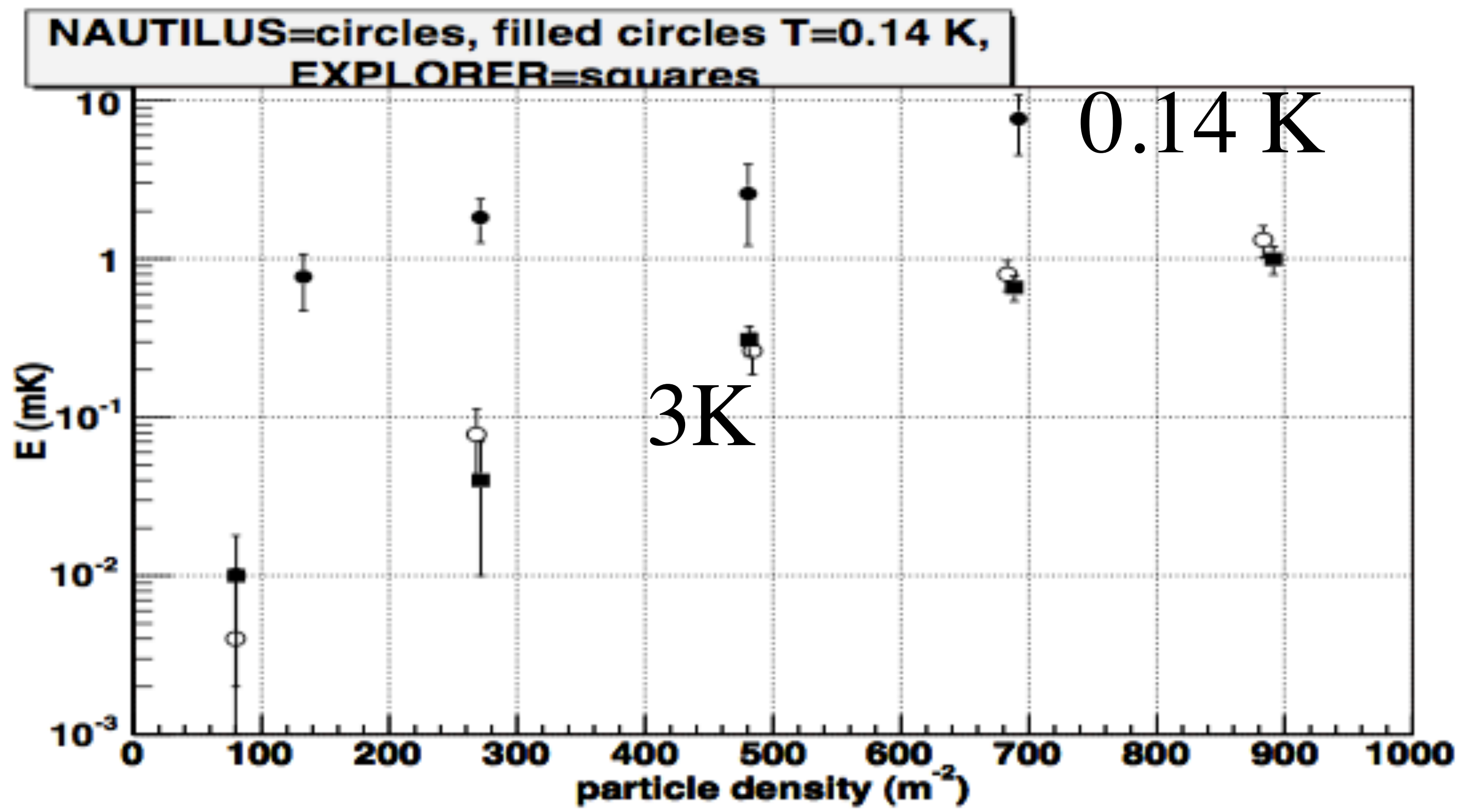
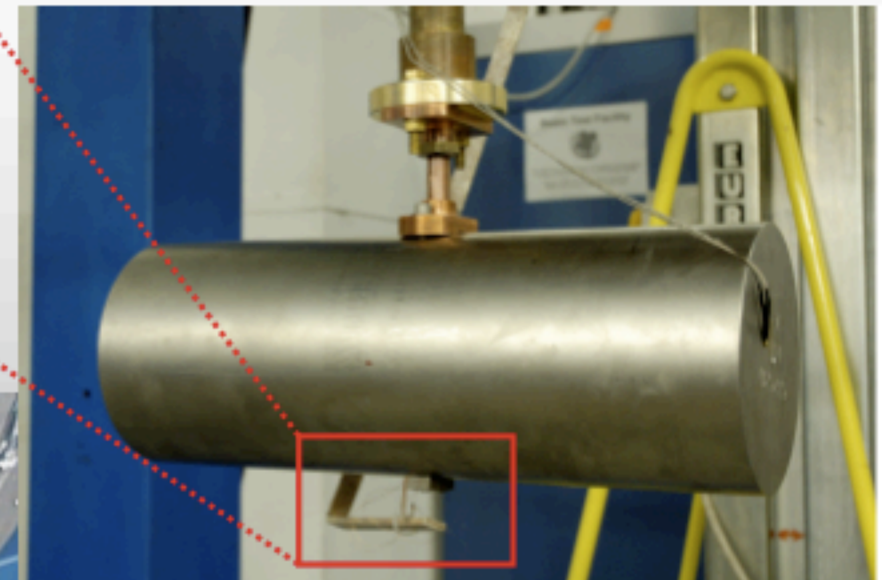
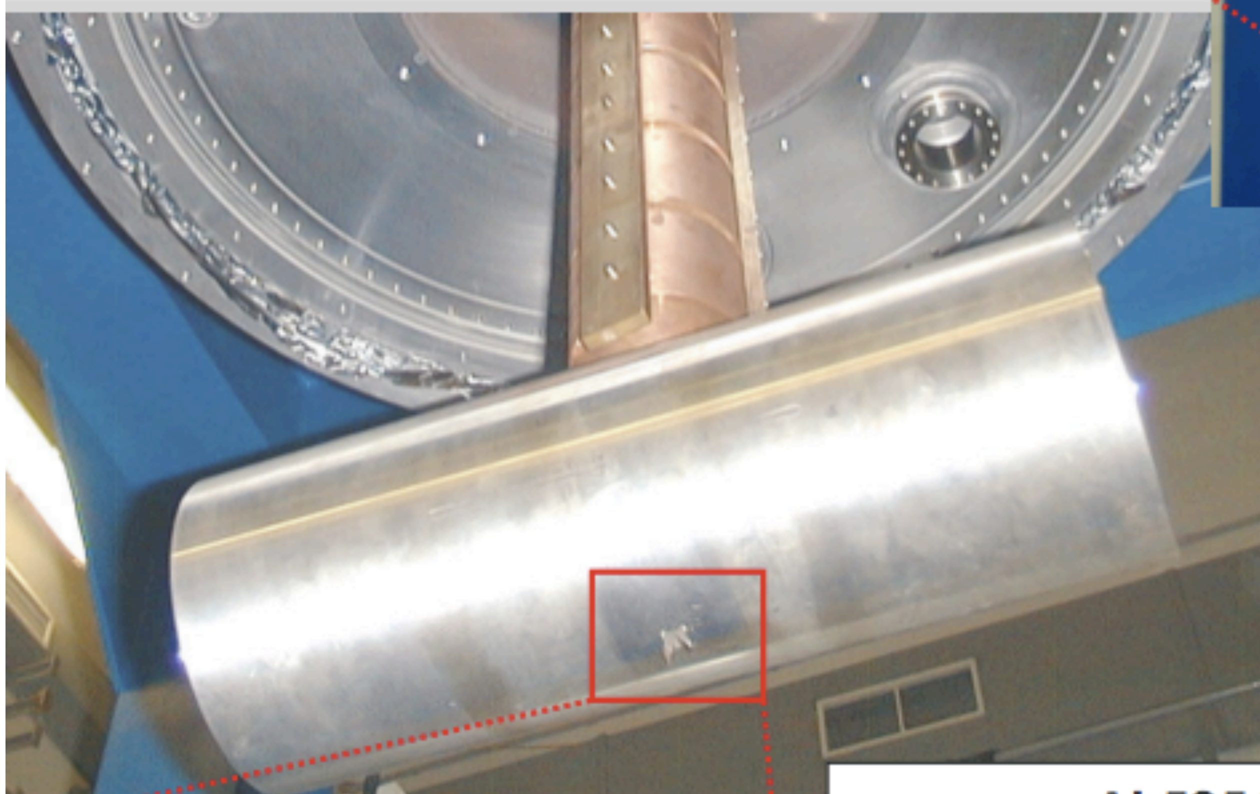


Fig. 3. Averages of signals with energy $E_{exp} \leq 0.1\ K$, grouping data in ranges of particle density Λ. Filled circles NAUTILUS at T = 0.14 K, open circles NAUTILUS at $T = 3\ K$, filled squares EXPLORER at $T = 3\ K$. The data gathered at $T = 0.14\ K$ are almost one order of magnitude larger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

Experimental Setup

Rivelazione Acustica di Particelle



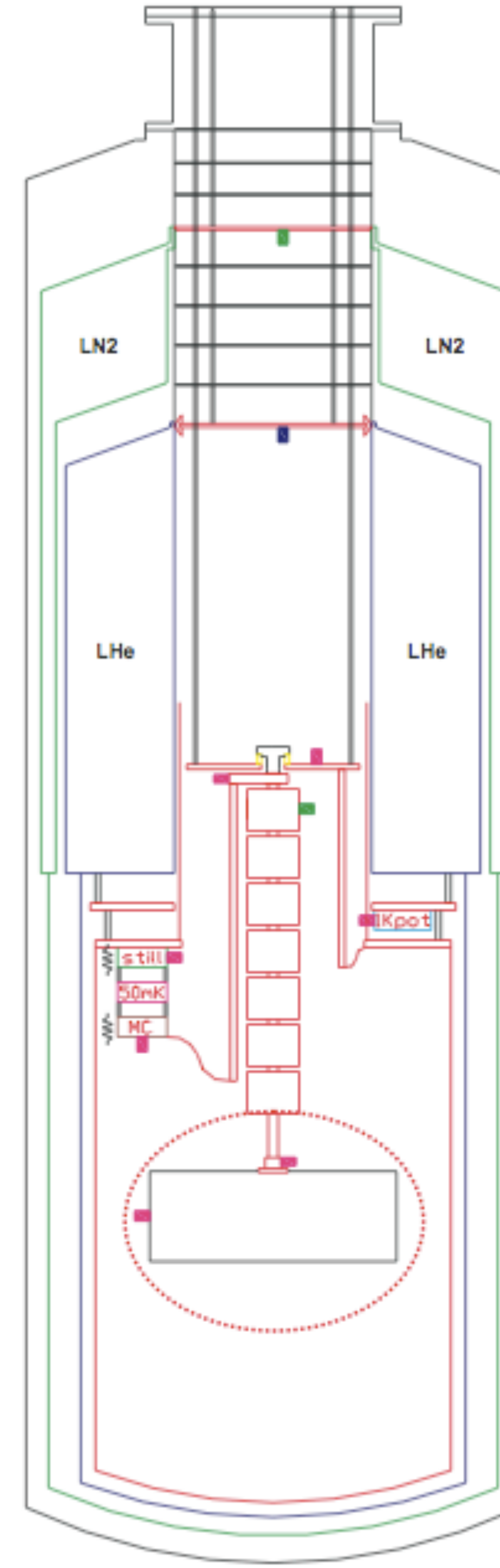


Niobium Bar

- 27.4x10 cm, 18.4 kg
- ν = 6373 Hz @ 290 K
- annealed, purity > 99%
- 2 PZ24 ceramics in parallel glued to the bottom center
- $\lambda \sim 10^6$ V/m

Al 5056 Bar

- 50x18.1 cm, 34.1 kg
- ν = 5096 Hz @ 296 K
- 2 Pz24 ceramics in parallel embedded in the bar
- $\lambda \sim 10^7$ V/m



Al5056 Measurement Results

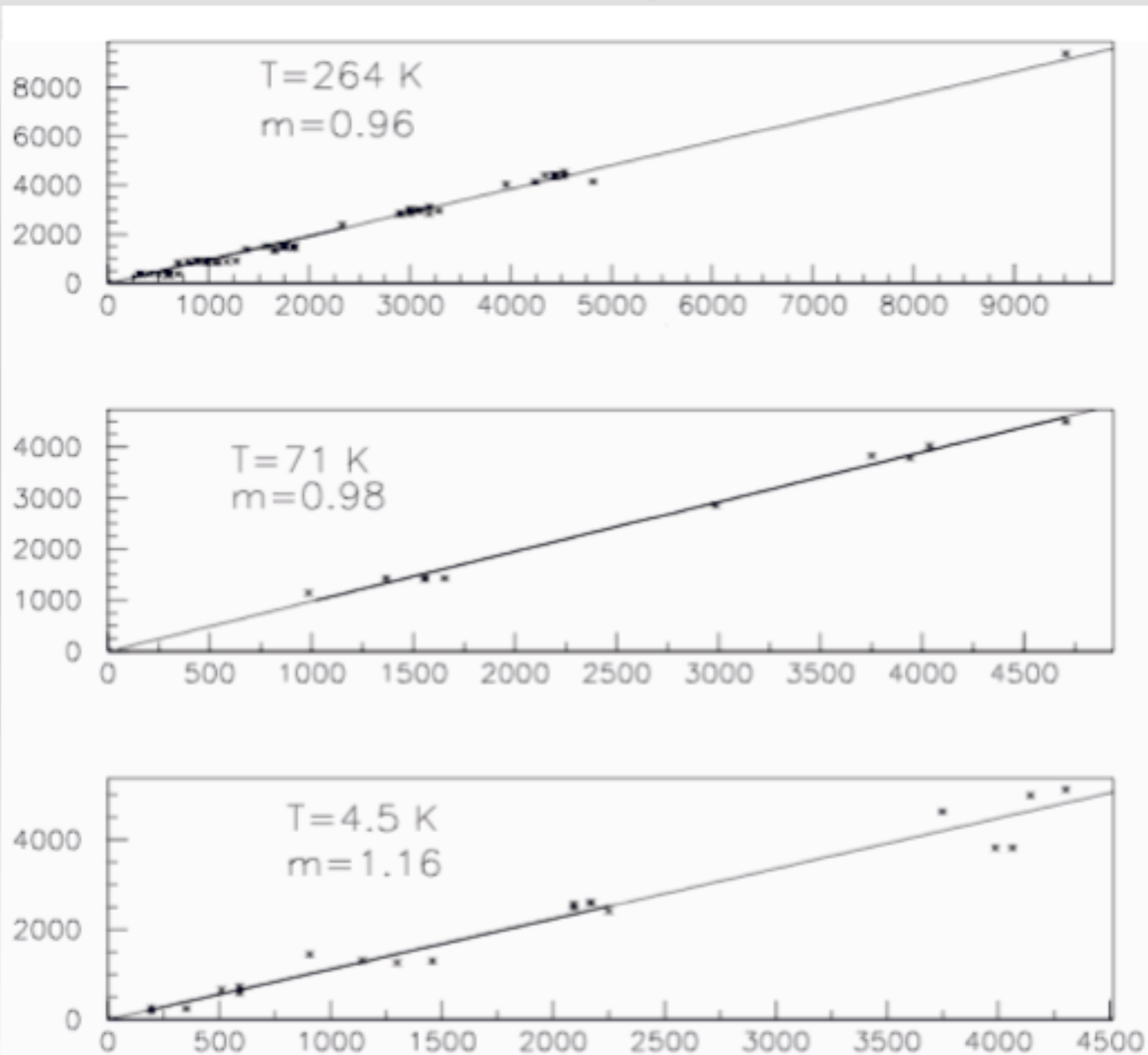
- normal state -

AstroParticle Physics **24**, 65-74 (2005)

full agreement with the thermo-acoustical model

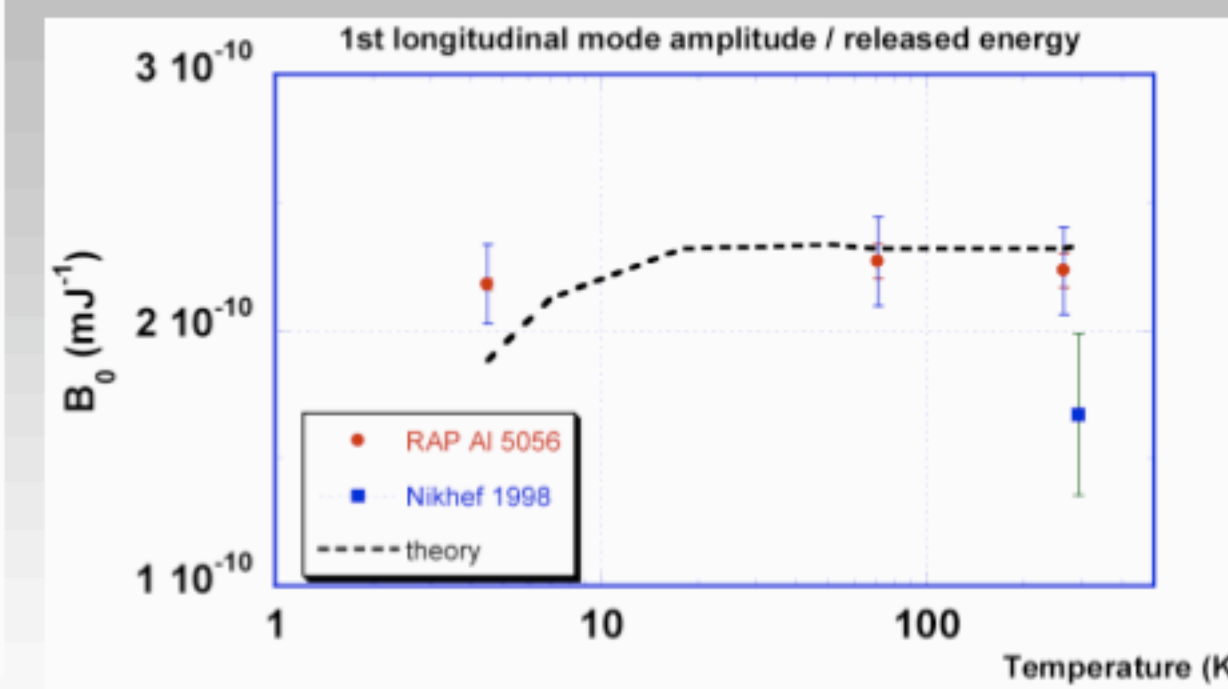
$$B_{MEAS} = mB_{TH}$$

measured vs calculated 1st longitudinal mode amplitude



B_{MIS} vs B_{TH} (10^{-16} m)

T [K]	B_{TH} [10^{-10} m/J]	m	Δm
264	2.32	0.96	0.01
71	2.32	0.98	0.03
4.5	1.88	1.16	0.03

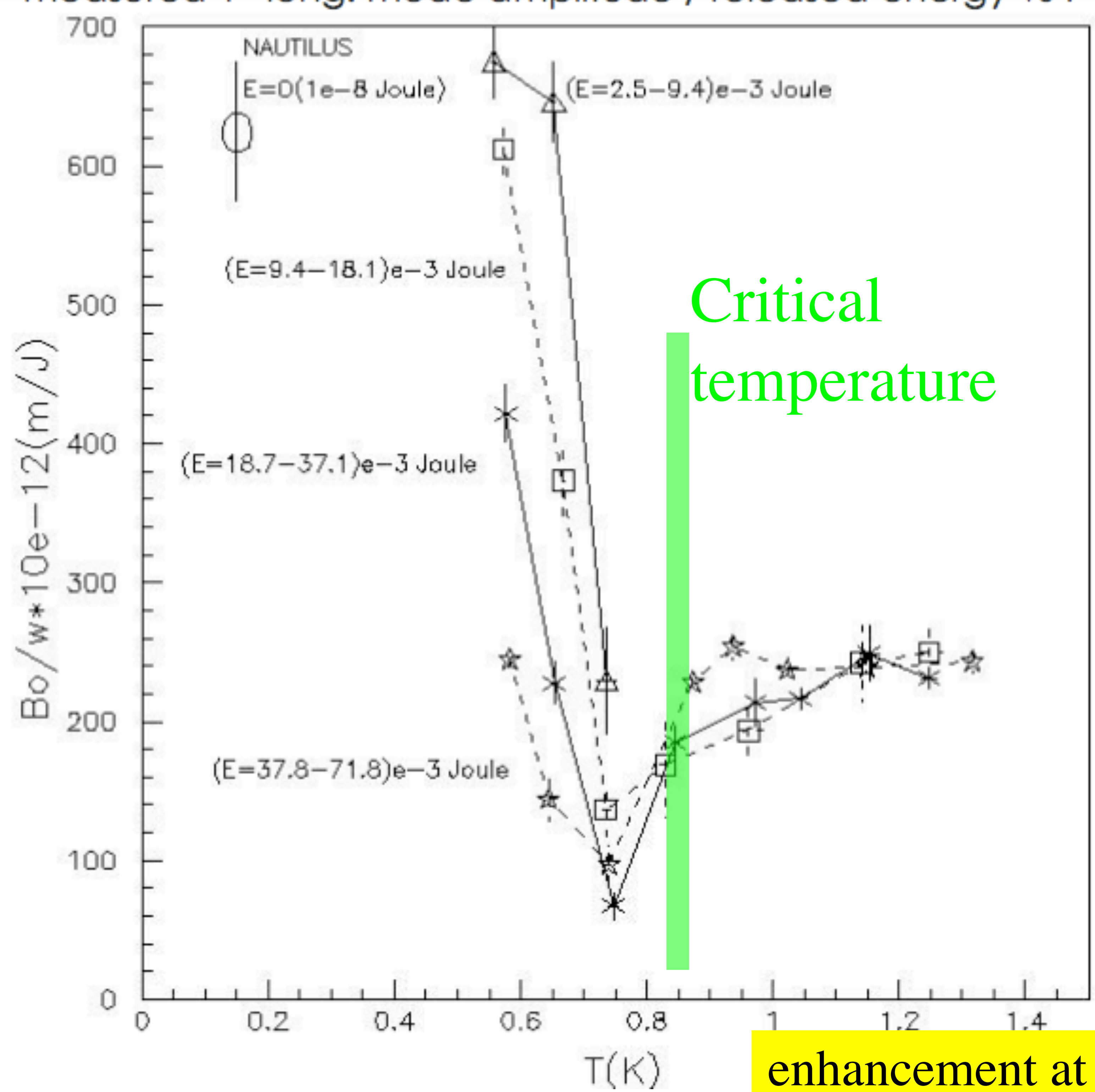


Al5056 Measurement Results

- superconducting state -

Much more complicated!!!

measured 1st long. mode amplitude / released energy vs *T*



- Comparison between the RAP measurements and the superconducting NAUTILUS data
- Single shots are grouped in different released energy ranges. In this way a released-energy-dependence has been pointed out
- Measurements at the lowest T seem to be compatible with the cosmic rays NAUTILUS measure
- At present the response depression in the range 0.7 *K* < T < 0.9 *K* has not yet well understood, even though it could be related to a two-components process

enhancement at very low temperature confirmed!!!!

Modification of the thermo-acustical model in a superconductive state

- in addition to the expansion due to the heating we could have a release of additional energy if a local transition from the superconductive (***s***) state to a normal (***n***) state occur, due to the different energies of the ***s*** and ***n*** state. This effect has been demonstrated in the "superconductive strip" detector

so two possibilities:

1) no local ***s - n*** transition : normal thermo-acustical model with low temperature parameters

2) ***s - n*** transition : overlapping of two effects :
thermo-acustical with normal state parameters + ***s - n*** transition pressure wave

the two effects could have different sign ("interference")

$$\frac{X}{W} = \left[\left(\frac{X}{W}\right)_{trans}\right] + \left[\left(\frac{X}{W}\right)_{norm}\right] =$$

$$\left[\mathcal{F}\left(H_c, \frac{\partial H_c}{\partial T}, \frac{\partial H_c}{\partial P}\right)\right] + \left[B\left(\frac{\alpha}{c_V}\right)_{norm}\right]$$

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

A. De Rujula & B. Lautrup, Nucl Phys. B242 (1984

However we are unable to explain quantitatively the measurements

Event rate putting everything together

using the RAP measurement and correction factors for the different locations
NAUTILUS at 0.14 Kelvin

- continuos line : prediction
- now reasonable agreeement taking into account the large uncertainties

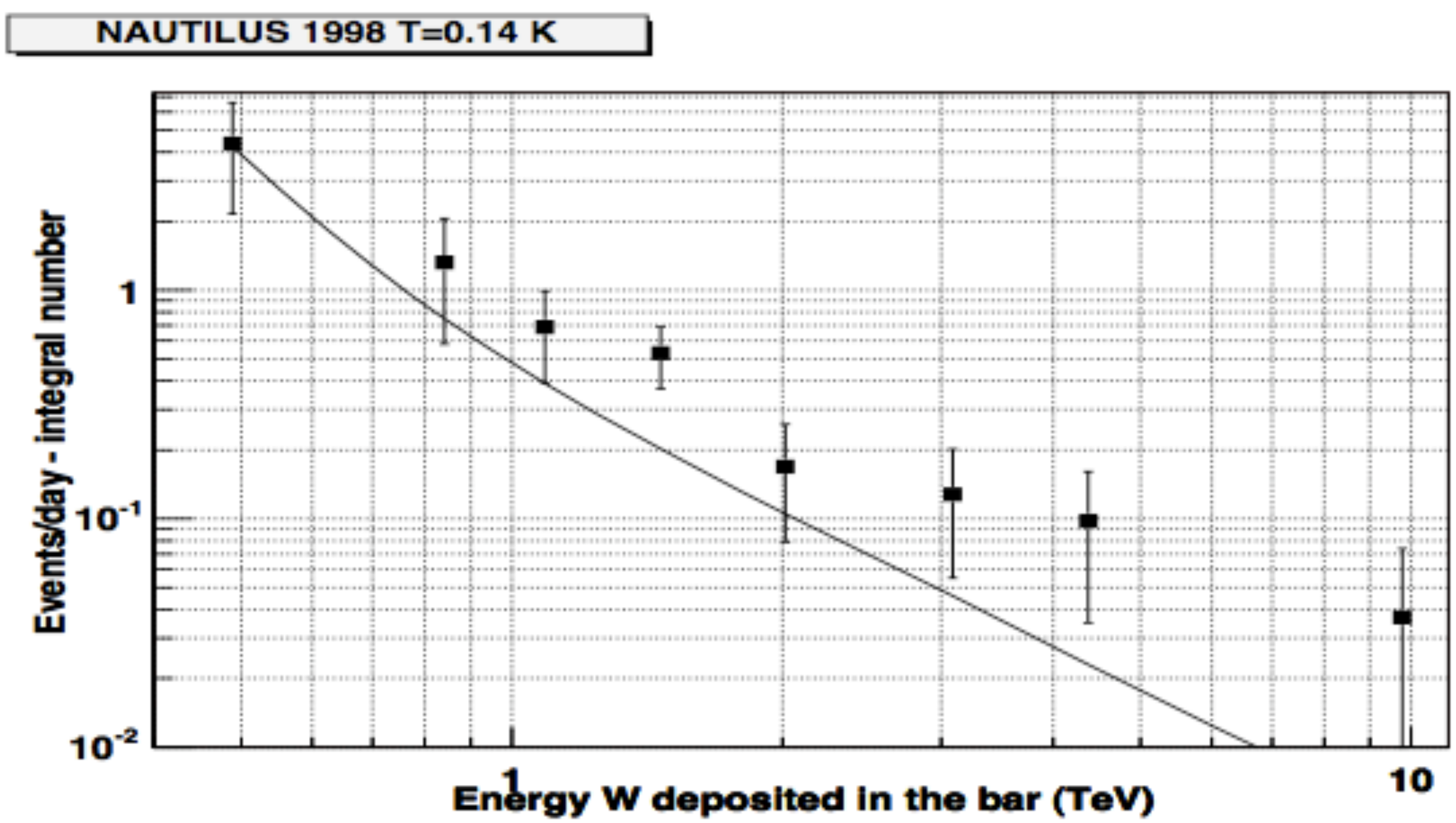
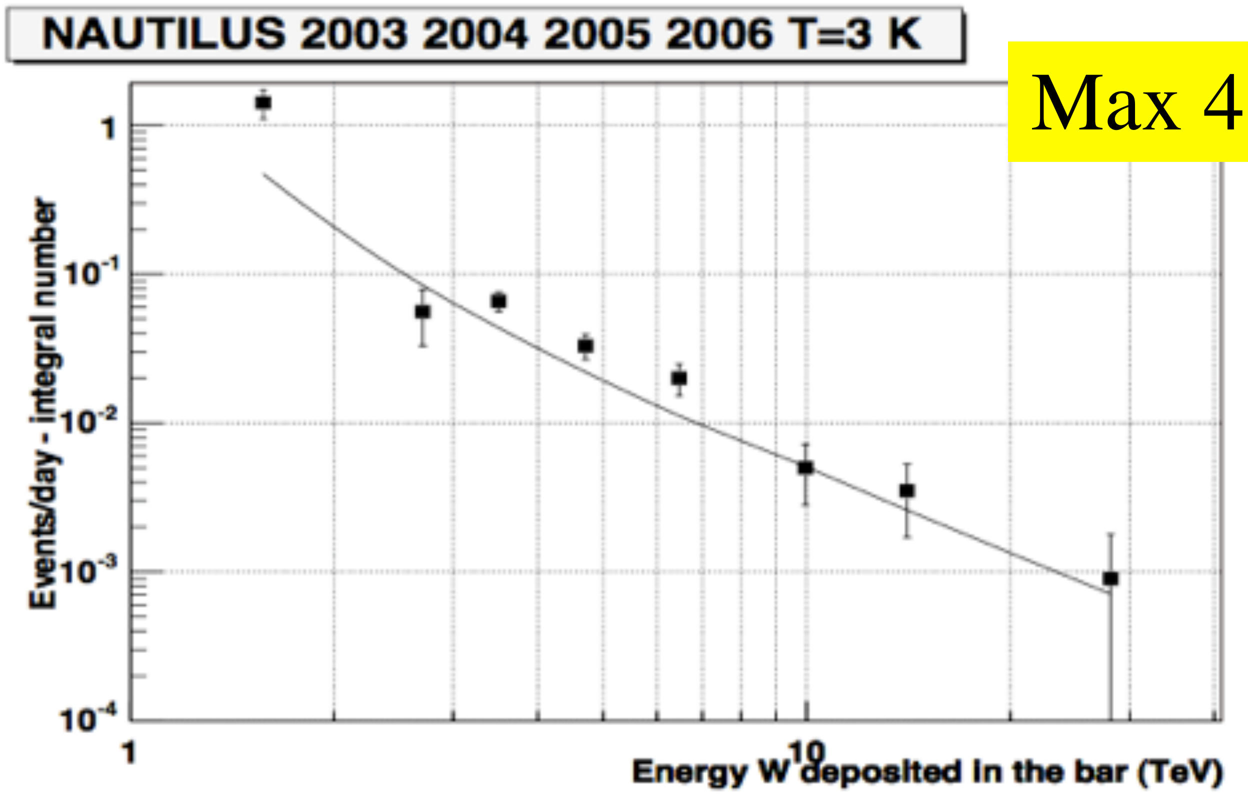


Fig. 5. NAUTILUS 1998. The integral distribution of the event rate after the background unfolding, compared with the expected distribution (continuous line). The prediction is computed using the data of Table 1 and using the appropriate value $\alpha_s = 3.7$.

Event rate putting everything together

using the RAP measurement and correction factors for the different locations

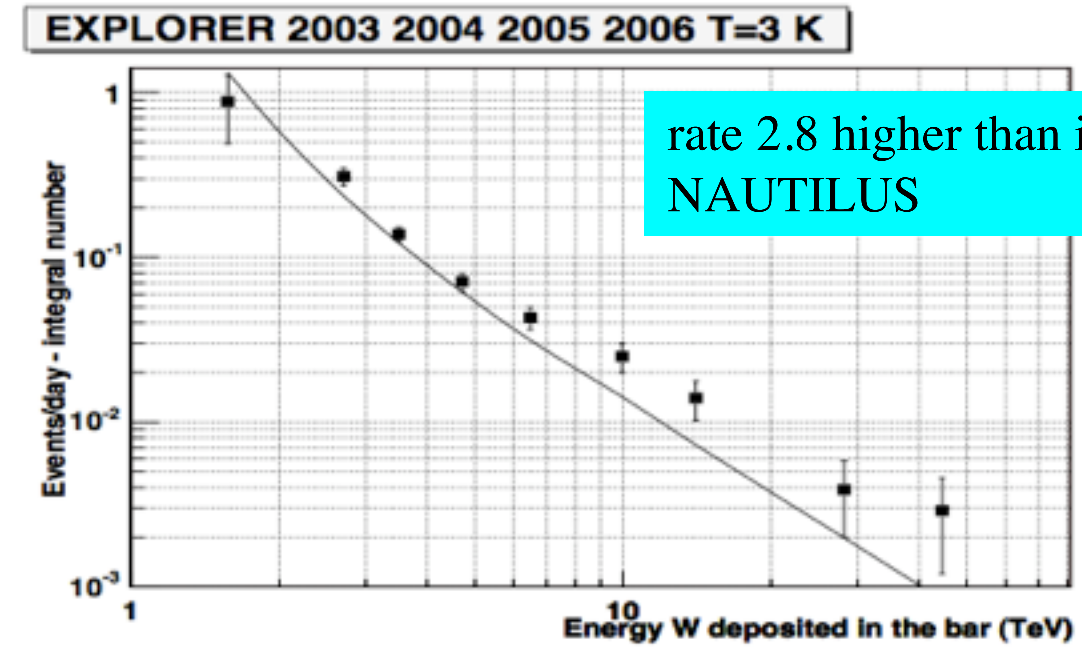
Normal state



Max 4.1 K ~ 28 TeV in the bar

Fig. 8. NAUTILUS 2003-2006 : The integral distribution of the event rate after th background unfolding, as in fig.5, for the four years 2003-2006, compared with th expected distribution (continuous line). The prediction is computed using the dat of Table 1.

Max 670 K ~ 360 TeV in the bar

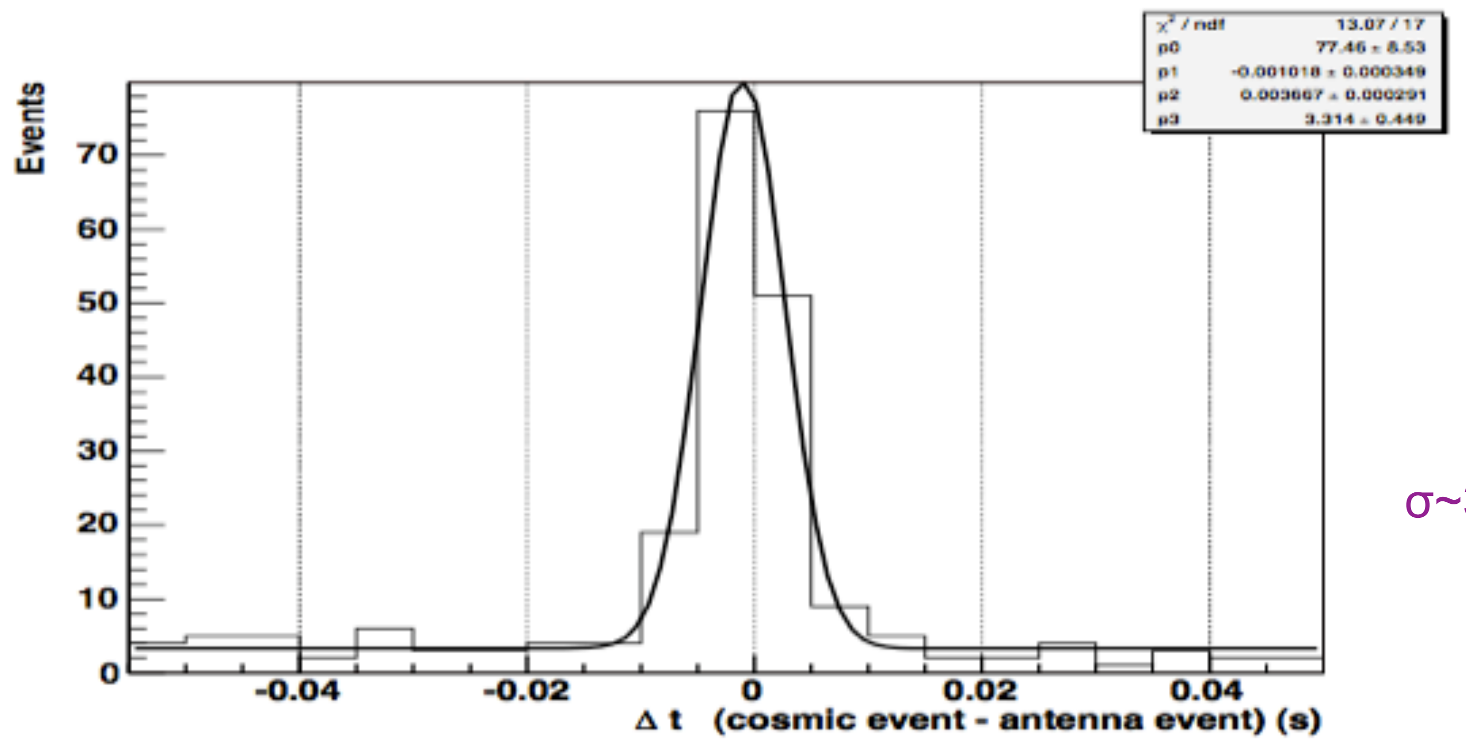


rate 2.8 higher than in NAUTILUS

In Explorer biggest event
~360 TeV in 1022 days - expected ~0.1
from the extrapolation at lower energies

Fig. 11. EXPLORER 2003-2006 : The integral distribution of the event rate after the background unfolding, as in Fig.5, compared with the expected distribution (continuous line). The prediction is computed using Table 1 multiplied by a factor 2.8 (see text).

Application antenna monitoring and performances study: time resolution



σ~3.7ms

Fig. 12. EXPLORER 2003-2006 : Time difference (seconds) between cosmic rays with $\Lambda \geq 100 \ \frac{particles}{m^2}$ and the maximum of the filtered antenna signal, with a cut $E \geq 36 \ T_{eff}$. The fit with a gaussian , with parameters p0=peak, p1=mean, p2=σ and a constant background p3, gives $\sigma = 3.7ms$. The value of the mean (-1±0.35 ms) should be compared to the expected value of -0.6 ms due to the delay of the antenna electronic chain.

Applications for "exotics particles" searches

(nuclearites ecc..)

- limits are higher than the one in other experiment (SLIM 1.4 10^{-15} MACRO 3 10^{-16})
- but some interest because the detection mechanism is quite simple, no threshold in β

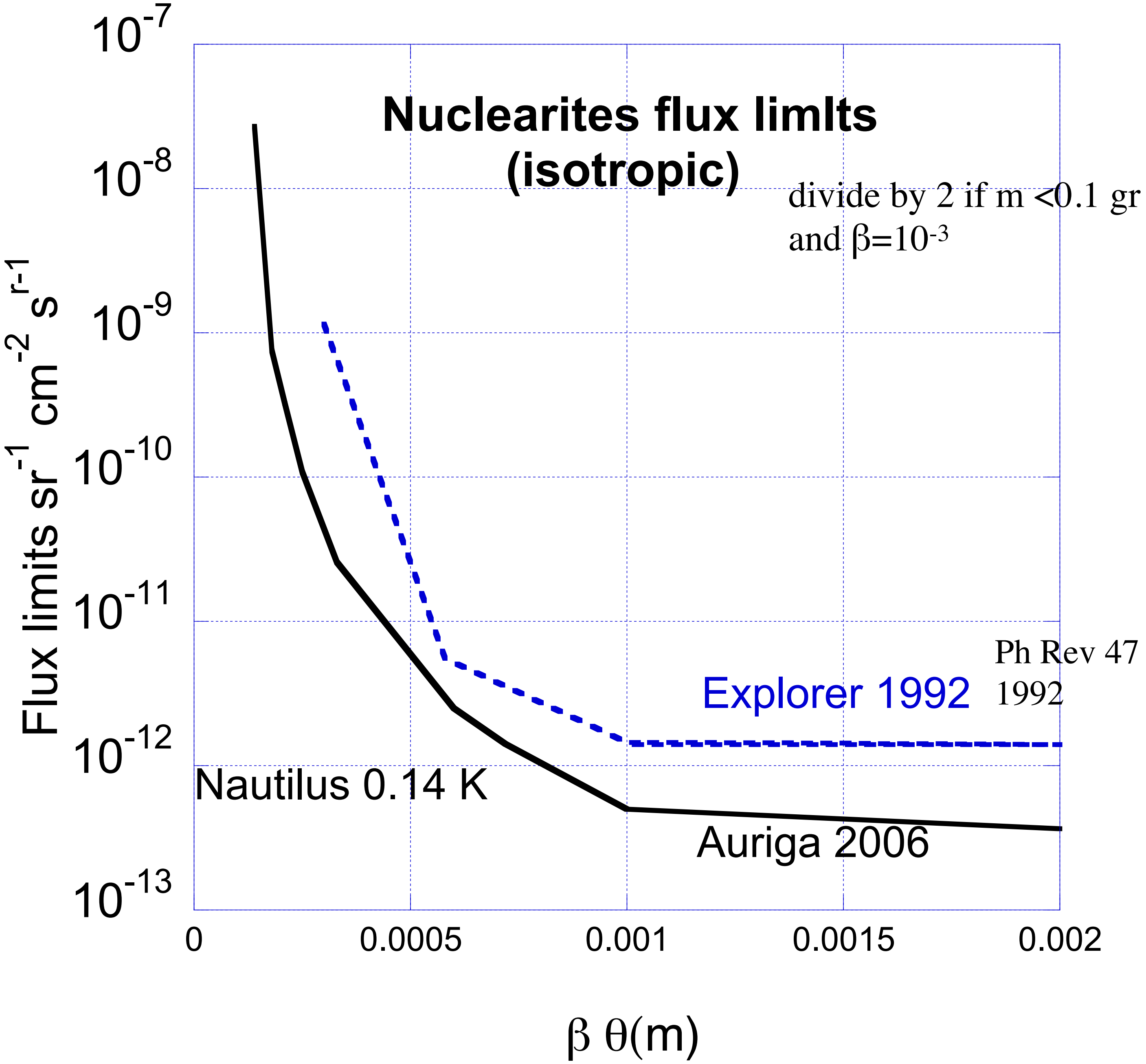
"calorimetric measurement"

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

where the mass dependence is

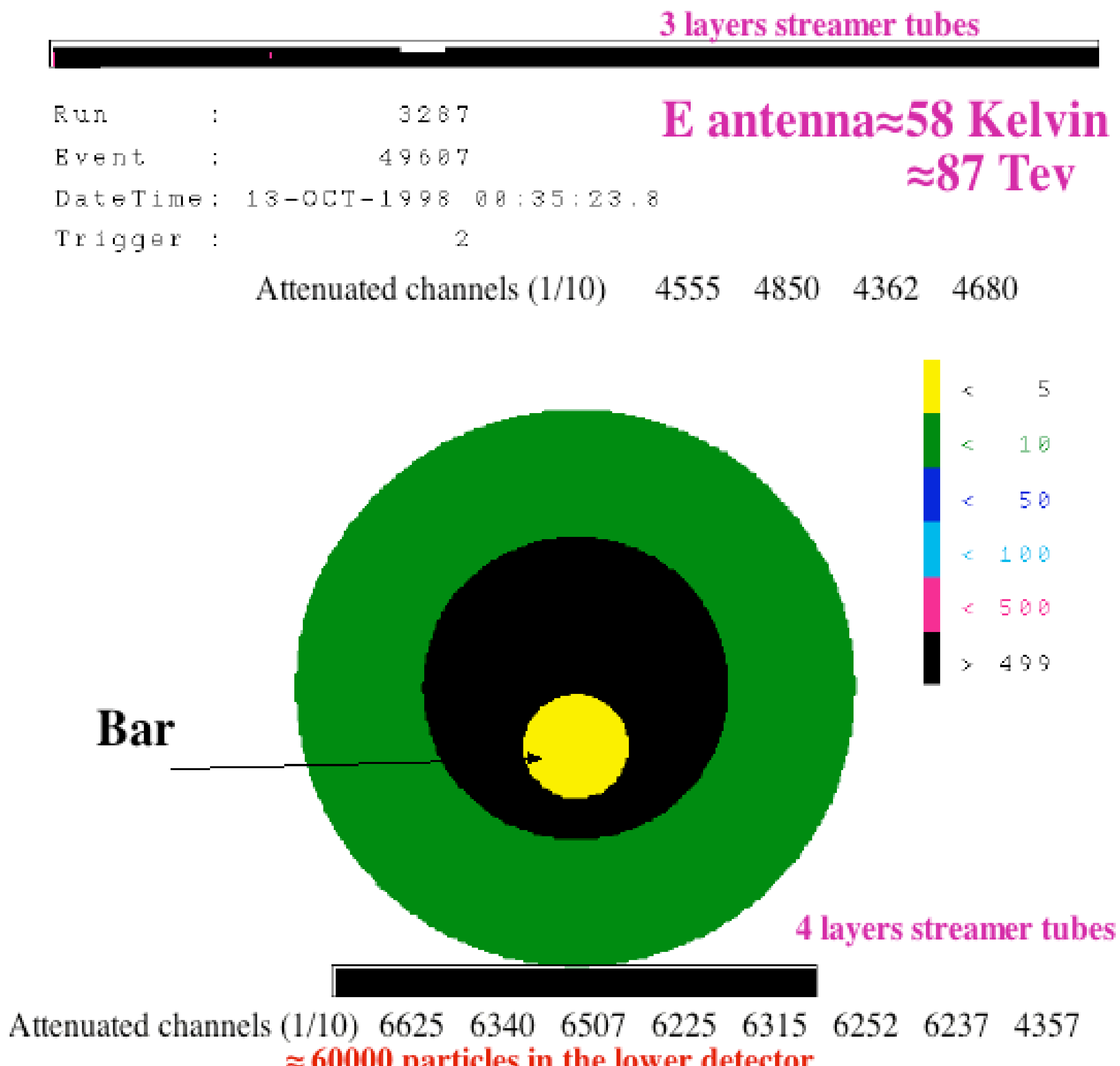
$$\theta(m)=1 \quad \text{if } m\leq 1.5 \text{ ng},$$

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



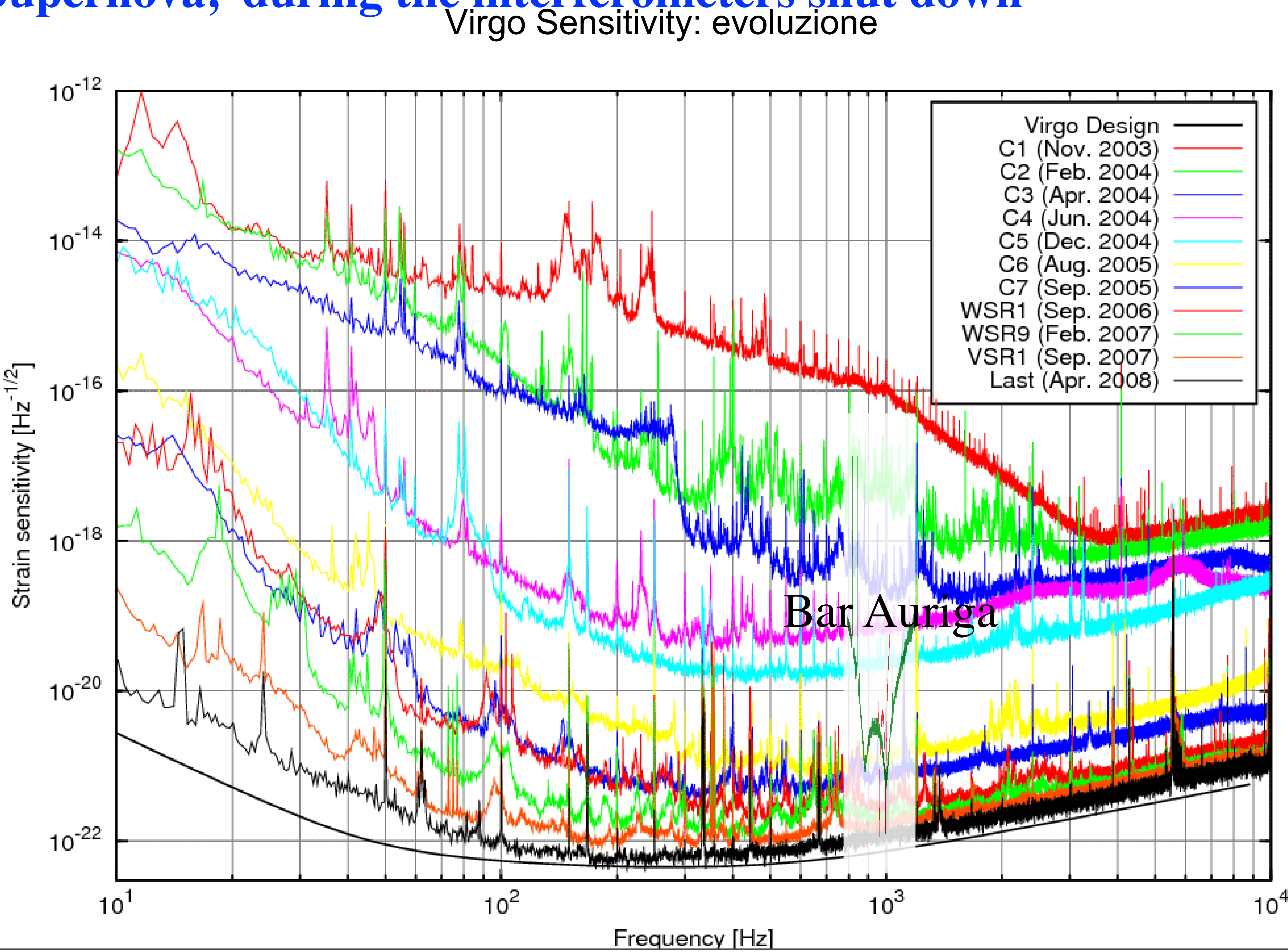
The END

- No **anomaly** found in the cosmic rays interaction with the bar
- GW like antennas very good **"real" calorimeter** for cosmic ray showers. Detectors of this kind (at room temperature) could be considered as hadron calorimeters in future arrays(if any..)
- **Very strange behavior** in superconductive aluminum : interesting problem for solid state



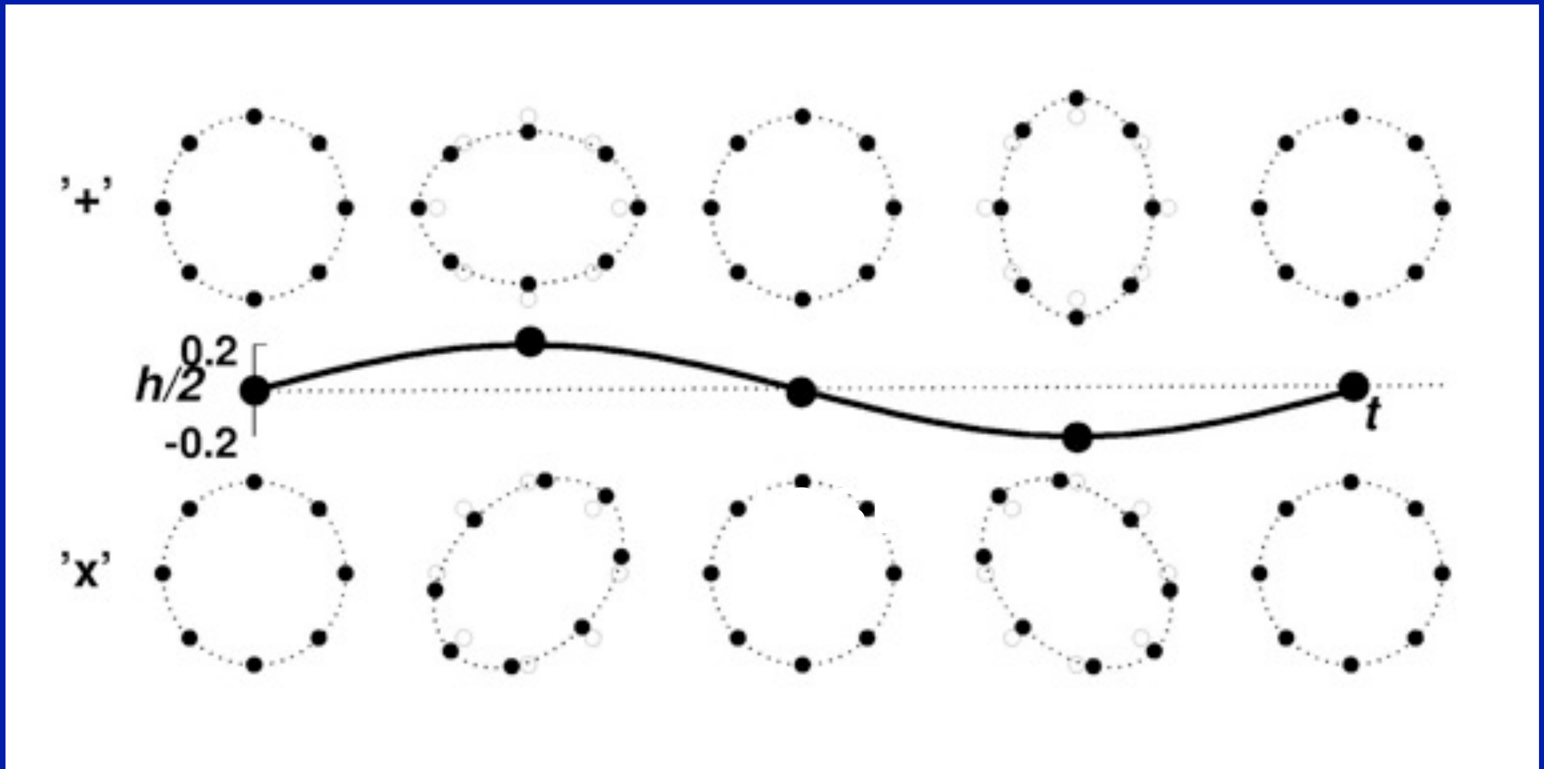
3 layers streamer tubes
Run : 3287
Event : 49607
DateTime: 13-OCT-1998 00:35:23.8
Trigger : 2
E antenna≈58 Kelvin
≈87 Tev
Attenuated channels (1/10) 4555 4850 4362 4680
< 5
< 10
< 50
< 100
< 500
> 499
Bar
4 layers streamer tubes
Attenuated channels (1/10) 6625 6340 6507 6225 6315 6252 6237 4357
≈ 60000 particles in the lower detector

Bar Detector : sensitivity no more competitive with interferometers. But can be useful to monitor galactic events as Supernova, during the interferometers shut down



Two polarizations “+” and “x”

The two independent polarization are shown in the following example (bar and interferometer)



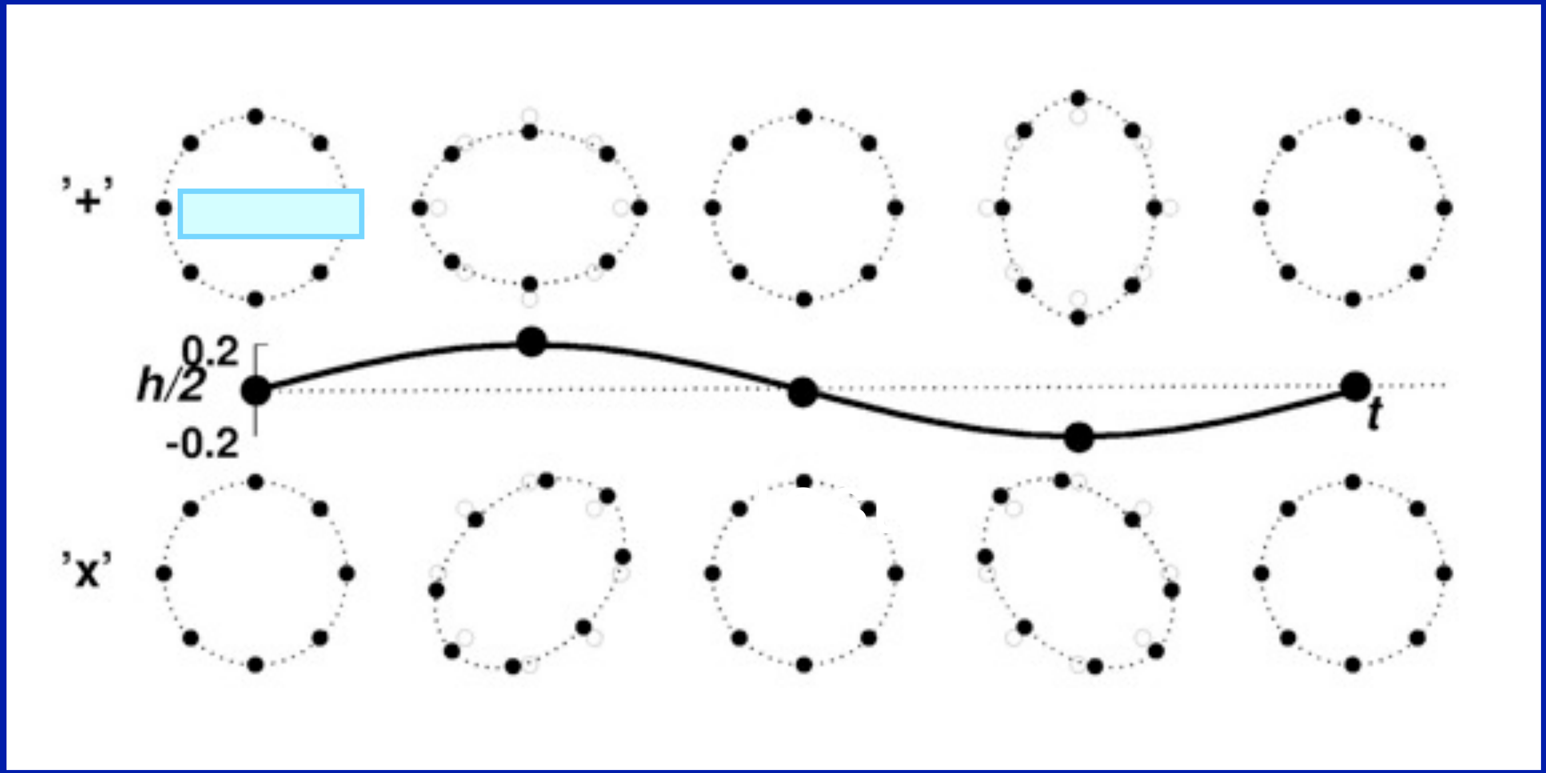
Detectors are sensitive to the polarization and to the angle of incidence

A measurement of the degree of circular polarization determines the inclination of a simple binary orbit.

To fully reconstruct a gravitational wave several cylinders or interferometers are need

Two polarizations “+” and “x”

The two independent polarization are shown in the following example (bar and interferometer)



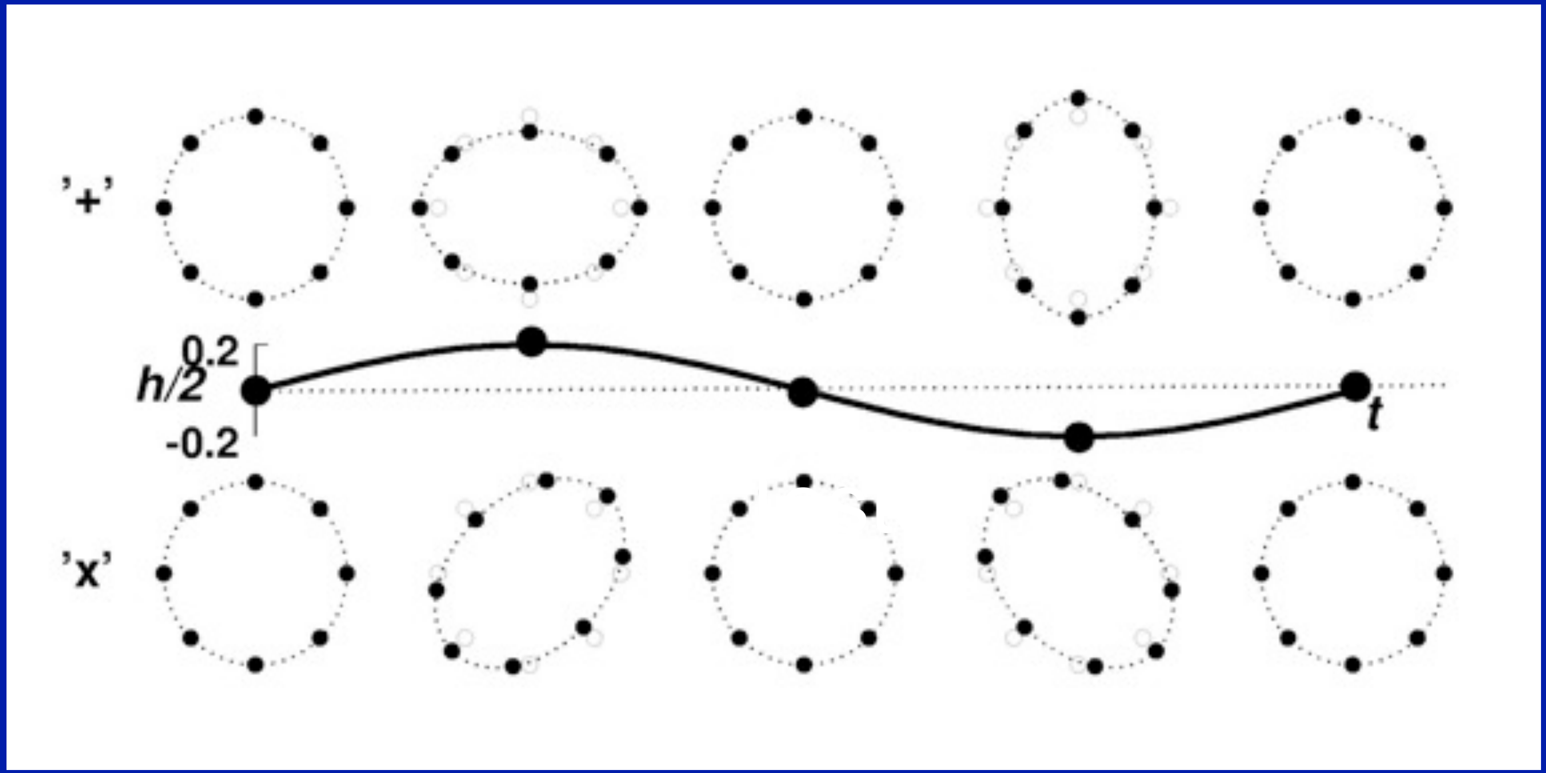
Detectors are sensitive to the polarization and to the angle of incidence

A measurement of the degree of circular polarization determines the inclination of a simple binary orbit.

To fully reconstruct a gravitational wave several cylinders or interferometers are need

Two polarizations "+" and "x"

The two independent polarization are shown in the following example (bar and interferometer)



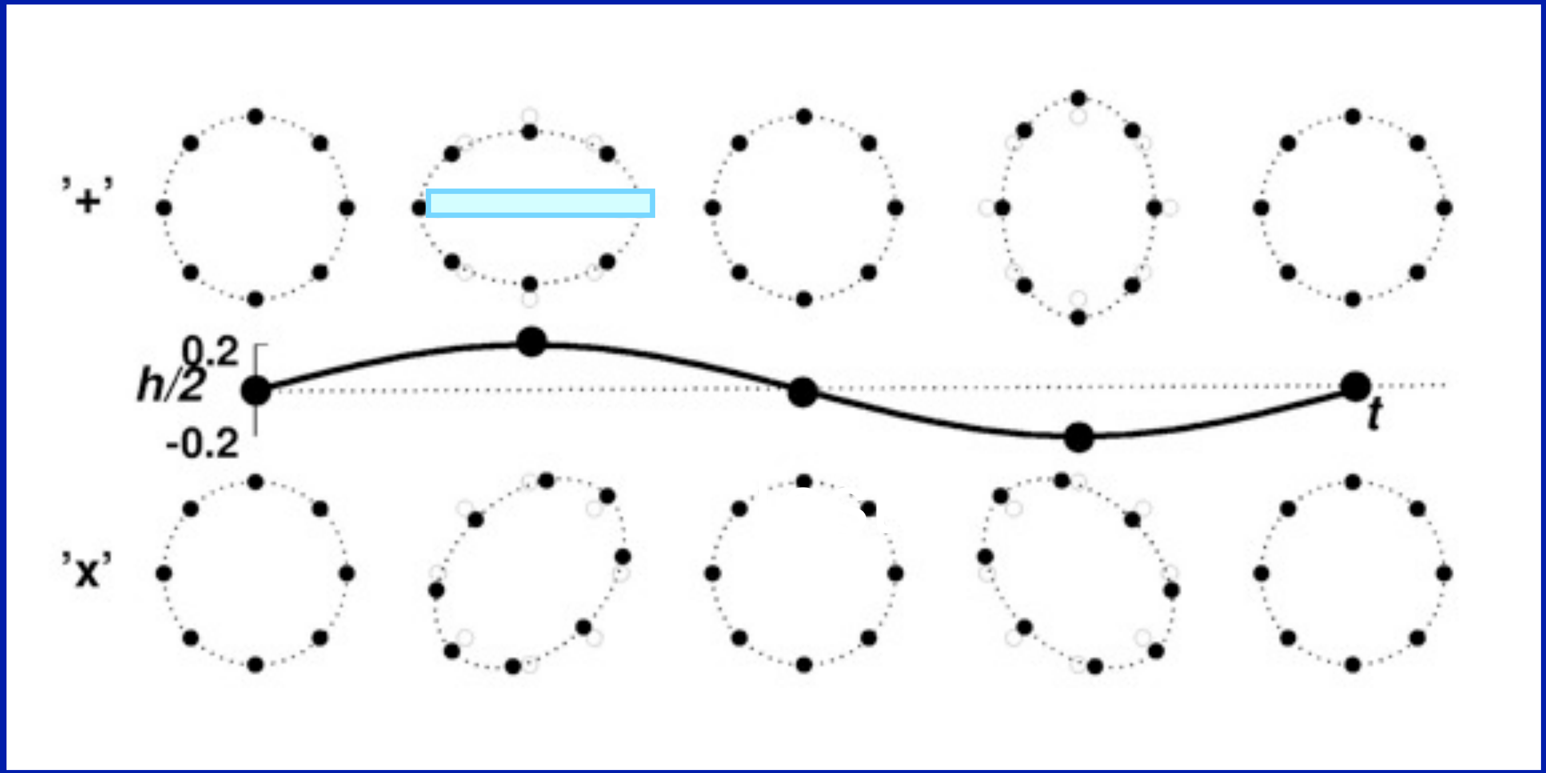
Detectors are sensitive to the polarization and to the angle of incidence

A measurement of the degree of circular polarization determines the inclination of a simple binary orbit.

To fully reconstruct a gravitational wave several cylinders or interferometers are need

Two polarizations “+” and “x”

The two independent polarization are shown in the following example (bar and interferometer)



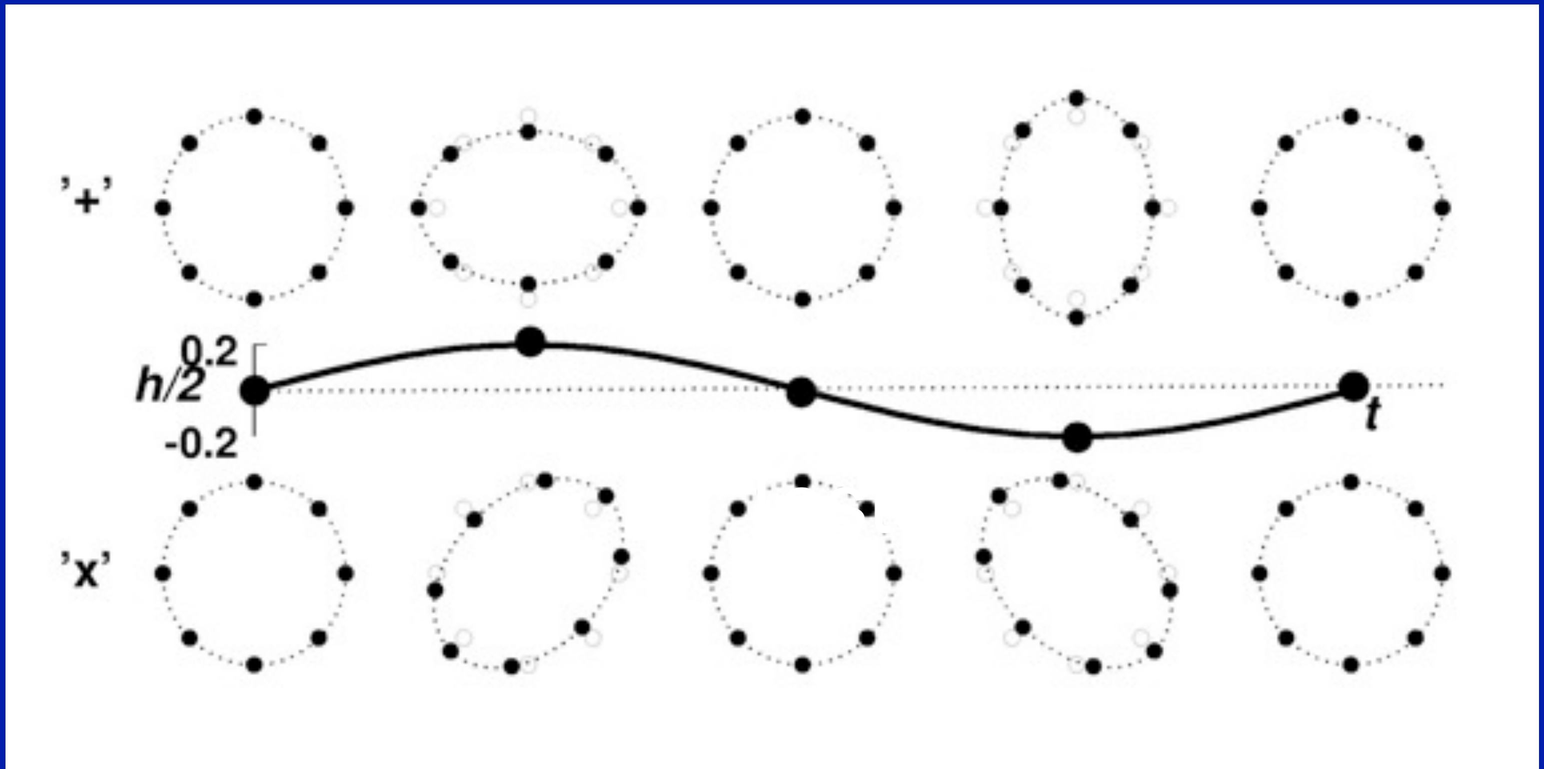
Detectors are sensitive to the polarization and to the angle of incidence

A measurement of the degree of circular polarization determines the inclination of a simple binary orbit.

To fully reconstruct a gravitational wave several cylinders or interferometers are need

Two polarizations "+" and "x"

The two independent polarization are shown in the following example (bar and interferometer)



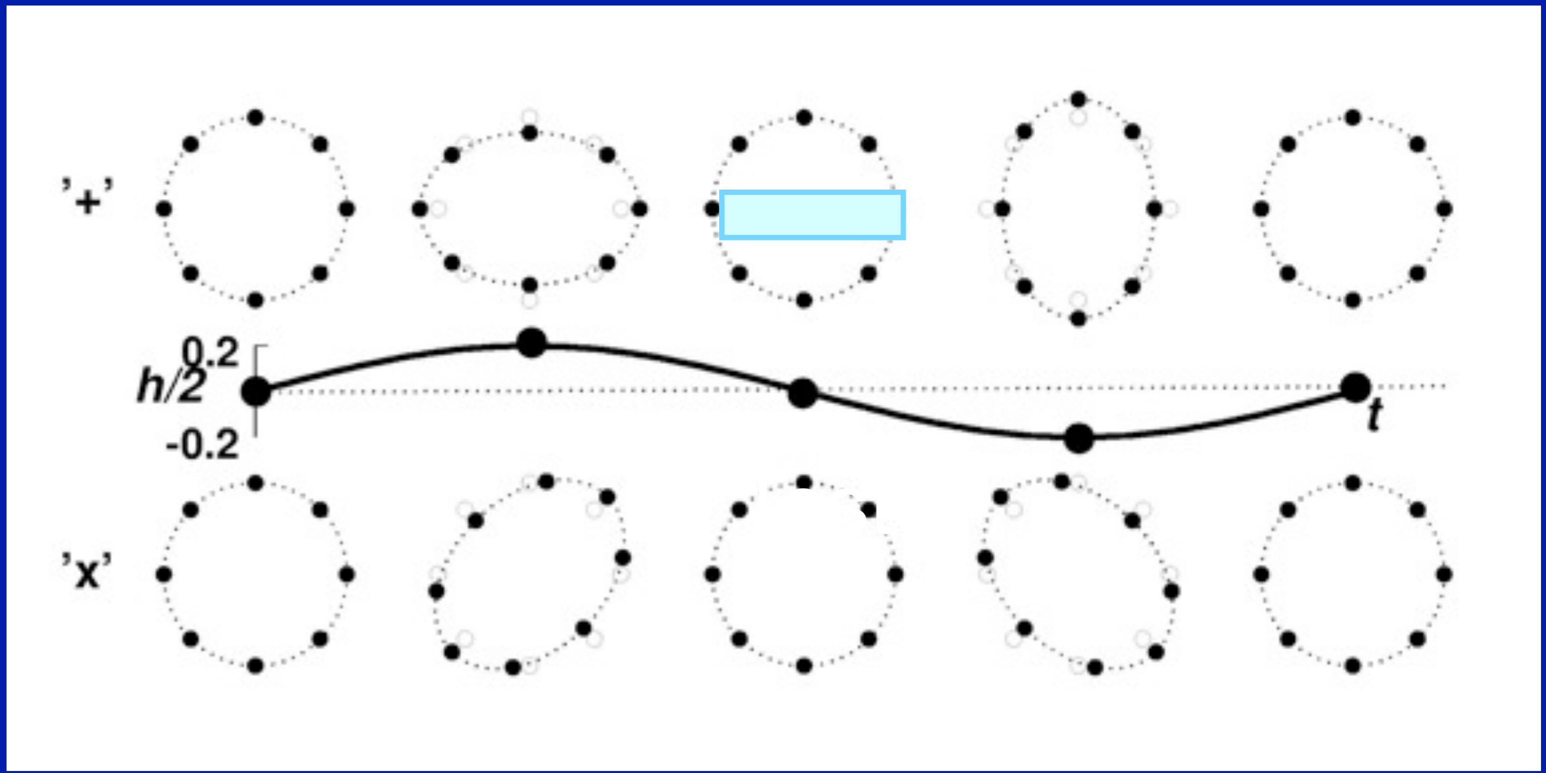
Detectors are sensitive to the polarization and to the angle of incidence

A measurement of the degree of circular polarization determines the inclination of a simple binary orbit.

To fully reconstruct a gravitational wave several cylinders or interferometers are need

Two polarizations "+" and "x"

The two independent polarization are shown in the following example (bar and interferometer)



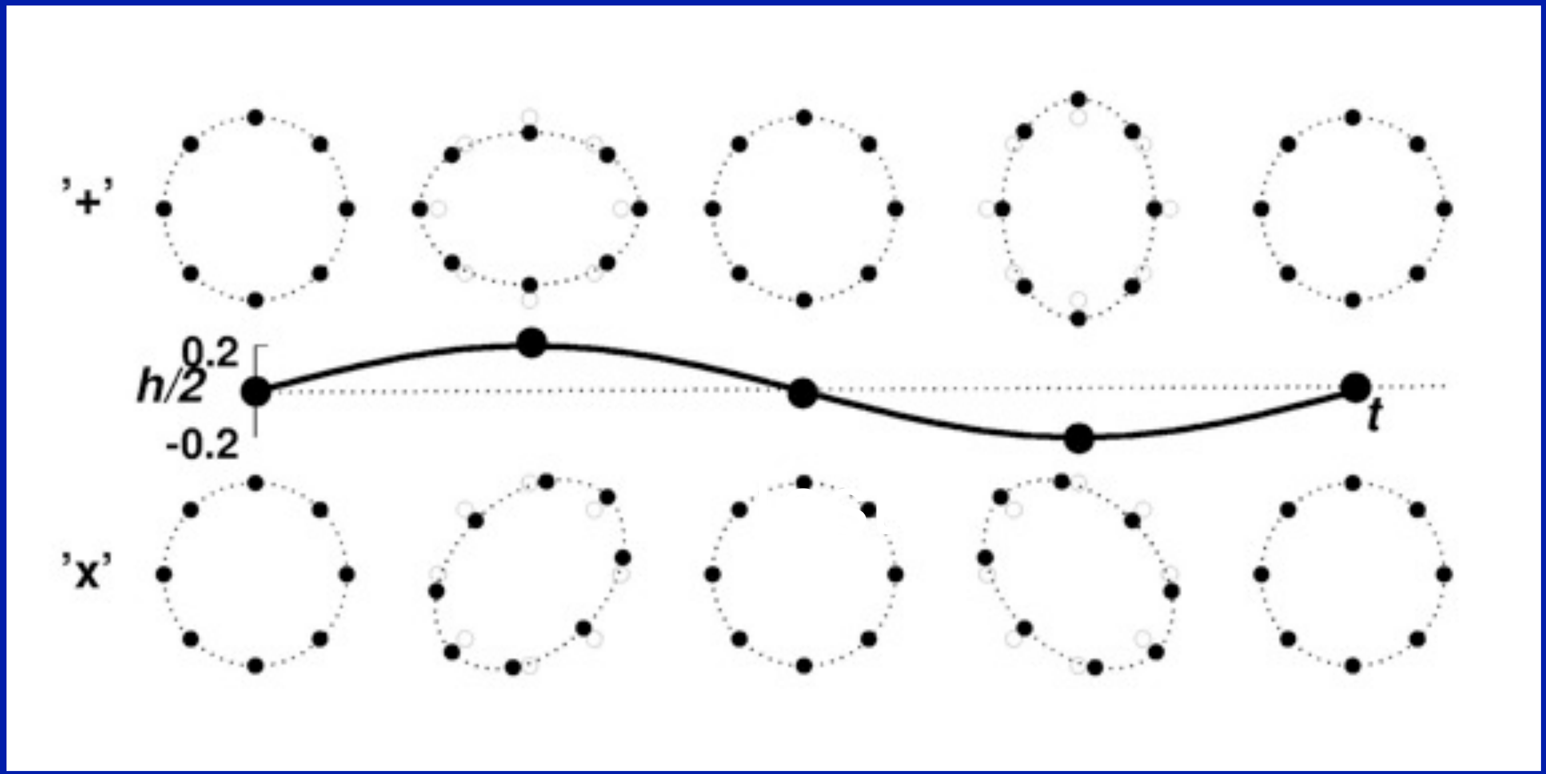
Detectors are sensitive to the polarization and to the angle of incidence

A measurement of the degree of circular polarization determines the inclination of a simple binary orbit.

To fully reconstruct a gravitational wave several cylinders or interferometers are need

Two polarizations "+" and "x"

The two independent polarization are shown in the following example (bar and interferometer)



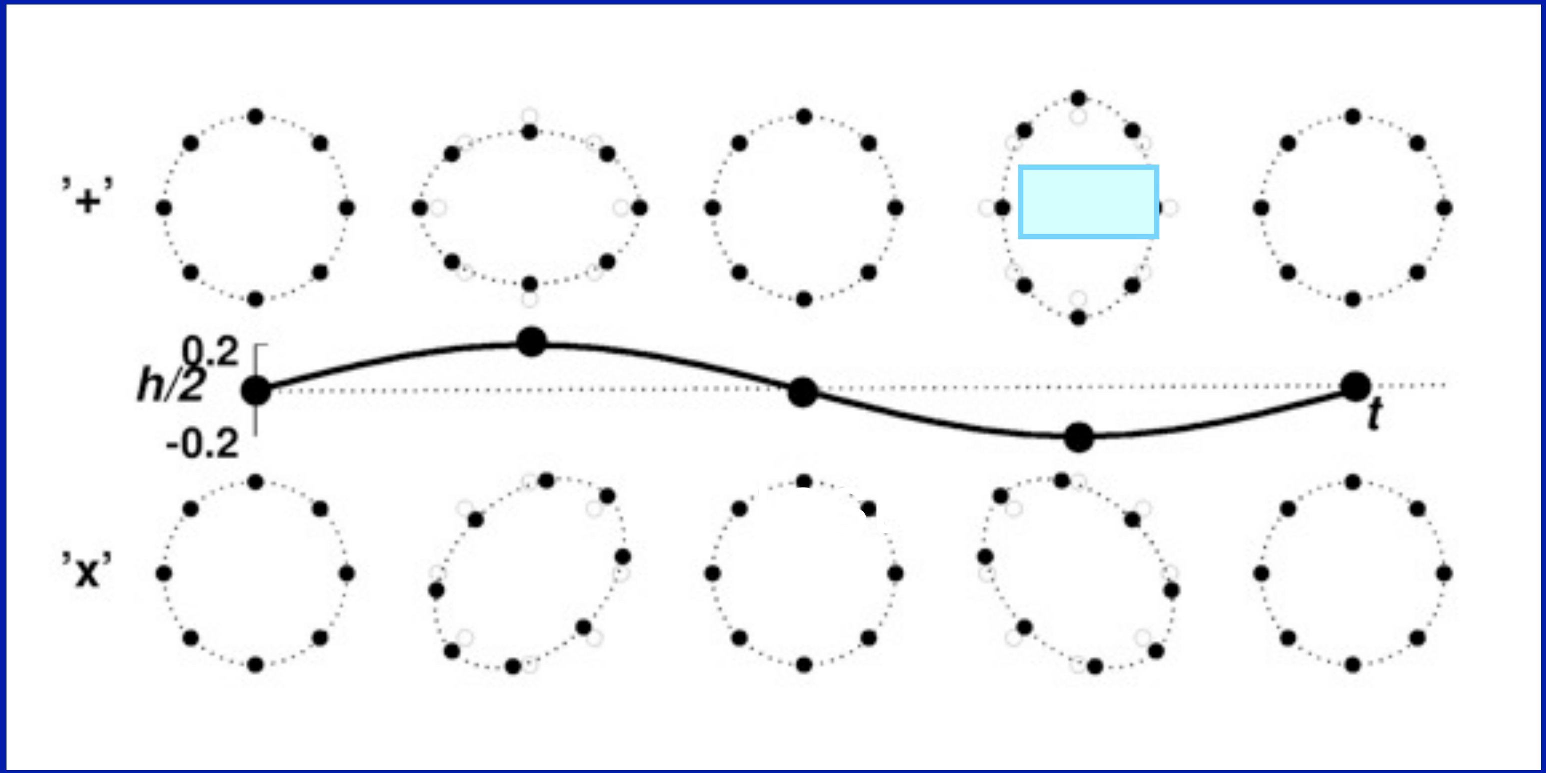
Detectors are sensitive to the polarization and to the angle of incidence

A measurement of the degree of circular polarization determines the inclination of a simple binary orbit.

To fully reconstruct a gravitational wave several cylinders or interferometers are need

Two polarizations "+" and "x"

The two independent polarization are shown in the following example (bar and interferometer)



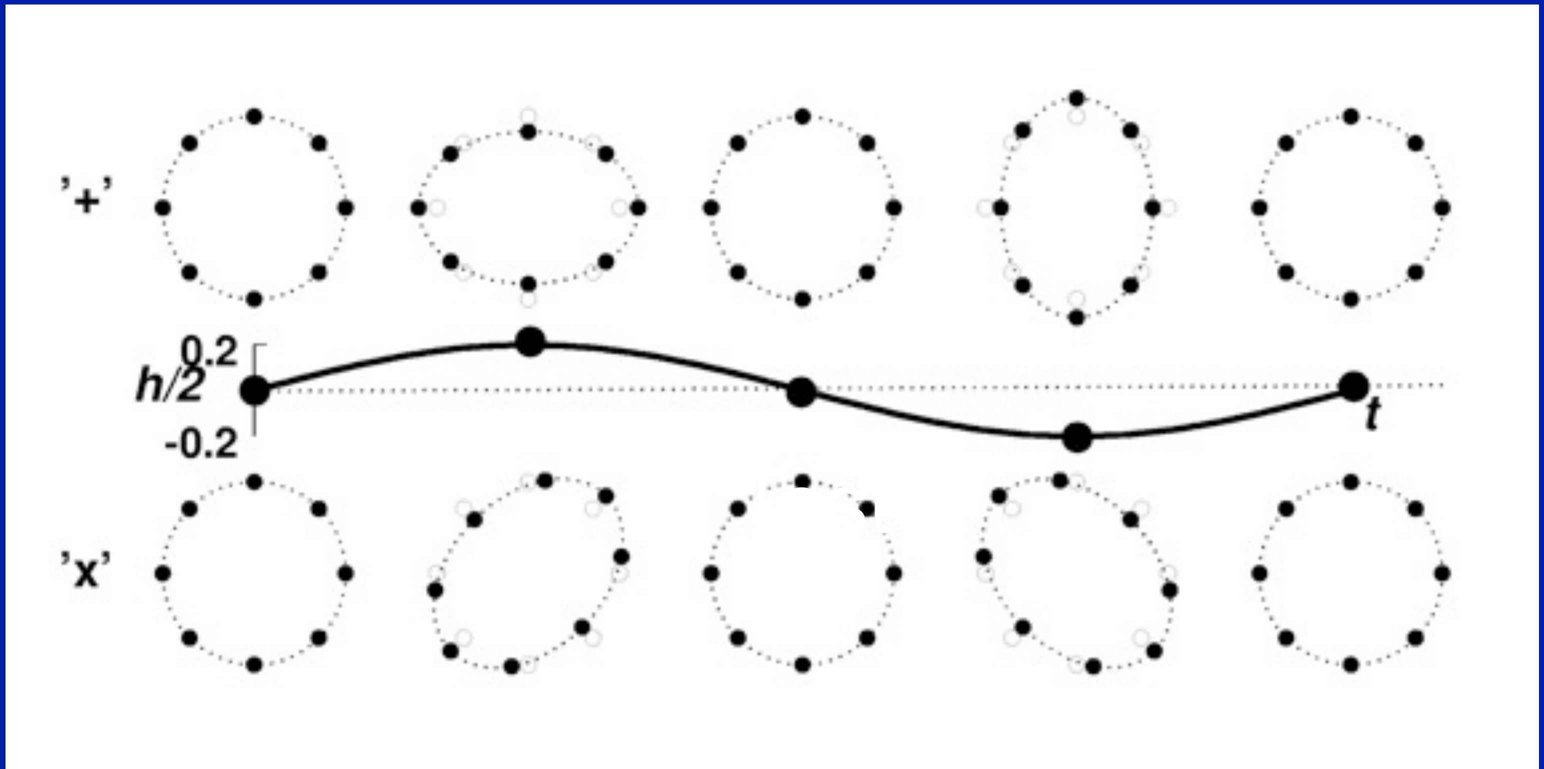
Detectors are sensitive to the polarization and to the angle of incidence

A measurement of the degree of circular polarization determines the inclination of a simple binary orbit.

To fully reconstruct a gravitational wave several cylinders or interferometers are need

Two polarizations "+" and "x"

The two independent polarization are shown in the following example (bar and interferometer)



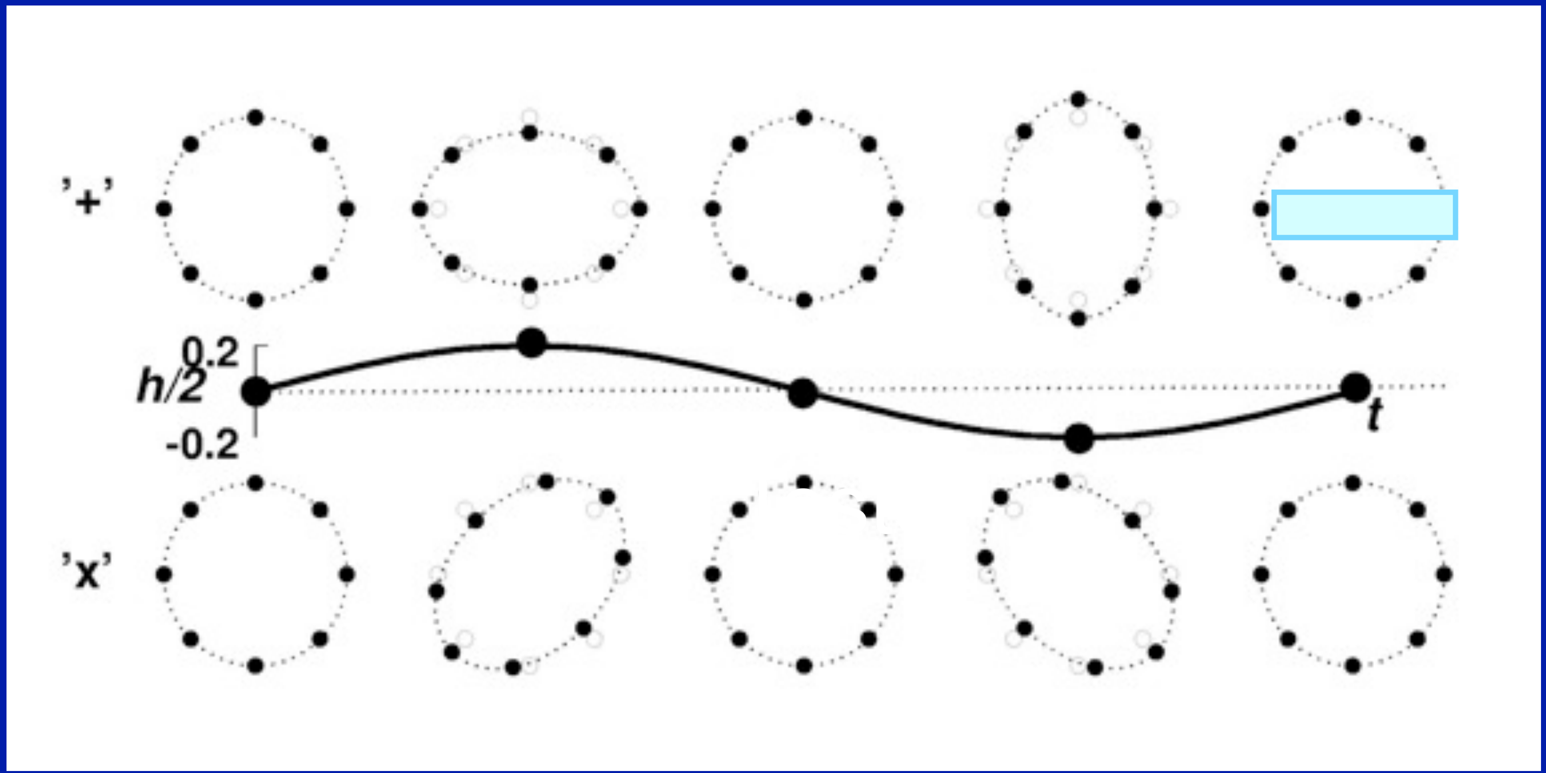
Detectors are sensitive to the polarization and to the angle of incidence

A measurement of the degree of circular polarization determines the inclination of a simple binary orbit.

To fully reconstruct a gravitational wave several cylinders or interferometers are need

Two polarizations “+” and “x”

The two independent polarization are shown in the following example (bar and interferometer)



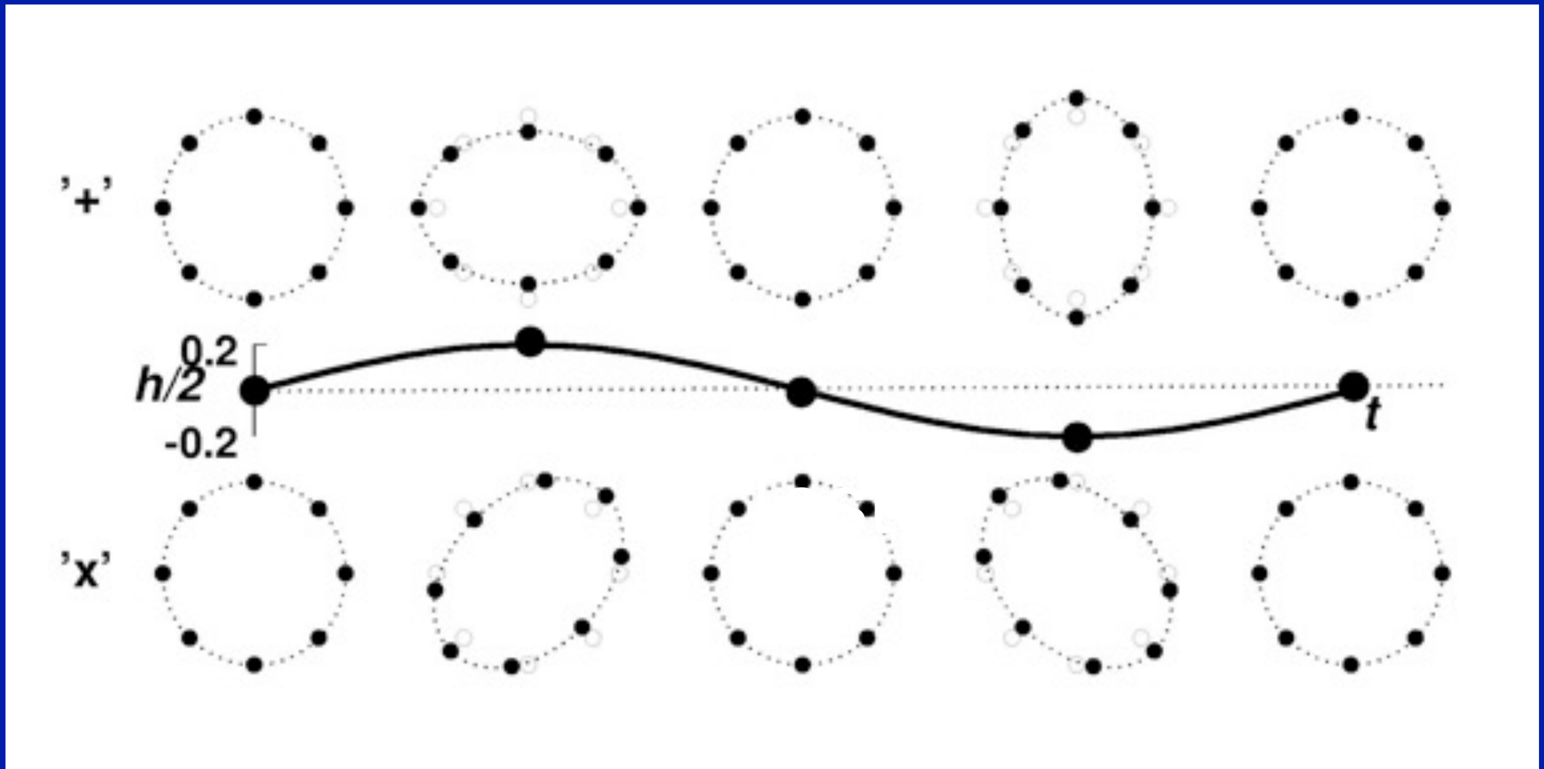
Detectors are sensitive to the polarization and to the angle of incidence

A measurement of the degree of circular polarization determines the inclination of a simple binary orbit.

To fully reconstruct a gravitational wave several cylinders or interferometers are need

Two polarizations “+” and “x”

The two independent polarization are shown in the following example (bar and interferometer)



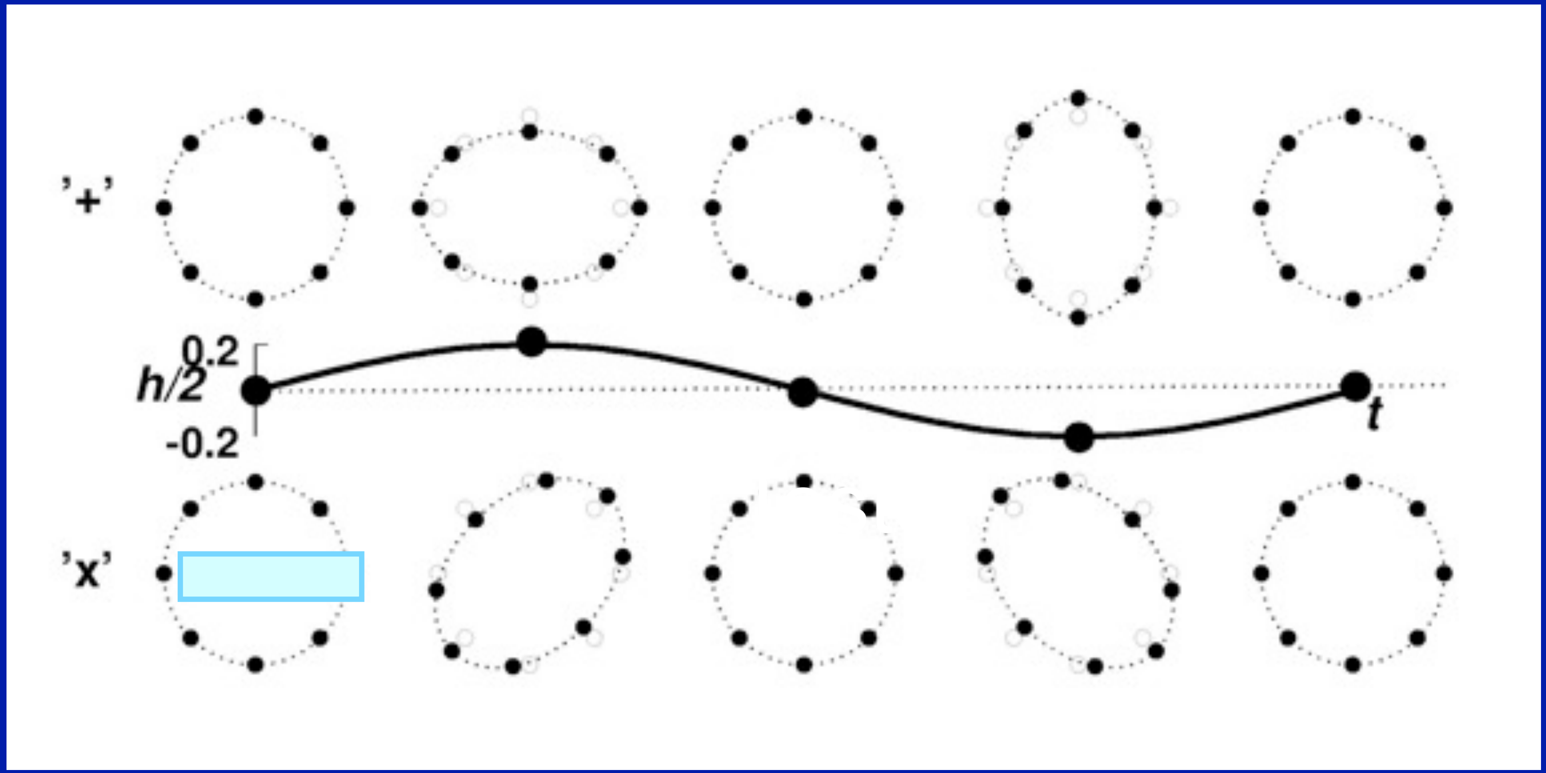
Detectors are sensitive to the polarization and to the angle of incidence

A measurement of the degree of circular polarization determines the inclination of a simple binary orbit.

To fully reconstruct a gravitational wave several cylinders or interferometers are need

Two polarizations “+” and “x”

The two independent polarization are shown in the following example (bar and interferometer)



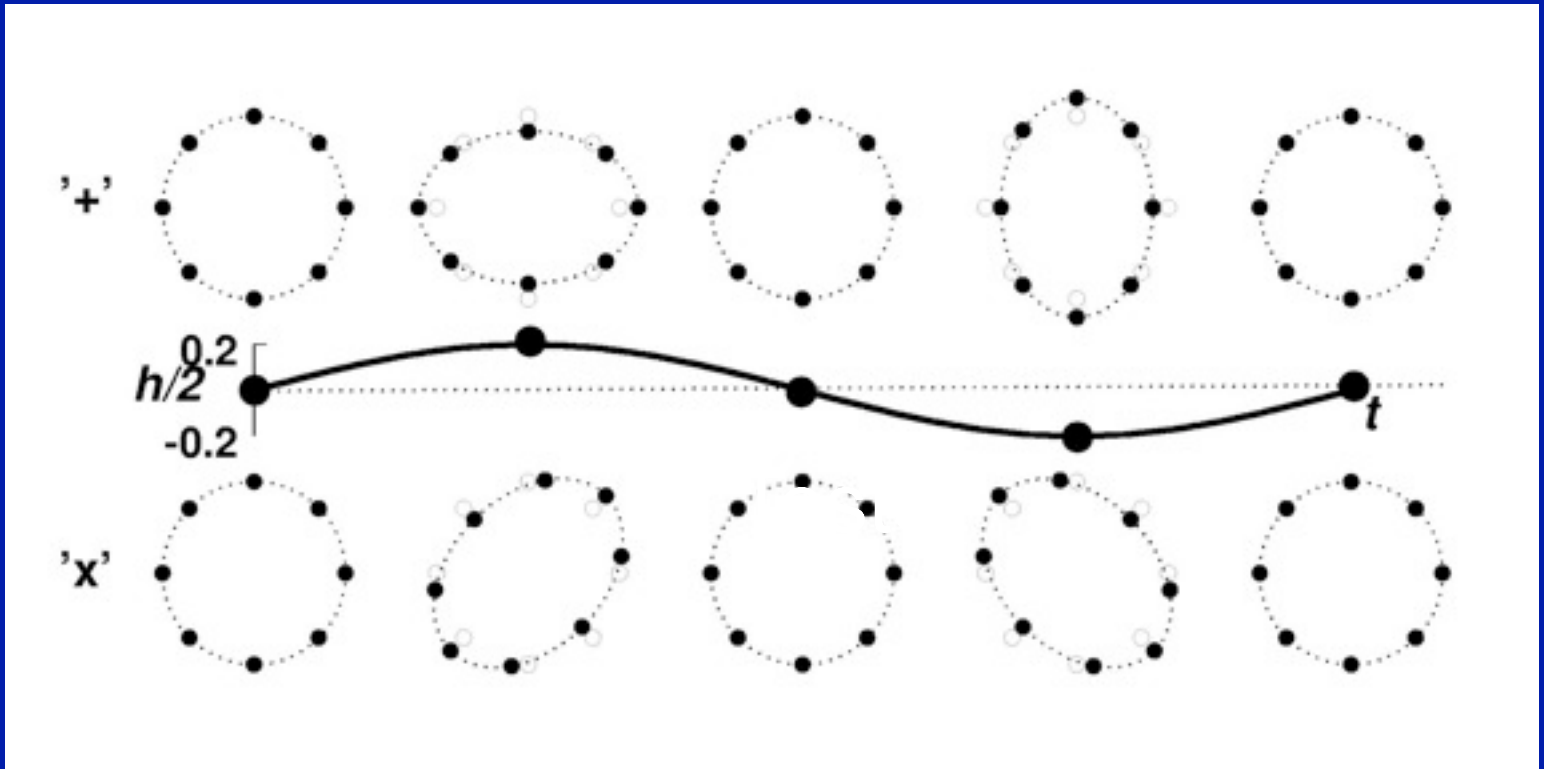
Detectors are sensitive to the polarization and to the angle of incidence

A measurement of the degree of circular polarization determines the inclination of a simple binary orbit.

To fully reconstruct a gravitational wave several cylinders or interferometers are need

Two polarizations “+” and “x”

The two independent polarization are shown in the following example (bar and interferometer)



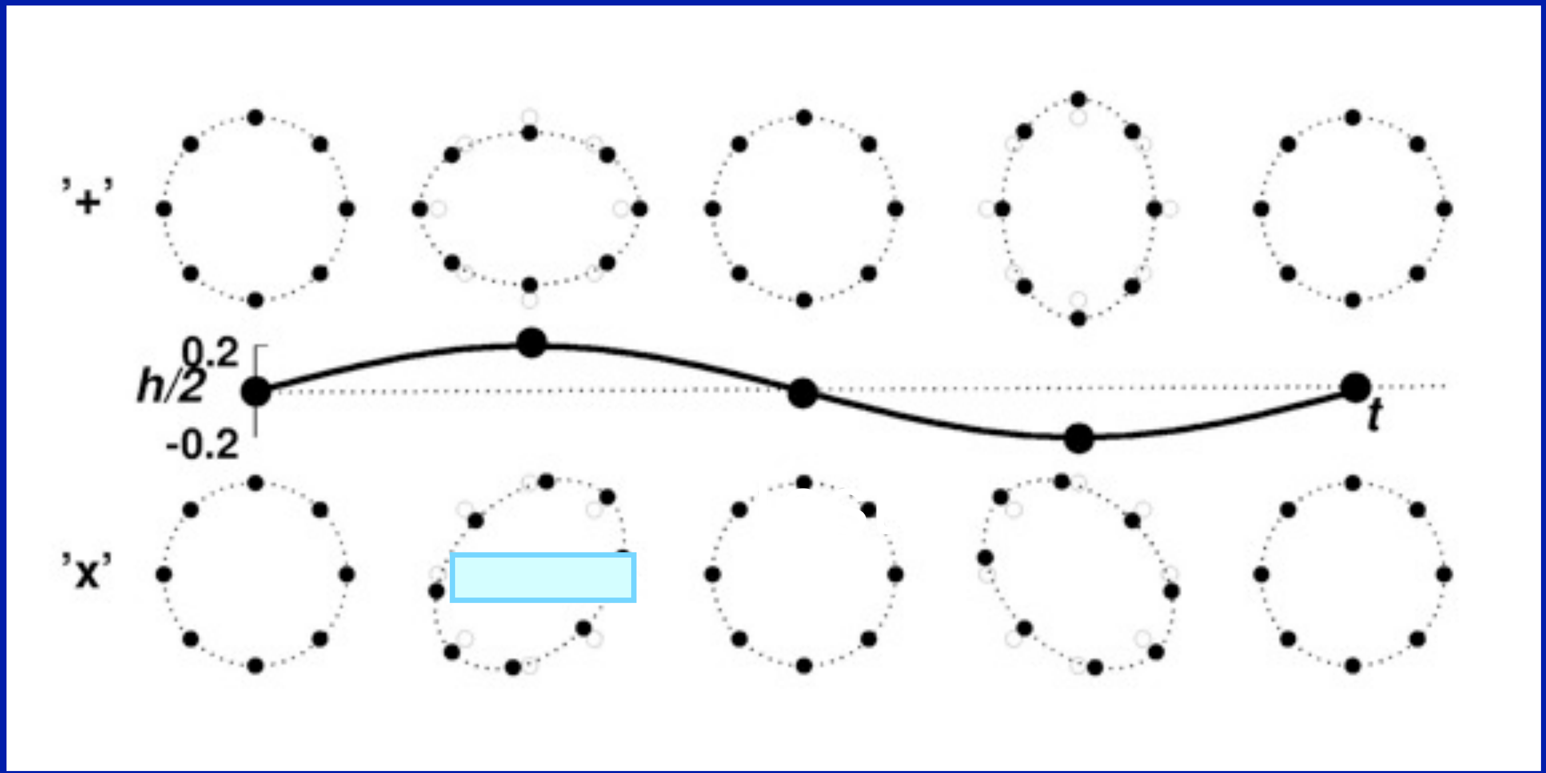
Detectors are sensitive to the polarization and to the angle of incidence

A measurement of the degree of circular polarization determines the inclination of a simple binary orbit.

To fully reconstruct a gravitational wave several cylinders or interferometers are need

Two polarizations "+" and "x"

The two independent polarization are shown in the following example (bar and interferometer)



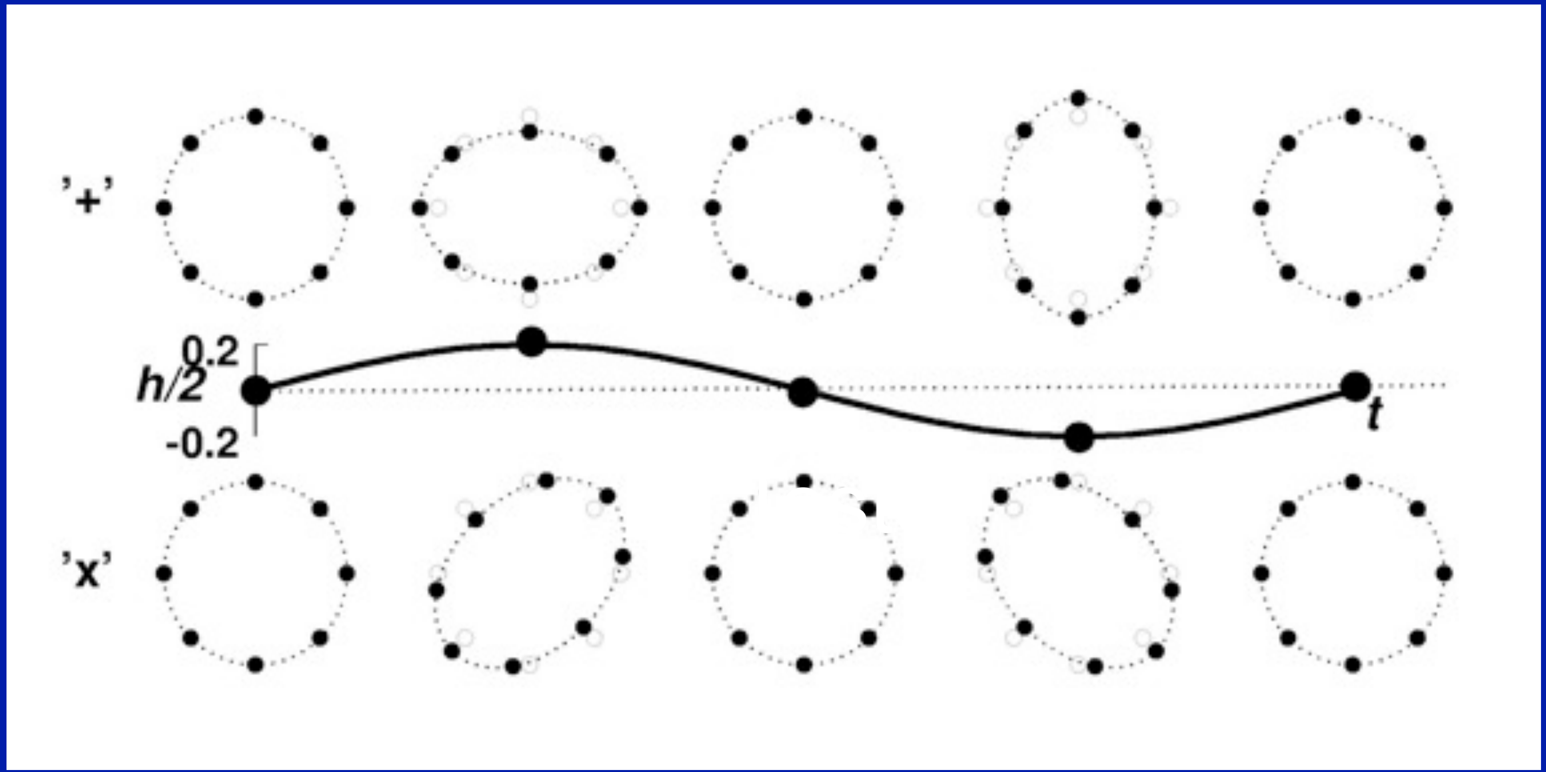
Detectors are sensitive to the polarization and to the angle of incidence

A measurement of the degree of circular polarization determines the inclination of a simple binary orbit.

To fully reconstruct a gravitational wave several cylinders or interferometers are need

Two polarizations “+” and “x”

The two independent polarization are shown in the following example (bar and interferometer)



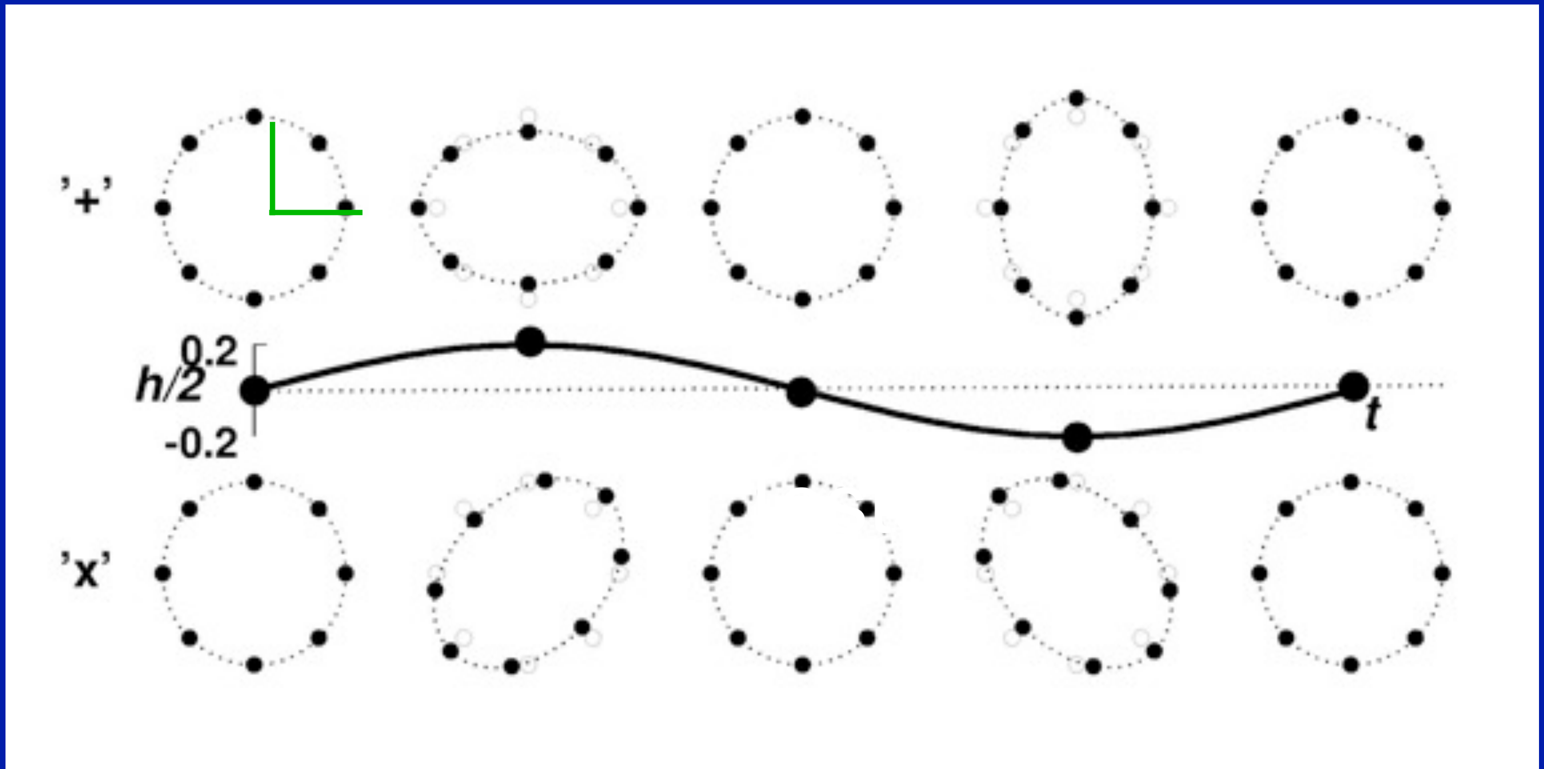
Detectors are sensitive to the polarization and to the angle of incidence

A measurement of the degree of circular polarization determines the inclination of a simple binary orbit.

To fully reconstruct a gravitational wave several cylinders or interferometers are need

Two polarizations “+” and “x”

The two independent polarization are shown in the following example (bar and interferometer)



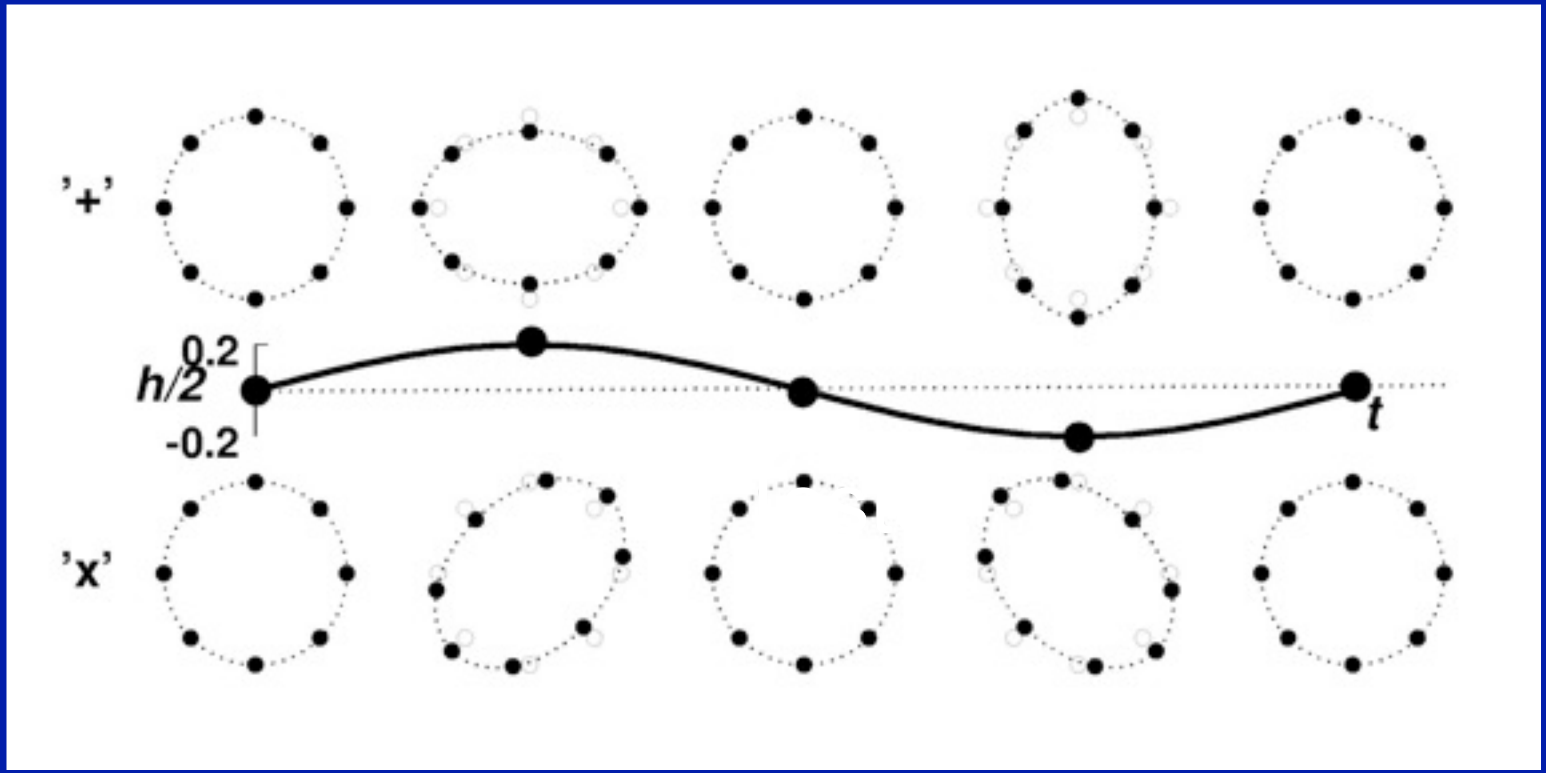
Detectors are sensitive to the polarization and to the angle of incidence

A measurement of the degree of circular polarization determines the inclination of a simple binary orbit.

To fully reconstruct a gravitational wave several cylinders or interferometers are need

Two polarizations "+" and "x"

The two independent polarization are shown in the following example (bar and interferometer)



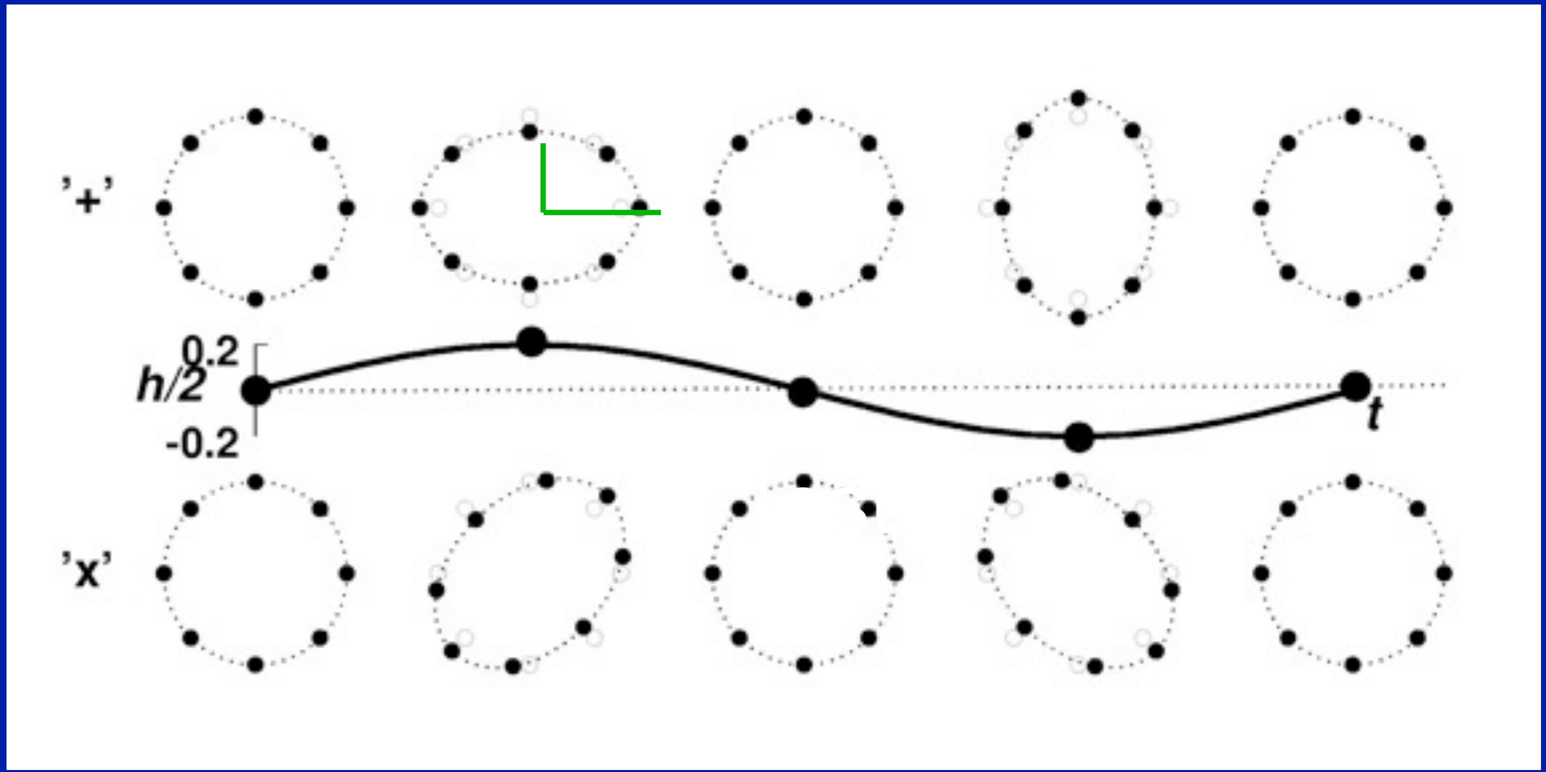
Detectors are sensitive to the polarization and to the angle of incidence

A measurement of the degree of circular polarization determines the inclination of a simple binary orbit.

To fully reconstruct a gravitational wave several cylinders or interferometers are need

Two polarizations “+” and “x”

The two independent polarization are shown in the following example (bar and interferometer)



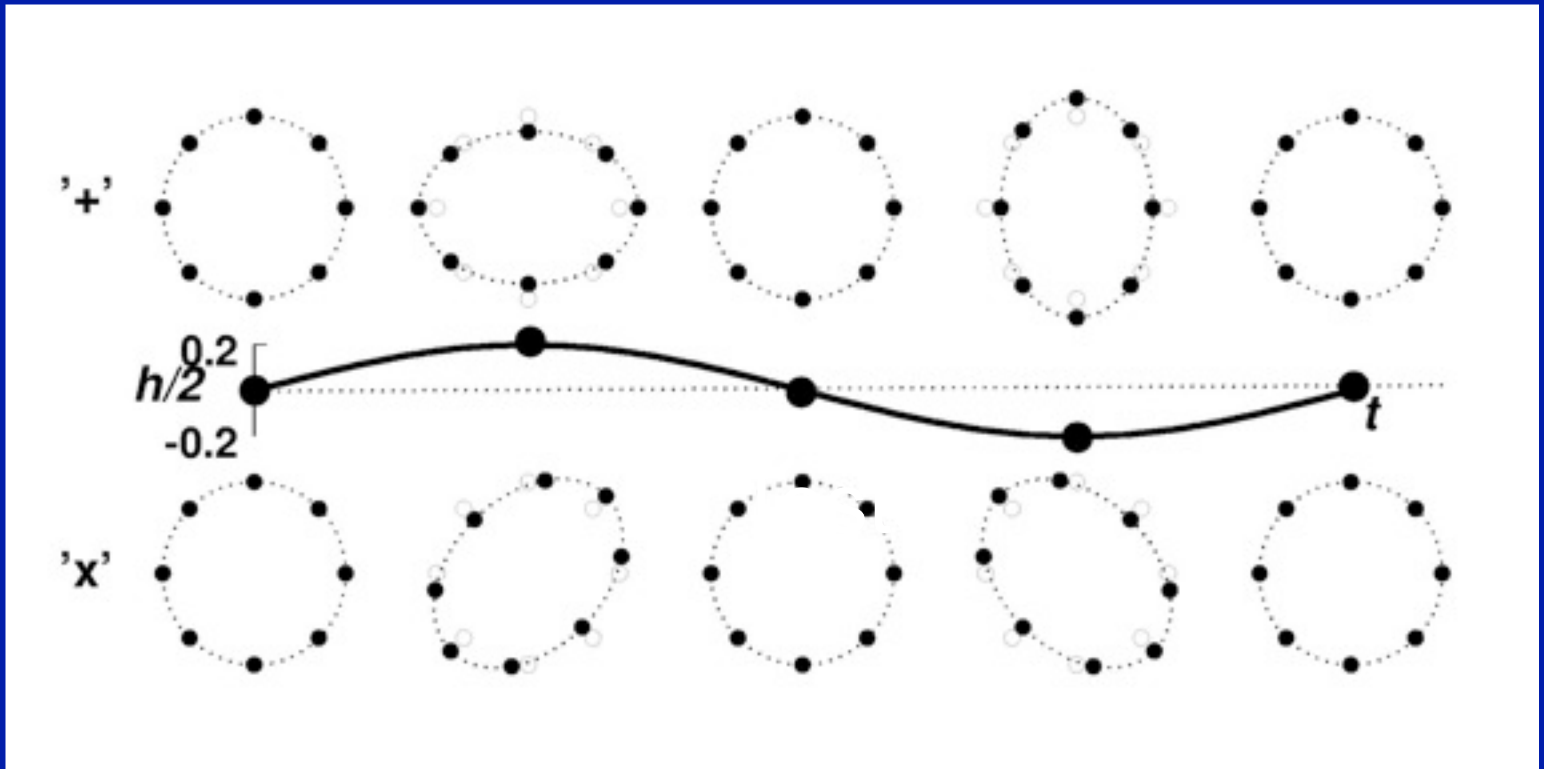
Detectors are sensitive to the polarization and to the angle of incidence

A measurement of the degree of circular polarization determines the inclination of a simple binary orbit.

To fully reconstruct a gravitational wave several cylinders or interferometers are need

Two polarizations "+" and "x"

The two independent polarization are shown in the following example (bar and interferometer)



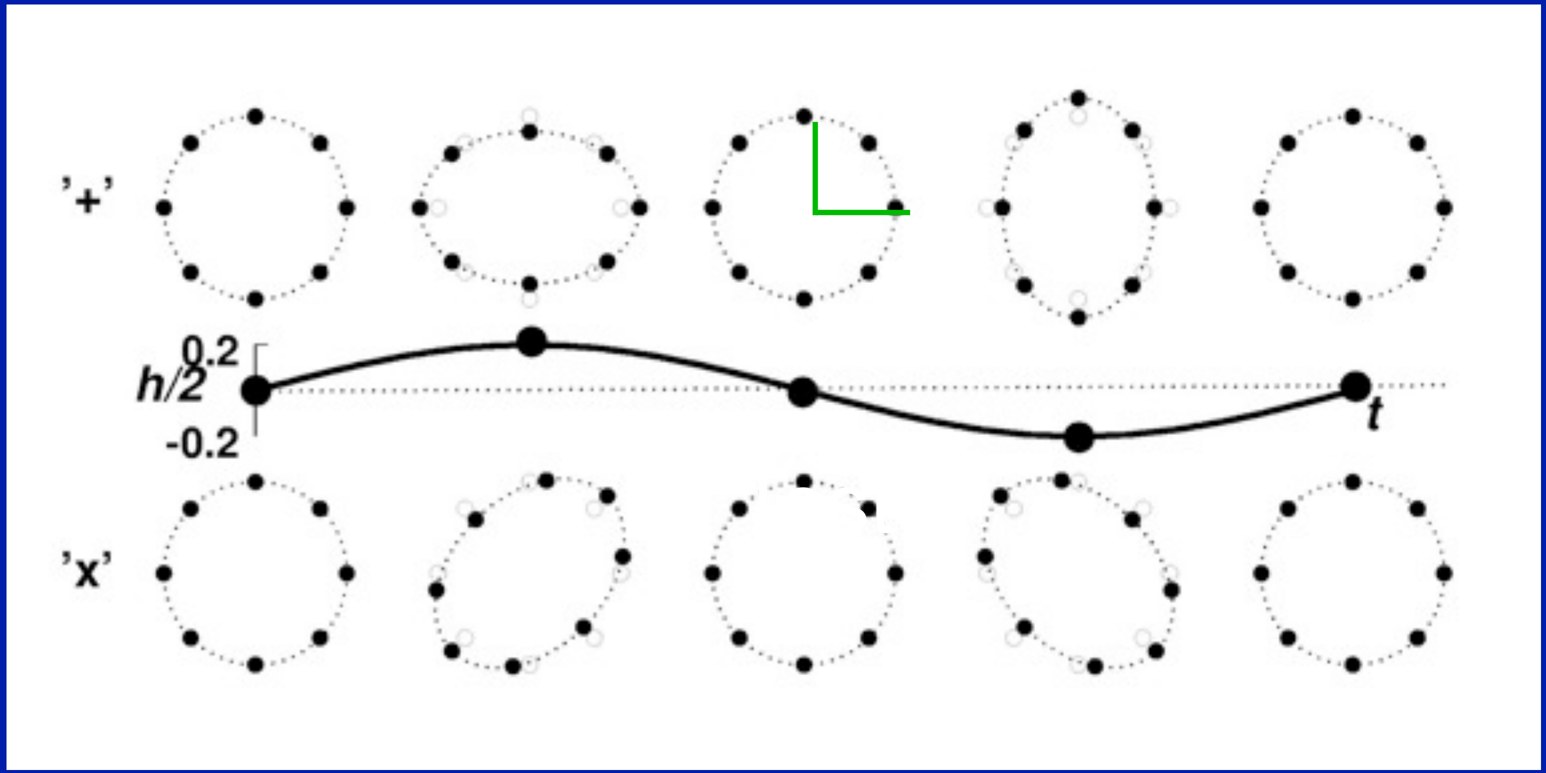
Detectors are sensitive to the polarization and to the angle of incidence

A measurement of the degree of circular polarization determines the inclination of a simple binary orbit.

To fully reconstruct a gravitational wave several cylinders or interferometers are need

Two polarizations “+” and “x”

The two independent polarization are shown in the following example (bar and interferometer)



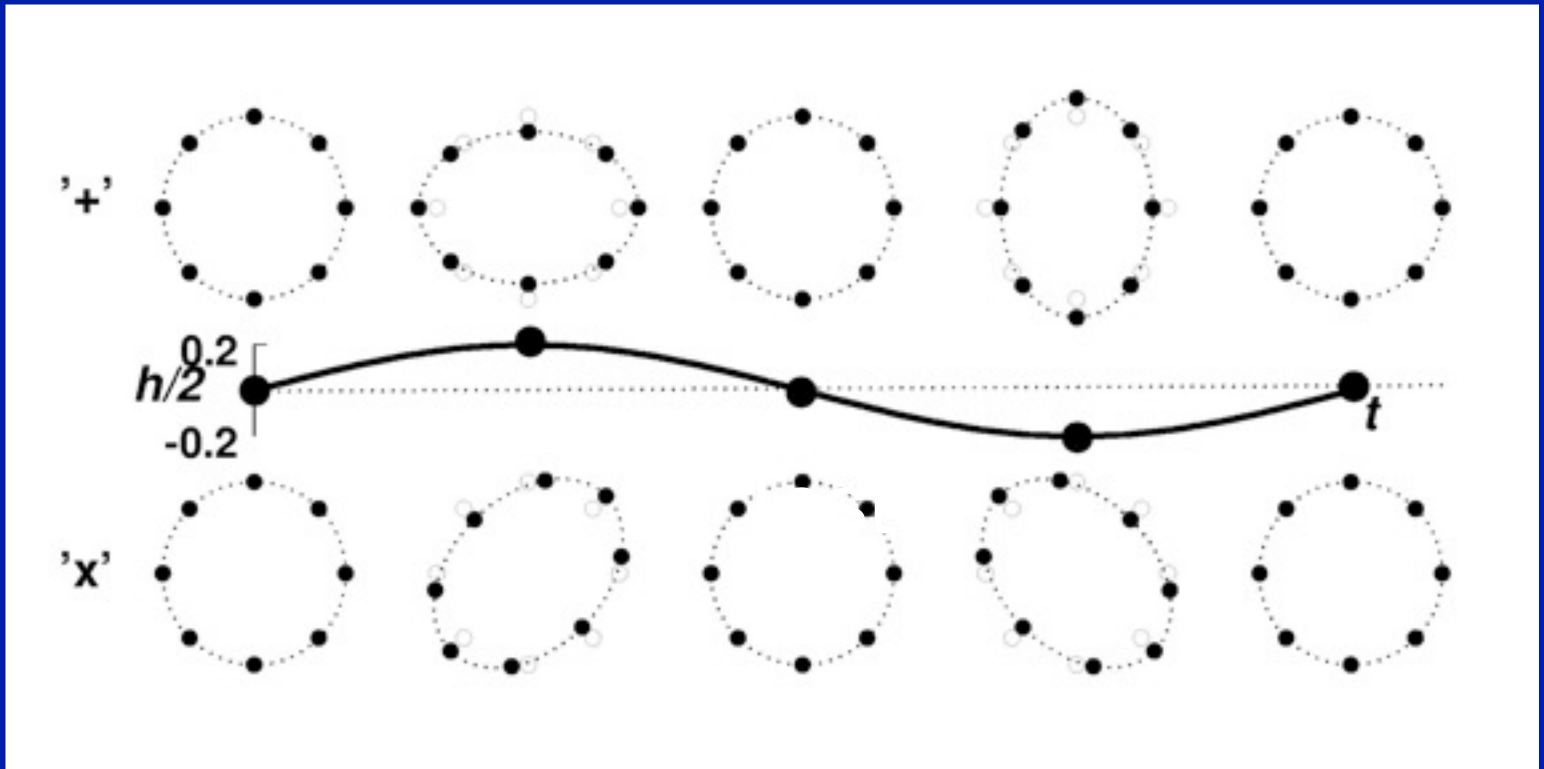
Detectors are sensitive to the polarization and to the angle of incidence

A measurement of the degree of circular polarization determines the inclination of a simple binary orbit.

To fully reconstruct a gravitational wave several cylinders or interferometers are need

Two polarizations "+" and "x"

The two independent polarization are shown in the following example (bar and interferometer)



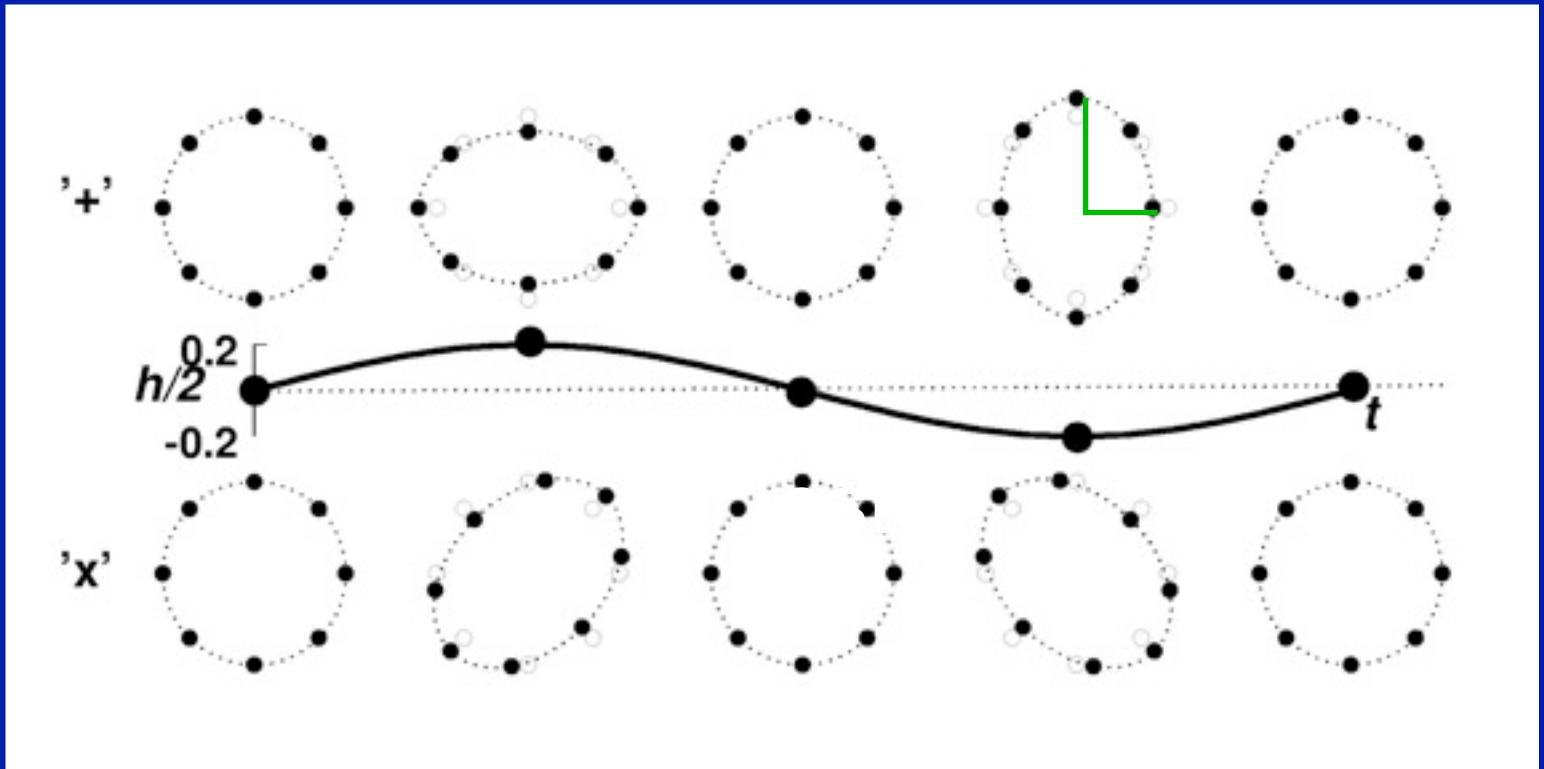
Detectors are sensitive to the polarization and to the angle of incidence

A measurement of the degree of circular polarization determines the inclination of a simple binary orbit.

To fully reconstruct a gravitational wave several cylinders or interferometers are need

Two polarizations “+” and “x”

The two independent polarization are shown in the following example (bar and interferometer)



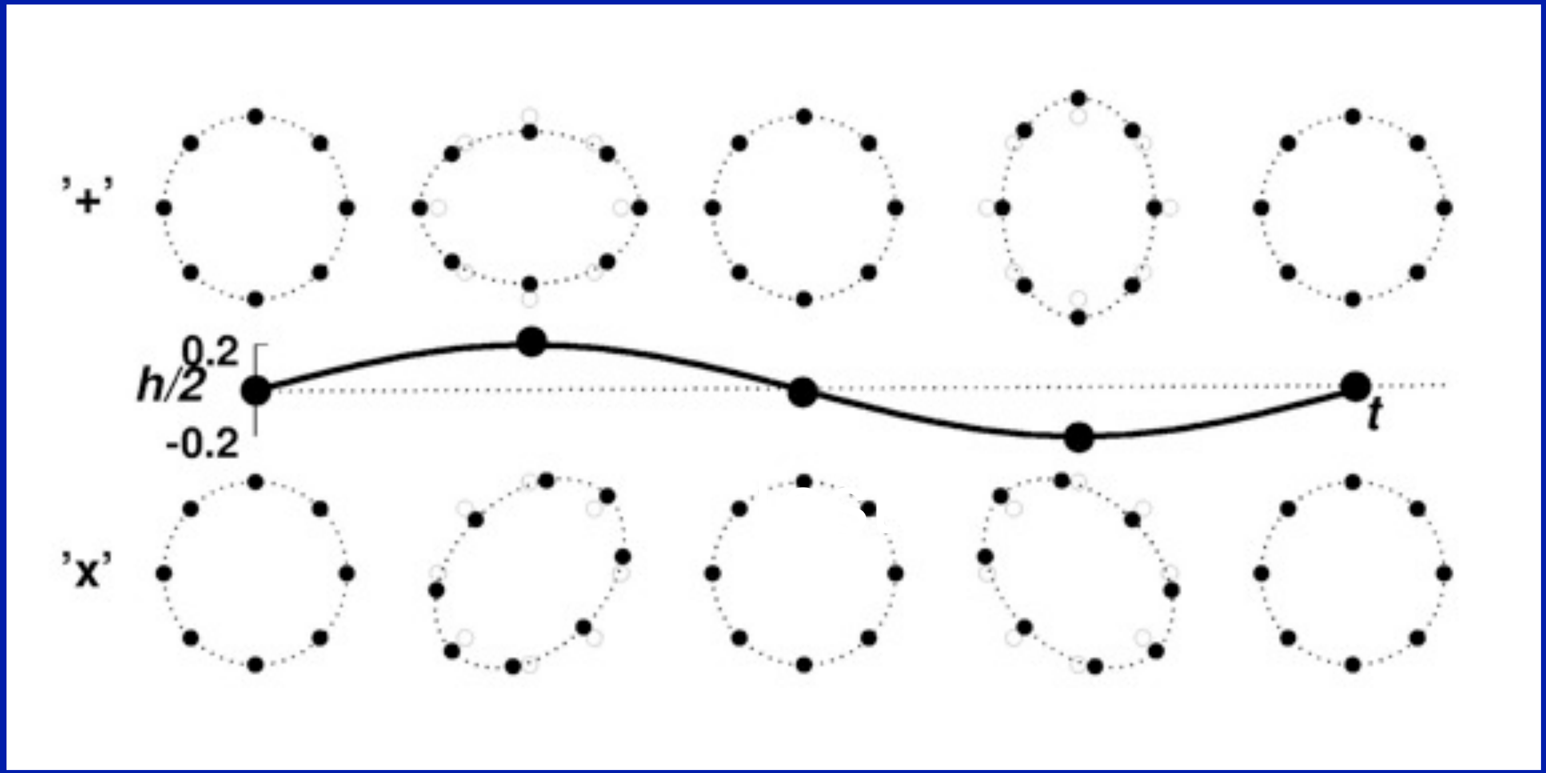
Detectors are sensitive to the polarization and to the angle of incidence

A measurement of the degree of circular polarization determines the inclination of a simple binary orbit.

To fully reconstruct a gravitational wave several cylinders or interferometers are need

Two polarizations “+” and “x”

The two independent polarization are shown in the following example (bar and interferometer)



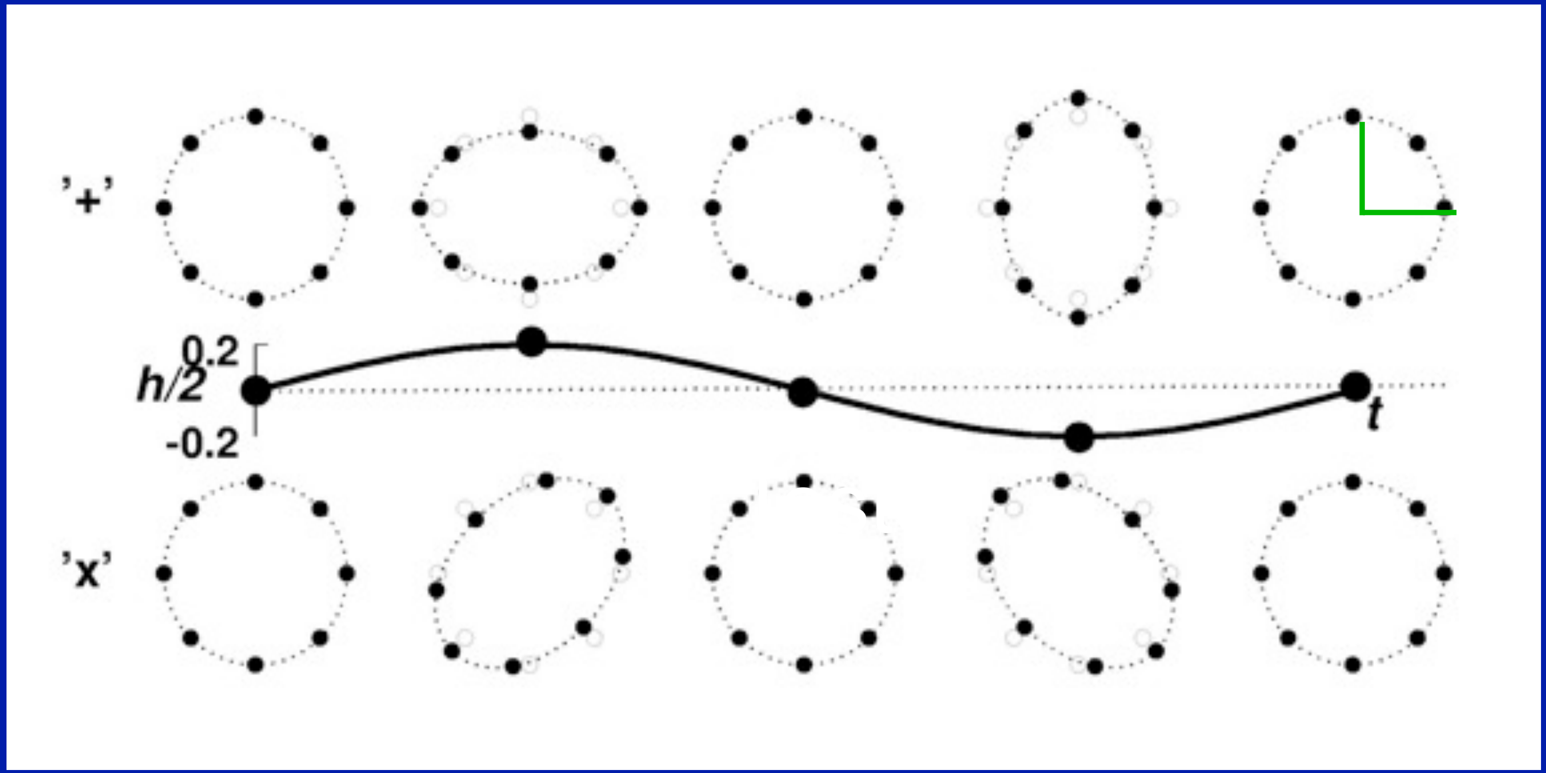
Detectors are sensitive to the polarization and to the angle of incidence

A measurement of the degree of circular polarization determines the inclination of a simple binary orbit.

To fully reconstruct a gravitational wave several cylinders or interferometers are need

Two polarizations "+" and "x"

The two independent polarization are shown in the following example (bar and interferometer)



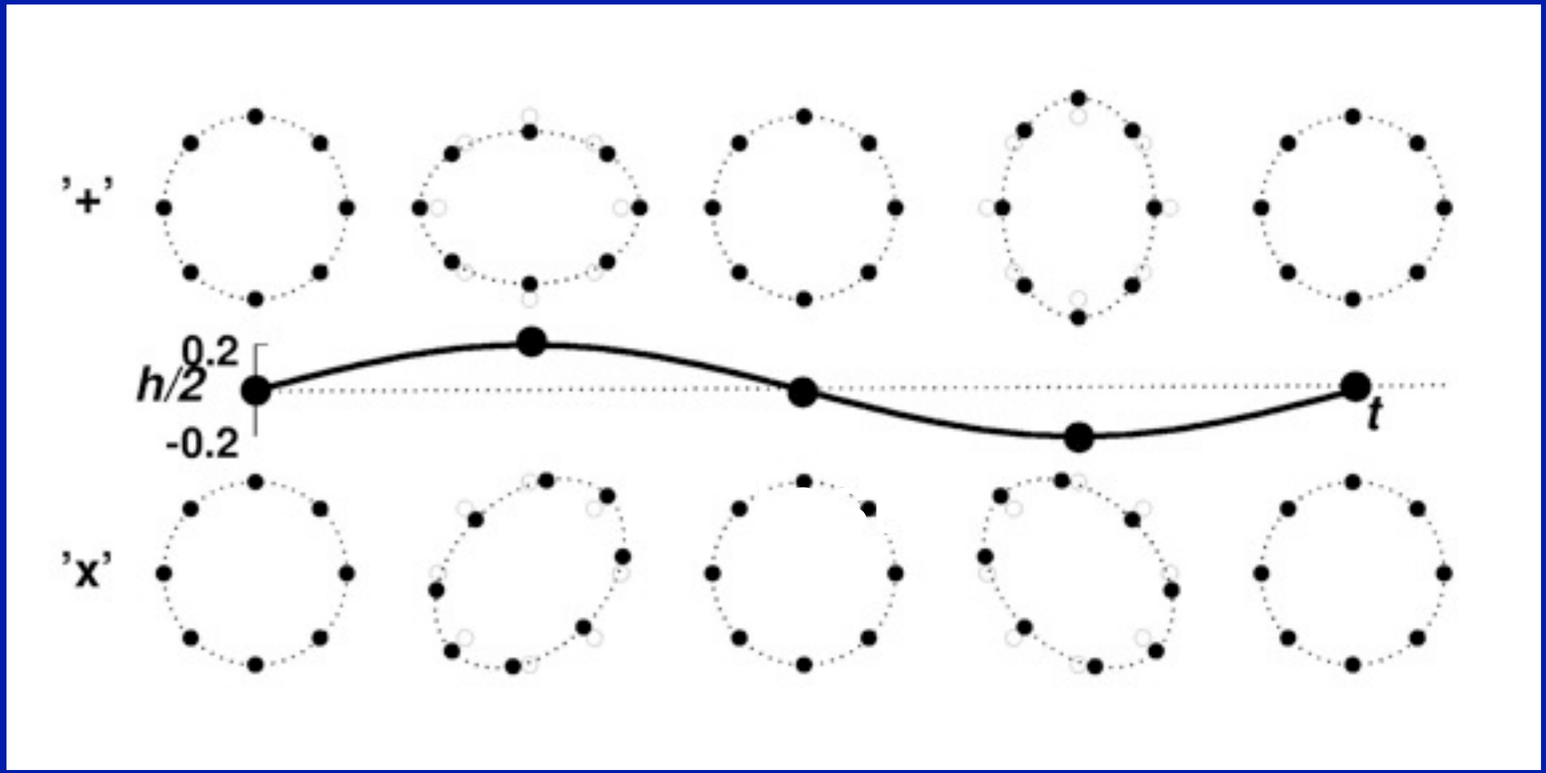
Detectors are sensitive to the polarization and to the angle of incidence

A measurement of the degree of circular polarization determines the inclination of a simple binary orbit.

To fully reconstruct a gravitational wave several cylinders or interferometers are need

Two polarizations “+” and “x”

The two independent polarization are shown in the following example (bar and interferometer)



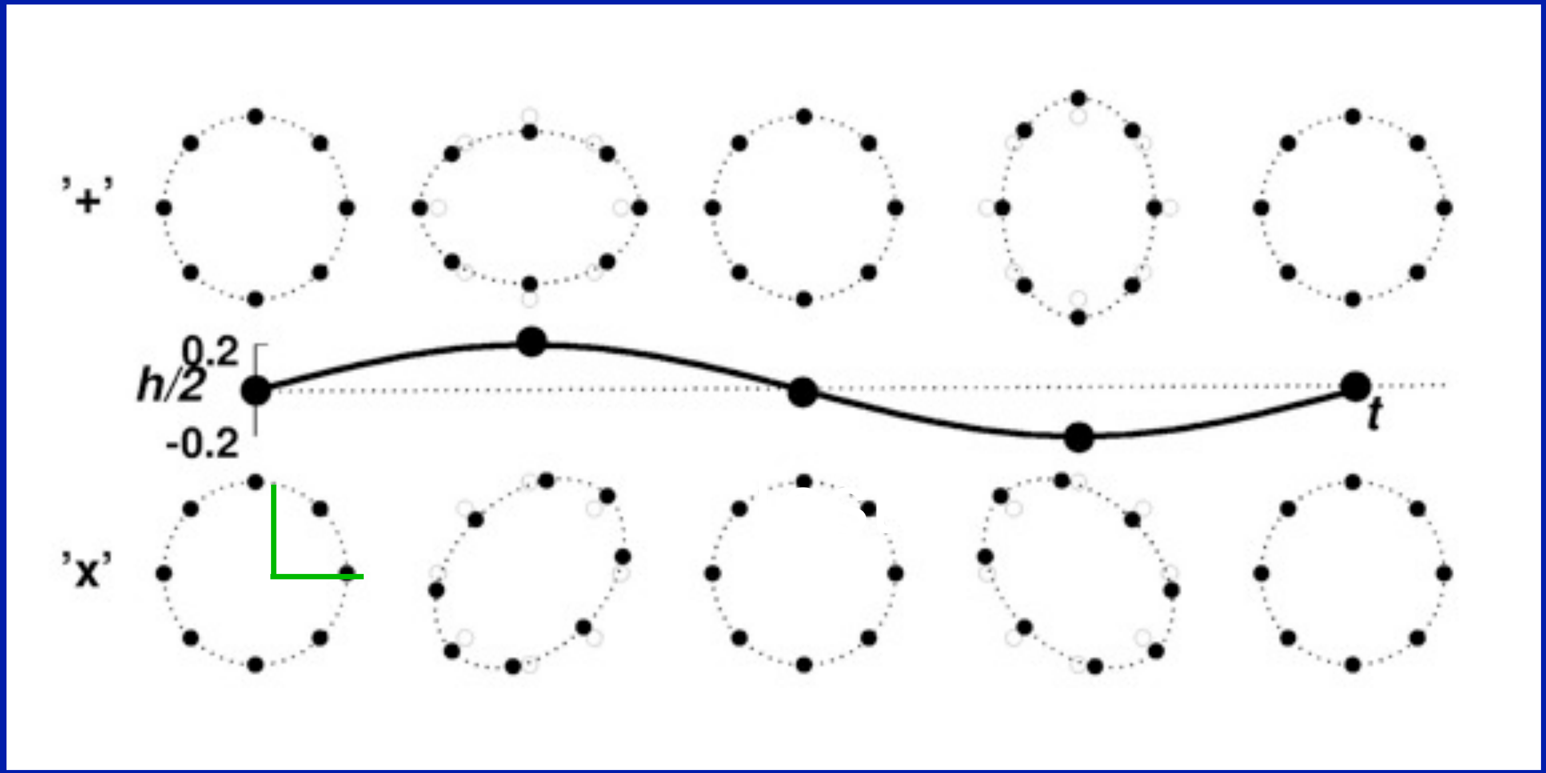
Detectors are sensitive to the polarization and to the angle of incidence

A measurement of the degree of circular polarization determines the inclination of a simple binary orbit.

To fully reconstruct a gravitational wave several cylinders or interferometers are need

Two polarizations "+" and "x"

The two independent polarization are shown in the following example (bar and interferometer)



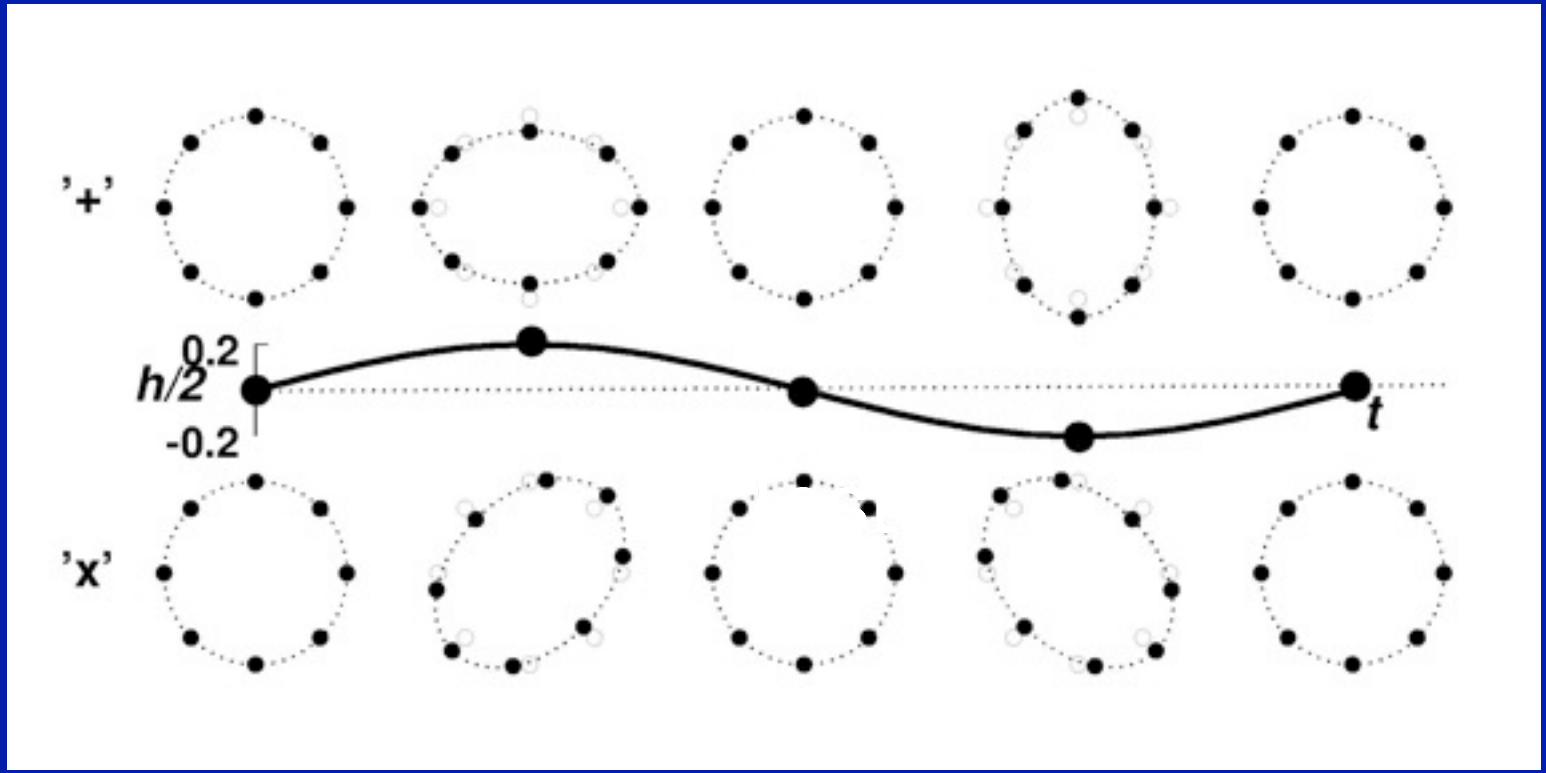
Detectors are sensitive to the polarization and to the angle of incidence

A measurement of the degree of circular polarization determines the inclination of a simple binary orbit.

To fully reconstruct a gravitational wave several cylinders or interferometers are need

Two polarizations “+” and “x”

The two independent polarization are shown in the following example (bar and interferometer)



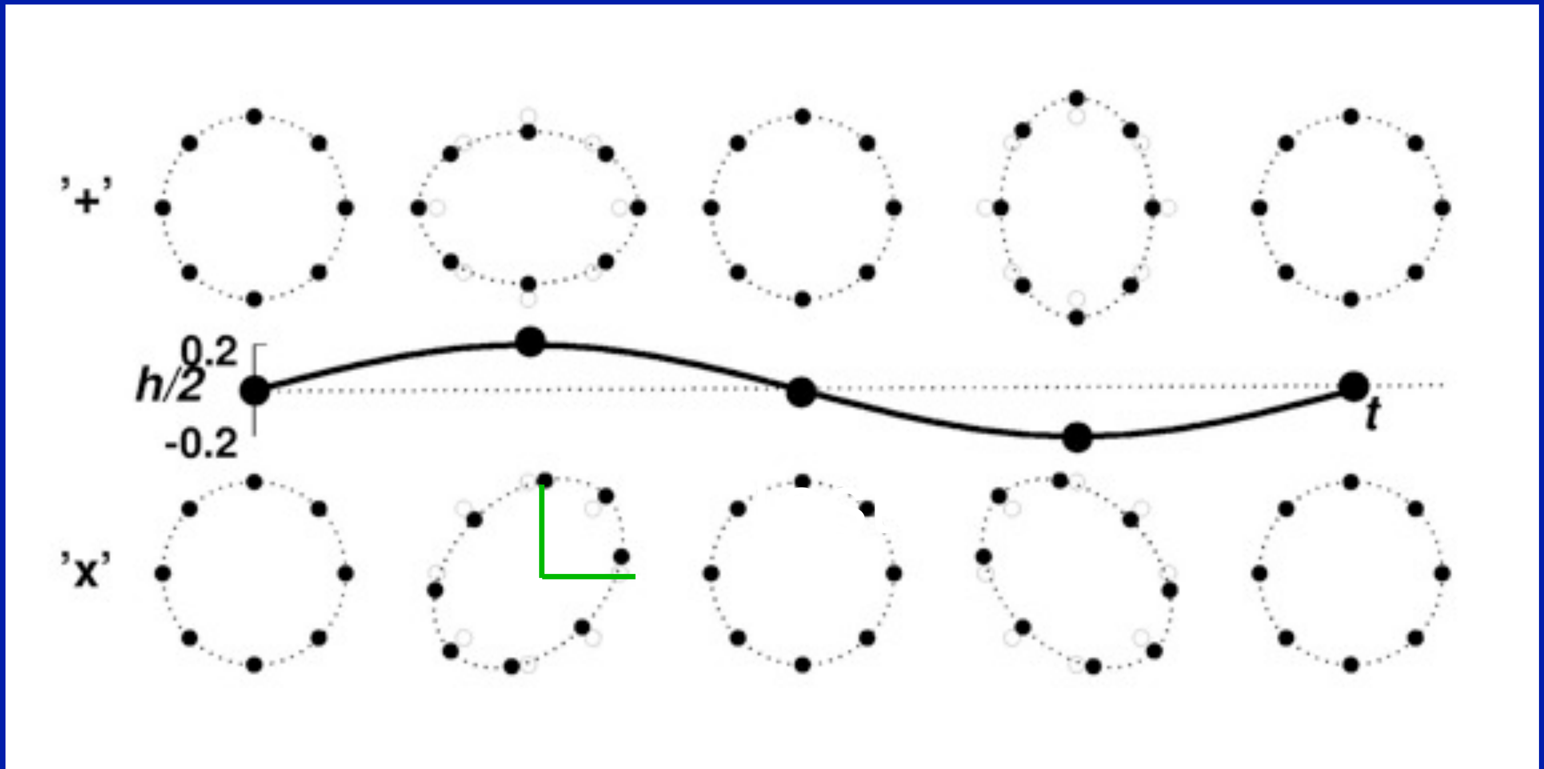
Detectors are sensitive to the polarization and to the angle of incidence

A measurement of the degree of circular polarization determines the inclination of a simple binary orbit.

To fully reconstruct a gravitational wave several cylinders or interferometers are need

Two polarizations “+” and “x”

The two independent polarization are shown in the following example (bar and interferometer)



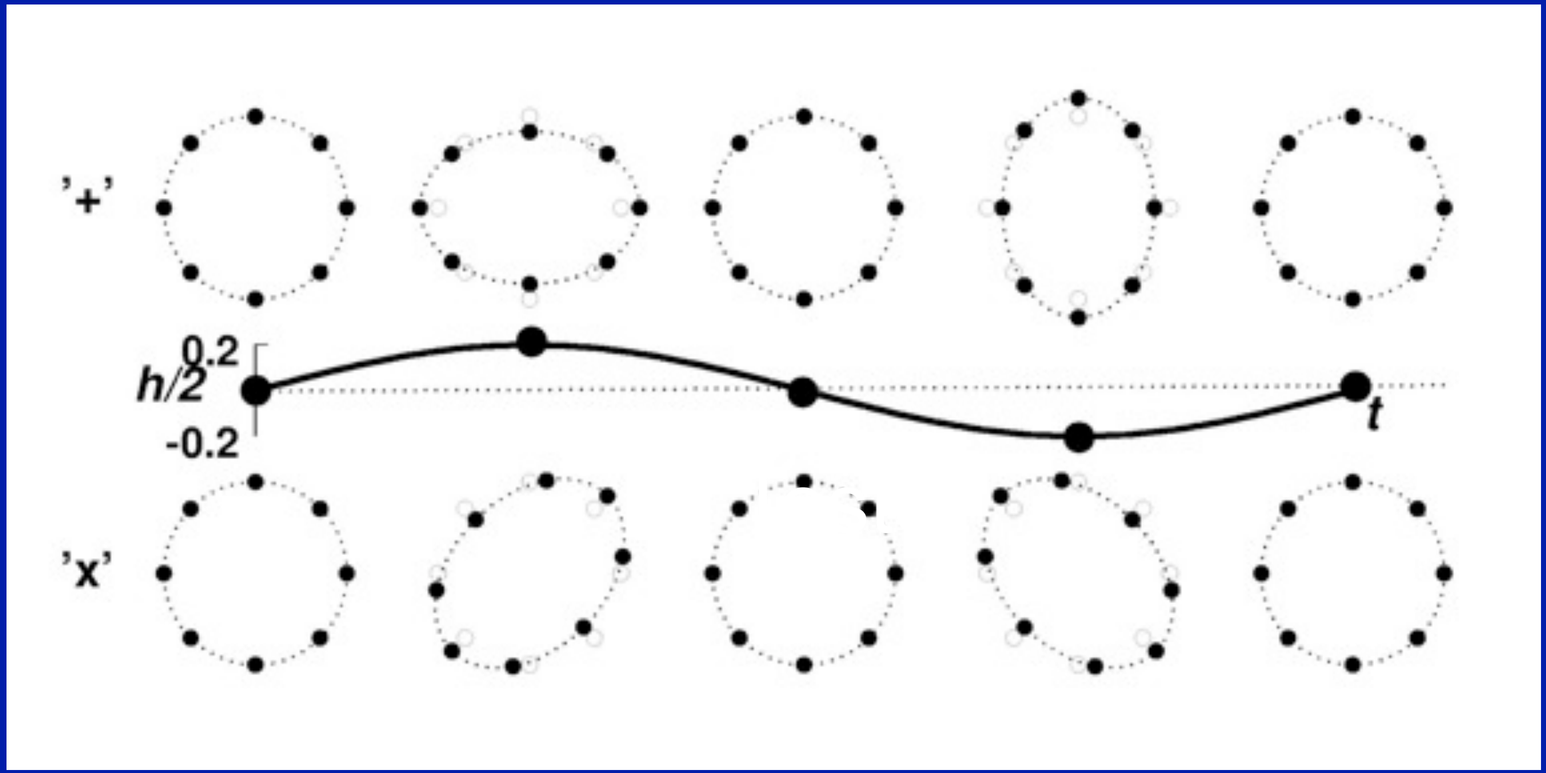
Detectors are sensitive to the polarization and to the angle of incidence

A measurement of the degree of circular polarization determines the inclination of a simple binary orbit.

To fully reconstruct a gravitational wave several cylinders or interferometers are need

Two polarizations “+” and “x”

The two independent polarization are shown in the following example (bar and interferometer)



Detectors are sensitive to the polarization and to the angle of incidence

A measurement of the degree of circular polarization determines the inclination of a simple binary orbit.

To fully reconstruct a gravitational wave several cylinders or interferometers are need

Interaction of a gravitational wave or an Extensive air shower with a cylindrical resonant antenna

Cylindrical bar equivalent to an oscillator with two masses and a spring:

M/2

$$l = \frac{4L}{\pi^2}$$

$$\ddot{\xi}(t) + \omega_0 \frac{\dot{\xi}}{2Q} + \omega_0^2 \xi(t) = l \frac{\ddot{h}(t)}{2} \qquad Q = \frac{1}{2}\tau\omega_0$$

Excitation due to a continuous gravitational wave h_+:

$$\xi(t) = \frac{1}{2} \frac{l\Omega^2 h_0}{\sqrt{(\omega_0 - \Omega)^2 + 4\frac{\Omega^2 \omega_0{}^2}{Q^2}}} \cos(\Omega t)$$

if $\Omega = \omega_o$:

$$\xi_0 = \frac{Q}{2} l h_0$$

High Q needed! Very small numbers!
for a 1 msec GW burst h = 10^{-20} m
$\xi_0 \sim 10^{-20}$m E~10^{-29} joules

Computing the rates in a gravitational bar detector

- three components (muons, hadrons, Extensive Air Showers) -separate calculations up to now
- **the maximum energy is** in the shower center near the primary original direction
- very large uncertainty in the calculations, particularly for very energetic showers

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)*

Nautilus group 2001 Corsika+Geant