Yale seminar

Palacký University
Olomouc

Non-Gaussian quantum optics

Radim Filip

Department of Optics, Faculty of Science, Palacky University, Olomouc

MINISTERSTVO ŠKOLSTVÍ, MLÁDEŽE A TĚLOVÝCHOVY

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THEORY GROUP

Quantum Coherence and Nonclassicality

Petr Marek

Students:
Lukáš Lachman
Josef Hloušek

Quantum Nonlinear Operations

Petr Marek
Kimin Park

Students:
Petr Zapletal
Jan Provazník

Quantum Communication

Vladyslav Usenko
Lazslo Ruppert

Students:
Ivan Derkač
Olena Kovalenko

Quantum Optomechanics

Andrey Rakhubovsky

Students:
Nikita Vostrosablin

Interaction of Light with Atoms

Lukáš Slodička
Petr Marek

Students:
Petr Obšil
Lukáš Podhora

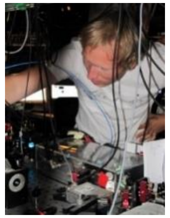
Stochastic Mechanics and Thermodynamics

Michal Kolář
Giacomo Guarnieri

Students:
Luca Ornigotti
Maria Gumberidze





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CENTRE OF EXCELLENCE

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Institute of Scientific Instruments of the CAS, Brno

Palacký University
Olomouc

INTERNATIONAL COLLABORATION

Max Planck Institute for Science of Light
G. Leuchs, M. Chekhova, S. Götzinger

Danish Technical University, Lyngby
U.L. Andersen

University of Innsbruck
G. Weihs, R. Blatt

University of Tokyo
A. Furusawa

Laboratoire Kastler Brossel, Sorbone, Paris
J. Laurat, N. Treps

University of Vienna
M. Aspelmeyer

NONCLASSICAL LIGHT

"non-classical state" = **not mixture of coherent states**

$$\rho \neq \int \mathcal{P}(\lambda)|\lambda\rangle\langle\lambda|d\lambda,\ |\lambda\rangle = D(\beta)|0\rangle$$

R.J. Glauber, *Phys. Rev.* **131** 2766 (1963)

Nonclassical state cannot be prepared in **linear oscillator** driven by **classical external force** (with arbitrary fluctuations).

For low emission and collection efficiency, HBT measurement with two APDs can simply verify it.

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QUANTUM NON-GAUSSIAN LIGHT

"quantum non-Gaussian state" = **not mixture of Gaussian states**

$$\rho \neq \int \mathcal{P}(\lambda)|\lambda\rangle\langle\lambda|d\lambda,\ |\lambda\rangle = S(r,\psi)D(\beta)|0\rangle$$

Quantum non-Gaussian state cannot be prepared by **linearized dynamics (maximally quadratic Hamiltonians)** with arbitrary fluctuating coupling coefficients (common in nonlinear optics, quantum optomechanics, etc.)

For low emission and collection efficiency, **direct verification** of quantum non-Gaussian light was always limited.

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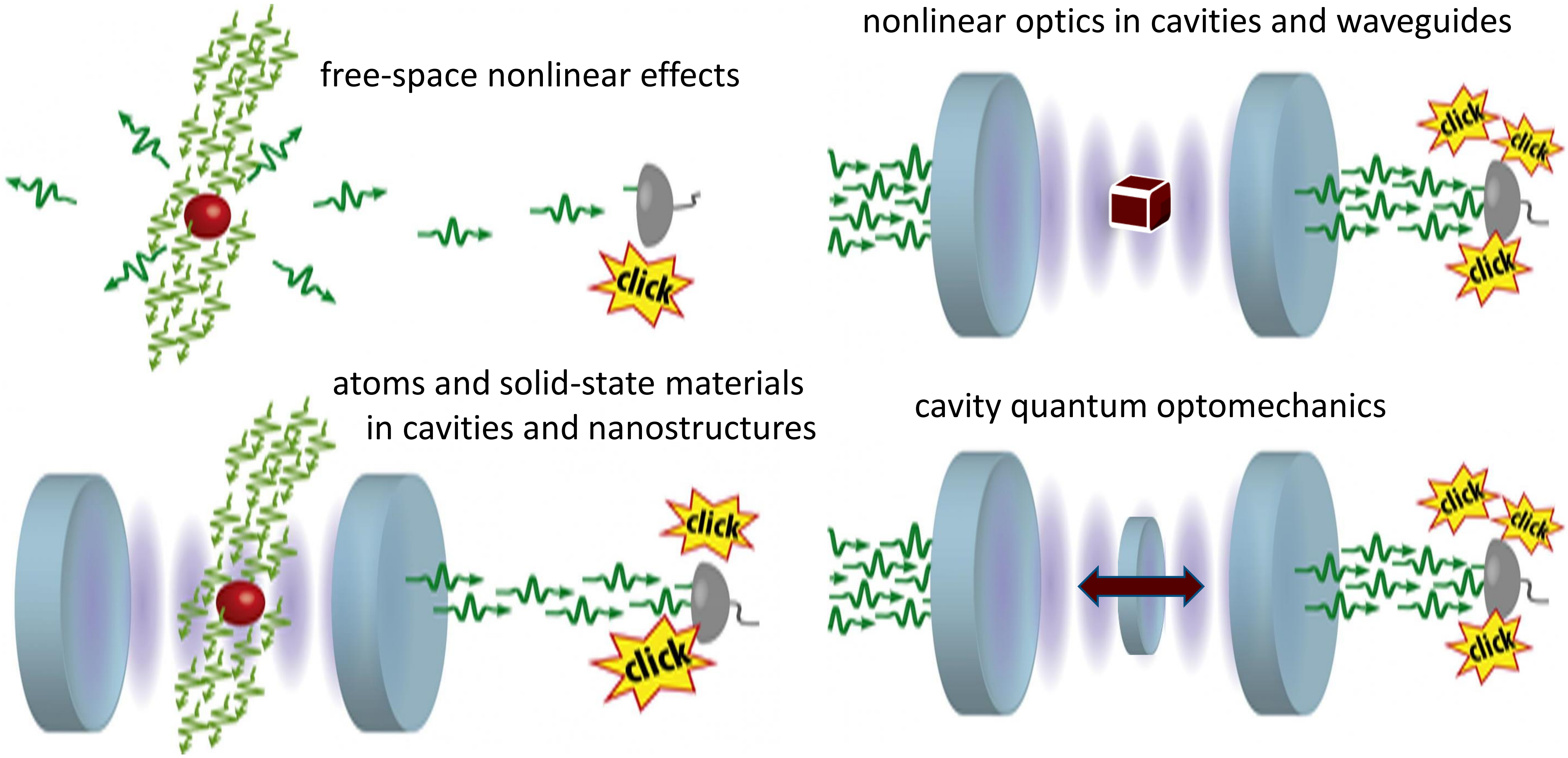
QUANTUM NON-GAUSSIAN LIGHT WITNESSES HIGHLY NONLINEAR QUANTUM EFFECTS



https://phys.org/news/2017-04-physicists-quantum-effect-limits-emitted.html

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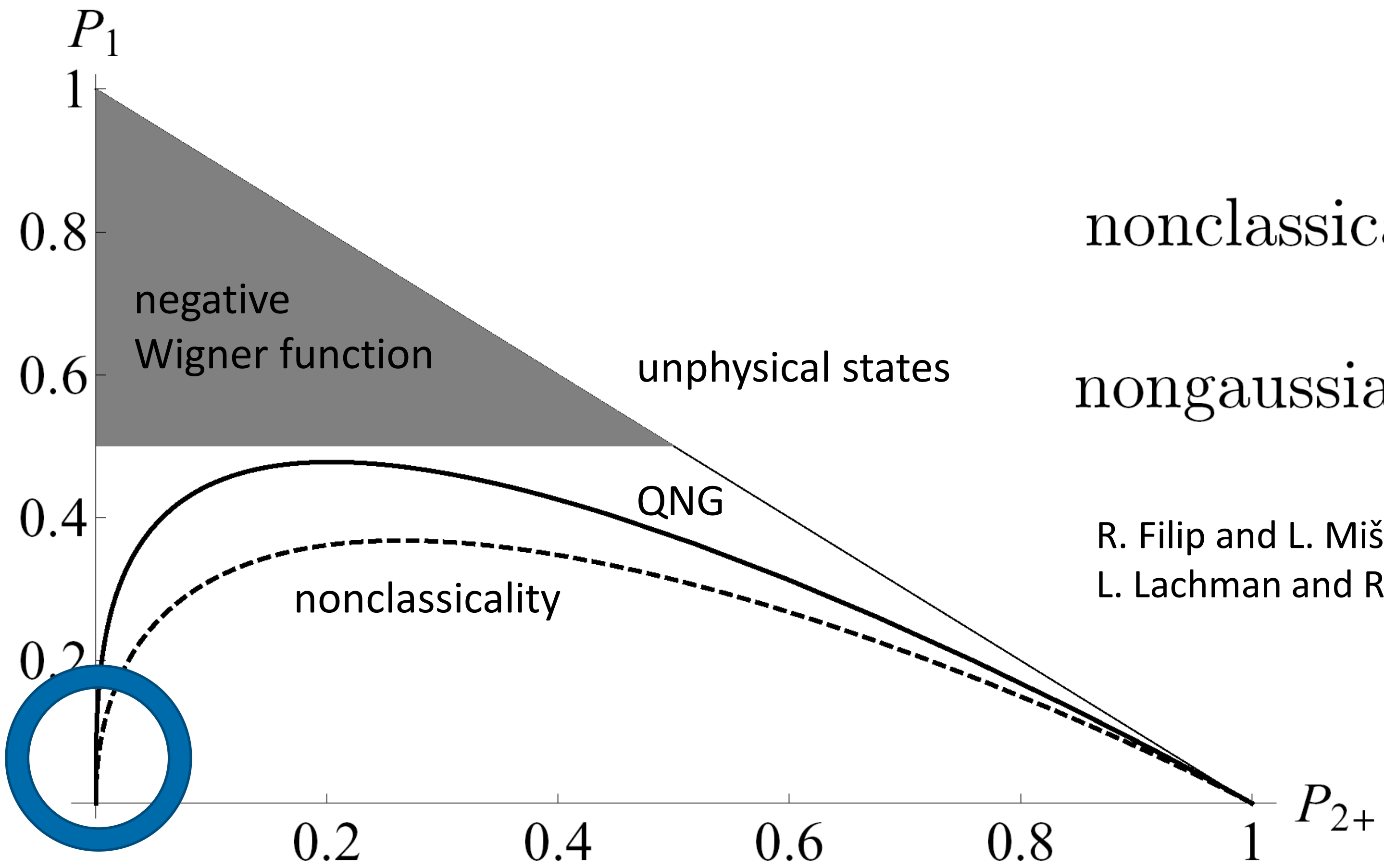
QUANTUM NON-GAUSSIAN LIGHT

$$\rho_c \neq \int \mathcal{P}(\lambda)|\lambda\rangle\langle\lambda|d\lambda, \quad |\lambda\rangle = S(r,\psi)D(\beta)|0\rangle$$



$$P_{2+} \ll P_1$$

nonclassicality: $P_{2+} < \frac{P_1^2}{2}$

nongaussianity: $P_{2+} < \frac{2}{3} P_1^3$

R. Filip and L. Mišta, Phys. Rev. Lett. 106, 200401 (2011)
L. Lachman and R. Filip, Phys. Rev. A 88, 063841 (2013)

EXPERIMENT

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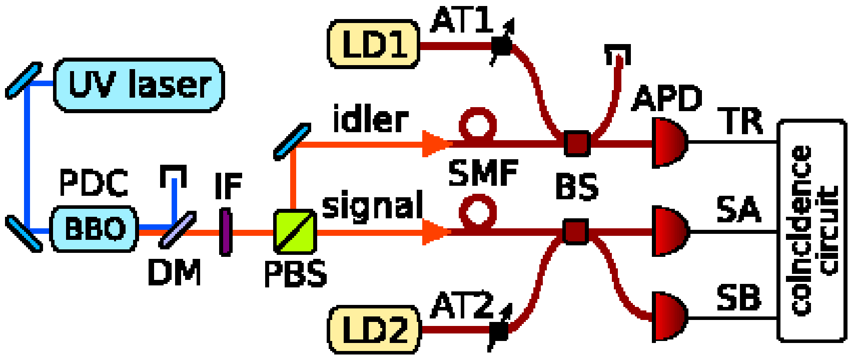
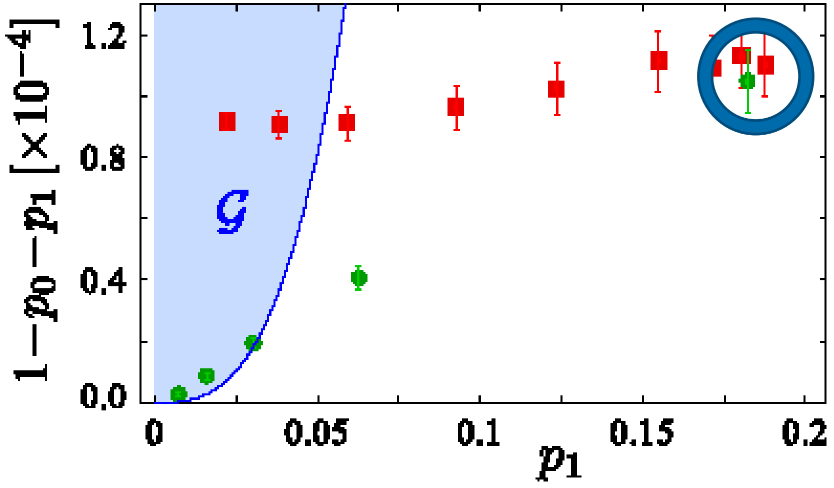
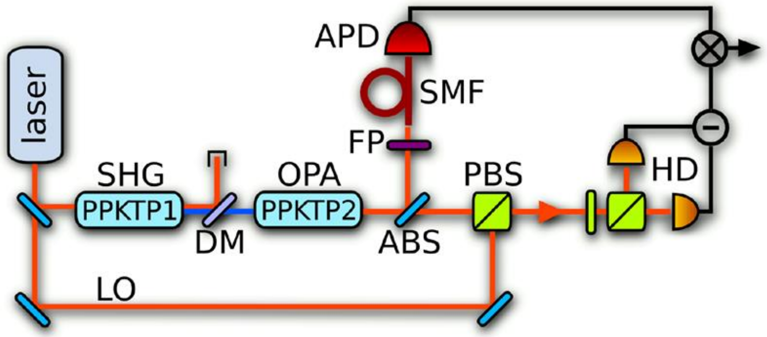
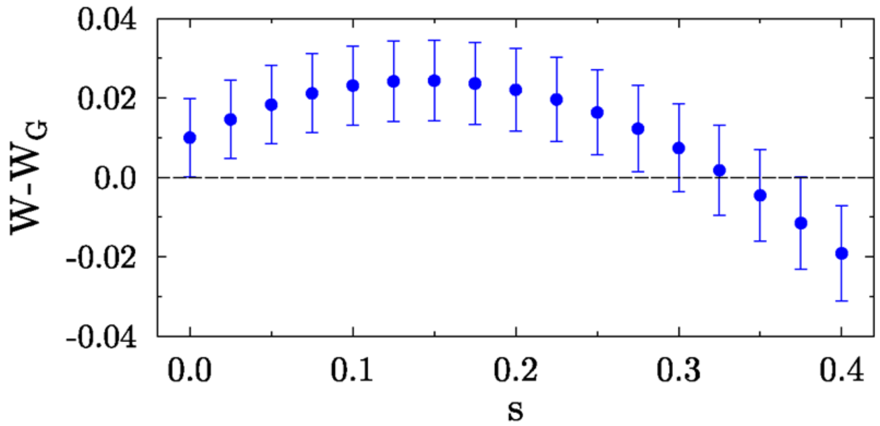




M. Jezek, I. Straka, M. Micuda, M.Dusek, J. Fiurasek, R. Filip, Phys. Rev. Lett. 107, 213602 (2011).





M. Ježek, A. Tipsmark, R. Dong, J. Fiurášek, L. Mišta Jr, R. Filip, and U.L. Andersen, Phys. Rev. A 86, 043813 (2012)
H. Song, K. Kuntz and E. Huntington, New J. Phys. 15, 1 (2013)

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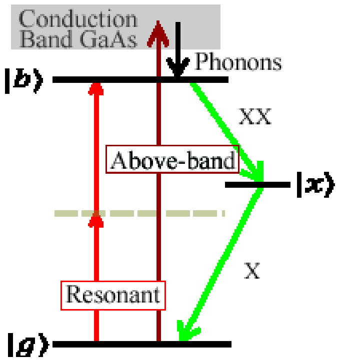
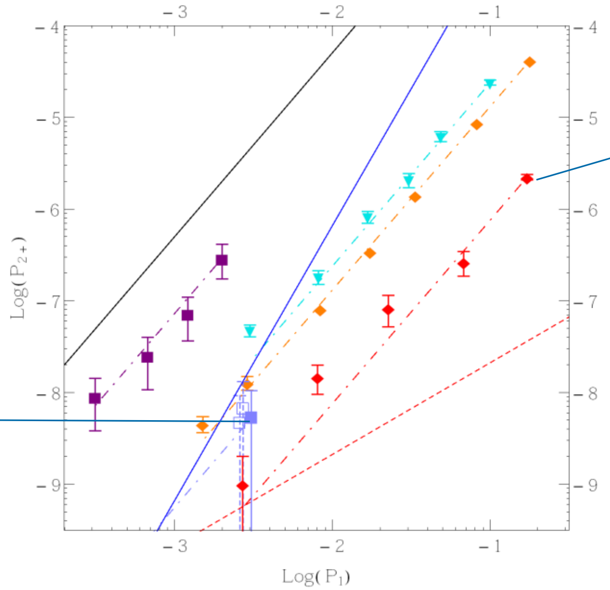
EXPERIMENT



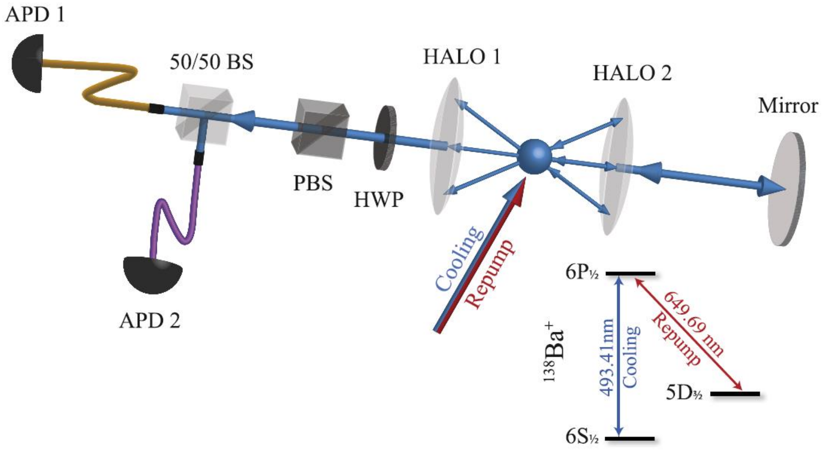
quantum dot

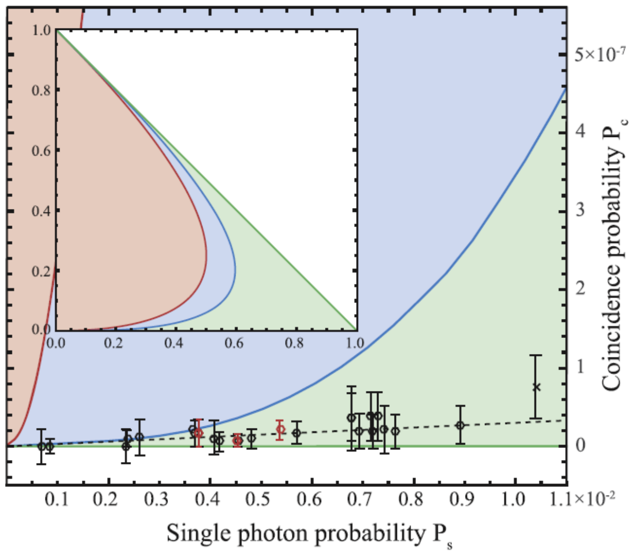


Depth:

18 dB

I. Straka, A. Predojević, T. Huber, L. Lachman, L. Butschek, M. Miková, M. Mičuda, G.S. Solomon, G. Weihs, M. Ježek, and R. Filip, Phys. Rev. Lett. 113, 223603 (2014).





D.B. Higginbottom, L. Slodička,G. Araneda, L. Lachman, R. Filip, M. Hennrich and R. Blatt, New J. Phys. 18, 093038 (2016).

APPLICATION OF QNG

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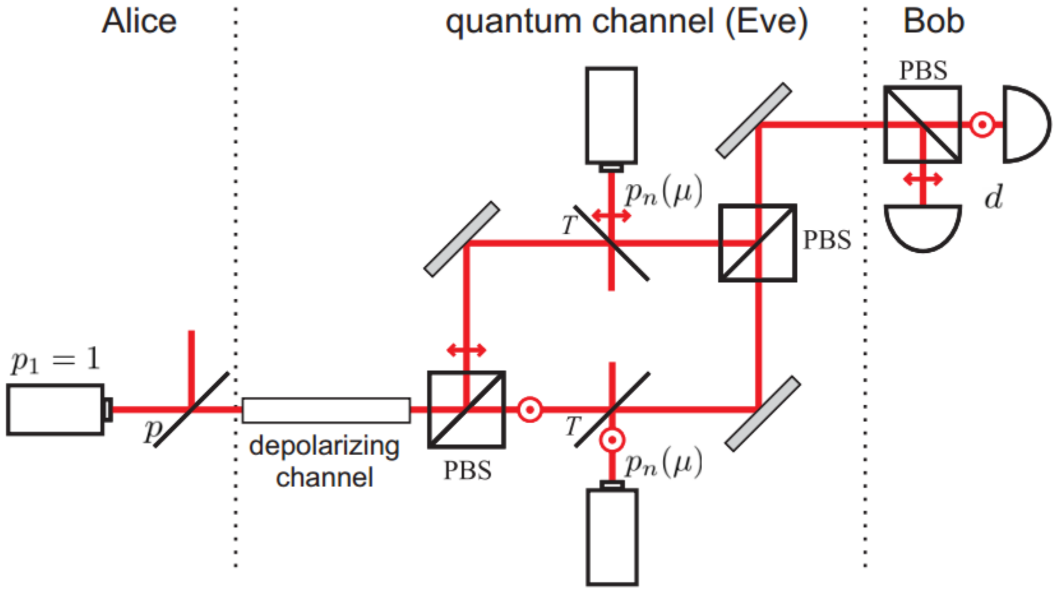
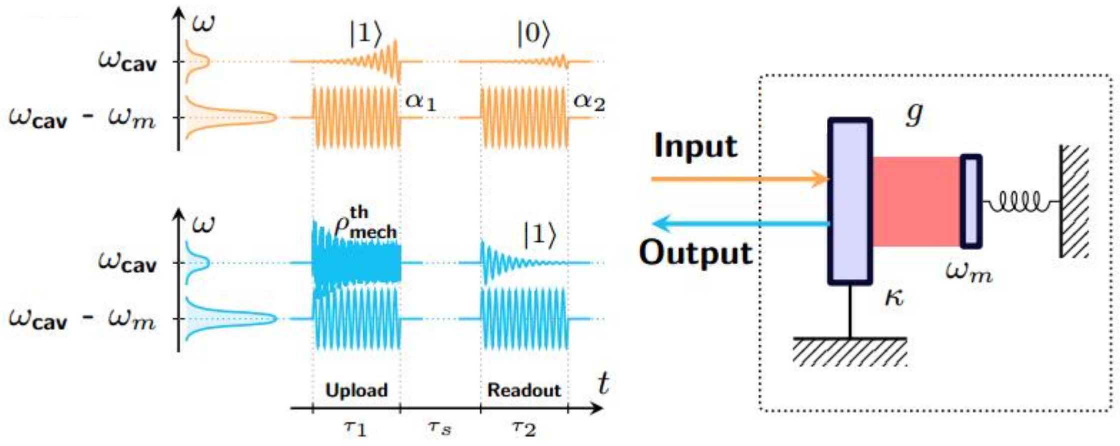
Security indicator for QKD BB84 single-photon protocol



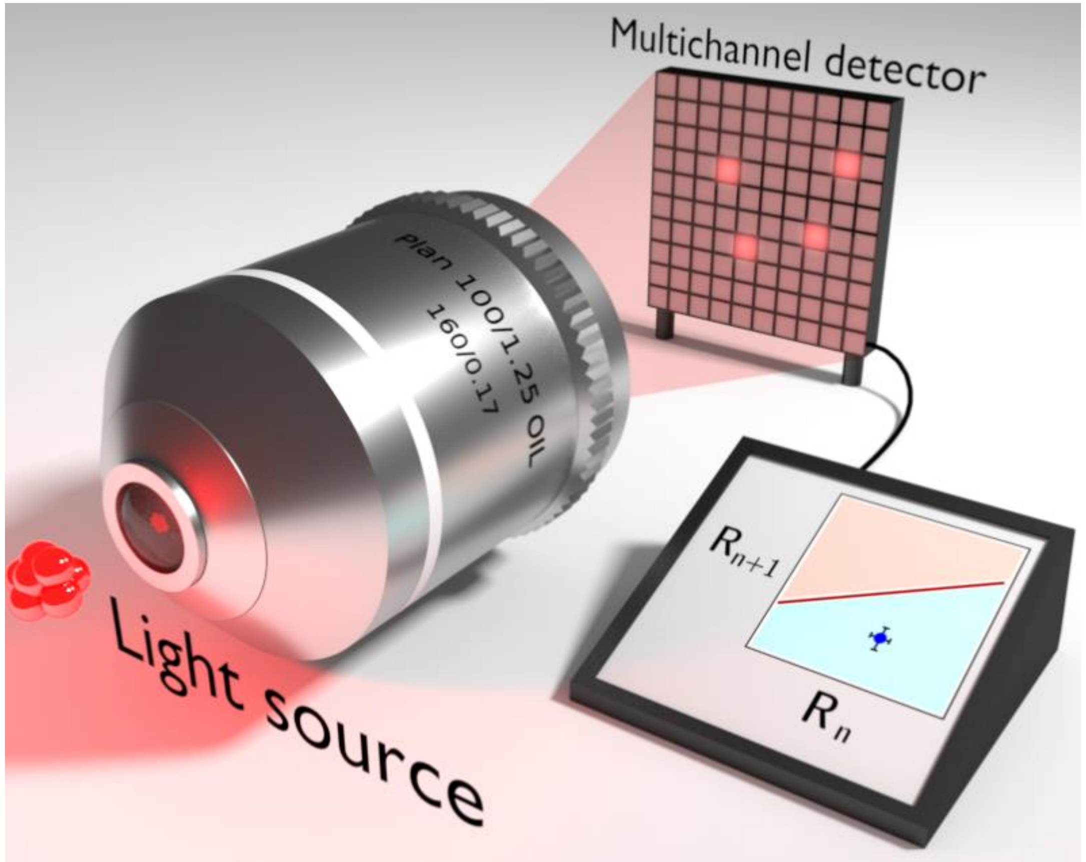
M. Lasota, R. Filip, and V.C. Usenko, Phys. Rev. A 96, 012301 (2017)

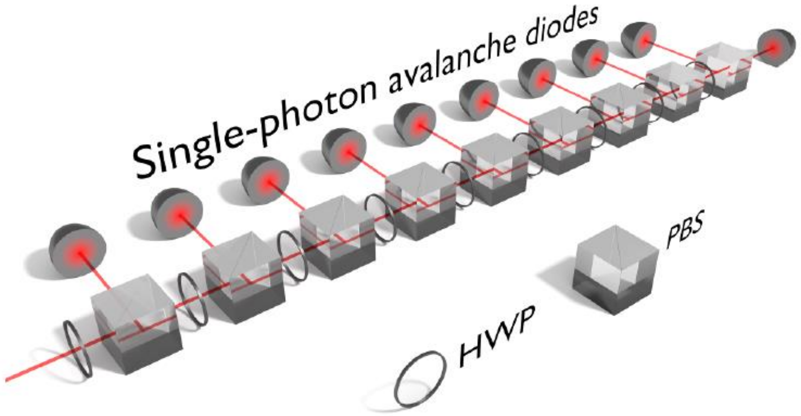
Verification of single photon-phonon-photon transfer



A.A. Rakhubovsky and R. Filip, Scientific Reports 7, 46764 (2017)

QUANTUM NON-GAUSSIANITY OF MANY PHOTONS





$$R_n^{n+2} > H_n^4(x)\left[\frac{R_{n+1}}{2(n+1)^3}\right]^n$$

I. Straka, L. Lachman, J. Hloušek, M. Miková, M. Mičuda, M. Ježek, R. Filip, Quantum Non-Gaussian Multiphoton Light, arXiv:1611.02504

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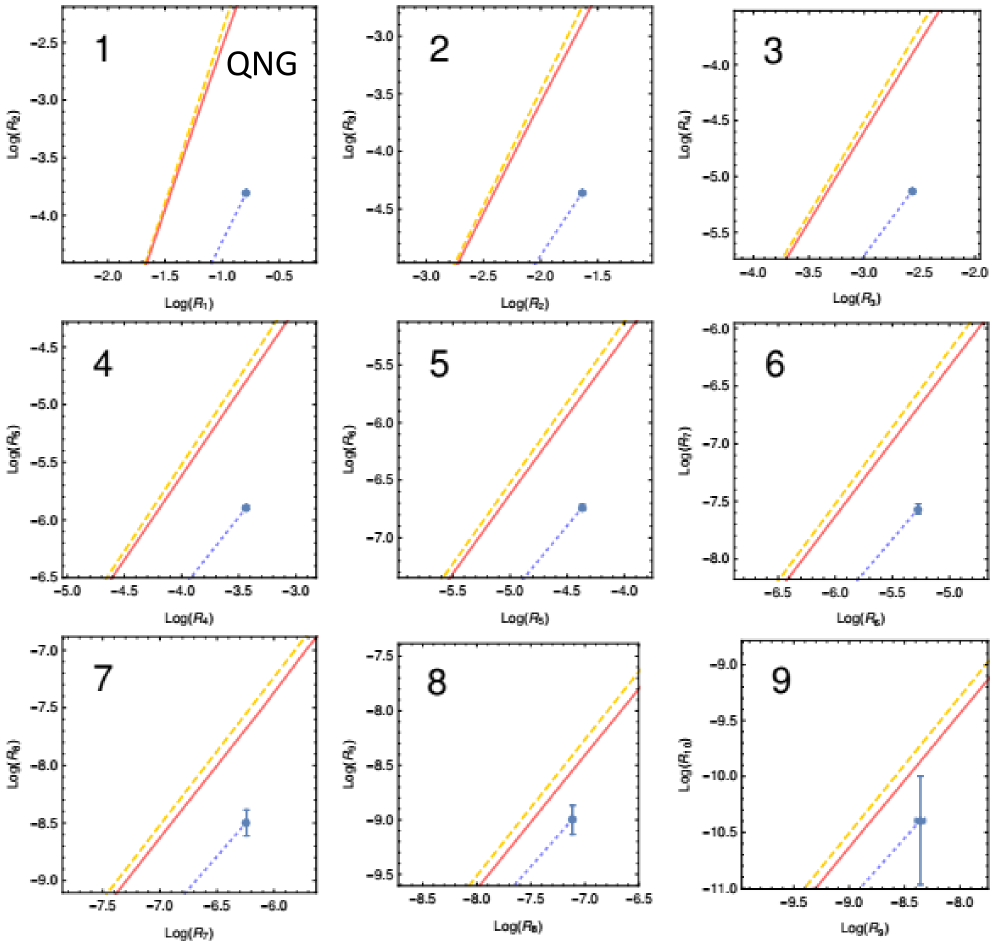
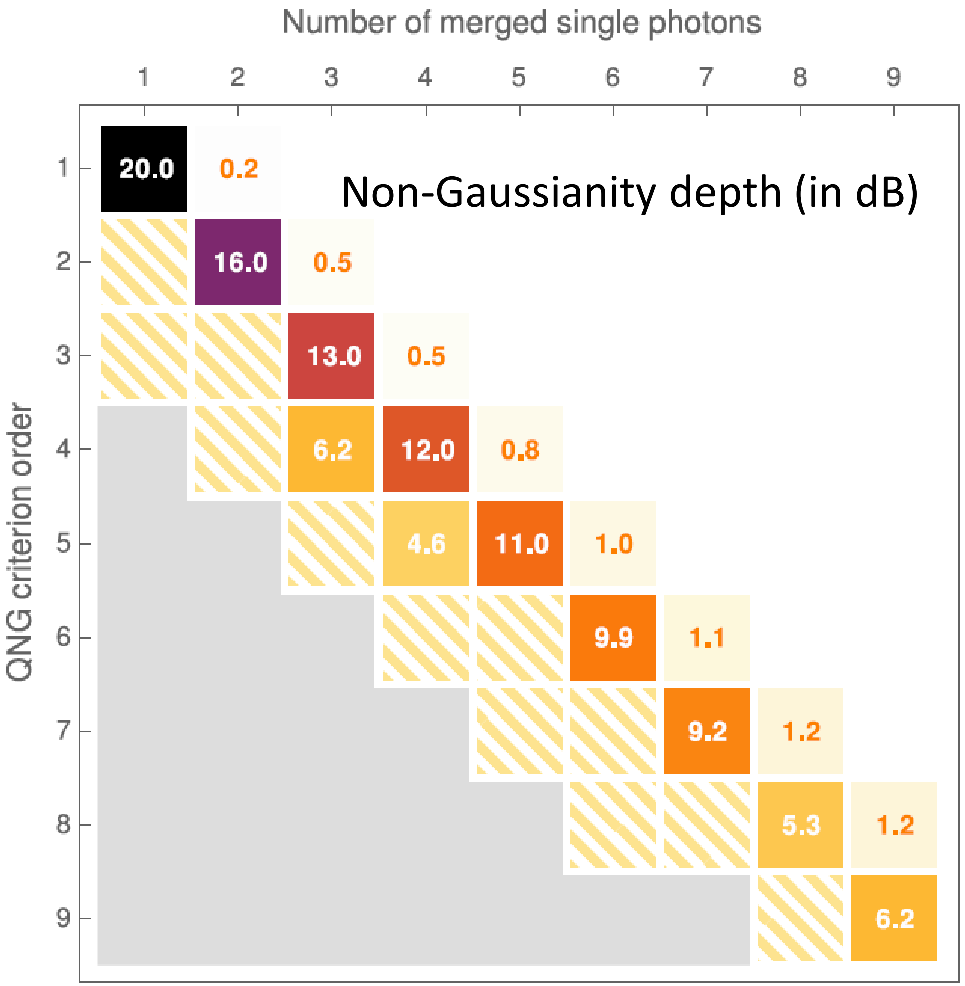
EXPERIMENT





I. Straka, L. Lachman, J. Hloušek, M. Miková, M. Mičuda, M. Ježek, R. Filip, Quantum Non-Gaussian Multiphoton Light, arXiv:1611.02504

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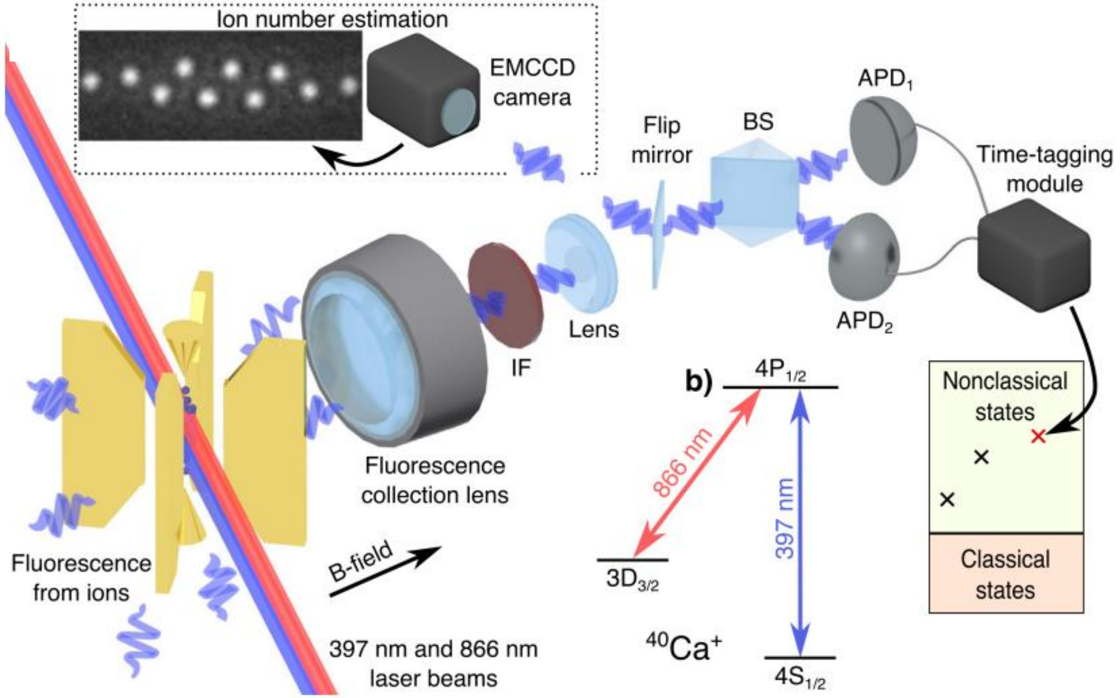
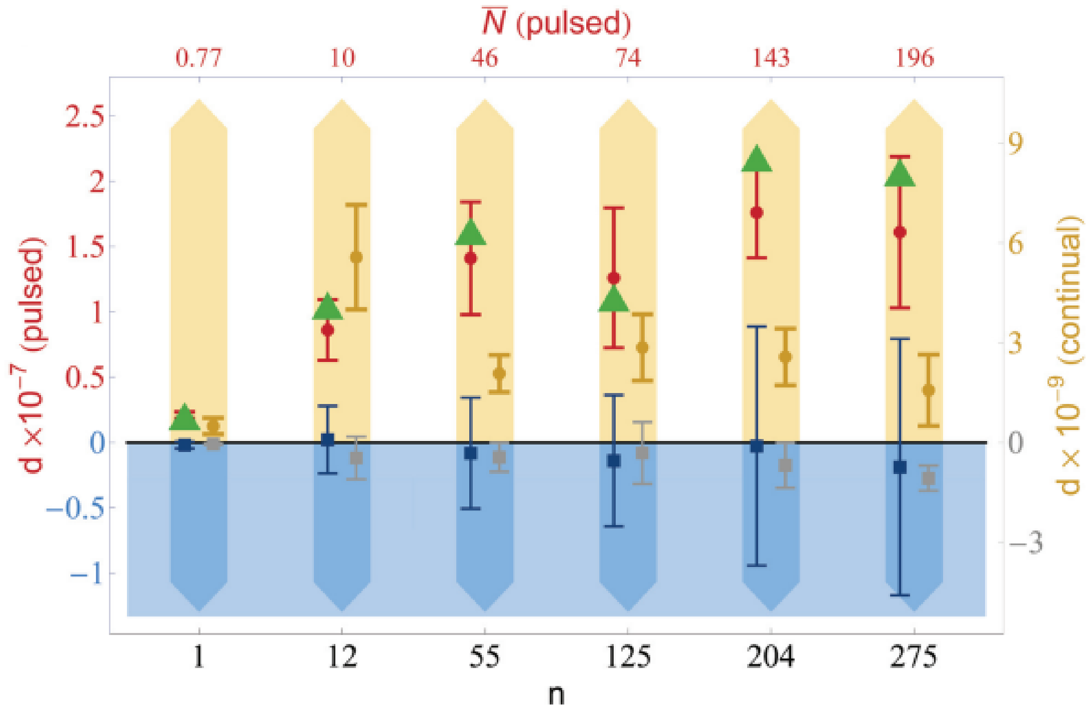
NONCLASSICALITY OF MANY PHOTONS



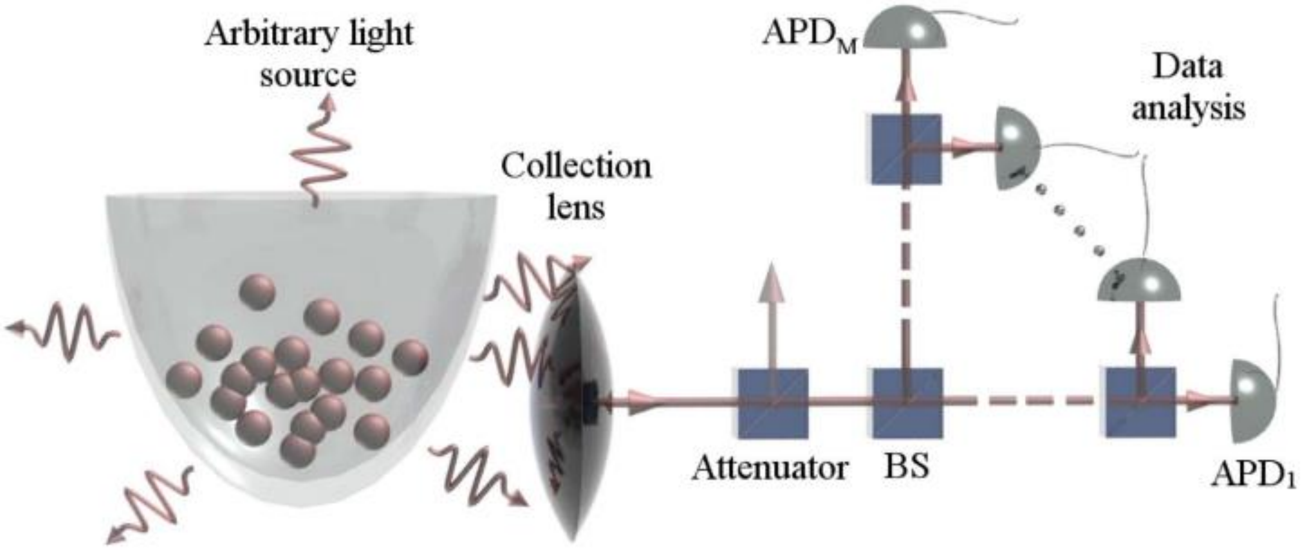


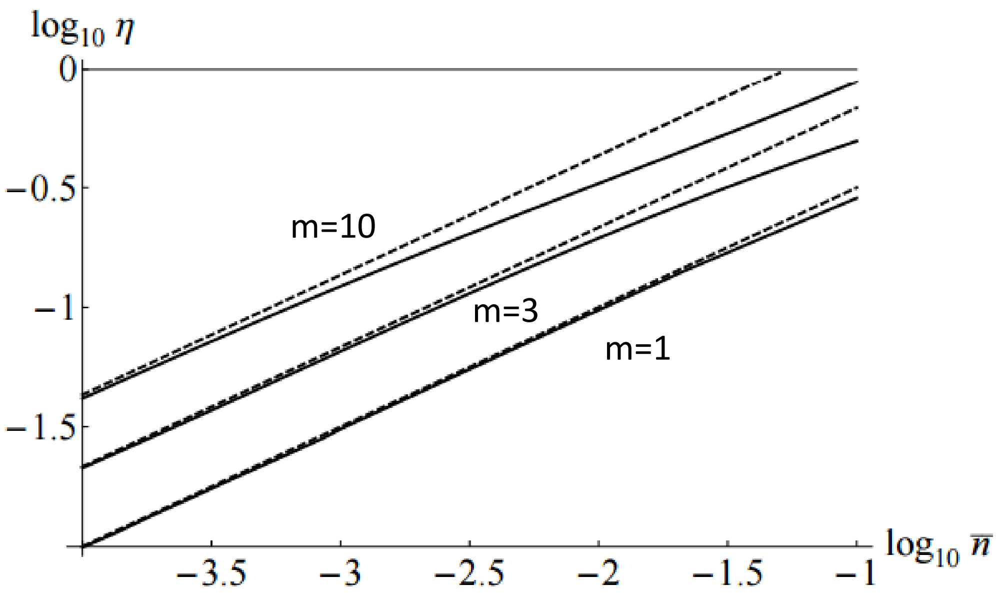
Nonclassicality of light can be detected for bright light from many emitters (>1000).

P. Obsil, L. Lachman, T. Pham, A. Lesundak, V. Hucl, M. Cızek , J. Hrabina, O. Cip, L. Slodicka and R. Filip, Nonclassical light from large ensemble of trapped ions, arXiv:1705.04472

E. Moreva, P. Traina, J. Forneris, I. P. Degiovanni, S. Ditalia Tchernij, F. Picollo, G. Brida, P. Olivero, M. Genovese, Direct experimental observation of nonclassicality in ensembles of single photon emitters, arXiv:1705.03079

QUANTUM NON-GAUSSIANITY OF MANY PHOTONS





Quantum non-Gaussianity from large ensemble is detectable!

$$\eta > \frac{H_m^{2/m}(x)}{\sqrt[m]{m!}}\sqrt{\frac{m\bar{n}}{2(m+1)}}$$

where x satisfies $H_{m+1}(x) = 0$ and $m\bar{n} \ll \eta$

NEXT?

L. Lachman and R. Filip, Opt. Express 24, 27352 (2016)

FOCK STATE CAPABILITY

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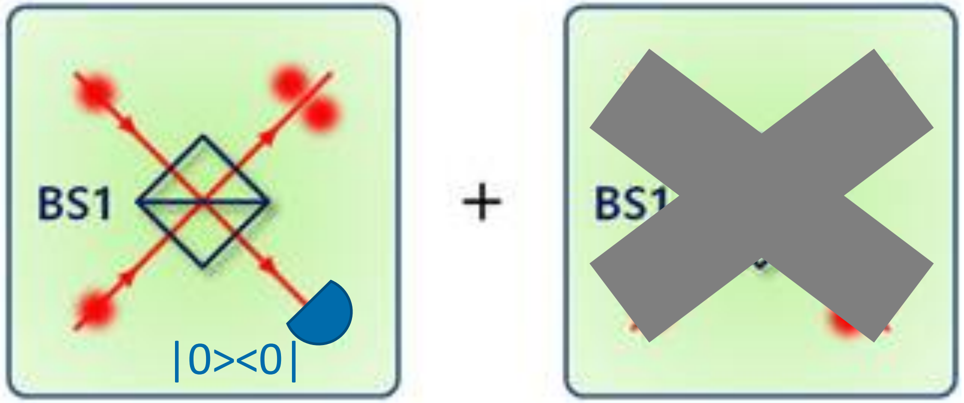
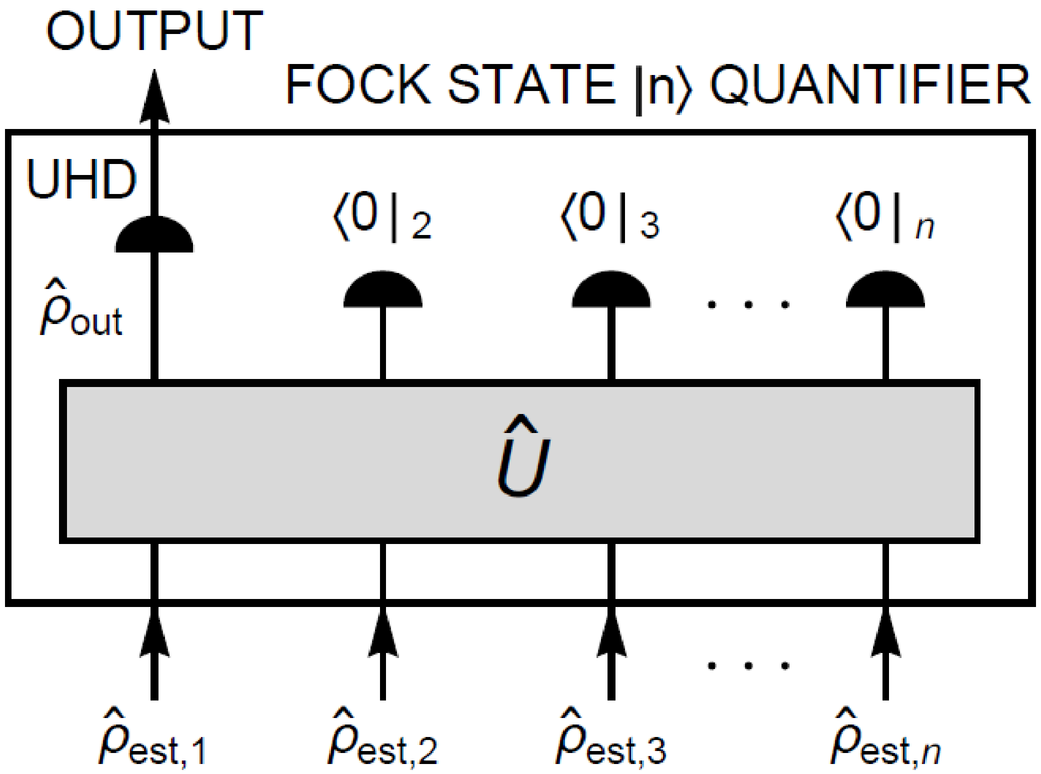
Photon bunching

Fock state generation by photon bunching



C. K. Hong; Z. Y. Ou and L. Mandel, Phys. Rev. Lett. 59, 2044–2046 (1987)

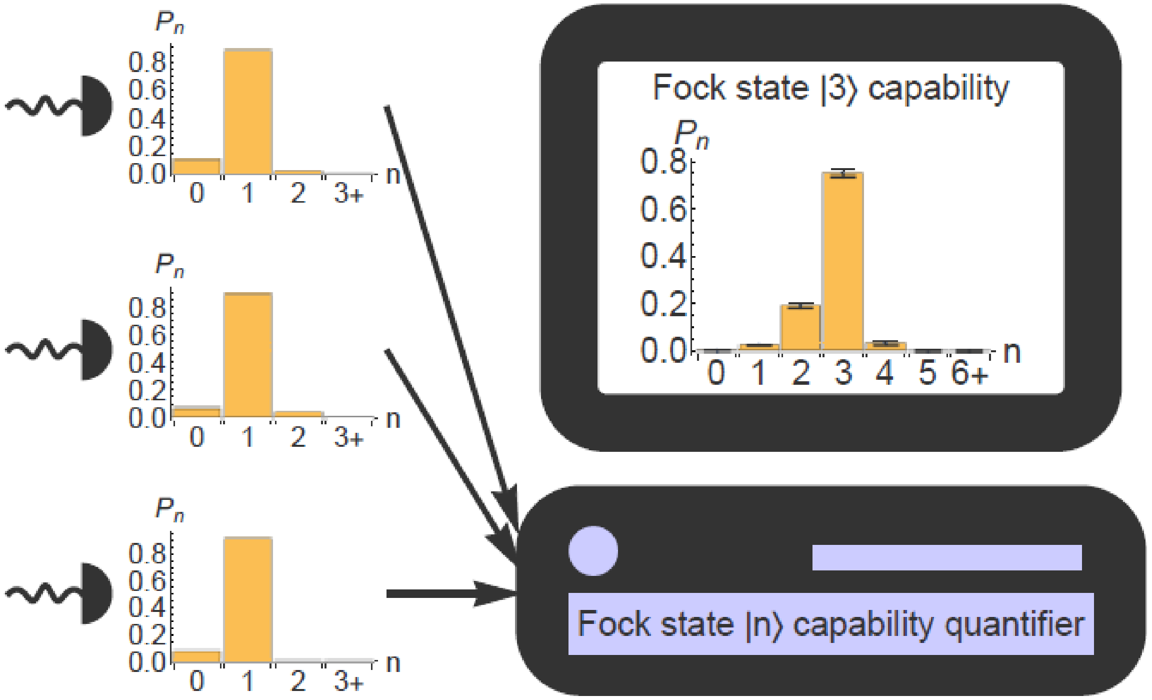
Does output state exhibit oscillations of Wigner function corresponding to Fock state |n> ?



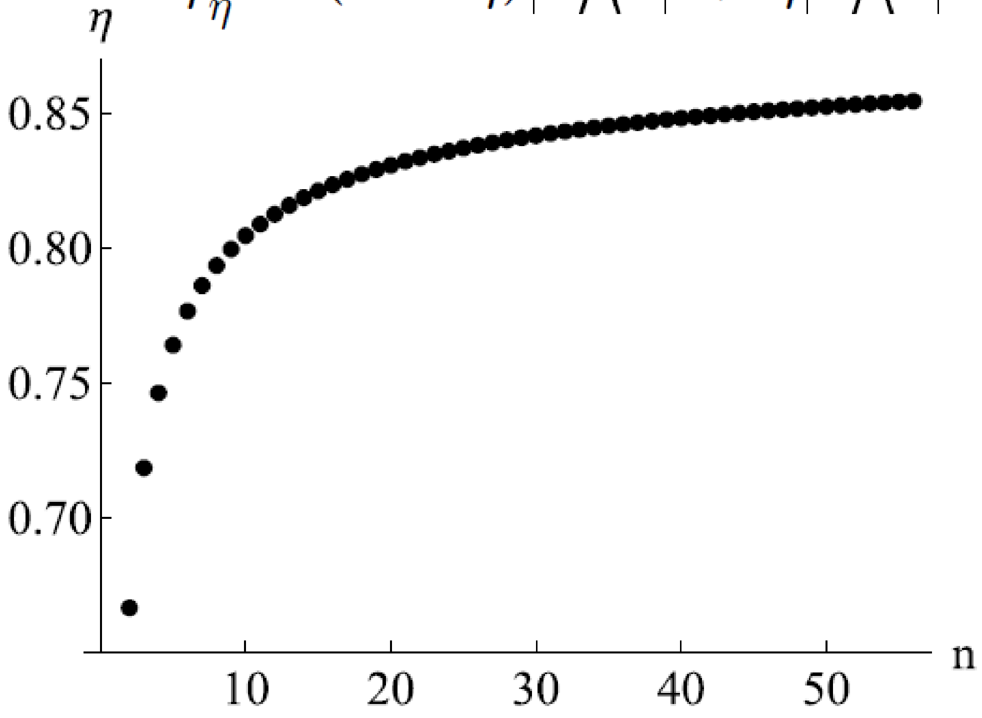
Independent estimated states from n single photon sources

P. Zapletal and R. Filip, Sci. Rep. 7, 1484 (2017)

FOCK STATE CAPABILITY



$$\hat{\rho}_\eta = (1-\eta)|0\rangle\langle 0| + \eta|1\rangle\langle 1|$$



P. Zapletal and R. Filip, Sci. Rep. 7, 1484 (2017)

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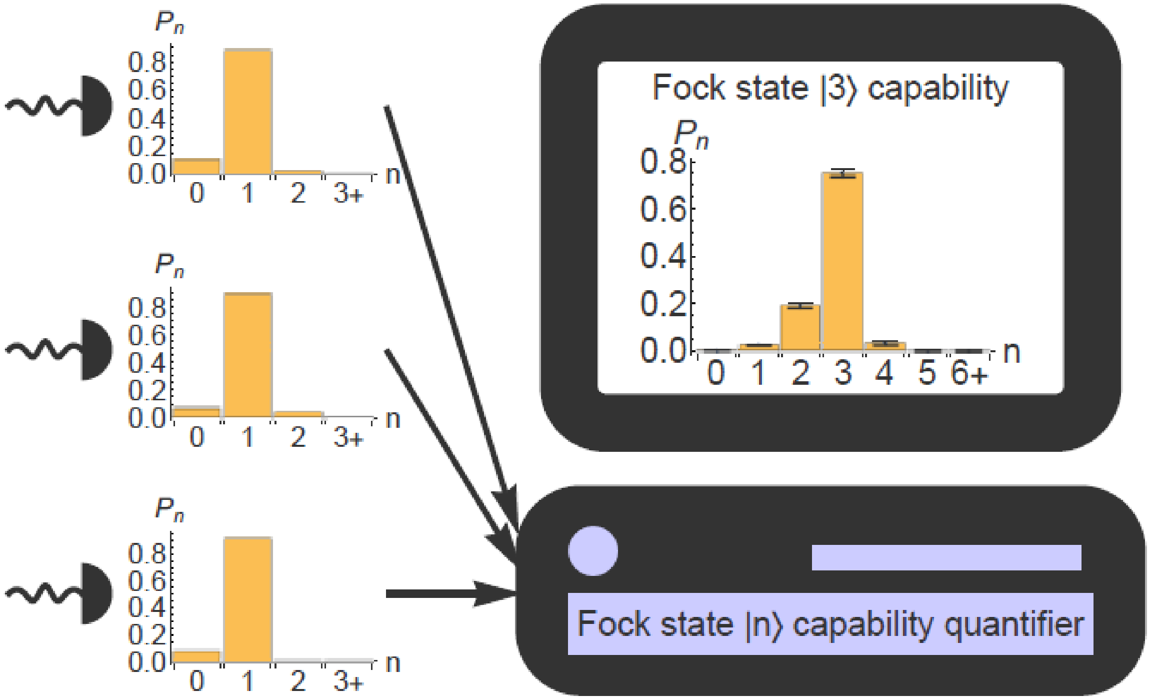
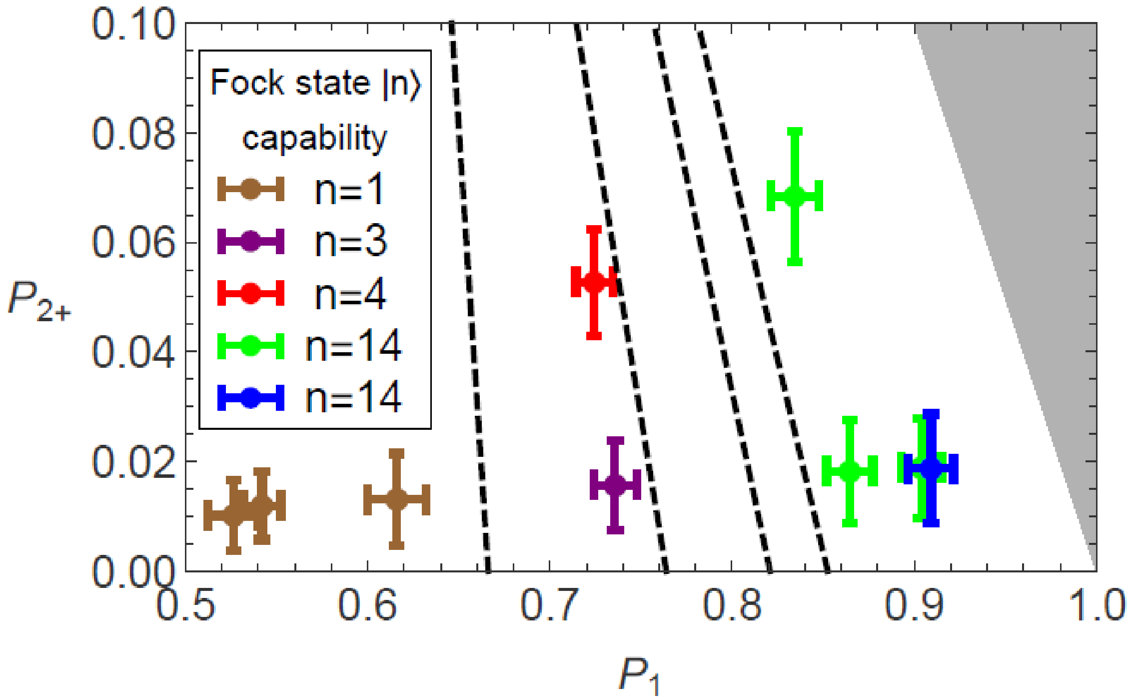
FOCK STATE CAPABILITY





NEXT?

H. Le Jeannic, A. Cavaillès, K. Huang, P. Zapletal, R. Filip, J. Laurat, Experimental verication of Fock state capability for single-photon states, submitted.

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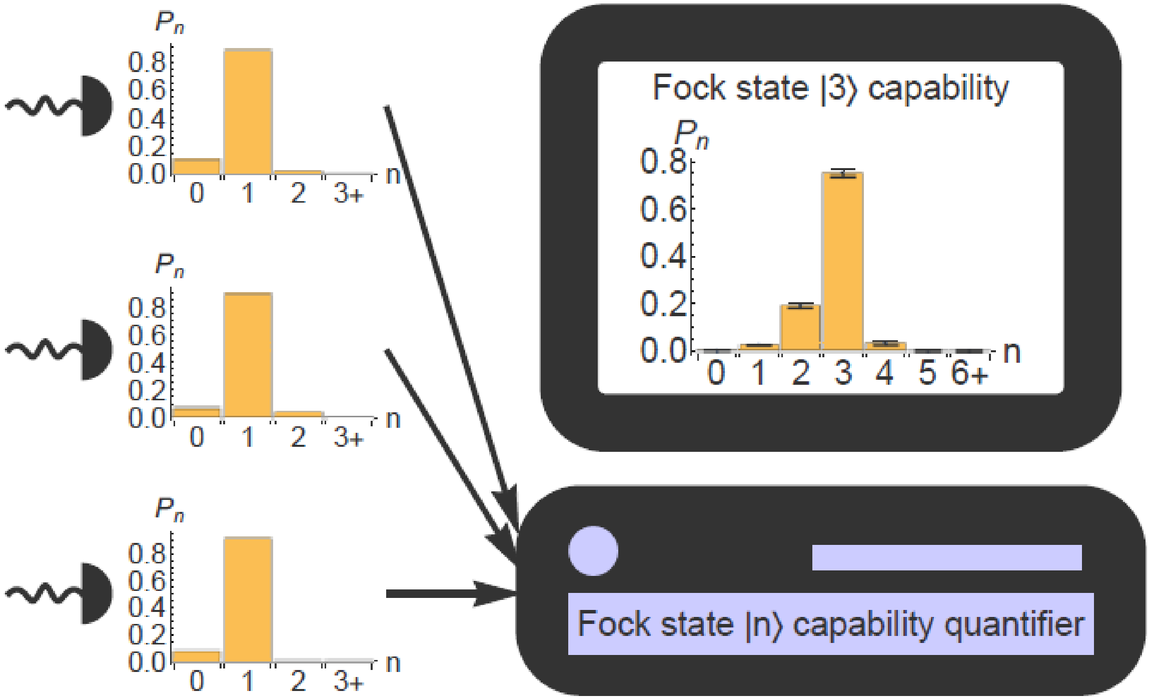
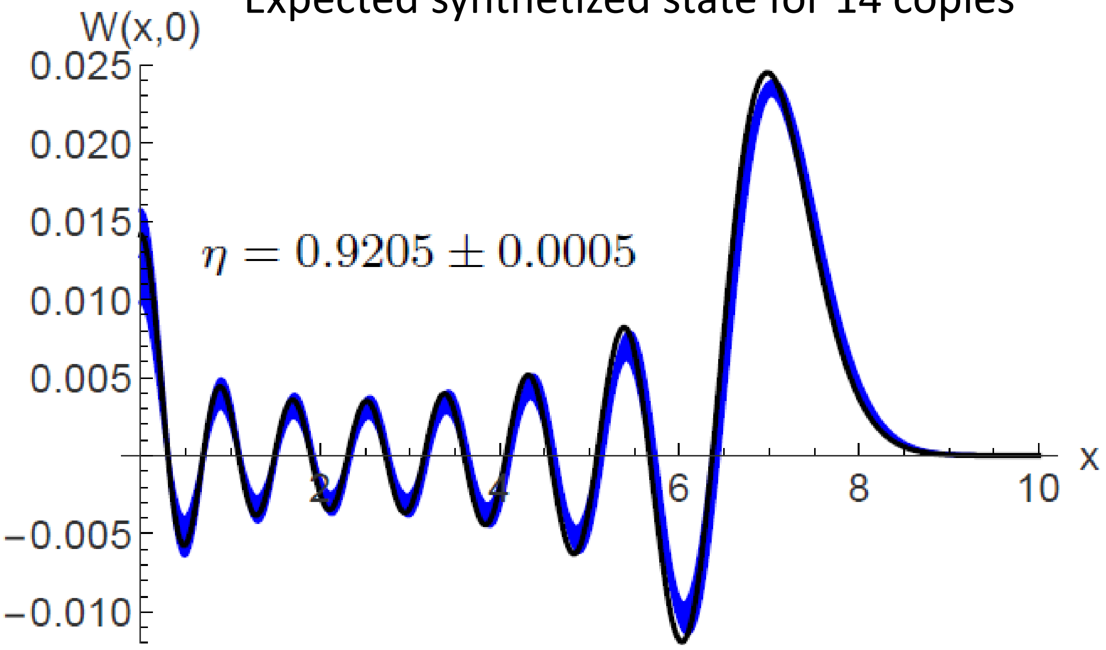
FOCK STATE CAPABILITY



Expected synthetized state for 14 copies



Almost perfectly attenuated Fock state |14>.

H. Le Jeannic, A. Cavaillès, K. Huang, P. Zapletal, R. Filip, J. Laurat, Experimental verication of Fock state capability for single-photon states, submitted.

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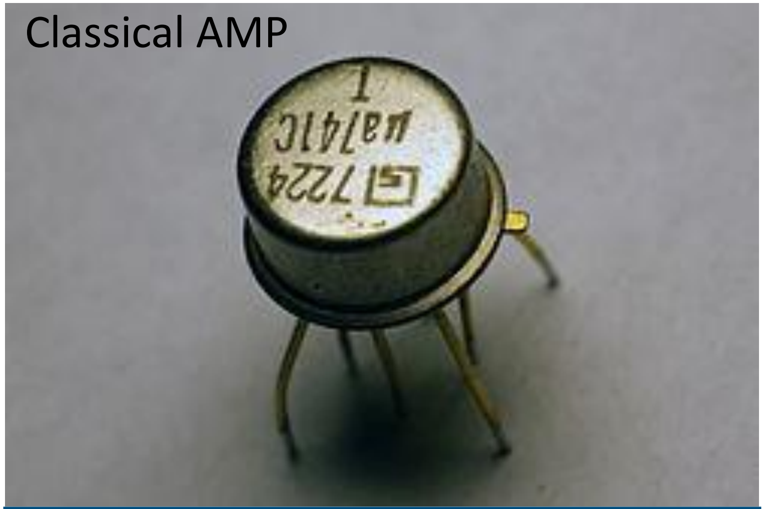
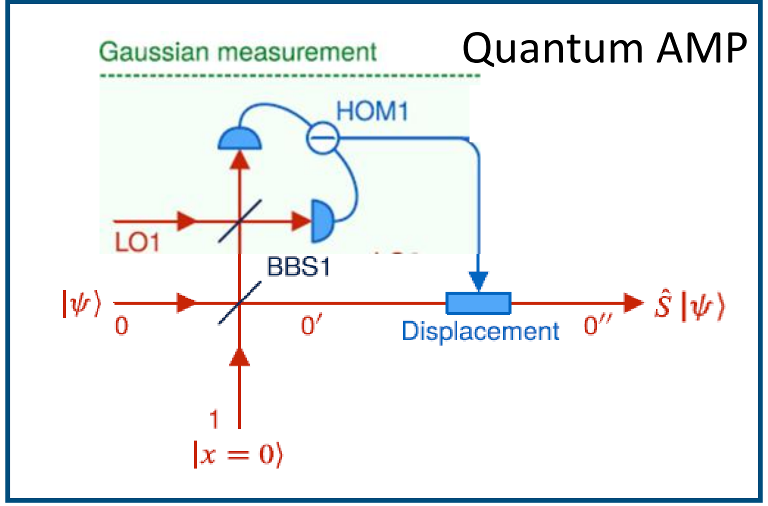
QUANTUM OPERATIONAL AMPLIFIER/SQUEEZER

From off-line squeezed state to on-line linear amplifiar/ squeezer for any travelling light.

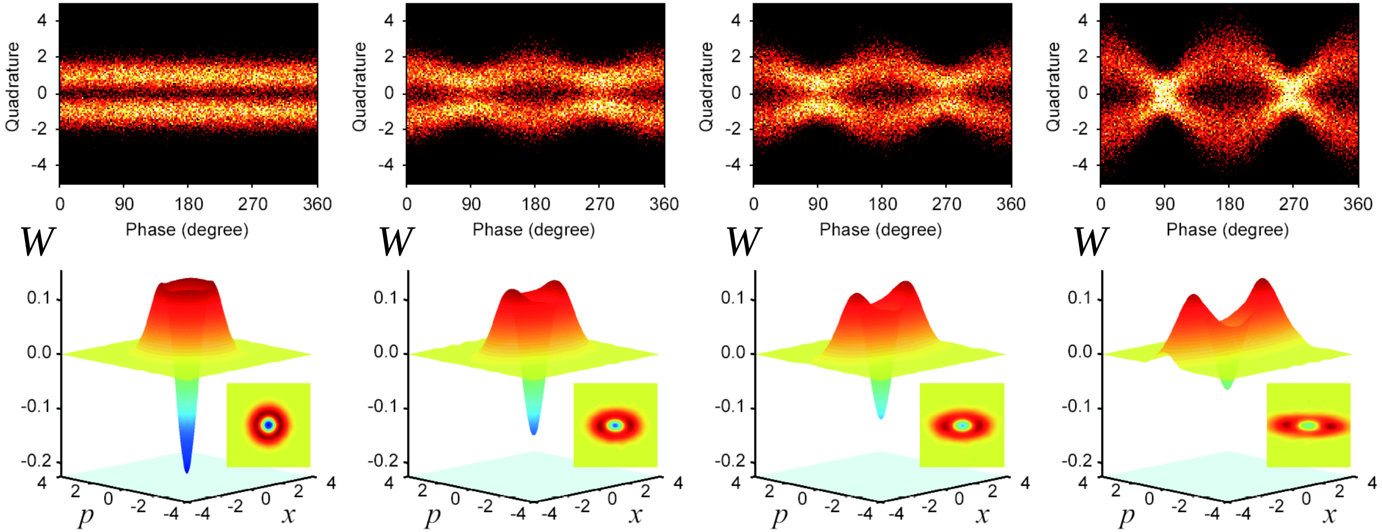
Classical AMP



Quantum AMP



Single-photon amplification/squeezing



Y. Miwa, J. Yoshikawa, N. Iwata, M. Endo, P. Marek, R. Filip, P. van Loock, and A. Furusawa, Phys. Rev. Lett. 113, 013601 (2014)

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

QUANTUM OPERATIONAL AMPLIFIER/SQUEEZER

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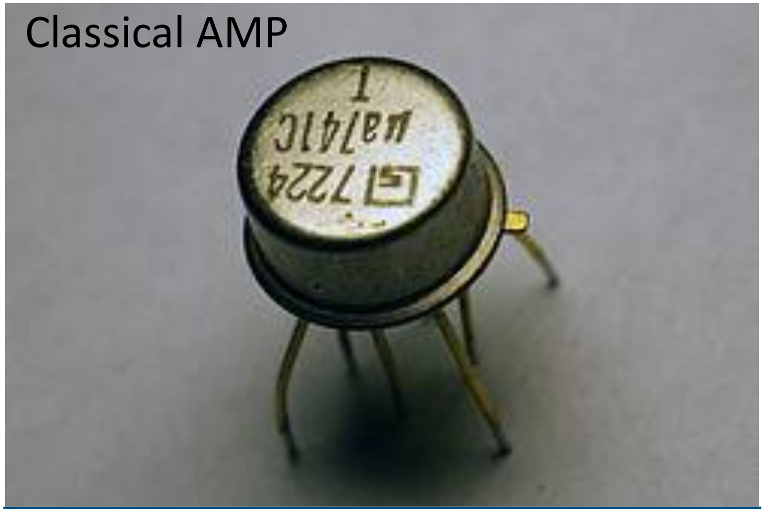
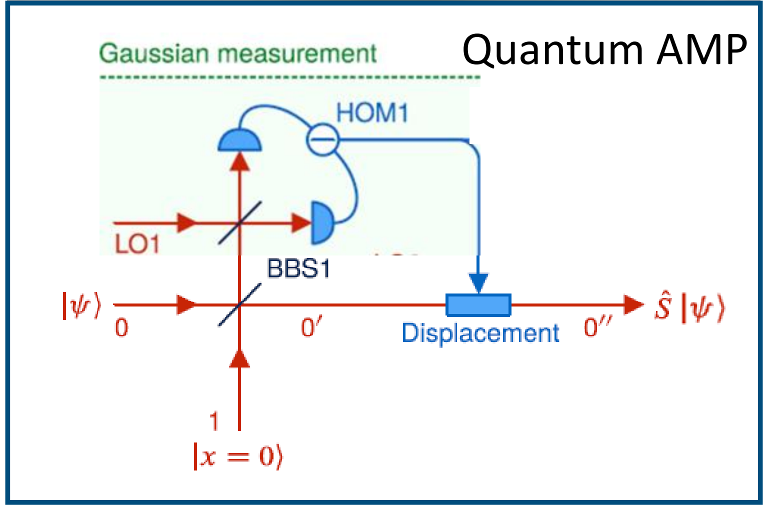
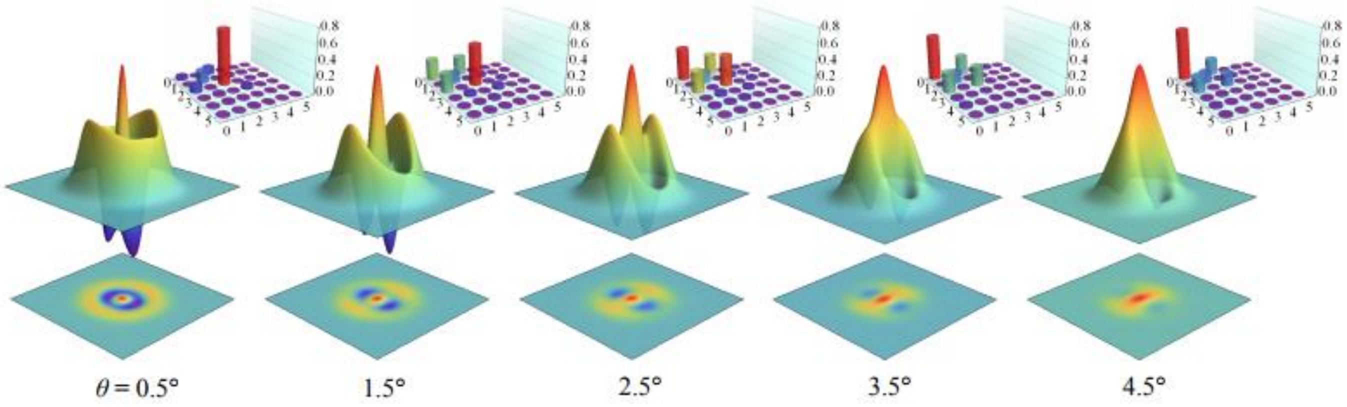
From off-line squeezed state to on-line linear amplifiar/ squeezer for any travelling light.





Amplification reduces a demand on state preparation

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, Phys. Rev. Lett. 115, 023602 (2015)

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

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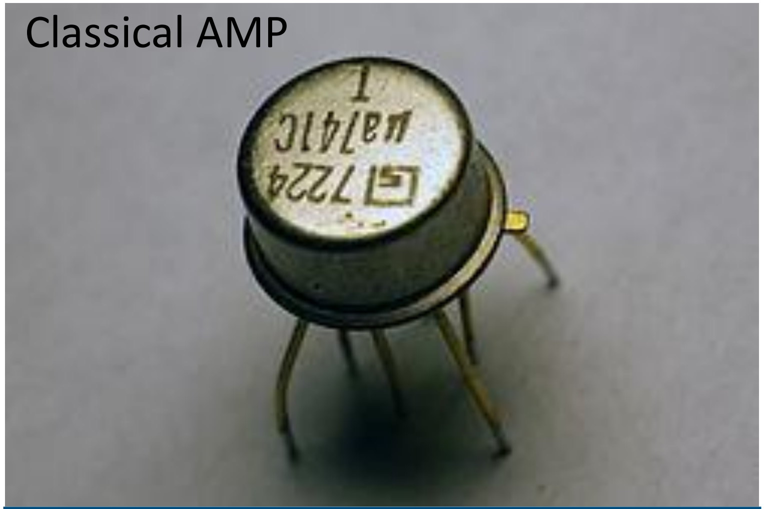
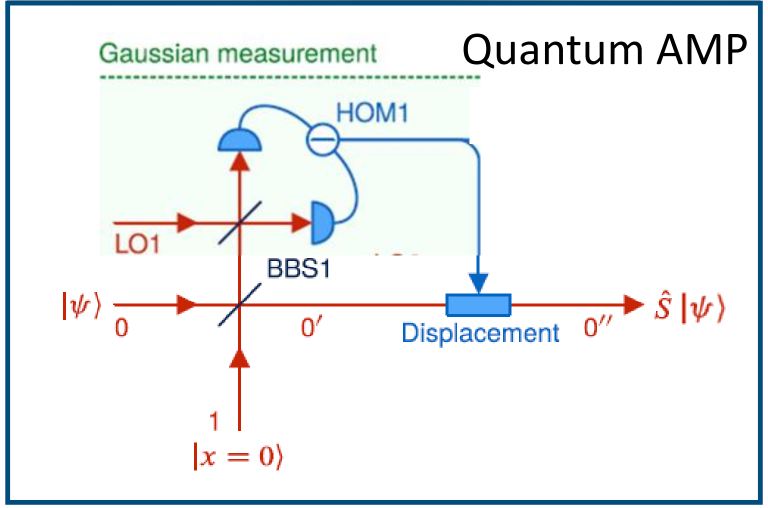
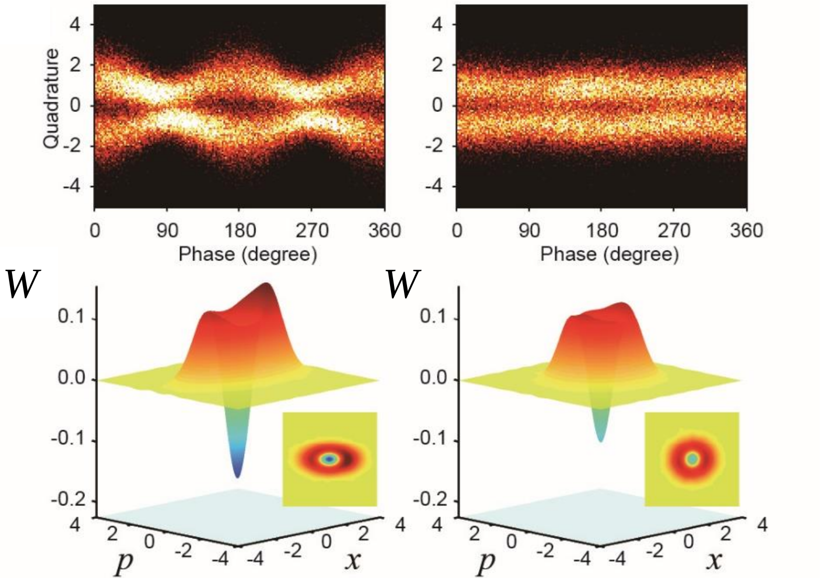
QUANTUM OPERATIONAL AMPLIFIER/SQUEEZER

From off-line squeezed state to on-line linear amplifiar/ squeezer for any travelling light.





Single-photon de-amplification/squeezing



Y. Miwa, J. Yoshikawa, N. Iwata, M. Endo, P. Marek, R. Filip, P. van Loock, and A. Furusawa, Phys. Rev. Lett. 113, 013601 (2014)

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

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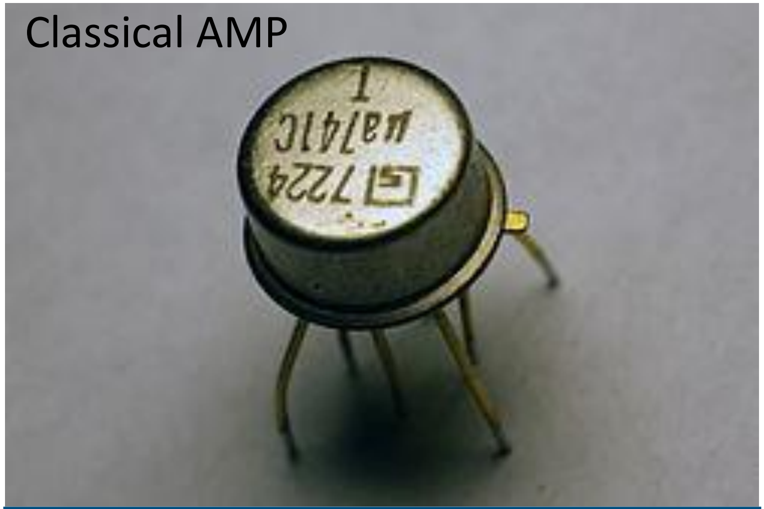
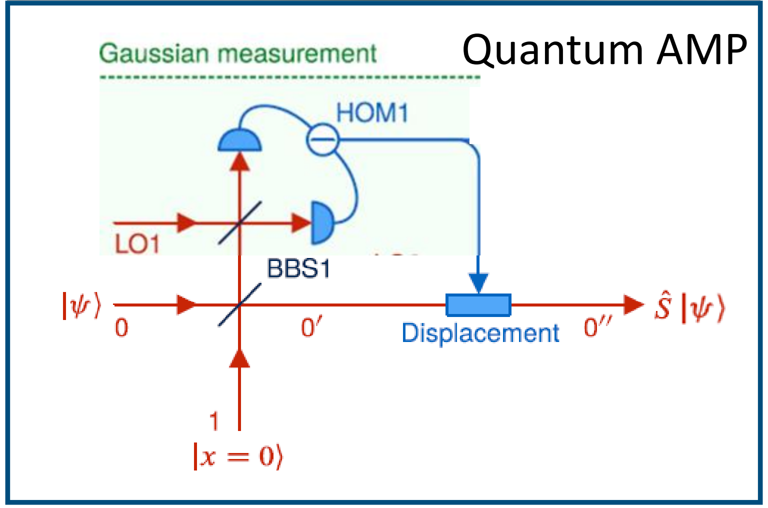
QUANTUM OPERATIONAL AMPLIFIER/SQUEEZER

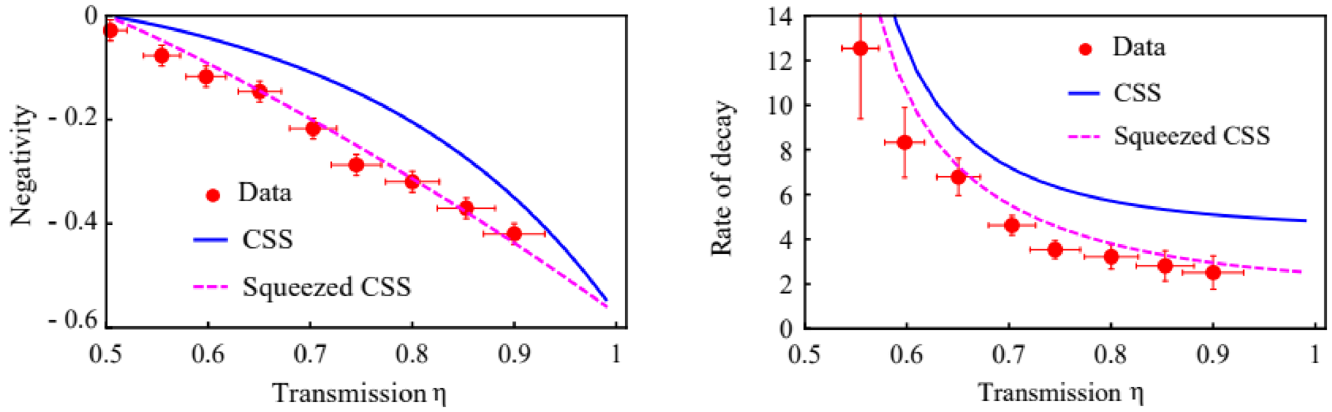
From off-line squeezed state to on-line linear amplifiar/ squeezer for any travelling light.





<u>Amplification slows down quantum interference decay</u>

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



H. Le Jeannic, A. Cavaillès, K. Huang, R. Filip, J. Laurat, arXiv:1707.06244

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

NEXT?

DETERMINISTIC CUBIC NONLINEARITY

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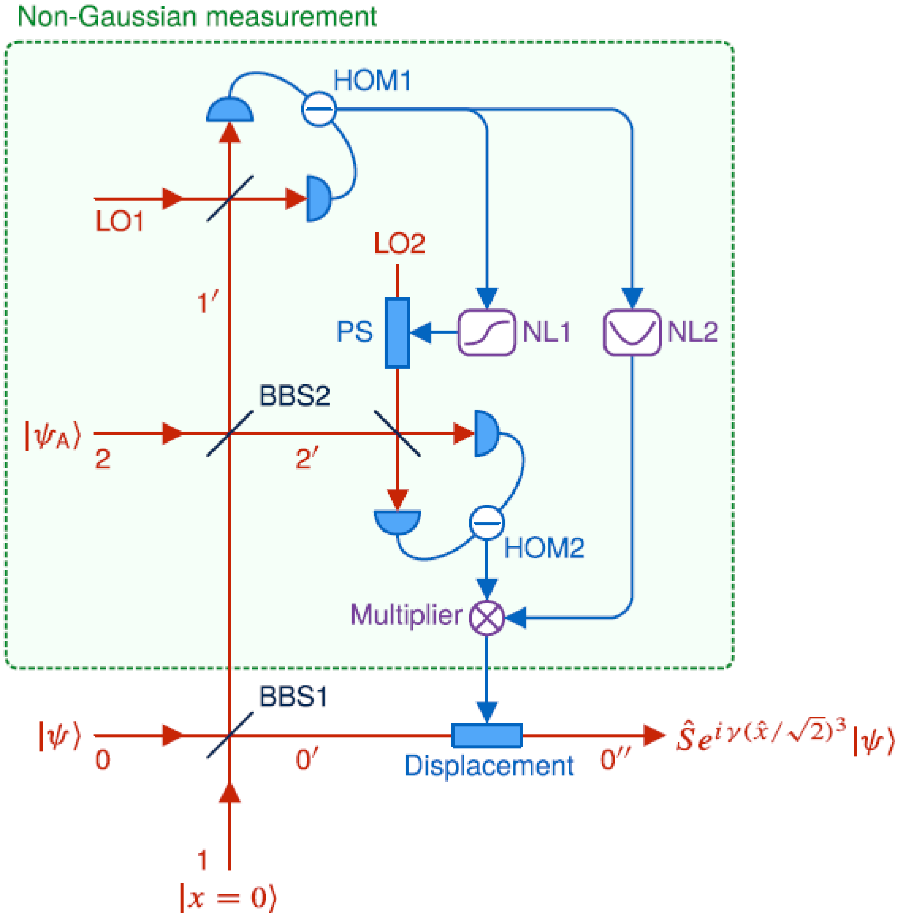
$$\hat{U} = e^{i\gamma\hat{x}^3} \qquad \hat{x}' = \hat{x}, \quad \hat{p}' = \hat{p} + 3\gamma\hat{x}^2$$



- adaptive measurement strategy
- nonlinear feedforward control
- fast time-resolved regime

$$\hat{x}_0'' = \frac{1}{\sqrt{2}}\hat{x}_0 - \frac{1}{\sqrt{2}}\hat{x}_1,$$

mode 1

$$\hat{p}_0'' = \sqrt{2}\left(\hat{p}_0 + \frac{3\gamma}{2\sqrt{2}}\hat{x}_0^2\right) + (\hat{p}_2 - 3\gamma\hat{x}_2^2) + 3\gamma\left(\hat{x}_0\hat{x}_1 + \frac{1}{2}\hat{x}_1^2\right)$$

mode 0

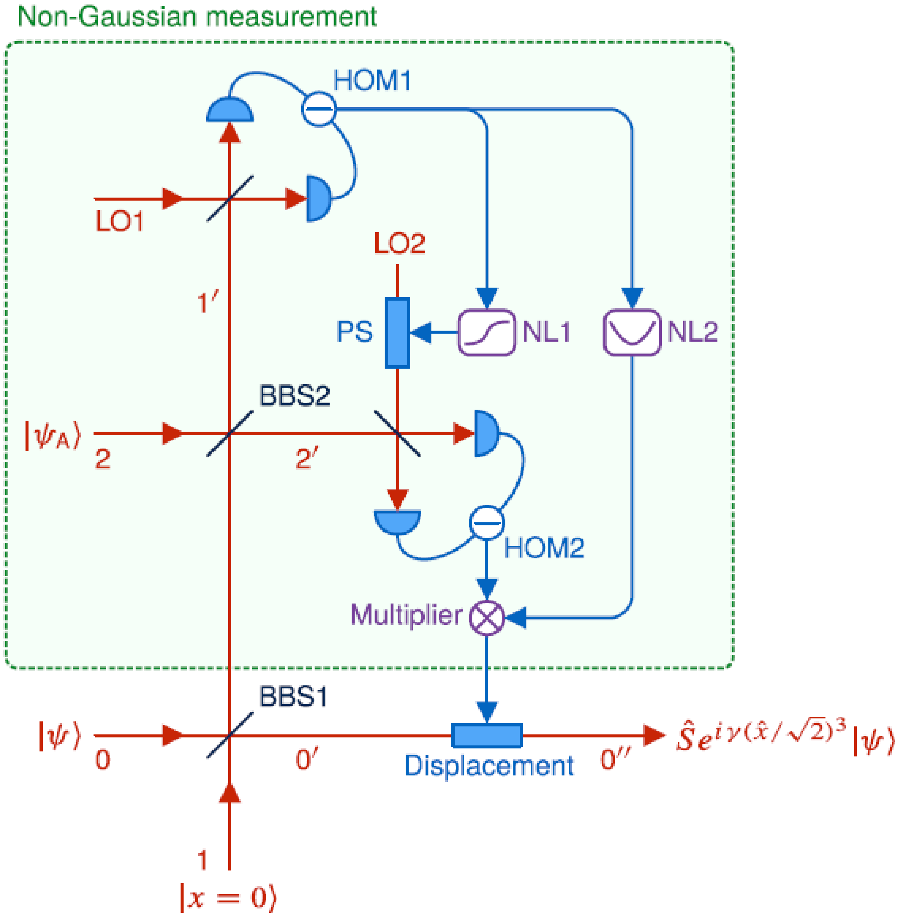
mode 2

mode 1

K. Miyata, H. Ogawa, P. Marek, R. Filip, H. Yonezawa, J. Yoshikawa, and A. Furusawa, Phys. Rev. A 93, 022301 (2016).

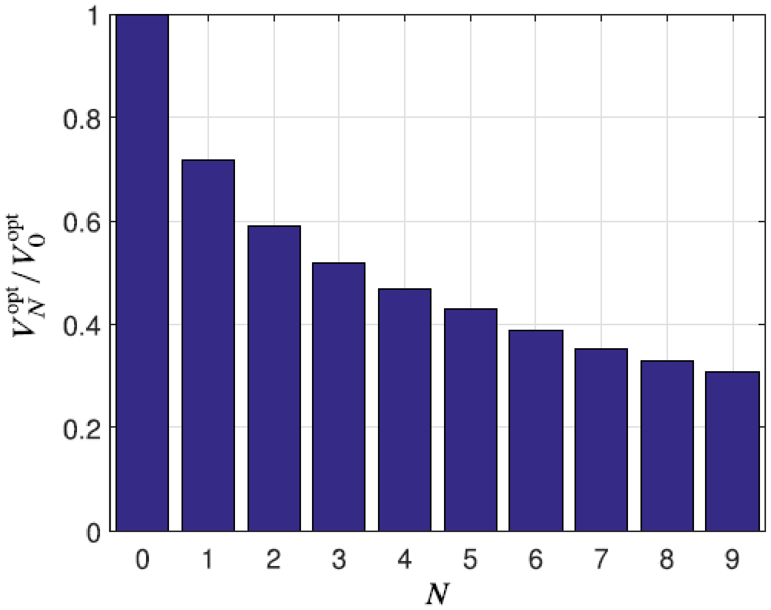
DETERMINISTIC CUBIC NONLINEARITY

$$\hat{U} = e^{i\gamma\hat{x}^3} \qquad \hat{x}' = \hat{x}, \quad \hat{p}' = \hat{p} + 3\gamma\hat{x}^2$$



- nonlinear squeezed states (cubic) $(\hat{p}_2 - 3\gamma\hat{x}_2^2)$

variance of added noise

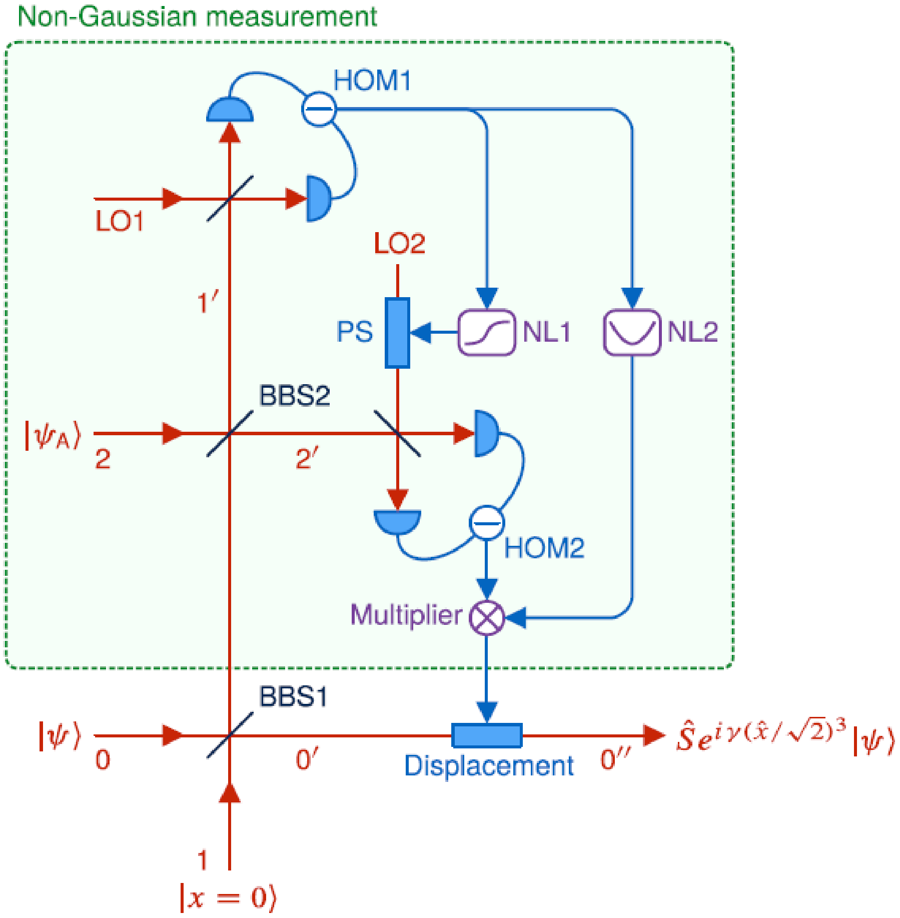


N-photon superposition for ancilla $|\psi_A>$

K. Miyata, H. Ogawa, P. Marek, R. Filip, H. Yonezawa, J. Yoshikawa, and A. Furusawa, Phys. Rev. A 93, 022301 (2016).

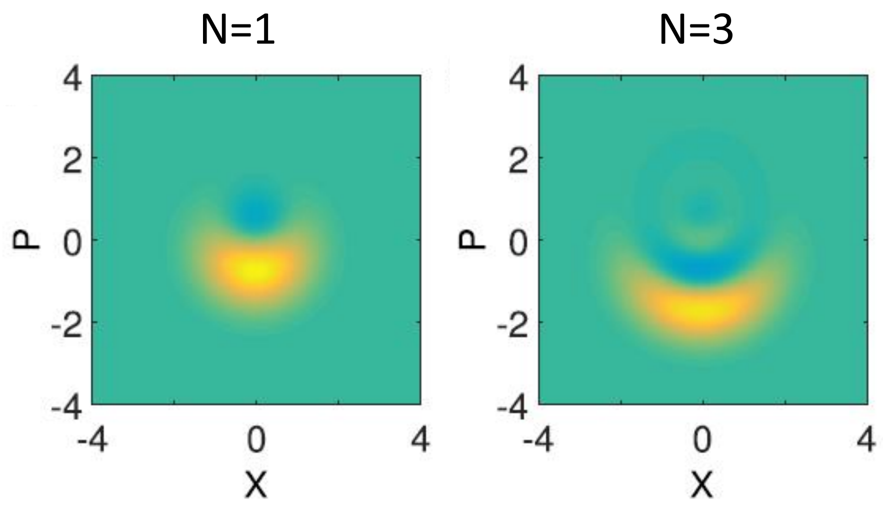
DETERMINISTIC CUBIC NONLINEARITY

$$\hat{U} = e^{i\gamma\hat{x}^3} \qquad \hat{x}' = \hat{x}, \quad \hat{p}' = \hat{p} + 3\gamma\hat{x}^2$$



- nonlinear squeezed states (cubic) $(\hat{p}_2 - 3\gamma\hat{x}_2^2)$

Wigner function

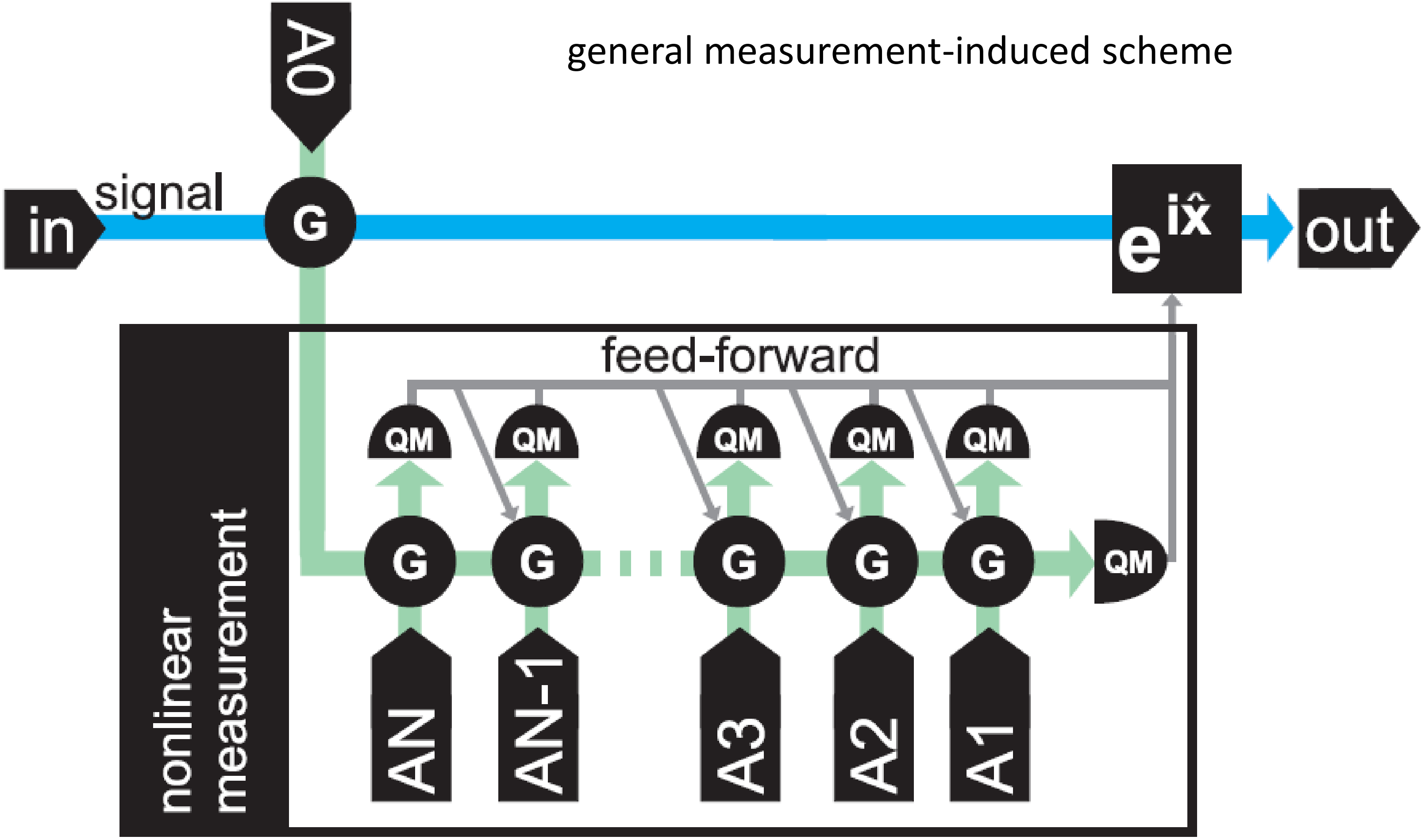


N-photon superposition for ancilla $|\psi_A>$

K. Miyata, H. Ogawa, P. Marek, R. Filip, H. Yonezawa, J. Yoshikawa, and A. Furusawa, Phys. Rev. A 93, 022301 (2016).

DETERMINISTIC V(x) NONLINEARITY

general measurement-induced scheme



P. Marek, R. Filip, H. Ogawa, A. Sakaguchi, S. Takeda, J. Yoshikawa and A. Furusawa, General implementation of arbitrary nonlinear quadrature phase gates, quant-ph 1708.02822 (2017)

FUTURE APPLICATIONS

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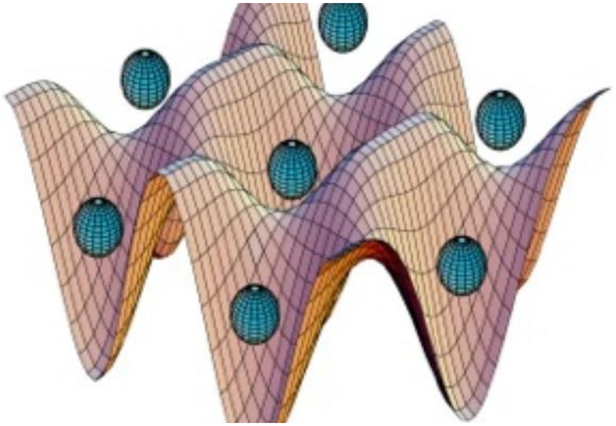
analog quantum simulators

I.H. Deutsch, Scientific American (2015)

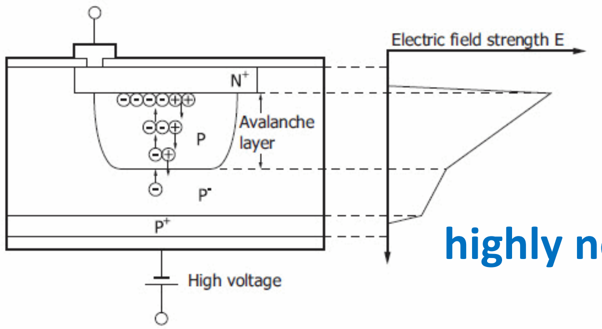


highly nonlinear

analog quantum sensing

L. Degen, F. Reinhard, P. Cappellaro
Rev. Mod. Phys. 89, 035002 (2017)

APD structure

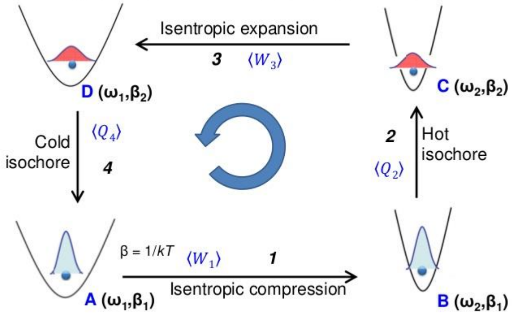


highly nonlinear

analog quantum engines

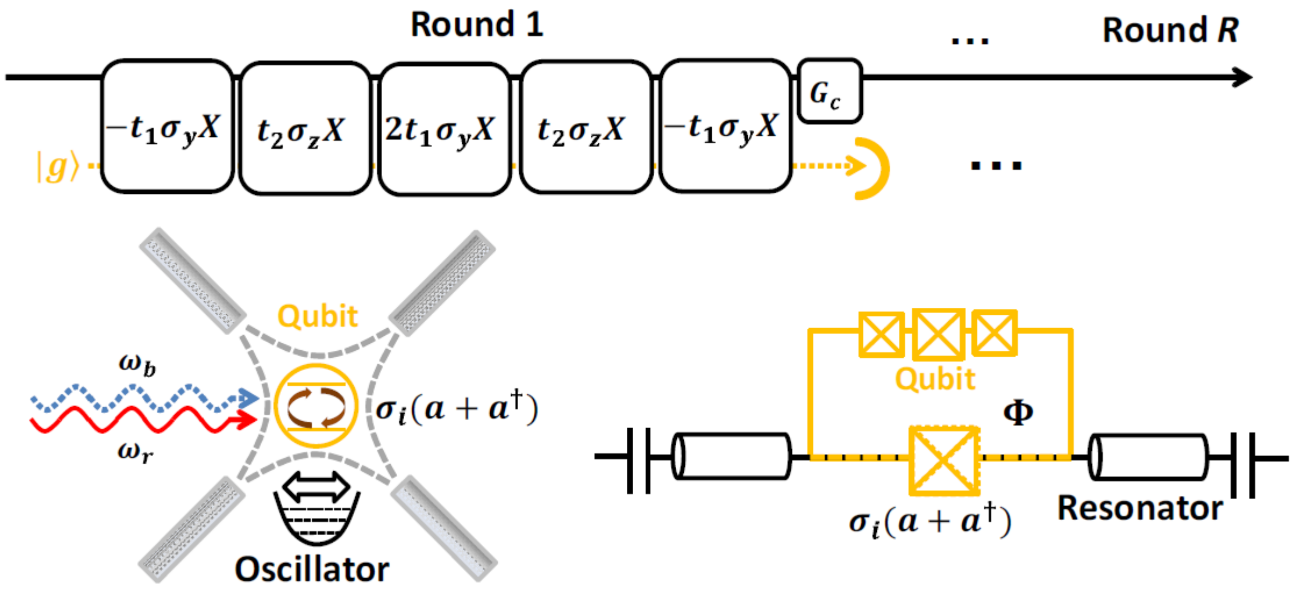
J. Millen, A. Xuereb, NJP (2016)

Quantum Otto Cycle: principle



highly nonlinear

DETERMINISTIC CUBIC NONLINERITY



$$\Gamma[\rho] = \hat{G}_c(\hat{O}_{3,s}\rho\hat{O}_{3,s}^\dagger + \hat{O}_f\rho\hat{O}_f^\dagger)\hat{G}_c^\dagger$$

$$\hat{O}_{3,s} \approx \langle g|\exp[i2t_2\hat{X}\cos[2t_1\hat{X}]\sigma_z]\,|g\rangle$$
$$= \exp[i2t_2\hat{X}\cos[2t_1\hat{X}]].$$

$$\exp[i2t_2\hat{X}\left(1-(2t_1\hat{X})^2/2\right)]$$

$$\hat{O}_f = -\sin^2(t_2\hat{X})\sin(4t_1\hat{X})$$

- deterministic without measurement
- many rounds with pulsed control (ions, cavity/circuit QED)
- feasible **Rabi coupling** (J-C interaction beyond RWA)
- correction by simple Gaussian transformation

K. Park, P. Marek, and R. Filip, Deterministic nonlinear phase gates induced by a single qubit ArXive quant-ph 1706.09660 (2017)

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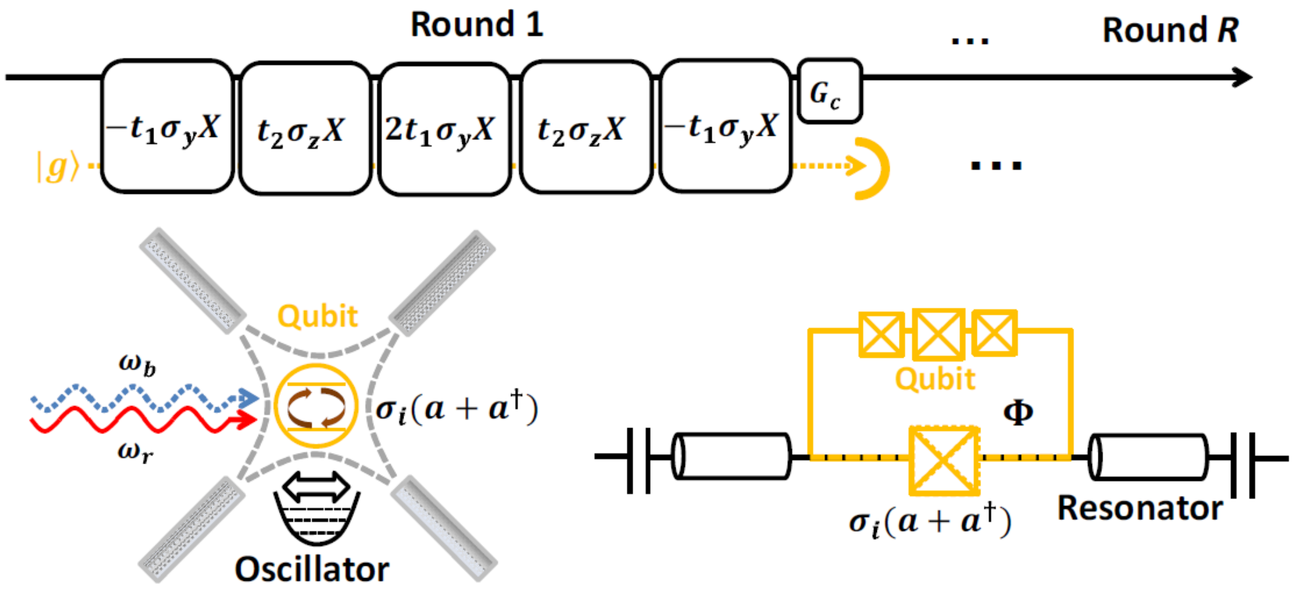
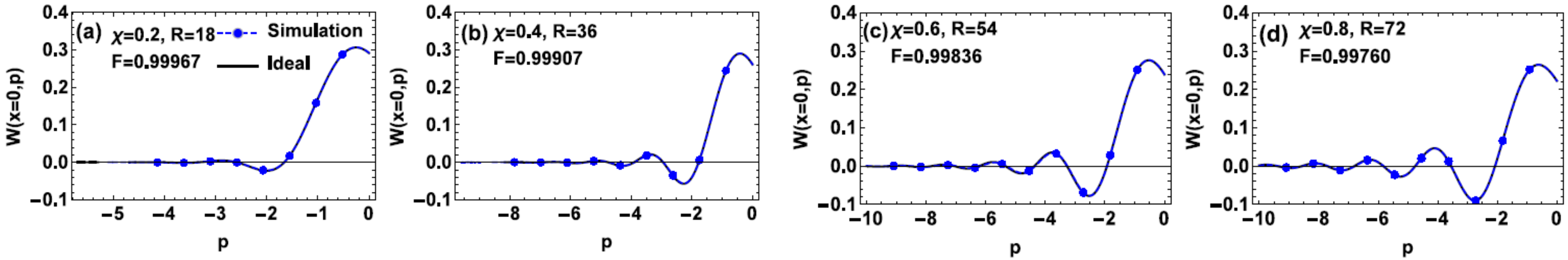
DETERMINISTIC CUBIC NONLINEARITY



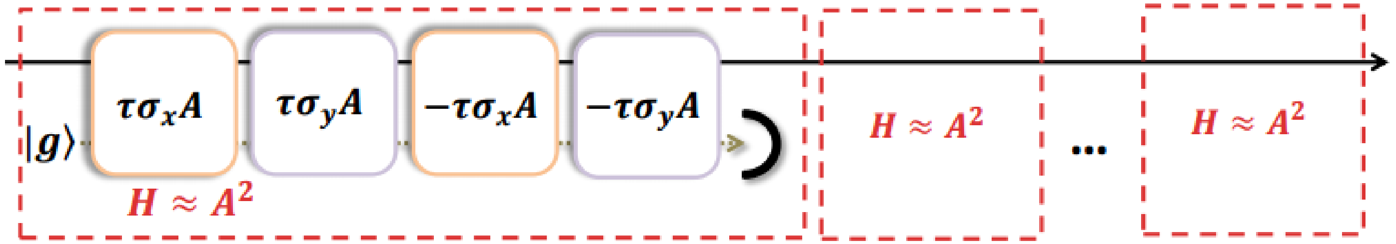
NEXT?



K. Park, P. Marek, and R. Filip, Deterministic nonlinear phase gates induced by a single qubit ArXive quant-ph 1706.09660 (2017)

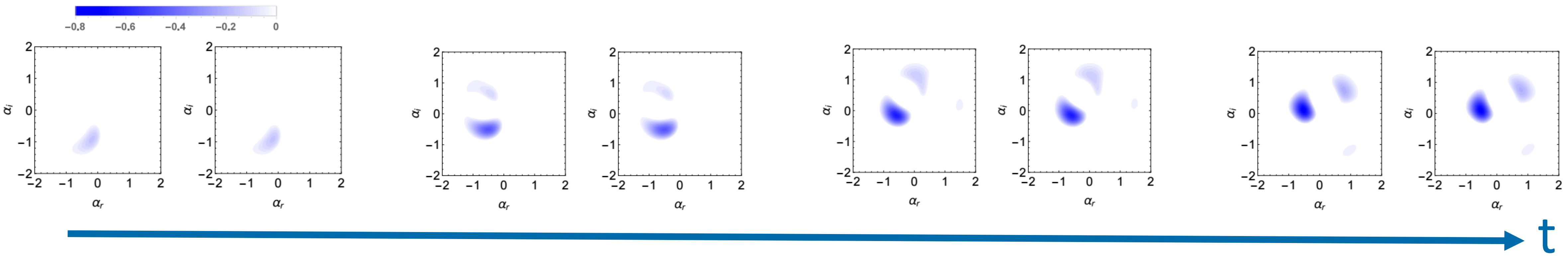
DETERMINISTIC KERR NONLINEARITY

Palacký University Olomouc



- deterministic without measurement
- many rounds with pulse control
- we can already use dispersive and Rabi coupling

Dynamics of negative part of Wigner function: splitting of negativity

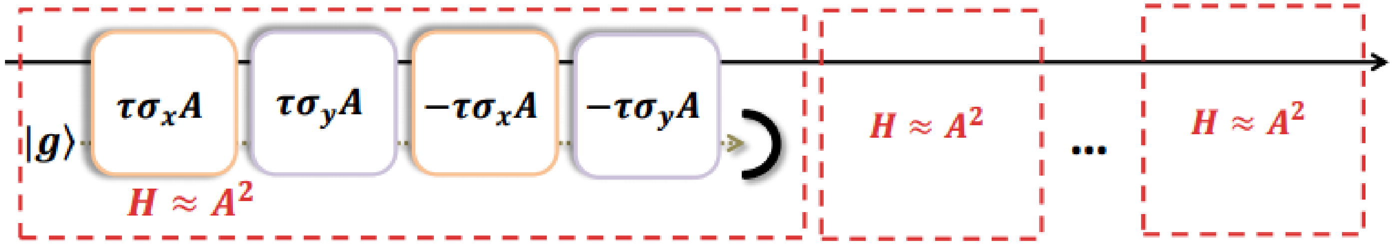


KERR EFFECT

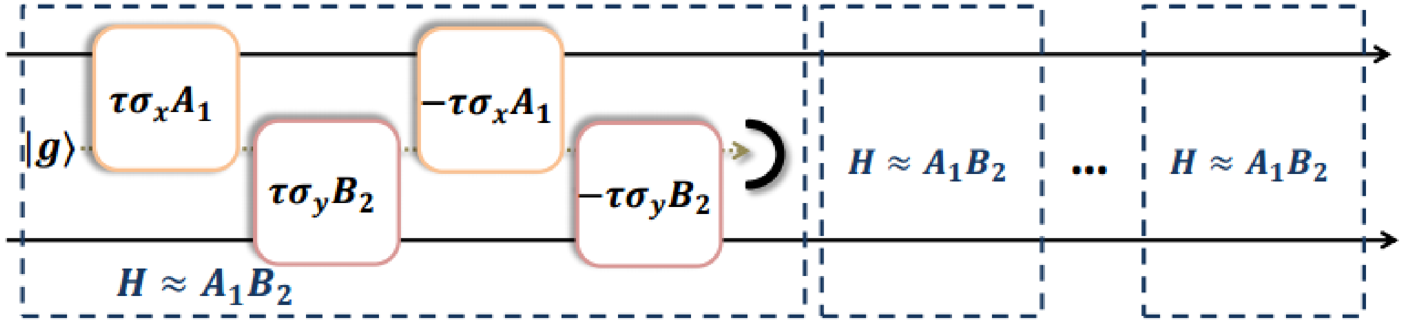
NEXT?

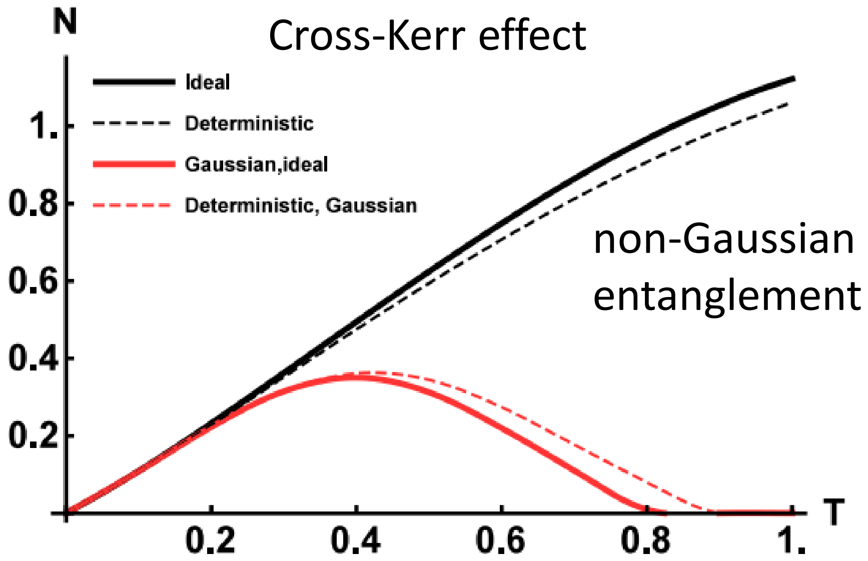
K. Park, P. Marek, and R. Filip, Sci. Rep. 7, 11536 (2017).

DETERMINISTIC CROSS KERR EFFECT



- deterministic without measurement
- many rounds with pulse control
- we can already use **dispersive** and Rabi coupling



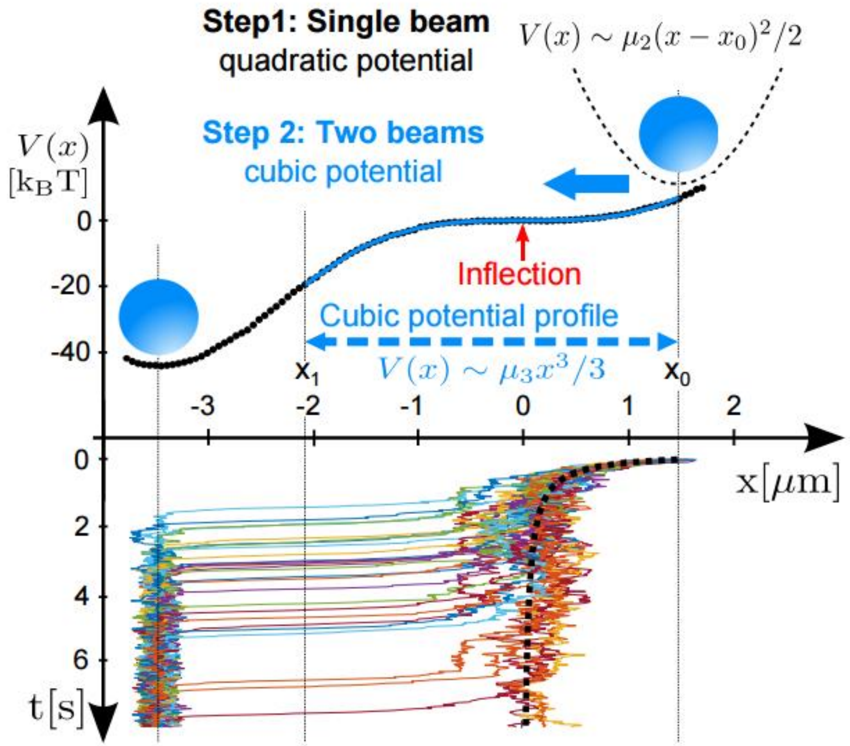


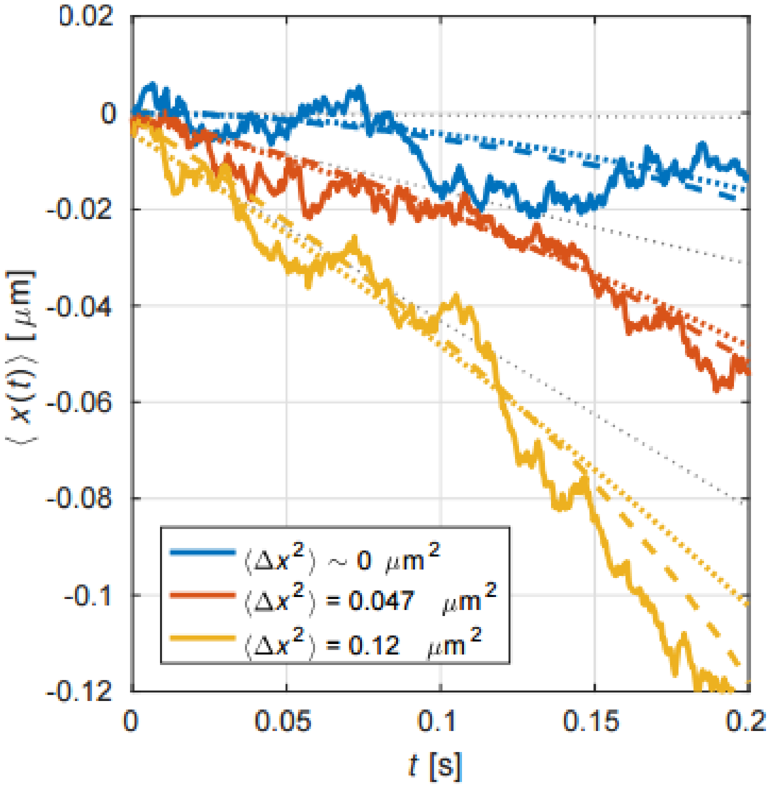
NEXT?

K. Park, P. Marek, and R. Filip, Sci. Rep. 7, 11536 (2017).

MECHANICAL CUBIC NONLINEARITY

$$\langle x(t)\rangle \simeq \langle x(0)\rangle - \kappa\langle x^2(0)\rangle t - \kappa\frac{k_B T}{\gamma}t^2 + \kappa^2\langle x^3(0)\rangle t^2$$



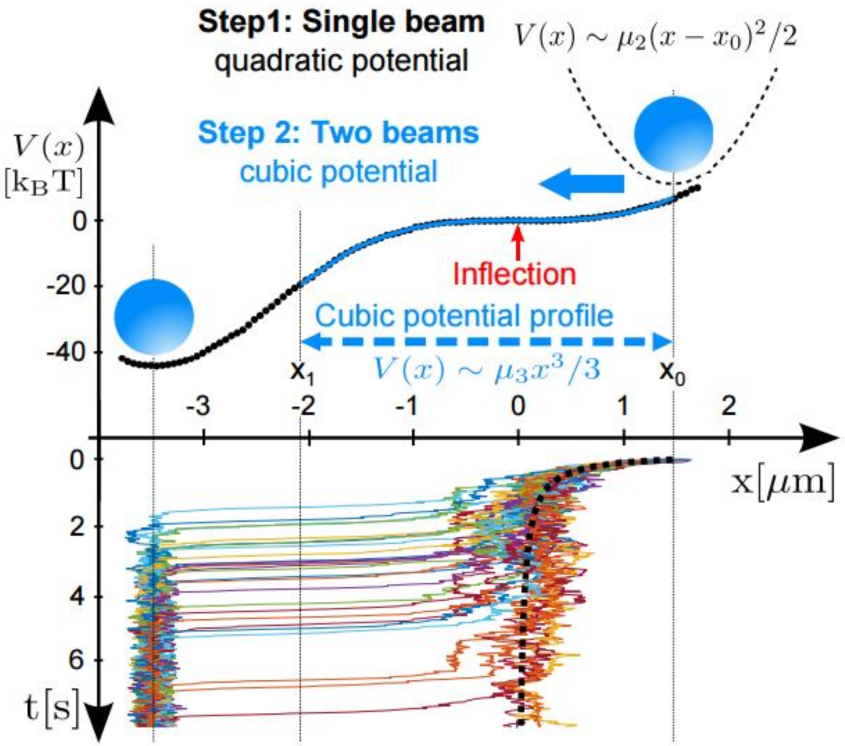


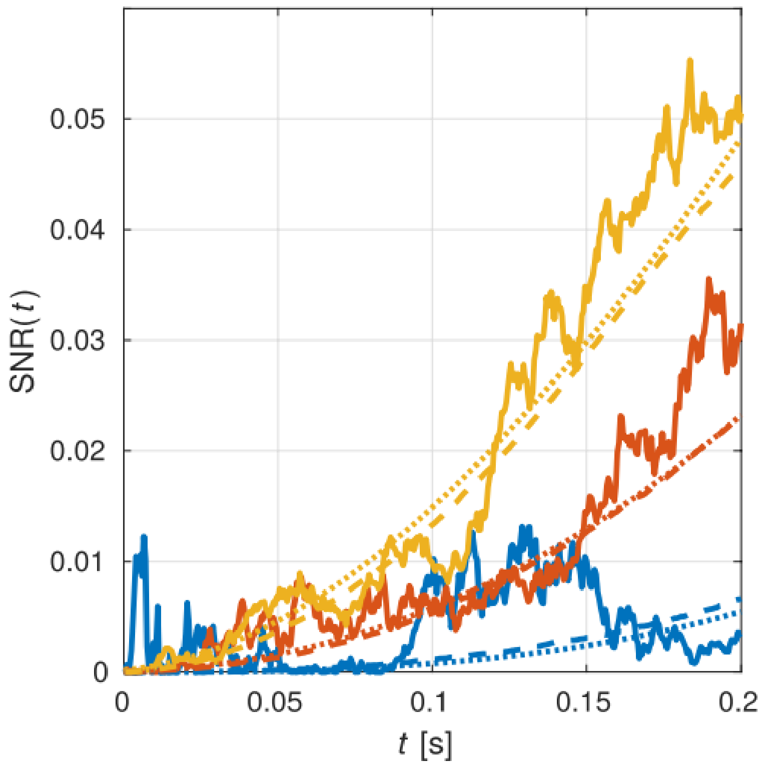
R. Filip and P. Zemánek, J. Opt. 18, 065401 (2016). A. Ryabov, P. Zemánek, and R. Filip, Phys. Rev. E 94, 042108 (2016)

M. Siler, P. Jakl, O. Brzobohaty, A. Ryabov, R. Filip and P. Zemanek, Sci. Rep. 7, 1697 (2017).

MECHANICAL CUBIC NONLINEARITY

$$\langle x(t)\rangle \simeq \langle x(0)\rangle - \kappa\langle x^2(0)\rangle t - \kappa\frac{k_BT}{\gamma}t^2 + \kappa^2\langle x^3(0)\rangle t^2$$





R. Filip and P. Zemánek, J. Opt. 18, 065401 (2016). A. Ryabov, P. Zemánek, and R. Filip, Phys. Rev. E 94, 042108 (2016)

M. Siler, P. Jakl, O. Brzobohaty, A. Ryabov, R. Filip and P. Zemanek, Sci. Rep. 7, 1697 (2017).

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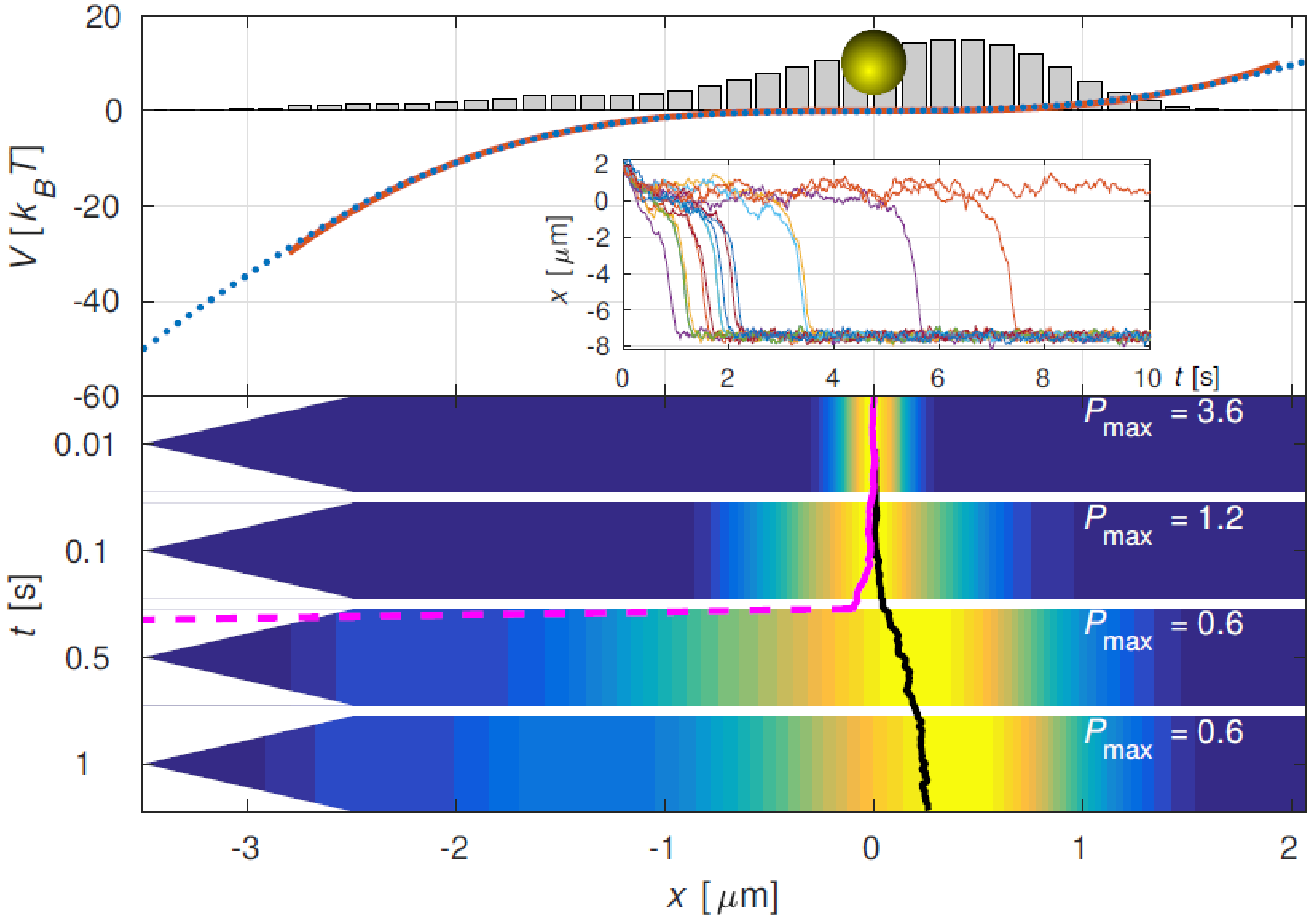

M. Siler, L. Ornigotti, O. Brzobohaty, P. Jakl, A. Ryabov, P. Zemanek, and R. Filip, The-most-likely motion of Brownian particle in an instable cubic potential, submitted (2017).

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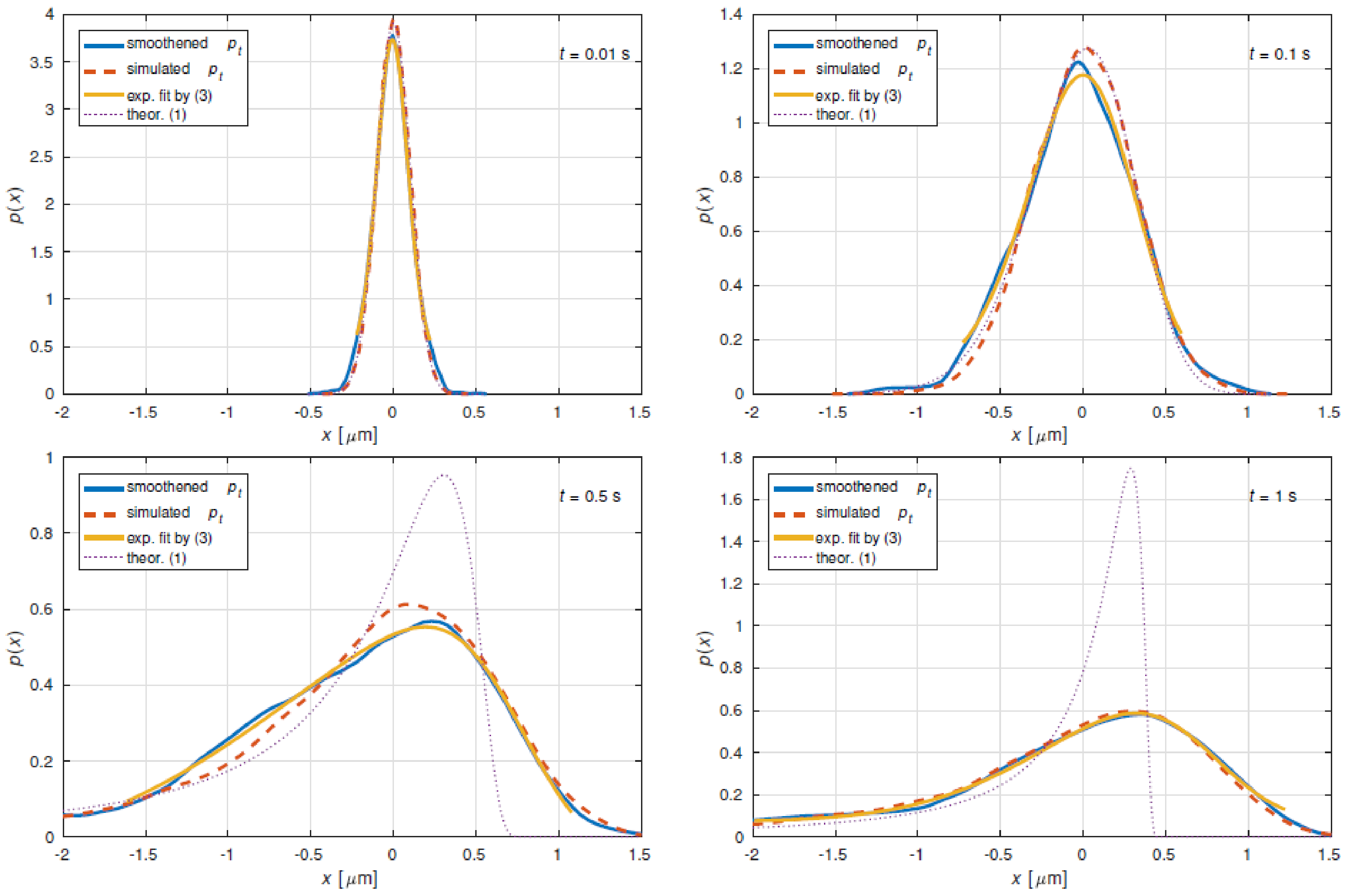
MECHANICAL CUBIC NONLINEARITY



M. Siler, L. Ornigotti, O. Brzobohaty, P. Jakl, A. Ryabov, P. Zemanek, and R. Filip, The-most-likely motion of Brownian particle in an instable cubic potential, submitted (2017).

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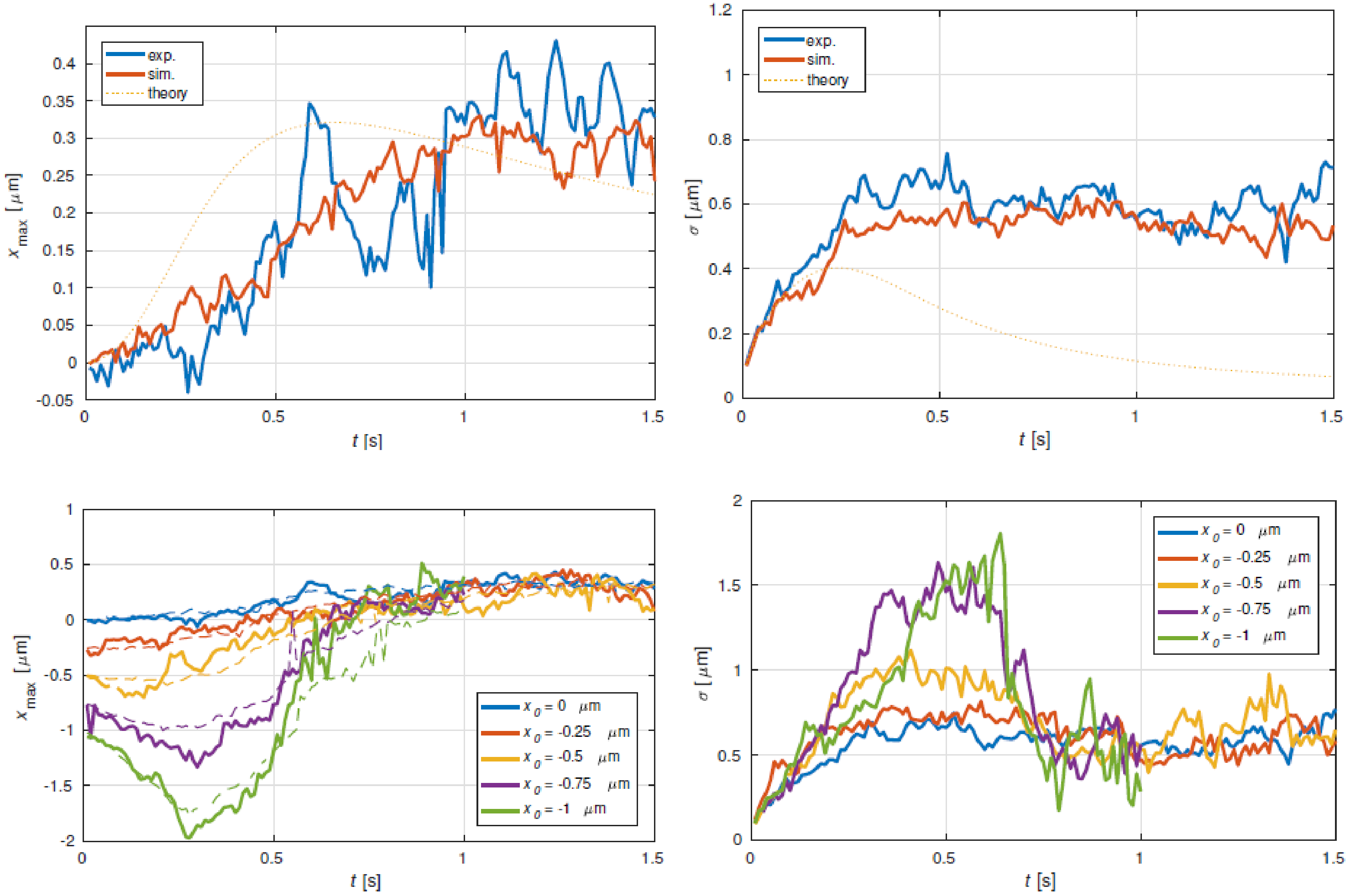
MECHANICAL CUBIC NONLINEARITY



NEXT?

M. Siler, L. Ornigotti, O. Brzobohaty, P. Jakl, A. Ryabov, P. Zemanek, and R. Filip, The-most-likely motion of Brownian particle in an instable cubic potential, submitted (2017).

MECHANICAL CUBIC NONLINEARITY

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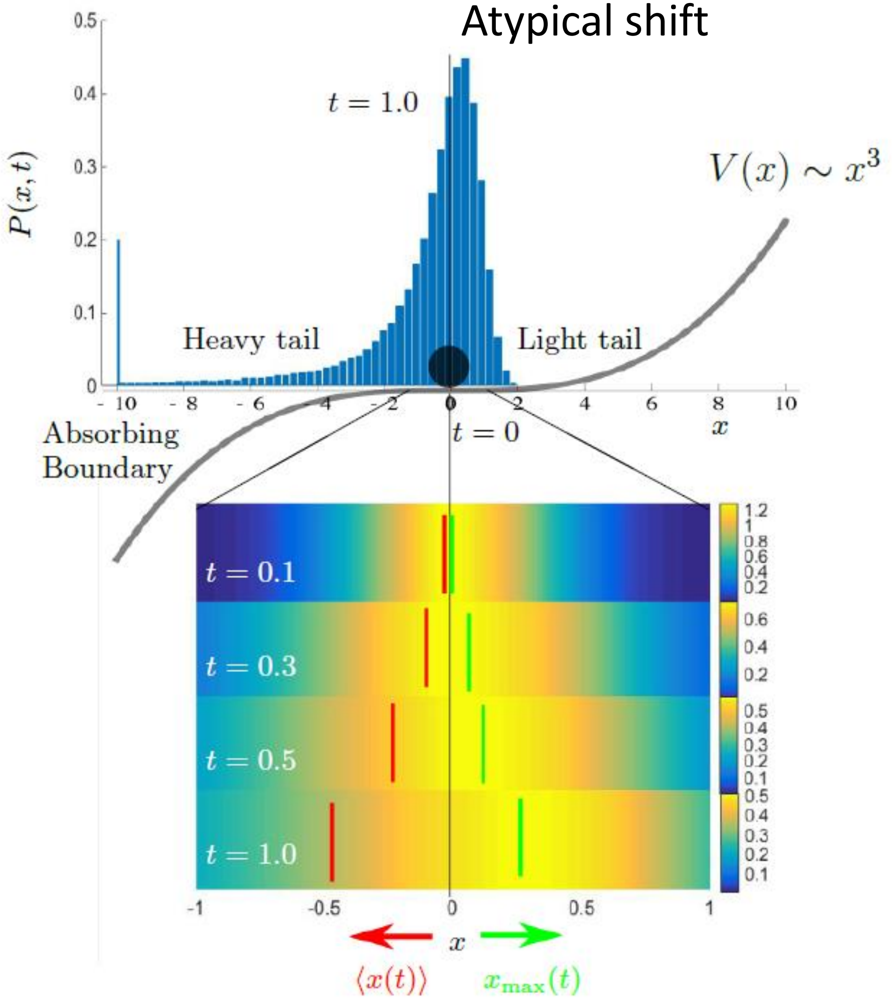
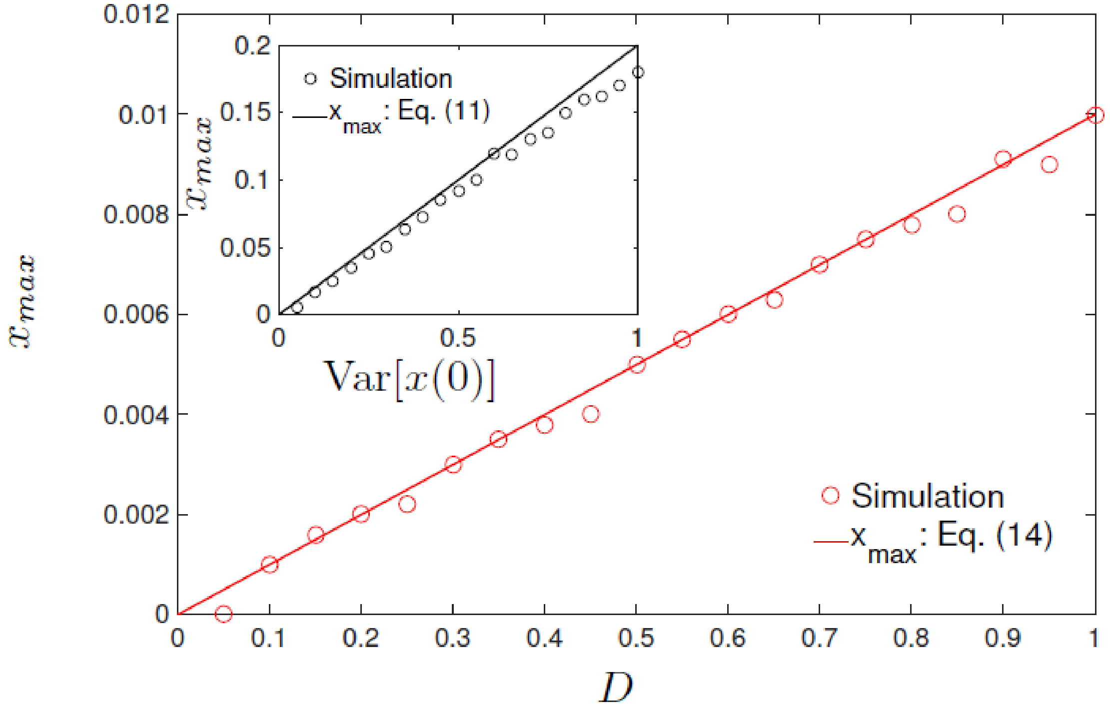




$$x_{\max}(t) \approx kDt^2 \qquad \sigma^2(t) \approx 2Dt$$

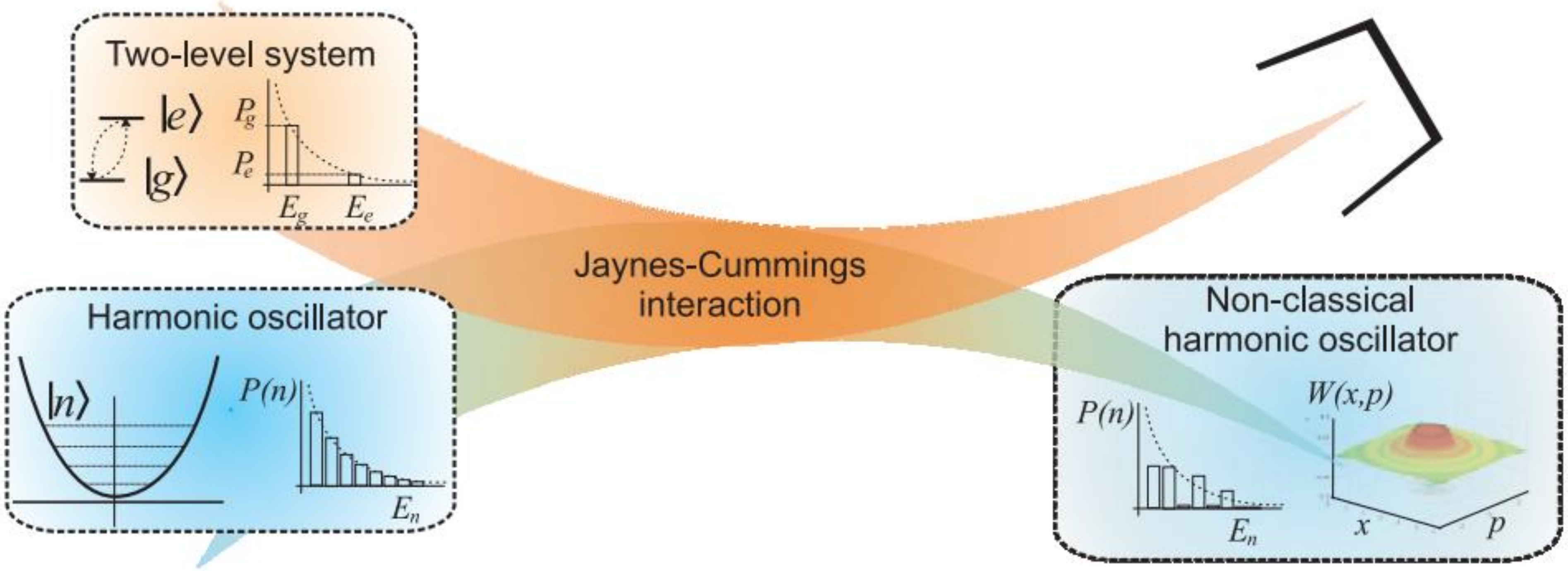
$$\langle x(t) \rangle \approx -kDt^2 \qquad \mathrm{Var}[x(t)] \approx 2Dt$$

L. Ornigotti, R. Filip, A. Ryabov and V. Holubec, Brownian Motion surviving in unstable cubic potential and Maxwell's demon behind, submitted (2017).

NOISE-INDUCED NONCLASSICALITY

Palacký University Olomouc

Energy-conserving resonant J-C interaction: $\hbar g(\sigma_+ a + a^\dagger \sigma_-)$



P. Marek, L. Lachman, L. Slodička, and R. Filip, Phys. Rev. A 94, 013850 (2016)
L. Slodička, P. Marek and R. Filip, Optics Express 24, 7858 (2016)

NOISE-INDUCED NONCLASSICALITY

Palacký University Olomouc

Energy-conserving resonant J-C interaction: $\hbar g(\sigma_+ a + a^\dagger \sigma_-)$

Nonclassicality test (Klyshko's criteria): $(n+1)P_{n-1}P_{n+1} - nP_n^2 < 0$

Entanglement potential (BS coupling): $LN(\rho_{split}) = \log_2 \|\rho_{split}^{PT}\|$

$$\rho(t) = \sum_{n=0}^{\infty} \frac{\bar{n}^n}{(1+\bar{n})^{1+n}} \cos^2(gt\sqrt{n}) |n\rangle\langle n| + \sum_{n=1}^{\infty} \frac{\bar{n}^n}{(1+\bar{n})^{1+n}} \sin^2(gt\sqrt{n}) |n-1\rangle\langle n-1|$$

Simple analytical formula, but complex and not simply predictable behavior.

MIXTURE OF ANHARMONIC OSCILLATIONS

P. Marek, L. Lachman, L. Slodička, and R. Filip, Phys. Rev. A 94, 013850 (2016)
L. Slodička, P. Marek and R. Filip, Optics Express 24, 7858 (2016)

NOISE-INDUCED NONCLASSICALITY

Palacký University Olomouc

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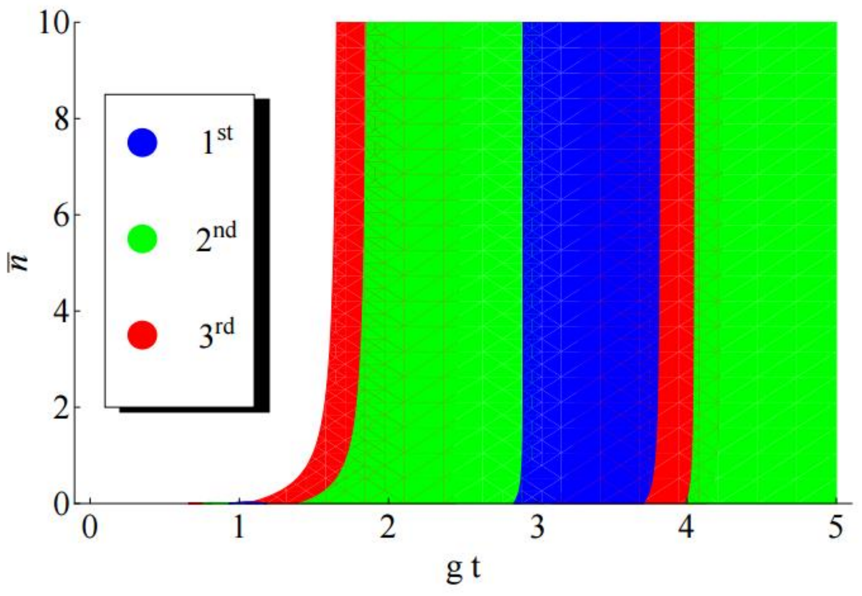
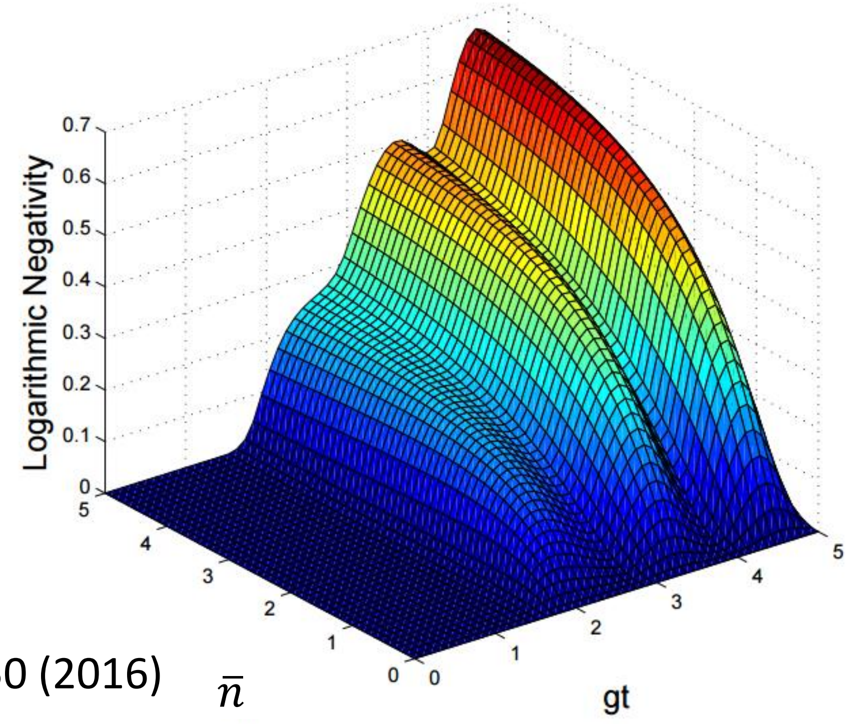




P. Marek, L. Lachman, L. Slodička, and R. Filip, Phys. Rev. A 94, 013850 (2016)
L. Slodička, P. Marek and R. Filip, Optics Express 24, 7858 (2016)

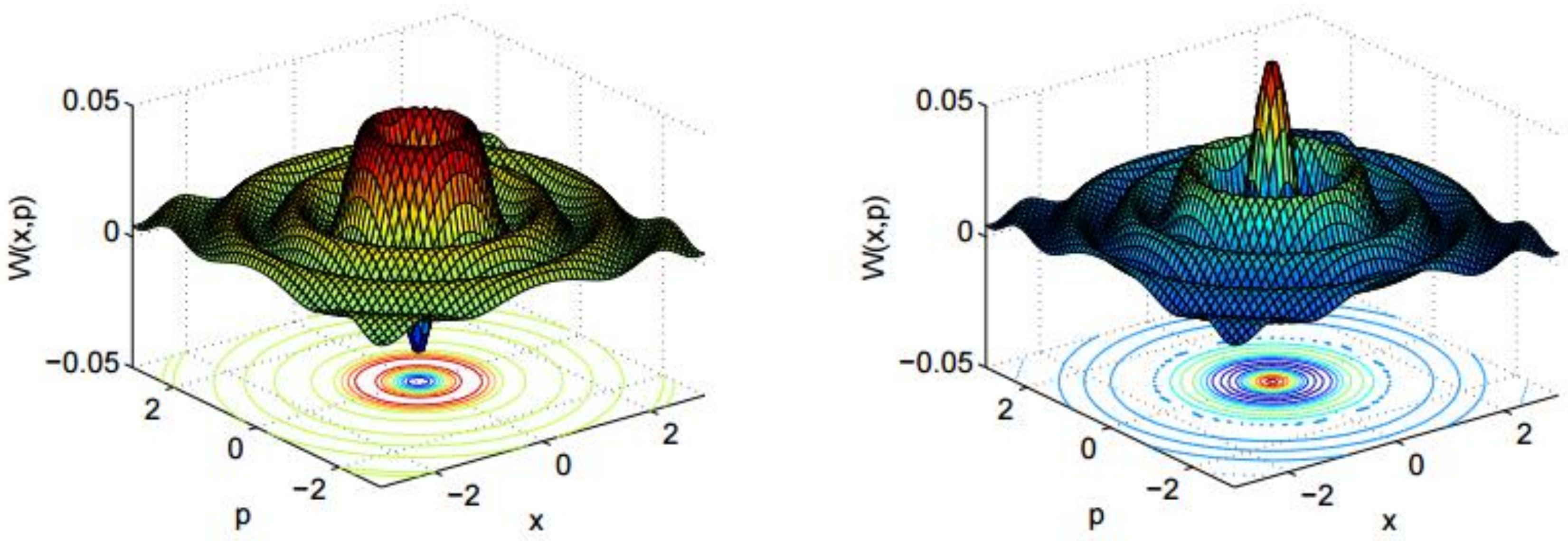
Palacký University Olomouc

NOISE-ENHANCED NONCLASSICALITY

Energy-conserving resonant J-C interaction: $\hbar g(\sigma_+ a + a^\dagger \sigma_-)$

Negative Wigner function:

$\bar{n} = 10, gt = 5.5$ $\bar{n} = 10, gt = 2\pi$



P. Marek, L. Lachman, L. Slodička, and R. Filip, Phys. Rev. A 94, 013850 (2016)
L. Slodička, P. Marek and R. Filip, Optics Express 24, 7858 (2016)

Palacký University Olomouc

NOISE-ENHANCED NONCLASSICALITY

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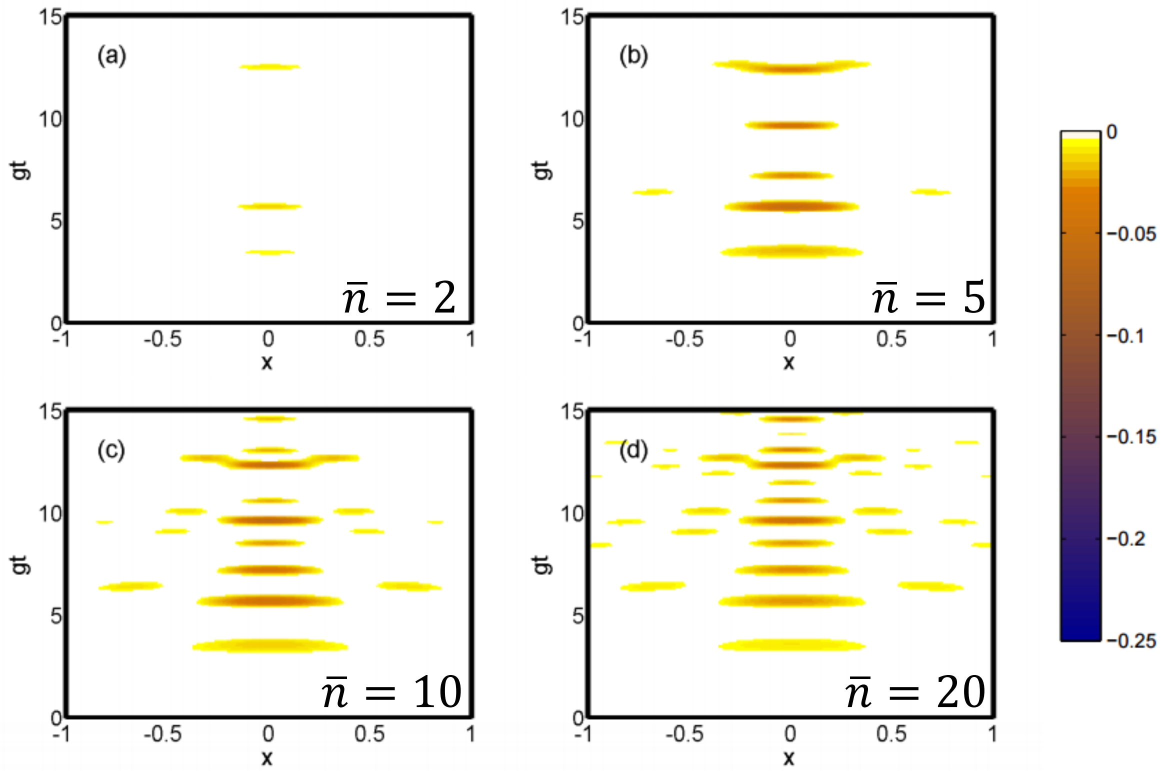
Negative Wigner function:



NEXT?

P. Marek, L. Lachman, L. Slodička, and R. Filip, Phys. Rev. A 94, 013850 (2016)
L. Slodička, P. Marek and R. Filip, Optics Express 24, 7858 (2016)

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FLIP - BASIC QUANTUM OPERATION

$$F(|\psi\rangle \otimes |\phi\rangle) = |\phi\rangle \otimes |\psi\rangle$$

Flip operator defines exchange of quantum states on two distinguishable particles, atoms, oscillators etc.

1. State transfer $$F(|\psi\rangle \otimes |\phi\rangle) = |\phi\rangle \otimes |\psi\rangle$$

2. Overlap measurement $$\mathrm{Tr} F(\rho_A \otimes \rho_B) = \mathrm{Tr} \rho_A \rho_B$$

linear

nonlinear

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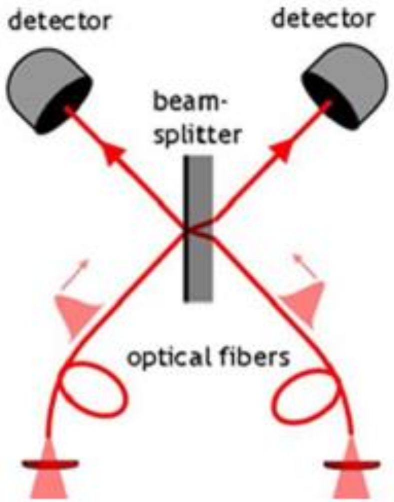
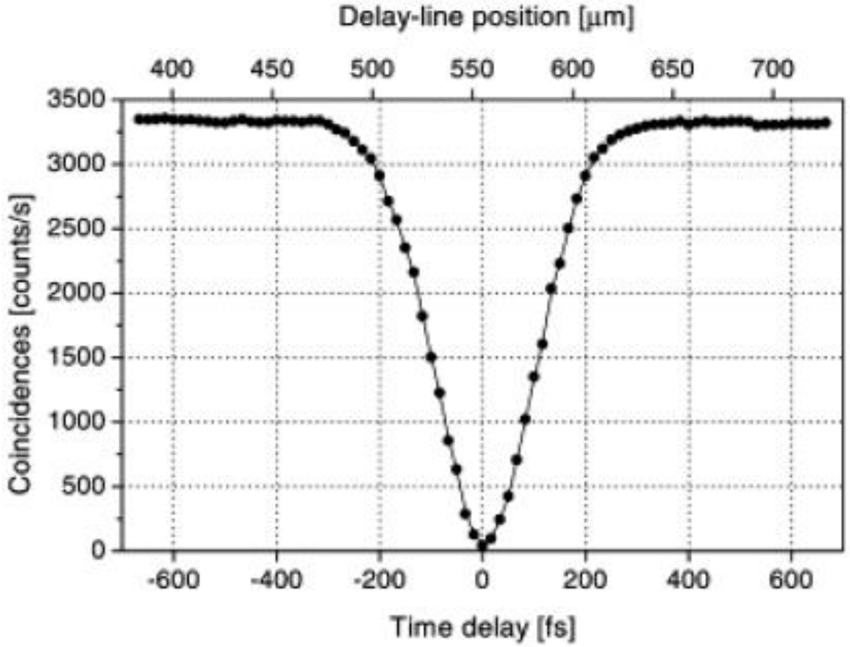
OVERLAP MEASUREMENT

QUANTUM EXPERIMENT (HONG-OU-MANDEL 1987) :



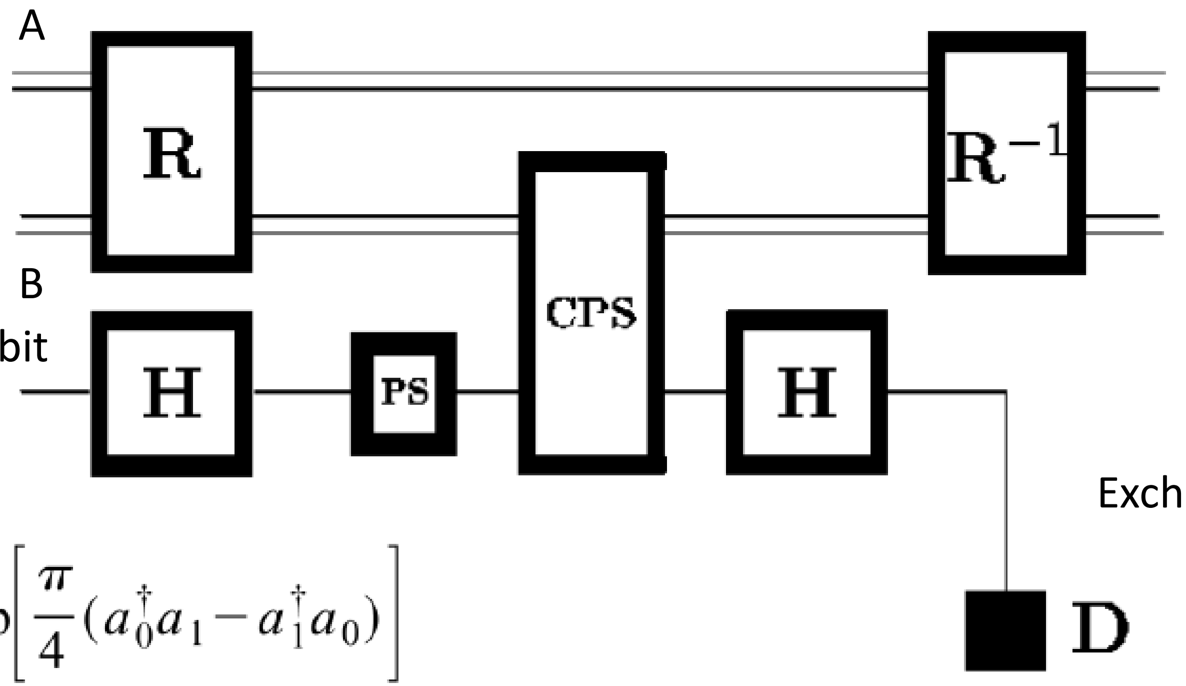
$|1\rangle_A\langle 1| \otimes \rho_A \qquad |1\rangle_B\langle 1| \otimes \rho_B$



$$\mathrm{Tr}(\varrho_A \varrho_B) = 1 - \frac{C_0}{C_{\mathrm{off}}}$$

C. Santori et al., Indistinguishable photons from a single-photon device“, Nature 419 594 (2002).

OVERLAP MEASUREMENT



Exchange symmetry measurement

modes k_0, k_1

$$U_R = \exp\left[\frac{\pi}{4}(a_0^\dagger a_1 - a_1^\dagger a_0)\right]$$

$$U_{CPS} = \exp(i\pi a_0^\dagger a_0 |\uparrow\rangle\langle\uparrow|)$$

Cavity QED, SQUIDS, trapped ions

$$V = \mathrm{Tr}(\varrho_A \varrho_B) = \mathrm{Tr}(F_{AB}\, \varrho_A \otimes \varrho_B)$$

Radim Filip, Phys. Rev. A 65, 062320 (2002)

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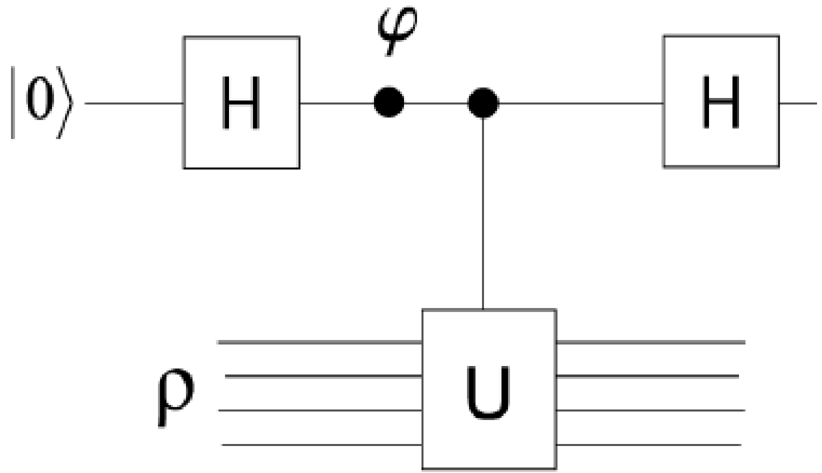
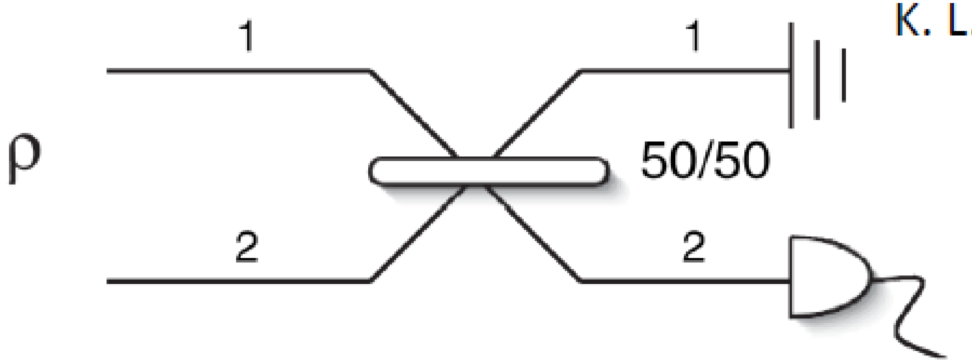
OVERLAP MEASUREMENT



Estimation of nonlinear functional of state

extendable to $\mathrm{Tr}\,\varrho^k = \sum_{i=1}^{m} \lambda_i{}^k$

A.K. Ekert et al., Phys. Rev. Lett. 88, 217901 (2002)
and many other publications.



K. L. Pregnell , Phys. Rev. Lett. **96**, 060501 (2006)

PARITY MEASUREMENT
(photon number measurement)

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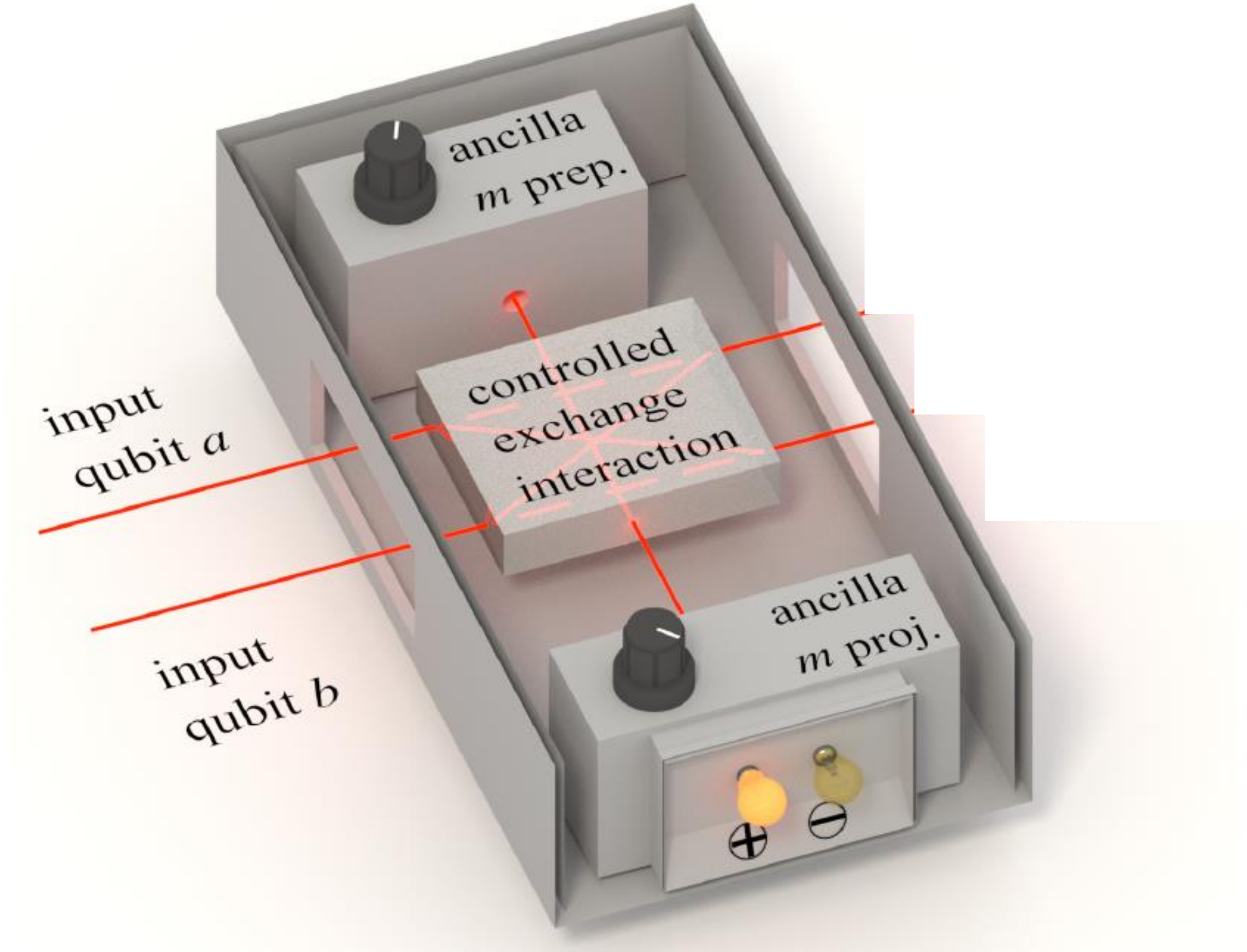
OVERLAP MEASUREMENT OF QUBITS



Patel, R. B., Ho, J., Ferreyrol, F., Ralph, T. C., and Pryde, G. J. Sci. Adv. 2(3) (2016).

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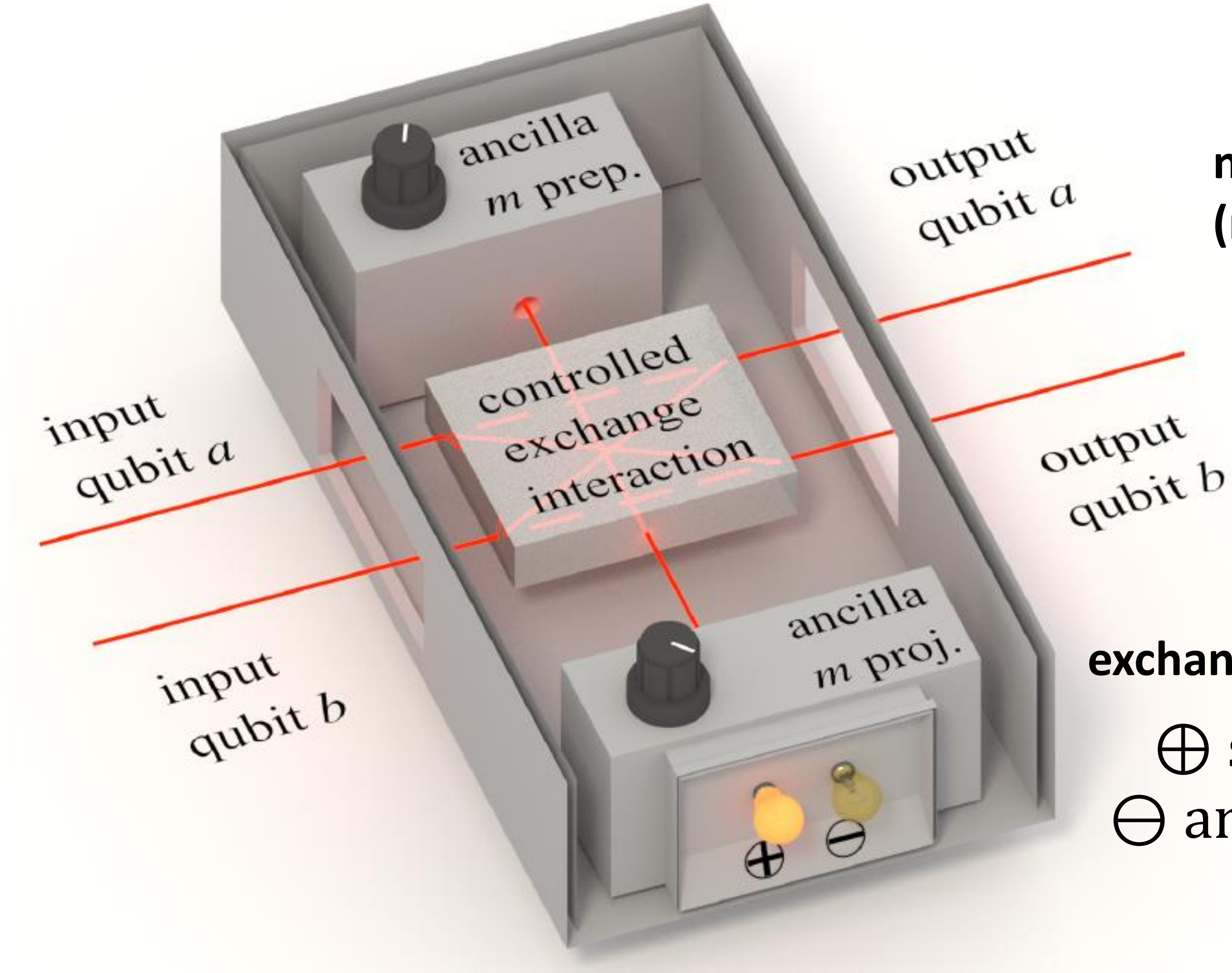
NONDESTRUCTIVE VERSION



nondestructive (not absorptive)

exchange symmetry detector

⊕ symmetrization

⊖ antisymmetrization

R. Starek, M. Micuda, M. Mikova, I. Straka, M. Dusek, P. Marek, M. Jezek, R. Filip, J. Fiurasek, submitted.

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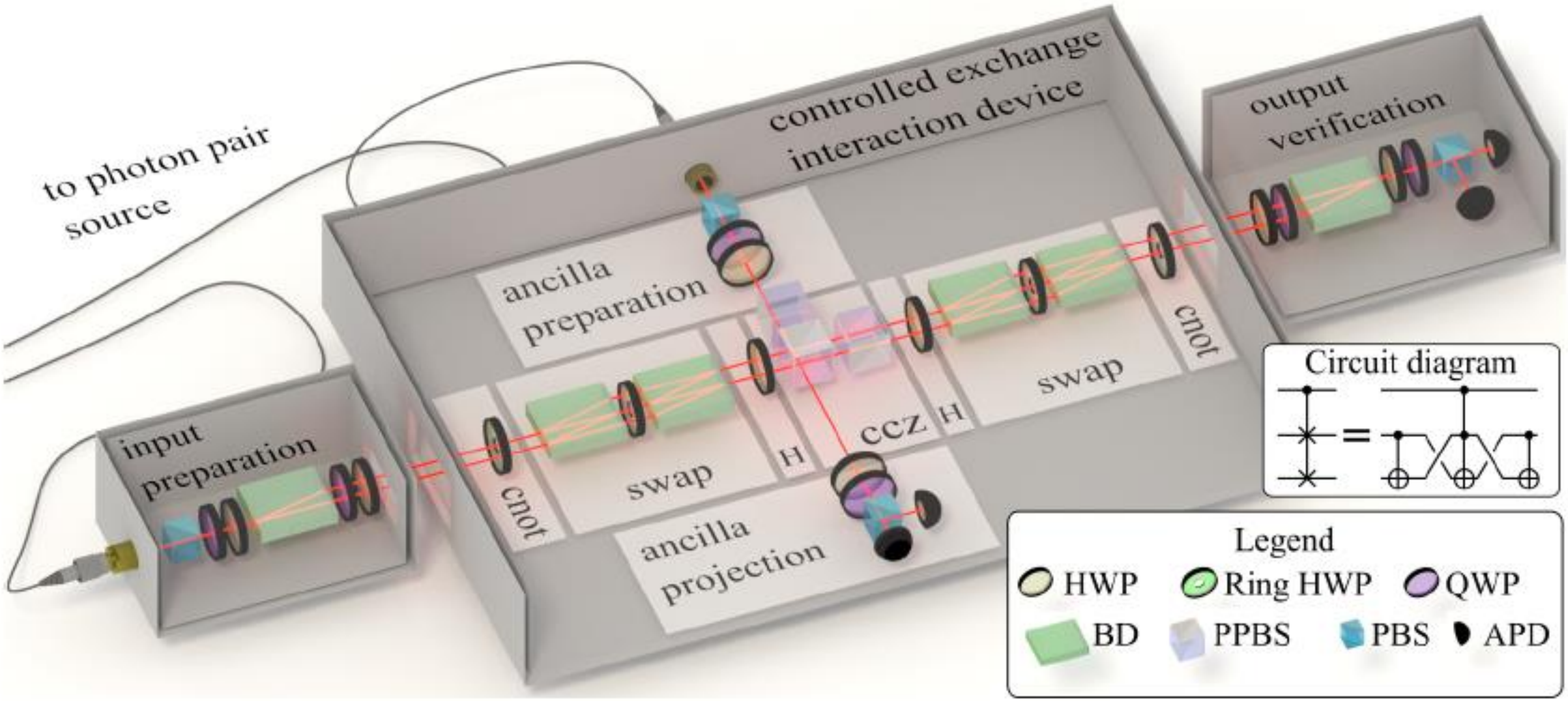
FOR TWO QUBITS



R. Starek, M. Micuda, M. Mikova, I. Straka, M. Dusek, P. Marek, M. Jezek, R. Filip, J. Fiurasek, submitted.

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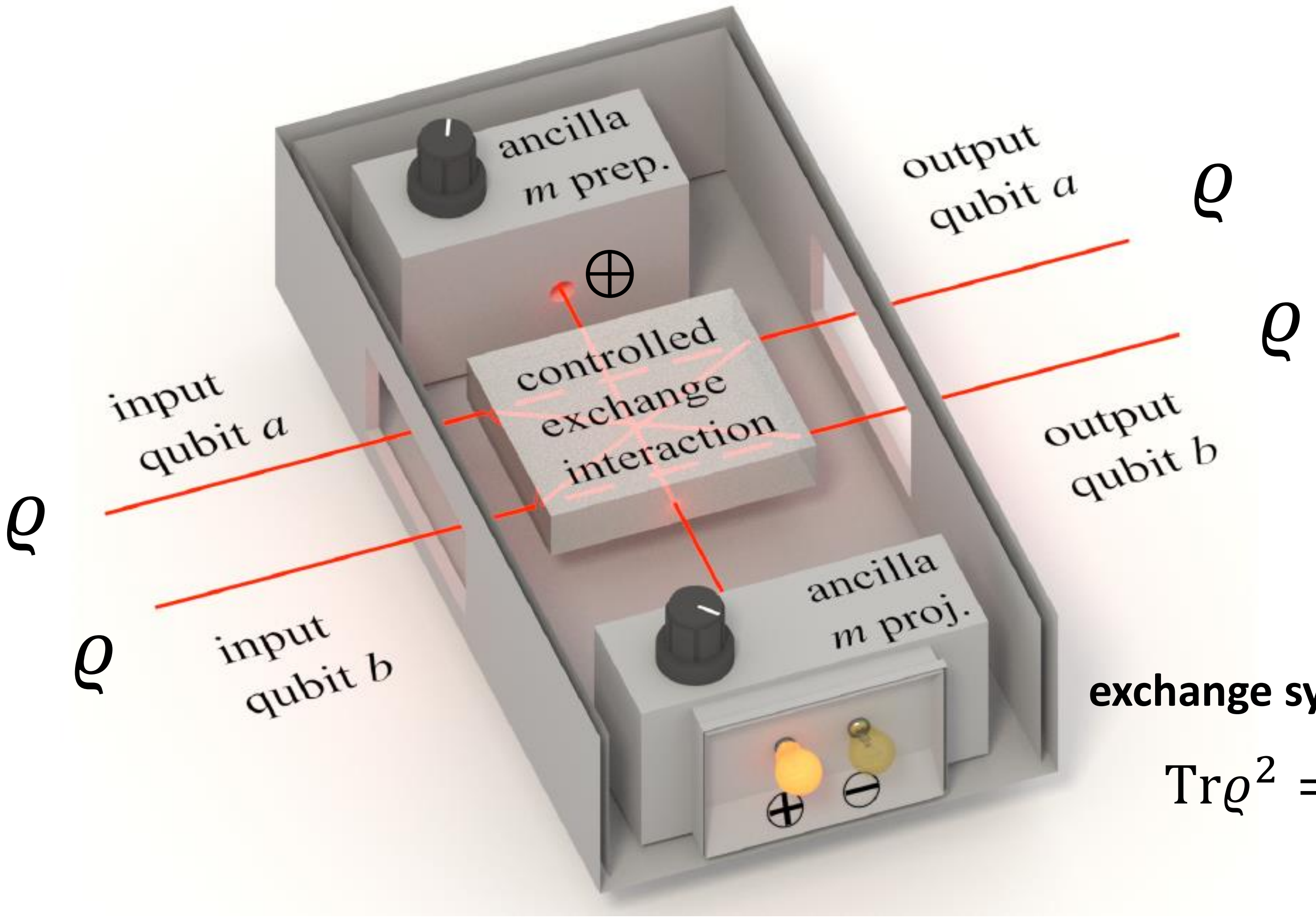
NONDEMOLITION PURITY DETECTION



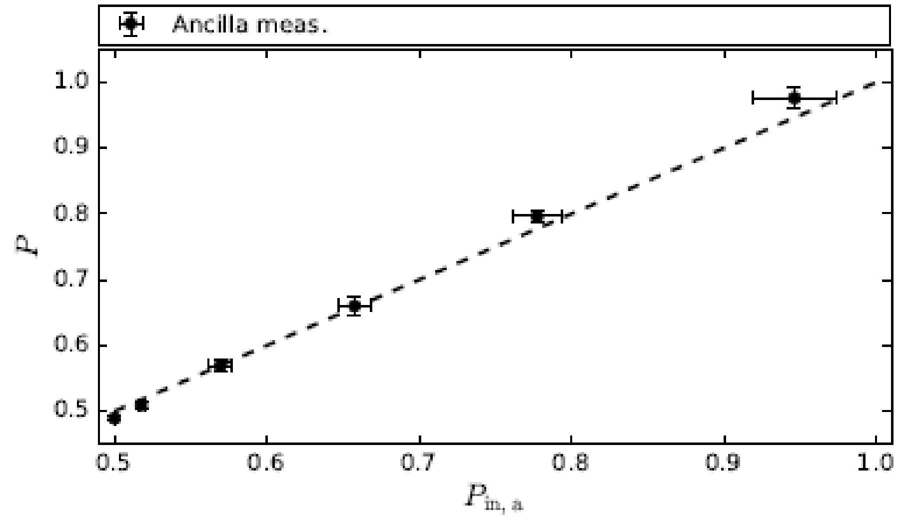
nondemolition detection

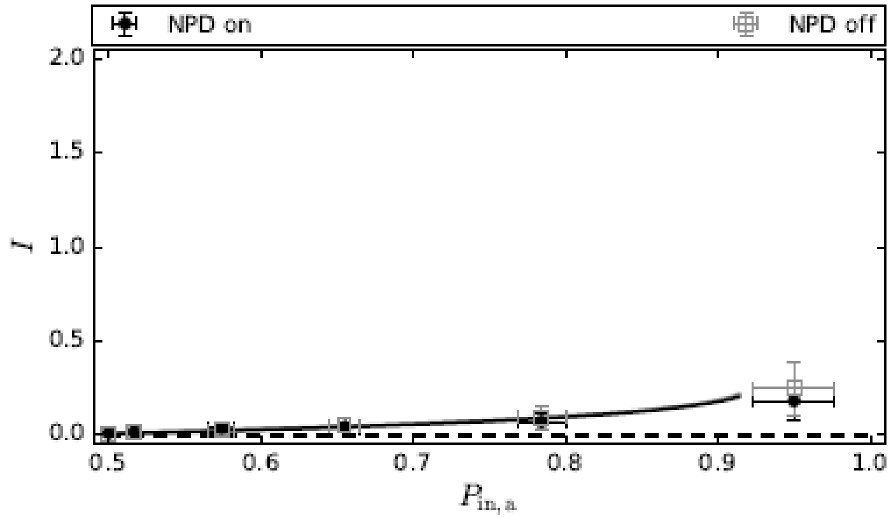
exchange symmetry detector

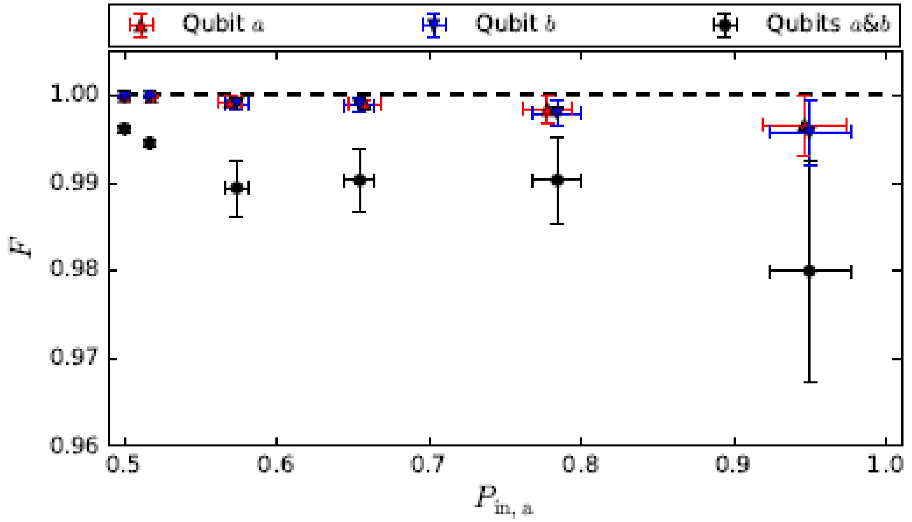
$$\mathrm{Tr}\varrho^2 = |p_{\oplus} - p_{\ominus}|$$

R. Starek, M. Micuda, M. Mikova, I. Straka, M. Dusek, P. Marek, M. Jezek, R. Filip, J. Fiurasek, submitted.

NONDEMOLITION PURITY DETECTION



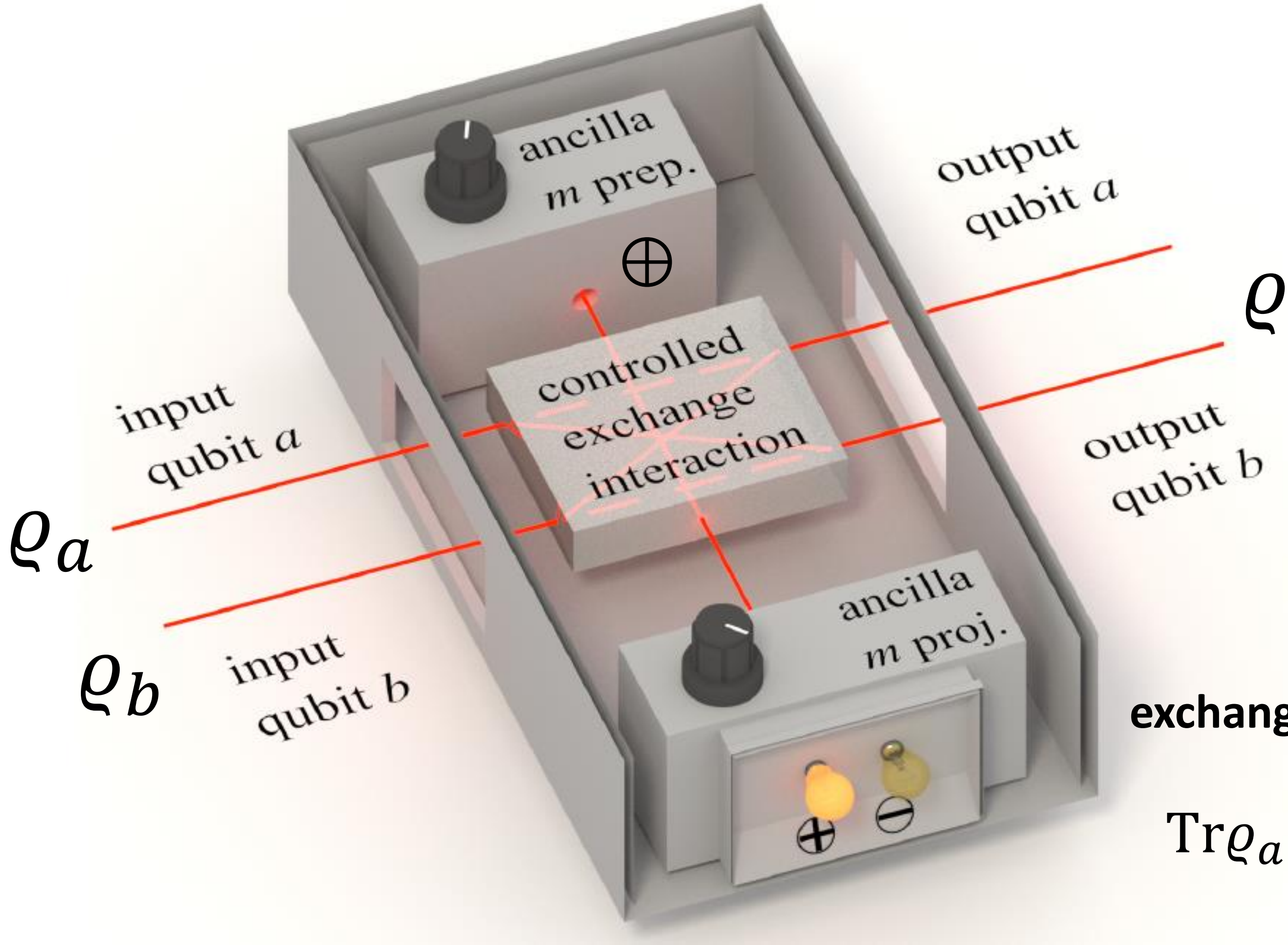




- **detector quality verified**
- **nondemolition feature verified**
- **no-correlation verified**
- next step: sequential detection

R. Starek, M. Micuda, M. Mikova, I. Straka, M. Dusek, P. Marek, M. Jezek, R. Filip, J. Fiurasek, submitted.

OVERLAP DETECTOR



classically correlated states

$$\varrho'_{ab} = \frac{1}{2}(\varrho_a\varrho_b + \varrho_b\varrho_a)$$

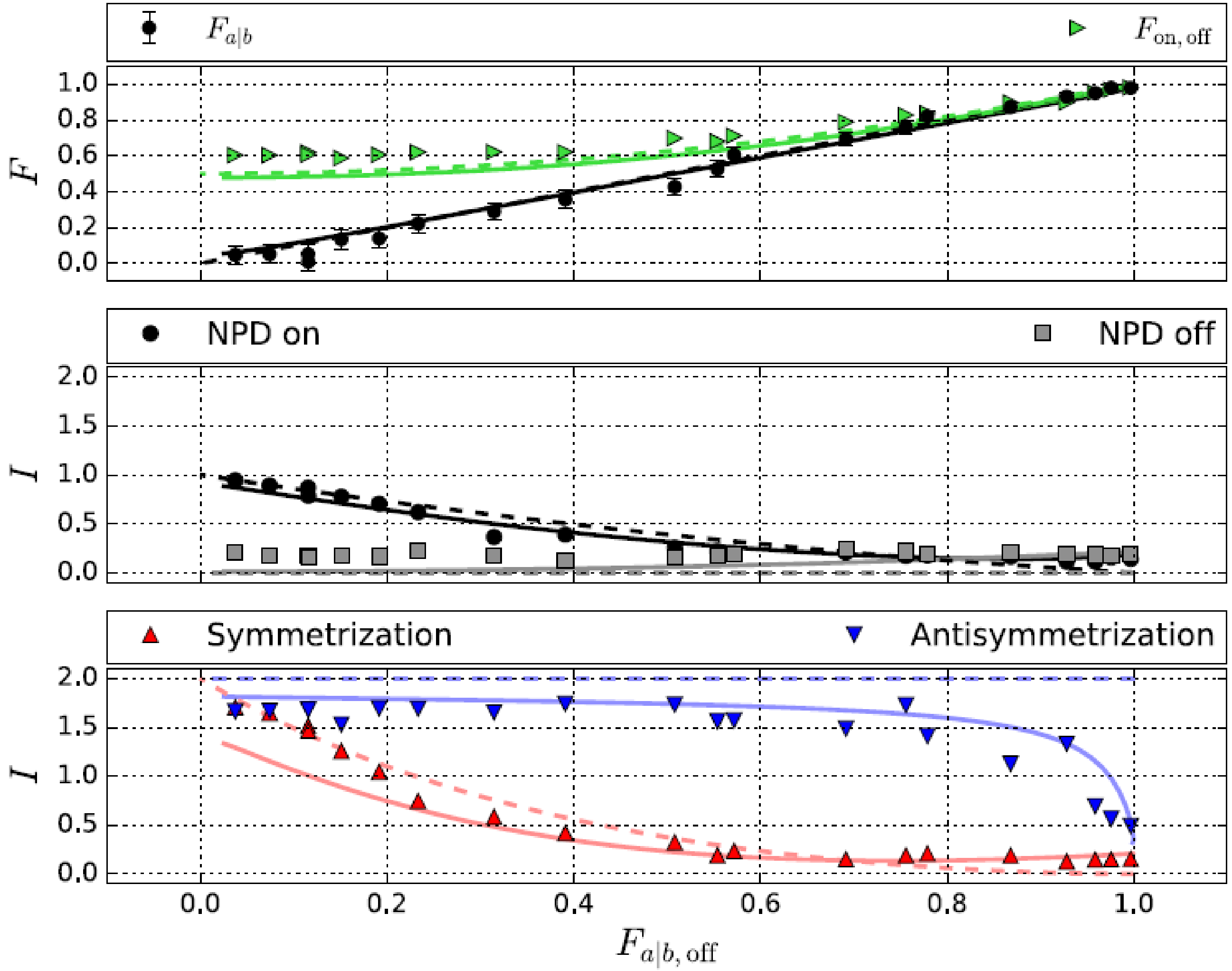
exchange symmetry detector

$$\mathrm{Tr}\varrho_a\varrho_b = |p^{\oplus} - p^{\ominus}|$$

R. Starek, M. Micuda, M. Mikova, I. Straka, M. Dusek, P. Marek, M. Jezek, R. Filip, J. Fiurasek, submitted.

Palacký University Olomouc

NONDESTRUCTIVE OVERLAP DETECTION (PURE STATES)

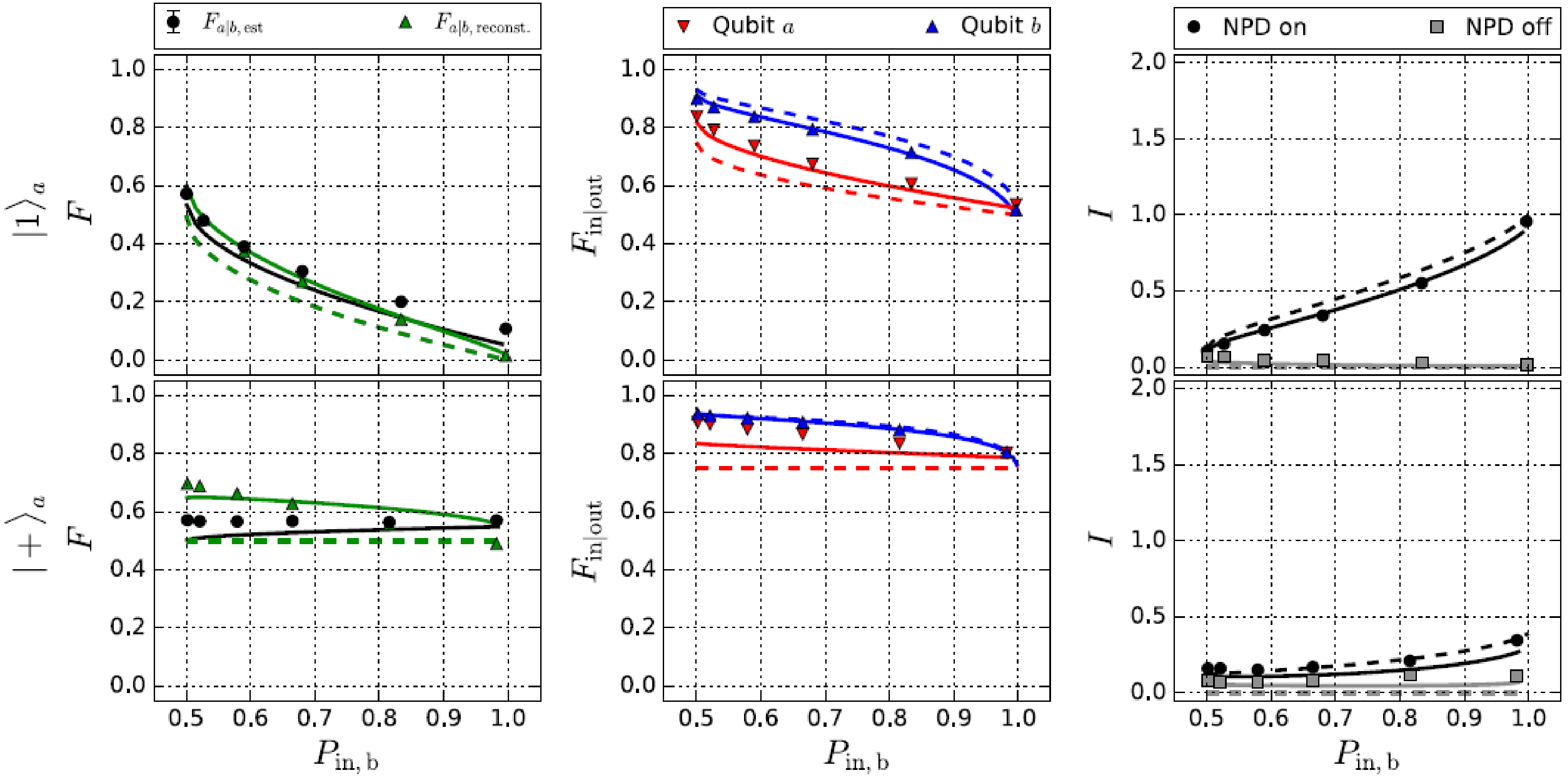


maximally entangled

no entanglement

R. Starek, M. Micuda, M. Mikova, I. Straka, M. Dusek, P. Marek, M. Jezek, R. Filip, J. Fiurasek, submitted.

NONDESTRUCTIVE OVERLAP DETECTION (MIXED STATES)



$$\varrho_b = p|0\rangle\langle 0| + \hat{1}/2$$

NEXT?

R. Starek, M. Micuda, M. Mikova, I. Straka, M. Dusek, P. Marek, M. Jezek, R. Filip, J. Fiurasek, submitted.

NON-GAUSSIAN QUANTUM TASKS

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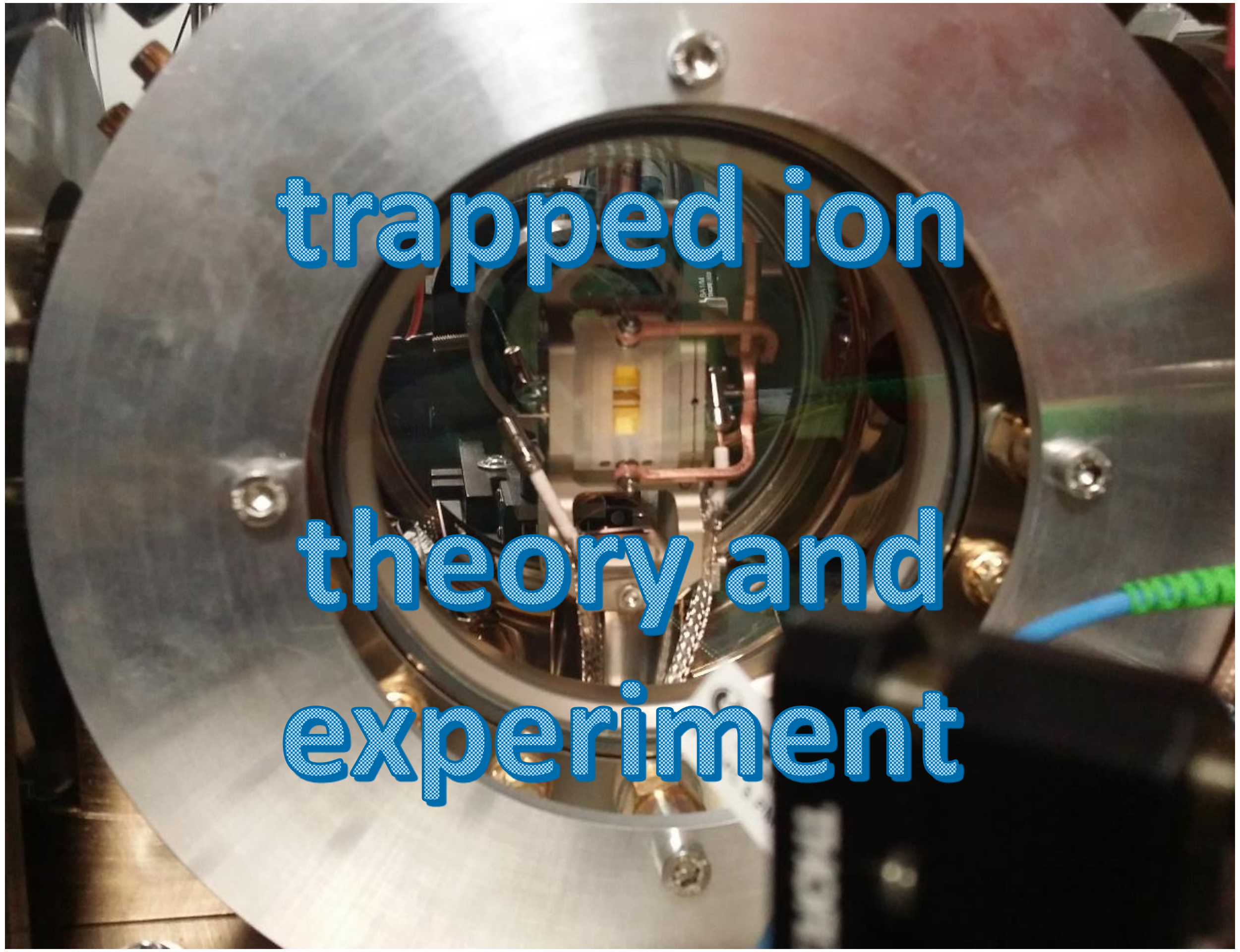
- quantum non-Gaussianity for $n > 9$
- collective interference tests for complex quantum non-Gaussian states
- minimal decoherence for large squeezed cat states
- quantum cubic nonlinearity
- formation of interference fringes with negative Wigner function from Kerr effect
- non-Gaussian entanglement from cross-Kerr effect
- noise-induced nonclassical effects
- flip gate and overlap measurement for oscillators



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- quantum non-Gaussianity for $n > 9$
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  for complex quantum non-Gaussian states
- minimal decoherence for large squeezed cat states
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- formation of interference fringes
  with negative Wigner function
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