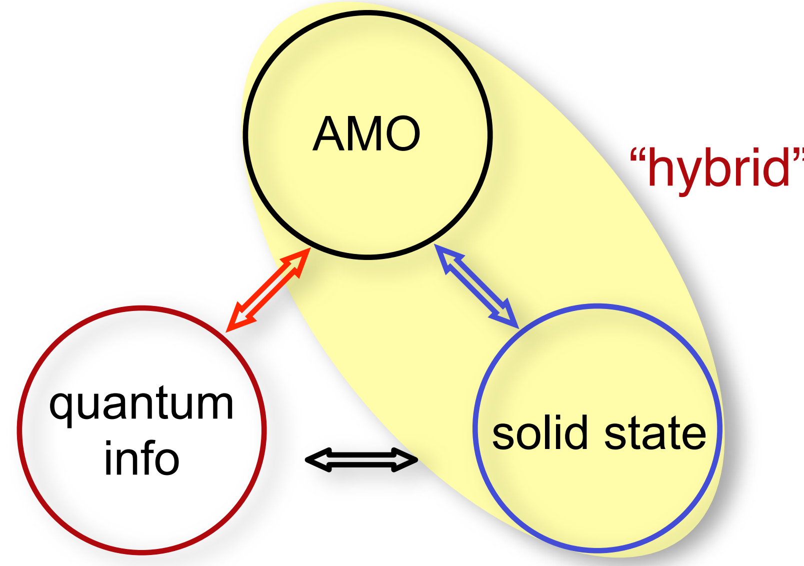

Hybrid Systems & Quantum Interfaces: Atomic Physics - Solid State

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

<u>Innsbruck:</u>
K. Hammerer
K. Stannigel
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P. Rabl & M. Lukin (Harvard)
H.J. Kimble & D. Chang (Caltech)
E. Polzik (Niels Bohr Institute)
M. Aspelmeyer (Vienna)
F. Marquardt & P. Treutlein (LMU)

Hybrid Quantum Systems

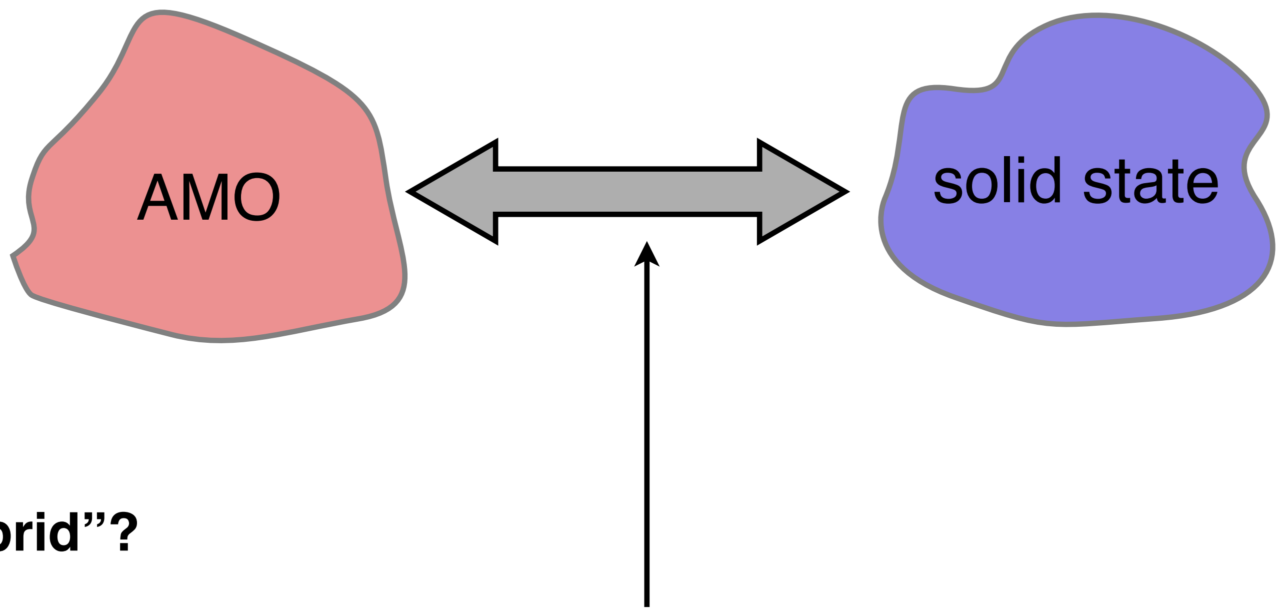
common goals:

- 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.

Hybrid Quantum Systems



what is "hybrid"?

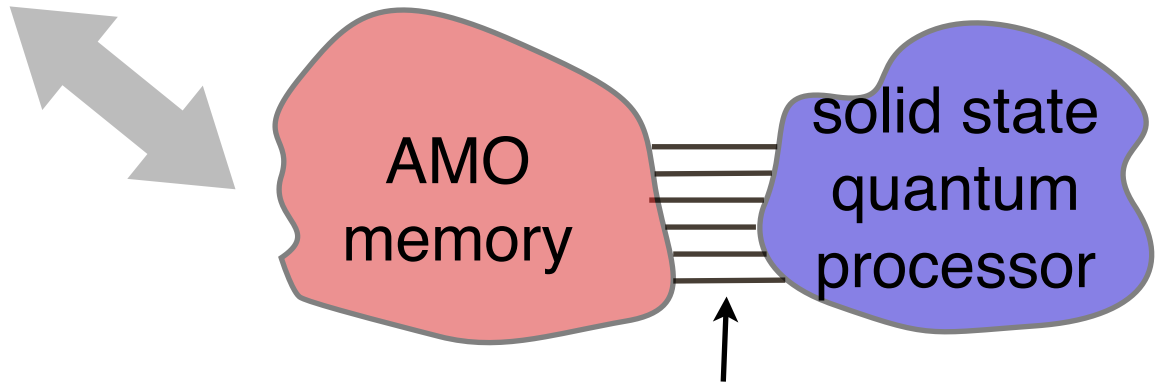
quantum interface
("quantum bus")

- **Answer 1:**

Hybrid Quantum Systems

whatever

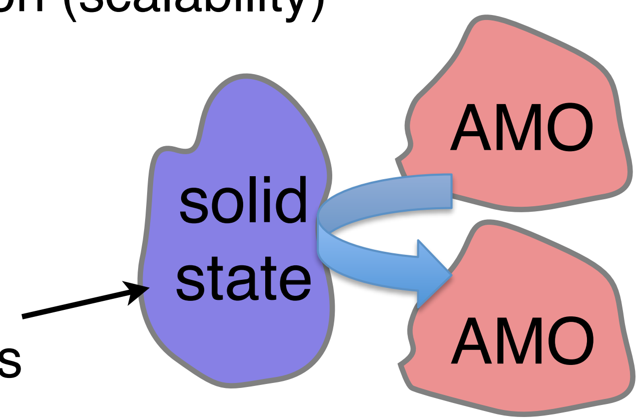
example:



read / write via bus

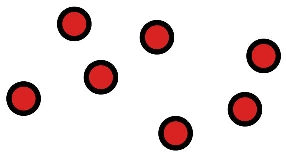
quantum interface:

- hybrid quantum processor
- ...
- solid state traps / elements for AMO physics
  - benefit from nanofabrication / integration (scalability)
  - new physics ...

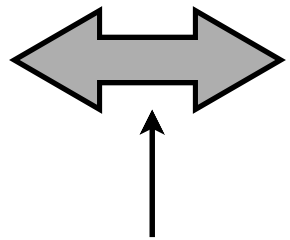


- nanotraps / scalable
- mediated interactions

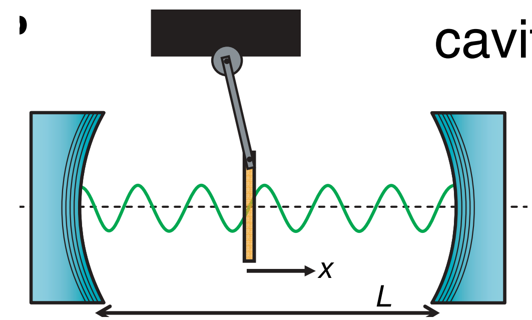
Hybrid: Atom - Opto-Nanomechanics



single / many atom
- internal state
- motional state



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

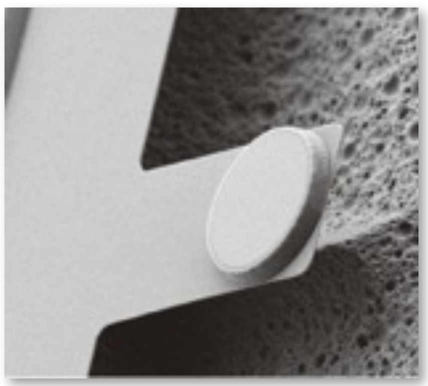


nanomechanical
***quantum* oscillator**

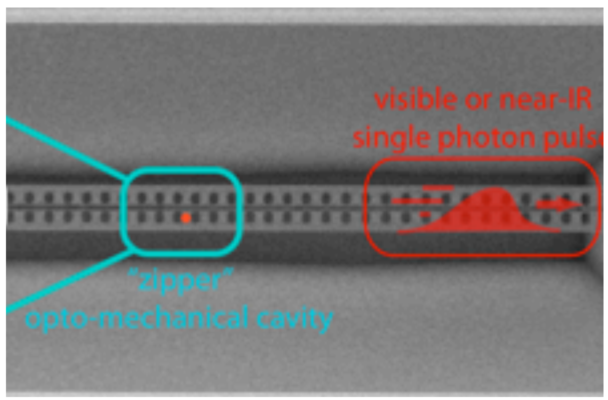
“Opto-nanomechanics”

… also: electro-nanomechanics

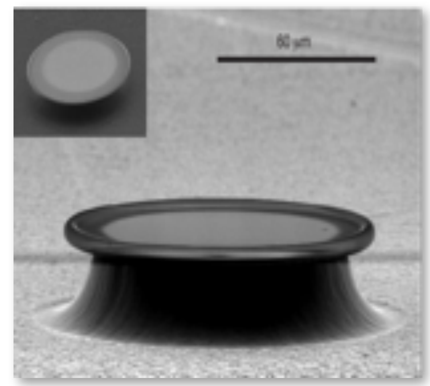
- **system:** High-quality mechanical oscillators coupled to high-quality, high-finesse optical cavities
- **goal: see quantum effects & applications in quantum technologies**
  - ground state cooling of the oscillator
  - entanglement …
  - why? … fundamental / applications



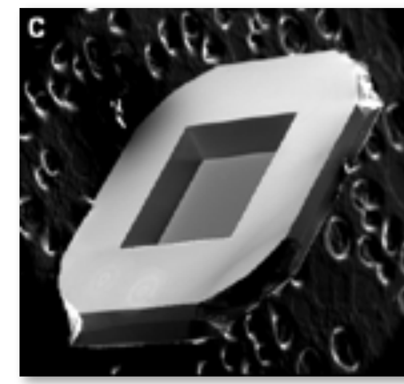
Micromirrors



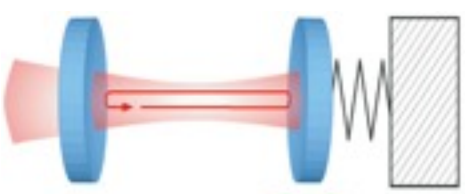
photonic & phononic cyrstals



Microtoroids

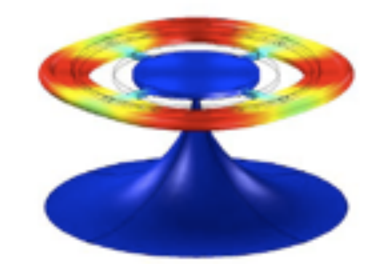


Micromembranes

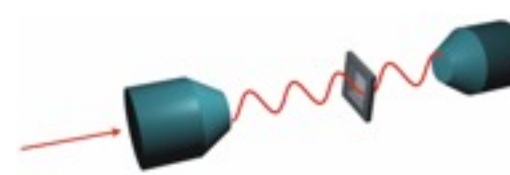


Aspelmeyer (Vienna)
Heidmann (Paris)

O. Painter (Caltech)



Kippenberg (MPQ)
Vahala (Caletch)
Bowen (UQ)



Harris (Yale)
Kimble (Caltech)

Hybrid Quantum Systems

what is "hybrid"?

- **Answer 2:**

concepts developed / successful in atomic quantum optics → … translated / adapted to solid state

Examples & Overview:
Hybrid AMO - Nanomechanical Systems

- **AMO concepts → solid state**

    ✓ Nanomechanics with Levitated Objects

    ✓ Electro- and Optomechanical Transducers for Quantum Computing and Quantum Communications

- **AMO - solid state quantum interfaces**

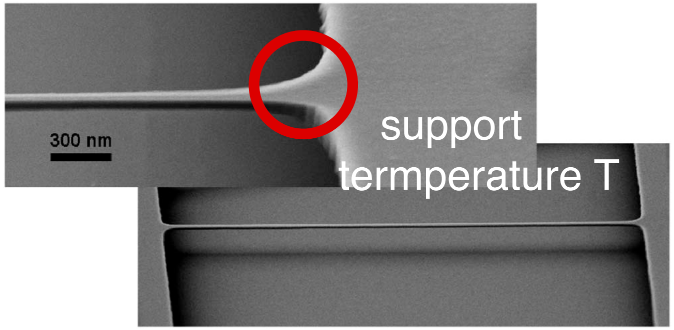
Example: Levitation

- trapping of atoms, molecules and ions
- laser cooling

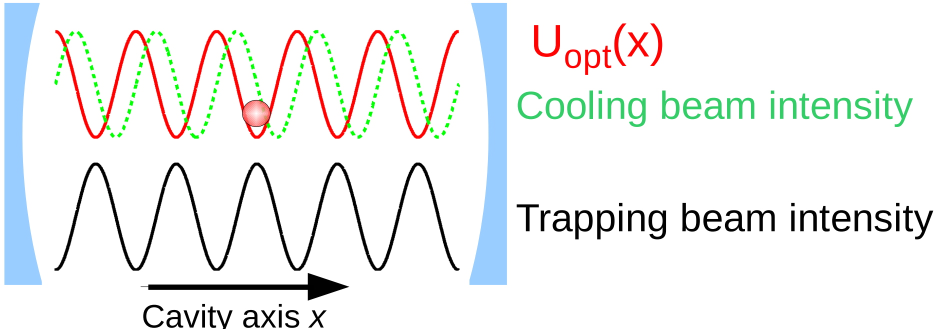
1a) Levitated Nanomech Oscillators: “AMO approach”

- **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

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

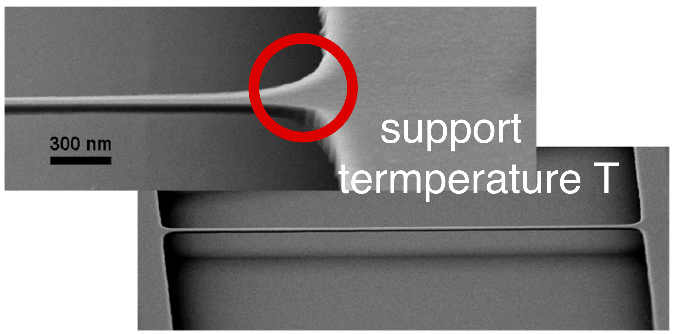
?

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

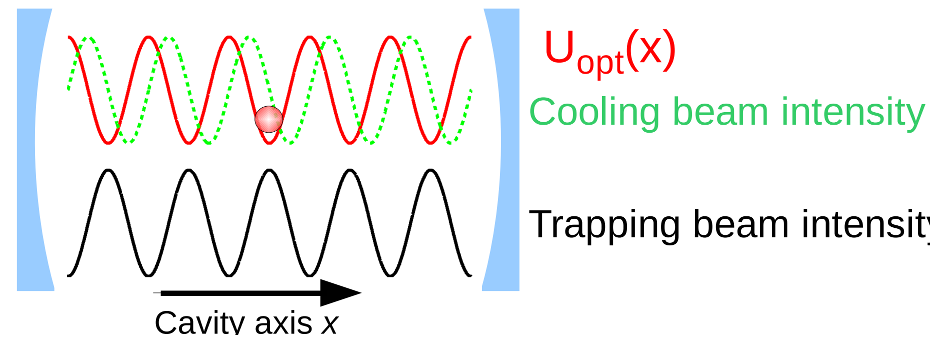
1a) Levitated Nanomech Oscillators: “AMO approach”

- **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

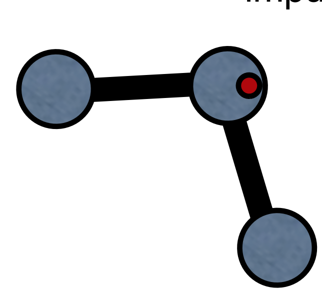
✓thermalization with support

… get rid of supporting structures

✓ here: center-of-mass

? internal modes of composite structures

? coupling to internal two-level atoms



Cavity opto-mechanics using an optically levitated nanosphere

PNAS,
Dec 31 2009

D. E. Chang[a], C. A. Regal[b], S. B. Papp[b], D. J. Wilson[b], J. Ye[b,c], O. Painter[d], H. J. Kimble[b,1], and P. Zoller[b,e]

[a]Institute for Quantum Information and Center for the Physics of Information, California Institute of Technology, Pasadena, CA 91125;[b]Norman Bridge Laboratory of Physics 12-33, California Institute of Technology, Pasadena, CA 91125;[c]JILA, National Institute of Standards and Technology, and Department of Physics, University of Colorado, Boulder, CO 80309;[d]Department of Applied Physics, California Institute of Technology, Pasadena, CA 91125; and [e]Institute for Quantum Optics and Quantum Information of the Austrian Academy of Sciences, A-6020 Innsbruck, Austria

Contributed by H. Jeffrey Kimble, November 10, 2009 (sent for review October 17, 2009)

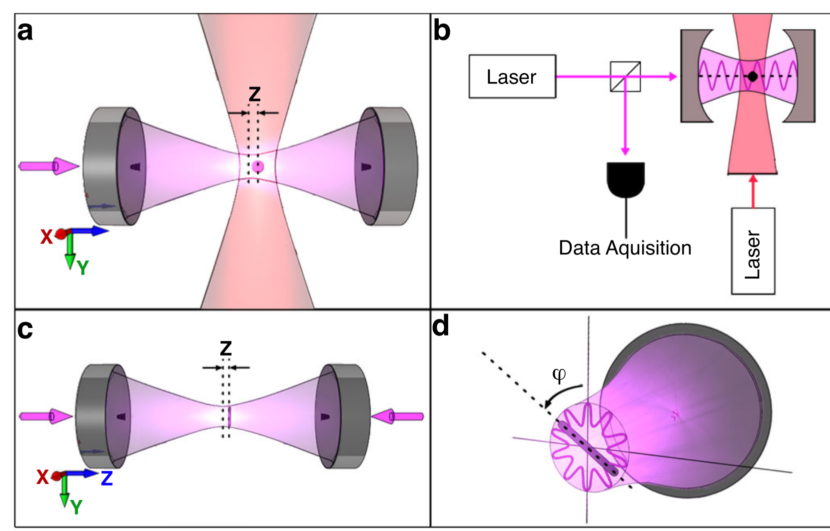
Recently, remarkable advances have been made in coupling a number of high-Q modes of nano-mechanical systems to high-finesse optical cavities, with the goal of reaching regimes in which quantum behavior can be observed and leveraged toward new applications. To reach this regime, the coupling between these systems and their thermal environments must be minimized. Here we propose a novel approach to this problem, in which optically levitating a nano-mechanical system can greatly reduce its thermal contact, while simultaneously eliminating dissipation arising from clamping. Through the long coherence times allowed, this approach potentially opens the door to ground-state cooling and coherent manipulation of a single mesoscopic mechanical system or entan-

decoupled from the internal degrees of freedom in addition to being mechanically isolated by levitation. In this case, the decoherence and heating rates are fundamentally limited by the momentum recoil of scattered photons and can be reduced simply by using smaller spheres. The long coherence time allowed by small spheres enables the preparation of more exotic states through *coherent* quantum evolution. Here, we consider in detail two examples. First, we describe a technique to prepare a squeezed motional state, which can subsequently be mapped onto light leaving the cavity using quantum state transfer protocols (15–18). Under realistic conditions, the output light exhibits up to ~15 dB of squeezing relative to vacuum noise levels, poten-

Toward quantum superposition of living organisms

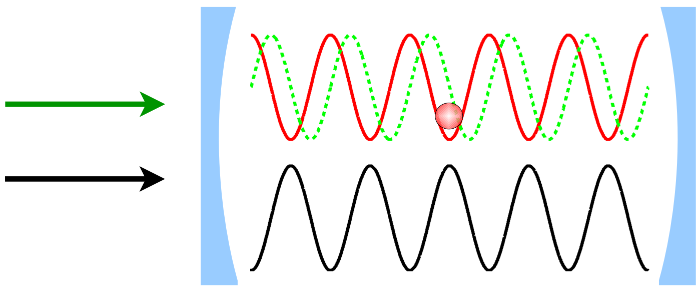
Oriol Romero-Isart[1,4], Mathieu L Juan[2], Romain Quidant[2,3] and J Ignacio Cirac[1]

New Journal of Physics **12** (2010) 033015



Optical forces and noise acting on a dielectric sphere

- **dielectric nanosphere:** $r << \lambda_L$, with radius r and wavelength λ_L
- **setup:** dielectric sphere interacting with two standing-wave optical modes of a Fabry-Perot cavity



- **trapping beam** provides a gradient force similar to "optically tweezer" (Ashkin)

sphere $r << \lambda_L$ acts as a point dipole: $p_{\rm ind} = \alpha_{\rm ind} E(x)$

optical potential: $U_{\rm opt}(x) = -(1/4)(\text{Re}\ \alpha_{\rm ind})|E(x)|^2$

polarizability: $\alpha_{\rm ind} = 3\epsilon_0 V \left(\frac{\epsilon-1}{\epsilon+2}\right)$ V volume, ϵ electric permittivity

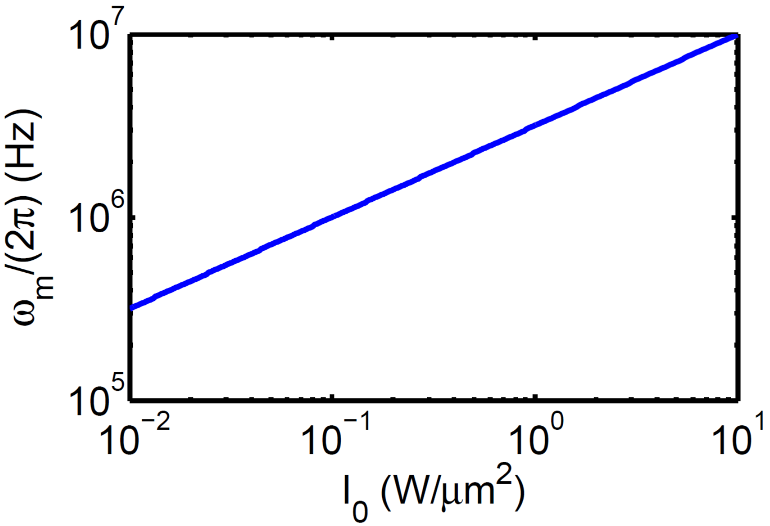
standing wave $E(x) = E_0 \cos kx$ ($k \equiv 2\pi/\lambda$) near anti-node: harmonic potential

mechanical frequency $\omega_m = \left(\frac{6k^2 I_0}{\rho c}\text{Re}\frac{\epsilon-1}{\epsilon+2}\right)^{1/2}$

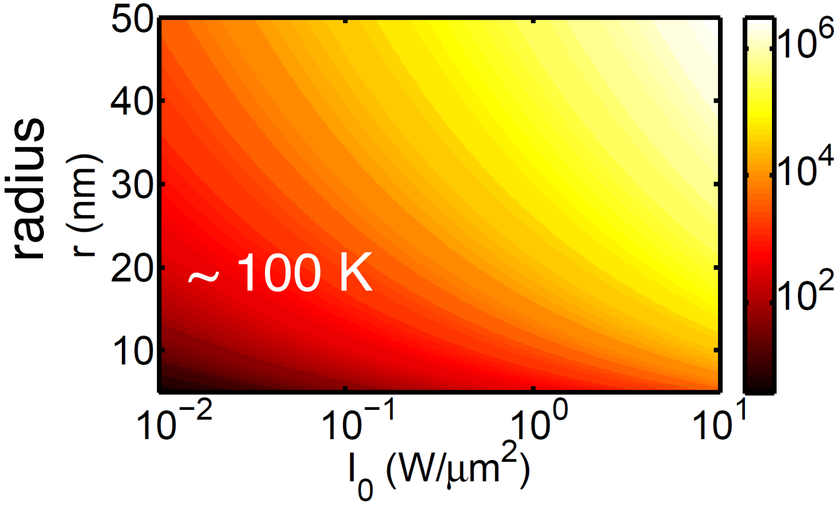
I_0 intensity, ρ mass density

trap depth $U_0 = (3I_0 V/c)\text{Re}\frac{\epsilon-1}{\epsilon+2}$

trapping frequency



trap depth in Kelvin

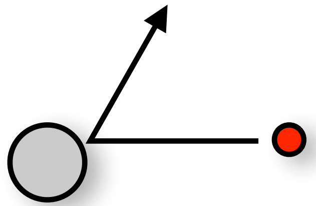


Frequencies of several MHz are achievable using an intra-cavity intensity of $I_0 \sim 1$ W/μm^2.

Absorption

Dominant Noise Forces

- **collisions with background gas:** $\lambda_{mf} >> r$



$$\gamma_g/2 = (8/\pi)(P/\bar{v}r\rho)$$

For a sphere of radius $r = 50$ nm, $\omega_m/(2\pi) = 1$ MHz, and a room-temperature gas with $P = 10^{-10}$ Torr, one finds $\gamma_g{\sim}10^{-6}$ s^{-1}, $Q_g{\sim}6{\times}10^{12}$, $N_{\rm osc}^{(g)}{\sim}10^5$.

- **Photons scattering out of the cavity lead to heating via momentum recoil kicks:** compare trapped ions

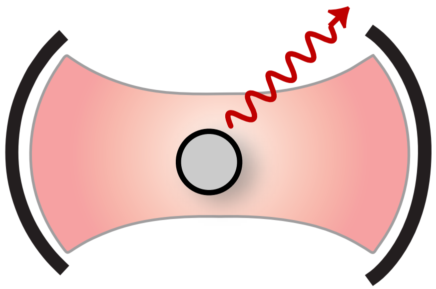
$$\gamma_{\rm sc} = (2/5)(\omega_r/\omega_m)R_{\rm sc}$$

recoil frequency : $\omega_r = \hbar k^2/2\rho V$

photon scattering rate: $R_{\rm sc} = 48\pi^3 \frac{I_0 V^2}{\lambda^4 \hbar\omega}(\frac{\epsilon-1}{\epsilon+2})^2$

number of coherent oscillations

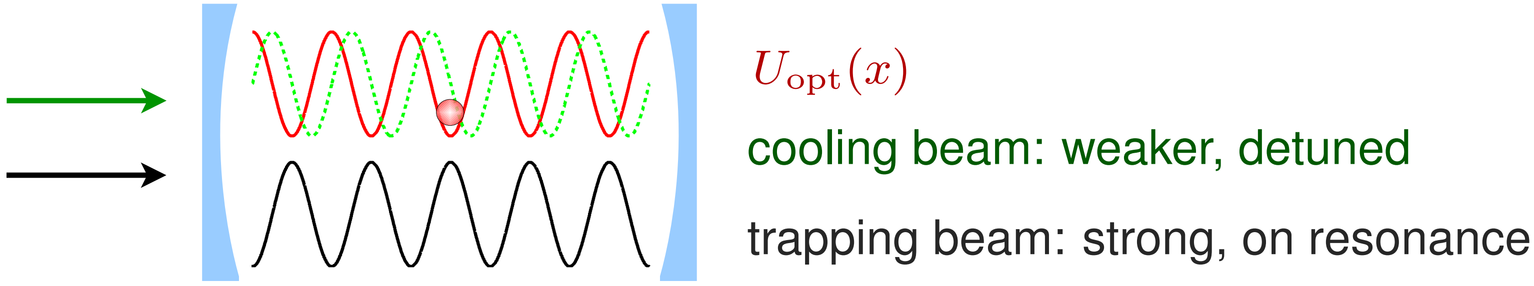
$$N_{\rm osc}^{(\rm sc)} \equiv \frac{\omega_m}{2\pi\gamma_{\rm sc}} = \frac{5}{8\pi^3}\frac{\epsilon+2}{\epsilon-1}\frac{\lambda^3}{V}$$ >>1



Recoil heating dominates $N_{\rm osc}$ for sphere sizes $r \gtrsim 5$ nm.

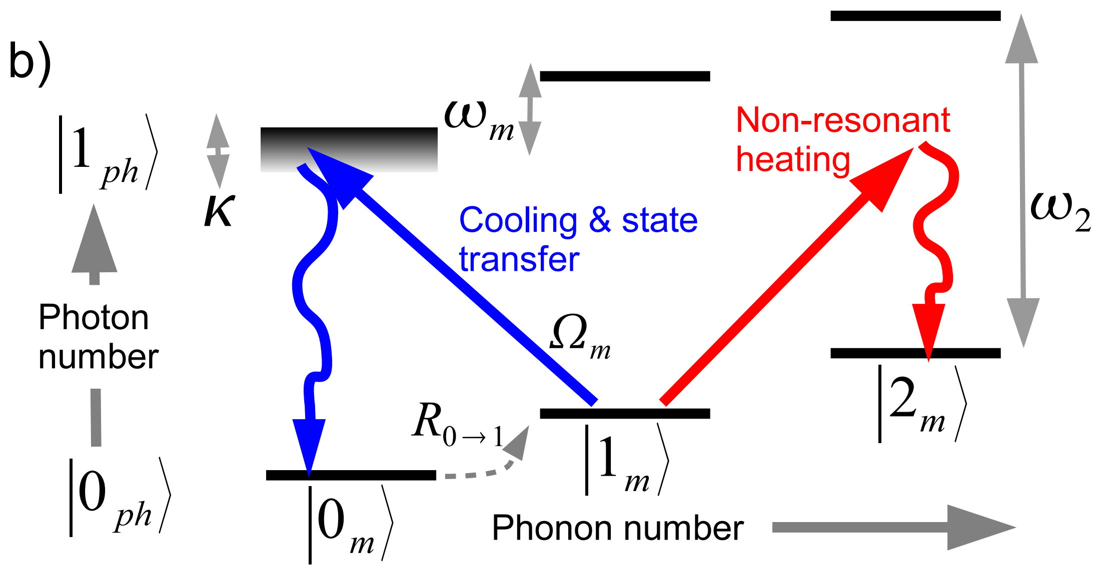
Laser cooling ... to the ground state

- optical cooling due to the weaker, second cavity mode



- ... equivalent to standard laser cooling of a nanomechanical oscillator

I. Wilson-Rae et al.,
F. Marquard et al. 2007



- steady-state phonon number

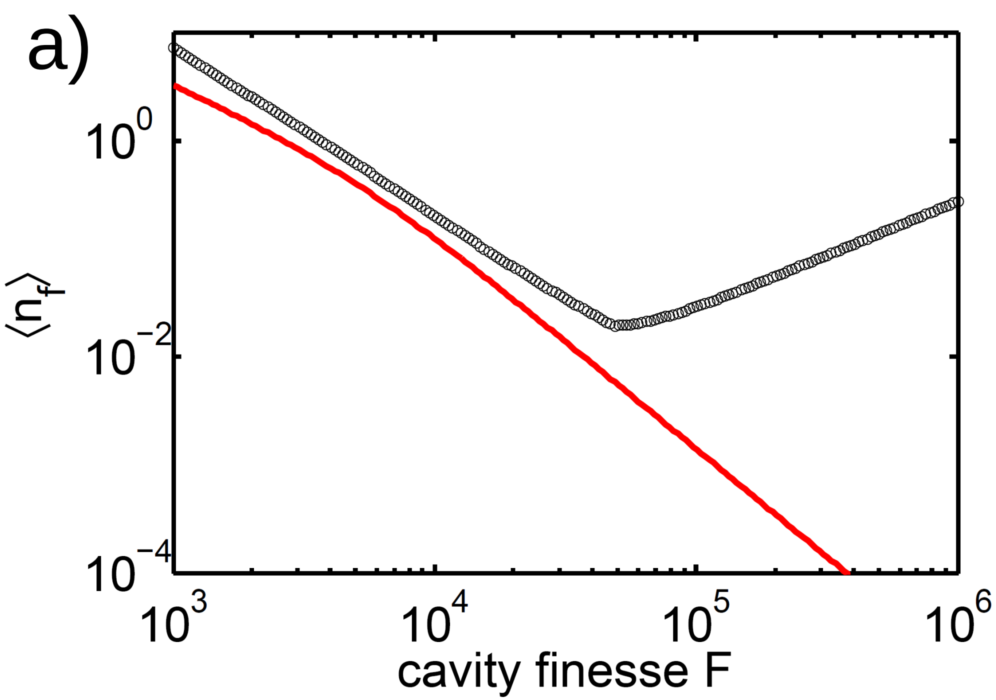
$$\langle n_f \rangle \approx \frac{\kappa^2}{16\omega_m^2} + \phi \frac{\omega_m}{\kappa} \qquad (\omega_m \gg \kappa)$$

recoil heating

with $\phi = (4\pi^2/5)(V/\lambda^3)\frac{\epsilon-1}{\epsilon+2}$ ($<< 1$)

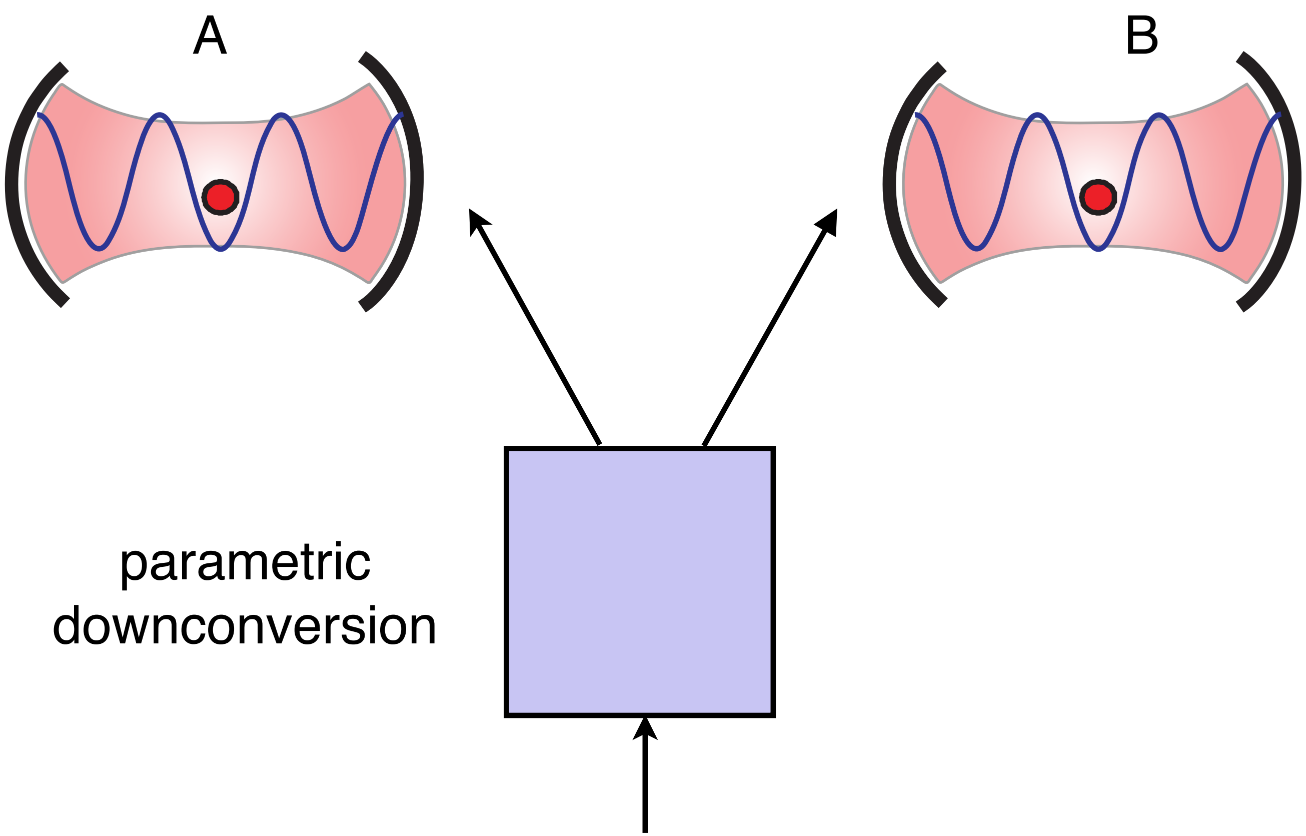
- numbers: $r = 50$ nm and $\omega_m/(2\pi) = 0.5$ MHz levitated inside a cavity of length $L = 1$ cm and mode waist $w = 25$ μm ($V_c = (\pi/4)Lw^2$)

  cavity finesse $\mathcal{F} \equiv \pi c / 2\kappa L$



Entangled spheres

- Broadband squeezed light is mapped onto mechanical motion in resolved side band limit, generating EPR correlations between two spatially separate spheres

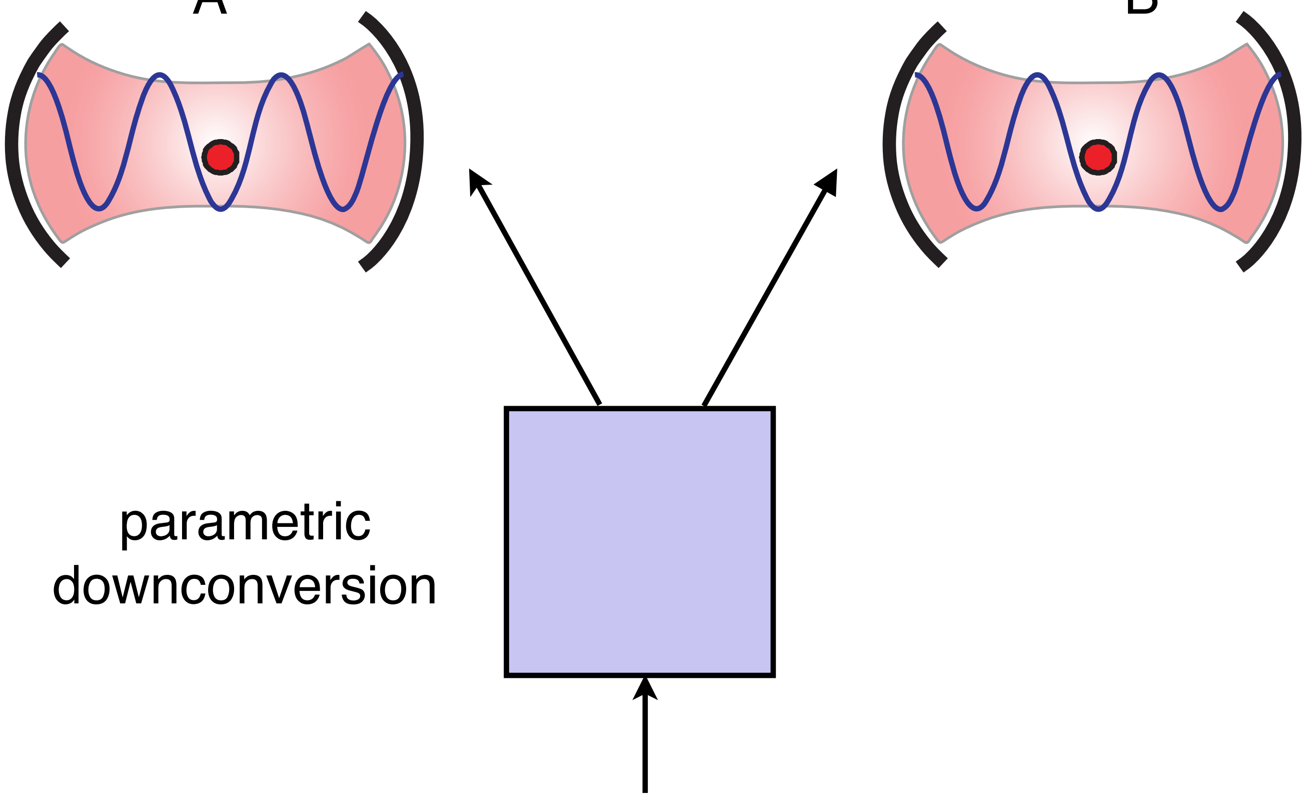


- quadrature operators for the input light for each of the two systems $j = A, B$

$$\langle (X_{+,\mathrm{in}}^{(A)}(\omega) + X_{+,\mathrm{in}}^{(B)}(\omega))^2 \rangle / 2 = \langle (X_{-,\mathrm{in}}^{(A)}(\omega) - X_{-,\mathrm{in}}^{(B)}(\omega))^2 \rangle / 2 = e^{-2R} < 1.$$

Entangled spheres

- Broadband squeezed light is mapped onto mechanical motion in resolved side band limit, generating EPR correlations between two spatially separate spheres

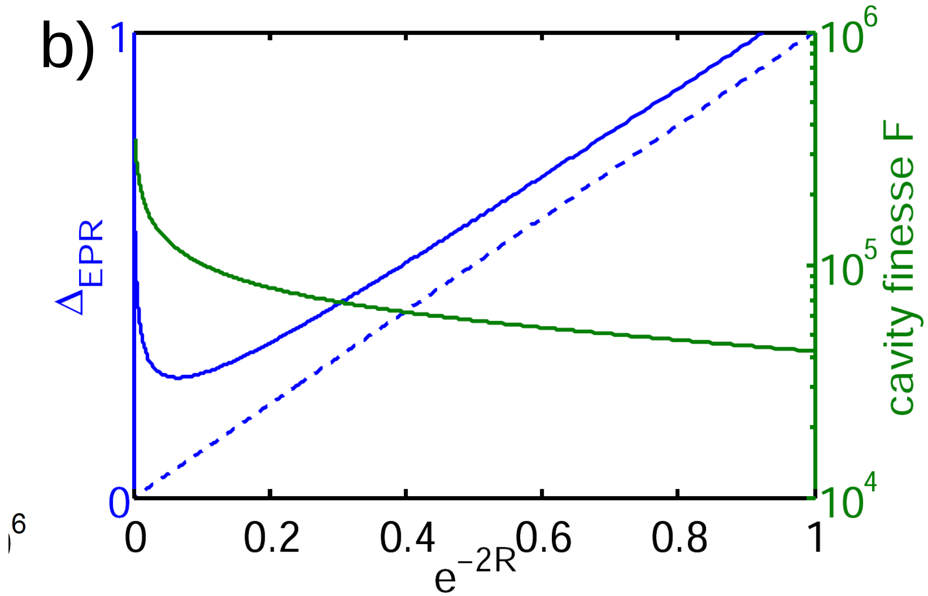


- state transfer yields

$$\Delta_{\mathrm{EPR}} \equiv \langle (X^{(A)}_{\pm,m}(t) \mp X^{(B)}_{\pm,m}(t))^2 \rangle /2 = e^{-2R} + \frac{\kappa^2}{16\omega_m^2}(3e^{2R} + 2\sinh 2R) + \frac{4\phi\omega_m}{\kappa}$$

anti-Stokes recoil heating

- **plot $\Delta_{\mathrm{EPR,min}}$ as a function of e^{-2R}**



Solid blue curve: optimized EPR variance between two levitated spheres, as a function of squeezing parameter e^{-2R}. System parameters: $r = 50$ nm, cavity length $L = 1$ cm, waist $w = 25\ \mu$m

Dashed curve: EPR variance in limit of perfect state transfer, $\Delta_{\mathrm{EPR}} = e^{-2R}$.

Green curve: cavity finesse corresponding to optimal EPR variance.

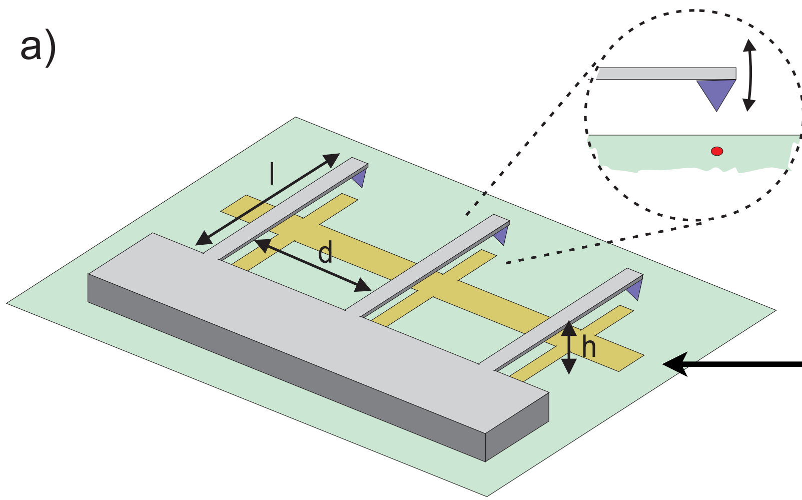
For the moderate values of e^{-2R} typically obtained in experiments, EPR correlations in the motion can be achieved with reasonable cavity finesse $F < 10^5$.

Example: Transducers

Quantum Spin Transducer: “Quantum Piano”

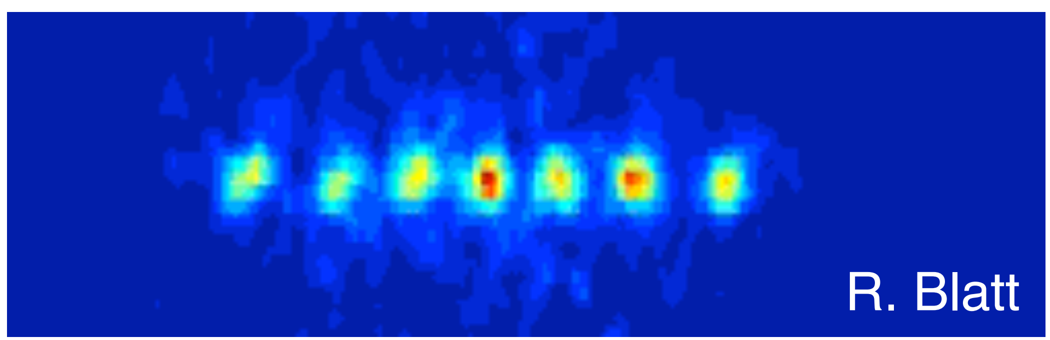
P. Rabl, S. J. Kolkowitz, F.H.L. Koppens, J.G.E. Harris, PZ, M.D. Lukin, Nature Phys 2010

- **quantum spin transducer based on nanoelectrical resonator arrays**



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

- **… in analogy to trapped ions:**



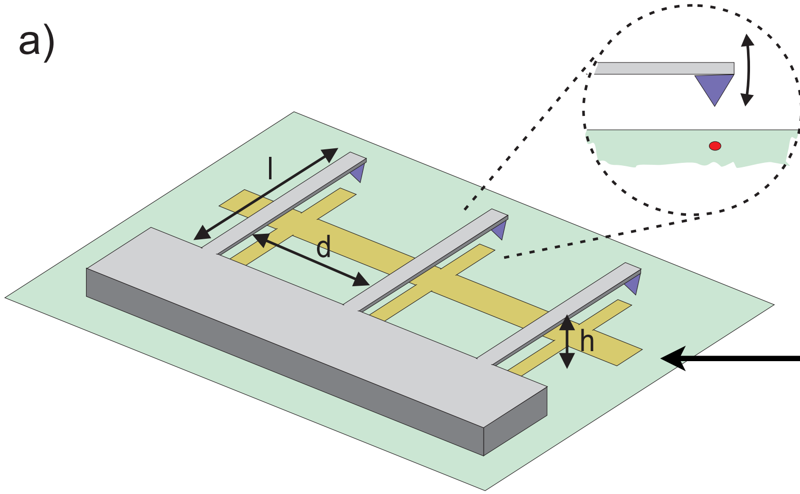
$$|\Psi\rangle = \sum_x c_x |x_{N-1}, \ldots, x_0\rangle \otimes |0\rangle_{\text{phonon}}$$

Quantum Spin Transducer: "Quantum Piano"

P. Rabl, S. J. Kolkowitz, F.H.L. Koppens, J.G.E. Harris, PZ, M.D. Lukin, Nature Phys 2010

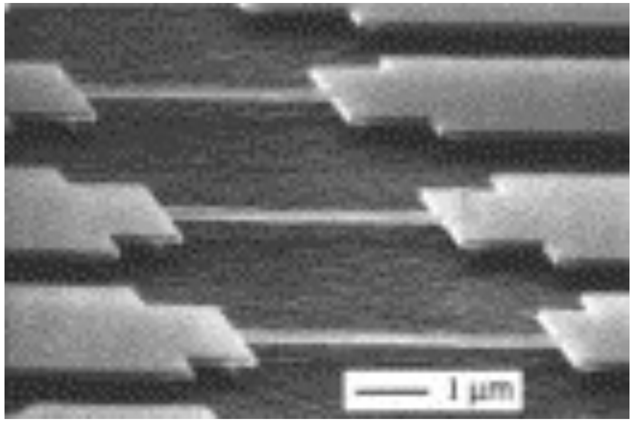
- **quantum spin transducer based on nanoelectrical resonator arrays**

a)



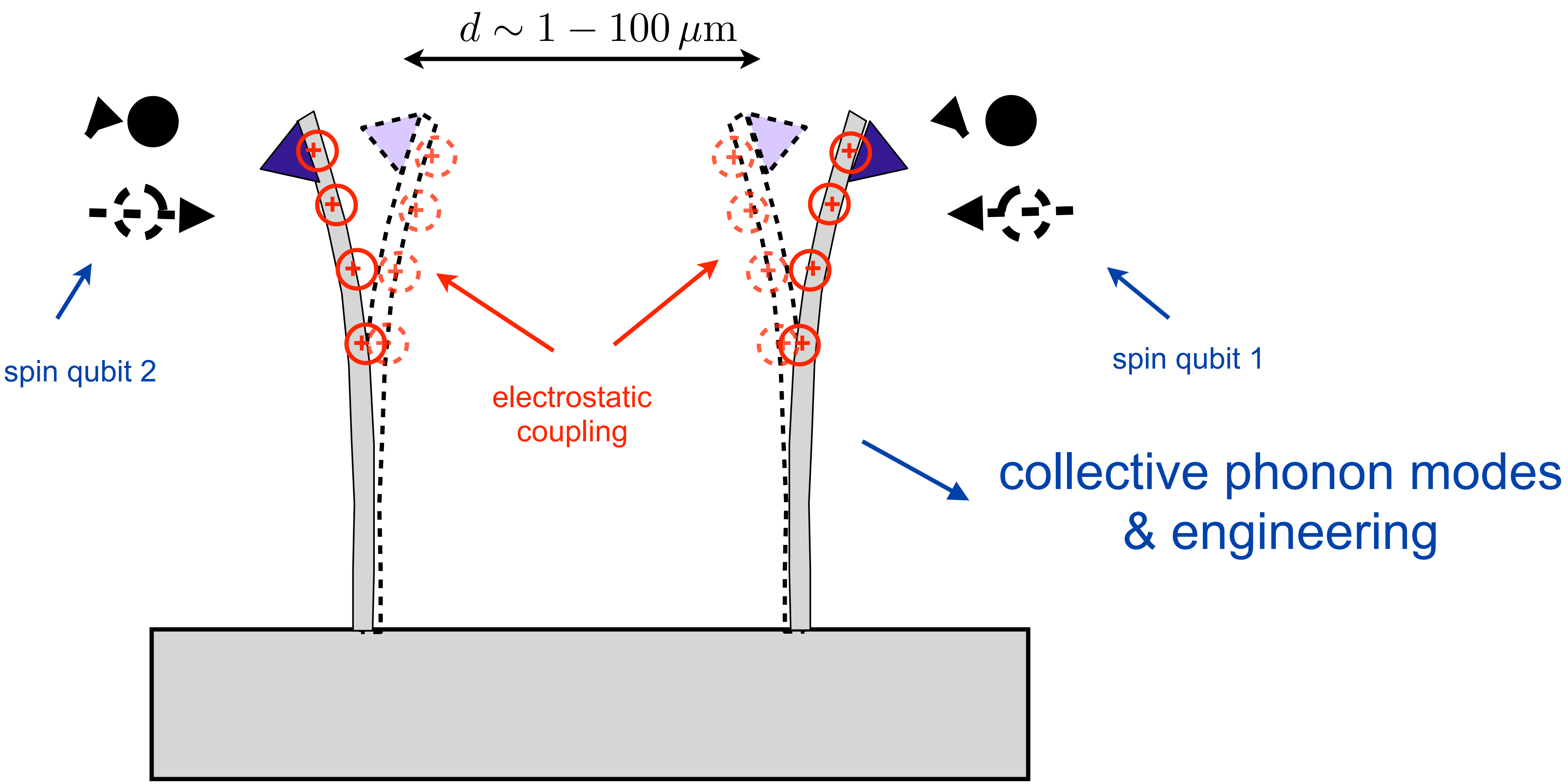
- cantilever with magnetic tip
- NV centers as qubits (+ microwave)
- capacitive coupling of cantilevers: phonon bus

- **resonator array**



A. Cleland, UCSB

Electro-mechanical transducer



long-range spin-spin interactions !

Phonon-mediated spin-spin coupling

$$H = \sum_i \frac{\Omega_i(t)}{2}\sigma_x^i + \sum_n \omega_n a_n^\dagger a_n + \frac{1}{2}\sum_{i,n}\lambda_{i,n}(a_n^\dagger + a_n)\sigma_z^i$$

$\Omega_i(t) = 0$

Polaron transformation
(≡ displaced oscillator basis)

$$U = e^{\sum_{i,n} \frac{\lambda_{n,i}}{\omega_n}(a_n^\dagger - a_n)\sigma_z^i}$$

$$\tilde{H} = \sum_n \omega_n a_n^\dagger a_n - \sum_{i\neq j} M_{ij}\sigma_z^i\sigma_z^j$$

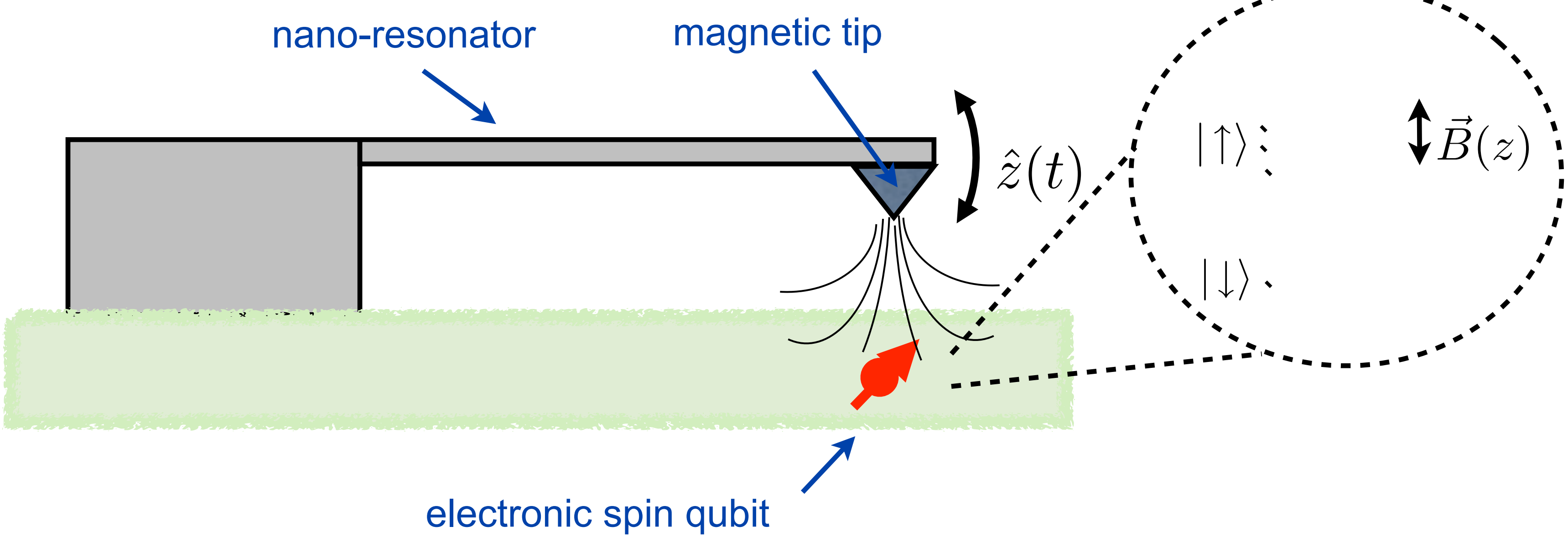
free phonons

$$M_{ij} = \frac{1}{4}\sum_n \frac{\lambda_{n,i}\lambda_{n,j}}{\omega_n}$$

(phonon frequencies, mode functions)

long-range spin-spin interactions !

Spin-resonator coupling



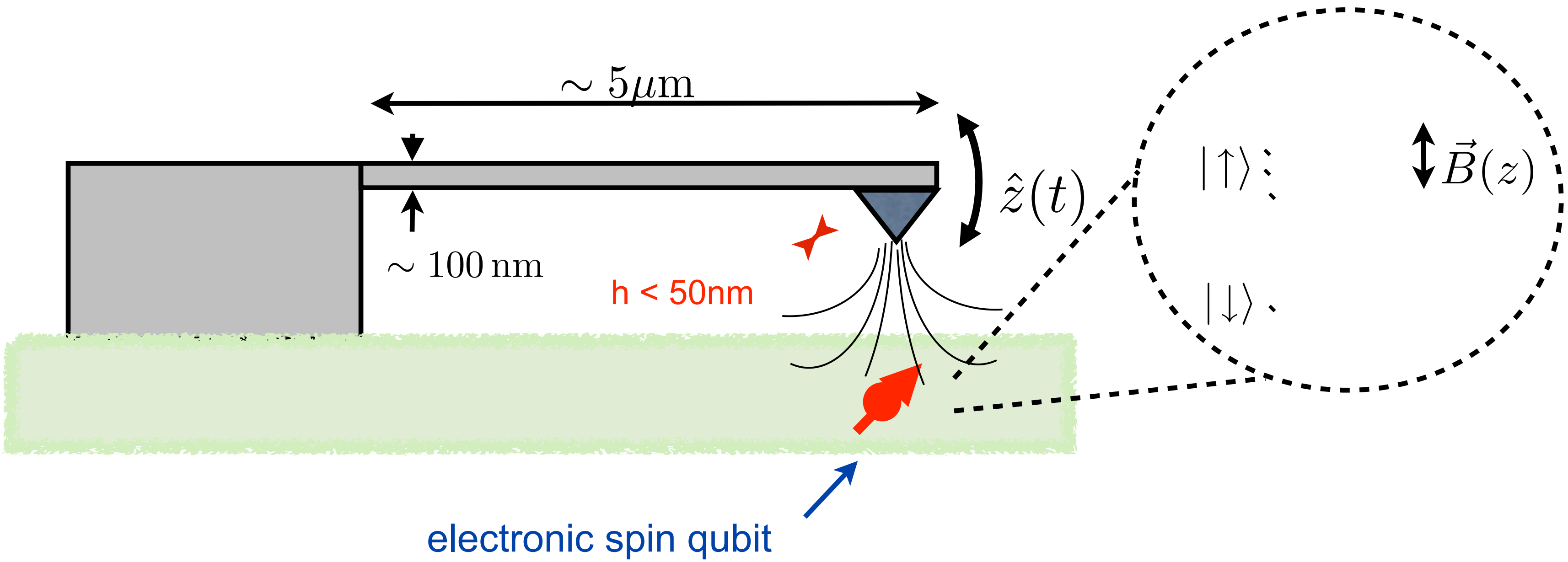
magnetic coupling: $$H_{\text{int}} = \lambda(a + a^\dagger)\sigma_z$$

$$\lambda = g_s \mu_B a_0 \nabla B / \hbar$$

zero point motion

"Zeeman shift per vibrational quanta"

Spin-resonator coupling



magnetic coupling:

$$H_{\text{int}} = \lambda(a + a^\dagger)\sigma_z$$

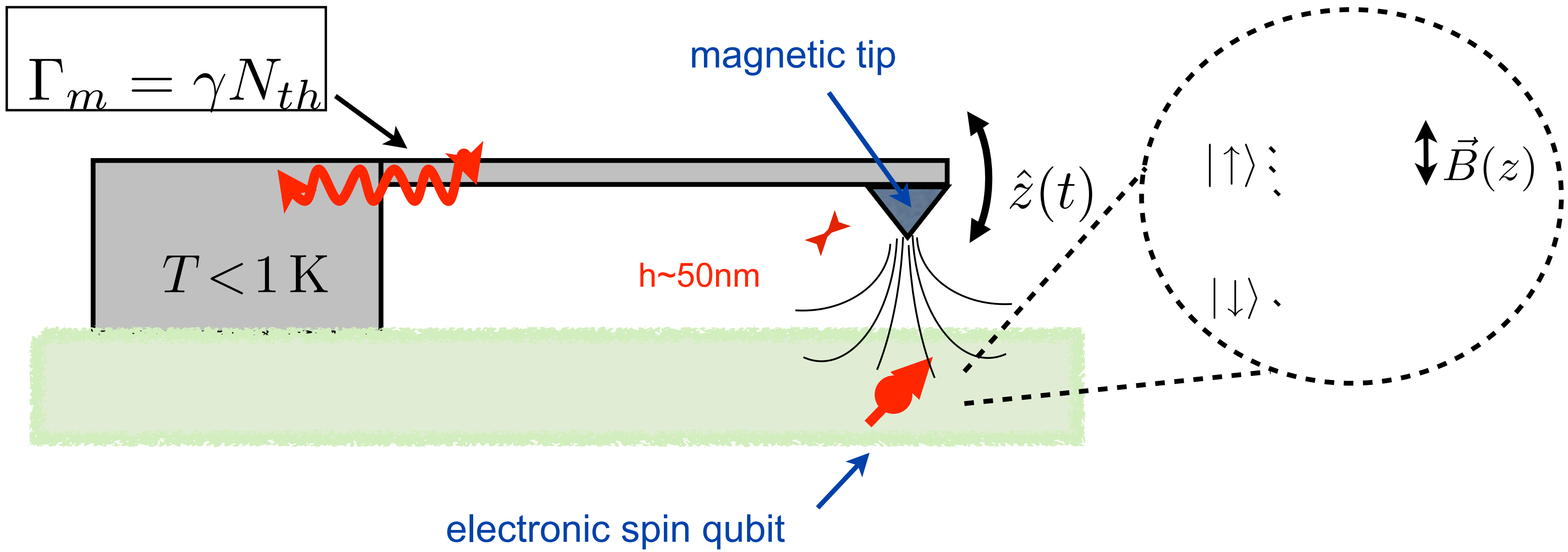
$$\lambda = g_s \mu_B a_0 \nabla B / \hbar$$

zero point motion

$$\lambda \approx 100\,\text{kHz}$$

"Zeeman shift per vibrational quanta"

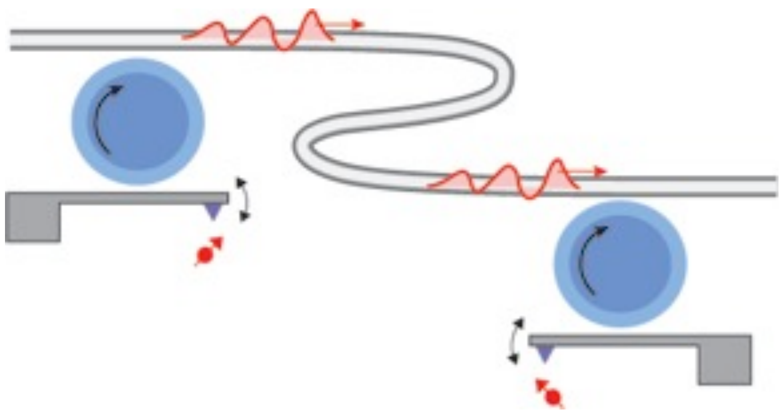
Spin-resonator coupling



coherent coupling		spin dephasing	motional dephasing
$\lambda \approx 100\,\mathrm{kHz}$	$\gg$	$1/T_2$,	$\Gamma_m = k_B T/Q$
		$(\sim\ 1\,\mathrm{kHz})$	$(1-10\,\mathrm{kHz})$

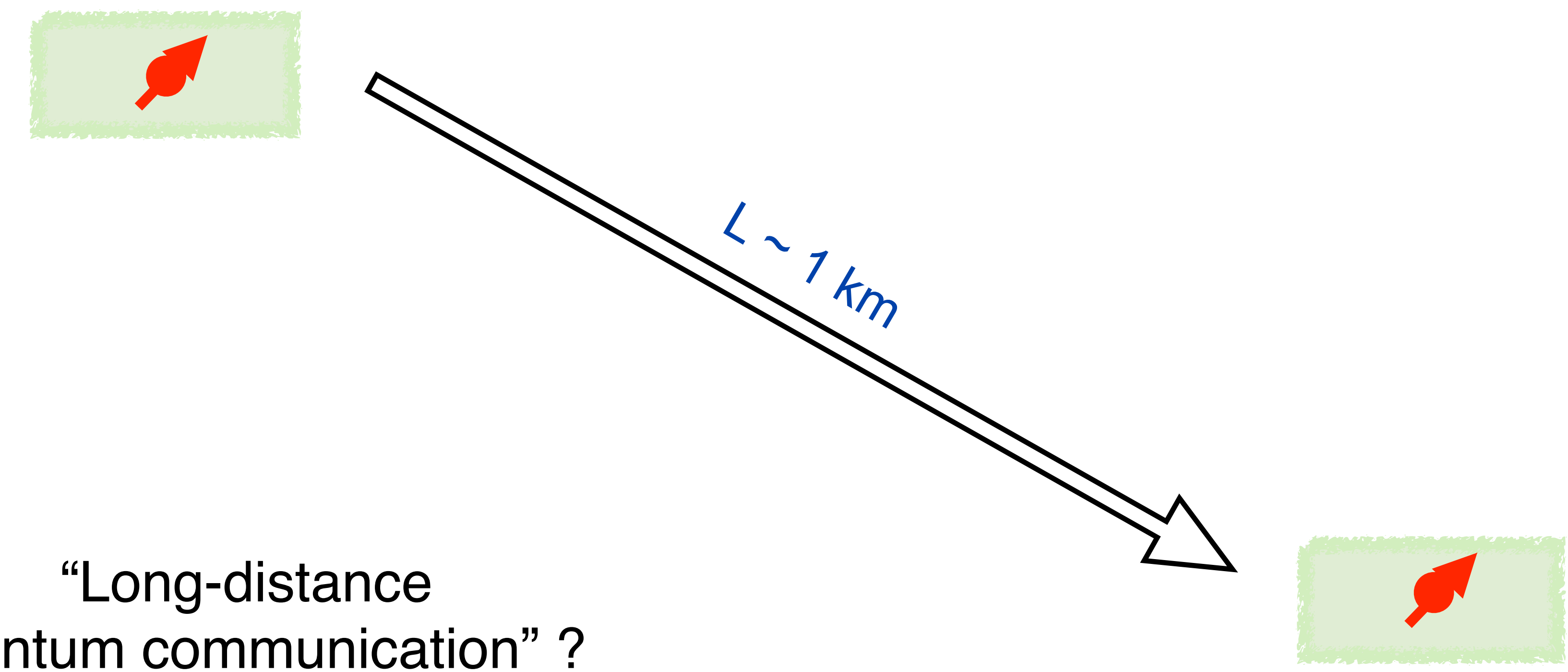
strong coupling conditions !

Opto-nanomechanical transducers for long-distance quantum communications



Quantum communication

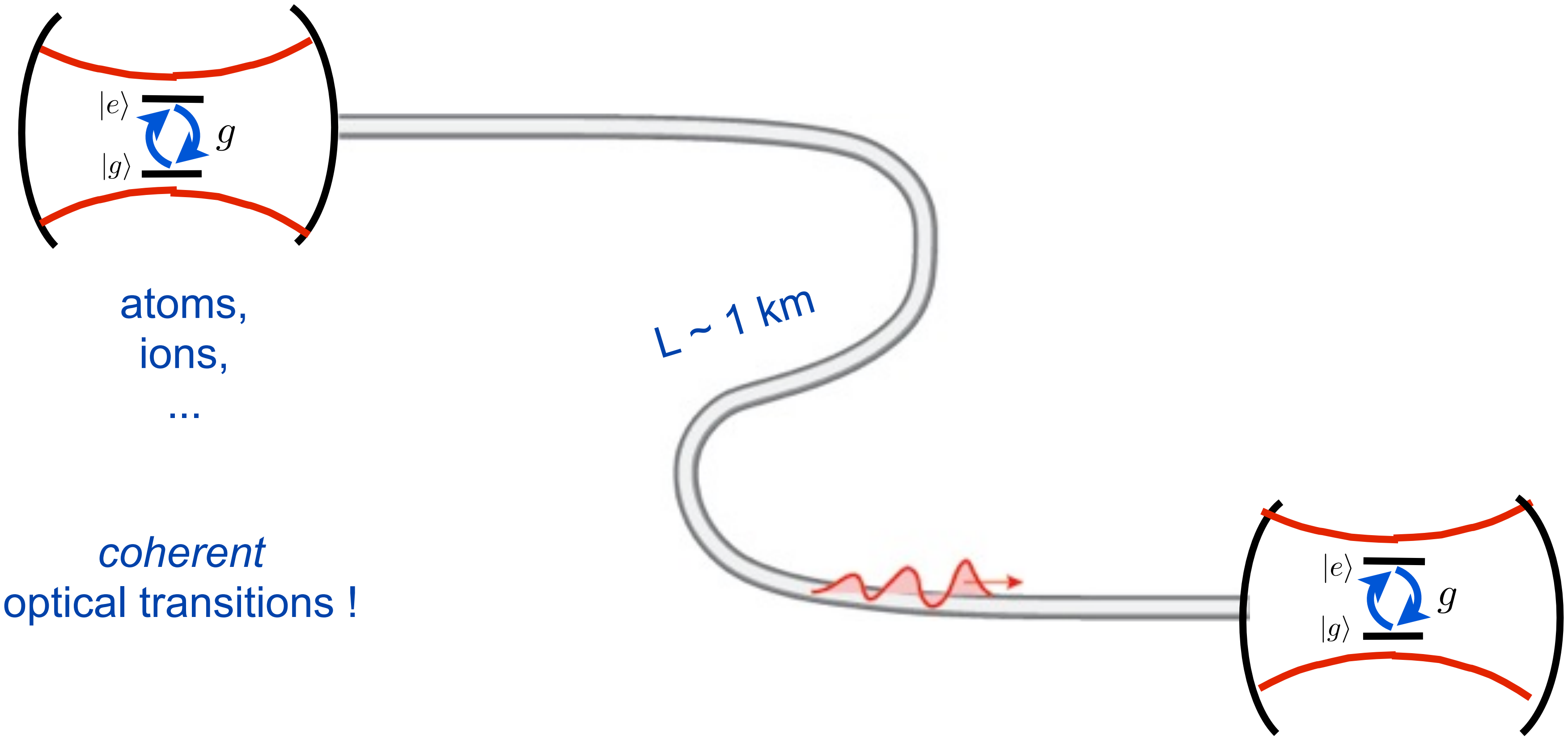
$$(\alpha|0\rangle_1 + \beta|1\rangle_1\rangle)\,|0\rangle_2 \quad \longrightarrow \quad |0\rangle_1\,(\alpha|0\rangle_2 + \beta|1\rangle_2\rangle)$$



"Long-distance
quantum communication" ?

Quantum communication

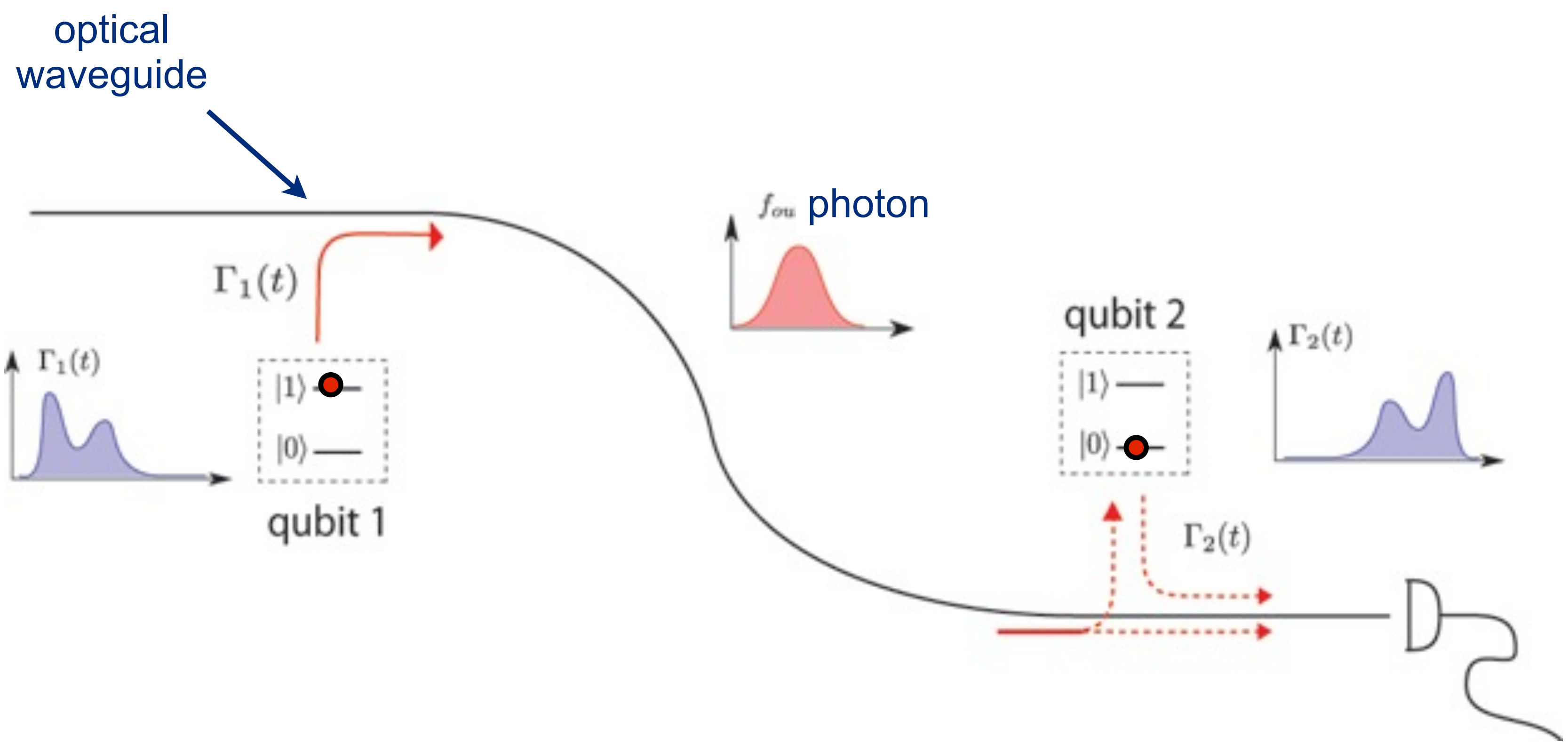
$$(\alpha|0\rangle_1 + \beta|1\rangle_1)\,|0\rangle_2 \longrightarrow |0\rangle_1\,(\alpha|0\rangle_2 + \beta|1\rangle_2)$$



atoms,
ions,
...

coherent
optical transitions !

Quantum state transfer ...

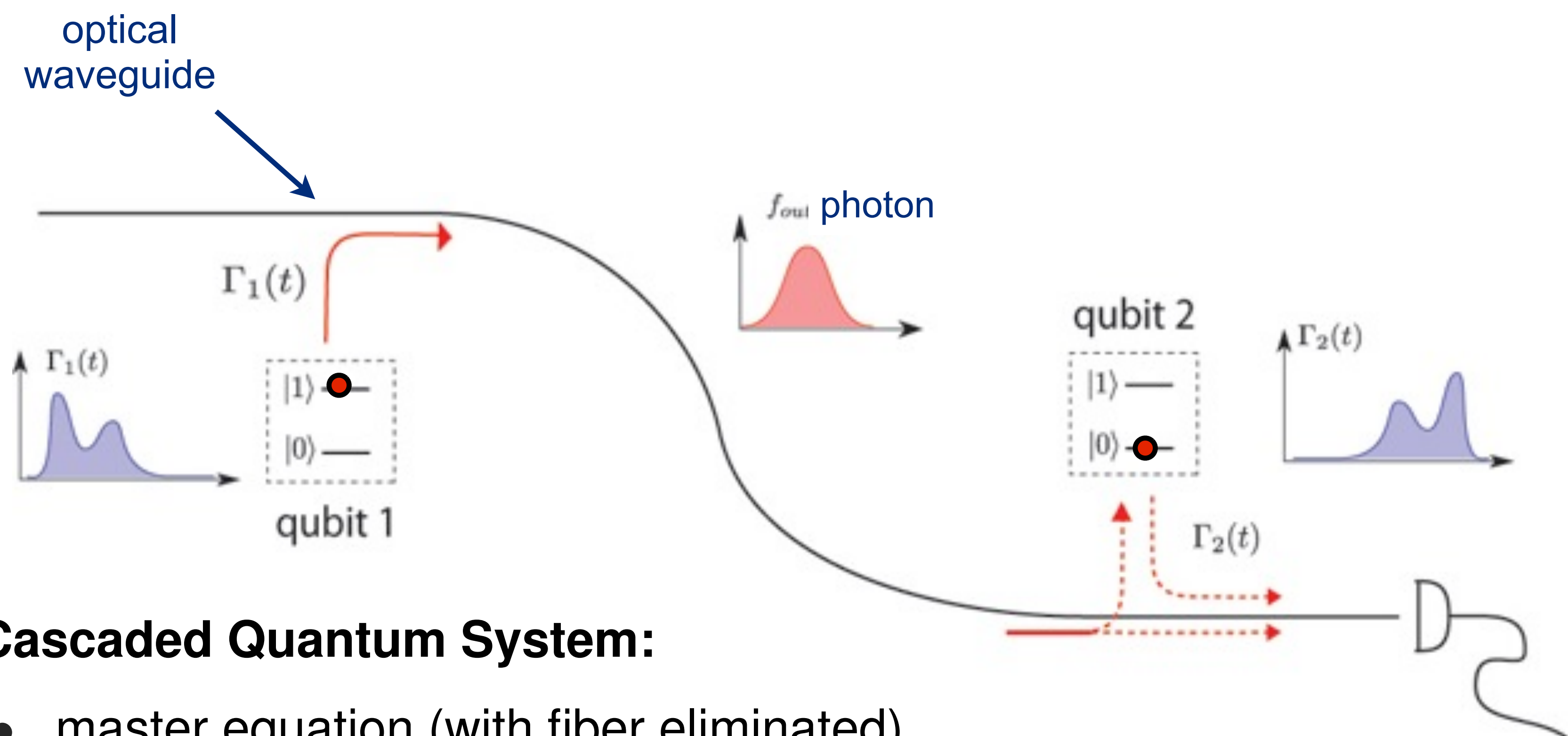


- cascaded quantum network
- adjustable decay rates $\Gamma_{1,2}(t)$

} *perfect* quantum state transfer

J. I. Cirac, P. Zoller, H. J. Kimble, and H. Mabuchi, PRL. **78**, 3221 (1997)

Quantum state transfer ...



Cascaded Quantum System:

- master equation (with fiber eliminated)

$$\dot{\rho} = -i(H_{\text{eff}}(t)\rho - \rho H_{\text{eff}}^{\dagger}(t)) + \Sigma^{\dagger}(t)\rho\Sigma(t) + \cancel{\mathcal{L}_{\text{noise}}(\rho)}$$

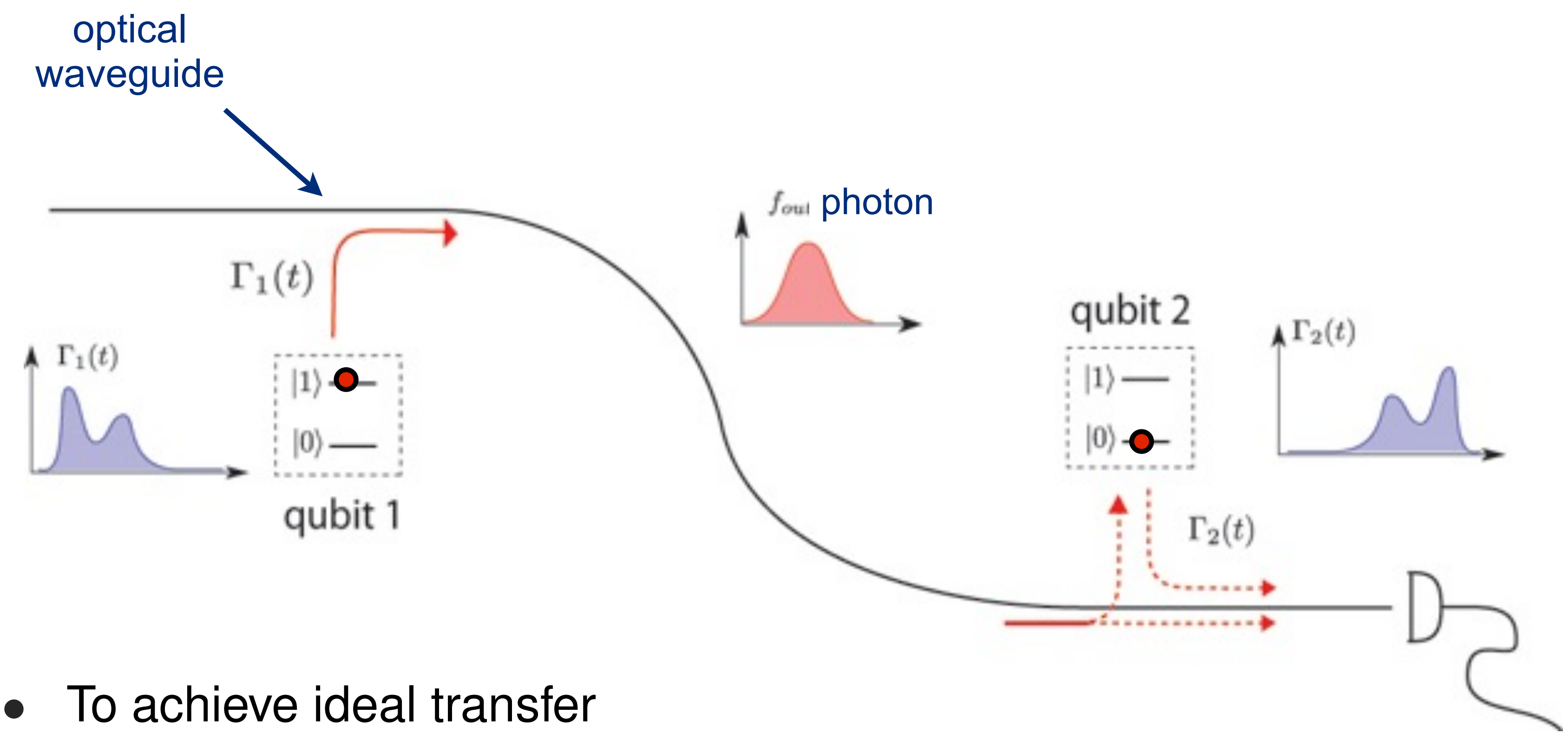
- effective Hamiltonian

$$H_{\text{eff}} = \frac{1}{2}\sum_{i<j} J_{ij}(t)(\sigma_-^i\sigma_+^j + \sigma_+^i\sigma_-^j) - i\frac{1}{2}\Sigma^{\dagger}(t)\Sigma(t)$$

exchange coupling $J_{ij}(t) = \sqrt{\Gamma_i(t)\Gamma_j(t)}$

jump operator $\Sigma(t) = \sum_i \sqrt{\Gamma_i(t)}\sigma_-^i$

Quantum state transfer ...



- To achieve ideal transfer

$$(\alpha|0\rangle_i + \beta|1\rangle_i)\,|0\rangle_j \rightarrow |0\rangle_i(\alpha|0\rangle_j + \beta|1\rangle_j)$$

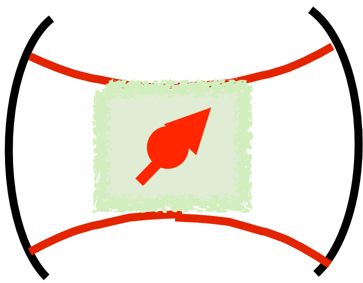
- we require

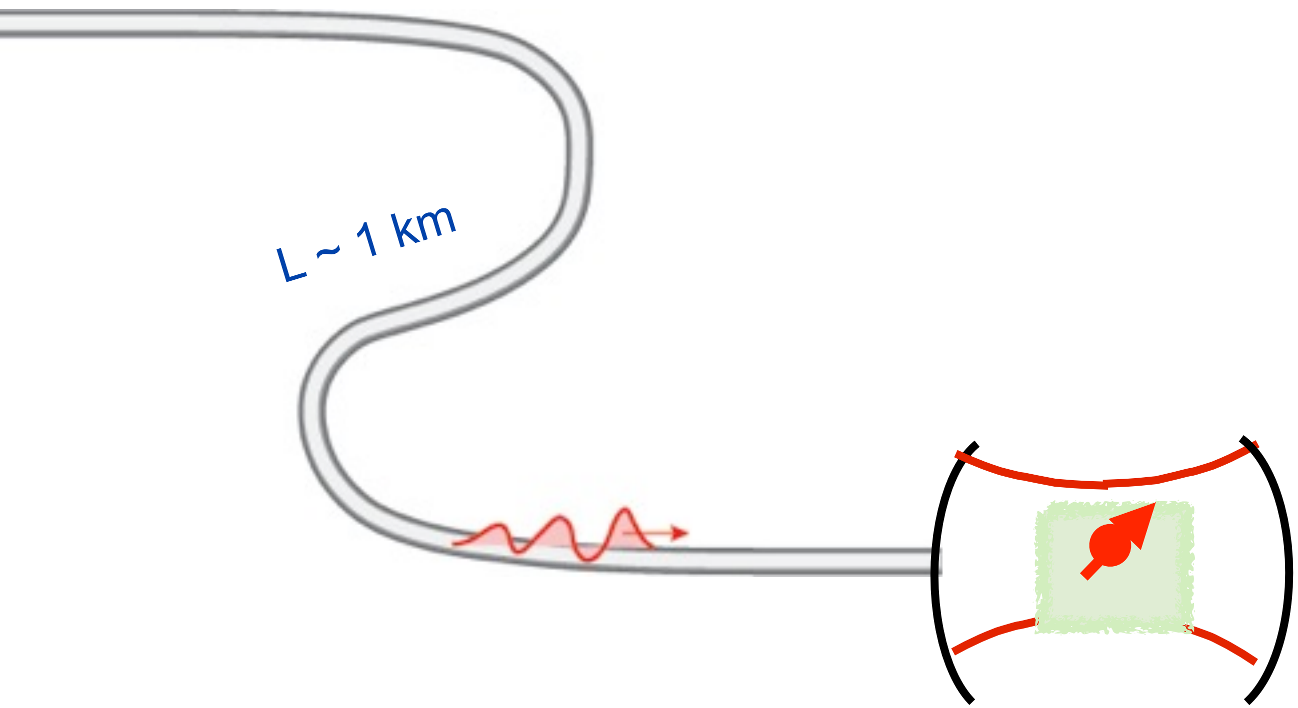
$$\rho(t) = |\psi(t)\rangle\langle\psi(t)| \qquad \Sigma(t)\,|\psi\rangle = 0$$ dark state

- which can be fulfilled with an appropriate pulse sequence $\Gamma_1(t) = \Gamma_2(-t)$ etc. and $\mathcal{L}_{\text{noise}} = 0$

Quantum communication ...

$$(\alpha|0\rangle_1 + \beta|1\rangle_1\rangle)\,|0\rangle_2 \quad \longrightarrow \quad |0\rangle_1\,(\alpha|0\rangle_2 + \beta|1\rangle_2\rangle)$$

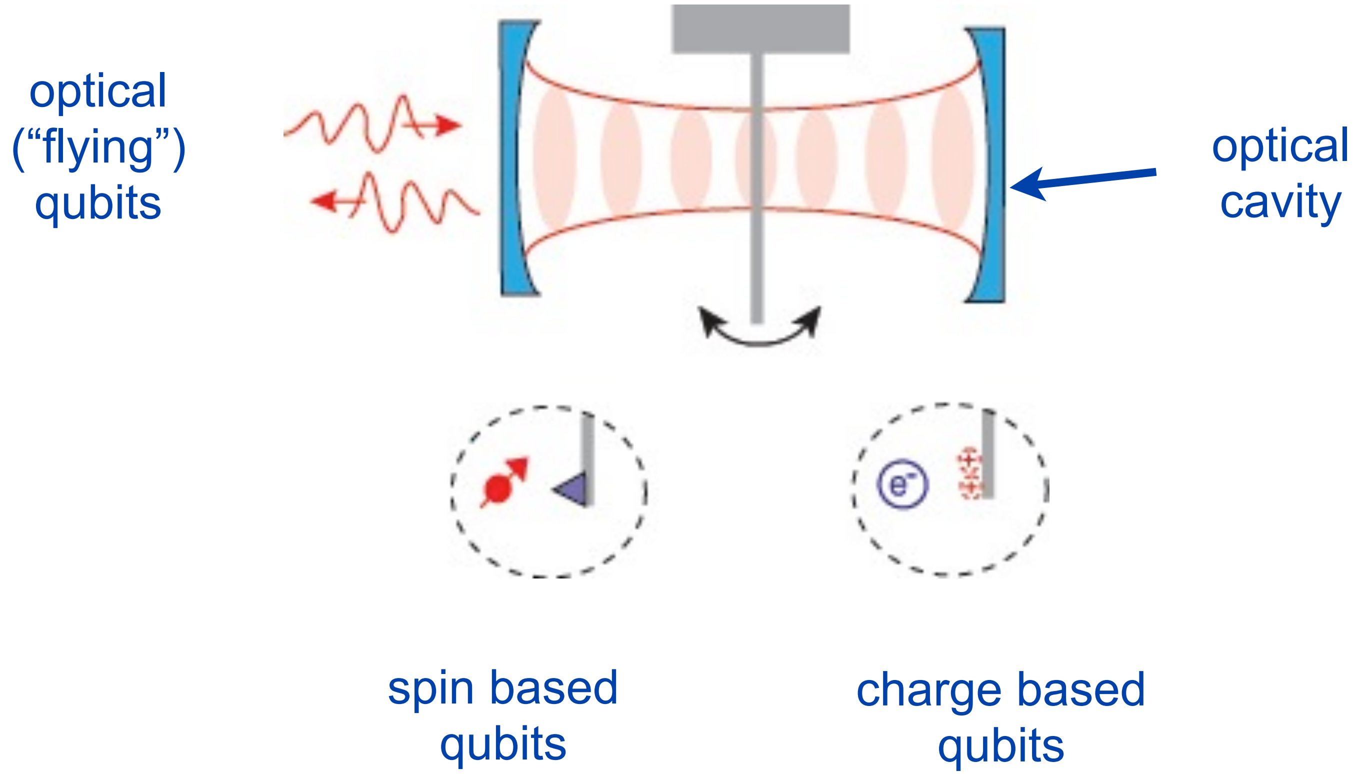




- superconducting qubits
- spin qubits:
  defect centers
  gate defined QD ...
- ...

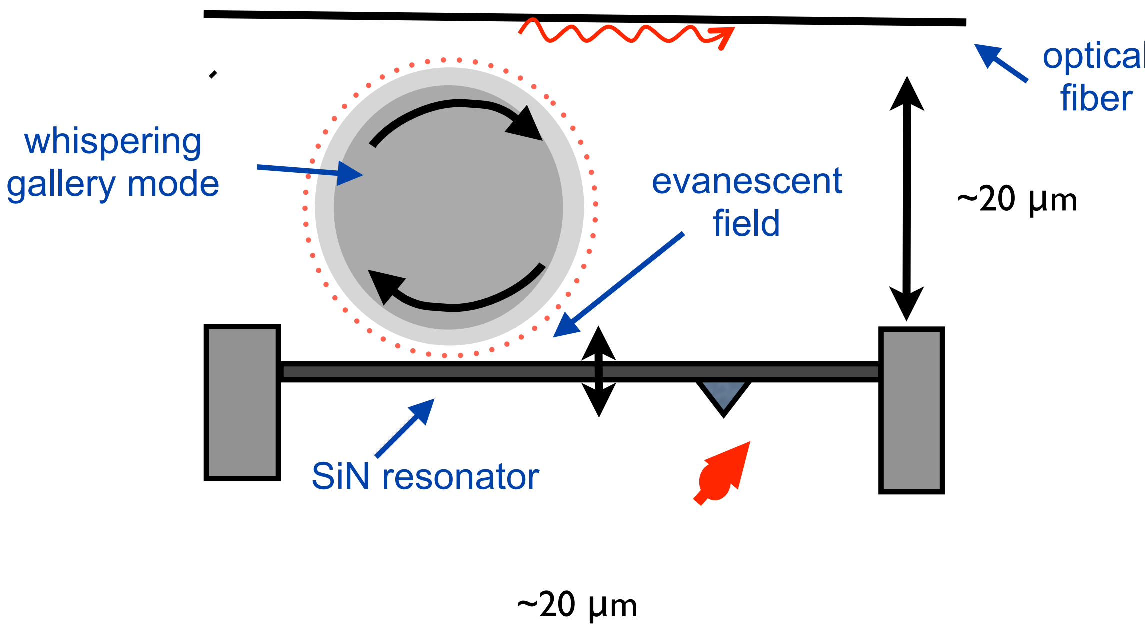
coherent
optical transitions !

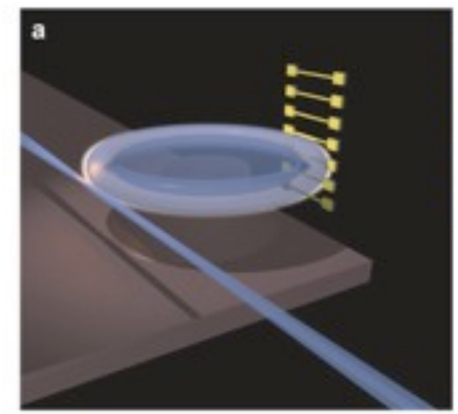
Idea: opto-nanomechanical transducer



Indirect cavity QED interactions !

Nano-scale opto-mechanics

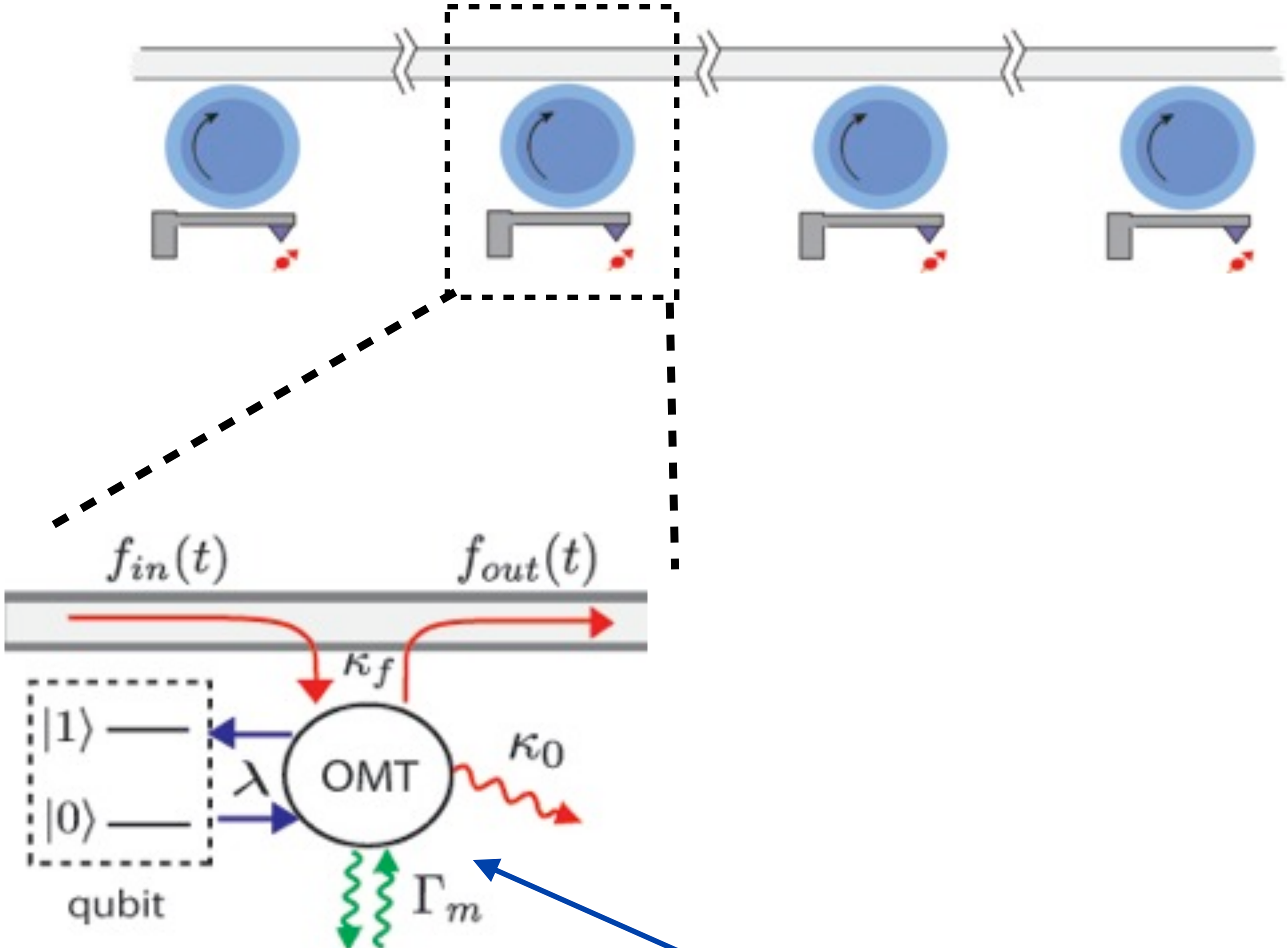




- high Q optical cavity
- low mass mechanical beam
- spatially separated qubit and photons

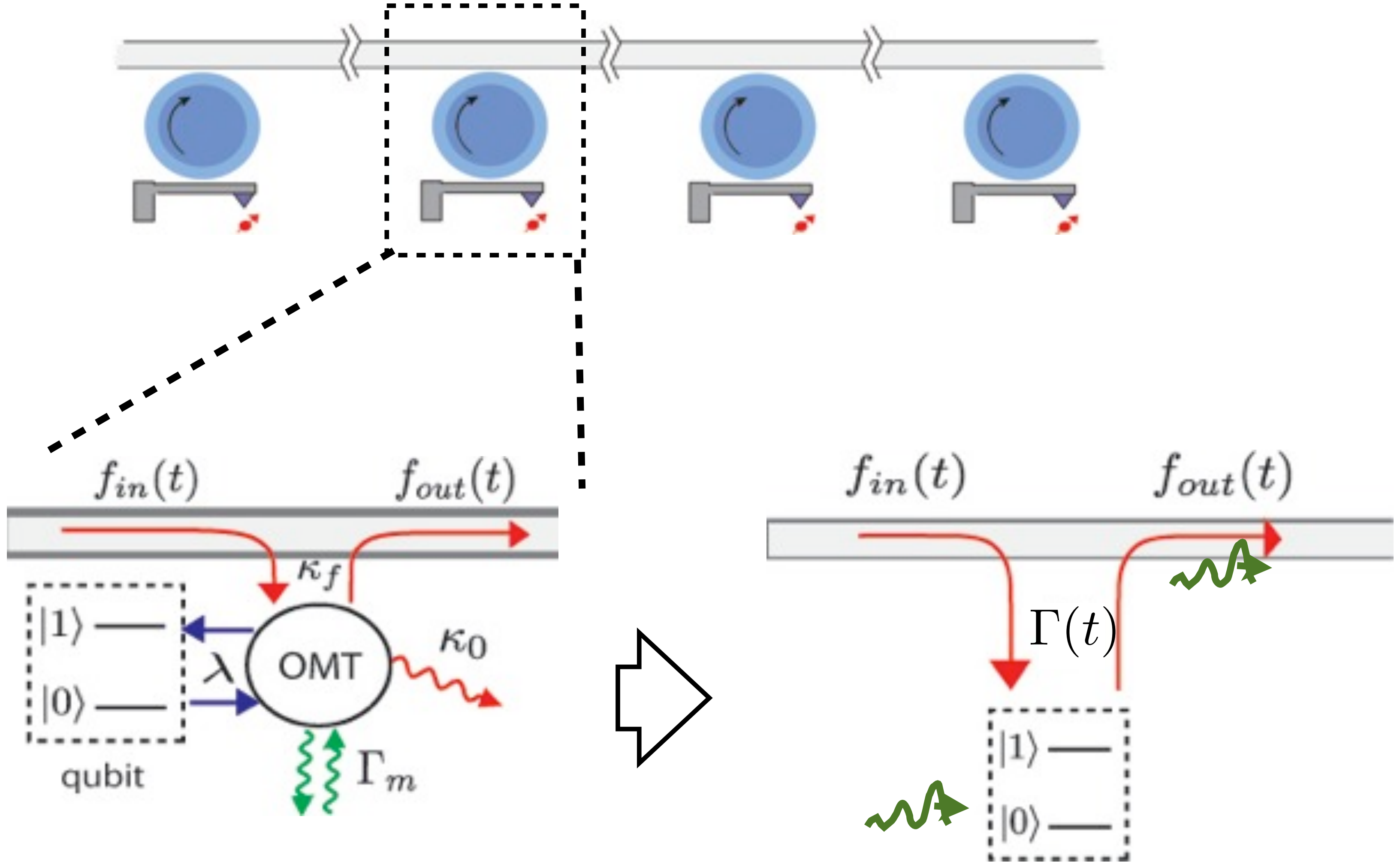
G. Anetsberger et al., Nature Physics **5**, 909 (2009).

Quantum network

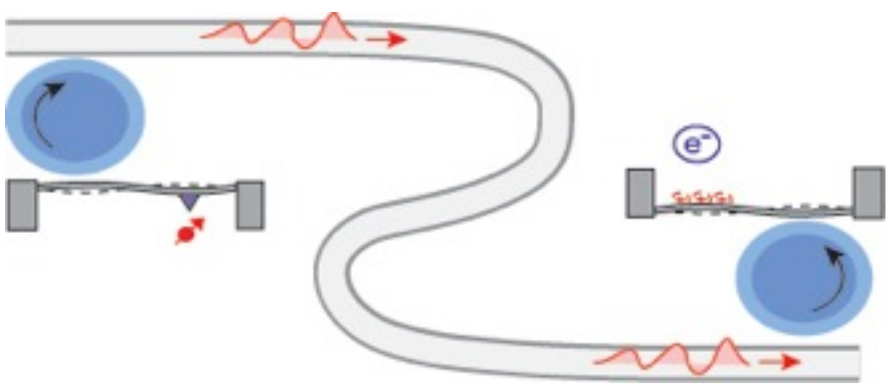


opto-mechanical transducer (OMT)

Quantum network



Model



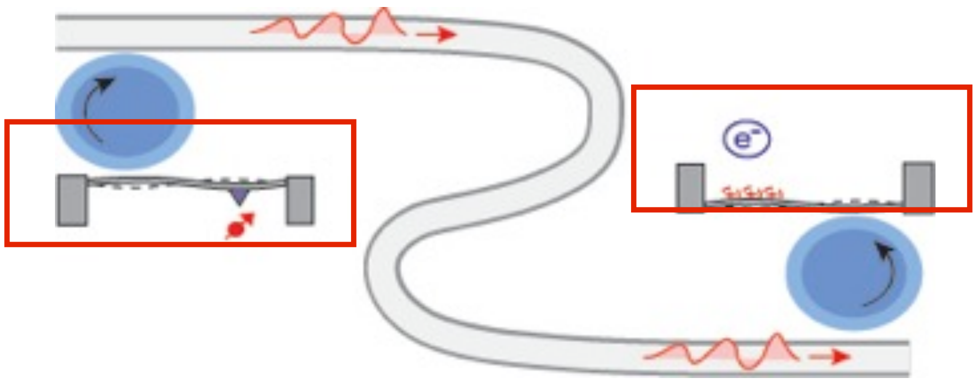
Quantum network N>2:

$$H = \sum_{i=1}^{N} H^{i}_{\text{node}} + H_{\text{fib}}$$

$$H_{\text{node}} = \frac{\omega_q}{2}\sigma_z + \omega_r b^\dagger b + \frac{\lambda}{2}\left(\sigma_- b^\dagger + \sigma_+ b\right)$$

$$+\omega_c c^\dagger c + g_0 c^\dagger c(b + b^\dagger) - i(c^\dagger \mathcal{E} e^{-i\omega_L t} - h.c)$$

Model



Quantum network N>2:

$$H = \sum_{i=1}^{N} H^i_{\text{node}} + H_{\text{fib}}$$

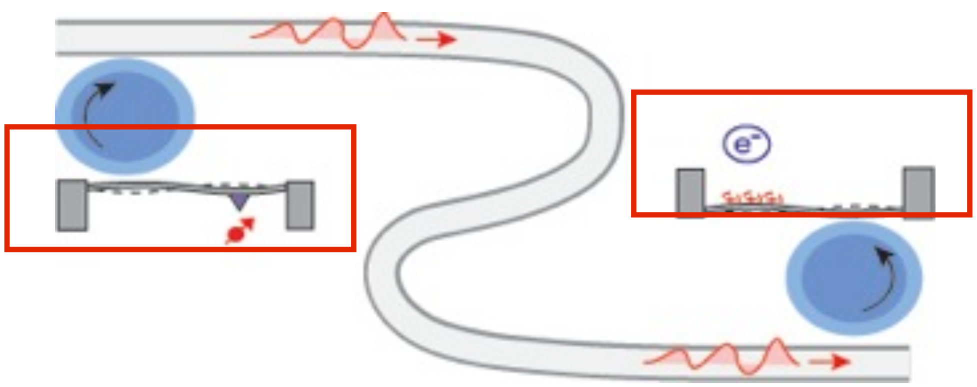
$$H_{\text{node}} = \boxed{\frac{\omega_q}{2}\sigma_z + \omega_r b^\dagger b + \frac{\lambda}{2}\left(\sigma_- b^\dagger + \sigma_+ b\right)}$$

$$+\omega_c c^\dagger c + g_0 c^\dagger c(b + b^\dagger) - i(c^\dagger \mathcal{E} e^{-i\omega_L t} - h.c)$$

qubit-resonator interaction [1,2]

[1] charge qubits: exp: Schwab, Cleland, Roukes, ...
theory: A. Shnirman, L. Tian, G. Milburn, F. Nori, A. Clerk, A. Armour, M. Blencowe, ...
[2] spin qubits: P. Treutlein et al. PRL 2006, PR. et al. PRB 2009

Model



Quantum network N>2:

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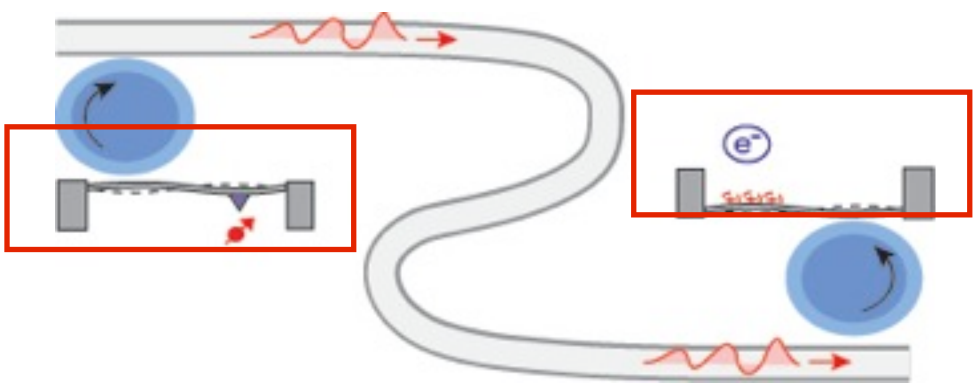
$$+\omega_c c^\dagger c + g_0 c^\dagger c(b + b^\dagger) - i(c^\dagger \mathcal{E} e^{-i\omega_L t} - h.c)$$

single photon OM - coupling

coherent driving field

Reviews: T. J. Kippenberg, K. J. Vahala, Science **321**, 1172 (2008);
F. Marquardt, S. M. Girvin, Physics **2**, 40 (2009).

Model



Quantum network N>2:

$$H = \sum_{i=1}^{N} H^{i}_{\rm node} + H_{\rm fib}$$

$$H_{\rm node} = \frac{\omega_q}{2}\sigma_z + \omega_r b^\dagger b + \frac{\lambda}{2}\left(\sigma_- b^\dagger + \sigma_+ b\right)$$

$$+\Delta_c c^\dagger c + (G c^\dagger + G^* c)(b + b^\dagger)$$

laser detuning

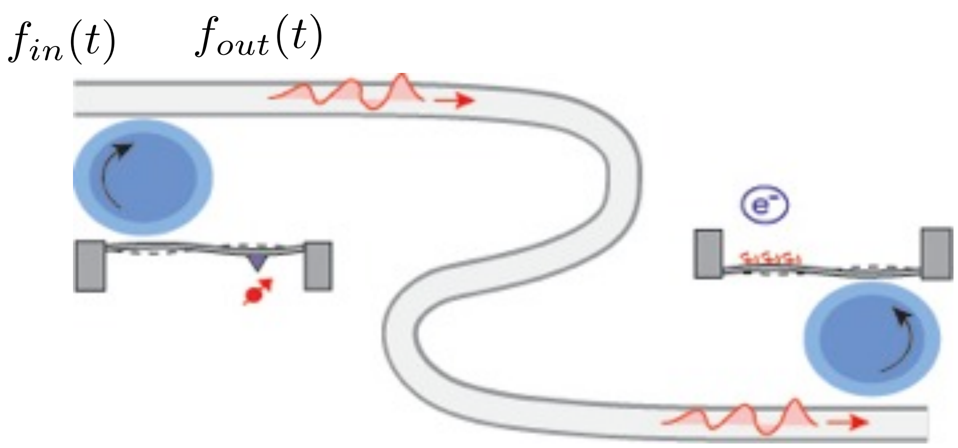
enhanced OM coupling

$$c \rightarrow \alpha + c$$

$$G = \alpha g_0$$

Reviews: T. J. Kippenberg, K. J. Vahala, Science **321**, 1172 (2008);
F. Marquardt, S. M. Girvin, Physics **2**, 40 (2009).

Model



Quantum network N>2:

$$H = \sum_{i=1}^{N} H^i_{\text{node}} + H_{\text{fib}}$$

Quantum Langevin equations:

$$\dot{c}_i(t) = i[H^i_{\text{node}}, c_i(t)] - (\kappa_f + \kappa_0)c_i(t) - \sqrt{2\kappa_f} f_{in,i}(t)$$

$$f_{out,i}(t) = f_{in,i}(t) + \sqrt{2\kappa_f} c_i(t)$$

intrinsic cavity loss

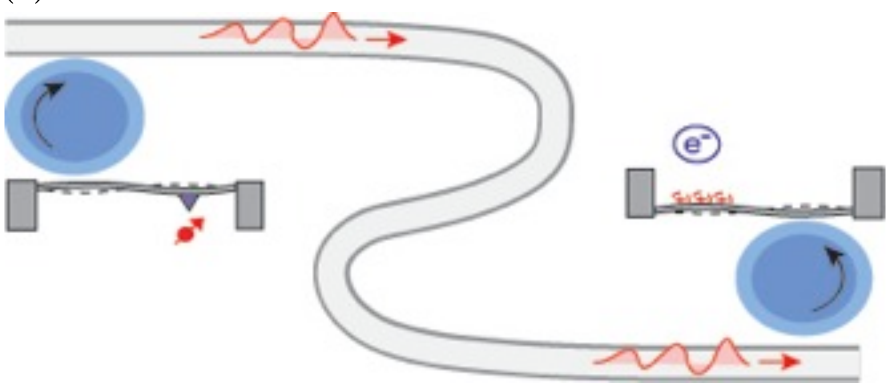
"cascaded" quantum network [1]:

$$f_{in,i}(t) = f_{out,i-1}(t - (z_i - z_{i-1})/c)$$

[1] C. W. Gardiner, PRL (1993); H. J. Carmichael, PRL (1993).

Model

$f_{in}(t)$ $f_{out}(t)$



Quantum network N>2:

$$H = \sum_{i=1}^{N} H^i_{\text{node}} + H_{\text{fib}}$$

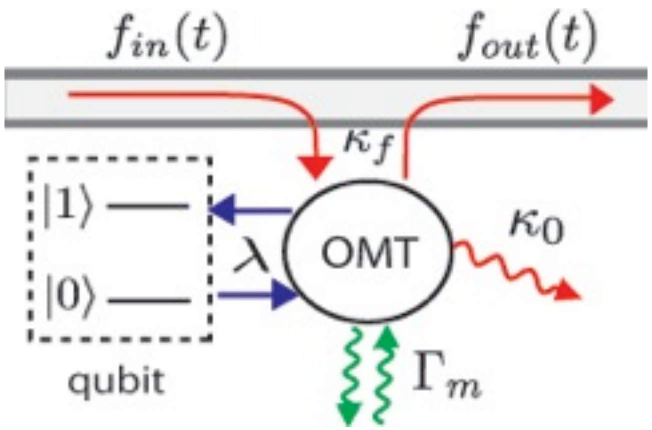
thermal noise:

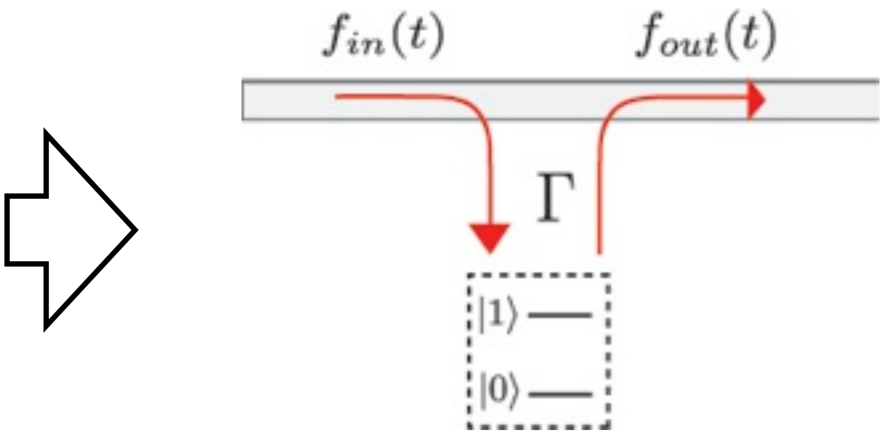
$$\dot{b}_i(t) = i[H^i_{\text{node}}, b_i(t)] - \sqrt{\Gamma_m}\xi_i(t)$$

thermal diffusion rate

$$\Gamma_m = \frac{k_B T}{\hbar Q_m}$$

Adiabatic elimination

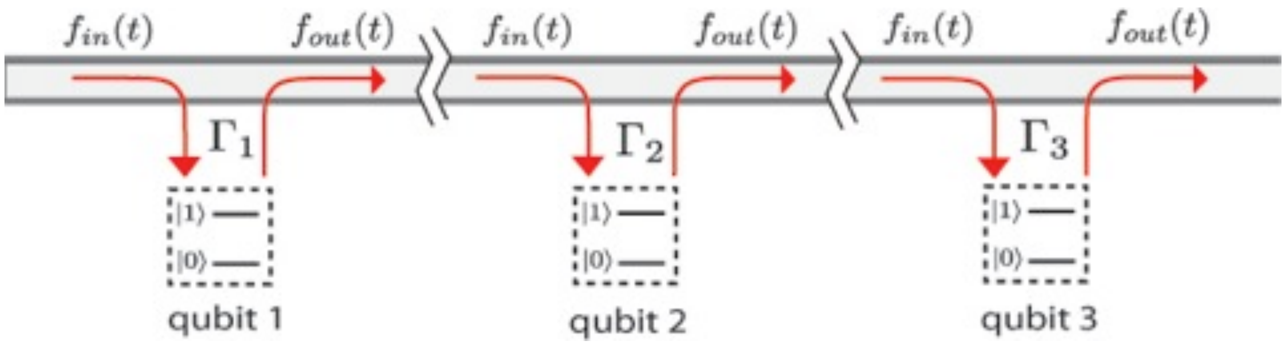




$$\lambda \ll \gamma_{op} \approx G^2/\kappa$$

opto-mechanical damping rate

Qubit network



effective QLEs:

$$\dot{\sigma}^i_-(t) = -\left(i\tilde{\omega}^i_q + \frac{\Gamma_i}{2}\right)\sigma^i_-(t) - \sum_{j<i} J_{ij}\sigma^j_-(t) + \sqrt{\Gamma_i}\sigma^i_z(t)F_{in,i}(t)$$

qubit decay rate

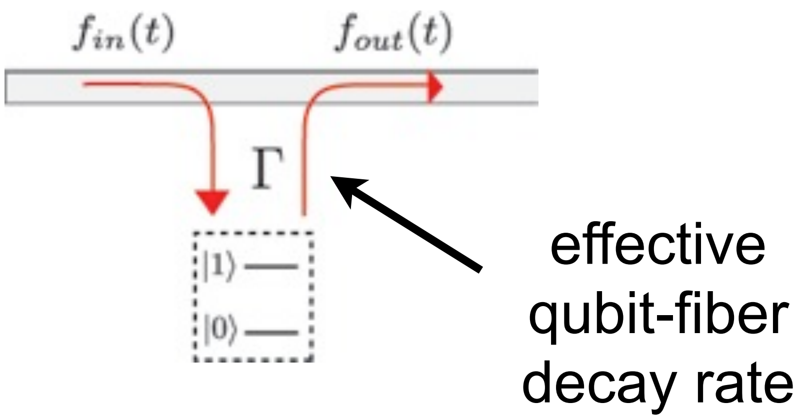
uni-directional qubit-qubit coupling

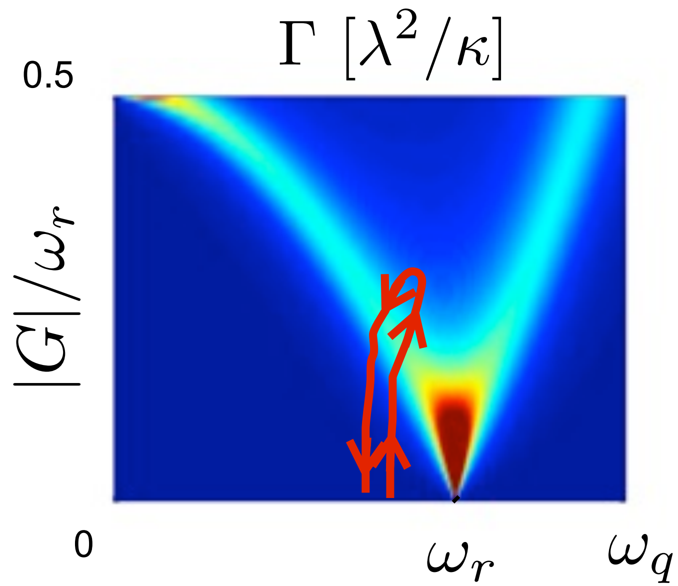
added noise

in-/out-fields:

$$f_{out,i}(t) = f_{in,i}(t) + \sqrt{\Gamma_i}e^{i\theta_i}\sigma^i_-(t) + \sqrt{2\kappa_f}c_{0,i}(t)$$

Decay rate



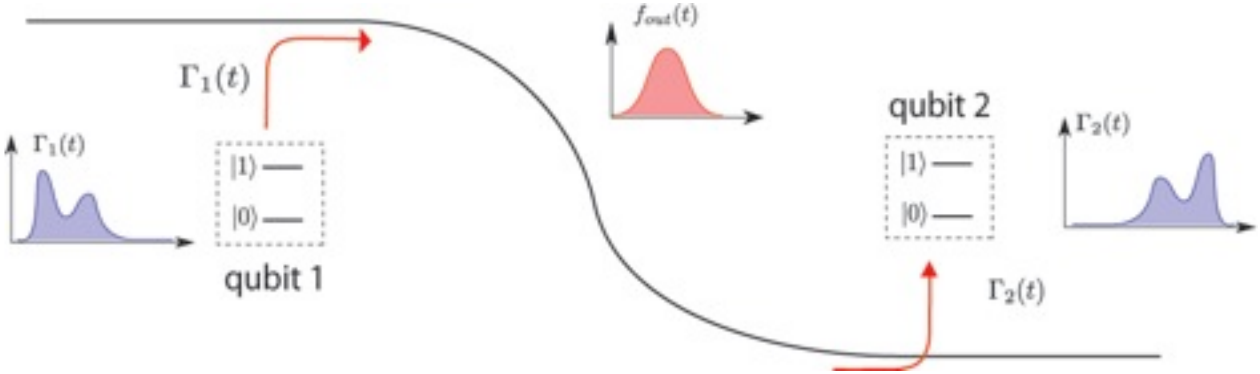


$$\Gamma(t) \equiv \Gamma(\omega_q(t), G(t), \Delta_c(t))$$

time-dependent control !

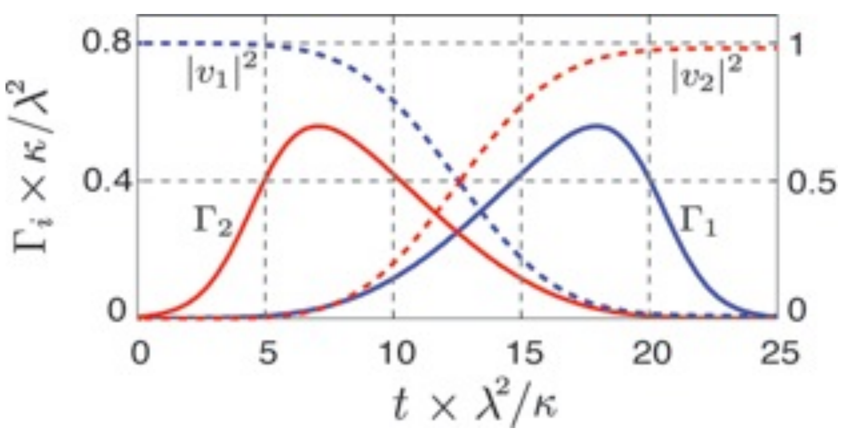
Quantum state transfer

Step 1:



Example:
(time symmetric pulse [1])

$$\Gamma_1\left(\tilde{t}=t-\frac{t_f}{2}\right)=\frac{\Gamma_0\exp(-c\tilde{t}^2)}{(1-\sqrt{\pi}\Gamma_0/2c\,\mathrm{Erf}(c\tilde{t}))}$$

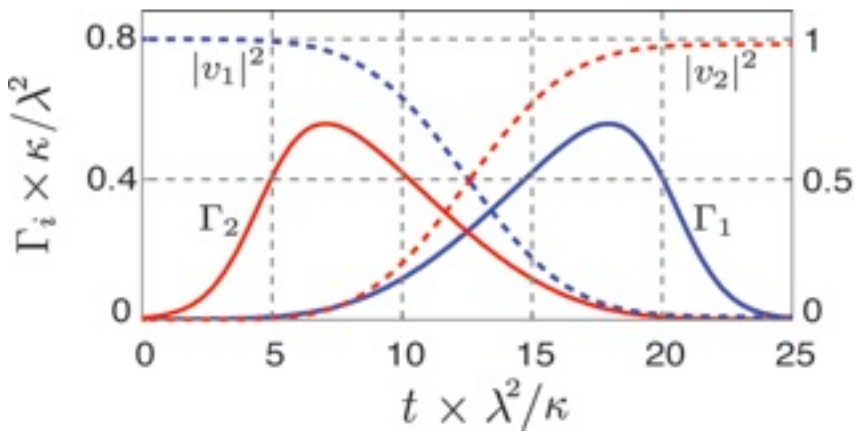


[1] J. I. Cirac, P. Zoller, H. J. Kimble, and H. Mabuchi, PRL. **78**, 3221 (1997)

Quantum state transfer

Step 1:

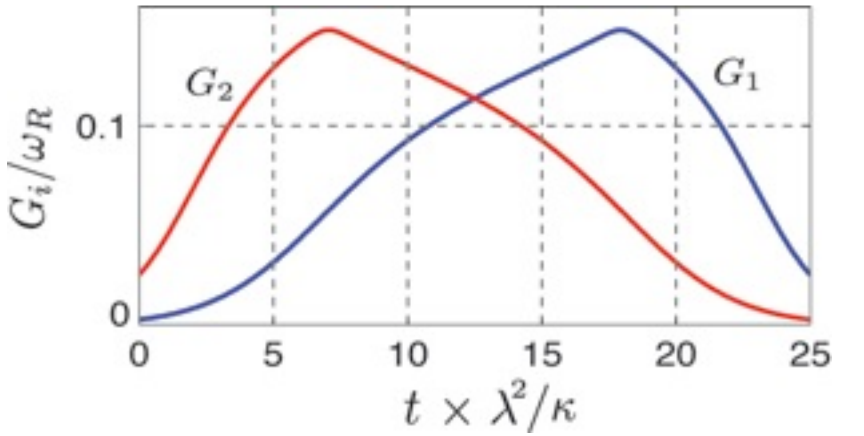
$$\Gamma_1\left(\tilde{t}=t-\frac{t_f}{2}\right)=\frac{\Gamma_0\exp(-c\tilde{t}^2)}{\left(1-\sqrt{\pi}\Gamma_0/2c\,\mathrm{Erf}(c\tilde{t})\right)}$$



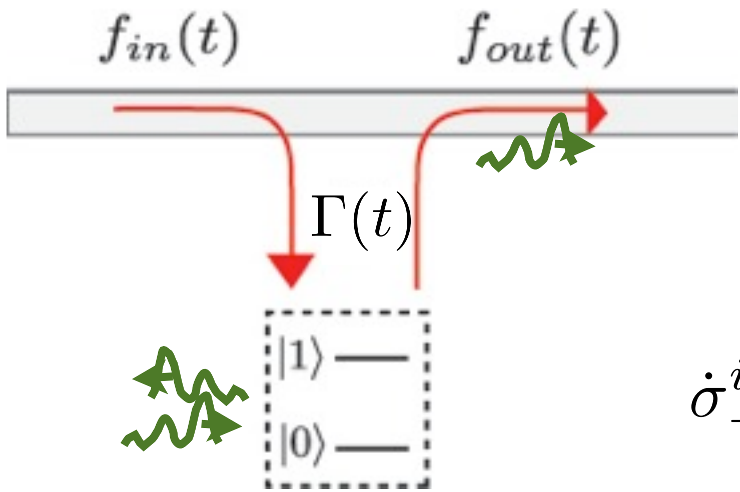
Step 2:

$$\Gamma_i(t)\equiv\Gamma(\omega_{q,i}(t),G_i(t),\Delta_{c,i}(t))$$

control parameters



Noise



"delta-correlated" noise operator

$$\dot{\sigma}_-^i(t) = \cdots + \sqrt{\Gamma_i}\sigma_z^i(t)F_{in,i}(t)$$

effective thermal occupation number:

$$N_i = 2\mathrm{Re}\int_0^\infty d\tau \langle F_{in,i}^\dagger(\tau)F_{in,i}(0)\rangle e^{-i\omega_q\tau}$$

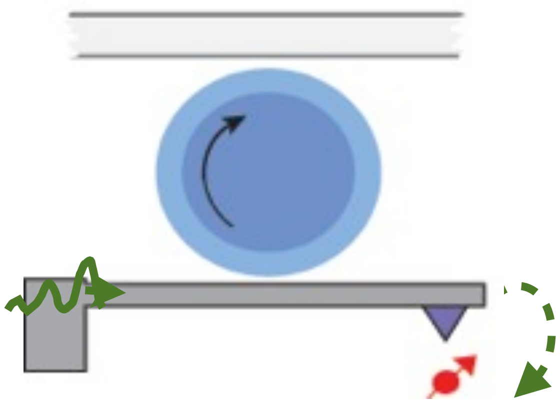
Noise

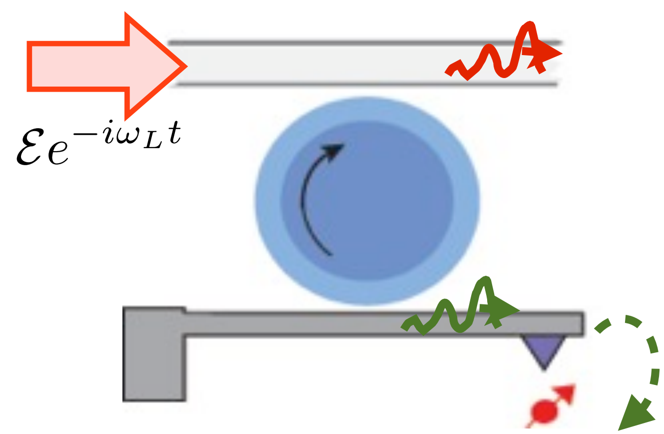
- **single node**

$$N(\omega_q) \approx \frac{\Gamma_m}{2\kappa}\,\frac{\kappa^2 + (\Delta_c - \omega_q)^2}{|G|^2} + \frac{\kappa^2 + (\Delta_c - \omega_q)^2}{4\Delta_c \omega_q}$$

thermal noise

Stokes heating





$$H_{op} = \ldots G c^\dagger b^\dagger$$

Noise

- **single node**

$$N(\omega_q) \approx \frac{\Gamma_m}{2\kappa} \frac{\kappa^2 + (\Delta_c - \omega_q)^2}{|G|^2} + \frac{\kappa^2 + (\Delta_c - \omega_q)^2}{4\Delta_c \omega_q}$$

- **on resonance**

$$N(\omega_q = \omega_{\pm}) \approx \langle b^\dagger b \rangle_0$$

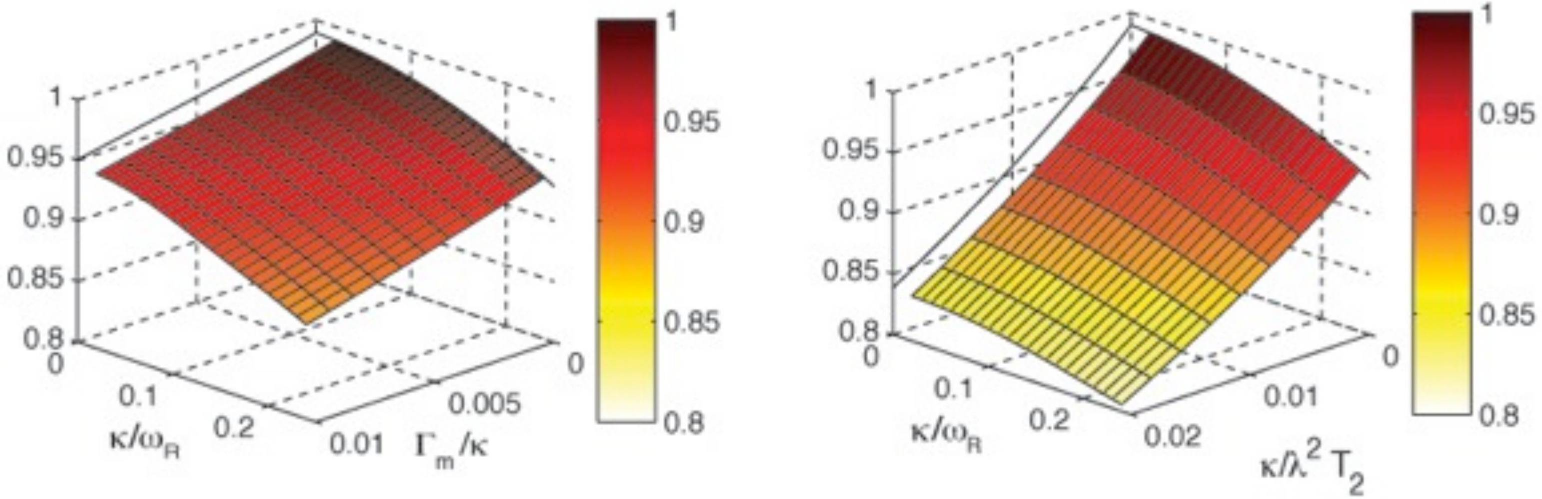
high transfer fidelities

$\Leftrightarrow$

ground state cooling conditions

☺

State transfer fidelities



$$\mathcal{F} \approx 1 - \frac{\kappa_0}{\kappa} - \mathcal{C}_1 \frac{\Gamma_m}{\kappa} - \mathcal{C}_2 \frac{\kappa^2}{\omega_r^2} - \mathcal{C}_3 \frac{\kappa}{\lambda^2 T_2} \qquad \mathcal{C}_i = \mathcal{O}(1)$$

intrinsic cavity loss

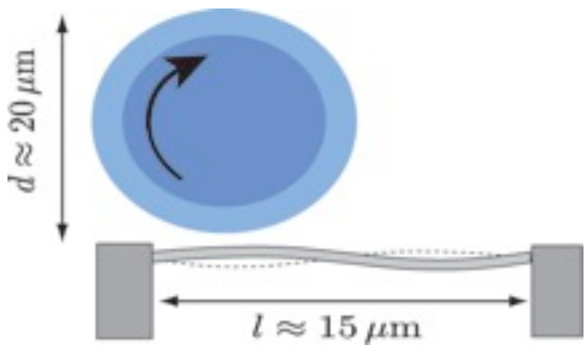
thermal noise

Stokes heating

qubit dephasing

control pulse shape

Example



SiN resonator: $(l, w, t) \approx (15, 0.05, 0.05)\,\mu\mathrm{m}$

$\omega_r/2\pi \approx 5 - 50\,\mathrm{MHz}$

$a_0 \approx (1.6 - 0.16) \times 10^{-13}\,\mathrm{m}$

$Q_m \sim 10^5 \qquad T = 100\,\mathrm{mK}$

cavity [1]: $Q_c > 10^9$

$\kappa_0/2\pi < 50\,\mathrm{kHz}$

$$\Gamma_m, \kappa_0 \ll \kappa \ll \omega_r$$

---

spin qubit [2]:

$\lambda/2\pi \approx 45\,\mathrm{kHz}$

$T_2 \approx 10\,\mathrm{ms}$

charge qubit [3]:

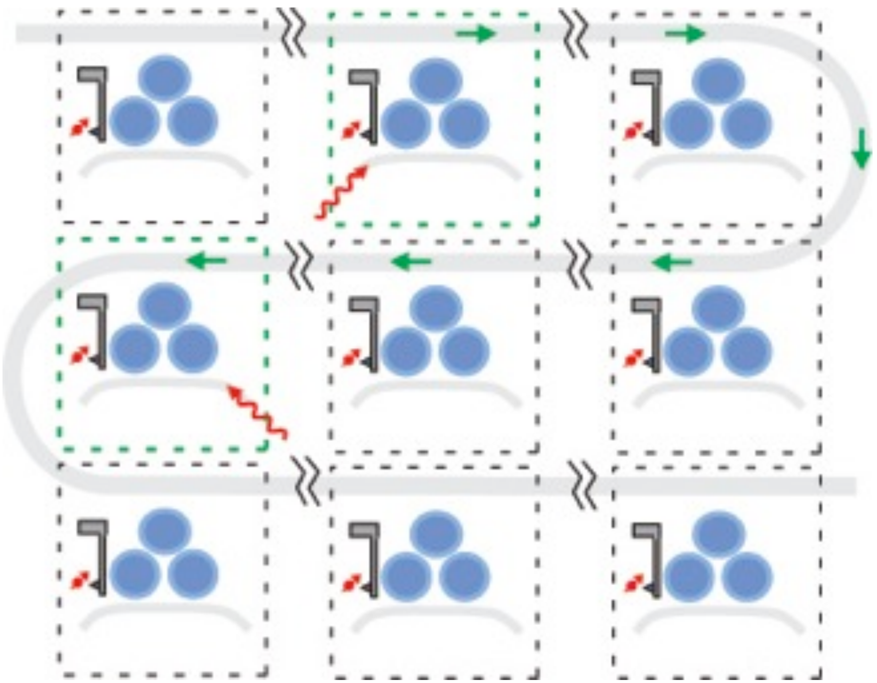
$\lambda/2\pi \geq 5\,\mathrm{MHz}$

$T_2 \approx 1\,\mu\mathrm{s}$

$$\mathcal{F} \approx 0.9 - 0.99$$

[1] S. Spillane, et al. PRA (2005); [2] PR et al., PRB (2009); [3] A. Armour et al., PRL (2002).

Scalable quantum networks



- suppression of laser noise
- selective activation of individual nodes
- directed photon emission
- ...

Examples & Overview:
Hybrid AMO - Nanomechanical Systems

- **AMO concepts → solid state**

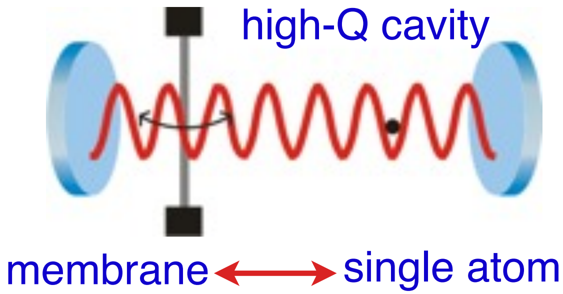
  ✓ Nanomechanics with Levitated Objects

  ✓ Electro- and Optomechanical Transducers for Quantum Computing and Quantum Communications

➡ • **AMO - solid state quantum interfaces**

Quantum Inferfaces: Opto-Nanomechanics + Atom(s)

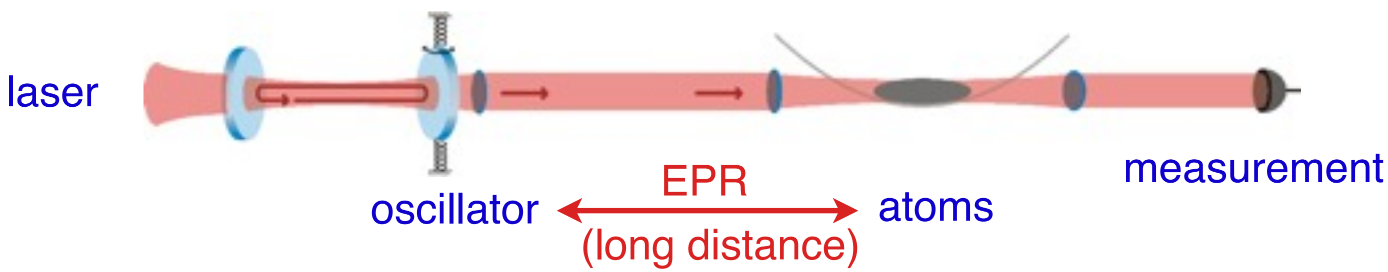
- **Strong coupling between a *single* atom and a membrane**



with existing experimental setups & parameters :-)

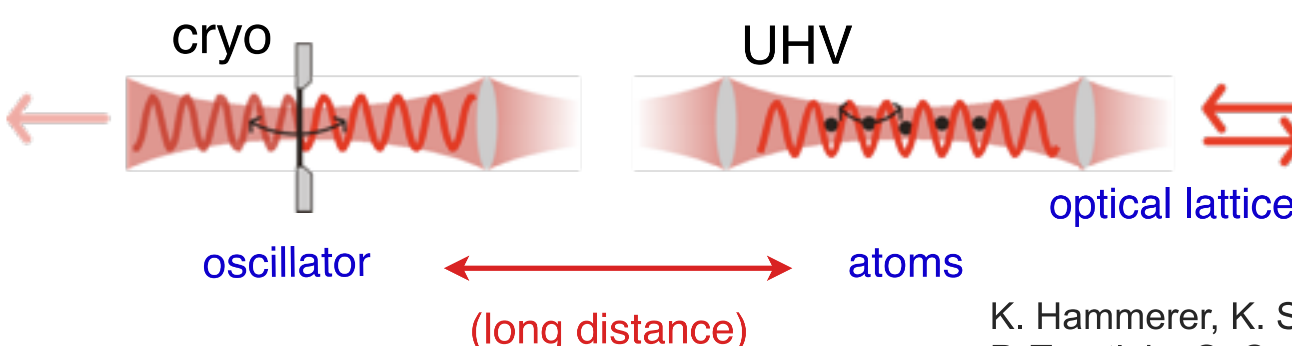
KH, M. Wallquist, C. Genes, PZ, M. Ludwig, F. Marquardt, P. Treutlein, J. Ye, H. J. Kimble, PRL 2009 & PRA 2010

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



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

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



K. Hammerer, K. Stannigel, C. Genes, M. Wallquist, PZ
P. Treutlein, S. Camerer, D. Hunger, T. W. Hänsch
arXiv 2010