Experimental Requirements

1) momentum kick imparted by photon has to be larger than the initial quantum uncertainty of the mirror's momentum

$$\frac{2\hbar N^3 L}{\pi c M \lambda^2} \gtrsim 1$$

Optimum 700 nm 10x10x10 μm SiO_2/Ta_2O_5 mirror

$N \sim 10^5 - 10^6$

$L \sim 1 - 5\,cm$

$\omega_m \sim 2\,kHz \longrightarrow \Delta x_{mirror} = 10^{-13}\,m$

Experimental Requirements

2) environmental decoherence time ~ 1 period

$$\gamma_D = \gamma_m k_B T M (\Delta x)^2 / \hbar^2 \qquad \text{(Zurek et al)}$$

$\uparrow$ damping rate cantilever

$$\rightarrow Q = \omega_m / \gamma_m \gtrsim 10^5 \qquad \text{(@3mK Rugar et al)}$$

Q=150.000 leads to required T<8mK for bulk material

Experimental Requirements

3) Stability of order $\lambda / 20N \sim 10^{-14}$ m

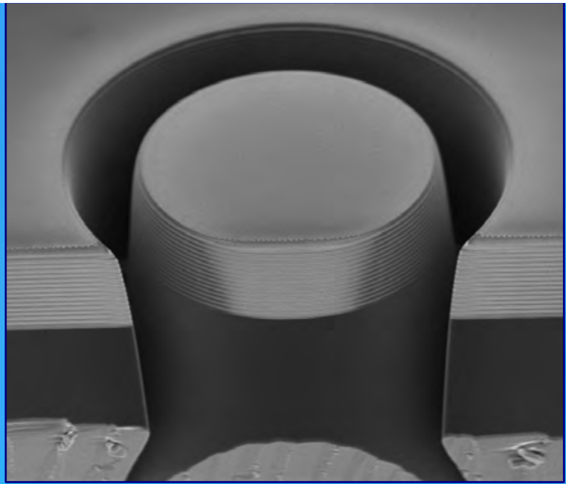
on timescale of experiment.

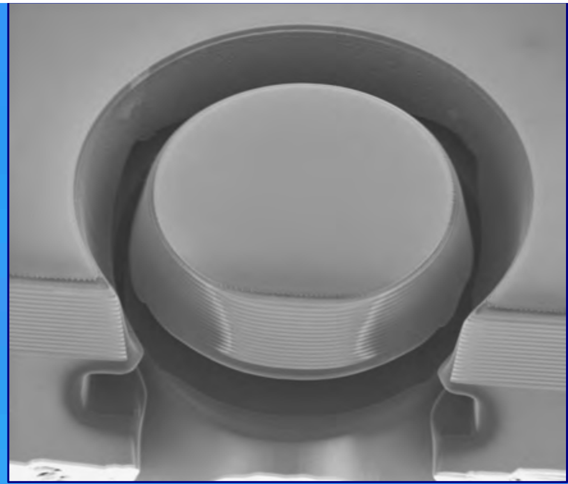
(STM 10^{-13} m/min

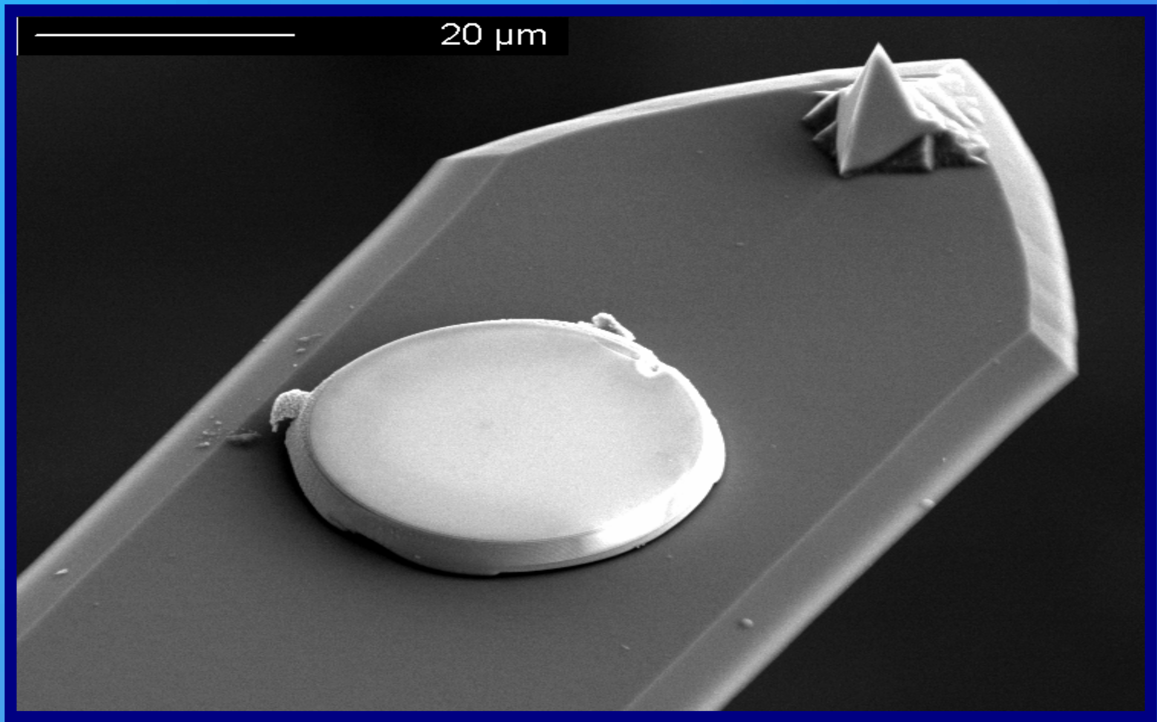
Gravitational wave detection 10^{-19} m/ms)

Great help <u>Switchable</u> mirrors

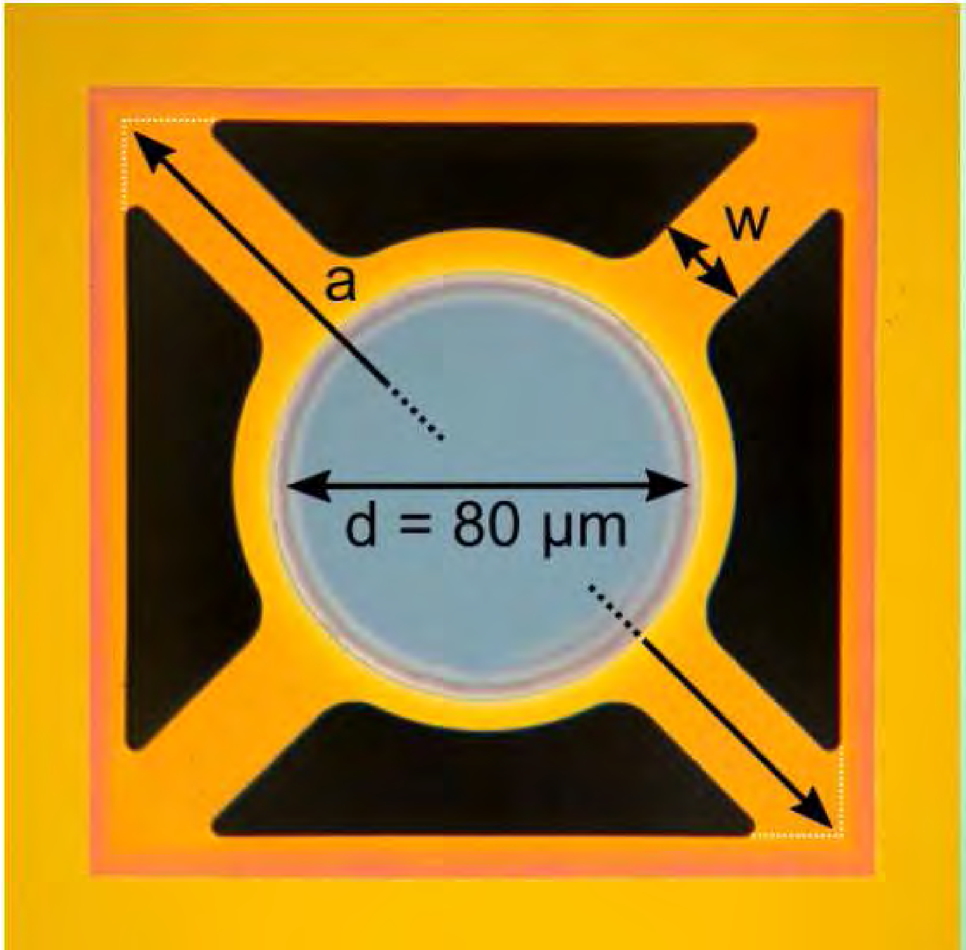
4) UUHV background density ~ 100 particles/cm^3

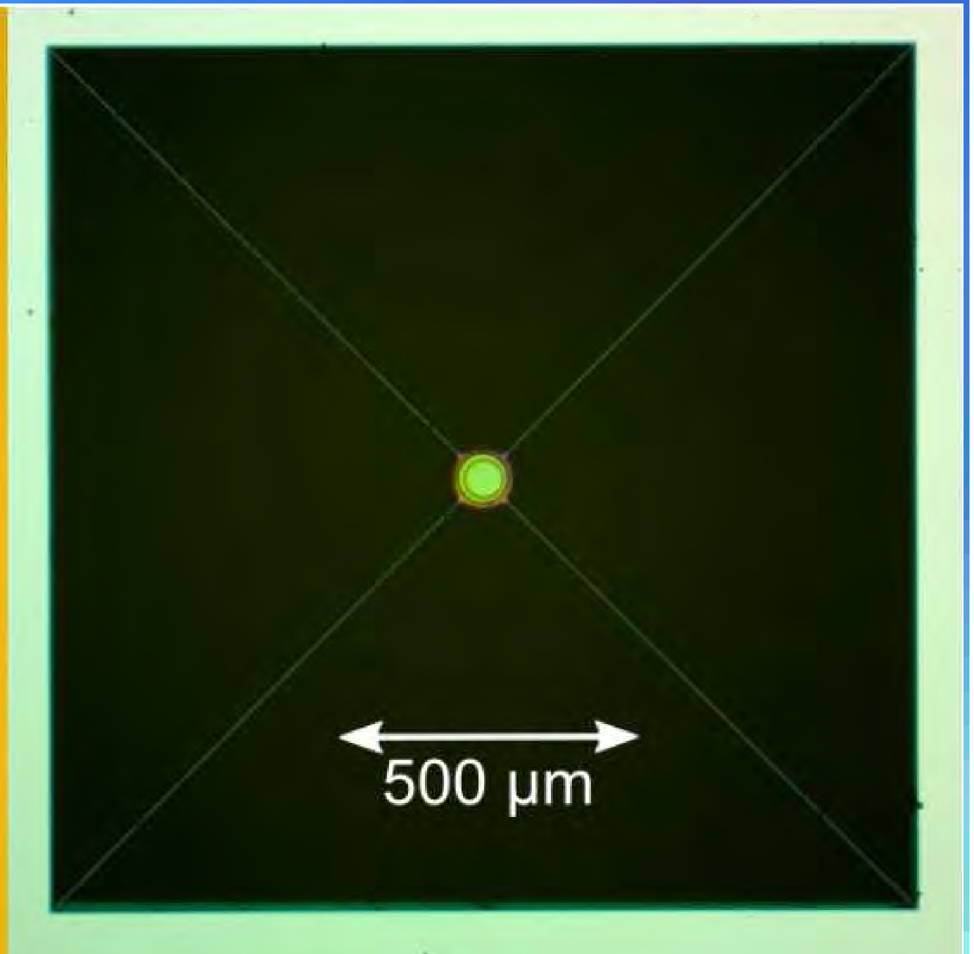






Optical Q=2100
Mechanical Q=137.000
PRL **96**, 173901 (2006)





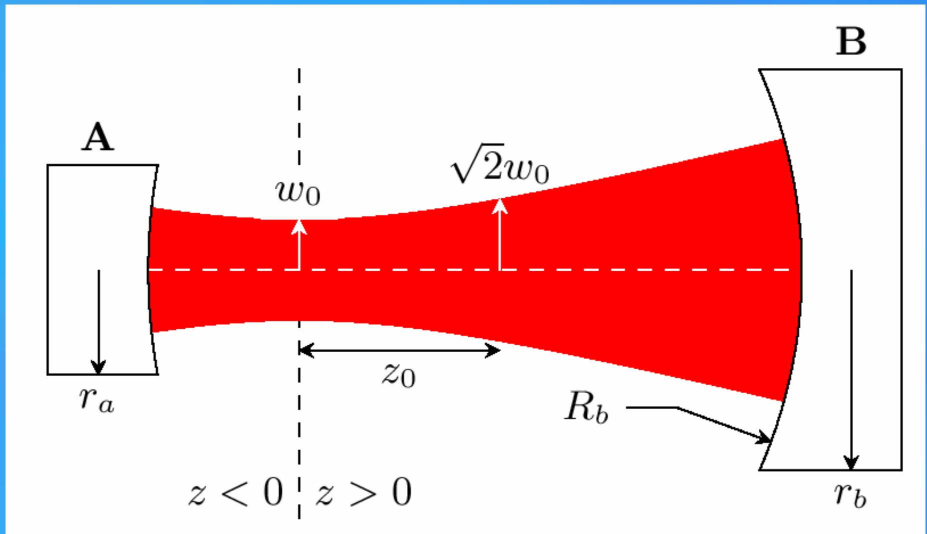
80 µm mirror

60 µm mirror

Best performance at 300K: mechanical Q>900.000, Finesse~40.000

Sideband resolved

Dustin Kleckner et al, *diffraction limited high-finesse optical cavities*
Phys. Rev. A **81**, 043814 (2010)

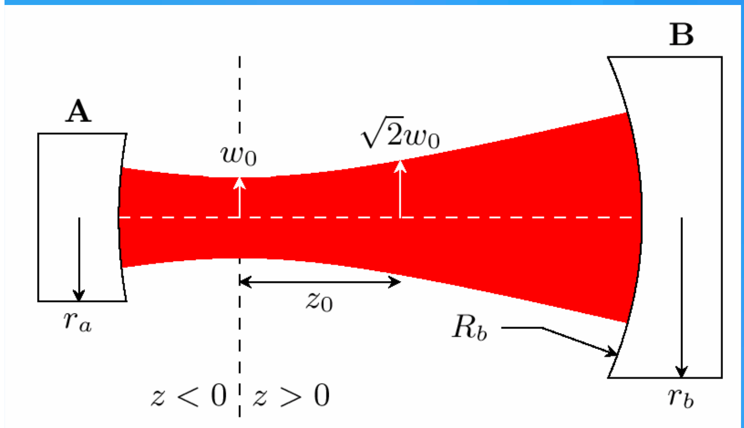


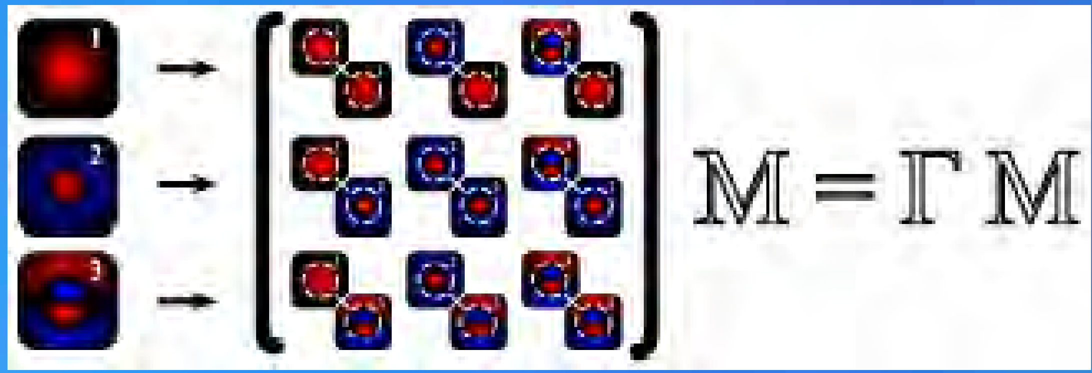
Laguerre Gaussian mode decomposition

$$
\begin{aligned}
E^{\pm}_{n,m}(r,\phi,z) &\propto \left[\frac{r^{|m|}}{w(z)^{|m|+1}}\right] L_n^{|m|}\left[\frac{2r^2}{w(z)^2}\right] \exp\left[-\left(\frac{r}{w(z)}\right)^2 - im\phi \pm i\Theta(r,z)\right] \\
\Theta(r,z) &= (2n+|m|+1)\tan^{-1}\left(\frac{z}{z_0}\right) - k\left(z + \frac{r^2}{2R(z)}\right) \\
z_0 &= \frac{kw_0^2}{2} \\
w(z) &= w_0\sqrt{1+\left(\frac{z}{z_0}\right)^2} \\
R(z) &= z\left[1+\left(\frac{z_0}{z}\right)^2\right]
\end{aligned}
$$

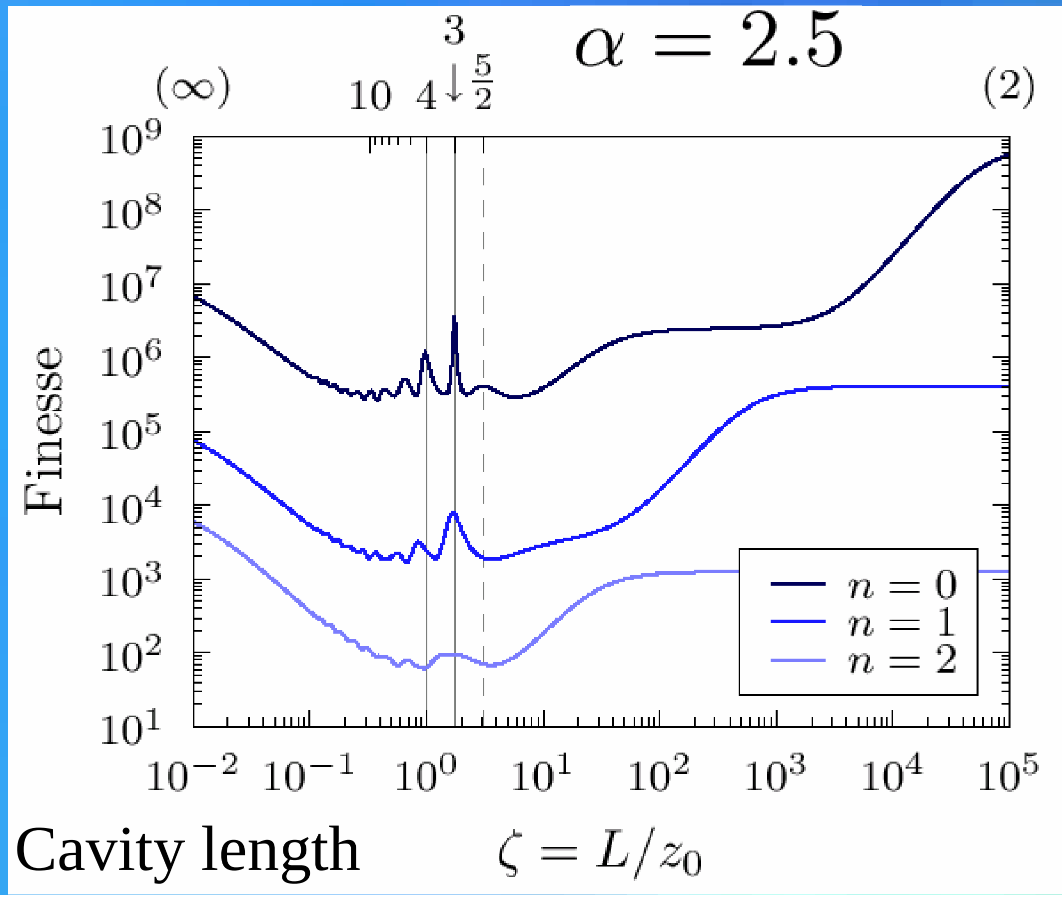
Gouy shift

Simulate diffraction limited finesse

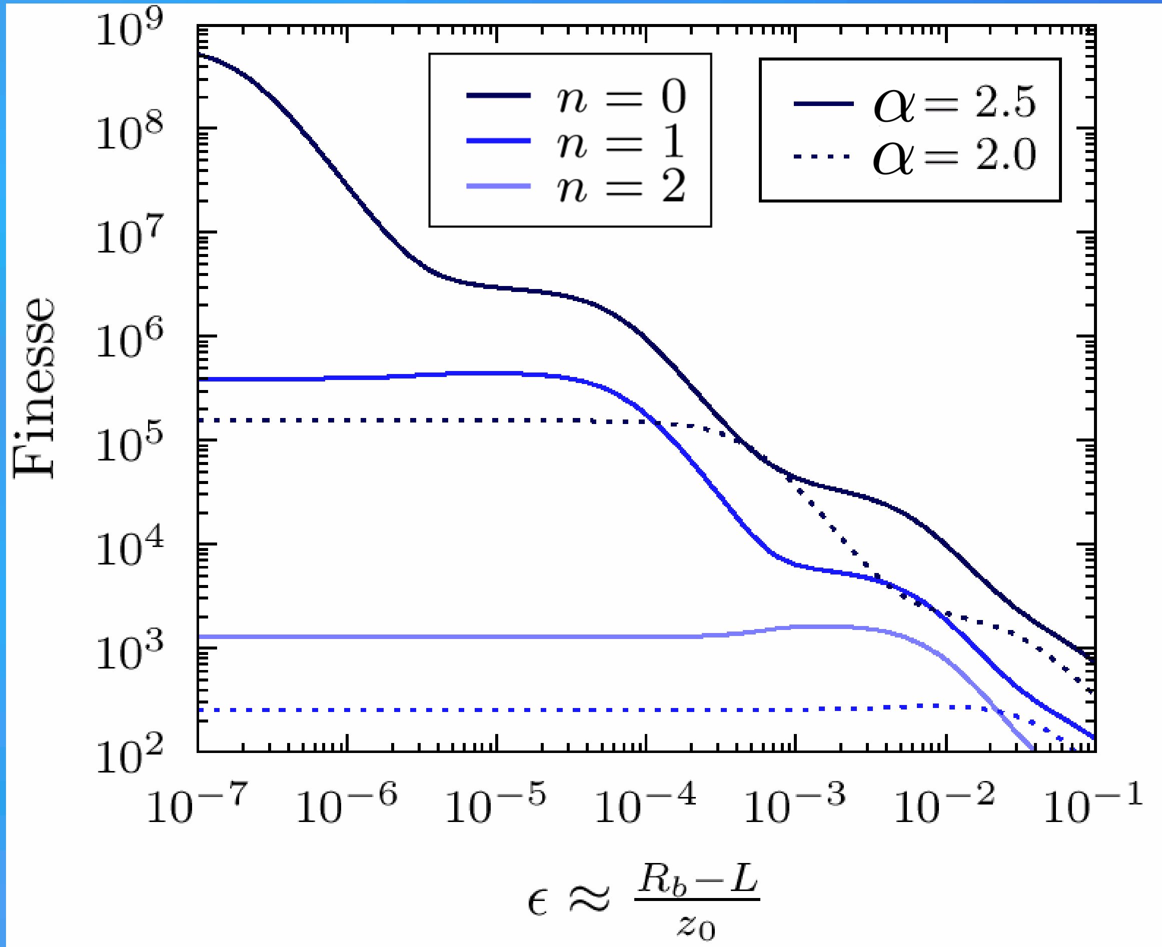




$$
\begin{aligned}
r_a &= \alpha w_0 \\
R_a &= \infty \\
z_a &= 0 \\
r_b &= \alpha w(z_b) \\
R_b &= R(z_b) \\
z_b &= L = \zeta z_0
\end{aligned}
$$



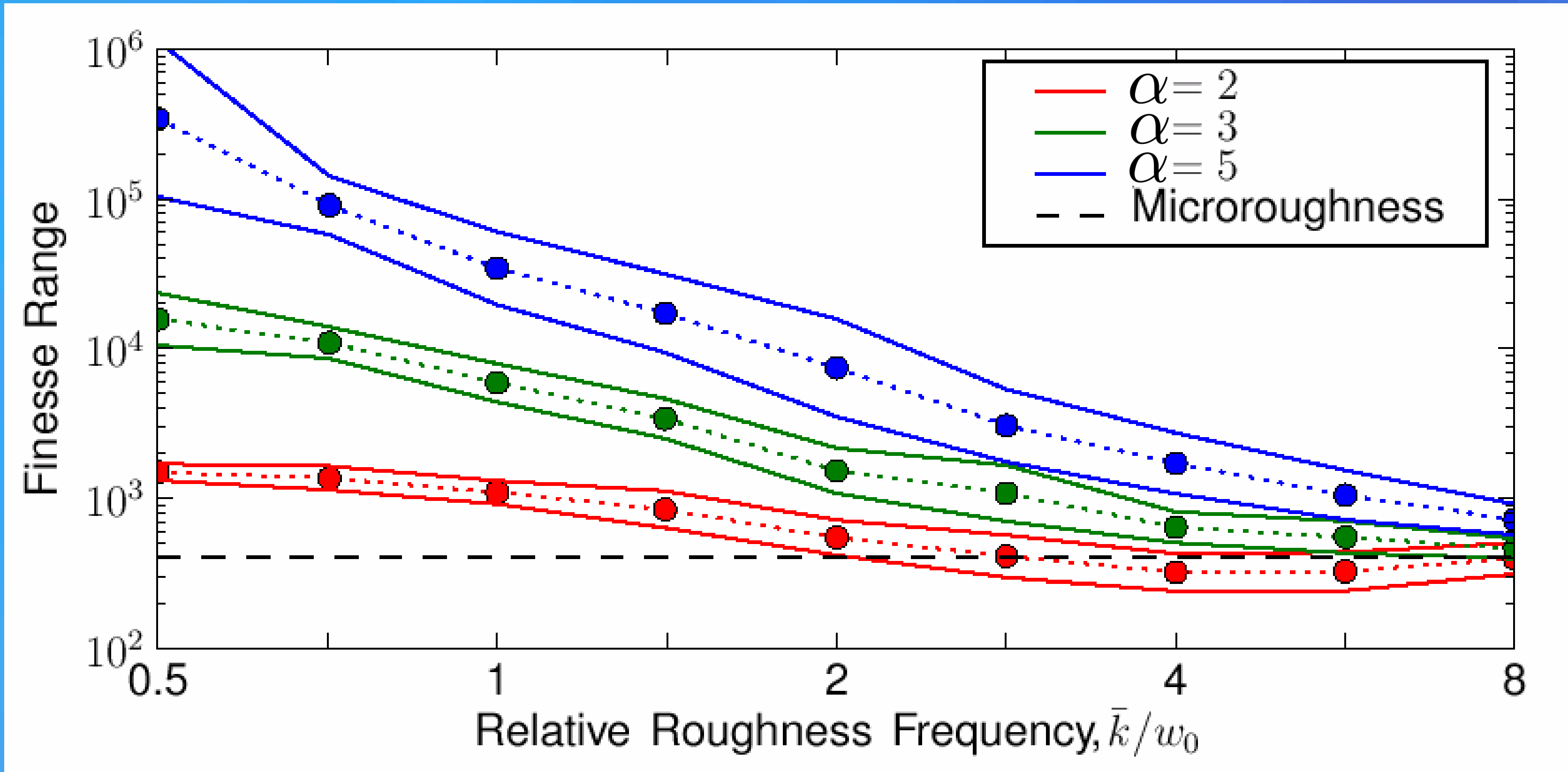
Effect of defocusing: radial phase shift $\exp[-2i\epsilon\rho^2]$



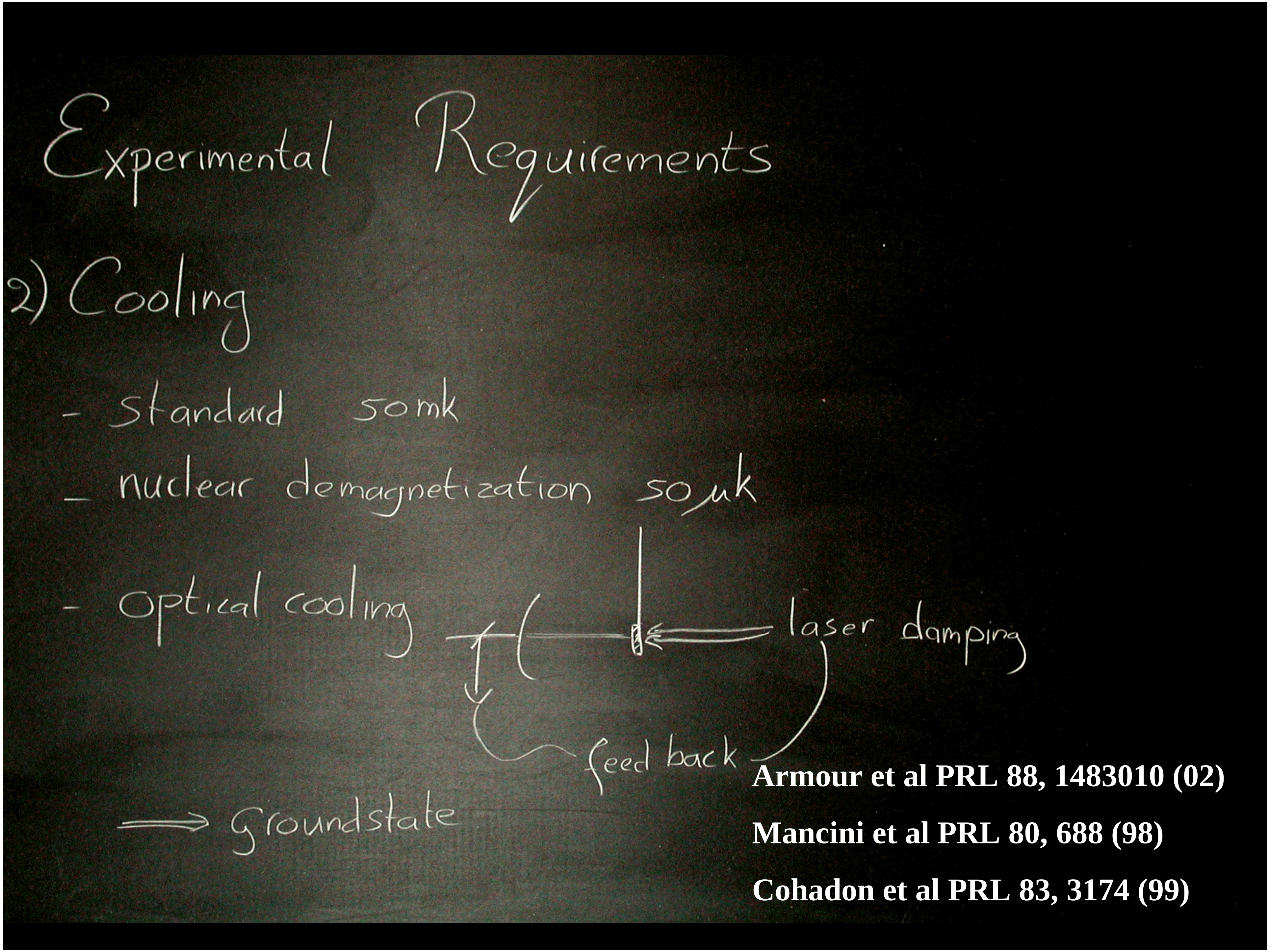
For Finesse 10^6 and z_0=10μm alignment accuracy 1nm required!

Effect of mirror roughness

$\sigma = 10^{-2}\lambda$



Surface quality of curved mirror is expected bottle neck for reaching ultra high finesse 10^6-10^7

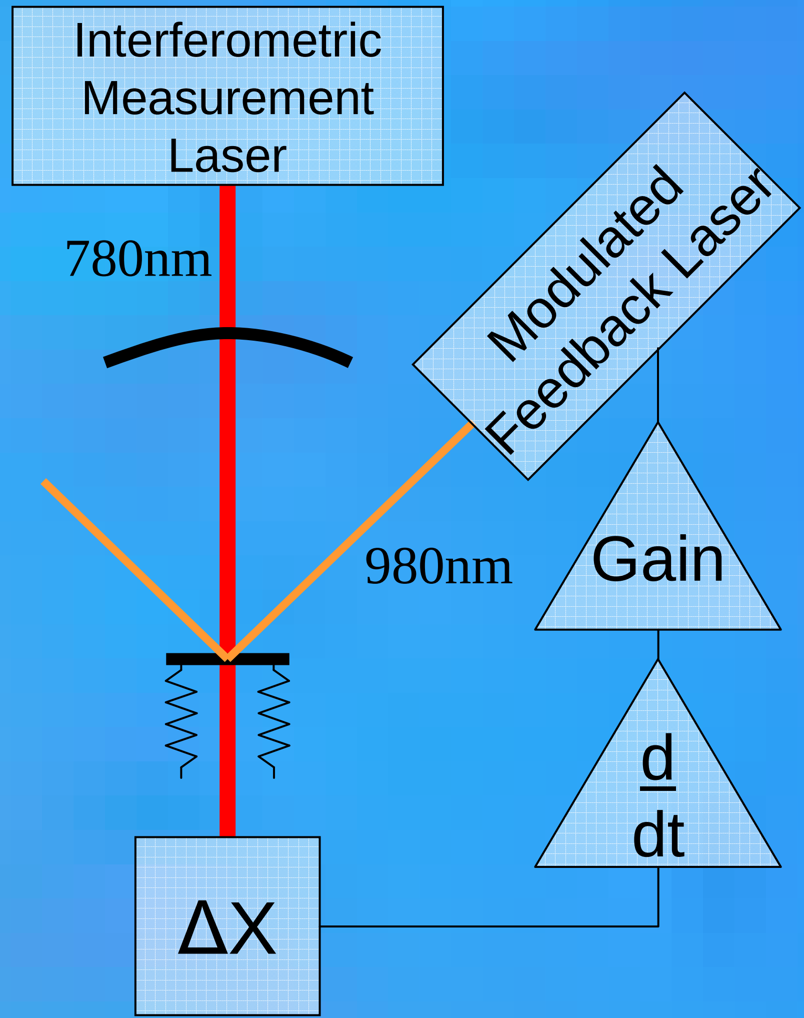


Armour et al PRL 88, 1483010 (02)

Mancini et al PRL 80, 688 (98)

Cohadon et al PRL 83, 3174 (99)

Optical Cooling



Final energy of cooled mirror

$$E_c = \frac{\hbar\omega_m}{2}\frac{1}{2(1+g)}\left[\frac{4k_B T_E}{\hbar\omega_m} + 2\xi + \frac{g^2}{\eta\xi}\right]$$

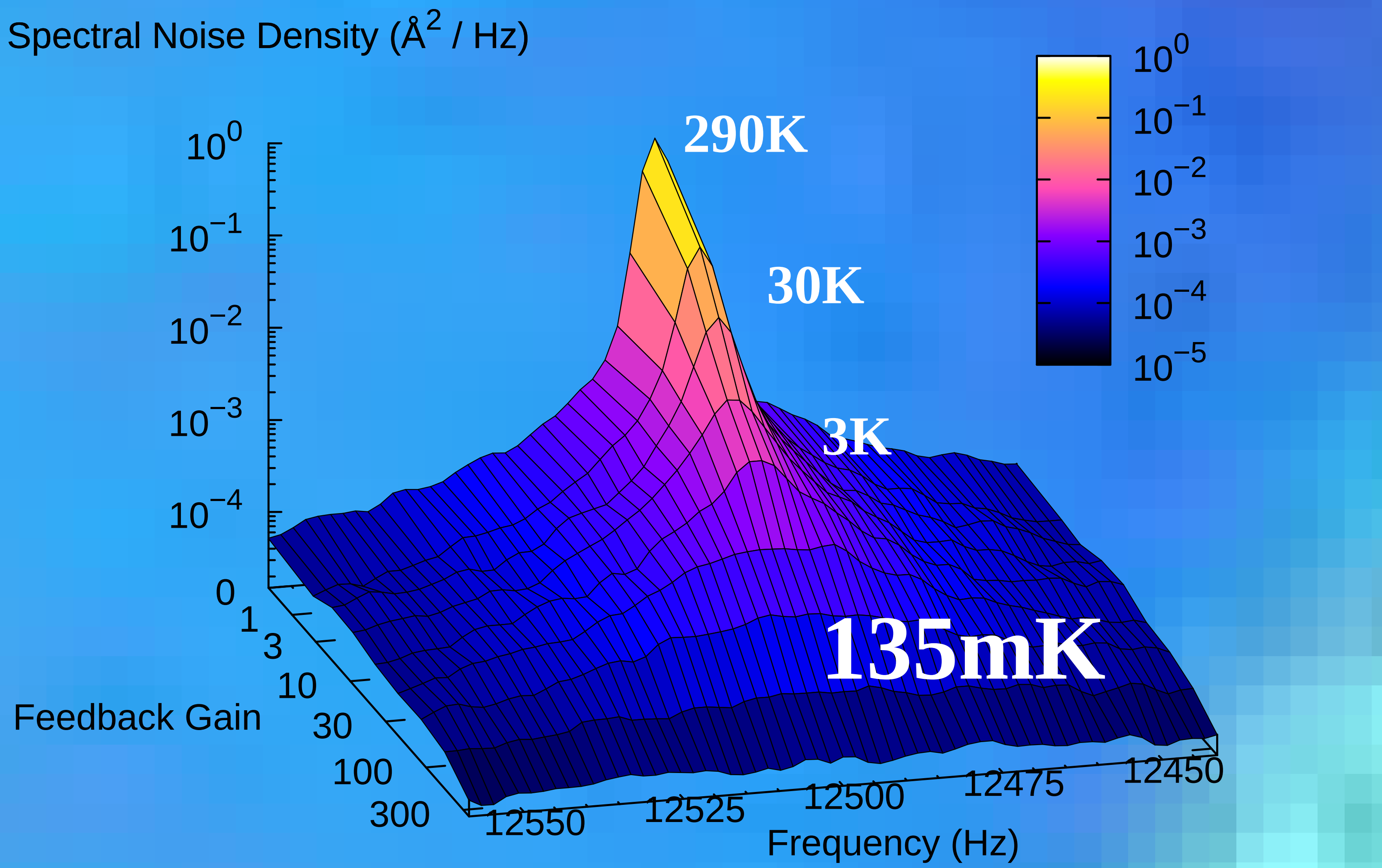
$$\xi = \left(64\pi c P / M\gamma_m \omega_m \lambda \gamma_c^2 L^2\right)$$

P: light intensity incident on measurement cavity

η: detection efficiency

Optical Cooling

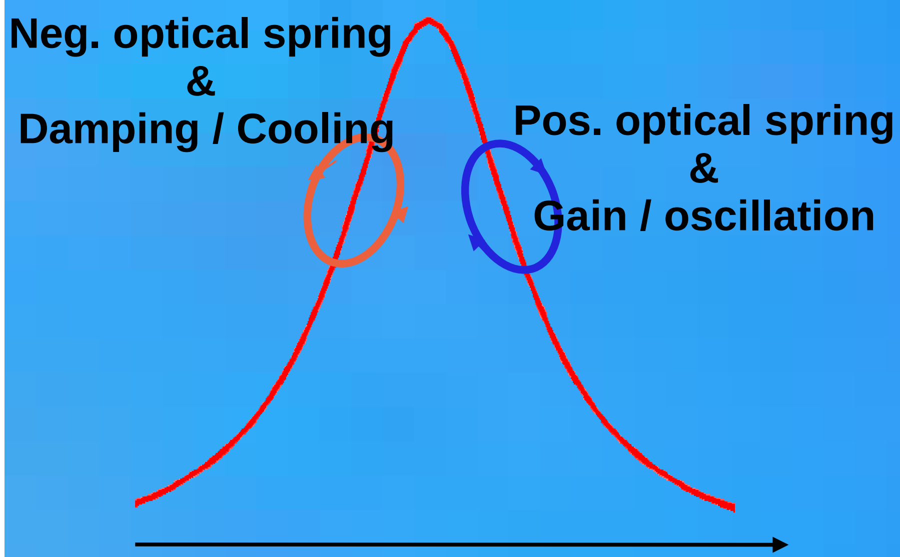
Gain factor 2500



D. Kleckner and D.B. Nature **444**, 75 (2006).

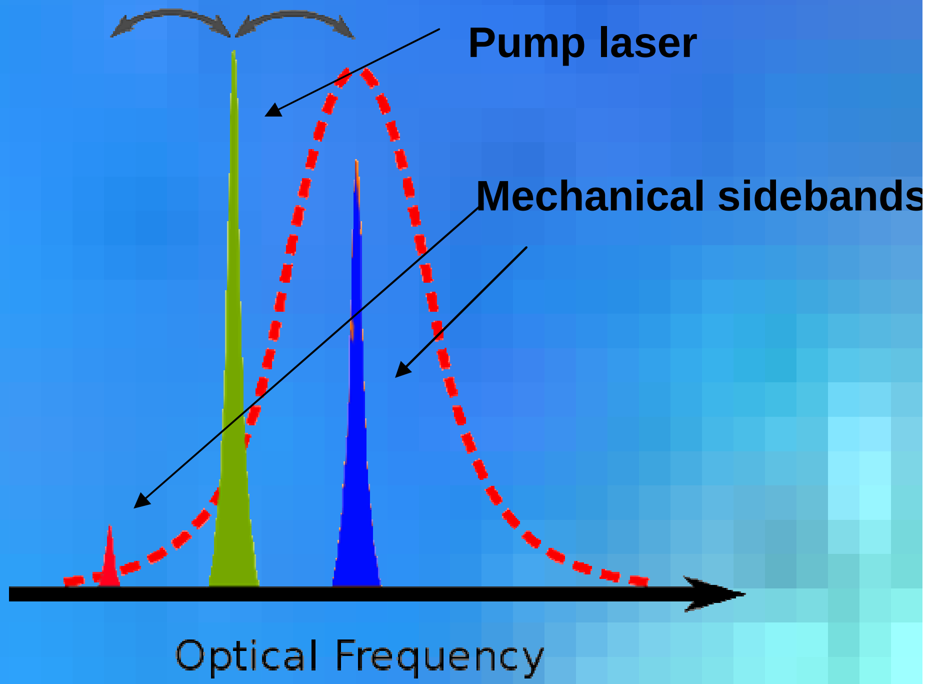
Passive Optical Cooling

Non-sideband resolved



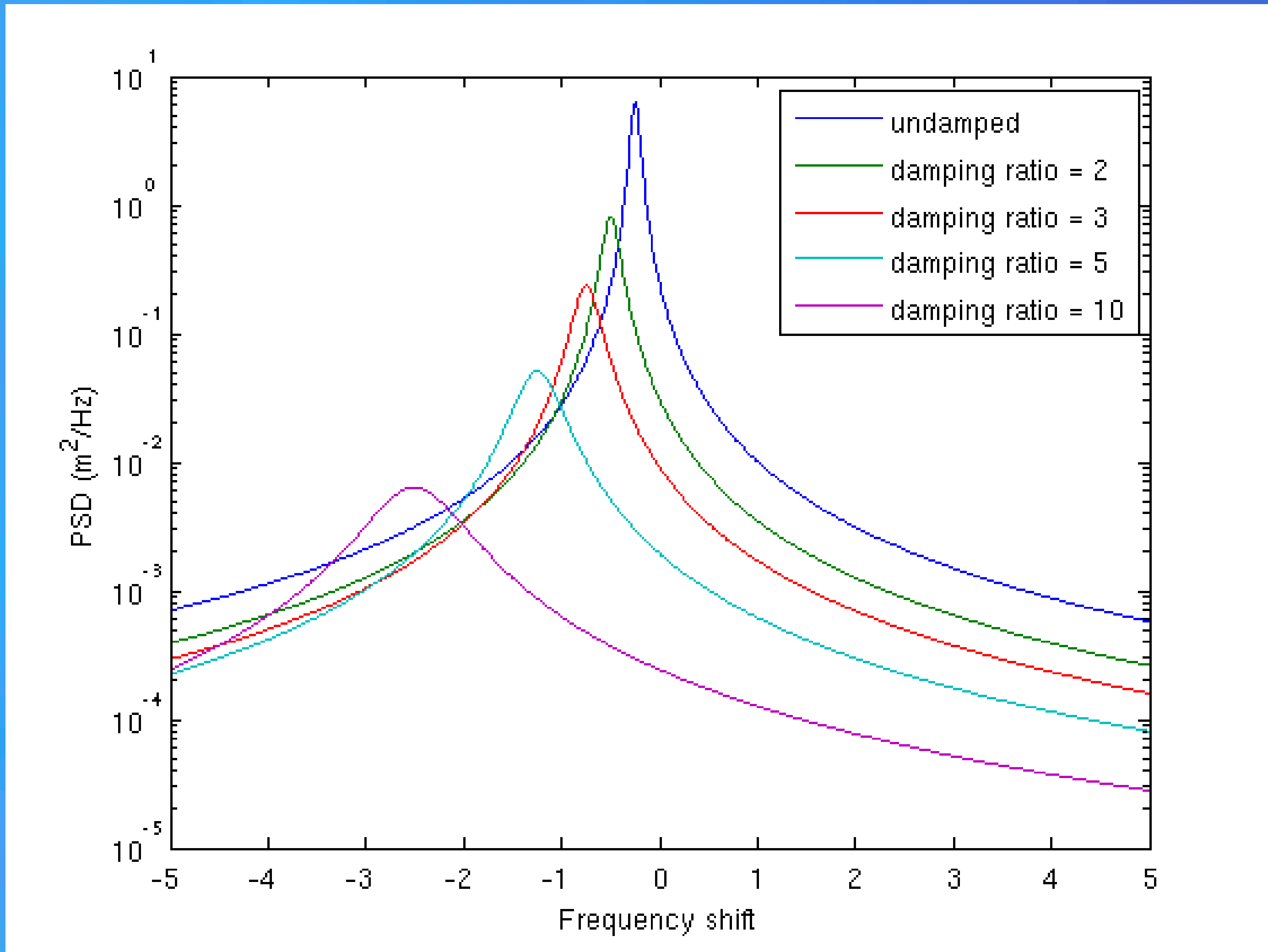
- High finesse cavity causes phase lag
- Red detuning gives damping
- Blue detuning causes amplification

Sideband resolved



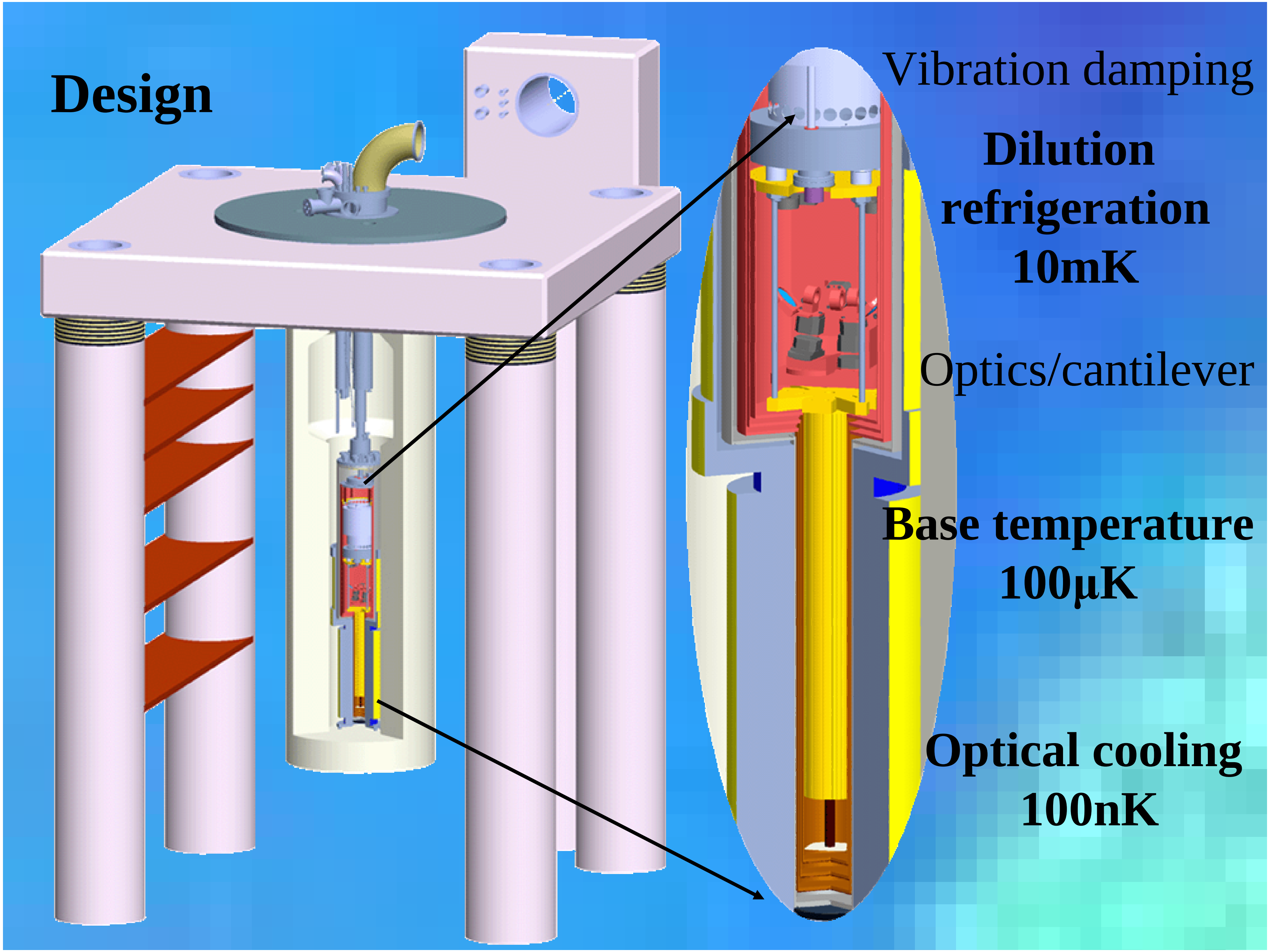
- Cavity enhances anti-stokes shift
- Suppression of stokes shifted line

Expected results (without laser noise)

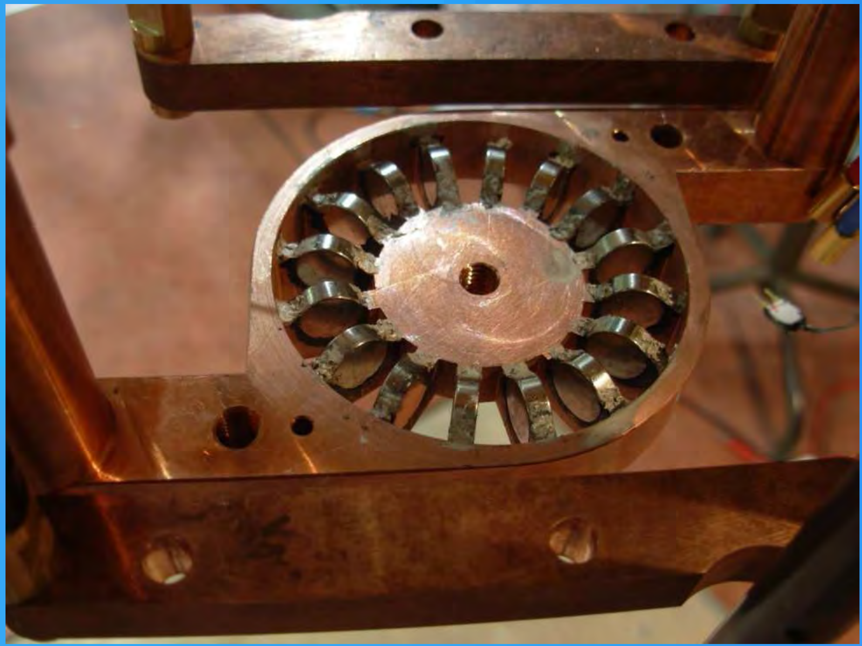


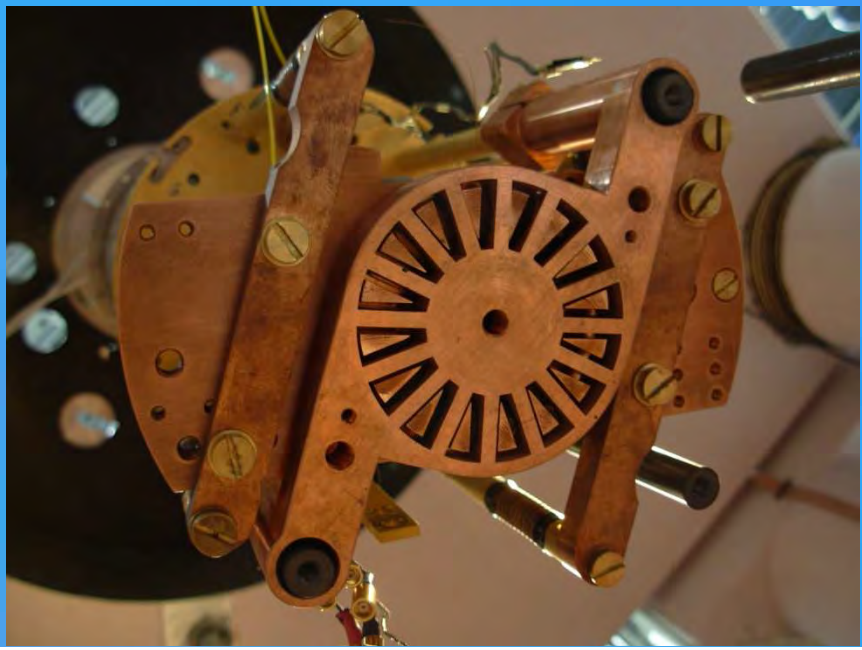
Leiden, the Netherlands

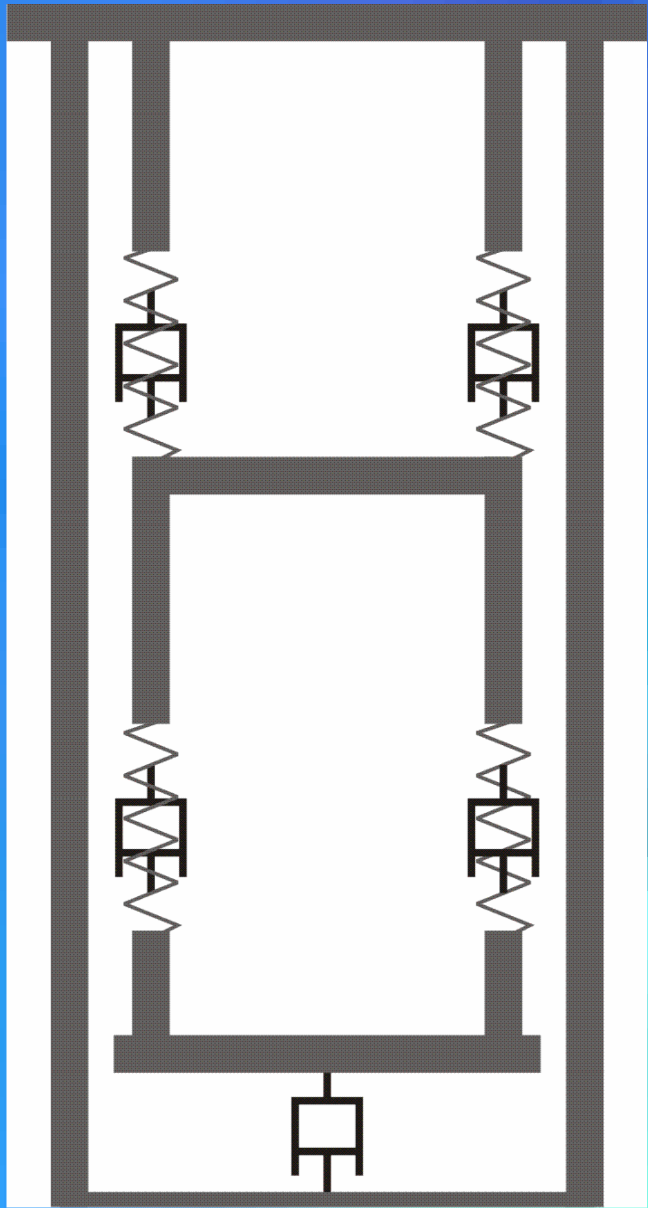
Design


Vibration damping
Dilution refrigeration 10mK
Optics/cantilever
Base temperature 100µK
Optical cooling 100nK

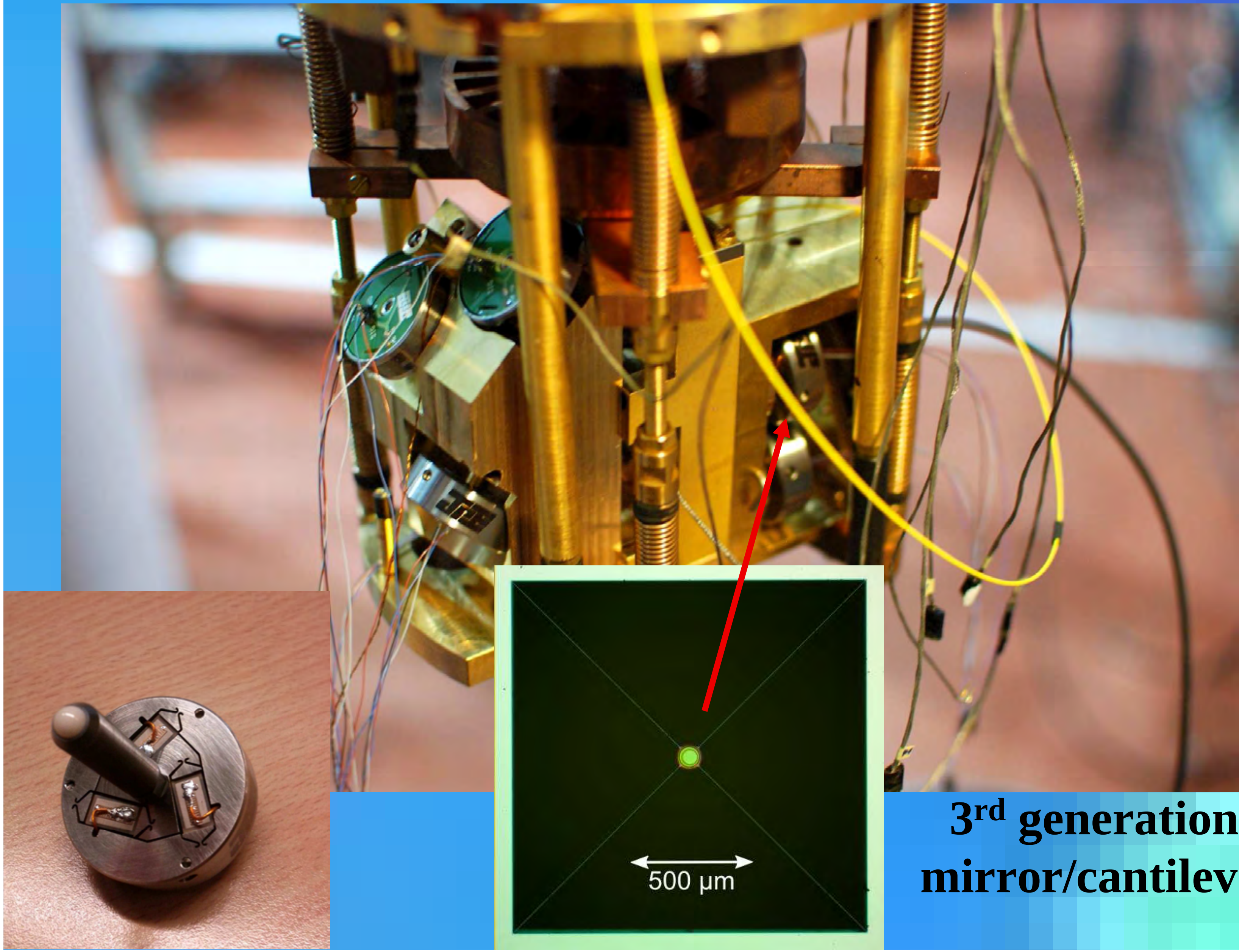
Vibration damping: Multi stage Eddy current damping



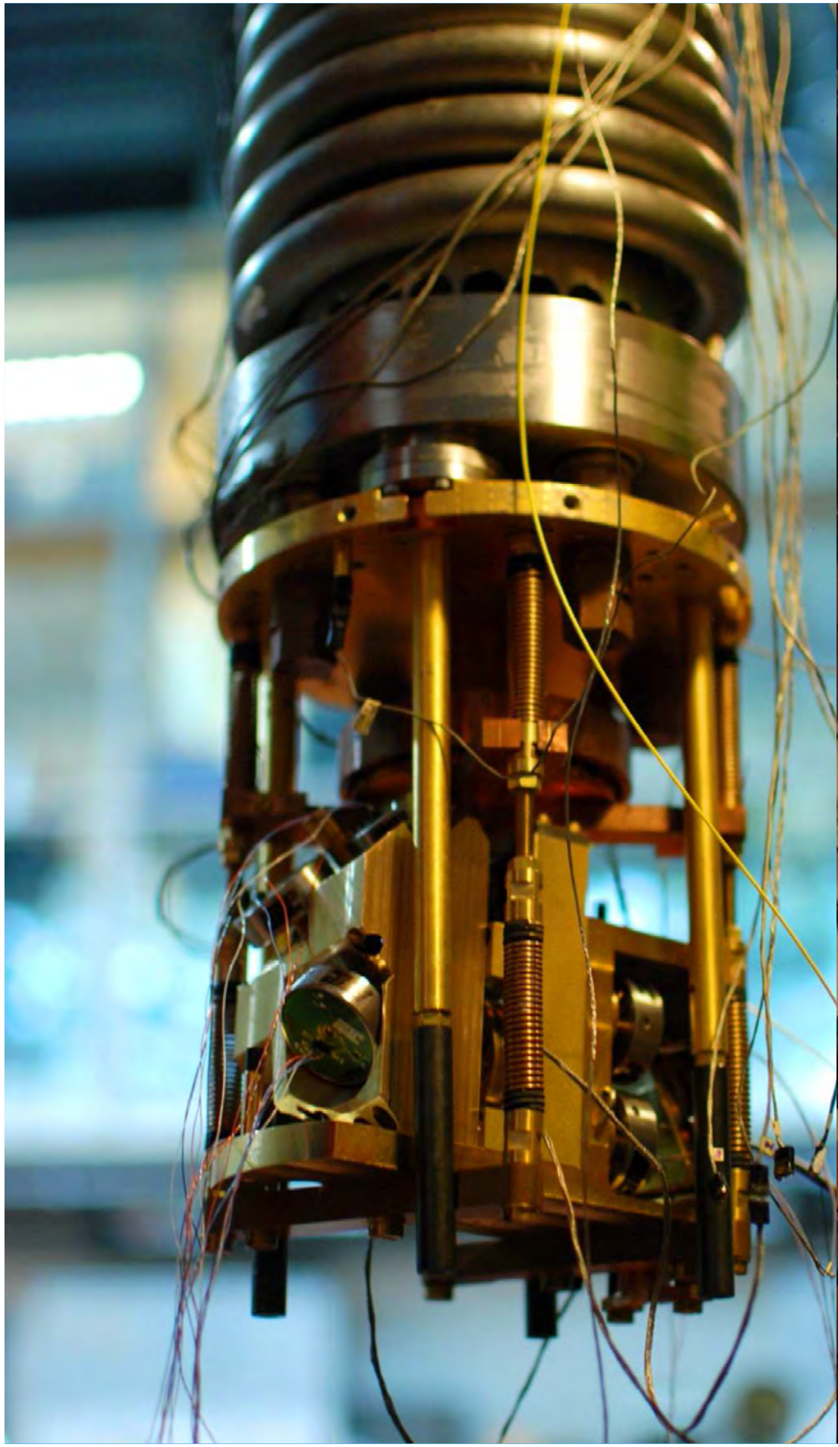


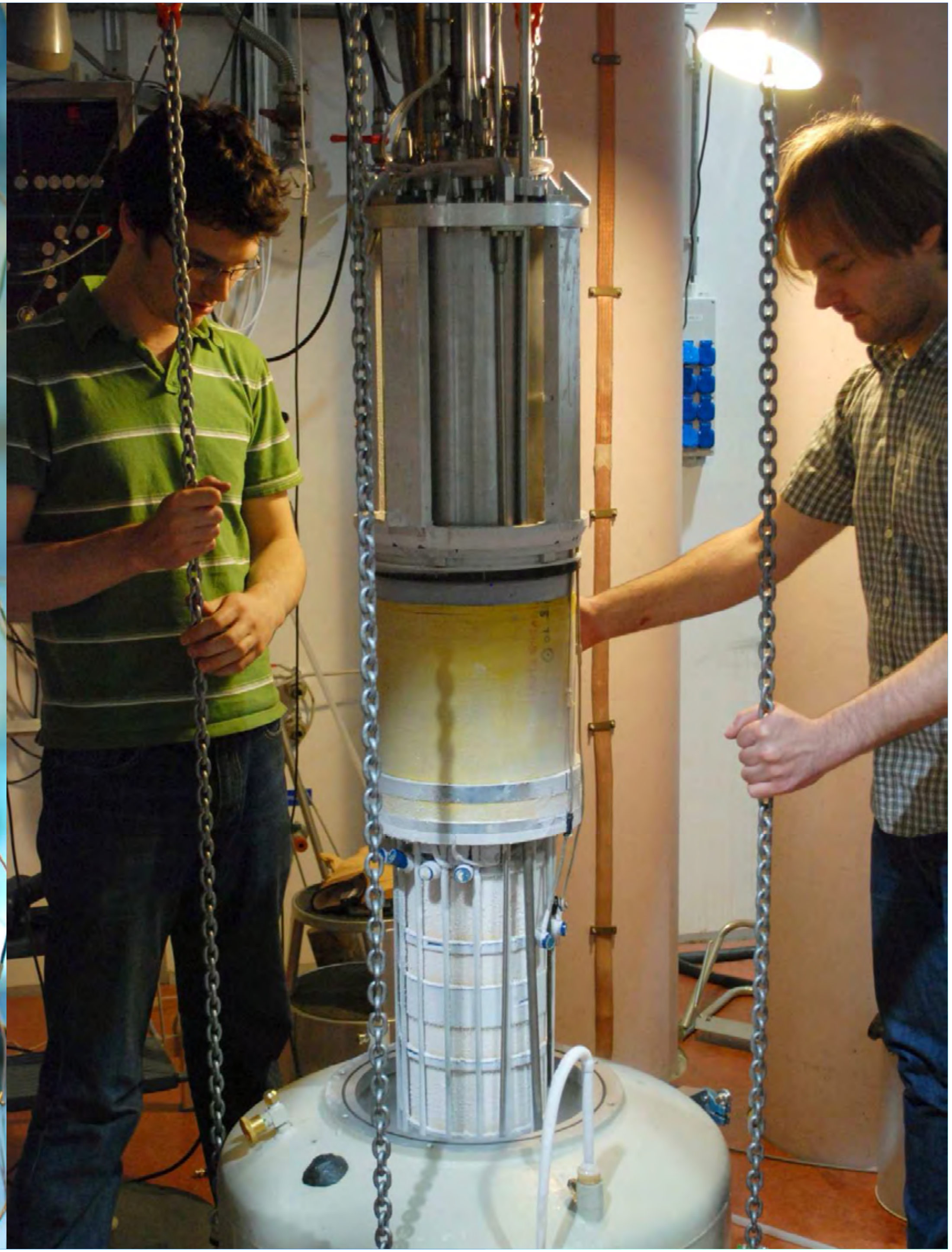


3rd generation optical setup

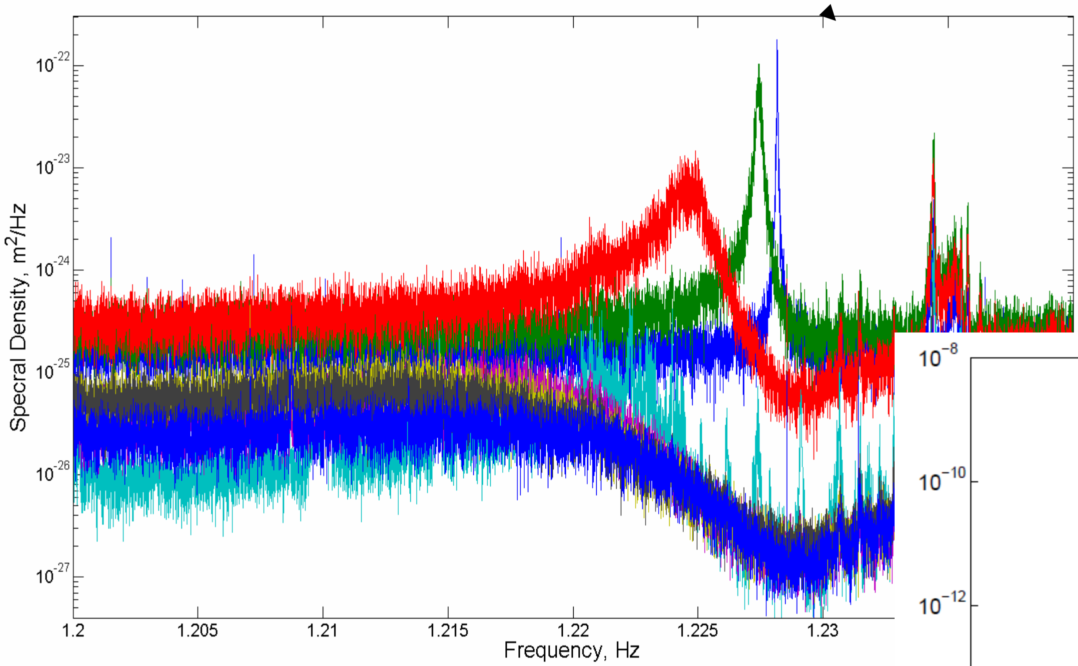


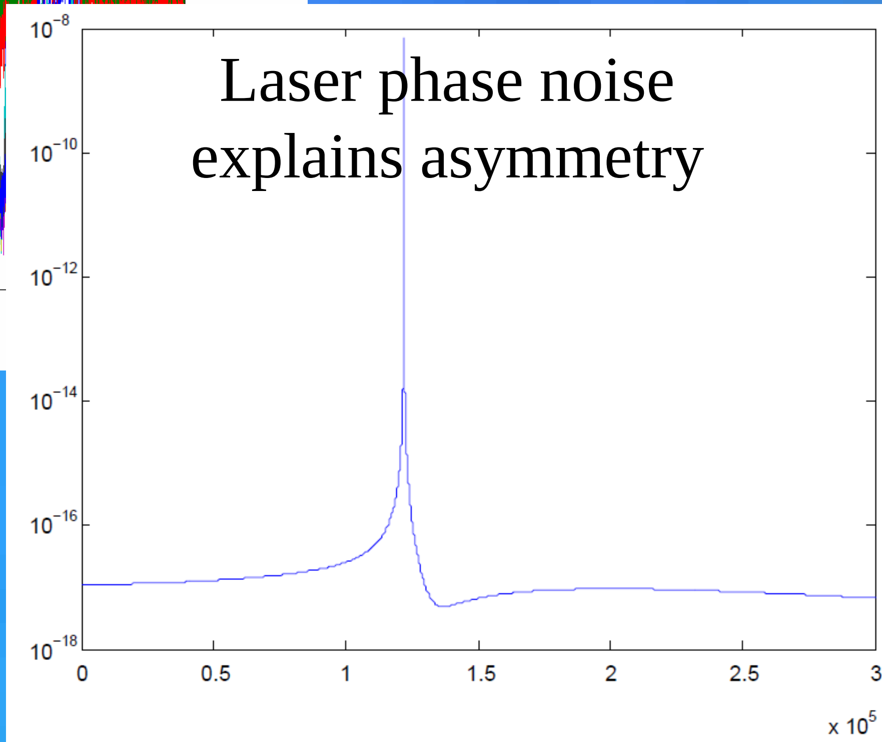
3rd generation mirror/cantilever



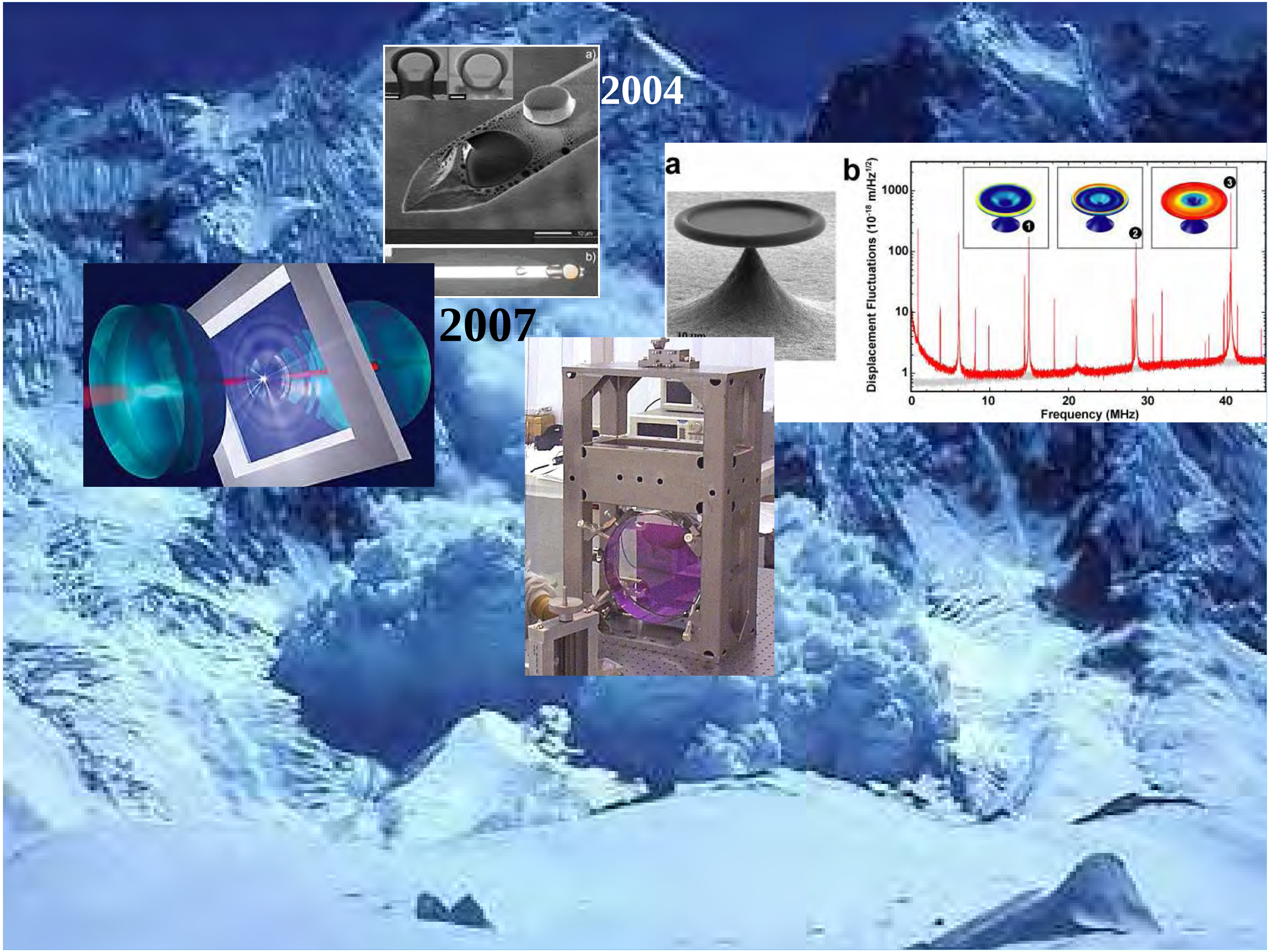


Obtained results

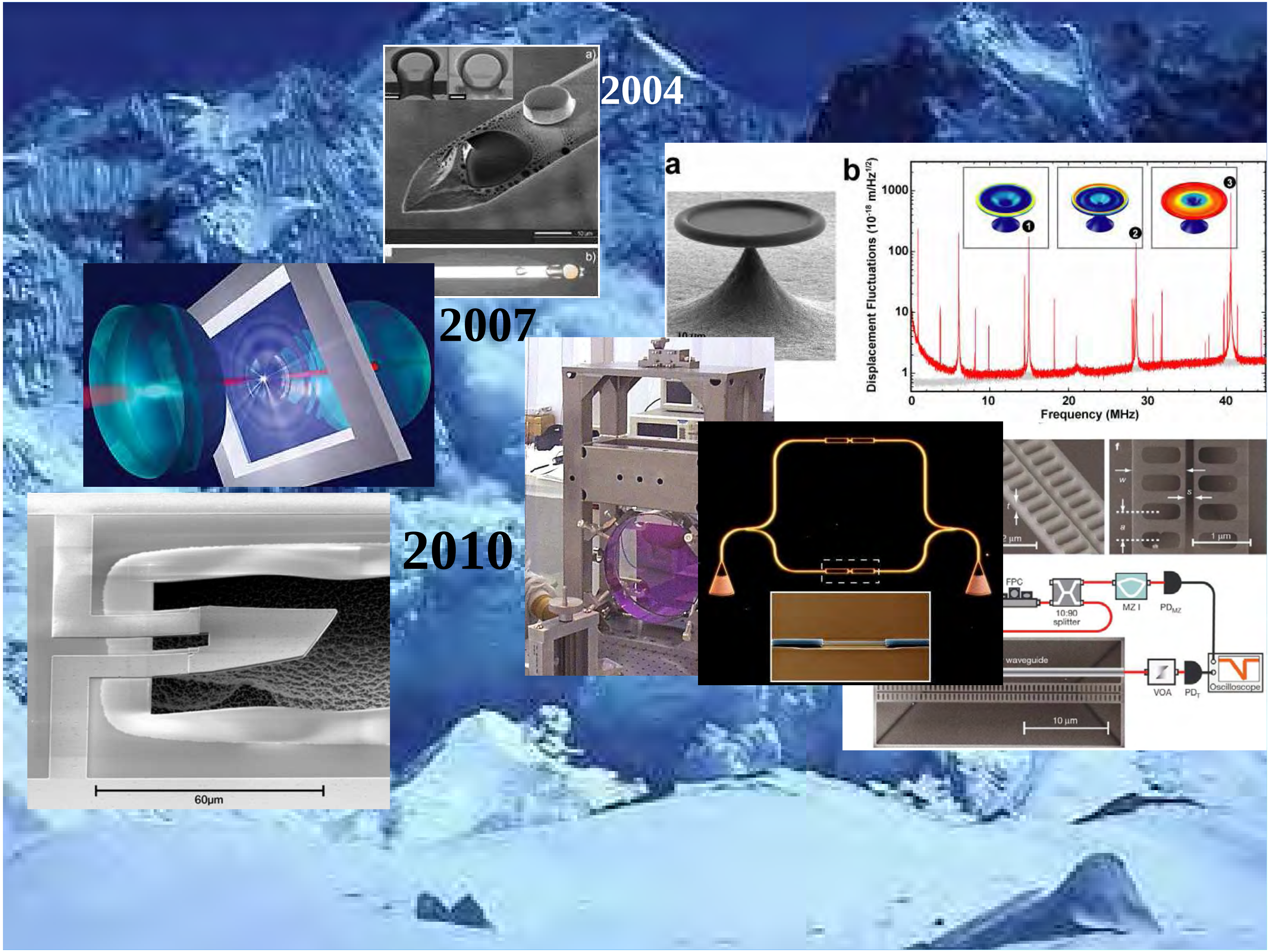




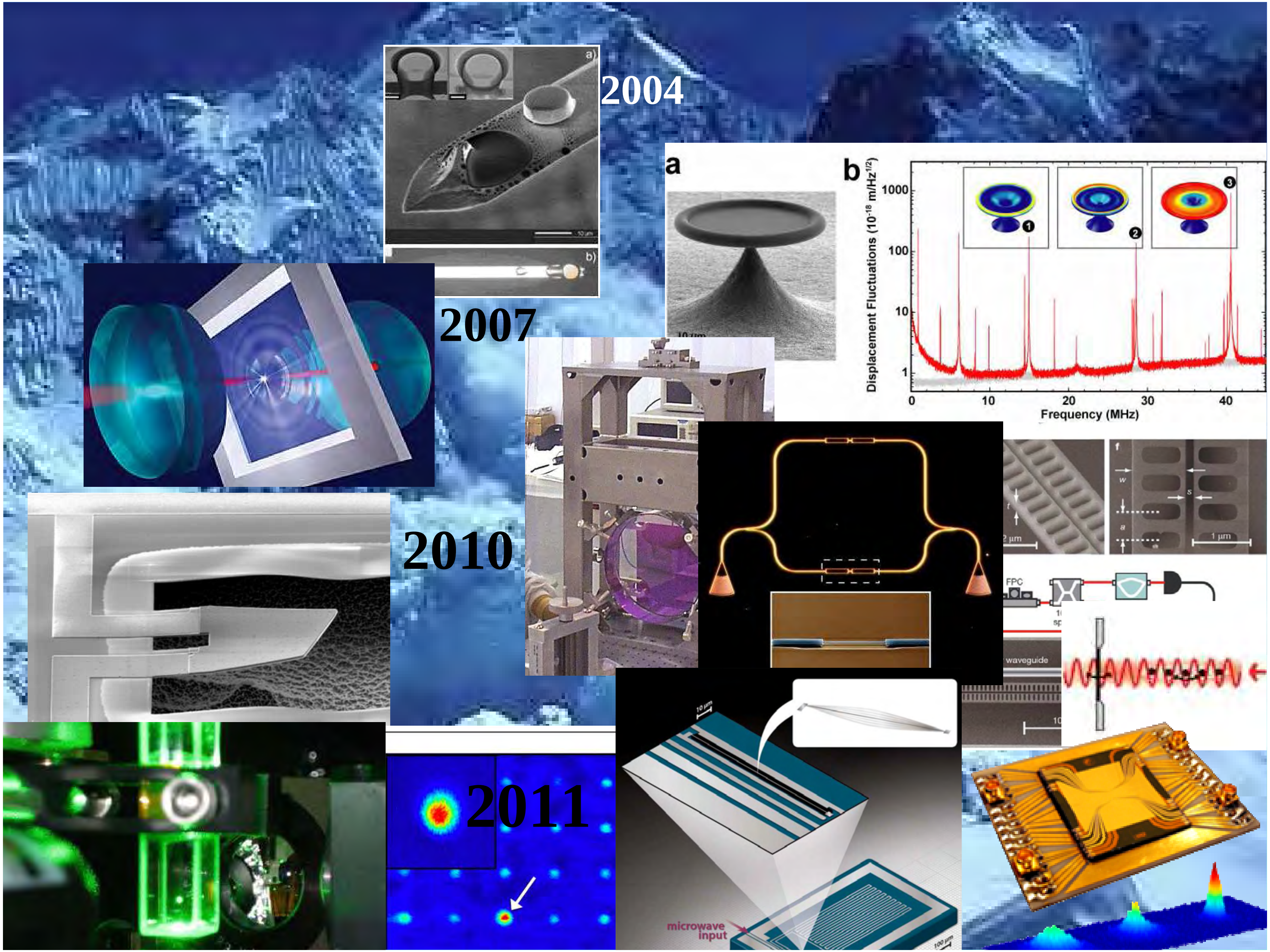

2004
a)
b)



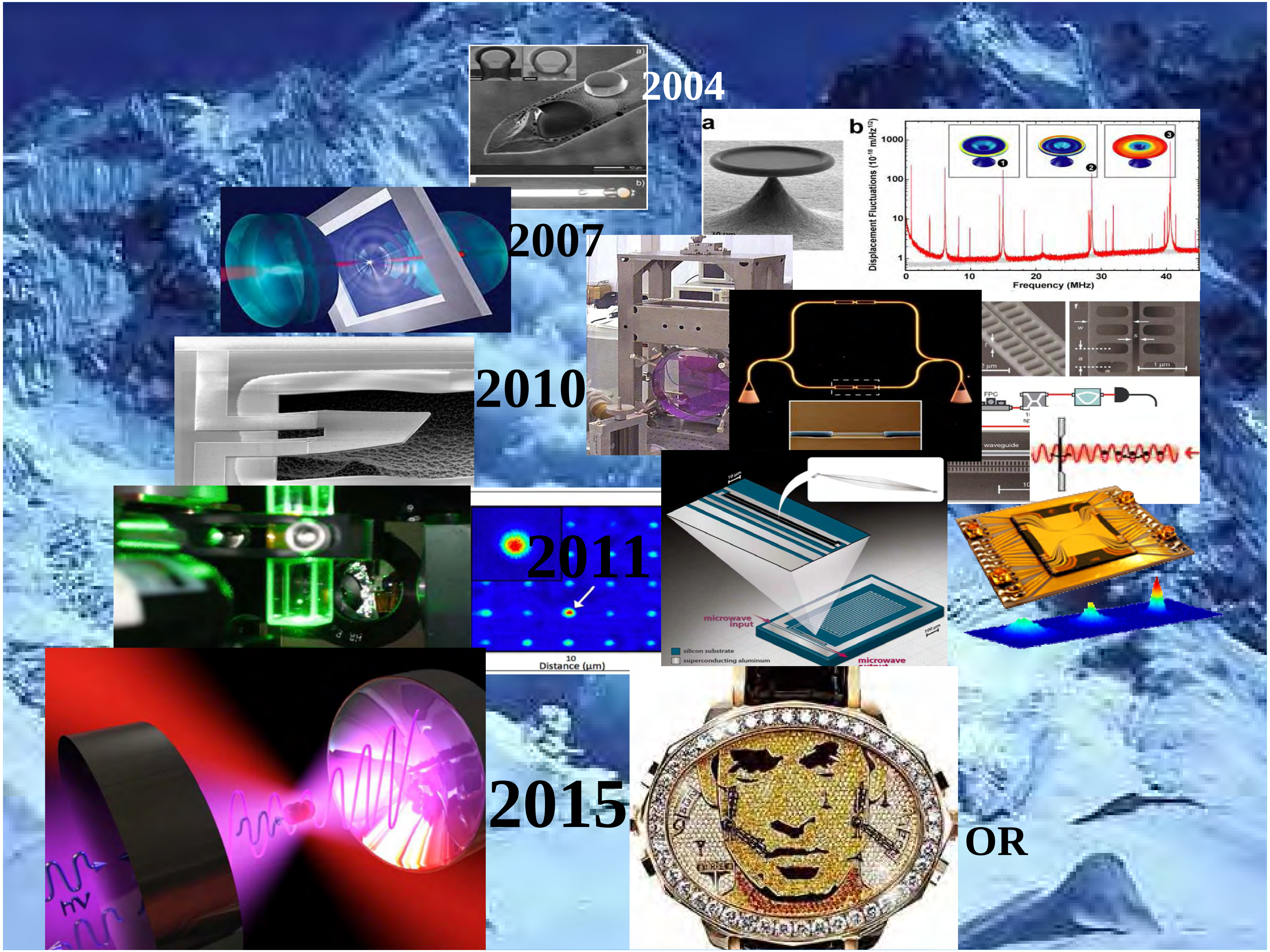
2004
2007
a
b
Displacement Fluctuations (10^-18 m/Hz^1/2)
Frequency (MHz)
1000
100
10
1
0
10
20
30
40



2004
2007
2010
a)
b)
60µm
a
b
Displacement Fluctuations (10^-18 m/Hz^1/2)
1000
100
10
1
0
10
20
30
40
Frequency (MHz)
FPC
10:90 splitter
MZ I
PD_MZ
waveguide
VOA
PD_T
Oscilloscope
1 µm
10 µm



2004
2007
2010
2011
a
b
Displacement Fluctuations (10^-18 m/Hz^1/2)
1000
100
10
1
0
10
20
30
40
Frequency (MHz)
FPC
waveguide
microwave input


2004
2007
2010
2011
2015
OR
a
b
Displacement Fluctuations (10^{-18} m/Hz$^{1/2}$)
Frequency (MHz)
FPC
waveguide
microwave input
silicon substrate
superconducting aluminum
Distance (μm)


2004
2007
2010
2011
2015
a
b
Displacement Fluctuations (10^-18 m/Hz^1/2)
Frequency (MHz)
FPC
waveguide
microwave input
Distance (μm)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Workshop: 4 - 7 October 2011 Leiden, the Netherlands
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• Dirk Bouwmeester, Santa Barbara & Leiden
• Eva Weig, Munich
• Herre van der Zant, Delft
Invited Speakers
• Markus Aspelmeyer, Vienna
• Miles Blencowe, Hanover
• Hans Briegel, Innsbruck*
• Andrew Cleland, Santa Barbara
• Rosario Fazio, Pisa
• Jack Harris, New Haven
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• Wojciech Zurek, Los Alamos
* to be confirmed
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The role of quantum dynamics in the navigation of European robins has been investigated. Aptly, this robin has picked an up-side-down Ψ - symbol for quantum states- as its resting place.
Image © David Aubrey/Science Photo Library.
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