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Advanced Workshop on Nanomechanics

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Noise-Resilient Quantum Information Protocols in An Optomechanical Quantum Interface

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ICTP, Sept. 2013

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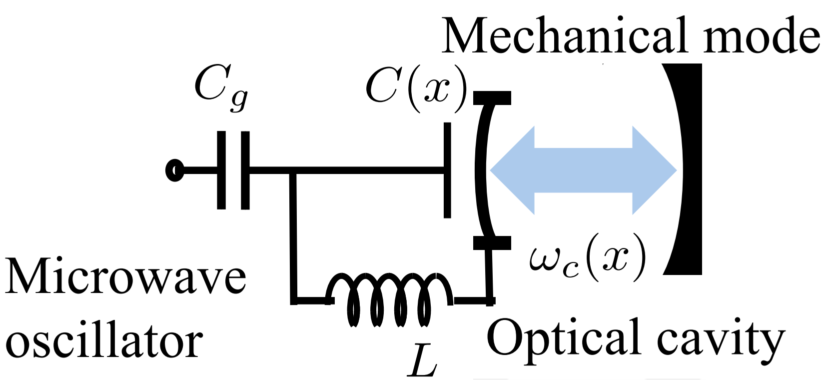
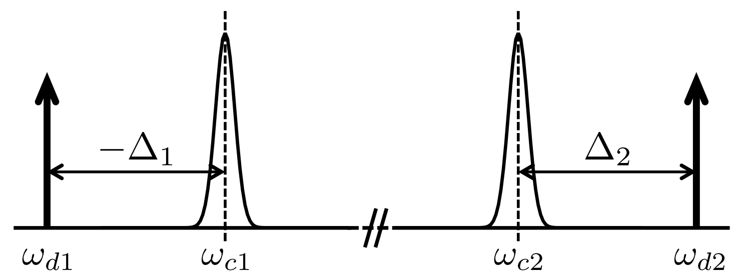




Supported by NSF, UC Merced, DARPA, COINS

Outline

1. What are mechanical systems useful for?
-- connect hybrid systems/different channels/noise

2. Optomechanical quantum interface
-- quantum operations/protocols
-- Overcome mechanical noise via dark modes

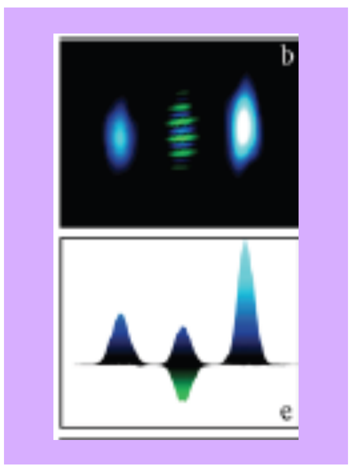
3. Another mechanical mode coupling with superconducting resonator

4. Emulating phonons …

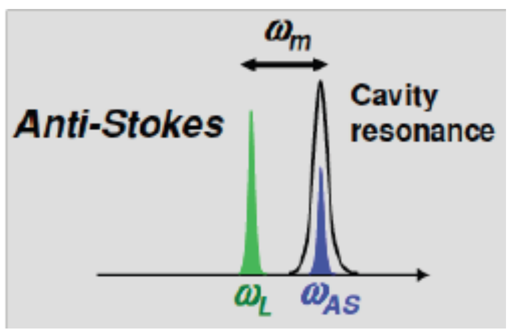
What Are Mechanical Systems Useful For?

theory & exp advancements in mechancial system

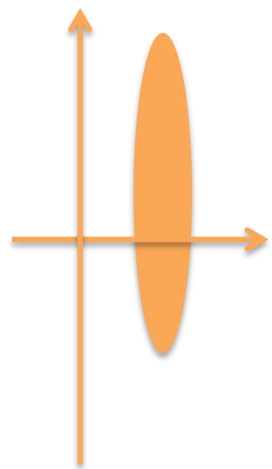
quantum state engineering



ground state cooling



squeezing



Material/ sample engineering

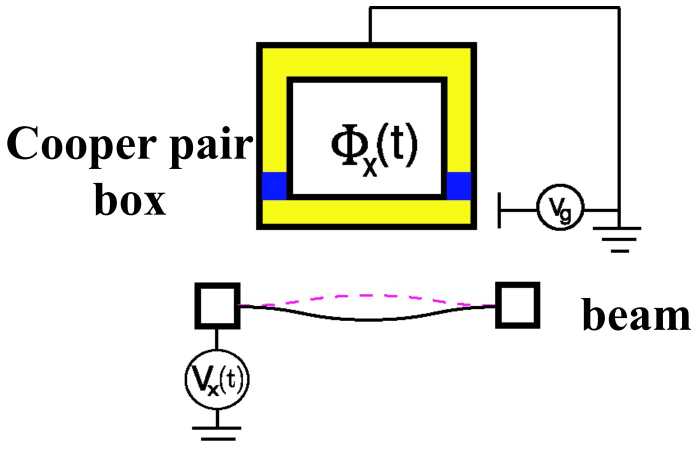
Q-factor 10,000,000…

Freq. range

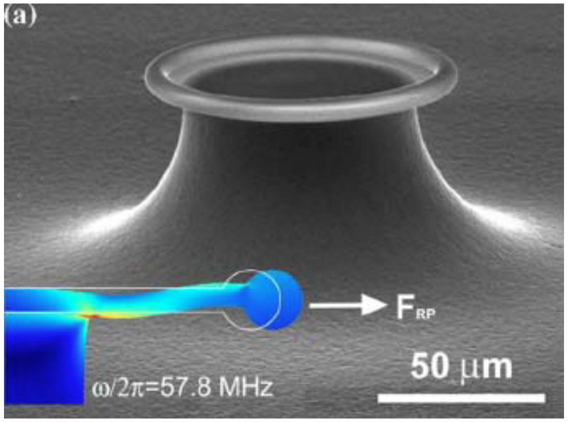
Coupling
Strong
Ultra-strong…

Any applications besides studying quantum features of macroscopic systems?

Mechanical systems can couple with numerous other systems



Qubit-resonator coupling
Armour, Blencowe, Schwab, PRL (2002)



Cavity-mechanical mode
Different frequency range
Kippenberg, Vahala, Science (2008)

- Coupling with qubits, cavity modes, spins in solids etc…
- Coupling with systems in different frequency range – microwave – optical…
- Coupling with systems in different setup – atomic systems, solid-state, …
- Weak coupling, strong coupling, ultra-strong coupling (?) …

What Are Mechanical Systems Useful For?

The mechanical systems can be exploited as an interface to connect Systems with very different frequency or property

- Connecting qubits as a quantum bus
- Connecting qubit with cavity
- Connecting optical cavities at different frequency
- Connecting optical cavity and microwave cavity
- Connecting solid-state device and atomic systems …

Cavity optomechanics – Aspelmeyer, Kippenberg, Marquardt, arxiv:1303.0733

- Strong coupling between light and mechanical modes demonstrated

(in both microwave and optical systems, $g/\kappa > 1$)

- Mechanical modes approach quantum ground state

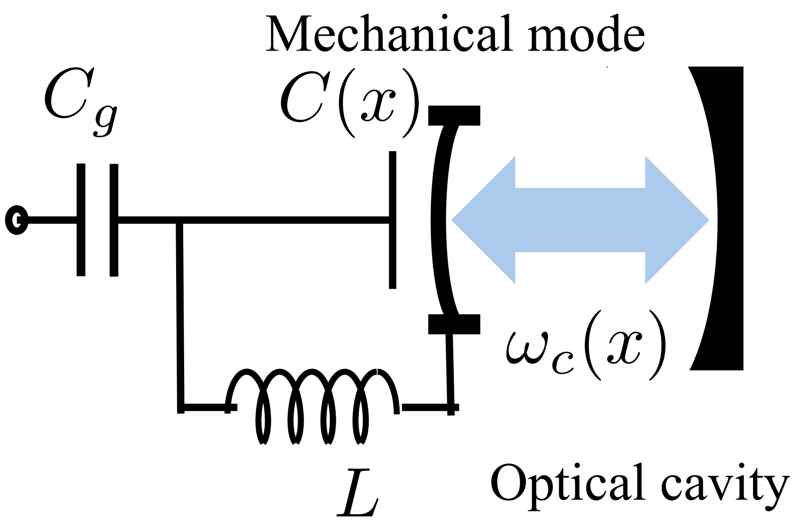
O'Connell et al, Nature (2010), Teufel et al, Nature (2011), Riviere et al, PRA (2011), Chan et al, Nature (2011), Brahms et al, PRL (2012)

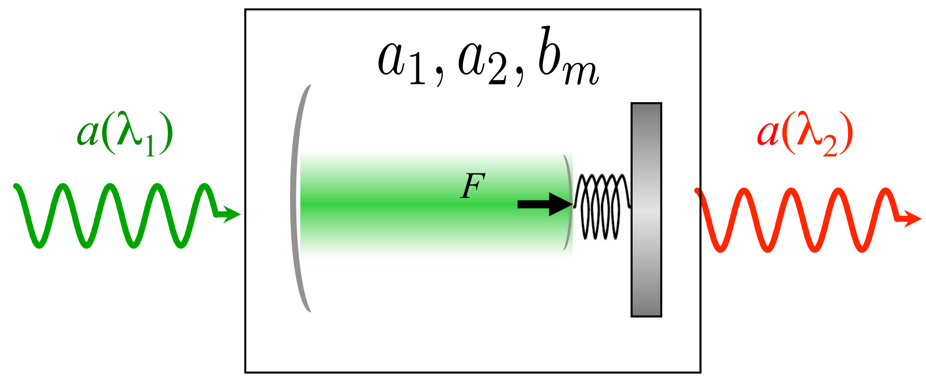
- Optomechanically induced transparency, mechanical dark mode, etc

Weis et al, Science (2010), Teufel et al, Nature (2011), Safavi-Naeini et al Nature (2011), Dong et al Science (2012), Karuza et al, PRA (2013),

Optomechanical Quantum Interface

- Strong/controllable light-matter coupling/large cooperativity
- Mechanical mode connects cavities with different frequencies
  e.g. optical cavity – mechanical mode - microwave cavity





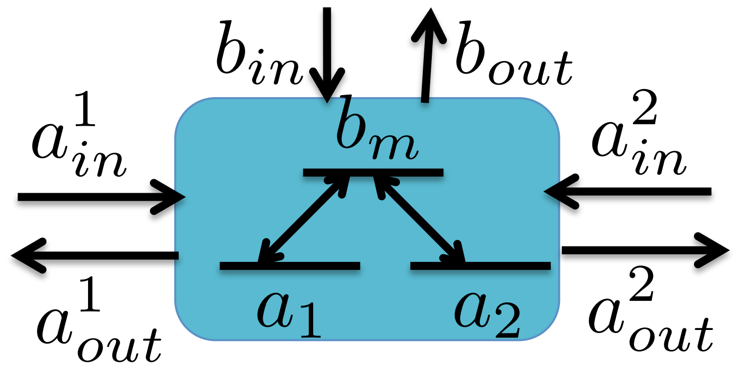
- Connect different parts of a hybrid quantum network/transducer

K. Stannigel, P. Rabl, A. S. Sørensen, P. Zoller, and M. D. Lukin, PRL (2010)

- Achieve quantum operations through mechanical mode

Optomechanical Quantum Interface

Two cavity modes (information carrier) and a mechanical mode (interface)
Cavity modes can have distinct frequency – microwave, optical … (hybrid)
Input, output channels for all three modes – mechanical thermal noise

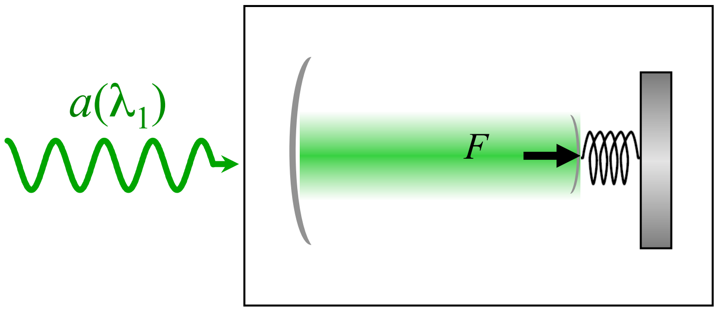


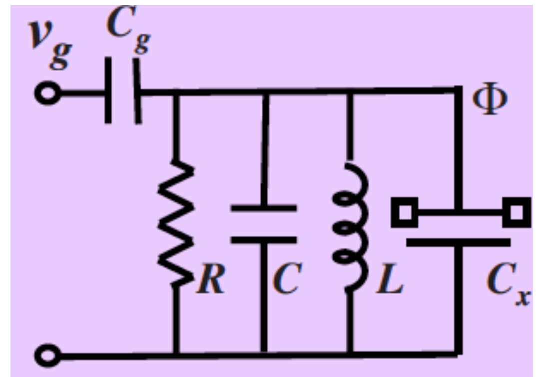
Goal: manipulate quantum states in the cavity channels/modes using their coupling with the mechanical mode

- Transfer of quantum states – quantum wavelength conversion
- Generate entanglement between cavity modes of different frequencies

Mechanical Effects of Light

Radiation pressure force on the mirror – cavity backaction





Optical cavity + movable mirror
Photon scattered by mirror
Forces on mirror ~ photon number

Superconducting resonator - NEMS
Mechanical motion changes capacitance
Forces on NEMS ~ photon number

$$H_{int} = G_0 a^\dagger a \hat{x} = F \cdot \hat{x} = \hbar \Delta\omega \cdot a^\dagger a$$

e.g. C.K. Law, PRA (1995), Interaction between a moving mirror and radiation pressure: A Hamiltonian formulation

Mechanical Effects of Light

Radiation pressure force and effective linear coupling

Cavity-mechanical mode coupling: mechanical shift of cavity resonance

$$H_G = -G_i a_i^\dagger a_i q$$

Pumping on cavity mode – steady state amplitude, Δ_i: laser detuning

$$a_{is} = \frac{-iE_i}{\kappa_i/2 - i(\Delta_i + G_i q_s)}$$

Red sideband driving – effective linear coupling

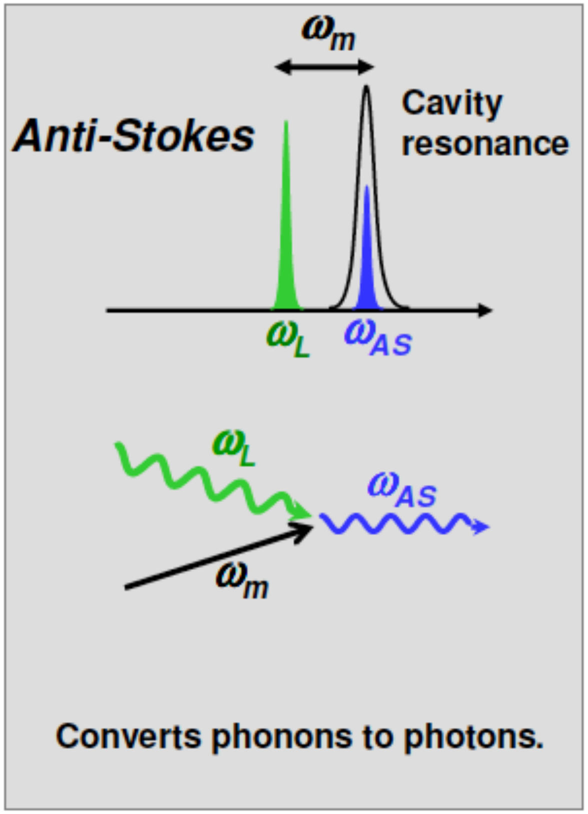
$$\boxed{H_{eff} = \epsilon_i a_i^\dagger b_m + \epsilon_i^\star b_m^\dagger a_i}$$

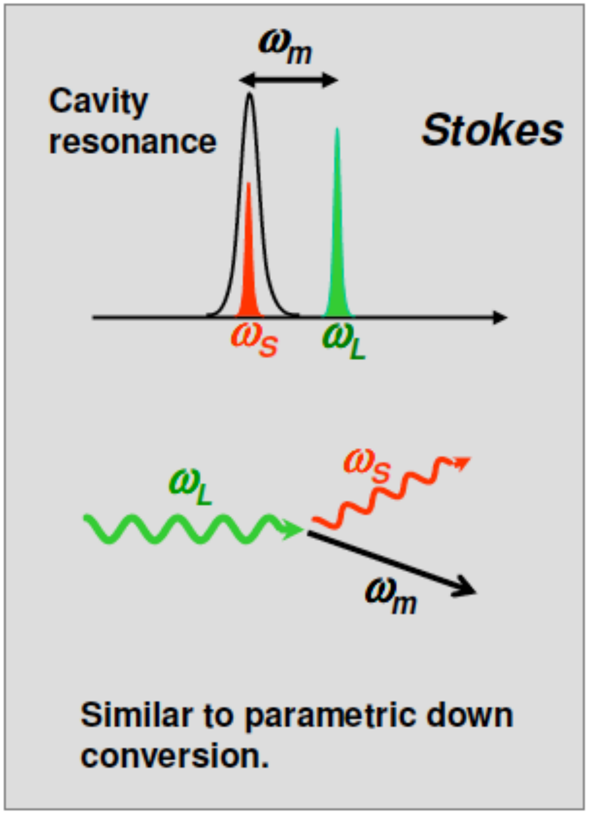
Blue sideband driving – effective linear coupling (instability etc…)

$$\boxed{H_{eff} = i\epsilon_i \left(a_i^\dagger b_m^\dagger - b_m a_i\right)}$$

Mechanical Effects of Light

Radiation pressure force and effective linear coupling





Red detuned driving

Blue detuned driving

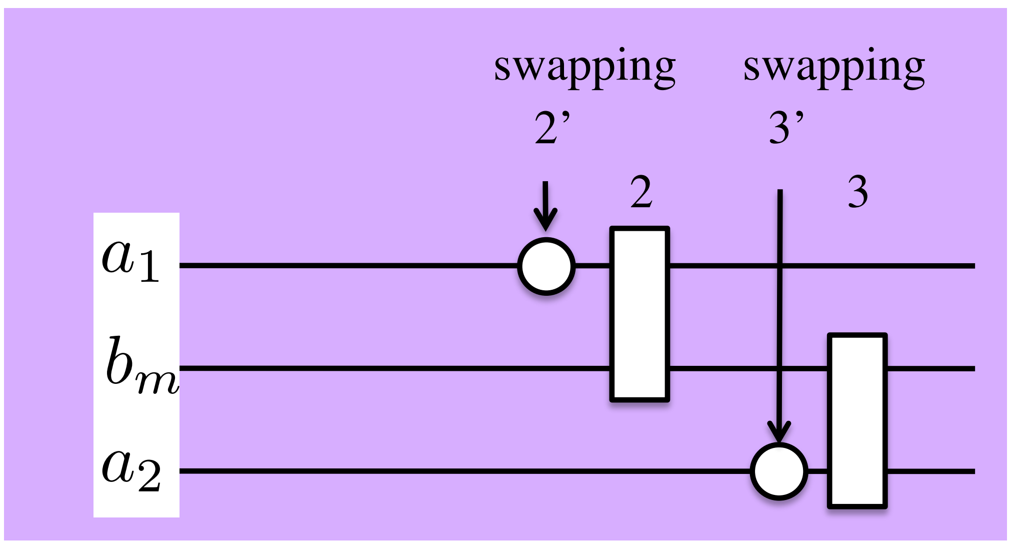
Simple quantum wave length conversion scheme

Red sideband driving – beam-splitter operation

$$\boxed{H_{eff} = \epsilon_i a_i^\dagger b_m + \epsilon_i^\star b_m^\dagger a_i}$$

Generate transformation - transfer of state with two swap pulses $\epsilon_i t = \pi/2$

$$a_i(t) = \cos(\epsilon_i t) a_i(0) + i \sin(\epsilon_i t) b_m(0)$$
$$b_m(t) = \cos(\epsilon_i t) b_m(0) + i \sin(\epsilon_i t) a_i(0)$$



Double-swap scheme:

1. Swap modes a_1 and b_m
   - initial state to b_m

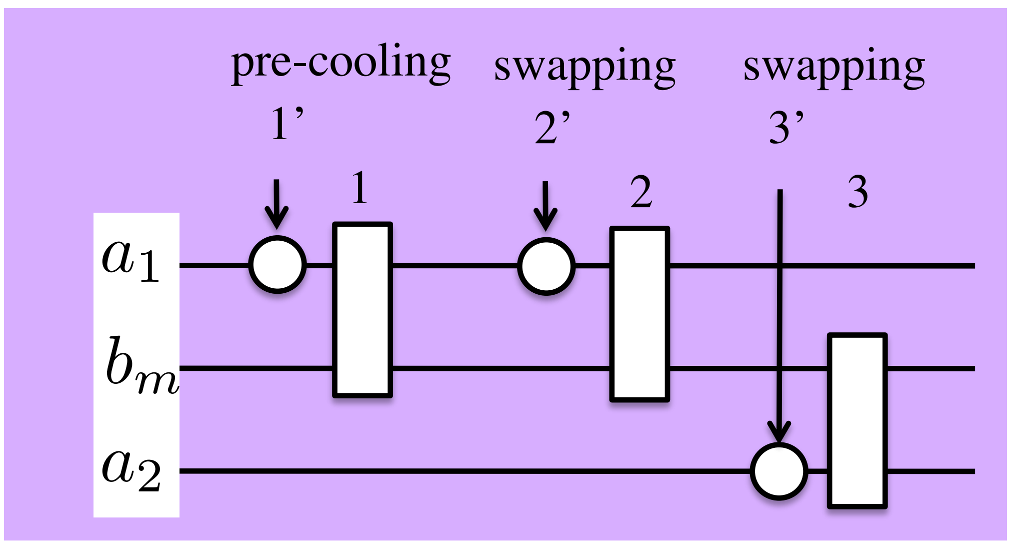
2. Swap modes b_m and a_2
   - initial state to a_2

Simple quantum wave length conversion scheme

- Swapping via mechanical mode, thermal noise degrades conversion fidelity
- Cavity damping degrades conversion fidelity
- Fidelity for gaussian states reduces as: $-\gamma_m T(2n_{th}+1)\cosh(2r)/4$

T = time of operation, n_{th}=thermal number

Pre-cooling pulse '1': swap a_1 (ground state) and b_m (thermal state)
Transient cooling: partially remove thermal noise, improve state transfer



Pre-cooling pulse:

- Effective temperature for mechanical mode
- Improve fidelity of state transfer
- Cooling pulse is affected by noise itself !

Tian, Wang, PRA 82, 053806 (2010)

Simple entanglement generation

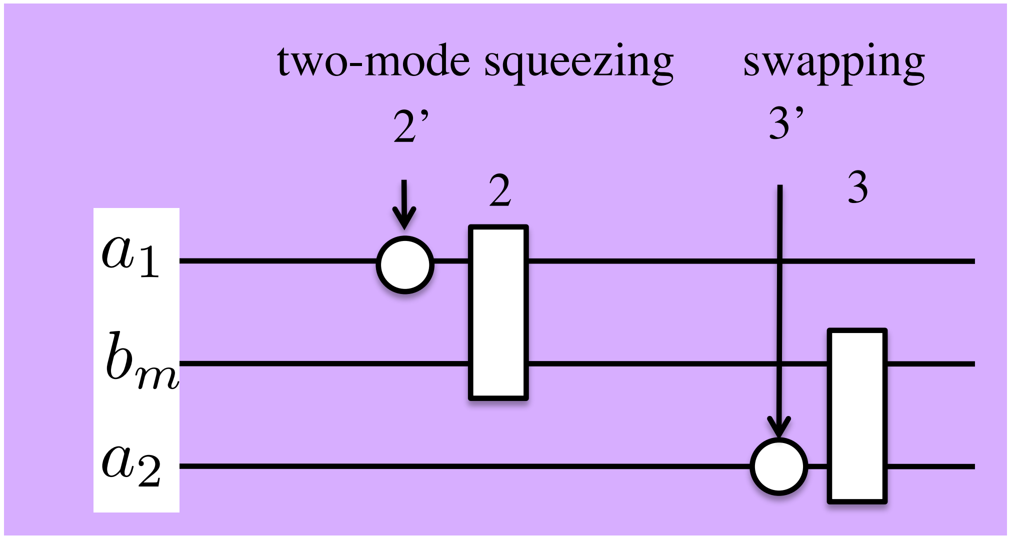
Blue sideband driving – parametric amplification

$$\boxed{H_{eff} = i\epsilon_i \left(a_i^\dagger b_m^\dagger - b_m a_i \right)}$$

Generate two-mode squeezing – between cavity and mechanical mode

$$a_i(t) = \cosh(\epsilon_i t) a_i(0) + i \sinh(\epsilon_i t) b_m^\dagger(0)$$
$$b_m(t) = \cosh(\epsilon_i t) b_m(0) + i \sinh(\epsilon_i t) a_i^\dagger(0)$$

Combine this with swap pulse between other cavity and mechanical mode
Continuous variable entanglement between cavities

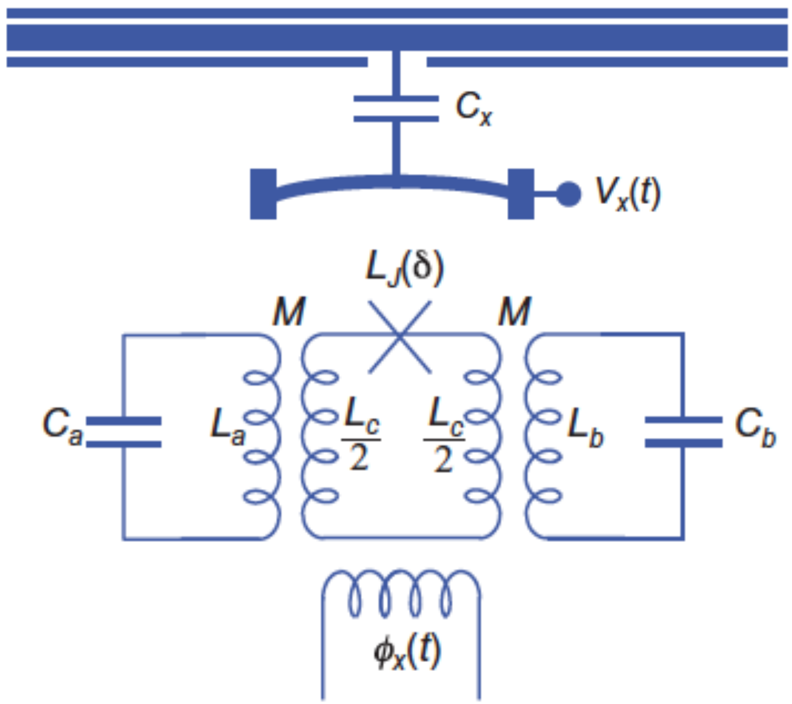


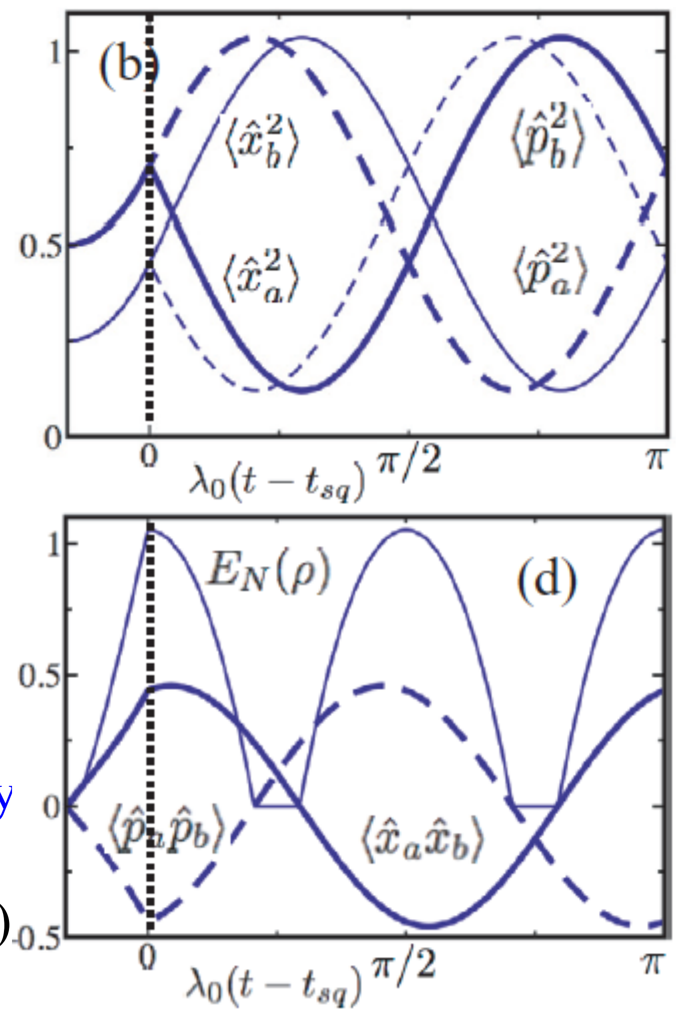
- Also subject to mechanical noise
- Noise propagates to all modes after two pulses
- Stability issue
- …

Simple entanglement generation

Previous work: design parametrically coupled mechanical/electrical resonators for two-mode squeezing, then squeezing

Generate parametric amplifier interaction, followed by beam-splitter operation





Can be extended to two cavity entanglement by swap gate on mechanical mode and 2nd cavity

Tian, Allman, Simmonds, NJP 10, 115001 (2008)

Previous work

Various approaches and system setups: (photons, photon-phonon)

- Stationary state schemes – e.g. Vitali et al, PRL (2007), Wipf et al, NJP (2008), Barzenjeh et al, PRL (2012)
- Pulsed scheme – Hofer et al, PRA 2011, Vanner et al, PNAS (2011)
- Measurement schemes/reservoir engineering – Muschik et al, PRA (2011), Wang&Clerk, PRL (2013), Tan&Meystre, PRA (2013)

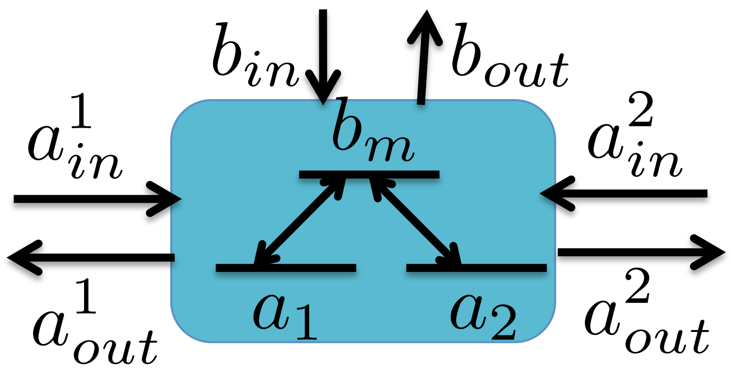
Potential issues:

- Instability under the blue-detuned drive and nonlinearity
- Entanglement/couplings constrained by stability conditions
- Thermal noise in mechanical mode

Why want entanglement:

- Key resource for quantum network, quantum teleportation …
- Quantum feature in macroscopic system, quantum-classical boundary
- Hybrid quantum systems: bridging very different frequency scales

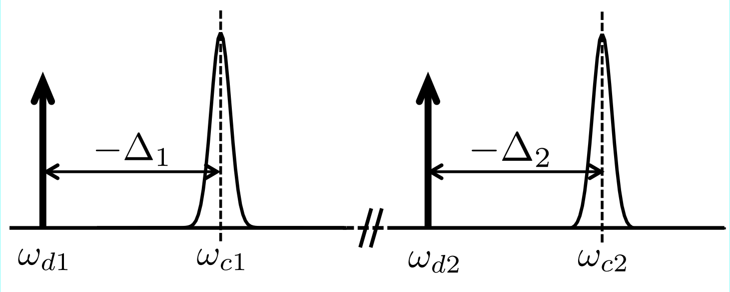
Overcome Mechanical Noise?!

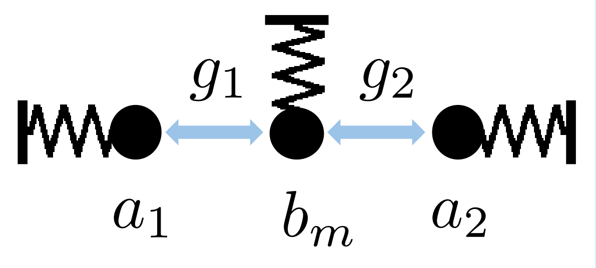


Optomechanical Quantum Interface

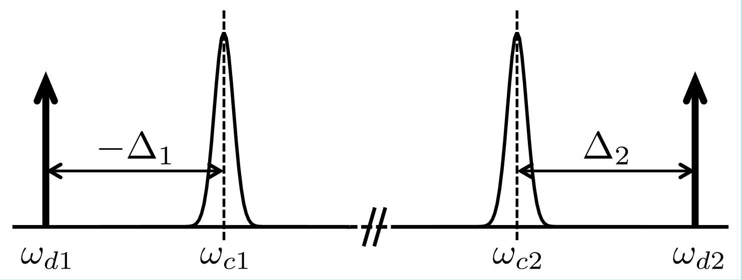
- For simplicity, detunings in resonance with mechanical frequency
- Simultaneous driving on two cavities

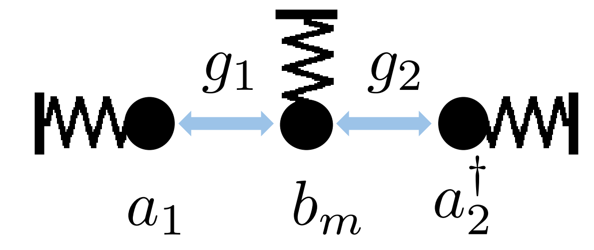
Red-detuned – Red-detuned
- quantum wavelength conversion
- discrete state entanglement





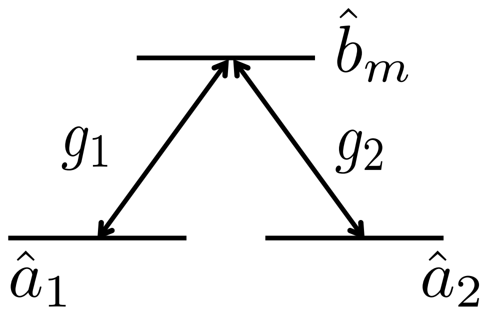
Red-detuned – Blue-detuned
- continuous variable entanglement



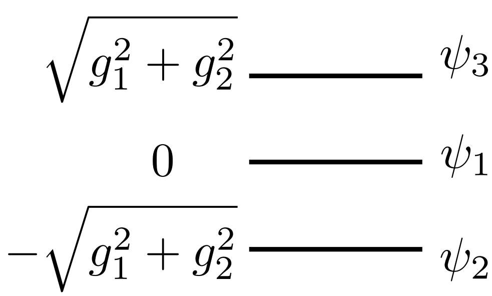


Red-Red detuned driving – Mechanical dark mode

$$H = \sum_{i=1,2} -\hbar\Delta_i a_i^\dagger a_i + \boxed{\hbar g_i (a_i^\dagger b_m + b_m^\dagger a_i)} + \hbar\omega_m b_m^\dagger b_m$$



Eigenmodes at $-\Delta_i = \omega_m$



Mechanical dark mode

$$\psi_1 = (-g_2 a_1 + g_1 a_2)/g_0$$

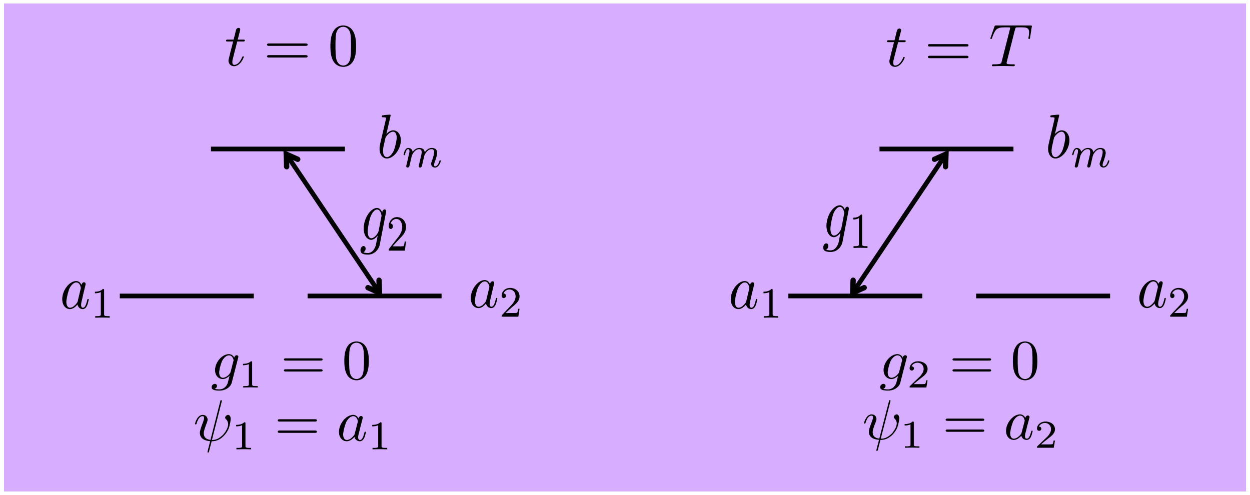
Dark mode energy separated from other modes $g_0 = \sqrt{g_1^2 + g_2^2}$

$$\lambda_1 = 0,\ \lambda_{2,3} = \pm\sqrt{g_1^2 + g_2^2}$$

Remains in dark mode when adjusting coupling $g_{1,2}$ adiabatically (Landau-Zener condition)

$$|dg_i/dt|/g_0 \ll g_0$$

Adiabatic quantum wave length conversion of cavity state



$$\psi_1 = (-g_2 a_1 + g_1 a_2)/g_0$$

time t=0, g_1=0, g_2=-g_0, dark mode $a_1(0)$
time t=T, g_1=g_0, g_2=0, dark mode $a_2(T)$
Initial state in mode a_1 is transferred to mode a_2

$$\boxed{a_2(T) = a_1(0)}$$

Finite damping, solve Langevin equation $\quad id\vec{v}(t)/dt = M(t)\vec{v}(t) + i\sqrt{K}\vec{v}_{in}(t)$

$$\psi_1 = \left(-\frac{g_2}{g_0}a_1 \boxed{-\frac{i(\kappa_1-\kappa_2)g_1 g_2}{2g_0^3}b_m} + \frac{g_1}{g_0}a_2\right)^{\mathrm{T}} \qquad \vec{v}(t) = [a_1, b_m, a_2]^{\mathrm{T}}$$

Not totally dark!

Adiabatic quantum wave length conversion of cavity state

Fidelity for gaussian states at time *T*: $F = F_1 F_2$

$$F_1 \approx 1 - f(0,T)(\cosh(2r) - 1) - \boxed{f_s \cosh(2r)} \quad f(0,T) \sim (\kappa_1 + \kappa_2)T/4$$

$$F_2 \approx 1 - f^2(0,T)y(\alpha)/2. \qquad f_s \lesssim \gamma_m (2n_{th} + 1)T\boxed{((\kappa_1 - \kappa_2)/4g_0)^2}$$

F_1, linear vs κ_1, F_2, quadratic vs κ_1

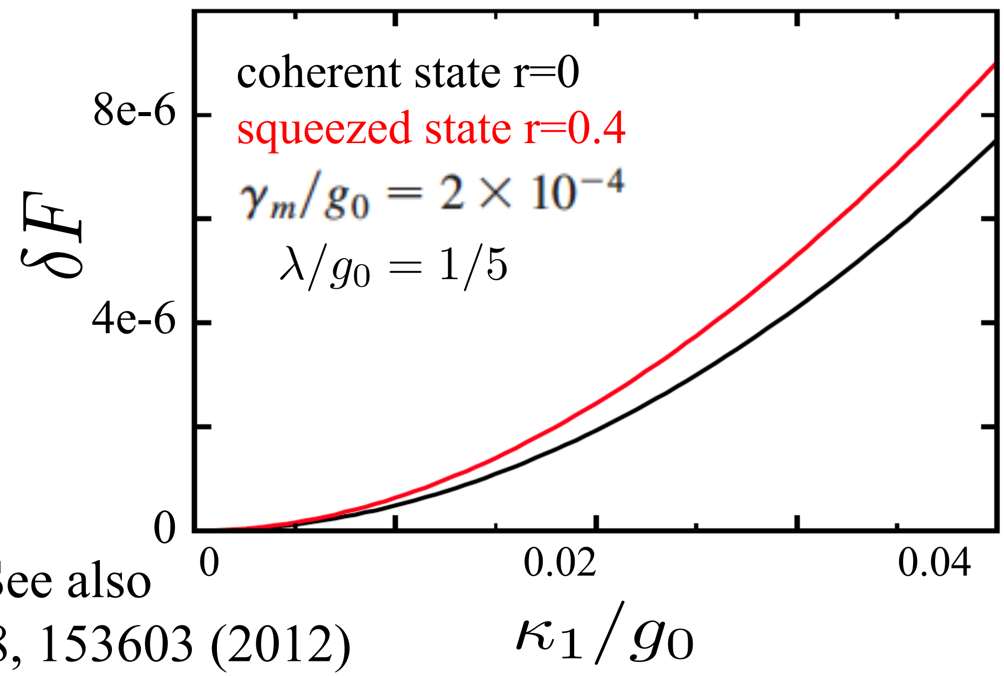
Effect of mechanical noise reduces by significant ratio

Special case of $\kappa_1 = \kappa_2$: **mechanical noise cancals**

$$g_1 = g_0 \sin(\lambda t)$$
$$g_2 = -g_0 \cos(\lambda t)$$
$$t = \pi/2\lambda$$

$\delta F = F(0) - F(\gamma_m)$ at $\kappa_2 = 0$,
(effect of mechanical noise)

Increases quadraticly with κ_1
Larger for finite squeezing *r*



L. Tian, PRL 108, 153604 (2012). See also
Y. D. Wang & A. A. Clerk, PRL 108, 153603 (2012)

High-fidelity swapping of cavity state

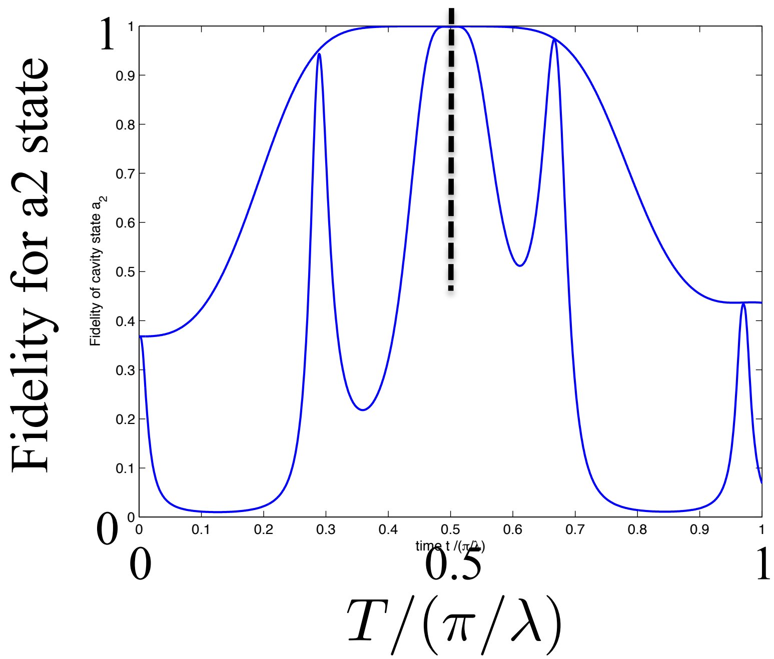
Could we achieve a two-way process for exchange of states?

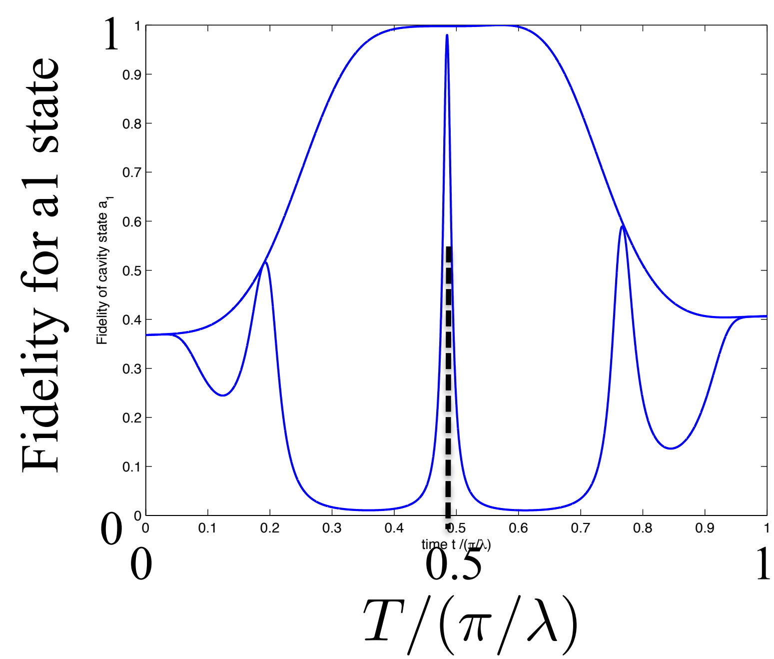
- State from a1 to a2
- State from a2 to a1

$$a_2(T) = a_1(0) \qquad a_1(T) = a_2(0)$$

How to? --- Destructive interference to cancel mechanical components

Condition: $\lambda/g_0 \approx 1/2n$. Numerical results for n=2:

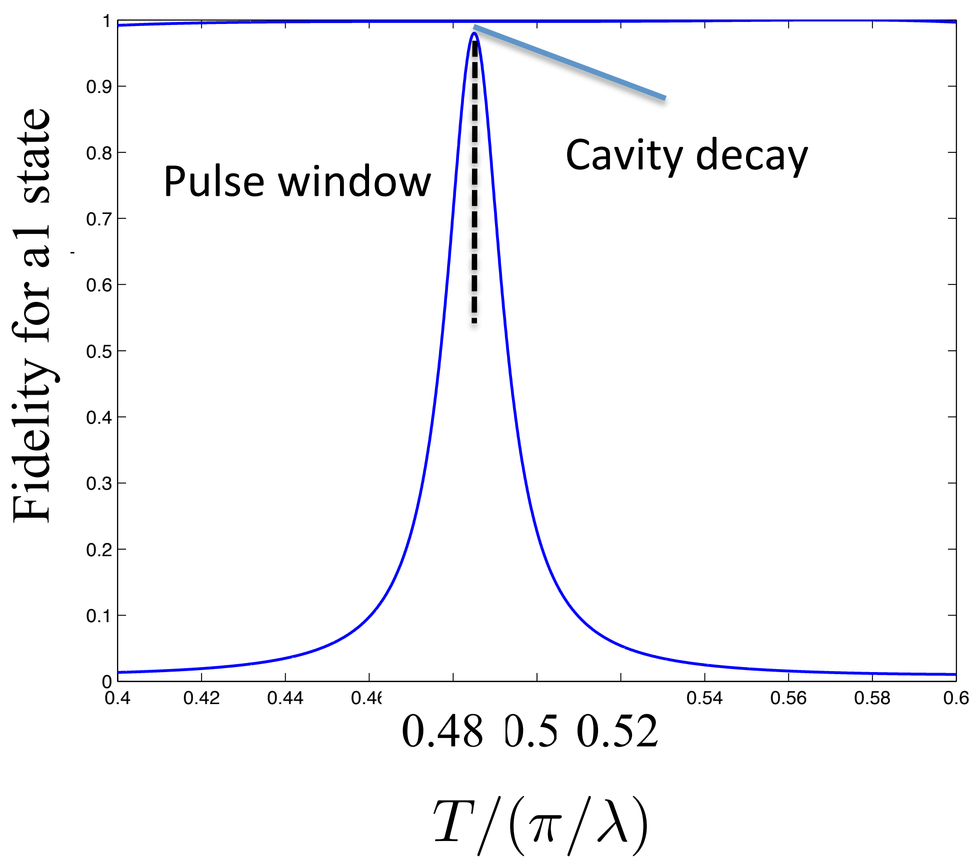




Initial states: a1 = coherent state α=1, a2=vacuum; two curves n_{th}=0, 100;

Target states: a1= vacuum, a2= coherent state α=1

Fidelity for a1 state – Zoomed in

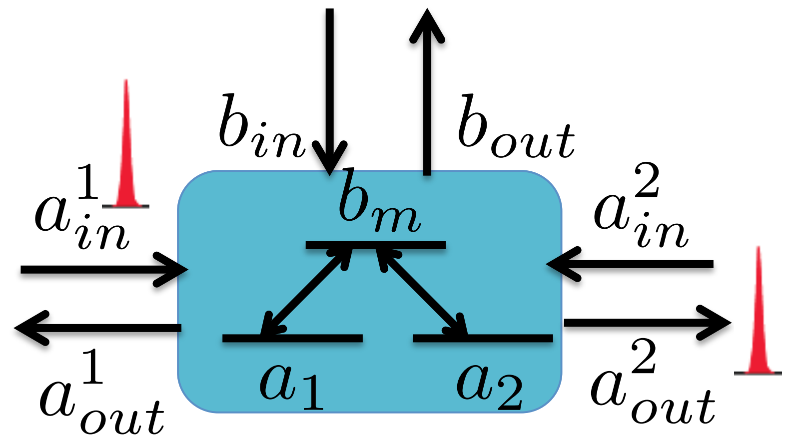


Time window:
5 – 10 nsec.

More details see
S. Huang & L. Tian, coming soon …

High-fidelity pulse transmission with impedance matching

Input $a^1_{in}(t)$ transferred to output $a^2_{out}(t)$
Noise operators $a^2_{in}(t)$ and $b_{in}(t)$



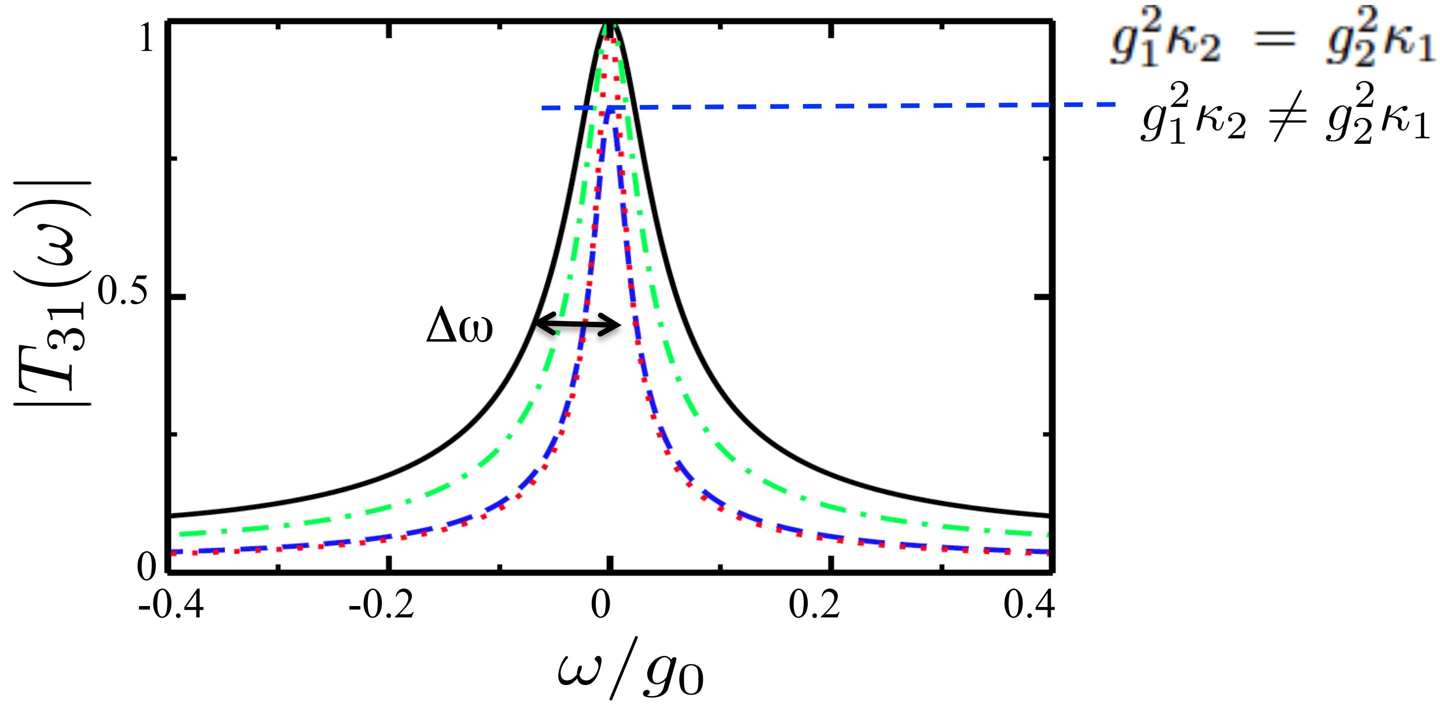
Langevin equation in frequency space
Input-output relation
Transmission matrix – unitary operator

$$\vec{v}_{out}(\omega) = \widehat{T}(\omega)\vec{v}_{in}(\omega)$$

Output operator $a^2_{out}(\omega) = \widehat{T}_{31}(\omega)a^1_{in}(\omega) + \widehat{T}_{32}(\omega)b_{in}(\omega) + \widehat{T}_{33}(\omega)a^2_{in}(\omega)$

Condition for high fidelity $\widehat{T}_{31}(\omega) \to 1 \quad \widehat{T}_{32}(\omega), \widehat{T}_{33}(\omega) \to 0$

High-fidelity pulse transmission with impedance matching



- **Optimal transmission condition: impedance matching** $\widehat{T}_{31}(\omega) \to 1$
- Half width ~ cavity bandwidth, $\Delta\omega \sim \kappa_i$
- Fidelity drops with input pulse spectral width σ_ω $\sigma_\omega \ll \Delta\omega$

Related work: A. H. Safavi-Naeini and O. Painter, NJP 13, 013017 (2011)
C. A. Regal and K. W. Lehnert, J. of Phys. Conf. Series 264, 012025 (2011)

L. Tian, PRL 108, 153604 (2012). See also
Y. D. Wang & A. A. Clerk, PRL 108, 153603 (2012); NJP (2012)

Coherent optical wavelength conversion via cavity optomechanics

Jeff T. Hill[1,*], Amir H. Safavi-Naeini[1,*], Jasper Chan[1] & Oskar Painter[1]

Nat. Comm. (2013)

Optomechanical Dark Mode

Chunhua Dong, Victor Fiore, Mark C. Kuzyk, Hailin Wang*

Science (2013)

Coherent state transfer between itinerant microwave fields and a mechanical oscillator

T. A. Palomaki[1,2], J. W. Harlow[1,2], J. D. Teufel[3], R. W. Simmonds[3] & K. W. Lehnert[1,2]

Nature (2013)

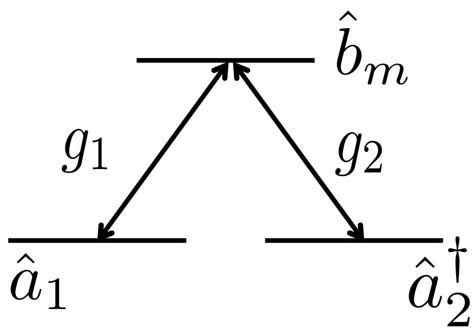
UCSB work, see talk by Andrew Cleland, Monday

Red-Blue detuned driving – Bogoliubov dark mode

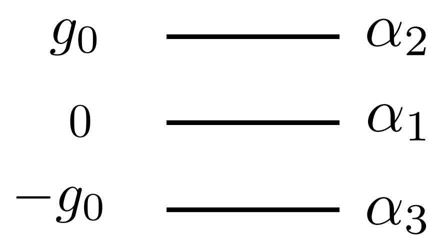
$$H_I = \hbar g_1 (a_1^\dagger b_m + b_m^\dagger a_1) + i\hbar g_2 (a_2^\dagger b_m^\dagger - a_2 b_m)$$

1. Coupling diagram, energy spectrum

$$g_0 = \sqrt{g_1^2 - g_2^2}$$



Eigenmodes



One "dark" mode and two bright modes separated by energy g_0

2. Stability condition
(strong coupling regime)

$$\frac{g_1^2}{g_2^2} > \max\left\{\frac{\kappa_2}{\kappa_1}, \frac{\kappa_1}{\kappa_2}\right\}$$

$$g_1 = g_0 \cosh(r) \qquad g_2 = g_0 \sinh(r)$$

Red-Blue detuned driving – Bogoliubov dark mode

1. "Dark" mode, λ_1=0 $\alpha_1 = -i\sinh(r)a_1 + \cosh(r)a_2^\dagger$

2. Two bright modes $\lambda_{2,3} = \pm g_0$

$$\alpha_{2,3} = \frac{1}{\sqrt{2}}\left(\cosh(r)a_1 \pm b_m + i\sinh(r)a_2^\dagger\right)$$

3. Bogoliubov modes

Two modes under parametric amplifier coupling $H_s = -g_s\left(a_1a_2 + a_1^\dagger a_2^\dagger\right)$

System operators evolve in terms of Bogoliubov modes $r = g_s t$

$$a_1(t) = \boxed{\beta_1(r) = \cosh(r)\,a_1 + i\sinh(r)\,a_2^\dagger}$$
$$a_2(t) = \boxed{\beta_2(r) = \cosh(r)\,a_2 + i\sinh(r)\,a_1^\dagger}$$

4. Relation to eigenmodes $\boxed{\alpha_1 = \beta_2^\dagger;\ (\alpha_2+\alpha_3)/\sqrt{2} = \beta_1}$

5. finite damping

(eigenvalues modified too) $\boxed{\alpha_1 = \beta_2^\dagger + x_1 b_m;\ (\alpha_2+\alpha_3)/\sqrt{2} = \beta_1 - \sqrt{2}x_3 b_m}$

$-i\delta\lambda_i$

Robust Entanglement Generation

Central idea

- Entanglement generated via mechanical mode – effect of noise
- Excitation of dark mode doesn't involve mechanical mode => $\beta_2(r)$
- Excitation of bright modes mix cavity and mechanical modes
- Quantum interference cancels mechanical modes => $\beta_1(r)$
- Cavity/cavity output operators have forms of Bogoliubov operators to leading order, mechanical noise suppressed

Entanglement in cavity state in time domain

Solve Langevin equation in time domain for operator evolution

Dark mode; bright modes with phase factors including mechanical component

$$\alpha_1(t) = \alpha_1(0);\ \alpha_{2,3}(t) = \exp(\mp i\varphi(t))\alpha_{2,3}(0)$$

Bogoliubov modes for cavity at time t $\beta_2(t) = \beta_2(0)$

$$\beta_1(t) = \beta_1(0)\cos\varphi(t) - ib_m(0)\sin\varphi(t)$$

Cavity at time t includes $b_m(0)$

Choose time t_n to cancel mechanical component, $\varphi(t_n) = n\pi$

At t_n, $g_1 = g_0\cosh(r)$ $g_2 = g_0\sinh(r)$

Couplings can have many choices of time dependence

$$\begin{pmatrix} a_1(t) \\ a_2^\dagger(t) \end{pmatrix} = \begin{pmatrix} \cosh(r) & -i\sinh(r) \\ i\sinh(r) & \cosh(r) \end{pmatrix} \begin{pmatrix} \cosh(r_0)(-1)^n & i\sinh(r_0)(-1)^n \\ -i\sinh(r_0) & \cosh(r_0) \end{pmatrix} \begin{pmatrix} a_1(0) \\ a_2^\dagger(0) \end{pmatrix}$$

Entanglement in cavity state in time domain

Solving Langevin equation at finite damping rates

Cavity at time t_n

$$a_1(t_n) = \boxed{\left[(-1)^n \cosh(r) a_1(0) - i \sinh(r) a_2^\dagger(0)\right]} + \boxed{f_1(a_1(0), a_2^\dagger(0))} + \boxed{y_1 b_m(0)} + \boxed{\text{noise integral}}$$

$$a_2^\dagger(t_n) = \boxed{\left[i(-1)^n \sinh(r) a_1(0) + \cosh(r) a_2^\dagger(0)\right]} + \boxed{f_2(a_1(0), a_2^\dagger(0))} + \boxed{y_2 b_m(0)} + \boxed{\text{noise integral}}$$

Ideal terms
zero damping

Eigenmode
damping
$O(\kappa_i/g_0)$

Bath
fluctuations
$O(\kappa_i/g_0)$

Effect of initial mechanical noise is eliminated to leading order!

$O(\gamma_m/g_0)n_{th}$

$O(\kappa_i^2/g_0^2)n_0$ First-order mixing
with mechanical mode

Distinguish thermal number of initial state n_0 and of bath n_{th}

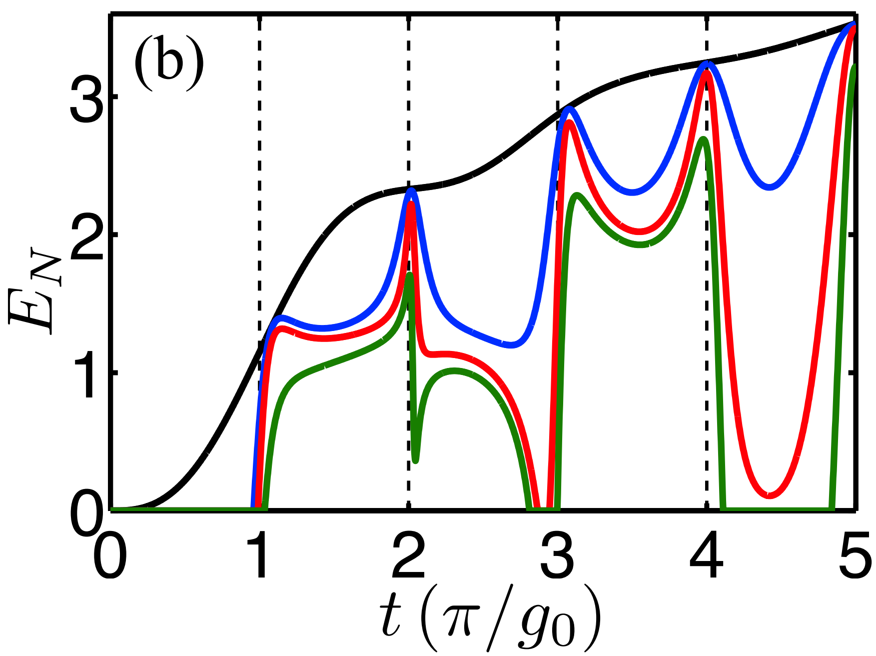
Couplings are $g_1(t) = g_0 \cosh(\lambda t)$ and $g_2(t) = g_0 \sinh(\lambda t)$

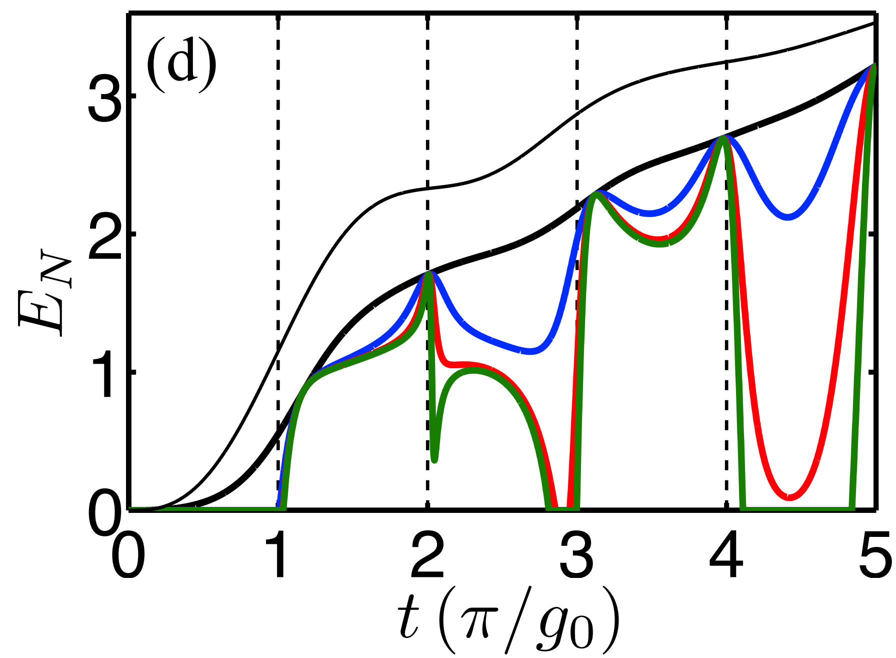
Entanglement in cavity state in time domain

Numerical simulation of time evolution with $r(t_2) = 1$

Peaks appear for finite thermal number at $t_n = n\pi/g_0$

- Peak height slowly varies with n_{th}
- Peak width depends on n_0





$n_0 = n_{th} = 0, 10, 100, 1000$

$n_0 = 0, 10, 100, 1000,\ n_{th} = 1000$

$\boxed{g_1(t) = g_0 \cosh(\lambda t) \text{ and } g_2(t) = g_0 \sinh(\lambda t)}$

$\kappa_0/g_0 = 0.1$

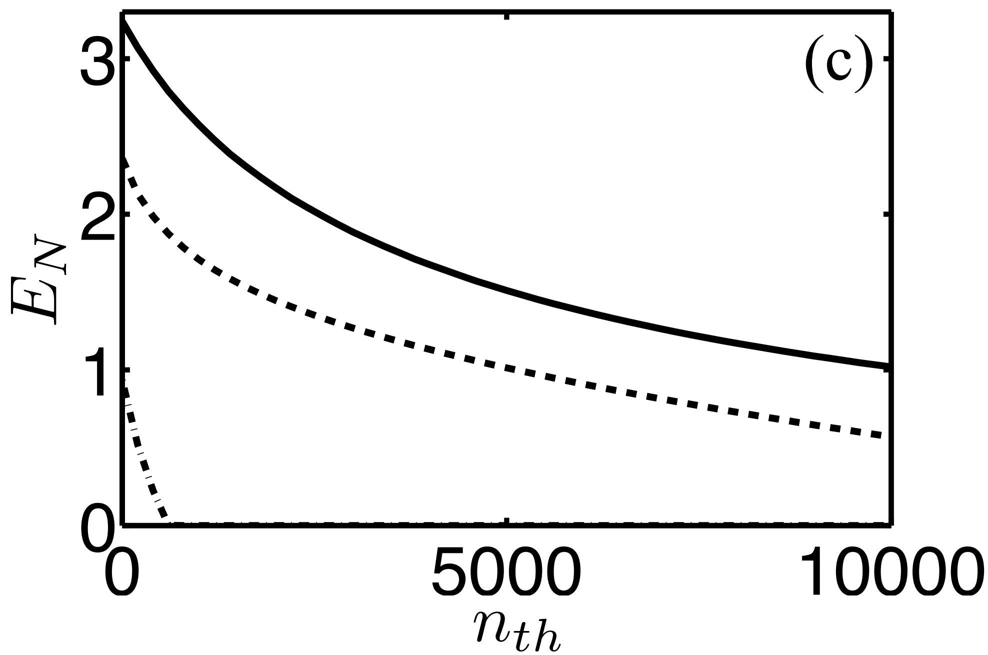
$\gamma_m/g_0 = 0.0003$

Entanglement in cavity state in time domain

Entanglement at selected peak values

- solid: constant coupling $r = 1$
- dashed: adiabatic increase of coupling $r(t_2) = 1$
- dotted: stationary scheme

Sizable entanglement at large n_{th}



L. Tian, PRL 110, 233602 (2013)

Entanglement in cavity output in frequency domain

Operators in input and output – x = in, out – g: profile function

$$a_x^{(i)}(\omega_n) = \int d\omega g(\omega - \omega_n) a_x^{(i)}(\omega)$$

Eigenmode excitation at given frequency, crucial for the effect

$$\vec{\alpha}(\omega_n) = i(I\omega_n - \Lambda)^{-1} U^{\mathrm{T}} \sqrt{K} \vec{v}_{in}(\omega_n)$$

Strong excitation when ω_n near eigenvalues

At $\omega_n=0$, dark mode strongly excited $\sim 1/\delta\lambda_1$,
bright modes weakly excited $\sim 1/g_0$

At $\omega_n=g_0$, one bright mode strongly excited $1/\delta\lambda_2$, (similarly at $-g_0$)
dark mode weakly excited $\sim 1/g_0$
other bright mode weakly excited $\sim 1/2g_0$

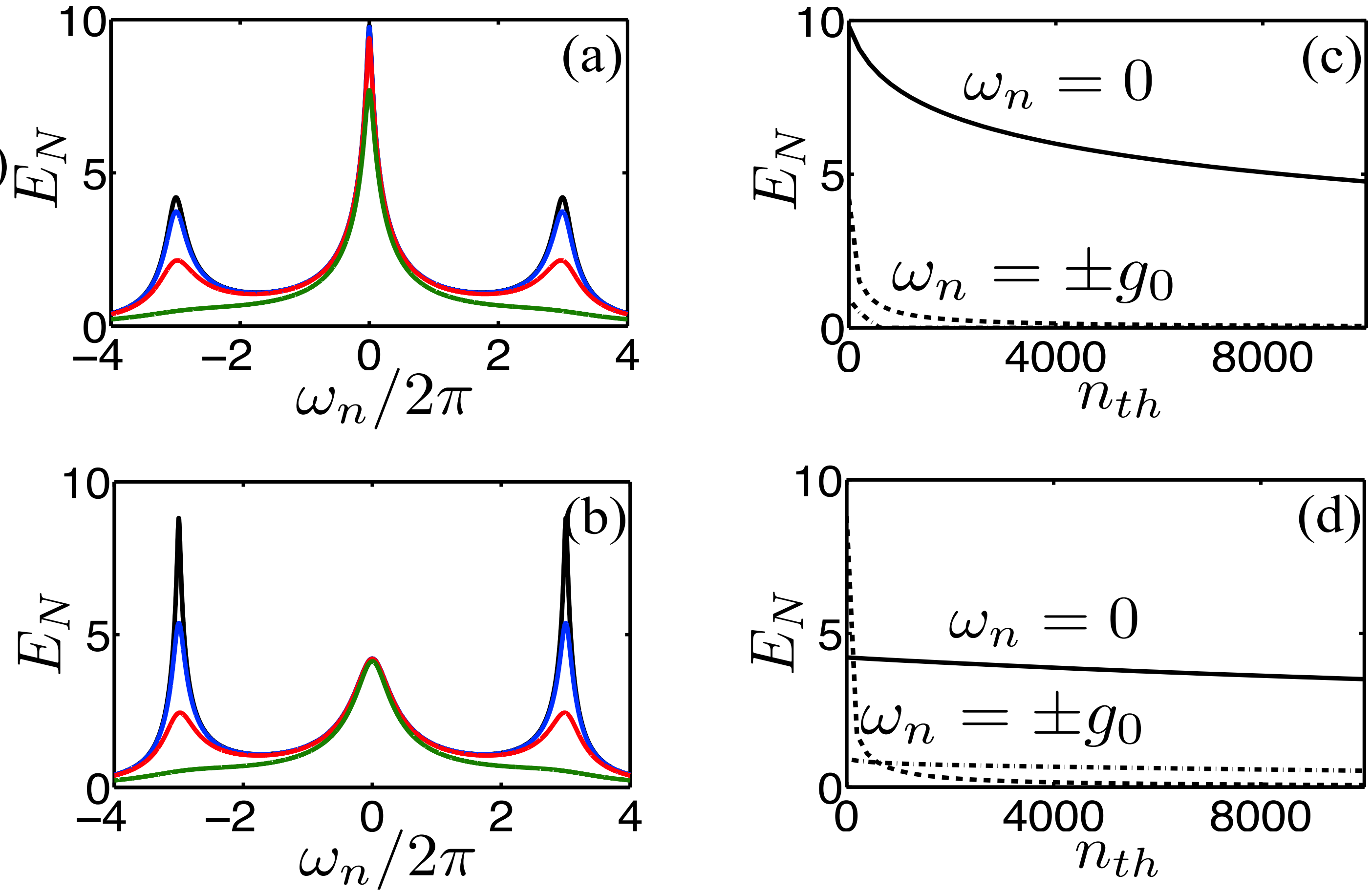
Entanglement can be strong at these frequencies

Entanglement in cavity output in frequency domain

Top panels:
($\kappa 1$, $\kappa 2$) =(0.3, 0.2)

Bottom panels:
($\kappa 1$, $\kappa 2$)=(0.2, 0.3)

Dependence on damping rates due to effect on $\delta\lambda_i$



n_{th}=0, 10, 100, 1000
Strong entanglement at 0, g_0, -g_0

At 0, strong & robust
Side peaks, strong & non-robust

See results in Barzanjeh et al, PRL 109, 130503 (2012)
"Reversible Optical-to-Microwave Quantum Interface"

Entanglement in cavity output in frequency domain

At ω_n=0, dark mode strongly excited ~ $1/\delta\lambda_1$, $\alpha_1 \approx \beta_2^\dagger$

$$\alpha_1(\omega_0) = \left(\frac{\sinh(r)}{\delta\lambda_1} \quad \frac{ix_1}{\delta\lambda_1} \quad \frac{i\cosh(r)}{\delta\lambda_1} \right) \cdot \sqrt{K}\vec{v}_{in}(\omega_0)$$

Bright modes weakly excited ~ $1/g_0$

$$\alpha_{2,3}(\omega_0) = \left(\mp\frac{\cosh(r)}{\sqrt{2}g_0} \quad -\frac{1}{\sqrt{2}g_0} \quad \mp\frac{i\sinh(r)}{\sqrt{2}g_0} \right) \cdot \sqrt{K}\vec{v}_{in}(\omega_0)$$

Symmetry in bright modes gives

$$\beta_1(\omega_0) \approx (\alpha_2(\omega_0) + \alpha_3(\omega_0))/\sqrt{2} = -\sqrt{\gamma_m} b_{in}(\omega_0)/g_0$$

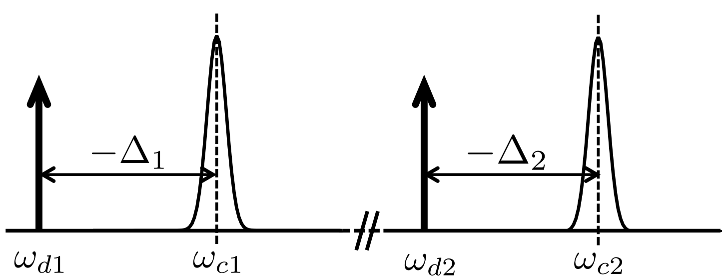
Again, in cavity modes, mechanical input ~ $1/g_0$; cavity inputs ~$1/\delta\lambda_1$

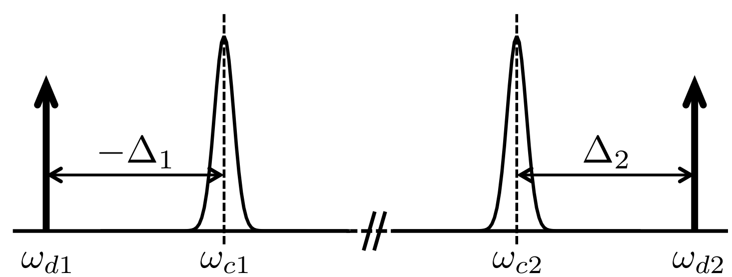
At ω_n=g_0, one bright mode strongly excited $1/\delta\lambda_2$, (similarly at $-g_0$)
dark mode weakly excited ~ $1/g_0$
other bright mode weakly excited ~ $1/2g_0$

L. Tian, PRL 110, 233602 (2013)

Optomechanical Quantum Interface

- Optomechanical quantum interface connects quantum states in different cavities – facilitate scalable quantum systems
- High fidelity quantum wave length conversion via dark mode
- Robust entanglement generation via excitation of dark mode and quantum interference of the mechanical mode



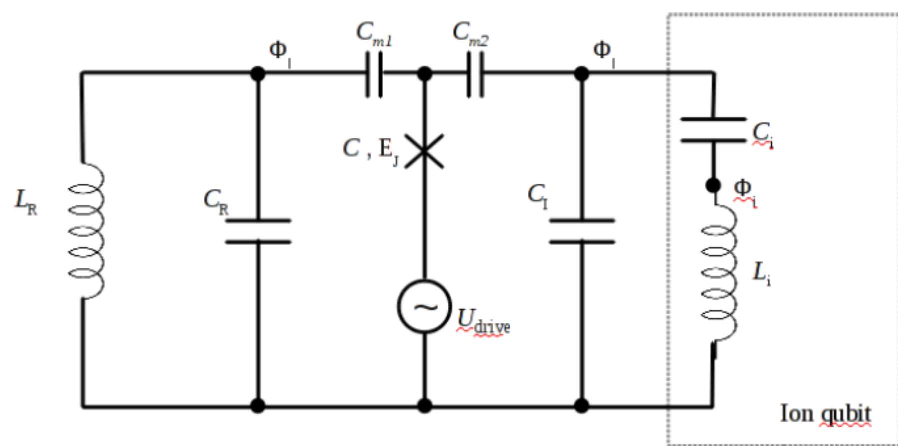


Trapped Particle and Superconducting Circuits

- Hybrid system connects trapped particle and superconducting circuits
- Trapped motion: 10 – 500 MHz, Superconducting resonator: 10 GHz
- Parametric coupling that converts resonator state to motion state

Previous work: Heinzen and Wineland PRA (1990), Kielpinski et al PRL (2012)

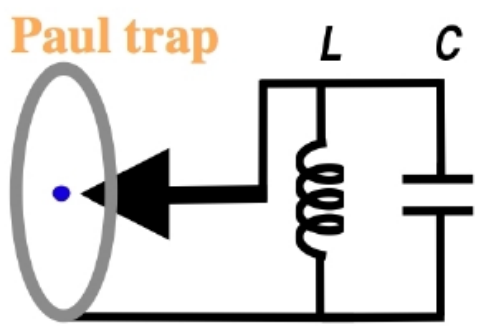
Circuit approach and challenges – our initial thoughts

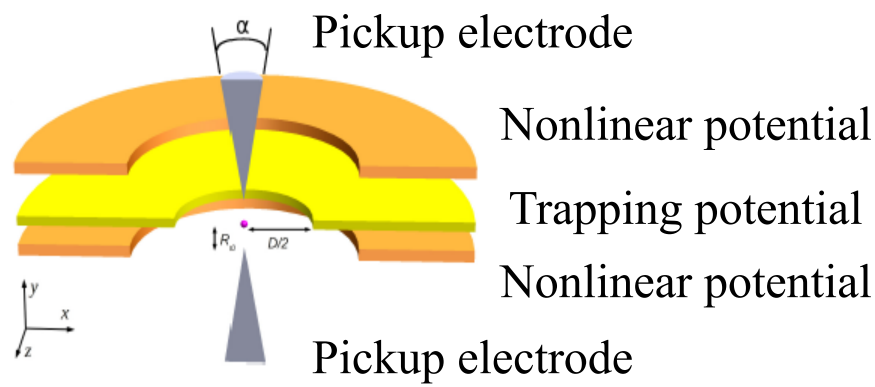


Excess circuit noise kills quantum signal on pickup electrodes

Trapped Particle and Superconducting Circuits

Solution – driven electron motion in nonlinear potential, classical motion becomes the parametric source





- Solution – driven electron motion in nonlinear potential, classical motion becomes the parametric source (different from micromotion)

$$U_{eff} = g x^2 \dot{\varphi}$$

$$x_i = A_d \cos(\Omega_d t) + \hat{x}_i$$

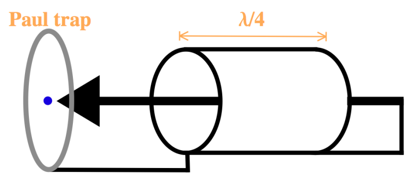
Daniilidis, Gorman, Tian, Haeffner, New J. Phys. 15, 073017 (2013)

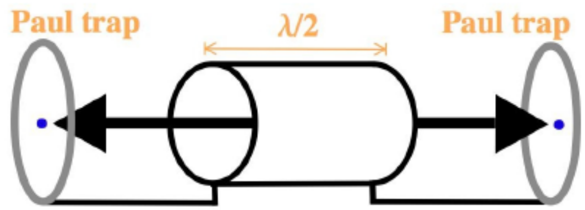
Trapped Particle and Superconducting Circuits

- Effective coupling: beam-splitter operation, parametric amplifier operation

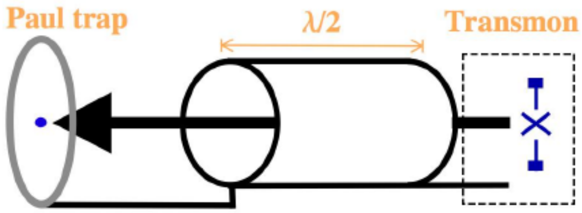
$$H_{\mathrm{er}} = \hbar g \cos(\Omega_{\mathrm{d}} t)\left(e^{i(\Omega-\omega_y)t} a_\phi^\dagger a_y + e^{i(\Omega+\omega_y)t} a_\phi^\dagger a_y^\dagger + h.c.\right)$$

Applications
Transfer electron motion with superconducting LC oscillators or other electrons



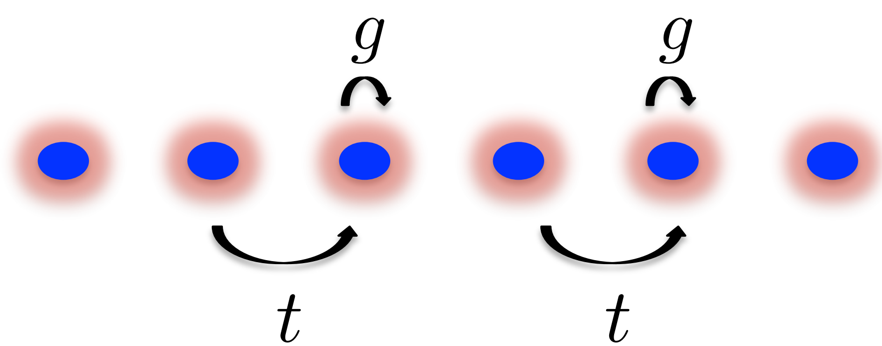


Electron-transmon coupling – with 3D transmon (long decoherence time)



Electron spin-motion conversion – similar to ion trap
Architecture for large scale quantum computer …

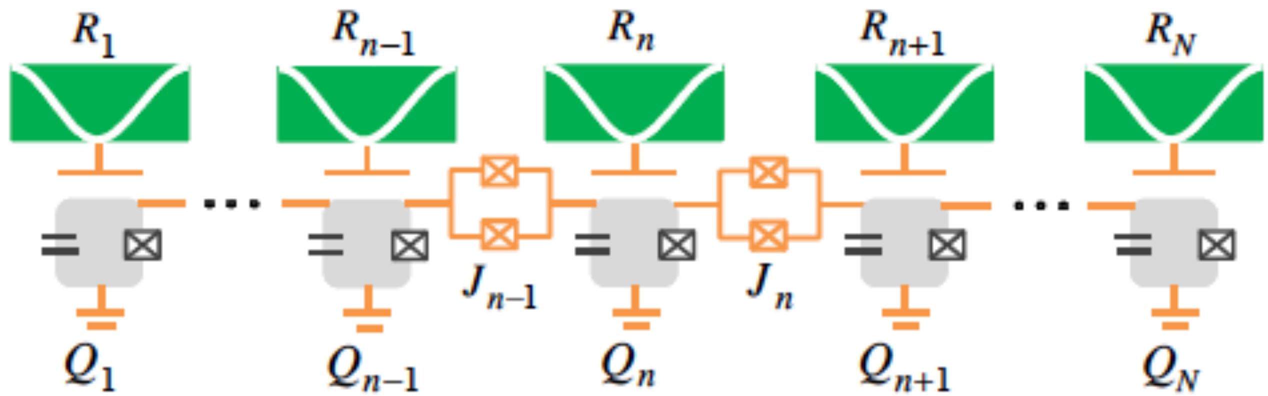
Emulating Phonons with Circuit QED



$$H = \hbar\omega \sum_i a_i^+ a_i - t \sum_{<i,j>} c_i^+ c_j + \hbar g \sum_i c_i^+ c_i (a_i^+ + a_i)$$

- Electron-phonon interaction – fundamental effect in condensed matter
  BCS – electron pairing via phonons, Peierls instability and Jahn-Teller effect
- Small polaron formation: lattice distortion in small regime
  L.D. Landau (1933) …
- Features: larger effective mass, lattice distortion, anomalous fluctuations
- Holstein model for local electron-phonon interaction, molecular crystals … (vs SSH model)
- Coupled fermionic and bosonic degrees of freedom
- Can't be exactly solved or numerically calculated, simple system with interesting many-body physics

Emulating Phonons with Circuit QED



Optical phonon $\downarrow$ Boson $\uparrow$ Cavity Photon

Electron $\downarrow$ Spinless Fermion $\uparrow$ Qubit

- Transmon qubit emulates electrons
- CPW resonator emulates optical phonons
- Tunable coupling (electron hopping) via SQUID loop
- Jordan-Wigner transformation on qubit spins

Emulating Phonons with Circuit QED

$$H = \hbar\omega \sum_i a_i^+ a_i - t \sum_{<i,j>} c_i^+ c_j + \hbar g \sum_i c_i^+ c_i (a_i^+ + a_i)$$

Parameter regimes: $g/\omega > 1$ (strong coupling) $t/\omega > 1$ (adiabatic)
Small polaron formation $\lambda = g^2/\omega t > 1$

Advantage of system:
Can access all regimes of interest (adiabatic, anti-adiabatic, …)
Real nearest neighbor coupling, dispersionless phonons
We developed generic scheme for the preparing of polaron excitations by exploring translational symmetry – using pulses

$$\Omega(q) = \frac{\hbar g(t)}{\sqrt{N}} \sum_n \left(\sigma_n^+ e^{-iqn} + \sigma_n^- e^{iqn} \right)$$

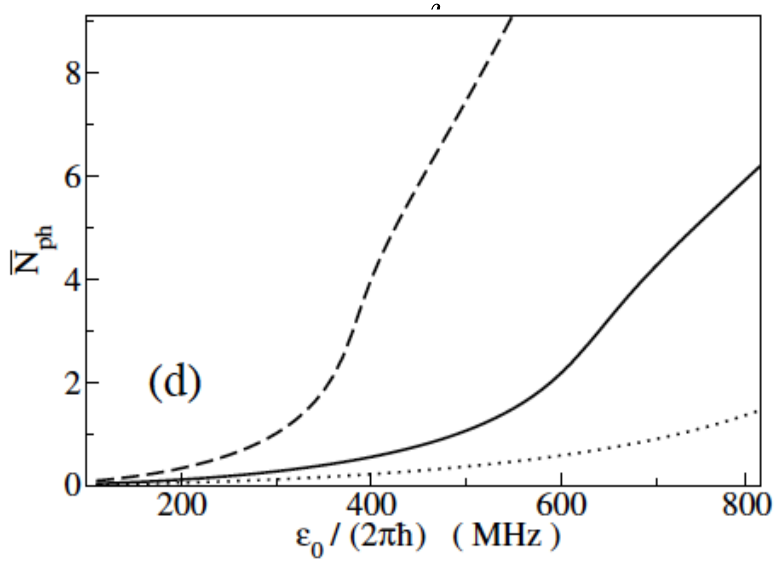
Previous work:
Stojanovic, Shi, Bruder,Cirac, PRL 109, 250501 (2012) ion trap systems
Mezzacapo et al, PRL 109, 200501 (2012) digital quantum simulation
Also, works on polar molecules, Rydberg atoms

Emulating Phonons with Circuit QED

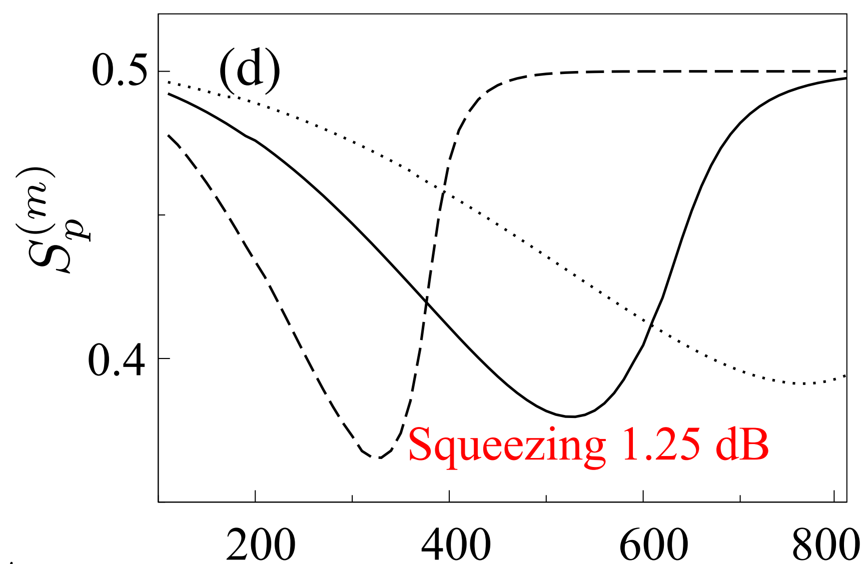
How to calculate? – use Toyozawa-type variational Ansatz to test system behavior

Phonon number

$$\bar{N}_{\rm ph} \equiv \langle \tilde{\psi}_{\kappa=0} | \sum_i a_i^\dagger a_i \, | \tilde{\psi}_{\kappa=0} \rangle$$



Variances of resonators based on measurement of qubit flip



$\cdots\cdots$ $\delta\omega/2\pi = 100\,\mathrm{MHz}$

—— $\delta\omega/2\pi = 80\,\mathrm{MHz}$

— — $\delta\omega/2\pi = 60\,\mathrm{MHz}$

$g_H = g/\omega \propto \epsilon$

$t/2\pi = 80\,\mathrm{MHz}$

Mei, Stojanovic, Siddiqi, Tian, arXiv:1307.0906

Emulating Phonons with Circuit QED

- Circuit QED gives a tunable platform to emulate e-ph physics in the Holstein model in all interesting parameter regimes, without the restriction of phonon dispersion and long-range coupling

- We develop a state preparation scheme which can be applied to other systems

- Squeezing in resonator can be generated during small polaron formation

Acknowledgement

Optomechanical quantum interface:
Group members: Dan Hu (graduate student), Sumei Huang (postdoc)
Collaborators: Hailin Wang and group (U Oregon)

Trapped electron – resonator hybrid system
Collaborators: Hartmut Haeffner, Nikos Daniilidis, Dylan Gorman (Berkeley)

Emulator for electron-phonon physics
Group member: Feng Mei (postdoc)
Collaborators: Vladimir Stojanovic (U Basel), Irfan Siddiqi (Berkeley)

Optomechanical Quantum Interface

- Strong coupling between light and mechanical modes

  microwave: Teufel et al Nature (2011)

  $\omega_m/2\pi, 10\,\mathrm{MHz}$ $\kappa/2\pi, 100\,\mathrm{kHz}$ $g/2\pi, 1\,\mathrm{MHz}$

  optical experiment: Verhagen et al Nature (2012)

  $\omega_m/2\pi, 100\,\mathrm{MHz}$ $\kappa/2\pi, 7\,\mathrm{MHz}$ $g/2\pi, 10\,\mathrm{MHz}$

Quantum Wavelength Conversion

Adiabatic scheme via mechanical dark mode

Langevin eq. in interaction picture

$$i d\vec{v}(t)/dt = M(t)\vec{v}(t) + i\sqrt{K}\vec{v}_{in}(t)$$
$$\vec{v}(t) = [a_1, b_m, a_2]^{\mathrm{T}}$$

$$M(t) = \begin{pmatrix} -i\frac{\kappa_1}{2} & g_1(t) & 0 \\ g_1(t) & -i\frac{\gamma_m}{2} & g_2(t) \\ 0 & g_2(t) & -i\frac{\kappa_2}{2} \end{pmatrix}$$

<u>Finite damping:</u> we treat damping terms in M(t) as perturbation terms
Dark mode contains small contribution from mechanical mode

$$\psi_1 = \left(-\frac{g_2}{g_0} a_1 \boxed{- \frac{i(\kappa_1 - \kappa_2) g_1 g_2}{2 g_0^3} b_m} + \frac{g_1}{g_0} a_2 \right)$$

<u>Not totally dark!</u>

Eigenenergy is modified – causes damping

$$\lambda_1 = -i\left(\frac{g_1^2}{2g_0^2}\kappa_2 + \frac{g_2^2}{2g_0^2}\kappa_1 \right)$$

Hence, adiabatic conversion can be affected by mechanical noise
How to characterize these effects?

Simple entanglement generation

PHYSICAL REVIEW B **74**, 125314 (2006)

Scheme for quantum teleportation between nanomechanical modes

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(Received 22 August 2006; published 21 September 2006)

We study a quantum teleportation scheme between two nanomechanical modes without local interaction. The nanomechanical modes are linearly coupled to and connected by the continuous variable modes of a superconducting circuit consisting of a transmission line and Josephson junctions. We calculate the fidelity of transferring Gaussian states at finite temperature and nonunit detector efficiency. For coherent states, a fidelity above the classical limit of 1/2 can be achieved for a large range of parameters.