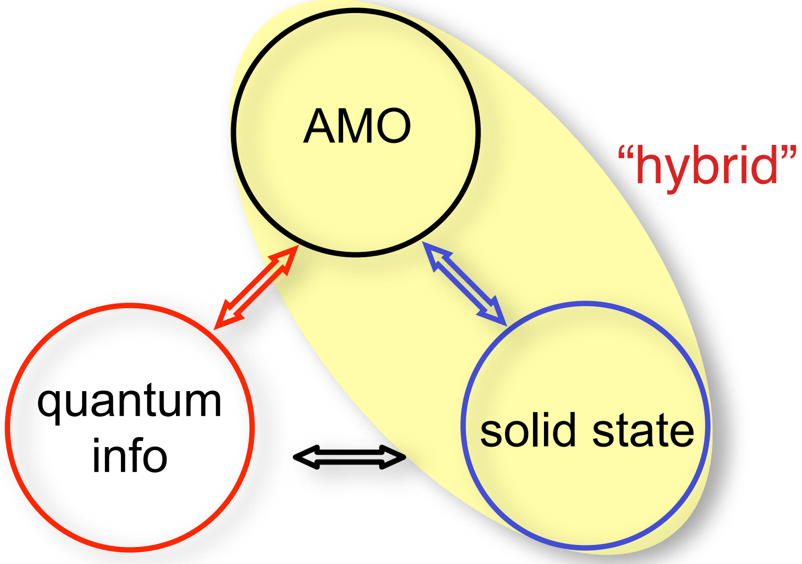


Opto-Nanomechanics + Atom(s)

- **quantum interfaces AMO + solid state**
  - *future* directions & challenges in quantum optics … light of new experimental developments
- **… applications**

P. Zoller,
Univ of Innsbruck & IQOQI Austrian Academy of Sciences

Hybrid Quantum Systems

common goals:

- coherent control on single quantum level >> dissipation
- fundamental aspects & applications
  - quantum information processing / communication / simulation
  - quantum metrology
  - quantum technology

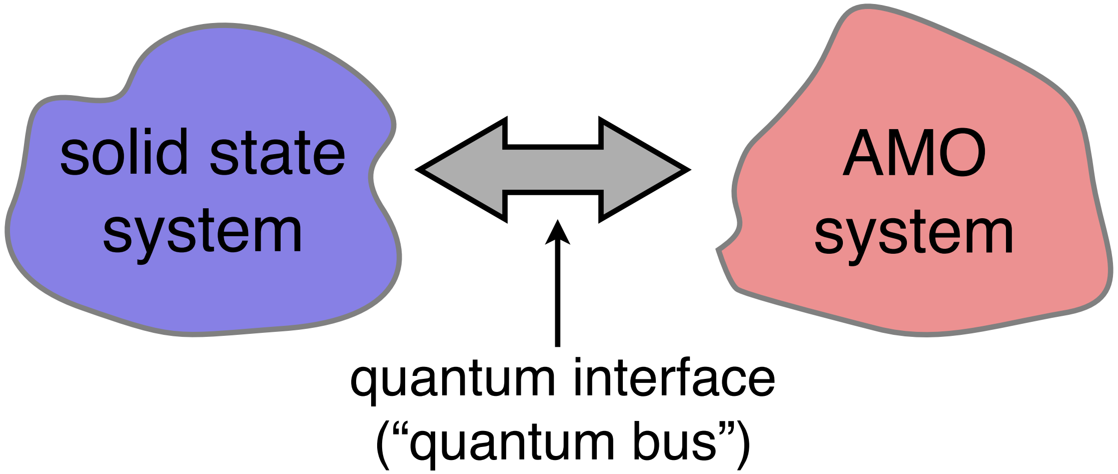
common concepts:

- … behind quantum memory, gates, read out etc.

very different physical systems:

- … with their own features, “+” and “-”

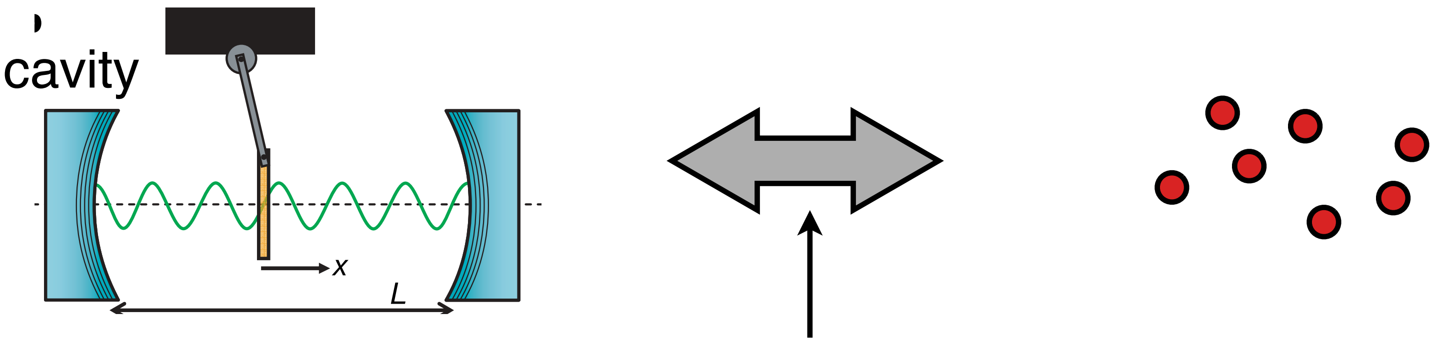
Hybrid Quantum Systems



challenge: “hybrid systems”

- develop coherent quantum interface *between solid state and AMO systems*
  - basic building block
  - goal: combining advantages (benefit from complementary toolboxes) with compatible experimental setups

Hybrid: Opto-Nanomechanics + Atoms



nanomechanical oscillator*

quantum interface
- photons as bus
- [or: direct interaction]

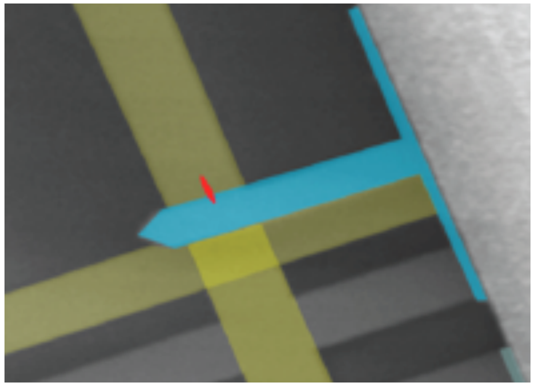
single / many atom
- internal state
- motional state

challenge: “hybrid systems”

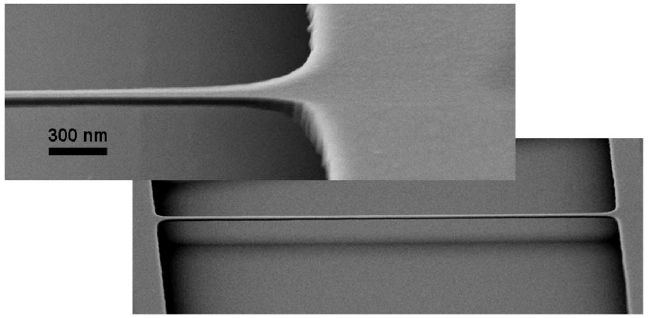
- develop coherent quantum interface *between solid state and AMO systems*

  - basic building block
  - goal: combining advantages (benefit from complementary toolboxes) with compatible experimental setups

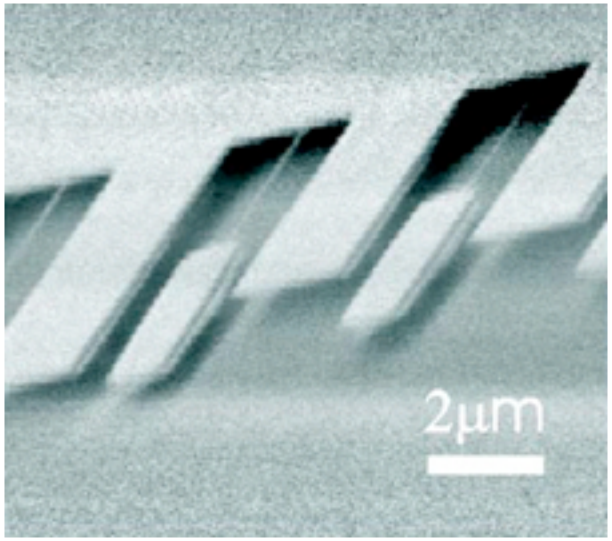
Micro- and Nanomechanical Oscillators



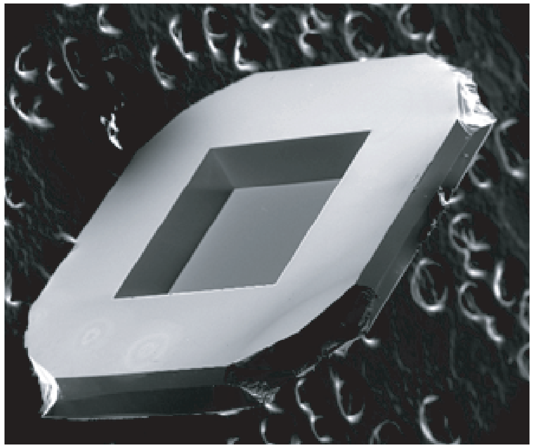
AFM cantilever



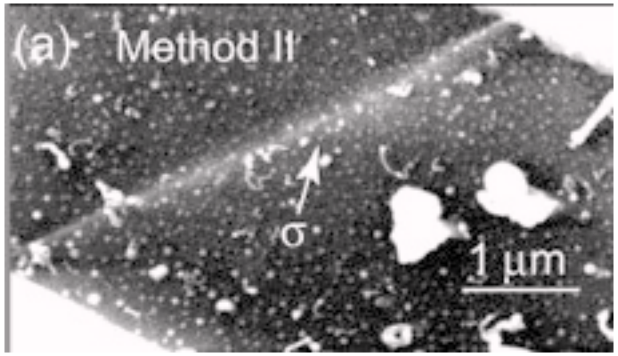
SiN nanostring



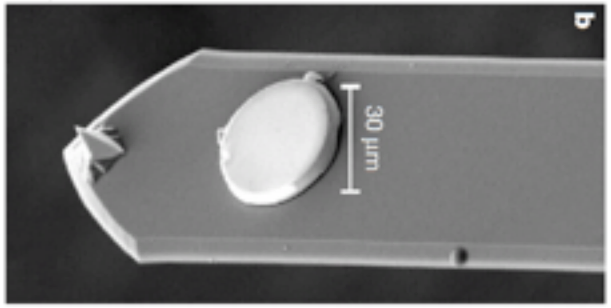
Si cantilever with paddle



SiN membrane

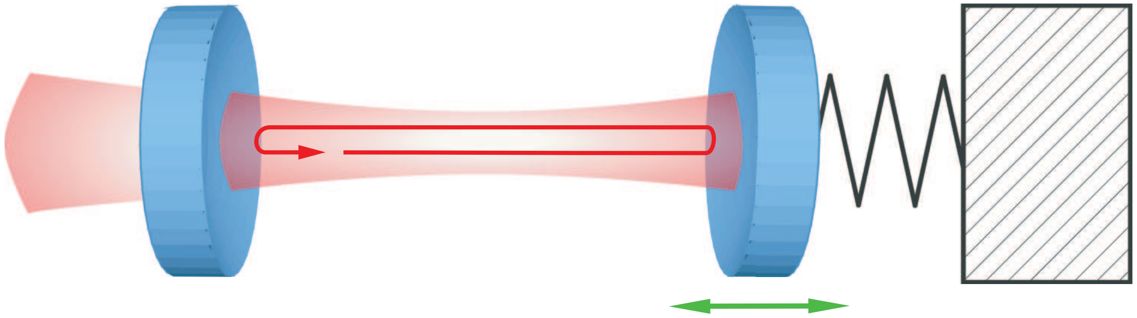


C nanotube (single wall)



- Harmonic oscillators
- Quantum oscillators?

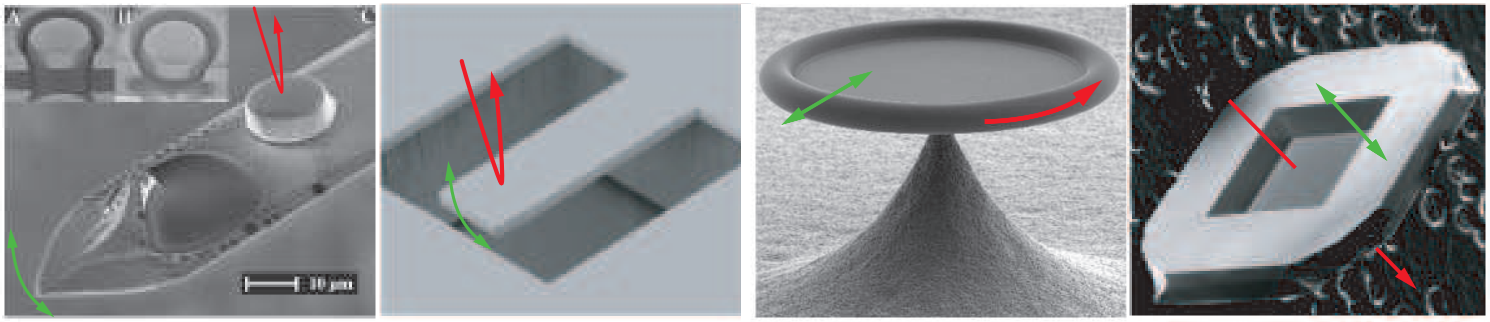
“Opto-nanomechanics”



- **experimental developments ...**
- **goal: see quantum effects**
  - ground state cooling of the oscillator
  - entanglement …
  - why? … fundamental / applications

requirement: (strongly)
couple to … ?
(radiation pressure)

(b)



$\mathcal{F}$	200	30,000	22,000	15,000
$\Omega_\mathrm{m}/2\pi$	12.5 kHz	814 kHz	57.8 MHz	134 kHz
Q_m	18,400	10,000	2,900	$1.1\cdot 10^{6}$
m_eff	24 ng	190 µg	15 ng	40 ng
	cantilever Bouwmeester	micromirrors Aspelmeyer Heidmann	micro-torroids Kippenberg Valhala	membrane Harris (Girvin, Marquardt)

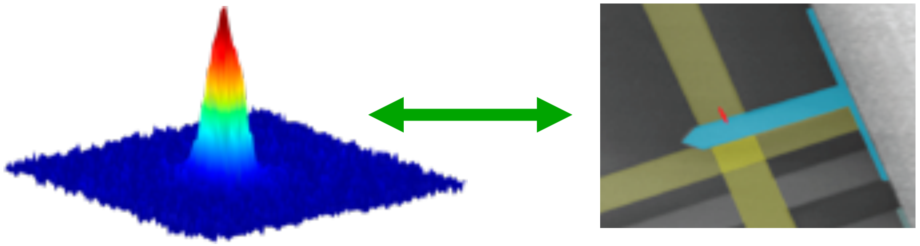
Why couple atoms to nanomechanical oscillators?

- **How to observe and prepare (nonclassical) quantum states of oscillator, and entangle oscillators?**
  - couple to other microscopic quantum systems (atoms, NV centers, Cooper pair boxes, … two-level systems)
- **Atoms … AMO toolbox for preparation, coherent manipulation and measurement of quantum states is well developed.**
  - make AMO toolbox available for readout, cooling and control of mechanical oscillators by coupling them to atoms
  - hybrid quantum systems for precision force sensing
  - test of quantum mechanics for macroscopic systems
- **Mechanical oscillators can serve as ...**
  - local probe (sub-wavelength) for manipulation of atomic systems
  - engineer long distance interations between atoms via oscillators

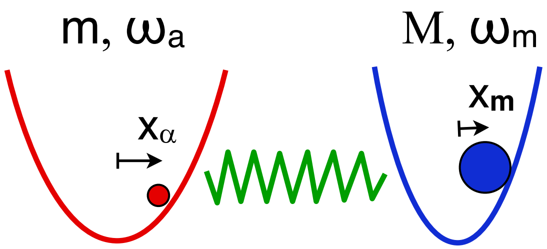
… new physics & challenges

How? … strategies for coupling

- **Goal: couple atoms**
  - strongly
  - to a single resonator mode
  - with low damping



- **Challenge: huge impedance mismatch**



$(\omega_a \approx \omega_m)$

direct mechanical coupling:

$$\boxed{g \simeq \omega_a \sqrt{\frac{m}{M}}}$$

for single atom
\+ nanooscillator: $\sqrt{\frac{m}{M}} = 10^{-7} - 10^{-4}$

- **Solutions**
  - small M, e.g. carbon nano tubes
  - many atoms: $g \rightarrow g\sqrt{N}$
  - coupling to internal atomic states
  - use cavities or other “levers” to mediate couplings

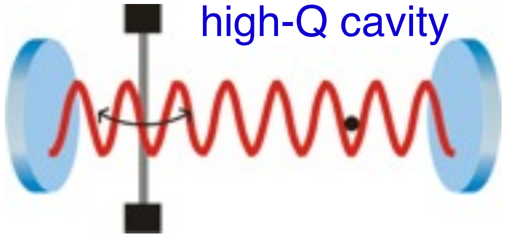
Overview:

What is realistic today?

Future & Perspectives?

Innsbruck Projects: Opto-Nanomechanics + Atom(s)

- **Strong coupling between a *single* atom and a membrane**

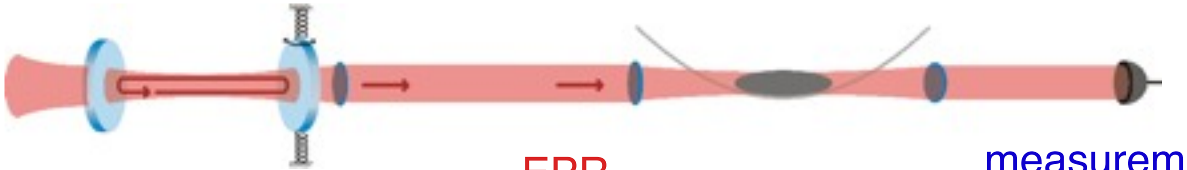


membrane ⟷ single atom

with existing experimental
setups & parameters :-)

Caltech + LMU +
Innsbruck
J Kimble, J. Ye,
K. Hammerer, et al.,
F. Marquardt,
P. Treutlein
PRL 2009

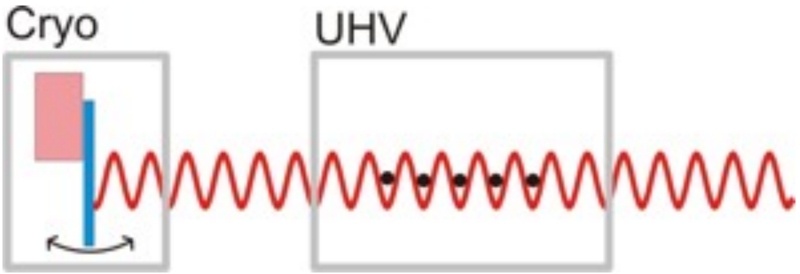
- **EPR entanglement between oscillator + atomic ensembles**



oscillator ⟷ atoms
EPR
(long distance)

K. Hammerer,
M. Aspelmeyer,
E. Polzik,
PZ
PRL 2009

- **Free space coupling between nanomechanical mirror + atomic ensemble**



oscillator ⟷ atoms

LMU + Innsbruck
P. Treutlein et al.,
C. Genes,
K. Hammerer,
M. Wallquist
K. Stannigel
PZ

Overview:

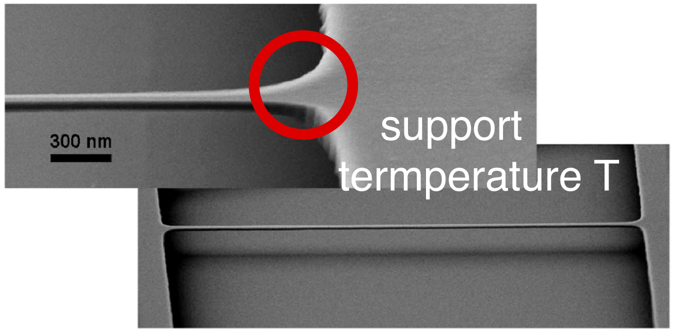
What is realistic today?

Future & Perspectives?

Levitation: “AMO approach”

- **Challenges**
  - minimize coupling to (thermal) environment [& strong coupling regime]

- **Instead of “solid-state cryogenic setup” ...**



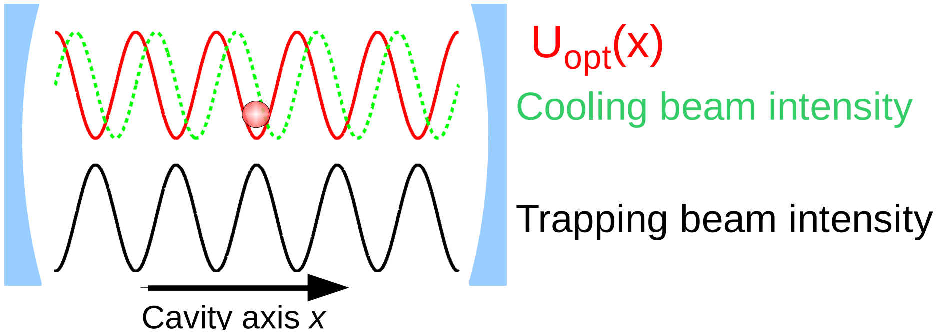
Remarks:

✓clamping ~ damping = Q

✓thermalization with support

… get rid of supporting structures

- **… atomic physics like: e.g. optical levitation**



“classical” trapping of dielectric spheres:
low damping (Ashkin)

?

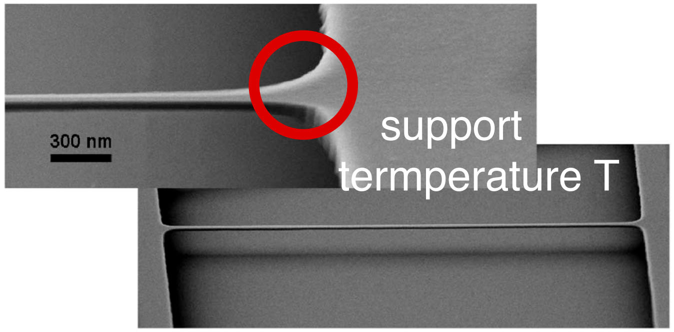
“quantum” tweezer:

- @ room temperature
- self-cooling to ground state
- approach fundamental damping limit
- here: center-of-mass

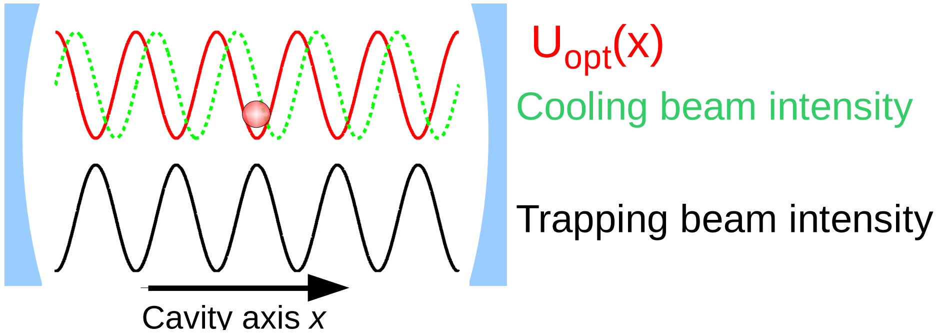
Levitation: “AMO approach”

- **Challenges**
  - minimize coupling to (thermal) environment [& strong coupling regime]

- **Instead of “solid-state cryogenic setup” ...**



- **… atomic physics like: e.g. optical levitation**



Remarks:

✓clamping ~ damping = Q

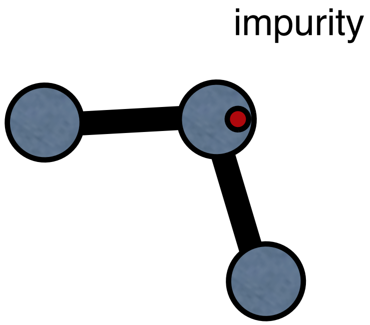
✓thermalization with support

… get rid of supporting structures

✓ here: center-of-mass

? internal modes of composite structures

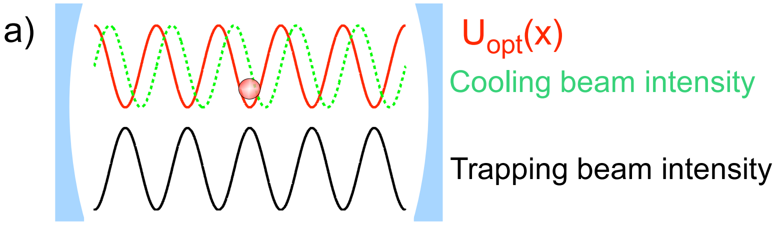
? coupling to internal two-level atoms

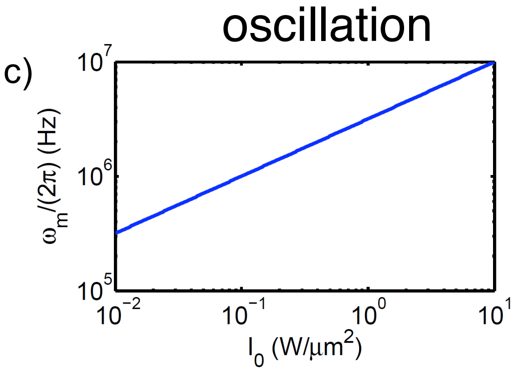


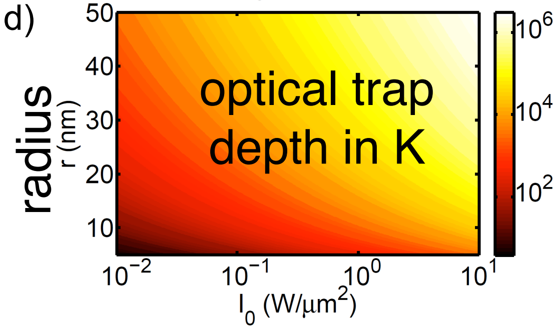
Cavity optomechanics using an optically levitated nanosphere

D.E. Chang[*], C.A. Regal[†], S.B. Papp[†], D.J. Wilson[†], J. Ye[†][‡], O. Painter[§], H.J. Kimble[†], and P. Zoller[†][¶]

- optically leviated sphere & laser cooling of center-of-mass motion







- noise sources:
  - background gas collisions
  - scattered photons,
  - black body radiation, …
- entangled photons → entanglement of two spheres
- squeezed motion of spheres → squeezed light

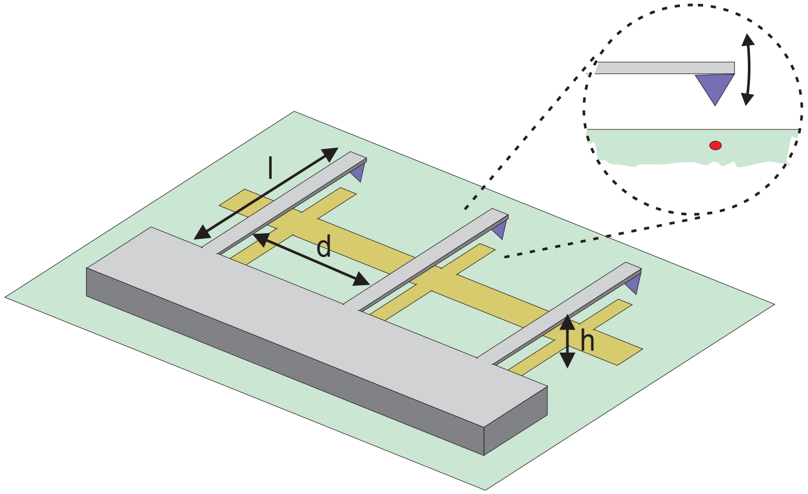
---

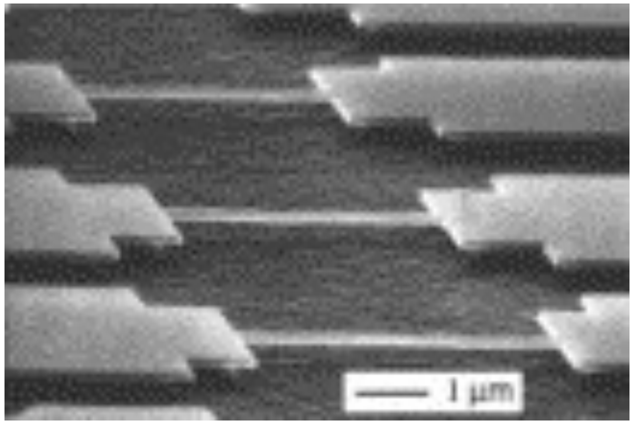
see also: ICFO & MPQ arxiv.org/abs/0909.1469

ETH, Berkley: COM motion of a BEC (quantum *liquid*) in a cavity as nanomechanical oscillators

A quantum spin transducer based on nano electro-mechancial resonator arrays

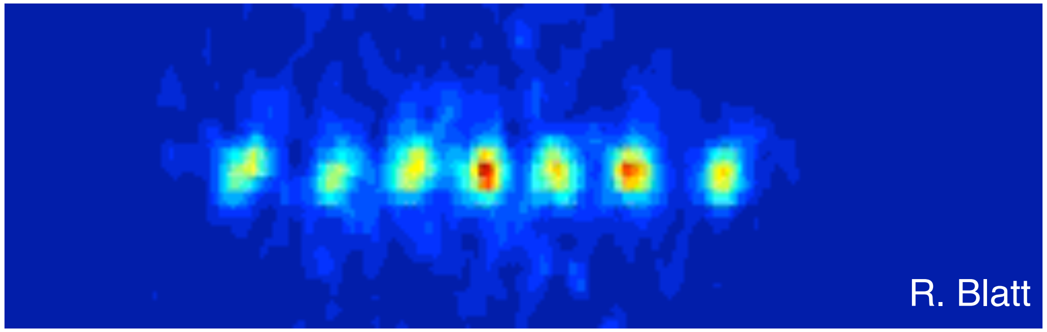
P. Rabl, S. Kolkowitz, F. Koppens, J. Harris, P. Zoller, and M. Lukin, arxiv July 2009





A. Cleland et al.,

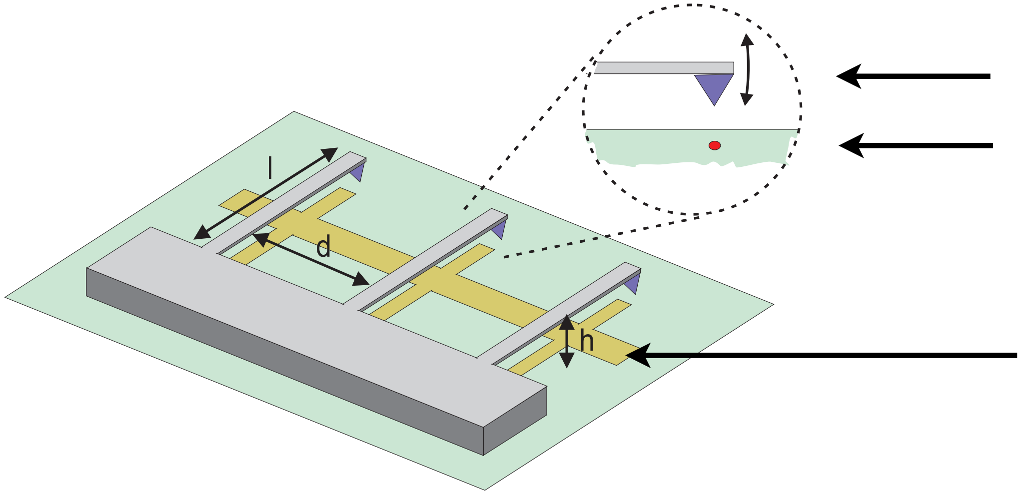
… in analogy to trapped ions:



$$|\Psi\rangle = \sum_x c_x |x_{N-1}, \ldots, x_0\rangle \otimes |0\rangle_{\text{phonon}}$$

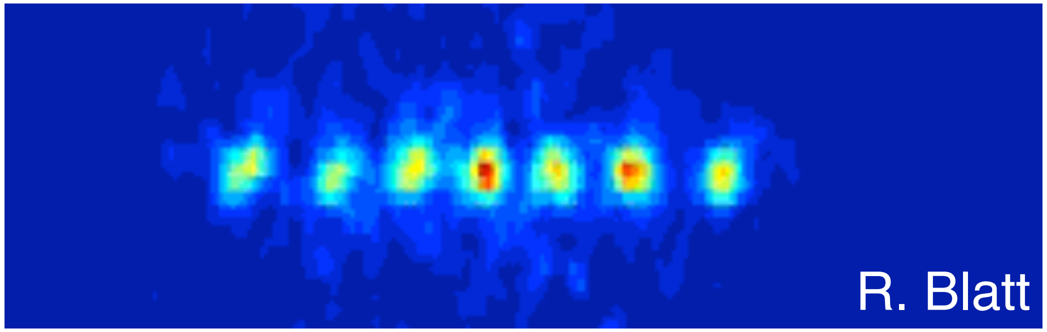
A quantum spin transducer based on nano electro-mechancial resonator arrays

P. Rabl, S. Kolkowitz, F. Koppens, J. Harris, P. Zoller, and M. Lukin, arxiv July 2009



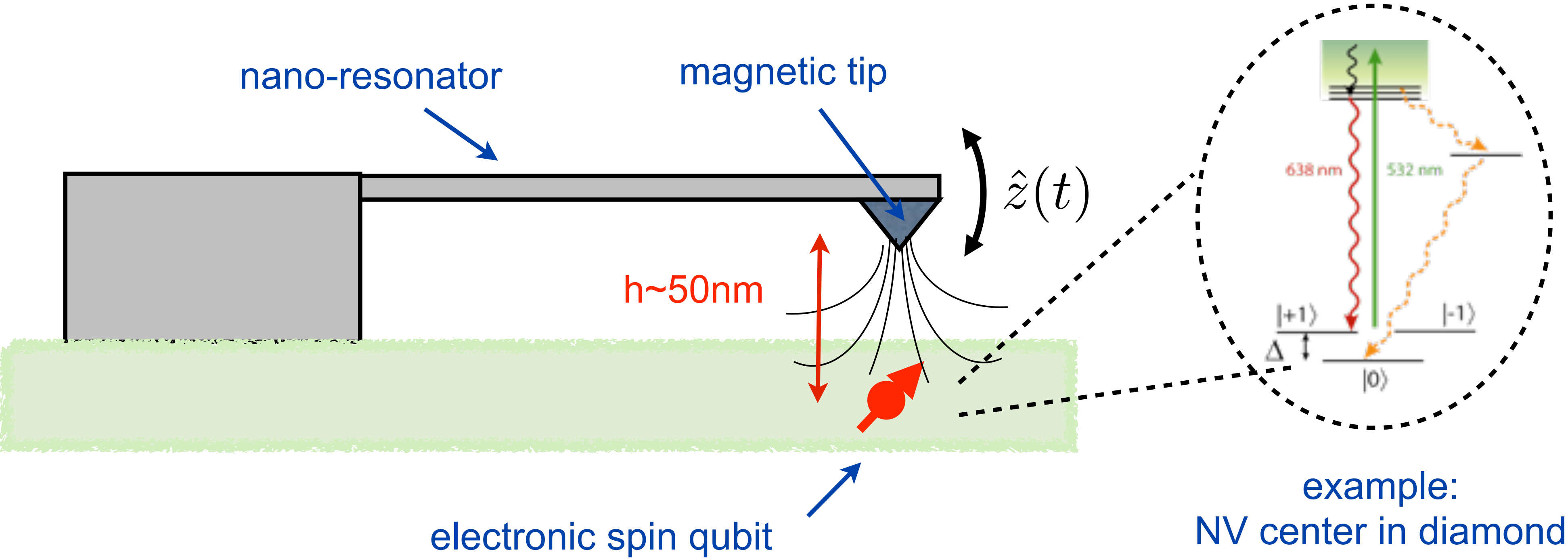
- cantilever with magnetic tip
- NV centers as qubits (+ microwave)
- capacitive coupling of cantilevers: phonon bus

… in analogy to trapped ions:



$$|\Psi\rangle = \sum_x c_x |x_{N-1}, \ldots, x_0\rangle \otimes |0\rangle_{\text{phonon}}$$

A mechanical transducer ...



example:
NV center in diamond

- Hamiltonian

$$H = \omega_0 S_z + \omega_r a^\dagger a + \lambda(a + a^\dagger) S_z$$

- Position dependent Zeeman shift: shift per vibrational quantum

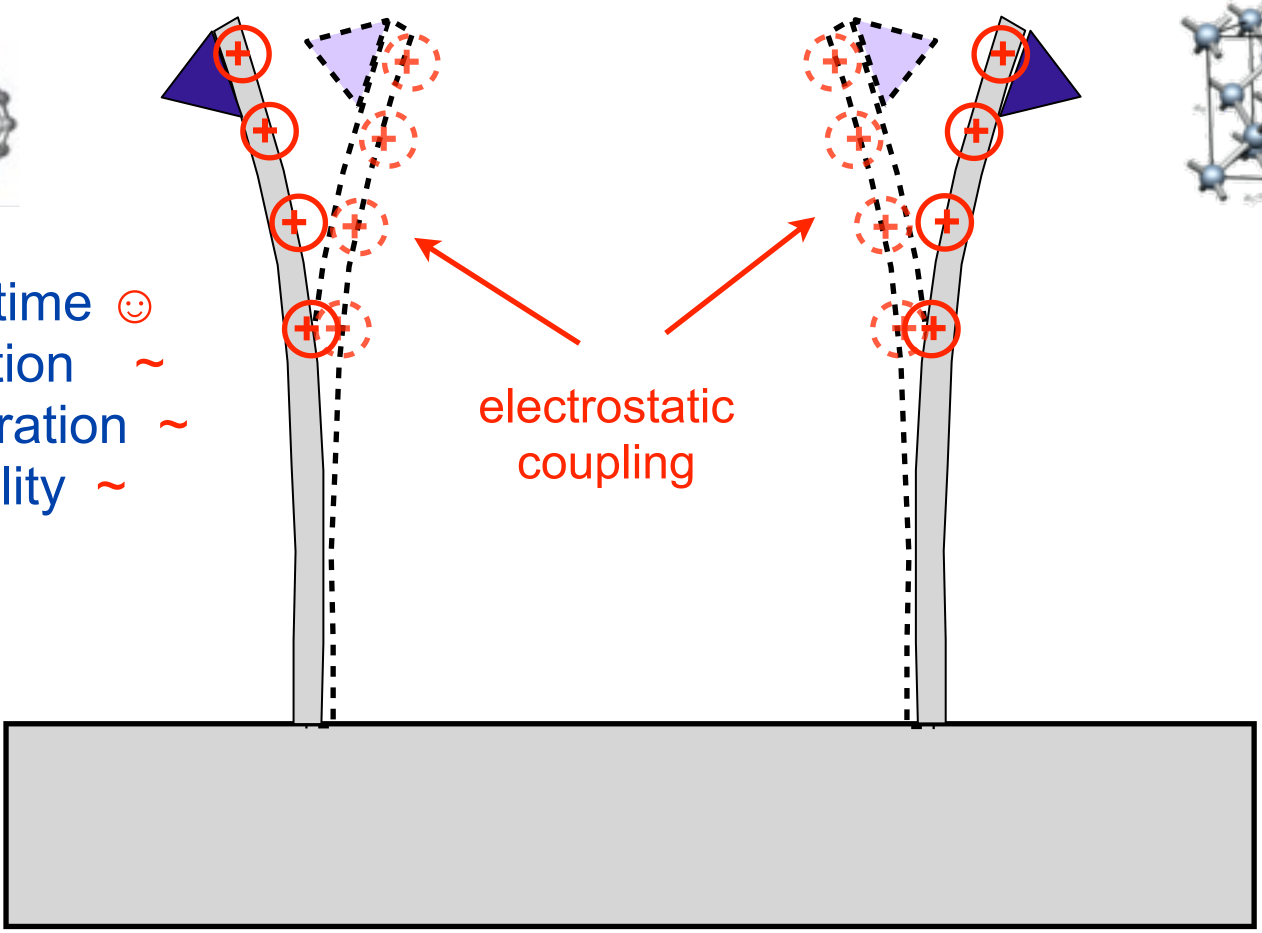
$$\hbar\lambda = g_s \mu_B a_0 \nabla B \sim h^{-4}$$

$$\lambda \approx 100\,\mathrm{kHz} \qquad \gg \qquad \overset{\text{spin dephasing}}{\overset{\downarrow}{1/T_2}}, \qquad \overset{\text{motional dephasing}}{\overset{\downarrow}{\Gamma_m = k_B T/Q}}$$

A mechanical quantum transducer ...

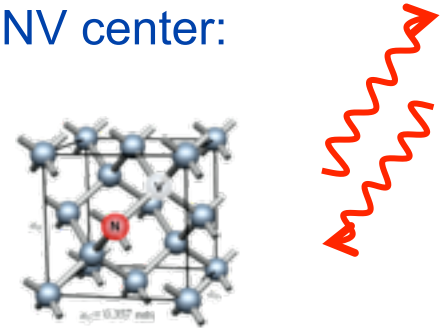
"Bucky ball qubit"

- coherence time ☺
- state detection ~
- state preparation ~
- addressablility ~



electrostatic
coupling

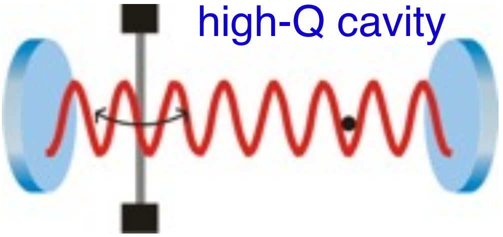
NV center:



manipulation and optical readout of "dark" spins

Innsbruck Projects: Opto-Nanomechanics + Atom(s)

- **Strong coupling between a *single* atom and a membrane**



high-Q cavity

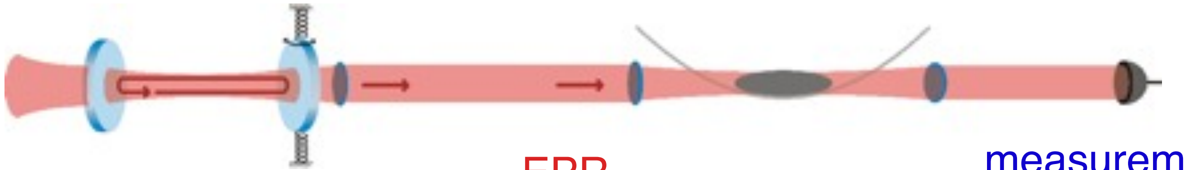
membrane ⟷ single atom

with existing experimental
setups & parameters :-)

Caltech + LMU +
Innsbruck
J Kimble, J. Ye,
K. Hammerer, et al.,
F. Marquardt,
P. Treutlein
PRL 2009

- **EPR entanglement between oscillator + atomic ensembles**

laser

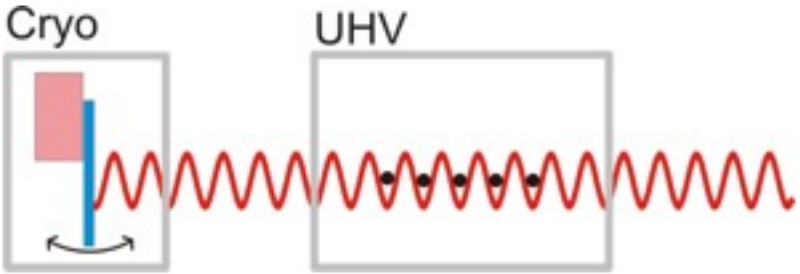


oscillator ⟷ atoms
EPR
(long distance)

measurement

K. Hammerer,
M. Aspelmeyer,
E. Polzik,
PZ
PRL 2009

- **Free space coupling between nanomechanical mirror + atomic ensemble**



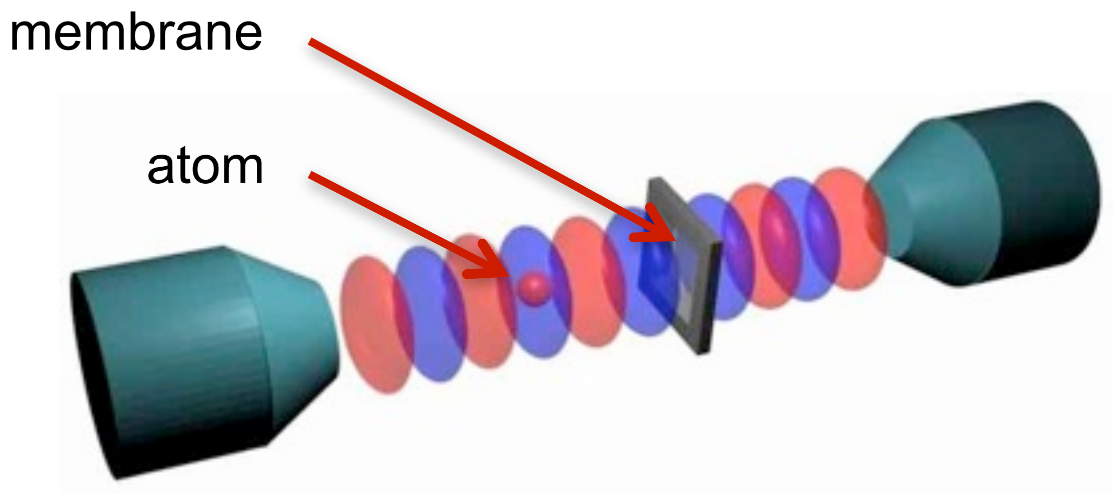
optical lattice

oscillator ⟷ atoms

LMU + Innsbruck
P. Treutlein et al.,
C. Genes,
K. Hammerer,
M. Wallquist
K. Stannigel
PZ

Strong Coupling of a Single Atom to a Membrane

- **Challenge:** strong coherent coupling between two masses $m_{\text{atom}} \ll M_{\text{membrane}}$



$$\sqrt{\frac{m_{\text{atom}}}{M_{\text{membrane}}}} \sim 10^{-7}$$

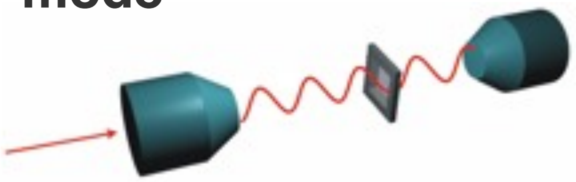
- **Idea:** Use cavity field to mediate interactions
- **Conditions for strong coupling**

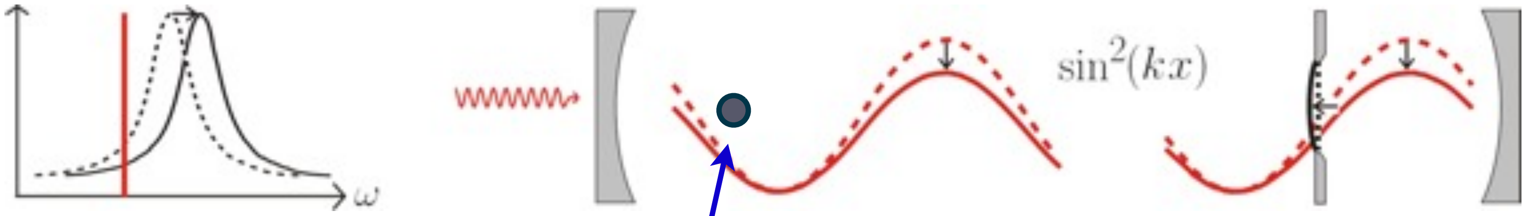
$$g_{\text{atom}-\text{membrane}} \gg \Gamma_{\text{atom}}, \Gamma_{\text{membran}}, \Gamma_{\text{cavity}}$$

- **Applications:** quantum coherent effects, state transfer, measurement

Cavity Mediated Interaction (1)

- **Opto-mechanical coupling of membrane and cavity mode**



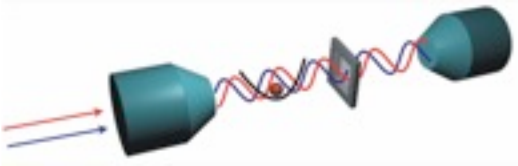


Linear displacements of membrane result in amplitude modulation of cavity field.

- **Atom - membrane coupling: version 1**

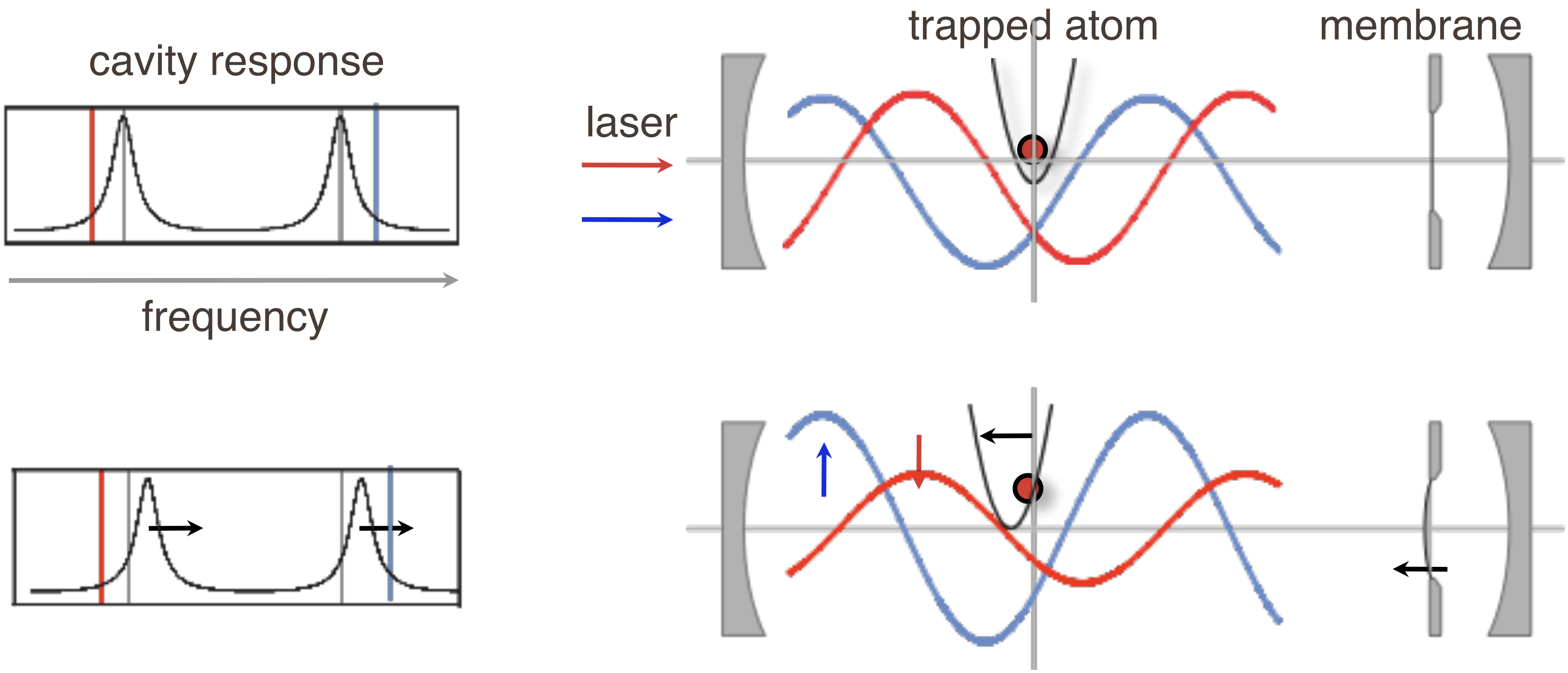
an atom in the optical lattice: $\sim x_a^2 x_m$
parametric coupling

- **Atom - membrane coupling: version 2**



linear coupling (?) $\sim x_a x_m$

Cavity Mediated Interaction (2)



moving membrane displaces atom trap

coupling ~ finesse

- **coupling >> dissipation**

$$H = \omega_{\mathrm{m}} a_m^\dagger a_m + \omega_{\mathrm{t}} a_a^\dagger a_a + g(a_m^\dagger a_a + \mathrm{h.c.})$$

oscillator atom linear in displacement

- **(quantum) noise & imperfections**

membrane:
✓damping
✓temperature
✓laser heating

atom + cavity:
✓cavity damping
✓spontaneous emission
✓...

Applications of Strong Coupling

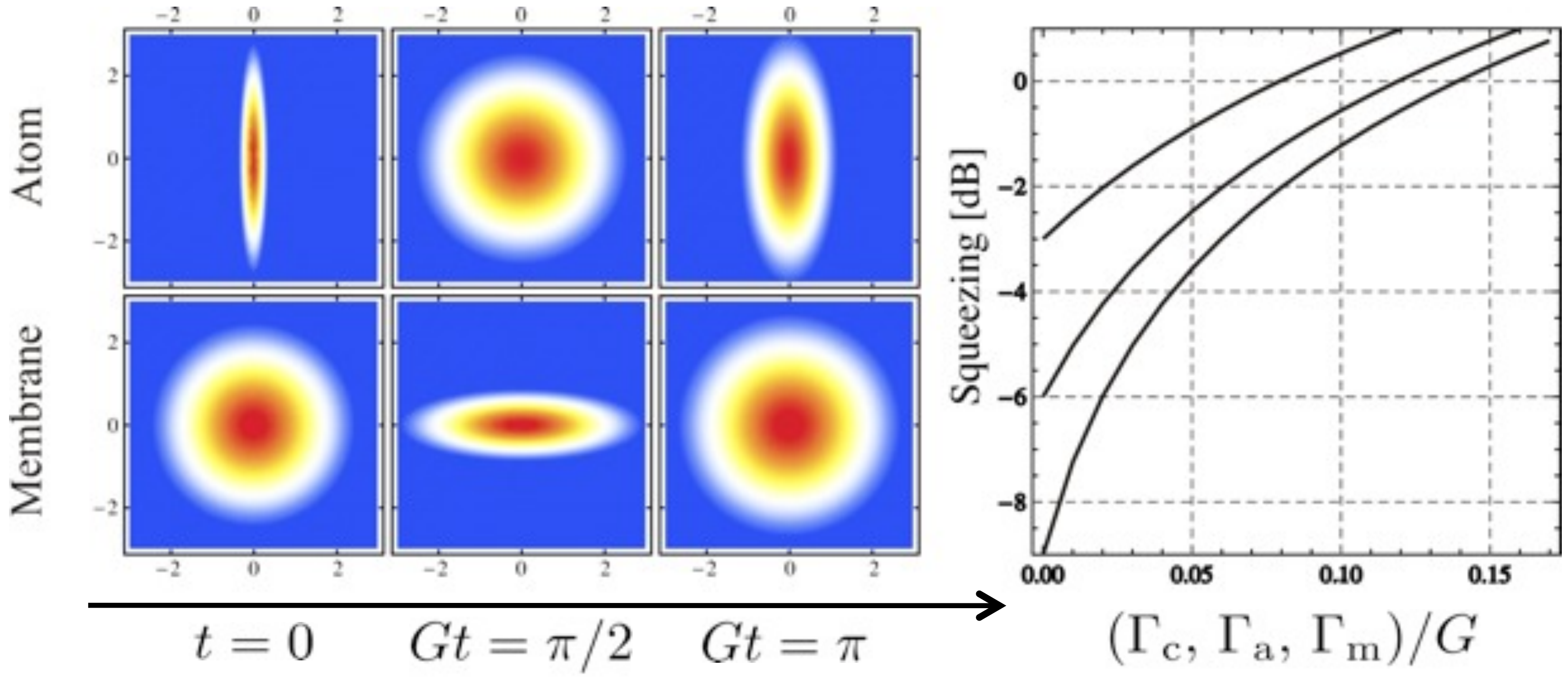
- **Coherent dynamics** for $\Gamma_{\mathrm{c}}, \Gamma_{\mathrm{a}}, \Gamma_{\mathrm{m}} = 0.1 \times G$

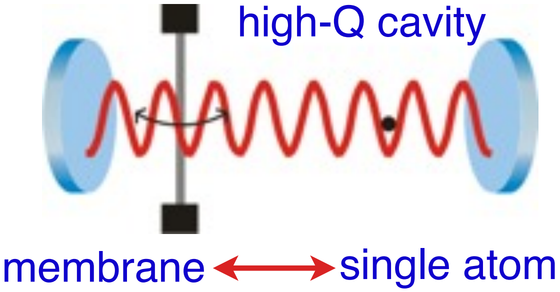
  In rotating wave approximation $G \ll \omega_m, \omega_a$

  $$H_{\mathrm{am}} = G_{\mathrm{am}}(a_{\mathrm{a}} + a_{\mathrm{a}}^\dagger)(a_{\mathrm{m}} + a_{\mathrm{m}}^\dagger) \simeq G_{\mathrm{am}}(a_{\mathrm{a}} a_{\mathrm{m}}^\dagger + a_{\mathrm{a}}^\dagger a_{\mathrm{m}})$$

  Generates state exchange between systems (‘beam splitter Hamiltonian’)

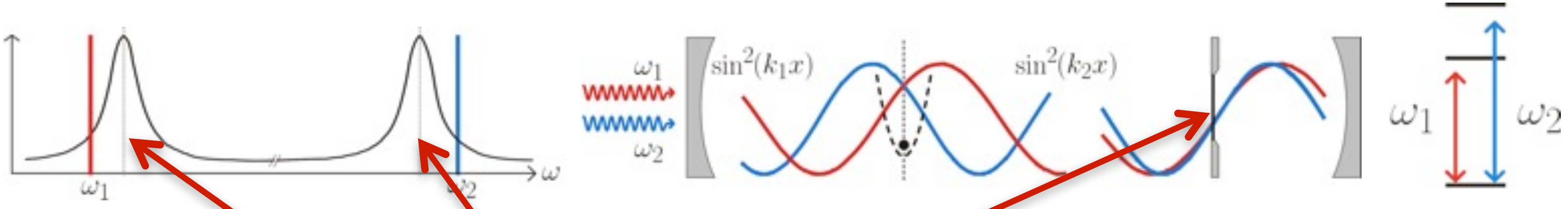
- **Transfer of squeezed states** from atom to membrane





Hamiltonians and Master Equations

1. Membrane - Cavity Interaction



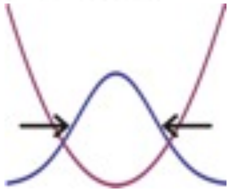
- **Opto-mechanical Interaction**

$$H_{\mathrm{mc}} = g_{\mathrm{mc}}(a_1^\dagger a_1 + a_2^\dagger a_2)(a_{\mathrm{m}} + a_{\mathrm{m}}^\dagger)$$

$$g_{\mathrm{mc}} = \omega_i \frac{\ell_{\mathrm{m}}}{L} f(r, \bar{x}_m)$$

Driven cavity receives a mean coherent amplitude

$$\ell_{\mathrm{m}} = \sqrt{\frac{\hbar}{2M\omega_{\mathrm{m}}}}$$



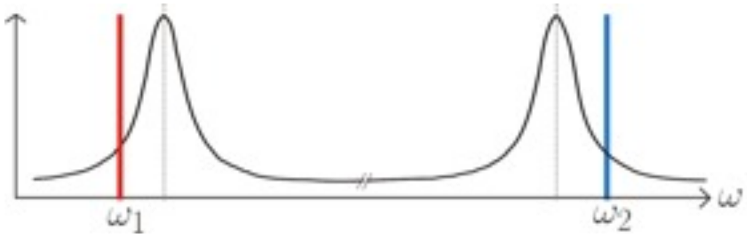
$$a_i \rightarrow a_i + \alpha$$

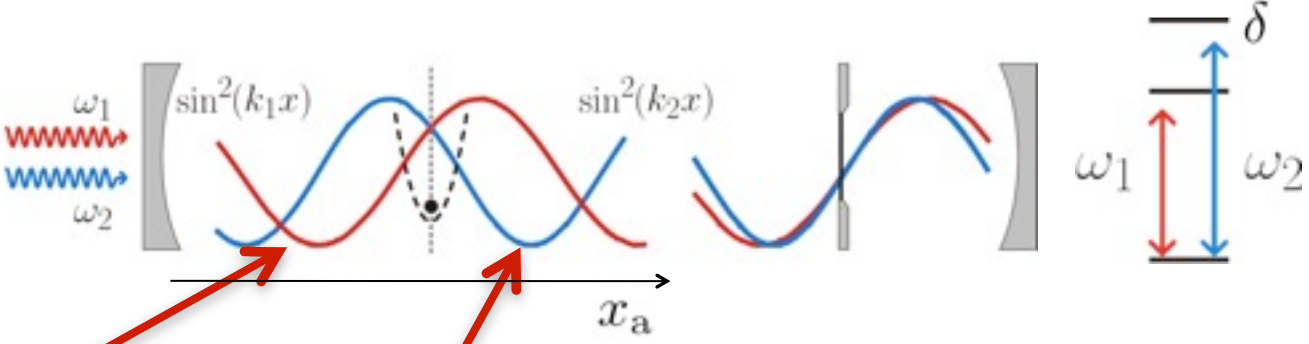
Linearized interaction

$$\boxed{H_{\mathrm{mc}} \simeq \alpha g_{\mathrm{mc}} \left[(a_1 + a_1^\dagger) + (a_2 + a_2^\dagger) \right] (a_{\mathrm{m}} + a_{\mathrm{m}}^\dagger)} + \text{mean force on membrane}$$

Linear effect of mechanical displacement on amplitude and vice versa

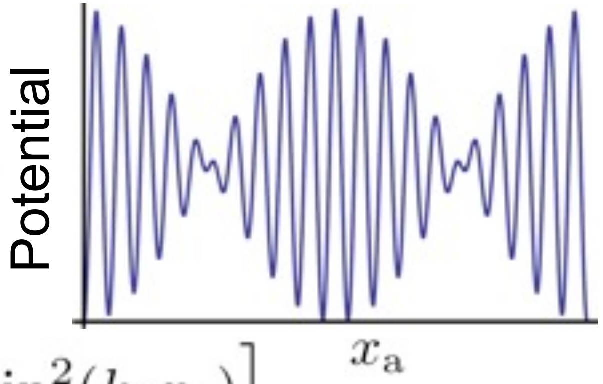
2. Atom - Cavity Interaction





- **Stark-Shift Hamiltonian**

$$H_{\rm ac} = U_0 \left[a_1^\dagger a_1 \sin^2(k_1 x_{\rm a}) + a_2^\dagger a_2 \sin^2(k_2 x_{\rm a})\right] \qquad U_0 = \frac{\Omega_0^2}{\delta}$$



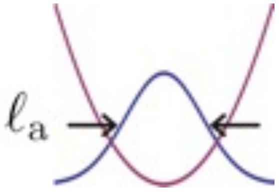
Linearization with respect to cavity fluctuations

$$a_i \rightarrow a_i + \alpha$$

$$H_{\rm ac} \simeq \alpha^2 U_0 \left[\sin^2(k_1 x_{\rm a}) + \sin^2(k_2 x_{\rm a})\right]$$

$$+\,\alpha\, U_0 \left[(a_1 + a_1^\dagger) \sin^2(k_1 x_{\rm a}) + (a_2 + a_2^\dagger) \sin^2(k_2 x_{\rm a})\right]$$

Linearization with respect to position fluctuations

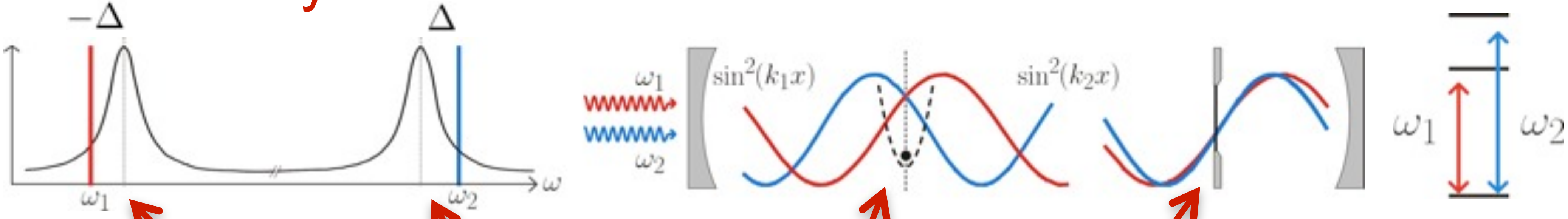


$$x_{\rm a} \rightarrow \bar{x} + \delta x_{\rm a} \qquad \delta x_{\rm a} = \ell_{\rm a}(a_{\rm a} + a_{\rm a}^\dagger)$$

$$\boxed{H_{\rm ac} \simeq \frac{m\omega_{\rm a}^2}{2}\delta x_{\rm a}^2 + \alpha U_0 k \ell_{\rm a} \left[(a_1 + a_1^\dagger) - (a_2 + a_2^\dagger)\right] (a_{\rm a} + a_{\rm a}^\dagger)}$$

Linear effect of atomic displacement on amplitude and vice versa

3a. Cavity Mediated Interaction



- **Full Hamiltonian:**

$$H = H_0 + H_{\mathrm{mc}} + H_{\mathrm{ac}}$$

Free energy

$$H_0 = -\Delta a_1^\dagger a_1 + \Delta a_2^\dagger a_2 + \omega_{\mathrm{a}} a_{\mathrm{a}}^\dagger a_{\mathrm{a}} + \omega_{\mathrm{m}} a_{\mathrm{m}}^\dagger a_{\mathrm{m}}$$

Membrane – Cavity interaction

$$H_{\mathrm{mc}} = \alpha g_{\mathrm{mc}} \left[(a_1 + a_1^\dagger) + (a_2 + a_2^\dagger) \right] (a_{\mathrm{m}} + a_{\mathrm{m}}^\dagger) \qquad g_{\mathrm{mc}} = \omega_i \frac{\ell_{\mathrm{m}}}{L} f(r, \bar{x}_m)$$

$$\propto \kappa \mathcal{F}(k\ell_{\mathrm{m}})$$

Atom – Cavity interaction

$$H_{\mathrm{ac}} = \alpha g_{\mathrm{ac}} \left[(a_1 + a_1^\dagger) - (a_2 + a_2^\dagger) \right] (a_{\mathrm{a}} + a_{\mathrm{a}}^\dagger) \qquad g_{\mathrm{ac}} = U_0 k \ell_{\mathrm{a}}$$

$$\propto \kappa (\mathcal{C} \tfrac{\gamma}{\delta})(k\ell_{\mathrm{a}})$$

Analogy opto-mechanics
To BEC in cavity:

Y. Colombe et al., Nature 450, 272 (2007).
K. W. Murch et al., Nat. Phys. 4, 561 (2008).
F. Brennecke et al., Science 322, 235 (2008).

4. Cavity Mediated Interaction

- **Large detuned cavity drive:**

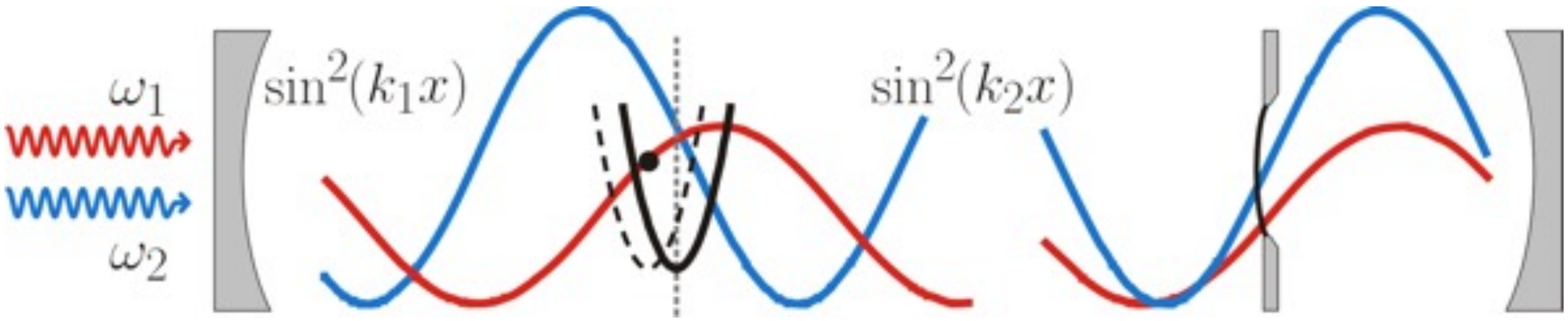
$$|\Delta| \gg \omega_{\mathrm{m}},\, \omega_{\mathrm{a}},\, \alpha g_{\mathrm{mc}},\, \alpha g_{\mathrm{ac}}$$

Cavity field fluctuations will adiabatically follow membrane/atom fluctuations
Can be eliminated from dynamics

- **Second order Hamiltonian** for cavity mediated interaction

$$\boxed{H_{\mathrm{am}} = G_{\mathrm{am}}(a_{\mathrm{a}} + a_{\mathrm{a}}^\dagger)(a_{\mathrm{m}} + a_{\mathrm{m}}^\dagger)} \qquad G_{\mathrm{am}} \simeq \frac{\alpha^2 g_{\mathrm{ac}} g_{\mathrm{mc}}}{\Delta}$$

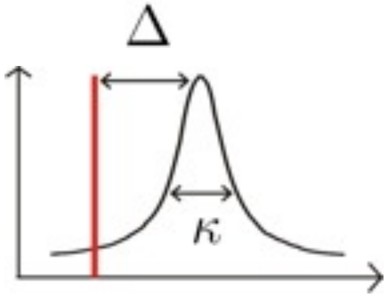
Linear effect of atomic displacement on membrane and vice versa



4a. Strong Coupling

- **Open system dynamics:** Atom and Membrane dissipate through
  - cavity decay
  - heating of atom due to spontaneous emission
  - thermal coupling/heating due to absorption of membrane

Master Equation $\dot{\rho} = -i[H,\rho] + L_{\mathrm{c}}\rho + L_{\mathrm{a}} + L_{\mathrm{m}}\rho$



- Decoherence due to **cavity decay**

$\Gamma_{\mathrm{c}} \simeq \dfrac{\kappa\alpha^2(g_{\mathrm{ac}}^2 + g_{\mathrm{mc}}^2)}{\Delta^2} \ll G$ requires $1 \gg \dfrac{\kappa}{\Delta}$ $\qquad g_{\mathrm{mc}} \simeq g_{\mathrm{ac}}$

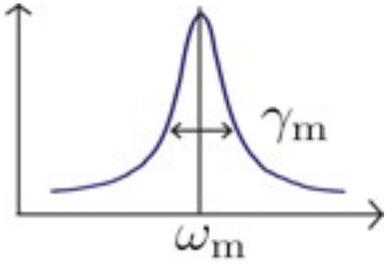
- Heating due to **spontaneous emission**

$\Gamma_{\mathrm{a}} \simeq \gamma \dfrac{U_0\alpha^2}{\delta}(k\ell_{\mathrm{a}})^2 =$ (rate of spont. em.) *x* (prob. to be excited) *x* (Lamb Dicke)^2

$\Gamma_{\mathrm{a}} \ll G$ requires a large cooperativity parameter $\mathcal{C} = \dfrac{\Omega_0^2}{\kappa\gamma} \gg \dfrac{\Delta}{\kappa}$

4b. Strong Coupling

- **Thermal heating of membrane**



$$\Gamma_{\rm m} = \gamma_{\rm m}\bar{n} \simeq \frac{k_B T}{\hbar Q_{\rm m}}$$

For sufficient cooling the environment temperature T will be limited by laser power absorption:

- if the cavity Finesse was limited only by power absorption:

Absorbed power $P_{\rm abs} = \frac{2\pi}{\mathcal{F}} P_{cav} \propto \alpha^2$

- temperature increase for a thermal link $\kappa_{\rm th}$: $\Delta T \simeq \frac{1}{\kappa_{\rm th}} P_{\rm abs}$

- if base temperature is lower than this increase, the thermal decoherence rate:

$$\Gamma_{\rm m} \simeq \frac{k_B \Delta T}{\hbar Q_{\rm m}} \propto \alpha^2$$

$\Gamma_{\rm m} \ll G$ requires $\frac{\gamma_{\rm m}}{(\kappa_{\rm th}/k_B)} \frac{\hbar\omega_1}{Mc^2} \mathcal{F} \gg \frac{\Delta}{\kappa}$

4c. Strong Coupling

- **Conditions for strong coupling**

$$1 \gg \frac{\kappa}{\Delta} \qquad \mathcal{C} = \frac{\Omega_0^2}{\kappa\gamma} \gg \frac{\Delta}{\kappa} \qquad \frac{(\kappa_{\mathrm{th}}/k_B)}{\gamma_{\mathrm{m}}}\frac{\hbar\omega_1}{Mc^2}\mathcal{F} \gg \frac{\Delta}{\kappa}$$

  - does *not* depend on the intracavity amplitude: requirements on the single photon/phonon level
  - trade-off between small mechanical line-width and large thermal link

- **Case study** for $\boxed{\Gamma_{\mathrm{c}}, \Gamma_{\mathrm{a}}, \Gamma_{\mathrm{m}} = 0.1 \times G \qquad G = 2\pi \times 45\mathrm{kHz}}$

SiN Membrane

$100\mu\mathrm{m} \times 100\mu\mathrm{m} \times 50\mathrm{nm}$

$M = 0.4\mathrm{ng}$

$\omega_{\mathrm{m}} = 2\pi \times 1.3\mathrm{MHz}$

$Q_{\mathrm{m}} = 10^7$

$r = 0.45$

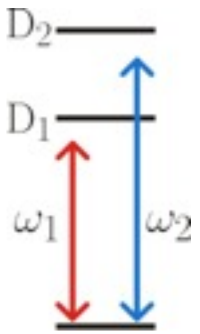
$\mathrm{Im}(n) \simeq 10^{-5}$ (measured)

$\kappa_{\mathrm{th}} \simeq 10\mathrm{nW}/K$

Inferred from

B. L. Zink, et al. Solid State Comm. 129, 199 (2004).

Cs Atom



$\frac{\delta}{\gamma} \simeq 450$

Cavity

$\mathcal{F} \simeq 2 \times 10^5$

$w_0 = 10\mu\mathrm{m}$ waist

$L = 50\mu\mathrm{m}$

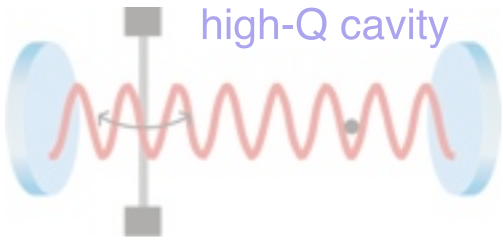
$C = 140$

$\frac{\Delta}{\kappa} = 18$

$P_{\mathrm{cav}} = 850\mu\mathrm{W}$ Circulating power

Innsbruck Projects: Opto-Nanomechanics + Atom(s)

- Strong coupling between a *single* atom and a membrane



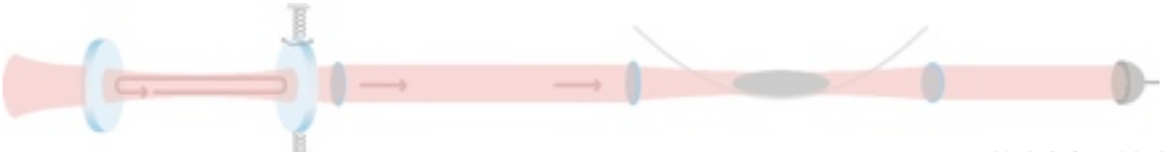
high-Q cavity

membrane ⟷ single atom

with existing experimental
setups & parameters :-)

Caltech + LMU +
Innsbruck
J Kimble, J. Ye,
K. Hammerer, et al.,
F. Marquardt,
P. Treutlein
PRL 2009

- EPR entanglement between oscillator + atomic ensembles



laser

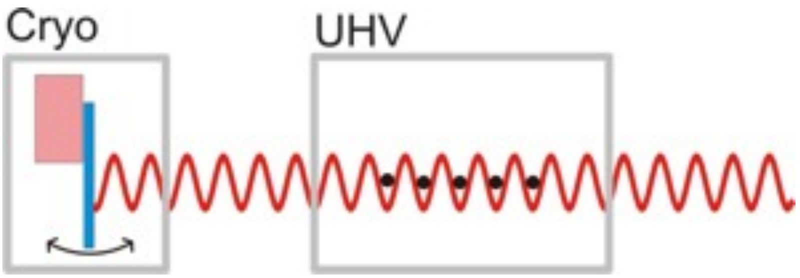
measurement

oscillator ⟷ atoms

EPR
(long distance)

K. Hammerer,
M. Aspelmeyer,
E. Polzik,
PZ
PRL 2009

- **Free space coupling between nanomechanical mirror + atomic ensemble**



optical lattice

oscillator ⟷ atoms

LMU + Innsbruck
P. Treutlein et al.,
C. Genes,
K. Hammerer,
M. Wallquist
K. Stannigel
PZ

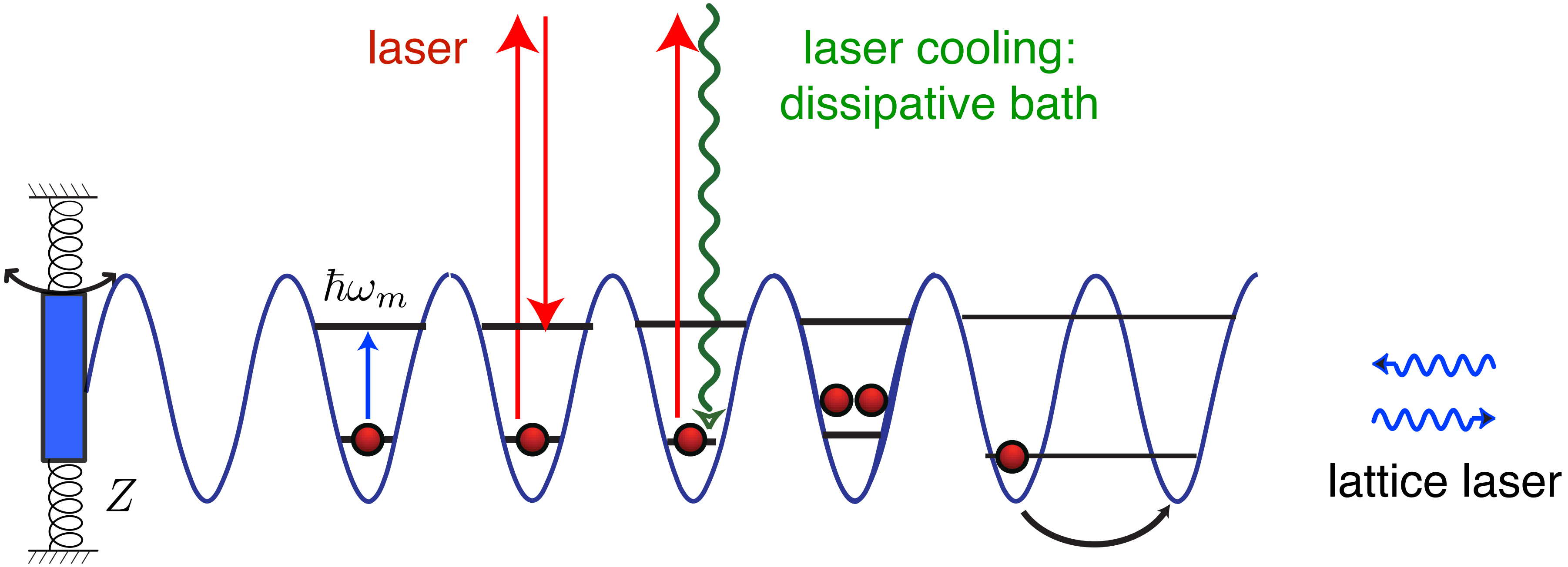
Basic ideas

- **Formally equivalent to opto-mechanical coupling**

$$H = \omega_{\rm at} a^\dagger_{\rm com} a_{\rm com} + \omega_{\rm mec} a^\dagger_{\rm mec} a_{\rm mec} + g(a_{\rm com} + a^\dagger_{\rm com})(a_{\rm mec} + a^\dagger_{\rm mec})$$

$$g = g_{\rm m} g_{\rm at} = \frac{\omega_{\rm at}}{2} \frac{\ell_{\rm m}}{\ell_{\rm at}} \sqrt{N_{\rm at}}$$

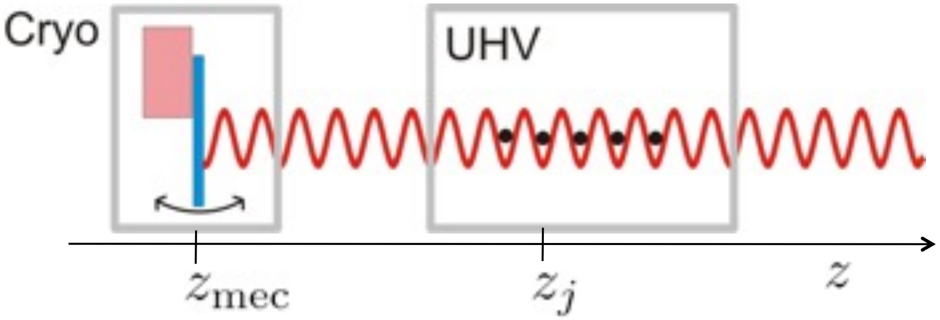
- **Sympathetic cooling of mirror** via laser cooling of atoms



laser cooling = “engineered atomic reservoir”

decoherence set by mechanical system $g > \gamma_{\rm m} \bar{n}$

1. Direct Coupling of Atoms to Nanomechanical Oscillators

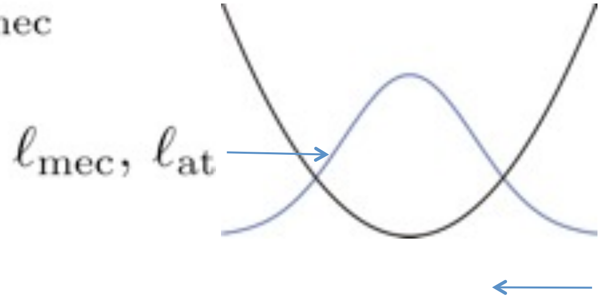


- **First approach:**

Field modes with boundary condition $E(z) \sim \sin[k(z - z_{\text{mec}})]$

Lattice potential $V(z_j) = \frac{m\omega_{\text{at}}^2}{2}(z_j - z_{\text{mec}})^2 \sim z_j z_{\text{mec}}$

Effective coupling



$$H_{\text{int}} = \sum_j g_0 \; (a_j + a_j^\dagger)(a_{\text{mec}} + a_{\text{mec}}^\dagger)$$

$$g_0 = \frac{\omega_{\text{at}}}{2} \frac{\ell_{\text{mec}}}{\ell_{\text{at}}} \qquad \frac{\ell_{\text{mec}}}{\ell_{\text{at}}} = \sqrt{\frac{m_{\text{at}}\omega_{\text{at}}}{m_{\text{mec}}\omega_{\text{mec}}}} \sim \sqrt{\frac{m_{\text{at}}}{m_{\text{mec}}}} \sim 10^{-7}$$

naive

2a. Direct Coupling in Free Space

- **First approach:**

$$H_{\rm int} = \sum_j g_0 \; (a_j + a_j^\dagger)(a_{\rm mec} + a_{\rm mec}^\dagger)$$

Collectively enhanced coupling to com mode

$$a_{\rm com} = \frac{1}{\sqrt{N}} \sum_j a_j$$

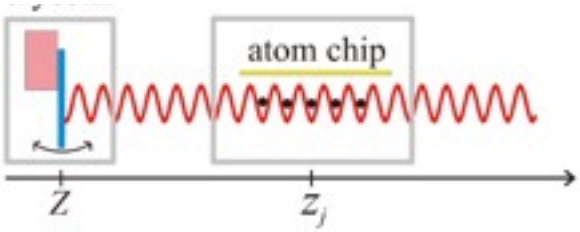
$$H_{\rm int} = g(a_{\rm com} + a_{\rm com}^\dagger)(a_{\rm mec} + a_{\rm mec}^\dagger) \qquad g = g_0 \sqrt{N_{\rm at}}$$

- **Retardation & Causality?**

2b. Direct Coupling in Free Space: Quantum Noise

- **Second approach** along the route of cavity opto-mechanics:
  - Start from a non-linear model including the EM field

$$H = \sum_j \frac{p_j^2}{2m_{at}} + \hbar\omega_m a_m^\dagger a_m + \int d\omega \hbar\omega b_\omega^\dagger b_\omega + \frac{A}{2\mu_0} B^-(0) B^+(0) z_m - \sum_j \frac{d^2}{\Delta} E^-(z_j) E^+(z_j)$$



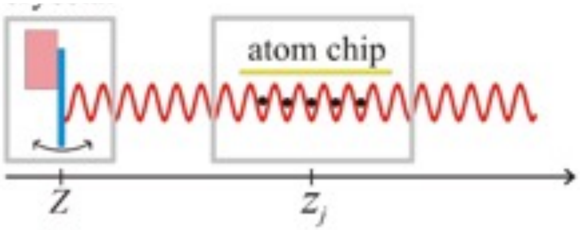
Radiation pressure on conducting mirror

AC Stark potential

2b. Direct Coupling in Free Space: Quantum Noise

- **Second approach** along the route of cavity opto-mechanics:
  - Start from a non-linear model including the EM field

$$H = \sum_j \frac{p_j^2}{2m_{at}} + \hbar\omega_m a_m^\dagger a_m + \int d\omega \hbar\omega b_\omega^\dagger b_\omega + \frac{A}{2\mu_0} B^-(0)B^+(0) z_m - \sum_j \frac{d^2}{\Delta} E^-(z_j)E^+(z_j)$$



Radiation pressure on conducting mirror

AC Stark potential

  - Linearize around laser field creating the lattice potential

$$H = H_0 + g_{\mathrm{m}} \left[b(t) + b^\dagger(t)\right] x_{\mathrm{m}} - i\frac{g_{\mathrm{at}}}{2} \left[b(t - \tfrac{\bar{z}}{c}) - b^\dagger(t - \tfrac{\bar{z}}{c}) - b(t + \tfrac{\bar{z}}{c}) + b^\dagger(t + \tfrac{\bar{z}}{c})\right] x_{\mathrm{at}}$$

$t \pm \frac{\bar{z}}{c}$ mirror and atoms couple to the same white noise process (EM field fluctuations) at time t and advanced/retarded times

  - Eliminate field in Born-Markov approximation (stochastic calculus for cascaded systems) yields master equation

$$\dot{\rho} = -i[H_0 + g_{\mathrm{m}} g_{\mathrm{at}} x_{\mathrm{m}} x_{\mathrm{at}}, \rho] + \frac{g_{\mathrm{m}}^2}{2} \left(2x_{\mathrm{m}}\rho x_{\mathrm{m}} - \rho x_{\mathrm{m}}^2 - x_{\mathrm{m}}^2 \rho\right),$$

confirms naive + quantum noise

2c. Direct Coupling in Free Space

- **Master equation:**

$$\dot{\rho} = -i[H_0 + g_{\mathrm{m}} g_{\mathrm{at}} x_{\mathrm{m}} x_{\mathrm{at}}, \rho] + \frac{g_{\mathrm{m}}^2}{2} \left(2 x_{\mathrm{m}} \rho x_{\mathrm{m}} - \rho x_{\mathrm{m}}^2 - x_{\mathrm{m}}^2 \rho\right),$$

Effective interaction (confirms result of first approach)

$$g = g_{\mathrm{m}} g_{\mathrm{at}} = \frac{\omega_{\mathrm{at}}}{2} \frac{\ell_{\mathrm{m}}}{\ell_{\mathrm{at}}} \sqrt{N_{\mathrm{at}}}$$

Radiation pressure noise on mirror: Momentum diffusion at rate

$$\Gamma_{\mathrm{rp}} = \frac{g_{\mathrm{m}}^2}{2} = \frac{P_{\mathrm{laser}}}{Mc^2} \frac{\omega_{\mathrm{laser}}}{\omega_{\mathrm{m}}}$$

K. Karrai, I. Favero, C. Metzger,
PRL 100, 240801 (2008)

(Not the dominant heating process)

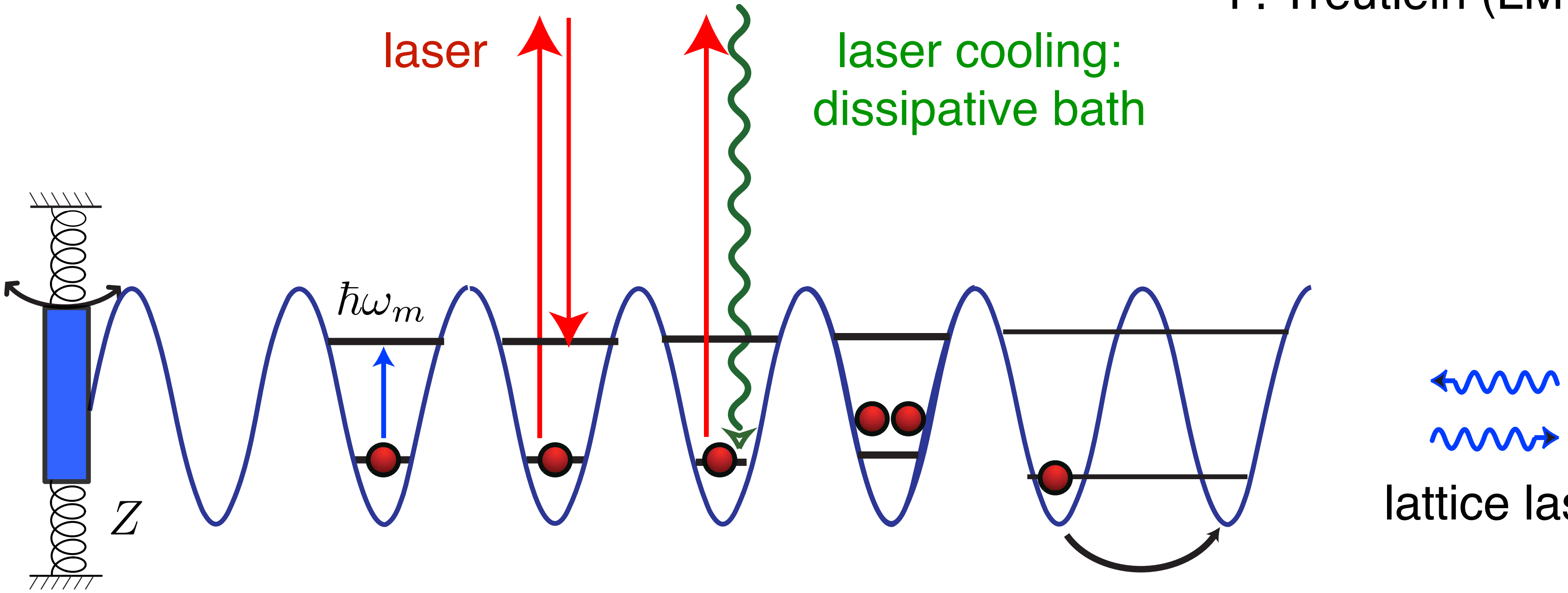
- **Extensions:** Works also for partially reflective membrane

- **1D Model?** Requires atomic ensemble of ~unit Fresnel number.

3. Application

- Formally equivalent to radiation pressure opto-mechanical coupling
- Sympathetic cooling of the mirror with laser cooling of atoms

experiment in progress:
P. Treutlein (LMU)



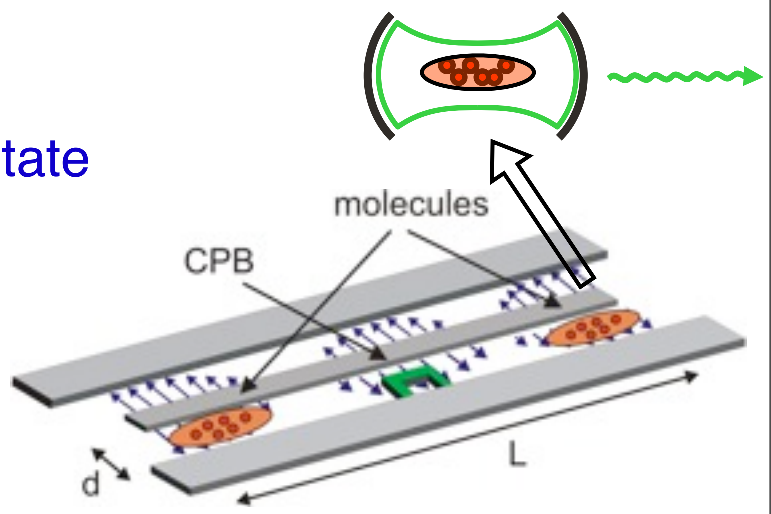
laser cooling = “engineered atomic reservoir”

decoherence set by mechanical system $g > \gamma_{\mathrm{m}}\bar{n}$

- Hubbard models with nanomechanics (?)

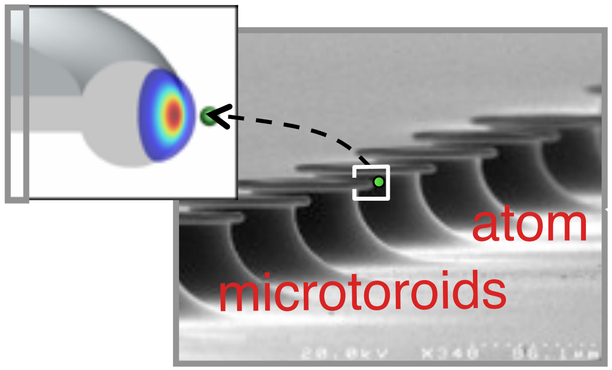
Conclusions and Outlook

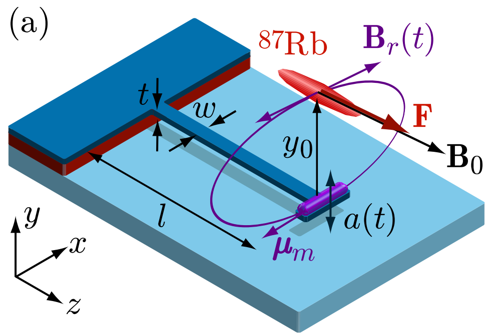
Hybrid Quantum Processors

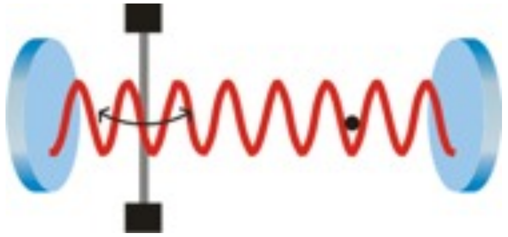


- develop coherent quantum interface between solid state and AMO systems
  - basic building block
  - goal: combining advantages (benefit from complementary toolboxes) with compatible experimental setups
- hybrid quantum processor
- AMO based preparation / measurement / sensors
- solid state traps / elements for AMO physics
  - benefit from nanofabrication / integration (scalability)
  - new physics ...

Quantum Networks

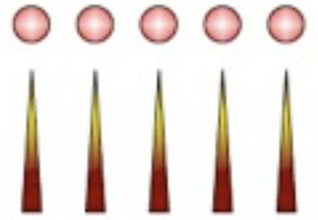






membrane ↔ single atom

Nanoscale AMO



members:


K. Hammerer


M. Wallquist


K. Stannigel

A. Glätzle

former members:


C. Genes


K. Jähne

collaborations:

M. Aspelmeyer (Vienna)
E. Polzik (Copenhagen)

H.J. Kimble (Caltech)
J. Ye (JILA)
D. Chang (Caltech)

M. Lukin (Harvard)
P. Rabl (Harvard)

P. Treutlein (LMU)
F. Marquardt (LMU)