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Quantum operations with light

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MINISTERSTVO ŠKOLSTVÍ, MLÁDEŽE A TĚLOVÝCHOVY

GAČR
CZECH SCIENCE FOUNDATION

SEVENTH FRAMEWORK PROGRAMME

Palacký University Olomouc

OUR GROUP

Quantum Coherence and Nonclassicality

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Petr Marek

Students:
Lukáš Lachman
Josef Hloušek

Quantum Nonlinear Operations

Petr Marek
Kimin Park

Students:
Petr Zapletal
Jan Provazník

Quantum Communication

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Ivan Derkač

Quantum Optomechanics

Andrey Rakhubovsky

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Nikita Vostrosablin

Interaction of Light with Atoms

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Many thanks to Lucka Čelechovská, Míla Dušek, Jaromír Fiurášek, Martin Hendrych, Jirka Herec, Mirek Ježek, Mikolaj Lasota, David Menzies, Michal Mičuda, Martina Míková, Laďa Mišta, Honza Soubusta, Ivo Straka, Jarda Řeháček etc.

Long-term support: Jan Peřina, Richard Horák a Zdeněk Hradil







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INTERNATIONAL COLLABORATION

Max Planck Institute for Science of Light
Gerd Leuchs, Christoph Marquardt

Danish Technical University, Lyngby
Ulrik Lund Andersen

University of Tokyo
Akira Furusawa

Laboratoire Kastler Brossel, Sorbone, Paris
Julien Laurat, Nicolas Treps

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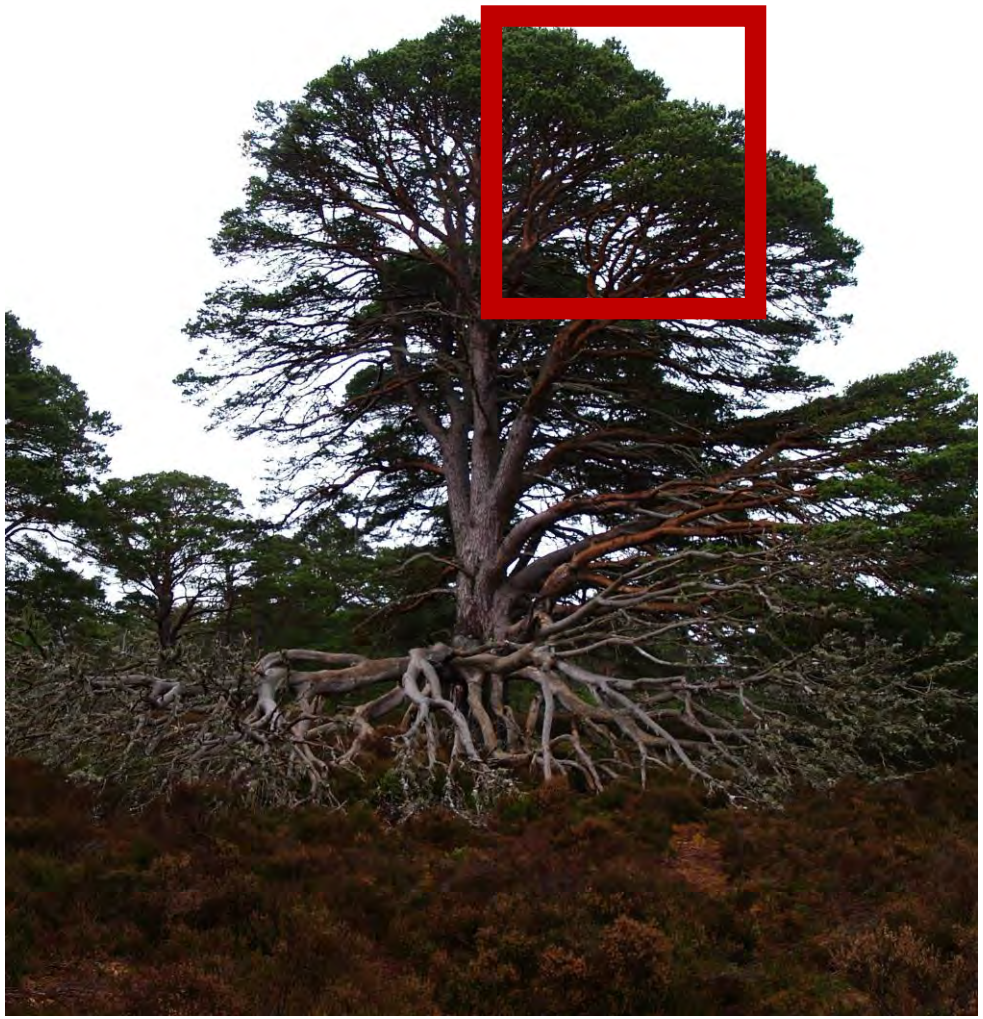
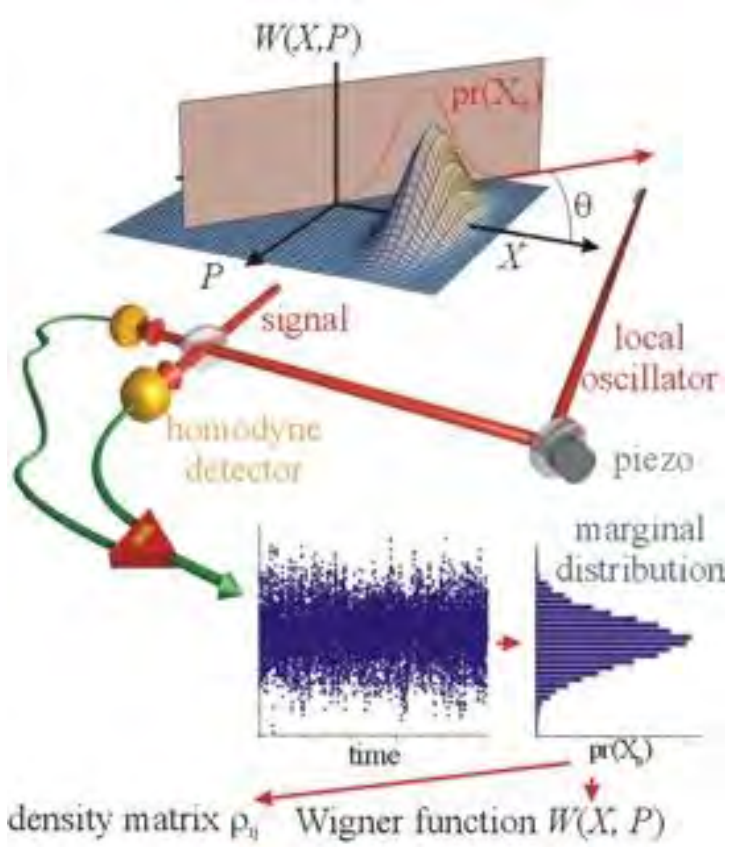
SHORT OVERVIEW OF CV QUANTUM OPERATIONS WITH LIGHT



- Quantum communication:
  quantum distillation and noiseless amplification
  by weak measurement
  coherent quantum error-correction
  entanglement-based quantum key distribution
- Quantum amplifiers and interfaces:
  universal squeezer and its applications
  effective manipulation with non-Gaussian states
  amplification of optomechanical coupling
- Quantum nonlinear dynamics:
  deterministic cubic quantum operation
  simulations of quantum nonlinearity
  noise-enhanced quantum effects

INTRO: CV QUANTUM NOISE



Homodyne detection
(from A. Lvovsky's web)

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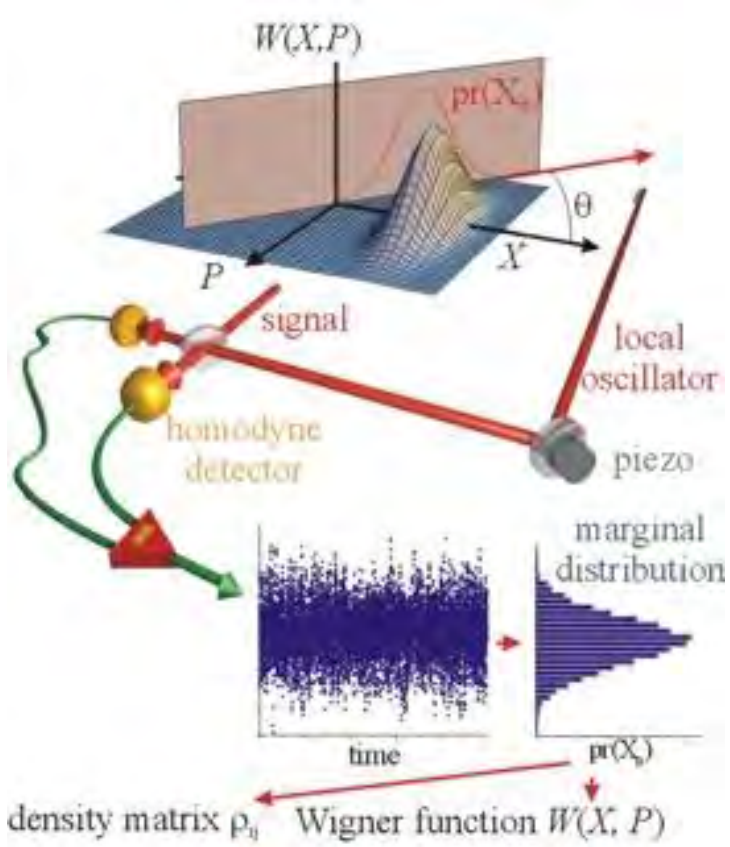
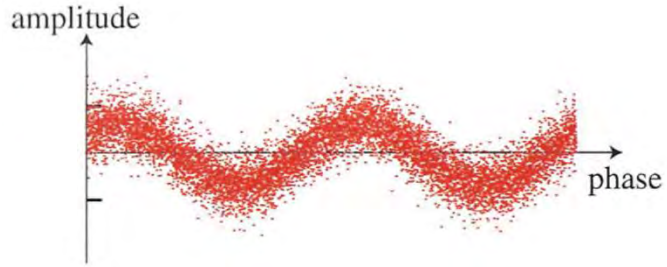
INTRO: CV QUANTUM NOISE



Homodyne detection
(from A. Lvovsky's web)

vacuum state



coherent state

data from Furusawa lab

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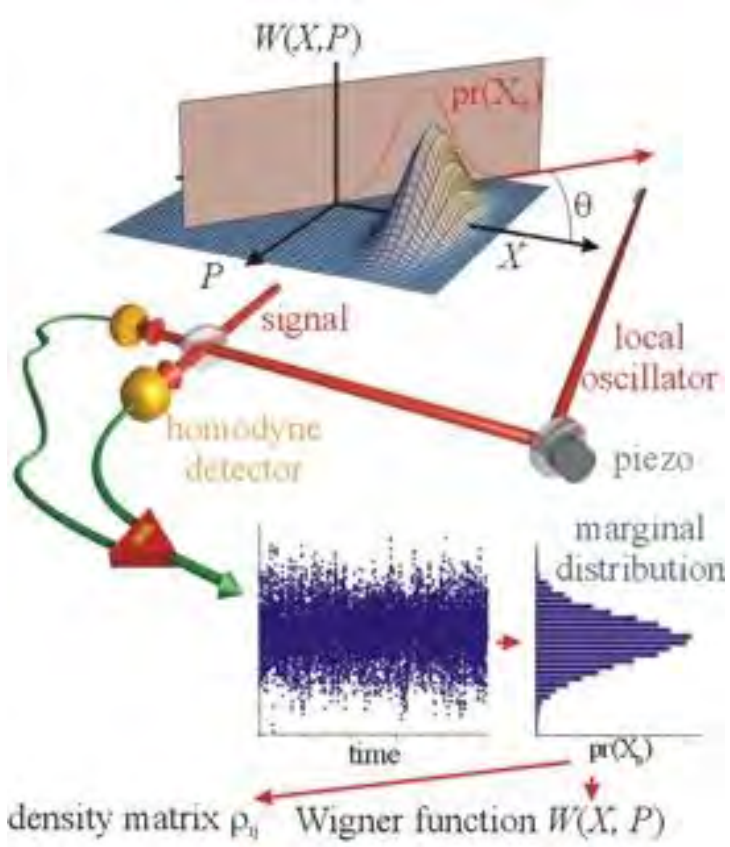
INTRO: CV QUANTUM NOISE



Homodyne detection
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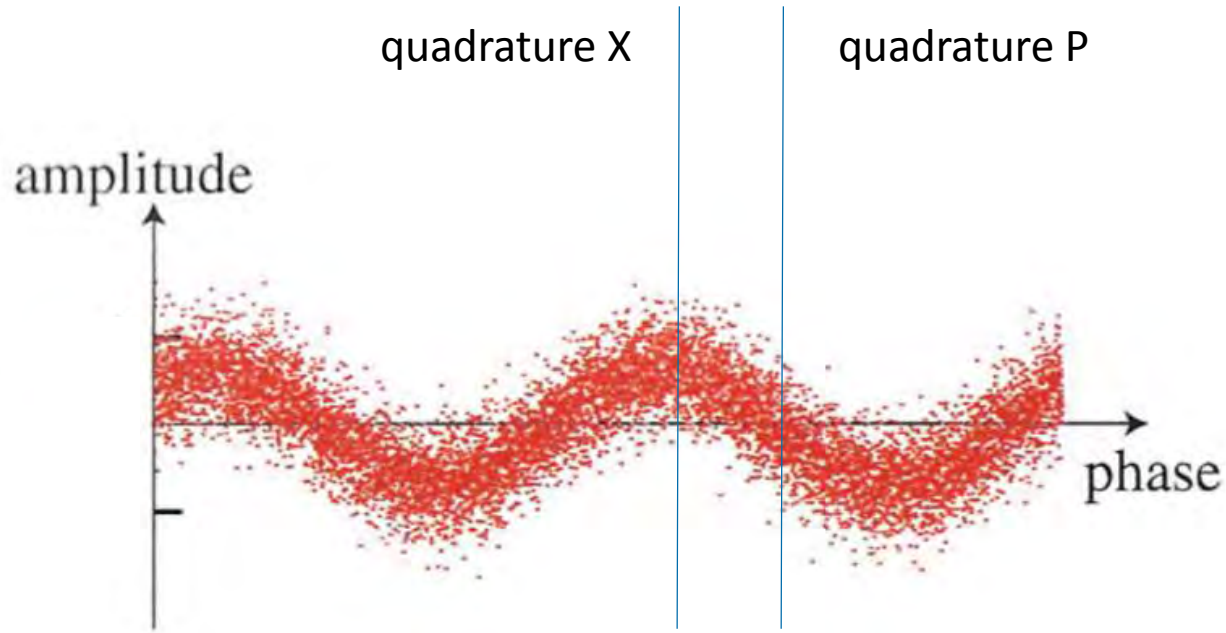

$$V_X V_P \geq 1 \qquad [\hat{X},\hat{P}] = 2i$$

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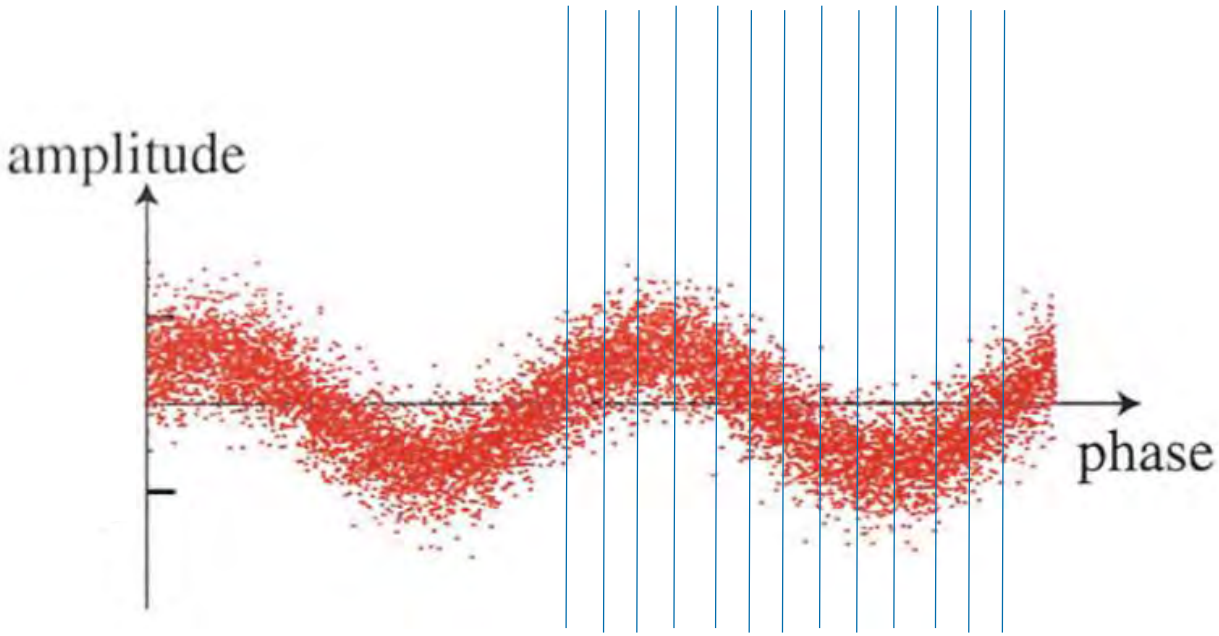
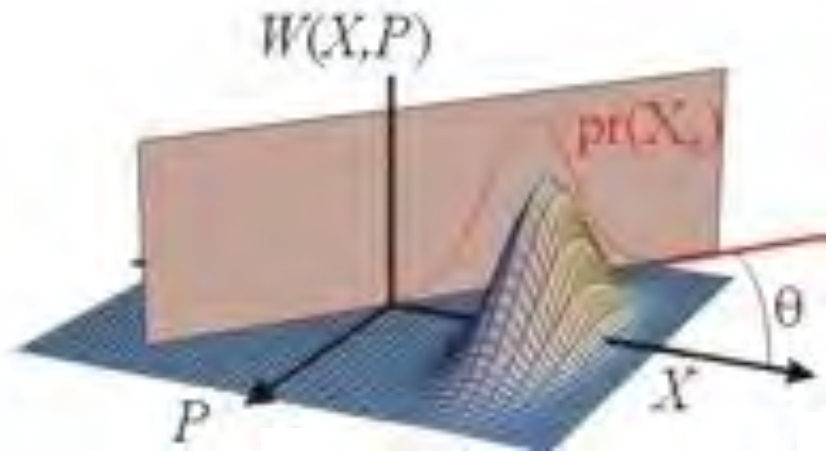
INTRO: CV QUANTUM NOISE

quantum tomography



X_θ

Wigner function



$$W(x,p) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \langle x - x'|\rho|x + x'\rangle \exp(\mathrm{i}x'p)\mathrm{d}x'$$

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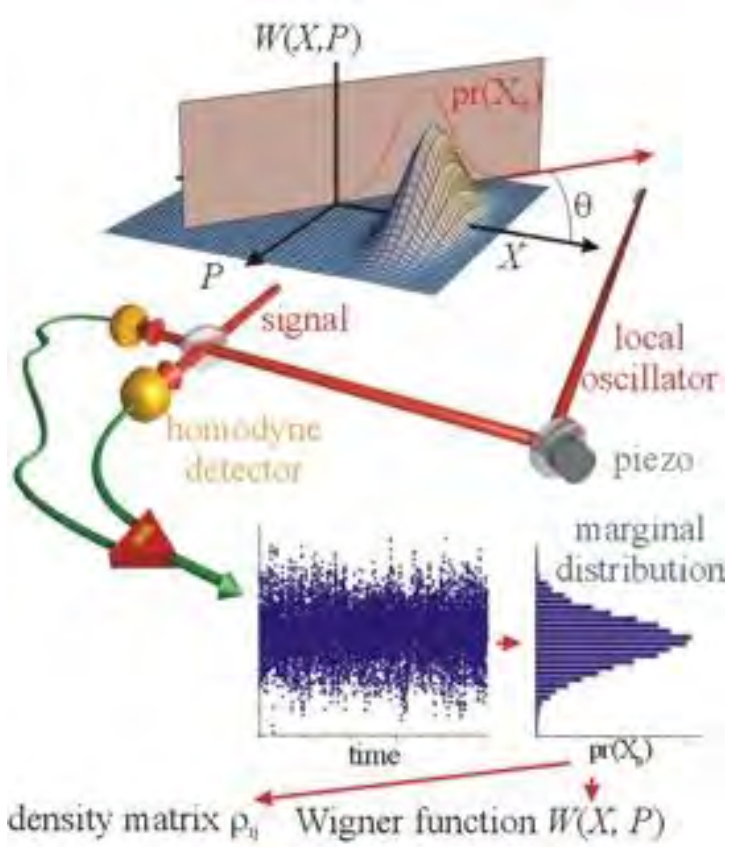
INTRO: CV QUANTUM NOISE



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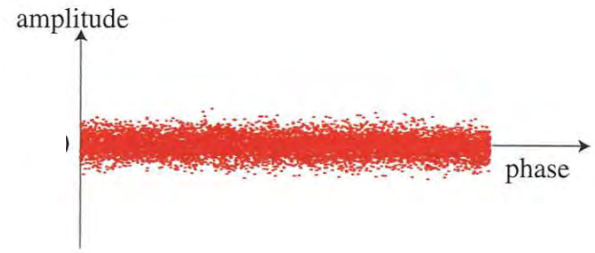
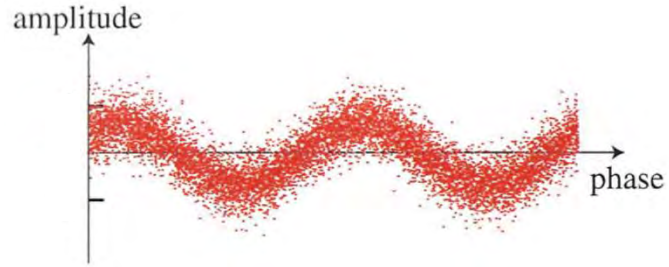
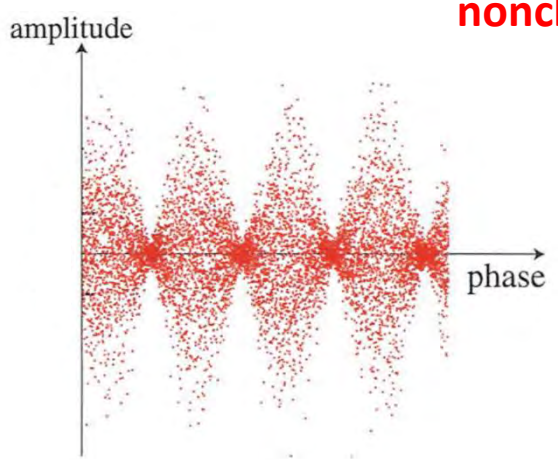


vacuum state



coherent state

nonclassical states:



nonclassical squeezed state

nonclassical Fock |1> state

data from Furusawa lab

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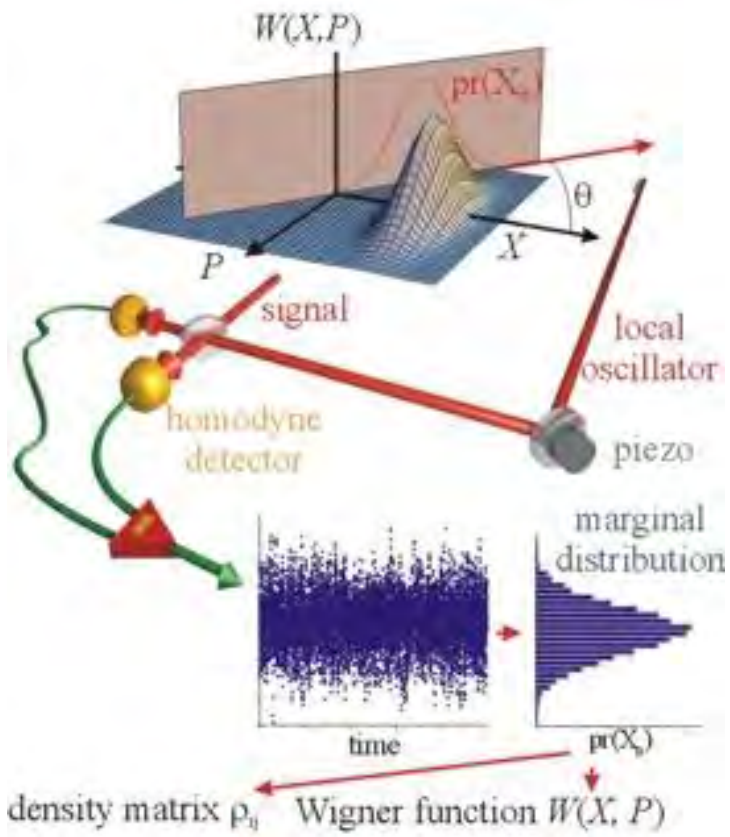
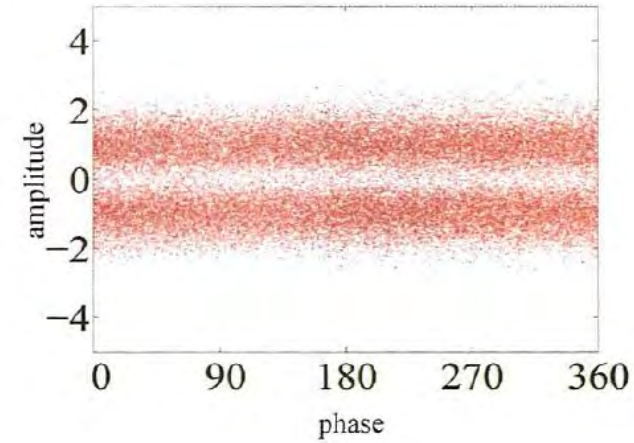
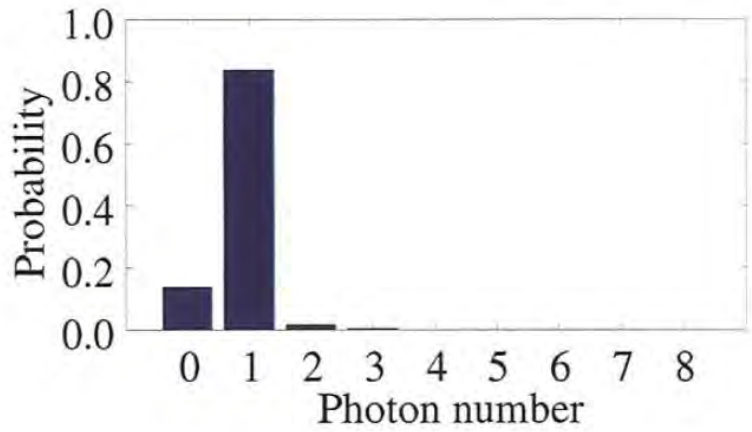
INTRO: CV QUANTUM NOISE

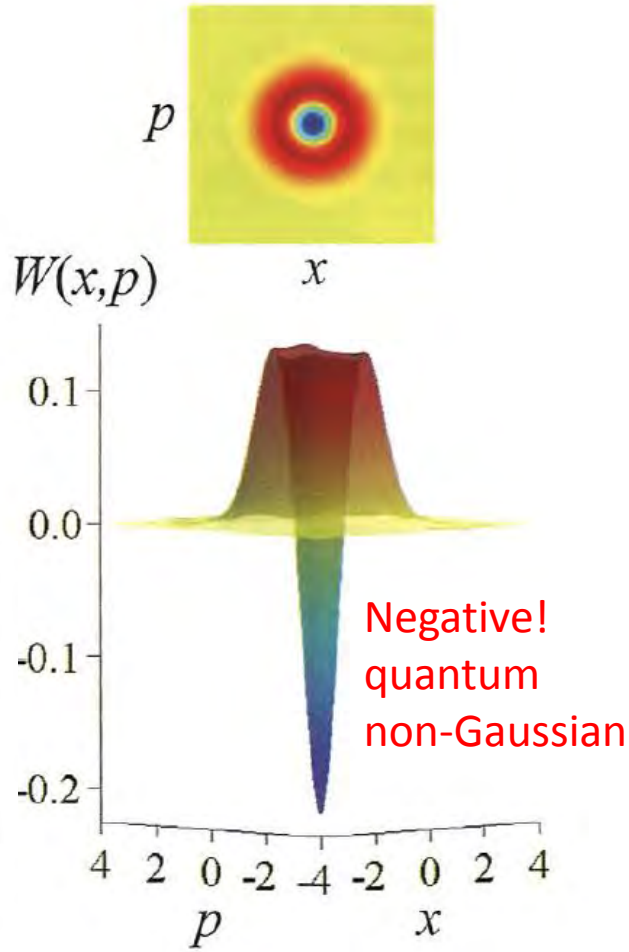


Homodyne detection
(from A. Lvovsky's web)





High quality single photon state



data from Furusawa lab

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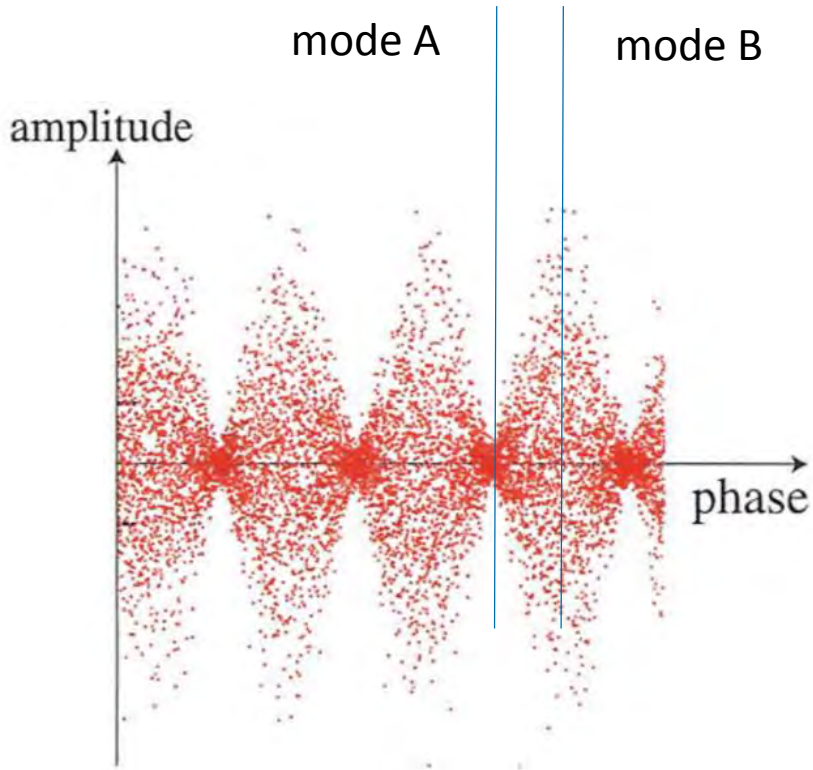
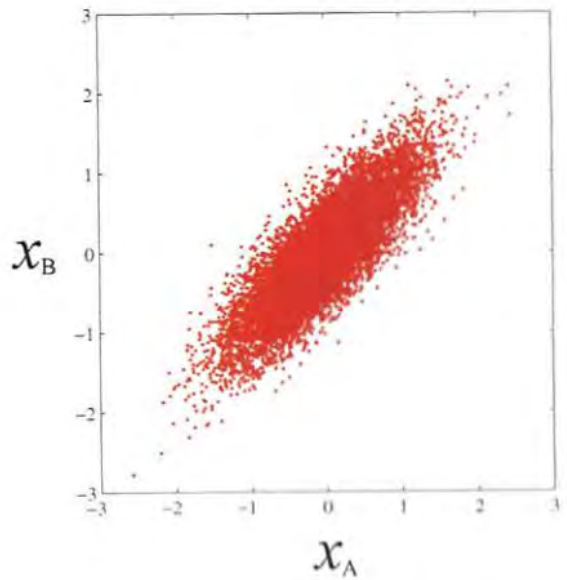
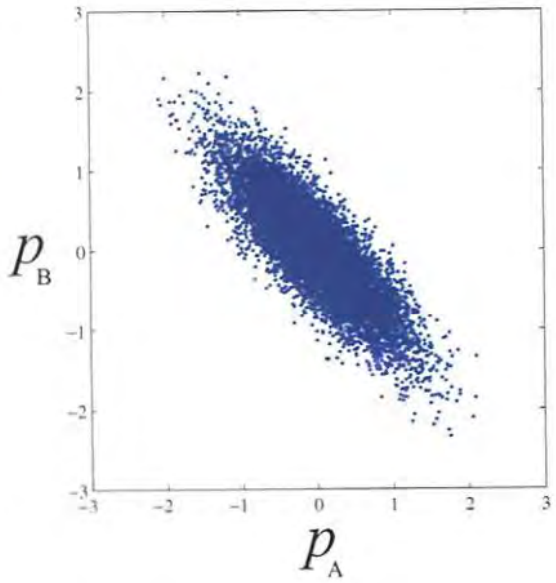
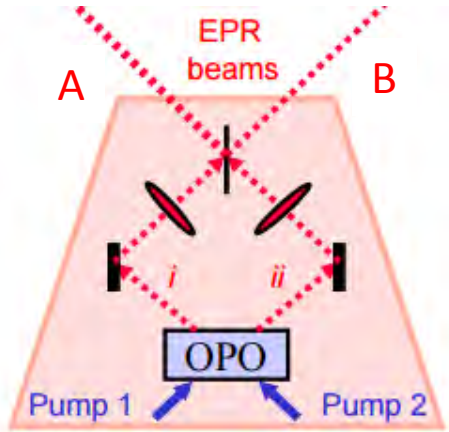
INTRO: CV QUANTUM NOISE

quantum interference at beam splitter









EPR quantum entanglement

$$V(x_A - x_B) \rightarrow 0$$

$$V(p_A + p_B) \rightarrow 0$$

data from Furusawa lab

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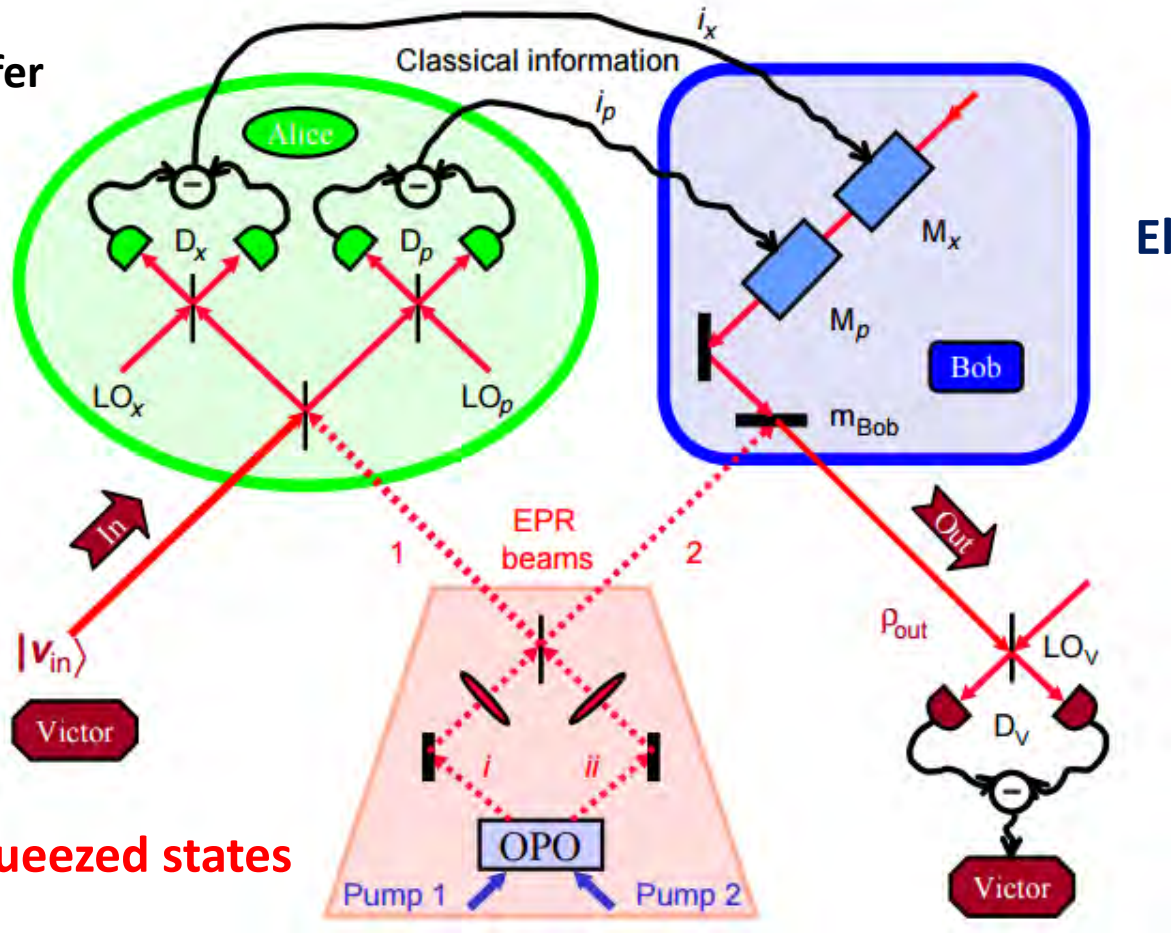
INTRO: CV QUANTUM NOISE

quantum teleportation =
measurement-induced transfer

measurement
(erasing)



Electro-optical quantum control

squeezed states

A. Furusawa, J. L. Sørensen, S. L. Braunstein, C. A. Fuchs, H. J. Kimble, E. S. Polzik, Science 282, 706 (1998).

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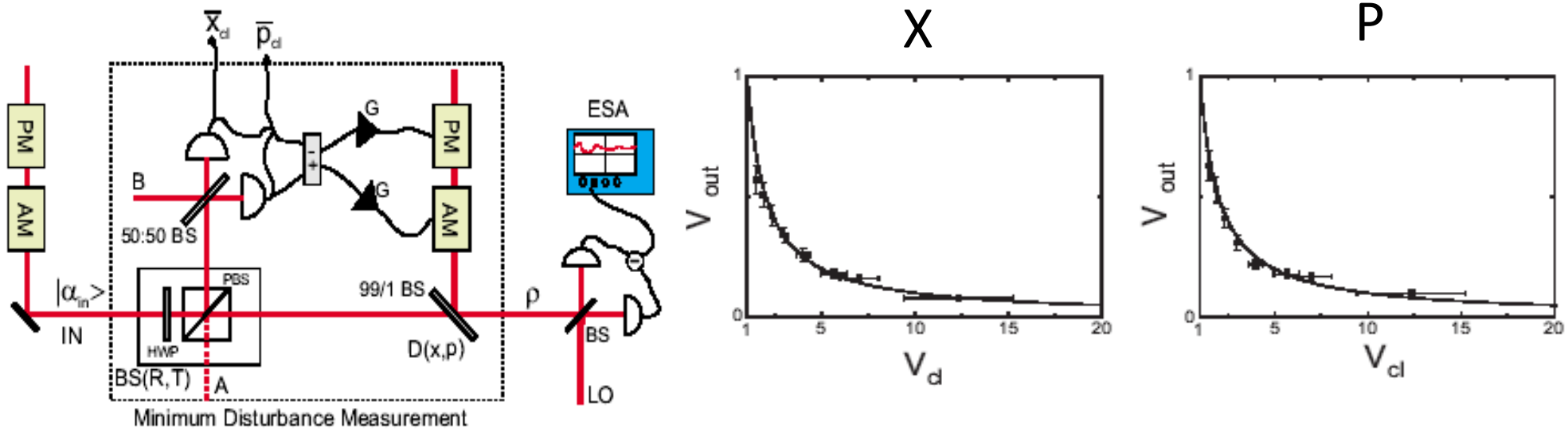
CV QUANTUM MEASUREMENT (OPERATION)

- CV quantum **measurement and erasing** using squeezed light, homodyne detection, linear optics and quantum feedforward control.
- **Minimum disturbance measurement** by linear optics, homodyne measurements and quantum feedforward control.



U.L. Andersen, O. Glöckl, S. Lorenz, G. Leuchs, and R. Filip, Phys. Rev. Lett. 93, 100403 (2004)
U.L. Andersen, M. Sabuncu, R. Filip, G. Leuchs, Phys. Rev. Lett. 020409 (2006).

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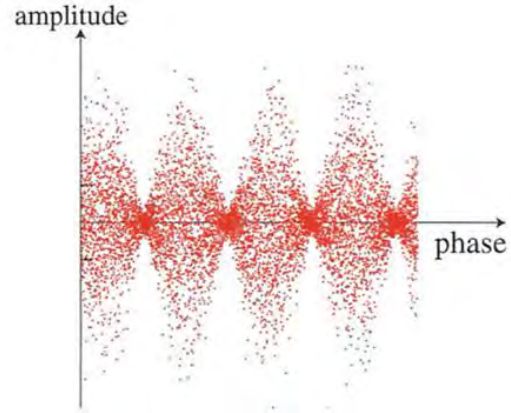
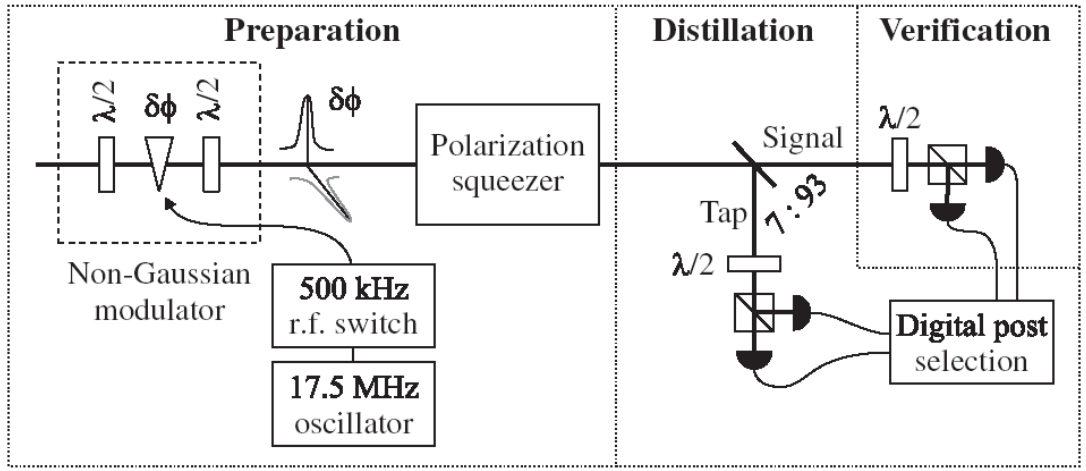
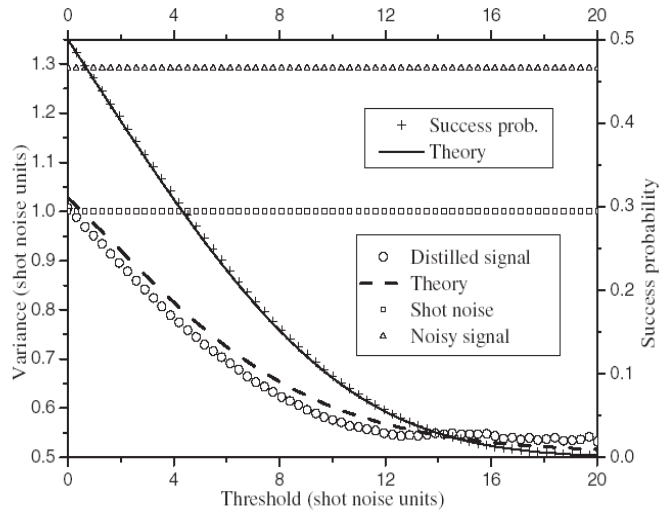
CV QUANTUM DISTILLATION BY WEAK MEASUREMENT

Quantum squeezing is **reduced or lost** by fluctuating pump or fading in transmission channel.

Distillation by measurement can recover it.







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

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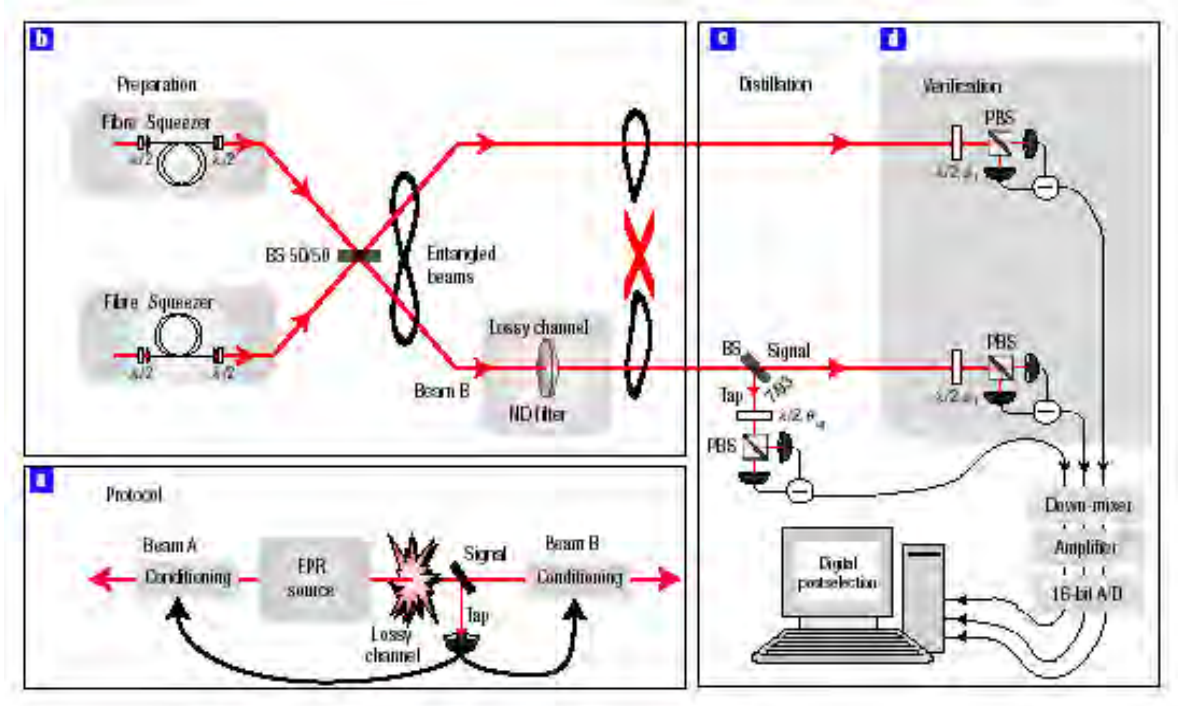
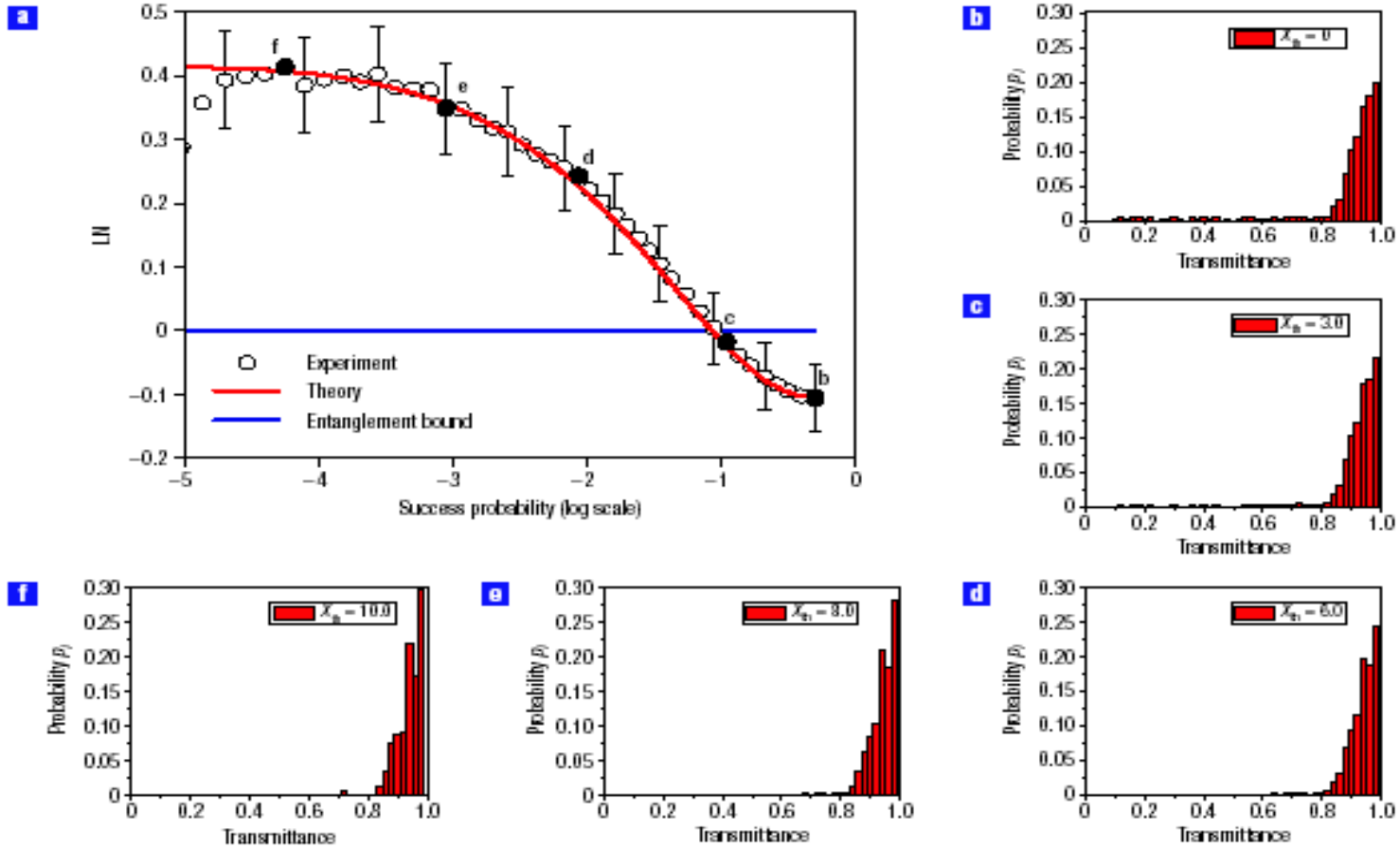
CV ENTANGLEMENT DISTILLATION



- Quantum entanglement **vanishes** by fading in free-space transmission channel.
- **Distillation** by measurement can recover quantum entanglement.

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

CV ENTANGLEMENT DISTILLATION



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

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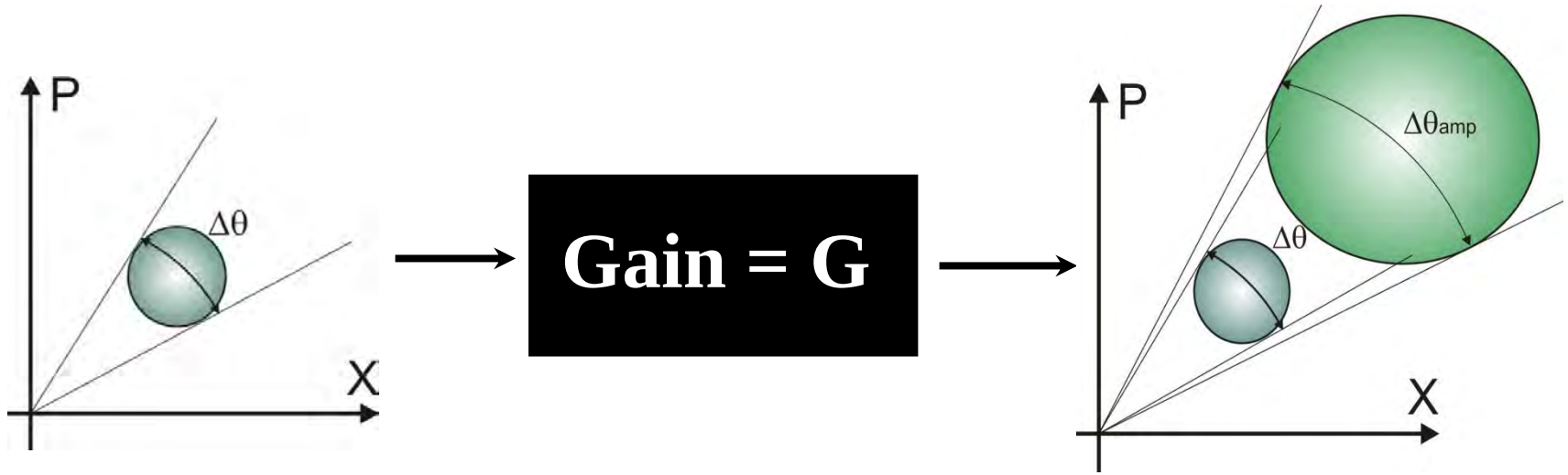
QUANTUM AMPLIFICATION



Quantum operation:

$$a_{out} = \sqrt{G}a_{in} + \sqrt{G-1}v^{+}$$

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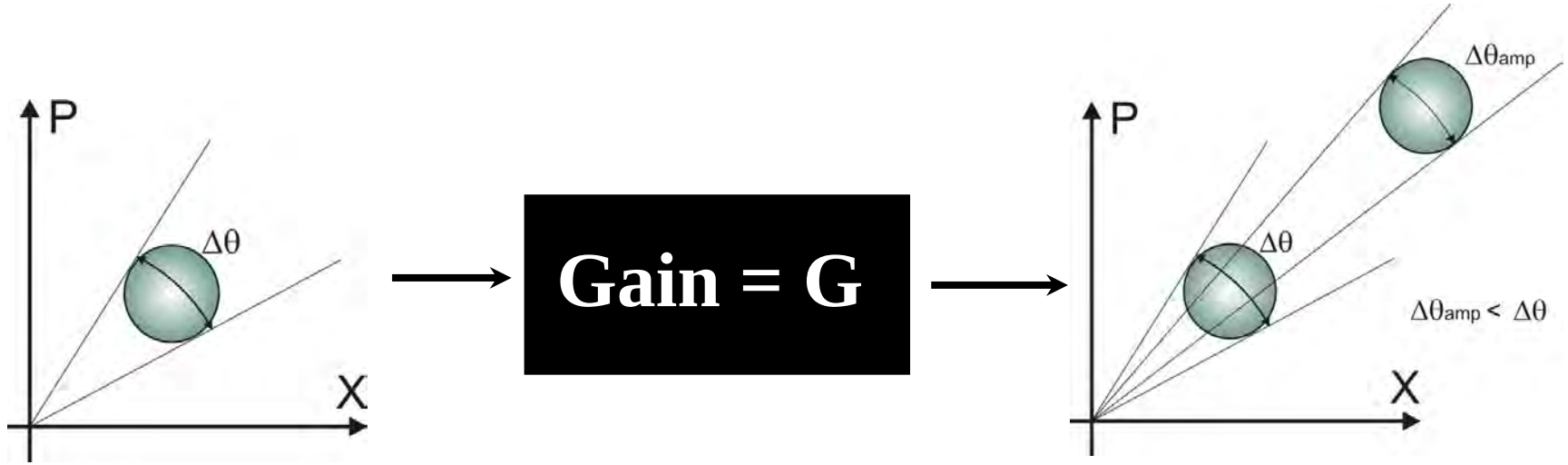
NOISELESS AMPLIFICATION

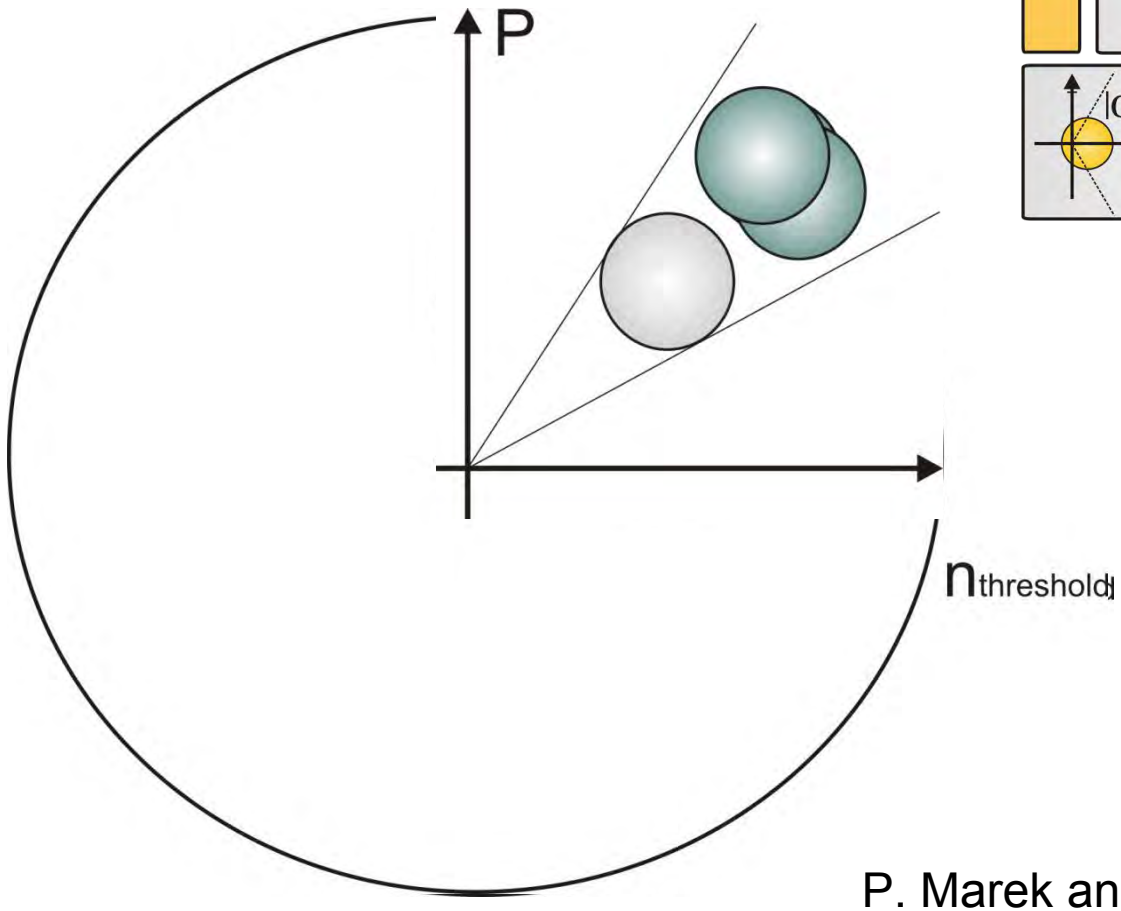


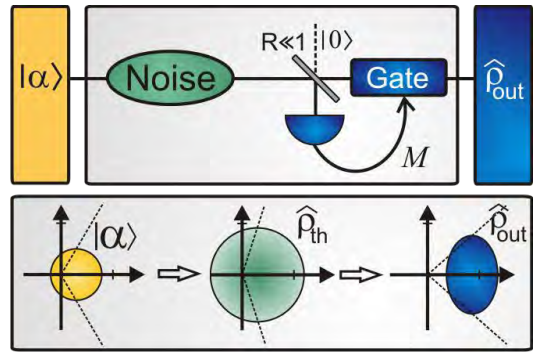
Unphysical operation:

$$a_{out} = \sqrt{G}\,a_{in} + \sqrt{G-1}\,v^{+}$$

Who first asked this question?

NOISELESS AMPLIFICATION





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

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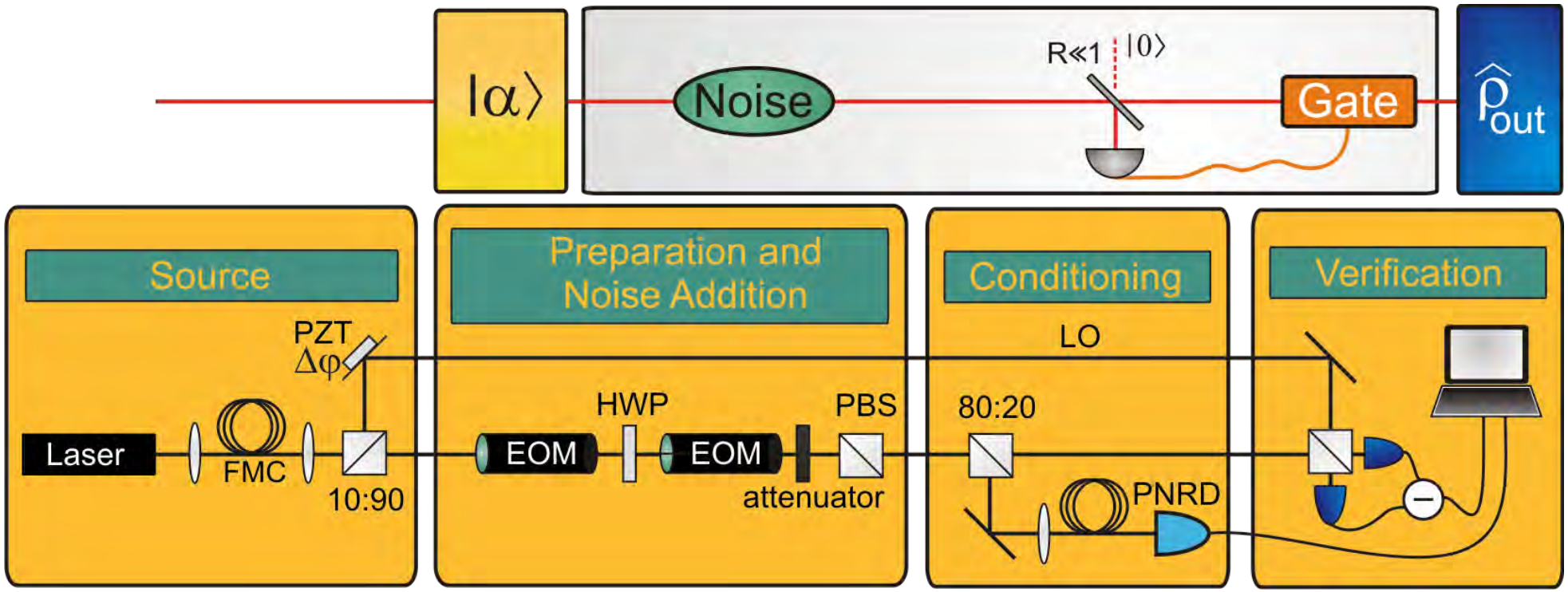
NOISELESS AMPLIFICATION



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

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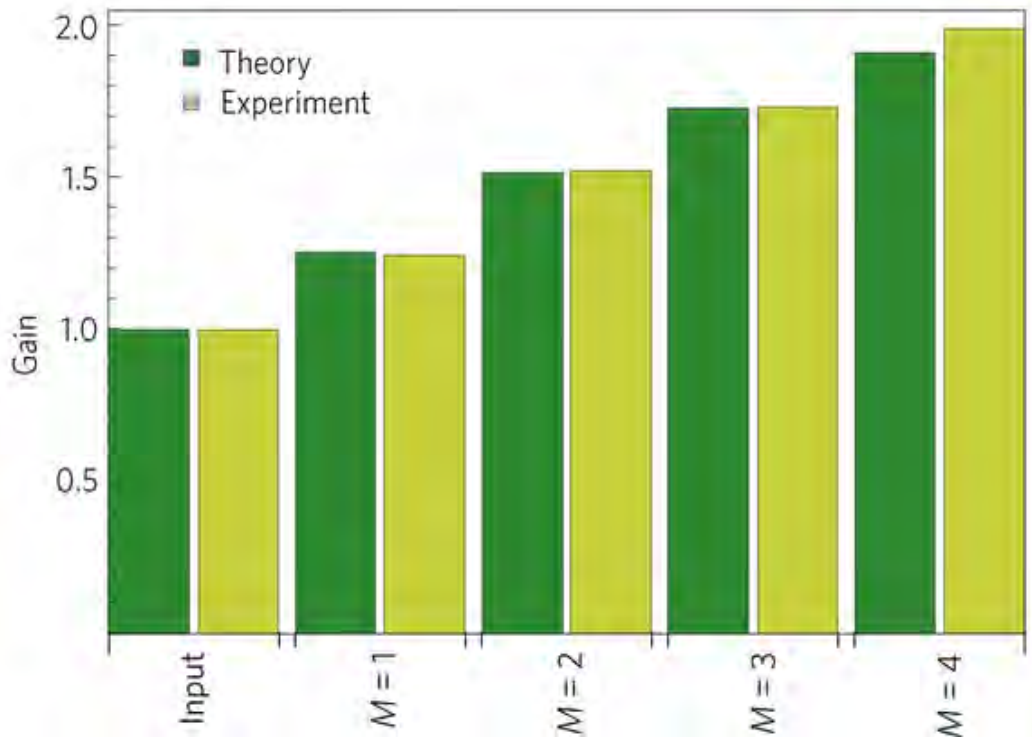
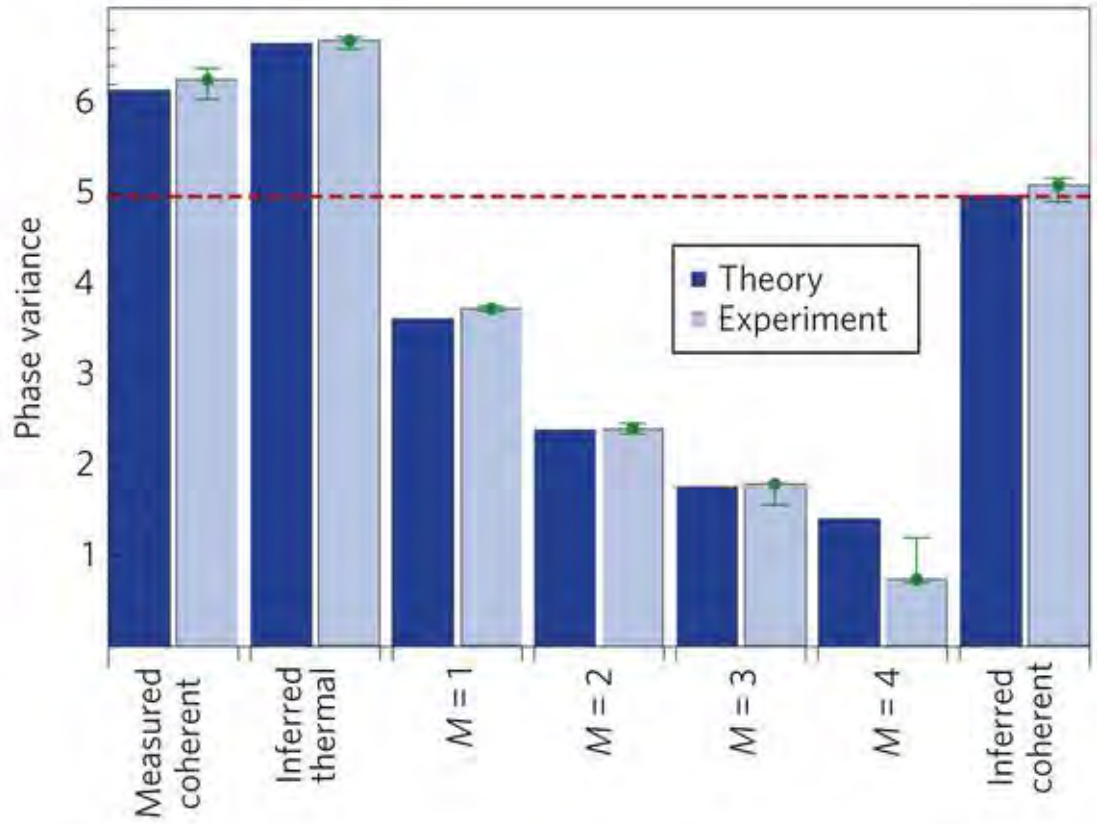
NOISELESS AMPLIFICATION





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

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NOISELESS AMPLIFICATION

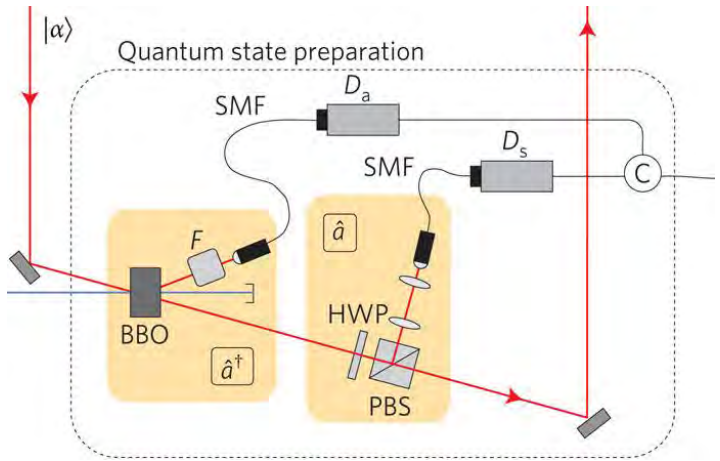
a^+ a

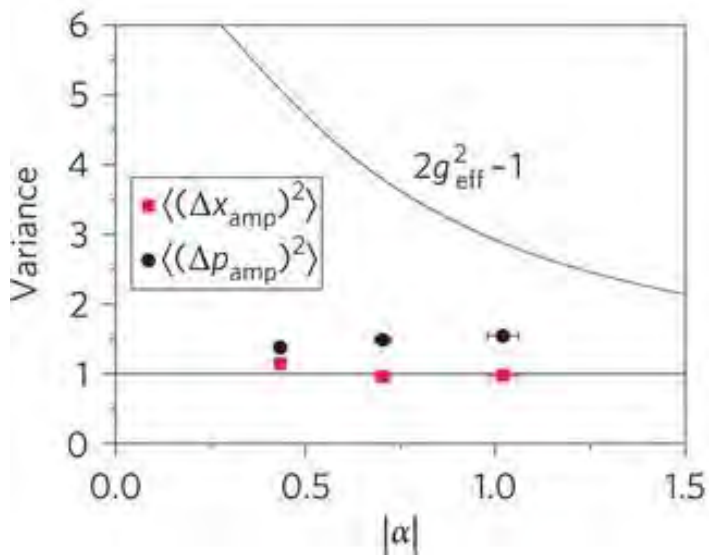
$|\alpha\rangle = |0\rangle + \alpha|1\rangle + \ldots$

$a^+|\alpha\rangle = |1\rangle + \mathbf{2^{1/2}}\,\alpha|2\rangle + \ldots$ $\rightarrow g^{\hat{n}}, g > 1$

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

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





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

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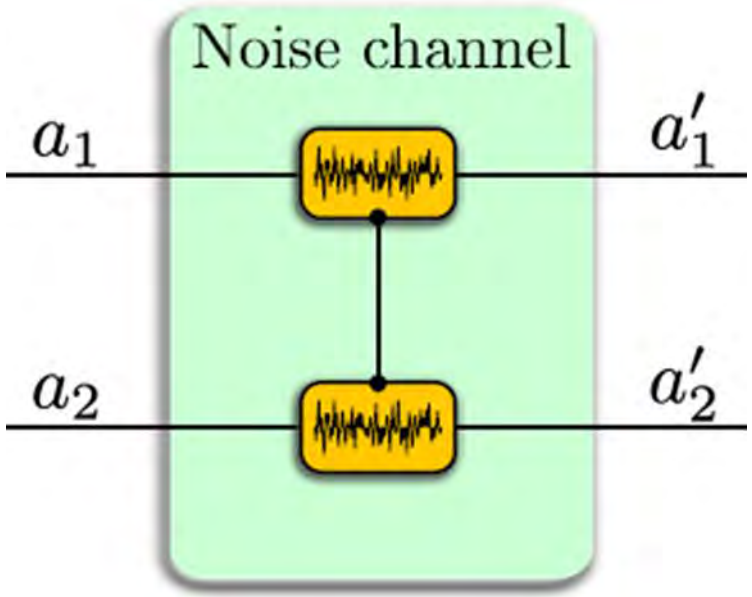
ERROR CORRECTION FOR CHANNEL WITH CLASSICALLY CORRELATED NOISE



Asymmetrical loss channels

$$\hat{a}'_1 = \sqrt{\eta_1}\hat{a}_1 + \sqrt{1-\eta_1}\hat{v}_1 + \sqrt{g_1}v_C$$

$$\hat{a}'_2 = \sqrt{\eta_2}\hat{a}_2 + \sqrt{1-\eta_2}\hat{v}_2 + \sqrt{g_2}v_C$$

Asymmetrical perfectly uncorrelated noise

Asymmetrical perfectly correlated noise

R. Filip, Phys. Rev. A 81, 032330 (2010)

M. Lassen, A. Berni, L.S. Madsen, R. Filip, U.L. Andersen, Phys. Rev. Lett 111, 180502 (2013)

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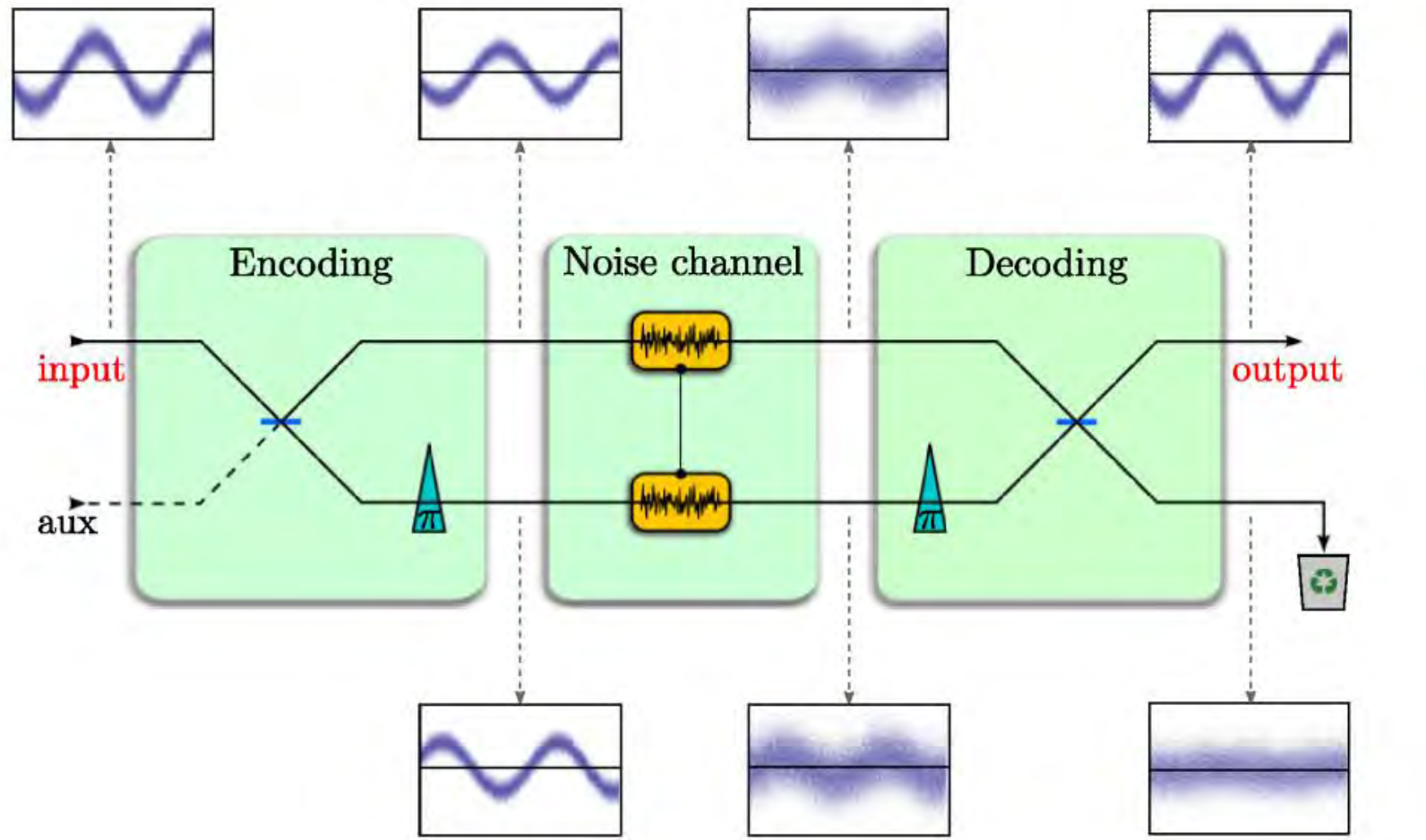

M. Lassen, A. Berni, L.S. Madsen, R. Filip, U.L. Andersen, Phys. Rev. Lett 111, 180502 (2013).

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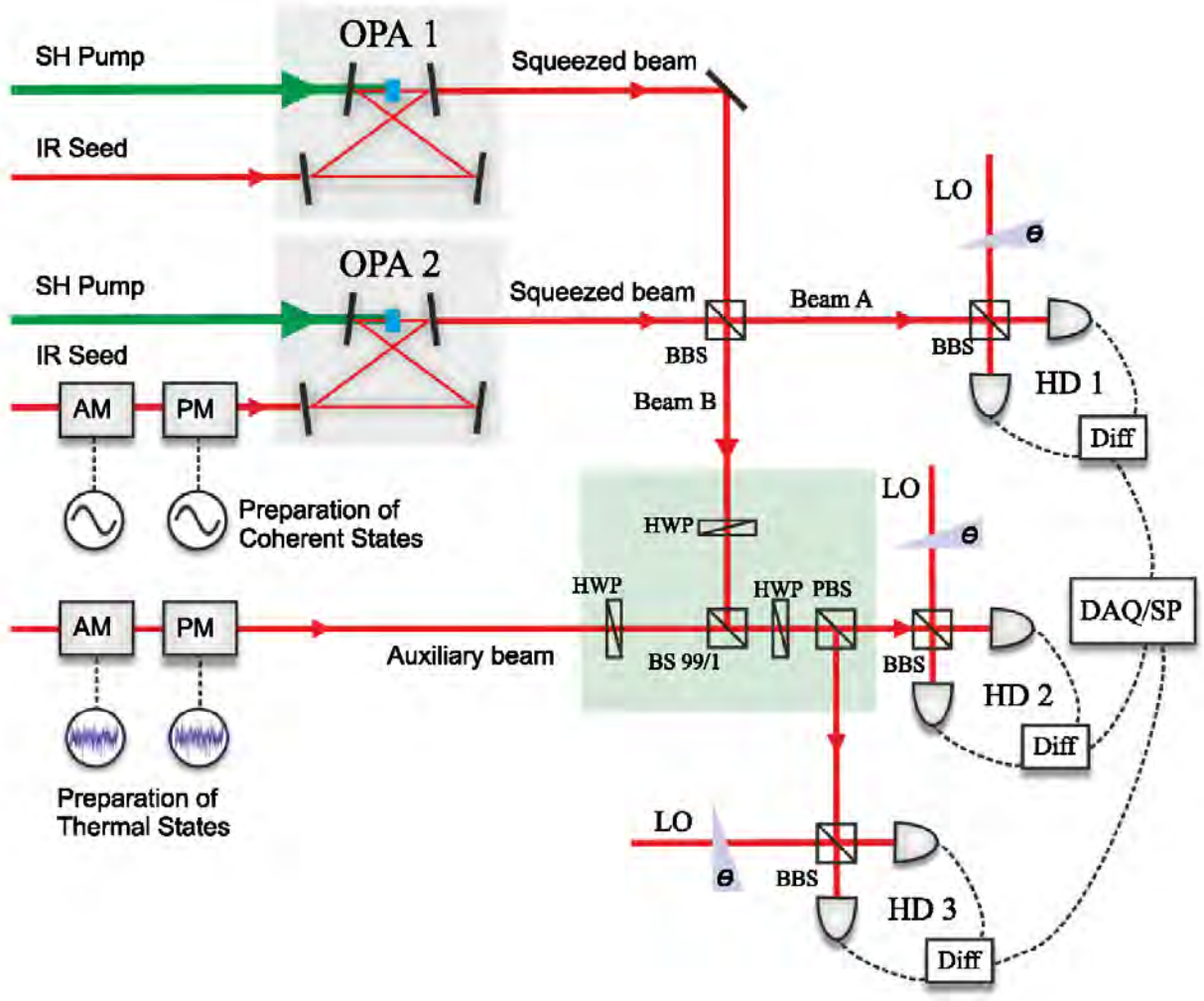

M. Lassen, A. Berni, L.S. Madsen, R. Filip, U.L. Andersen, Phys. Rev. Lett 111, 180502 (2013).

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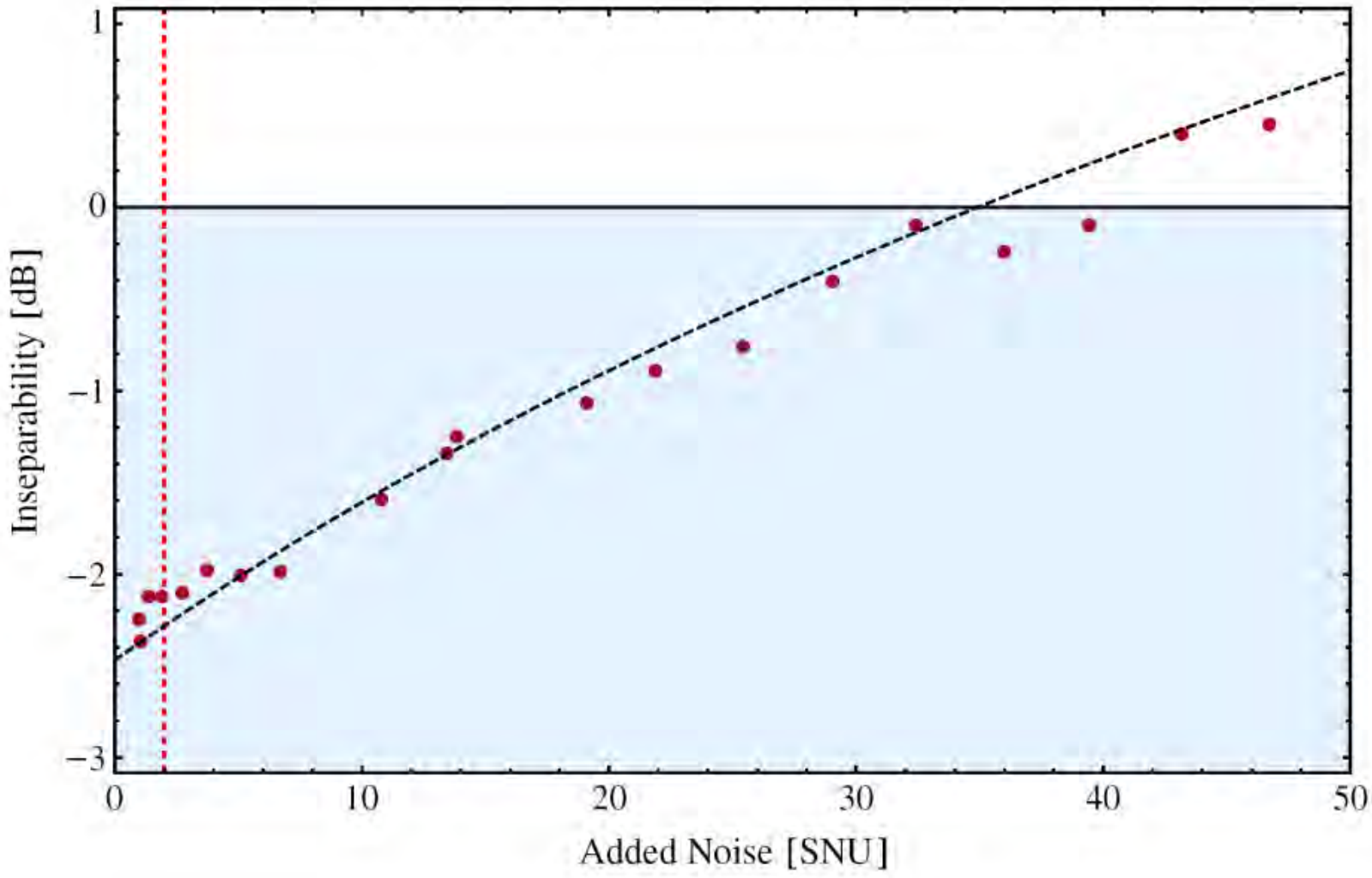

M. Lassen, A. Berni, L.S. Madsen, R. Filip, U.L. Andersen, Phys. Rev. Lett 111, 180502 (2013).

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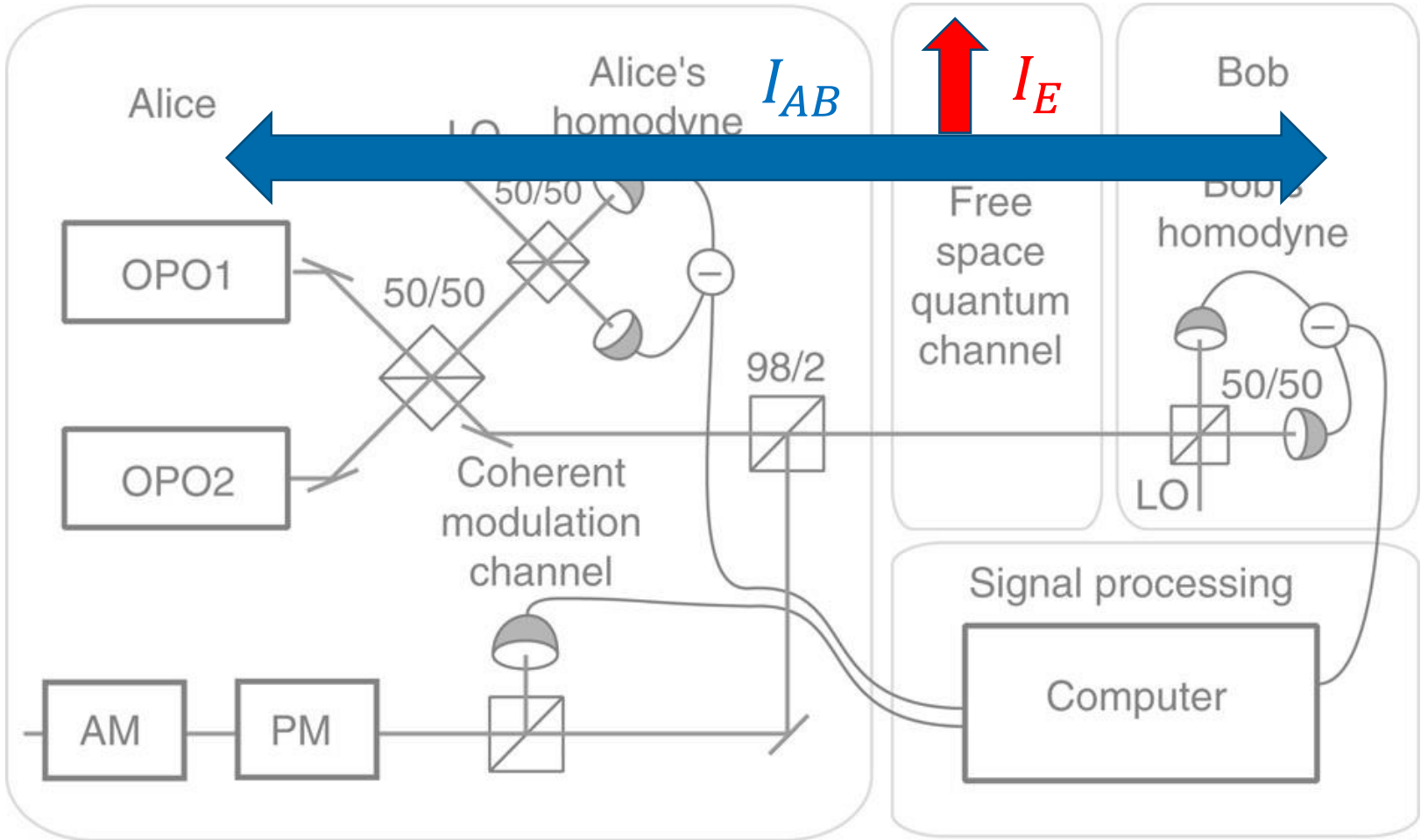
APPLICATION: CV QKD



$$I_{AB} > I_E$$

Csiszár and Körner's theorem

$$K = \beta I_{AB} - I_E$$

secure key rate

F. Grosshans et al., Quantum key distribution using gaussian-modulated coherent states, Nature 421, 238 (2003).

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

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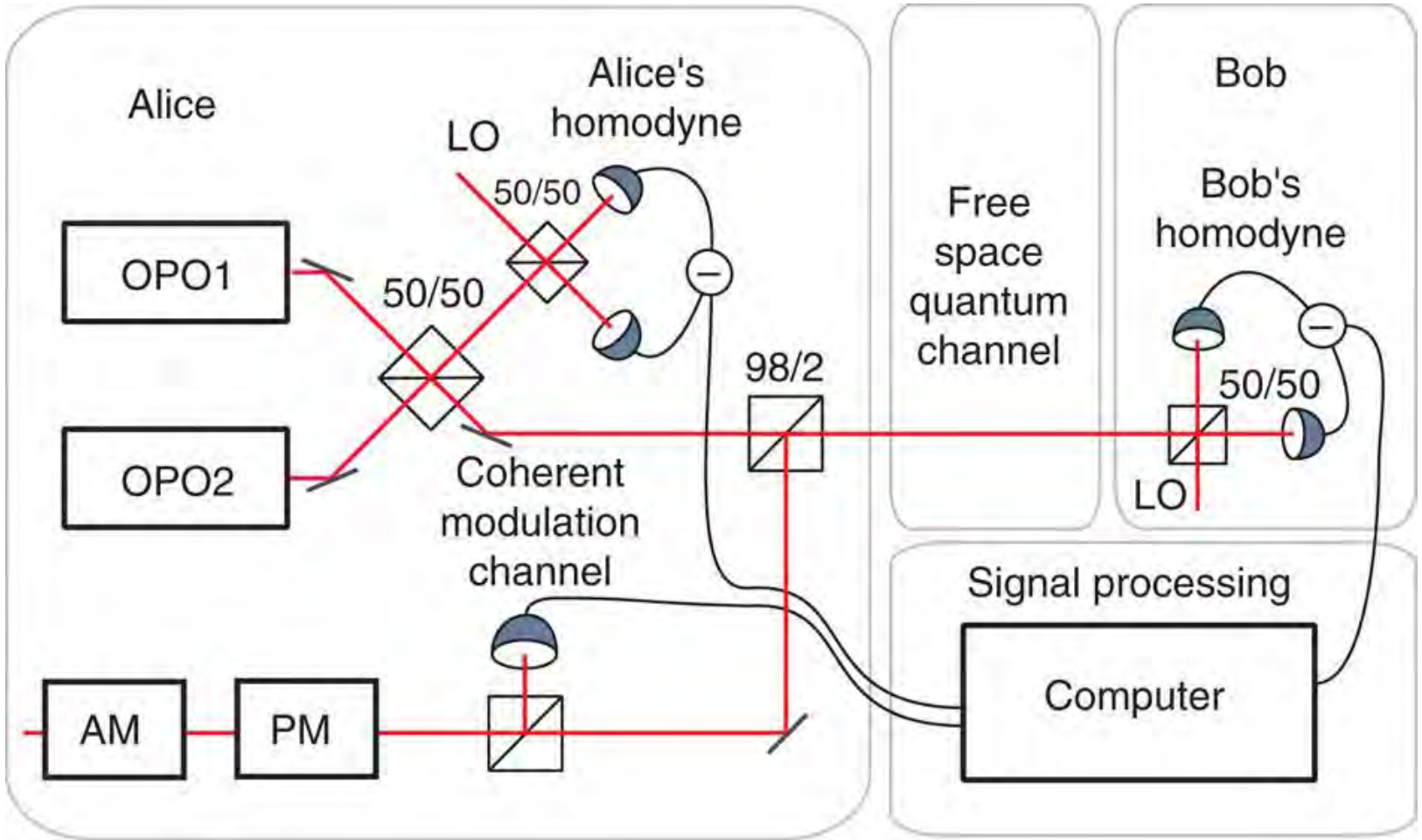
APPLICATION: ENTANGLED STATE CV QKD



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

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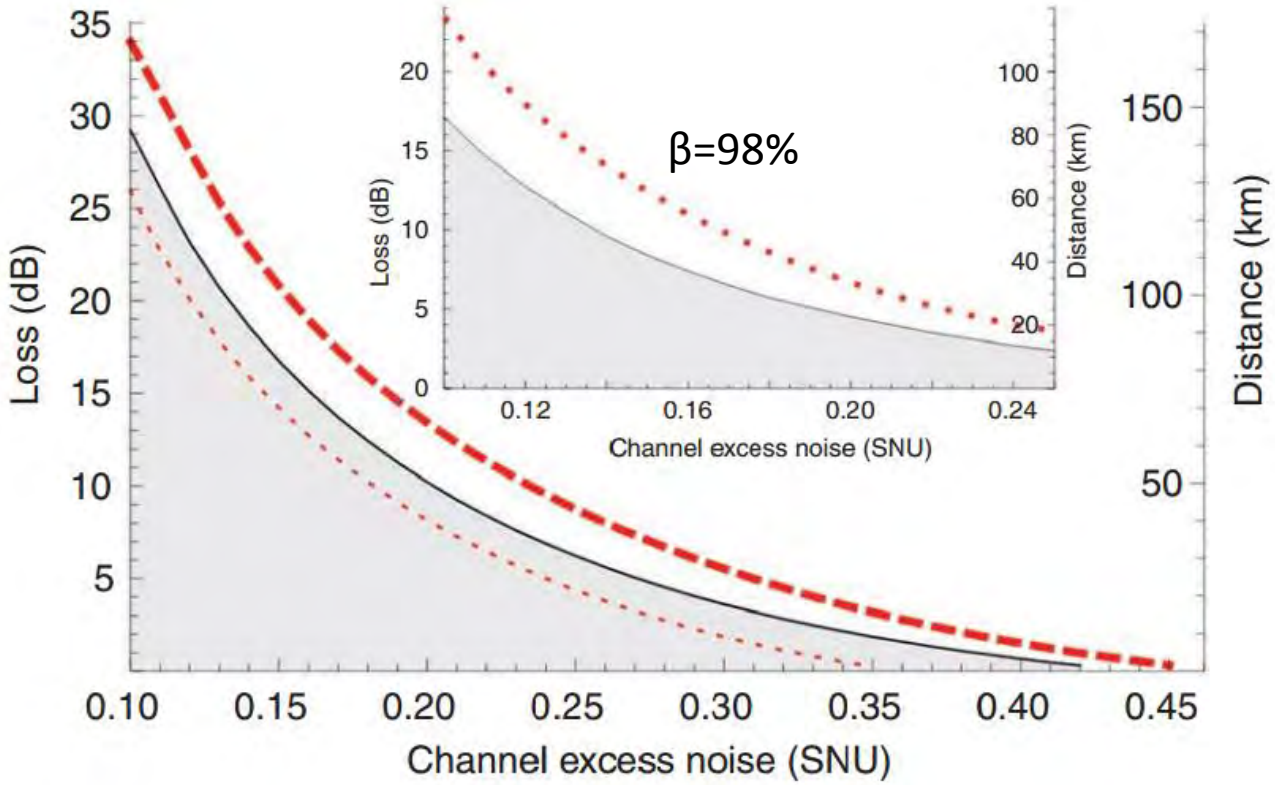
APPLICATION: ENTANGLED STATE QKD

It overcomes coherent state protocol.

Entanglement allows larger distance.



3.5 dB two-mode squeezing

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

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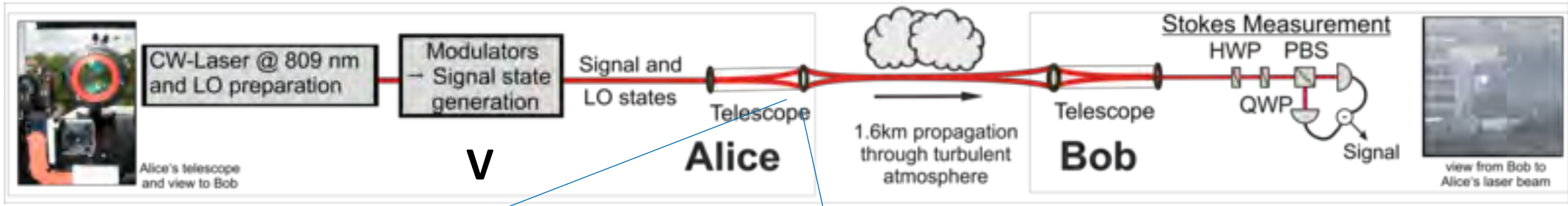
NEXT: FREE-SPACE CV QKD



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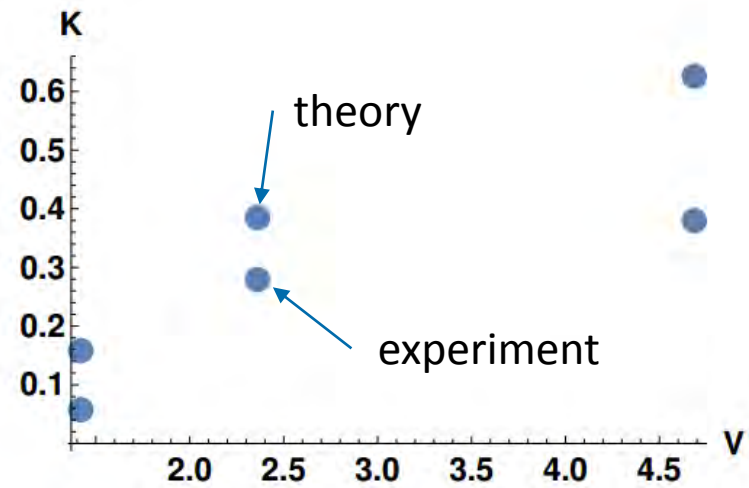
First data of CV free-space coherent state QKD



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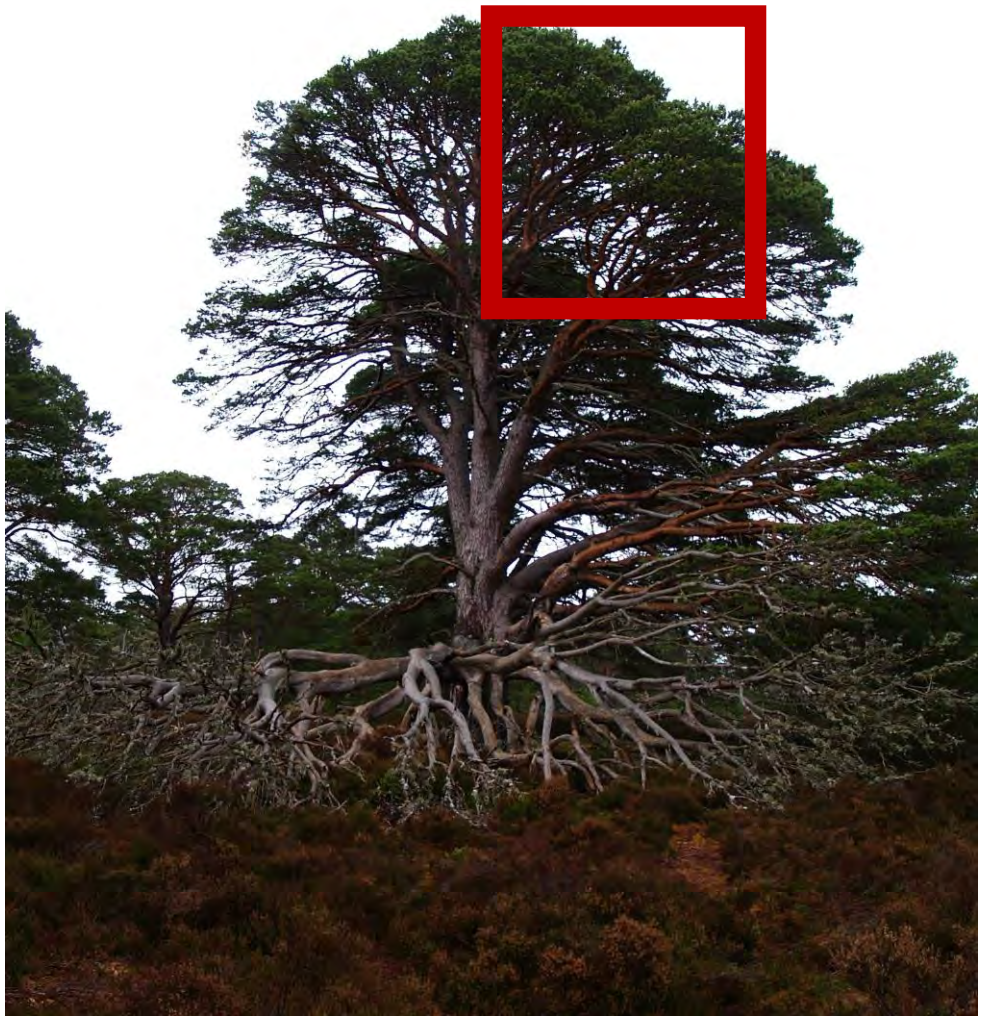
SUMMARY



- Minimal disturbance quantum measurements
- Quantum distillation of squeezing and entanglement
- Noiseless quantum amplification
- Quantum error correction for correlated noise
- Entangled based quantum key distribution
- Universal squeezer and its applications
- Optimal non-Gaussian state manipulation
- Amplification of optomechanical coupling
- Deterministic cubic quantum operation
- Simulations of quantum nonlinearity
- Noise enhanced quantum effects