MEASUREMENT INDUCED QUANTUM NONLINEAR OPERATIONS FOR TRAVELING BEAMS OF LIGHT

Radim Filip, Petr Marek, Kimin Park
Department of Optics, Palacky University

University of Tokyo (Akira Furusawa Lab)
Laboratoire Kastler Brossel, Paris (Julien Laurat Lab)



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Quantum Coherence and Nonclassicality

Miroslav Gavenda
Petr Marek

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Lukáš Lachman

Quantum Nonlinear Operations

Petr Marek
Kimin Park

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Quantum Communication

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Quantum Optomechanics

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Interaction of Light with Atoms

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Stochastic Dynamics and Thermodynamics

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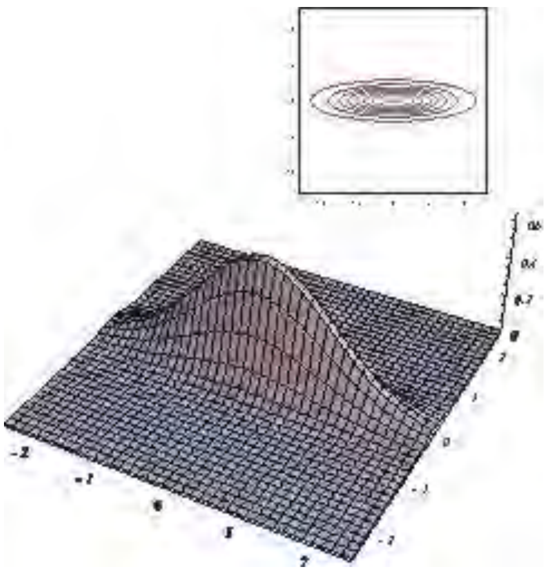
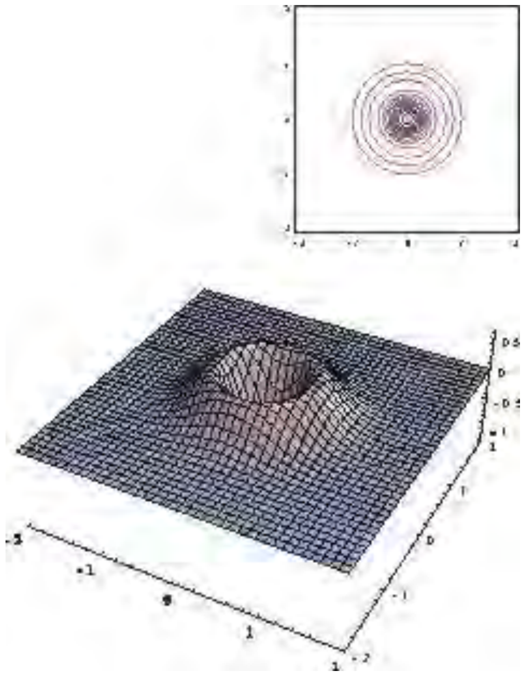
NONCLASSICAL QUANTUM RESOURCES:





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 variances above vacuum level

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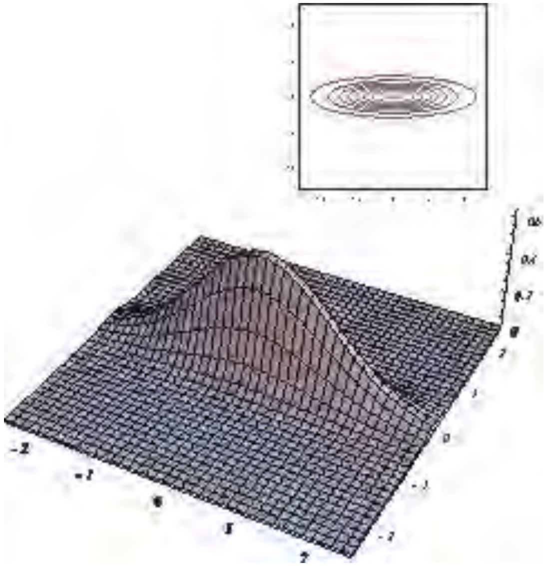

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Gaussian squeezed state:

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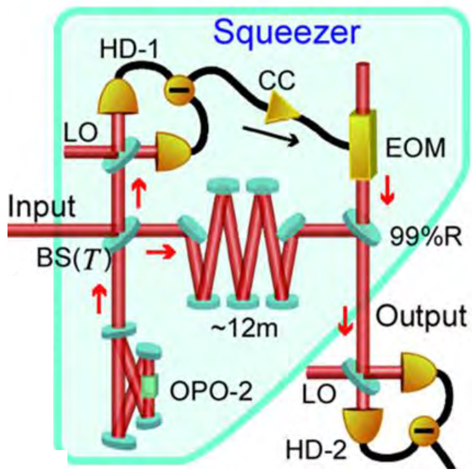
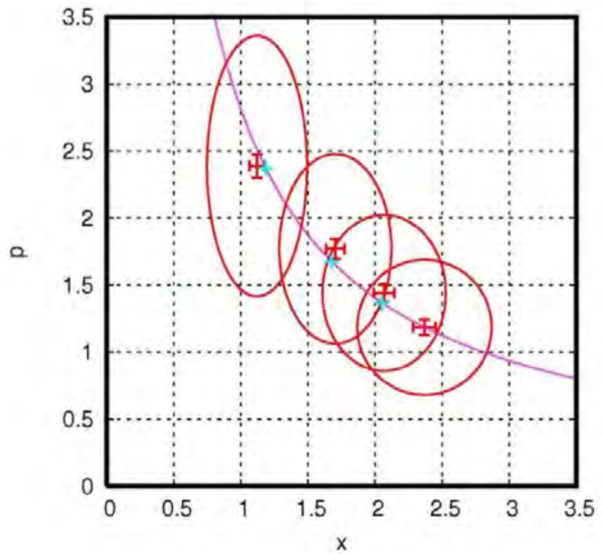
NOISE SQUEEZING = RESOURCE FOR SQUEEZER



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

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

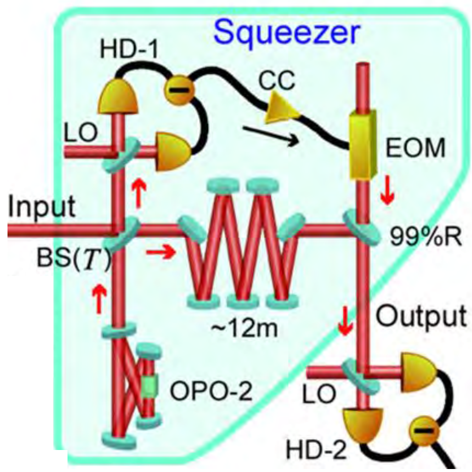
R. Filip, P. Marek and U.L. Andersen, Phys. Rev. A 71, 042308 (2005).



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

- **off-line squeezed state supplies on-line squeezer**
- **squeezer, amplifier, QND interaction**

NOISE SQUEEZING = RESOURCE FOR SQUEEZER



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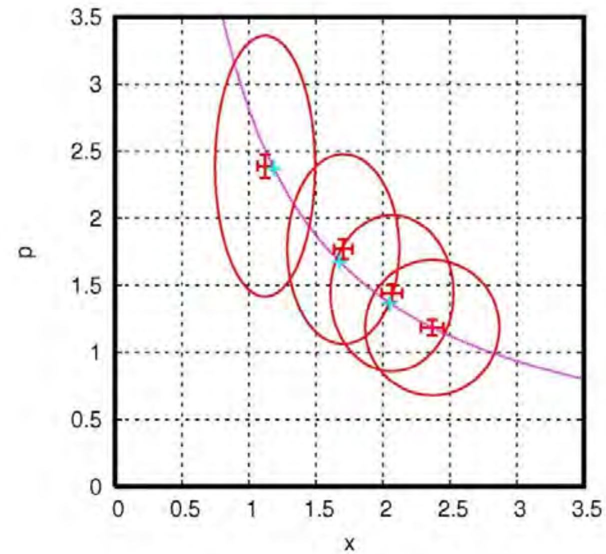

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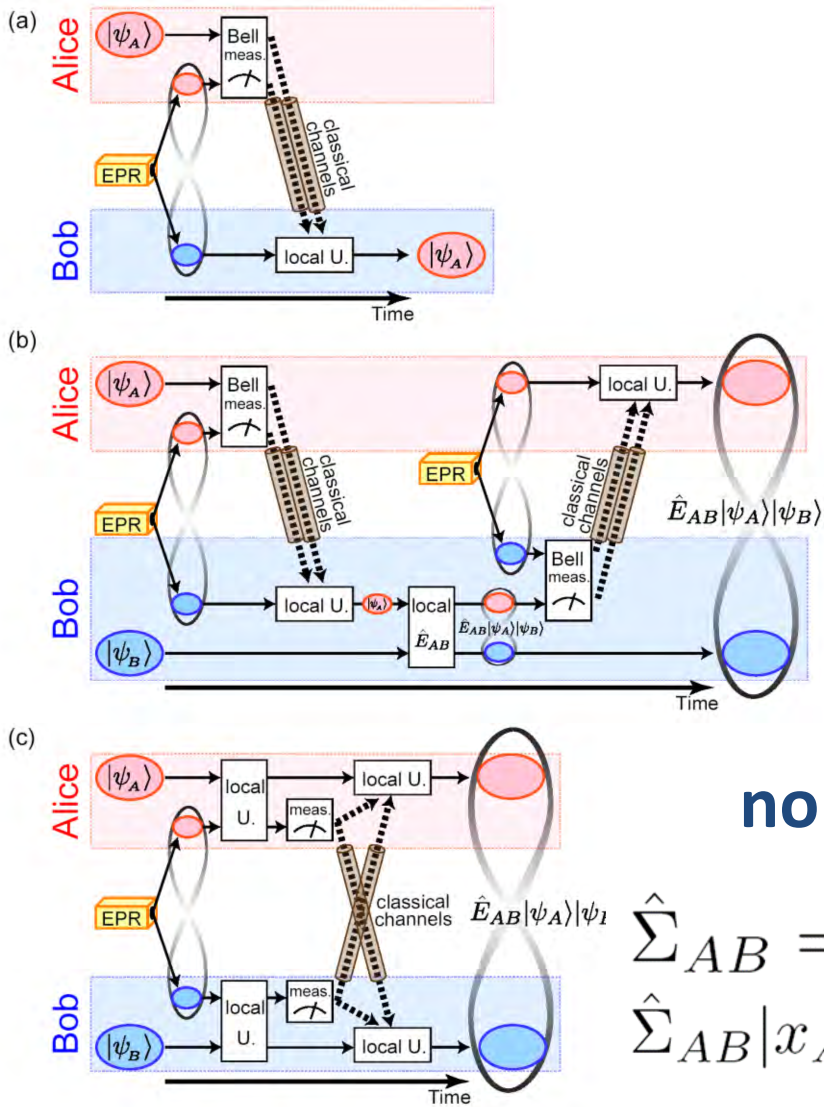
- **squeezer, amplifier, QND interaction**

NONLOCAL QND OPERATION



teleportation

double teleportation

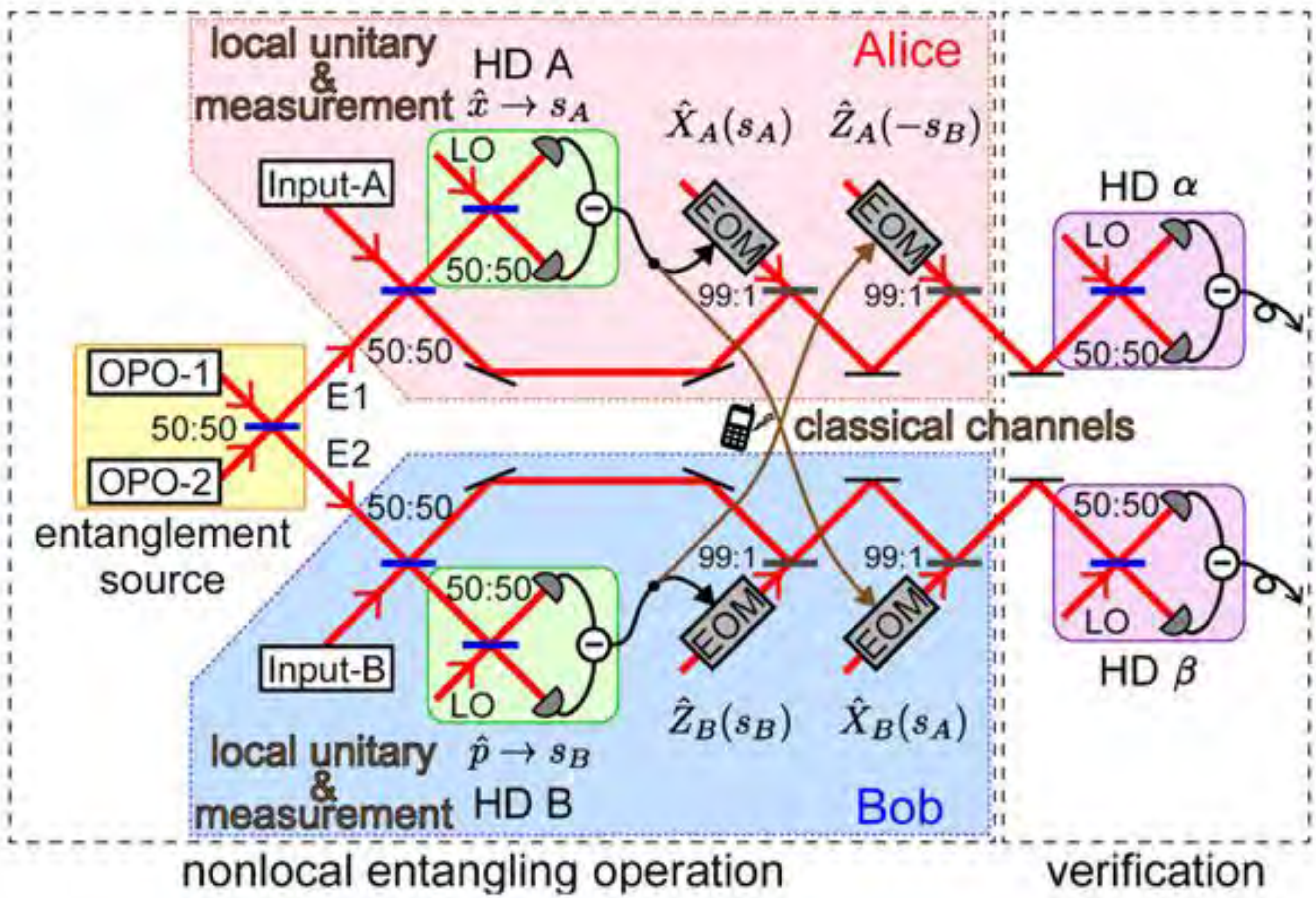
nonlocal parallel operation

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

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

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).

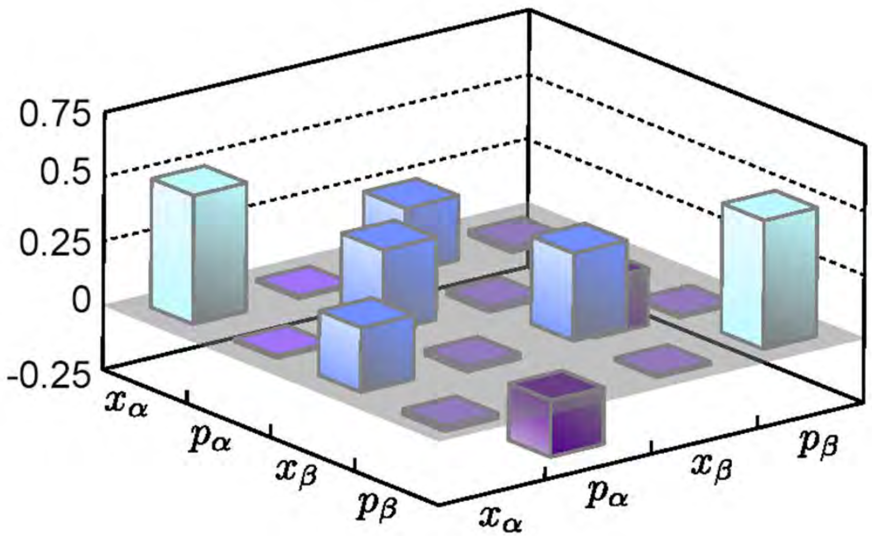
NONLOCAL QND OPERATION

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

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

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

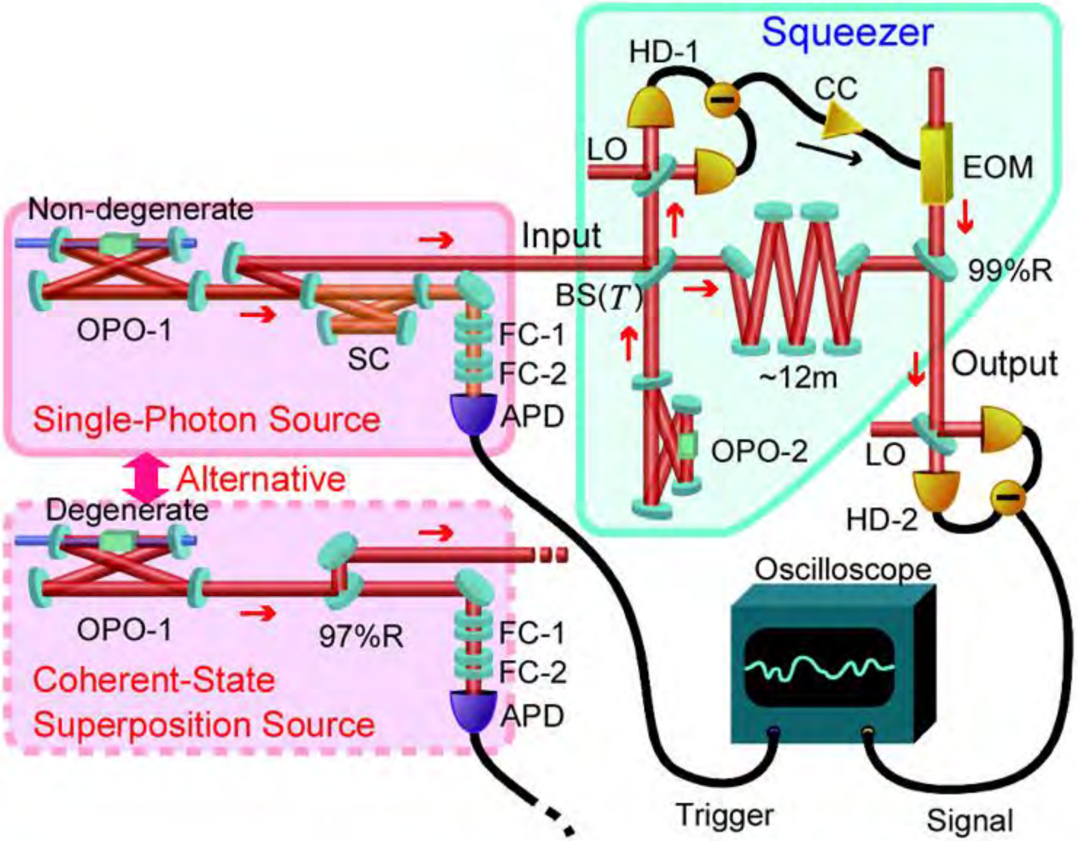
$$\hat{\boldsymbol{\delta}} = (0, \mathrm{e}^{-r}\hat{p}_2^{(0)}, \mathrm{e}^{-r}\hat{x}_1^{(0)}, 0)^T$$



QND entanglement

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

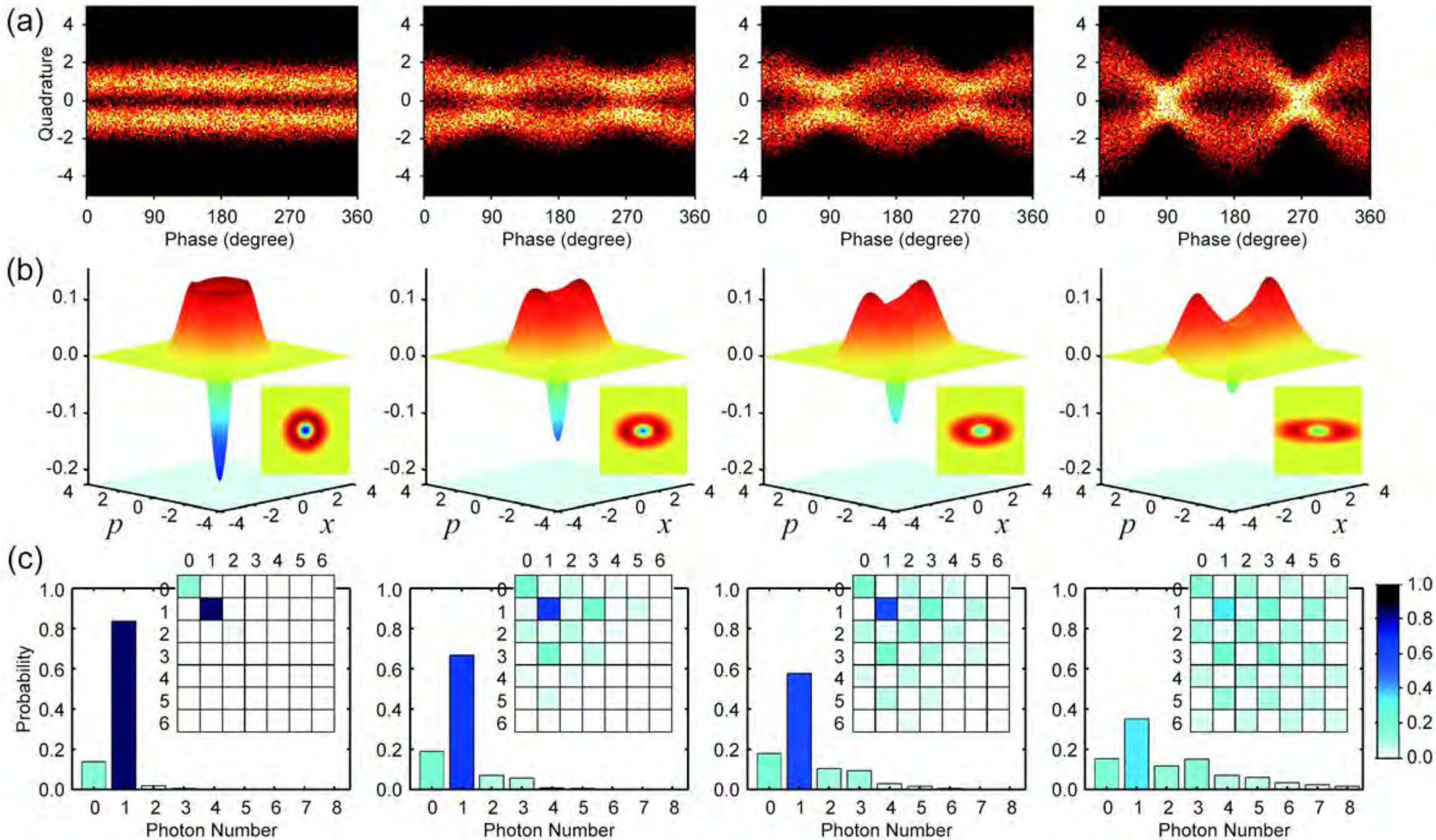
SQUEEZING OF SINGLE PHOTON



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

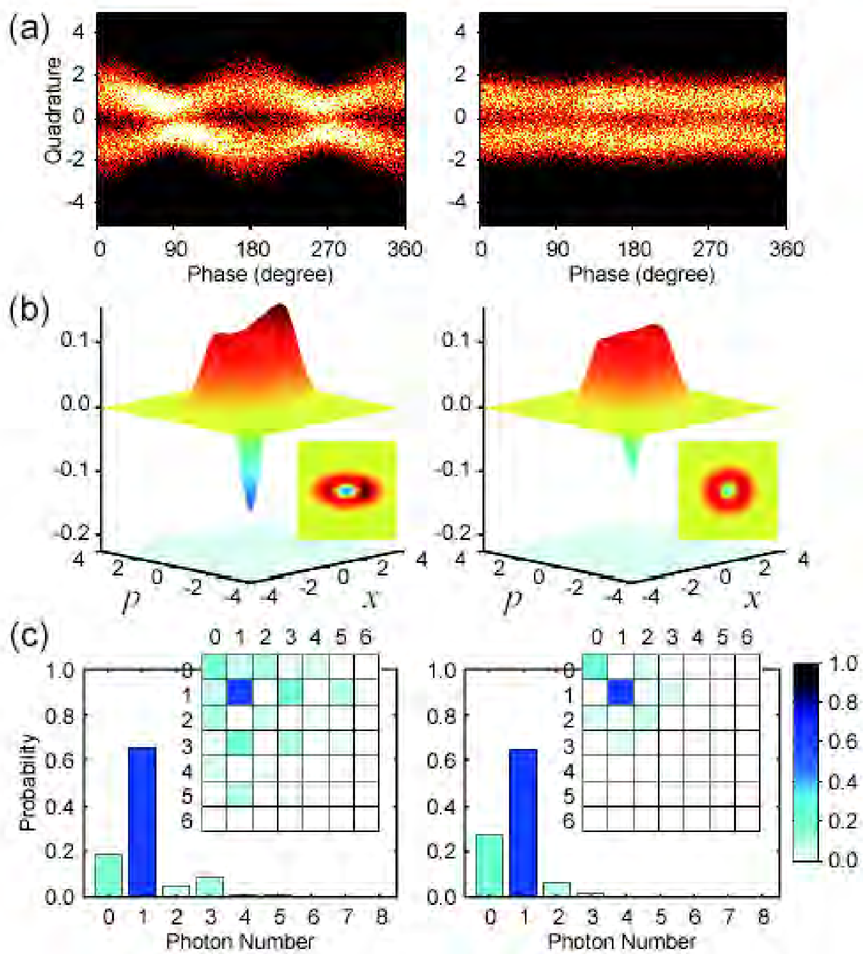
Yoshichika Miwa, Jun-ichi Yoshikawa, Noriaki Iwata, Mamoru Endo, Petr Marek, Radim Filip, Peter van Loock, and Akira Furusawa, Phys. Rev. Lett. 113, 013601 (2014).

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).

OPTIMAL STATE PREPARATION

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

OPTIMAL STATE PREPARATION

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

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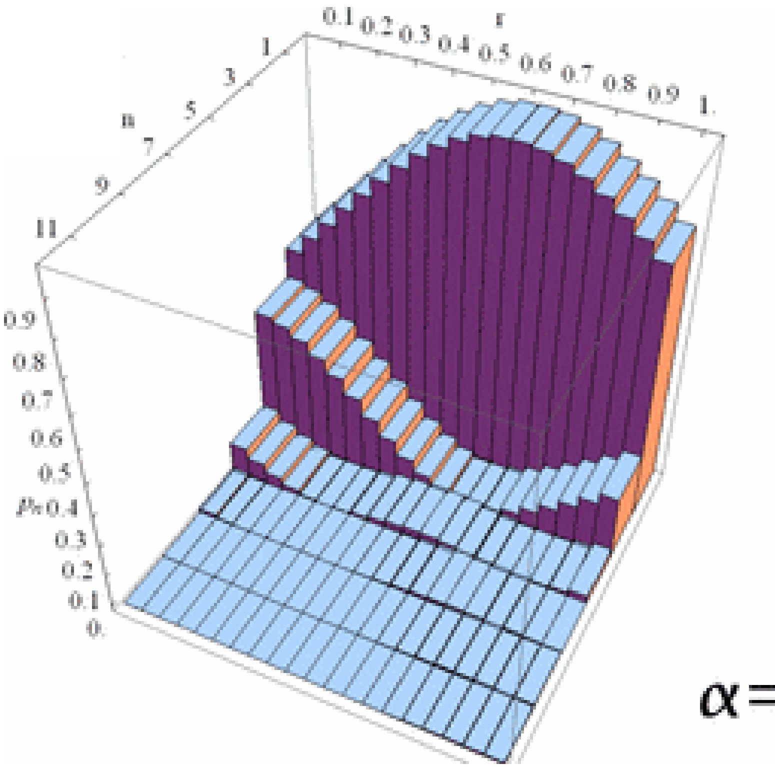
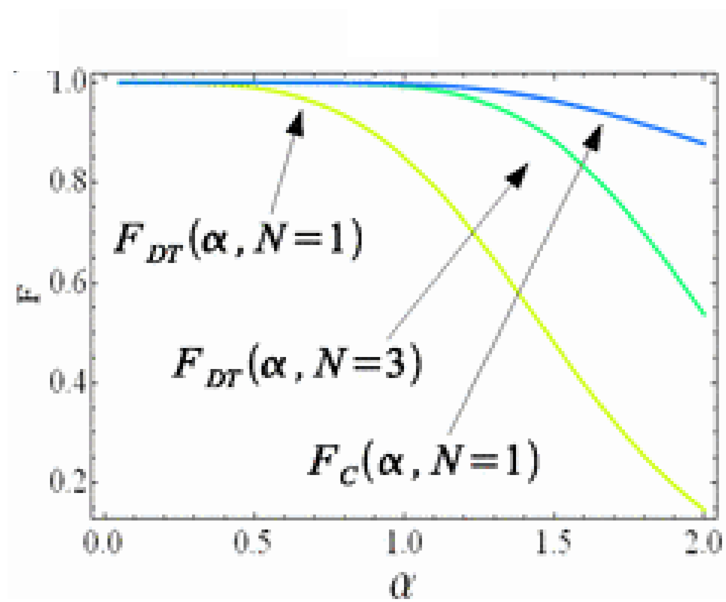




$\alpha = 1.5$

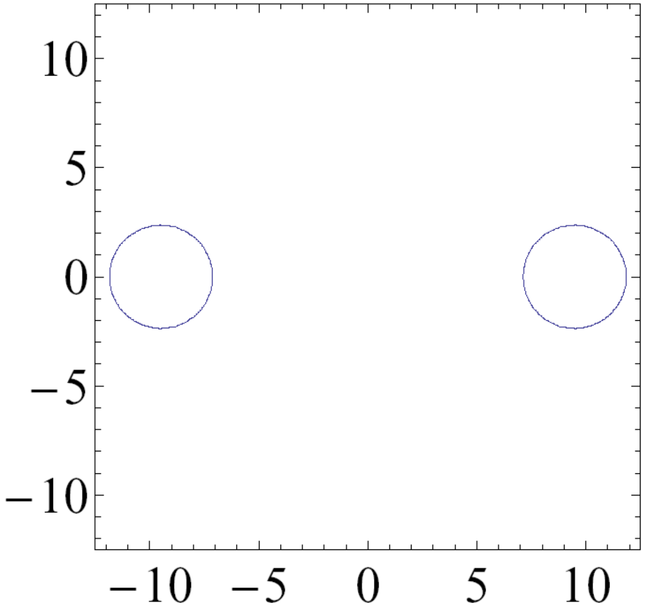
D. Menzies and R. Filip, Phys. Rev. A 79, 012313 (2009).

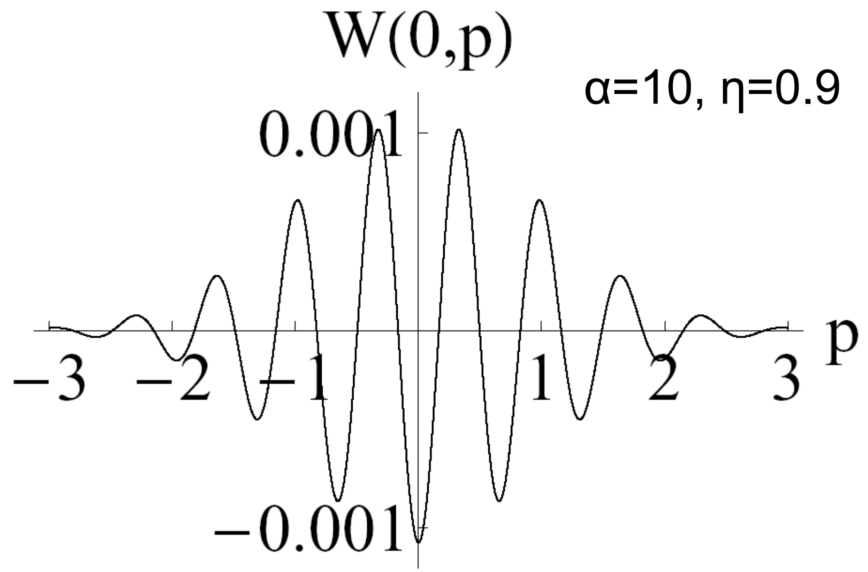
K. Huang, H. Le Jeannic, J. Ruaudel, V.B. Verma, M.D. Shaw, F. Marsili, S.W. Nam, E Wu, H. Zeng, Y.-C. Jeong, R. Filip, O. Morin, J. Laurat, arXiv:1503.08970, accepted in Phys. Rev. Lett.

QUANTUM DECOHERENCE

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

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

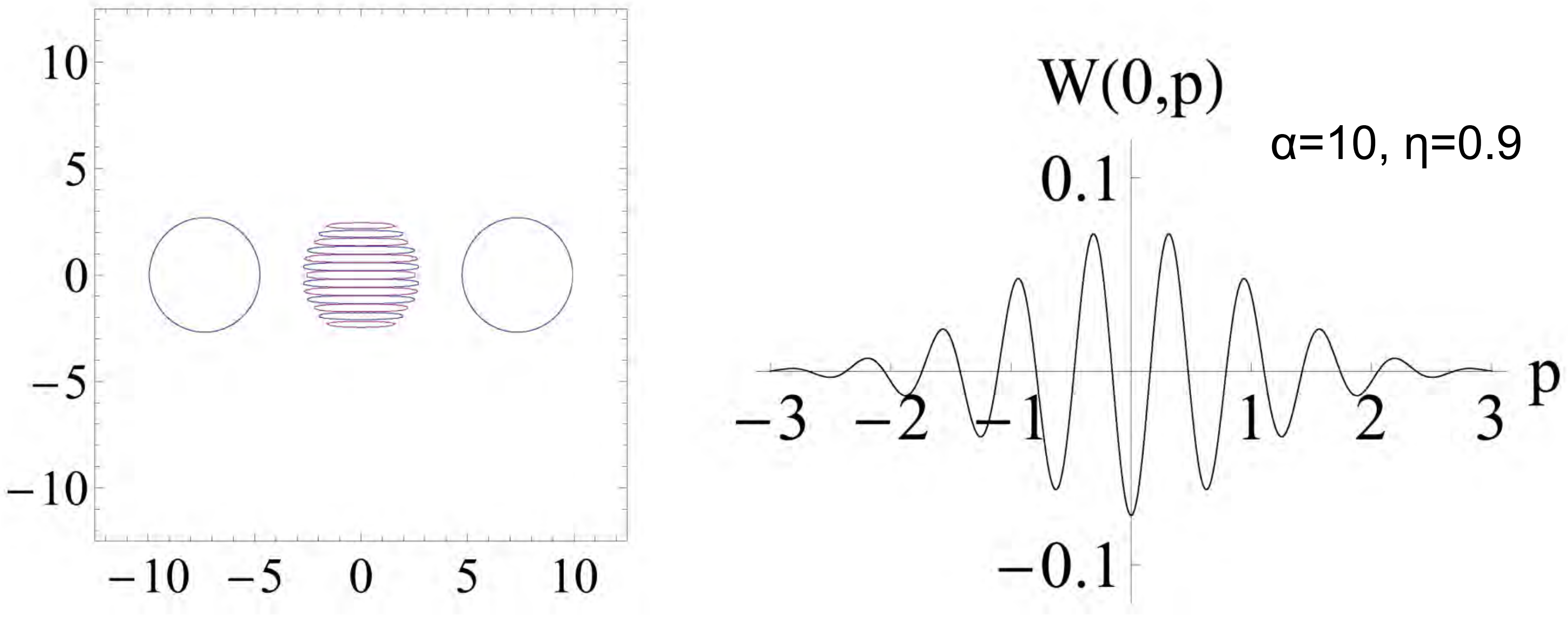




CONTROL OF DECOHERENCE

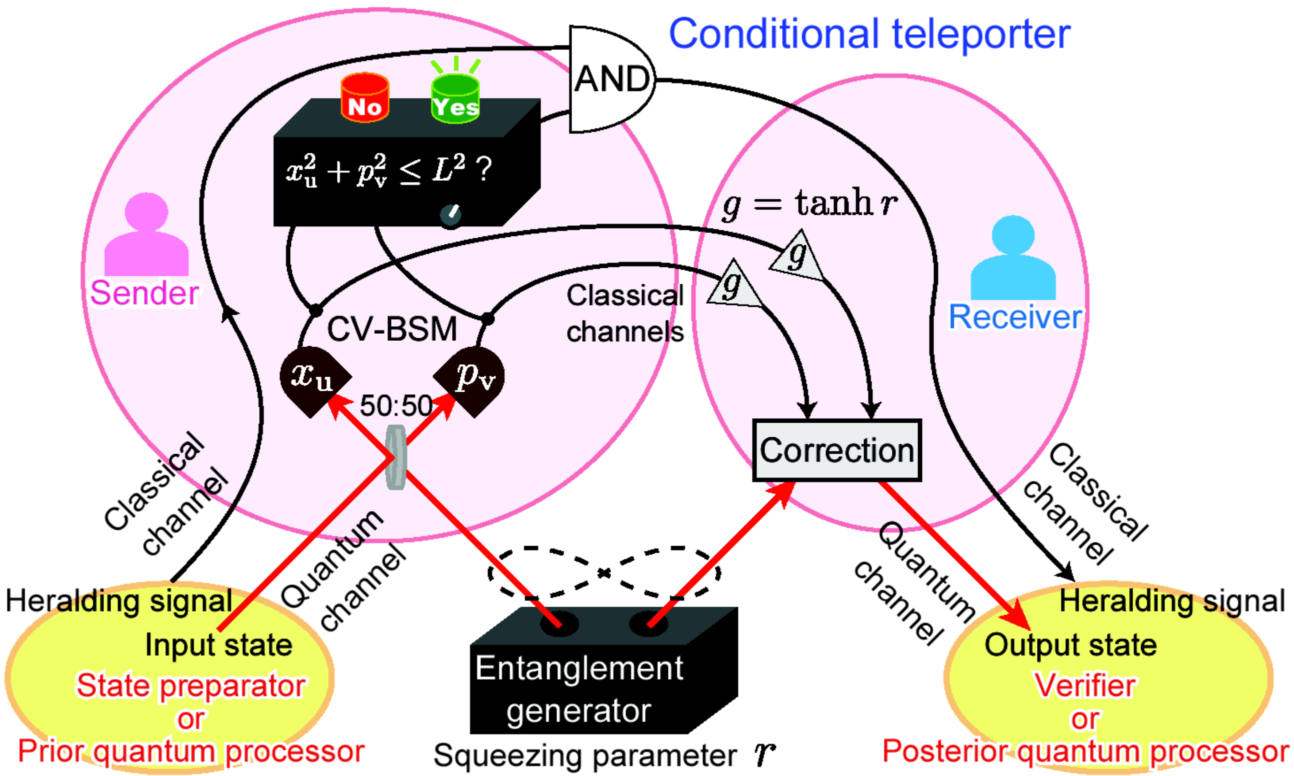
$$(|\alpha\rangle - |-\alpha\rangle)/\sqrt{2(1-\exp(-2|\alpha|^2))}$$

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



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

NOISELESS TELEPORTATION 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

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

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

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

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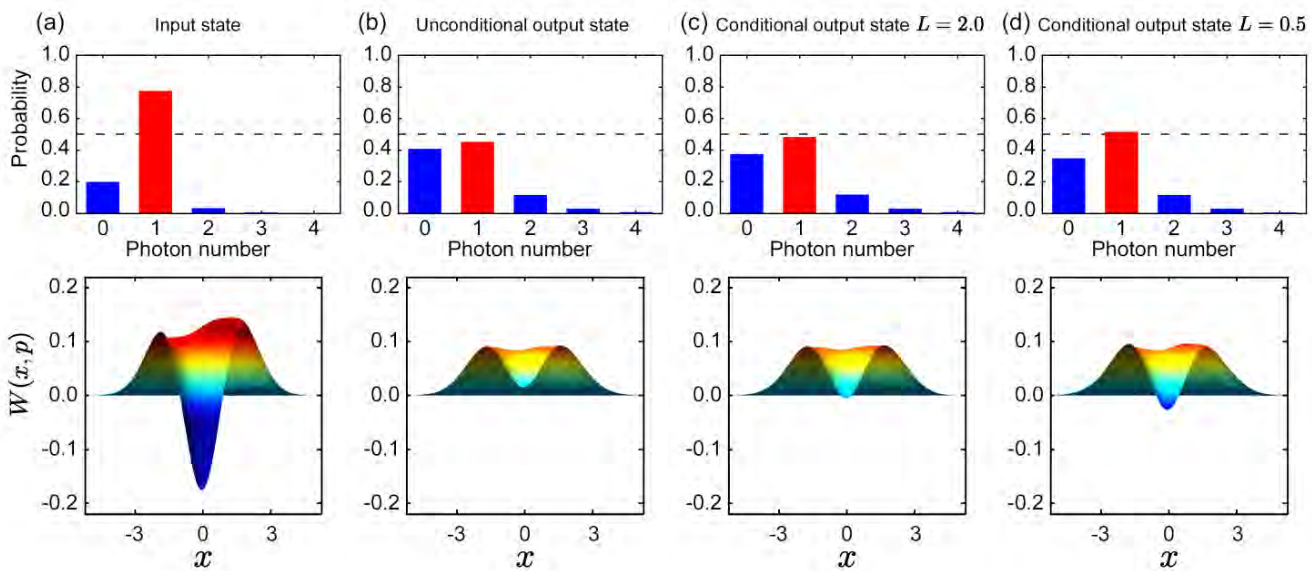

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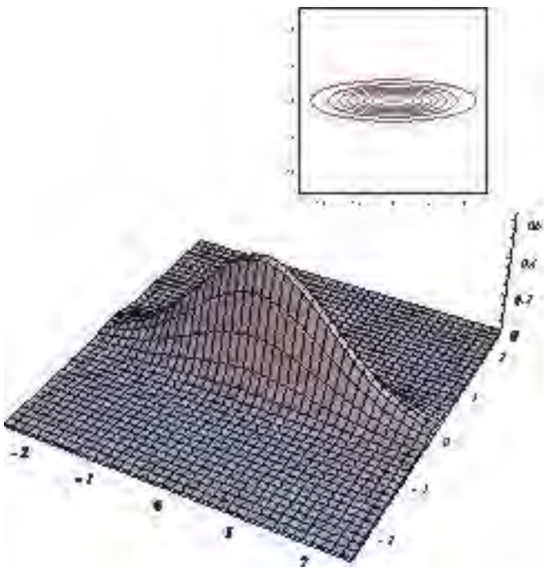

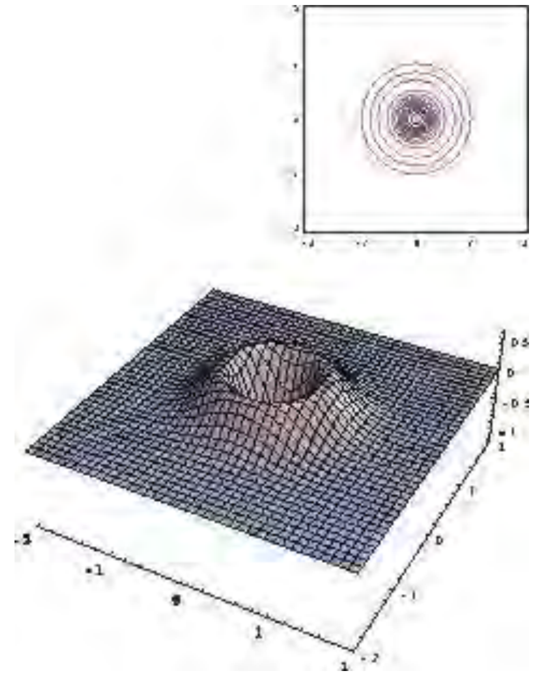

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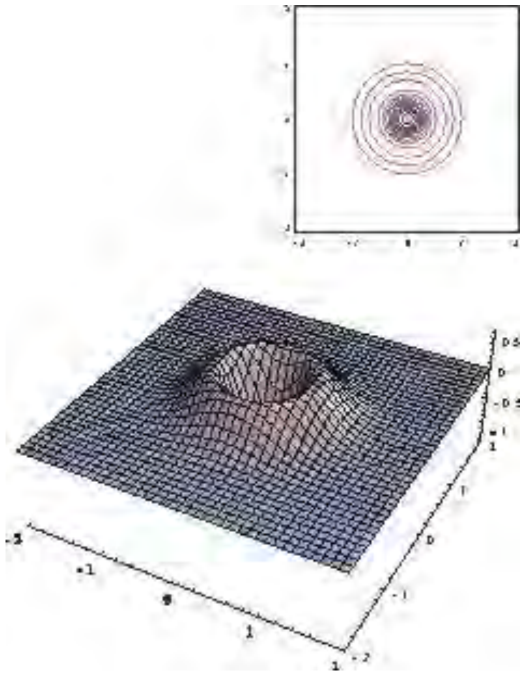

non-Gaussian Fock state:

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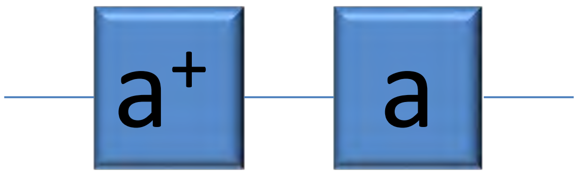
NOISELESS AMPLIFICATION



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

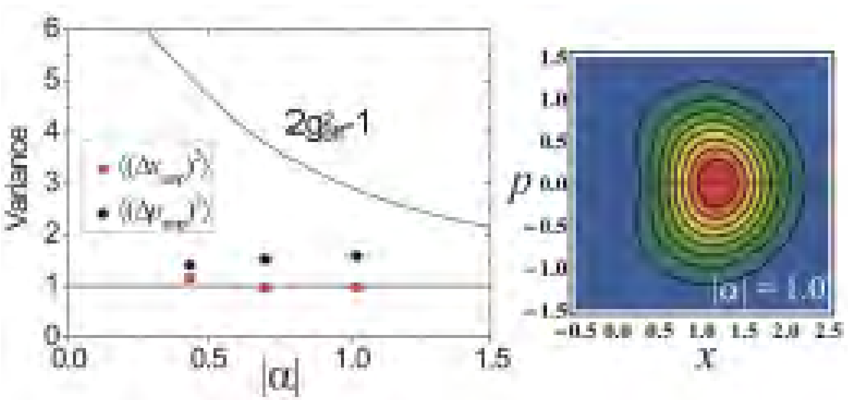
$a^{+}|\alpha\rangle = |1\rangle + \mathbf{2^{1/2}}\,\alpha|2\rangle + \ldots$

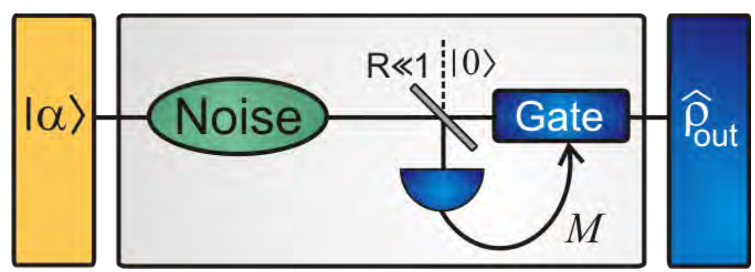
$aa^{+}|\alpha\rangle = |0\rangle + \mathbf{2}\alpha\,|1\rangle + \ldots$

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

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)

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





NONLINEAR POTENTIAL

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

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

ANY NONLINEARITY BY X-GATES

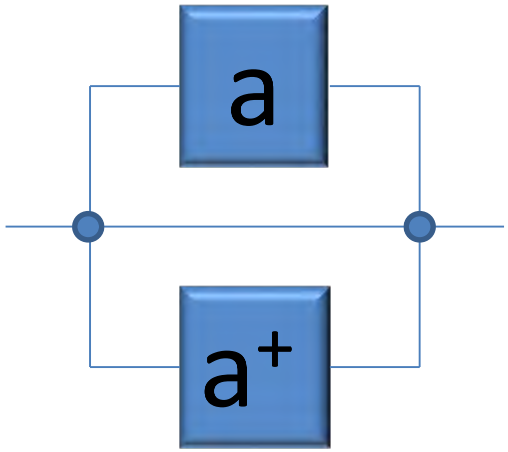
$$U(\hat{X},\tau) = \sum_{k=0}^{\infty} \frac{U^{(k)}(\bar{X})}{k!}(\hat{X} - \bar{X})^k$$

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

X-gate

K. Park, P. Marek, and R. Filip, Phys. Rev. A 90, 013804 (2014).

ANY NONLINEARITY BY X-GATES



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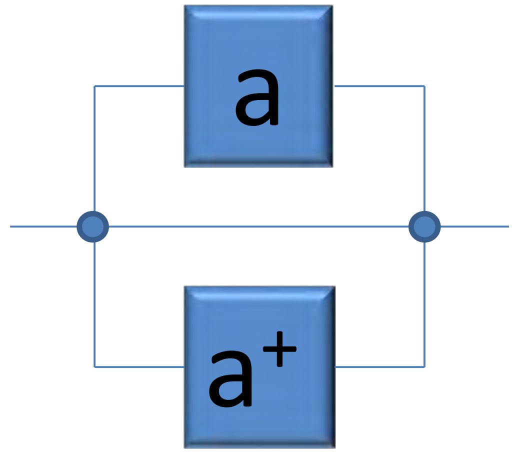
ANY NONLINEARITY BY X-GATES



X-gate

Cubic nonlinearity as a sequence of X gates:

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

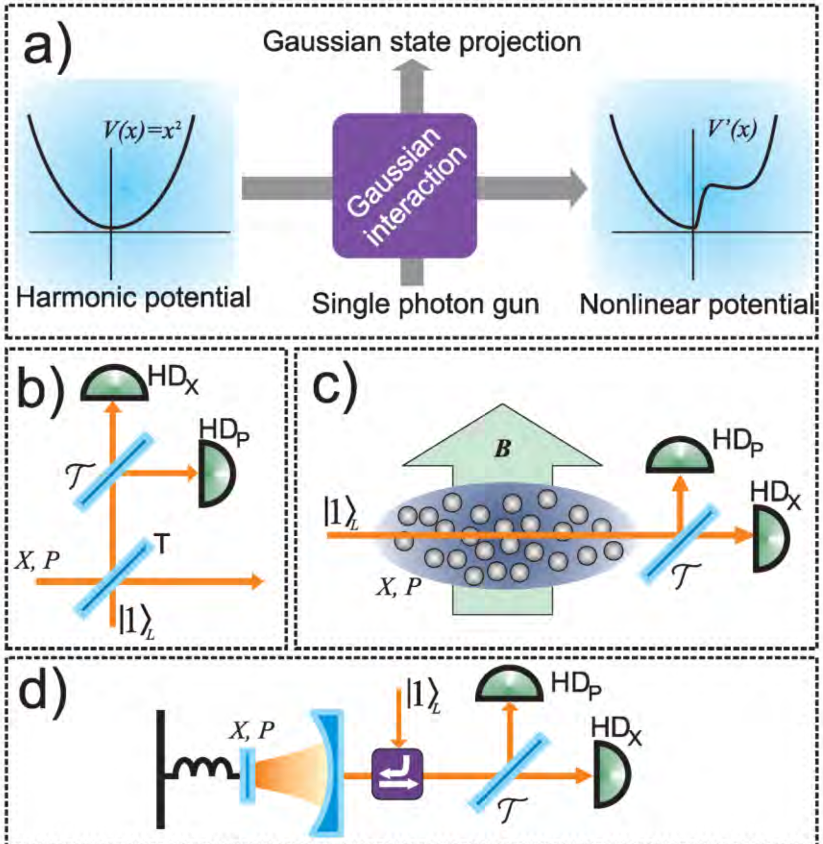
$$(1-(\tfrac{\chi}{-1+i})^{1/3}\hat{X})(1+(\tfrac{\chi}{1-i})^{1/3}\hat{X})$$

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

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

K. Park, P. Marek, and R. Filip, Phys. Rev. A 90, 013804 (2014).

CONDITIONAL X-GATES



a) conditional emulation of quantum oscillator (light mode) in any nonlinear potential based on multiple sequential applications of elementary X gate.
X gates exploit single photon gun to achieve highly non-classical affects from the nonlinear potential.

b) linear optical implementation

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

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

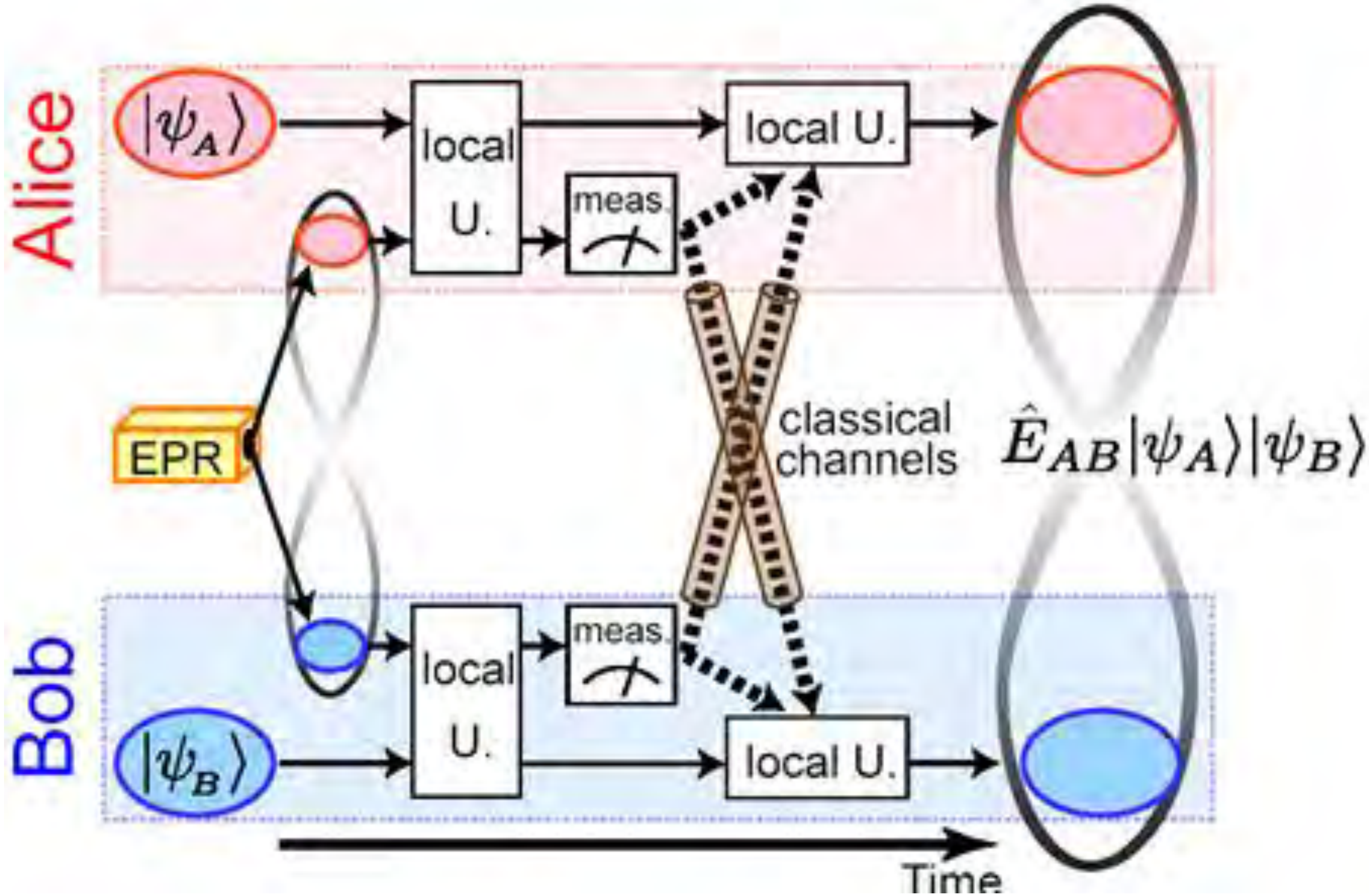
c) implementation with atomic ensemble
d) opto-mechanical implementation

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

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

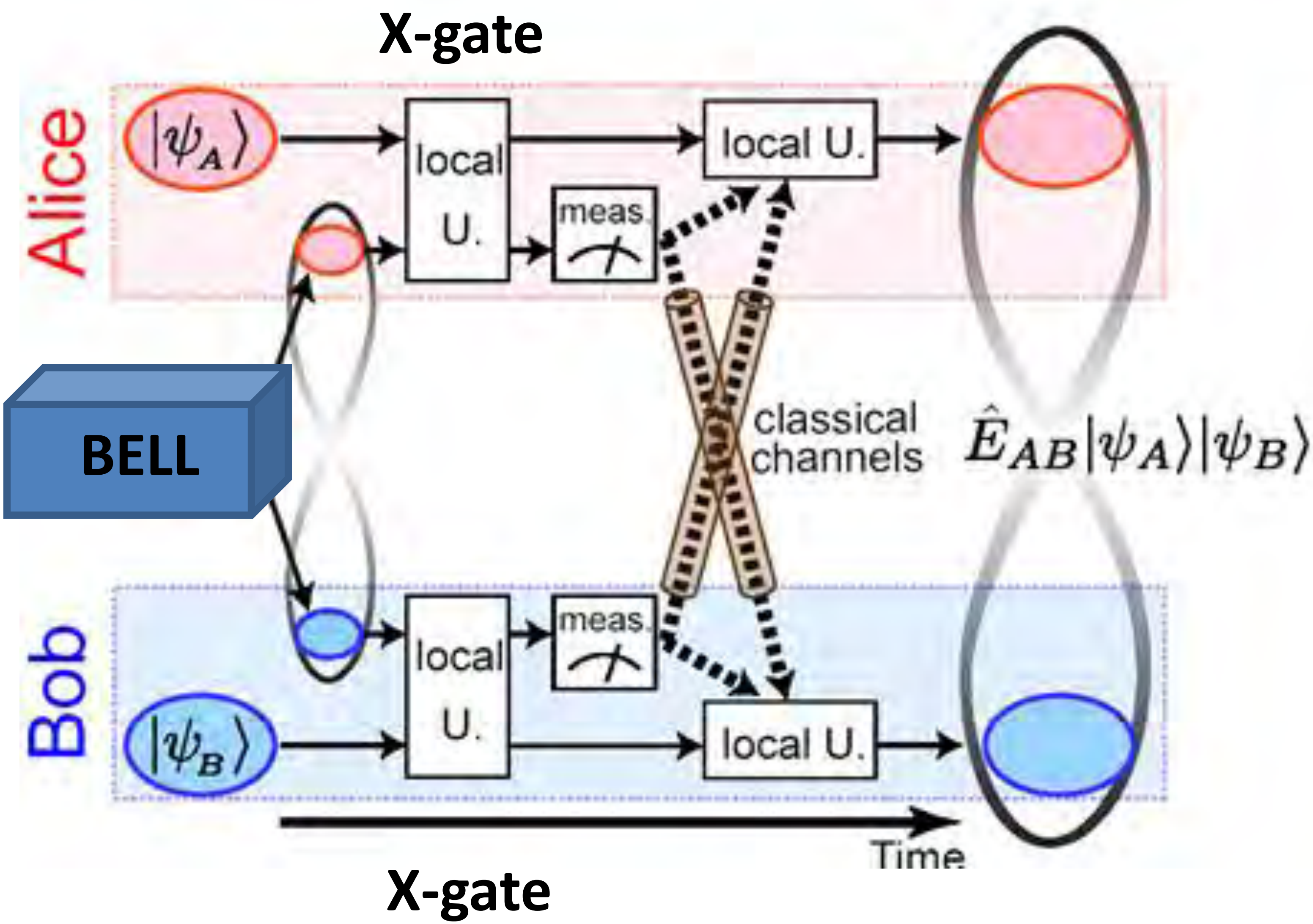
K. Park, P. Marek, and R. Filip, Phys. Rev. A 90, 013804 (2014).

NONLOCAL ENTANGLING X-GATES



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

NONLOCAL ENTANGLING X-GATES



K. Park, P. Marek, and R. Filip, Phys. Rev. A 91, 033814 (2015).

NONLOCAL ENTANGLING X-GATES

$$\hat{O}_p[\alpha] = e^{i\sqrt{2}\alpha\hat{X}_1} - e^{i\sqrt{2}\alpha\hat{X}_2}$$

$$\hat{O}_p[\alpha] \approx e^{i\frac{\sqrt{2}\alpha}{2}(\hat{X}_1+\hat{X}_2)}(\hat{X}_1 - \hat{X}_2) \equiv \hat{O}_p^{(1)}[\alpha]$$

$$\hat{O}_p^{(1)}[\alpha]|\beta\rangle_1|\beta'\rangle_2 = e^{i\frac{\alpha}{\sqrt{2}}(\hat{X}_1+\hat{X}_2)}D_1[\beta]D_2[\beta']$$

$$\times(\sqrt{2}(\beta - \beta') + \hat{X}_1 - \hat{X}_2)|00\rangle_{12}$$

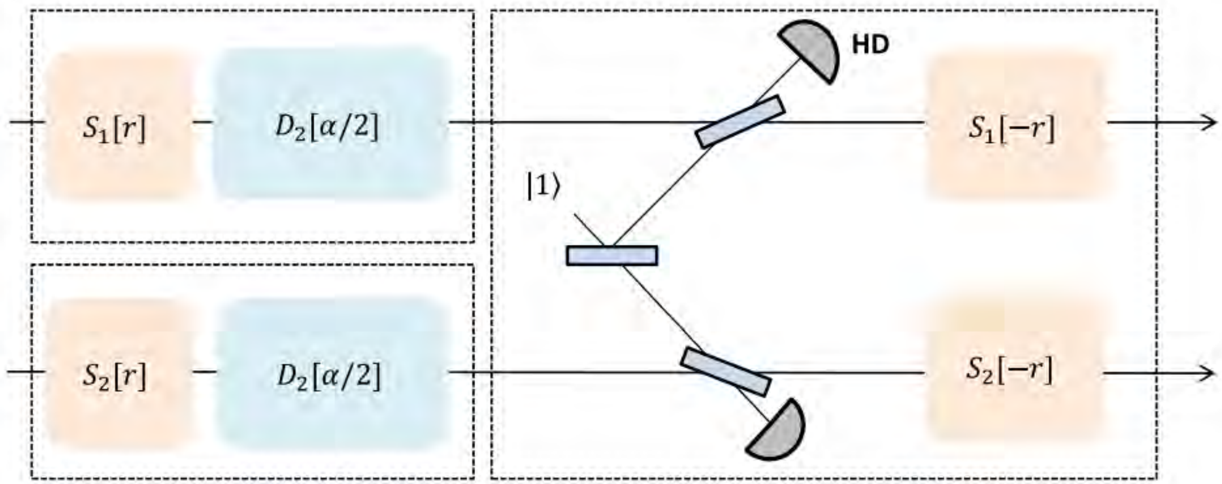
$$\sqrt{2}(\beta - \beta')|00\rangle_{12} + \frac{1}{\sqrt{2}}(|10\rangle_{12} - |01\rangle_{12})$$

K. Park, P. Marek, and R. Filip, Phys. Rev. A 91, 033814 (2015).

NONLOCAL ENTANGLING X-GATES

$$\hat{O}_p[\alpha] \approx e^{i\frac{\sqrt{2}\alpha}{2}(\hat{X}_1+\hat{X}_2)}(\hat{X}_1 - \hat{X}_2) \equiv \hat{O}_p^{(1)}[\alpha]$$

the simplest non-Gaussian quantum entangler by nonlocal X gates:

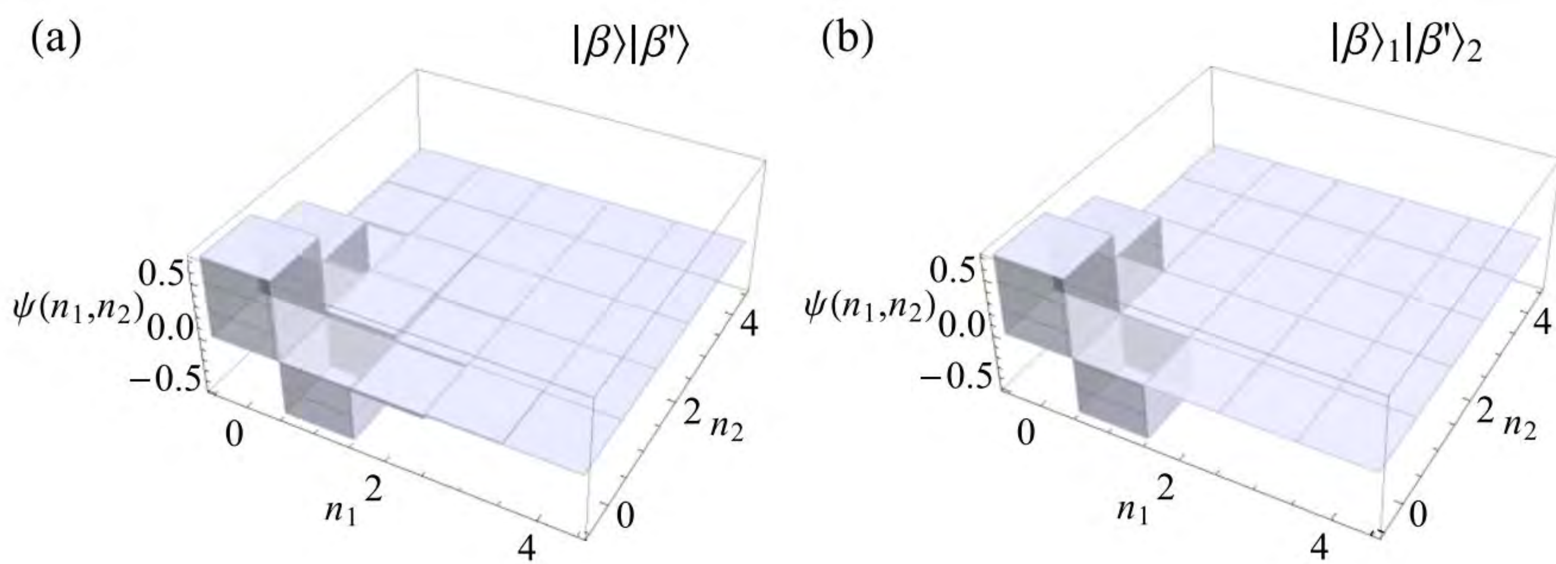


K. Park, P. Marek, and R. Filip, Phys. Rev. A 91, 033814 (2015).

ENTANGLING COHERENT STATES

a) ideal operation: $$N_- = \frac{1 - e^{-\alpha^2}}{1 - e^{-\alpha^2}\cos[2\alpha(\beta - \beta')]}$$

b) approximation: $$N_- \approx \frac{1}{1 + 2(\beta - \beta')^2} + O[\alpha^2]$$



K. Park, P. Marek, and R. Filip, Phys. Rev. A 91, 033814 (2015).

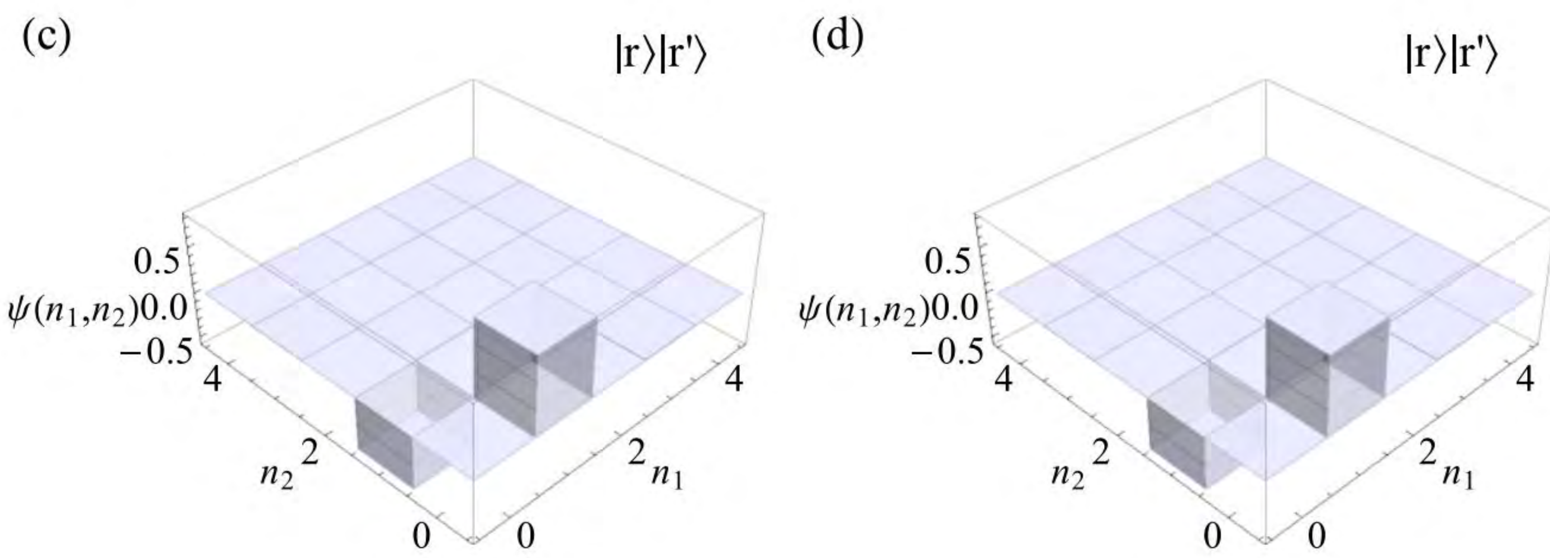
ENTANGLING SQUEEZED STATES

c) ideal operation:

$$N_- = \frac{\sqrt{(1-e^{-\alpha^2 e^{2r}})(1-e^{-\alpha^2 e^{2r'}})}}{1-e^{-\alpha^2(e^{2r}+e^{2r'})/2}}$$

d) approximation:

$$N_-^{(1)} = \frac{2}{e^{r-r'}+e^{r'-r}} = \mathrm{sech}[r-r']$$



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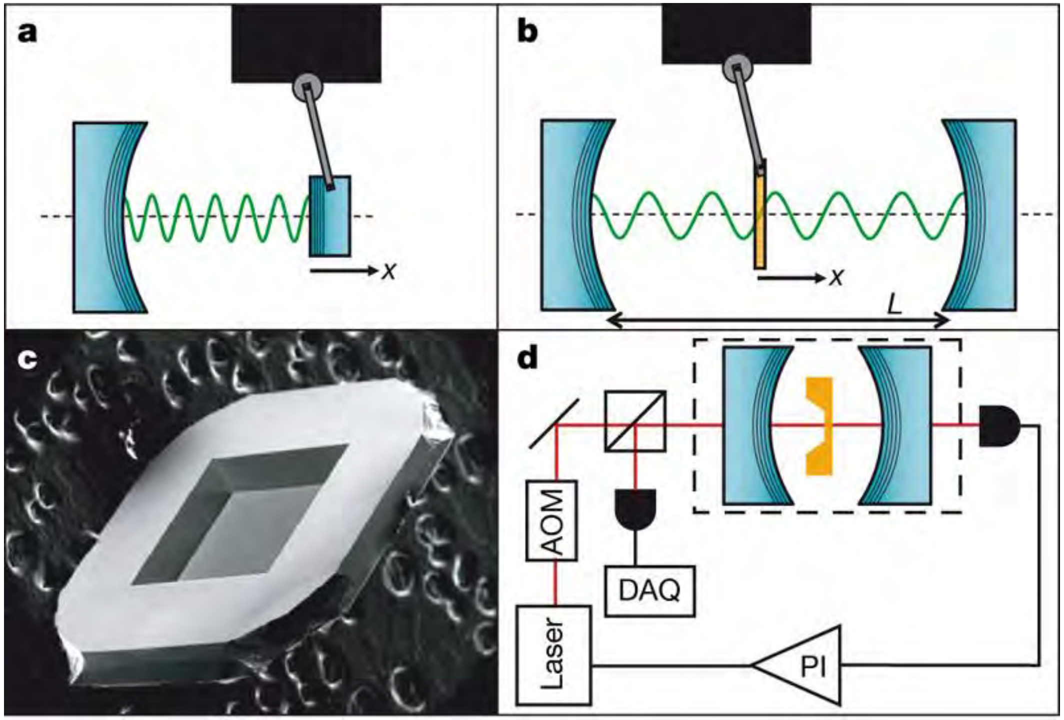
EMULATING THERMAL OPTOMECHANICS

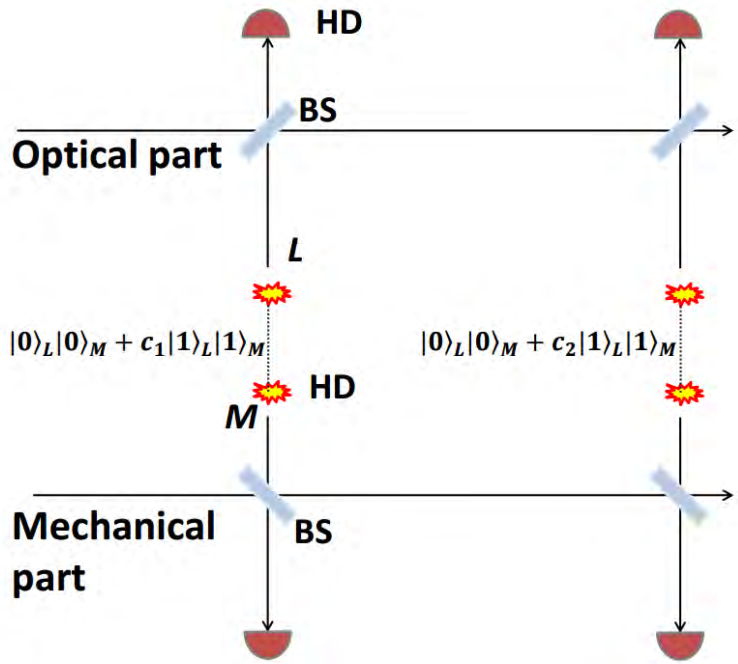


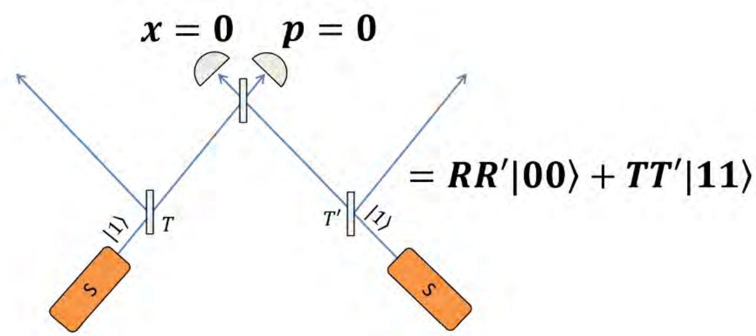
membrane-in-the-middle

$$\hat{H} \propto \hat{n}_L \hat{X}_M^2$$

A.M. Jayich, J.C. Sankey, B.M. Zwickl, C. Yang, J.D. Thompson, S.M. Girvin, A.A. Clerk, F. Marquardt and J.G.E. Harris, New J. Phys. 10, 095008 (2008).

EMULATING THERMAL OPTOMECHANICS





$$H = \chi \hat{X}_L^2 \hat{X}_M^2$$

K. Park, P. Marek and R. Filip, submitted.

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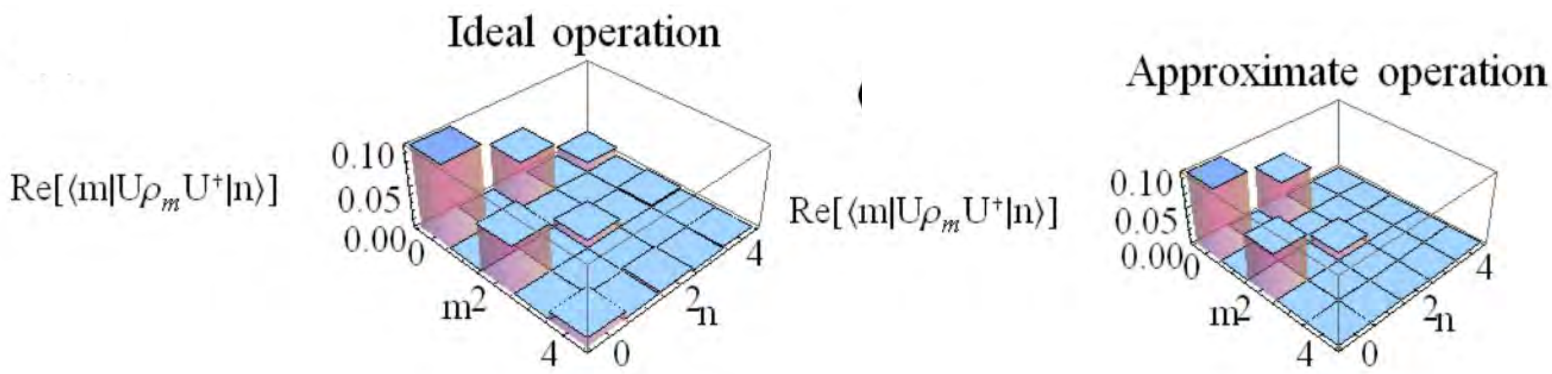
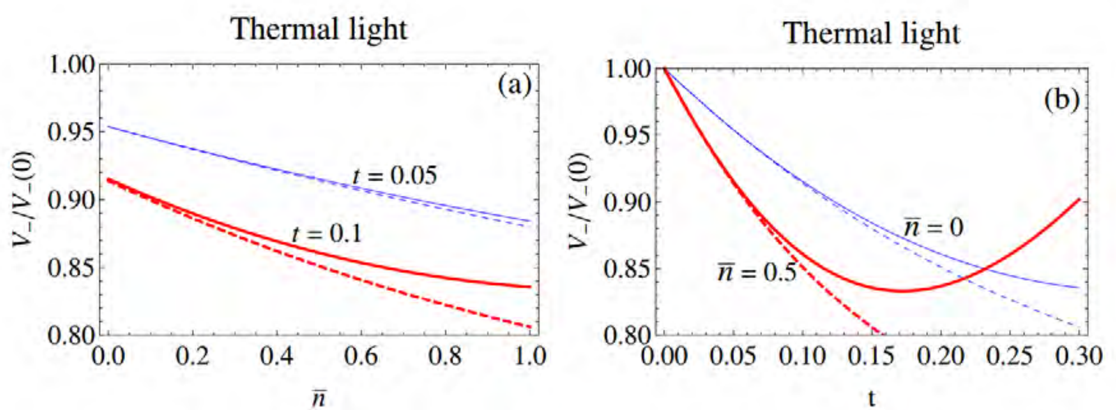


Thermal light generates nonclassical squeezing

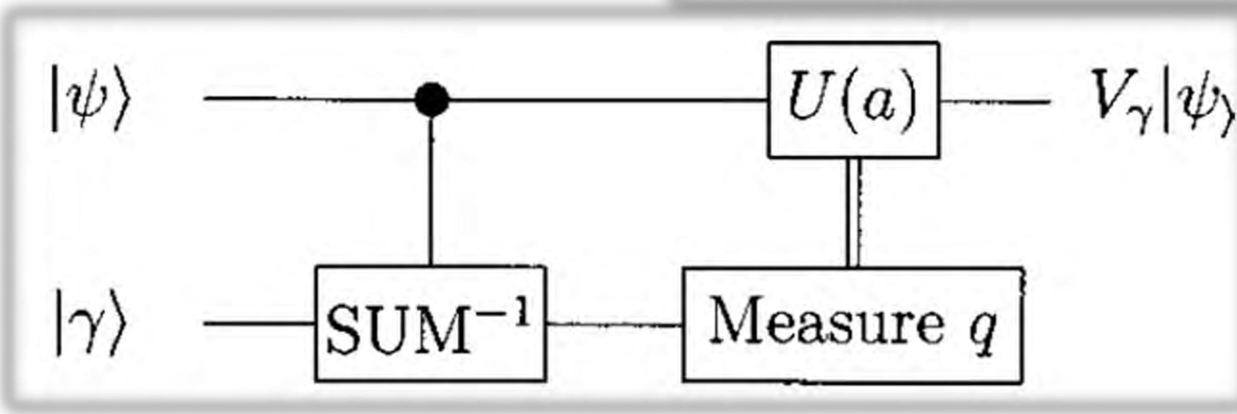


K. Park, P. Marek and R. Filip, submitted.

DETERMINISTIC CUBIC NONLINEARITY

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

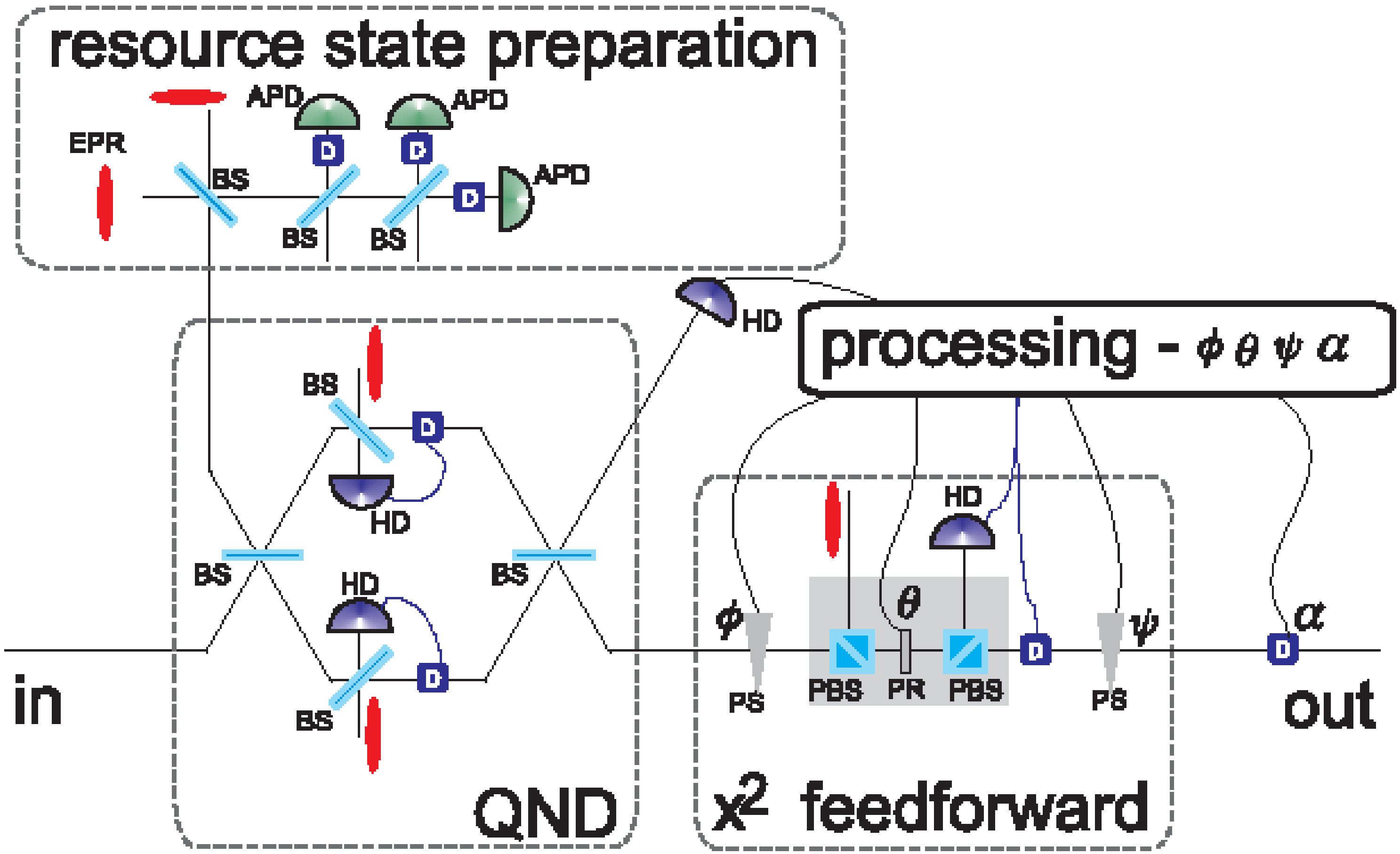
$$|\gamma\rangle = \int e^{i\chi x^3} |x\rangle dx$$



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

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

FEASIBLE CUBIC INTERACTION



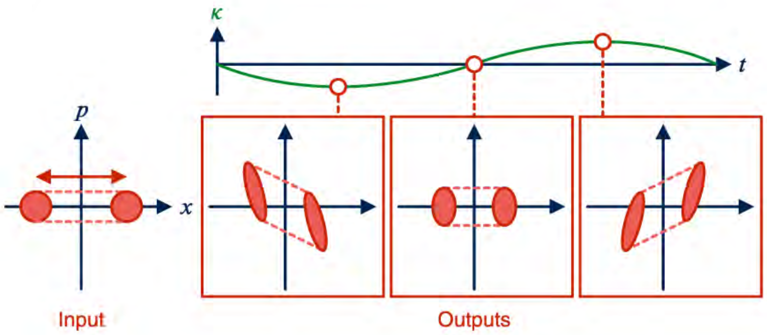
P. Marek, R. Filip, and A. Furusawa, Phys. Rev. A 84, 053802 (2011).

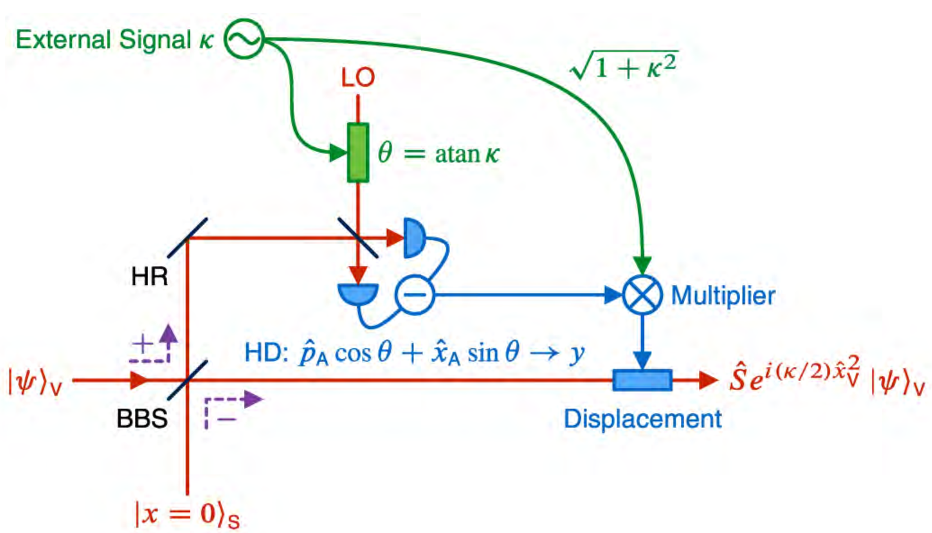
QUADRATIC X² FEEDFORWARD

X→ X, P→ P+κX

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

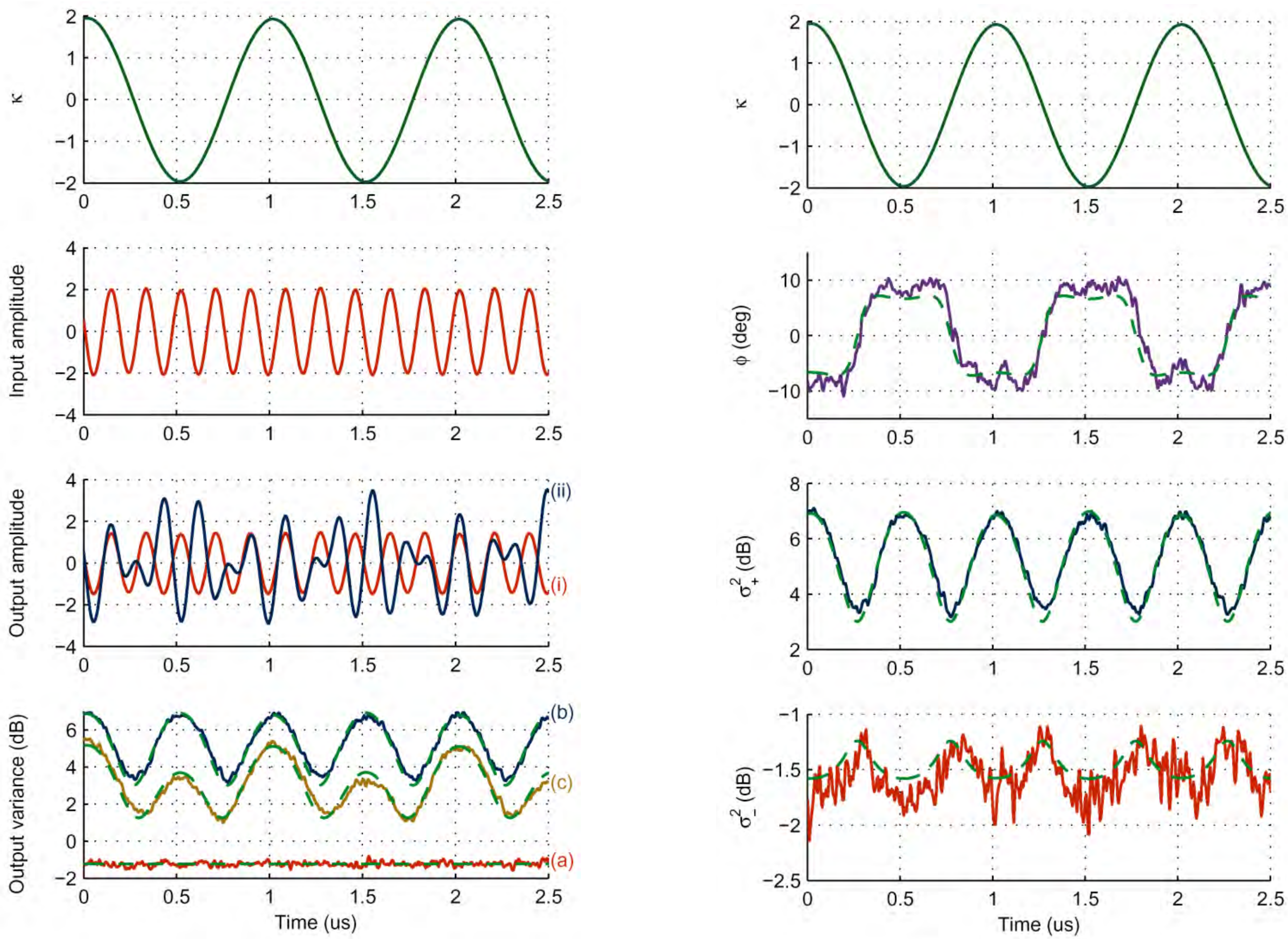
$$\hat{p} = \sqrt{2}\left(\hat{p}_{\mathrm{V}} + \frac{\kappa}{2}\hat{x}_{\mathrm{V}}\right) + \frac{\kappa}{\sqrt{2}}\hat{x}_{\mathrm{S}}^{(0)}$$





K. Miyata, H. Ogawa, P. Marek, R. Filip, H. Yonezawa, J. Yoshikawa, and A. Furusawa, Phys. Rev. A 90, 060302(R) (2014).

QUADRATIC X² FEEDFORWARD



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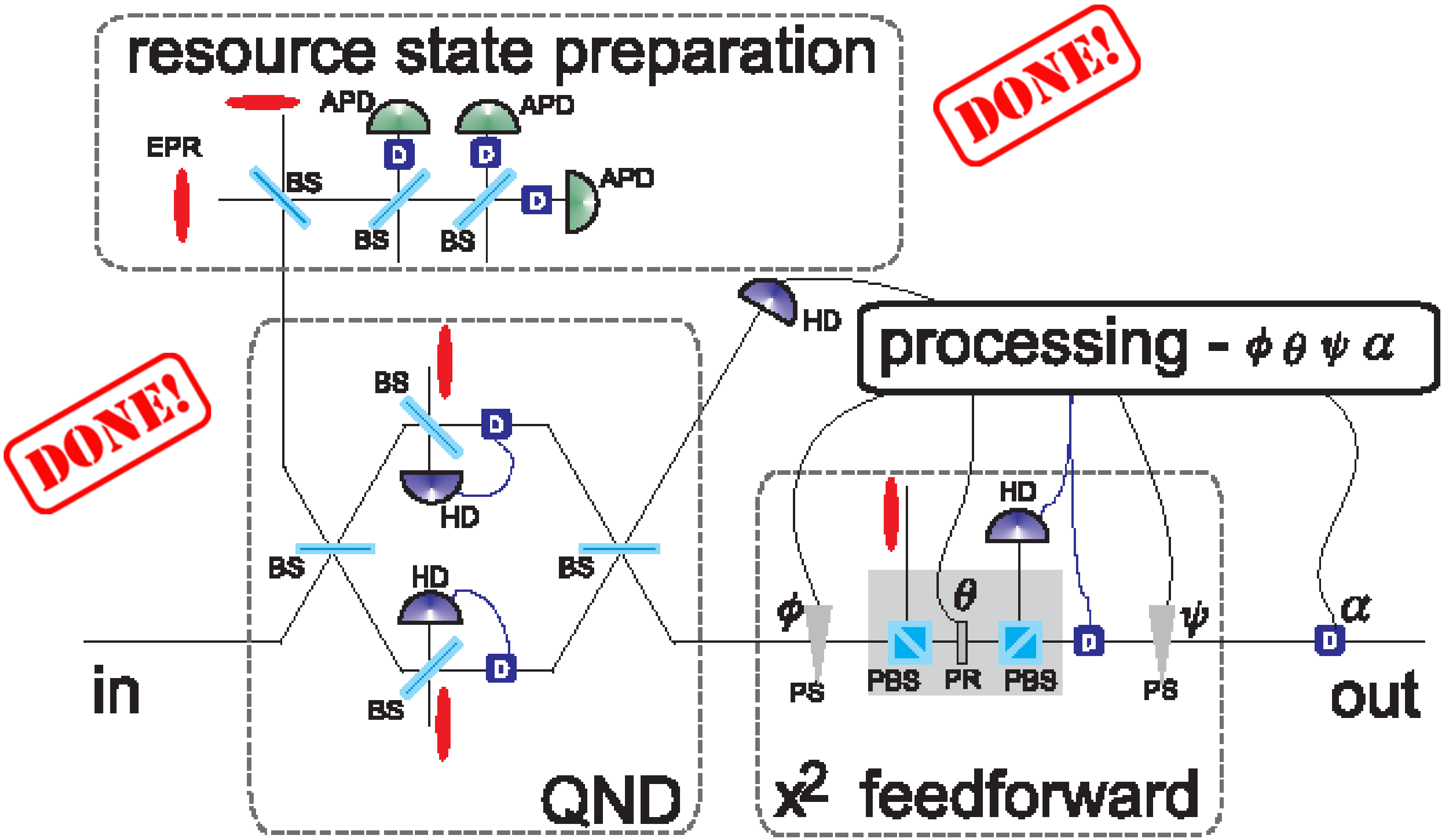

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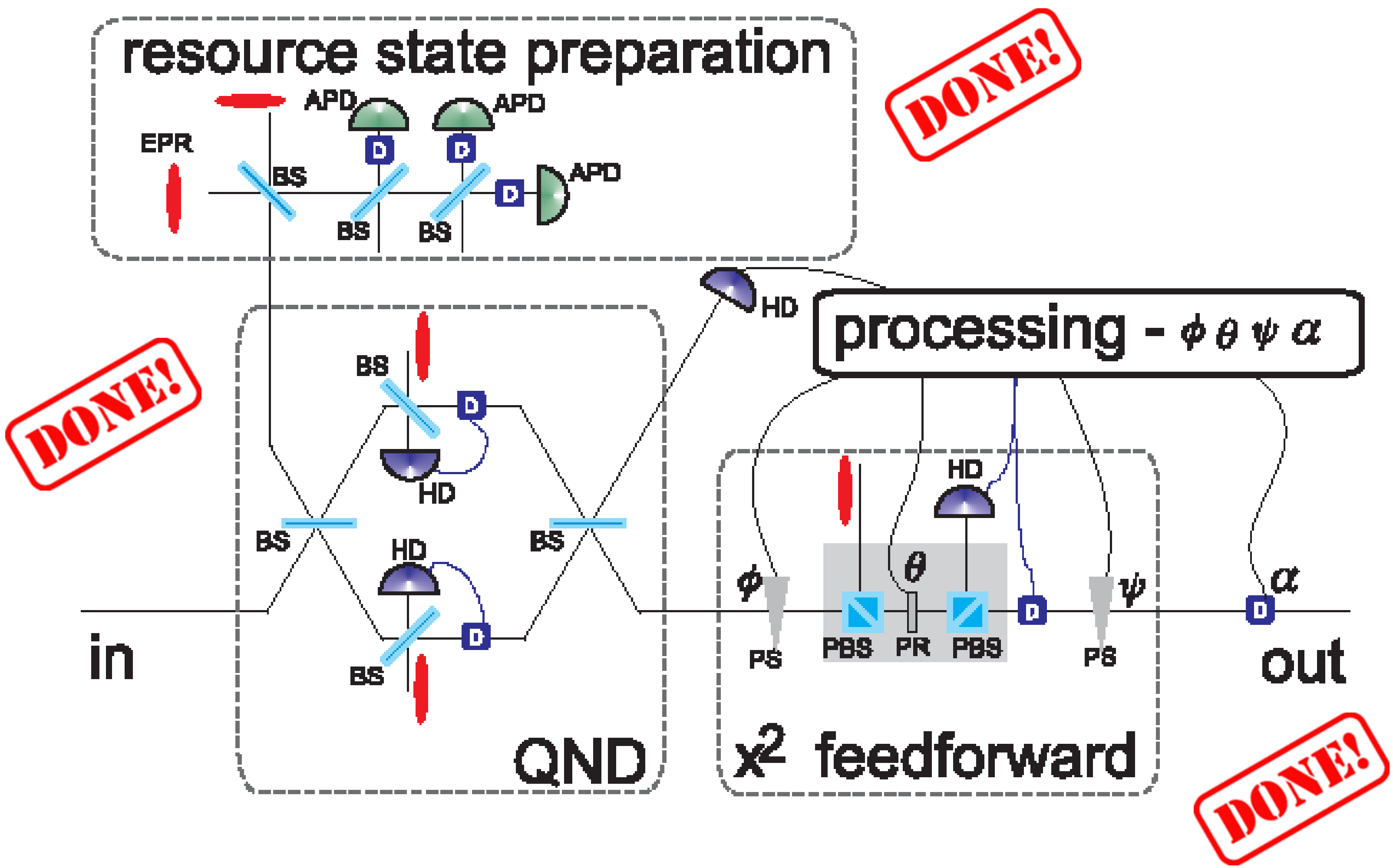

P. Marek, R. Filip, and A. Furusawa, Phys. Rev. A 84, 053802 (2011).

GOALS AND TARGETS ICSSUR 2017

Exploiting the squeezed light and single photons:

- optimized entangled state preparation
- control of quantum decoherence
- conditional simulations of quantum nonlinear effects
- nonlocal quantum operations with different platforms
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