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Olomouc

ROBUST QUANTUM ENTANGLEMENT AND INTERFACES WITH NOISY SYSTEMS

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GAČR
CZECH SCIENCE FOUNDATION

CENTER OF EXCELENCE FOR CLASSICAL
AND QUANTUM INTERACTIONS IN NANOWORLD

BRISQ2

QUANTUM OPTICS THEORY

Radim Filip

Quantum Coherence and Nonclassicality

Miroslav Gavenda
Petr Marek

Students:
Lukáš Lachman

Quantum Nonlinear Operations

Petr Marek
Kimin Park

Students:
Petr Zapletal
Vojta Kupčík

Quantum Communication

Vladyslav Usenko
Lazslo Ruppert
Mikolaj Lasota

Students:
Ivan Derkač

Quantum Optomechanics

Andrey Rakhubovsky

Students:
Nikita Vostrosablin

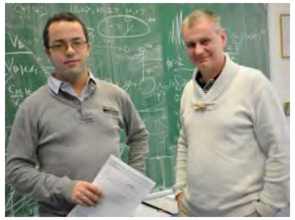
Interaction of Light with Atoms

Lukáš Slodička
Petr Marek

Students:
Petr Obšil

Stochastic Dynamics and Thermodynamics

Miroslav Gavenda
Michal Kolář

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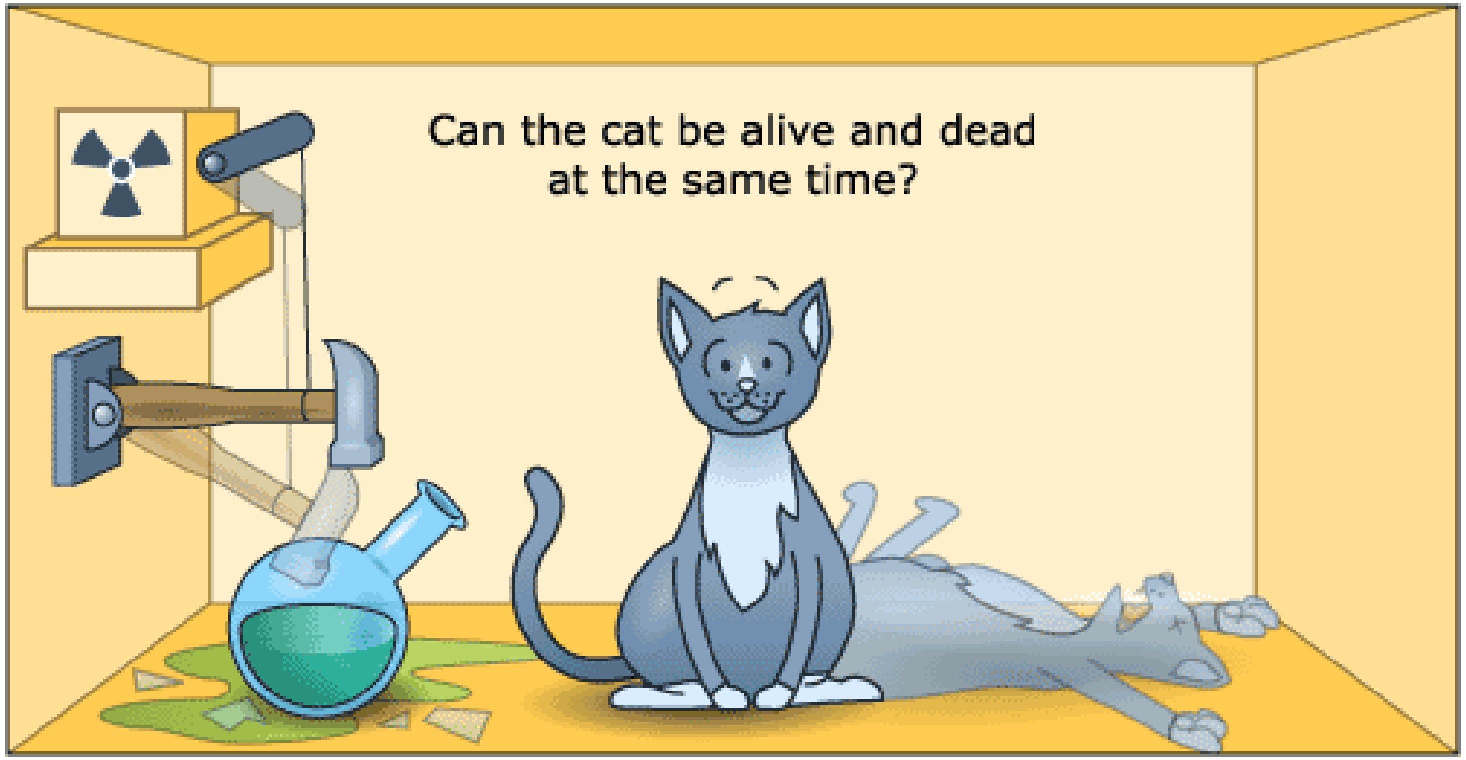
SCHRÖDINGER CAT



E. Schrödinger, Naturwissenschaften 23 (49): 807–812 (1935).

SCHRÖDINGER CAT

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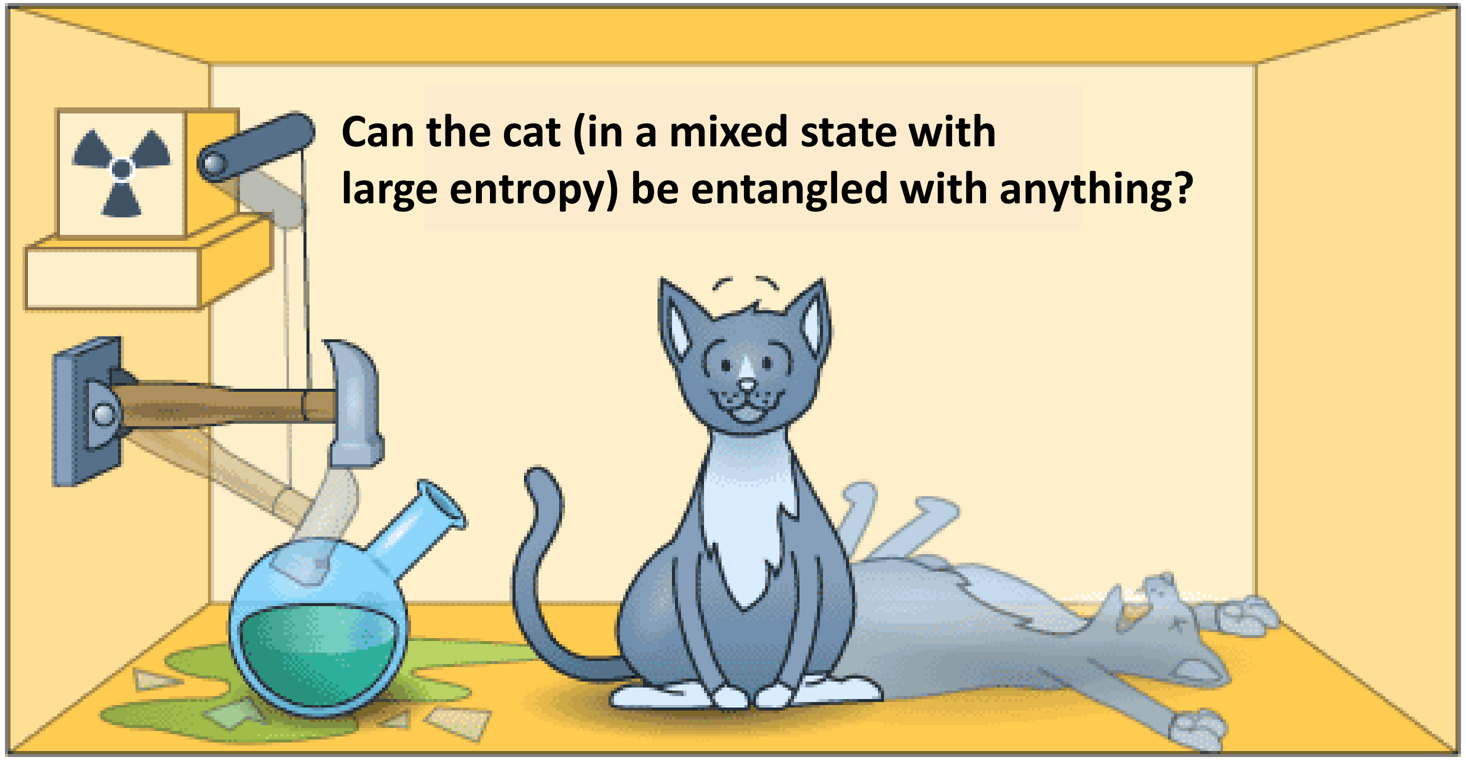
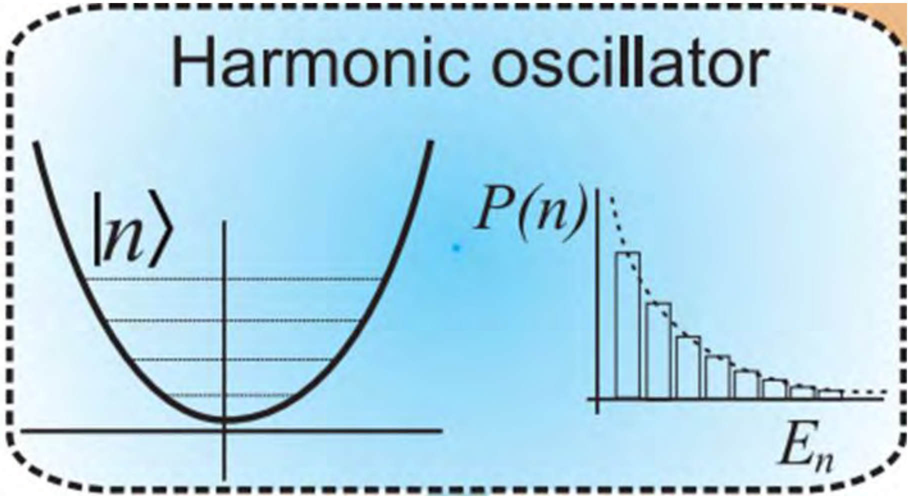
SCHRÖDINGER CAT



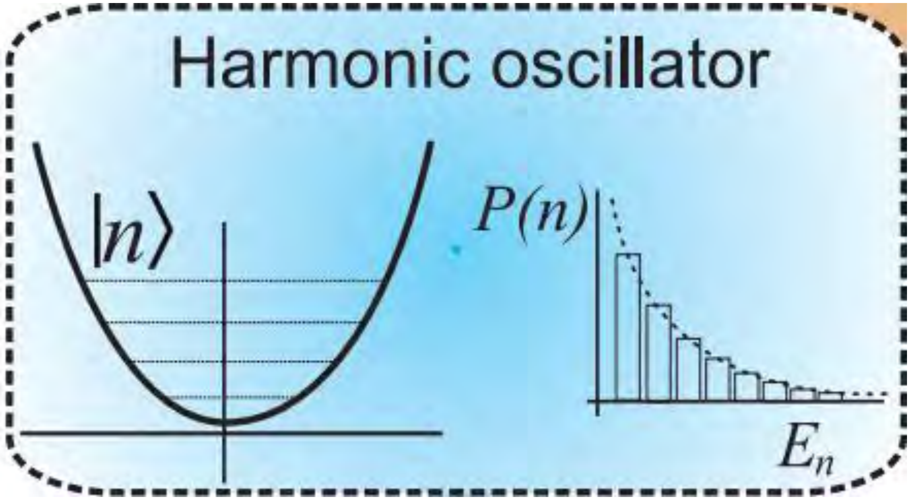
LINEAR HARMONIC OSCILLATORS

L



Thermal state

M



Thermal state

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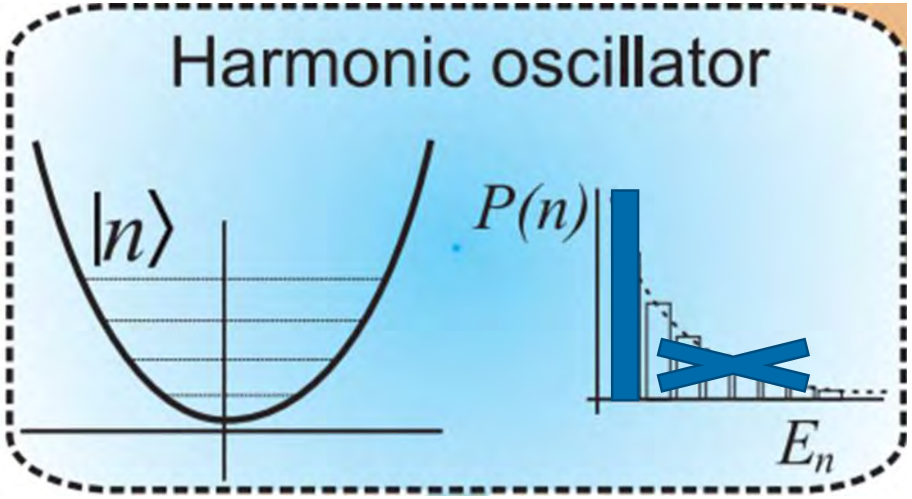
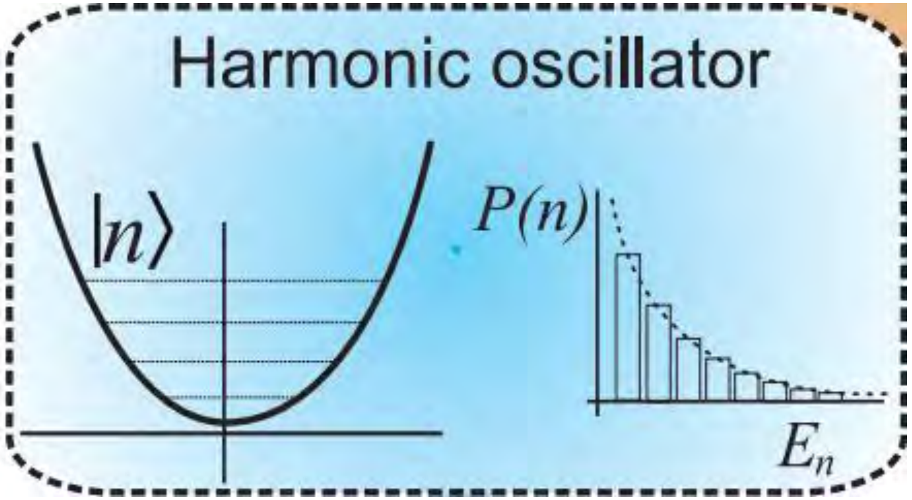
LINEAR HARMONIC OSCILLATORS

L



Ground state

M



Thermal state

LINEAR HARMONIC OSCILLATORS

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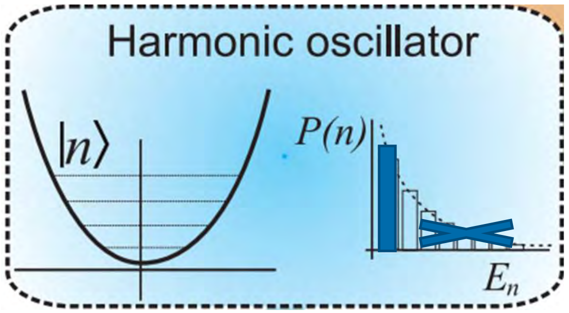
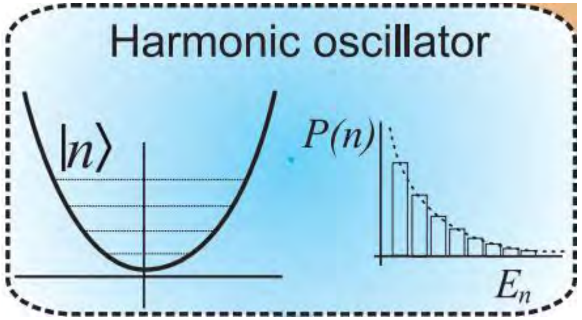
L

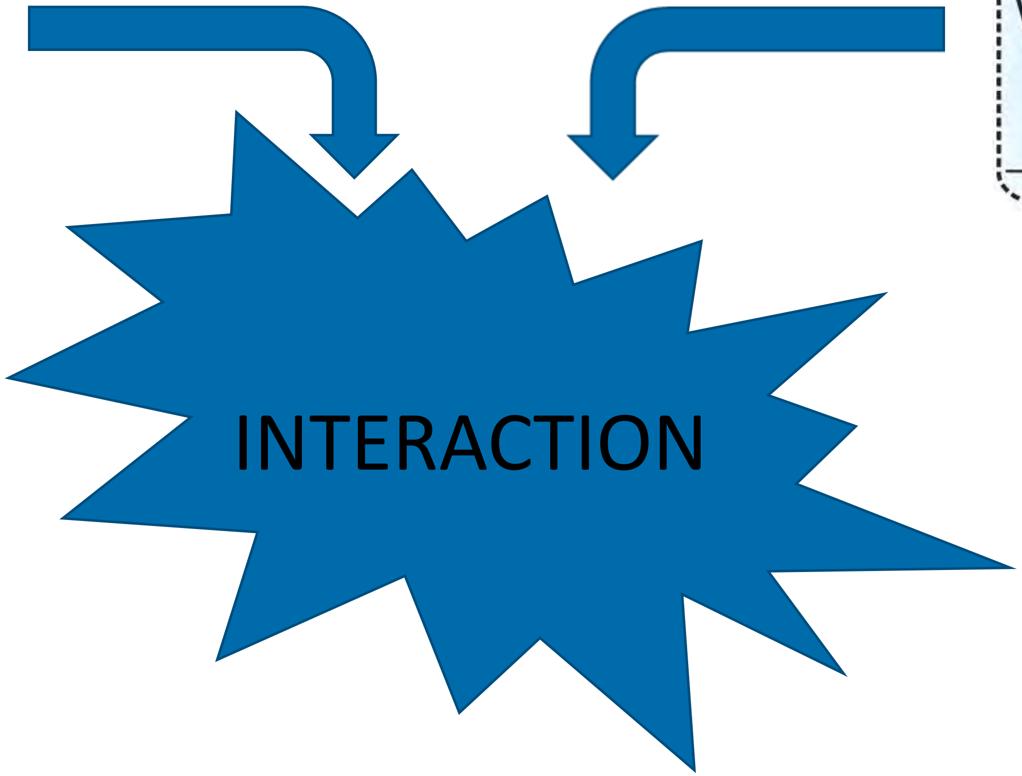


Ground state

M

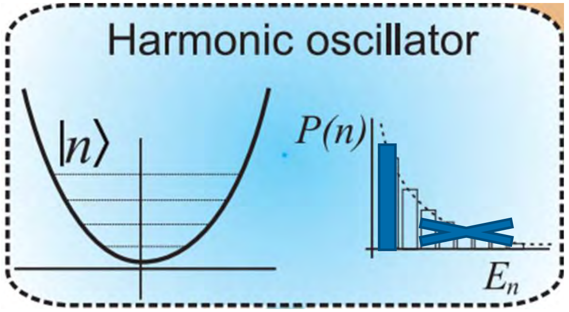


Thermal state



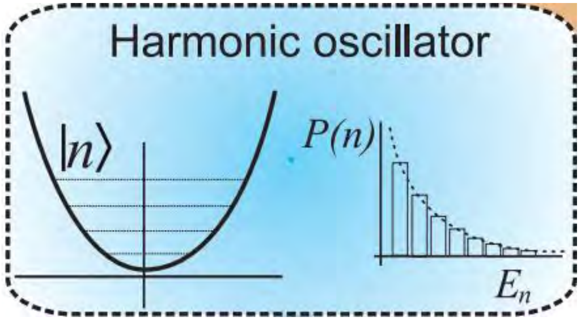
LINEAR HARMONIC OSCILLATORS

L



Ground state

M



Thermal state

GAUSSIAN
INTERACTION

LINEAR HARMONIC OSCILLATORS

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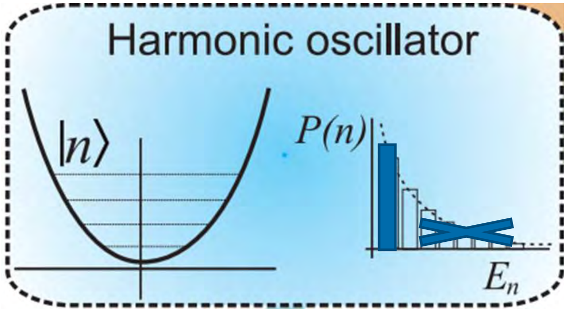
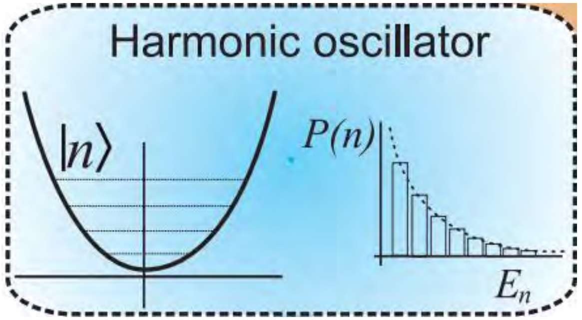
Light



Ground state

Mechanics

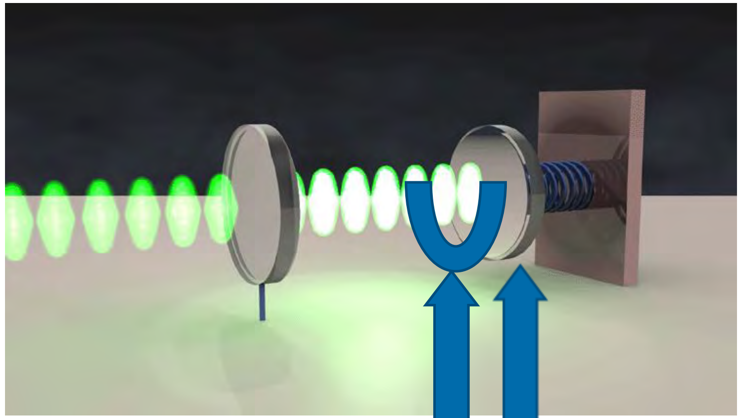


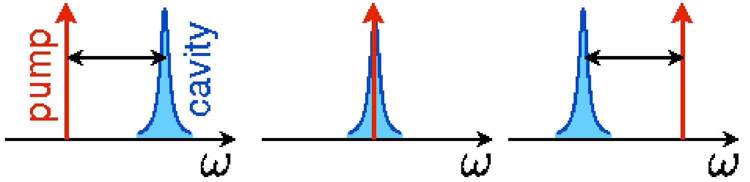
Thermal state

GAUSSIAN INTERACTION

OPTOMECHANICAL ENTANGLEMENT

QUANTUM OPTOMECHANICS

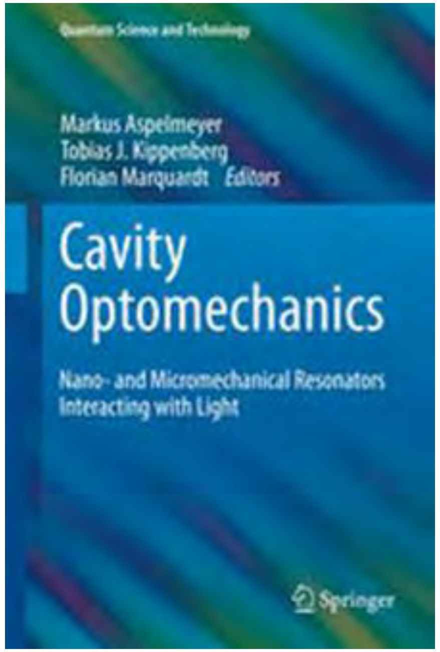




$\Delta = -\Omega_\mathrm{m}$	$\Delta = 0$	$\Delta = +\Omega_\mathrm{m}$
beam-splitter (cooling)	QND	squeezer (entanglement)
$\delta\hat{a}^\dagger\hat{b} + \hat{b}^\dagger\delta\hat{a}$	$\hat{x}_a\hat{x}_b$	$\delta\hat{a}^\dagger\hat{b}^\dagger + \hat{b}\delta\hat{a}$

INTERACTION GAIN G

THERMAL NOISE V_N



Cavity Optomechanics, M. Aspelmeyer, T.J. Kippenberg, F. Marquardt (Eds.), Springer Verlag, Berlin (2014).

Markus Aspelmeyer, Tobias J. Kippenberg, and Florian Marquardt, Rev. Mod. Phys. 86, 1391 (2014)

ENTANGLEMENT WITH THERMAL STATE

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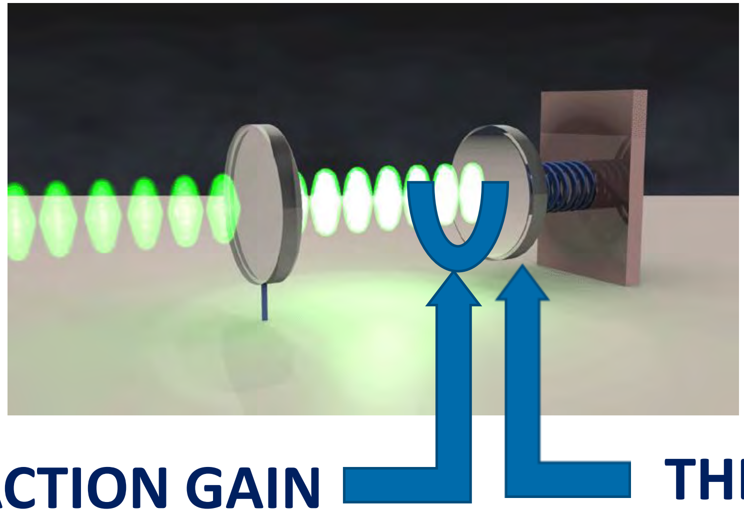
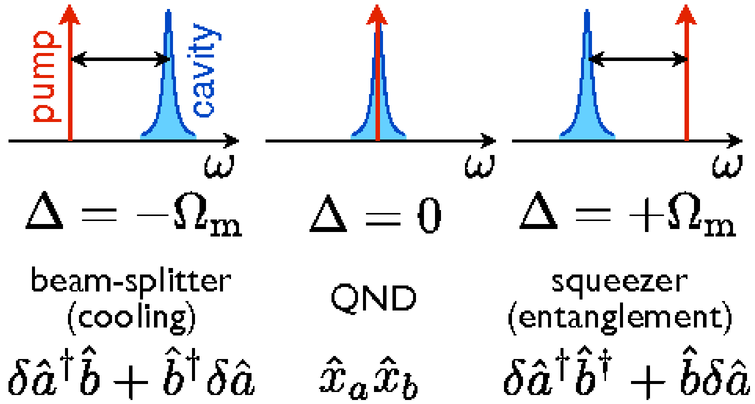
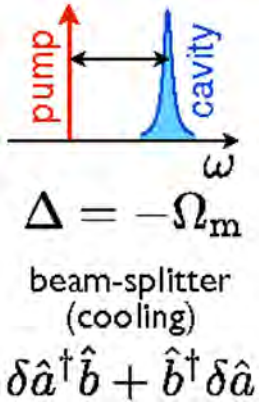
QUANTUM OPTOMECHANICS





INTERACTION GAIN G

THERMAL NOISE V_N



- entangled only if light is squeezed and $V_S < \frac{1}{V_N}$
- not robust against damping of L,M for large thermal noise
- beam splitter is not good candidate

Radim Filip and Vojtěch Kupčík, Robust Gaussian entanglement with a macroscopic oscillator at thermal equilibrium, Phys. Rev. A 87, 062323 (2013)

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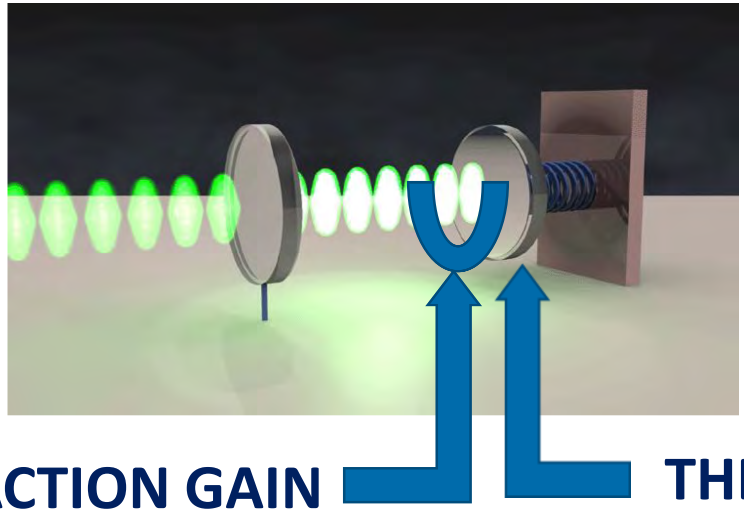
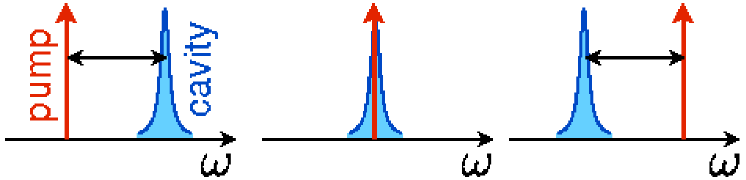
ENTANGLEMENT WITH THERMAL STATE

QUANTUM
OPTOMECHANICS





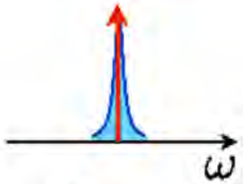
$\Delta = -\Omega_{\mathrm{m}}$	$\Delta = 0$	$\Delta = +\Omega_{\mathrm{m}}$
beam-splitter (cooling)	QND	squeezer (entanglement)
$\delta\hat{a}^{\dagger}\hat{b} + \hat{b}^{\dagger}\delta\hat{a}$	$\hat{x}_a\hat{x}_b$	$\delta\hat{a}^{\dagger}\hat{b}^{\dagger} + \hat{b}\delta\hat{a}$

INTERACTION GAIN G

THERMAL NOISE V_N

for the large V_N

$$\mathrm{E}_N^{\mathrm{QND}} \approx \frac{1}{2}\log_2\left(1 + \frac{4G}{V_N}\right)$$



$\Delta = 0$

QND

$\hat{x}_a\hat{x}_b$

- entangled for any $V_N \geq 1$
- not robust against damping of M
- conditional squeezing only in one variable of M

Radim Filip and Vojtěch Kupčík, Robust Gaussian entanglement with a macroscopic oscillator at thermal equilibrium, Phys. Rev. A 87, 062323 (2013)

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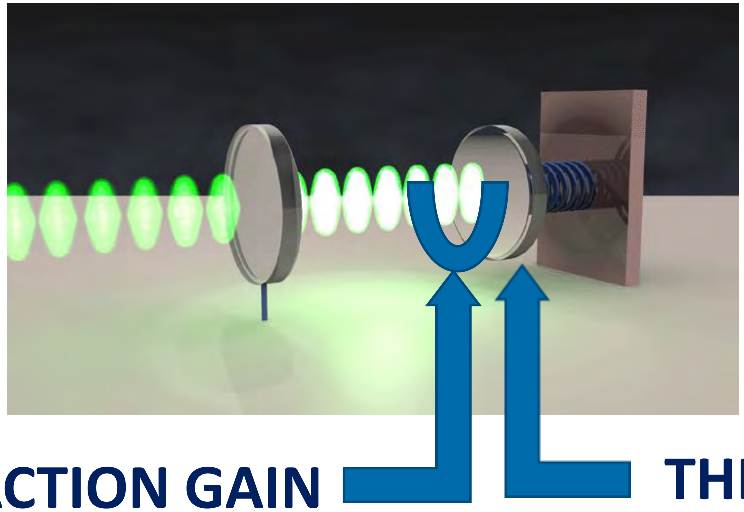
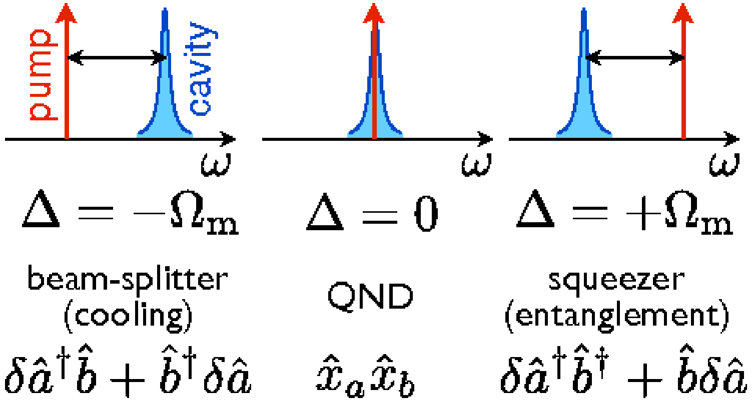
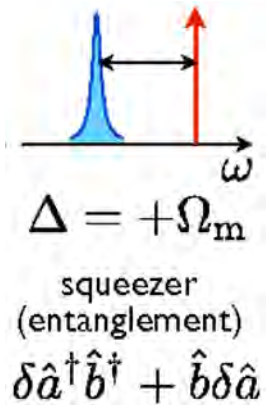




INTERACTION GAIN G

THERMAL NOISE V_N



- entangled for any $V_N \geq 1$ and $G > 1$
- robust against damping
- for G>2, conditional squeezing in both variables of M

for the large V_N

$$E_N^{AMP} \approx -\log_2\left(1 - \frac{2}{\frac{\frac{G}{G-1}}{\eta_L} + \frac{1}{\eta_M}}\right)$$

Radim Filip and Vojtěch Kupčík, Robust Gaussian entanglement with a macroscopic oscillator at thermal equilibrium, Phys. Rev. A 87, 062323 (2013)

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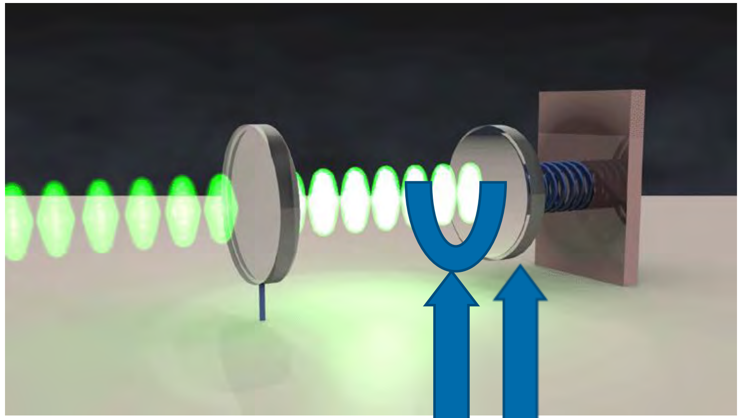
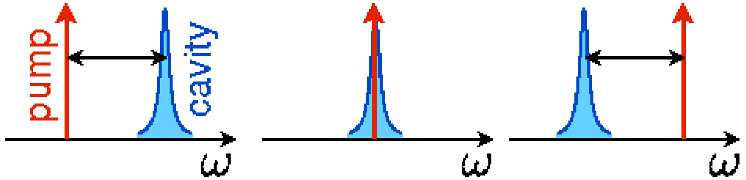
QUANTUM OPTOMECHNICS





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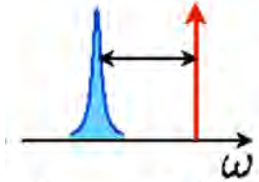
INTERACTION GAIN G

THERMAL NOISE V_N



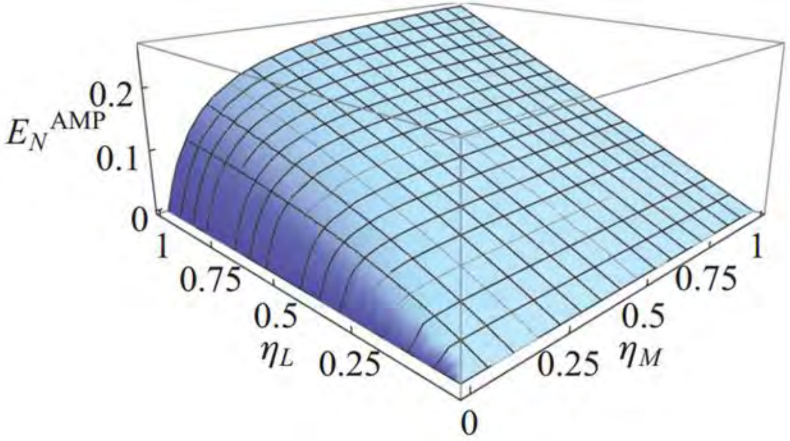
$\Delta = +\Omega_\mathrm{m}$

squeezer (entanglement)

$\delta\hat{a}^\dagger\hat{b}^\dagger + \hat{b}\delta\hat{a}$

- entangled for any $V_N \geq 1$ and $G > 1$
- robust against damping
- for G>2, conditional squeezing in both variables of M

$V_N = 10^3$, $V_S = 1$, $G = 1.1$.



Radim Filip and Vojtěch Kupčík, Robust Gaussian entanglement with a macroscopic oscillator at thermal equilibrium, Phys. Rev. A 87, 062323 (2013)

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ENTANGLEMENT WITH THERMAL STATE

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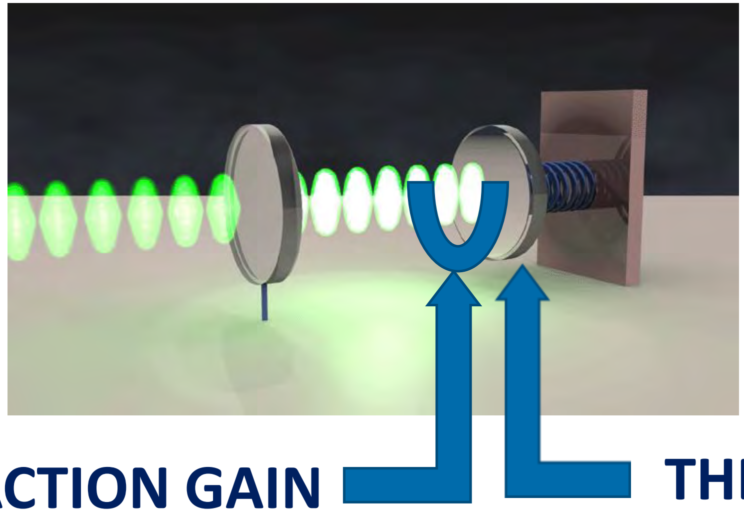

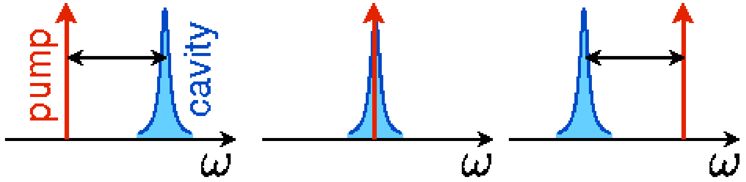

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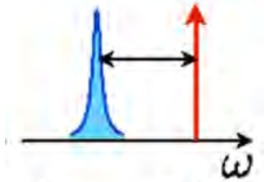
INTERACTION GAIN G

THERMAL NOISE V_N



$\Delta = +\Omega_m$

squeezer (entanglement)

$\delta\hat{a}^\dagger\hat{b}^\dagger + \hat{b}\delta\hat{a}$

- entangled for any $V_N \geq 1$ and $G > 1$
- robust against damping
- for G>2, conditional squeezing in both variables of M

for the large V_N

$$\sqrt{\frac{G-1}{G}} X_M + X_L$$

$$\sqrt{\frac{G-1}{G}} P_M - P_L$$

Radim Filip and Vojtěch Kupčík, Robust Gaussian entanglement with a macroscopic oscillator at thermal equilibrium, Phys. Rev. A 87, 062323 (2013)

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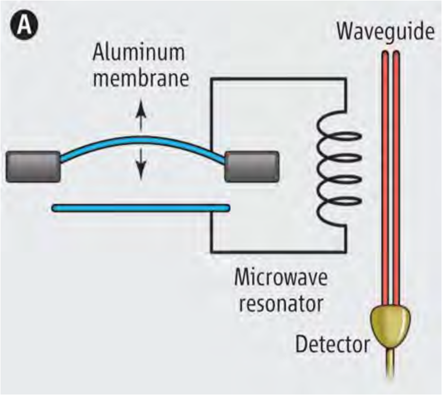
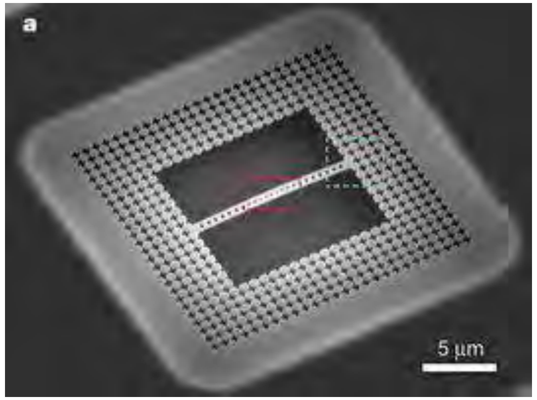


T. A. Palomaki, J. D. Teufel, R. W. Simmonds, and K. W. Lehnert, **Entangling Mechanical Motion with Microwave Fields**, Science 8, 710 (2013)



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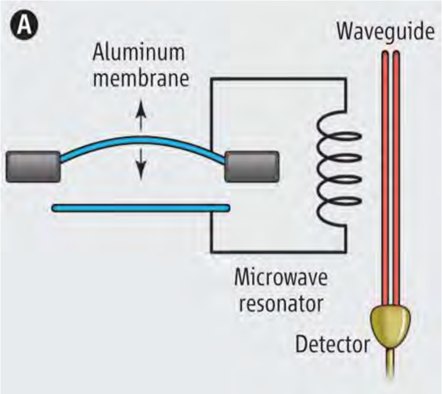

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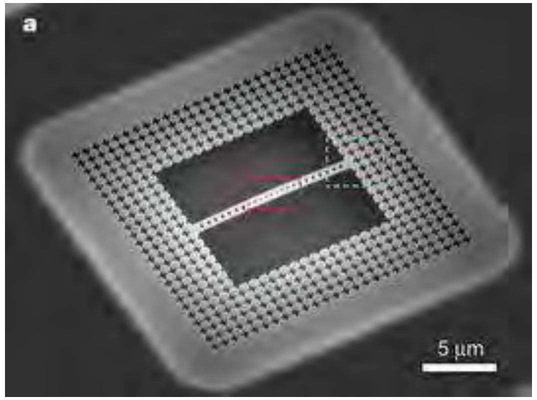

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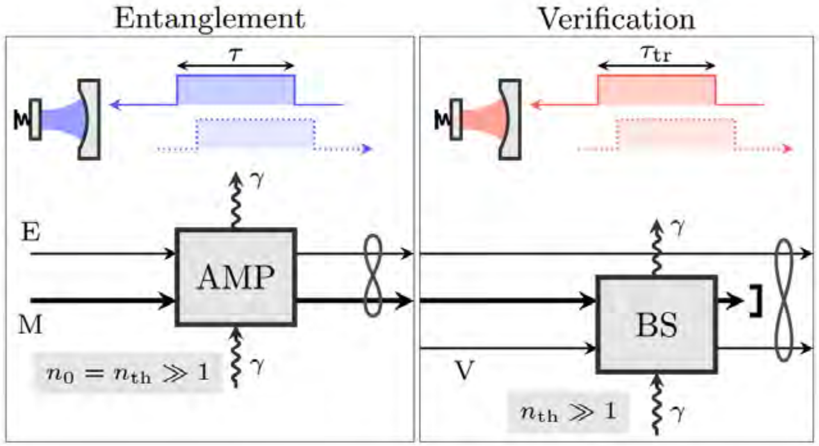

Andrey A. Rakhubovsky and Radim Filip, Robust entanglement with thermal mechanical oscillator, Phys. Rev. A91, 062317 (2015) .

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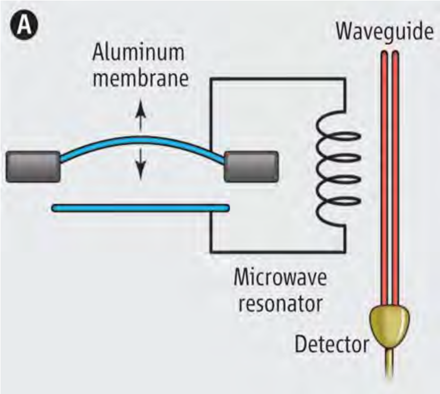

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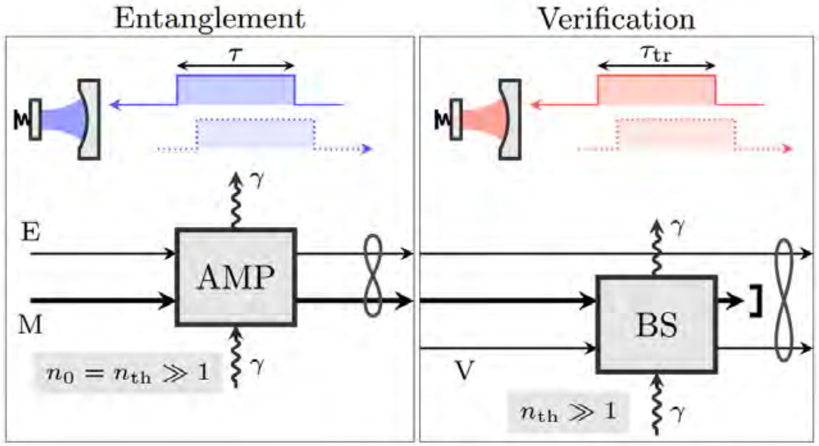

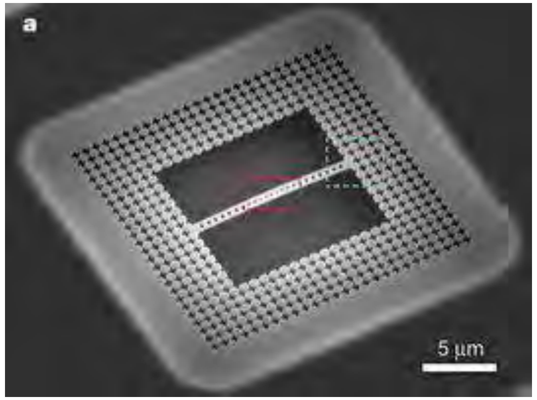

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Pulsed quantum optomechanics

S. G. Hofer, W. Wieczorek, M. Aspelmeyer, and K. Hammerer, Phys. Rev. A 84, 052327 (2011).

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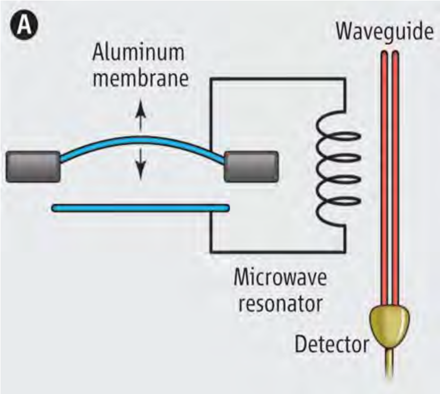

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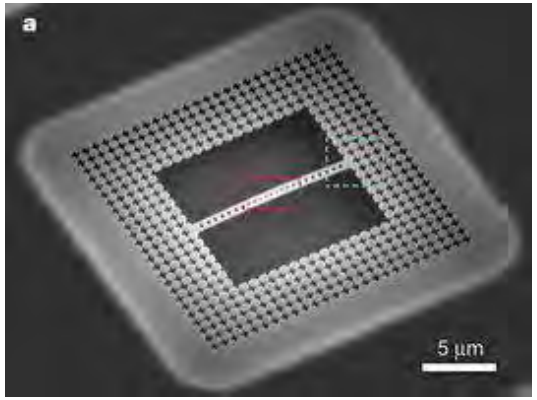

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$$\dot{q} = \omega p,$$
$$\dot{p} = -\omega q - \gamma p + g_0\sqrt{2n_{\mathrm{cav}}}(a + a^\dagger) + \sqrt{2\gamma}\xi,$$
$$\dot{a} = -(\kappa + i\Delta)a + ig_0\sqrt{2n_{\mathrm{cav}}}q + \sqrt{2\kappa}a^{\mathrm{in}},$$
$$n_{\mathrm{cav}} = 2\kappa P_i/(\hbar\omega_c(\kappa^2 + \Delta^2))$$

Input-output formalism in temporal domain

$$\left.\begin{aligned} n_{\mathrm{th}} &= k_B T/\hbar\omega \gg 1 \\ Q &= \omega/\gamma \to \infty \end{aligned}\right\} \text{Markovian mechanical reservoir}$$

Adiabatic elimination of intra-cavity mode: ideal amplification.
To derive limits, we need calculations beyond adiabatic elimination.

Andrey A. Rakhubovsky and Radim Filip, Robust entanglement with thermal mechanical oscillator, Phys. Rev. A91, 062317 (2015) .

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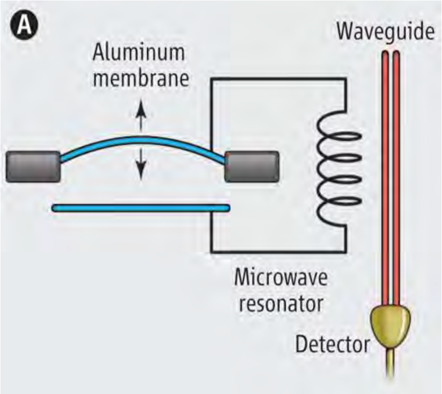
QUANTUM OPTOMECHANICS



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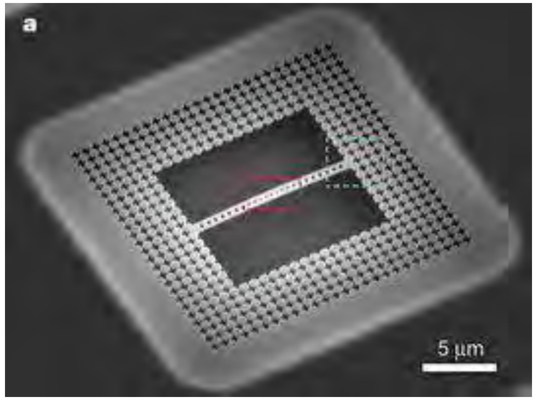

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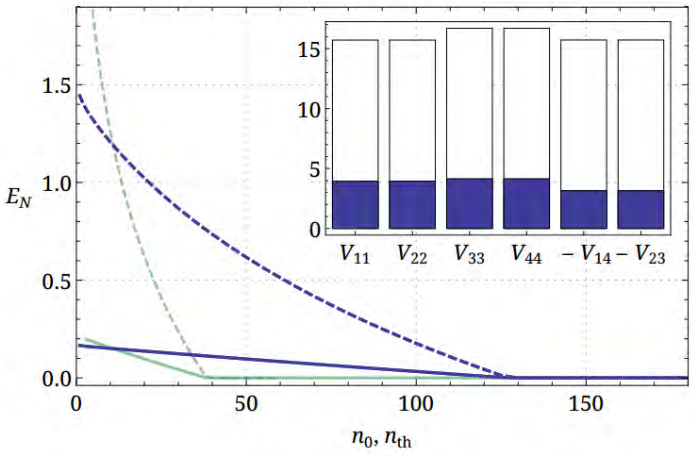
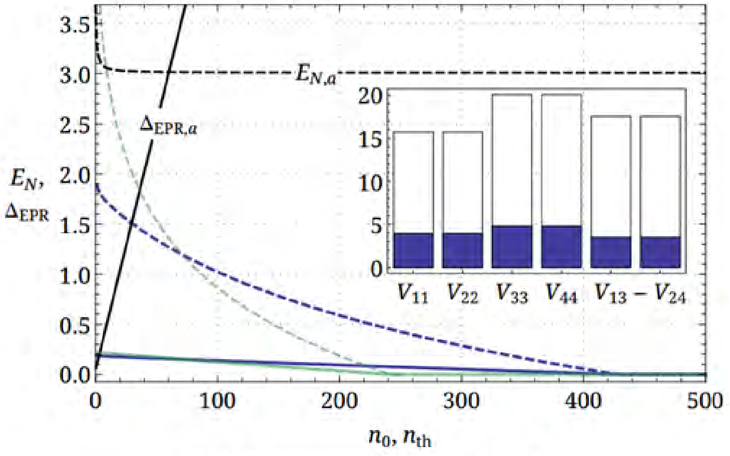


(a) Optical Entanglement

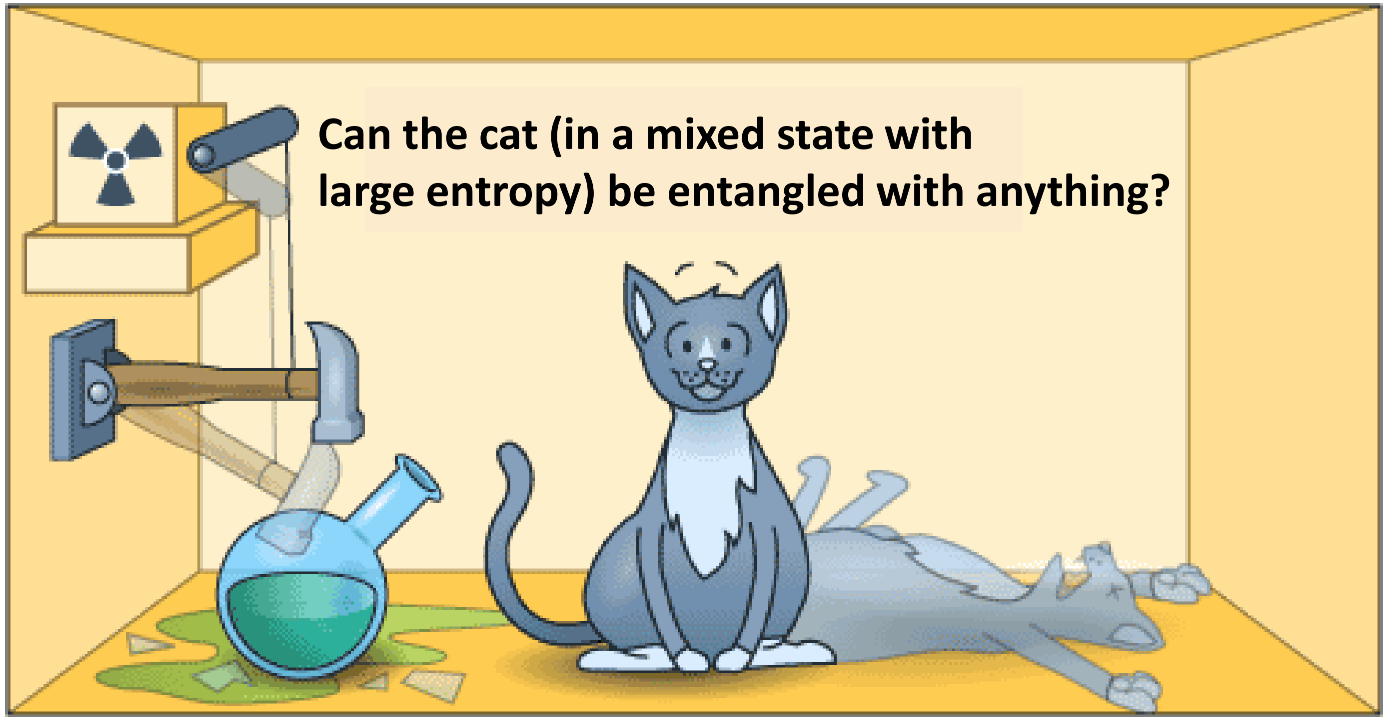


(b) Optomechanical Entanglement

- mechanical noise
- beyond adiabatic elimination

Andrey A. Rakhubovsky and Radim Filip, Robust entanglement with thermal mechanical oscillator, Phys. Rev. A91, 062317 (2015) .

MIXED GAUSSIAN SCHRÖDINGER CAT



- entanglement with thermal state
- entaglement appears also for large mixedness
- entanglement is robust against any damping
- measurement induced squeezing of mechanics is possible

Radim Filip and Vojtěch Kupčík, Robust Gaussian entanglement with a macroscopic oscillator at thermal equilibrium, Phys. Rev. A 87, 062323 (2013).
Q. Y. He and M. D. Reid, Einstein-Podolsky-Rosen paradox and quantum steering in pulsed optomechanics, Phys. Rev. A 88, 052121 (2013).
S. Kiesewetter, Q. Y. He, P. D. Drummond, and M. D. Reid, Phys. Rev. A 90, 043805 (2014).
Andrey A. Rakhubovsky and Radim Filip, Robust entanglement with thermal mechanical oscillator, Phys. Rev. A91, 062317 (2015) .

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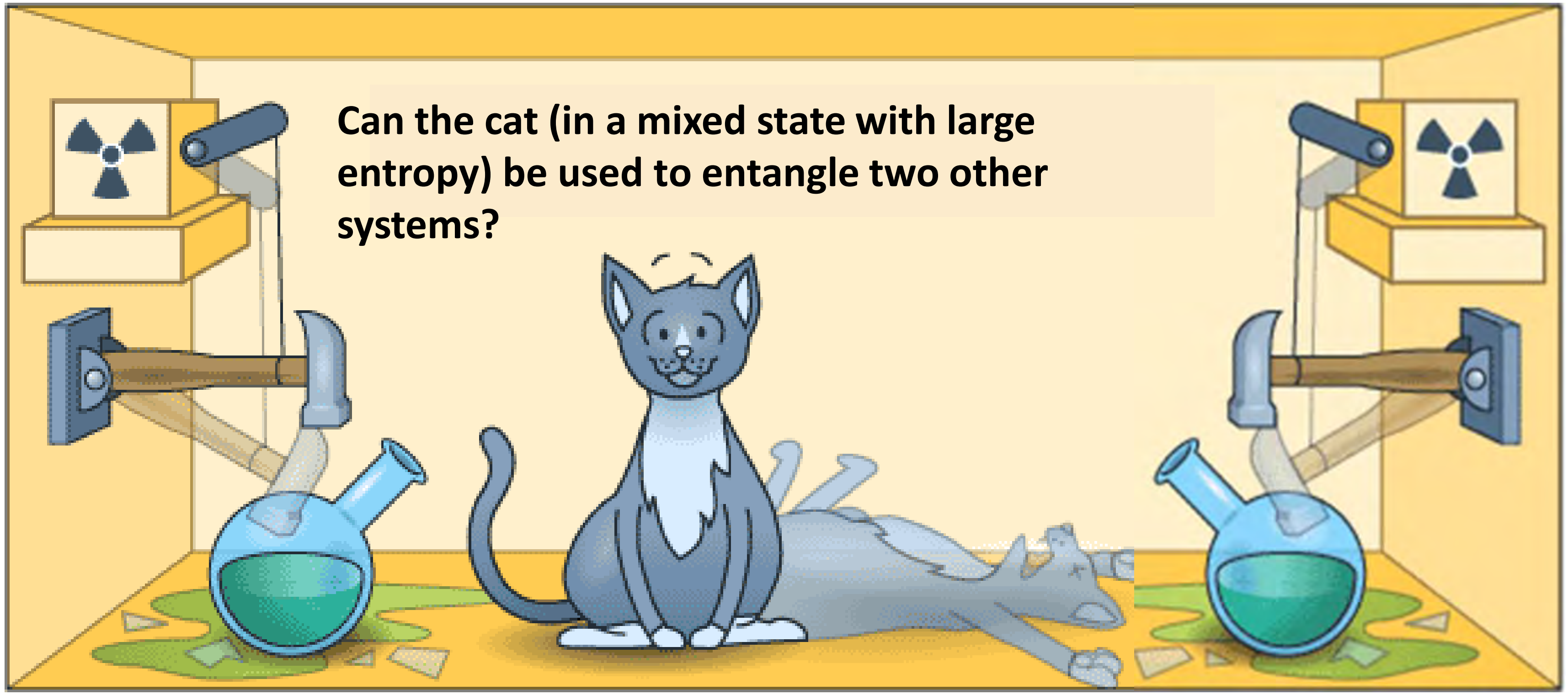
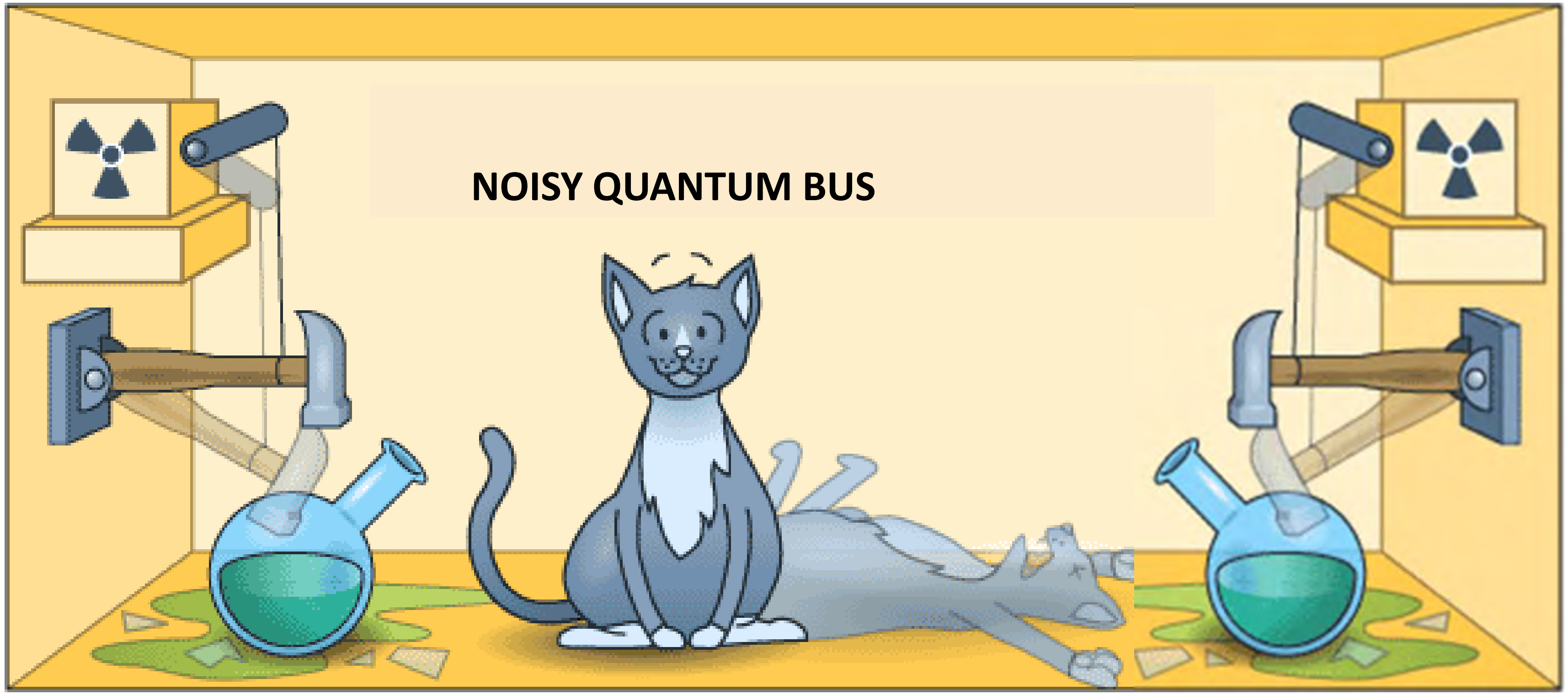
QUANTUM TRANSDUCER



QUANTUM TRANSDUCER



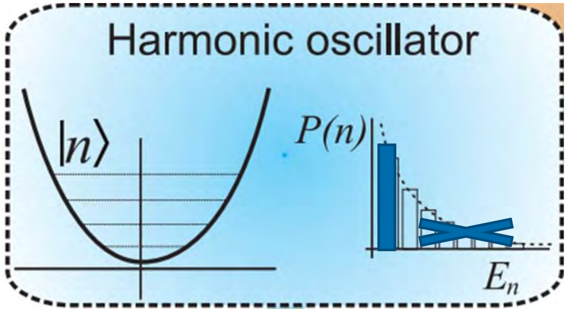
G. J. Milburn, S. Schneider, and D. F. V. James, Fort. der Physik 48, 801 (2000).

A. Sørensen and K. Mølmer, Phys. Rev. A 62, 022311 (2000).

D. Leibfried, B. DeMarco, V. Meyer, D. Lucas, M. Barrett, J. Britton, W. M. Itano, B. Jelenkovi´c, C. Lange, T. Rosenband, and D. J. Wineland, Nature 422, 412 (2003).

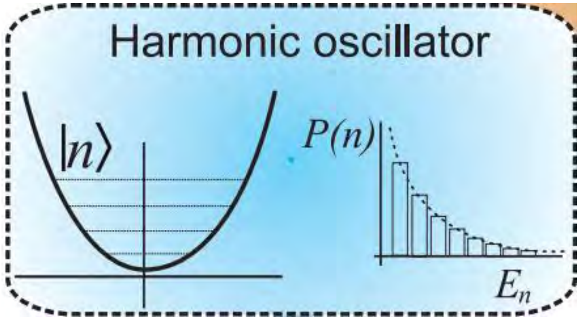
GAUSSIAN ENTANGLEMENT ASSISTED BY NOISY MEDIATOR

A



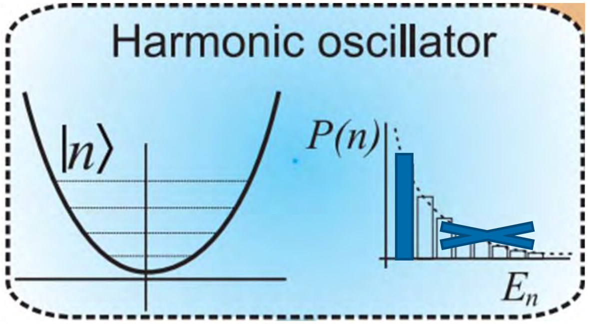
Ground state

M



Thermal state

B



Ground state

Vojtěch Kupčík and Radim Filip, Continuous-variable entanglement mediated by thermal oscillator, submitted.

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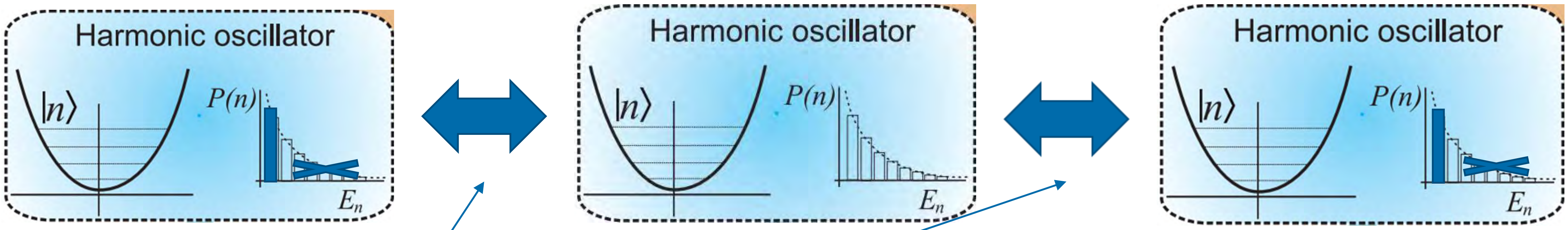
GAUSSIAN ENTANGLEMENT ASSISTED BY NOISY MEDIATOR

A M B



Ground state Thermal state Ground state

pulsed Gaussian interaction: beam splitter, QND, squeezer

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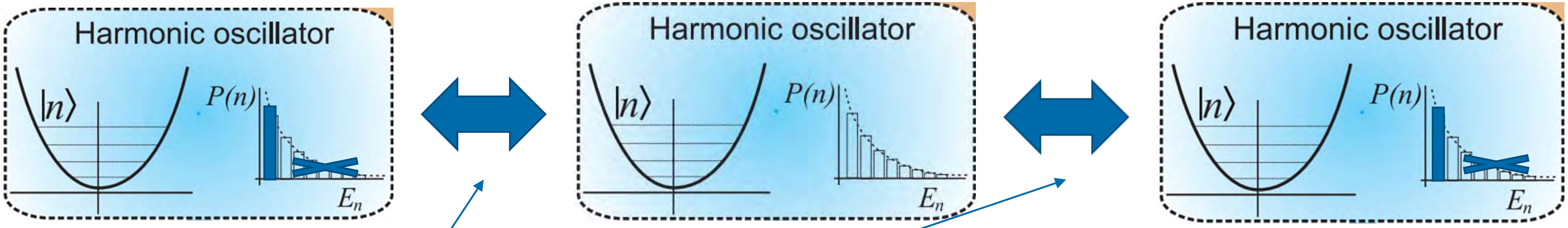
GAUSSIAN ENTANGLEMENT ASSISTED BY NOISY MEDIATOR

A | M | B



Ground state | Thermal state | Ground state

pulsed Gaussian interaction: beam splitter, QND, squeezer

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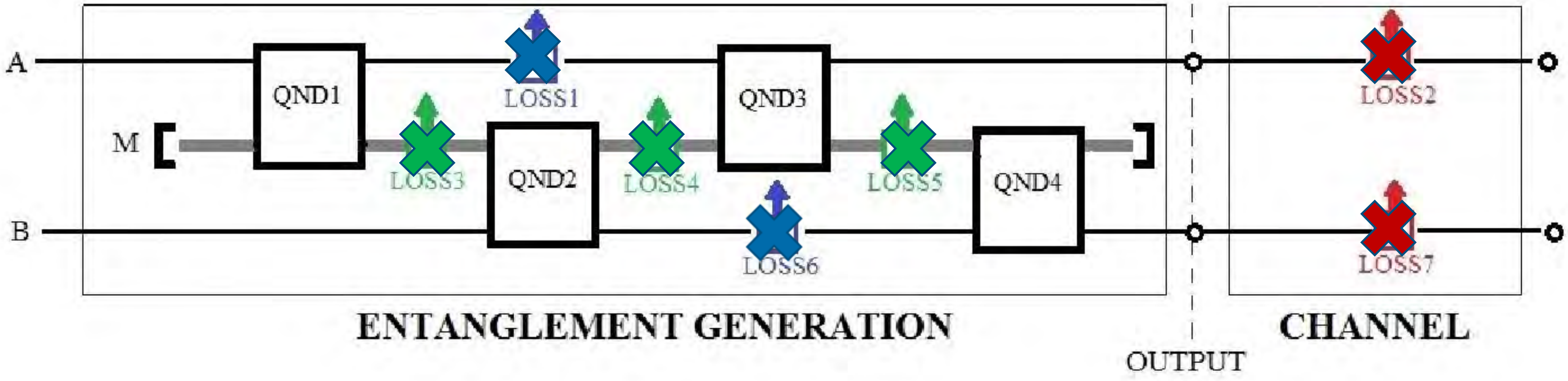
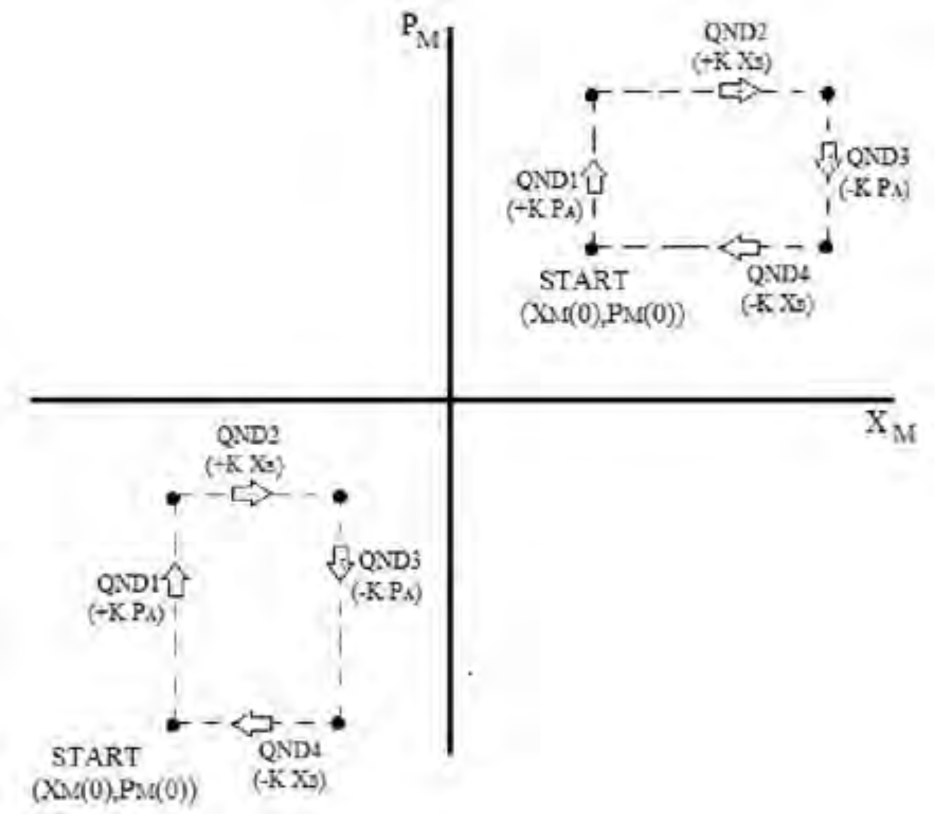
GAUSSIAN ENTANGLEMENT ASSISTED BY NOISY MEDIATOR



PULSED METHOD: M. R. Vanner, J. Hofer, G. D. Cole, M. Aspelmeyer, Cooling-by-measurement and mechanical state tomography via pulsed optomechanics, Nat. Comm. 4, 2295 (2013).

Vojtěch Kupčík and Radim Filip, Continuous-variable entanglement mediated by thermal oscillator, submitted.

QUANTUM GEOMETRIC PHASE EFFECT



$$\begin{aligned} \mathrm{QND1}: X'_A &= X_A - K_1 \cdot X_M, \quad P'_A = P_A, \\ X'_M &= X_M, \quad P'_M = P_M + K_1 \cdot P_A, \end{aligned}$$

$$\begin{aligned} \mathrm{QND2}: X'_B &= X_B, \quad P'_B = P_B - K_2 \cdot P'_M, \\ X''_M &= X'_M + K_2 \cdot X_B, \quad P''_M = P'_M, \end{aligned}$$

$$\begin{aligned} \mathrm{QND3}: X''_A &= X'_A + K_3 \cdot X''_M, \quad P''_A = P'_A, \\ X'''_M &= X''_M, \quad P'''_M = P''_M - K_3 \cdot P'_A, \end{aligned}$$

$$\begin{aligned} \mathrm{QND4}: X''_B &= X'_B, \quad P''_B = P'_B + K_4 \cdot P'''_M, \\ X''''_M &= X'''_M - K_4 \cdot X'_B, \quad P''''_M = P'''_M, \end{aligned}$$

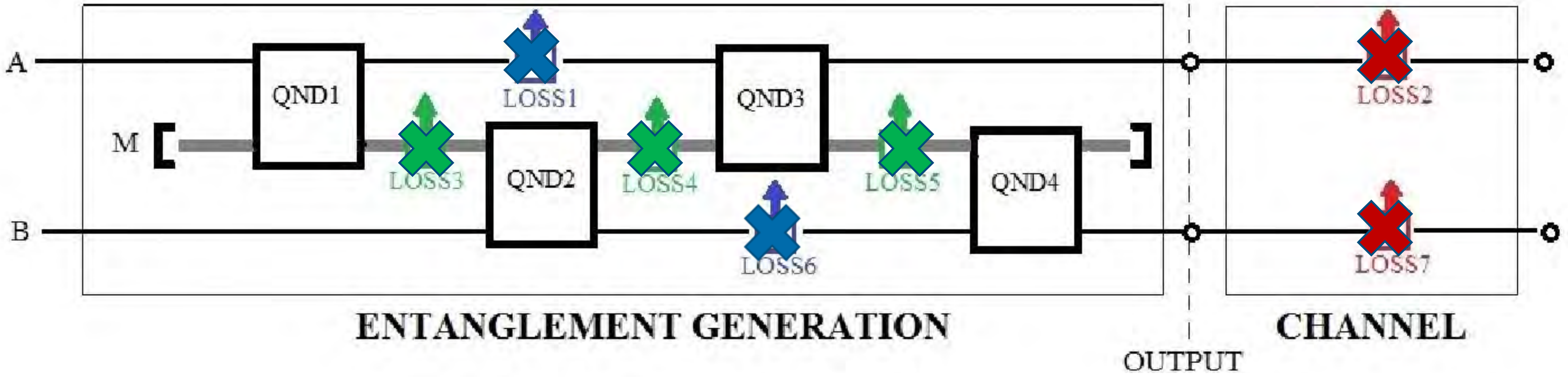
Ideal QND entanglement
not influenced by noisy mediator.

$$X''_A = X_A + K^2 \cdot X_B \quad P''_A = P_A$$

$$X''_B = X_B \quad P''_B = P_B - K^2 \cdot P_A$$

Vojtěch Kupčík and Radim Filip, Continuous-variable entanglement mediated by thermal oscillator, submitted.

GAUSSIAN ENTANGLEMENT ASSISTED BY NOISY MEDIATOR



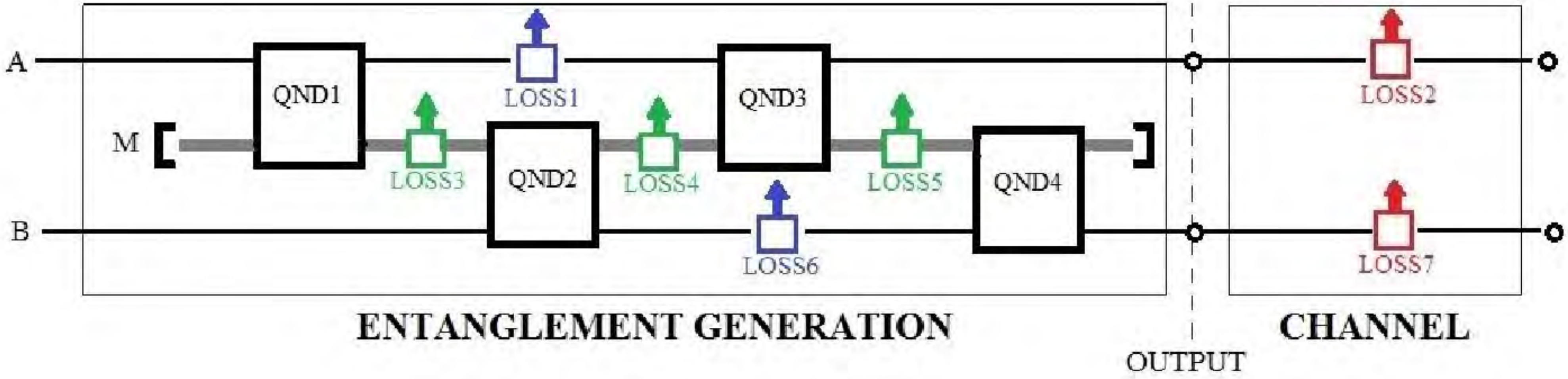
ground states with $V_{A,B} = 1$ $\quad LN_0 = -\frac{1}{2}\log_2\left[1 + 2K^4 - 2\sqrt{K^4 + K^8}\right]$

$V_A = V_B = V_T > 1$ $\quad LN = LN_0 - \frac{1}{2}\log_2 V_T^2$

Condition for entanglement: $K > \sqrt{\frac{V_T^2 - 1}{2V_T}}$

Vojtěch Kupčík and Radim Filip, Continuous-variable entanglement mediated by thermal oscillator, submitted.

ROBUSTNESS OF GAUSSIAN ENTANGLEMENT ASSISTED BY NOISY MEDIATOR



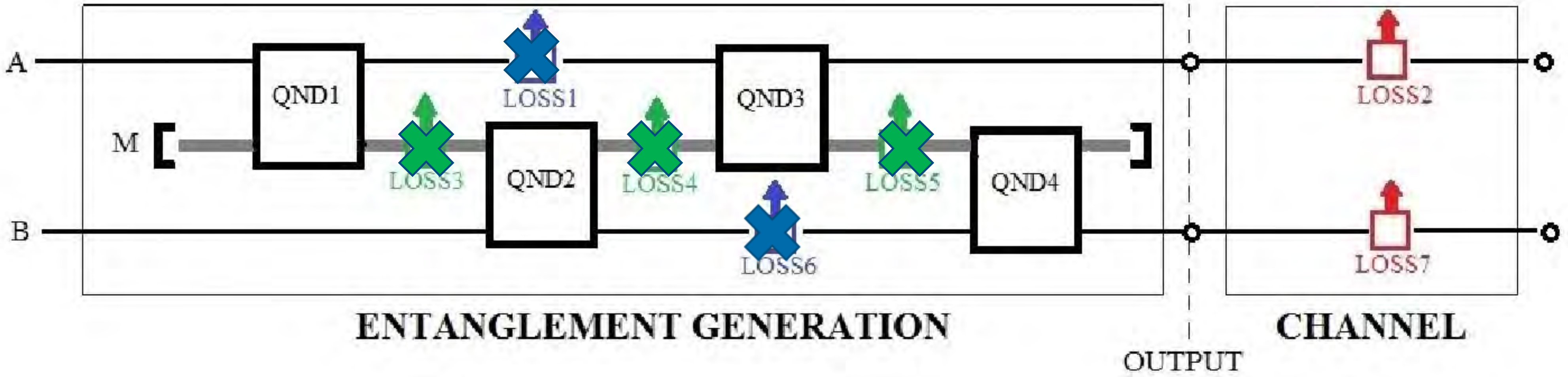
Basic test of robustness by in-coupling and out-coupling losses:

LOSS 1, LOSS 6: systems A,B
LOSS 3, LOSS 4, LOSS 5: mediator M
LOSS 2, LOSS 7: output channel

Vojtěch Kupčík and Radim Filip, Continuous-variable entanglement mediated by thermal oscillator, submitted.

GAUSSIAN ENTANGLEMENT ASSISTED BY NOISY MEDIATOR

$$\eta_2 = \eta_7 = \eta_{CH}$$



Condition for entanglement: $\eta_{CH} > 1 - \frac{2}{K^2}$

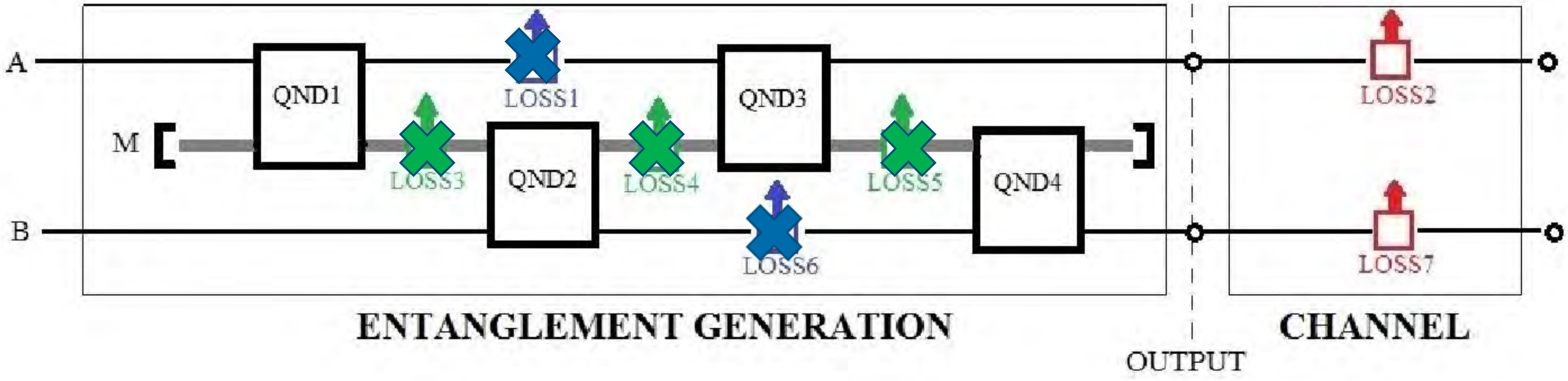
Absolutely robust entanglement: $K < \sqrt{2}$

Maximum of entanglement: $K = \frac{1}{\sqrt[4]{1-\eta_{CH}}}$

Vojtěch Kupčík and Radim Filip, Continuous-variable entanglement mediated by thermal oscillator, submitted.

GAUSSIAN ENTANGLEMENT ASSISTED BY NOISY MEDIATOR

$$\eta_2 = \eta_7 = \eta_{CH}$$



Condition for entanglement: $\eta_{CH} > 1 - \frac{2}{K^2}$

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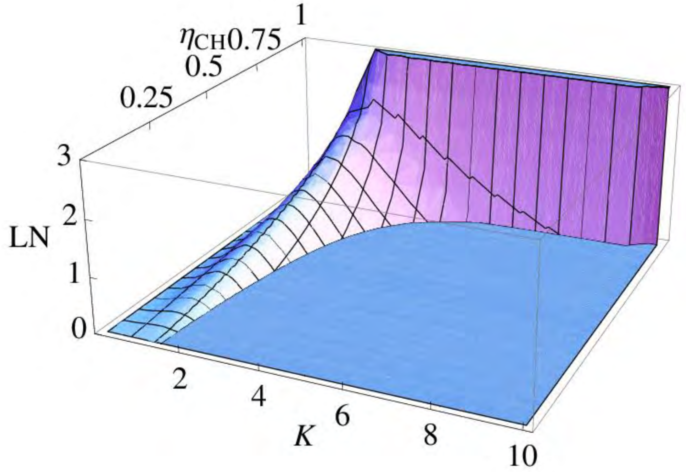
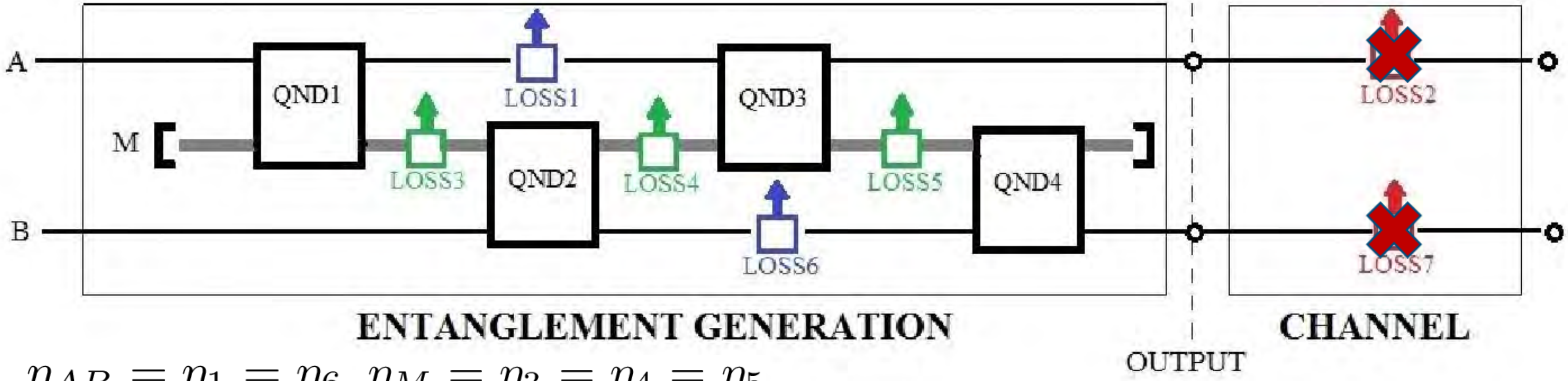


Vojtěch Kupčík and Radim Filip, Continuous-variable entanglement mediated by thermal oscillator, submitted.

ROBUSTNESS OF ENTANGLING PROCEDURE ASSISTED BY GROUND STATE MEDIATOR



$\eta_{AB} = \eta_1 = \eta_6 \quad \eta_M = \eta_3 = \eta_4 = \eta_5$

$V_N = 1 \text{ and all } K_1, K_2, K_3, K_4 = K$

Condition for entanglement:

$$\frac{1 + \eta_{AB} - 2\eta_M \sqrt{\eta_{AB}}}{\sqrt{\eta_M}} < 1 + \eta_{AB} + \sqrt{\eta_{AB}}(1 - \eta_M)$$

Vojtěch Kupčík and Radim Filip, Continuous-variable entanglement mediated by thermal oscillator, submitted.

ROBUSTNESS OF ENTANGLING PROCEDURE ASSISTED BY GROUND STATE MEDIATOR

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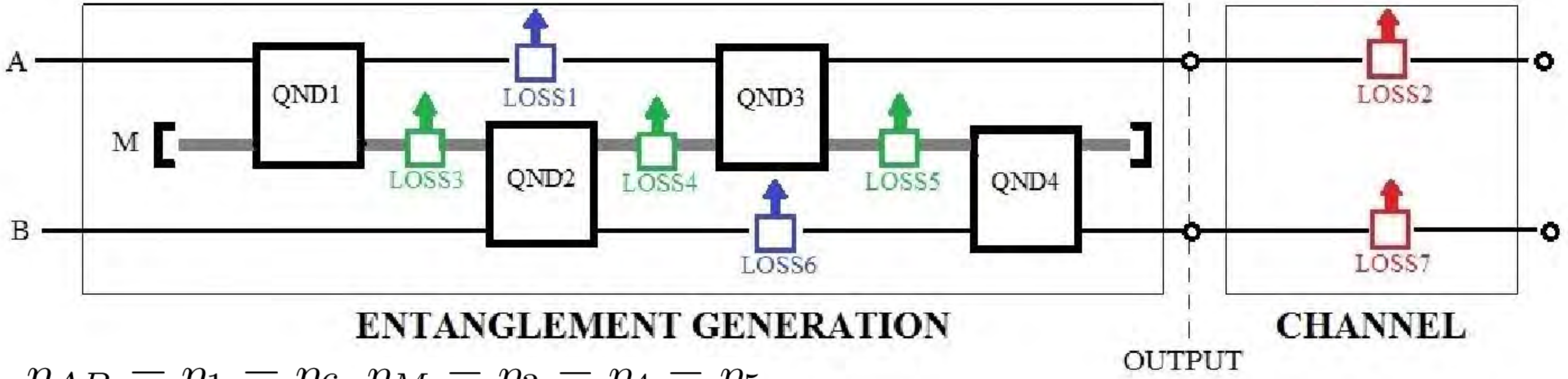

$$\eta_{AB} = \eta_1 = \eta_6 \quad \eta_M = \eta_3 = \eta_4 = \eta_5$$

$$V_N = 1 \text{ and all } K_1, K_2, K_3, K_4 = K$$

$$LN \approx -\frac{1}{2}\log_2\Big[1 + 2K^4 - 2\sqrt{K^4 + K^8} + K^2\left(\frac{2+3K^4}{\sqrt{1+K^4}} - 3K^2\right)(1-\eta_{CH}) + \frac{K^2}{2}\left(\frac{2+3K^4}{\sqrt{1+K^4}} - 3K^2\right)(1-\eta_{AB}) + 2K^2\left(\frac{K^2}{\sqrt{1+K^4}}\right)(1-\eta_M)\Big]$$

Vojtěch Kupčík and Radim Filip, Continuous-variable entanglement mediated by thermal oscillator, submitted.

ROBUSTNESS OF ENTANGLING PROCEDURE ASSISTED BY GROUND STATE MEDIATOR

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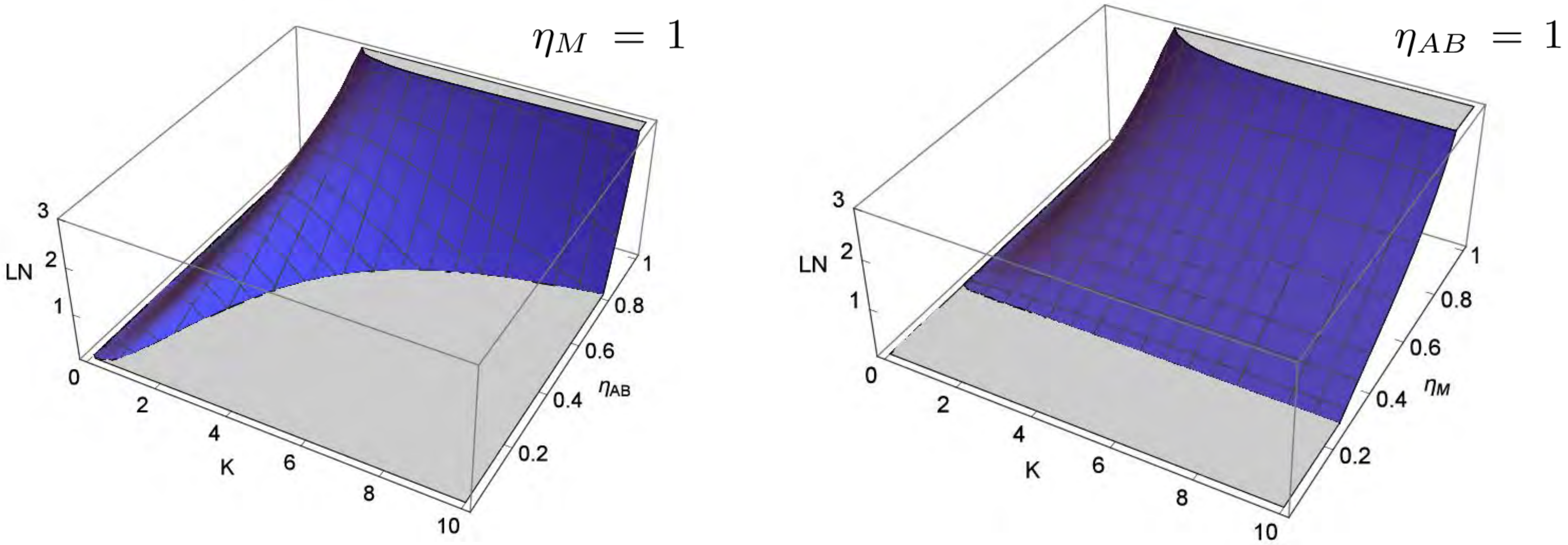
$V_N = 1$ and all $K_1, K_2, K_3, K_4 = K$



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ROBUSTNESS OF ENTANGLING PROCEDURE ASSISTED BY GROUND STATE MEDIATOR

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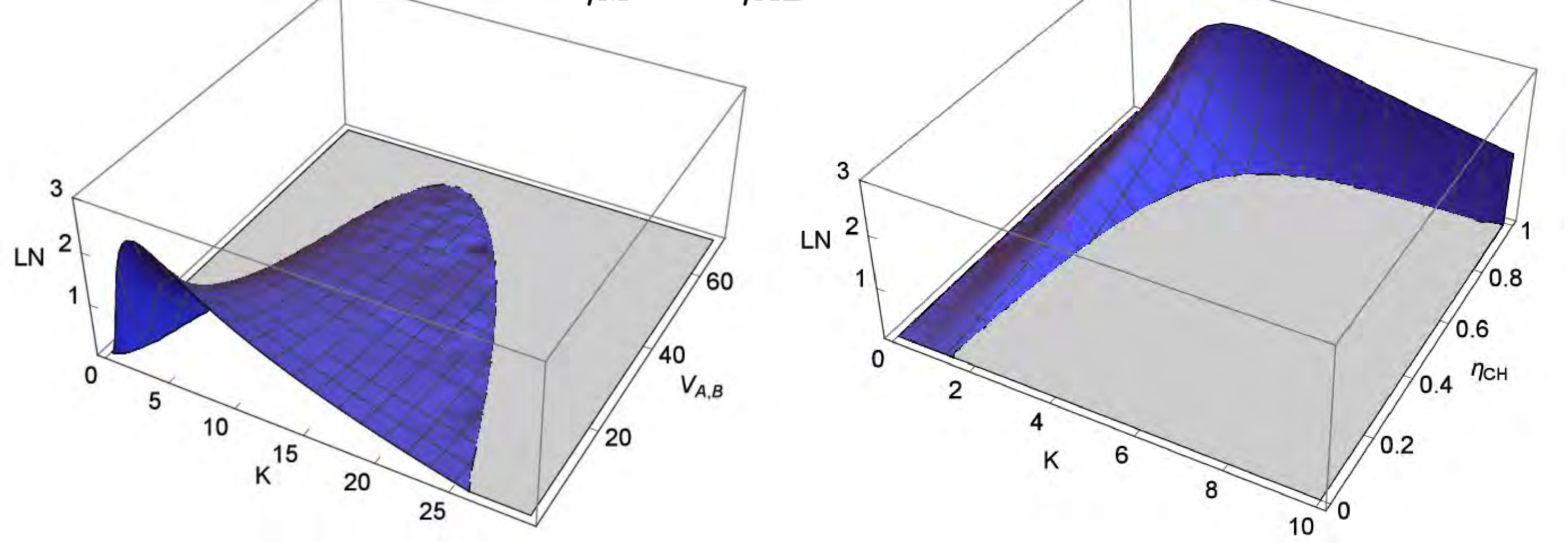
$V_N = 1$ and all $K_1, K_2, K_3, K_4 = K$

$$\eta_M = \eta_{AB} = 0.95$$



Vojtěch Kupčík and Radim Filip, Continuous-variable entanglement mediated by thermal oscillator, submitted.

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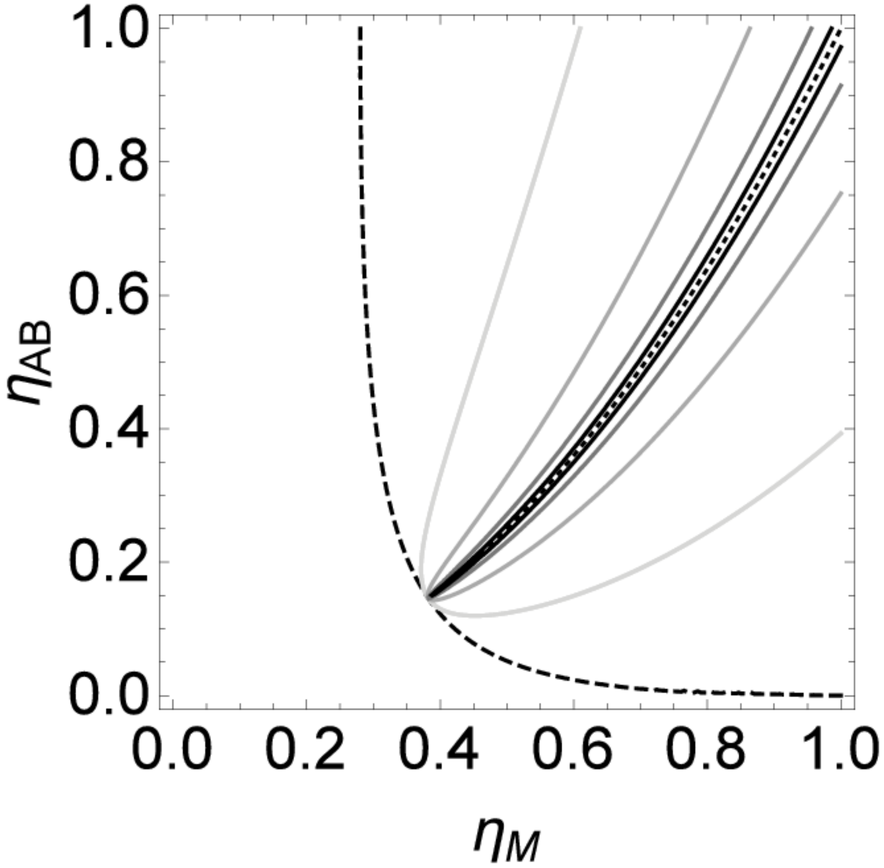
ROBUSTNESS OF ENTANGLING PROCEDURE ASSISTED BY NOISY MEDIATOR

$$\eta_{AB} = \eta_1 = \eta_6 \qquad \eta_M = \eta_3 = \eta_4 = \eta_5$$



$V_N = 1$ (dashed), $V_N = 10, 10^2, 10^3$
10^4 (full)

all $K_1, K_2, K_3, K_4 = K$

Vojtěch Kupčík and Radim Filip, Continuous-variable entanglement mediated by thermal oscillator, submitted.

ROBUSTNESS OF ENTANGLING PROCEDURE ASSISTED BY NOISY MEDIATOR

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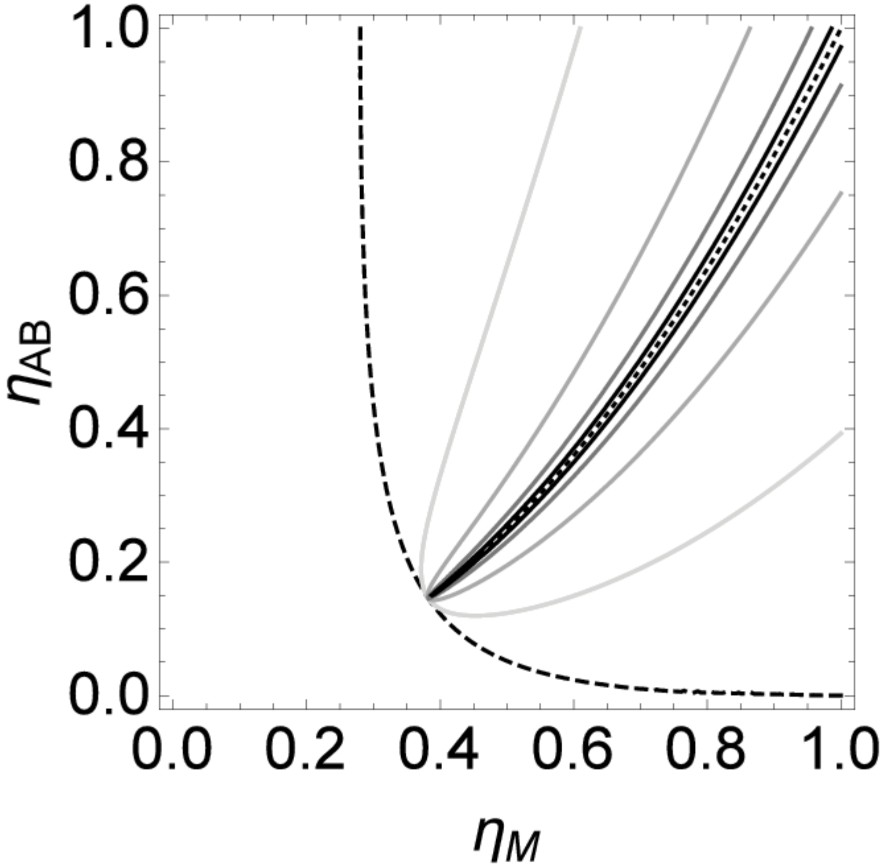
$\eta_{AB} = \eta_1 = \eta_6$ $\eta_M = \eta_3 = \eta_4 = \eta_5$



$V_N = 1$ (dashed), $V_N = 10, 10^2, 10^3$ 10^4 (full)

all $K_1, K_2, K_3, K_4 = K$

Entanglement is still observable.

Entangling procedure assisted by noisy mediator is possible but fragile!

Vojtěch Kupčík and Radim Filip, Continuous-variable entanglement mediated by thermal oscillator, submitted.

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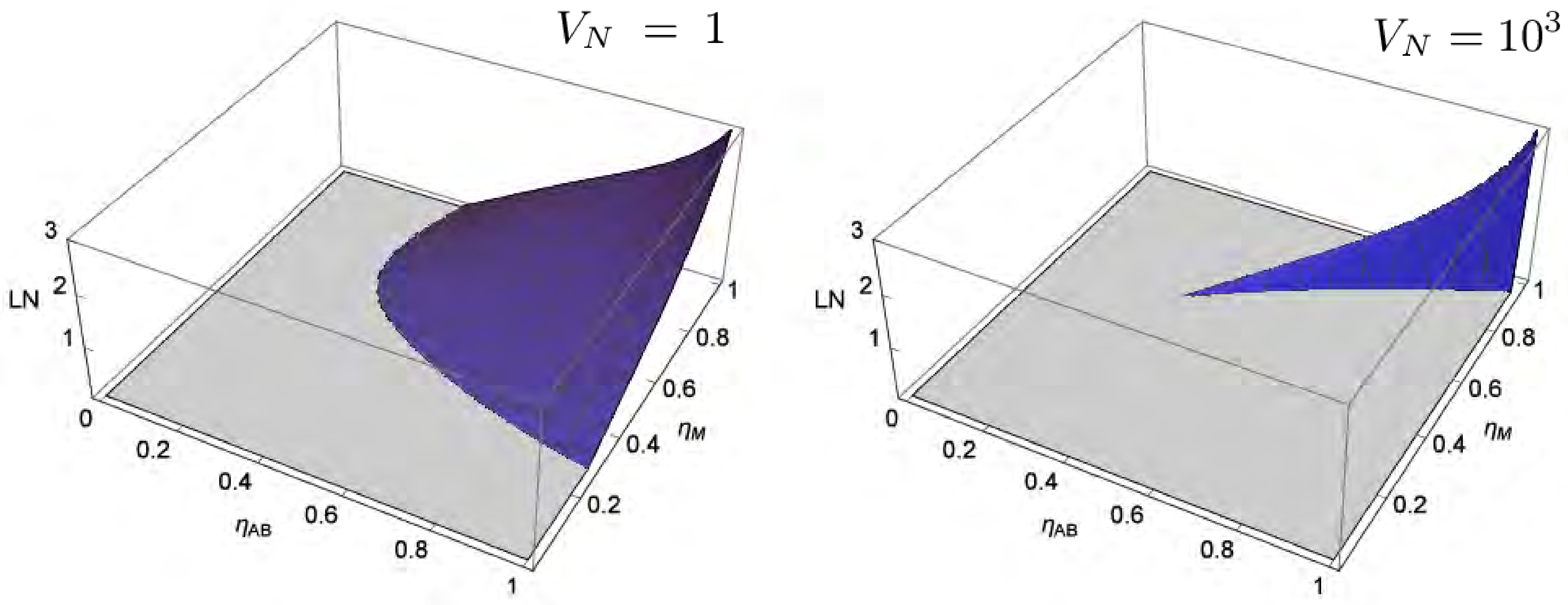
ROBUSTNESS OF ENTANGLING PROCEDURE ASSISTED BY NOISY MEDIATOR

$\eta_{AB} = \eta_1 = \eta_6 \qquad \eta_M = \eta_3 = \eta_4 = \eta_5 \qquad K_1, K_2, K_3, K_4 = 2$



Vojtěch Kupčík and Radim Filip, Continuous-variable entanglement mediated by thermal oscillator, submitted.

ROBUSTNESS OF ENTANGLING PROCEDURE ASSISTED BY NOISY MEDIATOR

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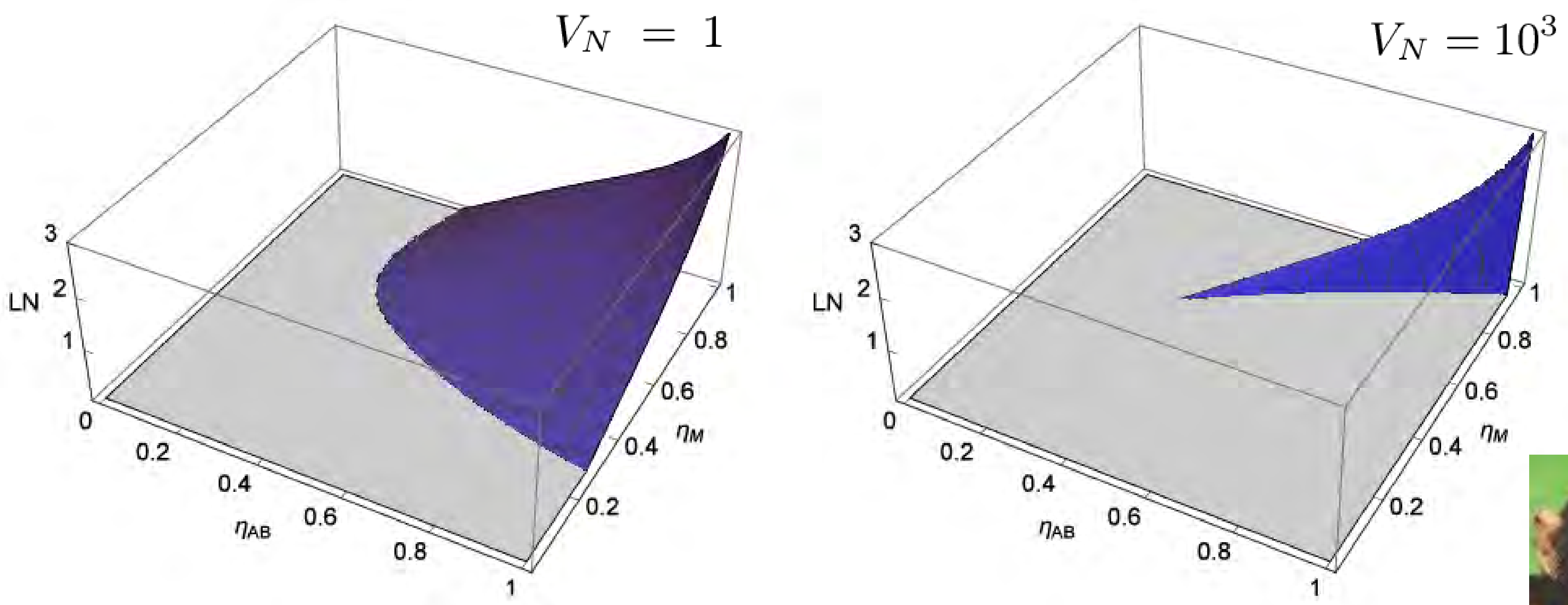

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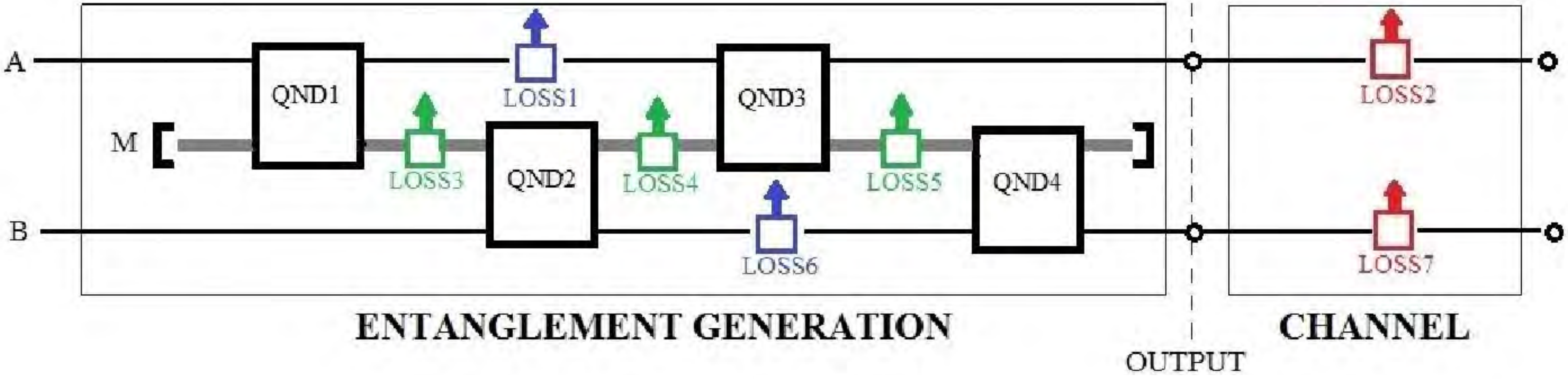
ROBUSTNESS OF OPTIMIZED ENTANGILING PROCEDURE



$$\mathrm{QND1}: X'_A = X_A - K_1 \cdot X_M, \quad P'_A = P_A,$$
$$X'_M = X_M, \quad P'_M = P_M + K_1 \cdot P_A,$$

$$\mathrm{QND2}: X'_B = X_B, \quad P'_B = P_B - K_2 \cdot P'_M,$$
$$X''_M = X'_M + K_2 \cdot X_B, \quad P''_M = P'_M,$$

$$\mathrm{QND3}: X''_A = X'_A + K_3 \cdot X''_M, \quad P''_A = P'_A,$$
$$X'''_M = X''_M, \quad P'''_M = P''_M - K_3 \cdot P'_A,$$

$$\mathrm{QND4}: X''_B = X'_B, \quad P''_B = P'_B + K_4 \cdot P'''_M,$$
$$X''''_M = X'''_M - K_4 \cdot X'_B, \quad P''''_M = P'''_M,$$

Vojtěch Kupčík and Radim Filip, Continuous-variable entanglement mediated by thermal oscillator, submitted.

ROBUSTNESS OF OPTIMIZED ENTANGILING PROCEDURE

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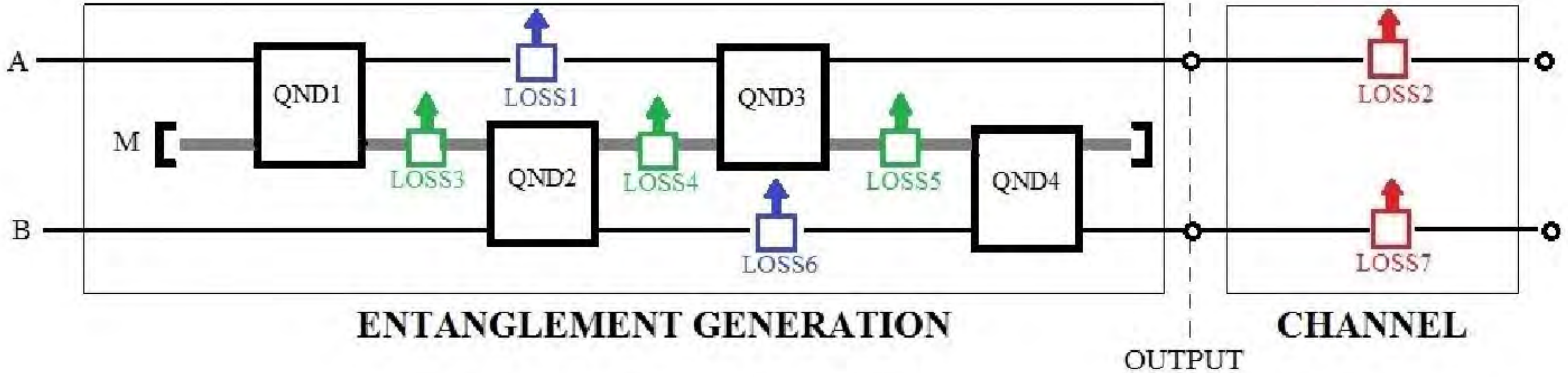

$$\mathrm{QND1}: X'_A = X_A - K_1 \cdot X_M, \quad P'_A = P_A, \quad X'_M = X_M, \quad P'_M = P_M + K_1 \cdot P_A,$$

$$\mathrm{QND3}: X''_A = X'_A + K_3 \cdot X''_M, \quad P''_A = P'_A, \quad X'''_M = X''_M, \quad P'''_M = P''_M - K_3 \cdot P'_A,$$

$$\mathrm{QND2}: X'_B = X_B, \quad P'_B = P_B - K_2 \cdot P'_M, \quad X''_M = X'_M + K_2 \cdot X_B, \quad P''_M = P'_M,$$

$$\mathrm{QND4}: X''_B = X'_B, \quad P''_B = P'_B + K_4 \cdot P'''_M, \quad X''''_M = X'''_M - K_4 \cdot X'_B, \quad P''''_M = P'''_M,$$

Optimization over all QND interaction strengths limited by maximal K

Vojtěch Kupčík and Radim Filip, Continuous-variable entanglement mediated by thermal oscillator, submitted.

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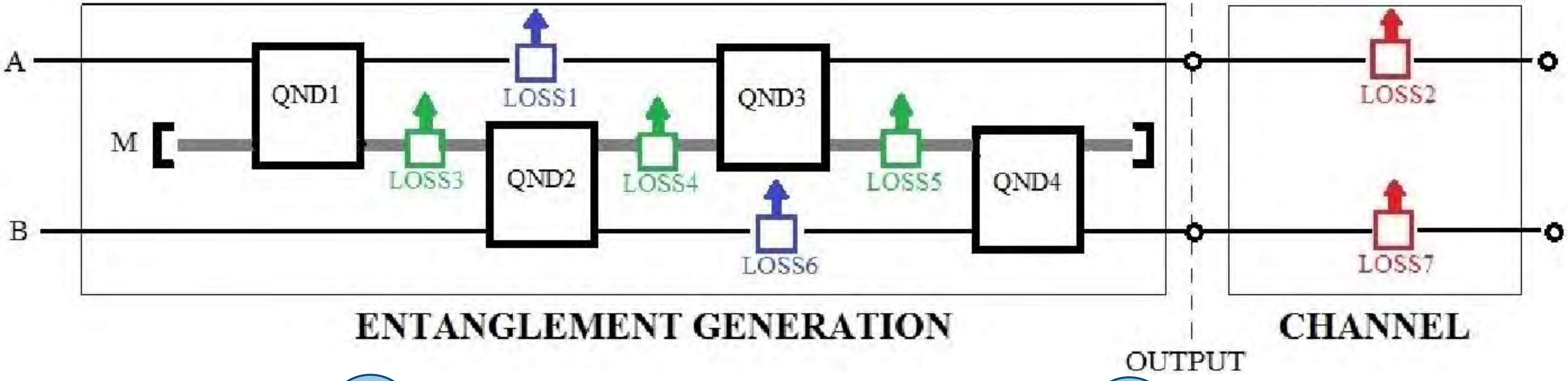
ROBUSTNESS OF OPTIMIZED ENTANGILING PROCEDURE



$$\text{QND1}: X'_A = X_A - K_1 \cdot X_M, \quad P'_A = P_A,$$
$$X'_M = X_M, \quad P'_M = P_M + K_1 \cdot P_A,$$

$$\text{QND2}: X'_B = X_B, \quad P'_B = P_B - K_2 \cdot P'_M,$$
$$X''_M = X'_M + K_2 \cdot X_B, \quad P''_M = P'_M,$$

$$\text{QND3}: X''_A = X'_A + K_3 \cdot X''_M, \quad P''_A = P'_A,$$
$$X'''_M = X''_M, \quad P'''_M = P''_M - K_3 \cdot P'_A,$$

$$\text{QND4}: X''_B = X'_B, \quad P''_B = P'_B + K_4 \cdot P'''_M,$$
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Optimization over all QND interaction strengths limited by maximal K

Vojtěch Kupčík and Radim Filip, Continuous-variable entanglement mediated by thermal oscillator, submitted.

ROBUSTNESS OF OPTIMIZAED ENTANGLING PROCEDURE ASSISTED BY NOISY MEDIATOR

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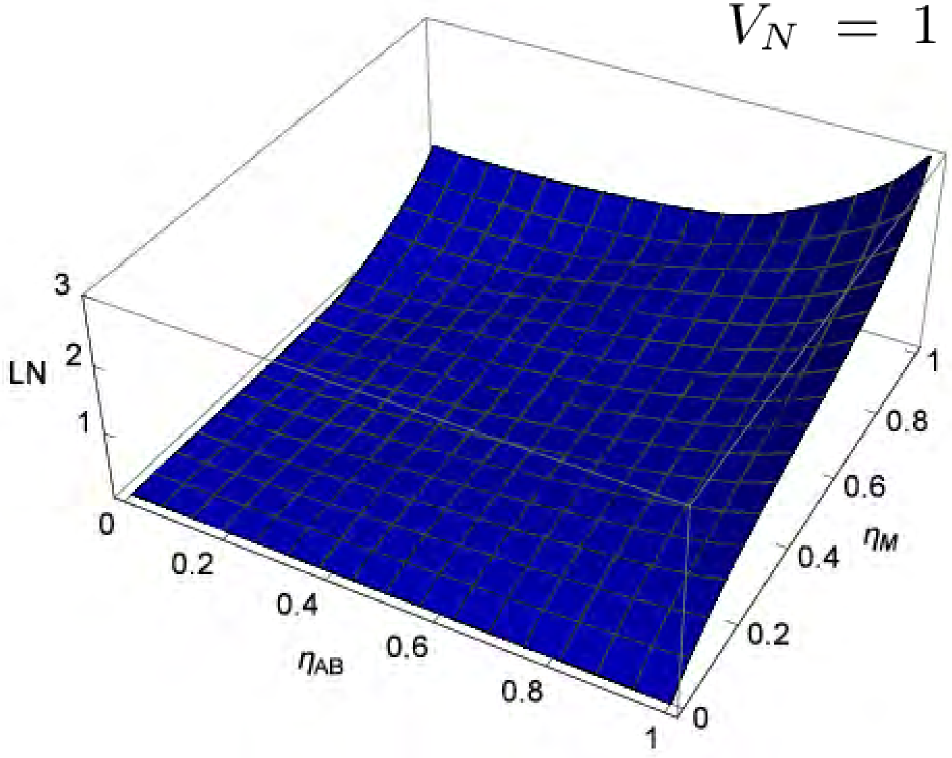
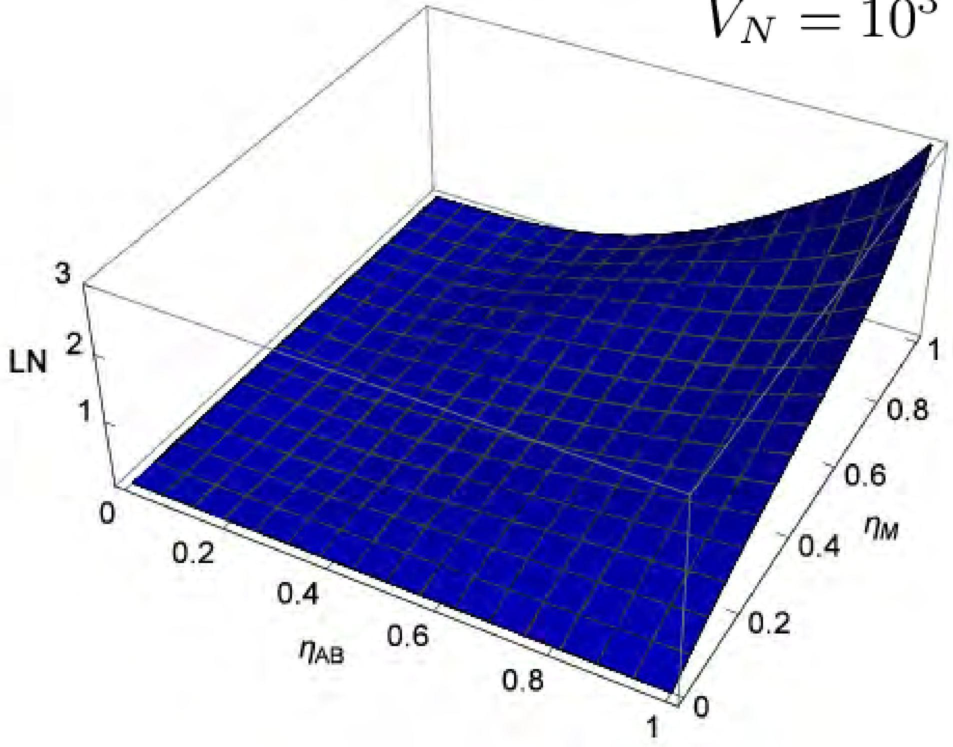
$\eta_{AB} = \eta_1 = \eta_6 \qquad \eta_M = \eta_3 = \eta_4 = \eta_5 \qquad K_1, K_2, K_3, K_4 \leq K_{max} = 2$

$V_N = 1$



$V_N = 10^3$



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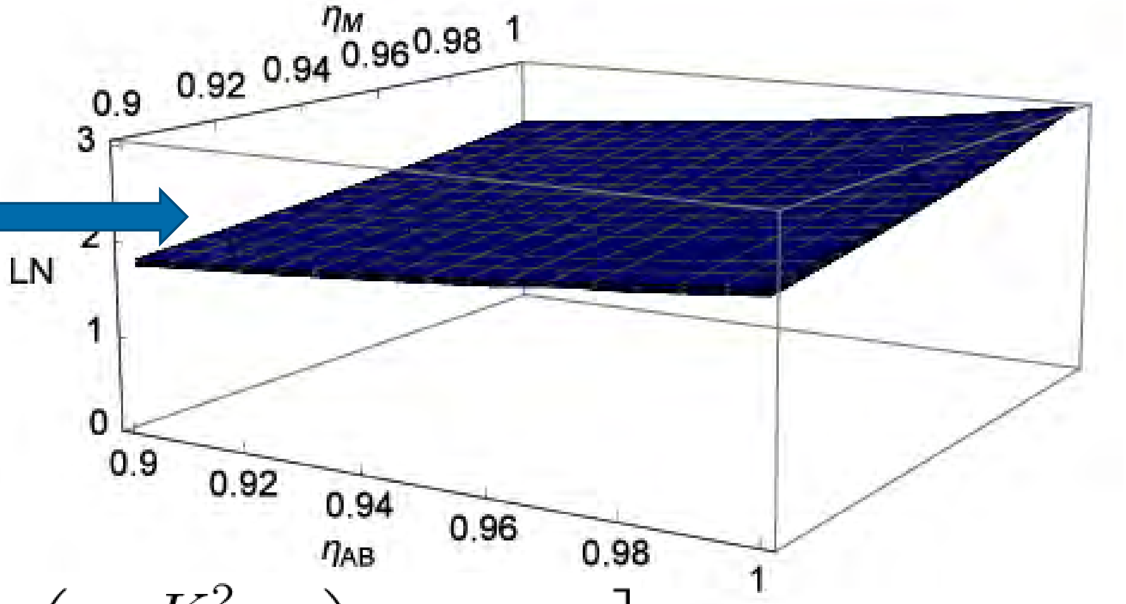
ROBUSTNESS OF OPTIMIZAED ENTANGLING PROCEDURE ASSISTED BY NOISY MEDIATOR

$\eta_{AB} = \eta_1 = \eta_6$ $\quad\quad$ $\eta_M = \eta_3 = \eta_4 = \eta_5$ $\quad\quad$ $V_N = 10^3$

$K_1, K_2, K_3, K_4 \leq K_{max} = 2$

$V_N = 1$ and all $K_1, K_2, K_3, K_4 = K$



$$LN \approx -\frac{1}{2}\log_2\left[1 + 2K^4 - 2\sqrt{K^4 + K^8 + K^2\left(\frac{2+3K^4}{\sqrt{1+K^4}} - 3K^2\right)(1-\eta_{CH}) + \frac{K^2}{2}\left(\frac{2+3K^4}{\sqrt{1+K^4}} - 3K^2\right)(1-\eta_{AB}) + 2K^2\left(\frac{K^2}{\sqrt{1+K^4}}\right)(1-\eta_M)}\right]$$

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ROBUSTNESS OF OPTIMIZAED ENTANGLING PROCEDURE ASSISTED BY NOISY MEDIATOR

Palacký University Olomouc

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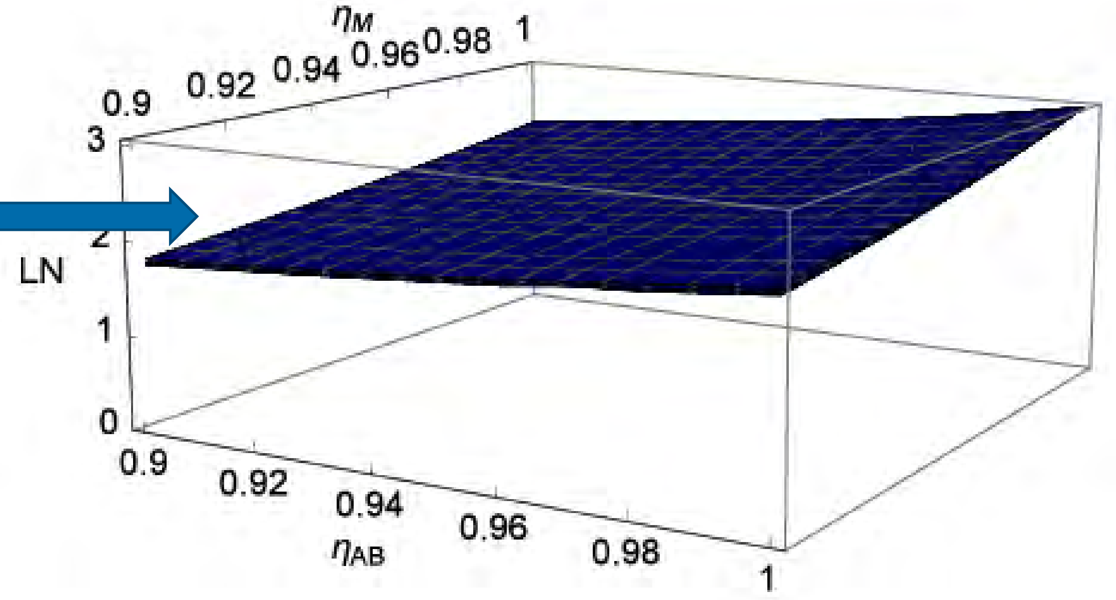

For the small losses, negative effect of mediator noise is completely removed by optimization of entangling procedure.

Vojtěch Kupčík and Radim Filip, Continuous-variable entanglement mediated by thermal oscillator, submitted.

ROBUSTNESS OF OPTIMIZAED ENTANGLING PROCEDURE ASSISTED BY NOISY MEDIATOR

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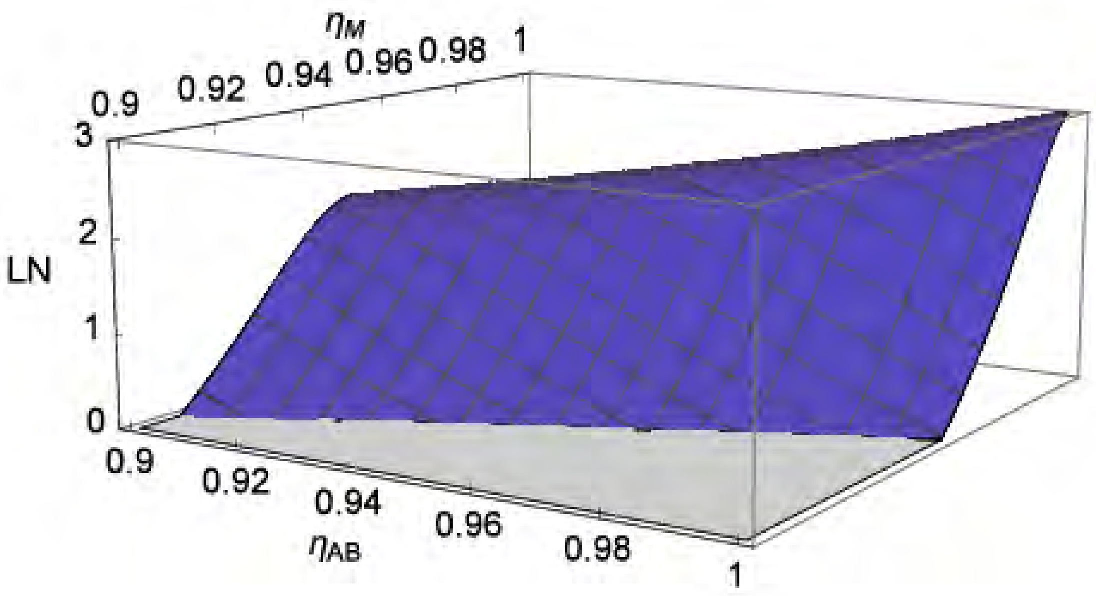
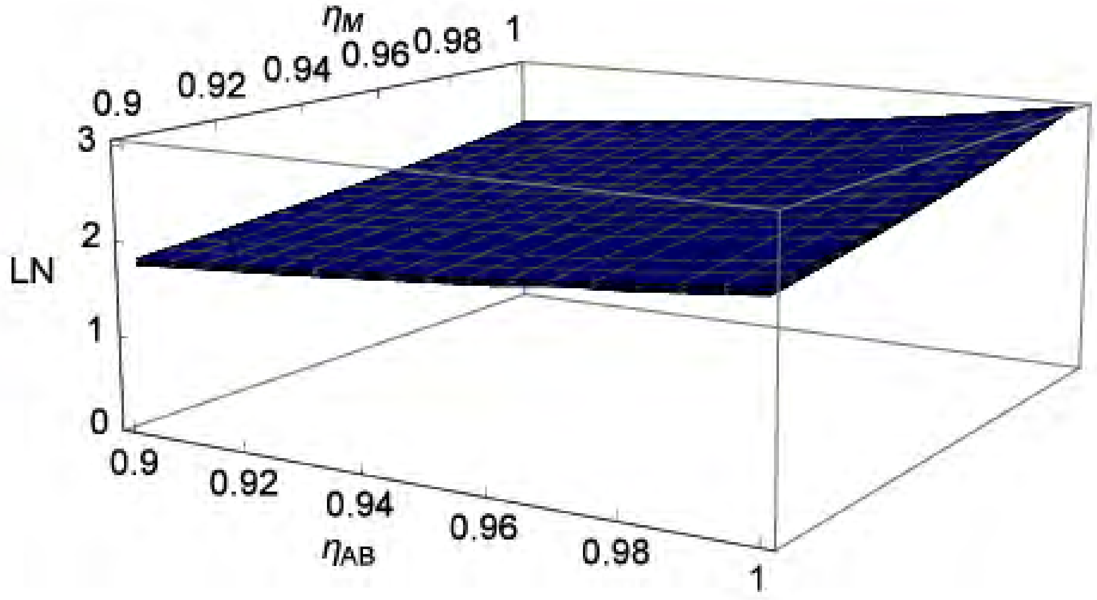
$\eta_{AB} = \eta_1 = \eta_6$ $\eta_M = \eta_3 = \eta_4 = \eta_5$ $V_N = 10^3$

$K_1, K_2, K_3, K_4 = 2$



$K_1, K_2, K_3, K_4 \leq K_{max} = 2$



Vojtěch Kupčík and Radim Filip, Continuous-variable entanglement mediated by thermal oscillator, submitted.

ROBUSTNESS OF OPTIMIZAED ENTANGLING PROCEDURE ASSISTED BY NOISY MEDIATOR

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$\eta_{AB} = \eta_1 = \eta_6$ $\eta_M = \eta_3 = \eta_4 = \eta_5$ $V_N = 10^3$

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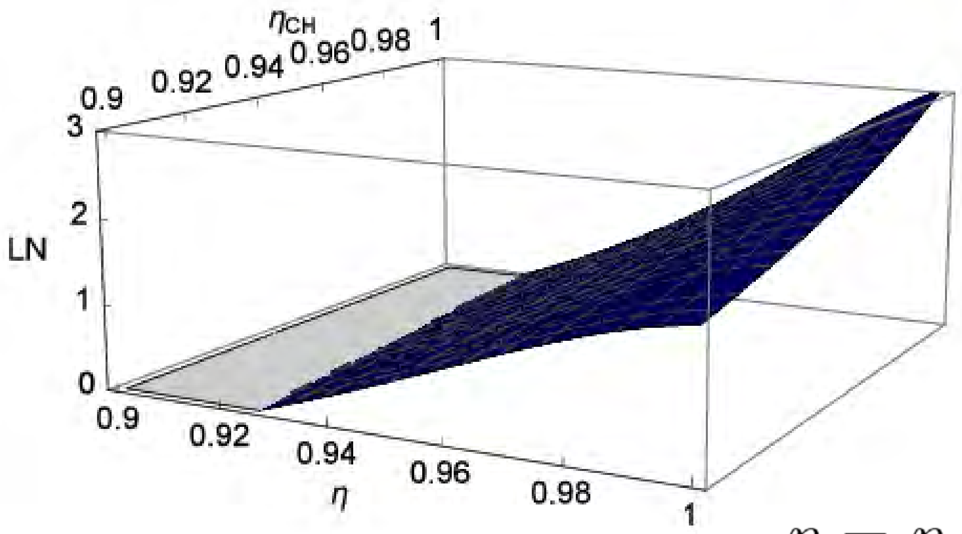

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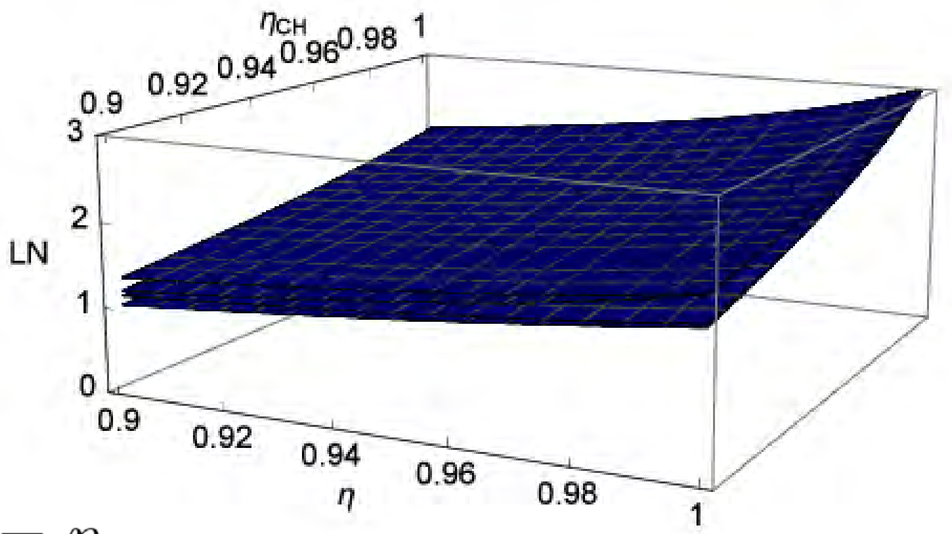

$\eta = \eta_{AB} = \eta_M$

Vojtěch Kupčík and Radim Filip, Continuous-variable entanglement mediated by thermal oscillator, submitted.

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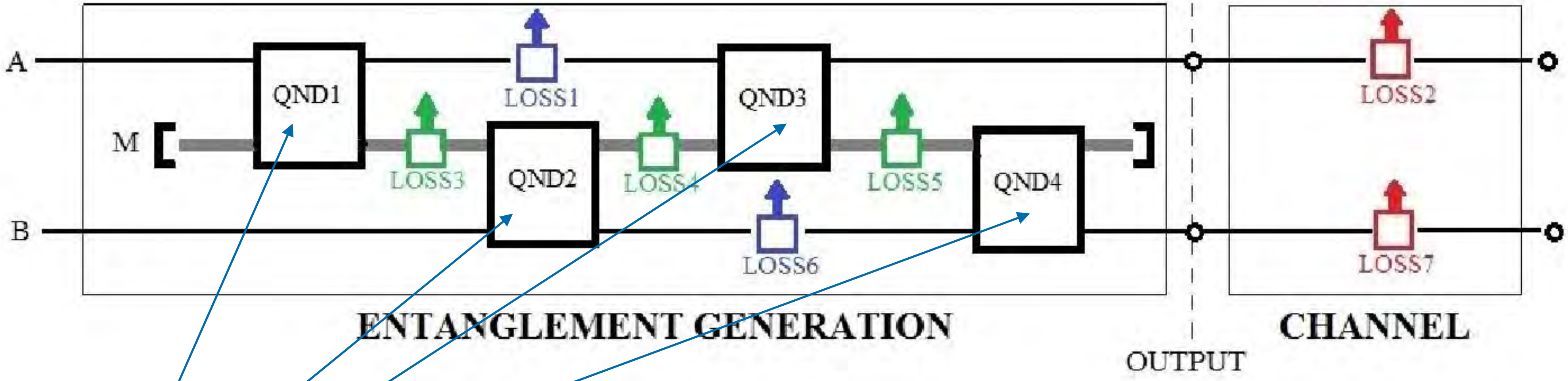
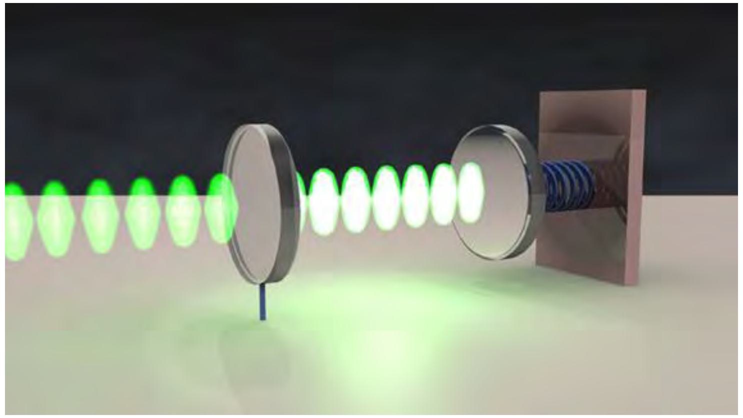
ROBUSTNESS OF GAUSSIAN ENTANGLEMENT ASSISTED BY NOISY MEDIATOR



OPTIMIZE!

Implementation with pulsed quantum optomechanics



Vojtěch Kupčík and Radim Filip, Continuous-variable entanglement mediated by thermal oscillator, submitted.

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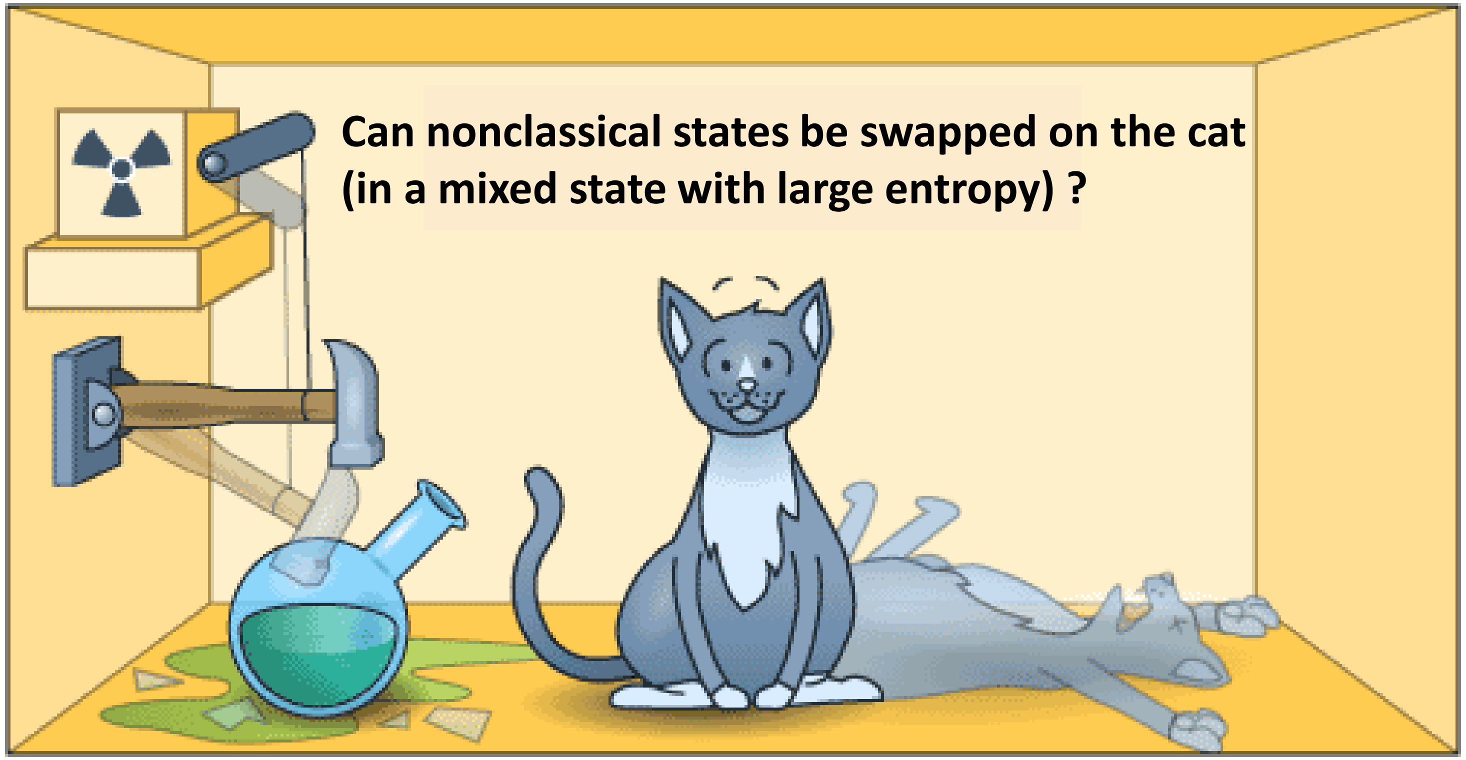
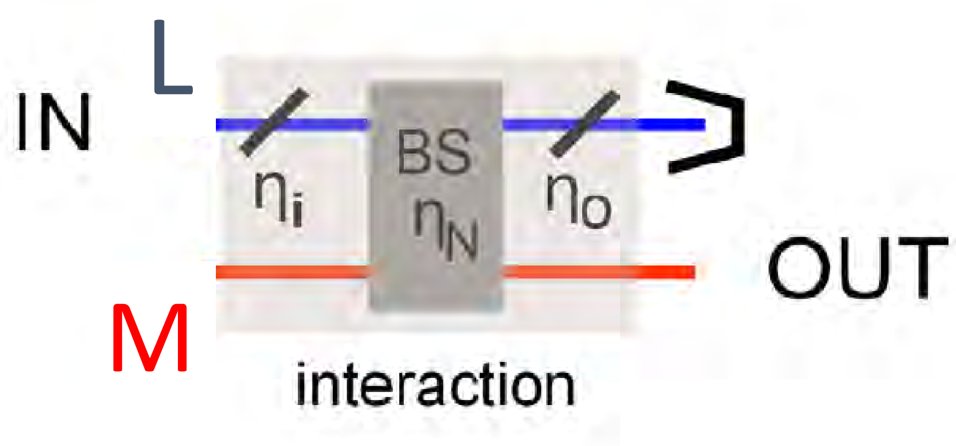
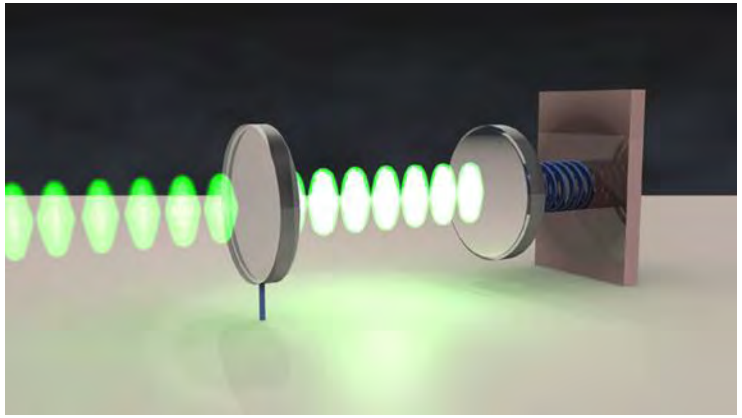
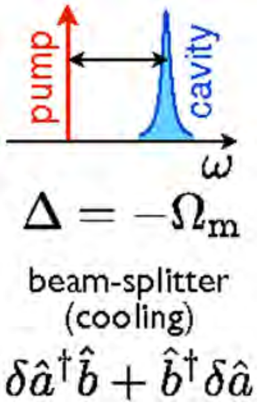
QUANTUM INTERFACE



FULL COHERENT SWAP







T. A. Palomaki, J. D. Teufel, R. W. Simmonds,
and K. W. Lehnert, Entangling Mechanical Motion with Microwave Fields, Science 8, 710 (2013)

If beam splitter coupling is strong and is not limited by decoherence, it swaps any state to any noise of mechanics. Just in-coupling optical losses matters.

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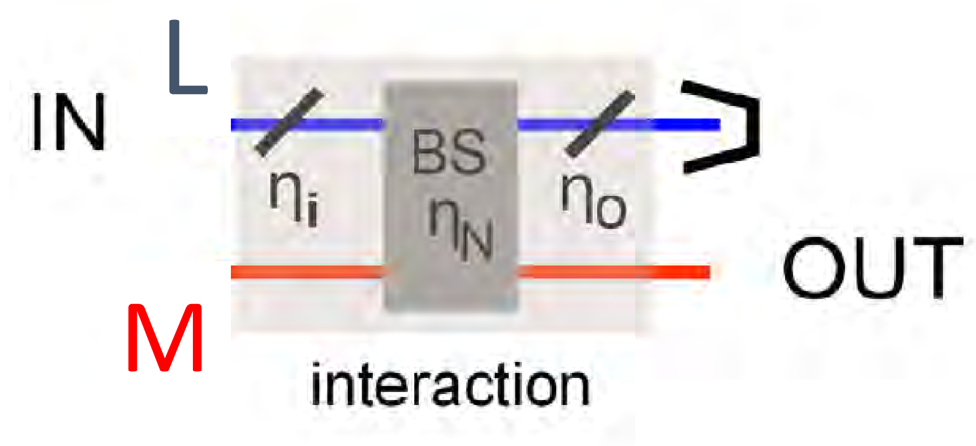
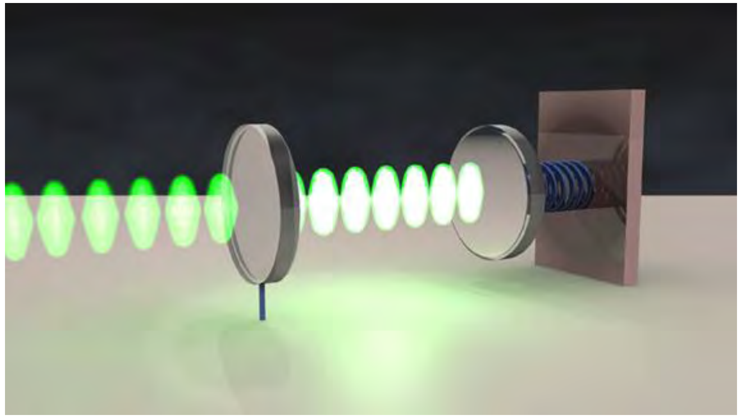
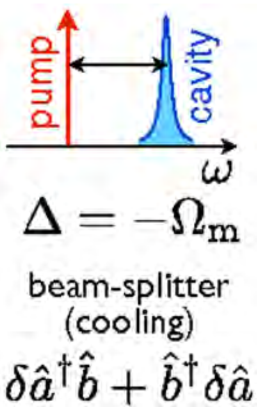
L-M FULL COHERENT SWAP







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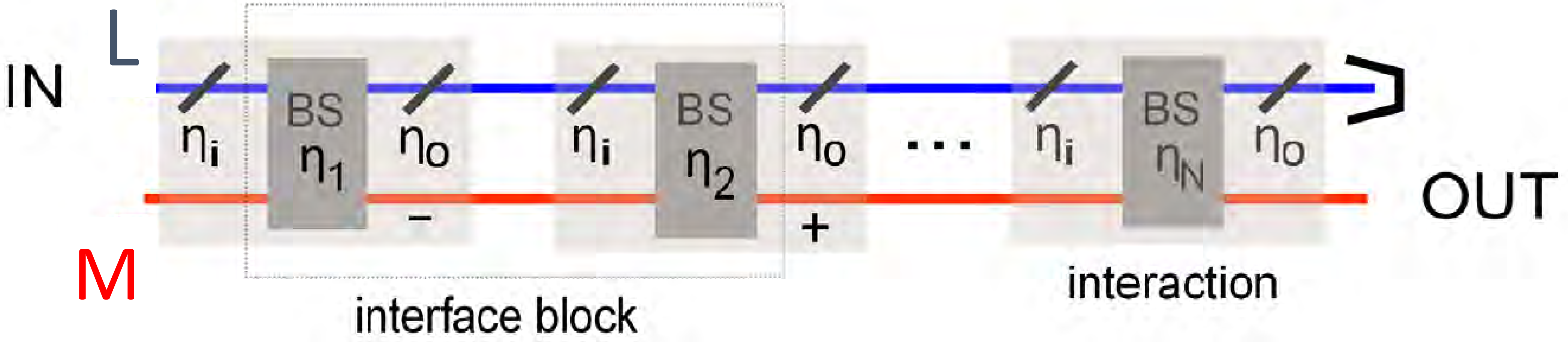
If beam splitter coupling is strong and is not limited by decoherence, it swaps any state to any noise of mechanics. Just in-coupling optical losses matters.

But what if not?

INTERFEROMETRIC QUANTUM INTERFACE



Interface block:

By optimization of $\eta_2 = \dfrac{1-\eta_1}{\eta_1\eta_i\eta_o + (1-\eta_1)}$ $\qquad \bar{\eta} = \dfrac{\eta_i\eta_o}{\eta_1\eta_i\eta_o + (1-\eta_1)}$

Just attenuation without any excess noise at the output for any noise of mechanical system!

Radim Filip and Petr Klapka, Purely lossy and robust quantum interfaces between light and matter, Opt. Exp. 22, 30697 (2014).

INTERFEROMETRIC QUANTUM INTERFACE

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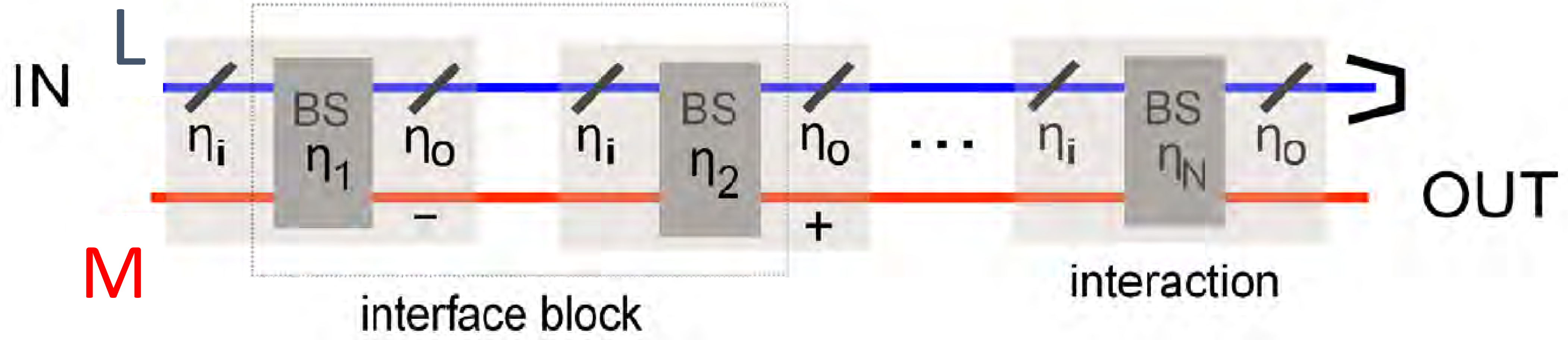

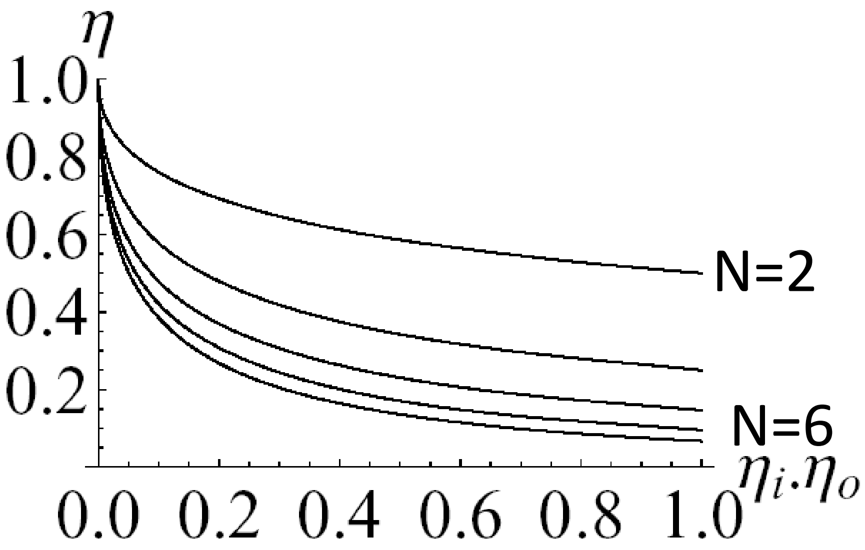

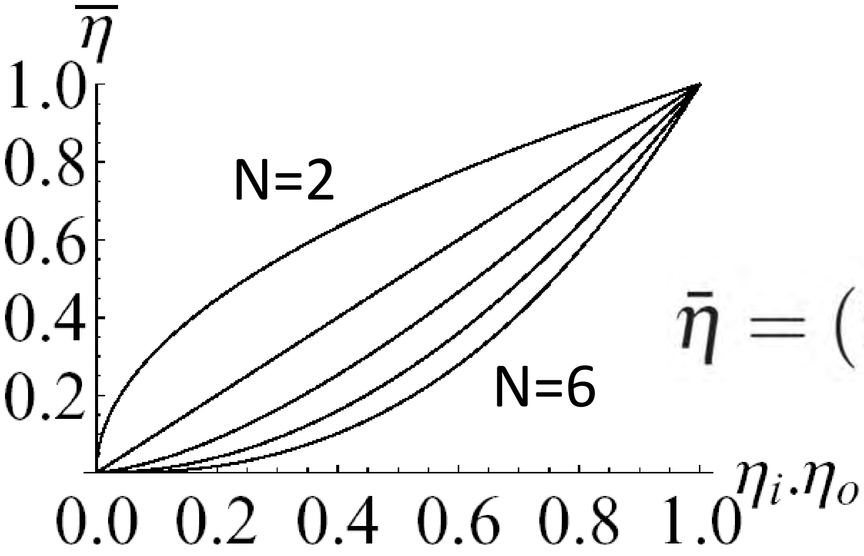

$$\bar{\eta} = (\eta_i \eta_o)^{\frac{N-1}{2}}$$

Radim Filip and Petr Klapka, Purely lossy and robust quantum interfaces between light and matter, Opt. Exp. 22, 30697 (2014).

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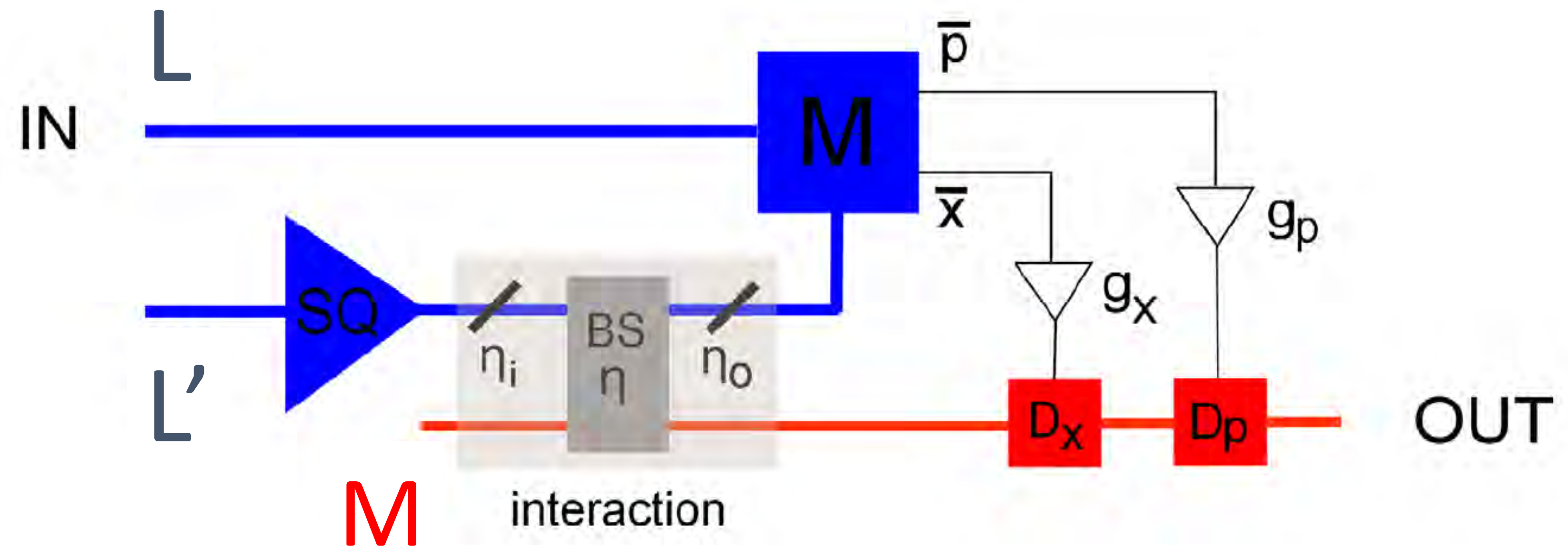
TELEPORTATION INTERFACE



For ground state of M, without losses and for large squeezing of L':

Just attenuation without any excess noise at the output. But very sensitive to noise of M and losses. Teleportation is not enough robust.

Alternative: conditional CV teleportation

Maria Fuwa, Shunsuke Toba, Shuntaro Takeda, Petr Marek, Ladislav Mista Jr., Radim Filip, Peter van Loock, Jun-ichi Yoshikawa, Akira Furusawa, Phys. Rev. Lett. 113, 223602 (2014).

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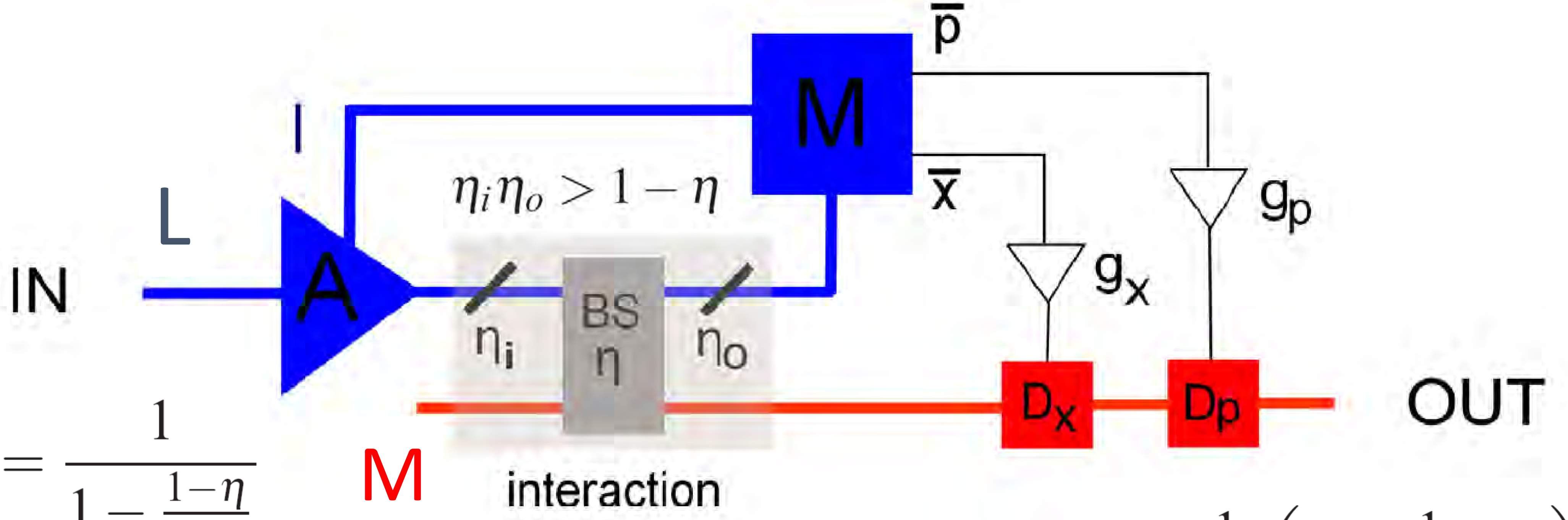
AMPLIFIER BASED QUANTUM INTERFACE



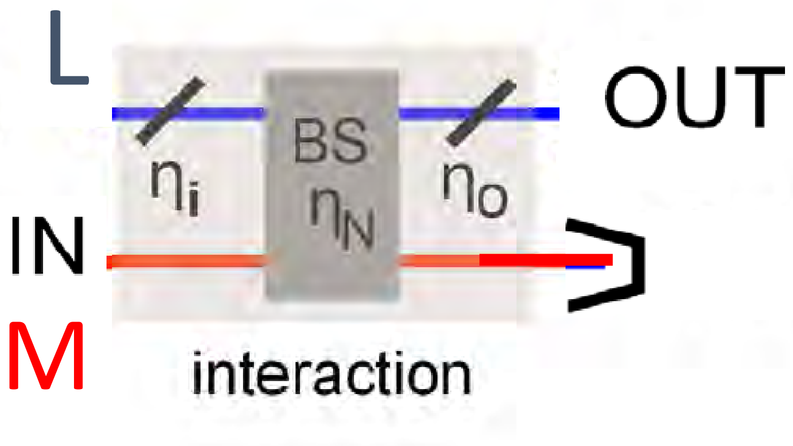
$$G = \frac{1}{1 - \frac{1-\eta}{\eta_i \eta_o}}$$

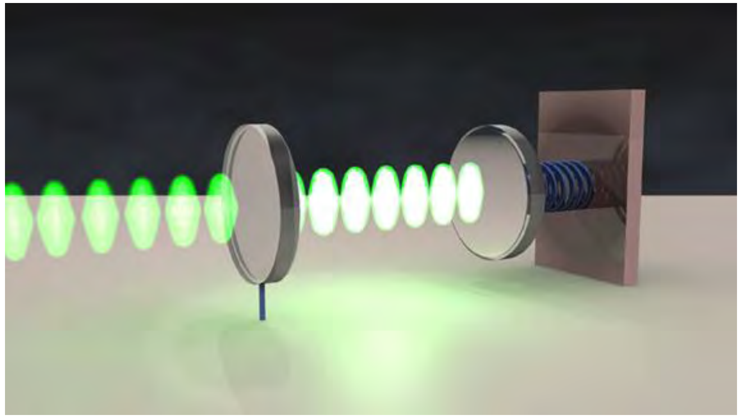
$$\bar{\eta} = \frac{1}{\eta}\left(\eta_i - \frac{1-\eta}{\eta_o}\right)$$

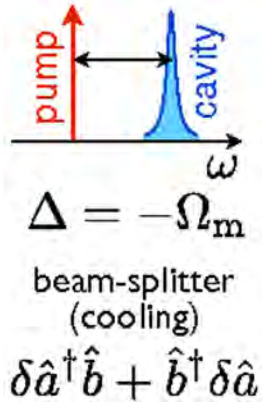
Just attenuation without any excess noise at the output for any noise of mechanical system! Deterministic! Robust!

Radim Filip, Quantum interface to a noisy system through a single kind of arbitrary Gaussian coupling with limited interaction strength, Phys. Rev. A 80, 022304 (2009).
Radim Filip and Petr Klapka, Purely lossy and robust quantum interfaces between light and matter, Opt. Exp. 22, 30697 (2014).

M-L FULL COHERENT SWAP







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If beam splitter coupling is strong and is not limited by decoherence, it solves the problem for any noise of mechanics. Just in-coupling optical losses matters.

But what if not?

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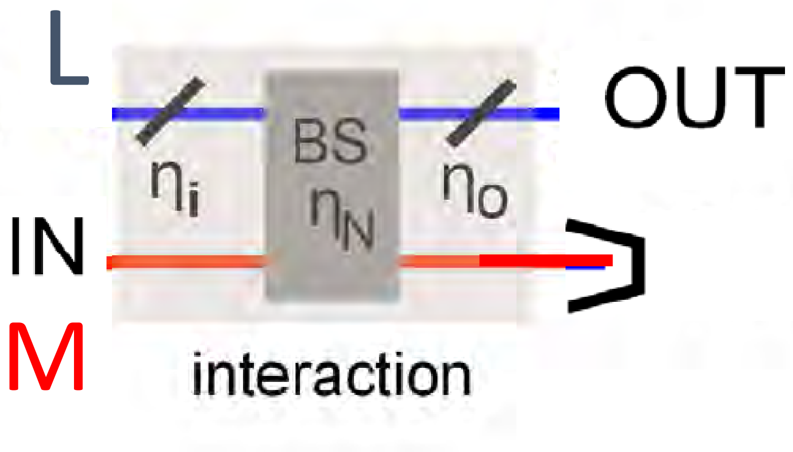
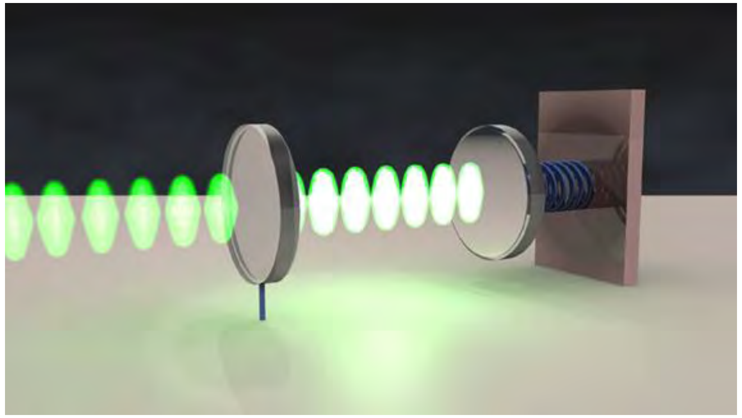
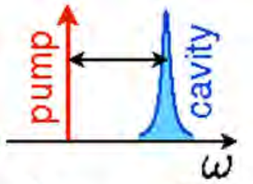






$\Delta = -\Omega_{\mathrm{m}}$

beam-splitter
(cooling)

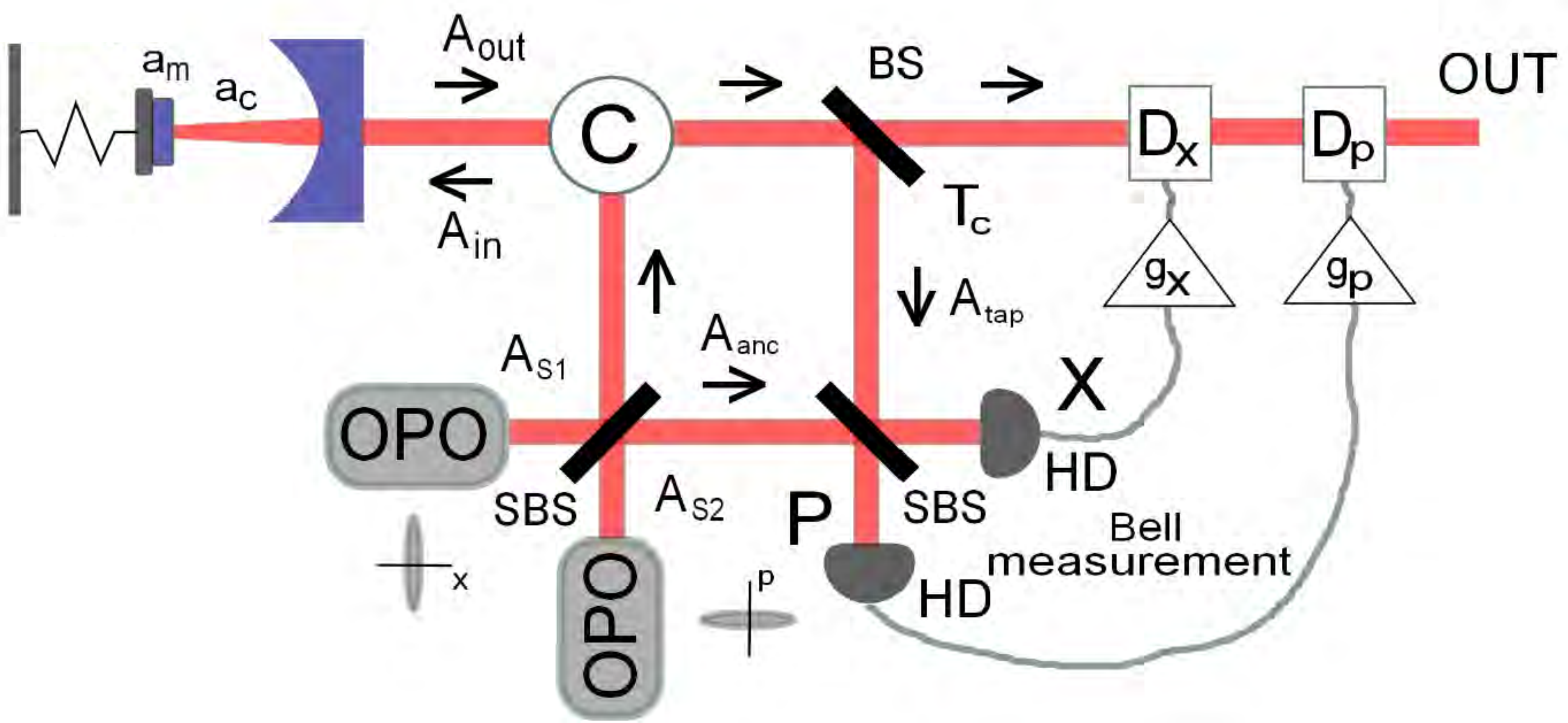
$\delta\hat{a}^{\dagger}\hat{b} + \hat{b}^{\dagger}\delta\hat{a}$

$$A_{\mathrm{out}} = \sqrt{T\eta_o}B_{\mathrm{in}} + \sqrt{T_L}A_{\mathrm{in}} + \sqrt{1 - T\eta_o - T_L}A_0$$

$$T_L = (1-T)\eta_i\eta_o \quad T = 1 - e^{-2g^2\Delta\tau/\kappa}$$

It fits imperfections observed in T. A. Palomaki, J. D. Teufel, R. W. Simmonds, and K. W. Lehnert, Science 8, 710 (2013)

READ OUT WITH ENTANGLEMENT



Radim Filip and Andrey A. Rakhubovsky, Transfer of non-Gaussian quantum states of mechanical oscillator to light, submitted.

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READ OUT WITH ENTANGLEMENT

$$Q=\sqrt{T'}Q_M+\sqrt{1-T'}Q_0+Q_N,\quad V_N'=\frac{(1-T_c)}{T_c}V_S$$

$$T_c=1-\eta_i\eta_o\left(1-T\right),\quad g_{x,p}=\sqrt{2\frac{\eta_i\eta_o\left(1-T\right)}{1-\eta_i\eta_o\left(1-T\right)}}$$

$$T'=\frac{\eta_o T}{1-\eta_i\eta_o\left(1-T\right)}$$

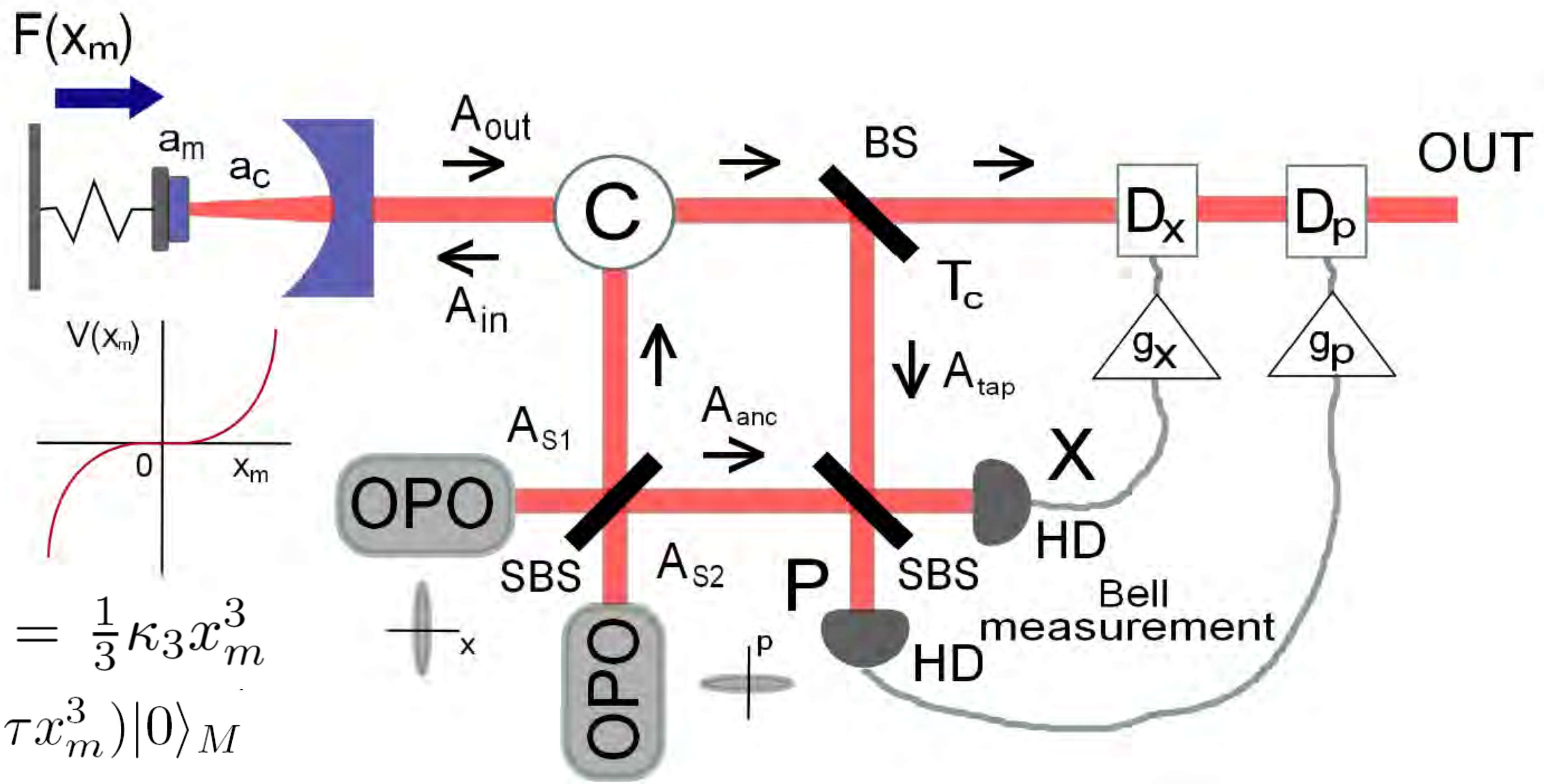
In the limit of feasible squeezing, the read out approaches pure damping without any excess noise.

$$T>\frac{1-\eta_i\eta_o}{(2-\eta_i)\eta_o}$$

In the limit of feasible squeezing, the read out can transfer negativity of Wigner function.

Radim Filip and Andrey A. Rakhubovsky, Transfer of non-Gaussian quantum states of mechanical oscillator to light, submitted.

READ OUT OF CUBIC STATE



$$V(x_m) = \frac{1}{3}\kappa_3 x_m^3$$

$$\exp(i\kappa_3 \tau x_m^3)|0\rangle_M$$

Daniel Gottesman, Alexei Kitaev, John Preskill, Phys.Rev. A 64, 012310 (2001).

Radim Filip and Andrey A. Rakhubovsky, Transfer of non-Gaussian quantum states of mechanical oscillator to light, submitted.

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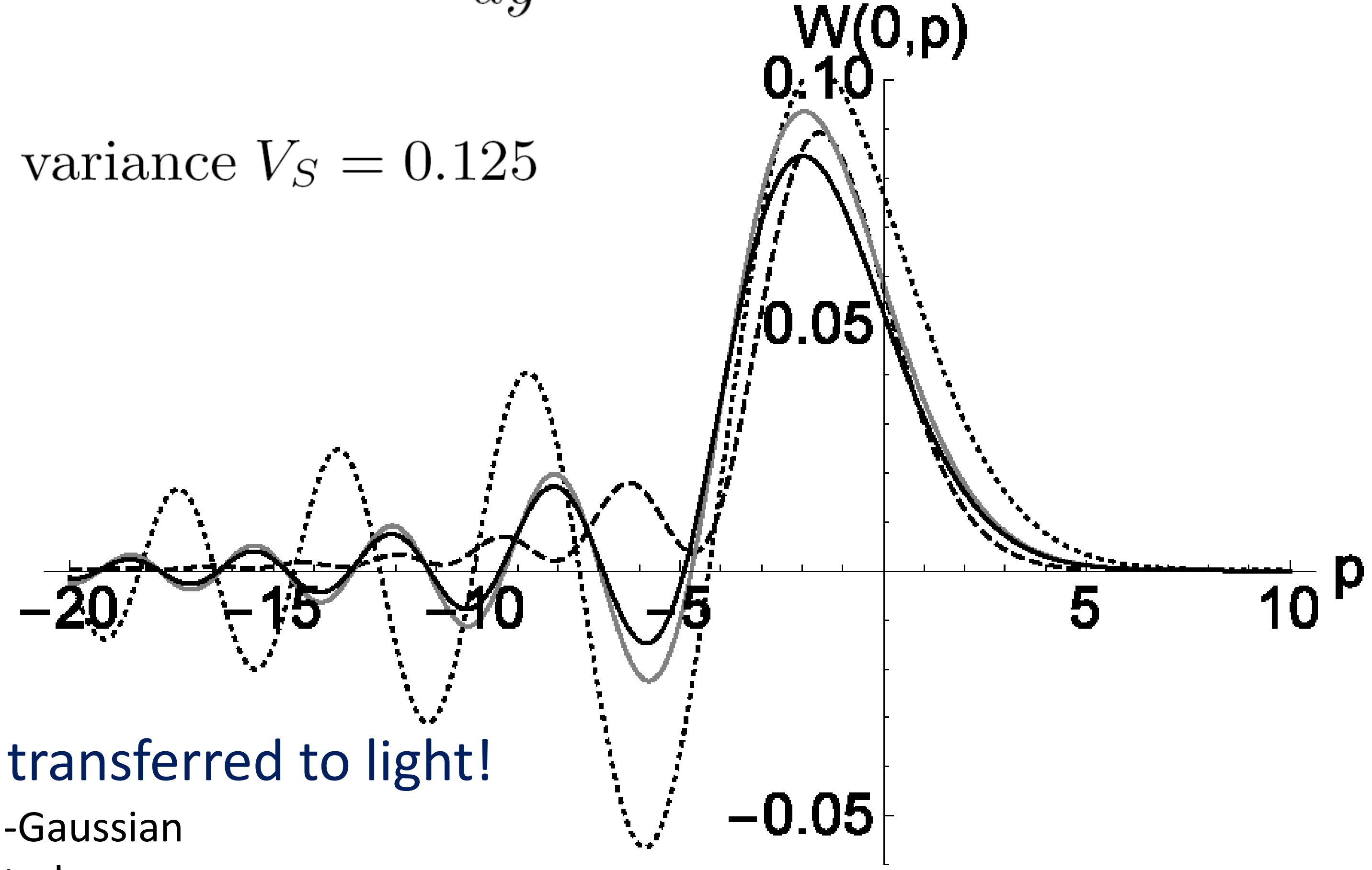
READ OUT OF CUBIC STATE

$$W_0(0,p_m) = \frac{1}{2\sqrt{2}\pi^{\frac{3}{2}}} \int_{-\infty}^{\infty} e^{-\frac{y^2}{2} - 2i\kappa_3 \tau y^3 - ip_m y} dy$$

$$T = 0.5,\ \eta_i = \eta_o = 0.9,\ \text{variance } V_S = 0.125$$



Multiple negativities of Wigner functions transferred to light!

Radim Filip and Andrey A. Rakhubovsky, Transfer of non-Gaussian quantum states of mechanical oscillator to light, submitted.

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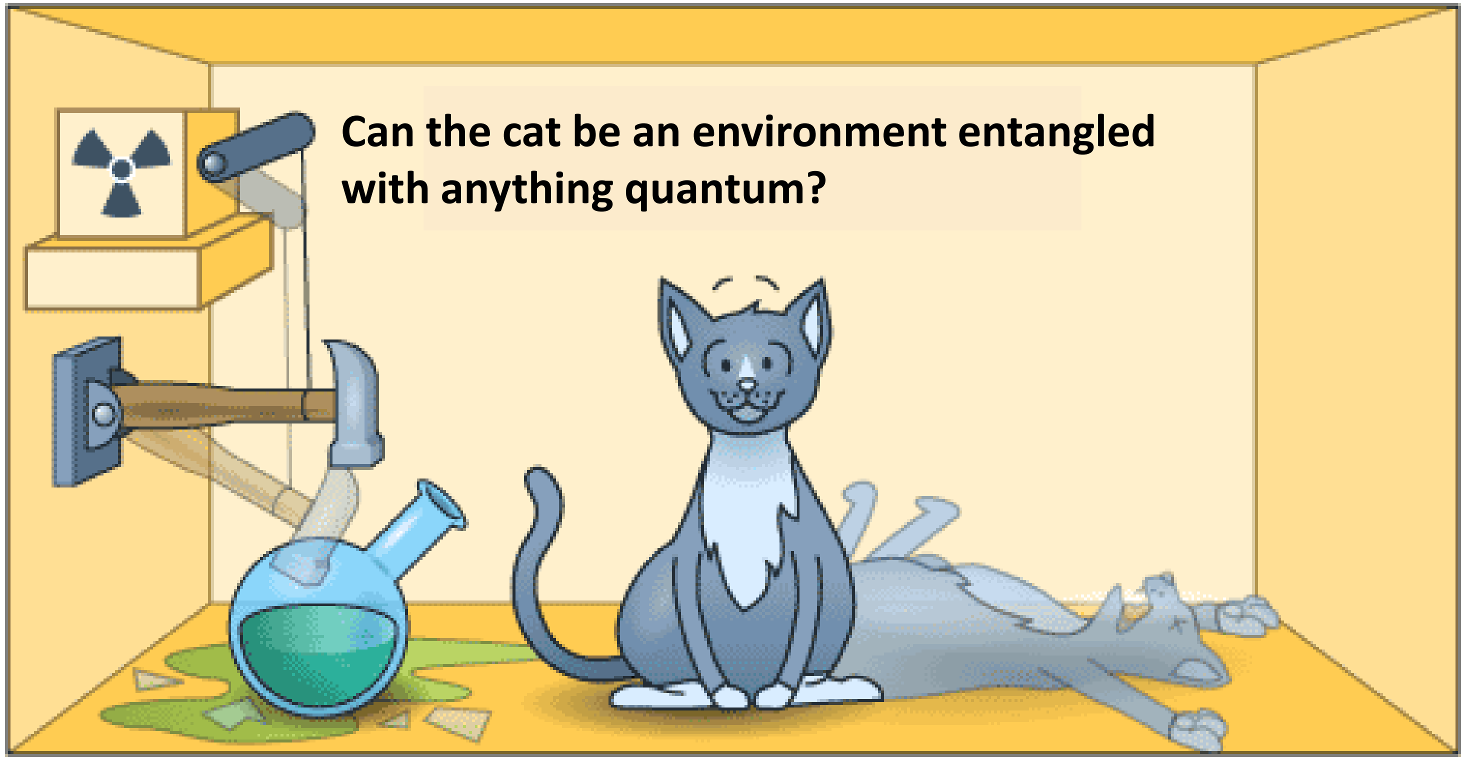
SCHRODINGER CAT AS ENVIRONMENT



- Highly speculative ?
- No so much, common as theoretical model for decoherence (W.H. Zurek)
- Beyond quantum optics (environment is too close to Markovian limit)

FIRST APPLICATION
THEN GENERALIZATION

Katarzyna Roszak, Radim Filip and Tomáš Novotný, Decoherence control by quantum decoherence itself, Scientific Reports 5, 9796 (2015).

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MAIN POINTS

- Optomechanical entanglement is feasible with highly noisy mechanics!
- It can be used to generate entanglement through noisy mechanics!
- Robust transducers through noisy systems can exist!

- Thermal entanglement can be also used in quantum interfaces to mechanics!
- Quantum amplifiers help to reach noiseless transfer to noisy mechanics!
- Quantum optics can help quantum optomechanics more than by laser!

- Highly nonclassical mechanical states can be transferred to light!
- Quantum optomechanics can help back quantum optics!

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OUTLOOK