VIRGO

Strategies for Future Improvements of the GW Sensitivity

Fulvio Ricci

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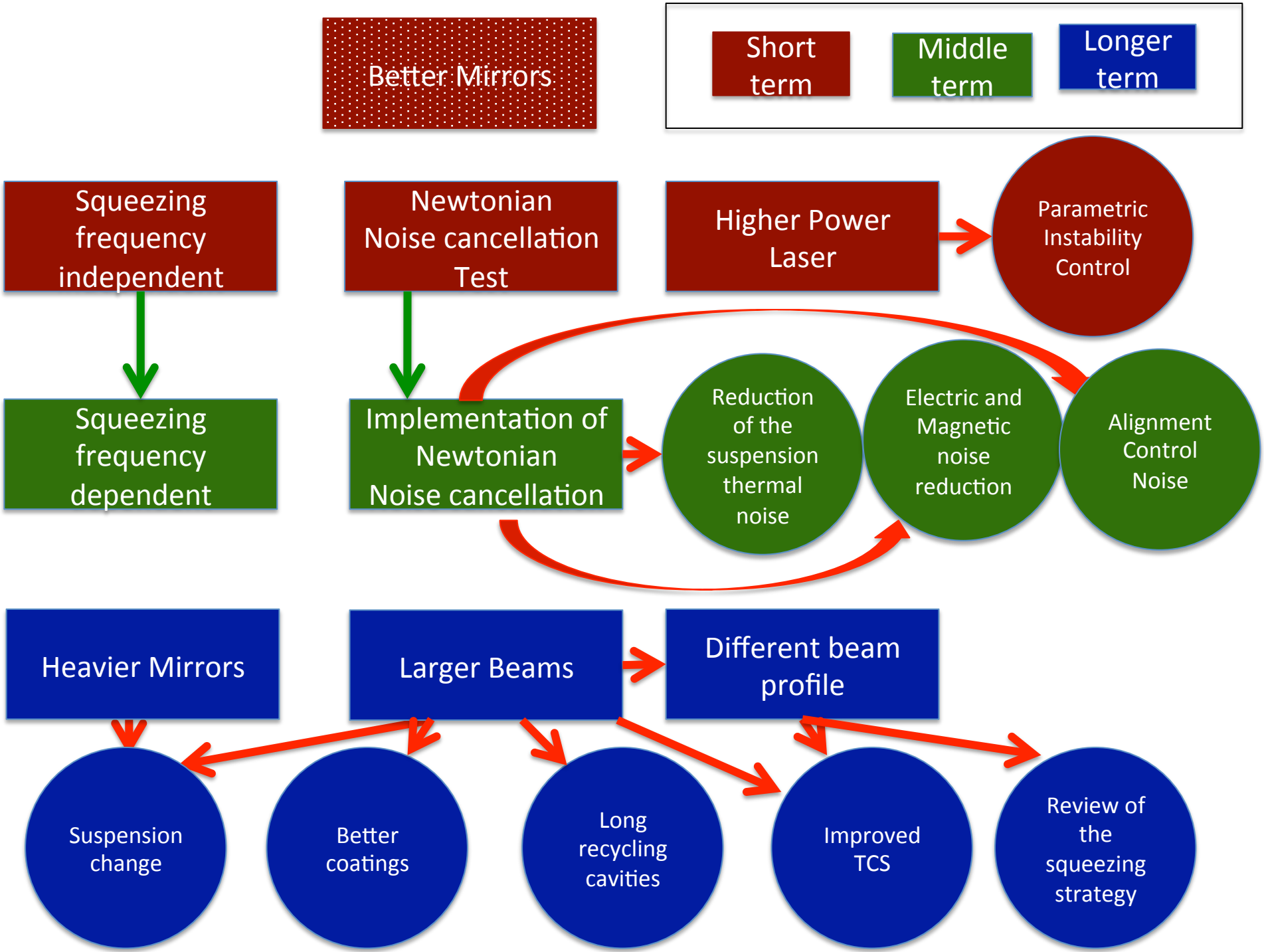
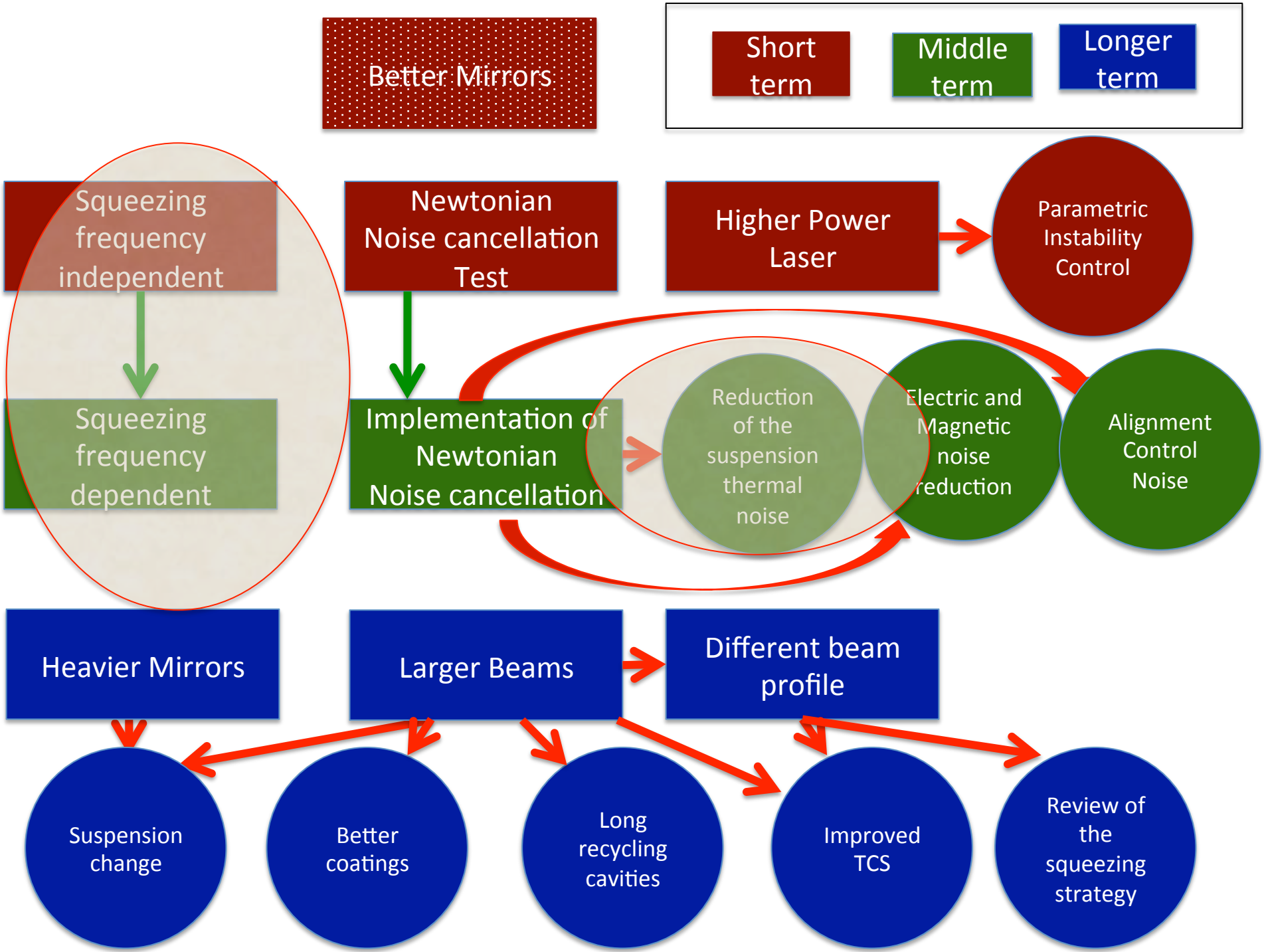

Better Mirrors
Short term
Middle term
Longer term
Squeezing frequency independent
Newtonian Noise cancellation Test
Higher Power Laser
Parametric Instability Control
Squeezing frequency dependent
Implementation of Newtonian Noise cancellation
Reduction of the suspension thermal noise
Electric and Magnetic noise reduction
Alignment Control Noise
Heavier Mirrors
Larger Beams
Different beam profile
Suspension change
Better coatings
Long recycling cavities
Improved TCS
Review of the squeezing strategy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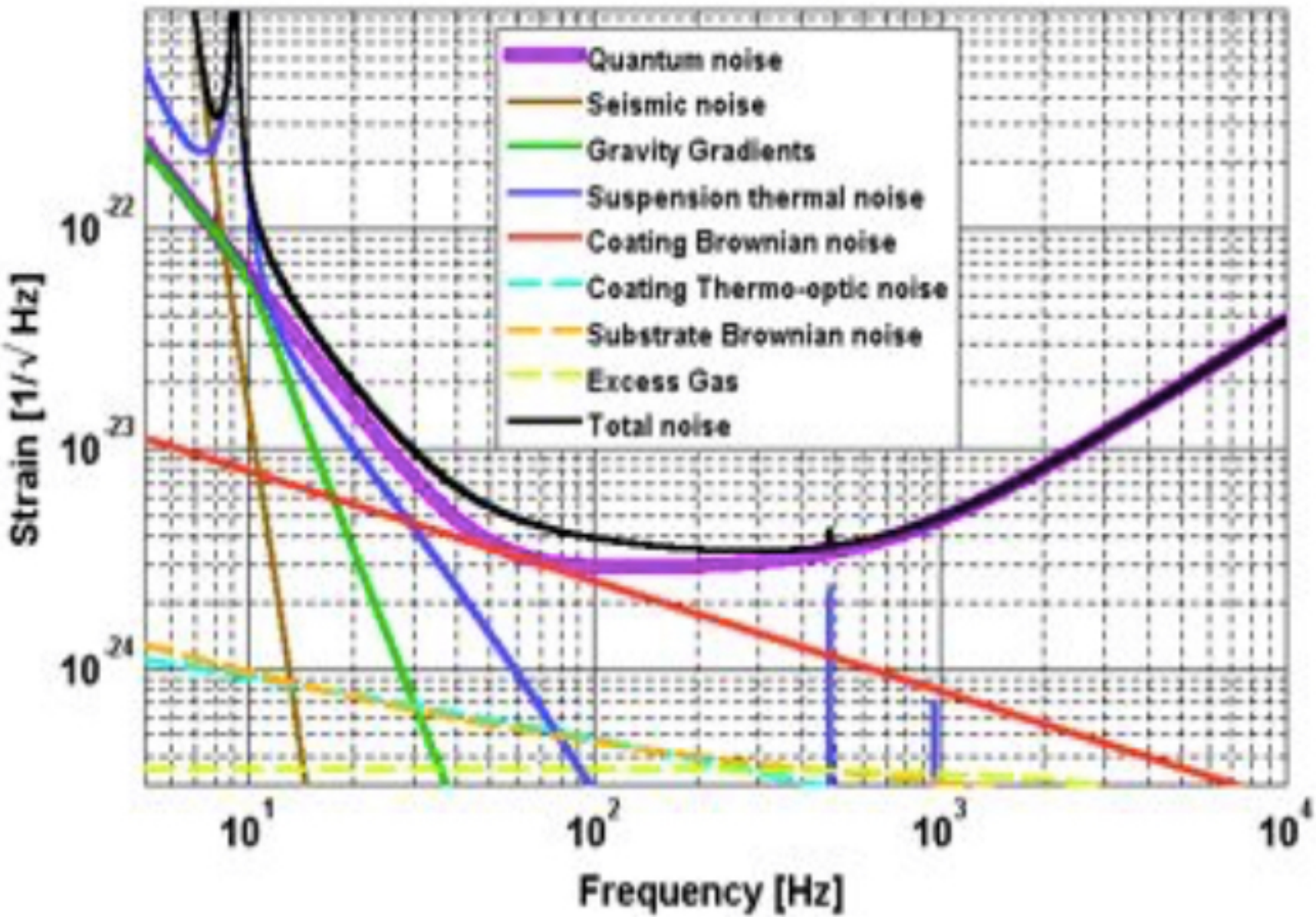
Advanced Detector sensitivity



To do better

- Circumvent the Quantum Noise ➔ squeezing

  and….

- Beat the thermal noise ➔better mirrors and cryogenics

Circumvent the Quantum Limit

credits to

Stephan Hilde

University of Glasgow

for several slides of this part of the talk

Squeezing Approach

- A bit of my personal history on the subject
- Introduction: basic on the GW ITF
- Squeezed states and modulation
- How to make squeezed light?
- Optical rigidity
  - What is an optical spring?
  - Optical Bar and Optical Lever schemes
  - Local Readout scheme for Advanced detectors
- Speed meter configurations

A bit of history: what do I remember

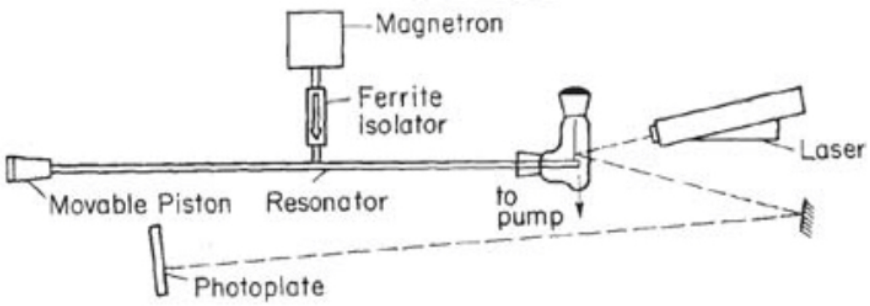
- Quantum-non-demolition' measurements are not a new topic, but it becomes more and more a hot topic, as the experimental realisation starts to come true

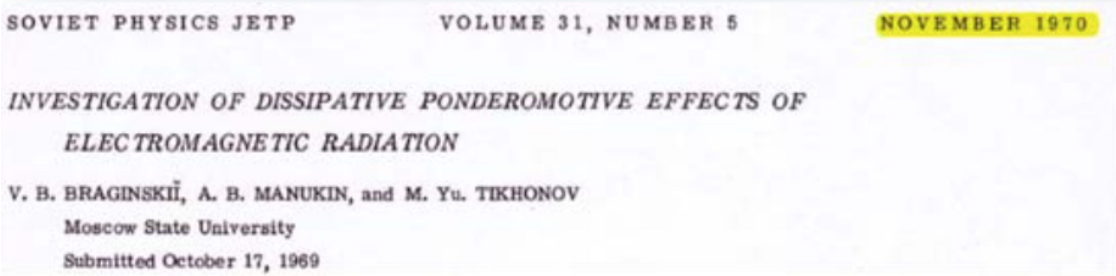
- Torsional pendulum and resonant bar experiments:
- 1970 the problem of the back action
  - First contribution of Vladimir Braginski

✓ *Torsional oscillator at the end of a microwave resonator*

✓ *Optical measurement of oscillations*

✓ *Observation of stiffness and damping changes under*





SOVIET PHYSICS JETP VOLUME 31, NUMBER 5 NOVEMBER 1970

INVESTIGATION OF DISSIPATIVE PONDEROMOTIVE EFFECTS OF ELECTROMAGNETIC RADIATION

V. B. BRAGINSKIĬ, A. B. MANUKIN, and M. Yu. TIKHONOV

Moscow State University

Submitted October 17, 1969

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$$H_{tot} = H_{system} + H_{interaction}$$

example $K\,\theta\,q$

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- ✓ *Optical measurement of oscillations*
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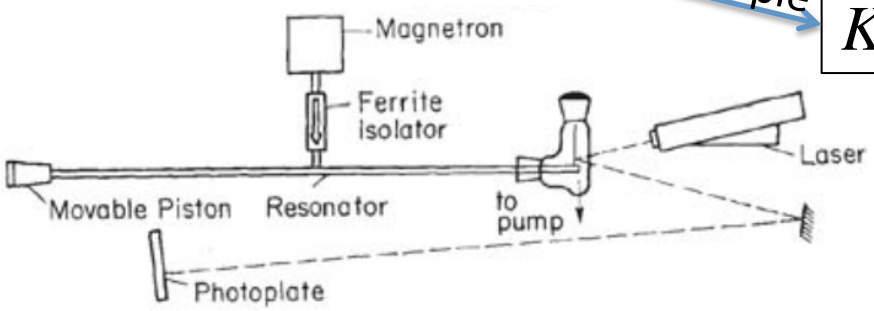

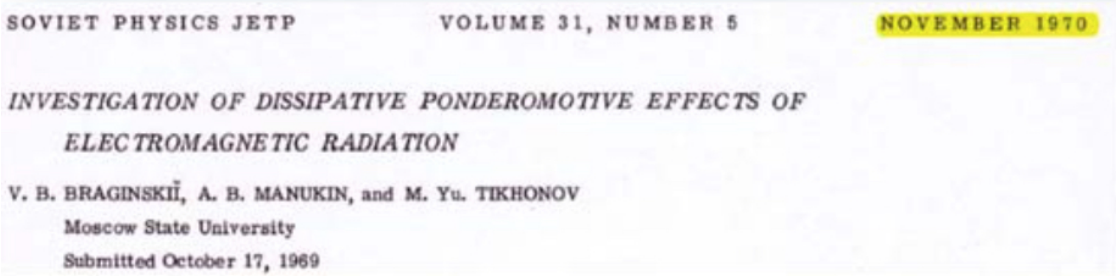

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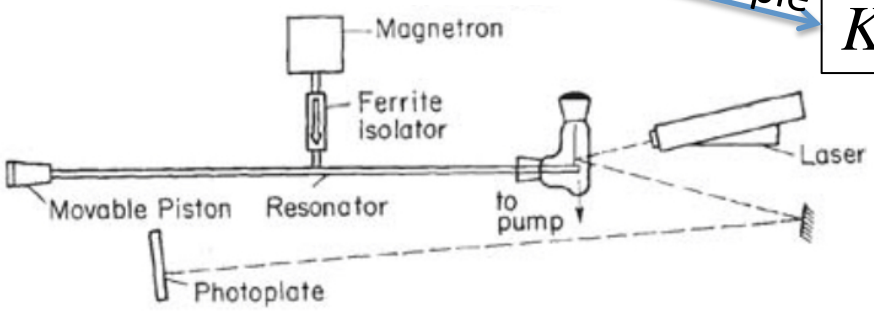
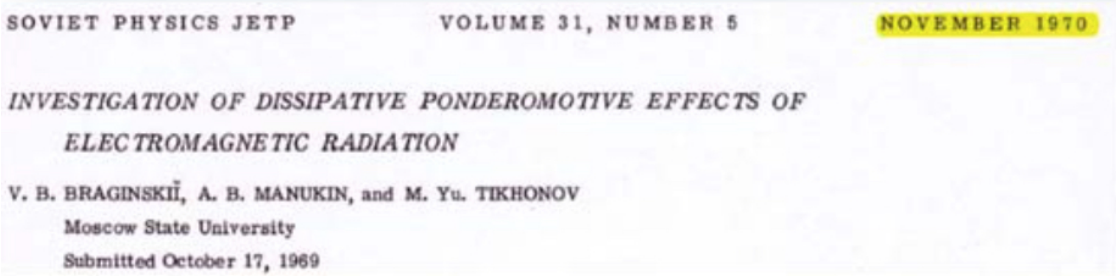
$$H_{tot} = H_{system} + H_{interaction}$$

Output variable

example $K\,x\,q$

- ✓ *Torsional oscillator at the end of a microwave resonator*
- ✓ *Optical measurement of oscillations*
- ✓ *Observation of stiffness and damping changes under*





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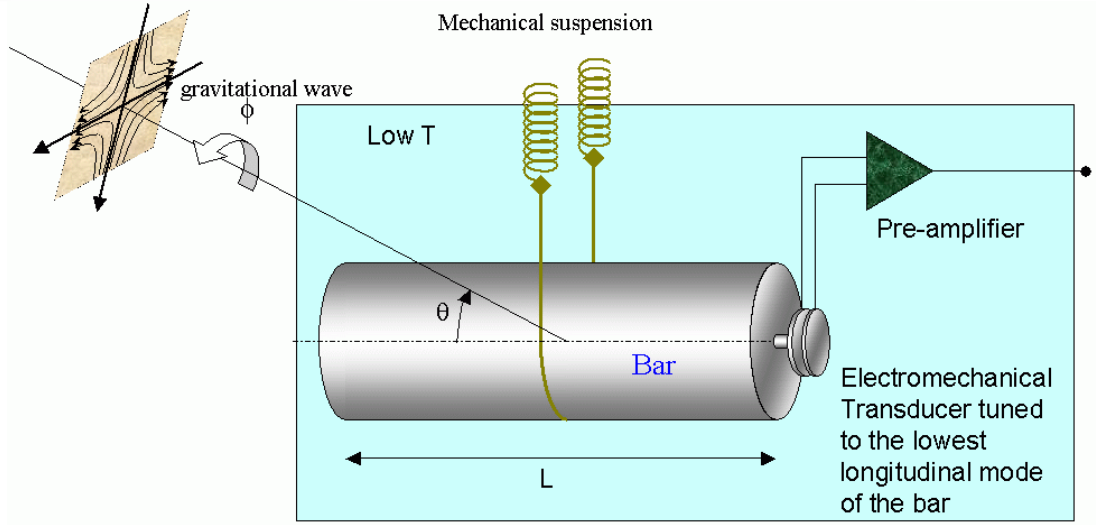
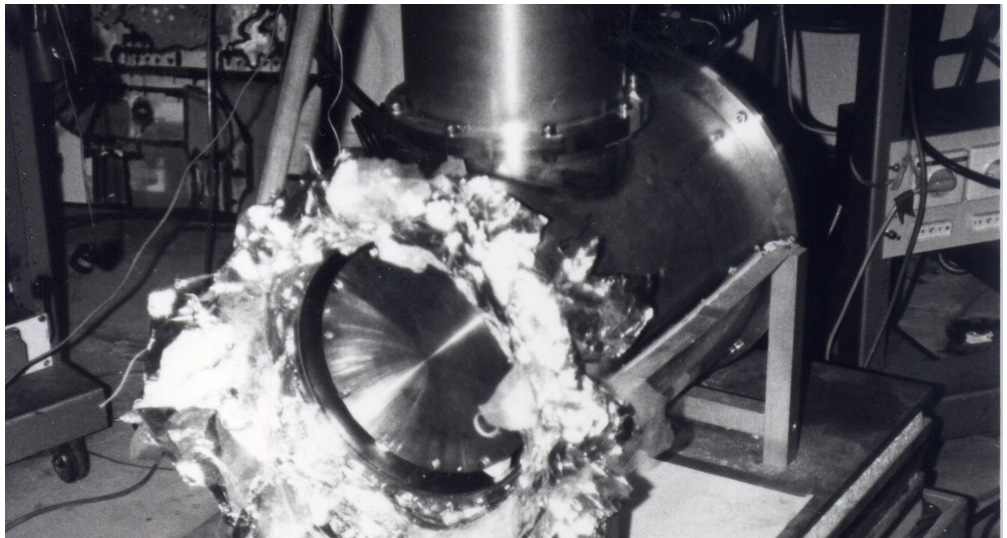
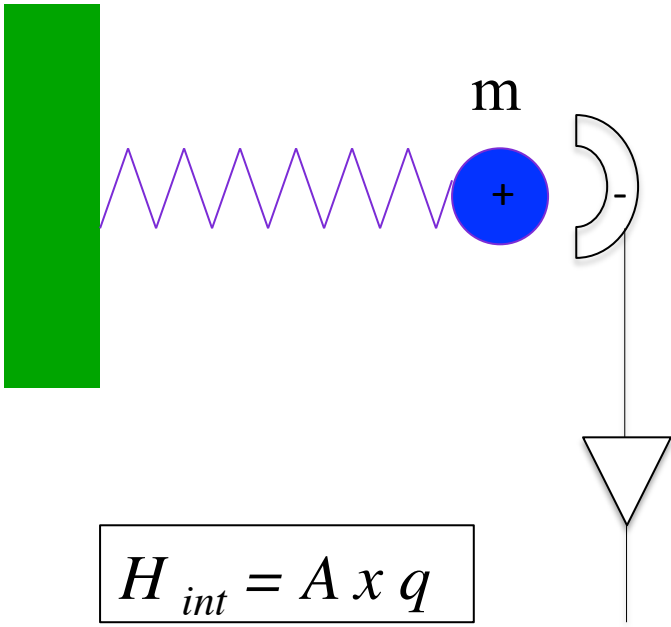
The resonant bars 1976-80







$$H_{int} = A\,x\,q$$

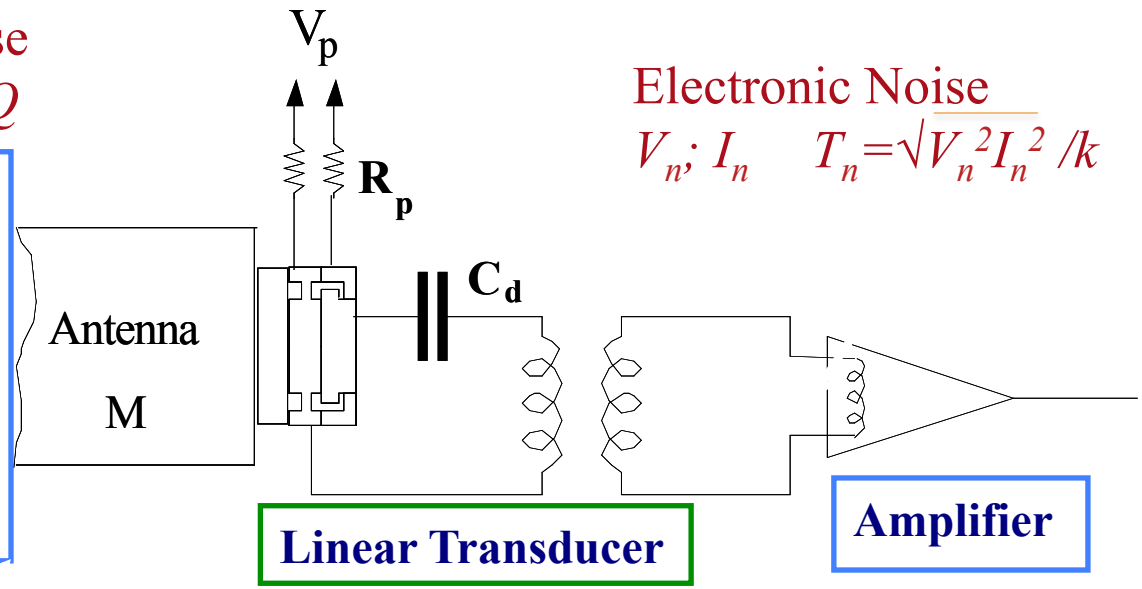
THE BACK ACTION

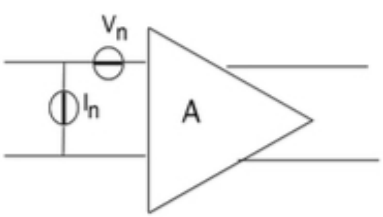
Thermal Noise
$S_F = MkT\omega_r/Q$

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

Mechanic oscillator

Mass **M**
Sound velocity $\mathbf{v_s}$
Temperature **T**
Merit Factor **Q**
Resonance frequency $\mathbf{f_r}$





Force $\rightarrow f(t) = Z_{11}\, x(t) + Z_{12}\, i(t)$

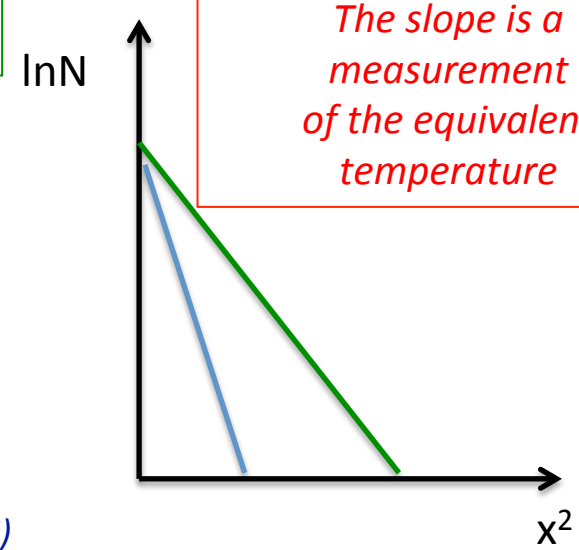
Velocity $\rightarrow v(t) = Z_{21}\, x(t) + Z_{22}\, i(t)$

$$S_{ff}^{(back-action)} = |Z_{12}|^2\, I_n^2$$

$$T_{equivalent} = T\left(1 + \frac{|Z_{12}|^2}{4mk_BT}\frac{I_n^2}{\Delta\nu}\right)$$

$N = A\, exp(-m\omega^2 x^2/k_B T_{eq})$

The slope is a measurement of the equivalent temperature



Quantum limit: Teff ~ 2T$_n$ $\rightarrow$ *R. Giffard Phys. Rev. D 14, 2378 (1976)*

Back action and Heisenberg Principle

Charge fluctuation

↓

Fluctuation of the force applied back to the monitored system

↓

Fluctuation of the momentum transferred to the oscillator Δp

↓

Error on Δp transferred to Δx via the time evolution of the system status

↓

Optimum measurement of the linear strategy of measurement

$$\Delta x \Delta p \geq \hbar$$

My bibliography

E. Barro, R. Onofrio, P. Rapagnani, F. Ricci: "Push pull resonant capacitive transducer for parametric measurements schemes on cryogenic gravitational wave antennas"; Proceeding of the International Symposium on "Experimental Gravitation", Guangzhou, China, 3 - 8 August 1987, P. F. Michelson editor, pag. 363, Word Scientific

C. Cinquegrana, E. Majorana, P. Rapagnani, F. Ricci: "Back-action-evading transducing scheme for cryogenic for gravitational wave antennas.", Physical Review D, 48, (1993), 448 – 465

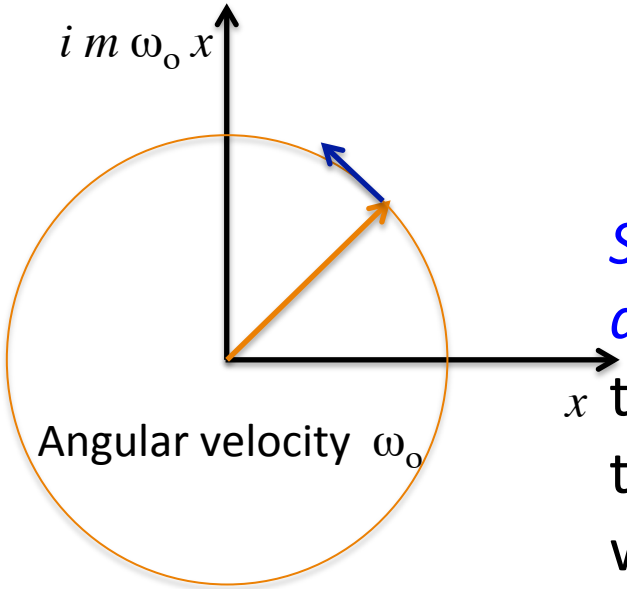
E. Majorana, N. Pergola, P. Puppo, P. Rapagnani, F. Ricci: "Observation of the Brownian motion of a mechanical oscillator by means of a Back Action Evading System", Physics Letters A, 180, (1993), 43-49

C. Cinquegrana, E. Majorana, N. Pergola, P. Puppo, P. Rapagnani, F. Ricci: "Signal-to-noise ratio analysis for a back action evading measurement on a double harmonic oscillator", Physical Review D, 50, (1994), 3596-3607

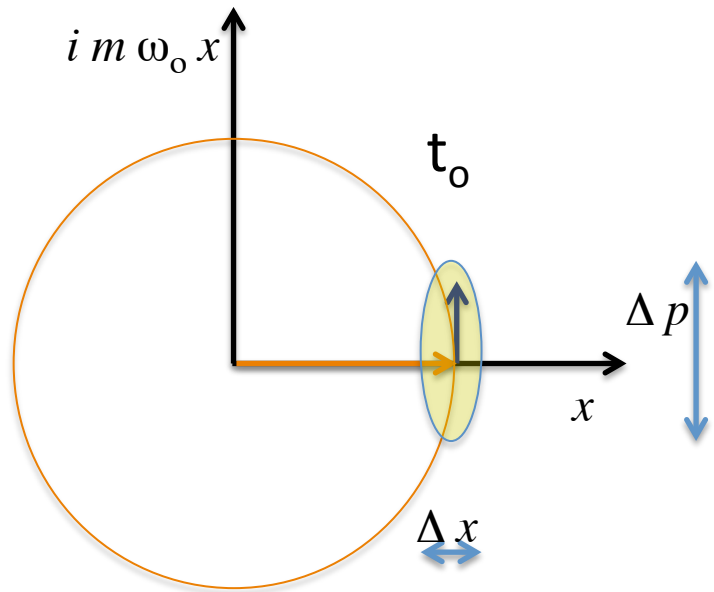
P.Bonifazi, C. Cinquegrana, E. Majorana, N. Pergola, P.Puppo, P. Rapagnani, F. Ricci, S. Vaselli, M. Visco: "Test of a Back Action Evading scheme on a cryogenic gravitational wave antenna.", Physics Letters A 215, 141-148, (1996)

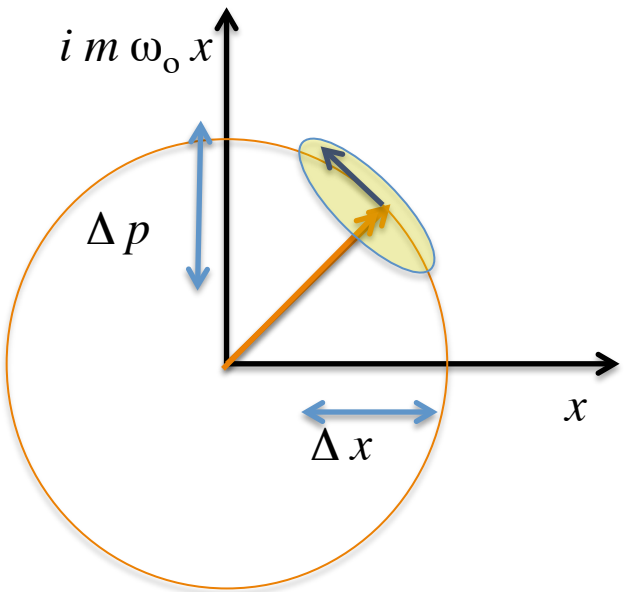
E. Majorana, P. Puppo, P. Rapagnani, F. Ricci,: "A macroscopic mechanical oscillator at the quantum limit level: a practical scheme." In Dark Matter in Cosmology, Quantum Measurements and Experimental Gravitation, 1996, Ansari R. Giraud-Heraud, Tran Thanh Van J. editors, pag. 289-292, Editions Frontieres

Mechanical oscillator in the phase plane

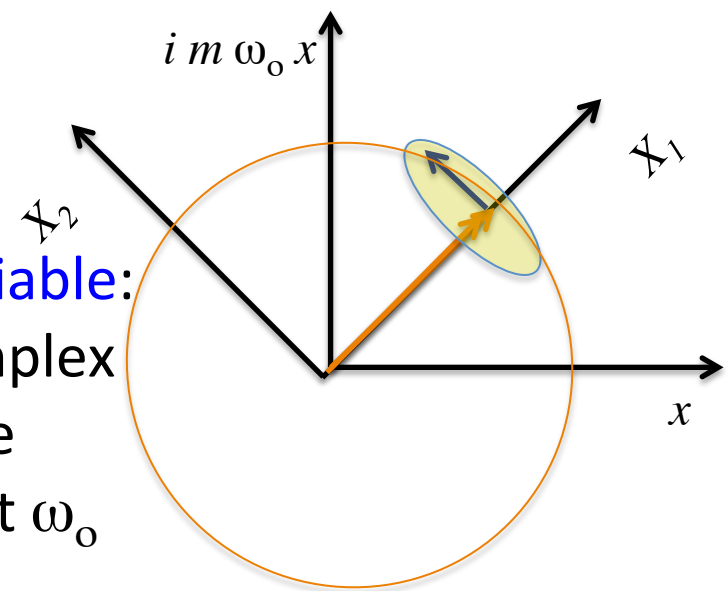


Stroboscopic approach: data taken just at $t_i = t_o + n\,(\pi/\omega_o)$ with $n=0,1\ldots N$



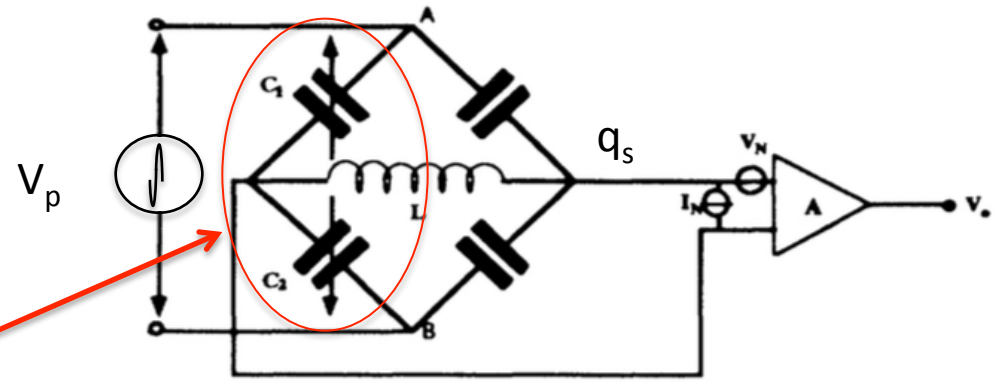


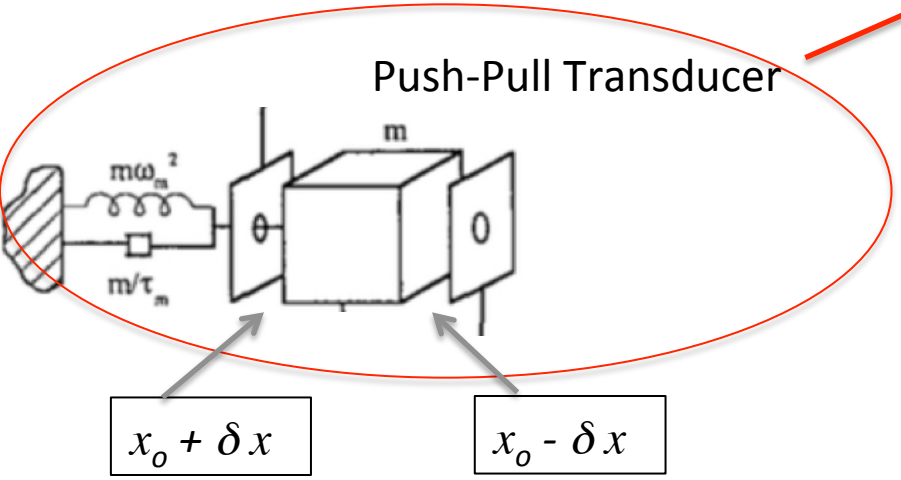
Continuous measurements of a different variable: X_1 or X_2 the complex amplitudes of the frame, rotating at ω_o



B.A.E. Practical Implementation

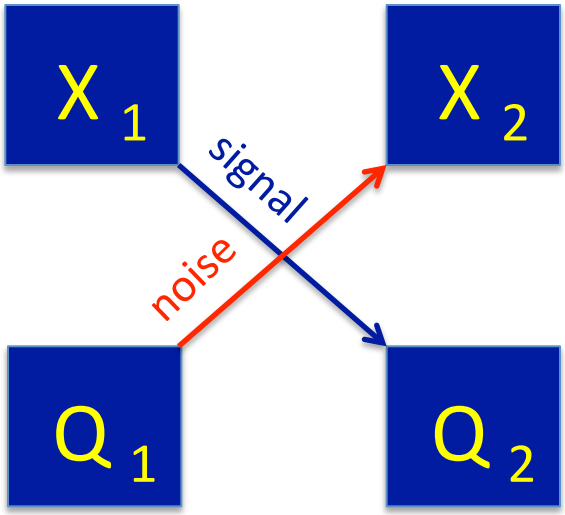
- The oscillator mass is inserted between two metallic plates and form a double capacitance.





Two arms both sensitive to the signal !

V_p ➔ Laser *Two arms ➔ Michelson ITF*



Back to the GW Interferometer

- We assume that the test masses are very quiet (quieter than the signal we want detect).
- We need to read out the test mass positions with very high accuracy, without introducing 'too much' noise due to measurement itself.

- Photon shot noise is the sensing noise (x monitor),
- Photon radiation pressure noise is the back-action-noise (inducing p fluctuation)

The Standard Quantum Limit

- Standard Quantum Limit of a free mass is equivalent to Heisenberg uncertainty.

- Arises when one tries to detect gravitational wave by continuously measuring free-mass displacement, since

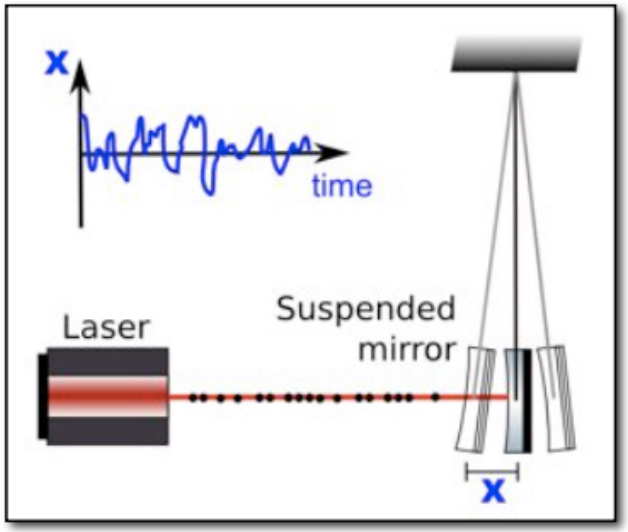
$$[\hat{x}(t), \hat{x}(t')] \neq 0$$

- Precise measurement on x has to perturb p. Perturbation in p converts to future error in x.

- In this case: Light fields enforce Heisenberg uncertainty through complementarity between Shot noise and Radiation Pressure noise.

Poisson statistics

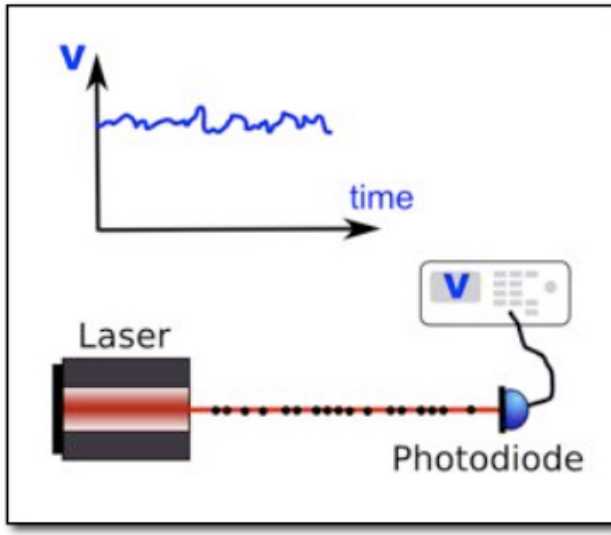
- Quantum noise is comprised of **photon shot noise** at high frequencies and **photon radiation pressure noise** at low frequencies.
- The photons in a laser beam are not equally distributed, but follow a Poisson statistic.



$$h_{\mathrm{sn}}(f) = \frac{1}{L}\sqrt{\frac{\hbar c \lambda}{2\pi P}}$$

$$h_{\mathrm{rp}}(f) = \frac{1}{m f^2 L}\sqrt{\frac{\hbar P}{2\pi^3 c \lambda}}$$

wavelength
optical power
Arm length
Mirror mass



photon radiation pressure noise

photon shot noise

Standard Quantum Limit

While shot noise contribution decreases with optical power, radiation pressure level increases:

wavelength

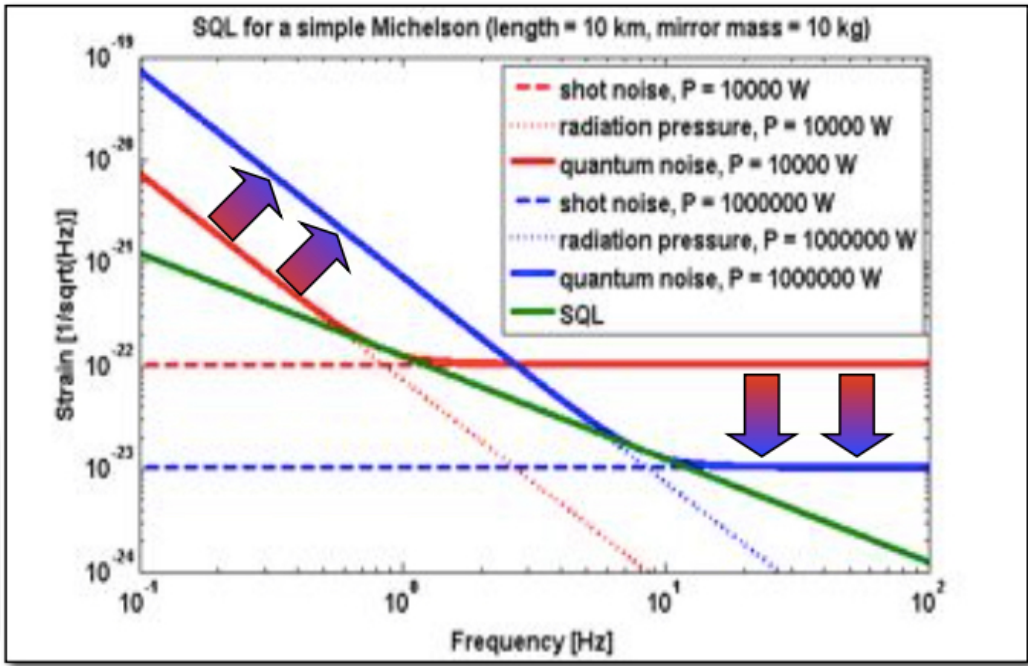
$$h_{\mathrm{sn}}(f) = \frac{1}{L}\sqrt{\frac{\hbar c \lambda}{2\pi P}}$$

optical power

Arm length

Mirror mass

$$h_{\mathrm{rp}}(f) = \frac{1}{m f^2 L}\sqrt{\frac{\hbar P}{2\pi^3 c \lambda}}$$



- The SQL is the minimal sum of shot noise and radiation pressure noise
- Using a classical quantum measurement the SQL represents the lowest achievable noise V.B. Braginsky and F.Y. Khalili: Rev. Mod. Phys. 68 (1996)

A bit of Mathematics (I)

The electric field:

$$\boldsymbol{E}(t)=E_o[a(\boldsymbol{r})\, e^{i\,\omega\, t} - a^*(\boldsymbol{r})\, e^{-i\,\omega\, t}]\; \boldsymbol{p}(r)$$ polarization

where

Complex amplitude $a(\boldsymbol{r}) = a_o\, e^{i\,\phi(\boldsymbol{r})}$ phase

We introduce new variables

$$X_1(r) = a^*(r) + a(r)$$ Amplitude quadrature

$$X_2(r) = i\,[\,a^*(r) - a(r)]$$ Phase quadrature

$$\boldsymbol{E}(t)=E_o[X_1(\boldsymbol{r})\cos\omega\, t - X_2(\boldsymbol{r})\sin\omega\, t\,]\;\boldsymbol{p}(r)$$

Quantum fields

$$\hat{X}_1 = \hat{a}^+ + \hat{a}$$ Amplitude quadrature operator

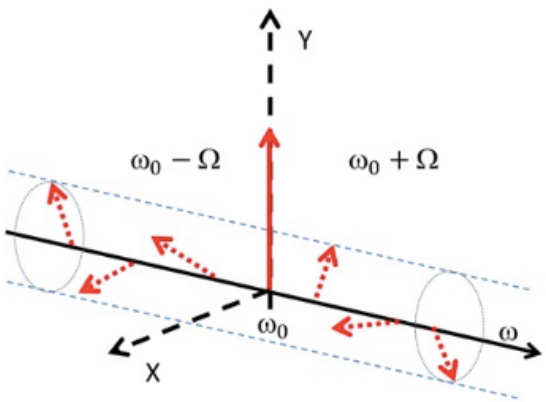
$$\hat{X}_2 = i[\hat{a}^+ - \hat{a}]$$ Phase quadrature operator

Quantum noise and random modulation

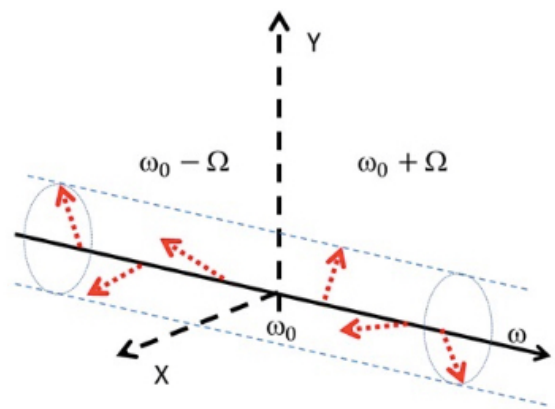
- *Quantum noise can be seen also as a continuum of sidebands spanning all frequencies due to the beating between the carrier and the vacuum fluctuations*

- Thus, these sidebands are uncorrelated and have white amplitude and phase noise

- <u>If uncorrelated amplitude and phase quadratures have the same noise distribution</u>



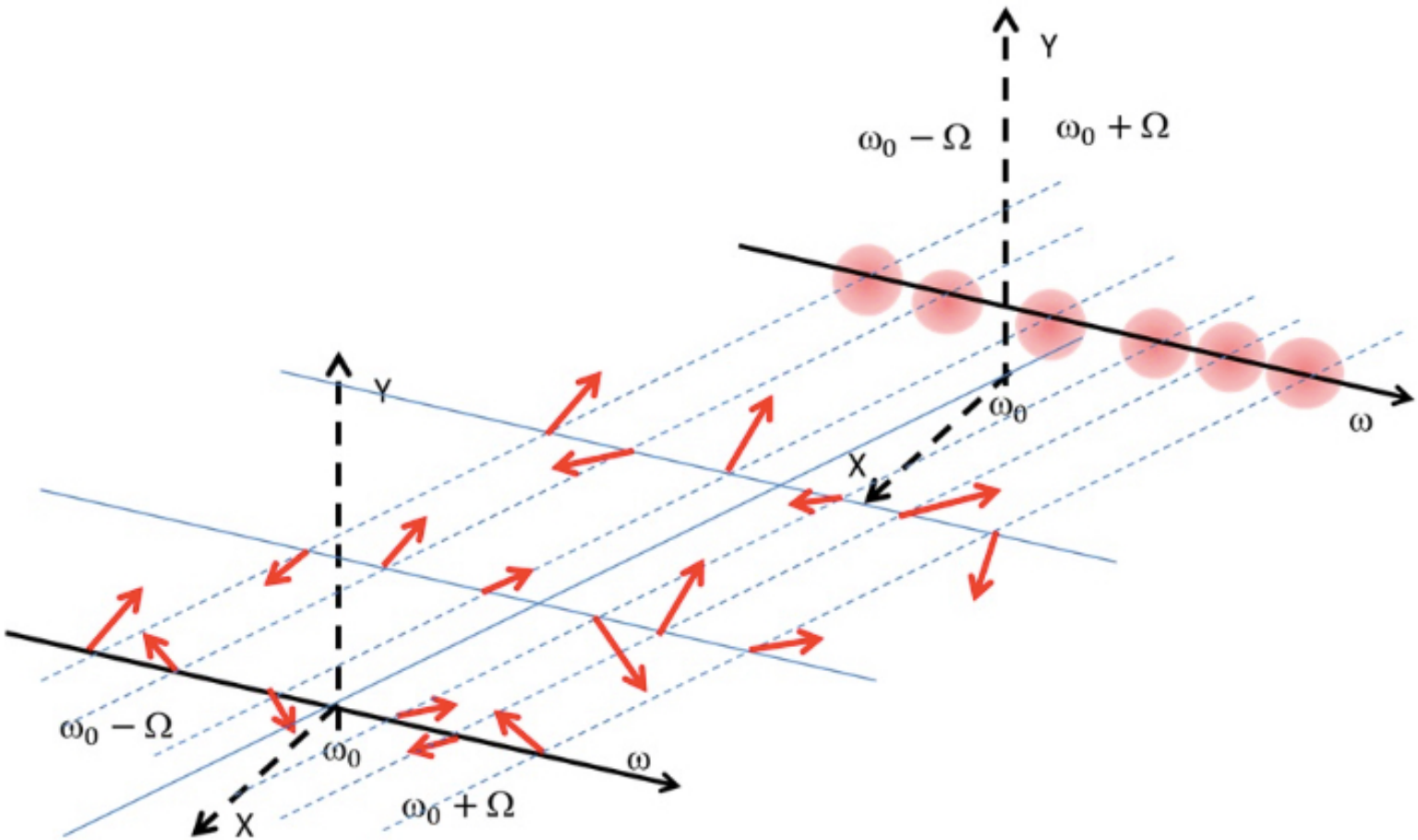
Coherent state



Vacuum state

<u>Squeezing process introduce a certain level of correlation between randomly fluctuating upper and lower sideband pairs</u>

Phasor diagram & Random Noise

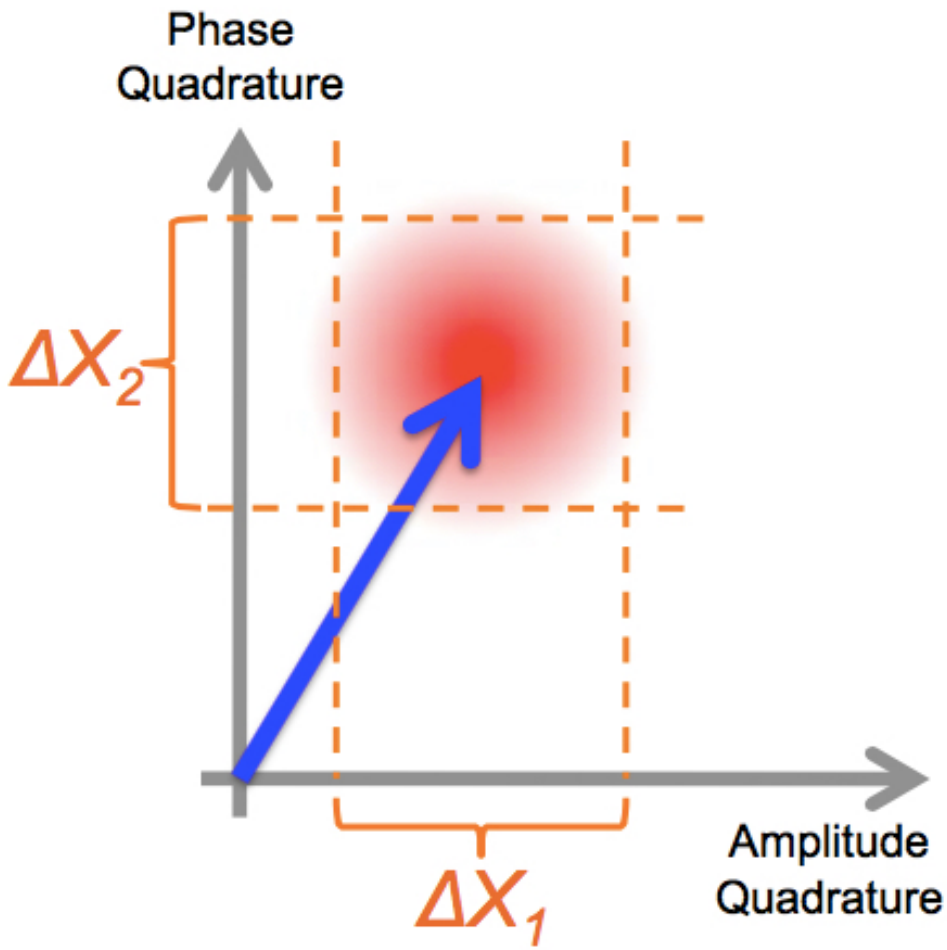


At each frequency $\omega_o \pm \Omega \quad \forall \quad \Omega$, there is a quantum mechanical oscillator that oscillates in amplitude and phase quadratures.
The time average of each sidebands is a two dimensional Gaussian distribution in phase space.

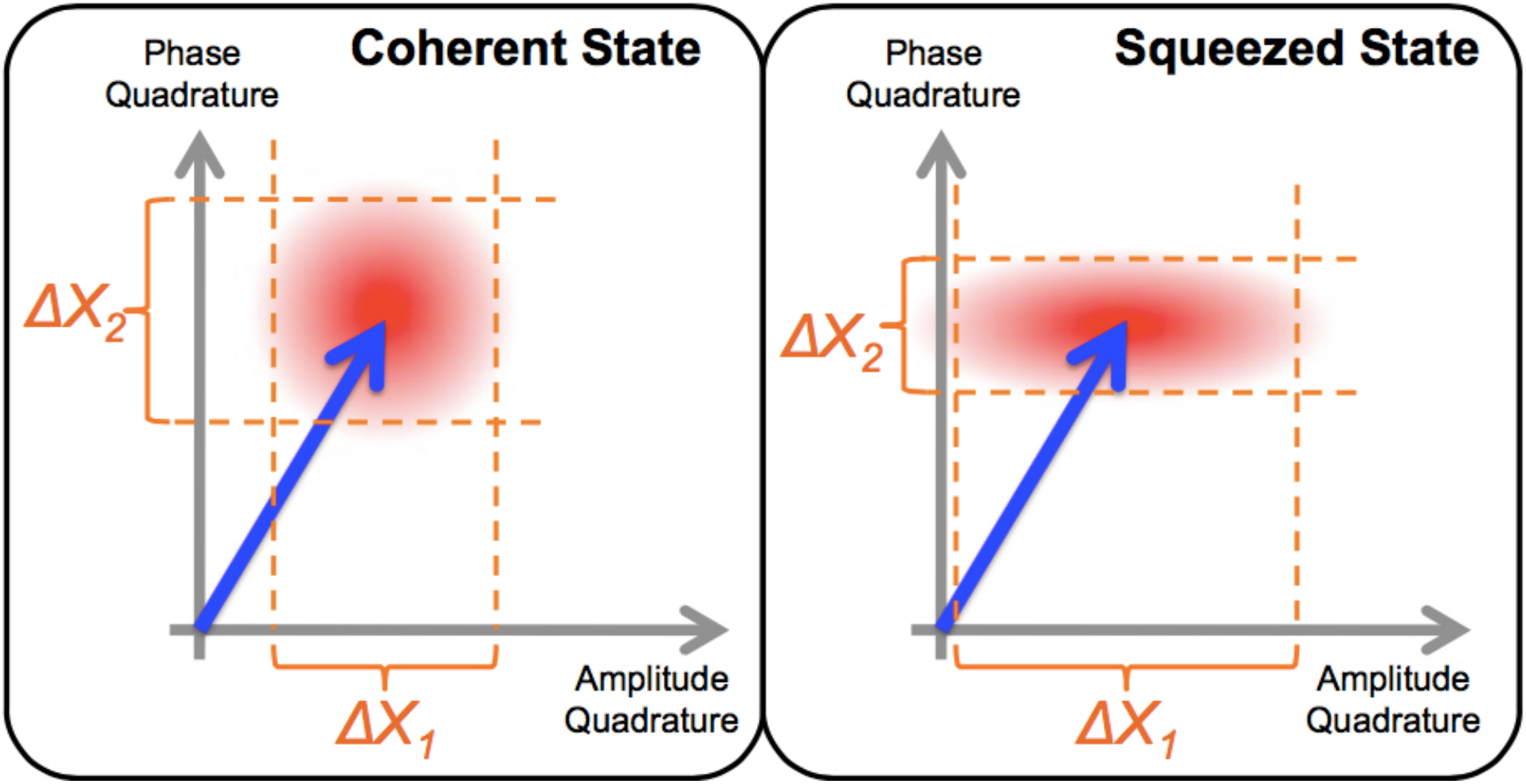
Light phase plane

- A laser sends out light with an average frequency and amplitude➔ the blue arrow

- Individual photons have a uncertainty, i.e. may have *slightly different frequency or amplitude* => this is indicated by the red ball.



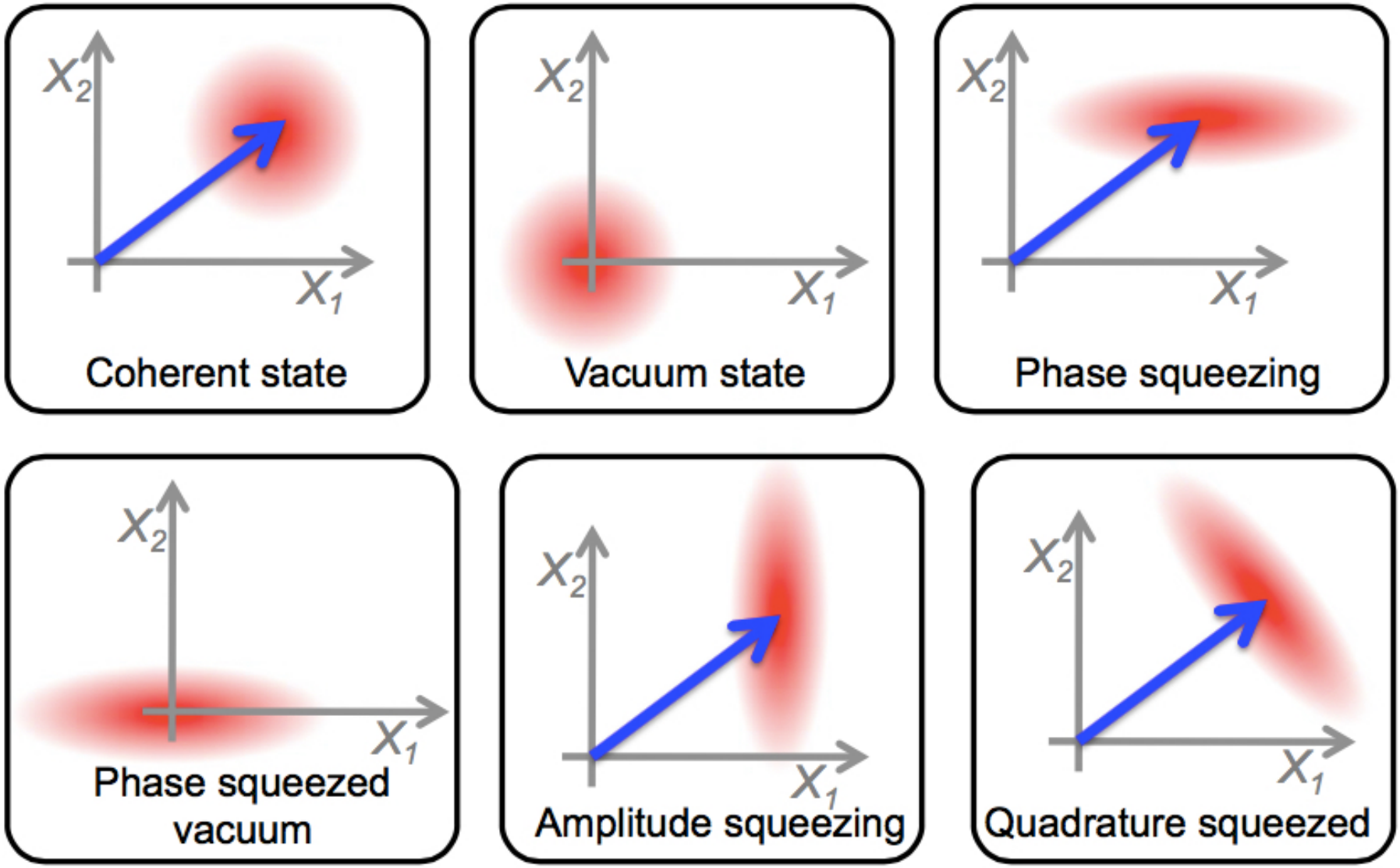
Squeezed state



Heisenberg uncertainty principle: there is a minimal area of the spot

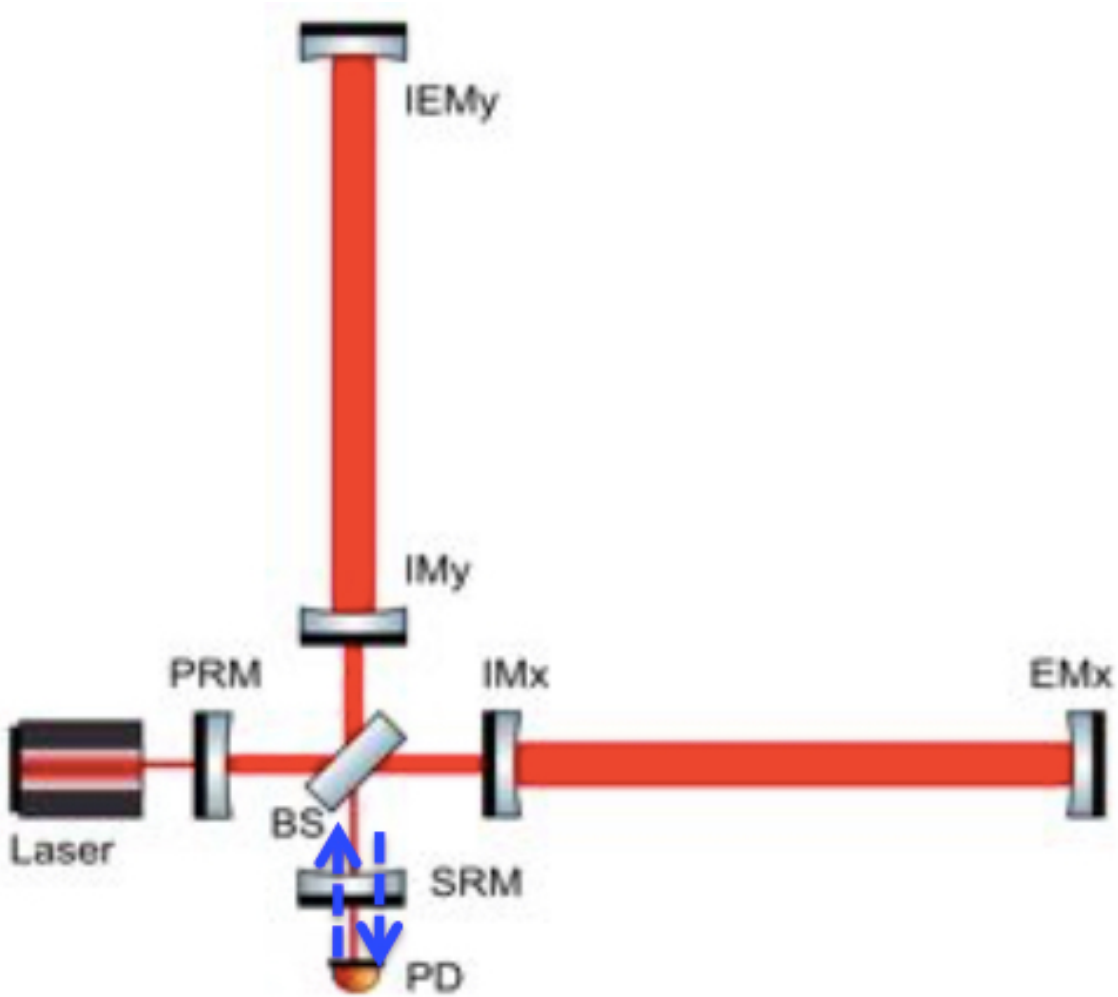
$$\Delta X_1 \; \Delta X_2 \geq 1$$

Examples of Light States



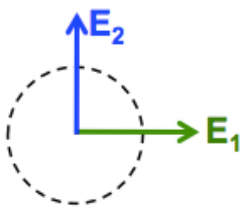
Light noise at ITF detection port: vacuum state

- ITF on the dark fringe
- A vacuum state *(fluctuation of the e.m. field)* is entering the interferometer from the output photodiode (anti-simmetric port, i.e. detection port).
- It is then reflected from the interferometer and it is detected together with the GW signal on the main photodiode.



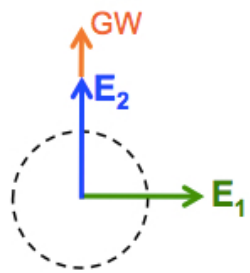
GW signal in phase plane

Shot noise shows up in both quadratures

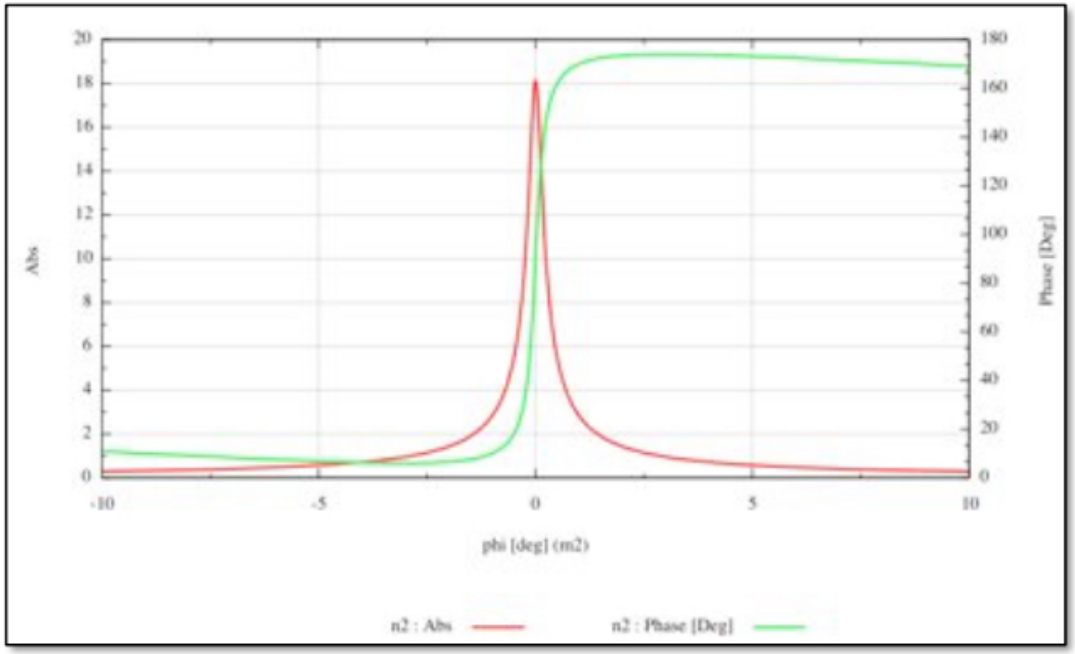


No correlations

GW signal shows up in phase quadrature



No correlations



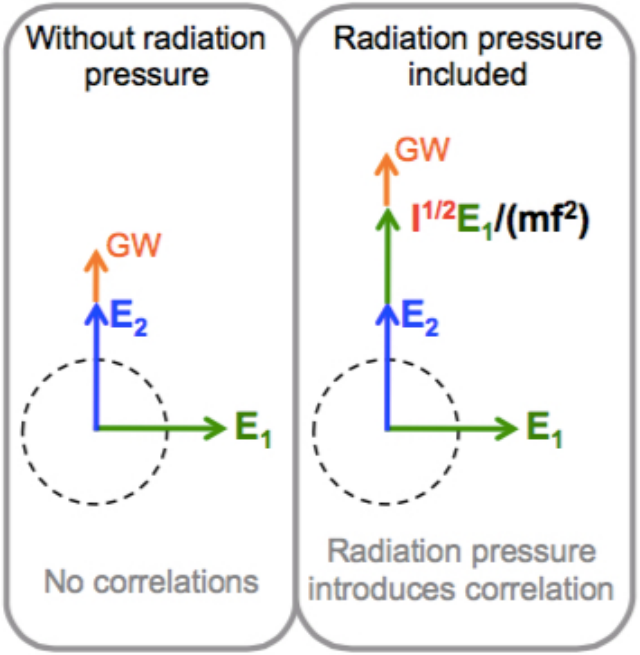
Change the length of a cavity around its resonance:

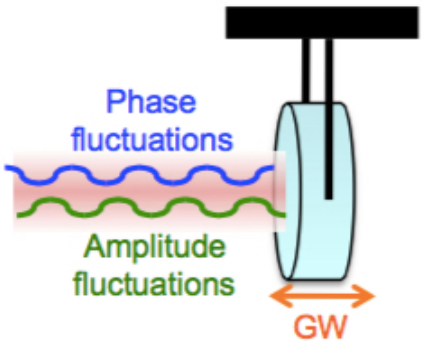
- slope of the amplitude is zero
- slope of the phase is maximal.

GW signal adds to phase quadrature

Radiation pressure noise and GW

Amplitude fluctuations act onto suspended mirror.
Mirror is moved and gives contribution in the phase quadrature.



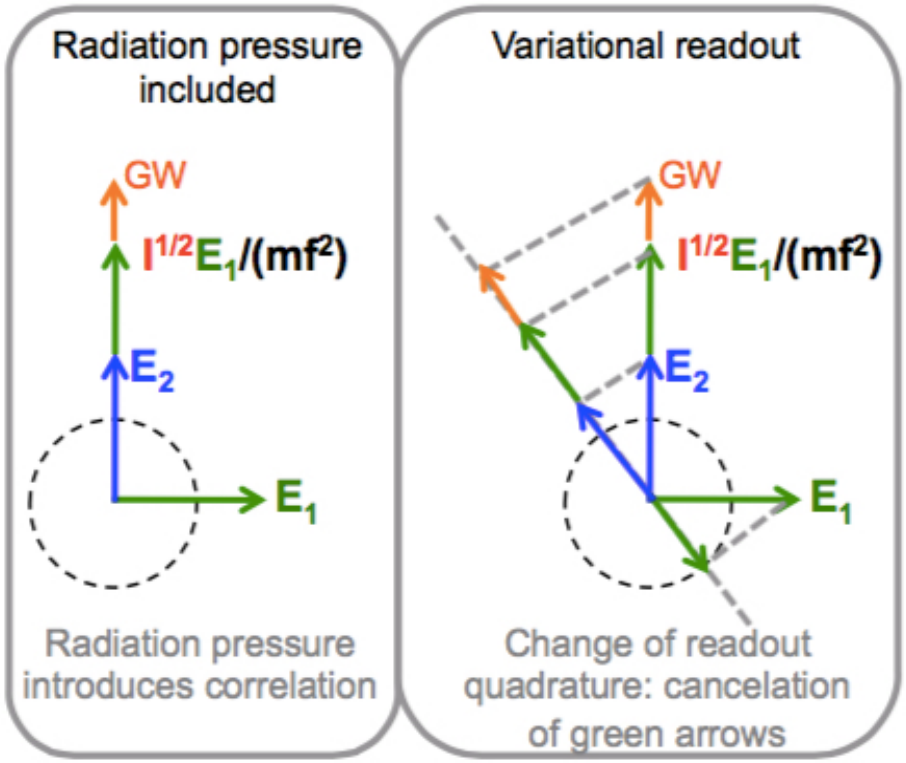


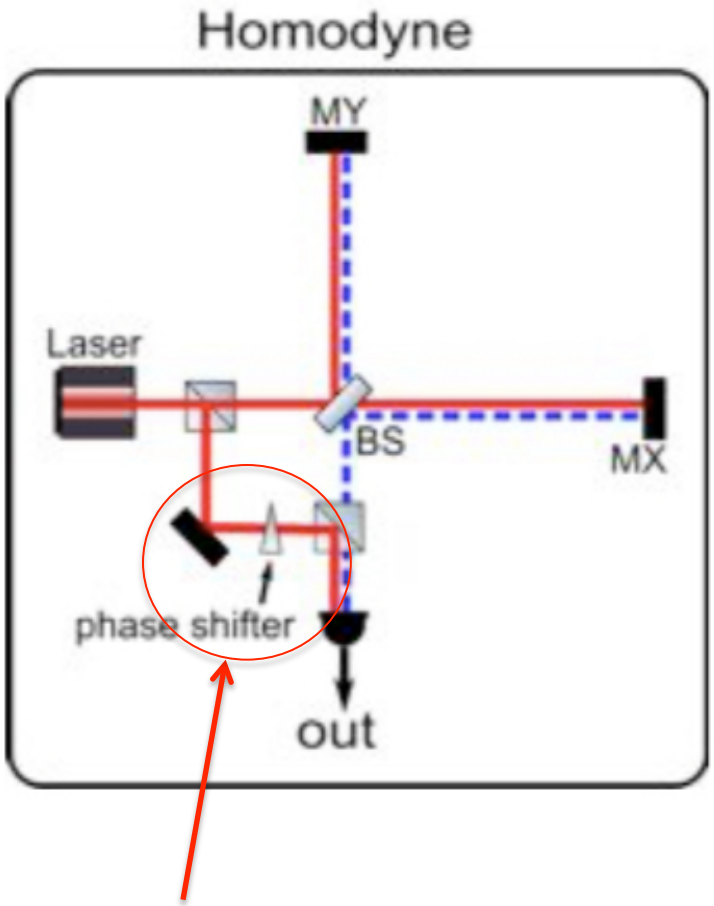
Pressure noise contribution

- *is correlated to E1*
- depends on the mirror mass
- Its magnitude goes with $1/f^2$ ➔ *No contribution at higher frequencies*

Strategies to beat the Quantum Limit (I)

Variational Readout -------- tested at AEI

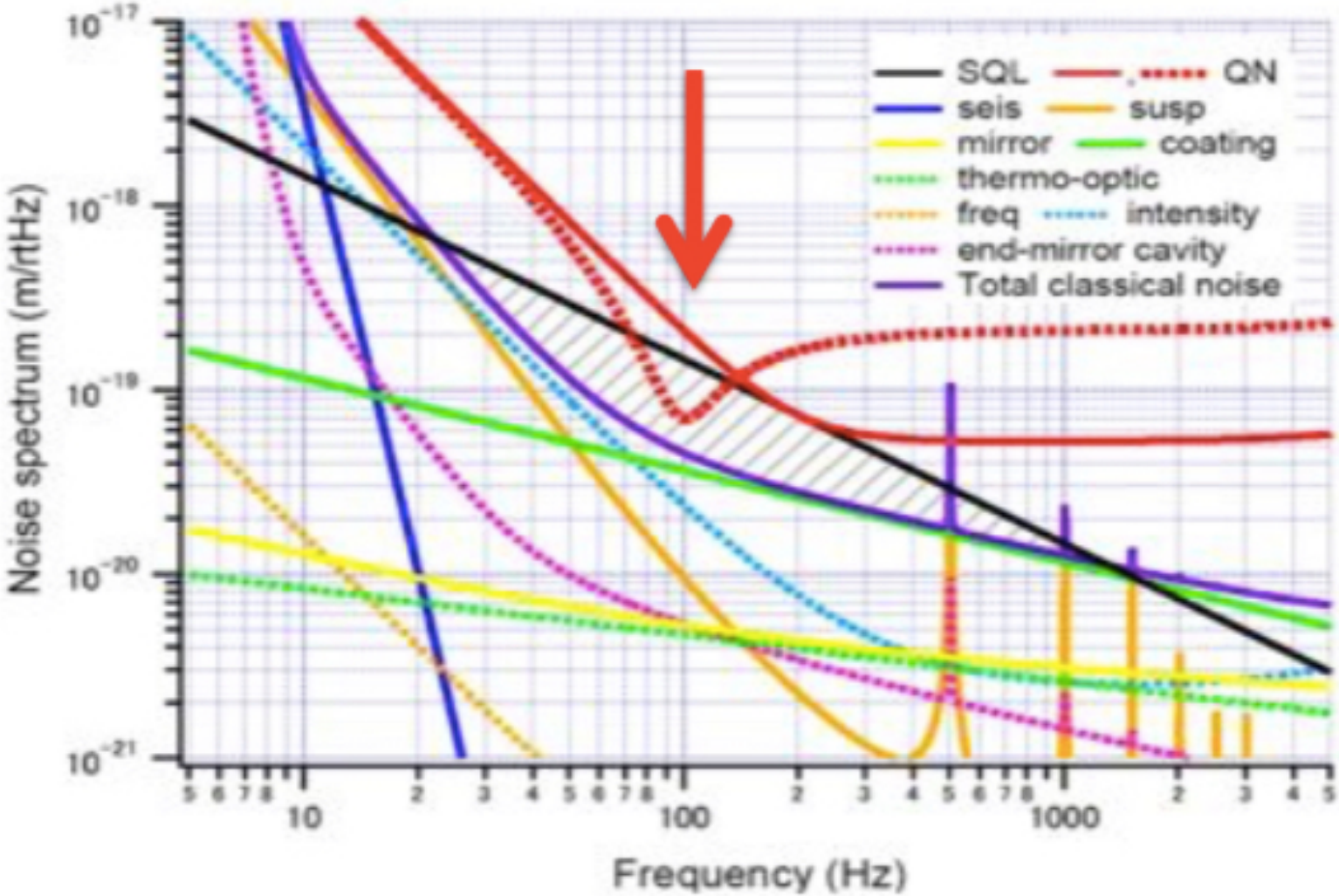




Partial cancellation of the radiation pressure noise by selecting the appropriate readout quadrature

Readout quadrature chosen by phase shifter

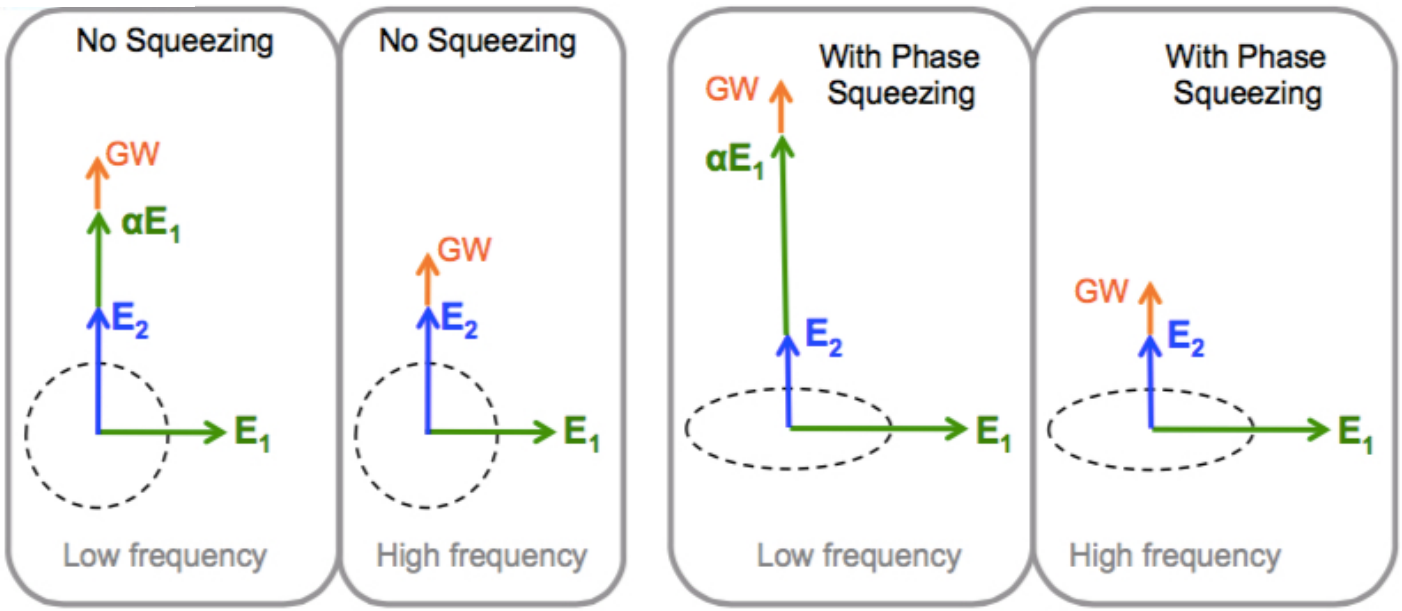
Effect of the variational readout

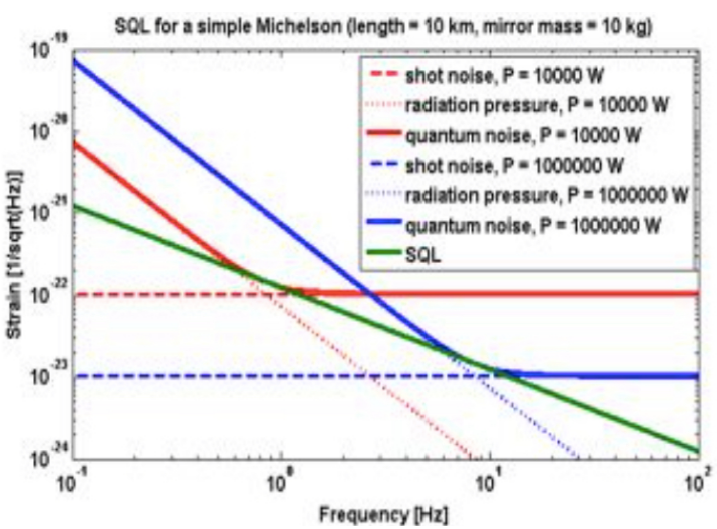


Using *variational readout*, we will be able to completely cancel the radiation pressure noise at **ONE** frequency (100Hz) and surpass the SQL a factor 2 to 3

Strategies to beat the Quantum Limit (II)

Squeezed vacuum injection



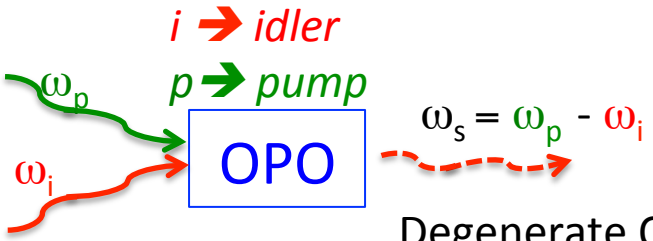


Injecting *phase squeezing* into detector output:

- High frequency sensitivity improved ↑
- Low frequency sensitivity decreased ↓

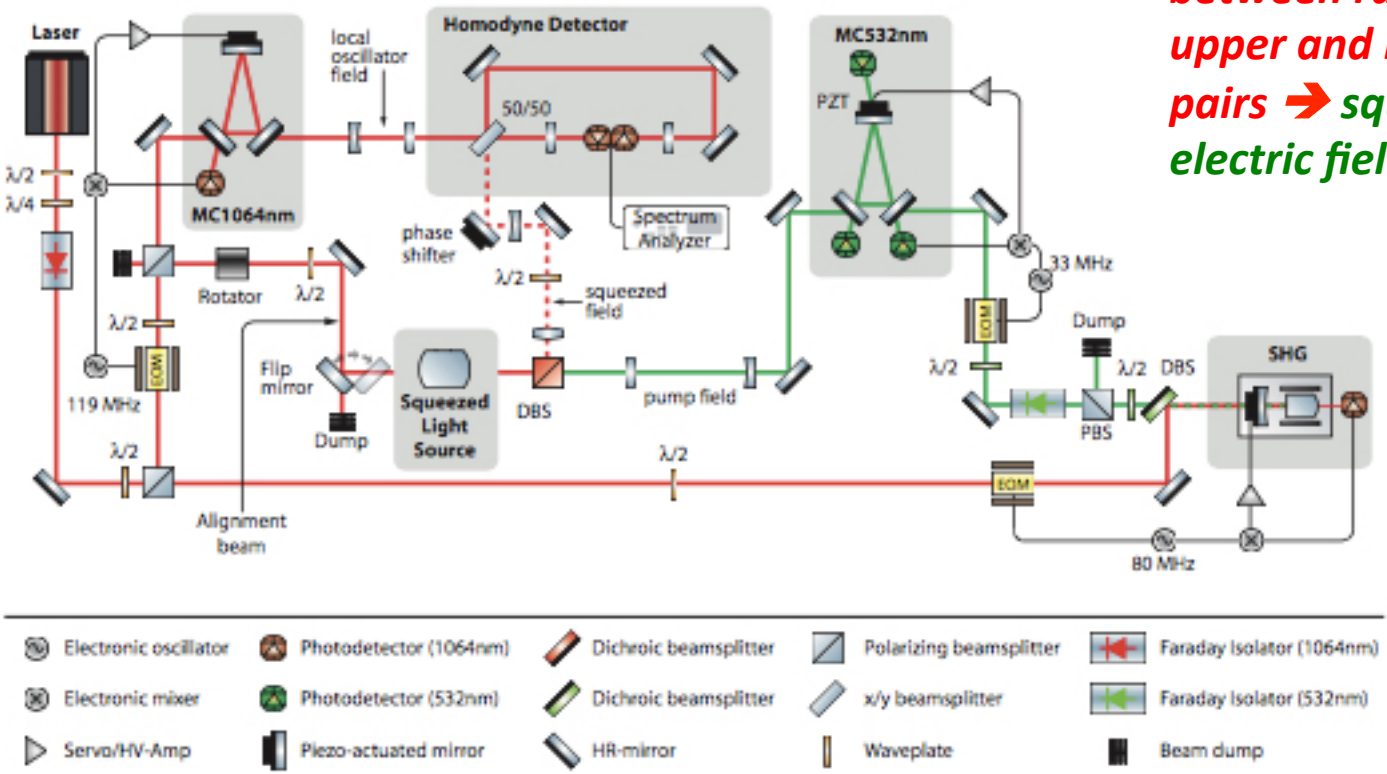
Squeezed vacuum generation via OPO

Squeezed states of light at 1064 nm were generated inside a monolithic, standing-wave cavity by an Optical Parametric Oscillation (OPO).



Degenerate OPO $\omega_s = \omega_i = \omega_p/2$

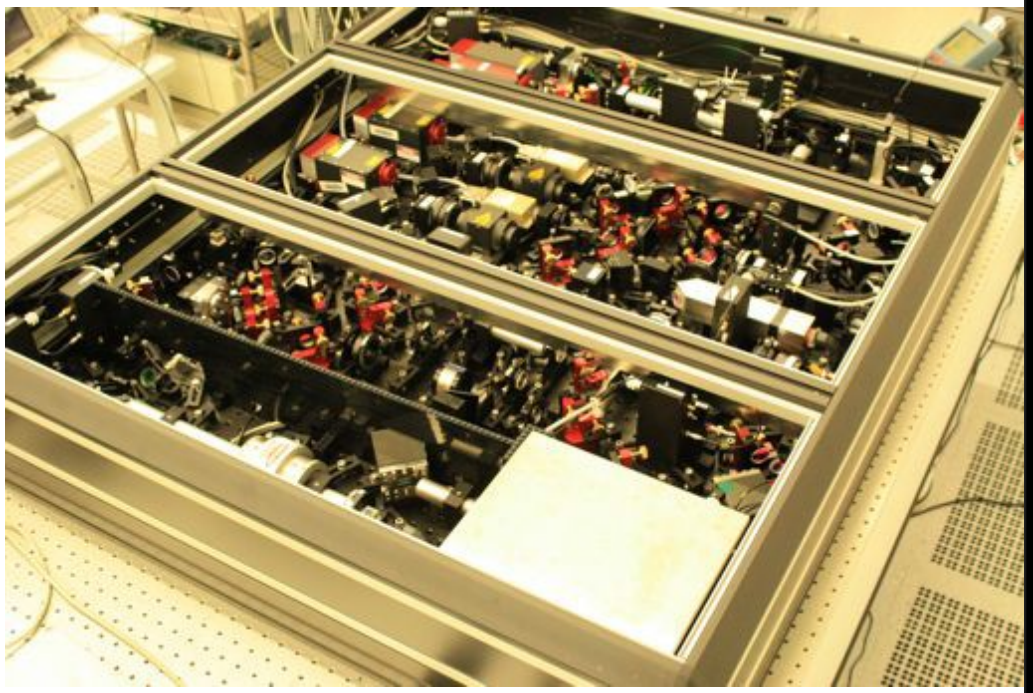
Degenerate OPO introduce a certain level of correlation between randomly fluctuating upper and lower sideband pairs → squeezing of the electric field fluctuations

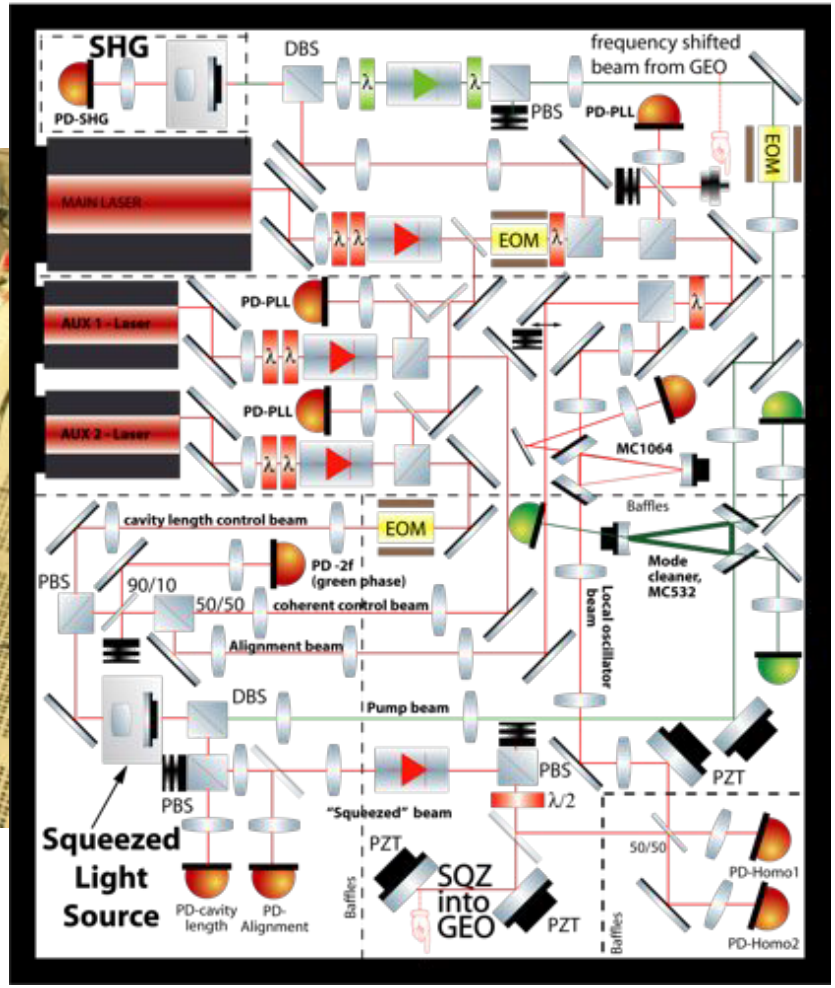


SHG: second harmonic generation, PBS: polarizing beam splitter, DBS: dichroic beam splitter; LO: local oscillator, PD: photo diode; EOM: electro-optical modulator.

The GEO squeezer

Record: 15 dB of squeezing gain



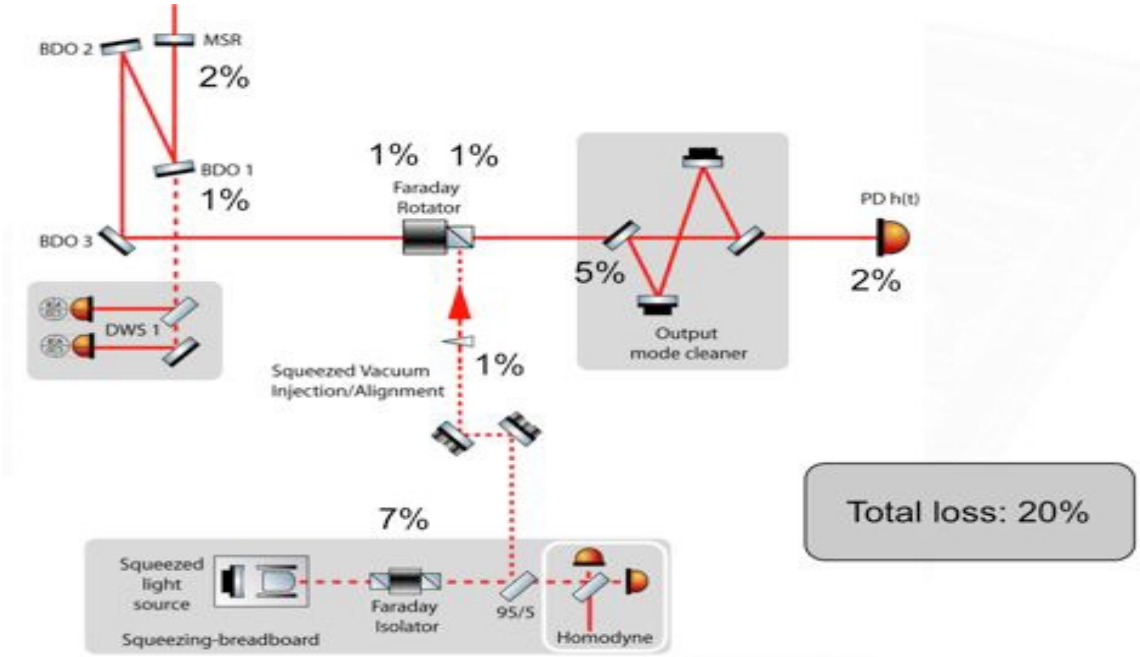


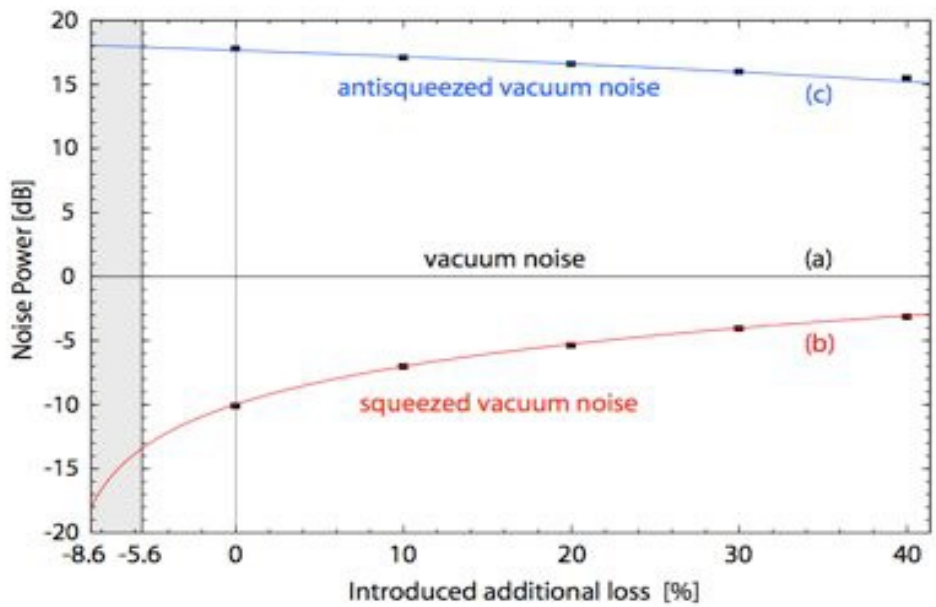
Squeezer based on the use of a non –linear optical device:
Optical Parametric Oscillator➔ OPO

Squeezed Vacuum Injected via ITF output

- Squeezed light is injected via a Faraday rotator into the back of the interferometer
- It is then reflected from the signal recycling mirror (MSR) and detected at the main photodiode (PD)

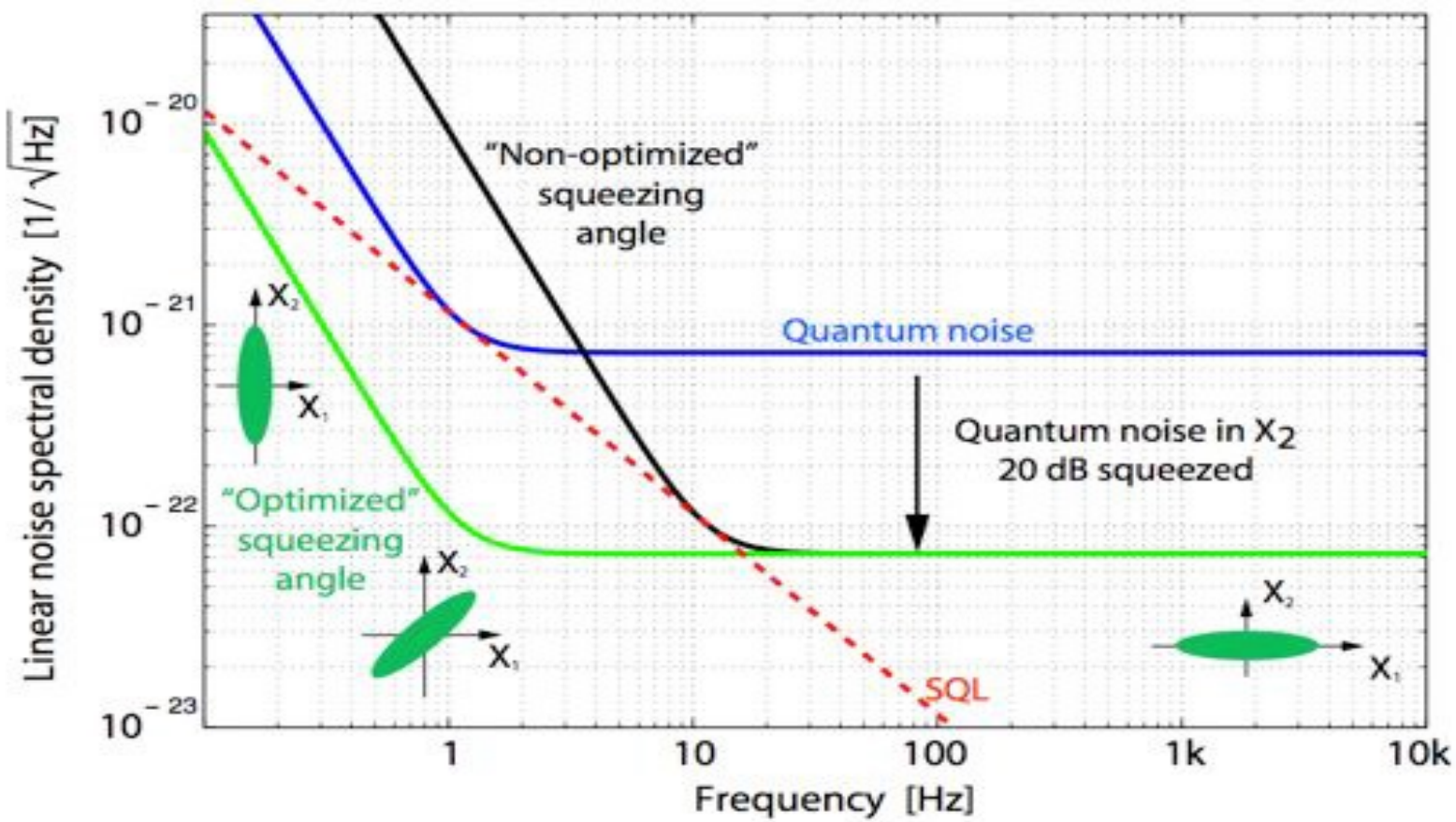
Squeezing requires low losses





Future Step: *Frequency dependent Squeezing*

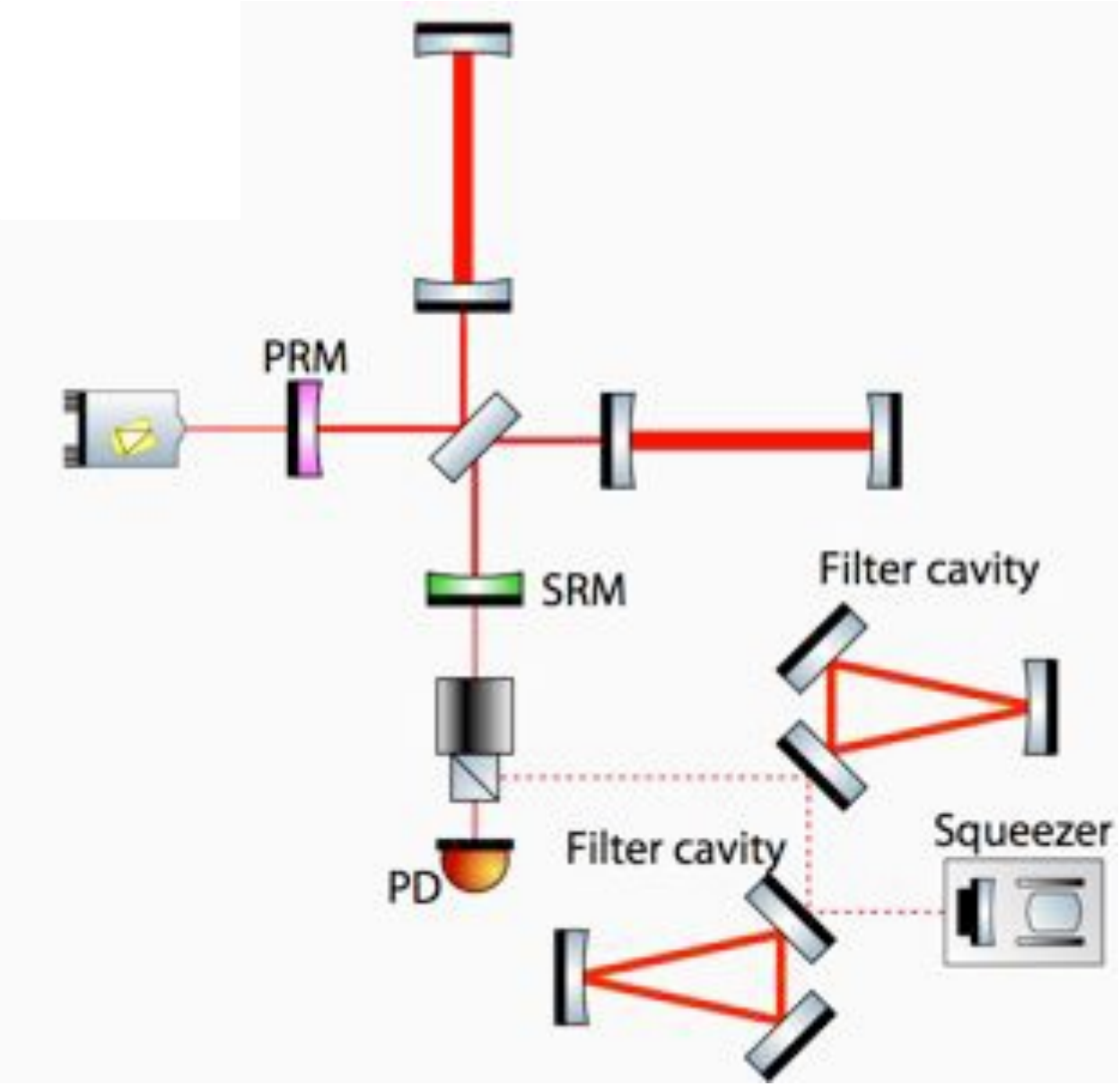
Beating SQL at all frequencies



If squeezed light should reduce shot noise and radiation pressure noise, you need a frequency dependent squeezing angle:

- Phase squeezing at high frequencies.
- Amplitude squeezing at low frequencies

Filter cavities for freq. dep. Squeez.

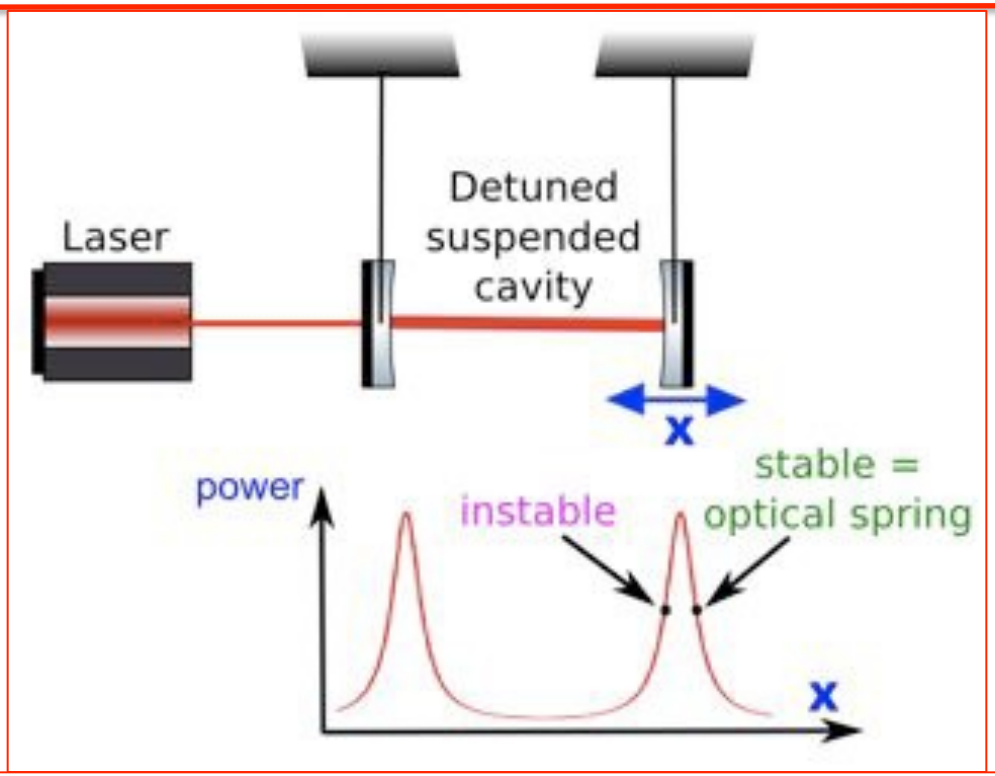


- Take advantage of the cavity's dispersion
- Frequency dependent squeezing realized by reflecting squeezid vacuum on a cavity before to inject it

Ponderomotive effect & the optical spring

Detuned cavities can be use to create optical springs.

- Position change of the mirror => power changes => radiation pressure force changes.
- Optical springs couple the mirrors of a detuned cavity with a spring constant that can be as stiff as diamond.
- Can be used as low-noise transducer for GW signals to mirror movement in the local frame



$$k_{opt} = \frac{8\pi(2r_2 + A_2)t_1\sqrt{r_1 r_2}}{\lambda c} \times \frac{\sin(\frac{4\pi x}{\lambda})}{[1 + r_1 r_2 - 2\sqrt{r_1 r_2}\cos(\frac{4\pi x}{\lambda})]^2}$$

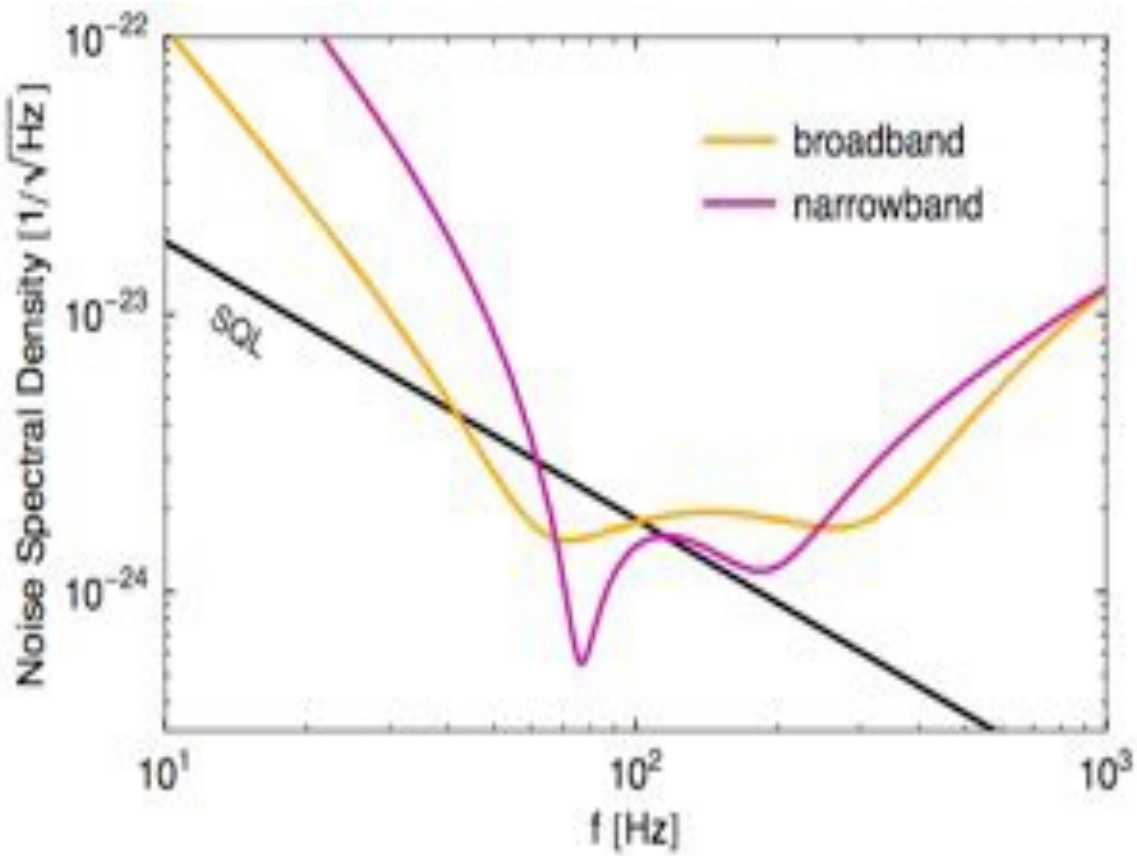
r_i , t_i , A_i ➔ reflectivity , transmissivity and loss
λ ➔ light wavelength $(i=1,2)$
P_{in} ➔ cavity input power
x ➔ cavity detuning

A. Di Virgilio et al.
*PHYSICAL REVIEW A **74**, 013813 2006*

Can k_{opt} beat SQL?

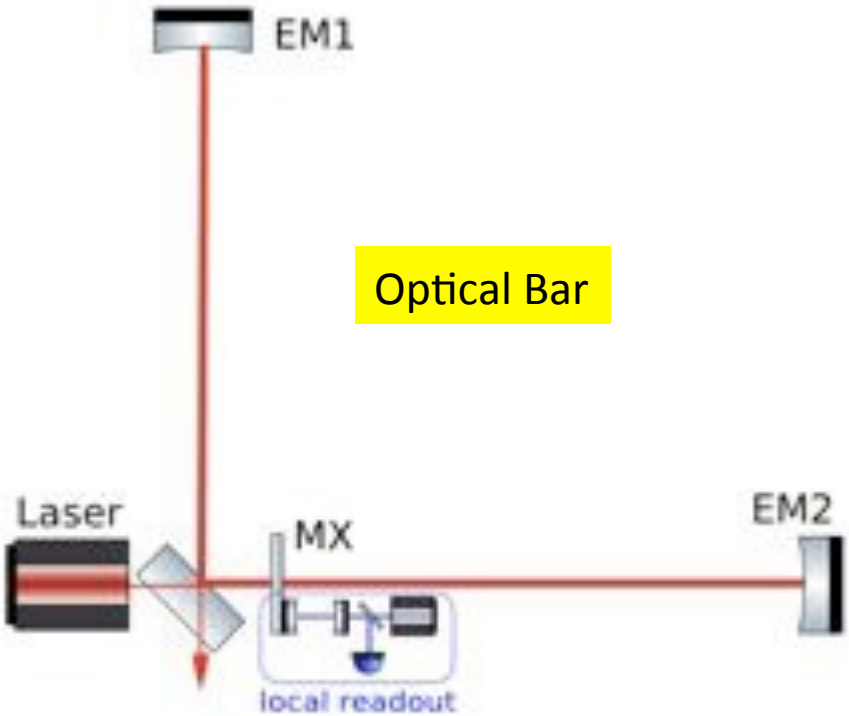
- Detuned Signal Recycling also creates a optical spring resonance => quantum noise shows two 'bumps', the optical spring (at low frequencies) and the pure optical resonance (at high frequencies).

- Advanced dtectors could beat the SQL, if the quantum noise at low frequencies would not be coverd by other noise sources.



Optical bar (Braginski again!!)

- Very light mirror (MX) is coupled to the movement of EM1 and EM2 via optical springs.
- MX can then locally read out by a small local meter without disturbing the quantum states in the main instrument (QND measurement).
- Split between GW transducer and readout allows separate optimisation of these two systems.

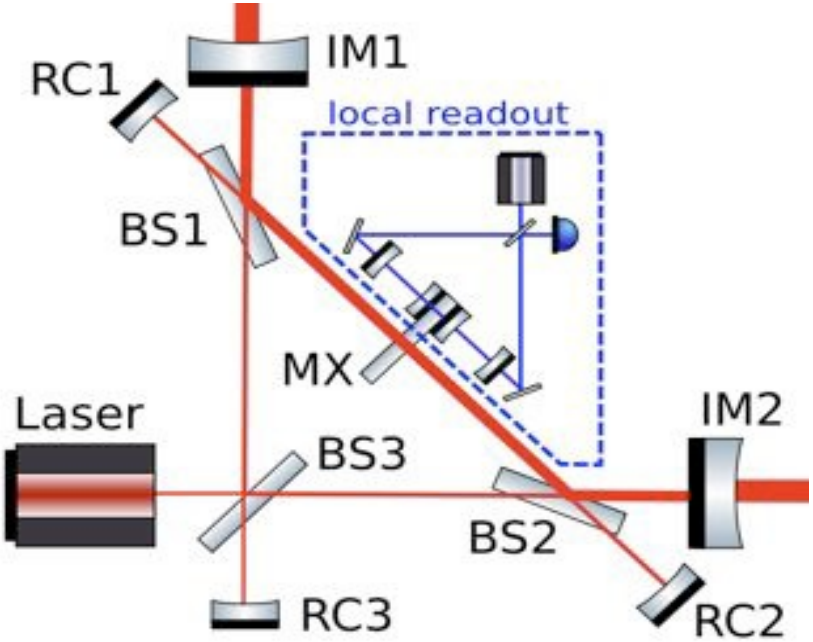


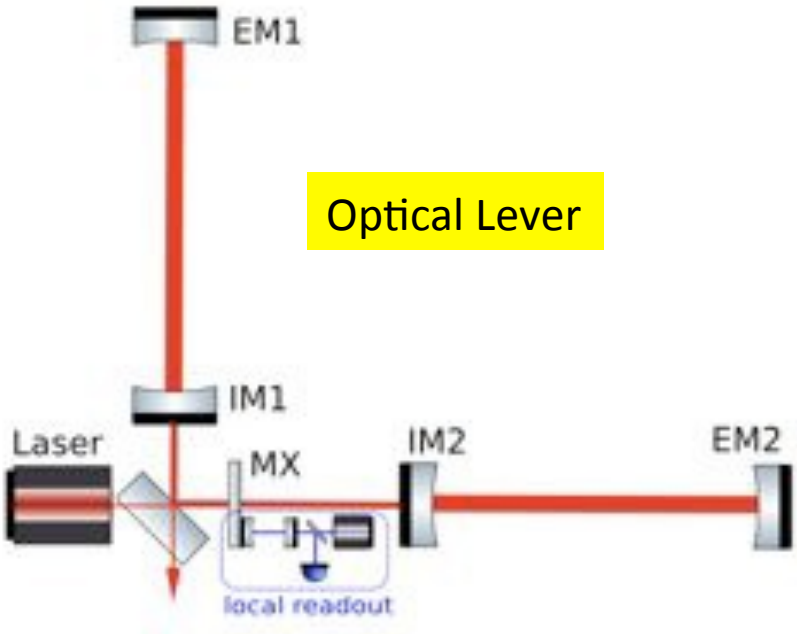
V.B. Braginsky and F.Y. Khalili: "Nonlinear meter for the gravitational wave antenna",Phys. Lett. A 218 (1996).

Optical Levers

F.Y. Khalili: “The ‘ptical lever’ intracavity readout scheme for gravitational-wave antennae”,Phys. Lett. A 298 (2002).

Proposed Implementation Scheme





Optical lever: introducing arm cavities increases the movement of MX by the Finesse of the arm cavity.

Squeezing Perspectives beyond GW

Quantum control of a resonator:
Thermometry of mechanical resonators

- Quantum optomechanical entanglement (Lehnert, Science 2013)
- *Study of decoherence of a massive mechanical object and fundamental tests of quantum mechanics, EPR experiments...*

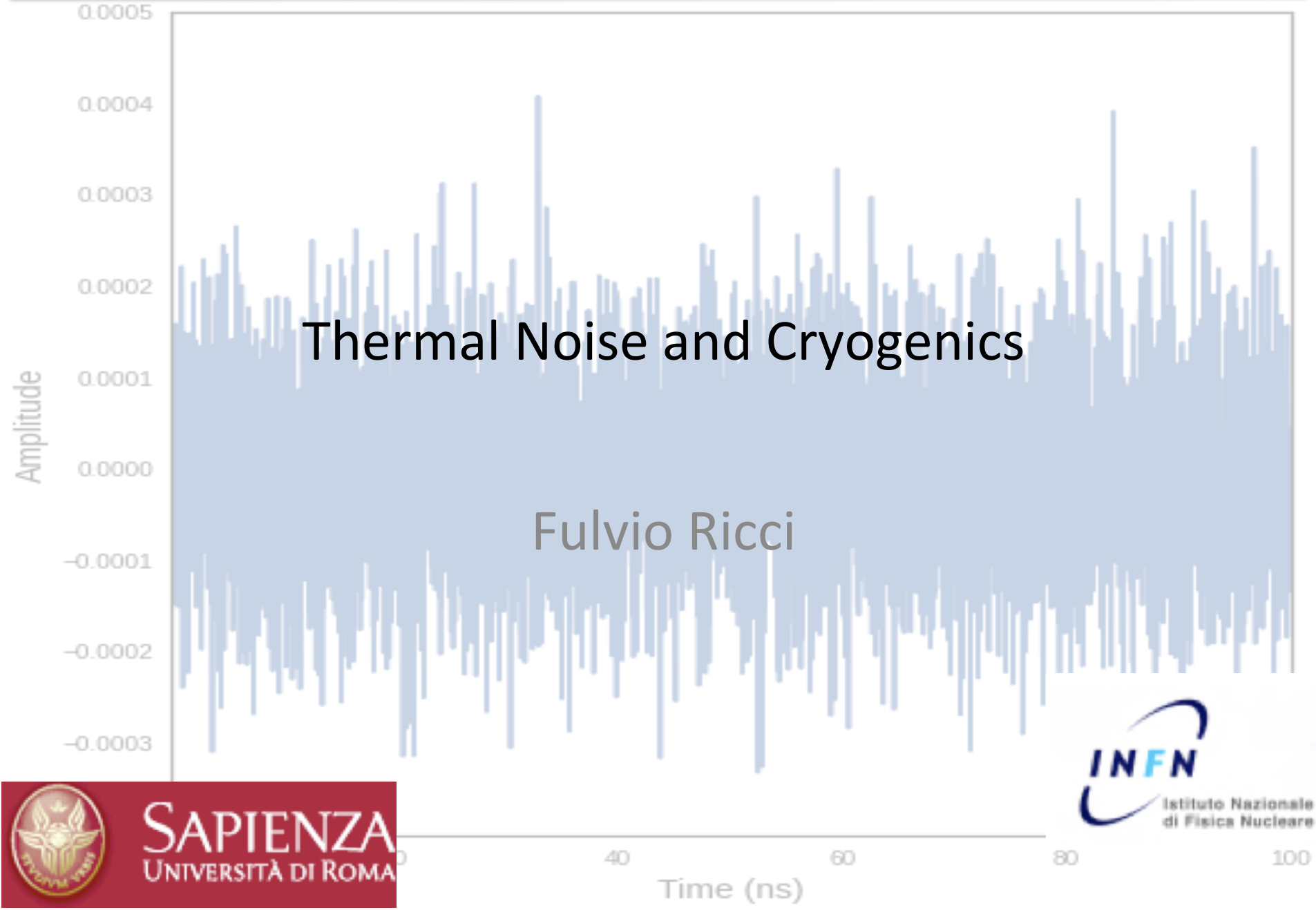
- Quantum coherent state transfer:
  - ✓ QuBit-resonator swap oscillations (Cleland, Nature 2010)
  - ✓ Coherent transfer between propagating microwave fields and a resonator (Lehnert, Nature 2013)
  - ✓ *Mechanics as a bus connecting hybrid components*
    Optomechanical circuits for quantum memory and quantum information processing

- Single photon optomechanical coupling:
  - ✓ Proposal for single-phonon preparation by single photon detection from an entangled state (Kippenberg, PRL 2014)

- *Nonlinear quantum effects, generation of non Gaussian states...*

Thermal Noise and Cryogenics

Fulvio Ricci

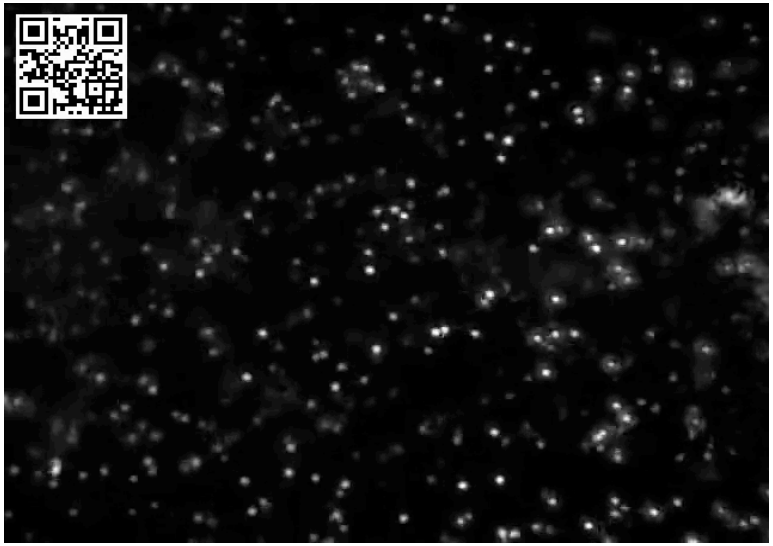


A bit of history

- 1828➔ The botanic expert Robert Brown, using a microscope, observed the chaotic motion of particle with different nature, small enough to stay suspended in the water solution

- He discarded the hypothesis that this was a biological phenomenon

- In practice, at that time, Brown observed the random interaction of the water molecules in thermal motion with the suspended particles



Brownian motion increases if

- Decrease the particle dimensions
- Decreases the particle density
- Decreases the viscosity of the liquid
- Increases the temperature of the hosting liquid

Fluctuation dissipation therorem

Equation of motion of a linear system in the frequency domain

$$X(\omega) = H(\omega)F(\omega) \qquad v(\omega) = \frac{F(\omega)}{Z(\omega)}$$

$H(\omega)$ ➔ system transfer function e $Z(\omega)$ system impedence

Synthesis : the fluctuation-dissipation theorem

$$S_{ff}^{thermal}(\omega) = 4k_bT \cdot \mathrm{Re}[Z(\omega)]$$

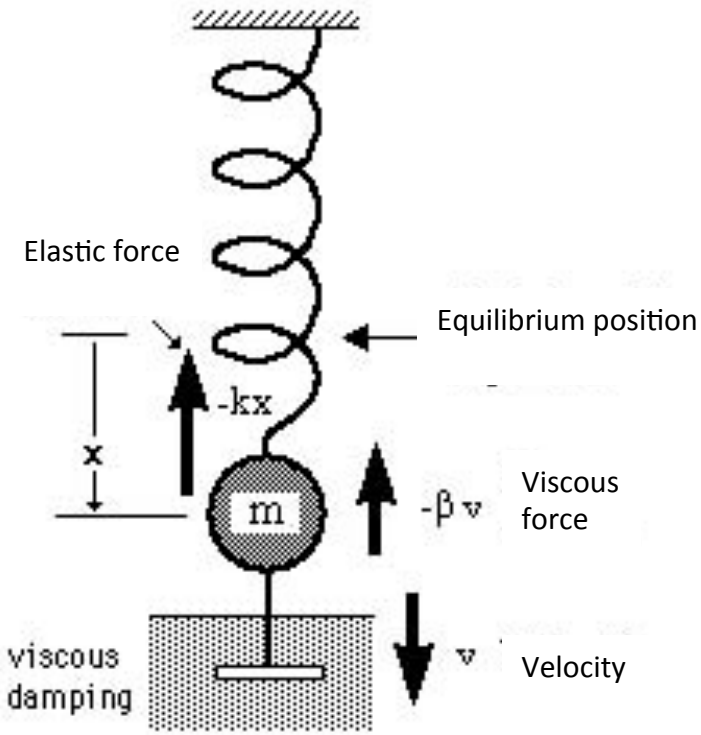
$$S_{xx}^{thermal}(\omega) = \frac{4k_bT}{\omega} \cdot \mathrm{Im}[H(\omega)]$$

$$X(\omega) = \int_{-\infty}^{+\infty} x(t)e^{i\omega t}dt$$

$$F(\omega) = \int_{-\infty}^{+\infty} f(t)e^{i\omega t}dt$$

The fluctuations are function of the frequency !!

Thermal noise of the harmonic oscillator



$$m\ddot{x} + \beta\ \dot{x} + kx = F(t)$$

$$-\omega^2 X(\omega) + i\omega\beta\ X(\omega) + k\ X(\omega) = F(\omega)$$

$$H(\omega) = \frac{X(\omega)}{F(\omega)} = \frac{1}{m\left((\omega_o^2 - \omega^2) + i\omega\frac{\beta}{m}\right)}$$

Applying the dissipation-fluctuation theorem

$$\omega_o = \sqrt{\frac{k}{m}}$$ Resonance frequency

$$Q = \frac{m\omega_o}{\beta}$$ Merit factor

$$S_{xx}^{therm}(\omega) = \frac{4k_bT}{\omega} \cdot \mathrm{Im}[H(\omega)]$$

$$S_{xx}^{therm}(\omega) = \frac{4k_bT}{m\,\cancel{\omega}} \cdot \frac{\cancel{\omega}\omega_o/Q}{\left((\omega_o^2-\omega^2)^2+\left(\omega\omega_o/Q\right)^2\right)}$$

Equipartition principle

$$\boxed{\frac{1}{2}\ m\omega_o^2\{E[x^2]\}_{therm} = \frac{1}{2}\ k_BT}$$

$$\{E[x^2]\}_{therm} = \frac{1}{\pi}\int_0^\infty S_{xx}^{therm}(\omega)\ d\omega = k_BT\cdot \mathrm{Re}[H(0)] = \frac{k_bT}{m\omega_o^2}$$

Resonance and out of resonance

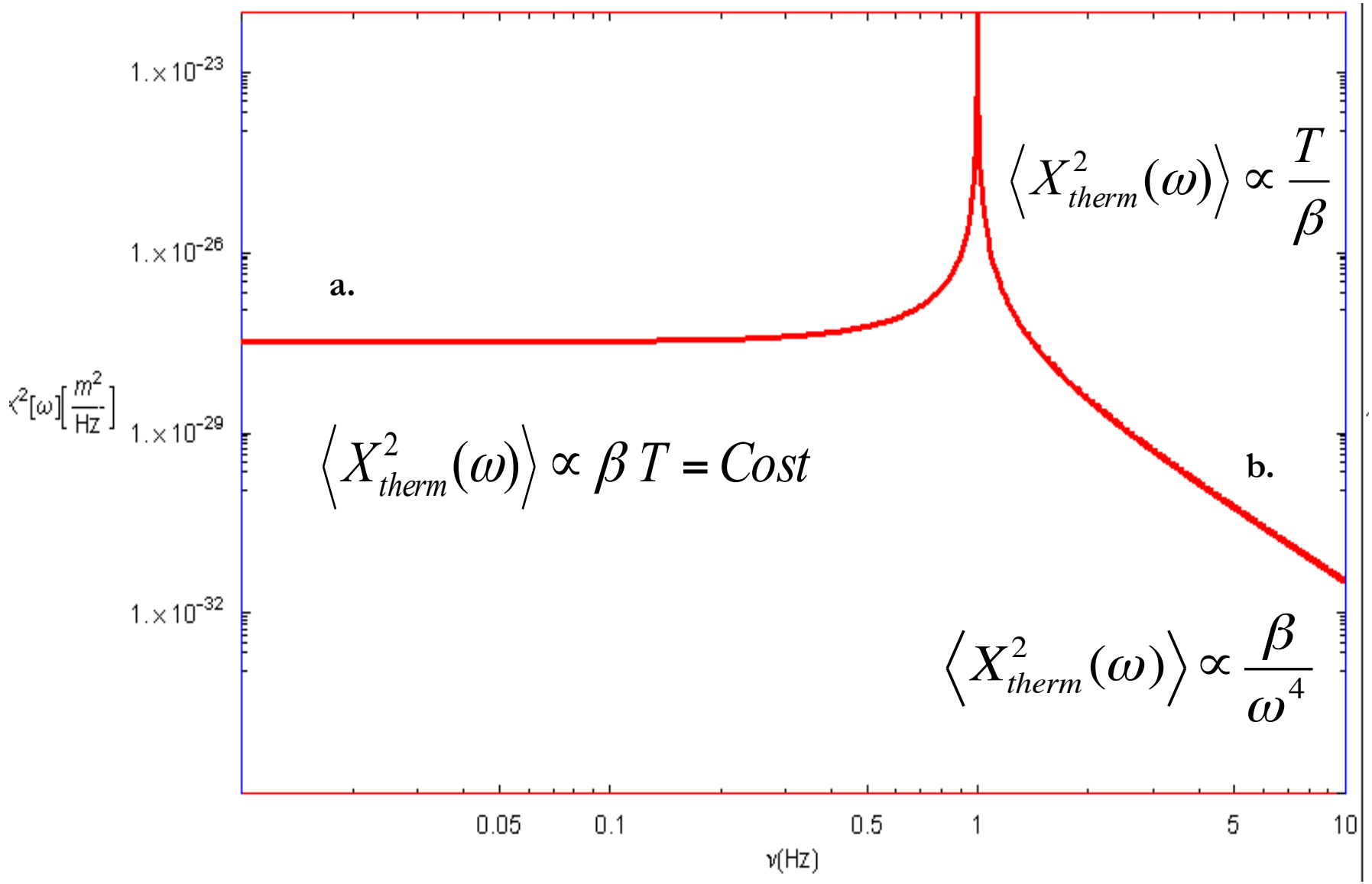
$$S_{xx}^{therm}(\omega) = \frac{4\pi\ k_b T}{m\omega_o^2}\frac{m}{\beta} \qquad \omega \approx \omega_o$$

Even the behavior out of resonance depends on dissipation

$$S_{xx}^{therm}(\omega) = \frac{4\pi\ k_b T}{m\omega_o^4}\frac{\beta}{m} \qquad \omega << \omega_o$$

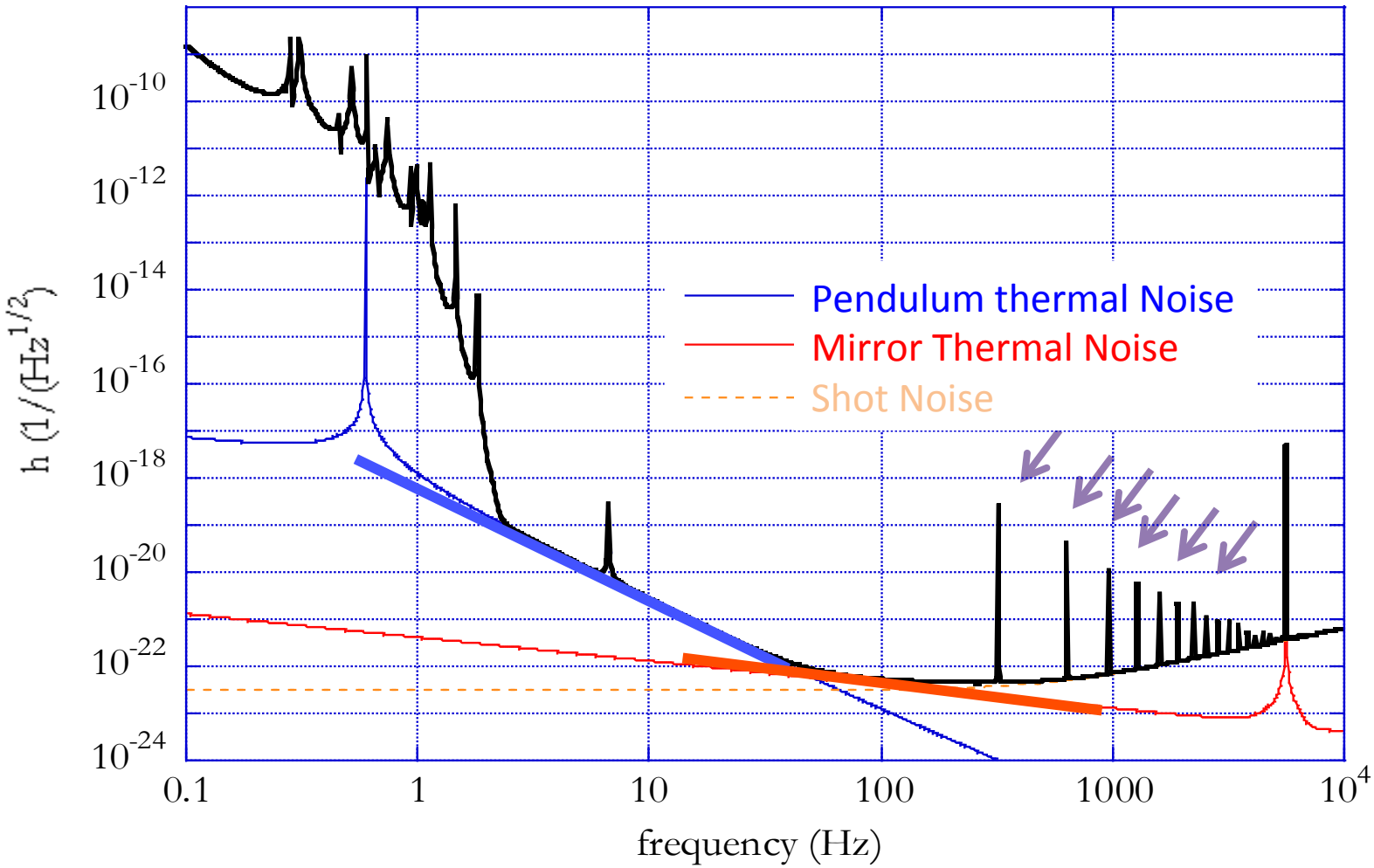
$$S_{xx}^{therm}(\omega) = \frac{4\pi\ k_b T}{m\omega^4}\frac{\beta}{m} \qquad \omega >> \omega_o$$

spectral density of harmonic oscillator



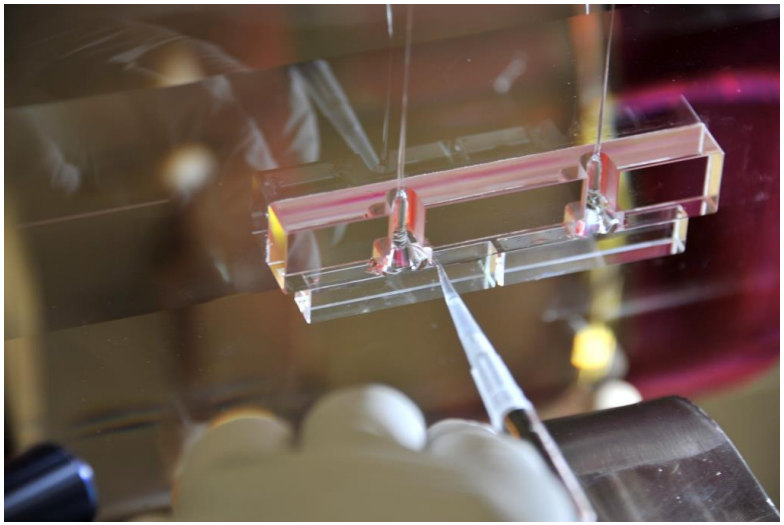
Low dissipation ➔ lower values in a. and b.

VIRGO


Pendulum thermal Noise
Mirror Thermal Noise
Shot Noise
h (1/(Hz^1/2))
10^-10
10^-12
10^-14
10^-16
10^-18
10^-20
10^-22
10^-24
0.1
1
10
100
1000
10^4
frequency (Hz)

Beating the thermal Noise

- Pendulum Mode



wire of fused silica

Reduced thermoelastic loss

low surface dissipation

- Mirror

reduce coating loss

reduce bulk dissipation

Lower the temperature

Cryogenics and Gravitational Waves

Low Temperature and G.W. Detectors: an old idea

JULY 1972, VARENNA (COMO) ITALY

V.B. BRAGYNSKY J.W. WEBER R.H. DICKE W.M. FAIRBANK

The Use of Low-Temperature Technology in Gravitational Experiments.

W. M. FAIRBANK
Stanford University - Stanford, Cal.

1. – Introduction.

One of the challenging problems of experimental gravitational physics is the very small size of the gravitational effects one wishes to measure. For example, the force of gravity of the entire Earth on an electron or positron is equal to the electrical force on it due to a single elementary charge situated at a distance of 5 meters from the electron or positron. The rotation with respect to the fixed stars of the axis of a perfect gyroscope in a polar Earth orbit when oriented perpendicular to the Earth's axes is predicted to be only 0.05 seconds of arc per year. The amplitude of vibration of a 5 ton aluminum bar 10 feet long excited by a spherically symmetric gravity wave emitted at the center of our Galaxy with energy, mc^2, of one solar mass 10^{54} erg, is predicted to be 10^{-14} cm. Furthermore, some gravitational experiments of great interest, such as a test of the equivalence principle, involve a search for minute deviations from null. A test of the equivalence principle at the level of weak interactions requires a check on the differences between gravitational and inertial mass to 1 part in 10^{14}.

The reason

These measurements require techniques of extreme sensitivity, low noise and great mechanical and electrical stability.
Two types of advantages emerge from cooling at very low temperature, one based on macroscopic quantum effect, namely superconductivity and superfluidity, and the other based on the general reduction of the *k T* thermal noise, thermal expansion, thermal electromotive force, creep, etc...

....

one

The

……but not easy to do!

Bill Fairbank theorem:

<< Any experiment is better, if it is done at low temperature>>

Bill Hamilton addendum:

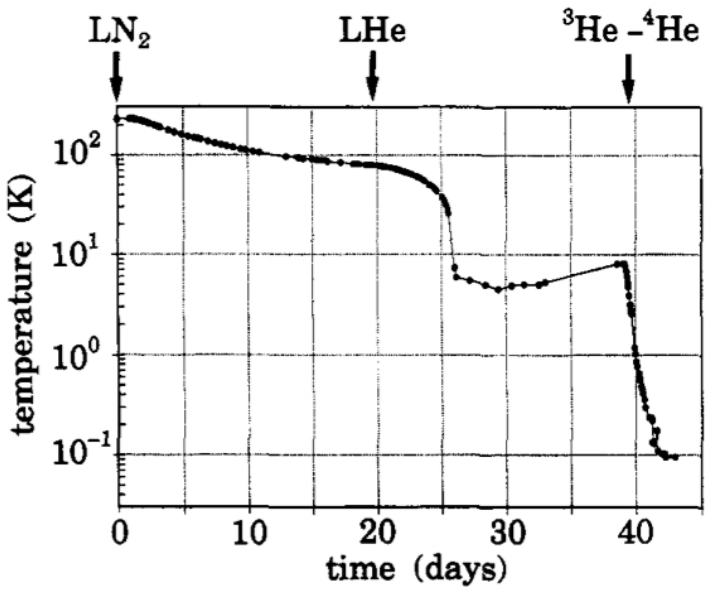
<< Any experiment will be harder, if it is done at low temperature>>

The GW massive detector achieving the lowest temperature

P. Astone, M. Bassan, P. Bonifazi, F. Bronzini, P. Carelli, M.G. castellano, G. Cavallari, E. Coccia, C. Cosmelli, V Fafone, S. Frasca, E. Majorana, I. Modena, G. V. Pallottino, G. Pizzella, P. Rapagnani, F. Ricci, M. Visco: "

First cooling below 0.1 K of the new gravitational wave antenna of the Rome group

Europhys. Lett., 16 (3), pp. 231-235 (1991)



T= 95 mK - M=2300 kg

NAUTILUS - INFN

Why cryogenics for GW ITF?

- **Test masses and suspensions thermal noise reduces at low temperature:**

$$< x^2 > \propto T$$

- **Thermoelastic noise both of the mirror substrates and coatings decrease:**

$$< x^2 > \propto \alpha T^2$$

  - Thermal expansion rate a decreases at low temperature;
- **Thermorefractive noise**

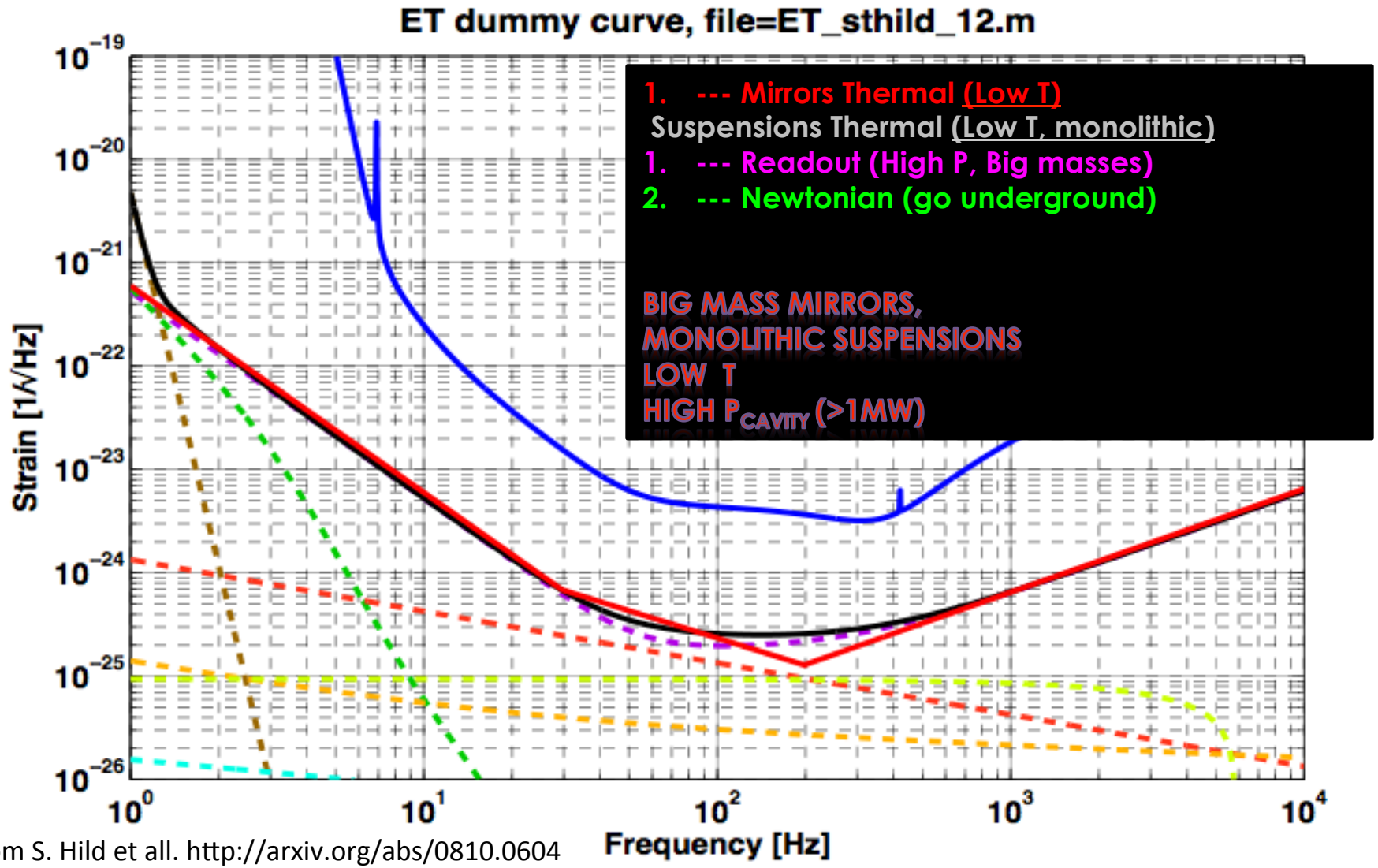
$$< x^2 > \propto T^2$$

  - Local fluctuation of the refraction index
- **Thermal lensing:**
  - Thermal conductivity increases and consequently reduces thermal gradients on the coating;
  - Refraction index variation with temperature is very small at low temperature;

- Losses of some materials decrease at low temperature

$$< x^2 > \propto T \ \Phi$$

CRYOGENIC 3° GENERATION GW DETECTOR



From S. Hild et all. http://arxiv.org/abs/0810.0604

How to cool down: a) Cryoliquids

- The simplest way to produce low temperature is still the use of cryoliquids (e.g. nitrogen, helium).
- Liquid oxygen and hydrogen are rarely used in refrigeration: the former because of its high chemical reactivity, the latter again for its flammability.
- Helium is the most interesting element and the most used in cryogenics. The enthalpy of the gas warming from 4.2 K to room temperature is used to increase the refrigeration efficiency of the cooling process.
- The full use of the ^{4}He enthalpy reduces the amount of liters of liquid helium at just 0.08 lt of liquid helium , $1/30_{th}$ of the amount needed using the ^{4}He latent heat only.

Thermodynamic properties of some liquids [16,17]

Substance	T_{bp} [K]	T_m [K]	T_{tr} [K]	p_{tr} [10^5Pa]	T_{cr} [K]	p_{cr} [MPa]	T_i [K]	p_i [10^5Pa]	Latent heat L [kJ/l]	Volume % in air
H_2O	373.15	273.15	273.16	0.00610	647.096	22.064	—	—	2252	—
NH_3	293.8	195	195.40	0.0607	405.5	11.35	—	—	—	—
SO_2	263	200.75	197.68	0.00167	430.8	7.88	—	—	—	—
CO_2	194.6	216	216.5	5.173	304.1	7.38	—	—	—	—
C_2H_4	169.5	104.1	104.0	0.00120	283.2	5.03	—	—	—	—
Xe	165.1	161.3	161.4	0.82	289.77	5.841	—	—	303	10^{-5}
Kr	119.9	115.8	114.9	0.73	209.41	5.50	—	—	279	1.1×10^{-4}
CH_4	111.8	90.8	90.67	0.117	190.6	4.6	>500	533	—	—
O_2	90.2	54.4	54.36	0.015	154.6	5.04	742	570	245	20.9
Ar	87.3	83.8	83.81	0.67	150.87	4.898	—	—	224	0.93
N_2	77.4	63.3	63.15	0.13	126.2	3.39	621	380	160	78.1
Ne	27.1	24.5	24.56	0.43	44.4	2.76	260	—	110	1.8×10^{-3}
n-D_2	23.7	18.7	18.69	0.17	38.2	1.650	—	—	50	—
n-H_2	20.3	14.0	13.80	0.07	33.19	1.315	200	164	31.8	0.5×10^{-4}
^{4}He	4.21	—	—	—	5.195	0.227	43	39	2.56	5.2×10^{-4}
^{3}He	3.19	—	—	—	3.32	0.115	—	—	0.48	—

T_{bp}: boiling point temperature a $p = 1$ bar, T_m: melting temperature at $p = 1$ bar, $T_{tr}(p_{tr})$: triple point temperature (pressure), $T_{cr}(p_{cr})$: critical point temperature (pressure), $T_i(p_i)$: inversion temperature (pressure) L: latent heat of vaporization at T_b.

^{4}He below 2.17 K is superfluid , its thermal conductivity is extremely high and bubbles do not form in the liquid during the evaporation process, since the temperature gradient is very close to zero.

Cryofluid: the boiling problem

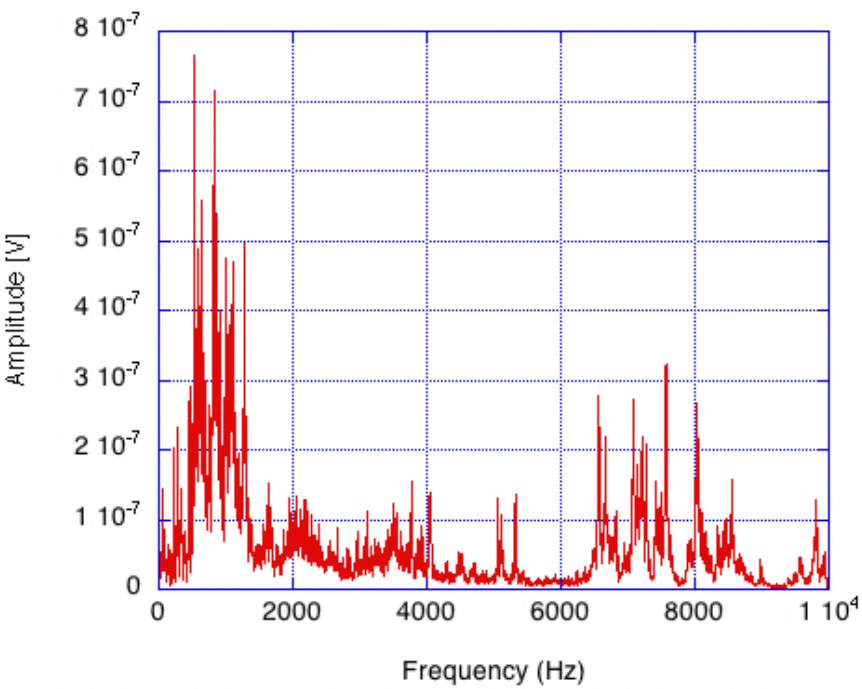
(absent in the superfluid case)

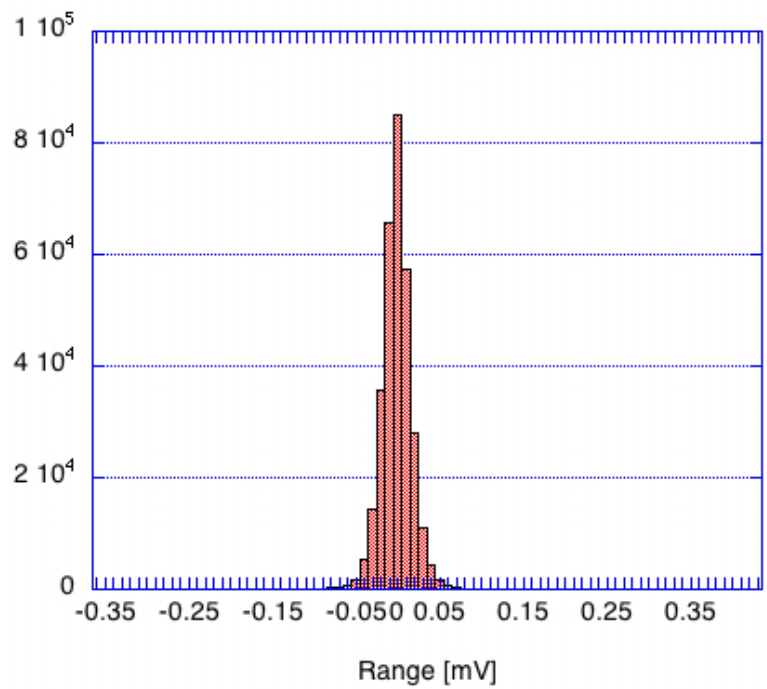
Displacement amplitude and frequency spectrum depend on the tank material and geometry: typical pressure fluctuation 20 dBa ➔ 2 10^{-4} Pa.

For example in the case of the GW resonant antenna Explorer x_{rms} ~ 10^{-10} m @ 4K with an evaporation rate of a liquid Helium ~2 lt/h

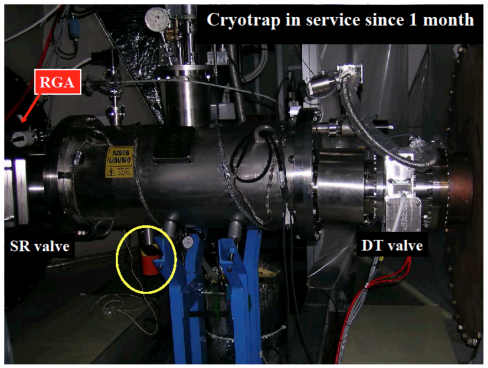
Example of the noise characteristics of a boiling fluid in cylindrical container

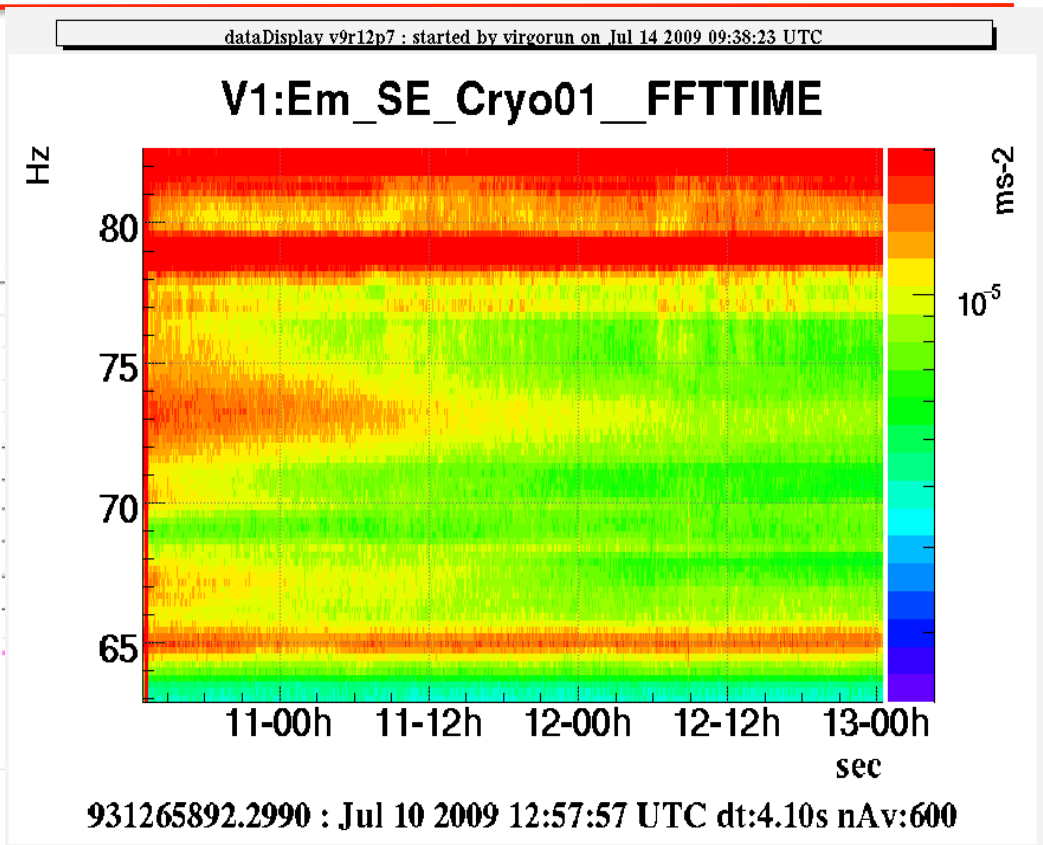
A simplest approach is to use supercritical helium at T>5.19 K (single phase status)



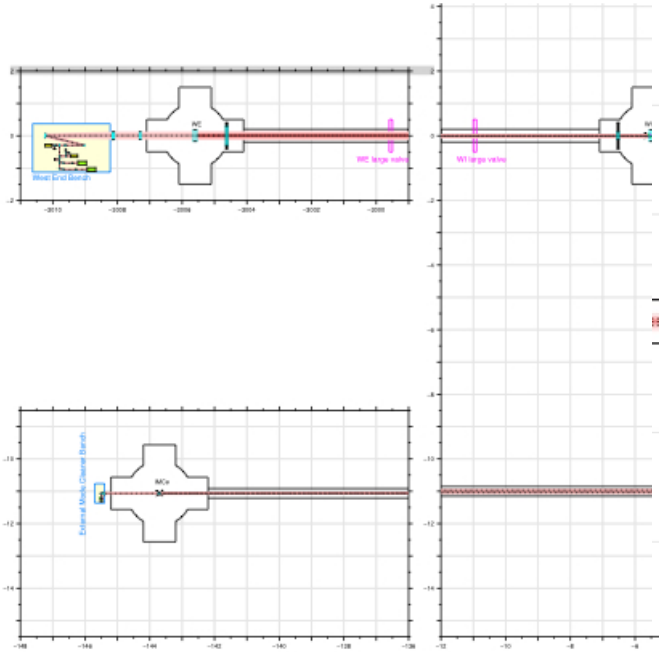


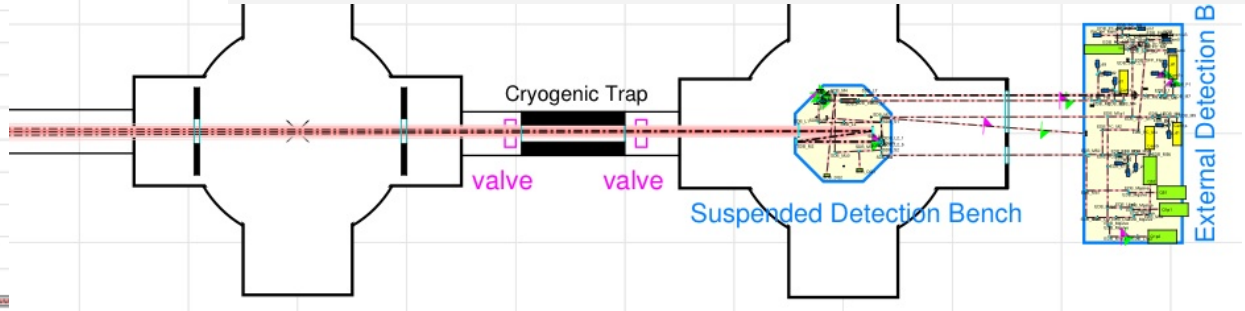
The bubble noise in VIRGO





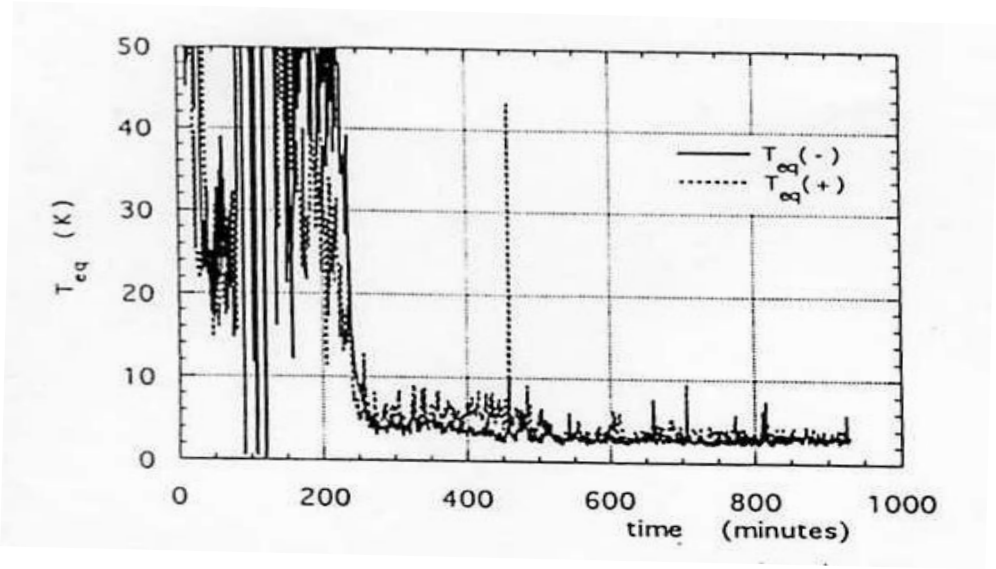
Time-frequency plot of the accelerometer near the VIRGO-N_2 trap after the refilling





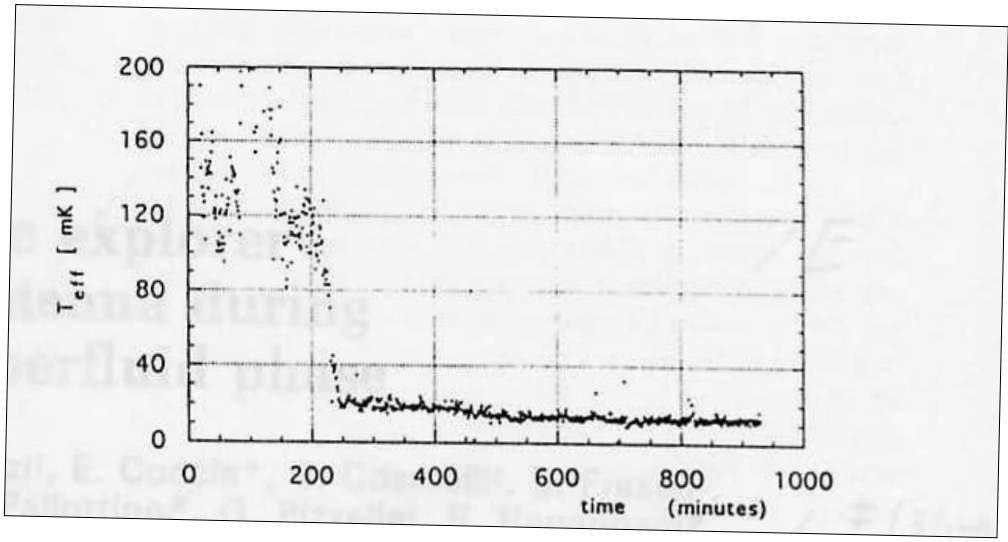
Resonant G.W. Detector : vibration due to the boiling of the cryogenic liquid: the liquid helium superfluid transition

Data from the Antenna
EXPLORER
installed at CERN



Relative displacement sensitivity
$\Delta L/L \sim 10^{-19}$

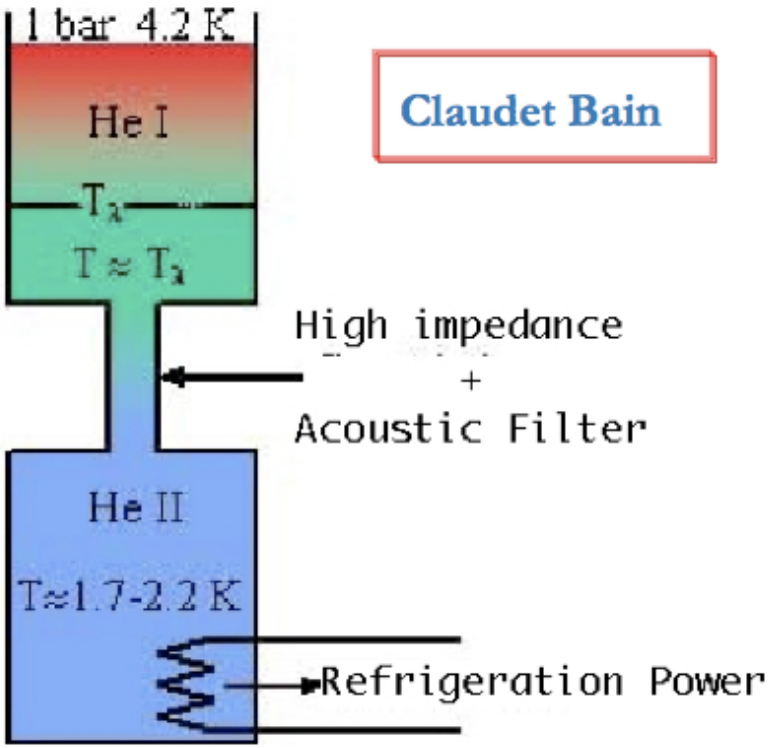
f ~ 900 Hz



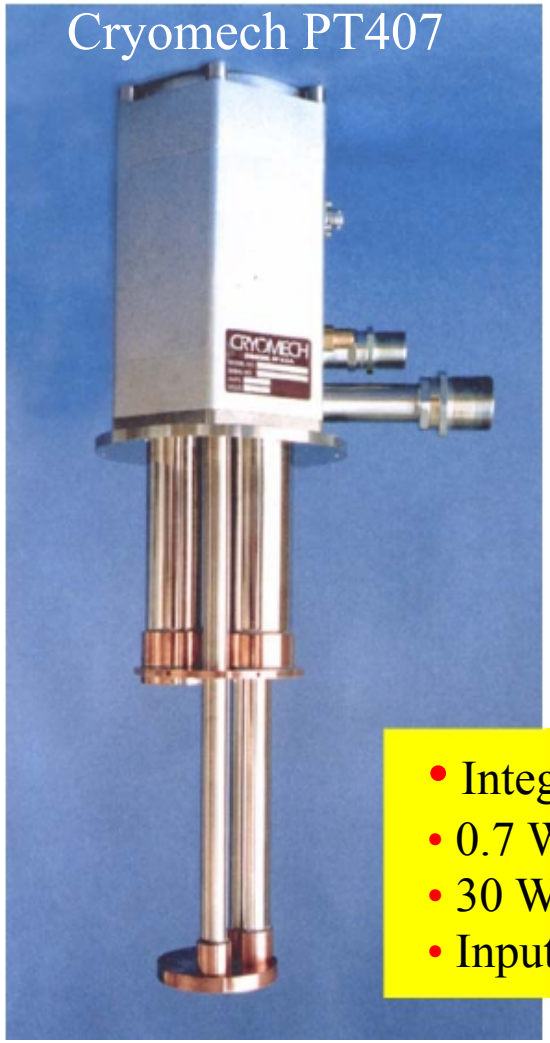
Scheme for cooling the mirror based on He II

*A possible configuration: the "**bain de Claudet** " permits to use super fluid helium at atmospherique pressure and to insure continuous refilling from the container of the helium in the normal state*

- Super fluid helium at atmosperique pressure !
- No boiling !
- Enhanced heat removal capability of unsaturated superfluid helium
- Massive use of Super fluid helium is possible: super fluid helium is widely used for cooling the LHC superconducting magnets



How to cool down: b) cryogenerators



- Integral-Design
- 0.7 W @ 4.2 K
- 30 W @ 55 K
- Input: ≈ 7 kW

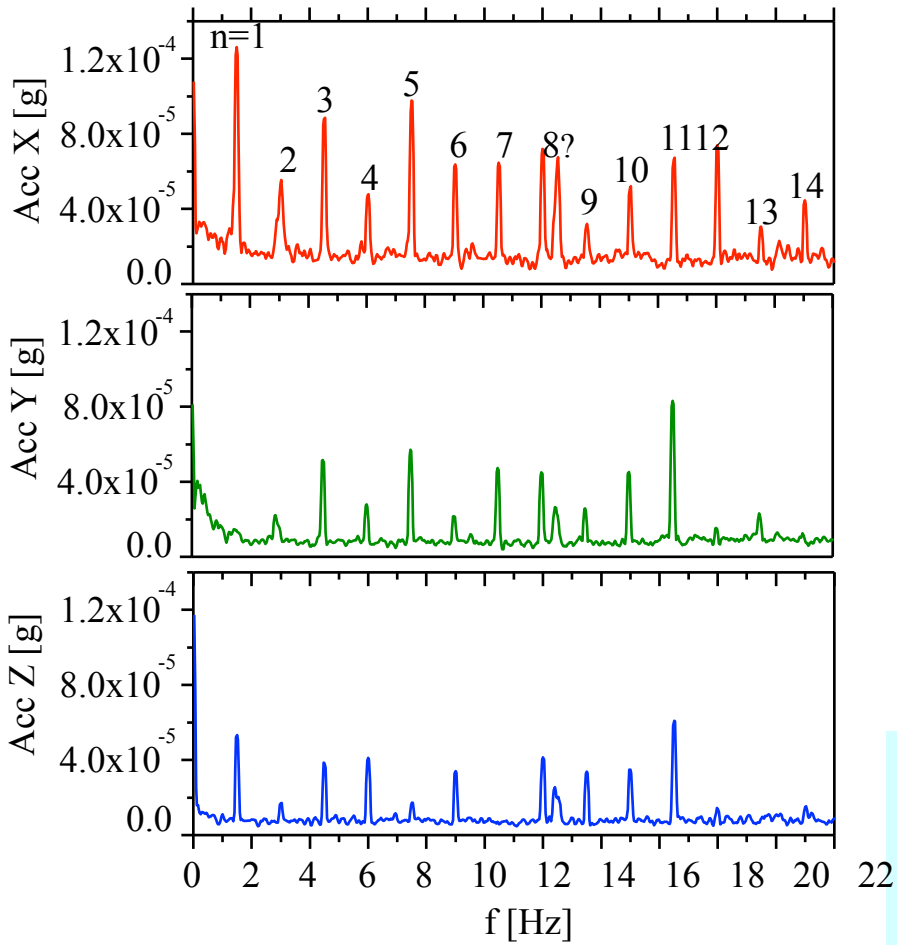
The KAGRA approach

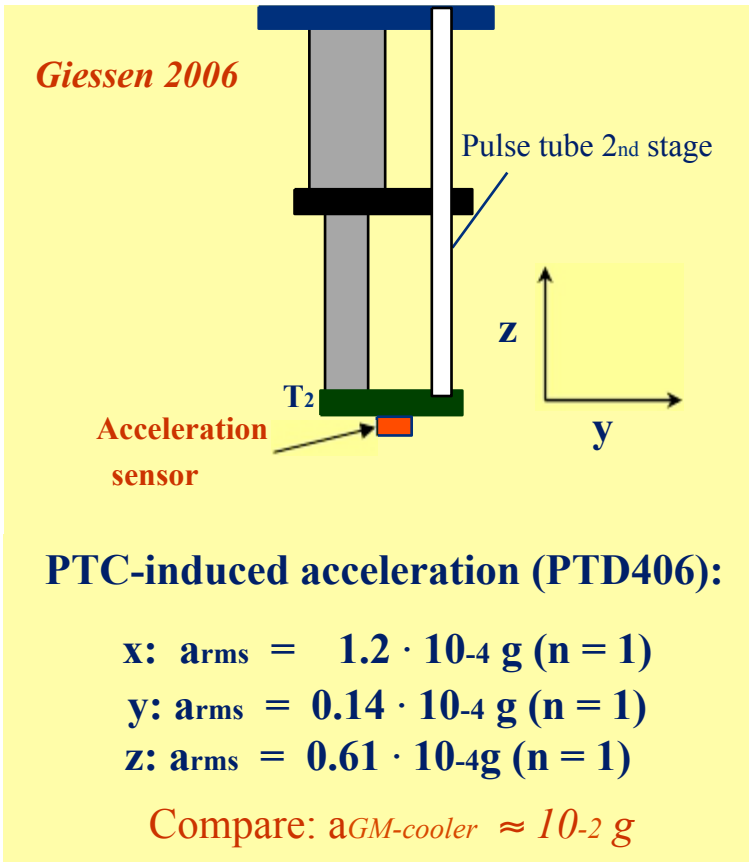
Pulse Tube Refrigerators

- Split-Design
- 0.5 W @ 4.2 K
- 20 W @ 45 K
- Input: ≈ 7.5 kW

Vibrations of 4 K PTCs: PTD406 (6 kW)

Acceleration-spectra of PTD406, f = 1.5 Hz, 6 kW-compressor, Δp = 13 bar, $T_2 \approx 0$ °C





<u>Origin:</u> Elastic deformation of the stainless steel tubes due to pressure oscillation

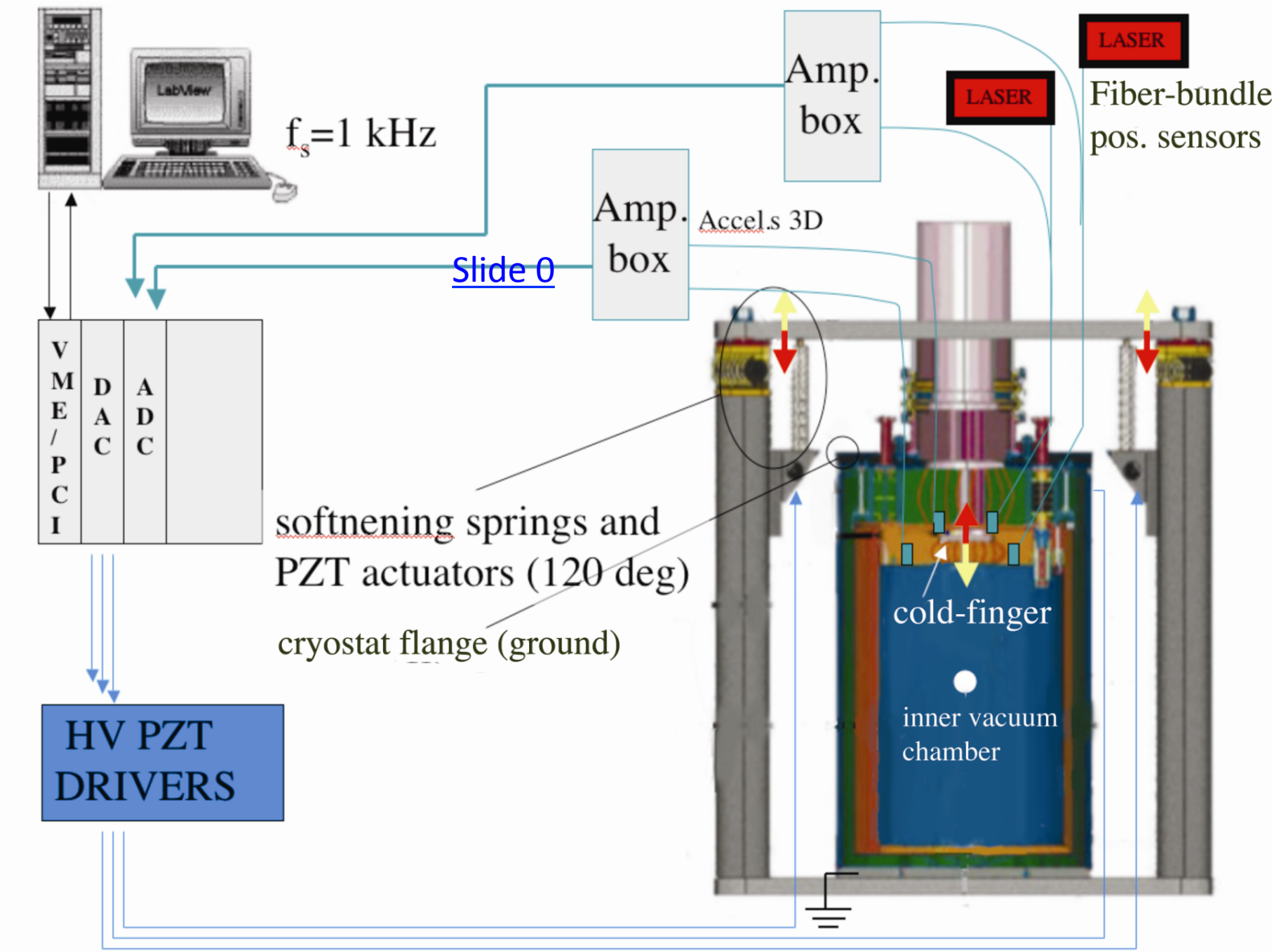
$$\Delta L/L \sim E^{-1} (r/s)\, \Delta p$$

r = tube radius s = wall thickness

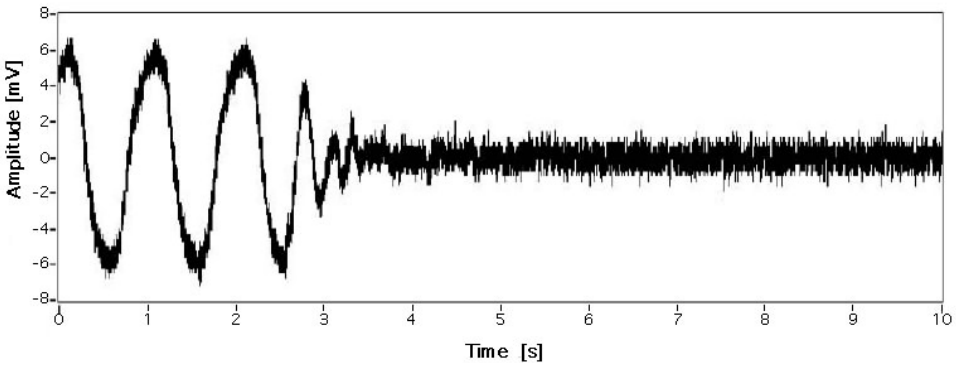
The Free Vibration Cryostat and its control chain

S. Caparrelli, et al. Rev. of Sci. Inst. 77, 095102 (2006).

T. Tomaru et al. Cryogenics, 44 (2004). *(Passive vibration insulation system for the cryocooler)* i

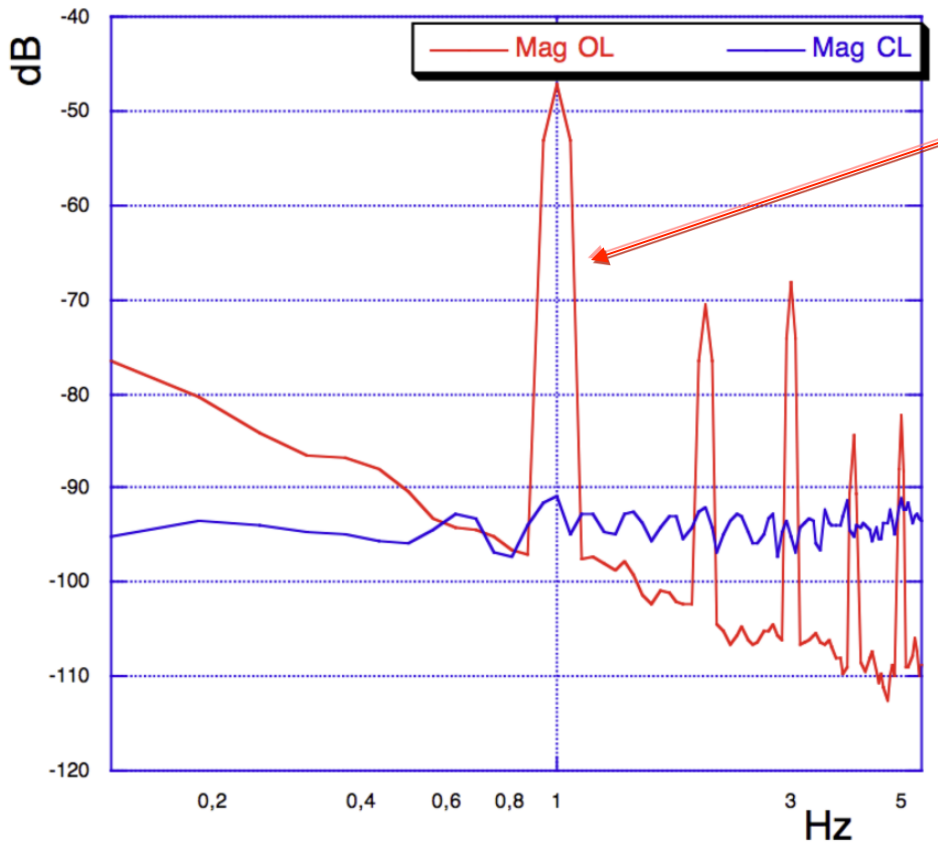


Active reduction of the vibration cold head reduced (@T=4K)



displacement noise density

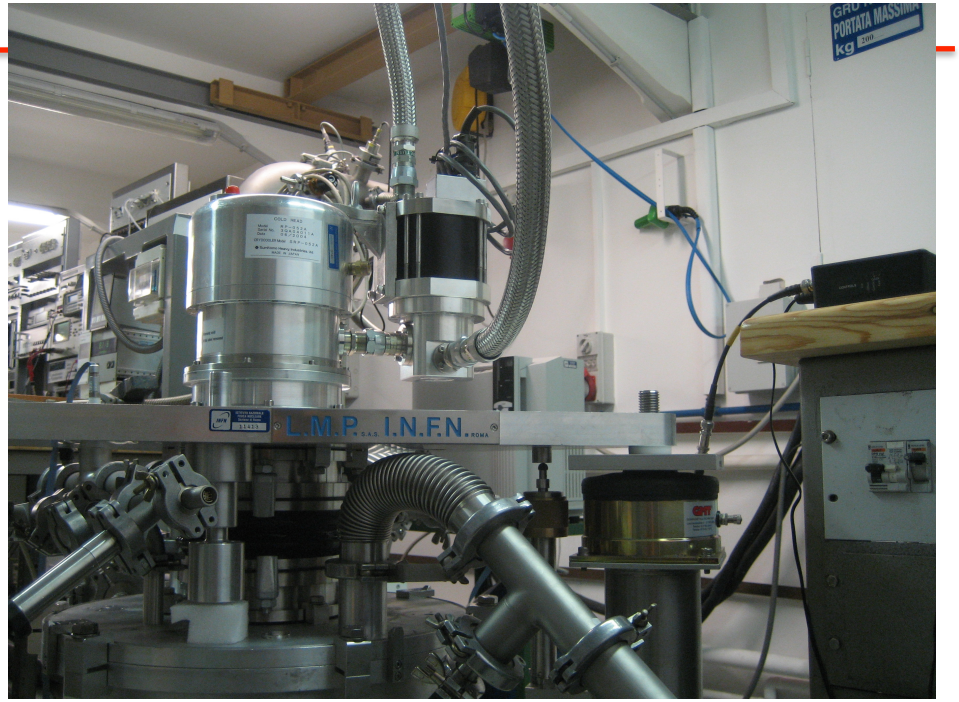
$$\Delta x = 29 \left[\mu m / \sqrt{Hz}\right] \quad @1\ Hz$$

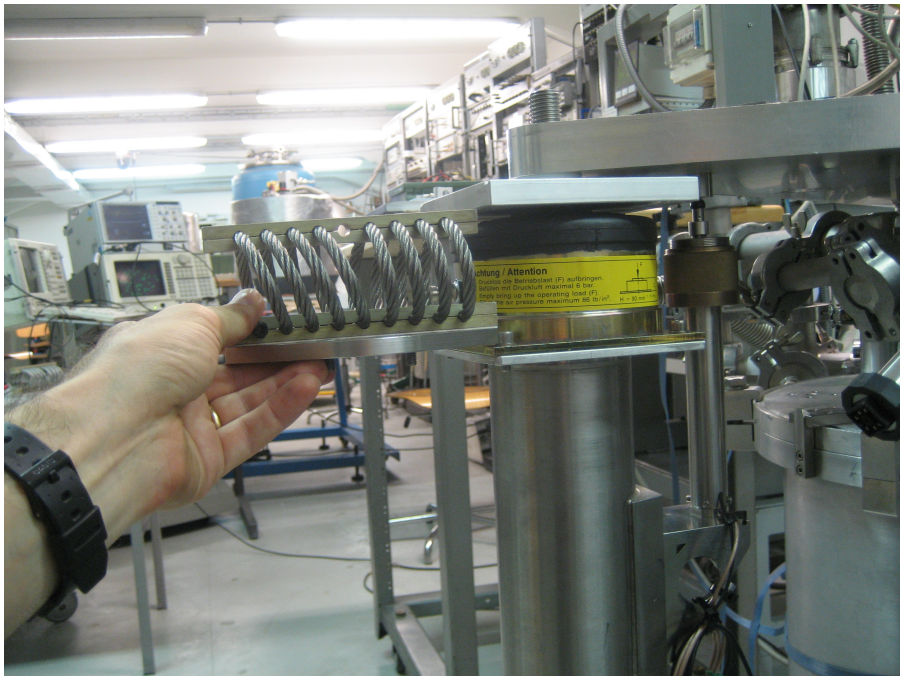


$$\frac{\Delta x_{OL}}{\Delta x_{CL}} = 220 \quad @\ 1Hz$$

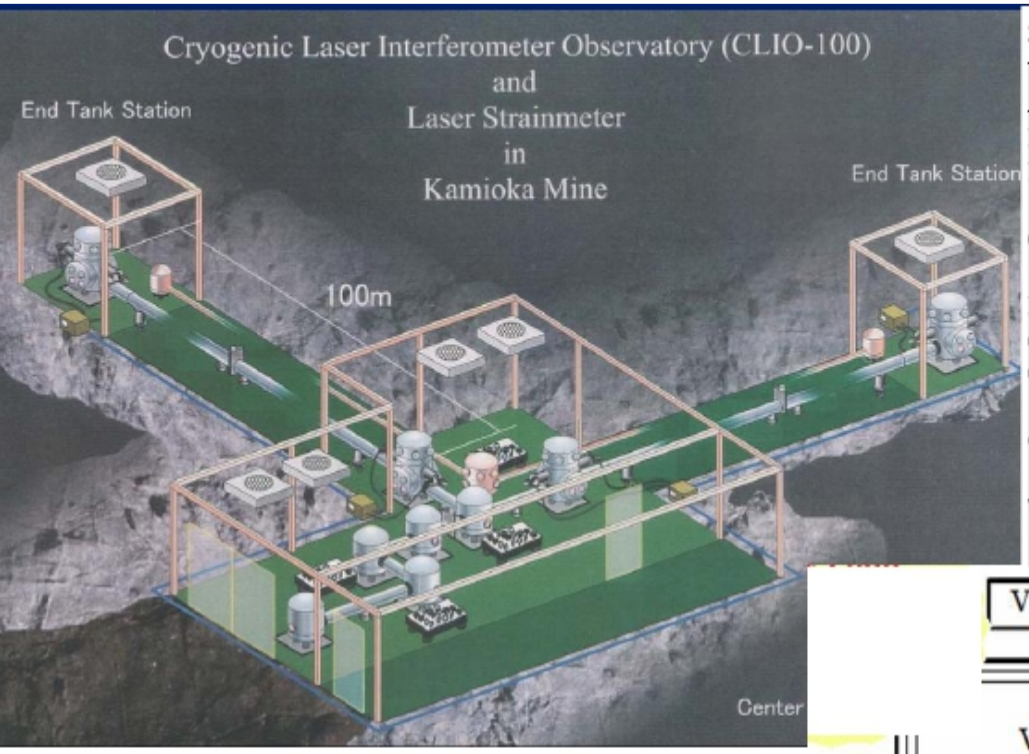
The vibration reduction scheme can be improved by modifing the sensing for reducing the noise floor at closed loop.

Photo gallery of the VFC



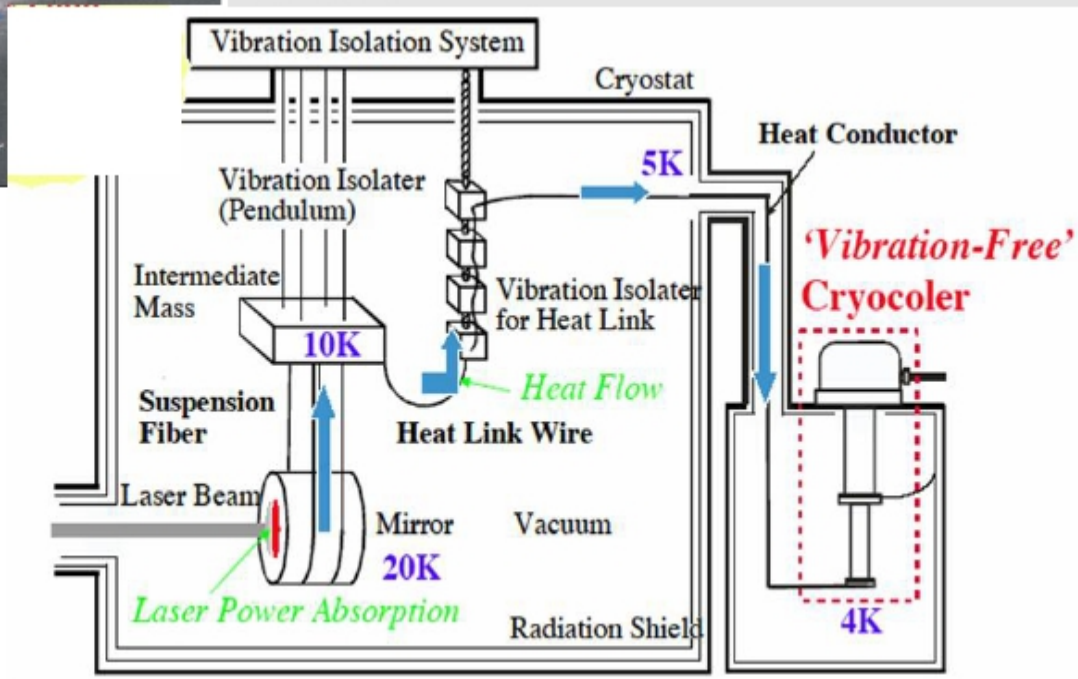


Advanced vibration isolation:4 K PTCs (CLIO-100)



Specification for the CLIO cryocooler system

	4 K cryocooler unit		80 K cryocooler unit
Number of cryocoolers	4 units		6 units
Basic cryocooler	Two stages pulse tube cryocooler		Single stage pulse tube cryocooler
Compressor power consumption	7 kW		7 kW
Power frequency	60 Hz		60 Hz
Cold stages	2nd stage	1st stage	80 K stage
Objects to be cooled	Mirror and inner shield	Outer shield	Laser-beam duct shield
Cooling performance requirement	0.5 W at 5 K	20 W at 50 K	50 W at 80 K
Vibration amplitude requirement	<±1 μm	<±1 μm	<±1 μm



"Vibration-free" 4 K PTC for CLIO, T. Tomaru et al., Cryocoolers 13 (2004), p. 695

Y. Matsubara, WEH-Workshop "Applied Cryoelectrics" (2006)

Y. Ikushima et al. , Cryogenics 48 (2008) p. 406

Conclusion

KAGRA is tracing the map for the future GW detectors. Still a lot of effort is required for

✓The material characterization,

✓The suspension improvement and its compatibility with the cryo temperatures ,

✓The development of new auxiliary sensors and actuators

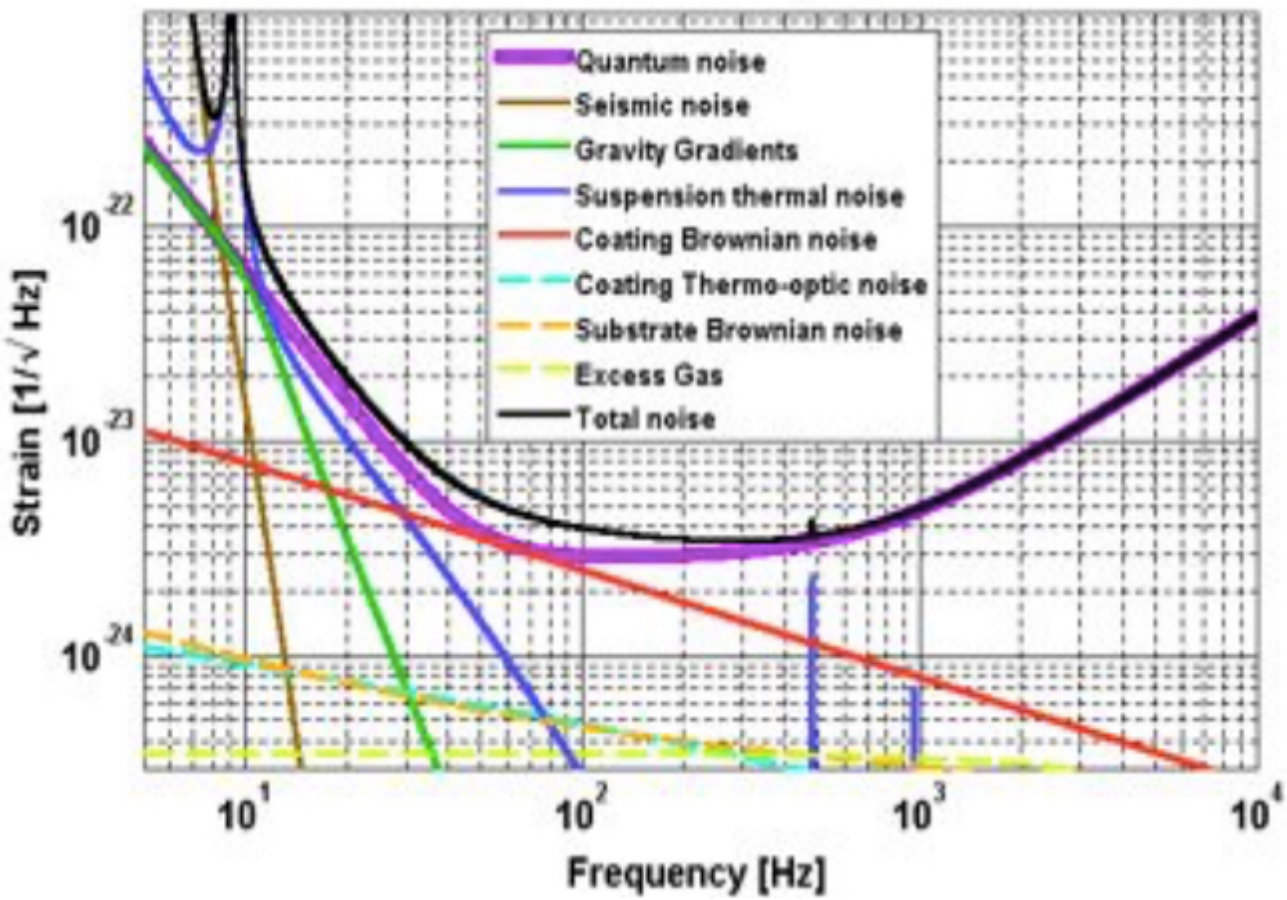
✓The noiseless cooling process

EXTRA SLIDES

Optical noise and GW ITF

- For future interferometers Quantum noise can be the ***main*** limiting noise source.

- Example: Broadband configuration of Advanced LIGO

(tuned Signal Recycling)

- For all frequencies above 12Hz Quantum noise is the limiting noise.