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Quantum Stroboscopic Nonlineari

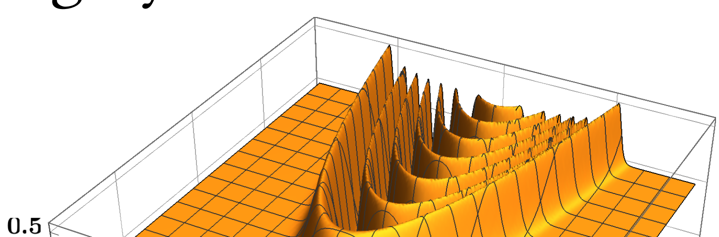
Introduction and Motivation

Recently reported ground state cooling of levitated nanoparticles (NP) combined with the ability to engineer nonlinear motional potential of these systems makes them a good candidate for truly quantum applications.

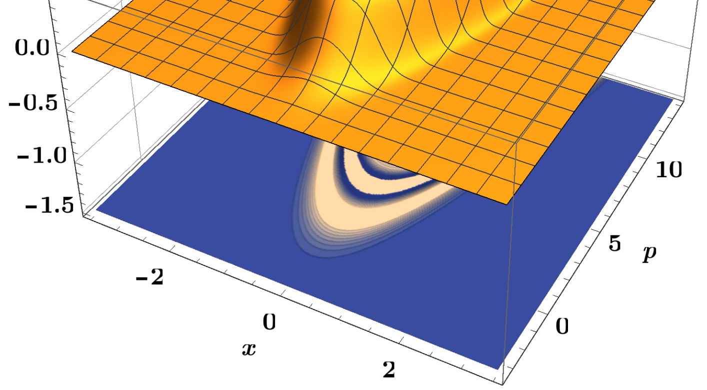
> We propose to engineer an approximate motional cubic phase state (CPS) of a levitated nanoparticle

Cubic phase space is a highly-nonclassical state:

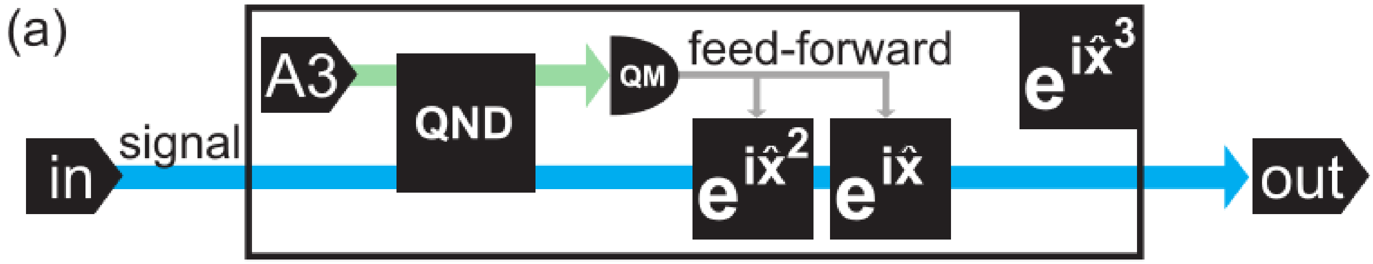
$$|\gamma\rangle = e^{-i\gamma\hat{x}^3}|p=0\rangle$$



$$\approx e^{-i\gamma\hat{x}^3}\hat{S}\,|0\rangle\,.$$



Has applications in measurement-based computing (Fig. from [1])



Figures of merit: negativity of Wigner function and

Broadcasting nonlinearity to a li

Motivation and preliminaries

Consider two harmonic oscillators that can have quantum non-demolition (QND) interaction (written as unitary with controllable gains $\chi_{1,2}$)

$$\hat{U}_{QND} = \exp[-i(\chi_1 qY + \chi_2 pX)].$$

One of the oscillators (*source*) also has an access to a nonlinear transformation

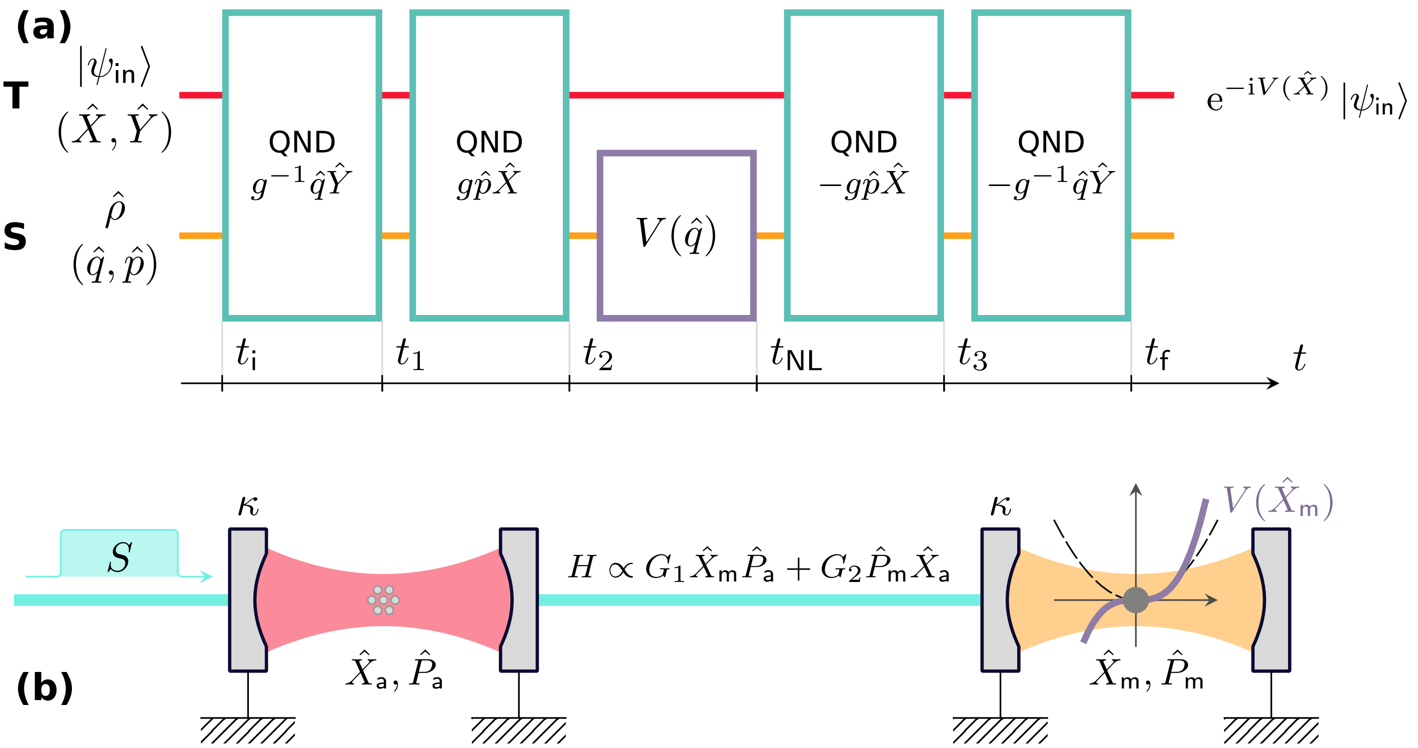
$$\hat{U}_{NL} = \exp[-i\alpha V(\hat{q})],$$

with $V(\bullet)$ being a regular nonlinear function [e.g., $V(\xi) \propto \xi^3$]

$V(\xi) \propto \xi^3$].

We propose to implement an ideal unitary non-linear transformation $e^{-iV(X)} |\psi_{in}\rangle$ on the linear target system using *only linear* QND interactions with the source system.

Principal setup



Above: a sequence of optimally arranged QND interactions between source and target system. Below: an

References

1. Marek, P. et al. *Physical Review A* **97,** 022329 (Feb. 2018). 2. Rakhu
Nature Physics, 1–6 (Sept. 2020). 5. Manukhova, A. D. et al. *npj Quan*

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nonlinear squeezing.

$$\exists\lambda \in \mathbb{R} : \sigma^{(3)}(\lambda) \equiv \operatorname*{Var}_{\rho}(p - \lambda x^2) < \sigma_{\text{vac}}$$

Compare with ordinary (linear) squeezing

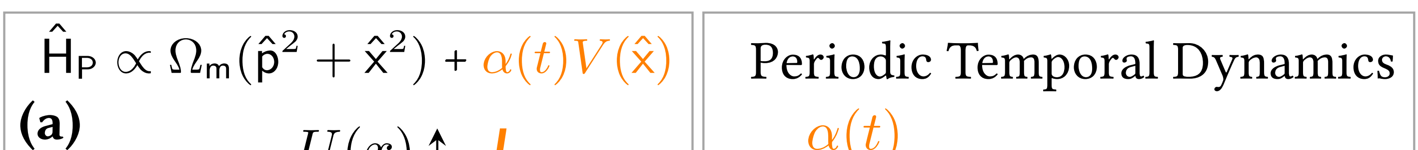
$$\mathrm{Var}(x \cos\theta - p \sin\theta) = (1+\lambda^2)^{-1}\,\mathrm{Var}(p - \lambda x) \propto \sigma^{(2)},$$

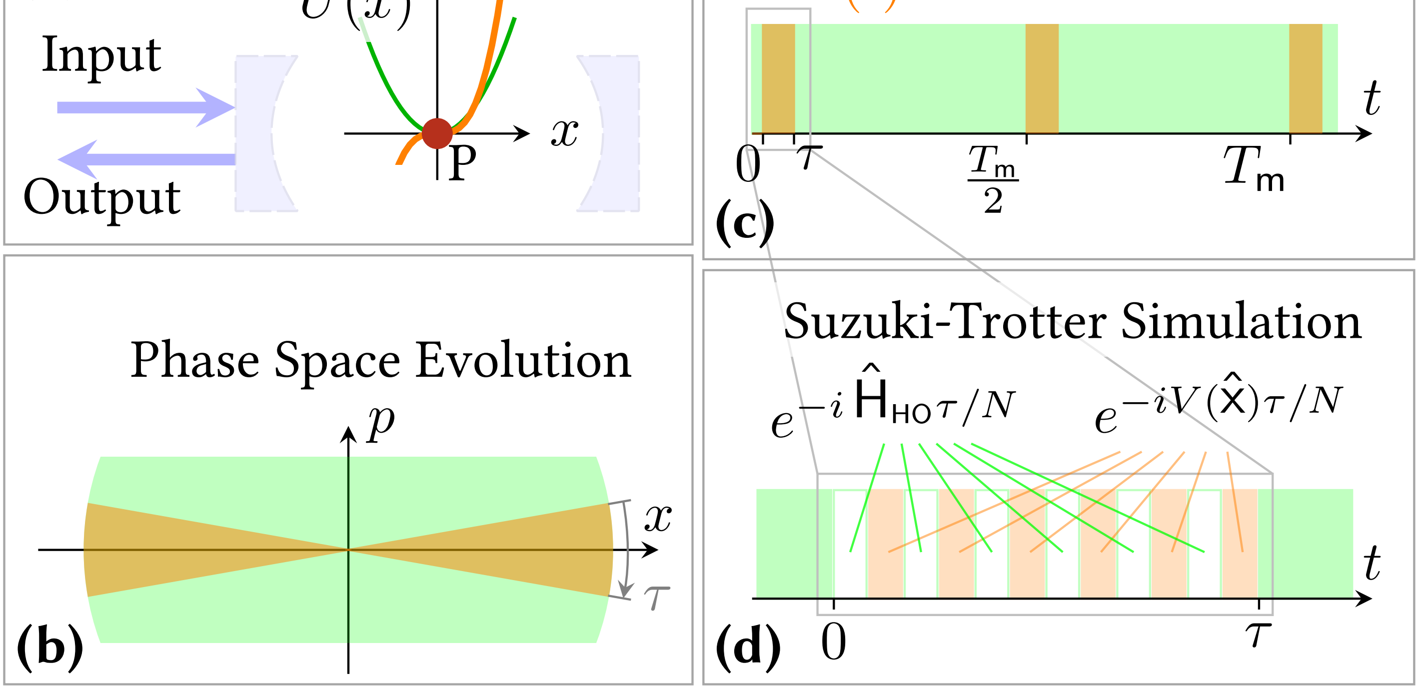
with $\lambda = \tan^{-1}\theta$. Squeezing condition: $\sigma^{(2)}(\lambda) < 1 + \lambda^2$.

Important thresholds for classical states and Gaussian states:

$$\sigma_{\text{NC}}(\lambda) = 1 + 2\lambda^2, \qquad \sigma_{\text{NG}}(\lambda) = 3\lambda^{2/3}/2^{1/3}.$$

Implementation with levitated optomechanics





Stroboscopic dynamics allows to simulate the desired purely nonlinear dynamics from the full dynamics including free motion ($\propto \mathsf{p}^2$):

…NEAR SYSTEM [ARXIV:230?.?????]

example implementation with spin ensemble and a levitated nanoparticle [4]. QND gate is implemented in a pulsed manner with help of squeezed light [5]. After the first two QND interactions (assuming arbitrary gains $\mathsf{g}_{(1,2)}$ the input-output relations read:

$$
\begin{aligned}
\hat{\mathsf{q}}_2 &= \mathsf{g}_2\hat{\mathsf{X}}_\mathsf{i} + (1 - \mathsf{g}_1\mathsf{g}_2)\hat{\mathsf{q}}_\mathsf{i},\\
\hat{\mathsf{p}}_2 &= \hat{\mathsf{p}}_\mathsf{i} + \mathsf{g}_1\hat{\mathsf{Y}}_\mathsf{i},\\
\hat{\mathsf{X}}_2 &= \hat{\mathsf{X}}_\mathsf{i} + \mathsf{g}_1\hat{\mathsf{q}}_\mathsf{i},\\
\hat{\mathsf{Y}}_2 &= \mathsf{g}_2\hat{\mathsf{p}}_\mathsf{i} + (1 - \mathsf{g}_1\mathsf{g}_2)\hat{\mathsf{Y}}_\mathsf{i}.
\end{aligned}
$$

Assuming $\mathsf{g}_2 = 1/\mathsf{g}_1 = \mathsf{g}$, the input $\hat{\mathsf{X}}$ quadrature is

Assuming $g_2 = 1/g_1 = g$, the input $\hat{X}$ quadrature is mapped onto $\hat{q}$ and amplified: $\hat{q}_2 = g\hat{X}_i$.
The nonlinear transformation maps $\hat{p}_3 = \hat{p}_2 + \alpha V'(\hat{q}_2)$. The two remaining QND (i) transfer the nonlinearity back to the target and (ii) cancel the effect of the source's initial state. Importantly, the nonlinearity is amplified:

$$\hat{X}_f = \hat{X}_i; \quad \hat{Y}_f = \hat{Y}_i - gV'(g\hat{X}_i).$$

Approximate Nonlinear Gate

An approximate gate on the target is implemented by $e^{-ig_2pX}e^{-iV(q)}e^{+ig_1pX}$.
The corresponding input-output relations for the target are

$$\hat{X}_f = \hat{X}_i; \quad \hat{Y}_f = \hat{Y}_i + g_2V'(g_1\hat{X}_i + \hat{q}_i).$$

The term $\propto \hat{q}_i$ contributes noise which can be compensated by initial squeezing of mechanical oscillator (available for NPs).

bovsky, A. A. & Filip, R. *npj Quantum Information* **7,** 120 (July 2021). 3. D
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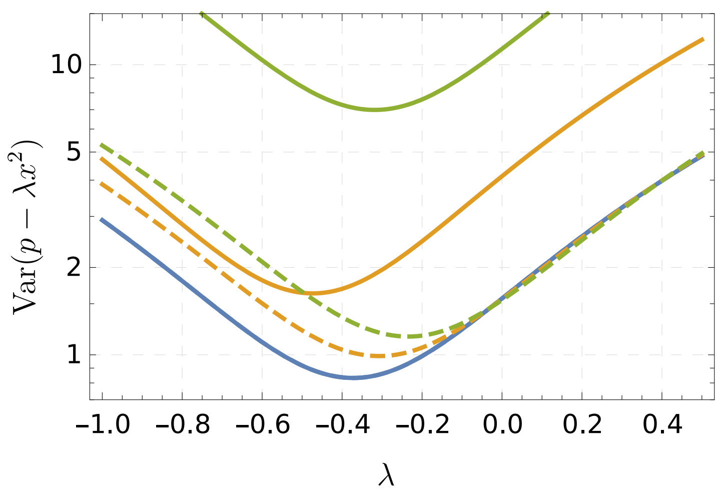
$$e^{-i[(p^2+x^2)+\alpha x^3]}$$

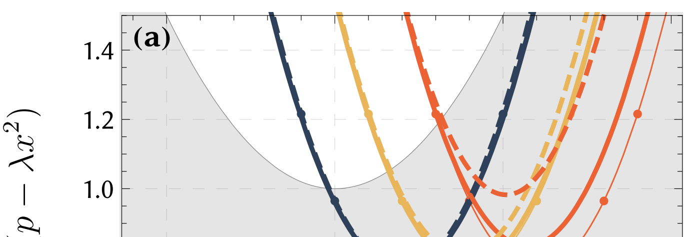
$$\rightsquigarrow e^{-i\alpha x^3}$$



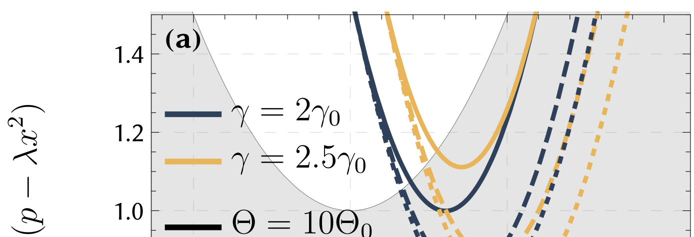
Evolution by full Hamiltonian does not produce the needed correlations to have nonlinear squeezing.

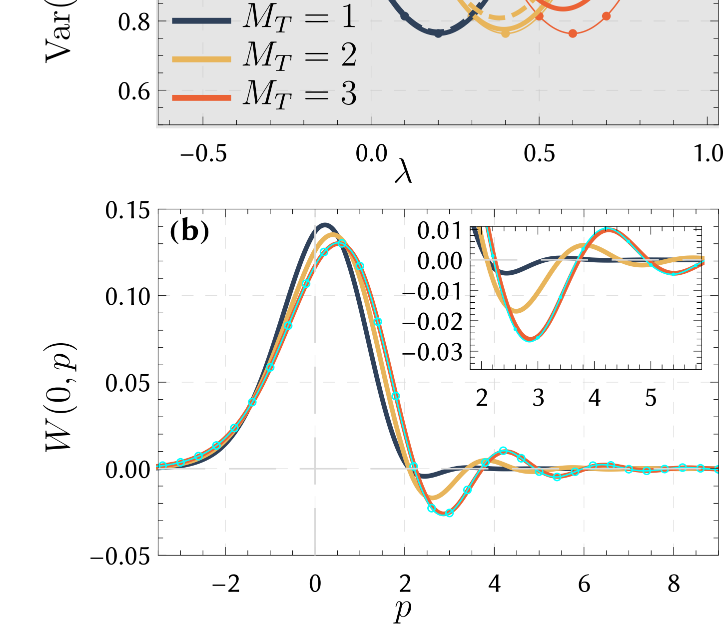
Results [2]

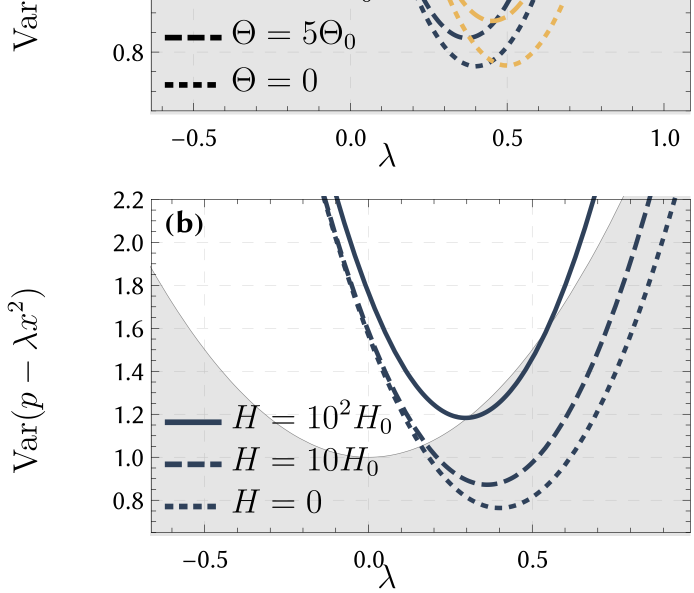
Nonclassicality



Robustness

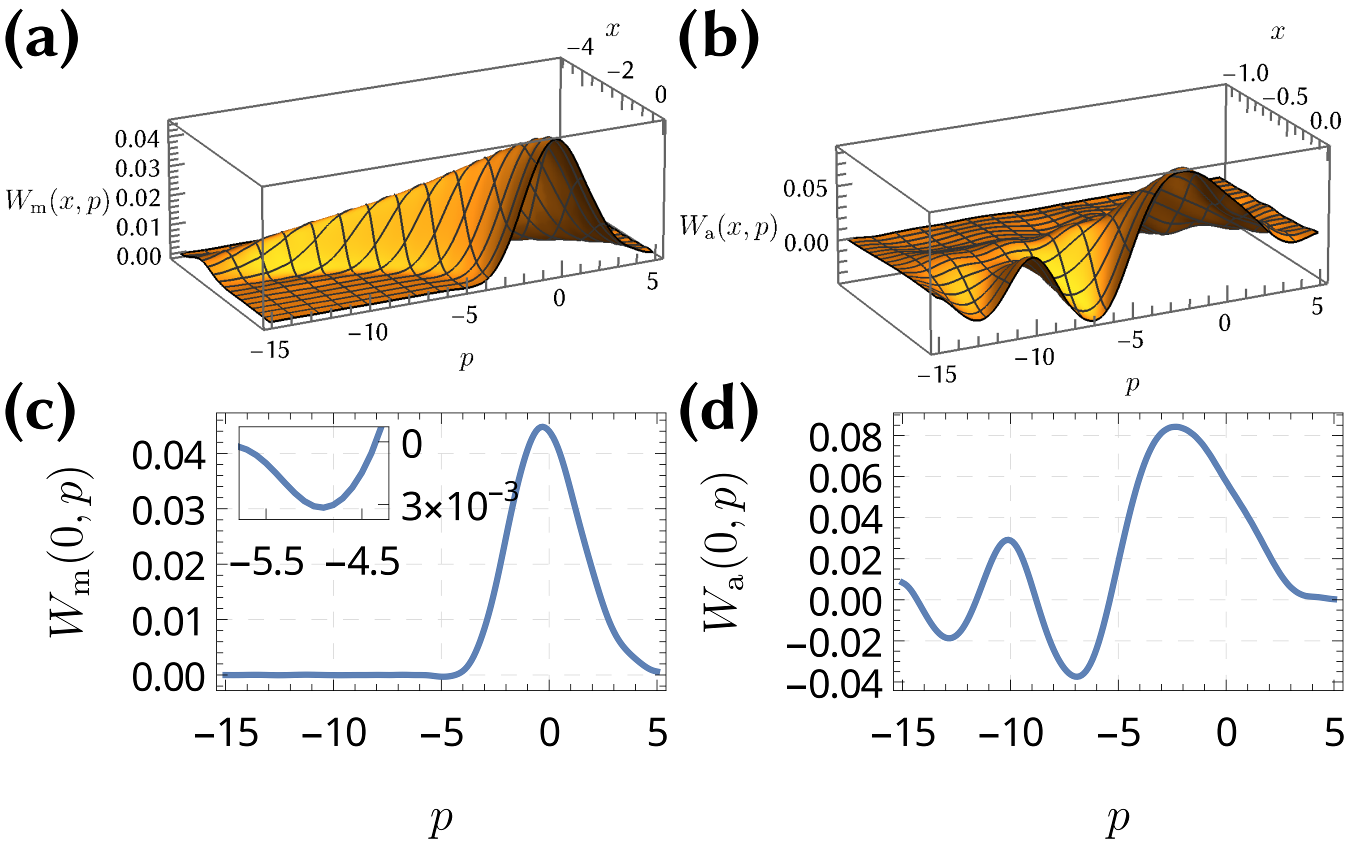






Created state shows negativity of Wigner function, nonlinear squeezing, and some robustness to environmental heating. Base decoherence level H_0 corresponds to decreased by 100 heating from [3].

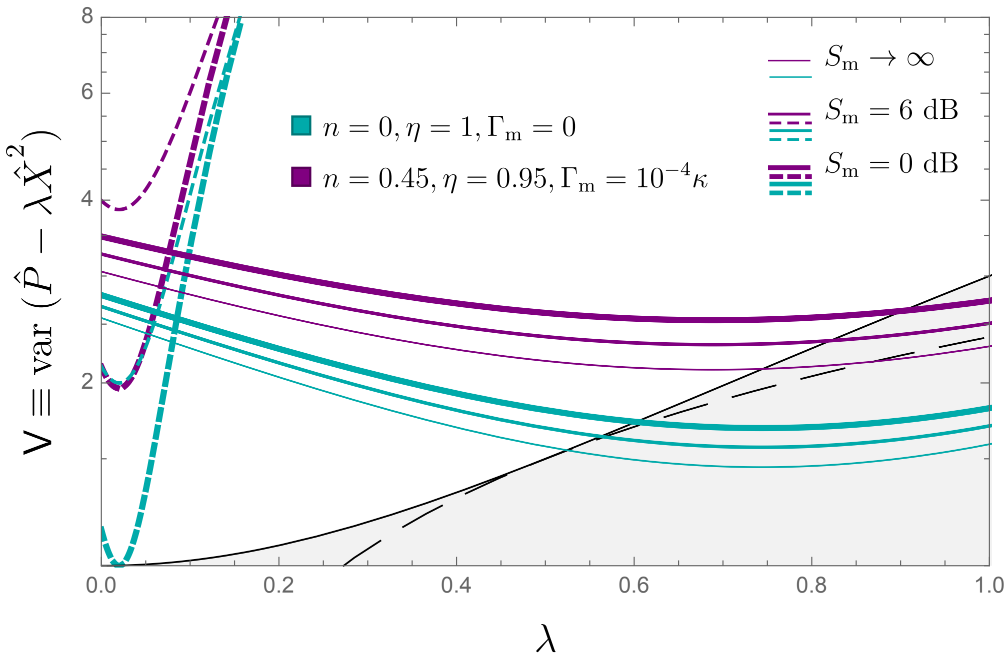
Simulation of Wigner functions



Numerical simulation of Wigner functions of (a,c)

Numerical simulation of Wigner functions of (a,c) mechanics at t_{NL}, and (b,d) atoms at t_f for idealized parameters. Numerical simulation assumes decoherence rates of atoms and mechanics [in units of cavity linewidth κ] $\gamma_a = 10^{-7}\kappa$, $\gamma_m = 10^{-10}\kappa$. Mechanical heating rate $\Gamma_m = 10^{-5}\kappa$.

Simulation of nonlinear squeezing



Gray lines: thresholds of non-classical and non-Gaussian states. Dashed lines: $\sigma^{(3)}$ of mechanics at t_{NL}. n: initial mechanical occupation, η — optical loss of the mediator, S — optical squeezing of mediator.

elić, U. et al. *Science* **367,** 892–895 (Feb. 2020). 4. Thomas, R. A. et al.