QUANTUM OPERATIONS WITH LIGHT

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Czech-Japan collaboration (Furusawa Lab)

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Quantum Coherence and Nonclassicality

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Students:
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Measurement-Induced Operations

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Andrey Rakhubovsky

Students:
Nikita Vostrosablin

Interaction of Light with Atoms

Lukáš Slodička
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Students:
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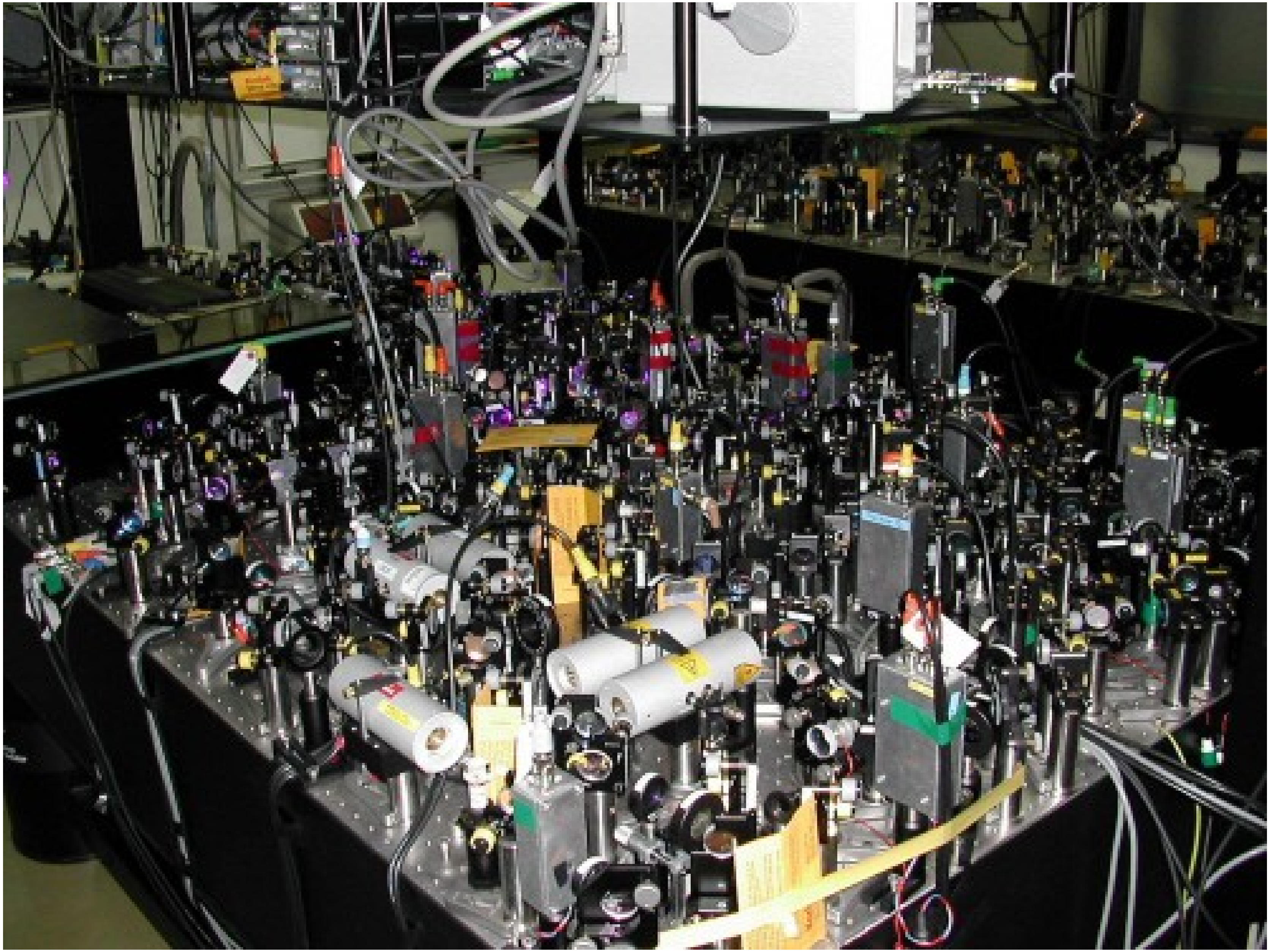
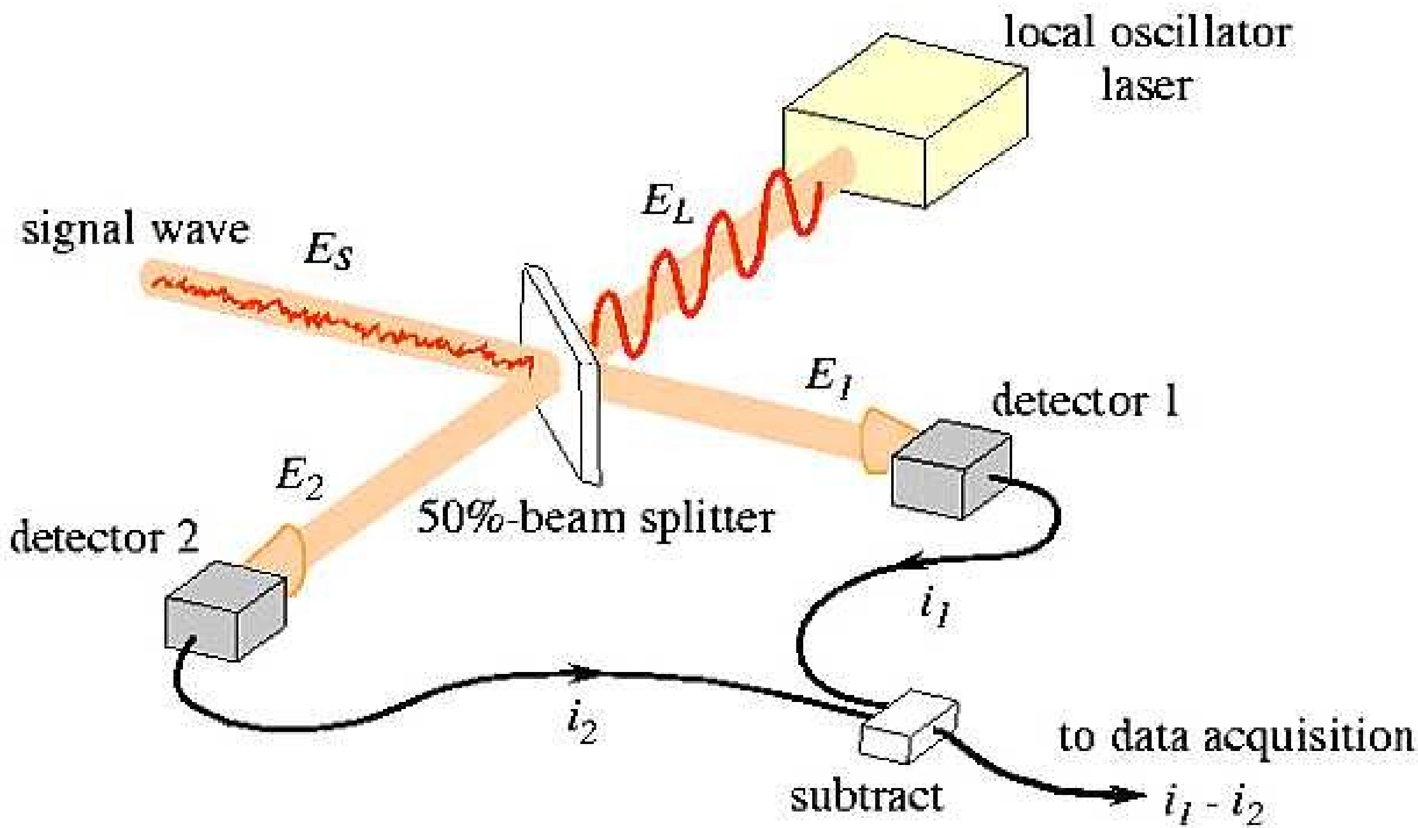
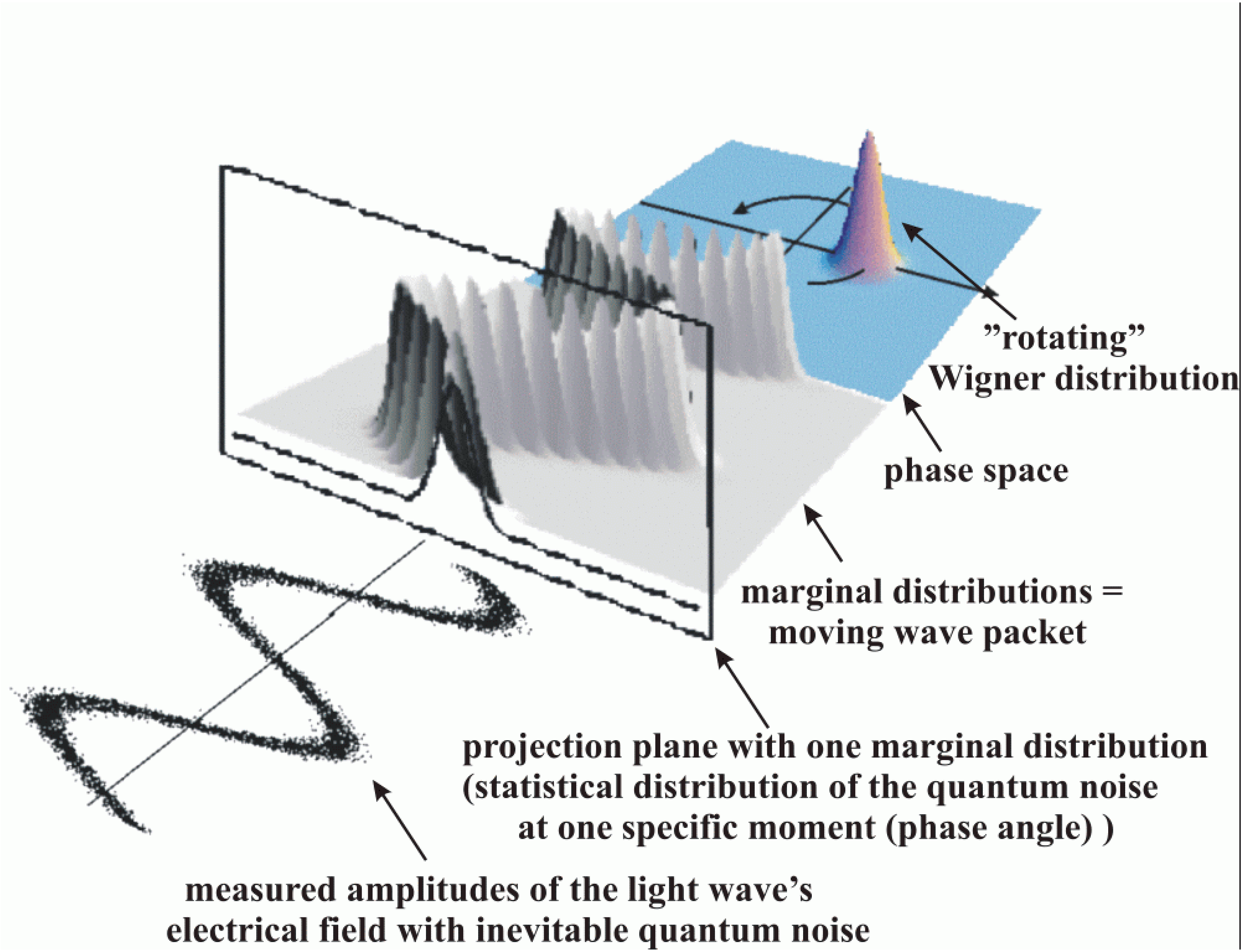


CV QUANTUM NOISE

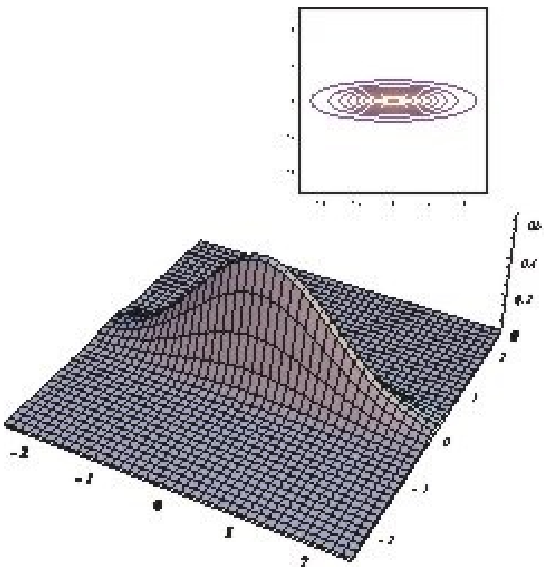


homodyne detection

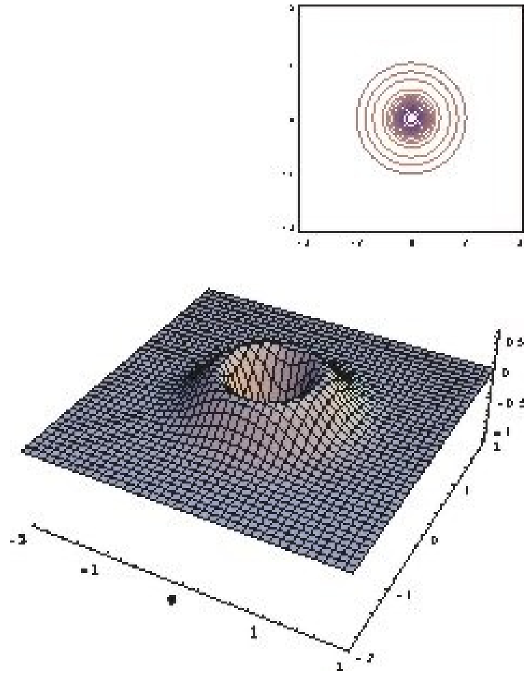
CV QUANTUM NOISE



NONCLASSICAL QUANTUM RESOURCES:



http://qis.ucalgary.ca/quantech/wiggalery.php



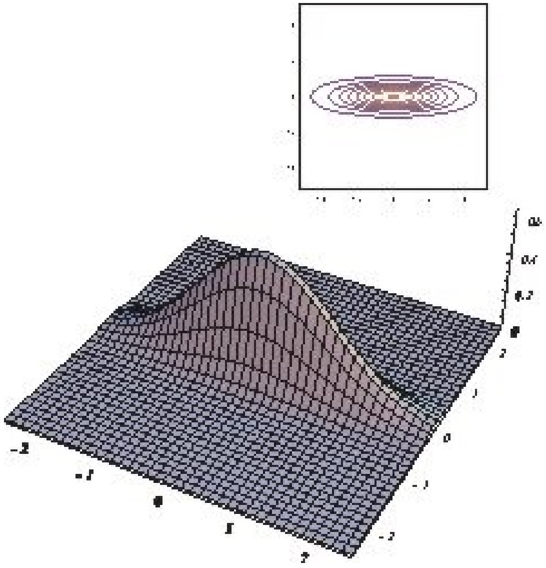
Gaussian squeezed state:

- positive Wigner function
- single quadrature variance bellow vacuum level

non-Gaussian Fock state:

- negative Wigner function
- photon number variance reduced

NONCLASSICAL QUANTUM RESOURCES:



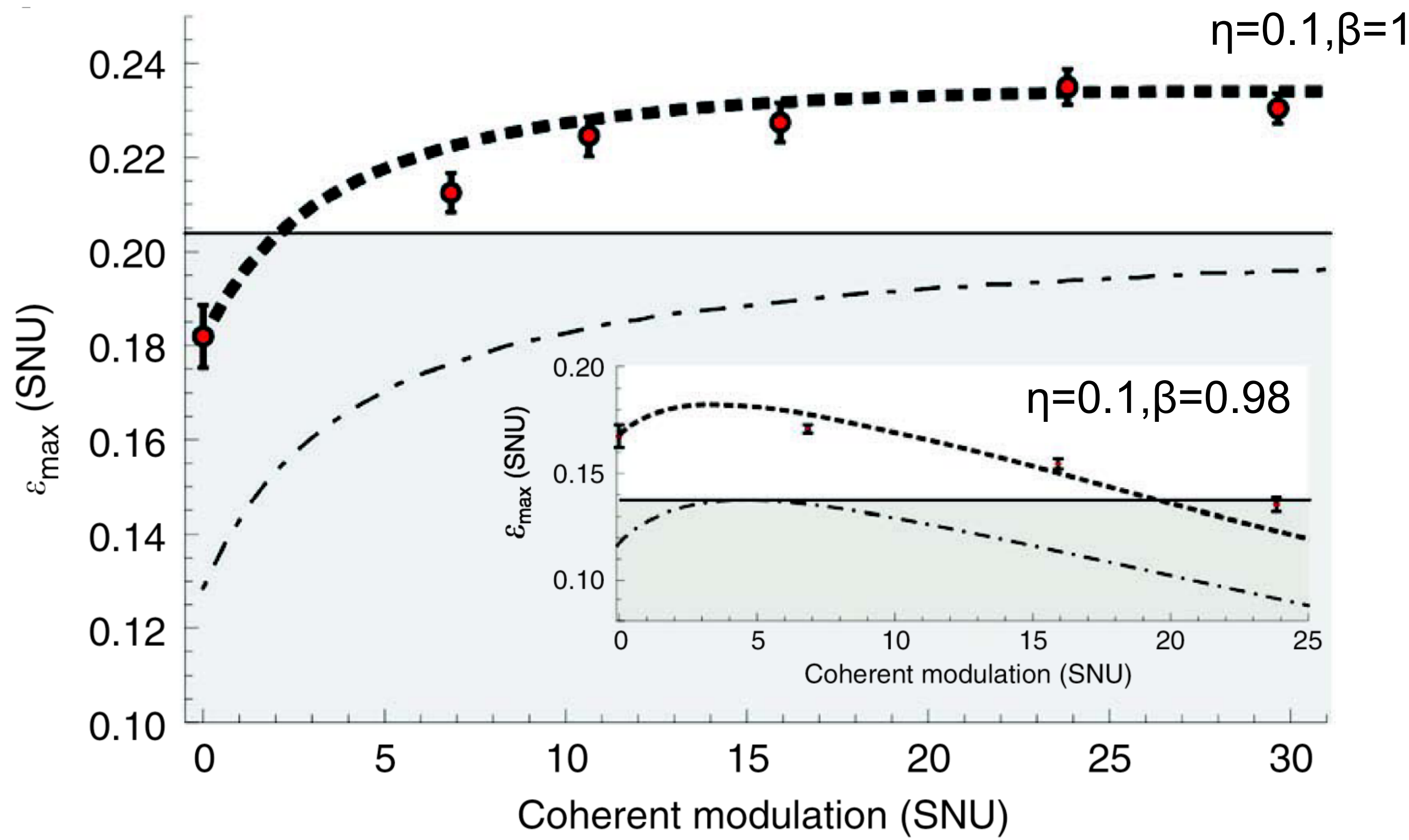
http://qis.ucalgary.ca/quantech/wiggalery.php

Gaussian squeezed state:

- positive Wigner function
- single quadrature variance bellow vacuum level

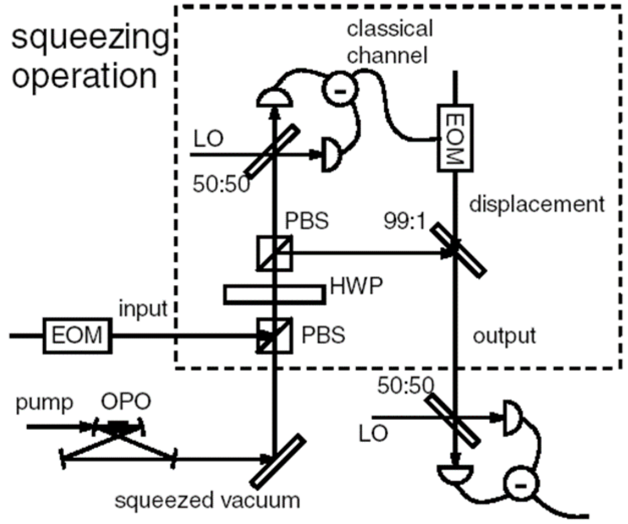
SQUEEZED STATE QKD

Overcoming coherent state protocol: arbitrary weak squeezing is useful to make protocol more robust.



L.S. Madsen, V.C. Usenko, M. Lassen, R. Filip and U.L. Andersen, Nature Comm. 3,1083 (2012).

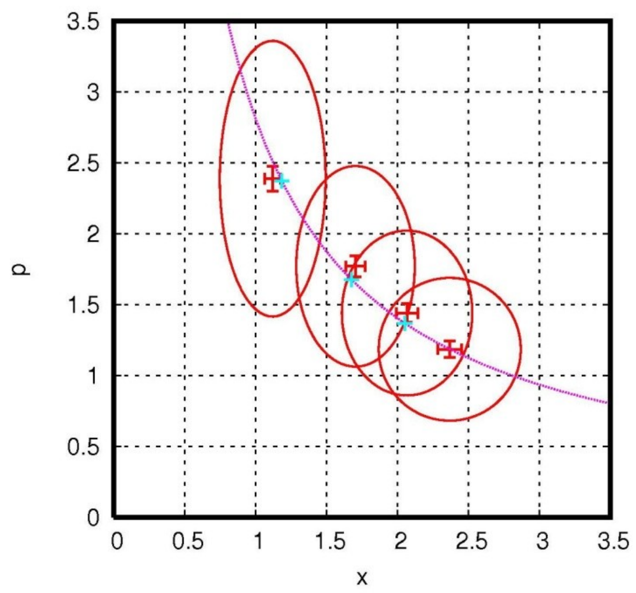
SQUEEZED STATE = RESOURCE FOR SQUEEZER



$$\hat{x}_{\rm out} = \frac{1}{\sqrt{T}}\hat{x}_{\rm in},$$

$$\hat{p}_{\rm out} = \sqrt{T}\hat{p}_{\rm in} + \sqrt{1-T}\hat{p}_{\rm vac}e^{-r}$$

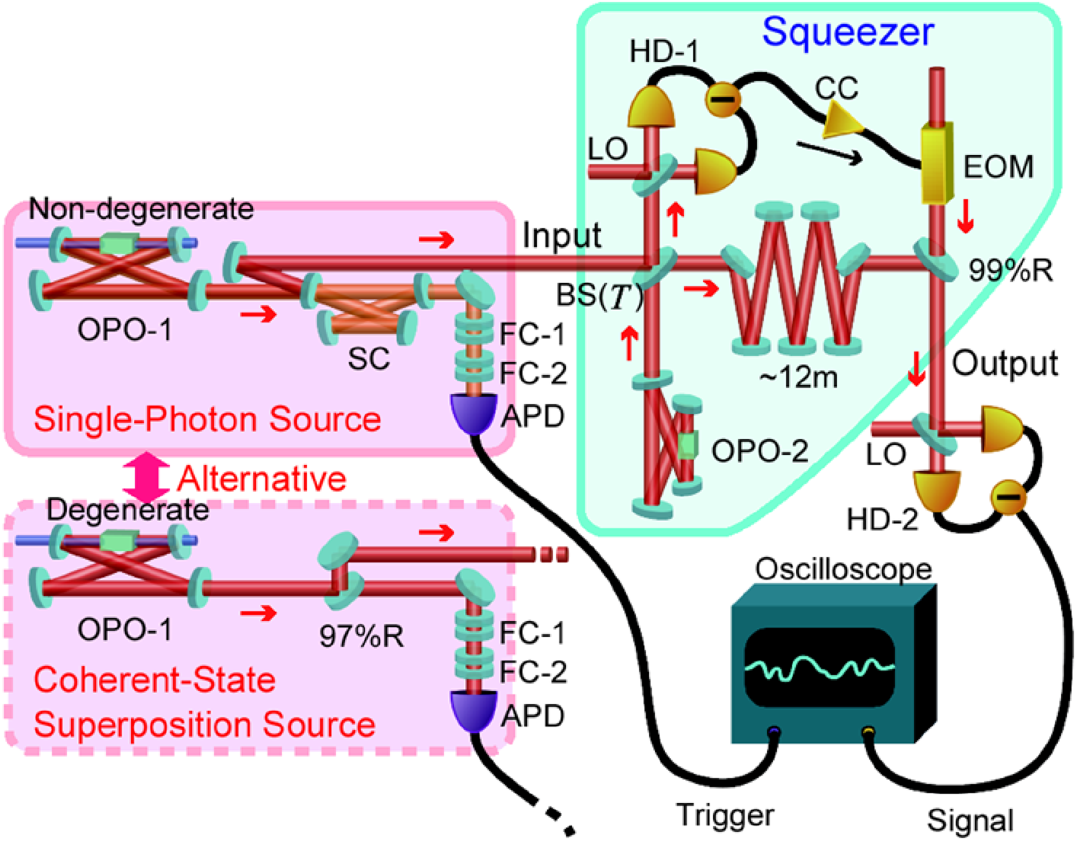
Off-line squeezed state -> On-line squeezer



R. Filip. P. Marek and U.L. Andersen, Phys. Rev. A 71, 042308 (2005).

J. Yoshikawa et al., Phys. Rev. A 76, 060301(R) (2007)

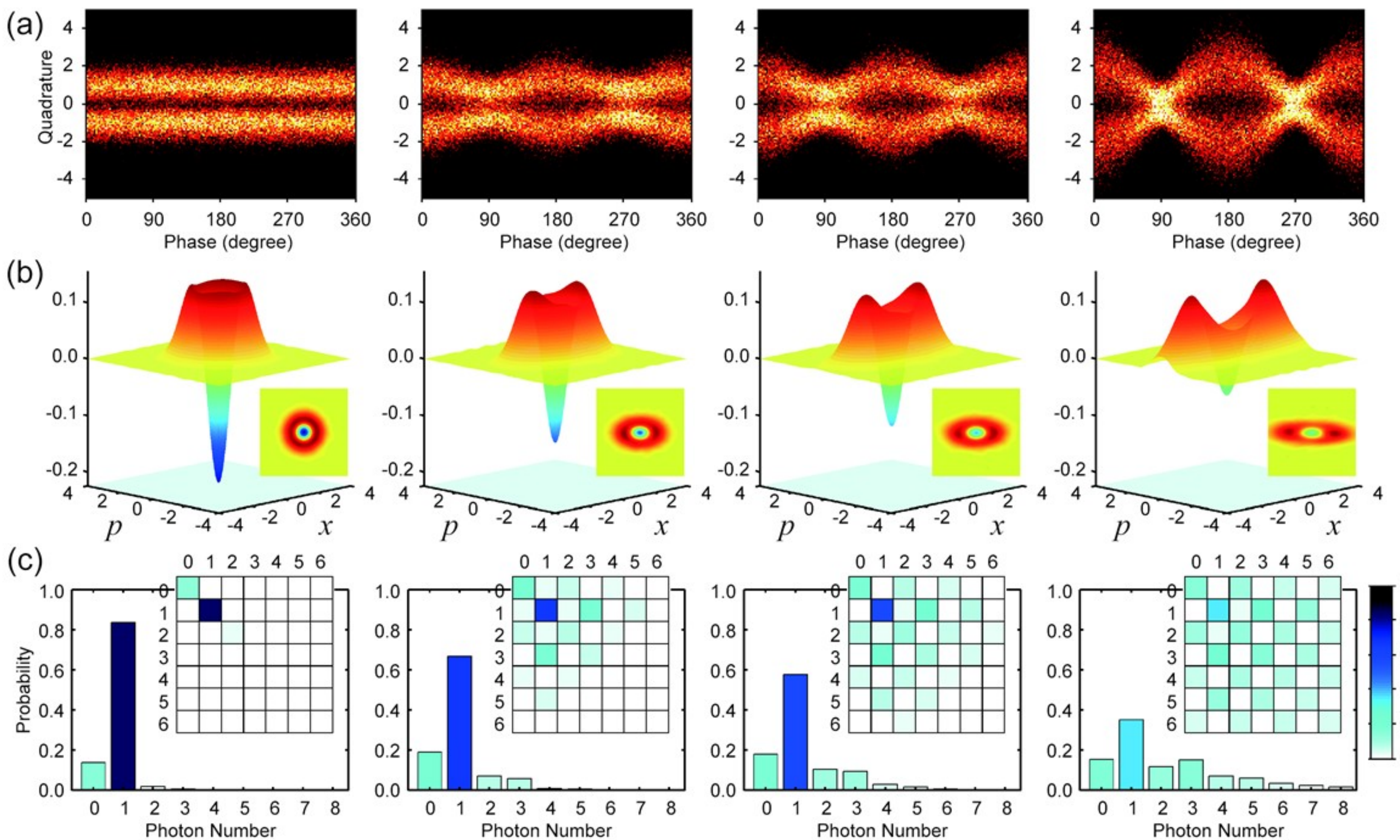
SQUEEZING OF SINGLE PHOTON



$$\hat{S}(\gamma) = e^{\gamma(\hat{a}^{\dagger 2} - \hat{a}^2)/2}$$

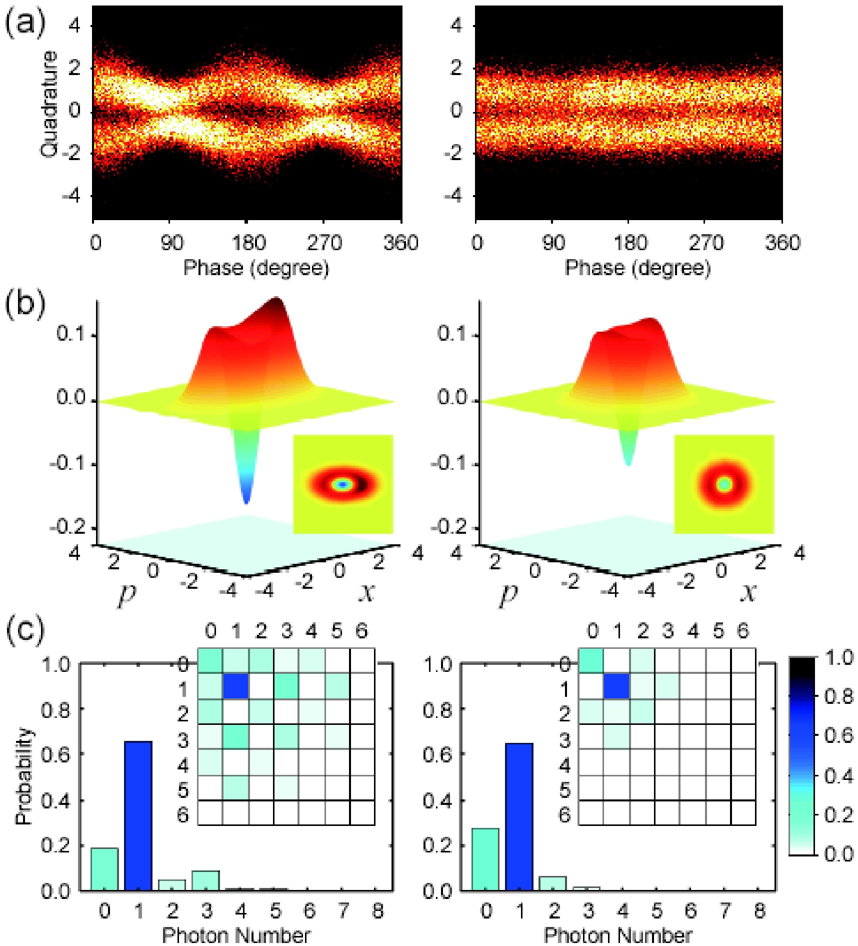
Yoshichika Miwa, Jun-ichi Yoshikawa, Noriaki Iwata, Mamoru Endo, Petr Marek, Radim Filip, Peter van Loock, and Akira Furusawa, Phys. Rev. Lett. 113, 013601 (2014).

SQUEEZING OF SINGLE PHOTON



Yoshichika Miwa, Jun-ichi Yoshikawa, Noriaki Iwata, Mamoru Endo, Petr Marek, Radim Filip, Peter van Loock, and Akira Furusawa, Phys. Rev. Lett. 113, 013601 (2014).

UNSQUEEZING OF SQUEEZED PHOTON

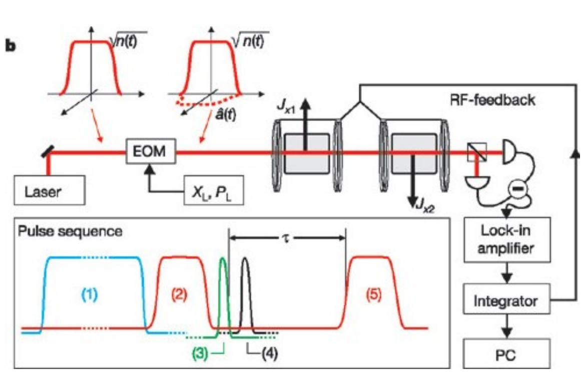


Outcomes:

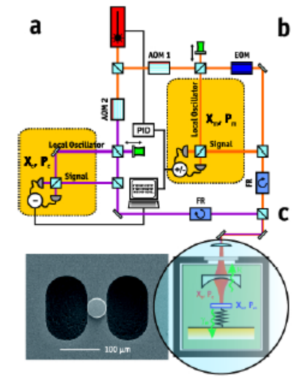
- reversible squeezer
- preserves negative Wigner function

Yoshichika Miwa, Jun-ichi Yoshikawa, Noriaki Iwata, Mamoru Endo, Petr Marek, Radim Filip, Peter van Loock, and Akira Furusawa, Phys. Rev. Lett. 113, 013601 (2014).

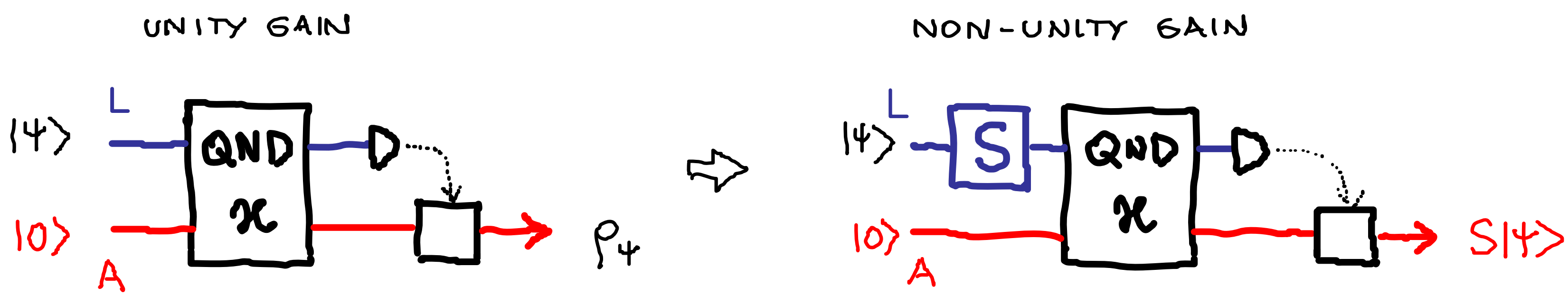
QUANTUM INTERFACES



Quantum memory



Quantum opto-mechanics



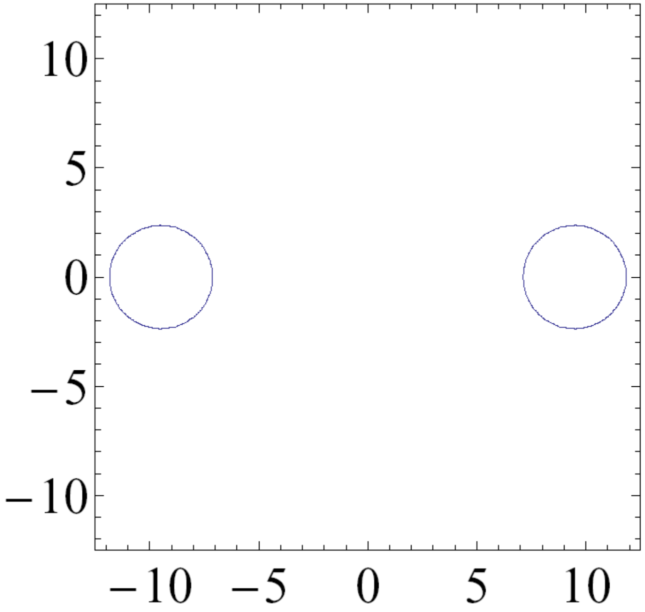
- Pre-squeezing effectively enhances interaction of light with matter.
- Transfer is limited only by optical loss.

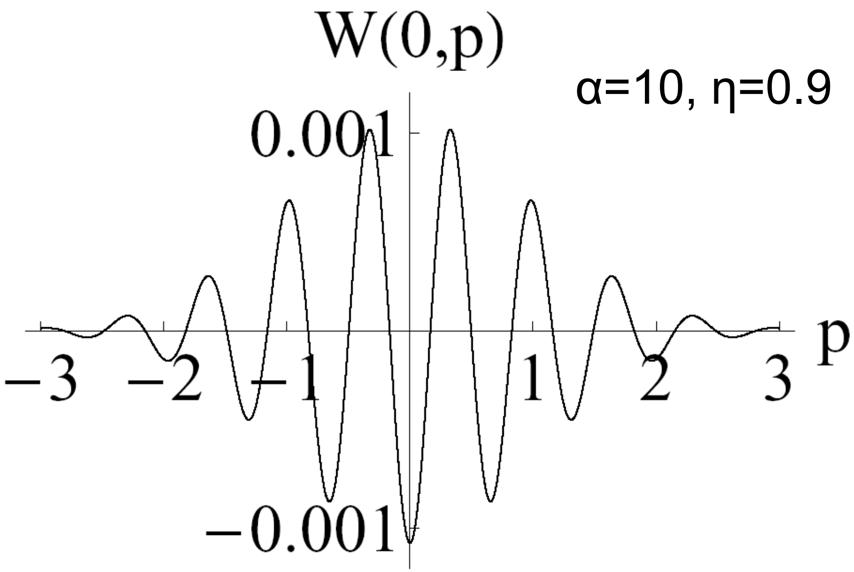
Radim Filip, Phys. Rev. A **78**, 012329 (2008).

QUANTUM DECOHERENCE

$$(|\alpha\rangle - |-\alpha\rangle)/\sqrt{2(1-\exp(-2|\alpha|^2))}$$

Losses with η>0.5 do not vanish the oscillations, but they are hardly visible.

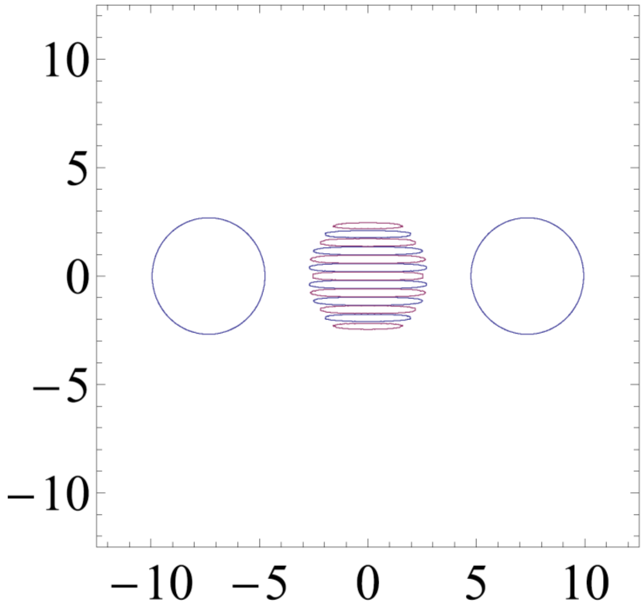


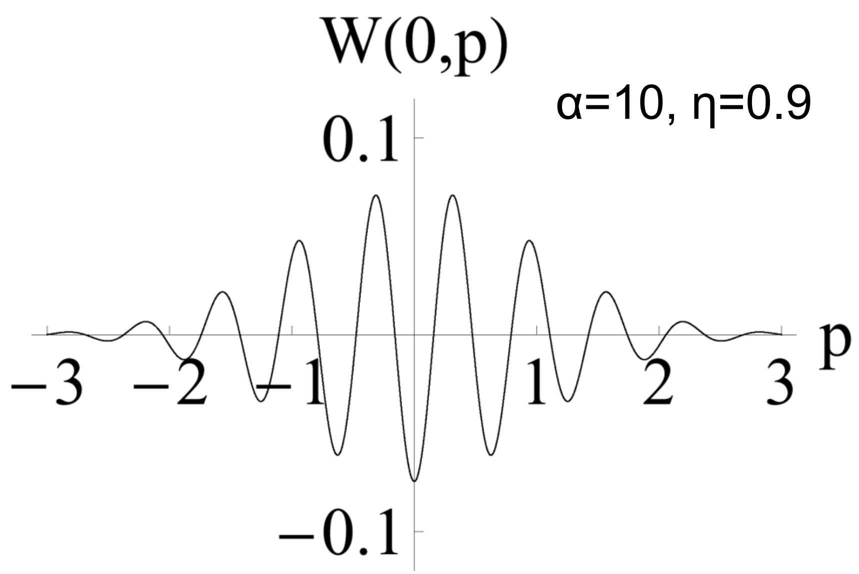


ERROR CORRECTION

$$(|\alpha\rangle - |-\alpha\rangle)/\sqrt{2(1-\exp(-2|\alpha|^2))}$$

For η>0.5, visibility of the oscillations is significantly improved by pre/post squeezing.

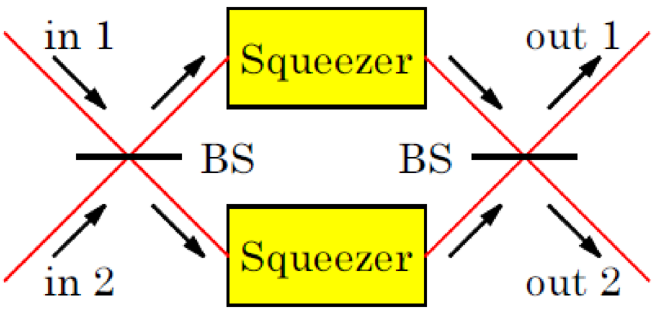


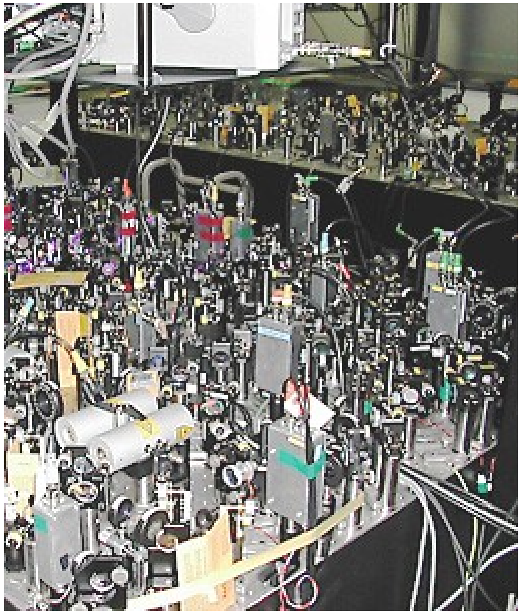


Radim Filip, Phys. Rev. A 87, 042308 (2013).

QUANTUM GAUSSIAN OPERATIONS

Quantum operations based on online squeezers:



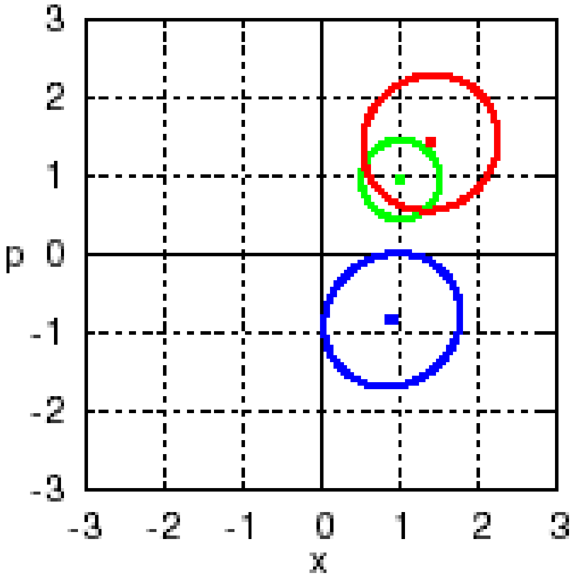


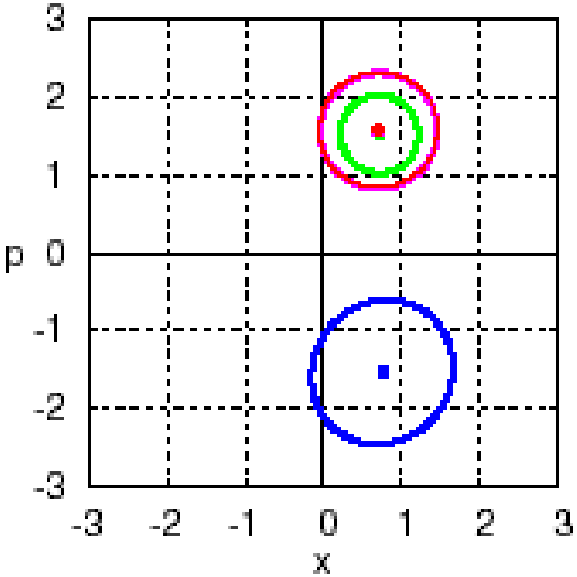
S.L. Braunstein, Phys.Rev. A71, 055801 (2005).

QND interaction: J. Yoskihawa et al., Phys. Rev. Lett. 101, 250501 (2008).

Phase-insensitive amplifier: J. Yoshikawa, Y. Miwa, R. Filip, A. Furusawa, Phys. Rev. A 83, 052307 (2011).

REVERSIBLE QUANTUM AMPLIFIER AND CLONER

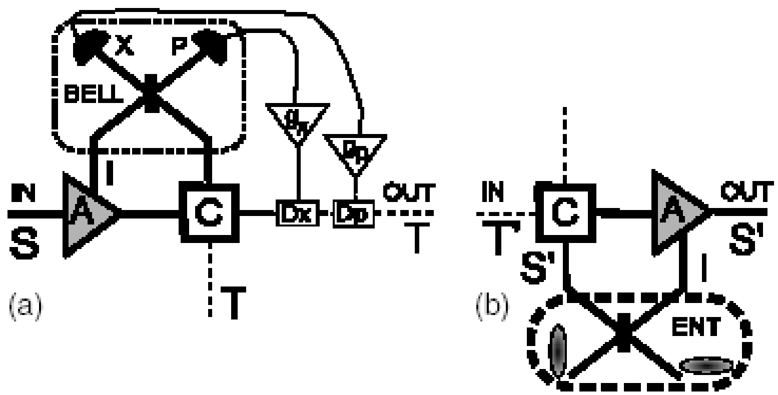


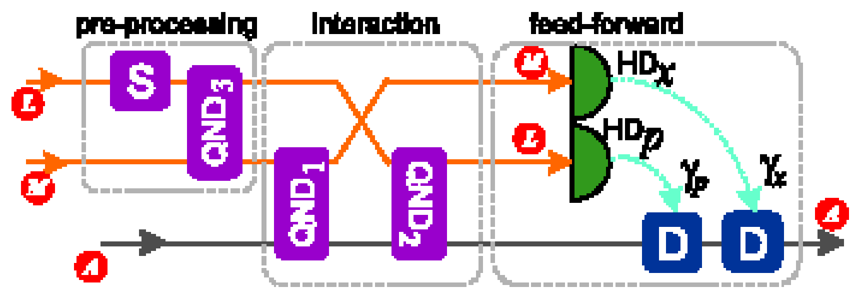


R. Filip, J. Fiurasek , P. Marek,
PRA 69 , 012314 (2004).

J. Yoshikawa, Y. Miwa, R. Filip, A. Furusawa, *Demonstration of reversible phase-insensitive optical amplifier,* Phys. Rev. A 83, 052307 (2011)

QUANTUM INTERFACES BETWEEN LIGHT AND MATTER

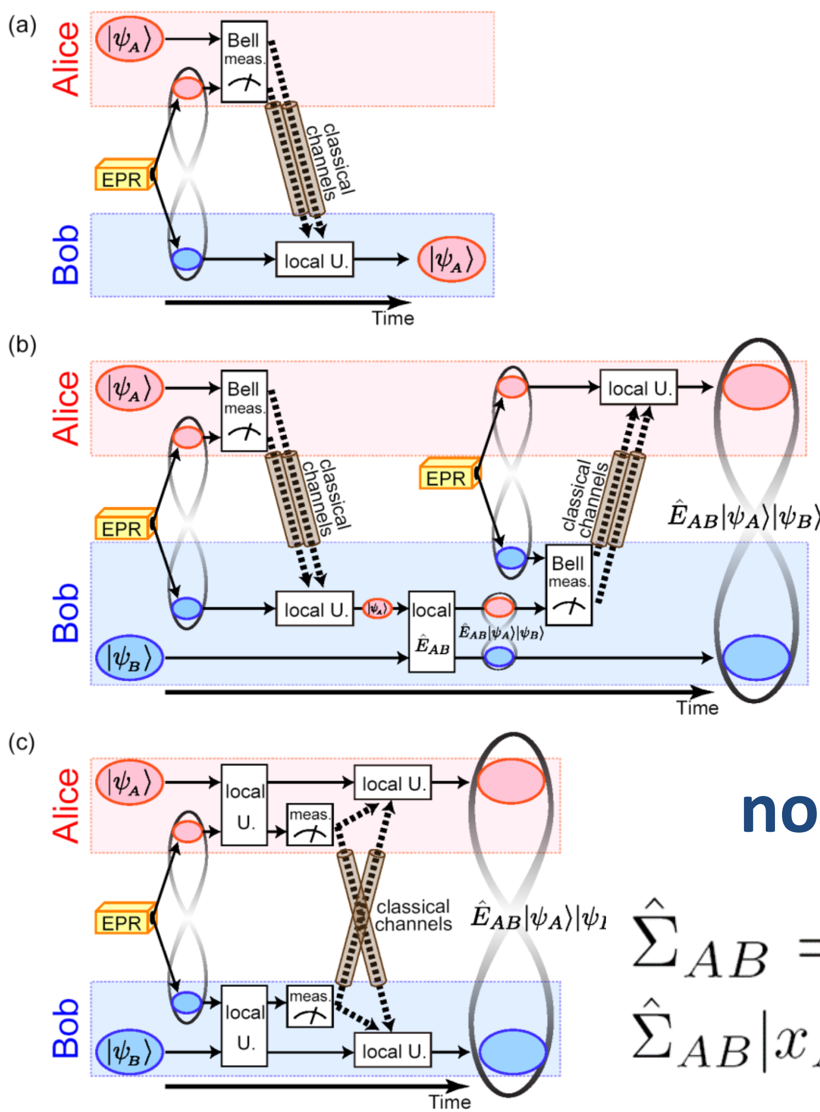




R. Filip, Phys. Rev. A 80, 022304 (2009); P. Marek and R. Filip, Phys. Rev. A 81, 042325 (2010).

- Quantum pre-amplification and feed-forward control **perfectly transfer** any quantum state to noisy system through arbitrarily weak coupling.
- **Full quantum linear amplifier and QND interaction are useful tool for quantum pre-processing!**

NONLOCAL QND OPERATION



teleportation

double teleportation

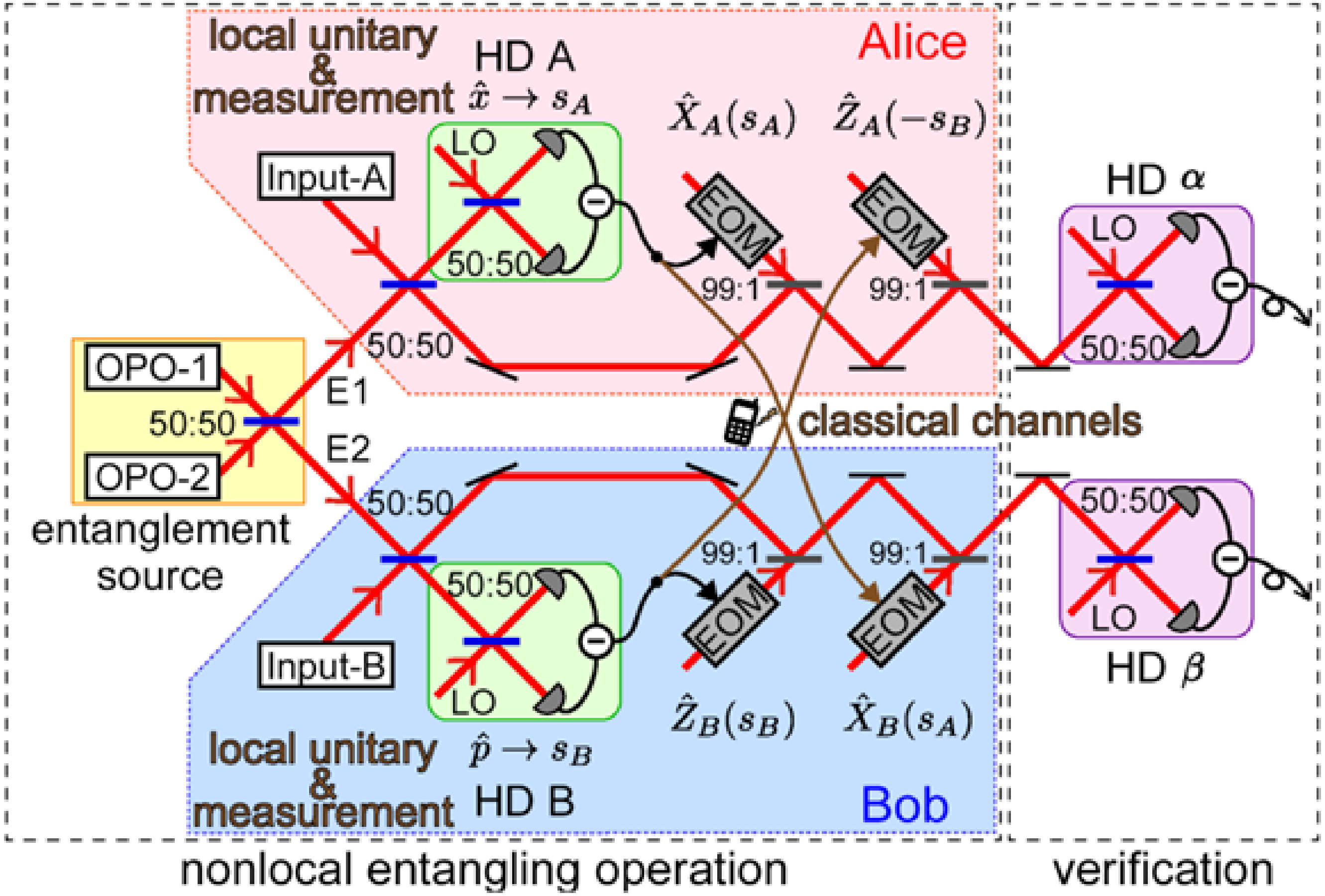
nonlocal parallel operation

$$\hat{\Sigma}_{AB} = \mathrm{e}^{-2i\hat{x}_A\hat{p}_B}$$

$$\hat{\Sigma}_{AB}|x_A\rangle_A \otimes |x_B\rangle_B = |x_A\rangle_A \otimes |x_B + x_A\rangle_B$$

Radim Filip, Phys. Rev. A 69, 052313 (2004)

NONLOCAL QND OPERATION



Shota Yokoyama, Ryuji Ukai, Jun-ichi Yoshikawa, Petr Marek, Radim Filip, and Akira Furusawa, Phys. Rev. A 90, 012311 (2014).

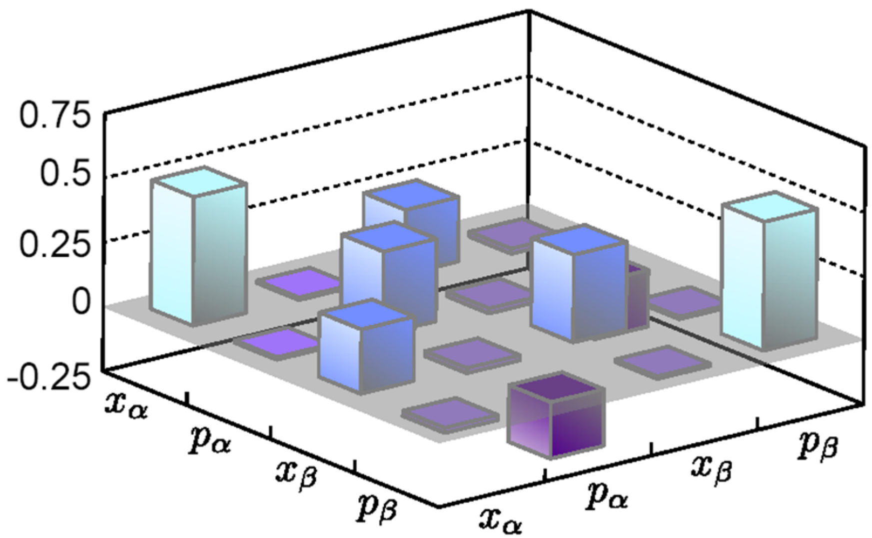
NONLOCAL QND OPERATION

$$\hat{\boldsymbol{\xi}}_{\alpha\beta} = \begin{pmatrix} \sqrt{2} & 0 & 0 & 0 \\ 0 & \frac{1}{\sqrt{2}} & 0 & -\frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & 0 & \frac{1}{\sqrt{2}} & 0 \\ 0 & 0 & 0 & \sqrt{2} \end{pmatrix} \hat{\boldsymbol{\xi}}_{AB} + \hat{\boldsymbol{\delta}}$$

$$\equiv \hat{E}^{\dagger}_{AB}\hat{\boldsymbol{\xi}}_{AB}\hat{E}_{AB} + \hat{\boldsymbol{\delta}},$$

$$\hat{\boldsymbol{\xi}}_{AB} = (\hat{x}_A, \hat{p}_A, \hat{x}_B, \hat{p}_B)^T,\ \hat{\boldsymbol{\xi}}_{\alpha\beta} = (\hat{x}_\alpha, \hat{p}_\alpha, \hat{x}_\beta, \hat{p}_\beta)^T$$

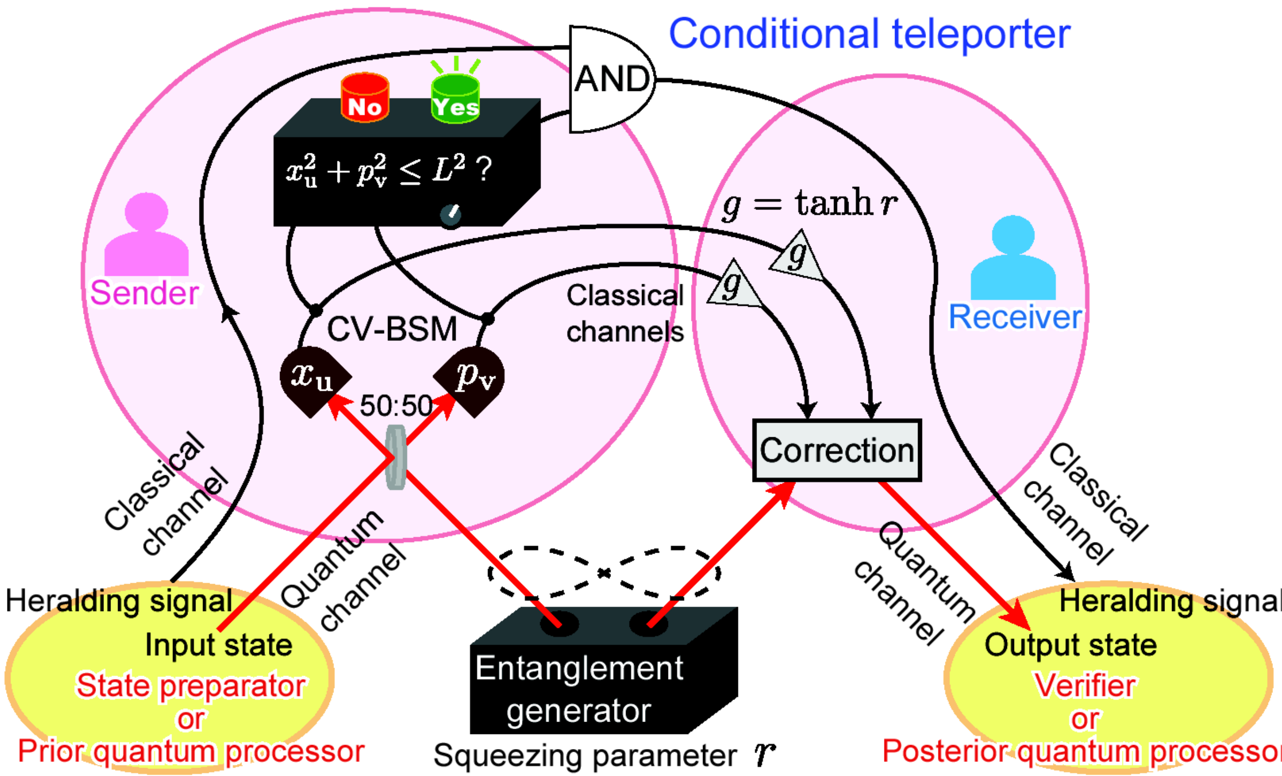
$$\hat{\boldsymbol{\delta}} = (0, \mathrm{e}^{-r}\hat{p}_2^{(0)}, \mathrm{e}^{-r}\hat{x}_1^{(0)}, 0)^T$$



QND entanglement!

Shota Yokoyama, Ryuji Ukai, Jun-ichi Yoshikawa, Petr Marek, Radim Filip, and Akira Furusawa, Phys. Rev. A 90, 012311 (2014).

CONDITIONAL TRANSFER OF SINGLE PHOTON



T. Ide, H. F. Hofmann, T. Kobayashi, and A. Furusawa, Phys. Rev. A 65, 012313 (2002).

Ladislav Mišta, Jr., Radim Filip, and Akira Furusawa, Phys. Rev. A 82, 012322 (2010)

LOSSY TELEPORTATION OF SINGLE PHOTON

$$|\psi\rangle \rightarrow \sum_{k=0}^{\infty} \frac{1}{k!\sinh^{2k} r} \hat{a}^k \left[(\tanh r)^{\hat{n}} |\psi\rangle \langle\psi| (\tanh r)^{\hat{n}} \right] \hat{a}^{\dagger k}$$

S. Takeda, T. Mizuta, M. Fuwa, P. van Loock and A. Furusawa, Nature 500, 315-318 (2013).

NOISELESS TELEPORTATION OF SINGLE PHOTON

$$|\psi\rangle \to \sum_{k=0}^{\infty} \frac{1}{k!\sinh^{2k} r}\left[(\tanh r)^{\hat{n}}|\psi\rangle\langle\psi|(\tanh r)^{\hat{n}}\right]$$

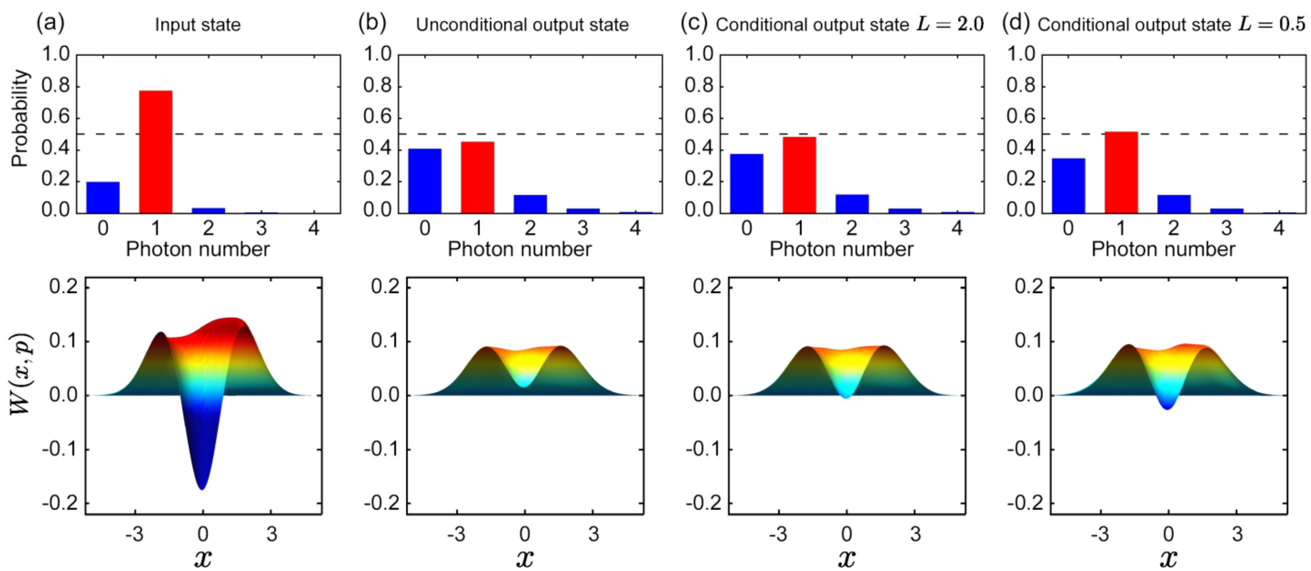
$$|\psi\rangle \to (\tanh r)^{\hat{n}}|\psi\rangle$$

Maria Fuwa, Shunsuke Toba, Shuntaro Takeda, Petr Marek, Ladislav Mista Jr., Radim Filip, Peter van Loock, Jun-ichi Yoshikawa, Akira Furusawa, quant-ph 1408.6406

NOISELESS TELEPORTATION OF SINGLE PHOTON

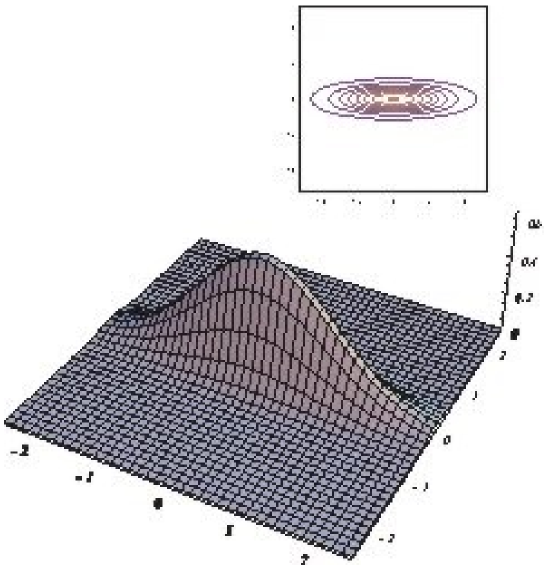
$$|\psi\rangle \rightarrow \sum_{k=0}^{\infty} \frac{1}{k!\sinh^{2k} r} \left[(\tanh r)^{\hat{n}}\,|\psi\rangle\langle\psi|\,(\tanh r)^{\hat{n}}\right]$$

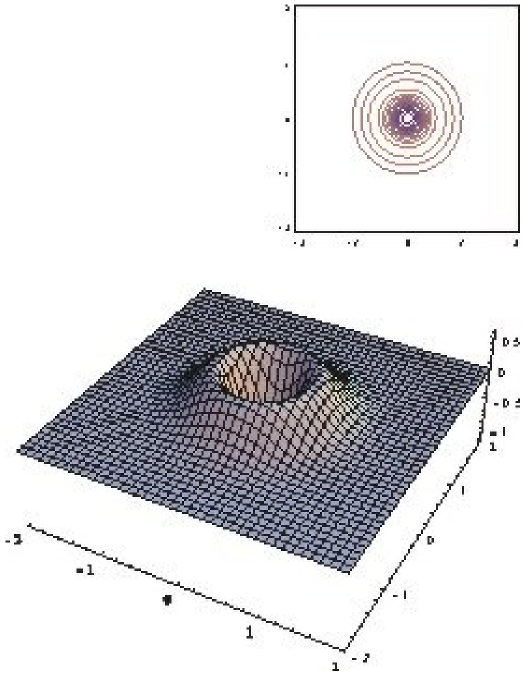
$$|\psi\rangle \rightarrow (\tanh r)^{\hat{n}}\,|\psi\rangle$$



Maria Fuwa, Shunsuke Toba, Shuntaro Takeda, Petr Marek, Ladislav Mista Jr., Radim Filip, Peter van Loock, Jun-ichi Yoshikawa, Akira Furusawa, quant-ph 1408.6406

NONCLASSICAL QUANTUM RESOURCES:





http://qis.ucalgary.ca/quantech/wiggalery.php

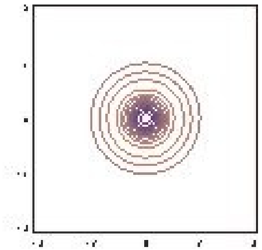
Gaussian squeezed state:

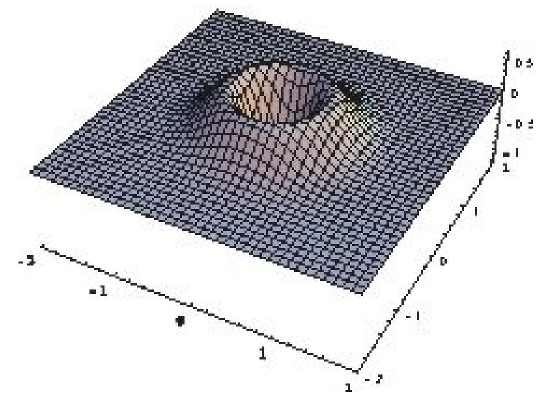
- positive Wigner function
- single quadrature variance bellow vacuum level

non-Gaussian Fock state:

- negative Wigner function
- all quadrature variance above vacuum level

NONCLASSICAL QUANTUM RESOURCES:

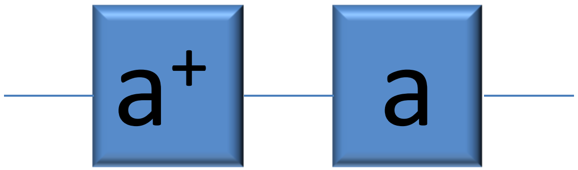




non-Gaussian Fock state:

- negative Wigner function
- all quadrature variance above vacuum level

NOISELESS AMPLIFIER BY aa^{+}



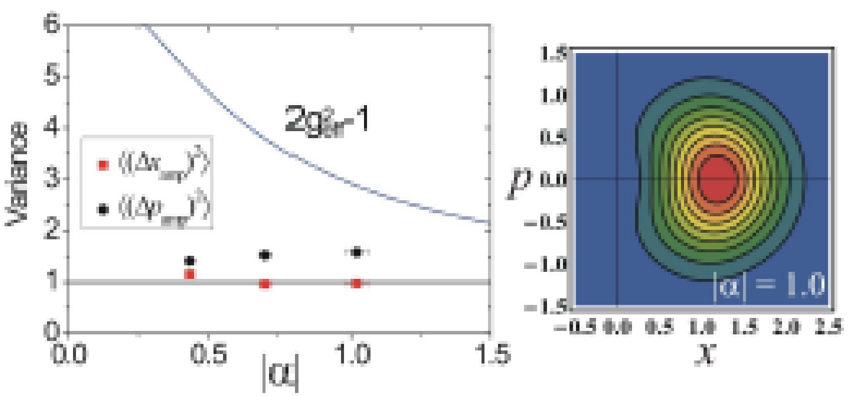
$|\alpha\rangle = |0\rangle + \alpha|1\rangle + \ldots$

$a^{+}|\alpha\rangle = |1\rangle + \mathbf{2^{1/2}}\,\alpha|2\rangle + \ldots$

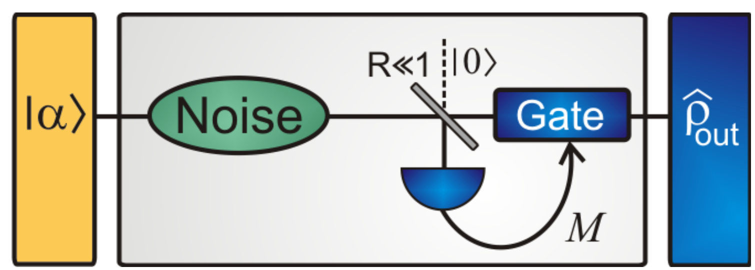
$aa^{+}|\alpha\rangle = |0\rangle + \mathbf{2}\alpha\,|1\rangle + \ldots$

P. Marek and R. Filip, Phys. Rev. A 81, 022302 (2010).

A. Zavatta, J. Fiurášek, M. Bellini, Nature Phot. 5, 52 (2011)

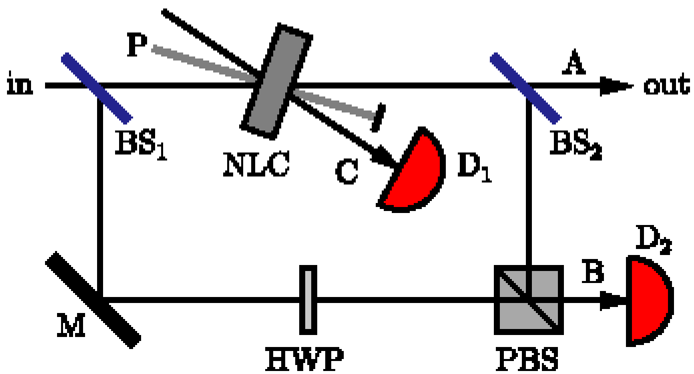


M.A. Usuga, Ch. R. Müller, Ch. Wittmann, P. Marek, R. Filip, Ch. Marquardt, G. Leuchs, U.L. Andersen, Nature Phys. 6, 767–771 (2010)



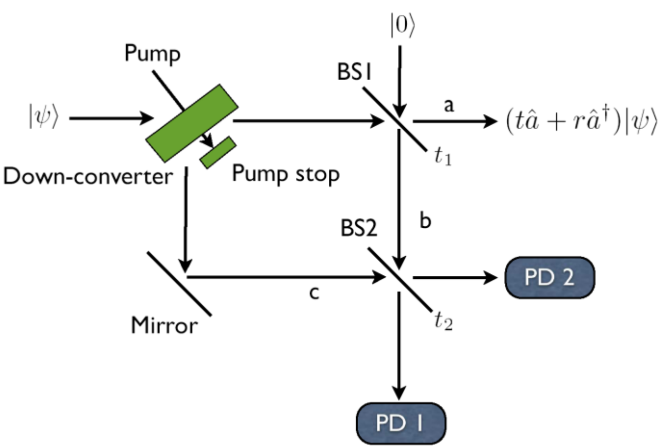
SUPERPOSITION of a,a⁺

Probabilistic Kerr effect



J. Fiurášek, Phys. Rev. A 80, 053822 (2009).

Implementation of $(a+a^+)|in>$



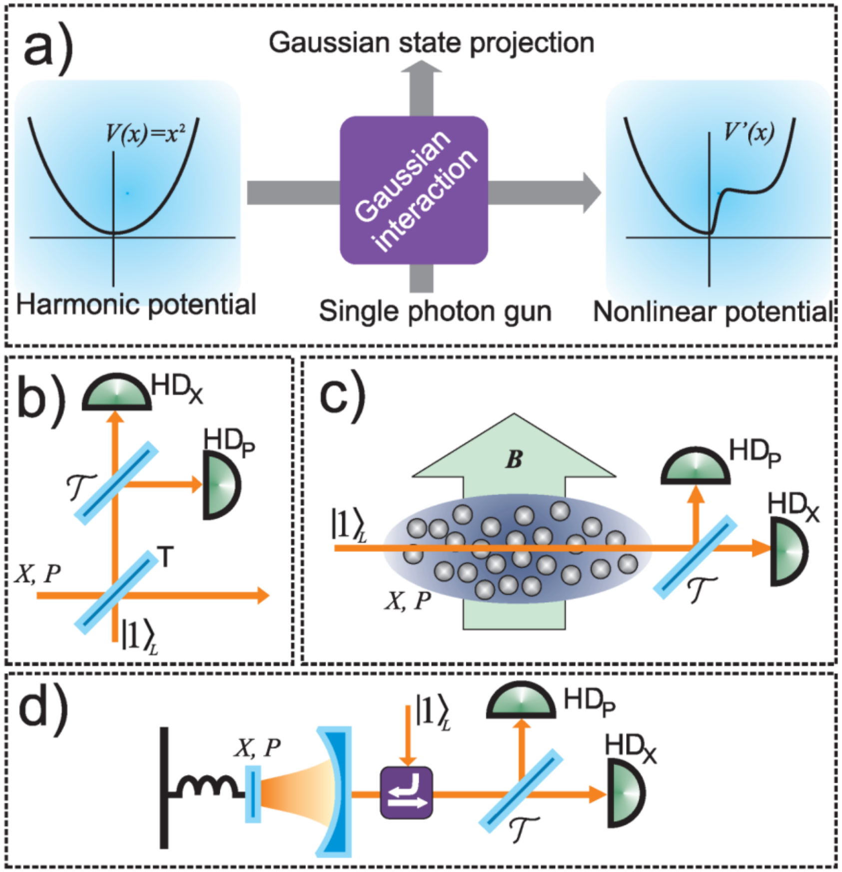
Su-Yong Lee, Hyunchul Nha, Phys. Rev. A 82, 053812 (2010)

NONLINEAR EFFECTS

$$\hat{H} = \hbar\omega\left(\hat{a}^{\dagger}\hat{a} + \frac{1}{2}\right) + V(\hat{X})$$

$$U(\hat{X},\tau) = e^{-\frac{i}{\hbar}V(\hat{X})\tau}$$

CONDITIONAL X-gate



$$U(\hat{X},\tau) = \sum_{k=0}^{\infty} \frac{U^{(k)}(\bar{X})}{k!}(\hat{X} - \bar{X})^k$$

$$U(\hat{X},\tau) = \prod_{k=0}^{N}(1 + \lambda_k \hat{X})$$

b) Linear optical implementation

$$\hat{A}_{\mathrm{BS}} = (T'T)^{\hat{n}}(A^* + 2B^*R^*\hat{a} + R\hat{a}^\dagger)$$

$$A = \sqrt{2}(x\mathcal{T} - ip\mathcal{R}) \quad B = 2^{-1}(\mathcal{R}^2 - \mathcal{T}^2)$$

c) Implementation with atomic ensemble

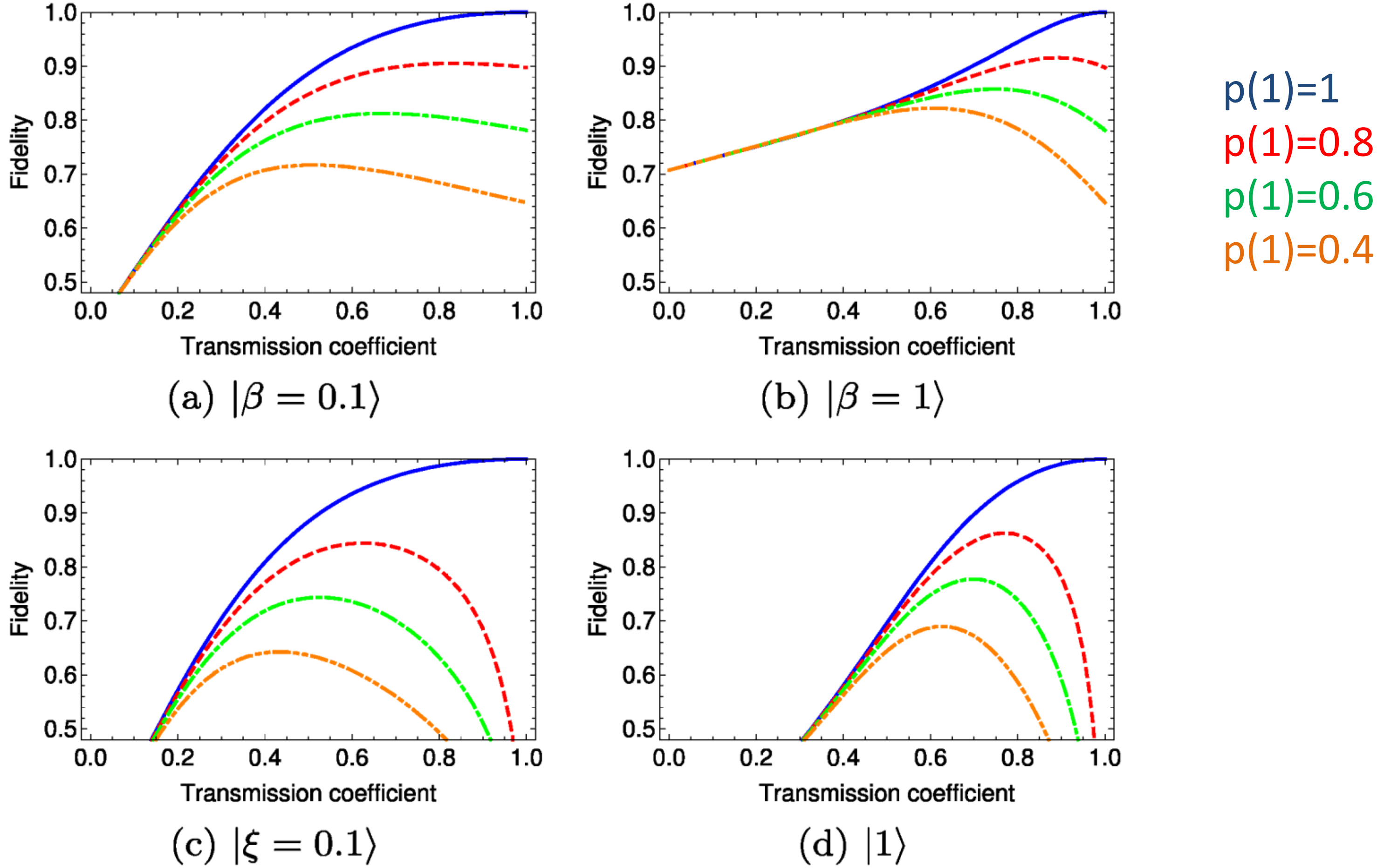
d) opto-mechanical implementation

$$_L\langle x_0 = 0|\, U_{\mathrm{QND}} f(\hat{X}_L)\, |0\rangle_L =_L \langle x_0 = 0|\, f(-\kappa\hat{X}) U_{\mathrm{QND}}\, |0\rangle$$

$$= f(-\kappa\hat{X})_L \langle x_0 = 0|\, U_{\mathrm{QND}}\, |0\rangle = F(\hat{X}) \exp[-\frac{1}{2}\kappa^2\hat{X}^2].$$

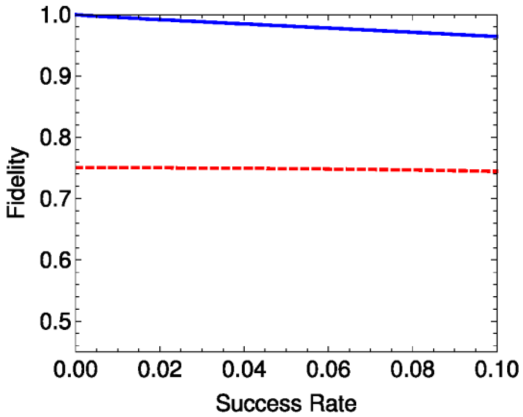
Kimin Park, Petr Marek, and Radim Filip, Phys. Rev. A 90, 013804 (2014).

QUALITY OF SINGLE PHOTON

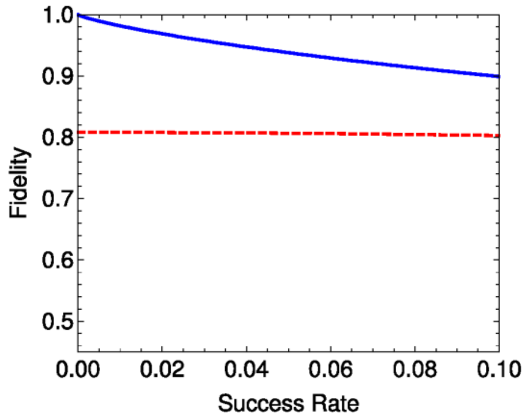


Kimin Park, Petr Marek, and Radim Filip, Phys. Rev. A 90, 013804 (2014).

FIDELITY VERSUS SUCCESS



(a) Single photon input $|1\rangle$



(b) Coherent state input $|\beta = 1\rangle$

EXAMPLE: CUBIC NONLINEARITY

$$\exp[i\chi\hat{X}^3] \approx 1 + i\chi\hat{X}^3 - \frac{\chi^2}{2}\hat{X}^6 \propto$$

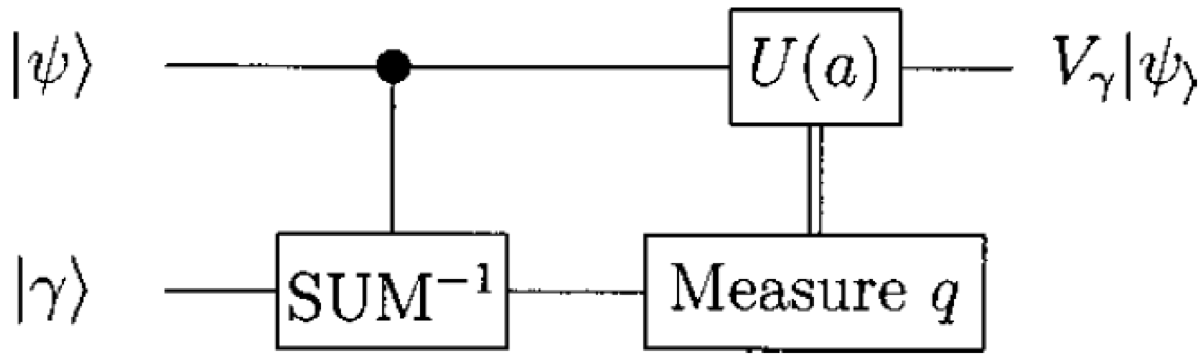
$$(1 - (\tfrac{\chi}{-1+i})^{1/3}\hat{X})(1 + (\tfrac{\chi}{1-i})^{1/3}\hat{X})$$

$$(1 - (-1)^{-2/3}(\tfrac{\chi}{-1+i})^{1/3}\hat{X})(1 - (\tfrac{\chi}{1+i})^{1/3}\hat{X})$$

$$(1 + (\tfrac{\chi}{-1-i})^{1/3}\hat{X})(1 - (-1)^{-2/3}(\tfrac{\chi}{1+i})^{1/3}\hat{X})$$

CUBIC NONLINEARITY = KEY TO NONLINEAR WORLD

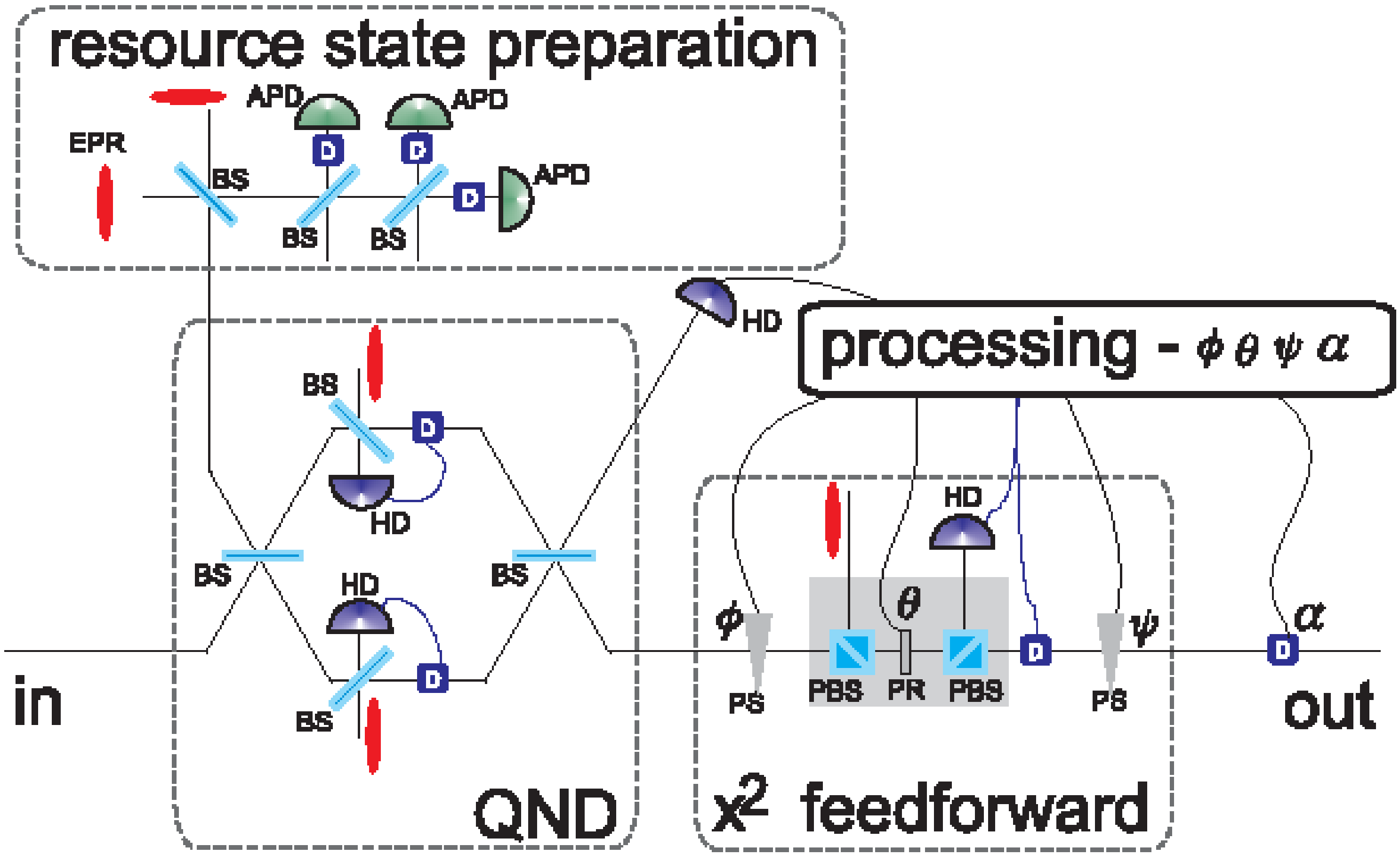
$$\hat{H}_3 = \omega_3 \hat{x}^3 \qquad |\gamma\rangle = \int e^{i\chi x^3} |x\rangle dx$$



[Gottesman and Preskill, PRA 64 012310 (2001)]

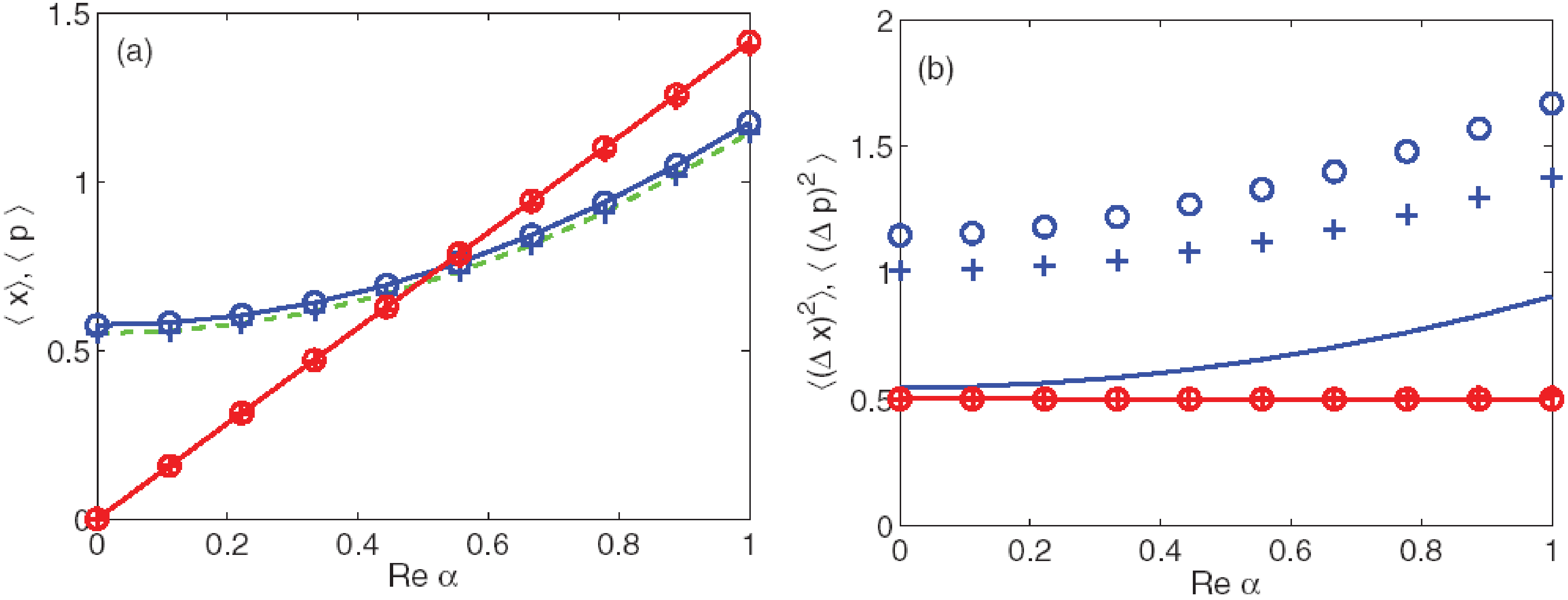
We have QND gate, we need cubic state, X^2 feed-forward correction techniques and then do it.

FEASIBLE CUBIC INTERACTION



P. Marek, R. Filip, and A. Furusawa, Phys. Rev. A 84, 053802 (2011).

X^3 NONLINEAR EFFECT



P. Marek, R. Filip and A. Furusawa, Phys. Rev. A 84, 053802 (2011).

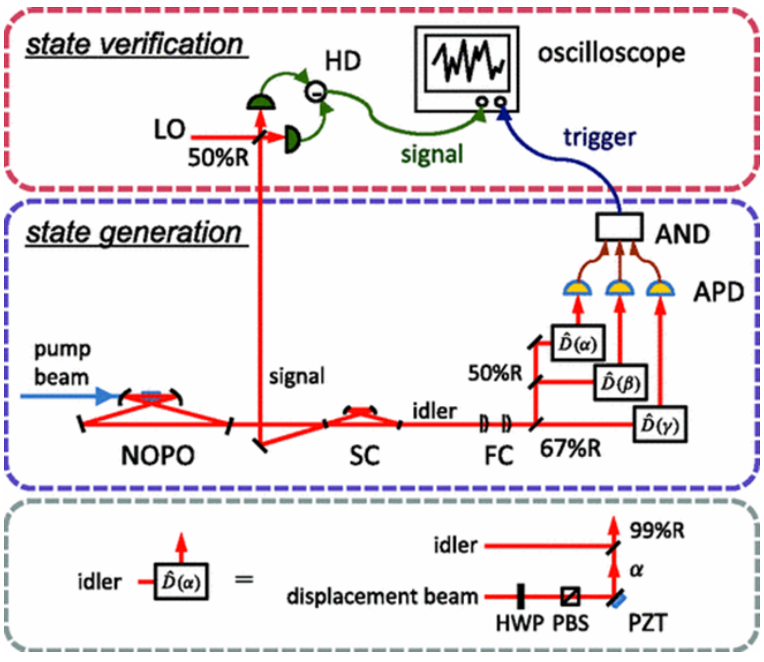
CUBIC (X^3) STATE

simplest approximation:

$$e^{i\chi\hat{x}^3}\hat{S}|0\rangle$$

$$(1 + i\chi\hat{x}^3)\hat{S}|0\rangle$$

$$\hat{S}\left(|0\rangle + \chi'\frac{3}{2\sqrt{2}}|1\rangle + \chi'\frac{\sqrt{3}}{2}|3\rangle\right)$$



P. Marek, R. Filip, and A. Furusawa, Phys. Rev. A 84, 053802 (2011).

Mitsuyoshi Yukawa, Kazunori Miyata, Hidehiro Yonezawa, Petr Marek, Radim Filip, and Akira Furusawa, Phys. Rev. A 88, 053816 (2013).

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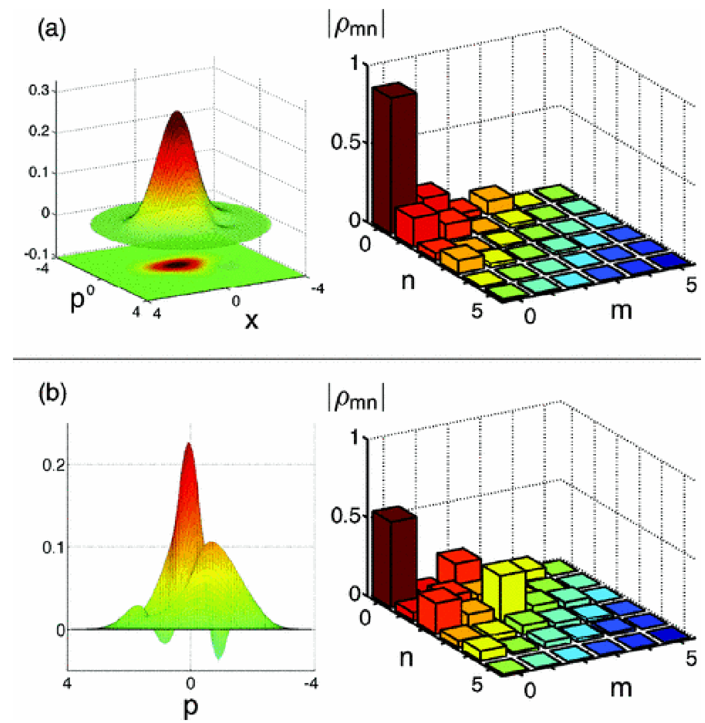

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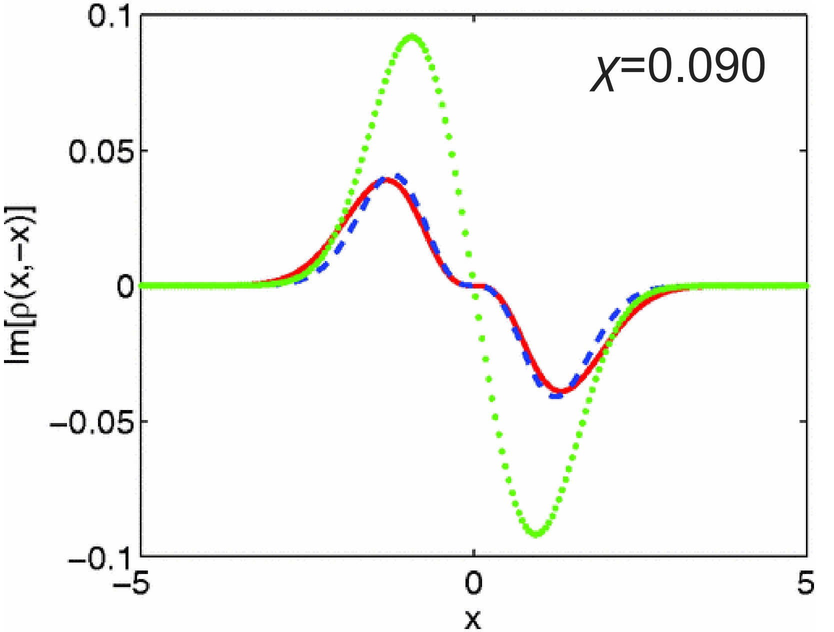


P. Marek, R. Filip, and A. Furusawa, Phys. Rev. A 84, 053802 (2011).

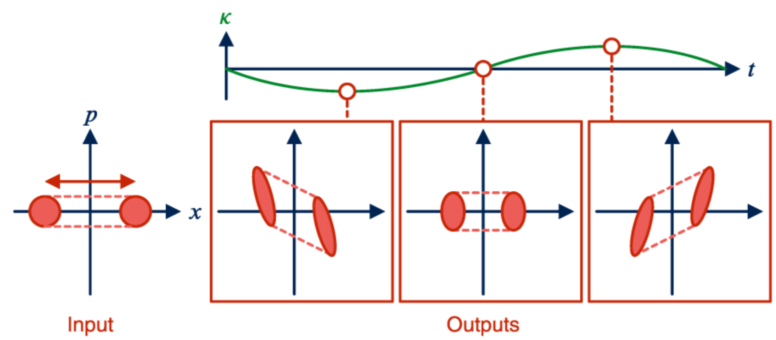
Mitsuyoshi Yukawa, Kazunori Miyata, Hidehiro Yonezawa, Petr Marek, Radim Filip, and Akira Furusawa, Phys. Rev. A 88, 053816 (2013).

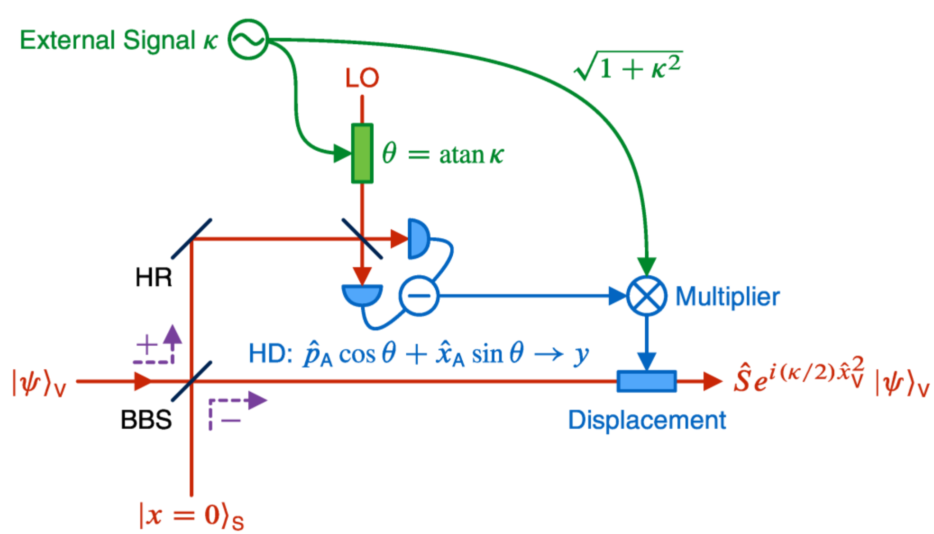
QUADRATIC (X^2) FEEDFORWARD

X→ X, P→ P+κX

$$\hat{x} = \frac{1}{\sqrt{2}}\hat{x}_{\mathrm{V}} - \frac{1}{\sqrt{2}}\hat{x}_{\mathrm{S}}^{(0)},$$

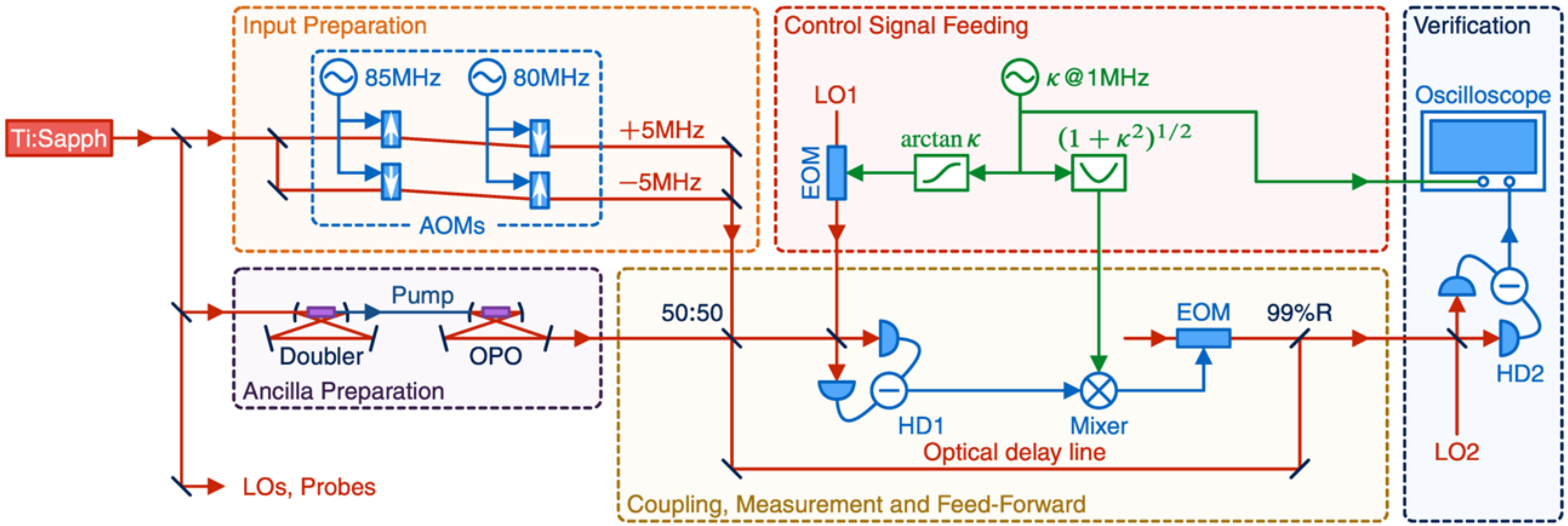
$$\hat{p} = \sqrt{2}\left(\hat{p}_{\mathrm{V}} + \frac{\kappa}{2}\hat{x}_{\mathrm{V}}\right) + \frac{\kappa}{\sqrt{2}}\hat{x}_{\mathrm{S}}^{(0)}$$





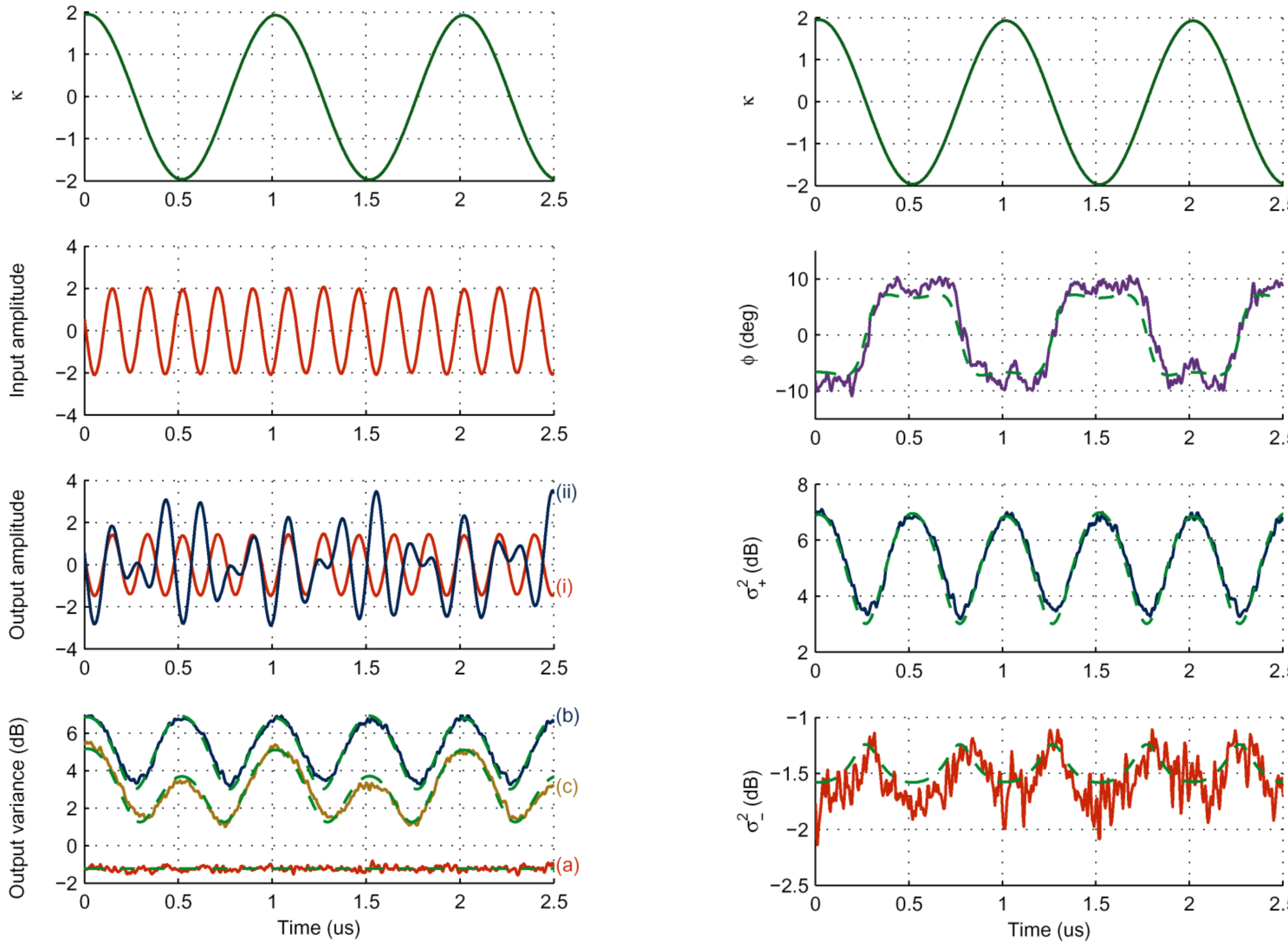
Kazunori Miyata, Hisashi Ogawa, Petr Marek, Radim Filip, Hidehiro Yonezawa, Jun-ichi Yoshikawa, and Akira Furusawa, Phys. Rev. A

QUADRATIC (X^2) FEEDFORWARD



Kazunori Miyata, Hisashi Ogawa, Petr Marek, Radim Filip, Hidehiro Yonezawa, Jun-ichi Yoshikawa, and Akira Furusawa, in preparation.

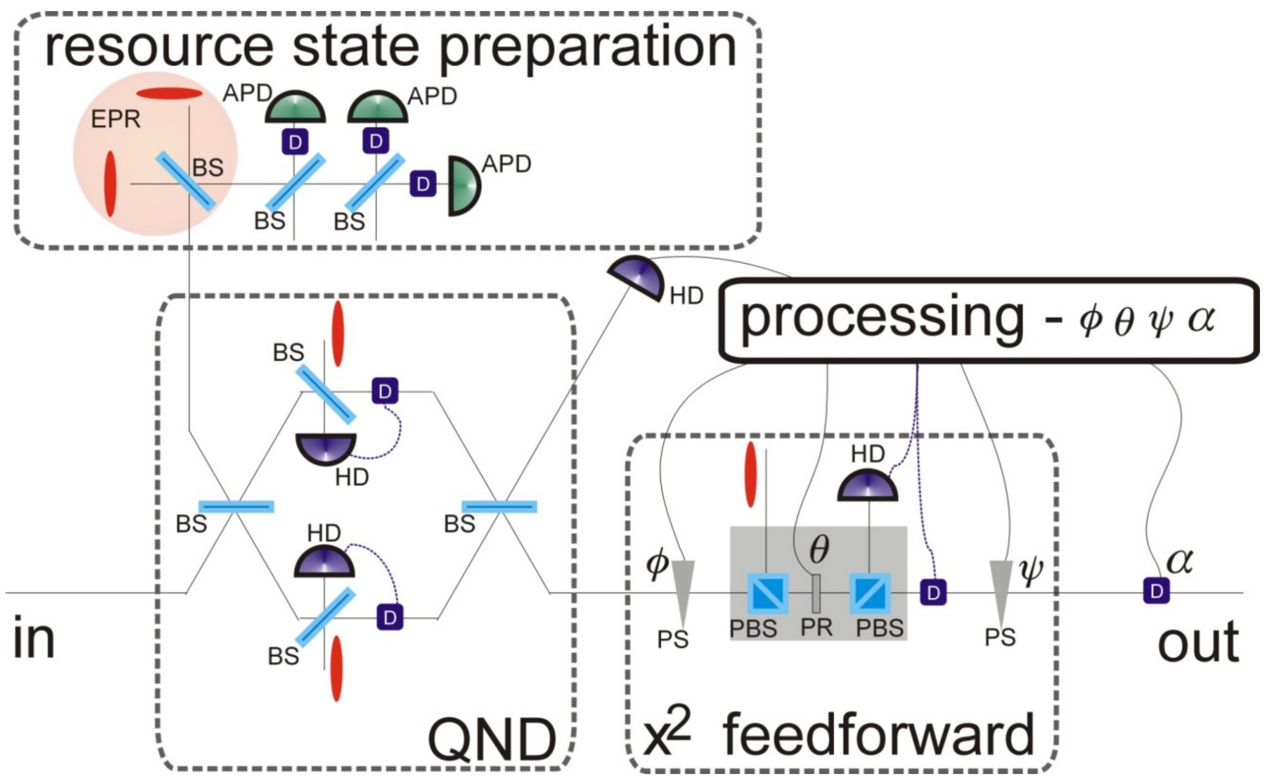
QUADRATIC (X^2) FEEDFORWARD



Kazunori Miyata, Hisashi Ogawa, Petr Marek, Radim Filip, Hidehiro Yonezawa, Jun-ichi Yoshikawa, and Akira Furusawa, in preparation.

FURTHER OPTIMIZATIONS

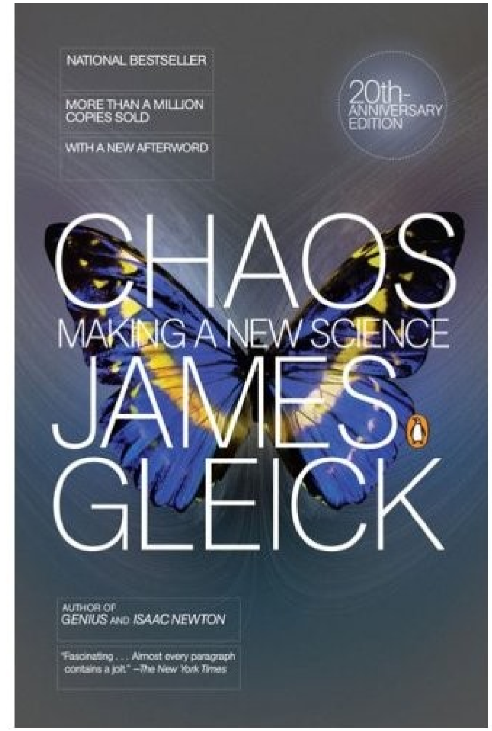
We jointly optimized resource state, coupling gate and feed-forward to reduce experimental imperfections.

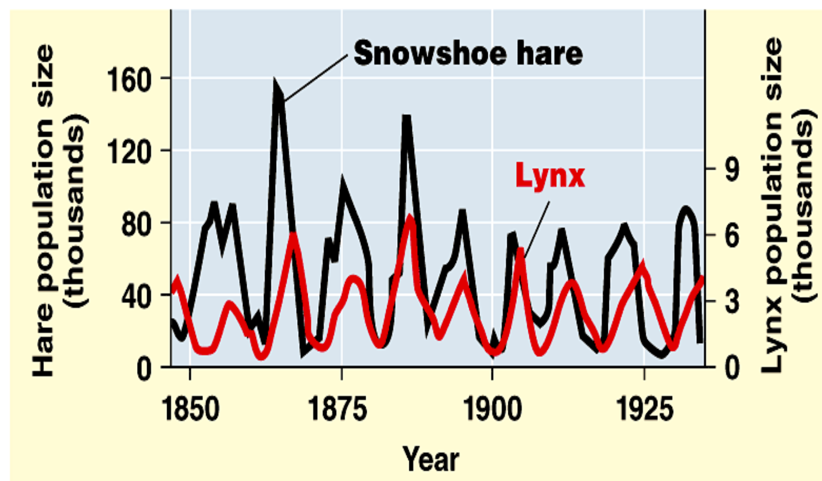


P. Marek, R. Filip, and A. Furusawa, Phys. Rev. A 84, 053802 (2011).

WHERE WE GO?

HIGHER QUANTUM NONLINEARITY





CENTER OF EXCELENCE FOR CLASSICAL AND QUANTUM INTERACTIONS IN NANOWORLD

GAČR

Department of Optics, Palacky University, Olomouc
(RF, Lukáš Slodička)

Institute of Scientific Instruments of the ASCR, Brno
(Pavel Zemánek, Ondřej Číp)

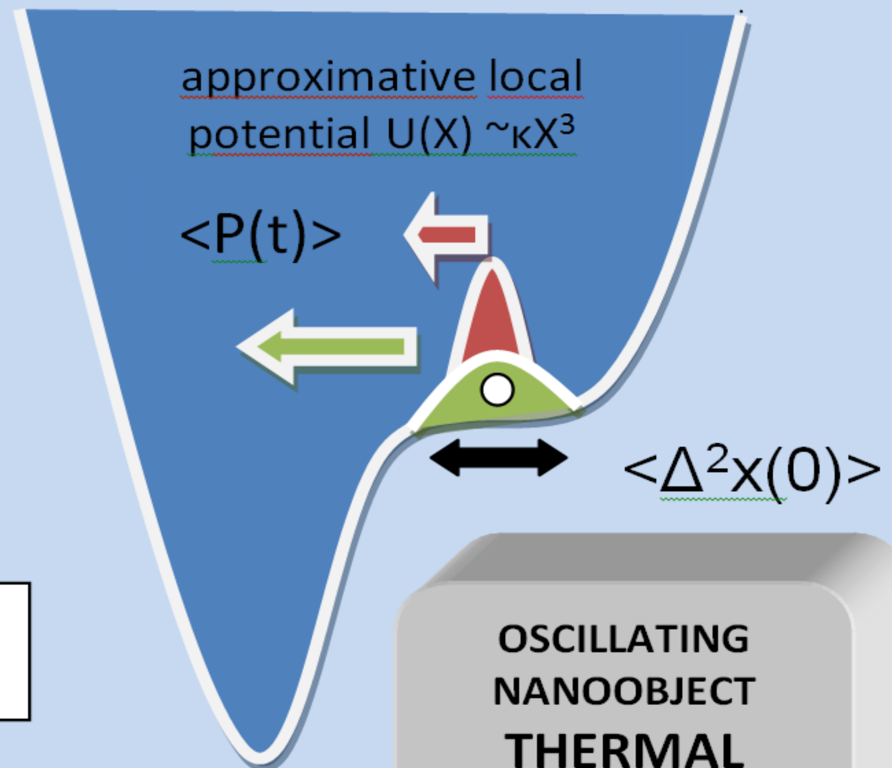
CLASSICAL TO QUANTUM WITH NANOOBJECT

Nonlinear noise-to-signal transfer:

$$\langle P(t)\rangle \sim \kappa t \langle \Delta^2 x(0)\rangle$$

Noise: variance in initial position around $\langle x(0)\rangle=0$

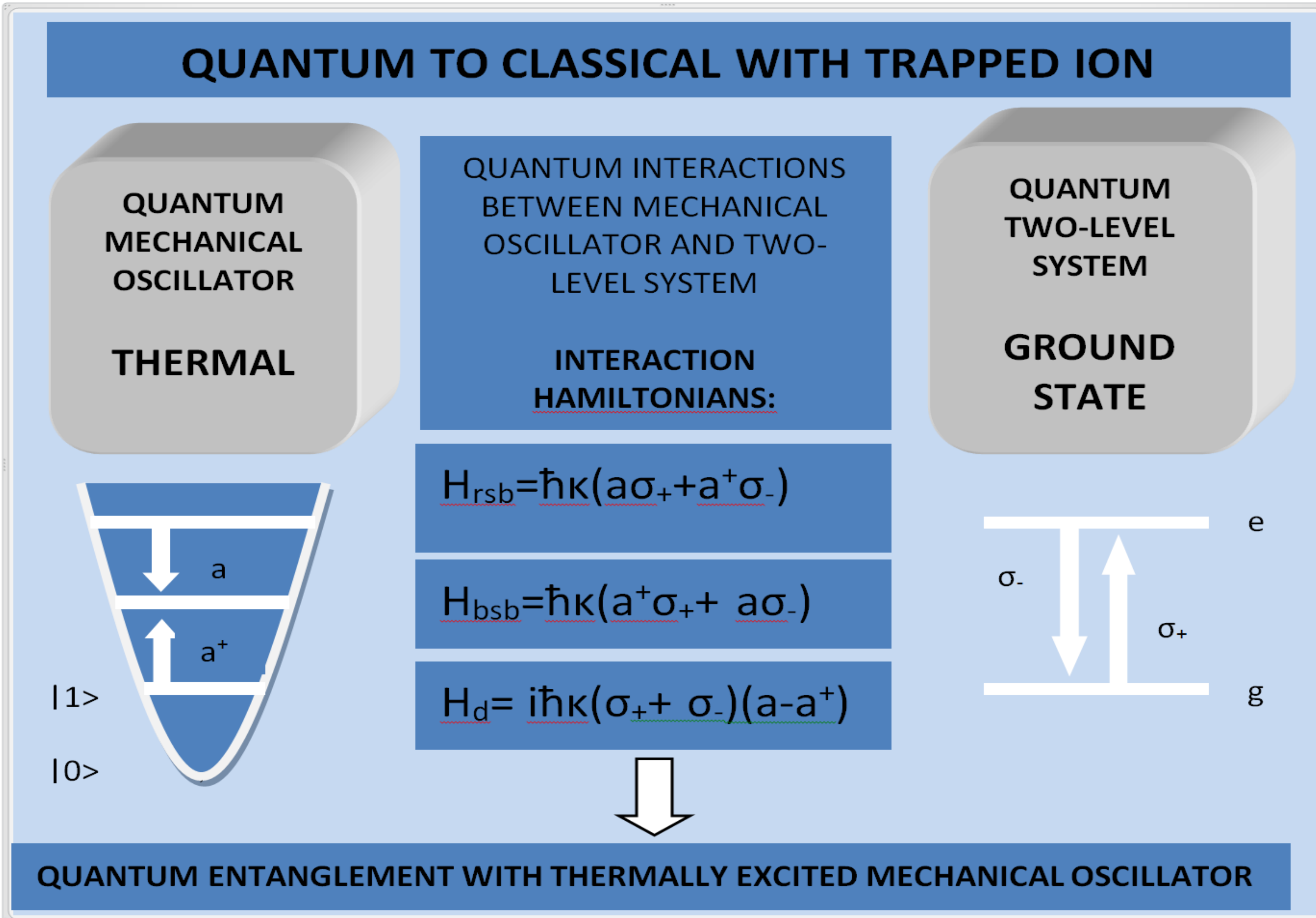
Signal: displacement in mean $\langle P(t)\rangle$ of momentum after evolution time t



OSCILLATING NANOOBJECT

THERMAL NONLINEAR

NONLINEAR DYNAMICS WITH TRAPPED COOLED NANOOBJECT TOWARDS NONLINEAR QUANTUM OPTOMECHANICS


QUANTUM TO CLASSICAL WITH TRAPPED ION
QUANTUM MECHANICAL OSCILLATOR
THERMAL
QUANTUM INTERACTIONS BETWEEN MECHANICAL OSCILLATOR AND TWO-LEVEL SYSTEM
INTERACTION HAMILTONIANS:
QUANTUM TWO-LEVEL SYSTEM
GROUND STATE
$H_{rsb}=\hbar\kappa(a\sigma_+ + a^+\sigma_-)$
$H_{bsb}=\hbar\kappa(a^+\sigma_+ + a\sigma_-)$
$H_d= i\hbar\kappa(\sigma_+ + \sigma_-)(a-a^+)$
a
a^+
|1>
|0>
e
g
σ_-
σ_+
QUANTUM ENTANGLEMENT WITH THERMALLY EXCITED MECHANICAL OSCILLATOR