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Manipulation of quantum noise of light

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european social fund in the czech republic

EUROPEAN UNION

MINISTRY OF EDUCATION, YOUTH AND SPORTS

OP Education for Competitiveness

INVESTMENTS IN EDUCATION DEVELOPMENT

- Petr Marek (postdoc):

  noiseless amplification

  nonlinear quantum operations

- Vladyslav Usenko (postdoc):

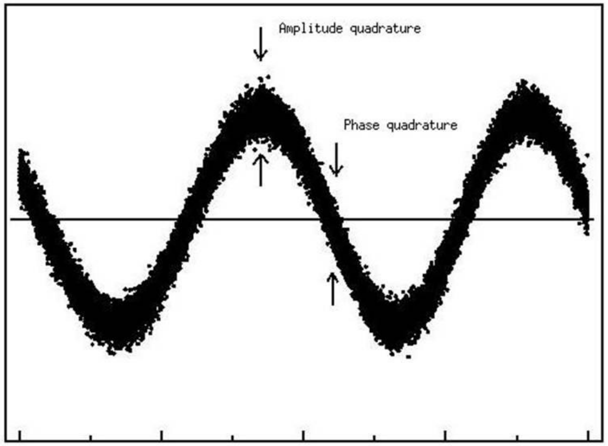
  QKD without/with squeezing

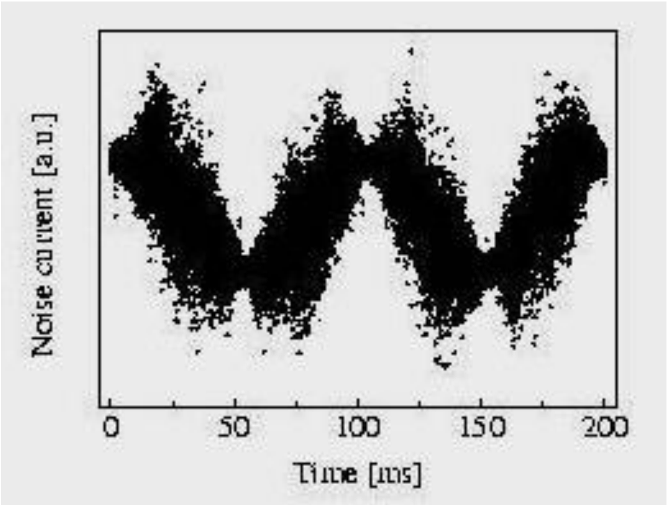
- Miroslav Gavenda (postdoc):

  quantum decoherence and error correction/rejection

Students: Lukáš Lachman, Vojta Kupčík, Petr Zapletal and Petr Klapka

CV QUANTUM NOISE



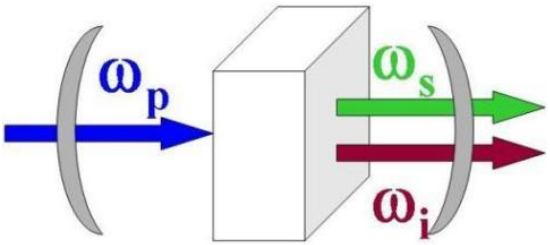


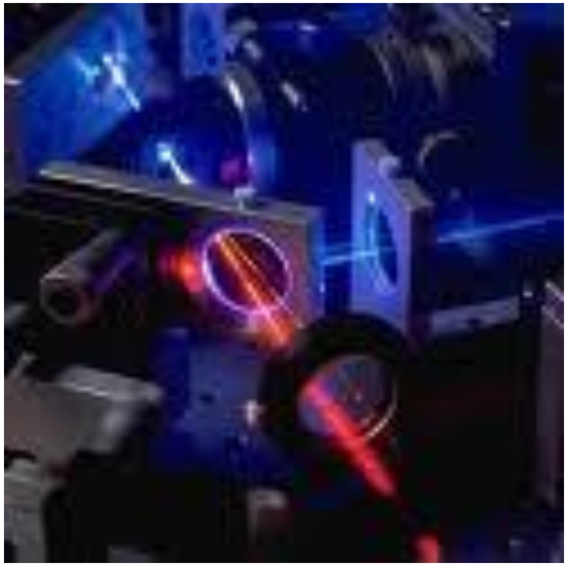
Continuous quantum noise of light can be measured by homodyne detection.

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: >12dB (who next?)

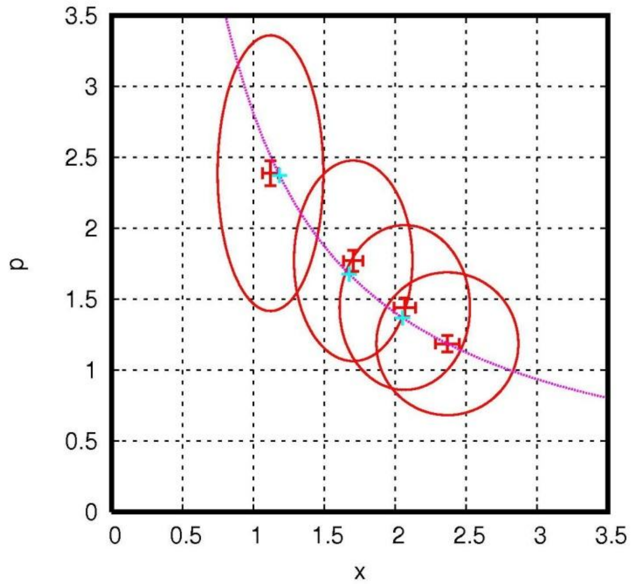
ON-LINE SQUEEZER WITH OFF-LINE SQUEEZING

- Universal Squeezer:

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

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

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



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

Memo:

Off-line squeezing -> On-line squeezer

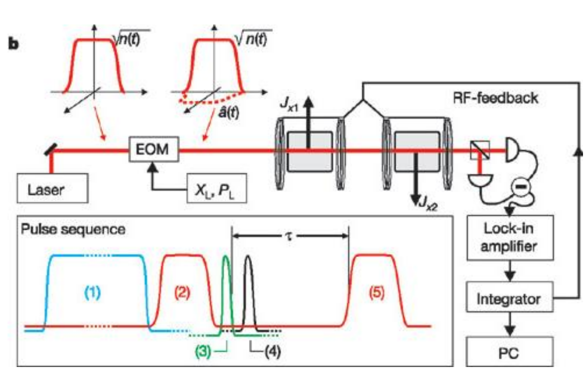
Akira Furusawa and Peter van Loock

WILEY-VCH

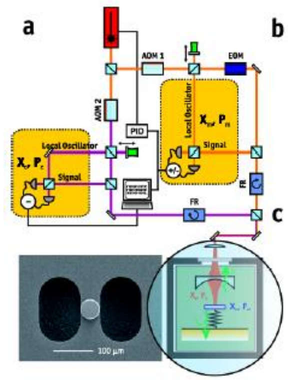
Quantum Teleportation and Entanglement

A Hybrid Approach to
Optical Quantum Information Processing

QND INTERACTION WITH MATTER



Quantum memory

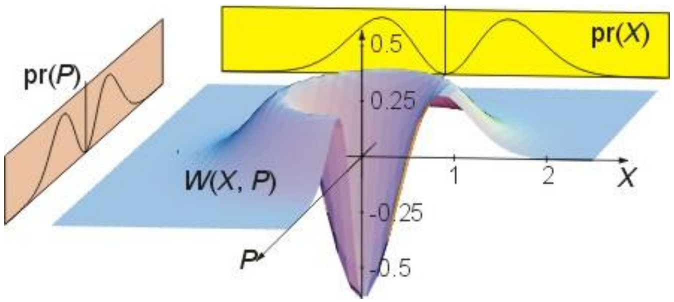


Quantum opto-mechanics

- single-mode pre-squeezing effectively enhances QND interaction with matter.
- upload can be limited only by loss (up to fixed squeezing)

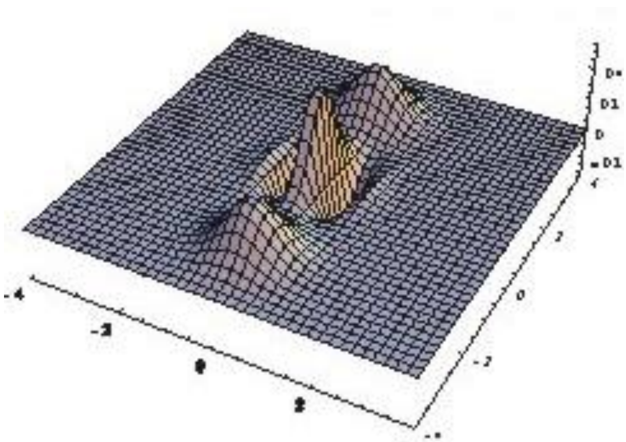
[R. Filip, PRA 08]

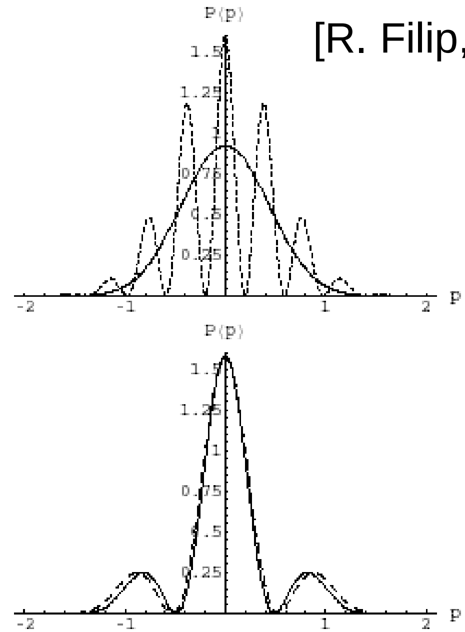
UPLOAD OF |1> OR "*CAT*" STATE



$$\langle x=0|_L \left(1+\frac{\kappa}{4}\tau(a_A+a_A^\dagger)(a_L^\dagger-a_L)\right)|1\rangle_L|0\rangle_A = -\frac{\kappa}{4}|1\rangle_A$$

[R. Filip, PRA 2008]





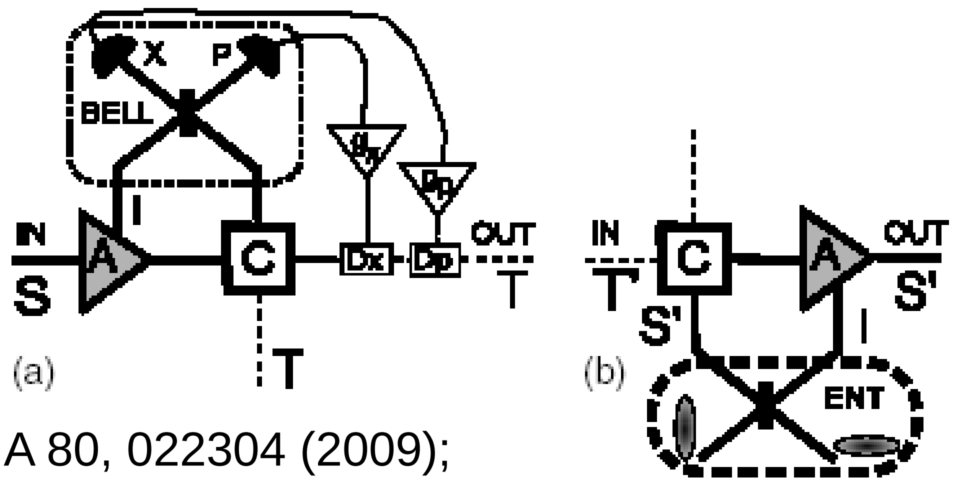
- Post-selection transforms loss to reduction of amplitude, uploaded state remains pure!
- Pre-squeezing helps to increase interference.

UNIVERSAL QUANTUM INTERFACE

[R. Filip, PRA 2009]

- **operations** on source are available, but operations on target are limited to single type of coupling (target is not well controllable)
- target is highly **noisy** (even breaking entanglement)
- **unitary coupling**: fast coupling = weak coupling

BS LIGHT-MATTER INTERACTION

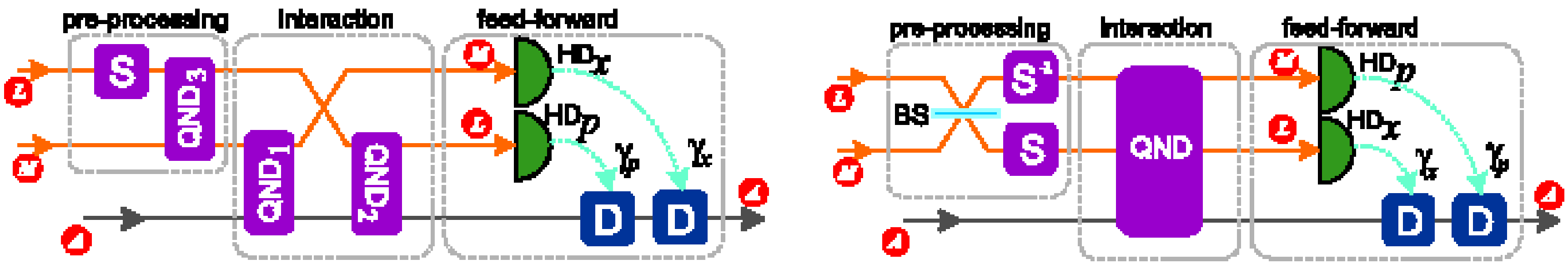


R. Filip, Phys. Rev. A 80, 022304 (2009);

- 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!**

GENERAL INTERFACE

- similar procedure can be found for any Gaussian coupling not mixing X,P together (except QND coupling).
- for QND type of coupling (CV memory & opto-mechanical oscillators)
- for transfer of quantum resource, feed-forward can be substituted by post-selection.

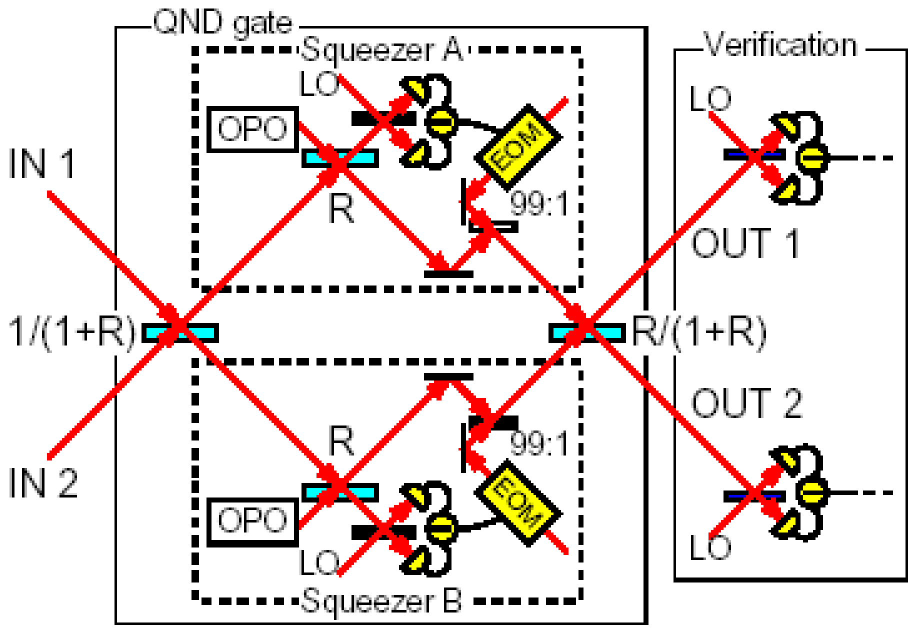


P. Marek and R. Filip, Phys. Rev. A 81, 042325 (2010).

ALL OPTICAL QND INTERACTION

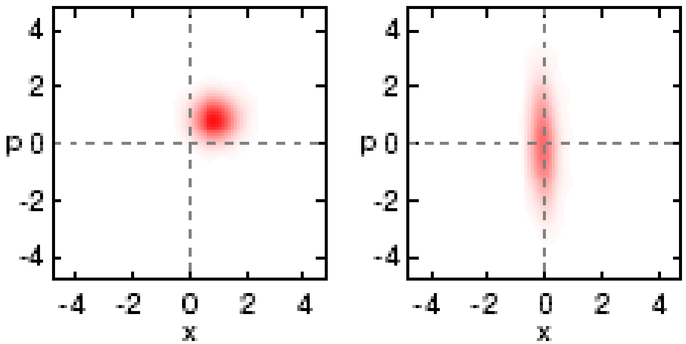
$$\hat{x}_1^{\text{out}} = \hat{x}_1^{\text{in}}, \qquad \hat{x}_2^{\text{out}} = \hat{x}_2^{\text{in}} + G\hat{x}_1^{\text{in}},$$

$$\hat{p}_1^{\text{out}} = \hat{p}_1^{\text{in}} - G\hat{p}_2^{\text{in}}, \qquad \hat{p}_2^{\text{out}} = \hat{p}_2^{\text{in}},$$

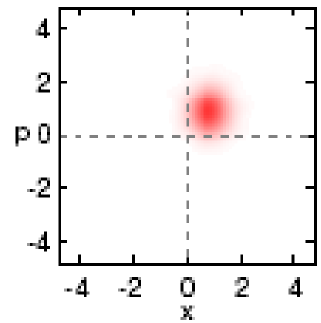


J. Yoshikawa, et al., Phys. Rev. Lett. 101, 250501 (2008)

WIGNER FUNCTION

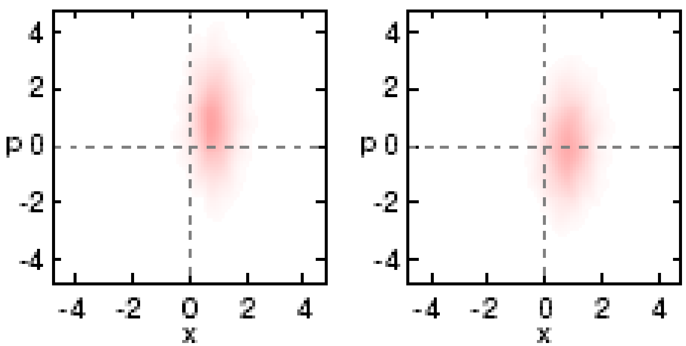


(a)Input state in each mode.



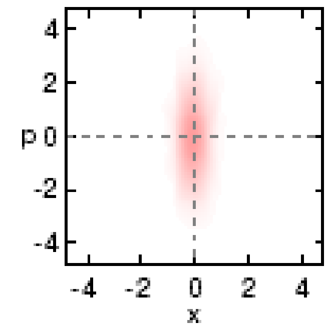
measured

(c)Resulting state of the first mode after erasing the second mode.



(b)After QND interaction.

measured



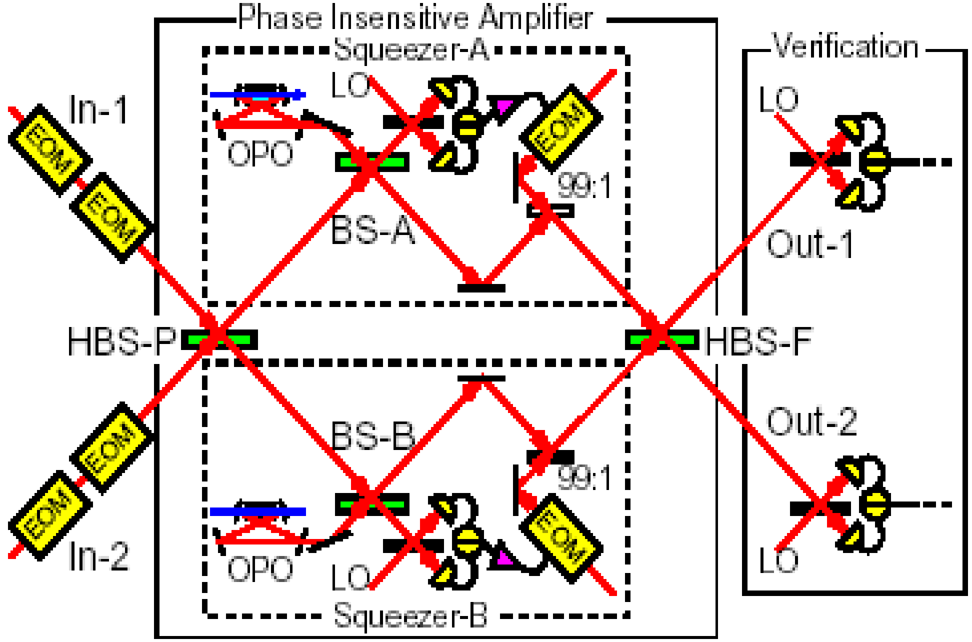
(d)Resulting state of the second mode after erasing the first mode.

[Y. Miwa, J. Yoshikawa, R. Ukai, R. Filip, A. Furusawa, *Universal Quantum Erasing for Continuous Variables*, arXiv:1007.0314]

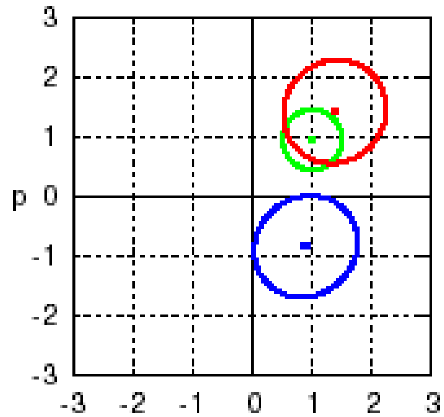
ALL OPTICAL AMPLIFIER

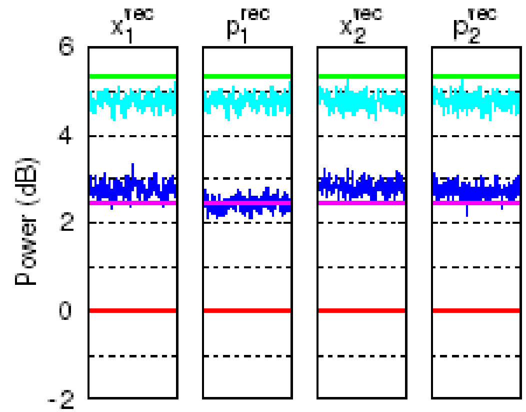
$$\hat{a}_{\mathrm{sig}}^{\mathrm{out}} = \sqrt{G}\,\hat{a}_{\mathrm{sig}}^{\mathrm{in}} + e^{i\theta}\sqrt{G-1}\left(\hat{a}_{\mathrm{idl}}^{\mathrm{in}}\right)^{\dagger}$$

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



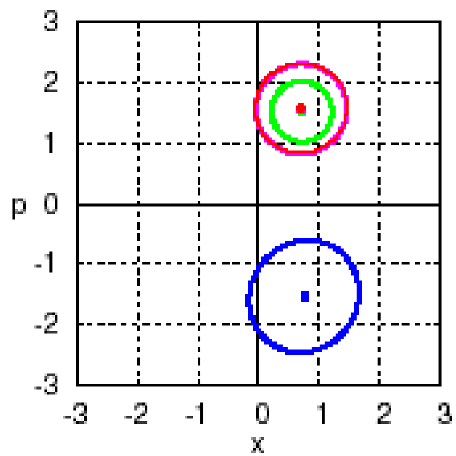
REVERSIBLE QUANTUM AMPLIFIER

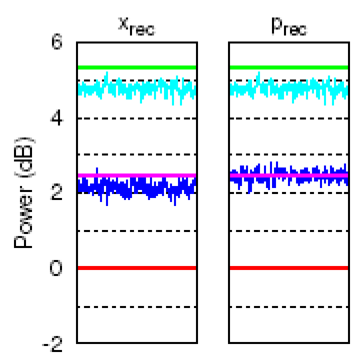




-5dB of squeezing in off-line ancillas

Normalized to inferred vacuum level.

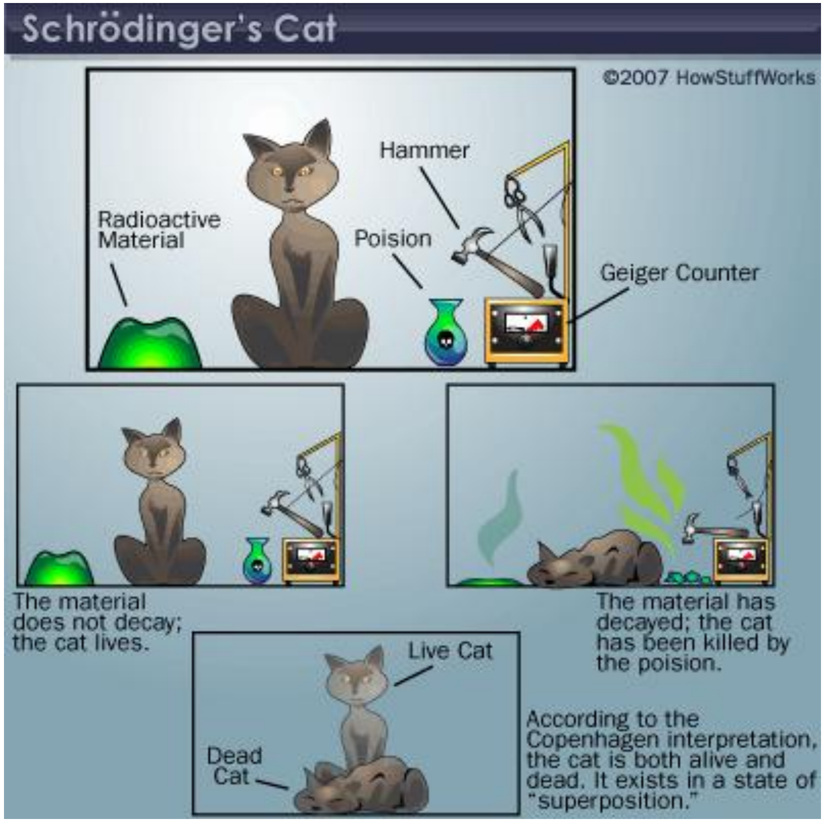


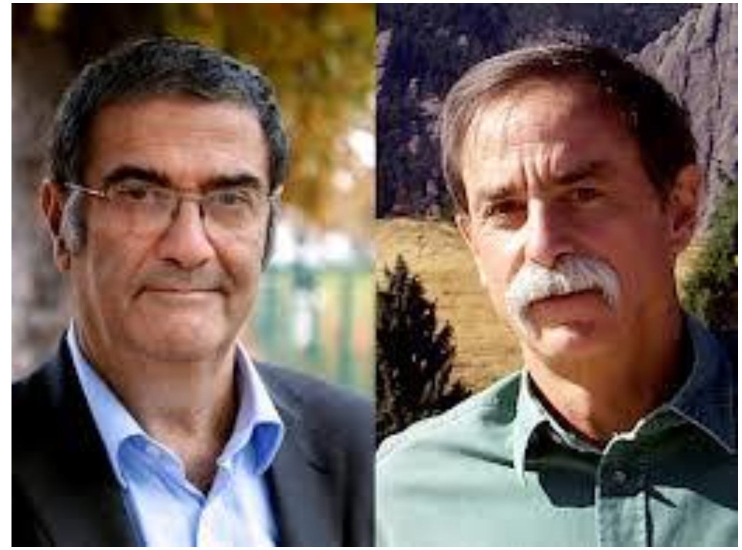


Reversible quantum cloning
R. Filip, J. Fiurasek , P. Marek,
PRA 69 , 012314 (2004).

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

QUANTUM SENSITIVITY





NOBEL PRIZE 2012

PROPAGATING OPTICAL „CAT“

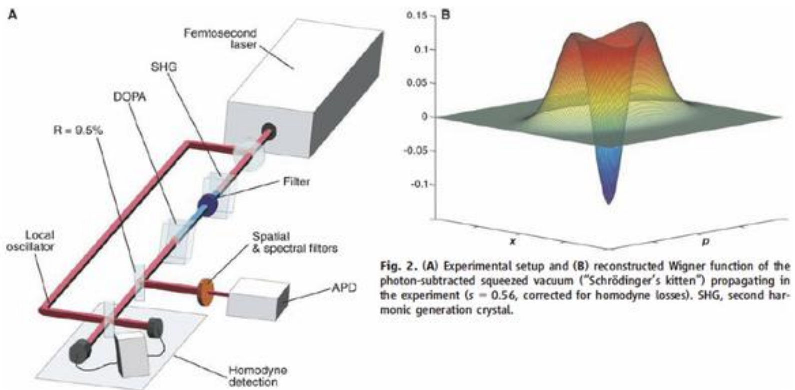
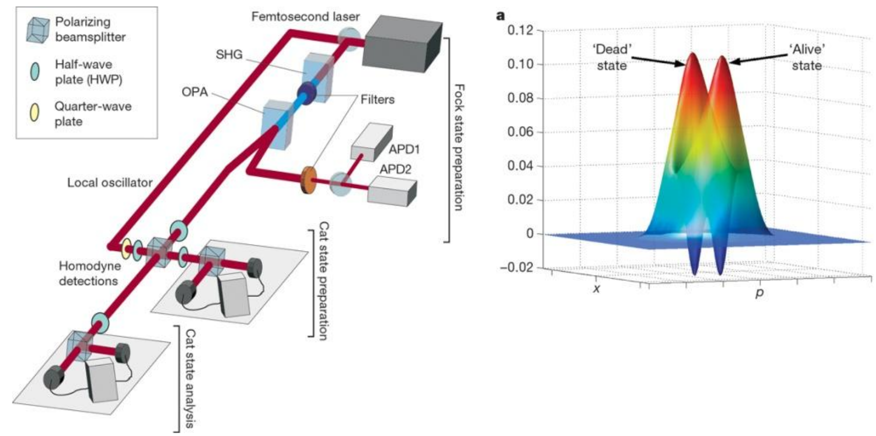


Fig. 2. (A) Experimental setup and (B) reconstructed Wigner function of the photon-subtracted squeezed vacuum ("Schrödinger's kitten") propagating in the experiment ($s = 0.56$, corrected for homodyne losses). SHG, second harmonic generation crystal.



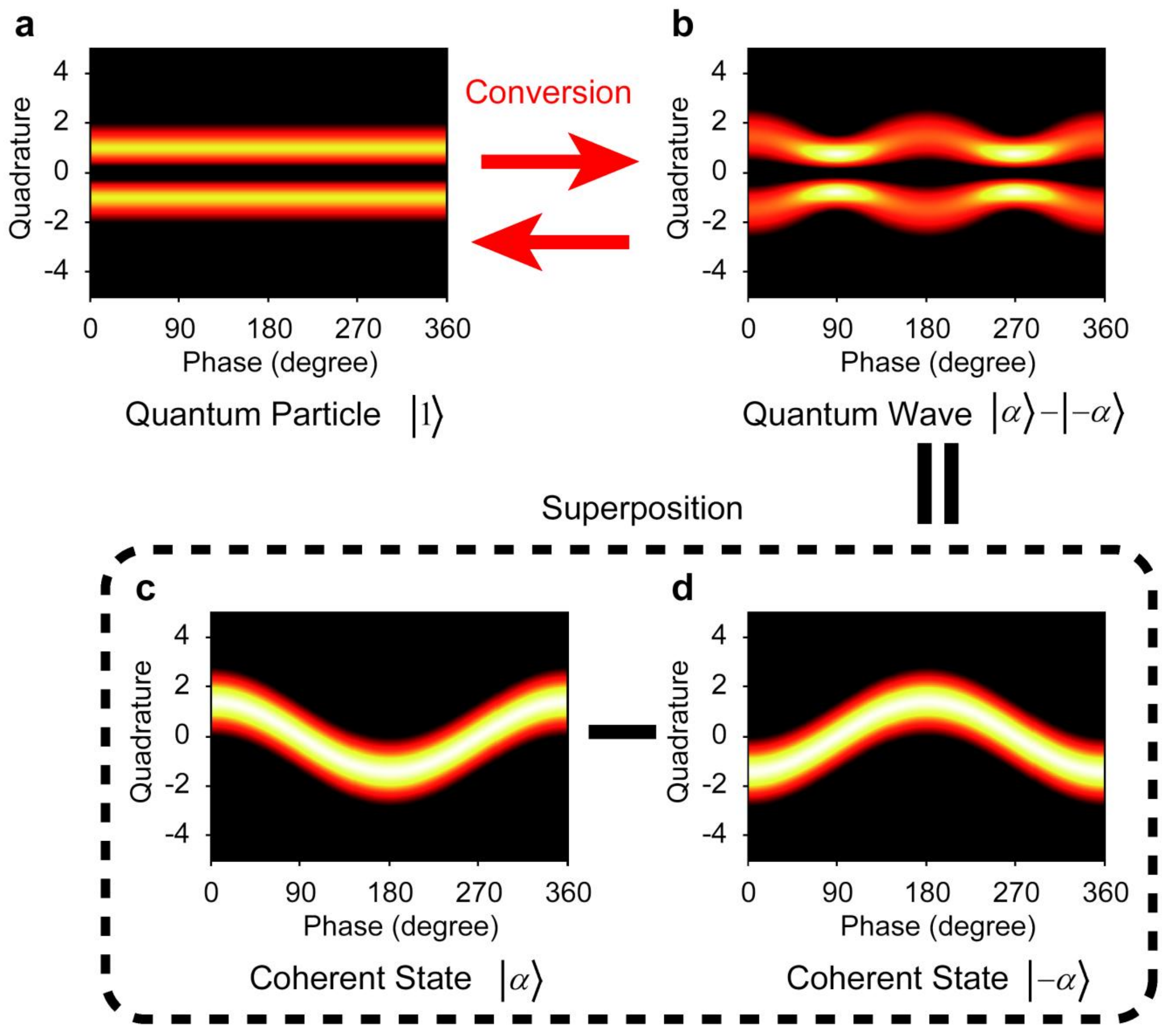
„CAT“ = $a|S>$

„CAT“ = $S(x=0)|2>$

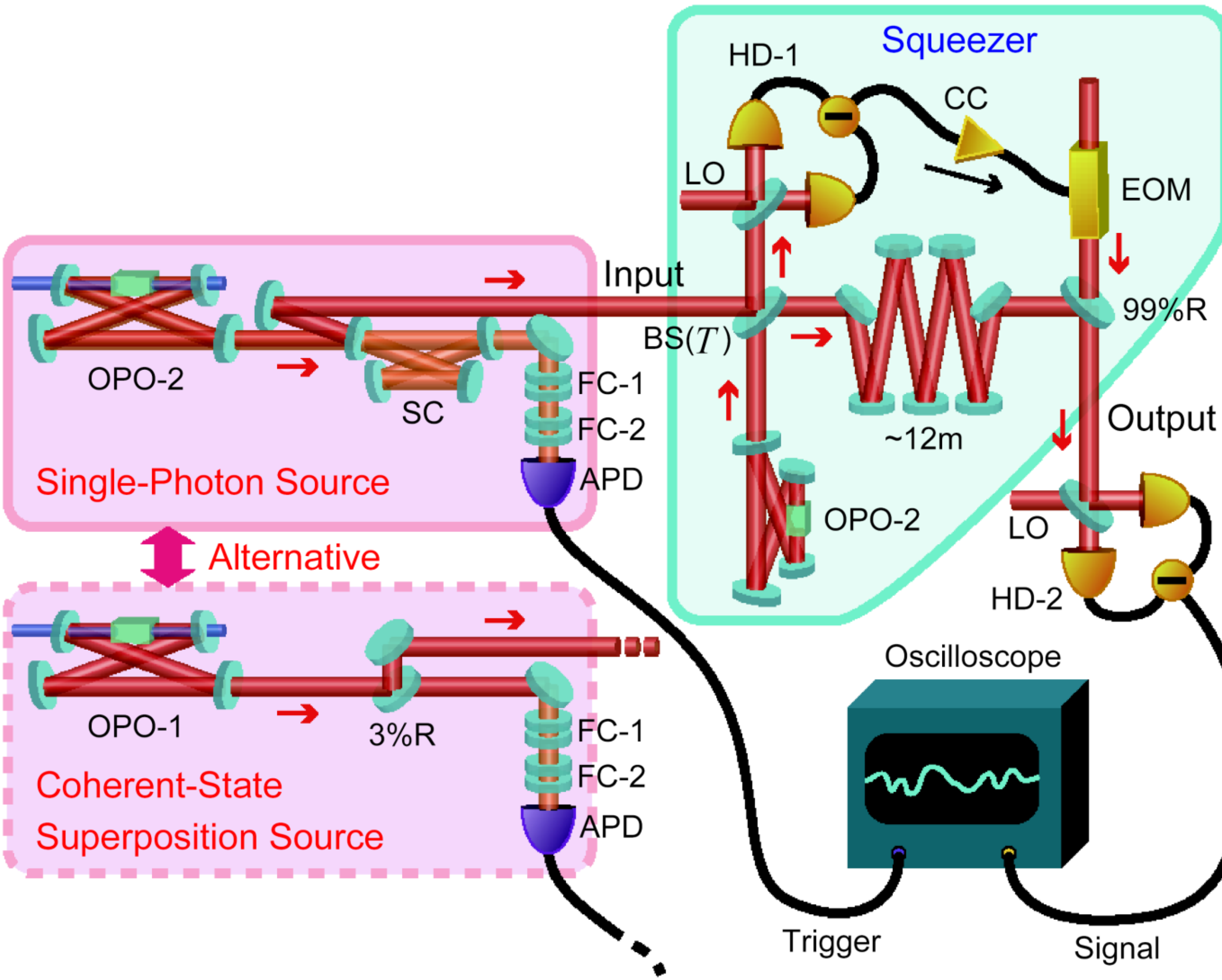
Probabilistic transformations of non-classical features

How is deterministic squeezing building “cat”?

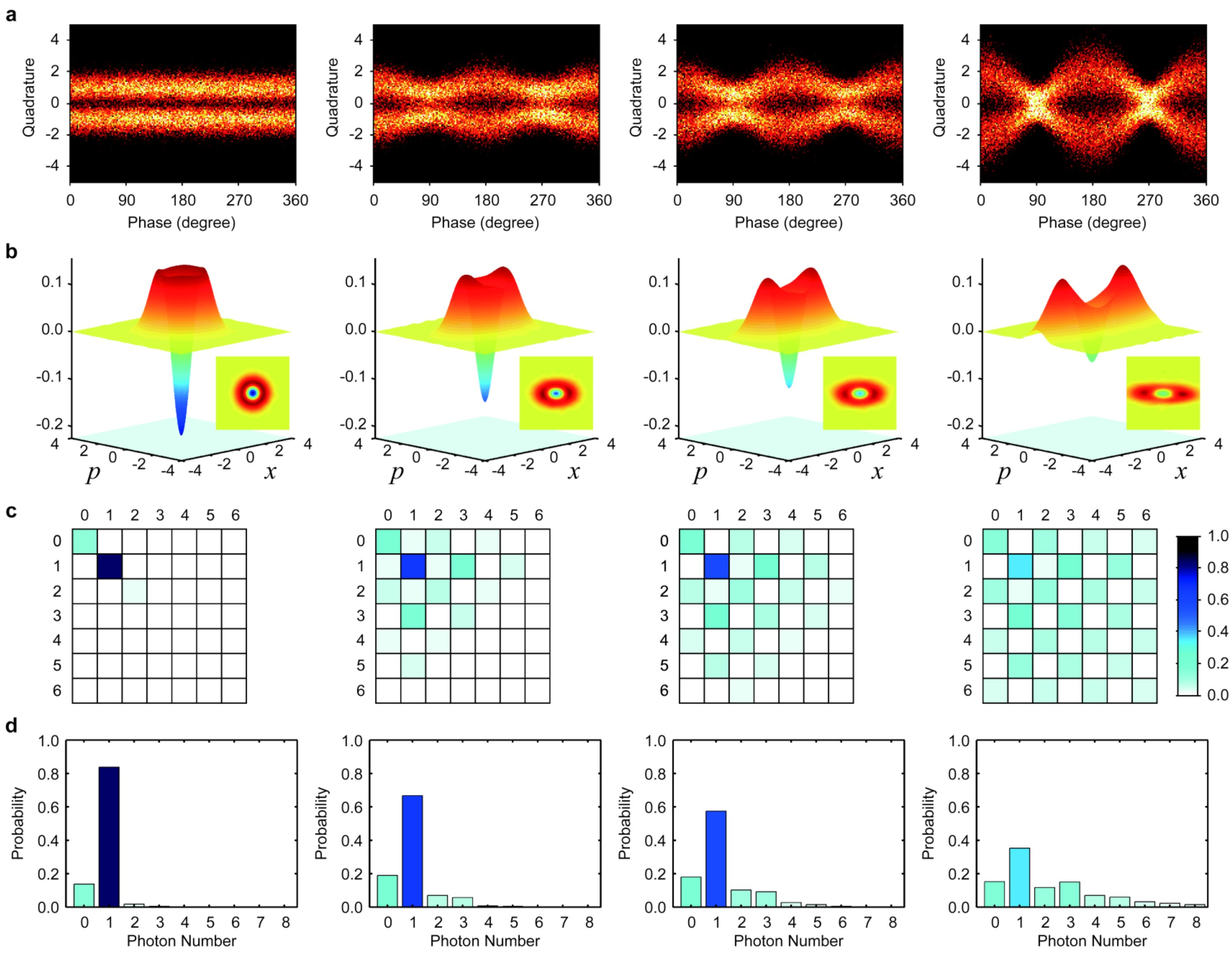
SQUEEZING & DE-SQUEEZING OF |1>



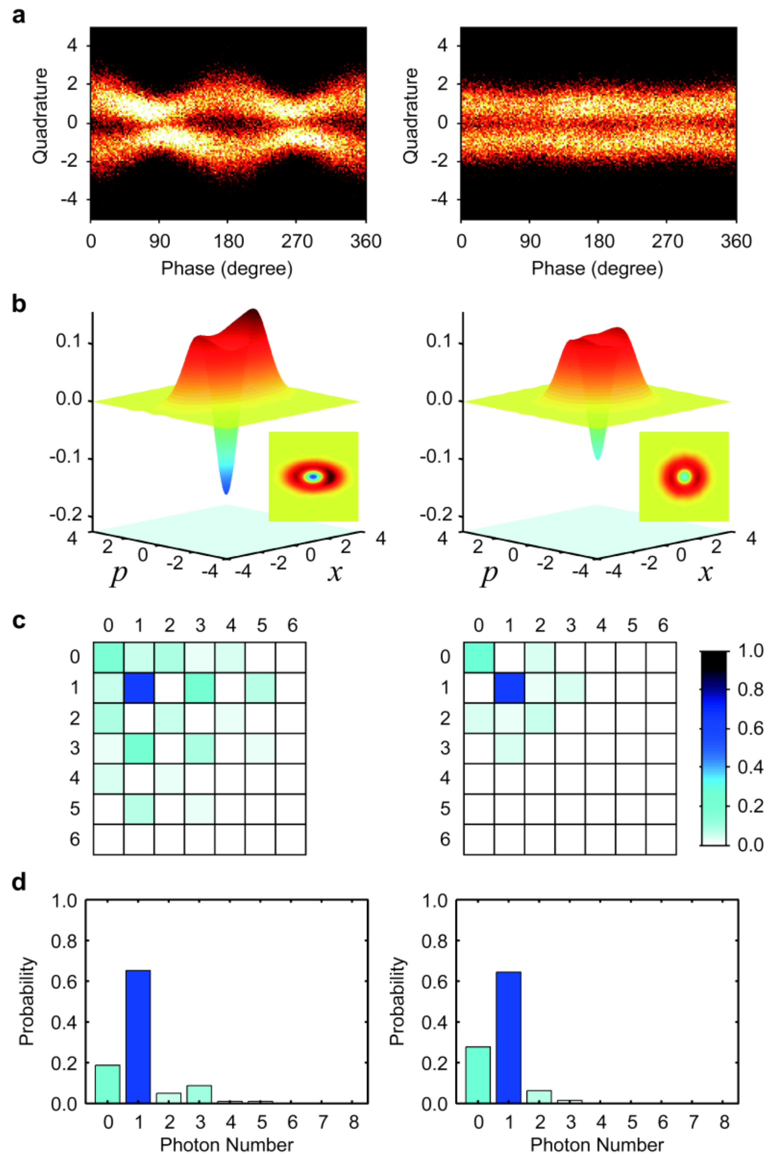
SQUEEZING & RESQUEEZING OF |1>



SQUEEZING OF |1>



DE-SQUEEZING OF S|1>



PARTICLE PICTURE

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

$$|1\rangle$$

$$|\alpha\rangle - |-\alpha\rangle \propto |1\rangle + \frac{\alpha^2}{\sqrt{6}}|3\rangle$$

WAVE PICTURE

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

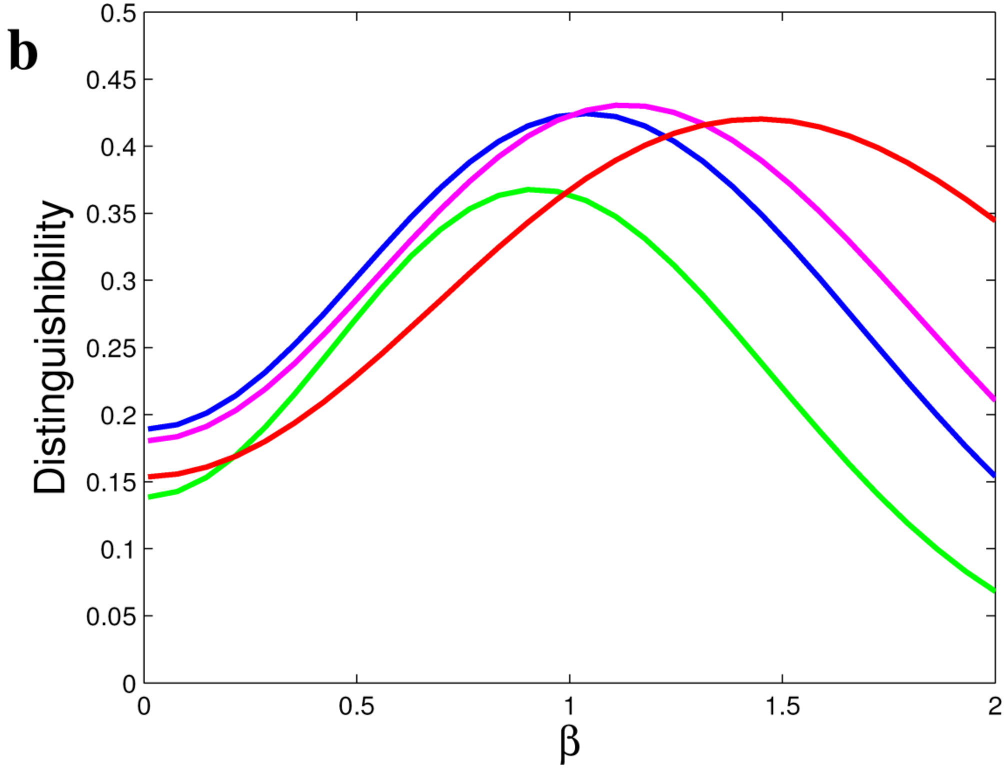
$$|1\rangle \propto \int (|\alpha e^{i\phi}\rangle - |-\alpha e^{i\phi}\rangle) d\phi$$

$$\hat{S}(\gamma)|1\rangle \approx |\alpha\rangle - |-\alpha\rangle$$

DISTINGUISHABILITY FACTOR:

$$D(\beta) = (\langle\beta|\rho|\beta\rangle + \langle-\beta|\rho|-\beta\rangle)/2$$

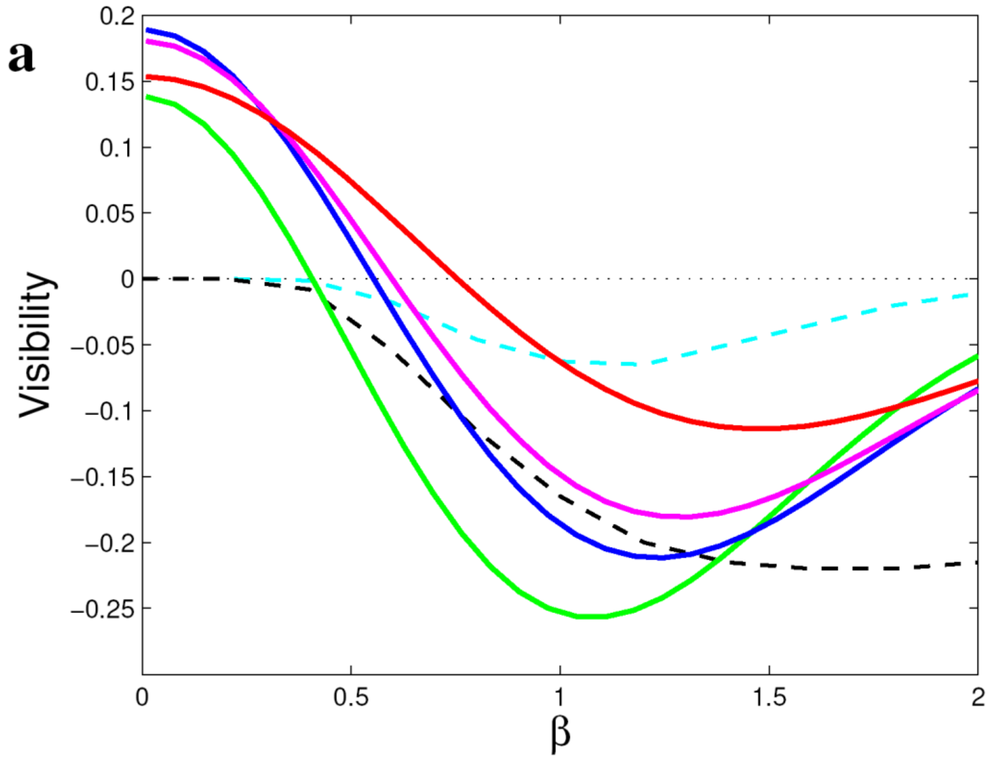
- overlap with (|β>< β|+|-β>< -β|)/2
- |1> has a maximal $D_1^{max} = 0.37$



INTERFERENCE FACTOR

$$V(\beta) = \left(\langle\beta|\rho| - \beta\rangle + \langle -\beta|\rho|\beta\rangle\right)/2$$

- overlap with (|β>< -β|+|-β>< β|)/2 (can be negative)
- |1> has minimal $V_1^{min} = -D_1^{max}$ at $\beta = 0.97$



PARTICLE PICTURE

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

$$|1\rangle \quad \Rightarrow \quad |\alpha\rangle - |-\alpha\rangle \propto |1\rangle + \frac{\alpha^2}{\sqrt{6}}|3\rangle$$

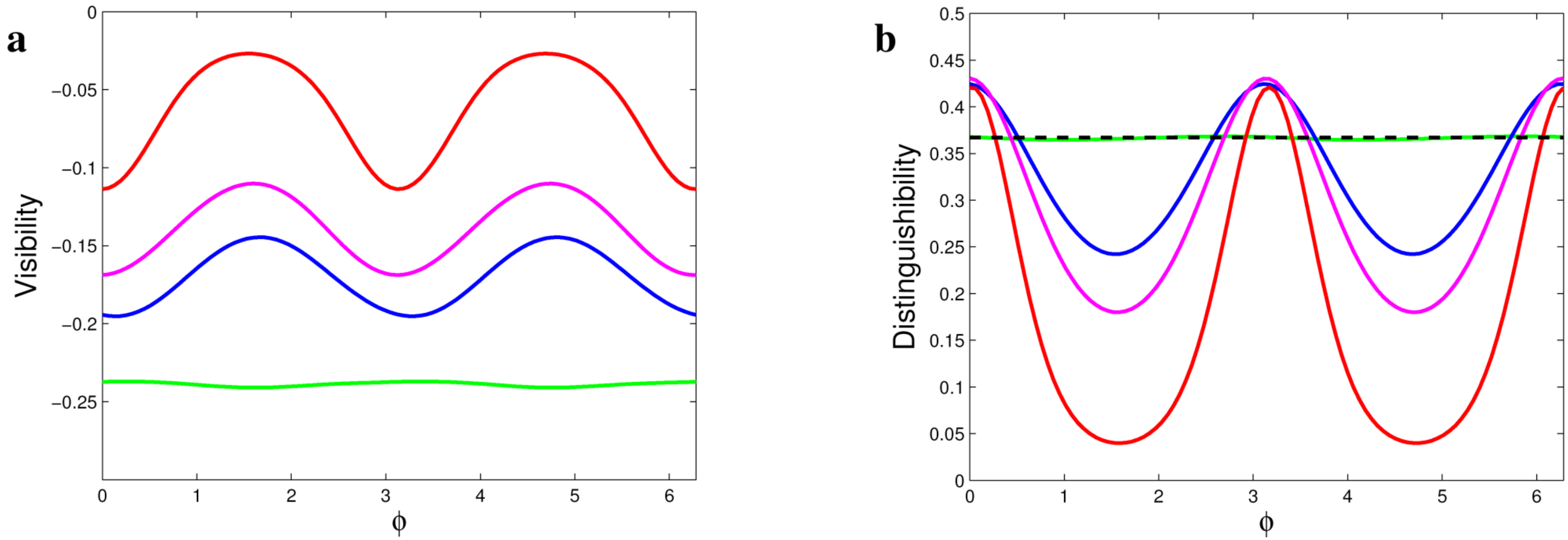
WAVE PICTURE

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

$$|1\rangle \propto \int (|\alpha e^{i\phi}\rangle - |-\alpha e^{i\phi}\rangle) d\phi \quad \Rightarrow$$

$$\hat{S}(\gamma)|1\rangle \approx |\alpha\rangle - |-\alpha\rangle$$

WAVE PICTURE EXPERIMENT



β chosen at maximal V and D

Squeezing is building phase sensitive quantum superposition from insensitive one presented in |1>.

QUADRATIC NONLINEARITY FOR UNIVERSAL QUANTUM INTERFACE

- Theoretical concept: universal quantum interface exists for any weak Gaussian interaction, specifically was proposed for BS and QND interactions.

  Next: tests of sensitivity to imperfections
- Optical tests: reversible all optical processing: squeezer, amplifier and QND interaction. More squeezing required. Still challenging for |1>.
- Implementation: in future