Mezinárodní centrum pro informaci a neurčitost
Univerzita Palackého v Olomouci

Optické nelineární operace na kvantové úrovni

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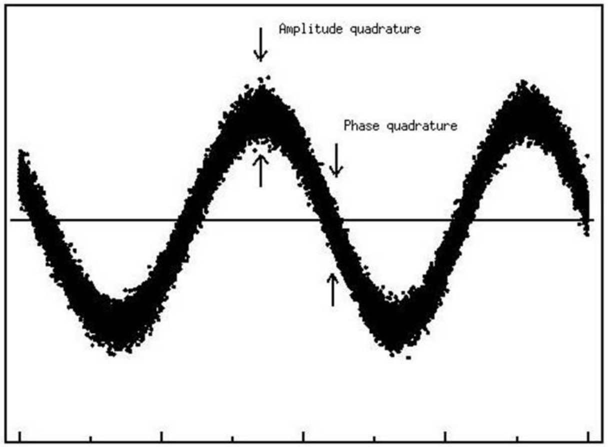
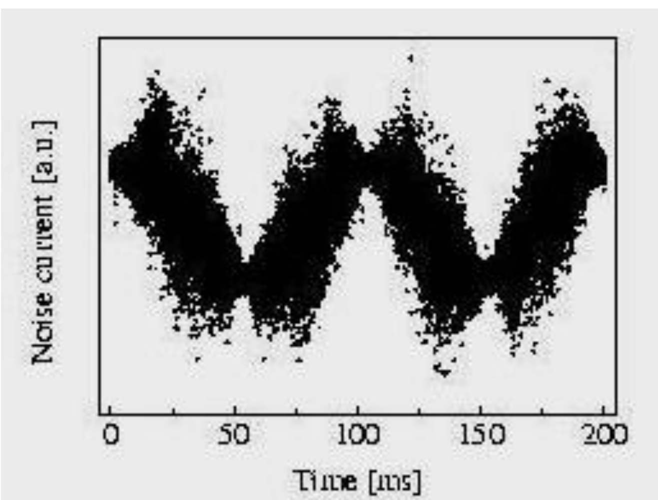
evropský sociální fond v ČR
EVROPSKÁ UNIE
MINISTERSTVO ŠKOLSTVÍ, MLÁDEŽE A TĚLOVÝCHOVY
OP Vzdělávání pro konkurenceschopnost
INVESTICE DO ROZVOJE VZDĚLÁVÁNÍ

CV QUANTUM NOISE



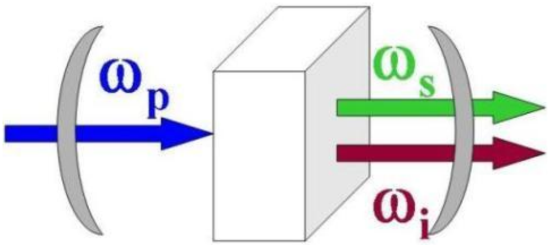


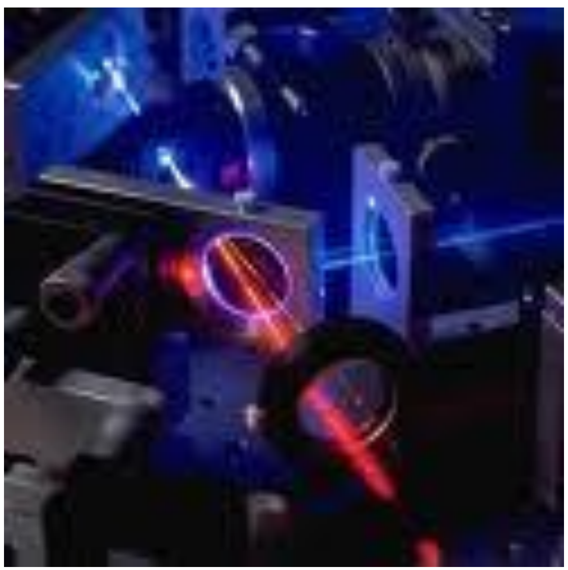
Continuous quantum noise of light can be measured by homodyne detection.

Quantum information is simultaneously in amplitude and phase “quadrature” of light.

A partial noise reduction is possible in nonlinear OPO and OPA – noise squeezing.

PARAMETRIC AMPLIFIER

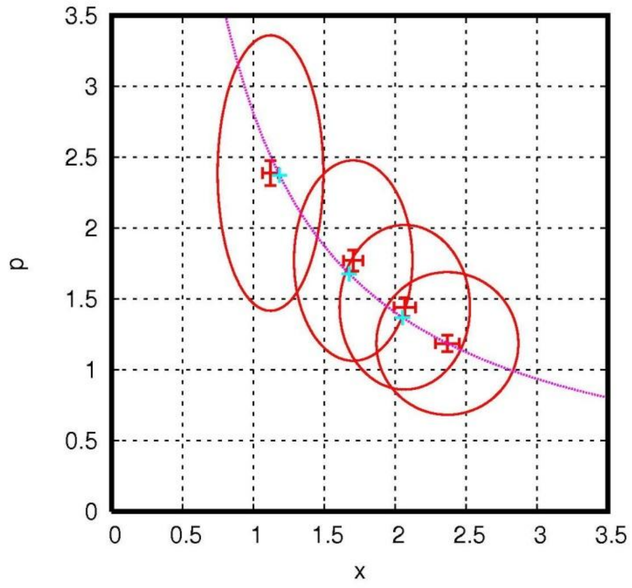




- Non-linear parametric process **on-line** in optical crystal.
- High-Q cavity enhances nonlinearity and filters single mode of light.
- **Off-line source of squeezed state.**
- Squeezing record: >10dB (who next?)

ON-LINE SQUEEZER WITH OFF-LINE SQUEEZING

- Universal Squeezer:



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

$$X_1' = \sqrt{T}X_1 + \sqrt{1-T}X_A,$$

$$P_1' = \frac{1}{\sqrt{T}}P_1 - \frac{\sqrt{(1-T)(1-\eta)}}{\sqrt{T\eta}}P_0,$$

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

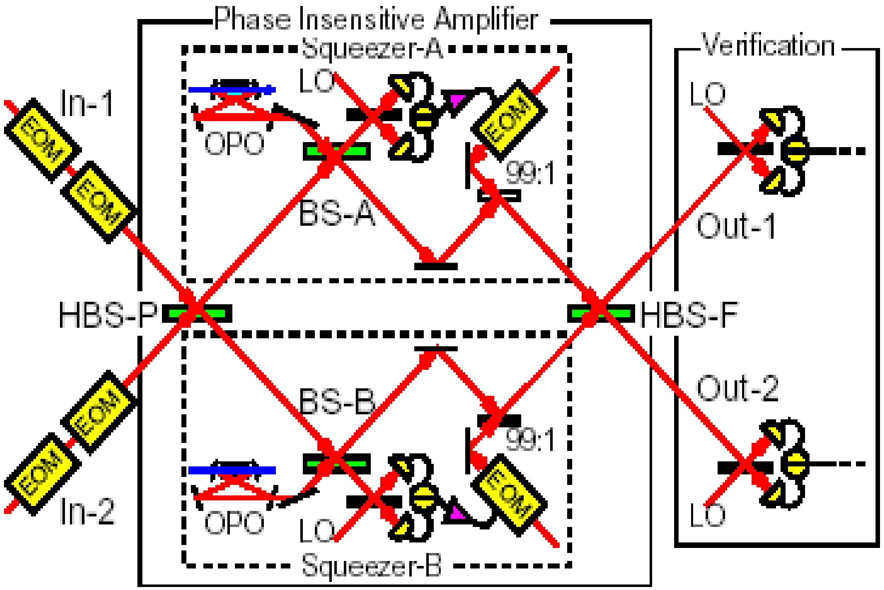
Memo:

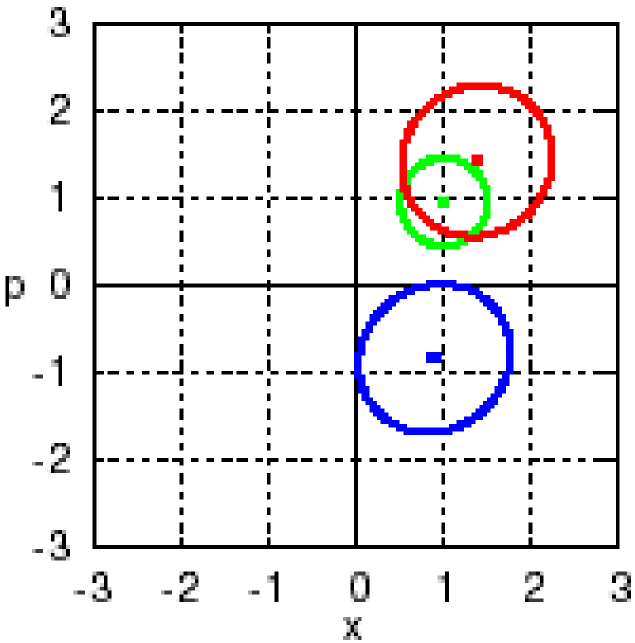
Off-line squeezing -> On-line squeezer

ALL OPTICAL AMPLIFIER

$$\hat{a}_{\mathrm{sig}}^{\mathrm{out}} = \sqrt{G}\,\hat{a}_{\mathrm{sig}}^{\mathrm{in}} + e^{i\theta}\sqrt{G-1}\,\left(\hat{a}_{\mathrm{idl}}^{\mathrm{in}}\right)^{\dagger}$$

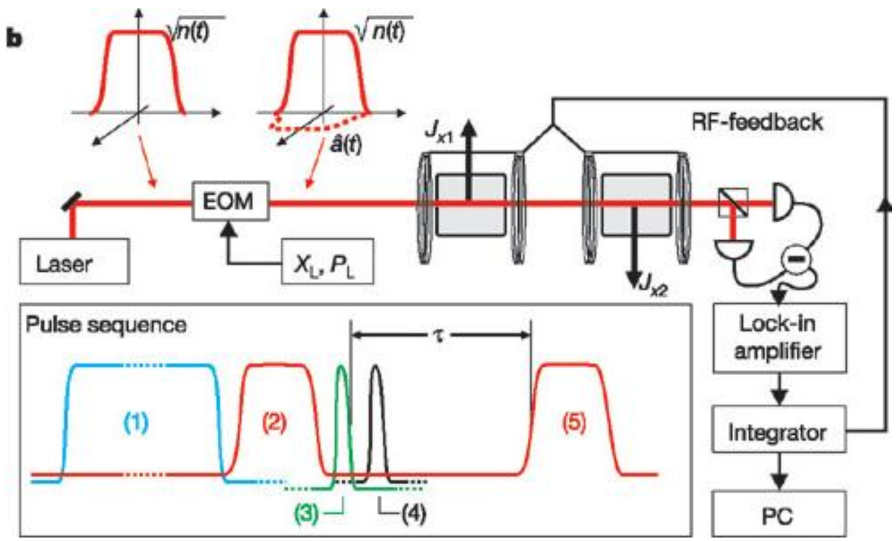
$$\hat{a}_{\mathrm{idl}}^{\mathrm{out}} = \sqrt{G}\,\hat{a}_{\mathrm{idl}}^{\mathrm{in}} + e^{i\theta}\sqrt{G-1}\,\left(\hat{a}_{\mathrm{sig}}^{\mathrm{in}}\right)^{\dagger}$$



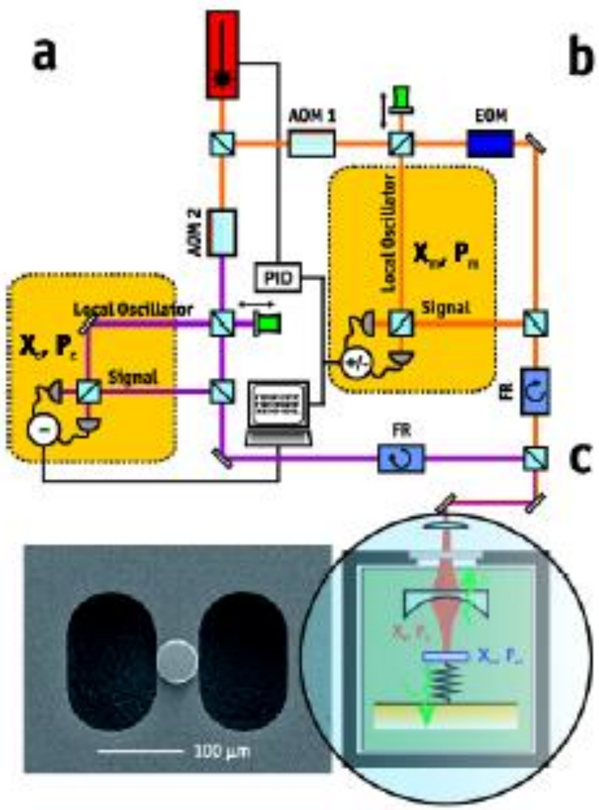


J. Yoshikawa, Y. Miwa, R. Filip, A. Furusawa, Phys. Rev. A 83, 052307 (2011)

INTERACTION WITH MATTER



Quantum memory



Quantum opto-mechanics

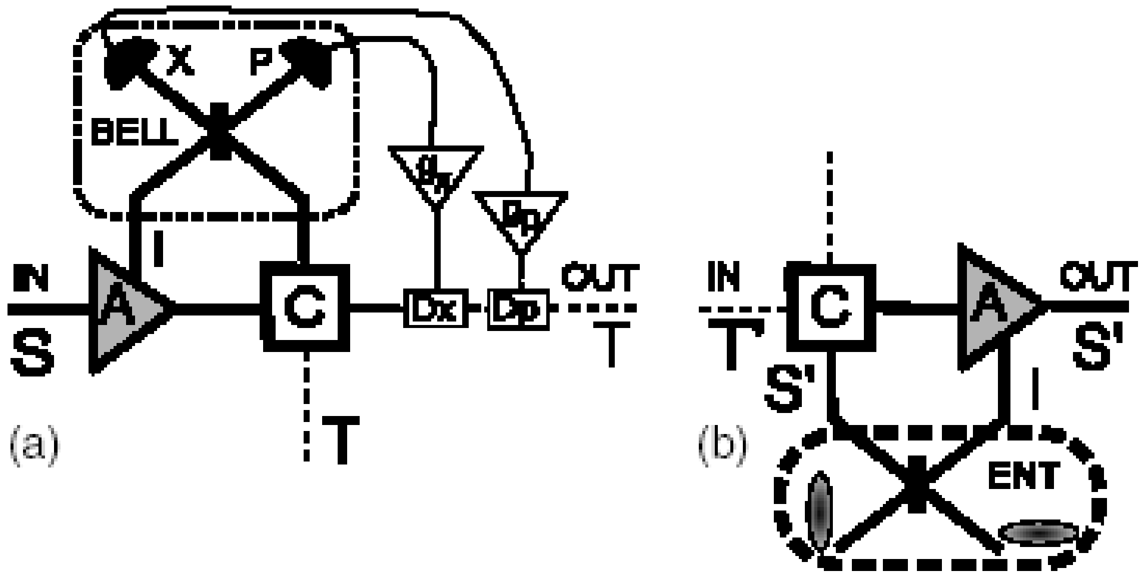
UNIVERSAL QUANTUM INTERFACE

- **operations** on source are available, but operations on target are limited to single type of coupling

- target is highly **noisy**

[R. Filip, PRA 2009]

- **unitary coupling**: fast coupling = weak coupling

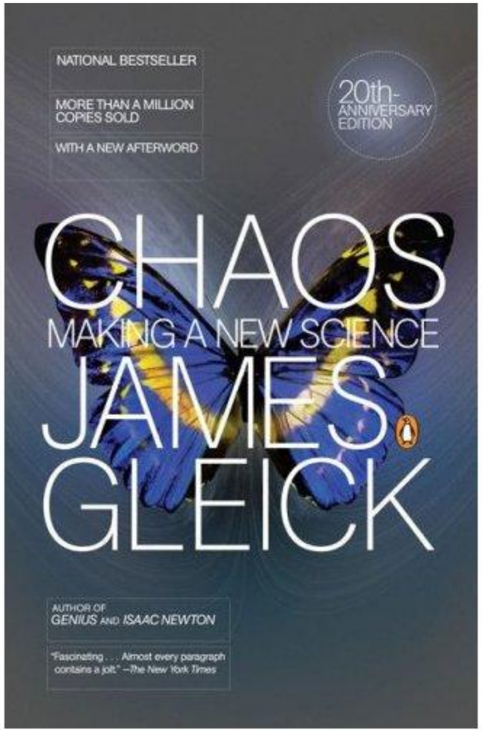


R. Filip, Phys. Rev. A 80, 022304 (2009);

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

WHERE TO GO?

WHERE TO GO?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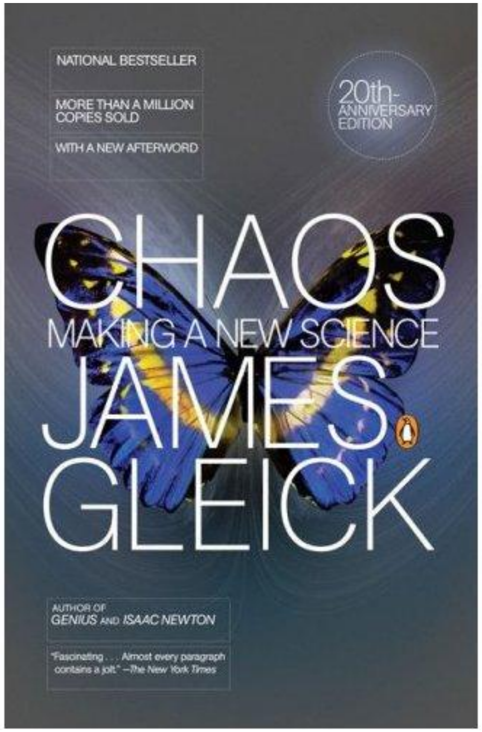
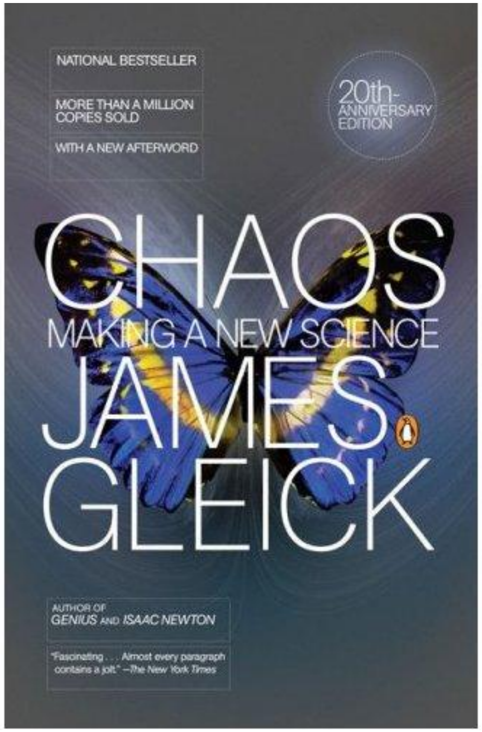
WHERE TO GO?

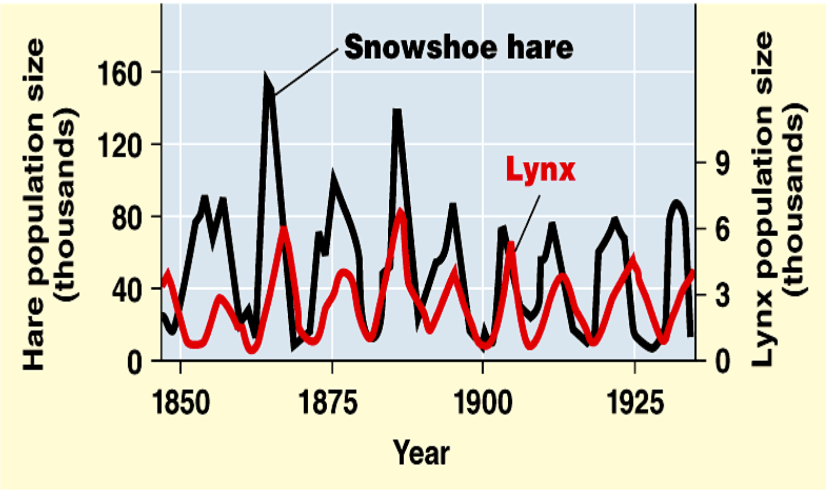
HIGHER QUANTUM NONLINEARITY



WHERE TO GO?

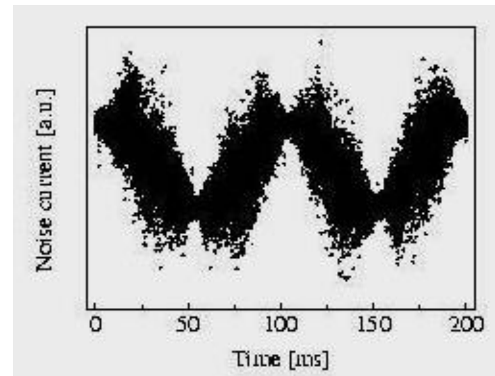
HIGHER QUANTUM NONLINEARITY

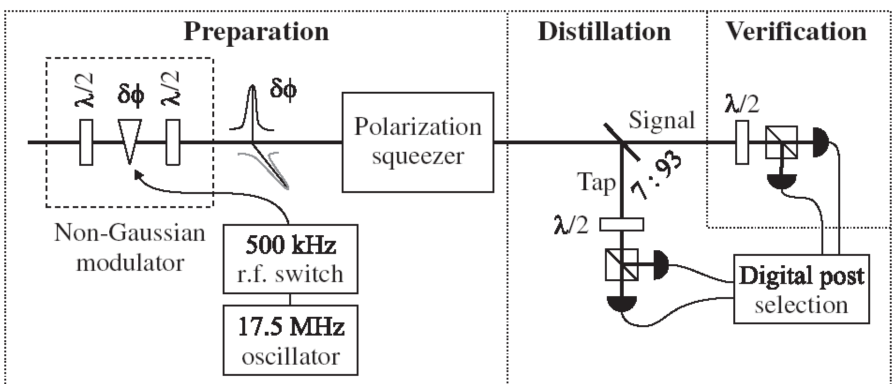


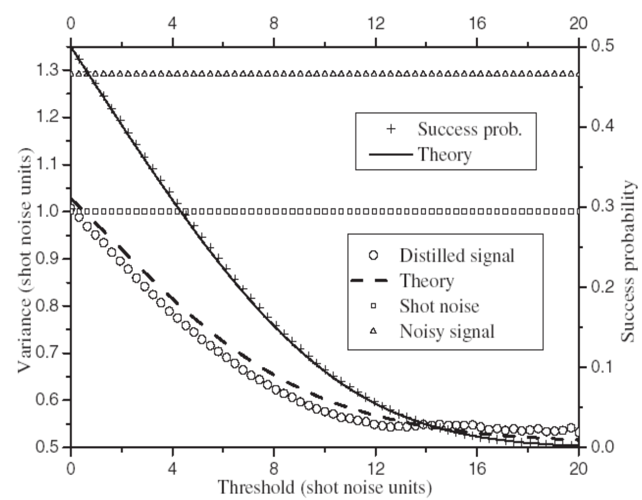


QUANTUM NON-LINEAR FILTRATION

Nonlinearity induced by homodyne measurement and **post-selection** reveal squeezed states from noise.

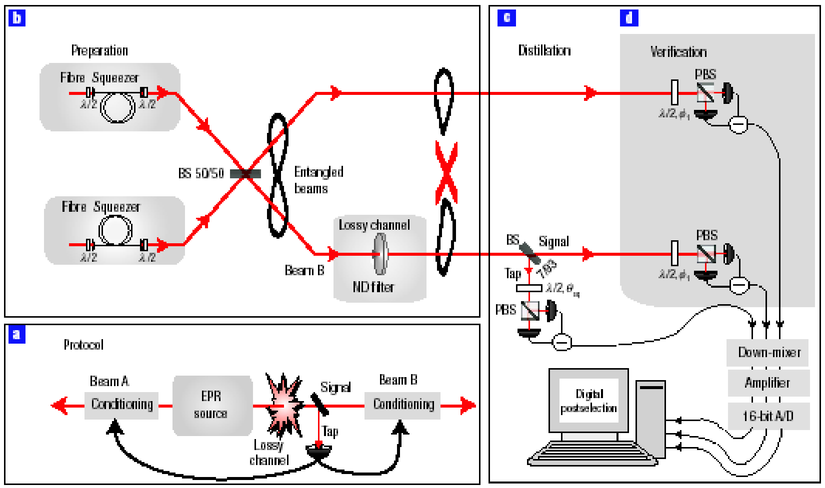


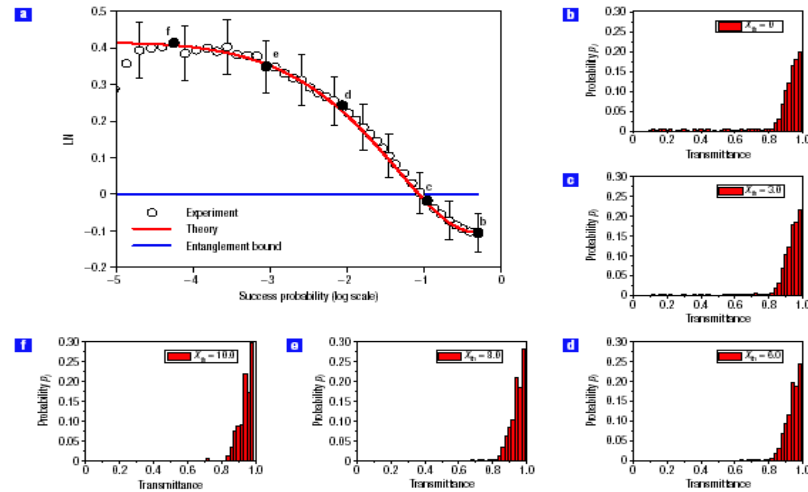




J. Heersink, Ch. Marquardt, R. Dong, R. Filip, S. Lorenz, G. Leuchs and U. L. Andersen**,** Phys. Rev. Lett. **96,** 253601 (2006).

ENTANGLEMENT FILTRATION

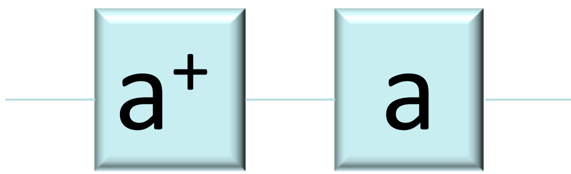




Nonlinear quantum filters based on homodyne detectors conditionally restore quantum correlations of non-Gaussian states – corrections to no-go theorems.

R.-F. Dong, M. Lassen, J. Heersink, Ch. Marquardt, R. Filip, G. Leuchs and U.L. Andersen, Nature Physics 4, 919 (2008).

NOISELESS AMPLIFIER



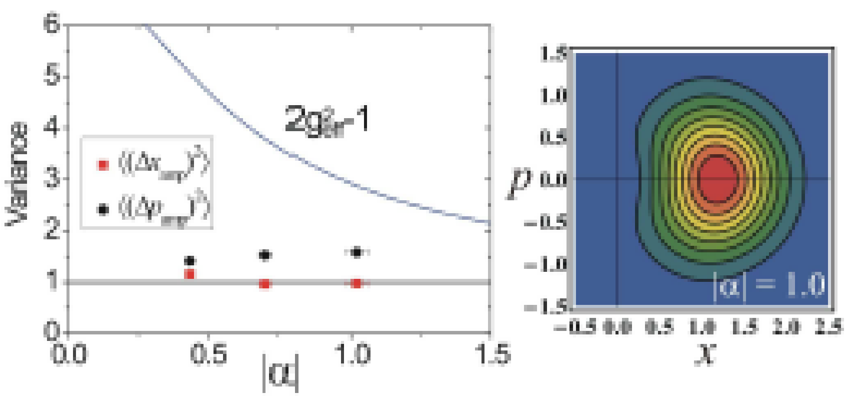
$|\alpha\rangle = |0\rangle + \alpha|1\rangle + \dots$

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

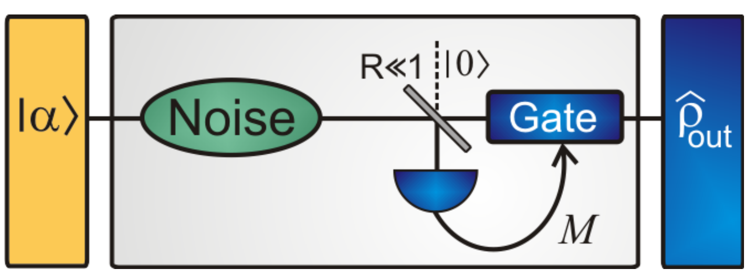
$aa^+|\alpha\rangle = |0\rangle + \mathbf{2}\alpha\,|1\rangle + \dots$

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

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



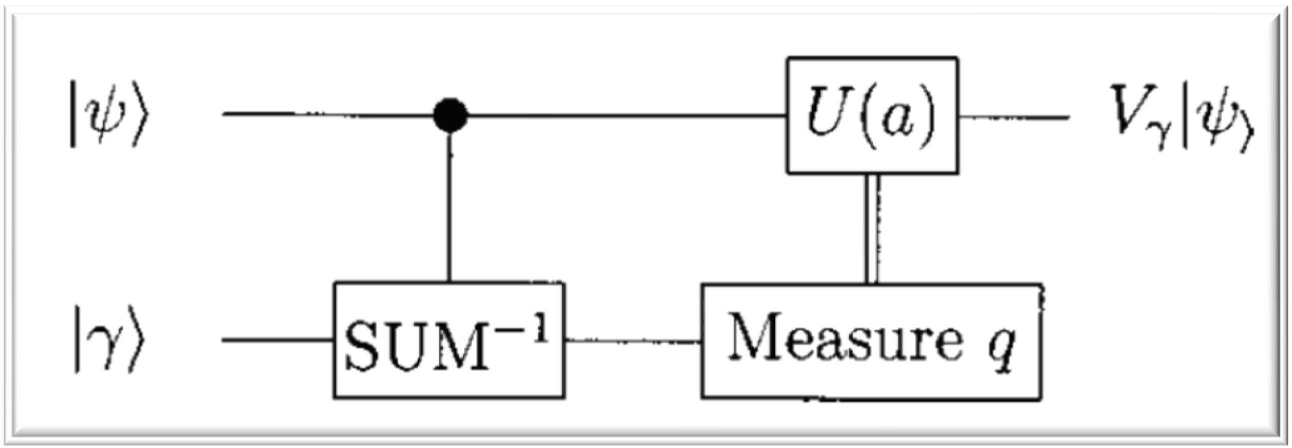
M.A. Usuga, Ch. R. Müller, Ch. Wittmann, P. Marek, R. Filip, Ch. Marquardt, G. Leuchs, U.L. Andersen, Nature Phys. 6, 767–771 (2010)



CUBIC NONLINEARITY

$$\hat{H}_3 = \omega_3 \hat{x}^3$$

$$|\gamma\rangle = \int e^{i\chi x^3} |x\rangle dx$$



We have QND gate, squeezers and feed-forward correction techniques.

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

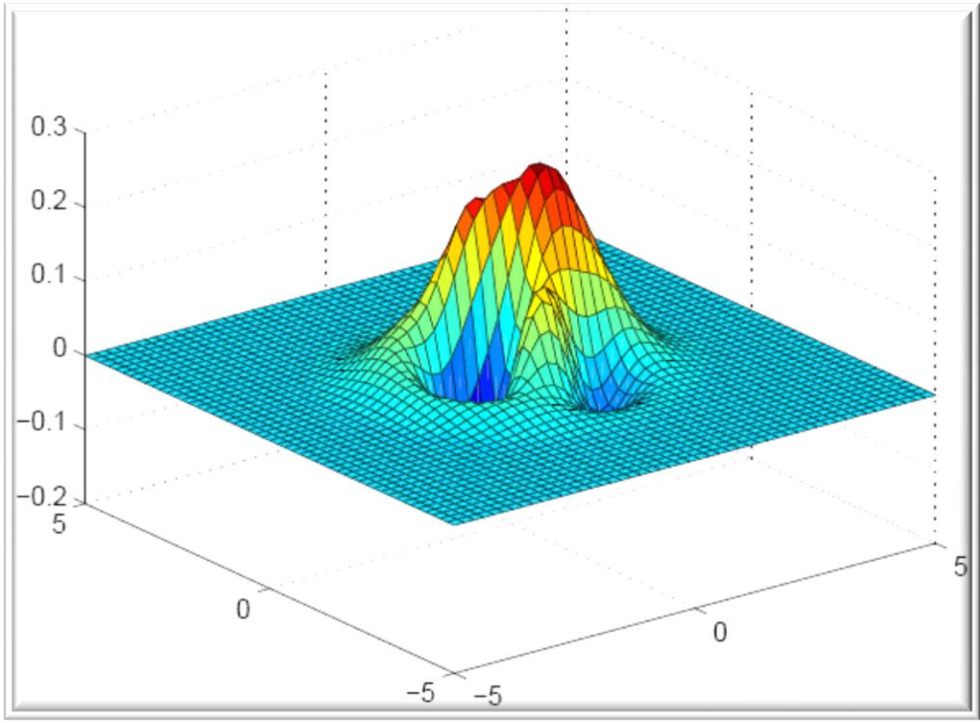
CUBIC X^3 STATE

- it has infinite energy …
- simplest approximation of X^3 state:

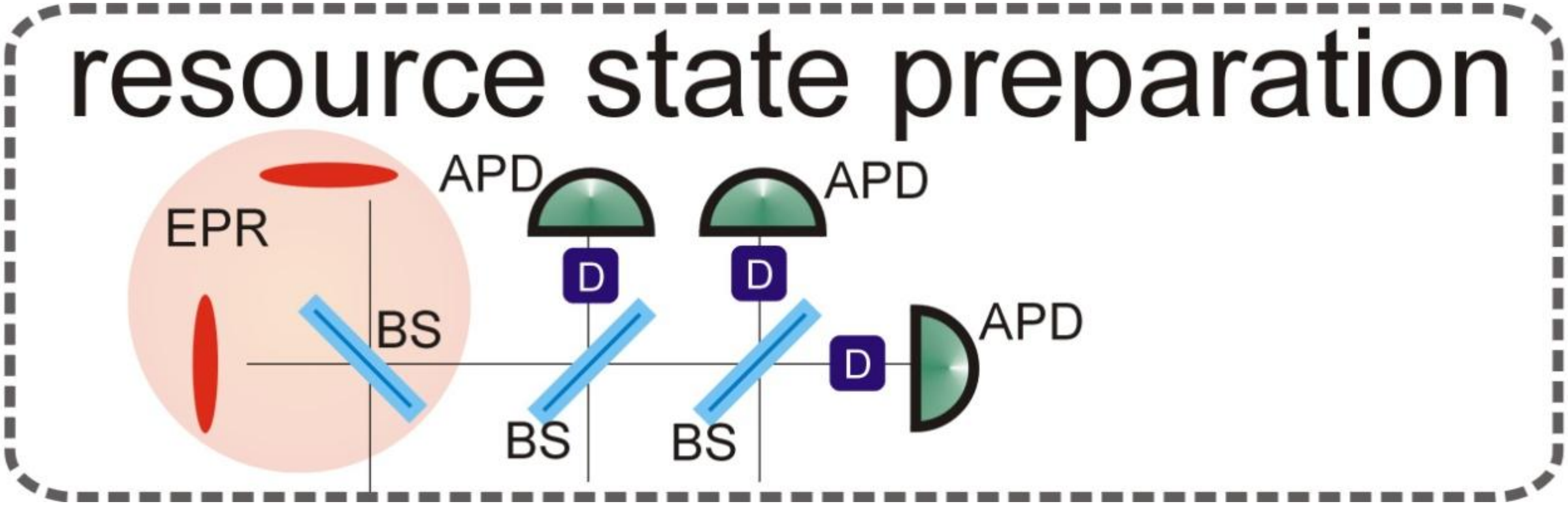
$$e^{i\chi\hat{x}^3}\hat{S}|0\rangle$$

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

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



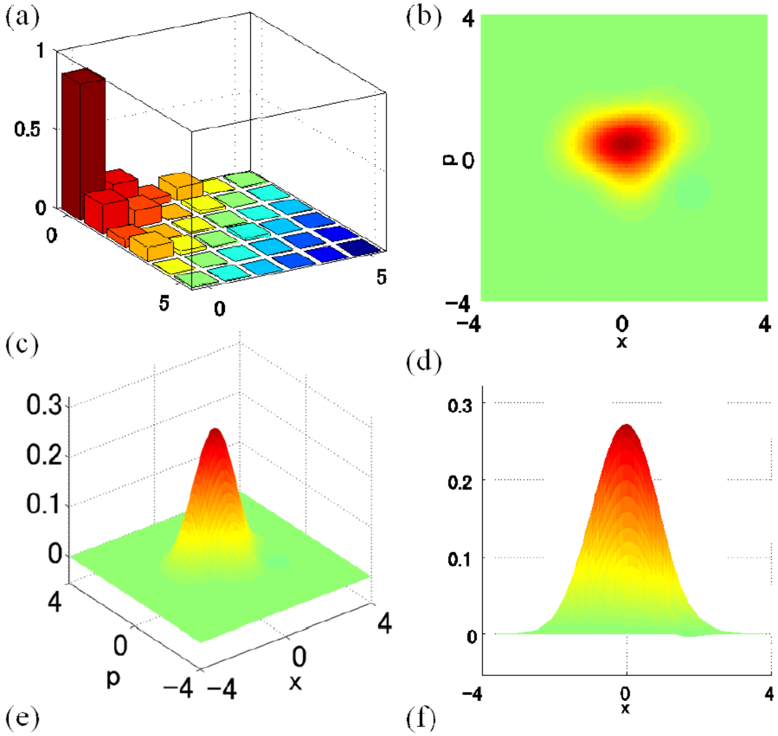
P. Marek, R. Filip, and A. Furusawa, Phys. Rev. A 84, 053802 (2011).



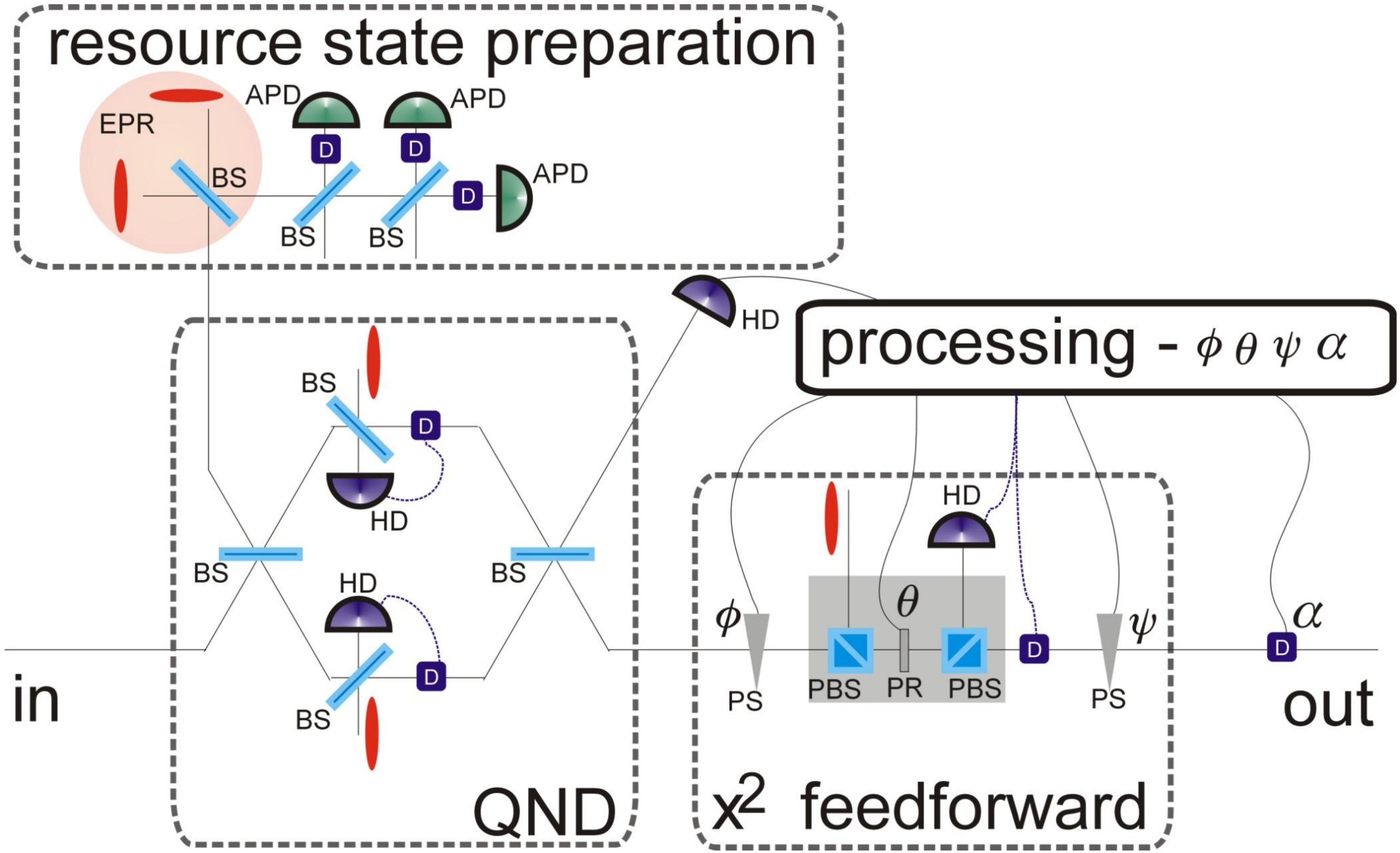
conditional

First experimental test: (Furusawa lab)

- optimization
- evaluation



CUBIC X³ GATE



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

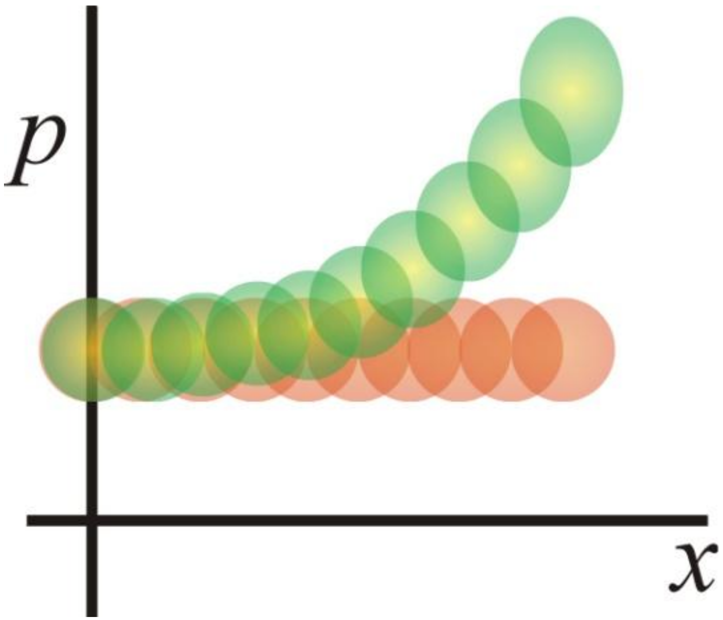
NONLINEAR EFFECT

- Nonlinear noise effect & non-demolition feature

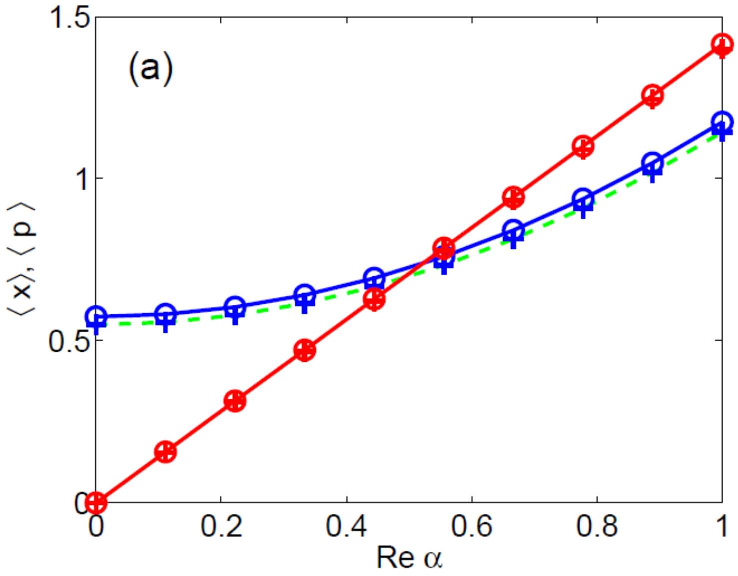
$$\hat{H}_3 = \omega_3 \hat{x}^3$$

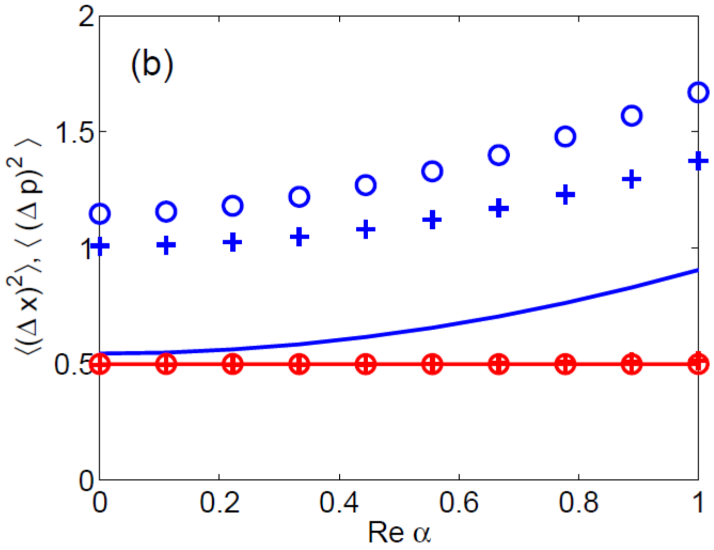
$$\hat{x} \rightarrow \hat{x}$$

$$\hat{p} \rightarrow \hat{p} + \chi \hat{x}^2$$



THEORY PREDICTION





$$\hat{a} = (\hat{x} + i\,\hat{p})/\sqrt{2}$$

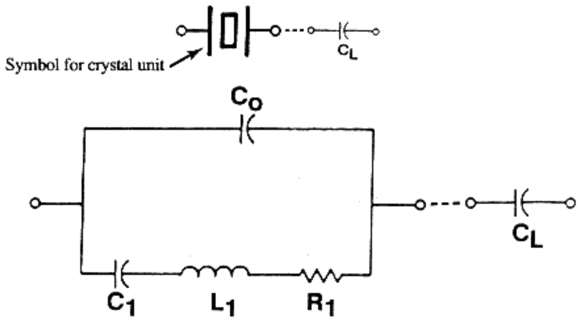
Blue – P variable, red – X variable

Blue, red lines – ideal deterministic X^3 gate (χ=0.03)

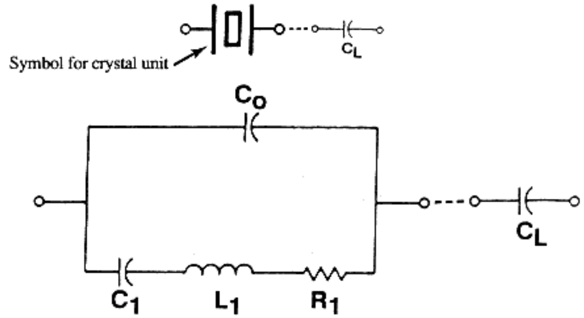
Blue, red cross – approximated deterministic X^3 gate

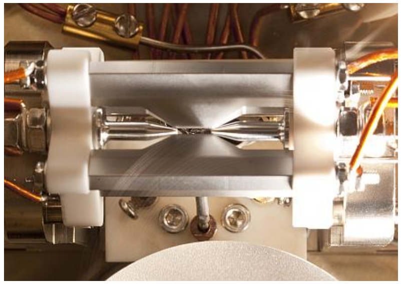
Blue, red circles – Gaussian version of deterministic X^3 gate (QND, homodyne detection giving x and nonlinear feed-forward correction)

QUANTUM EQUIVALENT CIRCUITS



QUANTUM EQUIVALENT CIRCUITS

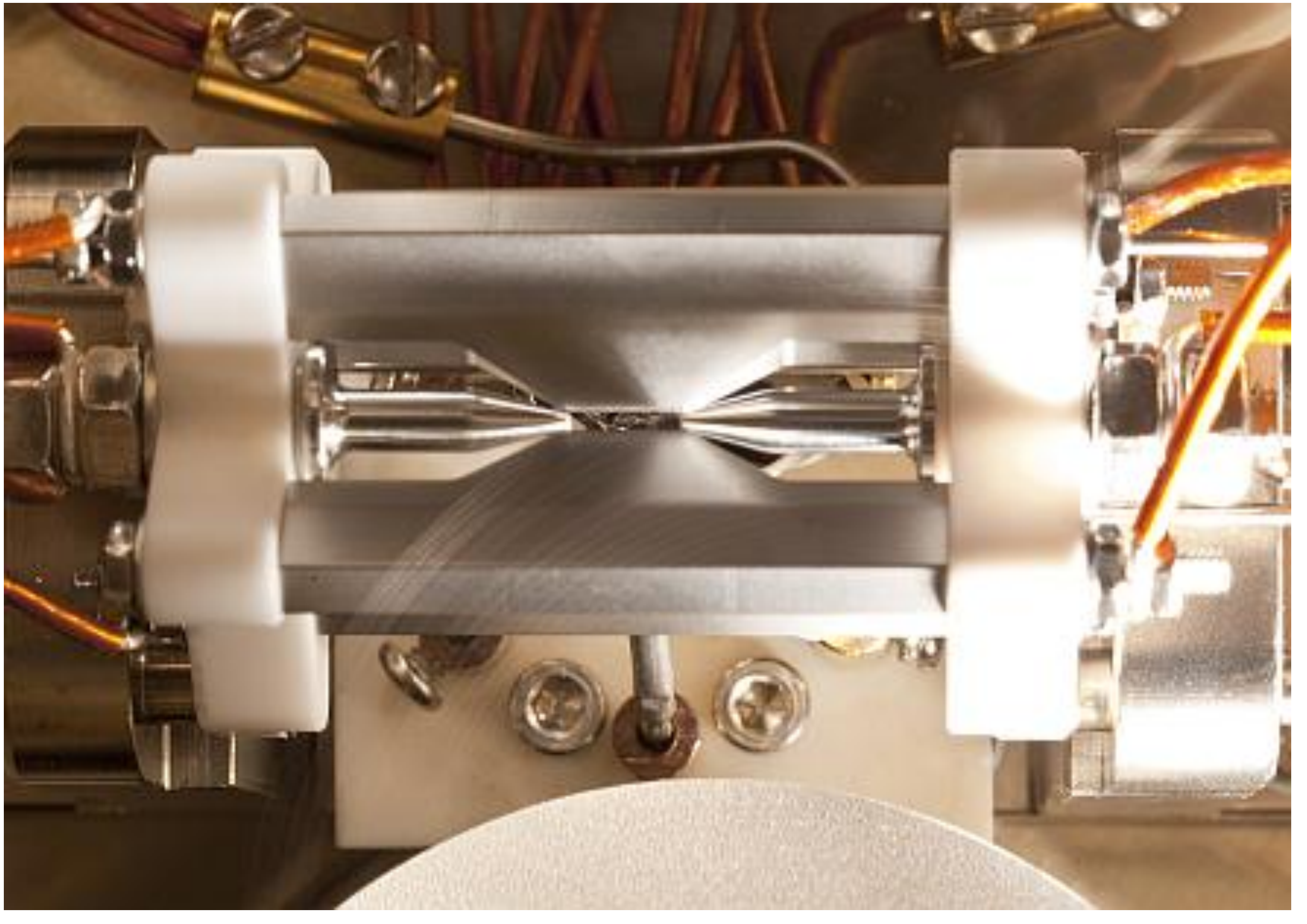




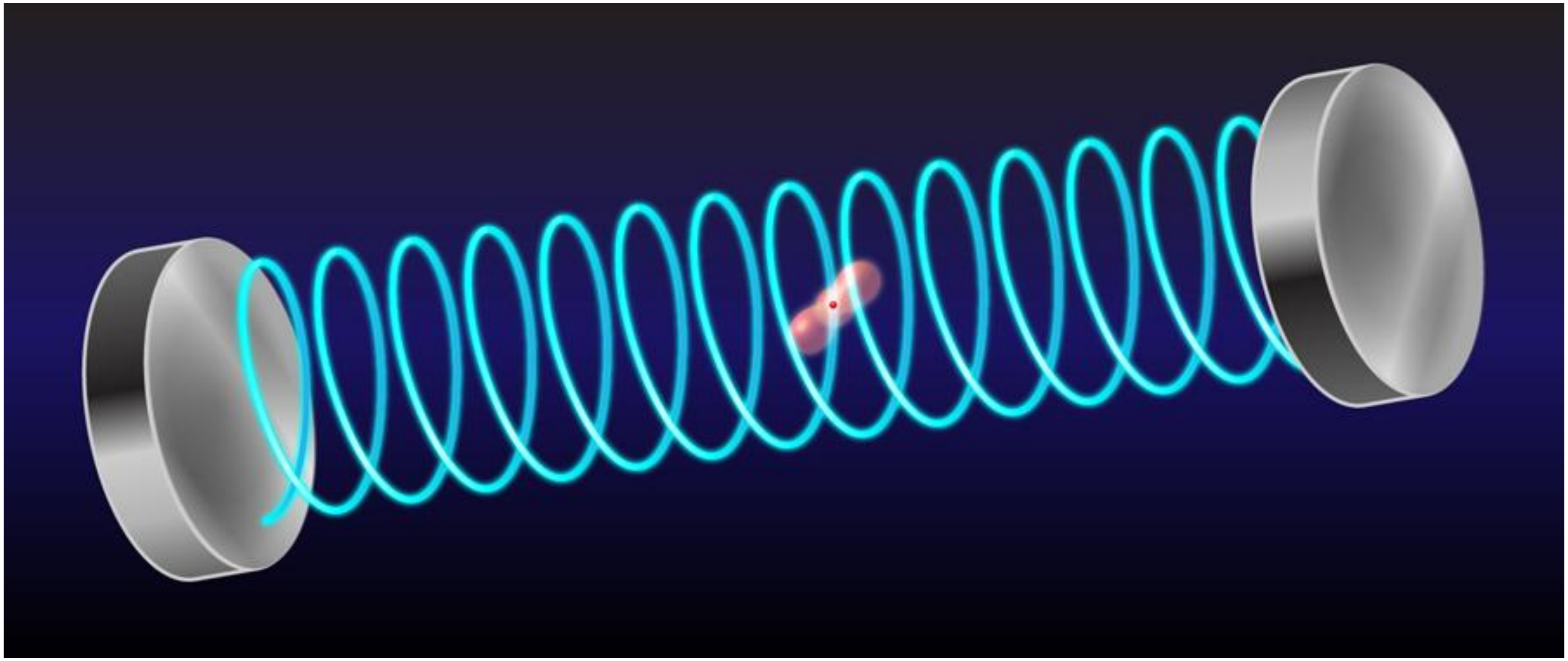
?

Quantum optics: decomposition and control of quantum nonlinearity.

QUANTUM NONLINEAR CIRCUIT



QUANTUM NONLINEAR CIRCUIT



$$\hat{H}_{\rm JC} = \hbar\nu\hat{a}^{\dagger}\hat{a} + \hbar\omega\frac{\hat{\sigma}_z}{2} + \frac{\hbar\Omega}{2}\left(\hat{a}\hat{\sigma}_{+} + \hat{a}^{\dagger}\hat{\sigma}_{-}\right).$$