united nations
educational, scientific
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international atomic
energy agency

the
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ICTP 40th Anniversary

H4.SMR/1574-10

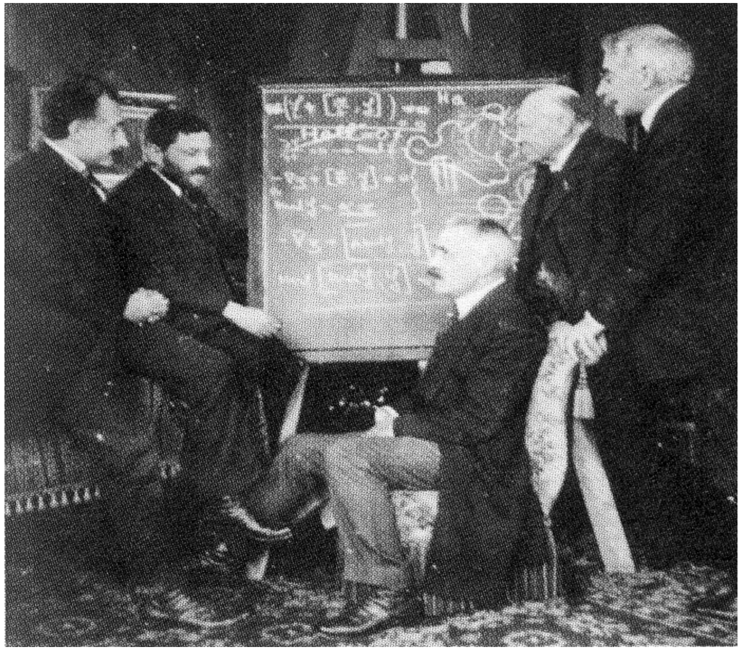
"VII School on Non-Accelerator Astroparticle Physics"

26 July - 6 August 2004

Searches for Gravitational Waves - I

Eugenio COCCIA

University of Rome "Tor Vergata"
& INFN Gran Sasso
Italy



Searches for Gravitational Waves
I

Eugenio Coccia
University of Rome “Tor Vergata”
and INFN Gran Sasso

I
How to detect gw
Detection principle and sensitivity of
Resonat masses and Interferometers

II
Results
Perspectives

Main features

- 2 transversal polarization states

- Associated with massless, spin 2 particles (gravitons)

- Emitted by time-varying quadrupole mass moment
  no dipole radiation because of conservation laws

$$-\frac{dE}{dt} = \cancel{\frac{2G}{3c^3}\left(\ddot{\vec{d}}\right)^2} + \frac{G}{45c^5}\left(\dddot{Q}\right)^2 + \dots$$

$$\vec{d} = \Sigma_i m_i \vec{x}_i \Rightarrow \ddot{\vec{d}} \equiv 0 \qquad\qquad Q_{ij} = \int \rho x_i x_j d^3x$$

$$h_{ij} = -\frac{4G}{c^4}\int\left(\frac{\tau_i^j}{r}\right)_{t-\frac{r}{c}} dV \qquad\qquad h_{ij}(t) = \frac{2G}{rc^4}\ddot{Q}_{ij}(t-r/c)$$

- **No laboratory equivalent of Hertz experiments for production of GWs**

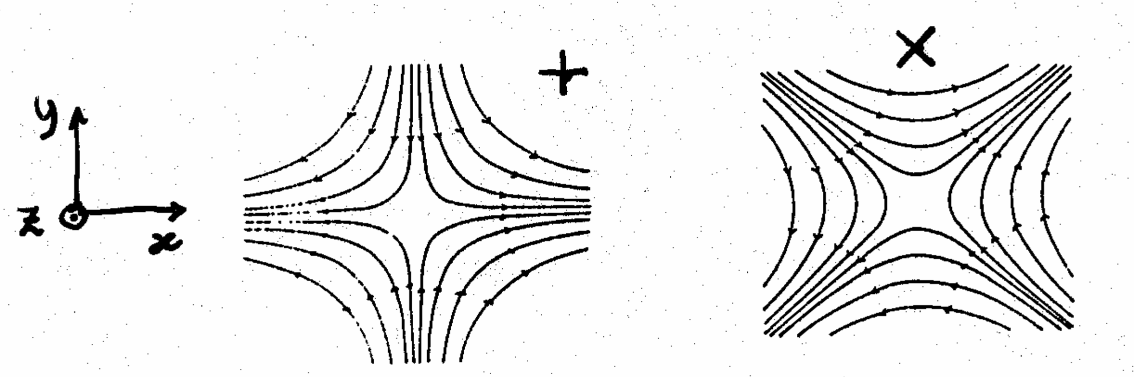
Luminosity due to a mass M and size R oscillating at frequency $\omega \sim v/R$:

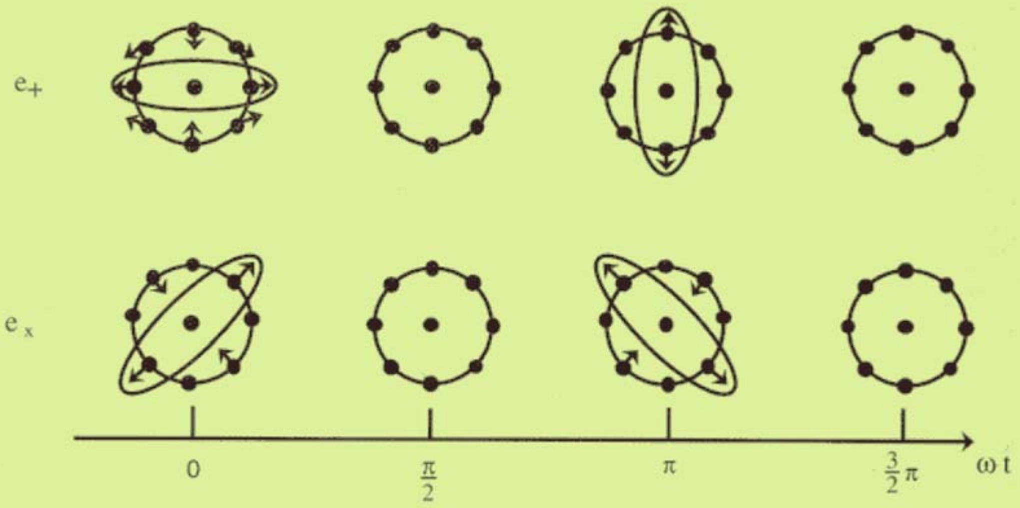
$$L = \frac{2G}{5c^5}\left\langle \dddot{Q}^2 \right\rangle \approx \frac{GM^2v^6}{R^2c^5} \qquad Q \approx MR^2 \sin \omega t$$

M=1000 tons, steel rotor, f = 4 Hz → L = 10^{-30} W
Einstein: “ .. *a pratically vanishing value*…”

Collapse to neutron star 1.4 M_o → L = 10^{52} W

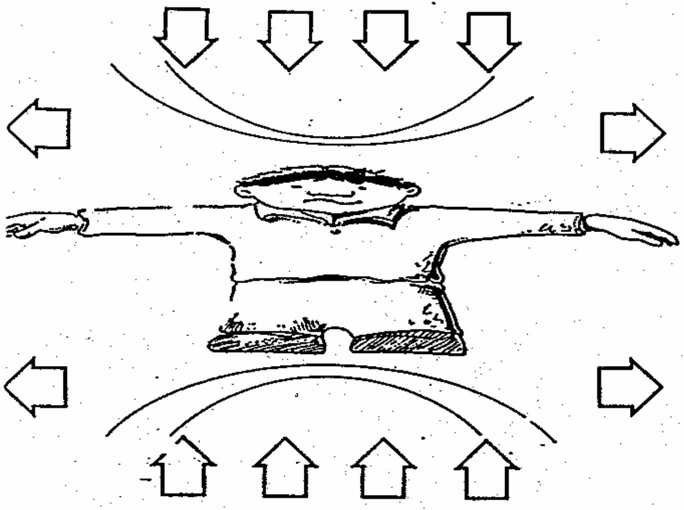
$h \sim W^{1/2} d^{-1}$*;** source in the Galaxy ***$h \sim 10^{-18}$*,** in VIRGO cluster ***$h \sim 10^{-21}$
Fairbank: “...*a challenge for contemporary experimental physics..”*





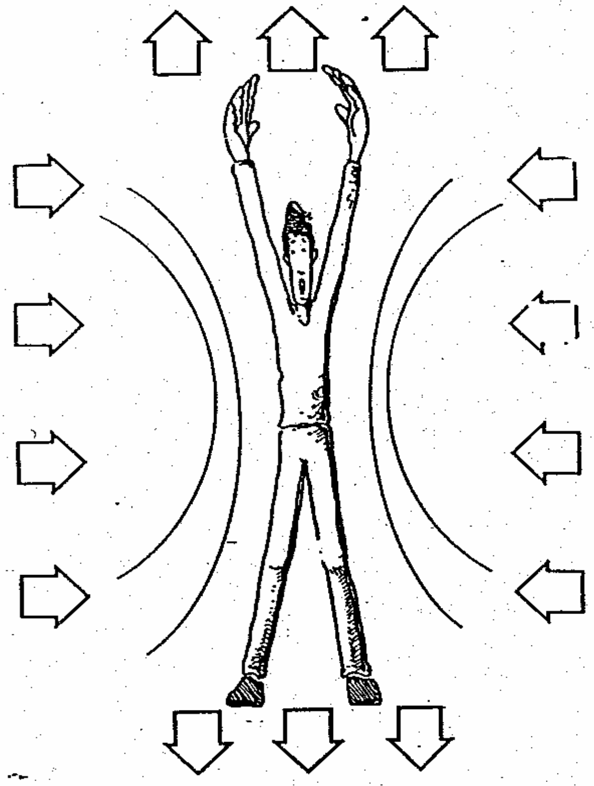
Le deformazioni (enormemente ingrandite) di un anello di punti materiali al passaggio di un'onda gravitazionale nelle due polarizzazioni "+" e "x".

CAUTION: GRAVITATIONAL RADIATION



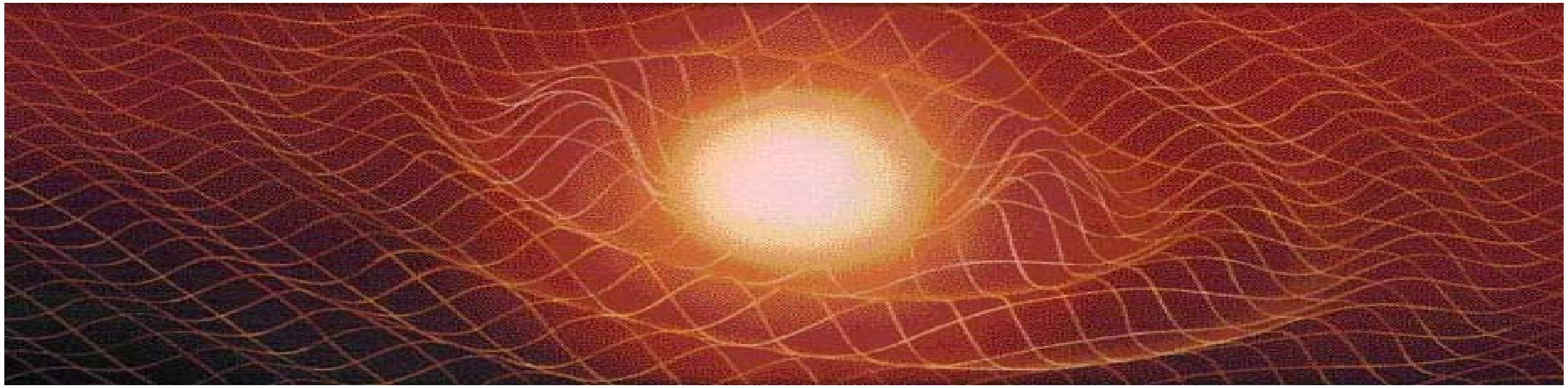
MAY BE DANGEROUS TO YOUR HEALTH

CAUTION: GRAVITATIONAL RADIATION



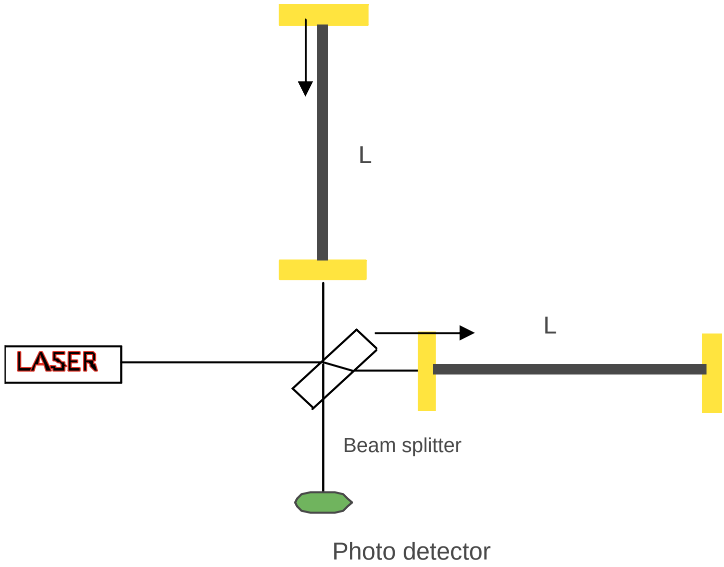
MAY BE DANGEROUS TO YOUR HEALTH

Gravitational collapse

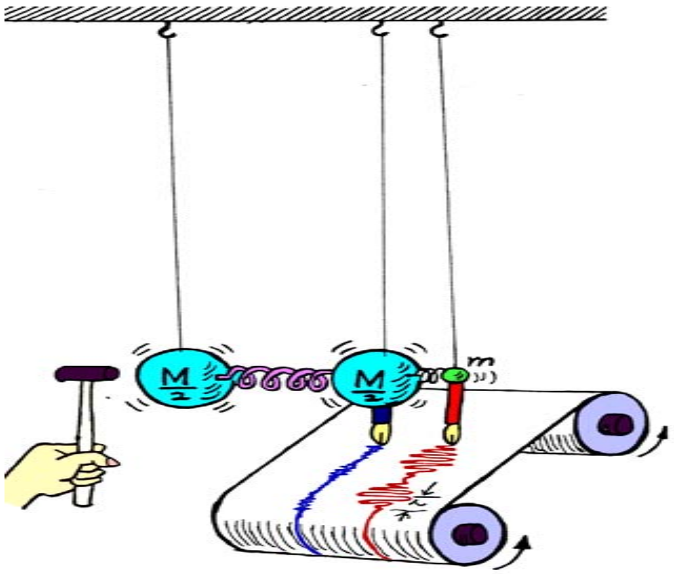


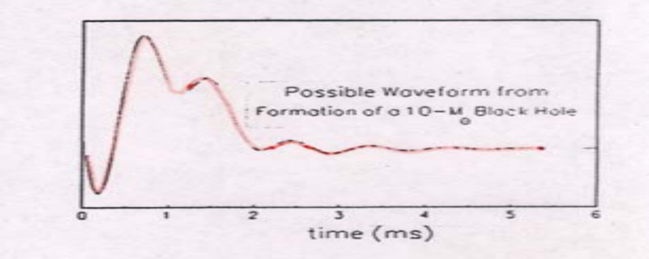
$$h = 1.4 \cdot 10^{-18} \left(\frac{10\,kpc}{r} \right) \sqrt{\frac{M_{GW}}{10^{-3} M_{\odot}}}$$

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



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

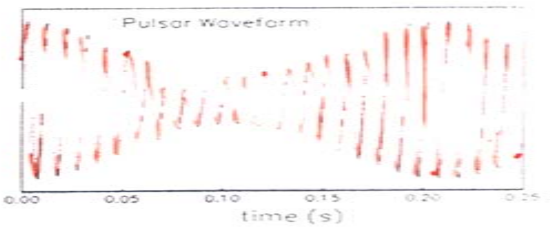




SUPERNOVAE.

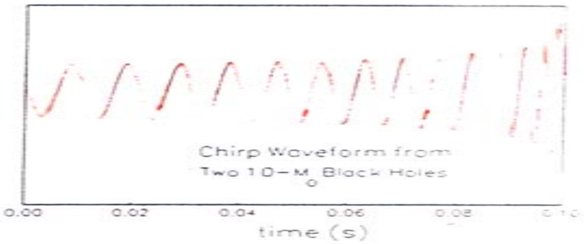
If the collapse core is non-symmetrical, the event can give off considerable radiation in a millisecond timescale.

Information
Inner detailed dynamics of supernova
See NS and BH being formed
Nuclear physics at high density



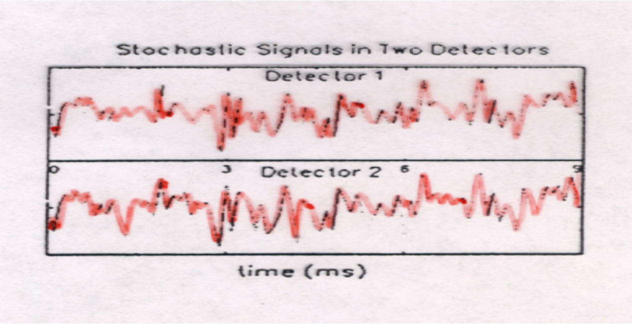
SPINNING NEUTRON STARS. Pulsars are rapidly spinning neutron stars. If they have an irregular shape, they give off a signal at constant frequency (prec./Dpl.)

Information
Neutron star locations near the Earth
Neutron star Physics
Pulsar evolution



COALESCING BINARIES.
Two compact objects (NS or BH) spiraling together from a binary orbit give a chirp signal, whose shape identifies the masses and the distance

Information
Masses of the objects
BH identification
Distance to the system
Hubble constant
Test of strong-field general relativity



STOCHASTIC BACKGROUND.
Random background, relic of the early universe and depending on unknown particle physics. It will look like noise in any one detector, but two detectors will be correlated.

Information
Confirmation of Big Bang, and inflation
Unique probe to the Planck epoch
Existence of cosmic strings

The search for gravitational waves

f	λ	***method***	***sources***
10^{-16} Hz	10^{9} ly	Anisotropy of CBR	- Primordial
10^{-9} Hz	10 ly	Timing of ms pulsars	- Primordial - Cosmic strings
10^{-4} - 10^{-1} Hz	0.01 - 10 AU	Doppler Tracking of spacecraft Laser interferometers in space ***LISA***	- Bynary stars - Supermassive BH (10^{3} -10^{7} M_o) formation, coalescence, inspiral
10 - 10^{3} Hz	300 - 30000 km	Laser interferometers on Earth ***LIGO, VIRGO, GEO, TAMA***	- Inspiral of NS and BH binaries (1-1000 M_o) - Supernovae - Pulsars
10^{3} Hz	300 km	Cryogenic resonant detectors ***ALLEGRO, AURIGA, EXPLORER, NAUTILUS, MiniGRAIL, Schenberg***	- NS and BH binary coalescence - Supernovae - ms pulsars

Gravitational Wave Detectors

Allegro, USA

MiniGRAIL
The Netherlands

Auriga, Italy

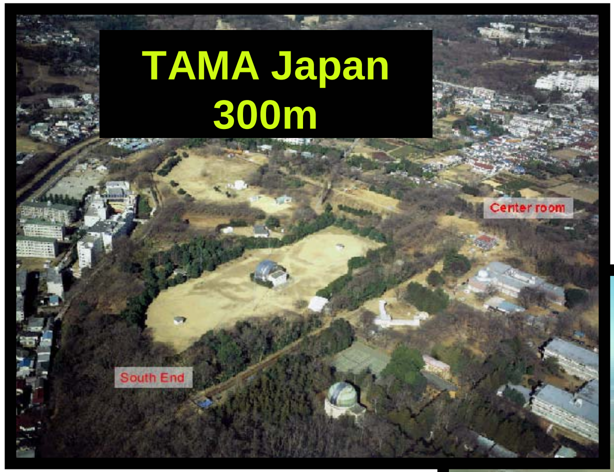
Explorer
Switzerland

Schenberg,
Brazil

Nautilus, Italy

Niobe
Australia

The Detectors



TAMA Japan
300m

Virgo Italy
3000m

LIGO Louisiana
4000m

AIGO Australia
future

LIGO Washington
2000m & 4000m

GEO Germany
600m

Una immagine di Joseph Weber, pioniere della ricerca delle onde gravitazionali, intento ad incollare le ceramiche piezoelettriche su una delle prime antenne a temperatura ambiente.

Gravitational Wave Detectors

Principle of operation of resonant-mass detectors

GWs excite those vibrational modes of a resonant body that have a mass quadrupole moment, such as the fundamental longitudinal mode of a cylindrical antenna.

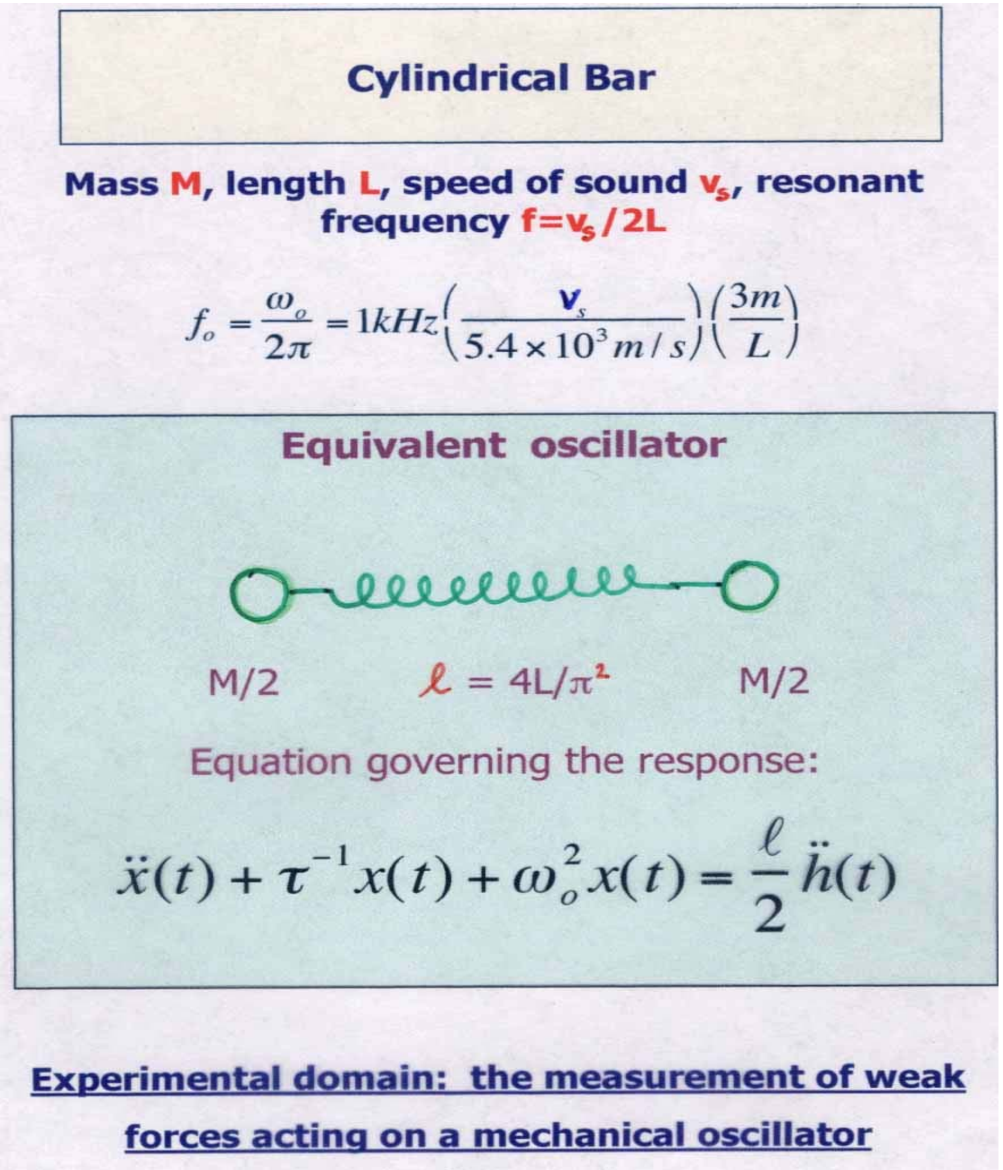
$$u(x,t) = \Sigma_n A_n(t)\psi_n(x)$$

$$\ddot{A}_n(t) + \tau^{-1}\dot{A}_n(t) + \omega_0^2 A_n(t) = F_n(t)$$

$$F_n(t) = M^{-1} R_{iojo} \int \psi_n^{i*} x^j \rho d^3x$$

Force acting on the n-mode,
described by the eigenfunction ψ_n

$$F_{1L} \neq 0 \; ; \quad F_{2L} = 0$$



Cylindrical Bar

Mass M, length L, speed of sound v_s, resonant frequency $f = v_s/2L$

$$f_o = \frac{\omega_o}{2\pi} = 1kHz\left(\frac{v_s}{5.4\times10^3\, m/s}\right)\left(\frac{3m}{L}\right)$$

Equivalent oscillator

Equation governing the response:

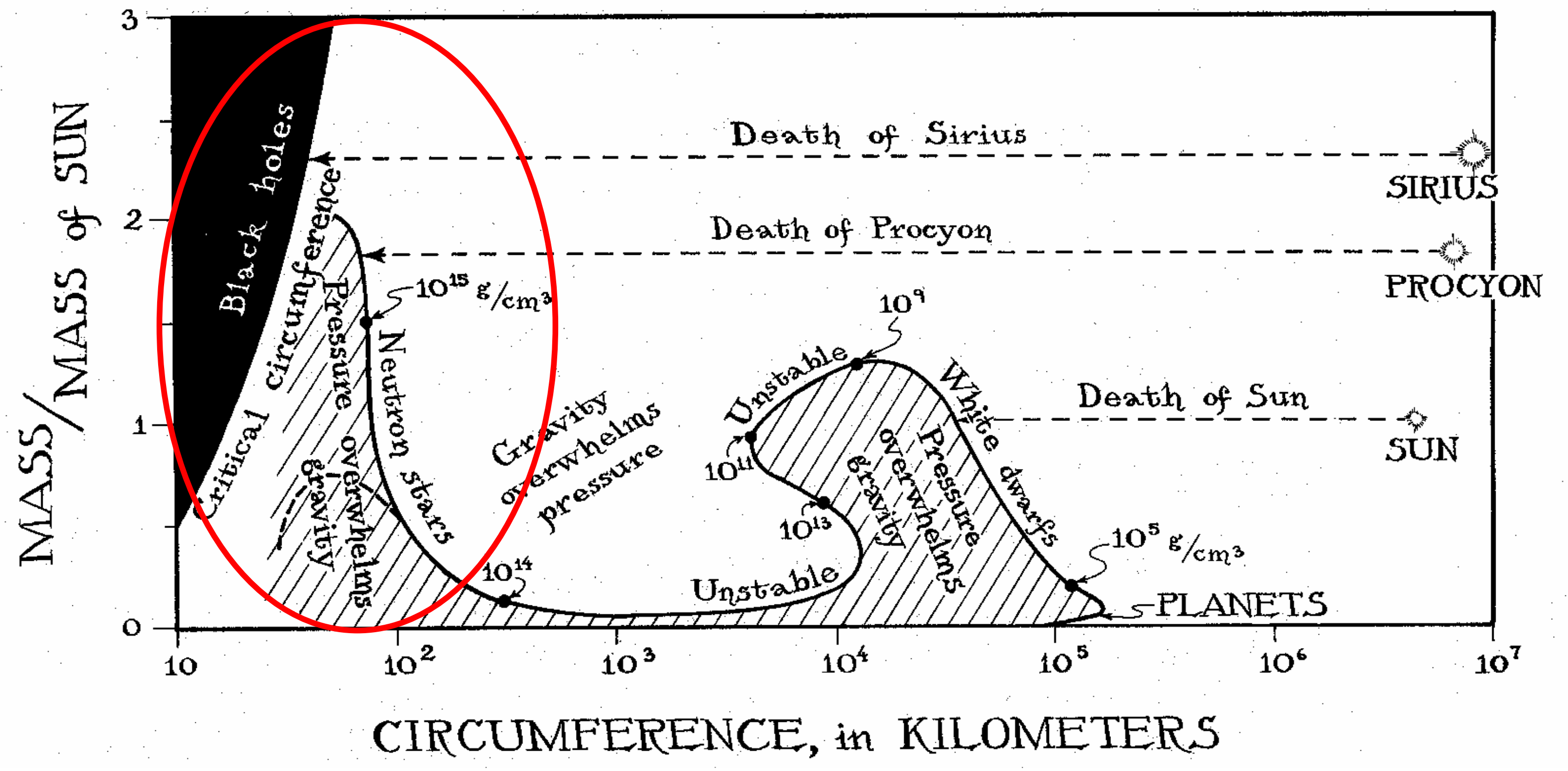
$$\ddot{x}(t) + \tau^{-1}x(t) + \omega_o^2 x(t) = \frac{\ell}{2}\ddot{h}(t)$$

Experimental domain: the measurement of weak forces acting on a mechanical oscillator

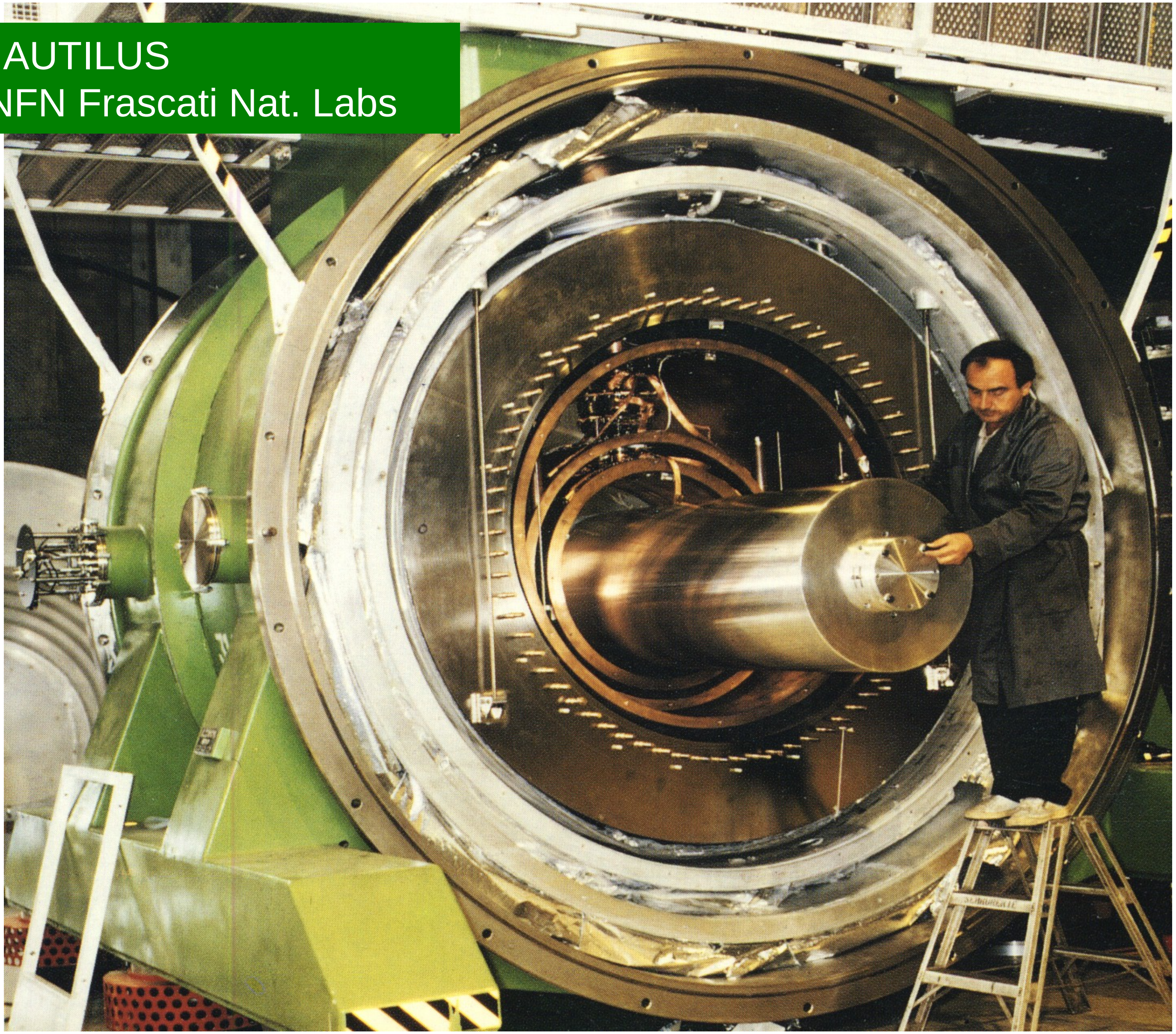
Frequency emitted by a dynamic system of density ρ :
kHz frequencies correspond to nuclear densities

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

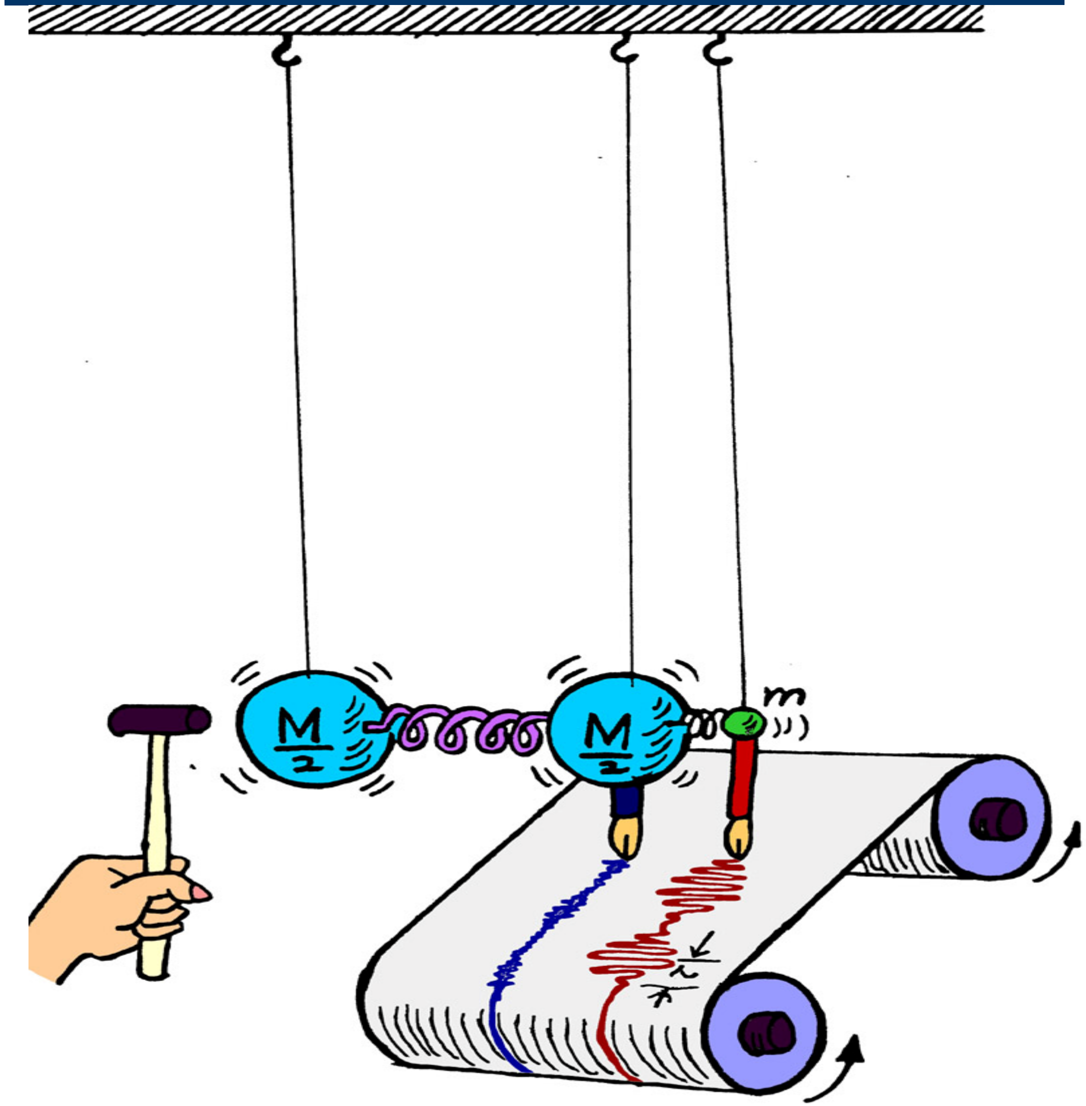
Sources: compact objects
pulsars, stellar gravitational collapse, last orbits of an inspiraling neutron star or black hole binary system, its merging, and its final ringdown.
Bar detectors can reveal unique features of matter at
extreme densities and **strong gravitational fields**



NAUTILUS
INFN Frascati Nat. Labs



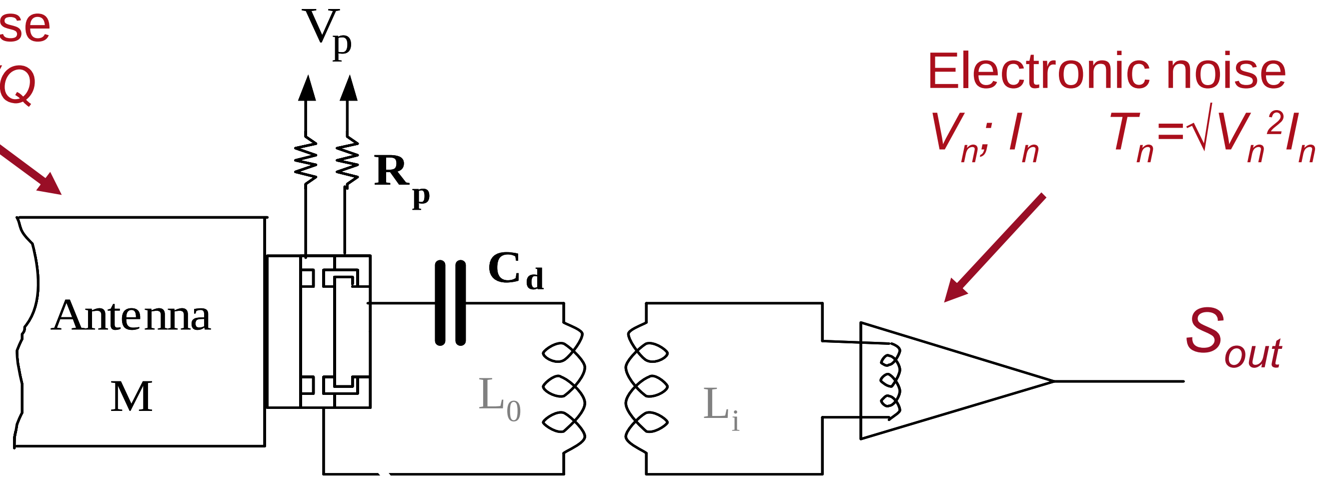
Principle of a Resonant Transducer



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

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

MAIN FEATURES



Thermal noise

$S_F = MkT\omega_r/Q$

Strain sensitivity

$$S_h = \left\lfloor \frac{1}{Hz} \right\rfloor$$

$$\tilde{h} = \frac{1}{\sqrt{Hz}}$$

Electronic noise

V_n; I_n $T_n=\sqrt{V_n^2 I_n^2}/k$

The mechanical oscillator

Mass **M**
Speed of sound **v_s**
Temperature **T**
Quality factor **Q**
Res. frequency **f_r**

The transducer

Efficiency β

The amplifier

Noise temperature **T_n**

NAUTILUS sensitivity

Strain sensitivity, i.e. minimum impulsive signal detectable with SNR = 1,

$$\tilde{h}_{min} \approx \left(\frac{T}{MQ}\right)^{1/2} \quad [1/\sqrt{Hz}]$$

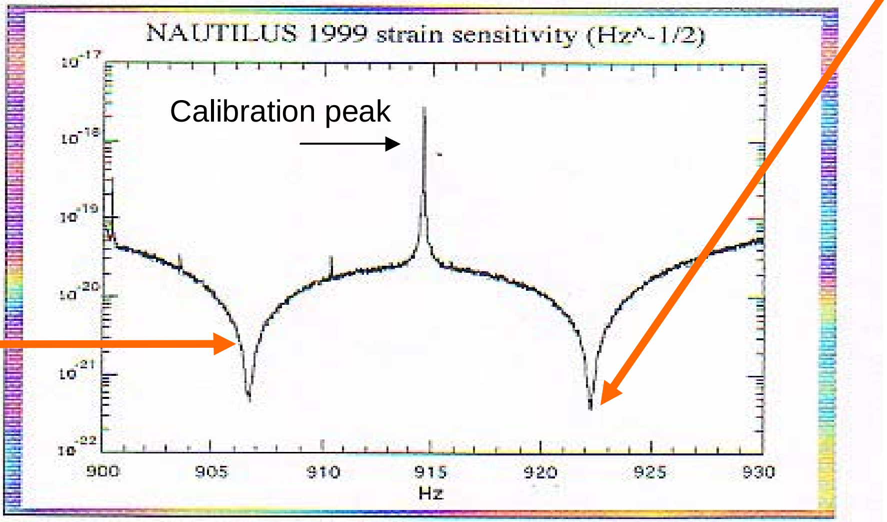
T Thermodynamic Temperature
M Mass
Q Quality Factor

$$\Delta f \approx \left(\frac{\beta}{T_n}\right)^{1/2} \quad [Hz]$$

ß Capacitive transducer efficiency
T_n Electronic temperature noise

The peak sensitivity depends on T/MQ

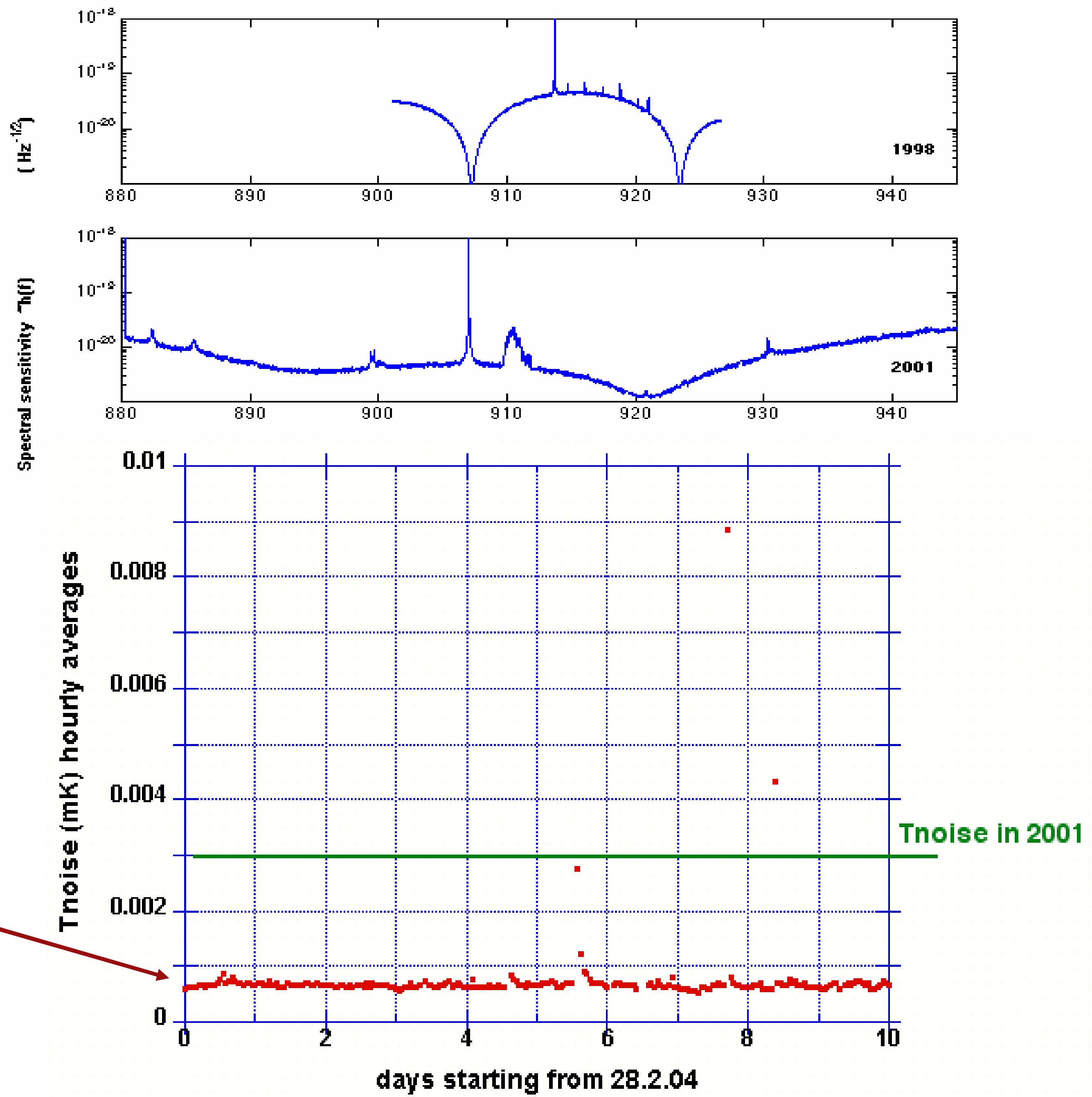
$$\tilde{h}_{min} \approx 3 \cdot 10^{-22} 1/\sqrt{Hz}$$



$$\Delta f \approx 1 Hz$$

The bandwidth depends mainly on the transducer and amplifier

The bandwidth of the antenna can be increased acting on the transducer-amplifier of the signals, by increasing ß and/or decreasing T_n



EXPLORER

Duty cycle > 90%

Astone et al.(ROG Collaboration)
PRL 2003

NAUTILUS 2004

Duty cycle > 90%

T noise = 690 μK

AURIGA II run *(12/2003)*: upgrades

new mechanical suspensions:

attenuation > 360 dB at 1 kHz FEM modelled

new capacitive transducer:

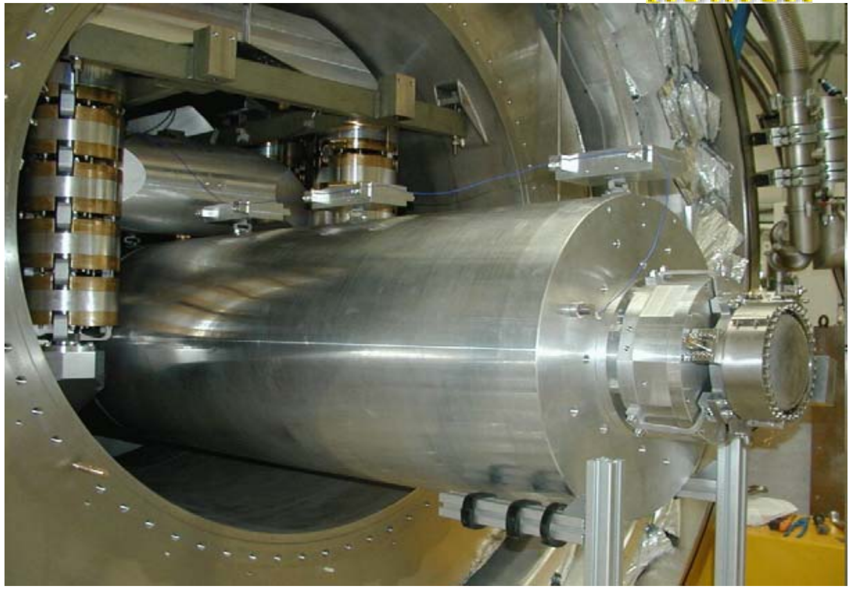
two-modes (1 mechanical+1 electrical) optimal mass

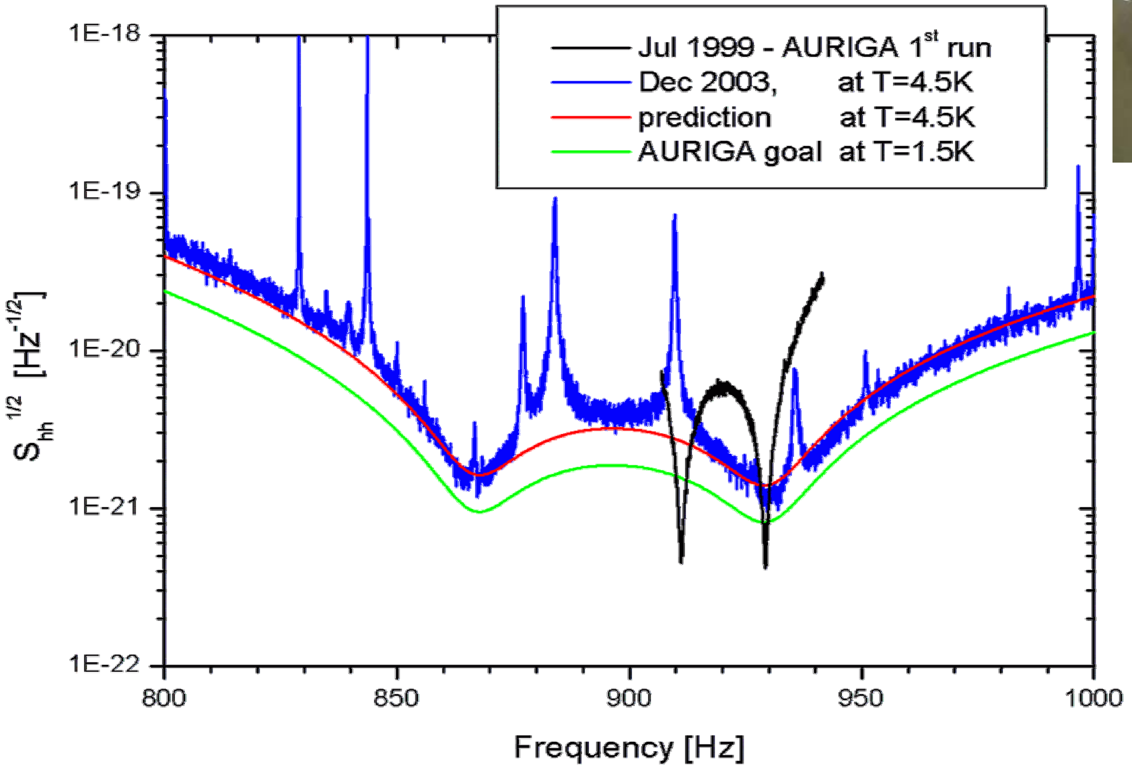
new amplifier:

double stage SQUID 200 h/ energy resolution

new data analysis:

C++ object oriented code frame data format





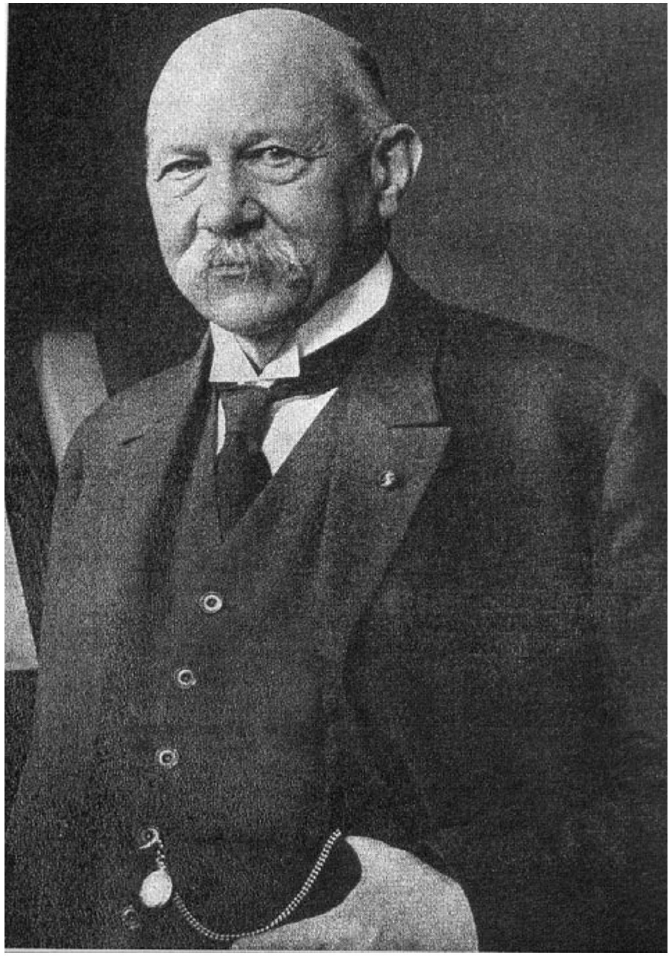
Present setting @ T = 4.5K

— = experimental. data

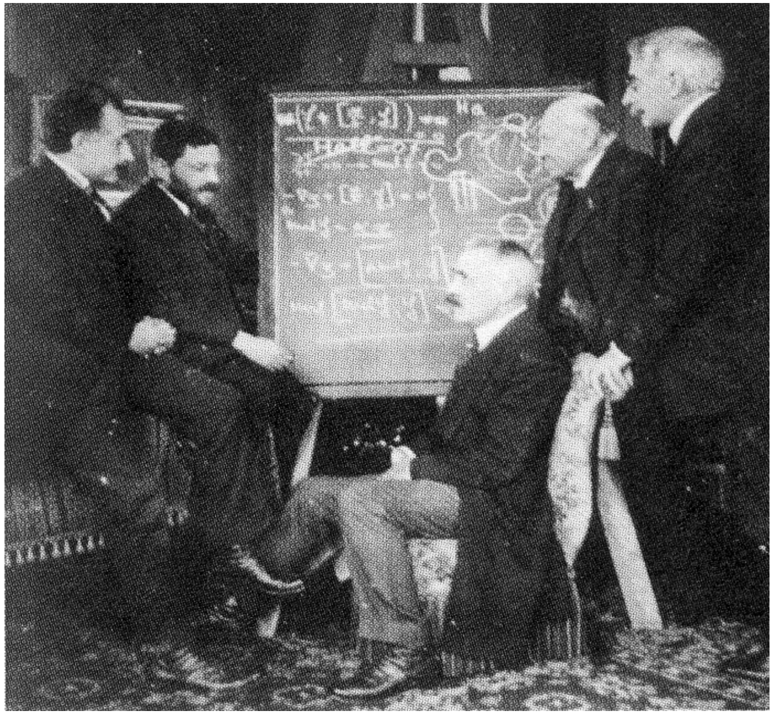
— = prediction

AURIGA goal @ T = 1.5K

— = prediction



Heike Kamerlingh Onnes



Leiden 1920

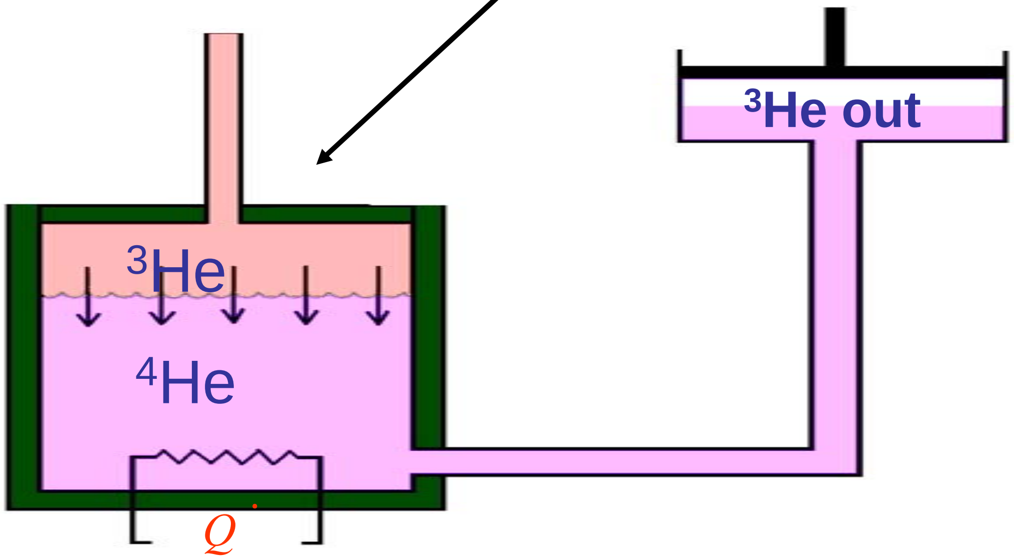
Quantum technology

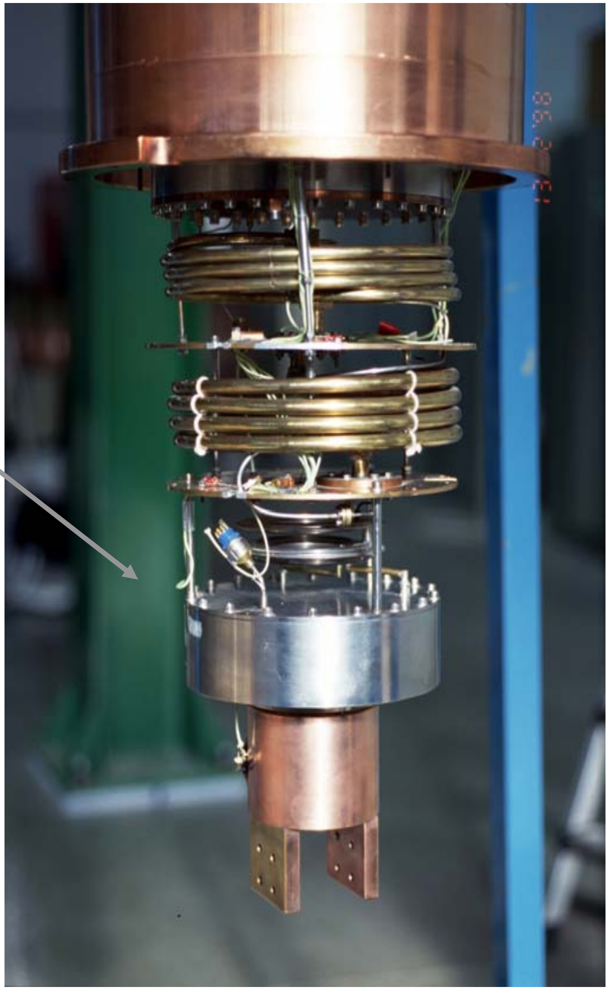
^{3}He-^{4}He Dilution Refrigerator

AURIGA and NAUTILUS
Largest masses cooled below 1 K

The liquid (the concentrated ^{3}He phase) is lighter and floats on a ^{4}He sea, in equilibrium with the 6.5% “vapor”. When ^{3}He passes from the low entropy liquid to the vapor phase (high entropy) it expands and absorbs heat.

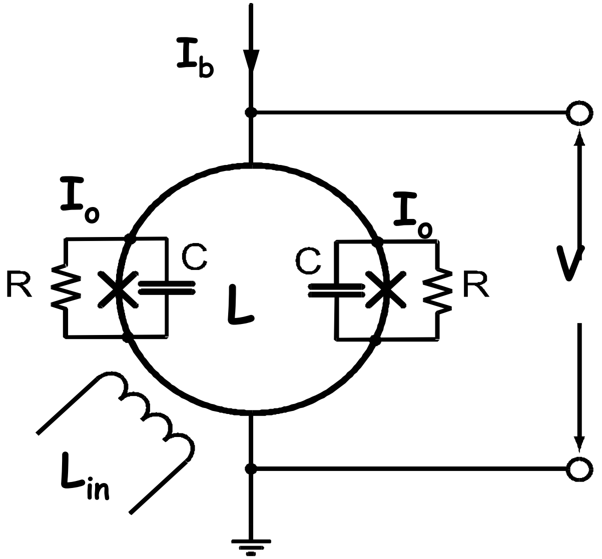
Mixing chamber



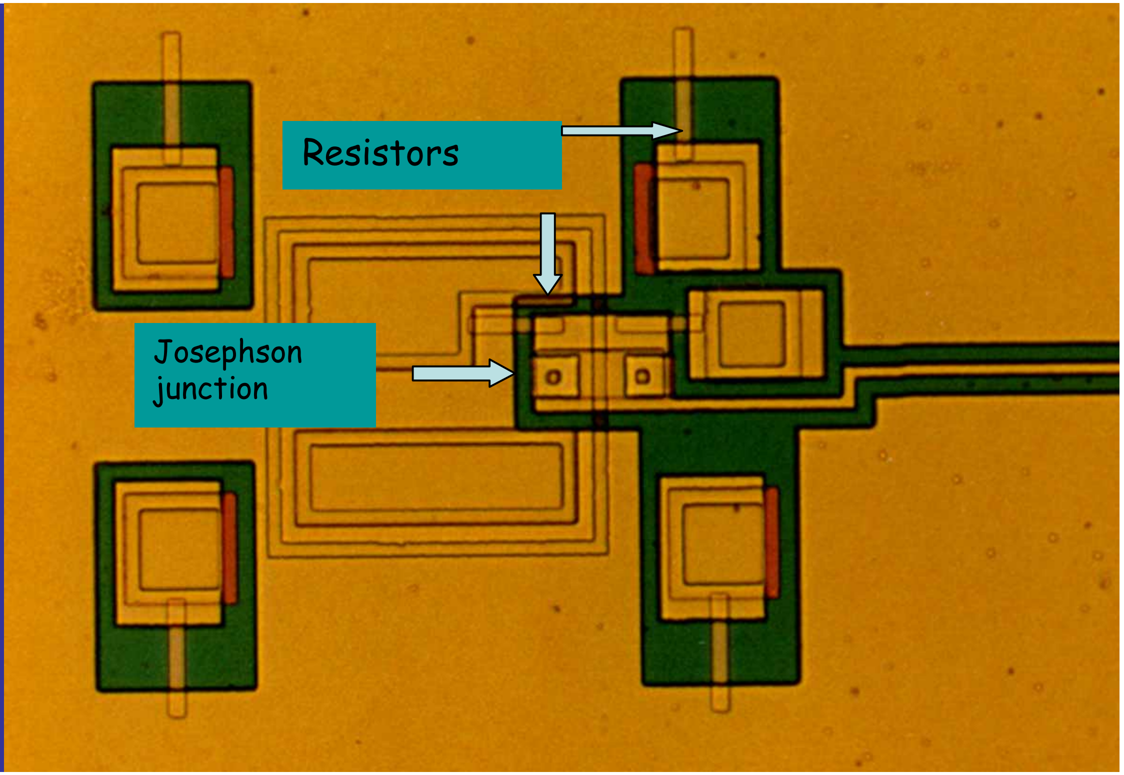


Quantum technology

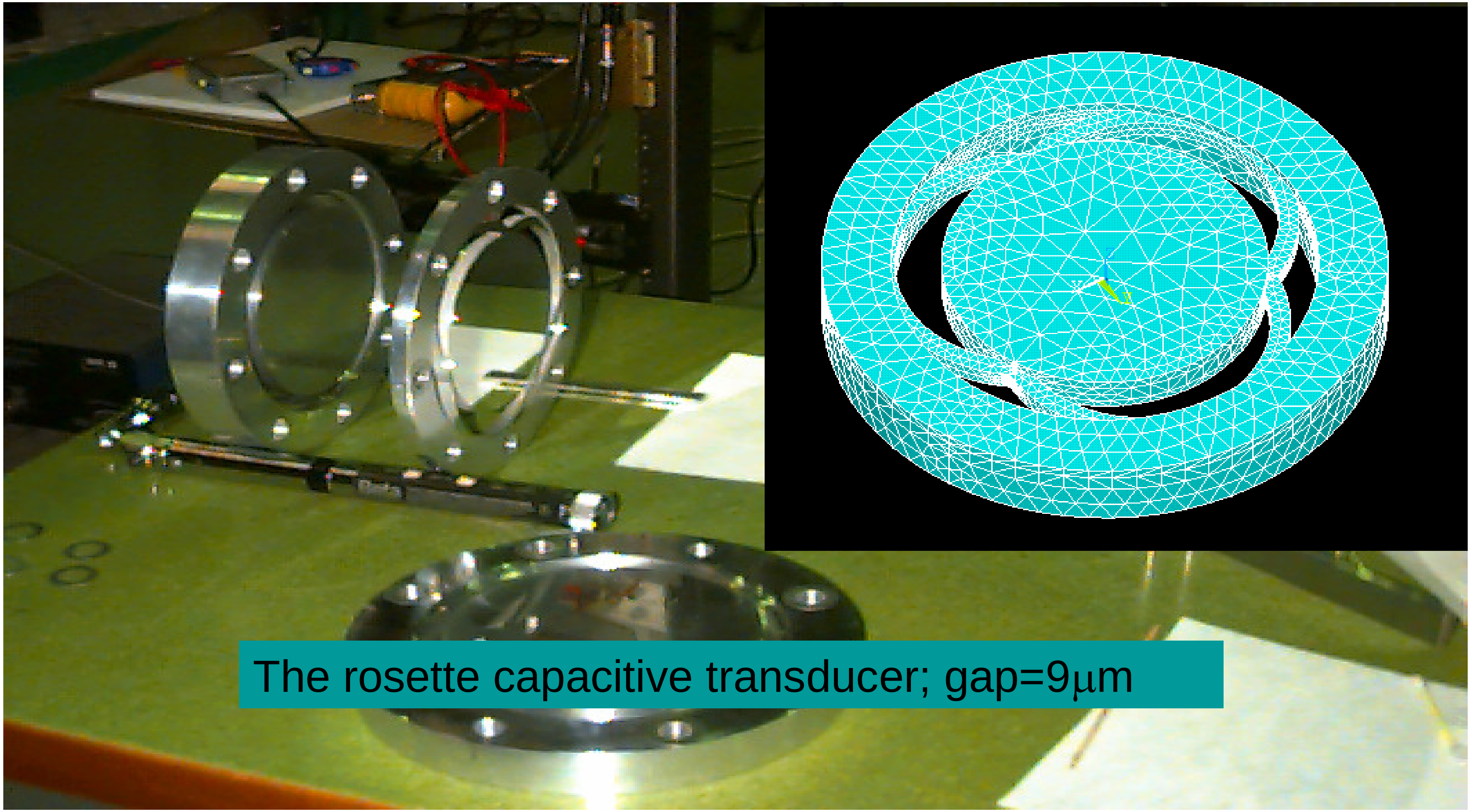
dc-SQUID



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

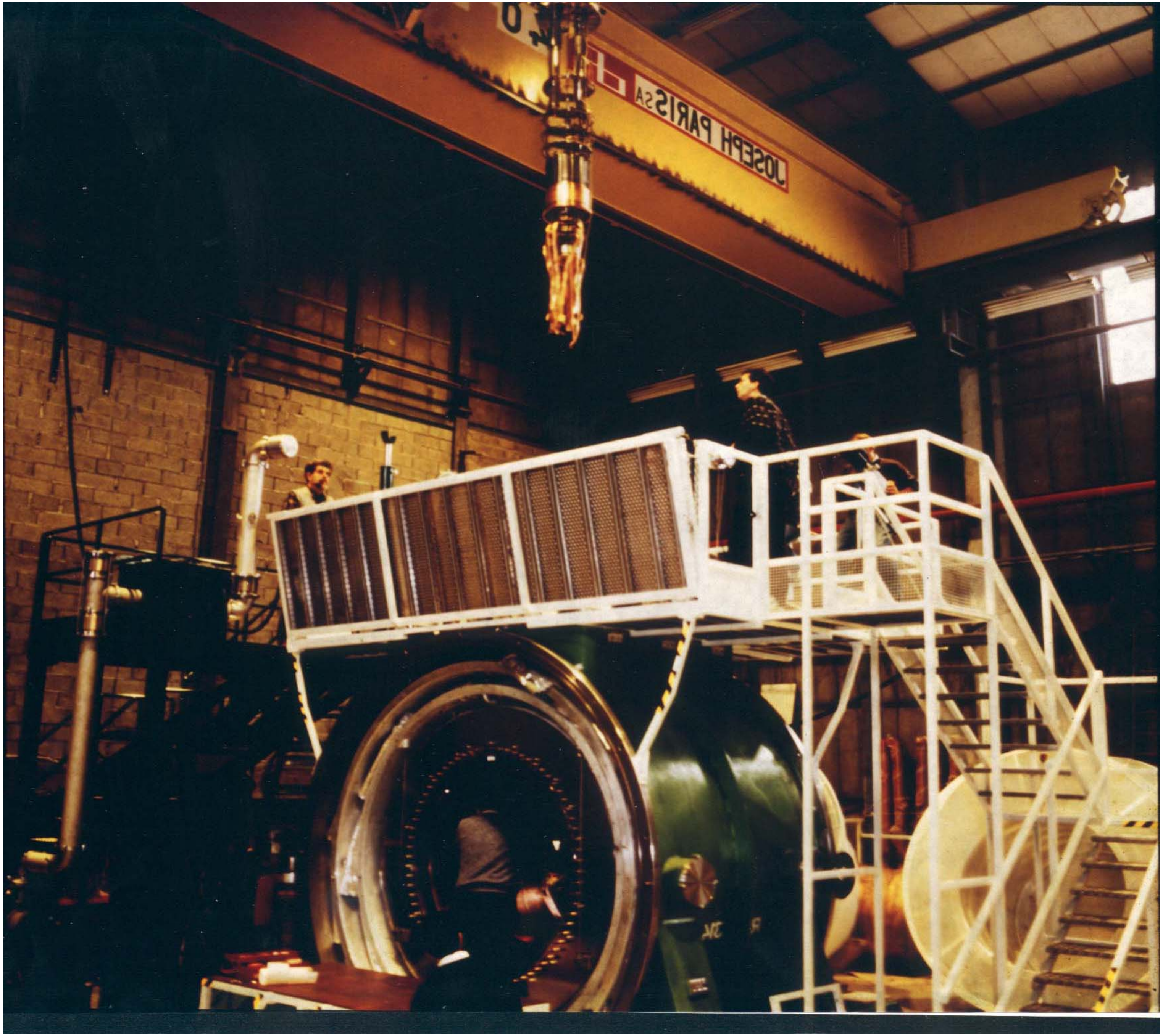


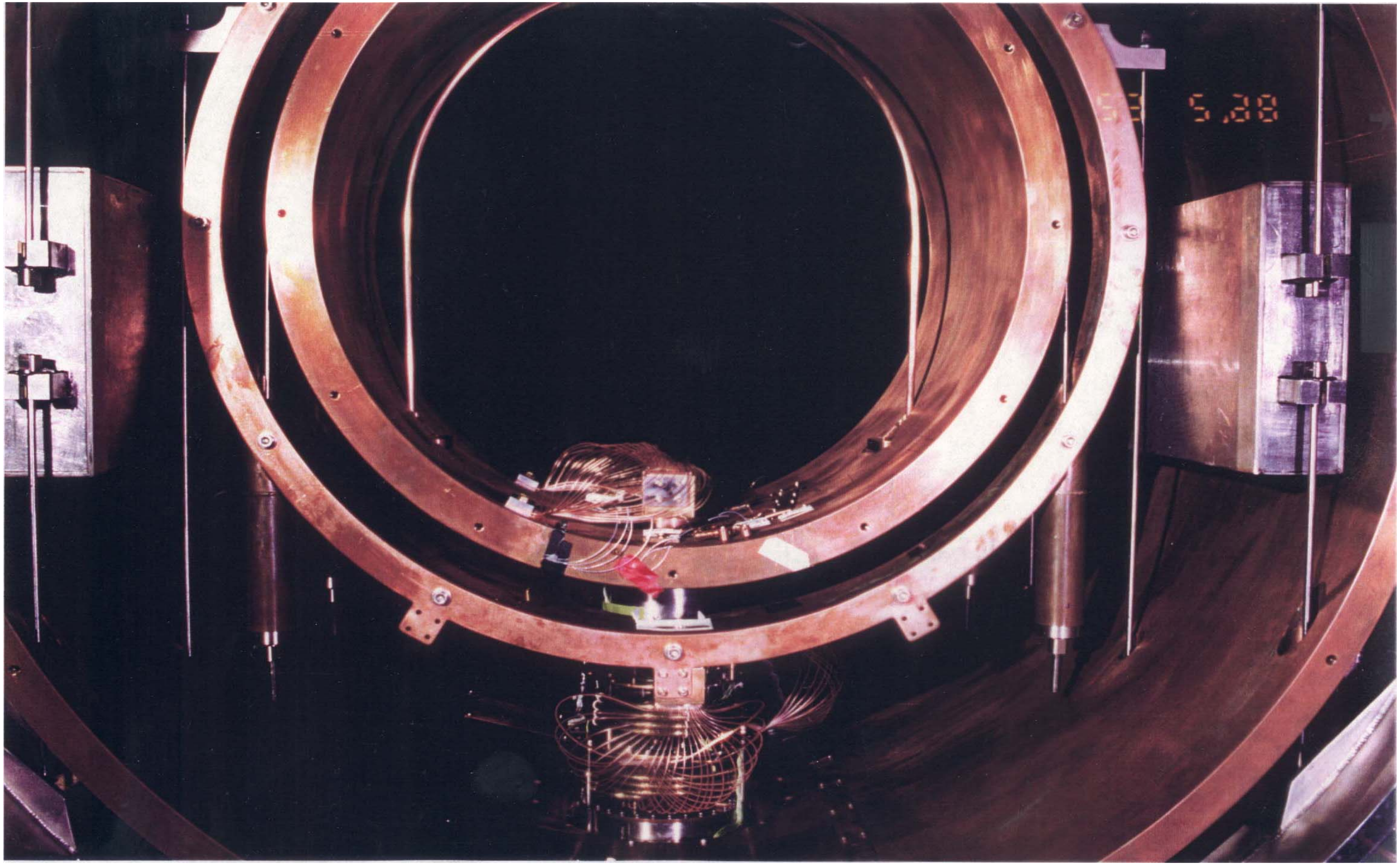
MICROMECHANICS



The rosette capacitive transducer; gap=9μm

Thermal contacts and acoustic isolation


JOSEPH PARIS SA


3 5,28

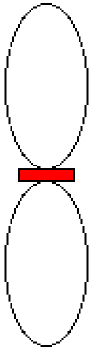
GW are described by a symmetric and traceless tensor h_{ij}

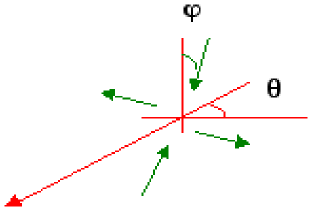
information:

h_+ h_x **H** δ h_s

ampl. of the 2 pol. states; source direction; scalar field (=0 in GR)

A resonant mass detector is characterized by those eigenmodes having the appropriate (quadrupole) symmetry





cylindrical bar

only one quadrupole mode interacts strongly with GWs

The cross section is dependent on the wave propagation direction. The *single* output is a (unknown) combination of the components (*same for an interferometer*)

sphere

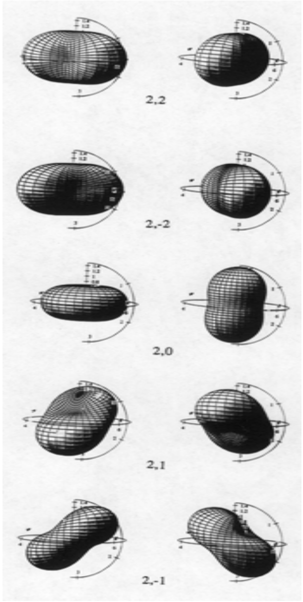
five degenerate quadrupole modes (described using the basis of the five spherical harmonics Y_{2m} with m=±2,±1,0;

the same basis can be used to express h_{ij} in the equivalent spherical components h_m)

The cross section is omnidirectional

The five outputs determine the five parameters:

h_+ h_x **H** δ h_s

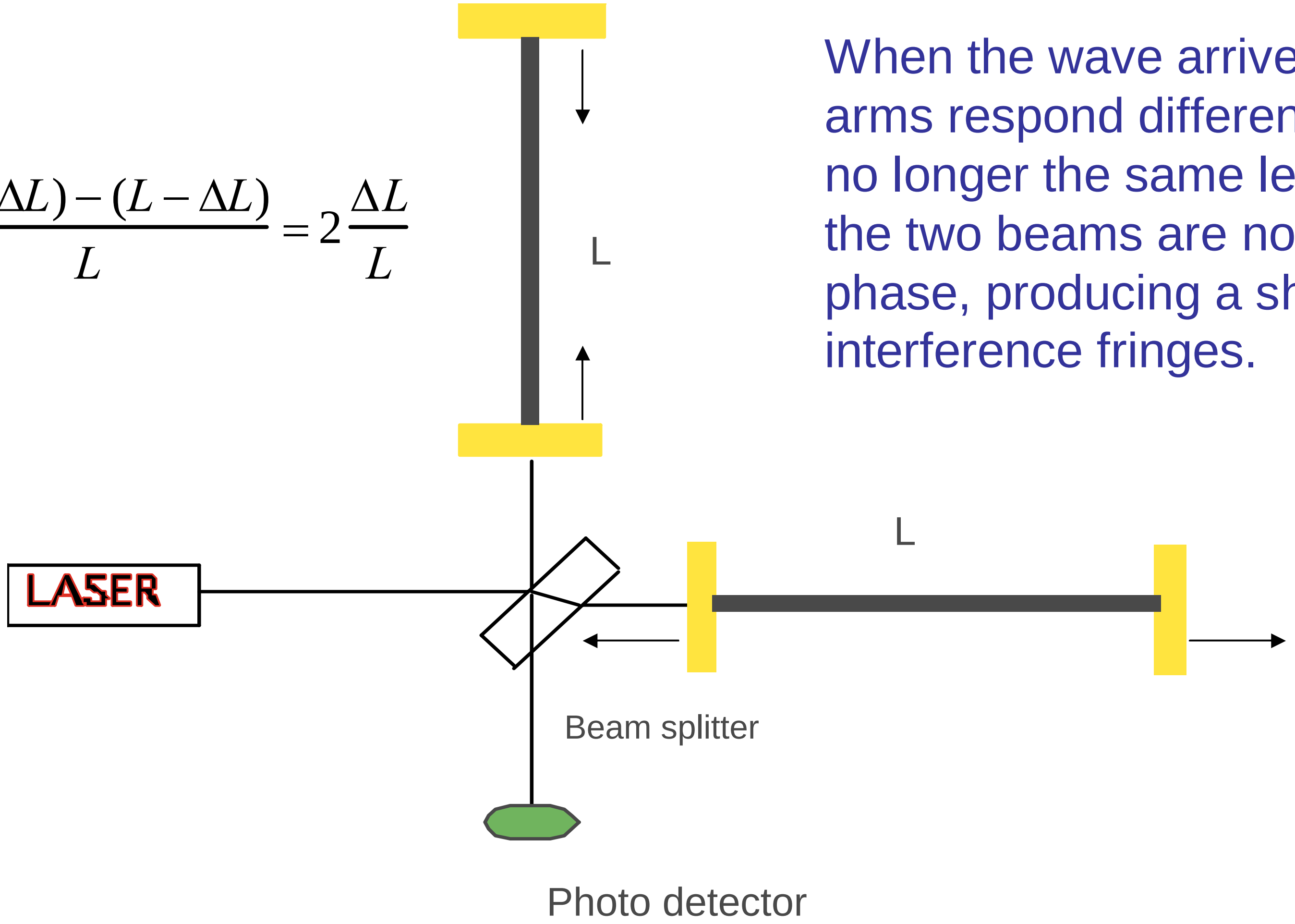


Principle of operation

Interferometers use laser light to compare the lengths of two perpendicular arms

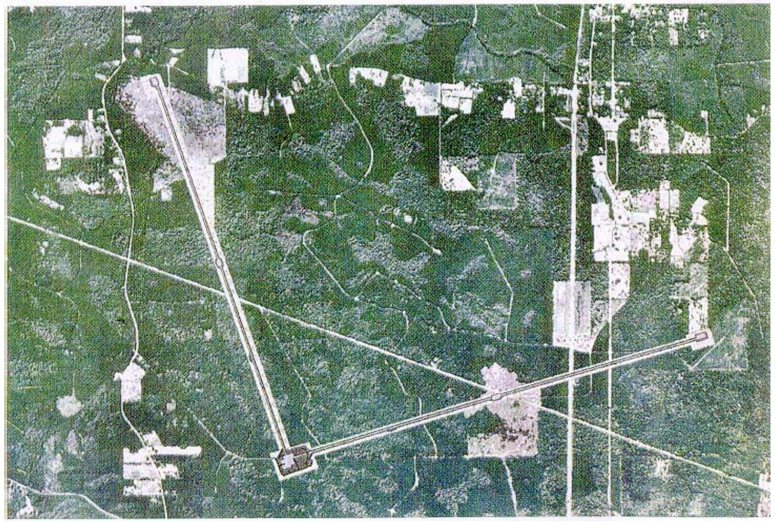
When the wave arrives, the two arms respond differently, they are no longer the same length, and so the two beams are no longer in phase, producing a shift in the interference fringes.

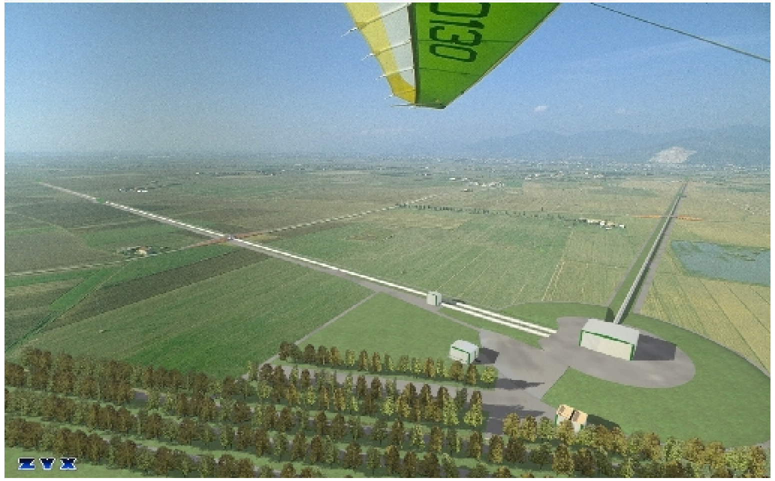
$$h = \frac{(L+\Delta L)-(L-\Delta L)}{L} = 2\frac{\Delta L}{L}$$



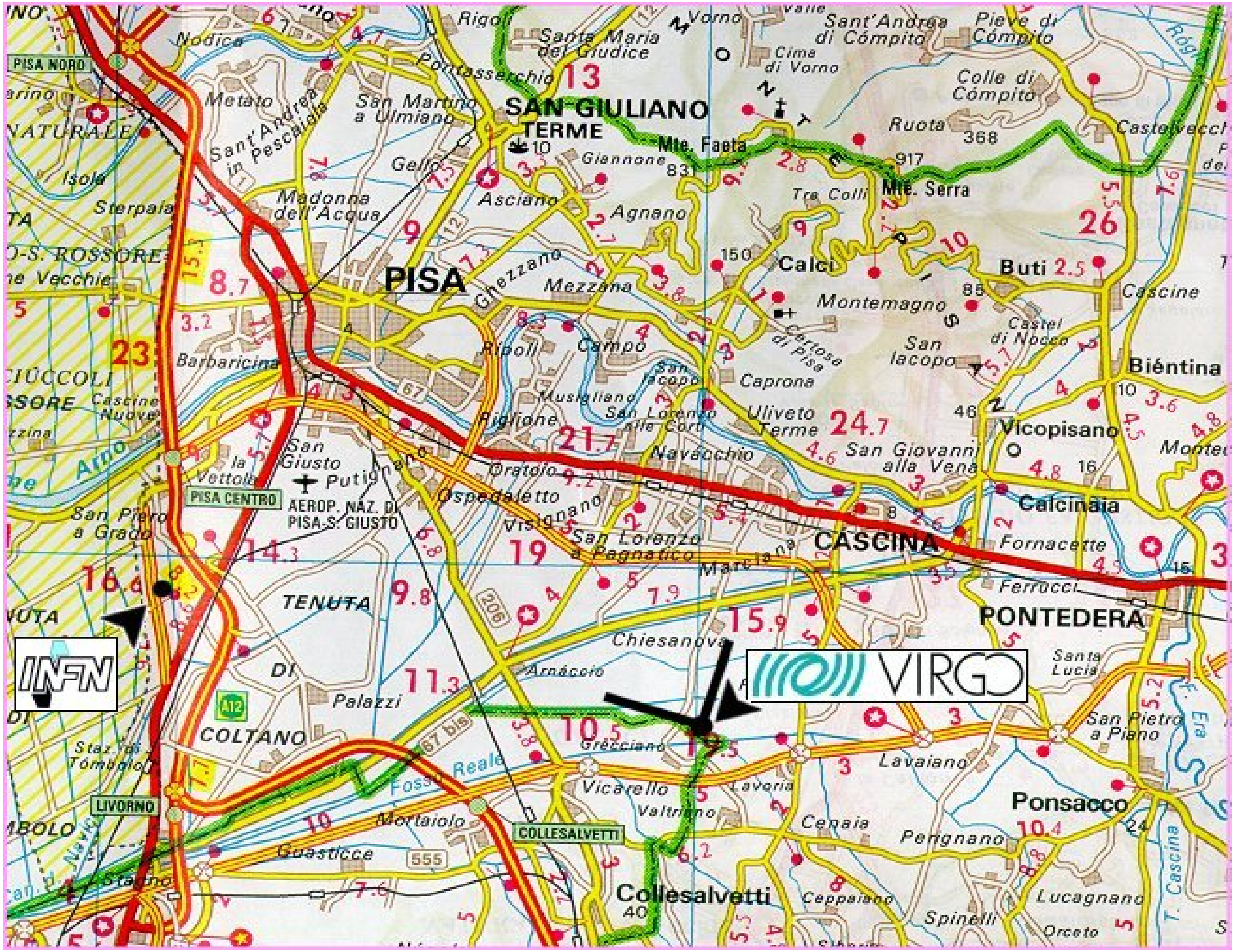
1999-2004: Large interferometers start operating

1999 **TAMA**
2001 **LIGO** **GEO**
2003 **VIRGO**






Hanford
3002 km
(L/c = 10 ms)
Livingston

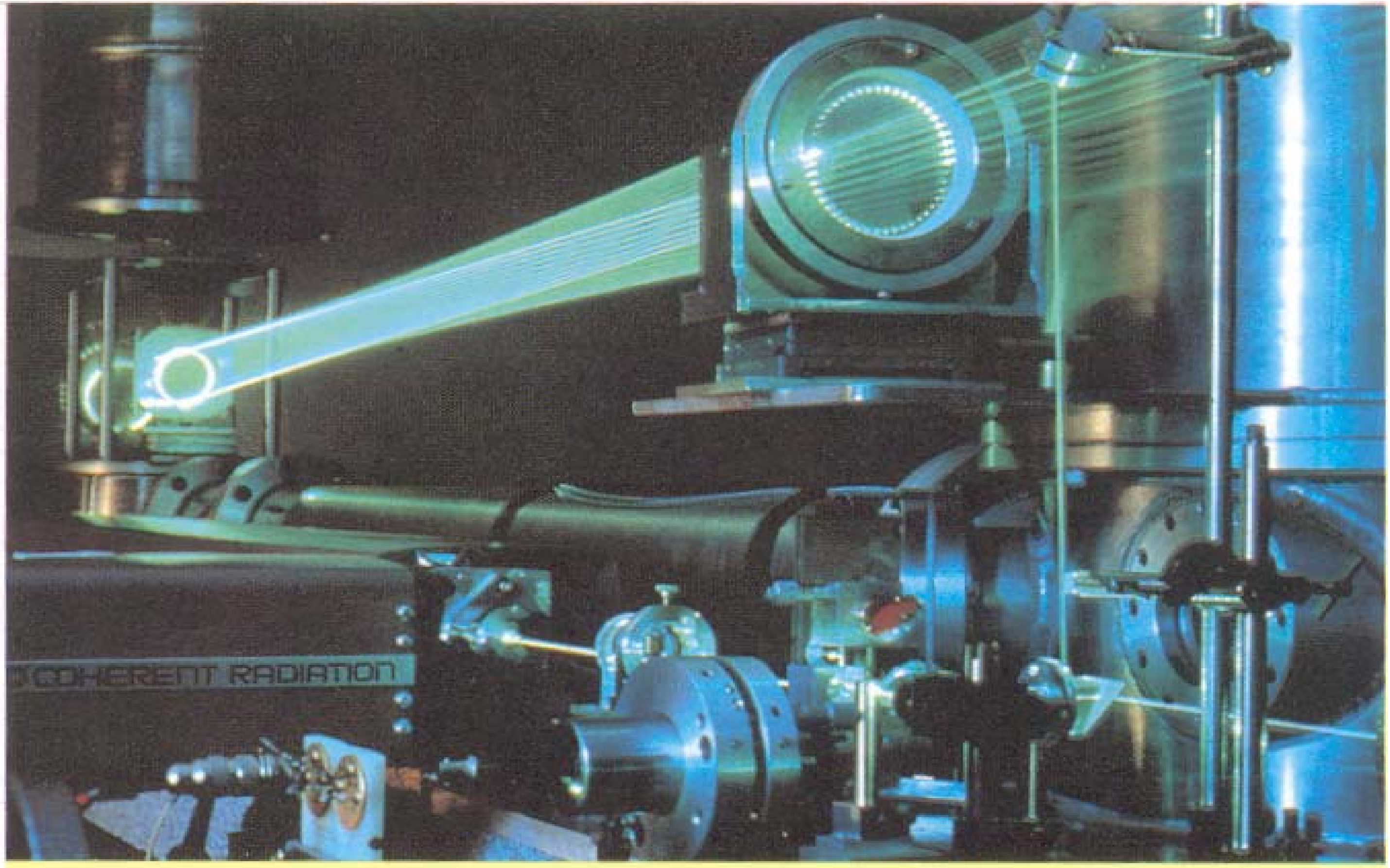

INFN
VIRGO
PISA
SAN GIULIANO TERME
CASCINA
PONTEDERA
Calci
Buti
Vicopisano
Calcinaia
Biéntina
Collesalvetti
Ponsacco
COLTANO
TENUTA DI Palazzi
Nodica
Metato
Sant'Andrea in Pescaiola
San Martino a Ulmiano
Pontasserchio
Rigoli
Santa Maria del Giudice
Cima di Vorno
Sant'Andrea di Cómpito
Pieve di Cómpito
Colle di Cómpito
Ruota
Mte. Faeta
Mte. Serra
Gello
Asciano
Agnano
Giannone
Madonna dell'Acqua
Ghezzano
Mezzana
Tre Colli
Montemagno
Castel di Nocco
San Iacopo
Cascine
Certosa di Pisa
Caprona
Campo
Ripoli
Barbaricina
Musigliano
San Lorenzo alle Corti
Uliveto Terme
Riglione
Navacchio
San Giovanni alla Vena
Oratoio
Ospedaletto
Visignano
San Lorenzo a Pagnatico
Marciana
Fornacette
Ferrucci
San Giusto
Putignano
AEROP. NAZ. DI PISA-S. GIUSTO
la Vettola
San Piero a Grado
Cascine Nuove
Sterpaia
Isola
Chiesanova
Arnáccio
Grécciano
Lavaiano
San Pietro a Piano
Santa Lucia
Vicarello
Lavoria
Valtriano
Cenaia
Perignano
Mortaiolo
Guasticce
Stagno
Staz. di Tómbolo
Ceppaiano
Spinelli
Lucagnano
Orceto
PISA NORD
PISA CENTRO
LIVORNO
COLLESALVETTI
A12
Fosso Reale
Arno
T. Cascina
F. Era

The simplest design, originated by Michelson, uses light that passes up and down each arm once.

Real detectors are designed to store the light in each arm for longer than just one reflection: it is optimum to store the light for half of the period of the GW

Ex.
200 Hz wave, τ_{stor}~ 3 ms, L=1000 Km

This impracticality has led to the development of schemes for folding a Long optical path into a shorter length:
delay lines ; Fabry-Perot cavities



Un prototipo di antenna interferometrica sviluppato al Max Planck Institute di Garching (Germania).

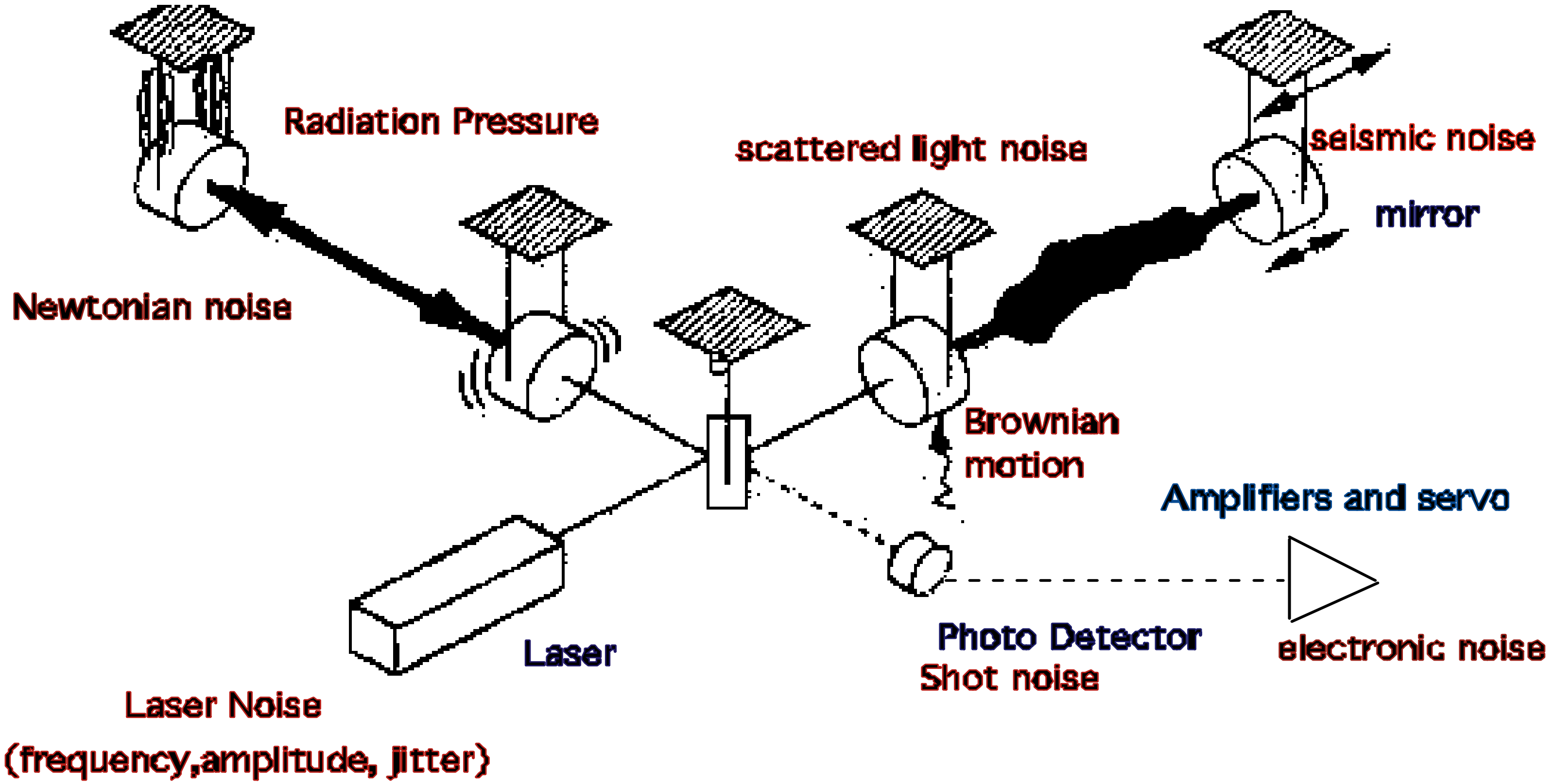
A GW interferometer as an active null experiment

The large magnitude of the low frequency seismic noise makes
A “passive” interferometer design unworkable.

The key is to use *feedback* to keep the interferometer fixed at a
chosen operating point (fixed power of a fringe)

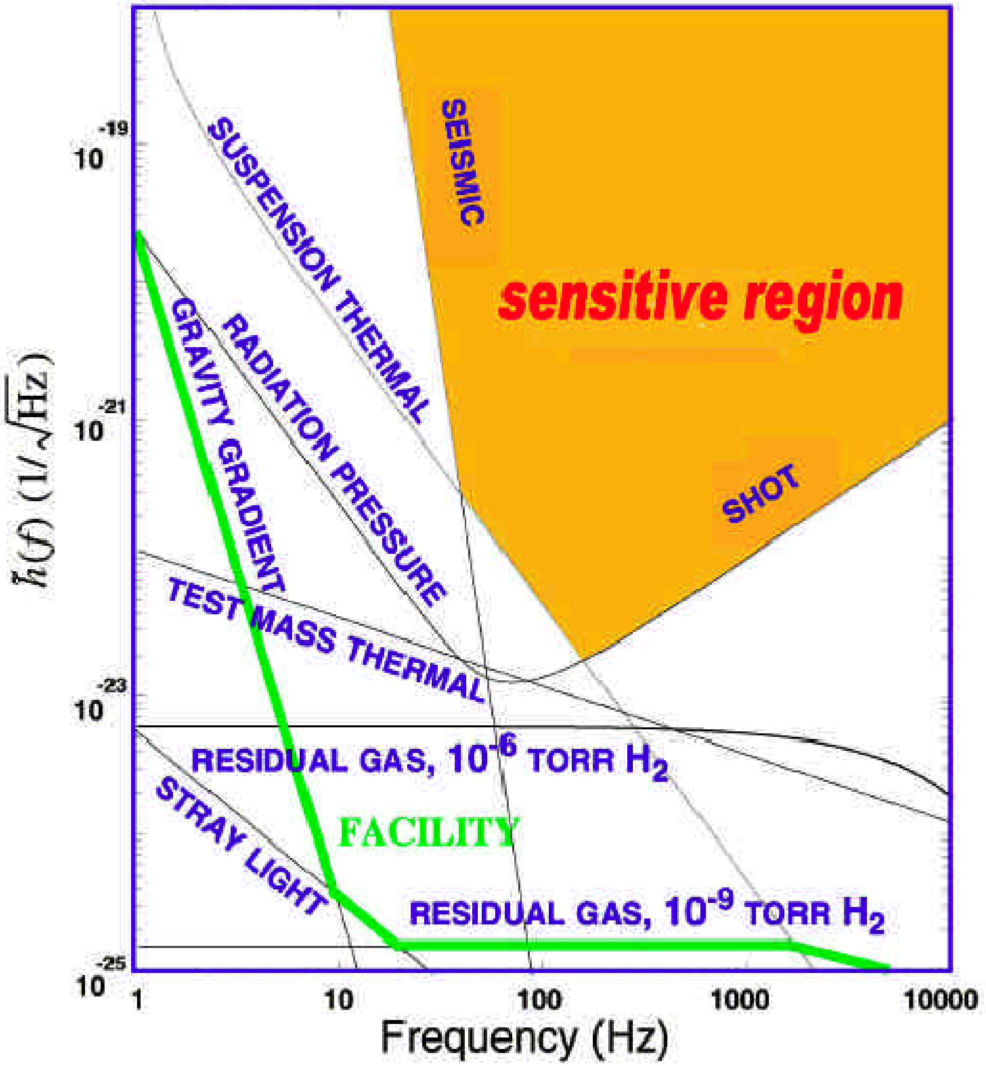
Needed:
sensor, producing an error signal measuring how far you are from
The desired operating point
Actuator, a device that takes the error signal as input and that
supplies the feedback influence to bring it toward this point

Take as the output of the detector not the output power (held near a fixed level) but the strength of the feedback influence necessary to hold the system at the operating point


Radiation Pressure
scattered light noise
seismic noise
mirror
Newtonian noise
Brownian
motion
Amplifiers and servo
Photo Detector
Shot noise
electronic noise
Laser
Laser Noise
(frequency,amplitude, jitter)

- Interferometry is limited by three fundamental noise sources
  - seismic noise at the lowest frequencies
  - thermal noise at intermediate frequencies
  - shot noise at high frequencies

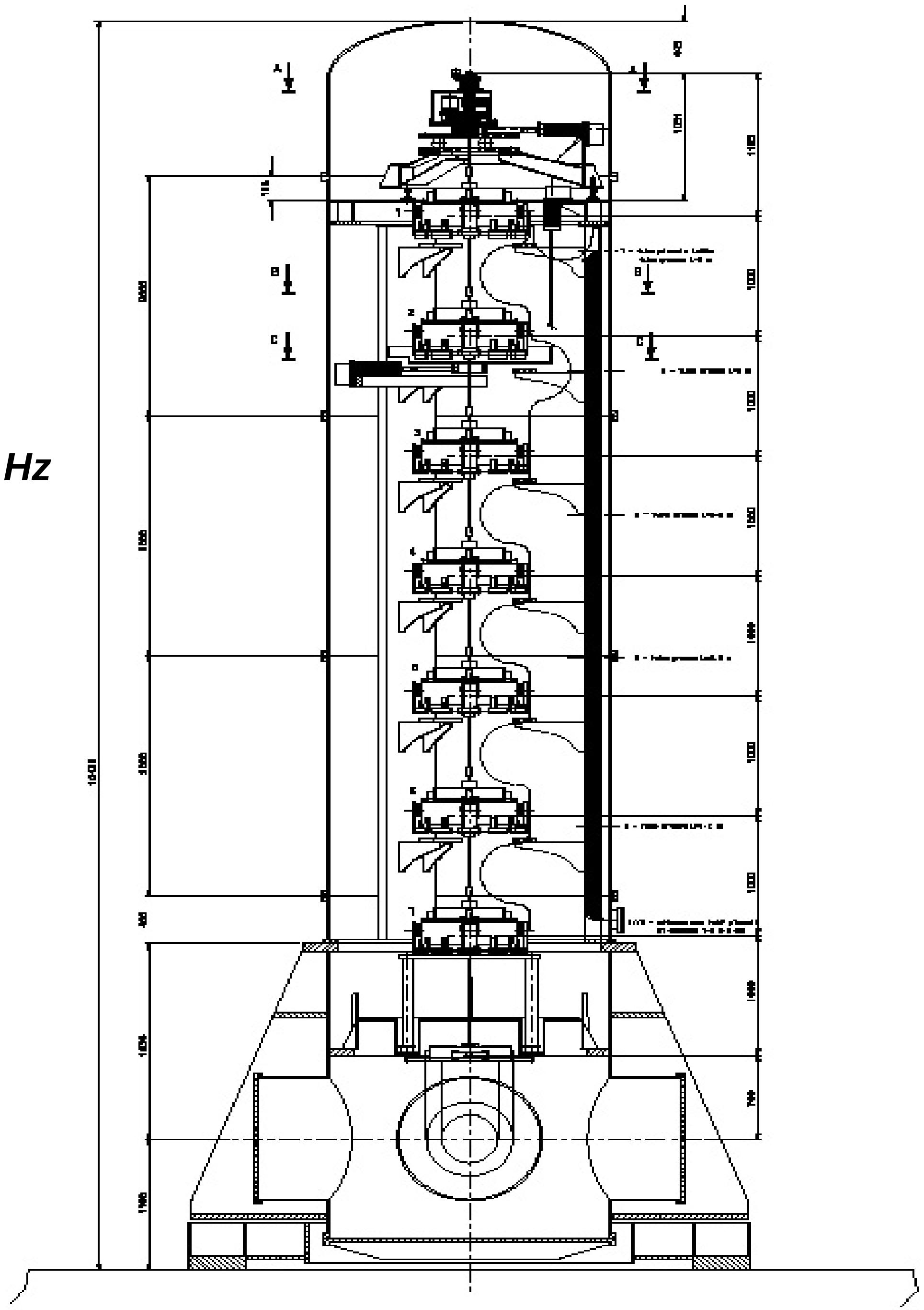
- Many other noise sources lurk underneath and must be controlled as the instrument is improved



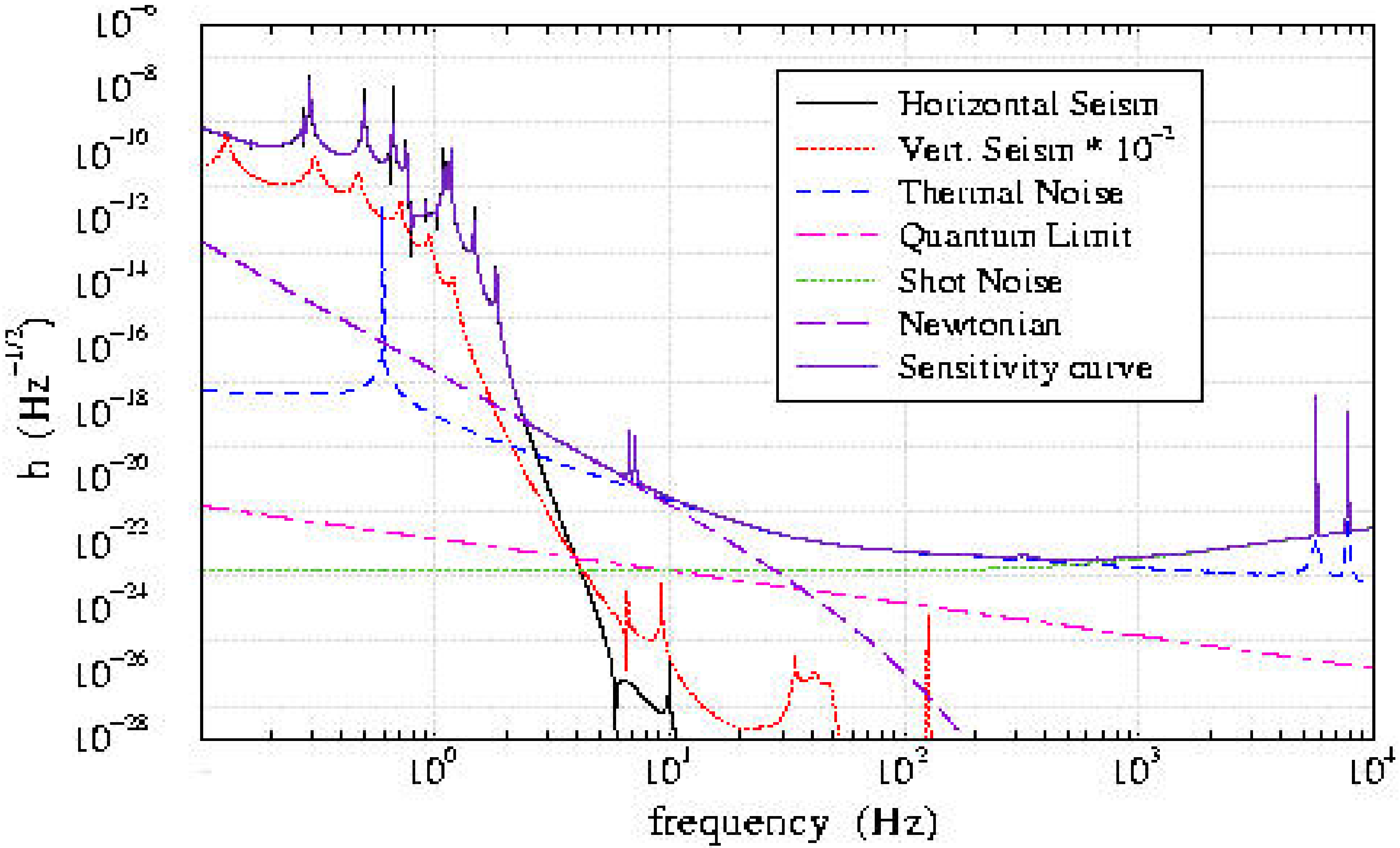
Seismic noise reduction: Superattenuators

- Need

10^{11} attenuation @ *10 Hz*



Virgo sensitivity

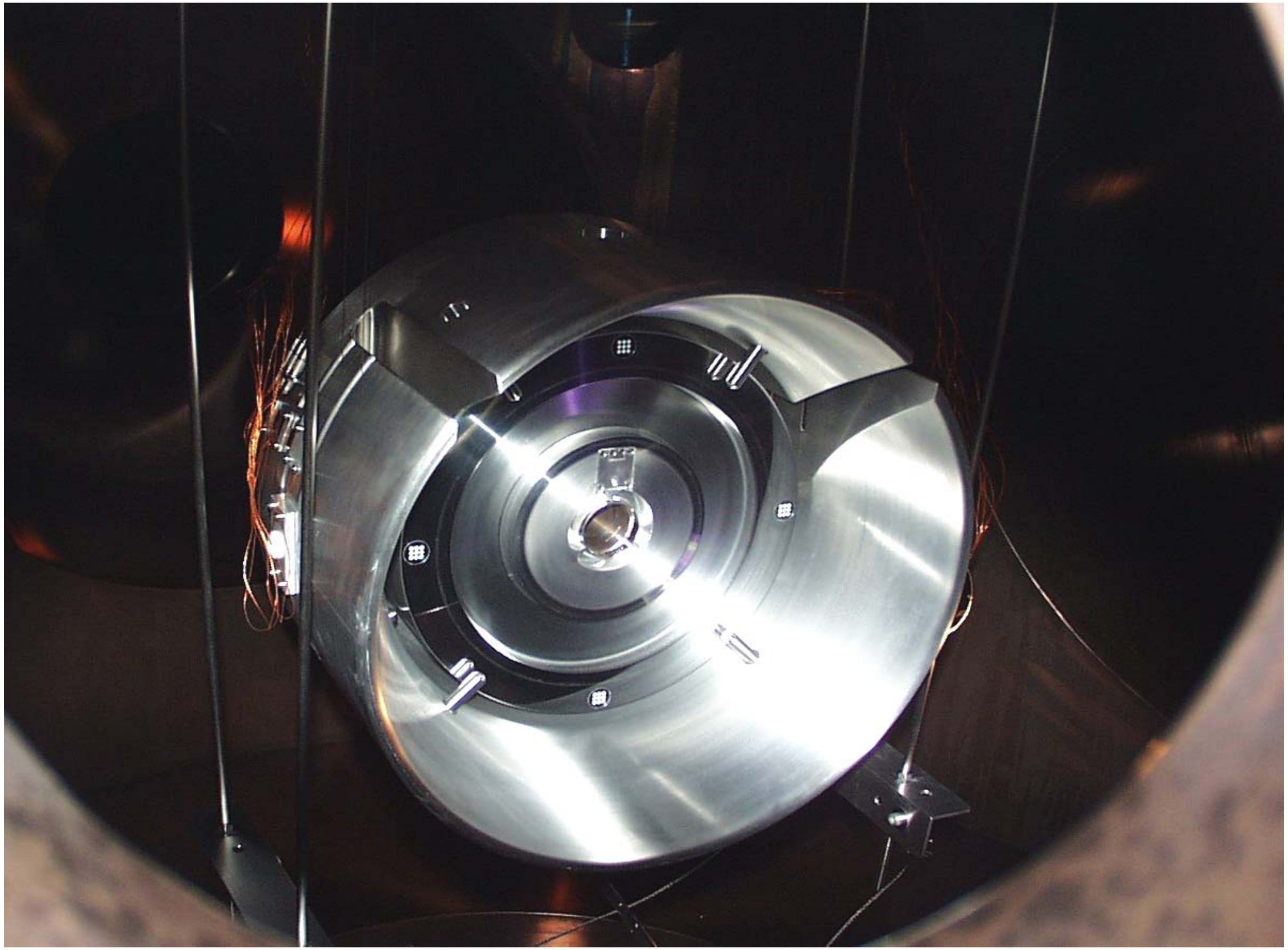


Virgo - inside the Central Building

Virgo - The North 3 km vacuum tube

Virgo - Main requirements

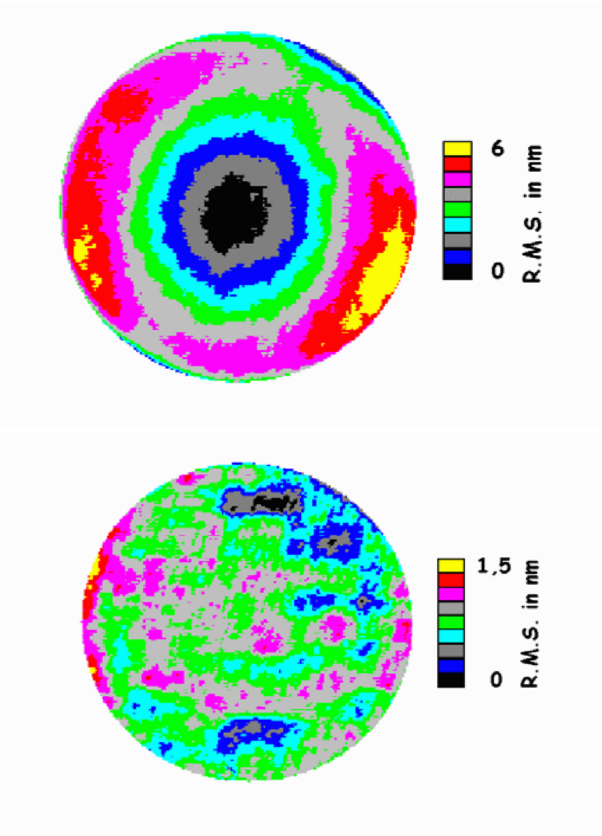
• Vacuum	
Base pressure (H_2)	10^{-9} mbar
Hydrocarbons	10^{-14} mbar
• Seismic attenuation	10^{11} at 10 Hz
• Nd-YAG Laser (at 1kHz)	
frequency	10^{-6} $Hz^{1/2}$
power	$3x10^{-7}$ $Hz^{-1/2}$
beam jitter	10^{-10} rad $Hz^{-1/2}$
• Mirrors	
Substrate losses and coating losses	ppm
Surface deformation	$\lambda/100$ ($0.01\mu m$)
• Data flow	4 Mbyte/s

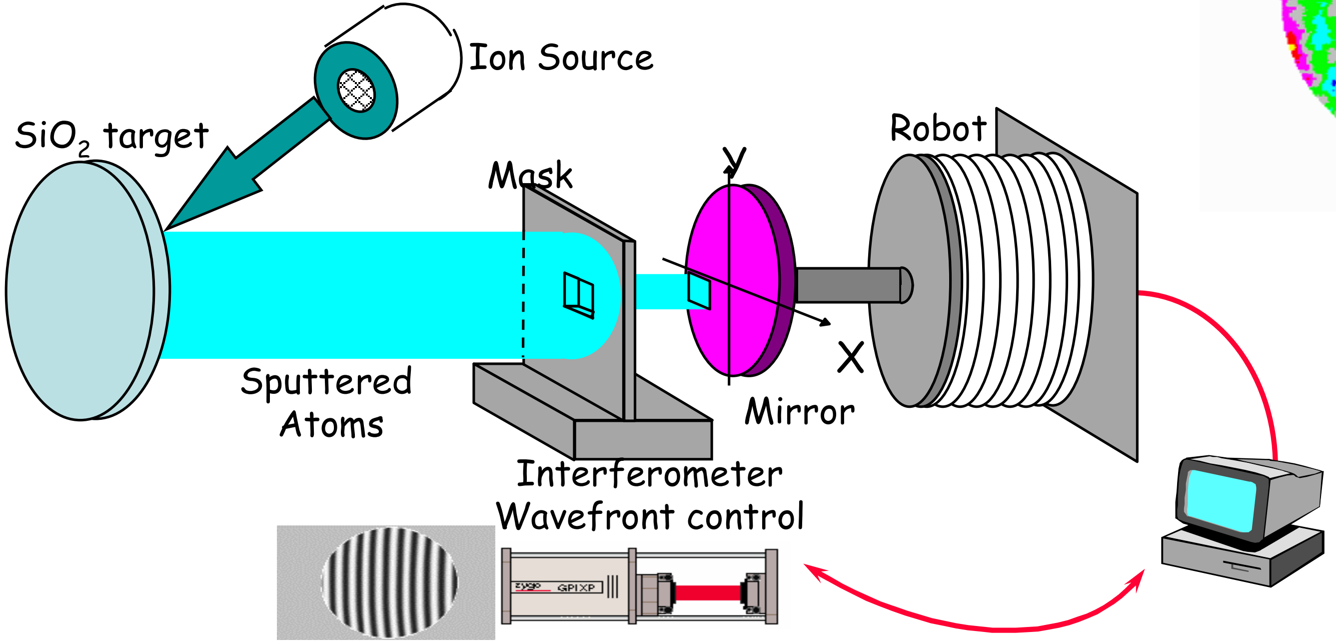


One of the CITF mirrors

Mirrors

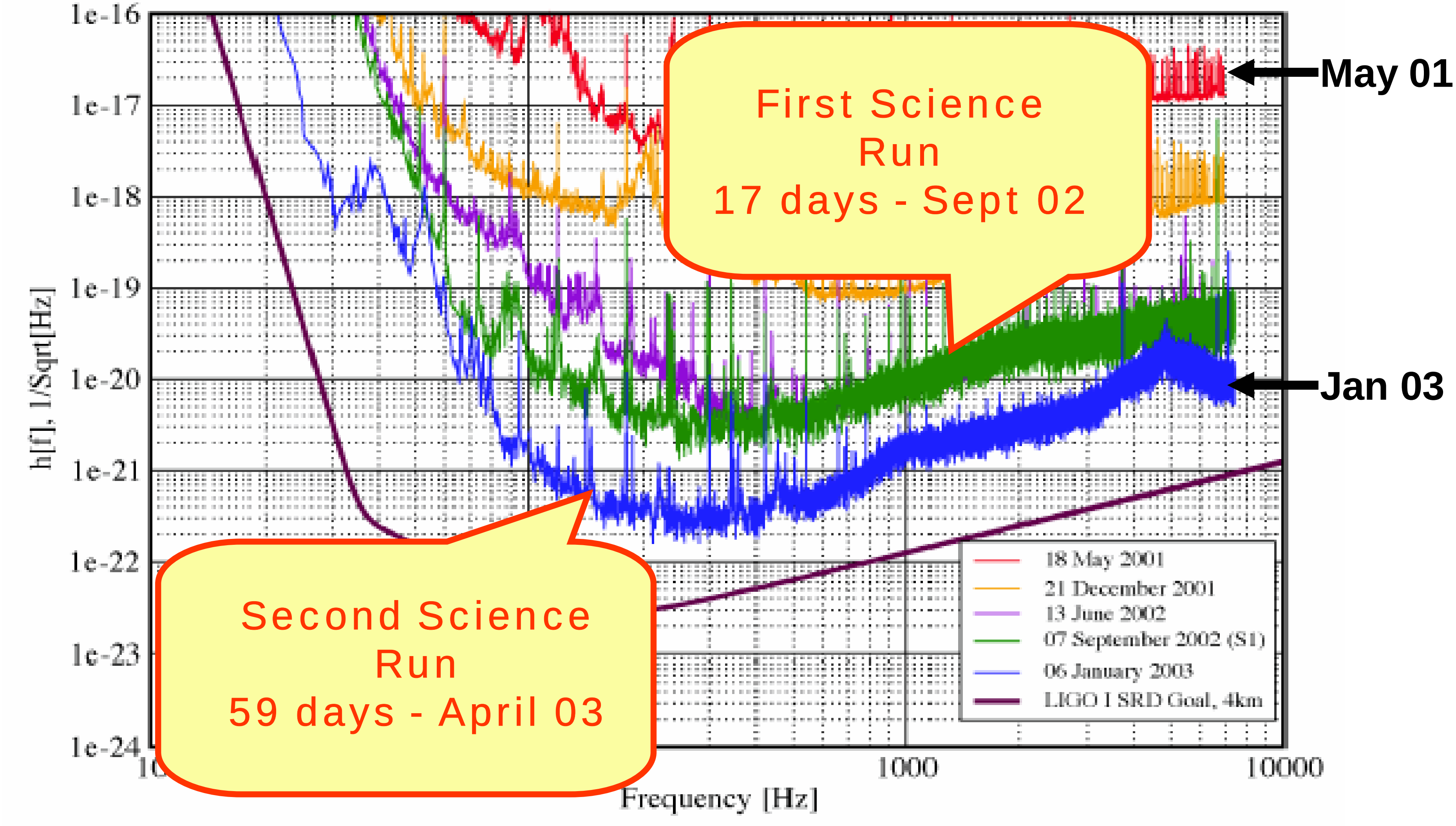
- High quality mirrors
  - Substrate losses: 1 ppm
  - Coating losses: <5 ppm
  - Surface deformation: $\lambda/100$
  - ΔR: $<10^{-4}$





LIGO Sensitivity

Louisiana Interferometer



First Science Run
17 days - Sept 02

Second Science Run
59 days - April 03

May 01

Jan 03