Continuous polarization variable QKD

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discrete vs. continuous

discrete

dichotomic variable

$$\Psi = \alpha |0\rangle + \beta |1\rangle = \sum_{i=1}^{2} \alpha_i |i\rangle$$

→ click detectors

discrete &

∞ dim Hilbert space

$$\Psi = \sum_{i=1}^{\infty} \alpha_i |i\rangle$$

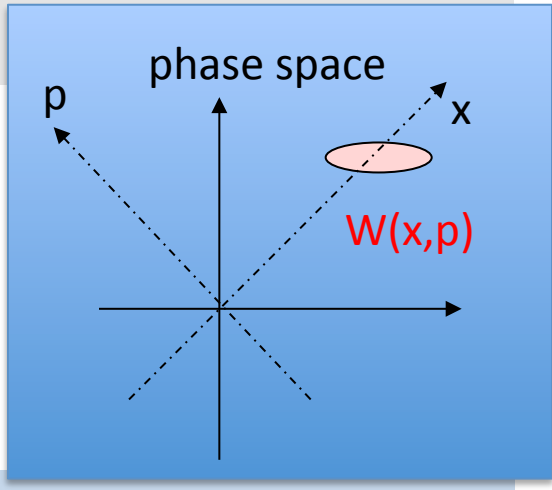
→ photon number resolving detectors

alternatively : **continuous variables** x , p

$$W(x,p) = \frac{1}{2\pi\hbar} \int_{-\infty}^{\infty} d\xi \, \exp(-\frac{ip\xi}{\hbar}) \, \Psi^*(x - \frac{1}{2}\xi) \, \Psi(x + \frac{1}{2}\xi)$$

Wigner function

→ homodyne detection



types of continuous quantum variables

- field quadratures
- Stokes variables (polarization)

QKD – based on the impossibility of perfectly measuring non-orthogonal quantum states

two strategies:

BB84

Alice prepares states which are eigen-states of Bob's measurement operator
- need to switch between different bases

Alice's state \ Bob's det.	click detector	PNR detector	homo-dyne detector
n=1, pol base	✓	✓	?
n>1, pol base	–	✓	?
coherent pol base	(↯↯)	(↯) *	(↯)
squeezed st.	–	–	(✓)

(↯) = no eigenstate → not perfect
(✓) = unrealistic – only if squeezing is infinite

B92

Alice prepares non-orthogonal states and Bob uses quantum state estimation

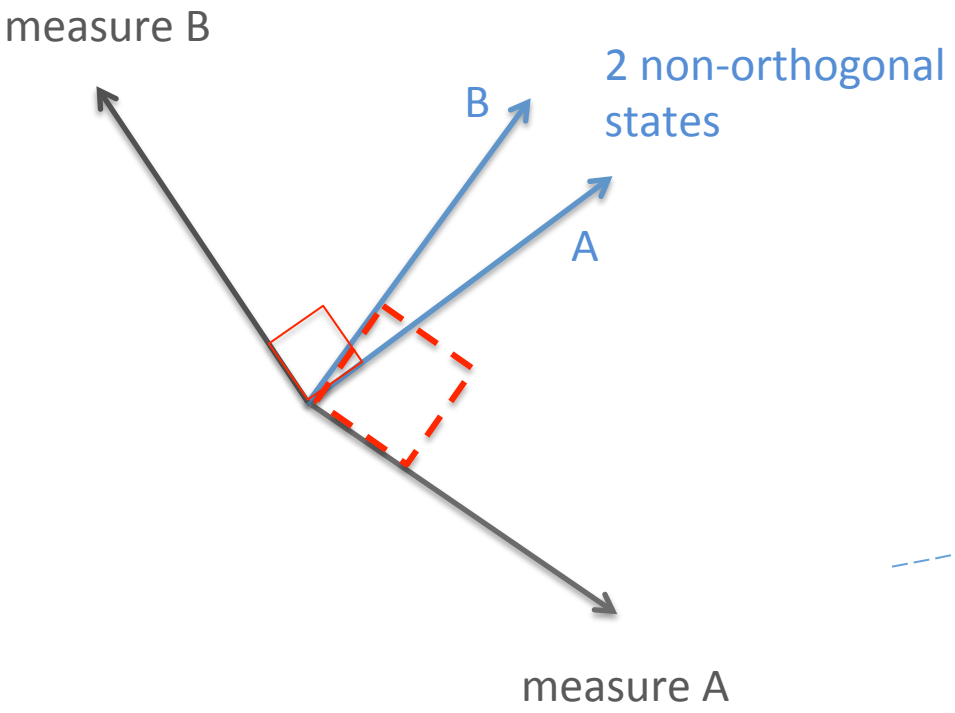
Alice's state \ Bob's det.	click detector	PNR detector	homo-dyne detector
n=1, diff pol	✓	✓	?
n>1, diff pol	–	✓	?
coherent two phases	✓	✓	✓
squeezed st.	–	–	✓

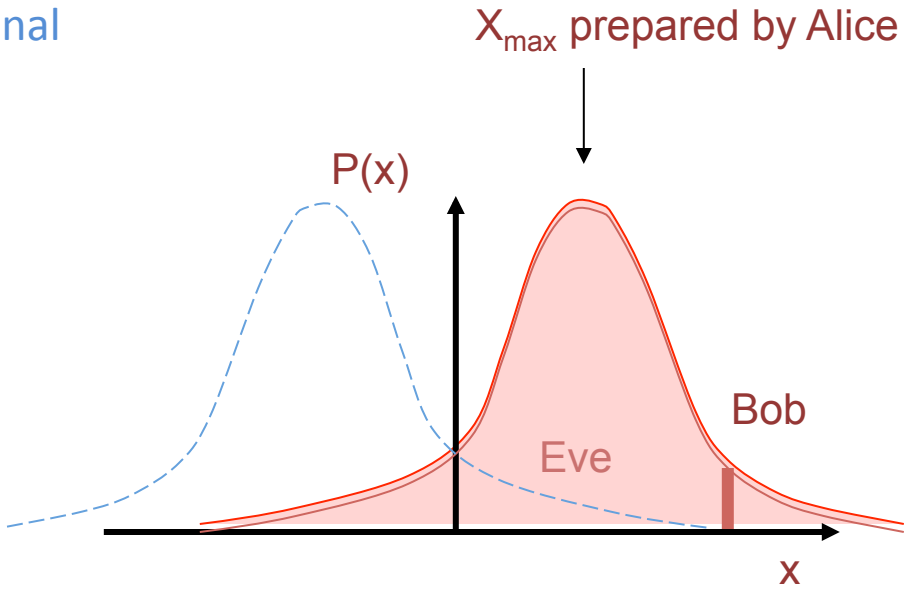
*Norbert's comment yesterday
? D. Bozyigit et al. Nat. Phys. 7,154 (2011)

Quantum state estimation

a single photon in either of two non-orthogonal polarizations

the continuous quantum variable case





Ch. Silberhorn, T.C. Ralph, N. Lütkenhaus, and G. L., PRL 89, 167901 (2002)

Quantum state estimation

PRL 96, 020409 (2006) PHYSICAL REVIEW LETTERS week ending 20 JANUARY 2006

Experimental Demonstration of Coherent State Estimation with Minimal Disturbance

Metin Sabuncu,[1] Radim Filip,[1,2] and Gerd Leuchs[1]

[1] Max-Planck-Forschungsgruppe, Universität Erlangen-Nürnberg,

PRL 101, 210501 (2008) PHYSICAL REVIEW LETTERS week ending 21 NOVEMBER 2008

Demonstration of Near-Optimal Discrimination of Optical Coherent States

Katiúscia N. Cassemiro,[4] Masahide Sasaki,

New Journal of Physics
The open-access journal for physics

24 July 2012

Quadrature phase shift keying coherent state discrimination via a hybrid receiver

C R Müller[1,2], M A Usuga[1,3], C Wittmann[1,2], M Takeoka[4], Ch Marquardt[1,2], U L Andersen[1,3,5] and G Leuchs[1,2,5]

[1] Max Planck Institute for the Science of Light, Erlangen, Germany

$|\alpha|^2 \leq 0.75$

$100kHz$

Advantage of homo-/heterodyning in free space

➔ measuring single mode

number of photons per mode in direct sun light:

$$N = 8\pi \frac{\nu^2}{c^3} \Delta\nu \frac{h\nu}{e^{\frac{h\nu}{kT}} - 1} \frac{c}{6} \cdot \left(\frac{D_{sun}}{R_{S-E}} \right)^2 \frac{1}{2\pi \cdot \Delta\nu} \frac{\pi\lambda^2}{4\left(\frac{D_{sun}}{R_{S-E}} \right)^2} \frac{1}{h\nu}$$

$$\approx \left(e^{\frac{h\nu}{kT}} - 1 \right)^{-1}$$

➔ direct sun light : 0.05 coherent photons @ 800 nm

➔ indirect sun light: even lower

propagation in turbulent medium → beam distortion
→ small homo-/heterodyne efficiency

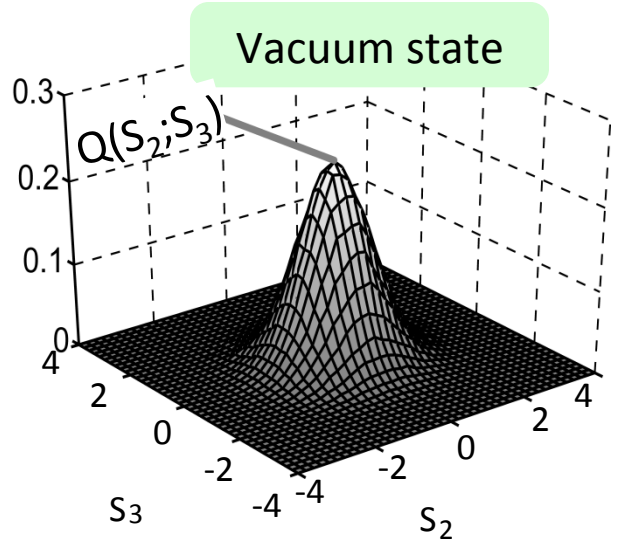
the cure: polarisation variables

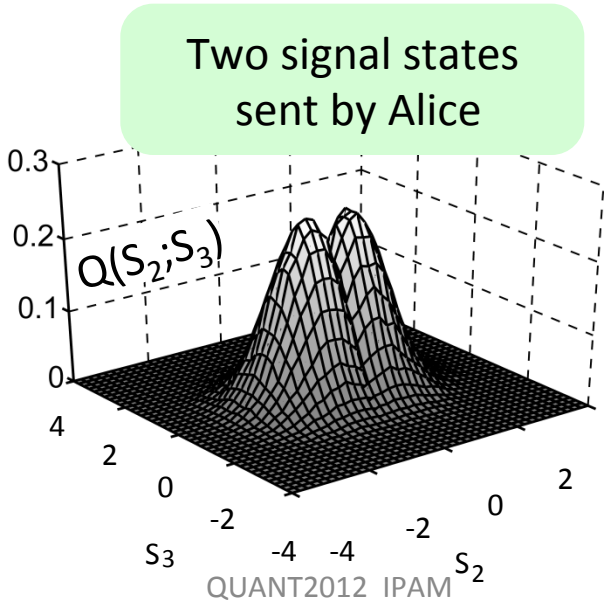
our approach

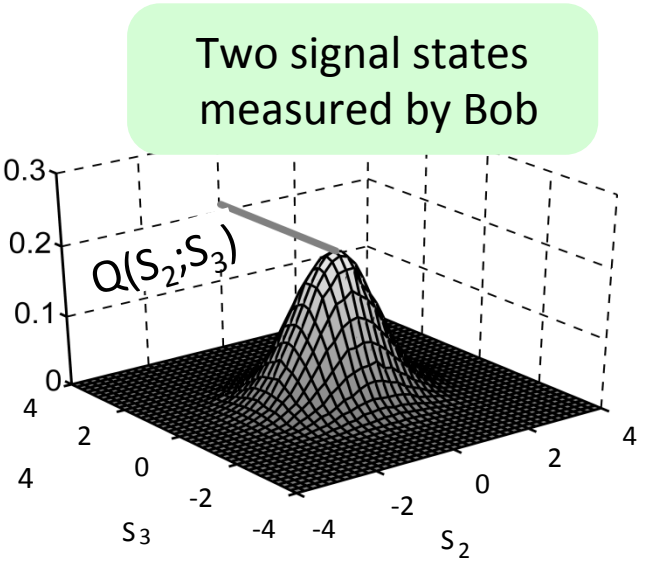
fiber/free space

Our approach

- CV QKD with discrete modulation
- „prototype“ experiments:
  Lorenz et al., Appl. Phys. B **79**, 273 (2004) &
  Lorenz et al., PRA, **74** (4), 042326 (2006)
- polarization encoding
- heterodyne detection of conjugate Stokes variables







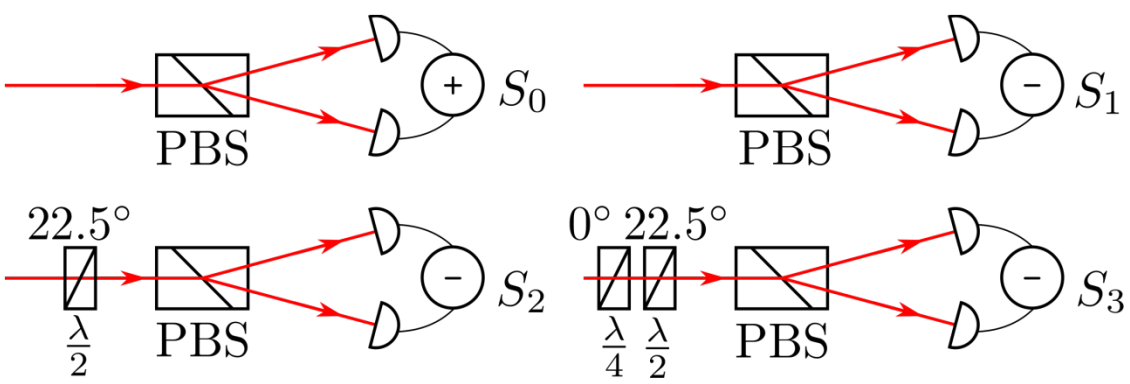
Lorenz *et al.*, PRA **74**, 042326 (2006)

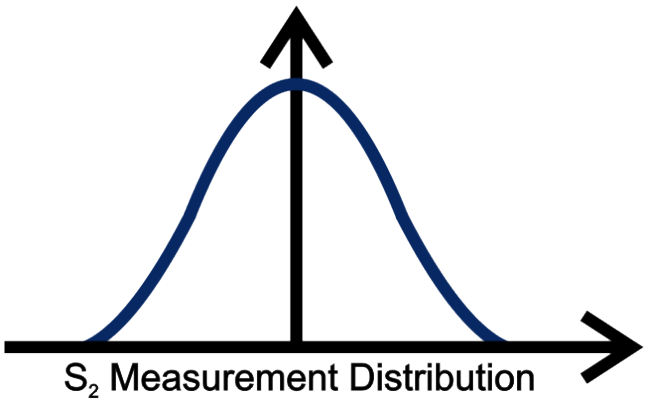
Quantum Stokes operators and measurement

$$\hat{S}_0 = \hat{a}_x^\dagger \hat{a}_x + \hat{a}_y^\dagger \hat{a}_y \ \text{(total intensity)}$$
$$\hat{S}_1 = \hat{a}_x^\dagger \hat{a}_x - \hat{a}_y^\dagger \hat{a}_y \quad (\leftrightarrow - \updownarrow)$$
$$\hat{S}_2 = \hat{a}_x^\dagger \hat{a}_y + \hat{a}_y^\dagger \hat{a}_x \quad (\swarrow\!\!\nearrow - \nwarrow\!\!\searrow)$$
$$\hat{S}_3 = i(\hat{a}_y^\dagger \hat{a}_x - \hat{a}_x^\dagger \hat{a}_y) \ (\circlearrowleft - \circlearrowright)$$

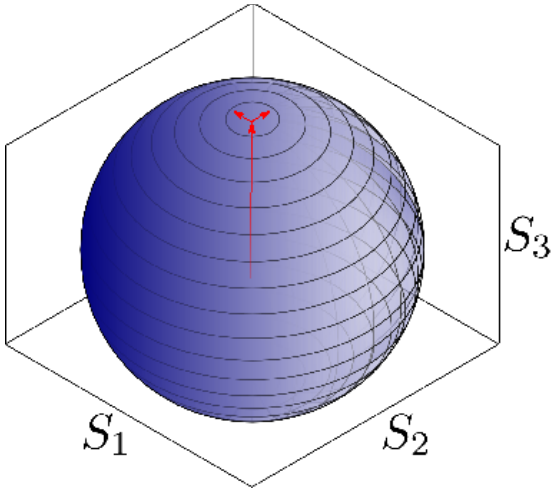
Uncertainty Relation:

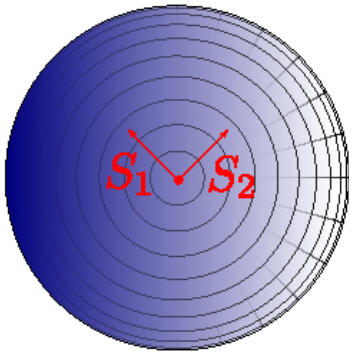
$$\mathrm{Var}(\hat{S}_1) \cdot \mathrm{Var}(\hat{S}_2) \geq |\langle \hat{S}_3 \rangle|^2$$



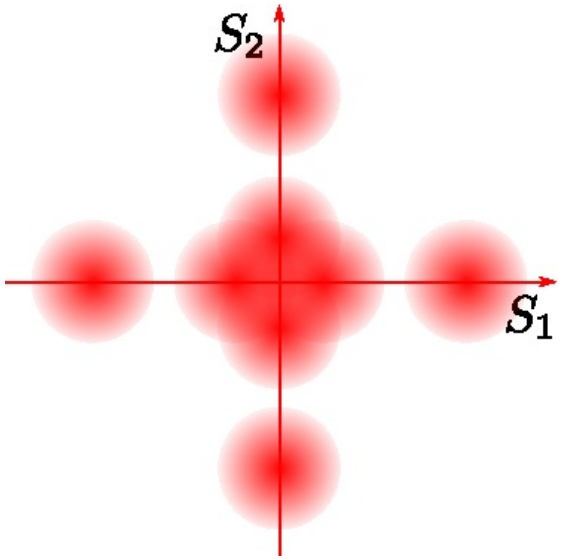


Polarization encoding





- start with circularly polarized LO
- signal modulation in S_1-S_2-darkplane using two commercial electro-optical modulators (EOMs)
- homodyne detection: weak signal detectable with help of bright LO (S_3)
- signal and LO travelling in one spatial mode
  → further advantages:



- excellent spatial interference
- no additional spatial filtering
- LO as spectral filter

→ precise adjustment of detection bandwidth

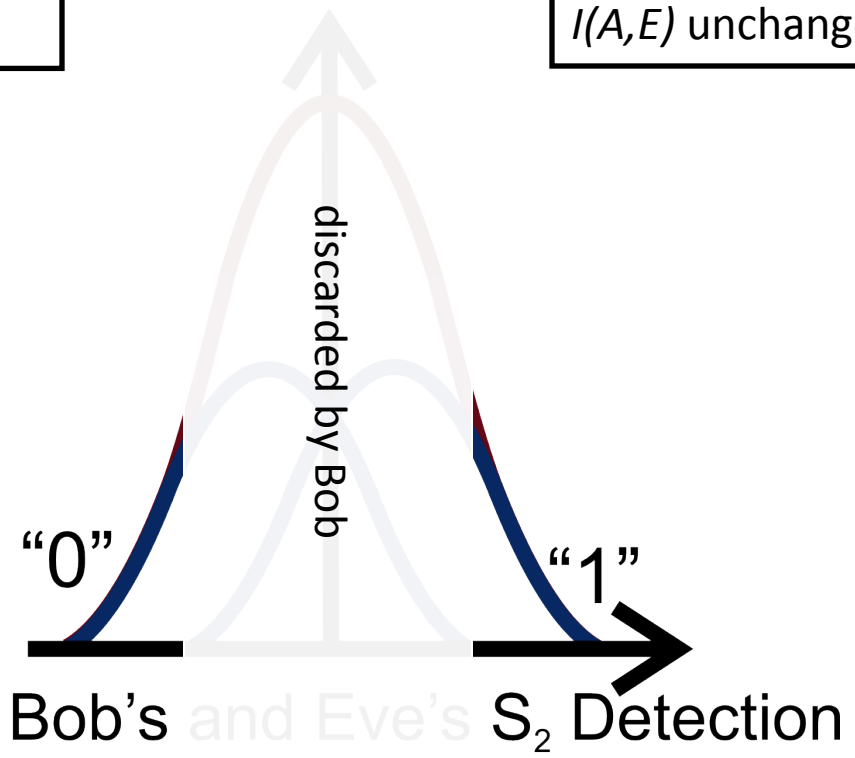
- daylight operation
- easy monitoring of atmospheric effects

Detection and Postselection

Post Selection:
Silberhorn et al.,
PRL 89, 167901 (2002)

I(A,B) increased

I(A,E) unchanged



Witnessing effective entanglement over a 2km fiber channel

Christoffer Wittmann[1,2,†], Josef Fürst[1,2,†], Carlos Wiechers[1,2,3], Dominique Elser[1,2], Hauke Häseler[2,4], Norbert Lütkenhaus[1,2,4], and Gerd Leuchs[1,2]

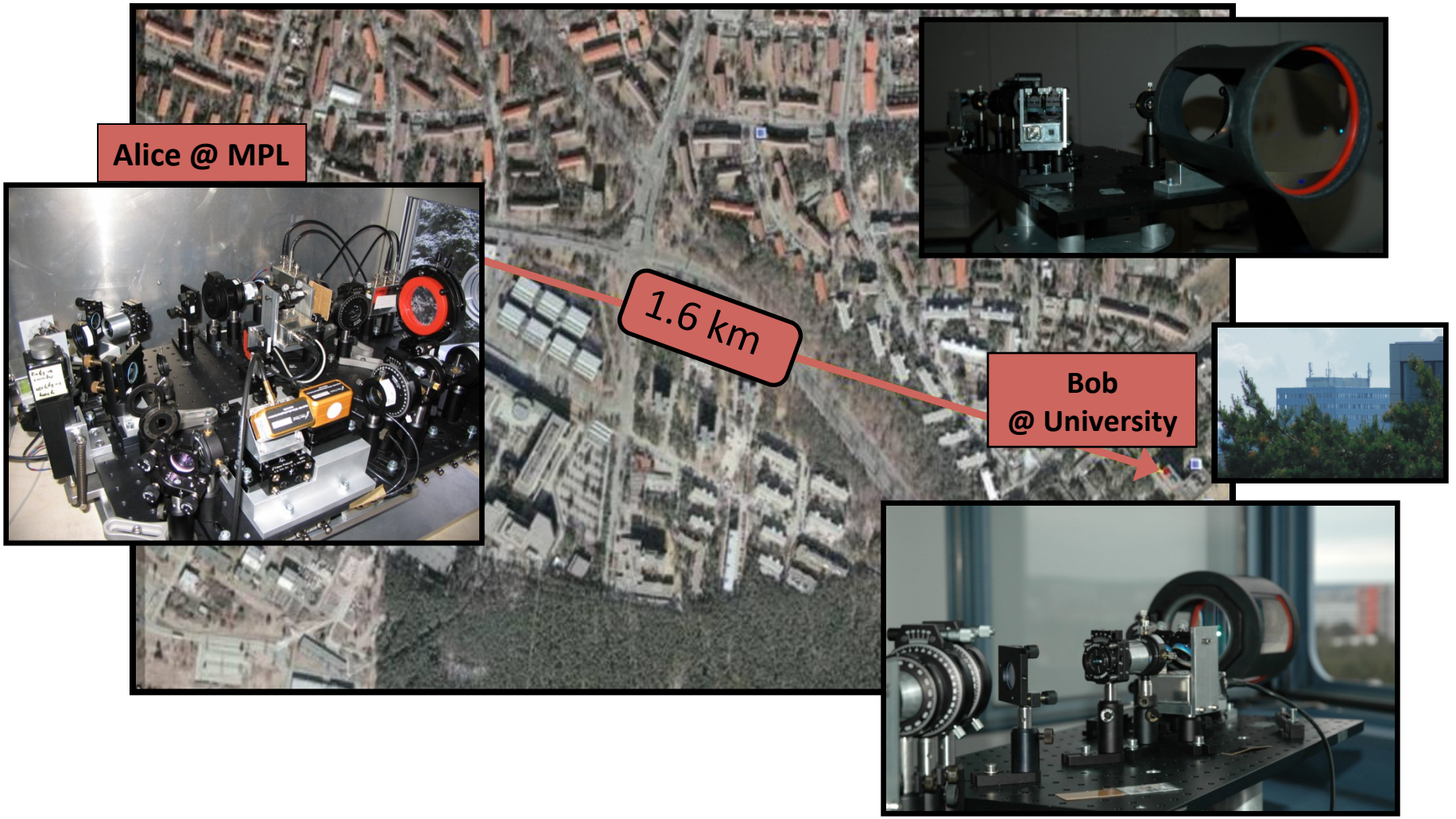
Optics Express **18**, 4499 (2010)

Abstract: We present a fiber-based continuous-variable quantum key distribution system. In the scheme, a quantum signal of two non-orthogonal weak optical coherent states is sent through a fiber-based quantum channel. The receiver simultaneously measures conjugate quadratures of the light using two homodyne detectors. From the measured Q-function of

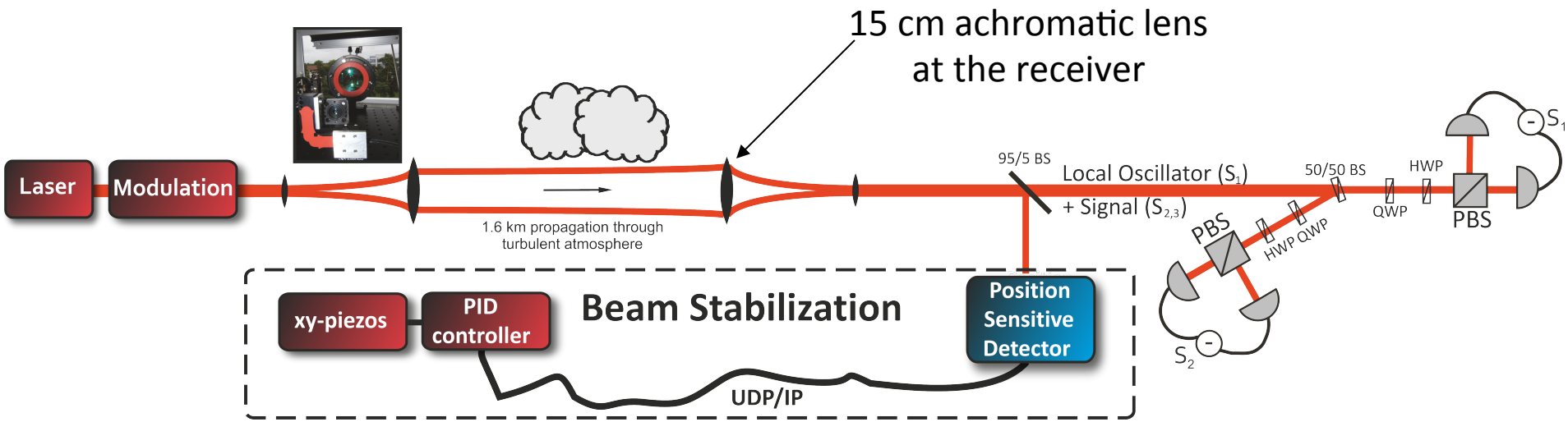
losses equivalent to > 15 km

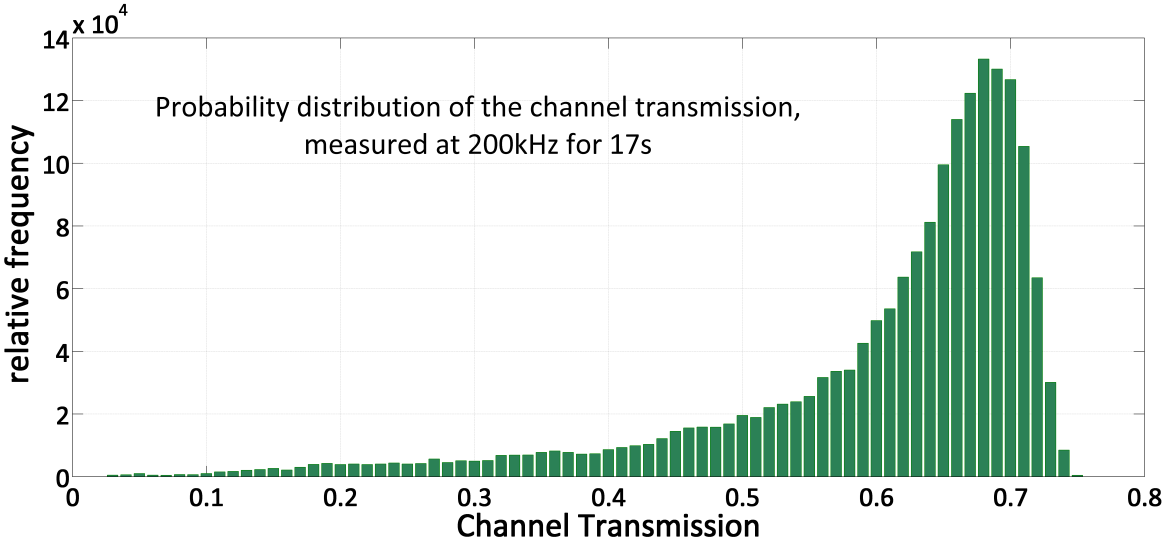
free space

1.6 km free space link – from MPL‘s roof to university tower



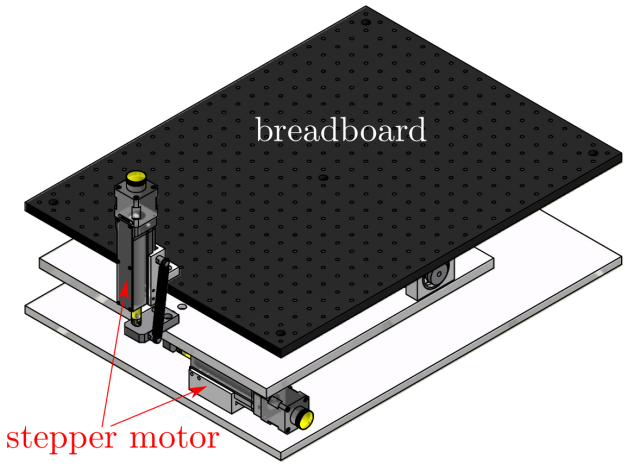
Receiver setup

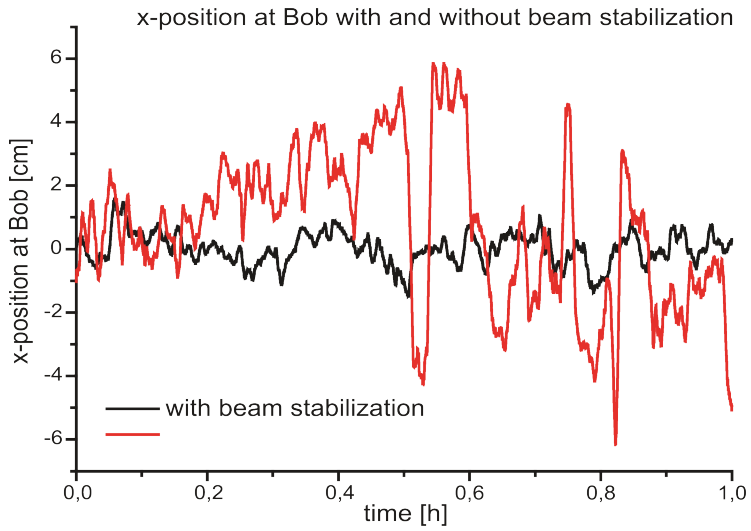


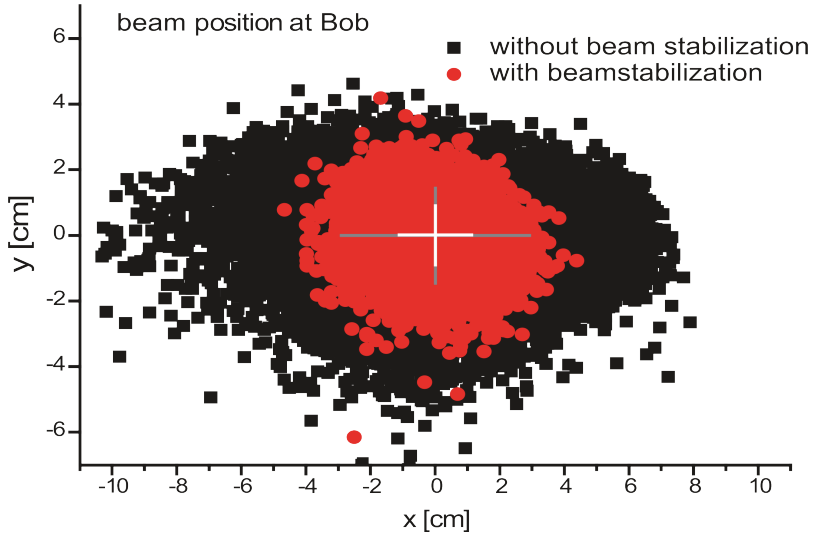


Beam Stabilization system

- software-based PID-controller
- beam tap-of at Bob and measurement by a position sensitive detector (PSD)
- movement of Alice ‘s small telescope lens
  according to PSD feedback signal
  → compensation of beam wandering
- ± 20 cm beam displacement at Bob´s side with an accuracy in the mm range
- additional movement of the whole breadboard by stepper motors

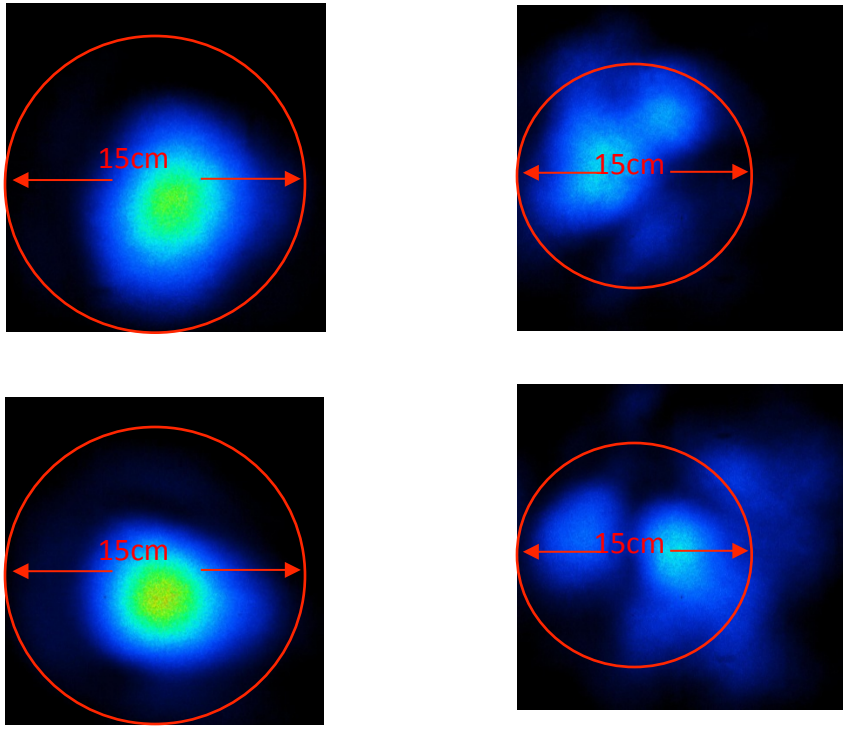




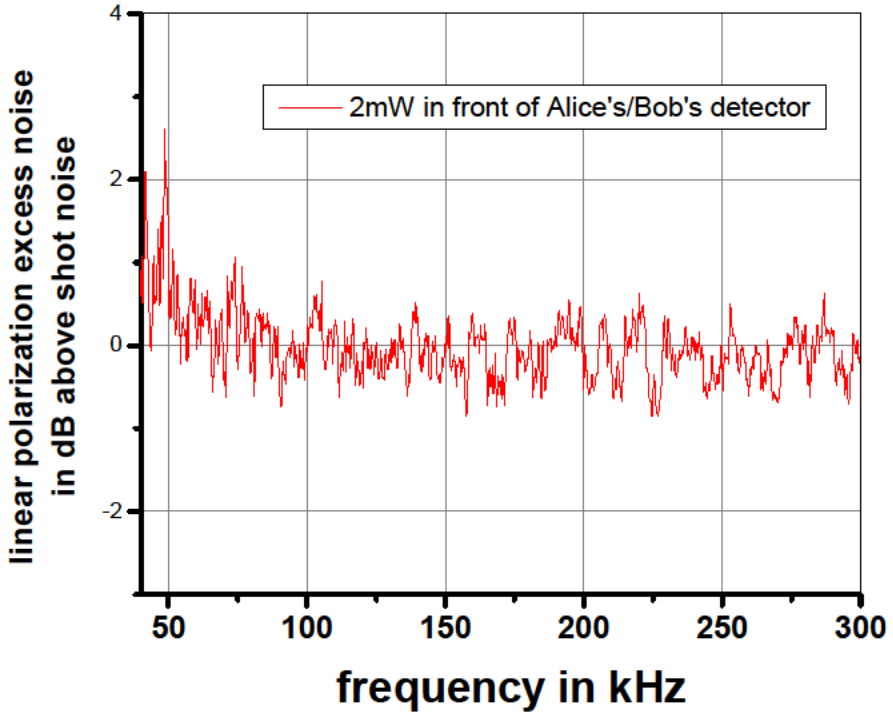


Beam profiles and polarization noise

Spatial beam profiles after transmission



Less turbulent atmosphere ...and more



Matthias Heid & Norbert Lütkenhaus

PHYSICAL REVIEW A **76**, 022313 (2007)

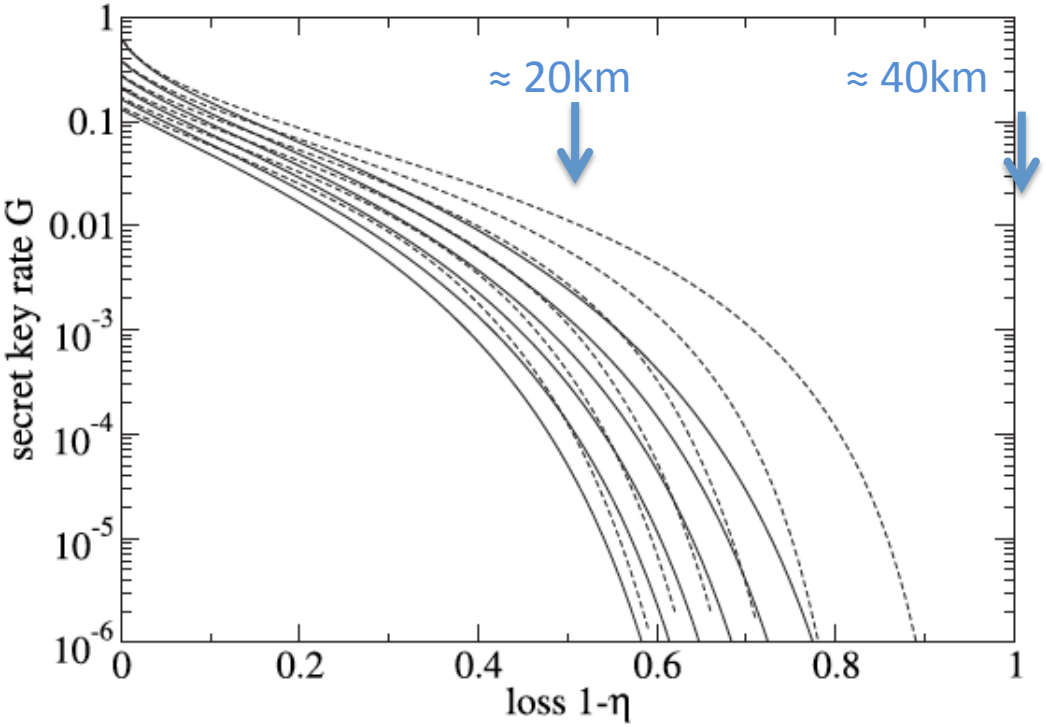


FIG. 5. Secret key rates G for post-selected protocols using the two-way error correction scheme CASCADE (solid lines). For comparison, key rates for the PS-RR protocol with one-way codes, that are as efficient as CASCADE are also shown (dashed lines). The excess noise δ varies between 0 and 0.1 as in Fig. 2.

SUMMARY

continuous quantum variables

sources : coherent light , change of wavelength straight forward

transmission : loss sensitivity > than for 1 photon technology

detectors : direct detection , shot noise sensitivity required

rates : high (no time filtering)

Higher order modes & multi level encoding → rate even higher

→→→ link to airplane