

# Nonclassicality and Higher-Order Nonlinearity in Levitated Optomechanics

Andrey A. Rakhubovsky, Darren W. Moore, Radim Filip

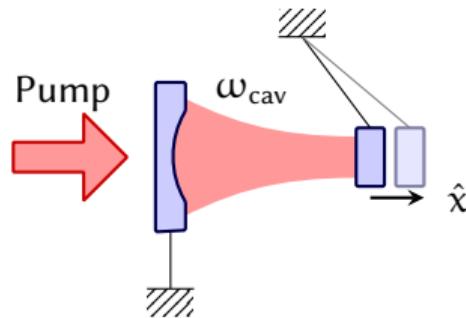
Department of Optics, Palacký University, Czech Republic

Quant. Sci. Technol. **4**, 024006 (2019),  
arXiv:1904.00772, 1904.00773 [quant-ph]

ICQOQI Minsk

15.05.2019

# Cavity Optomechanics



- ★ Radiation pressure drives mechanical motion
- ★ Mechanical displacement changes optical length of the cavity

# Experimental Realizations

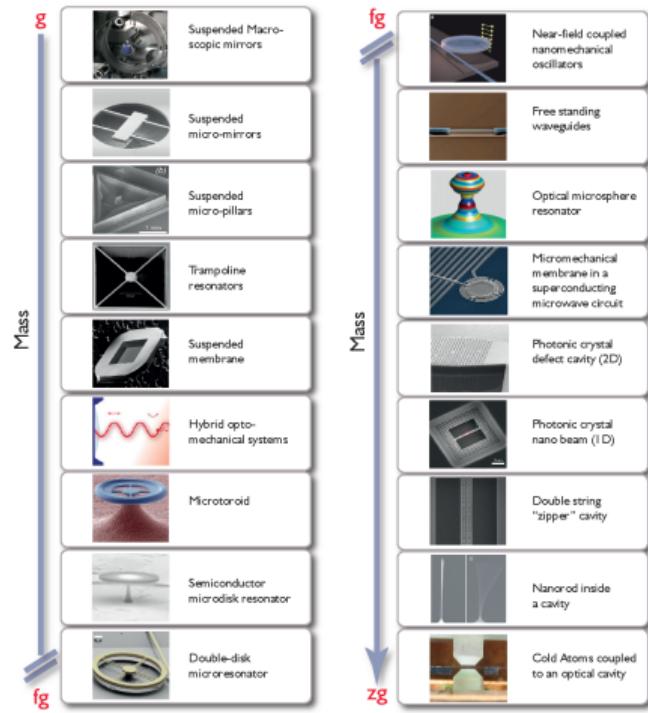


Figure source: <sup>1</sup>

<sup>1</sup> Aspelmeyer, Kippenberg and Marquardt, RMP **86**, 1391 (2014)

<sup>2</sup> Kashkanova *et al.*, Nat. Phys. **13**, 74 (2017)

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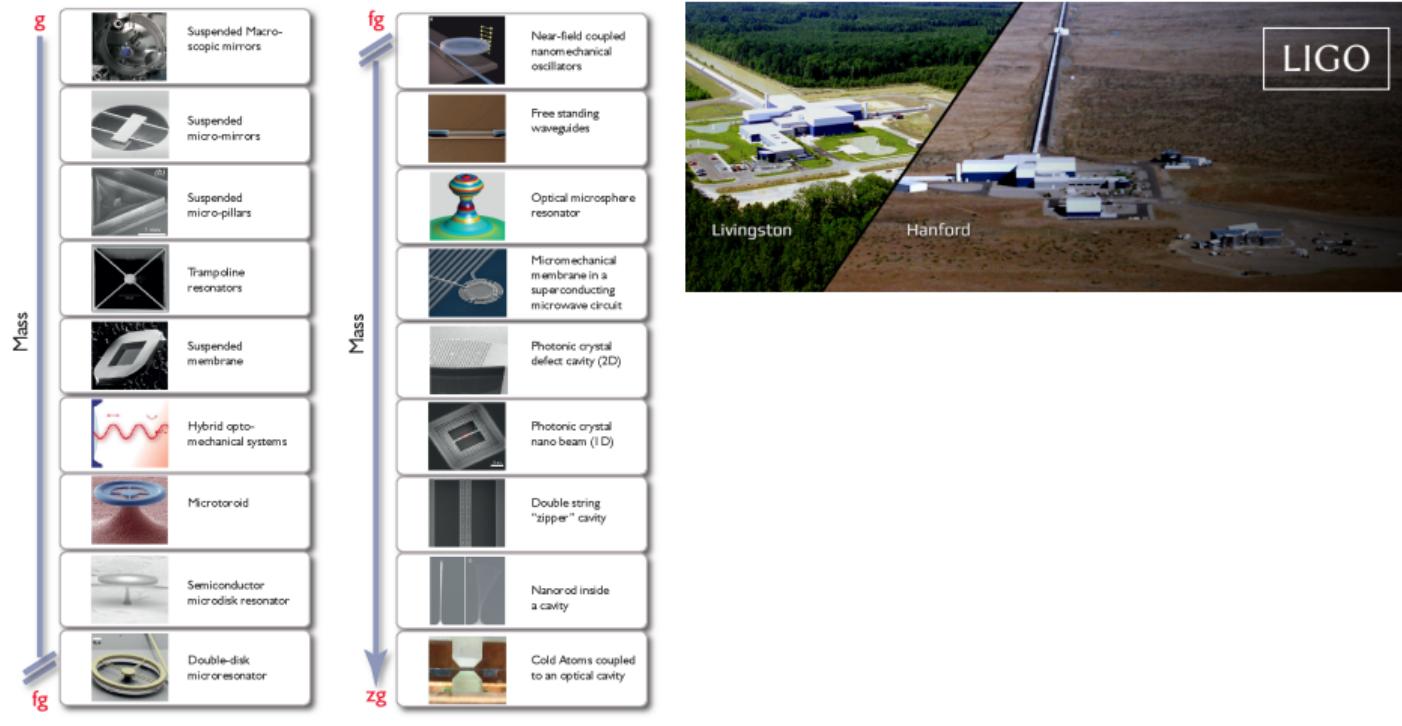


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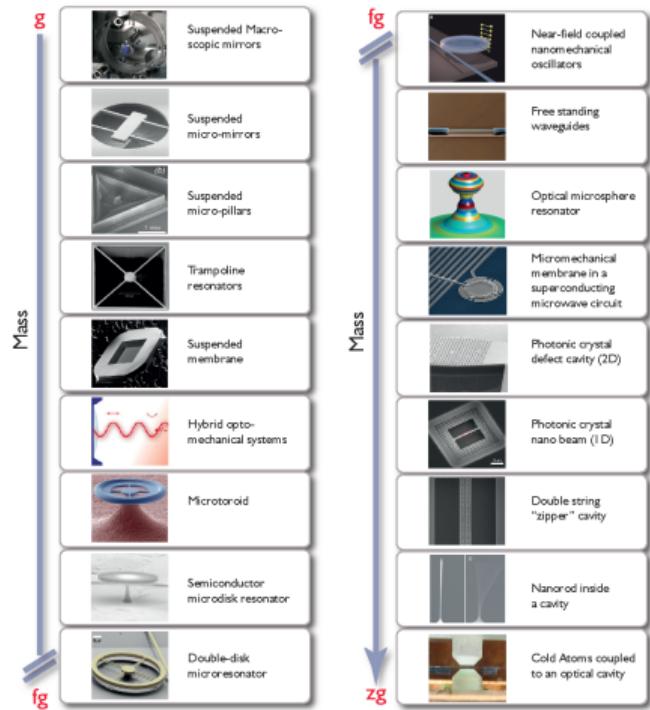


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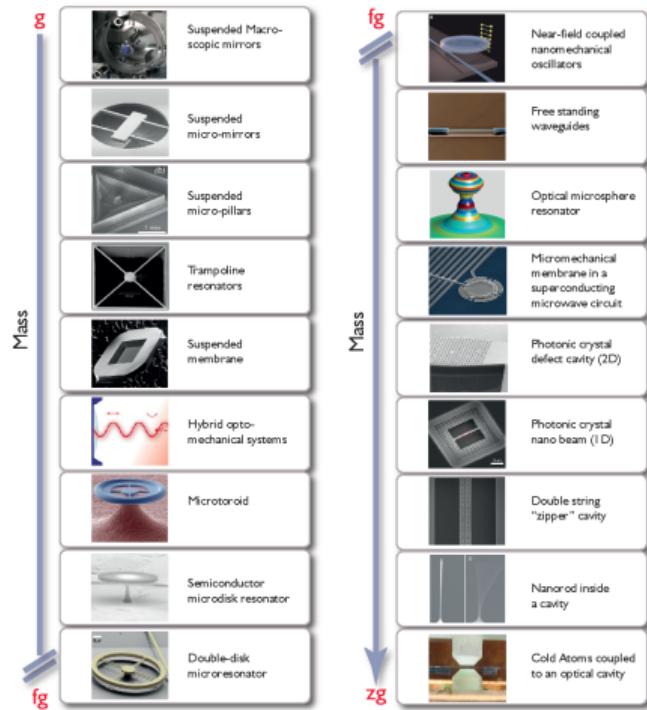


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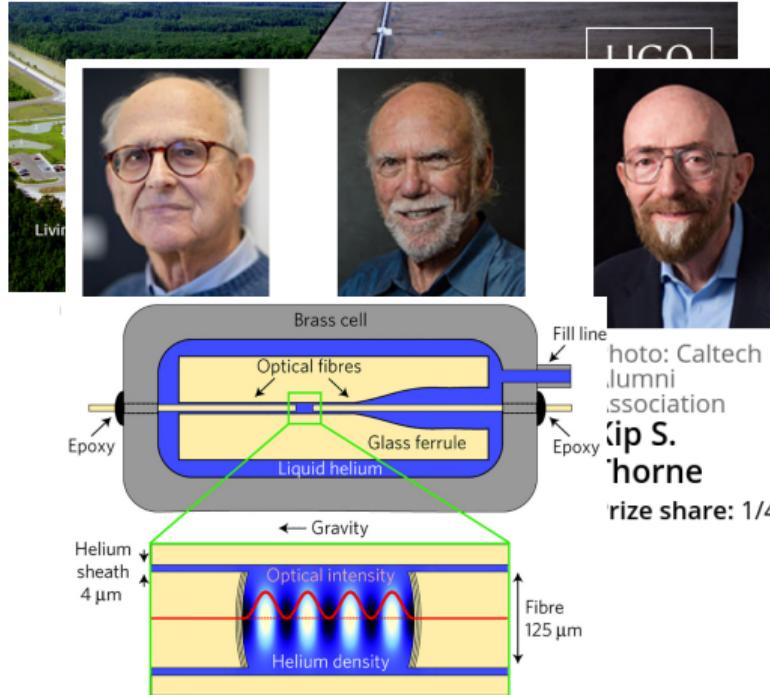
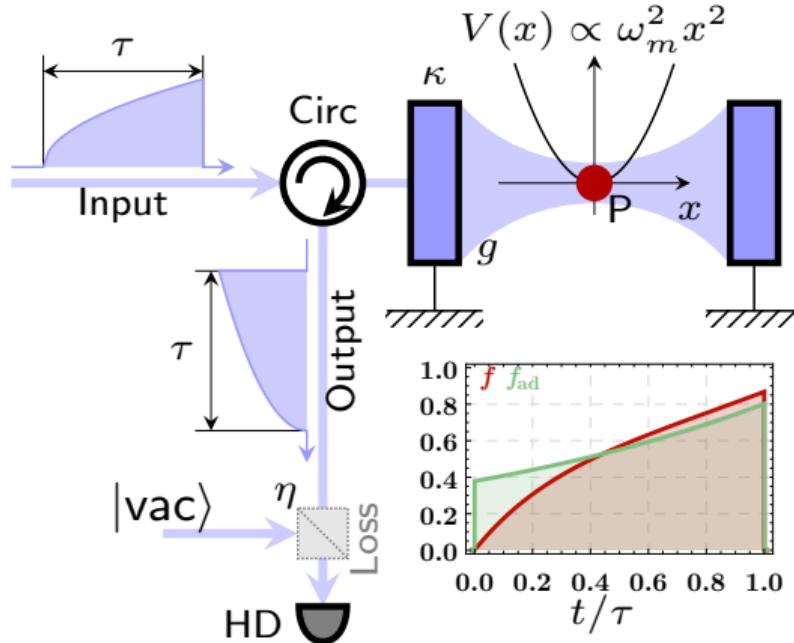


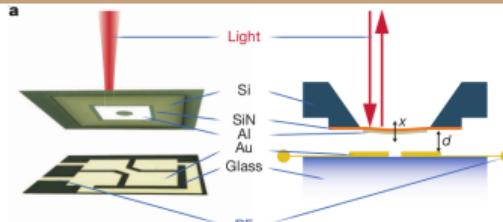
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# Levitated Optomechanics



# Advantages of Optomechanics for Quantum Technology

## Quantum Communication

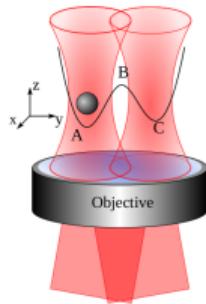


Bagci *et al.*, Nature 507, 81 (2014)

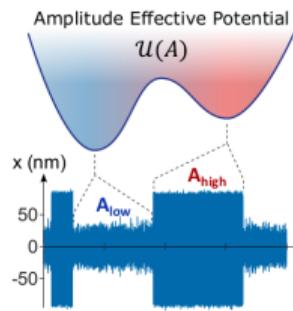
## Quantum Metrology

- ★ High-Q oscillators
- ★ Squeezed states

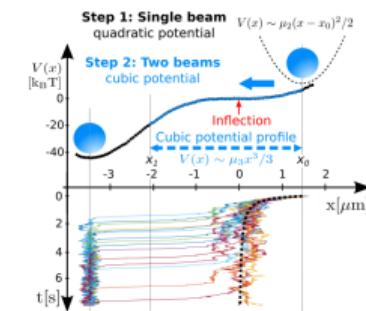
## Quantum Computation and Simulation: Nonlinear Potentials



Rondin *et al.*, Nat. Nano 12, 1130 (2017)



Ricci *et al.*, Nat. Comms 8, 15141 (2017)



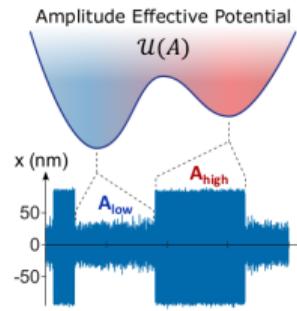
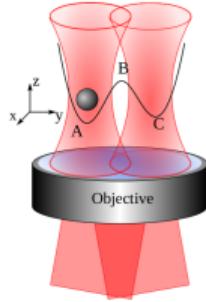
Siler *et al.*, Sci Rep 7, 1697 (2017)

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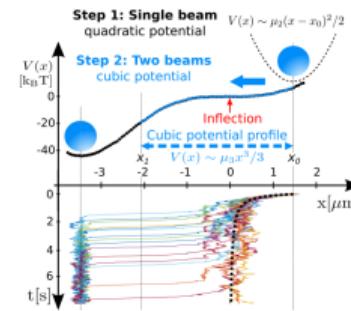
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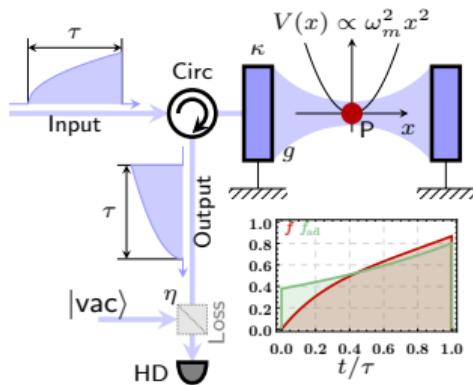
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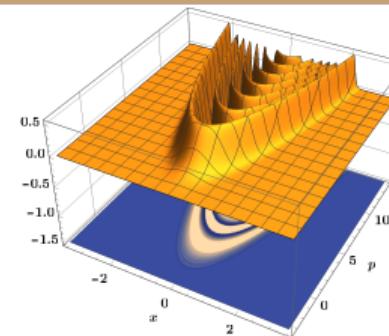
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# Main Results

## Squeezing Mechanical Motion



## Approximate Cubic Phase State



$$|\gamma\rangle = e^{i\gamma x^3} |p\rangle \approx e^{i\gamma x^3} \hat{S} |0\rangle$$

A soft-focus, monochromatic image of a city skyline. In the center-right, a large cathedral with two prominent spires is visible, surrounded by other historical and modern buildings. The sky is filled with large, white, billowing clouds.

Introduction

Linear Optomechanics

Quantum Squeezing and Entanglement

Pulsed Optomechanics

Mechanical Squeezing

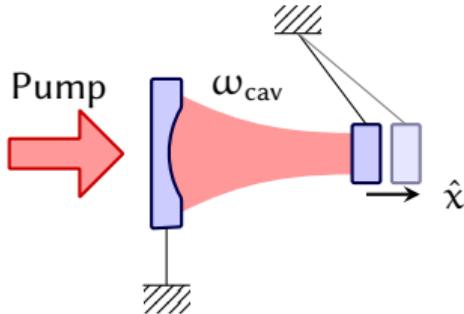
Cubic Phase State in Levitated Optomechanics

Introduction to Cubic Phase States

CPS Preparation

CPS Evaluation

# The Optomechanical systems



## Radiation

Standard quantization of the cavity field

$$\hat{E}(\mathbf{r}, t) = \sum_p \sum_k e_p u_k(\mathbf{r}) \hat{a}_k(t)$$

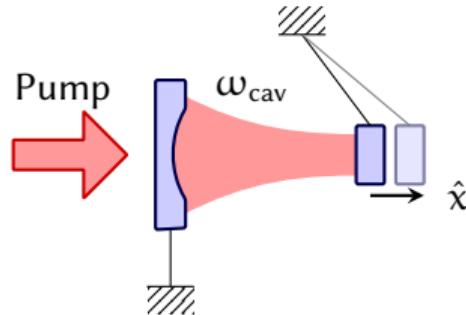
## Mechanics

Displacement field

$$\hat{v}(\mathbf{r}, t) = \sum_n v_n(\mathbf{r}) \hat{x}_n(t)$$

Only one field mode  $a$  and one mechanical  $x$  are considered.

# The Optomechanical interaction

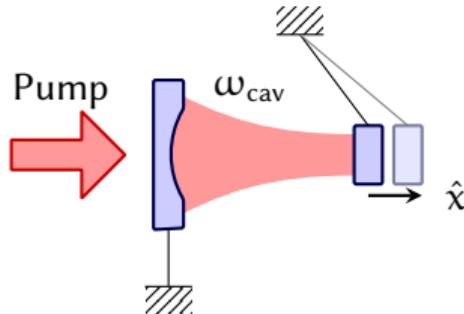


The single-mode cavity Hamiltonian

$$H_{\text{tot}} = \hbar\omega_{\text{cav}}[x] a^\dagger a + H_m$$

$g_0$  – single-photon optomechanical coupling, typically small

# The Optomechanical interaction

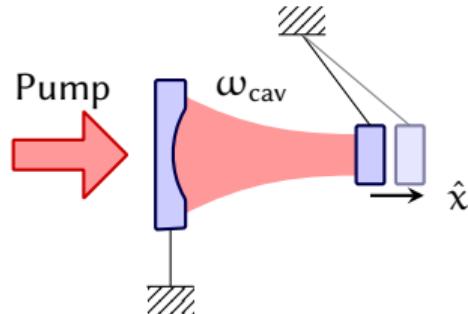


The single-mode cavity Hamiltonian

$$H_{\text{tot}} = \hbar \omega_{\text{cav}}[x] a^\dagger a + H_m = \hbar \left[ \omega_{\text{cav}} + \frac{\partial \omega_{\text{cav}}}{\partial x} \Big|_{x=0} \cdot x \right] a^\dagger a + H_m$$

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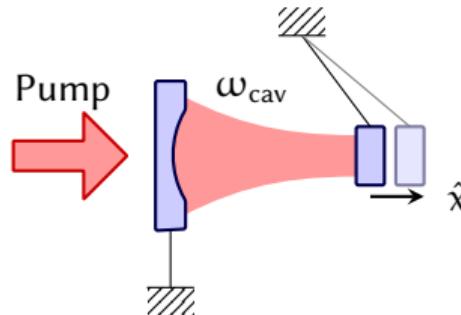


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$g_0$  – single-photon optomechanical coupling, typically small

# The Optomechanical interaction



The single-mode cavity Hamiltonian

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$g_0$  — single-photon optomechanical coupling, typically small

In presence of strong classical pump the interaction is linearized

$$H = \hbar\omega_{\text{cav}}a^\dagger a - \hbar g(a^\dagger + a)(b_m^\dagger + b_m) + \hbar\omega_m b_m^\dagger b_m.$$

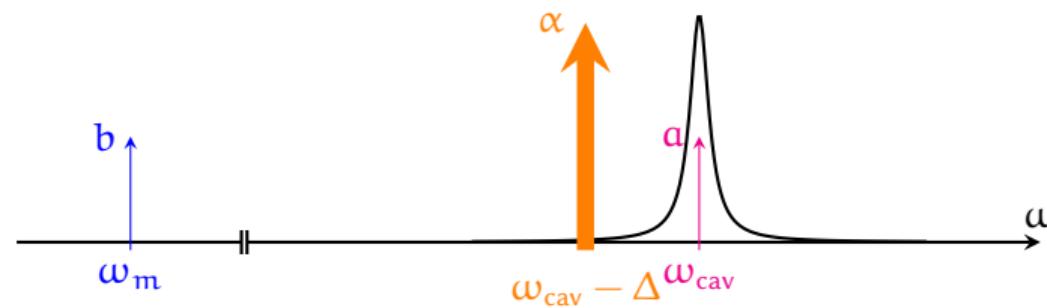
# Linearized Optomechanics

## The Hamiltonian

$$H = \hbar\Delta a^\dagger a + \hbar\omega_m b^\dagger b - \hbar g(a^\dagger + a)(b^\dagger + b)$$

## The main participants

- a quantum optical mode at  $\omega_{\text{cav}}$
- $\alpha$  strong classical pump at  $\omega_{\text{cav}} - \Delta$
- b quantized mechanical motion at  $\omega_m$

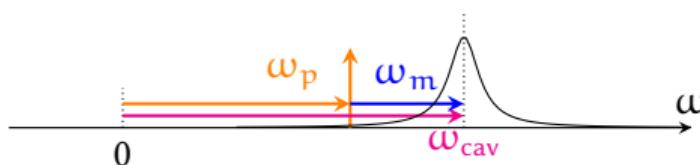


# Resolved-sideband optomechanics

## Lower Mechanical Sideband

Pump at the difference frequency

$$\omega_p = \omega_{\text{cav}} - \omega_m$$



$$H \propto ab^\dagger + a^\dagger b$$

- ★ Parametric Converter / Beam-splitter
- ★ State swap / Cooling

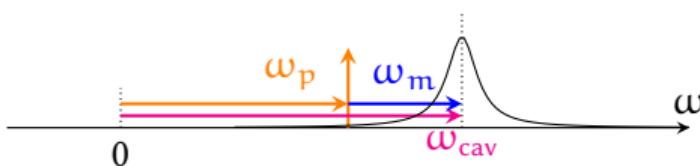
Required: resolved sideband  $\kappa \ll \omega_m$

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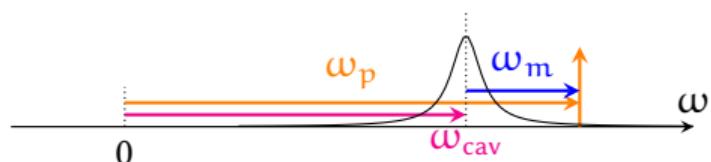
$$H \propto ab^\dagger + a^\dagger b$$

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## Upper Mechanical Sideband

Pump at the sum frequency

$$\omega_p = \omega_{\text{cav}} + \omega_m,$$



$$H = ab + a^\dagger b^\dagger$$

- ★ Parametric Amp / Two-mode squeezing
- ★ Entanglement

Required: resolved sideband  $\kappa \ll \omega_m$

# Digression: Optical Spring

## Radiation Pressure Force

$$\begin{aligned} F_{RP}(t) &\propto P(x) = -Kx \\ &= -Kx(t - \tau_*) \\ &\approx -Kx(x - \tau_* \dot{x}) = -Kx + \Gamma \dot{x} \end{aligned}$$

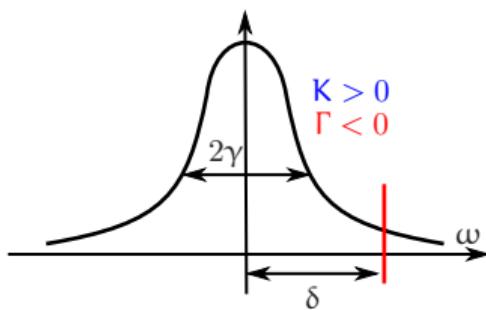
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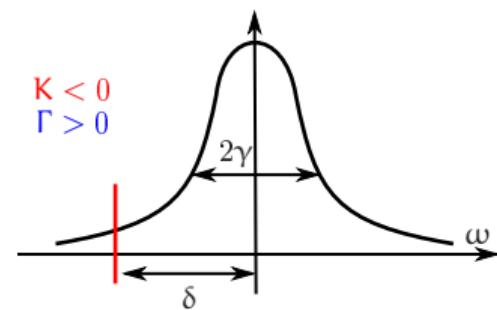
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Электромагнитная жесткость впервые наблюдалась В. Б. Брагинским <sup>3</sup>

Настройка на правый склон



Настройка на левый склон



Положительная жесткость и  
отрицательное затухание

Отрицательная жесткость и  
положительное затухание

▶ Назад

<sup>3</sup>V.B. Braginsky, I.I. Minakova Bull. MSU III 1, 83 (1964)  
А. Рахубовский (физфак МГУ)

A soft-focus photograph of a city skyline under a cloudy sky. In the center-right, a large Gothic-style cathedral with two prominent spires is visible. To its left are several smaller buildings, some with red roofs. In the foreground, there are more modern-looking buildings and trees.

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# Environment

## Optical Environment



$\kappa_{\text{ext}}$  detection channel,  $\kappa_L$  losses

Interacts with the modes of travelling light,  
(almost) each in vacuum. Collective operator  $a_i$

$$[a_i(t), a_i^\dagger(t')] = \delta(t - t');$$

$$\frac{1}{2} \left\langle a_i(t)a_i^\dagger(t') + a_i^\dagger(t')a_i(t) \right\rangle = \delta(t - t').$$

Typically the cavity is overcoupled with

$$\kappa_{\text{ext}} \gg \kappa_L$$

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## Mechanical Environment

Q-factor:

$$Q_{\text{tot}}^{-1} = Q_{\text{clamp}}^{-1} + Q_{\text{mat}}^{-1} + Q_{\text{air}}^{-1} + Q_{\text{scat}}^{-1} + \dots$$

At rate  $\gamma = \omega_m/Q$  coupled to a thermal bath with bosonic operator  $b^{\text{th}}$ :

$$\begin{aligned} [b^{\text{th}}(t), b^{\text{th}\dagger}(t')] &= \delta(t - t'), \\ \frac{1}{2} \langle \{b^{\text{th}}(t), b^{\text{th}\dagger}(t')\} \rangle &= (2n_{\text{th}} + 1)\delta(t - t'). \end{aligned}$$

$$n_{\text{th}} = \frac{1}{\exp[\hbar\omega_m/k_B t] - 1} \approx k_B T/\hbar\omega_m$$

## Equations of motion

Assume blue detuning  $\omega_p = \omega_{\text{cav}} + \omega_m$ , therefore  $H = -\hbar g(a^\dagger b^\dagger + ab)$ .

$$\dot{a} = igb^\dagger - \kappa a + \sqrt{2\kappa}a^{\text{in}},$$

$$\dot{b} = iga^\dagger - \frac{\gamma}{2}b + \sqrt{\gamma}b^{\text{th}}$$

Input-output relation for optics  $a^{\text{out}} = -a^{\text{in}} + \sqrt{2\kappa}a$

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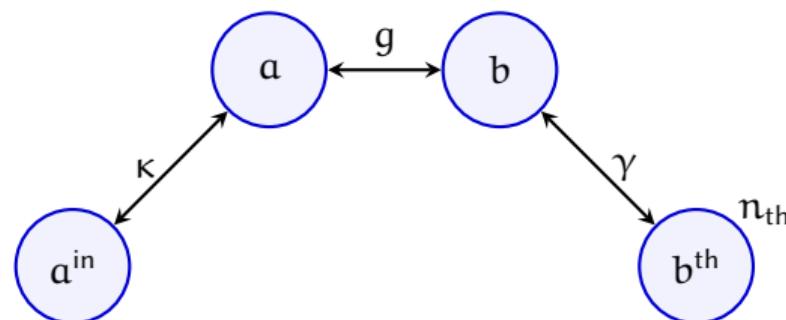
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Parameters:

- ★ Resolved sideband  $\kappa \ll \omega_m$
- ★ Weak coupling  $g \sim 10^{-3} \div -1 \kappa$
- ★ Slow mechanical decay  $\gamma \sim 10^{-7} \div -4 \kappa$
- ★ Not too hot bath  $\gamma n_{\text{th}} \leq \{g, \kappa\}$



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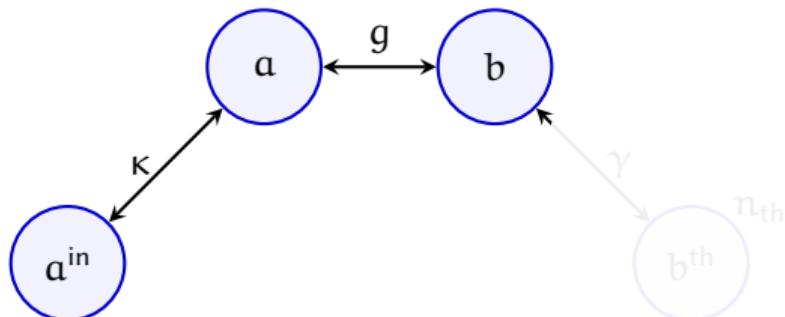
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That is,

- ★ mechanical decay can be approximately ignored



# Equations of motion

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$$0 = igb^\dagger - \kappa a + \sqrt{2\kappa}a^{\text{in}},$$

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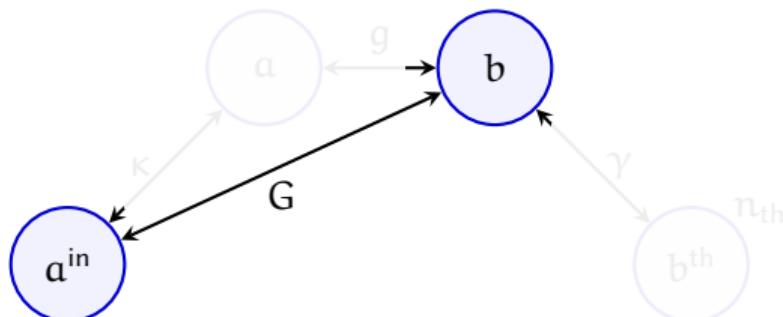
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- ★ cavity mode can be adiabatically eliminated



# Equations of motion

Assume blue detuning  $\omega_p = \omega_{\text{cav}} + \omega_m$ , therefore  $H = -\hbar g(a^\dagger b^\dagger + ab)$ .

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$$\dot{b} = iga^\dagger$$

Input-output relation for optics  $a^{\text{out}} = -a^{\text{in}} + \sqrt{2\kappa}a$

$$A^{\text{out}} = \sqrt{\mathfrak{G}}A^{\text{in}} + \sqrt{\mathfrak{G}-1}b^\dagger(0),$$

$$b(\tau) = \sqrt{\mathfrak{G}}b(0) + \sqrt{\mathfrak{G}-1}A^{\text{in},\dagger}.$$

$$A^{\text{in}} \propto \int_0^\tau dt a^{\text{in}}(t)e^{Gt}, \quad A^{\text{out}} \propto \int_0^\tau dt a^{\text{out}}(t)e^{-Gt}.$$

$$\left[ a^k(t), a^{k',\dagger}(t') \right] = \delta(t-t')\delta_{kk'}.$$

Parameters:

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## Two-mode squeezing

In general case (when adiabatic model does not hold,  $g \propto \kappa$ )

Define  $\mathbf{a} = (a, b)$ ,  $\mathbb{A}, \mathbf{f} = (\sqrt{2\kappa}a^{\text{in}}, \sqrt{\gamma}b^{\text{th}})$ , then

$$\dot{\mathbf{a}} = \mathbb{A} \cdot \mathbf{a} + \mathbf{f}$$

Formal solution (with  $\mathbb{M}(s) = \exp[-\mathbb{A}s]$ )

$$\mathbf{a}(t) = \mathbb{M}(t)\mathbf{a}(0) + \int_0^t ds \mathbb{M}(t-s).\mathbf{f}(s).$$

Input-output transformations

$$A^{\text{out}} = \sqrt{\mathfrak{G}} A^{\text{in}} + \sqrt{\mathfrak{G} - 1} b^\dagger(0) + \text{Noise},$$

$$b(\tau) = \sqrt{\mathfrak{G}} b(0) + \sqrt{\mathfrak{G} - 1} A^{\text{in},\dagger} + \text{Noise}.$$

Two-mode squeezing gain

$$\mathfrak{G} = \mathfrak{G}(\kappa, g, \gamma_m, \tau),$$

Input-output pulse bosonic operators

$$A^{\text{in}} = \int_0^\tau dt a^{\text{in}}(t) f^{\text{in}}(\tau - t),$$

$$A^{\text{out}} = \int_0^\tau dt a^{\text{out}}(t) f^{\text{out}}(\tau - t).$$

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A soft-focus, monochromatic image of a city skyline. In the center-right, a large cathedral with two prominent spires is visible. To its left are several smaller buildings, some with red roofs. In the foreground, there are more modern, low-rise buildings and trees. The sky is filled with wispy clouds.

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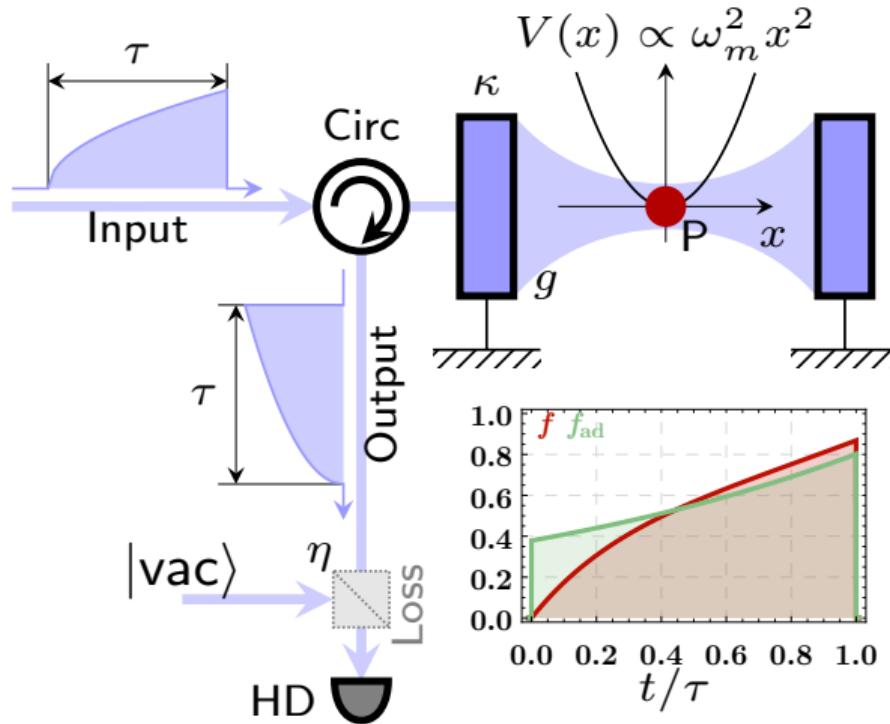
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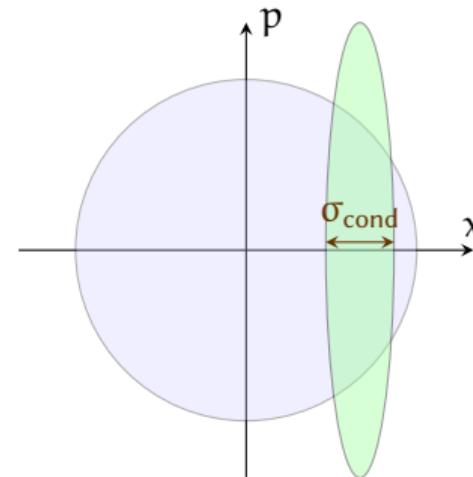
CPS Evaluation

# The Protocol for Squeezing [Quant. Sci. Technol. 4, 024006 (2019)]

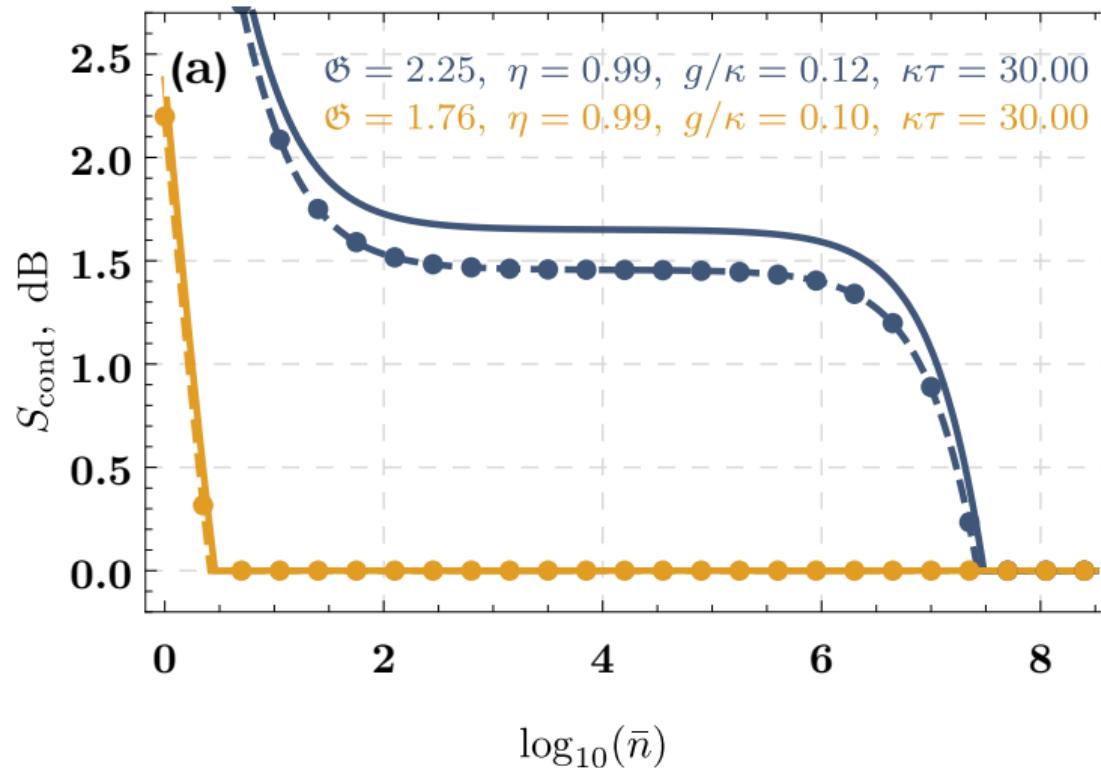


$$A^{\text{out}} = \int_0^\tau dt a^{\text{out}}(\tau - t) f^{\text{out}}(t).$$

$f^{\text{out}}(t)$  depends on the interaction type. Detecting proper  $A^{\text{out}}$  projects mechanical mode on a displaced squeezed state.

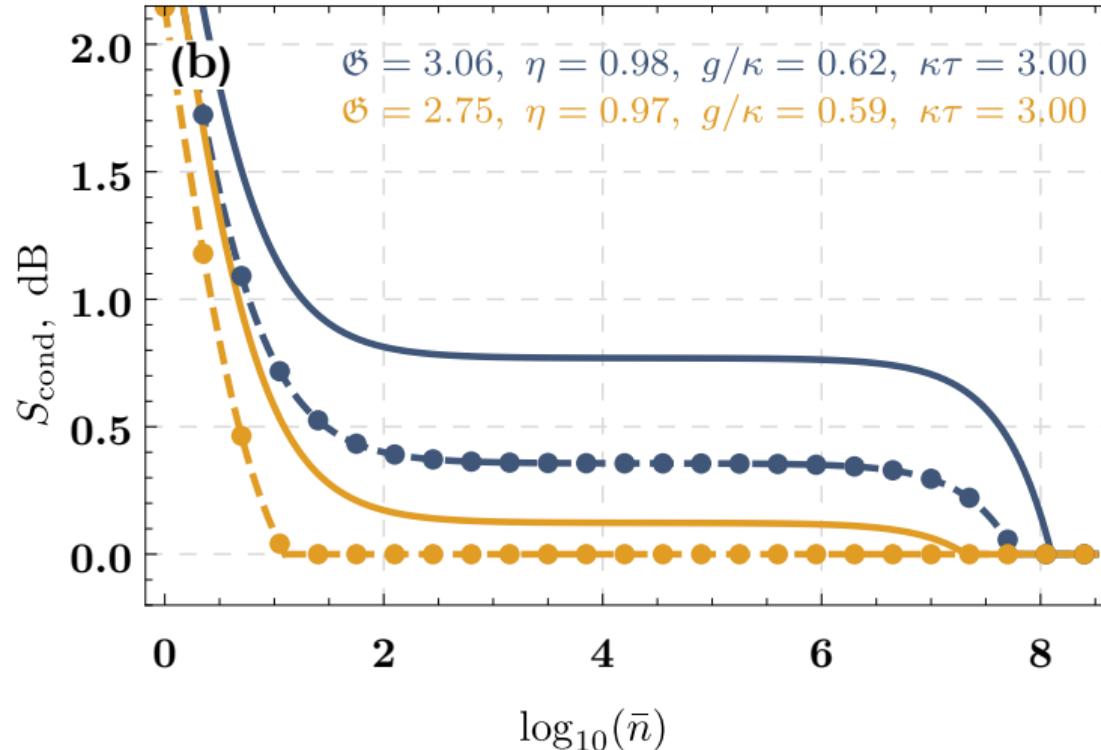


# Squeezing in Adiabatic Regime



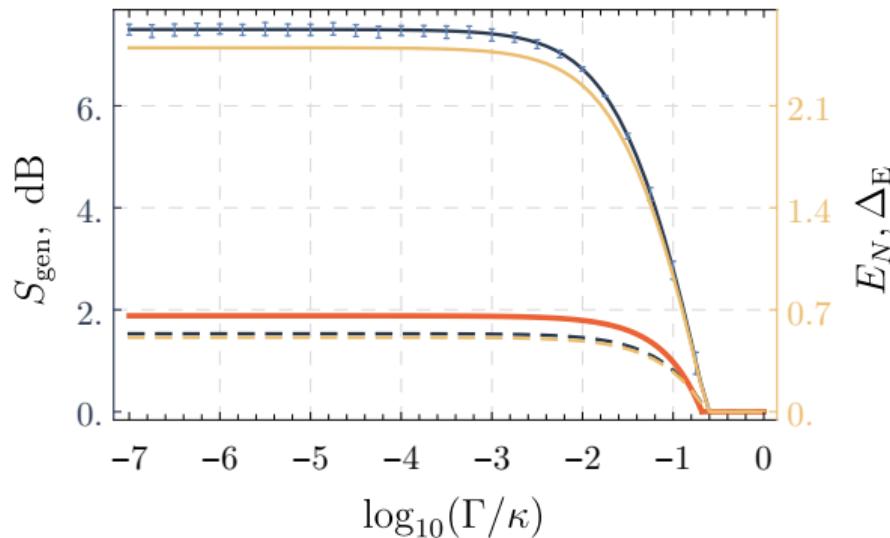
$$S_{\text{cond}} = -10 \log_{10} \sigma_{\text{cond}}$$

## Squeezing in Non-adiabatic Regime



$$S_{\text{cond}} = -10 \log_{10} \sigma_{\text{cond}}.$$

# Generalized Squeezing and Entanglement



$$S_{\text{gen}} = -10 \log_{10} \min \text{EigenVal}[V_{\text{cov}}].$$

$\Gamma = \gamma_m n_{\text{th}} - \text{reheating rate}$   
 $\Delta_E - \text{Duan's variance criterion violation.}$

A soft-focus, monochromatic image of a city skyline. In the center-right, a large cathedral with two prominent spires is visible, surrounded by other historical and modern buildings. The sky is filled with large, white, billowing clouds.

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Linear Optomechanics

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Mechanical Squeezing

Cubic Phase State in Levitated Optomechanics

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CPS Preparation

CPS Evaluation

# CPS state

Devised by Gottesman, Kitaev and Preskill<sup>3</sup>

$$|\gamma_{\text{GKP}}\rangle \propto \int dx e^{i\gamma x^3} |x\rangle = e^{i\gamma x^3} |p=0\rangle,$$

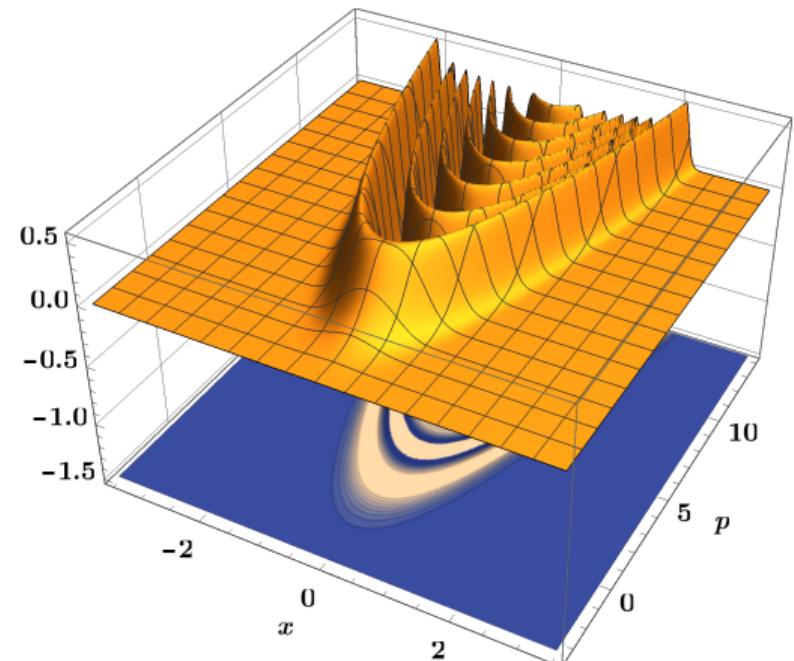
Wigner Function

$$W_{\text{GKP}}(x, p) \propto \text{Ai}\left[\left(\frac{4}{3\gamma}\right)^{1/3} (3\gamma x^2 - p)\right].$$

Nonlinear variance

$$(x, p) \rightarrow (x, p + \gamma x^2) \Rightarrow \langle \delta(p - \lambda x^2)^2 \rangle \rightarrow 0.$$

Required for (in particular) the  
measurement-based quantum computing.



<sup>3</sup>Gottesman, Kitaev, Preskill, PRA **64**, 012310 (2001)

# Measurement-based computing

PHYSICAL REVIEW A **97**, 022329 (2018)

## General implementation of arbitrary nonlinear quadrature phase gates

Petr Marek,<sup>1,\*</sup> Radim Filip,<sup>1</sup> Hisashi Ogawa,<sup>2</sup> Atsushi Sakaguchi,<sup>2</sup> Shuntaro Takeda,<sup>2</sup> Jun-ichi Yoshikawa,<sup>2,3</sup> and Akira Furusawa<sup>2,†</sup>

<sup>1</sup>*Department of Optics, Palacký University, 17. listopadu 1192/12, 77146 Olomouc, Czech Republic*

<sup>2</sup>*Department of Applied Physics, School of Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan*

<sup>3</sup>*Quantum-Phase Electronics Center, School of Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan*



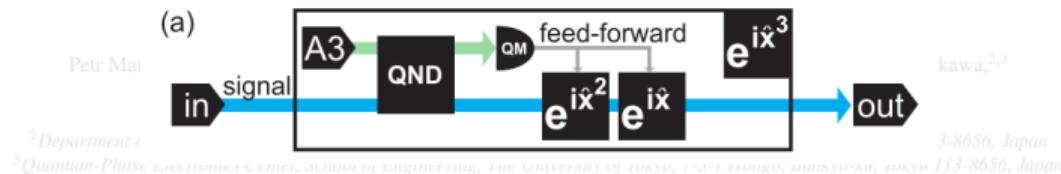
(Received 10 August 2017; published 20 February 2018)

We propose general methodology of deterministic single-mode quantum interaction nonlinearly modifying single quadrature variable of a continuous-variable system. The methodology is based on linear coupling of the system to ancillary systems subsequently measured by quadrature detectors. The nonlinear interaction is obtained by using the data from the quadrature detection for dynamical manipulation of the coupling parameters. This measurement-induced methodology enables direct realization of arbitrary nonlinear quadrature interactions without the need to construct them from the lowest-order gates. Such nonlinear interactions are crucial for more practical and efficient manipulation of continuous quadrature variables as well as qubits encoded in continuous-variable systems.

DOI: [10.1103/PhysRevA.97.022329](https://doi.org/10.1103/PhysRevA.97.022329)

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PHYSICAL REVIEW A 97, 022329 (2018)



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FIG. 1. Schematic circuits for various implementations of nonlinear gates. QND: quantum nondemolition interaction; QM: quadrature

This with measurement;  $A_k$ : ancillary state of the  $k$ th order squeezed in

prac vari  $\hat{p} - N \chi_N \hat{x}^{N-1}$ .  $e^{i\hat{x}^k}$ : unitary realization of  $k$ th-order nonlinear gate

with arbitrary strength. (a) Cubic gate with  $N = 3$ ; (b) ( $N + 1$ )th-

DOI: 10.1103/PhysRevA.97.022329

$$\text{Required } \text{Var}(p - \lambda x^2) \rightarrow 0$$

A soft-focus, monochromatic image of a city skyline. In the center-right, a large cathedral with two prominent spires is visible. To its left are several smaller buildings, some with red roofs. In the foreground, there are more modern-looking buildings and trees. The sky is filled with large, white, billowing clouds.

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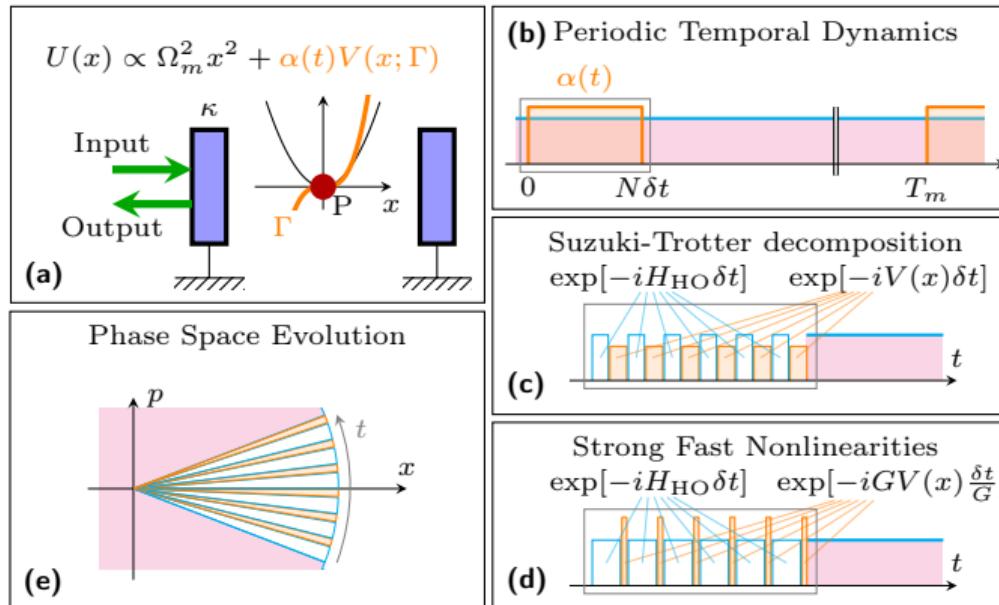
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# The Model

Rakhubovsky and Filip [arxiv:1904.00773]



$$\left[ \exp[-i(H_{HO} + V(x))\delta t] \right]^N \approx \left[ \mathcal{U}_{HO}(\delta t) \mathcal{U}_{NL}(\delta t) + O(\delta t^2) \right]^N,$$

# Numerical evaluation

## Cubic evolution

In coordinate basis

$$\rho(x, x') \rightarrow \rho(x, x') e^{-i\gamma(x^3 - x'^3)}.$$

## Harmonic evolution

Rotation in phase space

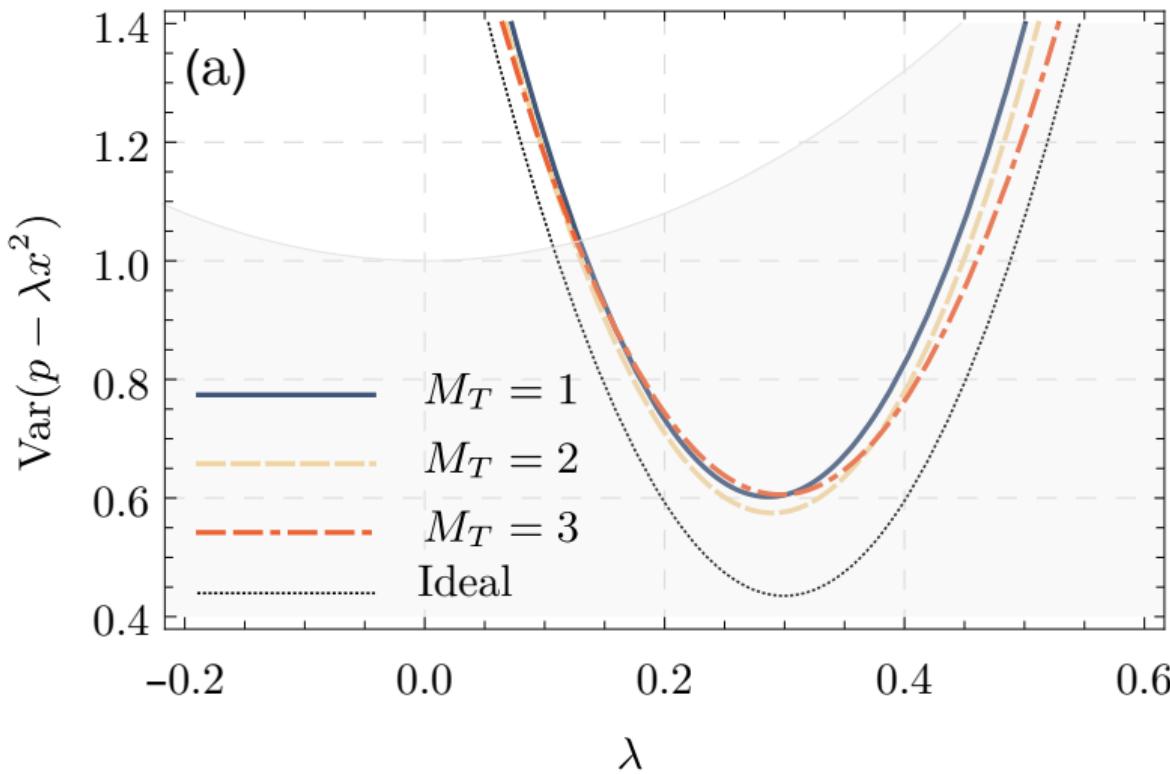
$$W(x, y) \rightarrow W(x \cos \delta + y \sin \delta, x \sin \delta + y \cos \delta).$$

## Decoherence

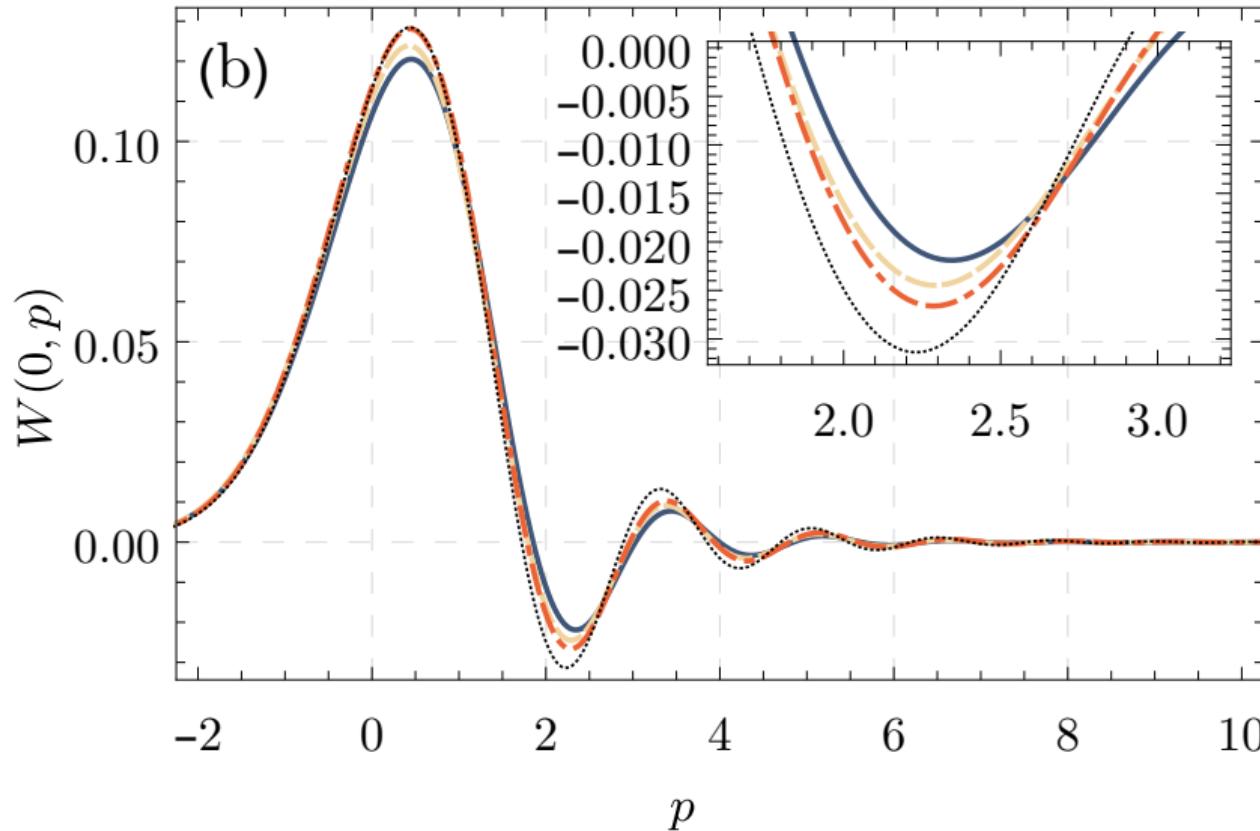
Convolution in phase space with a Gaussian kernel

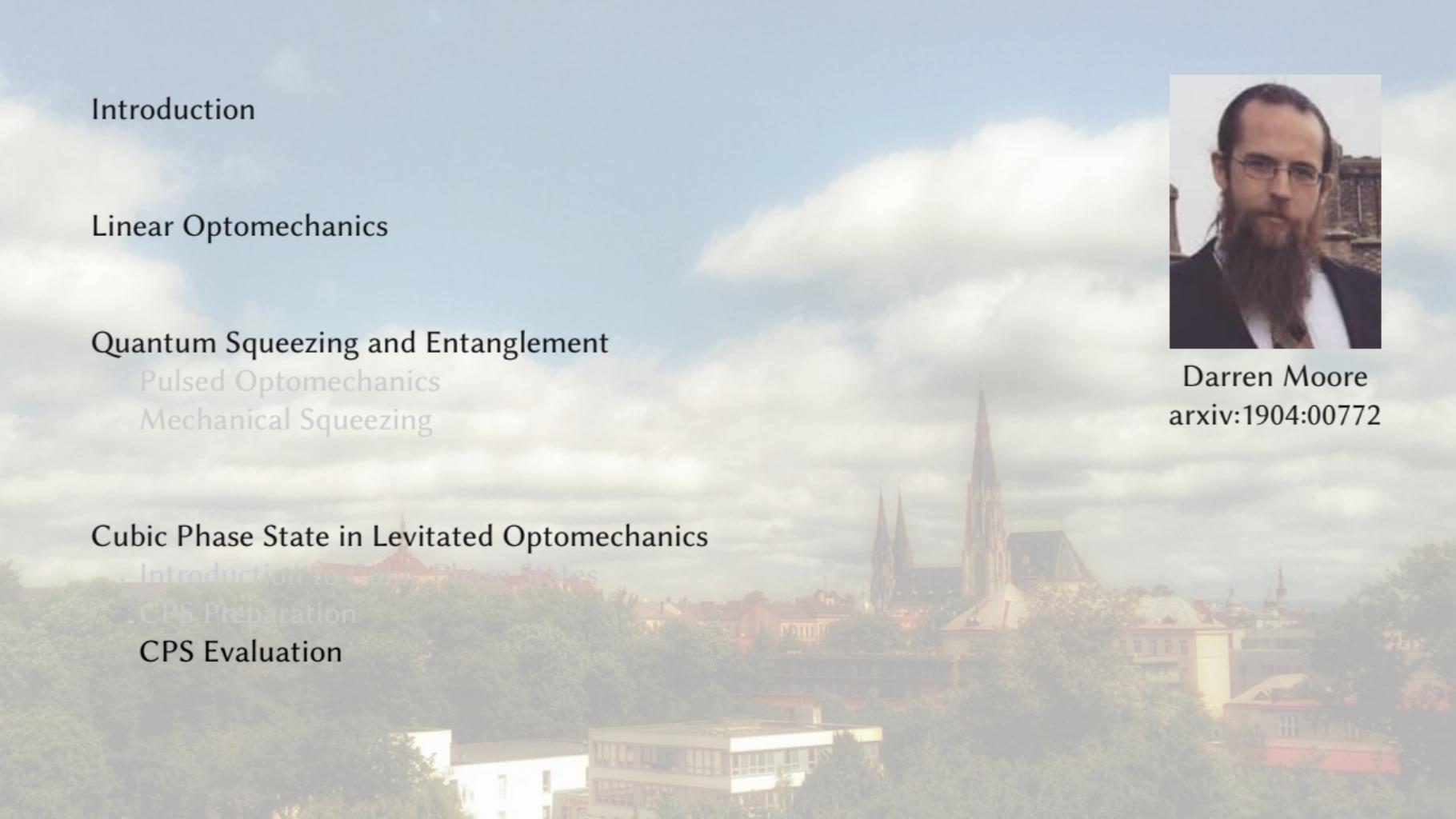
$$W(x, y) \rightarrow \iint d\xi d\eta W(x - \xi, y - \eta) W_{\text{th}}(\xi, \eta).$$

## Nonlinear Variance



## Wigner Function Cuts





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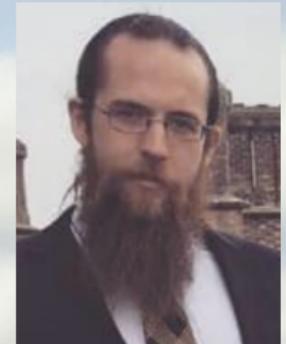
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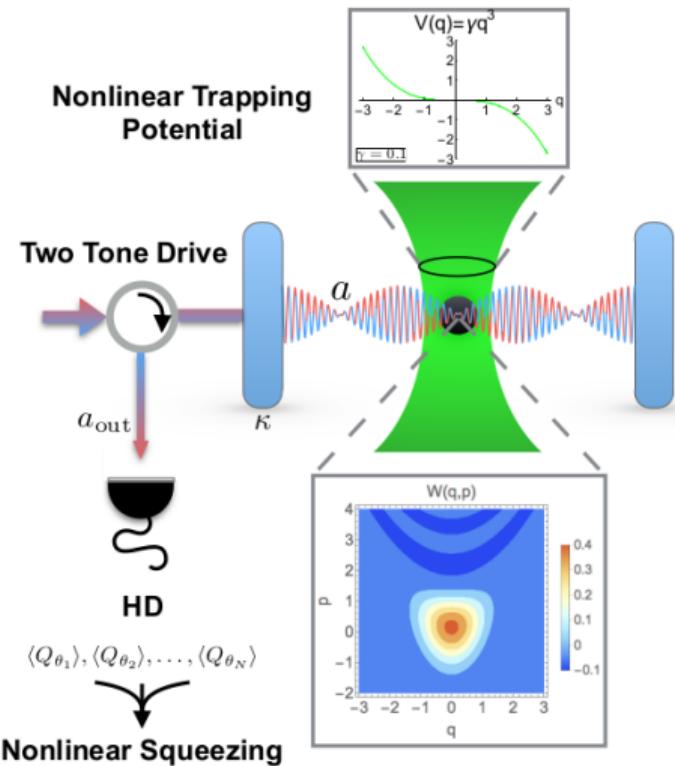
CPS Preparation

CPS Evaluation



Darren Moore  
arxiv:1904:00772

# The Model



Approximate cubic phase state in mechanics

$$e^{i\gamma q^3} |p=0\rangle .$$

Pulsed QND interaction

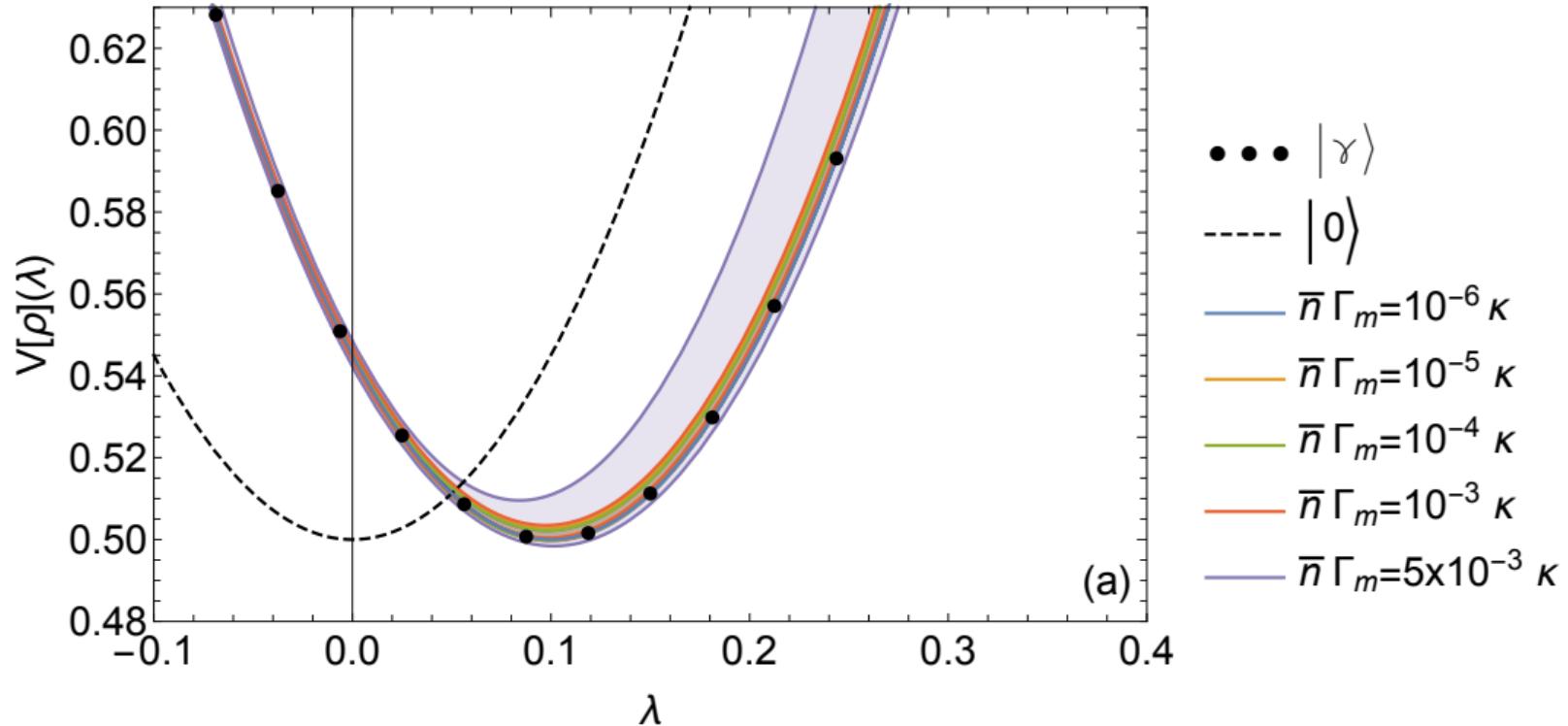
$$H_{\text{int}} \propto x_{\text{light}}(q \cos \phi + p \sin \phi).$$

Detect leaking light

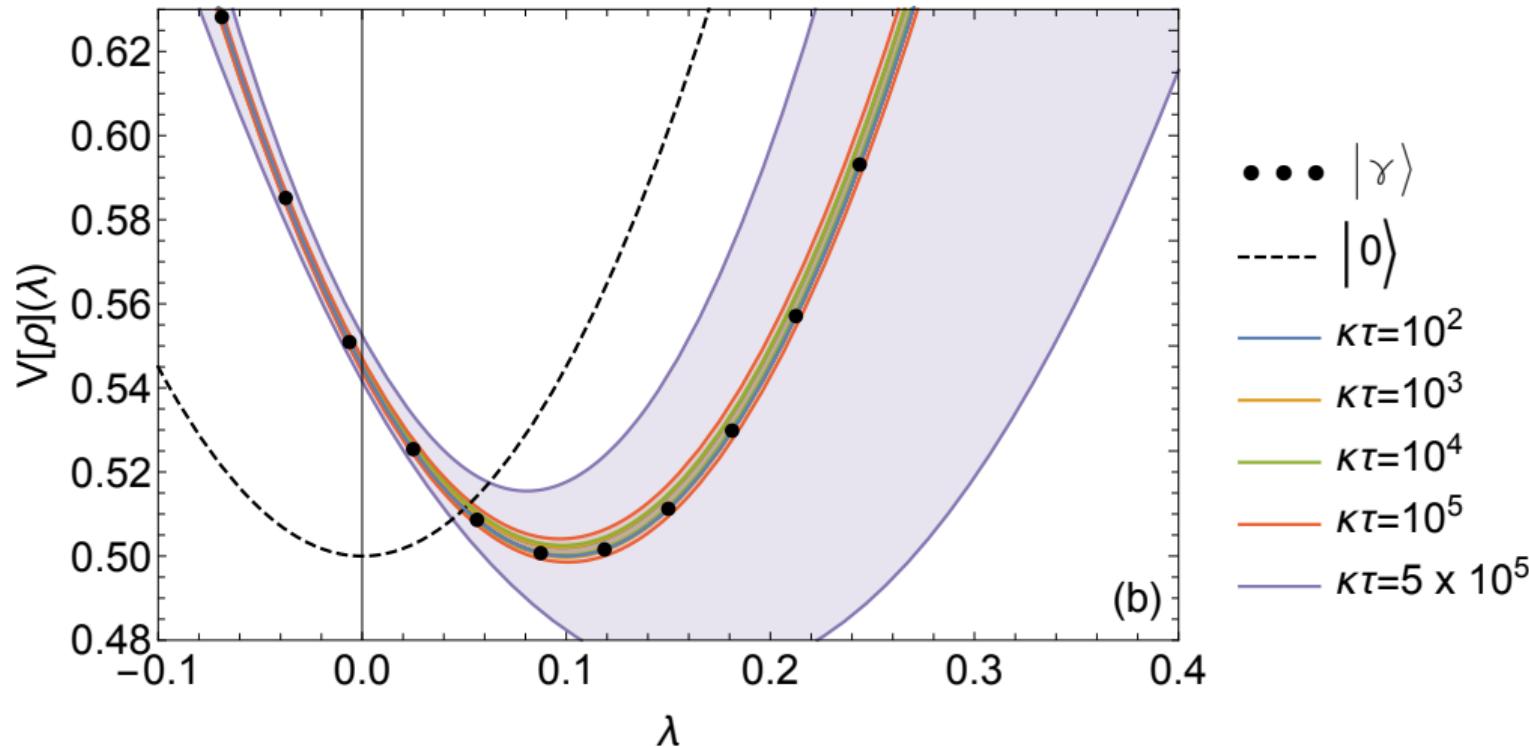
Estimate nonlinear variance

$$q_{\text{NL}} = p - \lambda x^2 \Rightarrow \text{Var}[q_{\text{NL}}]$$

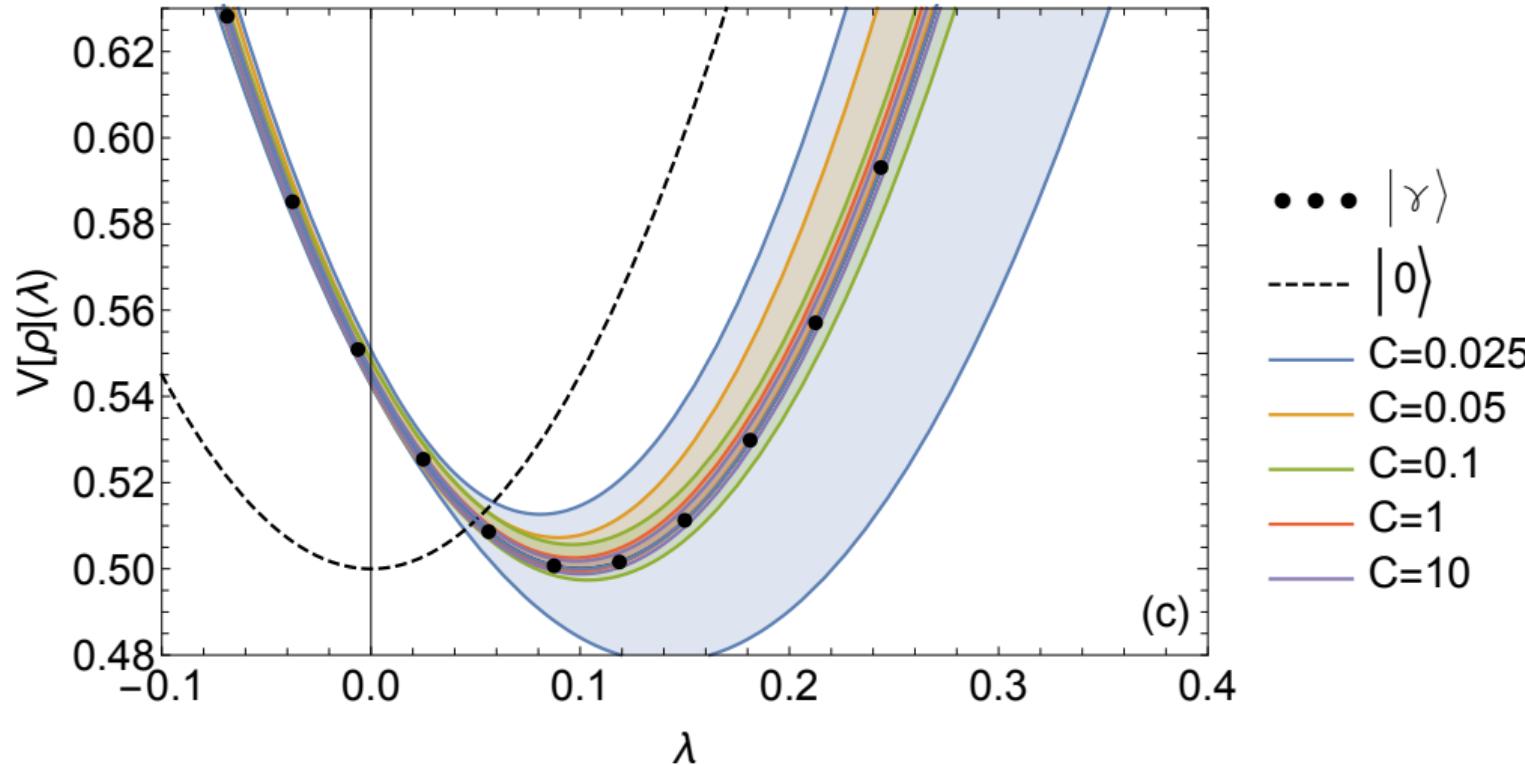
Evaluation  $V[\rho](\lambda) = \text{Tr}(\rho[\Delta(p - \lambda x^2)]^2)$



$$\text{Evaluation } V[\rho](\lambda) = \text{Tr}(\rho[\Delta(p - \lambda x^2)]^2)$$



$$\text{Evaluation } V[\rho](\lambda) = \text{Tr}(\rho[\Delta(p - \lambda x^2)]^2)$$



## Conclusion

- ★ Levitated optomechanics allows production of mechanical squeezed states in the linearized blue-detuned regime
- ★ Optomechanical entanglement is possible and can be witnessed
- ★ Approximate Cubic Phase State can be prepared and verified with optomechanics

# Thank You!

These slides: <http://bit.ly/ar-minsk-2019>

Phd positions available