Nonequilibrium issues in macroscopic experiments

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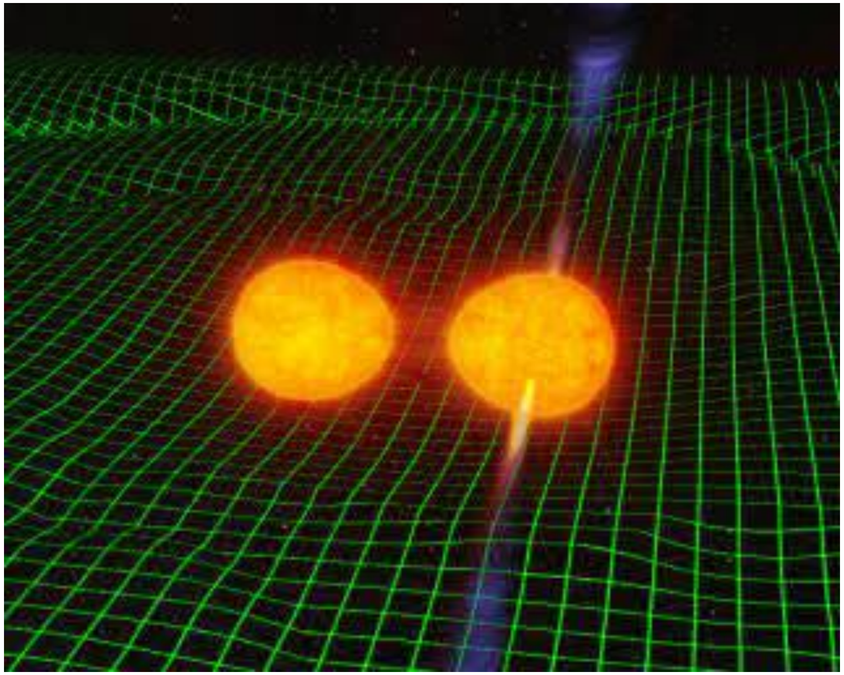
POLITECNICO DI TORINO
1859 · 1906

Gravitational Wave detector

Motivation: GWs will provide new and unique information about astrophysical processes

Gravitational Waves

GWs are ripples in the spacetime caused by violent events in the universe



Inspiral and merger of pulsar and NS (artist's view)

Sources for ground based detectors:

- Inspiral and merger coalescence of stellar size binary systems (NS-NS, NS-BH, BH-BH)
- rotating or unstable neutron stars
- Supernovae

Gravitational Wave detector

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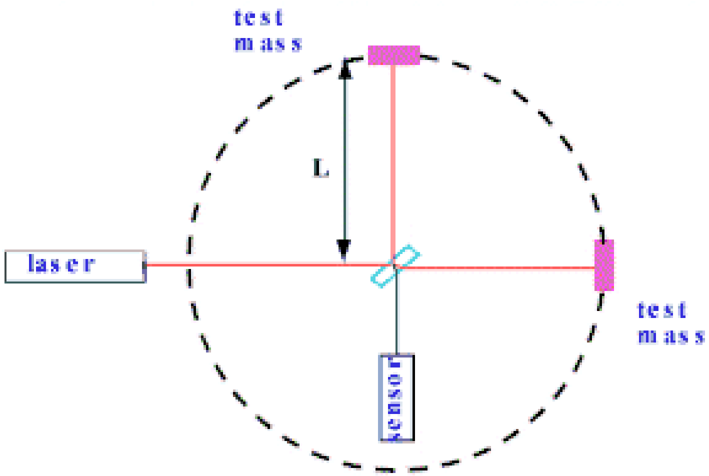
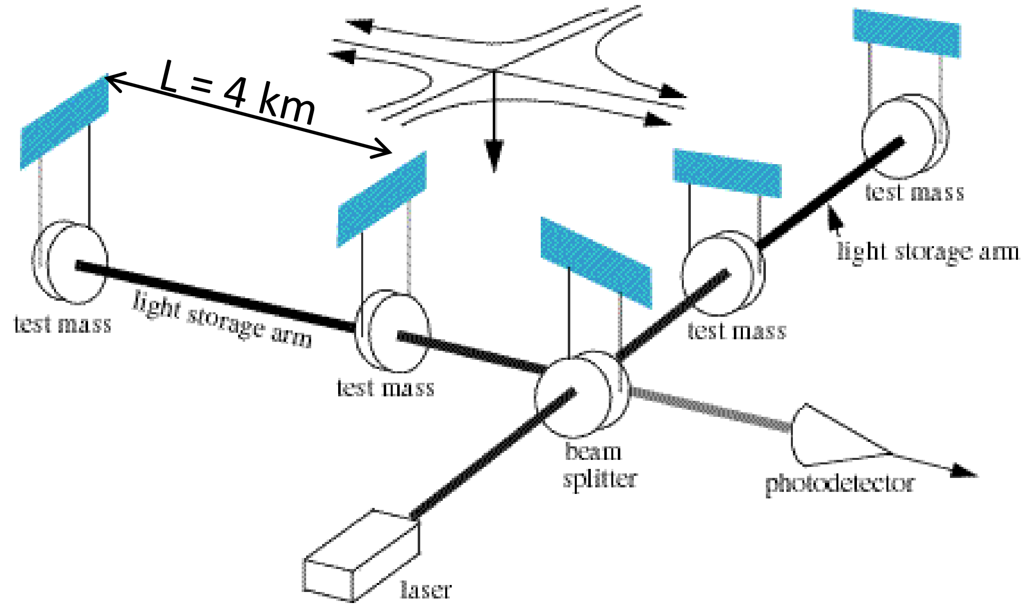




GW amplitude: $h \sim \frac{1}{2}\frac{\Delta L}{L}$

very tiny effect!!

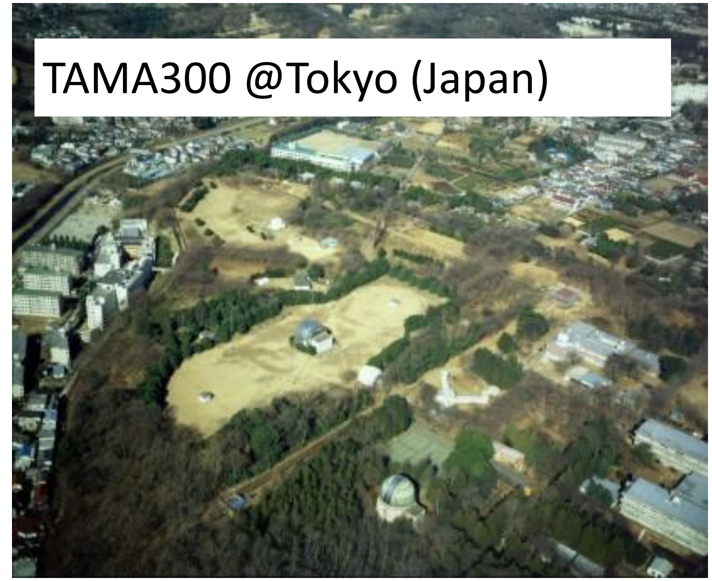
A detection rate of few events/year requires

sensitivity of $h \sim 10^{-22}$ over timescales as short as 1msec

small signal noise ⇒

noise sources must be reduced to very low levels

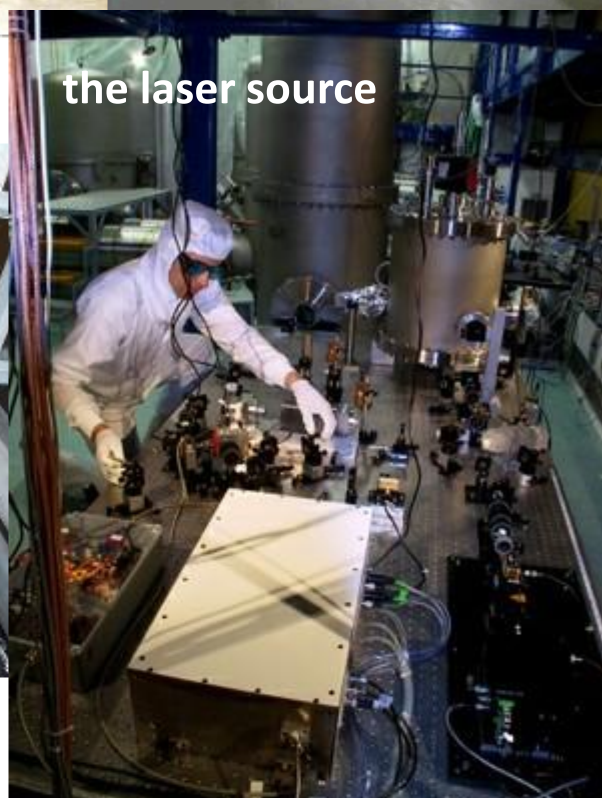
GW detectors (interferometers)

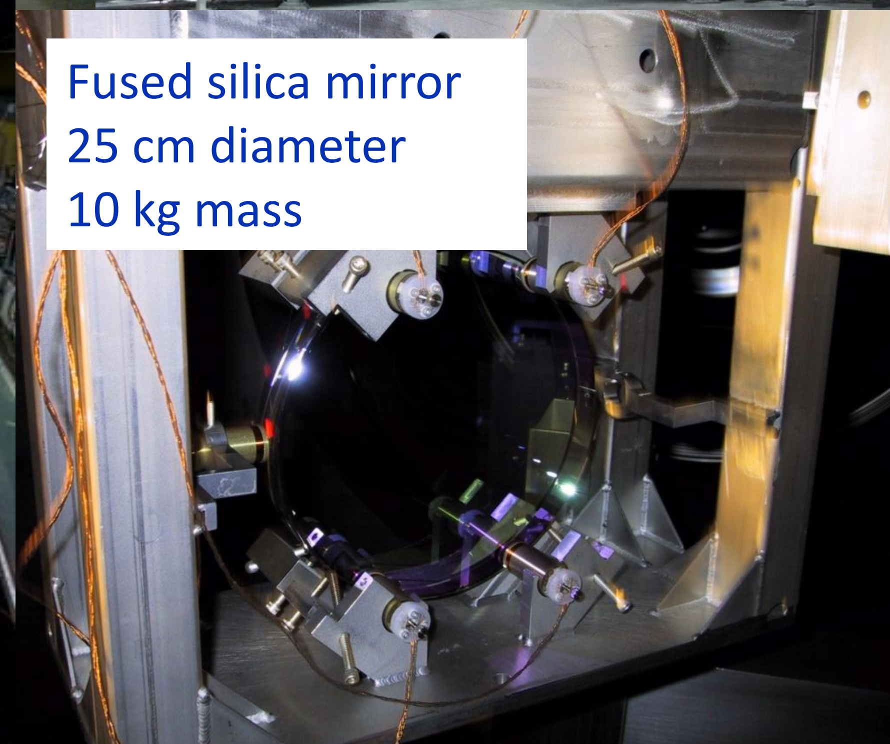


GW detector technology

Very sophisticated and complex apparatus

1.2 m diameter - 3mm stainless 50 km of weld
10^{-9} torr vacuum and no leaks!

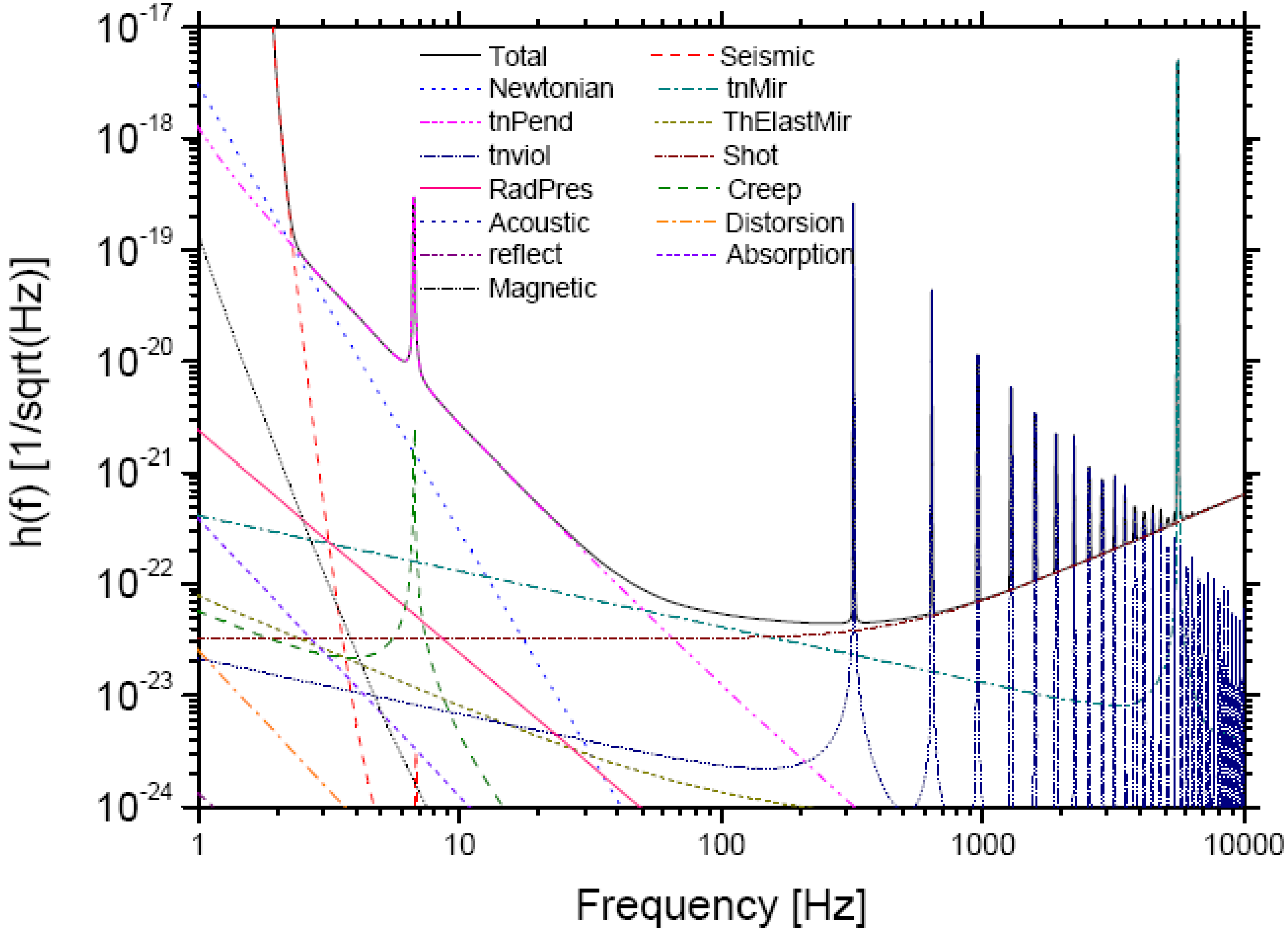




GW detector noise budget

Dominant Sources of Noise:

- seismic noise
- thermal noise
- photon shot noise



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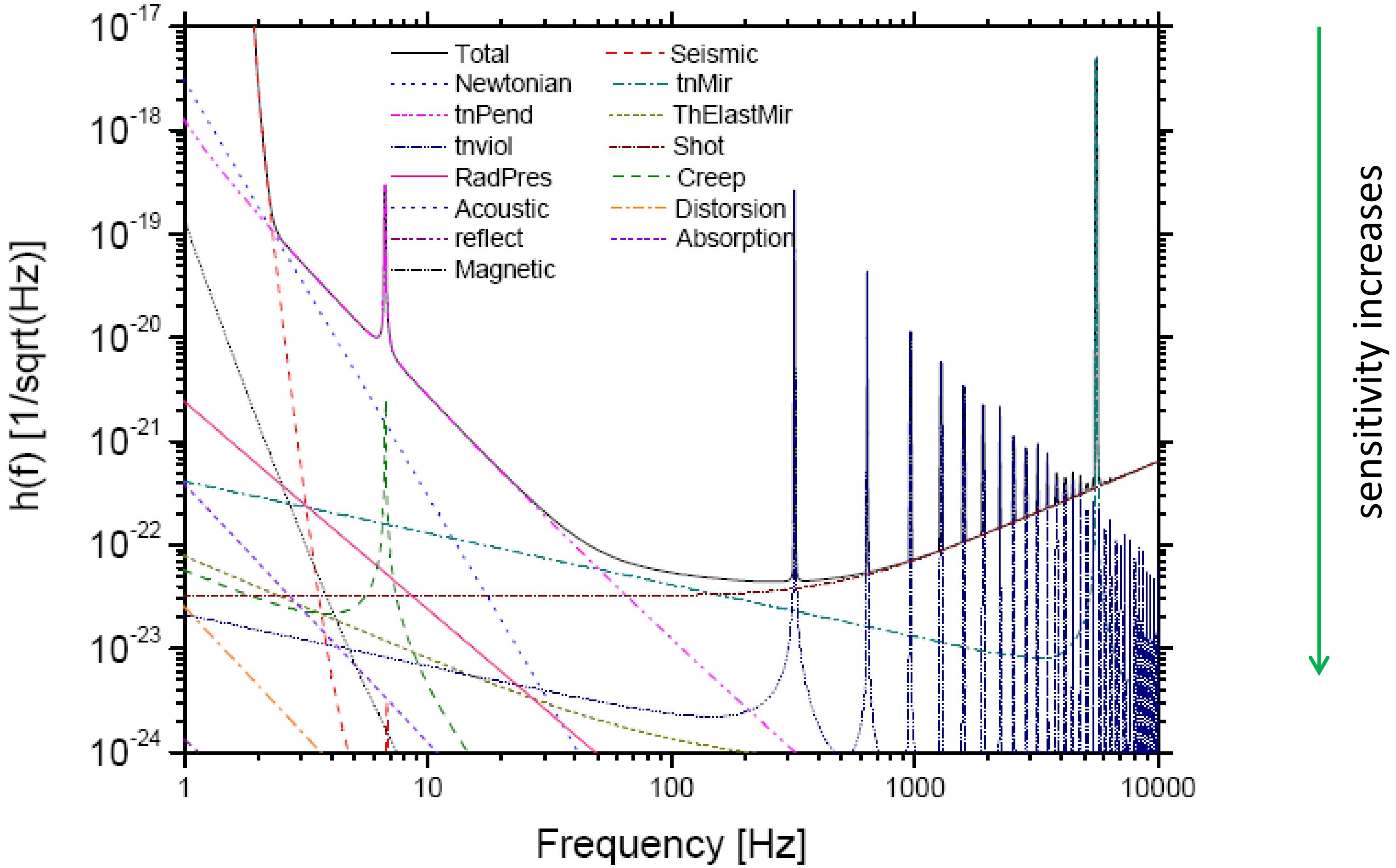

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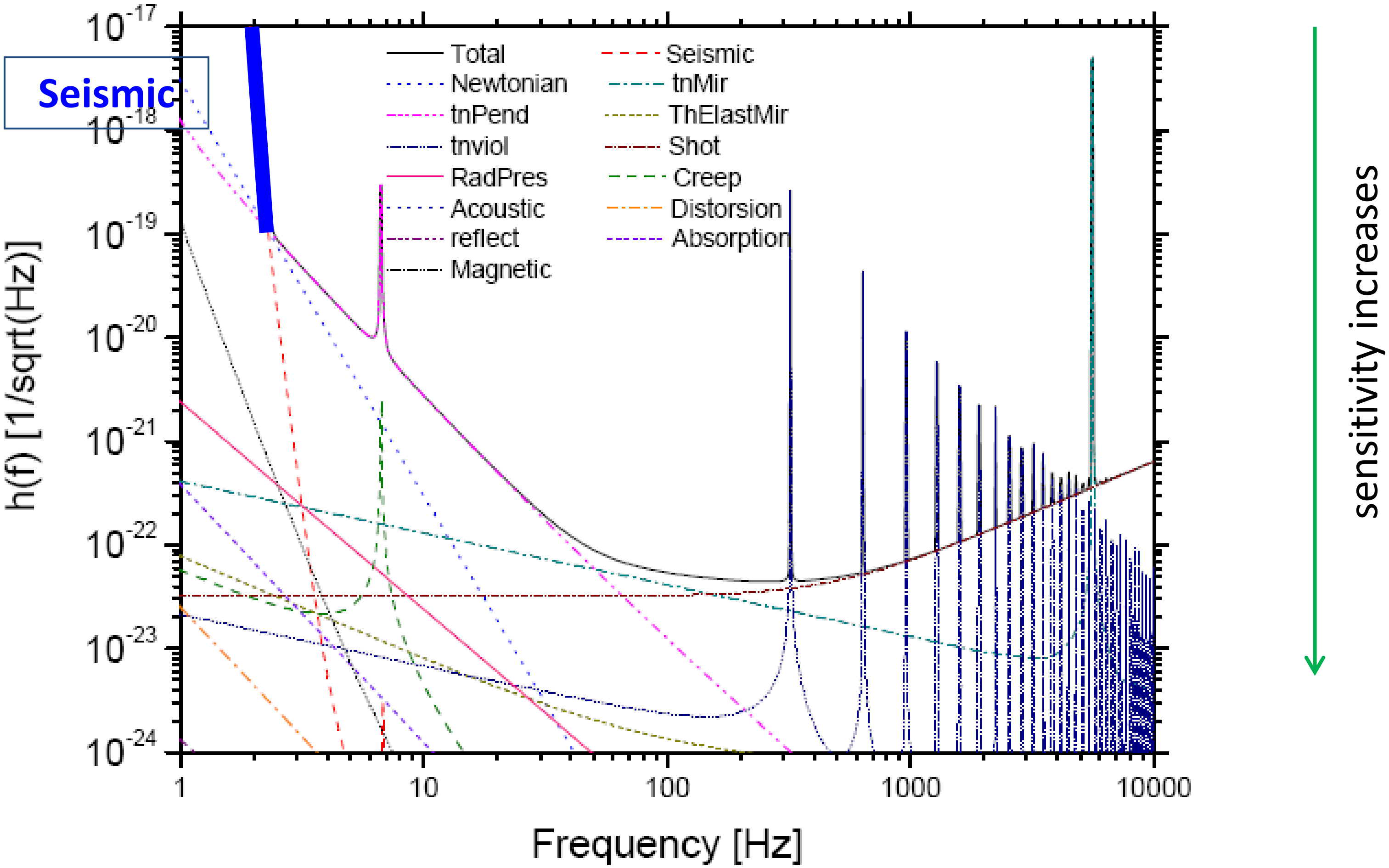

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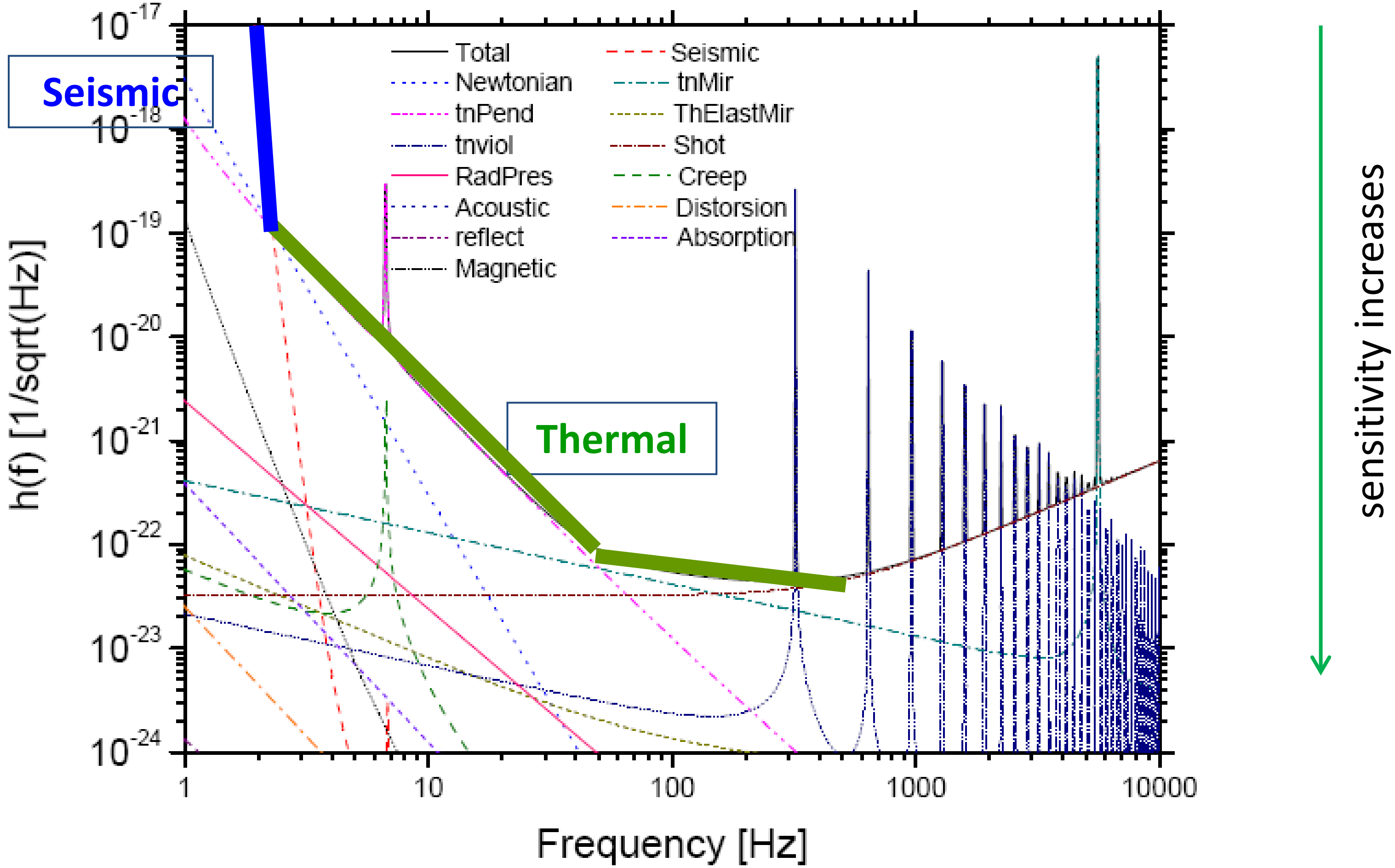

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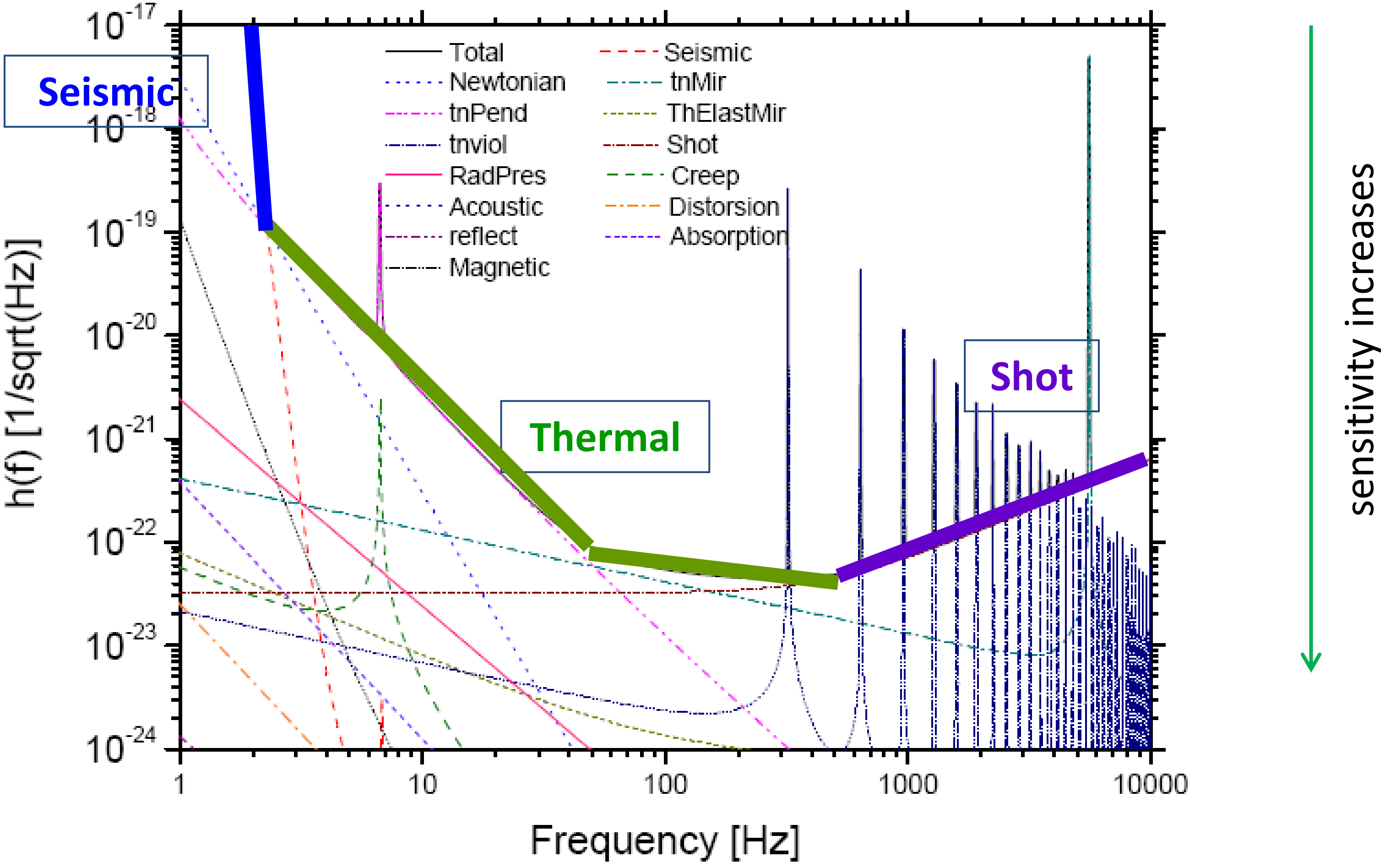
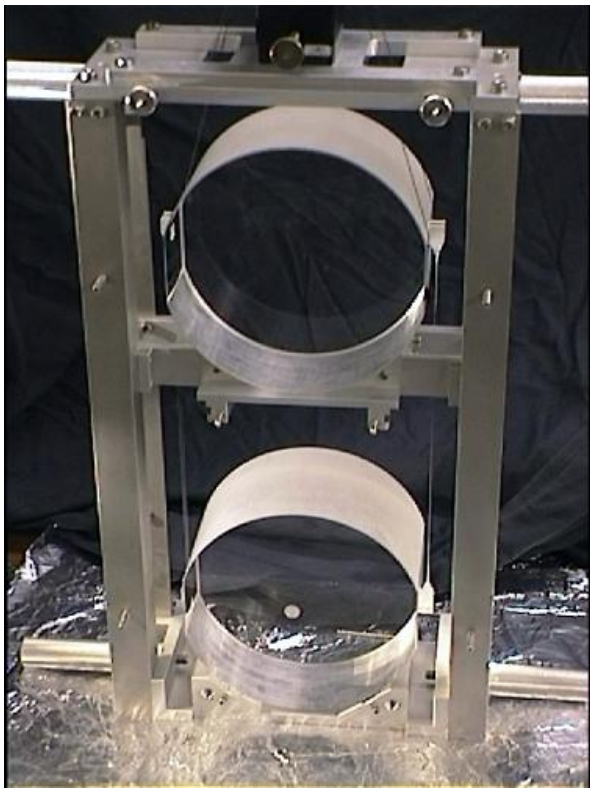


Thermal noise in GW detectors

Thermal noise of:
mirror masses
last stage of mirror suspension

The thermally induced and GW induced position fluctuations are indistinguishable.



To beat thermal noise:

- low mechanical losses of mirror masses
- low suspension (pendulum) resonances
- high frequency of mirror internal resonances

Mirror masses:
6kg - 40kg

so far equilibrium but…

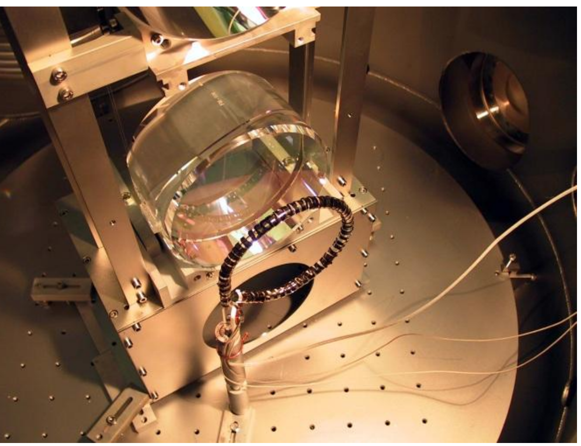
Thermal compensation

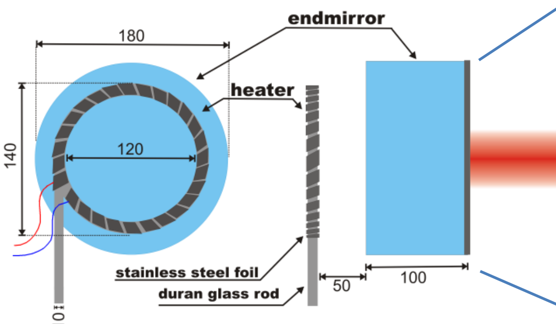
to correct mismatch of the mirror Radius Of Curvature (ROC) due to:

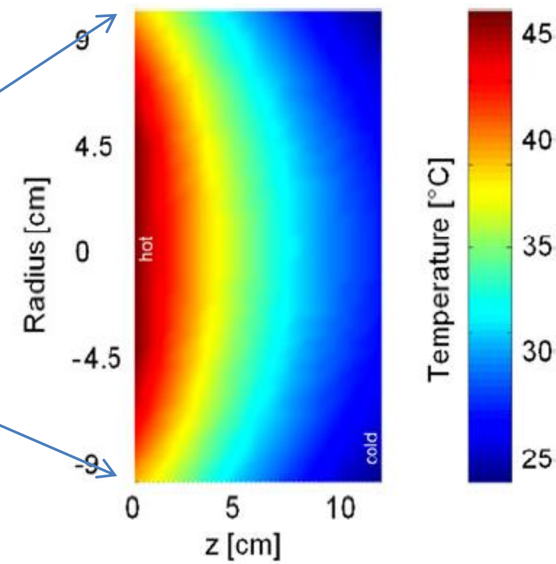
- fabrication
- thermal lensing
- thermo-elastic deformation

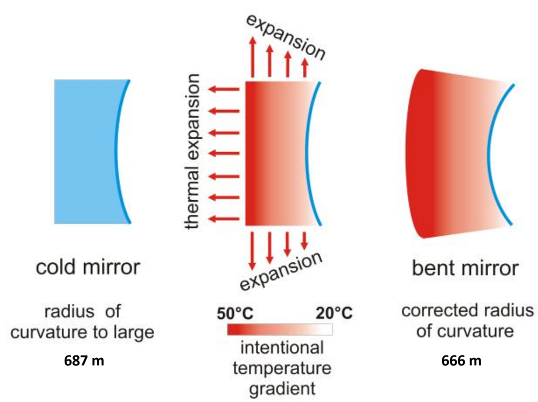
} due to absorbed power (up to ~0.5W)

Applied thermal gradient deforms the mirror and corrects the ROC



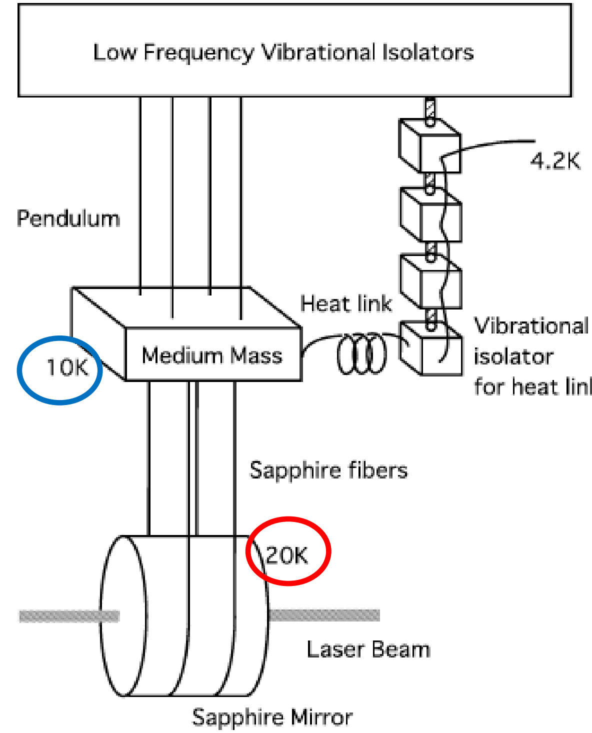




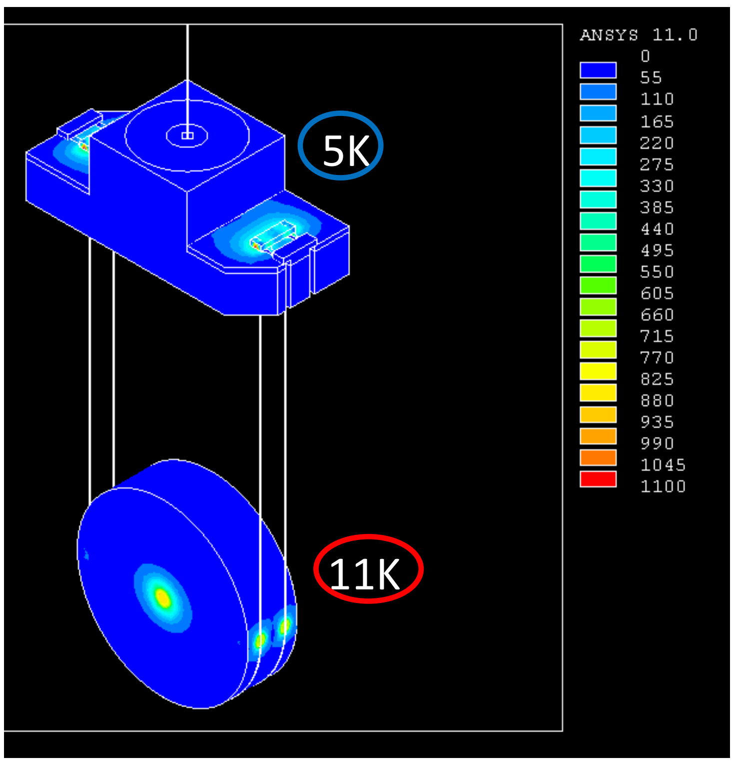


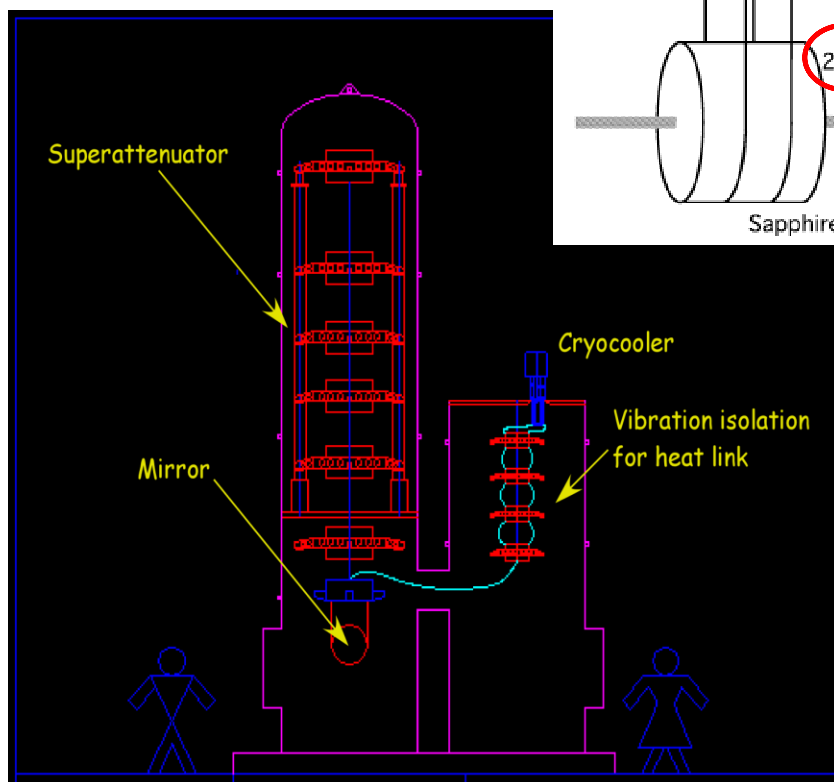
What is the 'thermal noise' of such a non-equilibrium body?

Next generation detector strategy to improve sensitivity: cryogenics



Goal temperature <20K



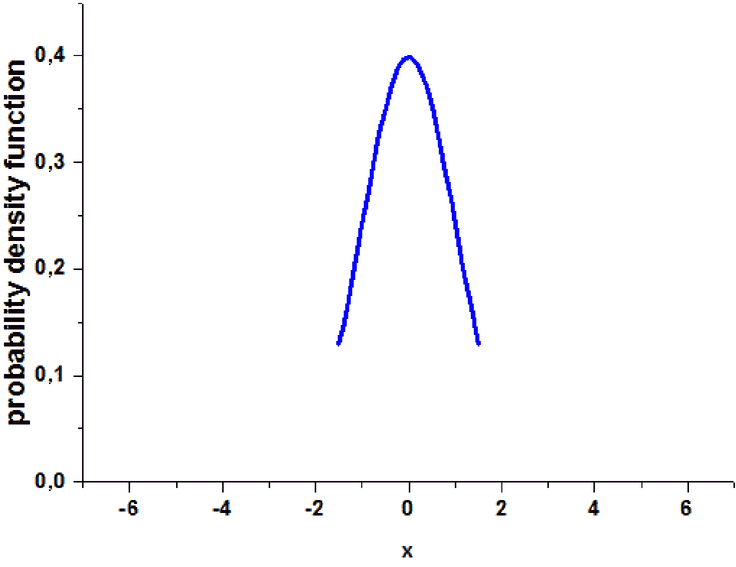


non-equilibrium issue

Non equilibrium noise in GW detectors

Question:
how to compute the spontaneous vibration fluctuations ('thermal noise') in non-equilibrium instruments?

For **small** fluctuations one could apply the Fluctuation-Dissipation theorem using position-dependent temperature: $T=T(x)$ (local equilibrium).



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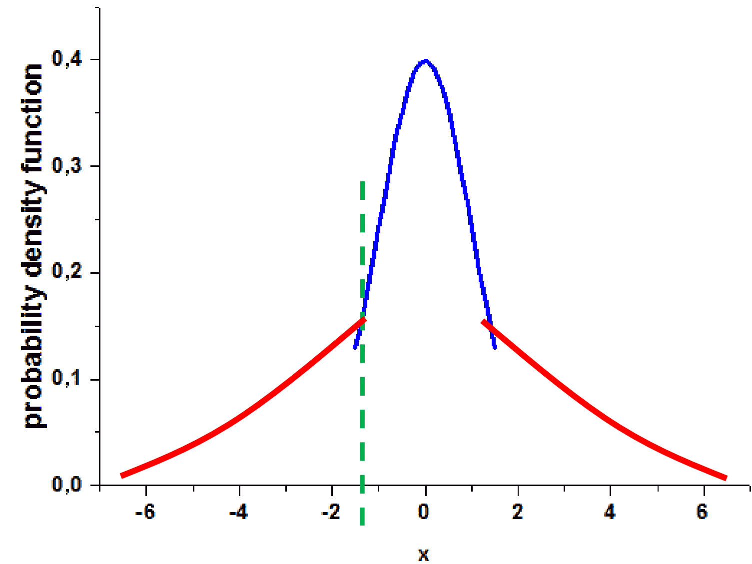
Where is the departure point between small and large flucuations?

But: what is the probability of the **large** fluctuations? Indications suggest that they are more frequent than if gaussian



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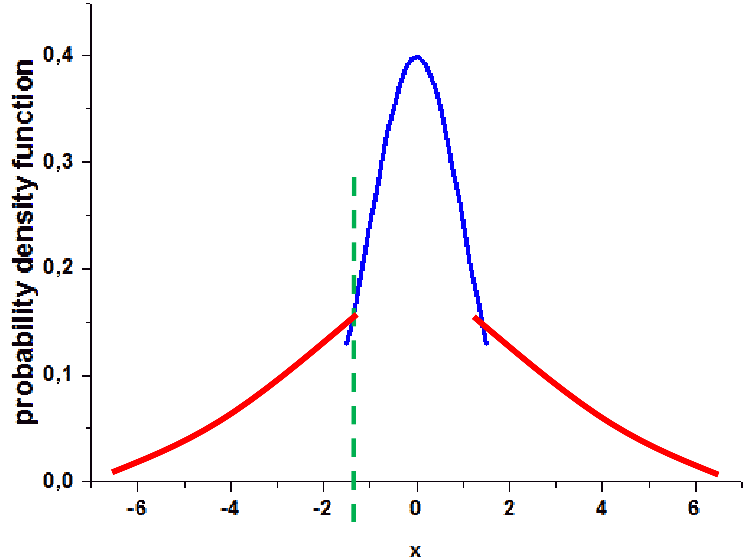


But: what is the probability of the **large** fluctuations? Indications suggest that they are more frequent than if gaussian

Moreover: what happens to the acoustic modes? The modes cannot be defined locally! The concept of local equilibrium does not apply to the acoustic modes.

So far the problem is addressed as if thermal equilibrium and normal mode expansion hold.

Why to care for?

GW experiments are modeled as systems in thermodynamic equilibrium:

is this justified?

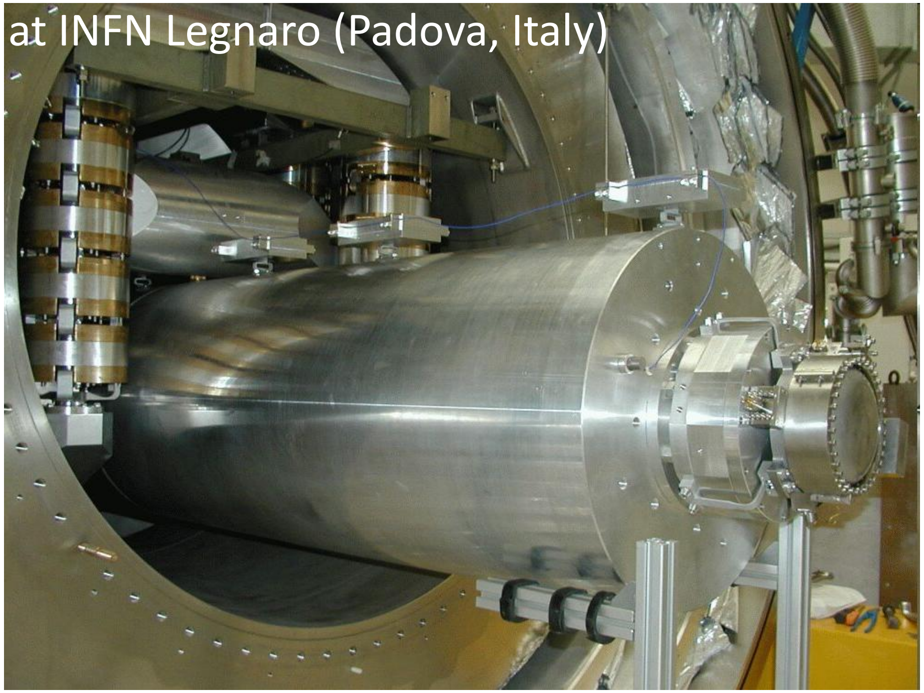
If nonequilibrium effects important :

likely deviations from equilibrium Gaussian distribution

(indistinguishable from true GW signals)

- > increased false alarm rate and worsen detector reliability

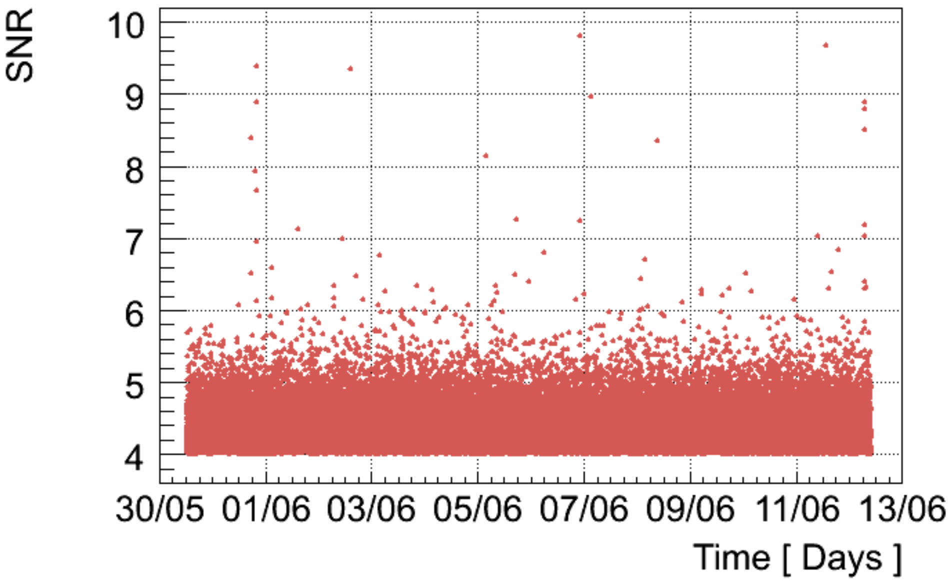
AURIGA: stationary gaussian GW detector

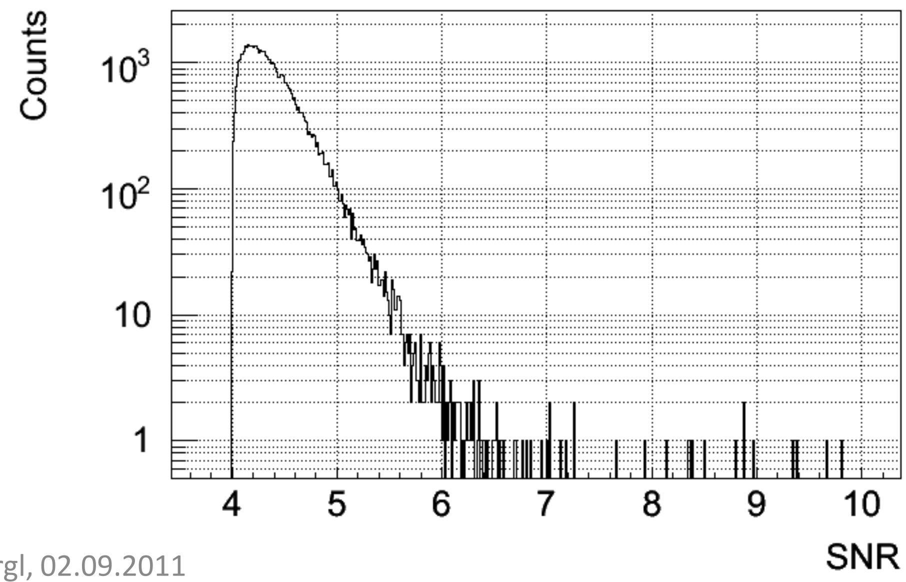


bar:

material	Al5056	mass	2300kg
length	3m	1st longitud. resonance	~900Hz
diameter	600mm	thermodynamic temperature	4.2K

- Very stationary Gaussian noise
- Outliers 9 events/day with SNR > 6
- Event rate 3700 /day with SNR > 4





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(indistinguishable from true GW signals)

- > increased false alarm rate and worsen detector reliability

But:

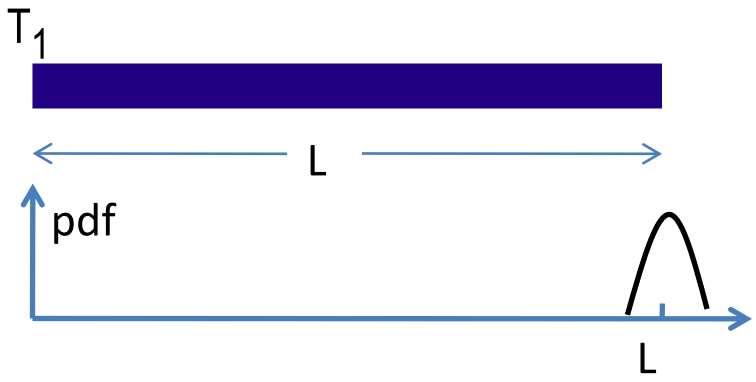
if we know, we can avoid or limit the problem

Hence we ask:

can we size nonequilibrium effects in GW detectors?

How to size the problem

Let us monitor the spontaneous length fluctuations of a rod of length L at temperature T_1



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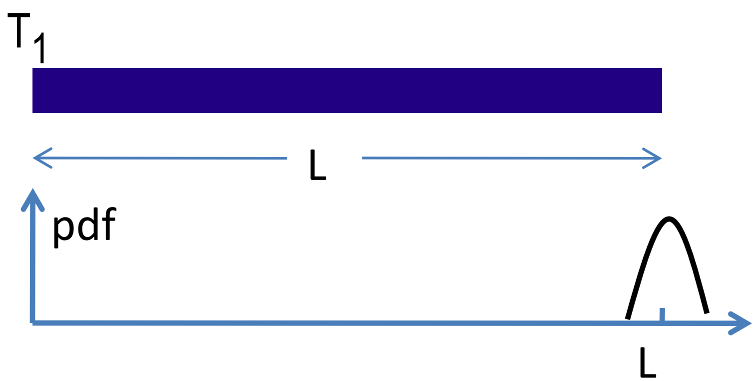
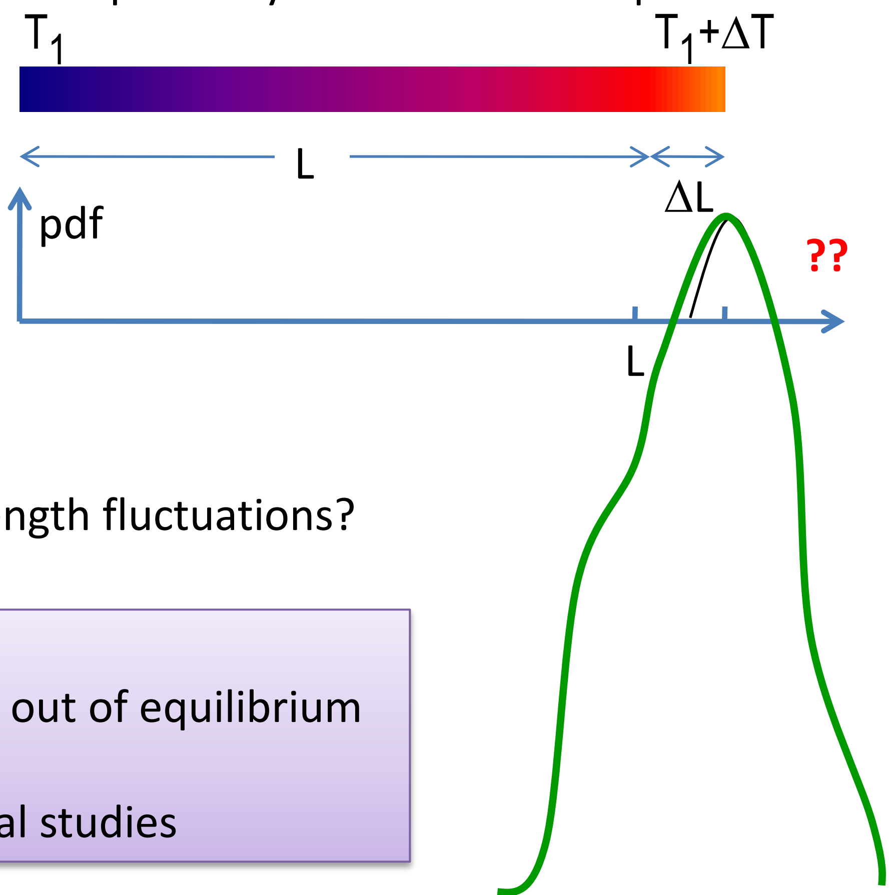


Now apply a steady-state thermal gradient ΔT between the ends by flowing power W=dQ/dt. The rod expands by ΔL via thermal expansion:



What is the pdf of the length fluctuations?

Our approch:
we reproduce situations that drive GW detectors out of equilibrium but on smaller-scale, simpler devices:
we perform experimental and numerical studies

The RareNoise project

www.rarenoise.lnl.infn.it

Capitalizing on Gravity Wave detectors' high sensitivity and long acquisition times, RareNoise proposes the GW detectors as the playground for NonEquilibrium Theories applied to macroscopic systems

Theoretical / numerical work: see next talk by P. De Gregorio

Experimental work:

- macroscopic mechanical oscillators in NESS
- focus on low losses, as in high sensitivity experiments (eg GW detectors)
- 2 types of materials (aluminum and silicon)
- down to low temperatures to change material parameters and to lower losses
- *observable*: displacement fluctuations of the oscillators

NESS: constant thermal gradients.

$\Delta T/T$ ~ 1%-20% at room T, up to >100% at 4K

Silicon: thermal expansion α reverses sign twice between 300K and 4K.

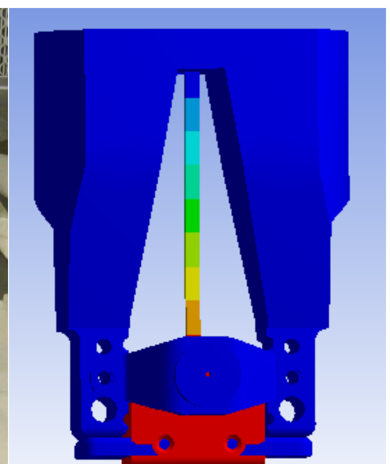
does the effect depend on α?

Class. Quantum Grav. 27 (2010) 084032

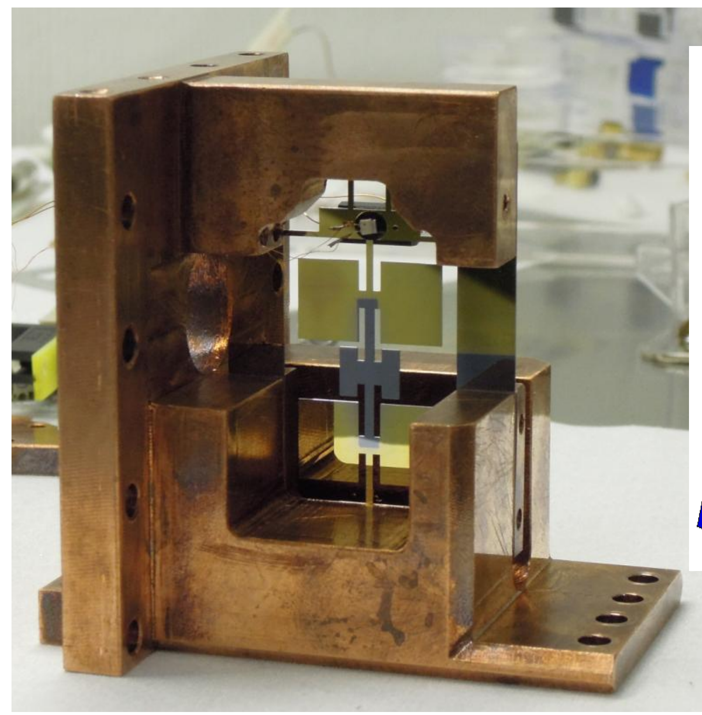
The oscillators

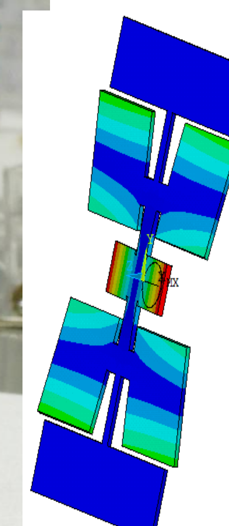
- 2 types of oscillators (resonance 1-4kHz):
  - Aluminum oscillators
    - at room T: losses 3e-4, ΔT_{max} 10K
    - produced in mechanical workshop
  - Silicon oscillators
    - at room T: losses 5e-6, ΔT_{max} 50K
    - need special litographic techniques

- capacitive readout of oscillator vibration
- Possibility to apply thermal gradient



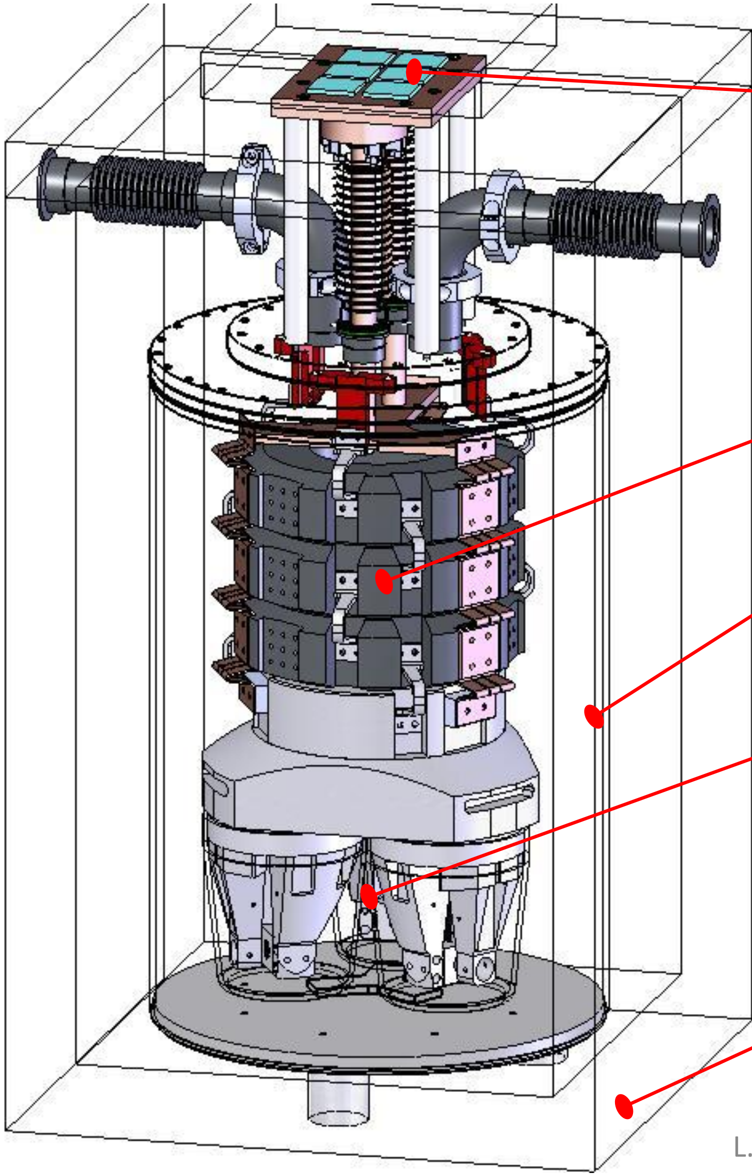
Aluminum Oscillator

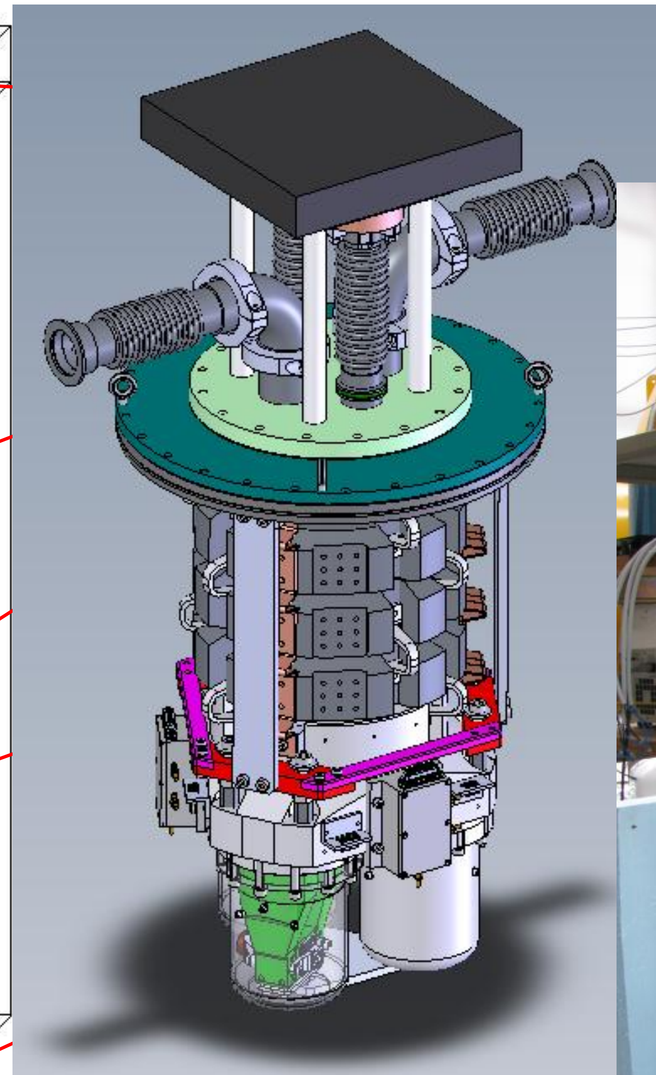


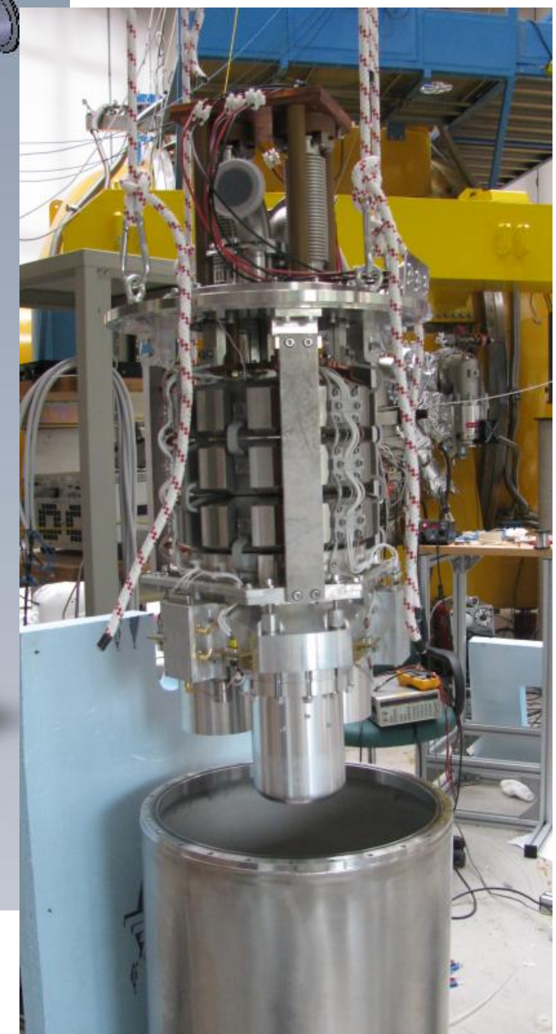


Silicon oscillator

Setup for room T campaign

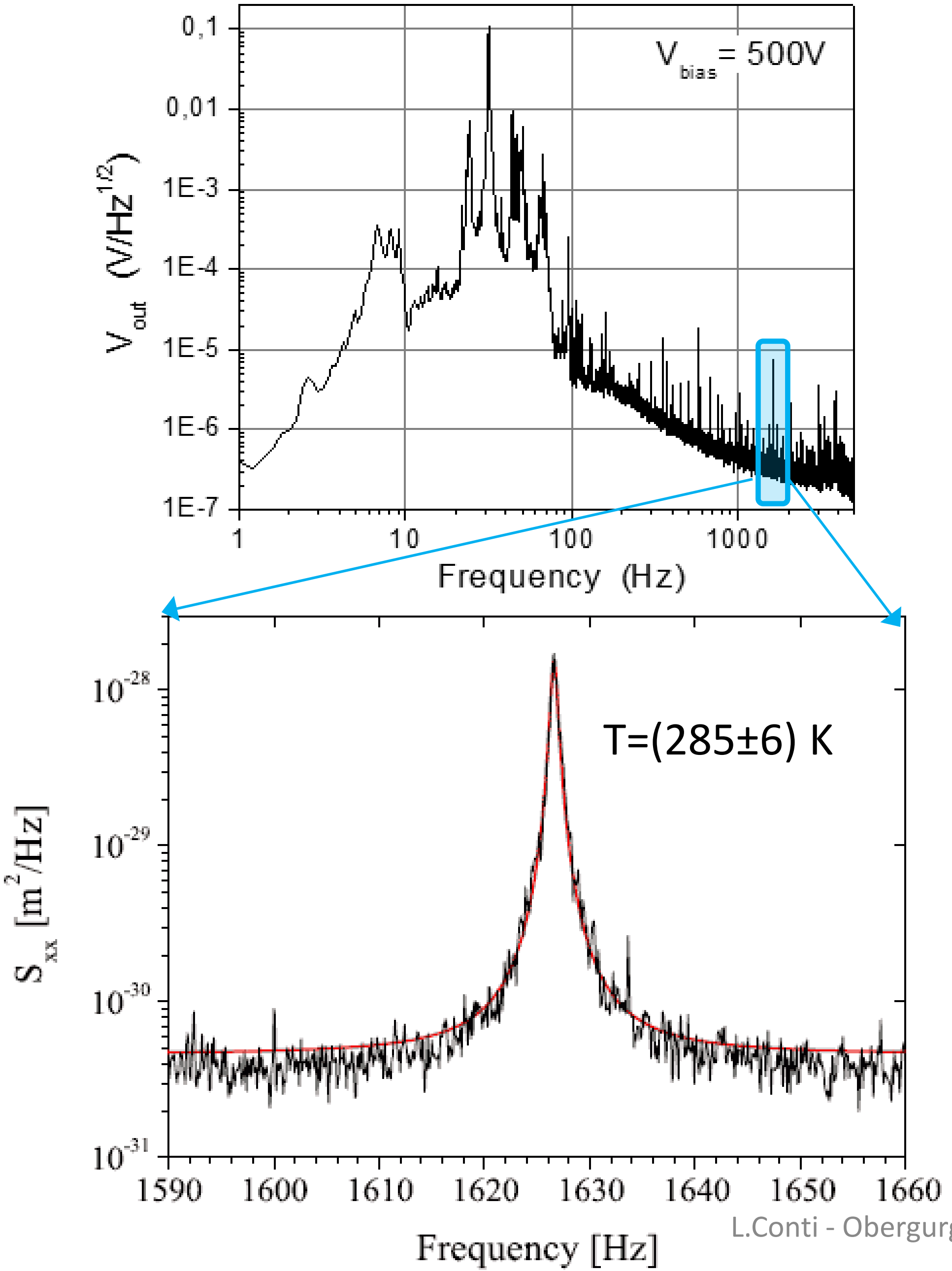






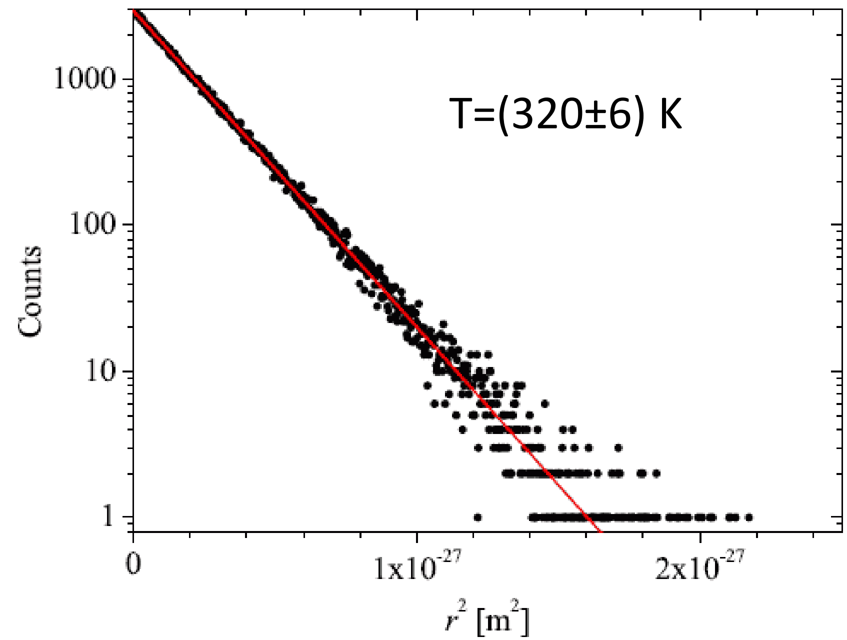
Equilibrium thermal noise measurements

Rev. Sci. Inst. 81, 035115 (2010)



0.2kg oscillator at 300K

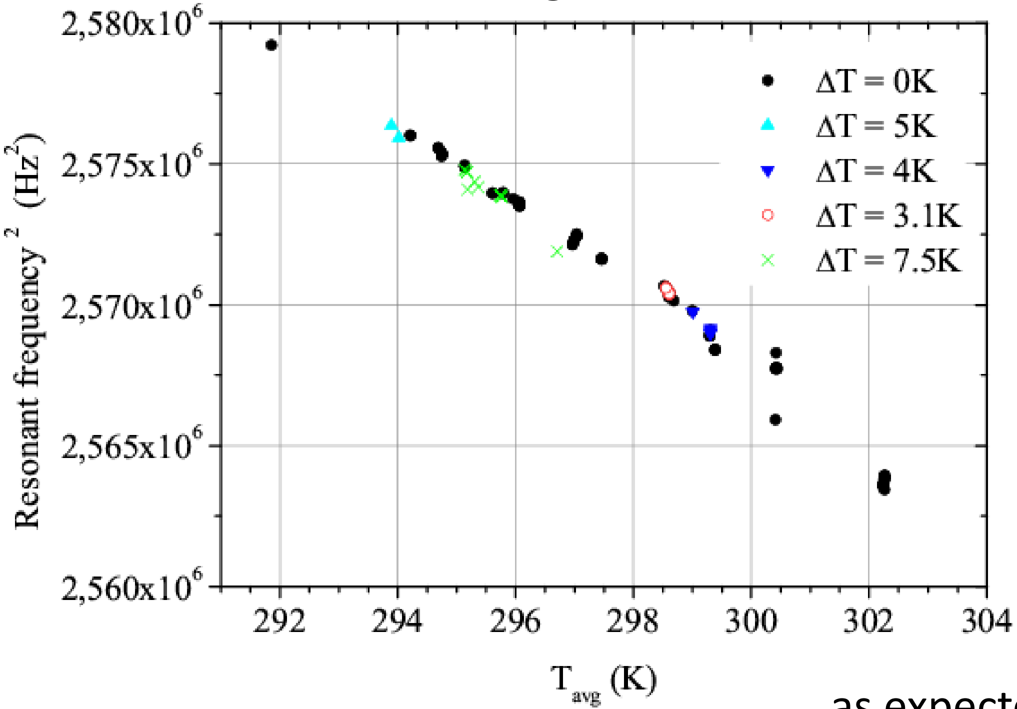
Histogram of data acquired in 7 hours:



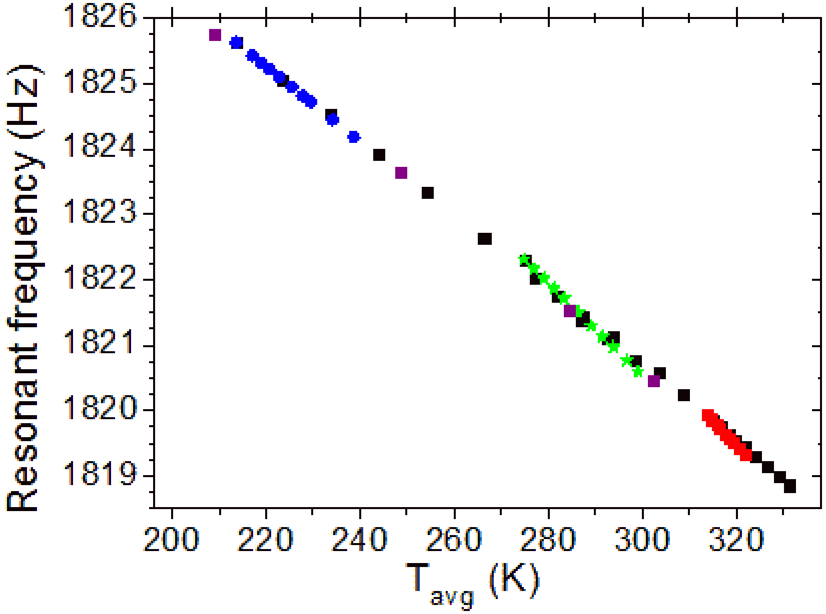
Thermal rms ~ $2 \times 10^{-14} m$

First NESS experimental results

Material: aluminum
≤0.3W through the oscillator



Material: silicon
≤0.4W through the oscillator



… as expected

We are now investigating the effect of the thermal gradient on the losses

In winter results on the statistics of oscillators in NESS

Summary

- introduction to Gravitational Wave detectors
- non-equilibrium issues in GW detectors
- experimental research plan
- oscillators (Al, Si) & experimental setup
- first experimental results

Acknowledgements:

The research leading to these results has received funding from the European Research Council under the European Community's Seventh Framework Programme (FP7/2007-2013) / ERC grant agreement n°~202680.