Broad band acoustic detectors

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www.auriga.lnl.infn.it

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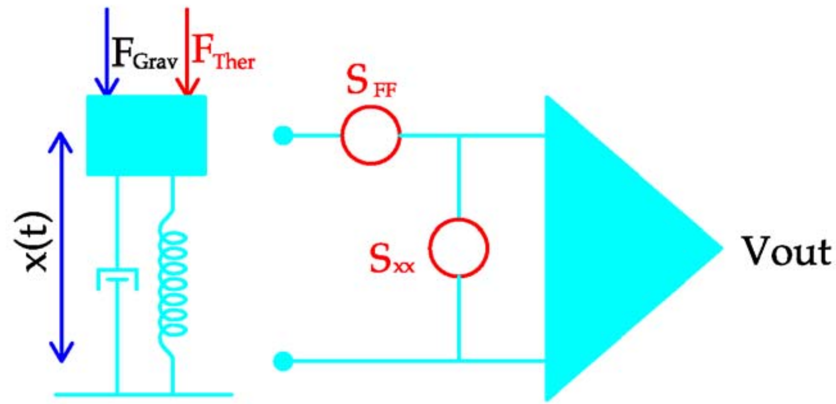
Acoustic detector noise budget:one dimensional lumped model

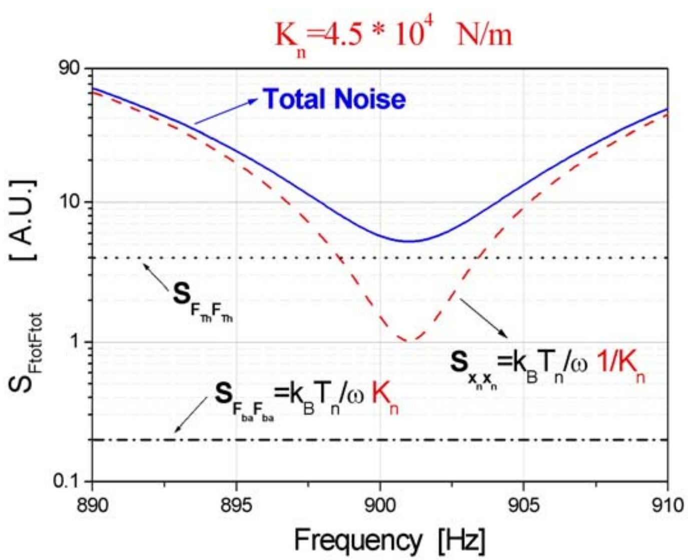


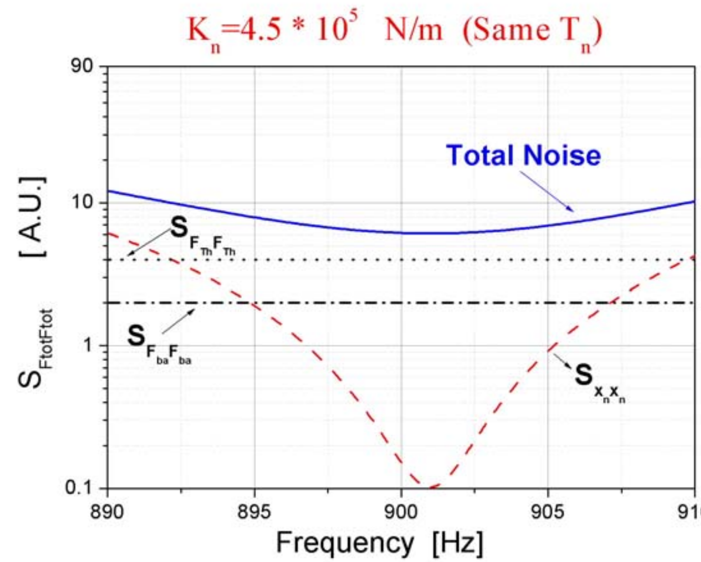
Quantum mechanics constrain T_n

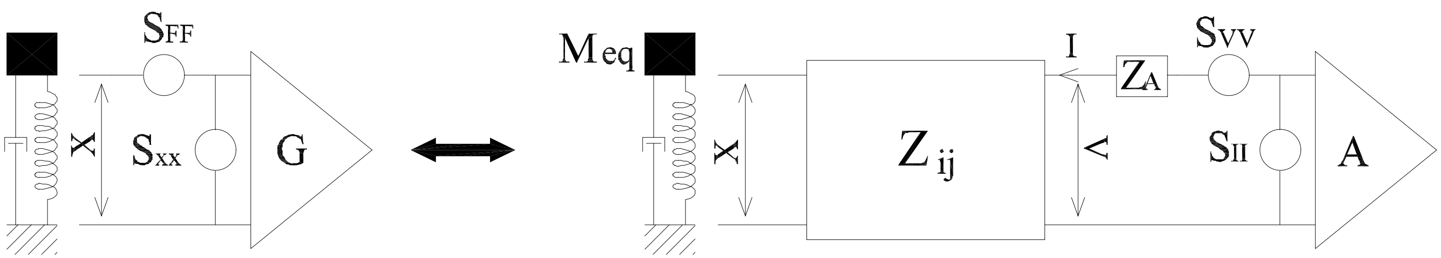
$$\frac{k_B^2 T_n^2}{\omega^2} \equiv S_{FF}(\omega)\cdot S_{XX}(\omega) \ge \frac{\hbar^2}{4}$$

The noise stiffness K_n is unconstrained

$$K_n = \sqrt{S_{FF}(\omega)/S_{XX}(\omega)}$$







Main resonator

Transducer and matching line

Current amplifier

$$\alpha \equiv \frac{\mathrm{I}}{\mathrm{X}} = \textit{Transducer Efficency}$$

General result:

$$S_{FF}(\omega) = |\alpha|^2 \times S_{VV}(\omega) \qquad S_{XX}(\omega) \approx |\alpha|^{-2} \times S_{II}(\omega)$$

$$\Downarrow$$

$$T_n \propto S_{FF}(\omega) \cdot S_{XX}(\omega) \approx S_{VV}(\omega) \cdot S_{II}(\omega)$$

$$K_n = \sqrt{S_{FF}(\omega) / S_{II}(\omega)} \approx \alpha^2 \sqrt{S_{VV}(\omega) / S_{II}(\omega)}$$

Practical limits to the K_n

Passive transducers

For instance capacitive

$$K_n \propto E_{bias}{}^2 \sqrt{S_{VV}(\omega)/S_{II}(\omega)}$$

$$\downarrow \qquad\qquad \downarrow$$

□ $10\, MV/m$ $\qquad 10^{-2}\ \Omega$

Breakdown

Active transducers

For instance optical

$$K_n \propto Finesse \times LaserPower$$

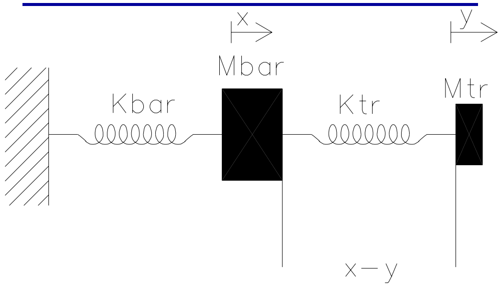
$$\downarrow \qquad\qquad \downarrow$$

K_n OK but problems for cryogenics $\qquad 10^5 \div 10^6 \qquad \geq Watt$

Methods to increase the efficiency: resonant transducers

Mechanical signal amplified before the transduction

One mode transducer H.J. Paik, *Jour. Appl. Phys.* **47**, 1168 (1976)

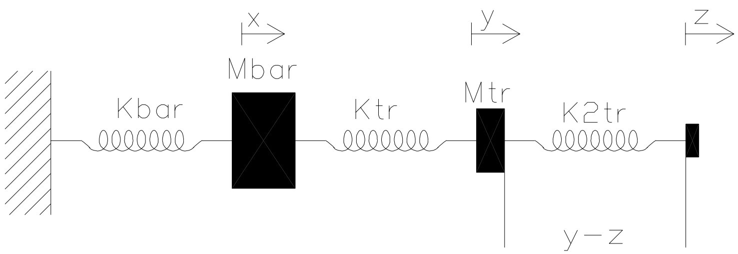


Required $\omega_{bar} = \omega_{Tr}$

Increment of a around resonance $= \sqrt{M_{BAR} / M_{TR}}$

Bandwidth upper limit $= \nu_{bar} \sqrt{M_{TR} / M_{BAR}}$

Two mode transducer J.P. Richard, *Phys. Rev. Let.* **52**, 165 (1984)



Required $\omega_{bar} = \omega_{First} = \omega_{Last}$

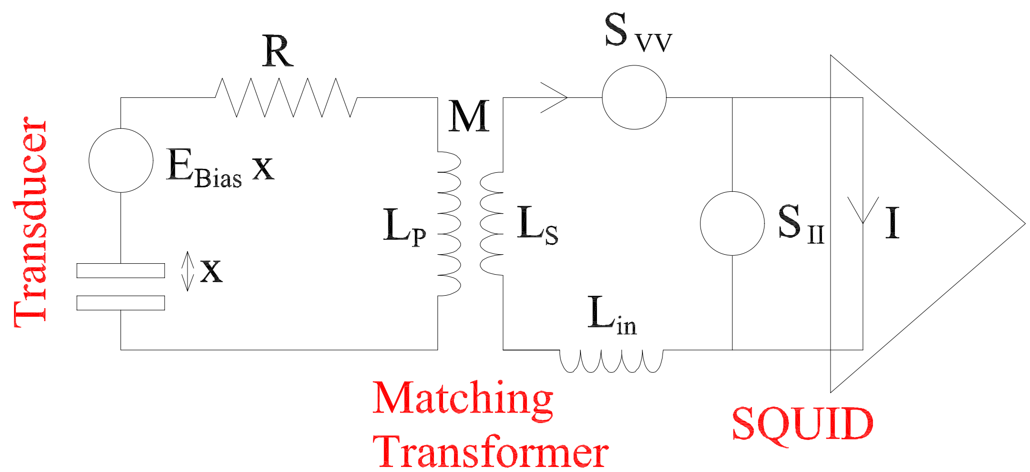
Increment of a around resonance $= \sqrt{M_{BAR} / M_{LAST}}$

Bandwidth upper limit $= \nu_{bar} \sqrt{M_{First} / M_{BAR}}$

Velocity transformer D. Blair et al, *Appl. Phys.* **20**, 162 (1987)

Broad Band amplification but still a complete thermal noise analysis is missing

Auriga method: Resonating matching line



$$\alpha(\omega) = \frac{\mathrm{I}(\omega)}{\mathrm{x}(\omega)} = \frac{i\omega M E_{Bias}}{(L_s + L_{in})L_{eff}} \frac{1}{\omega_{el}^2 - \omega^2 + i\omega\omega_{el}/Q_{el}}$$

$$L_{eff} \equiv L_P\left(1 - \frac{M^2}{L_P(L_{in} + L_S)}\right)$$

$$\omega_{el} \Rightarrow \omega_{mech}$$

$$\omega_{el} \equiv \frac{1}{\sqrt{L_{eff}C}}$$

$$Q_{el} \equiv \frac{\omega_{el} L_{eff}}{R}$$

Enhancement of the transducer efficiency around the mechanical modes

Tuning the electrical mode to the mechanical modes require a very high electrical Q quality factor

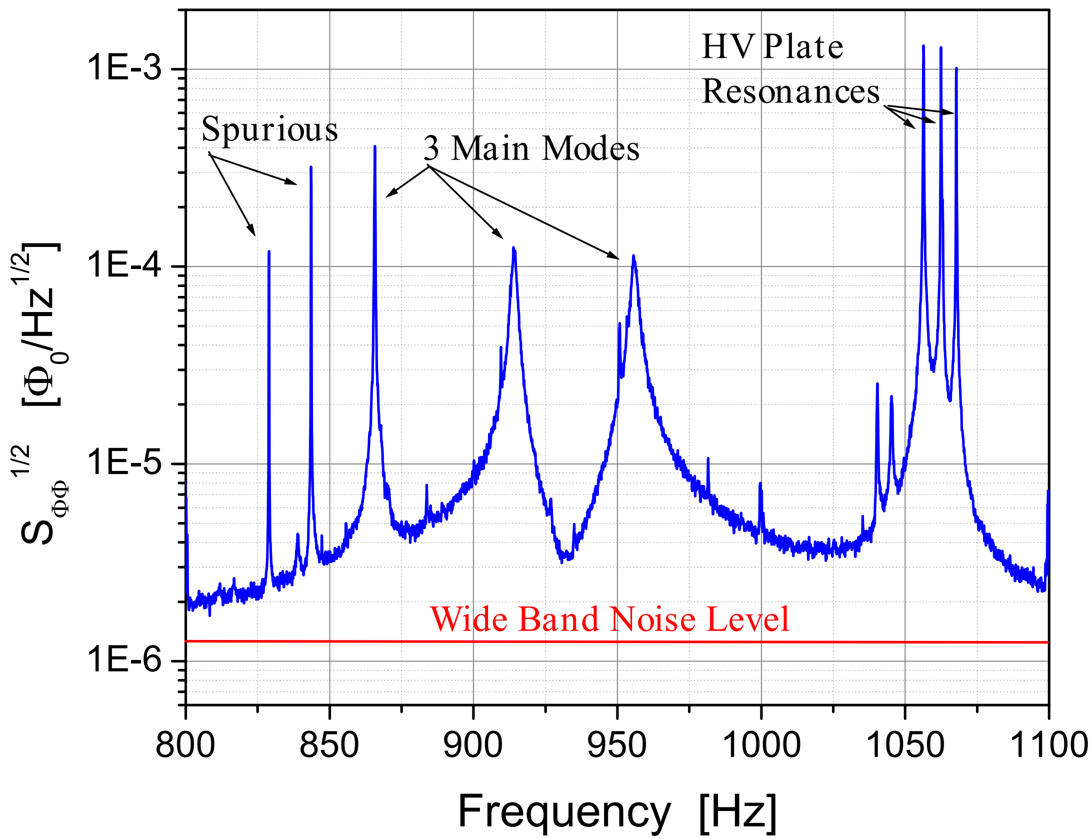
This because the equivalent electric mode mass is light

$$M_{el} = \frac{C_{Tr} E_{Bias}^2}{\omega_{el}^2} \approx 20\ gr.$$

$C_{Tr} =$ Transducer capacitance

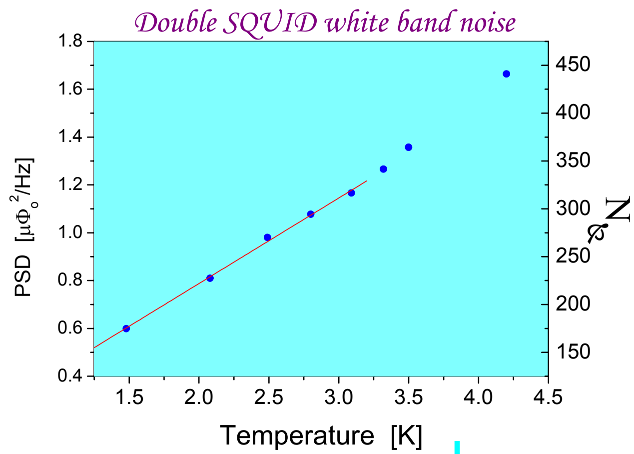
Auriga operate with a Q factor of ~ 500.000

Auriga Output PSD at 4.5 K



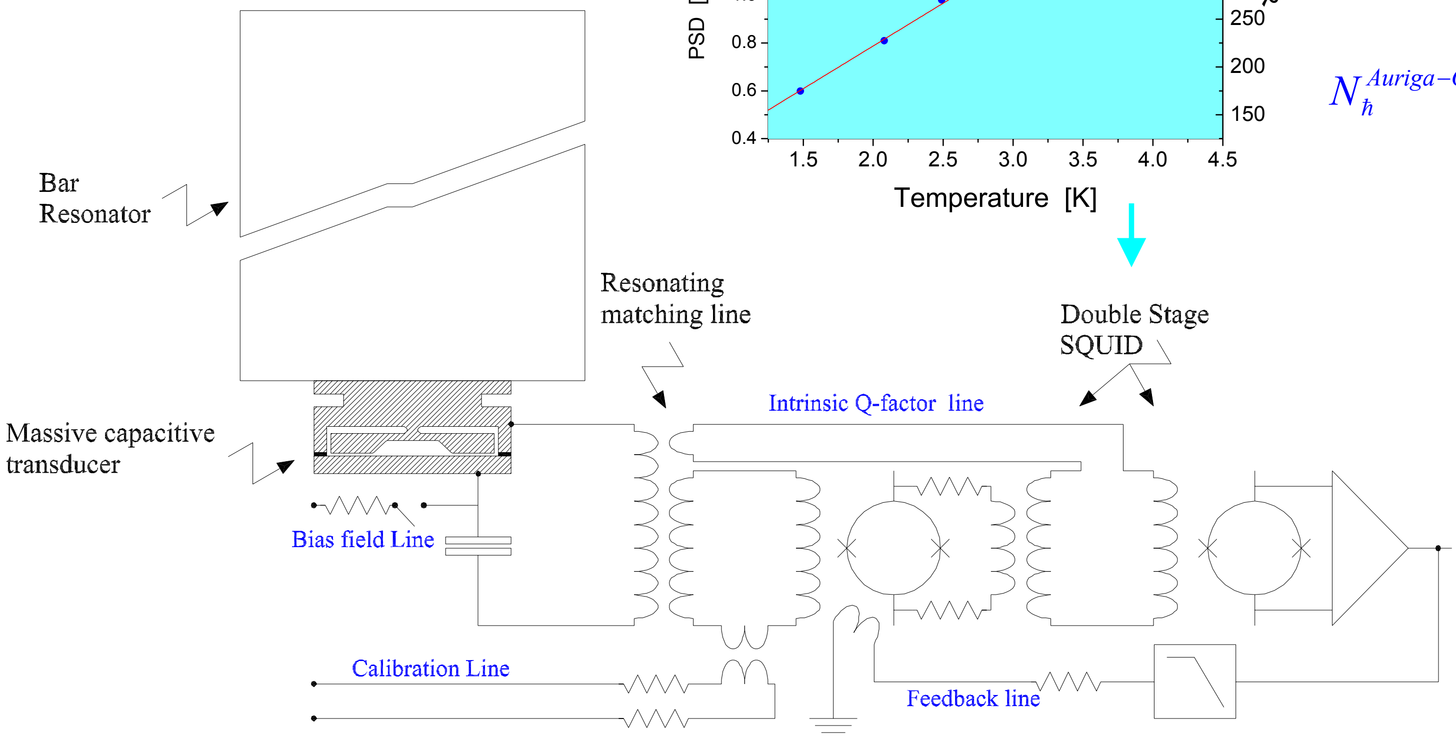
Around the sensitivity bandwidth Auriga noise is dominated by LC thermal noise

Auriga readout

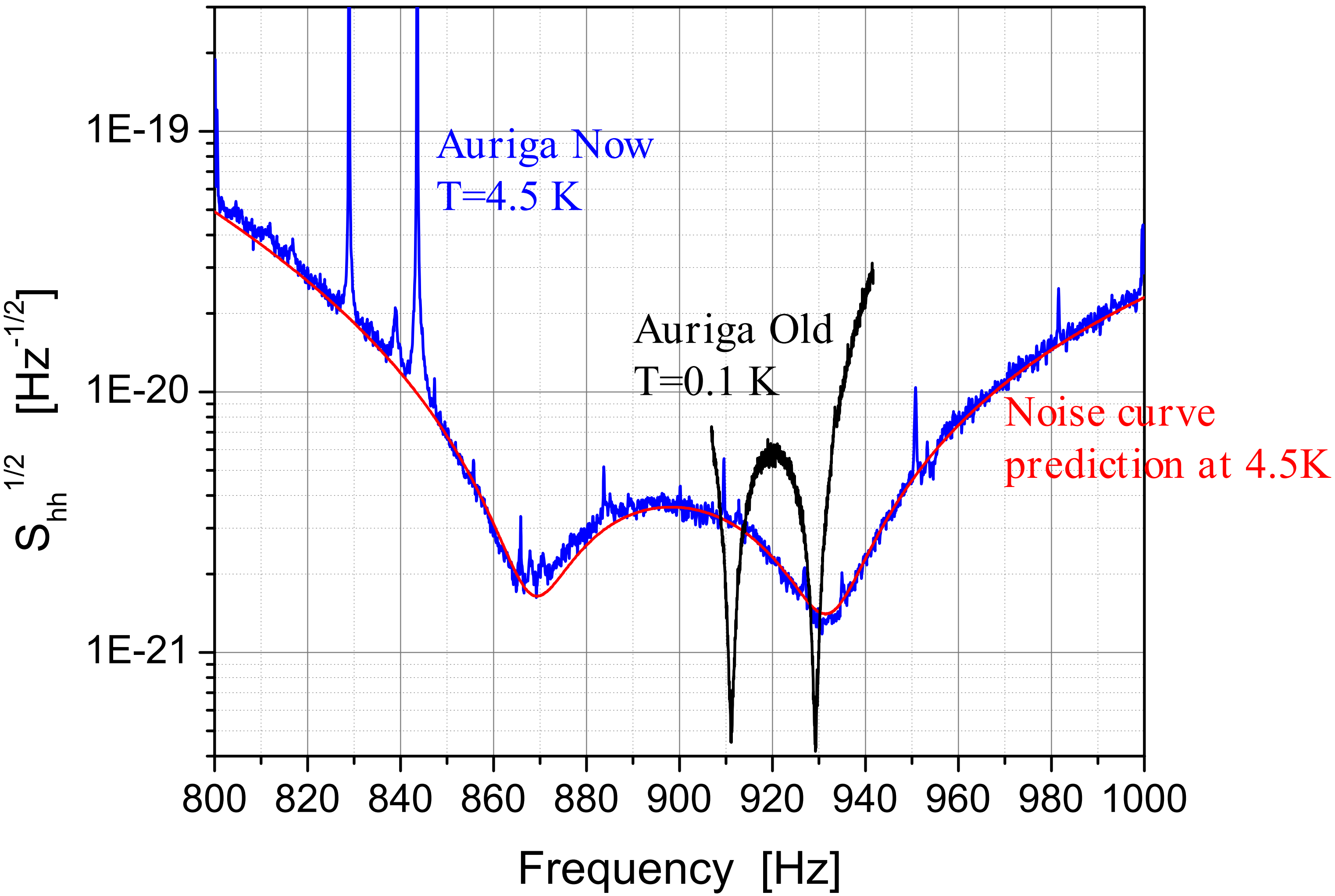


$$N_{\hbar} = \frac{k_B T_n}{\hbar\omega}$$

$$N_{\hbar}^{Auriga-Old} = 5000$$



AURIGA present Sensitivity



AURIGA

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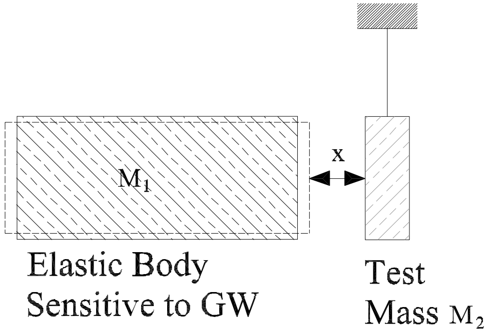
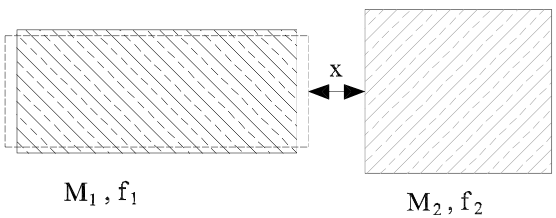
Increase the bandwidth: The Dual detector



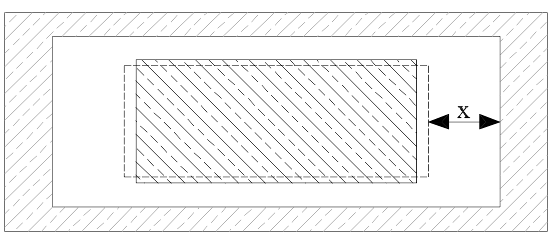
Solution One:

Wrong! Dominated by thermal and BA of the reference mass



Solution Two:

$M_2 \sim M_1$ but $CM_2 CM_1$

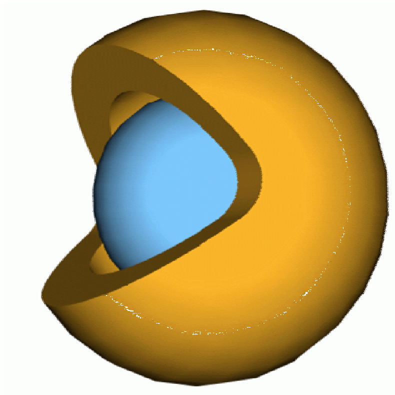


Solution Three:

$M_2 \sim M_1$ and same CM

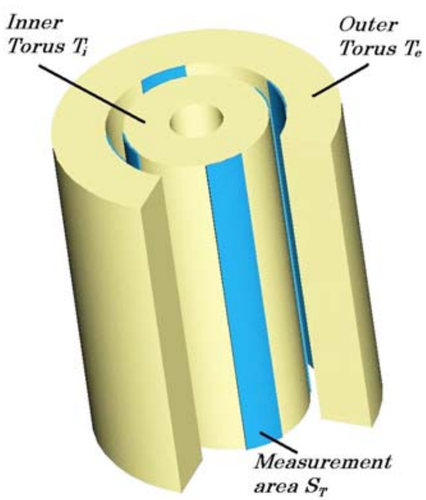
Dual Detector

Considered geometries for Dual



Dual Sphere

M.Cerdonio et. al., *Phys. Rev. Let.* ***87***, 031101 (2001)



Dual Torus

M.Bonaldi et. al., *Phys Rev.* **D62**, 102004 (2003)

Quantum Limited sensitivity curve (dual torus)

$K_{n-Mo} = 1.0 \cdot 10^{11}\ N/m$

$Q/T \geq 2 \cdot 10^{8}$

$r_1 = 0.25\ m\ \ r_{2-\text{int}} = 0.26\ m\ \ r_{2-ext} = 0.47\ m$

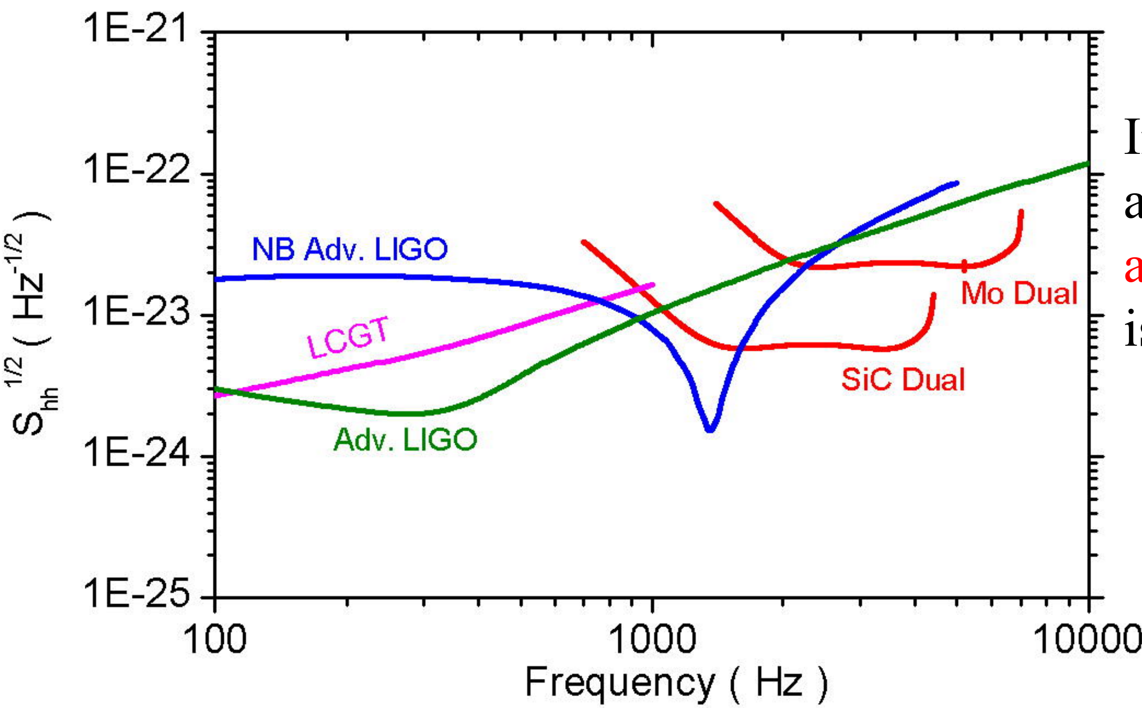
$h = 2.35\ m \quad Tot\ weigth = 16.4\ t$

$K_{n-SiC} = 1.8 \cdot 10^{11}\ N/m$

$Q/T \geq 2 \cdot 10^{8}$

$r_1 = 0.82\ m\ \ r_{2-\text{int}} = 0.83\ m\ \ r_{2-ext} = 1.44\ m$

$h = 3\ m \quad Tot\ weigth = 61.5\ t$

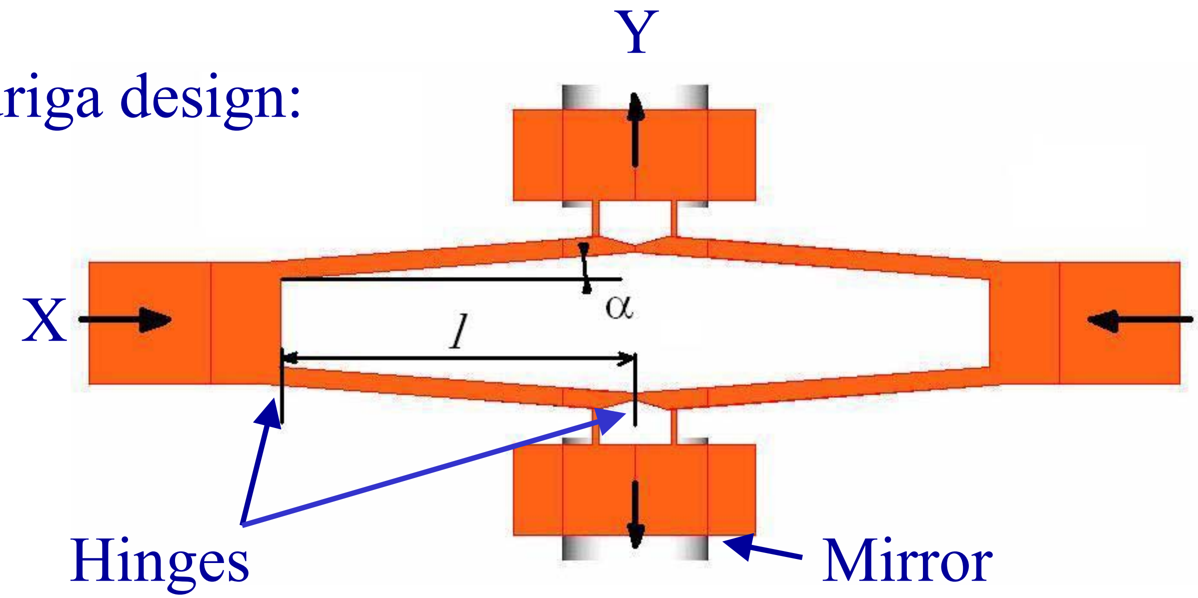


In order to get $K_n \sim 10^{11}$ N/m a lever geometrical amplification of at least 10 is required

Broad band lever amplification

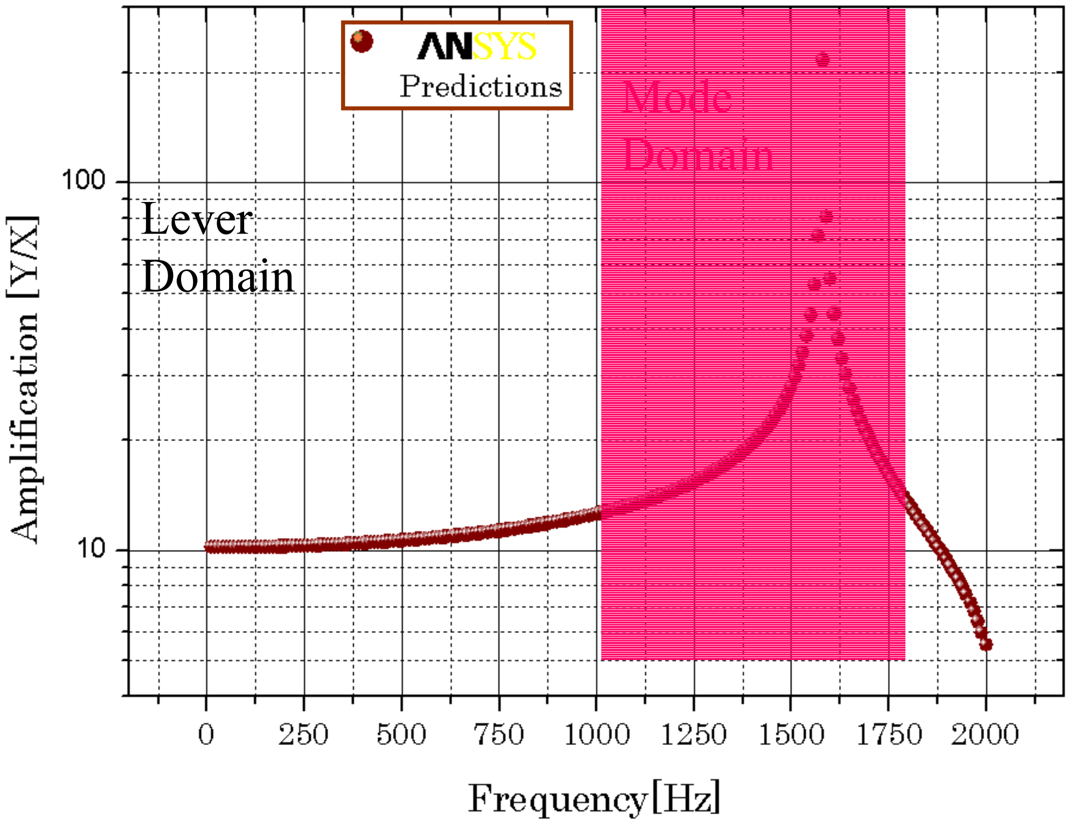
H.J. Paik et al, *Proc. Of the first Amaldi Meeting*, edited by E. Coccia et al, World scientific Singapore, p201 (1995)

Auriga design:

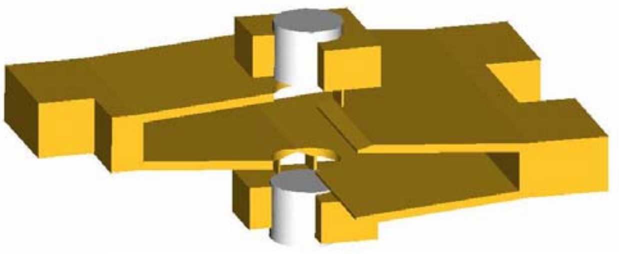


Mechanical amplification=Y/X=1/a>>1

Prototype under test:Amplification



Material Al7075



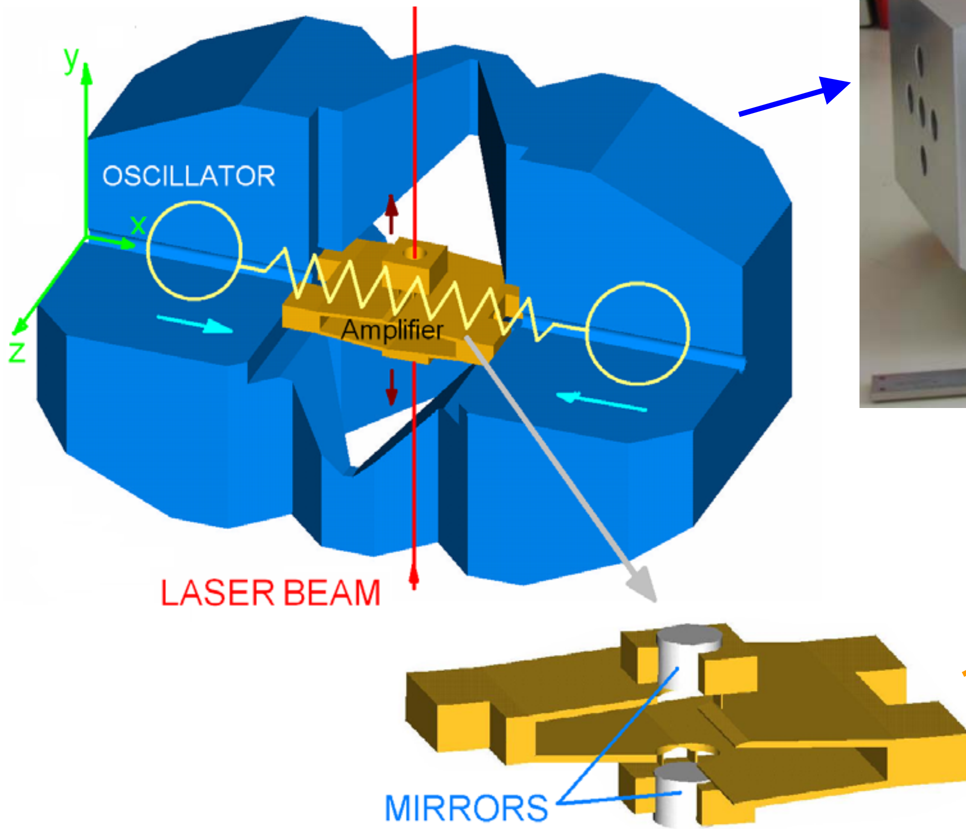
Parameters for simulation

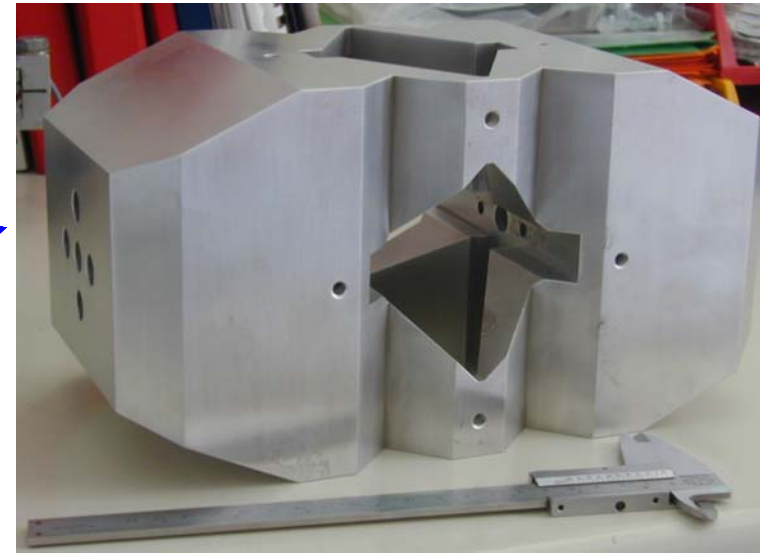
- T=300 K
- Gaussian Beam waste 0.375 mm
- Mirrors Fused silica

Geometrical gain factor=10

Prototype test:assembling procedure

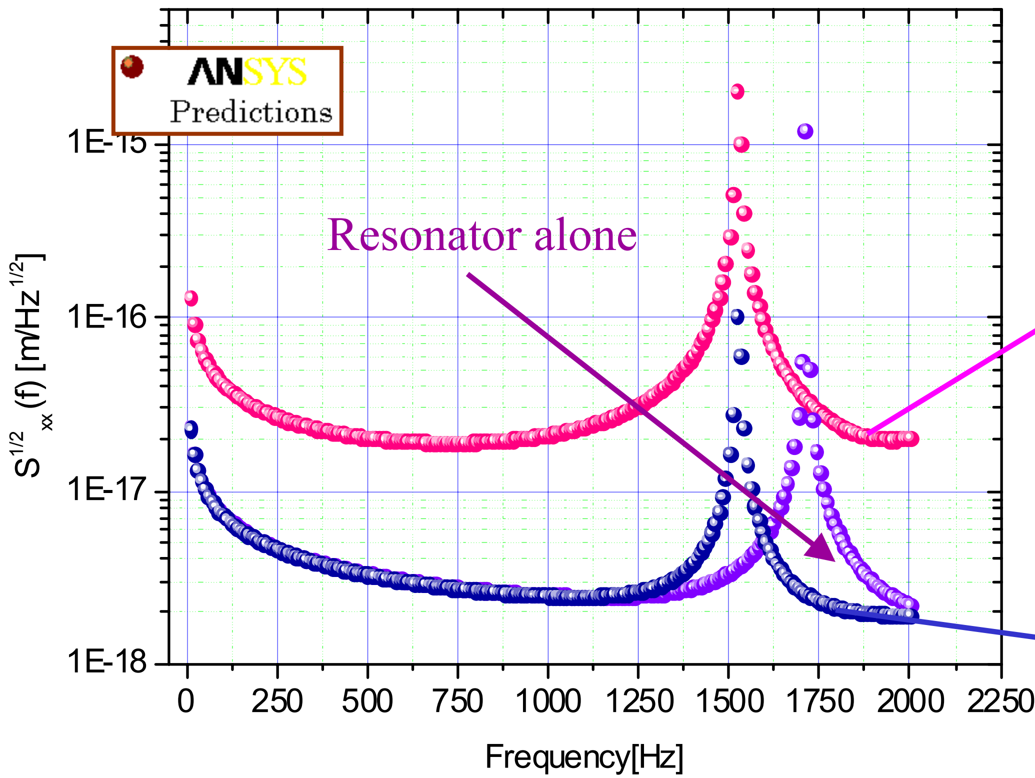
Harmonic oscillator

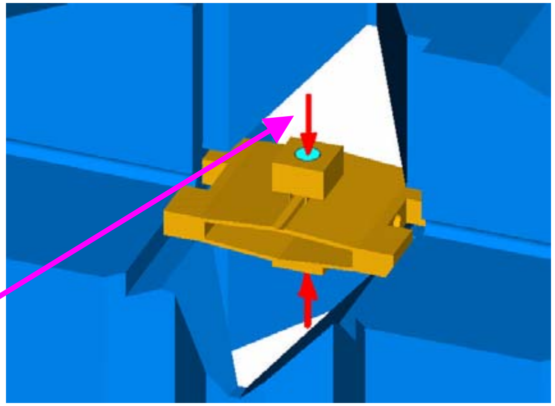


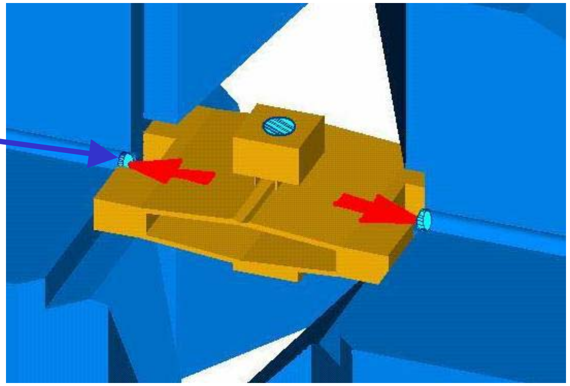


Amplifier

Prototype thermal noise estimation





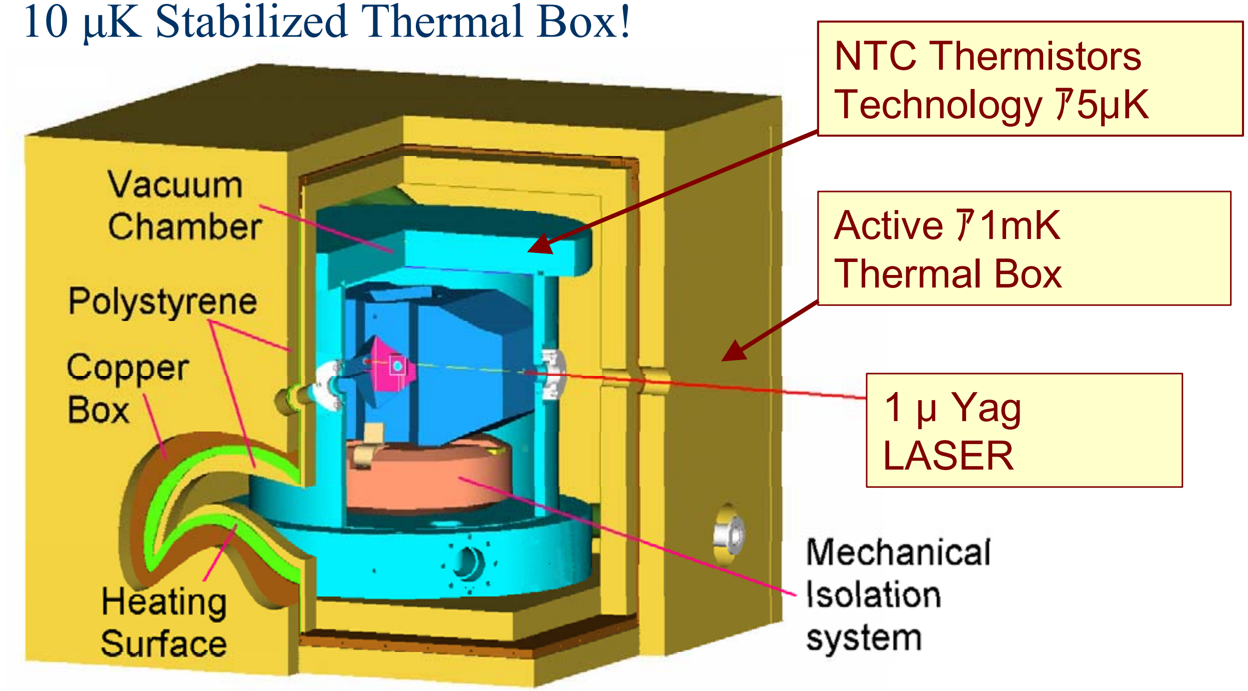


$$S^{Therm}_{xx-Amplifier-out} \approx Gain \times S^{Therm}_{xx-\mathrm{Resonator}}$$

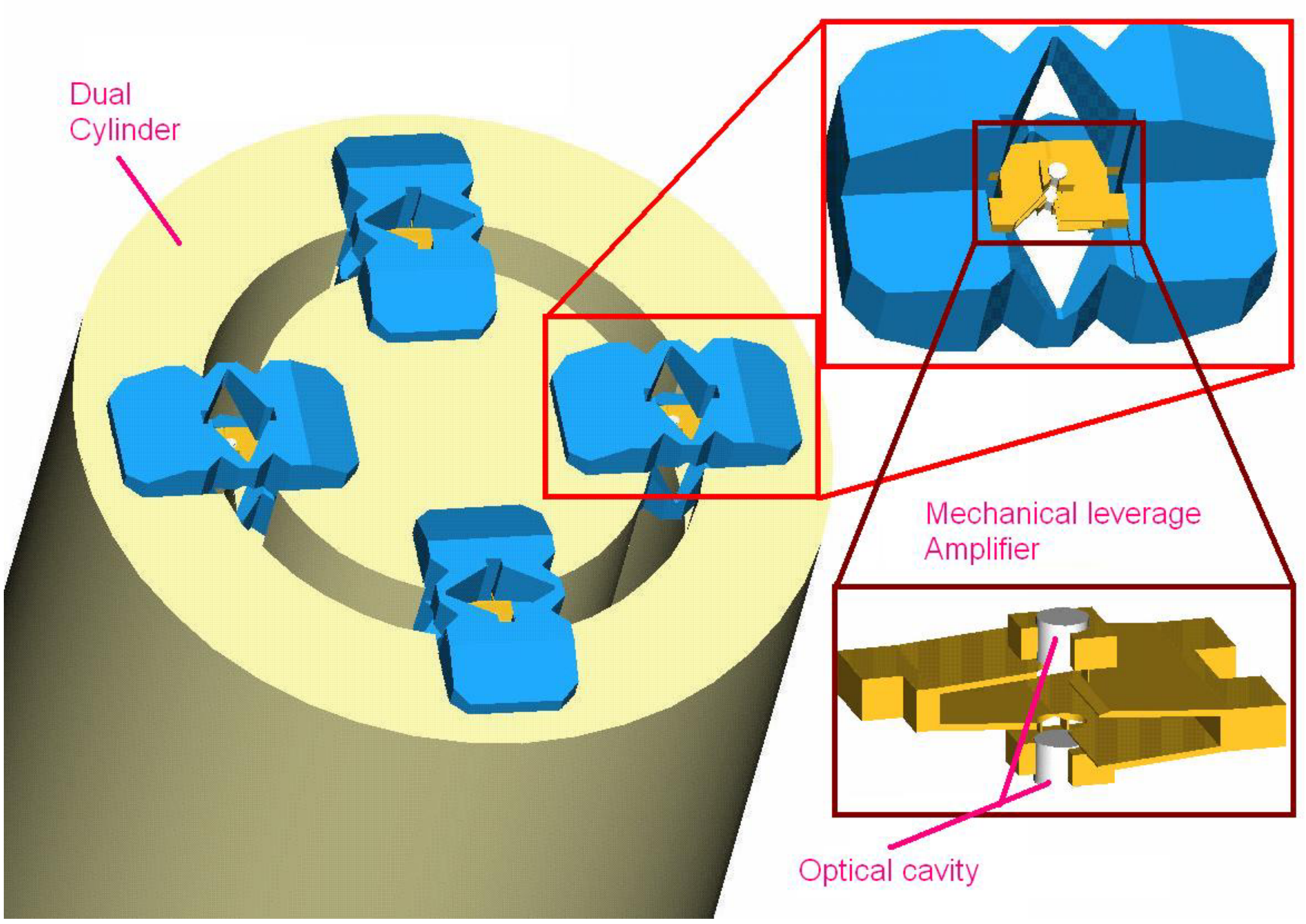
The amplifier thermal noise contribution is negligable

Prototype thermal noise measurement set-up

Room Temperature Thermal Noises Measurement:
10 μK Stabilized Thermal Box!



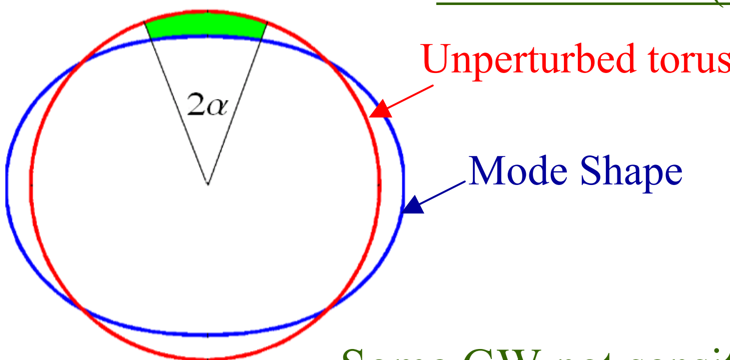
A possible implementation in Dual-Torus



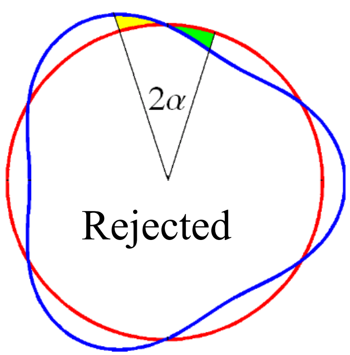
Dual Torus Therm. and BA noise reduction: Wide area sensing

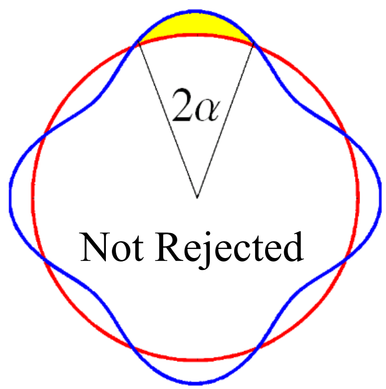
Signal=mean displacement over the readout area=Green surf.+Yellow surf.

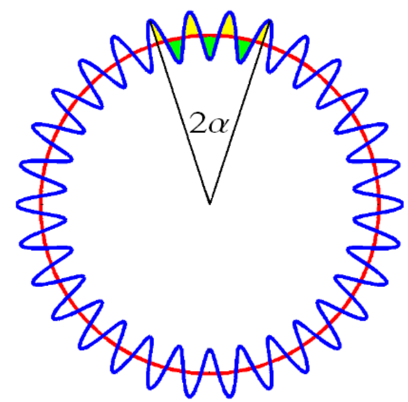
GW sensitive (quadrupolar) mode:



Some GW not sensitive mode which provide only noise:



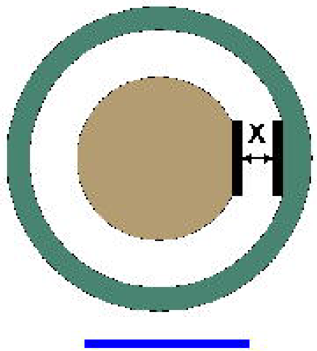




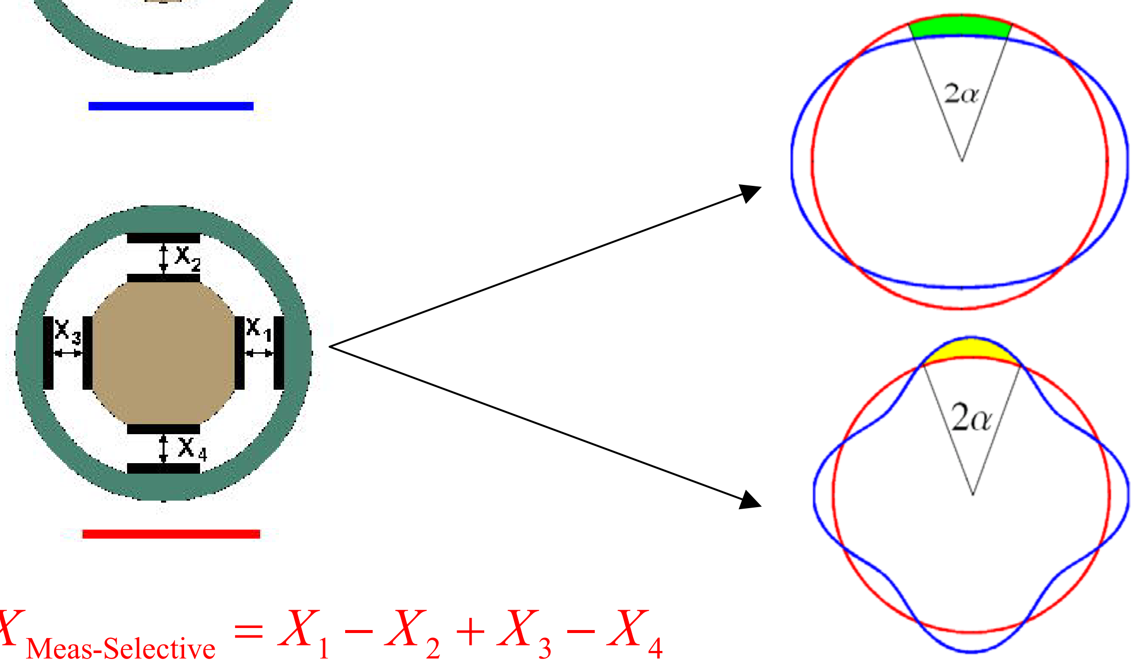
Some of the low order modes are averaged out

High order modes are averaged out

Dual Torus Therm. and BA noise reduction: Selective readout



$$X_{\text{meas-Standard}} = X$$



Quradrupolar mode (Signal)

$X_{\text{Meas-Selective}} \rightarrow$ Maximized

Octupolar (Noise)

$X_{\text{Meas-Selective}} \rightarrow 0$

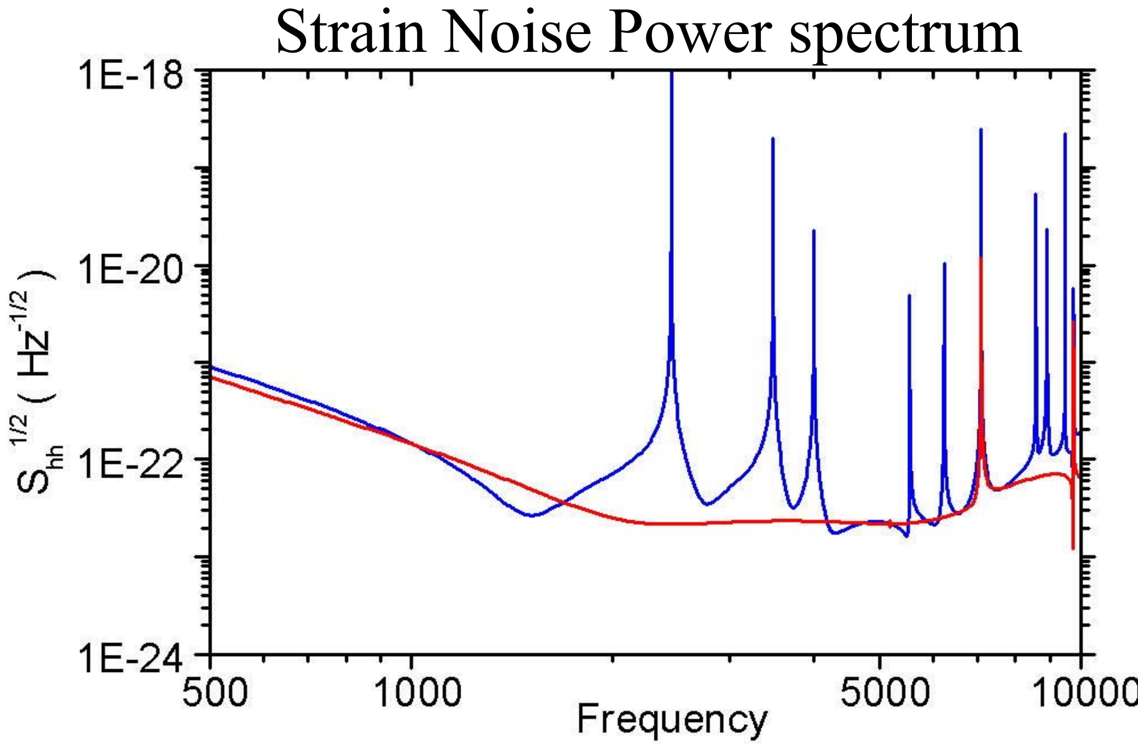
$$X_{\text{Meas-Selective}} = X_1 - X_2 + X_3 - X_4$$

Example of Thermal and BA noise reduction using selective readout

Material:Molybdenum:

Dimensions:

$$r_1 = 0.25\ cm$$
$$r_{2-\mathrm{int}} = 0.26\ cm$$
$$r_{2-ext} = 0.47\ cm$$



Red:Selective readout

Blue: Not Selective readout

Conclusions

•Well designed impedance matching lines between the main resonator and the amplifier has been used to widen the useful band of the Auriga detector more than one order of magnitude

• Broad band detectors should be obtained using lever transducers. In particular the proposed detector “dual” promises a sensitivity of the order of 10^{-23} $Hz^{-1/2}$ in the frequency range between 1kHz to 5 kHz.