Optimal working points for continuous-variable quantum channels

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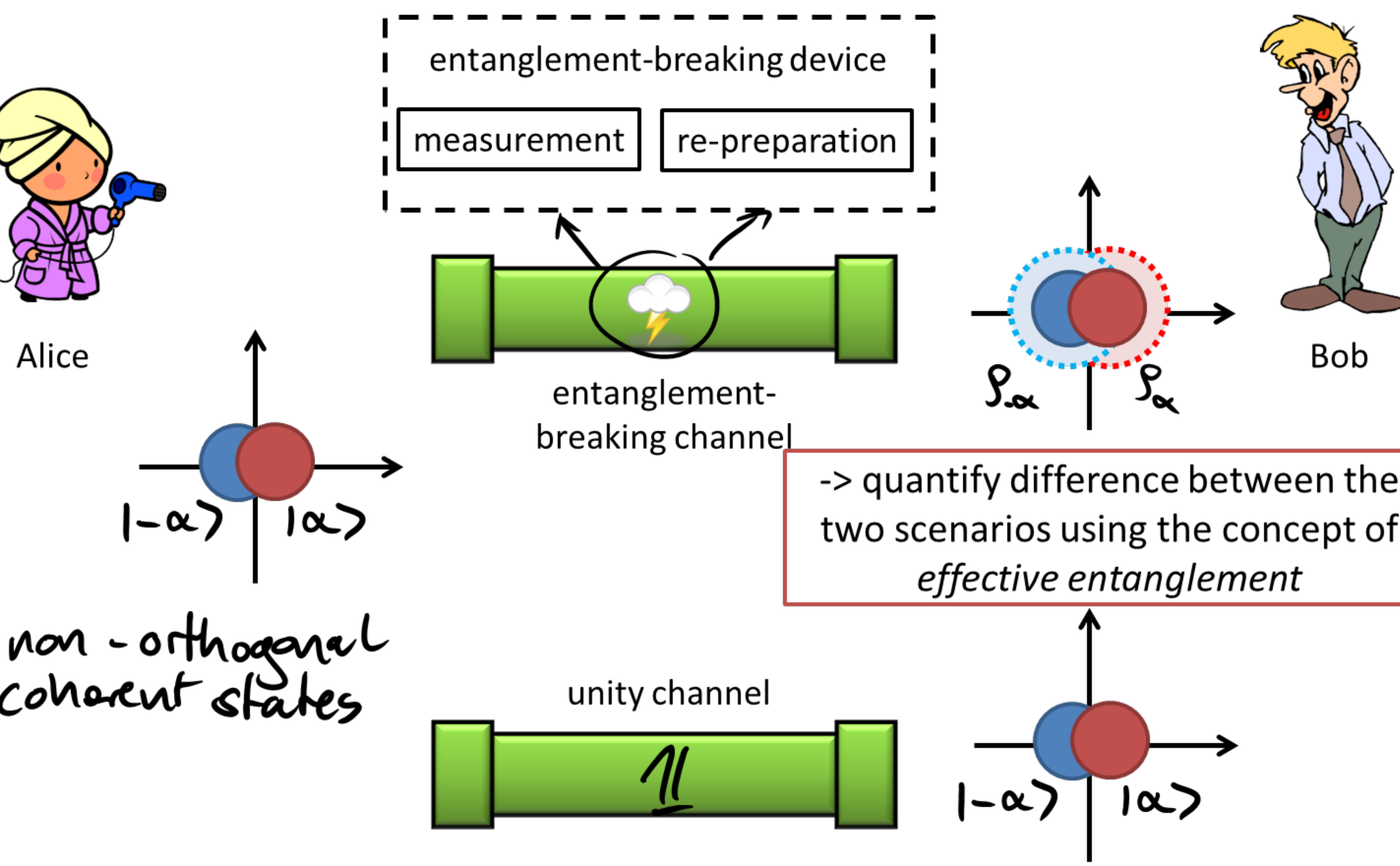
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How well does a quantum channel preserve quantum correlations?

entanglement-breaking device
measurement | re-preparation

Alice

entanglement-breaking channel

Bob

$|-\alpha\rangle$ $|\alpha\rangle$

non-orthogonal coherent states

-> quantify difference between the two scenarios using the concept of *effective entanglement*

unity channel

$\mathbb{1}$

$|-\alpha\rangle$ $|\alpha\rangle$

Effective entanglement... [1,2]

... uses negativity to quantify quantum correlations

$$\mathcal{N}(\rho) = \frac{||\rho^{T_B}||_1 - 1}{2}$$

$\mathcal{N} = 0 \Rightarrow \rho$ inconclusive
$\mathcal{N} > 0 \Rightarrow \rho$ entangled

logarithmic negativity: $E_N = \log_2(2\mathcal{N} + 1)$

Quantum domain
Classical domain

... requires measurement of
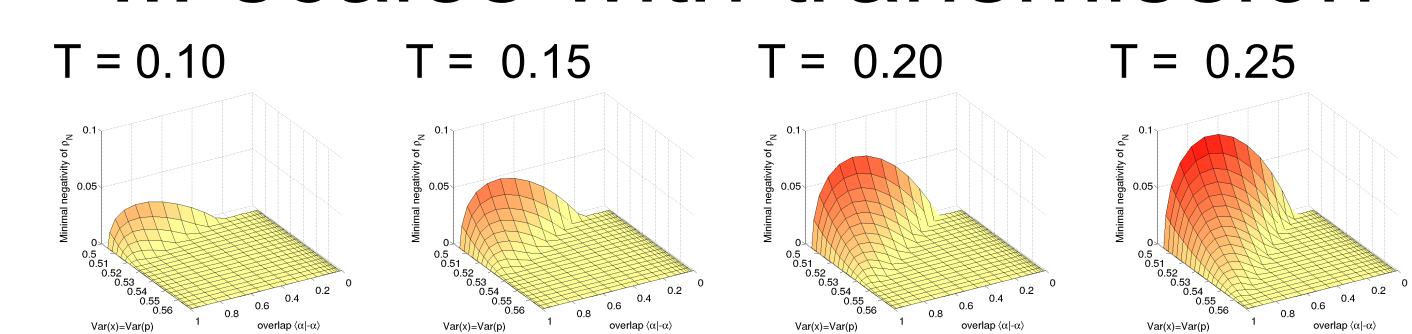
- Amplitude of received states
$$\alpha = \frac{1}{\sqrt{2}}(\langle\hat{X}\rangle + i\langle\hat{P}\rangle)$$
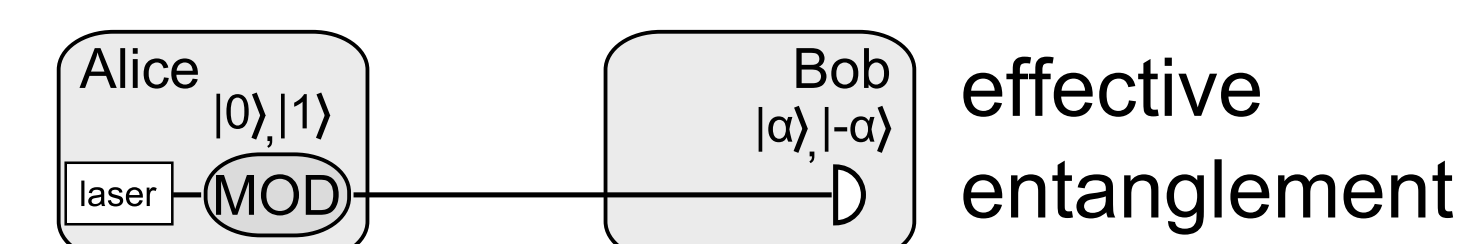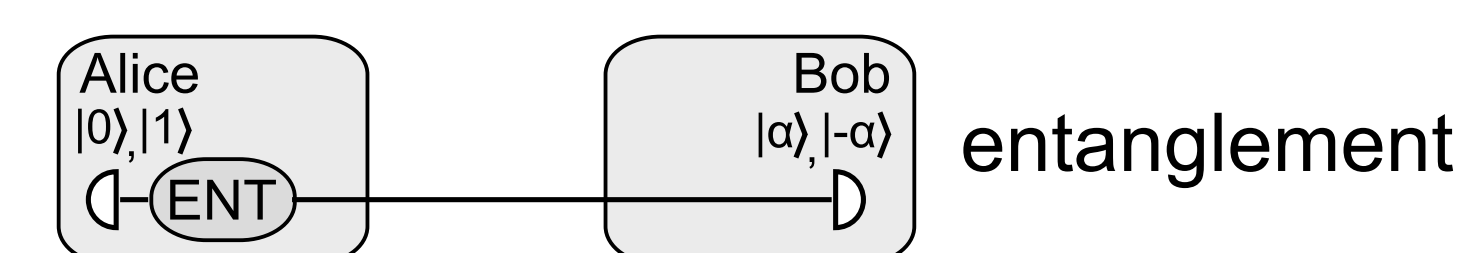
- Variance of received states
$$\mathrm{Var}(\hat{X}), \mathrm{Var}(\hat{P})$$
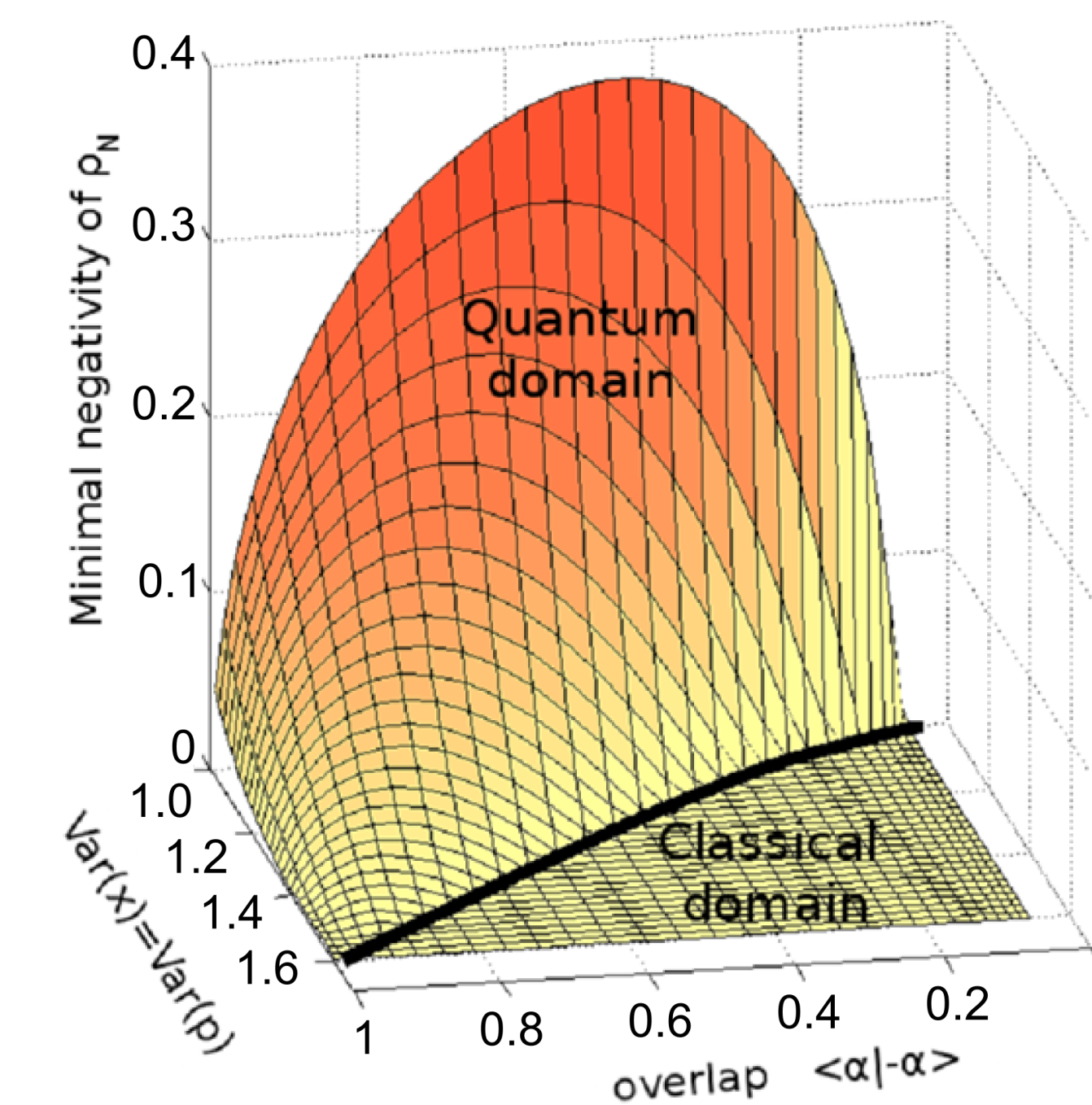
- Channel transmission

... scales with transmission

T = 0.10   T = 0.15   T = 0.20   T = 0.25

Why *effective* entanglement?

Alice $|0\rangle,|1\rangle$ — ENT — Bob $|\alpha\rangle,|-\alpha\rangle$ entanglement

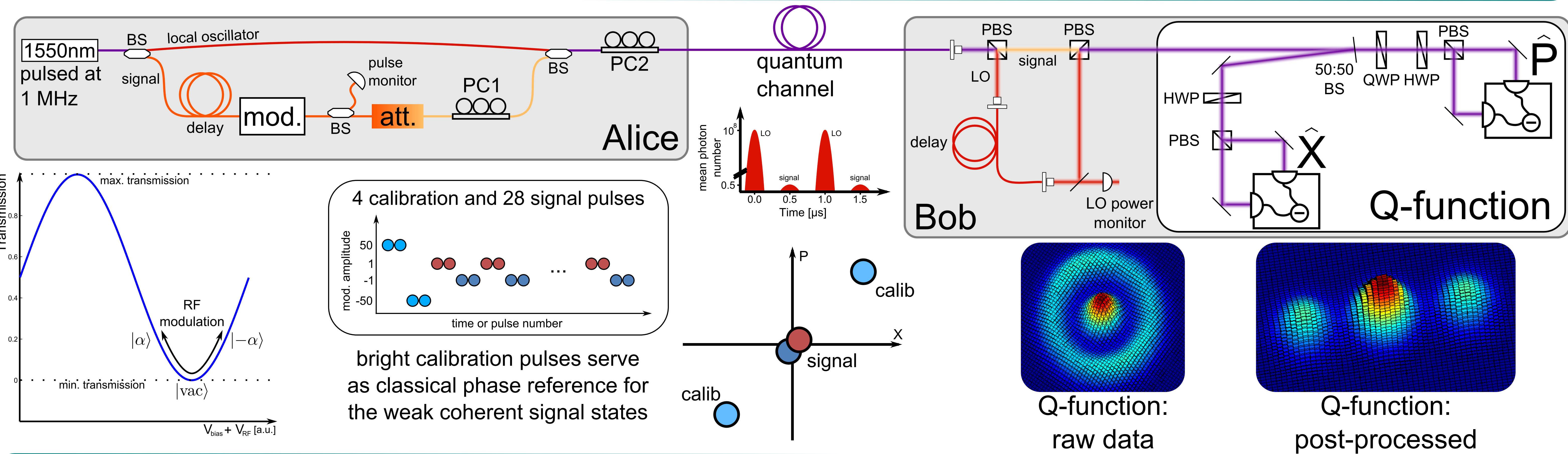Alice $|0\rangle,|1\rangle$ — laser — MOD — Bob $|\alpha\rangle,|-\alpha\rangle$ effective entanglement

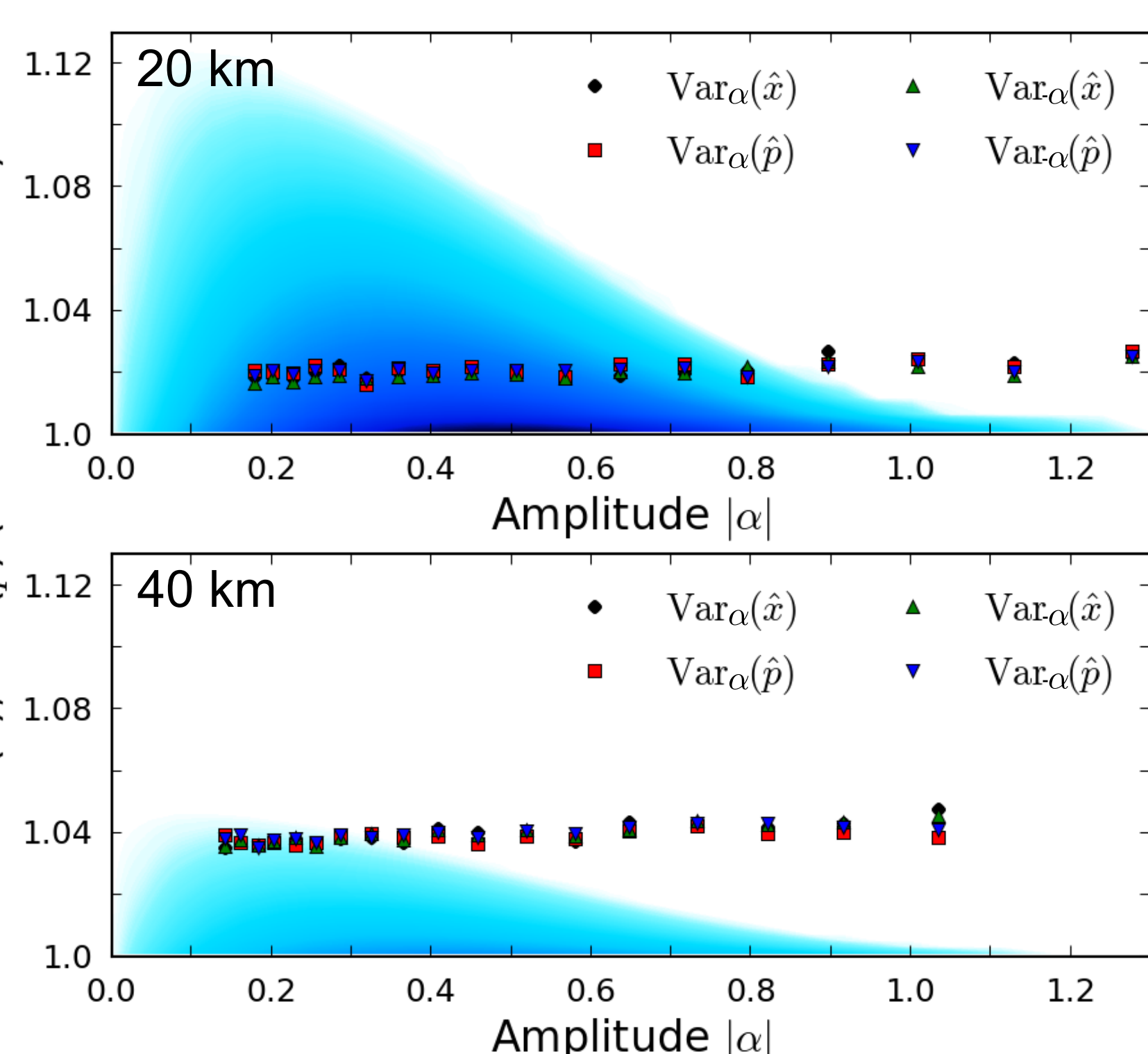$$|\Psi\rangle_{AB} = \frac{1}{\sqrt{2}}(|0\rangle_A|\alpha\rangle_B + |1\rangle_A|-\alpha\rangle_B)$$
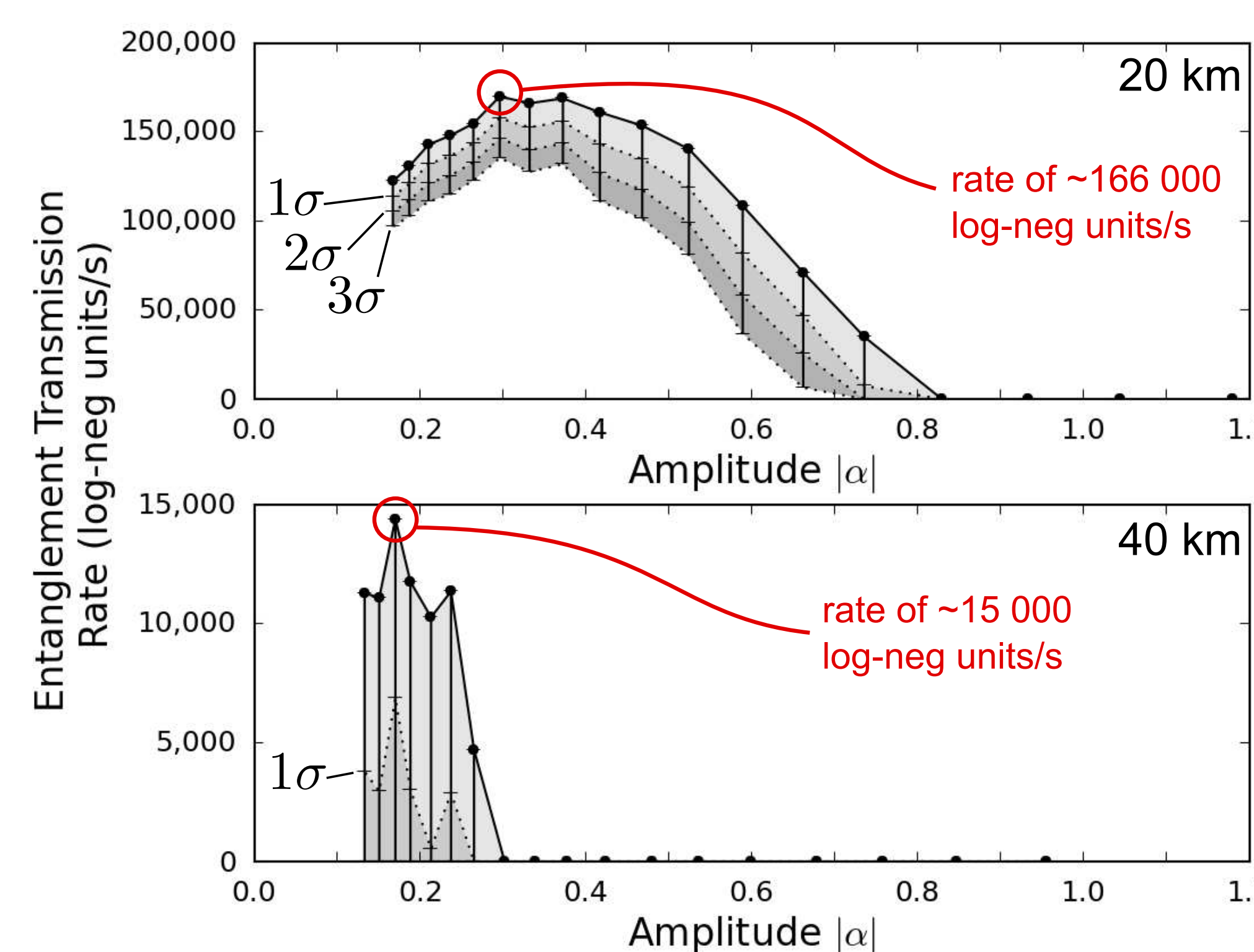
Experimental setup [3]

1550nm pulsed at 1 MHz

BS   local oscillator
signal
delay   mod.   BS   att.   pulse monitor   PC1
BS   PC2
Alice

quantum channel

mean photon number
LO   LO
signal   signal
Time [μs]

PBS   PBS
LO   signal
delay
LO power monitor
Bob

HWP   50:50 BS   QWP HWP   PBS $\hat{P}$
PBS $\hat{X}$
Q-function

max. transmission
RF modulation
$|\alpha\rangle$ $|-\alpha\rangle$
$|vac\rangle$
min. transmission
$V_{bias} + V_{RF}$ [a.u.]

4 calibration and 28 signal pulses
mod. amplitude   50 1 -1 -50
time or pulse number

bright calibration pulses serve as classical phase reference for the weak coherent signal states

P
calib
signal
X
calib

Q-function: raw data

Q-function: post-processed

Witnessing and quantifying effective entanglement [4]

Quantifying effective entanglement over a 20 and 40 km fiber link

20 km
$\mathrm{Var}_\alpha(\hat{x})$ $\mathrm{Var}_\alpha(\hat{x})$
$\mathrm{Var}_\alpha(\hat{p})$ $\mathrm{Var}_\alpha(\hat{p})$
Var($\hat{x}$), Var($\hat{p}$) (Shot Noise Units)
Amplitude $|\alpha|$
Negativity

40 km
Amplitude $|\alpha|$

Entanglement transmission rates

20 km
Entanglement Transmission Rate (log-neg units/s)
1σ 2σ 3σ
rate of ~166 000 log-neg units/s
Amplitude $|\alpha|$

40 km
1σ
rate of ~15 000 log-neg units/s
Amplitude $|\alpha|$

Noise parameters of the link impact effective entanglement

Var($\hat{x}$), Var($\hat{p}$) (Shot Noise Units)
phase-diffused coherent state
Var($\hat{x}$) theory   Var($\hat{x}$) exp.
Var($\hat{p}$) theory   Var($\hat{p}$) exp.
Classical domain
Quantum domain
Phase noise tuning parameter

Entanglement Transmission Rate (log-neg units/s)
1σ 2σ 3σ
Phase noise tuning parameter
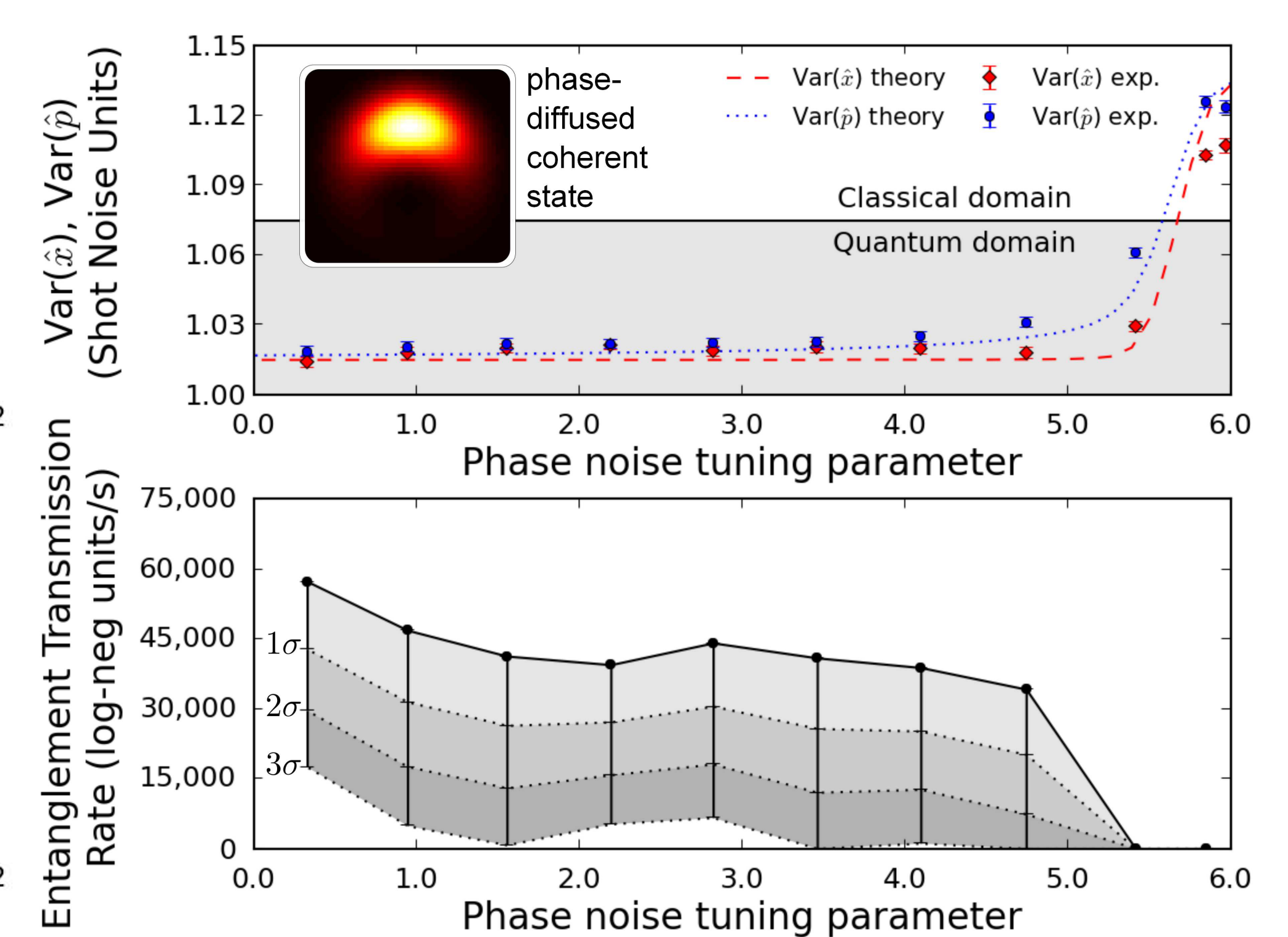
References

[1] N. Killoran et al. (Lütkenhaus), Phys. Rev. A **83**, 052320 (2011)

[2] H. Häseler et al. (Lütkenhaus), Phys. Rev. A **77**, 032303 (2008)

[3] C. Wittmann et al. (Leuchs), Opt. Express **18**, 4499 (2010)

[4] I. Khan et al. (Leuchs), PRA rapid comm. **88**, 010302 (2013)

Outlook

- Investigate different physical channels
- Connect theory to other entanglement measures