SCRF detectors for gravitational waves

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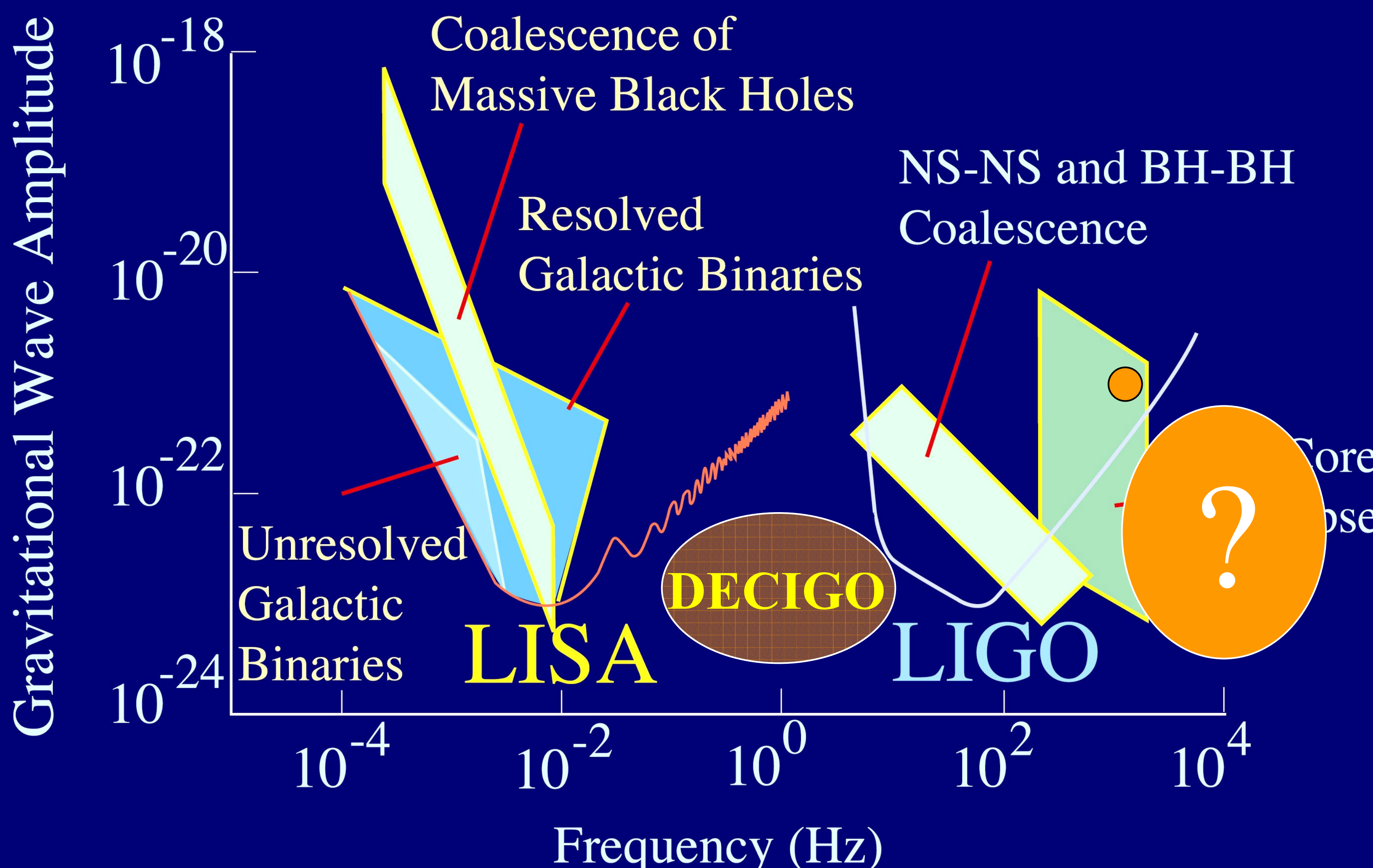
Gravitational Wave Detectors
Interferometric
Resonant-Mass
LISA
GEO
AURIGA
EXPLORER
TAMA
VIRGO
NAUTILUS
LIGO
LIGO
ALLEGRO
SCHEMBERG
NIOBE
AIGO
gravitational wave research

Gravitational wave detectors

- Two different "families":
  - Massive elastic solids (cylinders or spheres), $f \sim 10^3$ Hz
  - Michelson interferometers, $10 \text{ Hz} < f < 10^3 \text{ Hz}$
- A space interferometer (LISA) is planned to cover the very low frequency band, $10^{-4} \text{ Hz} < f < 10^{-1} \text{ Hz}$
- Both types are based on the mechanical coupling between the g.w. and a test mass
- In both types the e.m. field is used as motion transducer

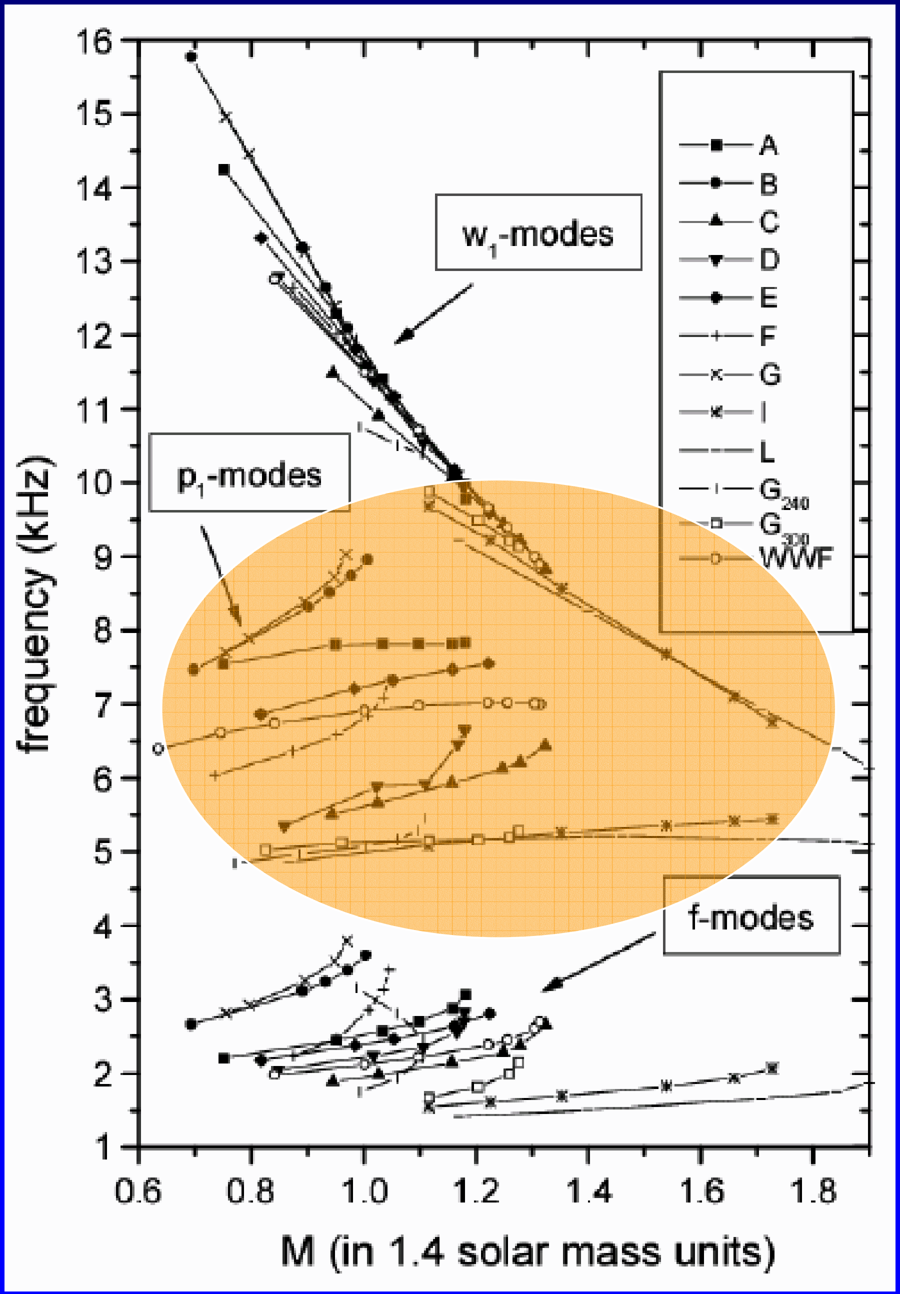

Gravitational Wave Amplitude
10^-18
10^-20
10^-22
10^-24
Coalescence of
Massive Black Holes
Resolved
Galactic Binaries
NS-NS and BH-BH
Coalescence
Unresolved
Galactic
Binaries
LISA
DECIGO
LIGO
?
10^-4
10^-2
10^0
10^2
10^4
Frequency (Hz)

Possible sources at

$f_{max} \sim c^3/(4\pi GM)$
$\sim 10^4(M_\odot/M)$ Hz

- Neutron stars in binary orbits: mergers, disruptions with black holes.
- Formation of neutron stars: ringdown after initial burst.
- Neutron star vibrations, wide spectrum up to 10 kHz. Can be excited by formation, merger or glitches.
- Stochastic background of primordial origin.
- Speculative possibilities:
  - Black holes below 3 $M_\odot$
  - Compact objects in dark matter
  - Thermal spectrum at microwave frequencies, but only if inflation did not happen!

Oscillation frequencies of neutron stars



- Figure from Kokkotas and Andersson, gr-qc/0109054, shows modes of non rotating stars
- Modes could be excited by violent events or by more modest **glitches**
- Glitches occur often in young pulsars, making Crab a good target
- Glitch energy < $10^{-10}\ M_{\odot}c^2$

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On the operation of a tunable electromagnetic detector for gra

Volume 104A, number 6,7 PHYSICS LETTERS 10 September 1984

OBSERVATION OF 4×10^{-17} cm HARMONIC DISPLACEMENT USING A 10 GHz SUPERCONDUCTING PARAMETRIC CONVERTER ☆

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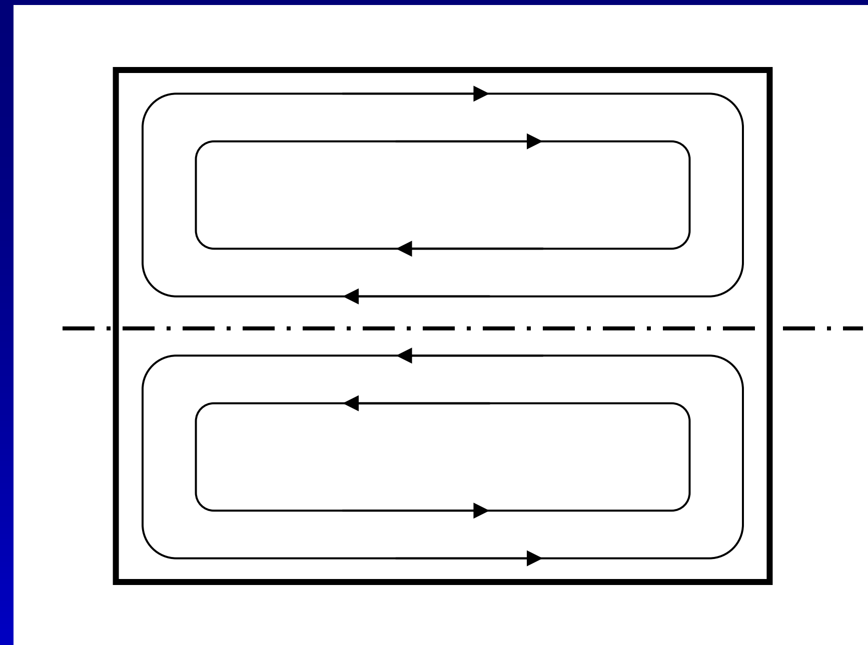
Revised manuscript received 12 July 1984

In 1978 Pegoraro et al. suggested that superconducting coupled cavities could be used as a sensitive detector of gravitational effects. We have constructed such a detector which operates as a parametric converter transducer in the 10 GHz frequency range. The detector responds to harmonic perturbations at its resonant frequency $\Delta f \sim 1$ MHz and we have demonstrated that it has a sensitivity to fractional deformations of order $\delta x/x = 4 \times 10^{-18}$. This was achieved by observing effective displacements of the end-wall of order 4×10^{-17} cm using a bandwidth of 10^{-3} Hz. Further improvement in sensitivity is possible.

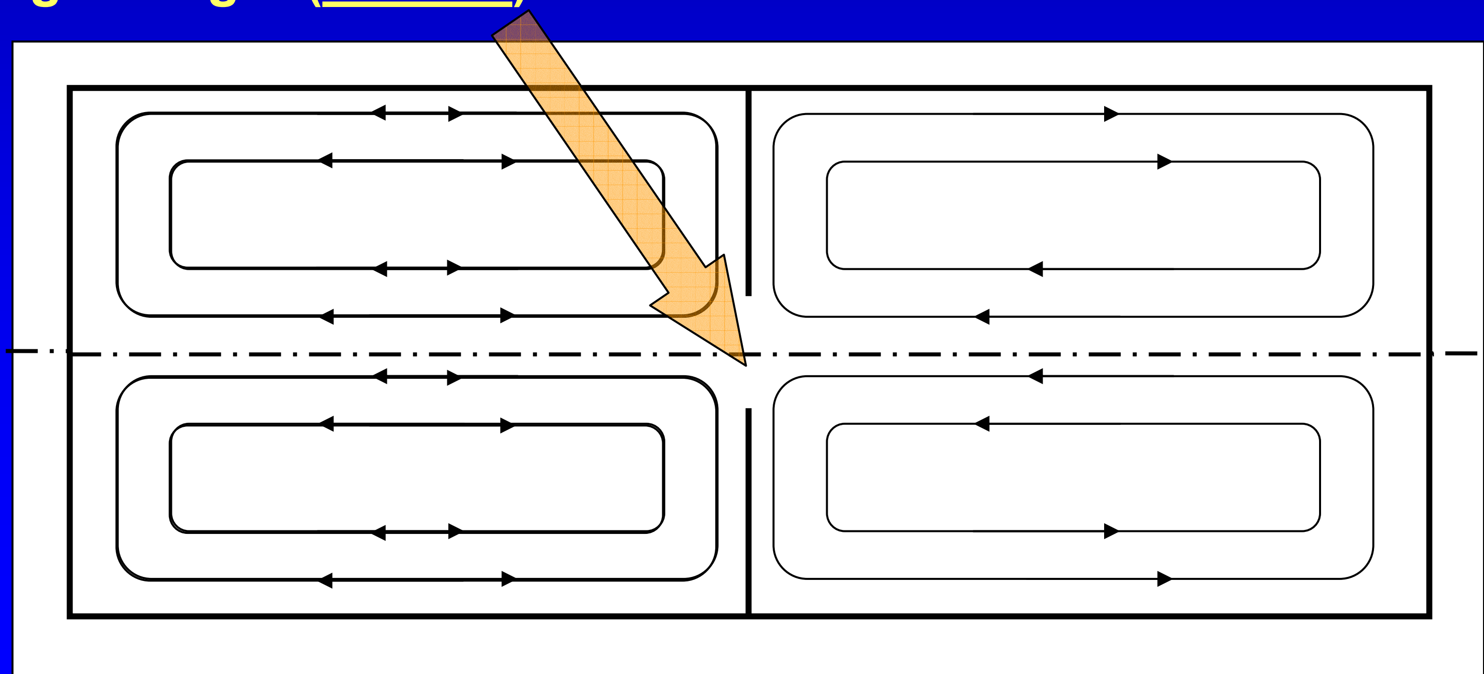
Pill-box cavity
TE011 mode



Symmetric mode: ω_s

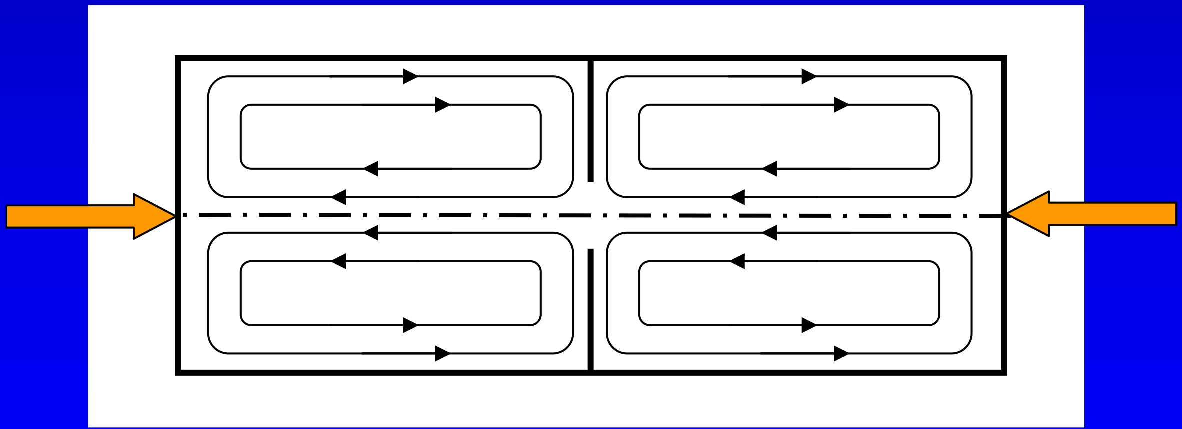
Antisymmetric mode: ω_a

$\omega_a - \omega_s$ proportional to the coupling strength (*tunable*)



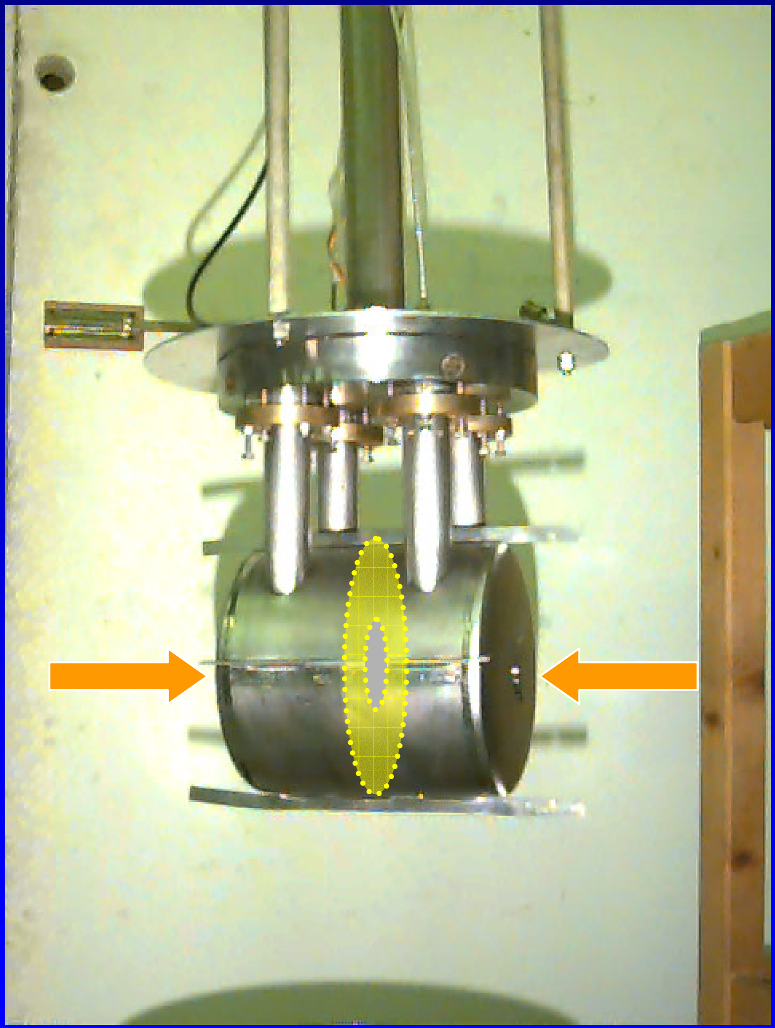
If the symmetric mode is initially excited and we perturb one system parameter (e.g. the length of the cavity) with a characteristic frequency much lower than the normal mode frequency ($\Omega \ll \omega_0$)...

… we can have a ***coupling*** between the two normal modes of the unperturbed system $\rightarrow$ there is transfer of energy from one mode to the other;



the energy transfer is maximum when the frequency of the external perturbation equals the normal modes frequency difference: $\Omega = \omega_a - \omega_s$

PArametricCOnverter (1998-2000)



Two **pill-box** niobium cavities mounted end-to-end and coupled trough a small aperture on the axis

Wall movement induced by piezo-electric crystals

Working frequency ~ 3 GHz

Mode splitting ~ 500 kHz

Quality factor (e.m.) **2×10^9 @ 1.8 K**

Stored energy **1.8 J**

$\delta x/x \sim 3 \times 10^{-20}$ (Hz)$^{-1/2}$

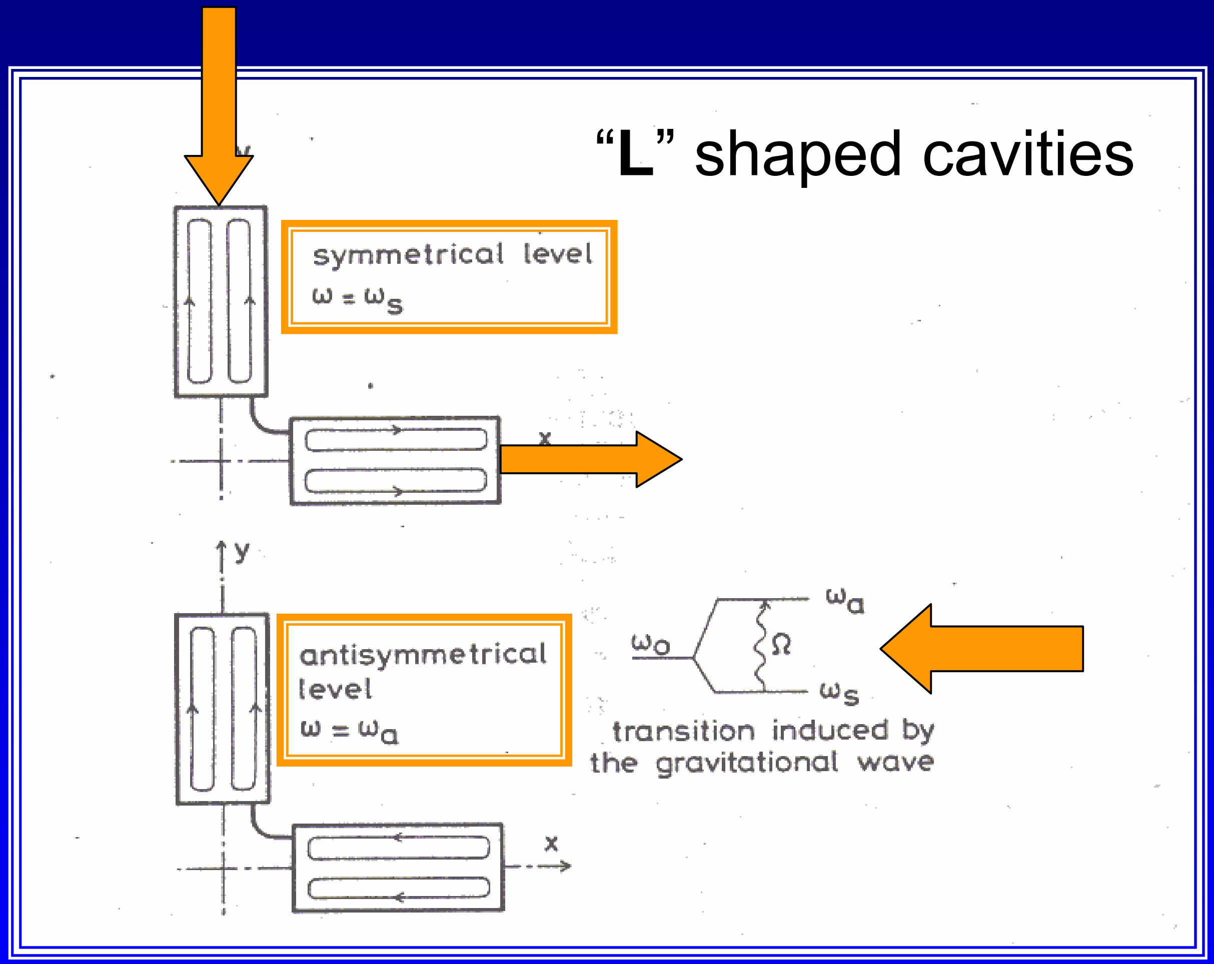
For more details see Poster MoP09 - MoP31

PACO - 2 (2001-2003)

- Lower detection frequency
- Variable coupling → tuning system
- Spherical cavities development (in collaboration with CERN)
- R&D on spherical Nb/Cu cavities (in collaboration with CERN)

When we take into account the quadrupolar character of the gw...

...we realize that the cavity shape has to be chosen in order to maximize the energy transfer between the two resonant modes



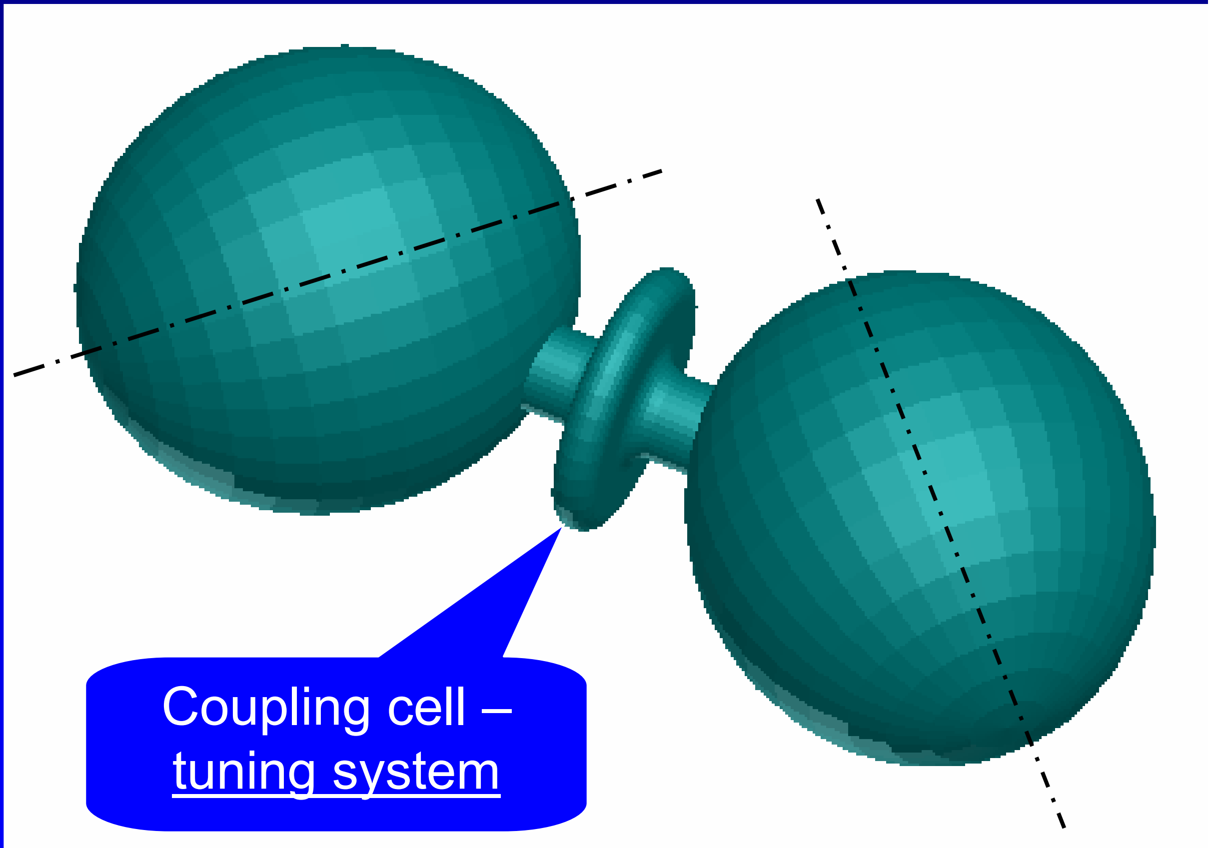
PACO-2 conceptual layout

Cavity internal radius: 100 mm

Operating rf frequency (TE_{011} mode) ≈ 2 GHz

Mode splitting ≈ 10 kHz

Stored energy ≈ 10 J

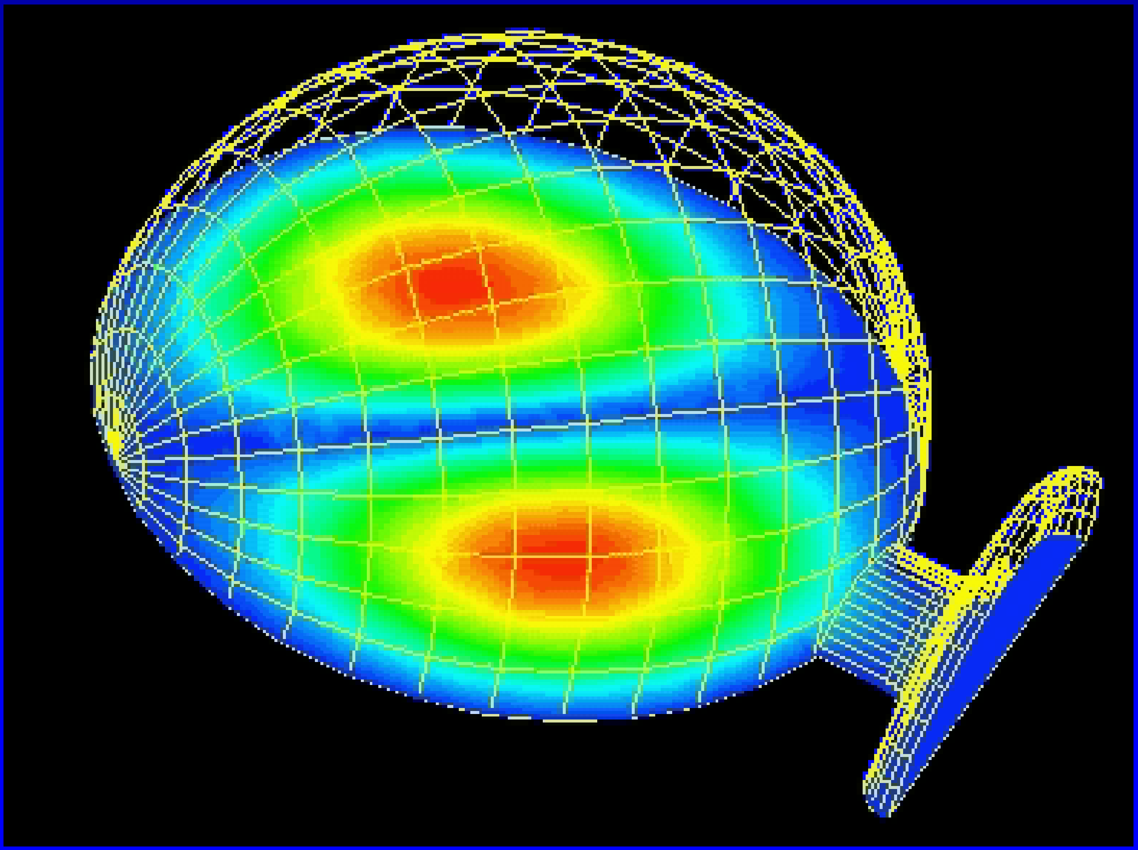


Why spherical cavities?

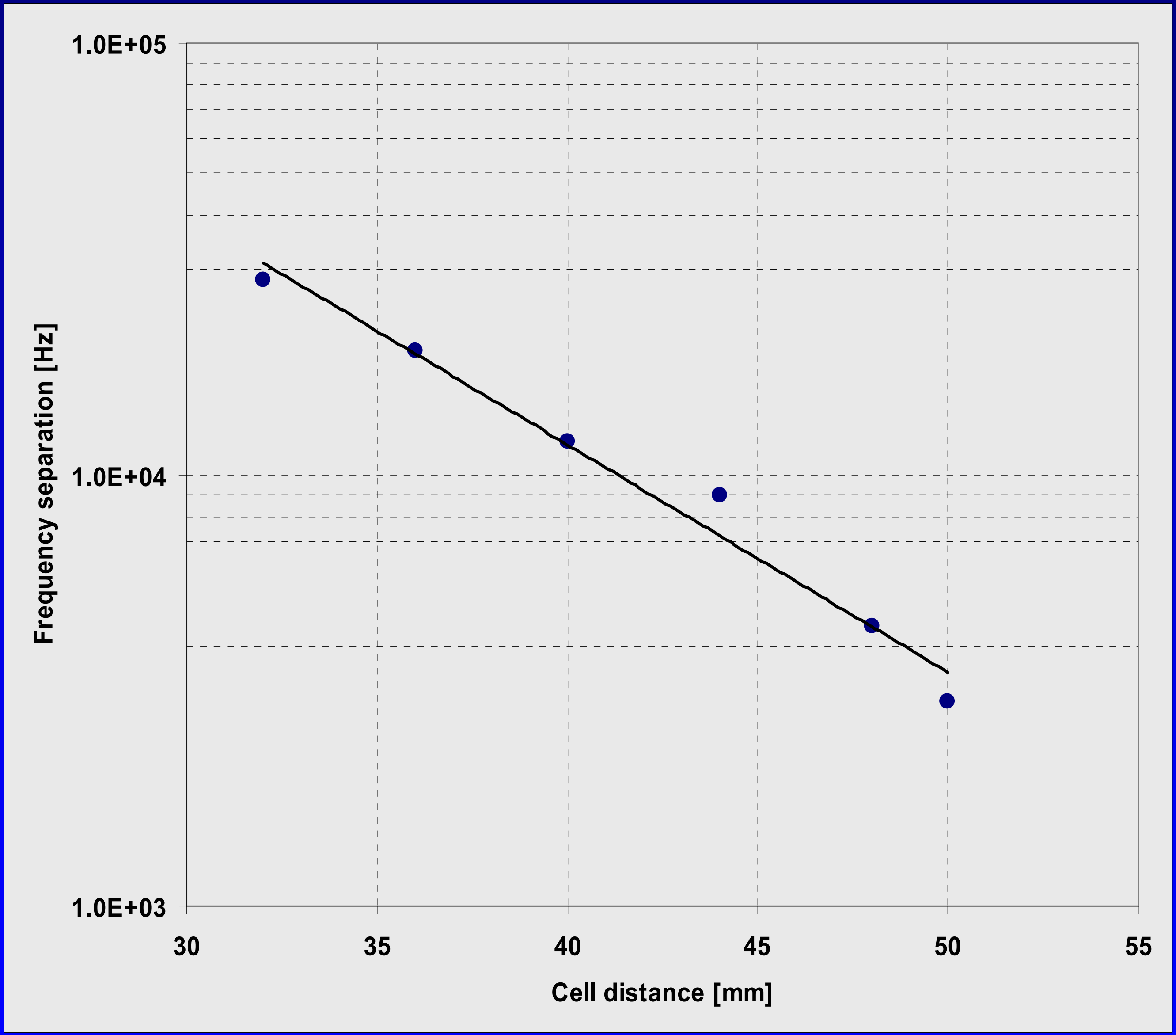
- Highest e.m. geometrical factor $\rightarrow$ **highest e.m. quality factor** for a given surface resistance (Q = G/Rs)
  - For the TE_{011} mode of a sphere G ~ 850 Ω,
  - For the TM_{010} mode of a standard elliptical accelerating cavity, G ~ 250 Ω
- Typical values of quality factor of accelerating cavities (TM modes) are in the range **10^{10} – 10^{11}**
- The quality factor of the TE_{011} mode of a spherical cavity may well exceed 10^{11}

- The spherical cell can be easily deformed in order to remove the e.m. modes degeneracy and to induce the field polarization suitable for g.w. detection
- The interaction between the stored e.m. field and the time-varying boundary conditions depends both on **how the boundary is deformed** and on **the spatial distribution of the fields** inside the resonator
- **The optimal field spatial distribution is with the field axis in the two cavities orthogonal to each other**
- The sphere has the **highest interaction cross-section** with a g.w. (a factor of four higher than a cylinder)

TE011 mode @ 2 GHz
Electric field magnitude



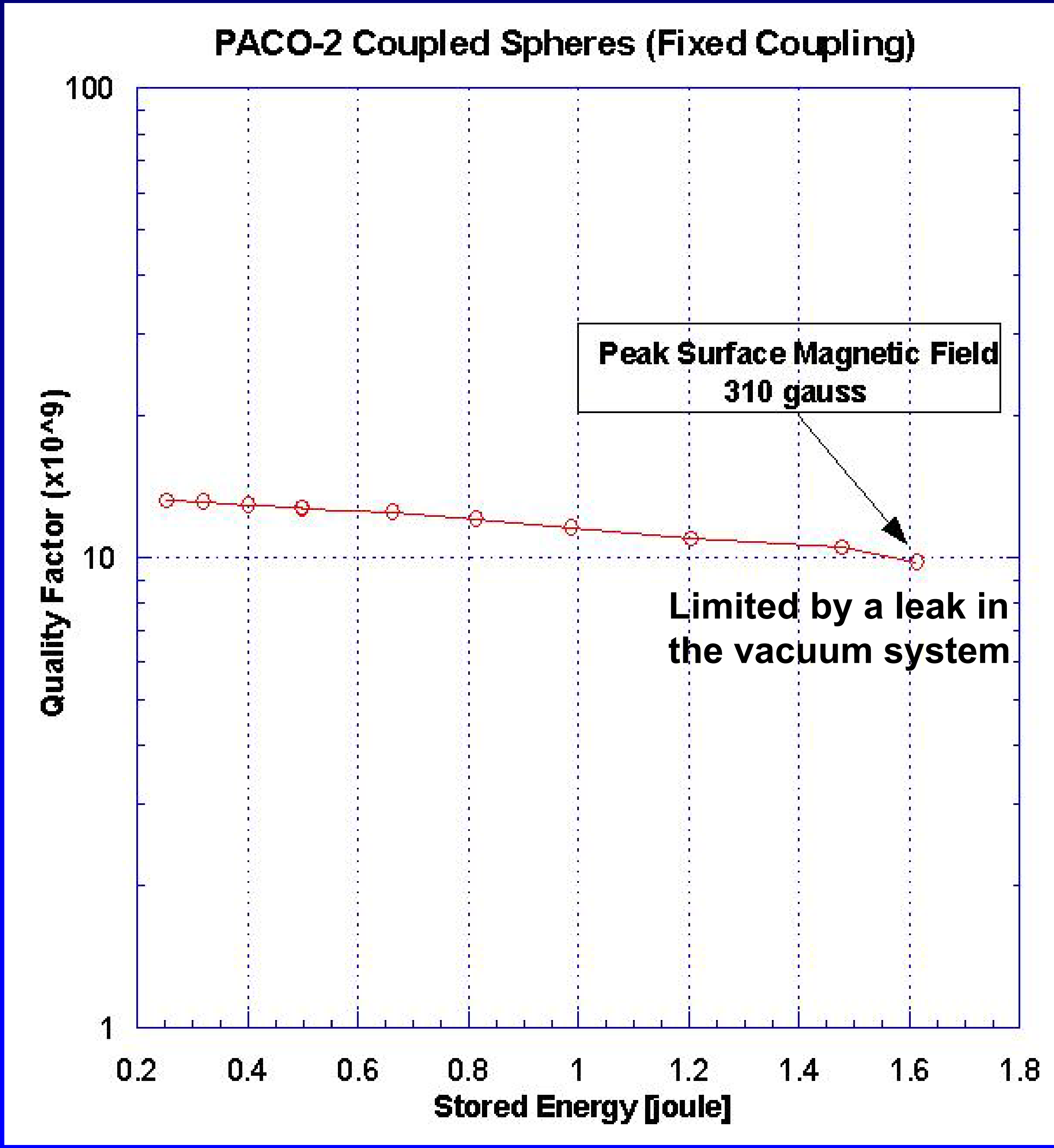
Mode splitting vs. coupling cell length



Experimental activity

Fixed coupling

Niobium cavity built and tested at CERN (E. Chiaveri, R. Losito, O. Aberle)

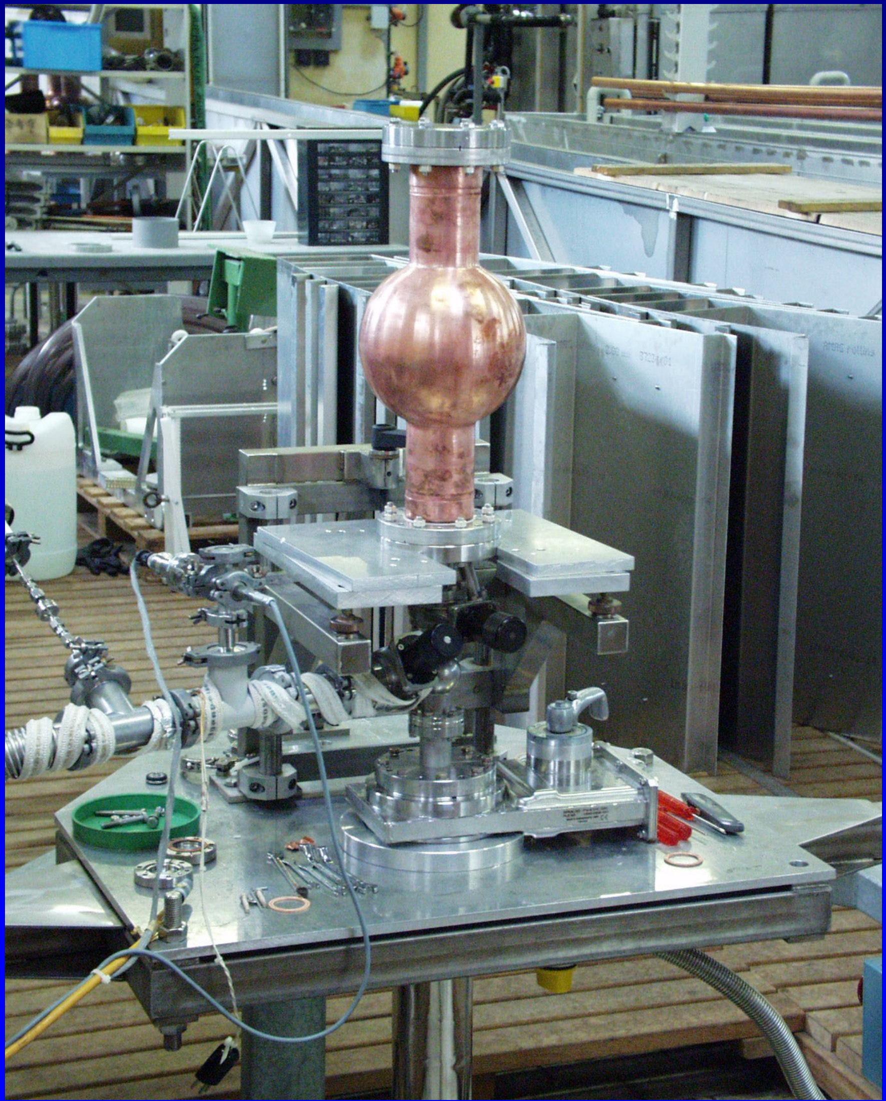


Electromagnetic test of the niobium cavity

Tunable cavity at CERN

(E. Chiaveri, R. Losito, O. Aberle)

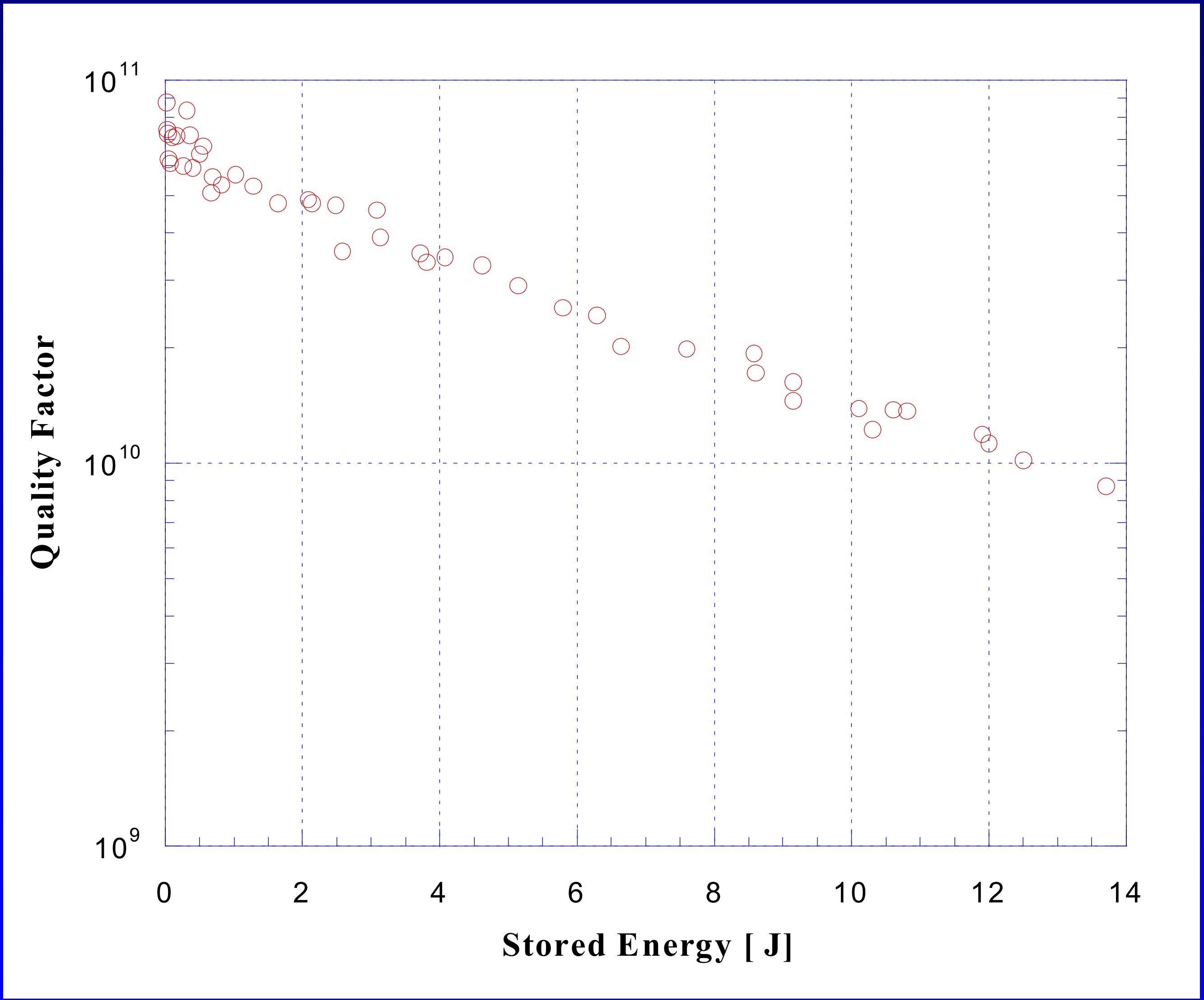
R&D on Nb/Cu cavities



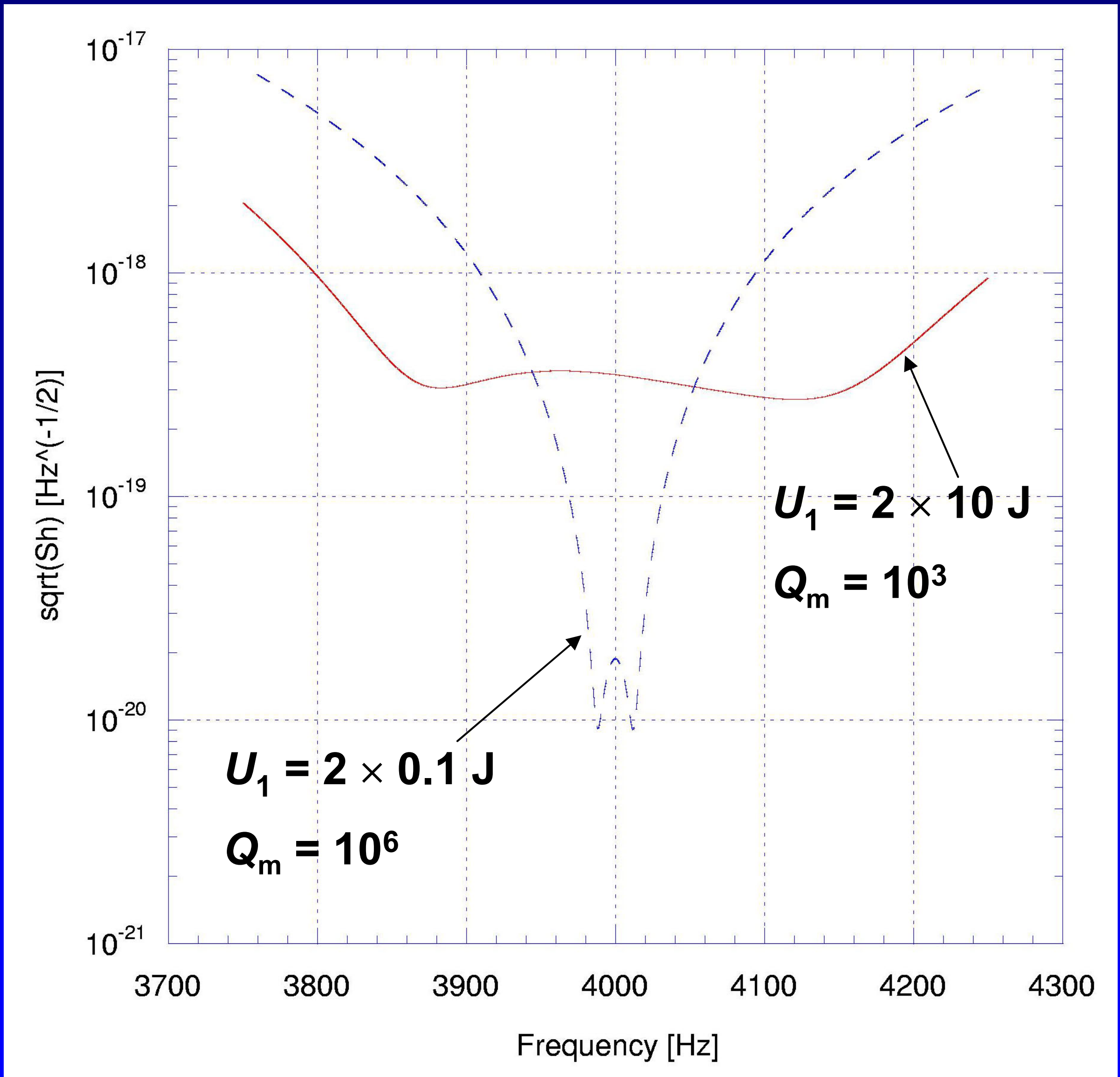
Spherical single-cell cavity built at INFN-LNL (E. Palmieri)

and sputtered at CERN (S.Calatroni)

Nb/Cu single sphere e.m. test



Expected sensitivity (small cavity)



Cavity internal radius: 100 mm

Operating rf frequency (TE_{011} mode) ≈ 2 GHz

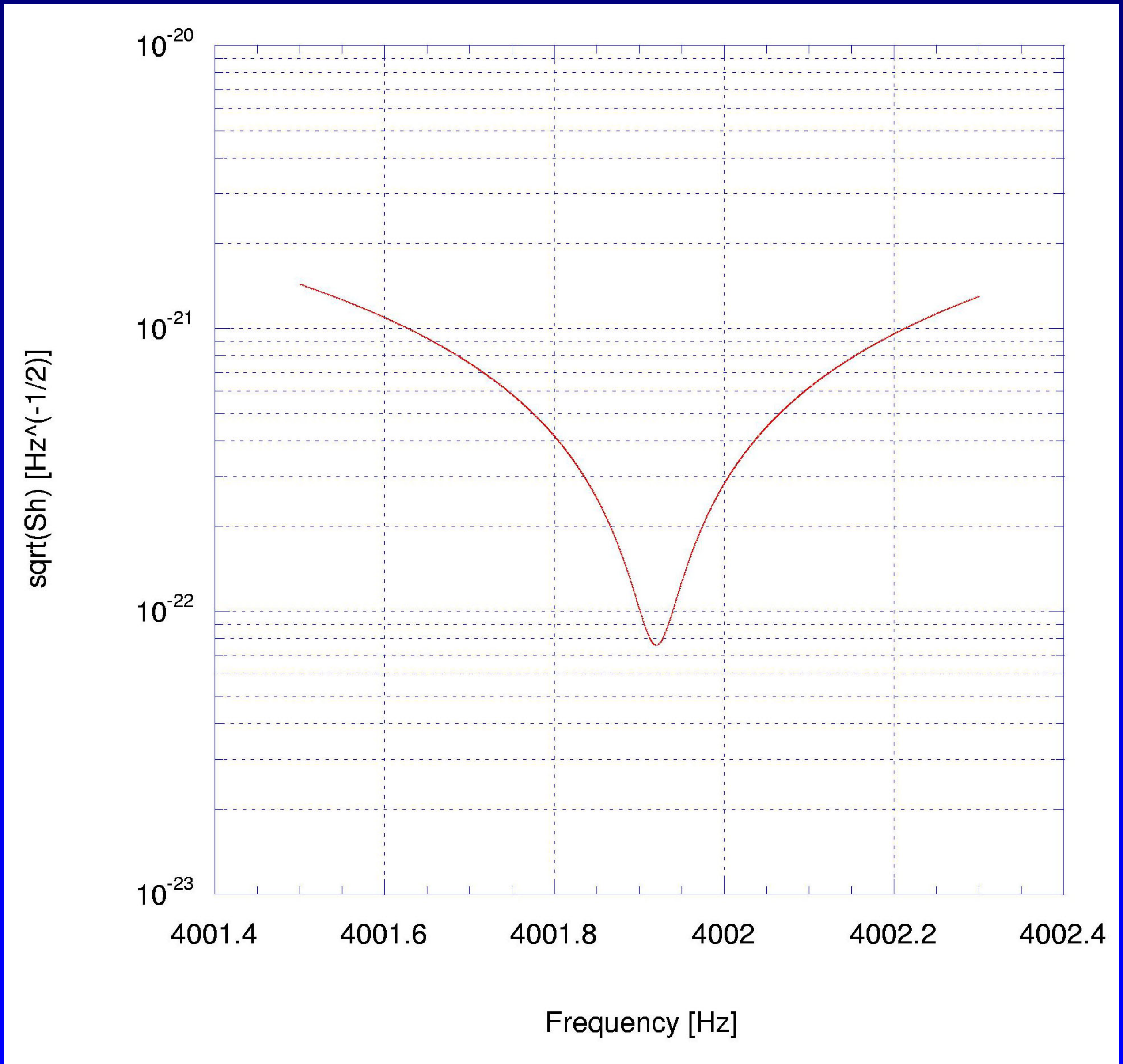
Detection frequency (mode splitting) = 4 kHz

Mechanical resonant frequency = 4 kHz

$Q = 10^{10}$

$T = 1.8$ K

$T_n = 1$ K



Expected sensitivity (large cavity)

Cavity internal radius: 400 mm

Operating rf frequency (TE_{011} mode) ≈ 500 MHz

Detection frequency (mode splitting) = 4 kHz

Mechanical resonant frequency = 1 kHz

$U_1 = 2 \times 1200$ J

$Q = 10^{10}$

$Q_m = 10^6$

$T = 1.8$ K

$T_n = 1$ K

MAGO (2004-2007)

Microwave Apparatus for Gravitational Waves Observation

- Design and realization of an experiment based on the existing ("small") cavities:
    - **$\omega \approx$ 2 GHz**
    - **detection frequency $\approx$ 10 kHz (tunable between 4 - 10 kHz)**
    - **$(S_h)^{1/2} \approx 10^{-21} - 10^{-20}$**
  - – Design of the cryogenic system;
  - – Design of the suspension system;
  - – Low noise electronics;
  - – Data analysis
- Timescale: four years (2004-2007)

MAGO collaboration

- INFN Genoa
  - R. Ballantini
  - A. Chincarini
  - S. Cuneo
  - G. Gemme
  - R. Parodi
  - A. Podestà
  - R. Vaccarone
  - S. Pepe
- CERN
  - Ph. Bernard
  - E. Chiaveri
  - S. Calatroni
  - R. Losito
  - O. Aberle
  - E. Picasso
- INFN Napoli-Salerno
  - R.P. Croce
  - V. Galdi
  - V. Pierro
  - I.M. Pinto
- SNS Pisa
  - E. Picasso

Conclusions

- The MAGO design is easily scalable
- It may be constructed to work at any chosen frequency 10^3 Hz $< f < 10^4$ Hz
- It is (relatively) cheap and lightweigth
- Ideal for many-detector networks (coincidence operation)
- Complementary to existing or planned detectors