The collapse of the quantum wave function

Dirk Bouwmeester,
Vitaliy Fedoseev, Wolfgang Löffler, Kier Heeck, Frank Buters, David Newsom
Hedwig Eerkens, Sven de Man, Fernando Luna, Matthew Weaver

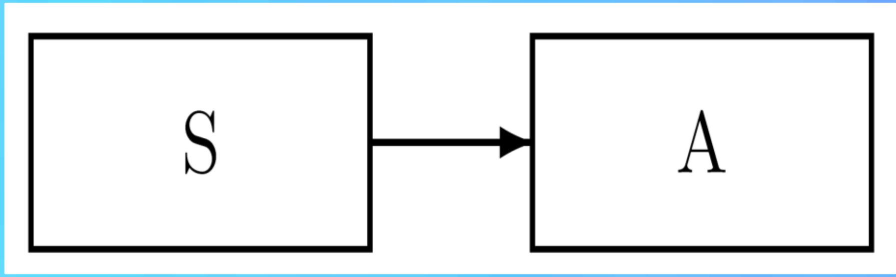
UBC Quantum Information: Quo Vadis? 14 November 2019

Bohr: The collapse is not a physical process because the wavefunction $|\Psi\rangle$ is to be regarded as merely referring to our knowledge of the system.

Everett: The wavefunction $|\Psi\rangle$ is a representation of a *real* physical state. (Many Worlds)

Zurek (and others): The collapse of the wave function (of a given system) follows from standard quantum dynamics

1932: John von Neumann: analysis of quantum measurements

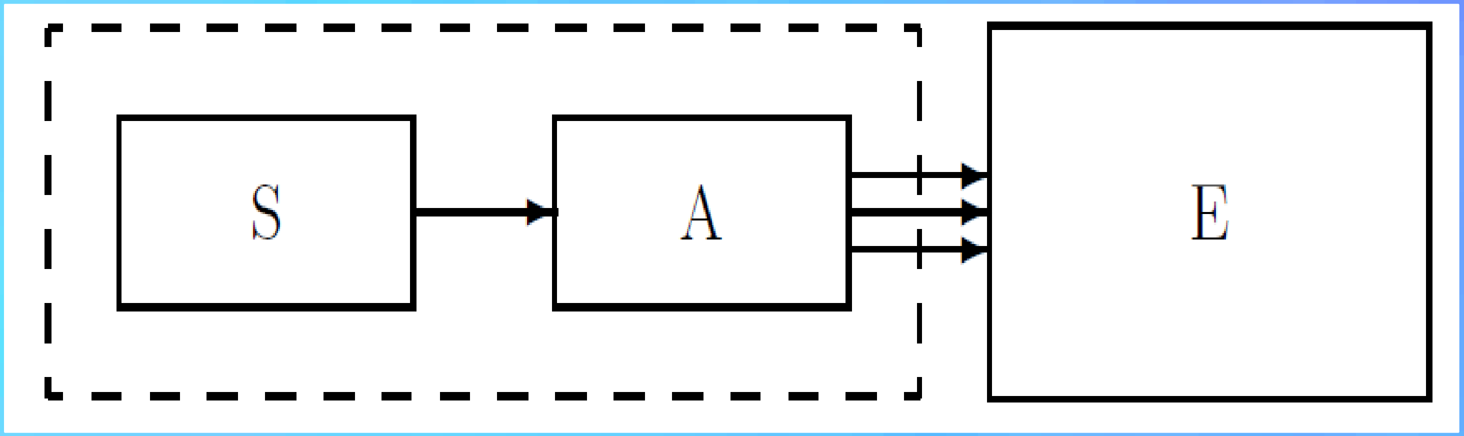


$$H_{int} = \sum_n |n\rangle\langle n| \otimes \hat{A}_n$$

$$\left(\sum_n c_n |n\rangle\right) |\Phi_0\rangle \xrightarrow{t} \sum_n c_n |n\rangle |\Phi_n(t)\rangle$$

Von Neumann postulated dynamical collapse of wave function with outcome probabilities $|c_n|^2$. This requires a preferred basis, the basis of pointer states of the measurement apparatus.

Environment induced decoherence



$$\left(\sum_n c_n|n\rangle|\Phi_n\rangle\right)|E_0\rangle \xrightarrow{t} \sum_n c_n|n\rangle|\Phi_n\rangle|E_n\rangle$$

Assuming that $\langle E_n|E_m\rangle = \delta_{nm}$ and trace out the degrees of freedom of the environment leads to the reduced density matrix:

$$\tilde{\rho}_{SA} \approx \sum_n |c_n|^2|n\rangle\langle n| \otimes |\Phi_n\rangle\langle\Phi_n|$$

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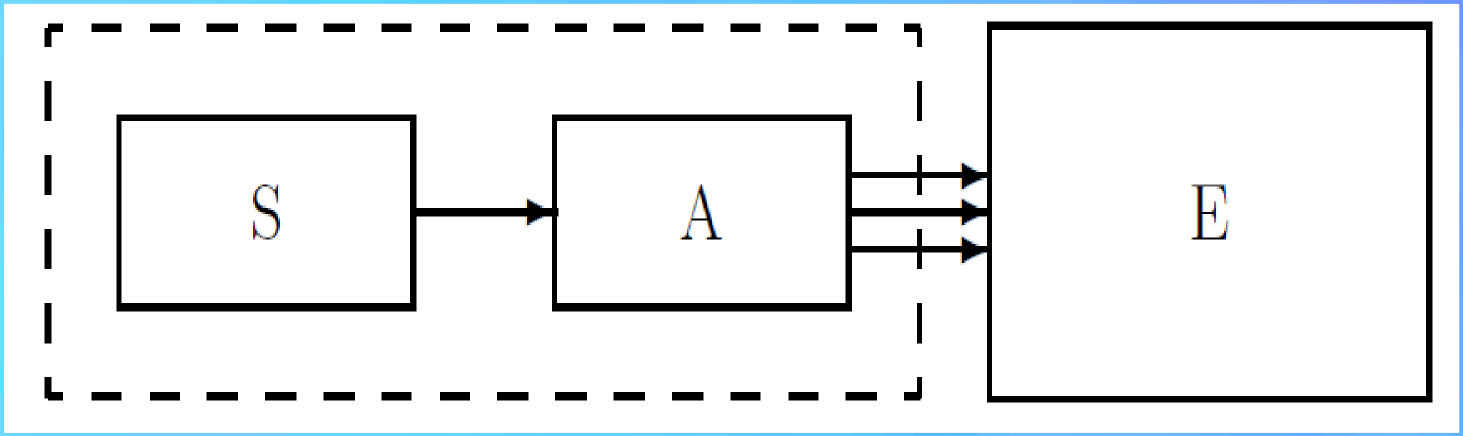

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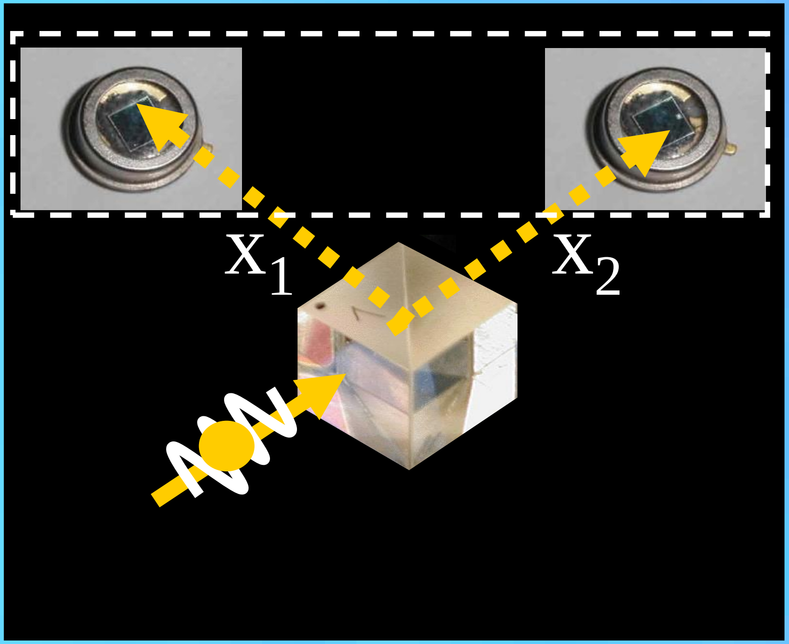
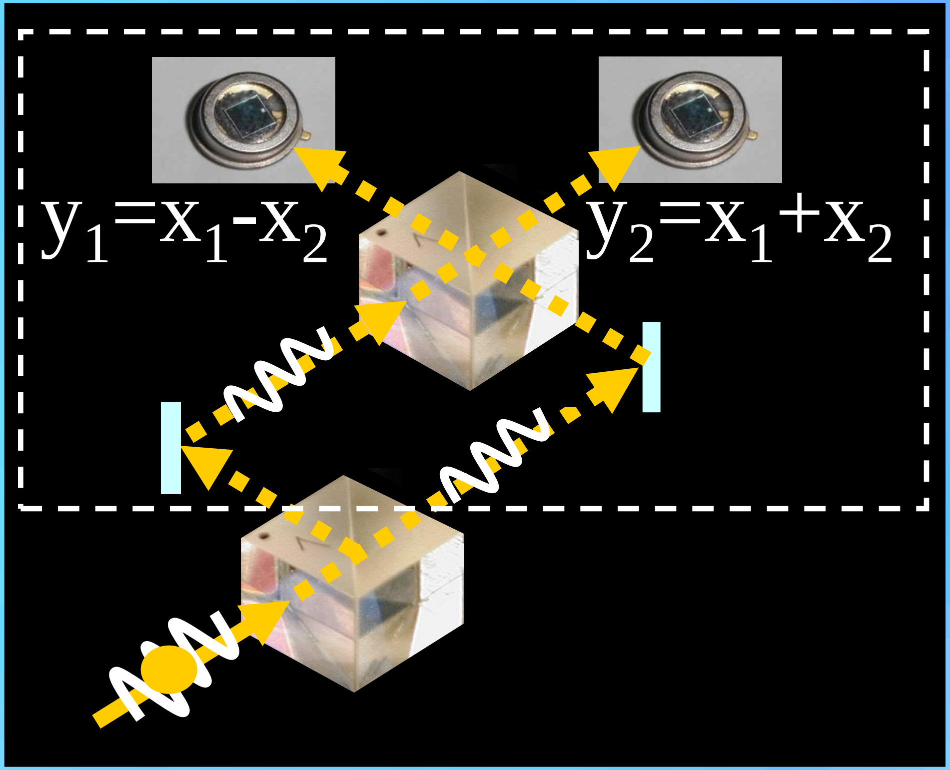
$$H_{Int} = \sum_{i=1,2} x_i A_i$$

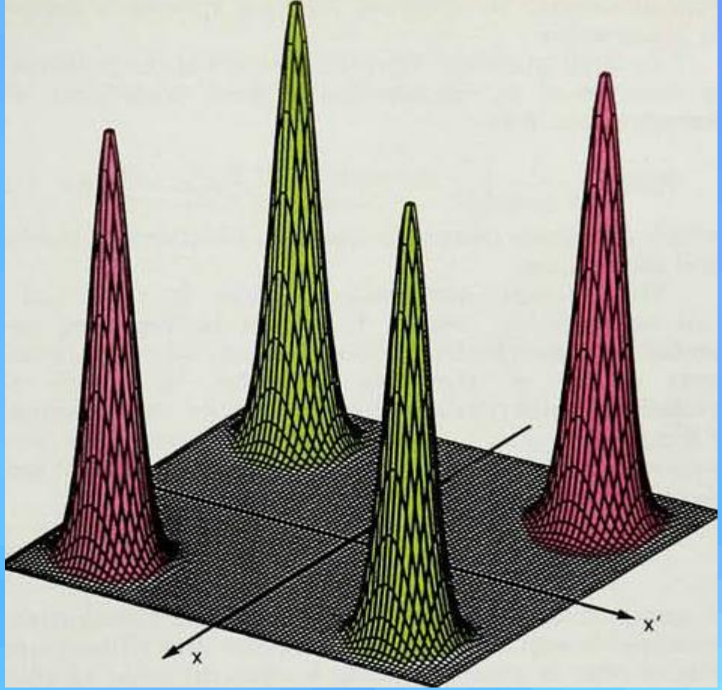


$$H_{Int} = \sum_{i=1,2} y_i A_i$$



Consider the following model
(Zurek and Unruh, PRD, **40** 1071 (1989)).

Initial pure density matrix $\rho(x,x')$
$\rho(x,x') = \chi(x)\chi^*(x')$
with $\chi(x) \sim \chi^+(x) + \chi^-(x)$ (sum of two gaussian wavepackets)



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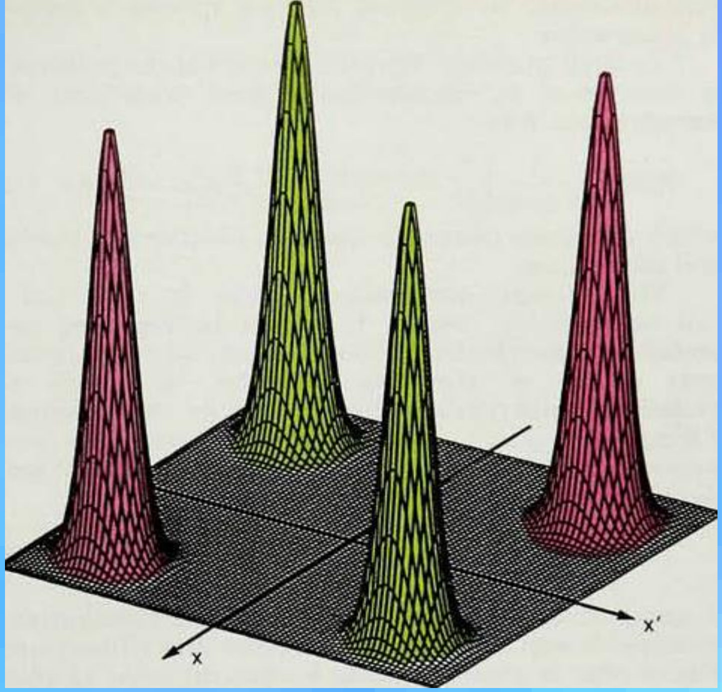
with a scalar field $\varphi(q, t)$ propagating in direction q.



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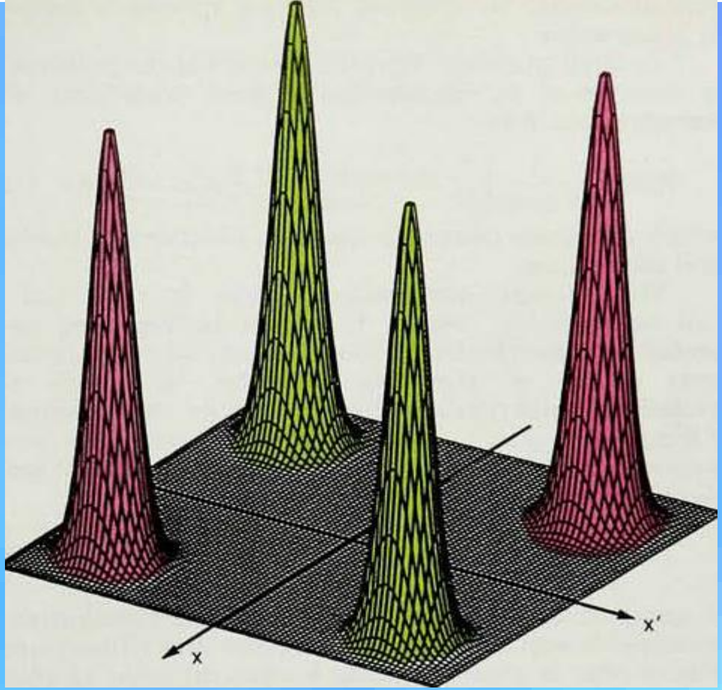

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$$H_{int} = \varepsilon x d\varphi / dt$$
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$$\frac{d\rho}{dt} = -\frac{i}{\hbar}[H, \rho] - \gamma(x - x')\left(\frac{d\rho}{dx} - \frac{d\rho}{dx'}\right) - \frac{2m\gamma k_B T}{\hbar^2}(x - x')^2 \rho$$

relaxation rate $\gamma = \varepsilon^2 / 4m$

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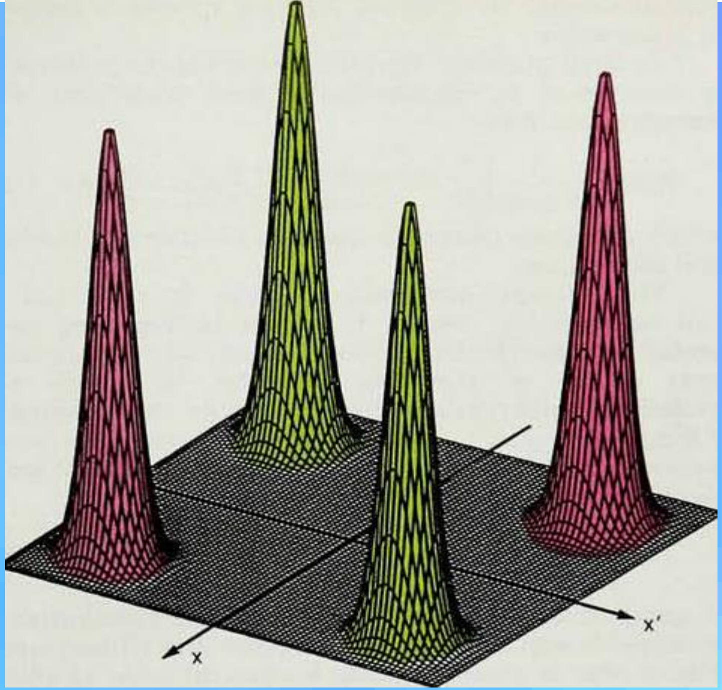

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relaxation rate $\gamma = \varepsilon^2/4m$

acts mainly on off-diagonal elements

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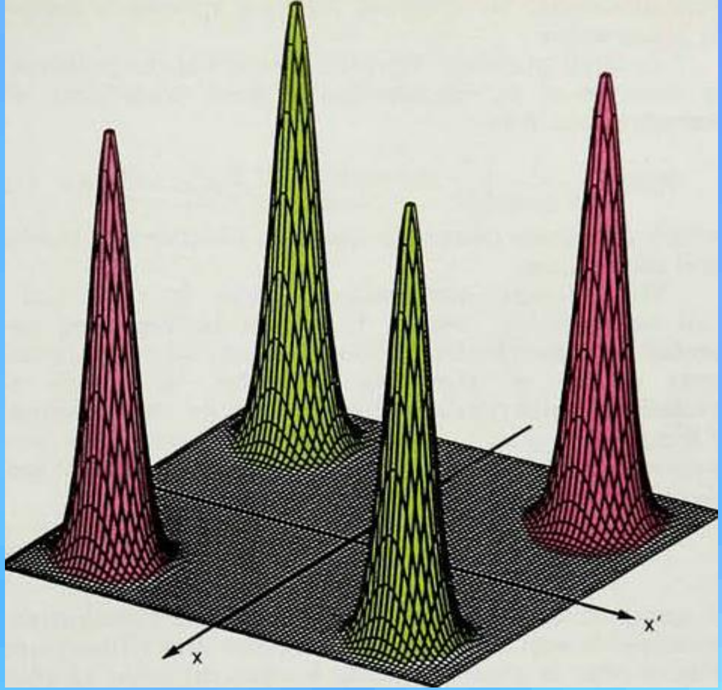

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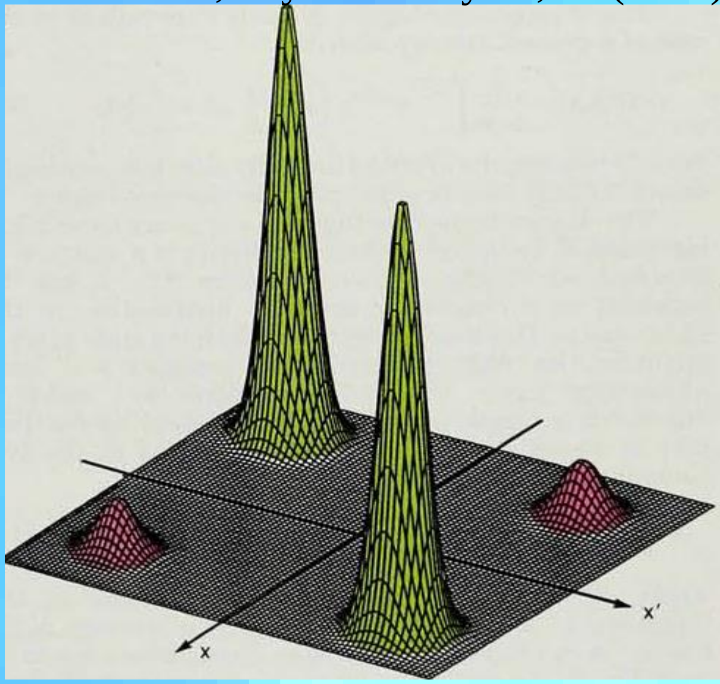

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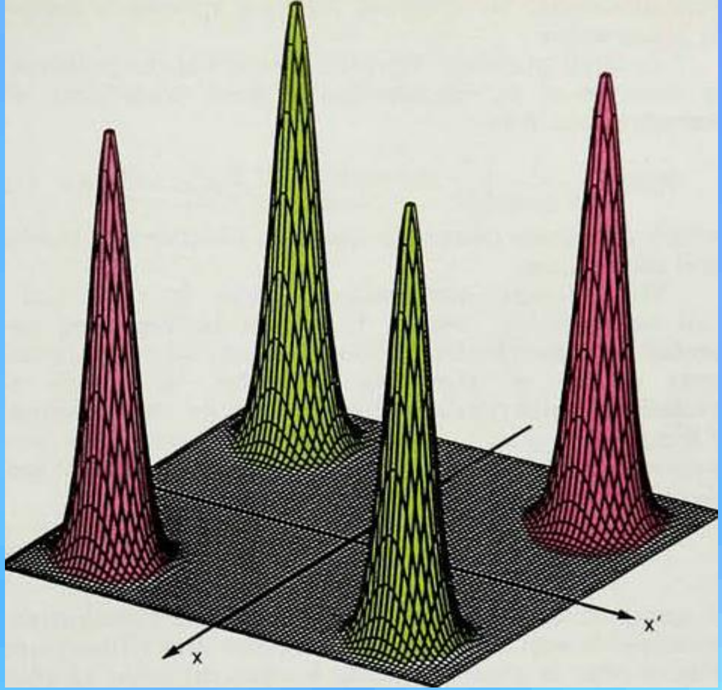

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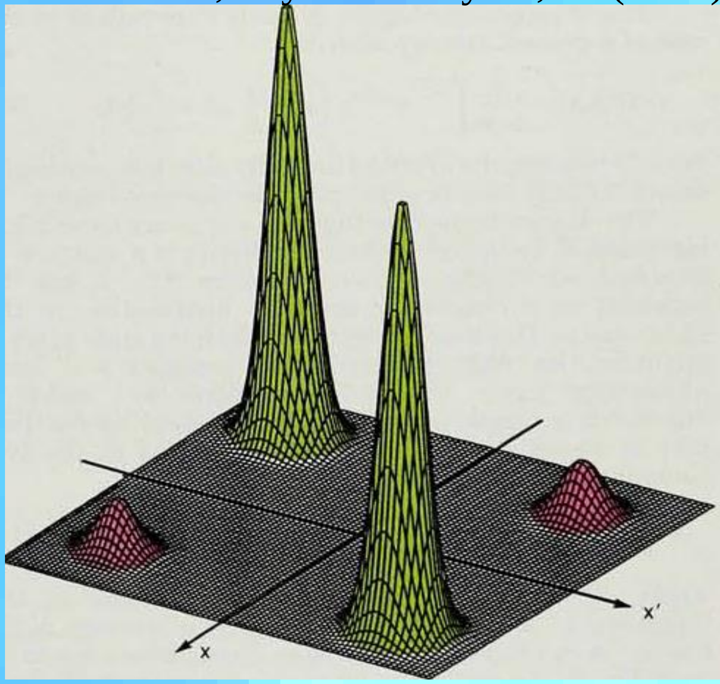

Example 1: T=300K, m=1gram, $\Delta x = 1$cm. If we define the relaxation time $\tau_r = \gamma^{-1}$the ratio of $\tau_D / \tau_r \approx 10^{-40}$!!

Example 2: T=300K, electron: m=10^{-27} on atomic scales $\Delta x \approx 10^{-10}$m: $\tau_D / \tau_r \approx 10^4$

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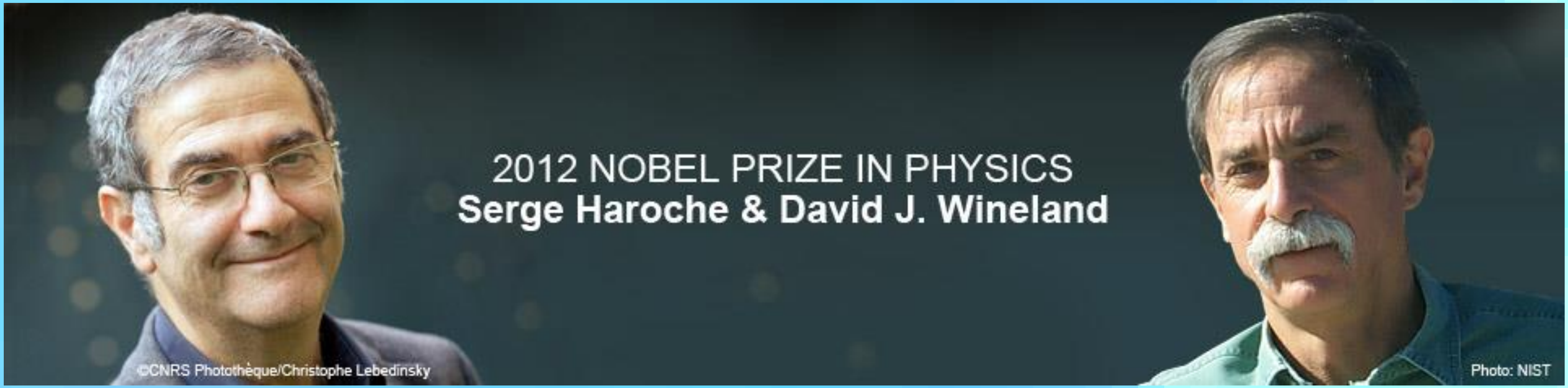
Two heroic experiments



Conclusion: The collapse is real (for the sub system).

The collapse is the result of unitairy quantum evolution of the entire system and leads to a reduced density matrix that mathematically has the same form as a classical probability distribution.

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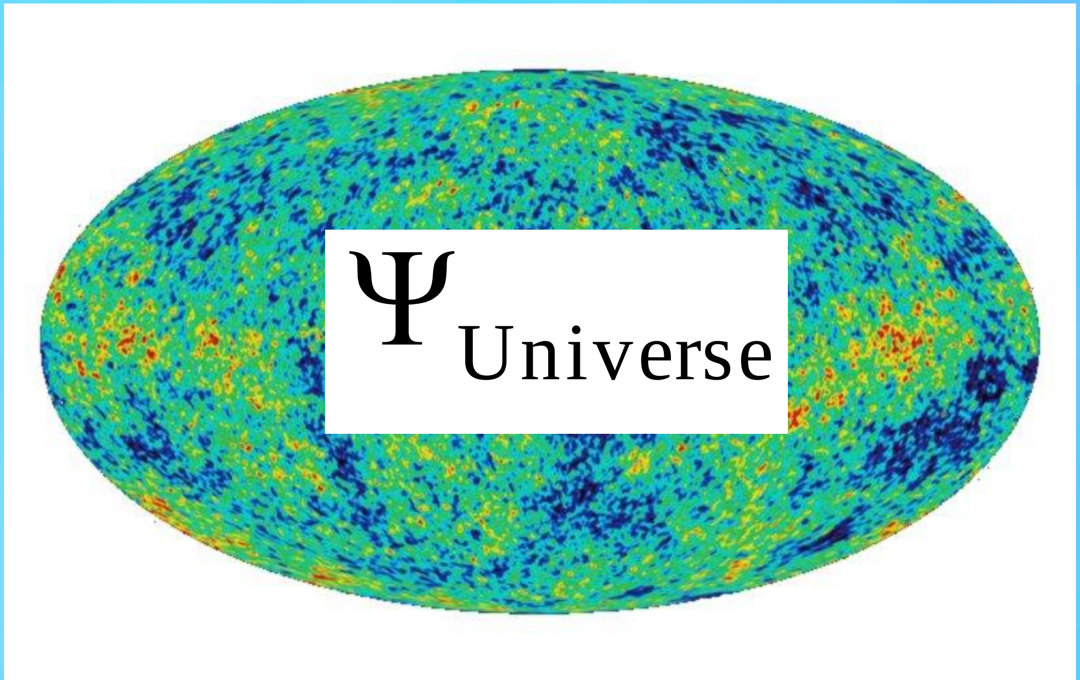

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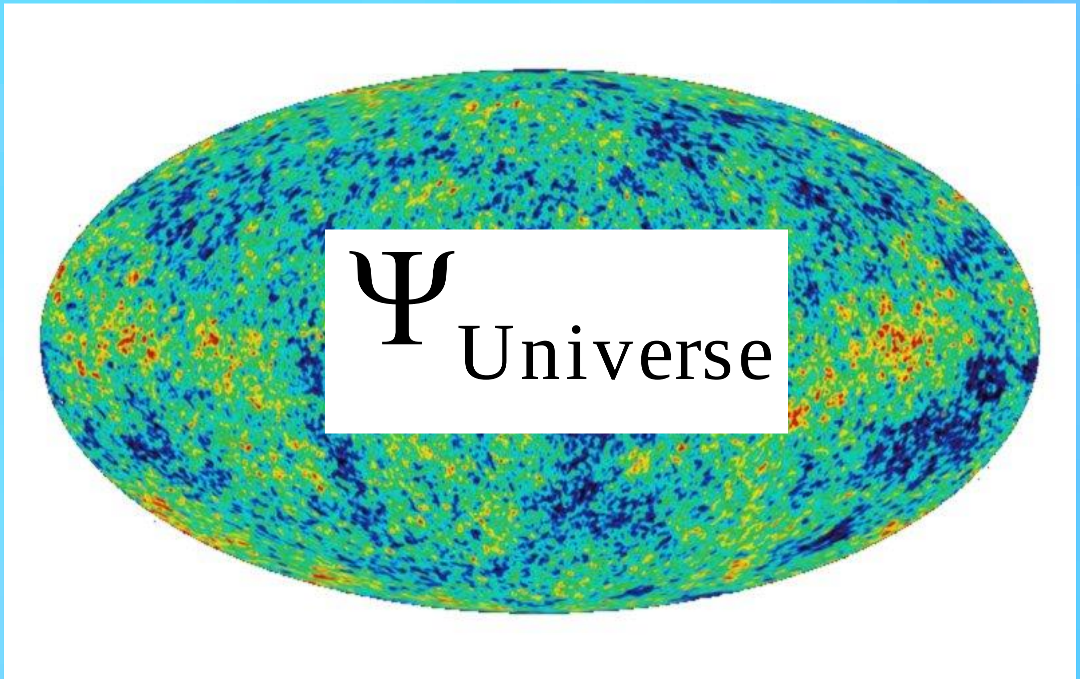
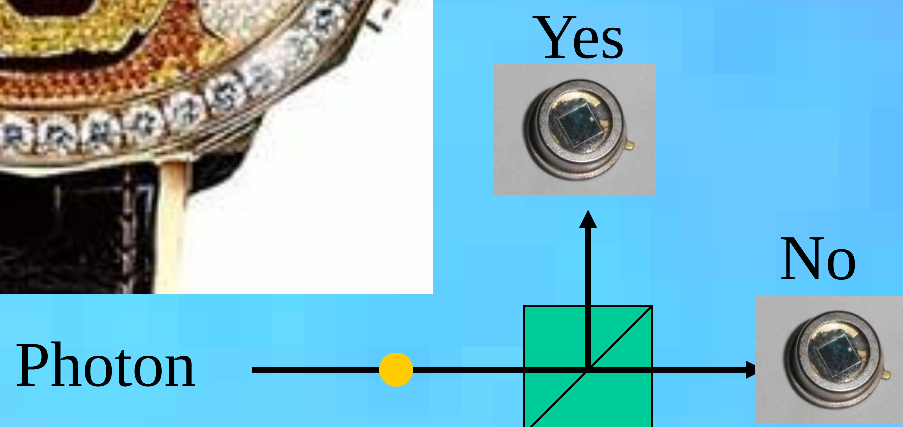


Many worlds!

Vaidman’s watch



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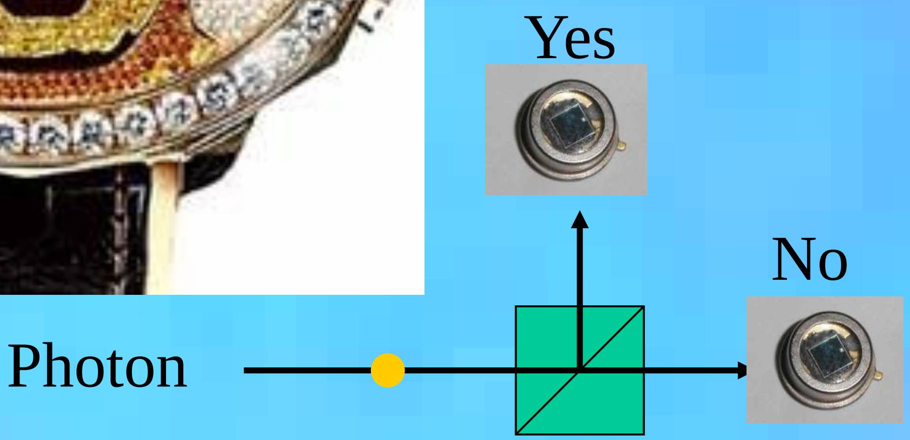


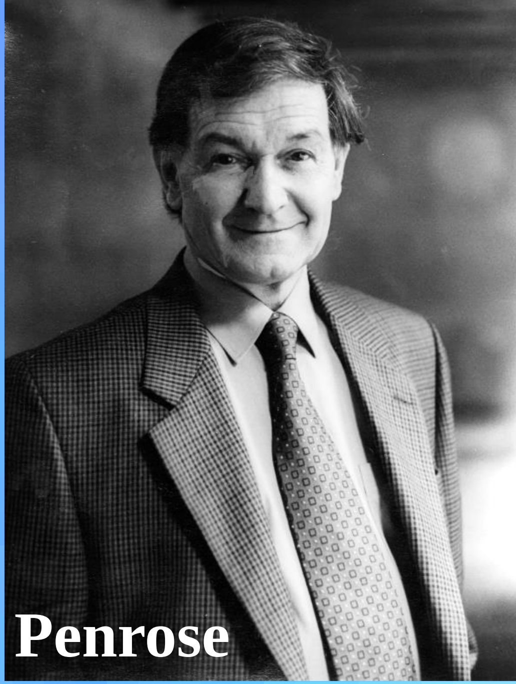
Many worlds!

Any objections?

Two alternative locations of a massive object will each have stationary states, and have wavefunctions $|\Psi\rangle$ and $|\Phi\rangle$, that are eigenstates of the $\partial/_{\partial t}$ operator with eigenvalues related to the energy.

$$\frac{\partial}{\partial t}\left|\Psi\right\rangle = -i\hbar E_{\Psi}\left|\Psi\right\rangle$$

$$\frac{\partial}{\partial t'}\left|\Phi\right\rangle = -i\hbar E_{\Phi}\left|\Phi\right\rangle$$



R. Penrose, **Wavefunction Collapse as a Real Gravitational Effect** General Relativity and Gravitation 28, 581 (1996).

But how to deal with superpositions

$$\frac{\partial}{\partial t}\Big)\left(\alpha\left|\Psi\right\rangle + \beta\left|\Phi\right\rangle\right) = ???$$

Consider an equal superposition $\frac{1}{\sqrt{2}}\left(\left|\Psi\right\rangle + \left|\Phi\right\rangle\right)$

f and **f'** are the acceleration 3-vectors of the free-fall motion in the two space-times (**f** and **f'** are gravitational forces per unit test mass).

Penrose postulate: at each point the scalar $(|\mathbf{f}-\mathbf{f}'|)^2$ is a measure of incompatibility of the identification. The total measure of incompatibility (or "uncertainty) Δ at time *t* is:

$$\Delta = \frac{1}{4\pi G}\int (\mathrm{f}\text{-}\mathrm{f}')^2 \, d^3x$$

$$\equiv E_G$$

This is the gravitational self energy associated to the superposition

Prediction: The superposition state is unstable and has a lifetime of the order of $\frac{\hbar}{E_G}$

(see also GRW, Diosi, others)

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Towards Quantum Superpositions of a Mirror

William Marshall,[1,2] Christoph Simon,[1] Roger Penrose,[3,4] and Dik Bouwmeester[1,2]

$$E_{i,j} = -G \int\int \mathrm{d}\vec{r}_1 \mathrm{d}\vec{r}_2 \frac{\rho_i(\vec{r}_1)\rho_j(\vec{r}_2)}{|\vec{r}_1 - \vec{r}_2|},$$

$$\Delta E = 2E_{1,2} - E_{1,1} - E_{2,2},$$

$$\Delta E = 2Gmm_1\left(\frac{6}{5a} - \frac{1}{\Delta x}\right), \qquad (\text{given} : \Delta x \geq 2a)$$

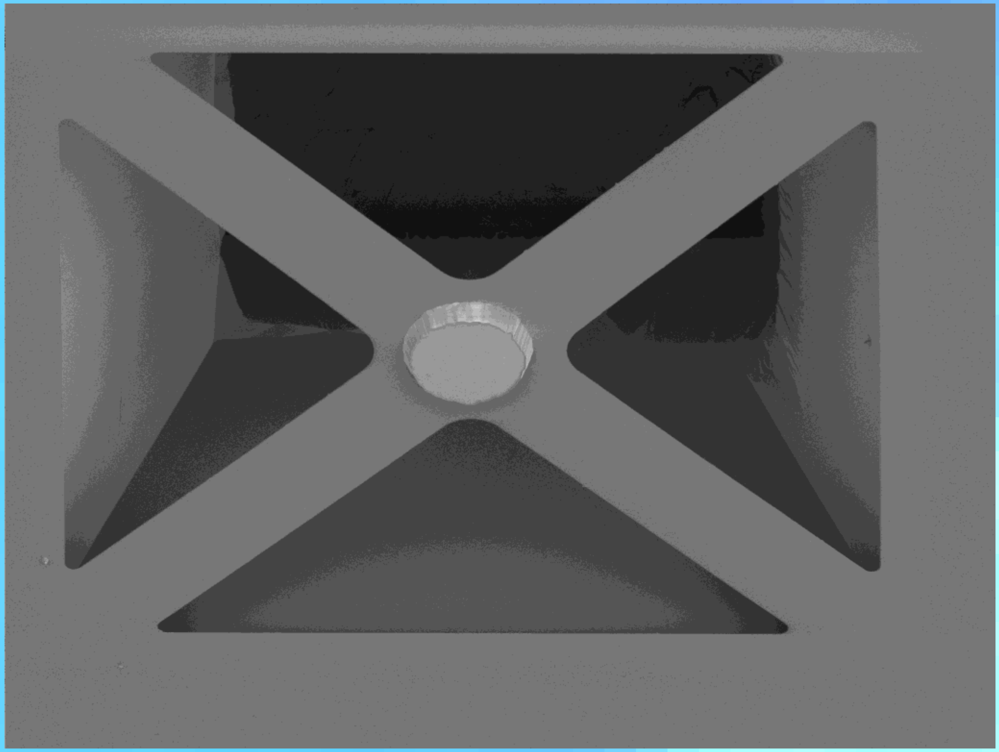
$m \sim 10^{-12}$kg,

$\omega_c \sim$1-10kHz

$\kappa \sim 1$

$m_1 = 4.7 \times 10^{-26}$kg

(Silicon nuclear mass)



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$m \sim 10^{-12}$kg,

$\omega_c \sim 1\text{-}10$kHz

$\kappa \sim 1$

$m_1 = 4.7 \times 10^{-26}$kg (Silicon nuclear mass)

Small problem: what is mass and what is the mass distribution of a piece of material?

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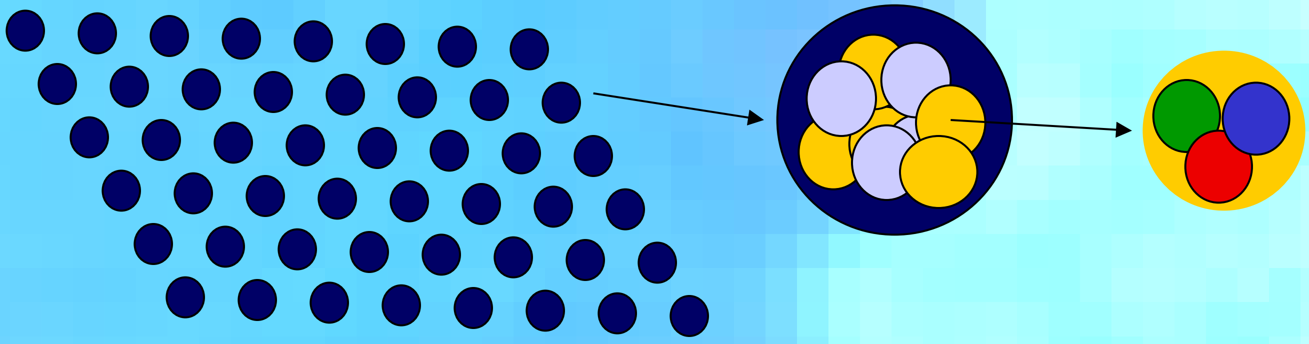

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$m \sim 10^{-12}$kg,

$\omega_m \sim 1\text{-}10$kHz

$\kappa \sim 1$

$m_1 = 4.7\times10^{-26}$kg (Silicon nuclear mass)

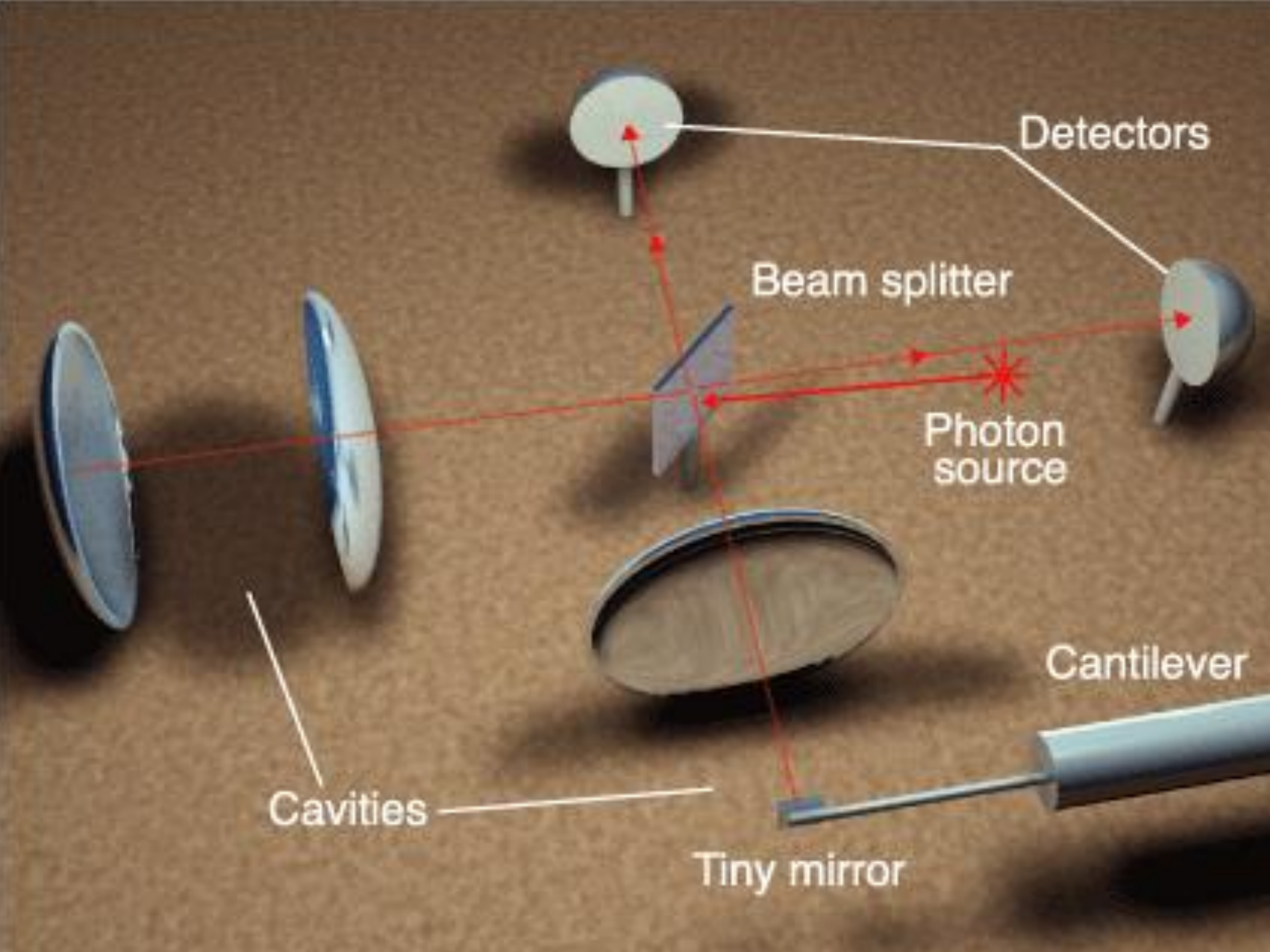
Take, $a \sim 10^{-15}$m size of nucleus, or

Decoherence time ~1 ms,

take $a \sim 10^{-13}$m size of ground-state wave function

~0.1-1s

Compare: For C_{60} experiments (Penrose) decoherence time is 10^{10}s


Detectors
Beam splitter
Photon
source
Cantilever
Cavities
Tiny mirror

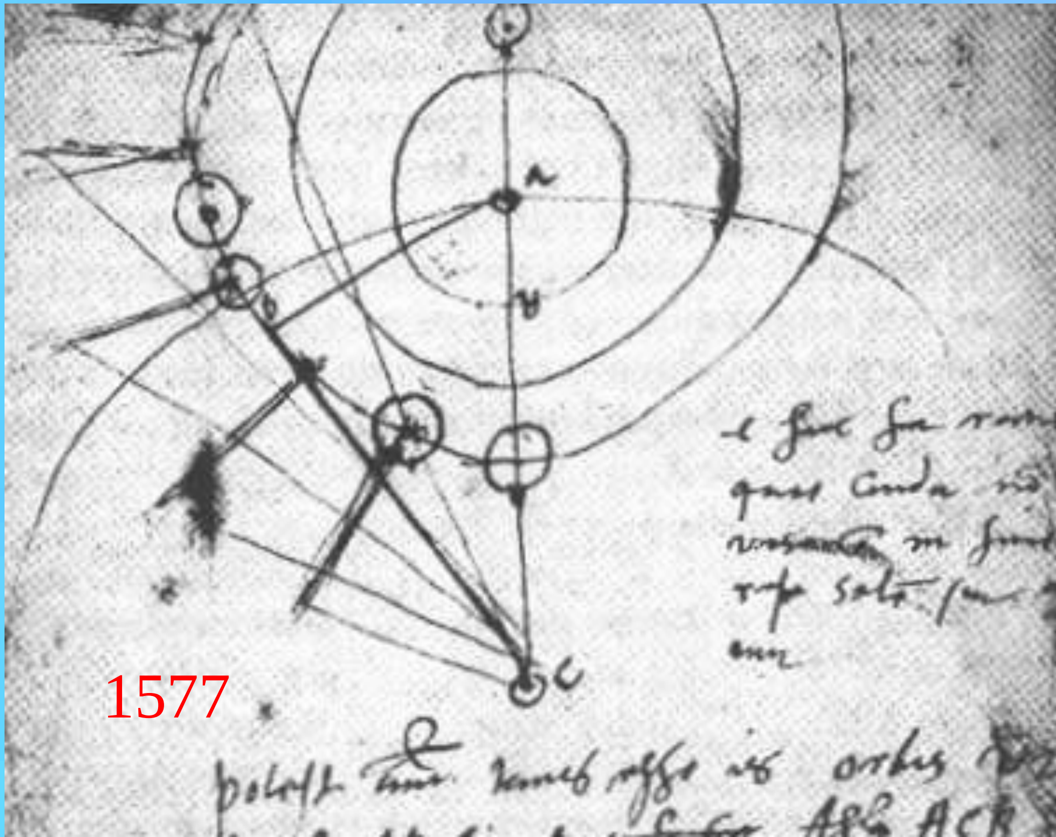
Basic opto-mechanics

$$\hat{H} = \hbar\omega_c(\hat{a}^\dagger\hat{a}) + \hbar\omega_m\left(\hat{b}^\dagger\hat{b}\right) - \kappa\hbar\omega_m\hat{a}^\dagger\hat{a}\left(\hat{b}+\hat{b}^\dagger\right)$$

$$\kappa = \frac{\omega_c}{\omega_m}\frac{1}{L}\sqrt{\frac{\hbar}{2m\omega_m}}$$

$$\frac{L}{L+x} \approx 1 - \frac{x}{L}$$

$$x \to \hat{x} = \sqrt{\hbar/2m\omega_m}\,(\hat{b}+\hat{b}^\dagger)$$



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Thermal mirror state, dissipation to thermal (bosonic) bath

$$\frac{d\hat{\rho}}{dt} = -\frac{i}{\hbar}\left[\hat{H},\hat{\rho}\right] + \frac{\gamma}{2}\left\{\left(\bar{N}+1\right)\left(2\hat{b}\hat{\rho}\hat{b}^\dagger - \hat{b}^\dagger\hat{b}\hat{\rho} - \hat{\rho}\hat{b}^\dagger\hat{b}\right) + \bar{N}\left(2\hat{b}^\dagger\hat{\rho}\hat{b} - \hat{b}\hat{b}^\dagger\hat{\rho} - \hat{\rho}\hat{b}\hat{b}^\dagger\right)\right\}$$

$\bar{N}$ is mean thermal phonon number, at resonance with the mechanical resonator at T_{bath}

....

$$1/\tau_{dec} = \frac{2\gamma m k_B T_B \left(\Delta x\right)^2}{\hbar^2}$$

Qmechanical

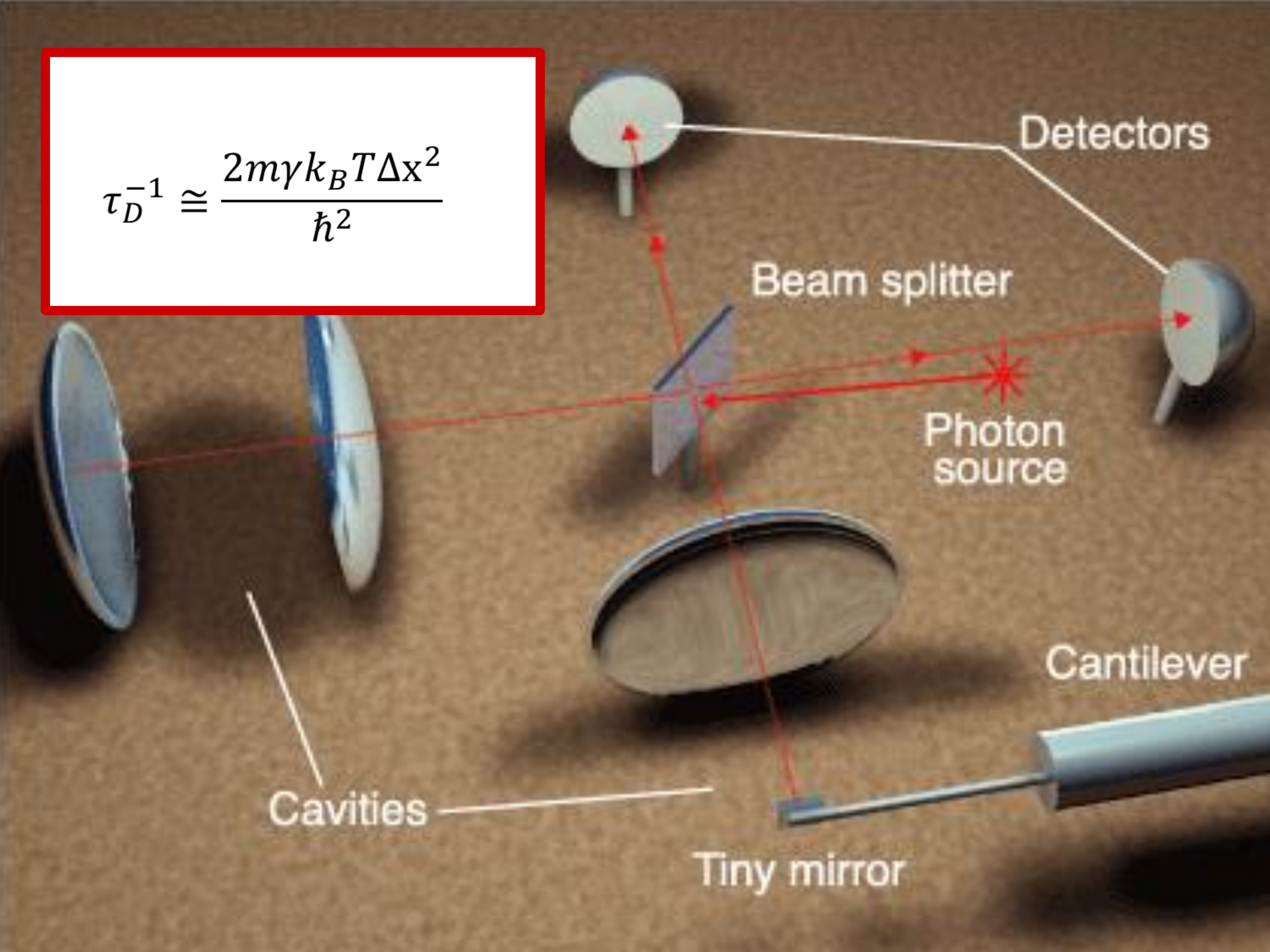
Final conclusion for $\kappa \sim 1/\sqrt{2}$, Q~100,000, m=10^{-12}kg, $T_{bath} = 1mK$,

the decoherence time is 0.1ms.

Q's up to 1,000,000 for small mechanical resonators are possible,

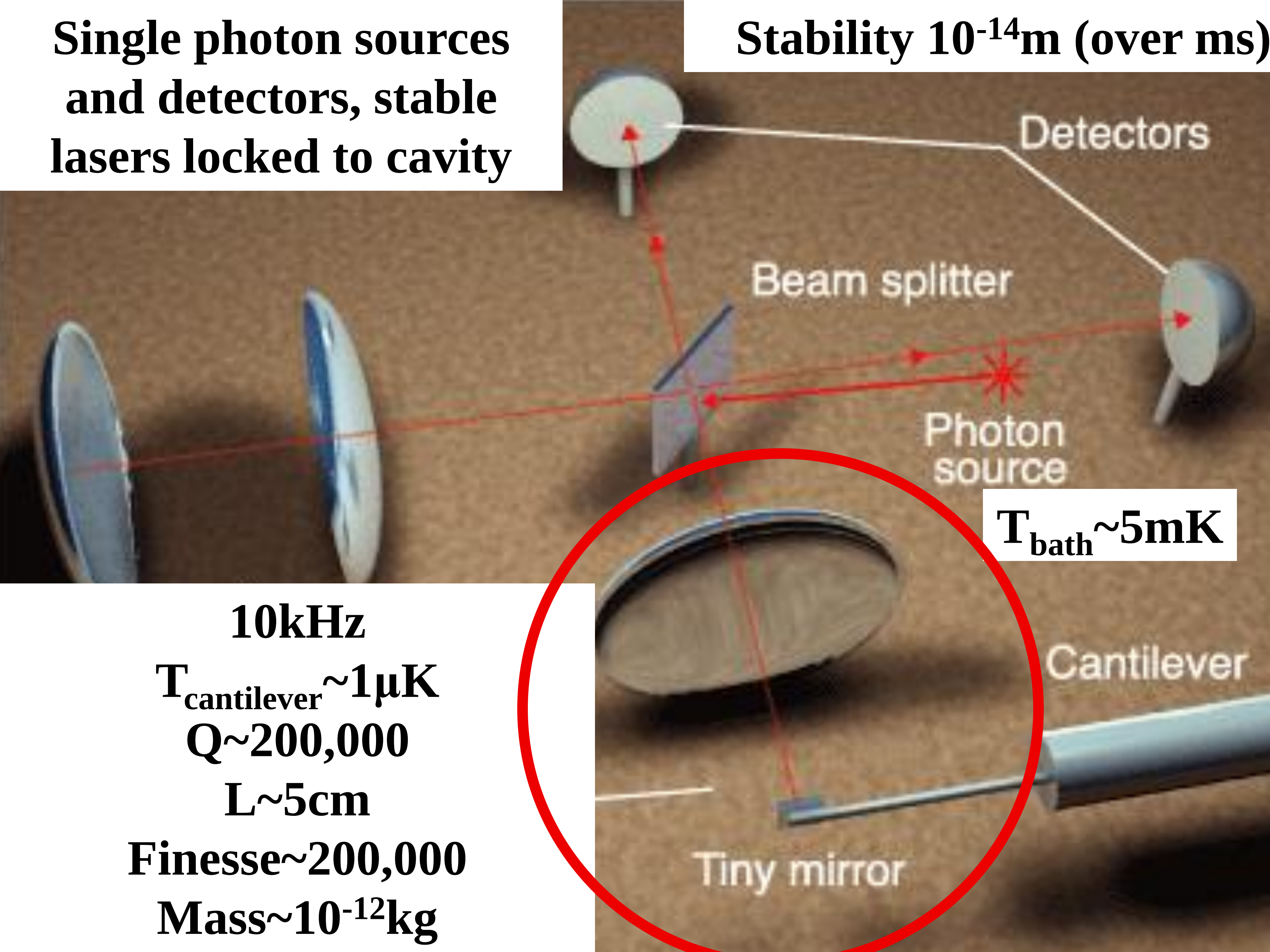
$T_{bath} \sim 10mK$ acceptable.

$$\tau_D^{-1} \cong \frac{2m\gamma k_B T \Delta x^2}{\hbar^2}$$



Single photon sources and detectors, stable lasers locked to cavity

Stability 10^{-14}m (over ms)



T_{bath}~5mK

10kHz

$T_{cantilever}$~1μK

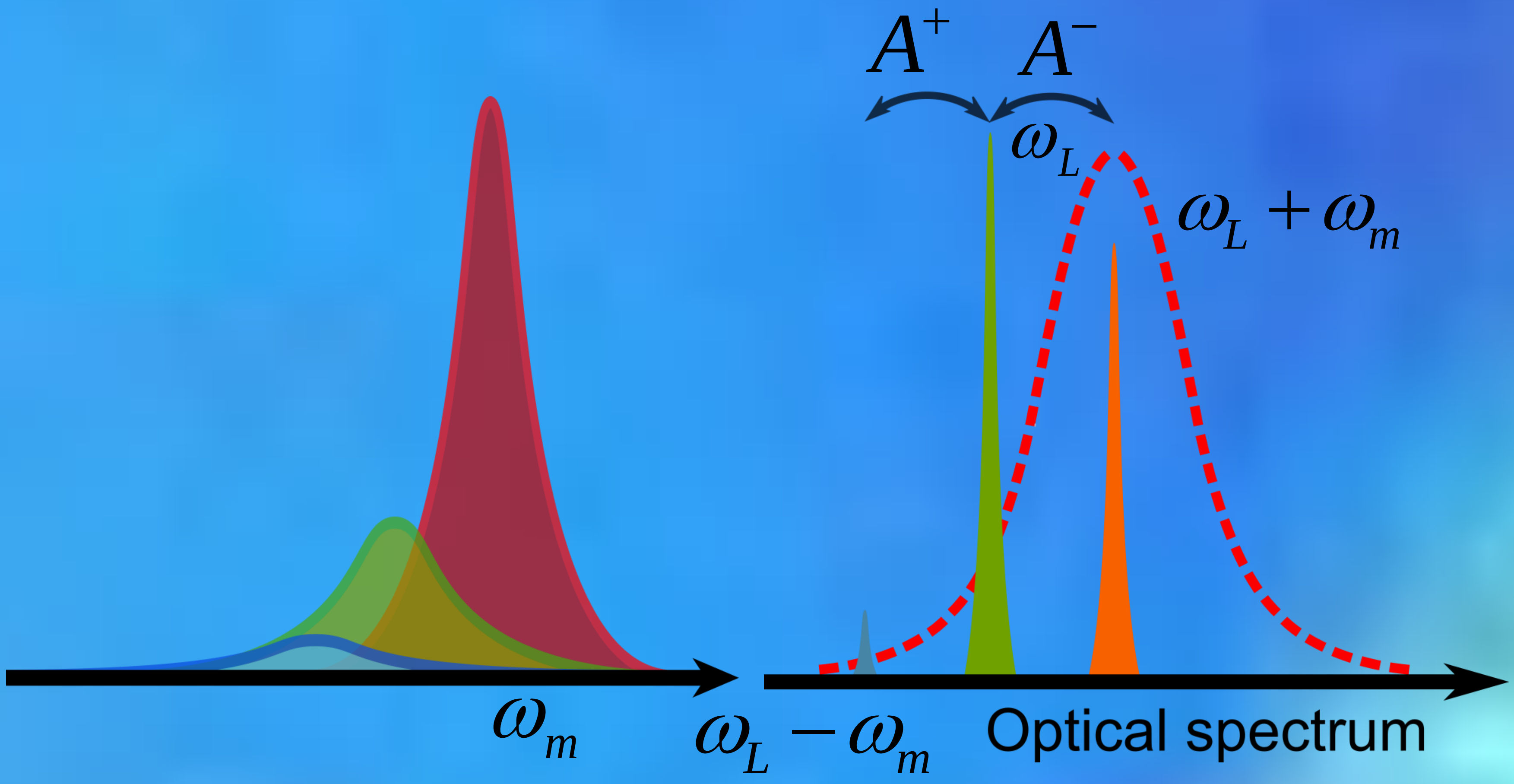
Q~200,000

L~5cm

Finesse~200,000

Mass~10^{-12}kg

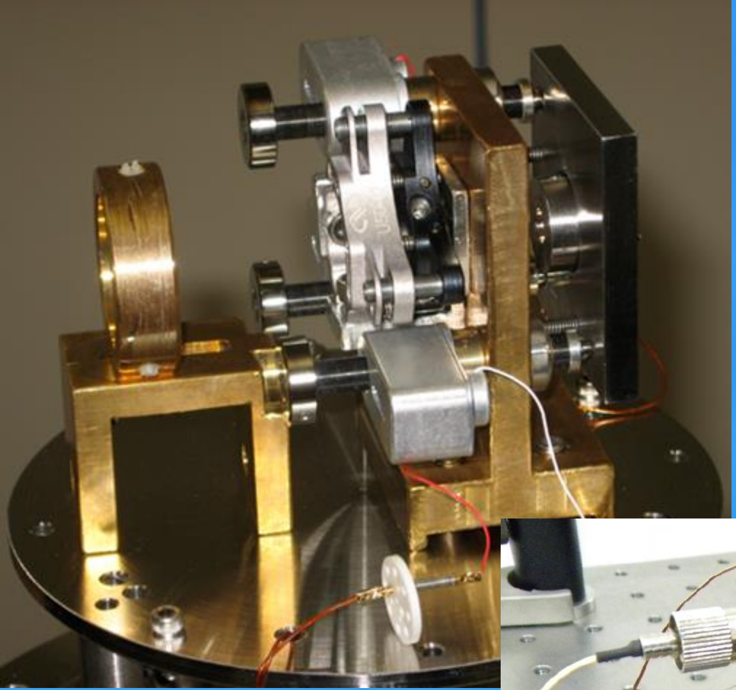
Passive optical cooling of the mechanical mode



Needed for ground state cooling:

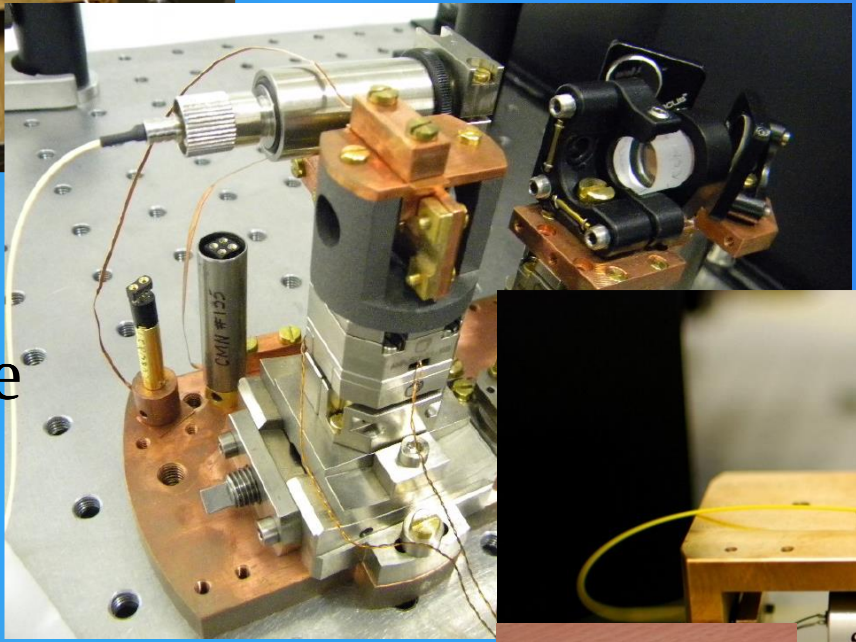
Work in side band resolved regime: $\omega_m > \gamma_{optical}$, Finesse>20,000

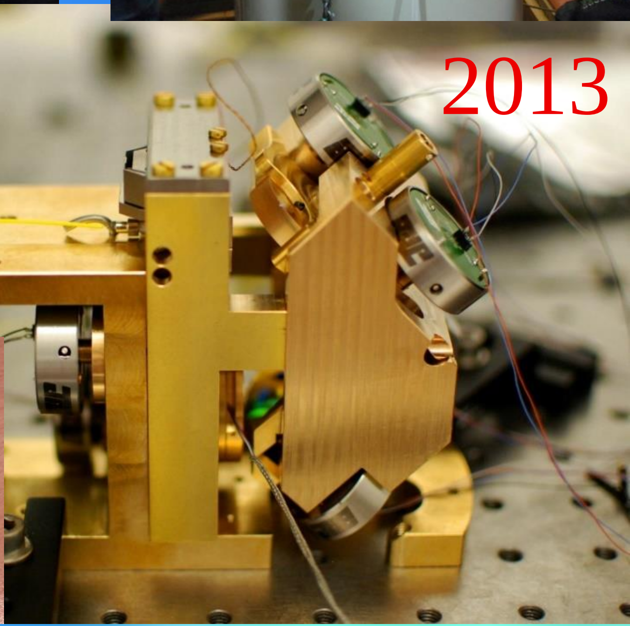
T_{bath}~100mK (compatible with previous requirements $F>10^5$, T_{bath}~5mK)



Generation 1
Room temperature
vacuum
2007

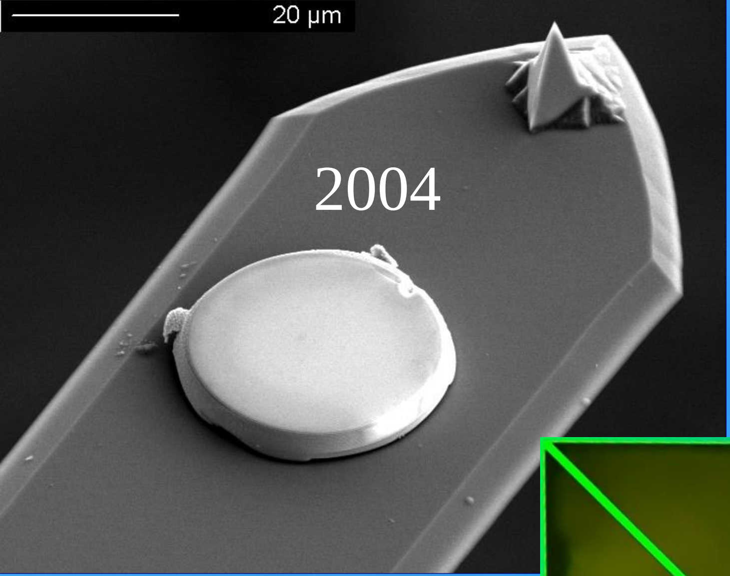
Generation 2
Low temperature
vacuum



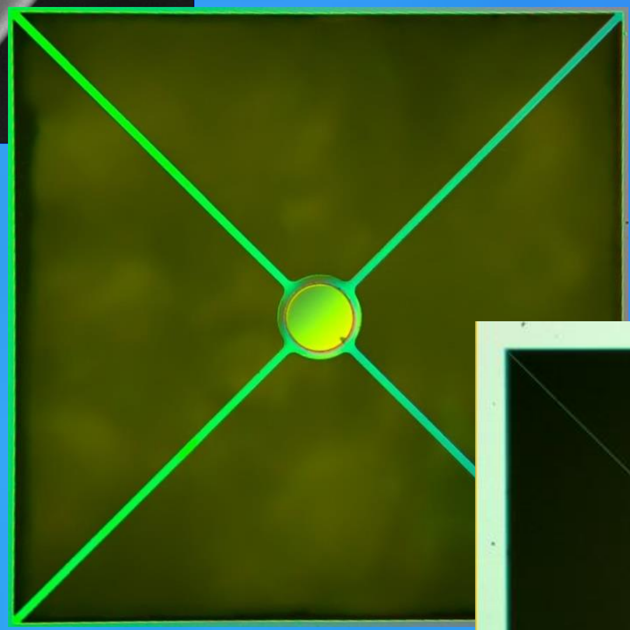


Generation 3
Low temperature vacuum
& stable

UCSB

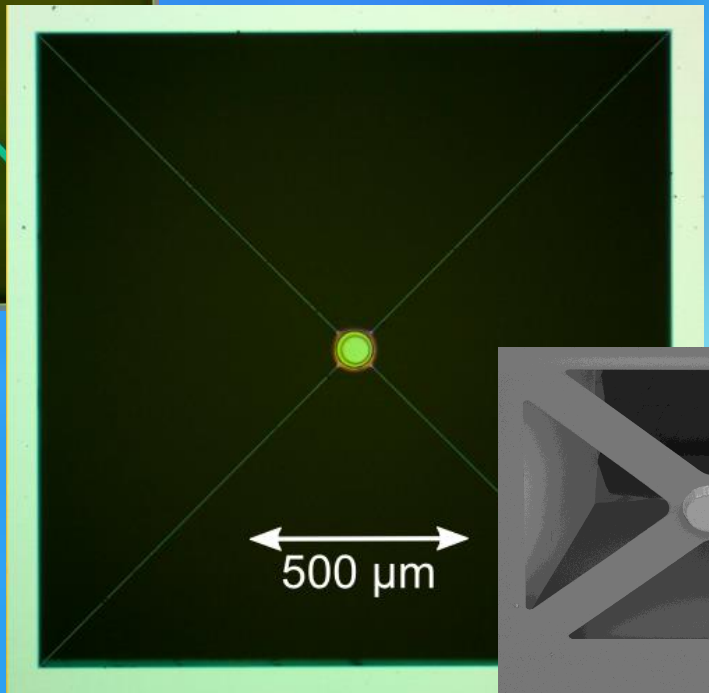


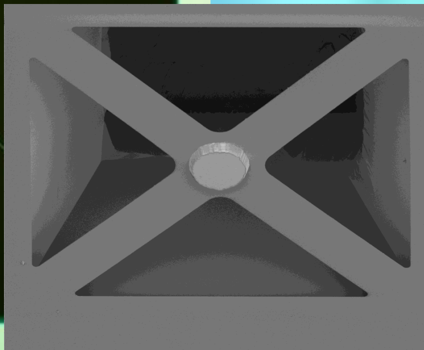
Generation 1
Finesse: 2100
Mechanical Q:130.000



Generation 2
Finesse: 3000
Q: 400.000

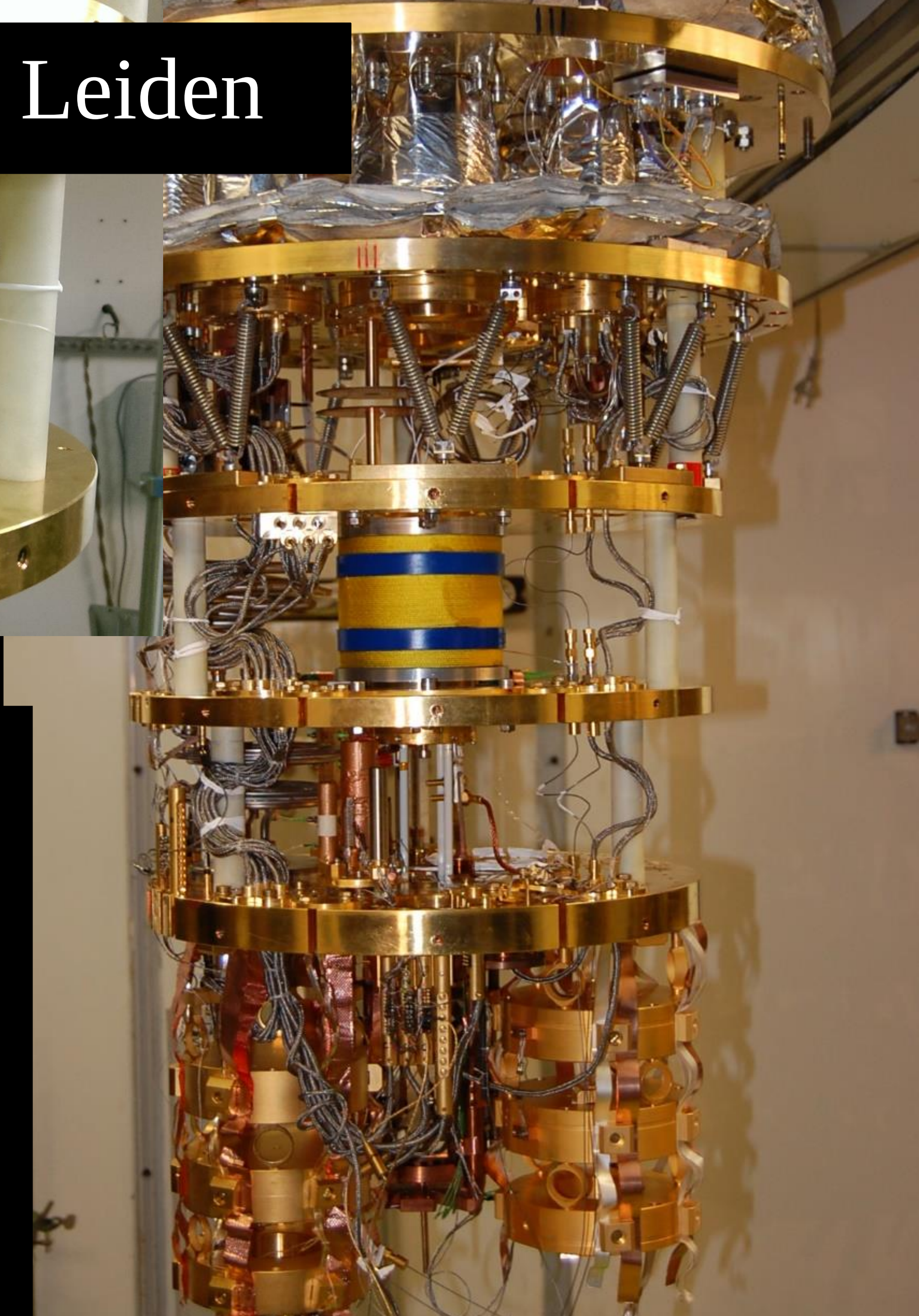
10-100kHz

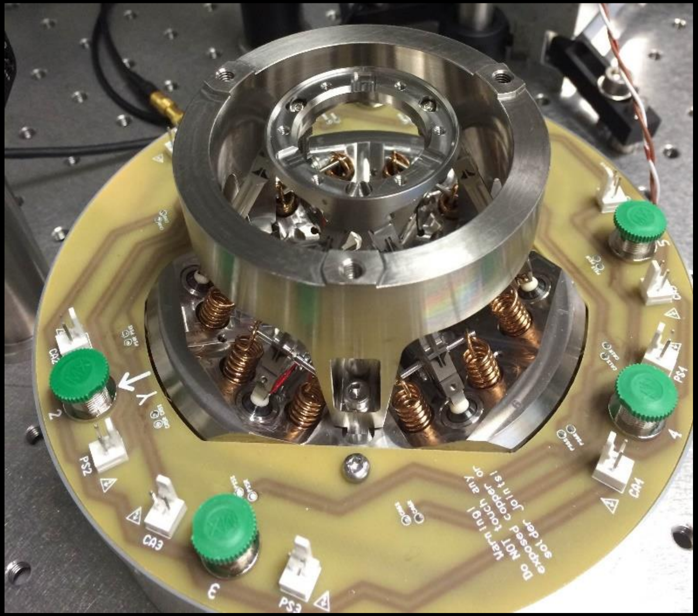


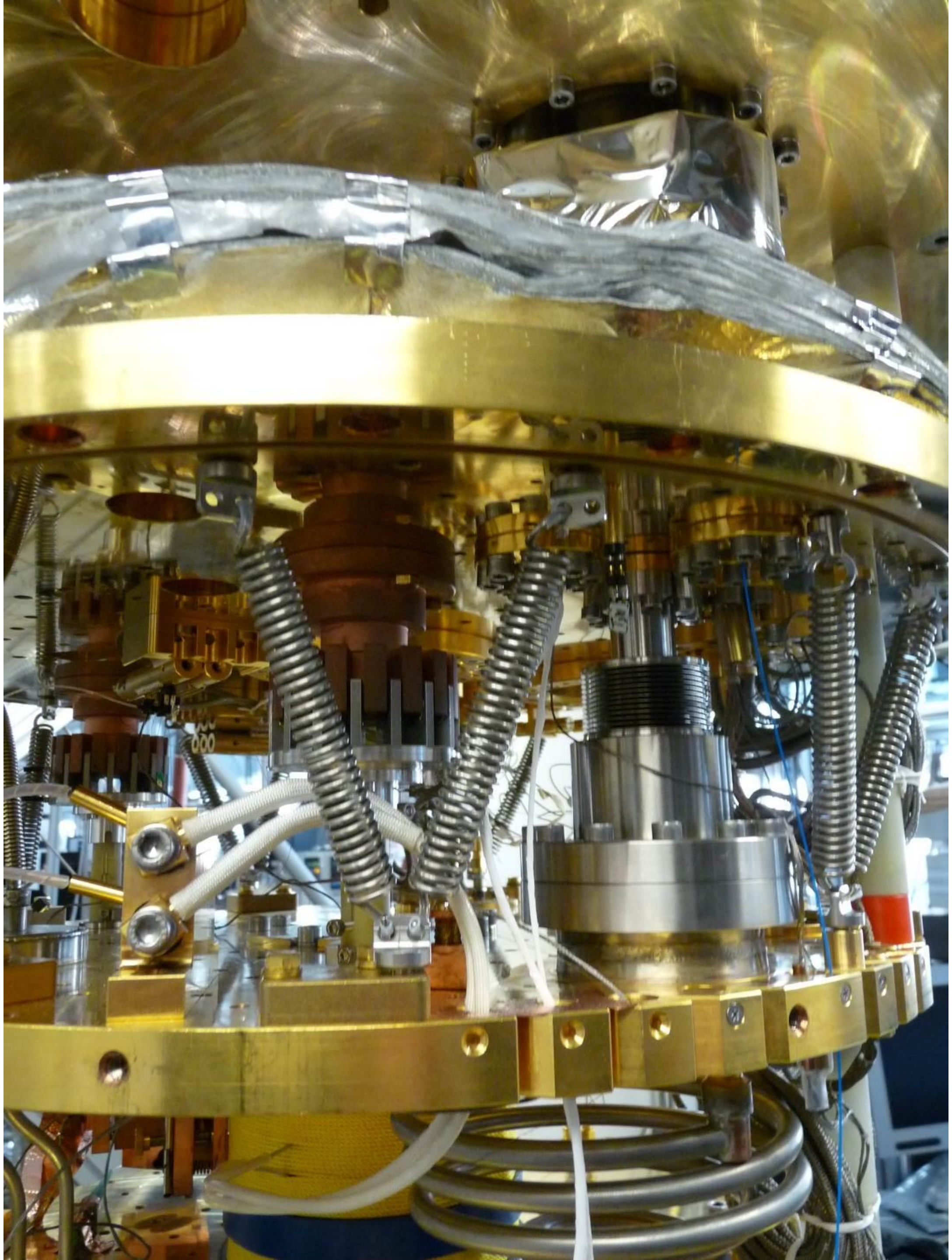


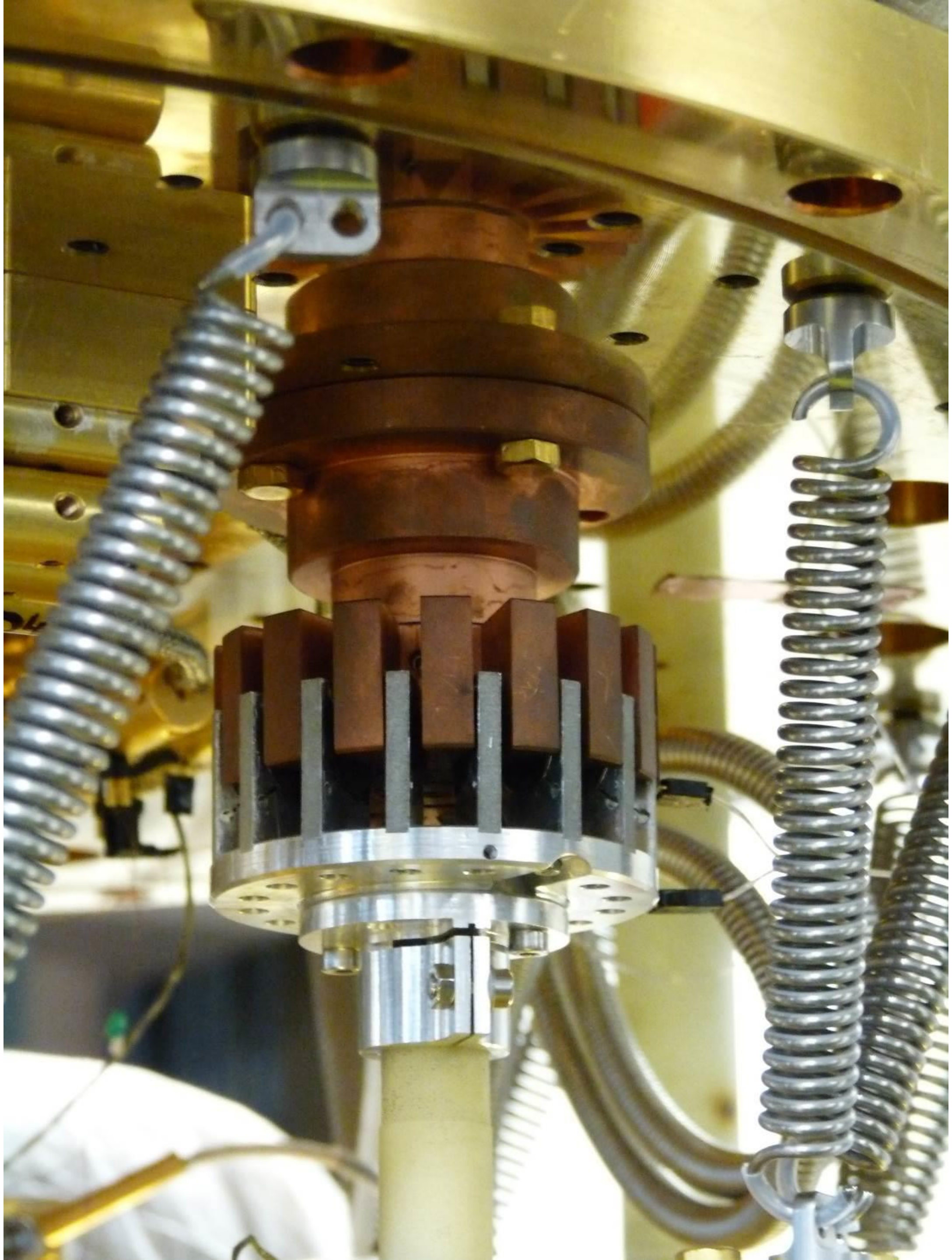
Generation 5
Finesse: 60.000
Q: 600.000

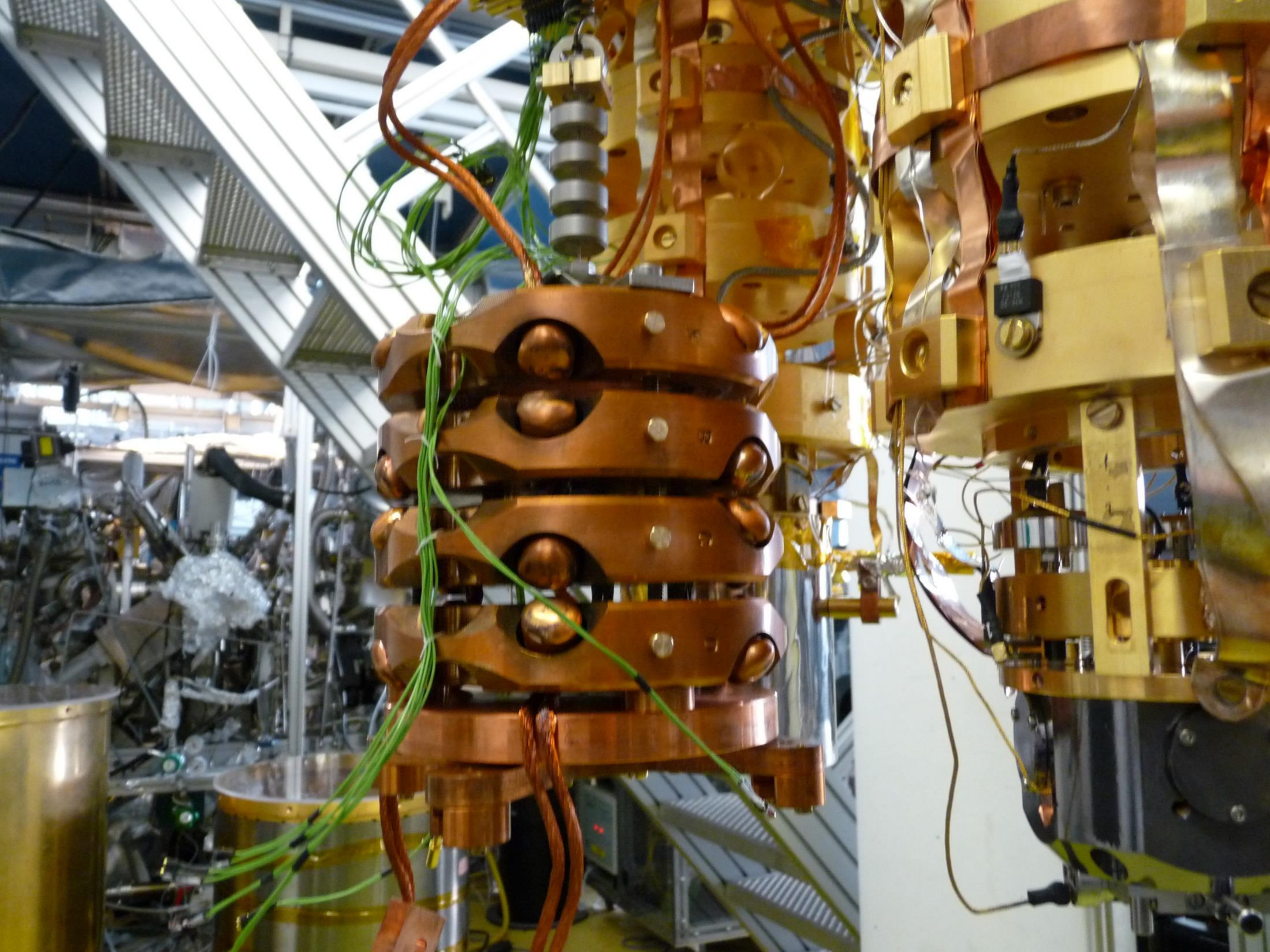
2015-2017 Leiden

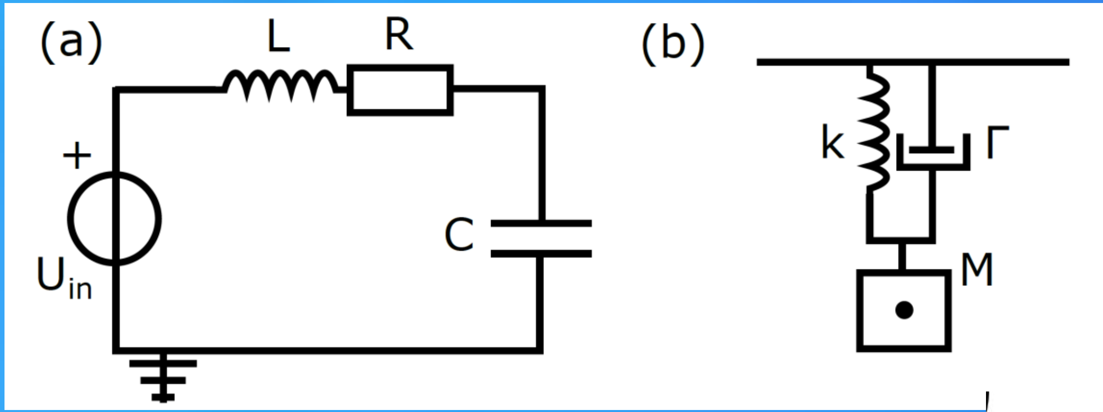






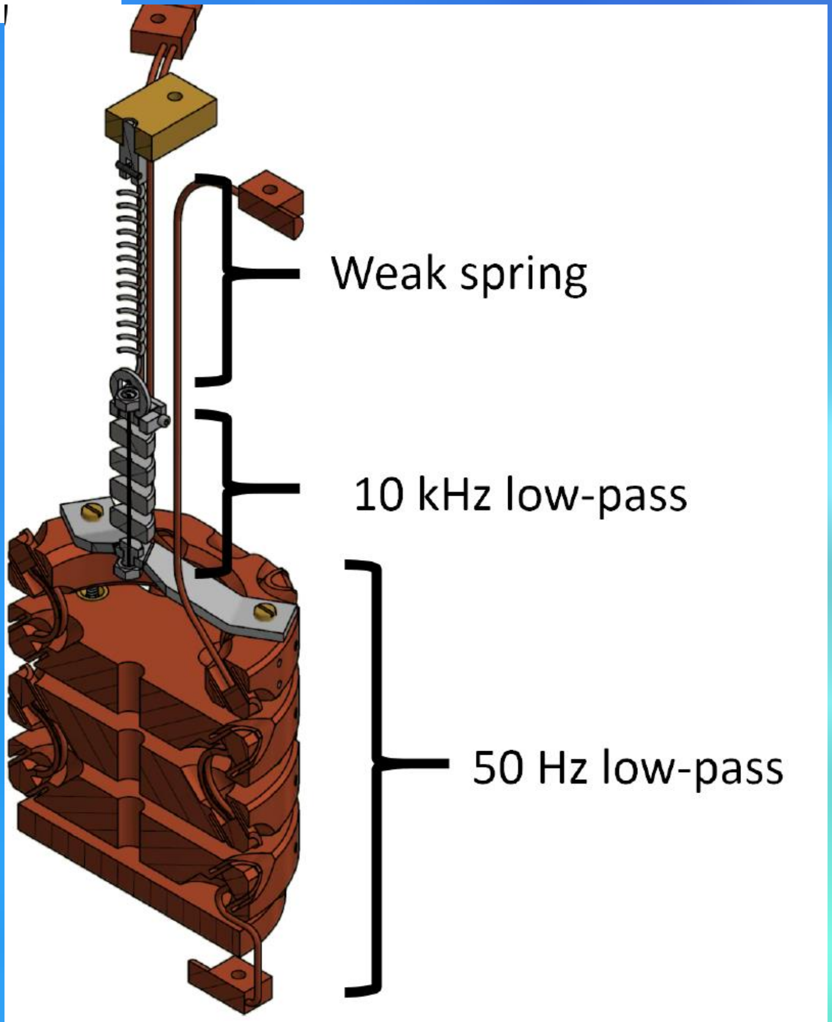




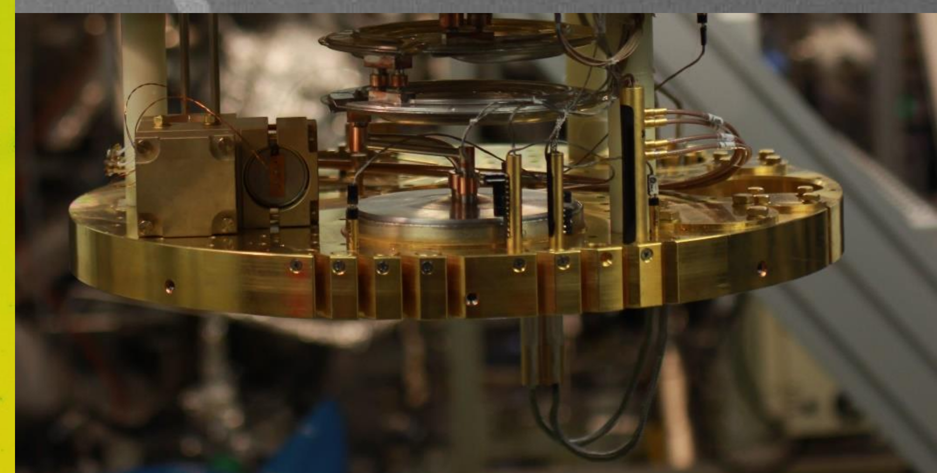


The responds of the LCR circuit in (a) and the damped harmonic oscillator in (b) can be described by the same differential equation. Use well-known electronic higher order low pass filter designes and translate to mechanics (design Kier Heeck).

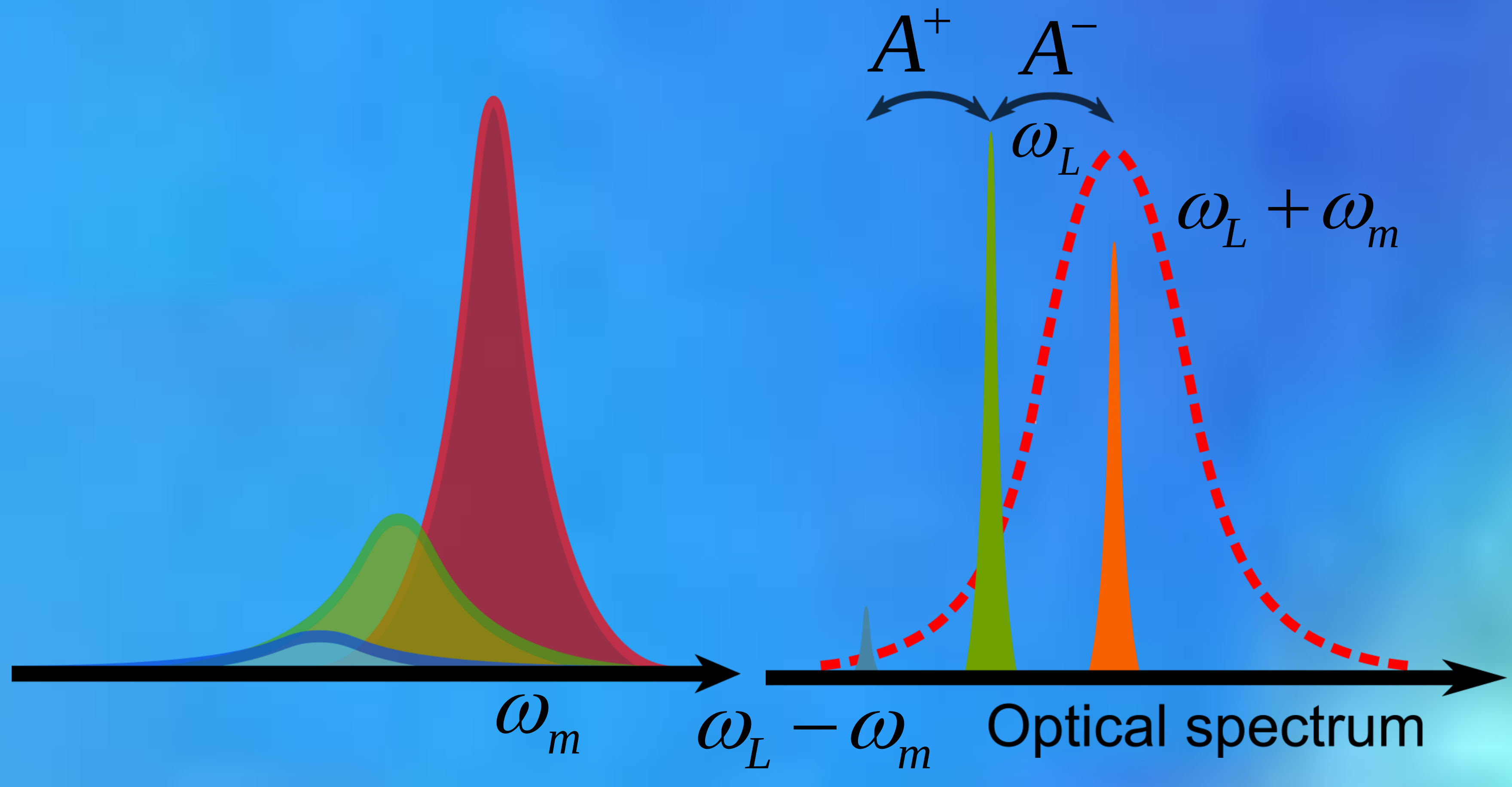
M. de Wit, G. Welkers et al.
arXiv:1810.06847



2015-2017 UCSB



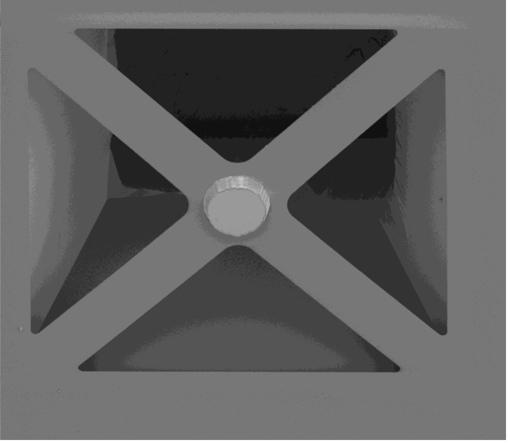
Passive optical cooling of the mechanical mode



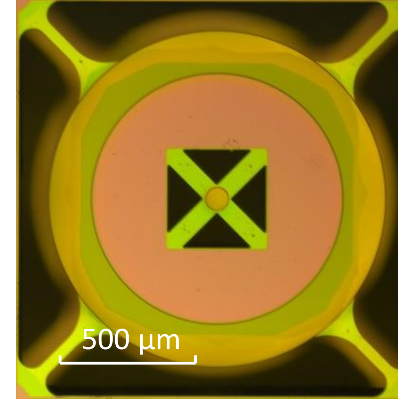
Needed for ground state cooling:

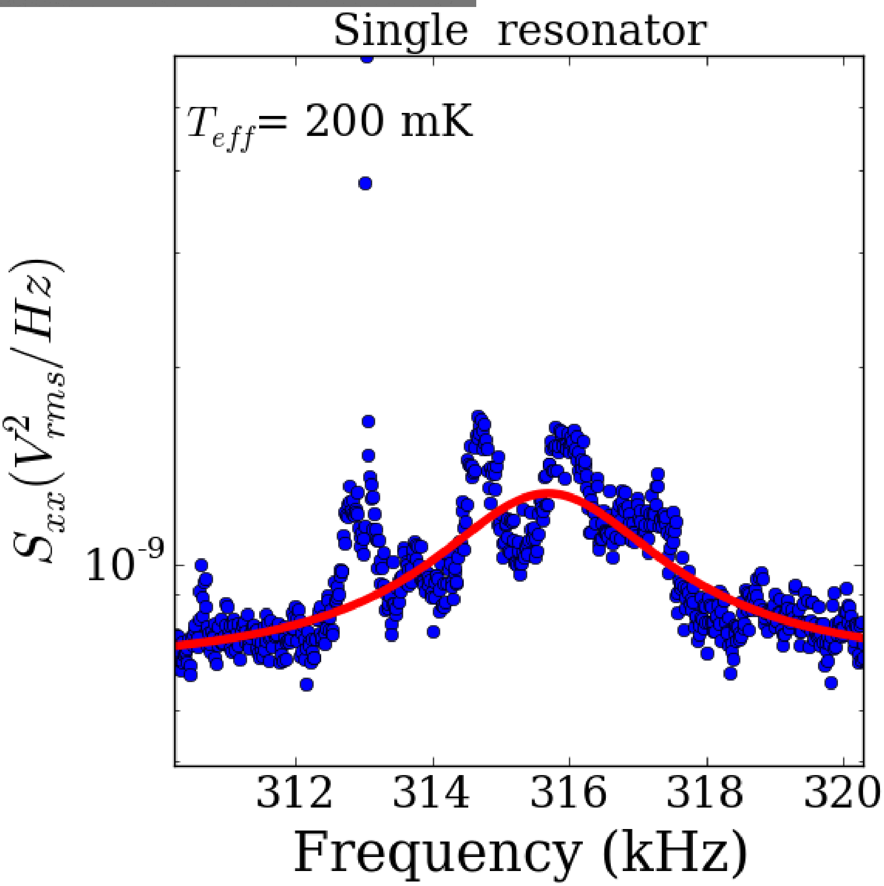
Work in side band resolved regime: $\omega_m > \gamma_{optical}$, Finesse>20,000

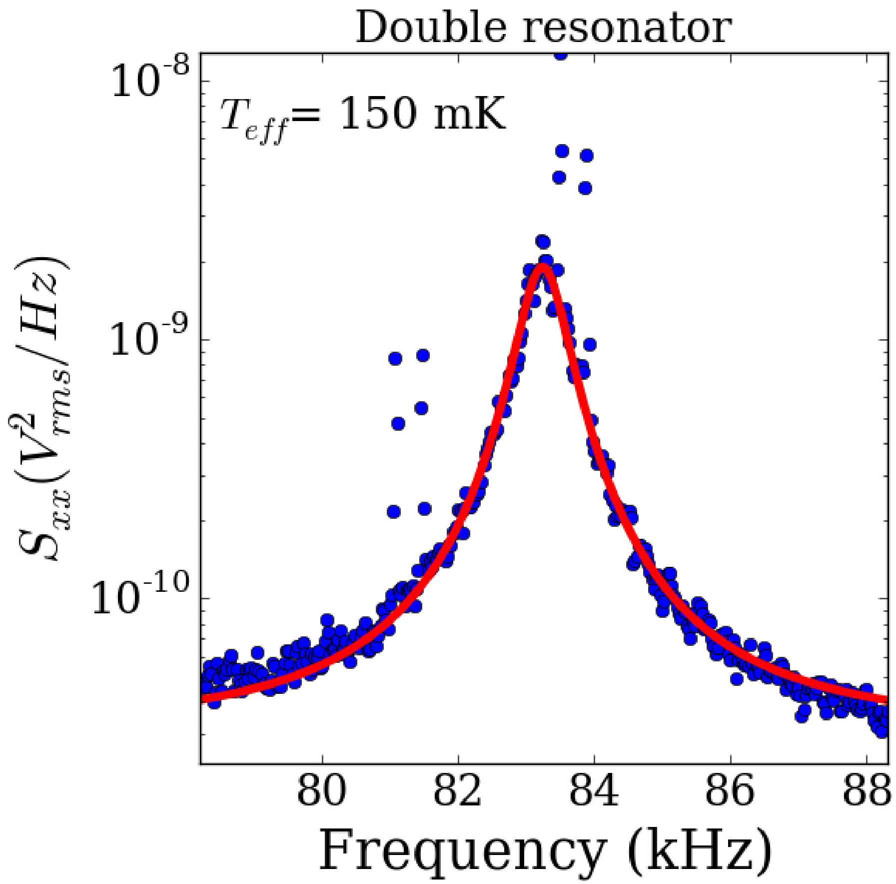
T_{bath}~100mK (compatible with previous requirements $F>10^5$, T_{bath}~5mK)



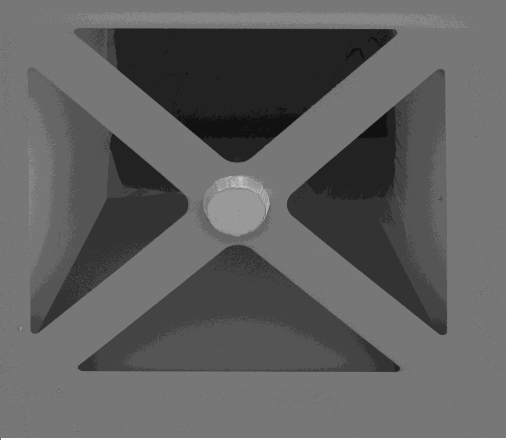
Sideband resolved optical cooling from room temperature

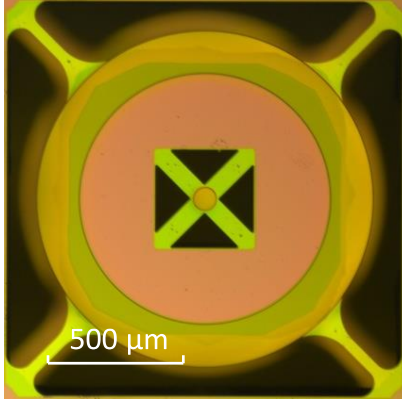


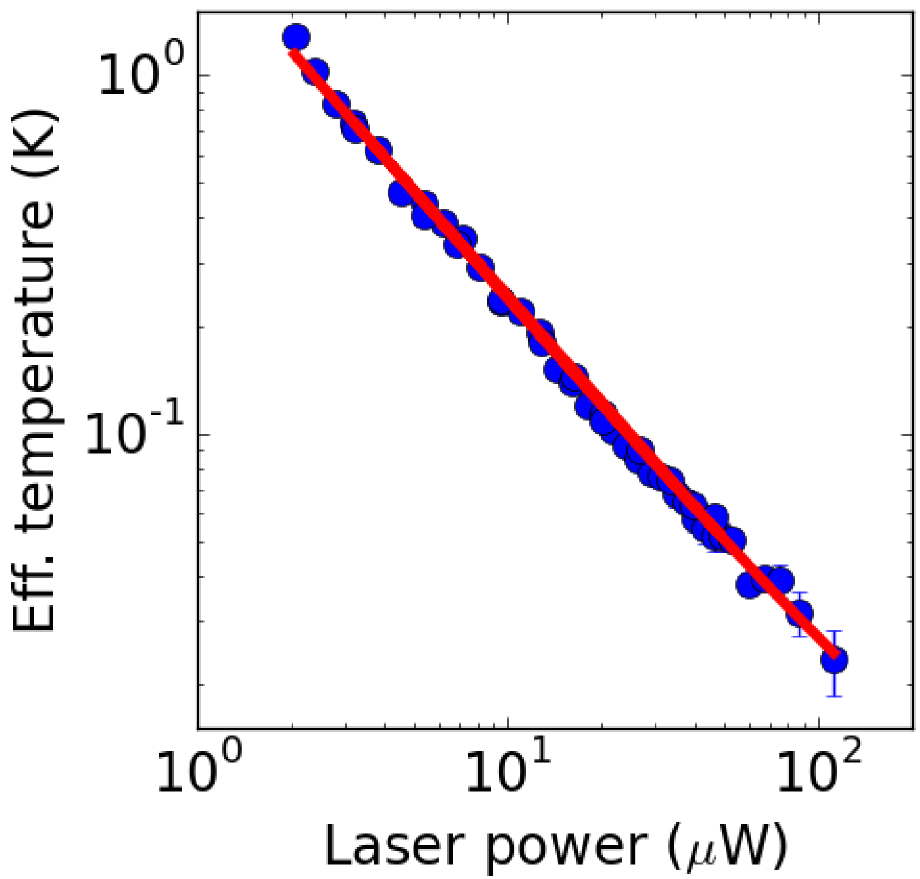


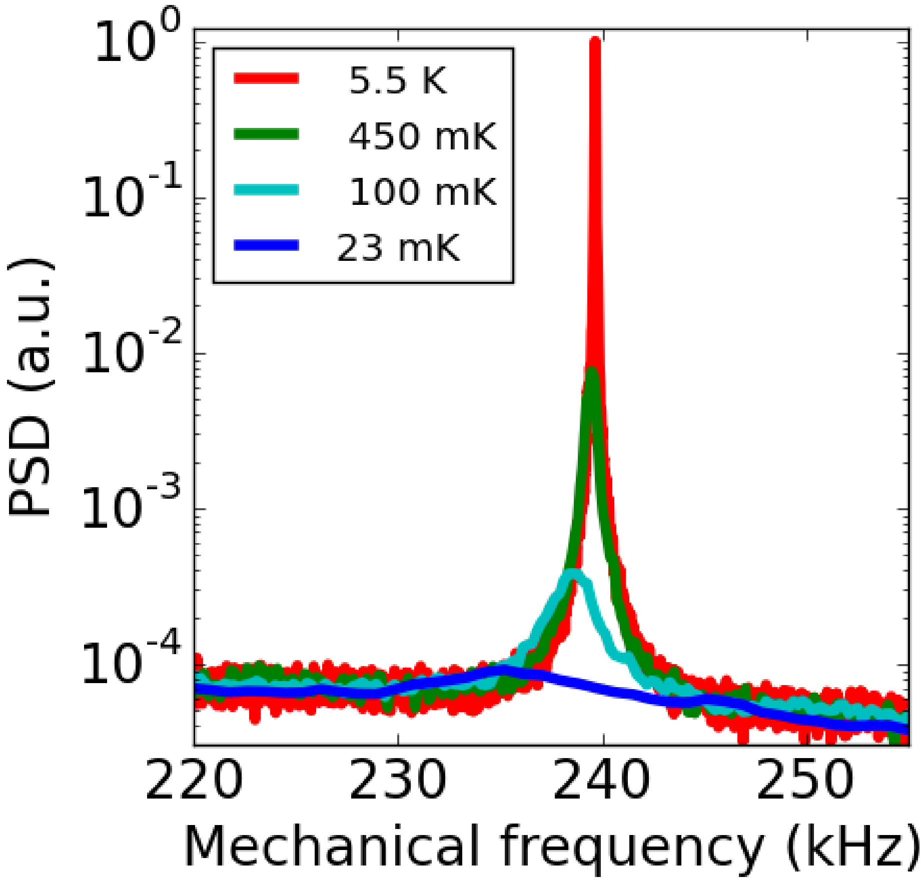


Sideband resolved optical cooling from room temperature

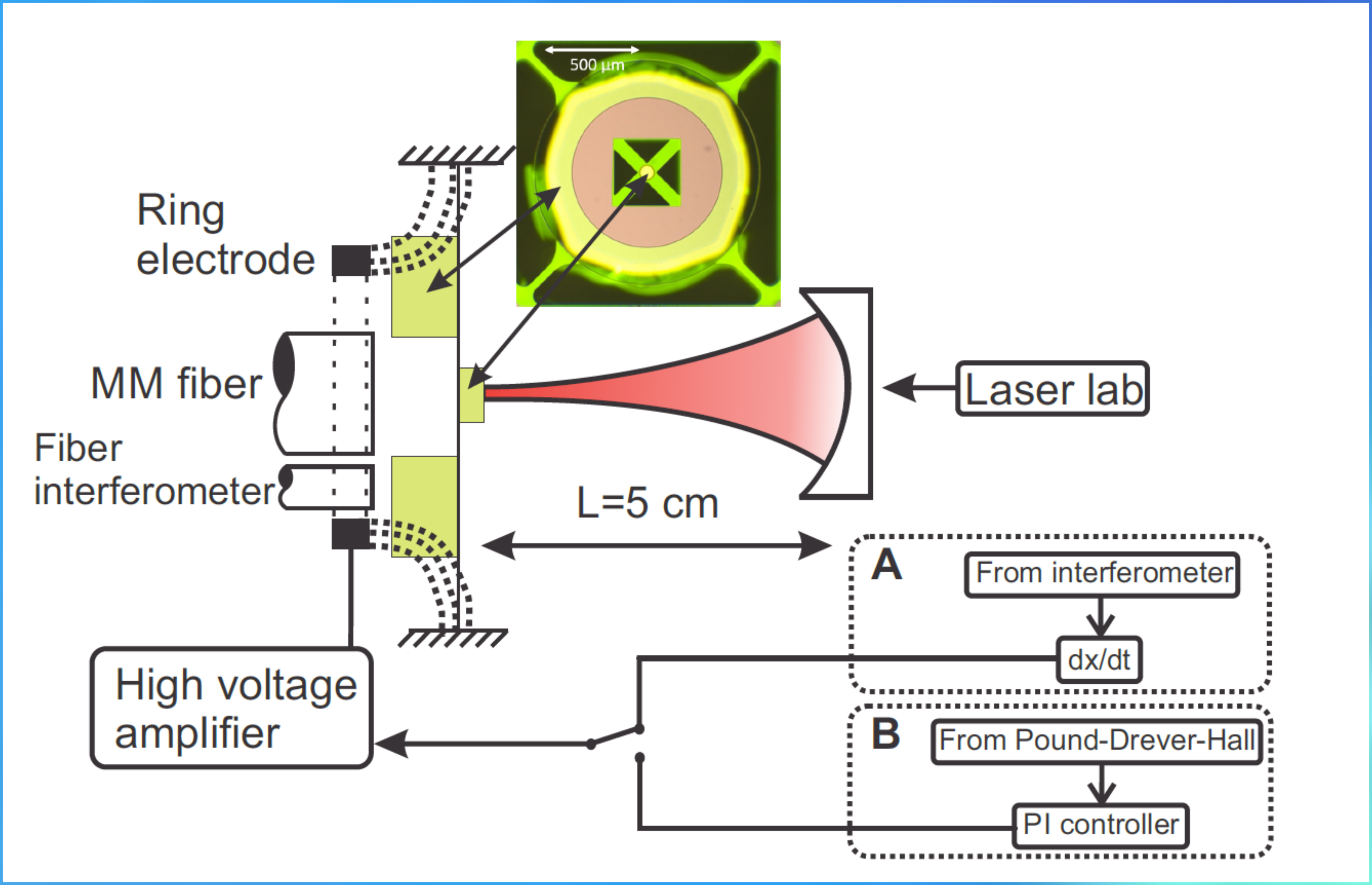






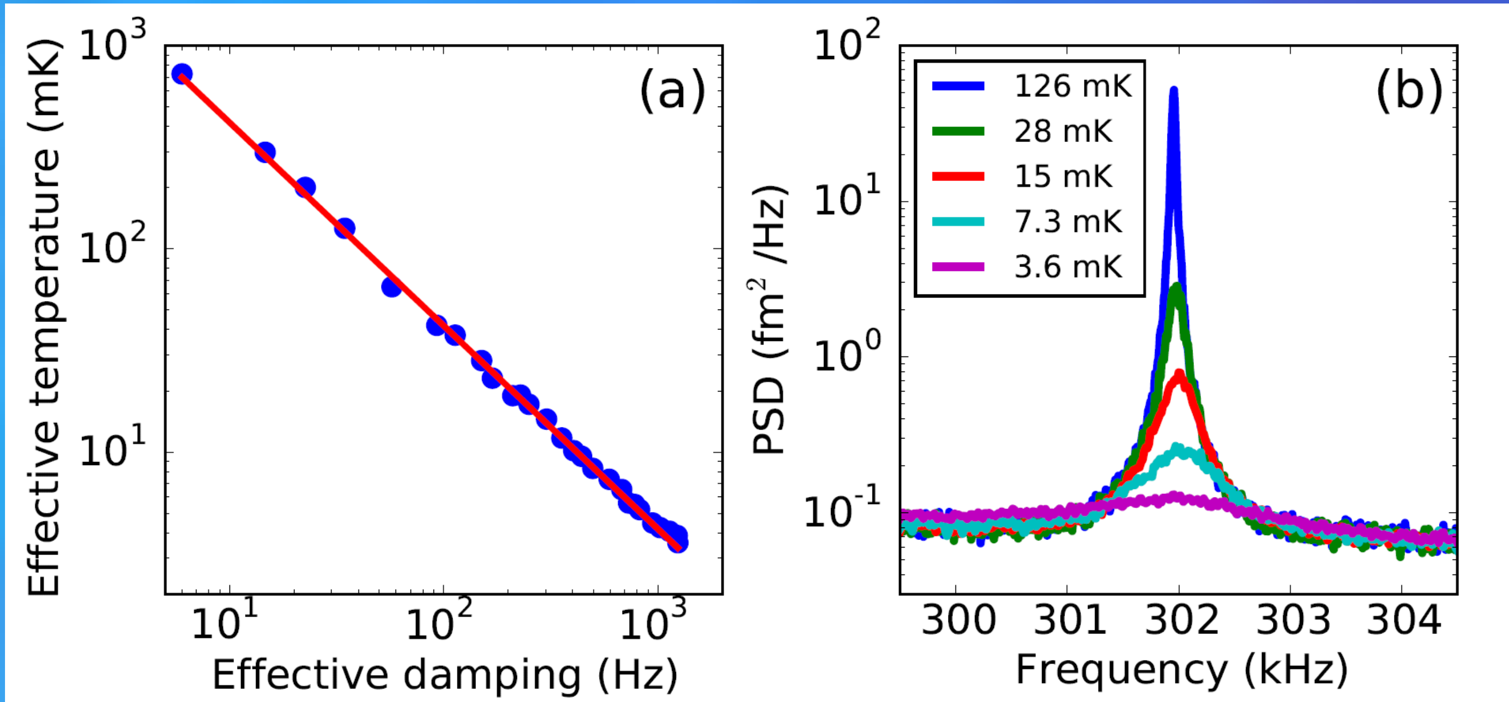


Outside resonator causes problems during cooldown. Solved by electrostatic feedback.

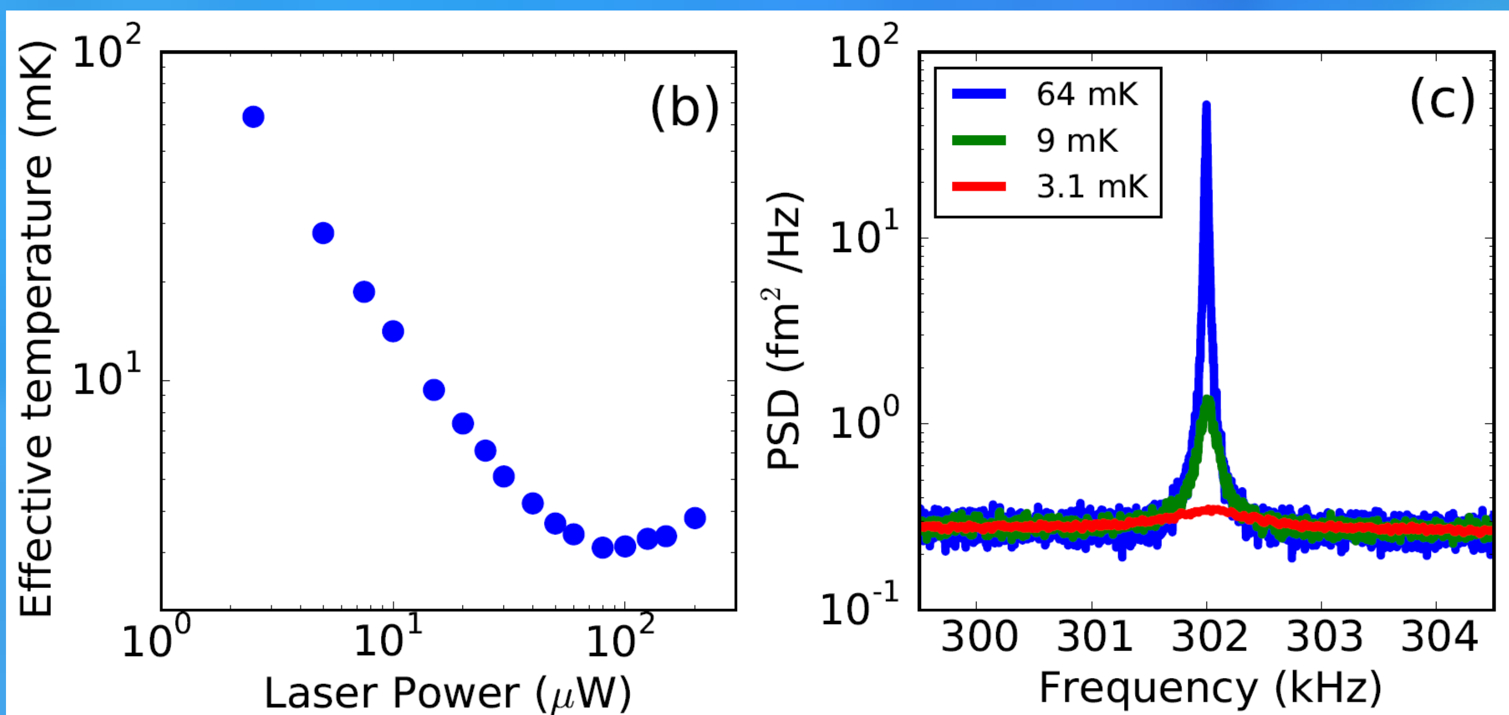


2017

Cryostat at 5K

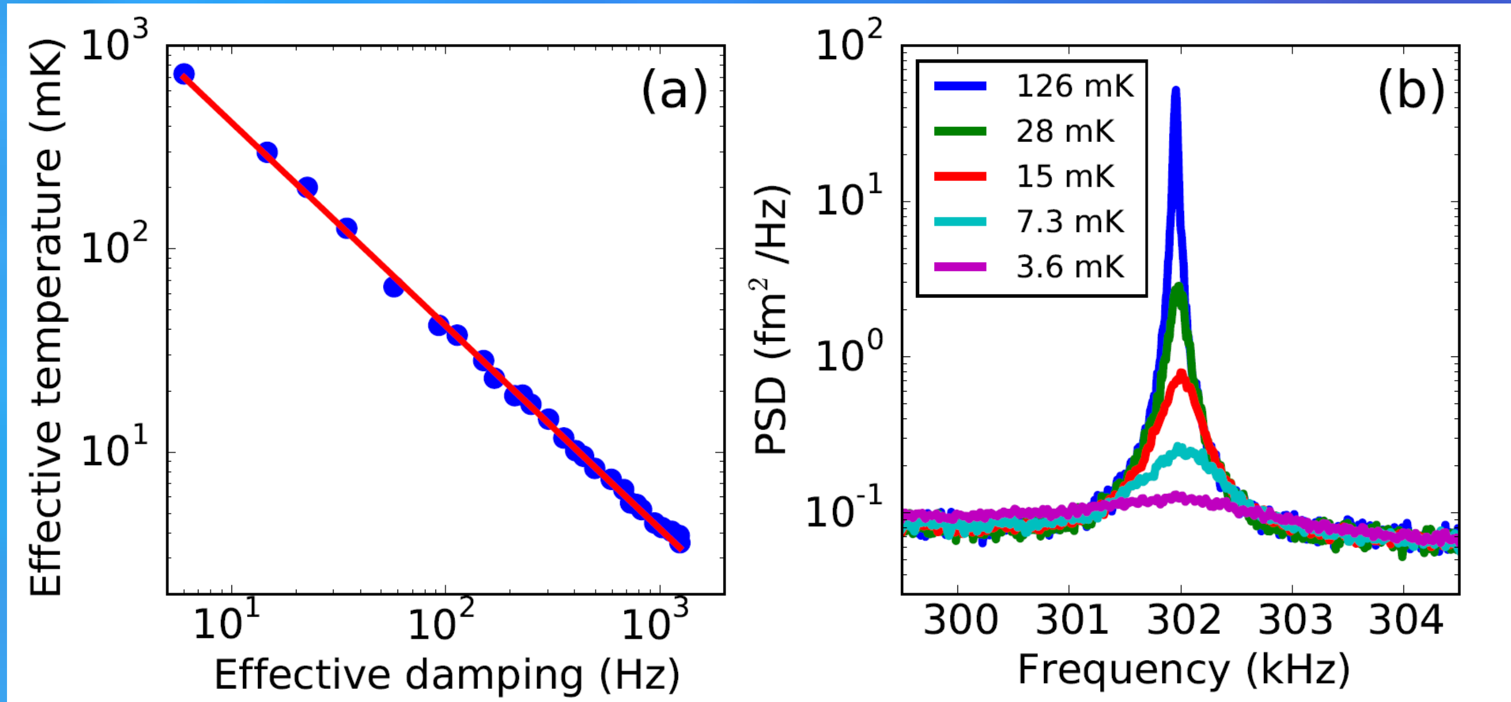


Cryostat at 100mK

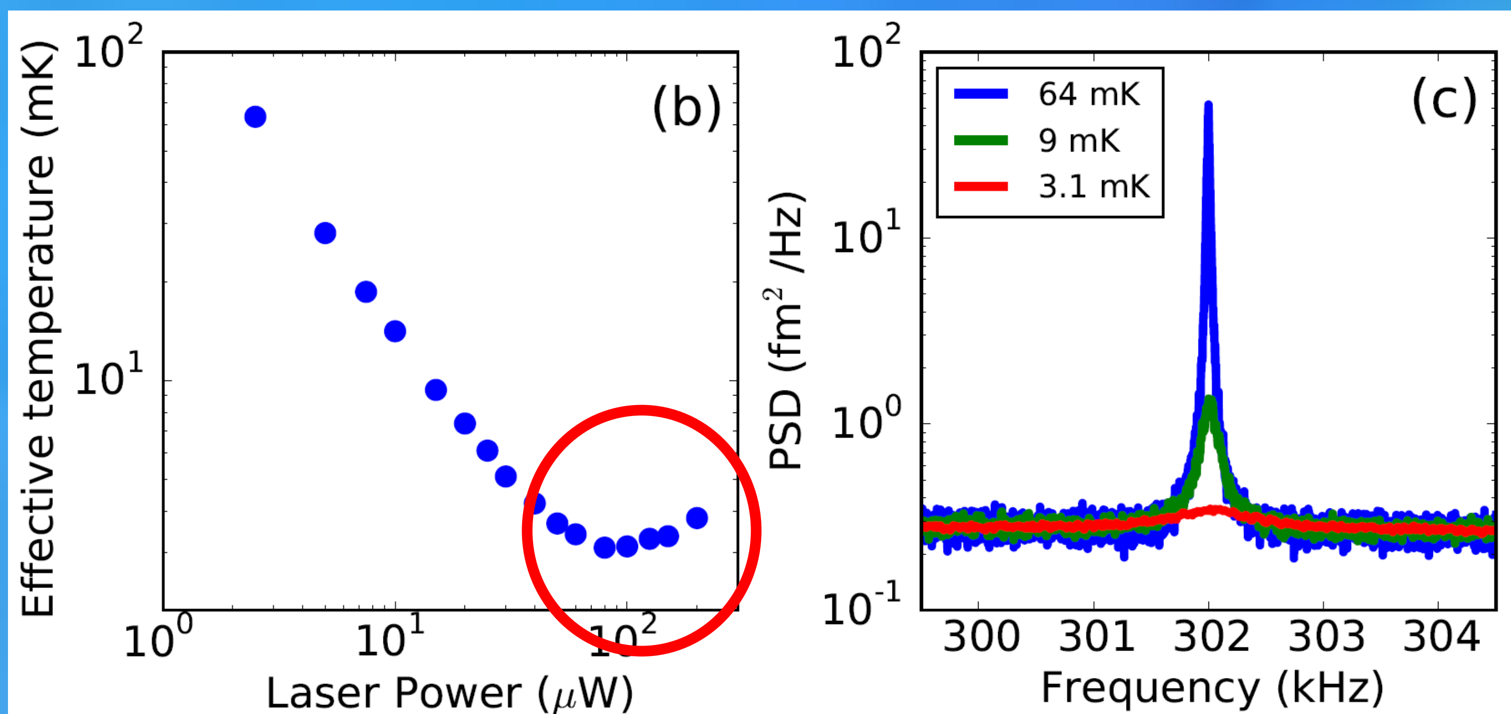


2017

Cryostat at 5K



Cryostat at 100mK



Three main technical complications:

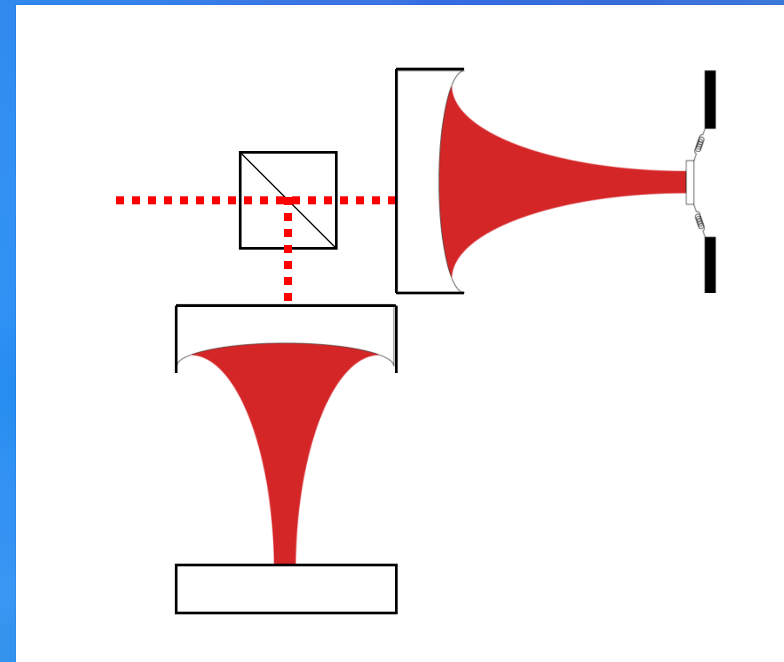
1) Optomechanical coupling not strong enough.

2) Mechanical Q's not high enough.

3) Optical heating.

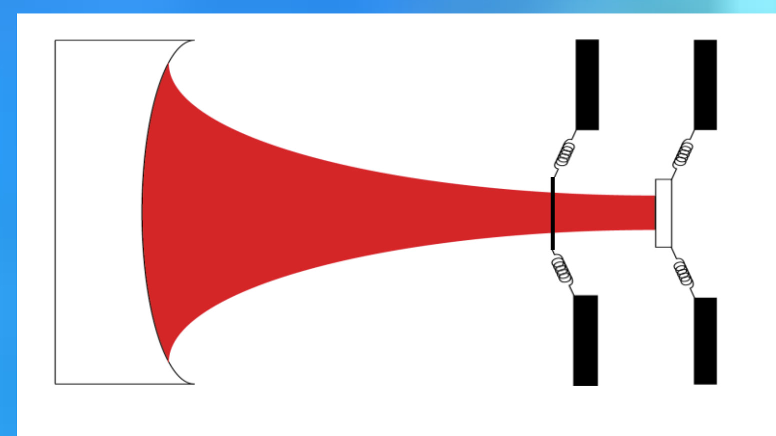
New approach for creating and testing macroscopic superpositions

1. Initial proposal : entangle light with a mechanical mode

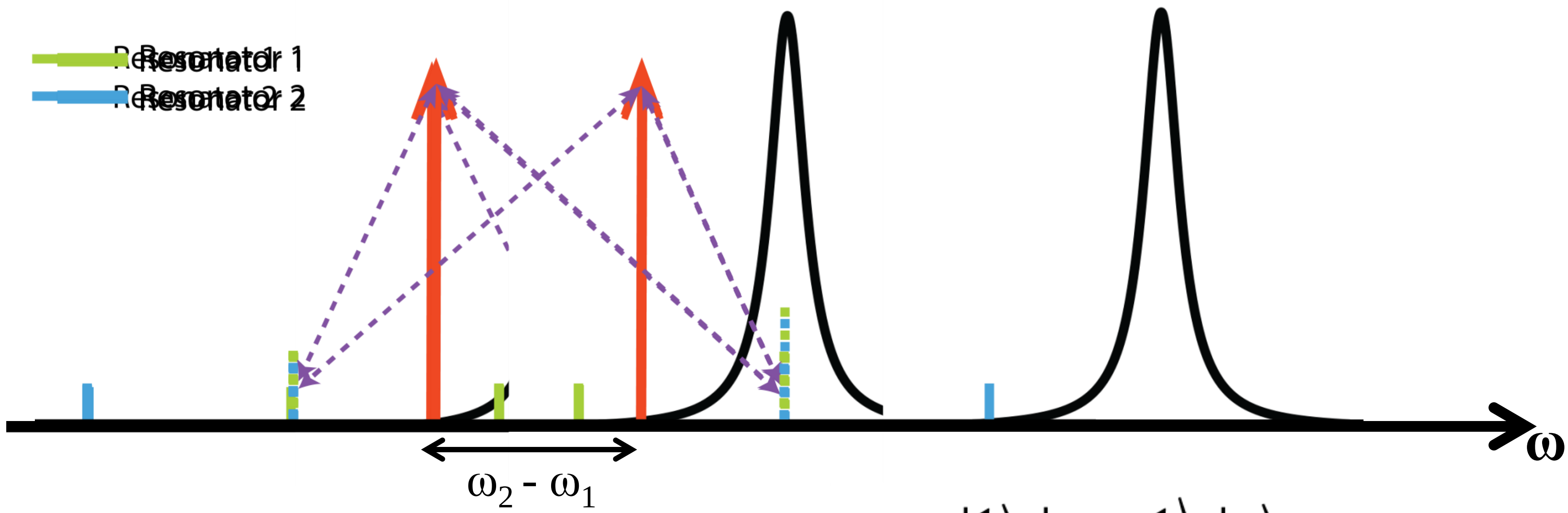


2. Many technical challenges arise from the scale difference between photons and phonons.

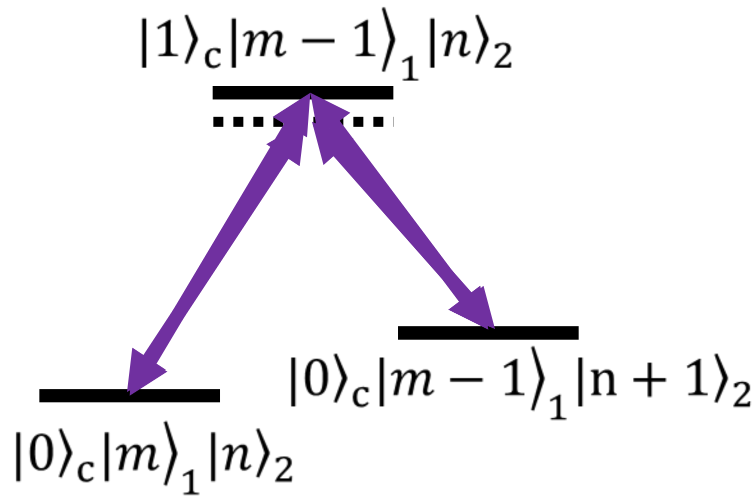
3. New scheme: Still use optomechanical systems but entangling two mechanical resonators.



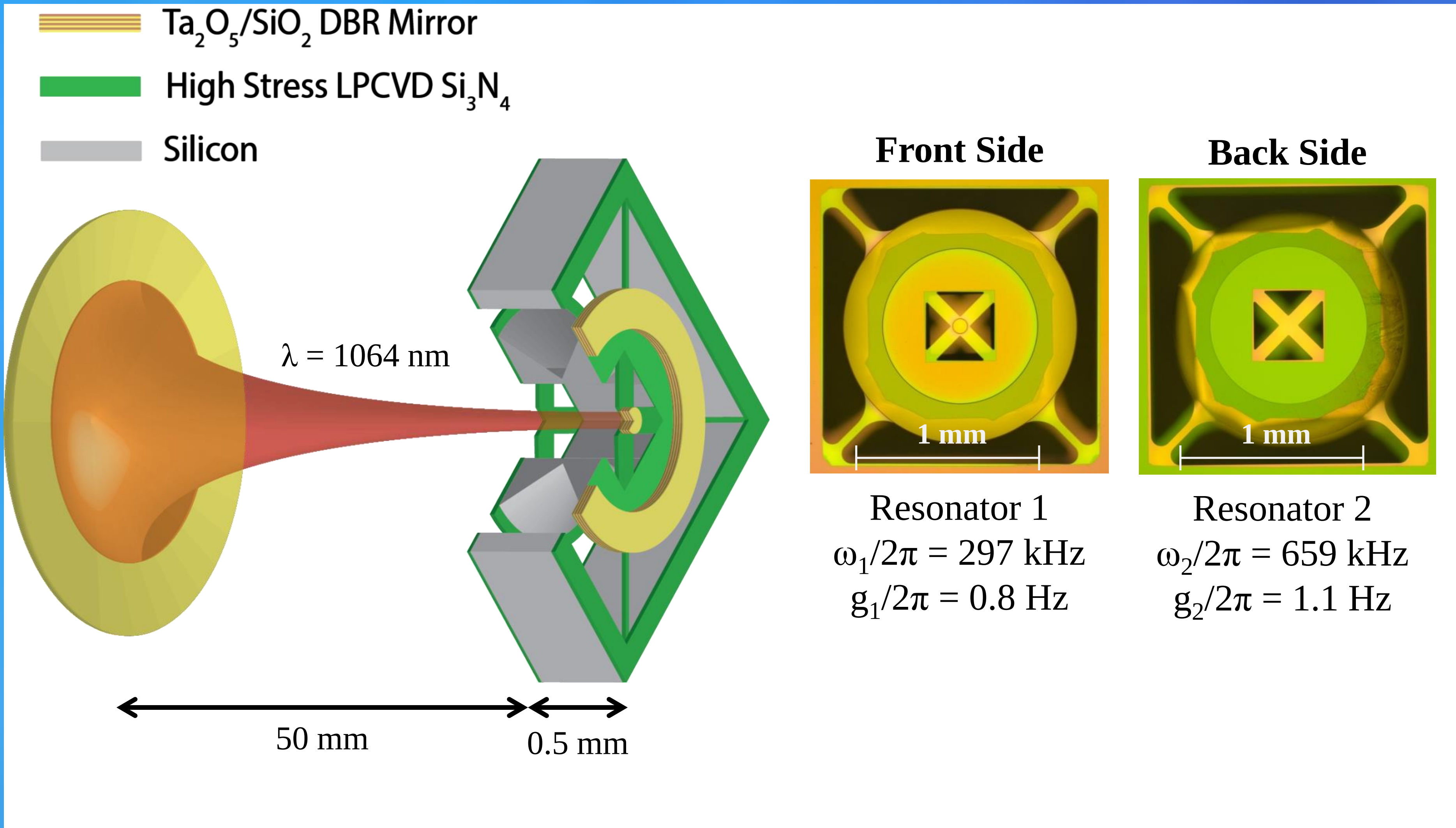
Two Tone Driving



$$H_{int} = \hbar J(b_1^{+} b_2 + b_2^{+} b_1)$$

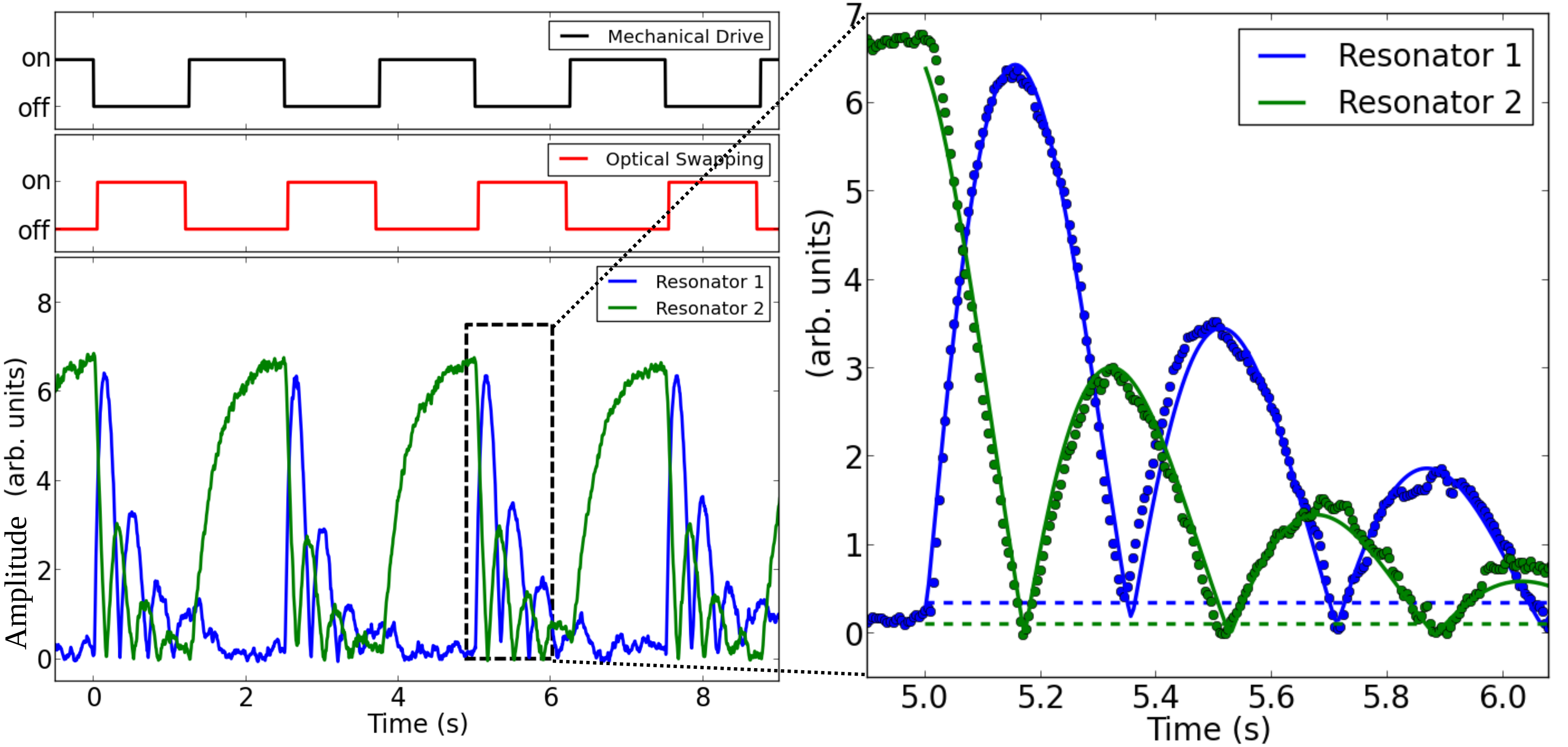


L. F. Buchmann & D. M. Stamper-Kurn**, Phys. Rev. A** (2015)



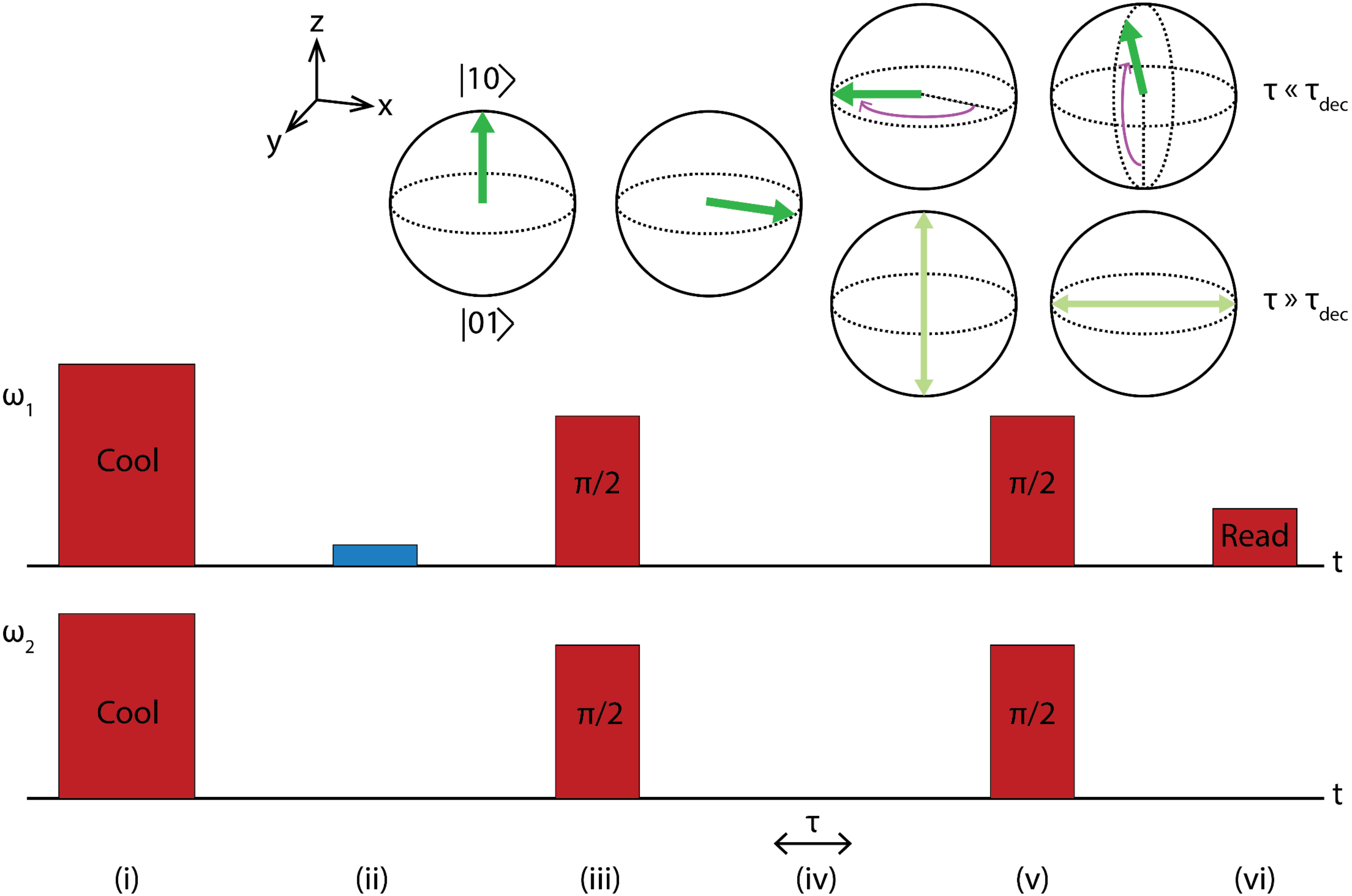
Ta_2O_5/SiO_2 DBR Mirror
High Stress LPCVD Si_3N_4
Silicon
λ = 1064 nm
50 mm
0.5 mm
Front Side
Back Side
1 mm
1 mm
Resonator 1
$\omega_1/2\pi$ = 297 kHz
$g_1/2\pi$ = 0.8 Hz
Resonator 2
$\omega_2/2\pi$ = 659 kHz
$g_2/2\pi$ = 1.1 Hz

Single Shot Measurement of the Optomechanical Swapping Interaction

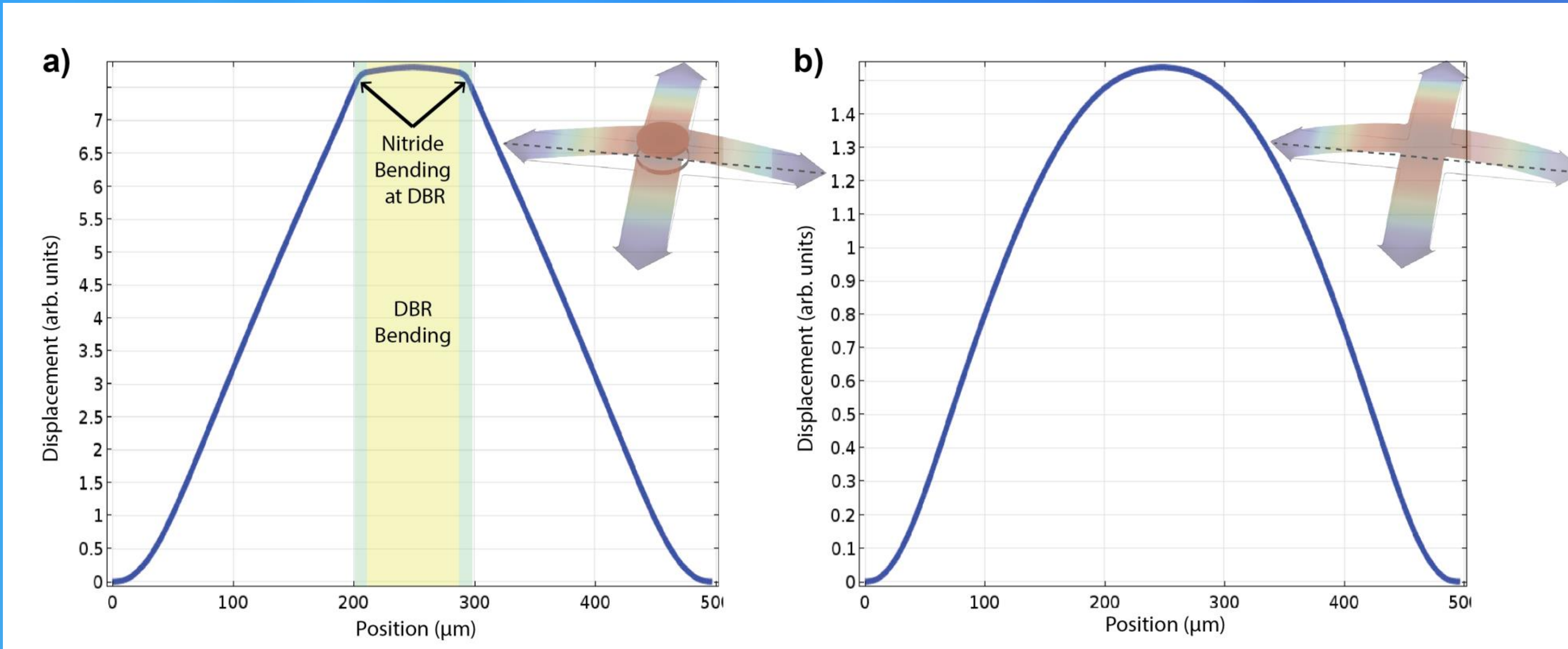


M.Weaver et al. Nature Comm.2017
M. Weaver, et al. PRA 2018

New scheme for creating and testing macroscopic superpositions

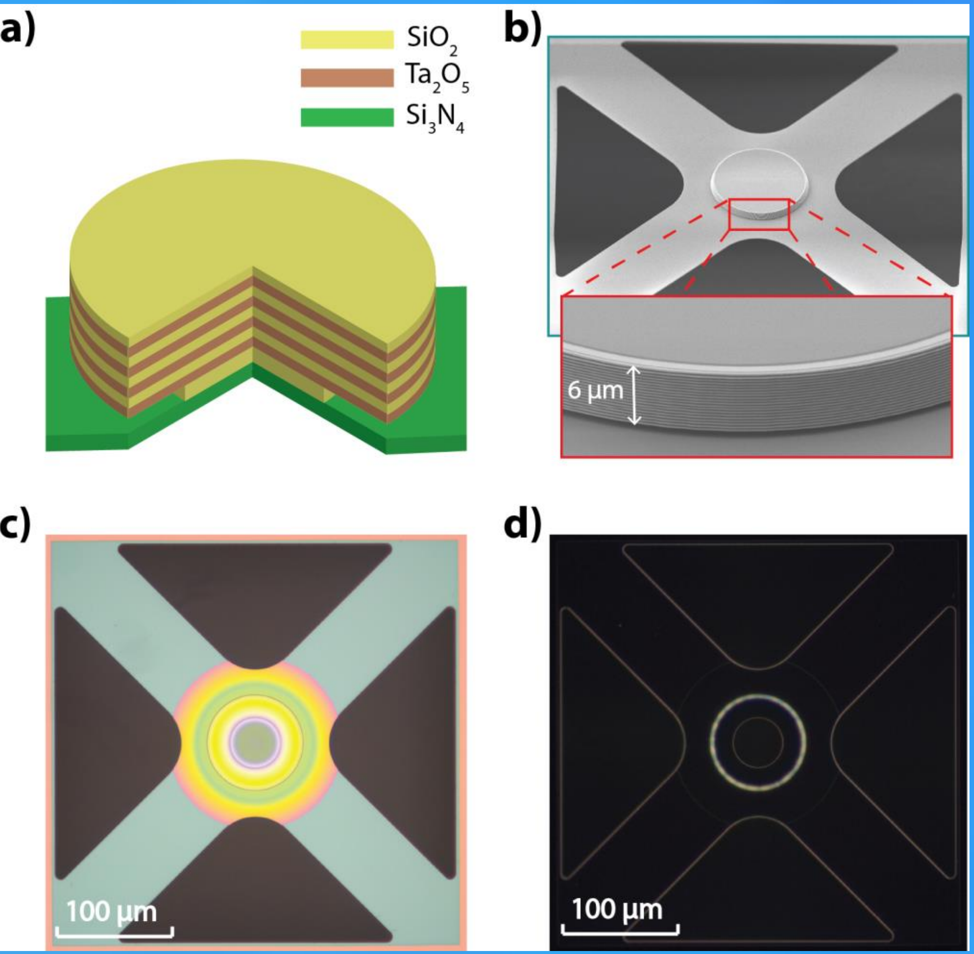


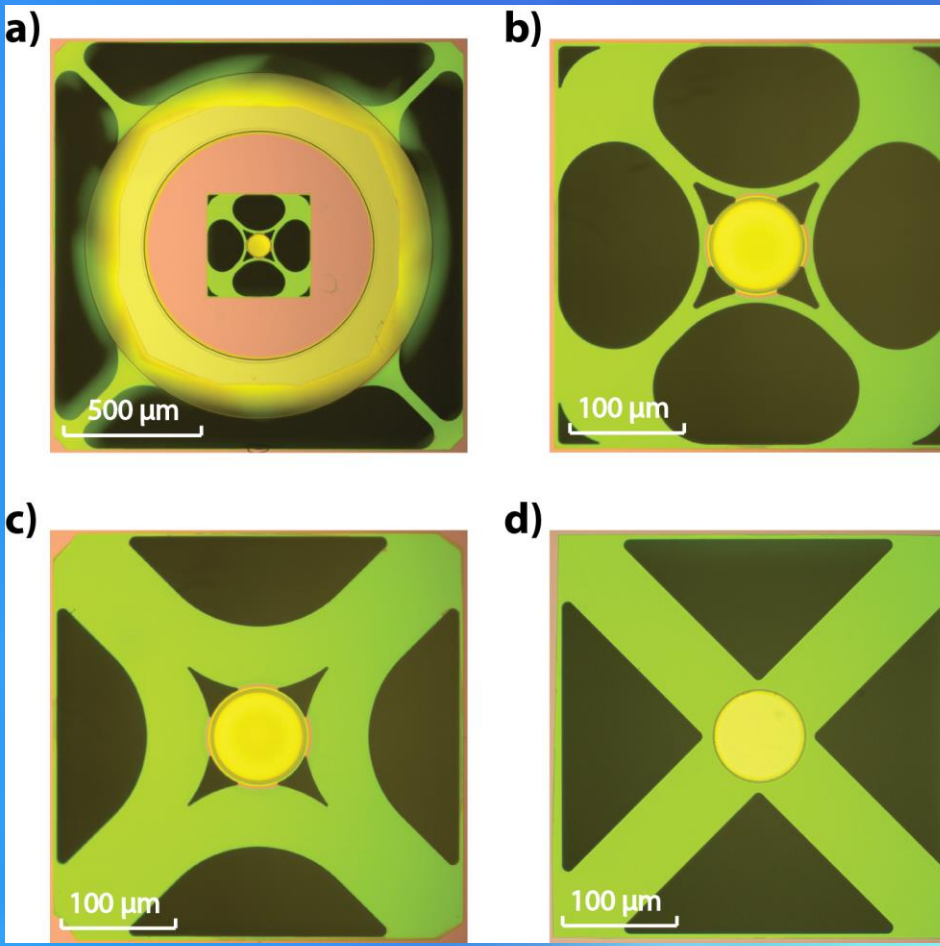
Complication 2



Bending in DBR mirror and clamping of mirror

Investigate bending in DBR mirror and clamping of mirror (M. Weaver)

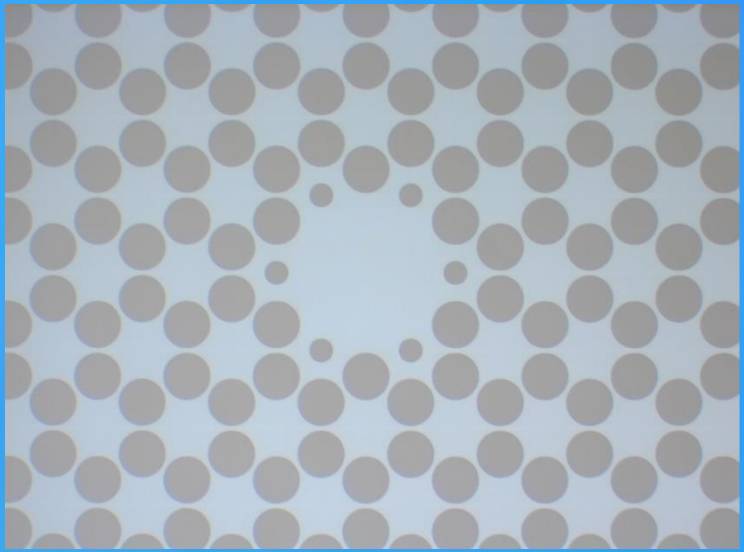


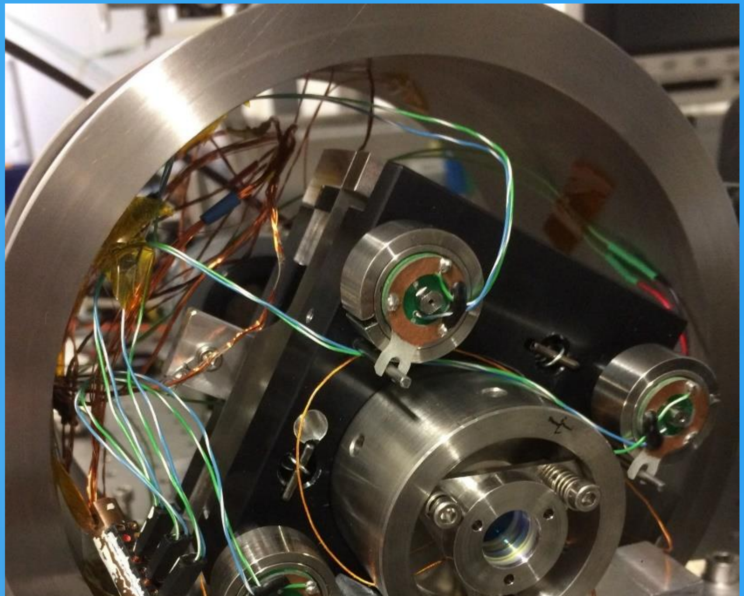


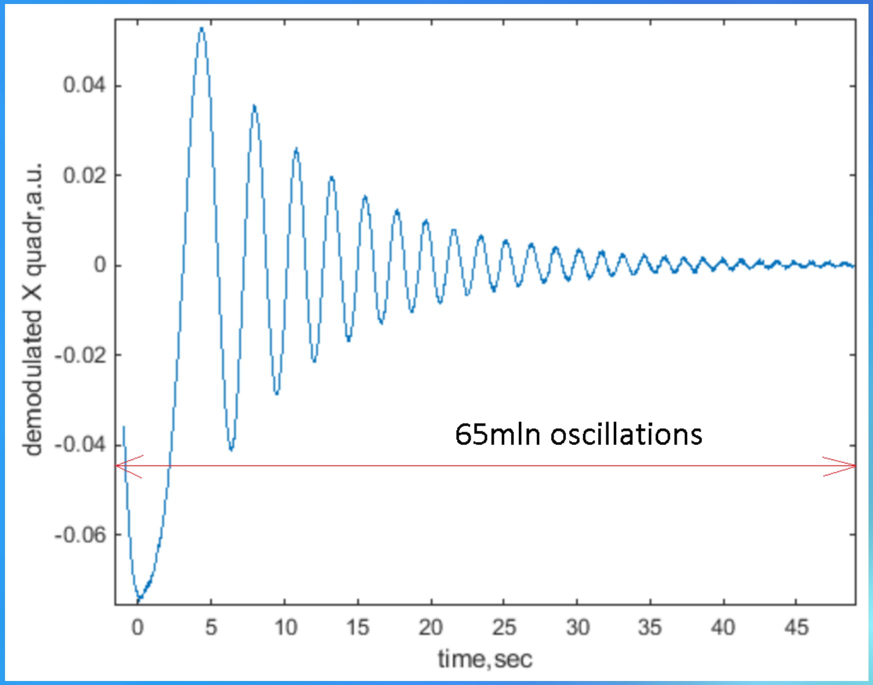
Mechanical quality factor stuck at max 1,000,000

Limitation caused by multilayer structures

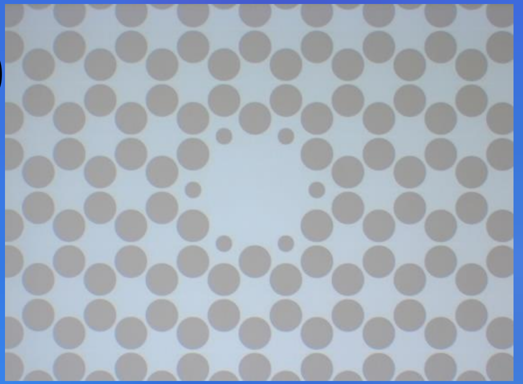
Phononic crystals membrane (F. Luna): Q= 50,000,000 at room temp! (following Y.Tsaturyan,…A. Schliesser, Nat. Nanotech. 12, 776 (2017))



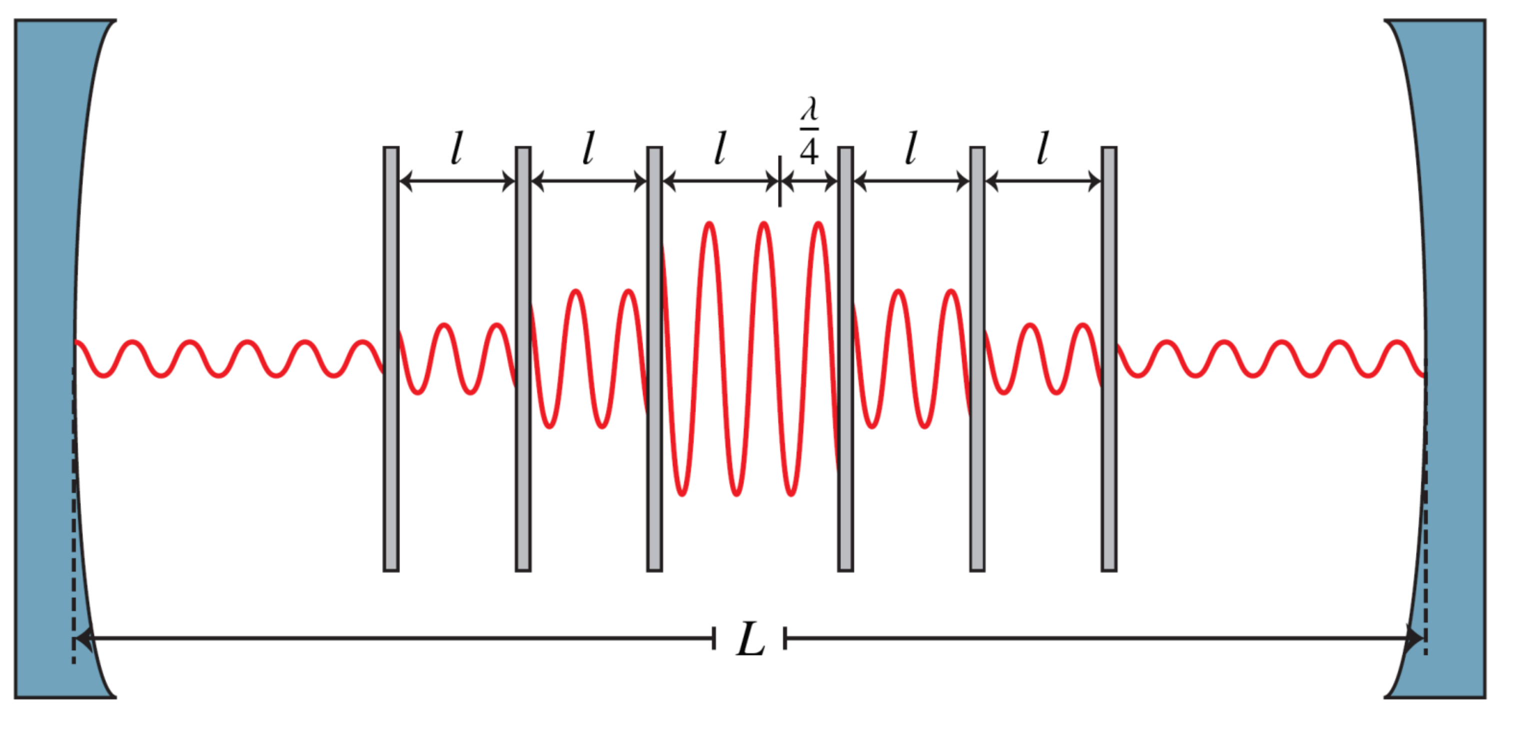




Phononic crystals membrane (D. Newsom, F. Luna)
Mass and interaction enhancement



$$g_i = q_{\mathrm{zpf}} \cdot A\frac{\omega}{L}(I_+^i - I_-^i)$$



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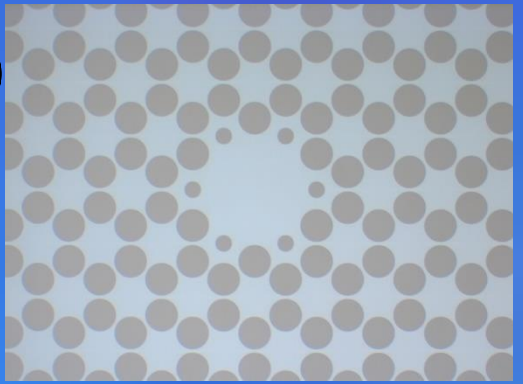
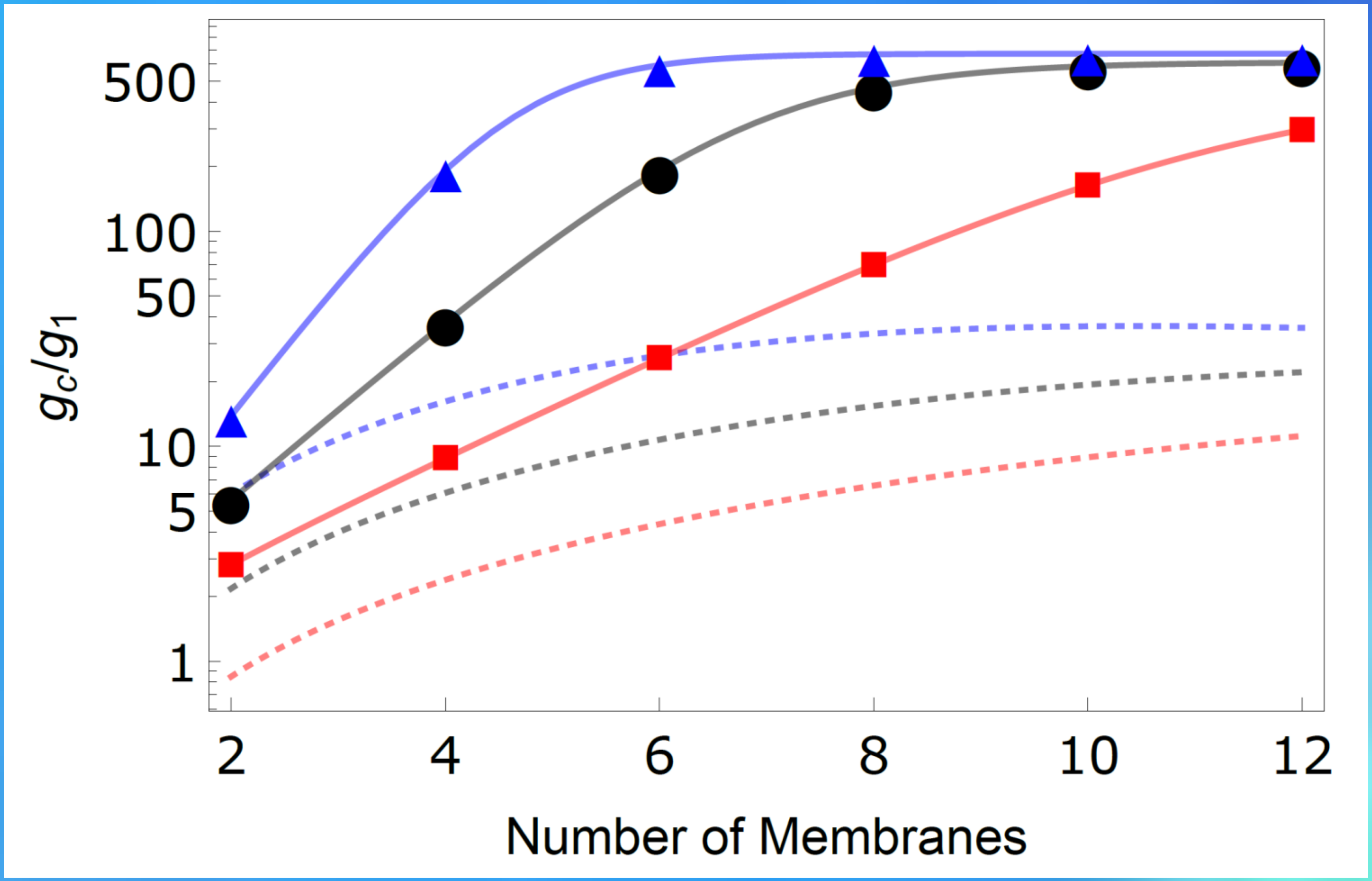
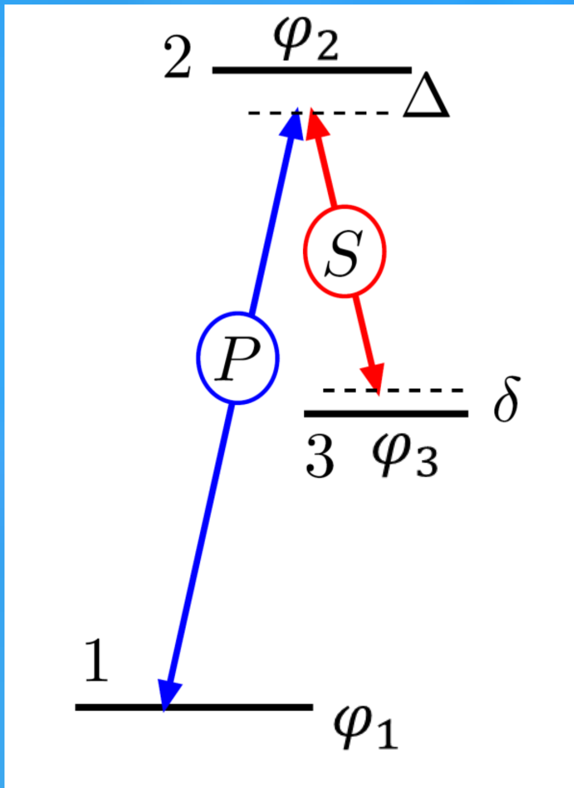
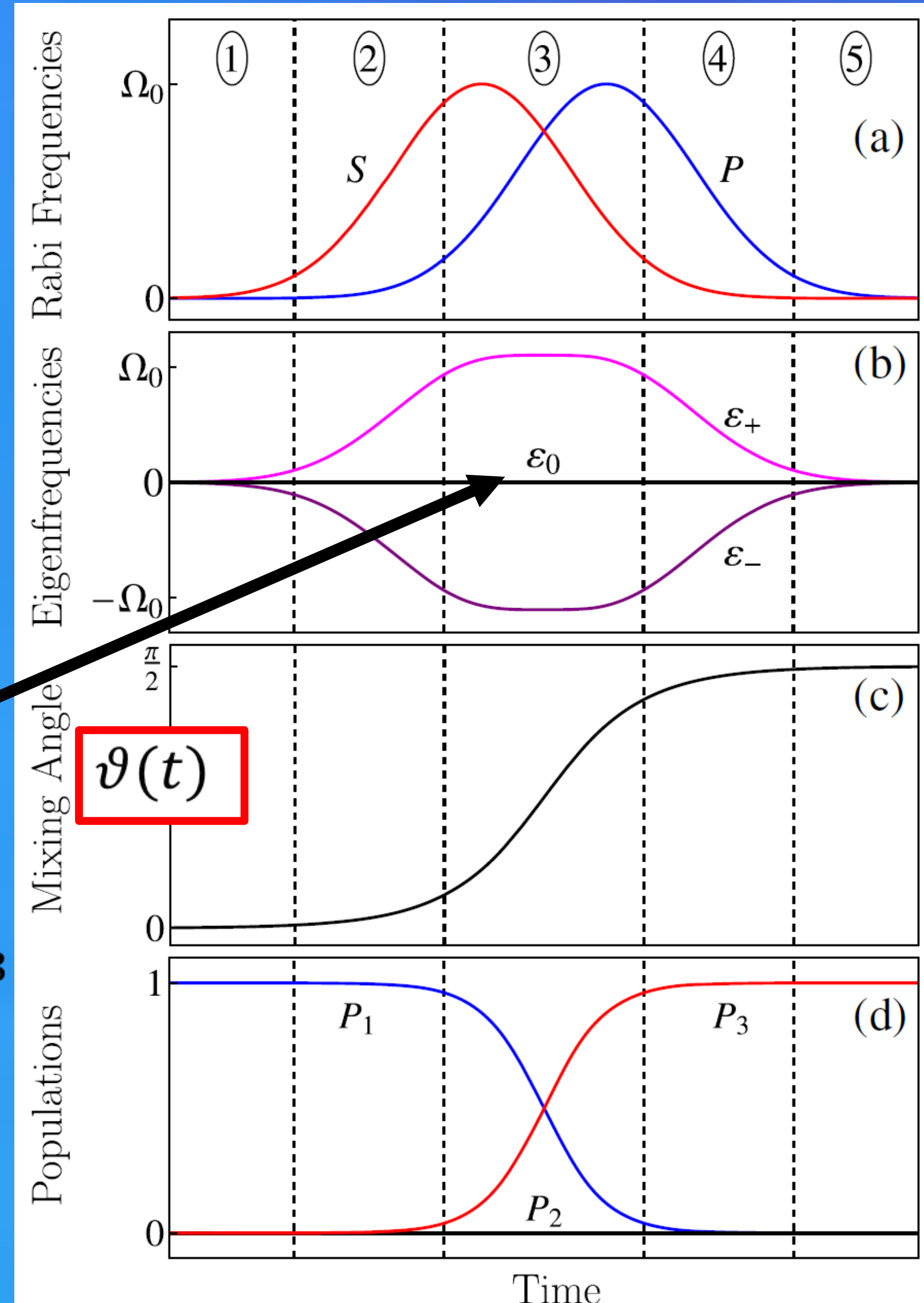




Complication 3: STIRAP (Stimulated Raman Adiabatic Passage)

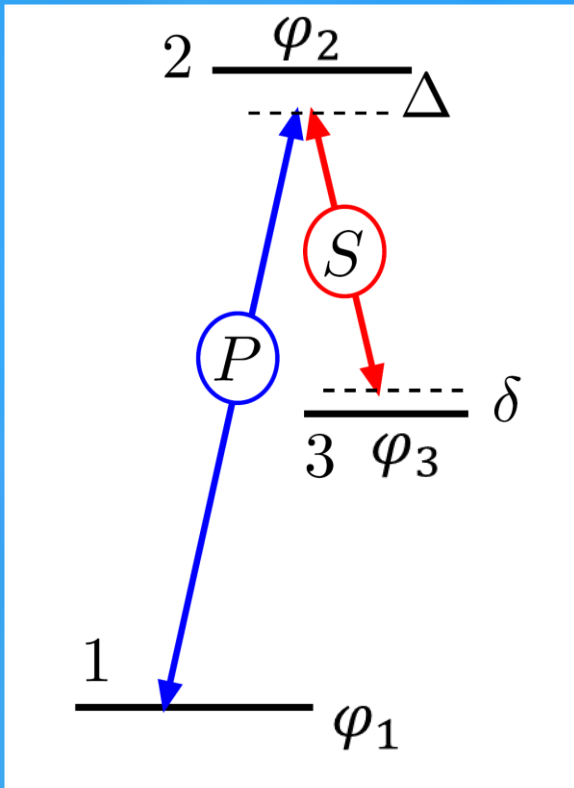


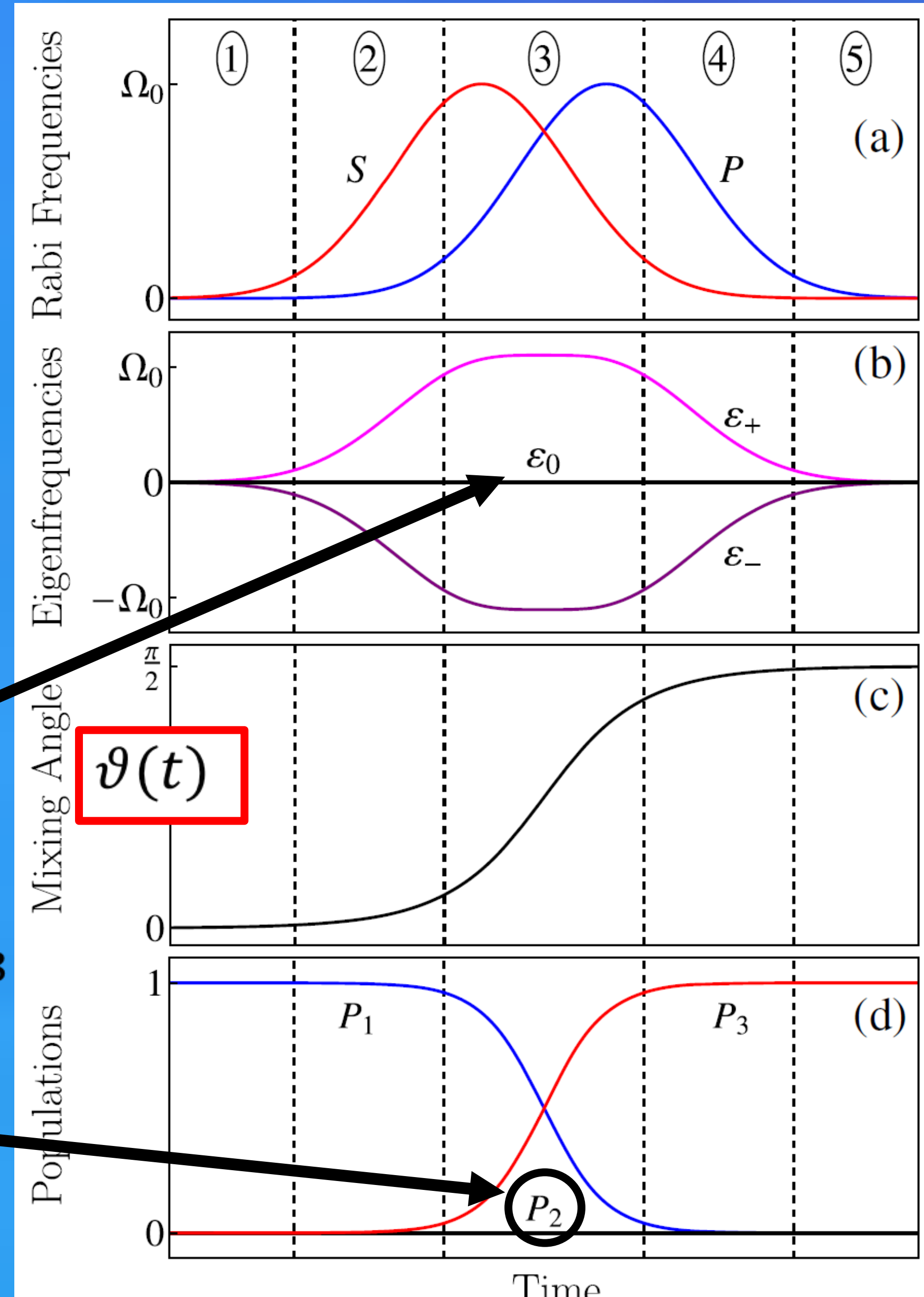


$$\varepsilon_0 = 0$$

$$\Phi_0(t) = \cos\vartheta(t)\,\varphi_1 + \sin\vartheta(t)\,\varphi_3$$

STIRAP (Stimulated Raman Adiabatic Passage)



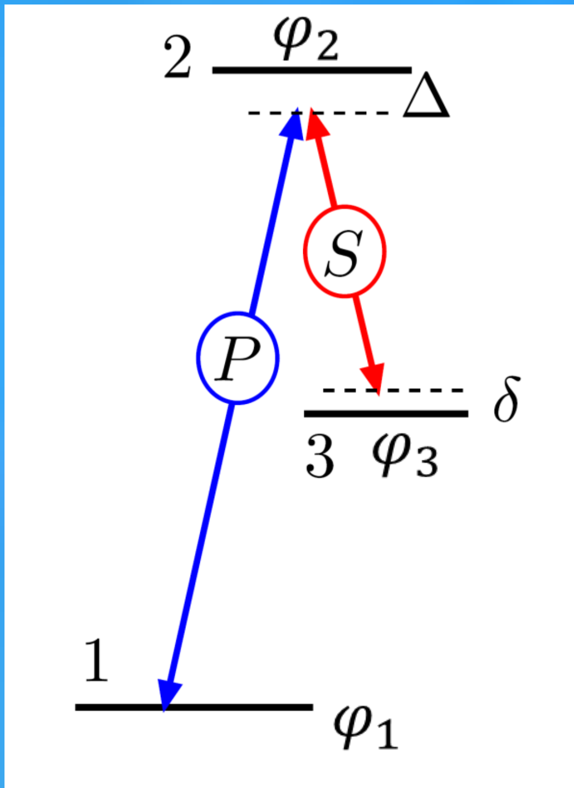


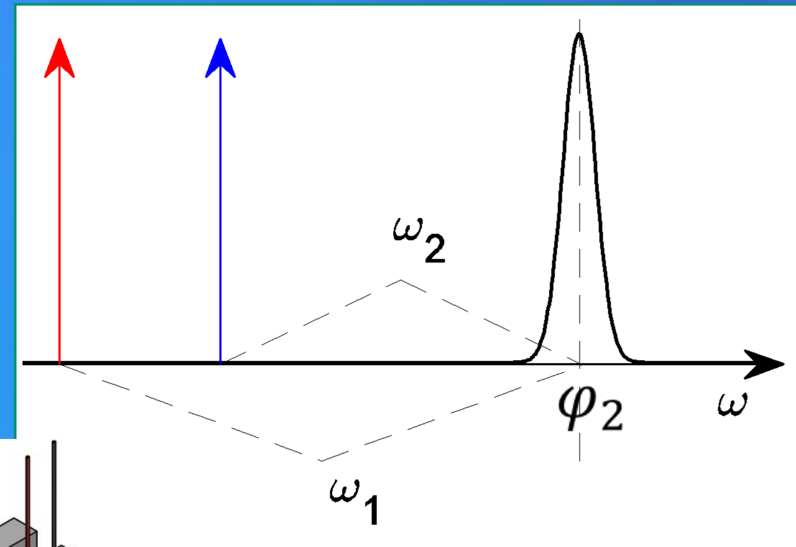
$\varepsilon_0 = 0$

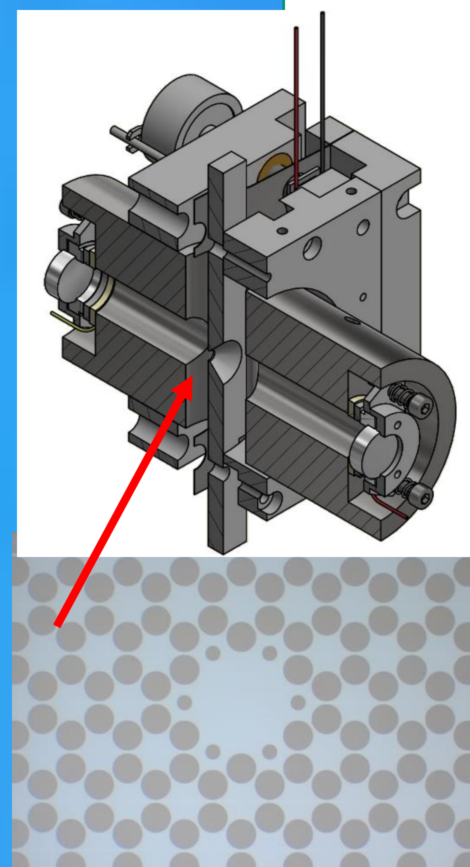
$$\Phi_0(t) = \cos\vartheta(t)\,\varphi_1 + \sin\vartheta(t)\,\varphi_3$$

Since P_2 remains zero, the decay rate of level 2 is irrelevant!!!

STIRAP (Stimulated Raman Adiabatic Passage)

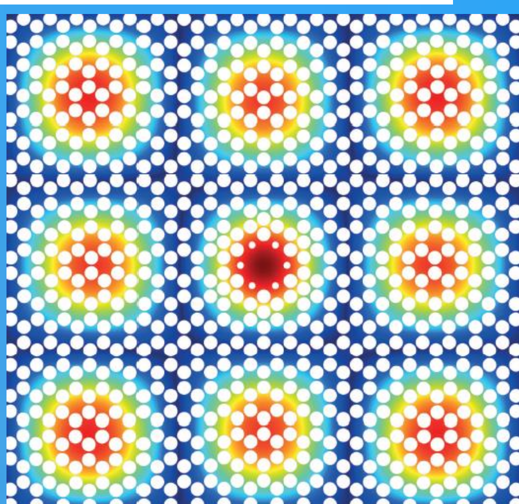


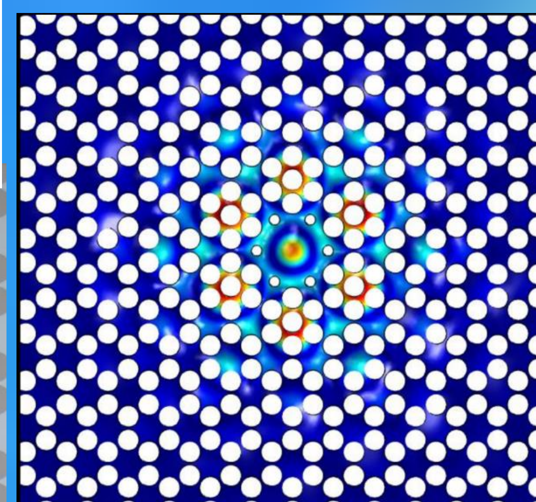




φ_1

ω_1

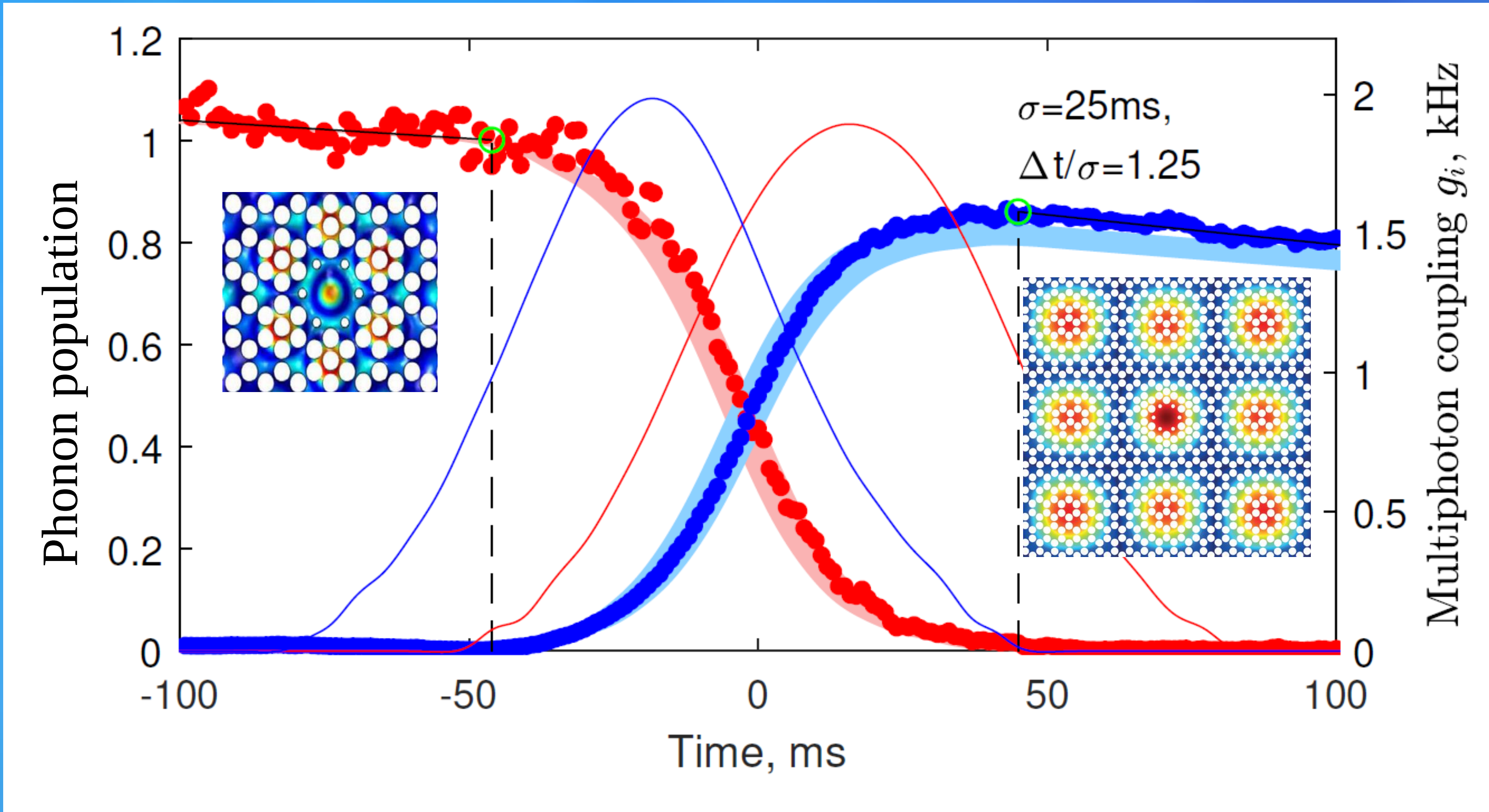




φ_3

ω_2

STIRAP (Stimulated Raman Adiabatic Passage)



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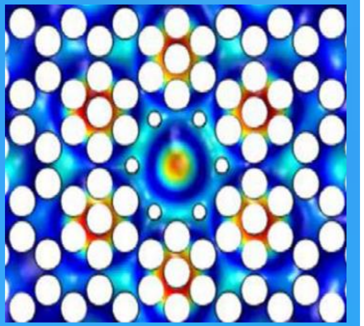

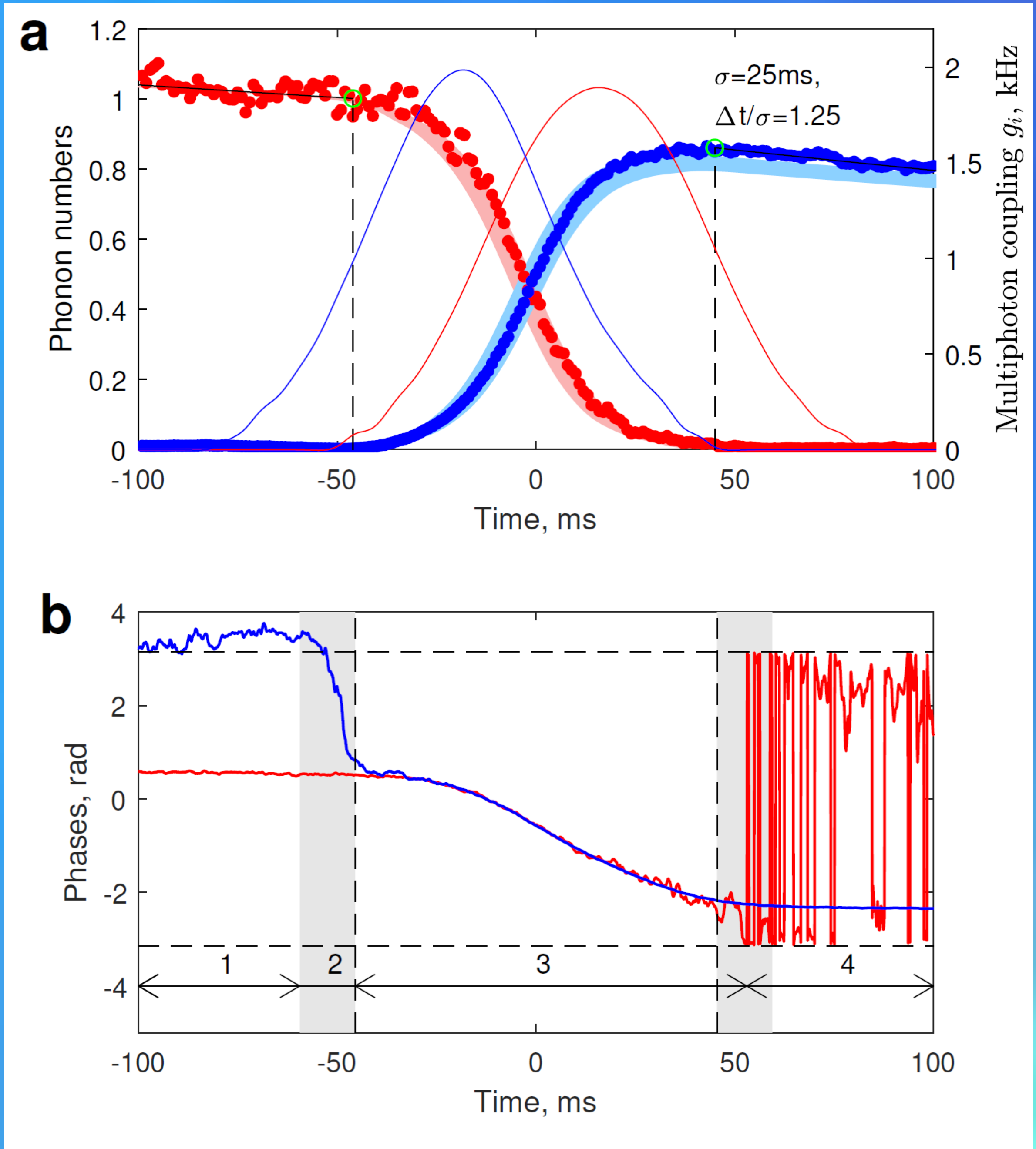

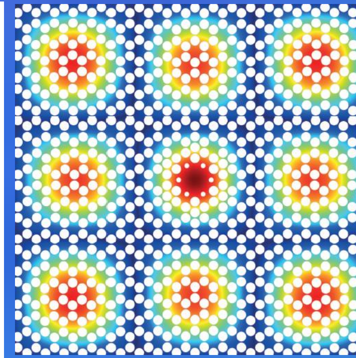

Three Main technical Complications:

1) Optomechanical coupling not strong enough.
   Solution: entangle two or more mechanical modes

2) Mechanical Q's not high enough.
   Solution: use phononic photonic crysta membranes

3) Optical heating.
   Solution: use STIRAP method

Currently installed in fridge